Hadronic Physics

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Université Grenoble Alpes/LPSC Grenoble

CS IN2P3
29/06/2021

Introduction: QCD and hadronic physics

Quantum Chromodynamics (QCD)

QCD: A QFT for the strong interactions

- Statement: Hadronic matter is made of spin-1/2 quarks [$\leftrightarrow$ $SU(3)_{\text{fl}}$]
- Baryons like $\Delta^{++} = |u^\uparrow u^\uparrow u^\uparrow\rangle$ forbidden by Pauli exclusion/Fermi-Dirac stat.
  Need additional colour degree of freedom!
- Local SU(3)-color gauge symmetry:

$$\mathcal{L}_{\text{QCD}} = \sum_{q=u,d,s,c,b,t} \bar{q}(i\not{\partial} - m_q)q - g\bar{q}\not{G}q - \frac{1}{4}G^a_{\mu\nu}G_a^{\mu\nu} + \mathcal{L}_{gf} + \mathcal{L}_{ghost}$$

- Fundamental d.o.f.: quark and gluon fields
- Free parameters:
  - gauge coupling: g
  - quark masses: $m_u, m_d, m_s, m_c, m_b, m_t$

"QCD is our most perfect physical theory", F. Wilczek, hep-ph/9907340
Beautiful, Asymptotic Freedom, Wide range of phenomena, Few input parameters

Quantum Chromodynamics (QCD)

Properties:

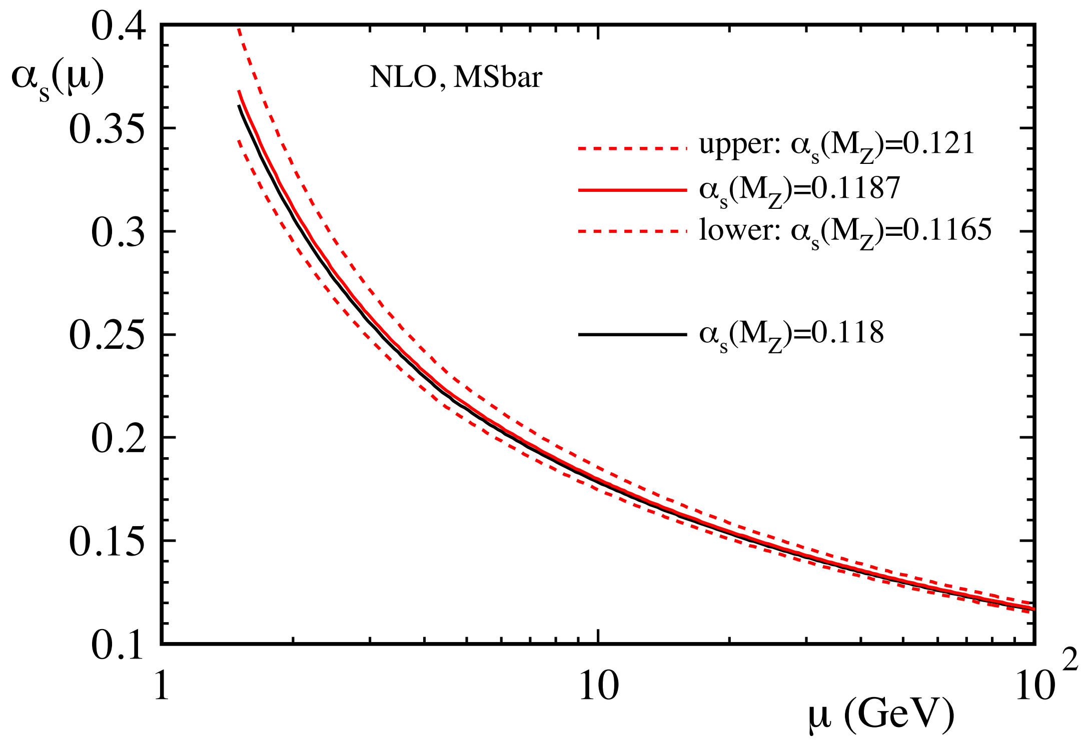
- **Confinement and Hadronization:**
  - Free quarks and gluons have not been observed:
    
    A) They are confined in color-neutral hadrons of size $\sim$ 1 fm.
    B) They hadronize into the observed hadrons.
  - Hadronic energy scale: a few hundred MeV [1 fm $\leftrightarrow$ 200 MeV]
  - Strong coupling large at long distances ($\gtrsim$ 1 fm): 'IR-slavery'
  - Hadrons and hadron masses enter the game

- **Asymptotic freedom:**
  - Strong couling small at short distances: perturbation theory
  - Quarks and gluons behave as free particles at asymptotically large energies

Asymptotic Freedom

Renormalization of UV-divergences:
Running coupling constant $a_s := \alpha_s/(4\pi)$

$$a_s(\mu) = \frac{1}{\beta_0 \ln(\mu^2/\Lambda^2)}$$



- Gross, Wilczek ('73); Politzer ('73)

Non-abelian gauge theories:
negative beta-functions

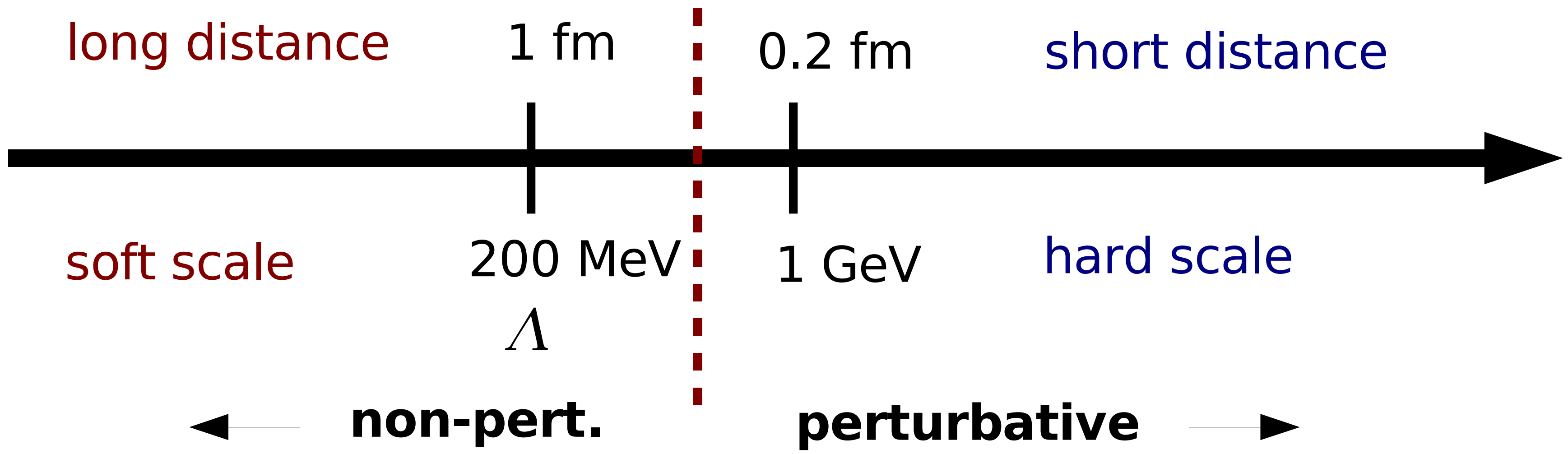
$$\frac{da_s}{d\ln\mu^2} = -\beta_0 a_s^2 + \ldots$$

where $\beta_0 = \frac{11}{3} C_A - \frac{2}{3} n_f$

$\Rightarrow$ asympt. freedom: $a_s \searrow$ for $\mu \nearrow$

- Nobel Prize 2004

Perturbative QCD (pQCD)



Asympt. freedom ➡ pQCD possible if **all** scales hard

Factorisation ➡ Possible to **separate** hard and soft scales

soft part : **universal**

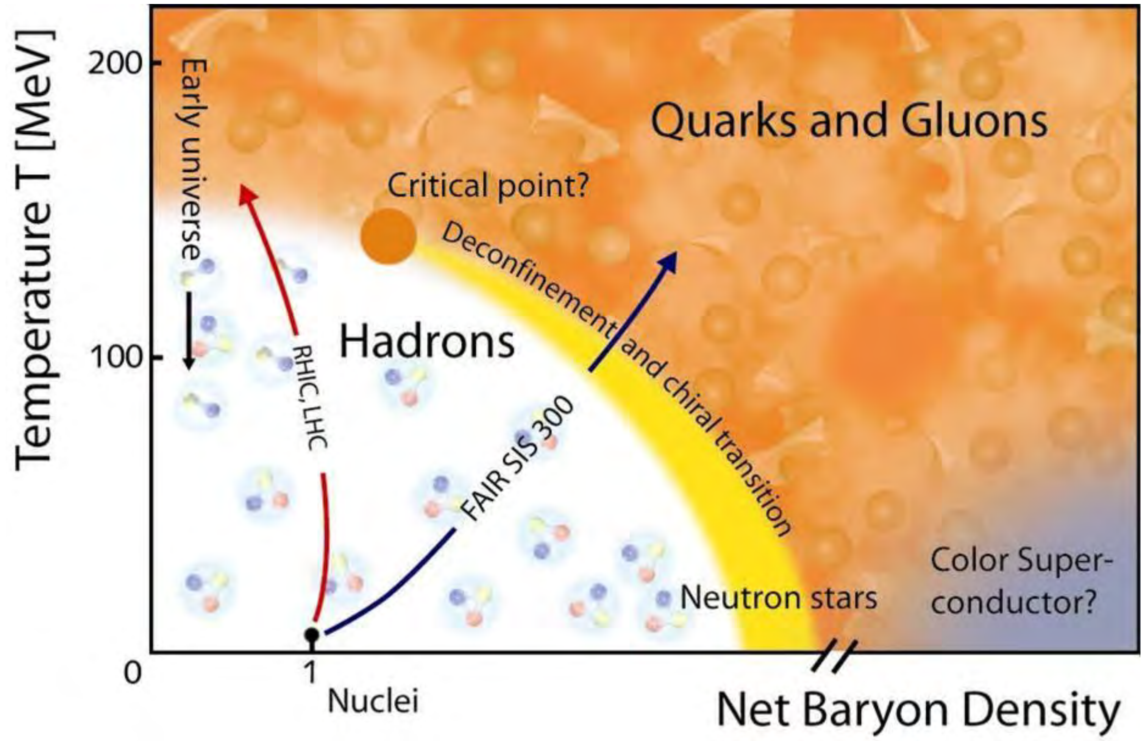
hard part : **perturbative**

QCD under extreme conditions

Understanding the dynamics of the strong interaction under extreme conditions of temperature and density

The QCD phase diagram connects to

- Cosmology -> Evolution of the early universe
- Compact stars at high net-baryon density
- Strongly coupled quantum fluids



GSI Helmholtzzentrum für Schwerionenforschung

Connect first principles QCD calculations with experimental observables via a realistic modeling of heavy ion collisions and astrophysical events

Key questions in QCD and hadronic physics

- **What is our degree of understanding of QCD?**
    - How precisely do we know the parameters of QCD?
    - What is the origin and the dynamics of confinement?
    - What is the origin and the dynamics of chiral symmetry breaking?
- **What is the structure of hadrons in terms of quarks and gluons?**
    - Which hadrons are there? How do they decay?
    - How does the hadron mass arise in terms of its constituents?
    - How are the quarks and gluons distributed inside the hadron?
    - How does the hadron spin arise in terms of its constituents?
- **What is the structure of nuclei in terms of quarks and gluons?**
- **What is the role of quarks and gluons in matter under extreme conditions?**
    - How does the QCD phase diagram look like? Existence of a phase transition with critical end point? Dof in the core of compact stars? Color super conductor phase?
    - What are the properties of the QGP?

Theoretical hadronic physics at the IN2P3

IN2P3 theorists working on hadronic physics

Lab	Name	Situation	Topics/Keywords
APC Paris	**J. Serreau**	University	IR QCD, QCD phase diagram, χSB
IJCLab Orsay	D. Becirevic	CNRS	Lattice QCD (ETMC), B decays, Flavor physics, Leptoquarks
	B. Blossier	CNRS	Lattice QCD, B, D, Charmonia decays
	S. Decotes-Genon	CNRS	b-hadron decays, flavor physics, CKM, BSM
	S. Friot	University	K/π decay const., χPT, multi-loop, $(g-2)_\mu$, hypergeom. functions
	E. Kou	CNRS	Flavor physics, B physics, hadronic τ decay
	J.-P. Lansberg	CNRS	Heavy quark(-onium) prod., PDFs, TMDs, CNM effects, DPS
	U. van Kolck	CNRS	Nuclear EFTs, χEFT, bound nucleon decay
	S. Wallon	University	GPDs, TMDs, Small-x, Diffractive exclusive processes, Saturation
IP2I Lyon	**G. Chanfray**	University	Neutrino-nucleon interactions, Dense matter
	M. Ericson	Emeritus	Neutrino-nucleon interactions
	H. Hansen	University	Grav. waves, Dense matter, QCD phase diagram, χEFT
	J.-M. Richard	Emeritus	Hadron spectroscopy, Tetraquarks, Pentaquarks
LLR Palaiseau*	**F. Arleo**	CNRS	Coherent energy loss in pA, R_{pA}: DY, J/Ψ, light hadrons, p_T-broad.
LPC Clermont	V. Morenas	University	Lattice QCD, Heavy flavour mesons
LPSC Grenoble	**M. Mangin-Brinet**	CNRS	Lattice QCD (ETMC), $m_{u,d,s,c}$, $F_\pi(Q^2)$, $\langle r^2\rangle_\pi$
	I. Schienbein	University	PDFs, HQ production, FFs, BSM: NLO QCD+PS calc., RGE
Subatech Nantes	**J. Aichelin**	University	HI, QGP, transport models, PJNL: phase diagram, EPOS-HQ
	J. Ghiglieri	CNRS	QGP, shear viscosity/hydrodynam. at NLO QCD, pert. thermal QCD
	P.-B. Gossiaux	University	HI, QGP: energy loss, HQ/Jets, EPOS-HQ, EPOS3-Jet
	T. Gousset	University	HI, QGP: energy loss, jet-correlations, HQ
	M. Nahrgang	University	HI, QGP, HQ, HQ transport, QCD phase diagram
	S. Peigné	CNRS	Coherent energy loss in pA, R^h_{pA}, p_T-broadening
	T. Sami	University	HI, QGP, Critical fluctuations near QCD critical point, energy loss
	K. Werner	University	EPOS3, EPOS-HQ, EPOS-Jet, EPOS and Air Showers, HQ transport

* F. Arleo on leave at Subatech Nantes

This table gives an overview of IN2P3 theorists having at least partly worked on topics relevant for hadronic physics. The names highlighted in bold have been identified as core contributors (in some cases the line is arbitrary).

15+2 Theorists: APC: 1, IJCLab: 2, IP2I: 1+2, LPSC: 2, Subatech: 9

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QCD parameters, IR-QCD: Serreau, Mangin-Brinet
Hadron spectroscopy: Richard
pQCD/factorization: Lansberg, Wallon, Schienbein
pQCD+Cold Nuclear Matter: Arleo, Peigné
Heavy Ion Collisions: Aichelin, Ghiglieri, Gossiaux, Gousset, Nahrgang, Sami, Werner
Neutrino-Nucleon interactions for LBL: Chanfray, Ericson, Schienbein
[Red: maj. hep-ph, Green: maj. nucl-th, black: hep-lat (roughly counted)]

pQCD formalism

Factorization Theorems:

- Provide (field theoretical) **definitions** of the **universal** PDFs
- Make the formalism **predictive**!
- Make a statement about the **error** of the factorization formula

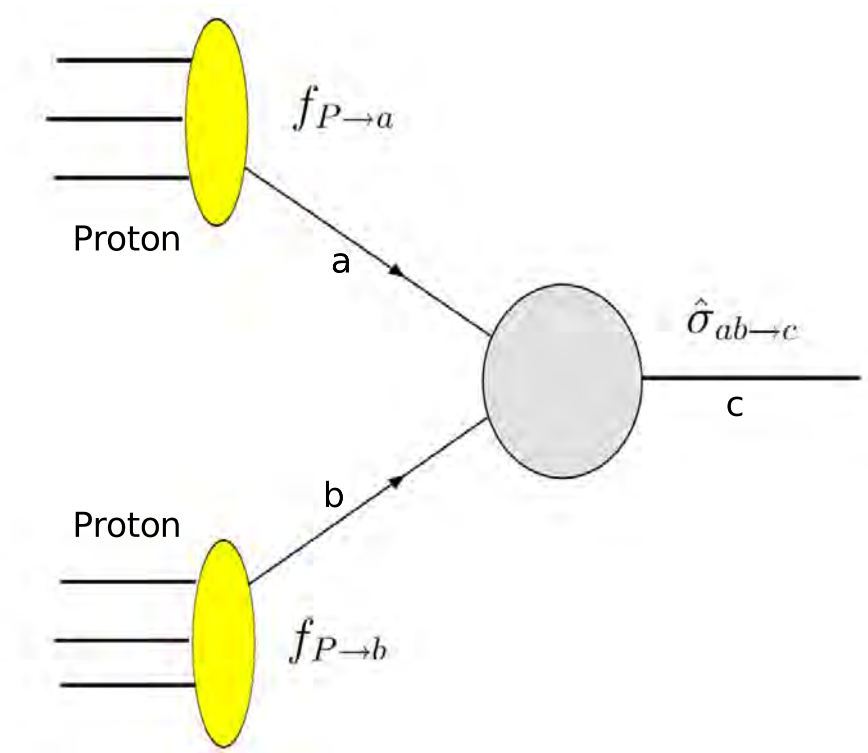
PDFs and predictions for **observables+uncertainties** **refer to this standard pQCD framework**

Need a solid understanding of the standard framework!

- For pp and ep collisions there a **rigorous factorization proofs**
- For pA and AA factorization is a **working assumption** to be tested phenomenologically

  There might be breaking of QCD factorization, deviations from DGLAP evolution, other nuclear matter effects to be included

Factorization for pp collisions



$$\sigma = f_{P\to a} \otimes f_{P\to b} \otimes \hat{\sigma}_{ab\to c}$$

From experiment

Calculable from theoretical model

Parton Distribution Functions (PDFs) $f_{P\to a,b}(x,\mu^2)$

- Universal
- Describe the structure of hadrons
- Obey DGLAP evolution equations

The hard part $\hat{\sigma}_{ab\to c}(\mu^2)$

- Free of short distance scales
- Calculable in perturbation theory
- Depends on the process

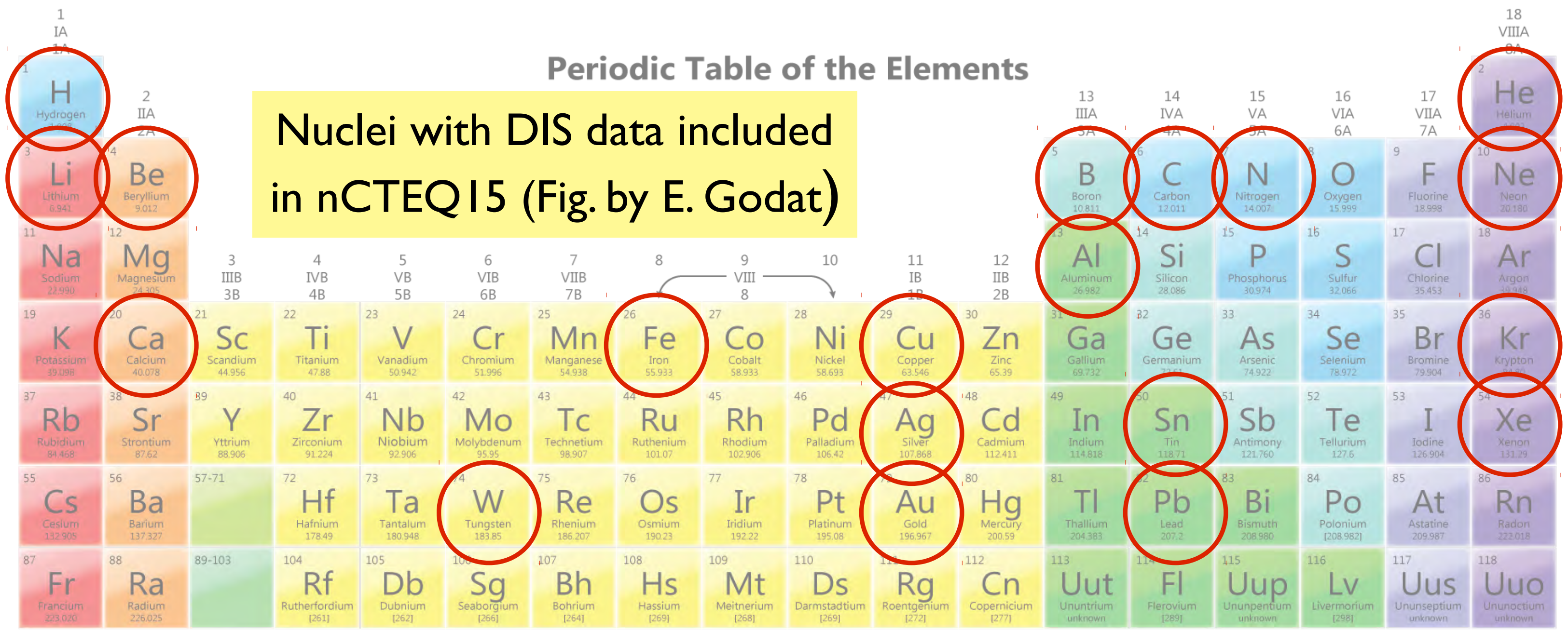
Million Dollar formula!
Need to improve both, PDFs and hard part, for better theoretical predictions

pQCD formalism

- nCTEQ nuclear PDFs: global QCD analysis (Schienbein)
- Small-x nuclear gluon PDF from heavy quark(-onium) data at LHC (Lansberg, Schienbein); FOCAL exp.
- TMDs (Lansberg, Wallon)
- GPDs (Wallon)
- PDFs, TMDs, GPDs on the lattice ([Mangin-Brinet*])
- Heavy quark FFs (Schienbein)

- Heavy Quark Production: NLO+NLL (Schienbein)
- Heavy Quarkonium Production: NNLO (Lansberg)
- High energy limit: small-x, saturation, non-linear evolution, CGC (Wallon)
- Hard exclusive processes, diffraction (Wallon)
- Double parton scattering (Lansberg)

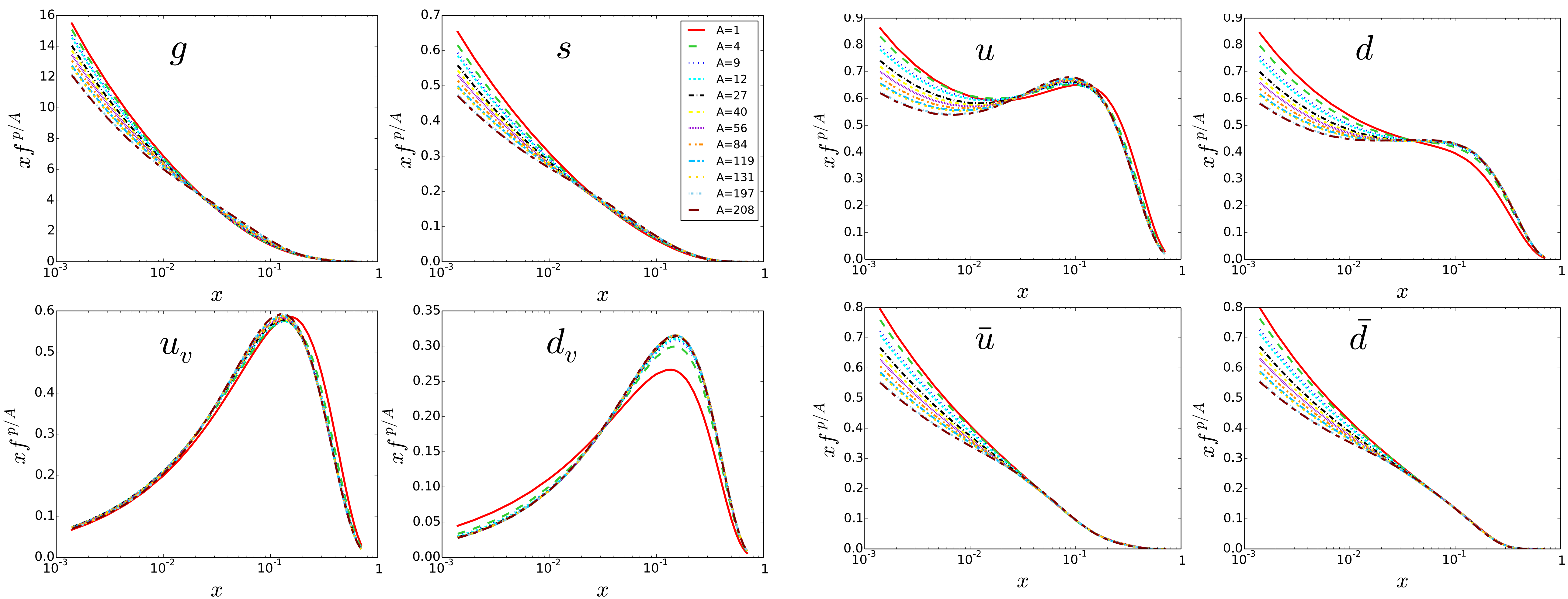
Partonic structure of nuclei



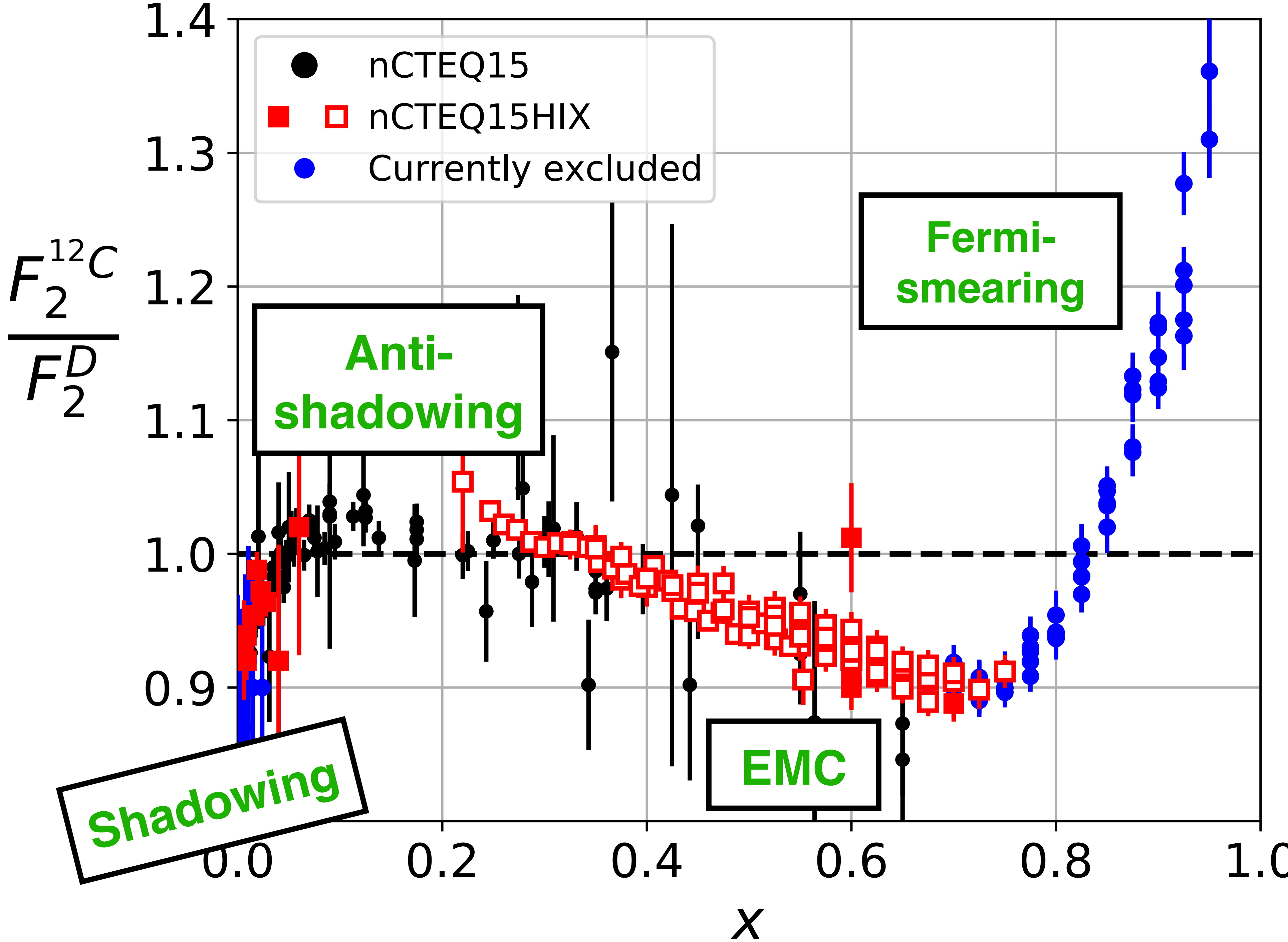
- Fundamental quest
- New data from LHC, EIC, LHeC, etc. will allow for a refined parametrization; zoom in on high-x region
- Ultimately, fits to lead only (or other targets); no need to combine different A in one analysis

nCTEQ15, arXiv:1509.00792

$$x f_i^{p/A}(x, Q_0) = x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4}x)^{c_5} \qquad c_k(A) = c_{k,0} + c_{k,1}(1 - A^{-c_{k,2}})$$



A nucleus is not a collection of free nucleons



Potential connection to nuclear theory

Global analysis of nuclear PDFs

Same approach as for proton PDF determinations

1. Boundary conditions:
Parameterize x-dependence of PDFs at initial scale Q_0

$$f(x,Q_0)=A_0 x^{A_1}(1-x)^{A_2} P(x;A_3,...);\ f=u_v,d_v,g,\bar{u},\bar{d},s,\bar{s}$$

2. Evolve from Q_0 to Q solving the DGLAP evolution equations: $f(x,Q)$

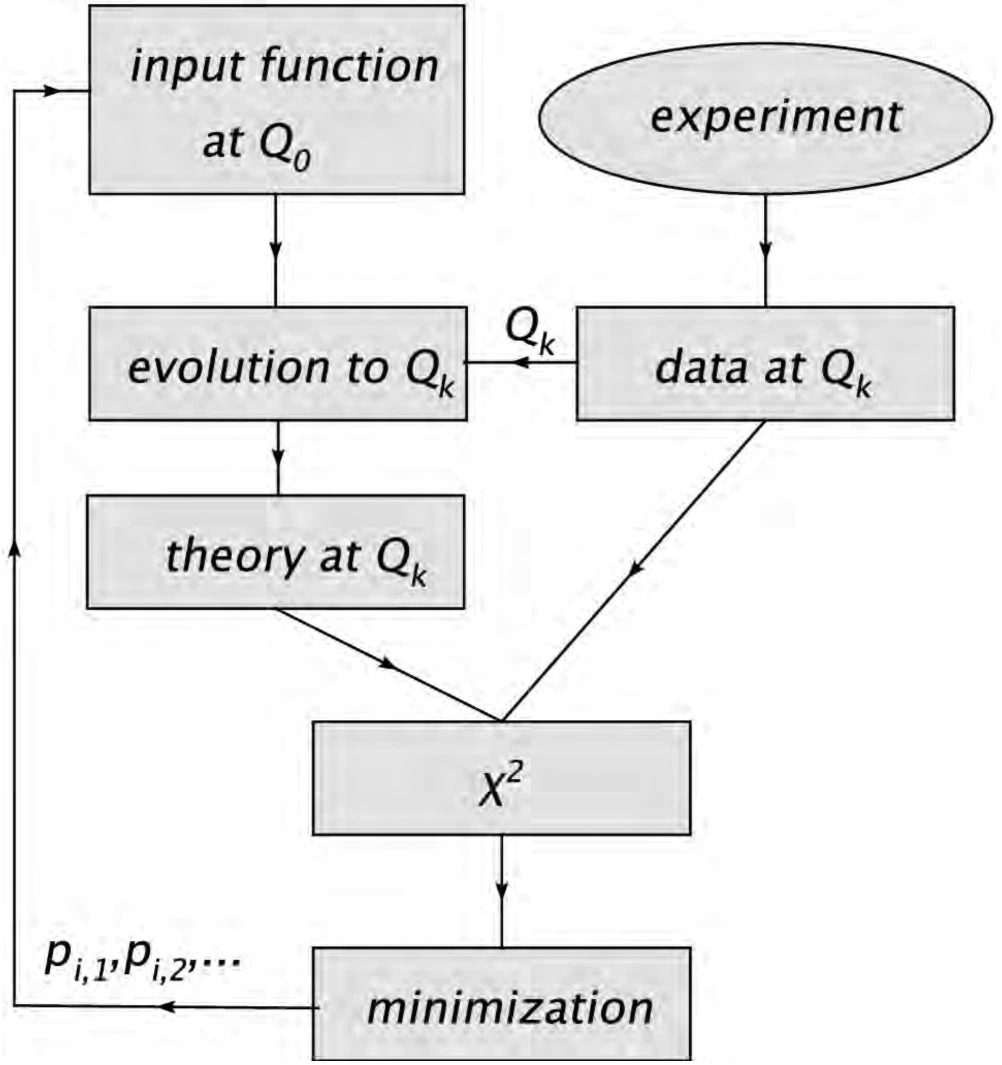
3. Define suitable χ^2 function and minimize w.r.t. fit parameters

$$\chi^2_{global}[A_i]=\sum_n w_n \chi^2_n;\ \chi^2_n=\sum_I \left(\frac{D_{nI}-T_{nI}}{\sigma_{nI}}\right)^2$$

Sum over experiments

Sum over data points

weights: default=1, allows to emphasize certain data sets

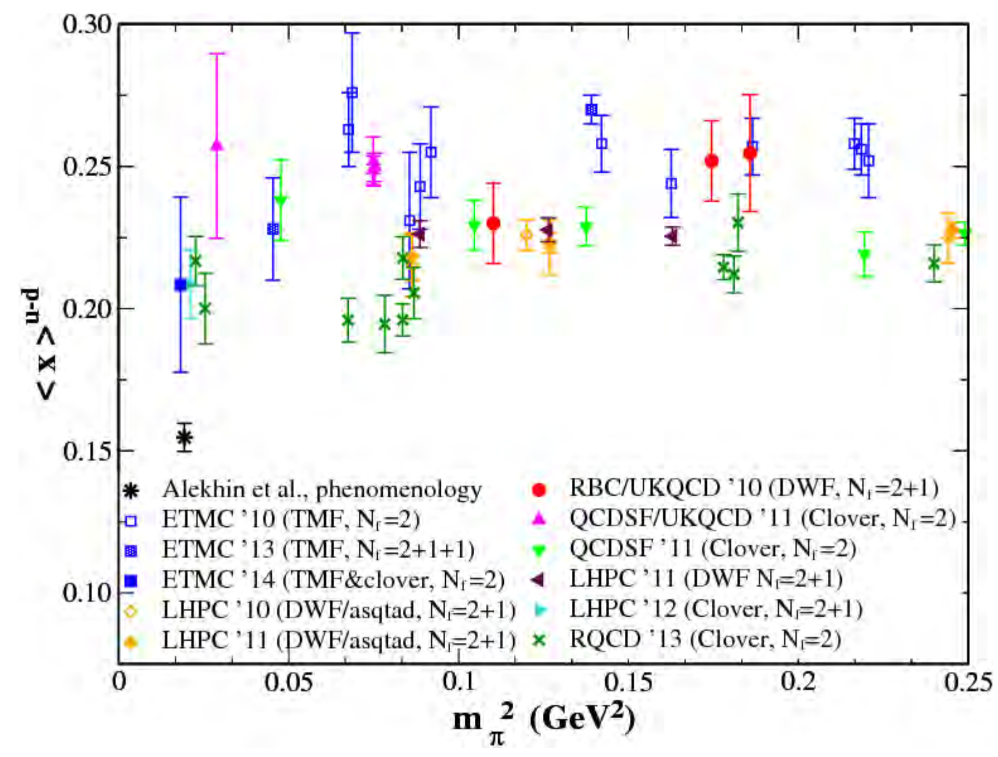


Complex code, entirely rewritten in C++ by my former PhD students F. Lyonnet, T. Jezo

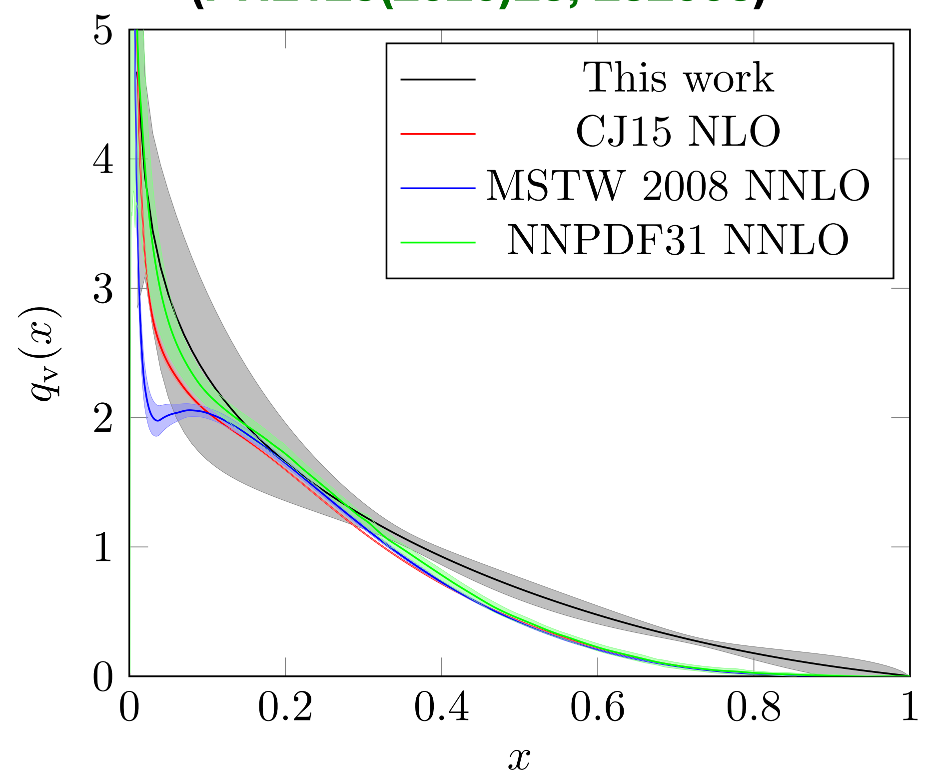
PDFs on the Lattice

- Ab initial calculations on the lattice:
  - Low Mellin-moments of PDFs
  - Quasi-PDFs
  - Pseudo-PDFs [**S. Zafeiropoulos et al.**]
- Calculations for protons, pions, kaons, even nuclei
- Calculations for TMDs and GPDs
- Expect **much interplay** between global fits and lattice results in next decade:
  - Proton: global fits provide benchmark for lattice; lattice results still may help for strange PDFs and large-x PDFs
  - Less well-known distributions (Pion PDFs, Spin-dependent PDFs, TMDs, GPDs): input from lattice calculations for global analyses ("lattice data")
- See PDFLattice white papers **2006.08638**, **1711.07916**

Mellin Moments (Constantinou 2015)

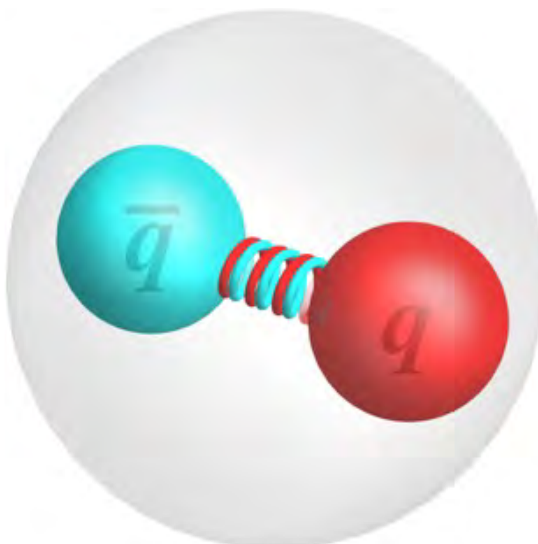


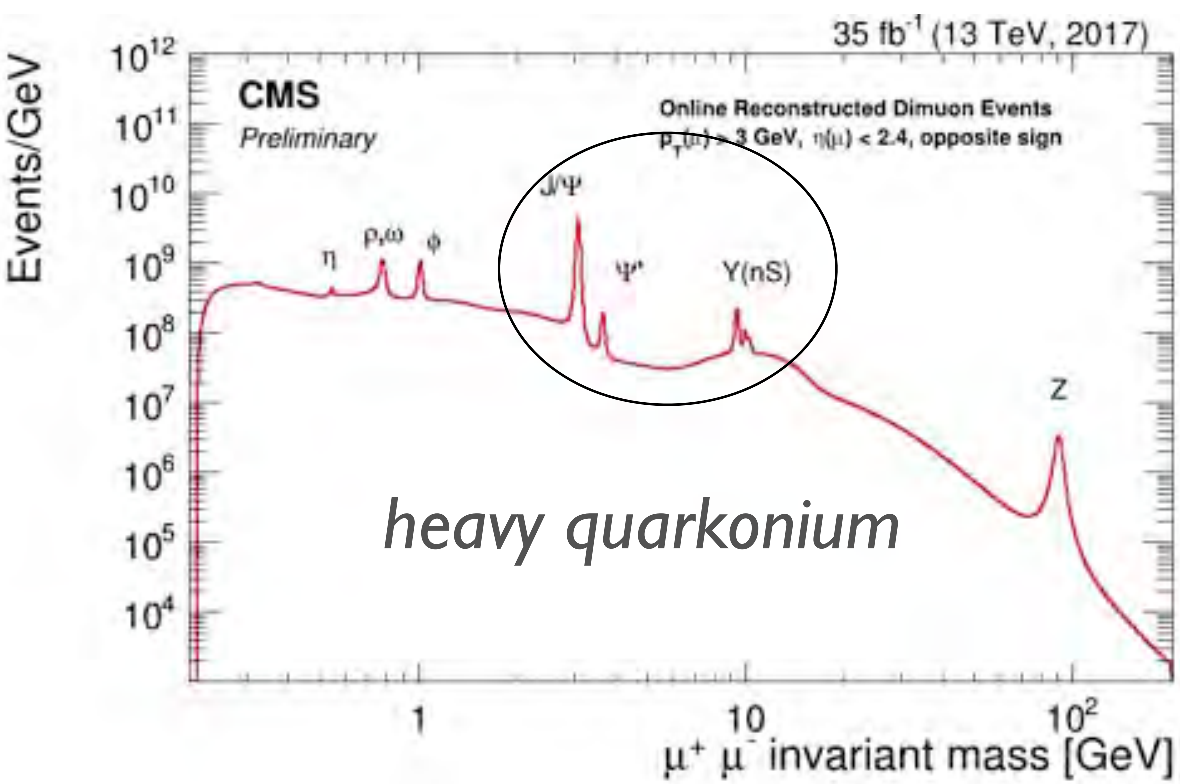
Nucleon valence PDF from lattice (PRL125(2020)23, 232003)

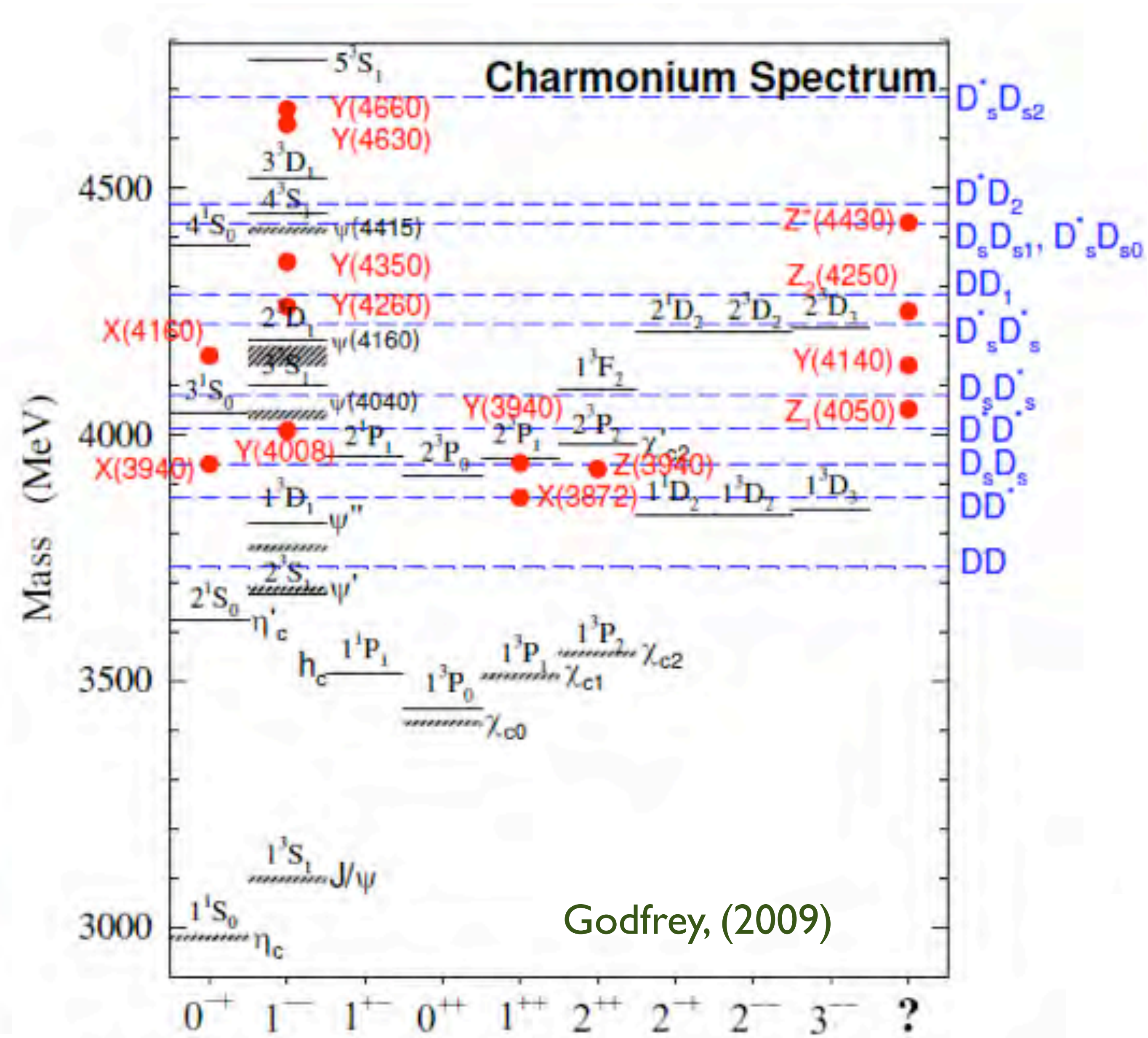


Heavy Quarkonia: What?

Mesons composed of two heavy quarks |Q Q'bar>





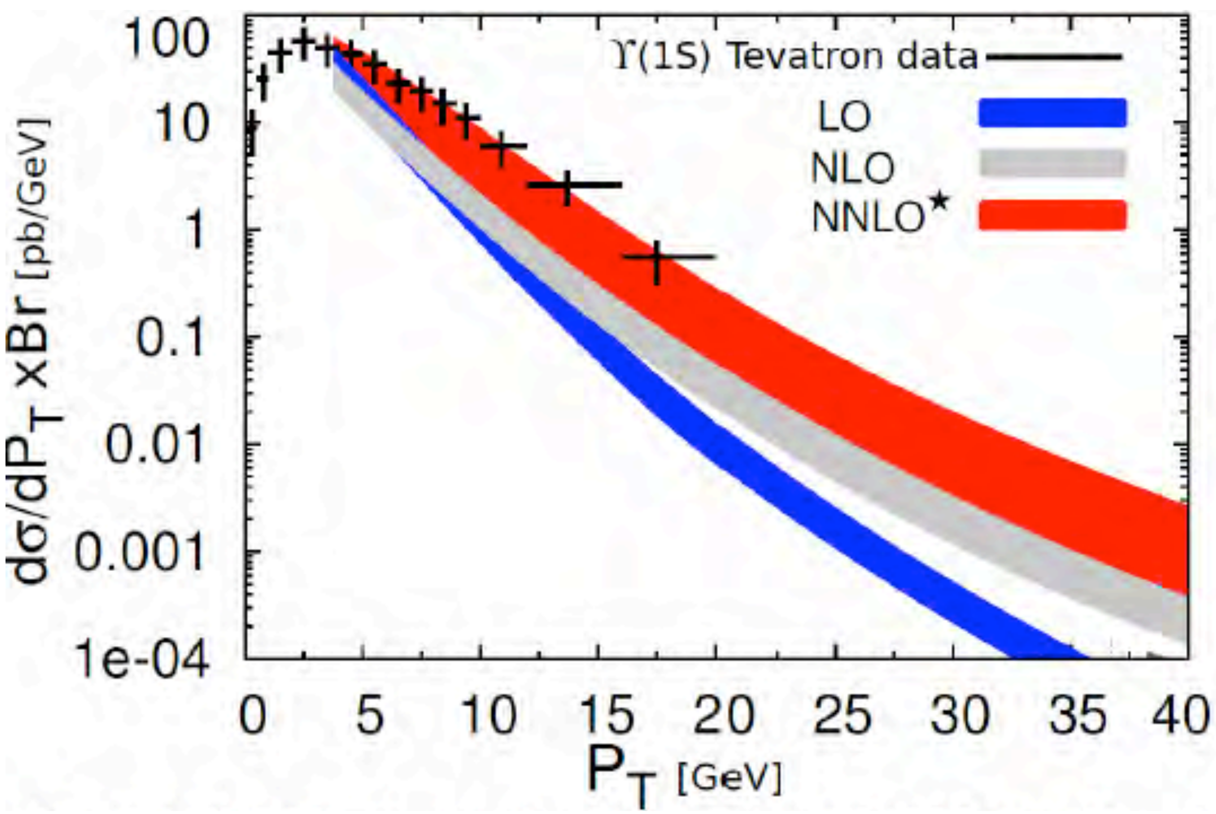


Heavy Quarkonia: Why?

- Ideal laboratory to test pQCD and the underlying non-perturbative dynamics
- Studied in almost all high-energy experiments since discovery of J/Psi
  - Fundamental parameters: α_s, CKM
  - Probe gluon distribution: collinear/transverse dynamics
  - Multiple parton (hard) scatterings
  - QGP "thermometer", cold nuclear effects, CP violation, etc
- A reliable and precise understanding of quarkonium production is fundamental and not yet fully achieved!

Heavy Quarkonia: How?

- WP1: Perform first truly global NLO analysis of NRQCD parameters
- WP2: Pioneering NNLO computations for quarkonium production with 2->1, then 2->2 processes
- WP3: Implementation in NLOAccess; Pheno with TMD factorisation at NLO+NNLL

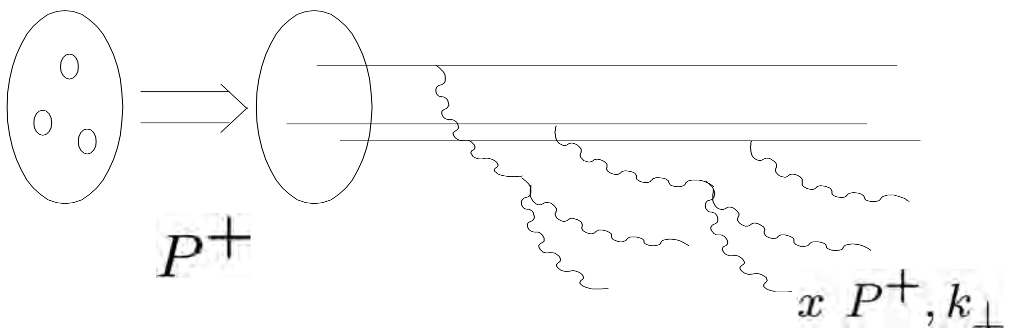


- Partial NNLO* calculation done (by us) in 2007 (red band)
- Such corrections needed to describe data but larger uncertainties since partial
- Complete NNLO computation needed!

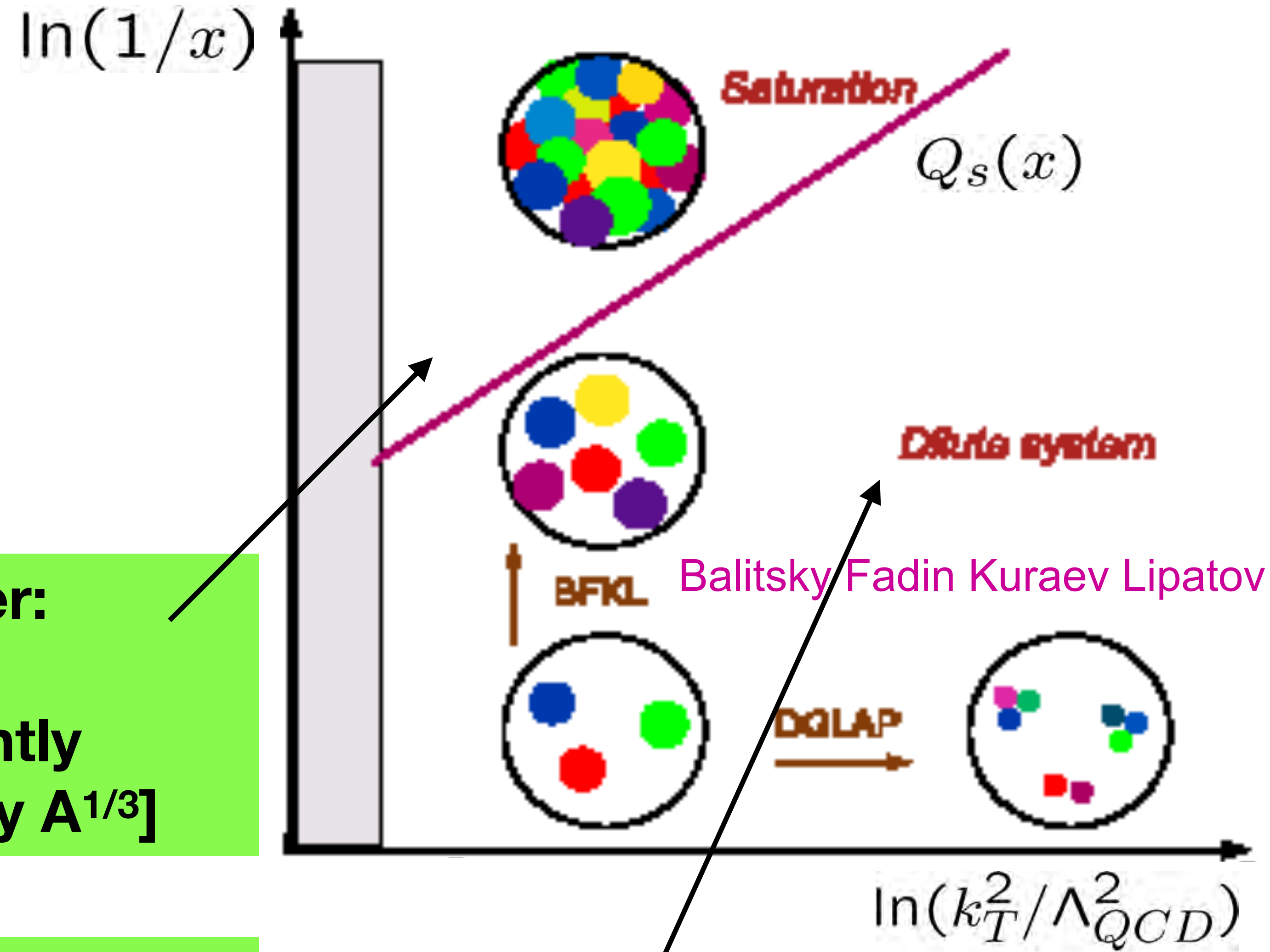
Expected outcomes: Precision for long distances, Precision for short distances, Precision for Spin/QGP physics

The parton content of high-energy hadrons

C. Marquet*, R. Boussarie, S. Munier (CPHT), S.Wallon (IJClab), E. Iancu, F. Gelis, G. Soyez (IPhT)



$1/k_T$ ~ parton transverse size



When x gets smaller and smaller:
Hadron is no longer dilute
Partons start interacting coherently
[Nuclei: density effects enhanced by $A^{1/3}$]

Alternative long/short-distance factorisation

Effective d.o.f. (Wilson lines, Reggeized gluons)
Effective action (Color Glass Condensate,…)

EFT to describe physics at large parton densities

Hadron is dilute system of hadrons

Interact incoherently

Standard QCD factorisation

pQCD + energy loss effects

- In-medium QCD radiation (Arleo, Peigné, Sami)

  New regime: fully coherent energy loss (FCEL) from first principles QCD: $\Delta E \sim E$

- Nuclear modification factors for DY, J/Psi, light hadrons in pA collisions (Arleo, Peigné)

- To be taken into account in nPDF determinations (non-trivial)

- Effect of FCEL on cosmic ray air showers; neutrino fluxes measured by IceCube

Heavy Ion Collisions (HIC)

- **Advanced fluid dynamics** (Nahrgang, Sami)
  improve conventional fluid dynamical models
  include thermal fluctuations near the critical point

- **Jet modification in HIC** (jet shape, substructure)

  - Vacuum vs medium radiation (Ghiglieri, Gousset, Gossiaux)
    Expertise in EFT and Thermal Field Theory

  - MC simulation EPOS-Jet (Aichelin, Gossiaux, Gousset, Werner)
    coupled jet-hydrodynamics scheme: uses EPOS for the initial state; evolves soft parsons hydrodynamically; in-medium energy loss to hard partons propagating through background of soft partons; hard partons are hadronized and jet algorithm applied

- **Quarkonium production in HIC** (Gossiaux)

- **EPOS-HQ** (Aichelin, Gossiaux, Gousset, Nahrgang, Werner)
  implement heavy quark-medium interactions in EPOS

- **Dynamical thermalisation in HIC** (Werner)
  EPOS+PHSD: study effect of initial non-equilibrium stage of HIC on final observables

French community & Funding

The French community working on QCD > PH is wellorganized within the GDR QCD

Close interaction EXP-THEO

https://gdrqcd.in2p3.fr/author/marquet/

French theorists Participating in the GDR QCD

IN2P3 labs are in bold

Lab	Name	Situation	Topics/Keywords
APC Paris	**J. Serreau**	University	IR QCD, QCD phase diagram, χSB
CPHT Palaiseau	**R. Boussarie**	CNRS	TMDs, Small-x, Saturation, CGC, Diffraction
	C. Lorcé	University	GPDs, TMDs, Nucleon spin and mass
	C. Marquet	CNRS	TMDs, Small-x, Saturation, CGC, Diffraction, Quarkonia
	S. Munier	CNRS	Diffraction, Quarkonia, Parton branching
	B. Pire	Emeritus	GPDs, DVCS, TCS, Diffraction
	U. Reinosa	CNRS	IR QCD, QCD phase diagram, χSB, QCD at finite T
CPT Marseille	**A. Bharucha**	CNRS	B and D decays, BSM: Flavor, Compositeness, DM, SUSY
	J. Charles	CNRS	Lattice QCD, $(g-2)_\mu$, B decays, Flavor, CKM, BSM
	E. De Rafael	Emeritus	Lattice QCD, $(g-2)_\mu$, hadronic vacuum polarization (HVP)
	A. Gérardin	University	Lattice QCD, $(g-2)_\mu$, HVP, B decays, HQET
	M. Knecht	CNRS	K decays, $(g-2)_\mu$, HVP, Compositeness, Higgs-ew chiral L
	L. Lellouch	CNRS	Lattice QCD, $(g-2)_\mu$, HVP, $m_{u,d,s}$, decay constants
	S. Zafeiropoulos	CNRS	Lattice QCD, pseudo-PDFs (nucleon, pion), $\alpha_s^{\overline{\text{MS}}}(M_Z)$
DphN Saclay	**C. Mézrag**	CEA	GPDs, pion/kaon valence PDFs from DSE, α_s^{eff}
	H. Moutarde	CEA	GPDs, TMDs
IJCLab Orsay	**D. Becirevic**	CNRS	Lattice QCD (ETMC), B decays, Flavor physics, Leptoquarks
	B. Blossier	CNRS	Lattice QCD, B, D, Charmonia decays
	J. Carbonell	CNRS	Few body systems, relativistic bound states
	S. Decotes-Genon	CNRS	b-hadron decays, flavor physics, CKM, BSM
	S. Friot	University	K/π decay const., χPT, multi-loop, $(g-2)_\mu$, hypergeom. functions
	M. Fontannaz	Emeritus	last paper from 2017, prompt photons, photon-jet correlations
	E. Kou	CNRS	Flavor physics, B physics, hadronic τ decay
	J.-P. Lansberg	CNRS	Heavy quark(-onium) prod., PDFs, TMDs, CNM effects, DPS
	U. van Kolck	CNRS	Nuclear EFTs, χEFT, bound nucleon decay
	S. Wallon	University	GPDs, TMDs, Small-x, Diffractive exclusive processes, Saturation
IPhT Saclay	**J.-P. Blaizot**	Emeritus	QGP: fluid dynamics, heavy quark(-onia), $\hat{q}$, diffractive J/Ψ prod.
	F. Gelis	CEA	CGC, initial state of heavy ion collisions
	E. Iancu	CNRS	Small-x, CGC, non-linear evolution, Saturation, Jets in QGP
	G. Korchemsky	CNRS	Conformal theories, scatt. amplitudes, $\mathcal{N}=4$ SYM, $\mathcal{N}=2$ SYM
	D. Kosower	CEA	Conformal theories, scattering amplitudes, $\mathcal{N}=4$ SUGRA
	J.-Y. Ollitrault	CNRS	HI collisions: initial conditions, particle flow, hydrodynamic sim.
	G. Soyez	CNRS	Jets: substructure, in medium, small-x, BK evol., Parton Showers
IP2I Lyon	**H. Hansen**	University	Grav. waves, Dense matter, QCD phase diagram, χEFT
LAPTH Annecy	**J.-P. Guillet**	CNRS	Two-loop integrals, JetPHOX, FFs
	E. Pilon	CNRS	Two-loop integrals, Higgs
	E. Re	CNRS	Precision calc: NNLO+PS, N^3LL+NNLO, Higgs, VV, $t\bar{t}$, DY
L2C Montpellier	**J.-L. Kneur**	CNRS	RG improved QCD pressure, Higgs compositeness
LLR Palaiseau	**F. Arleo**	CNRS	Coherent energy loss in pA, R_{pA}: DY, J/Ψ, light hadrons, p_T-broad.
LPC Clermont	J.-F. Mathiot	CNRS	RGEs, TLRS regularization: axial anomaly
	V. Morenas	University	Lattice QCD, Heavy flavour mesons
LPSC Grenoble	**M. Mangin-Brinet**	CNRS	Lattice QCD (ETMC), $m_{u,d,s,c}$, $F_\pi(Q^2)$, $\langle r^2\rangle_\pi$
	I. Schienbein	University	PDFs, HQ production, FFs, BSM: NLO QCD+PS calc., RGE
LPTHE Paris	**M. Cacciari**	University	Higher order QCD/QED, Jets, HQ production, VBF Higgs at NNLO
	B. Fuks	University	BSM: VLQ, DM, Z', LR, Higgs, SUSY, Reinterpret.: MADAnalysis
	H.-S. Shao	CNRS	Heavy quark(-onium) prod., Higher orders, Automation, SM, BSM
Subatech Nantes	**J. Aichelin**	University	HI, QGP, transport models, PJNL: phase diagram, EPOS-HQ
	J. Ghiglieri	CNRS	QGP, shear viscosity/hydrodynam. at NLO QCD, pert. thermal QCD
	P.-B. Gossiaux	University	HI, QGP: energy loss, HQ/Jets, EPOS-HQ, EPOS3-Jet
	T. Gousset	University	HI, QGP: energy loss, jet-correlations, HQ
	M. Nahrgang	University	HI, QGP, HQ, HQ transport, QCD phase diagram
	S. Peigné	CNRS	Coherent energy loss in pA, R^h_{pA}, p_T-broadening
	T. Sami	University	HI, QGP, Critical fluctuations near QCD critical point, energy loss
	A. Smilga	University	Mathematical physics
	K. Werner	University	EPOS3, EPOS-HQ, EPOS-Jet, EPOS and Air Showers, HQ transport

The STRONG-2020 initiative

Project duration: from 1 June 2019 to 31 May 2023

Total Budget: 10 M €

32 Work Packages (WPs):

- **MAN:** Management and Coordination
- **DISCO:** Dissemination and Communication
- 7 Transnational Access Research Infrastructures (**TA**)
- 2 Virtual Infrastructures (**VA**)

Experimental /Theoretical /Instrumentation Activities:

- 7 Networking Activities (**NA**)
- 14 Joint Research Activities (**JRA**)

Web site: http://www.strong-2020.eu/

Consortium Agreement

- **45 participating institutions** (beneficiaries) in
- **16 countries:**
- Austria, Belgium, Switzerland, Germany, Spain, Finland, France, Croatia, Ireland, Italy, Montenegro, Netherlands, Poland, Portugal, Sweden, United Kingdom
- **Location details can be found on online Google map**
- **134 other Involved Institutions** (not receiving EU funding)

The STRONG-2020 infrastructures

Transnational Access

TA1-COSY **Dieter Grzonka** (Julich)

TA2-MAMI **Achim Denig** (Mainz)

TA3-LNF **Catalina Curceanu/Carlo Guaraldo (INFN, Frascati)**

TA4-FTD/ELSA **Hartmut Schmieden** (Bonn)

TA5-GSI **Yvonne Leifels (GSI, Darmstadt)**

TA6-ECT* **Gert Aarts (Jochen Wambach) (Trento)**

TA7-CERN **David d'Enterria (CERN, Geneva)**

Virtual Access:

Provide open-access to state-of-the-art computer codes necessary for the high-precision phenomenology of heavy ion reactions and studies of the quark gluon plasma as well as for nucleon and nuclei parton structure research.

VA1-NLOAccess ***Automated perturbative NLO calculations for heavy ions and quarkonia***

Jean-Philippe Lansberg (CNRS, Orsay) : *Extension of the well-known MadGraph automated on-line code for the novel computation of perturbative QCD cross sections in high-energy hadronic collisions at next-to-leading- order (NLO) accuracy, using meson and heavy-ion beams, and for quarkonia final-states.*

Web page: https://nloaccess.in2p3.fr/HO/

Coordinated by French theorists

VA2-3DPartons ***Virtual Access to 3DPartons***

Hervé Moutard (CEA, Saclay) : *Development of a new combined framework to extract generalized (GPDs) and transverse momentum-dependent (TMDs) parton distributions, with higher-order fixed and twist corrections, from fits to experimental e-p and p-p data (handled in a Rivet-like format).*

Web page: http://partons.cea.fr/partons/doc/html/index.html

The STRONG-2020 research activities

Hadron Physics:

JRA7-HaSP *Light-and heavy-quark hadron spectroscopy* Marco Battaglieri (INFN, Genova), Juan Nieves (UVEG, Valencia)

NA1-FAIRnet *QCD physics at GSI/FAIR* Fritz-Herbert Heinsius (RUB, Bochum)

NA5-THEIA *Strange Hadrons and the Equation-of-State of Compact Stars* Josef Pochodzalla (Umainz)

NA6-LatticeHadrons LatticeHadrons Michael Peardon (TCD, Dublin)

Precision Physics:

NA4-PREN *Proton Radius European Network* Dominique Marchand (CNRS, Orsay), Randolf Pohl (UMainz)

JRA3-PrecisionSM *Precision Tests of the Standard Model* Mikhail Gorshteyn (UMainz), Andrzej Kupsc (University of Uppsala)

Heavy Ions:

JRA1-LHC-Combine *Inter-experiment combination of heavy-ion measurements at the LHC* Raphaël Granier de Cassagnac (CNRS, Palaiseau)

JRA2-FTE@LHC *Fixed Target Experiments at the LHC* Cynthia Hadjidakis (CNRS, Orsay), Pasquale Di Nezza (INFN, Frascati)

NA3-Jet-QGP *Quark-Gluon-Plasma characterisation with jet* Marco van Leeuwen (Nikhef, Amsterdam), Guilherme Milano (LIP, Lisbon)

NA7-Hf-QGP *Quark-Gluon Plasma characterisation with heavy flavour probes* Joerg Aichelin (CNRS, Nantes), Giuseppe Bruno (INFN, Bari)

GPD/TMD/PDFs:

JRA4-TMD-neXt *3D structure of the nucleon in momentum space* Alessandro Bacchetta (INFN, Pavia)

JRA5-GPD-ACT *Generalized Parton Distributions* Silvia Niccolai (CNRS, Orsay), Kresimir Kumericki (UNIZG, Zagreb)

JRA6-Next-DIS *Challenges for next generation DIS facilities* Daria Sokhan (UGlasgow), Francesco Bossu (CEA, Saclay)

NA2-Small-x *Small-x Physics at the LHC and future DIS experiments* Néstor Armesto (USC, Santiago de C.), Tuomas Lappi (JYU, Jyväskylä)

IN2P3 Theory Master projects et ANR

- PDFs and processes (2017-2019)
  [Schienbein (PI), Lansberg, Shao]
- TMD@NLO (2017-2019)
  [Lansberg (PI), …]
- Medium-induced gluon radiation (2017-2019)
  [Arleo (PI), Peigné]
- EPOS-HQ (2017-2019, renewed 2020)
  [Werner (PI), Gossiaux, Aichelin, Gousset, Nahrgang]
- GLUE@NLO (2020-2022)
  [Lansberg (PI), Shao, Schienbein, Wallon]
- Speedy Charmonia (2020-2022)
  [Blossier (PI), Morenas, …]
- ANR COLDLOSS (-2023) [F. Arleo (PI)]
- ANR PrecisOnium (2021-2025) [J.-P. Lansberg (PI)]

Thank you!

Atelier Physique Théorique des deux infinis

QCD at high energy at the LHC and the future EIC	*Cyrille Marquet*	11:30 - 11:40
Nuclear PDFs	*Ingo Schienbein*	11:40 - 11:50
Energy loss efects in pA collisions	*François Arleo*	11:50 - 12:00
Extracting PDFs from lattice QCD	*Savvas Zafeiropoulos*	12:00 - 12:10
NLO Access a virtual access for STRONG 2020	*Jean-Philippe LANSBERG*	12:10 - 12:20
Advancing precision predictions of transverse momentum effects in high energy hadron collisions	*Emanuele Re*	12:20 - 12:30
Quarkonium production	*Hua-Sheng Shao*	12:30 - 12:40
Associated production of a photon and a heavy quark jet in hadronic collisions	*Jean-Philippe Guillet*	12:40 - 12:50
Heavy quark production in pp and AA collisions	*Pol Bernard Gossiaux*	12:50 - 13:00
Dynamical Thermalization in Heavy Ion collisions	*Mahbobeh JAFARPOUR*	13:00 - 13:10
A perturbative window to the IR regime of QCD	*Julien Serreau*	13:10 - 13:20
The phase diagram of QCD from heavy-ion collisions to compact stars	*Marlene Nahrgang*	13:20 - 13:30

nCTEQ collaboration

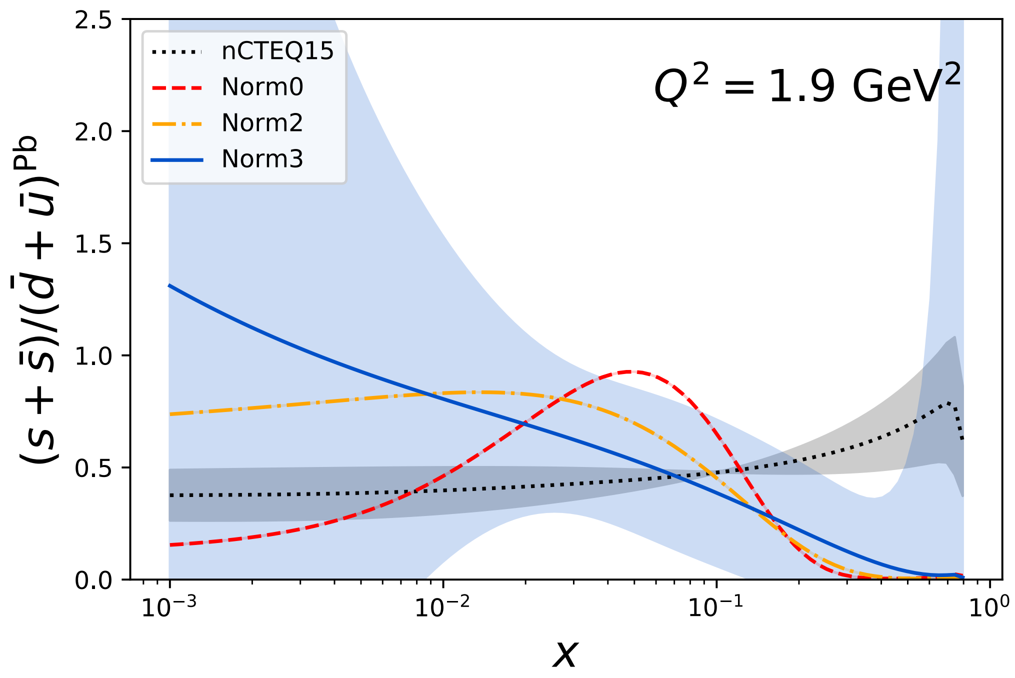
nCTEQ
nuclear parton distribution functions

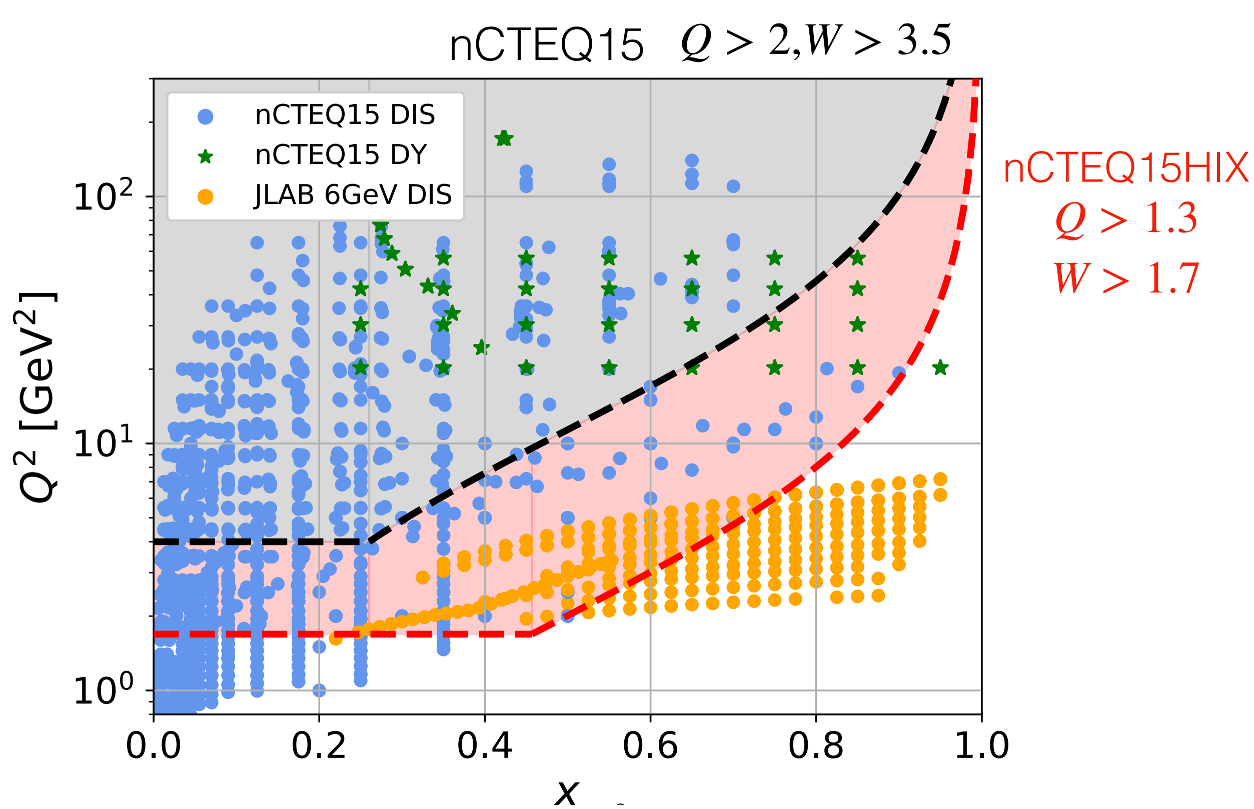
- **nCTEQ** is part of **CTEQ** (The Coordinated Theoretical-Experimental Project on QCD)
- Devoted to understanding **QCD** at the **interface between nuclear and particle physics**:
  - Understand **nuclei** in terms of **quark and gluon degrees of freedom**
  - Understand **nuclear corrections** needed to use nuclear data in **studies of nucleon structure**
- Webpage: https://ncteq.hepforge.org/

- **Initiated in 2006** by **Fred Olness**, **IS** and **Ji-Young Yu** (**SMU Dallas**) joined by the CTEQ members **C. Keppel** (**Hampton Univ./ JLAB**), **J. G. Morfin** (**FNAL**), and **J. Owens** (**Florida State Univ.**)
- **Members in 2021** **[3rd generation! underlined: (former) LPSC]**:
  - **SMU Dallas**: F. Olness (CTEQ), J.-Y. Yu
  - **FNAL**: J. G. Morfin (CTEQ), T. Hobbs
  - **LPSC Grenoble:** I. Schienbein (CTEQ), C. Léger (PhD)
  - **JLAB**: C. Keppel (CTEQ)
  - **INP Krakow**: A. Kusina, R. Ruiz (Post-Doc)
  - **Univ. Münster**: M. Klasen (CTEQ), K. Kovarik (CTEQ), F. Muzakka (PhD), P. Duwentäster (PhD), P. Risse (PhD)
  - **Univ. Karlsruhe**: T. Jezo (senior Post-Doc)

Recent and ongoing work

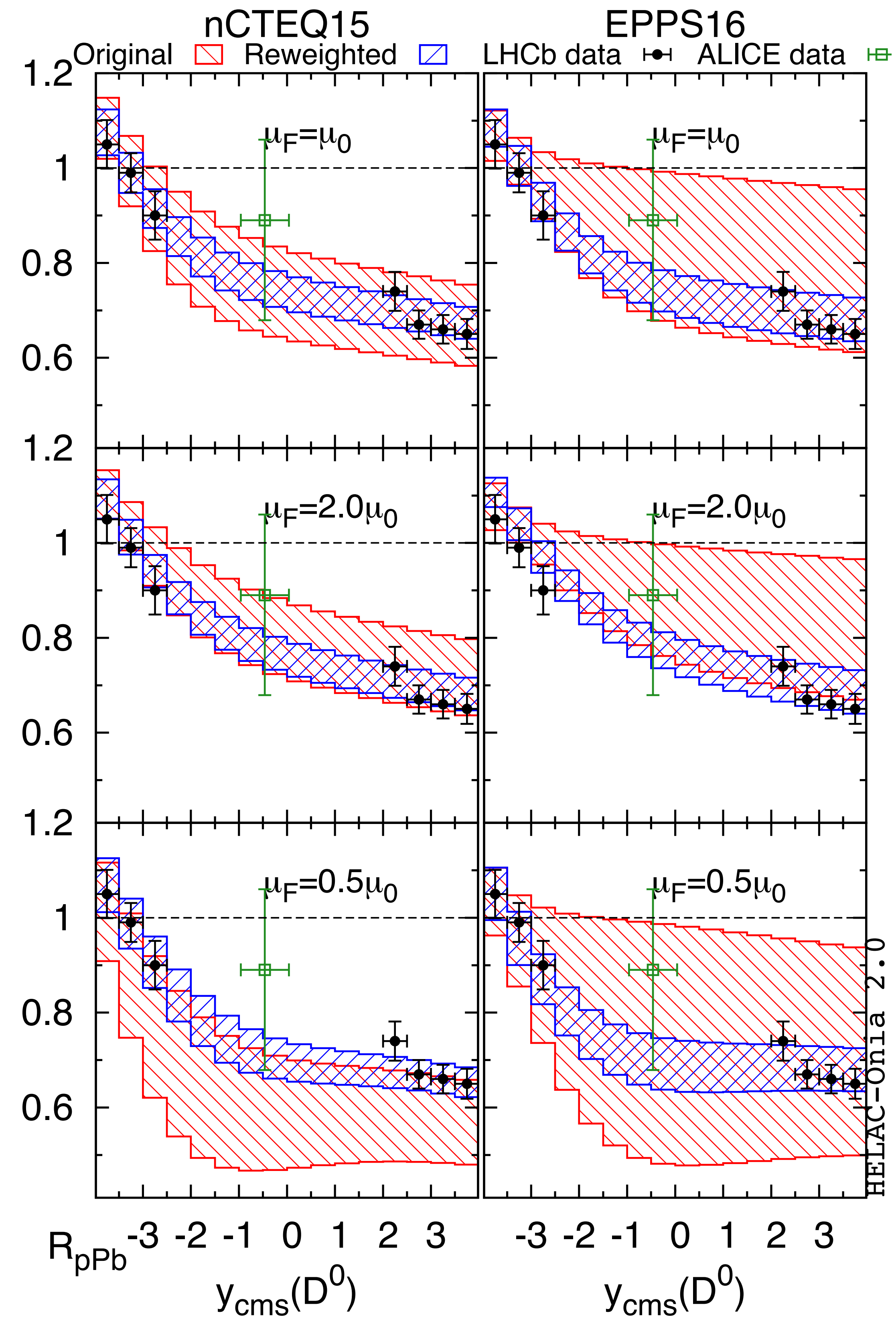
- Global Analysis including LHC W/Z data: **nCTEQ15WZ** [2007.09100]
- Global Analysis including high-x, low-Q^2 data from JLAB: **nCTEQ15HIx** [2012.11566]
- Global Analysis including new single inclusive hadron (SIH) data from ALICE and RHIC: **nCTEQ15SIH** [2105.09873]
- Global Analysis including **neutrino-nucleus DIS** data:
  soon to appear
- Paper on nuclear DIS in terms of quarks and gluons **without** describing the nucleus in terms of nucleons; clearer and more solid basis for defining nuclear PDFs
- Heavy flavour production at the LHC and the nuclear gluon distribution:
  Kusina, Lansberg, Shao, IS,
  [2103.00876,PRL121(2018)052004]





The small-x gluon content (GLUE@NLO)

- First analysis of LHC heavy quark(-onium) data in the standard pQCD approach: PRL121(2018)052004
  - Consistent with a strongly shadowed gluon at small-x (alternative explanations: energy loss, saturation, …)
  - Reweighting analysis of nCTEQ15 and EPPS16 performed [2012.11462]
- Need to include heavy quark data in global analysis
- Include also prompt photon data (gluon sensitive, other systematics): **FOCAL** to cover small-x



(a) Prompt D^0

More hadron structure

Links:

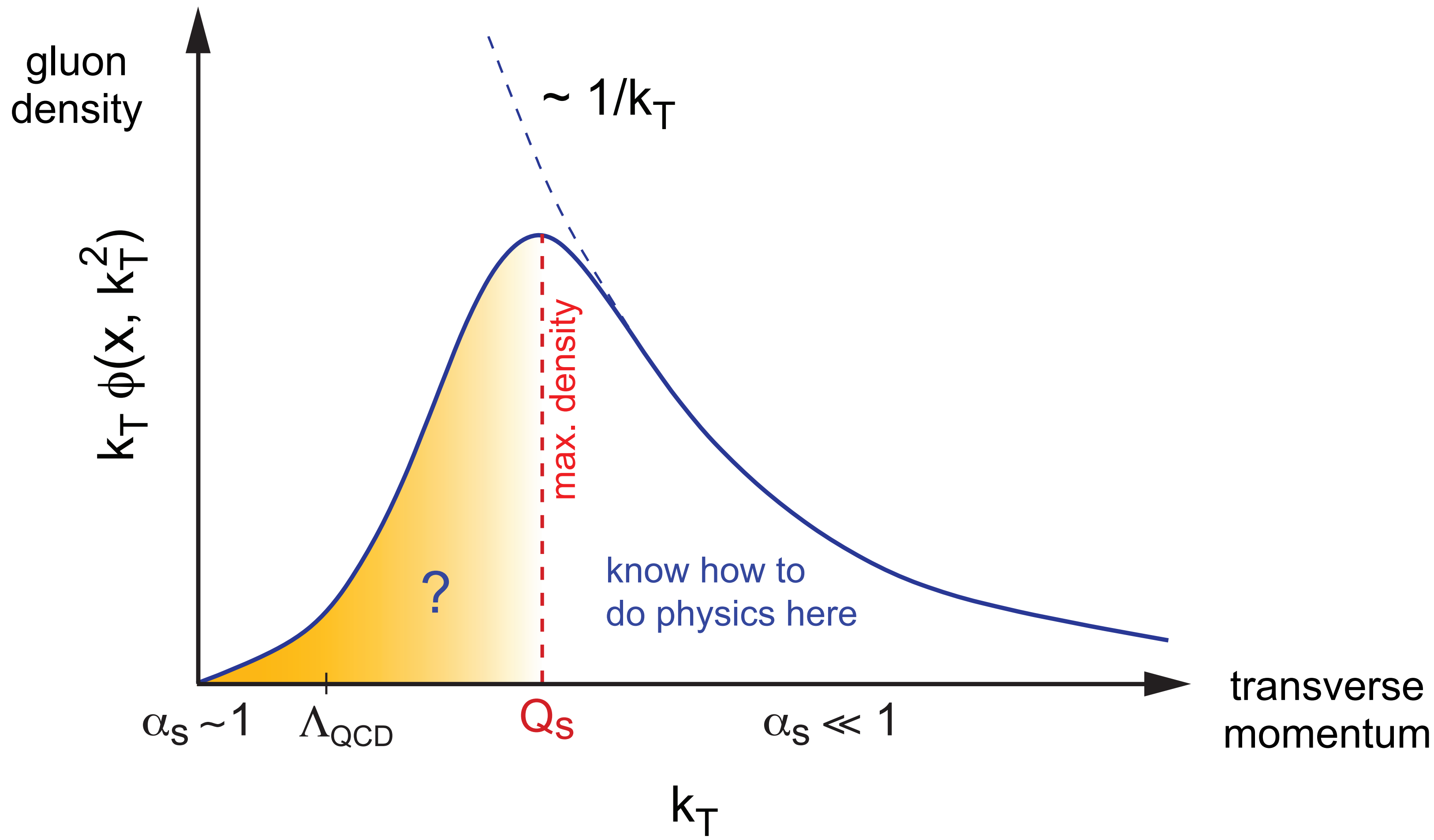
- Global analysis of proton PDFs
  - simultaneous fits of proton PDFs and nuclear PDFs
  - Proton fits use data taken on nuclei! Need to understand nuclear corrections
- There are other collinear PDFs: helicity dependent PDFs, transversity PDFs
- Generalized PDFs: H. Moutarde (CEA Saclay), C. Mezrag (CEA Saclay), C. Lorce (Palaiseau), S. Wallon (IJCLab)
- Transverse Momentum Dependent PDFs (TMD): J.-P. Lansberg, S. Wallon (IJCLAb)
- PDFs inside nucleons, nuclei but also pions, kaons, even photons
  pion structure: COMPASS experiment (S. Platchkov (CEA Saclay, …)
- Fragmentation Functions
- Ab initio lattice calculations: S. Zafeiropoulos (Marseille), M. Mangin-Brinet (LPSC), …

Goal: Understanding the 3D-structure of hadrons

The saturation scale

The saturation scale $Q_s(x)$ is the momentum scale which characterises the transition between the dilute and dense regimes

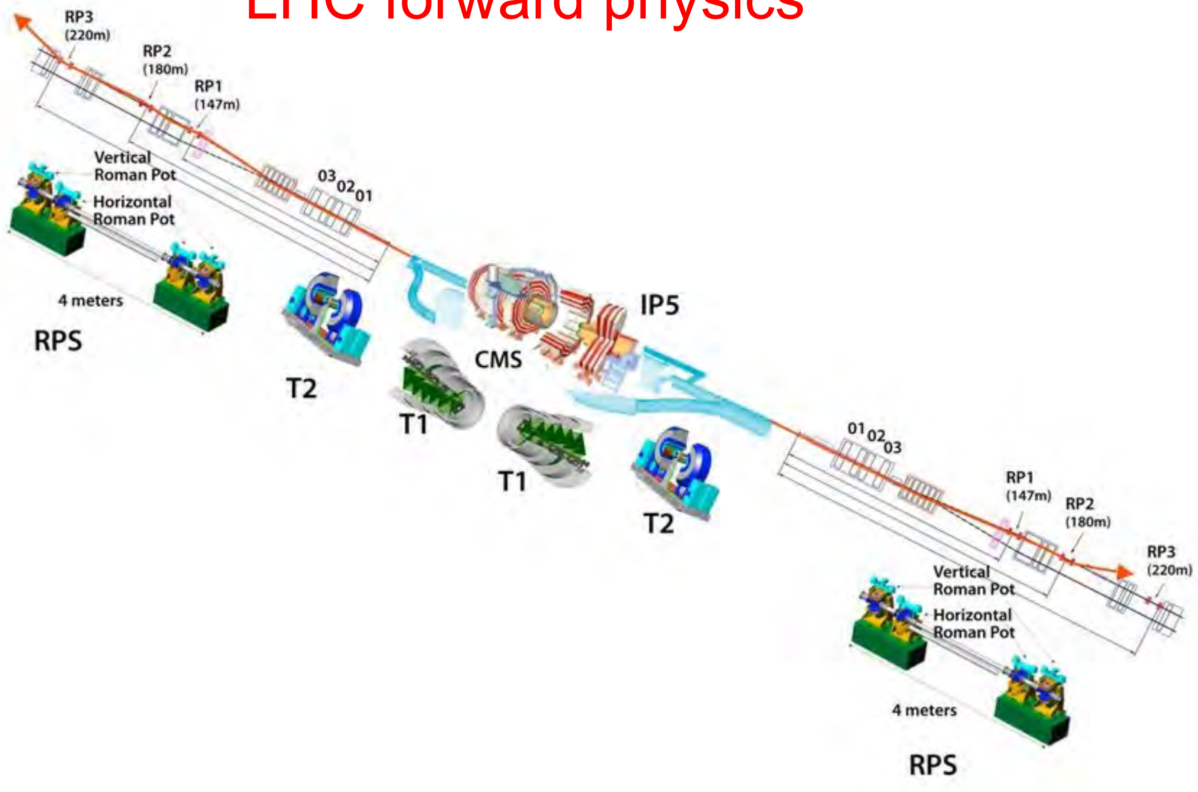
At small-x, the typical gluon k_T is no more Λ_{QCD}, it is instead $Qs(x)$



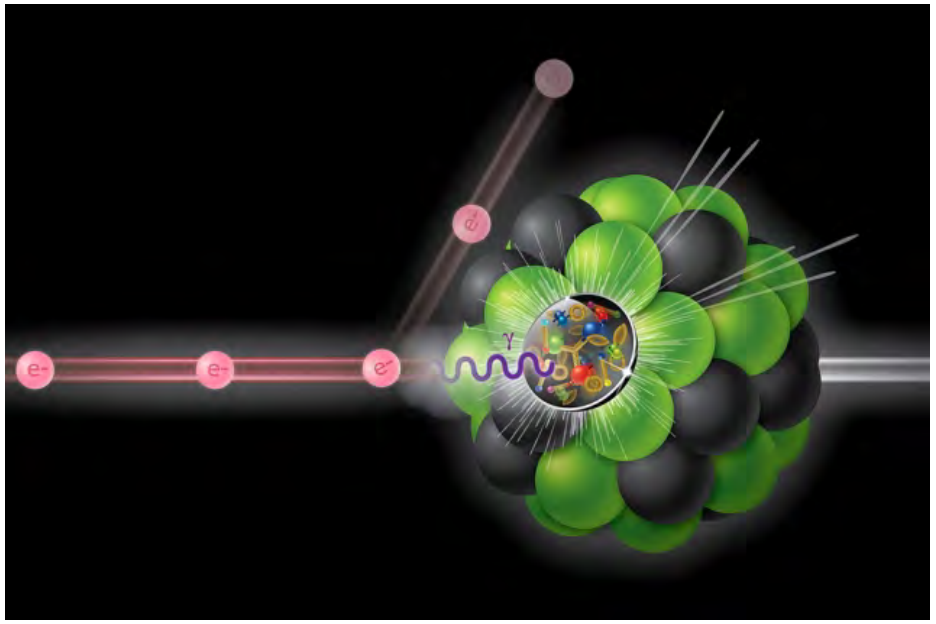
The dynamics is non-linear, but the theory stays weakly coupled: $\alpha_s(Q_s) << 1$

Where is it important?

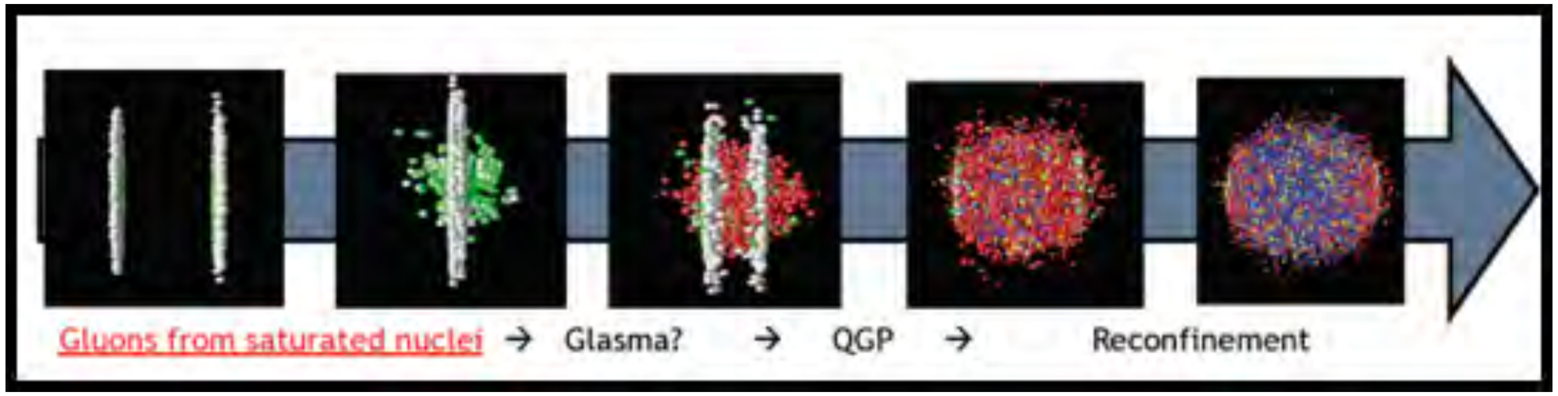
LHC forward physics



Electron Ion Collider (EIC)



initial stages of heavy-ion collisions



high-energy cosmic rays

Future prospects I

The field of high energy QCD has recently entered the NLO era:
Higher order corrections of several kind to be computed

- **NLO in α_s:**
  - Essential to prove factorisation and asses robustness of predictions
  - In many cases fixed order perturbation theory + resummations of various large logarithms
- **Next-to-eikonal corrections:** energy-suppressed but gives access to spin-dependent observables
- **Next-to-planar corrections:** going beyond the large-N_c limit

To be addressed for less and less inclusive observables measured in experiments:
exclusive and diffractive cross sections, correlation measurements, ...

Future prospects II

establish the connections with the "standard" hadron-structure lore

especially important in the context of the EIC

Generalized TMDs

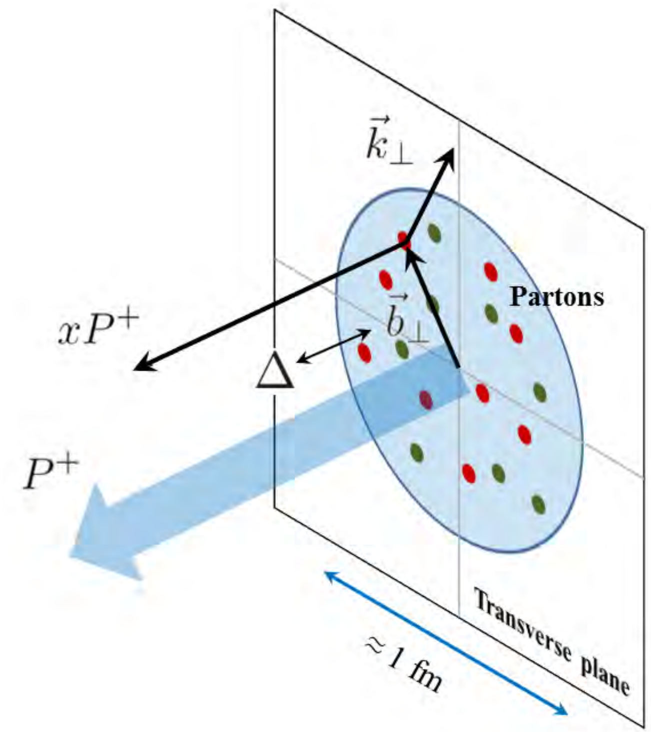
GTMDs $x, \vec{k}_\perp, \Delta$ $\qquad \langle p'|O(x,\vec{k}_\perp)|p\rangle$

$\int d^2b_\perp$ $\qquad$ $\int d^2k_\perp$

TMDs $x, \vec{k}_\perp$ $\qquad$ GPDs x, Δ

$\int d^2k_\perp$ $\qquad$ $\int d^2b_\perp$

PDFs x



what does small-x physics has to say
about those various parton distributions?
from protons to heavy nuclei ?
about multi-parton distributions?
about multi-parton interactions ?

NLOAccess

https://nloaccess.in2p3.fr

The STRONG-2020 WP **VA1-NLOAccess**:

- a virtual access for automated perturbative calculation for heavy ions and quarkonia
- automation and versatility:
  - everyone would be able to evaluate physical observables related to hadron scatterings
  - no need to pre-code
  - test the code
- any code that could be compiled and launched via a shell could be added

✓ MadGraph and its extension to nPDFs are being included

✓ HELAC-Onia is included