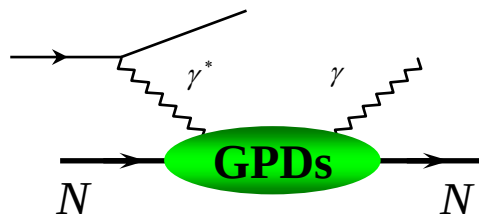
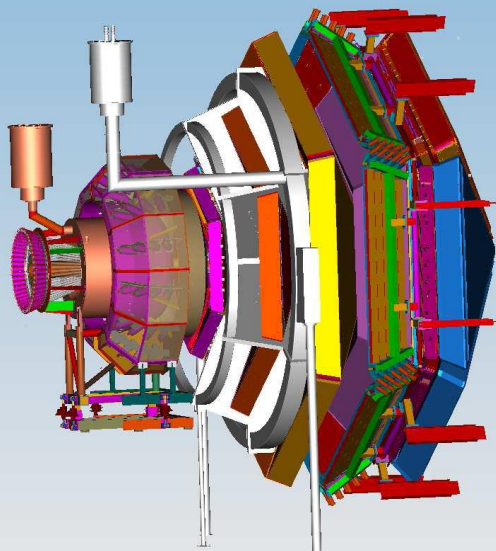


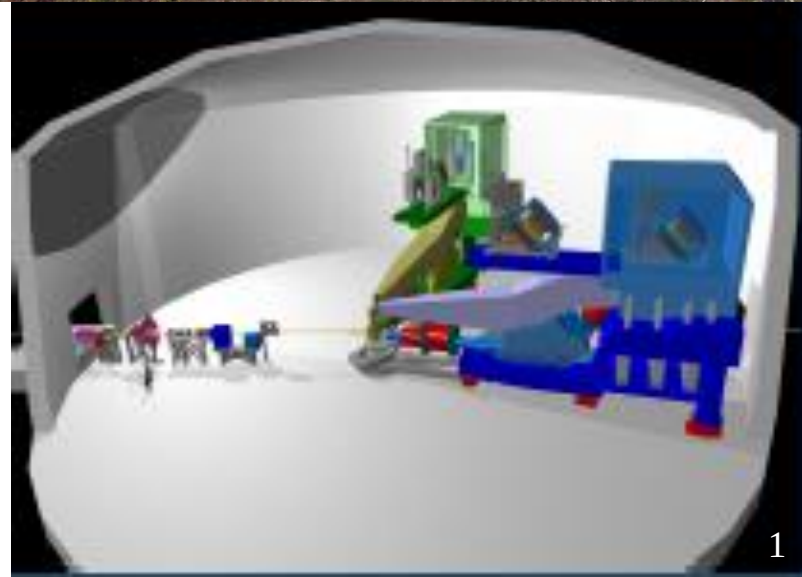
Physique hadronique à Jefferson Lab

- Historique
- « Highlights » (JLab@6 GeV)
- Plans pour JLab@12 GeV
- Projets techniques

• Futur à l'horizon 2025 : Electron-Ion Collider

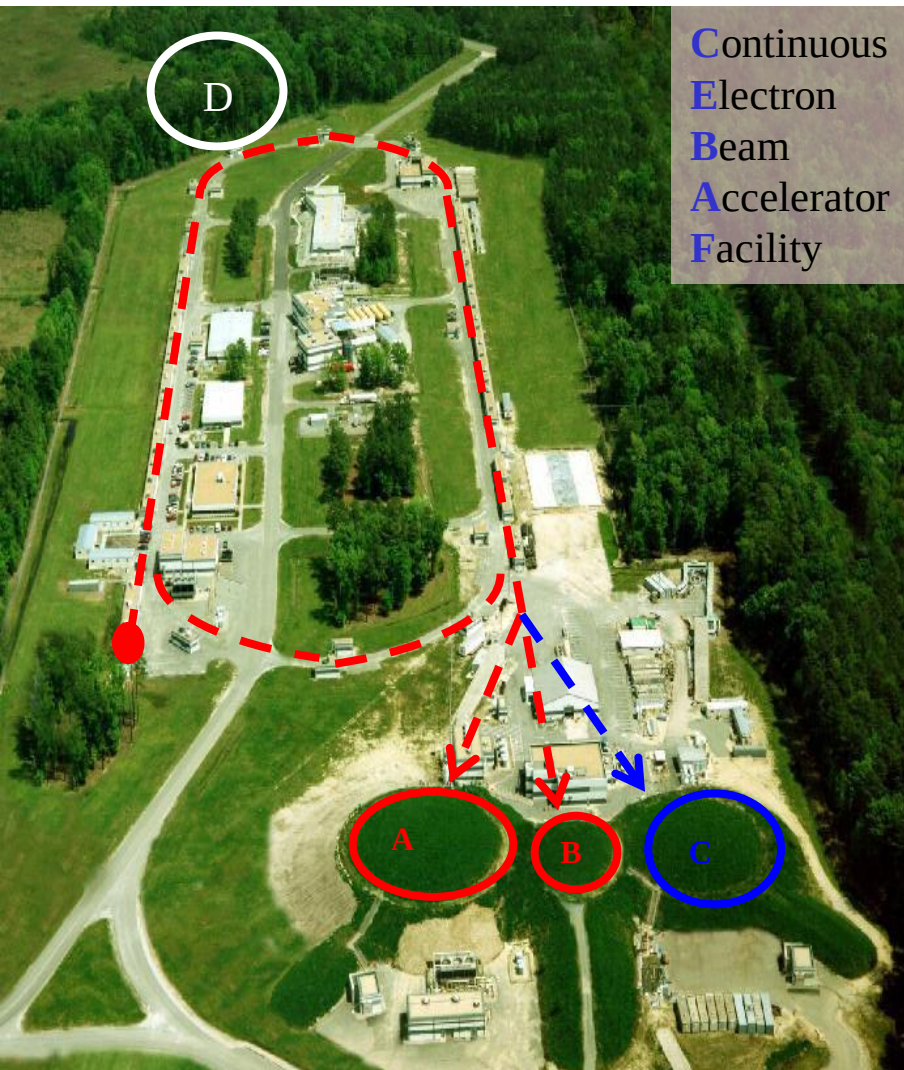


Silvia Niccolai (IPNO)
Conseil Scientifique
IN2P3
8/2/2018



Jefferson Lab

(Newport News, VA, USA)

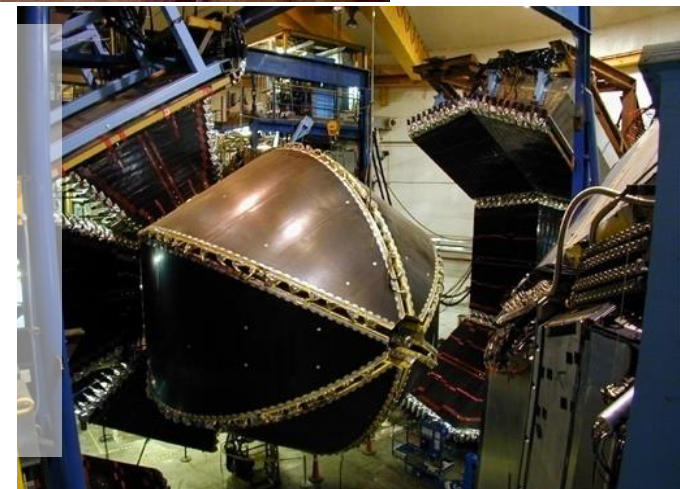


Continuous
Electron
Beam
Accelerator
Facility



Hall A : 2
spectromètres
à haute
résolution
 $L \sim 10^{37} \text{ cm}^{-2} \text{ s}^{-1}$

Hall B : CLAS
($\rightarrow$ CLAS12)
Grande
acceptance
Etats finaux à
multi-particules
 $L \sim 10^{34} (10^{35})$
 $\text{cm}^{-2} \text{ s}^{-1}$



Hall C : 2
spectromètres
(HMS, SOS
 $\rightarrow$ SHMS)
 $L \sim 10^{37} \text{ cm}^{-2} \text{ s}^{-1}$

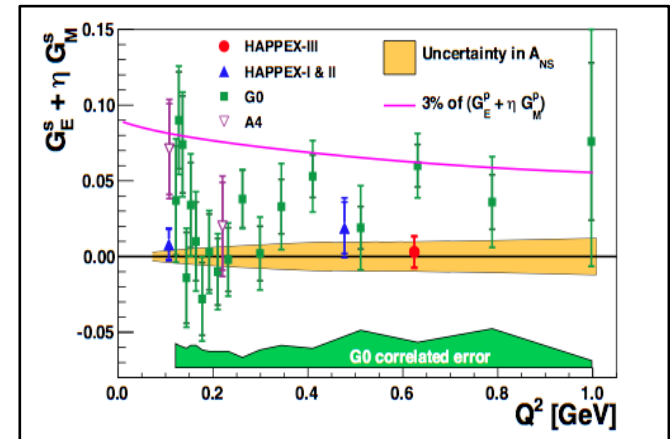
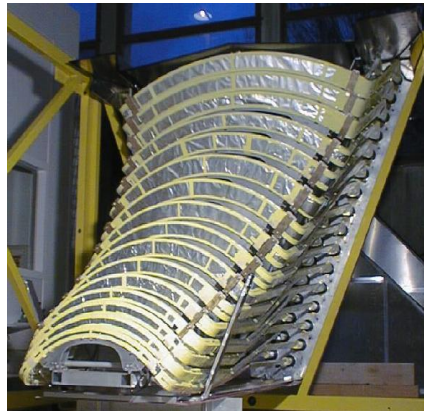
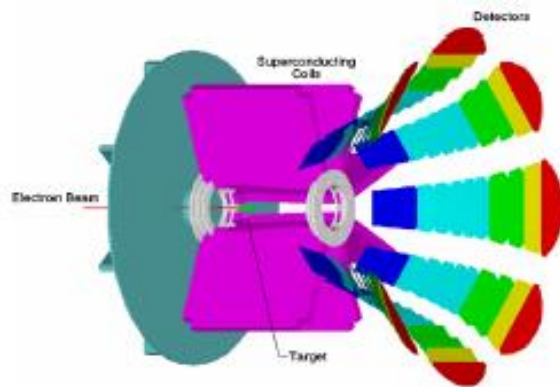
- $E_{\text{max}} \sim 6.0 \text{ GeV}$ (**12 GeV depuis 2016**)
- Haute intensité ($I_{\text{max}} \sim 200 \mu\text{A}$), cycle utile $\sim 100\%$
- Haute polarisation du faisceau ($\sim 85\%$)

France-JLab: ~25 ans de collaboration

Projets « hardware » pour JLab réalisés par l'IN2P3 (~1994-2010) (Clermont, Grenoble, Orsay) :

- Dispositif à haute précision pour **mesures d'énergie du faisceau** dans le **Hall A**
- **Polarimètre** pour le deuton (**Hall C**)
- Moitié du **détecteur** et de l'**électronique**, pour l'expérience de violation de parité **G0** (**Hall C**)
- **Collimateurs** pour le faisceau de photons réels du **Hall B**
- **Electronique** pour l'expérience **DVCS Hall A**
- Design et construction de moitié des **Cherenkov** pour la phase 2 de **G0** (**Hall C**)
- « **Inner calorimeter** » (structure mécanique et électronique) pour l'expérience **DVCS Hall B**
- **Détecteur « veto »** pour les protons dans l'expérience **neutron-DVCS** du **Hall A**
- **Polarimètre Compton** du **Hall A**
- **Polarimètre Compton** pour **PEPPo**

Investissement ~3 M€



...pour les sujets de physique associés :

- **Facteurs de forme étranges**, avec l'expérience **G0**
- **Polarisabilités du nucléon** dans le VCS (**ep**→**epy**)
- **Facteur de forme du deuton** (t20) dans **ed**→**ed**
- Diffusion quasi-élastique sur les **noyaux légers** (**eA** → **ep(A-1)**)
- Premières études des **GPDs** dans le DVCS (**ep**→**epy**) et la production exclusive de mésons (**ep**→**epM**)
- Recherche des **pentaquarks** en photo-production

IPN Orsay

R. Dupré
D. Marchand ~30%
C. Munoz
S. Niccolai
E. Voutier ~50%
[M. Guidal]
+1 postdoc
+5 doctorants
~ 10 FTE

DPhN-Saclay

~3 permanents
+2 doctorants

Theorie

IPNO - Polytechnique
LPT - Saclay

LPC Clermont-Ferrand

LPSC Grenoble

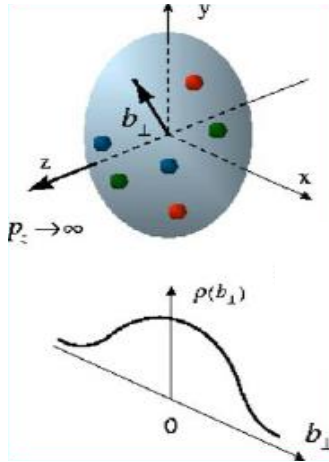
Aujourd'hui

Objectif commun :
étude de la structure
du nucléon

Diffusion d'électrons : le microscope pour étudier la structure du nucléon

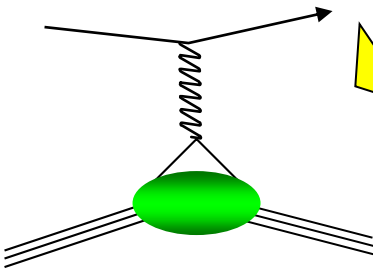
GPDs: $H, E, \tilde{H}, \tilde{E}$

Distributions des corrélations
entre position et impulsion pour
les quarks et les gluons

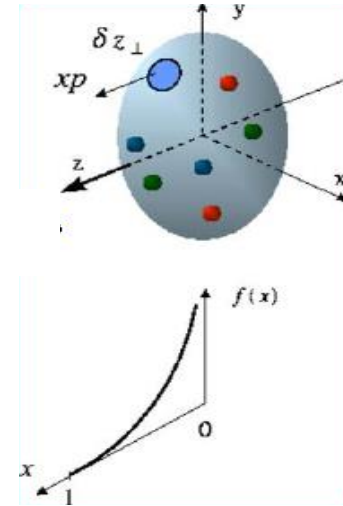


Facteurs de forme :
**Distributions des
positions transverses
des quarks**

$F_1(t), F_2(t)$

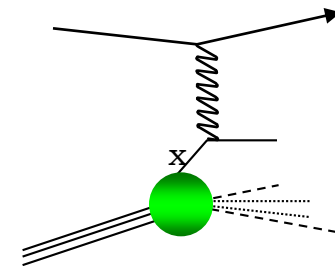


Diffusion élastique $ep \rightarrow e'p'$
(Hofstadter, prix Nobel 1961)



Distributions des partons :
**Distributions de
l'impulsion longitudinale
des quarks**

$q(x), \Delta(x)$



Diffusion profondément inélastique (DIS) $ep \rightarrow e'X$
(Friedman, Kendall, Taylor, prix Nobel 1990)

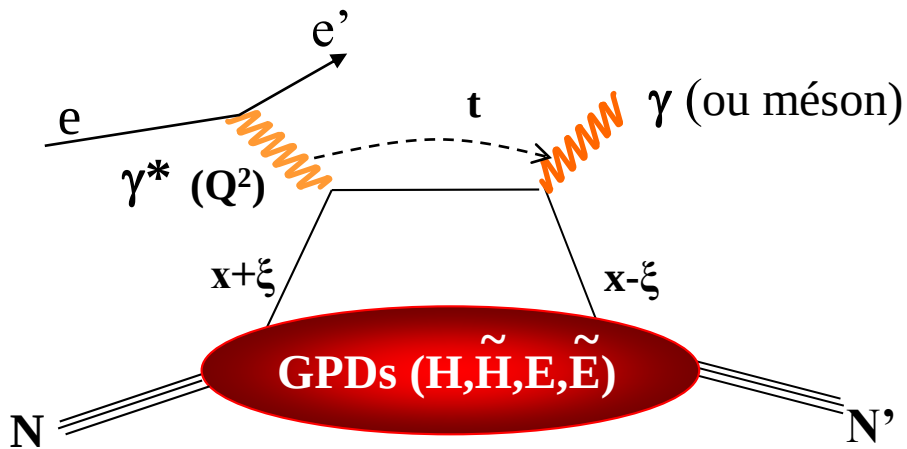
Distributions généralisées de partons (GPDs)

Corrélations entre position, impulsion et spin des partons (quarks et gluons) dans le nucléon → **tomographie du nucléon, moment angulaire des quarks,...**

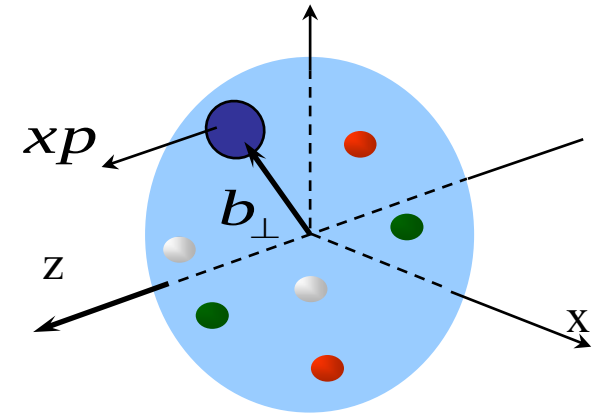
$$\frac{1}{2} \int_{-1}^1 x dx (H(x, \xi, t=0) + E(x, \xi, t=0)) = J = \frac{1}{2} \Delta \Sigma + \Delta L$$

Les GPDs sont accessibles dans l'**électroproduction exclusive** à grande impulsion transférée (Q^2)

→ **diffusion de photons virtuels sur les quarks**



DVCS (Deeply Virtual Compton Scattering) $eN \rightarrow e'N'\gamma$



- Chaque GPD dépend de **3 variables** (x, ξ, t)
- Les observables DVCS contiennent des **intégrales sur x** des GPDs (CFF)

➔ **Phénoménologie** : observables → GPDs

- Sections efficaces **petites** ($\sim \text{pb}$)
- Etats finaux à **multi-particules**
- **4 GPDs** pour chaque saveur de quark
- **Plusieurs observables** à mesurer

→ Faisceau d'électrons de **haute intensité**
→ **Polarisation** du faisceau et des cibles

➔ **JLab**

GPDs à JLab : impact

Notre équipe est **leader** dans le programme expérimental des GPDs au JLab depuis ~20 ans

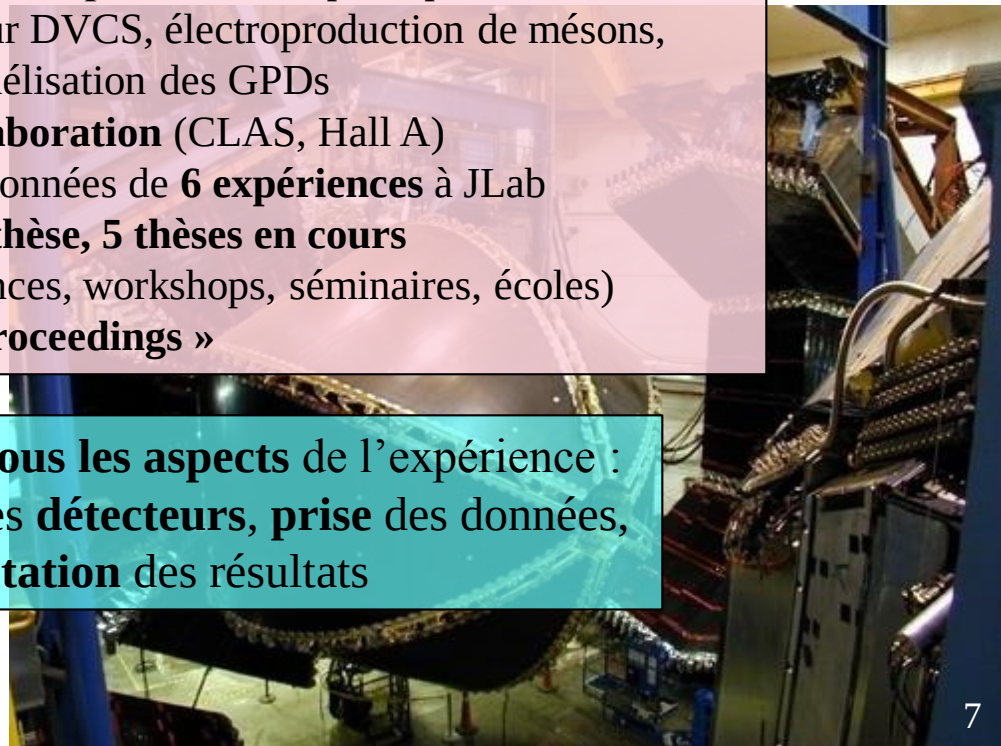
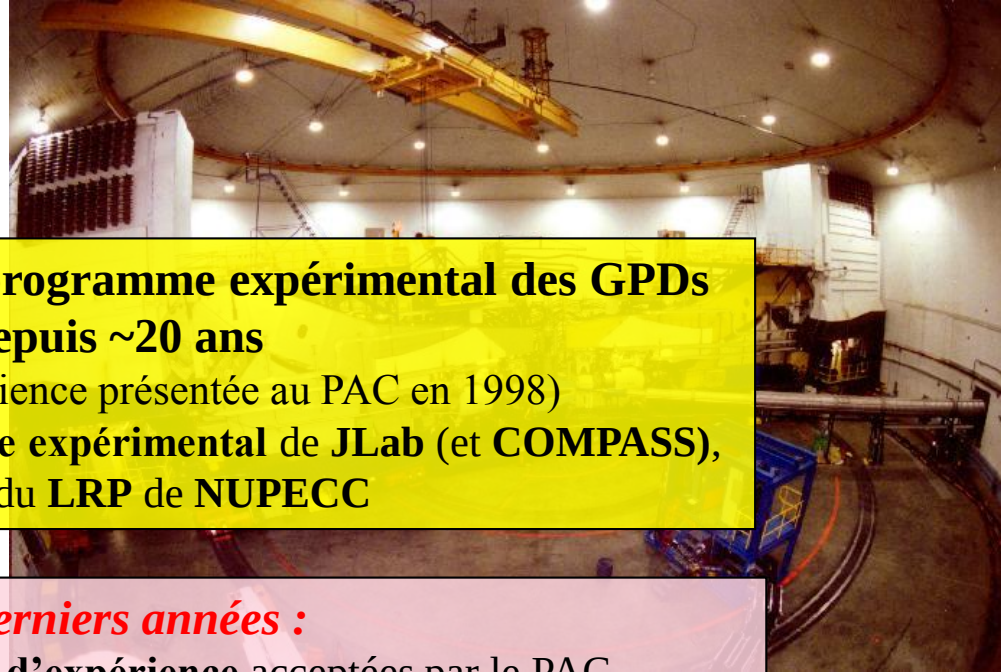
(première proposition d'expérience présentée au PAC en 1998)

Les GPDs sont au **cœur du programme expérimental de JLab** (et COMPASS), et elles font partie du **LRP de NUPECC**

Dans les 10 derniers années :

- Porte-paroles de **8 propositions d'expérience** acceptées par le PAC
- « **Lead author** » de ~25 articles sur DVCS, électroproduction de mésons, extraction et modélisation des GPDs
 - ~ **100 articles de collaboration** (CLAS, Hall A)
- Participation aux prises de données de **6 expériences** à JLab
 - **10 soutenances de thèse, 5 thèses en cours**
- >100 « **invited talks** » (conférences, workshops, séminaires, écoles)
 - > **60 « proceedings »**

Implication de l'équipe dans **tous les aspects** de l'expérience : **proposition**, développement des **détecteurs**, **prise des données**, **analyse**, **interprétation** des résultats



« Highlights » : DVCS sur le proton à JLab@6 GeV

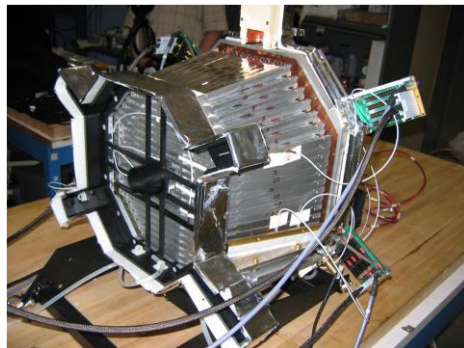
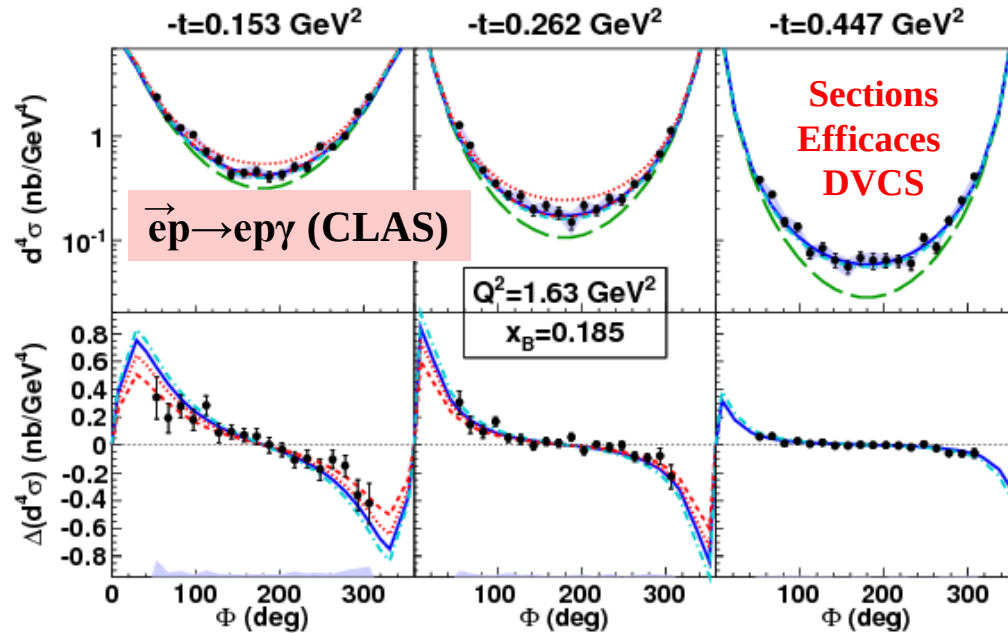
- Sections efficaces du DVCS sur le proton (CLAS et Hall A) : tomographie du proton, test de validité du formalisme des GPDs
- Asymétries de cible polarisée (single et double) du pDVCS : GPDs polarisées, charge axiale du proton

PRL 114, 089901(2015)

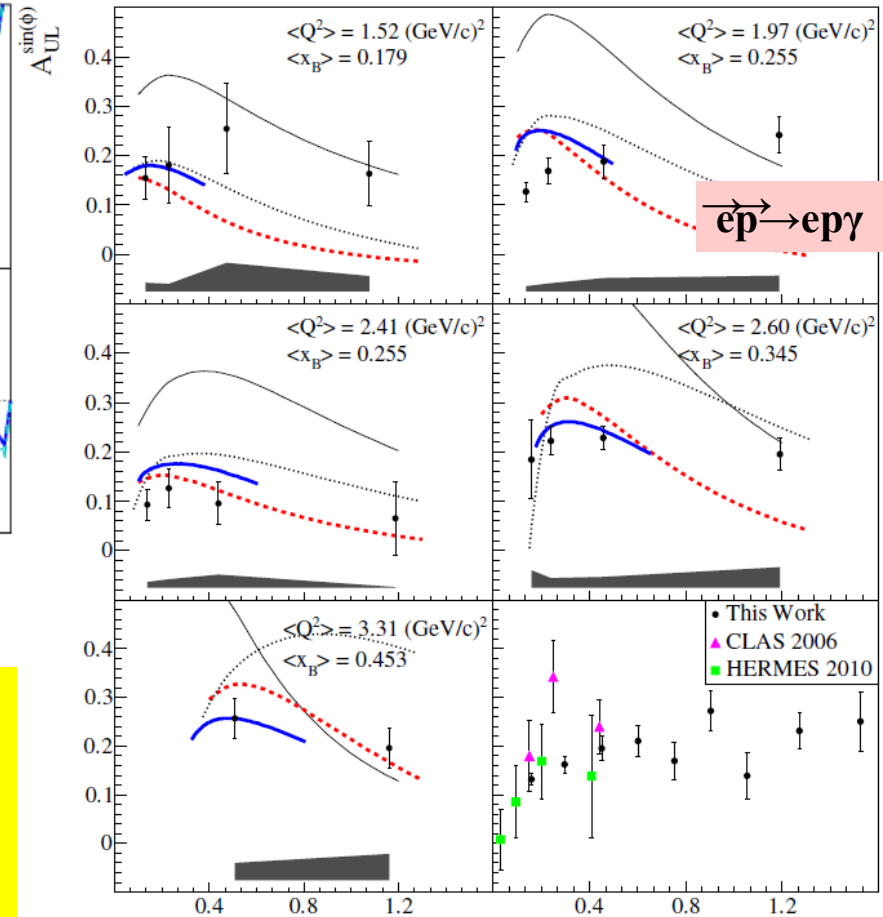
PRD 91, 052014 (2015)

PRL 115, 212003 (2015)

PRC 92, 055202 (2015)



Contribution technique IPNO :
calorimètre
électromagnétique
pour CLAS



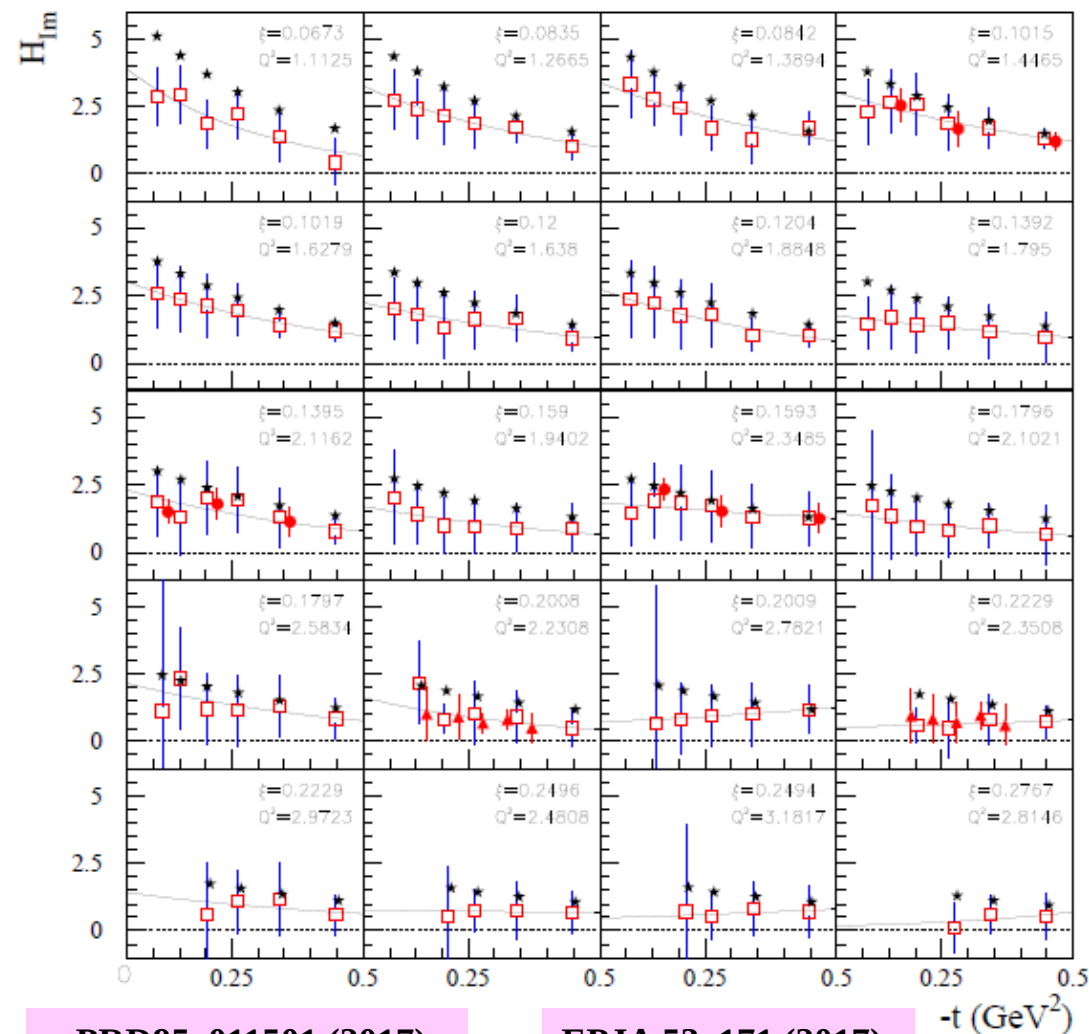
Asymétrie de cible DVCS

Tomographie du proton

Des observables aux GPDs: Fit des observables DVCS pour extraire les 8 CFFs

M. Guidal, Eur. Phys. J. A 37 (2008) 319, etc...

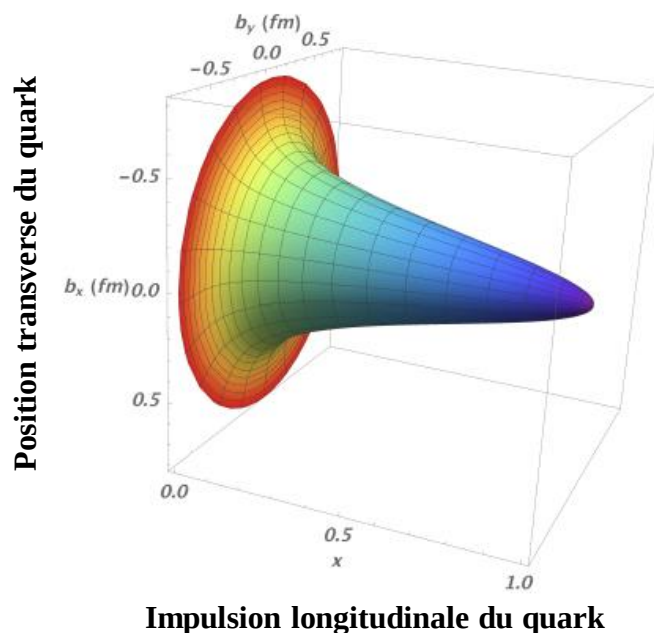
Fit de toutes les données, CLAS-2015 et Hall A



PRD95, 011501 (2017)

EPJA 53, 171 (2017)

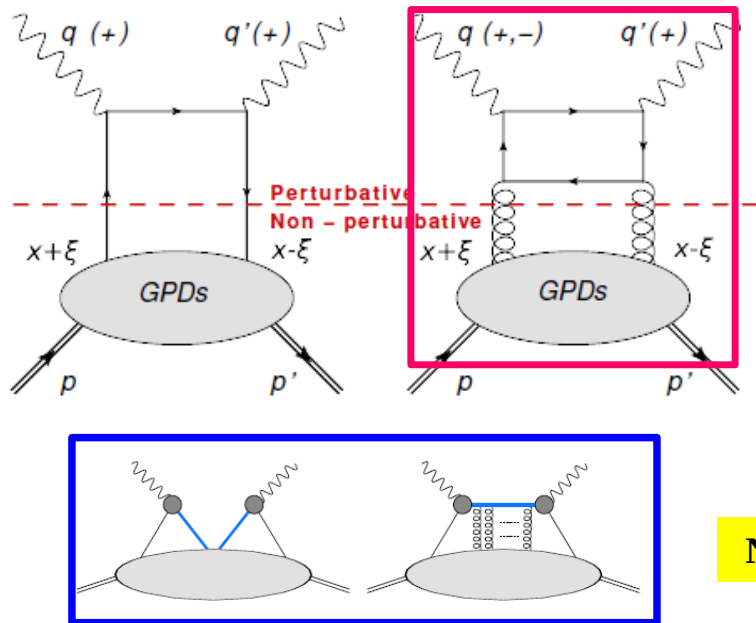
$$\text{Im}\mathcal{H}_q = \pi e_q^2 \left[H^q(\xi, \xi, t) - H^q(-\xi, \xi, t) \right]$$



Tomographie du proton :

- Les quarks de valence sont au centre du nucléon, les quarks de la mer sont à la périphérie

DVCS : derniers résultats (2017)

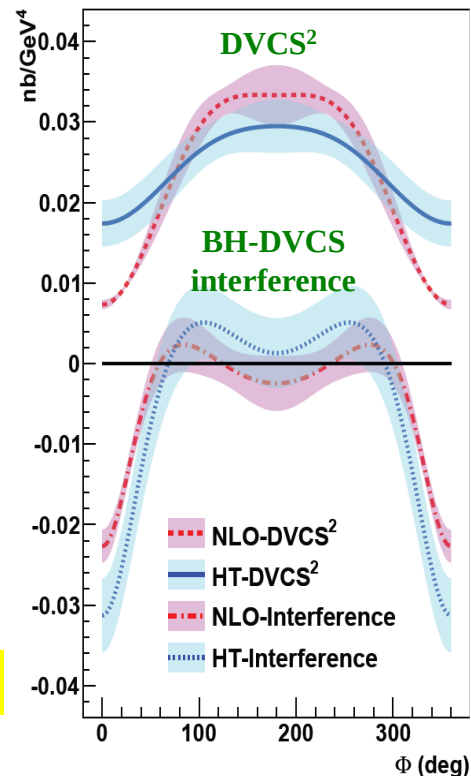


$$\vec{e}p \rightarrow e\gamma(p)$$

Hall A : Sections efficaces
DVCS à haute précision et
énergies de faisceau
différentes :

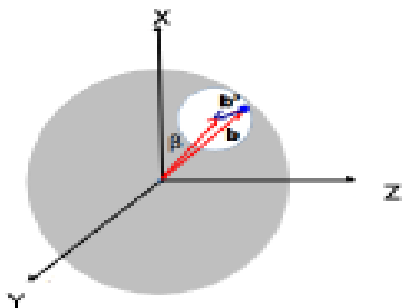
Sensibles aux « **higher twist** »
(HT) ou contributions **LT-NLO**
(échange de gluons)

Nature Communications 8, 1408 (2017)



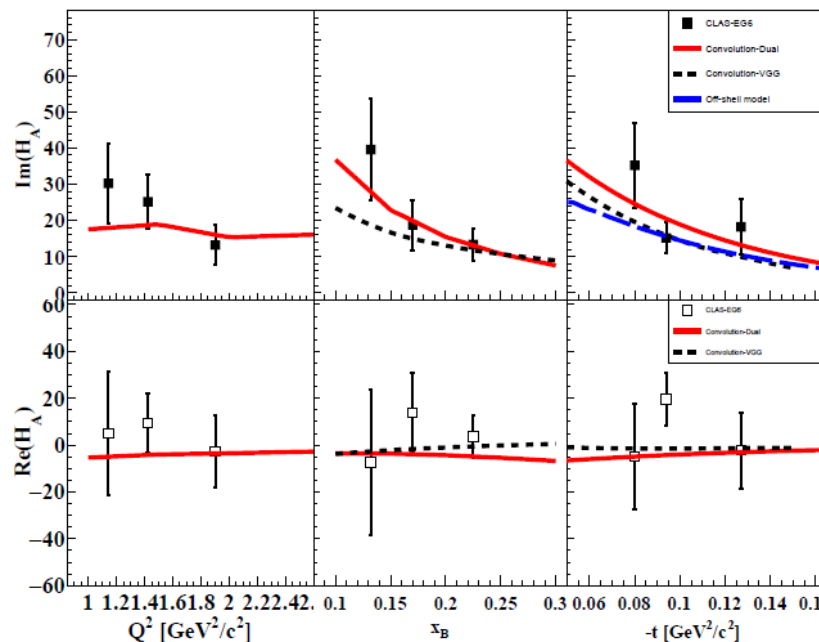
CLAS : DVCS **cohérent** et **incohérent** sur l'⁴He :
GPDs des noyaux, « **effet EMC** »

⁴He a **spin 0** : à l'ordre dominant **une seule GPD**
contribue à l'asymétrie de faisceau du DVCS



$$\vec{e}^+{}^4\text{He} \rightarrow e^+{}^4\text{He} \gamma$$

PRL 119, 202004 (2017)



Au-delà de la structure du nucléon : PEPPo & HPS

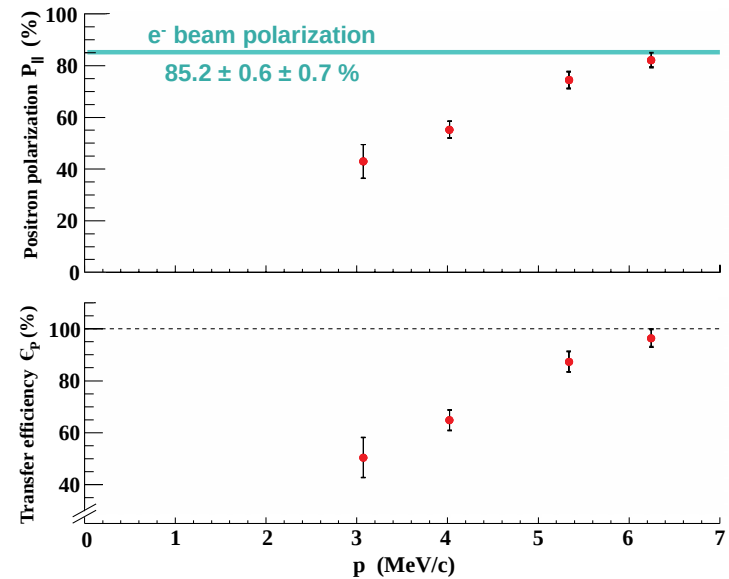
(Polarized Electrons for Polarized Positrons)

L'expérience **PEPPo** à l'injecteur de **CEBAF** a démontré un **transfert efficace de polarisation** entre **électrons et positrons**. Elle ouvre la possibilité de produire des positrons polarisés avec **des accélérateurs ~MeV**

Les positrons polarisés apportent des observables supplémentaires pour l'étude des GPDs

D. Abbott, E. Voutier et al., PRL 116 (2016) 214801

Editor's choice, Physics Focus

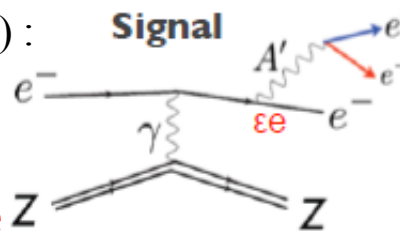


Expérience Heavy Photon Search (Hall B)

Recherche d'un nouveau **boson vecteur** (A') :

- masse entre 20 MeV et 1000 MeV
- décroissance en pair électron-positron
- produit par brehmmstralung sur cible lourde

Possible connexion avec la **matière sombre**



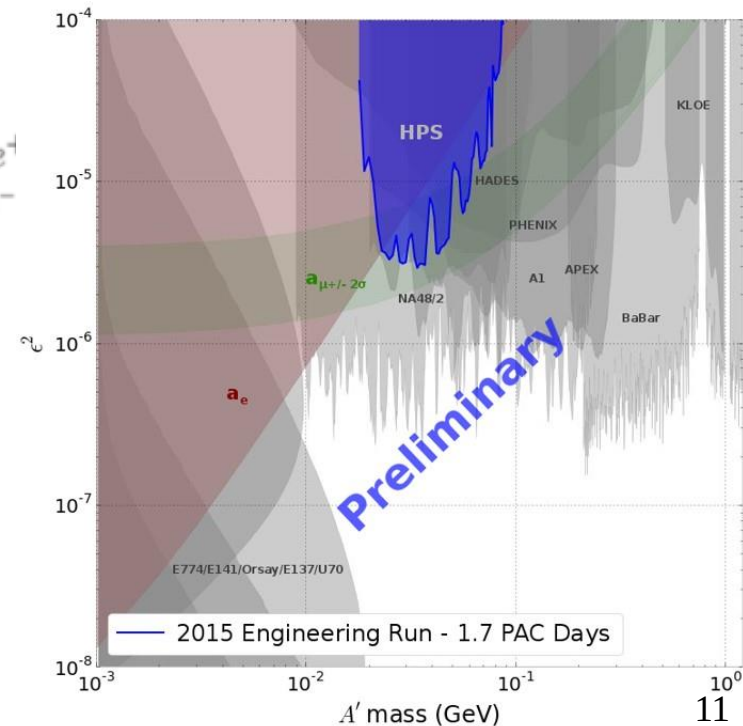
➤ **Prises de données en 2015, 2016, 2019**

Analyse en cours (thèse soutenue à l'IPNO 12/2017)

Détecteur : « silicon tracker » et calorimètre (IPNO+INFN)

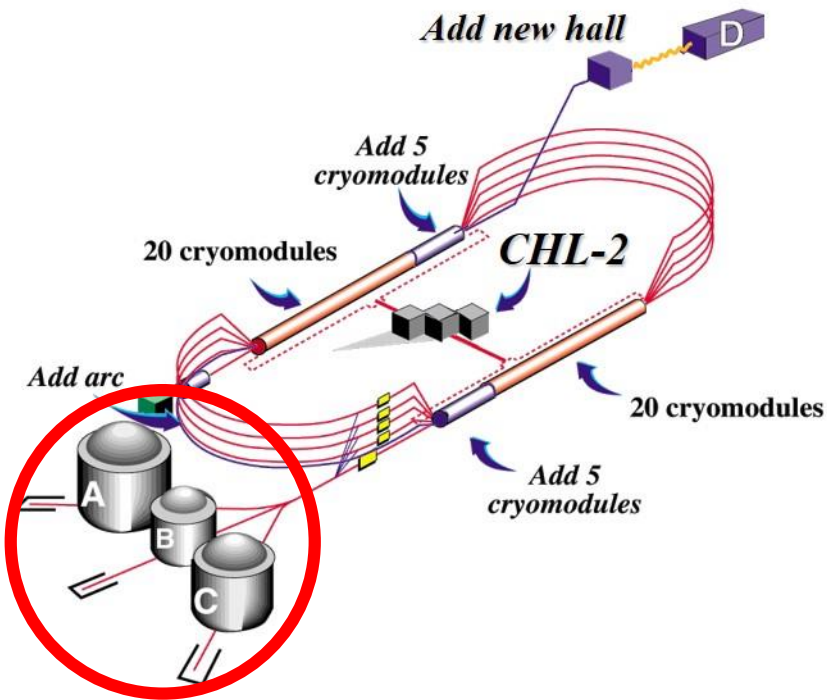
Financements : **ANR JCJC (250 k€)**, **SESAME (200 k€)**

→ **Raphael Dupré chef du projet**



Upgrade JLab@12-GeV

$$E_{\max}(A,B,C) = 11 \text{ GeV}$$

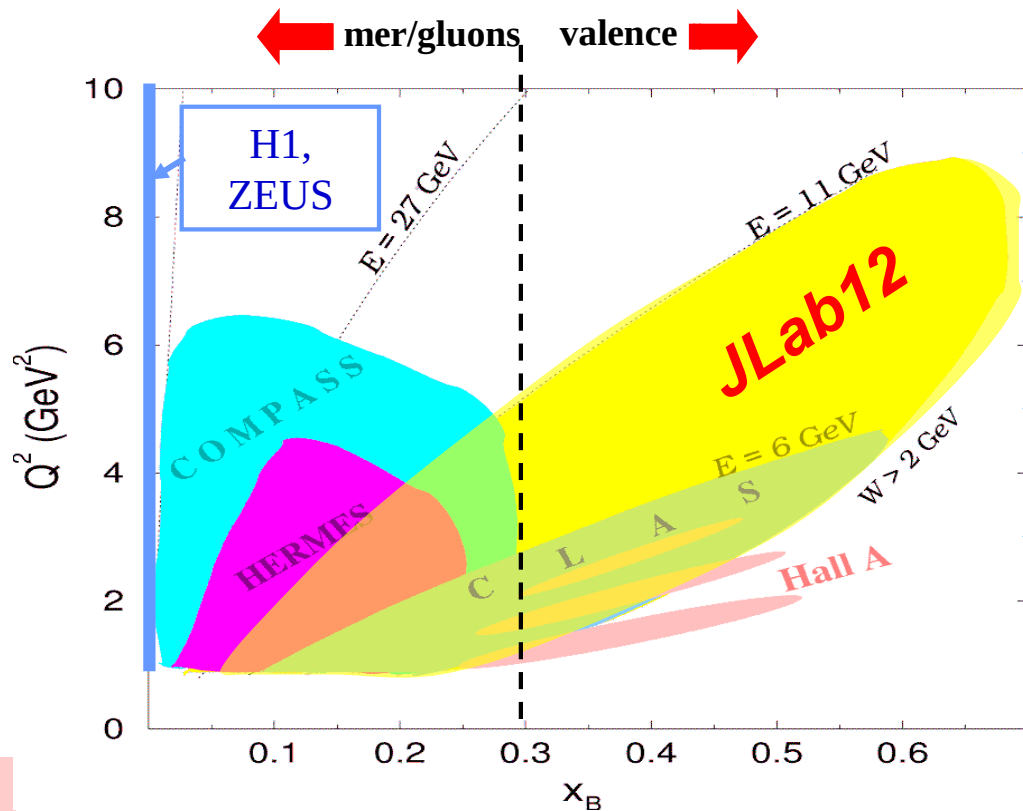


Upgrade de l'accélérateur accompli en 2015

Expériences de GPDs à 11 GeV sont prévues pour les **halls A, B, et C**.

Programmes complémentaires :

- cinématiques différentes
- précisions/résolutions différentes
- observables différentes



Notre équipe a des porte-parole dans toutes les expériences de GPDs pour la phase à 12 GeV de JLab
(CLAS12, Hall A et Hall C)

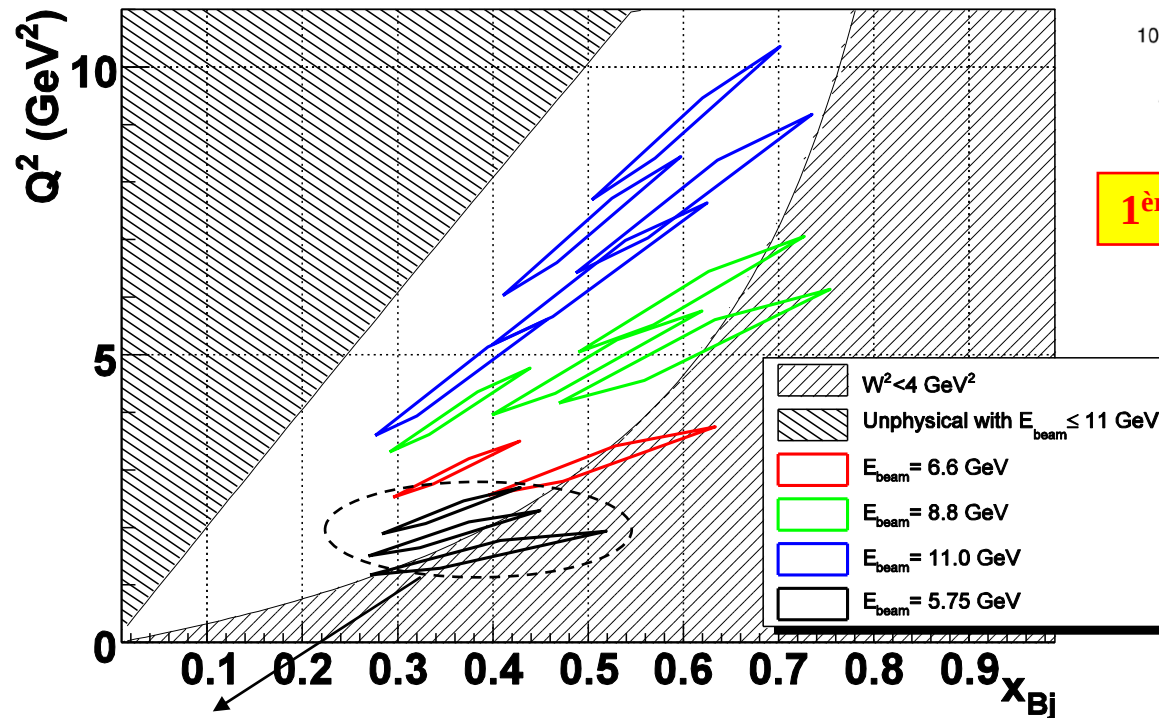
Projets techniques associés aux expériences

DVCS à 11 GeV dans le Hall A

- Mesures de sections efficaces à haute précision
- Test du “scaling” : dépendance en Q^2 de $d\sigma$ à x_{Bj} fixé
- Couverture cinématique augmentée

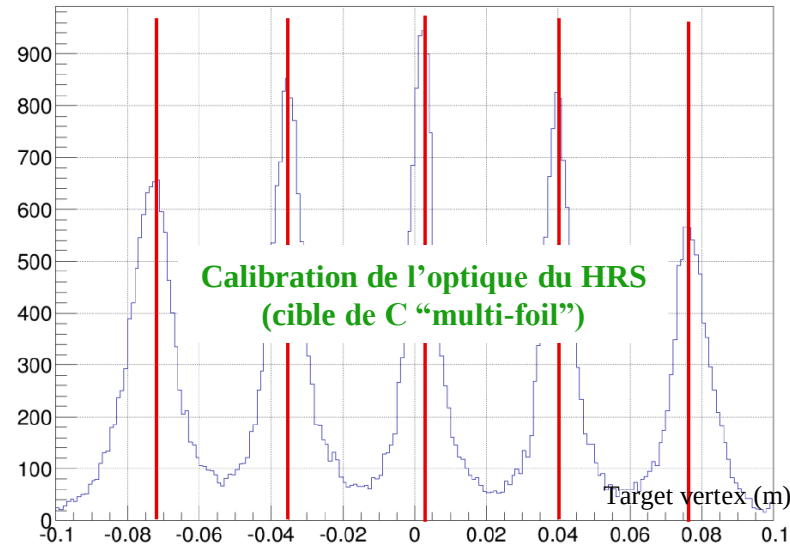
JLab12 à 3, 4, 5 passes du faisceau (6.6, 8.8, 11.0 GeV)

DVCS measurements in Hall A/JLab



JLab @ 6 GeV

Expérience « High Impact » de JLab



1^{ère} expérience après l'upgrade à 12-GeV

Prise des données
accomplie en fin 2016

Toutes les **calibrations** sont finies
Analyse DVCS en cours
Résultats préliminaires : **automne 2018**

C. Munoz Camacho porte-parole
Thèse en cours

DVCS sur le neutron avec CLAS12

$$(H, E)_u(\xi, \xi, t) = \frac{9}{15} [4(H, E)_p(\xi, \xi, t) - (H, E)_n(\xi, \xi, t)]$$

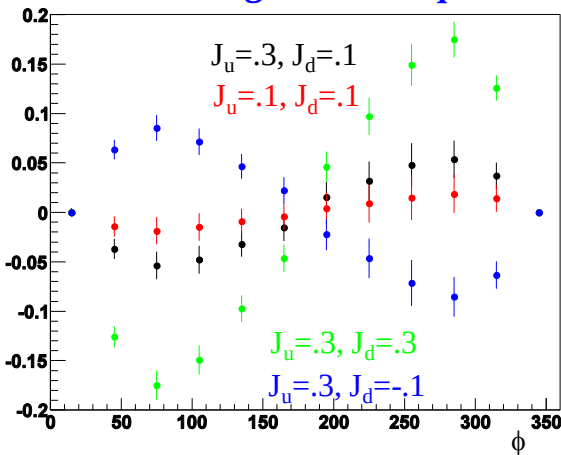
$$(H, E)_d(\xi, \xi, t) = \frac{9}{15} [4(H, E)_n(\xi, \xi, t) - (H, E)_p(\xi, \xi, t)]$$

Asymétrie du spin du faisceau du nDVCS:
l'observable plus sensible à la GPD **E**

$\vec{e}d \rightarrow e(p)n\gamma$

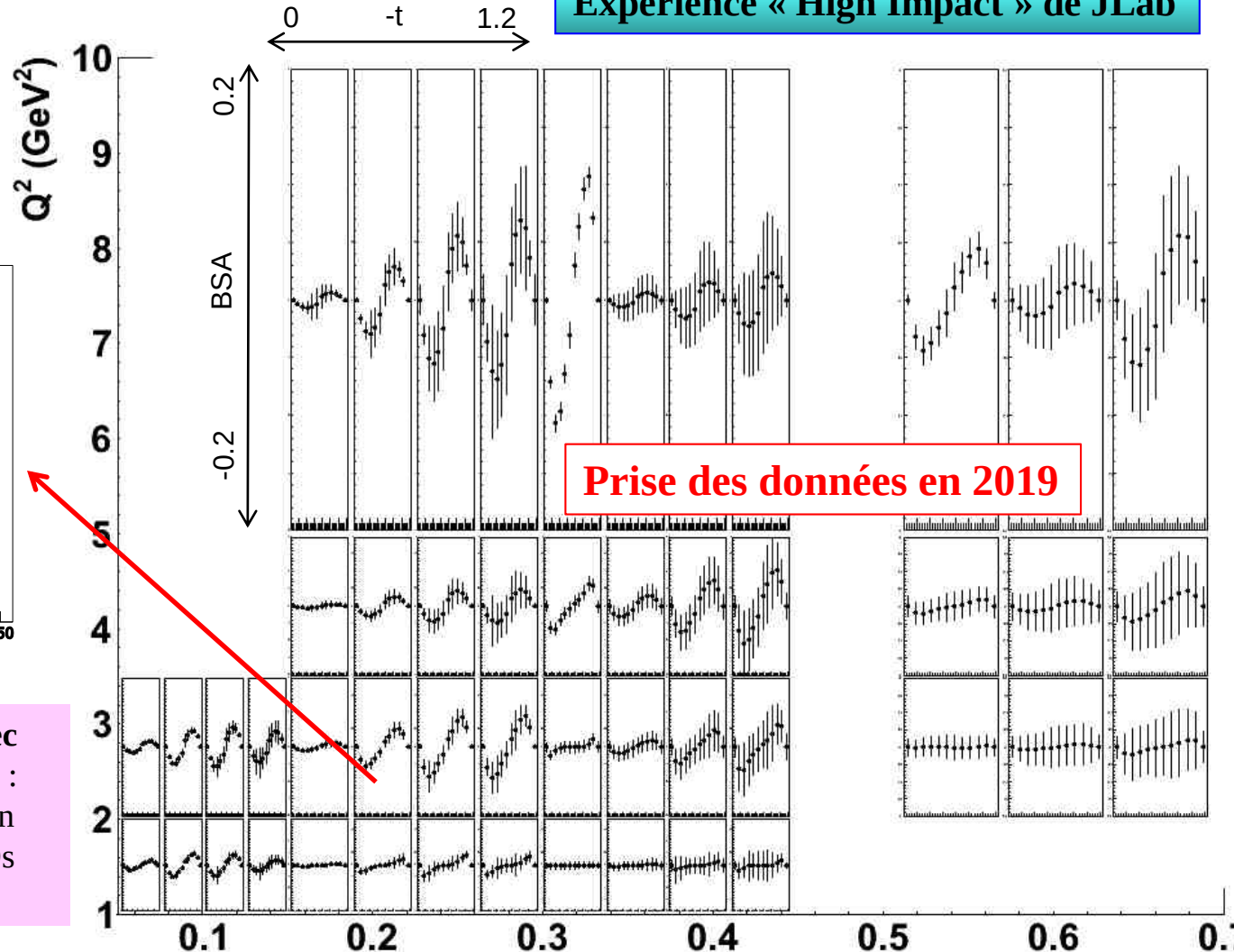
(Central Neutron Detector)

Prédictions pour valeurs
différentes du
moment angulaire des quarks



Expérience « High Impact » de JLab

Prise des données en 2019



Deuxième expérience, nDVCS avec
cible polarisée longitudinalement :

- Extraction des GPDs du neutron
- Séparation en saveurs des GPDs
- Prévues en 2020

S. Niccolai porte-parole

Projet technique : “Central Neutron Detector” pour CLAS12

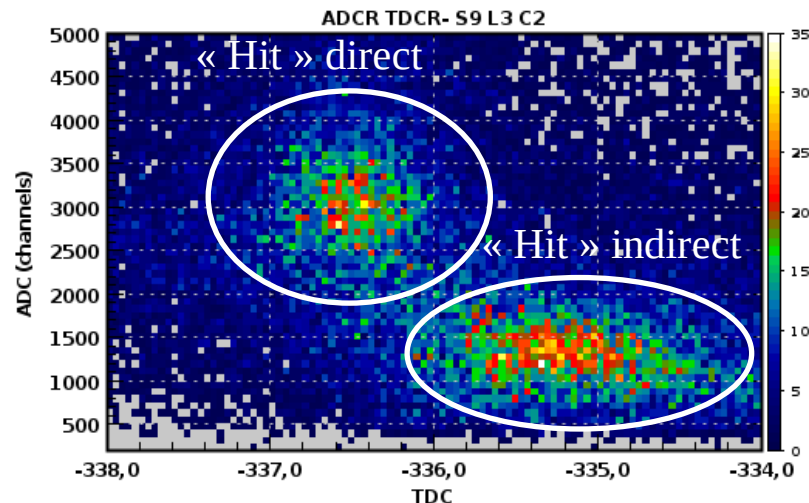
But : détection du **neutron de recul du nDVCS**

→ Le CND doit assurer **bonne séparation neutron/photon**

→ **Résolution en temps de ~ 150 ps**

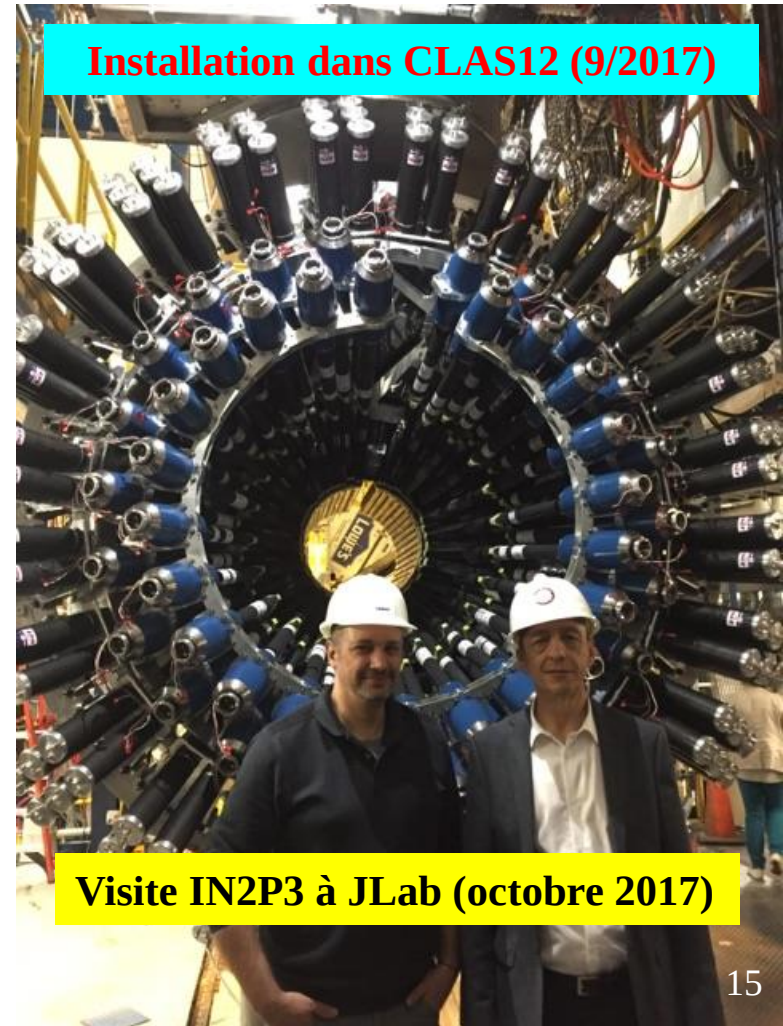
Contraintes : espace limité, champ magnétique (5T)

Design du CND : **barreau de scintillateurs**, 3 couches radiales, 48 barreaux par couche couplés 2-par-2 par un guide “u-turn”, PMTs à l’arrière



- Financement **IN2P3** (300 k€)
- **Conçu et construit à l'IPNO**
 - Article soumis à **NIM A**
- **Prise des données en cours** (cible de protons)

Installation dans CLAS12 (9/2017)

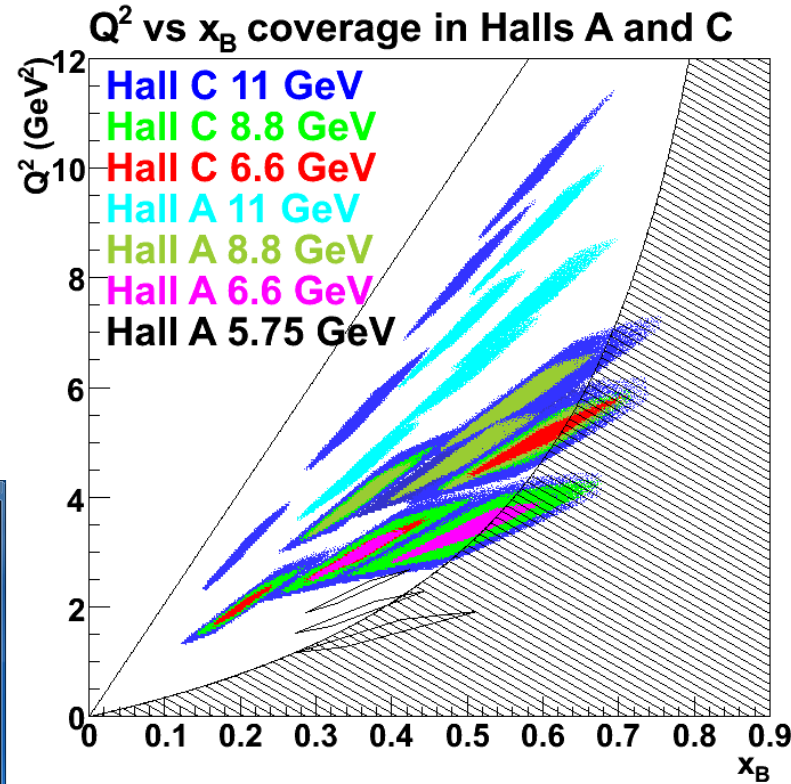


Visite IN2P3 à JLab (octobre 2017)

DVCS à 11 GeV dans le Hall C

Les spectromètres du Hall A sont limités à 4 GeV/c $\Rightarrow$
poursuite programme DVCS de précision dans le Hall C

- Séparation en énergie de la section efficace DVCS
- Haut Q^2 : mesures des contributions “higher twist”
- Extension à bas- x_B (grâce au « sweeping magnet »)



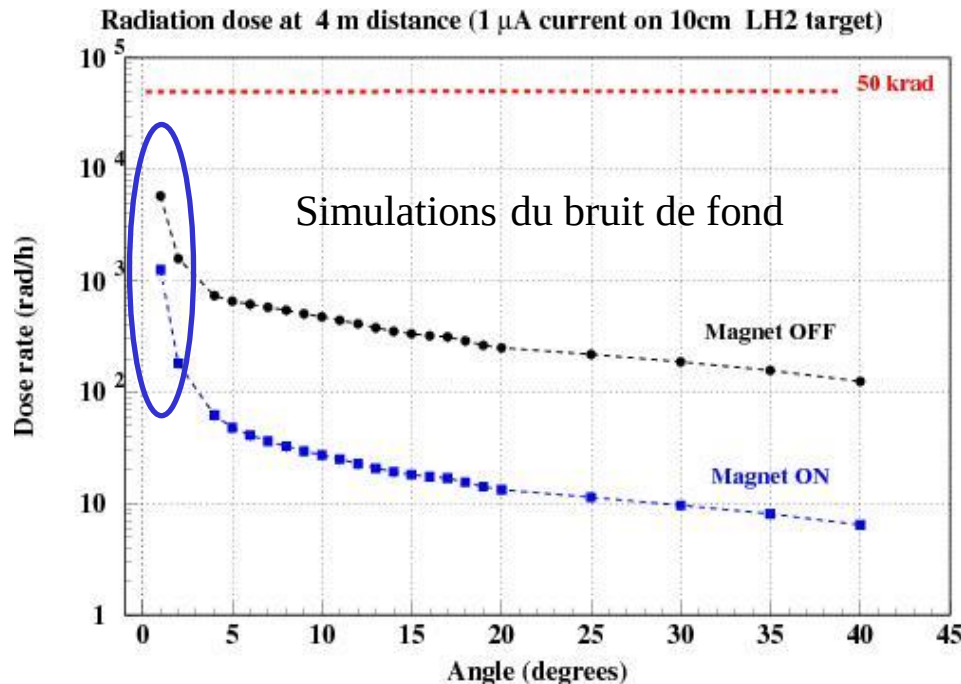
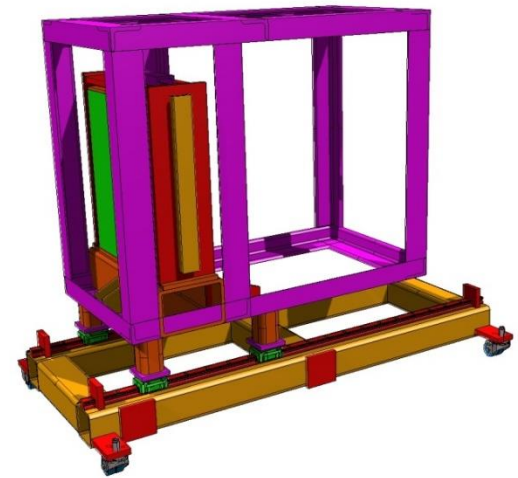
- Expérience approuvée avec A « rating »
- Financée par NSF, JLab & IN2P3
- **Prévue en 2020**

C. Munoz Camacho porte-parole

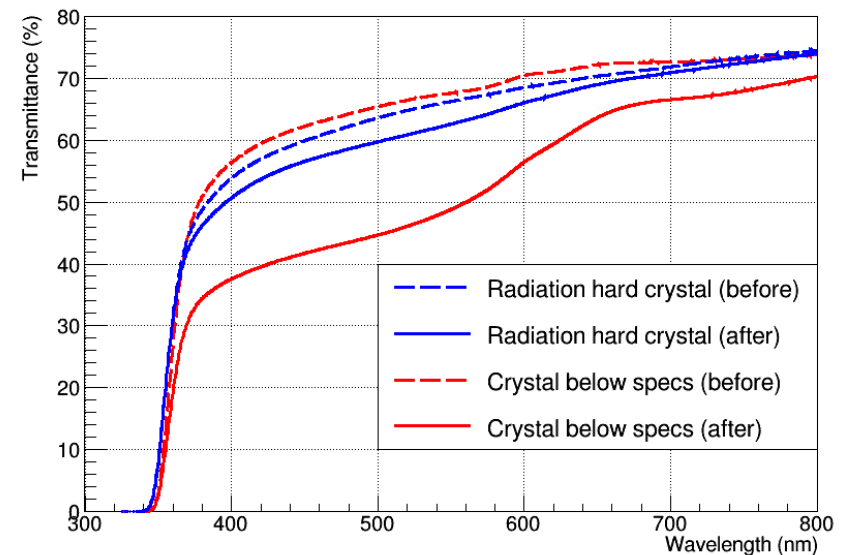
DVCS@Hall C : contribution technique – calorimètre NPS

- **Mécanique** : Conception et construction du cadre contenant les 1116 cristaux de PbWO_4
- Système de **monitorage** du gain
- Système de **régénération** des cristaux
- Régulation en **température**

Défi expérimental : dommage du aux radiations



Transmittance variation after 30 Gy radiation dose



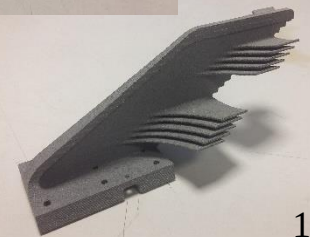
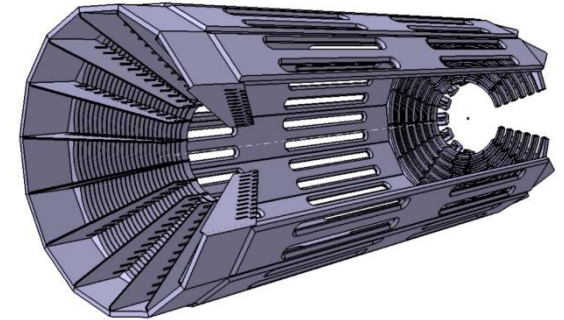
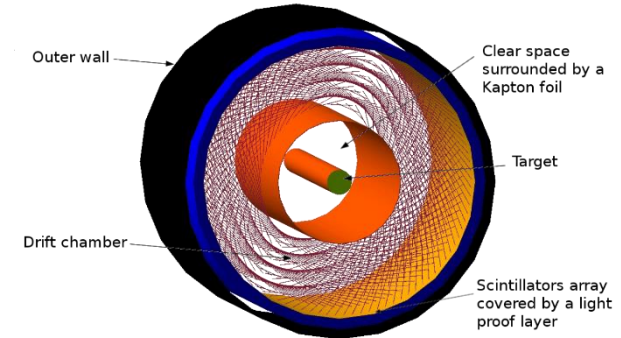
Échéance : fin 2019/début 2020

Financement IN2P3 demandé : **200 k€**
(2017-2019)

140 k€ accordés en 2017-2018

Projet technique : ALERT

- « A Low Energy Recoil Tracker »
 - Nouveau **détecteur de fragments nucléaires** pour CLAS12
 - Chambre à fil parabolique (15 cm diam. / 30 cm long)
 - Scintillateurs placés directement autour
 - Partie prise en charge par ANL (USA)
- **Expériences proposées avec ALERT** (approuvées en 7/2017) :
 - DVCS et production de Φ exclusive sur l'hélium
 - **Tomographie de l'hélium** en quarks et en **gluons**
 - Diffusion inélastique (DIS) et DVCS incohérentes
 - Etude des **effets nucléaires** (EMC, anti-shadowing...)
 - Dynamique du **noyau** $\leftrightarrow$ effets **partoniques**
- **Projet technique à l'IPN** :
 - Financement **P2IO** de 50k€ (2015-2018)
 - Le CEA prend en charge la partie électronique
 - Travail important sur la **mécanique** à l'IPN
 - **R&D** pour l'utilisation de **fils carbone** (NIM A855, 154 (2017))
 - Une thèse a démarré sur la phénoménologie et le détecteur



R. Dupré porte-parole

Plan pour JLab @ 12 GeV

pDVCS @ Hall A : 1^{ère} expérience de JLab @ 12 GeV, achevée 12/2016, analyse et thèse en cours à l'IPNO

Installation du CND (10/2017), démarrage de **CLAS12** sur cible de protons (12/2017), thèse à l'IPNO à partir d'octobre 2017

Sur toutes ces expériences nous sommes **porte-paroles** et/ou il y a une **contribution technique** de l'IPNO

Prise de données de **nDVCS @ CLAS12** (2019)

pDVCS et nDVCS @ CLAS12 sur cibles polarisées longitudinalement (2020)

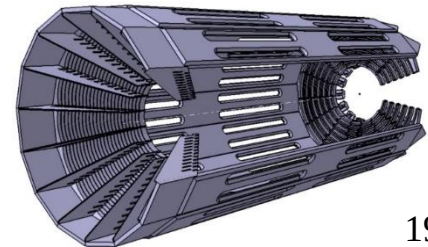


Prise de données de **HPS @ 4.4 GeV** (été 2019)

pDVCS & π^0 @ Hall C + NPS (2020)



DVCS sur les noyaux– ALERT @ CLAS12 (2021)



+ études en cours pour le **double DVCS** et **faisceau polarisé de positrons**

Conclusions - JLab

- Notre équipe est **très active et visible** à JLab et dans la communauté internationale de physique hadronique, en particulier avec nos **études expérimentales de la structure du nucléon au moyen des GPDs**
- Nombreux **résultats récents** des expériences à **6 GeV**
- Interprétation phénoménologique → **première image tomographique du proton**
- Synergie avec les **services techniques** de l'IPNO, fort engagement dans la **R&D**
- **Futur** à court-moyen terme : **JLab@12 GeV**
 - ✓ **Expériences**, dont nous sommes porte-paroles, prévues pour les prochaines années (→ **~2025** incluant analyse)
 - ✓ **Projets techniques** réalisés et en cours (CND, NPS, ALERT)
→ Besoin de **renforcement humain** (1 poste CR)

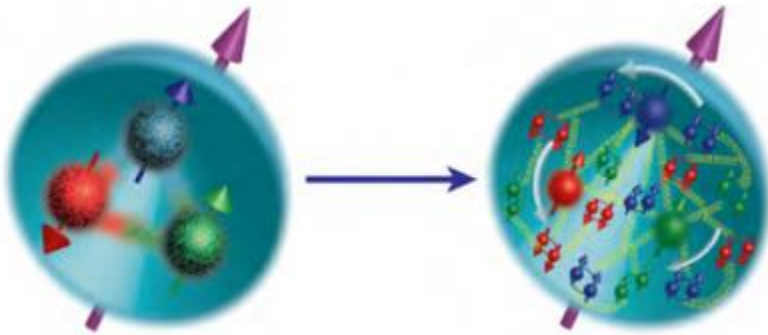
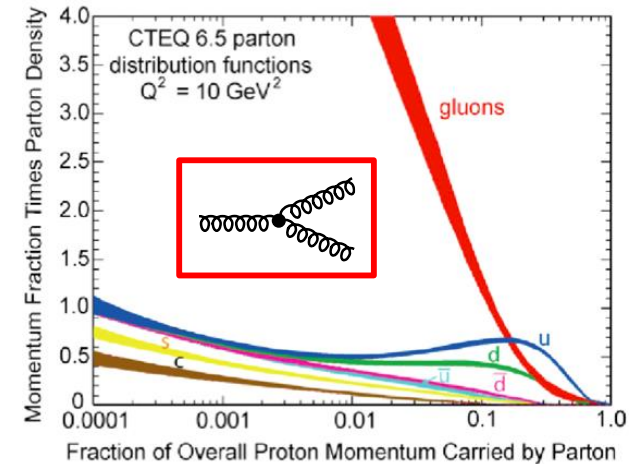
→ **Futur au long terme (>2025) : Electron-Ion Collider**

EIC – motivations : questions ouvertes en QCD

Saturation : un nouvel état de la matière hadronique ?

Comment se comporte la **densité des gluons** dans les noyaux à haute énergie ? Elle ne peut pas croître infiniment...

Y-a-t-il une **saturation** dans une matière gluonique avec des propriétés universelles ?



Structure partonique des nucléons et des noyaux

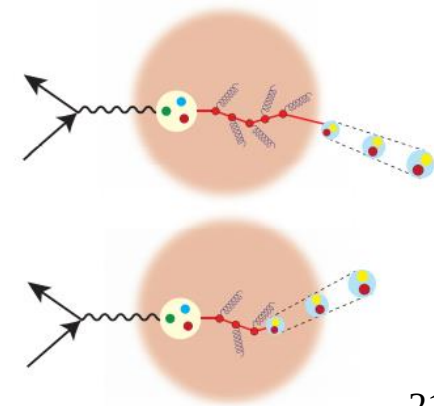
Comment les **gluons et quarks de la mer** sont distribués en position et impulsion et spin dans le nucléon et les noyaux légers ?

Quel est le rôle du **moment angulaire orbital** ?

Le rôle des gluons dans la matière nucléaire

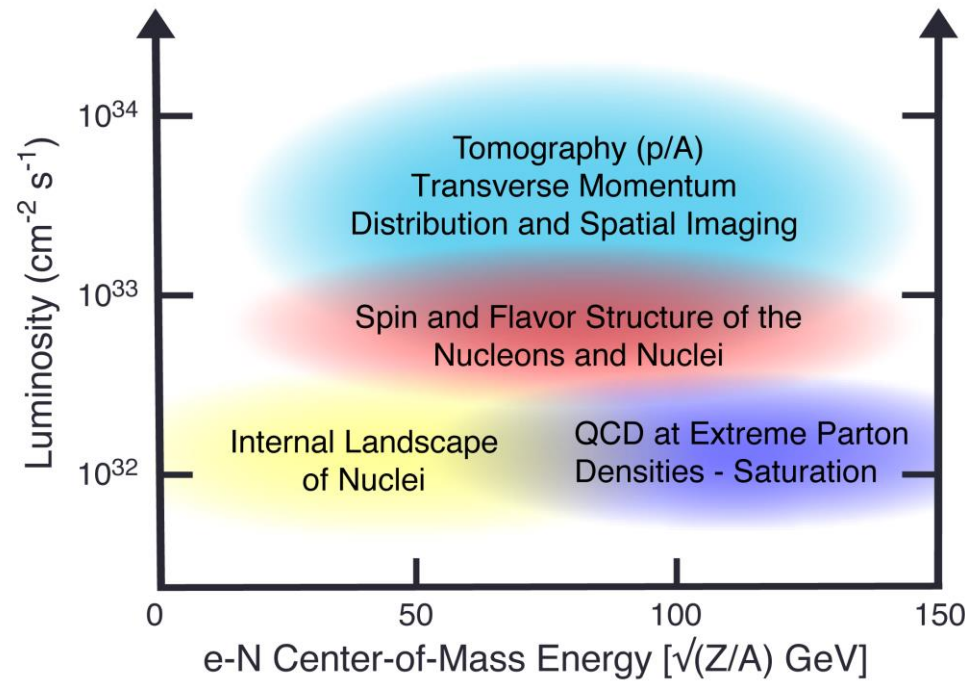
Comment les gluons et quarks de la mer contribuent à la force nucléon-nucléon ? Comment la **matière nucléaire** affecte-t-elle le passage d'une charge colorée qui la traverse ?

Comment la matière nucléaire affecte les distributions de quarks et gluons et leur interaction dans les noyaux ?



Tout cela (et plus !) pourra être étudié au EIC

EIC : cahier des charges

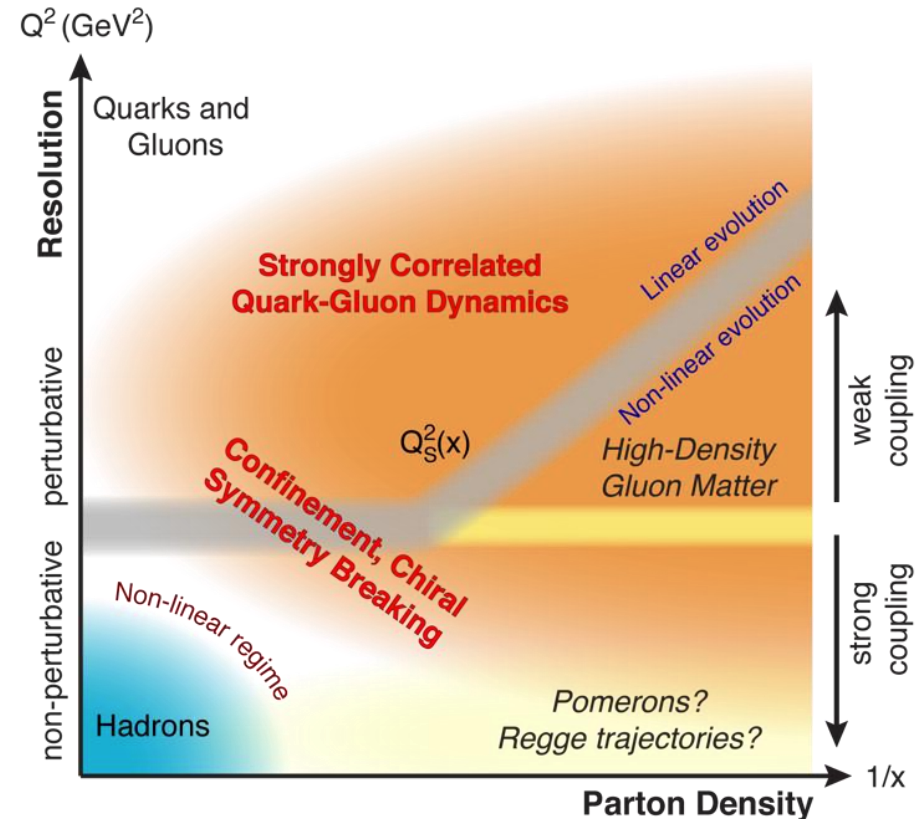


Plusieurs régimes à explorer

→ Grande couverture en Q^2 et x

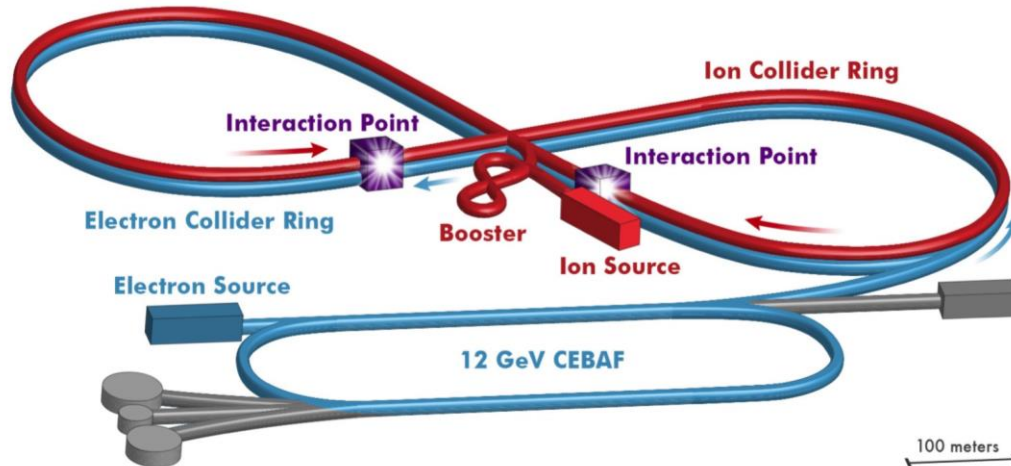
Dès réactions **inclusives** à celles **exclusives**

→ Haute énergie et luminosité



Projets pour EIC

Premier collisionneur au monde en modes $\vec{e}-\vec{p}/\text{noyau léger}$ et aussi en mode électron-noyau

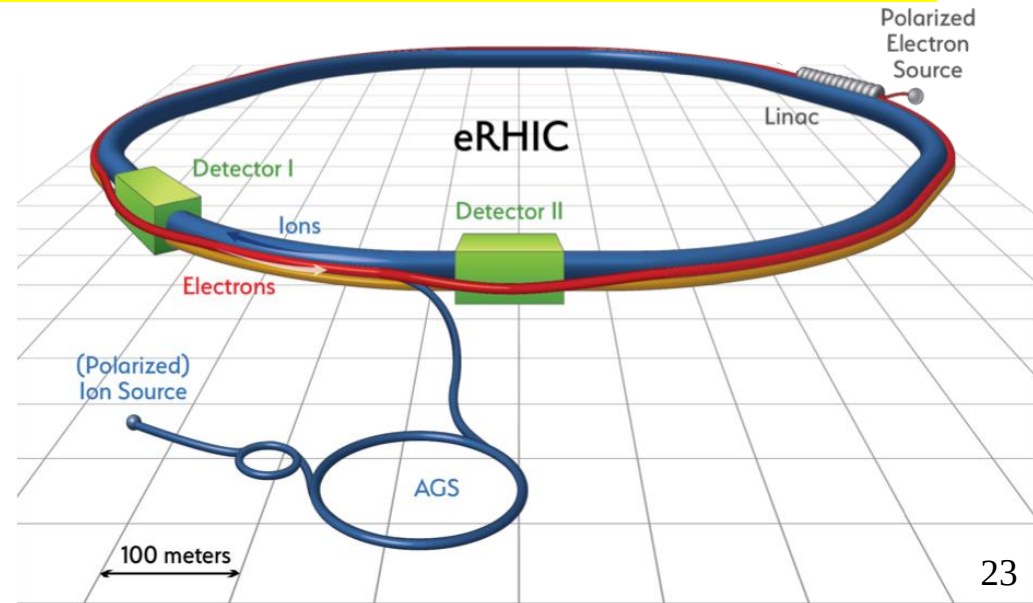


Jefferson Lab

- **Réutilise CEBAF** comme injecteur d'électrons polarisés
- **Ion ring à "8"** : optimisé pour haute polarisation des ions → deutons polarisés
- Energie $\sqrt{s}$: 20 to 65 - 140 GeV (selon la technologie choisie)
- **JLEIC : haute luminosité et polarisation**

Intérêt des Divisions Accélérateurs de l'IPNO et du LAL (Energy Recovery Linac – PERLE)

BROOKHAVEN
NATIONAL LABORATORY

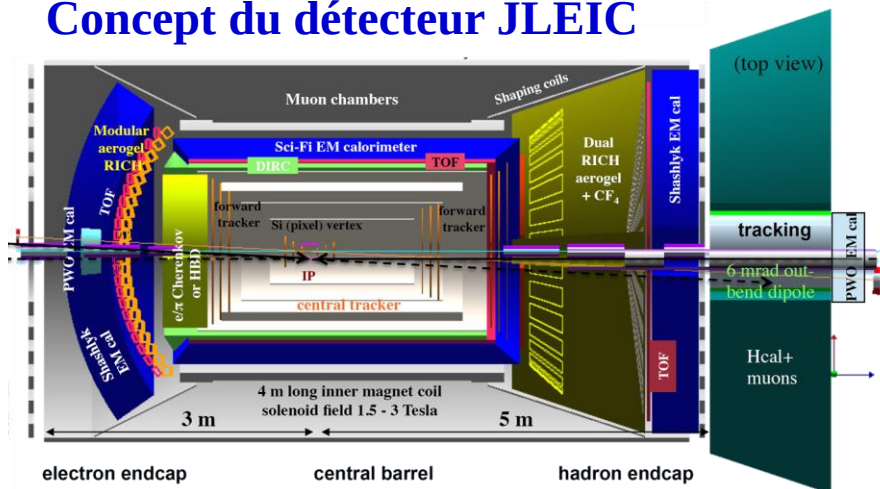


- **Réutilise RHIC**
- Ajoute **accélérateur d'électrons** de 18-GeV dans le même tunnel
- Energie max : protons 250-GeV, électrons 15 GeV
- **eRHIC : haute luminosité, haute énergie e-p/A**

Activités EIC à l'IPNO

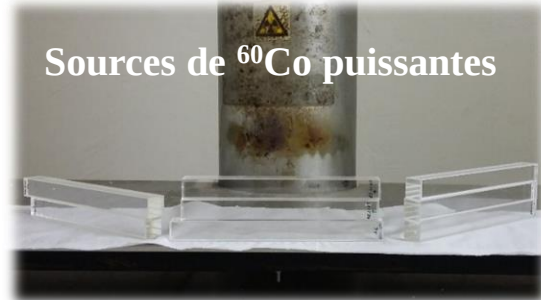
- IPNO fait partie du « Consortium on Calorimetry at EIC » depuis 2014
- Le R&D EIC à l'IPNO est financé par des fonds du BNL

Concept du détecteur JLEIC



Test d'irradiation
(en collaboration avec le LCP)

Sources de ^{60}Co puissantes



Etudes de R&D sont en cours à l'IPNO :

- Procédures de **caractérisations des cristaux de PbWO_4** : transmission optique, « light yield »...
- Mesures de **tenue aux radiations**, méthodes de **régénération des dommages**
- Collaborations : CUA, Caltech, BNL (USA), Giessen (Germany), Crytur (République Tchèque)

L'IPNO participe aussi au **développement du « physics case »** (phénoménologie et simulations) :

- Etudes pour l'**hadronisation** et le « **geometrical tagging** » au EIC
- Résultats publiés dans les **2 White Papers** du EIC
- Participation à un « **Laboratory Directed R&D program** » de JLab

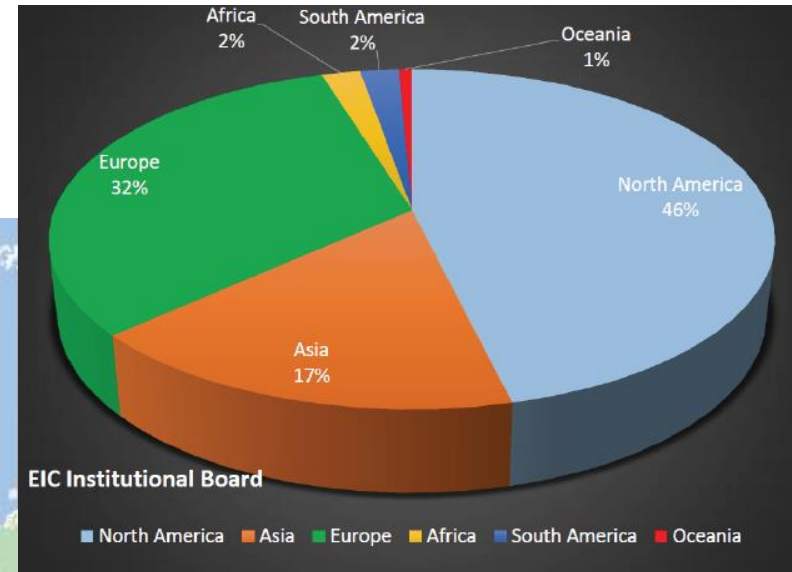
*EIC: The next QCD frontier,
EPJA 52 (2016)*

Nouveau « working group » sur l'utilisation d'un **faisceau de positrons polarisés au EIC** (suite de **PePPO**)

EIC Users Group

700 chercheurs (+étudiants & ingénieurs), 29 pays, 160 institutions

Fort investissement Européen



Forte participation de la communauté des ions lourds

Conclusions - EIC

- EIC est l'endroit optimal pour l'étude de la QCD au **futur au long terme (>2025)**
- C'est un futur **à préparer** avec un **engagement** dès aujourd'hui
- Il s'agit d'un **projet fédérateur** pour la communauté de **physique hadronique** en France :
 - ✓ L'**équipe JLab** participe à la **conception du détecteur** et à la définition du **programme de physique**, en parallèle aux expériences en cours à JLab@12 GeV
 - ✓ Fort intérêt des **théoriciens français** dans la physique du EIC
 - ✓ Fort intérêt et **engagement du CEA/Irfu** (nouvelle embauche dédiée au EIC)
 - ✓ Intérêt d'une partie de la **communauté LHC** :
 - Intérêt exprimé par plusieurs chercheurs du **groupe ALICE de Nantes** pour s'impliquer dans le projet EIC à l'horizon 2024. Un chercheur de ce groupe soumettra une ERC la semaine prochaine sur le EIC
- Possibles contributions dans le **développement de l'accélérateur** par les Divisions Accélérateurs d'Orsay

Back up

Nom	Grade	Pourcentage
P. Chatagnon	Doctorant	100
R. Dupré	Chargé de Recherche	95
M. Ehrhart	Doctorant	100
M. Guidal	Directeur de Recherche	5
F. Georges	Doctorant	100
H.S. Ko	Doctorant	100
C. Muñoz-Camacho	Chargé de Recherche	95
S. Niccolai	Directrice de Recherche	95
D. Marchand	Chargée de Recherche	30
E. Voutier	Directeur de Recherche	50
R. Wang	Post-doctorant	100
S. Zhao	Doctorant	100

TABLE 2 – Liste des chercheurs de l’IPN Orsay impliqués à ce jour (janvier 2018) dans JLab, avec pourcentages consacrés.

Année	Montant	Source	Détails
2018	87 k€	IN2P3	Projet NPS
2018	63 k€	IN2P3	Missions JLab
2018	23 k\$	Financement DoE/BNL	Equipement R&D EIC
2017	53 k€	IN2P3	Projet NPS
2017	50 k€	IN2P3	Missions JLab
2017	15 k\$	Financement DoE/BNL	Equipement R&D EIC
2016	70 k€	IN2P3	Missions + equipement JLab
2016	41 k€	LabEx P2IO	Projet ALERT
2016-2019	9-10 k€/an	PICS (CNRS-USA)	Missions et échanges avec JLab
2016	9 k\$	Financement DoE/BNL	Equipement R&D EIC
2015	50 k€	IN2P3	Missions JLab
2015	30 k\$	Financement DoE/BNL	Equipement R&D EIC
2013-2017	206 k€	ANR	HPS (post-doc, missions)
2013	200 k€	SESAME	HPS - equipement
2012-2015	300 k€	IN2P3	CND - equipement

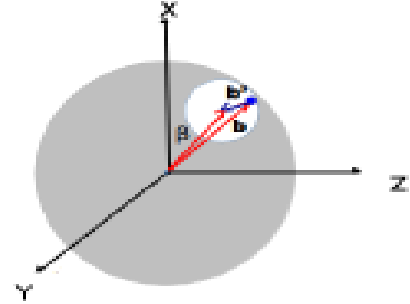
TABLE 3 – Budgets et sources de financement pour le projet “JLab” dans les dernières années.

DVCS sur les noyaux : expérience eg6 à CLAS

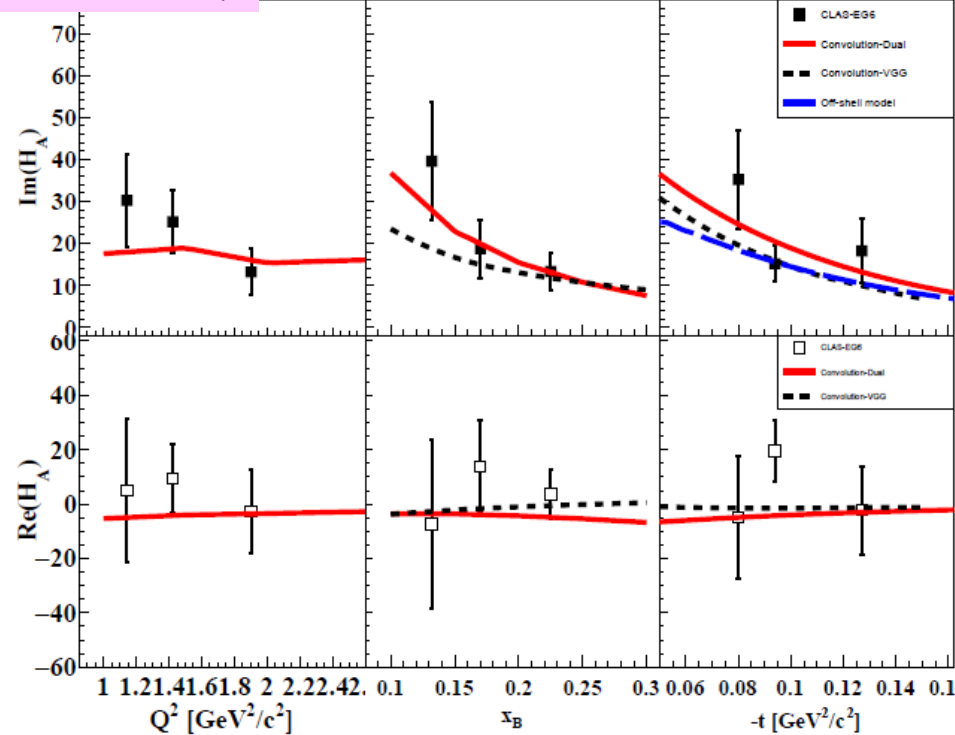
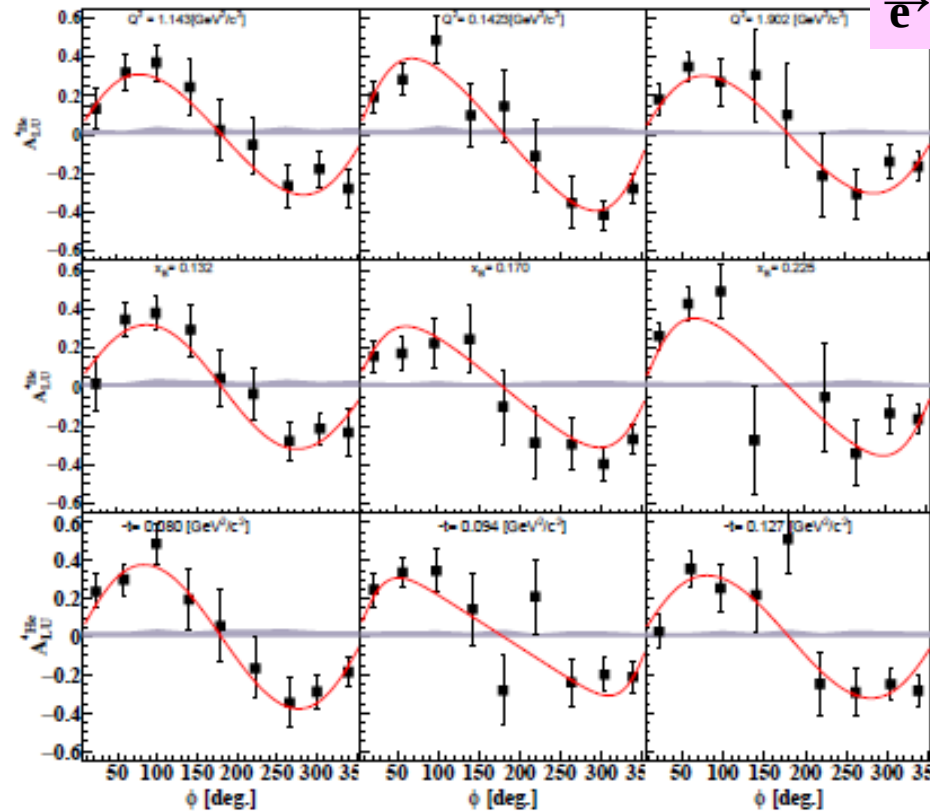
- CLAS+calorimetre e.m. + détecteur de recul + cible de ^4He ; $E \sim 6.065$ GeV
- DVCS **cohérent** et **incohérent** : **GPDs des noyaux**, « effet EMC »

^4He a spin 0 : à l'ordre dominant **une seule GPD** contribue à l'asymétrie de faisceau du DVCS

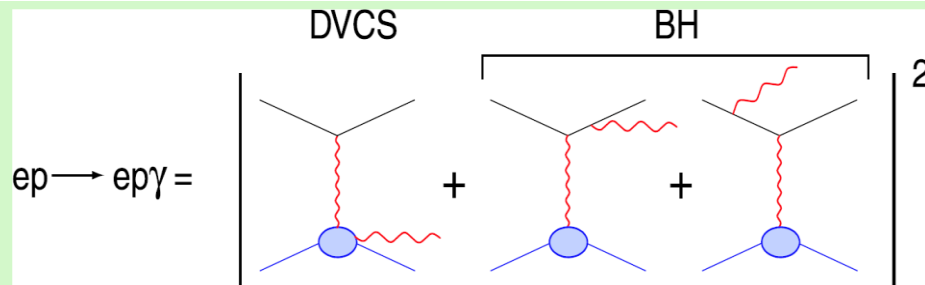
$$A_{LU}^{^4\text{He}}(\varphi) = \frac{\alpha_0(\varphi) F_A(t) \Im m[\mathcal{H}_A]}{\alpha_1(\varphi) F_A^2(t) + \alpha_2(\varphi) F_A(t) \Re e[\mathcal{H}_A] + \alpha_3(\varphi) \Re e[\mathcal{H}_A]^2 + \alpha_3(\varphi) \Im m[\mathcal{H}_A]^2}$$



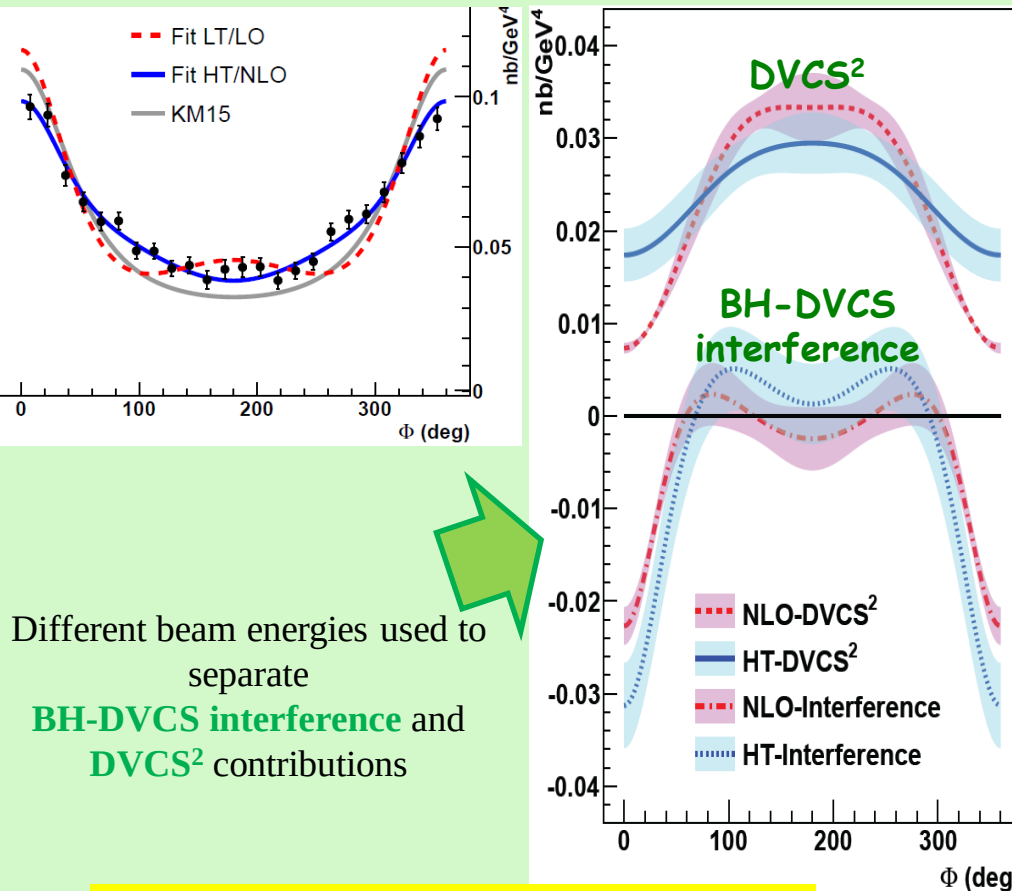
$\bar{e} \rightarrow ^4\text{He} \rightarrow e ^4\text{He} \gamma$



DVCS and π^0 - recent results from JLab @ 6 GeV (Hall A)



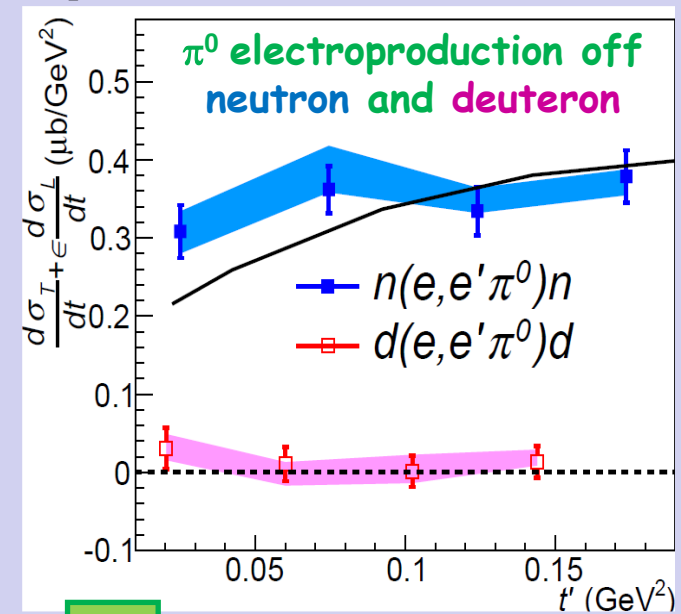
High precision DVCS cross sections from Hall A:
sensitivity to higher twist (HT) or NLO contributions



Different beam energies used to separate
BH-DVCS interference and
DVCS² contributions

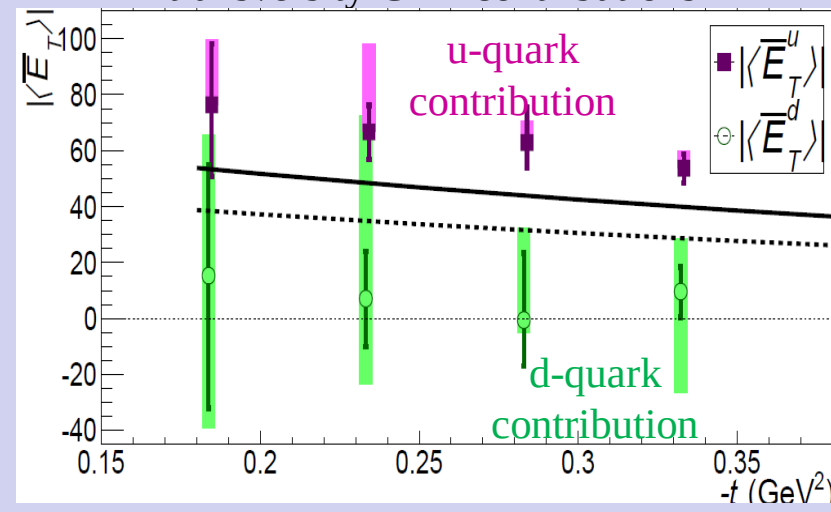
Nature Communications 8, 1408 (2017)

Hall A experiment E08-025:



Phys. Rev. Lett. 118 (2017)

Flavor separation of different
transversity GPD contributions



Electron-Ion Collider : caractéristiques

Premier collisionneur au monde en mode $\vec{e}-\vec{p}/\overrightarrow{\text{noyau léger}}$ et aussi en mode électron-noyau

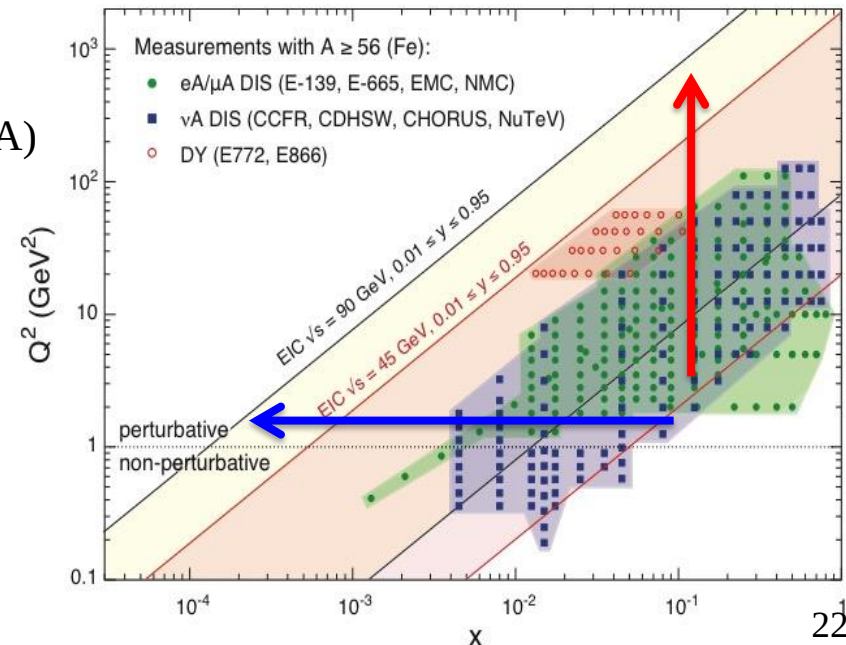
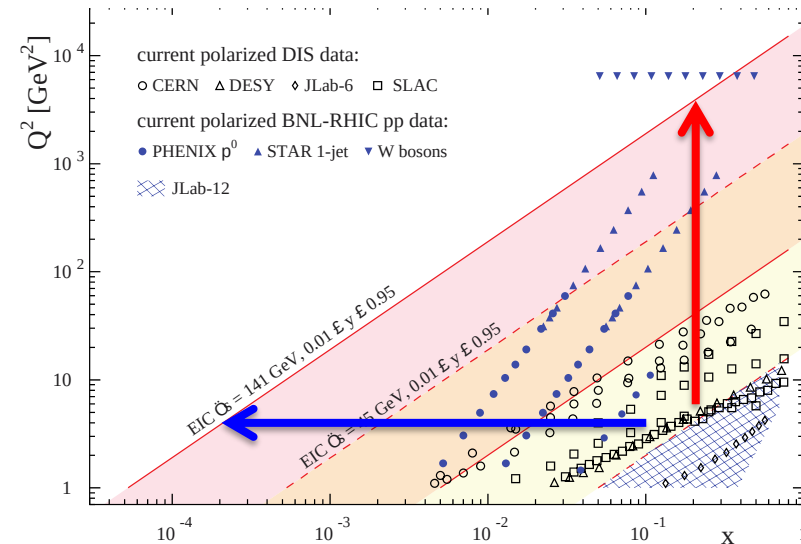
Pour les collisions e-p/n :

- Faisceaux polarisés de e, p, deuton ou ^3He
- Energie du faisceau d'électrons $\sim 5\text{-}20\text{ GeV}$
- Energie du faisceau de protons $\sim 50\text{ - }250\text{ GeV}$
- Luminosité $L_{ep} \sim 10^{33-34}\text{ cm}^{-2}\text{sec}^{-1}$
- Energie $s \sim \sqrt{4E_p E_e} \sim 30\text{ - }140\text{ GeV}$

Pour les collisions e-A :

- Grande variété de noyaux (proton $\rightarrow$ uranium)
- Luminosité par nucléon idem que e-p (100-1000 x HERA)
- Energie variable

Deux plans, dans deux laboratoires aux USA, sont en cours de développement :



Au-delà de la structure du nucléon : Heavy Photon Search

Expérience HPS au JLab (Hall B)

Recherche d'un nouveau **boson vecteur** (A') :

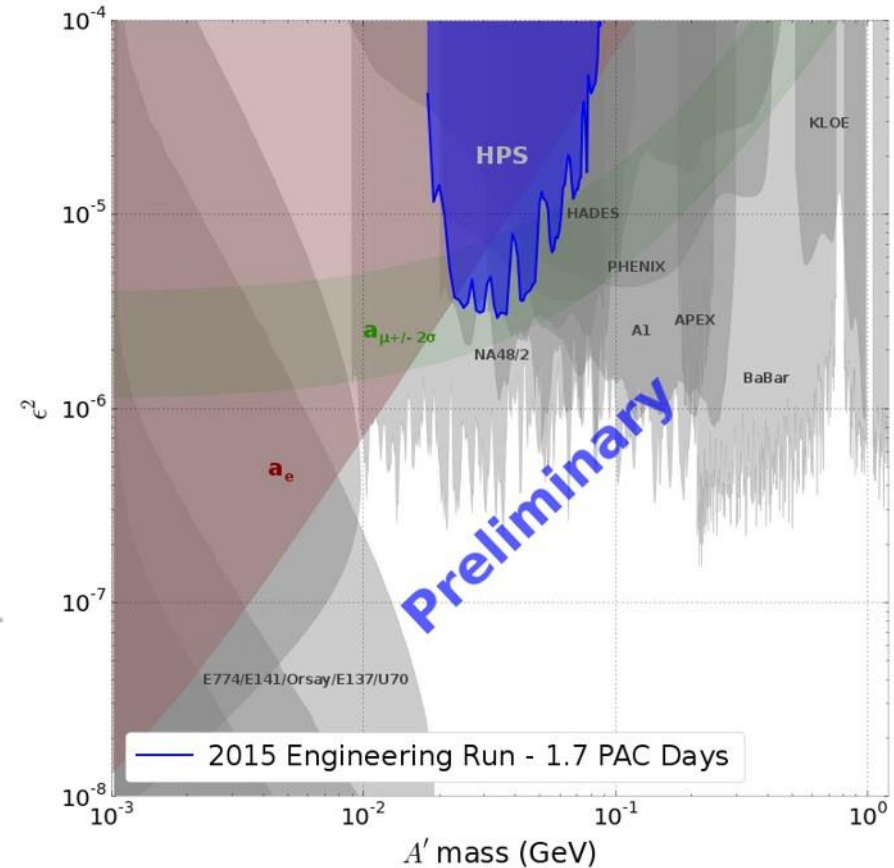
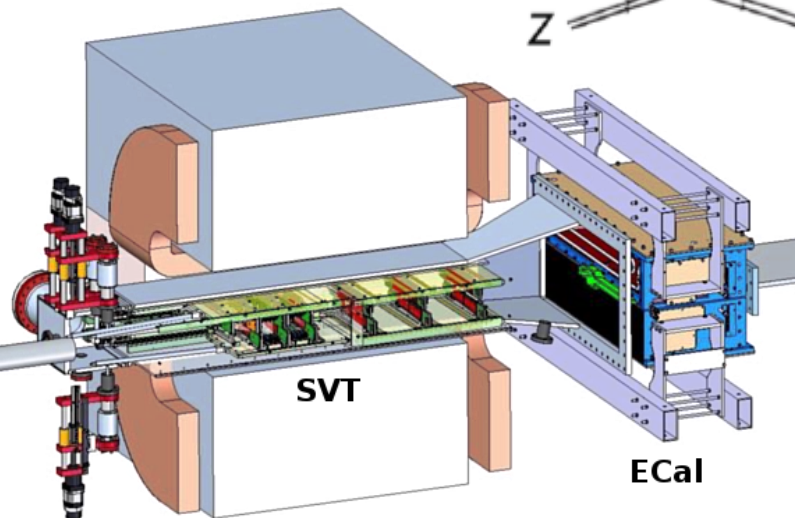
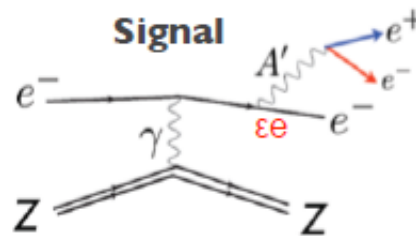
- masse entre 20 MeV et 1000 MeV
- décroissance en pair électron-positron
- produit par brehmmstrahlung sur cible lourde

Possible connexion avec la **matière sombre**

Faibles contraintes théoriques → grand espace à échantillonner pour les **masses** et le **couplage** à la matière ordinaire

➤ **Prises de données en 2015, 2016, 2018**

Analyse en cours (thèse à l'IPNO)



Détecteur : « silicon tracker » et calorimètre

IPNO a construit la plupart du **calorimètre** + INFN

Financements : ANR JCJC (250 k€), SESAME (200 k€)

→ Raphael Dupré chef du projet

Besoin de soutien IN2P3 pour les missions de 2018

Upgrade du calorimètre : besoins techniques

Fin de l'ANR cette année

Au delà de la structure du nucléon : PEPPo

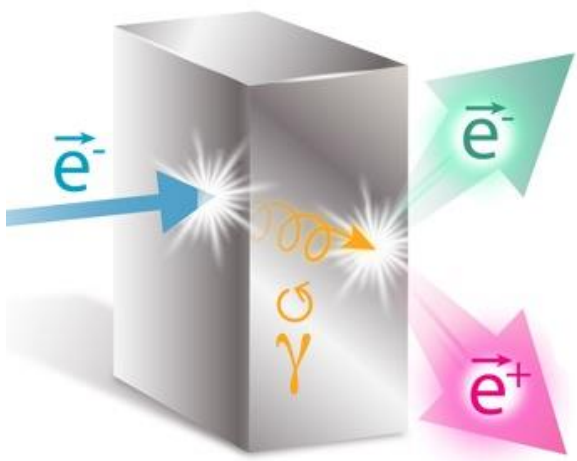
(Polarized Electrons for Polarized Positrons)

(PEPPo Collaboration) J. Grames, E. Voutier et al. , JLab Experiment E12-11-105, 2011

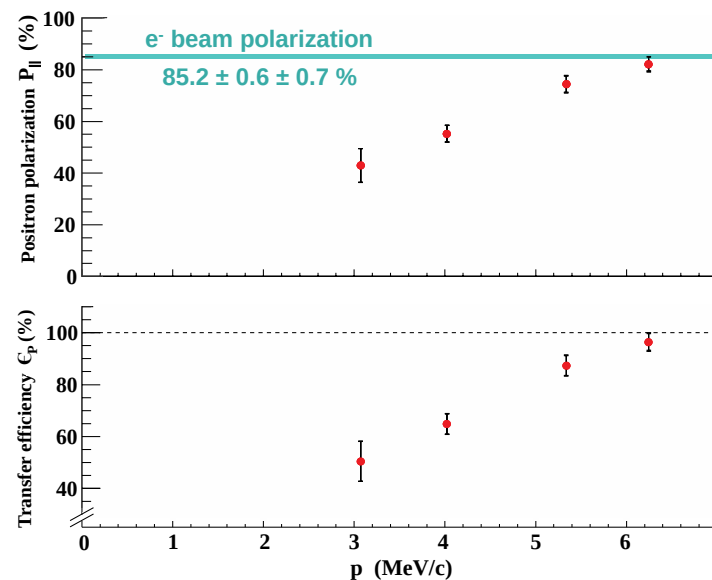
D. Abbott et al. Phys. Rev. Lett. 116 (2016) 214801

Editor's choice, Physics Focus

L'expérience **PEPPo** à l'**injecteur de CEBAF** a démontré un **transfert efficace de polarisation** entre **électrons et positrons**. Elle ouvre la possibilité de produire positrons polarisés avec **accélérateurs ~MeV**



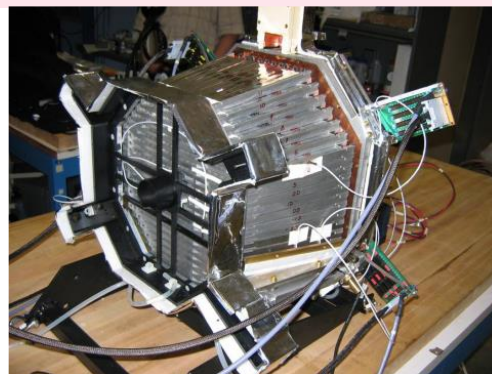
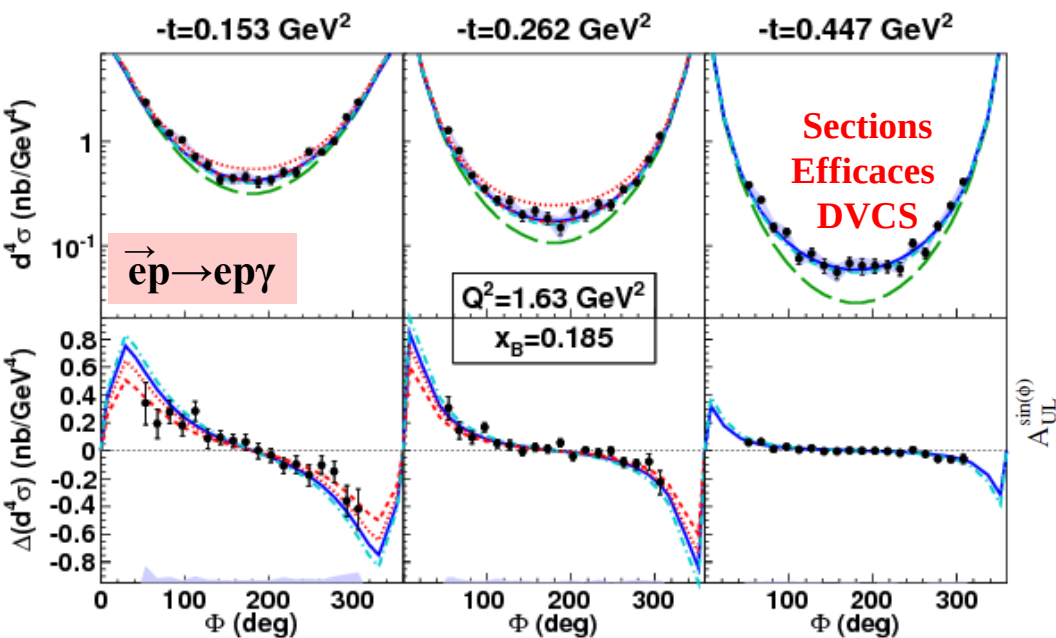
Lorsqu'on produit positrons à partir des électrons, les positrons seront polarisés si le faisceau initial est polarisé



Les positrons polarisés apportent des observables supplémentaires pour l'étude du DVCS

« Highlights » : DVCS à CLAS

Contribution technique IPNO :
calorimètre e.m. pour CLAS

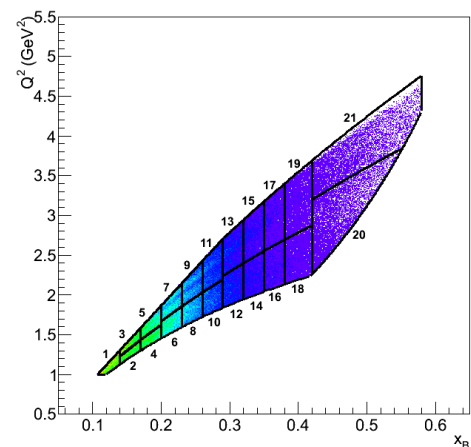
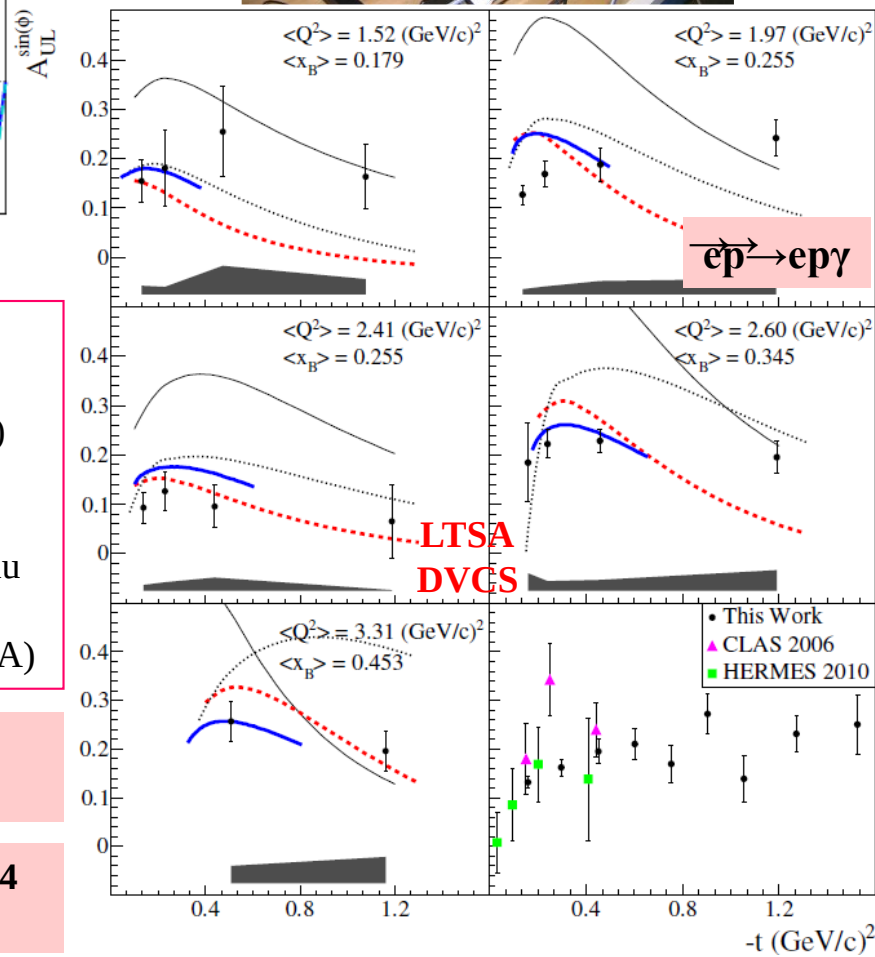


H.S. Jo et al., PRL 115, 212003 (2015)

- La plus grande **couverture cinématique** pour le DVCS
- Deux expériences (2005, 2009)
- **5 observables** : sections efficaces, différences de s. e. polarisées, asymétries de faisceau (BSA), de cible longitudinale (LTSA) et de cible-faisceau (DSA)

E. Seder et al., PRL 114 (2015) 032001

S. Pisano et al., PRD 91, 052014 (2015)

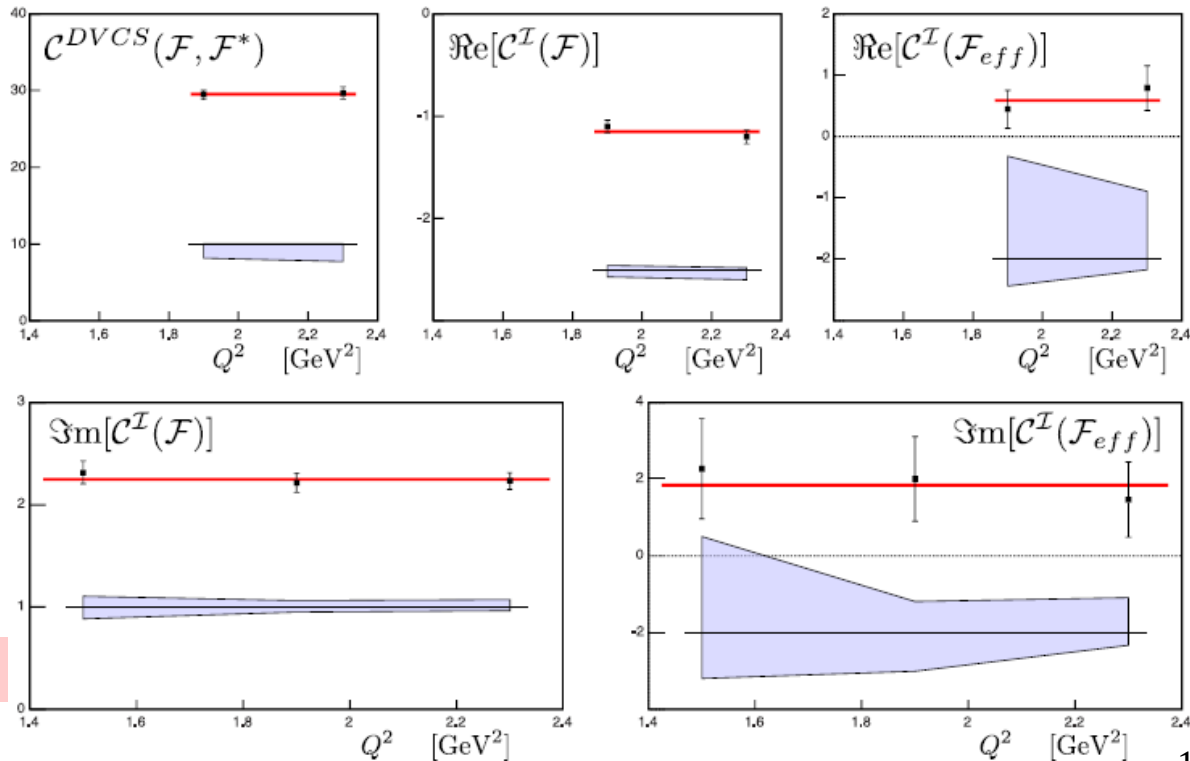
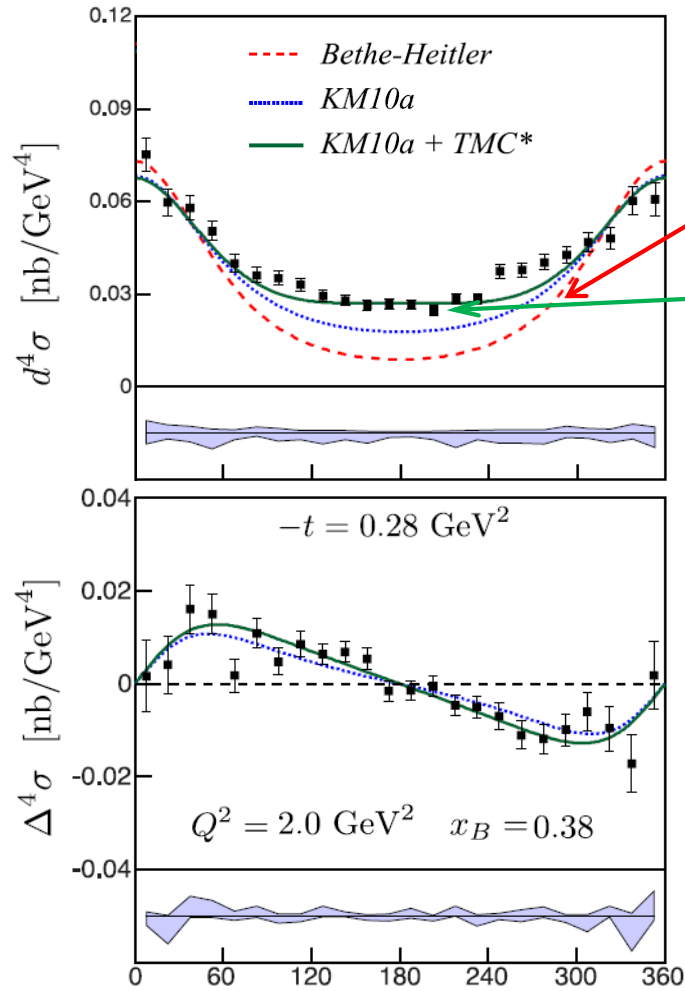


« Highlights »: DVCS sur le proton dans le Hall A

$$\vec{e}\vec{p} \rightarrow e\gamma(p)$$

$$\sigma(eN \rightarrow eN\gamma) = \left| \text{DVCS} + \text{Bethe-Heitler (BH)} \right|^2$$

- Déviation significative du Bethe-Heitler
- $I(\text{BH} \cdot \text{DVCS})$ et DVCS^2 contribuent aux sections efficaces
- Corrections “Twist-4” sont nécessaires pour bien décrire les données

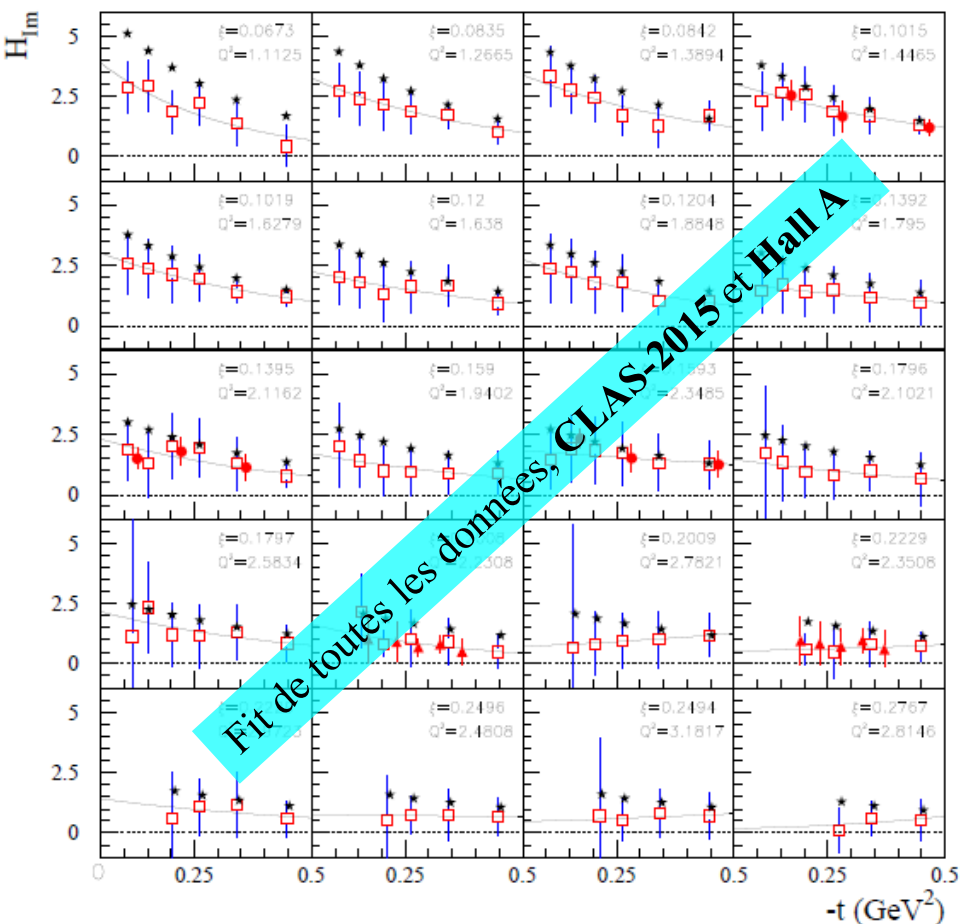


M. Defurne et. al., PRC 92, 055202 (2015)

Tomographie du proton

Fit indépendant du modèle, à cinématique fixée (Q^2 , x_B , t) des observables DVCS

8 paramètres (les CFFs), peu de contraintes ($\pm 5 \times$ prédiction du modèle VGG) *M. Guidal, Eur. Phys. J. A 37 (2008) 319, etc...*

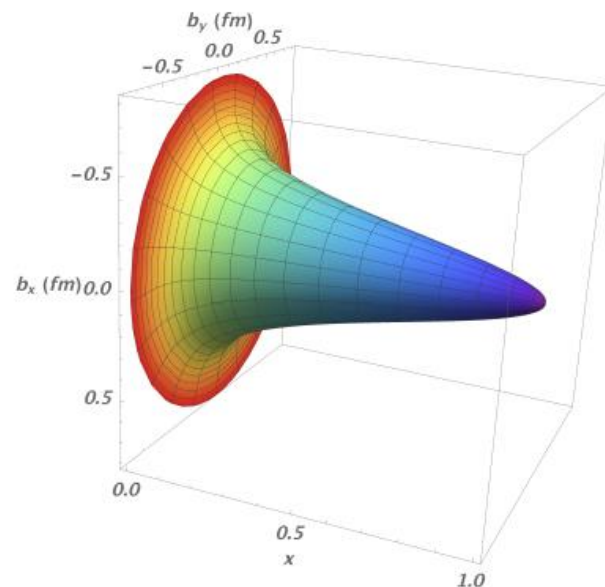


R. Dupré, M. Guidal, M. Vanderhaeghen,
PRD95, 011501 (2017)

R. Dupré, M. Guidal, S. Niccolai,
M. Vanderhaeghen, [arXiv:1704.07330](https://arxiv.org/abs/1704.07330)

$$Im\mathcal{H}_q = \pi e_q^2 [H^q(\xi, \xi, t) - H^q(-\xi, \xi, t)]$$

Position transverse du quark



Impulsion longitudinale du quark

Extraction de $Im(\mathcal{H})$ et $Im(\tilde{\mathcal{H}})$:

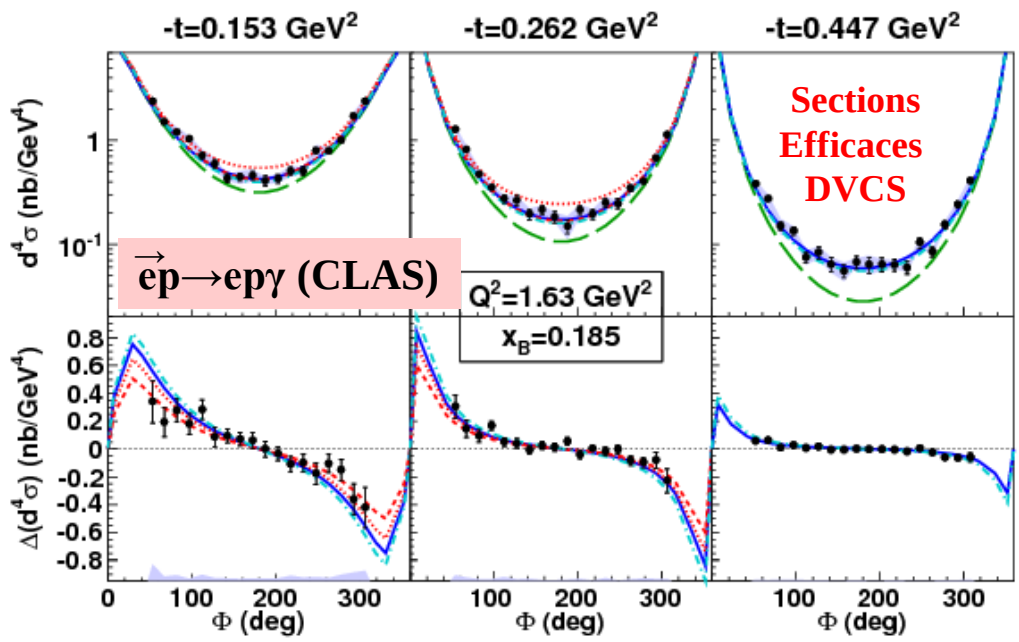
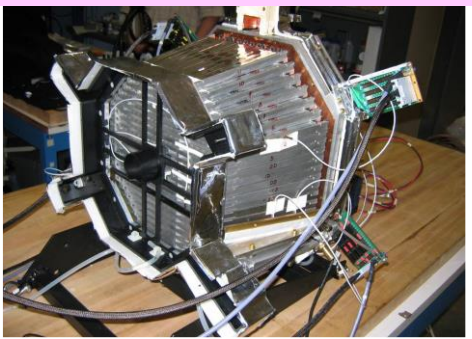
- Les quarks de valence sont au centre du nucléon, les quarks de la mer sont à la périphérie
- La charge axiale est plus concentrée au centre du proton que la charge électrique

« Highlights » : DVCS à JLab@6 GeV

Contribution technique IPNO :
calorimètre e.m. pour CLAS

Implication directe de l'équipe dans tous les aspects de l'expérience : proposition, développement des détecteurs, prise des données, analyse, interprétation des résultats

2015: 2 PRL, 1 PRD, 1 PRC (« lead authors » et porte-paroles)

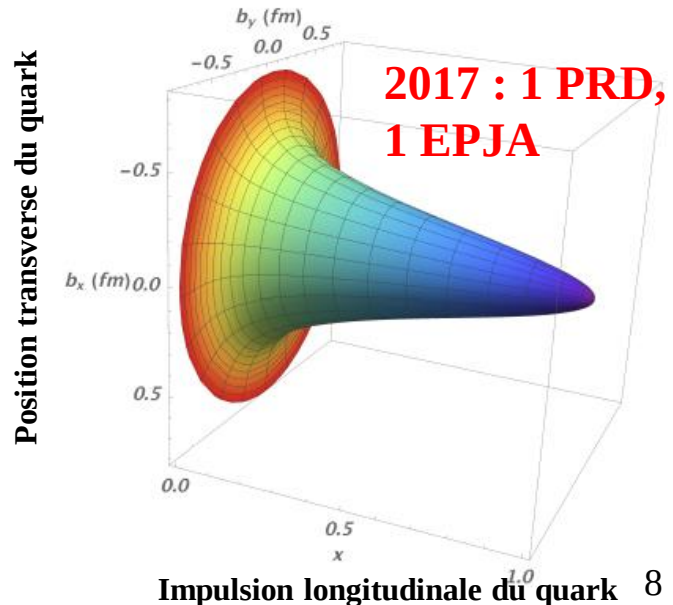


Extraction des GPDs

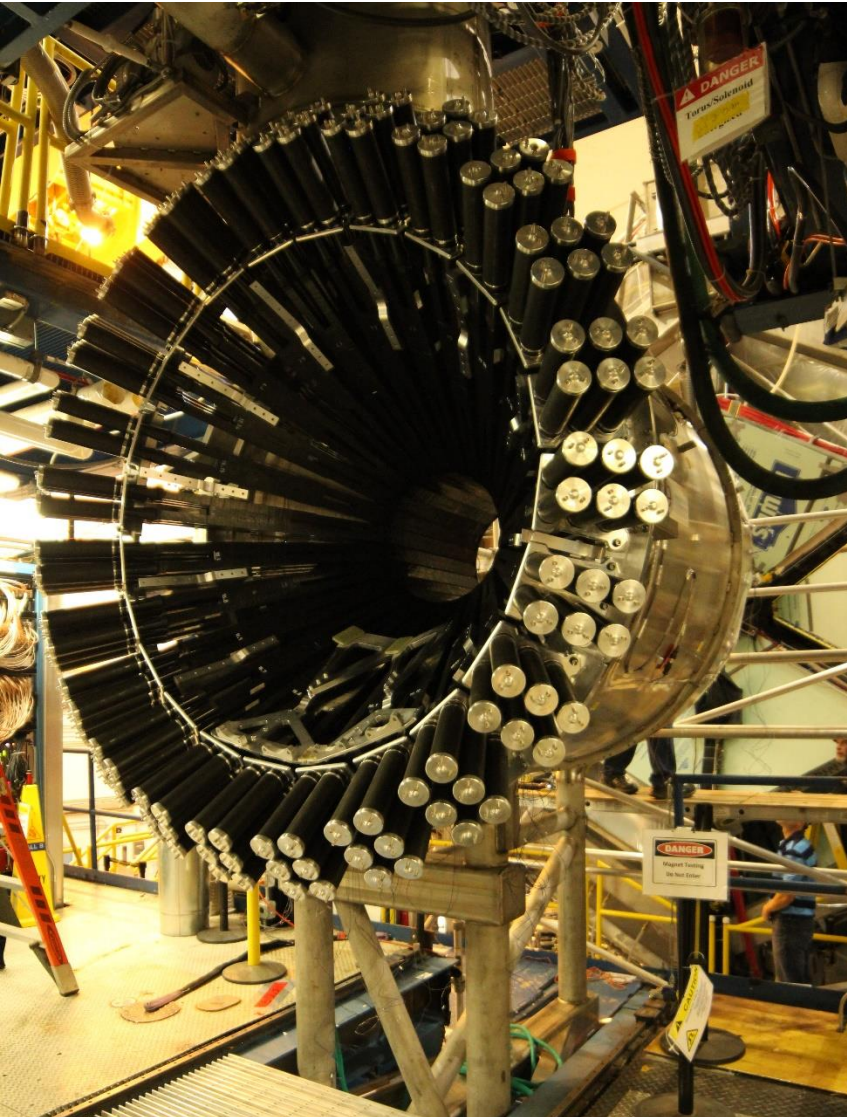
- ✓ Quarks de valence au centre du nucléon, quarks de la mer à la périphérie.
- ✓ Charge axiale plus concentrée au centre du proton que la charge électrique

→ TOMOGRAPHIE DU PROTON

- Sections efficaces du DVCS sur le proton (CLAS et Hall A) : tomographie du proton, test de validité du formalisme des GPDs
- Asymétries de cible polarisée (single et double) du pDVCS : GPDs polarisées, charge axiale du proton



Installation of the CND at JLab (20-26/9/2017)



**CND installed, cabled, tested and commissioned
Data taking of CLAS12 started mid-December 2017**



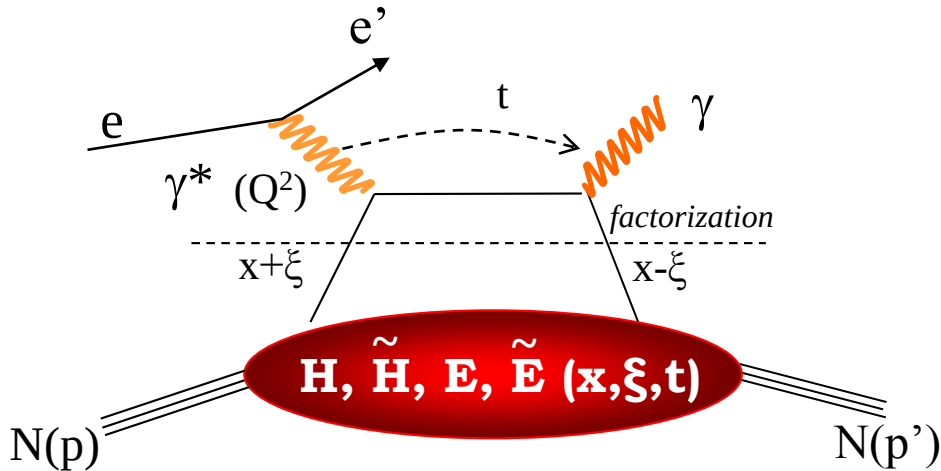
Equipe JLab at IPNO

6 permanents : R. Dupré, M. Guidal (**5%**), C. Munoz-Camacho, S. Niccolai, E. Voutier, D. Marchand

1 post-docs : R. Wang (**100%**)

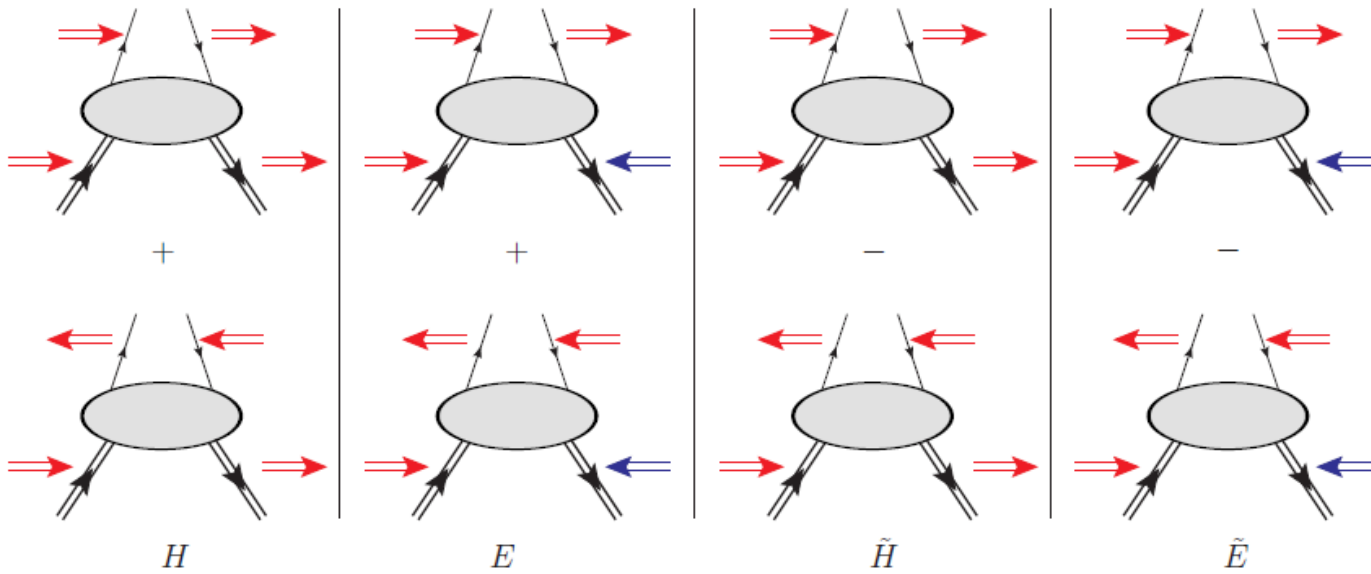
5 étudiants en cours : S. Zhao, 2^{nde} année (**100%**), F. Georges, 3^{ème} année (**100%**), P. Chatagnon, 1^{ère} année (**100%**), M. Ehrhart, 1^{ère} année (**100%**)

Deeply Virtual Compton Scattering and GPDs



- $Q^2 = -(e-e')^2$
- $x_B = Q^2/2M\nu$ $\nu = E_e - E_{e'}$
- $x+\xi, x-\xi$ longitudinal momentum fractions
- $t = \Delta^2 = (p-p')^2$
- $\xi \cong x_B/(2-x_B)$

« Handbag » factorization valid in the **Bjorken regime**:
high Q^2 , ν (fixed x_B), $t \ll Q^2$



conserve nucleon spin Vector: $H(x, \xi, t)$ Axial-Vector: $\tilde{H}(x, \xi, t)$
flip nucleon spin Tensor: $E(x, \xi, t)$ Pseudoscalar: $\tilde{E}(x, \xi, t)$

GPDs: Fourier transforms of **non-local, non-diagonal QCD operators**

At leading order QCD, twist 2, chiral-even (quark helicity is conserved), quark sector
 → 4 GPDs for each quark flavor

Properties and “virtues” of GPDs

$$\left. \begin{aligned} \int H(x, \xi, t) dx &= F_1(t) \quad \forall \xi \\ \int E(x, \xi, t) dx &= F_2(t) \quad \forall \xi \\ \int \tilde{H}(x, \xi, t) dx &= G_A(t) \quad \forall \xi \\ \int \tilde{E}(x, \xi, t) dx &= G_P(t) \quad \forall \xi \end{aligned} \right\} \text{Link with FFs}$$

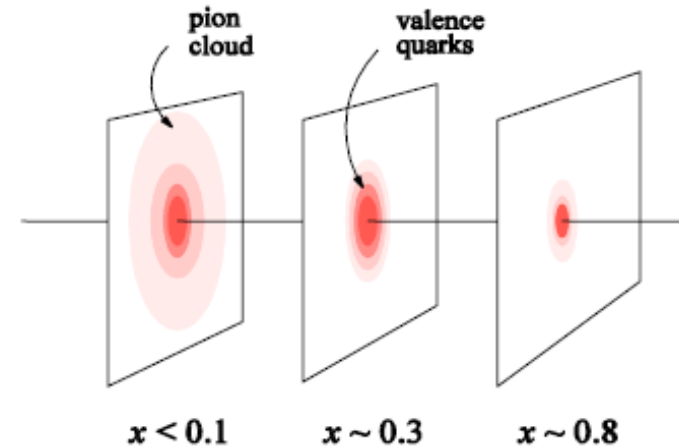
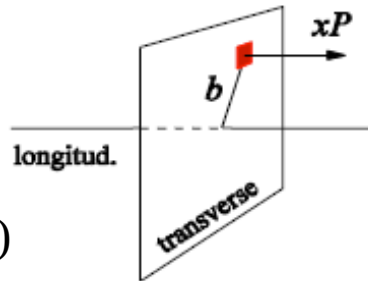
$$\left. \begin{aligned} H(x, 0, 0) &= q(x) \\ \tilde{H}(x, 0, 0) &= \Delta q(x) \end{aligned} \right\} \text{Forward limit: PDFs (not for E, } \tilde{E})$$

Nucleon tomography

$$q(x, b_{\perp}) = \int_0^{\infty} \frac{d^2 \Delta_{\perp}}{(2\pi)^2} e^{i\Delta_{\perp} b_{\perp}} H(x, 0, -\Delta_{\perp}^2)$$

$$\Delta q(x, b_{\perp}) = \int_0^{\infty} \frac{d^2 \Delta_{\perp}}{(2\pi)^2} e^{i\Delta_{\perp} b_{\perp}} \tilde{H}(x, 0, -\Delta_{\perp}^2)$$

M. Burkardt, PRD 62, 71503 (2000)



Quark angular momentum (Ji's sum rule)

$$\frac{1}{2} \int_{-1}^1 x dx (H(x, \xi, t=0) + E(x, \xi, t=0)) = J = \frac{1}{2} \Delta \Sigma + \Delta L$$

X. Ji, Phy.Rev.Lett.78,610(1997)

$$\text{Nucleon spin: } \frac{1}{2} = \underbrace{\frac{1}{2} \Delta \Sigma + \Delta L}_{J} + \Delta G$$

Intrinsic spin of the quarks $\Delta \Sigma \approx 25\%$

Intrinsic spin on the gluons $\Delta G \approx 0$ (??)

Orbital angular momentum of the quarks ΔL ?

Extraction des Facteurs de Forme Compton des observables DVCS

On ne peut extraire directement les GPDs des observables DVCS, nous avons accès aux **Facteurs de Forme Compton**:

$$\begin{array}{l} \text{8 CFF} \left\{ \begin{array}{l} \text{Re}(\mathcal{H}) = P \int_0^1 dx [H(x, \xi, t) - H(-x, \xi, t)] C^+(x, \xi) \\ \text{Re}(\mathcal{E}) = P \int_0^1 dx [E(x, \xi, t) - E(-x, \xi, t)] C^+(x, \xi) \\ \text{Re}(\tilde{\mathcal{H}}) = P \int_0^1 dx [\tilde{H}(x, \xi, t) + \tilde{H}(-x, \xi, t)] C^-(x, \xi) \\ \text{Re}(\tilde{\mathcal{E}}) = P \int_0^1 dx [\tilde{E}(x, \xi, t) + \tilde{E}(-x, \xi, t)] C^-(x, \xi) \\ \text{Im}(\mathcal{H}) = H(\xi, \xi, t) - H(-\xi, \xi, t) \\ \text{Im}(\mathcal{E}) = E(\xi, \xi, t) - E(-\xi, \xi, t) \\ \text{Im}(\tilde{\mathcal{H}}) = \tilde{H}(\xi, \xi, t) - \tilde{H}(-\xi, \xi, t) \\ \text{Im}(\tilde{\mathcal{E}}) = \tilde{E}(\xi, \xi, t) - \tilde{E}(-\xi, \xi, t) \end{array} \right. \\ \text{with } C^\pm(x, \xi) = \frac{1}{x - \xi} \pm \frac{1}{x + \xi} \end{array}$$

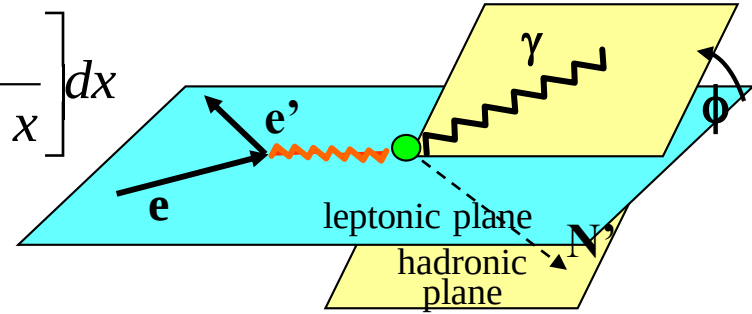
M. Guidal: Fit indépendant du modèle, à cinématique fixée (Q^2 , x_B , t) des observables DVCS
8 paramètres (les CFFs), peu de contraintes (+/- 5 x prédiction du modèle VGG)

M. Guidal, Eur. Phys. J. A 37 (2008) 319 & plein d'autres articles...

Sensitivity to GPDs of DVCS spin observables

$$Re\mathcal{H}_q = e_q^2 P \int_0^{+1} \left(H^q(x, \xi, t) - H^q(-x, \xi, t) \right) \left[\frac{1}{\xi - x} + \frac{1}{\xi + x} \right] dx$$

$$Im\mathcal{H}_q = \pi e_q^2 \left[H^q(\xi, \xi, t) - H^q(-\xi, \xi, t) \right]$$

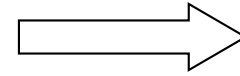


$$\xi = x_B / (2 - x_B) \quad k = -t / 4M^2$$

Proton Neutron

Polarized **beam**, unpolarized target:

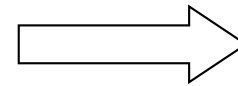
$$\Delta\sigma_{LU} \sim \sin\phi \, \text{Im}\{F_1 \mathcal{H} + \xi(F_1 + F_2) \tilde{\mathcal{H}} - k F_2 \mathcal{E}\} d\phi$$



$$\begin{aligned} & Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\} \\ & Im\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n\} \end{aligned}$$

Unpolarized beam, **longitudinal** target:

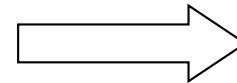
$$\Delta\sigma_{UL} \sim \sin\phi \, \text{Im}\{F_1 \tilde{\mathcal{H}} + \xi(F_1 + F_2)(\mathcal{H} + x_B/2 \mathcal{E}) - \xi k F_2 \tilde{\mathcal{E}} + \dots\} d\phi$$



$$\begin{aligned} & Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\} \\ & Im\{\mathcal{H}_n, \mathcal{E}_n, \tilde{\mathcal{E}}_n\} \end{aligned}$$

Polarized **beam**, **longitudinal** target:

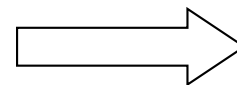
$$\Delta\sigma_{LL} \sim (A + B \cos\phi) \, \text{Re}\{F_1 \tilde{\mathcal{H}} + \xi(F_1 + F_2)(\mathcal{H} + x_B/2 \mathcal{E}) \dots\} d\phi$$



$$\begin{aligned} & Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\} \\ & Re\{\mathcal{H}_n, \mathcal{E}_n, \tilde{\mathcal{E}}_n\} \end{aligned}$$

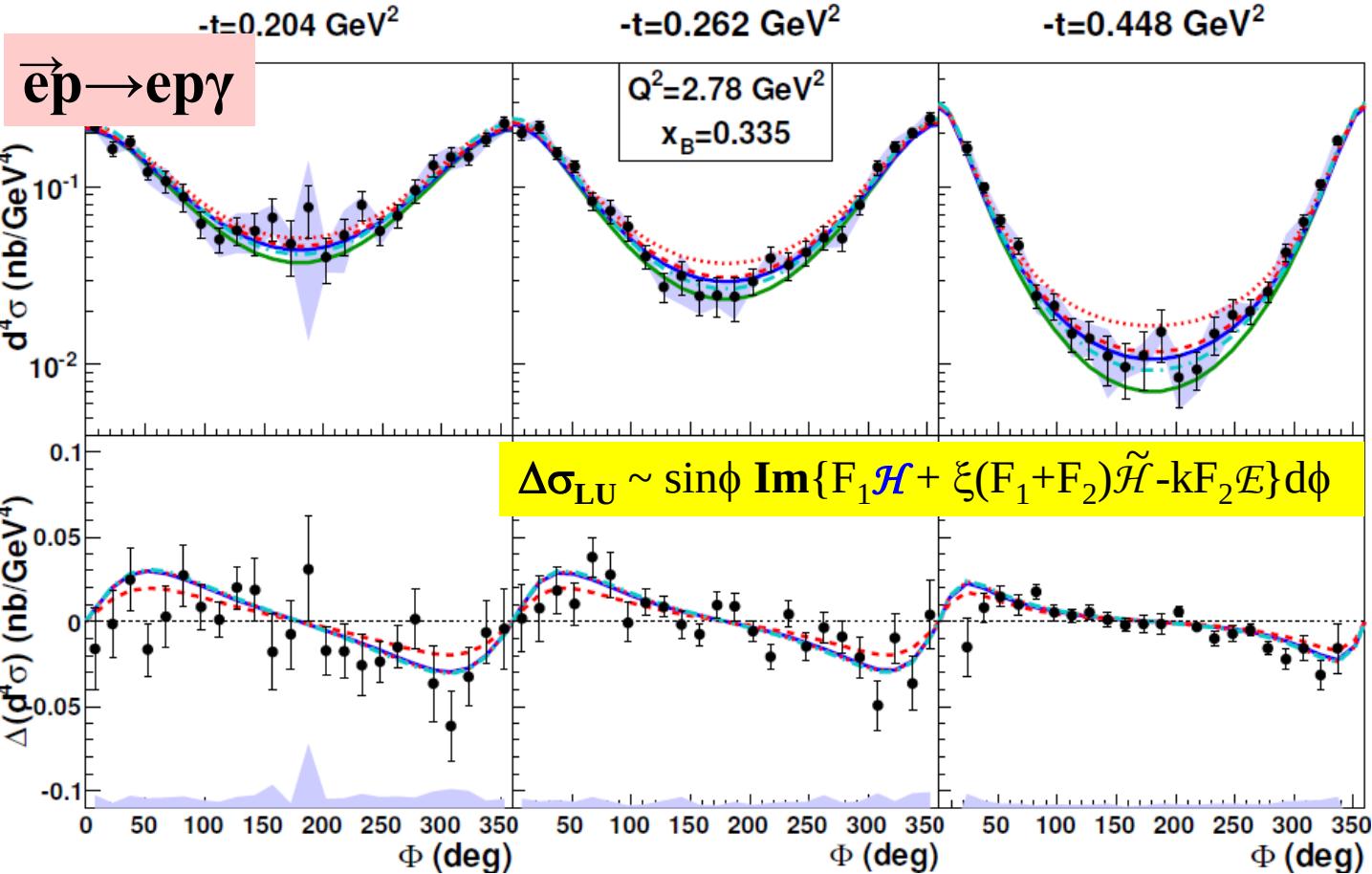
Unpolarized beam, **transverse** target:

$$\Delta\sigma_{UT} \sim \sin\phi \, \text{Im}\{k(F_2 \mathcal{H} - F_1 \mathcal{E}) + \dots\} d\phi$$



$$\begin{aligned} & Im\{\mathcal{H}_p, \mathcal{E}_p\} \\ & Im\{\mathcal{H}_n\} \end{aligned}$$

CLAS: unpolarized and beam-polarized cross sections



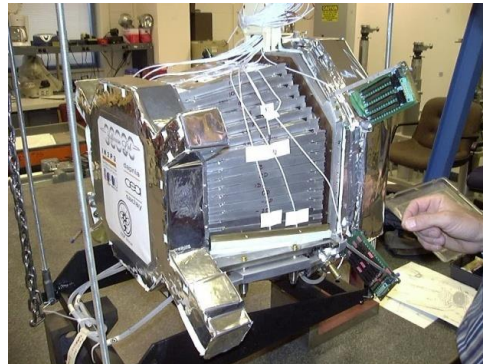
H.S. Jo et al., PRL
115, 212003 (2015)

- Largest kinematic ever covered
- Two observables extracted

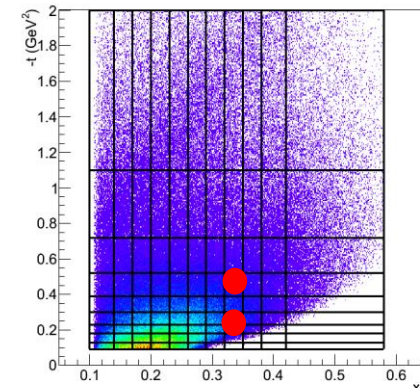
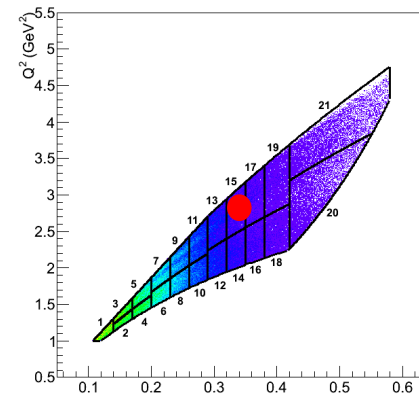
— BH — VGG
..... KM10 --- KM10a

KM10 model fits Hall A
2006 data using
« anomalous » H

- Data taken in 2005, e1-dvcs
- Beam energy $\sim 5.75 \text{ GeV}$
- Beam polarization $\sim 80\%$
- Target LH_2
- Inner Calorimeter (IC)



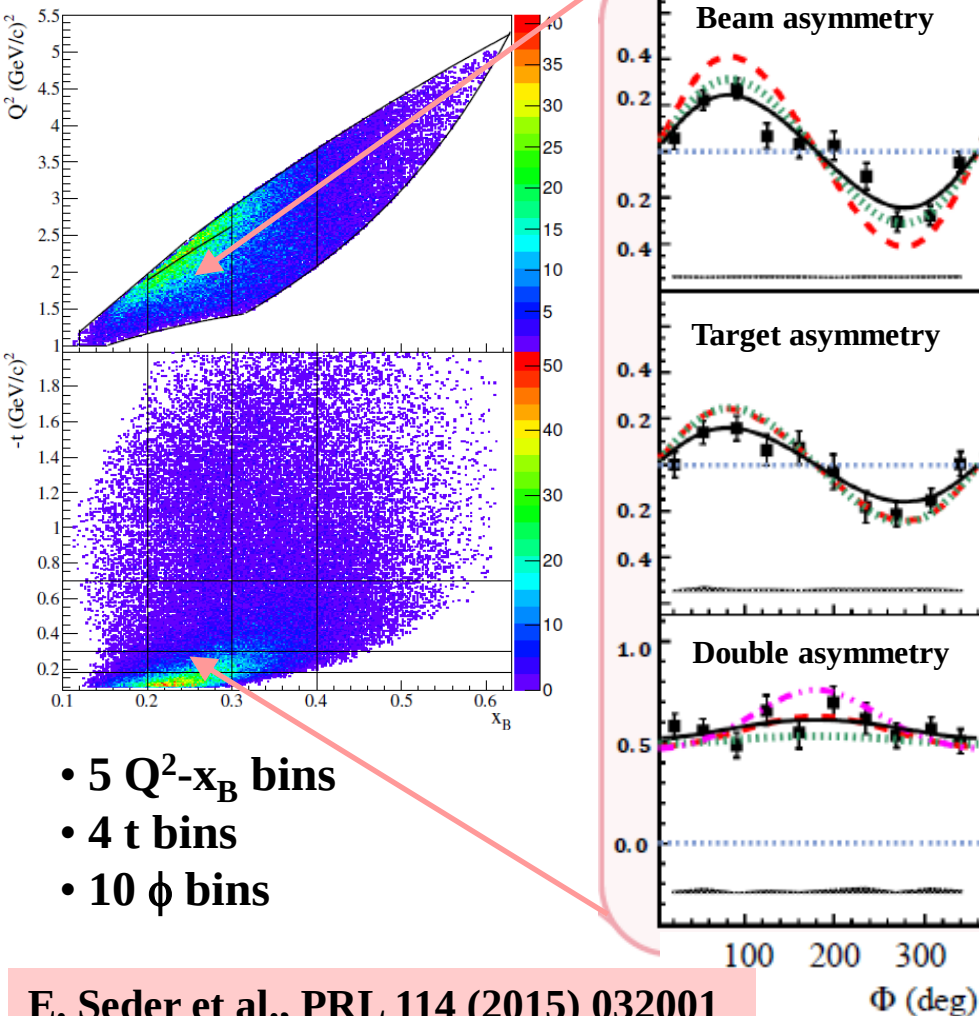
21 Q^2 - x_B bins, 9 t
bins, 24 ϕ bins



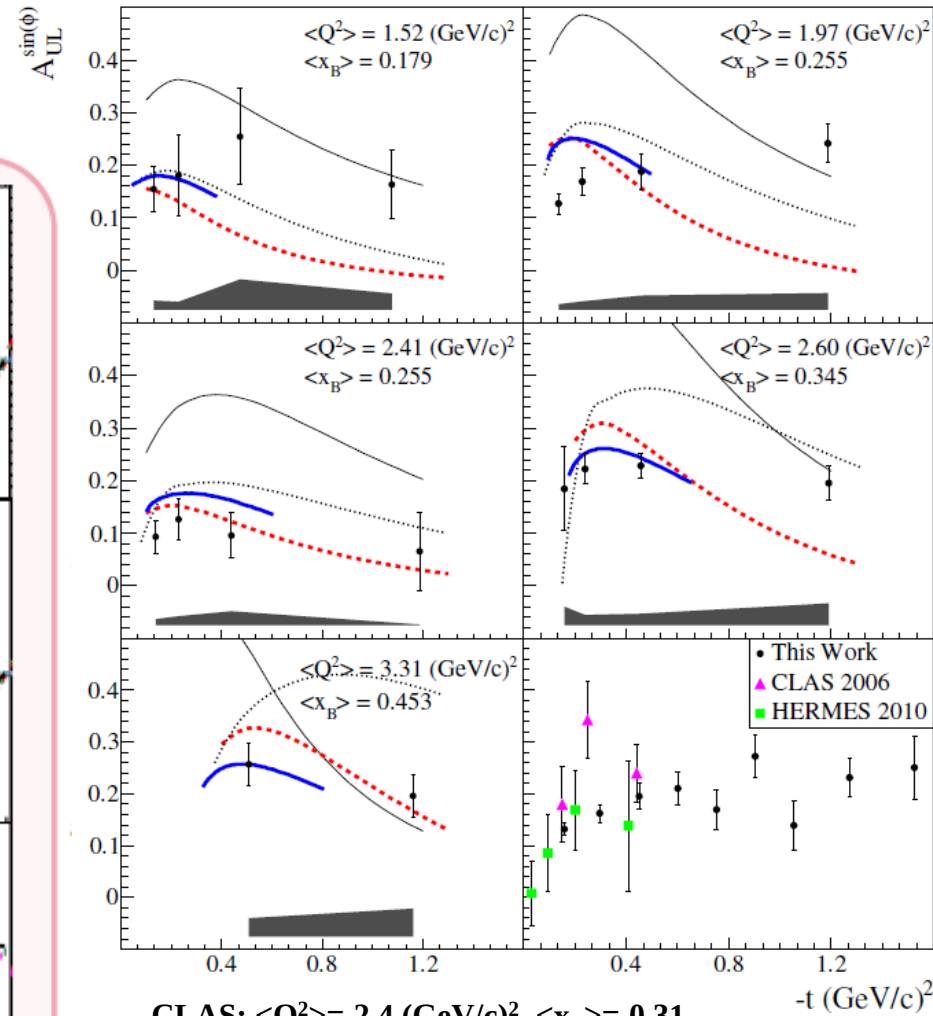
CLAS: DVCS avec cible polarisée longitudinalement

$$\vec{e}\vec{p} \rightarrow e\vec{p}\gamma$$

- Données prises en 2009, eg1-dvcs
- Energie faisceau ~ 5.9 GeV
- CLAS + IC
- Cible de NH_3 polarisée longitudinalement ($P \sim 80\%$)
- **3 observables DVCS**



$$\text{TSA} \sim \text{Im}\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$$



CLAS: $\langle Q^2 \rangle = 2.4 \text{ (GeV/c}^2)^2$, $\langle x_B \rangle = 0.31$

HERMES: $\langle Q^2 \rangle = 2.459 \text{ (GeV/c}^2)^2$, $\langle x_B \rangle = 0.096$

CLAS2006: $\langle Q^2 \rangle = 1.82 \text{ (GeV/c}^2)^2$, $\langle x_B \rangle = 0.28$

- Statistique améliorée x10 à bas $-t$
- Couverture cinématique plus grande

Extraction des CFFs des TSA, BSA, DSA de CLAS

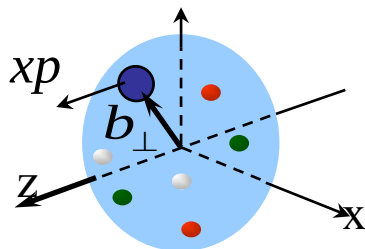
Programme de fit de M. Guidal
(7 CFFs inclus dans le fit)

$Im\tilde{\mathcal{H}}$: pente en t plus forte que $Im\mathcal{H}$
 $\rightarrow$ la charge axiale est plus
 “concentrée” de la charge
 électrique
 $\rightarrow$ TOMOGRAPHIE DU PROTON

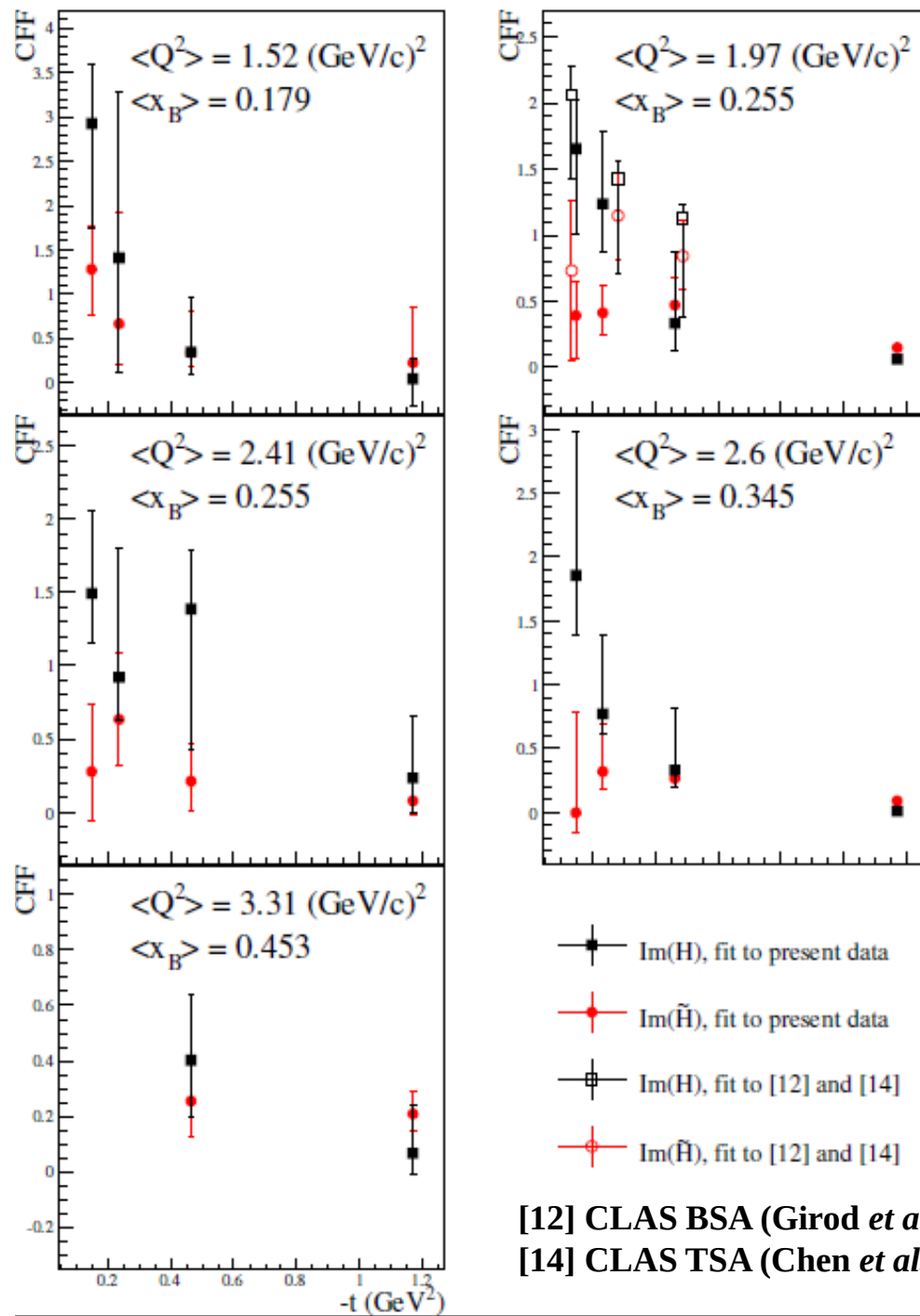
$$\Delta q(x, b_{\perp}) = \int_0^{\infty} \frac{d^2 \Delta_{\perp}}{(2\pi)^2} e^{i\Delta_{\perp} b_{\perp}} \tilde{H}(x, 0, -\Delta_{\perp}^2)$$

$$\int H(x, \xi, t) dx = F_1(t)$$

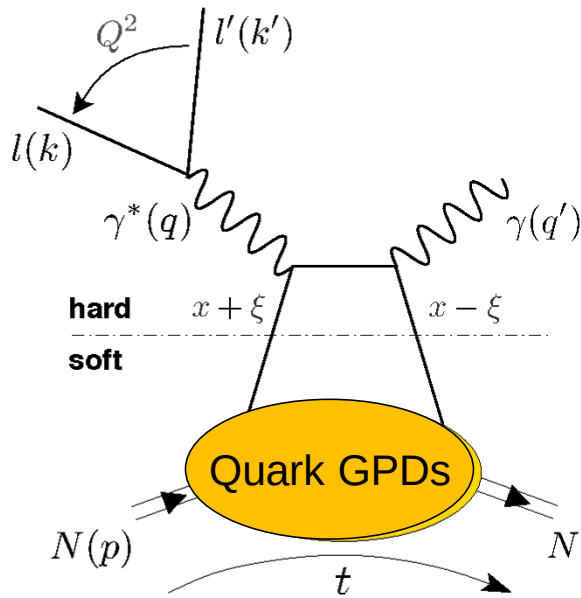
$$\int \tilde{H}(x, \xi, t) dx = G_A(t)$$



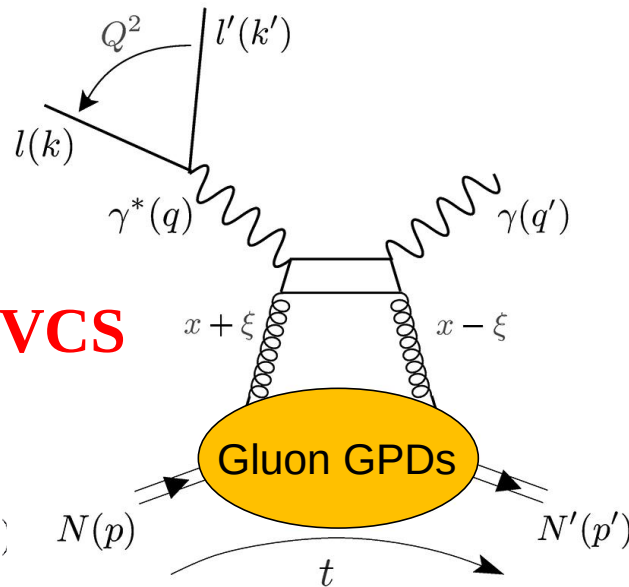
S. Pisano et al., PRD 91, 052014 (2015)



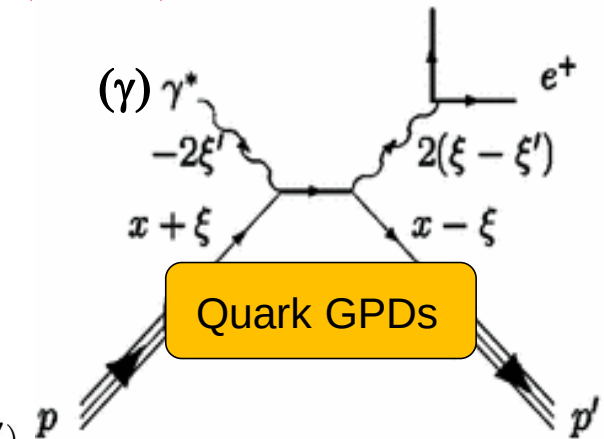
Exclusive reactions giving access to GPDs



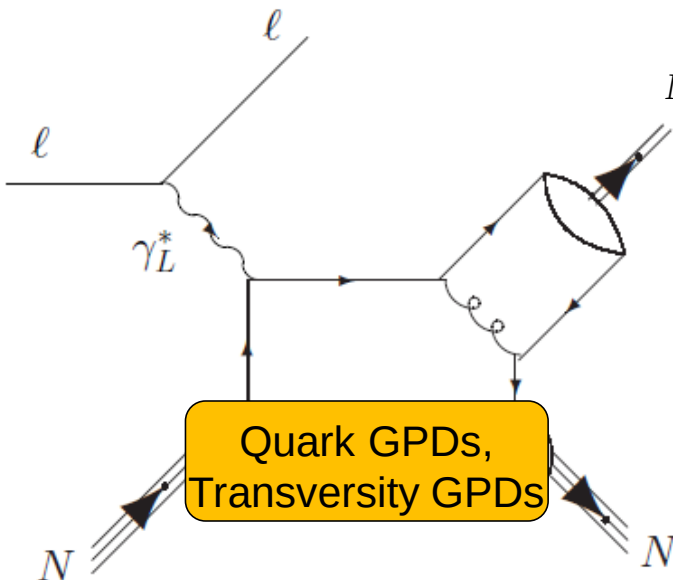
DVCS



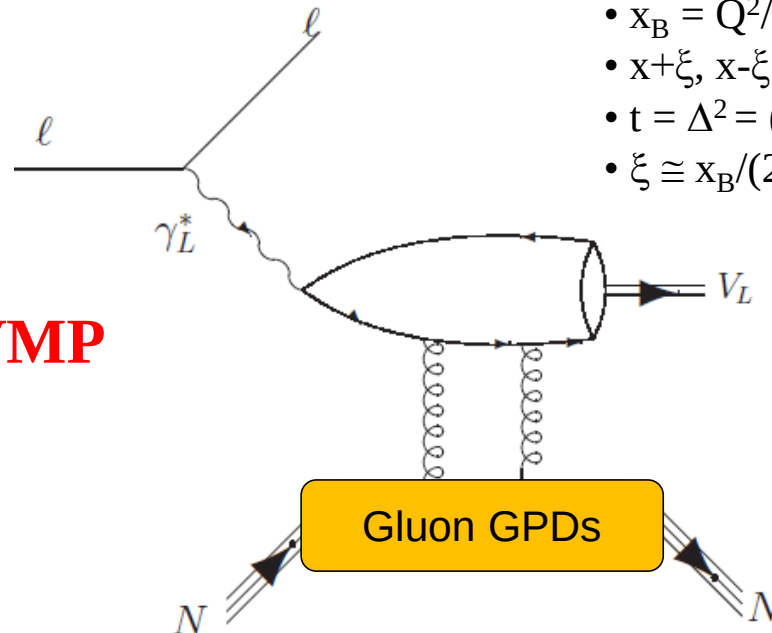
(TCS), DDVCS



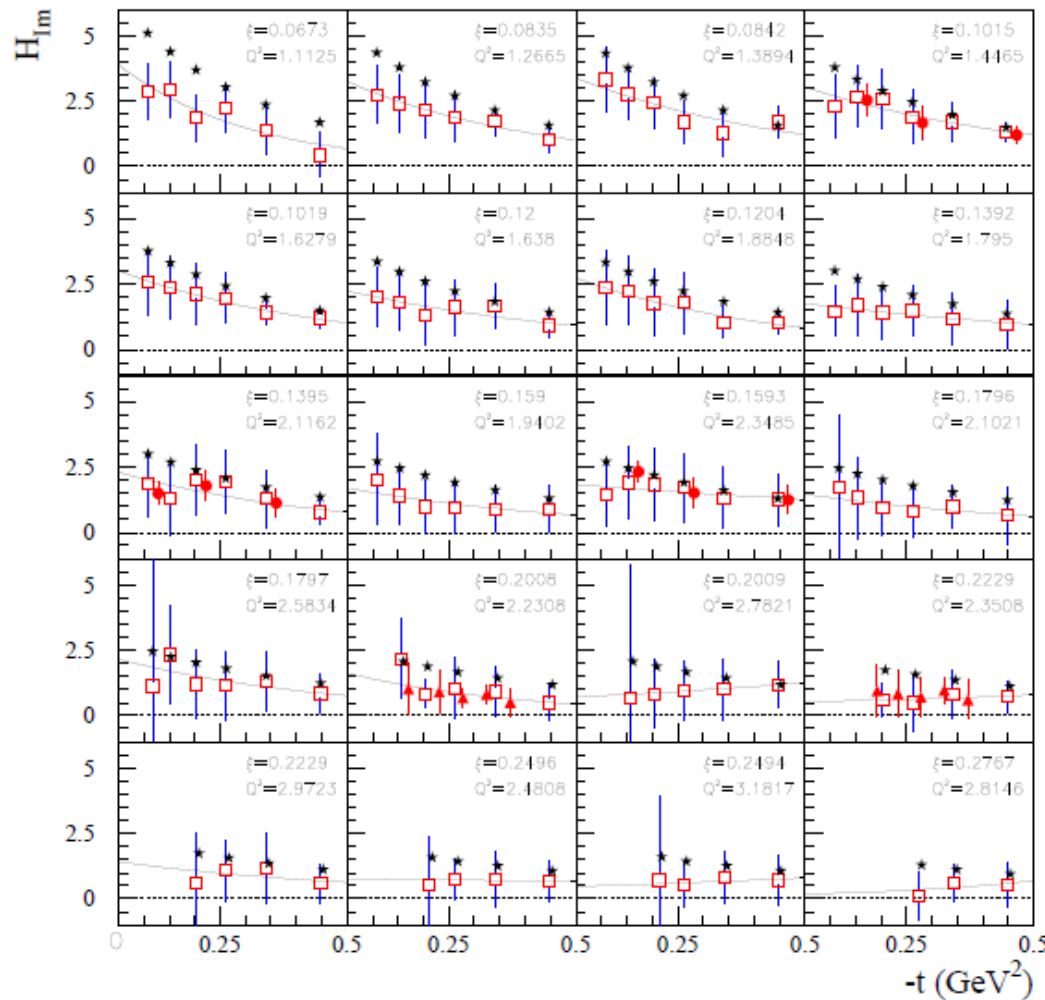
- $Q^2 = -(k-k')^2$
- $x_B = Q^2/2Mv$ $v = E_e - E_{e'}$
- $x + \xi, x - \xi$ long. mom. fract.
- $t = \Delta^2 = (p-p')^2$
- $\xi \cong x_B/(2-x_B)$



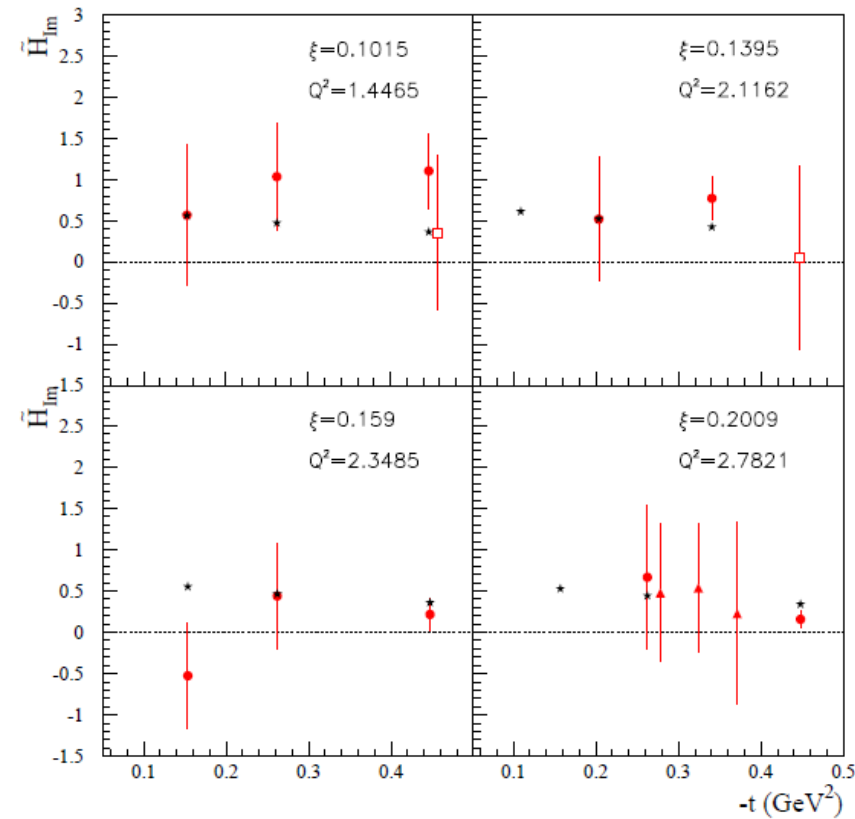
DVMP



Results for H_{Im} and $\tilde{H}_{Im}$ from the fits of JLab 2015 data



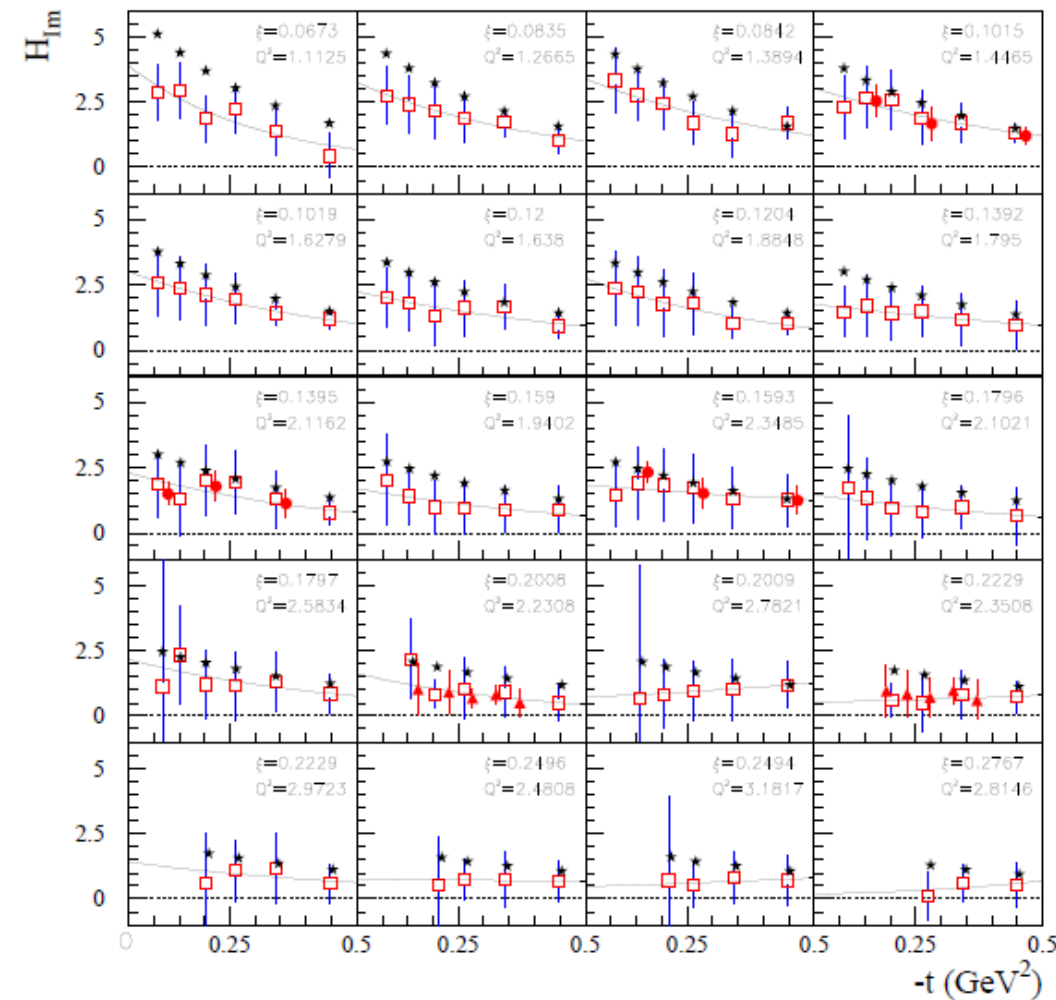
- Fit to CLAS c.s. and beam pol. c.s.
- Fit to CLAS c.s., beam pol. c.s., ITSA, DSA
- ▲ Fit to Hall A c.s. and beam pol. c.s.
- ★ VGG model



H_{Im} has steeper t -slope than $\tilde{H}_{Im}$: the axial charge ($\sim \Delta u - \Delta d$) is more “concentrated” than the electric charge

R. Dupré, M. Guidal, S. Niccolai,
M. Vanderhaegen, arXiv: 1704.07330

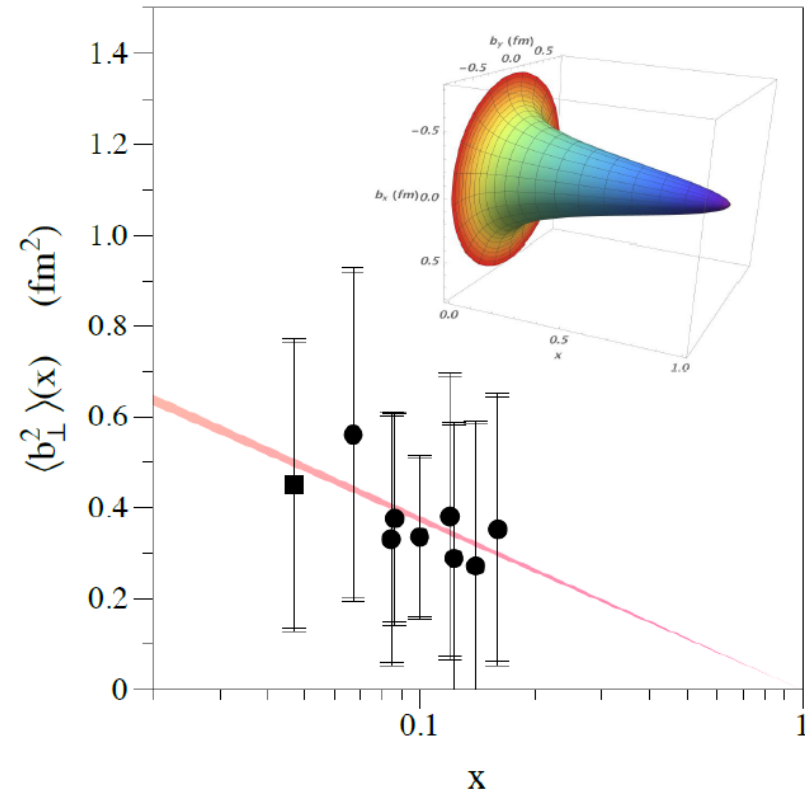
From CFFs to proton tomography



$$\mathcal{H}_{Im}(\xi, t) = A(\xi)e^{B(\xi)t}$$

$$A(\xi) = a_A(1 - \xi)/\xi \quad a_A = 0.36 \pm 0.06$$

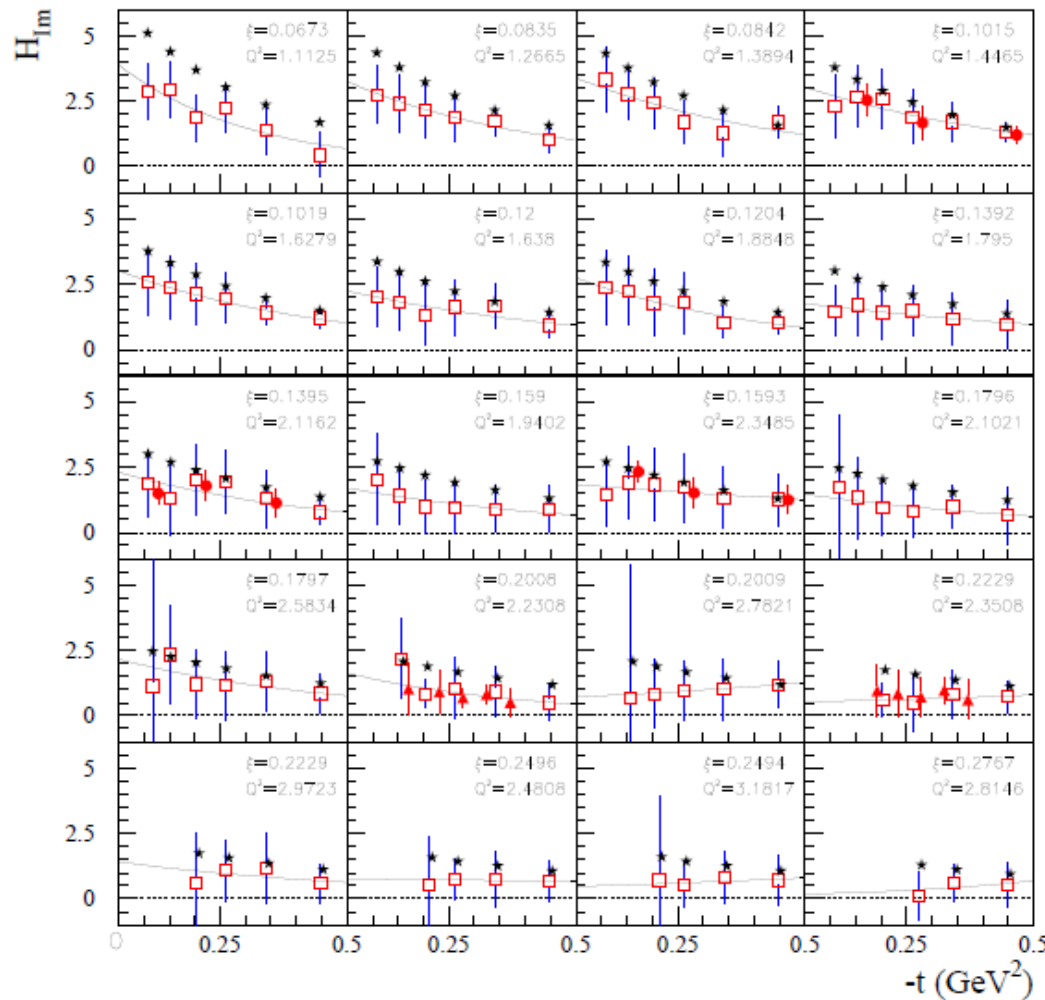
$$B(\xi) = a_B \ln(1/\xi) \quad a_B = 1.07 \pm 0.26 \text{ GeV}^{-2}$$



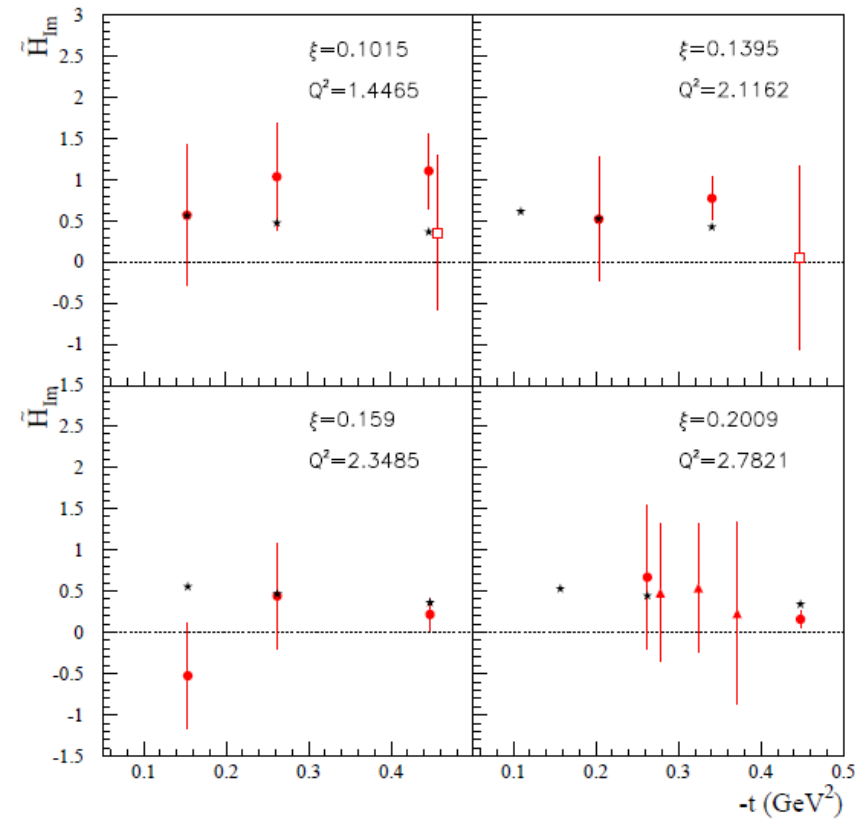
« Integrated » radius from elastic form factor F_1 :

$$\langle b_{\perp}^2 \rangle = 0.43 \pm 0.01 \text{ fm}^2$$

Results for H_{Im} and $\tilde{H}_{Im}$ from the fits of JLab 2015 data

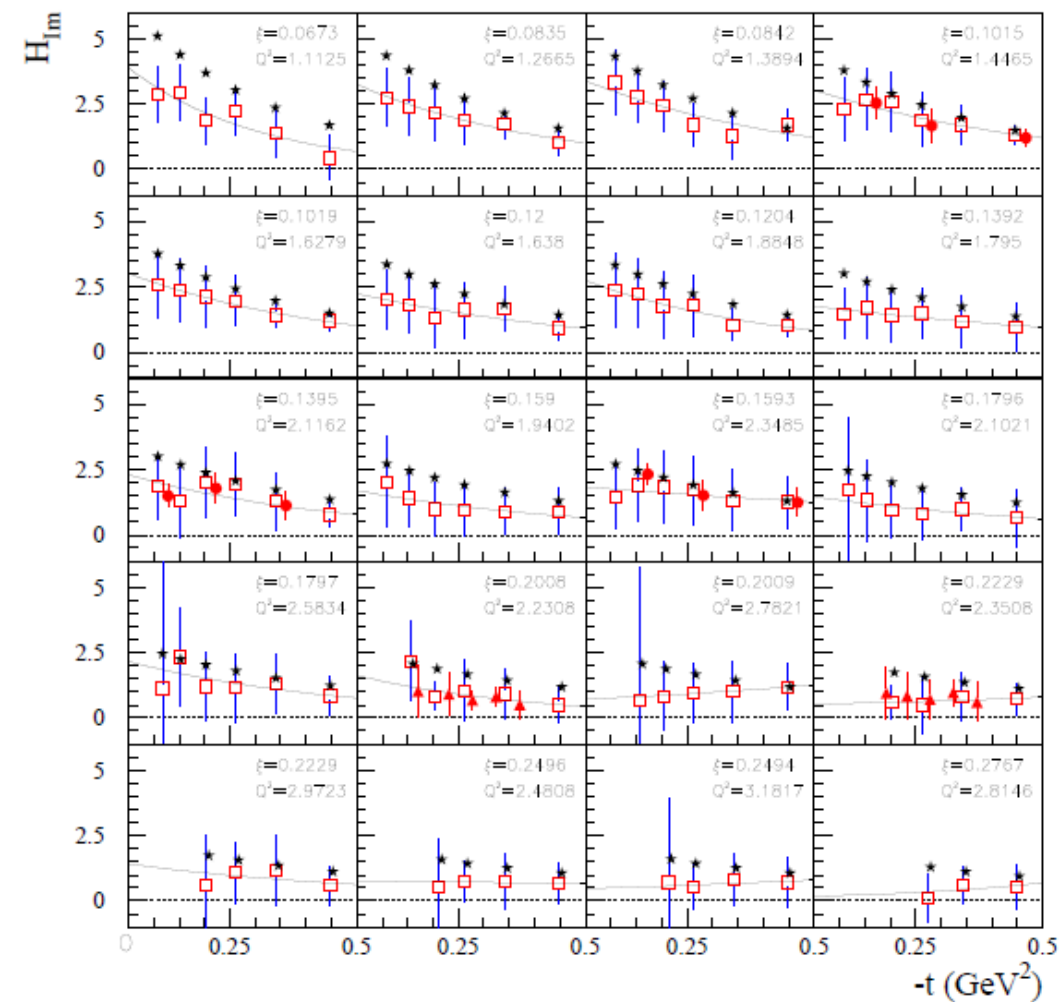


- Fit to CLAS c.s. and beam pol. c.s.
- Fit to CLAS c.s., beam pol. c.s., ITSA, DSA
- ▲ Fit to Hall A c.s. and beam pol. c.s.
- ★ VGG model



H_{Im} has steeper t -slope than $\tilde{H}_{Im}$: the axial charge is more “concentrated” than the electric charge

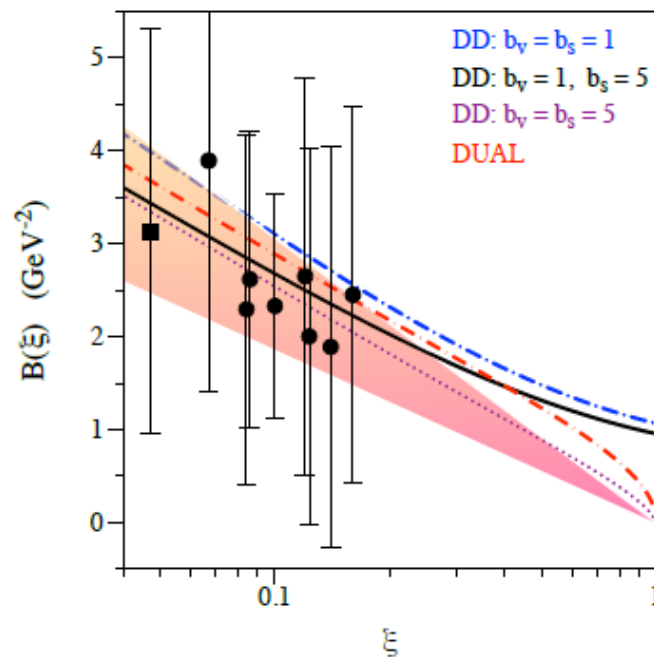
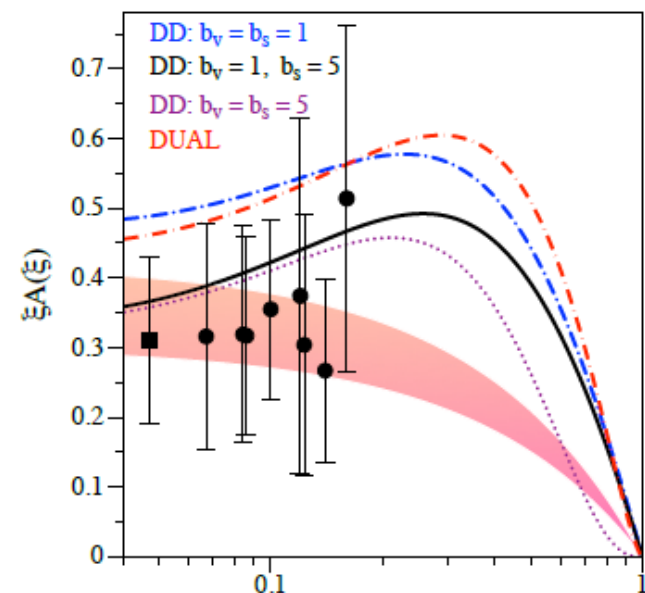
From CFFs to proton tomography



$$\mathcal{H}_{Im}(\xi, t) = A(\xi) e^{B(\xi)t}$$

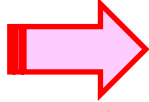
$$A(\xi) = a_A (1 - \xi) / \xi \quad a_A = 0.36 \pm 0.06$$

$$B(\xi) = a_B \ln(1/\xi) \quad a_B = 1.07 \pm 0.26 \text{ GeV}^{-2}$$



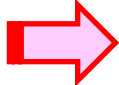
From CFFs to proton tomography

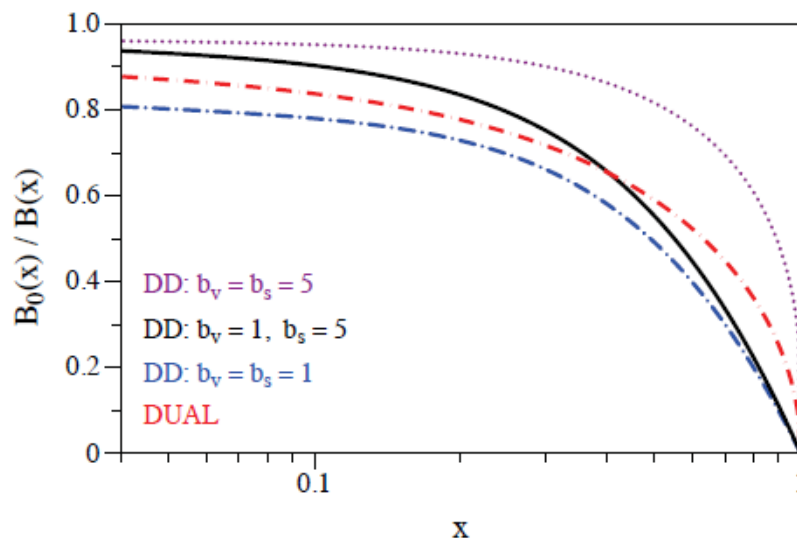
$$\rho^q(x, \mathbf{b}_\perp) = \int \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{-i\mathbf{b}_\perp \cdot \Delta_\perp} H_-^q(x, 0, -\Delta_\perp^2) \quad \langle b_\perp^2 \rangle^q(x) = -4 \frac{\partial}{\partial \Delta_\perp^2} \ln H_-^q(x, 0, -\Delta_\perp^2) \Big|_{\Delta_\perp=0}$$

If $H_-^q(x, 0, t) = q_v(x) e^{B_0(x)t}$  $\langle b_\perp^2 \rangle^q(x) = 4B_0(x)$.

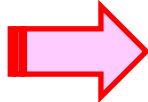
However, this formula involves: $H_-^q(x, 0, t) \equiv H^q(x, 0, t) + H^q(-x, 0, t)$

While we extract: $H_+^q(x, \xi, t) \equiv H^q(x, \xi, t) - H^q(-x, \xi, t)$

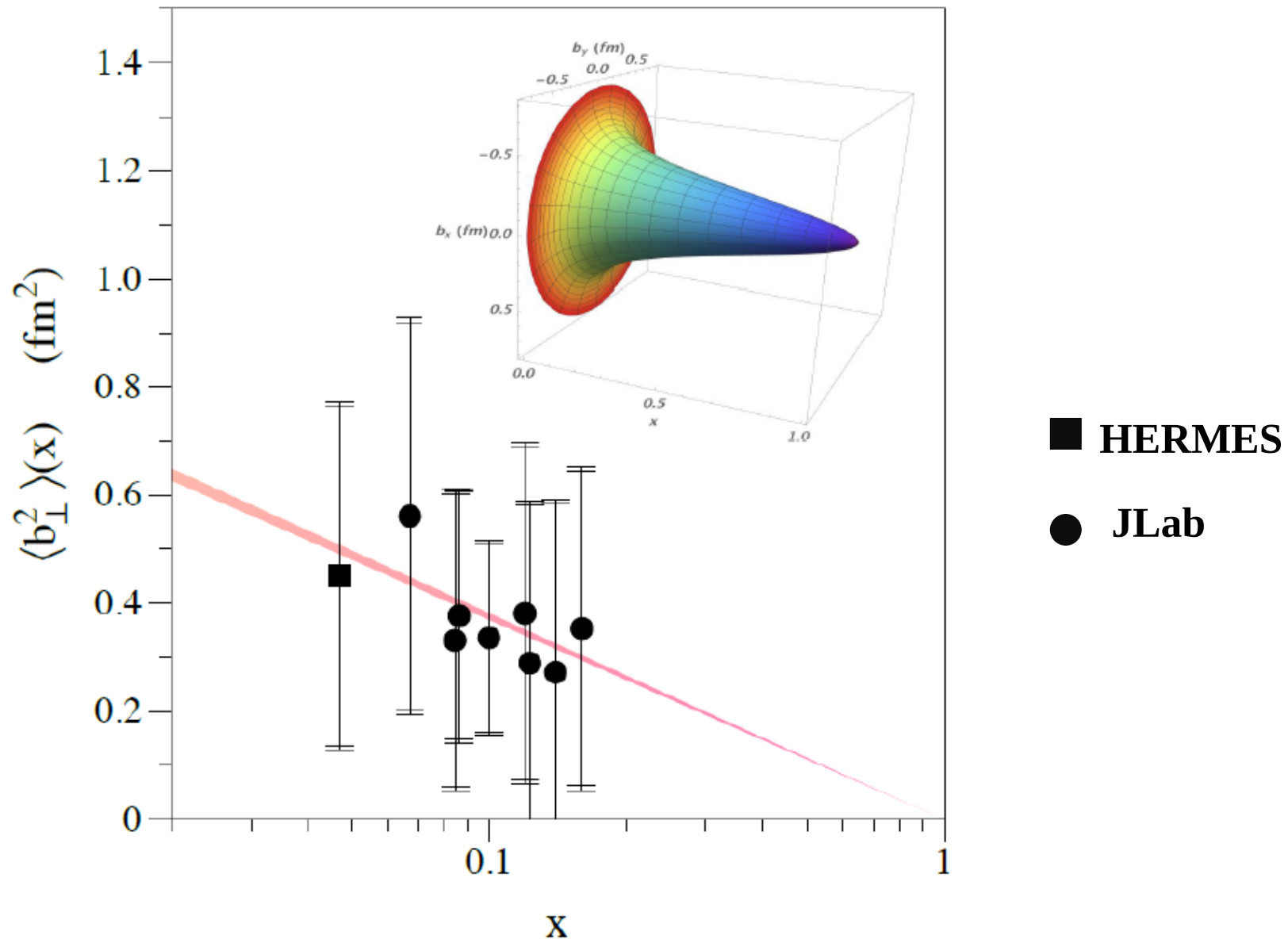
 **Need to estimate:** $B_0(x)/B(x)$ (assuming $H_-^q(x, 0, t) = q_v(x) e^{B_0(x)t}$)



$$0.90 < B_0/B < 0.95 \quad \text{for} \quad 0.05 \lesssim x \lesssim 0.2$$

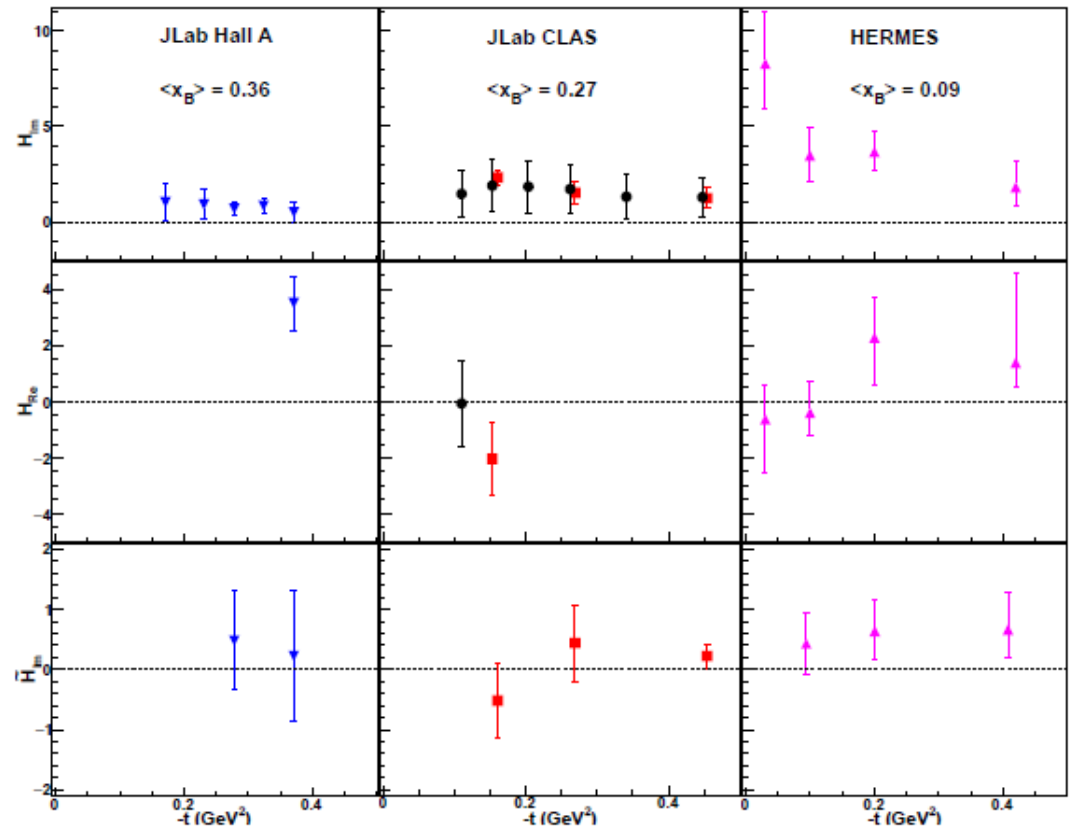
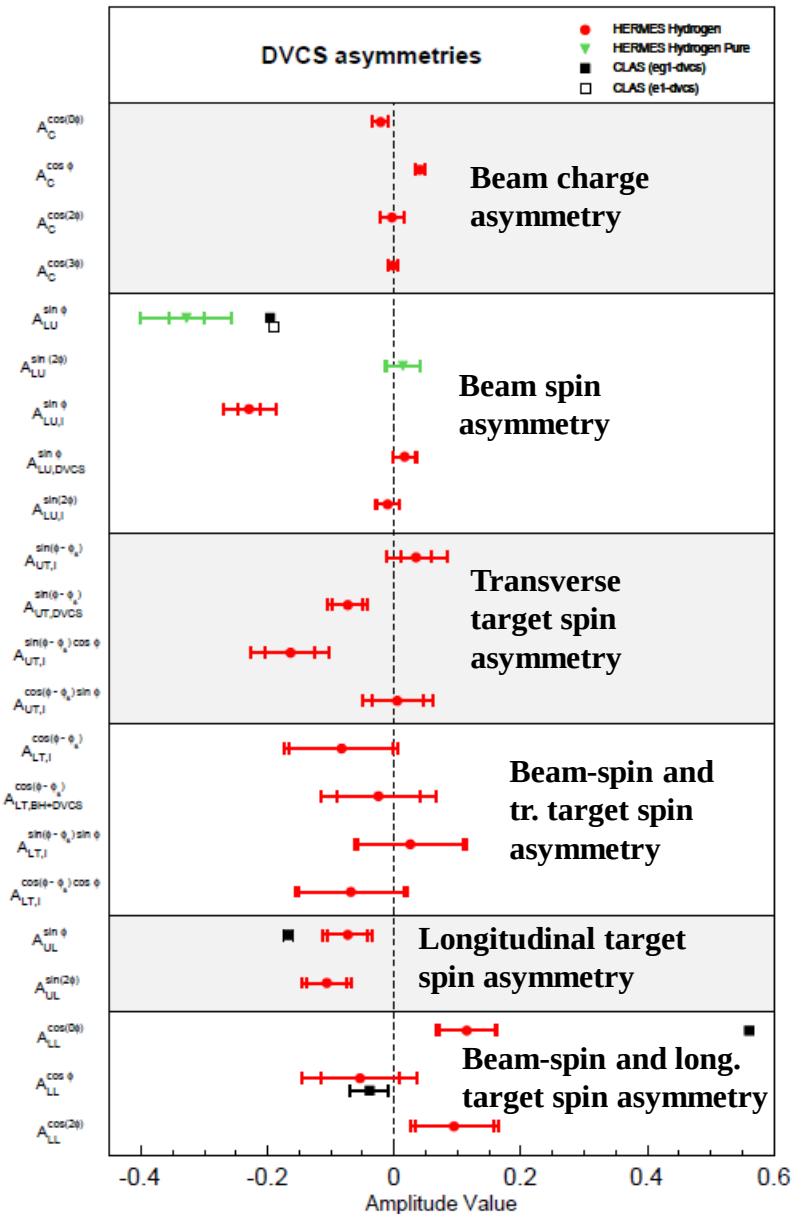
 $B_0/B \simeq 0.925 \pm 0.025$

From CFFs to proton tomography



« Integrated » radius from elastic form factor F1: $\langle b_{\perp}^2 \rangle = 0.43 \pm 0.01 \text{ fm}^2$

Summary of proton-DVCS spin observables and GPDs extraction



Hall A (2015)

CLAS C.S.
CLAS C.S.
+TSA+DSA

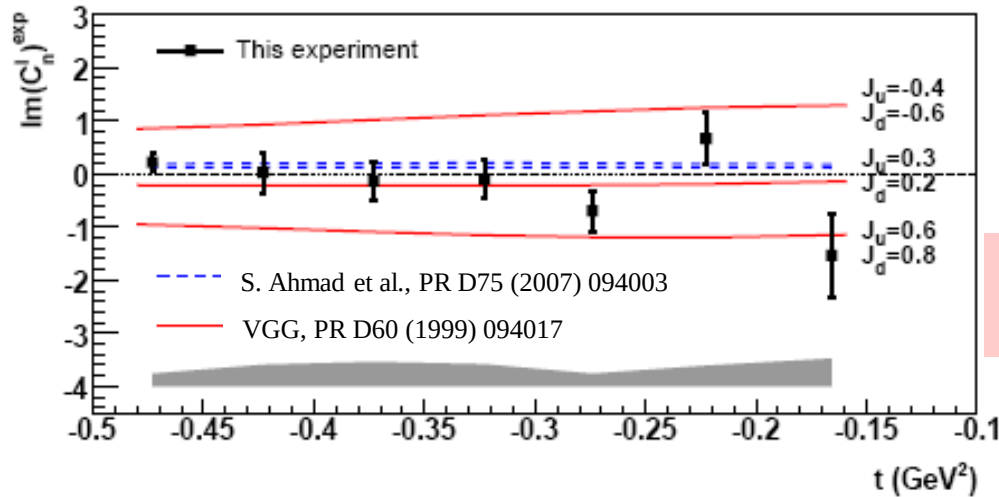
HERMES

**Beam Charge
Asymmetry: strong
constraint for H_{Re}**

$\vec{e}d \rightarrow e\gamma(np)$

DVCS on the neutron in Hall A

M. Mazouz et al., PRL 99 (2007) 242501



Proton and neutron GPDs (and CFFs) are **linear combinations** of quark GPDs

$$\mathcal{H}_p(\xi, t) = \frac{4}{9} \mathcal{H}_u(\xi, t) + \frac{1}{9} \mathcal{H}_d(\xi, t)$$

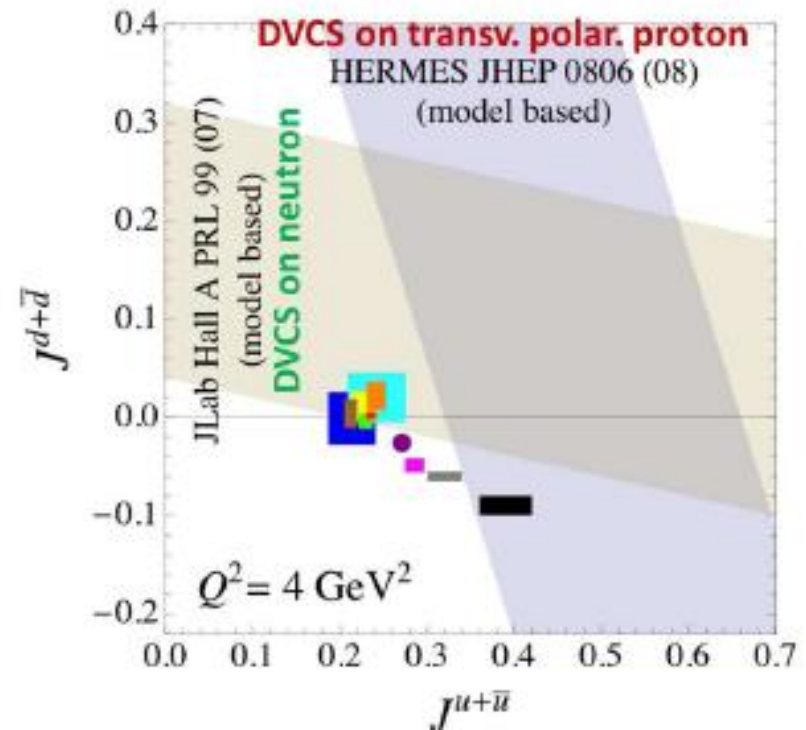
$$\mathcal{H}_n(\xi, t) = \frac{1}{9} \mathcal{H}_u(\xi, t) + \frac{4}{9} \mathcal{H}_d(\xi, t)$$

A **combined analysis** of DVCS observables for **proton and neutron targets** is necessary to perform a **quark-flavor separation** of the GPDs

$$\Delta\sigma_{LU} \sim \sin\phi \operatorname{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E}\}$$

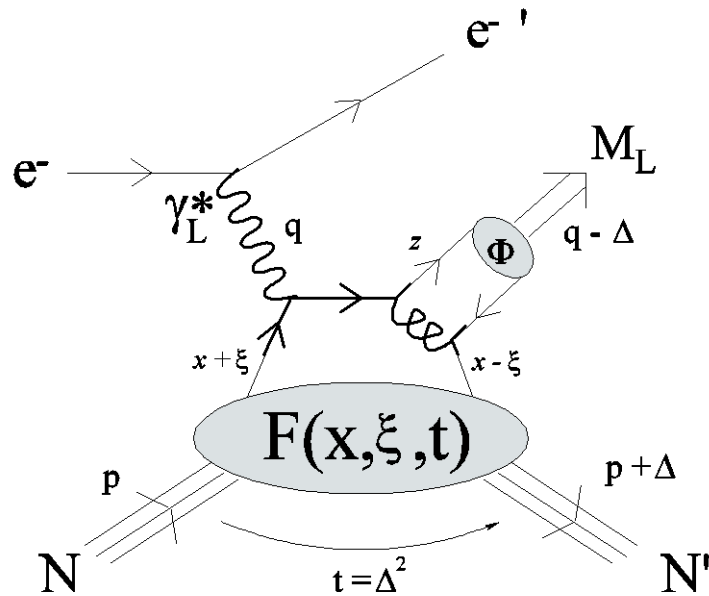
$$\frac{1}{2} \int_{-1}^1 x dx (H(x, \xi, t=0) + E(x, \xi, t=0)) = J$$

• **E03-106: First-time measurement of $\Delta\sigma_{LU}$ for nDVCS, model-dependent extraction of J_u, J_d**



• **E08-025: Beam-energy « Rosenbluth » separation of nDVCS CS using an LD2 target**

Deeply virtual meson production and GPDs



Different mesons → different sensitivity to GPDs

H
E
↓

Vector mesons
(ρ , ω , ϕ)

$\tilde{\mathbf{H}}$
 $\tilde{\mathbf{E}}$
↓

Pseudoscalar
mesons (π , η)

π^0	$2\Delta u + \Delta d$
η	$2\Delta u - \Delta d$
ρ^0	$2u + d$
ω	$2u - d$
ρ^+	$u - d$

Factorization proven only for
longitudinally polarized virtual photons

quark flavor decomposition
accessible via meson production

$$\mathcal{A}_L = -\frac{2ie}{9} \left(\int_0^1 dz \frac{\Phi(z)}{z} \right) \frac{4\pi\alpha_S(Q^2)}{Q} \int_{-1}^{+1} dx \left\{ \left[\frac{1}{x - \xi + i\epsilon} + \frac{1}{x + \xi - i\epsilon} \right] F(x, \xi, t) \right\}$$

Complications: effective scale in the hard scattering process, meson distribution amplitude

Production exclusive de mésons (DVMP) à CLAS

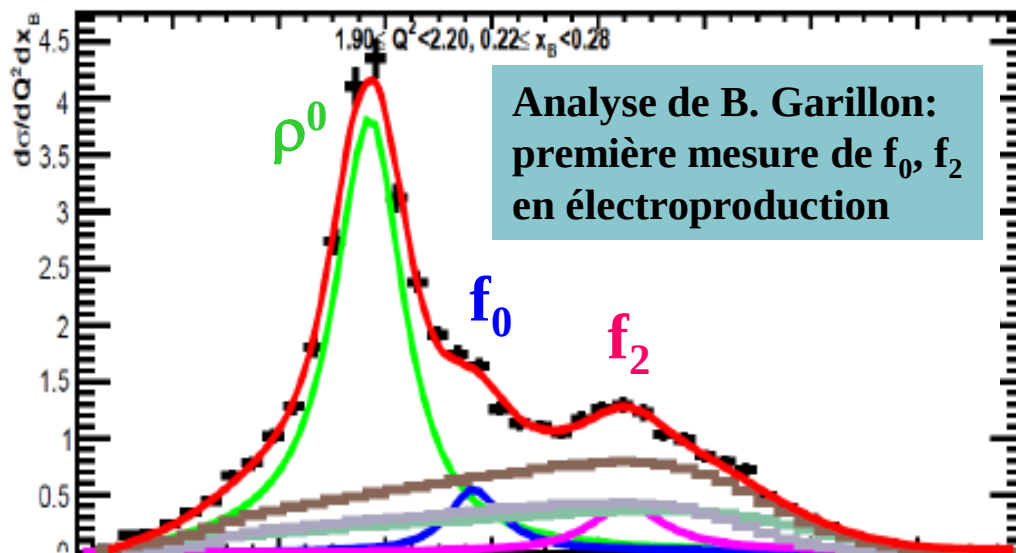
80% des analyses de DVMP à CLAS ont la participation directe de l'équipe IPN

- K. Lukashin *et al.*, Phys. Rev. C 63, 065205, 2001 (ϕ @4.2 GeV)
 C. Hadjidakis *et al.*, Phys. Lett. B 605, 256-264, 2005 (ρ^0 @4.2 GeV)
 L. Morand *et al.*, Eur. Phys. J. A 24, 445-458, 2005 (ω @5.75 GeV)
 J. Santoro *et al.*, Phys. Rev. C 78, 025210, 2008 (ϕ @5.75 GeV)
 S. Morrow *et al.*, Eur. Phys. J. A 39, 5-31, 2009 (ρ^0 @5.75 GeV)
B. Garillon, IPN PhD thesis (2015) (f_0, f_2 @5.75 GeV)
 K. Park *et al.*, Phys. Rev. C 77, 015208, 2008 (π^+ @5.75 GeV)
A. Fradi, IPN PhD thesis (2009) (ρ^+ @5.75 GeV)
 R. De Masi *et al.*, Phys. Rev. C 77, 042201(R), 2008 (π^0 @5.75 GeV)
 I. Bedlinskiy *et al.*, Phys. Rev. Lett. 109, 112001, 2012
 et Phys. Rev. C 90, 039901, 2014 (π^0 @5.75 GeV)

e1-b
(1999)

e1-6
(2001)

e1-DVCS
(2005)



Mésons vecteurs : ρ^0, ω, ϕ and ρ^+
 → sensibles aux GPDs H et E

Mésons pseudoscalaires : π, η →
 sensibles aux GPDs de transversité

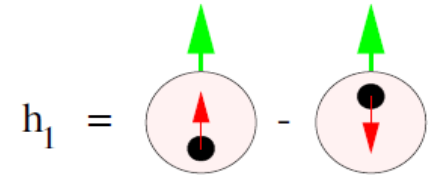
Chiral-odd GPDs

- 4 chiral-odd GPDs (parton helicity flip)
- Difficult to access (helicity flip processes are **suppressed**)
- Chiral-odd GPDs are very **little constrained**
- Anomalous tensor magnetic moment:

$$\kappa_T = \int_{-1}^{+1} dx \bar{E}_T(x, \xi, t=0) \quad \bar{E}_T = 2\tilde{H}_T + E_T$$

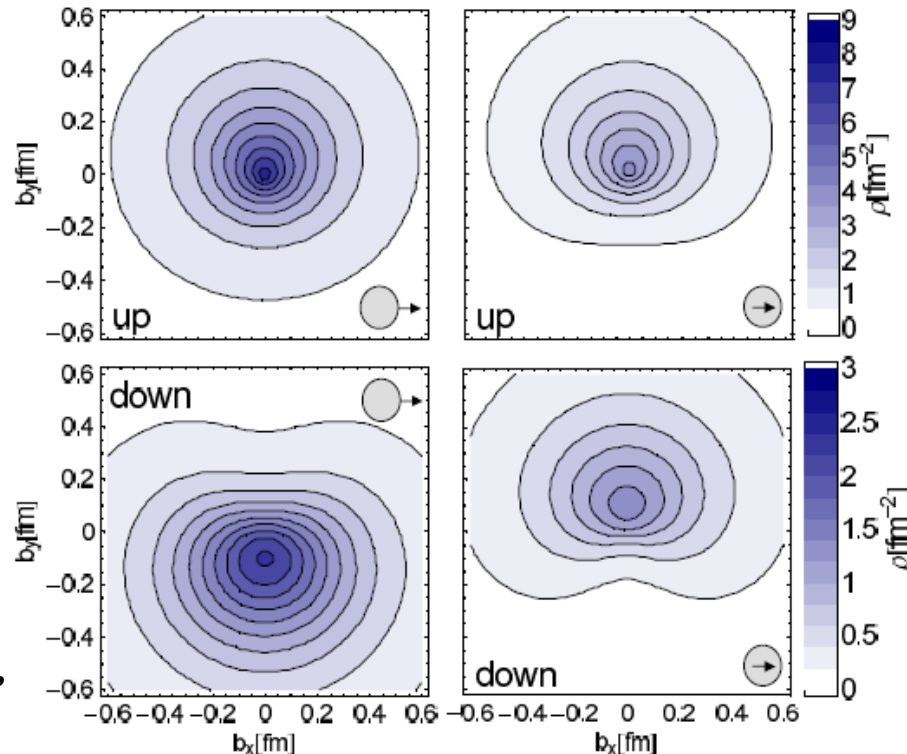
- Link to the **transversity** distribution: $H_T^q(x, 0, 0) = h_1^q(x)$

$$H_T, \tilde{H}_T, E_T, \tilde{E}_T$$



Transverse Densities for u and d quarks in the nucleon

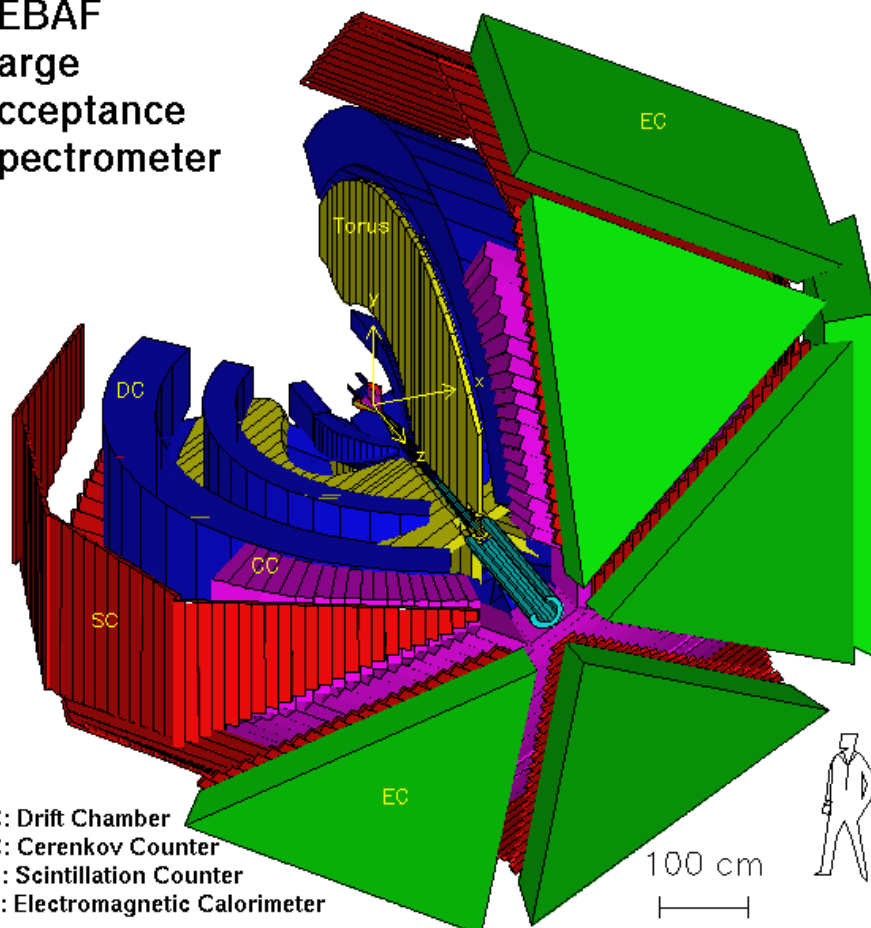
Distributions of
unpolarized
quarks in a
transversely
polarized nucleon,
linked to E



Distribution of
transversely
polarized
quarks in an
unpolarized
nucleon,
linked to $\bar{E}_T$

The CLAS detector (Hall B)

CEBAF
Large
Acceptance
Spectrometer



- **Toroidal magnetic field (6 supercond. coils)**
- **Drift chambers (argon/CO₂ gas, 35000 cells)**
- **Time-of-flight scintillators**
- **Electromagnetic calorimeters**
- **Cherenkov Counters (e/π separation)**

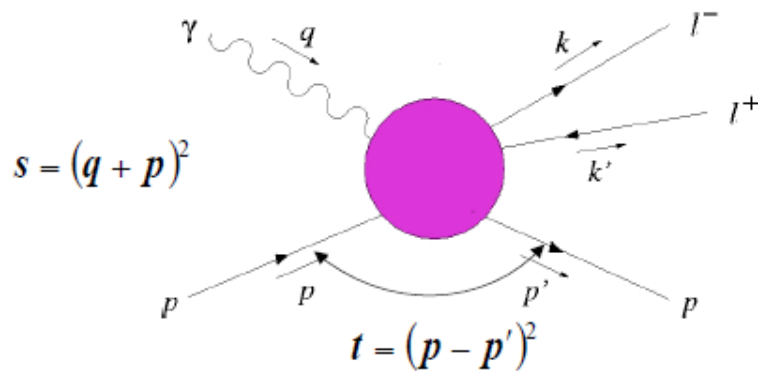
Performances:

- **large acceptance** for charged particles
 $8^\circ < \theta < 142^\circ$, $p_p > 0.3 \text{ GeV}/c$, $p_\pi > 0.1 \text{ GeV}/c$
- **good momentum and angular resolution**
 $\Delta p/p \leq 0.5\% - 1.5\%$, $\Delta\theta, \Delta\phi \leq 1 \text{ mrad}$

Optimal for measurements of exclusive reactions with multi-particle final states

After ~15 years of honored service, CLAS has completed its program in May 2012

Timelike Compton Scattering with CLAS12



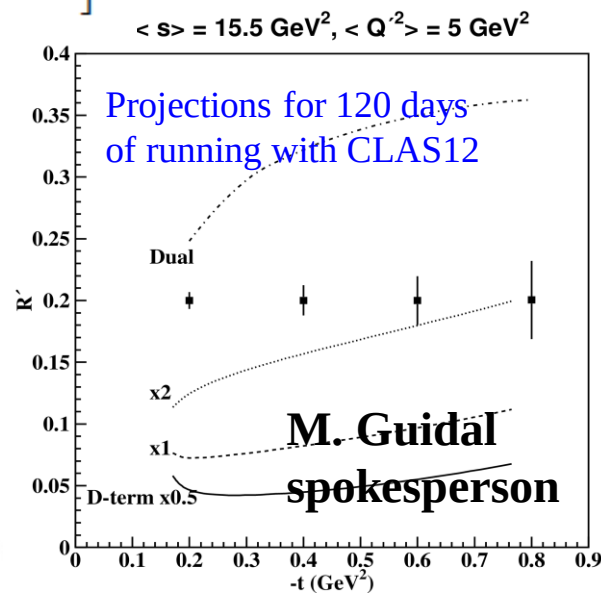
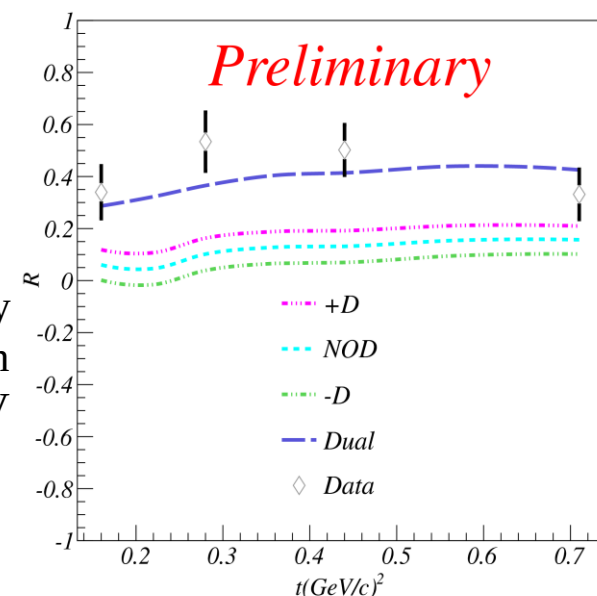
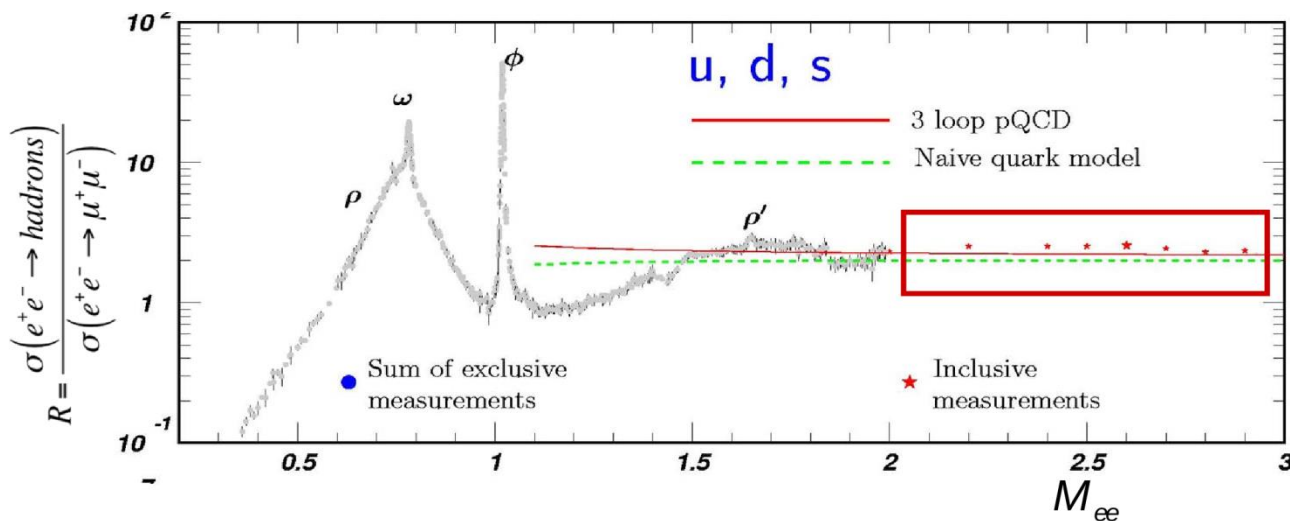
$$Q'^2 = M_{l^+l^-}^2 = (k + k')^2$$

$$\eta = \frac{Q'^2}{2s - Q'^2}$$

Exploratory
measurement with
CLAS@6 GeV

TCS: sensitivity to the real part of CFFs

$$R = \frac{2 \int_0^{2\pi} d\phi \cos \phi \frac{dS}{dQ'^2 dt d\phi}}{\int_0^{2\pi} d\phi \frac{dS}{dQ'^2 dt d\phi}} \propto \tilde{M}^{--} = \frac{2\sqrt{t_0 - t}}{m} \frac{1 - \eta}{1 + \eta} \left[F_1 \mathcal{H} - \eta(F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4m^2} F_2 \mathcal{E} \right]$$



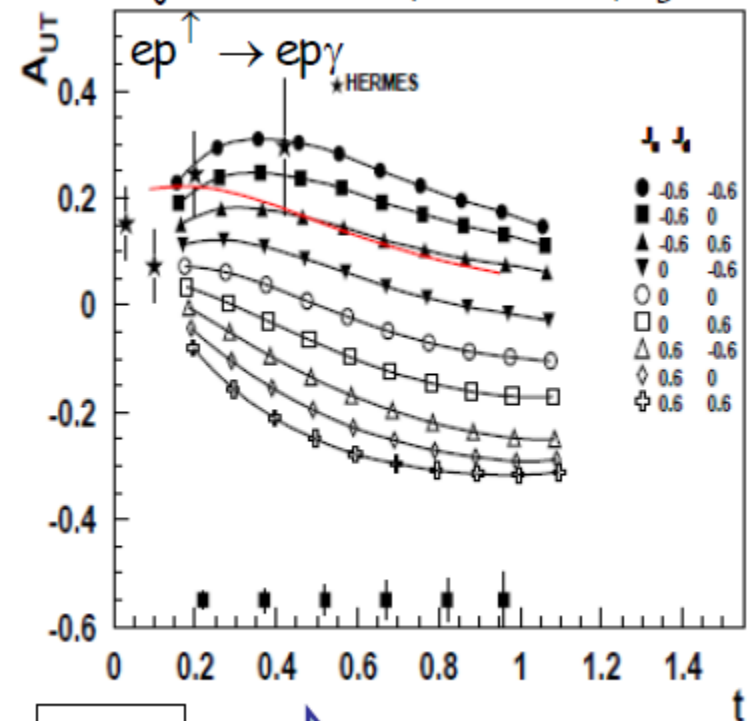
CLAS12: p-DVCS *transverse* target-spin asymmetry

100 days of beam time

Beam pol. = 80% ; **target pol. (HDIce) = 60%** ; Luminosity = $5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

$1 < Q^2 < 10 \text{ GeV}^2$, $0.06 < x_B < 0.66$, $-t_{\min} < -t < 1.5 \text{ GeV}^2$

Projections for $Q^2 = 2.5 \text{ GeV}^2$, $x_B = 0.2$

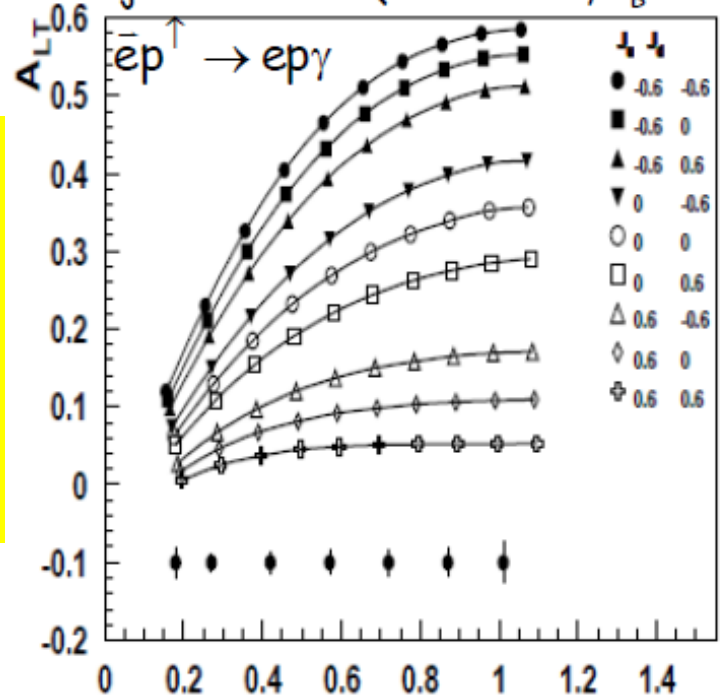


Transverse-target
spin asymmetry
for p-DVCS is
highly sensitive
to the **u-quark**
contributions to
proton spin.

$\Delta\sigma_{UT} \Rightarrow \text{Im}\{\mathcal{H}_p, \mathcal{E}_p\}$

Proposal conditionally approved by PAC39

Projections for $Q^2 = 2.5 \text{ GeV}^2$, $x_B = 0.2$



$\Delta\sigma_{LT} \Rightarrow \text{Re}\{\mathcal{H}_p, \mathcal{E}_p\}$

M. Guidal co-spokesperson

Hall B@12 GeV: CLAS12

Design luminosity
 $L \sim 10^{35} \text{ cm}^{-2}\text{s}^{-1}$

Acceptance for
charged particles:

- Central (CD), $40^\circ < \theta < 135^\circ$
- Forward (FD), $5^\circ < \theta < 40^\circ$

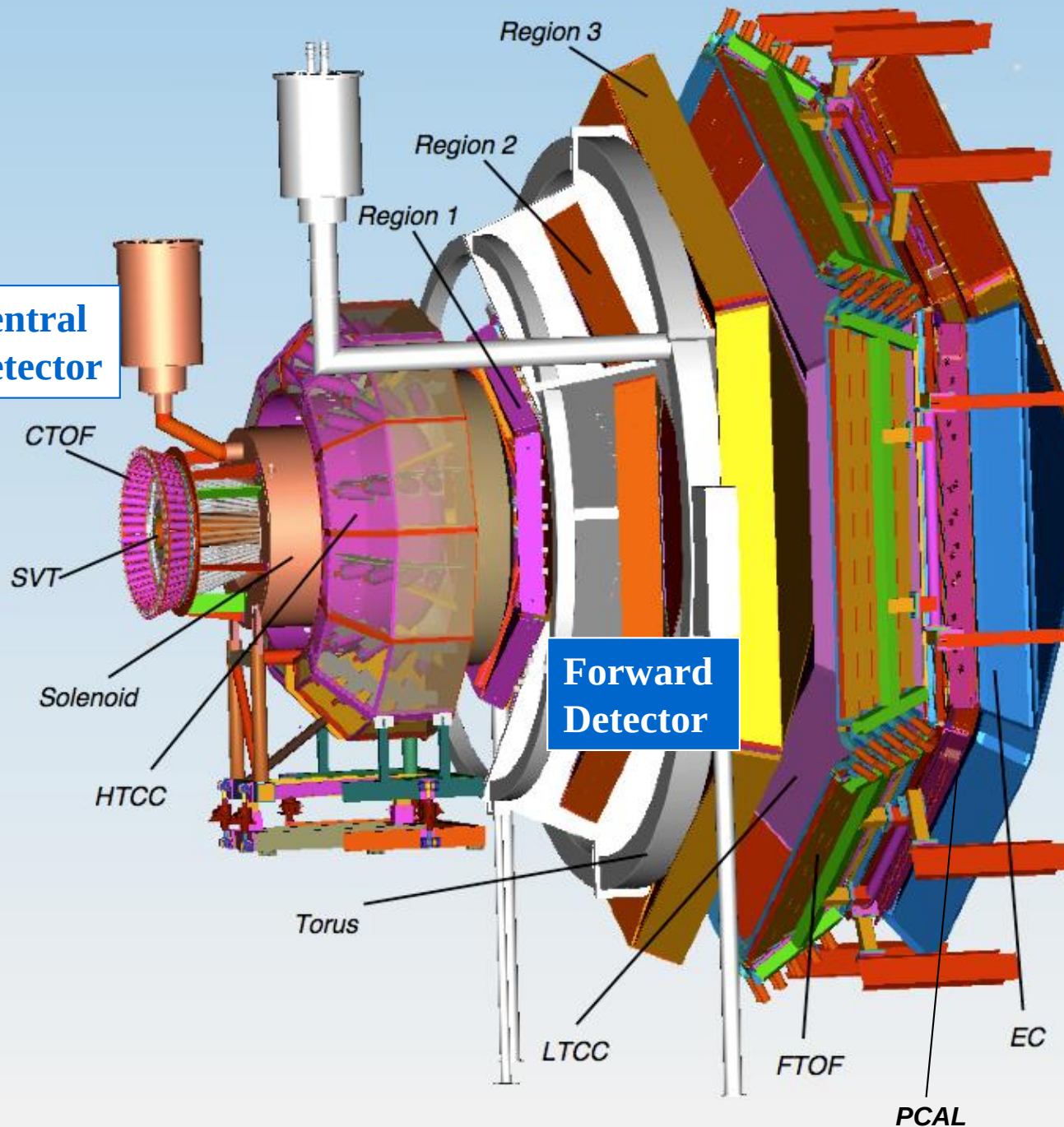
Acceptance for photons:

- IC $2^\circ < \theta < 5^\circ$
- EC, $5^\circ < \theta < 40^\circ$

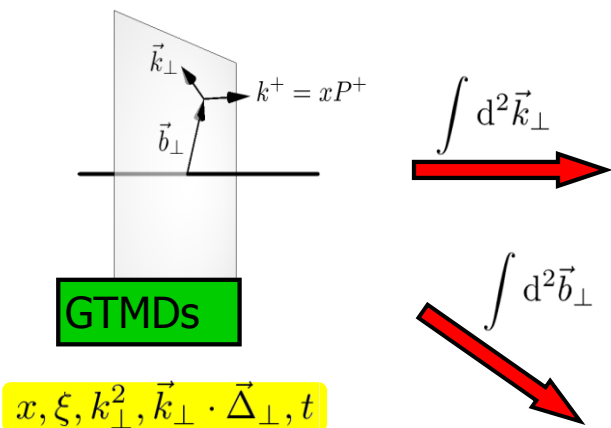
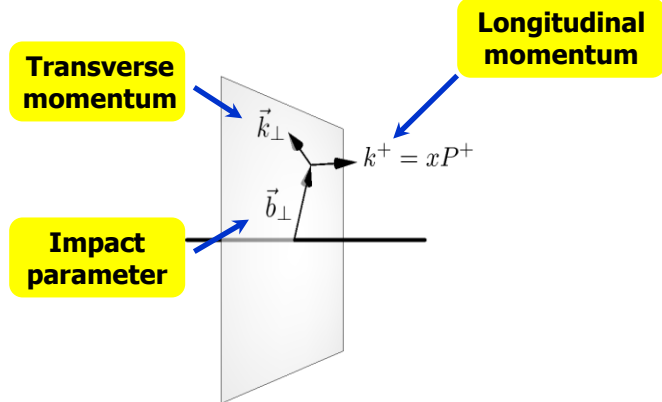
High luminosity & large
acceptance:

Concurrent measurement
of deeply virtual **exclusive**,
semi-inclusive,
and **inclusive** processes

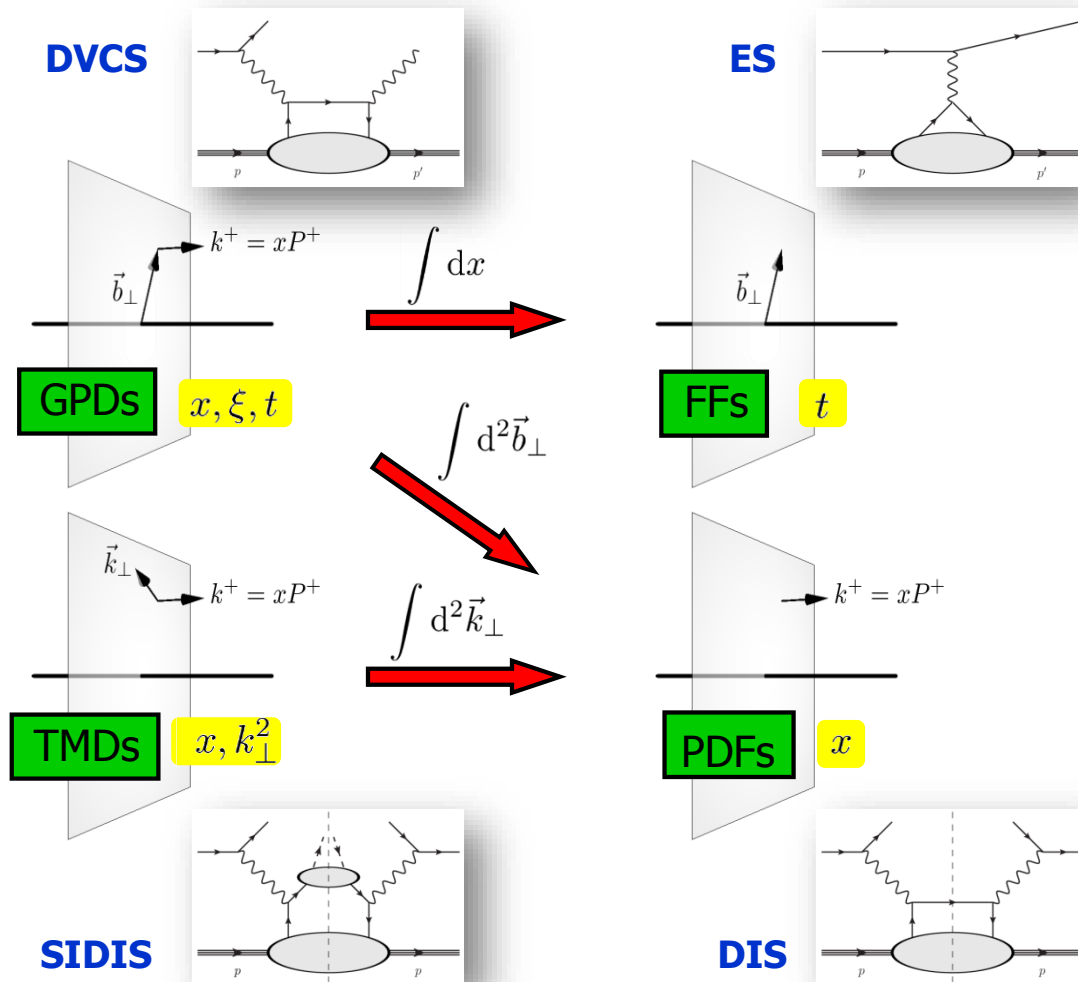
Central
Detector



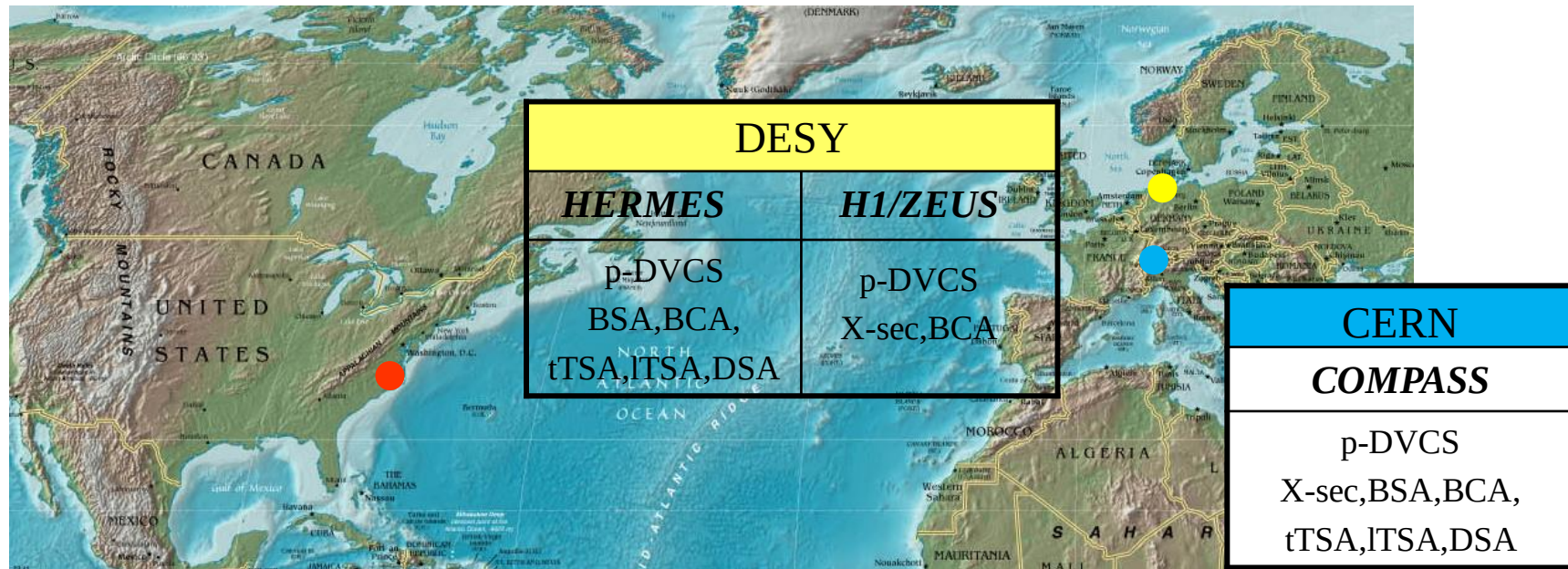
Interplay between parton distributions and reaction channels



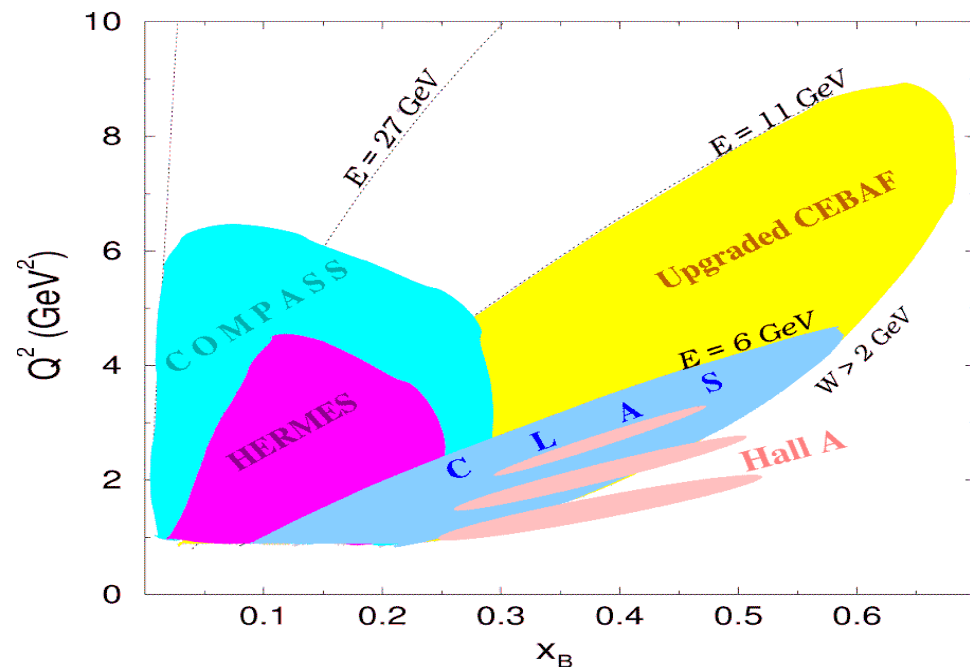
Thanks to C. Lorcé



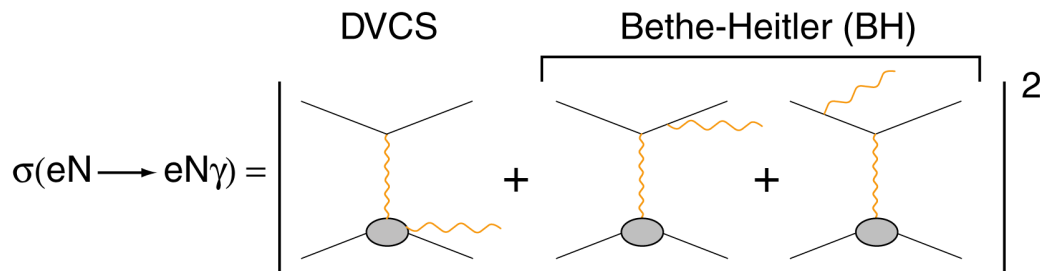
DVCS experiments worldwide



JLAB	
Hall A	Hall B
p,n-DVCS (Bpol.) X-sec	p-DVCS BSA,ITSA,DSA,X-sec



Accessing GPDs through DVCS

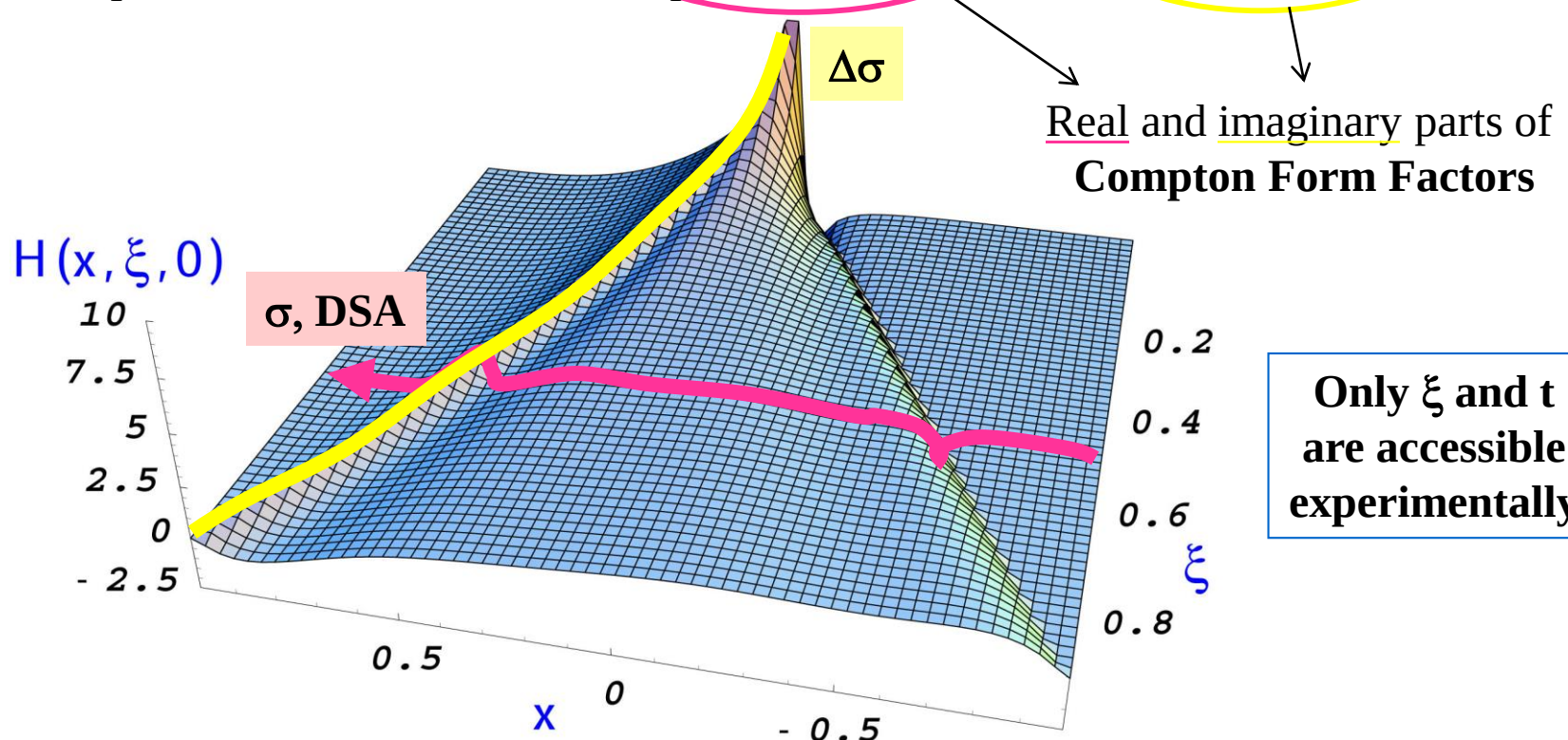


$$\sigma \sim |T^{\text{DVCS}} + T^{\text{BH}}|^2$$

$$\Delta\sigma = \sigma^+ - \sigma^- \propto \text{I}(\text{DVCS} \cdot \text{BH})$$

$$A = \frac{\Delta\sigma}{2\sigma} \propto \frac{\text{I}(\text{DVCS} \cdot \text{BH})}{|BH|^2 + |DVCS|^2 + I}$$

$$T^{\text{DVCS}} \sim \int_{-1}^{+1} \frac{GPD(x, \xi, t)}{x \pm \xi + i\varepsilon} dx + \dots \sim P \int_{-1}^{+1} \frac{GPD(x, \xi, t)}{x \pm \xi} dx \pm i\pi GPD(\pm\xi, \xi, t) + \dots$$



Hall A (JLab): first dedicated DVCS experiment

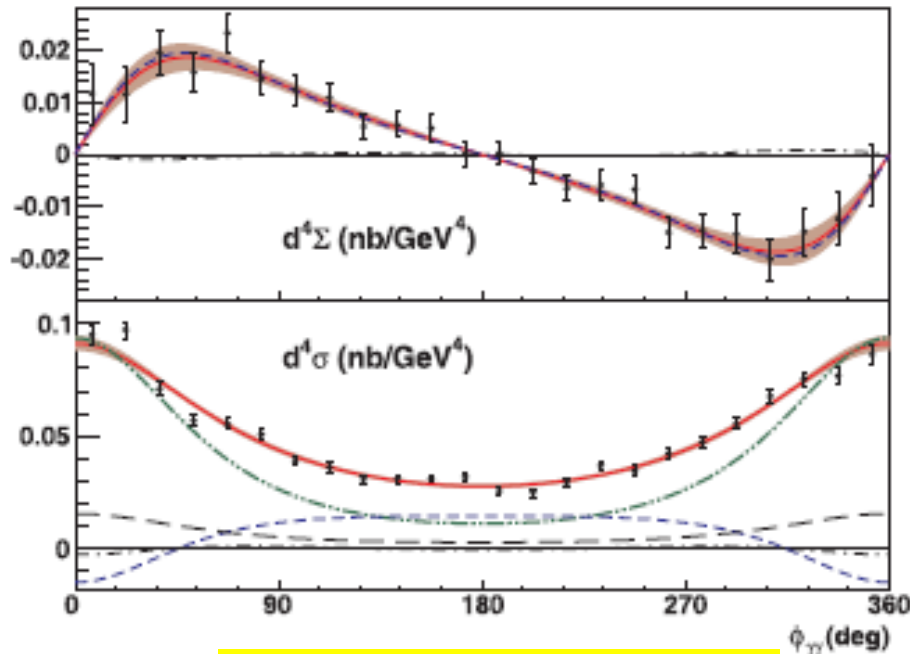
$ep \rightarrow e\gamma X$

Polarized cross
section difference

C.M. Camacho et al., PRL 97 (2006)

Q^2 evolution $\rightarrow$ evidence for scaling

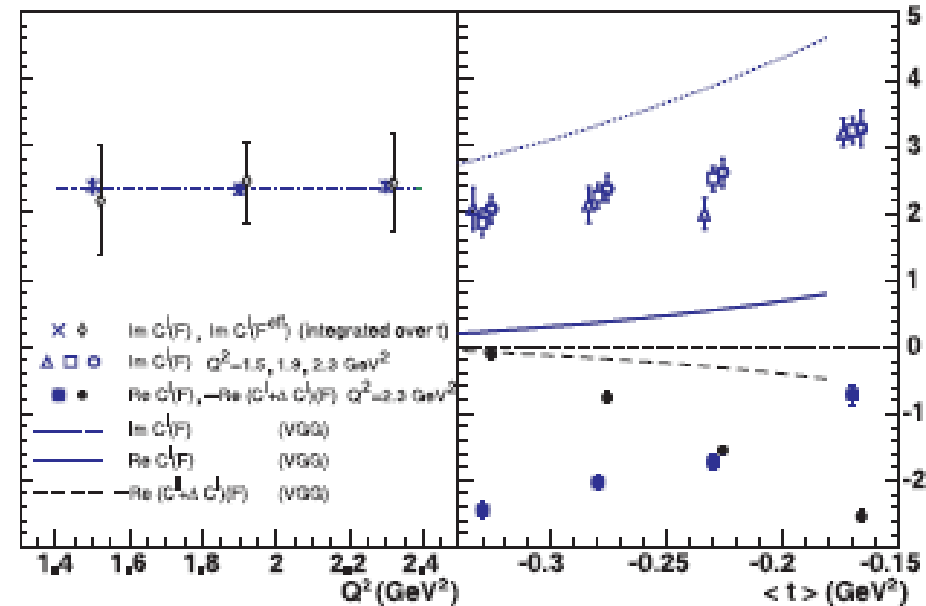
(small Q^2 range)



Unpolarized cross section

$$\langle Q^2, -t \rangle = (2.3, -0.28)$$

- Fit
- · — $|BH|^2$
- - - Inteferece BH-DVCS



Formalism of Belitsky, Mueller, Kirchner

High resolution $\rightarrow$ exclusivity

High luminosity $\rightarrow$ precision

Limited phase space

DVCS BSA and TSA with CLAS12 & 11 GeV beam

85 days of beam time

$P_{\text{beam}} = 85\%$

$L = 10^{35} \text{ cm}^{-2}\text{s}^{-1}$

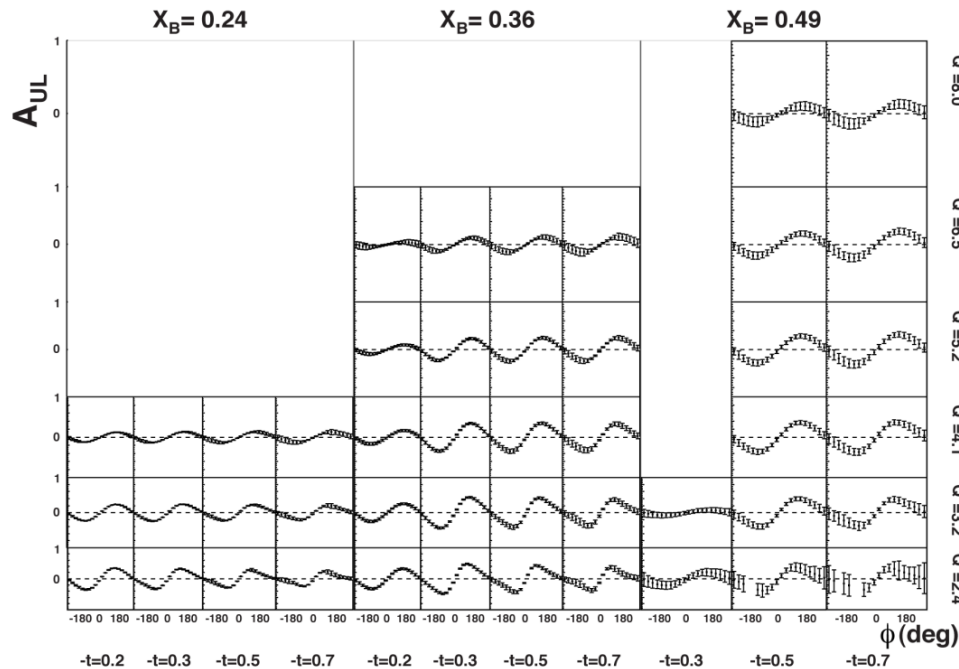
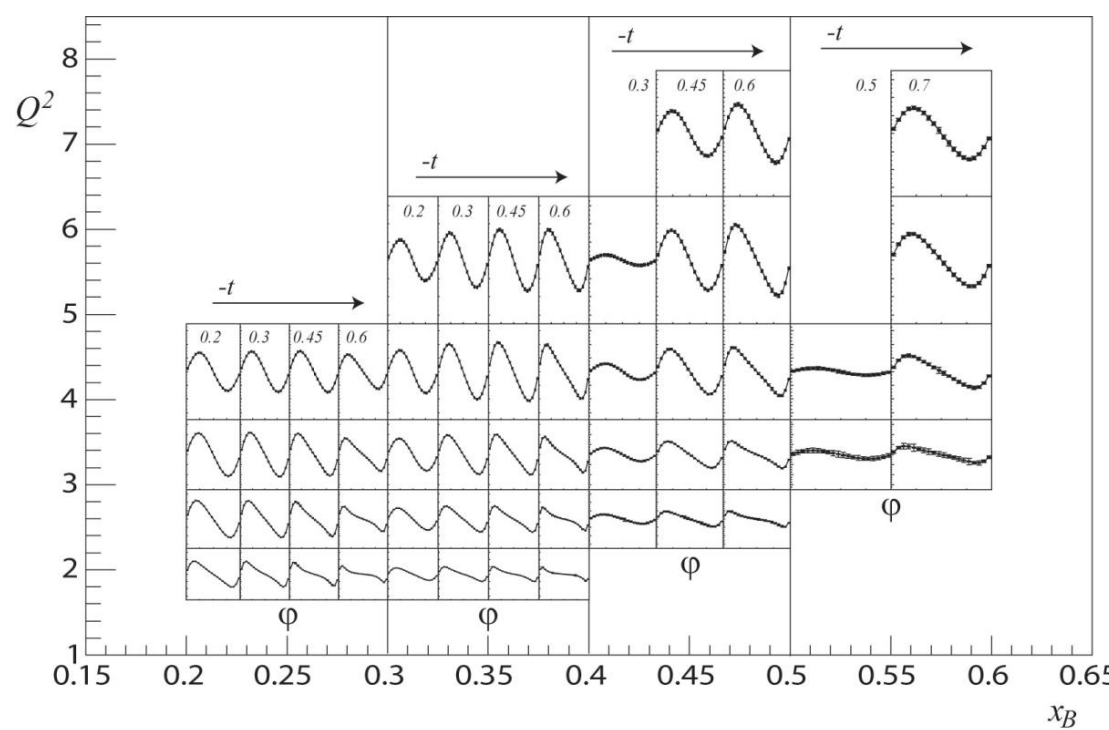
$1 < Q^2 < 10 \text{ GeV}^2$

$0.1 < x_B < 0.65$

$-t_{\text{min}} < -t < 2.5 \text{ GeV}^2$

Statistical error: 1% to 10%
on $\sin\phi$ moments

Systematic uncertainties: ~6-8%



120 days of beam time

$P_{\text{beam}} = 85\%$, $P_{\text{target}} = 80\%$

$L = 2.10^{35} \text{ cm}^{-2}\text{s}^{-1}$

$1 < Q^2 < 10 \text{ GeV}^2$

$0.1 < x_B < 0.65$

$-t_{\text{min}} < -t < 2.5 \text{ GeV}^2$

Statistical error: 2% to 15%

on $\sin\phi$ moments

Systematic uncertainties: ~6-8%

DVCS BSA and TSA with CLAS12 & 11 GeV beam

85 days of beam time

$P_{\text{beam}} = 85\%$

$L = 10^{35} \text{ cm}^{-2}\text{s}^{-1}$

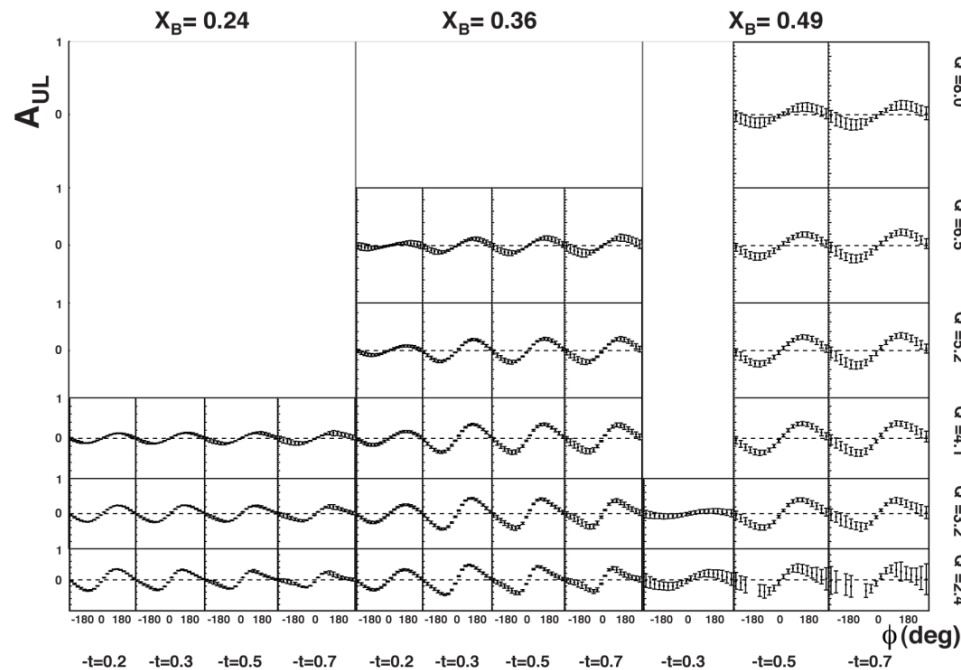
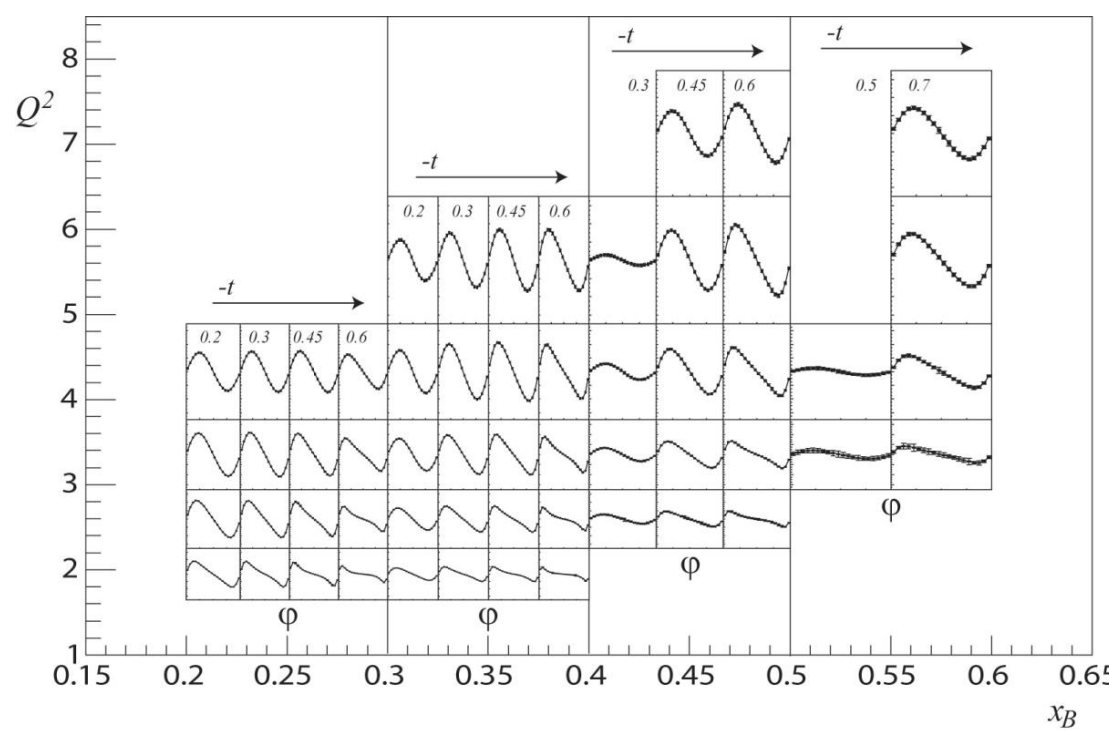
$1 < Q^2 < 10 \text{ GeV}^2$

$0.1 < x_B < 0.65$

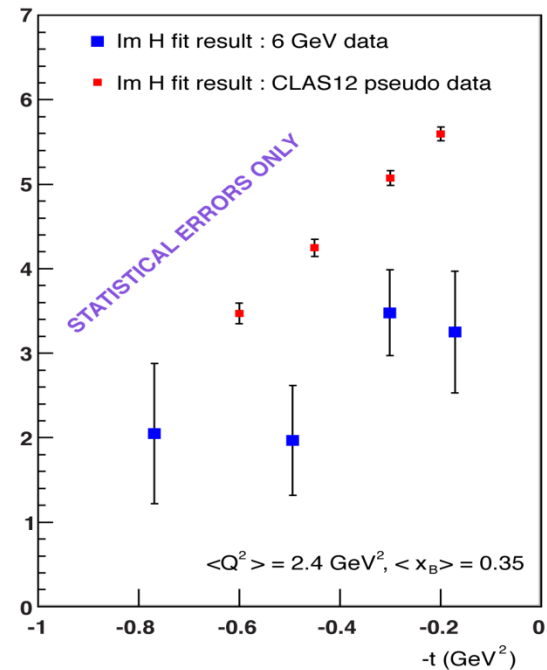
$-t_{\text{min}} < -t < 2.5 \text{ GeV}^2$

Statistical error: 1% to 10%
on $\sin\phi$ moments

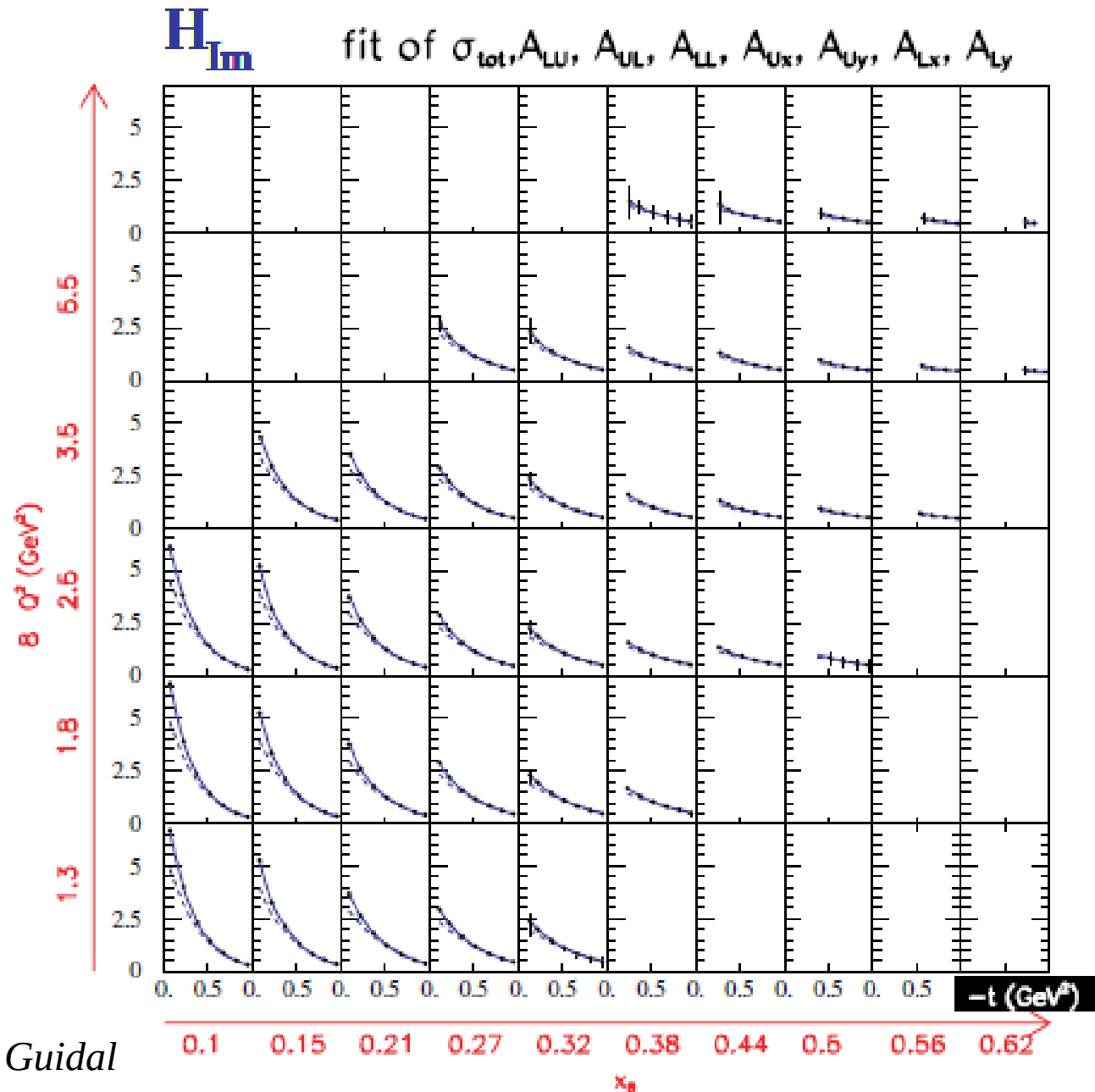
Systematic uncertainties: $\sim 6\text{-}8\%$



**Impact of
CLAS12
DVCS-BSA
data
on model-
independent
fit to extract
 $\text{Im}(H)$**



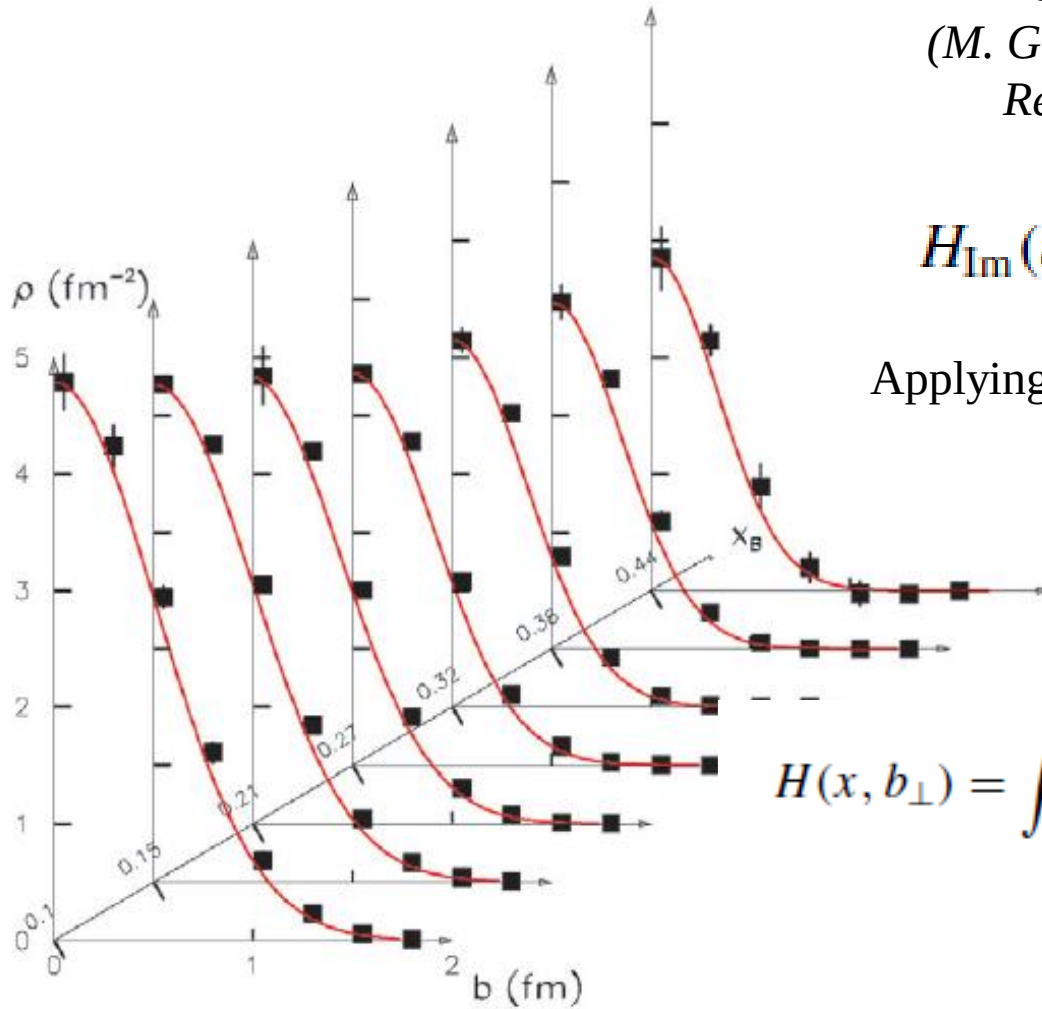
Projections for CLAS12 for H_{Im}



From CFFs to spatial densities

How to go from momentum coordinates (t)
to space-time coordinates (b) ?

(M. Guidal, H. Moutarde, M. Vanderhagen,
Rept.Prog.Phys. 76 (2013) 066202)



$$H_{\text{Im}}(\xi, t) \equiv H(\xi, \xi, t) - H(-\xi, \xi, t)$$

Applying a model-dependent “deskewing” factor:

$$\frac{H(\xi, 0, t)}{H(\xi, \xi, t)}$$

$$H(x, b_{\perp}) = \int_0^{\infty} \frac{d\Delta_{\perp}}{2\pi} \Delta_{\perp} J_0(b_{\perp} \Delta_{\perp}) H(x, 0, -\Delta_{\perp}^2)$$

Burkardt (2000)

Projections for CLAS12

E12-11-003: BSA for DVCS on the neutron with CLAS12

$$(H, E)_u(\xi, \xi, t) = \frac{9}{15} [4(H, E)_p(\xi, \xi, t) - (H, E)_n(\xi, \xi, t)]$$

$$(H, E)_d(\xi, \xi, t) = \frac{9}{15} [4(H, E)_n(\xi, \xi, t) - (H, E)_p(\xi, \xi, t)]$$

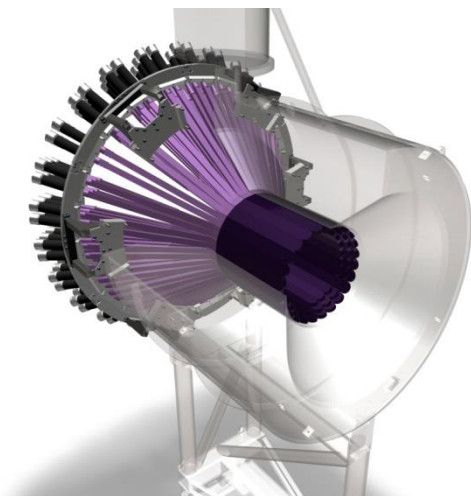
$$\Delta\sigma_{\text{LU}} \sim \sin\phi \operatorname{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi$$

The most sensitive observable to the GPD $\mathcal{E}$

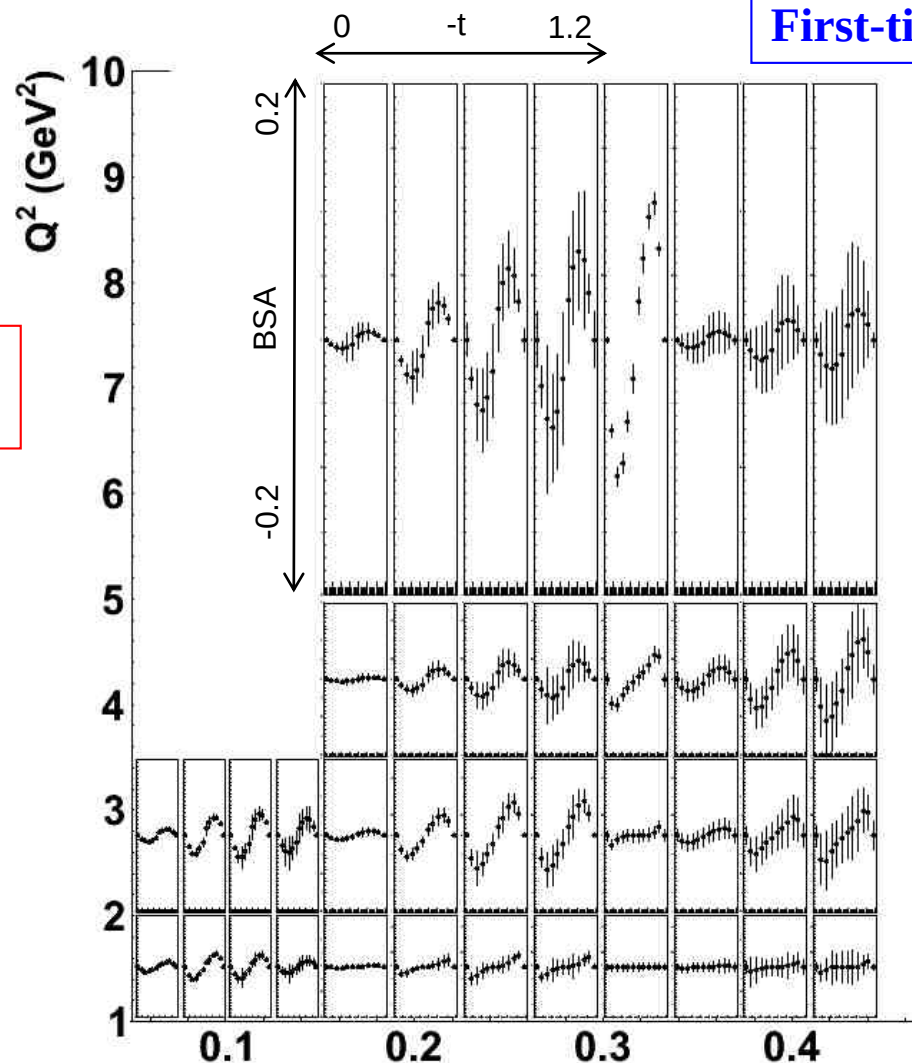
$ed \rightarrow e(p)n\gamma$

CLAS12 +
Forward Calorimeter +
Neutron Detector

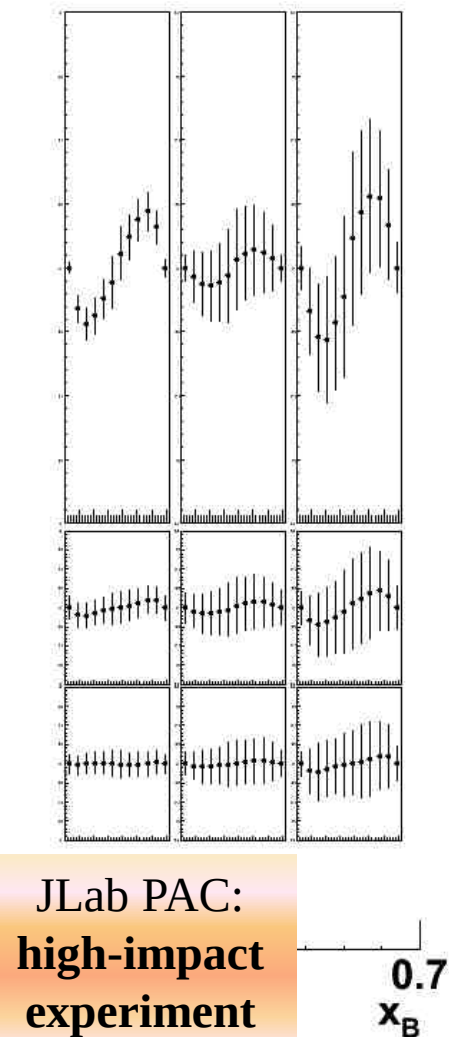
80 days of data taking
 $L = 10^{35} \text{ cm}^{-2}\text{s}^{-1}/\text{nucleon}$



Installation in 3 weeks
(IPN Orsay)



First-time measurement



JLab PAC:
high-impact
experiment

E12-11-003: BSA for DVCS on the neutron with CLAS12

$$(H, E)_u(\xi, \xi, t) = \frac{9}{15} [4(H, E)_p(\xi, \xi, t) - (H, E)_n(\xi, \xi, t)]$$

$$(H, E)_d(\xi, \xi, t) = \frac{9}{15} [4(H, E)_n(\xi, \xi, t) - (H, E)_p(\xi, \xi, t)]$$

$$\Delta\sigma_{\text{LU}} \sim \sin\phi \operatorname{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi$$

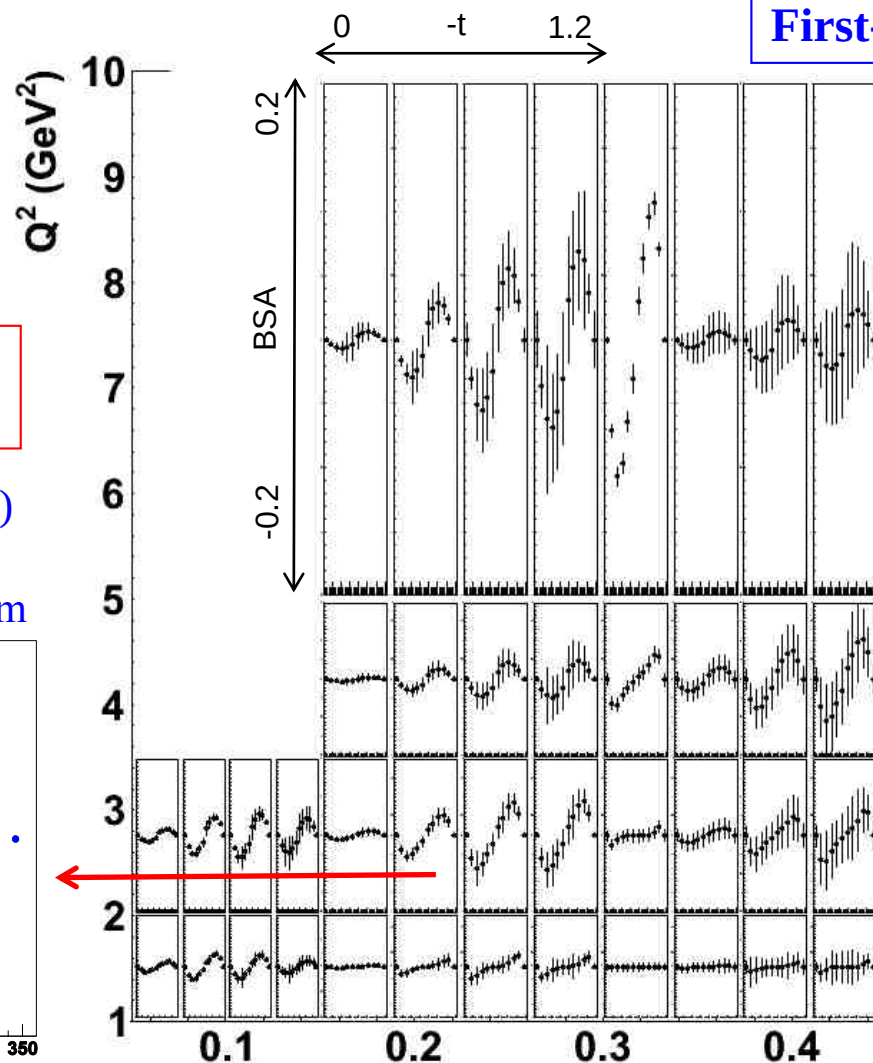
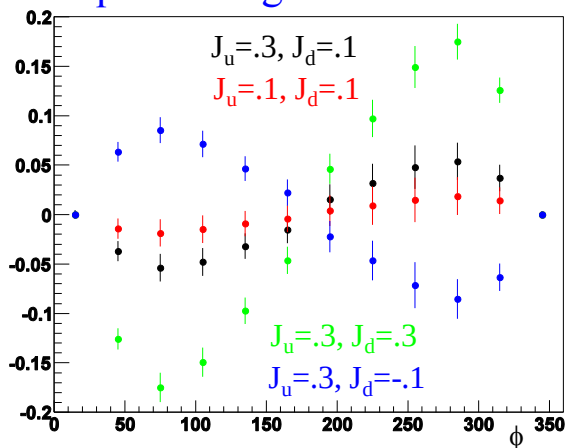
The most sensitive observable to the GPD $\mathcal{E}$

$ed \rightarrow e(p)n\gamma$

CLAS12 +
Forward Calorimeter +
Neutron Detector

80 days of data taking
 $L = 10^{35} \text{ cm}^{-2}\text{s}^{-1}/\text{nucleon}$

Model predictions (VGG)
for different values of
quarks' angular momentum



First-time measurement

JLab PAC:
high-impact
experiment

x_B

E12-06-109a: nDVCS, target-spin asymmetry

$$\sigma_A = \frac{1}{P_t} \cdot \frac{\sqrt{(1 - P_t \cdot A)^2}}{\sqrt{N}}$$

$$\Delta\sigma_{UL} \sim \sin\phi \operatorname{Im}\{F_1\tilde{\mathcal{H}} + \xi(F_1 + F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi k F_2 \tilde{\mathcal{E}} + \dots\}$$

TSA ~ 0.2

$L = 3/20 \cdot 10^{35} \text{cm}^{-2} \text{s}^{-1}$
Time = 50 days
 $P_t = 0.4$

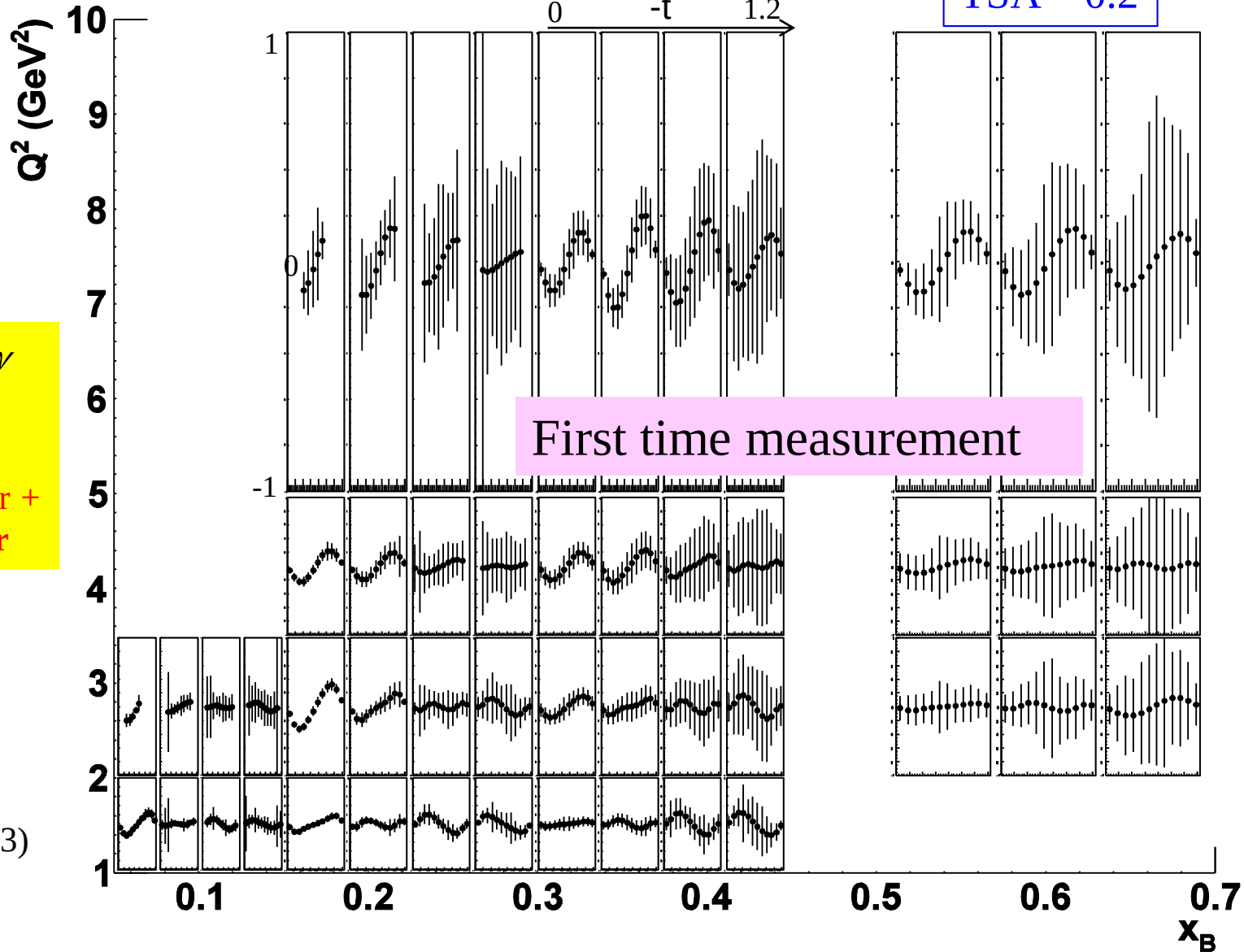
$eND_3 \rightarrow e(p)n\gamma$

CLAS12 +

Long. pol. target

Forward Calorimeter +
Neutron Detector

- 4 bins in Q^2
 - 4 bins in $-t$
 - 4 bins in x_B
 - 12 bins in ϕ
- (Same as E12-11-003)



E12-06-109a: nDVCS, double spin asymmetry

$$\Delta\sigma_{LL} \sim (\mathbf{A} + \mathbf{B}\cos\phi) \operatorname{Re}\{F_1\tilde{\mathcal{H}} + \xi(F_1 + F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi k F_2 \tilde{\mathcal{E}} + \dots\}$$

DSA up to 0.8

$$\sigma_A = \frac{1}{P_b P_t} \cdot \frac{\sqrt{(1 - P_b P_t \cdot A)^2}}{\sqrt{N}}$$

$$L = 3/20 \cdot 10^{35} \text{cm}^{-2} \text{s}^{-1}$$

Time = 50 days

$$P_t = 0.4; P_b = 0.85$$

$eND_3 \rightarrow e(p)n\gamma$

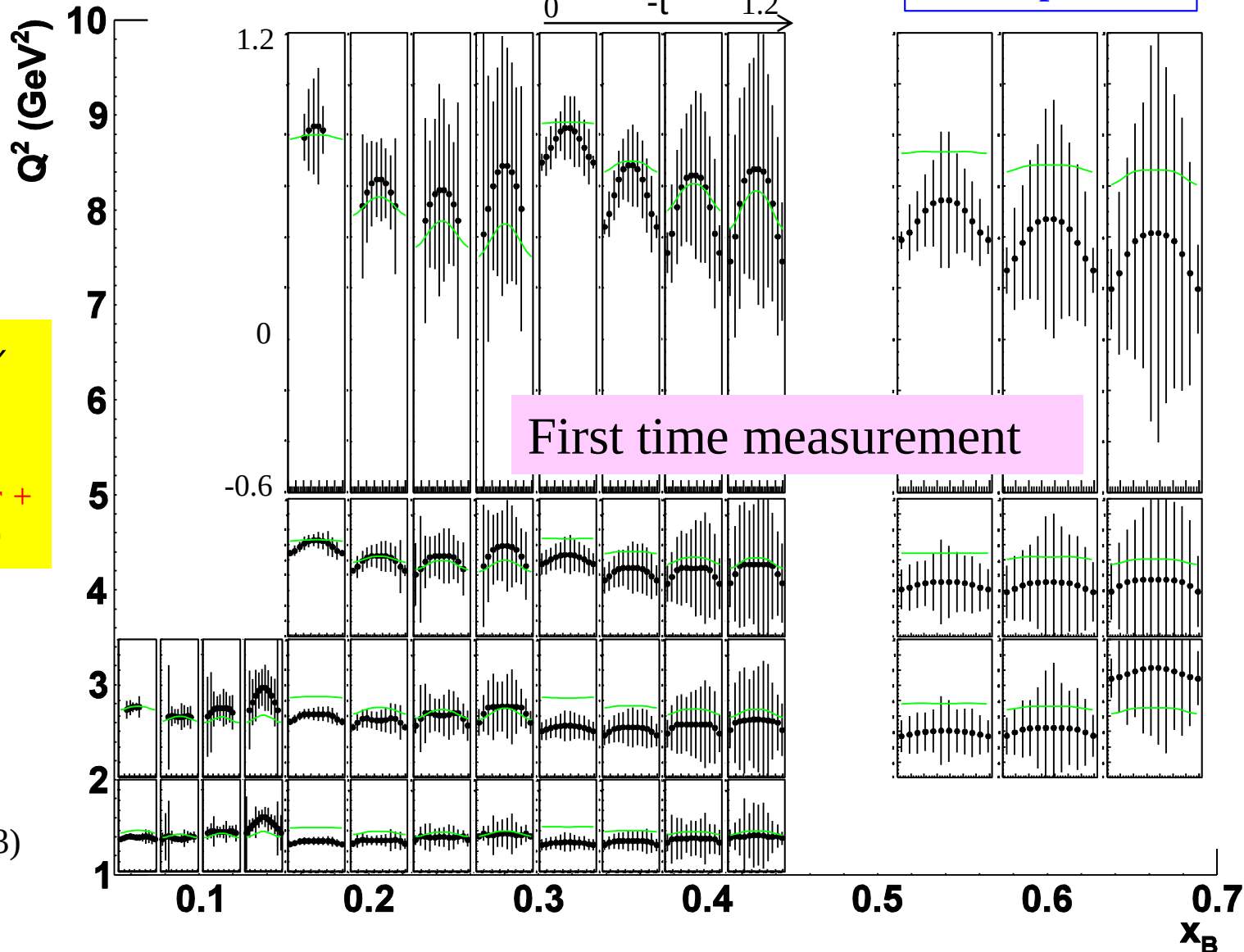
CLAS12 +

Long. pol. target

Forward Calorimeter +
Neutron Detector

- 4 bins in Q^2
 - 4 bins in $-t$
 - 4 bins in x_B
 - 12 bins in ϕ
- (Same as E12-11-003)

Green curves:
Bethe-Heitler



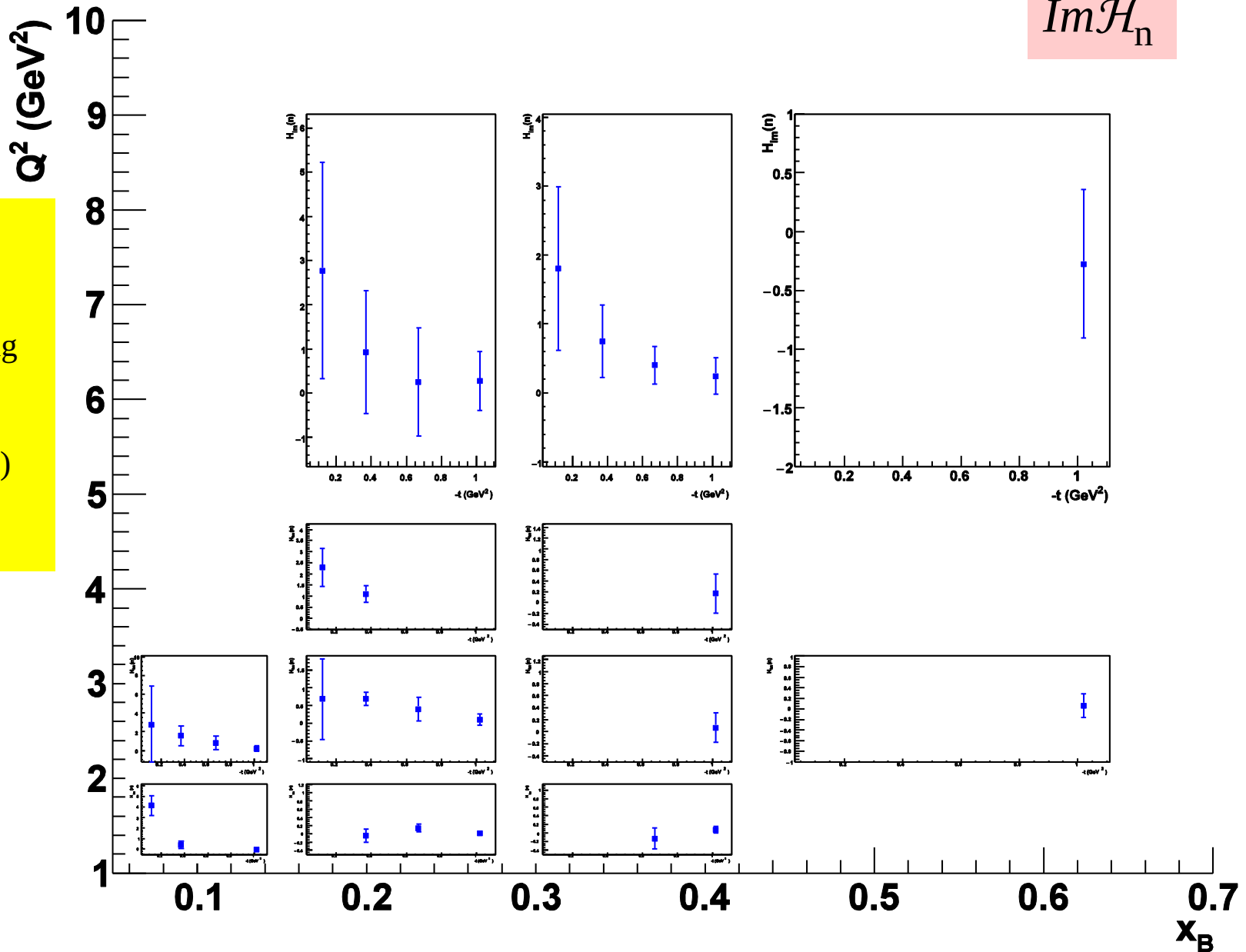
Combined analysis of all nDVCS CLAS12 projections

$$\text{Im}\mathcal{H}_n$$

Extraction of neutron CFFs using M. Guidal's fitting code. Fit of TSA, DSA (E12-06-109a) and BSA (E12-11-003)

7 CFFs as free fit parameters

$$\text{Im}\tilde{\mathcal{E}} = 0$$



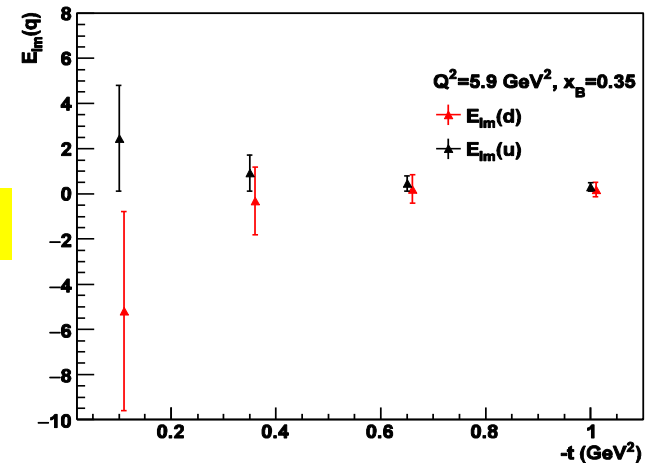
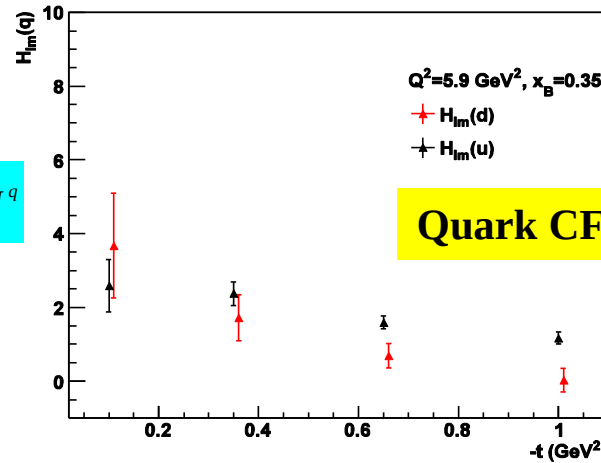
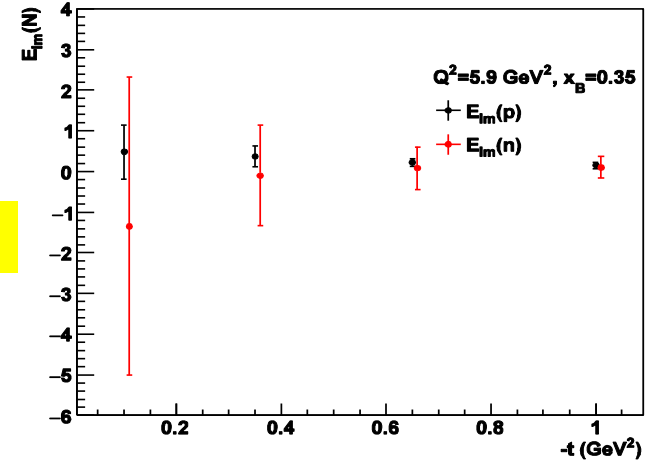
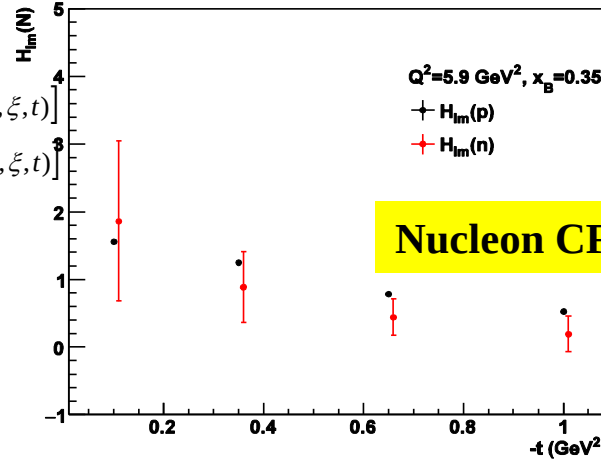
CLAS12: projections for flavor separation ($Im\mathcal{H}$, $Im\mathcal{E}$)

$$(H, E)_u(\xi, \xi, t) = \frac{9}{15} [4(H, E)_p(\xi, \xi, t) - (H, E)_n(\xi, \xi, t)]$$

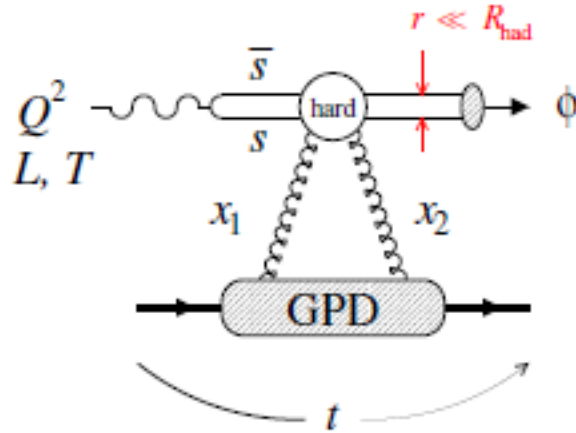
$$(H, E)_d(\xi, \xi, t) = \frac{9}{15} [4(H, E)_n(\xi, \xi, t) - (H, E)_p(\xi, \xi, t)]$$

Fits done to all the projected
observables for **pDVCS**
(BSA, lTSA, lDSA, tTSA,
CS, Δ CS) and **nDVCS**
(BSA, lTSA, lDSA) of the
CLAS12 program

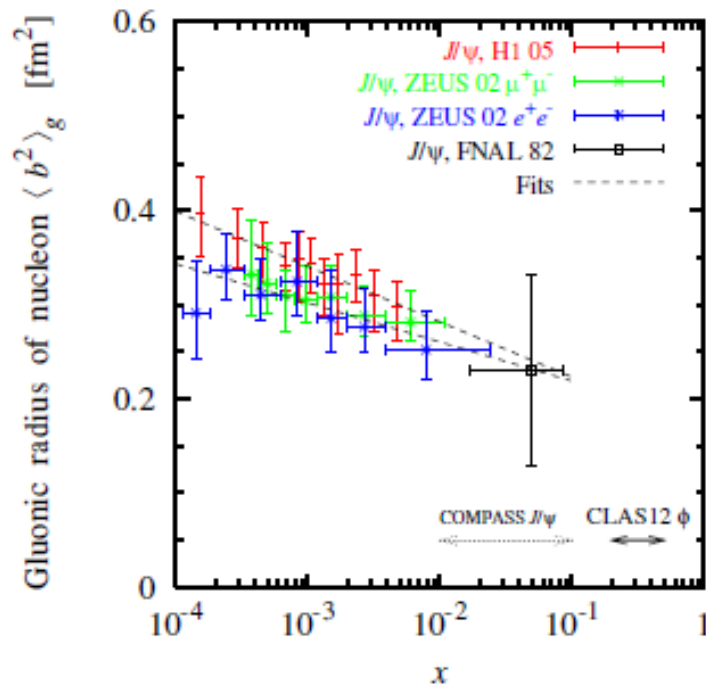
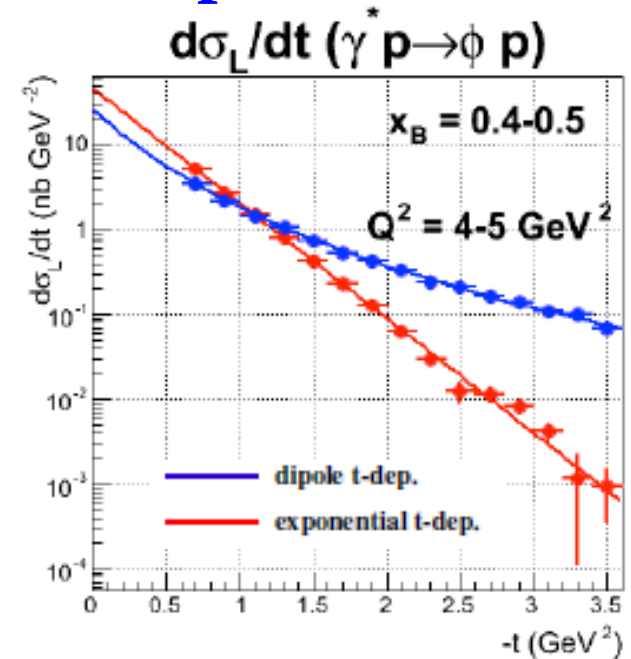
$$\frac{1}{2} \int_{-1}^1 x dx (H^q(x, \xi, t=0) + E^q(x, \xi, t=0)) = J^q$$



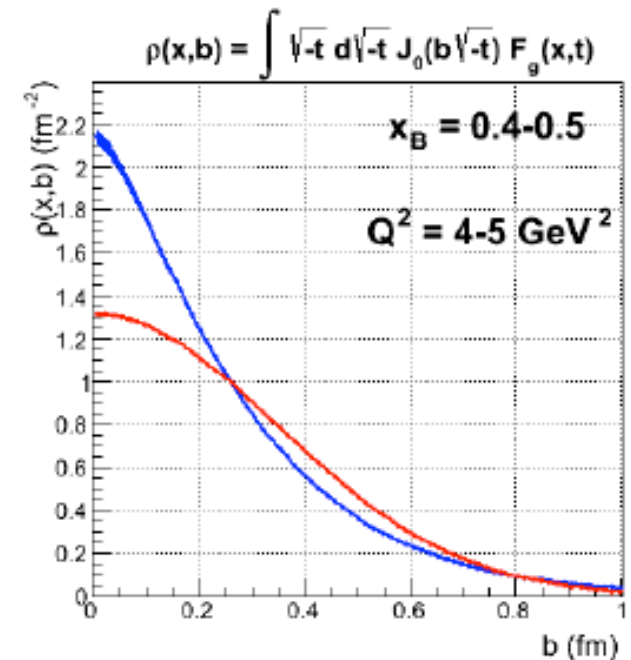
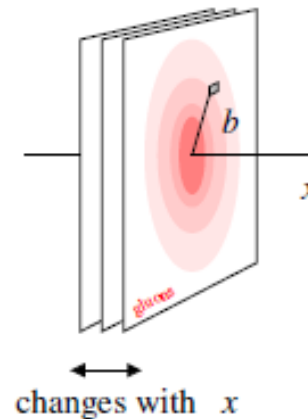
DVMP @ CLAS12: exclusive ϕ electroproduction



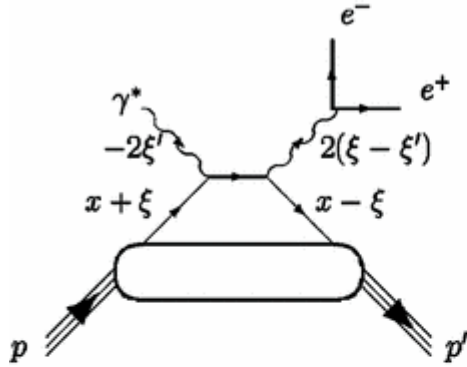
- Differential c.s. $\rightarrow$ extraction of **structure functions**
- **L-T separation** from $\phi \rightarrow KK$ decay distributions
- t dependence of $d\sigma_L/dt$



Transverse distribution of gluons in the proton



GPDs: beyond DVCS

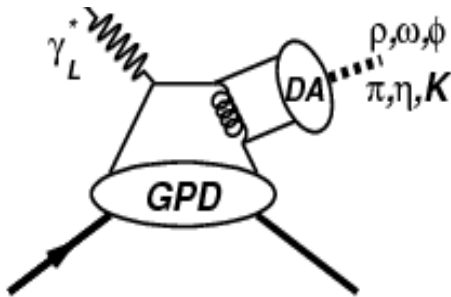
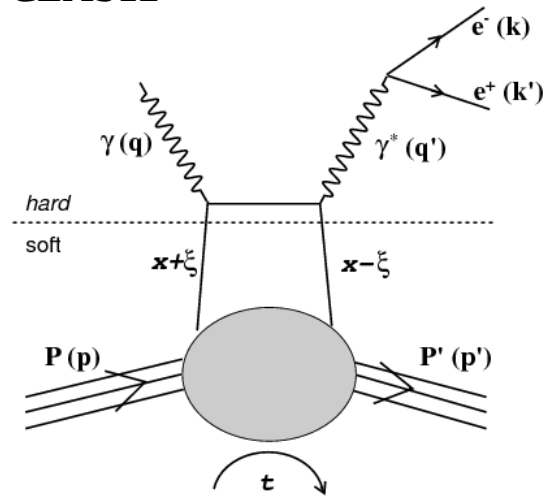


Double DVCS: $\gamma^* p \rightarrow p \gamma^* \rightarrow p l^+ l^-$

- Access to **x dependence** of GPDs, decorrelated from ξ
- LOI for SOLID (Hall A), and plans for CLAS12

Time-like Compton Scattering: $\gamma p \rightarrow p \gamma^* \rightarrow p l^+ l^-$

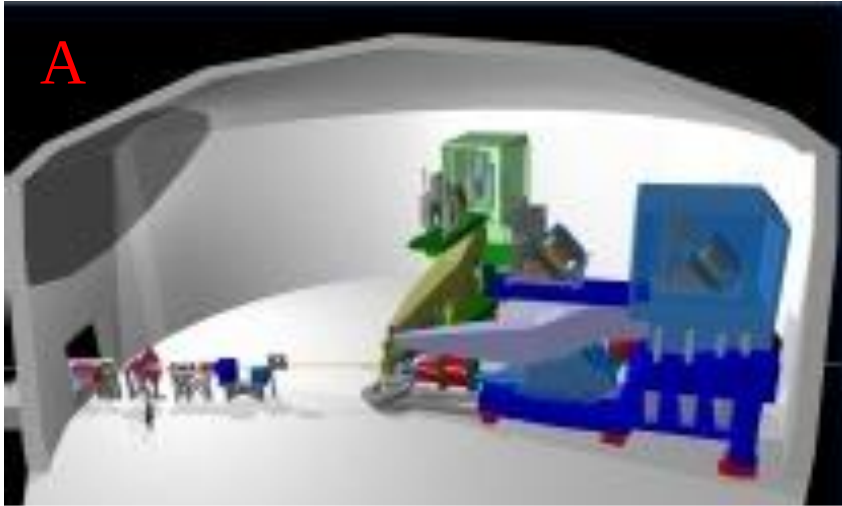
- Sensitive to **real part** of CFFs, test of **universality** of GPDs
- CLAS12 experiment running in 2017, with pDVCS



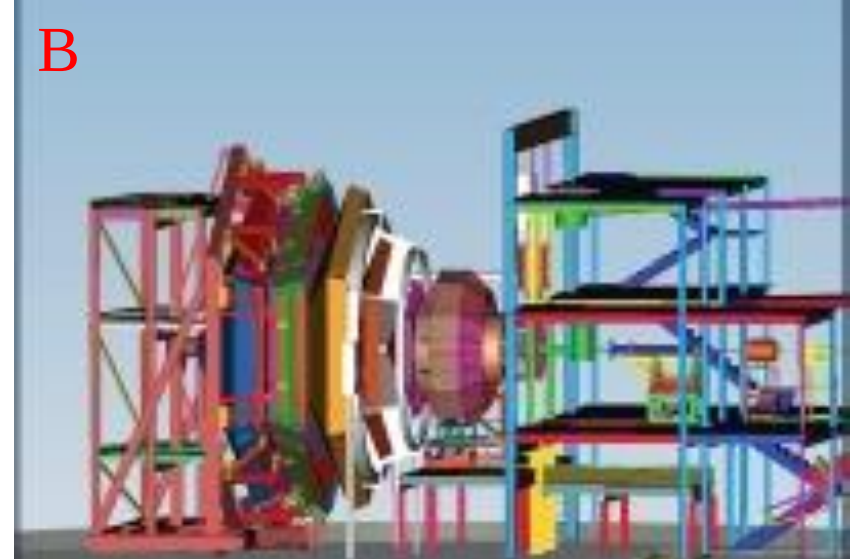
Deeply virtual meson production: $\gamma^* p \rightarrow p M$

- **Flavor separation** of GPDs, **universality**
- **Transversity GPDs** (pseudoscalars mesons)
- Experiments in Hall A, CLAS12

New capabilities in Halls A, B & C



**High Resolution Spectrometer (HRS) pair
and specialized large installation experiments**



CLAS12: large acceptance, high luminosity



**Super High Momentum Spectrometer (SHMS)
at high luminosity and forward angles**

DVCS experiments at 11 GeV have been approved for each of these **three halls**.

Complementary programs:

- different kinematic coverage
- different precisions/resolutions
- focus on different observables

NPS Collaboration

CUA (Tanja HORN et al.):

Project coordination, crystal testing

Ohio University (Julie ROCHE et al.) :

PMT base fabrication

Old Dominion University (Charles HYDE et al.):

Small angle magnet construction

Jefferson Lab (Bogdan Wojtsekhowski, Rolf Ent et al):

Magnet and general design, crystal and PMT procurement

IPN-Orsay (Carlos Munoz Camacho et al.):

Calorimeter frame design and construction

UVa (Donald Day et al.):

Target design for large angle experiments

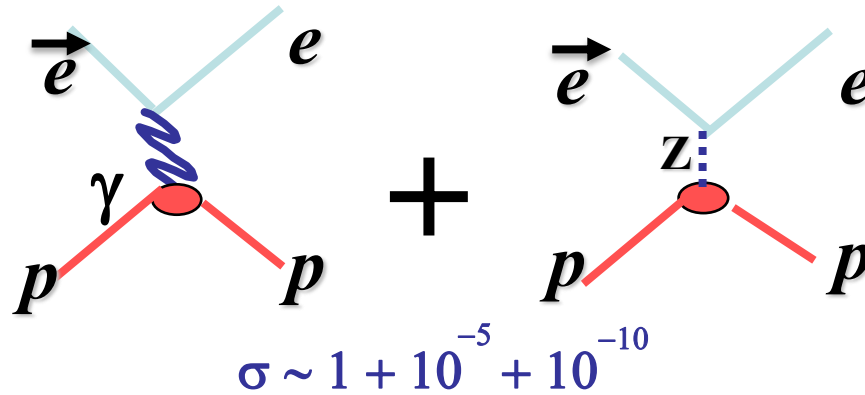
Yerevan University (Hamlet Mkrtchyan et al) :

PMT base design

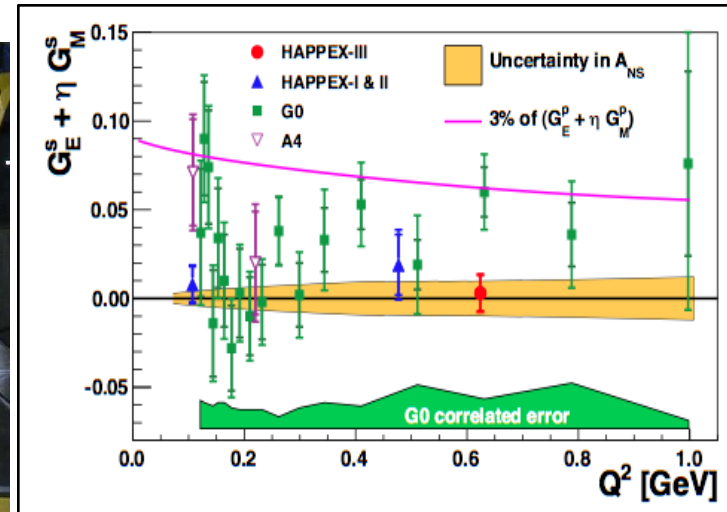
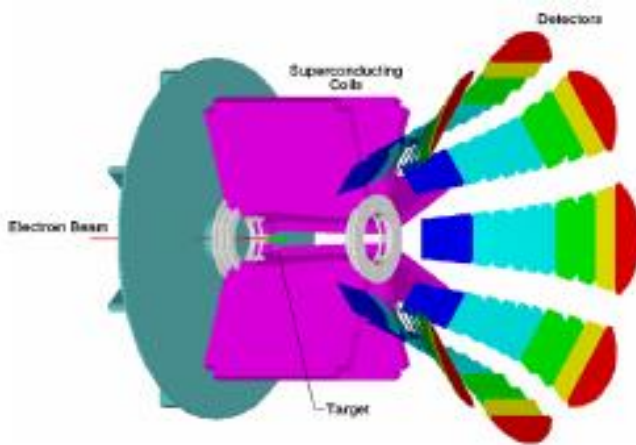
University of Glasgow (David Hamilton et al) :

Large angle magnet construction

Parity violation experiments (G0, HAPPEX) : beam spin asymmetry in $\vec{e}p \rightarrow ep$



$$\mathcal{A} = \frac{\vec{\sigma} \cdot \vec{\sigma} - \vec{\sigma} \cdot \vec{\sigma}}{\vec{\sigma} \cdot \vec{\sigma} + \vec{\sigma} \cdot \vec{\sigma}}$$

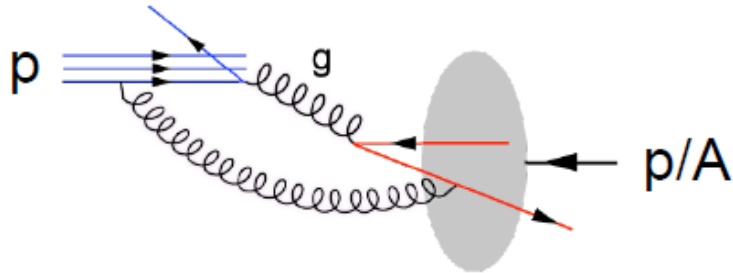


Also:

- *Nucleon polarizabilities through VCS ($\vec{e}p \rightarrow ep\gamma$)
- *Deuteron form factor (t20) through $\vec{e}d \rightarrow \vec{e}d$
- *pQCD studies through $\gamma p \rightarrow p\phi$ at large momentum transfer
- *First GPD studies through DVCS ($\vec{e}p \rightarrow ep\gamma$) and deep meson e-prod ($\vec{e}p \rightarrow epM$)
- *Pentaquarks

Why do we need an electron-ion collider?

Hadron-hadron

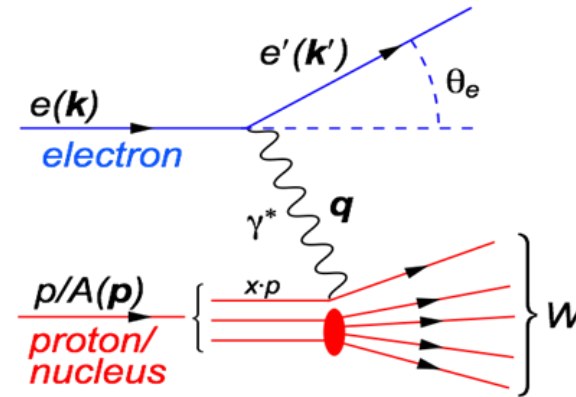


Probe and target have a complex structure

Soft interactions before collisions
can destroy factorization

Kinematics imprecisely determined

Electron-hadron (DIS)



Point-like probe

No initial-state soft interactions,
factorization preserved

Kinematics precisely determined

Kinematic variables:

$Q^2 = -(\mathbf{k} - \mathbf{k}')^2$
(Resolution)

$x = Q^2 / 2M\nu =$

$Q^2 / (2pq)$

(mom. fraction)

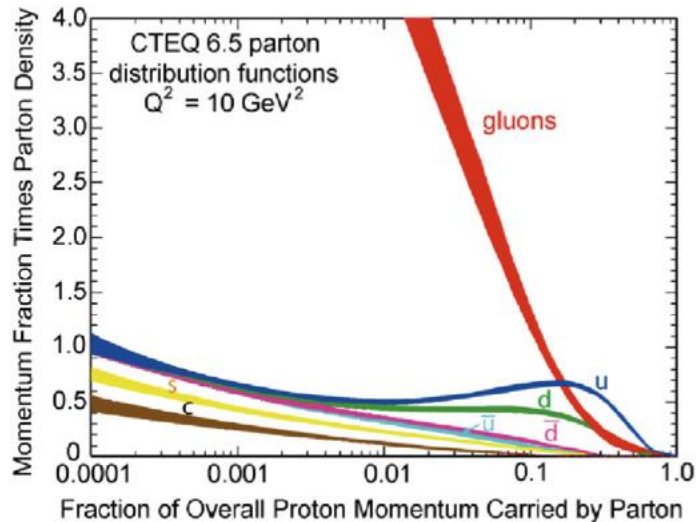
$\nu = E_e - E_{e'}$

$s = (\mathbf{p} + \mathbf{k})^2 = 4E_e E_p$

An EIC, with **high luminosity**, versatile beam **species** and beam **polarizations**, covering $0.1 < Q^2 < 1000 \text{ GeV}^2$, $10^{-4} < x < 10^{-1}$ is needed to:

- explore both the region of **non-perturbative** effects and the **gluon dominated** region
- precisely image the **sea quarks and gluons** in nucleons and nuclei
- resolve outstanding issues in understanding nucleons and nuclei in terms of fundamental building blocks of QCD

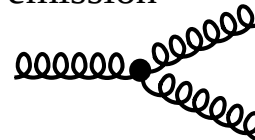
Gluon saturation at low x ($\rightarrow$ high energy)



What tames the low-x rise?

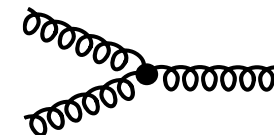
- Evolution equations at low x and moderate Q^2 are used to understand the onset of the **high gluon-density phase**
- “Black disk limit”: unitarity bound on cross section
- **Saturation scale $Q_s(x)$** : where gluon emission and recombination become comparable (BK-JIMWLK evolution, non linear)

gluon emission

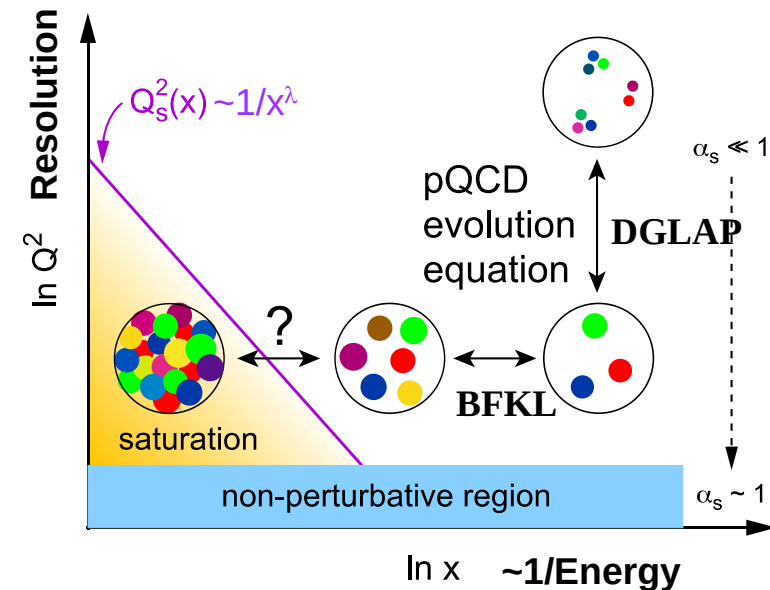


=

gluon recombination



At Q_s

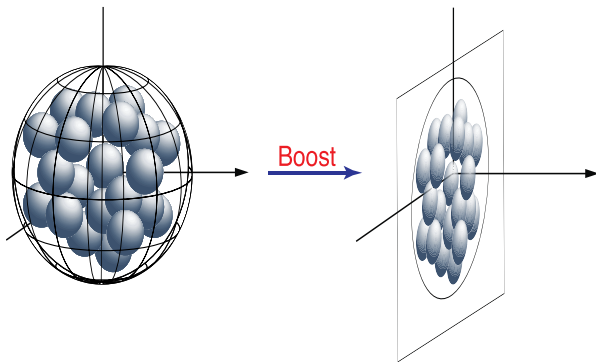


- **Saturation occurs when recombination becomes relevant**
 - Gluon recombination leads to a **collective gluonic system**
 - It is a **universal** phenomenon, for both nucleons and nuclei
 - Its presence has been hinted in many heavy-ion experiments
- $\rightarrow$ **High potential for discovery and study at an EIC**

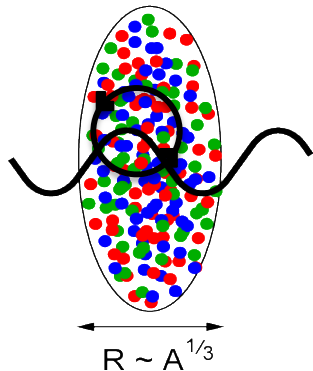
How to explore/study this new phase of matter?

(multi-TeV) e-p collider (LHeC) OR a (multi-10s GeV) e-A collider

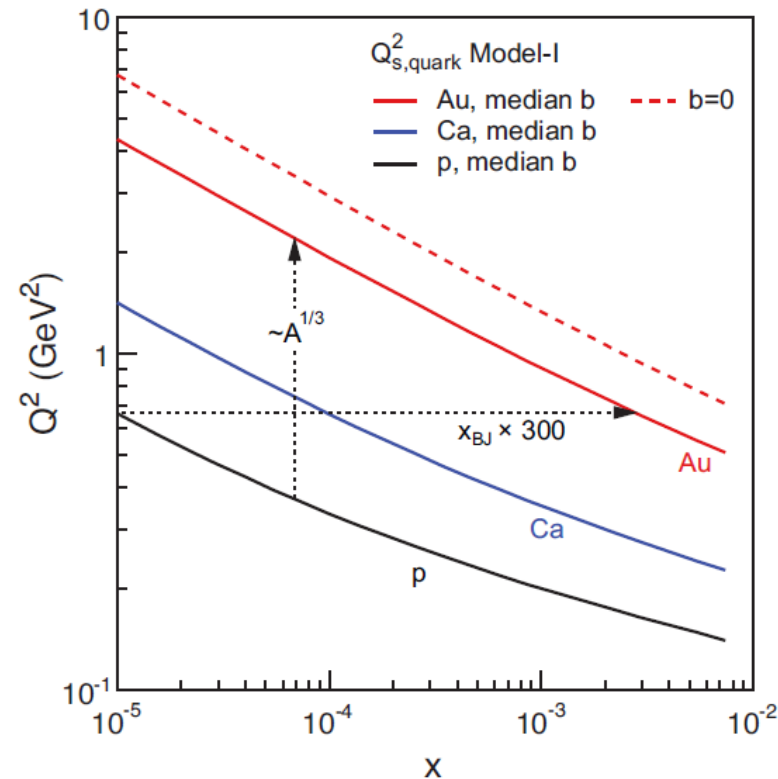
Advantage of nucleus →



Boosted nucleus:
**High parton
density in the
transverse plane**



$$(Q_s^A)^2 \approx c Q_0^2 \left[\frac{A}{x} \right]^{1/3}$$



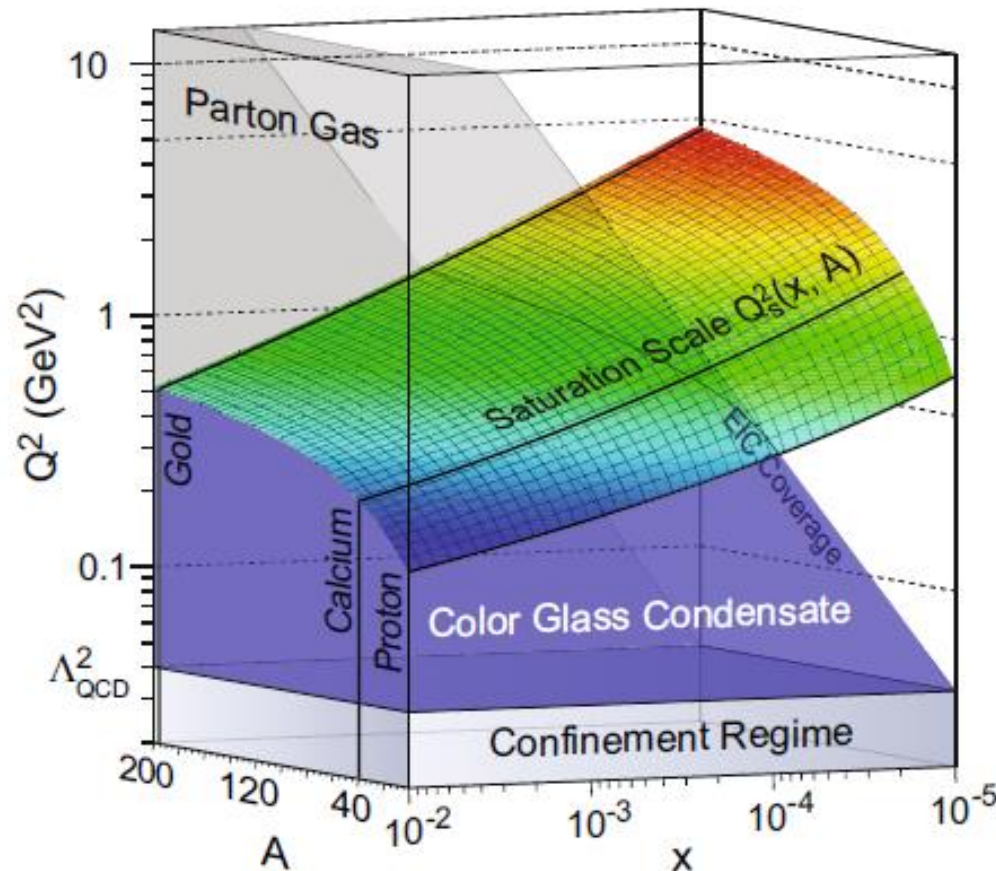
Enhancement of Q_s with A (“nuclear oomph factor”):

Saturation regime reached at significantly lower energy (=cost) in nuclei than for the proton

→ **need for ion beams at EIC**

How to explore/study this new phase of matter?

(multi-TeV) e-p collider (LHeC) OR a (multi-10s GeV) e-A collider



Enhancement of Q_s with A (“nuclear *oomph* factor”):

Saturation regime reached at significantly lower energy (=cost) in nuclei than for the proton

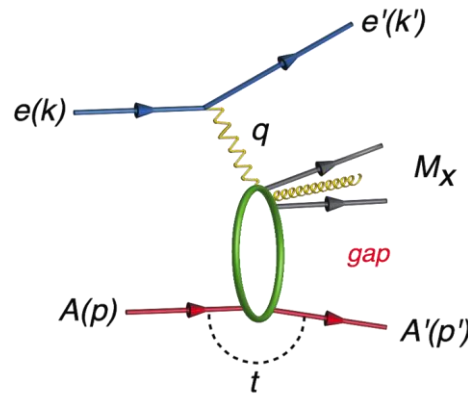
→ need for ion beams at EIC

Diffraction as a tool to study gluon densities

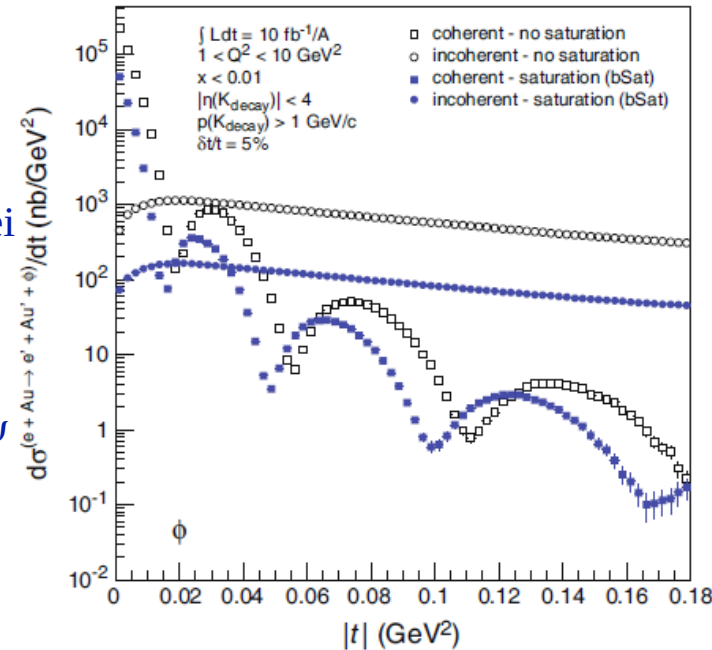
Diffraction cross-sections have strong discovery potential:

High sensitivity to gluon density in linear regime: $\sigma \sim [g(x, Q^2)]^2$

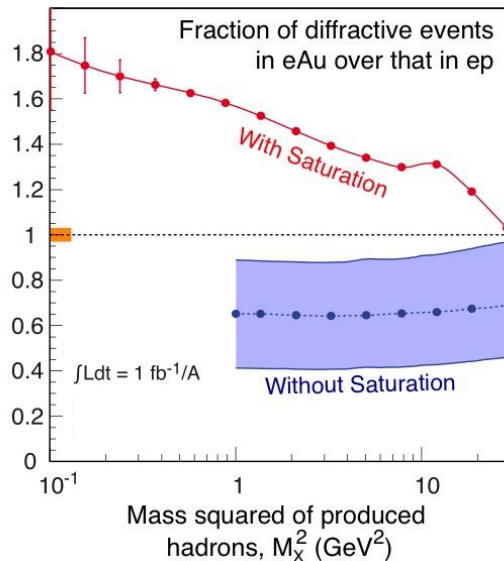
Dramatic changes in cross-sections with onset of non-linear strong color fields



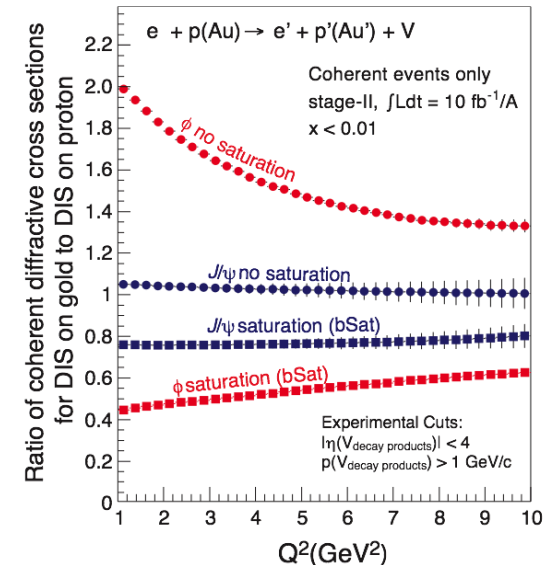
Extraction of the gluon distribution $\rho(b_T)$ of nuclei via Fourier transform of $d\sigma/dt$ in diffractive J/ψ and ϕ production



Probing gluon saturation through measuring $\sigma_{\text{diffractive}}/\sigma_{\text{tot}}$

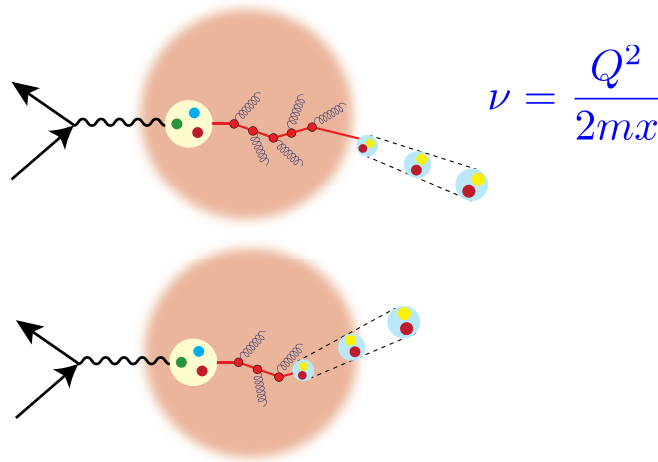


Probing Q^2 dependence of gluon saturation in diffractive vector meson production

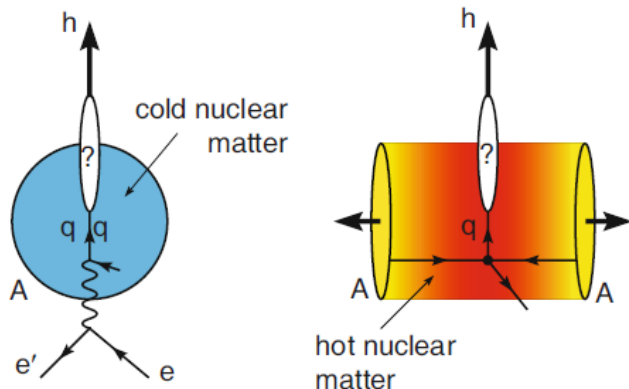


Emergence of hadrons from partons

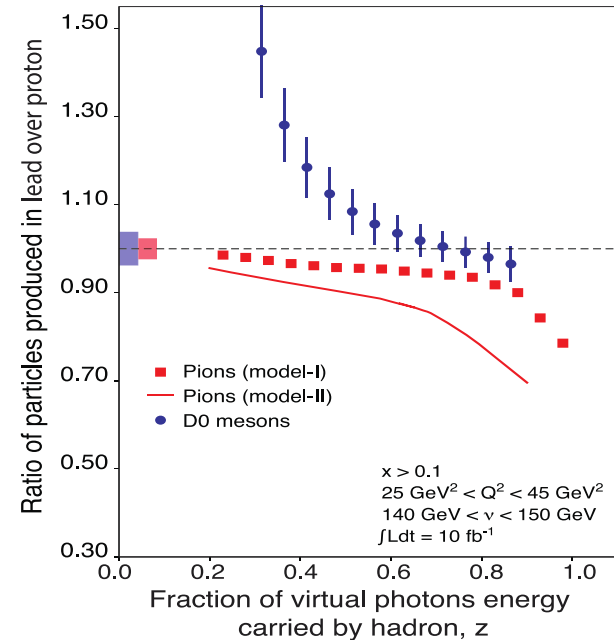
Unprecedented ν , the virtual photon energy range at EIC : precision & control on kinematics to study **hadronization**



Colored quark emerges as color neutral hadron → What is the impact of colored media on confinement?



Energy loss by light vs. heavy quarks:
Multiplicity ratios



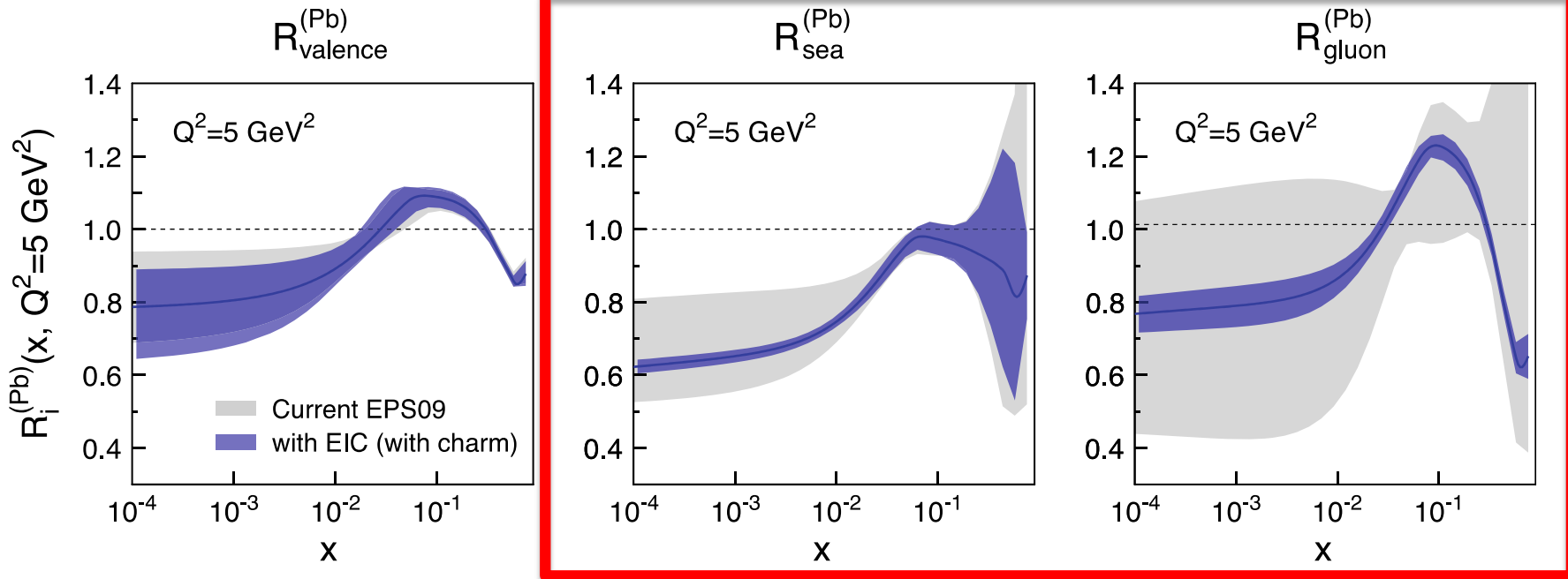
Identify light vs. charm hadrons in **e-A (SIDIS)**:
Understand **energy loss** of light vs. heavy quarks in **cold nuclear matter**

*Provides insight into energy loss
in Quark-Gluon Plasma*

**SIDIS at collider energies enables control of
parton/event kinematics**

Effect of the nuclear environment on partons

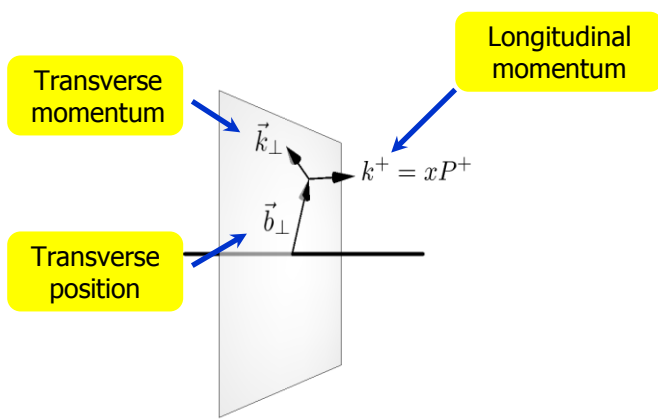
→ impact of the EIC on the knowledge of nPDFs



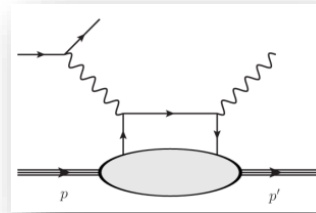
Ratio of Parton Distribution Functions of Pb over Proton:

- Without EIC, large uncertainties in **nuclear sea quarks and gluons**
- EIC **significantly reduces uncertainties**
- Impossible to achieve for current and future pA data at RHIC & LHC

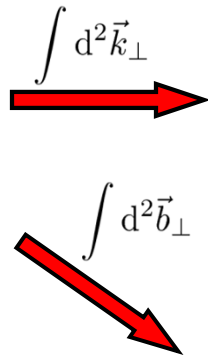
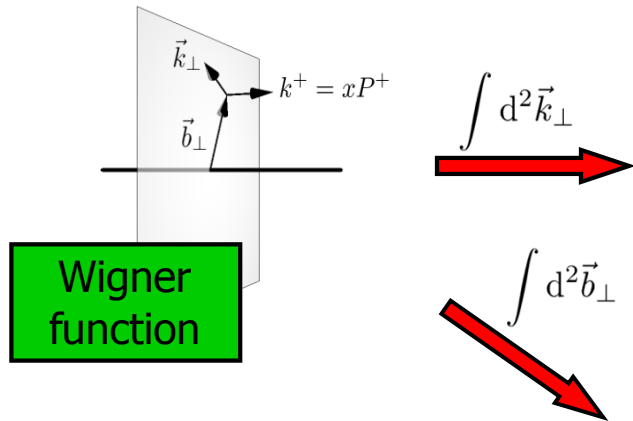
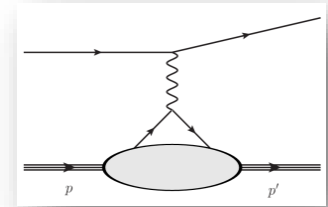
Multi-dimensional mapping of the nucleon



DVCS, DVMP



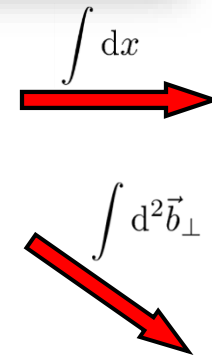
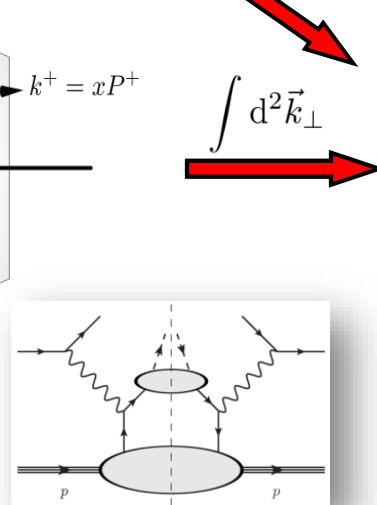
Elastic Scattering



GPDs

TMDs

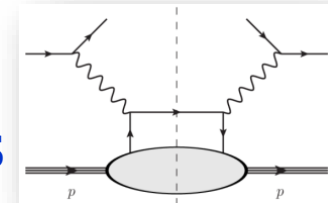
SIDIS



Form Factors

PDFs

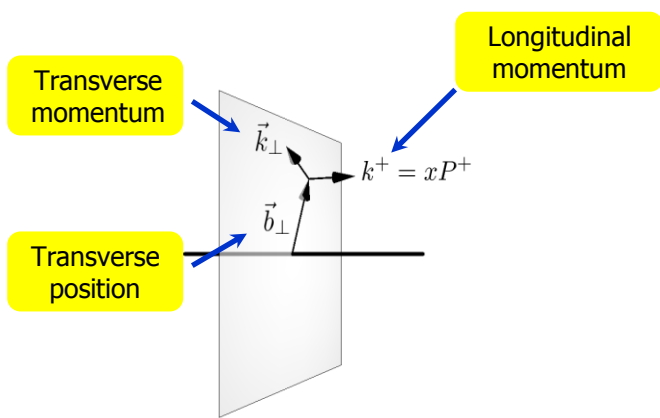
DIS



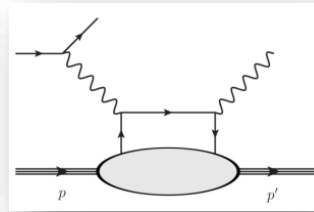
Legend:
GPDs: Generalized Parton Distributions
TMDs: Transverse Momentum Dependent Distributions
PDFs: Parton Distribution Functions

DVCS: deeply Virtual Compton scattering
DVMP: deeply Virtual meson production
SIDIS: semi-inclusive DIS

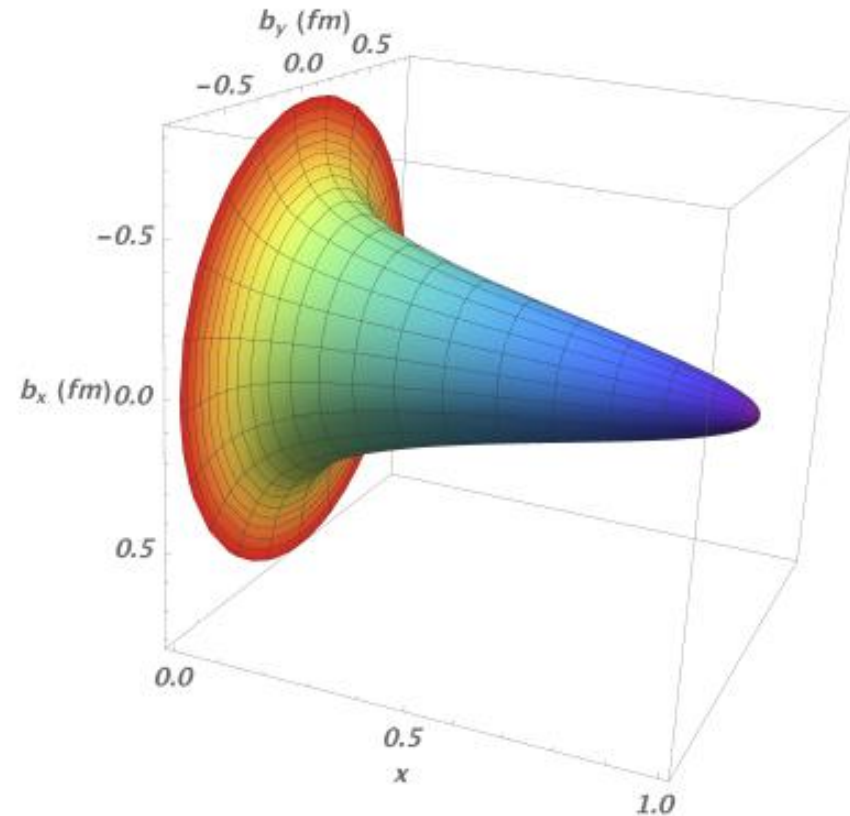
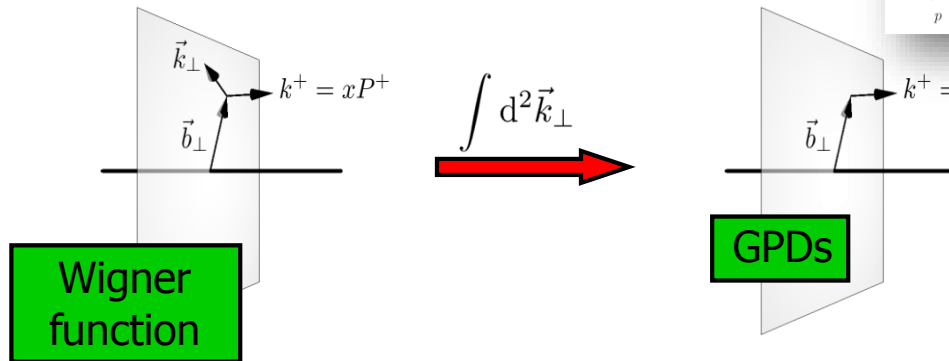
Multi-dimensional mapping of the nucleon



DVCS, DVMP



Proton tomography from JLab data at 6 GeV on DVCS



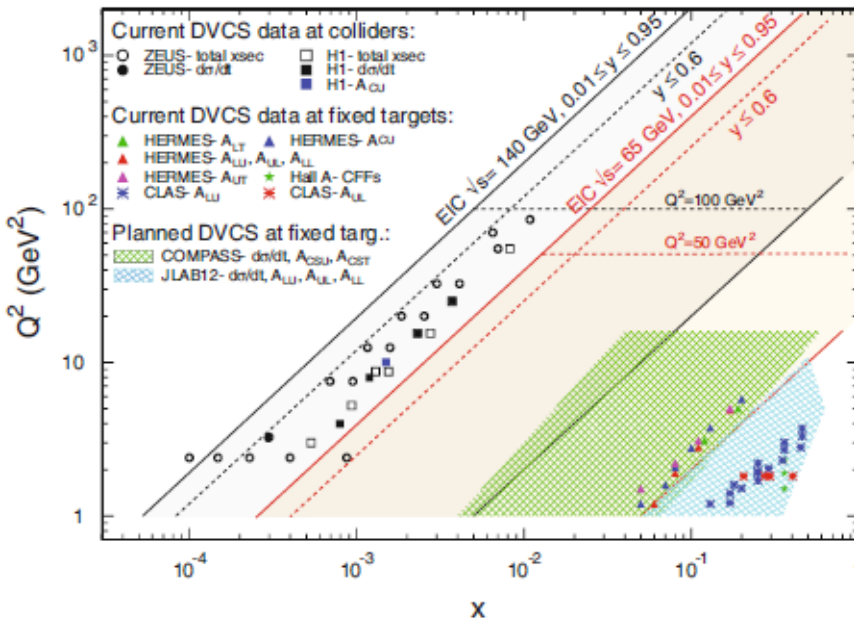
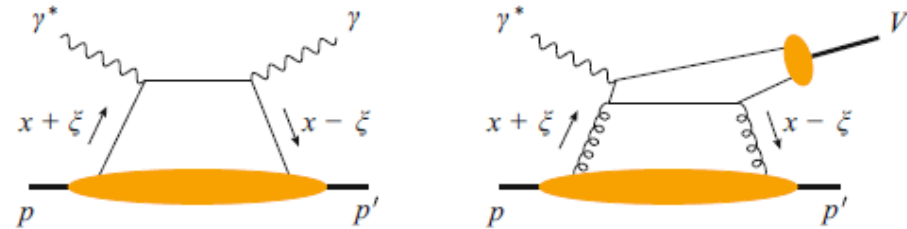
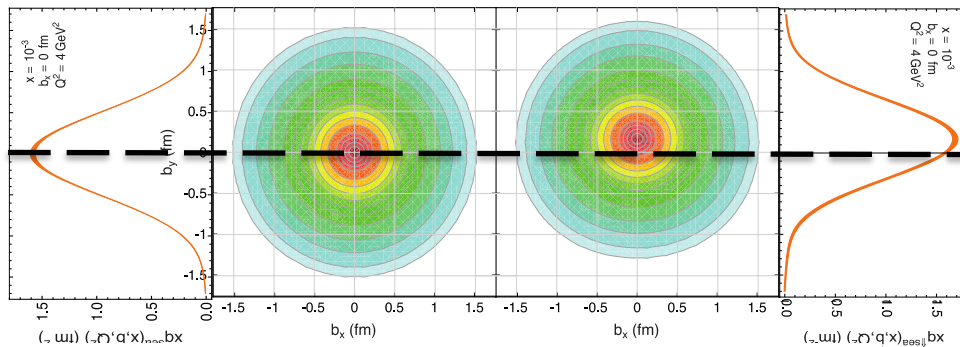
Ongoing intense research effort at **JLab** and **COMPASS** in the valence (and sea) quark regimes

Multi-D partonic image of the nucleon with the EIC

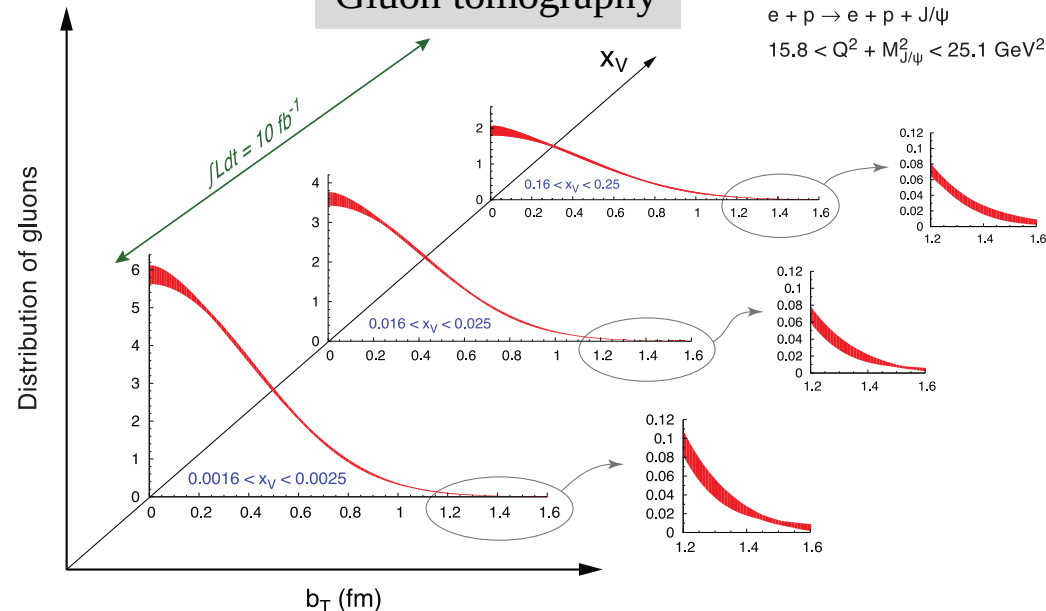
Spin-dependent 2D **coordinate space** (transverse) + 1D (longitudinal momentum)
Measurable via **exclusive scattering**

Sea quarks
unpolarized polarized

Generalized Parton Distributions



Gluon tomography

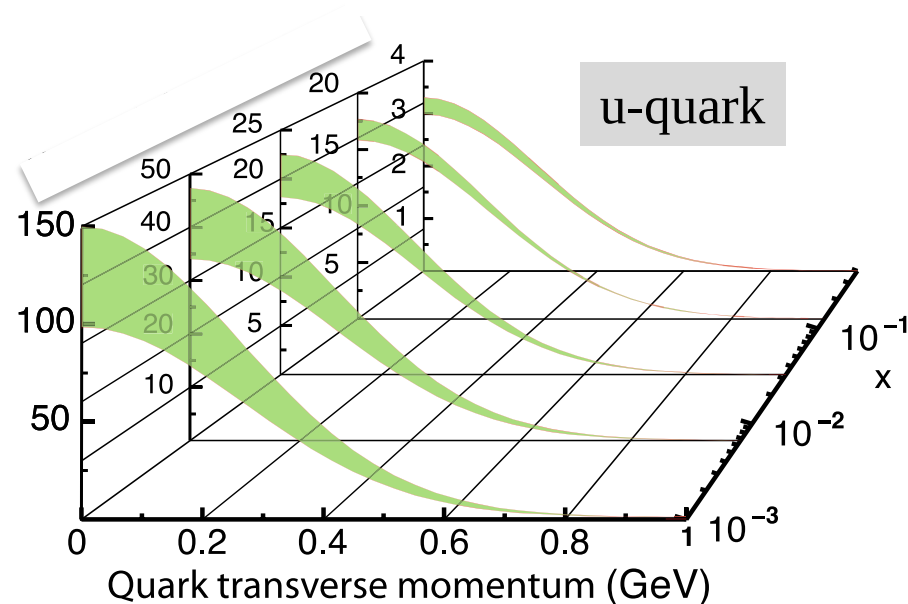
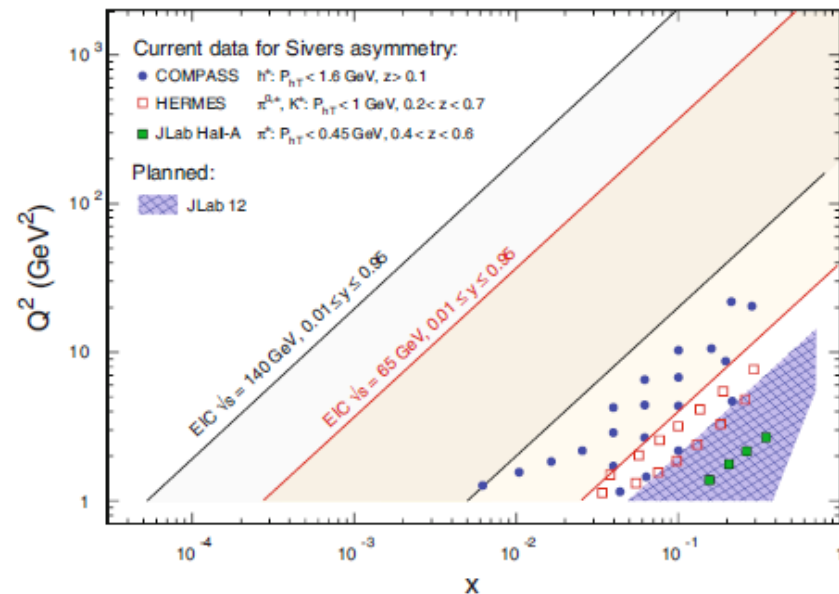
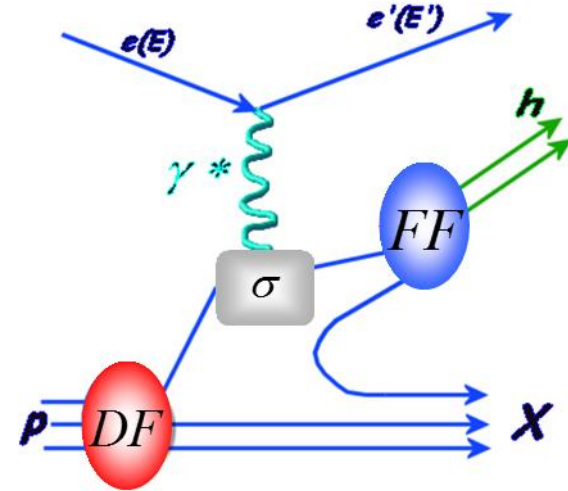
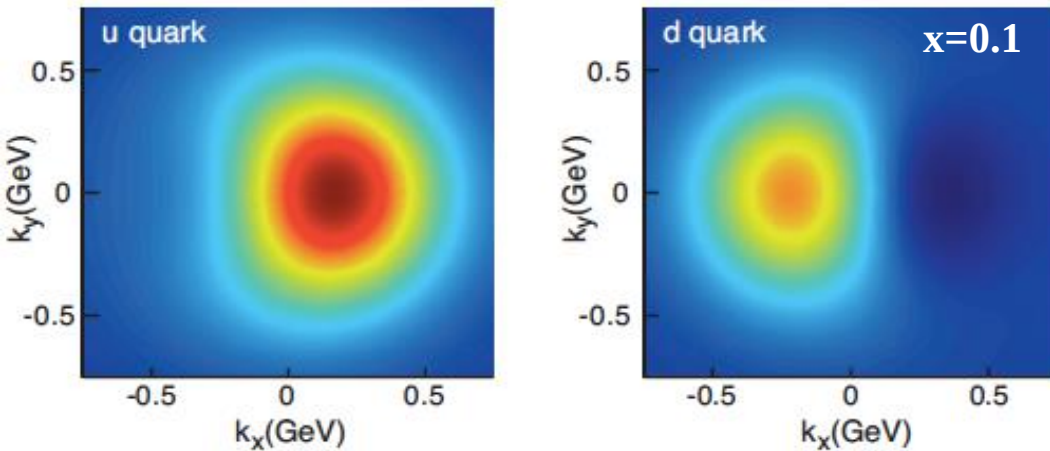


$e + p \rightarrow e + p + J/\psi$
 $15.8 < Q^2 + M_{J/\psi}^2 < 25.1 \text{ GeV}^2$

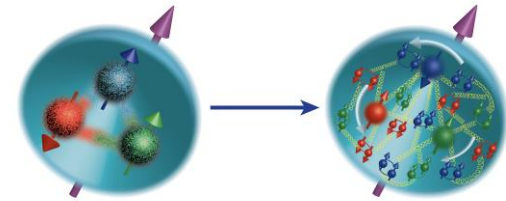
Multi-D partonic image of the nucleon with the EIC

Spin-dependent 3D momentum space – Measurable in **semi-inclusive scattering**

Transverse Momentum Distributions



Understanding nucleon spin



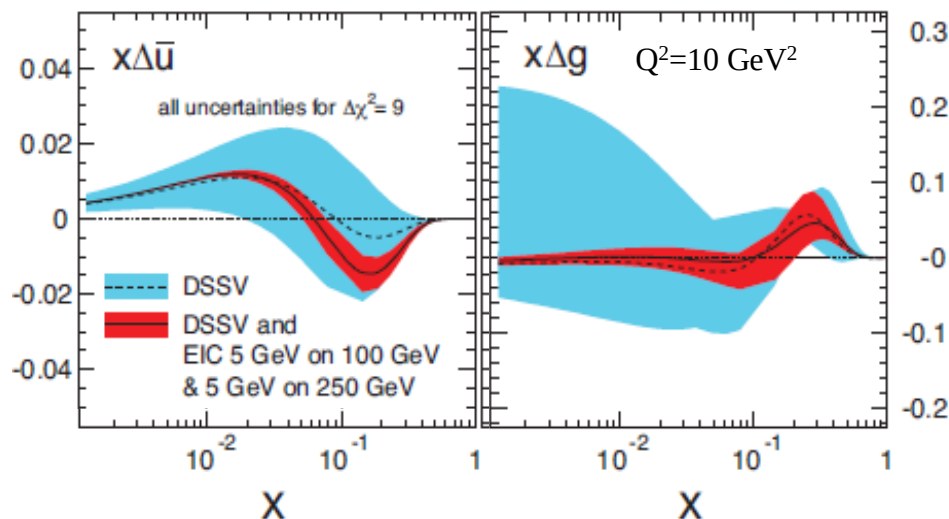
“Helicity sum rule”

$$\frac{1}{2}\hbar = \underbrace{\frac{1}{2}\Delta\Sigma}_{\text{quark contribution}} + \underbrace{\Delta G}_{\text{gluon contribution}} + \underbrace{\sum_q L_q^z + L_g^z}_{\text{orbital angular momentum}}$$

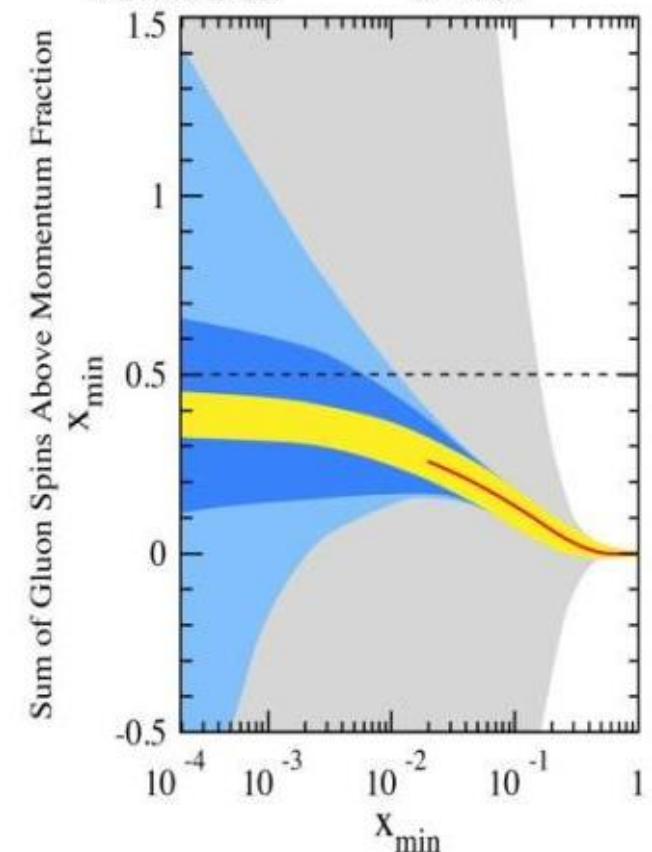
EIC projected measurements:

precise determination of polarized PDFs of quark sea and gluons → precision ΔG and ΔS

→ A clear idea of the magnitude of $\sum L_q + L_g$



DIS + SIDIS with 90% C.L. band
RHIC projection including 500 GeV data
DIS + SIDIS + RHIC with 90% C.L. band
EIC projection $\sqrt{s} = 78$ GeV



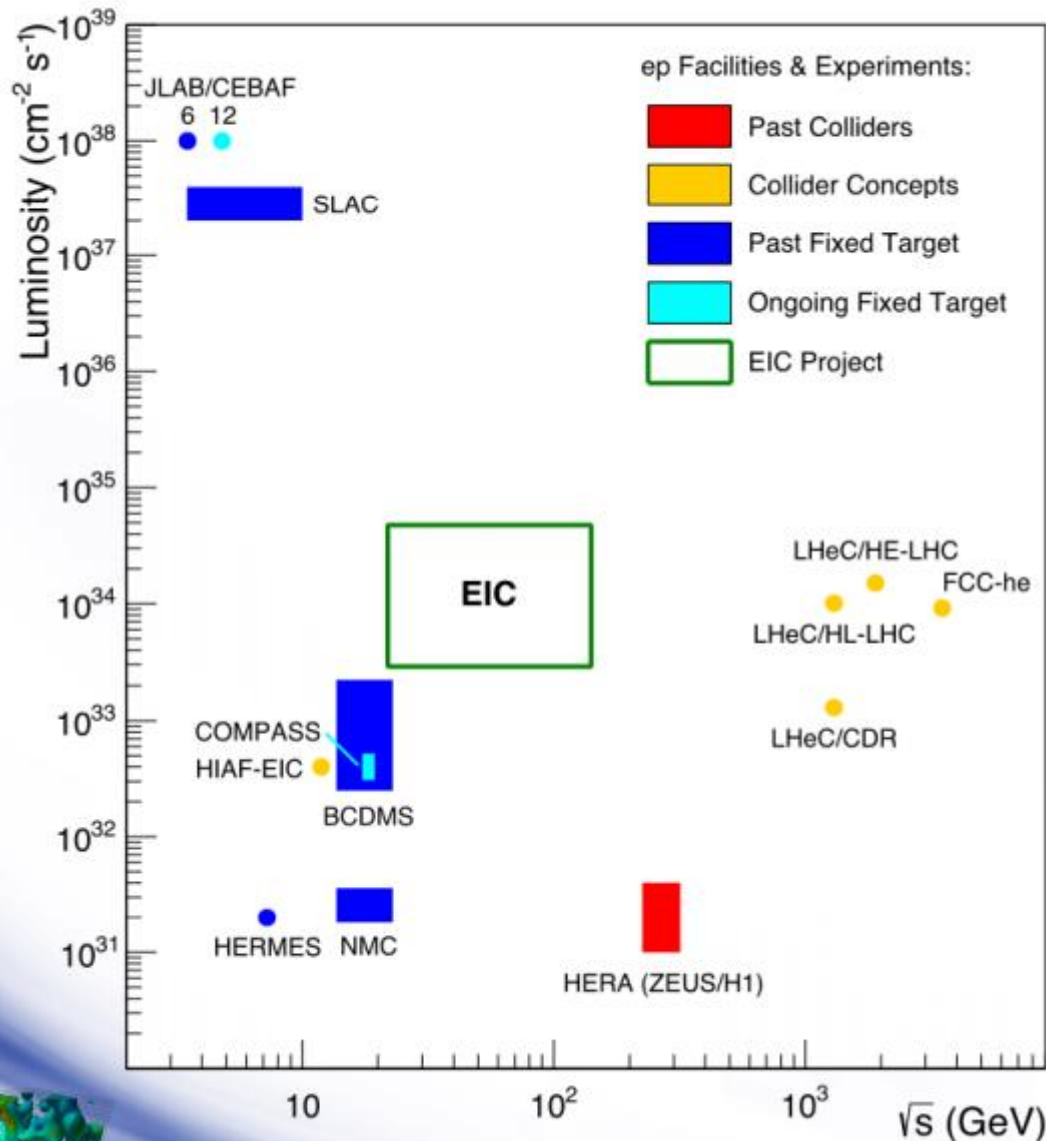
Spin and Lattice: Recent Activities

- ❑ Gluon's spin contribution on Lattice: $S_G = 0.5(0.1)$
Yi-Bo Yang et al. PRL **118**, 102001 (2017)
- ❑ J_q calculated on Lattice QCD:
 χ QCD Collaboration, PRD91, 014505, 2015

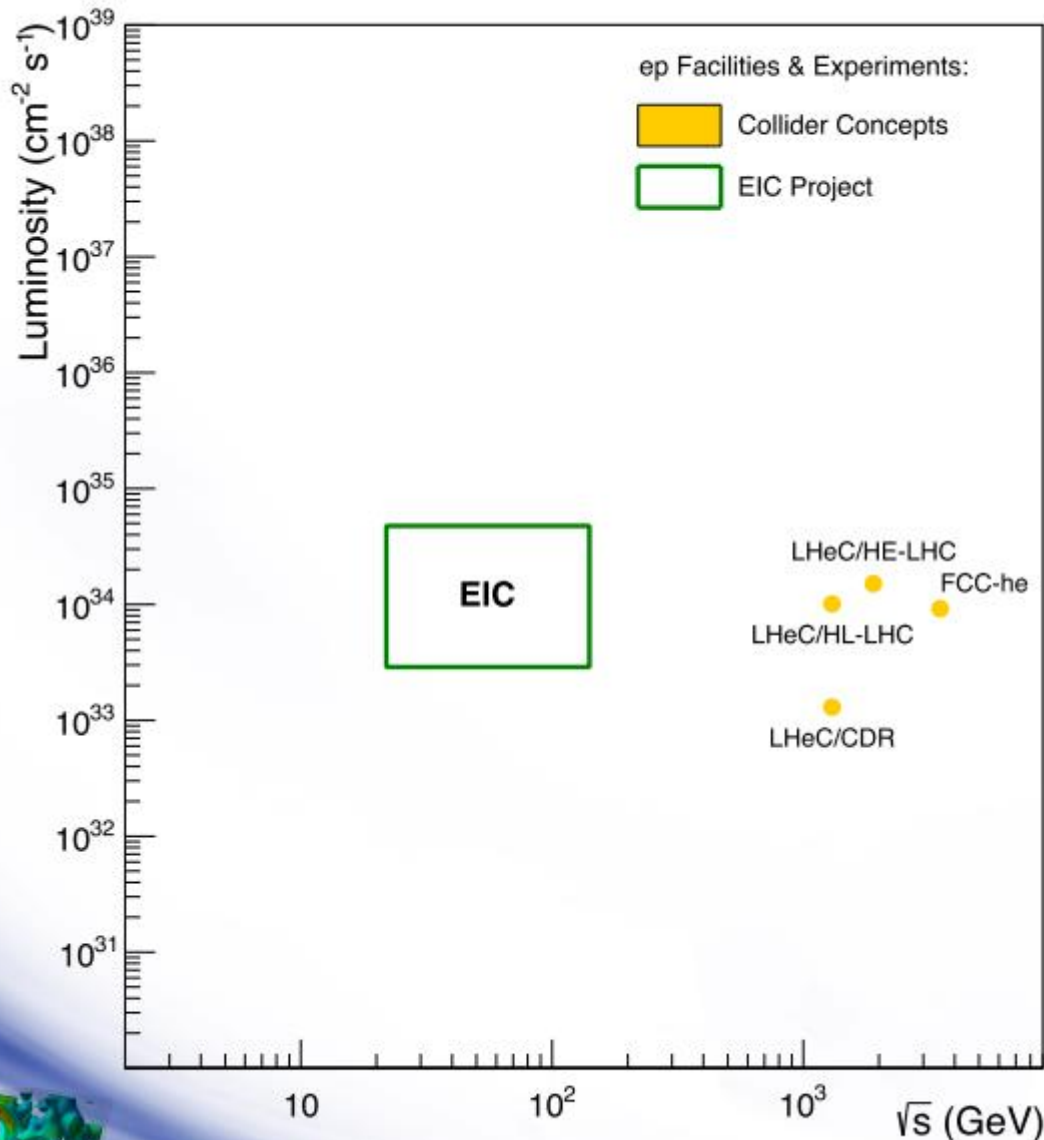
Uniqueness of EIC among all DIS facilities

All DIS facilities in the world.

However, if we ask for:



Uniqueness of EIC among all DIS facilities

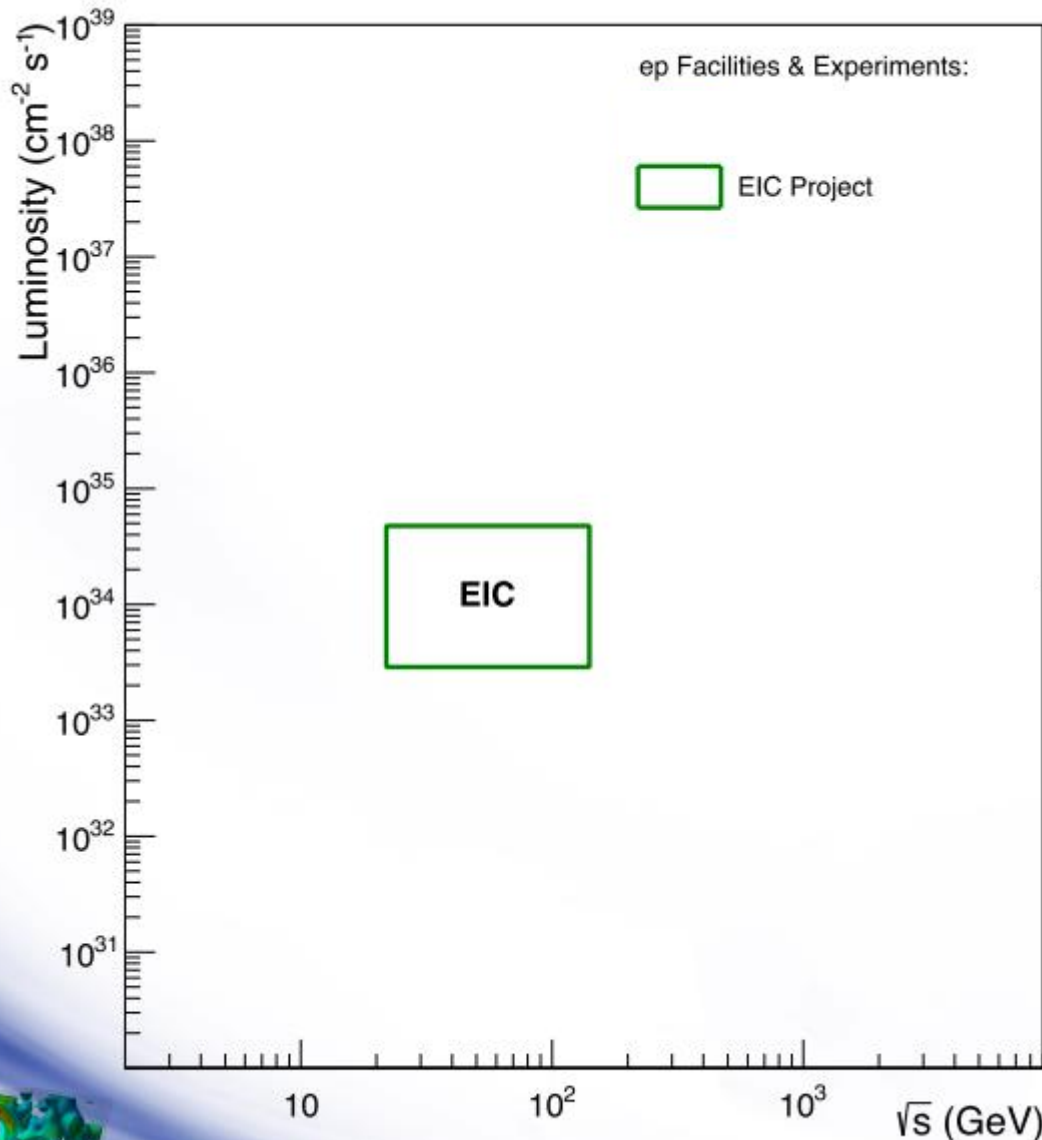


All DIS facilities in the world.

However, if we ask for:

- High luminosity and wide reach in $\sqrt{s}$

Uniqueness of EIC among all DIS facilities



All DIS facilities in the world.

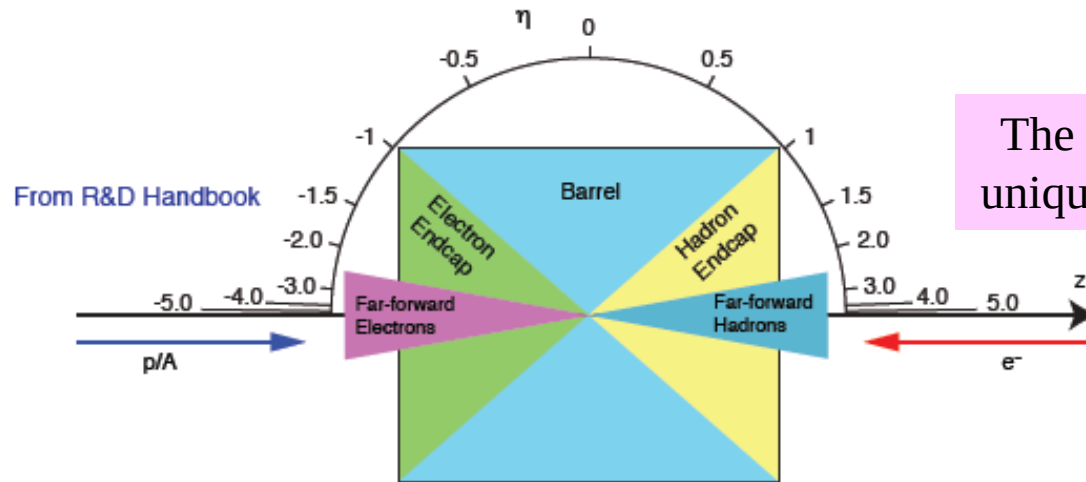
However, if we ask for:

- **High luminosity and wide reach in $\sqrt{s}$**
- **Polarized lepton and hadron beams**
- **Nuclear beams**

EIC stands out as a unique facility...

EIC detector requirements

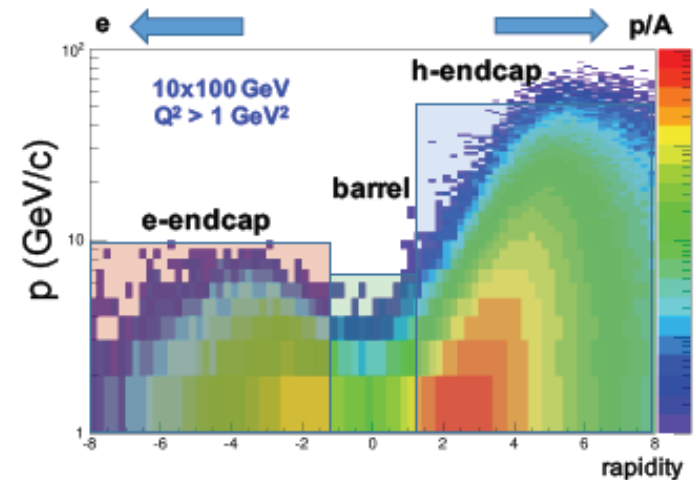
Detector requirements are mostly **site-independent**, with some slight differences in the forward region (IR integration)



The physics characteristics bring unique challenges to EIC detectors

General requirements:

- Hermetic detector
- Low mass inner tracking, good PID ($e, \pi/K/p$) at wide angle, calorimetry, forward and backwards tracking
- Moderate radiation hardness requirements, low pile-up, low multiplicity



EIC Detector Concepts: BNL

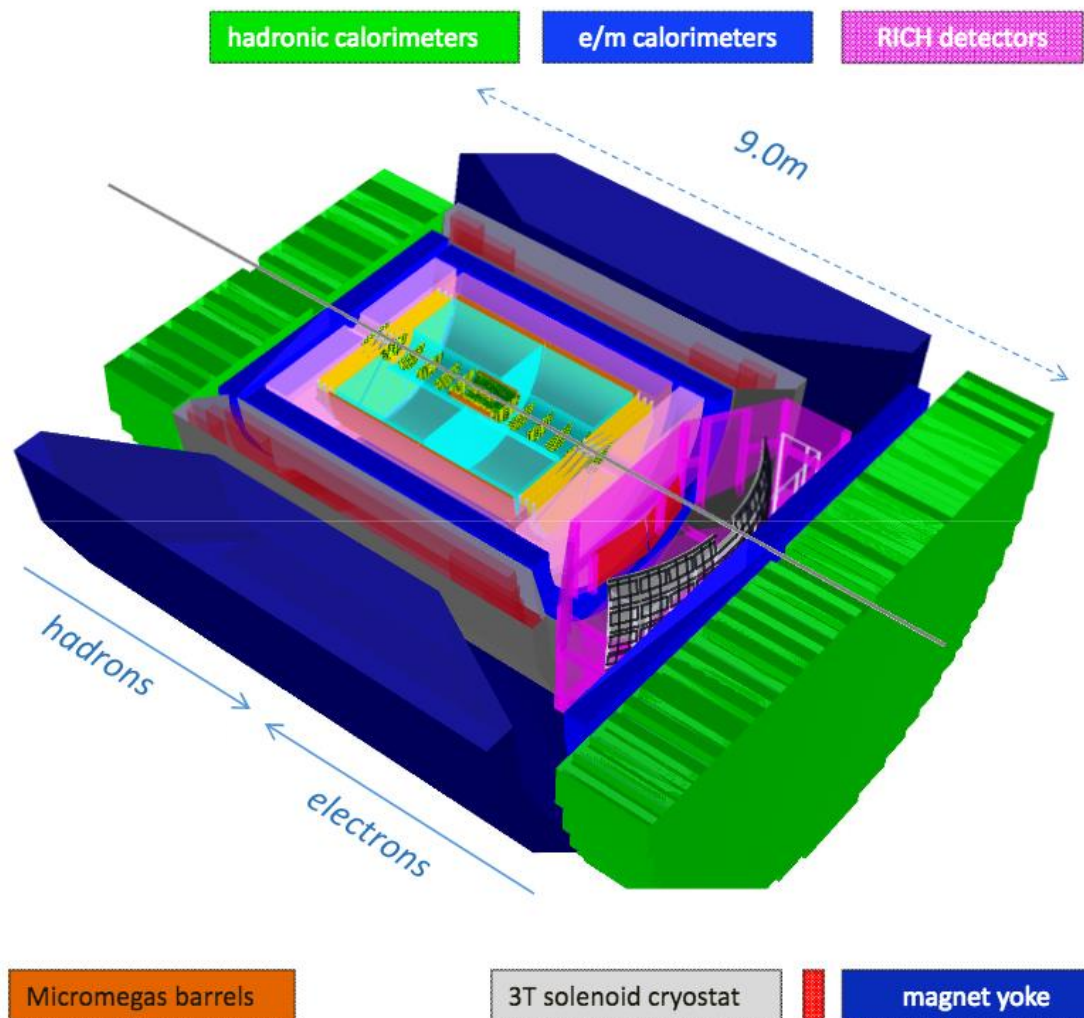
BeAST (**B**rookhaven **eA** **S**olenoidal **T**racker)

- **From the center outwards:**

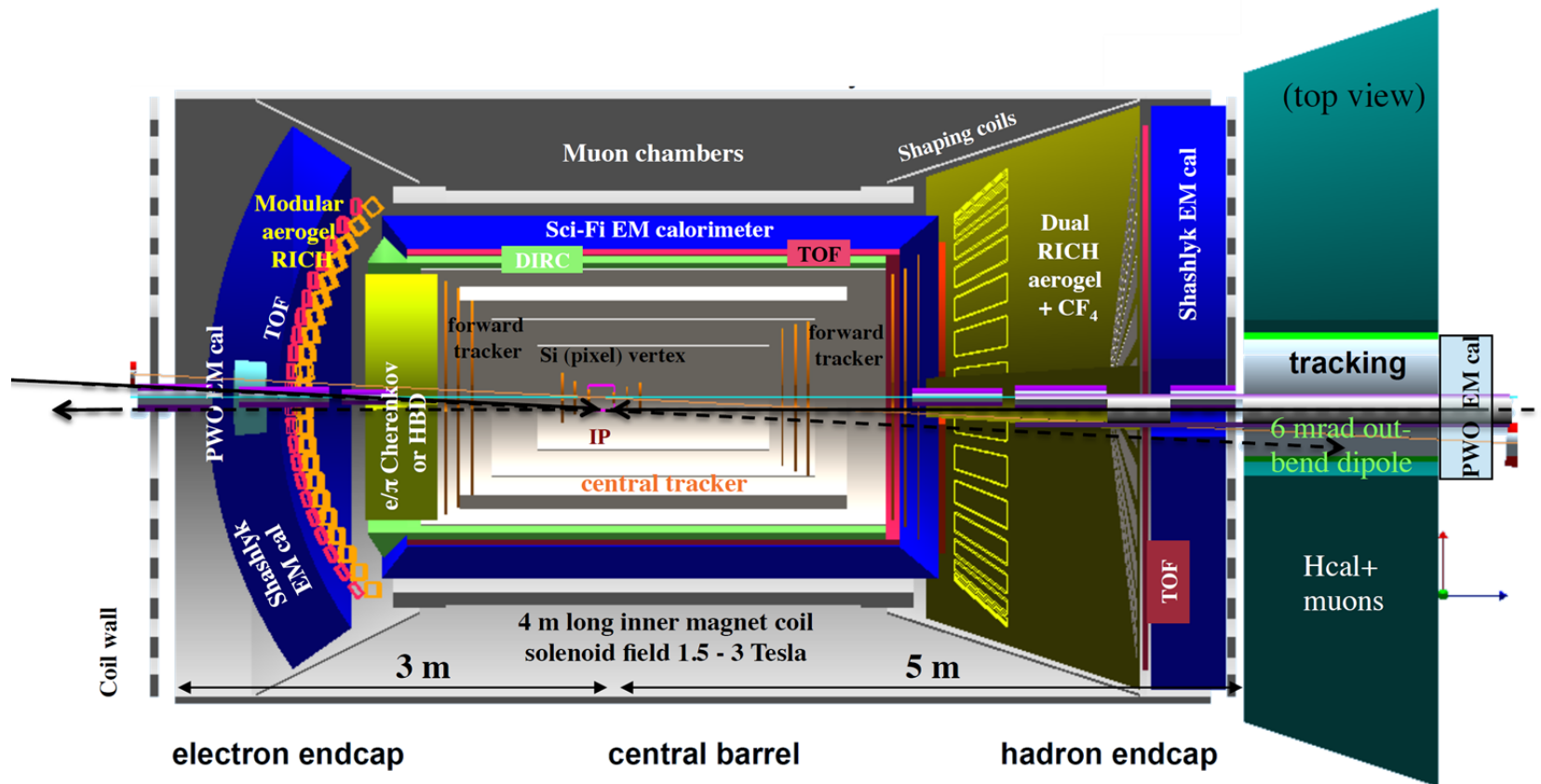
- ✓ Silicon vertex in the center
- ✓ Trackers
- ✓ Cerenkov detectors
- ✓ EM and hadronic calorimeters
- ✓ Solenoid

- **Detectors are standard collider designs, using latest technologies**

- ✓ Very similar to RHIC or LHC detectors, with emphasis on PID capabilities
- ✓ Asymmetry between the hadron and electron sides, with different PID requirements



EIC Detector Concepts: JLab



- **Similar concept to BNL**

- ✓ With lots of room devoted to RICH detectors
- ✓ The low multiplicity expected in e-A allows for better Particle ID

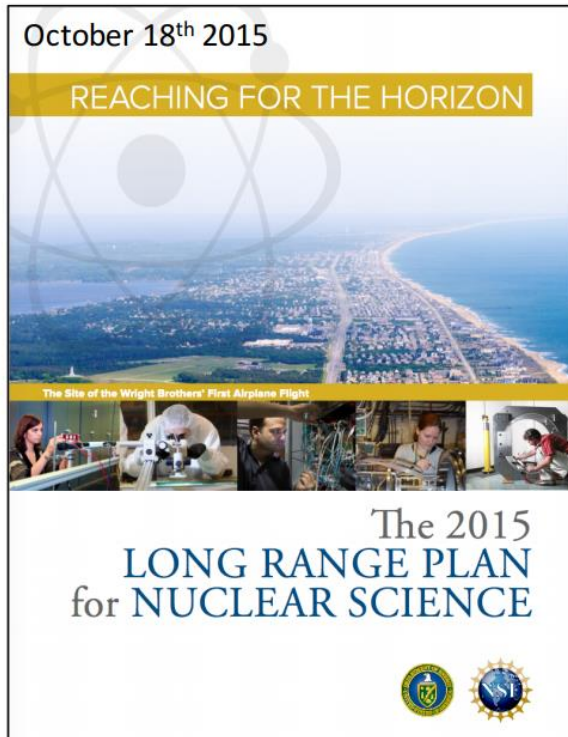
- **Low angle capabilities**

- ✓ Critical for many processes
 - Coherent scatterings
 - Centrality measurements
- ✓ Unique in comparison to the many fixed target facilities performing e-A

New Users → New Physics → Lots of activities

- Jet studies at the EIC:
 - Systematic investigations of general issues in jet-finding at an EIC
 - Understanding of “micro-jets” – jets with only few hadrons
 - Understanding the jet structure modifications in nuclei vs. protons
 - Energy loss in cold QCD matter (Nuclei) vs. hot QCD matter at RHIC and LHC
- Precision measurements of the “initial state” for collisions leading to the QGP being studied at RHIC and LHC
- Precision PDF measurements in proton, neutron & photons at the EIC:
 - Study the free neutron PDFs through tagging and on-shell extrapolation
 - Study the gluon PDFs at large Bjorken x through evolution and open-charm production
 - Study of gluons TMDs
 - Study the potential impact on Higgs studies in the High-Luminosity LHC era
 - Study the impact of TMDs @ EIC on W-production at the LHC
 - Polarized and unpolarized photon PDFs
- Measurements of PDFs in pions and kaons through the Sullivan process
 - Theoretical studies of the equivalence of near-off-shell and on-shell pions and kaons
 - Study the extraction of, and expected differences of, quark and gluon PDFs in pions, kaons and nucleons, and the relation to their physical masses
- Nucleon structure with electroweak probes, and precision BSM physics (i.e. $\text{Sin}^2 Q_W$)
- Heavy quark & quarkonia production with 100-1000 times HERA luminosity
- In view of new discoveries of multi-quark XYZ states: what could EIC contribute?

It is the ideal time to get involved in the EIC!

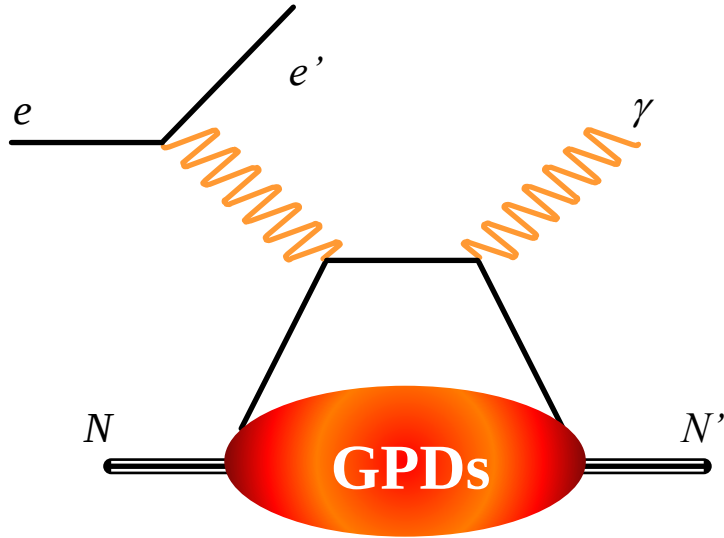


1. The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.
 - **12 GeV** – unfold quark & gluon structure of hadrons and nuclei
 - **FRIB** – understanding of nuclei and their role in the cosmos
 - **Fundamental Symmetries Initiative** – physics beyond the SM
 - **RHIC** – properties and phases of quark and gluon matter

The ordering of these four bullets follows the priority ordering of the 2007 plan
2. We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.
3. We recommend a high-energy high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB.
4. We recommend increasing investment in small and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

- A review by the National Academy of Sciences has begun. The Charge is: “Assess the scientific justification for a U.S. domestic electron ion collider facility” (report expected for June 2018)
- DOE project “CD0” (Establish Mission Need) after NAS review: 2018
- EIC construction must start after FRIB is completed, which will not happen before 2020.
- Most optimistic scenario: start EIC construction (CD3) in FY20. More realistic: FY22-23
- According to the NSAC/LRP recommendations, the best estimate for construction completion of EIC is 2025-2030

Motivation: DVCS on the Neutron with CLAS12 (E12-11-003)



A combined analysis of DVCS observables for **proton and neutron** targets is necessary for **flavor separation** of GPDs

$$(H, E)_u(\xi, \xi, t) = \frac{9}{15} [4(H, E)_p(\xi, \xi, t) - (H, E)_n(\xi, \xi, t)]$$

$$(H, E)_d(\xi, \xi, t) = \frac{9}{15} [4(H, E)_n(\xi, \xi, t) - (H, E)_p(\xi, \xi, t)]$$

JLab PAC: **high-impact experiment**

To start an experimental program on nDVCS we will measure the **beam-spin asymmetry**, the observable the most sensitive to **the least constrained GPD, $E \rightarrow J_q$**

Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\phi \operatorname{Im}\{F_1\mathcal{H} + \xi(F_1 + F_2)\tilde{\mathcal{H}} + kF_2\mathcal{E}\}d\phi$$

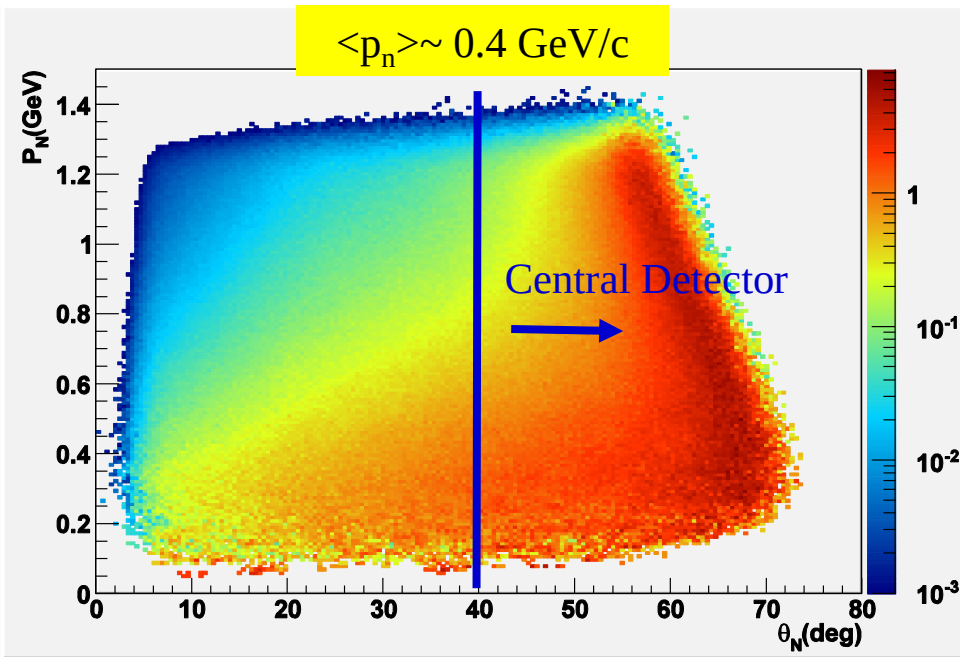
Proton
Neutron

$$\begin{array}{l} \operatorname{Im}\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\} \\ \operatorname{Im}\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n\} \end{array}$$

The BSA for nDVCS:

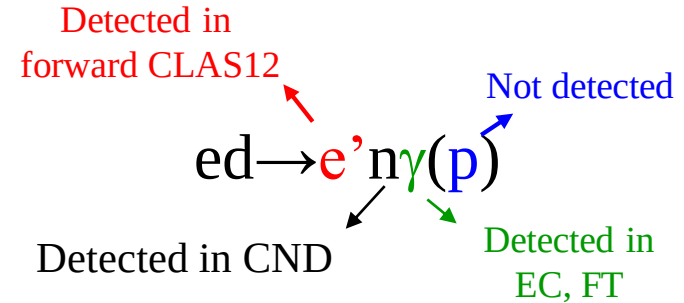
- is complementary to the **TSA for pDVCS** on transverse target, aiming at **E**
- depends strongly on the **kinematics** → **wide coverage needed**

CND: requirements and constraints



More than 80% of the neutrons have $\theta > 40^\circ$
 → Neutron detector in the Central Detector
 Free space between CTOF and solenoid

Resolution on $MM(en\gamma)$ studied with nDVCS event generator + electron and photon resolutions obtained from CLAS12 FastMC + design specs for EC and Forward Tagger
 → dominated by photon resolutions



$$p_e^\mu + p_n^\mu + p_p^\mu = p_{e'}^\mu + p_{n'}^\mu + p_{p'}^\mu + p_\gamma^\mu$$

In the hypothesis of **absence of FSI**:

$p_p^\mu = p_{p'}^\mu \rightarrow$ **complete kinematics** detecting $e'n\gamma$

Requirements:

- good neutron/photon separation for $0.2 < p_n < 1$ GeV/c → ~150 ps time resolution (obtained from GEMC simulations)
- momentum resolution below 10%
- no stringent requirements for angular resolutions

Constraints:

- **limited available space** (~10 cm radially)
 → limited efficiency
 → no space for light guides downstream (CTOF)
- **strong magnetic field** (~5 T) → light readout?

Chosen design for the CND

- Plastic scintillator: compromise between neutron efficiency ($\sim 1\%$ /cm) and fast response
- Photon-neutron separation $\rightarrow$ measurement of β via Time-Of-Flight

$$\beta = \frac{l}{TOF \cdot c}$$

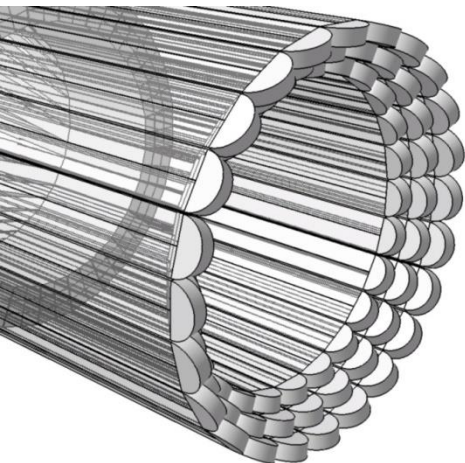
TOF : time from the interaction vertex to the impact point; l : path length
 $\beta + PID$ (m) $\rightarrow$ momentum

$$l = \sqrt{z^2 + h^2}$$

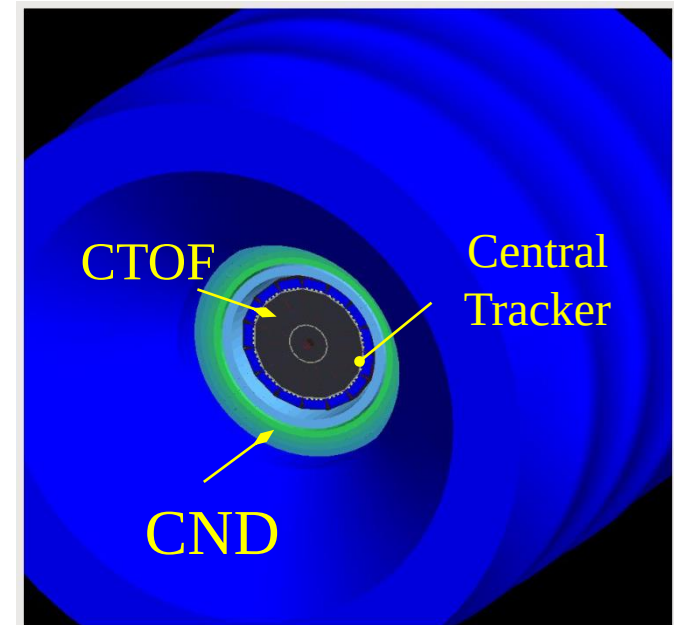
z : hit position along the scintillator bar;
 h : radial distance of the hit from the vertex $\rightarrow$ requires radial segmentation

$$z = \frac{1}{2} v_{eff} (t_{left} - t_{right})$$

v_{eff} : light velocity in the scintillator bar;
 $t_{left,right}$: time measured at the two ends of the bar $\rightarrow$ double readout
 $z \rightarrow \theta$



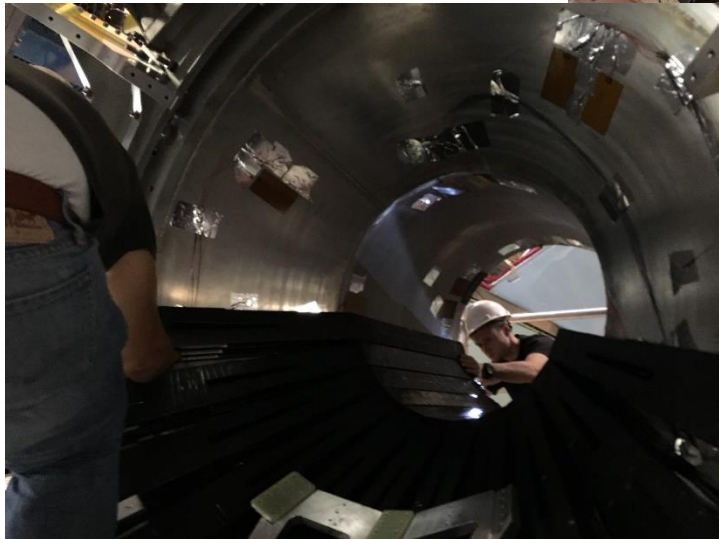
CND design: **scintillator barrel**
 3 radial layers, 48 bars per layer
 coupled two-by-two by “**u-turn**”
lightguides (24 2x3 “blocks”), light
 read **upstream** by PMTs connected to
 the bar via **1.5m-long light guides**



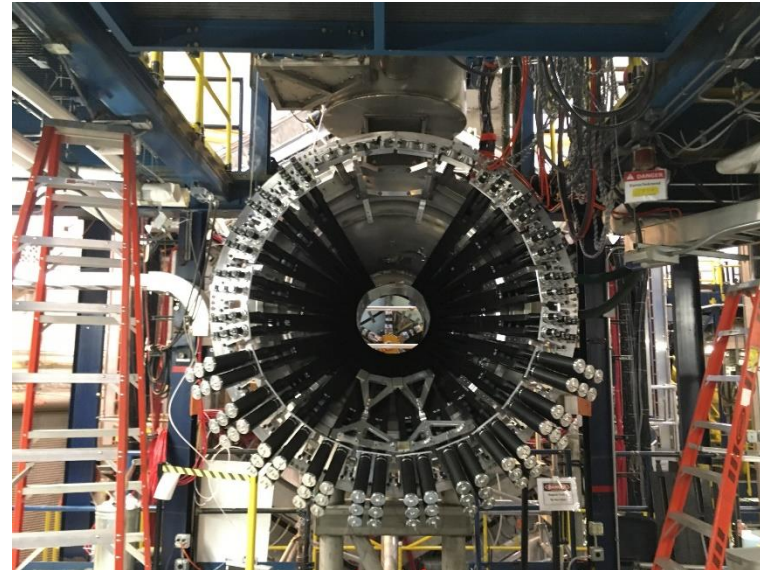
CND: project history and current status

- **Simulations and R&D** for detector conception started in **2008** (summer student project...)
 - **LOI** for nDVCS@CLAS12 endorsed by PAC34 (2009)
 - **Proposal** for nDVCS@CLAS12 approved by **PAC37** and rated (**A**) by PAC38 (2011)
 - CND project presented at **Conseil Scientifique of IN2P3**, obtained **300 k€** (fall 2011)
 - Partial support also received from the HP3 program of the European 7th Framework
 - **JLab review of the CND** in February 2012
- R&D and choice of all components finalized the same year
- All the components were procured and received at IPN Orsay between 2012 and 2014
 - The 24 2x3 blocks of the CND were **assembled at IPN Orsay** between 12/2014 and 2/2015
 - The 144 PMTs **were calibrated**
 - Each block was **tested in cosmic rays** upon assembly to check time resolution
 - A **mock-up of the solenoid** was constructed at IPN
 - **Full installation** of the CND in the mock-up was performed at IPN
 - The components of the **mechanical support structure** were designed at IPN Orsay and procured
 - The blocks, the structure, and the electronics were **shipped to JLab** in June 2015
 - Since then the CND has been **stored in the ESB building**

September 23rd: the longest day



At 9PM:
20 blocks,
72 PMTs



Hadronisation à EIC: simulations

• Simulations et phénoménologie

- L'évaluation des taux de comptage et de la force du signal attendu ont permis de clarifier les objectifs pour EIC

• Motivations pour EIC

- Permet de mesurer pour la première fois l'hadronisation des charmonia
 - Permet une comparaison avec les résultats du LHC dans un environnement mieux contrôlé
- L'interaction avec la matière nucléaire est dominée par les gluons de basse énergie
 - Donne un accès indirect à la saturation

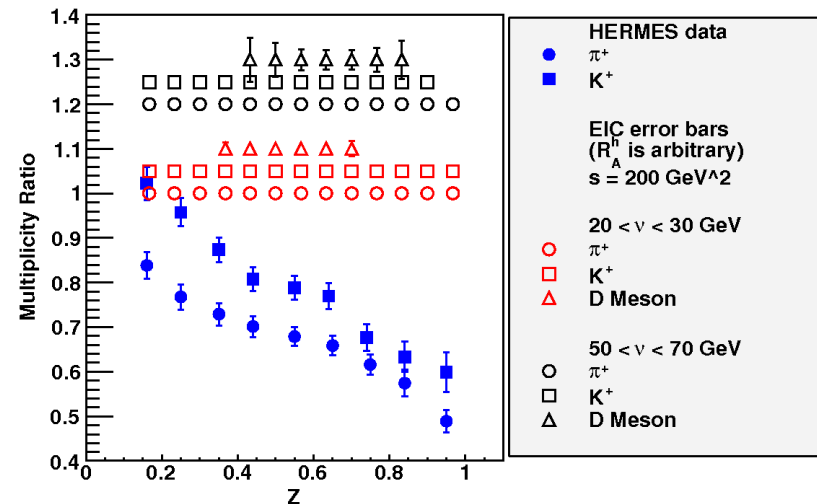
• Problématiques

- Les hautes énergies réduisent le signal
- La luminosité est l'éléments clés pour les mesures de quarkonia (bottomia seront difficiles)

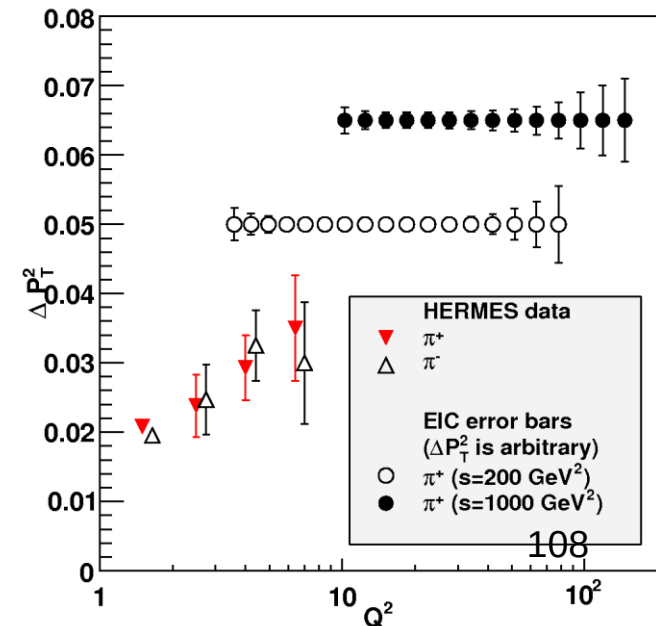
• Résultats publiés dans les 2 White Papers pour la physique de l'EIC

(ArXiv:1108.1713 et Eur.Phys.J. A52 (2016) no.9, 268)

Rapport particules produite en Pb vs proton

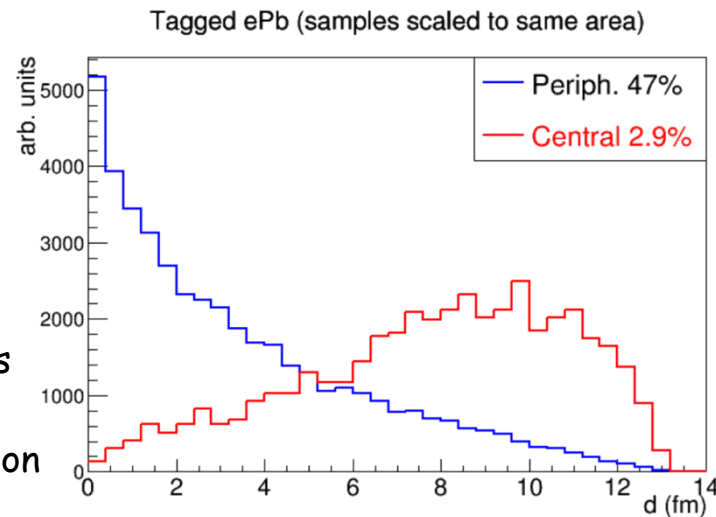
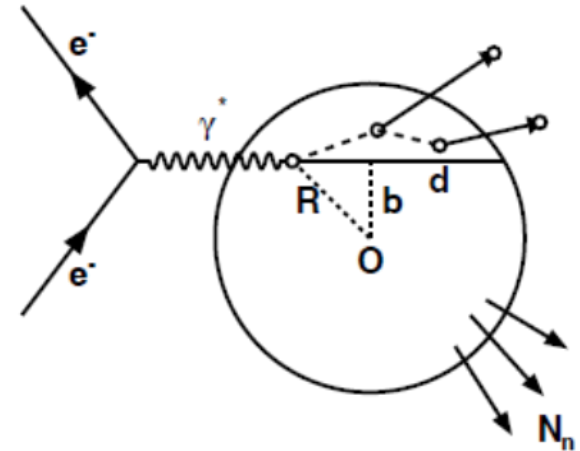


Différence du spread en P_T en Pb vs proton



Geometrical tagging

- **Mesure du paramètre d'impact**
 - Une manière de concentrer les effets nucléaires
 - Tache difficile en p-Pb et en diffusion de leptons (petit nombre de particules produites)
 - Possible en mesurant les nucléons provenant de la fragmentation de la cible
- **Développement d'un groupe sur le sujet à Jlab (LDRD Geometry tagging)**
 - Mise en place de simulations
 - Utilise une partie des codes développés pour l'hadronisation
 - Partie accélérateur et détecteur importante
- **Motivations au delà de l'hadronisation**
 - Étude des effets nucléaires en fonction de la centralité (shadowing en particulier)
 - Isolation des processus cohérents
- **Développements pour CLAS12**
 - L'une des propositions du groupe: calibrer les générateurs d'événements avec CLAS12 et cibles nucléaires
 - Cela permettra d'obtenir de premier résultat dans la région de valence, complémentaire aux futures mesures à l'EIC



Positrons

- ✓ Dans la continuation de l'expérience PEPPo, l'effort actuel porte sur le développement du programme de physique accessible avec un faisceau polarisé de positrons dans le contexte de JLab 12 GeV et du futur collisionneur EIC.

International Workshop on Physics with Positrons at Jefferson Lab

JPos17

SEPTEMBER 12-15, 2017
Jefferson Lab

TOPICS

- Multi-photon physics
- Deeply virtual Compton scattering
- Electroweak structure of hadrons
- Heavy quark production
- Beyond the Standard Model physics
- Low energy polarized positron beam applications
- Polarized electron and positron sources
- Multi-turn accumulation and fast kickers
- Positron beams at CEBAF, JLEIC and LERF

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www.jlab.org/conferences/JPos2017

Jefferson Lab

JLab IPN

- ❖ Le Workshop JPos17 qui se tiendra à JLab en septembre prochain fera le point sur la physique avec des positrons et les aspects techniques de la production de faisceaux polarisés, en vue de la publication d'un "Positron White Paper".
- ❖ Un Positron Working Group (PWG) a été constitué pour soutenir cet effort
<https://wiki.jlab.org/pwggwiki/>
- ❖ Une prochaine étape pourrait être la réalisation à CEBAF d'un faisceau de positrons d'intensité 10 nA et de polarisation 60%.

