LHCb Overview

June 24, 2019

Burkhard Schmidt (CERN)
on behalf of the LHCb collaboration

Outline

- Introduction
  - The LHCb Detector and its Fixed Target system
  - Kinematic reach and data samples
- Recent heavy-ion results from LHCb
  - Results from the Fixed Target program
  - Heavy-flavor production in *p*Pb collisions
  - Photo-production in ultra-peripheral PbPb collisions
- LHCb detector upgrade
  - Potential of the upgraded detector and its Fixed Target system
- Summary and Conclusions

LHCb Detector

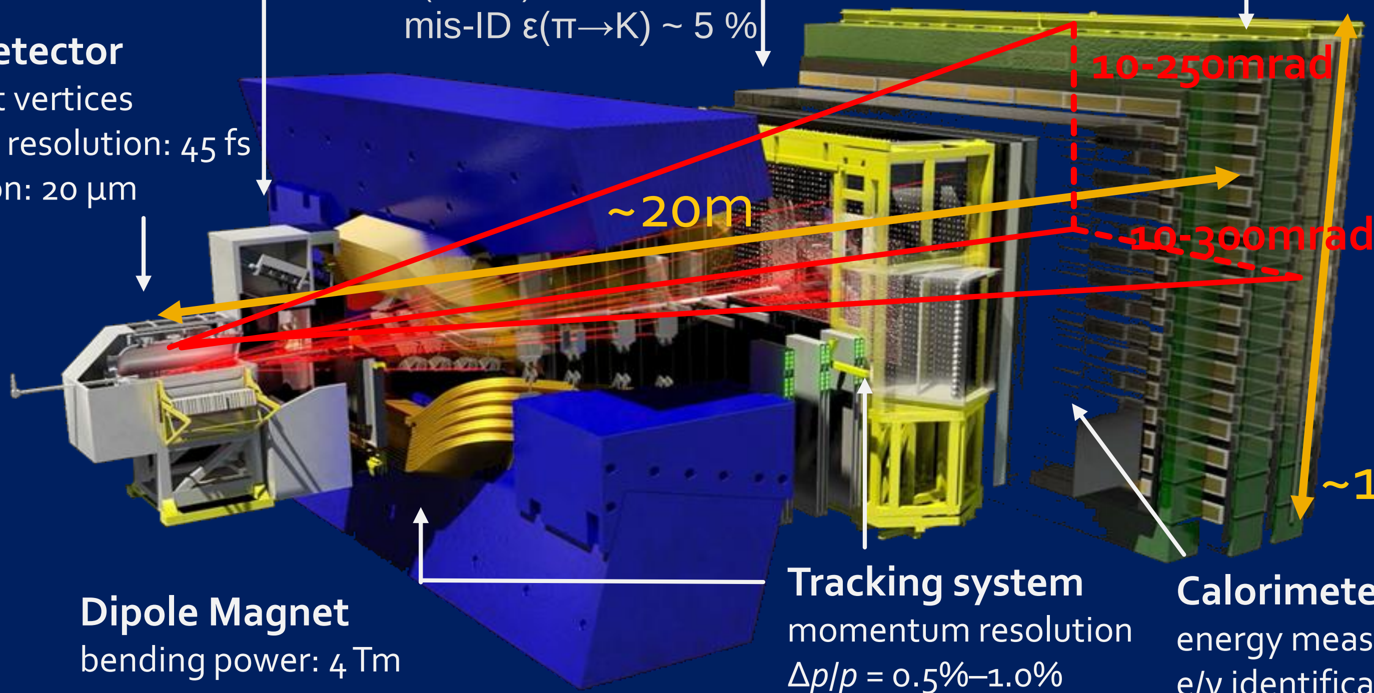
- Single arm spectrometer in the forward direction
  - designed for heavy flavour physics, but capable to address many other topics …
  - fully instrumented in $2 < y < 5$ with unique forward kinematics
  - Flexible trigger down to very low p_T

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

RICH detectors
K/π/p separation
$\varepsilon(K\rightarrow K) \sim 95$ %,
mis-ID $\varepsilon(\pi\rightarrow K) \sim 5$ %

Muon system
μ identification $\varepsilon(\mu\rightarrow\mu) \sim 97$ %,
mis-ID $\varepsilon(\pi\rightarrow\mu) \sim 1$-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)

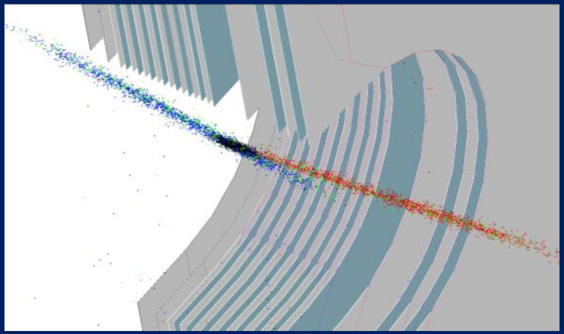
Calorimeters
energy measurement
e/γ identification
$\Delta E/E = 1\,\% \oplus 10\,\%/\sqrt{E}$ (GeV)

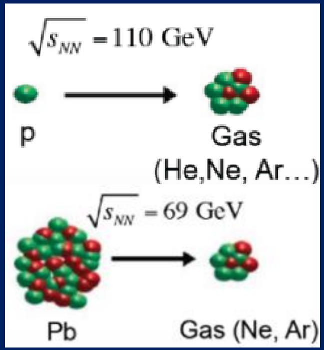
Fixed Target Physics with LHCb

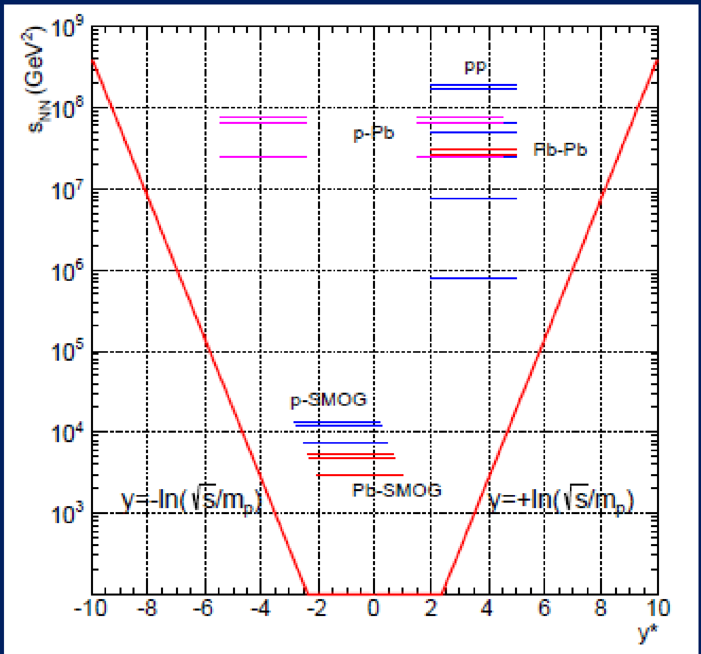
SMOG: System for Measuring Overlap with Gas

- 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





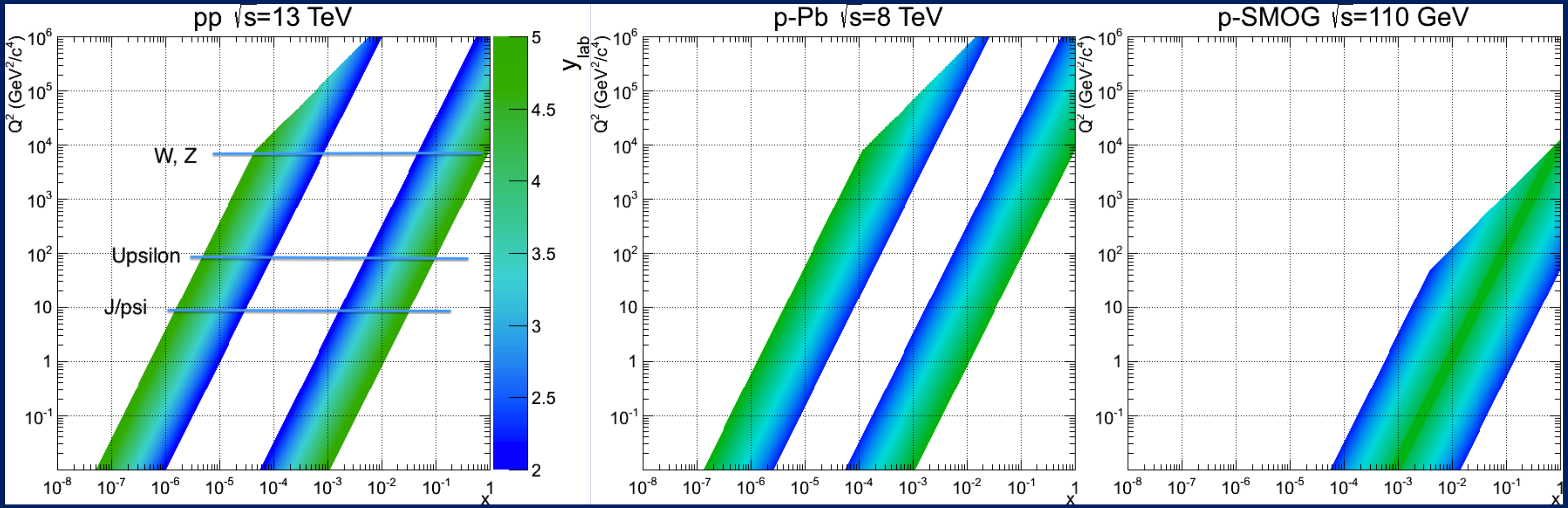


- Originally used to determine the luminosity, but since 2015 also to collect physics data.
- Allows to measure *p*-gas and Pb-gas interactions at $\sqrt{s_{NN}}$ between 69 - 110 GeV at central to backward rapidity (in nucleon-nucleon centre-of-mass system)

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



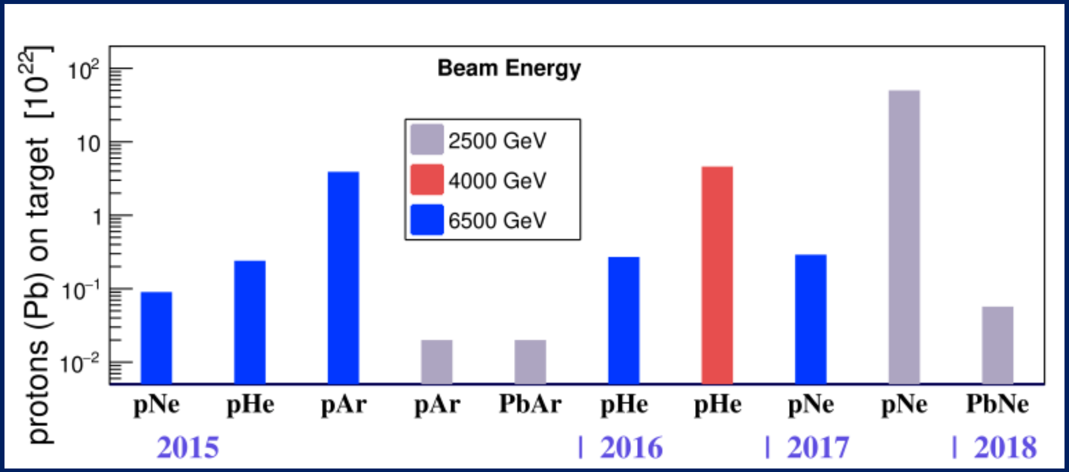
  - Dynamics of hadronization process
    - Measurement of total cross sections, energy flow measurement, particle multiplicities
  - Complementary probes of QCD
    - Ultra-peripheral collisions: exclusive ρ^0 production, exclusive photo-production of J/ψ…

Data Samples acquired so far

- Colliding beam mode:
  - *pp* from 2010 to 2018 at $\sqrt{s_{NN}}$ = 2.76, 5, 7, 8 and 13 TeV : $L_{int} \approx 9\ fb^{-1}$
  - *p*Pb & Pb*p* at $\sqrt{s_{NN}}$ = 5 TeV (2013) & 8.16 TeV (2016): $L_{int} \approx 2\ nb^{-1}$ & $34\ nb^{-1}$
  - PbPb in 2015 & 2018 at $\sqrt{s_{NN}}$ = 5 TeV, $L_{int} \approx 10\ \mu b^{-1}$ & $210\ \mu b^{-1}$

- Fixed Target mode (SMOG):
  - Data taken in parallel to collider mode, using non-colliding bunches
  - $\sqrt{s_{NN}}$: 69 - 110 GeV

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



Recent HI results from LHCb

For details, see talk of P. Di Nezza on Wed. PM

- Charm production in fixed-target configuration
  - LHCb-PAPER-2018-023, PRL 122 (2019) 132002
- Antiproton production in fixed-target configuration
  - LHCb-PAPER-2018-031, PRL 121 (2018) 222001

- Heavy flavour production in *p*Pb collisions:
  - D^o at 5.02 TeV: LHCb-PAPER-2017-015, JHEP (2017) 090
  - Λ_c^+ at 5.02TeV: LHCb-PAPER-2018-021, JHEP 02 (2019) 102
  - J/ψ at 8.16TeV: LHCb-PAPER-2017-014, PLB774 (2017) 159
  - $Y(nS)$ at 8.16TeV: LHCb-PAPER-2018-035, JHEP 11 (2018) 194
  - B^+, B^o, Λ_b^o at 8.16TeV: LHCb-PAPER-2018-048, PRD 99 052011 (2019)

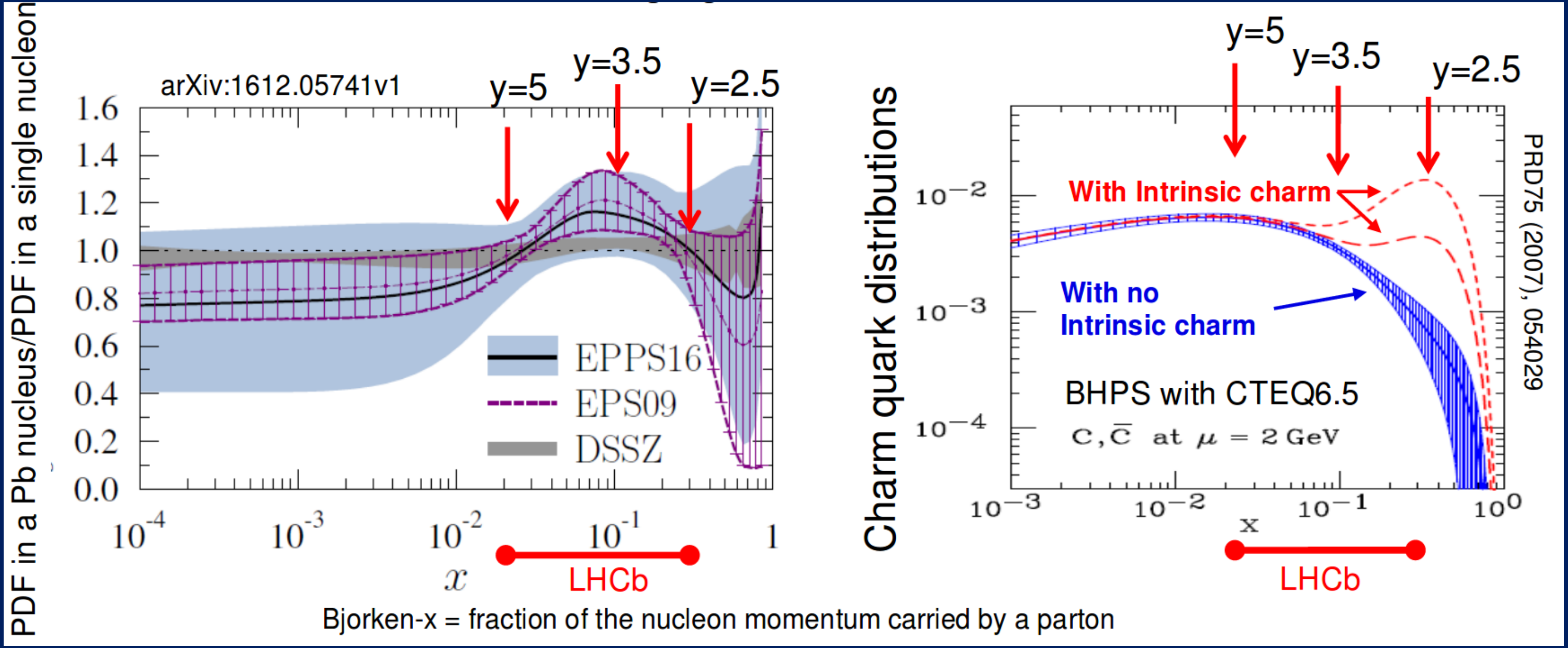
- Exclusive photonuclear J/ψ production in UPC of PbPb at 5TeV
  - LHCb-CONF-2018-003

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*^{o}…) down to low p_T
- ➢ Large rapidity coverage (~3 rapidity units) at large x_{Bj}

Charm production in pHe collisions

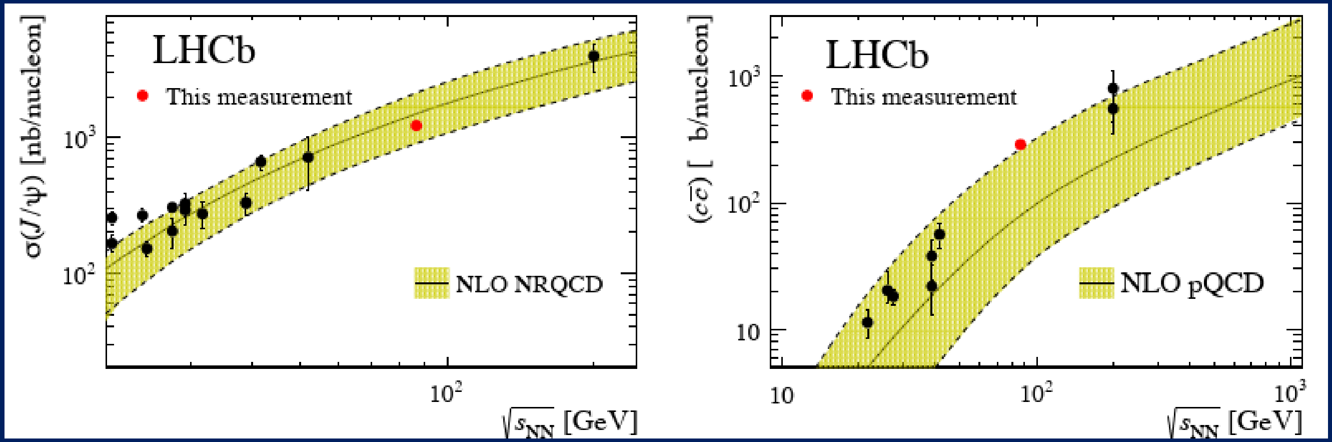
- J/ψ and D^0 inclusive cross section in pHe collisions $\sqrt{s_{NN}} = 86.6$ GeV:
  - Cross section measured in $J/\psi \rightarrow \mu^+\mu^-$ and $D^0 \rightarrow K^- \pi^+$ decays

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

PRL 122 (2019) 132002

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

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

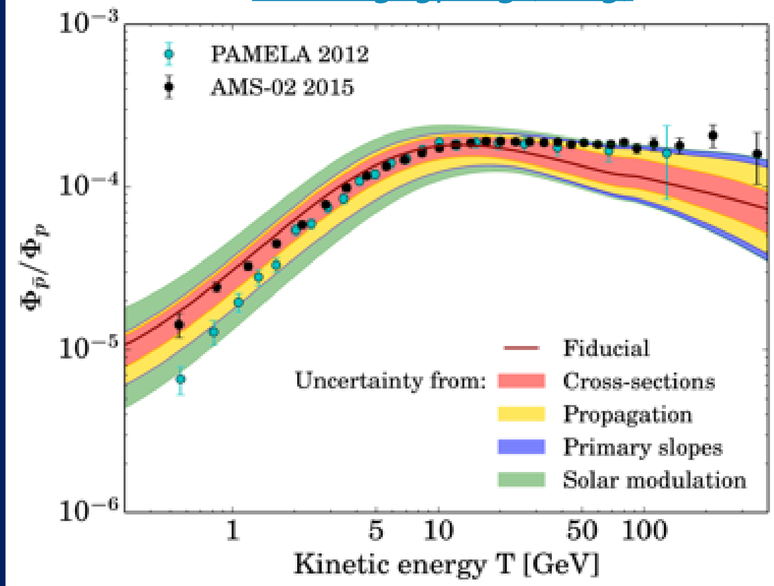


➢ LHCb results in good agreement with NLO NRQCD fit (J/ψ, left) and NLO pQCD predictions ($c\bar{c}$, right) and other measurements

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)

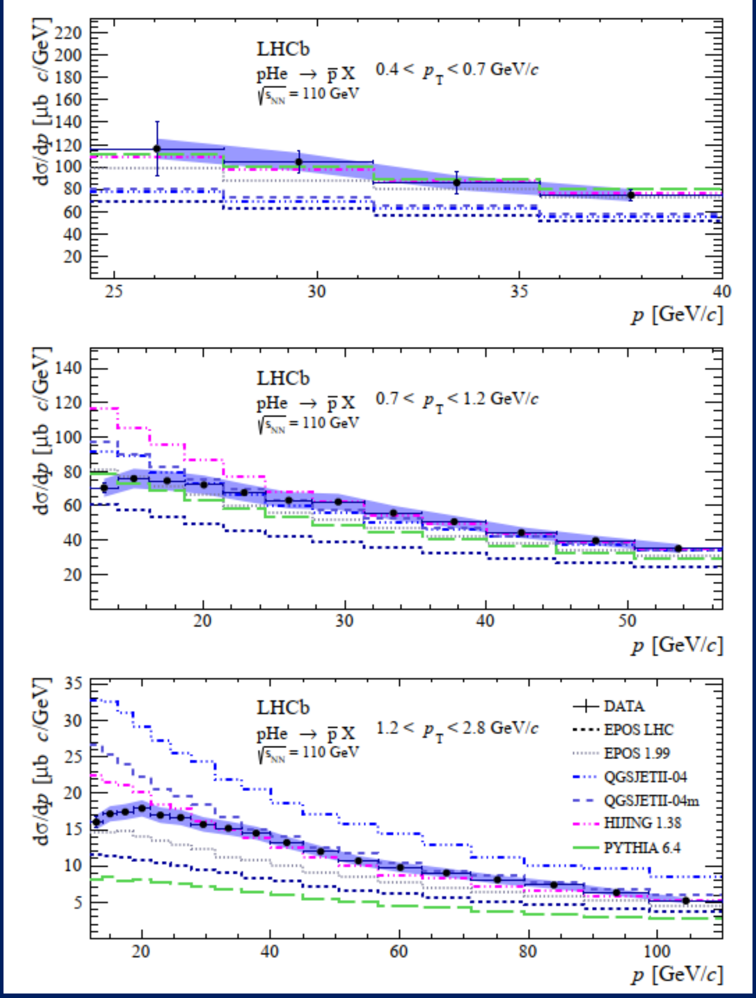


➢ The energy scale of LHCb in fixed target mode is well suited to measure the p-He cross-section

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

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

[PRL 121 (2018) 222001]



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

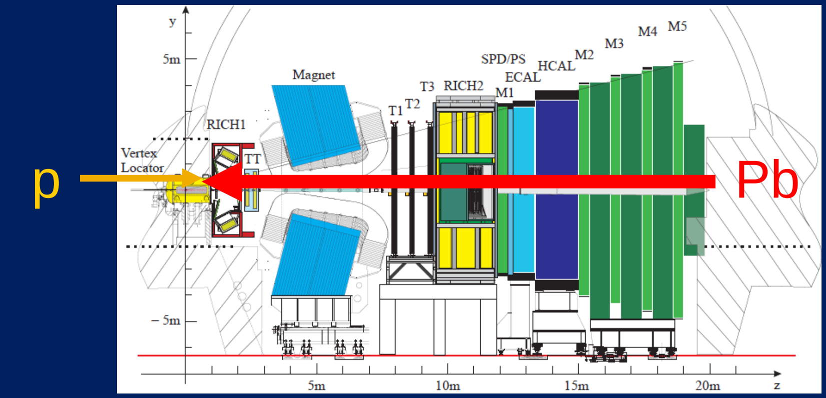
- Uncertainties smaller than model spread

- EPOS LHC tuned on LHC collider data underestimates $\bar{p}$-production

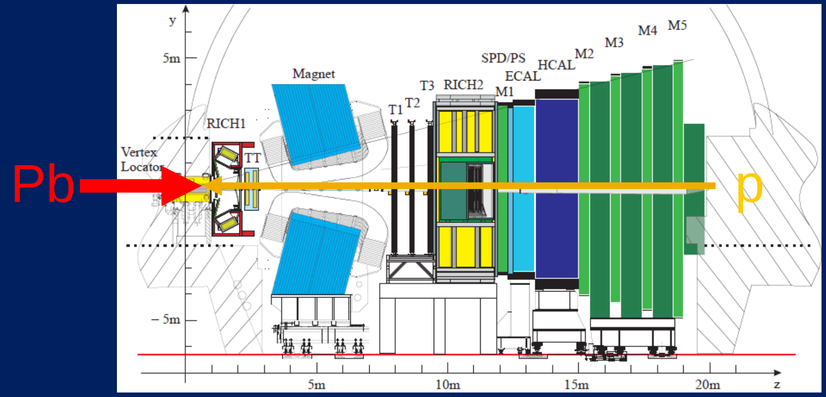
➢ Unique and precise:
  decisive contribution to shrink background
  uncertainties in dark matter searches in space

Setup for proton-lead physics

Forward production (*p*Pb)



Backward production (Pbp)



Rapidity defined w.r.t. proton direction
y* : rapidity in the nucleon-nucleon rest frame

Centre-of-mass energies:

- 2013: $\sqrt{s_{NN}} \approx 5$ TeV
- 2016: $\sqrt{s_{NN}} \approx 8.2$TeV

The nucleon-nucleon system boosted is in the lab. frame: $y_{lab} = y_{pA}$ +/- 0.47

Rapidity coverage in LHCb:

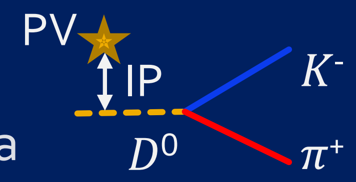
- in *pp:* $2 < y^* < 5$
- in *p*Pb: $1.5 < y^* < 4.5$
- in Pbp: $-5 < y^* < -2.5$
- Common range: $2.5 < |y^*| < 4$

Data samples:

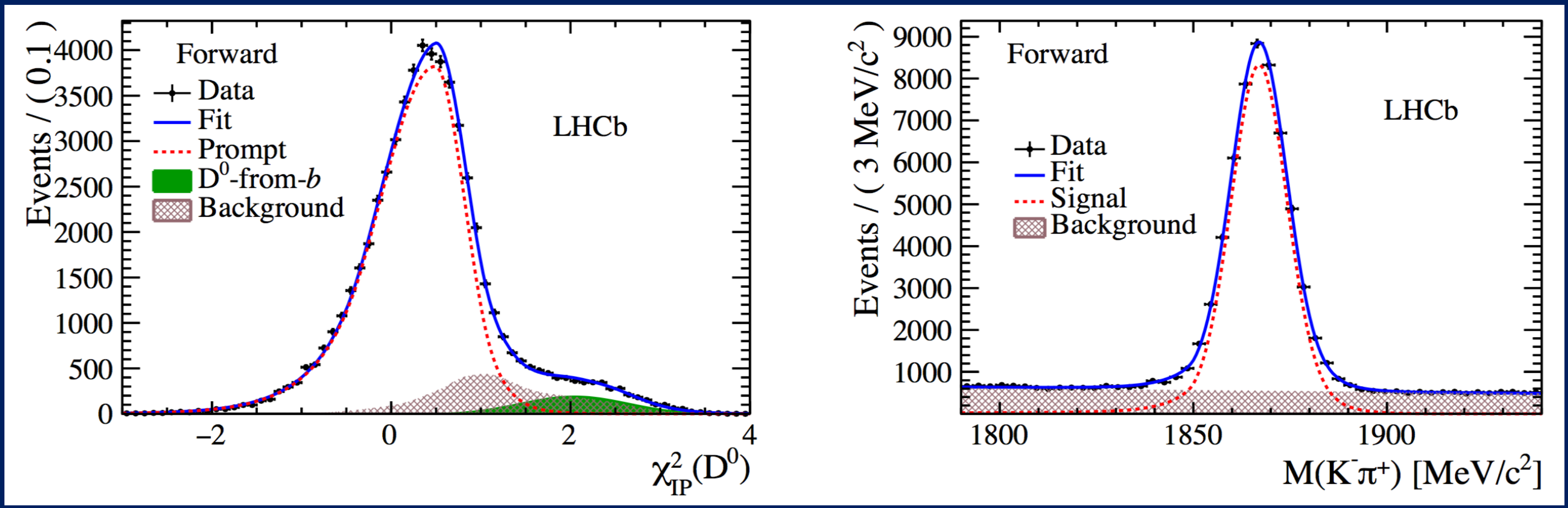
- 2013: Fwd: ~1.1/nb Bwd: ~0.5/nb
- 2016: Fwd: ~13.6/nb Bwd: ~20.8/nb
- Huge increase of data-set

Prompt D^0 production in pPb

JHEP (2017) 090



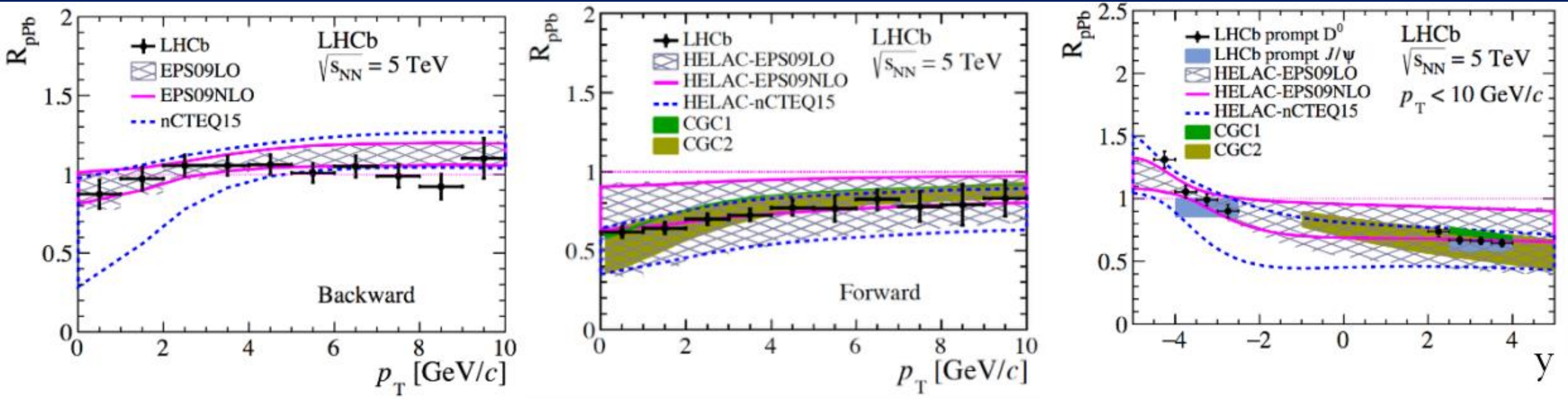
- D^0 fully reconstructed through $D^0 \to K^{\mp}\,\pi^{\pm}$ decays
  - Minimum selections using Particle ID and vertex displacement
- Reconstruction and particle ID efficiency determined from data
- Prompt D^0 yields obtained from fit to invariant mass distribution
- D^0-from-b component determined from fit to impact parameter $\chi^2_{IP}(D^0)$
- ➢ LHCb unique to remove D^0-from-b component down to zero-p_T



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 $D^0 \rightarrow K^- \pi^+$ decays

JHEP (2017) 090

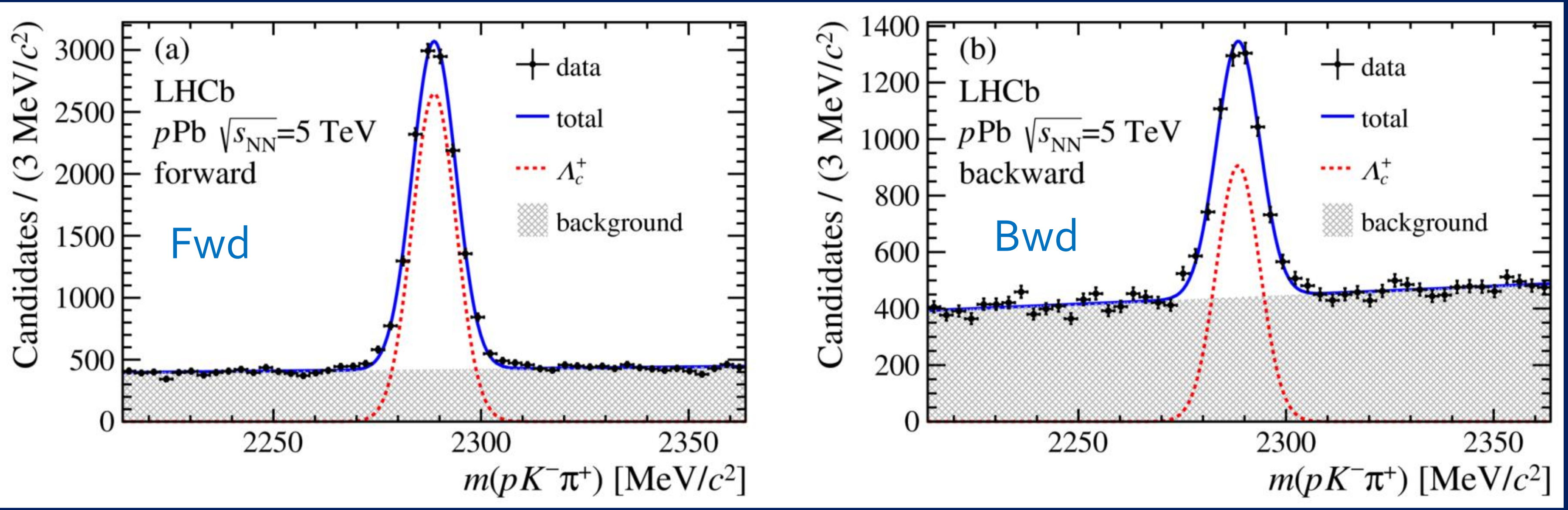


- R_{pPb} suppressed in forward region (~30%), no suppression in backward region, hint of small excess at large at backward rapidity (y*<-4)
- Measurements consistent with predictions using nPDFs or CGC framework
  EPJC 77 (2017) 1 , Comp. Phys. Com. 198 (2016) 238 , Comp. Phys. Com. 184 (2013) 2562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

Prompt Λ_c^+ production in pPb

- Λ_c^+ fully reconstructed through $\Lambda_c^+ \longrightarrow p\, K^-\, \pi^+$ decays

JHEP 02 (2019) 102

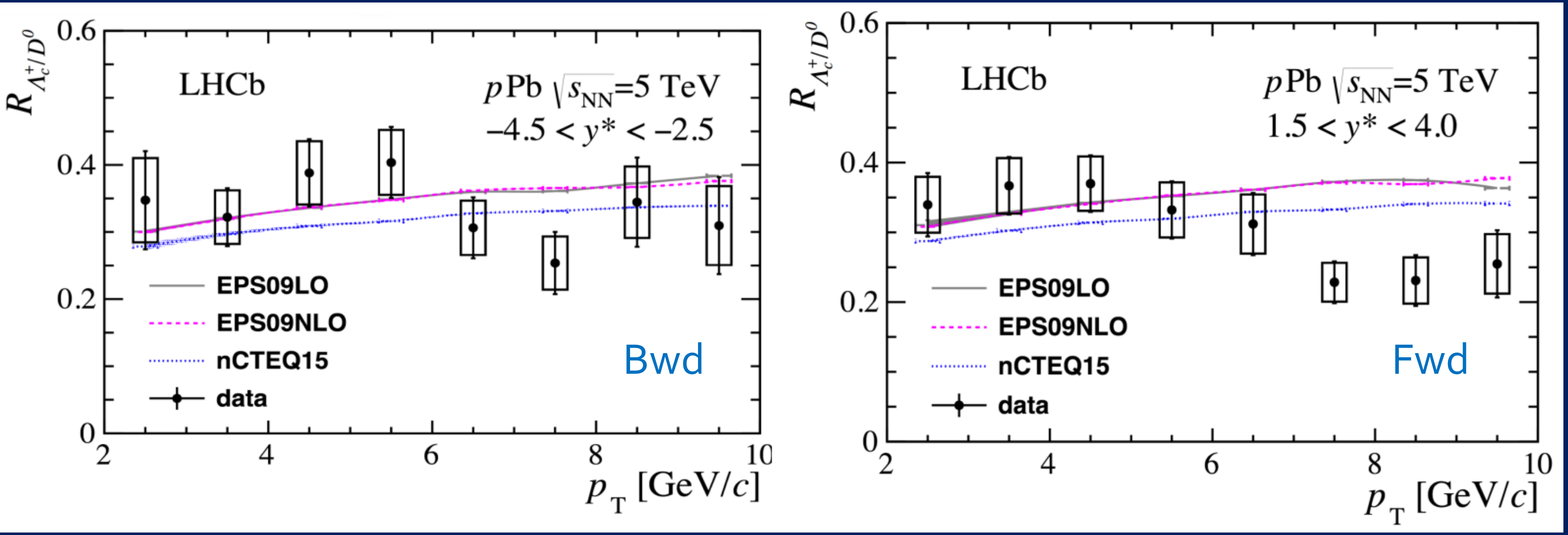


- Similar analysis strategy as D^0

Prompt Λ_c^+ production in *p*Pb

- Λ_c^+ / D^0 ratio

JHEP 02 (2019) 102

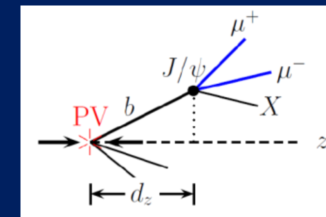


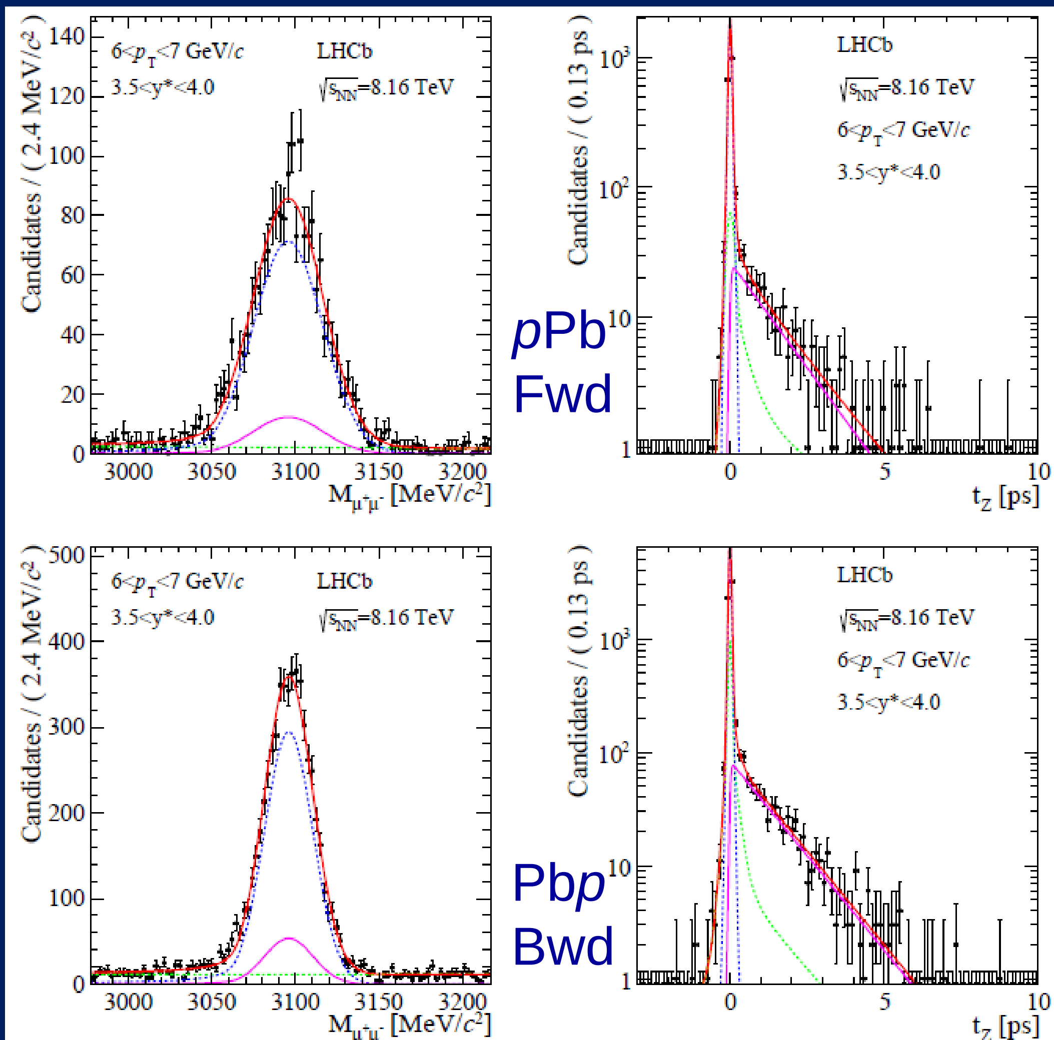
- Λ_c^+ / D^0 ratio similar in forward and backward direction
- Generally consistent with expectations from *pp* data: Λ_c^+ / D^0 ~ 0.3
- Comparison with nPDFs shows hint of discrepancy at high p_T in the Fwd direction
  JHEP 04 (2009) 065 , EPJC 77 (2017) 1 , Comp. Phys. Com. 198 (2016) 238

J/ψ production in pPb

PLB774 (2017) 159

- Prompt J/ψ and J/ψ from b are extracted by simultaneous fit of mass and pseudo-proper time : $t_z = (Z_{J/\psi} - ZPV) \times M_{J/\psi} / p_Z$





Mass distributions:

- Signal : Crystal-Ball
- Bkg : exponential

t_z distributions:

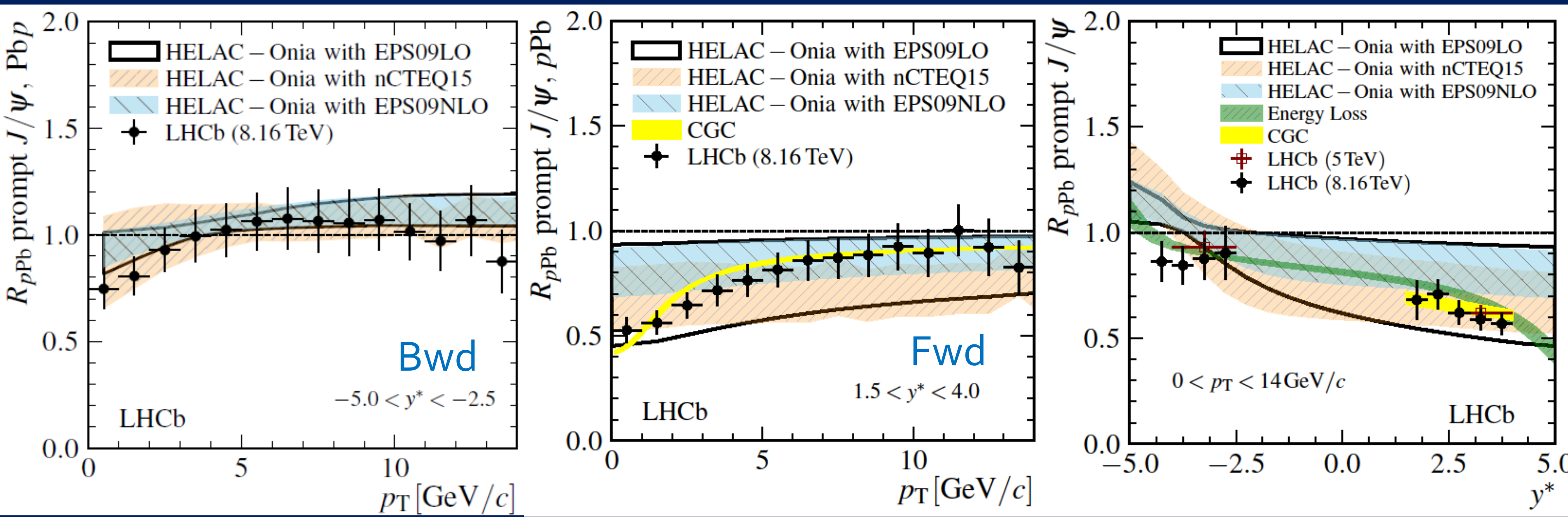
- Signal:
  - $\delta(t_z)$ for prompt J/ψ
  - expo. for b-component
  - bkg: empirical function from sideband

Total yields:

	prompt	from b
pPb:	3.8×10^5	6.7×10^4
Pbp:	5.6×10^5	7.1×10^4

Prompt J/ψ modification factor

PLB774 (2017) 159

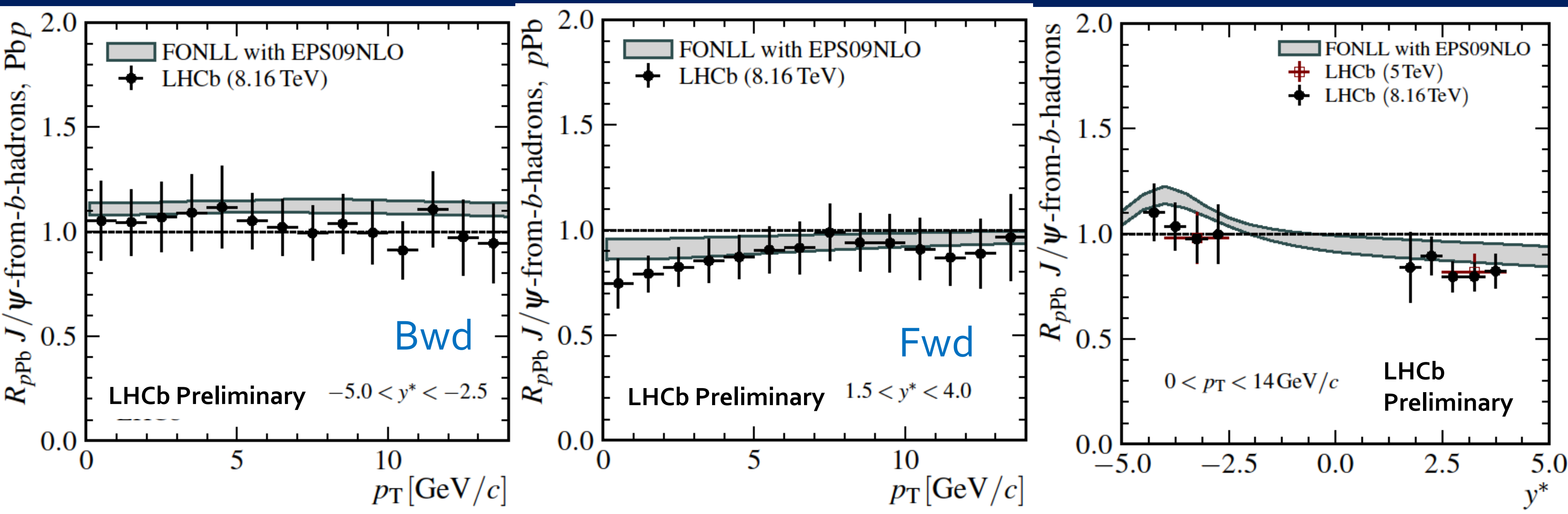


- In Bwd region: R_{pPb} closer to unity, intriguing low values at low p_T
- In Fwd region: up to 50% suppression at low p_T, converging to unity at high p_T
- Overall agreement with models good, but some have large uncertainties
- Results are compatible with those at 5 TeV   JHEP 02 (2014) 072

- Models: HELAC: EPJC 77 (2017) 1 , Comp. Phys. Com. 198 (2016) 238 , EPS09: JHEP 04 (2009) 065 , arXiv :0902.4154 , nCTEQ15: Phys. Rev D93 (2016) 085037 CGC: Phys. Rev. D91 (2015) 114005

Non-prompt J/ψ modification factor

PLB774 (2017) 159



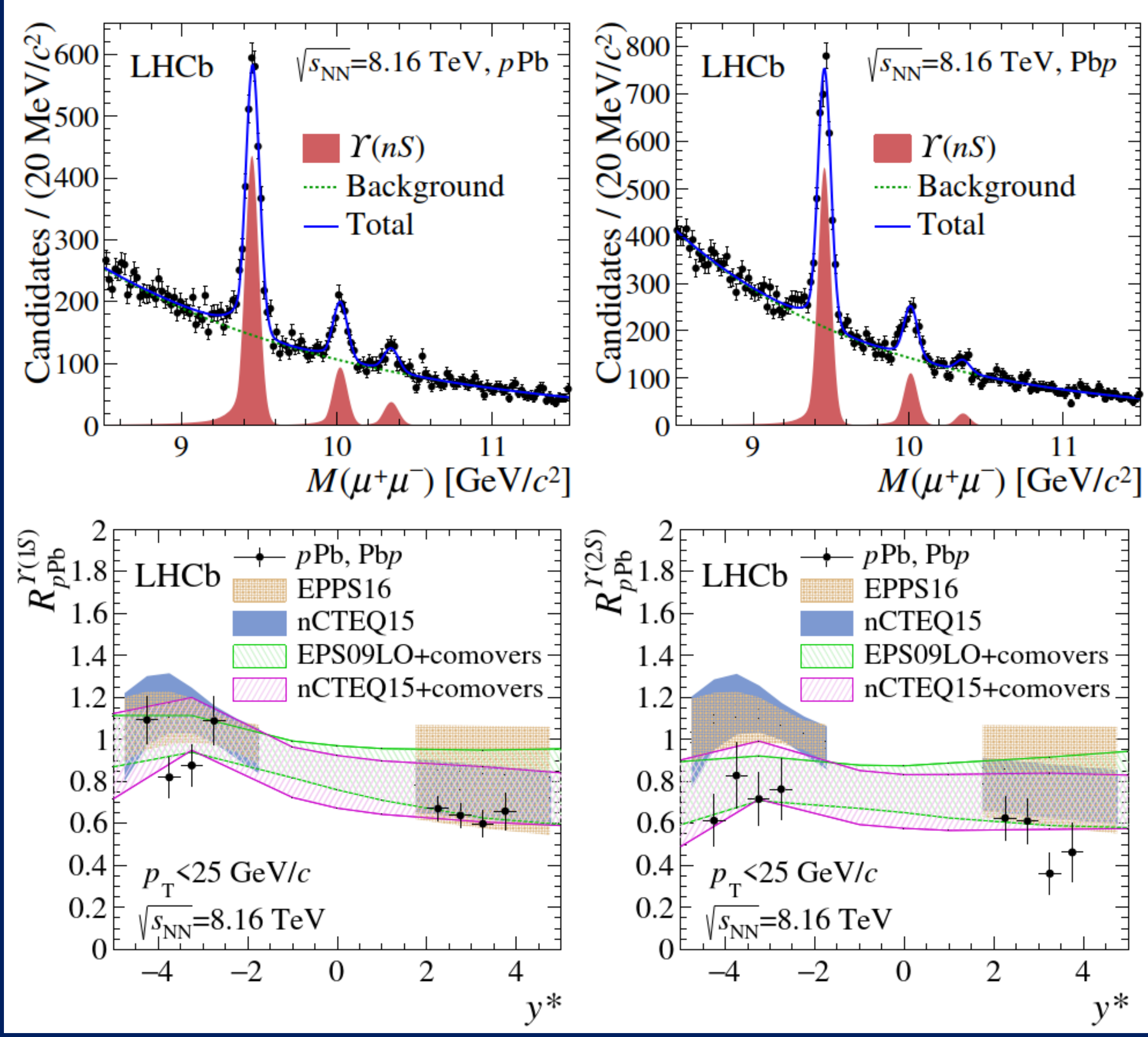
- In Bwd region: R_{pPb} slightly above unity with no p_T dependence
- In Fwd region: up to 30% suppression at low p_T, converging to unity at high p_T
- Overall agreement with Modell (FONLL nPDF) JHEP 05 (1998) 007 , JHEP 03 (2001) 006
- Results are compatible with LHCb results at 5 TeV, but much higher (unprecedented) precision JHEP 02 (2014) 072

Υ(nS) production in pPb

JHEP 11 (2018) 194

- LHCb observed *Υ(2S, 3S)* suppression in pPb/Pbp at low-p_T in Run I at 5 TeV, but statistics limited

- Run II: 20x more luminosity
- Clear *Υ(3S)* signal in both fwd and bwd rapidity



Modification factor:

- *Υ(1S)* fwd suppressed by ~30%
- *Υ(1S)* bwd compatible with 1 within nPDF uncertainties
- *Υ(2S)* suppression confirmed; it is larger than the *Υ(1S)* supp.

Models:

- EPPS16: EPJ C (2017) 77 163
- EPS09: JHEP 04 (2009) 065
- nCTEQ15: PRD93 (2016) 085037
- Comovers: PLB 749 (2015) 98

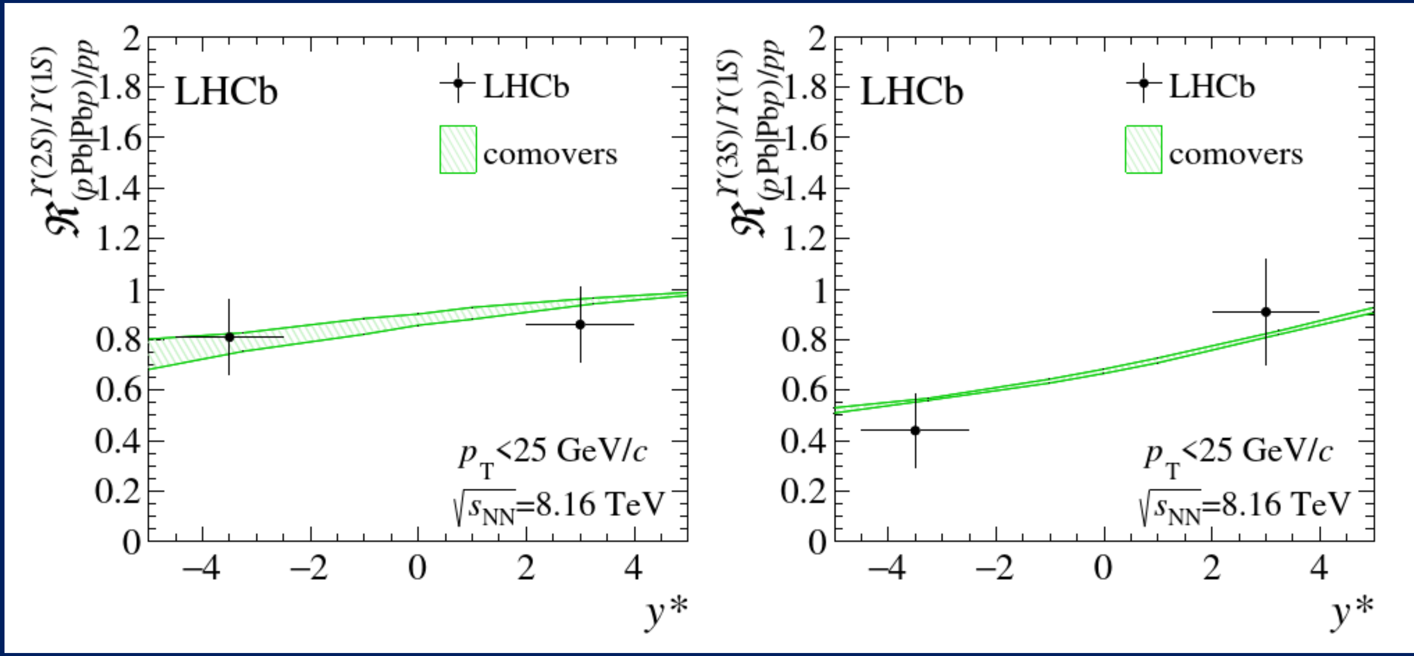
More on *Υ(nS)* modification factors

JHEP 11 (2018) 194

- Double ratio of *Υ(2S)* and *Υ(3S)* over *Υ(1S)* in *p*Pb over that in *pp:*

$$\mathfrak{R}^{\Upsilon(nS)/\Upsilon(1S)}_{(p\mathrm{Pb}|\mathrm{Pb}p)/pp} = \frac{R(\Upsilon(nS))_{p\mathrm{Pb}|\mathrm{Pb}p}}{R(\Upsilon(nS))_{pp}}$$

- Most of the uncertainties cancel

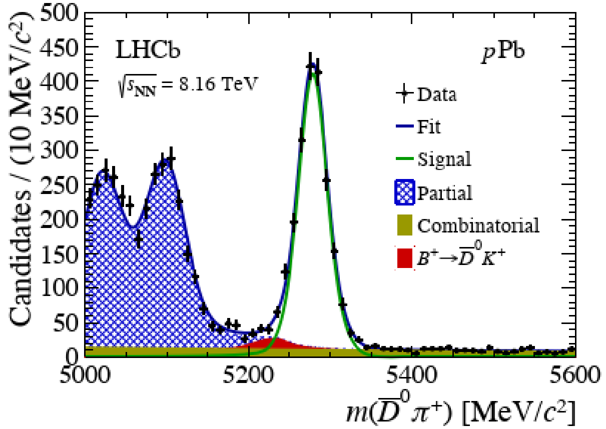


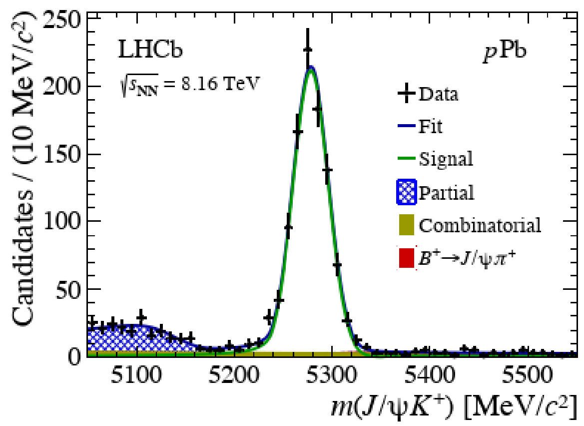
- The suppression is even larger for *Υ(3S)* than for *Υ(2S)*
- Ratio is consistent with comovers model PLB 749 (2015) 98

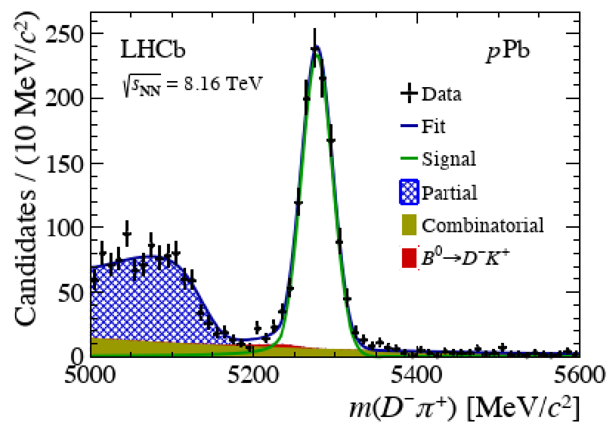
b – hadron production in pPb

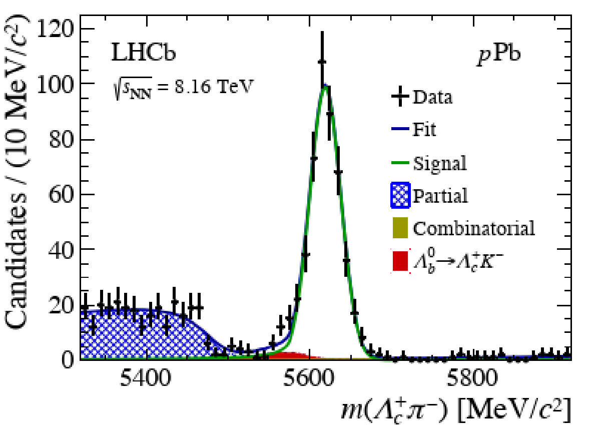
Exclusive decay modes:

$B^+ \to J/\psi\, K^+$, $B^+ \to D^o\, \pi^+$, $B^o \to D^-\, \pi^+$, $\Lambda_b{}^o \to \Lambda_c{}^+\, \pi^-$ PRD 99 052011 (2019)





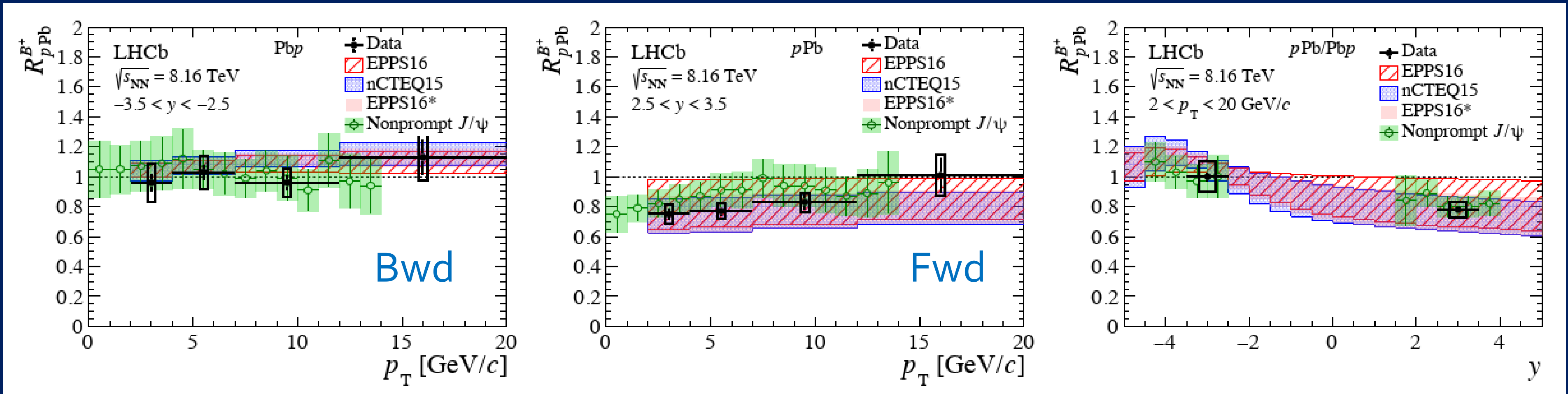




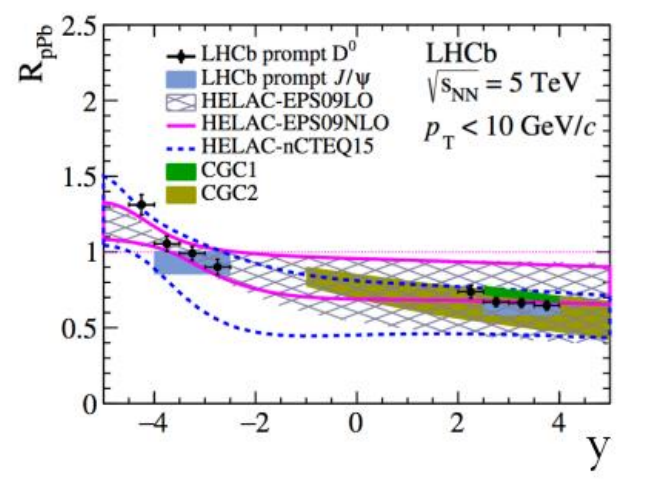
Decay	pPb	Pbp
$B^+ \to D^o\, \pi^+$	1948 ± 58	1824 ± 64
$B^+ \to J/\psi\, K^+$	883 ± 32	905 ± 33
$B^o \to D^-\, \pi^+$	1155 ± 39	886 ± 34
$\Lambda_b{}^o \to \Lambda_c{}^+\, \pi^-$	484 ± 24	397 ± 23

B^+ nuclear modification factor

PRD 99 052011 (2019)



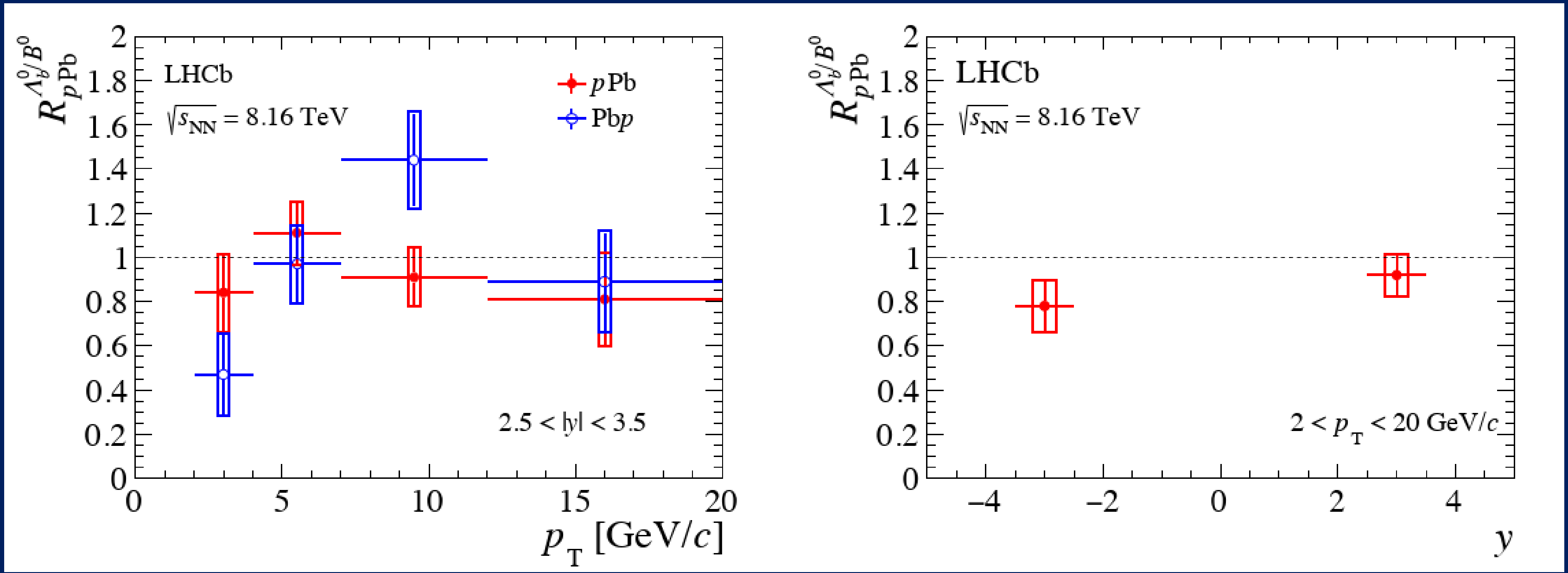
- R_{pA} is consistent with unity at backward rapidity
- Significant suppression (≈ 25%) in Fwd rapidity, suppression decreases at large p_T
- Measurements in good agreement with *J/ψ*-from-*b* decay data and calculations using nPDFs
- EPJC 77 (2017) 1 , CPC 198 (2016) 238 , JHEP 04 (2009)
- Pattern consistent with R_{pA} of D^0 mesons



Λ_b^0 and B^0 relative modification

PRD 99 052011 (2019)

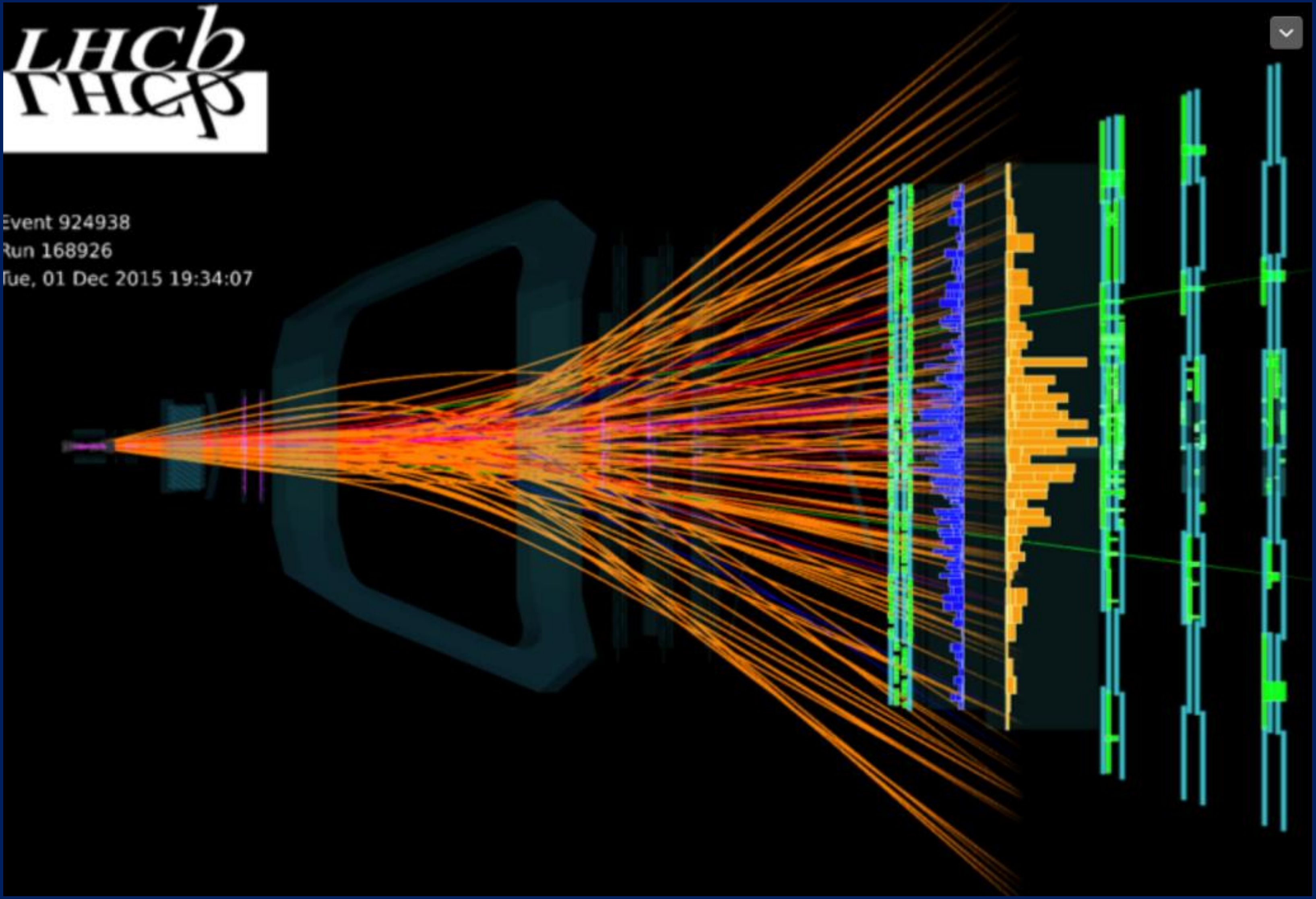
- Ratio of R_{pA} between Λ_b^0 and B^0 hadrons



- Forward Rapidity: consistent with unity in all kinematic bins
- b-quark fragmentation function at forward rapidity similar to *pp*

- Backward rapidity: hint of stronger suppression for Λ_b^0 compared with B^0.
- Demanding more statistics for a firm conclusion.

PbPb collisions

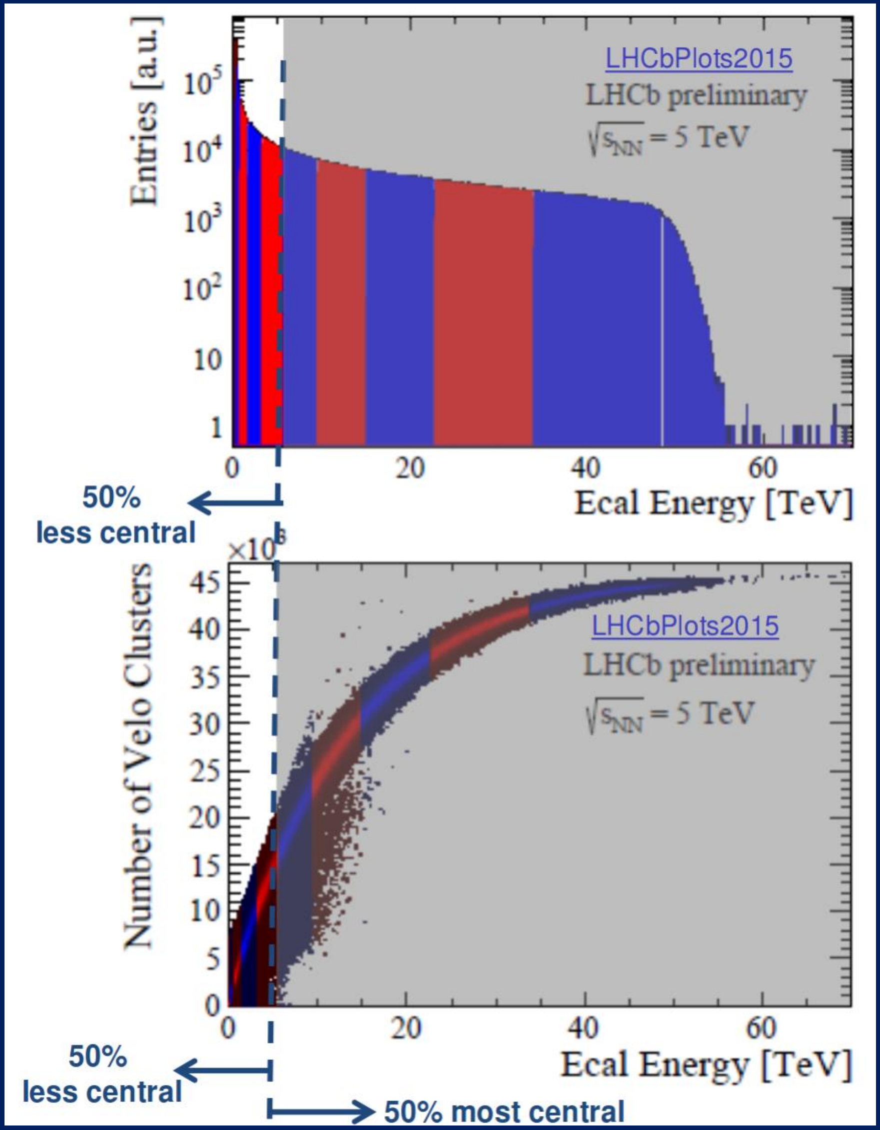


Centrality of PbPb collisions

- 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

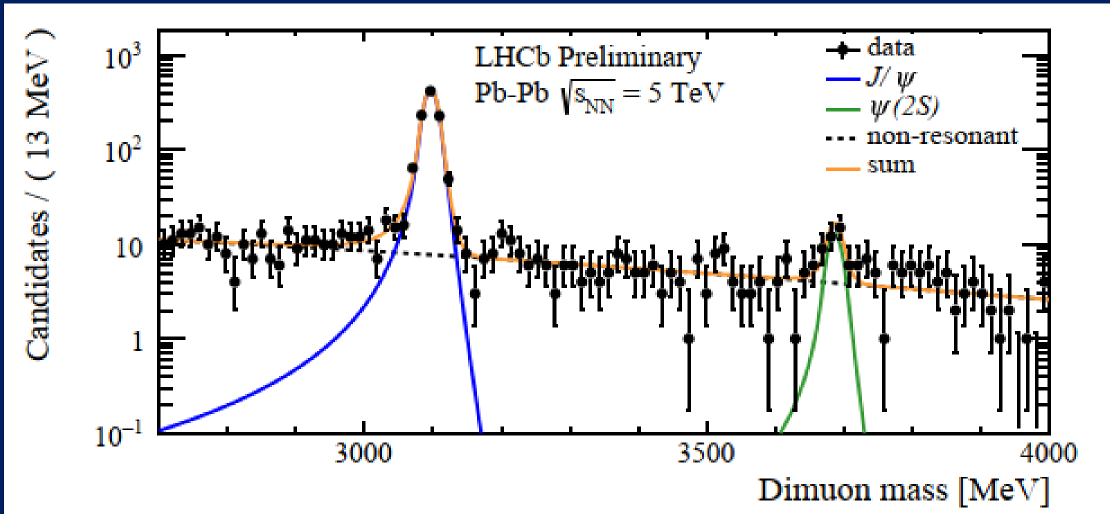


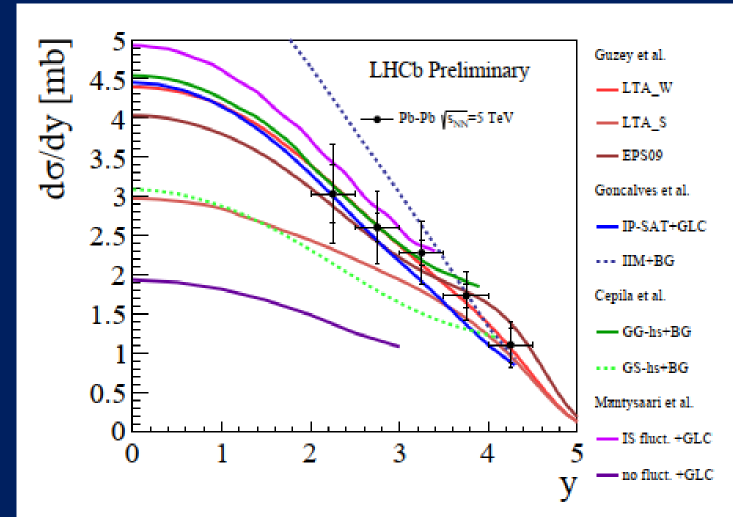
J/ψ photo-production in UPC

- Interaction between the electromagnetic field of the ions
  $\rightarrow$ 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





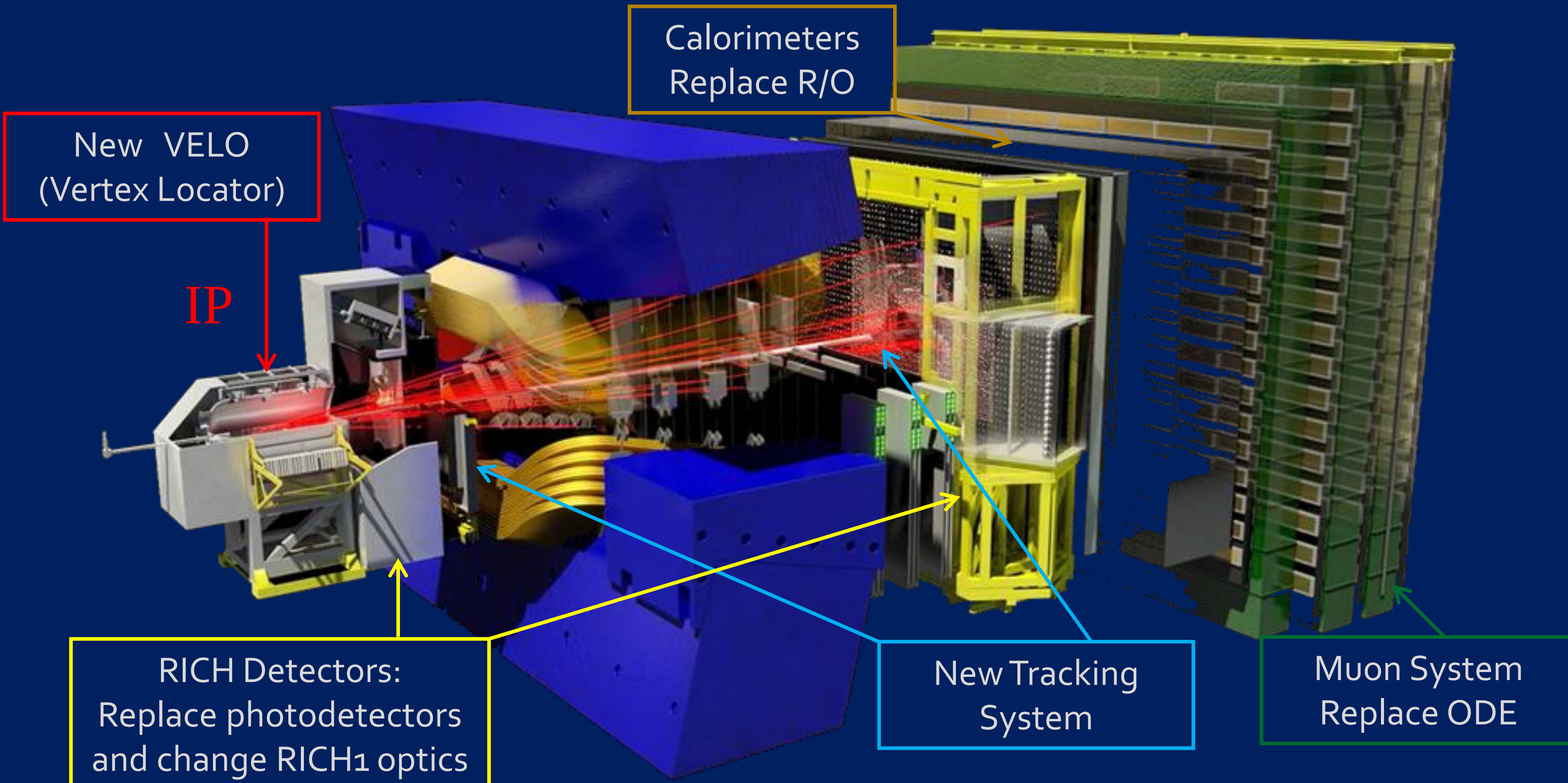
- Phenomenological models:
  PRC 97 024901 (2018), PRD 96 094027 (2017), PRC 93 055206 (2016), PLB 772 (2017) 832

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

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:

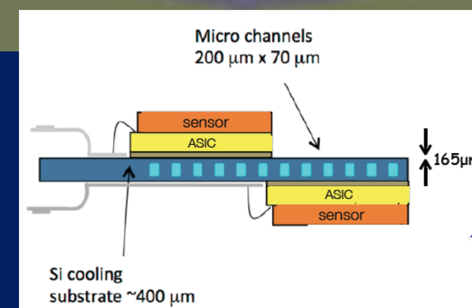
- withstand increased radiation
- handle high data volume
- improve current performance
  - lower materiel budget
  - enlarge acceptance

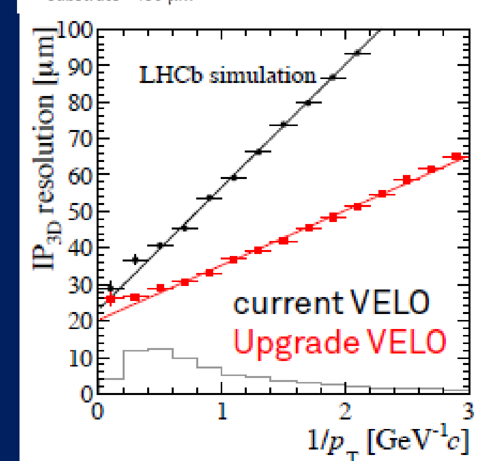
Technical choices :

- 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 $L = 2\cdot10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

➢ **Allows to improve significantly the centrality reach of LHCb**

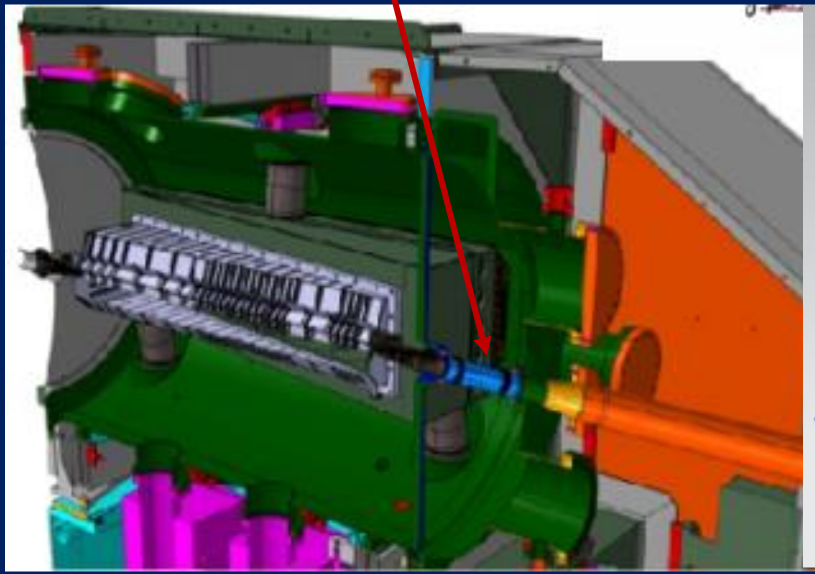


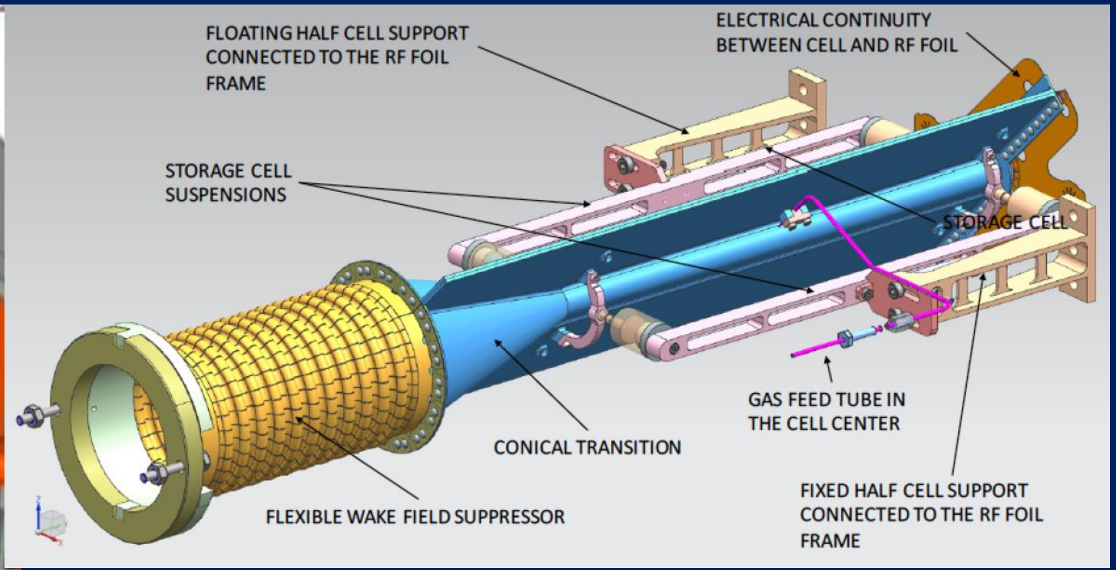


Upgrade of the SMOG system

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

CERN/LHCC-2019-005





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

For details, see talk of P. Di Nezza on Wed. PM

- 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 pAr foreseen at 115 GeV : ~ 45/pb
- PbAr at 72 GeV ~ 5/nb ; pAr at 72 GeV ~ 1/pb

For details, see talk of P. Di Nezza on Wed. PM

LHCb-PUB-2018-015

Physics reach:

	SMOG published result pHe@87 GeV	SMOG largest sample pNe@69 GeV	SMOG2 example pAr@115 GeV
Integrated luminosity	7.6 nb^{-1}	$\sim$ 100 nb^{-1}	$\sim$ 45 pb^{-1}
syst. error on J/ψ x-sec.	7%	6 - 7%	2 - 3 %
J/ψ yield	400	15k	15M
D^0 yield	2000	100k	150M
Λ_c^+ yield	20	1k	1.5M
$\psi(2S)$ yield	negl.	150	150k
$\Upsilon(1S)$ yield	negl.	4	7k
Low-mass Drell-Yan yield	negl.	5	9k

Comments:

- The above list is far from being exhaustive;
- extrapolations are estimates 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 .

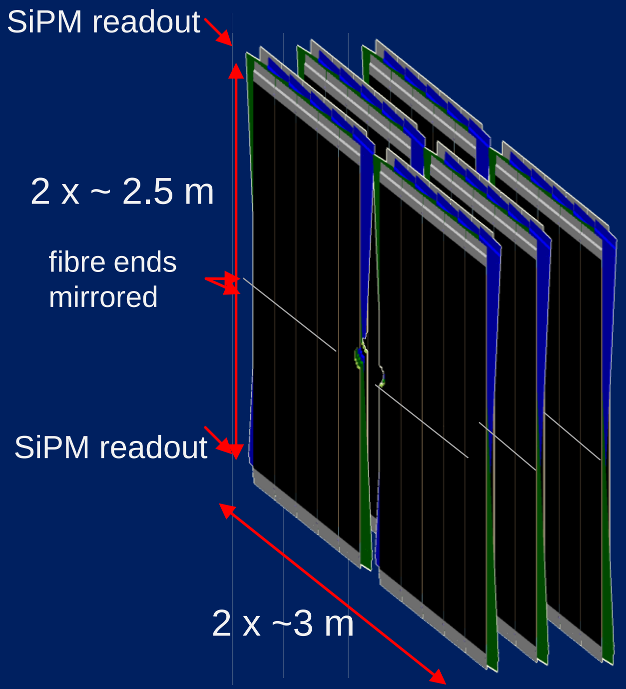
Summary and Conclusions

- The LHCb detector has unique capabilities for heavy flavour measurements at LHC in collider and fixed-target modes
- Heavy flavour production in *p*Pb collisions :
  - Tested heavy-flavour bound state hadronization & fragmentation down to low-p_T
  - Tested different suppression mechanisms for quarkonia with different binding energies
  - Nuclear suppressions in *p*Pb forward at low-p_T :
    up to 50% for charm and 20-30% for beauty
- 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
  - Upgrade 2: intention to reach full centrality in PbPb (design phase is ongoing)
- 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.

Backup

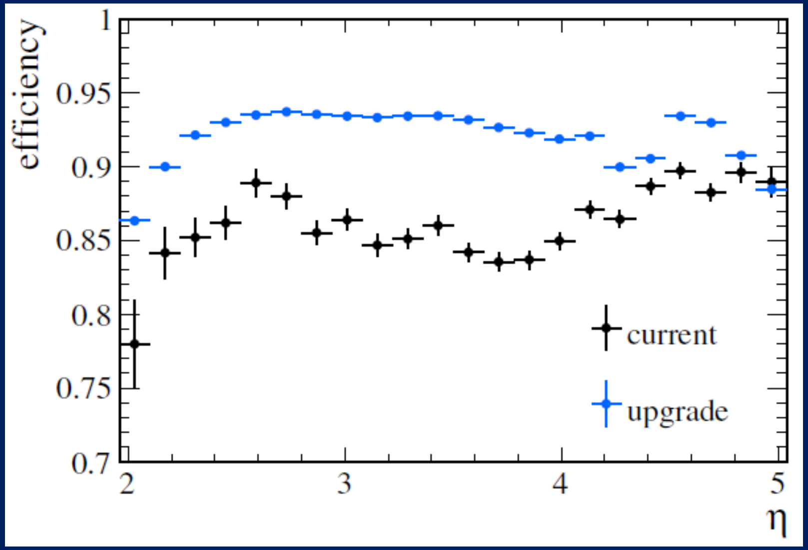
T-stations upgrade: Fibre Tracker

- 3 stations of X-U-V-X ($\pm 5^\circ$ 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