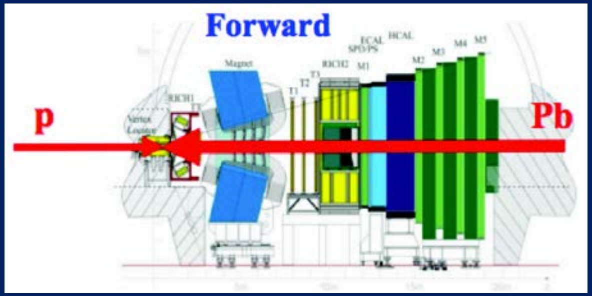
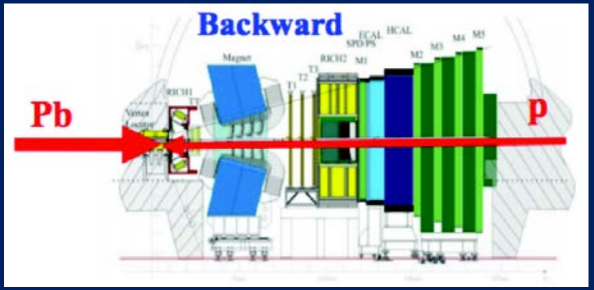
New Heavy Flavor Results in Heavy Ion Collisions from LHCb





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University of Michigan
On behalf of the LHCb Collaboration

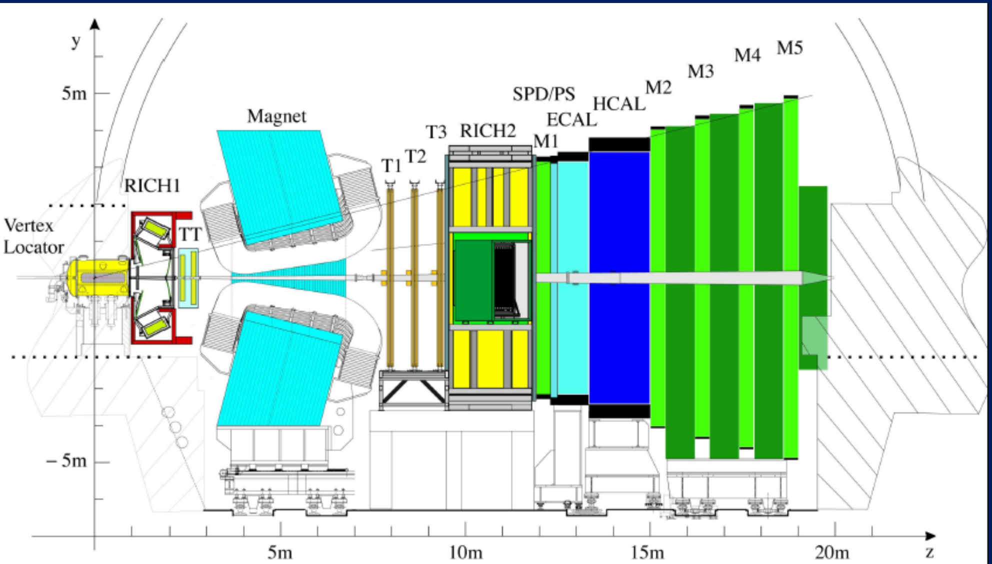
Santa Fe Jets and Heavy Flavor Workshop
Los Angeles, CA
January 28-30, 2019

The LHCb experiment

LHCb is the experiment devoted to heavy flavor at the LHC

Detector design:

- Forward geometry to optimize acceptance for $b\bar{b}$ pairs: $2 < \eta < 5$
- Tracking: Momentum resolution <1% for p < 200 GeV/c
- Particle ID: Excellent capabilities to select exclusive decays

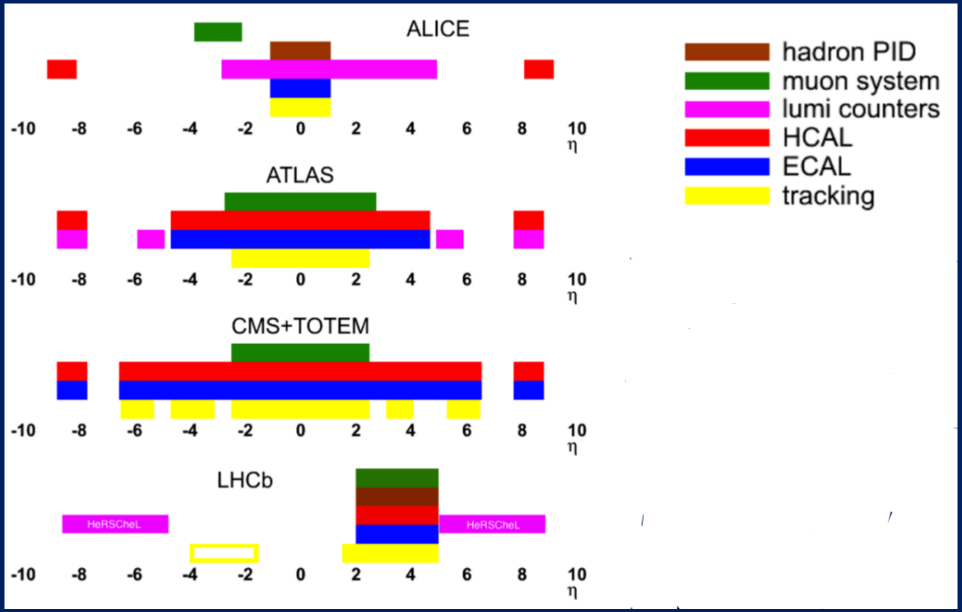


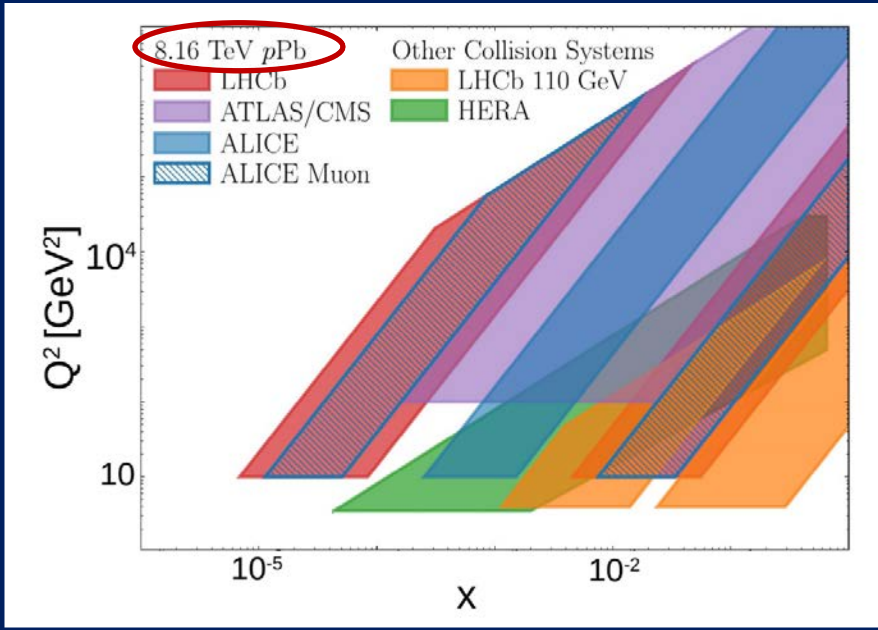
JINST 3, (2008) S08005
Int.J.Mod.Phys.A30 (2015) 1530022

Some unique features attractive for heavy ion physics:

- Excellent detector performance for heavy flavor
- Forward acceptance
- Possibility to run in fixed-target mode

Key feature: Forward acceptance



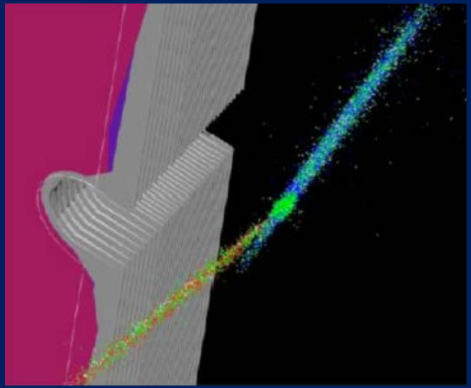


- Sensitivity to small parton momentum fraction x (down to ~10^{-5})
- Rapidity dependence can disentangle nuclear effects
- Nicely complements other LHC experiments

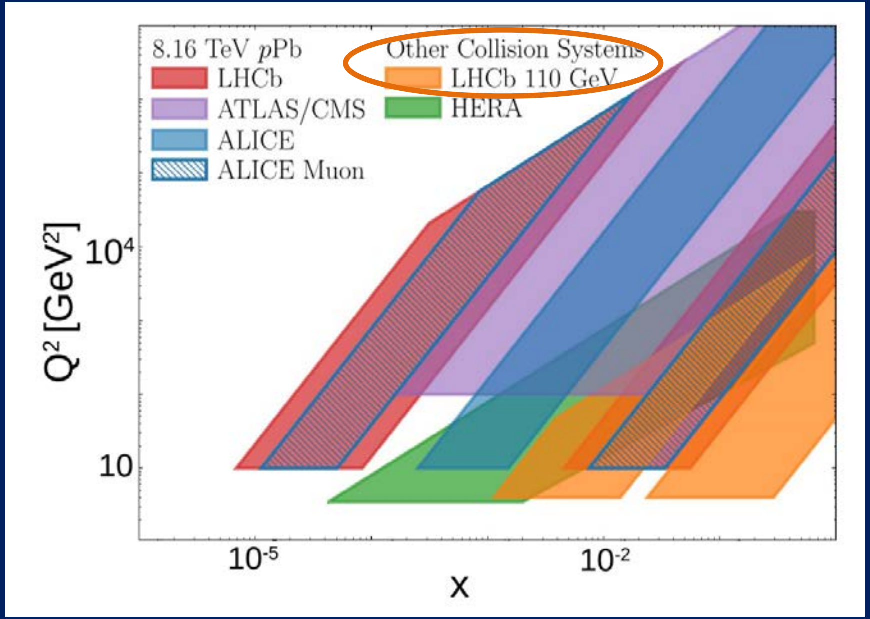
Key feature: Fixed-target capabilities

"Fixed-target-like" geometry well suited for . . . fixed-target physics!

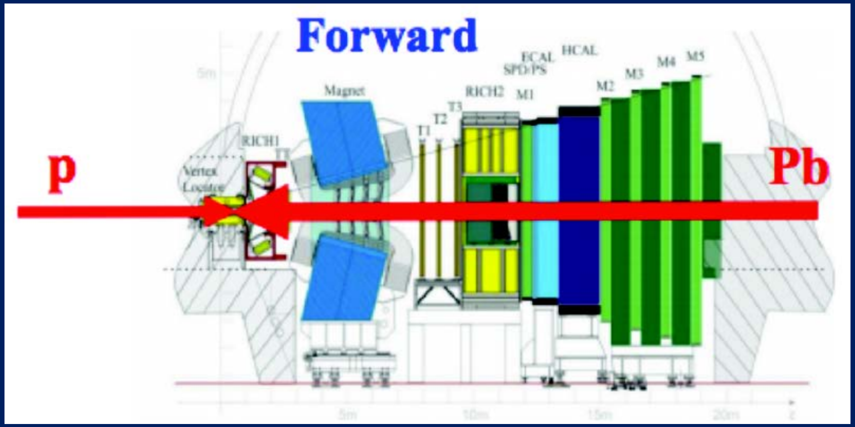
- System for Measuring Overlap with Gas (SMOG) allows injection of small amounts of noble gas into LHC beam pipe around LHCb collision region. **Turns LHCb into a fixed-target experiment!** Luminosity up to 10^{30} cm^{-2} s^{-1}

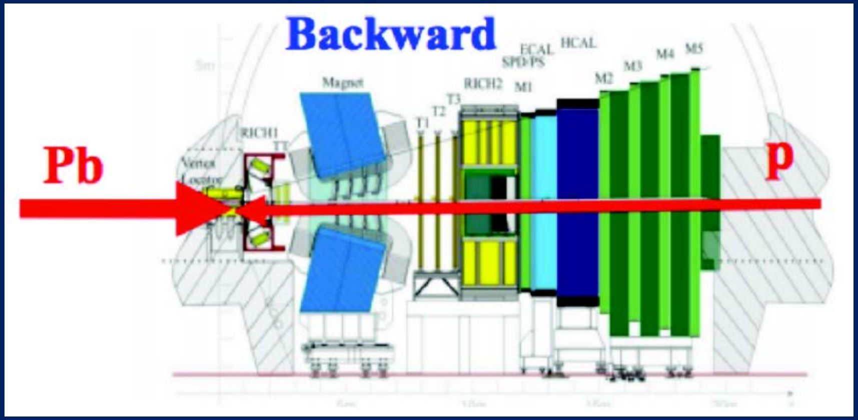


- Collisions at $\sqrt{s_{NN}} = \sqrt{2E_{beam}M_p}$ 41-110 GeV for E_{beam}= 0.9-6.5 TeV
  - Between SPS and (main) RHIC energies
- At $\sqrt{s_{NN}} = 110$ GeV, c.m. rapidity is -2.8 < y* < 0.2 **backward** detector with access to large x value in target for different nuclear targets
  - Study nuclear PDFs in antishadowing/EMC region



pPb data sets





Forward region:

- $y^{*} = y_{lab} - 0.465$
- pPb: 1.5 < y* < 4.0

Backward region:

- $y^{*} = -(y_{lab} + 0.465)$
- Pbp: -5.0 < y* < -2.5

2013: $\sqrt{s_{NN}} = 5.02$ TeV

- 1.1 nb^{-1} (fwd), 0.5 nb^{-1} (bwd)

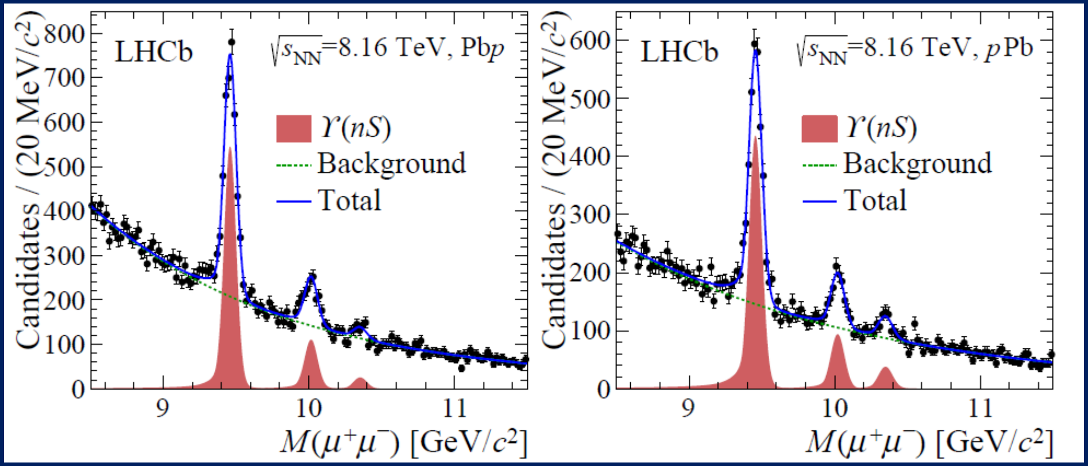
2016: $\sqrt{s_{NN}} = 8.16$ TeV

- 13.6 nb^{-1} (fwd), 20.8 nb^{-1} (bwd)

JHEP 1811, 194 (2018)

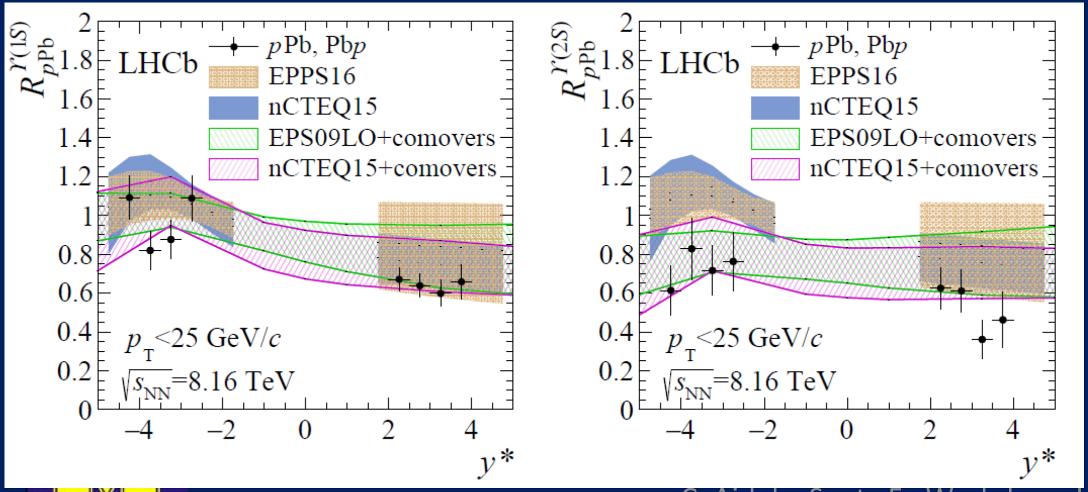
Bottomonia in pPb at 8 TeV: $R_{pPb}^{Y(nS)}$

Backward Forward



- Clean separation of Y(nS) resonances

R_{pPb} vs. y*, Y(1S) R_{pPb} vs. y*, Y(2S)



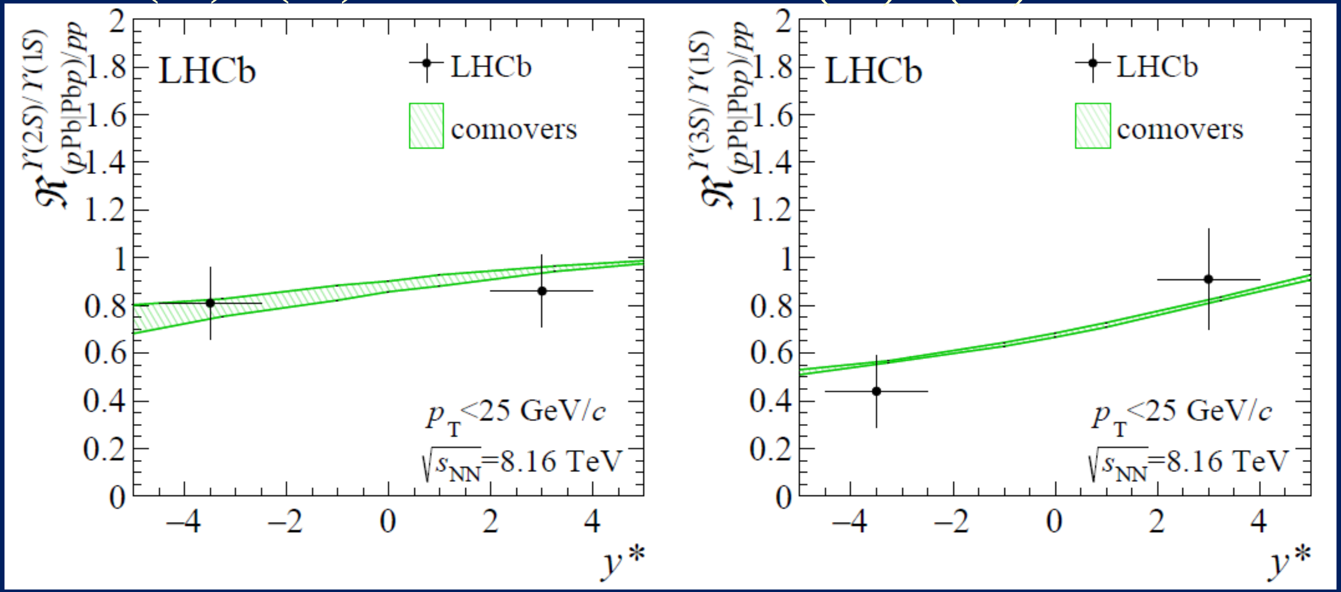
- Model including interactions between Y and comoving particles predicts large final-state effects, larger for excited states and in backward direction
  - Ferreiro and Lansberg, JHEP 10, 094 (2018)
- Consistent with patterns observed in data . . .

JHEP 1811, 194 (2018)

Bottomonia in pPb at 8 TeV: Double ratio

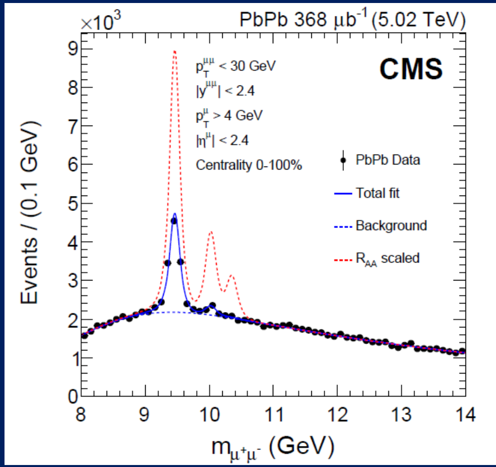
Double ratio, Υ(nS)/Υ(1S) in pPb with respect to pp

Υ(2S)/Υ(1S) Υ(3S)/Υ(1S)



Additional suppression seen for Υ(3S), in particular in backwards region. Consistent with comovers model.

Understanding this effect is crucial to interpretation of sequential quarkonium suppression observed in PbPb by CMS! (arXiv:1805.09215)



JHEP 1811, 194 (2018)

Bottomonia in pPb at 8 TeV: $R_{pPb}^{\Upsilon(nS)}$

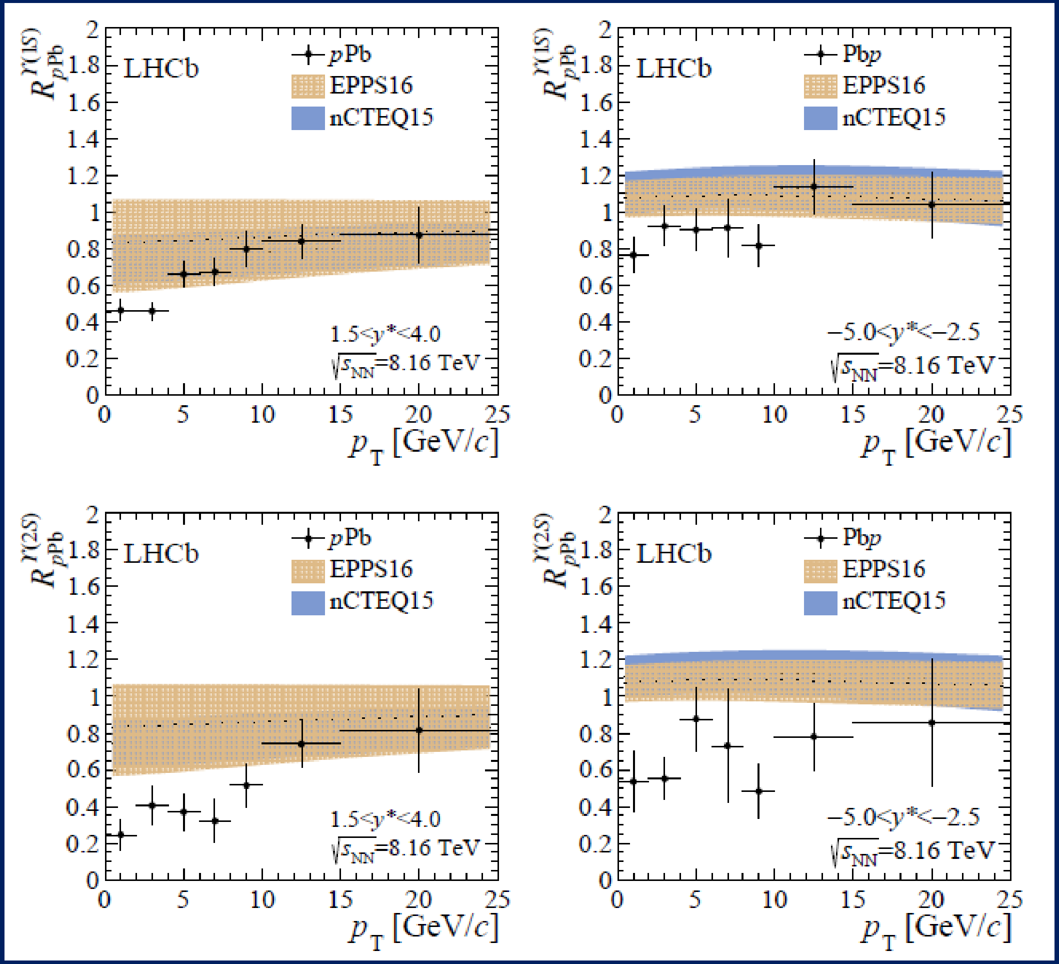
Rising p_T dependence, not observed in the calculations

- HELAC-Onia: Lansberg + Shao, EPJC77, 1 (2017); Shao, Comput. Phys. Commun. 184, 2562 (2013)
- No interactions with comovers included—p_T dependence not available

Forward | Backward

R_{pPb} vs. p_T, Y(1S)

R_{pPb} vs. p_T, Y(2S)

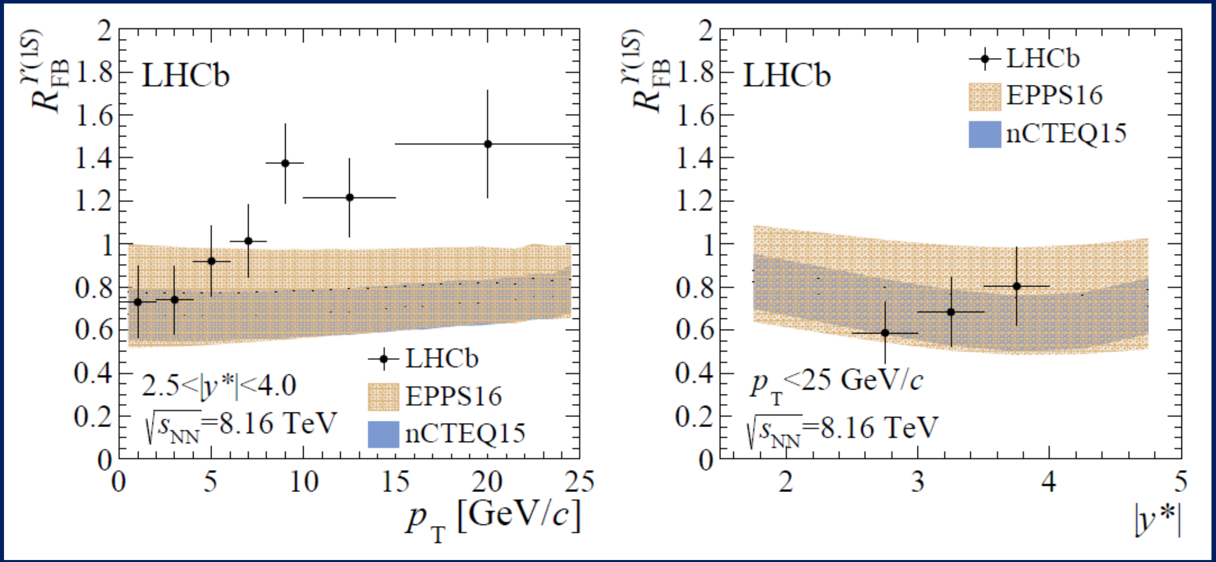


JHEP 1811, 194 (2018)

Bottomonia in pPb at 8 TeV : R_{FB}

vs. p_T vs. |y*|

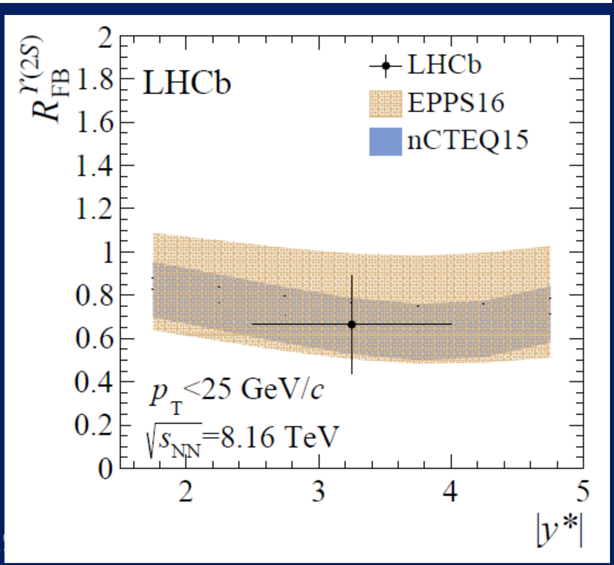
R_{FB} Y(1S)



Forward-backward ratio

- Rising p_T dependence
- Hint of rising |y*| dependence
- Compared to calculations using HELAC-Onia

R_{FB} Y(2S)

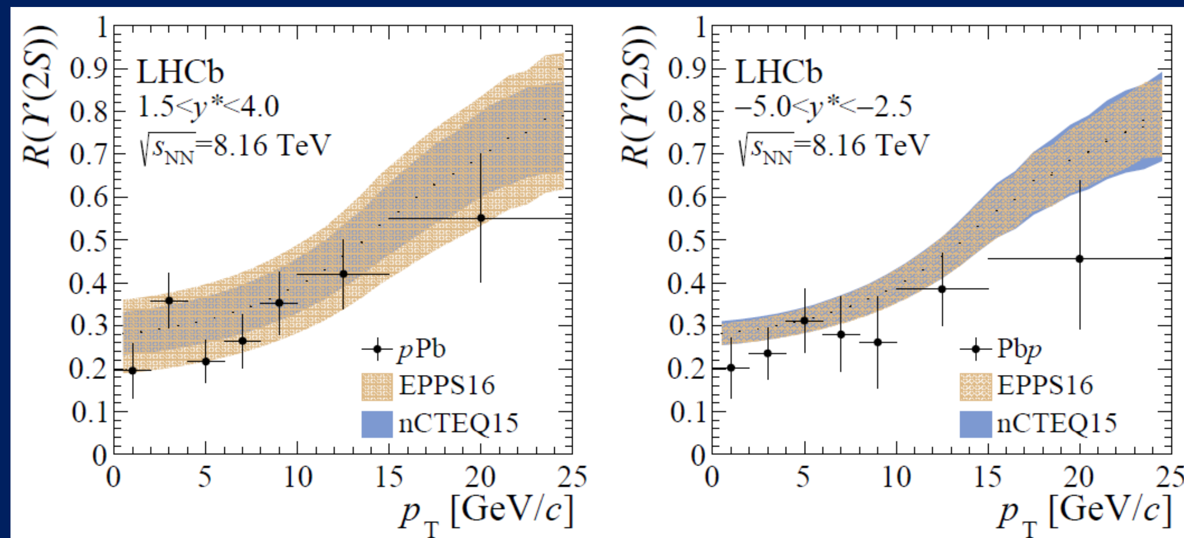


JHEP 1811, 194 (2018)

Bottomonia in pPb at 8 TeV: $R_{\Upsilon(2S)}$

Forward Backward

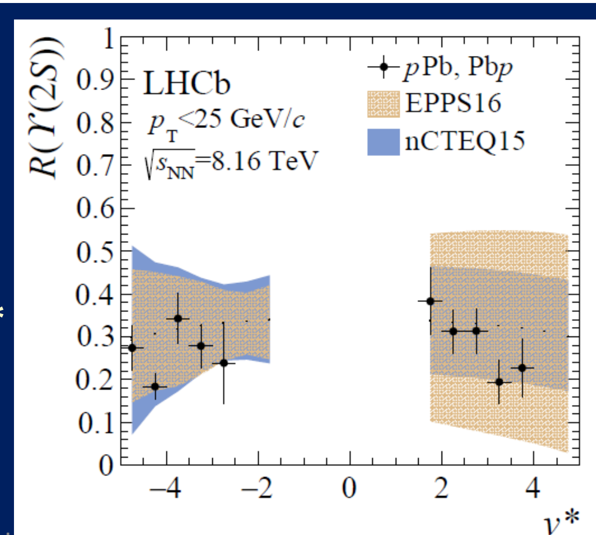
vs. p_T



Y(2S)-to-Y(1S) ratio

Hint of less agreement for backward production suggests comover interactions could be relevant?

vs. y*



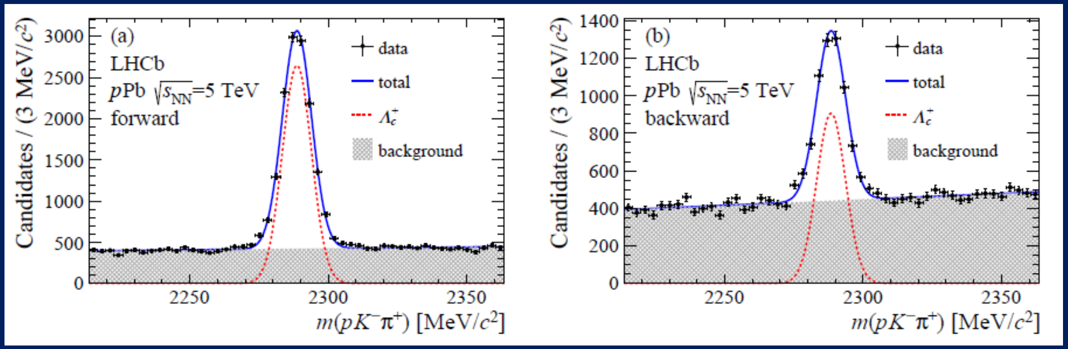
arXiv:1809.01404

Charmed baryons in pPb at 5 TeV: Prompt Λ_c^+

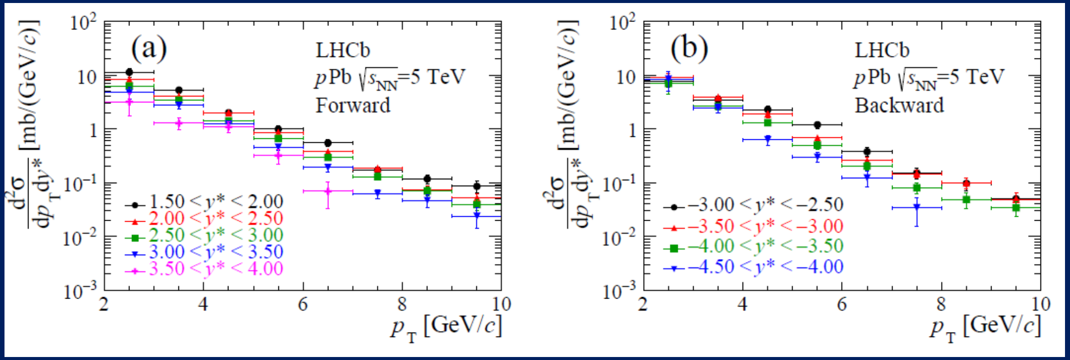
- Contribution from b decays subtracted using impact parameter distribution

- Single- and double-differential cross sections measured for forward (pPb) and backward (Pbp)

Forward Backward



Forward Backward



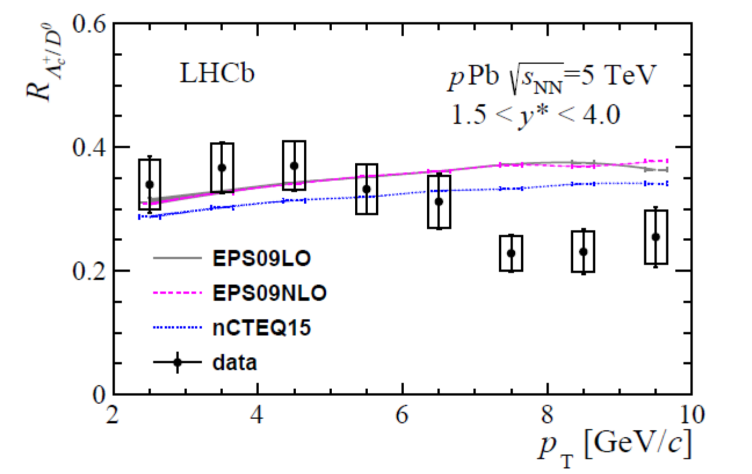
$\sigma(y^*, p_T)$

arXiv:1809.01404

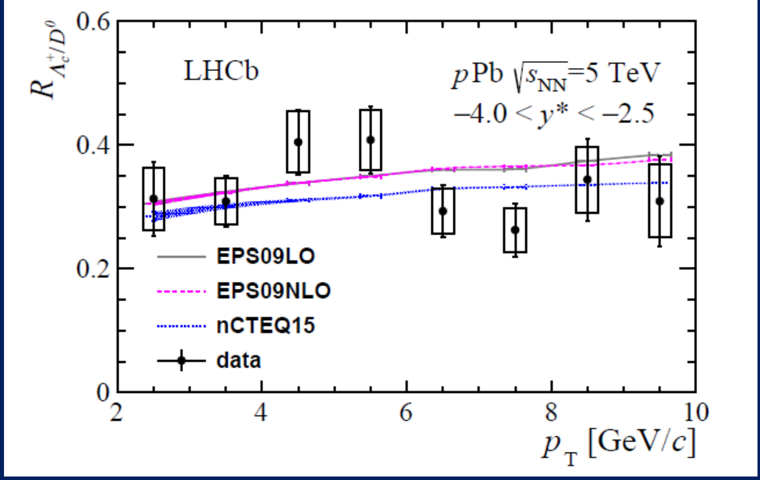
Charmed baryons in pPb at 5 TeV: $R_{\Lambda_c/D}$

- Λ_c^+/D^0 ratio important input to hadronization phenomenology: crucial comparison with other collision systems
  - In ratio most nPDF uncertainties cancel
- Baryon enhancement expected from production via coalescence in nuclear collisions, also affected by thermal properties of nuclear medium
  - Large charmed baryon enhancement observed in central AuAu collisions by STAR
  - But no enhancement seen in pPb collisions by ALICE

Forward



Backward



LHCb pPb:

- Substantial agreement with collinear factorization predictions based on pp data; no strong kinematic dependence observed
- Need update with 8 TeV data to determine dependence on event activity

arXiv:1809.01404

Charmed baryons in pPb at 5 TeV: $R_{\Lambda_c/D}$

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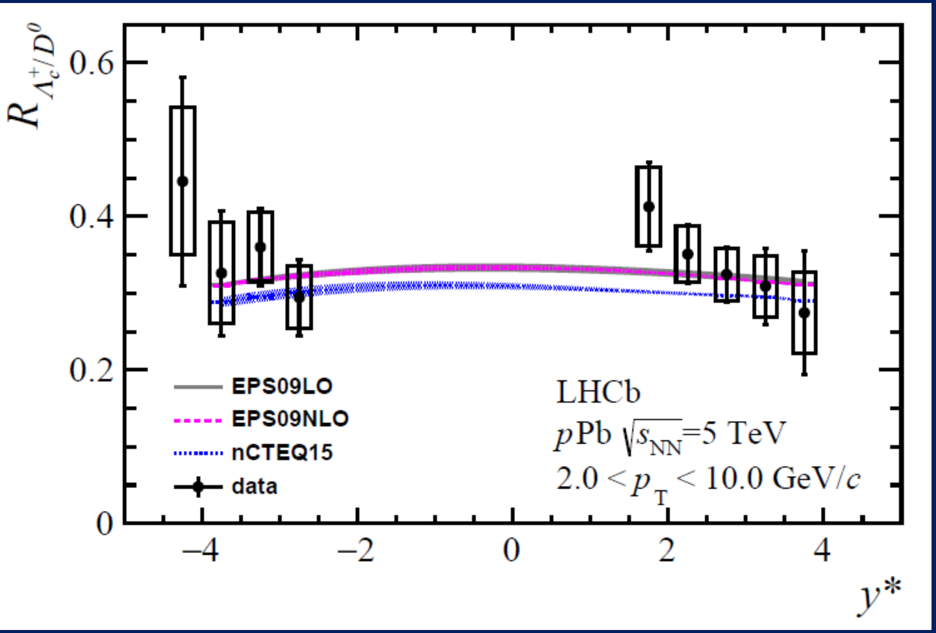


LHCb pPb:

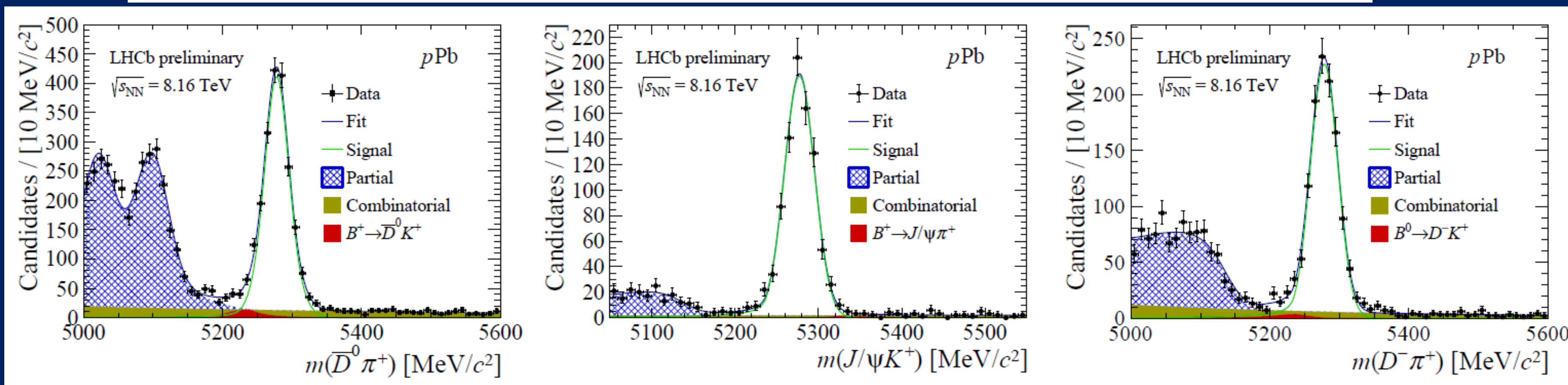
- Substantial agreement with collinear factorization predictions based on pp data; no strong kinematic dependence observed
- Need update with 8 TeV data to determine dependence on event activity

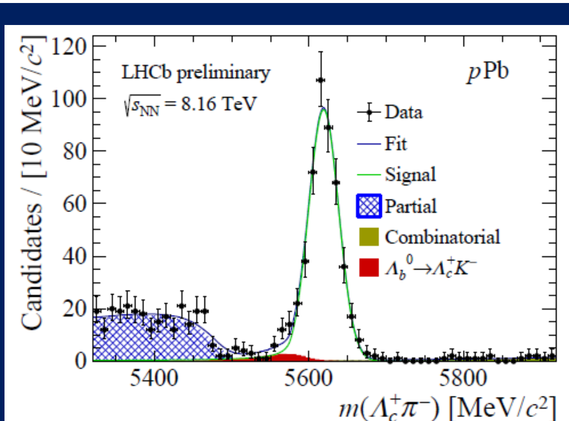
LHCb-CONF-2018-004

Open beauty in pPb at 8 TeV

Clean signals in exclusive decay modes:

$$B^+ \to \bar{D}^0\pi^+,\ B^+ \to J/\psi\, K^+,\ B^0 \to D^-\pi^+,\ \Lambda_b^0 \to \Lambda_c^+\pi^-$$





Decay	pPb	Pbp
$B^+ \to \bar{D}^0\pi^+$	1943 ± 58	1824 ± 64
$B^+ \to J/\psi\, K^+$	883 ± 32	905 ± 33
$B^0 \to D^-\pi^+$	1155 ± 39	886 ± 34
$\Lambda_b^0 \to \Lambda_c^+\pi^-$	484 ± 24	397 ± 23

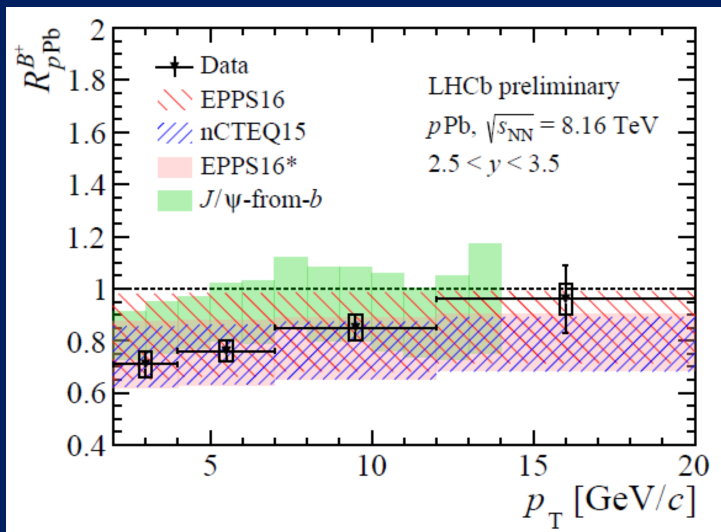
Yields

- First measurement of Λ_b^0 in nuclear collisions
- First measurement of B mesons in nuclear collisions down to low p_T (< hadron mass)

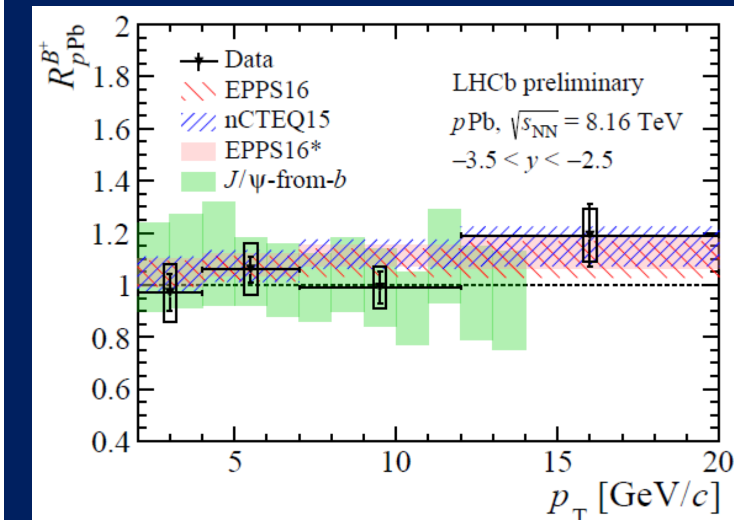
LHCb-CONF-2018-004

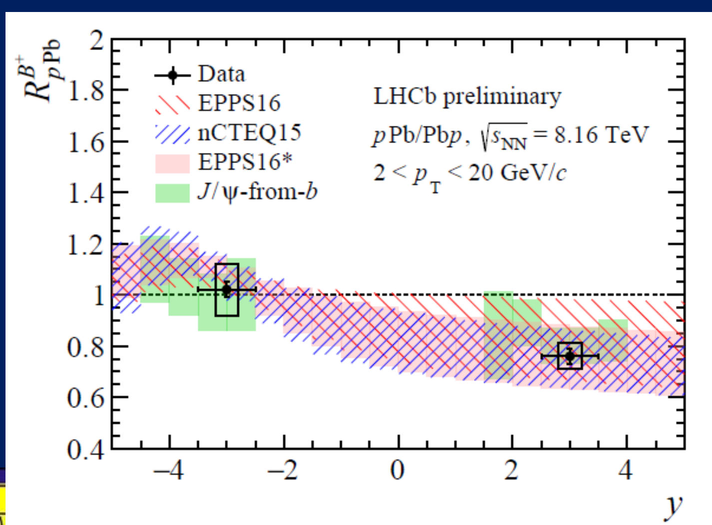
Open beauty in pPb at 8 TeV: $R_{pPb}^{B^+}$

Forward



Backward





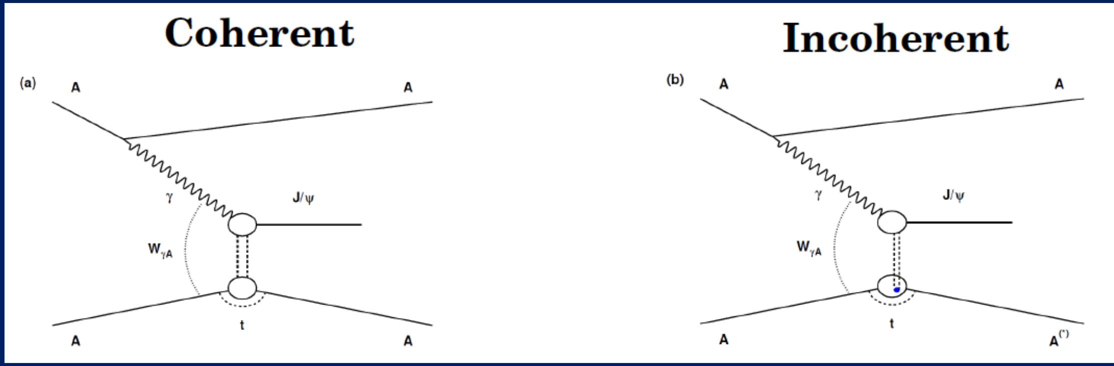
- Confirms suppression pattern observed in J/ψ from b, consistent with nPDF effects
- Calculations consistent with data, without interactions with comovers—more relevant for quarkonium than open heavy flavor
- Λ_b^0/B^0 ratio also measured and found consistent with nPDF effects

LHCb-CONF-2018-003

Ultraperipheral charmonium production in PbPb

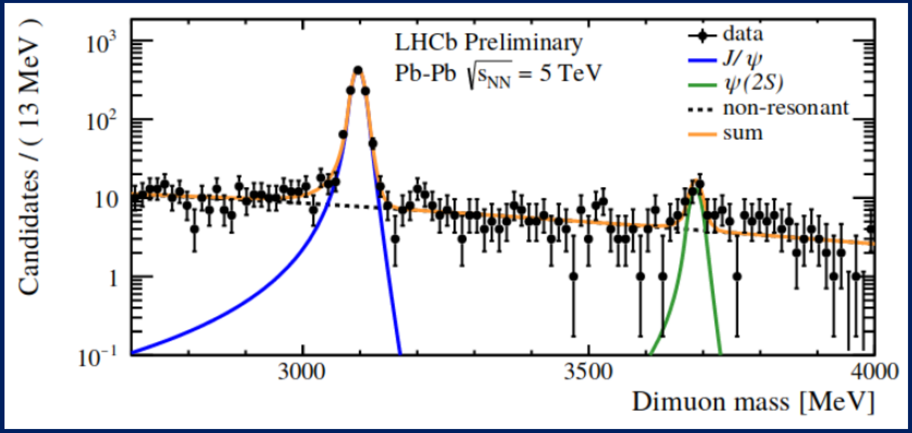
- First preliminary result by LHCb from PbPb collisions
- Goal is to study coherent J/ψ production in PbPb collisions at 5 TeV
- Hadron photo-production enhanced by photon flux ($\propto Z^2$) in PbPb
- Sensitive to gluon distribution down to x ~ 10^{-5}
- Integrated luminosity ~10 μb^{-1}
- J/ψ $p_T < 1$ GeV, rapidity $2.0 < y < 4.5$

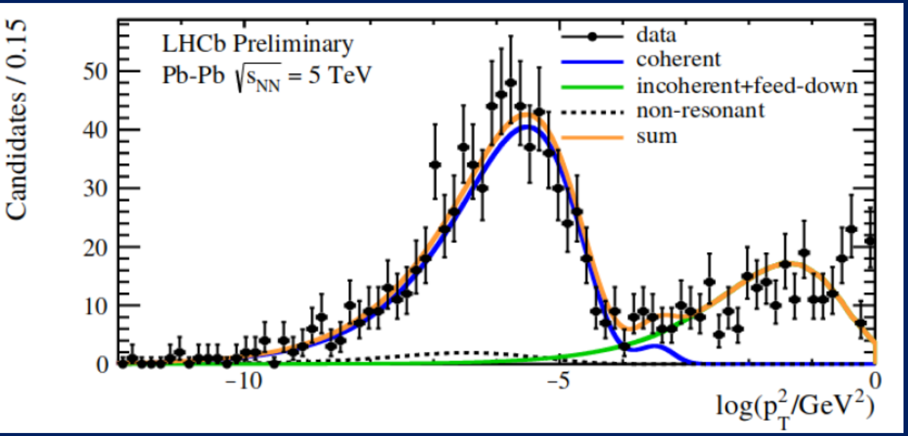
- The collisions are either
  - Coherent, where the photon couples coherently to all nucleons
  - Or incoherent, where the photon couples to a single nucleon

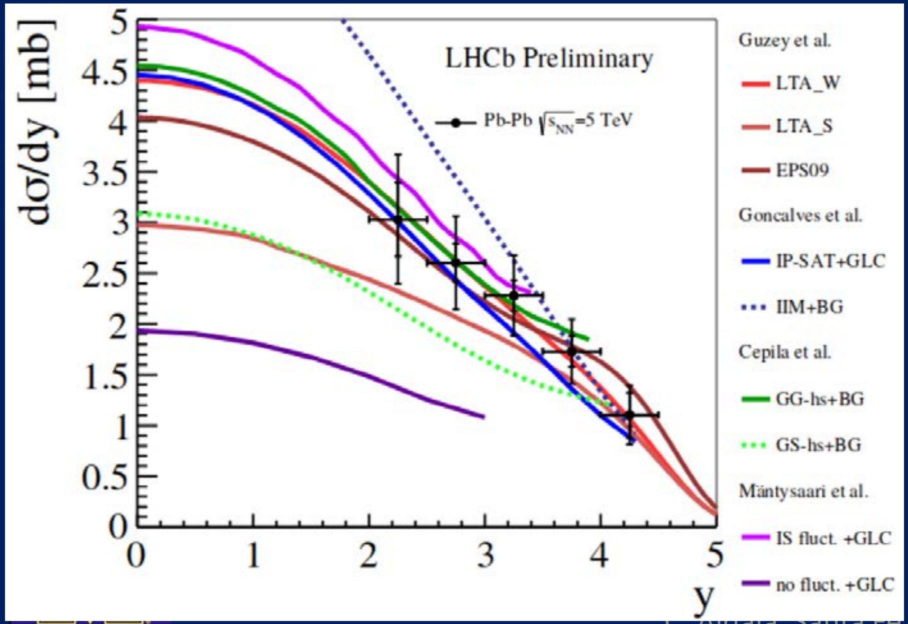


LHCb-CONF-2018-003

Ultraperipheral charmonium production in PbPb

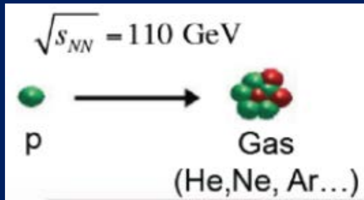




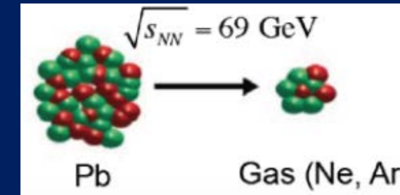


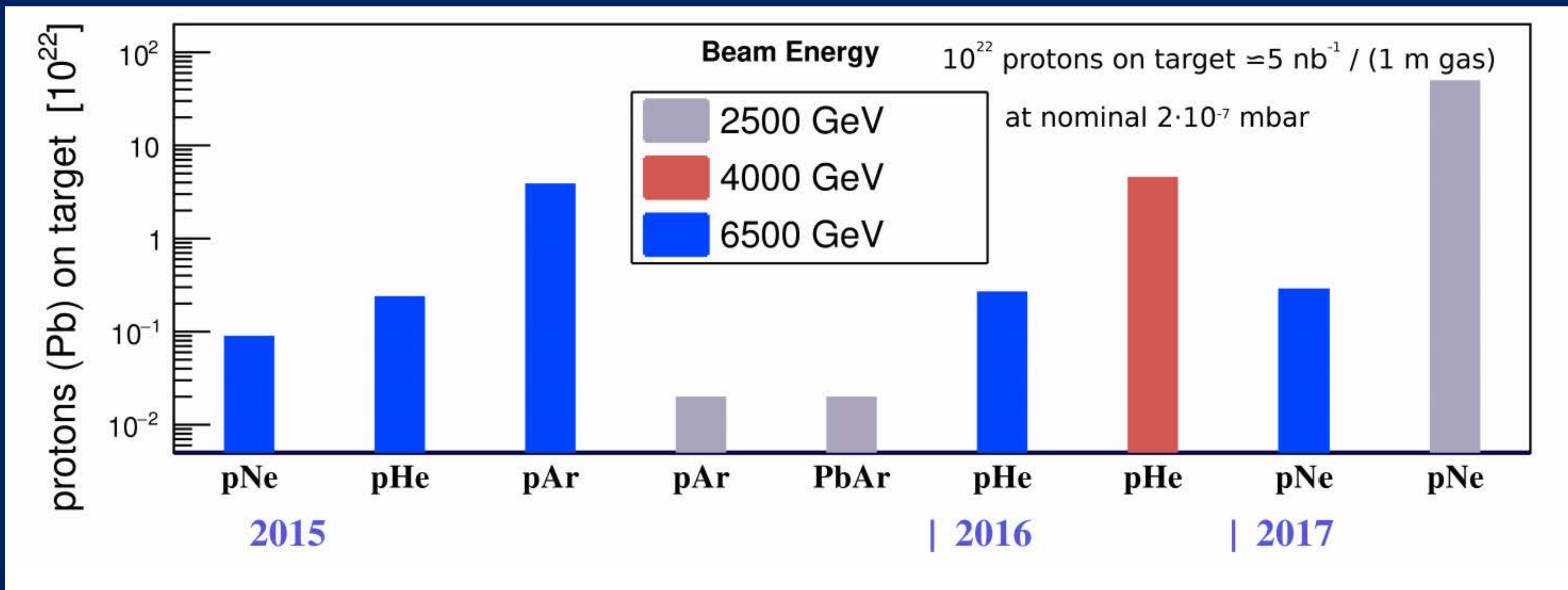
STARlight MC used for templates:
Comp. Phys. Comm. 212, 258 (2017)

- Coherent J/ψ cross section measured and compared to phenomenological models
- Limited statistics, but precision of measurement demonstrated
- Good prospects for 2018 data, with 20x more luminosity



Fixed-target samples

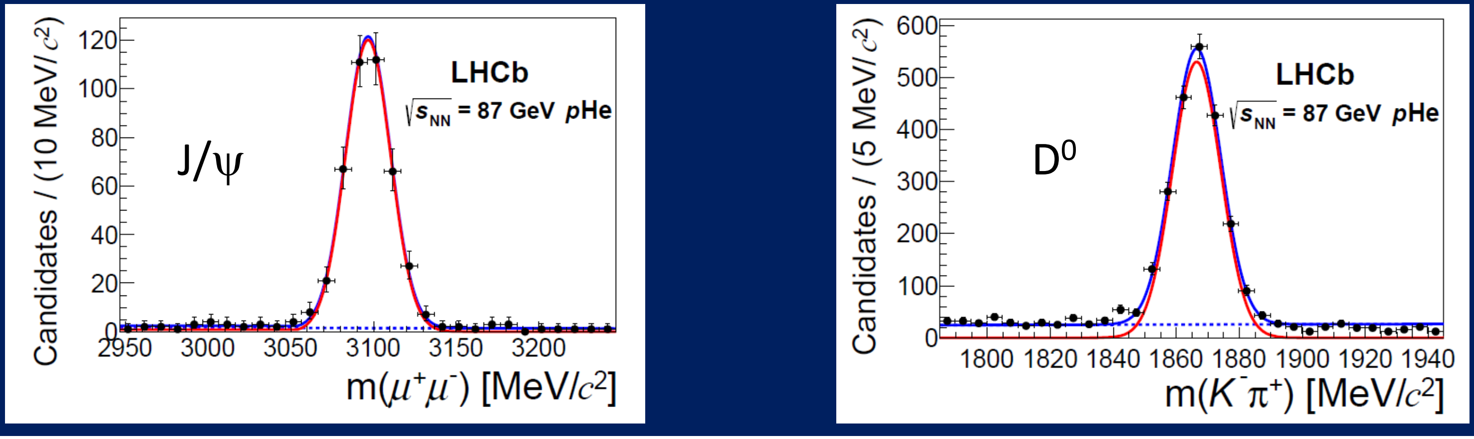


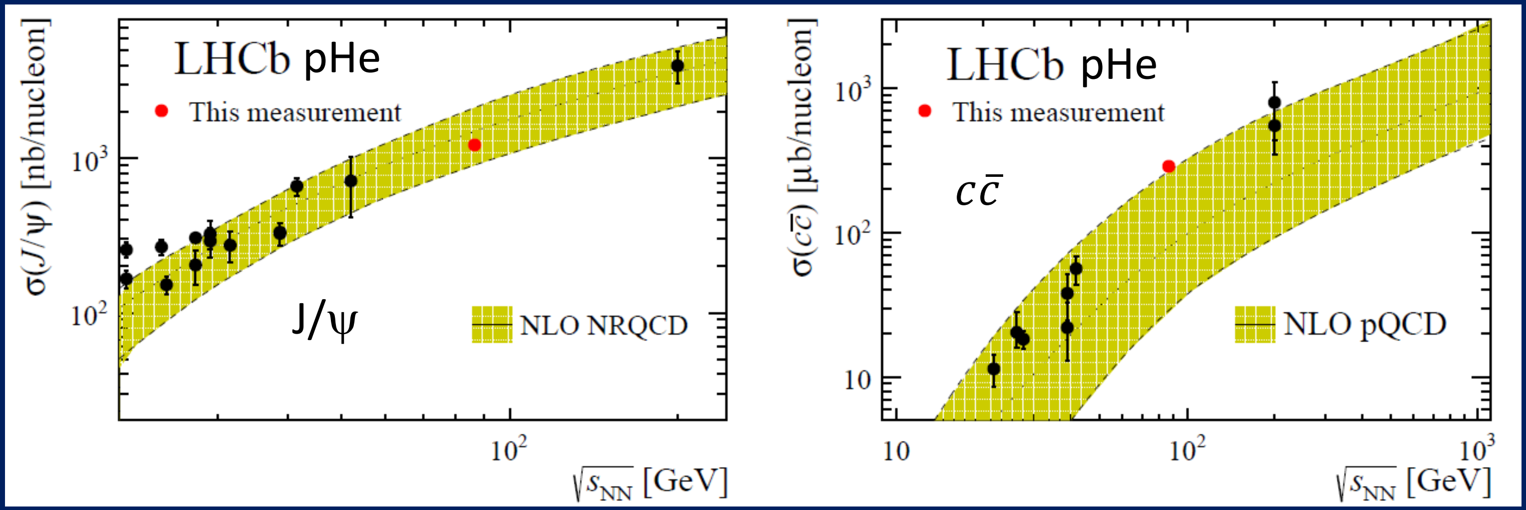


- First papers from the first samples collected in 2015 and 2016:
  - Antiproton production in pHe – PRL 121, 222001 (2018) (not shown here)
  - Charm production in pAr and pHe – arXiv:1810.07907

arXiv:1810.07907

Charm production in fixed targets



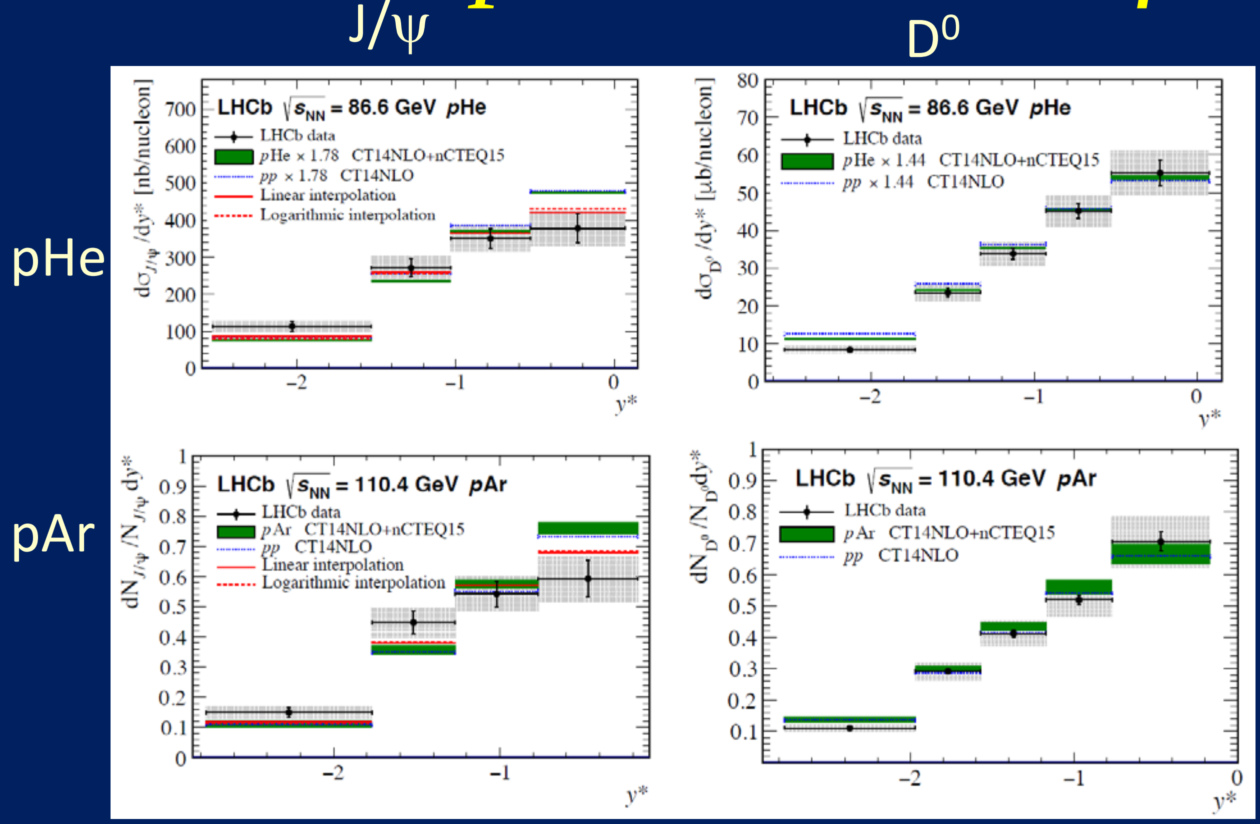


LHCb results in good agreement with world data,

- and with NLO NRQCD calculation based on fit to other world data (J/ψ)
- and with NLO pQCD predictions ($c\bar{c}$)

arXiv:1810.07907

Charm production in fixed targets



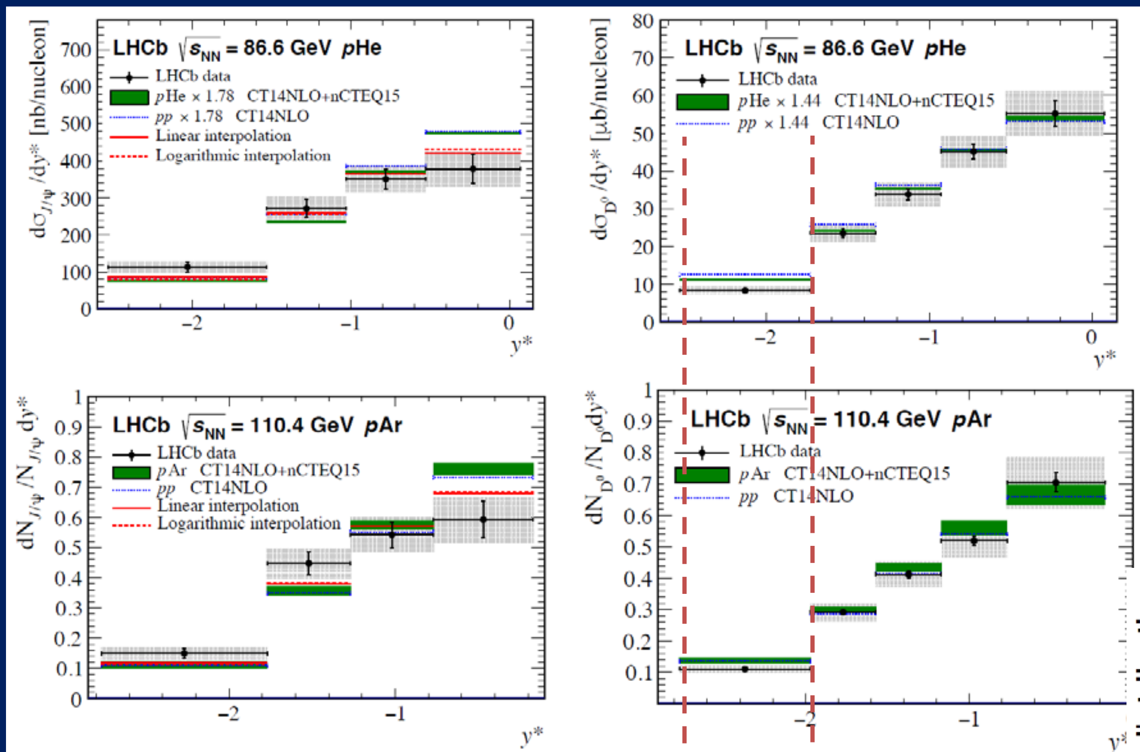
arXiv:1810.07907

Charm production in fixed targets

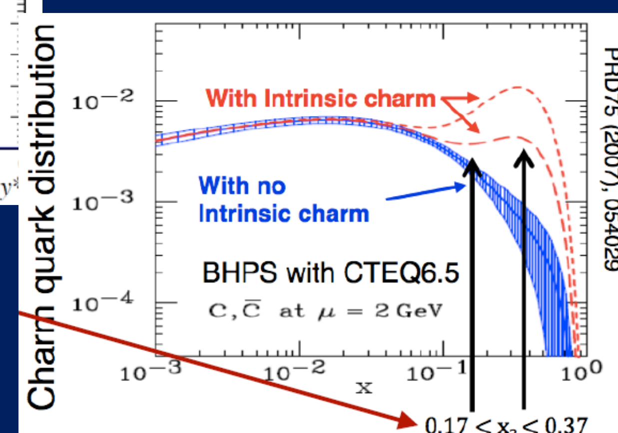
J/ψ D⁰

pHe

pAr



$-2.53 < y^* < -1.73$
$0.12 < x_2 < 0.37$



No evidence for sizable valence-like intrinsic charm contribution

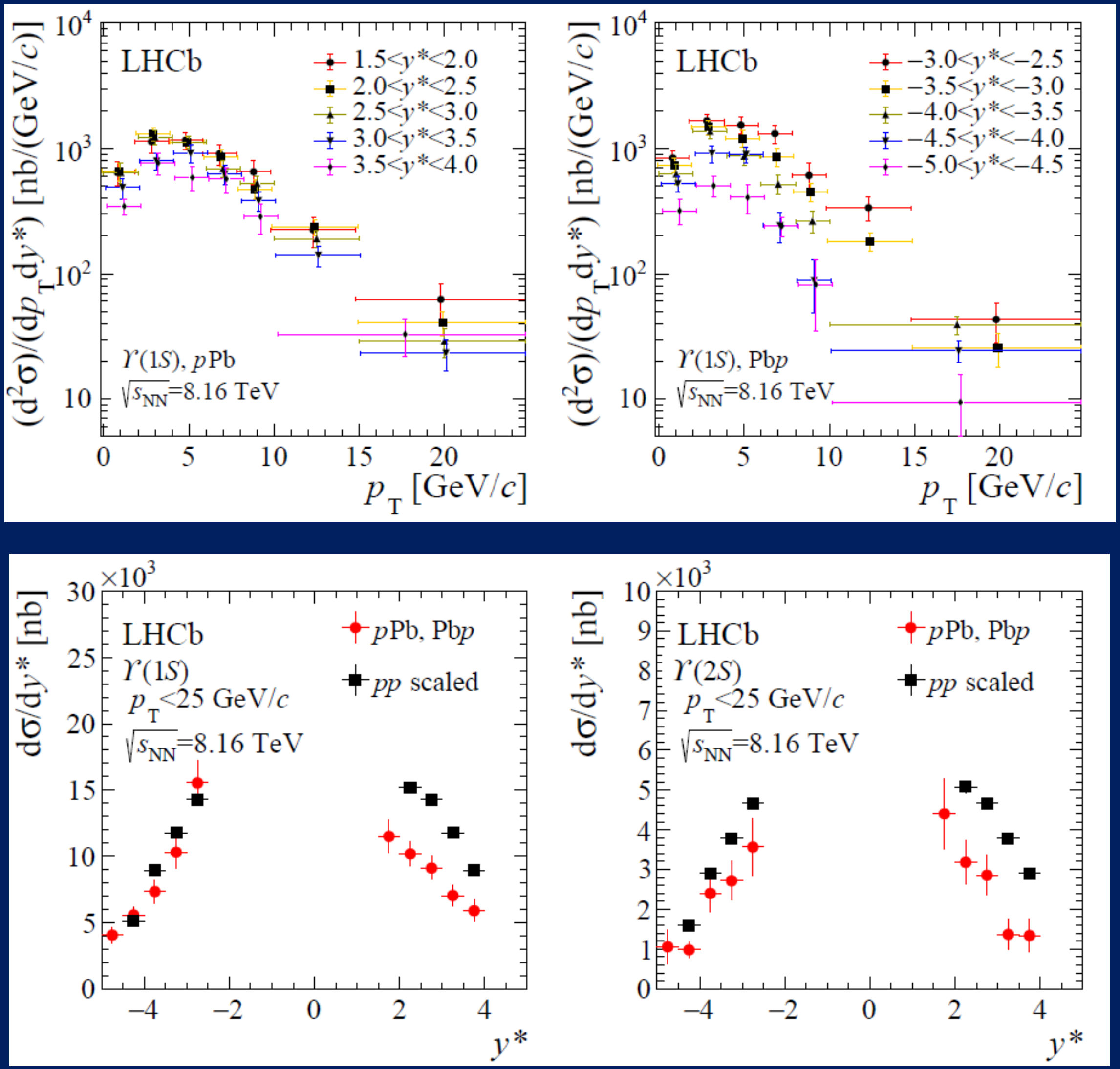
Summary and outlook

- LHCb has developed a growing heavy ion program, with very specific capabilities and unique acceptance at a hadron collider
  http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_IFT.html
- Much more data from Run 2 still to be analyzed!
  - Manpower limited
- Substantial development of the program in the near future for Run 3
  - Upgraded spectrometer
    - Improved centrality reach for PbA, PbPb due to upgraded tracking
  - Target storage cell: Up to 2 orders of magnitude higher luminosity, improved lumi determination, reduced backgrounds, wider variety of target species: H_2, D_2, He, N_2, O_2, Ne, Ar, Kr, Xe
- Stay tuned for more results in the near future!

Extra

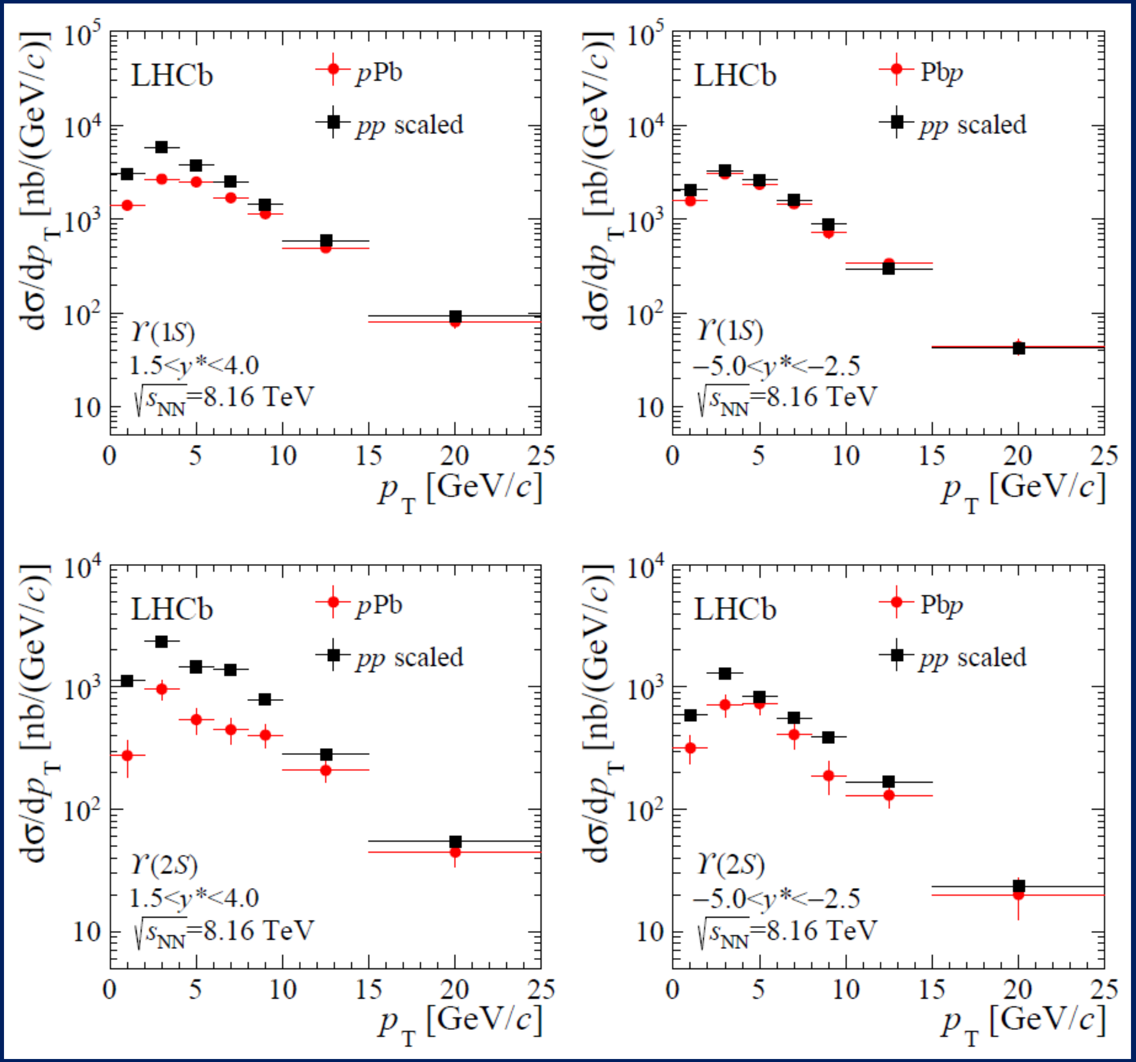
JHEP 1811, 194 (2018)

Bottomonia in pPb at 8 TeV



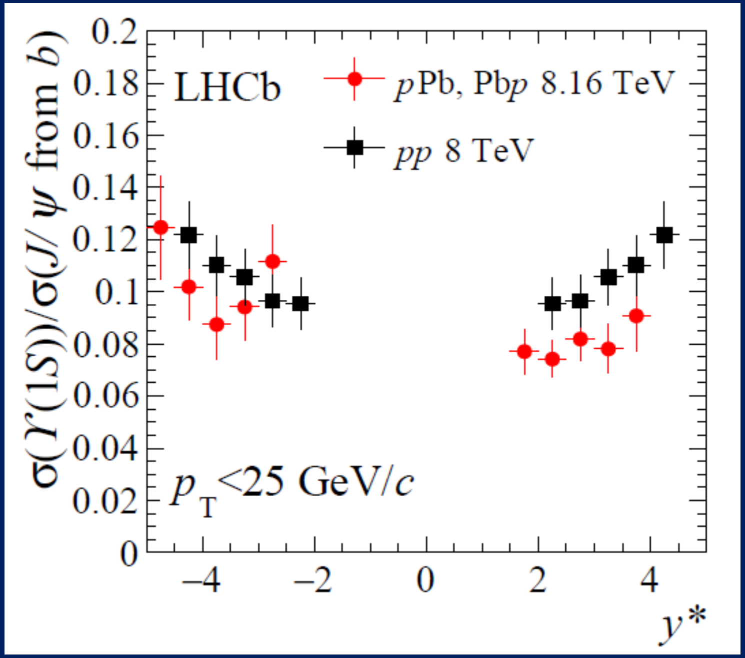
JHEP 1811, 194 (2018)

Bottomonia in pPb at 8 TeV



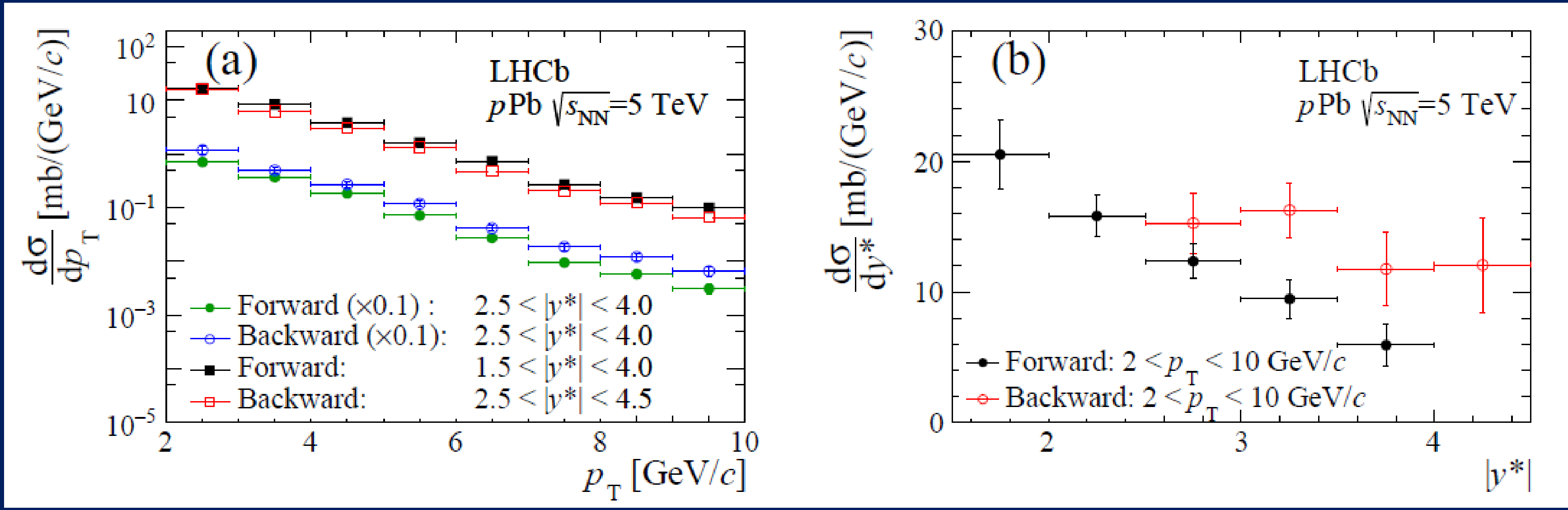
JHEP 1811, 194 (2018)

Bottomonia in pPb at 8 TeV



arXiv:1809.01404

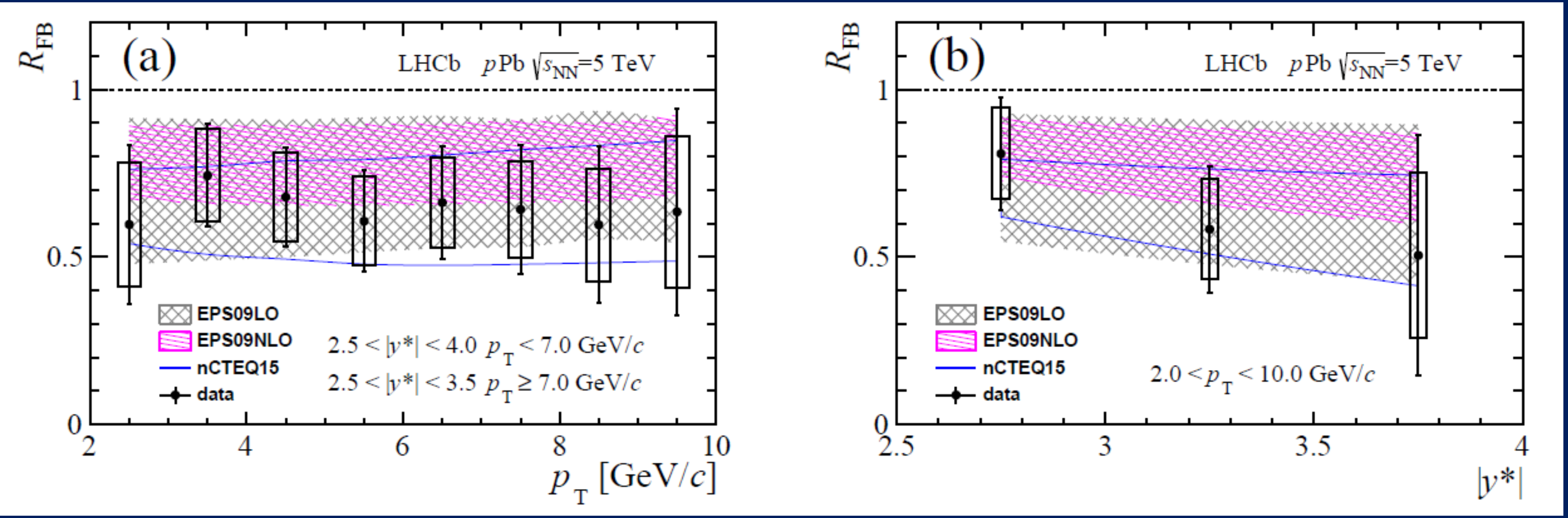
Charmed baryons in pPb: Prompt Λ_c^+



- Single-differential cross sections

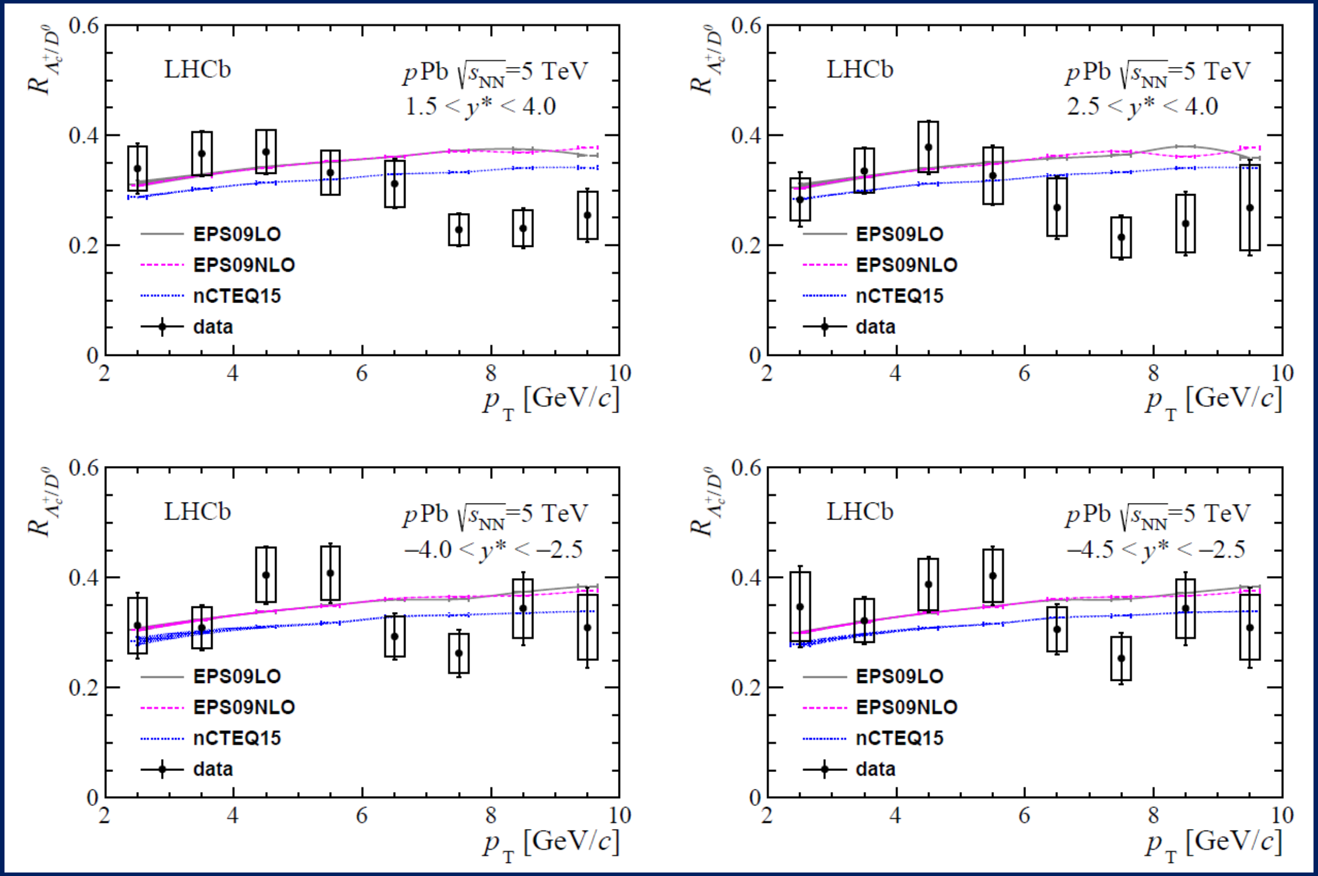
arXiv:1809.01404

Charmed baryons in pPb: Prompt Λ_c^+ R_{FB}



- R_{FB} < 1, consistent with calculations (within large uncertainties)

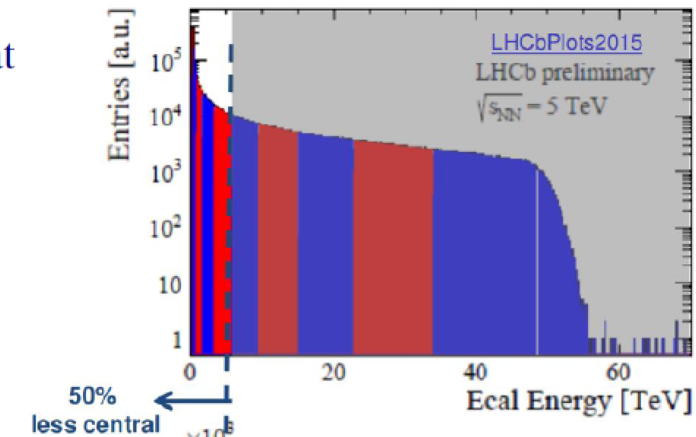
Charmed baryons in pPb: $R_{\Lambda_c/D}$



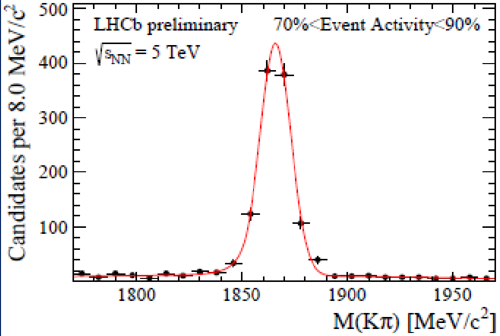
p_T dependence, 4 different bins in rapidity

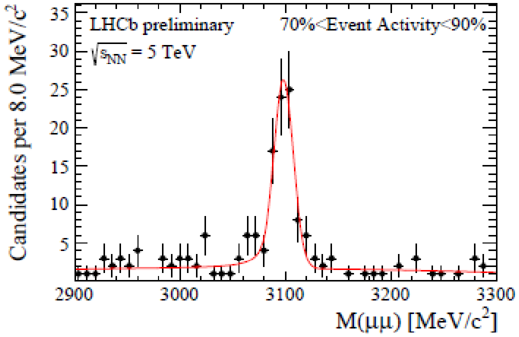
PbPb at LHCb

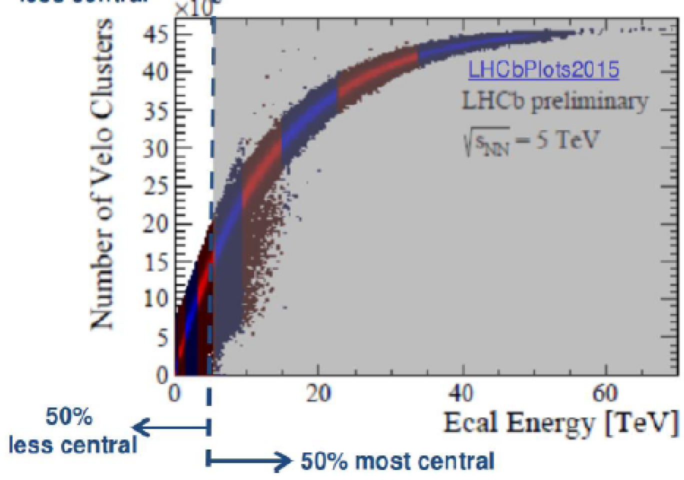
- LHCb entered PbPb data taking in 2015.
  About 10 μb recorded by LHCb
- Tracking performance studied: saturation occurs at about 50% centrality
- 2018 PbPb run just finished, collected 210μb



- Still interesting physics from peripheral collisions:
  - J/ψ photoproduction (low-p_T "excess")
  - J/ψ/D^0 ratio and Υ states vs centrality
  - flow for D^0







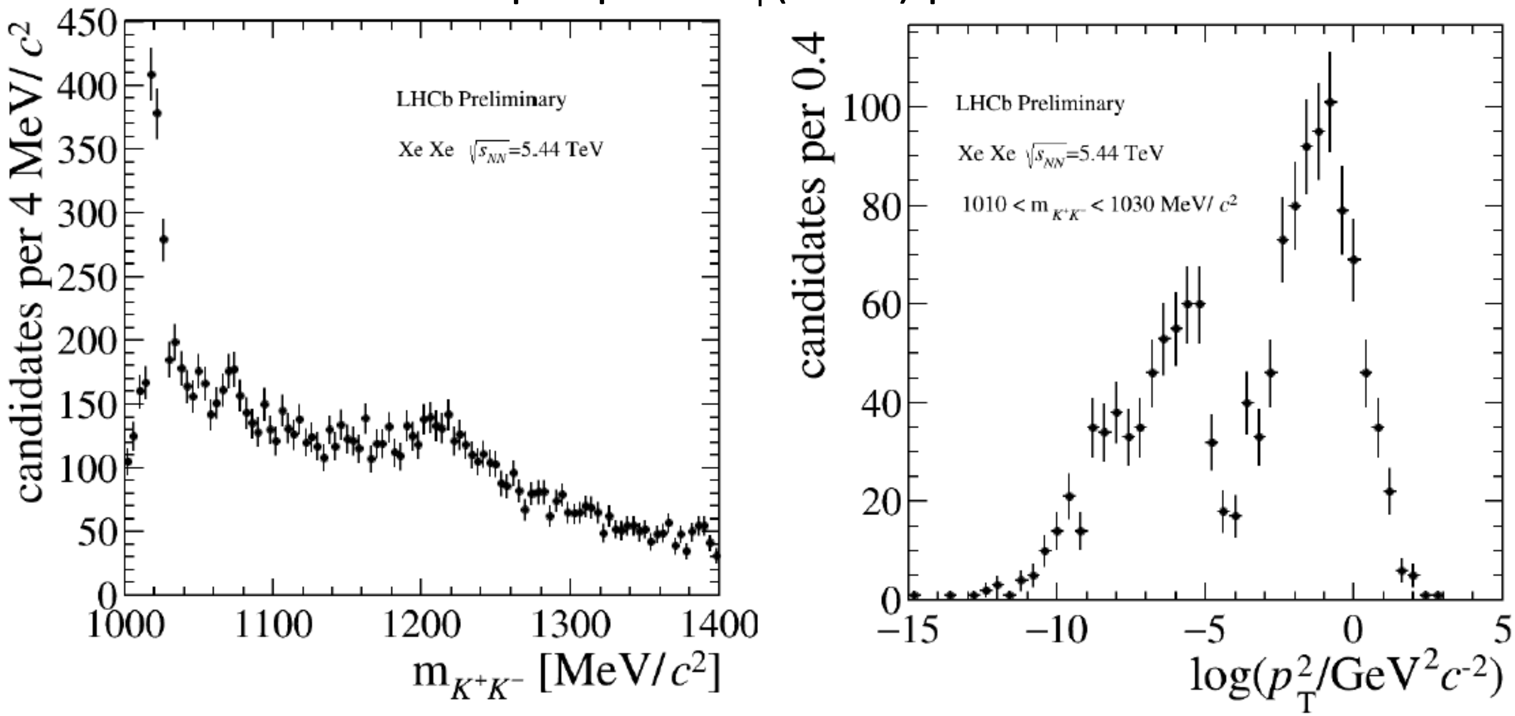
Slide from G. Graziani

XeXe Collisions @ 5.44 TeV

- We started analysing the XeXe Run collected in 2017
- Collisions at 5.44 TeV and Luminosity 0.2-0.4 μb^{-1}
- We had a preliminary look at K+K- pairs: nice features appearing
- Preliminary plots, no background subtraction, etc.
- Very small Q^2 in the decay and is produced pretty much at rest

- We need to measure different states in each system to constrain the uncertainties from theory

Ultraperipheral ϕ(1020) production

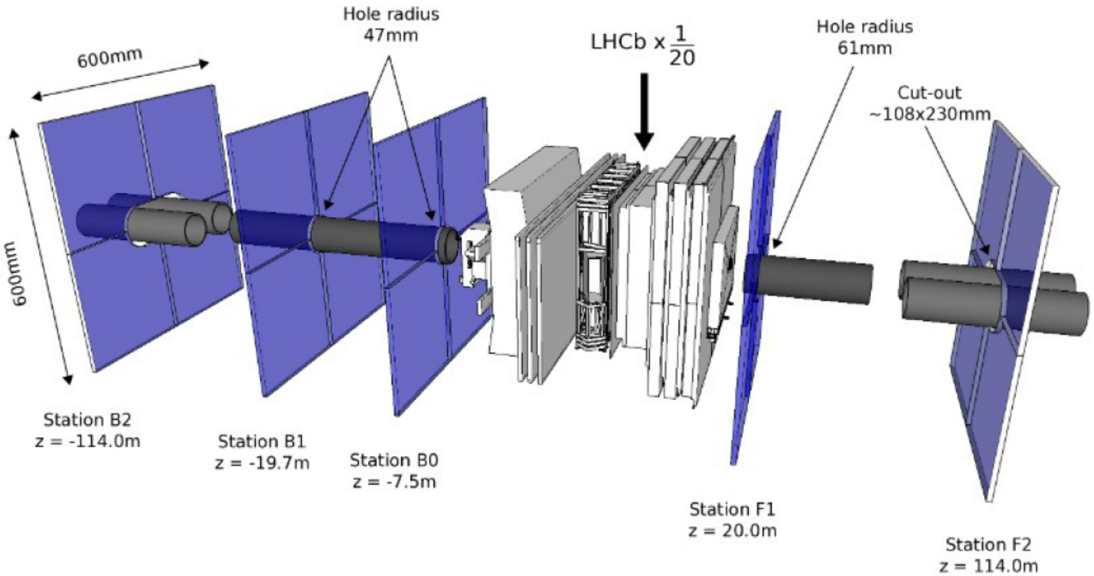


HeRSCheL veto detector for coherent exclusive production

The HeRSCheL detector: high-rapidity shower counters for LHCb

JINST 13 (2018) P04017

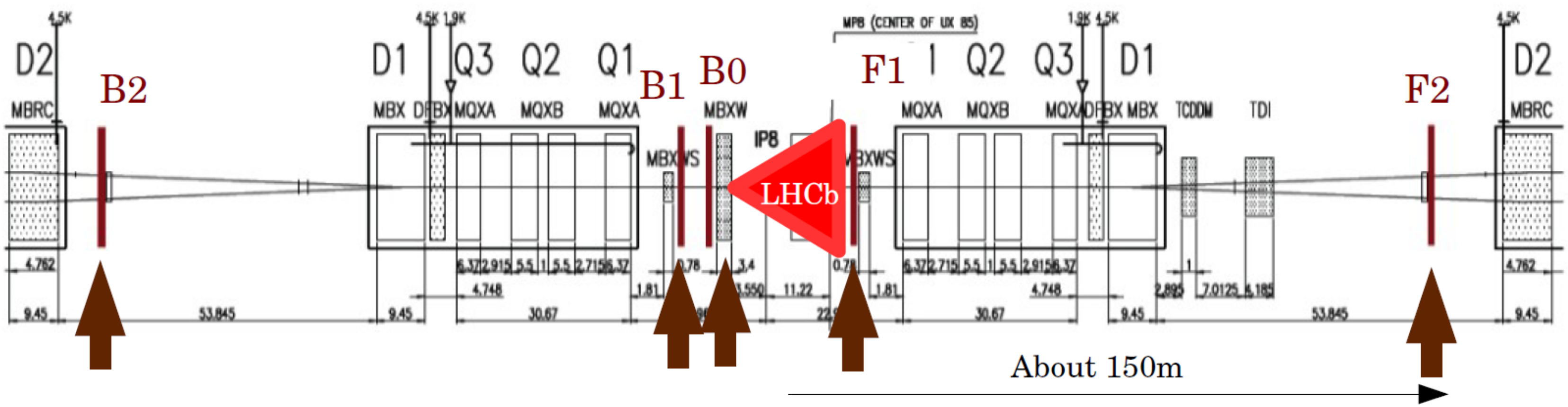
- Forward detector installed for Run2: increase η coverage
- Idea: scintillators in the tunnel where beampipe is accessible
- High Rapidity Shower Counters for LHCb: HERSCHEL
- Five planes of scintillators: 4 quadrants, 20mm thick
- Built in 2014 and installed at the beginning of 2015.
- Use same electronics of Preshower Detector
- Can be used to veto forward and backward activity



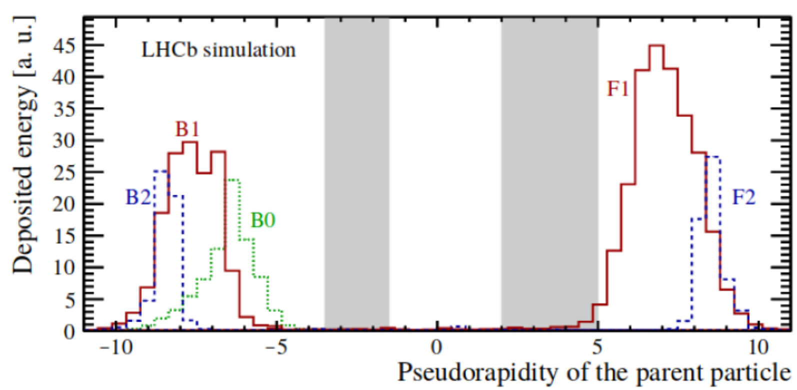
HeRSCheL veto detector for coherent exclusive production

- New detector installed for Run2 → Increase η coverage in the forward region

To get an idea on distances



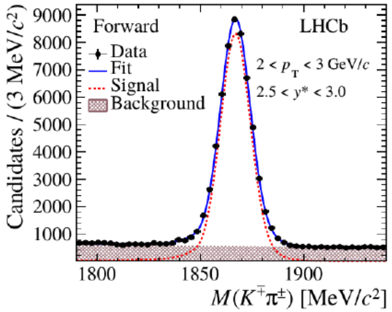
To get an idea on the coverage



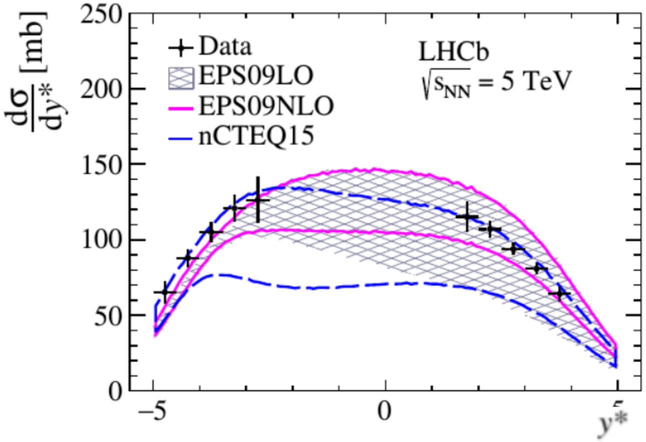
D^0 production in pPb collisions at 5.02 TeV

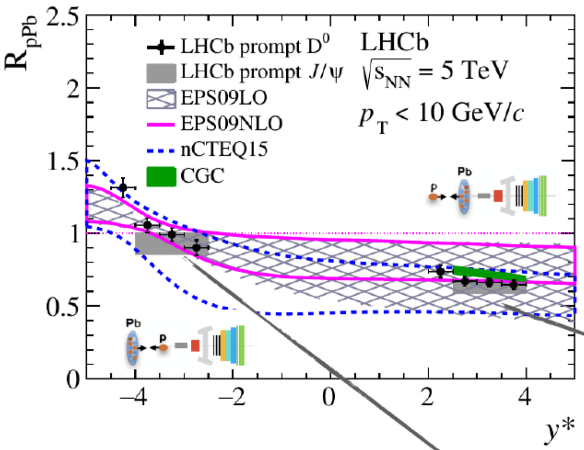
HF are unique probes in HI collision:

- *$m_Q >> \Lambda_{QCD}$ allows perturbative calculations*
- *$t_{prod} << t_{QGP}$ experiences the whole time evolution of the collision*



precision data





$$R_{pPb}(p_T, y^*) \equiv \frac{1}{A} \frac{d^2\sigma_{pPb}(p_T, y^*)/dp_T dy^*}{d^2\sigma_{pp}(p_T, y^*)/dp_T dy^*}$$

strong suppression wrt pp at forward rapidity (shadowing region)

increasing in the most backward bins (anti-shadowing region)

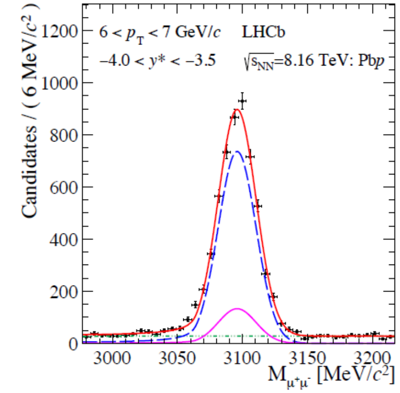
JHEP 10 (2017) 090

- *Both cross section (left) and Nuclear Modification Factor (right) are fairly described by nPDFs and Color Glass Condensate calculations*
- *LHCb data already used to constrain nPDFs in the unexplored region at low-x (PRL 121 (2018) 052004)*

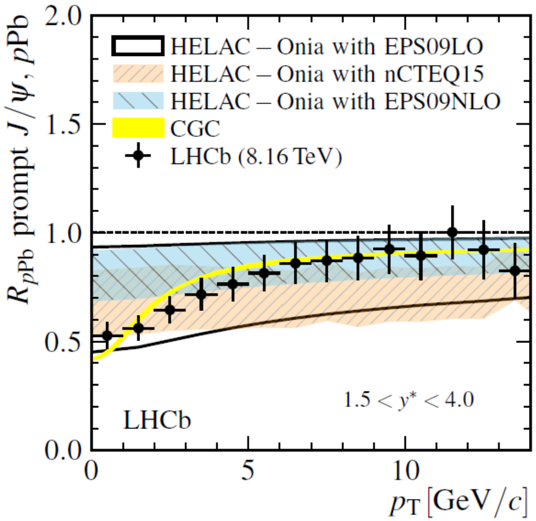
Slide from P. Di Nezza

J/ψ production in pPb collisions at 8.16 TeV

PLB 774 (2017) 159

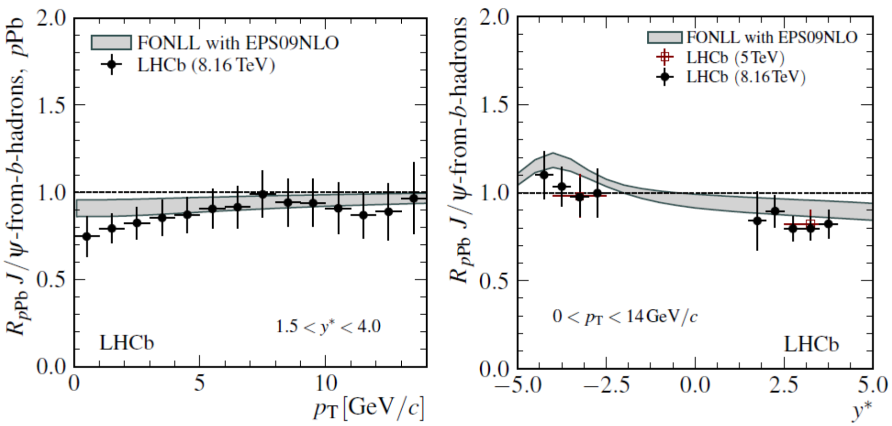


Prompt production



- strong suppression at forward rapidity: increasing from 0.5 at lowest p_T reaching 1 at highest p_T
- nPDFs & Color Glass Condensate calculations account for observations
- for rapidity dependence (not shown here) also the coherent energy-loss accounts for observation

Non-prompt production

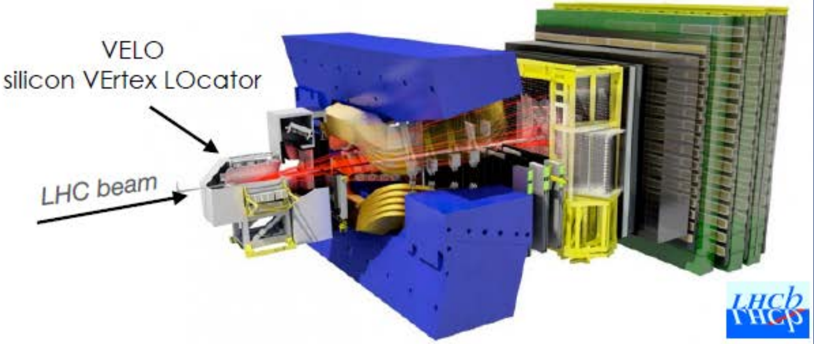


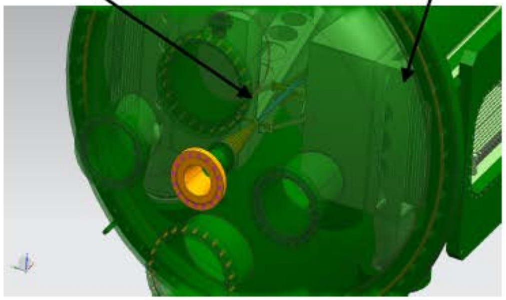
- first precise b-production measurement in pPb down to p_T~0
- suppression at forward rapidity, modification factor close to 1 at backward rapidity
- crucial input for the HI phenomenology

Very valuable constraint of nPDFs in unexplored area at low-x (PRL 121, 052004 (2018))

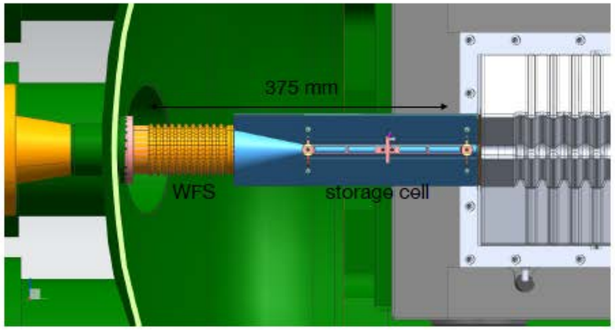
5

A real storage cell - **SMOG2** - will be installed during the LHC LS2 and start taking data from 2021





inside the LHC primary vacuum



Internal side view

- Increase of the luminosity by up to 2 orders of magnitude using the same gas load as SMOG
- Injection of $H_2, D_2, He, N_2, O_2, Ne, Ar, Kr, Xe$
- New Gas Feed System will give a strong improvement on the luminosity determination
- Well defined interaction region upstream the nominal IP: strong background reduction and also the possibility to run in parallel with pp collisions

HELAC-Onia: an automatic matrix element generator for heavy quarkonium physics

Comput. Phys. Commun. 184, 2562 (2013)

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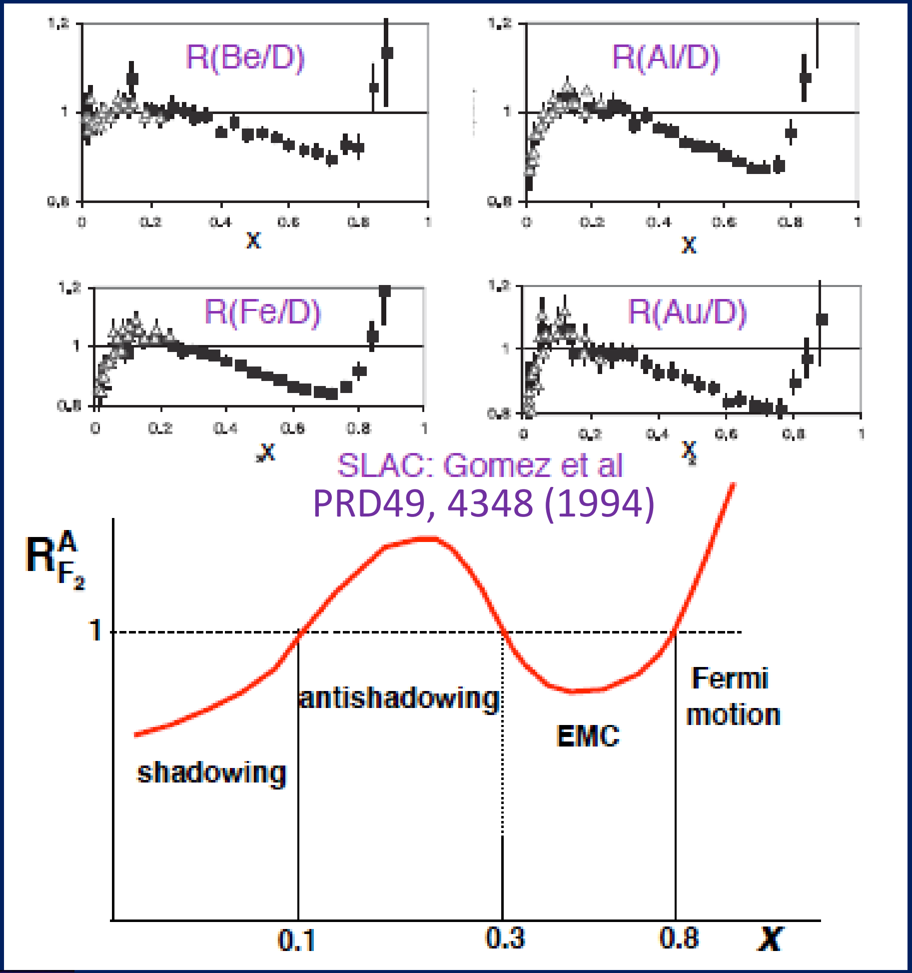
ABSTRACT

By the virtues of the Dyson-Schwinger equations, we upgrade the published code `HELAC` to be capable to calculate the heavy quarkonium helicity amplitudes in the framework of NRQCD factorization, which we dub `HELAC-Onia`. We rewrote the original `HELAC` to make the new program be able to calculate helicity amplitudes of multi P-wave quarkonium states production at hadron colliders and electron-positron colliders by including new P-wave off-shell currents. Therefore, besides the high efficiencies in computation of multi-leg processes within the Standard Model, `HELAC-Onia` is also sufficiently numerical stable in dealing with P-wave quarkonia (e.g. $h_{c,b}, \chi_{c,b}$) and P-wave color-octet intermediate states. To the best of our knowledge, it is a first general-purpose automatic quarkonium matrix elements generator based on recursion relations on the market.

Partonic momentum structure of nuclei: Not just superposed protons and neutrons



$$R_A \equiv \frac{1}{A}\frac{F_{2A}}{F_{2N}} \neq 1$$

- Ratio of cross section for e+A compared to scaled e+p collisions, shown vs. parton momentum fraction *x*
- Regions of both enhancement and depletion—only Fermi motion reasonably understood