Town Meeting
Relativistic Heavy Ion Physics

LHCb
Future Plans

October 24, 2018

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on behalf of the LHCb collaboration

Outline

- Introduction to the LHCb Detector and its SMOG system
  - Kinematic reach and data samples
  - Some recent results in Heavy Ion physics
- LHCb detector upgrade I and SMOG upgrade (LS2)
  - Short overview of the upgrade for Runs 3 and 4
  - Possibilities with the upgraded detector in Heavy Ion physics
- Further LHCb detector upgrade plans (upgrade II, LS4)
  - Possibilities in Heavy Ion physics with the upgrade II
- Summary and Conclusions

LHCb Detector

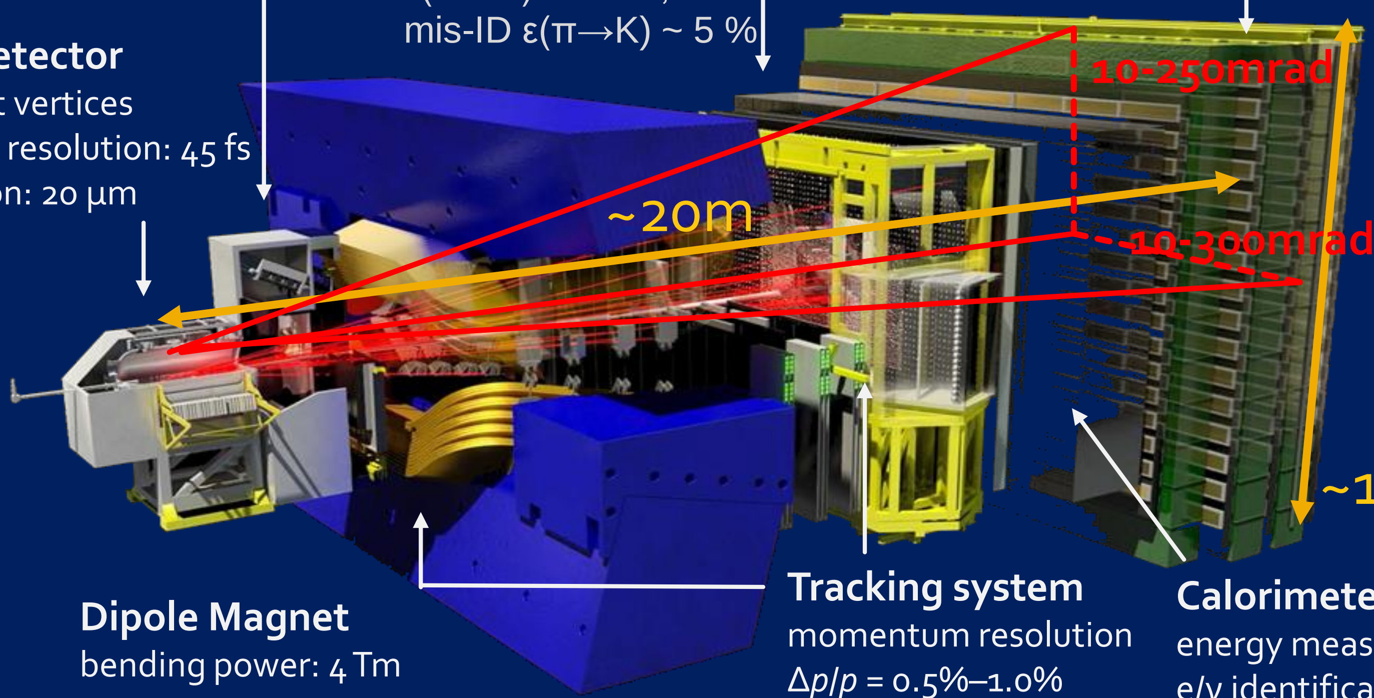
- Single arm spectrometer in the forward direction
  - designed for heavy flavour physics, but capable to address many other topics ...
  - fully instrumented in 2 < y < 5 with unique forward kinematics
  - Flexible trigger down to very low p_T

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

RICH detectors
K/π/p separation
ε(K→K) ~ 95 %,
mis-ID ε(π→K) ~ 5 %

Muon system
μ identification ε(μ→μ) ~ 97 %,
mis-ID ε(π→μ) ~ 1-3 %

Vertex Detector
reconstruct vertices
decay time resolution: 45 fs
IP resolution: 20 μm



Dipole Magnet
bending power: 4 Tm

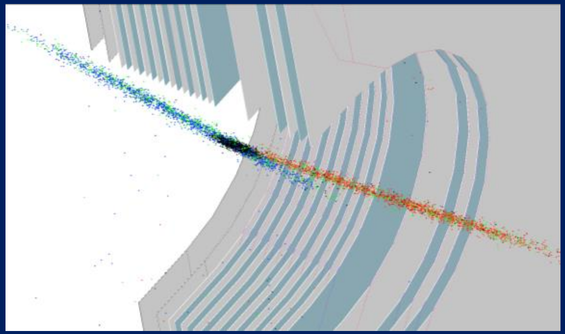
Tracking system
momentum resolution
$\Delta p/p$ = 0.5%–1.0%
(5 GeV/c – 100 GeV/c)

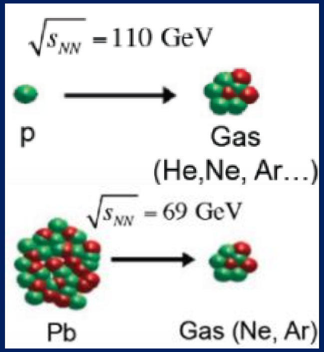
Calorimeters
energy measurement
e/γ identification
$\Delta E/E = 1\,\% \oplus 10\,\%/\sqrt{E}$ (GeV)

Fixed Target Physics with LHCb

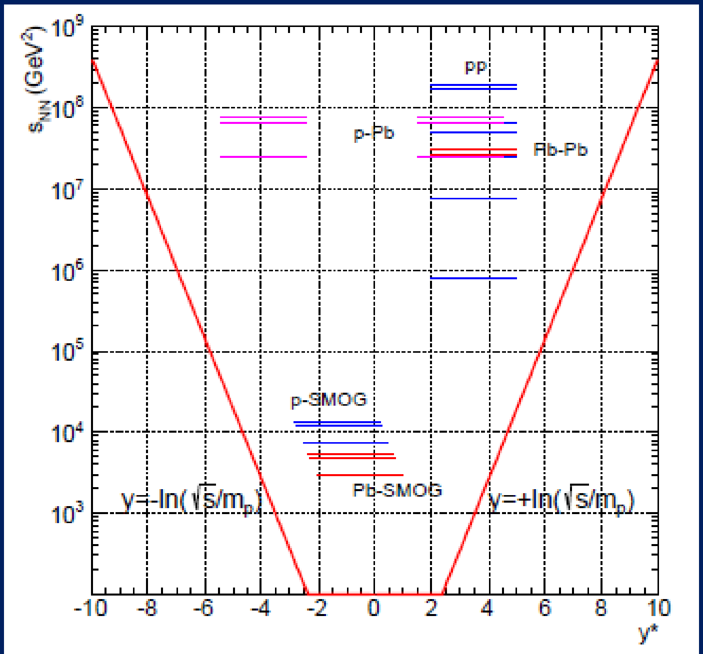
SMOG: System for Measuring Overlap with Gas

- Unique Fixed Target configuration at the LHC
- Inject noble gas (He, Ne, Ar) at ~2 x 10^{-7} mbar into the LHC vacuum around the interaction region.
- The gas spreads in the beam pipe around LHCb: collision vertices over ~1m (usable range)





kinematic acceptance

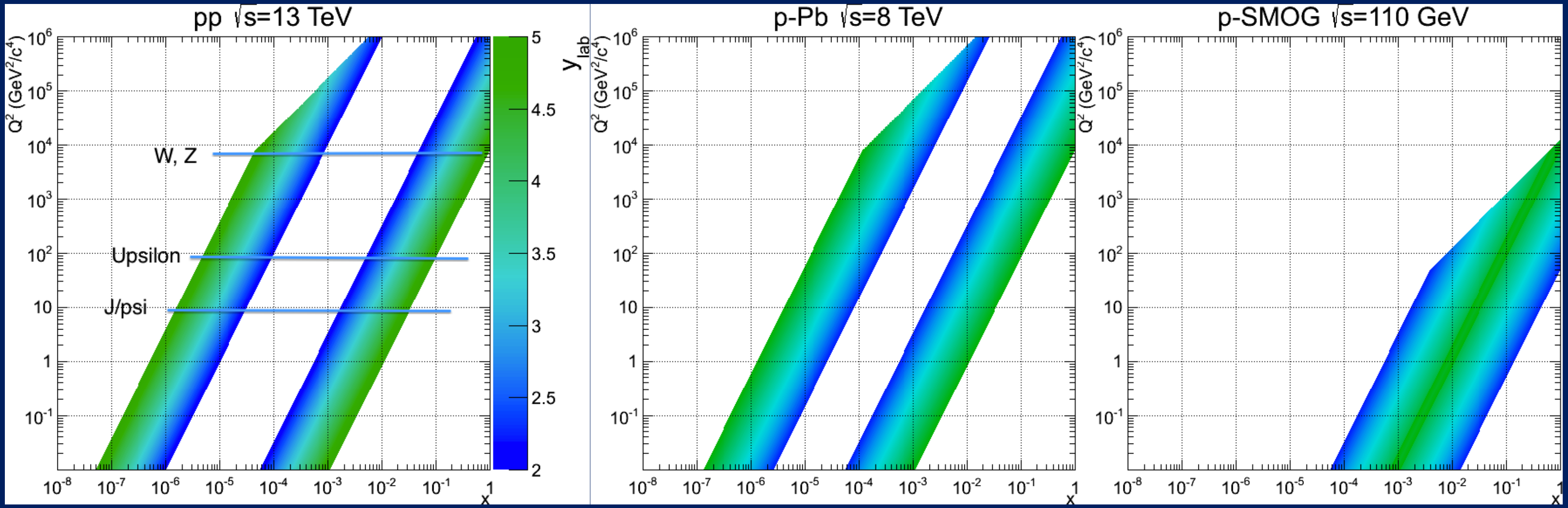


- Originally used to determine the luminosity, but since 2015 also to collect physics data.
- Allows to measure p-gas and Pb-gas interactions at between 69 - 110 GeV at central to backward rapidity (in nucleon-nucleon centre-of-mass system)

➢ Bridging the gap between the SPS (20 GeV) and RHIC (200 GeV) energy scales

Kinematic reach of LHCb

- Measurements at different √s and in different setups allows to investigate:
  - The nucleon structure of free (*pp*) versus bound nucleons (*p*A) inside the nucleus
    - PDFs can be probed via quarkonia, electroweak bosons, Drell-Yan measurements
    - Access to **very small x (colliding beam mode)** and **large x (fixed target mode)**



  - Dynamics of hadronization process
    - Measurement of total cross sections, energy flow measurement, particle multiplicities
  - Complementary probes of QCD
    - Ultra-peripheral collisions: exclusive ρ° production, exclusive photo-production of J/ψ…

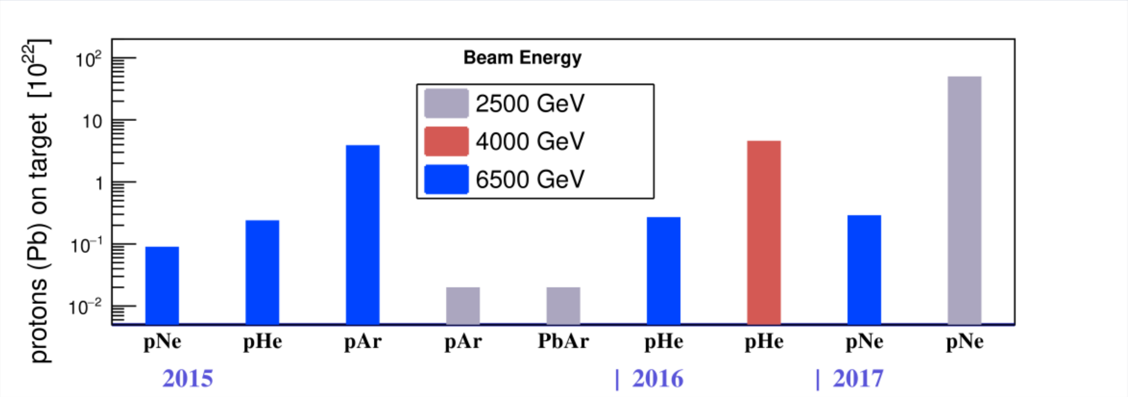
Data Samples acquired so far

- Colliding beam mode (*p*Pb and PbPb):
  - 1.1 nb $^{-1}$ *p*Pb, 0.5 nb $^{-1}$ Pb*p* at $\sqrt{s_{NN}}$ = 5.02 TeV (2013)
  - 13.6 nb $^{-1}$ *p*Pb, 20.8 nb $^{-1}$ Pb*p* at $\sqrt{s_{NN}}$ = 8.16 TeV (2016)
  - 10 μb $^{-1}$ PbPb at $\sqrt{s_{NN}}$ = 5.02 TeV (2015) and 0.4 μb $^{-1}$ XeXe (2017)

    → aim at factor 10-20 more luminosity for the 2018 PbPb run

- Fixed Target mode (SMOG):
  - $\sqrt{s_{NN}}$: 69 - 110 GeV

$$\int \mathcal{L}dt \sim 5\ \mathrm{nb}^{-1} \times \frac{pot}{10^{22}} \times \frac{p_{gas}}{2 \times 10^{-7}\mathrm{mbar}} \times \mathrm{Exp\_Efficiency}$$



Some recent LHCb results

- Charm production in fixed-target configuration
  - LHCb-PAPER-2018-023, arXiv:1810.07907
- Antiproton production in fixed-target configuration
  - LHCb-PAPER-2018-031, arXiv:1808.06127

- Heavy flavour production in pPb collisions:
  - D^0 at 5.02TeV: LHCb-PAPER-2017-015, JHEP (2017) 090
  - Λ_c^+ at 5.02TeV: LHCb-PAPER-2018-021, arXiv:1809.01404
  - J/ψ at 8.16TeV: LHCb-PAPER-2017-014, PLB774 (2017) 159
  - B^+, B^0, Λ_b^0 at 8.16TeV: LHCb-CONF-2018-004
  - $\Upsilon(nS)$ at 8.16TeV: LHCb-PAPER-2018-035, arXiv:1810.07655

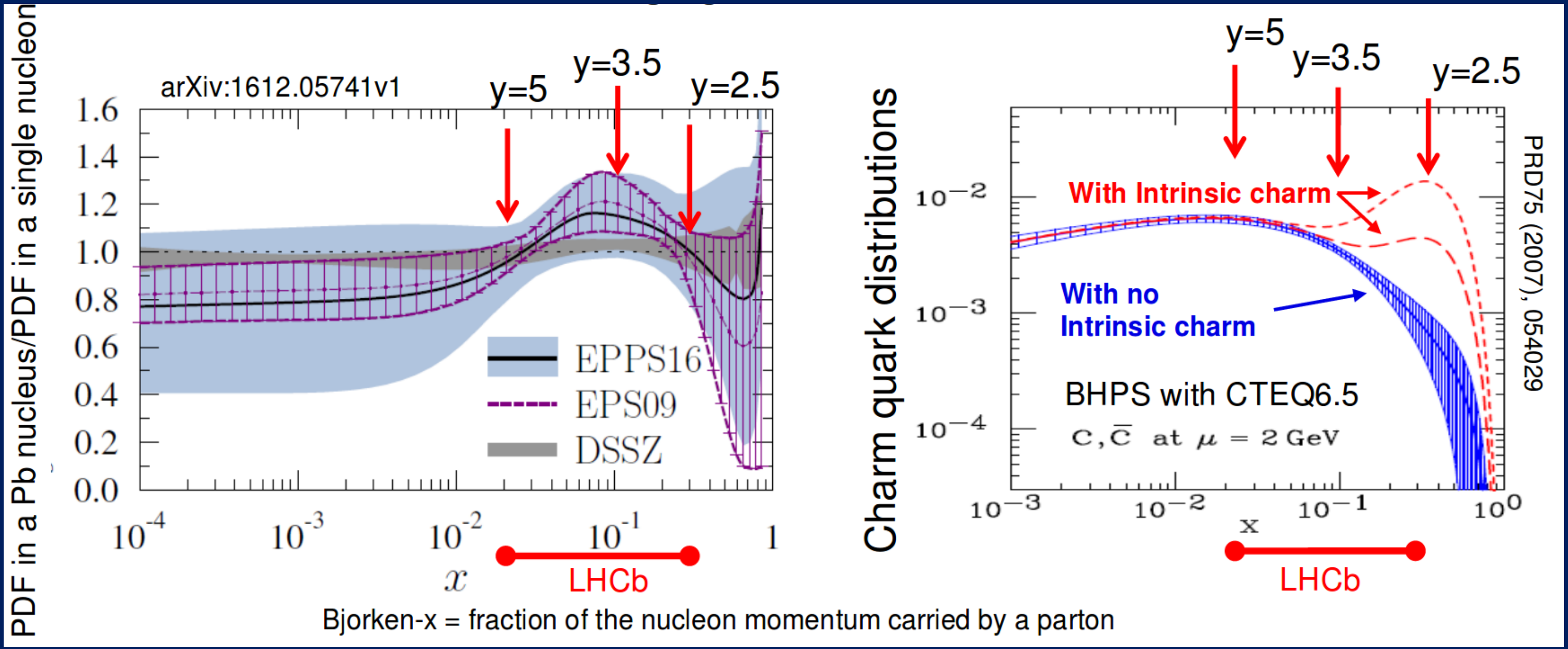
- Exclusive photonuclear J/ψ production in UPC of PbPb at 5TeV
  - LHCb-CONF-2018-003

Charm Production in *p*A collisions

- Motivation to perform fixed-target heavy ion physics at LHC:

Access to nPDF in **anti-shadowing region**

Access to **intrinsic charm content** in the nucleon



- Measurement of hidden and open charm production (*J/ψ*, *D°*…) down to low p_T
- Large rapidity coverage (~3 rapidity units) at large x_{Bj}

Charm production in pA collisions

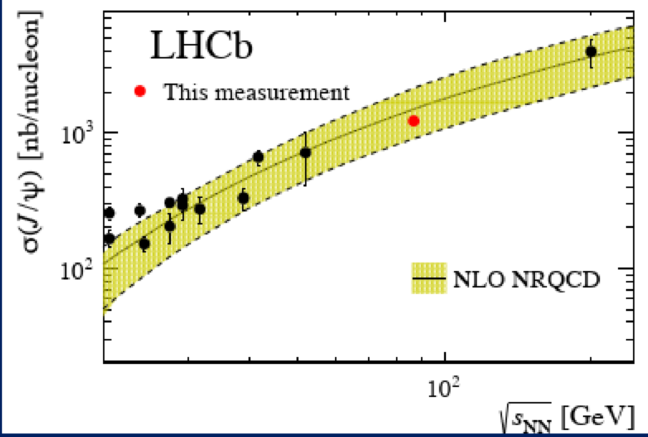
- J/ψ and D^0 inclusive cross section in pHe collisions $\sqrt{s_{NN}}$ = 86.6 GeV:
  - Cross section measured in $J/\psi \rightarrow \mu^+\mu^-$ and $D^0 \rightarrow K^- \pi^+$ decays

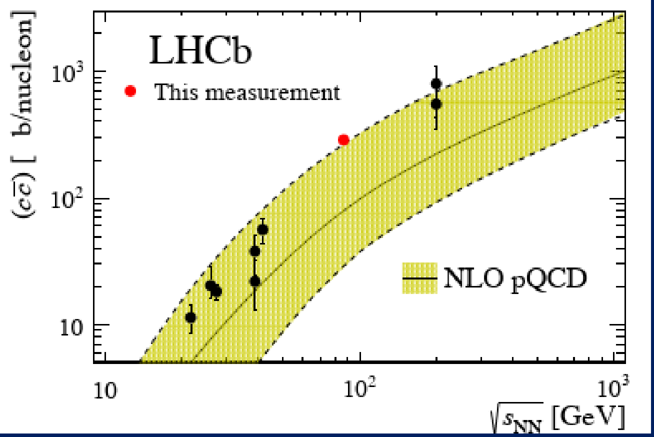
$$\sigma_{J/\psi}^{86.6\ \text{GeV}} = 1225.6 \pm 62.0(stat.) \pm 81.6(syst.)\ \text{nb/nucleon}$$
$$\sigma_{D^0}^{86.6\ \text{GeV}} = 156.0 \pm 4.6(stat.) \pm 12.3(syst.)\ \mu\text{b/nucleon}$$

LHCb-PAPER-2018-023
arXiv:1810.07907

- Scaling the D^0 cross-section with the global fragmentation ratio $f(c \rightarrow D^0)$ = 0.542±0.024, the $c\bar{c}$ production cross section can be obtained:

$$\sigma_{c\bar{c}}^{86.6\ \text{GeV}} = 287.8 \pm 8.5(stat.) \pm 25.7(syst.)\ \mu\text{b/nucleon}$$



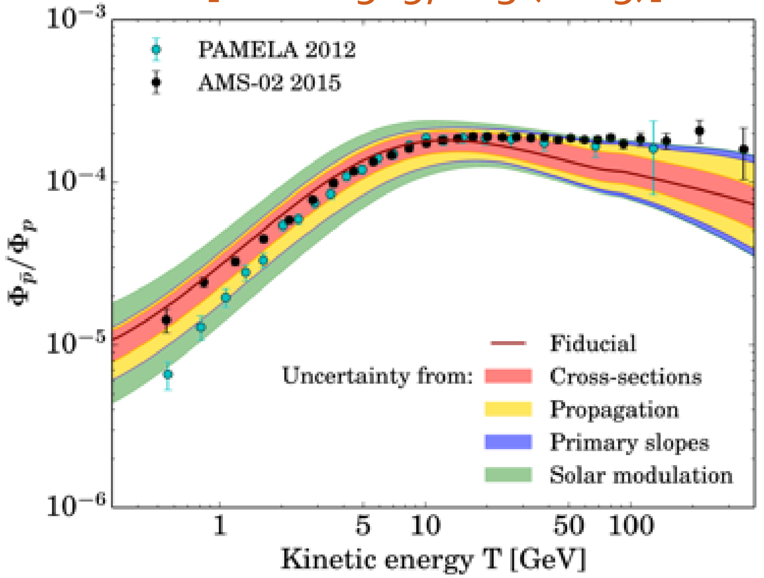


➢ LHCb results in good agreement with NLO NRQCD fit (J/ψ, left) and NLO pQCD predictions ($c\bar{c}$, right) and other measurements

Measurements of light flavor hadrons

- Antiproton/proton ratio known with great precision in cosmic rays
  - AMS 2 result: [PRL 117, 091103 (2016)]
  - PAMELA result [JETP Letters 96 (2013) 621]
- Hint for a possible excess of the $\bar{p}/p$ ratio at high energies with less energy dependence than expected
- The prediction for $\bar{p}/p$ ratio from spallation of primary cosmic rays on interstellar medium (H and He) is limited by uncertainties on $\bar{p}$-production cross-sections, particularly for p-He
- Predictions from soft QCD models vary within a factor 2

[JCAP 1509, 023 (2015)]



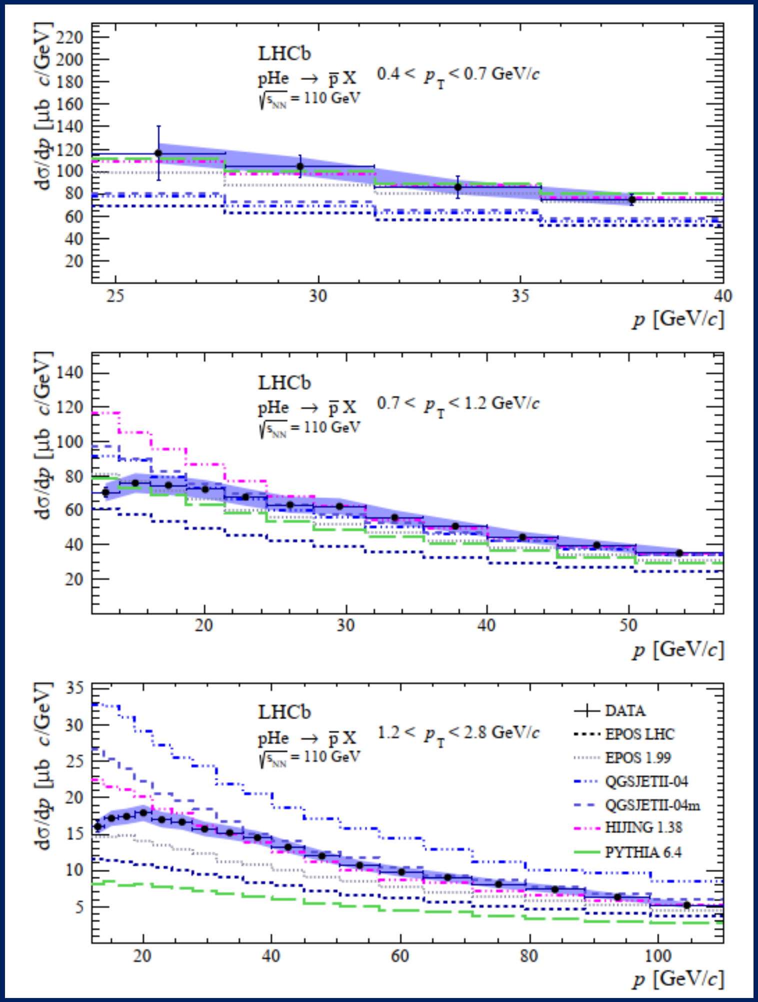
➢ The energy scale of LHCb in fixed target mode is well suited to measure the p-He cross-section

$\bar{p}$ - production cross-section

- Data collected in 2016 in pHe collisions at $\sqrt{s_{NN}}$ = 110 GeV

  [LHCb-PAPER-2018-031 , arXiv: 1808.06127]

- Measurement compared with
  - EPOS LHC, EPOS 1.99, QGSJET-II, QGSJETII-04m, Hijing, PYTHIA 6.4.
  - ICRC '17: difference summary by T. Pierog



- Uncertainties smaller than model spread

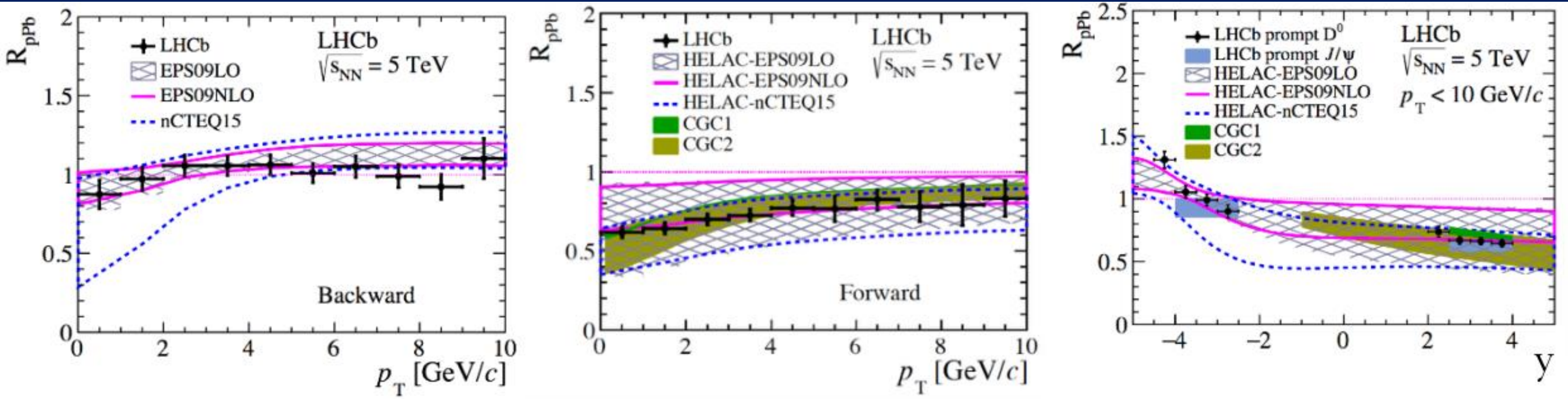
- EPOS LHC tuned on LHC collider data underestimates *p*-production

- Unique and precise:
  - decisive contribution to shrink background
  - uncertainties in dark matter searches in space

Prompt D^0 modification factor

- D^0 cross-section and modification factor in pPb at $\sqrt{s}$ = 5.02 TeV
- D^0 fully reconstructed through $D^0 \to K^- \pi^+$ decays

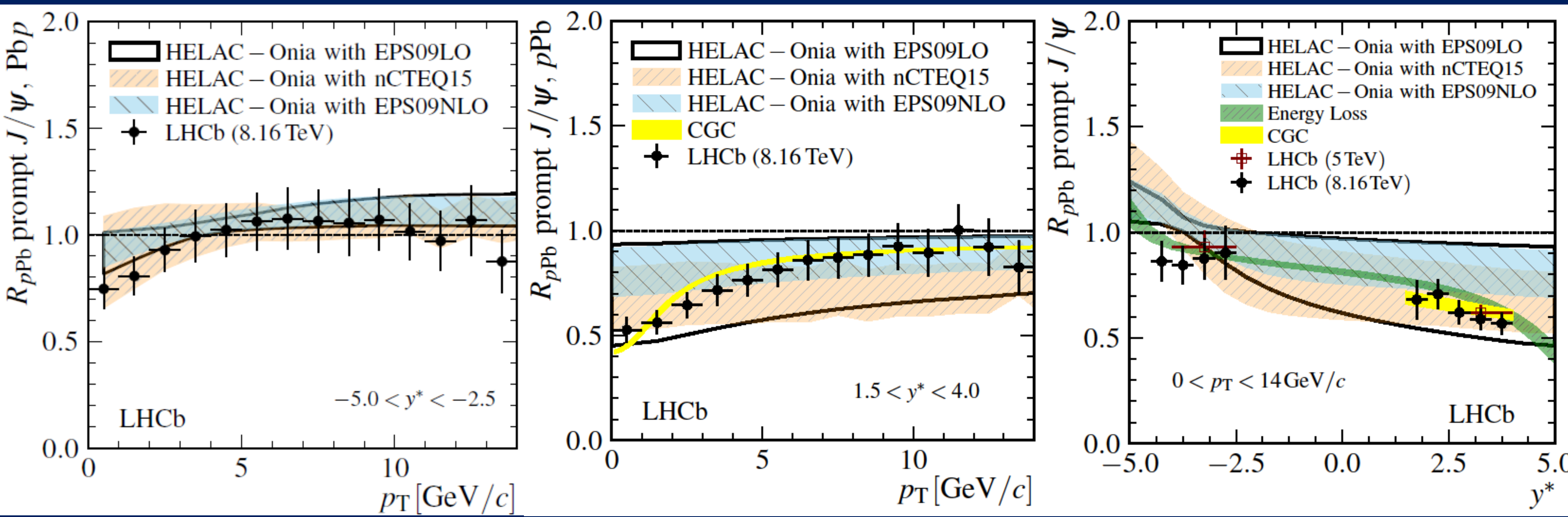
[JHEP 2017 090]



- R_{pPb} suppressed in forward region (~30%), no suppression in backward region, hint of small excess at large at backward rapidity (y*<-4)
- Measurements consistent with predictions using nPDFs or CGC framework
  [EPJC 77 (2017) 1, Comp. Phys. Com. 198 (2016) 238, Comp. Phys. Com. 184 (2013) 2562]
- At forward rapidity measurement also consistent with CGC models
  [Phys. Rev. D91 (2015) 114005, arXiv:1706.06728]

Prompt J/ψ modification factor

[PLB774 (2017) 159]



- In fwd region: up to 50% suppression at low p_T, converging to unity at high p_T
- In bwd region: R_{pPb} closer to unity, intriguing low values at low p_T
- Overall agreement with models good, but some have large uncertainties
- Results are compatible with LHCb results at 5 TeV [JHEP 02 (2014) 072]

- **Result on *Ψ(2S)* modification factor is coming soon**

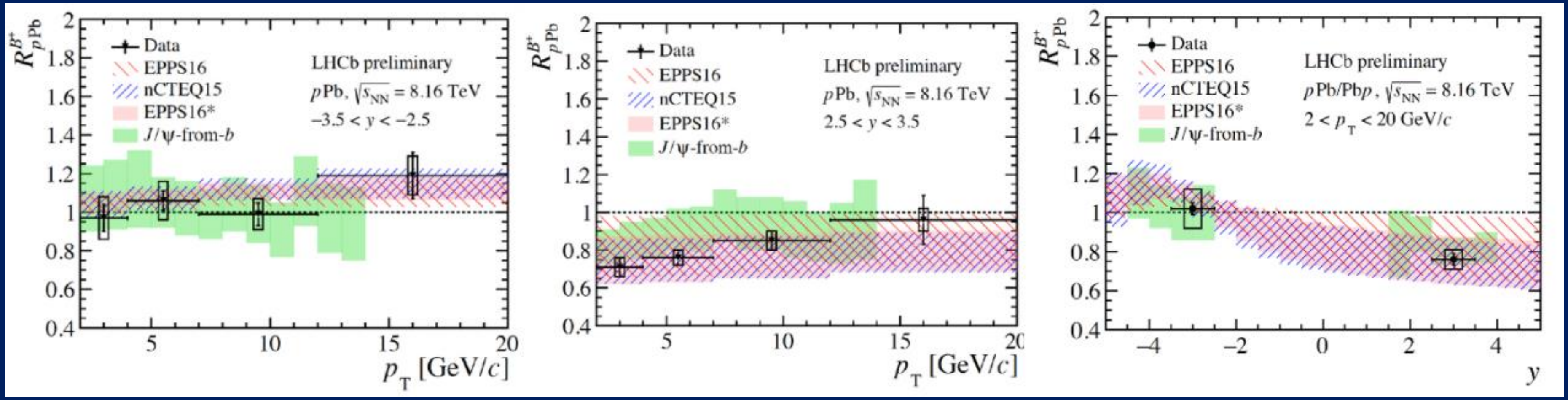
b – hadron production in pPb

Exclusive decay modes:

$B^+ \rightarrow J/\psi\, K^+$, $B^+ \rightarrow D^o \pi^+$, $B^o \rightarrow D^- \pi^+$, $\Lambda_b{}^o \rightarrow \Lambda_c{}^+ \pi^-$

B^+ nuclear modification factors:

LHCb-CONF-2018-004



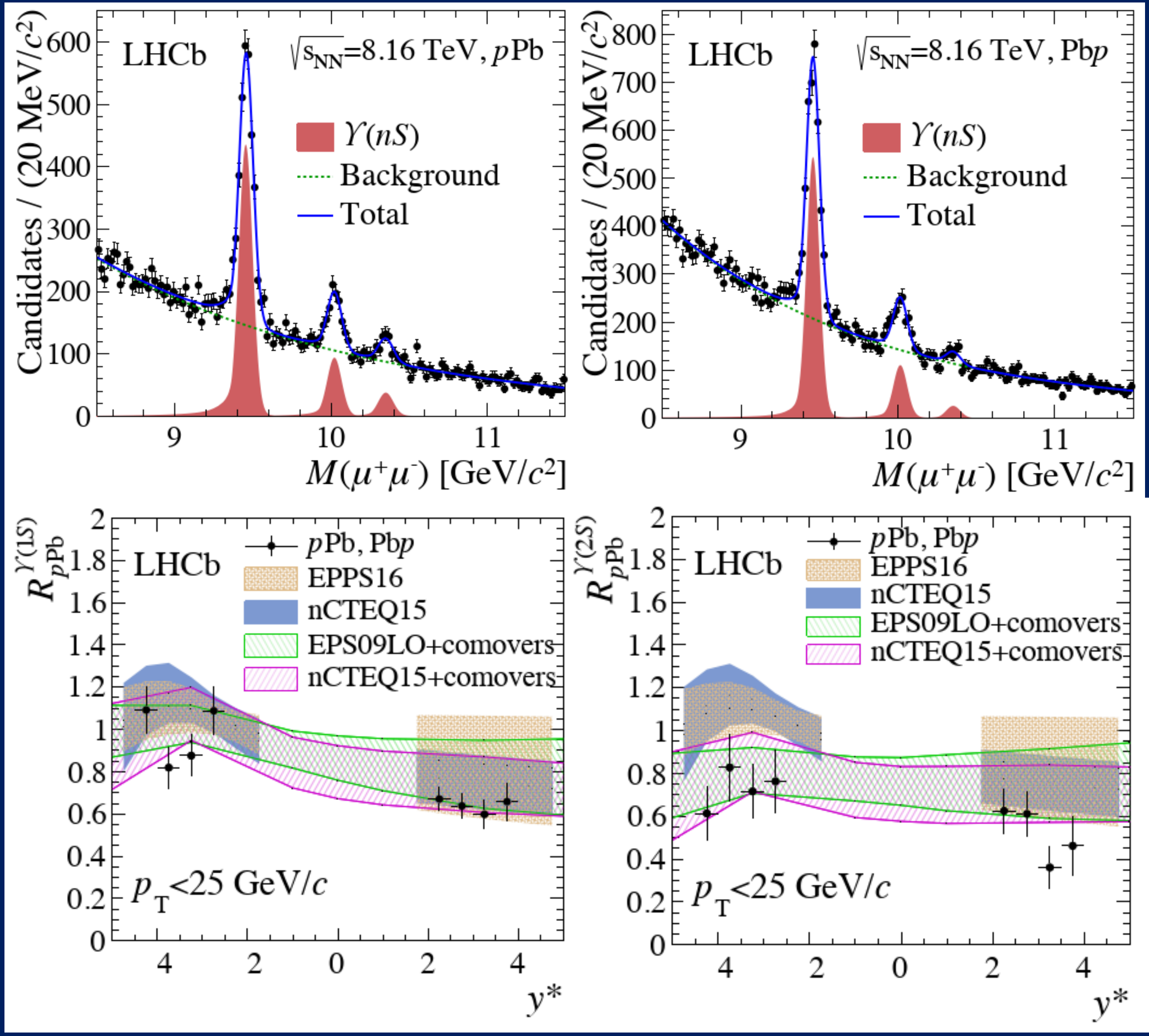
- Pattern consistent with R_{pA} of D^o mesons
- Significant suppression (≈ 25%) in fwd rapidity, suppression decreases at large p_T
- Consistent with unity at backward rapidity
- Measurements in good agreement with J/ψ-from-b decay data and calculations using nPDF sets [JHEP 04 (2009) 065, EPJ C77 (2017) 1, CPC. 198 (2016) 238]

Υ(nS) production in pPb

[arXiv : 181.07655]

- *Υ(nS)* suppression observed in PbPb and pPb/Pbp by CMS and ALICE at low-p_T

- LHCb observed clear *Υ(3S)* signal in both forward and backward rapidity



- *Υ(1S)* fwd suppressed by ~30%
- *Υ(1S)* bwd compatible with 1 within nPDF uncertainties
- *Υ(2S)* additional suppression confirmed

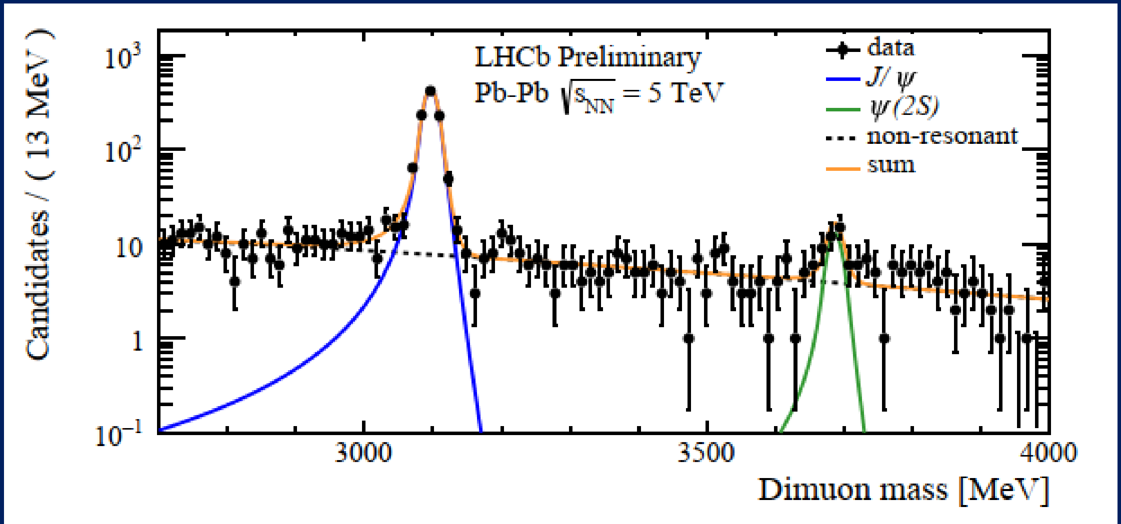
- Models:
  - EPPS16: Eur. Phys. J. C (2017) 77 163
  - EPS09: JHEP 04 (2009) 065
  - nCTEQ15: Phys.Rev.D93 (2016) 085037
  - Comovers: Phys. Lett. B749 (2015) 98

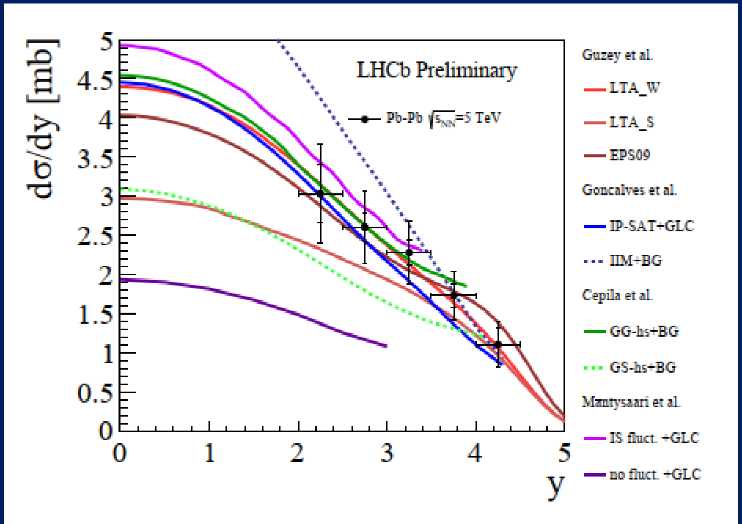
J/ψ photo-production in UPC

- Interaction between the electromagnetic field of the ions
  $\longrightarrow$ Coherent J/ψ photo-production, sensitive to nPDF, …
- Cross section for coherent J/ψ production:

$$\sigma = 5.3 \pm 0.2\ (stat) \pm 0.5\ (syst) \pm 0.7\ (lumi)\ mb$$

LHCb-CONF-2018-003





- Phenomenological models:
  PRC 97 024901 (2018), PRD 96 094027 (2017), PRC 93 055206 (2016), PLB 772 (2017) 832

➢ Measurement of $\psi(2S)$ / J/ψ ratio planned with 2018 PbPb data

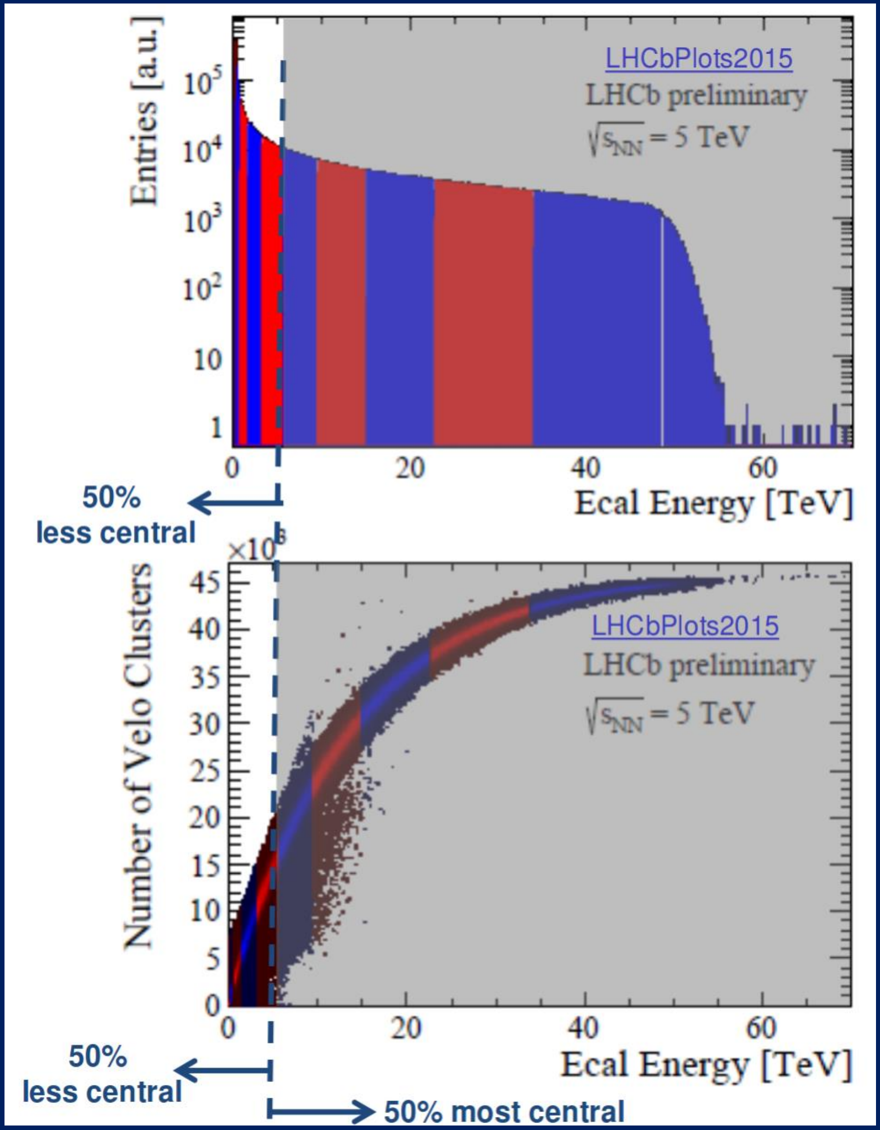
Centrality of PbPb collisions

- LHCb centrality reach
  - Measured by the calorimeter
  - Detector limitation:

    Saturation in the Vertex Locator and the Tracking System for the most central PbPb collisions

- Current LHCb tracking algorithm efficient to up to 50% of centrality

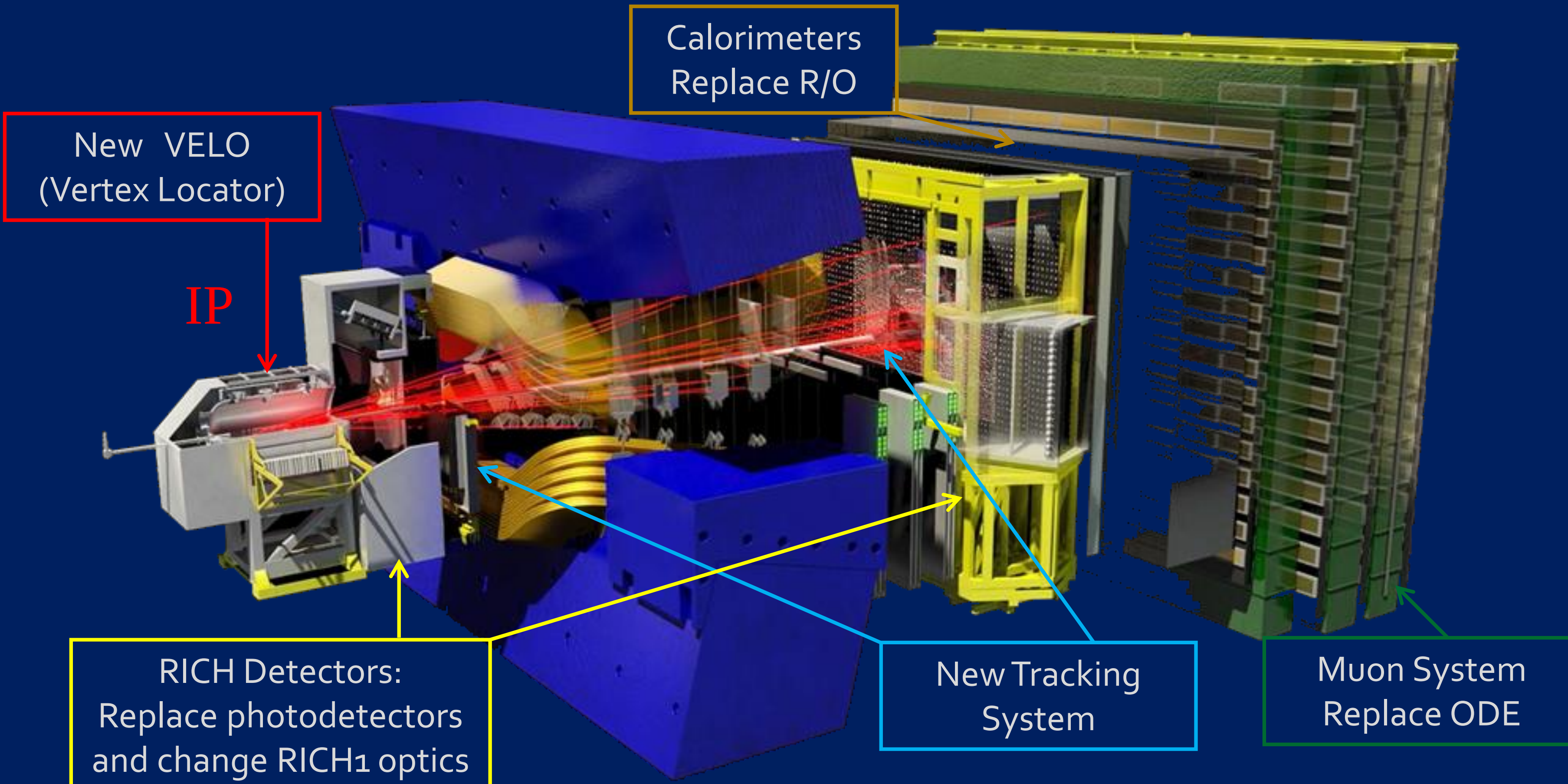
- Present limit for studies of nuclear PbPb interactions



LHCb Detector Upgrade I

- Better utilise LHC capabilities: collect > 50 fb^{-1} of *pp* data
- upgrade ALL sub-systems to 40 MHz FE-electronics; fully software trigger
- adapt sub-systems to increased occupancies due to 5 x higher luminosity

→ Go from $4 \times 10^{32}/cm^2/s$ to $2 \times 10^{33}/cm^2/s$ [CERN-LHCC-2012-007]

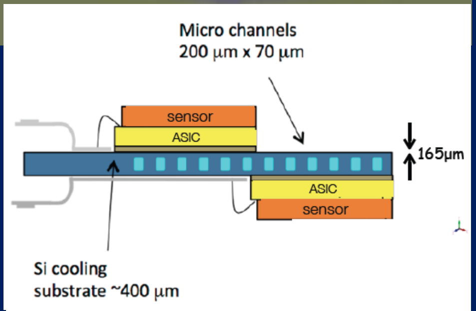


VELO upgrade

[CERN-LHCC-2013-021]

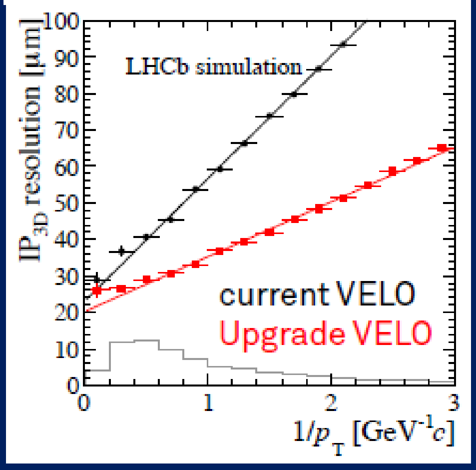
Upgrade challenge:

- withstand increased radiation
- handle high data volume
- improve current performance
  - lower materiel budget
  - enlarge acceptance



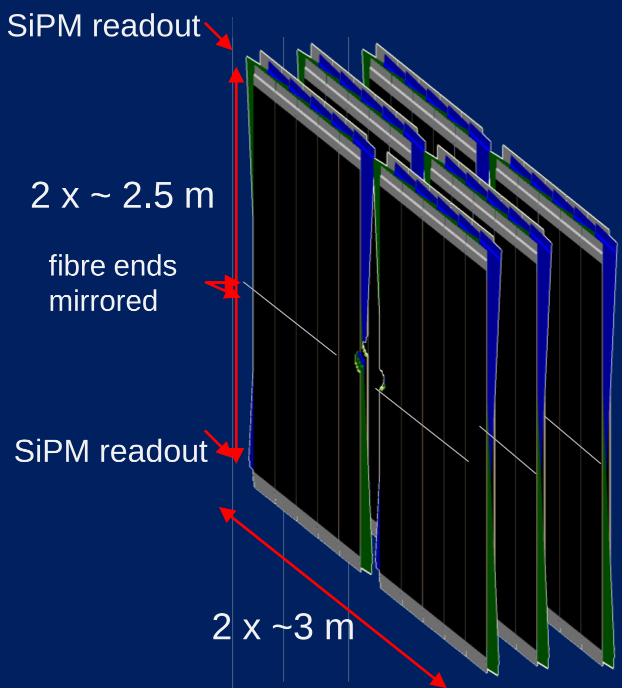
Technical choices :

- 55x55 μm² pixel sensors with micro channel CO_2 cooling
- 40 MHz VELOPIX
- replace RF-foil between detector and beam vacuum
  - reduce thickness from 300 μm ⟶ ≤ 250 μm
- move closer to the beam
  - reduce inner aperture from 5.5 mm ⟶ 3.5 mm
- ➢ better IP resolution due to reduced material budget
  - Figure: 3D IP resolution at $L = 2{\cdot}10^{33}\ \mathrm{cm^{-2}s^{-1}}$



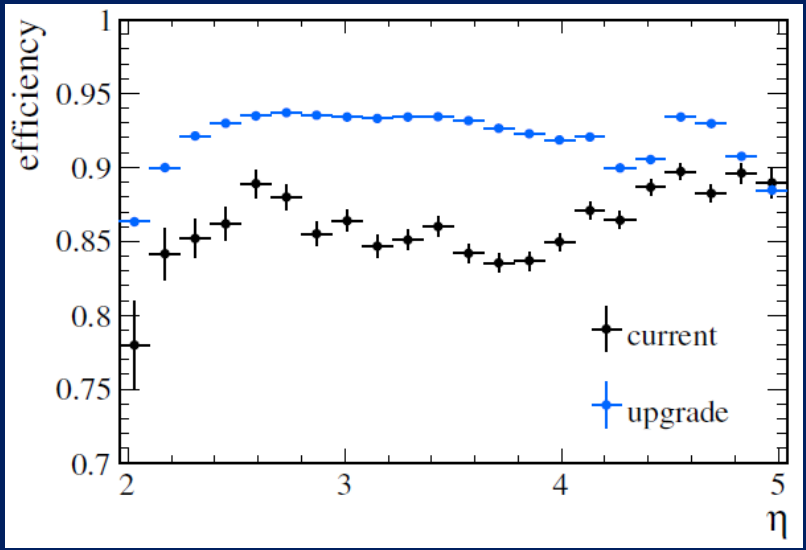
T-stations upgrade: Fibre Tracker

- 3 stations of X-U-V-X (±5° stereo angle) scintillating fibre planes
- every plane made of 5 layers of Ø=250 µm fibres, 2.5 m long
- x-position resolution of 50 – 75 µm;



R/O by dedicated
128 ch. 40 MHz
PACIFIC chip

Efficiency for $B_s \rightarrow \Phi\Phi$ events:
(under upgrade conditions)



→ improved tracking performance at upgrade luminosity with Fibre Tracker

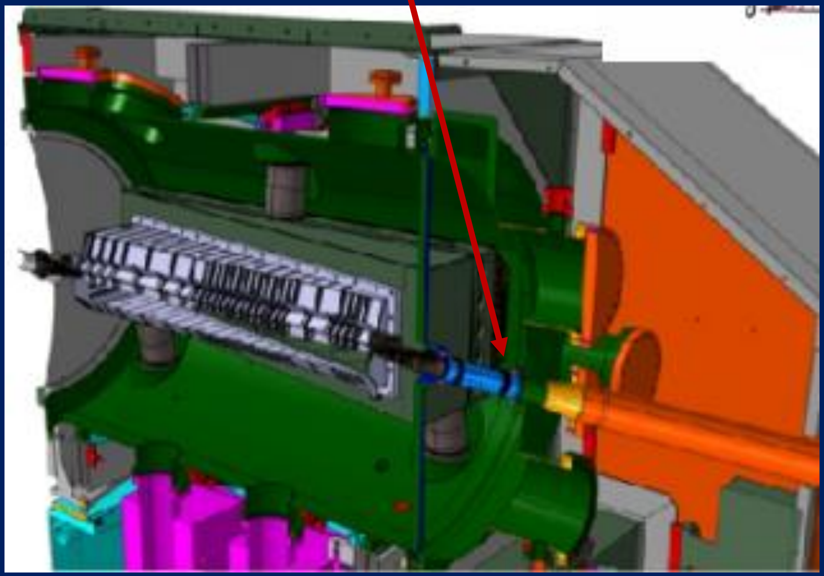
Benefits of SciFi concept:

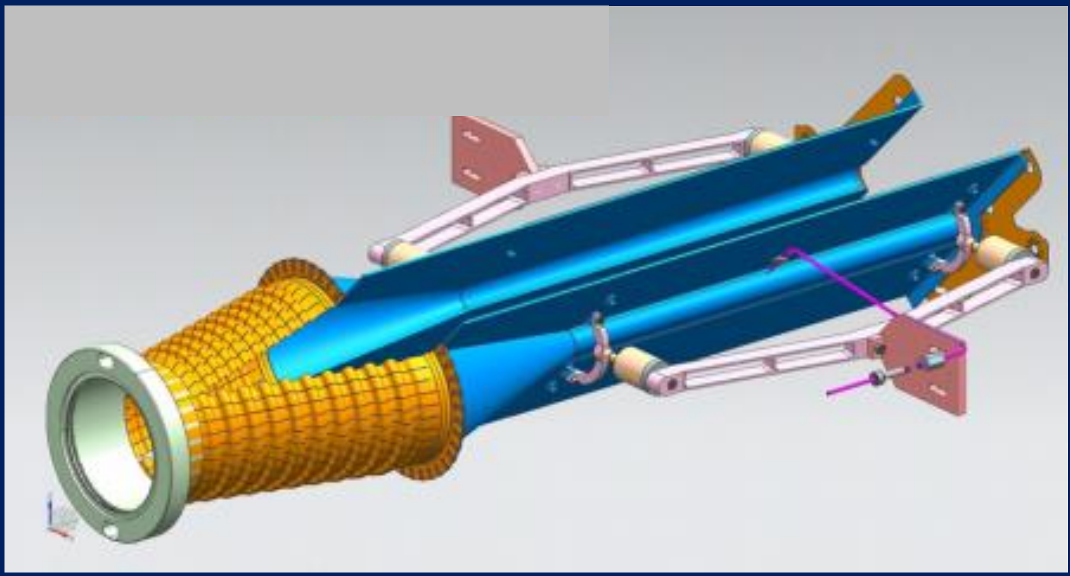
- a single technology with uniform material budget
- SiPM + infrastructure outside acceptance
- fast pattern recognition for HLT

[CERN-LHCC-2014-001]

Upgrade of the SMOG system

- Current LHCb fixed-target setup is planned to be upgraded for Run 3
- Insert a storage cell, placed upstream of the VELO during LS2





- Injection of noble gases but also H_2 , D_2 as references
- 10–100 times larger instantaneous luminosity per unit length

- Other upgrades (crystal target, polarised target, wire target) under discussion

Fixed Target scenario for Run 3

Planned data-sets for Run 3:

- Extended gas choice : pH_2 , pD_2 , pO_2 at 115 GeV
- Large dataset of *p*Ar foreseen at 115 GeV : ~ 10/pb
- PbAr at 72 GeV ~ 5/nb ; *p*Ar at 72 GeV ~ 1/pb

Physics reach:

	Current SMOG result pHe@86 GeV	SMOG largest sample pNe@68 GeV	SMOG2 example pAr@115 GeV
Int. Lumi.	7.6/nb	~ 100/nb	~ 10/pb
syst. error on J/ψ x-sec.	7%	6 - 7%	3 - 4 %
J/ψ yield	400	15k	3.5M
D^0 yield	2000	100k	35M
Λ_c yield	20	1k	350k
ψ' yield	negl.	150	35k
$\Upsilon(1S)$ yield	negl.	10	3k
DY $\mu^+\mu^-$ yield ($5 < M < 9$ GeV)	negl.	10	3k

Comments:

- The above list is far from being exhaustive;
- extrapolations are crude estimates, just to provide figures of merit;
- smaller systematic uncertainties with SMOG2 are expected from the reduction of the dominant uncertainty on the luminosity (6%) for SMOG data .

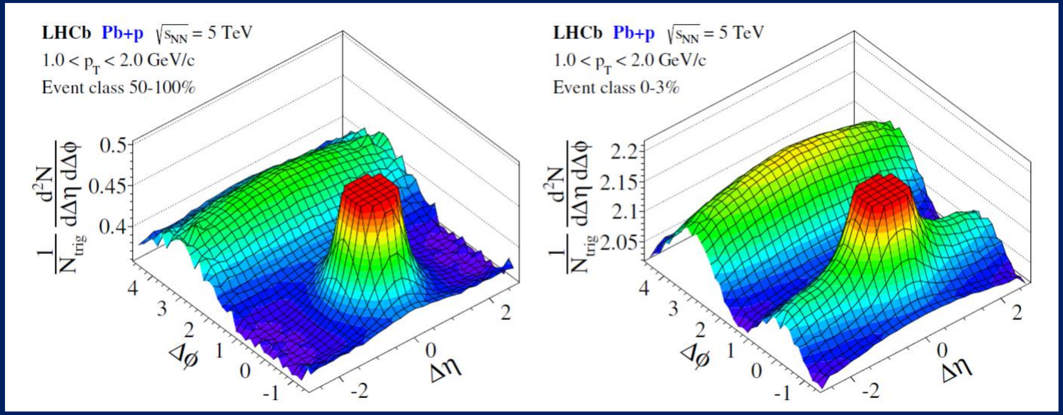
More possibilities with SMOG

UPC physics :

- Measure cross-section for photo-produced *J/ψ* in Fix-Target mode
- ~ 300 pb^{-1} in *p*Ar can complement studies ongoing by LHCb in collision mode (*pp*, *p*Pb, PbPb) [JHEP 1509 (2015) 087 ; arXiv:1709.09044, arXiv:1802.04713]

Potential to study elliptic flow over 3 units of pseudorapidity with full instrumentation at unique energy scale

- Di-hadron correlation studies already demonstrated by LHCb in pPb



- no studies in Fix Target mode performed yet
- yields with SMOG2 could allow flow studies with charmed particles

Possibilities with more *p*Pb data

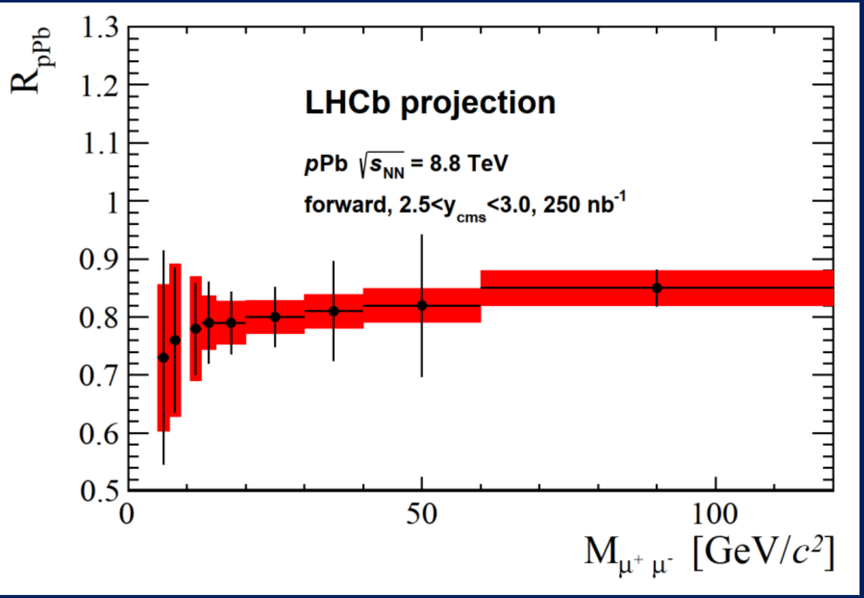
- LHCb looks forward to *p*Pb collisions in Run 3 and Run 4 at $\sqrt{s_{NN}}$ = 8.8 TeV with integrated luminosities of 250 nb^{-1} in each beam configuration.
- Precise measurements at low-Q^2 and low-x_{Bj} : crucial to constrain the nPDFs in the low-x regime.

Drell-Yan measurement in pPb

- Clean indirect probe of the gluon nPDF at small x_{Bj}
- Reference measurement to clarify the dominant source of nuclear modification observed for heavy-flavour production

- For the Drell-Yan measurement, the precision of the VELO and the forward acceptance allow to control the background from semi-leptonic heavy-flavour decays.

[LHCb-CONF-2018-005]



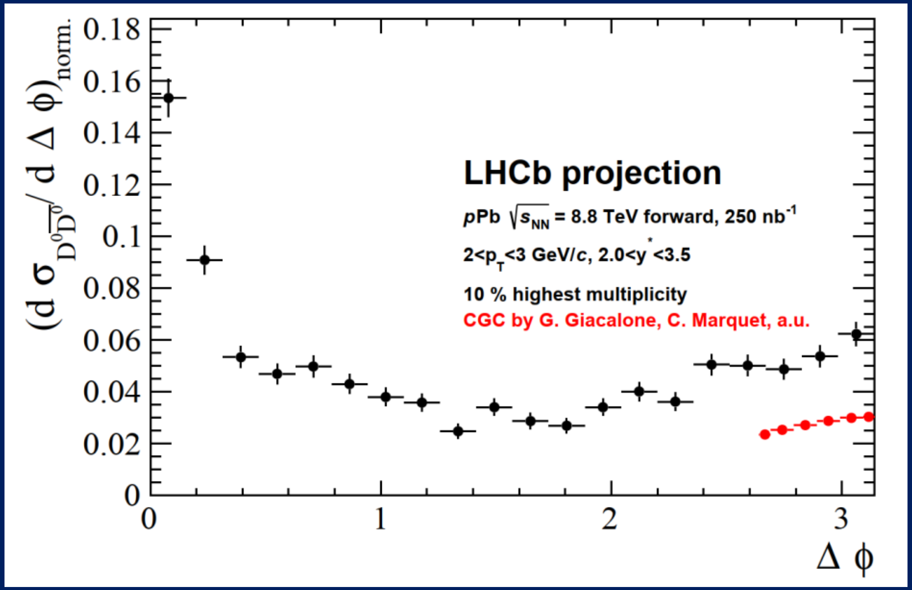
Possibilities with more pPb data

- $D^0\overline{D^0}$ correlation measurement
  - disentangle the contributions from different production mechanisms through the angular distribution
  - angular correlation is sensitive to intrinsic transverse momentum, which may be related to the saturation scale.
  - crucial piece of information for charm and beauty thermalisation within the QGP

- Azimuthal angular correlation $\Delta\phi$ between D^0 and $\bar{D}^0$ in $D^0 \to K^- \pi^+$ decays

$$\frac{d\sigma/d\Delta\phi}{\sigma} = N_{D\bar{D}}(\Delta\phi)/N_{D\bar{D}}(tot)$$

[LHCb-CONF-2018-005]

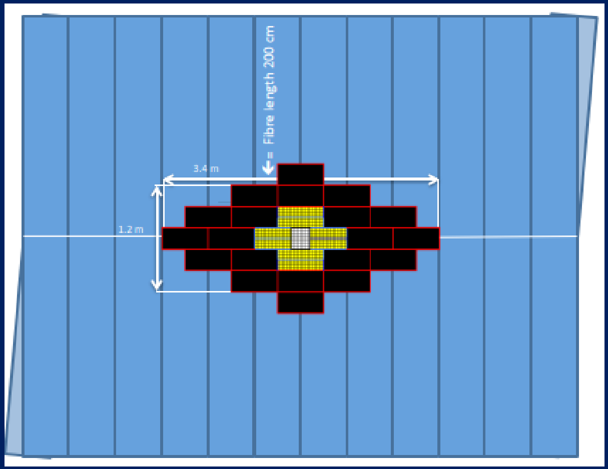


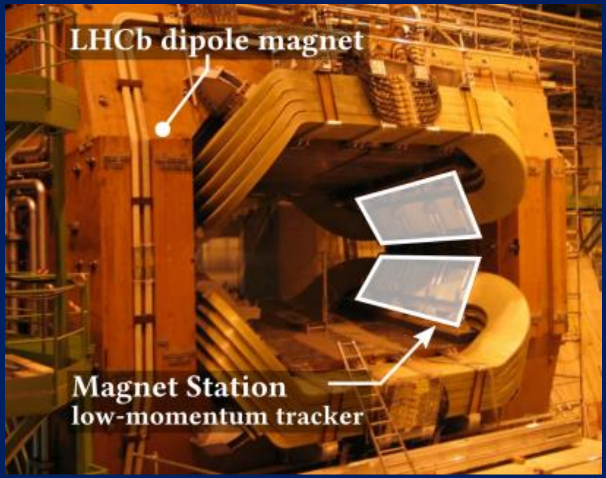
Further LHCb upgrades (Ib &II)

- To fully exploit the flavour physics potential of the HL-LHC, LHCb proposes an upgrade II in LS4. Target Luminosity: > 300 fb^{-1} (*pp*) at 1-2 x 10^{34} /cm^2/s [CERN-LHCC-2017-003]
- The upgrade II detector will have improved granularity and resolutions
- ➢ This offers the opportunity of a general purpose Heavy Ion experiment suited also for the most central PbPb collisions at forward rapidity.

- The main limitation will come from the SciFi Tracker, which would need to be upgraded: add Si-trackers (with two different granularities)

Detector	Maximum occupancy in most central PbPb at $\sqrt{s_{NN}} = 5$ TeV
VELO (Upgrade I)	4 %
VELO upgrade (Upgrade II)	1 %
SciFi (Upgrade II)	25%





Smaller upgrades are planned already for LS3 :

Improve tracking acceptance for low momentum particles

- Install tracking stations on the dipole magnet internal sides

  e.g. $D^{*+} \rightarrow D\, \pi_s^+$, 40% extra slow pions

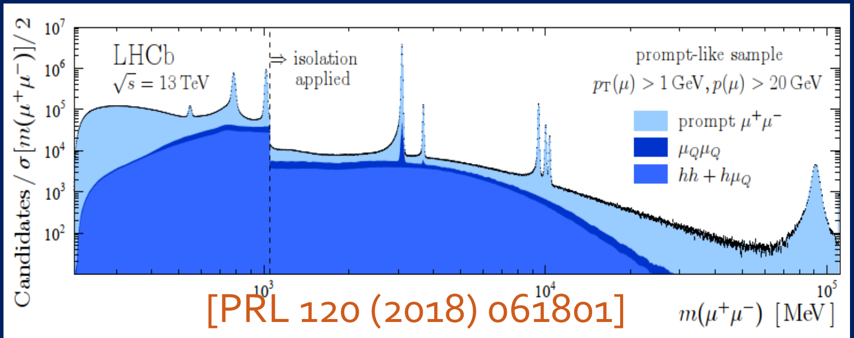
Heavy ion physics possibilities beyond LS4

- At upgrade II luminosities, the number of tracks in *pp* collisions will be close to that observed in central Pb-Pb collisions (dedicated studies are needed).

[CERN-LHCC-2017-027]

- **Quarkonium and open heavy flavour:**
  - *ψ(2S)* yield at low p_T remain statistically limited after Run 3+4, with low signal over noise ratio
  - P -wave states like χ_c states are challenging and particularly interesting to study colour charges
    - ➢ Main limitation for LHCb: integrated luminosity

- **Low-mass di-leptons and photons**
  - ρ^0 meson sensitive to chiral symmetry restoration in the QGP
  - thermal radiation in the intermediate mass region
  - LHCb Upgrade II has the potential to measure precisely di-lepton production in the di-muon channel at the LHC.
  - VELO detector allows for suppression of heavy flavour background



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- **Drell-Yan, $c\bar{c}$ and $b\bar{b}$ in *p*A or AA collisions in view of nuclear PDFs and saturation**
  - Precise low mass Drell-Yan (below masses of 10 GeV/c²) or low-p_T below 10 GeV/c² photon measurements are world-leading unique opportunities

Summary and Conclusions

- The LHCb detector has unique capabilities for heavy flavour measurements at LHC in collider and fixed-target modes

- The ongoing and proposed future upgrades of the detector will enhance the centrality reach of the LHCb experiment:
  - Upgrade 1: potentially up to 20-30% centrality (to be studied carefully)
  - Upgrade 2: intention to reach full centrality in PbPb (design phase is ongoing)

➢ The LHCb Upgrade II offers the opportunity of a general purpose heavy-ion experiment suited from *p*A up to most central AA collisions at forward rapidity.

- The SMOG2 proposal opens great possibilities for a substantial increase of data size and choice of gas species with respect to the current SMOG program already for Run3.

- Other upgrades for Fixed Target physics are under discussion:
  crystal target, polarised gas target, wire target