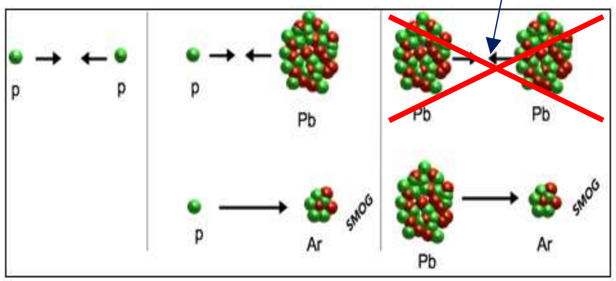
Heavy Ion Physics with LHCb

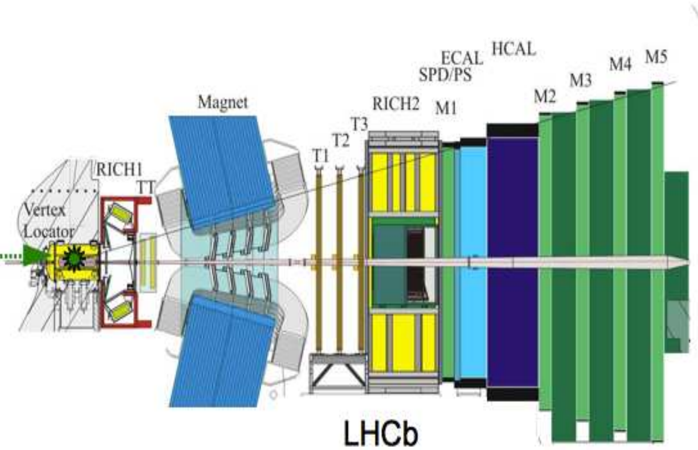
Frédéric Fleuret, LLR Palaiseau, Patrick Robbe, LAL Orsay, 8 Février 2017

LHCb « Heavy Ion » activities at IN2P3

- Study of strong interaction and QCD via the measurement of heavy flavour (charm and beauty) production in various environments at the LHC

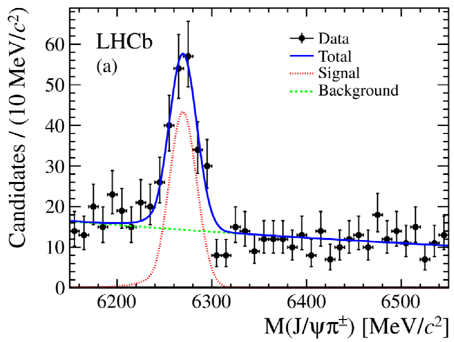
Not studied in IN2P3 groups



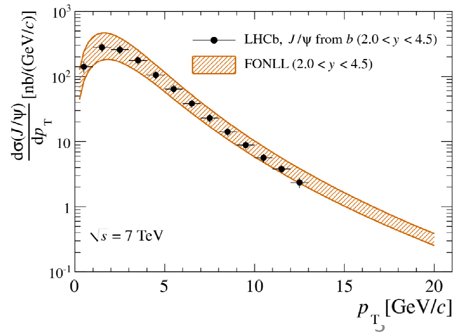


History of the project (1)

- Since the preparation of data taking (~2005), the LAL group is strongly involved in the study of heavy flavour production.
- Two main highlights:
  - *B_c production*:
    - ANR and FCPPL grants since 2006,
    - 5 publications (B_c cross-section, B_c mass, B_c branching fractions)
    - Several PhD theses and post-docs working on the subject
  - *Charmonium production*:
    - Leading first J/ψ measurement with 7 TeV data in 2011
    - One of the first LHCb publication
    - Continuing now with study of charmonium decays to $\bar{p}p$



B_c production [PRL 109 (2012) 232001]



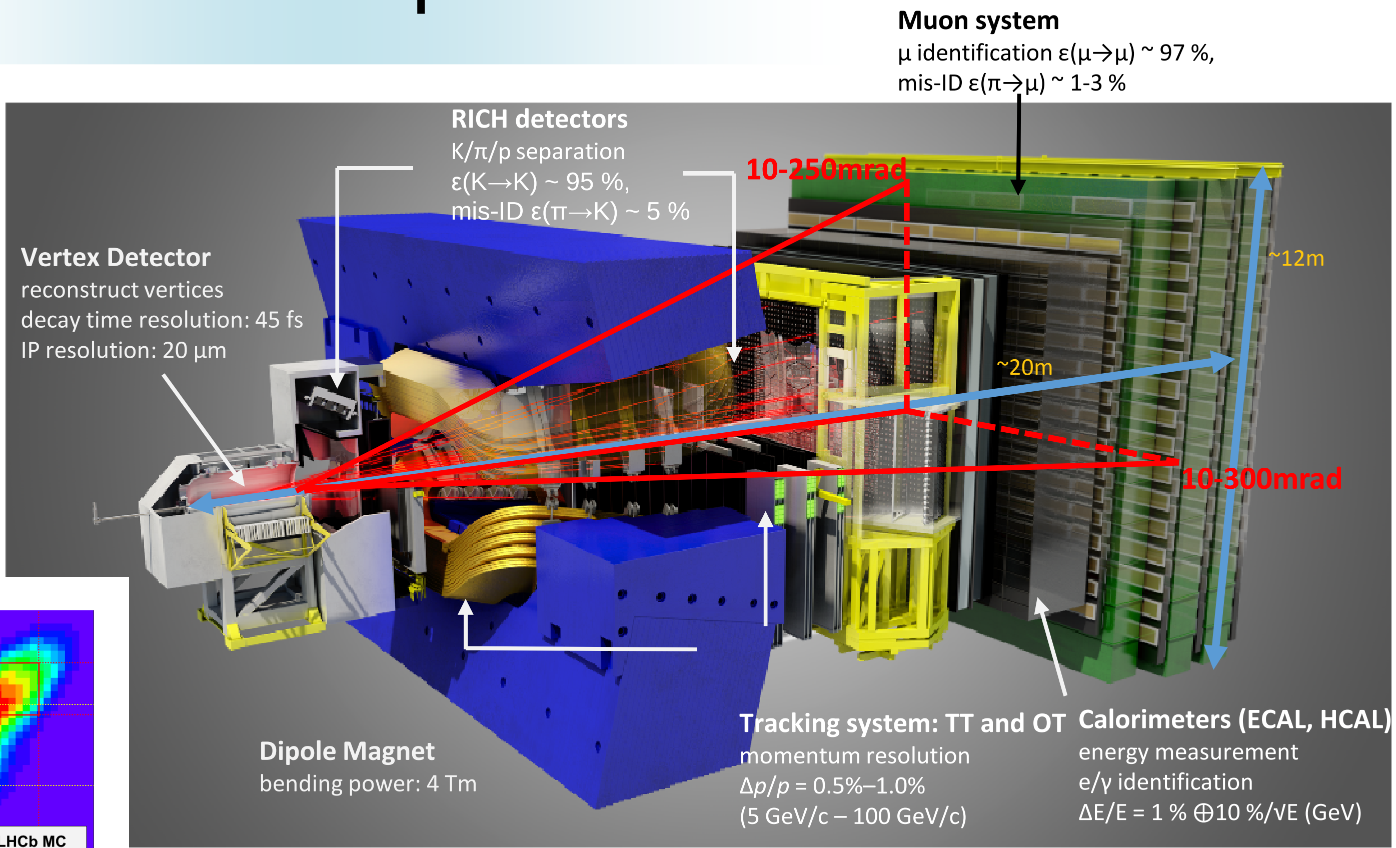
J/ψ production [EPCJ71 (2011) 1645]

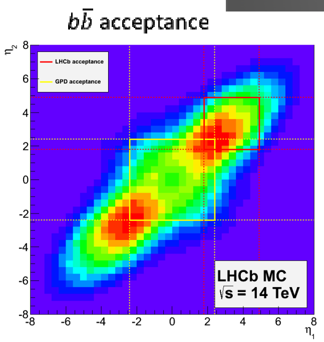
History of the project (2)

- Active groups in the Orsay area studying feasibility and physics reach of a fixed target experiment at the LHC.
- Lead by several IN2P3 physicists including Jean-Philippe Lansberg at IPNO and Frederic Fleuret at LLR, in the AFTER project for example.
- It was quickly realized that using an existing detector was the most effective solution, Patrick Robbe at LAL helped studying the feasibility
- LHCb has the ideal geometry for it.
- Merging the two efforts, the natural extension of the heavy flavour production measurements was to look at other collision systems, including a fixed target setup

The LHCb experiment

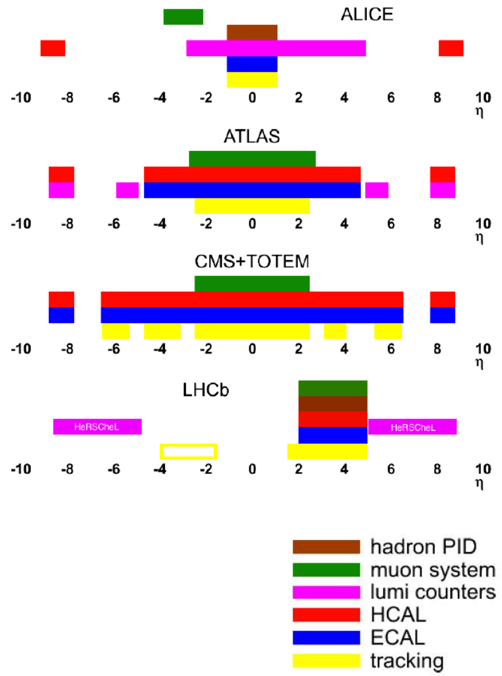
[IJMPA 30 (2015) 1530022]
[JINST 3 (2008) S08005]





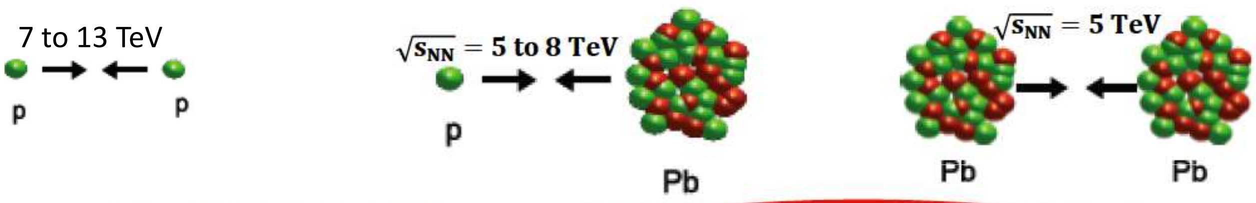
Why LHCb ?

- LHCb is specialised in heavy flavour precision physics, beauty and charm:
  - Optimised for low pile-up collisions (*ie* low multiplicity):
    - Precise reconstruction of production and decay vertices: time dependent CP violation
    - Correlations between particles: flavour tagging
- Some characteristics of the experiment make it attractive for measurements in Heavy ion physics too:
  - Instruments fully the forward region: $2<\eta<5$
  - Precise vertexing: separation of prompt production from *B* decay products
  - Precise tracking: reconstruction down to $p_T=0$
  - Particle identification: full reconstruction of hadronic decays of charm or beauty, such as $D^0 \to K\pi$

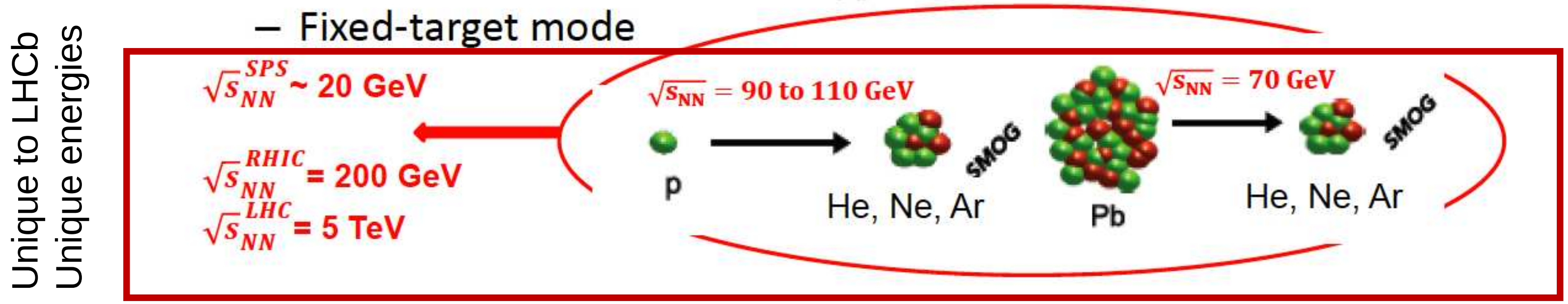


LHCb operation modes

– Collider mode



– Fixed-target mode

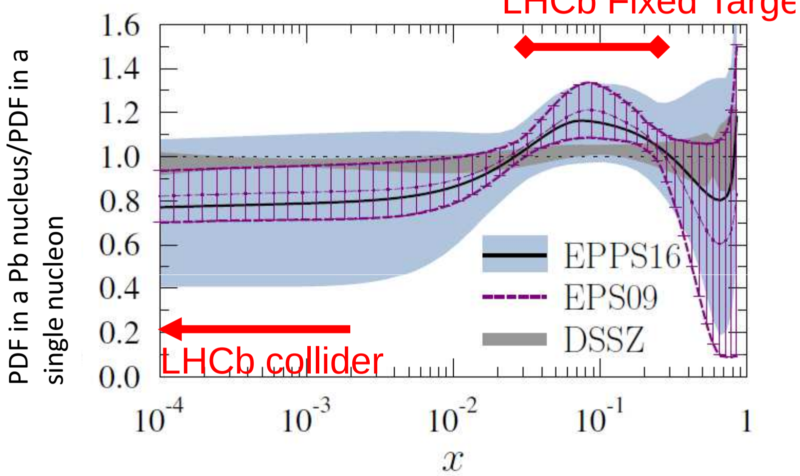


LHCb rapidity 2.5 < yLHCb < 4.5 $\Rightarrow \begin{cases} \text{7 TeV beam:} & -2.3 < y^{*}_{LHCb} < -0.3 \\ \text{2.75 TeV beam:} & -1.8 < y^{*}_{LHCb} < 0.2 \end{cases}$

Heavy Ion Physics with LHCb

- Proton-nucleus collisions
  - Serve as a baseline for nucleus-nucleus collisions
  - Nuclear parton distribution function (nPDF), nuclear absorption, saturation, energy loss…
  - Unique capabilities with LHCb in the heavy flavor sector to constraint nPDF at very small (*p*Pb collisions – charm and beauty) and large (fixed target - charm) Bjorken-*x*
- Nucleus-nucleus collisions in FT mode
  - 2.75 TeV Pb beam on fixed target: $\sqrt{s_{NN}}$~71 GeV (close to the 17 GeV regime reached at SPS)
    - Investigate the color screening
    - Thanks to unique capabilities, LHCb offers new opportunities in the charm sector: J/ψ, ψ', χ_c, D^0, $D^{+/-}$, D^*, Λ_c… (in the 90's the NA50/SPS experiment measured only J/ψ and ψ' in PbPb @ 17 GeV)
  - Accessing similar energy density regime than SPS: operate PbAr@71 GeV, lower multiplicity than PbPb collisions, central events should be accessible

arXiv:1612.05741v1



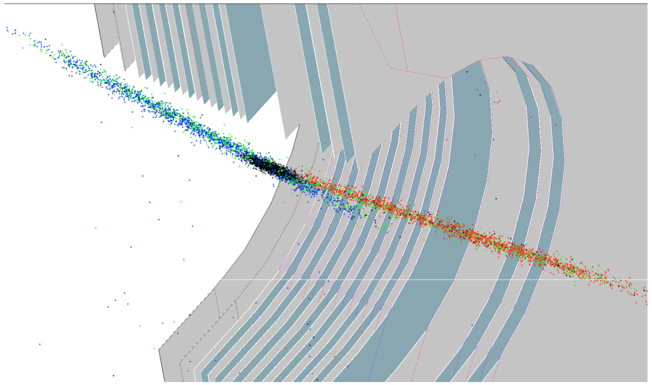
Bjorken-*x* = fraction of the nucleon momentum carried by a parton

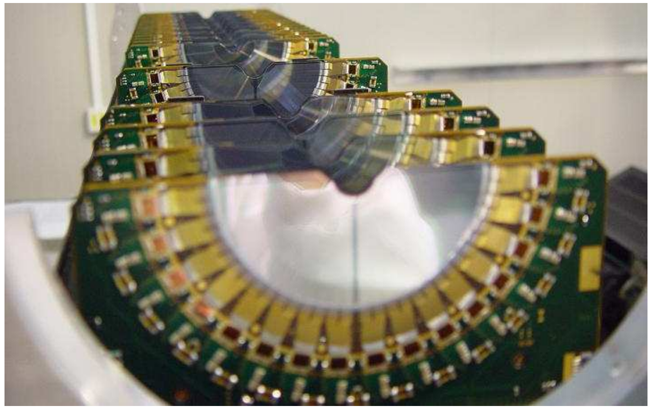
	System \ centrality	60 – 100%	40 – 50%	20 – 30%	0 – 10%
← LHC →	PbNe – 71 GeV	108.6	392.5	814.5	1494.9
	PbAr – 71 GeV	**123.6**	**496.5**	**1228.3**	**2372.7**
	PbKr – 71 GeV	196.9	919.1	2205.5	4084.3
SPS	**PbPb – 17 GeV**	**124.2**	**605.9**	**1338.7**	**2980.5**

(based on EPOS-LHC-v3400)

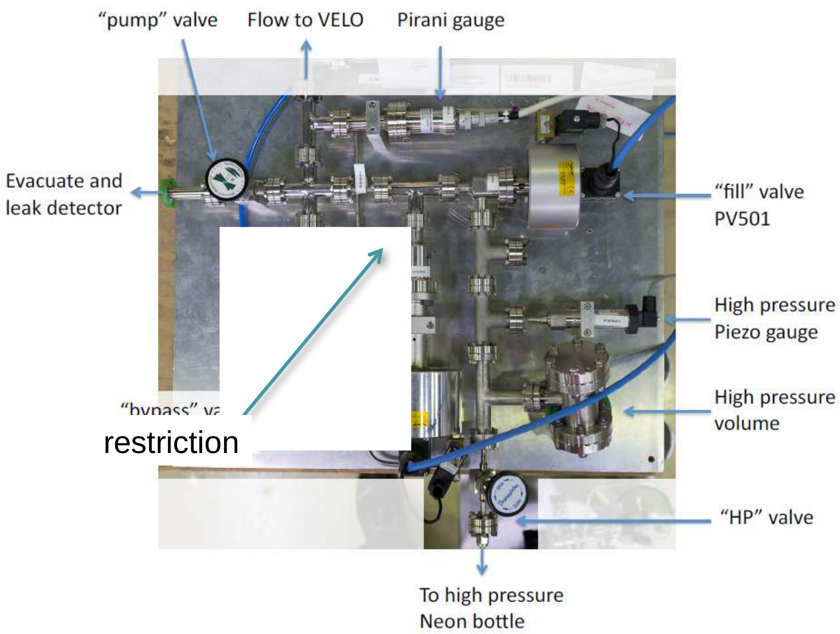
Fixed target mode – SMOG

- Gas can be injected in the interaction region of LHCb, in the VELO vaccuum (ie the LHC vaccuum)
- Initially this was designed to measure the luminosity of LHCb, by measuring the beam images with beam-gas vertices: used during LHC van der Meer scan sessions: 1.5% precision on integrated luminosity
- Other use cases emerged:
  - Measure LHC ghost charge (proportion of particles outside the colliding buckets) for the ALICE, ATLAS and CMS luminosity
  - Fixed target physics: strong involvement of LAL-LLR (with also IPN colleagues) for feasability studies





Fixed target mode – SMOG



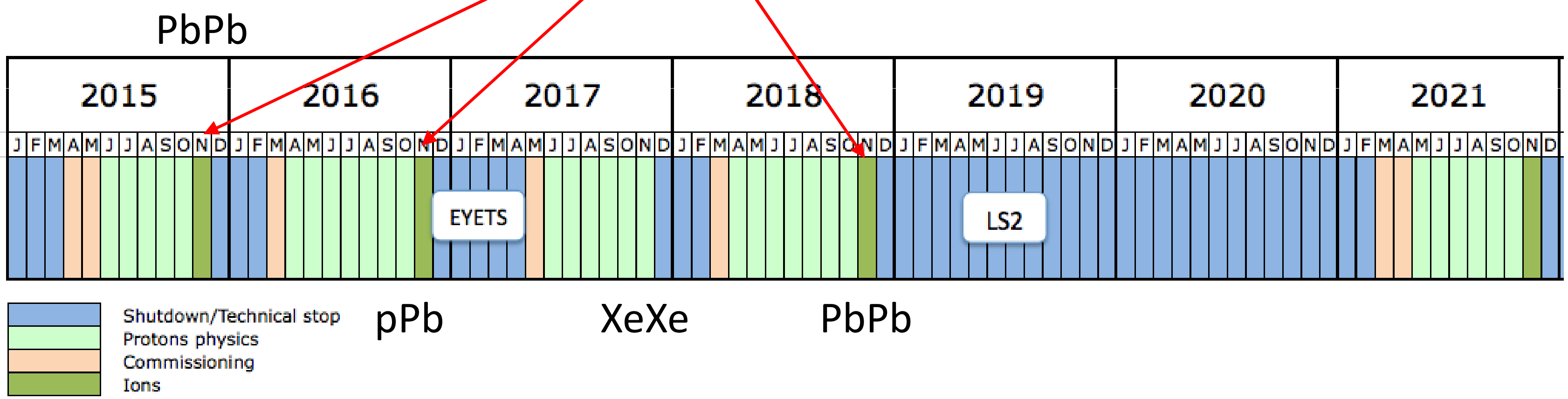
- Very simple system
- Originally use Neon gas
- Other non-getterable nobel gases can be used: in 2015, we used also Ar and He
- The pressure in the LHC when the gas is injected is ~$2x10^{-7}$ mbar (instead of 10^{-9} mbar with no injection)

History of the project (3)

- The proposal to participate in heavy ion runs (*p*Pb, PbPb, fixed target) was presented to the collaboration in 2015:
  - Accepted fully by LHCb
  - Is now part of the LHCb physics program: the collaboration covers shifts, operations of the detector and data handling
  - A dedicated physics working group (Ion and Fixed Target – IFT) was created
  - An ERC grant was obtained in 2016: 1.8 M€ total with 1.1 M€ for LAL
- The proposal was also presented and accepted by the LHCC in 2015:
  - LHC Machine plans include the LHCb participation to the heavy ion runs:
    - In *p*Pb collisions, L_{int}(LHCb) ~ L_{int}(ALICE)
    - In PbPb collisions, L_{int}(LHCb) ~ 0.1 x L_{int}(ALICE)
    - Gas can be injected in the LHC for our fixed target program on demand

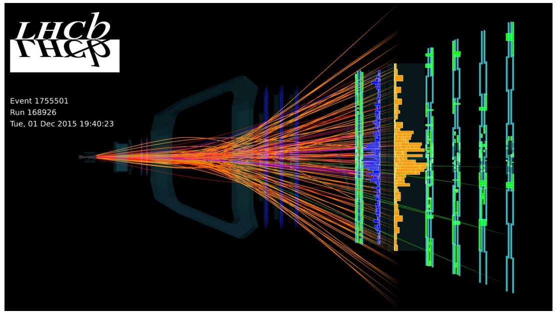
LHC schedule

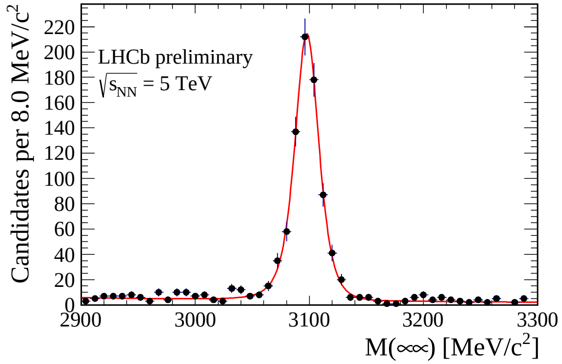
- The LHC uses ions (Pb) about 1 month per year



Collider mode: PbPb collisions (2015)

- LHCb took part for the first time to a LHC PbPb run end of 2015, with emphasis on low multiplicity events.
- Up to 54 colliding bunches, *ie* 10% of the luminosity provided to the other LHC experiments, and a total of 3-5 μb^{-1} integrated luminosity recorded with the detector running in standard conditions (same as with proton-proton collisions)
- <u>Centrality reach</u>: up to 50%, where measurements of J/ψ, D^0, K_s^0, Λ, … production can be done
- Analysis however difficult because of high multiplicity events, limiting tracking efficiency with the current detector. Not covered at IN2P3.
- But, as expected, good performances for Ultra Peripheral Collision Events

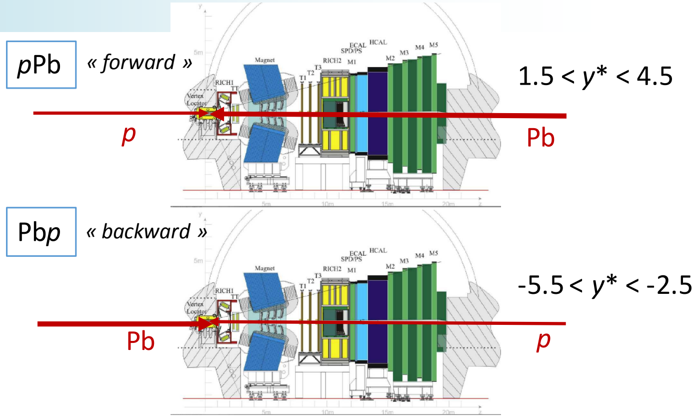




J/ψ in UPC events

Collider mode: *p*Pb collisions (2016)

- Due to geometry of detector: when reverting beams, two different coverages: statistics accumulated in both configurations
- No problem with multiplicities, similar to *pp* collisions with the usual pile-up
- *p*Pb (~13nb^{-1}) and Pb*p* (~17nb^{-1}) collisions at 8.2 TeV: more than 10 times the 2013 (pilot run) statistics. Possibility to perform several important measurements [LHCb-PUB-2016-011]



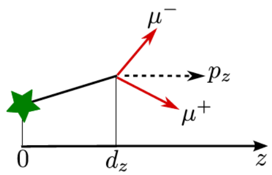
Channel	2013 yields	Yields expected in 2016 with 20 nb^{-1}
$\Upsilon(3S) \to \mu^+\mu^-$	–	300
$\psi(2S) \to \mu^+\mu^-$	500	10000
$Z \to \mu^+\mu^-$	12	250
Associated $J/\psi - D^0$ production	–	100
Drell Yan	–	1000

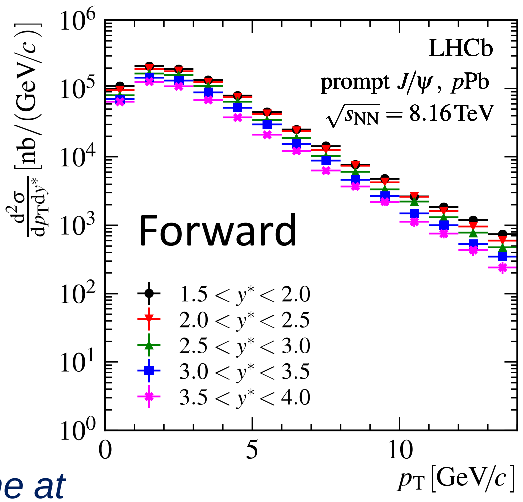
J/ψ production in *p*Pb at 8 TeV

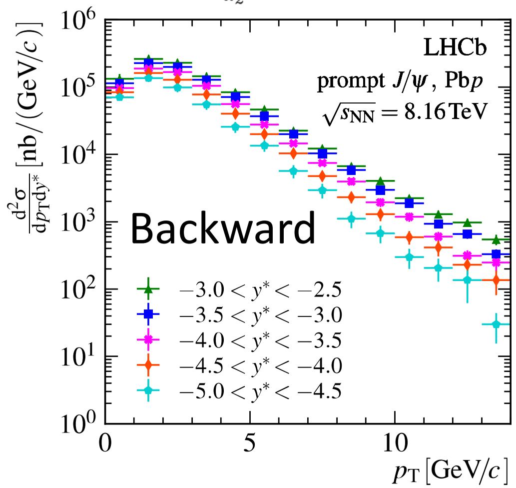
Fraction from *B* decays

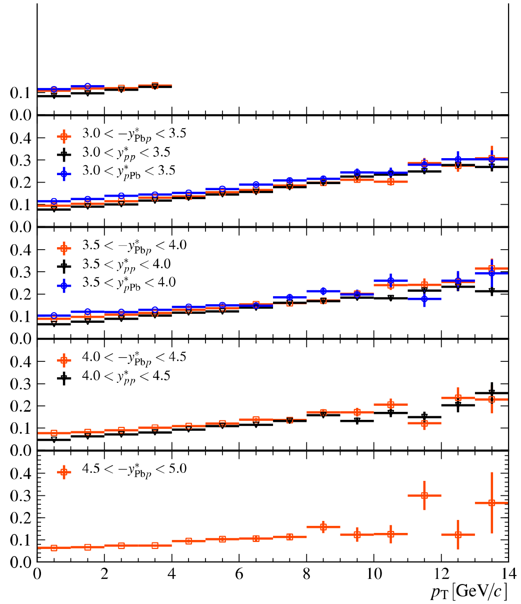
- J/ψ production is the first publication (of all LHC experiments) in this sample, using trigger candidates with no extra reconstruction
- Precise double differential cross-section of prompt and J/ψ from *b* [PLB 774 (201

$$t_z(J/\psi) = \frac{d_z \times M_{J/\psi}}{p_z}$$









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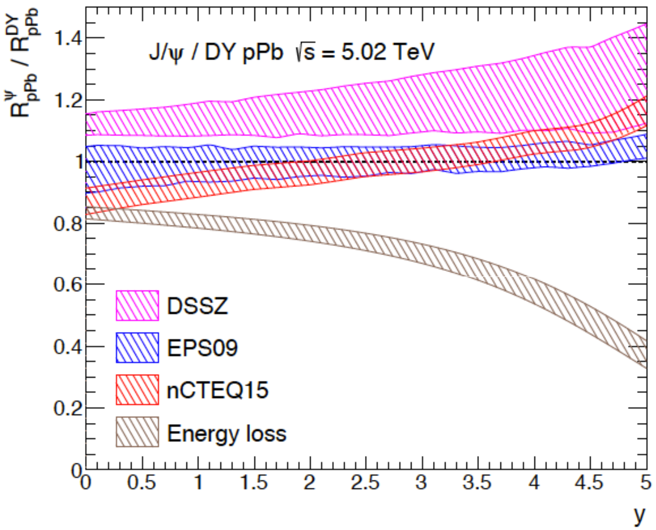
Collider mode – *p*Pb collisions (2016)

- Very good quality data set out of which several original measurements will be obtained in the next years, in the LAL/LLR groups:
  - χ_c in the decay $\chi_c \rightarrow J/\psi\ \gamma$: might be a first at the LHC, will give important information on cold nuclear matter effects on charmonium
  - *D* correlations: insight on multiple parton scattering
  - Drell Yan production
    - Measurement of Drell Yan (DY) production in the forward region is a method proposed to distinguish between shadowing and energy loss models.
    - LHCb acceptance is ideal for this measurement.
    - Capabilities to remove background from *b* decays with the VELO
    - About 1000 candidates are expected with the 2016 dataset.



[F. Arleo and S. Peigné, arXiv:1512.01794]

Fixed Target Physics With LHCb

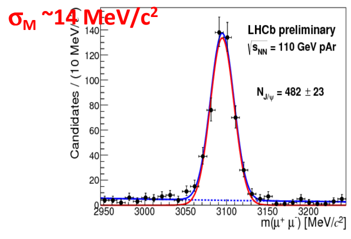
- Inject gas between 1 day and 2 weeks.
- The pressure is so low that it does not interfere with the running of the LHC and data can be collected also in parallel with *pp* collisions by LHCb.
- Operation in 2015 demonstrated that running with SMOG in completely transparent for the LHC: it is considered now as routine operation.

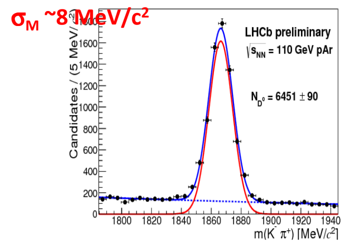
Year	Target	Beam energy	Proton on Target	Relative size
2015	Ne	6.5 TeV p	9×10^{20}	1
2015	He	6.5 TeV p	2.4×10^{21}	2.7
2015	**Ar**	**6.5 TeV p**	**3.9×10^{22}**	**43**
2015	Ar	2.5 TeV p	2×10^{20}	0.2
2015	Ar	2.5 TeV Pb	2×10^{20}	0.2
2016	He	6.5 TeV p	2.7×10^{21}	3
2016	**He**	**4 TeV p**	**4.6×10^{22}**	**51**
2017	He	6.5 TeV p	2.4×10^{20}	0.3
2017	Ne	6.5 TeV p	3×10^{21}	3.3
2017	Ne	2.5 TeV p	5×10^{23}	550 (180 h of data)

D^0 and J/ψ production in *p*Ar collisions at 110 GeV: data sample

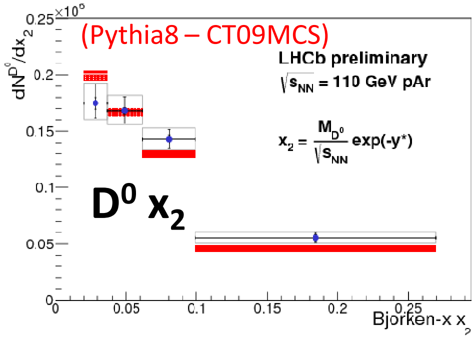
- Overall data (17h) : ~500 J/ψ   ~6500 D^0

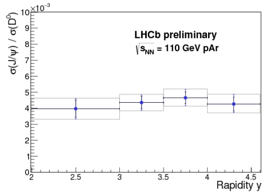
  $J/\psi \to \mu^+\mu^-$ $D^0 \to K\pi$





- Very clear signal, very small background
- Study $J/\psi/D^0$ as a baseline for QGP studies
- Bjorken-*x* range covered by the data
  - J/ψ $x_2 \in [0.03, 0.45]$
  - D^0 $x_2 \in [0.02, 0.27]$
  - Give access to intrinsic charm regime
- pHe @ 86.6 GeV analysis ongoing





[LHCb-CONF 2017-001]

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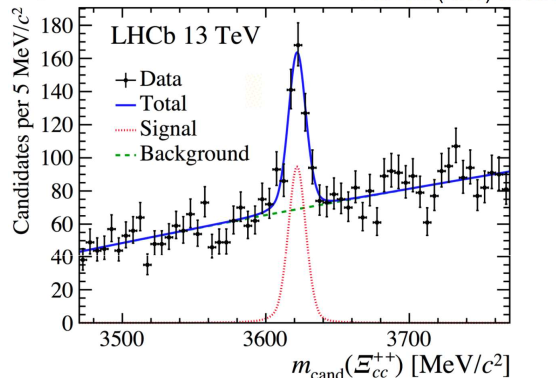
Group organisation

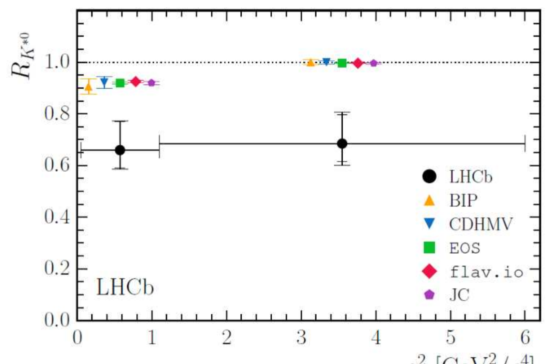
- Two groups in IN2P3:
  - LLR Ecole Polytechnique:
    - 1 DR (*Frederic Fleuret*, 100% CNRS), 1 Post-doc (*Emilie Maurice*, 2 years P2IO + 6 months Ecole Polytechnique)
  - LAL Orsay:
    - 1 DR (*Patrick Robbe*, 30% ERC), 2 Post-docs (*Michael Winn*, *Yanxi Zhang*, 3 years ERC)
    - Former members: *Laure Massacrier* (P2IO post-doc, now CR CNRS at IPNO), *Francesco Bossu* (ERC post-doc, now CEA permanent researcher)
- Responsabilities:
  - IFT Working group conveners: *Frederic Fleuret* and *Michael Winn* (replacing *Francesco Bossu* who replaced *Laure Massacrier*)
  - LHCb Luminosity working group convener: *Emilie Maurice* (in charge of SMOG operations)
  - LHCb Quarkonium working group convener: *Yanxi Zhang*
  - LHCb Run coordinator (2015 – 2017): *Patrick Robbe*
  - HL-LHC Heavy Ion working group co-convenor: *Michael Winn*

Group organisation

- Main contributions:
  - Heavy ion and SMOG data taking (help with detector and gas injection operation, shifts, monitoring, stripping, simulation, trigger,…)
  - Data analysis of the *pPb* and SMOG samples
- Important involvement in common LHCb activities:
  - Shifts and piquets during *pp* data taking (L0 and Calorimeter, which are the responsabilities of IN2P3) financed by ERC travel budget
  - Take part to other important analyses:
    - Calibration of *pp* luminosity
    - Ξ_{cc}^{++} discovery
    - Calibration of electron tracking for Lepton Flavor Universality tests R(K$^{(*)}$) with *p*Pb data

PRL 119 (2017) 112001





[JHEP 90 (2017) 055]

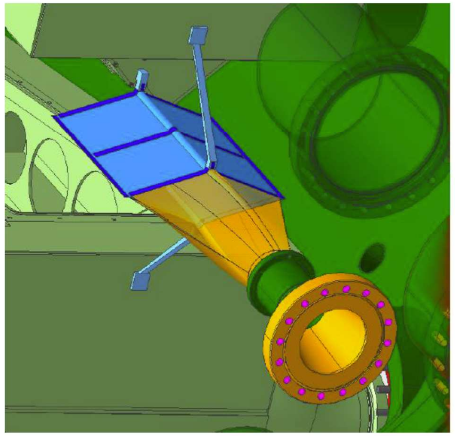
Future of the activity in LHCb

- New groups are joining the collaboration to participate to heavy ion studies (Los Alamos, Michigan, …) often contributing to the upgrade.
- New fixed target projects are emerging:
  - An upgrade of the SMOG system will be installed in LS2 (2019) to increase the pressure and allow to inject virtually any kind of gas. Lead by INFN Frascati: we will collaborate with them.
  - Further upgrades (after 2021) proposed already now, providing extra physics cases (discussed in a dedicated group during the Physics Beyond Collider workshops at CERN):
    - *Polarized* gas jet (INFN Frascati) for spin physics
    - *Solid* fixed target in beam halo (Kiev)
    - Fixed target + *crystal* with beam halo extracted with crystal to measure charm baryons MDM (LAL – A. Stocchi with UA9 expertise)
- The future of the activity is guaranteed inside LHCb

SMOG Upgrade in LS2

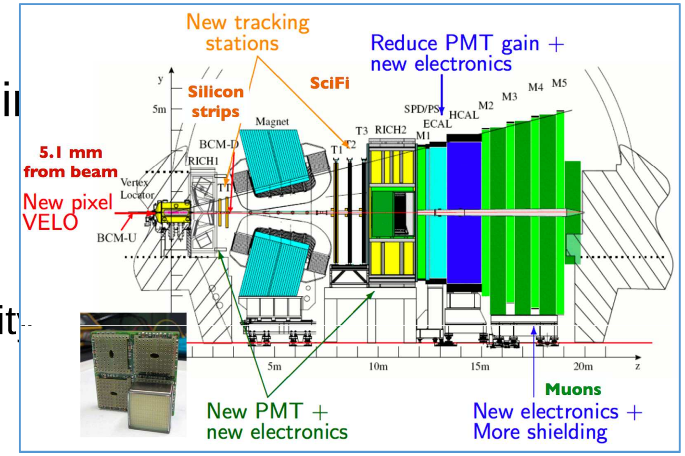
- Limitations of the current system:
  - Low pressure
  - Very little control of injected pressure
  - Gas limited to noble gases
- New design will allow:
  - Increase local pressure by one order of magnitude at least while keeping the overall pressure in the VELO at the same level

- Design and prototyping done at INFN Ferarra (see talk by V. Carassiti):
- Al Cell with coating (e.g. Graphite) - a couple of options under study, e.g. Wing type (see picture), or two parallel planes;
- Wake-Field Suppressor and Cell in two halves to open during injection.
- Goal is to install the SMOG2 system during LS2 !



Future of the activity in LHCb

- Detector will be upgraded to be able to run at higher luminosities: this also means that the centrality reach i heavy ion collisions will be improved:
  - <u>LS2 Upgrade I</u> (L_{inst} x5):
    - readout entire detector at 40 MHz and improve granularit of tracking detectors (Pixel vertex detector and Scintilating Fiber tracker).
    - In construction phase now, installation will start next year.
  - <u>LS4 Upgrade II</u> (L_{inst} x50):
    - expression of interest ([2017]) to run LHCb during the HL-LHC phase at much higher luminosities (means in general high multiplicity, but this is mitigated by the fact that individual pile-up interactions would be separated by precise timing)
    - R&D starting now: room for new groups to join and to integrate heavy-ion constraints to the design



Future of the activity in IN2P3

- Only 2 permanent researchers
- Group of 5 persons is a good number to maintain the same level of involvement:
  - Including PhD students and researcher exchanges (with Chinese institutes within FCPPL collaboration for example): will ensure full exploitation of the recorded datasets
  - Participation to upgrades will need more stable person-power
- We have a strong wish to maintain the links with the « main stream » LHCb physics program:
  - For example, devoting time to study detector choices for the LS4 Upgrade II.

Conclusions

- One very interesting *p*Pb dataset at 8 TeV: will take several years to fully exploit
- We proved the feasibility of a fixed target experiment at the LHC, both for operation and data analysis:
  - Most relevant dataset will be recorded end of 2018: PbNe to possibly study QGP
  - Triggered several ideas to improve the current setup and increase the statistics, first step will be installed during LS2 (2019-2020)
- Current size of the group (5 people) allows to have leadership in this area in LHCb, but will decrease quickly in two years

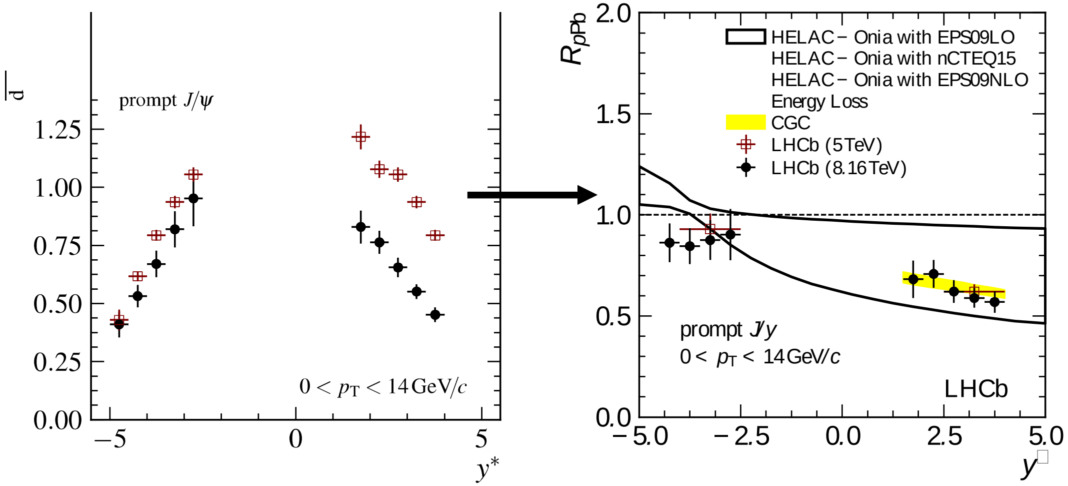
J/ψ production in *p*Pb at 8 TeV (2)

- Nuclear effects are seen in the comparison with *pp* collisions and in the comparison of *p*Pb with Pb*p*:

$$R_{p\mathrm{Pb}}(p_\mathrm{T},y^*) \equiv \frac{1}{A}\frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_\mathrm{T},y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{pp}(p_\mathrm{T},y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}$$

and

$$R_\mathrm{FB}(p_\mathrm{T},y^*) \equiv \frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_\mathrm{T},+y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_\mathrm{T},-y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}$$

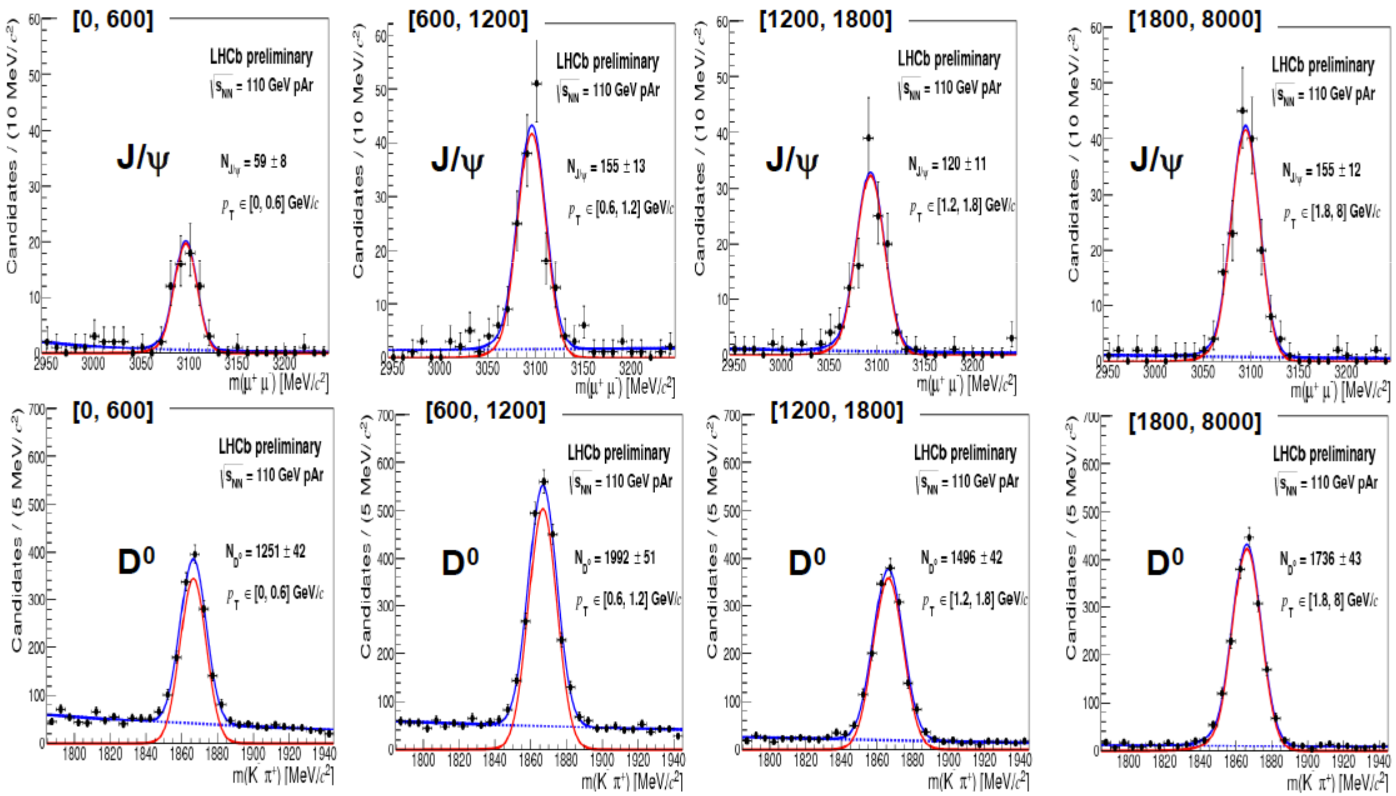


Modification of production is expected due to the well established modification of the parton density functions in the Pb ion (smaller at low x = shadowing and larger at high x = anti-shadowing).
Shown with HELAC-Onia generator: J/ψ are produced as in *pp* but using nuclear PDFs (EPS09, nCTEQ15)
In addition:

- CGC: color glass condensate, saturation of gluon density at low x
- Energy Loss: scattering of the colliding gluon in nuclear matter

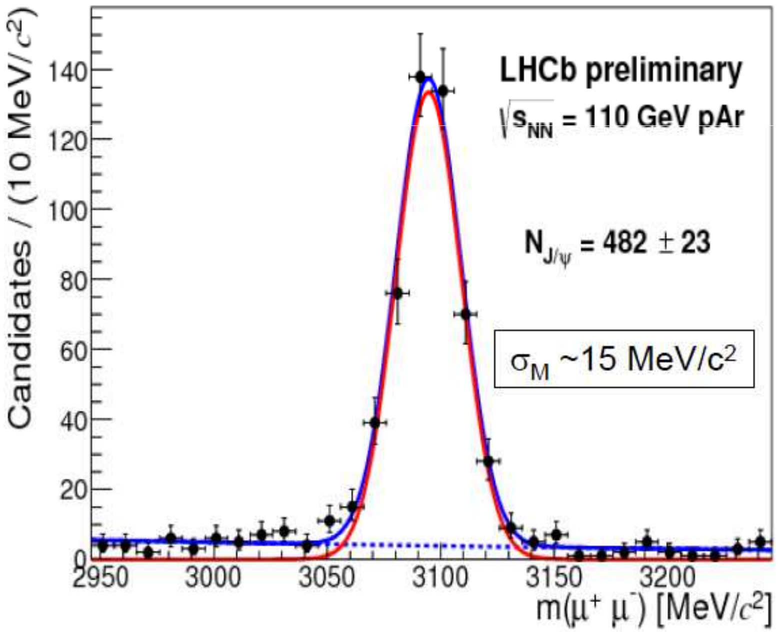
D^0 and J/ψ production in pAr collisions at 110 GeV: differential production

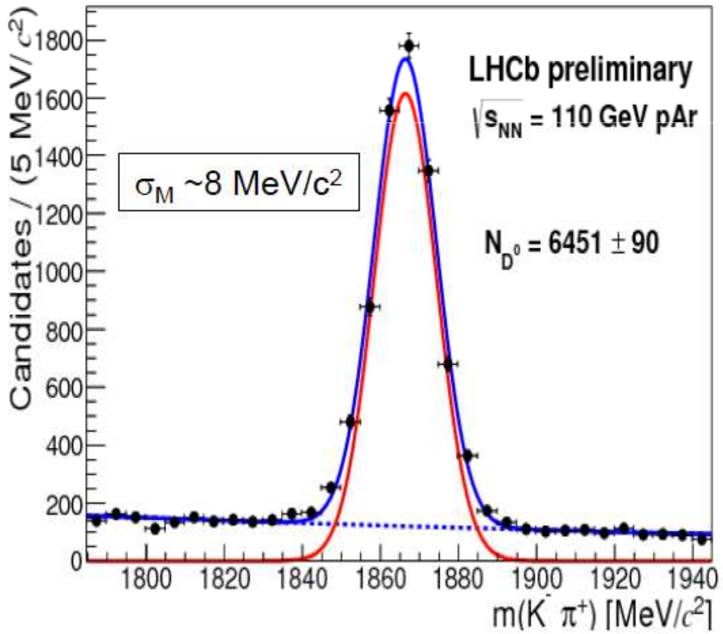
- **pT bins ∈ [0, 600] – [600, 1200] – [1200, 1800] – [1800, 8000] MeV/c**



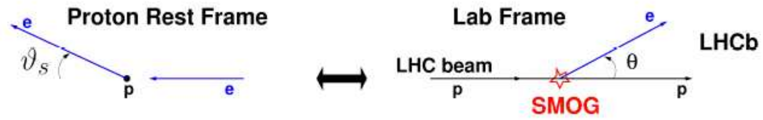
D^0 and J/ψ production in pAr collisions at 110 GeV: signal extraction

- **J/ψ and D^0 : Crystal ball functions to extract the signal**
  - Overall data (17h) : ~500 J/ψ ~6500 D^0
  - Very clear signal, very small background





Normalization

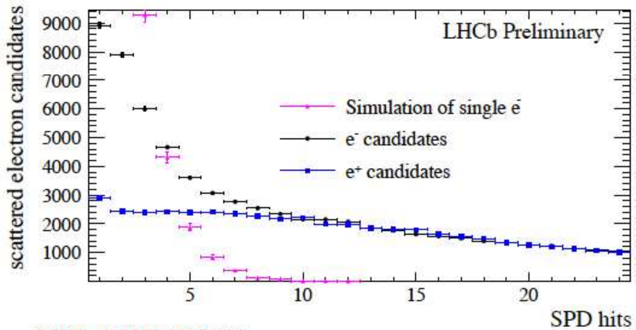


Using p-e$^-$ elastic scattering.

Pro:

- LHCb sees the purely elastic regime: $\theta > 10$mrad ➡ $\vartheta_s < 29$ mrad, $Q^2 < 0.01$ GeV^2
  ➡ cross-section very well known

- distinct signature with single low-p and very low p_T electron track, and nothing else
- background events mostly expected form very soft collisions, where candidate comes from γ conversion or pion from CEP event ➡ **background expected to be charge symmetric**, can use "single positrons" to model it in data



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Cons:

- cross-section is small (order 100 μb, 3 orders of magnitude below hadronic cross section)
- electron has very low momentum and showers through beam pipe/detectors
  ➡ low acceptance and reconstruction efficiency

Electron spectra

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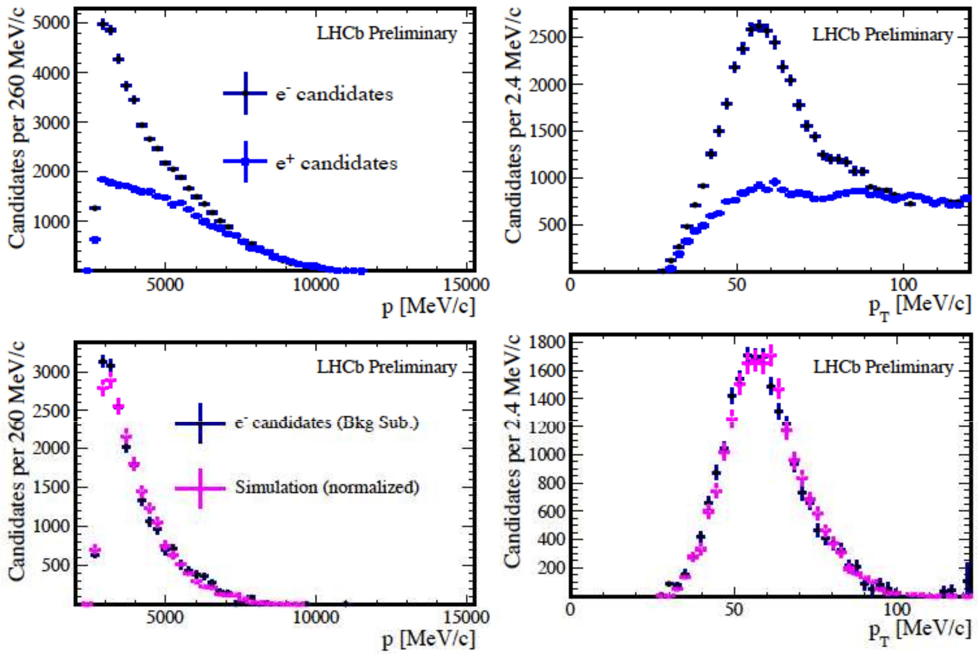

- Very good agreement with simulation of single scattered electrons
- Data confirm charge symmetry of background

$$\mathcal{L} = 0.443 \pm 0.011 \pm 0.027\,\mathrm{nb}^{-1}$$

- Systematic from variation of selection cuts, largest dependence is on azimuthal angle
- equivalent gas pressure is 2.4×10^{-7} mbar, in agreement with the expected level in SMOG