Quarkonia and open heavy flavor production in *p*A collisions

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VIRTUAL CONFERENCE

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Recent open HF and quarkonia results

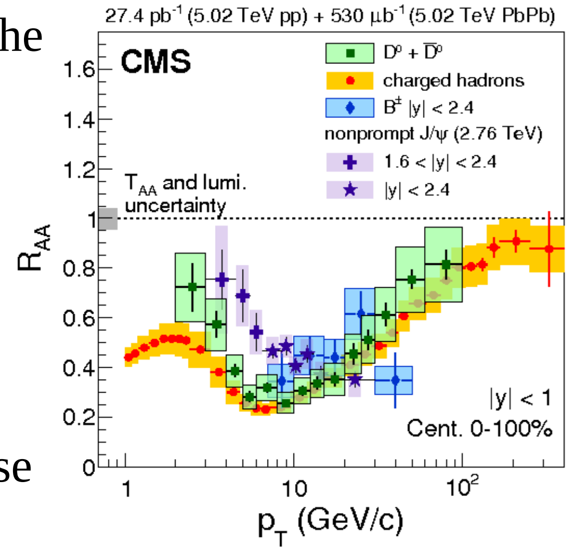
- Results in collider mode
  - Open heavy flavor in pPb collisions
    - Double charm pair production in pPb collisions at 8.16 TeV arXiv:2007.06945
    - Prompt $D^0$and Λ_c^+ production in pPb collisions D^0: LHCb-CONF-2019-004 (8.16 TeV) JHEP 10 (2017) 090 (5.02 TeV) Λ_c^+: JHEP 02 (2019) 102 (5.02 TeV)
    - B^+, $B^0$and Λ_b^0 production in pPb collisions at 8.16 TeV PRD99 052011 (2019)
  - Quarkonium in pPb collisions
    - J/ψ production in pPb collisions at 8.16 TeV PLB 774 (2017) 159
    - Upsilon $\Upsilon(nS)$ production in pPb collisions at 8.16 TeV JHEP 11 (2018) 194

- Results in fixed target mode
  - Charm production in pHe and pAr at 87, 110 GeV PRL 122 (2019) 132002

Heavy flavor in pPb collisions

- Heavy flavor states are sensitive probes to study the properties of the QGP created in AA collision.
  - Produced in the early stage of the collisions
  - Strong interaction with the medium
  - Quarkonium states sequential melting
  - Baryon/meson ratio in charm and bottom sectors probes hadronisation

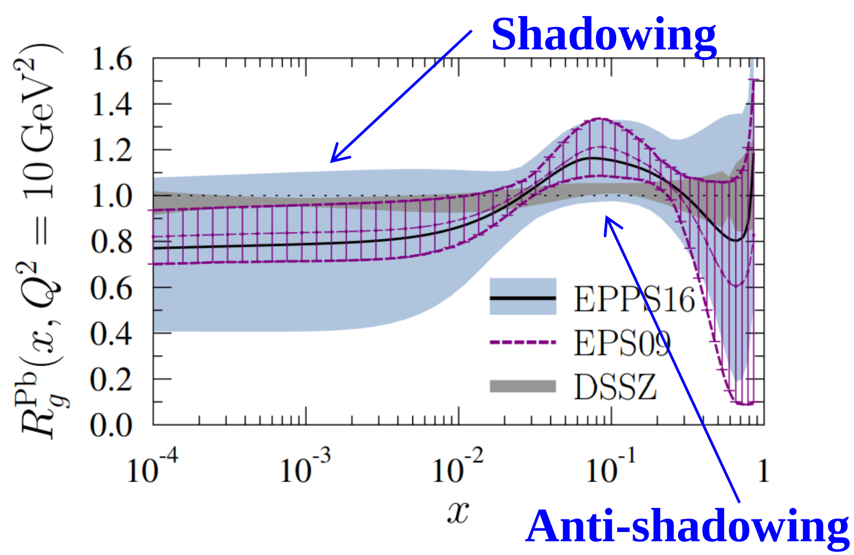
Phys. Lett. B 782 (2018) 474



- Heavy flavor in pA collisions provide baseline measurements to disentangle cold nuclear matter effects from effects of hot and dense medium.

- LHCb well suited for such measurements:
  - Heavy flavor measurement down to p_T close to 0
  - Separation of prompt and b decay components

- Cold Nuclear Matter effects
  - Initial state:
    - Modification of nuclear PDF
    - Gluon saturation
  - Multiple scattering of partons in the nucleus
  - Final state

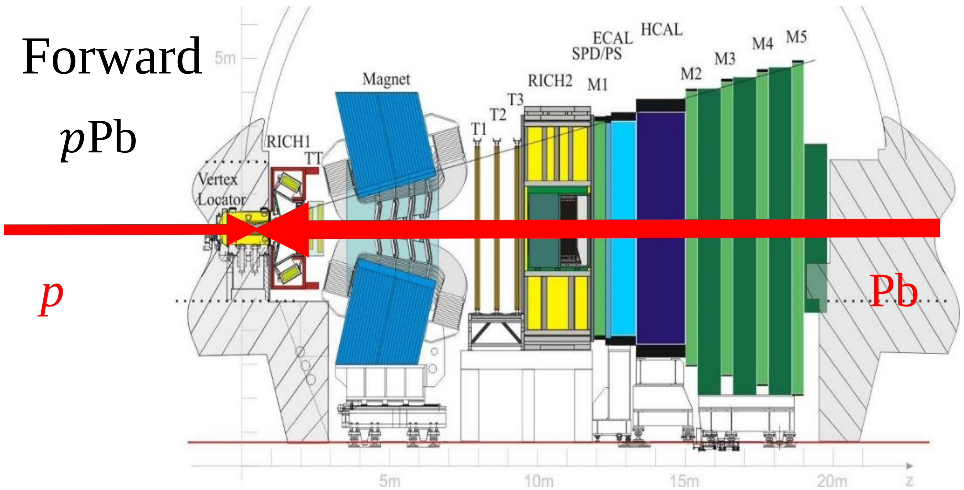


arXiv:1802.05927

LHCb pPb datasets

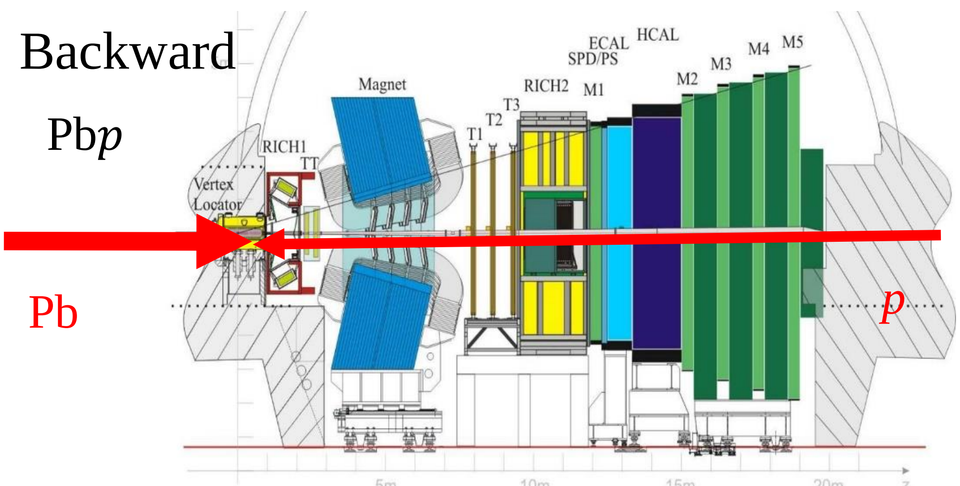
Forward

pPb

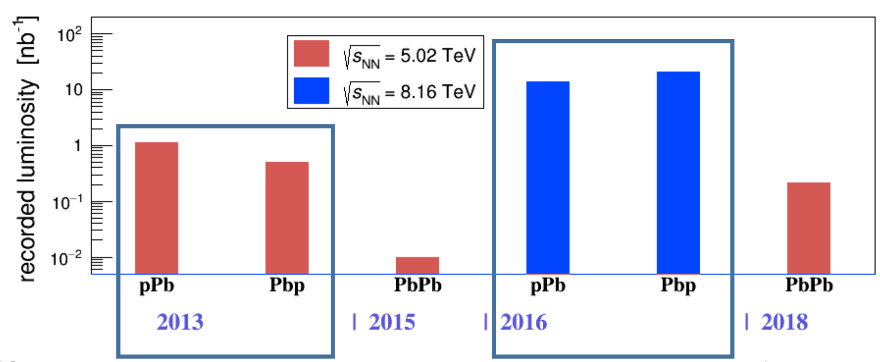


Backward

Pbp



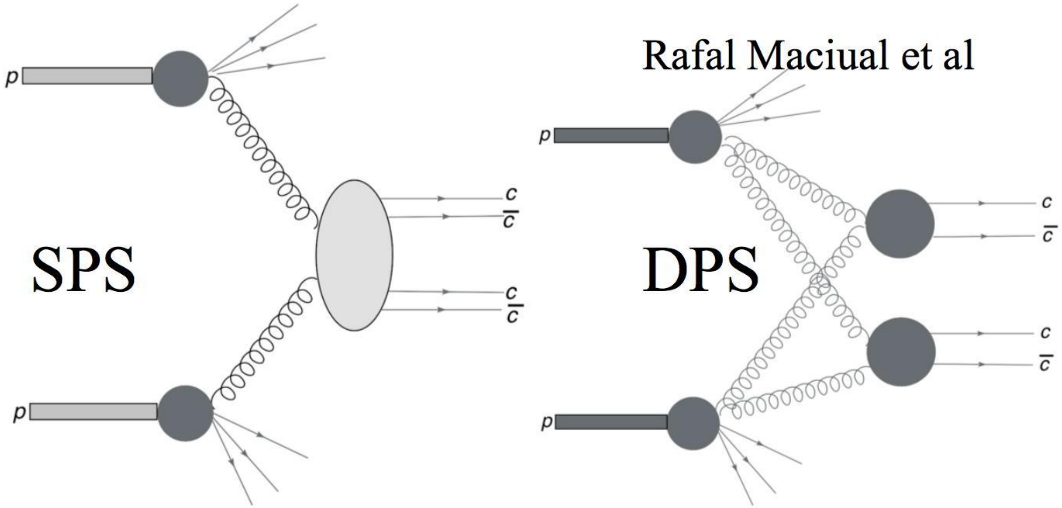
- Rapidity Coverage
  - y^*: rapidity in nucleon-nucleon cms
  - $y_{\text{cms}} = \pm 0.465$
  - Forward: $1.5 < y^* < 4.0$
  - Backward: $-5.0 < y^* < -2.5$
  - Common region: $2.5 < |y^*| < 4.0$
- $\sqrt{s_{NN}} = 5.02$ TeV (2013)
  - pPb (1.06 nb^{-1}) + Pbp (0.52 nb^{-1})
- $\sqrt{s_{NN}} = 8.16$ TeV (2016)
  - pPb (13.6 nb^{-1}) + Pbp (21.8 nb^{-1})

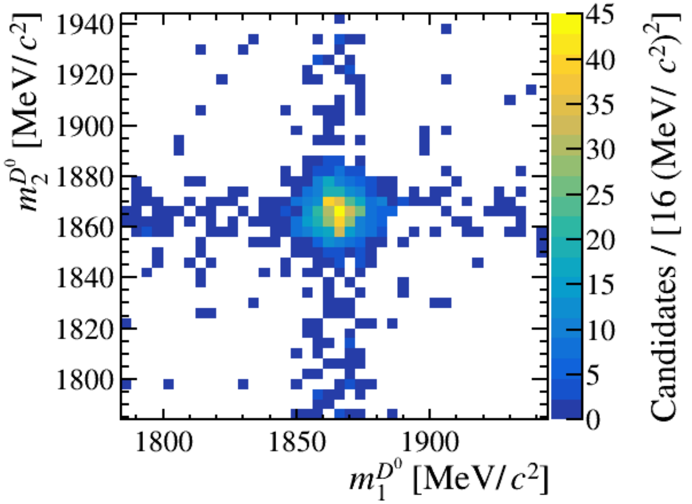


JINST 3 (2008) S08005

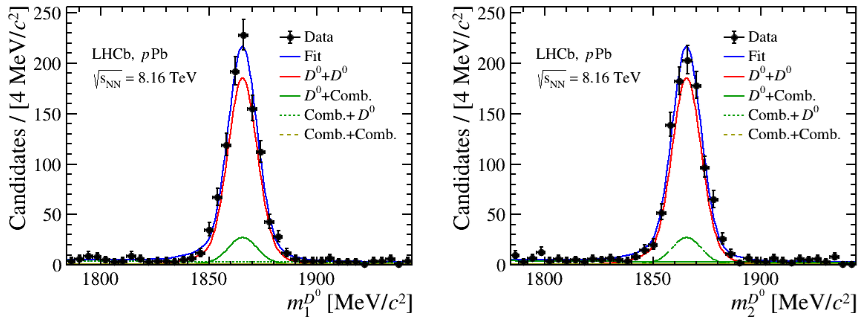
Double charm production in pPb at 8.16 TeV

- Single Parton Scattering vs. Double Parton Scattering





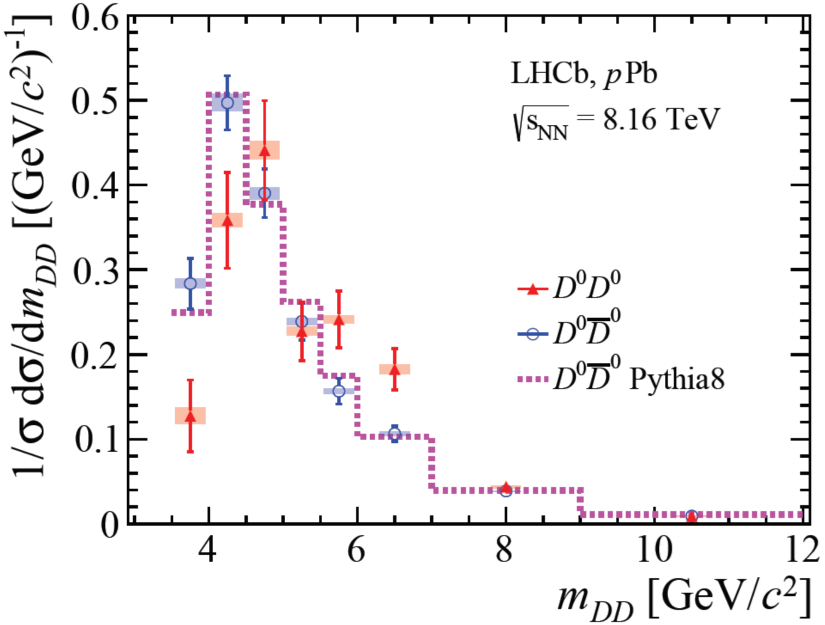
- DPS is predicted to be enhanced in heavy ion collisions
- Like-Sign (D^0D^0):
  - Expect DPS contribution
  - Uncorrelated if no parton correlation
- Opposite-sign ($D^0\overline{D}^0$):
  - Charm hadrons formed from $c\bar{c}$ via SPS

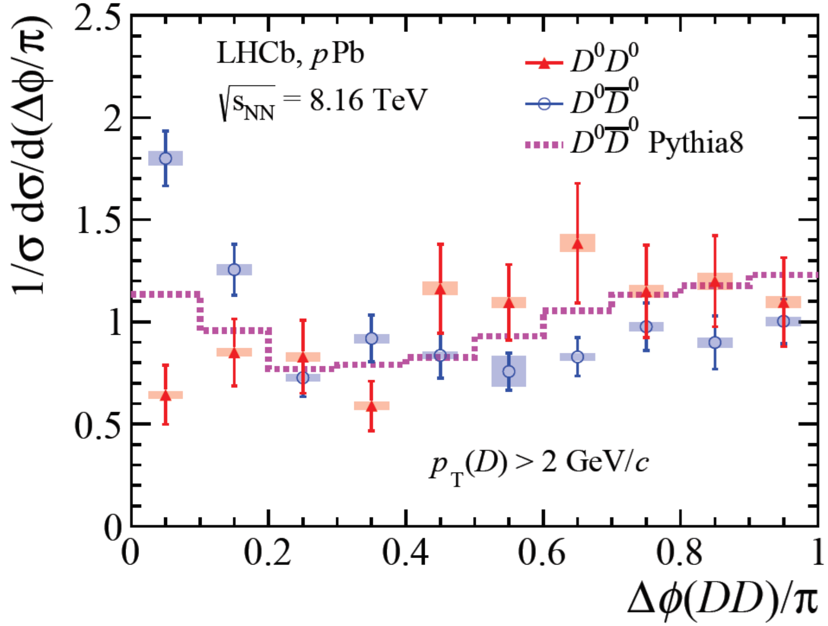


arXiv:2007.06945

Double charm pair correlations in pPb

- double charm hadron invariant mass $m_{D_1 D_2}$:
  - Hints of difference between like-sign and opposite-sign pairs
  - Opposite-sign pairs consistent with Pythia8
- azimuthal angle between the charm hadron pair $\Delta\phi(DD)$:
  - Difference in like-sign and opposite-sign pairs
  - Near side peak at $\Delta\phi \sim 0$ for opposite-sign pairs
  - Like-sign pairs consistent with flat distribution



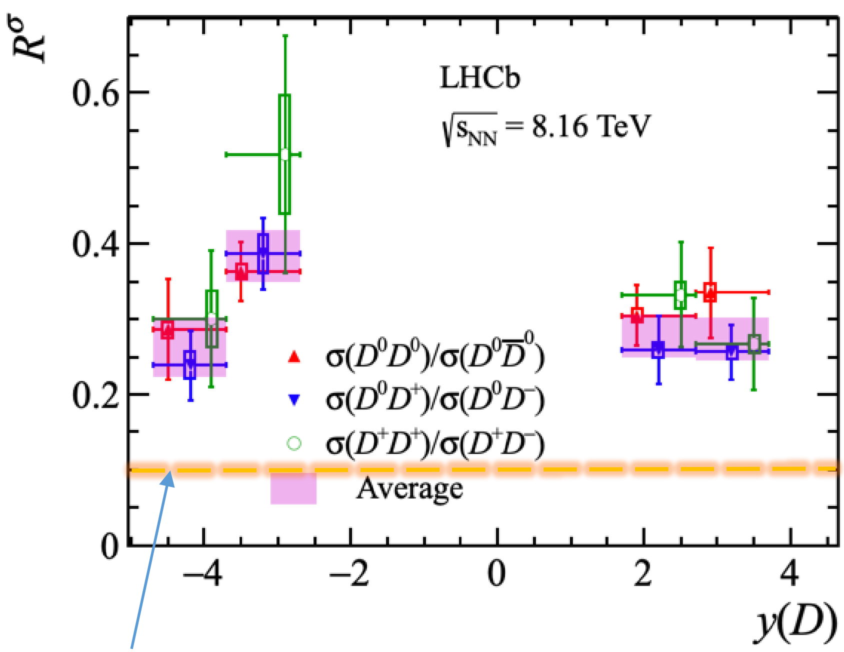


arXiv:2007.06945

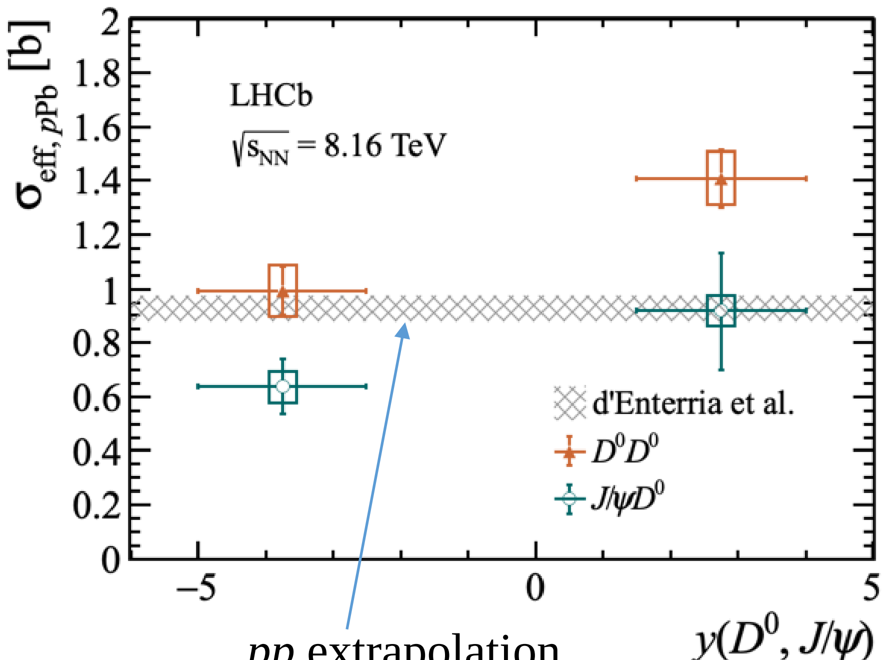
Double charm pair production in *p*Pb

$$\sigma_{DPS}^{AB} = \frac{\sigma^A \sigma^B}{\sigma_{eff}}$$

- like-sign/opposite-sign ratio enhanced in *p*Pb compared to *pp*
- DPS effective cross-section $\sigma_{\text{eff},\, p\text{Pb}}$ compatible with extrapolation from *pp* ~ 0.9*b*
    - ***DPS enhanced by a factor of 3 in pPb compared to pp***
- Smaller $\sigma_{\text{eff},\, p\text{Pb}}$ for $J/\psi D$ compared to DD pairs
- $\sigma_{\text{eff},\, p\text{Pb}}$ in *p*Pb > Pb*p*: indication of enhanced DPS production in Pb*p* compared to *p*Pb



Measured *pp* values JHEP06,141(2012)

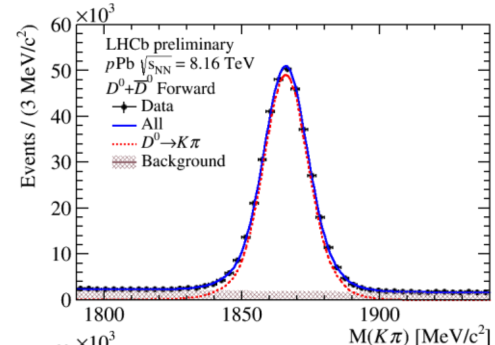


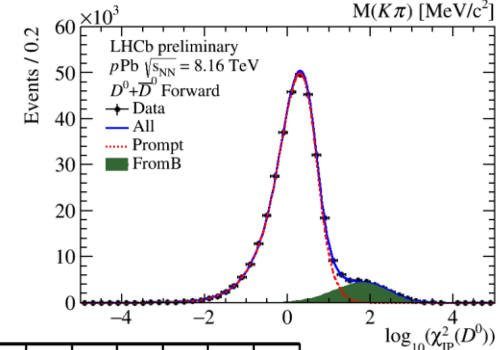
pp extrapolation
PLB718 (2013) 1395

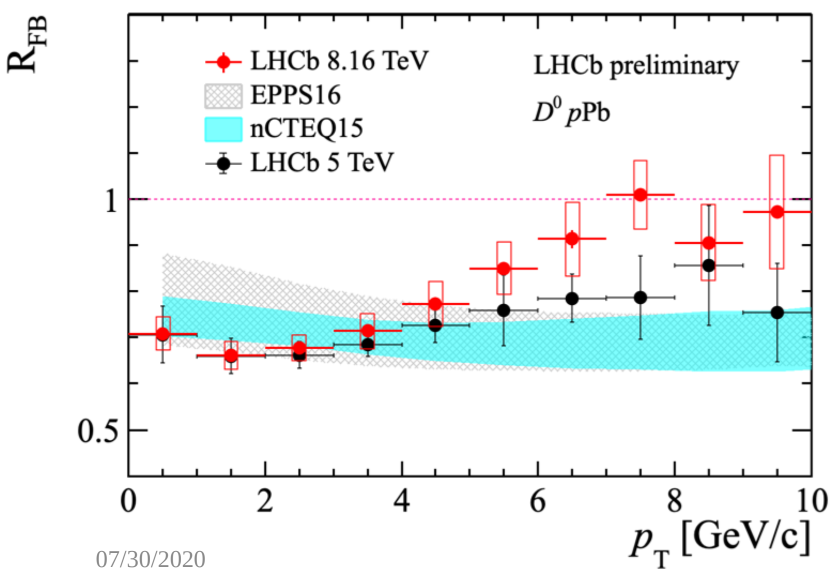
arXiv:2007.06945

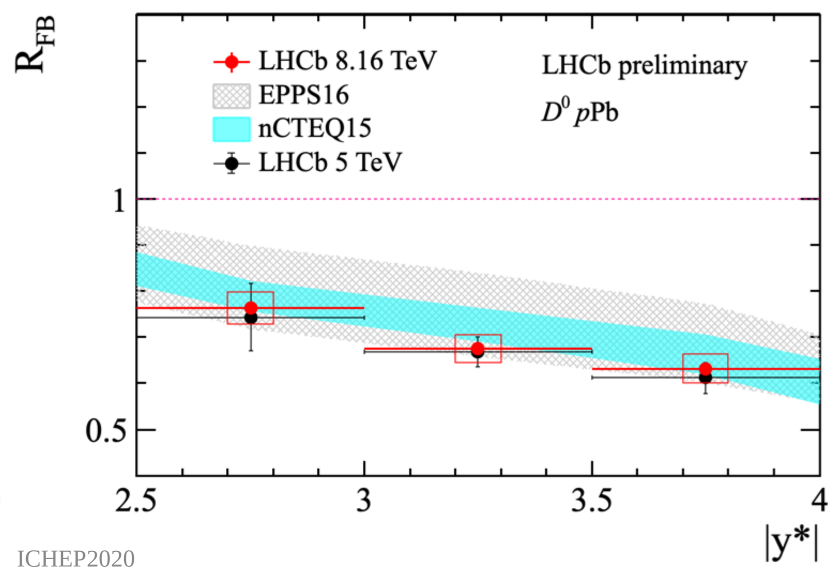
Prompt D^0 measurement in pPb at 8.16 TeV

- $D^0 \to K^- + \pi^+$
- Separation of prompt and from-b components using impact parameter
- Forward/backward ratio R_{FB} increases with increasing p_{T}
  - Lower p_{T}: consistent with 5.02 TeV results and nPDF
  - Higher p_{T}: above nPDF expectation
- R_{FB} decreases with increasing rapidity
  - Consistent with nPDF and 5.02 TeV measurement



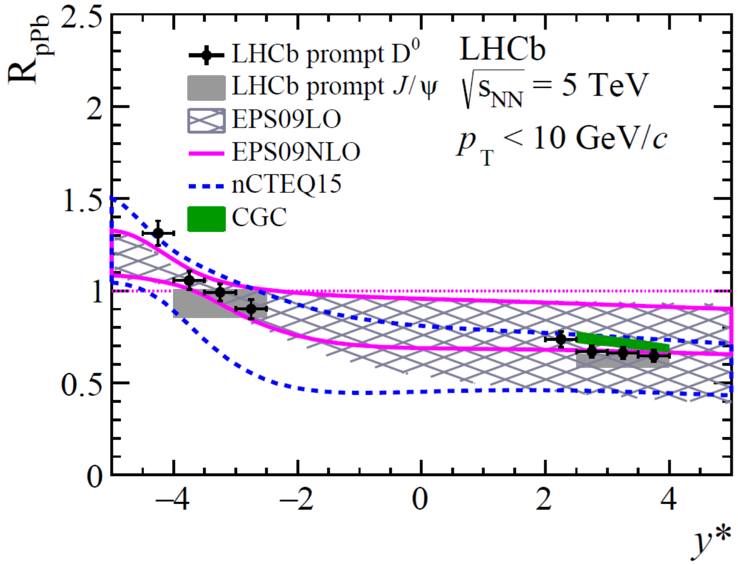






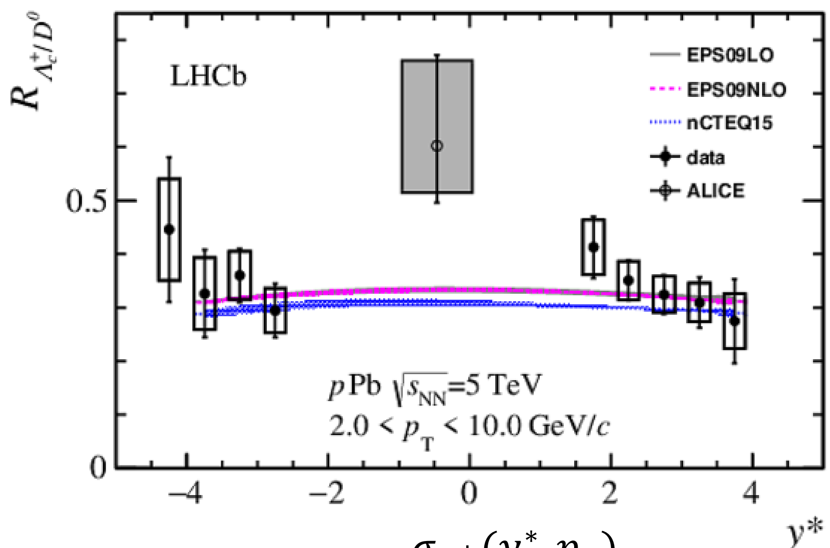
LHCb-CONF-2019-004

Prompt D^0 and Λ_c^+ measurements in pPb at 5.02 TeV



$$R_{p\mathrm{Pb}}(y^*, p_\mathrm{T}) = \frac{1}{A} \times \frac{\mathrm{d}\sigma_{p\mathrm{Pb}}(y^*, p_\mathrm{T}, \sqrt{s_\mathrm{NN}})/\mathrm{d}x}{\mathrm{d}\sigma_{pp}(y^*, p_\mathrm{T}, \sqrt{s_\mathrm{NN}})/\mathrm{d}x},\ A{=}208$$

- *pp* reference directly measured by LHCb
- $R_{p\mathrm{Pb}}$ suppressed at forward rapidity
- $R_{p\mathrm{Pb}}$ closer to 1 at backward rapidity
- Measurements consistent with models with nPDF, CGC
- **Results constrain nPDFs in low *x* region**



$$R_{\Lambda_c^+/D^0} = \frac{\sigma_{\Lambda_c^+}(y^*, p_\mathrm{T})}{\sigma_{D^0}(y^*, p_\mathrm{T})}$$

- Sensitive to charm hadronisation mechanisms
- Model based on measured *pp* cross-section
- nPDF uncertainty mostly cancel
- Consistent with LHCb *pp* results ~0.3
- Lower than ALICE points in midrapidity for both *pp* and *p*Pb

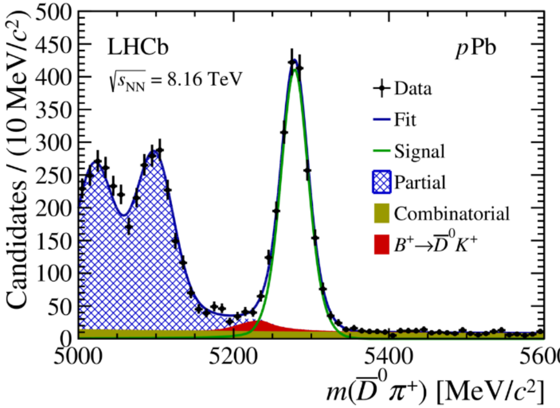
JHEP 10 (2017) 090

JHEP 02 (2019) 102

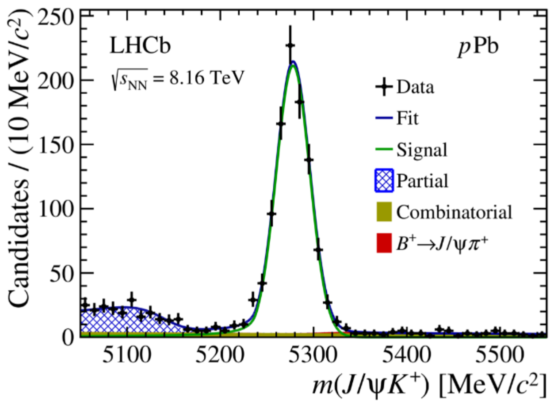
b-hadron production in pPb at 8.16 TeV
B^+ nuclear modification factor

PRD99 052011 (2019)

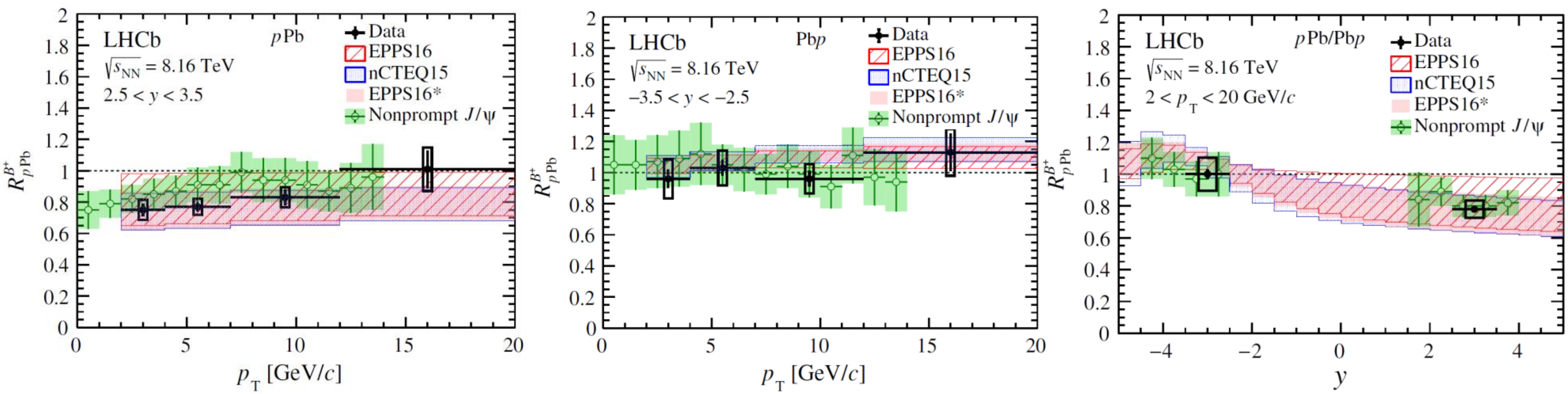
$B^+ \to \overline{D}^0\pi^+$



$B^+ \to J/\psi K^+$

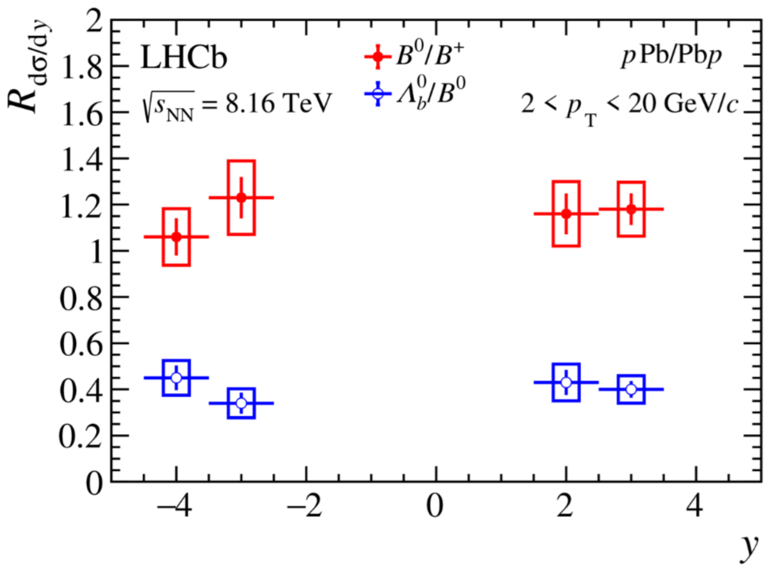


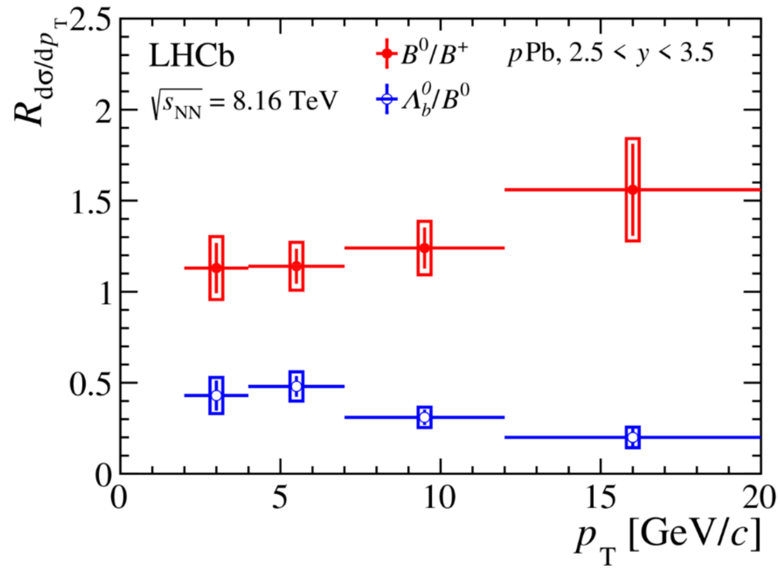
- $R_{p\text{Pb}}$ suppressed at forward rapidity
  - increase with increasing $p_{\rm T}$
- $R_{p\text{Pb}}$ ~ 1 at backward rapidity
- consistent with nPDFs EPPS16 and nCTEQ15
- Consistent with J/ψ-from-b



b-hadron production in pPb at 8.16 TeV
Production cross-section ratio

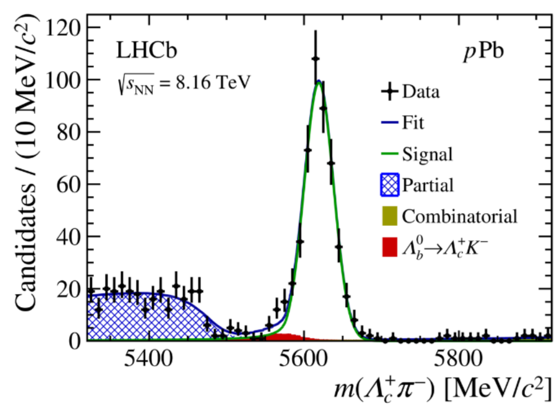
PRD99 052011 (2019)





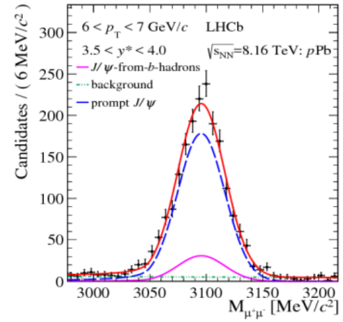
- R_{B^0/B^+}
  - No significant dependence on rapidity and p_T
- $R_{\Lambda_b^0/B^0}$
  - ~0.4, no strong rapidity dependence
  - Similar values observed in LHCb pp measurement JHEP 08 (2014) 143
  - Decreases with p_T when p_T > 5 GeV/c

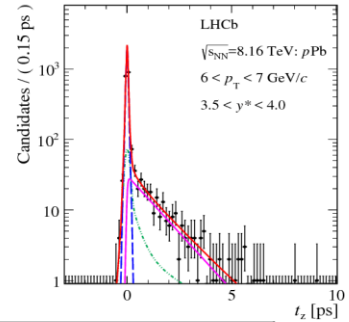
$\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$



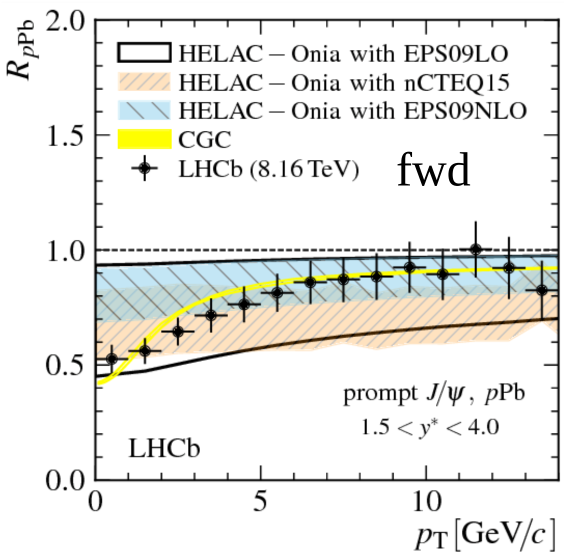
Prompt J/ψ at 8.16 TeV nuclear modification factor in pPb

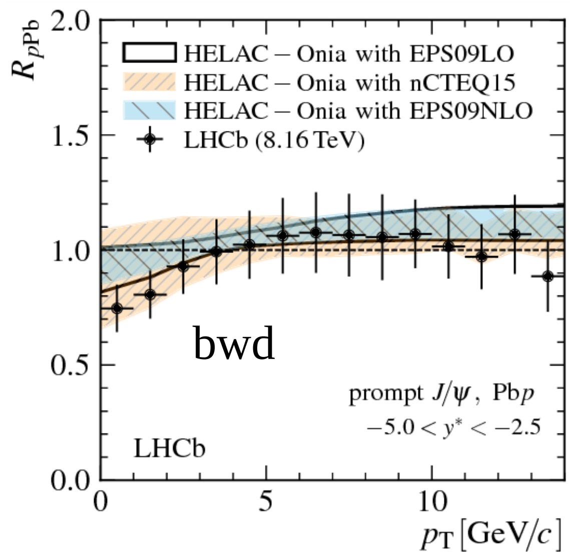
- $J/\psi \to \mu^+\mu^-$
- Prompt and from-b J/ψ separated: the pseudo proper decay time
- **Forward rapidity**: suppression up to 50% at low p_T, decreasing with increasing p_T
- **Backward rapidity**: closer to unity
- Overall agreement with models with large uncertainties on the gluon PDFs at low x
- **Results constrain nPDFs in low x down to $x \sim 7 \times 10^{-6}$**

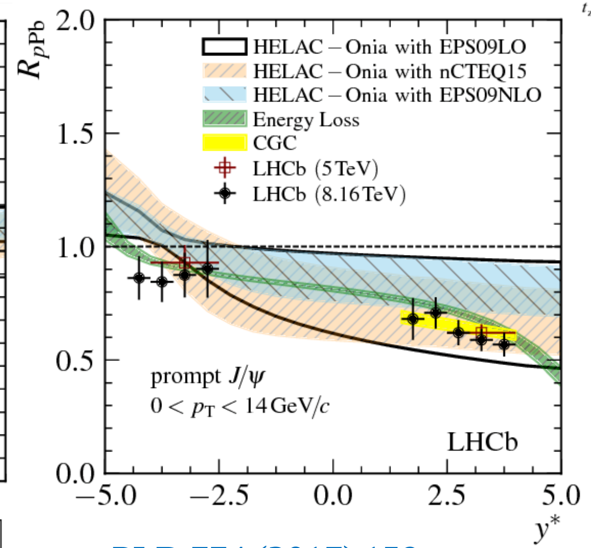




PRL 121,052004(2018)







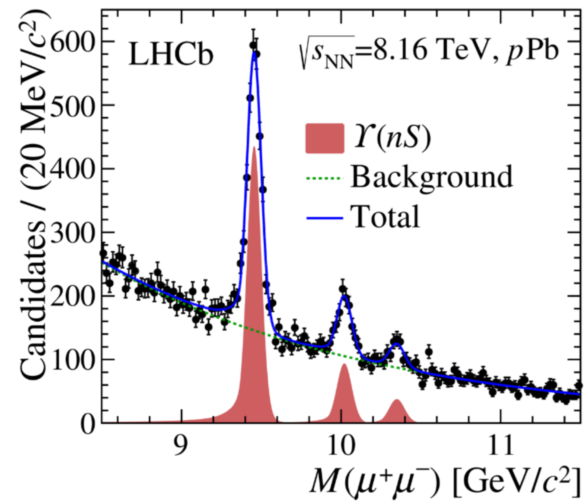
PLB 774 (2017) 159

$\Upsilon(nS)$ in pPb collisions at 8.16 TeV

JHEP 11 (2018) 194

- $\Upsilon(nS)$ sequential suppression observed in PbPb collisions
- Important to understand CNM effects in pPb collisions
- New differential analysis using large 2016 pPb data
- Nice $\Upsilon(3S)$ signals in forward and backward configurations

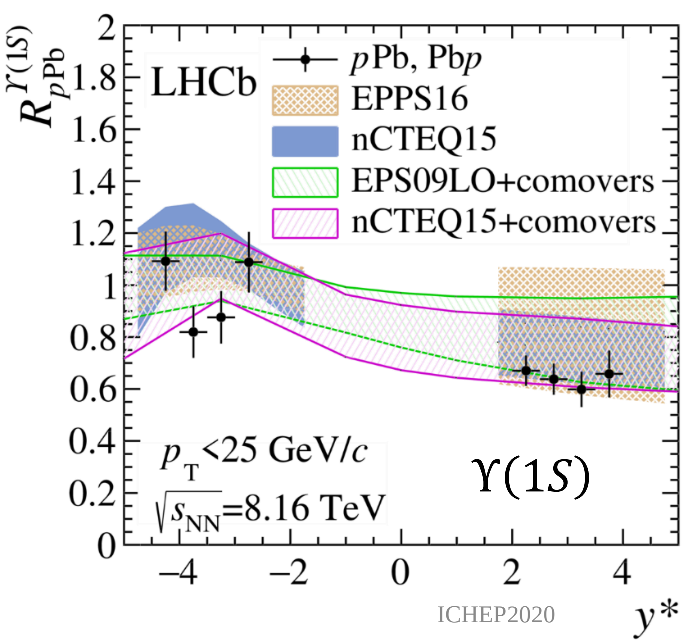
Samples	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
pPb	2705 ± 87	584 ± 49	262 ± 44
Pbp	3072 ± 82	679 ± 54	159 ± 39

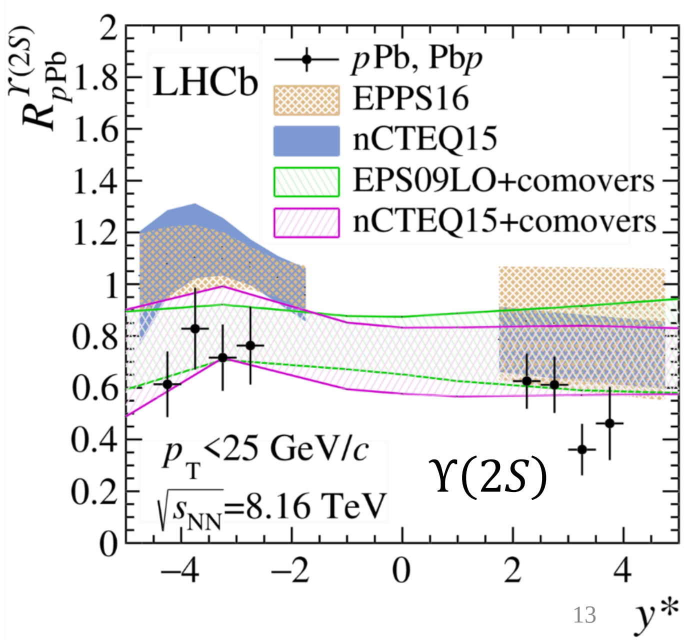


$\Upsilon(nS) \to \mu^+\mu^-$

Forward rapidity: suppression for both states, compatible with nPDFs

Backward rapidity: $\Upsilon(2S)$ more suppressed than $\Upsilon(1S)$, consistent with nPDFs+comovers calculation





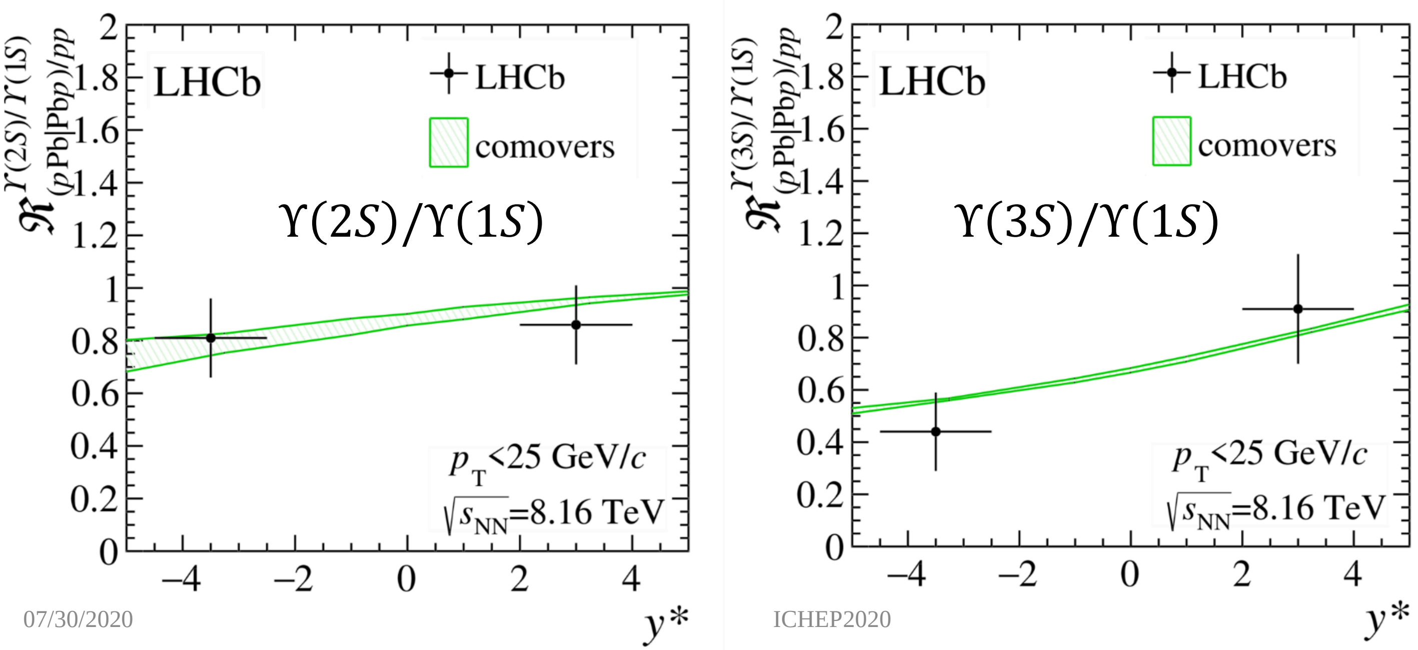
$\Upsilon(nS)/\Upsilon(1S)$ relative suppression

JHEP 11 (2018) 194

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

$$R(\Upsilon(nS)) = \frac{[\mathrm{d}^2\sigma/\mathrm{d}p_\mathrm{T}dy^*]\,(\Upsilon(nS))}{[\mathrm{d}^2\sigma/\mathrm{d}p_\mathrm{T}dy^*]\,(\Upsilon(1S))}$$

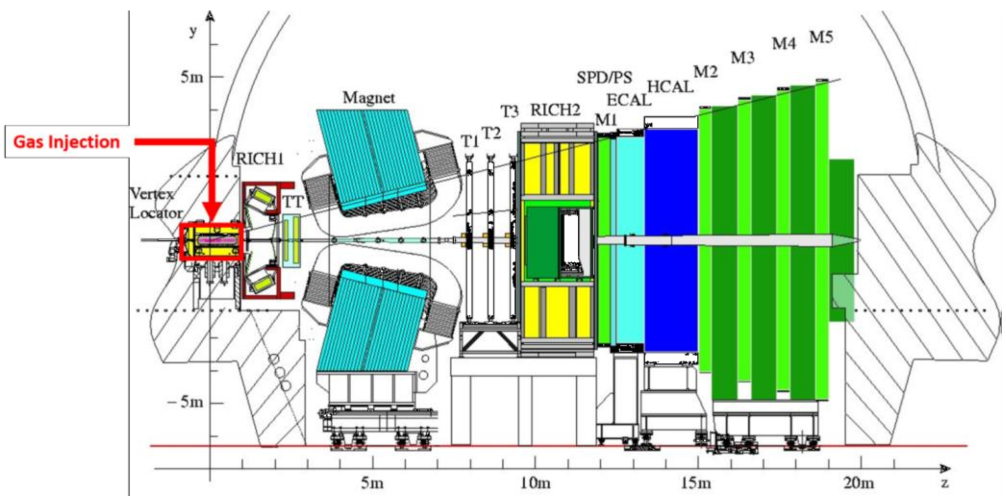
- Double ratio of $\Upsilon(nS)/\,\Upsilon(1S)$ in pPb and pp
- $\Upsilon(3S)$ more suppressed than $\Upsilon(2S)$ in the backward rapidity
- Suggests final state effects…
- Agrees with predictions of "comovers" model
  - Interaction with particles close in phase space dissociates the bound states

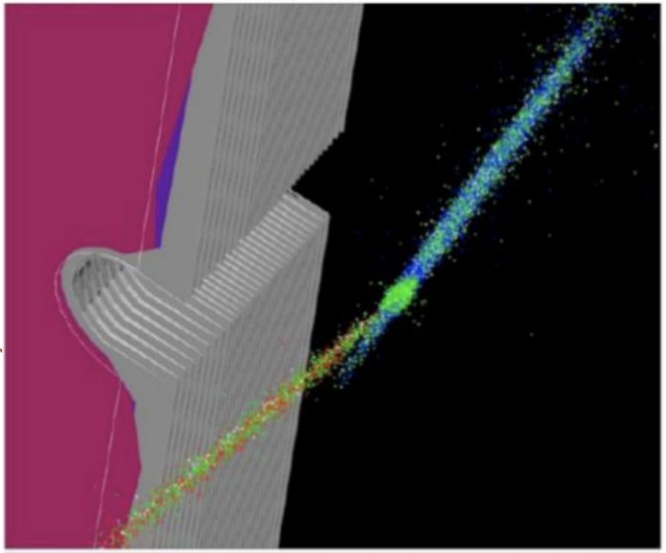


Fixed target physics

JINST 9 (2014) P12005

- **The System for Measuring Overlap with Gas (SMOG)** allows a small amount of noble gas injection inside the LHC beam close to the interaction point
- Allows p-gas and ion-gas collisions (He, Ne, Ar,… $\sim 2 \times 10^{7}$mbar)
- $\sqrt{s_{NN}}$ = 69-110 GeV between 20 GeV (SPS) and 200 GeV (RHIC)
- $-2.8 < y^{*} < 0.2$
- Access nPDF anti-shadowing region and intrinsic charm content in the nucleon





Distribution of vertices overlaid on detector display. z-axis is scaled by 1:100 compared to transverse dimensions to see the beam angle.
Beam 1 - Beam 2, Beam 1 - Gas, Beam 2 - Gas.

Fixed target physics

JINST 9 (2014) P12005

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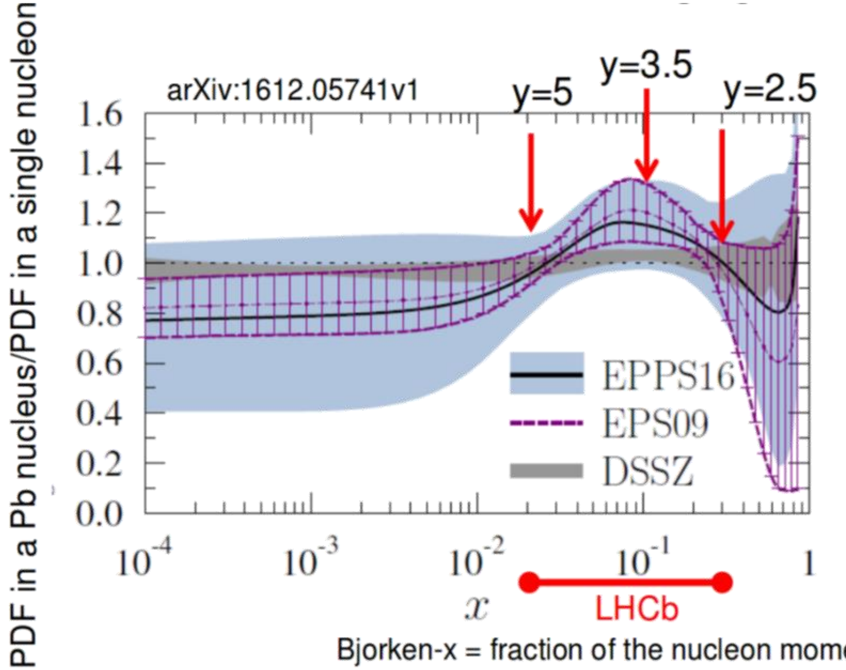
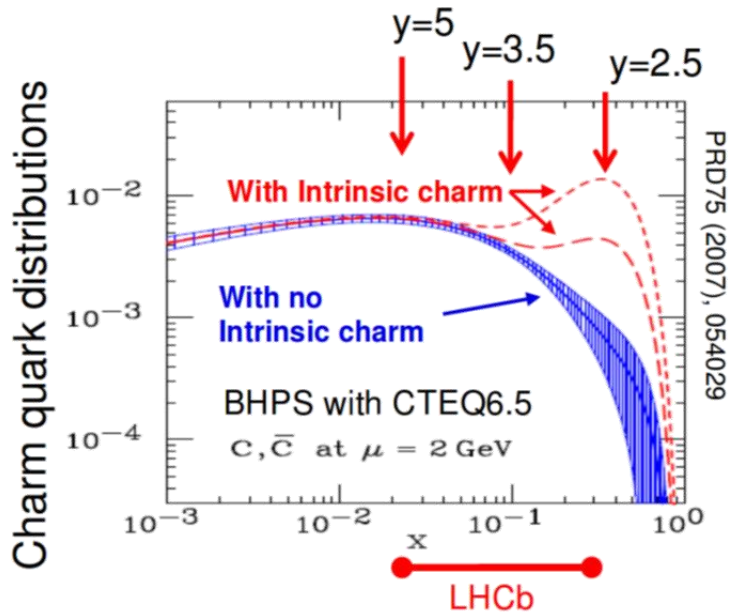


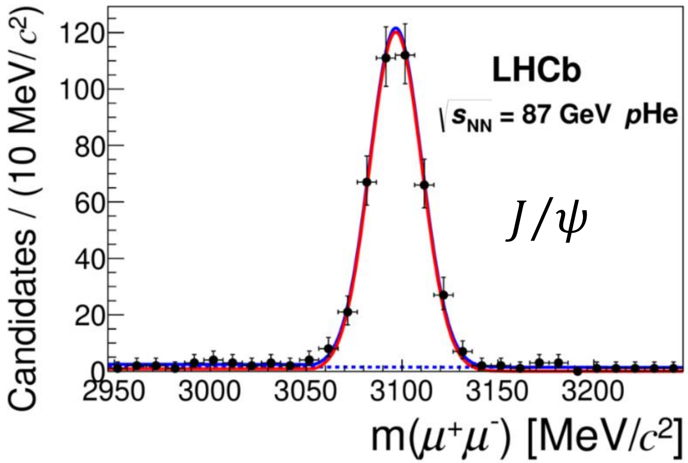


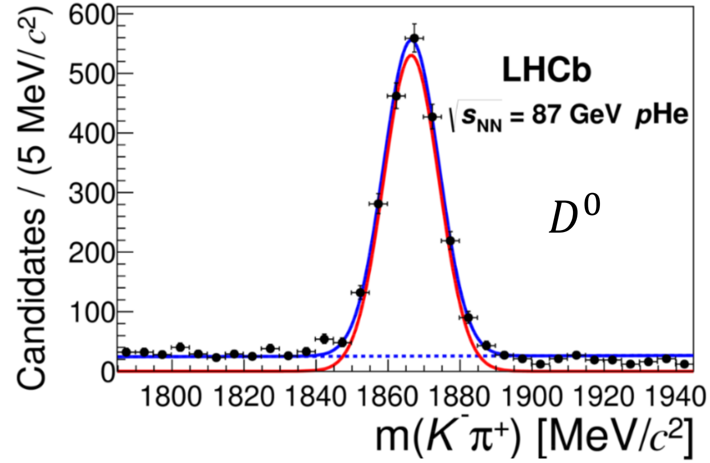
Bjorken-x = fraction of the nucleon momentum carried by a parton

Charm production in fixed-target pA collision

PRL 122 (2019) 132002
PRL 123 (2019) 239901

- J/ψ and D^0 inclusive cross-section in pHe collisions at 86.6 GeV
- First determination of $c\bar{c}$ cross-section at this energy scale
- Cross-section measurements agree with previous results and theoretical calculations



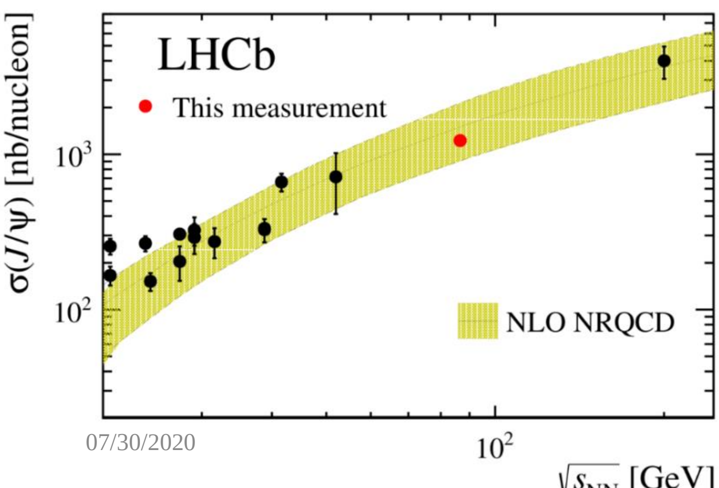


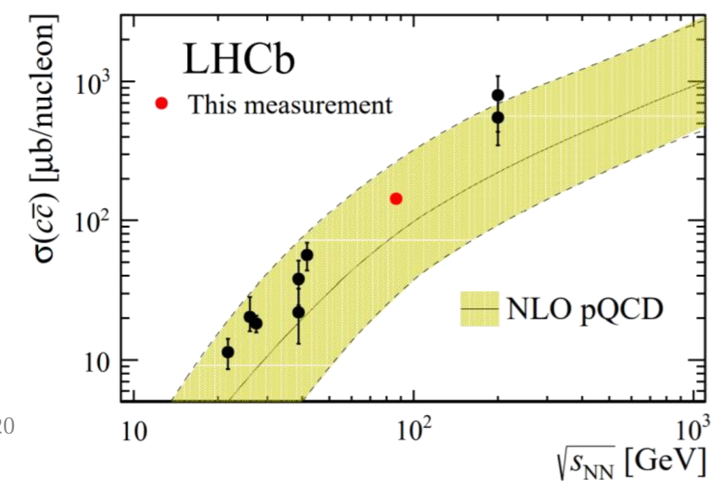
$\sigma_{D^0} = 156.0 \pm 13.1\ \mu\text{b/nucleon}$

With fraction $(c \rightarrow D^0) = 0.542 \pm 0.024$

$\sigma_{J/\psi} = 1225.6 \pm 100.7\ \text{nb/nucleon}$

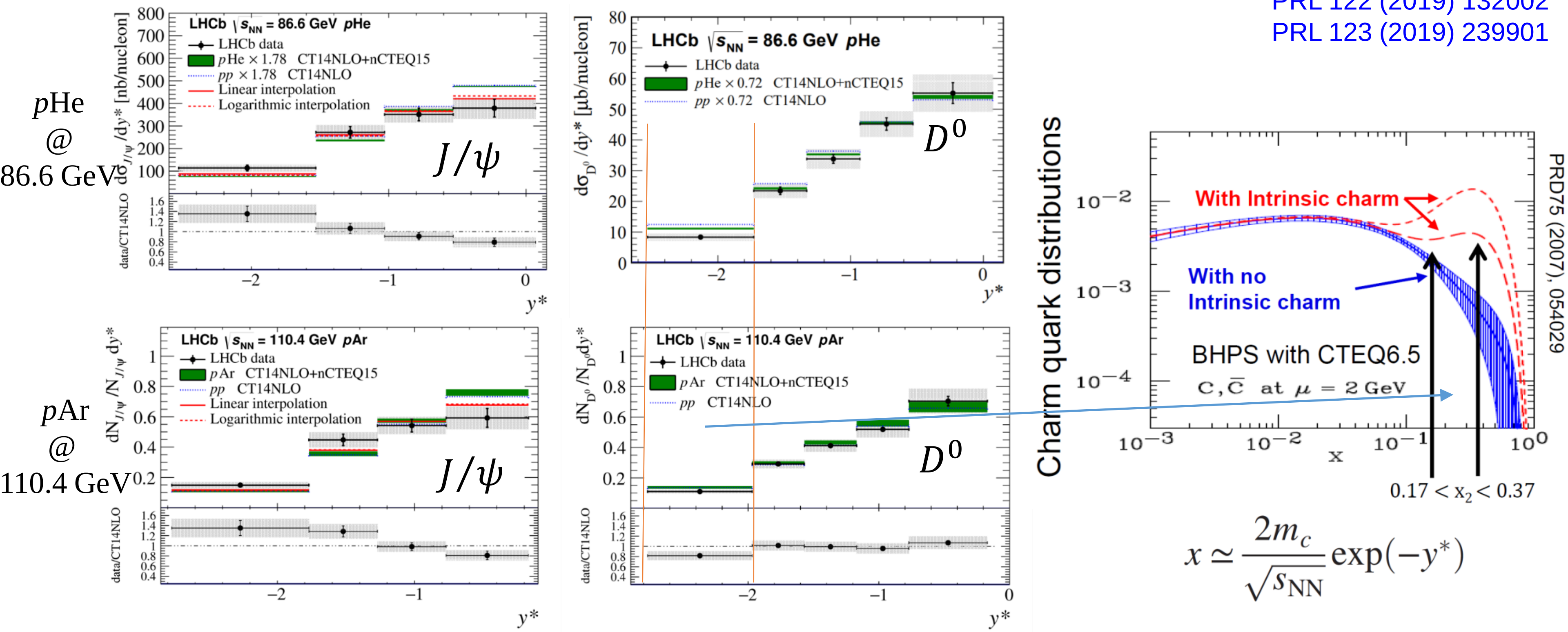
$\sigma_{c\bar{c}} = 144 \pm 12.1 \pm 3.5\ \mu\text{b/nucleon}$





Charm production in fixed-target pA collision

PRL 122 (2019) 132002
PRL 123 (2019) 239901

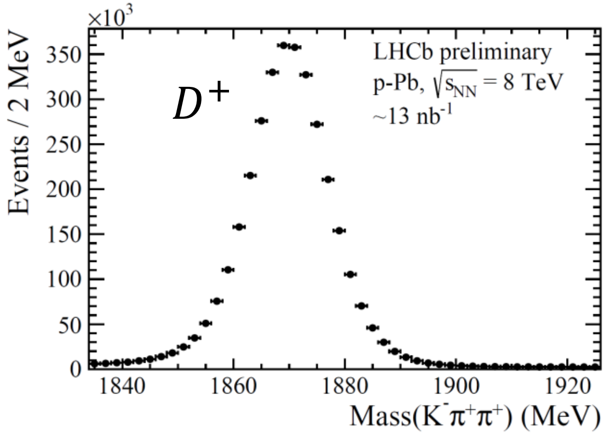


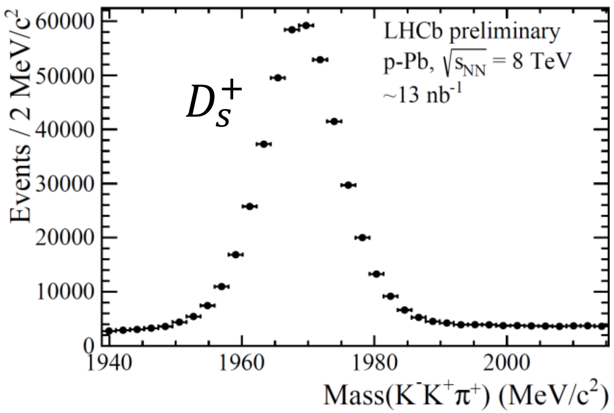
$$x \simeq \frac{2m_c}{\sqrt{s_{NN}}} \exp(-y^*)$$

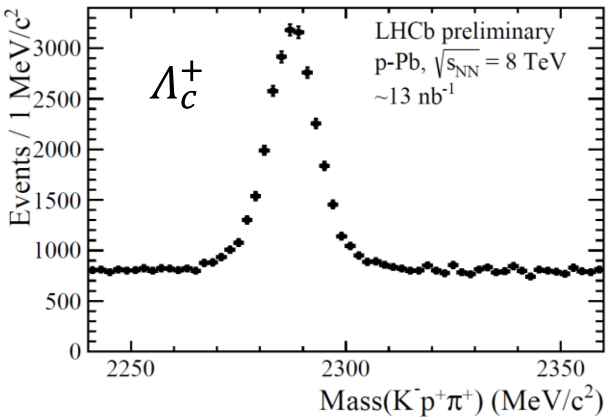
- Differential cross-section (pHe @ 86.6 GeV), differential yields (pAr @ 110.4 GeV)
- Reasonable agreement with Helac-Onia predictions in rapidity shape
- $-2.53<y^*<-1.73 \rightarrow 0.17<x<0.37$
- No evidence of strong intrinsic charm contribution observed

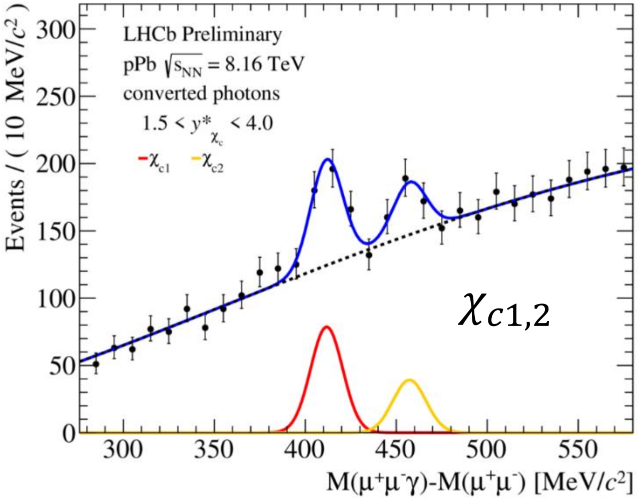
Models:
Eur. Phys. J. C77 (2017) 1
Comput. Phys. Commun. 184 (2013) 2562
Comput. Phys. Commun. 198 (2016) 238

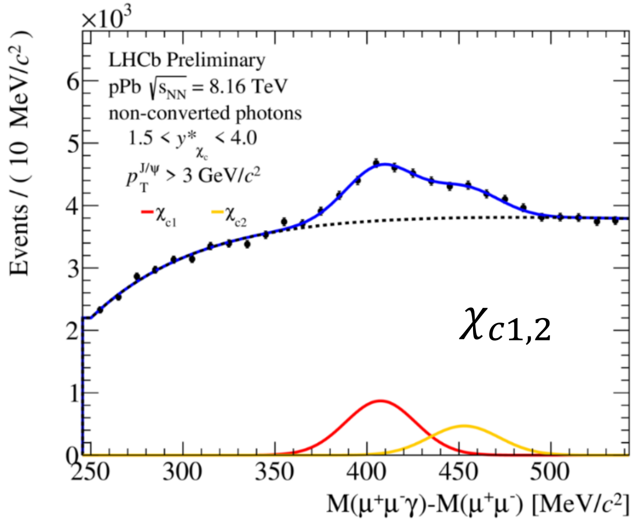
Upcoming measurements in pPb at 8.16 TeV











LHCb-FIGURE-2019-020

Conclusions

- Open heavy flavor hadrons in pPb collisions at 5.02 TeV and 8.16 TeV
  - Prompt double-charm hadron production: **DPS enhanced by a factor of 3 compared to *pp*.**
  - Precise prompt D^0 meson measurement down to zero p_{T}. **Relative suppression in the forward rapidity** compared to backward rapidity observed.
  - **Prompt $\boldsymbol{\Lambda_c^+/D^0}$ ratio** consistent with theoretical calculations and *pp* results
  - b-hadrons: **smaller relative suppression** in the forward rapidity than D^0 meson at low p_{T}.
  - First direct measurement of Λ_b^0 baryon in heavy ion collisions.

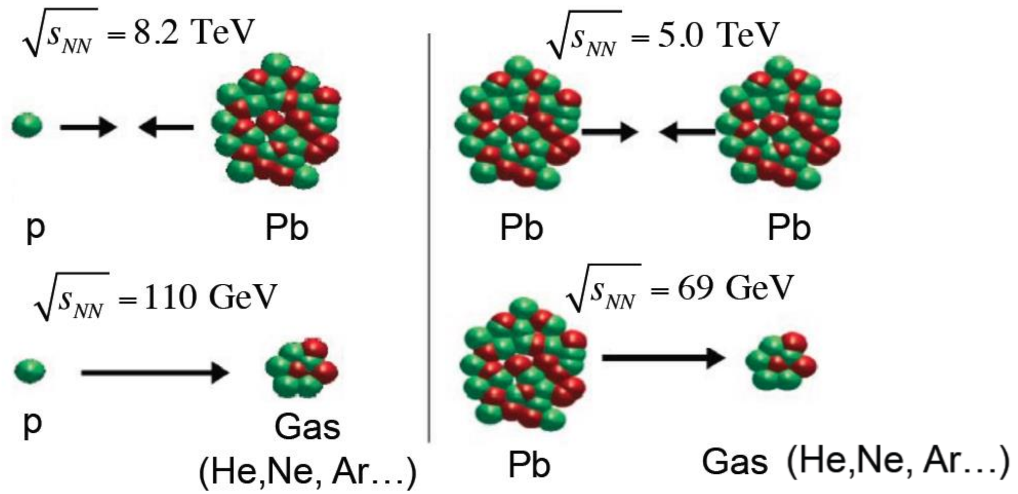
    $\boldsymbol{\Lambda_b^0/B^0}$ **ratio** ~ 0.4
- Production of quarkonia in pPb collisions at 8.16 TeV
  - J/ψ: **relative suppression** similar to open heavy flavor results
  - $\Upsilon(nS)$: **relative suppression of $\boldsymbol{\Upsilon(nS)}$ states** observed in *p*Pb
- Fixed-target mode (SMOG)
  - Charm production**: no evidence of strong intrinsic charm** contribution
- Upcoming results:
  - Open charm hadrons and χ_c production in *p*Pb data at 8.16TeV

backup

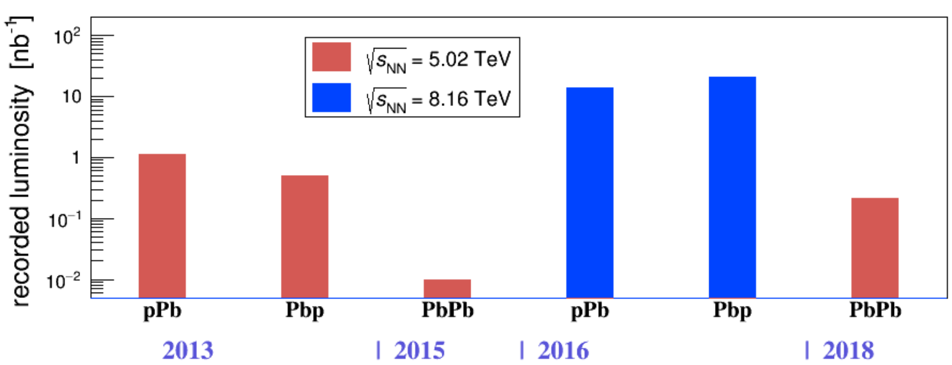
LHCb heavy ion collision modes

Collider mode

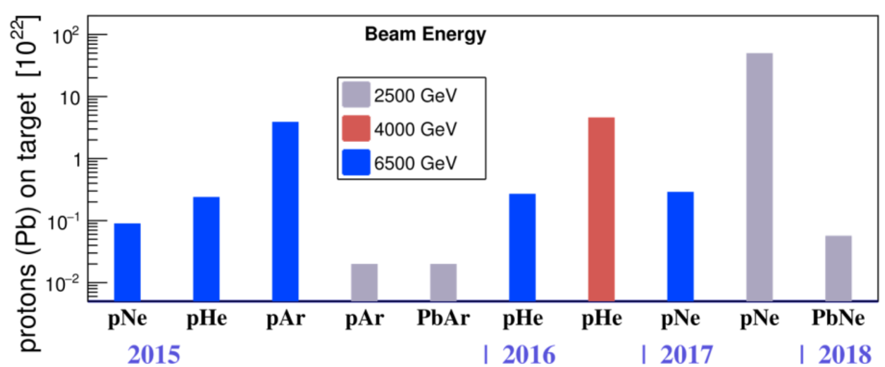
Fixed target mode



Collider mode

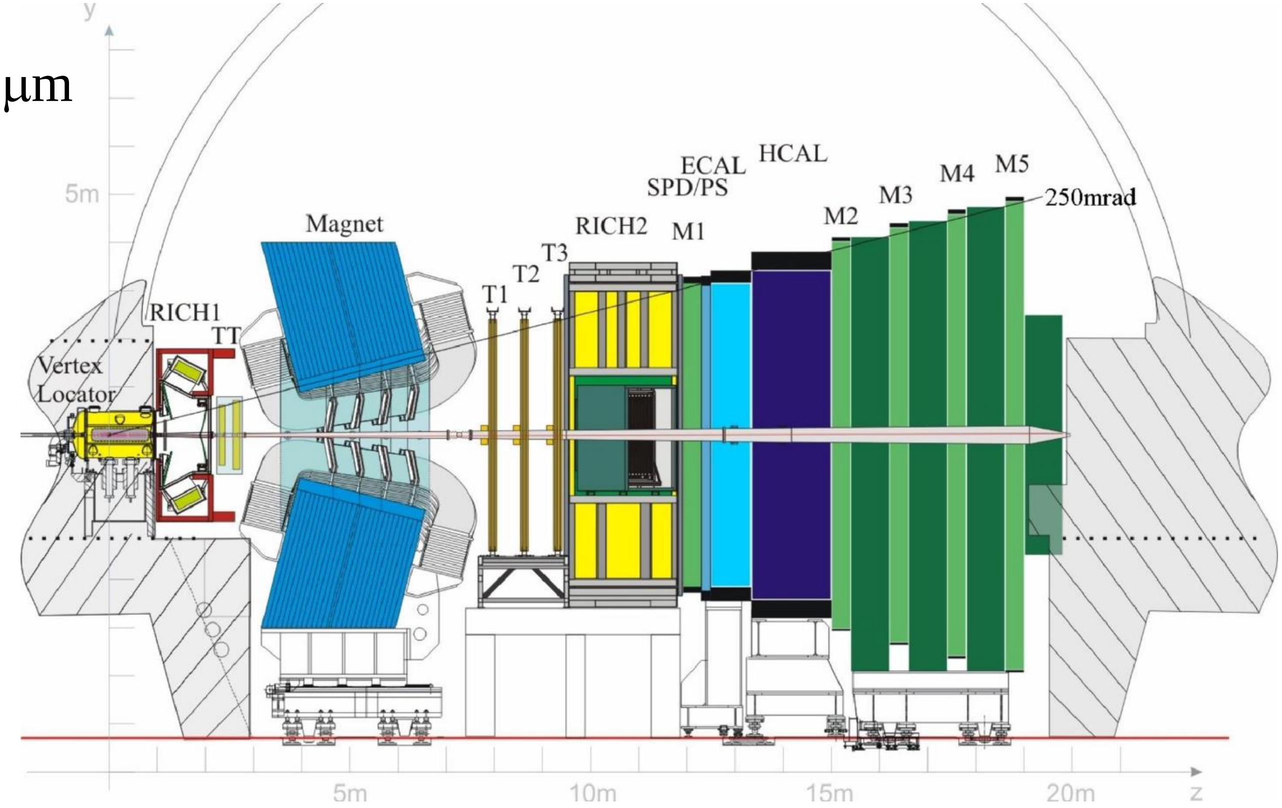


Fixed target mode



LHCb detector

- A single arm forward spectrometer designed for the study of particles containing *c* or *b* quark.
- Acceptance: $2 < \eta < 5$
- Vertex detector
  - IP resolution ~ 20 μm
- Tracking system
  - $\frac{\Delta p}{p} = 0.5\% - 1\%$ (5-200 GeV/c)
- RICH
  - K/π/p separation
- Electromagnetic + hadronic Calorimeters
- Muon systems



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