



Heavy-flavor hadron production at LHCb

Hans Dembinski¹ for the LHCb collaboration

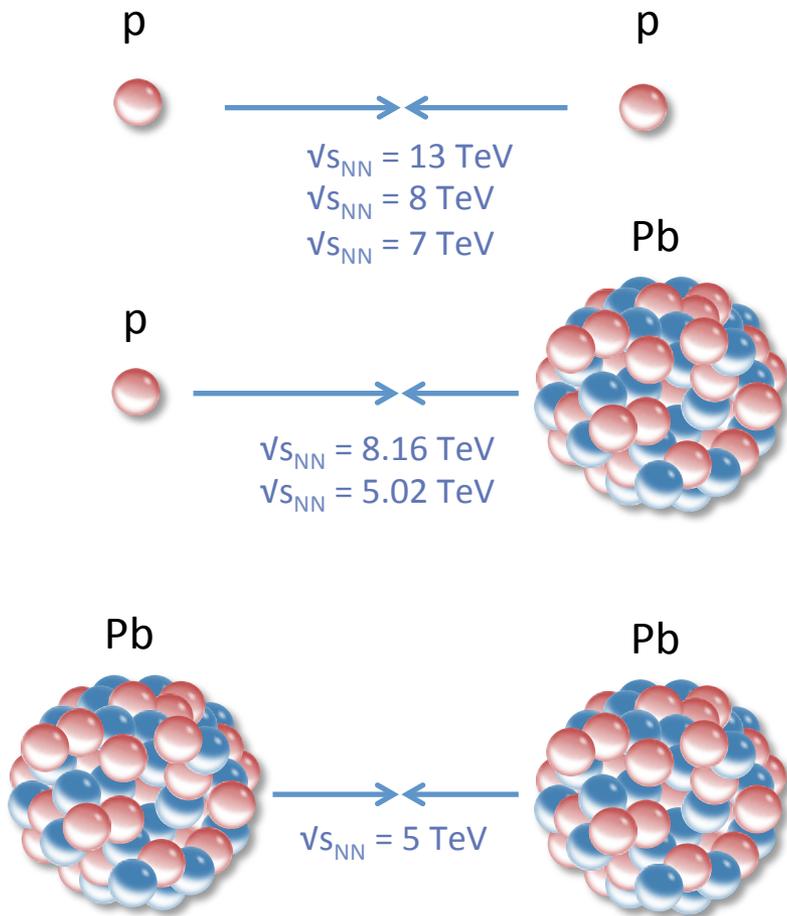
¹MPIK Heidelberg, Germany

DIS 2019, April 8-12, 2019

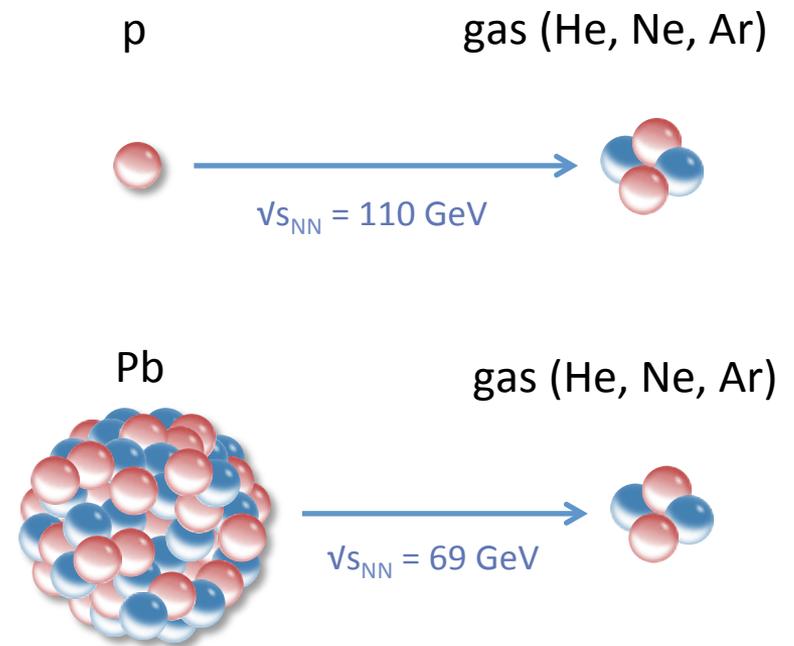


Collisions in LHCb

(not all energies shown)



Fixed target, LHCb only

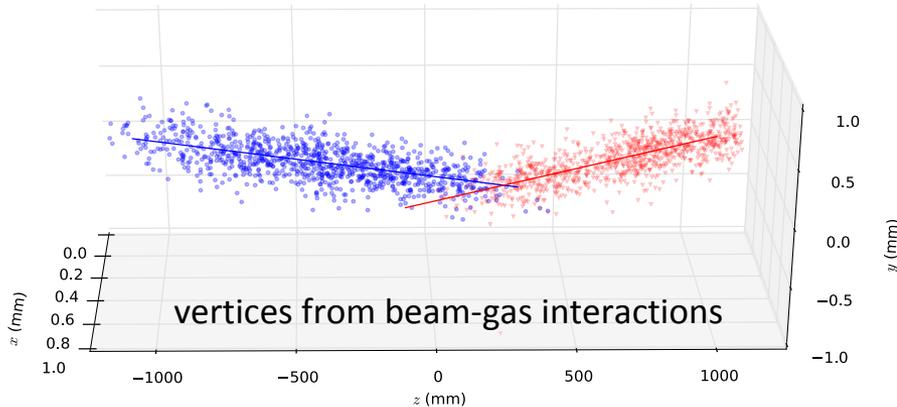


+ short Xe+Xe run in 2017

LHCb SMOG: fixed (gas) target

LHCb data

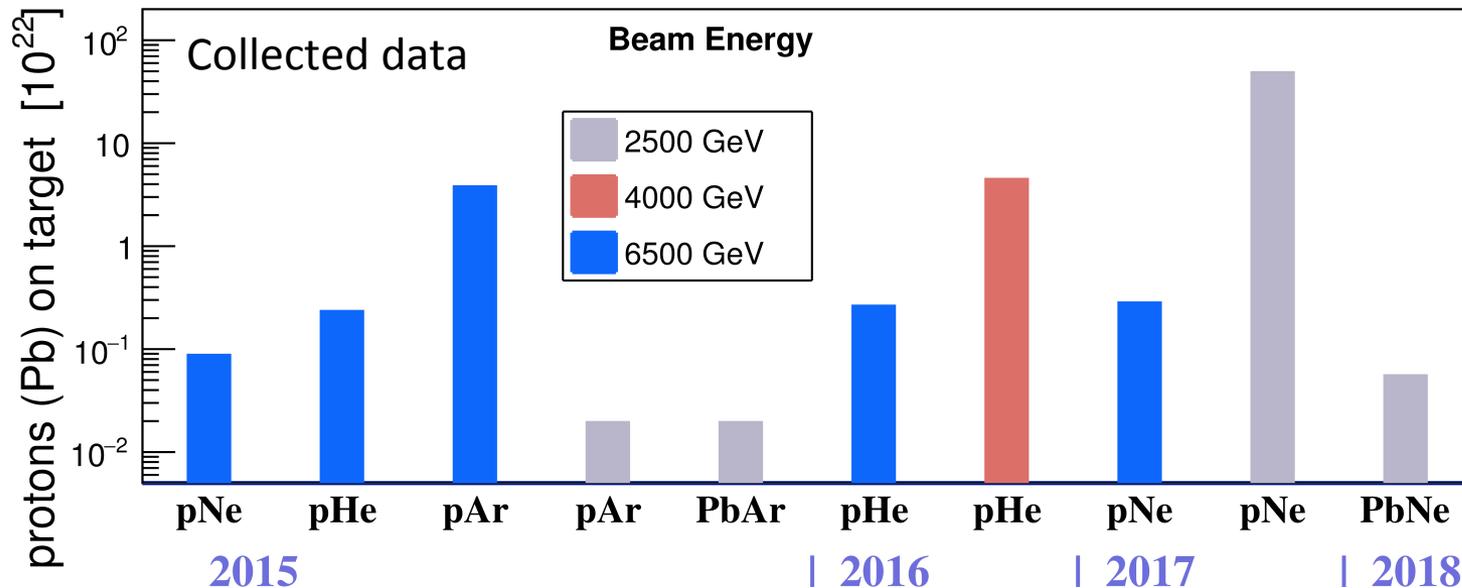
Colin Barschel, PhD thesis 2013



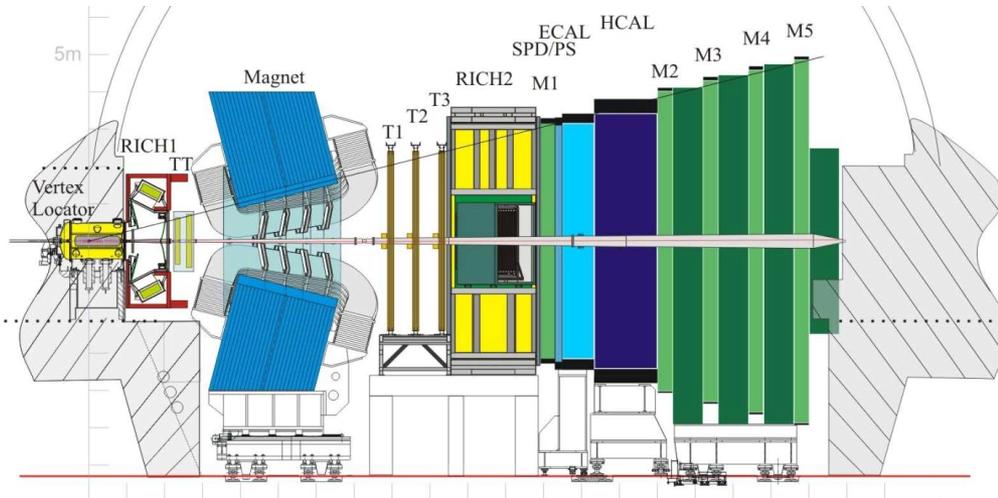
System for **M**asuring **O**verlap with **G**as

- Inject He, Ne, Ar into VELO at $\sim 2 \times 10^{-7}$ mbar
- Designed to measure beam profile
- Allows data taking in **fixed target mode**

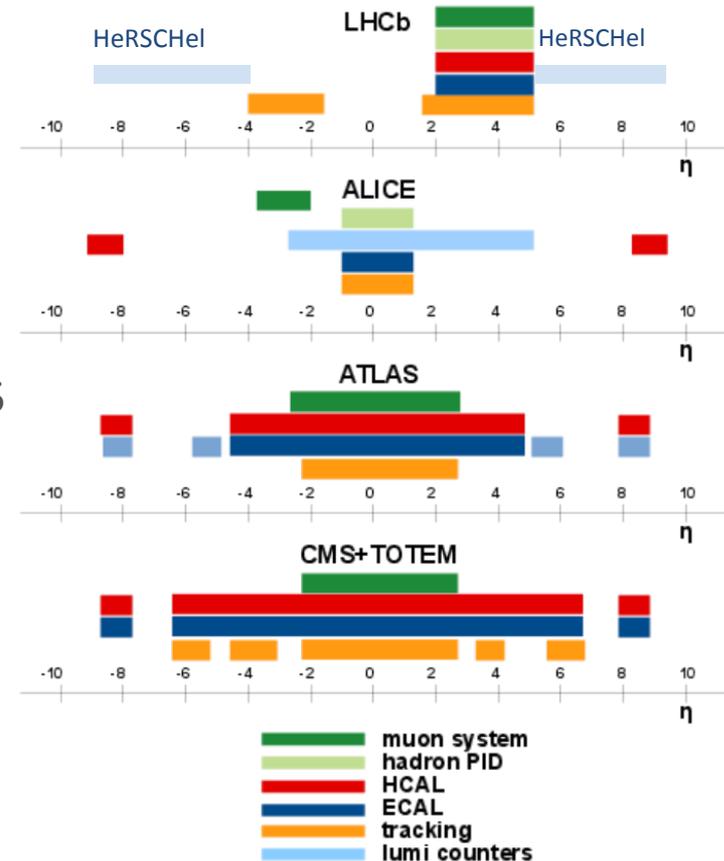
JINST 9 (2014) P12005



LHCb Experiment



JINST 3 (2008) S08005
IJMP A 30 (2015) 1530022

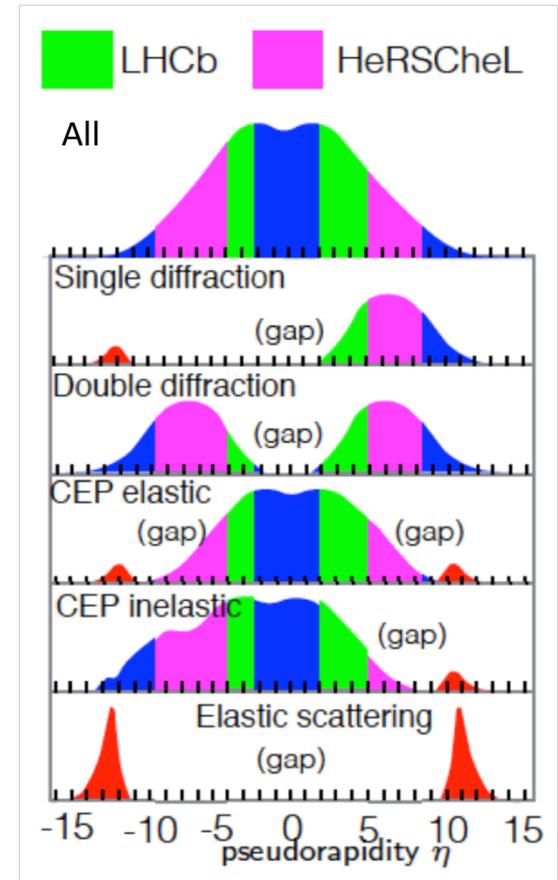
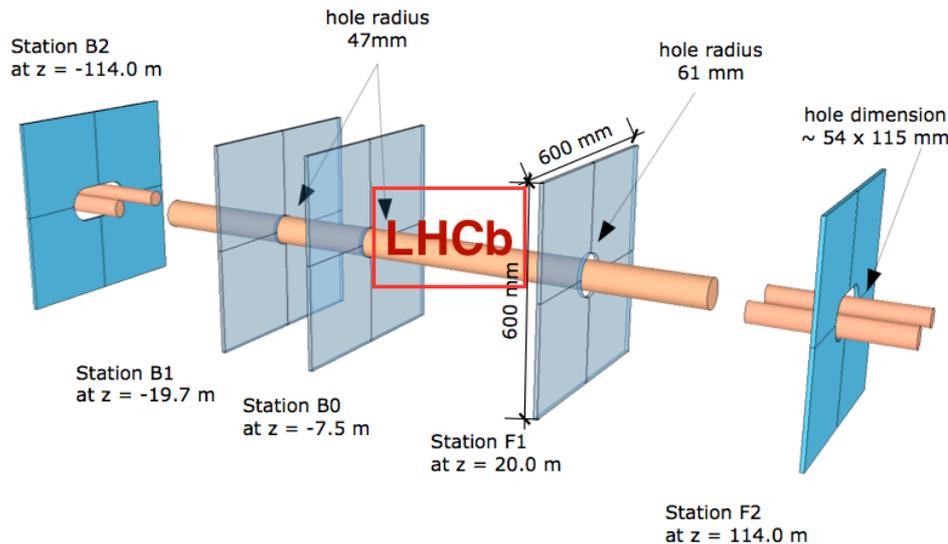
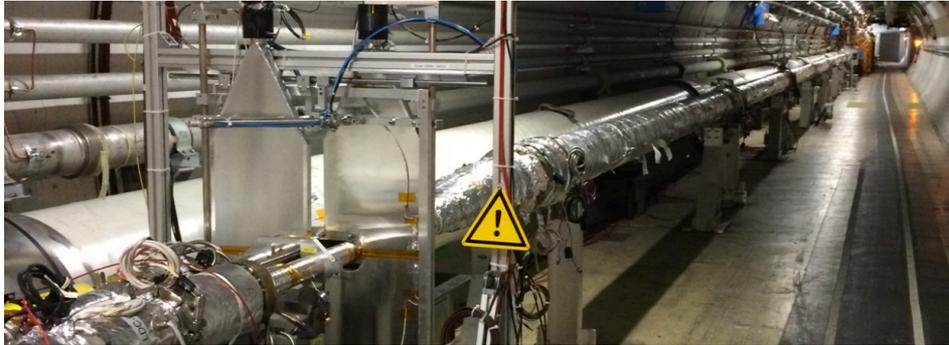


Forward spectrometer fully instrumented in $2 < \eta < 5$

- Very good momentum and vertex resolution
 $\delta p/p < 1\%$ for $0 < p < 200$ GeV/c, $\delta x \sim 20$ μm for high p_T tracks
- Good particle identification
 K : $\sim 90\%$ efficiency, mis-ID $< 5\%$
 μ : $\sim 97\%$ efficiency, mis-ID $\sim 1-3\%$
- **Optimal:** μ, p, K^+, π^+ produced inside Vertex Locator
- **Ok:** $K^0_S, \Lambda^0, \gamma, e, \pi^0$
- **Challenging:** stable neutral hadrons n, K^0_L

HeRSChel: forward scintillator

Carvalho Akiba et al. JINST 13 (2018) no.04, P04017



- Forward shower counters with acceptance $5 < |\eta| < 10$
- Better identification of diffractive events, important to identify CEP

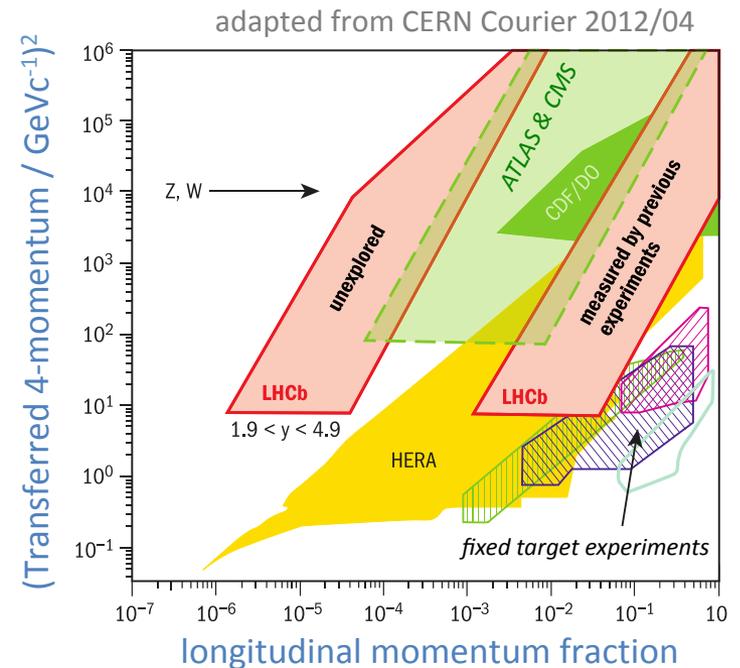
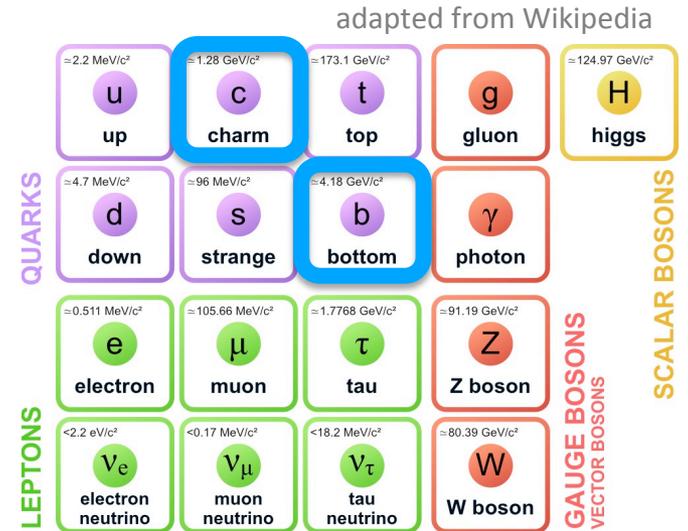
Why heavy flavor?

Charm and Beauty

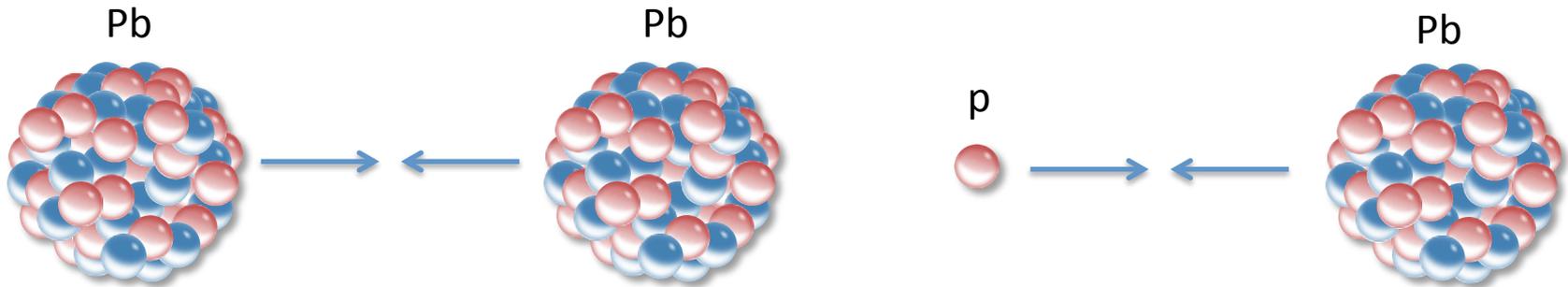
- Quark mass $\gg \Lambda_{\text{QCD}}$ acts as cut-off allowing pQCD calculations to low p_T
 - Tests of pQCD – FONLL calculations

fixed-order plus next-to-leading logs, see Cacciari et al. hep-ph/9803400

- Cross-sections sensitive to Parton Density Functions (PDFs)
 - Important input to theoretical calculations
 - Dominate uncertainties of predictions
 - Unexplored at low x
- Hadrons produced early in ion collisions
 - Experience evolution of nuclear medium
 - Probe nuclear medium via transport properties



Heavy-ion physics to explore

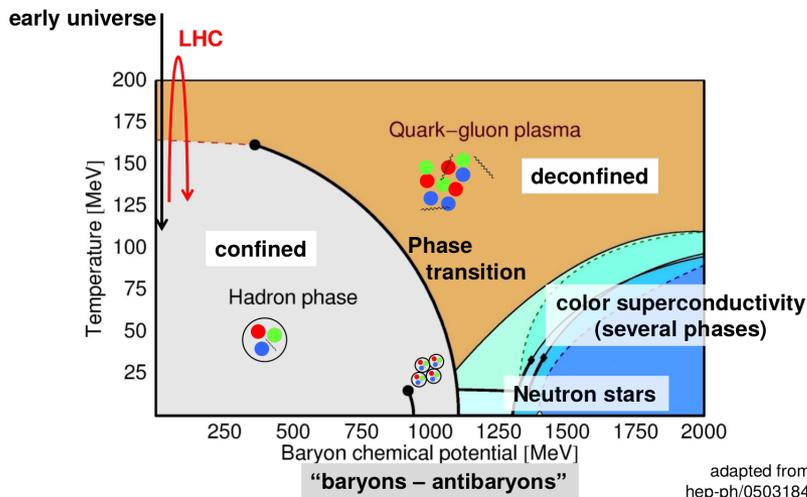


Hot nuclear matter in PbPb

- Possible formation of **Quark Gluon Plasma (QGP)**

Cold nuclear matter in pPb

- Modified parton distribution function: nuclear PDF
- Absorption and coherent energy loss in nuclear matter
- Possible formation of Color Glass Condensate



Study signatures separately in pp, pPb, PbPb to distinguish QGP effects

p-p: No nuclear effects

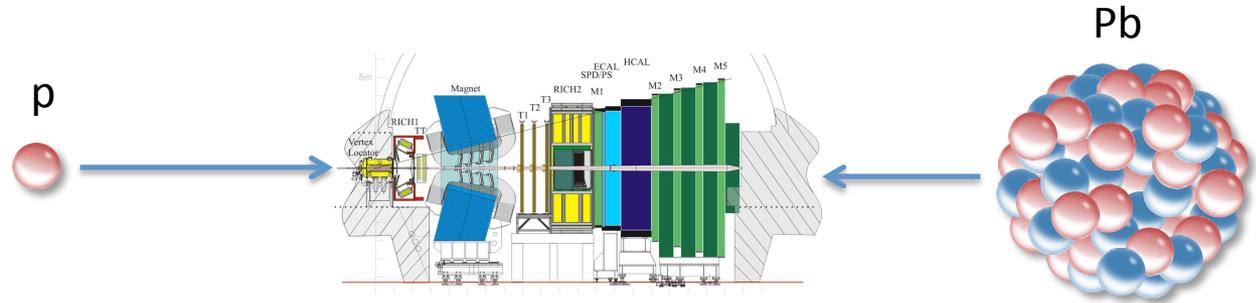
p-Pb: Adds cold matter effects

Pb-Pb: Adds hot matter effects

Nuclear effects & asymmetric acceptance

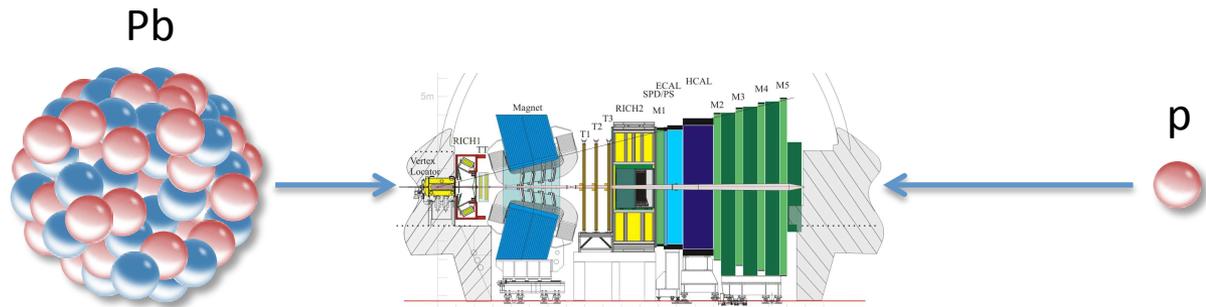
"forward"

Measured particles at $\eta > 0$
Probes low x in nuclear PDF



"backward"

Measured particles at $\eta < 0$
Probes high x in nuclear PDF



Nuclear modification factor

$$R_{pPb} = \frac{\text{cross-section for pPb}}{A_{Pb} \times \text{cross-section for pp}}$$

No nuclear effects: $R_{pPb} = 1$

Forward-Backward (FB) ratio

$$R_{FB} = \frac{\text{cross-section for pPb} + |y|}{\text{cross-section for pPb} - |y|}$$

Recent results

Hadrons with charm

$\psi(2S)$ in pp at 7,13 TeV

LHCb-PAPER-2018-049, submitted to JHEP

Asymmetry of $D_s^{+/-}$ in pp at $\sqrt{s_{NN}} = 7,8$ TeV

[JHEP 08 \(2018\) 008](#)

Prompt Λ_c^+ in pPb at $\sqrt{s_{NN}} = 5$ TeV

[JHEP 02 \(2019\) 102](#)

$J/\psi, D^0$ in p(Ar,He) at $\sqrt{s_{NN}} = 87, 110$ GeV

[arXiv:1810.07907](#), submitted to PRL

Hadrons with beauty

$Y(nS)_{n=1,2,3}$ in pp at $\sqrt{s_{NN}} = 13$ TeV

[JHEP 07 \(2018\) 134](#)

$Y(nS)_{n=1,2,3}$ in pPb at $\sqrt{s_{NN}} = 8.16$ TeV

[JHEP 11 \(2018\) 194](#)

B^0, B^+, Λ_b^0 in pPb at $\sqrt{s_{NN}} = 8.16$ TeV

[Phys. Rev. D 99 \(2019\) 052011](#)

Ξ_b^- in pp at $\sqrt{s} = 7,8,13$ TeV

[Phys. Rev. D 99 \(2019\) 052006](#)

Hadrons with Charm

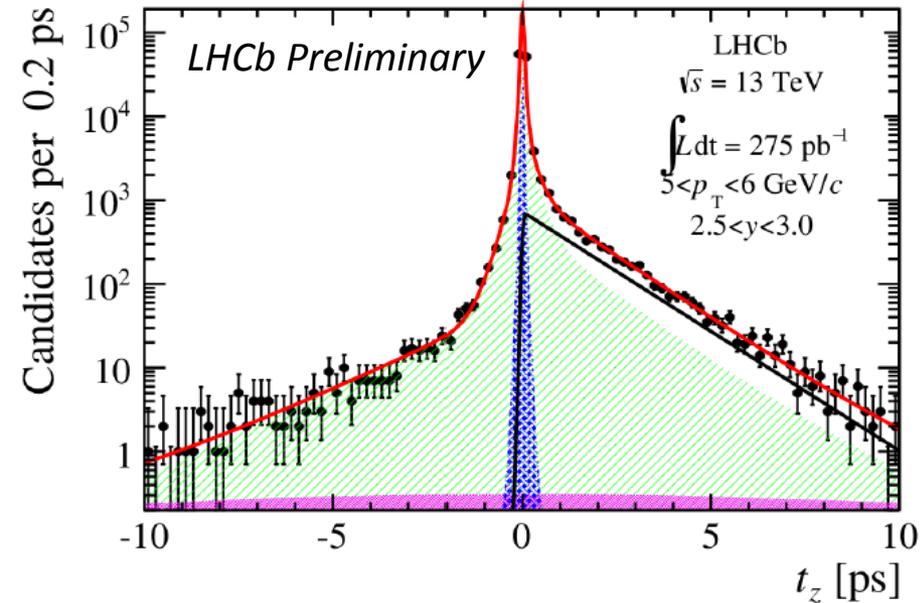
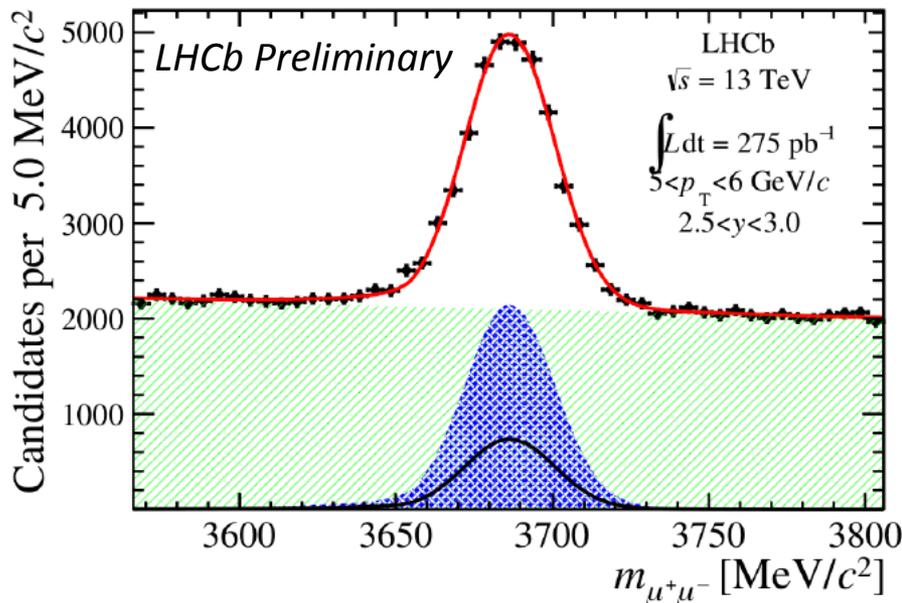
$\psi(2S)$ in pp at 7,13 TeV

- $\psi(2S)$ has negligible feed-down compared to J/ψ , easier to theoretically interpret
- Decay channel: $\psi(2S) \rightarrow \mu\mu$
- Double differential cross-section in y , p_T for prompt $\psi(2S)$ and $\psi(2S)$ from b -decay
- Cross-section $\sigma(pp \rightarrow b\bar{b} X)$ inferred
- Combined fit to invariant mass and pseudo decay time $t_z = \frac{(z_{\psi(2S)} - z_{PV}) \times m_{\psi(2S)}}{p_z}$

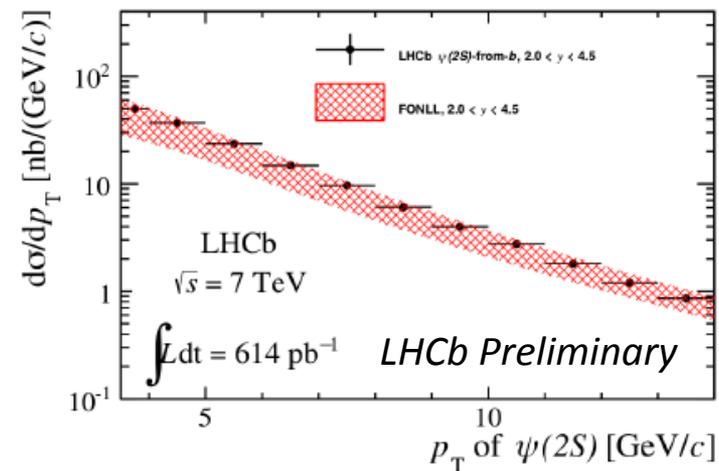
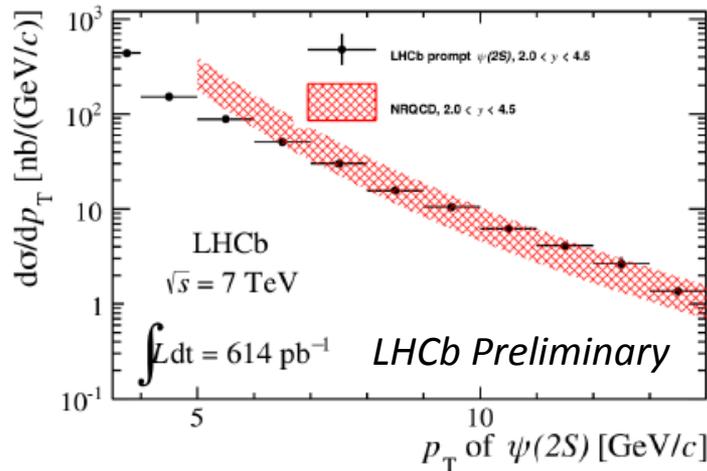
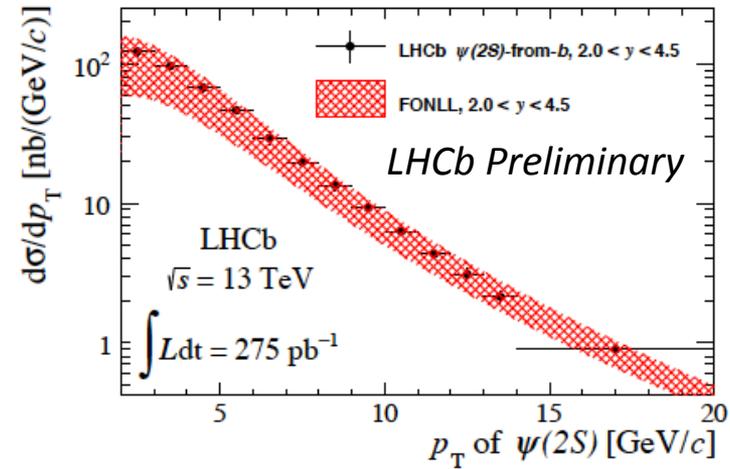
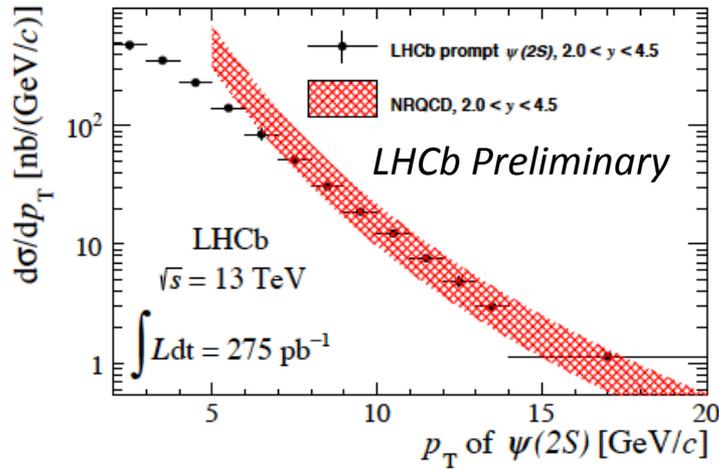
blue: prompt $\psi(2S)$

black line: from b-decay

green, magenta: backgrounds



$\psi(2S)$ in pp at 7,13 TeV



- Overall good agreement with predictions, some deviation at low p_T for prompt $\psi(2S)$
- New measurement at 7 TeV supersedes earlier result based on smaller event sample

Asymmetry of $D_s^{+/-}$ in pp at $\sqrt{s_{NN}} = 7,8$ TeV

Expected asymmetry in charmed mesons with u and d

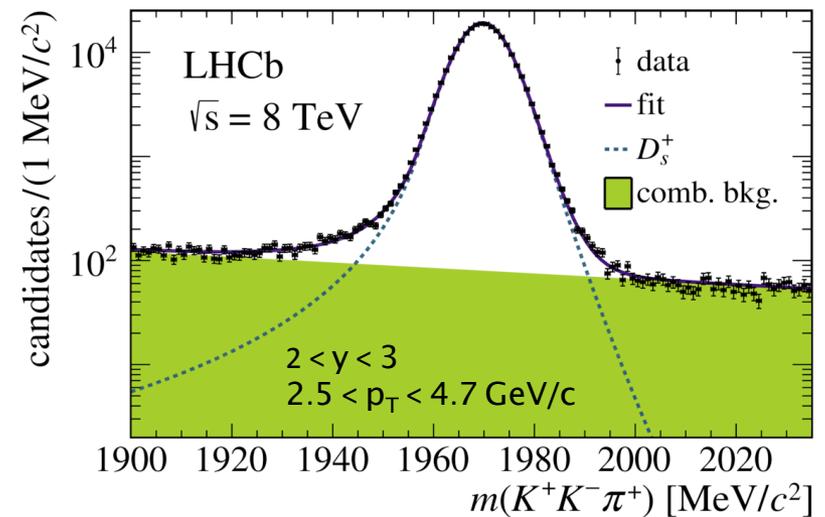
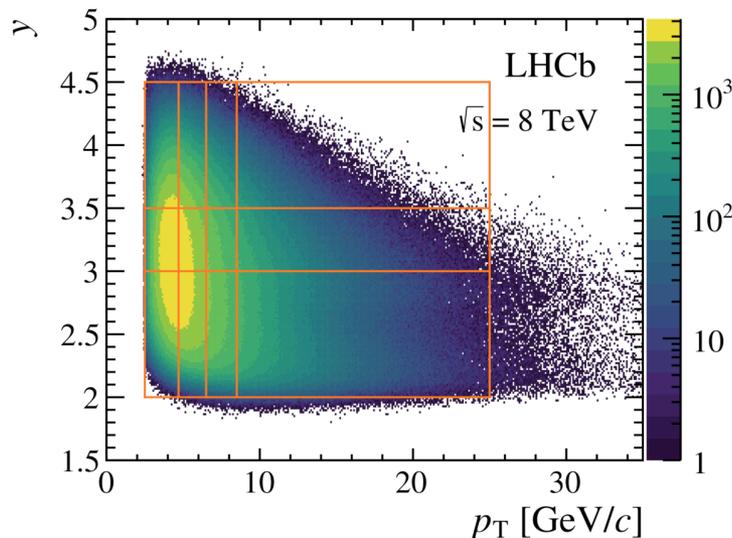
- c and c-bar hadronise differently due to the presence of u, d valence quarks
- c-bar preferably forms mesons, c can additionally form baryons with valence quarks

$D_s^{+/-}$ does not contain valence quarks, only indirect effect of asymmetry expected

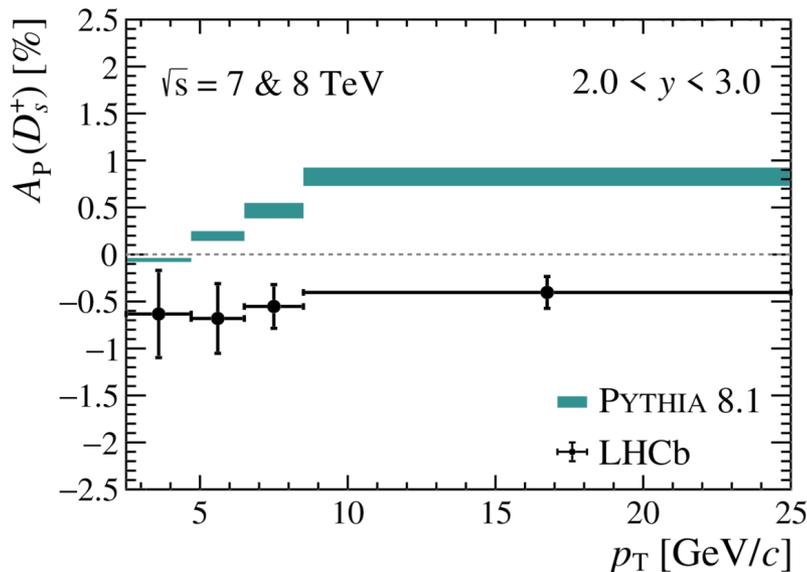
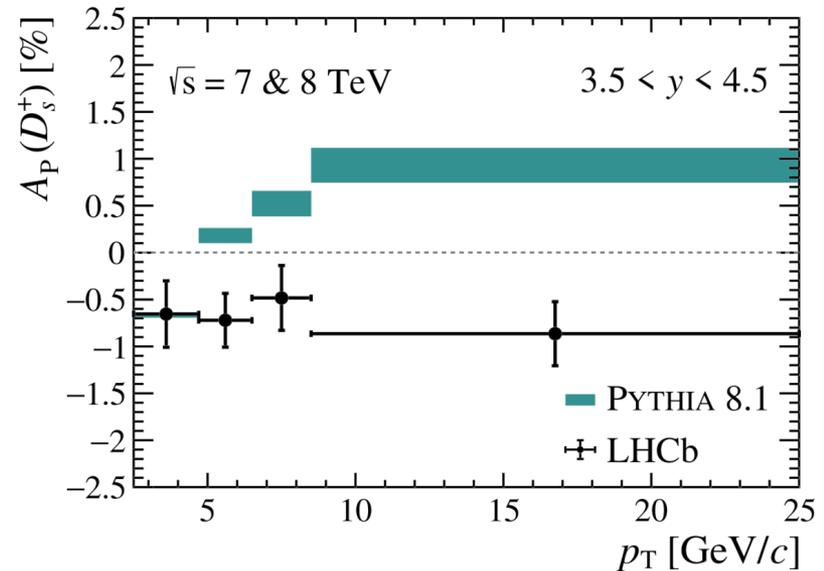
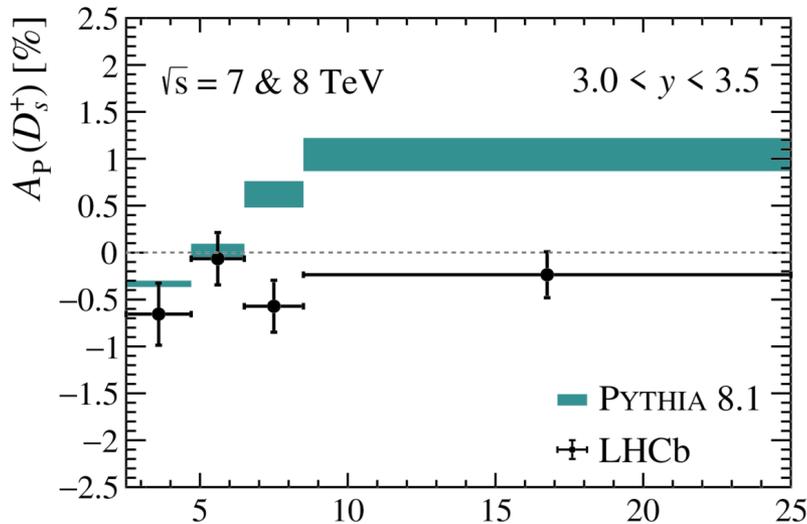
- Sensitive test for non-perturbative QCD models
- Essential input for direct CP violation in decays of D_s^+ mesons

$$\text{Asymmetry} \quad A_P(D_s^+) = \frac{\sigma(D_s^+) - \sigma(D_s^-)}{\sigma(D_s^+) + \sigma(D_s^-)}$$

Decay mode $D_s^+ \rightarrow \phi \pi^+$ with $\phi \rightarrow K^+K^-$, measurements includes $D_s^{+*} \rightarrow D_s^+ \gamma$ or $D_s^+ \pi^0$



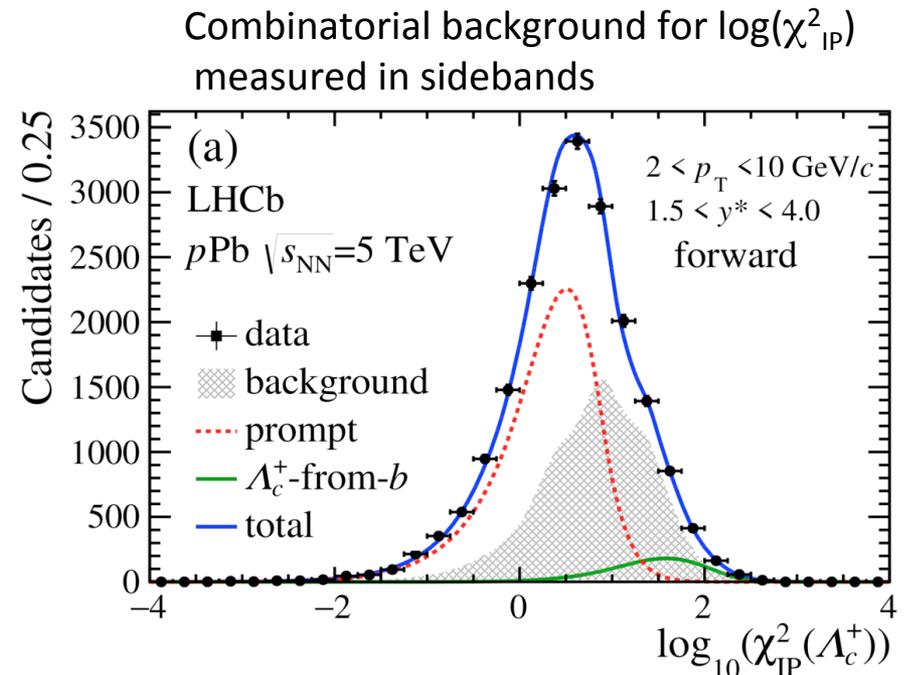
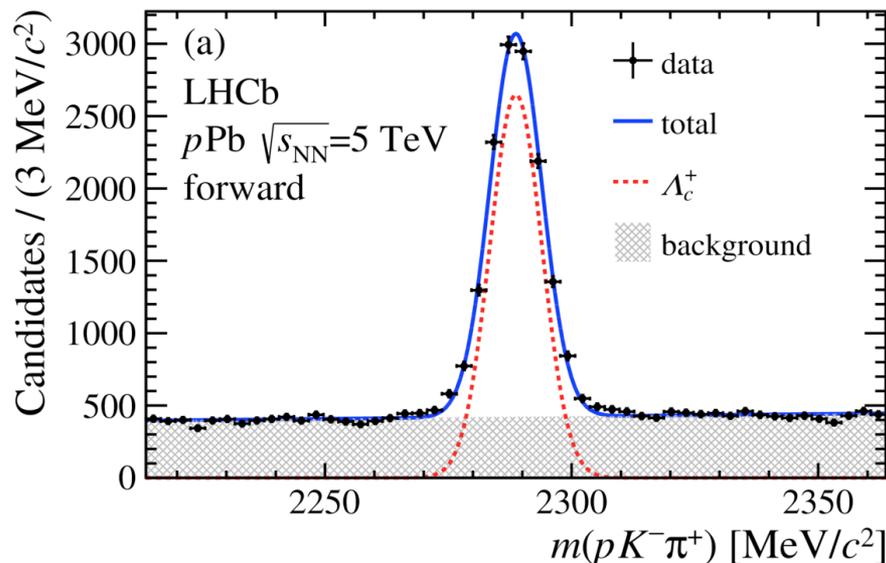
Asymmetry of $D_s^{+/-}$ in pp at $\sqrt{s_{NN}} = 7,8$ TeV



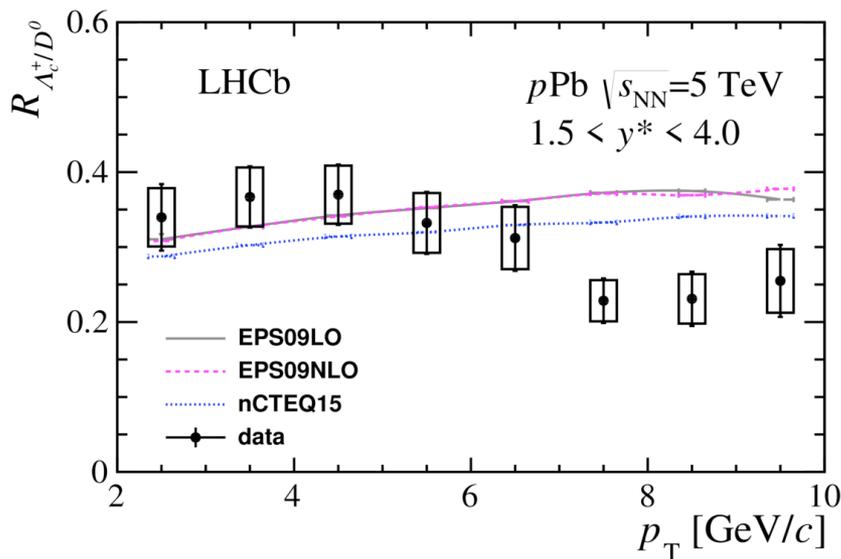
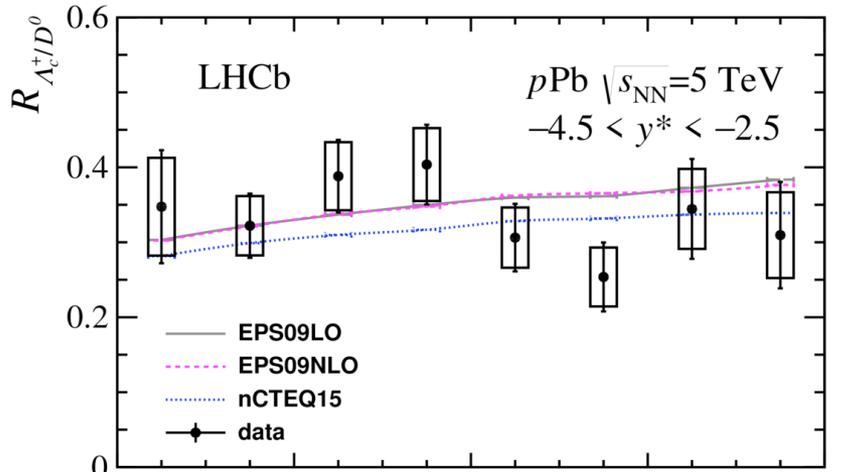
- 3.3σ non-zero asymmetry in combined data
- No significant dependence on \sqrt{s}_{NN} , y , p_T
- PYTHIA 8.1 prediction is off and shows stronger dependence on y and p_T than data

Prompt Λ_c^+ in pPb at $\sqrt{s_{NN}} = 5$ TeV

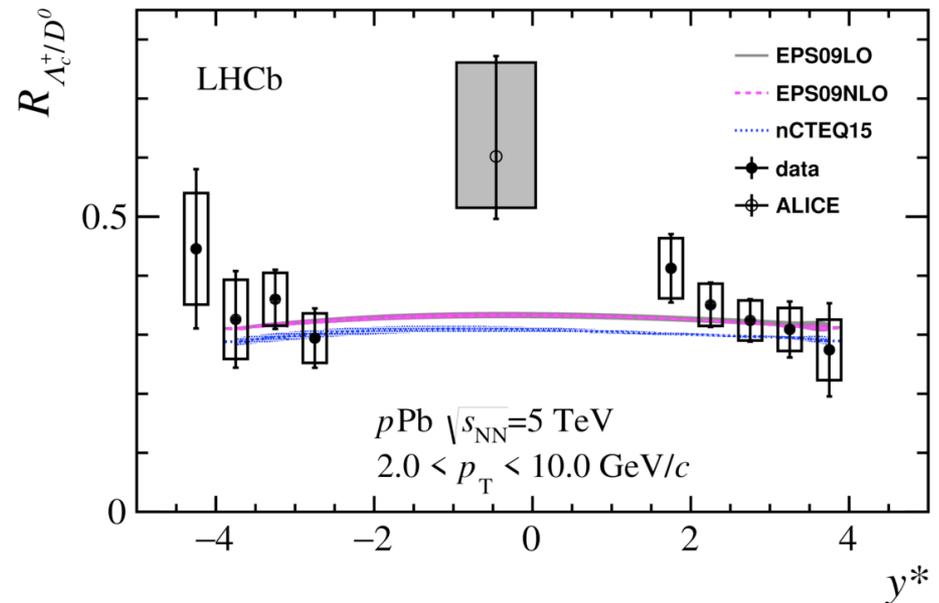
- Double differential cross-section in y^* , p_T
 y^* ... rapidity in cms of colliding nucleons
- Cross-section ratios: Forward-backward, baryon-to-meson
- Decay channel $\Lambda_c^+ \rightarrow p K^- \pi^+$ used to measure Λ_c^+ yield
- Prompt Λ_c^+ determined from fit of $\log(\chi^2_{IP})$ distribution
 χ^2_{IP} ... difference in χ^2 when fitting primary vertex with and without Λ_c^+ candidate



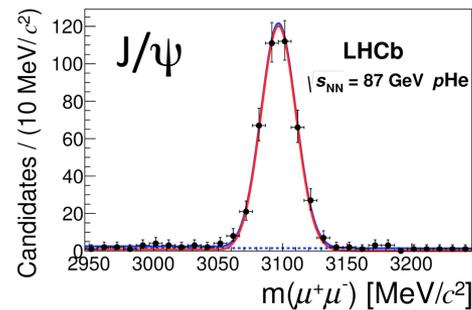
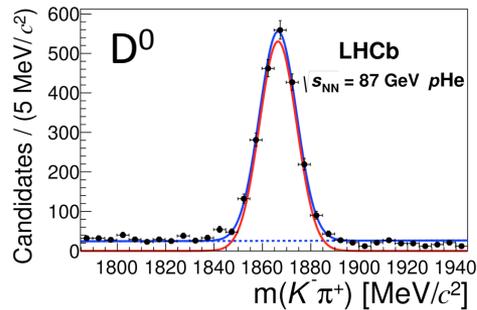
Prompt Λ_c^+ in pPb at $\sqrt{s_{NN}} = 5$ TeV



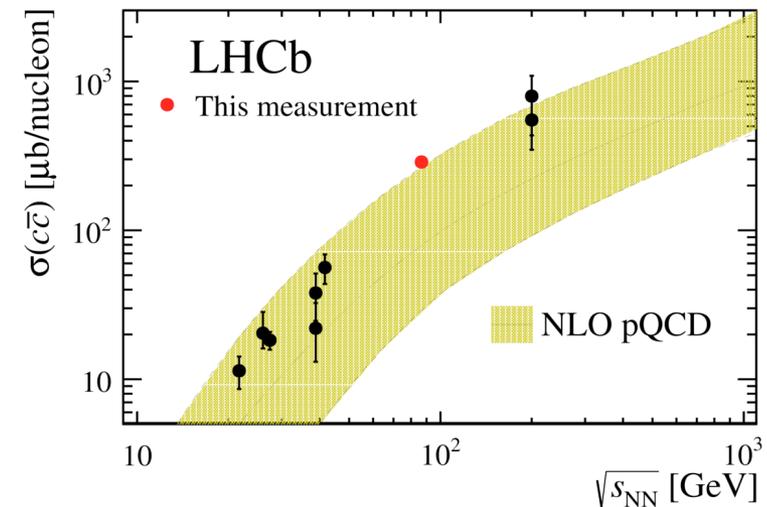
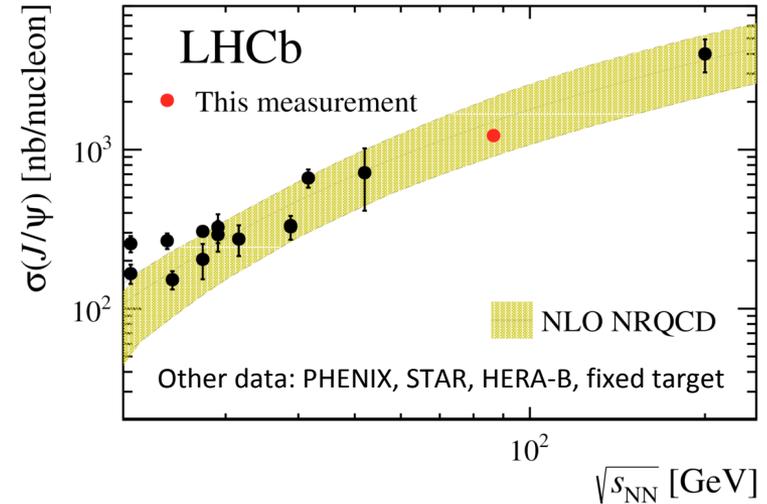
- FB ratios consistent with predictions
- Baryon-to-meson ratios
 - At forward rapidity lower at $p_T > 7$ GeV/c than predictions
 - Predictions slightly convex in y^* , ALICE + LHCb suggest more peaked shape at mid-rapidity



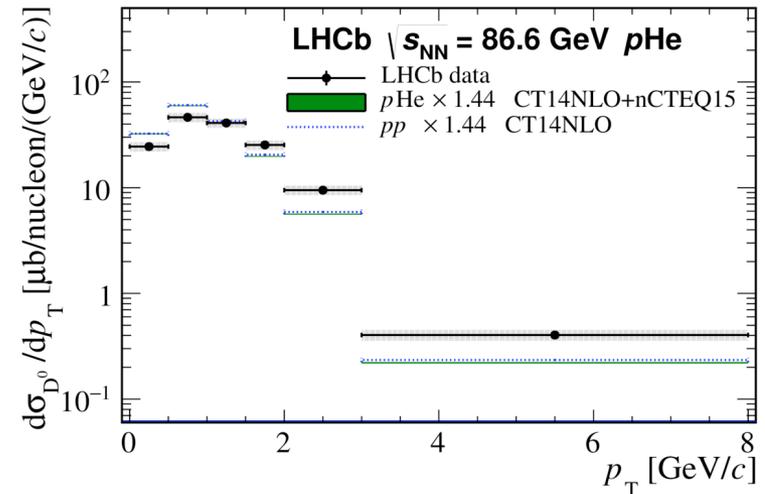
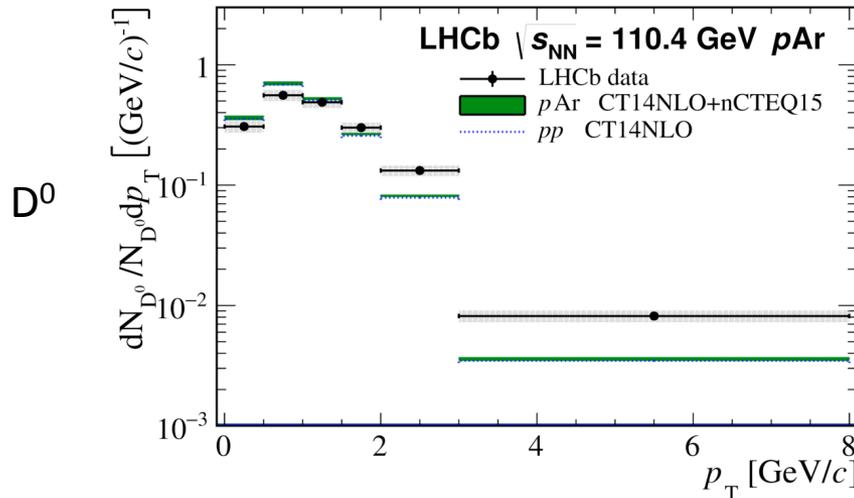
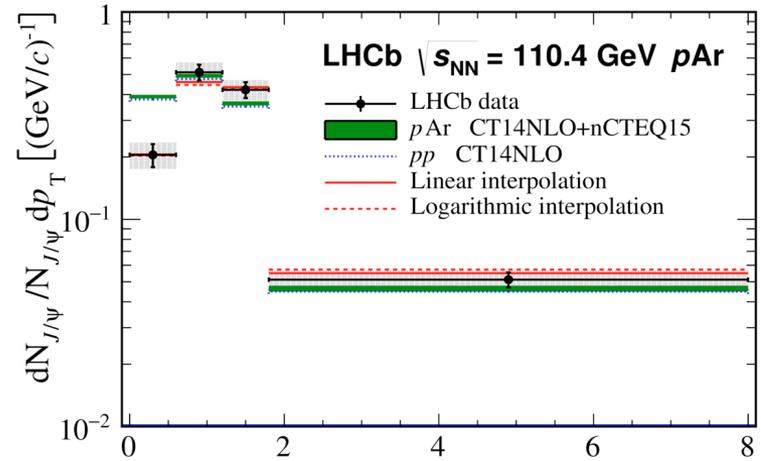
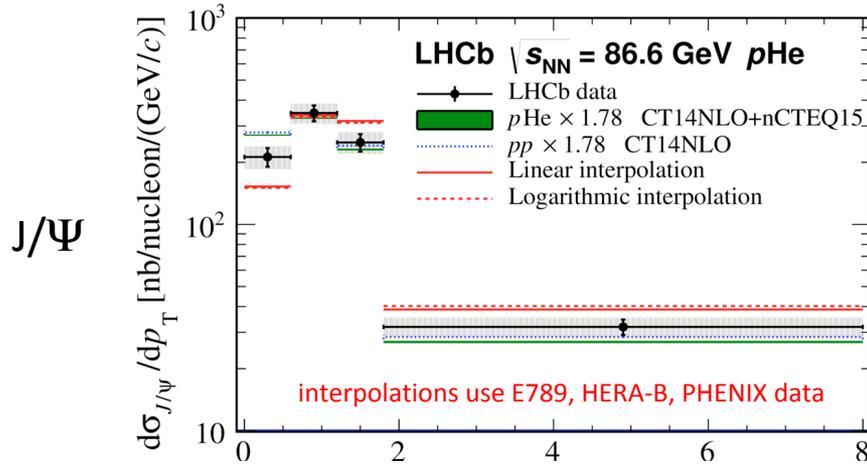
J/ ψ , D⁰ in p(Ar,He) at $\sqrt{s_{NN}} = 87, 110$ GeV



- First study of charm in fixed-target mode
- J/ ψ and D⁰ production in pAr(gas) and pHe(gas)
- Decay channels: D⁰ \rightarrow K⁺ π ⁻, J/ ψ \rightarrow $\mu^+\mu^-$
- Differential cross-section in y and p_T
- Low background in invariant mass distributions
- Right: Total cross-sections
 - Data measured at $y = [2, 4.6]$ extrapolated (about 10 % correction)
 - Measurements fill gap between 50 and 200 GeV
 - D⁰ to $c\bar{c}$ with global fragmentation factor
 - Very high precision compared to other data

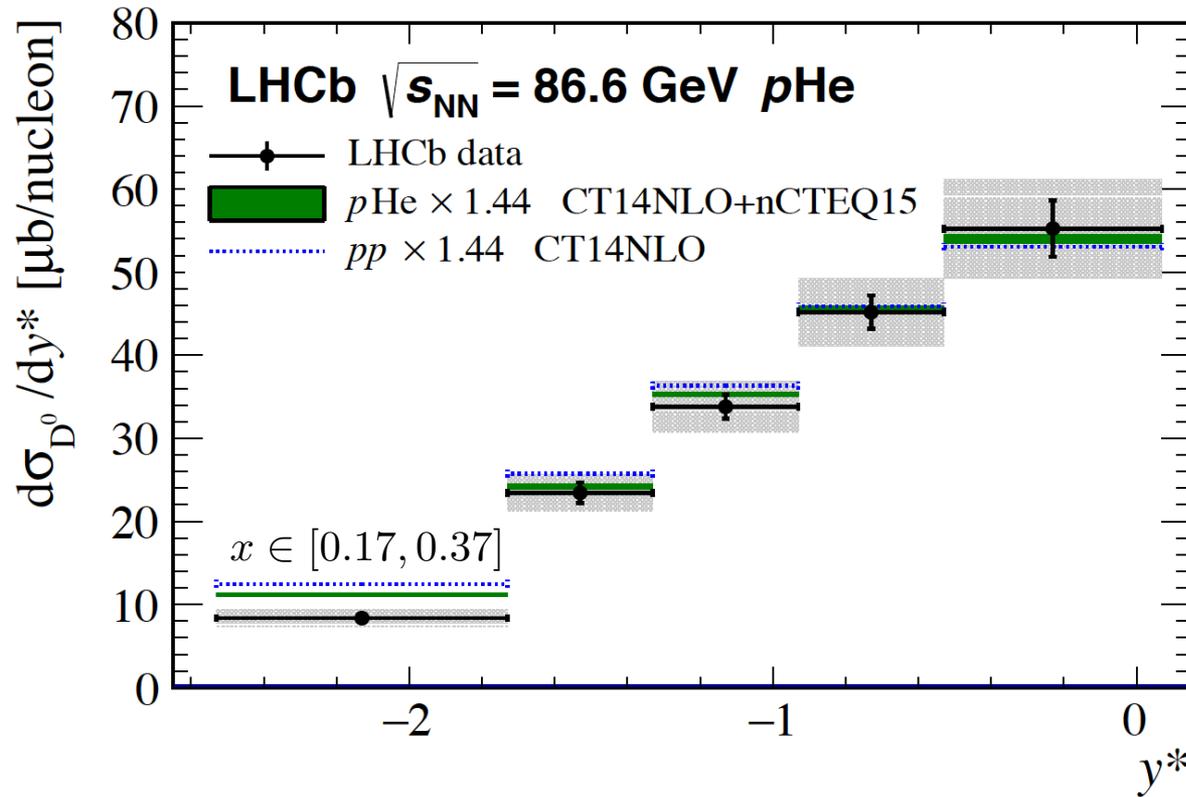


J/ψ, D⁰ in p(Ar,He) at $\sqrt{s_{NN}} = 87, 110$ GeV



HELAC-ONIA predictions differ in amplitude and shape

J/ ψ , D^0 in p(Ar,He) at $\sqrt{s_{NN}} = 87, 110$ GeV

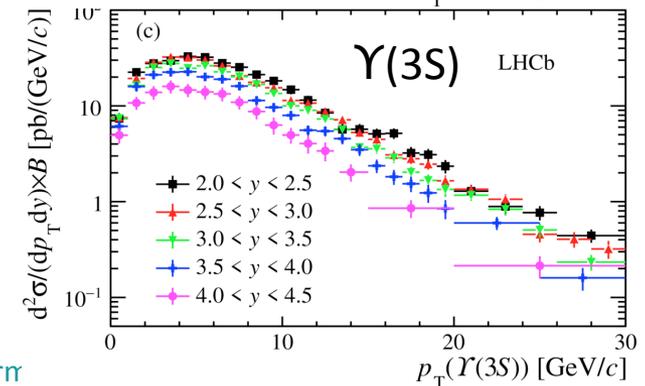
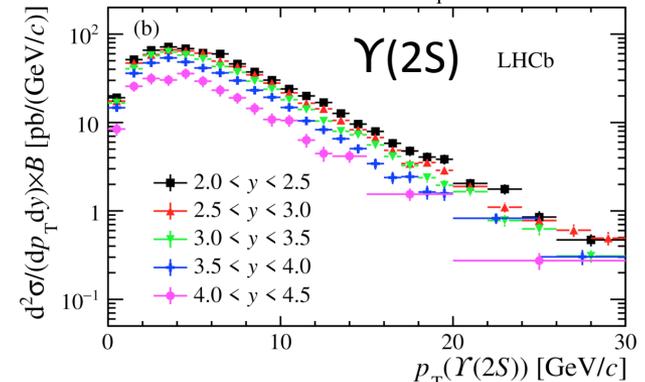
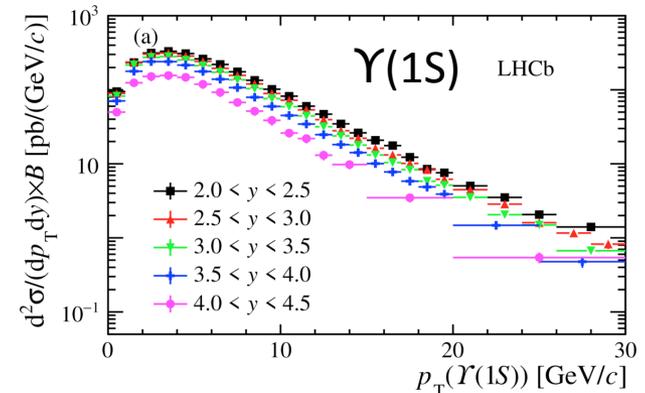
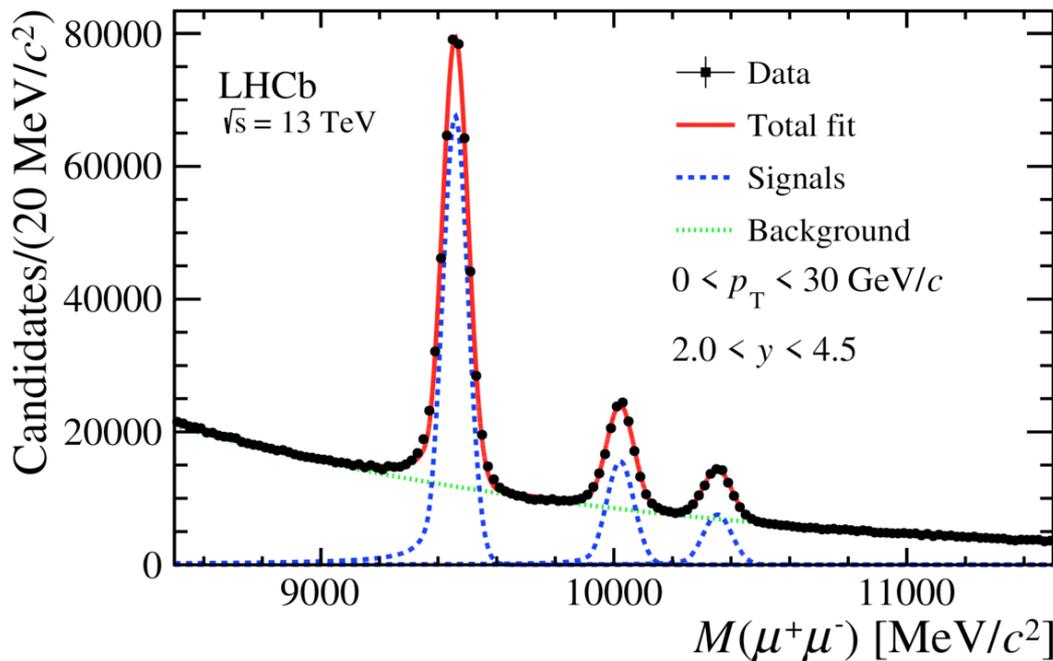


- Substantial intrinsic valence-like charm content of the nucleon expected in some theories
J. Pumplin, H. L. Lai, and W. K. Tung, PRD 75 (2007) 054029; S. Dulat et al, PRD 89 (2014) 073004
- Would contribute at large Bjorken- x and could be visible in most backward bin of $p\text{He}$ data
- Data seem to agree with predictions without any intrinsic valence-like charm contribution
- No evidence of substantial intrinsic charm content of the nucleon observed

Hadrons with Beauty

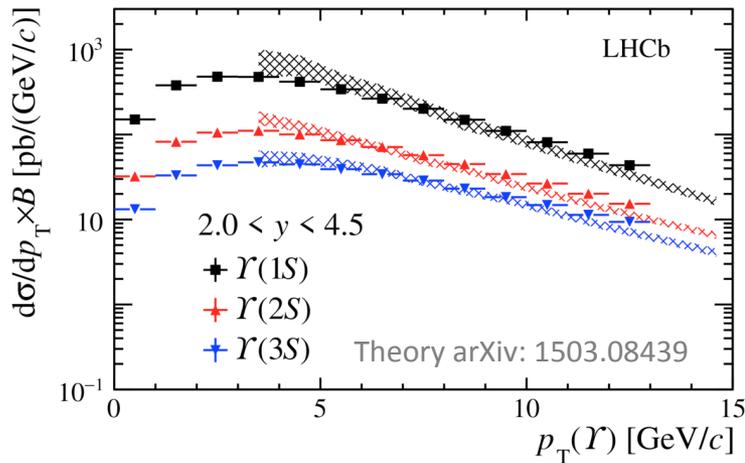
$\Upsilon(nS)_{n=1,2,3}$ in pp at $\sqrt{s_{NN}} = 13$ TeV

- Previous measurements (RHIC, LHC) showed increasing suppression of higher states ("melting")
- Decay channel: $\Upsilon(nS) \rightarrow \mu\mu$
- Double diff. cross-section $d^2\sigma/dp_T dy$ times muon branching fraction for $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$
- Also computed ratios of 13 TeV data to 8 TeV data

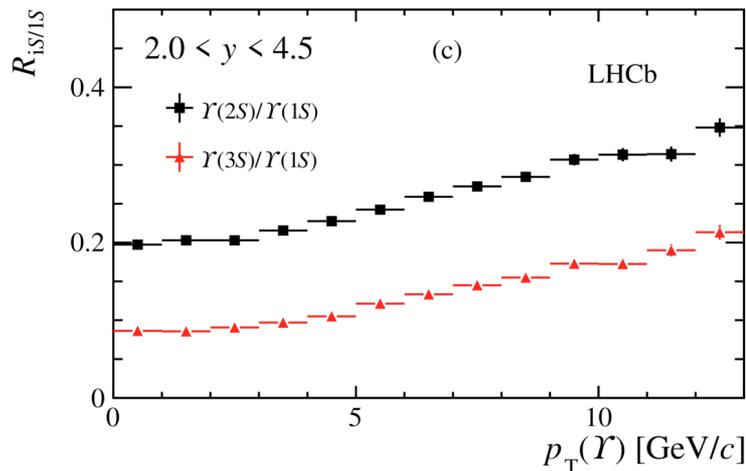


$\Upsilon(nS)_{n=1,2,3}$ in pp at $\sqrt{s_{NN}} = 13$ TeV

- Good agreement with NRQCD predictions

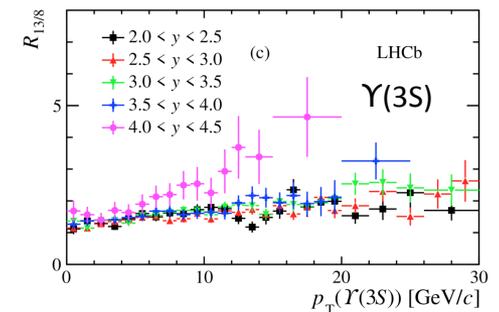
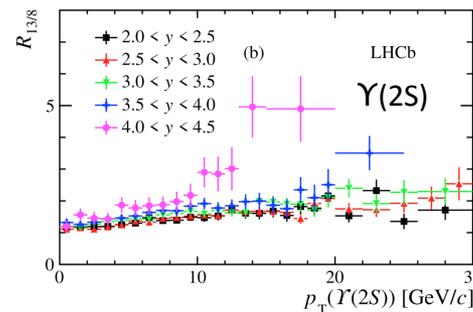
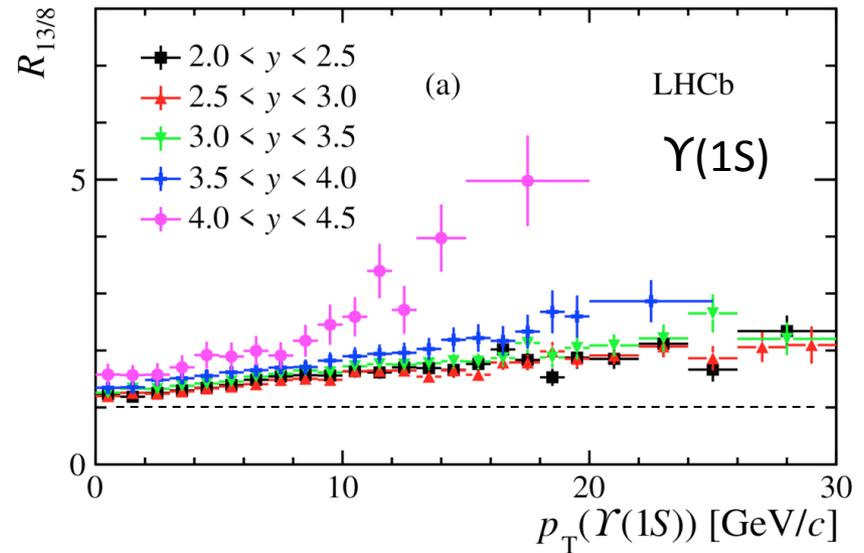


- Enhanced suppression of $n > 1$ states at low p_T
- No significant dependence observed on y



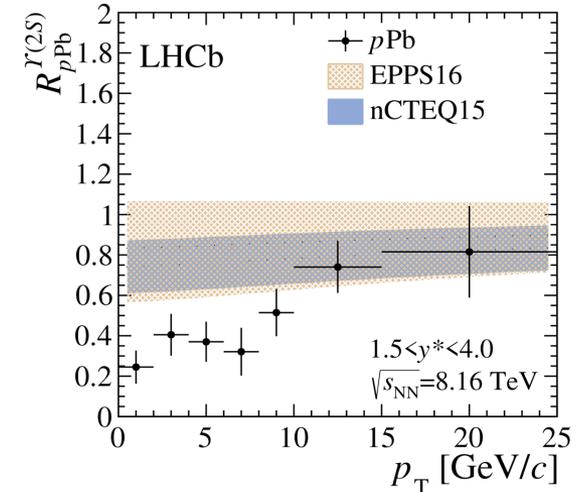
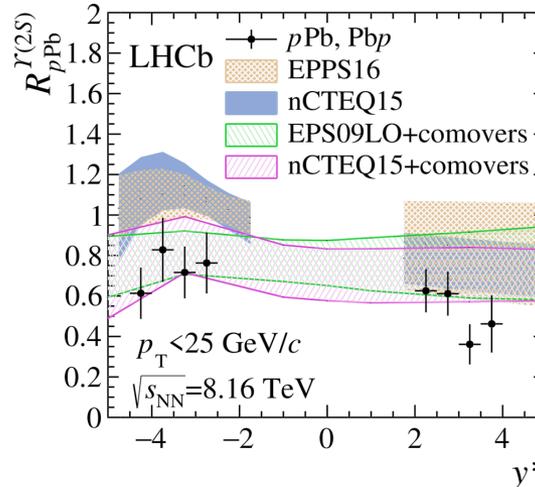
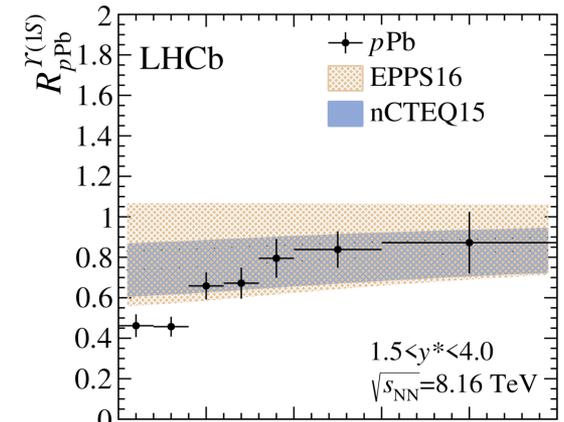
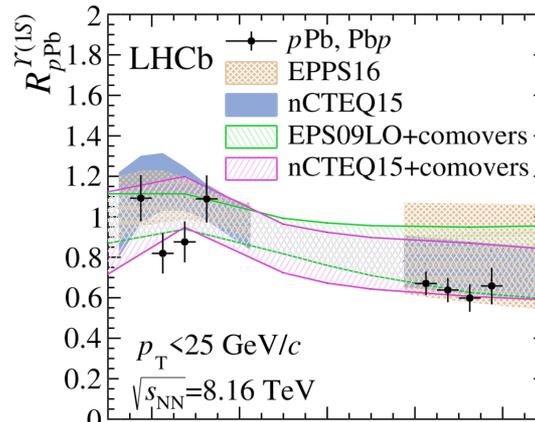
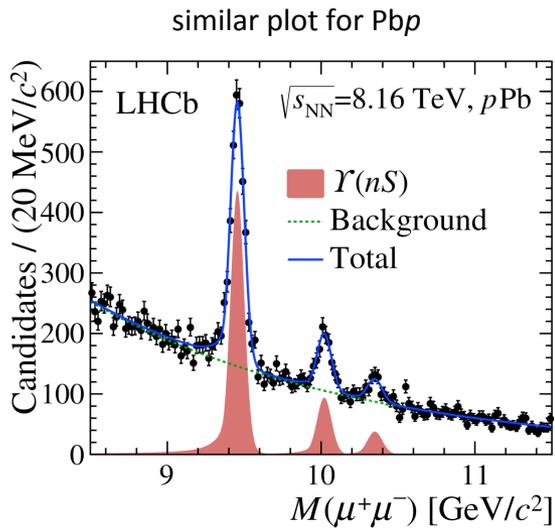
Ratios of 13 TeV data to 8 TeV data

- Consistently above unity
- Growths with p_T and y for all states



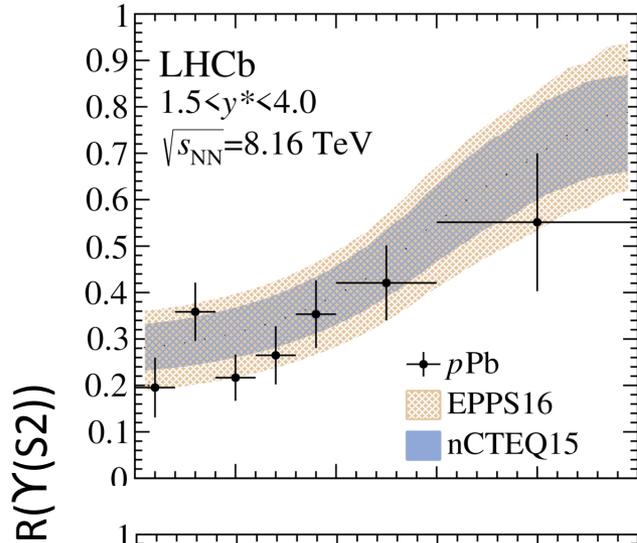
$\Upsilon(nS)_{n=1,2,3}$ in pPb at $\sqrt{s_{NN}} = 8.16$ TeV

- 21x luminosity compared to previous LHC measurement at 5 TeV
- Decay channel: $\Upsilon(nS) \rightarrow \mu\mu$
- Double diff. cross-section $d^2\sigma/dp_T dy$ for $\Upsilon(1S)$ and $\Upsilon(2S)$, integral for $\Upsilon(3S)$; multiple ratios measured



- Nuclear modification R enhanced at low p_T
- Agreement with HELAC-Onia predictions at high p_T
- Some disagreement at low p_T

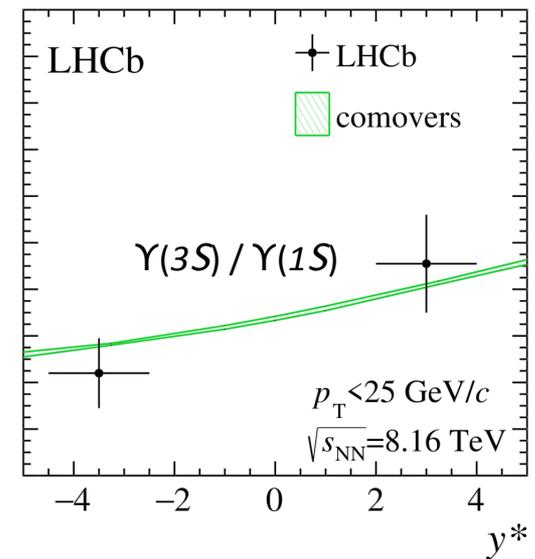
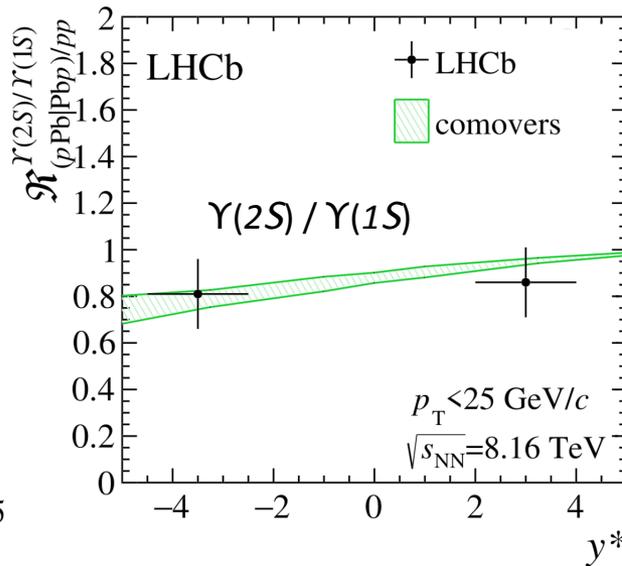
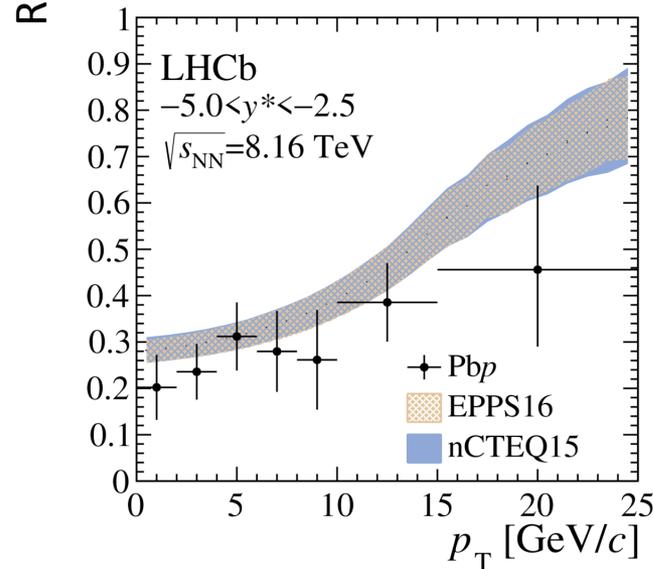
$\Upsilon(nS)_{n=1,2,3}$ in pPb at $\sqrt{s_{NN}} = 8.16$ TeV



"Suppression factor" "nuclear modification" of "suppression factor"

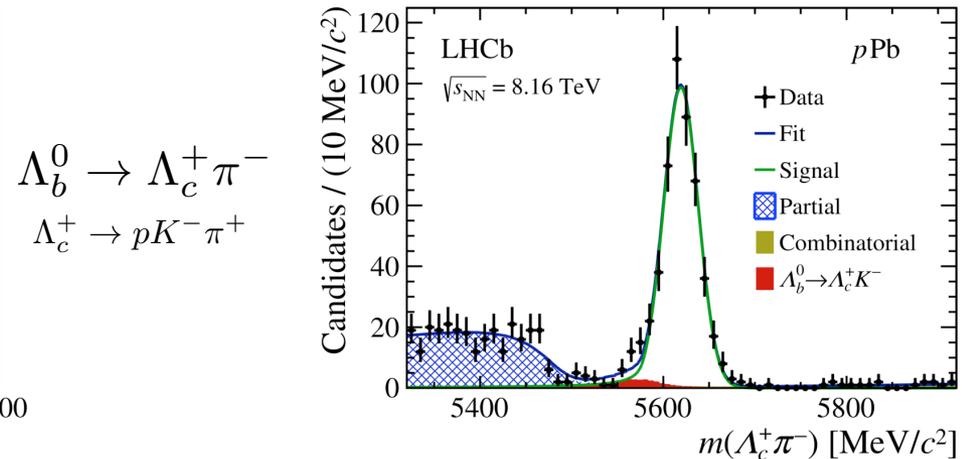
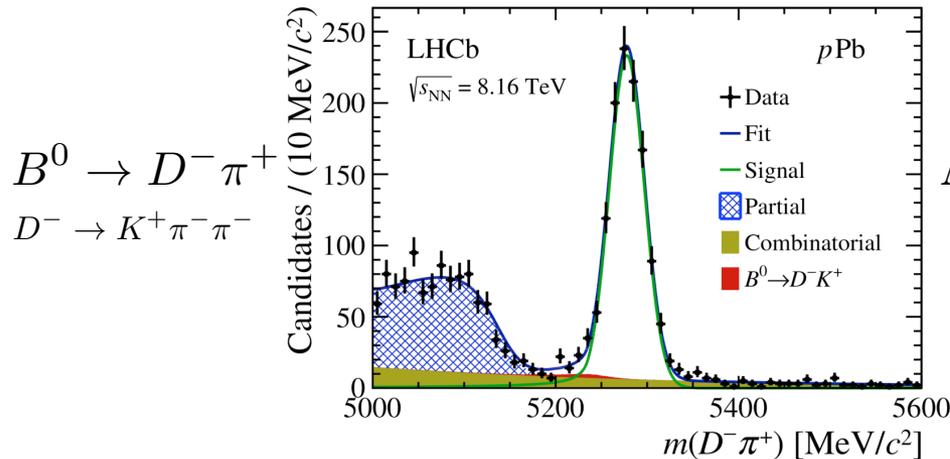
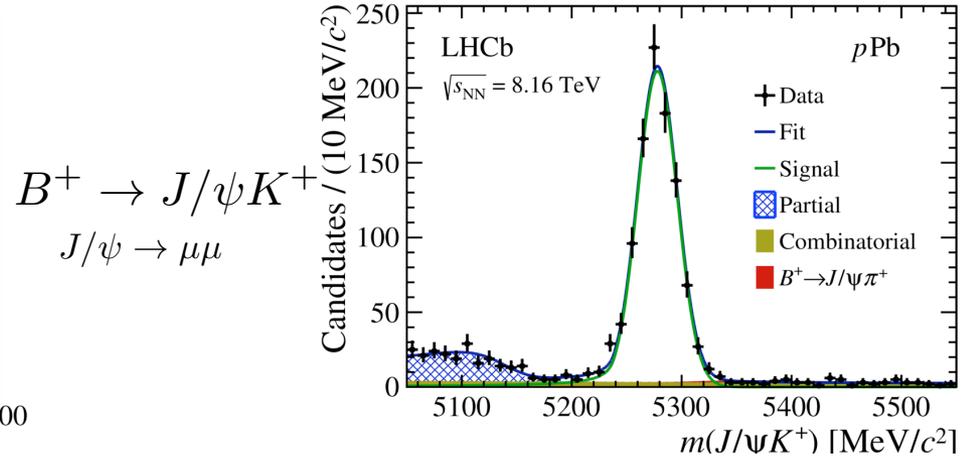
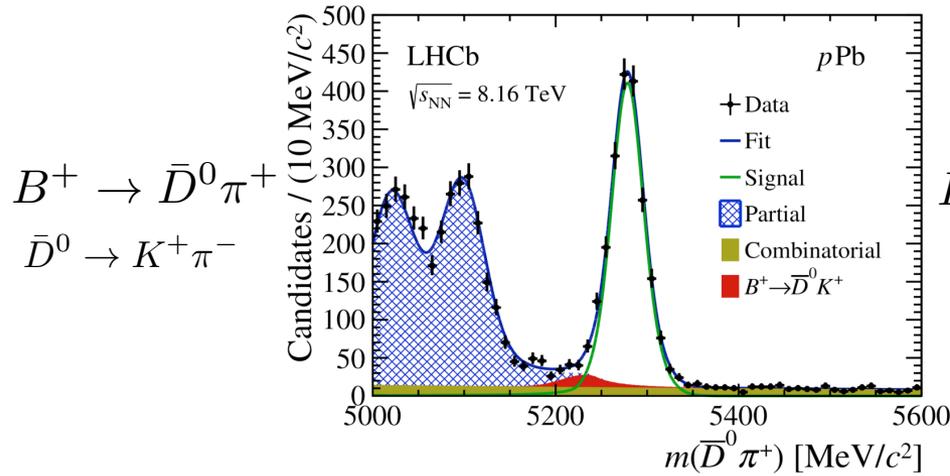
$$R(\Upsilon(nS)) = \frac{[d^2\sigma/dp_T dy^*](\Upsilon(nS))}{[d^2\sigma/dp_T dy^*](\Upsilon(1S))} \quad \mathfrak{R}^{\Upsilon(nS)/\Upsilon(1S)}_{(pPb|PbP)/pp} = \frac{R(\Upsilon(nS))_{pPb|PbP}}{R(\Upsilon(nS))_{pp}}$$

- Suppression of $n > 1$ states in good agreement with predictions and previous measurements
- Stronger suppression at low p_T
- Strongly enhanced suppression of $\Upsilon(3S)$ in pPb compared to pp at negative rapidity



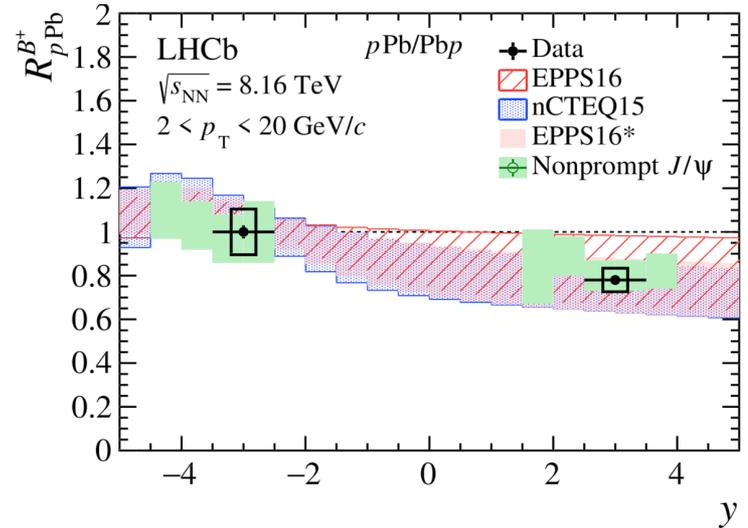
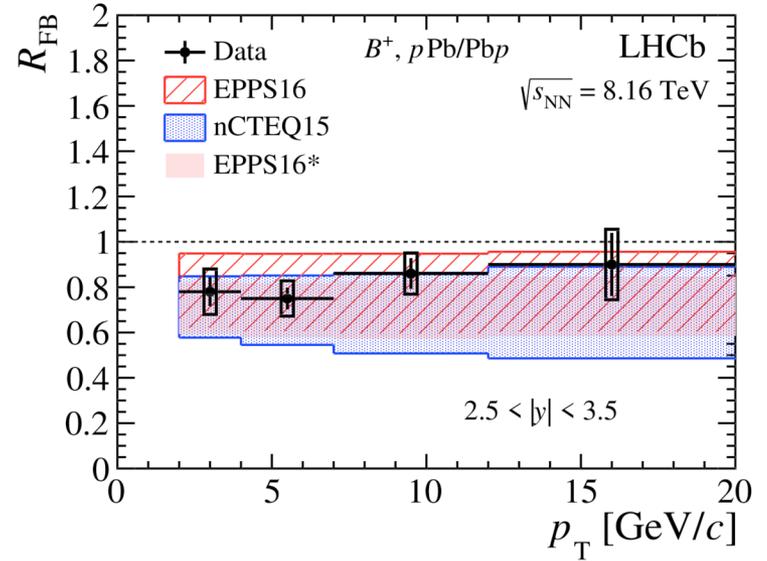
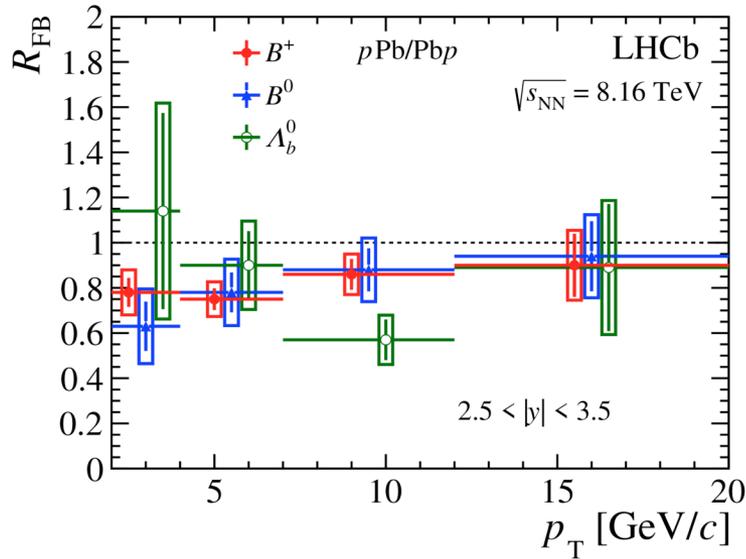
B^0, B^+, Λ_b^0 in pPb at $\sqrt{s_{NN}} = 8.16$ TeV

- Double diff. cross-section $d^2\sigma/dp_T dy$, see paper for many more plots & tables



Low backgrounds in invariant mass distributions

B^0, B^+, Λ_b^0 in pPb at $\sqrt{s_{NN}} = 8.16$ TeV

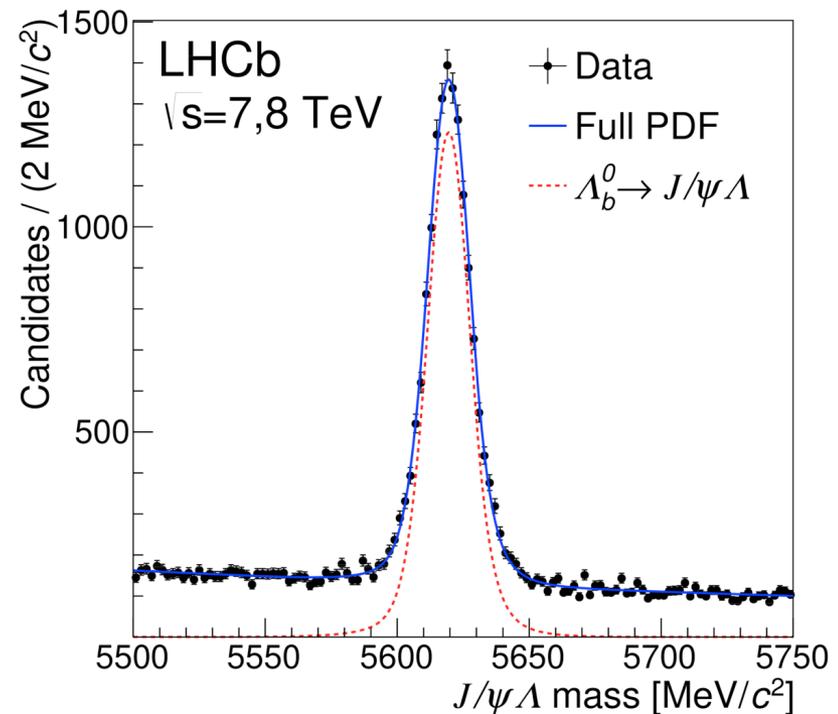
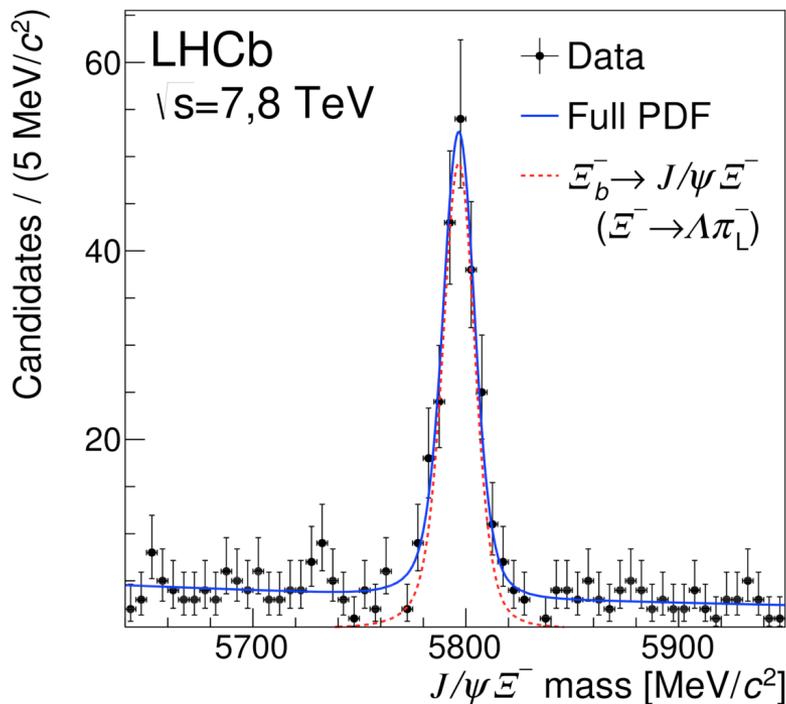


Nuclear effects

- Small effects in agreement with predictions
- Similar for all analyzed b-hadrons
- Comparable to non-prompt J/ψ from b-decays
- Smaller than for prompt J/ψ (as expected from b -mass $>$ c -mass)

Ξ_b^- in pp at $\sqrt{s} = 7,8,13$ TeV

- Measured production ratios, production asymmetry between Ξ_b^- and Ξ_b^+ , mass
- Decay channel $\Xi_b^- \rightarrow J/\psi \Xi^-$ and $\Xi^- \rightarrow \Lambda \pi^-$
- Measure production ratios instead of absolute branching fractions
 - Lack of knowledge of fragmentation fractions for decay products
 - Measure ratio to kinematically similar decay $\Lambda_b^0 \rightarrow J/\psi \Lambda$ instead (see next slide)



Ξ_b^- in pp at $\sqrt{s} = 7, 8, 13$ TeV

Trick: Replace branching fraction by decay width \times life-time

measured

$$R \equiv \frac{f_{\Xi_b^-} \mathcal{B}(\Xi_b^- \rightarrow J/\psi \Xi^-)}{f_{\Lambda_b^0} \mathcal{B}(\Lambda_b^0 \rightarrow J/\psi \Lambda)} = \frac{f_{\Xi_b^-} \Gamma(\Xi_b^- \rightarrow J/\psi \Xi^-) \tau_{\Xi_b^-}}{f_{\Lambda_b^0} \underbrace{\Gamma(\Lambda_b^0 \rightarrow J/\psi \Lambda)}_{3/2 \text{ in SU(3) flavor symmetry (assumed)}} \tau_{\Lambda_b^0}}$$

from PDG

↑
wanted: production fractions

3/2 in SU(3) flavor symmetry (assumed)

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (6.7 \pm 0.5 \pm 0.5 \pm 2.0) \times 10^{-2} \quad [\sqrt{s} = 7, 8 \text{ TeV}],$$

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (8.2 \pm 0.7 \pm 0.6 \pm 2.5) \times 10^{-2} \quad [\sqrt{s} = 13 \text{ TeV}].$$

- Production asymmetry of Ξ_b^- at 7,8 and 13 TeV compatible with zero (not shown)
- Mass of Ξ_b^- also measured relative to Λ_b^0 to cancel uncertainty of momentum-calibration

$$m(\Xi_b^-) = 5796.70 \pm 0.39 \pm 0.15 \pm 0.17 \text{ MeV}/c^2 \quad (\text{with PDG mass of } \Lambda_b^0)$$

Summary

- LHCb has rich and broad physics program:

Many new and updated precise inclusive production cross-sections for c - and b -hadrons

- $\psi(2S)$ in pp at 7,13 TeV *LHCb-PAPER-2018-049, submitted to JHEP*
 - Asymmetry of $D_s^{+/-}$ in pp at $\sqrt{s_{NN}} = 7,8$ TeV [JHEP 08 \(2018\) 008](#)
 - Prompt Λ_c^+ in pPb at $\sqrt{s_{NN}} = 5$ TeV [JHEP 02 \(2019\) 102](#)
 - $J/\psi, D^0$ in p(Ar,He) at $\sqrt{s_{NN}} = 87, 110$ GeV [arXiv:1810.07907](#), submitted to PRL

 - $Y(nS)_{n=1,2,3}$ in pp at $\sqrt{s_{NN}} = 13$ TeV [JHEP 07 \(2018\) 134](#)
 - $Y(nS)_{n=1,2,3}$ in pPb at $\sqrt{s_{NN}} = 8.16$ TeV [JHEP 11 \(2018\) 194](#)
 - B^0, B^+, Λ_b^0 in pPb at $\sqrt{s_{NN}} = 8.16$ TeV [Phys. Rev. D 99 \(2019\) 052011](#)
 - Ξ_b^- in pp at $\sqrt{s} = 7,8,13$ TeV [Phys. Rev. D 99 \(2019\) 052006](#)
- Comparison with predictions from perturbative QCD improve understanding of nuclear matter effects, mostly good agreement
 - Cross-section ratios useful to reduce uncertainties on experimental and theory side

CEP of J/ψ and $\psi(2S)$ in pp at 13 TeV [JHEP 10 \(2018\) 167](#)

Also see Marcin Kucharczyk talk at 11:05 on "Soft QCD and Central Exclusive Production at LHCb"

Backup

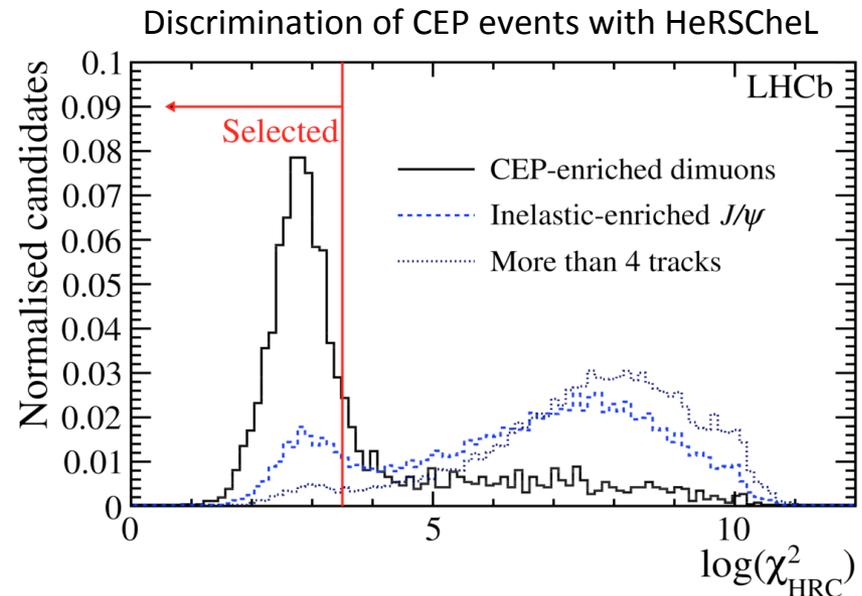
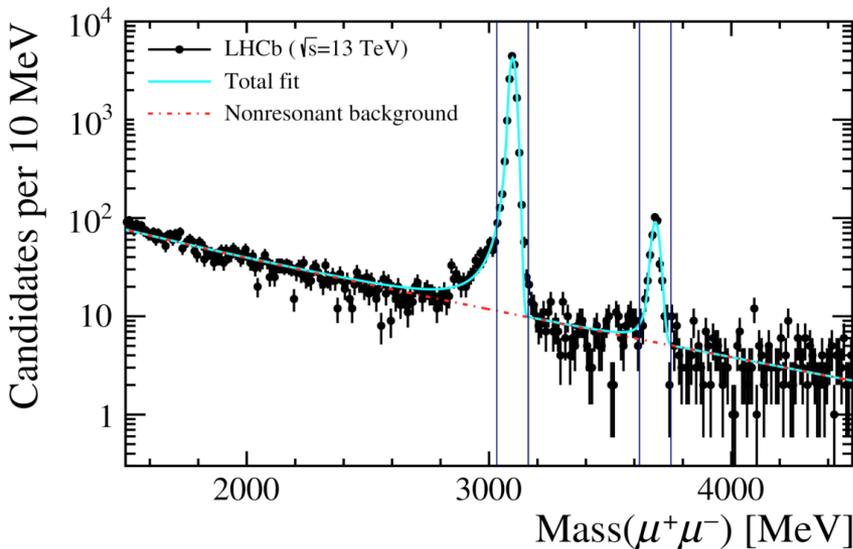
CEP of J/ψ , $\psi(2S)$ in pp at 13 TeV

Central exclusive production

- Diffractive process: $pp \rightarrow pXp$, $X = \text{meson}$, protons remain intact
- Fusion of photon and pomeron
 photon (spin 1) + pomeron (spin 0) = vector meson (spin 1)
- pQCD calculations available for charmonium production
- Probes gluon PDF down to $x = 2 \times 10^{-6}$, possibly showing saturation effects

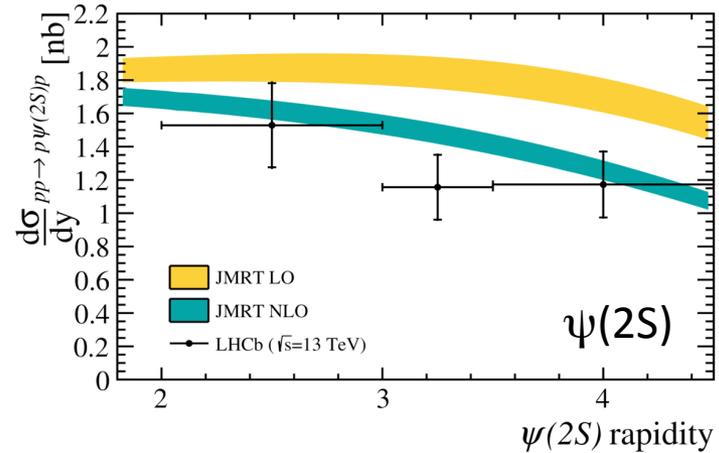
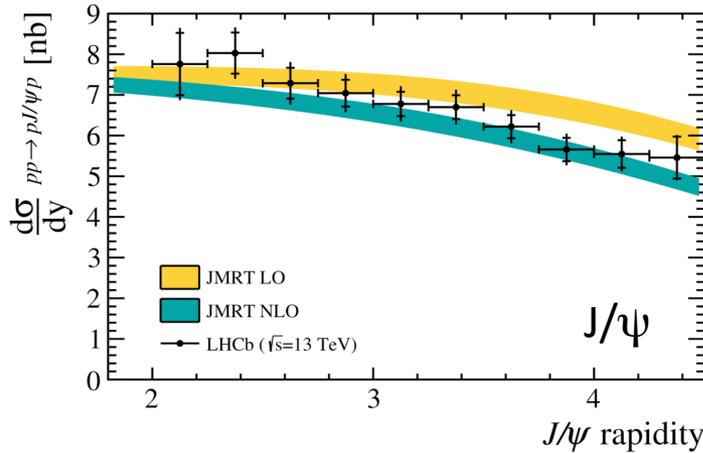
Experimental signature: no activity in LHCb except two muons, low activity in HeRSChel

Results: Differential cross-sections in y (MC corrected for fiducial acceptance to muons)

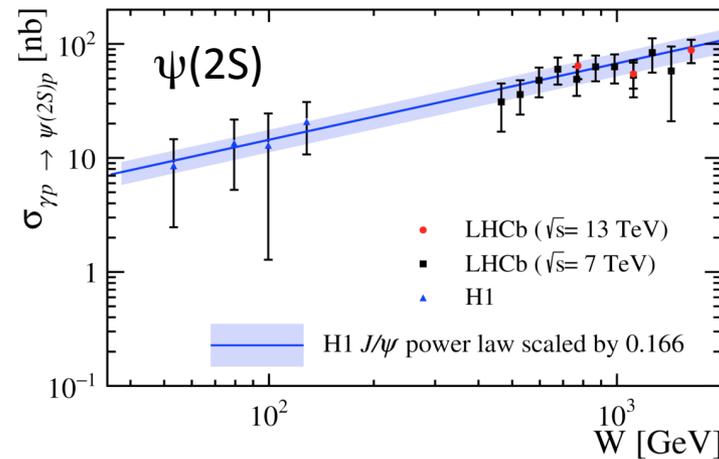
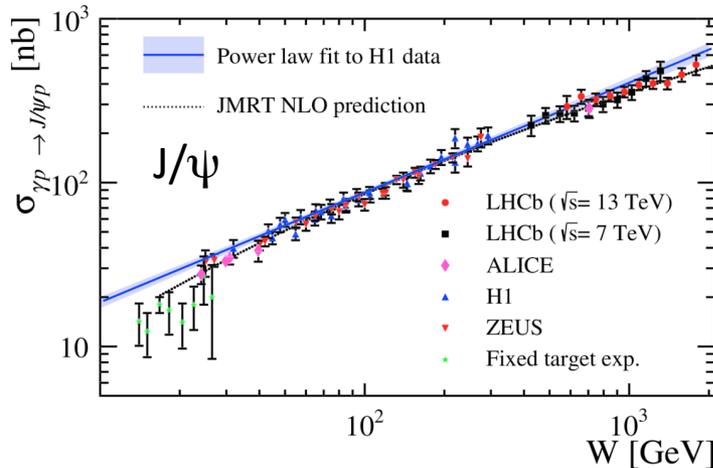


CEP of J/ψ , $\psi(2S)$ in pp at 13 TeV

Good agreement of data with NLO calculations



CEP cross-section $pp \rightarrow pXp$ are converted to photoproduction cross-section $\gamma p \rightarrow Xp$



Deviations from simple power-law observed for $\gamma p \rightarrow J/\psi p$, in agreement with JMRT prediction