Heavy Hadron Production and Quarkonia

Siim Tolk (CERN)
on behalf of the LHCb collaboration

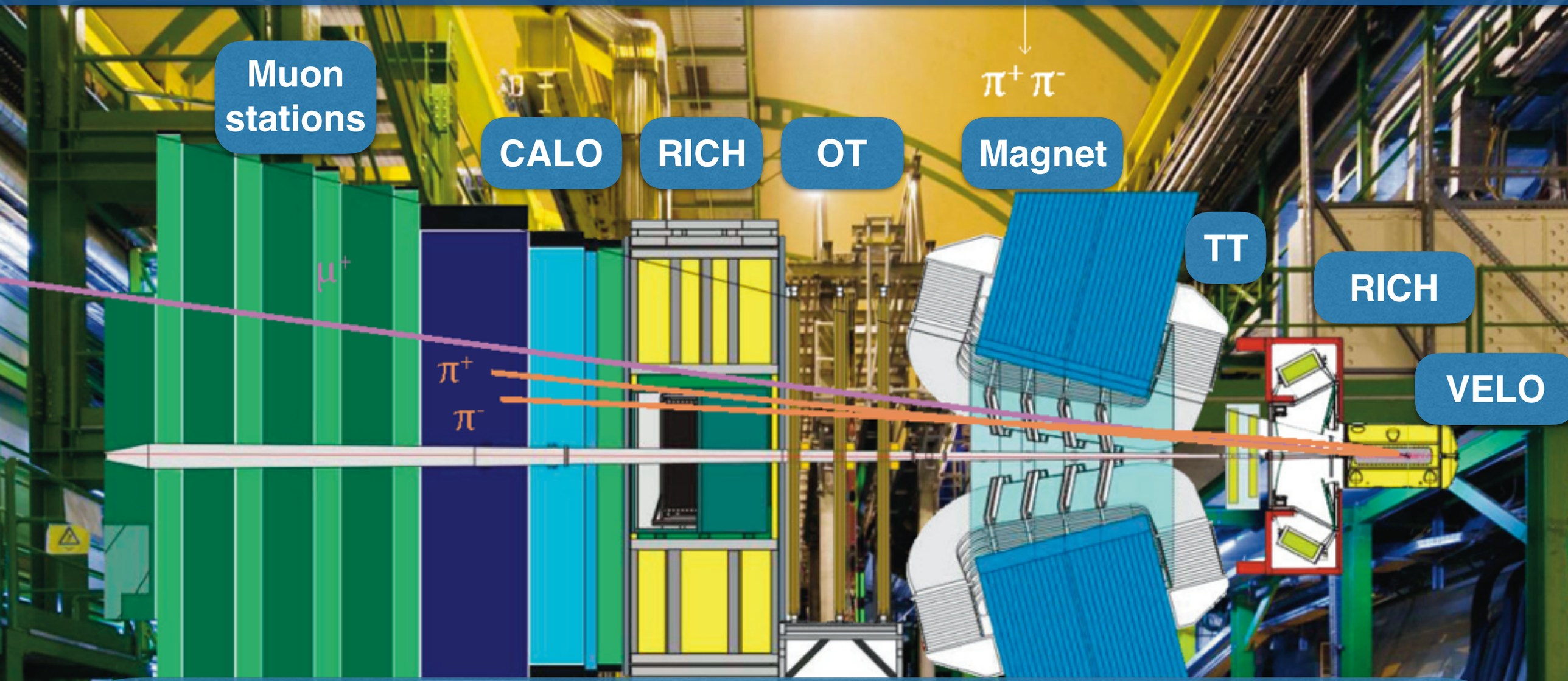
KRUGER 2018

LHCb's physics programme

- CP violation
- Indirect New Physics searches in rare decays
- Understanding QCD
  - Heavy flavour production, hadron spectroscopy (pentaquark states, bc states), unique fixed target programme
- Quark Gluon Plasma studies:
  - Rich heavy ion programs (production at p-Pb/Pb-p, fixed target p/pB-Ne)

[ALL LHCB PUBLICATIONS]

LHCb detector @ LHC

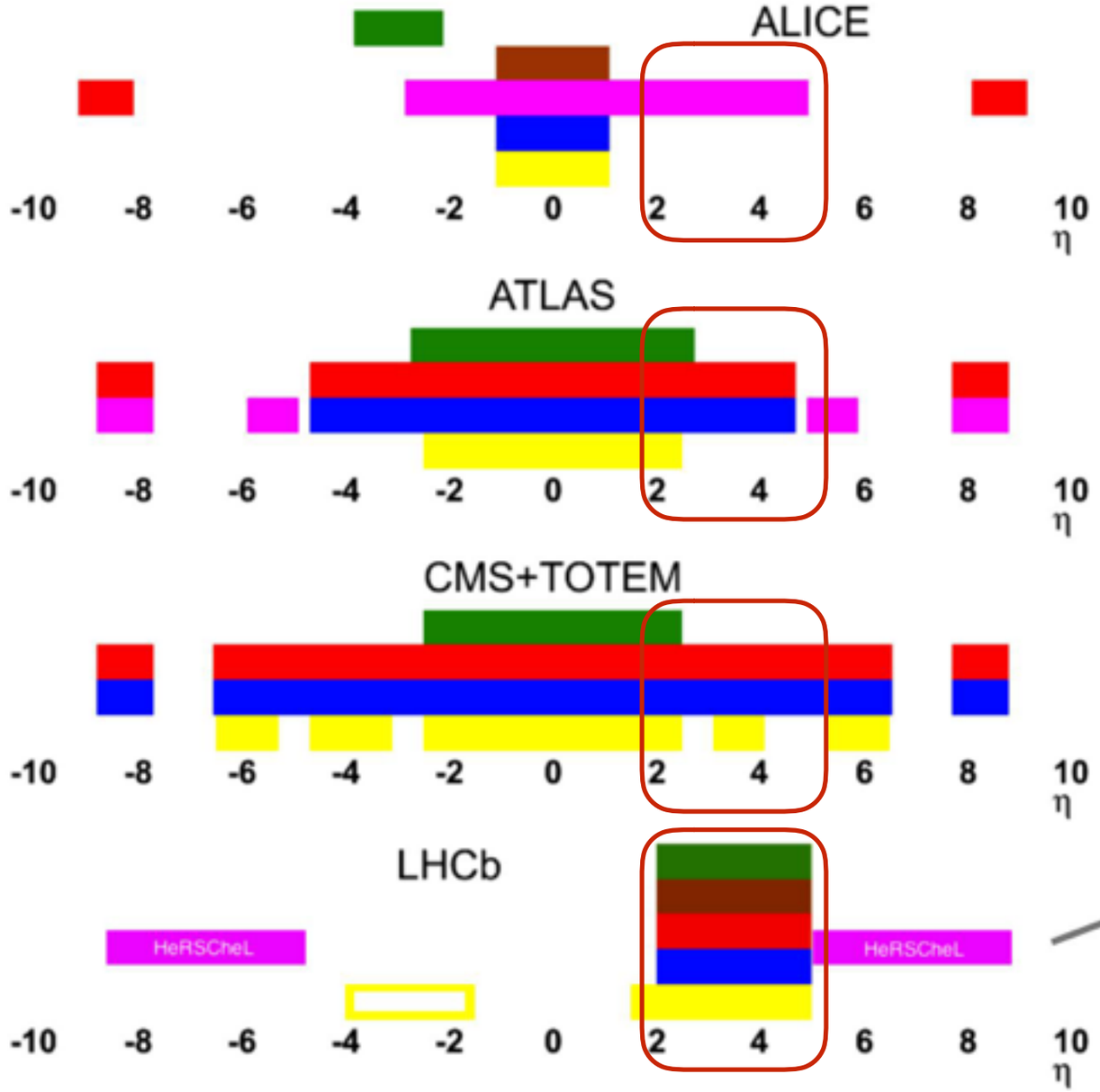


- **Clean collision environment** ($\mu \sim 1.6$) and high boost ($\gamma \sim 20$)
- **Good mass resolution** (~23 MeV for $B \to \mu^+\mu^-$)

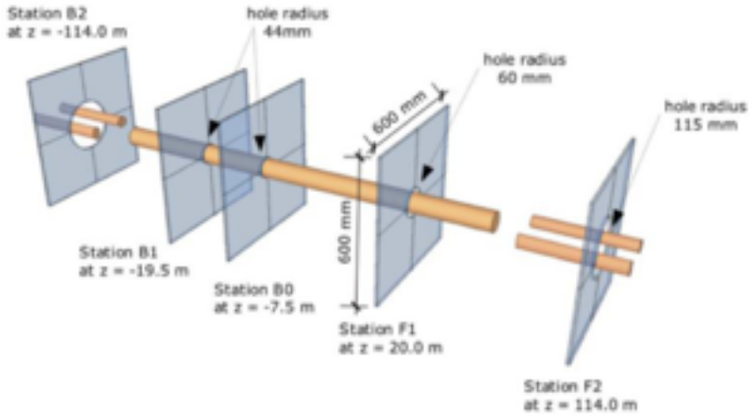
Excellent **charged hadron identification**, vertexing, high trigger and tracking efficiencies (>~90%) also in the low p_T range.

LHCb's niche:

fully instrumented at forward rapidity



(pseudo-rapidity)



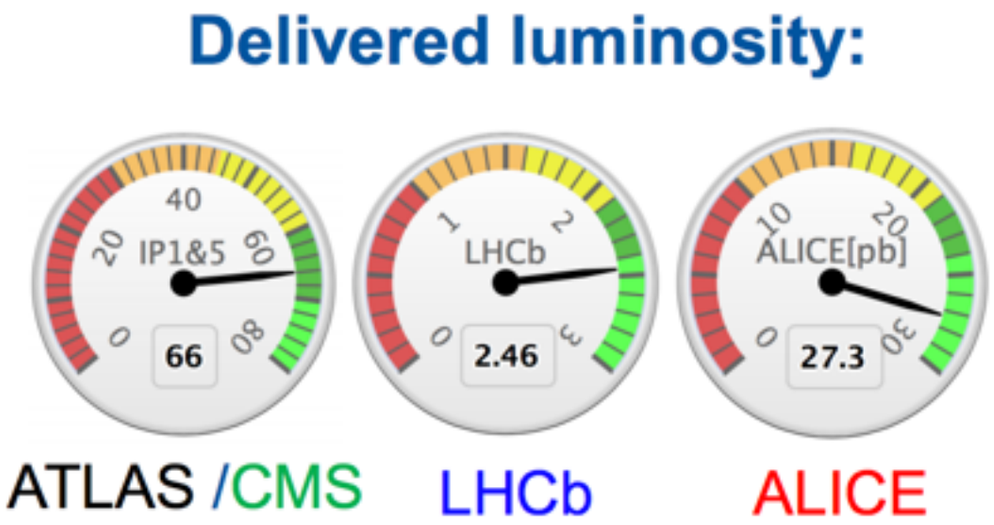
HeRSCHeL

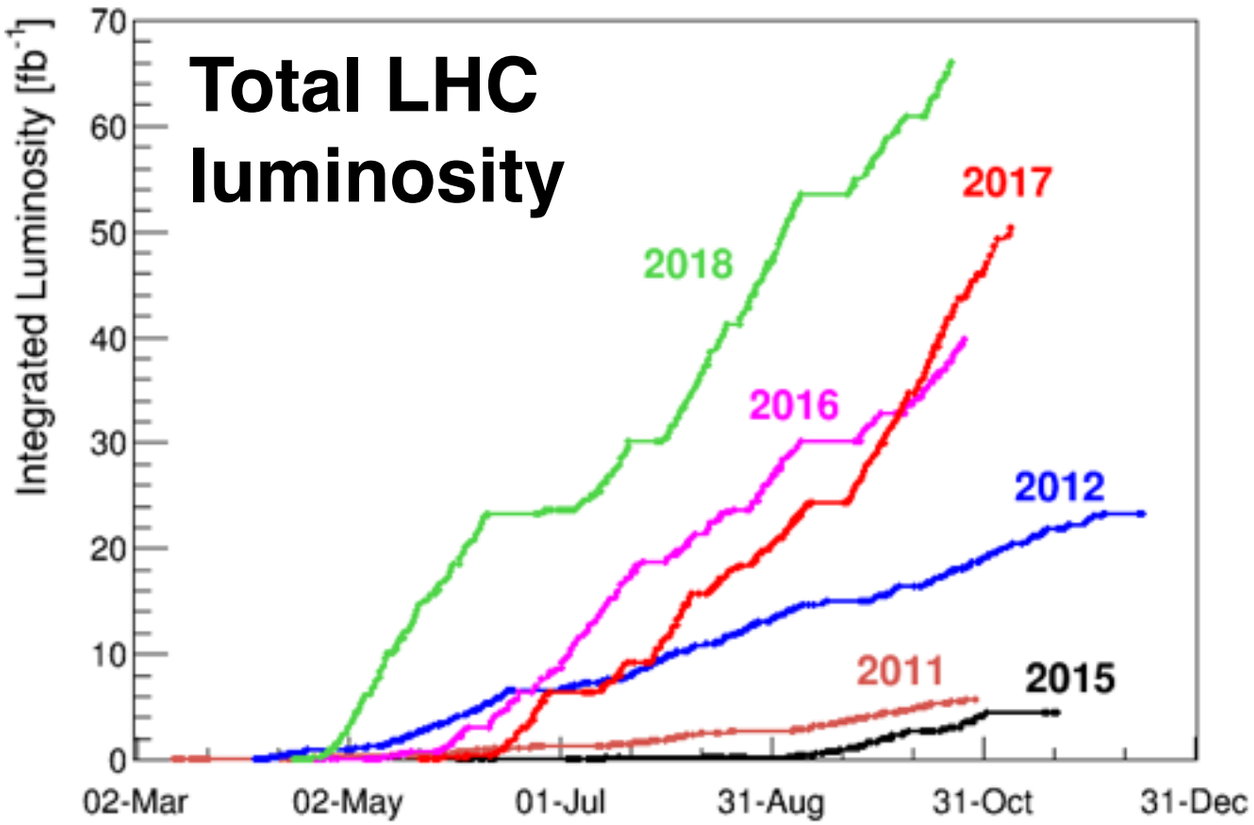
-7.5<η<-3.5

5.0< η <8.0

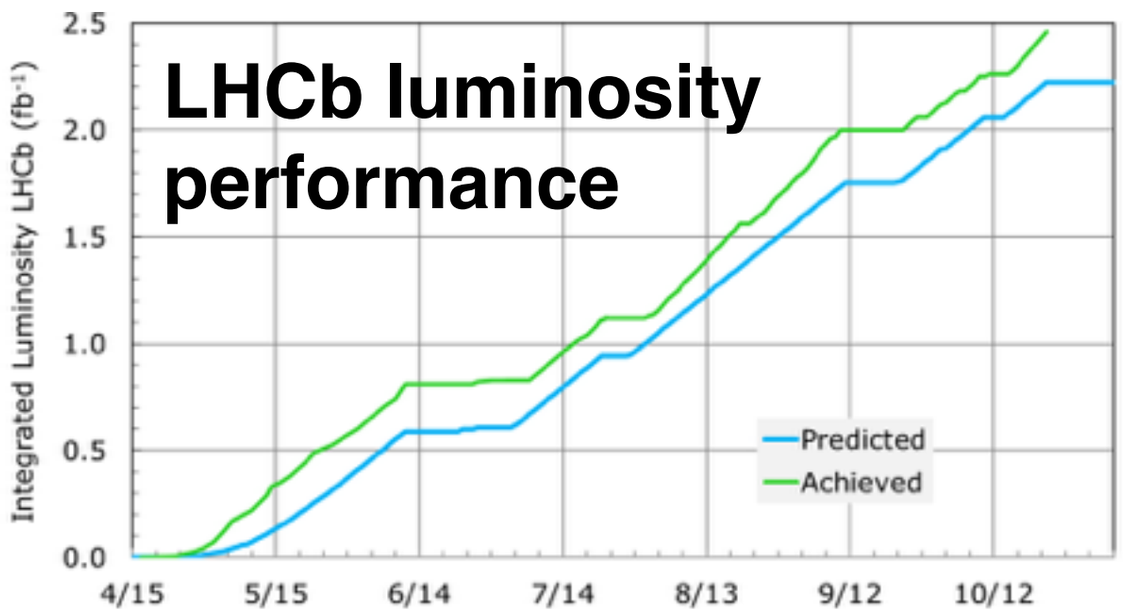
** offers extended coverage and physics reach (central exclusive production)*

The best luminosity year yet





- Yearly luminosity goals achieved and surpassed
- LHCb collected 2.46fb^{-1} in 2018 (compared to 1.8fb^{-1} in 2017)
- A successful Pb-Pb run ended last week



Heavy hadron production

An instrumental benchmark process in understanding QCD.

- *quark mass (m_q) defines the scale at which the strong-interaction coupling constant (α_s) is evaluated. High heavy quark mass $m_b \gg \Lambda_{QCD}$ allows the production properties to be estimated within the perturbation theory.*

Production cross-section measurements allow to study (in that order)

- perturbative QCD models (**proton-proton** collisions)
- (cold) nuclear matter interaction effects (**proton-lead** collisions)
- Quark Gluon Plasma formation (heavy **ion-ion** collisions)

B-meson production

The latest $B^{\pm}$ production cross-section measurement is performed by LHCb on 7 TeV and 13 TeV pp collision data [JHEP 12 (2017) 026]

Supersedes two previous LHCb measurements on smaller data samples:

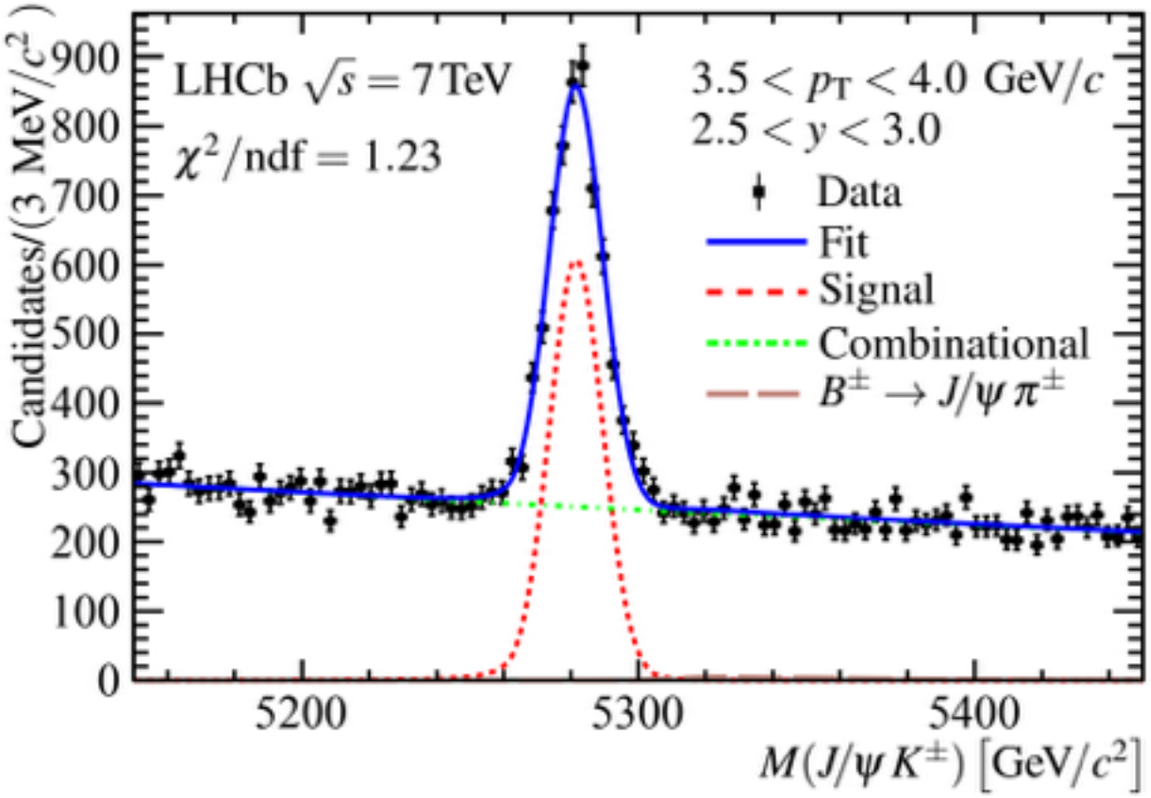
- on $35pb^{-1}$ 7 TeV pp data [JHEP 04 (2012) 93]
- on $362pb^{-1}$ of 7 TeV pp data [JHEP 08 (2013) 117]

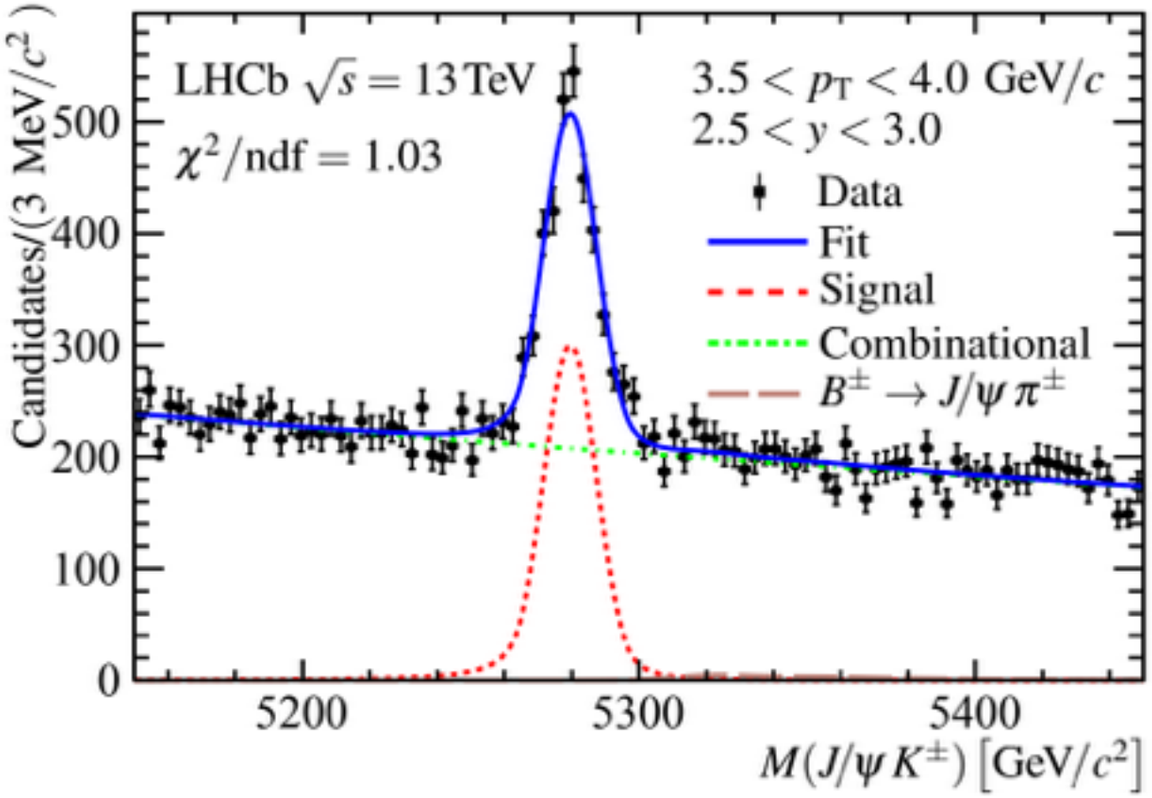
$B^{\pm}$ meson production at the LHCb

The $B^{\pm}$ mesons are reconstructed in the $B^{\pm} \to J/\psi K^{\pm}$ mode with $J/\psi \to \mu^{+}\mu^{-}$ in range $0 < p_T < 40$ GeV/c and $2.0 < y < 4$.

(abundant, clean, able to rely on performant and well understood muon triggers)

[JHEP 12 (2017) 026]





$B^{\pm}$ meson production at the LHCb

[JHEP 12 (2017) 026]

The measured production cross-sections in LHCb's acceptance at 7 and 13TeV ($0 < p_T < 40$ GeV/c^2, $2.0 < y < 4.5$) are

$$\sigma(pp \to B^{\pm}X, \sqrt{s} = \ \ 7\,\text{TeV}) = 43.0 \pm 0.2 \pm 2.5 \pm 1.7\,\mu\text{b},$$
$$\sigma(pp \to B^{\pm}X, \sqrt{s} = 13\,\text{TeV}) = 86.6 \pm 0.5 \pm 5.4 \pm 3.4\,\mu\text{b},$$

(stat.) (syst.) (BF)

The uncertainty stems mostly from the:

- branching fraction,
- luminosity determination
- trigger efficiency estimation

Sources	Uncertainty (%)		
	7 TeV	13 TeV	R(13 TeV/7 TeV)
Luminosity	1.7	3.9	3.4
Branching fractions	3.9	3.9	0.0
Binning	2.6	2.7	0.0
Mass fits	2.7	1.3	1.5
Acceptance	0.2	0.1	0.2
Reconstruction	0.1	0.1	0.2
Track	1.6	2.6	1.0
PID	0.4	0.1	0.4
Trigger	3.5	2.6	4.4
GEC	0.7	0.7	1.0
Selection	1.0	1.1	0.1
Weighting	0.2	0.2	0.3
Total	7.0	7.4	5.9

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(stat.) (syst.) (BF)

The experimental (and theoretical) uncertainties are reduced in the **ratio of production cross-sections at 7 and 13TeV**:

- *luminosity uncertainty (50% correlated)*
- *branching fraction, mass fit, selection and binning unc (fully correlated)*

R(13 TeV / 7 TeV) =
2.02 ± 0.02 (stat) ± 0.12 (syst)

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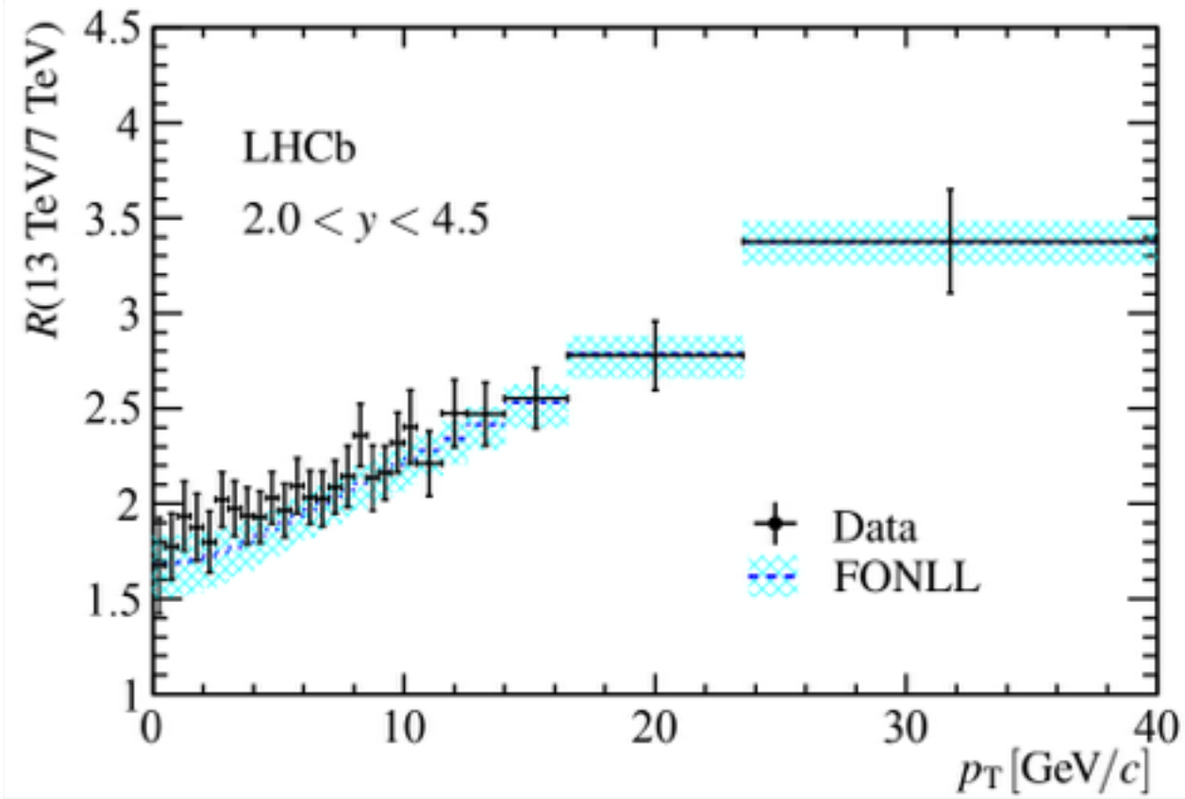
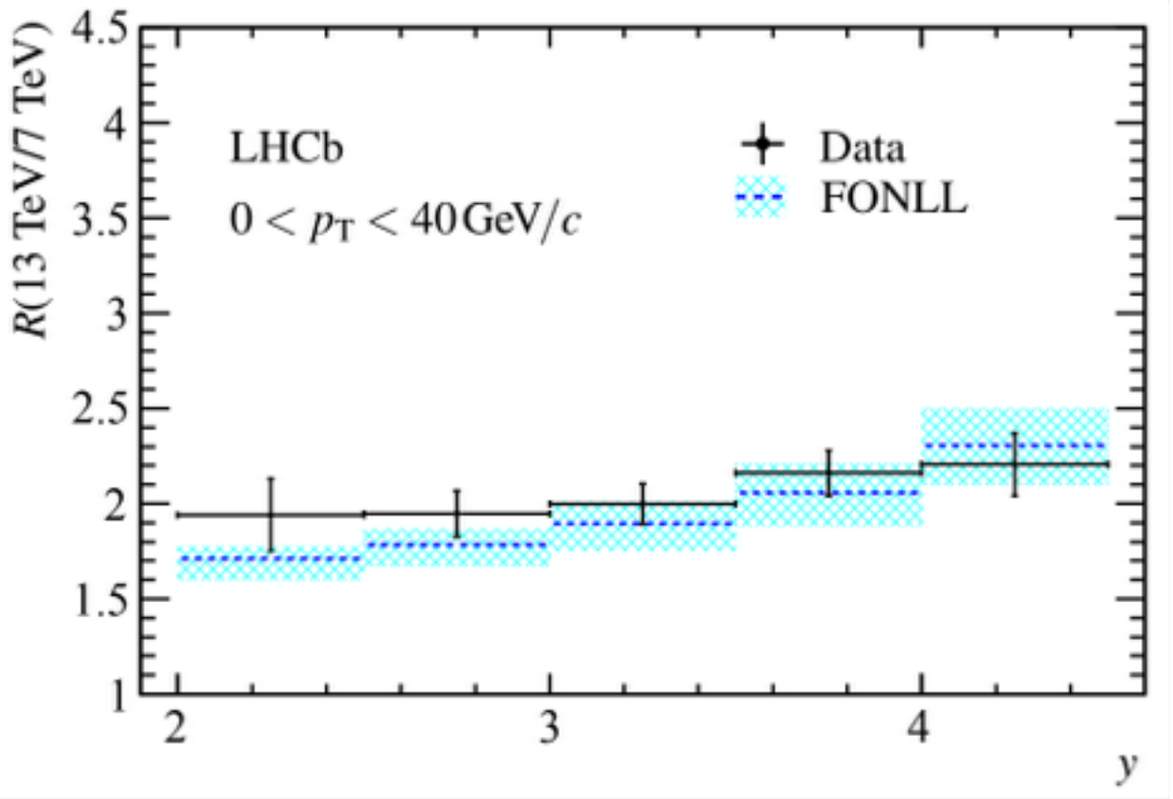
The 13/7TeV production ratio in transverse momentum and rapidy bins:





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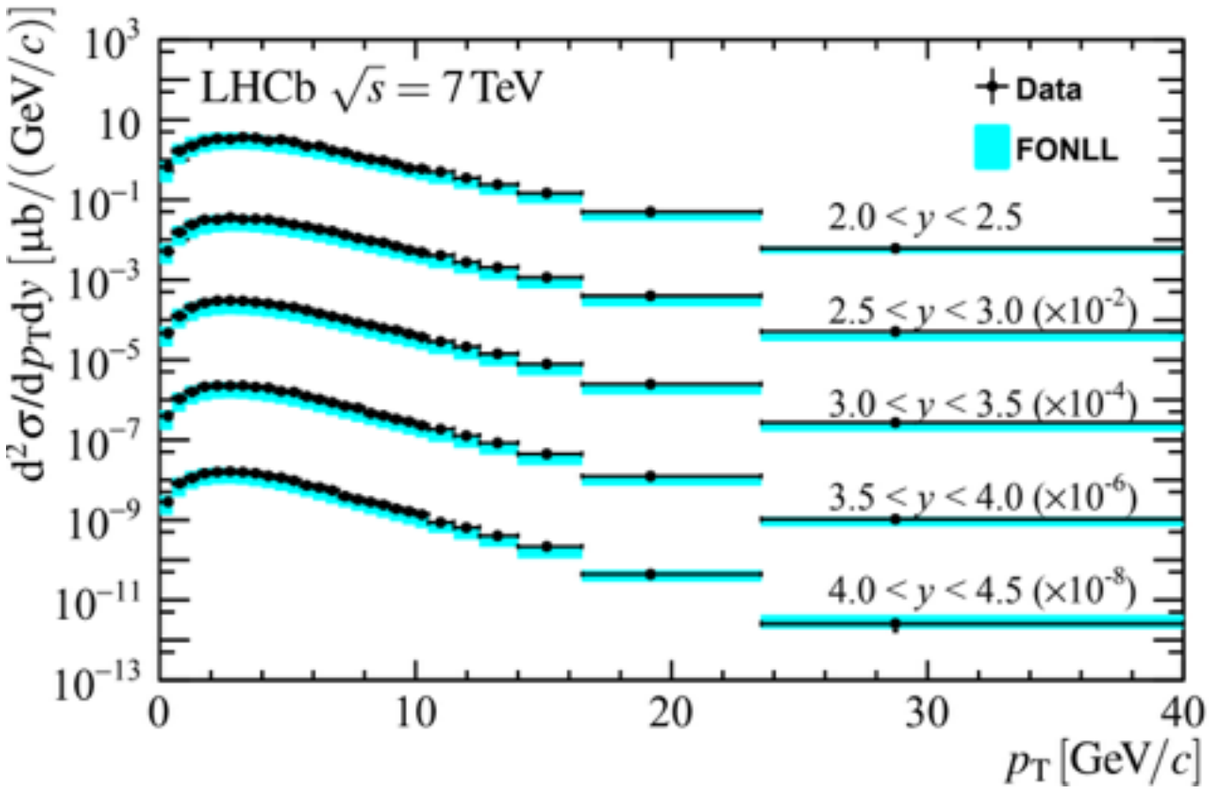
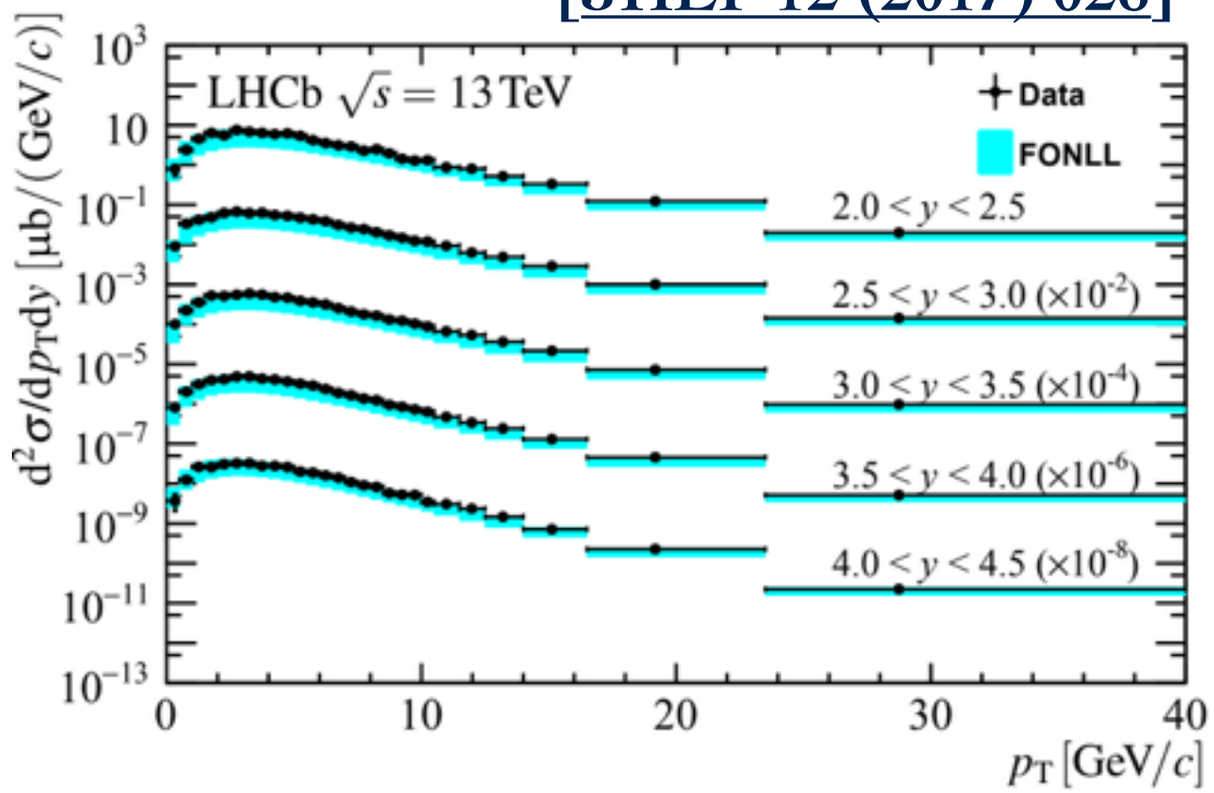
$B^{\pm}$ meson production at the LHCb

Double-differential cross-sections: a closer look at 27 transverse momentum bins in five rapidity regions

[JHEP 12 (2017) 026]





** the 7 TeV results are consistent with previously published results, with improved precision in the low y region*

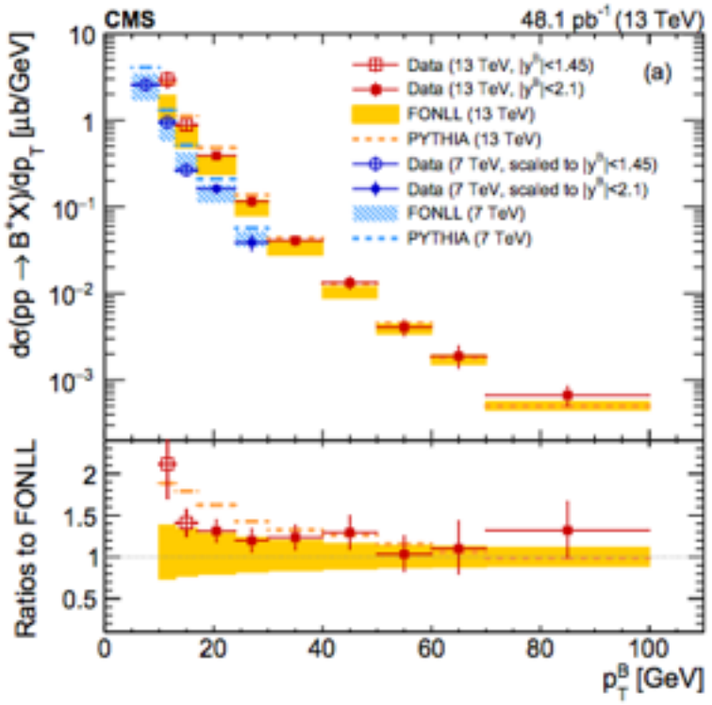
- Good agreement with the FONLL predictions

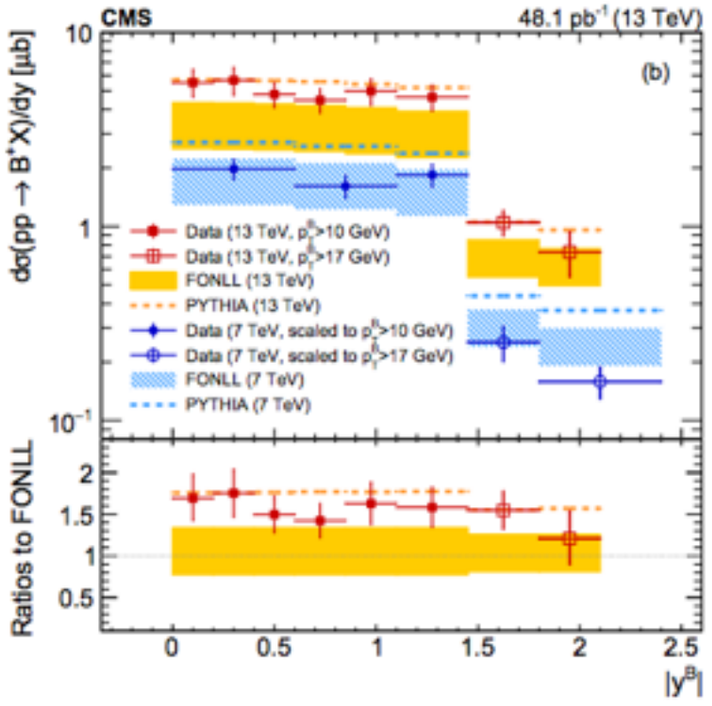
  The predictions depend on assumptions on the b-quark mass, the renormalization and factorization scales, and parton distribution functions (PDFs), and lead to large unc. (+-50%) at low p_T.

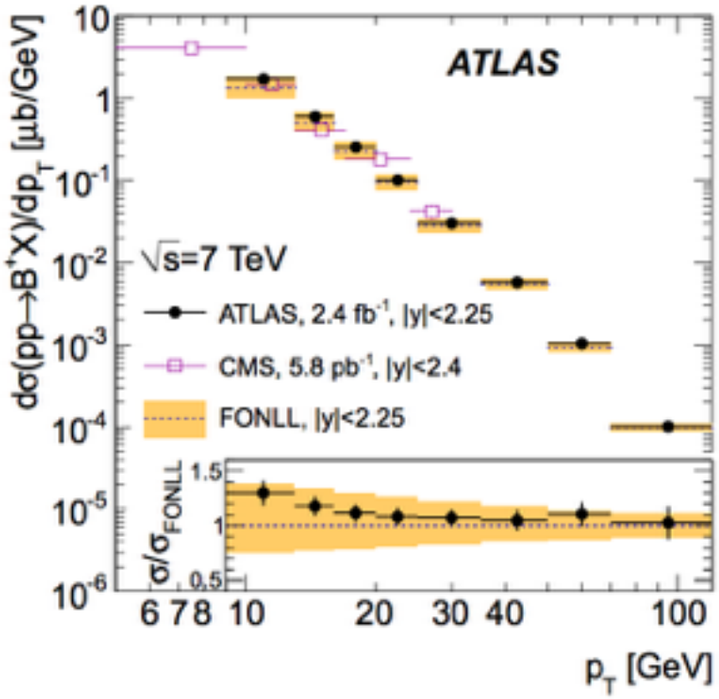
$B^{\pm}$ meson production at the LHC

ATLAS' (7TeV) and CMS' (7 and 13 TeV) cross section measurements in agreement with the predictions (less so for the R(13/7TeV))

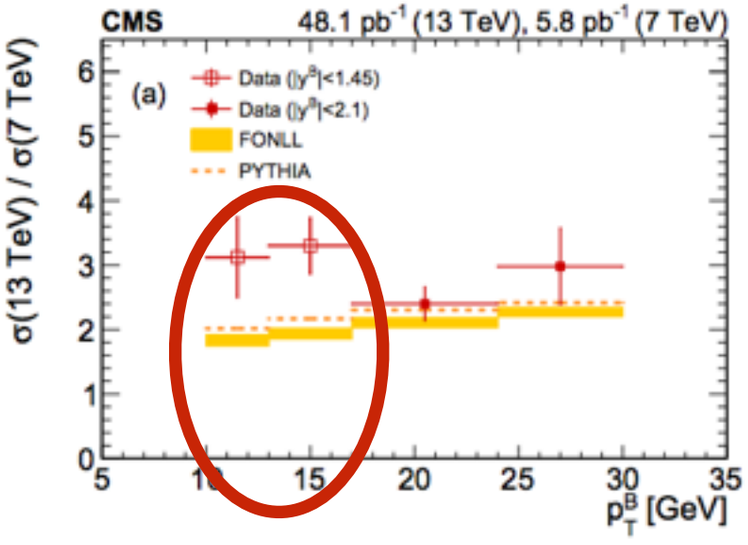
[JHEP 10 (2013) 042]

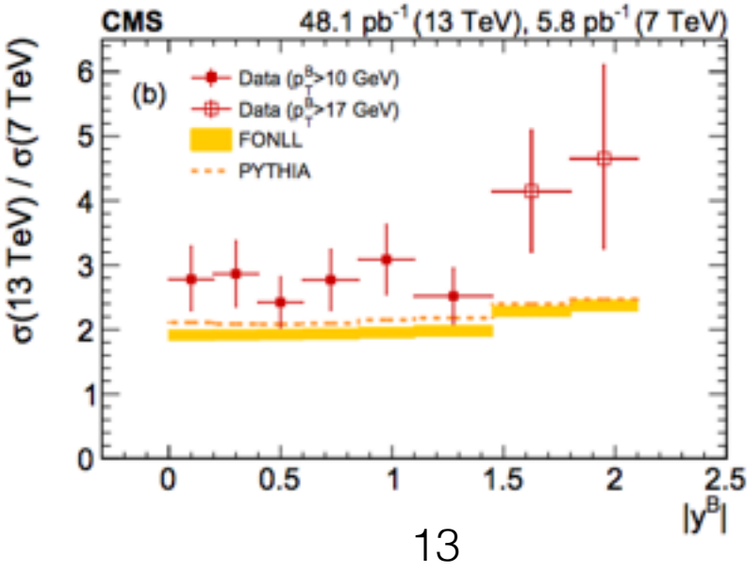


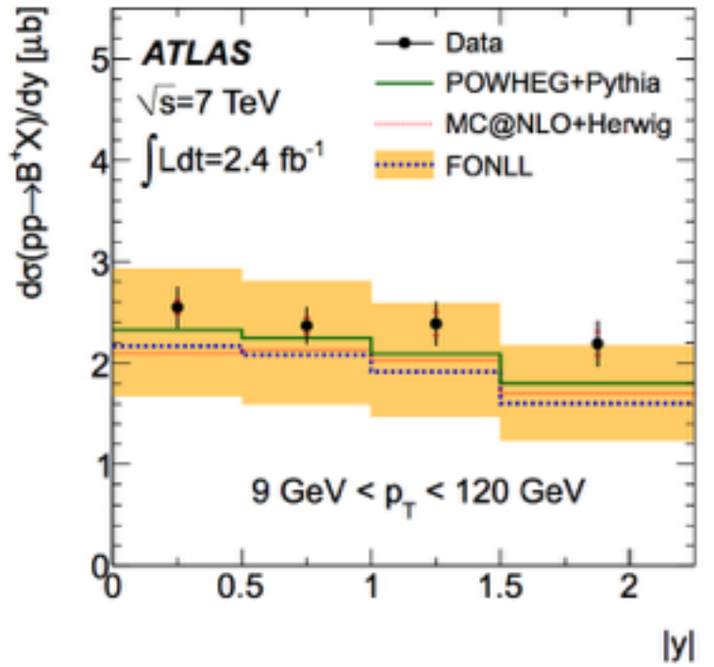




[PLB 771 (2017) 435]







Relative B_s and $B^{\pm}$ production

The production cross section can be expressed as as a convolution of the b-quark production cross section ($\sigma_{pp\to bb}$) and the fragmentation function ($D_{b\to H}$) :

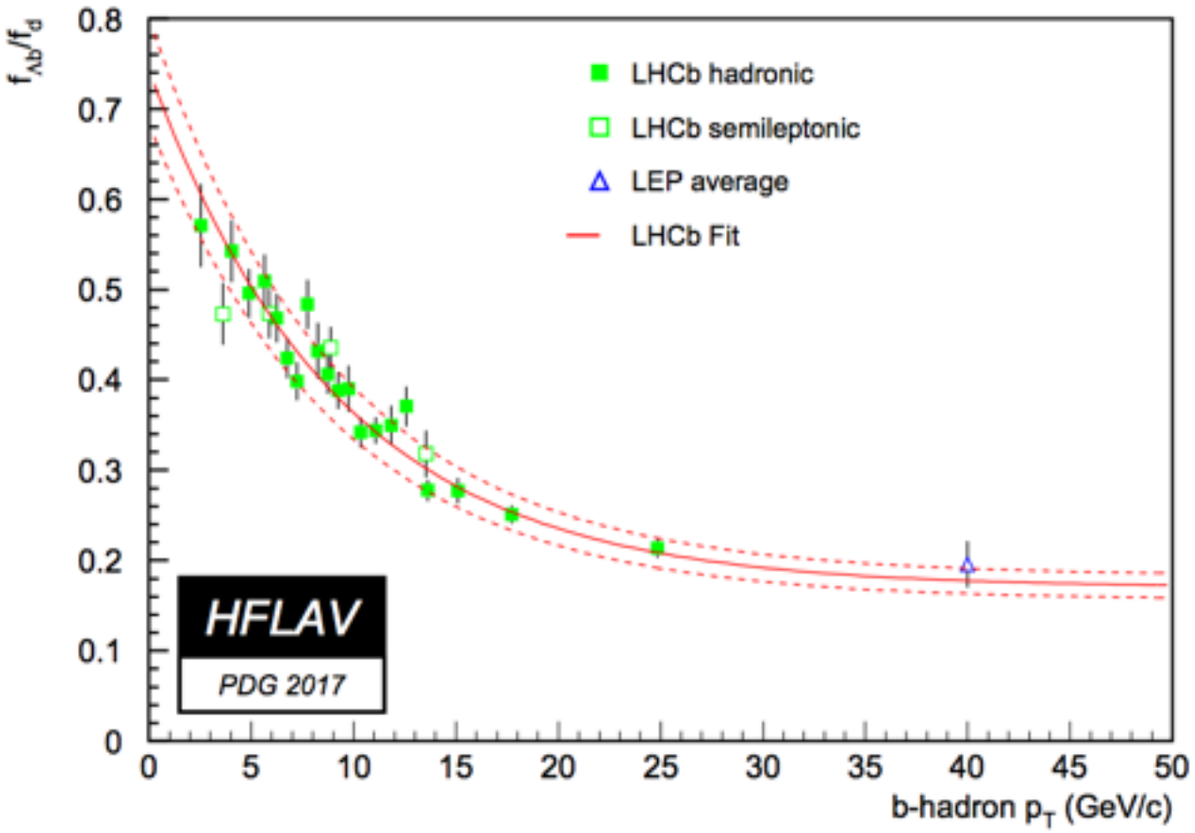
$$\frac{d\sigma_H}{dp_T}(p_T) = \int \frac{dx}{x} \frac{d\sigma_{pp\to b\bar{b}}}{dp_T}\left(\frac{p_T}{x}, m\right) \cdot \mathcal{D}_{b\to H}(x)$$

perturbative — non-perturbative

The relative B_s and $B^{\pm}$ production measurement in bins of B meson kinematic variables allows to experimentally probe the shape of the (non-perturbative) b-quark fragmentation functions (depend on m_q).

Kinematic dependence of (f_s/f_u) is very likely:

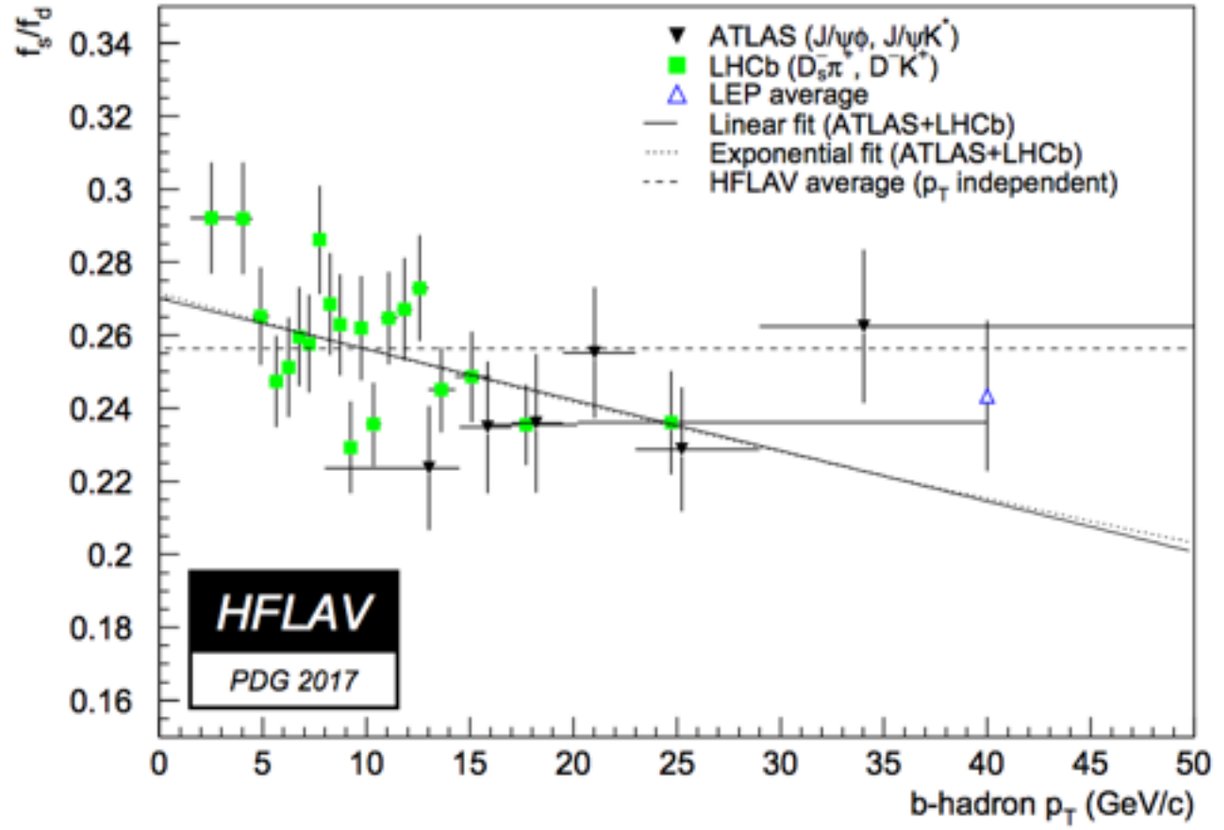
[HFLAV 2016]



a) Relative Λ_b and B^0 production ($f_{\Lambda b}/f_d$) varies strongly with the hadron transverse momentum

[JHEP 08(2014)143]

[HFLAV 2016]



b) Experimental hints for the relative B_s and B^0 production (f_s/f_d) dependence on meson transverse momentum

[JHEP 1304 (2013) 001]

Relative B_s and $B^{\pm}$ meson production measurement (in progress)

Measure the relative $B^{\pm} \rightarrow J/\psi K^{\pm}$ and $B_s \rightarrow J/\psi \Phi$ yields at 7, 8 and 13 TeV pp collision data.

Strengths:

- trigger on $J/\psi \rightarrow \mu^+\mu^-$ (greatly reduces trigger efficiency uncertainty)
- near identical selection (bar the additional Kaon and Φ)
- no hadron PID requirements necessary

Weakness:

- precise absolute f_s/f_u measurement not possible due to the uncertain branching fraction (after the excluding the measurements normalised to the $B^{\pm} \rightarrow J/\psi K^{\pm}$). Will scale to match the LHCb 7TeV f_s/f_d result.

Relative B_s and $B^{\pm}$ meson production measurement (in progress)

Measure the relative $B^{\pm} \rightarrow J/\psi K^{\pm}$ and $B_s \rightarrow J/\psi \Phi$ yields at 7, 8 and 13 TeV pp collision data.

The efficiency corrected yields will be used to measure:

- the R(8/7) and R(13/7) TeV to look for possible variation with the collision energy (crucial for any B_s branching fraction measurement relying on the 7TeV f_s/f_d)
- the relative production in various B-meson kinematic variables (momentum components, rapidity,..)

Bottomonium production in pp collisions

The latest $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ production cross-section measurement is performed by LHCb on 13 TeV pp collision data [JHEP 07 (2018) 134] **New!**

Supersedes previous LHCb measurements on lower collision energies:

- on 2.76 TeV pp data [EPJ C74 (2014) 2835]
- on 7 TeV pp data [EPJ C72 (2012) 2025]
- on 7 and 8 TeV pp data [JHEP 1509 (2015) 084], [JHEP 1511 (2015) 103], [JHEP 12 (2017) 110], [JHEP 06 (2013) 064]

The total cross-sections multiplied by dimuon branching fractions for the three states integrated over the ranges of $0 < p_T < 15$ GeV/c and $2.0 < y < 4.5$ are measured to be:

(stat) (syst)

$$\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) \times \sigma(\Upsilon(1S), 0 < p_{\rm T} < 15\,{\rm GeV}/c, 2 < y < 4.5) = 4687 \pm 10 \pm 294 \ \text{pb}$$
$$\mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-) \times \sigma(\Upsilon(2S), 0 < p_{\rm T} < 15\,{\rm GeV}/c, 2 < y < 4.5) = 1134 \pm 6 \pm 71 \ \text{pb}$$
$$\mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-) \times \sigma(\Upsilon(3S), 0 < p_{\rm T} < 15\,{\rm GeV}/c, 2 < y < 4.5) = 561 \pm 4 \pm 36 \ \text{pb}$$

The results are limited by the systematic uncertainty (luminosity, trigger,..):

Source	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	Comment
Fit models	1.9	1.8	2.5	Correlated
Simulation statistics	$0.4 - 4.6$	$0.5 - 5.1$	$0.5 - 4.4$	Bin dependent
Global event requirements	0.6	0.6	0.6	Correlated
Trigger	$3.9 - 9.8$	$3.9 - 9.8$	$3.9 - 9.8$	Bin dependent
Tracking	$(0.1 - 6.6) \oplus (2 \times 0.8)$	$(0.2 - 6.4) \oplus (2 \times 0.8)$	$(0.2 - 6.5) \oplus (2 \times 0.8)$	Correlated
Muon identification	$0.1 - 7.9$	$0.1 - 7.6$	$0.2 - 8.5$	Correlated
Vertexing	0.2	0.2	0.2	Correlated
Kinematic spectrum	$0.0 - 1.1$	$0.0 - 2.2$	$0.0 - 2.5$	Bin dependent
Radiative tail	1.0	1.0	1.0	Correlated
Luminosity	3.9	3.9	3.9	Correlated
Total	$6.2 - 14.3$	$6.2 - 14.6$	$6.4 - 14.9$	Correlated

[JHEP 07 (2018) 134]

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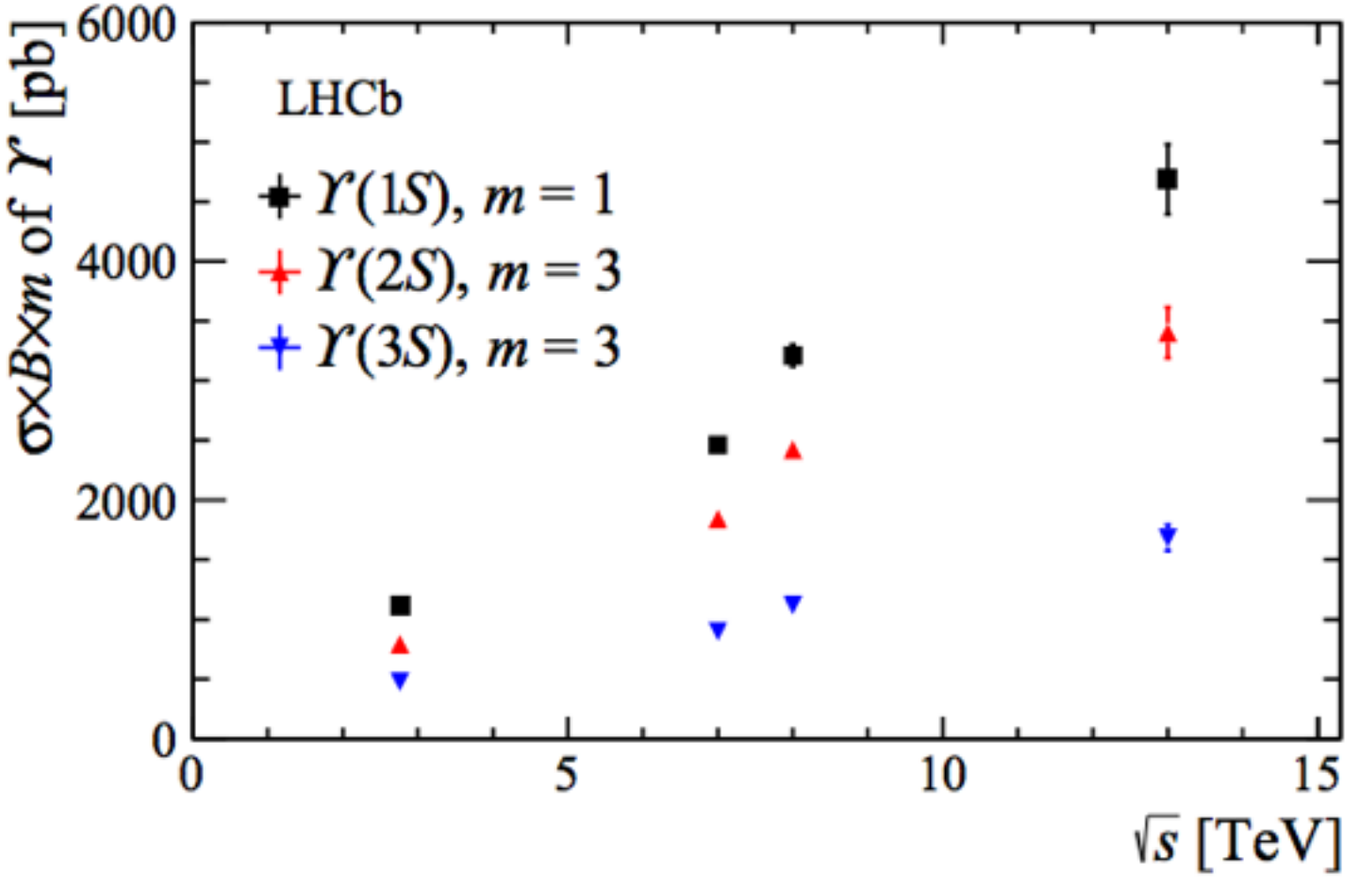
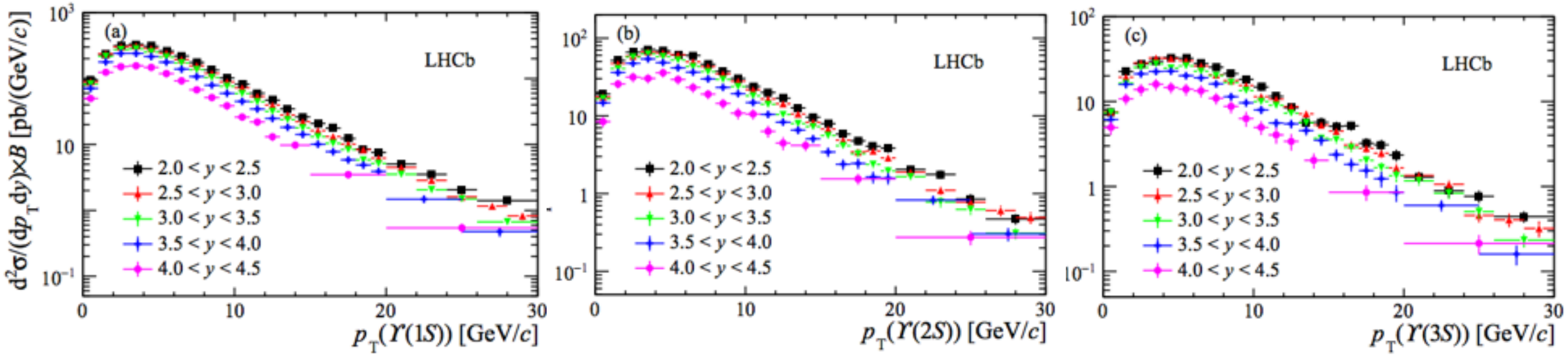
$$\mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-) \times \sigma(\Upsilon(3S), 0 < p_{\rm T} < 15\,{\rm GeV}/c, 2 < y < 4.5) = 561 \pm 4 \pm 36 \ {\rm pb}$$

The corresponding results as a function of pp centre-of-mass energy

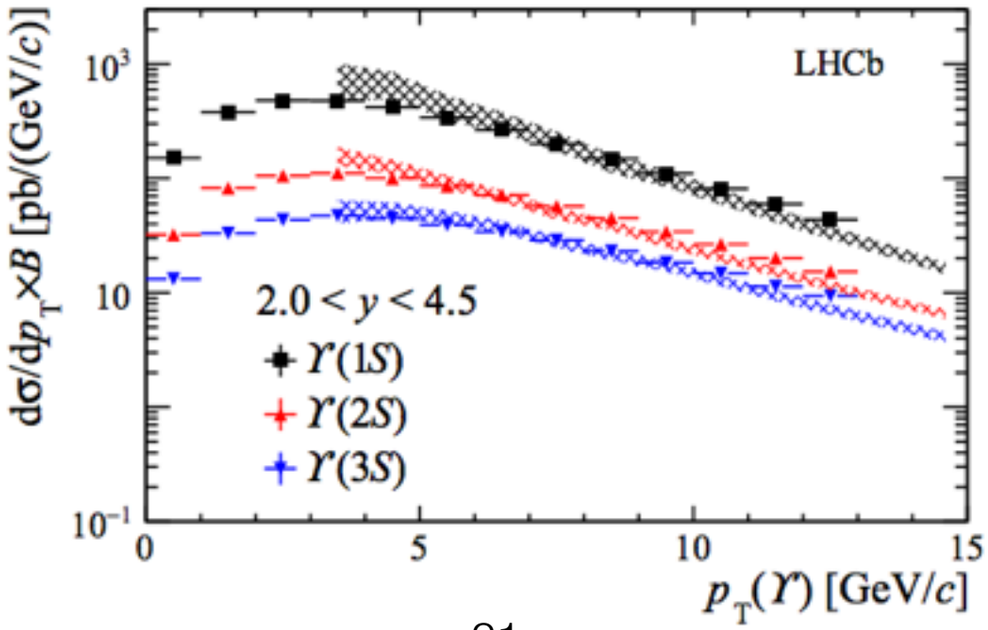
[JHEP 07 (2018) 134]



The double differential cross-sections times dimuon branching fractions of Υ mesons are measured as functions of transverse momentum and rapidity, in the kinematic range $0 < p_T < 30$ GeV/c and $2.0 < y < 4.5$.

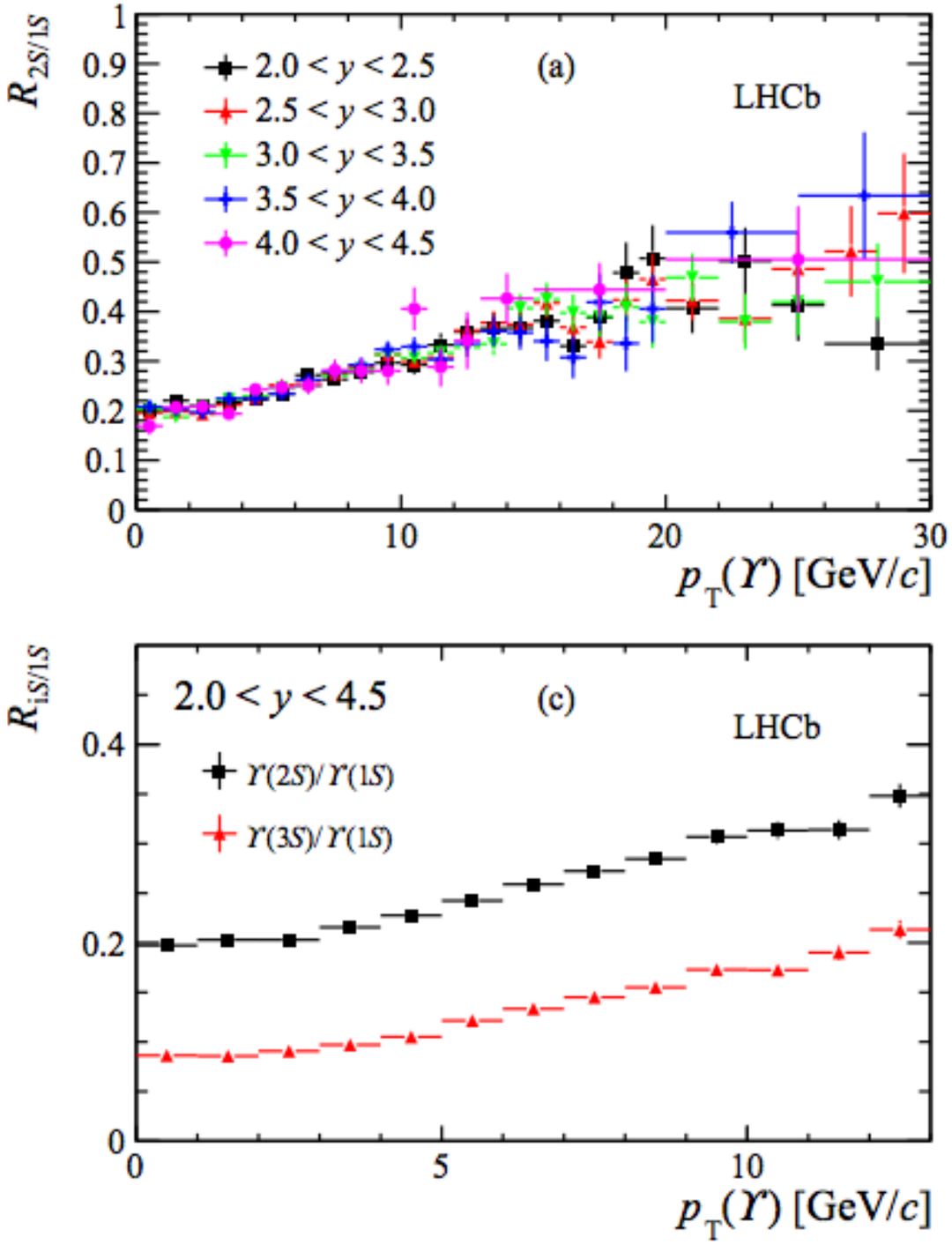


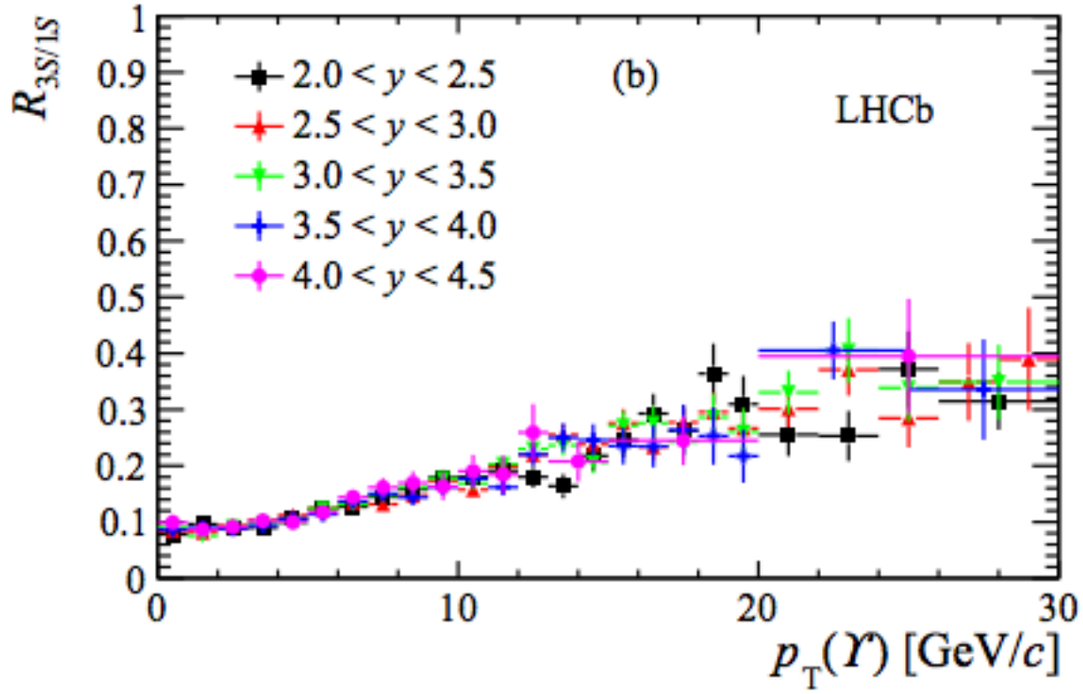
The differential cross sections times the dimuon branching fractions of Υ agree well in scale and shape to the NRQCD predictions [CPC 39 123102 (2015)]

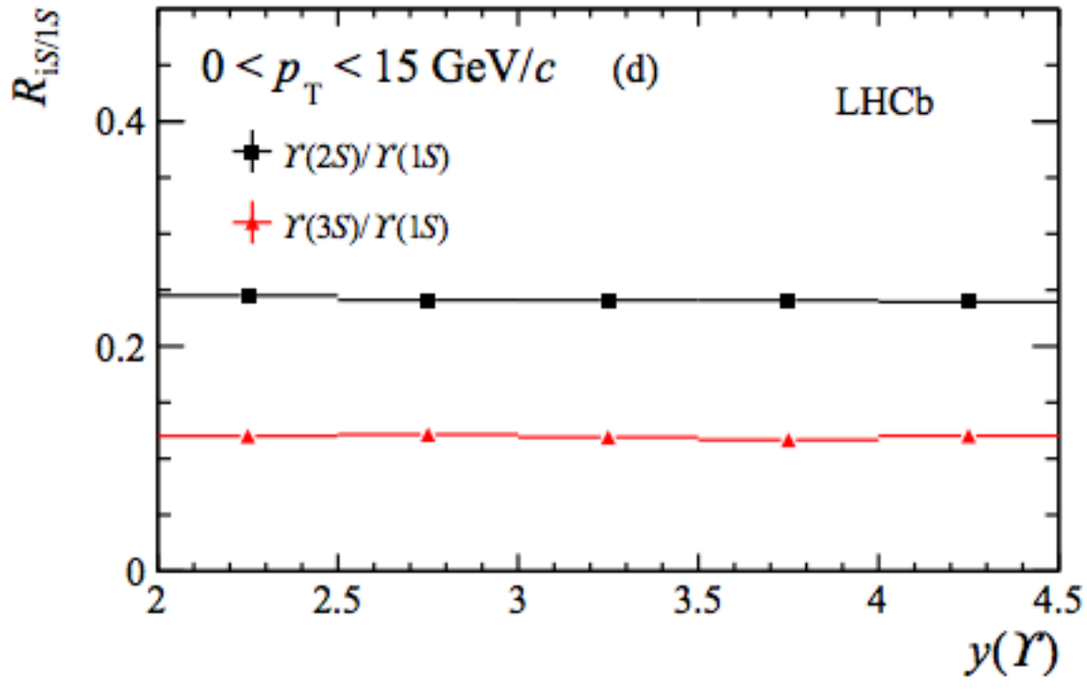


[JHEP 07 (2018) 134]

Relative cross-sections for the excited resonances increase at larger transverse momenta. In rapidity, the cross sections ratios between the resonances are stable.



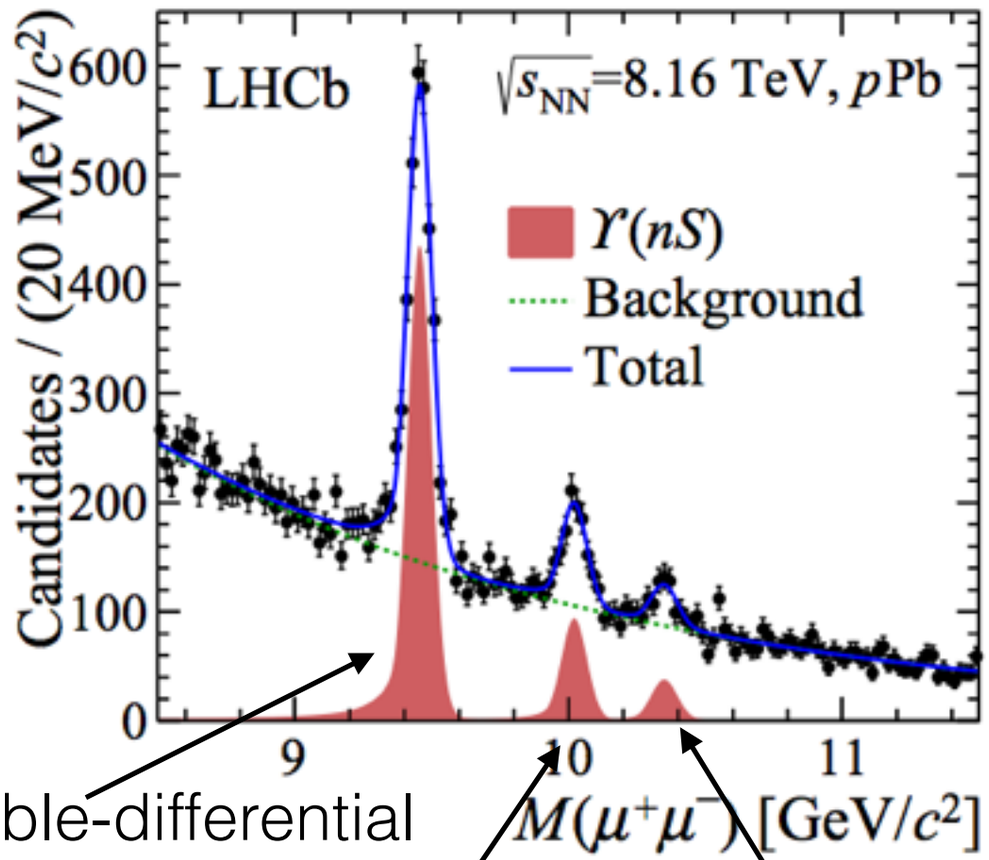


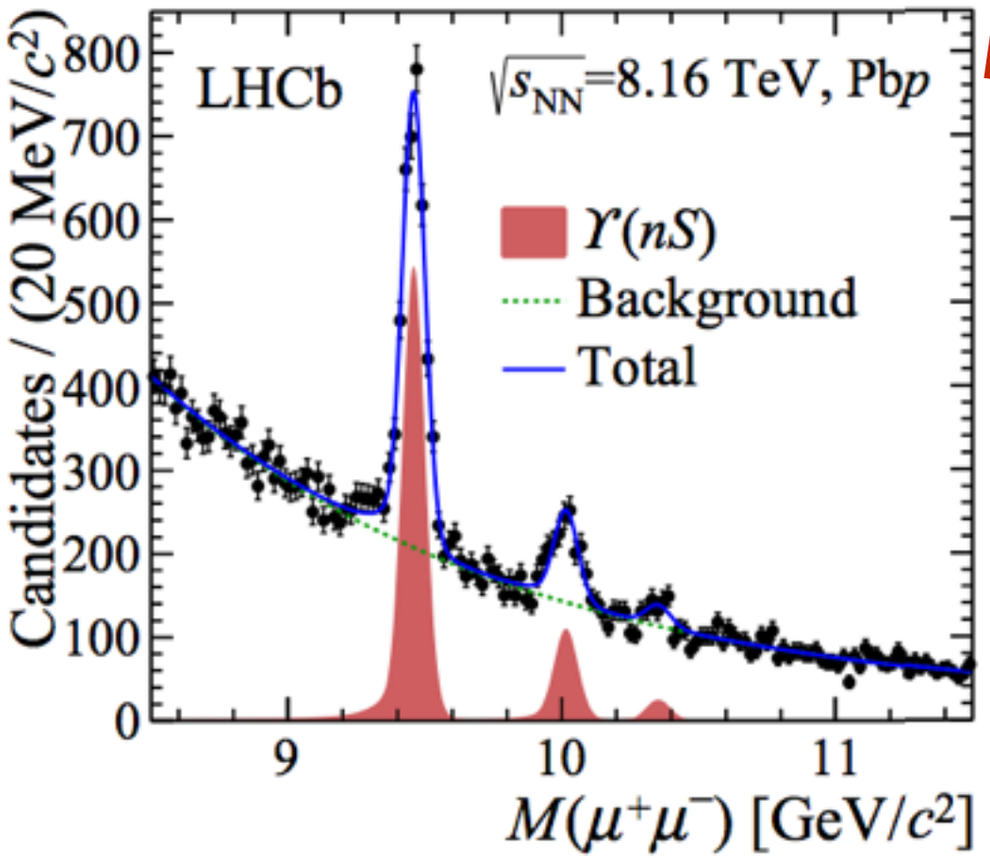


Bottomonium production in p-Pb collisions

All three resonances clearly seen in both forward (p-pP) and backward (Pb-p) collisions:

[1810.07655, submitted to JHEP]





New!

Y(1S): double-differential cross sections

Y(2S): single-differential cross sections

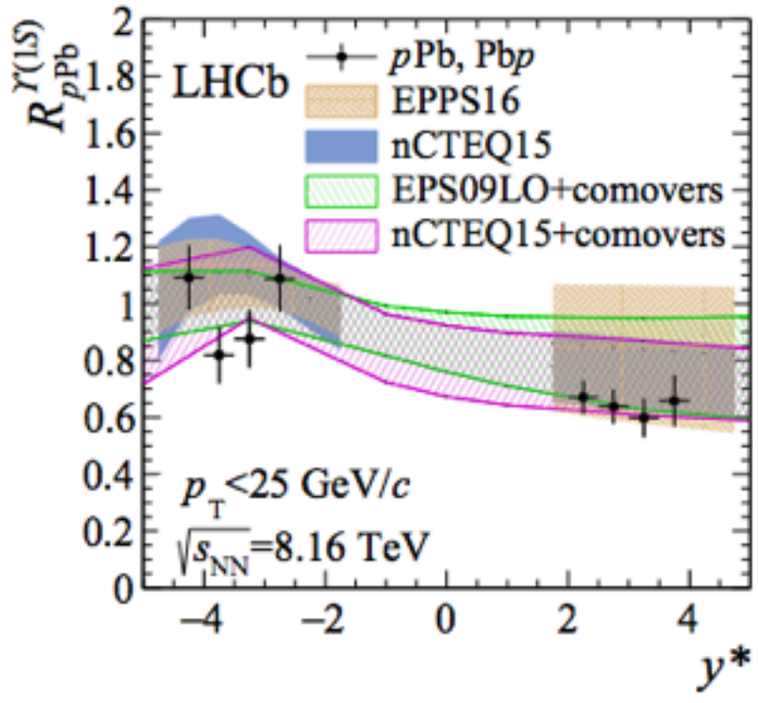
Y(3S): integrated cross sections

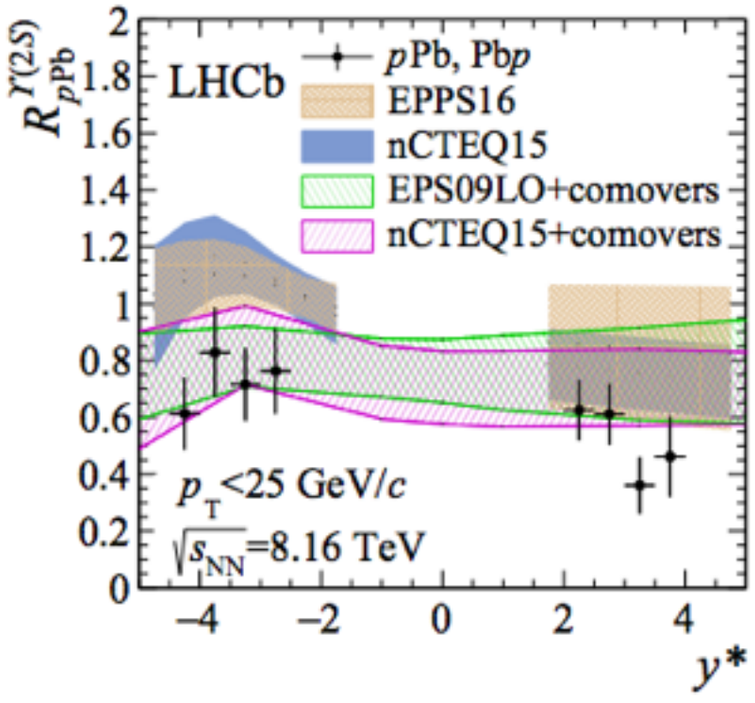
Prompt Υ(nS) production in p-Pb

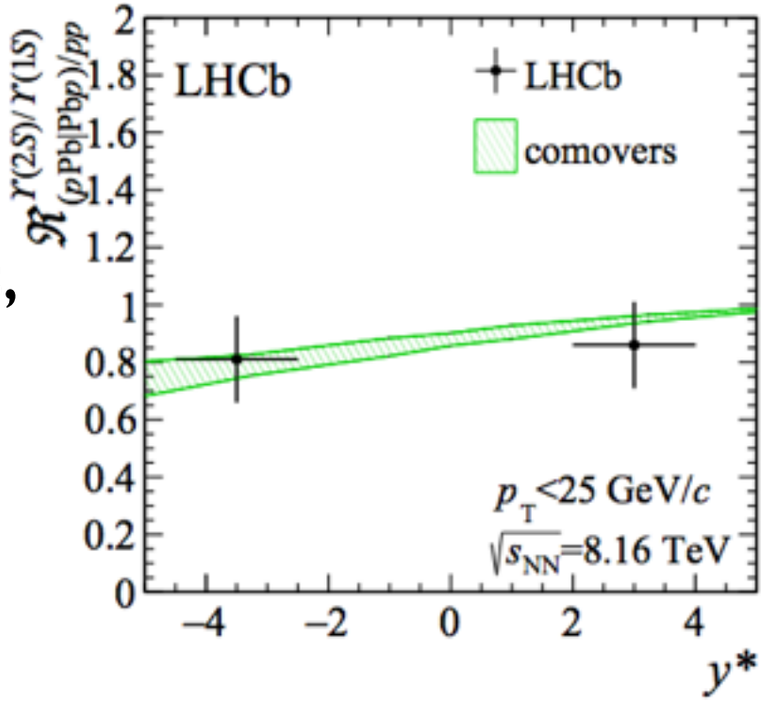
[1810.07655, submitted to JHEP] **New!**

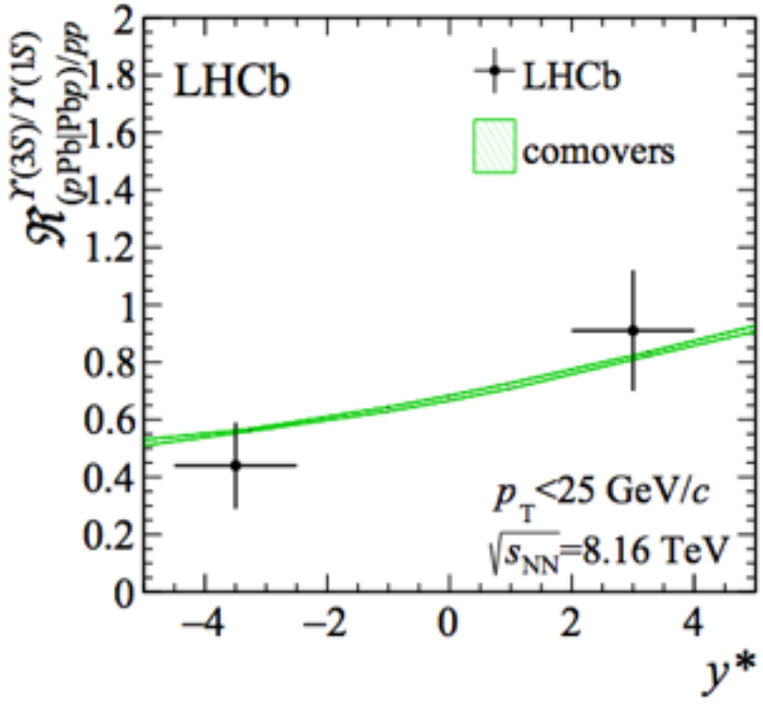
The nuclear modification factors for Υ(1S) and Υ(2S) lower in forward configuration:

CNM suppression is more effective for excited resonances, especially in backward collisions.









Summary

- The $B^{\pm}$ production measurements are in good agreement with the pQCD predictions

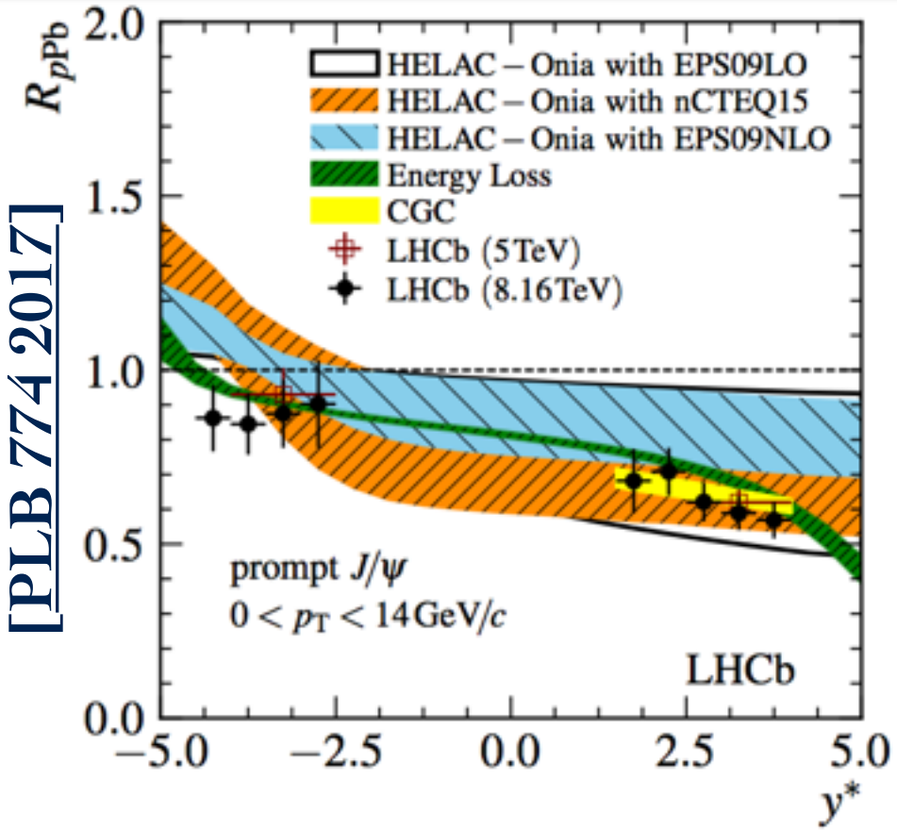
- The relative B_s/B^+ production on 7,8,13 TeV data is being studied to address the kinematic dependence of the fragmentation fraction ratio (f_s/f_u)

- The bottomonium production is studied at 13 TeV pp collisions and 8.16TeV per-nucleon p-Pb collisions:
  - cross sections at pp collisions in agreement with the NRQCD predictions
  - clear nuclear medium suppression observed in pPb collisions, pronounced for excited resonances

- Many heavy hadron production results were not covered (pp, pPb, fixed target: pAr, PHe) **[ALL LHCB PUBLICATIONS]**

Backups

LHCb has previously measured the production of **J/ψ** [JHEP 02 (2014) 072], **ϒ(1S)** [JHEP 07 (2014) 094], **ψ(2S)** [JHEP 1603 (2016) 133] and **D^0** [JHEP 1710 (2017) 090] at 5TeV and **J/ψ** [PLB 774 2017] at 8.16TeV.

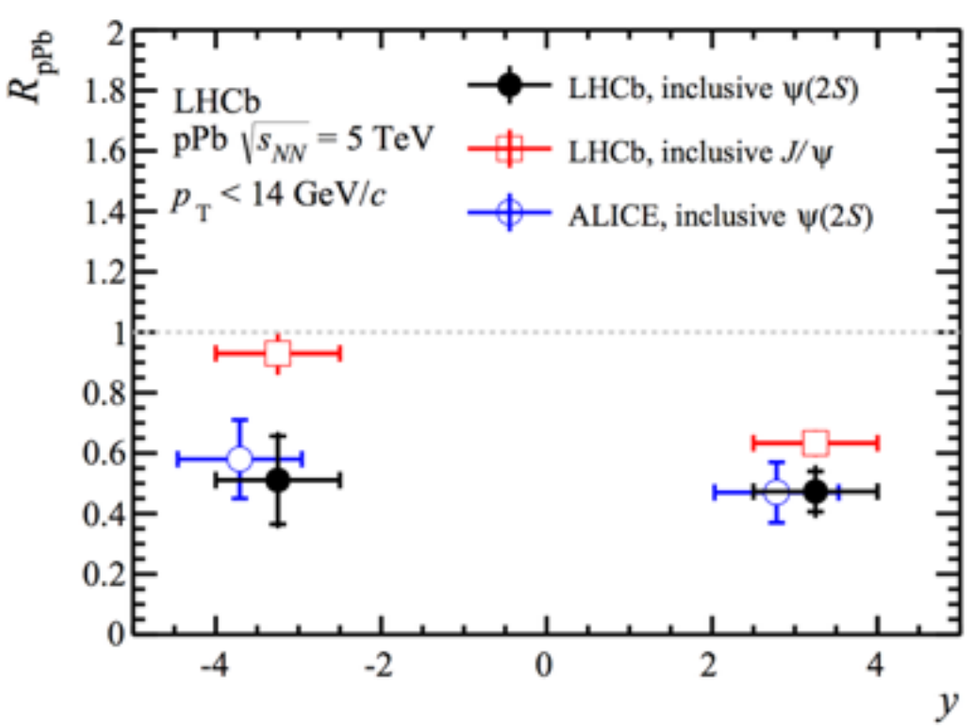


[PLB 774 2017]

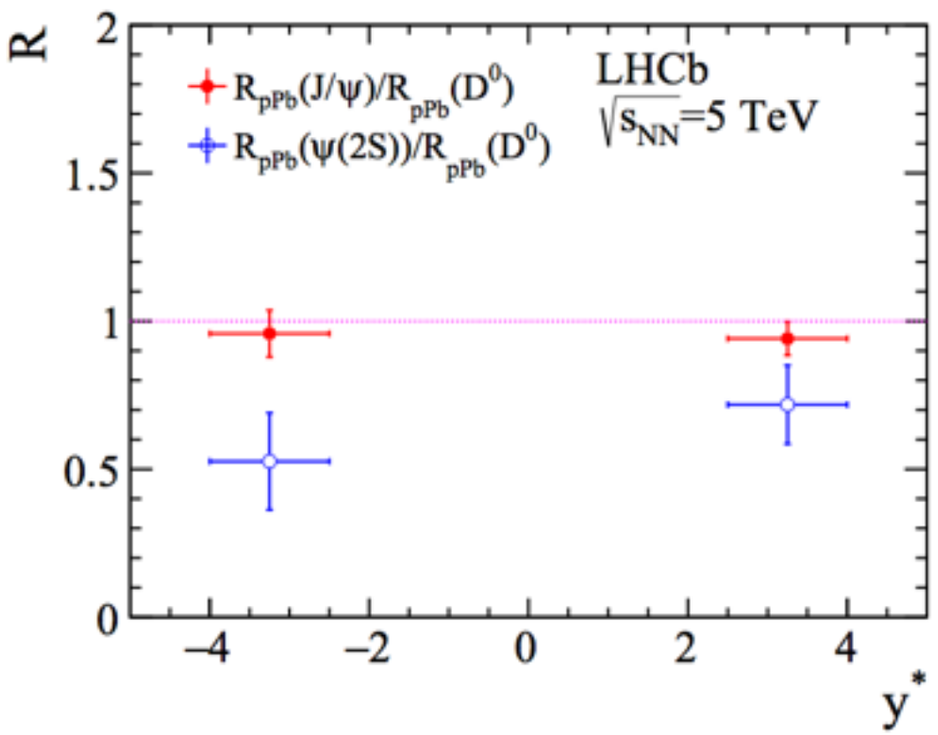
General conclusions:

- Clear signs of strong interactions between the prompt hadrons and nuclear medium
- Suppression of **J/ψ** and **D0 similar,** and larger in forward collisions.
- Pronounced suppression of **ψ(2S)**

[JHEP 1603 (2016) 133]



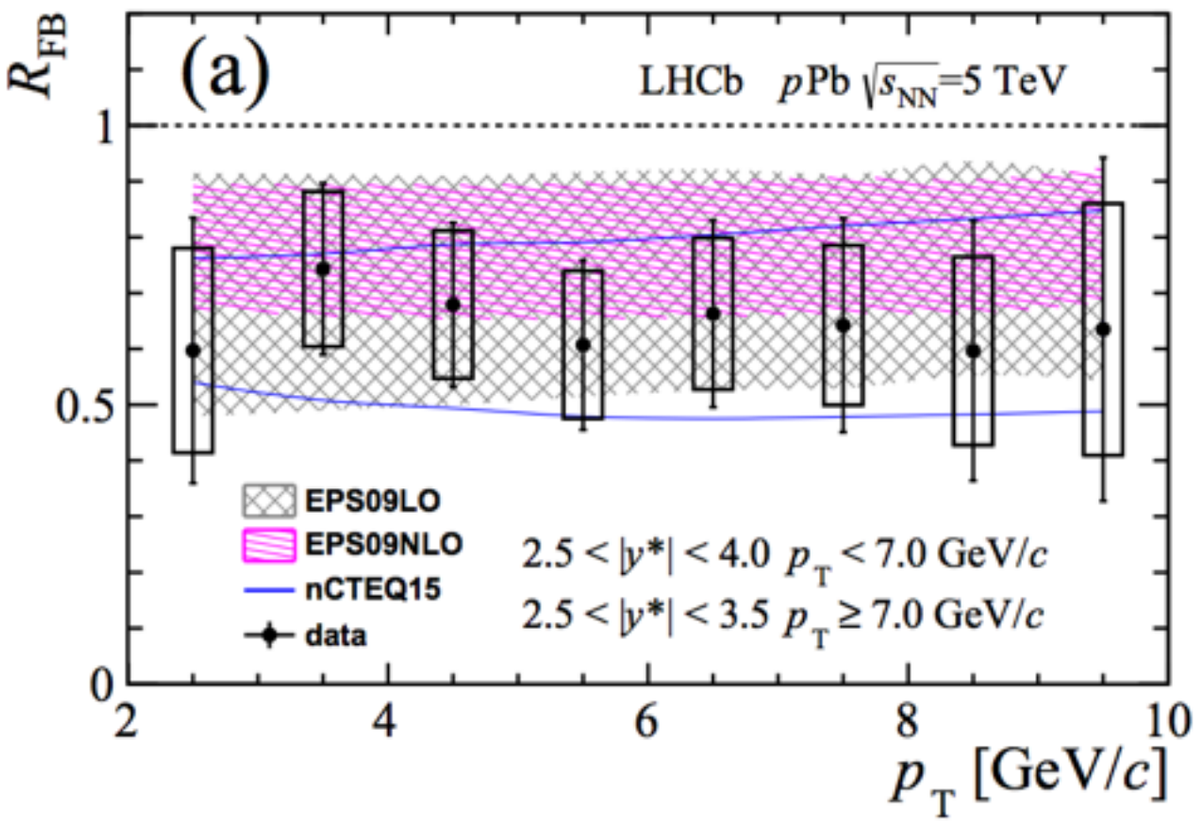
[JHEP 1710 (2017) 090]

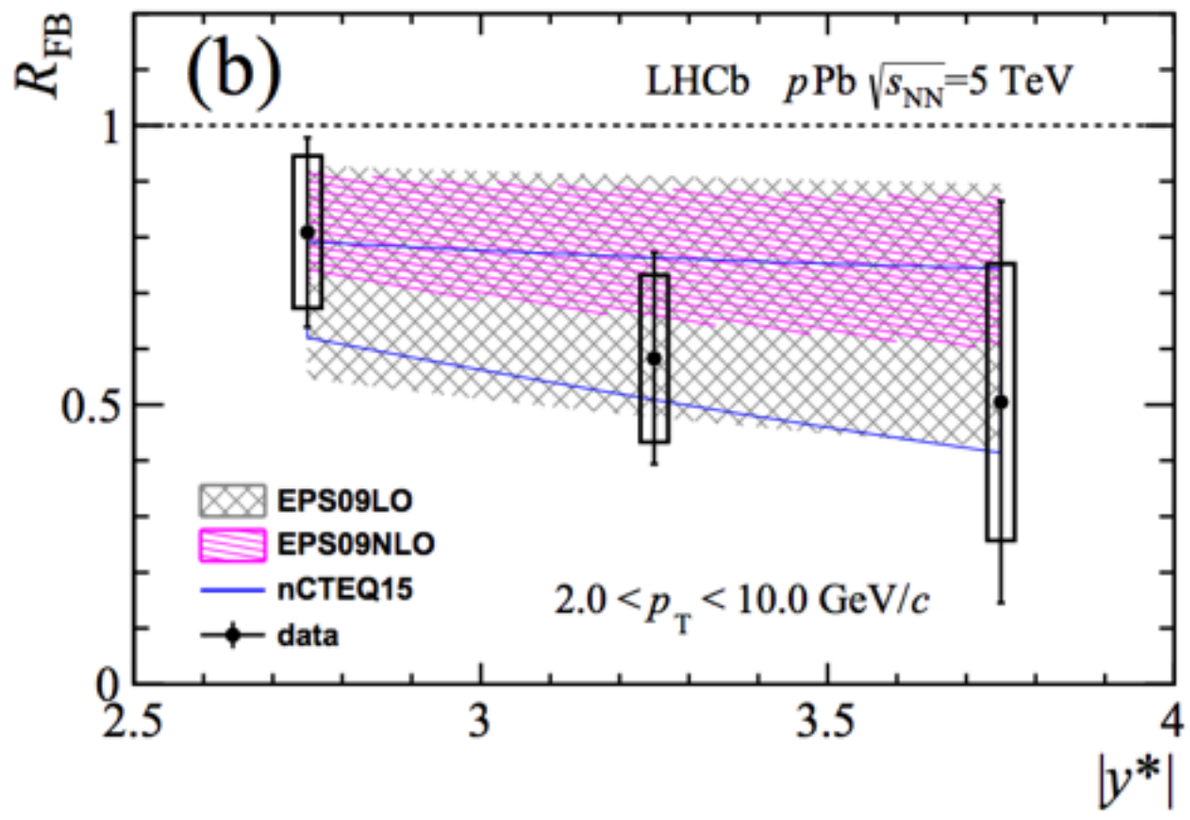


Prompt Λ_c production at 5TeV p-Pb

[1809.01404, submitted to JHEP] **New!**

The forward-backward production ratios (R_{FB})

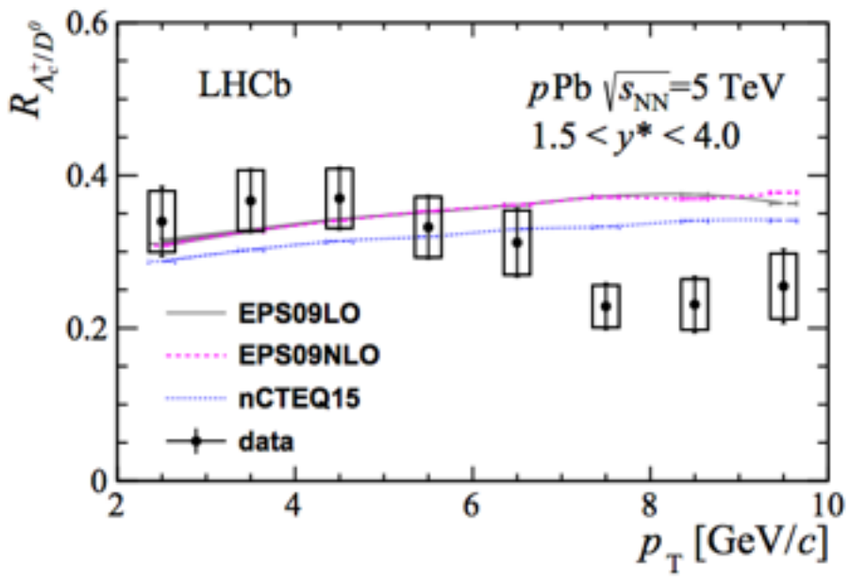


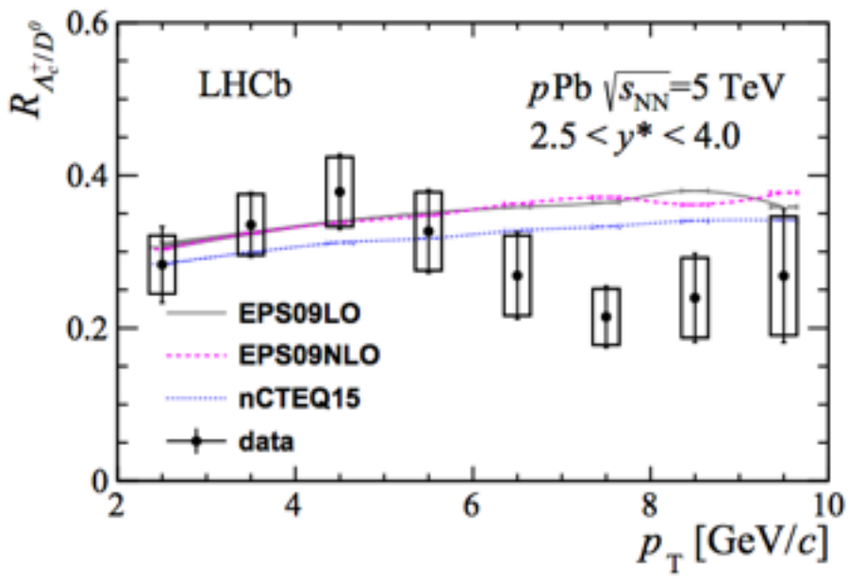


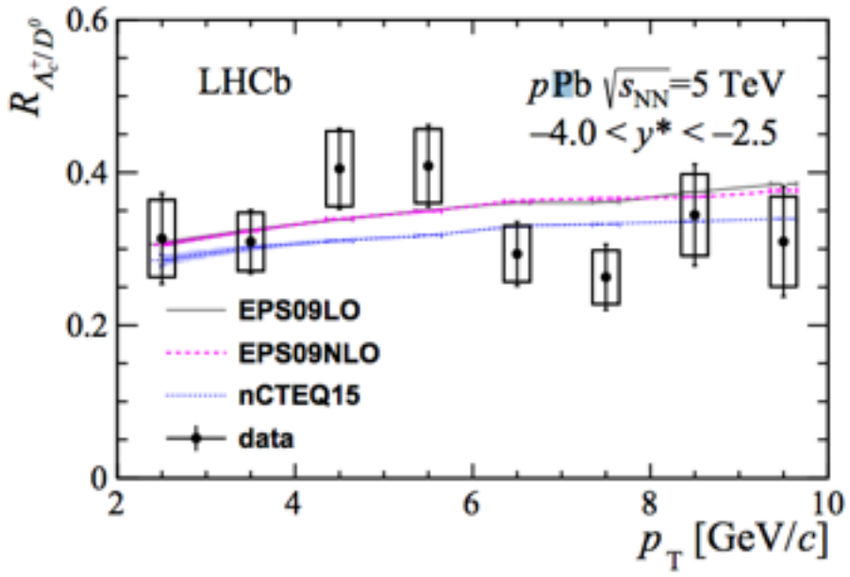
- Clear nuclear medium effects on Λ_c production, especially at high rapidity
- The measurements are in good agreement with the predictions.

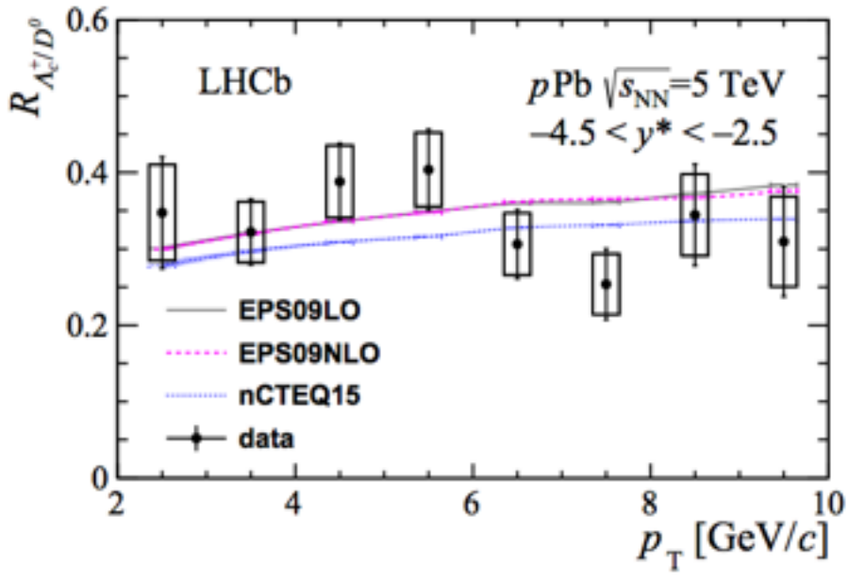
Prompt Λ_c production in 5TeV p-Pb

[1809.01404, submitted to JHEP] **New!**







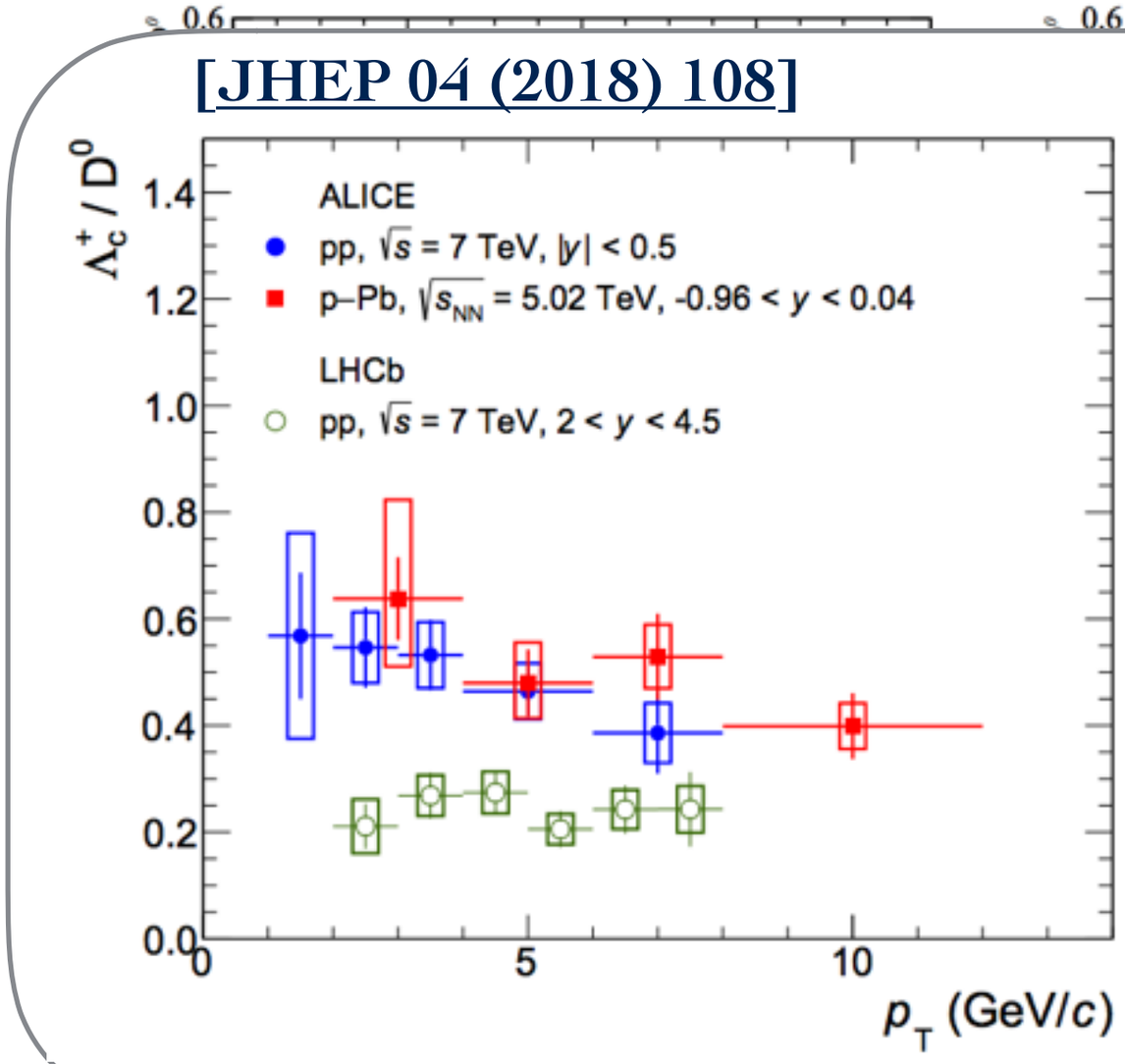


- Λ_c production suppressed w.r.t. D^0 production. No evidence for transverse momentum or rapidity dependence.
- Many nuclear modification effects cancel, sensitive to charm fragmentation

Prompt Λ_c production in 5TeV p-Pb

[1809.01404, submitted to JHEP] **New!**

[JHEP 04 (2018) 108]



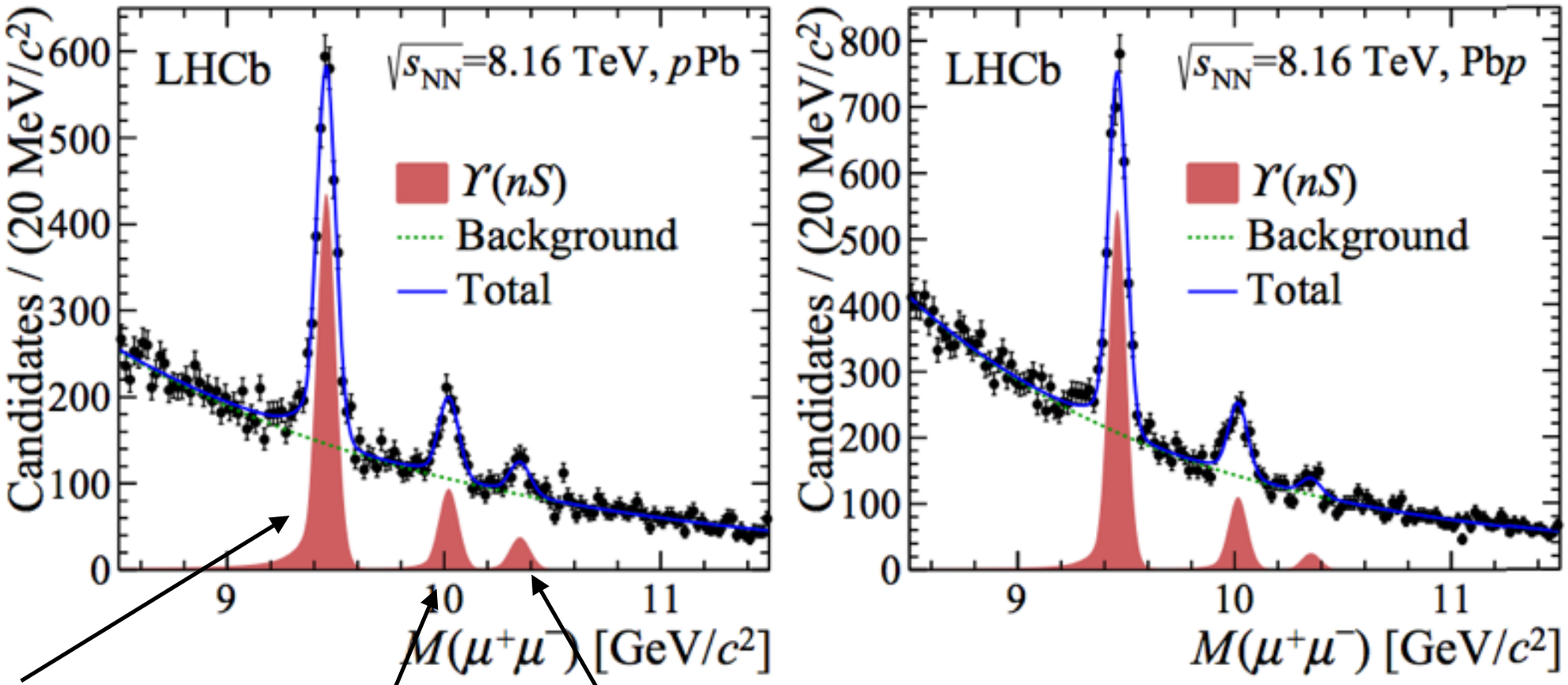
Discrepancy between the results from ALICE and LHCb needs to be understood.

- Λ_c production suppressed w.r.t. D^0 production. No evidence for transverse momentum or rapidity dependence.
- Many nuclear modification effects cancel, sensitive to charm fragmentation

Prompt Υ(nS) production in p-Pb

[1810.07655, submitted to JHEP] **New!**

All three resonances clearly seen in both forward and backward collisions:



Y(1S): double-differential cross sections

Y(2S): single-differential cross sections

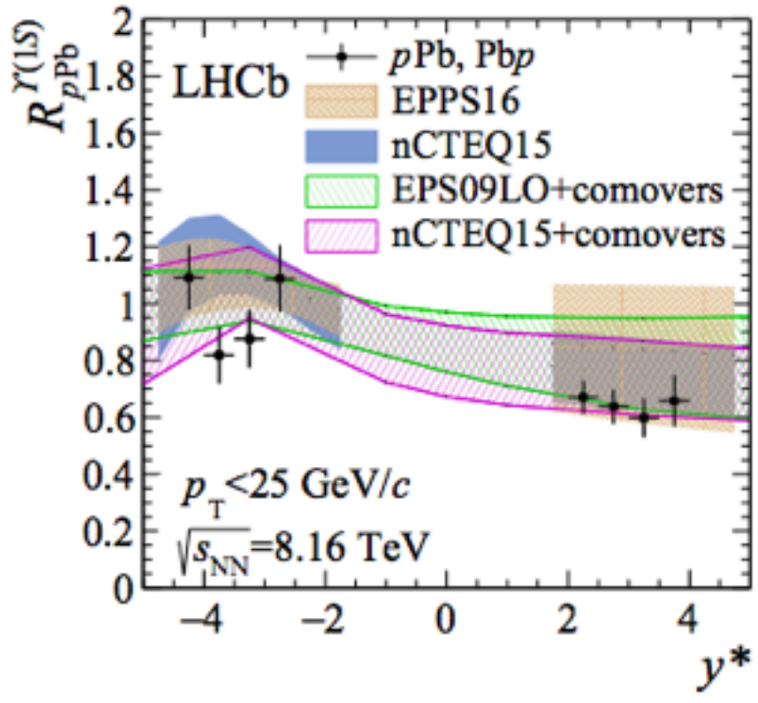
Y(3S): integrated cross sections

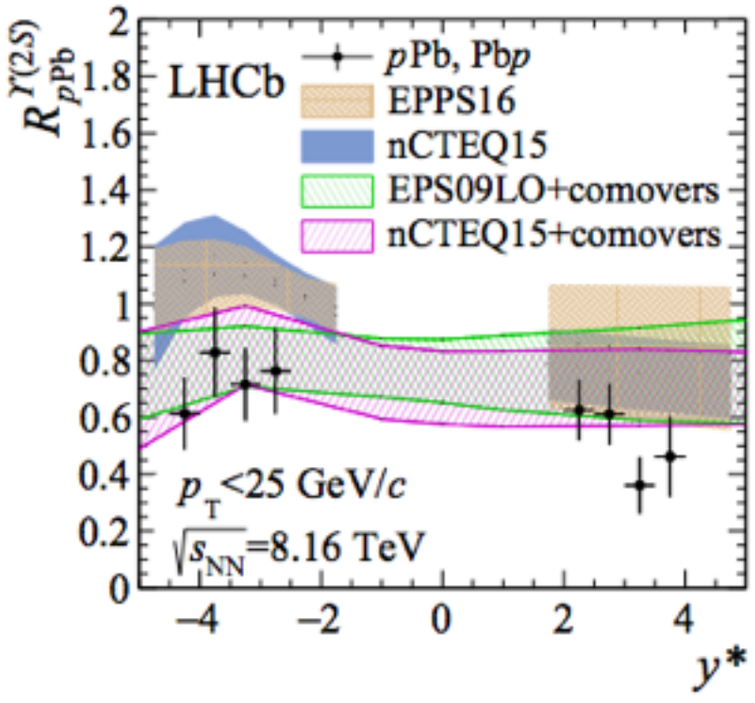
Prompt Υ(nS) production in p-Pb

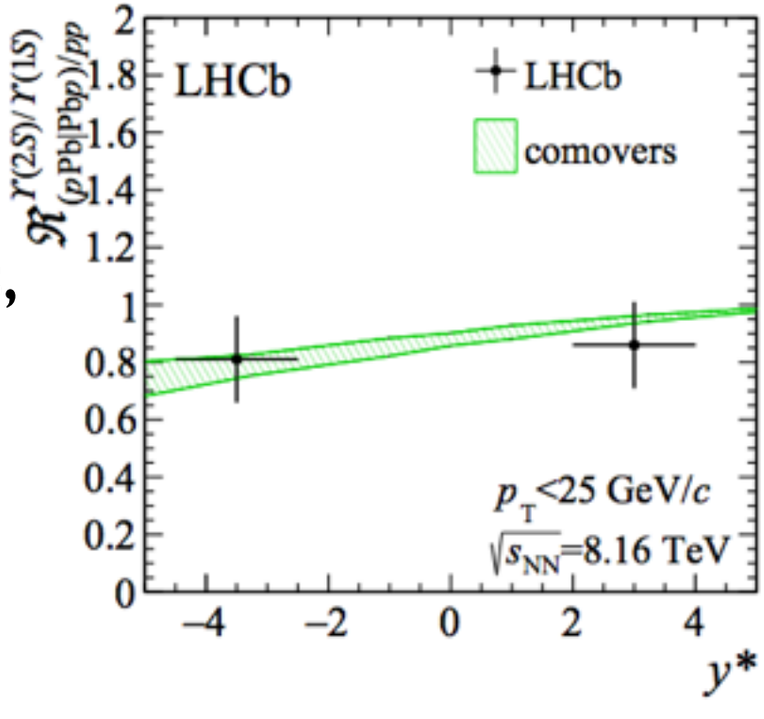
[1810.07655, submitted to JHEP] **New!**

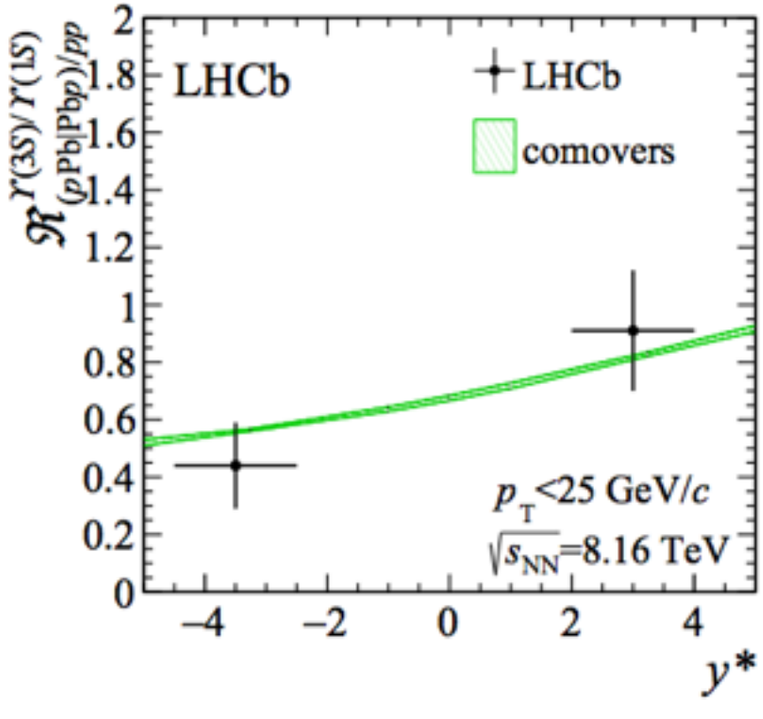
The nuclear modification factors for Υ(1S) and Υ(2S) lower in forward configuration:

CNM suppression is more effective for excited resonances, especially in backward collisions.





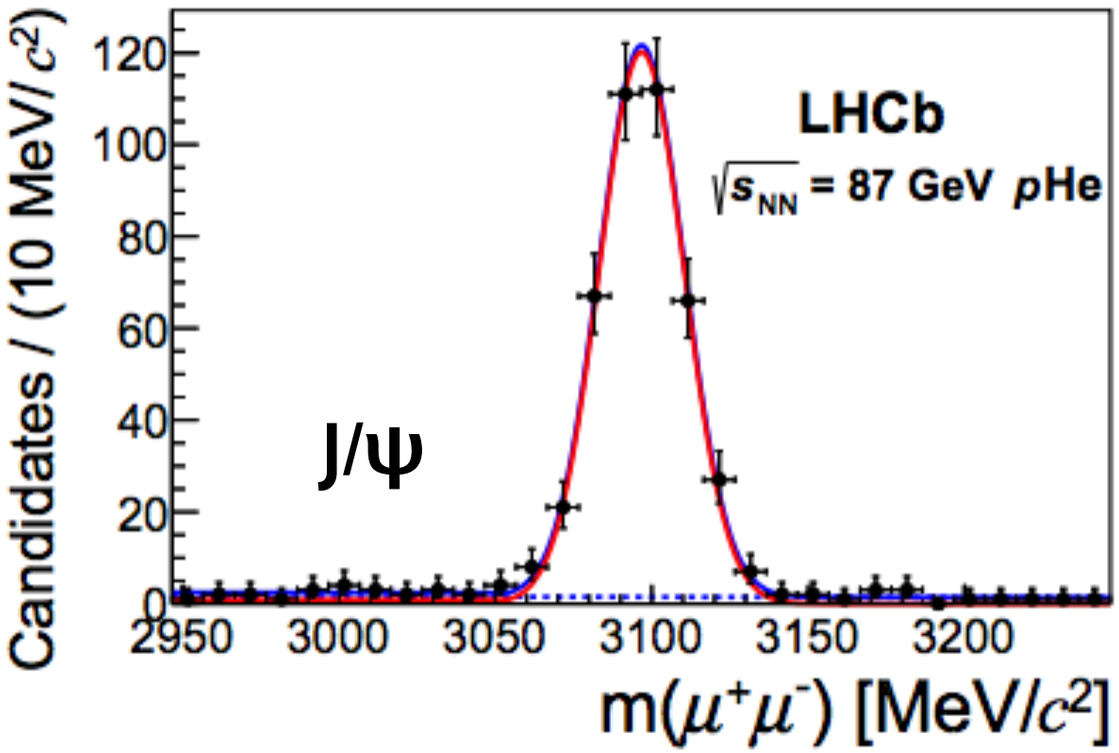


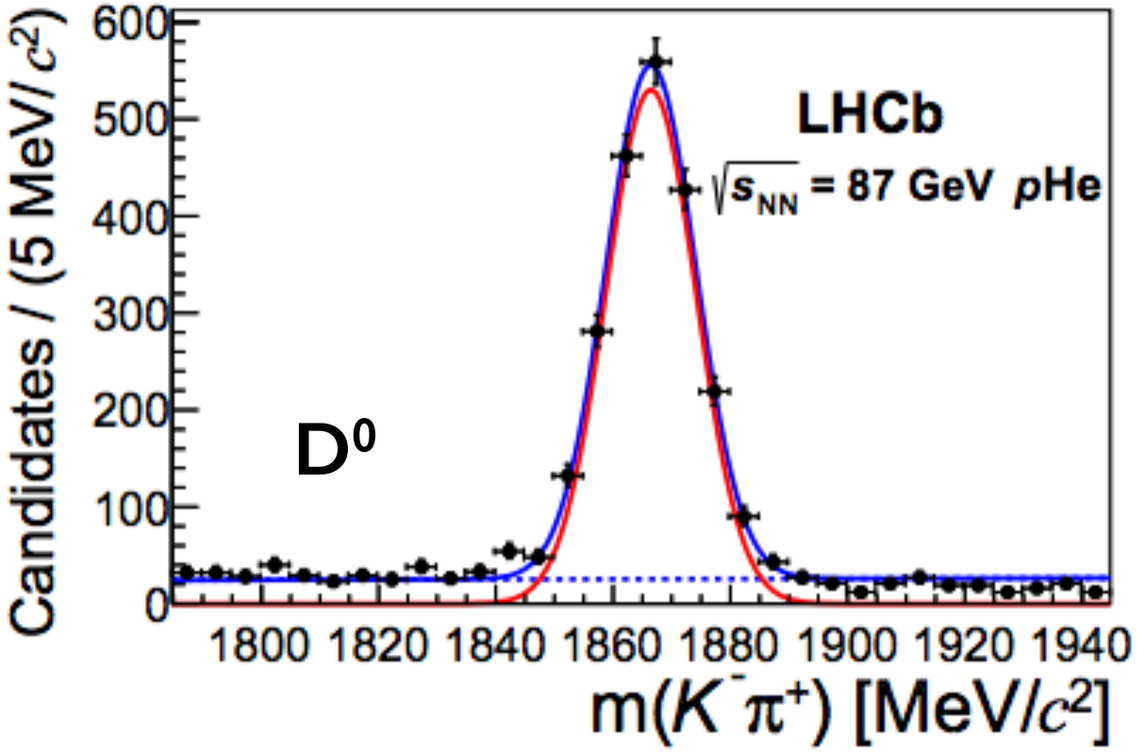


Charm production in pAr and pHe

New!

[1810.07907, submitted to PRL]



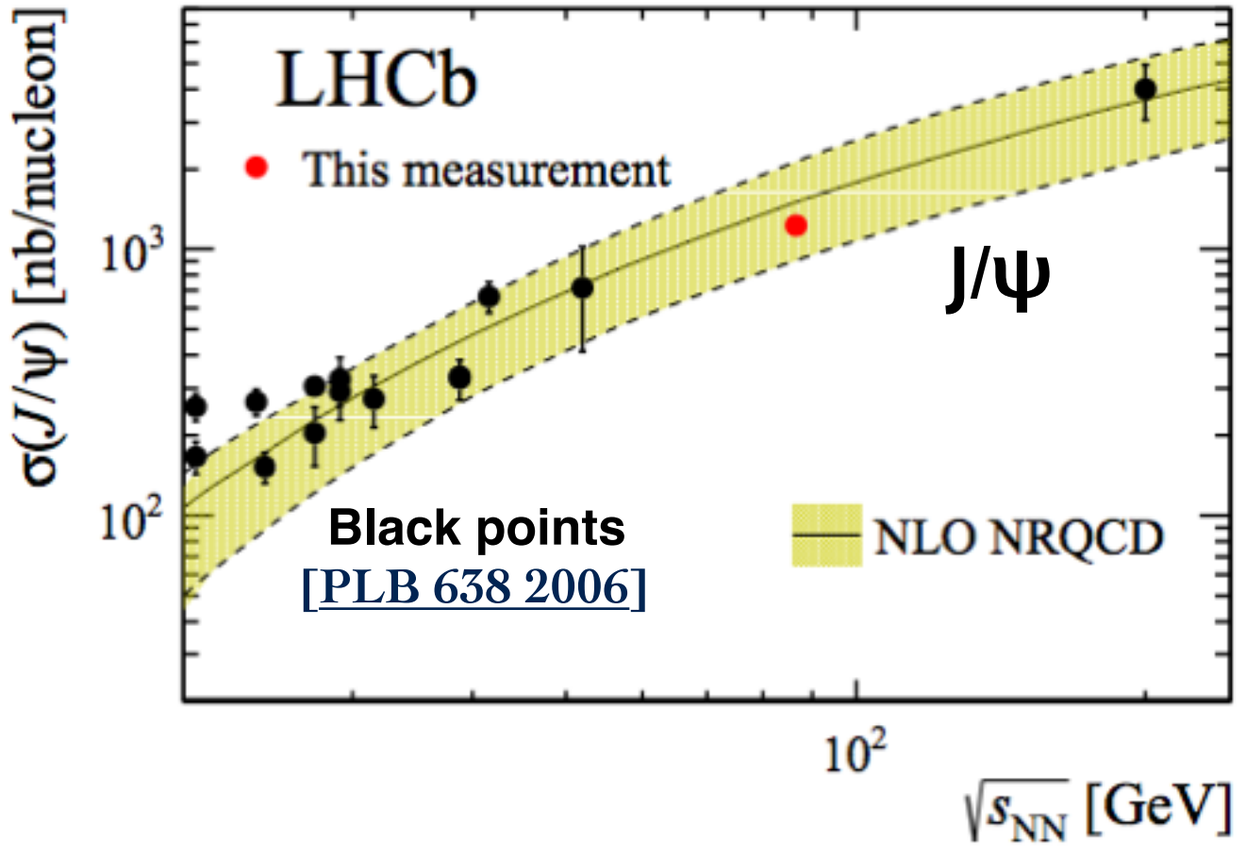


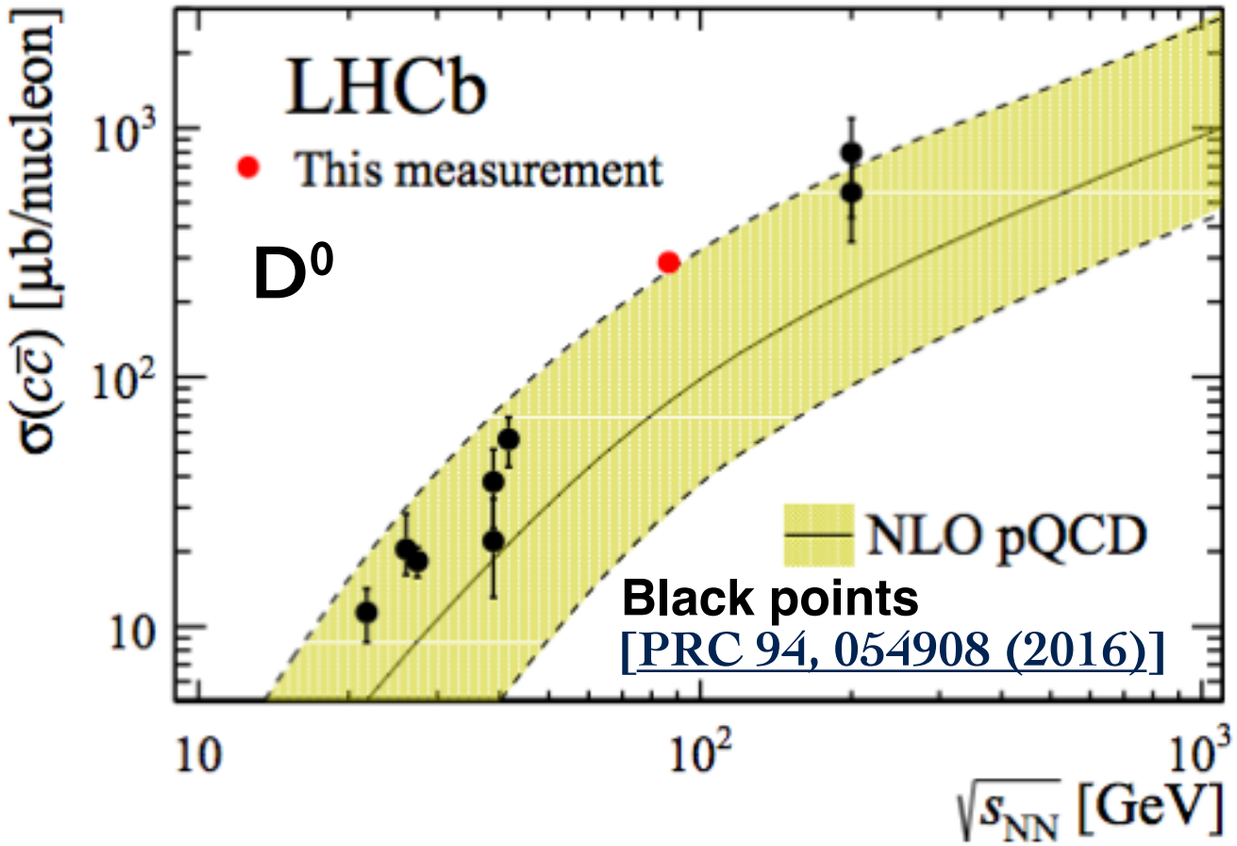
First measurement of heavy flavour production in fixed-target configuration using pHe and pAr data

Charm production in pAr and pHe

New!

[1810.07907, submitted to PRL]





- Luminosity determined from the secondary e-He collisions
- J/ψ and D0 cross-sections measured from pHe data in agreement with the pQCD predictions
- J/ψ and D0 differential cross-sections (pHe, 86.6 GeV) and differential yields (pAr, 110 GeV) also in agreement with the predictions