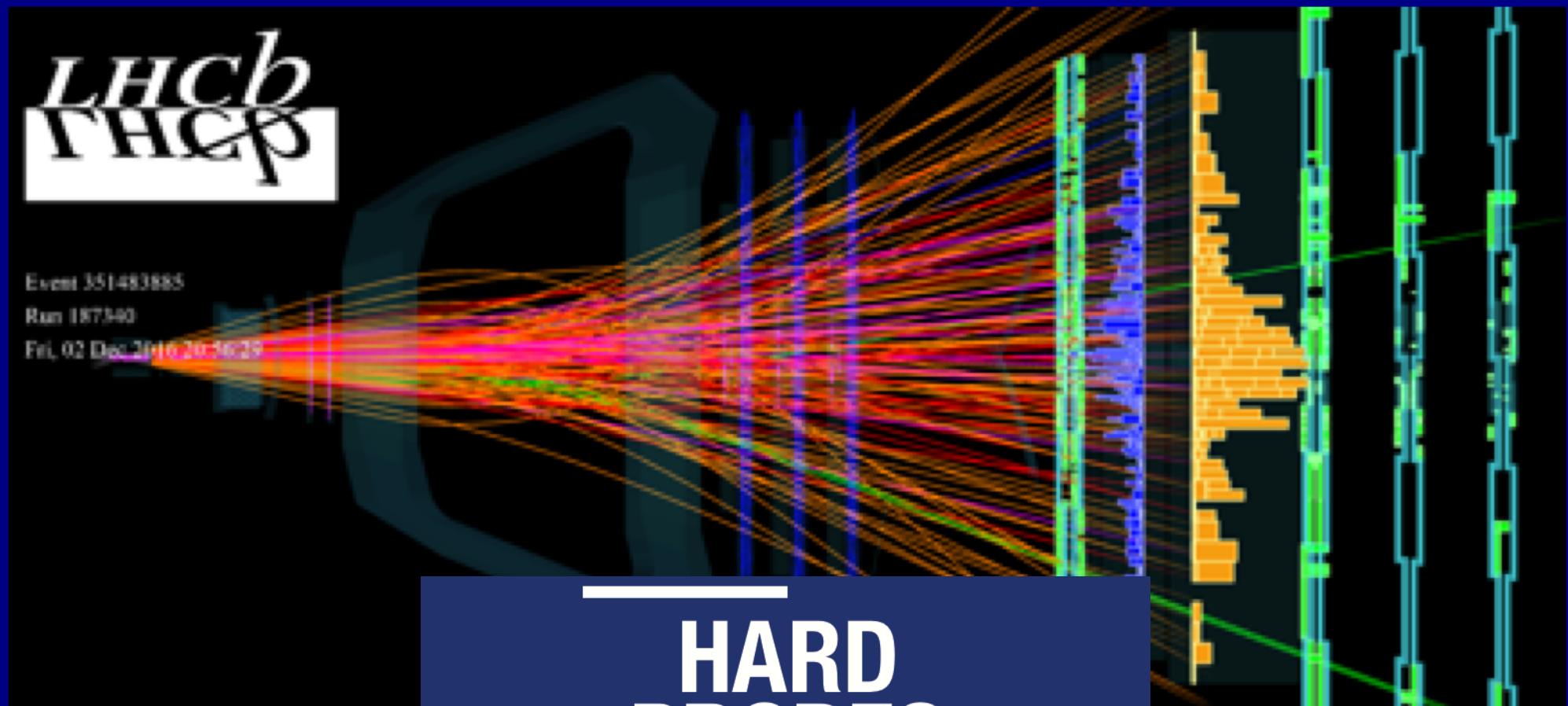


Quarkonium production in pPb collisions with LHCb

Giulia Manca,

Universita` degli studi di Cagliari (IT) & I.N.F.N.
on behalf of the LHCb collaboration



HARD
PROBES
2018

Aix Les Bains, 1-5 October 2018

Outline

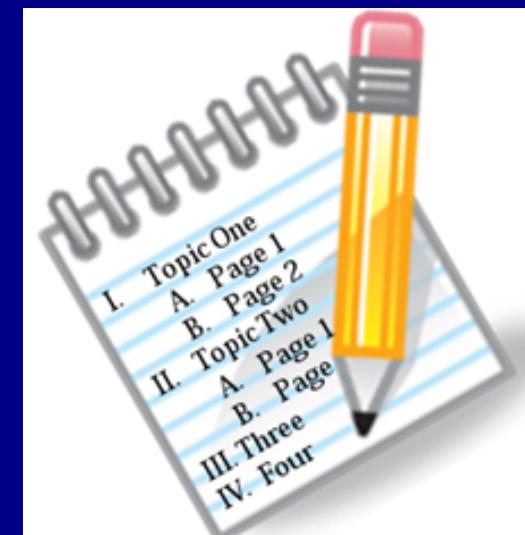
The LHCb detector at the LHC

Physics motivation

Quarkonium in proton-lead run at LHCb

- $\Upsilon(nS)$
- J/ψ

Conclusions and outlook



LHCb Detector at the LHC

Single arm spectrometer in the forward direction

- Designed for b-physics, becoming a General Purpose Detector
- Forward and backward coverage for asymmetric beams
- Precision in the forward region not achievable by others yet

[JINST 3 (2008) S08005]

[IJMPA 30 (2015) 1530022]

RICH detectors

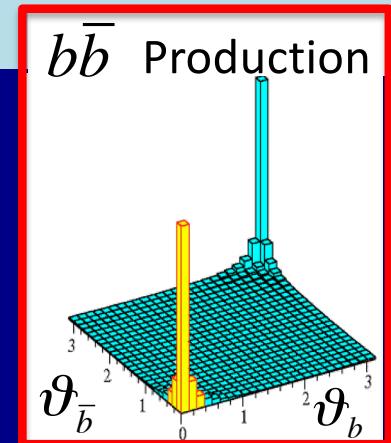
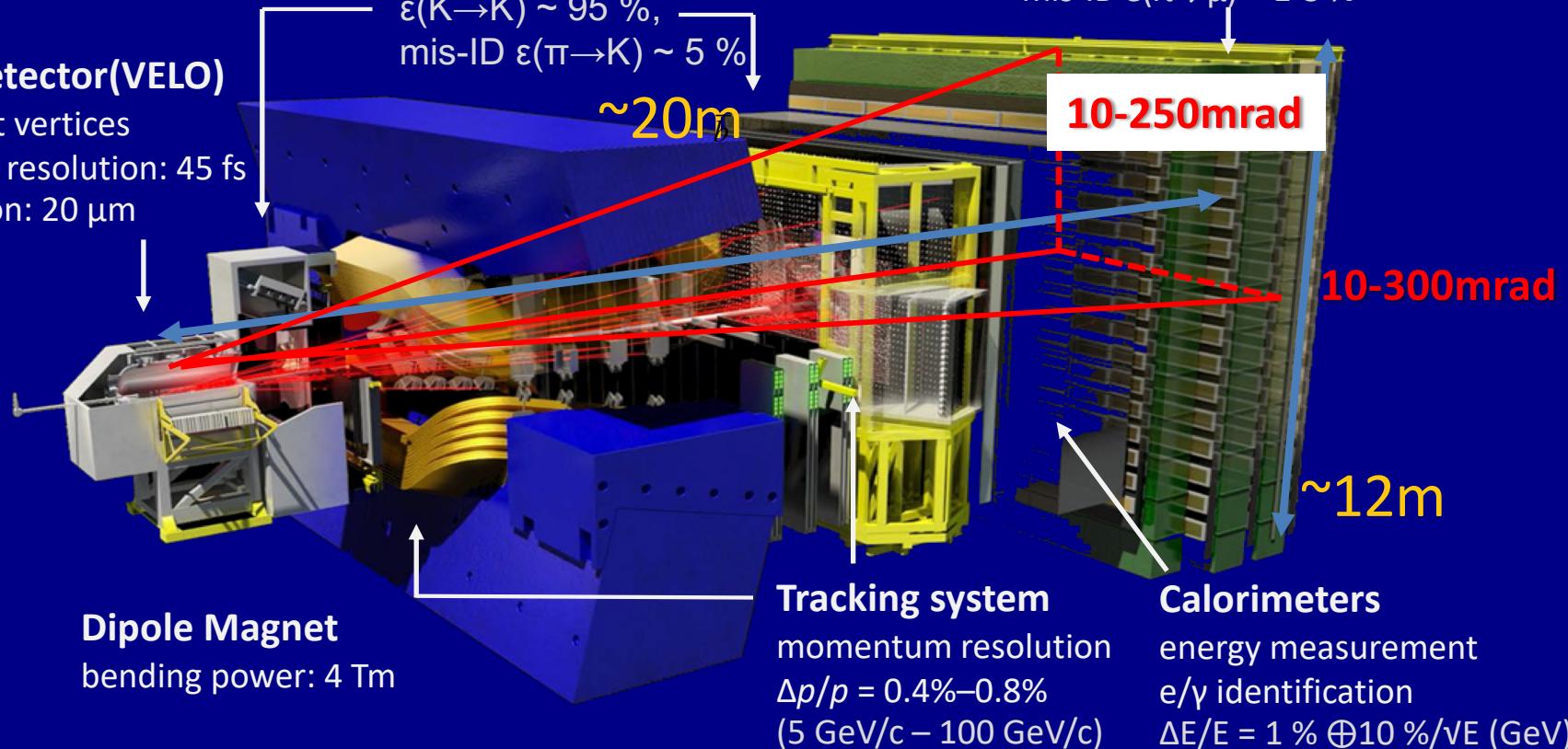
K/ π /p separation
 $\epsilon(K \rightarrow K) \sim 95\%$,
mis-ID $\epsilon(\pi \rightarrow K) \sim 5\%$

Muon system

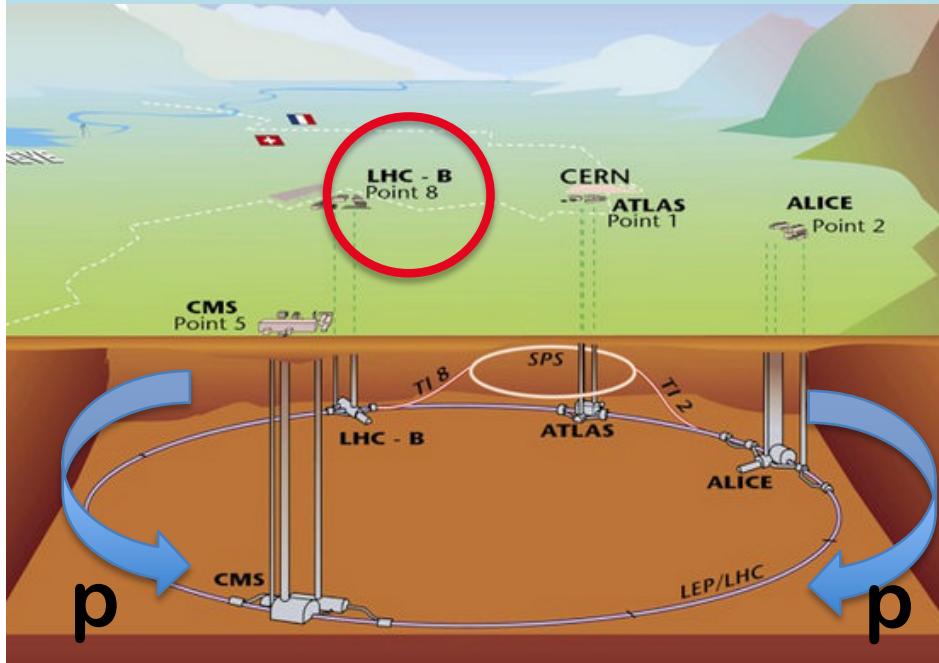
μ identification $\epsilon(\mu \rightarrow \mu) \sim 97\%$,
mis-ID $\epsilon(\pi \rightarrow \mu) \sim 1-3\%$

Vertex Detector(VELO)

reconstruct vertices
decay time resolution: 45 fs
IP resolution: 20 μm



LHC and LHCb



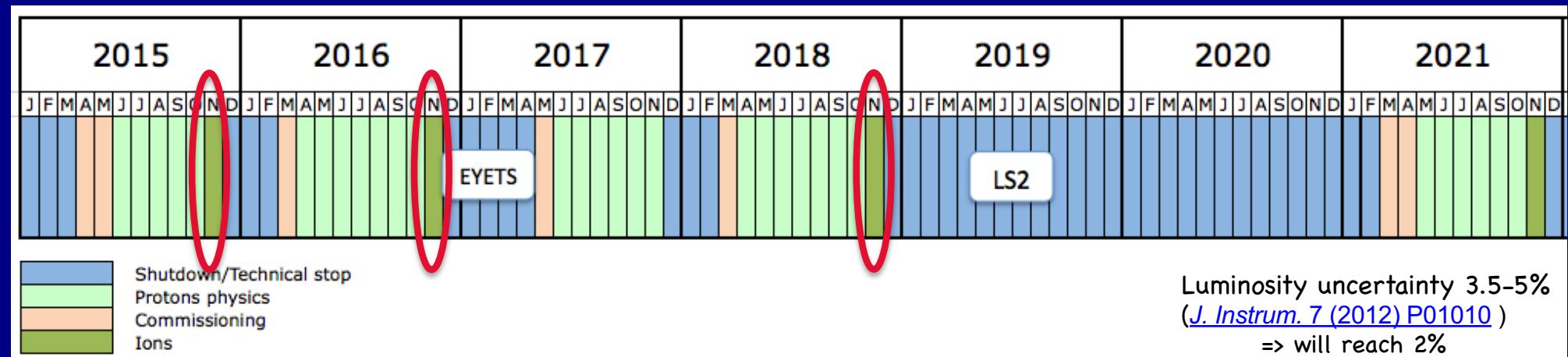
pp collider 2010-18@ $\sqrt{s} = 2.76, 5, 7, 8, 13$
TeV, $L \approx 9 \text{ fb}^{-1}$

In 2013 & 2016 collected pPb data at $\sqrt{s_{NN}}=5$ and 8.16 TeV, L=1.6 & 34 nb⁻¹

10^9 minimum bias collisions, $\approx 1M$ J/ψ 's

PbPb collisions at $\sqrt{s}=5\text{TeV}$, $L \approx 10 \mu\text{b}^{-1}$
successfully collected at LHCb for the
first time in 2015 (see S.Belin talk on
Tue); next run => end 2018

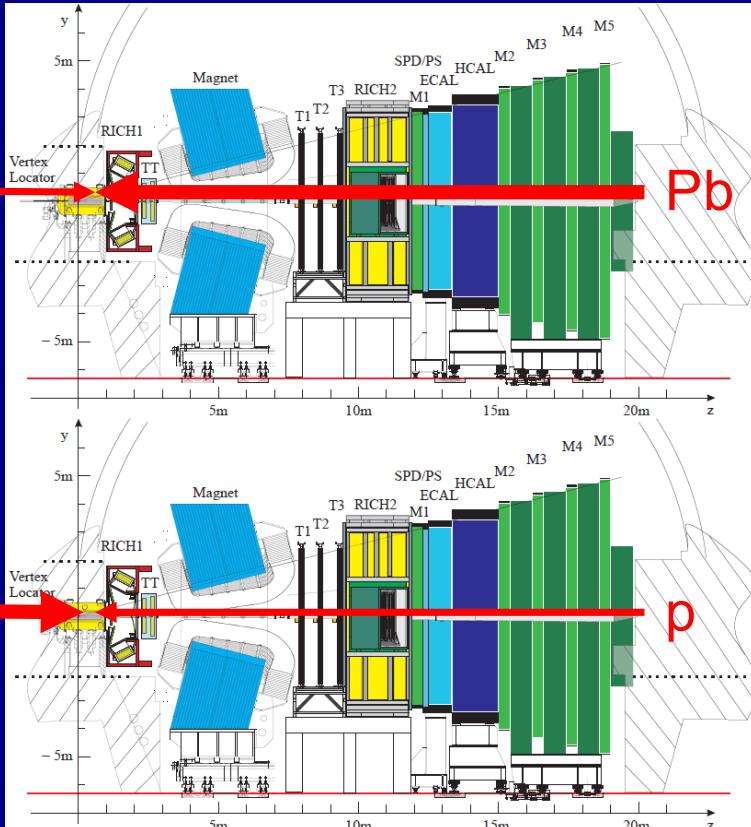
LHCb also able to collect data in “fixed target” mode (SMOG – see talk of F.Fleuret on Thu)



Setup for Proton-Ion physics

p-Pb
p —————
 $E_p = 6.5 \text{ TeV}$

Pb-p
Pb —————
 $E_N = 2.56 \text{ TeV}$



Rapidity coverage
 $pp: 2 < y < 5$

Forward production

$y = 0.47 \text{ in lab}$

$p\text{-Pb}: 1.5 < y^* < 4.5$

Data taken in 2016: $\sim 13.6/\text{nb}$

Backward production

$y = -0.47 \text{ in lab}$

$\text{Pb-p}: -5.5 < y^* < -2.5$

Data taken in 2016: $\sim 20.8/\text{nb}$

- Common range for measurements: $2.5 < |y^*| < 4.5$
- Centre of mass energy in 2016 : 8.16 TeV , $L=34 \text{ pb}^{-1}$, about $20\times$ 2013 !

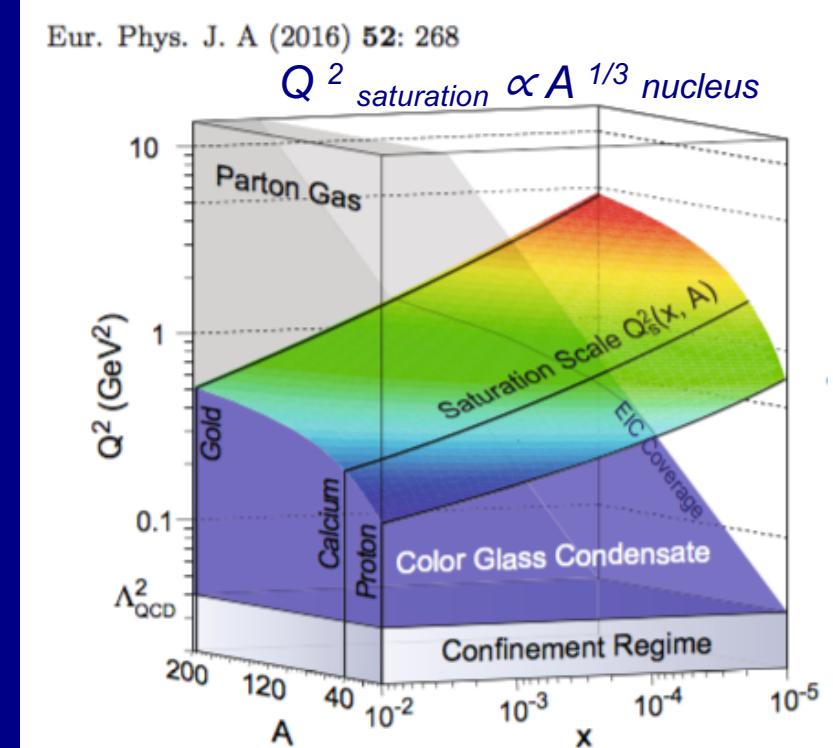
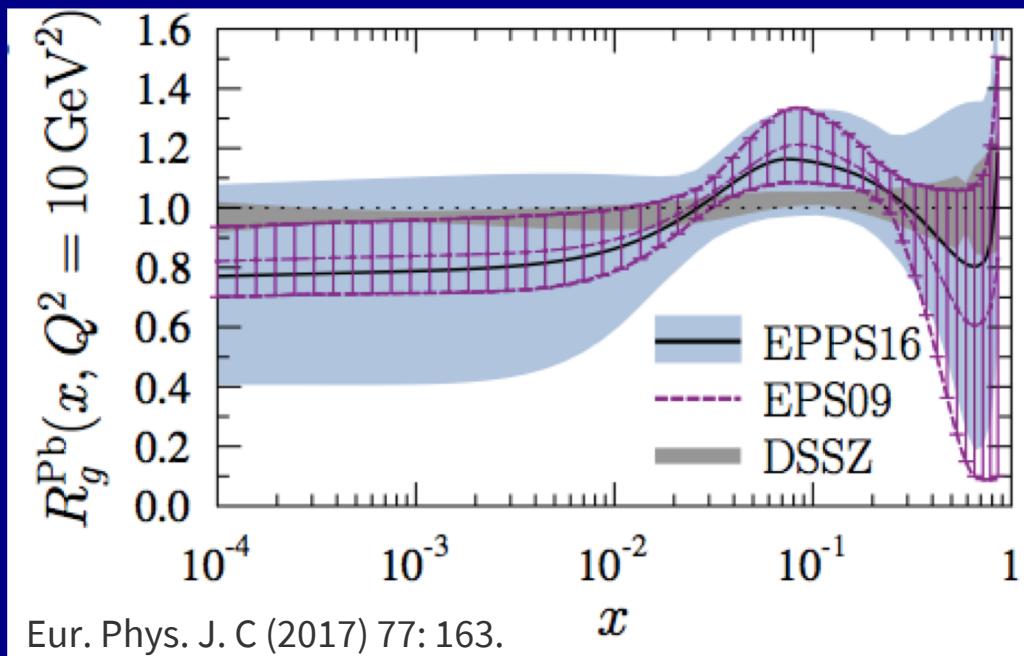
Why is pPb interesting?

Study of nuclear effects **initial** and **final state**

- Nuclear effects on parton densities (**shadowing/antishadowing**)=> EPS09,EPPS16
- Energy loss of incident partons (JHEP 1303 (2013) 122)
- Saturation: Color Glass Condensate (Ann.Rev.Nucl.Part.Sci.60:463-489,2010)
- Nuclear break-up, Comovers (Phys. Lett. B749(2015) 98, arXiv:1411.0549)

Partons largely unconstrained at LHC collisions energy in the forward region => LHCb can explore the low-Bjorken x region with high precision, especially @low Q^2 , down to 0 p_T

Crucial for understanding PbPb collisions



$\Upsilon(nS)$ analysis in $p\text{Pb}$ collisions

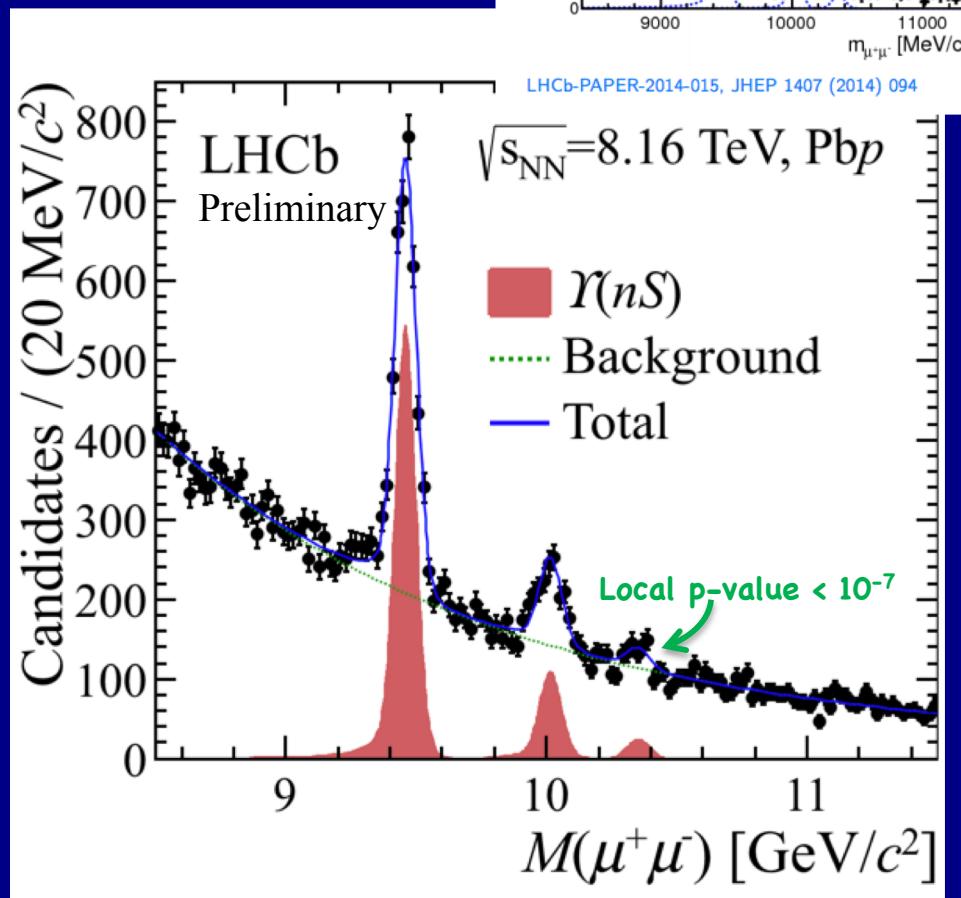
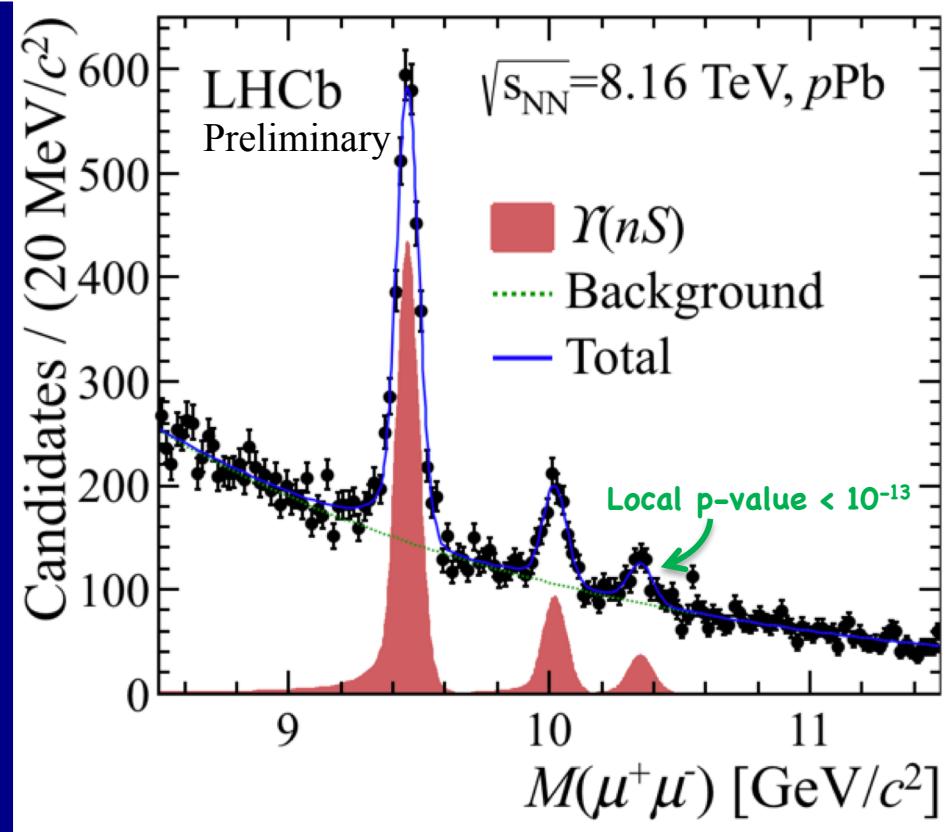
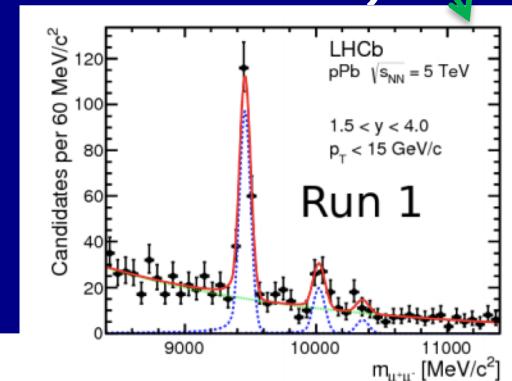
LHCb-PAPER-2018-035
To be submitted to JHEP

New differential analysis of Run II $p\text{Pb}$ sample ! (20xdata w.r.t. Run I) ↗

Cross-section, $R_{p\text{Pb}}$, R_{FB} measured for all $\Upsilon(nS)$ states

- double (single) differential in y and p_T for $\Upsilon(1S)$ ($\Upsilon(2S)$)
- Nice signal of $\Upsilon(3S)$ in p -lead collisions !

Yields	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	\mathcal{L}
$p\text{Pb}$	2705 ± 87	584 ± 49	262 ± 44	12.5 nb^{-1}
Pbp	3072 ± 82	679 ± 54	159 ± 39	19.3 nb^{-1}

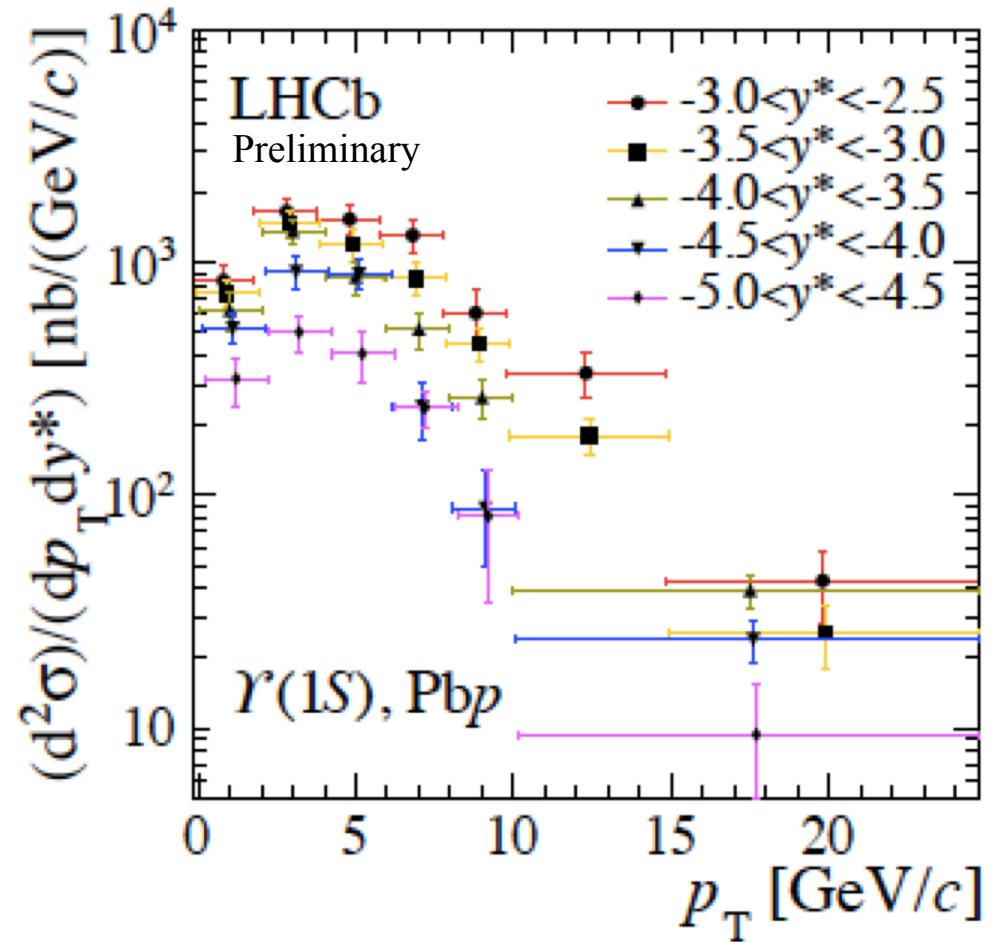
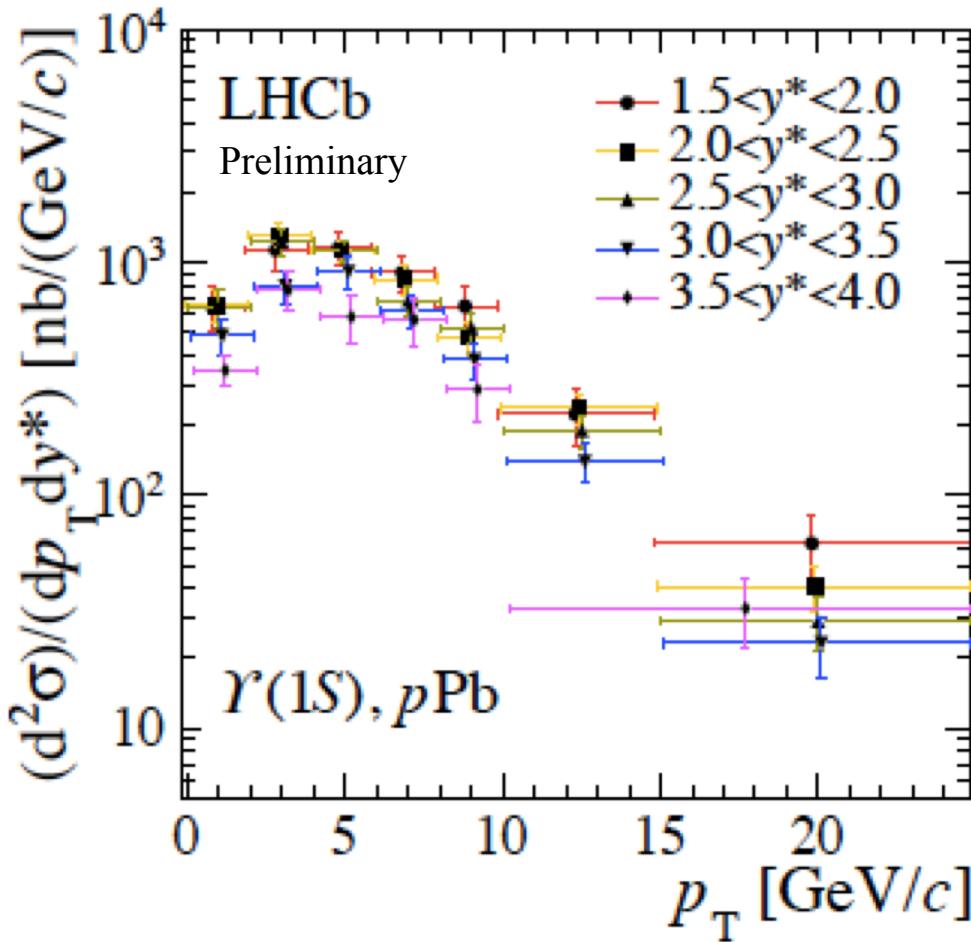


$\Upsilon(1S)$ double differential σ

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To be submitted to JHEP

Variable size bins in p_T and y^*

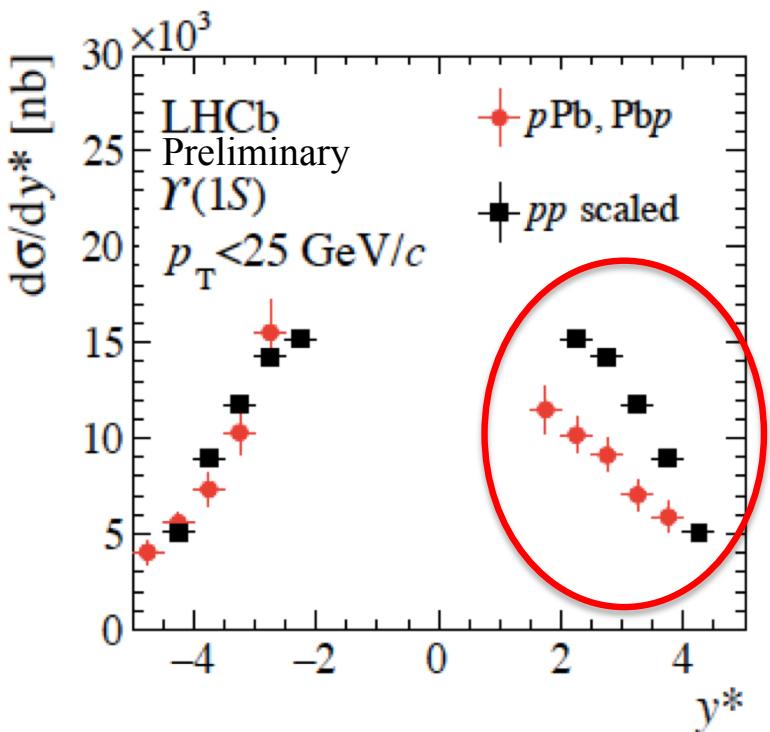
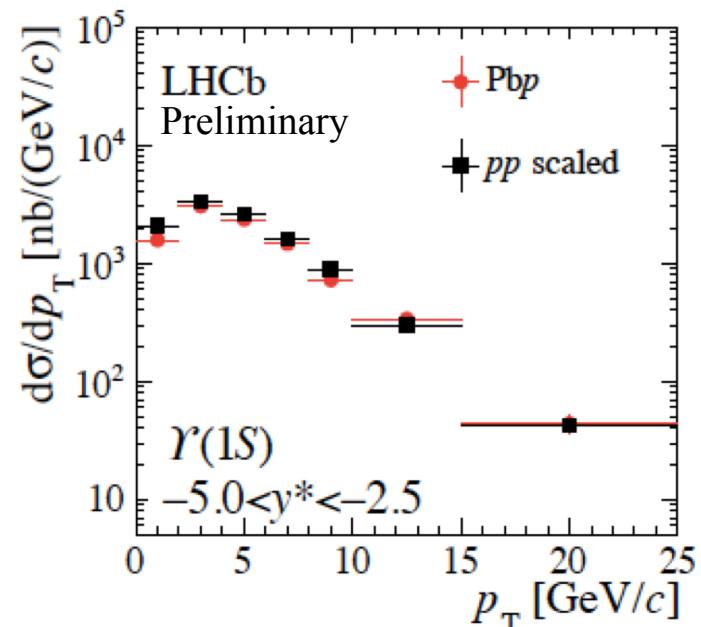
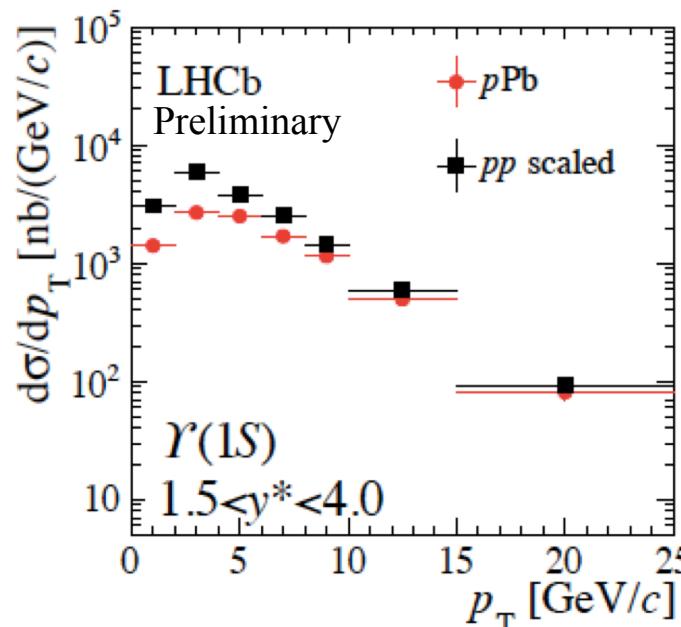
$$\frac{d^2\sigma}{dp_T dy^*} = \frac{N(\Upsilon(nS) \rightarrow \mu^+ \mu^-)}{\mathcal{L} \times \varepsilon_{\text{tot}} \times \mathcal{B}_{\mu\mu} \times \Delta p_T \times \Delta y^*}.$$



$\Upsilon(1S)$ integrated cross section

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To be submitted to JHEP

Integrated over
 y^* as a function
of p_T



Integrated over p_T as a function of y^*

- Slight suppression in the forward pPb region

$\gamma(1S)$ Nuclear Modification factor

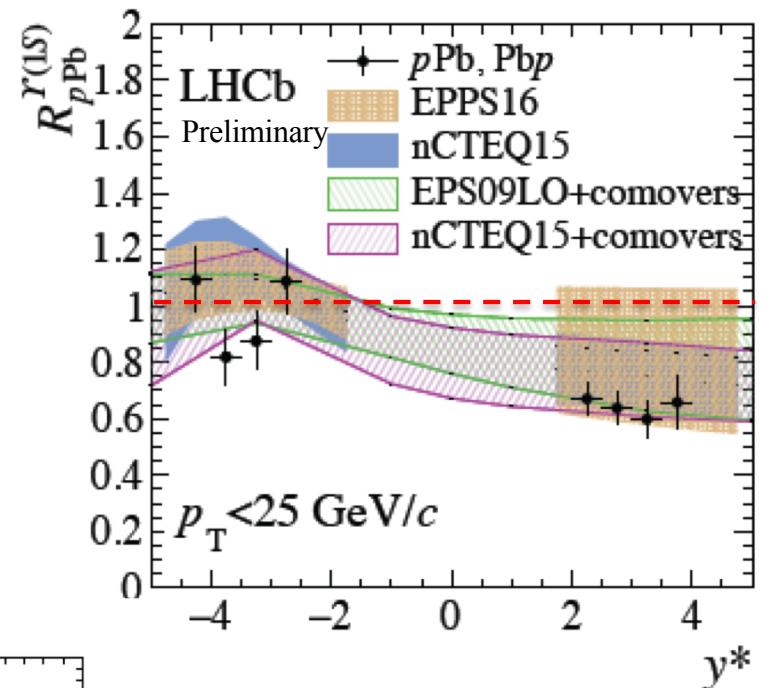
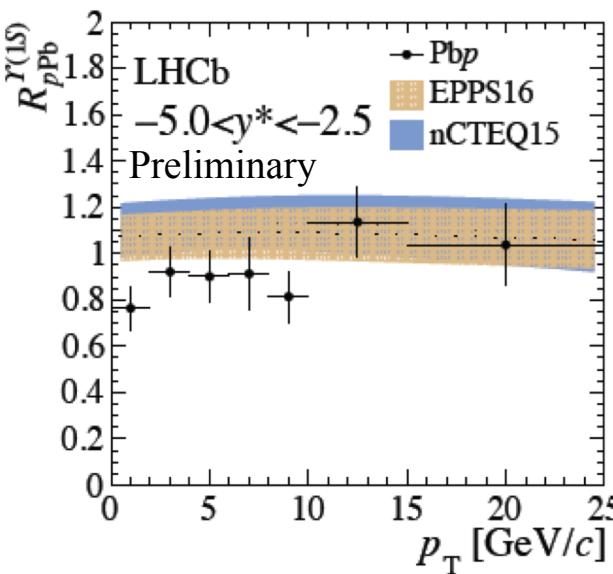
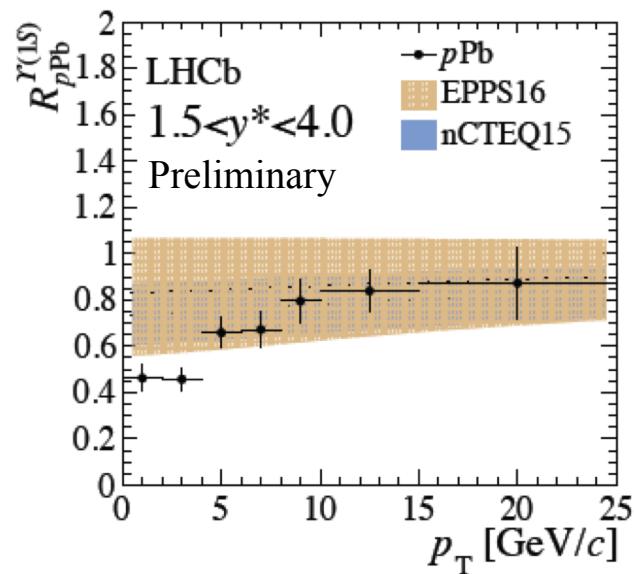
LHCb-PAPER-2018-035
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$$R_{p\text{Pb}}(p_{\text{T}}, y^*) = \frac{1}{208} \frac{d^2\sigma_{p\text{Pb}}(p_{\text{T}}, y^*)/dp_{\text{T}}dy^*}{d^2\sigma_{pp}(p_{\text{T}}, y^*)/dp_{\text{T}}dy^*},$$

Integrated over p_{T} as a function of y^*

- suppression in the forward pPb region confirmed

Integrated over y^* as a function of p_{T}



MODELS:

- EPPS16: Eur. Phys. J. C (2017) 77: 163
- EPS09: JHEP 04 (2009) 065, arXiv:0902.4154.
- nCTEQ15: Phys. Rev. D93 (2016) 085037.
- Comovers: arXiv:1804.04474; Phys. Lett. B749 (2015) 98, arXiv:1411.0549

$\Upsilon(1S)$ Nuclear Modification factor

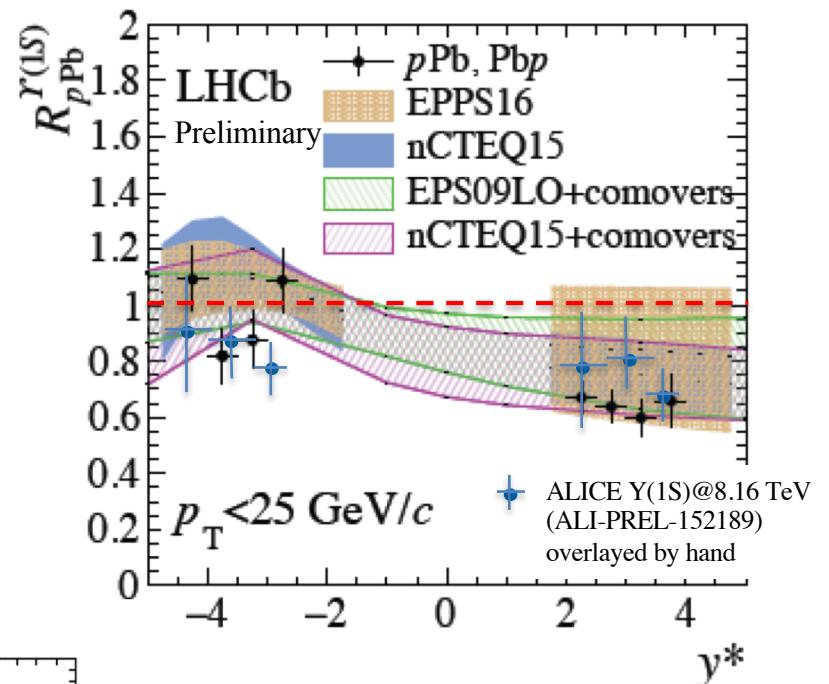
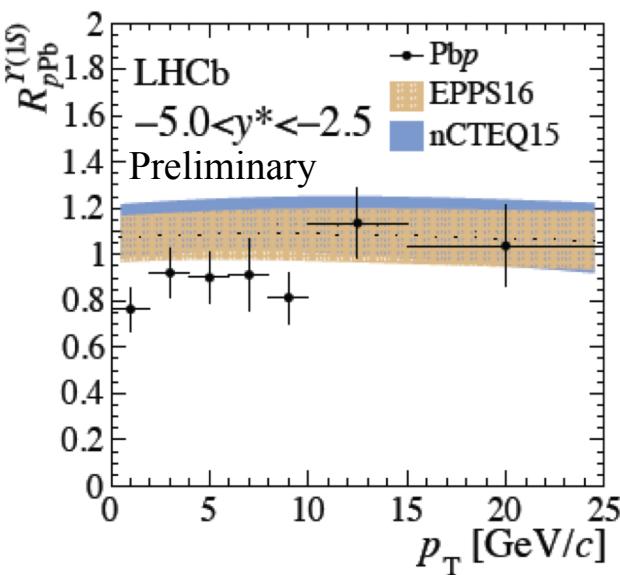
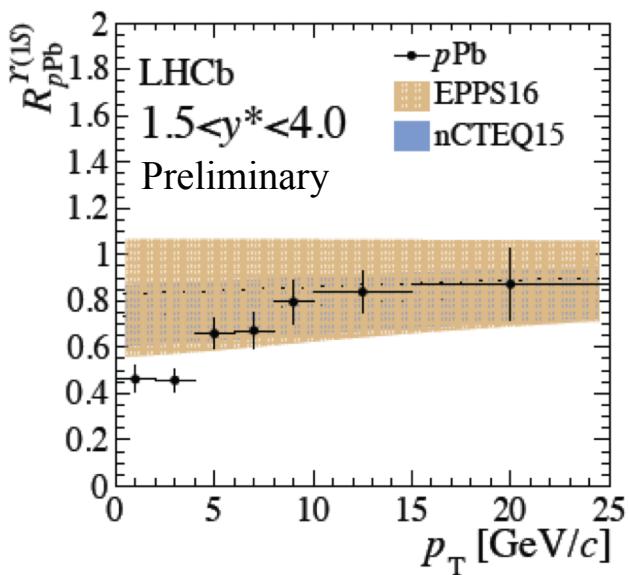
LHCb-PAPER-2018-035
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$$R_{p\text{Pb}}(p_{\text{T}}, y^*) = \frac{1}{208} \frac{d^2\sigma_{p\text{Pb}}(p_{\text{T}}, y^*)/dp_{\text{T}}dy^*}{d^2\sigma_{pp}(p_{\text{T}}, y^*)/dp_{\text{T}}dy^*},$$

Integrated over p_{T} as a function of y^*

- suppression in the forward pPb region confirmed

Integrated over y^* as a function of p_{T}



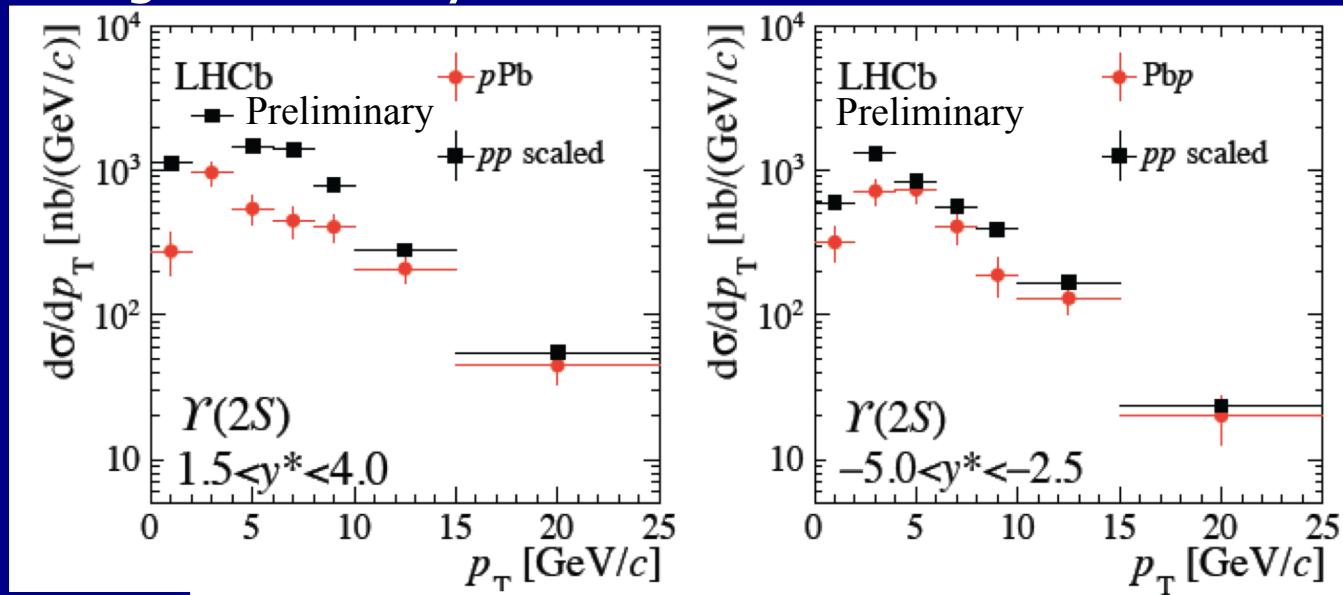
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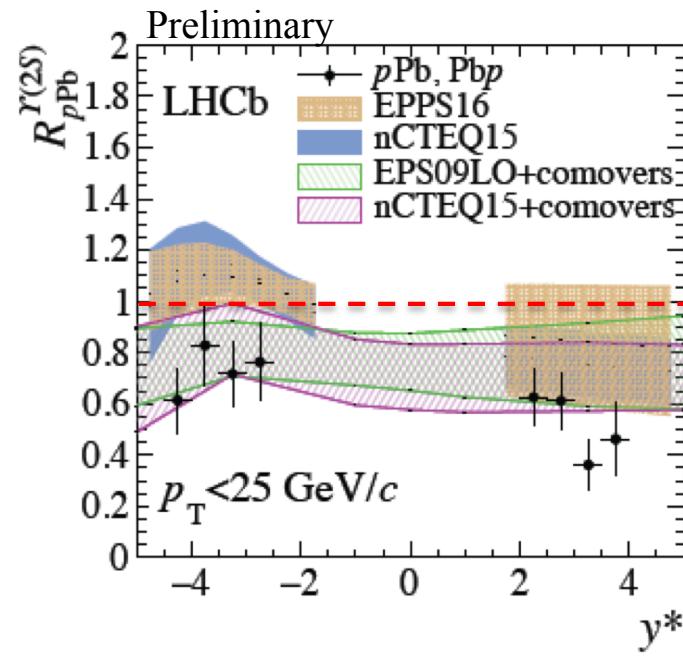
$\gamma(2S)$ Results

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To be submitted to JHEP

Differential in p_T and integrated over y^*



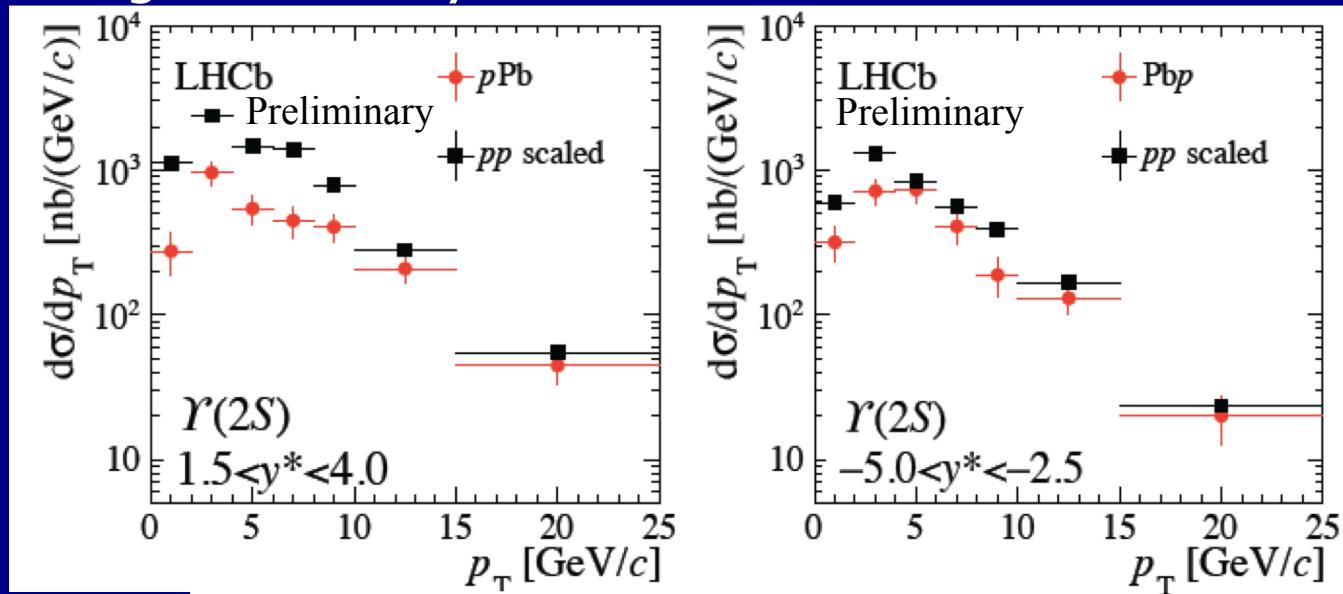
Nuclear modification factor



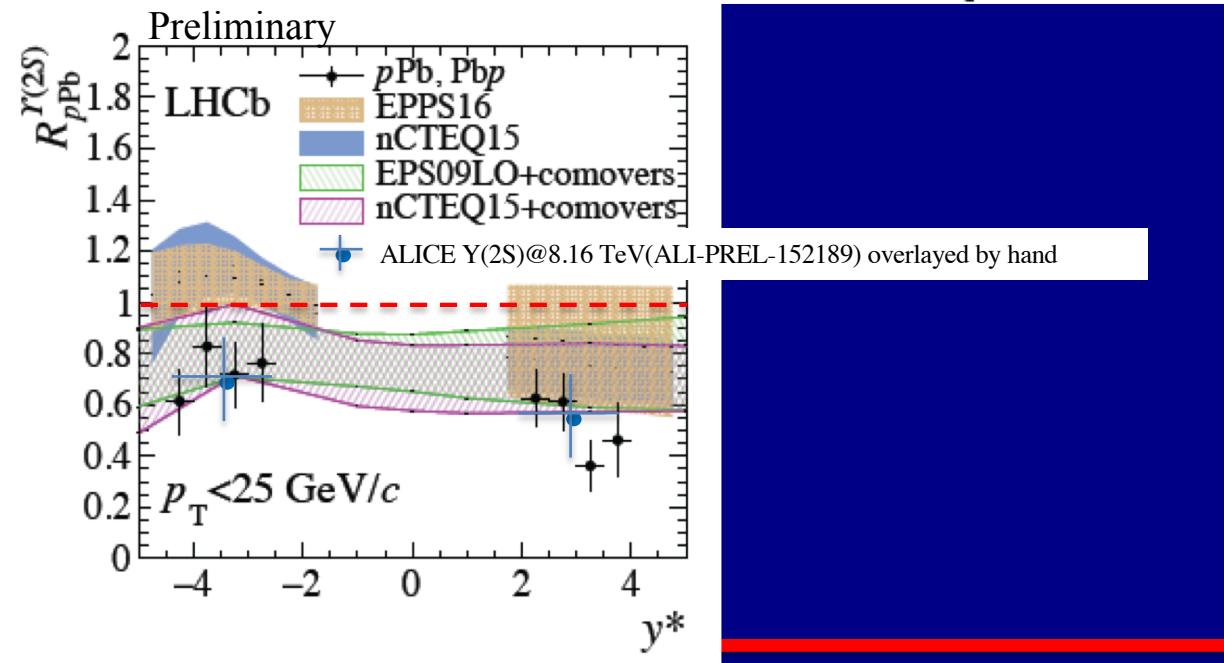
$\gamma(2S)$ Results

LHCb-PAPER-2018-035
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Differential in p_T and integrated over y^*



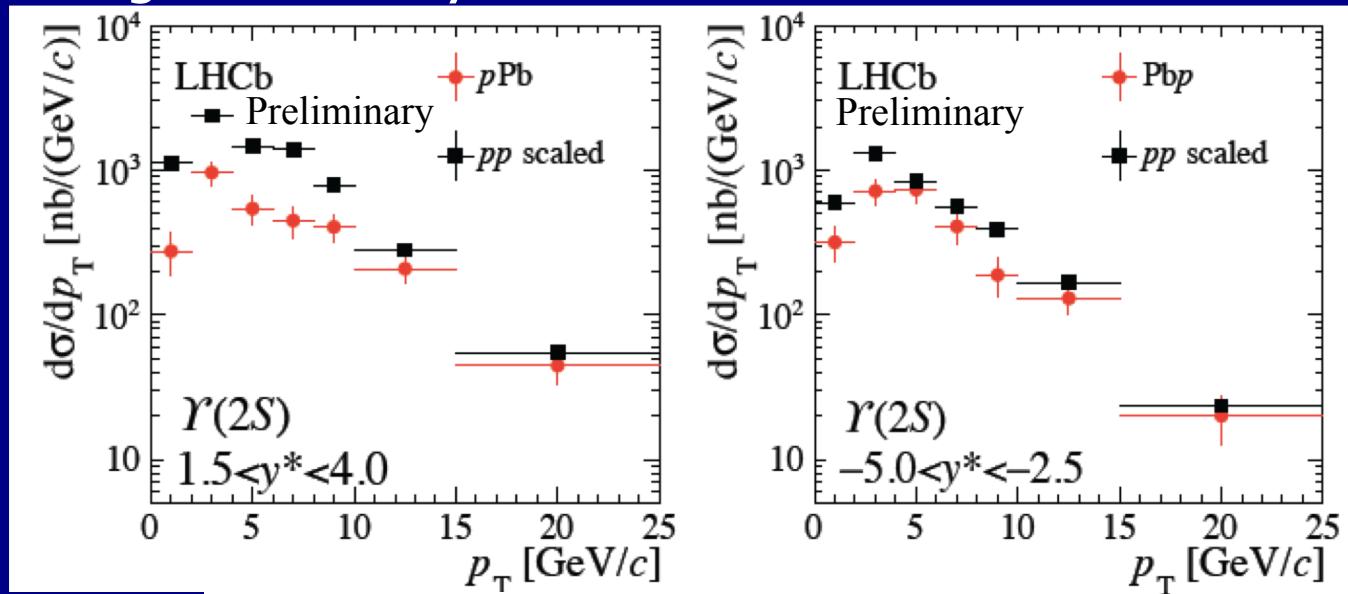
Nuclear modification factor:
Compared to ALICE



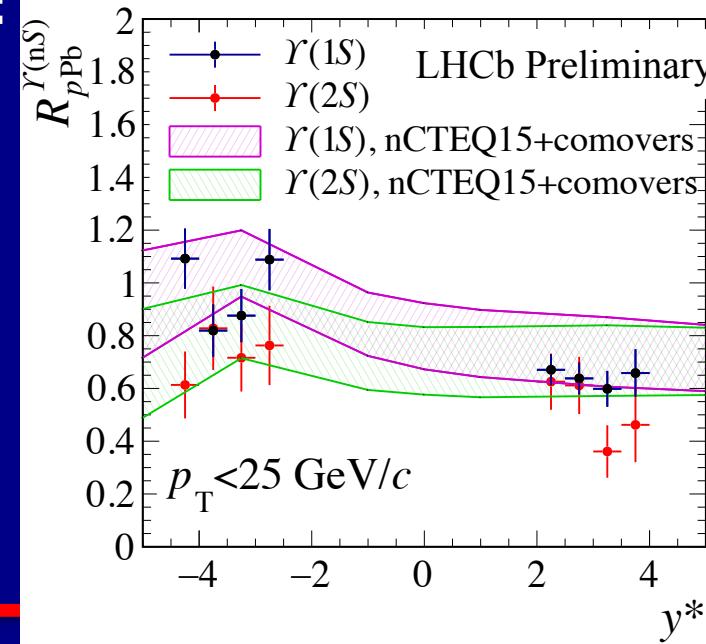
$\Upsilon(2S)$ Results

LHCb-PAPER-2018-035
To be submitted to JHEP

Differential in p_T and integrated over y^*



Nuclear modification factor:
Compared to $\Upsilon(1S)$



Ratios

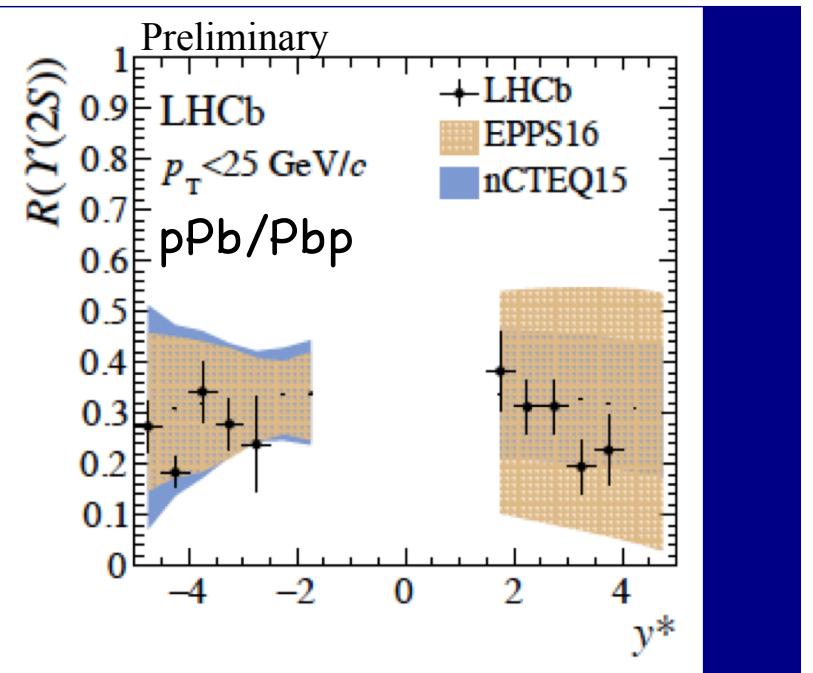
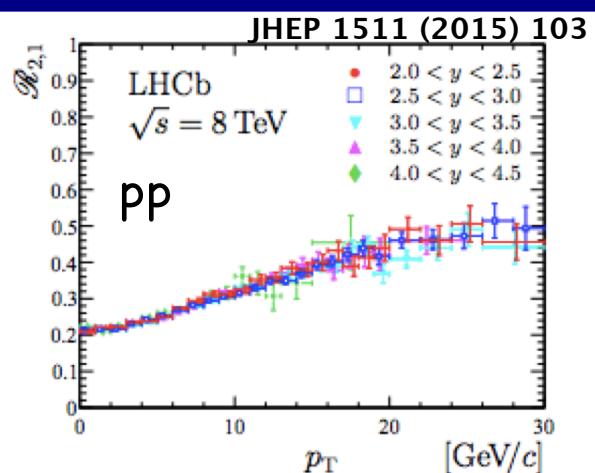
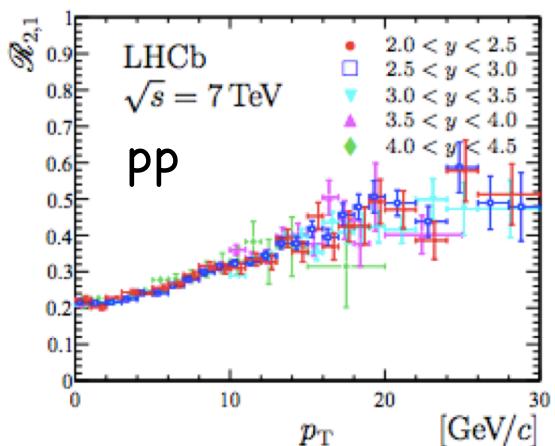
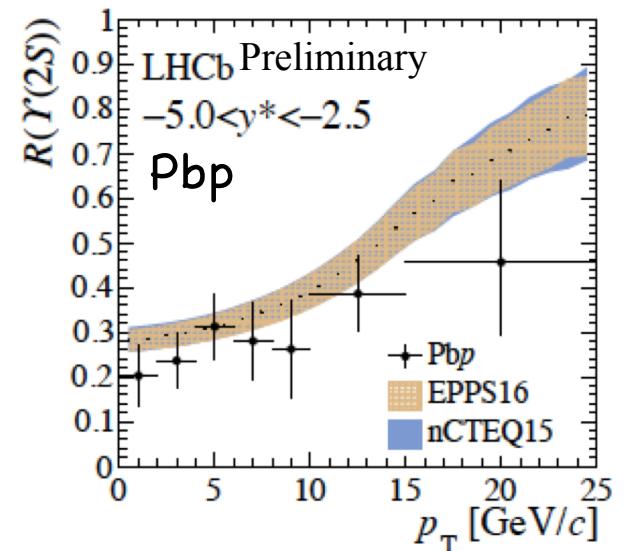
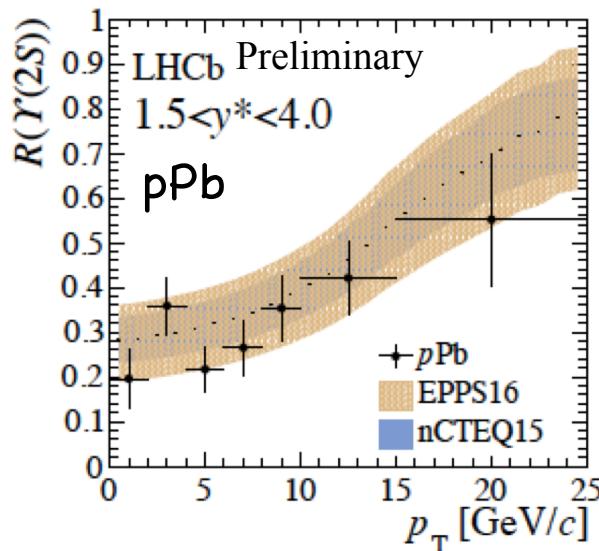
$$R(\Upsilon(nS)) = \frac{[d^2\sigma/dp_T dy^*] (\Upsilon(nS))}{[d^2\sigma/dp_T dy^*] (\Upsilon(1S))}$$

Ratio of $\Upsilon(2S)$ over $\Upsilon(1S)$

- Differential in p_T

- ...and y^*

pp results @8TeV



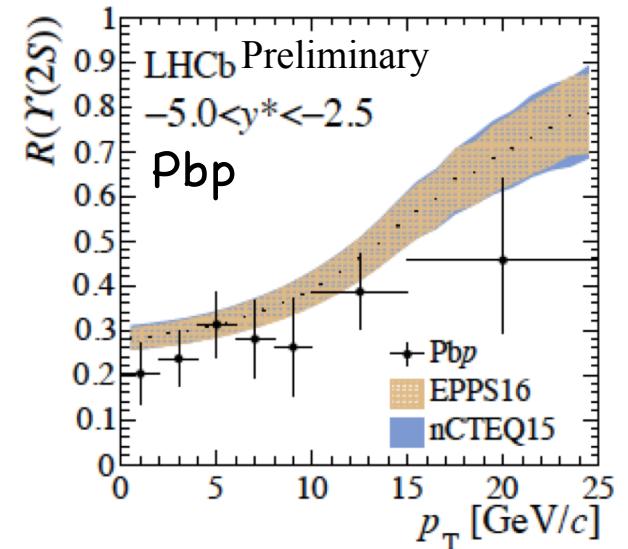
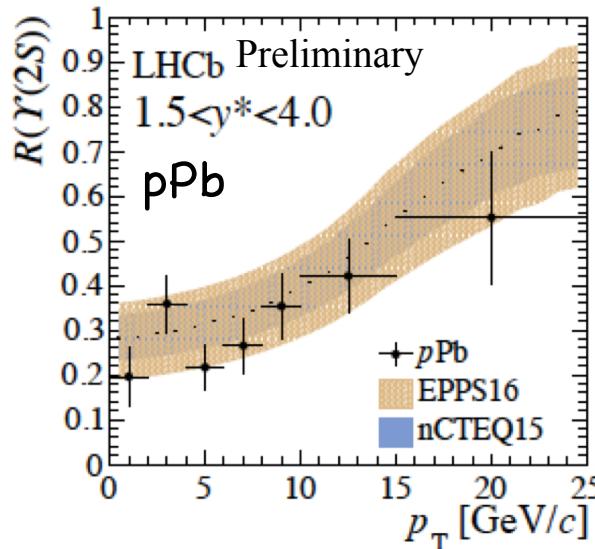
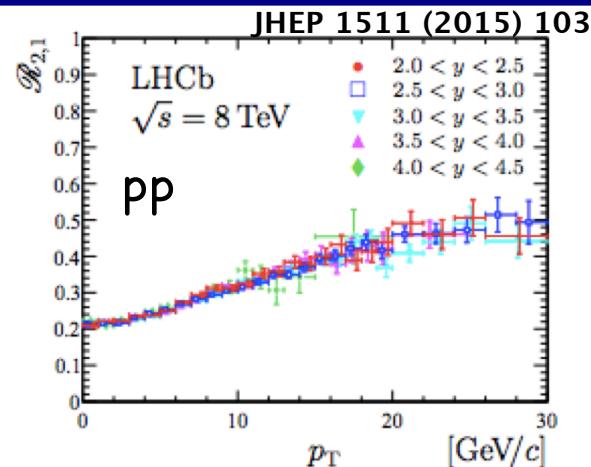
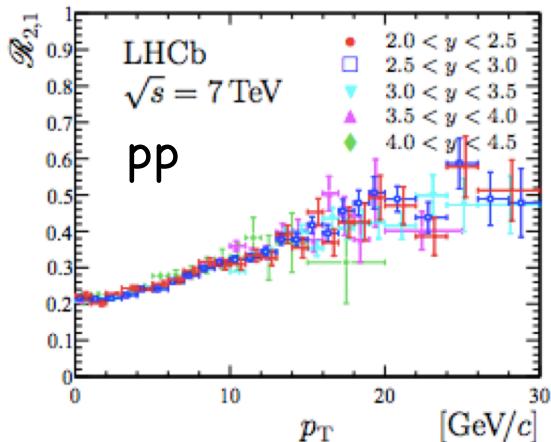
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Ratio of $\Upsilon(2S)$ over $\Upsilon(1S)$

- Differential in p_T

- ...and y^*

pp results @8TeV



Integrated Double Ratios

$$R(pPb/pp)[\Upsilon(2S)] = 0.86 \pm 0.15$$

$$R(pPb/pp)[\Upsilon(3S)] = 0.81 \pm 0.15$$

$$R(Pbp/pp)[\Upsilon(2S)] = 0.90 \pm 0.21$$

$$R(Pbp/pp)[\Upsilon(3S)] = 0.44 \pm 0.15$$

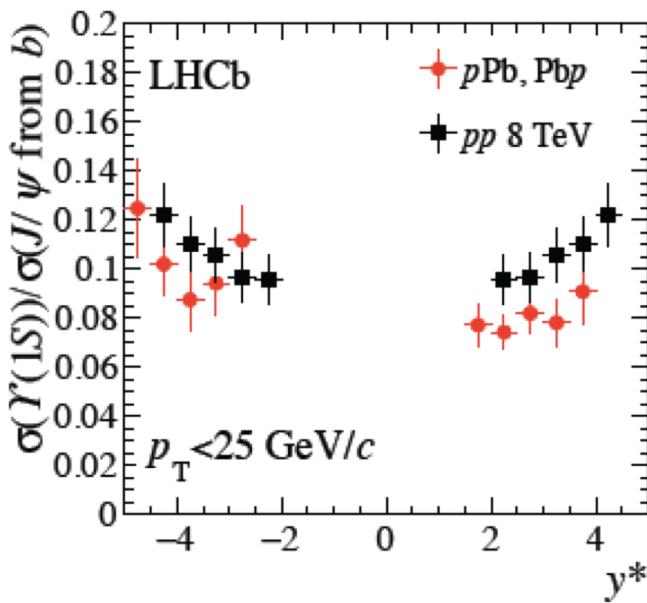
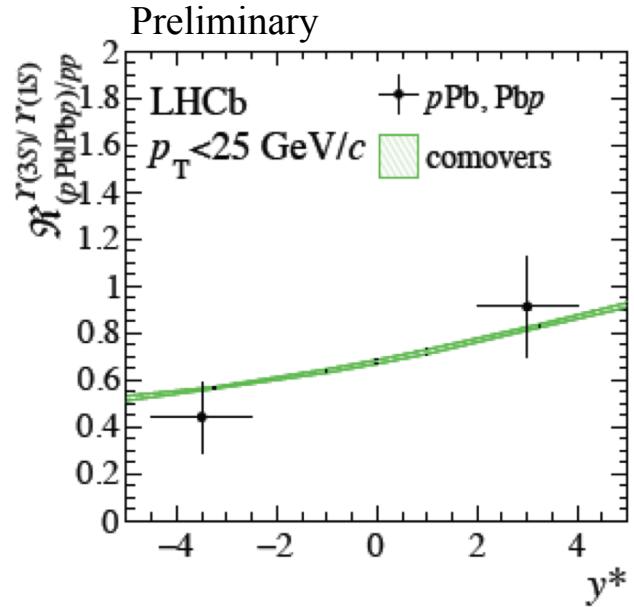
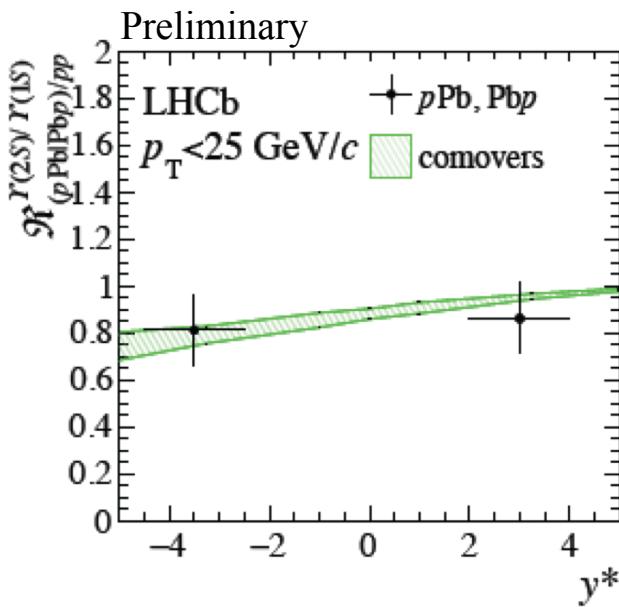


Double Ratios & open/hidden beauty

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

Double ratio of $\Upsilon(2S)$ and $\Upsilon(3S)$ over $\Upsilon(1S)$

- Consistent with the comovers model



Ratio of $\Upsilon(1S)$ over non-prompt J/ ψ

Integrated cross sections in the region

- $p_T < 25 \text{ GeV}/c$ and
 - $1.5 < y < 4.0$ ($-5.0 < y < -2.5$)
- for pPb (Pbp) sample

$$\sigma_{p\text{Pb}}^{T(1S)} = 22.8 \pm 0.9 \text{ (stat)} \pm 2.1 \text{ (syst)} \mu\text{b},$$

$$\sigma_{p\text{Pb}}^{T(2S)} = 6.4 \pm 0.6 \text{ (stat)} \pm 0.8 \text{ (syst)} \mu\text{b},$$

$$\sigma_{p\text{Pb}}^{T(3S)} = 2.5 \pm 0.4 \text{ (stat)} \pm 0.3 \text{ (syst)} \mu\text{b},$$

$$\sigma_{\text{Pbp}}^{T(1S)} = 20.3 \pm 0.8 \text{ (stat)} \pm 2.6 \text{ (syst)} \mu\text{b},$$

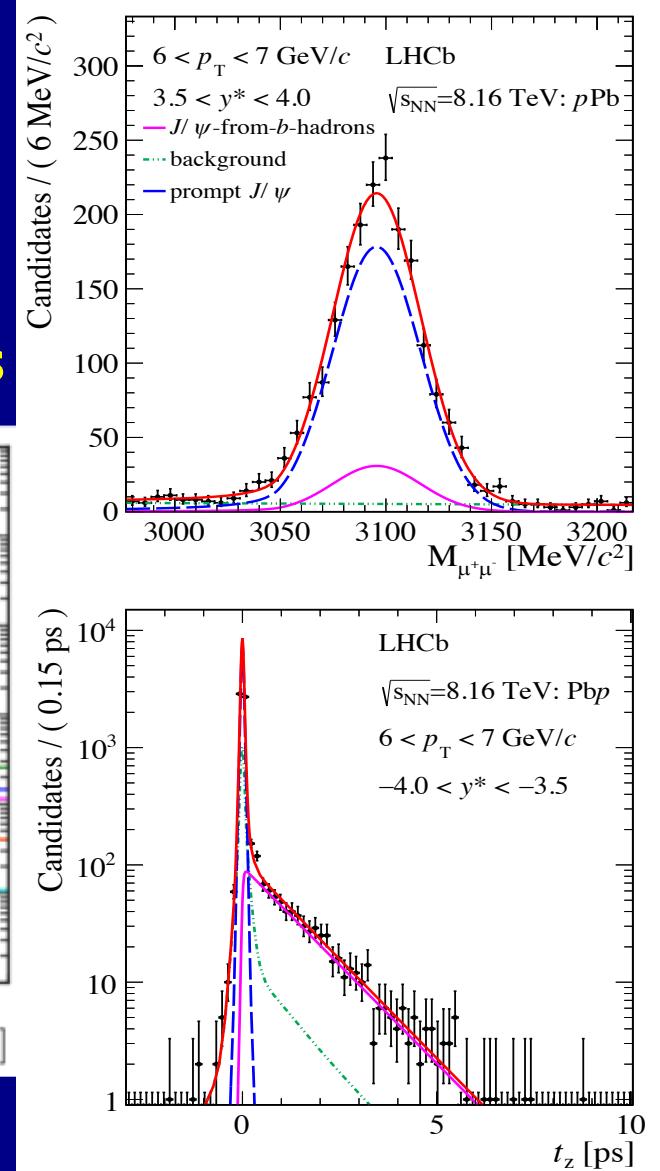
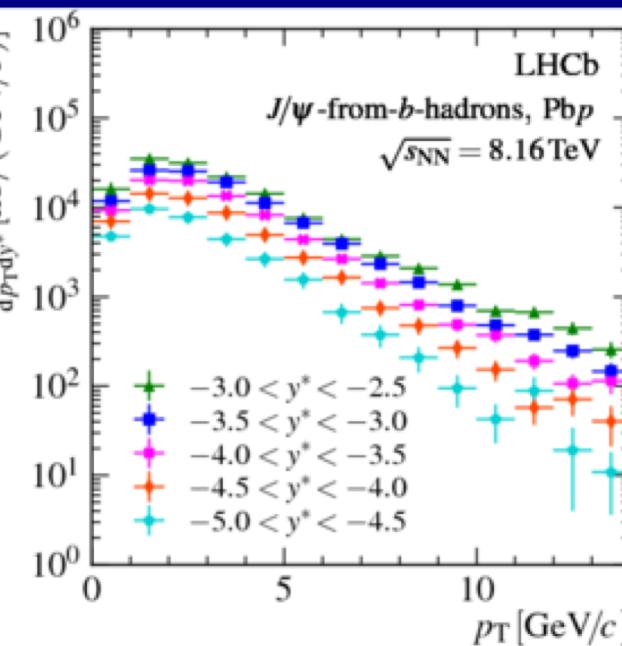
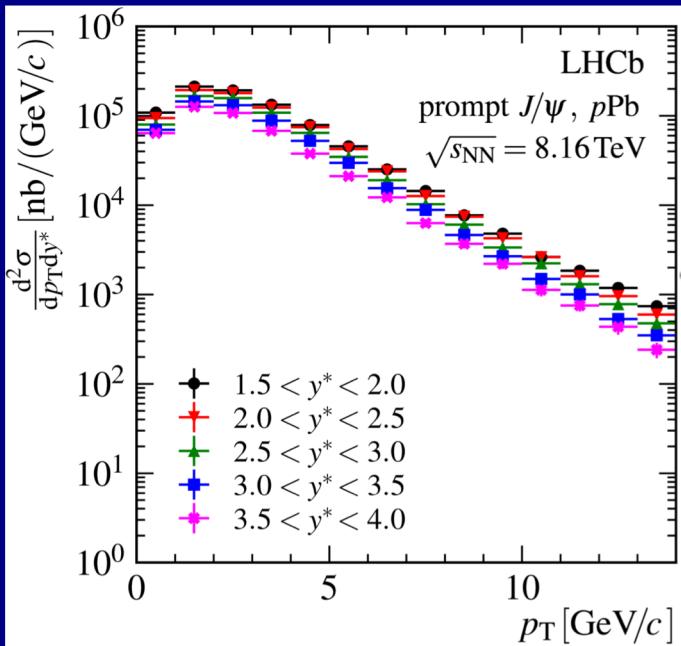
$$\sigma_{\text{Pbp}}^{T(2S)} = 6.0 \pm 0.5 \text{ (stat)} \pm 0.9 \text{ (syst)} \mu\text{b},$$

$$\boxed{\sigma_{\text{Pbp}}^{T(3S)} = 1.2 \pm 0.3 \text{ (stat)} \pm 0.2 \text{ (syst)} \mu\text{b.}}$$

J/ ψ analysis in pPb collisions

LHCb-PAPER-2017-014
PLB 774 (2017) 159

First analysis of run2 pPb sample !
 Double differential in y and p_T
 Prompt and non-prompt J/ ψ separated
 through pseudoproper time distribution
 Measured: double differential cross sections



J/ψ analysis in $p\text{Pb}$ collisions

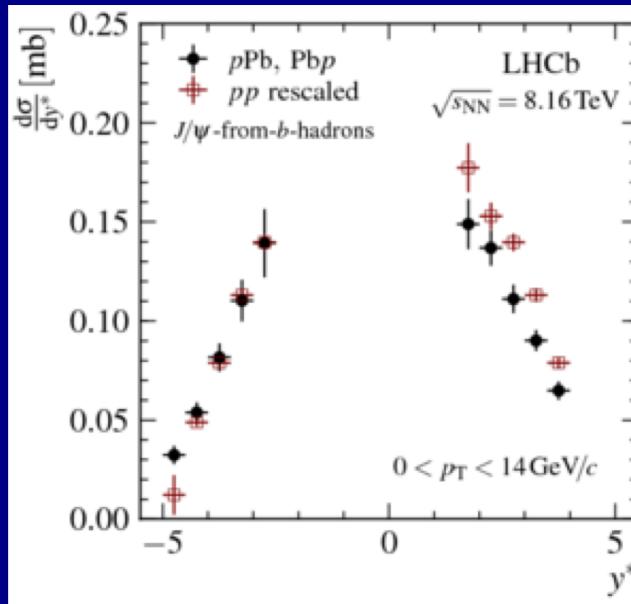
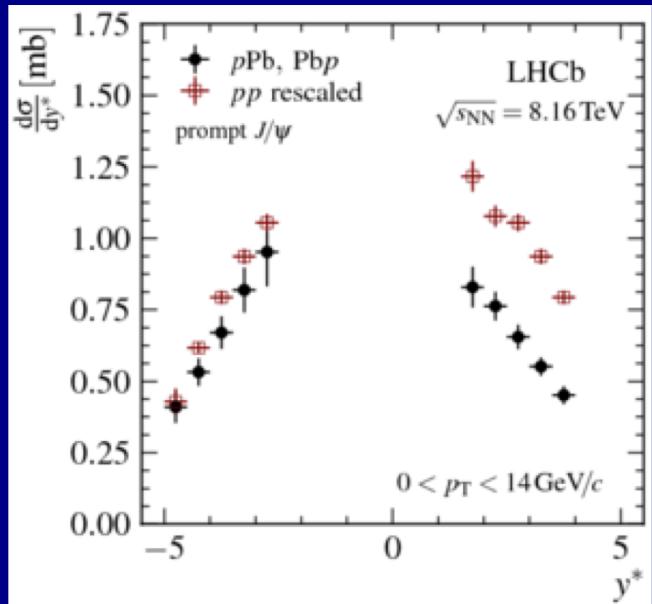
LHCb-PAPER-2017-014
PLB 774 (2017) 159

First analysis of run2 $p\text{Pb}$ sample !

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Measured: differential cross sections



Results compared with pp results properly scaled

J/ψ analysis in $p\text{Pb}$ collisions

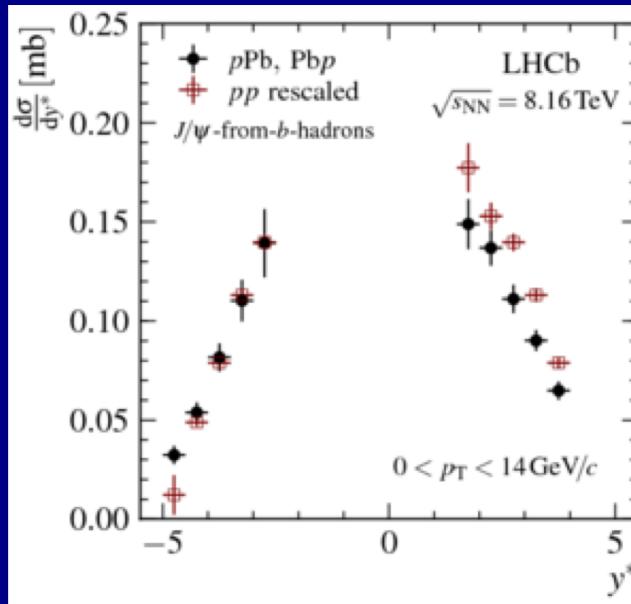
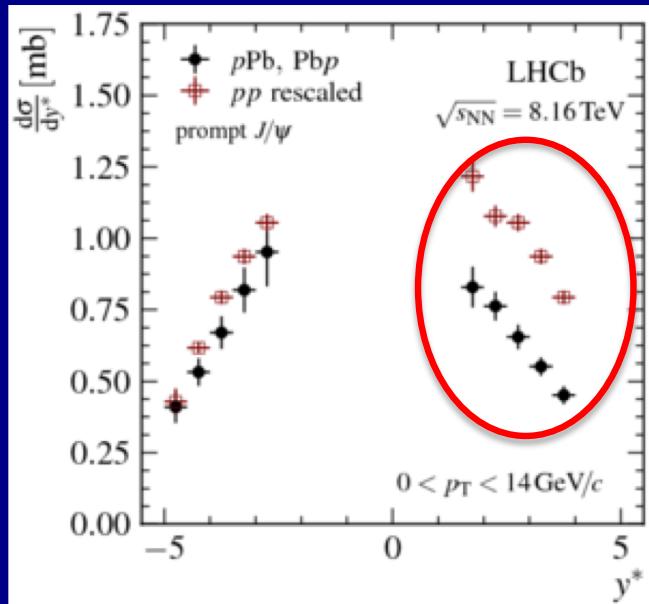
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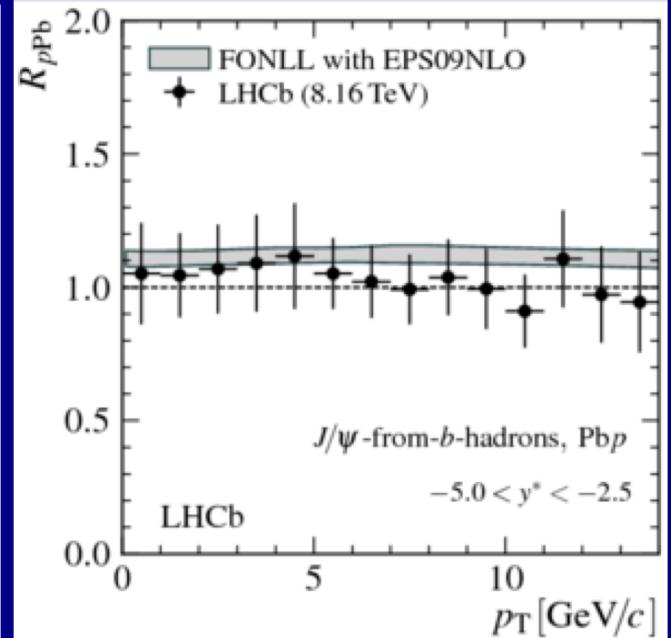
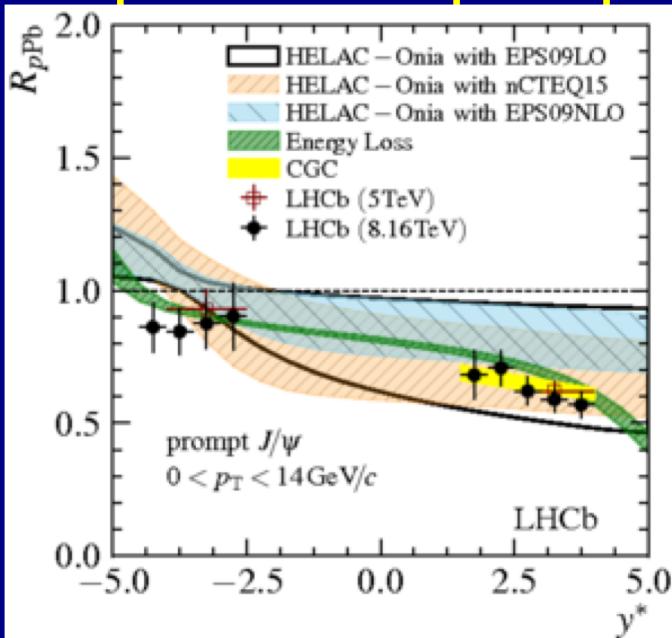
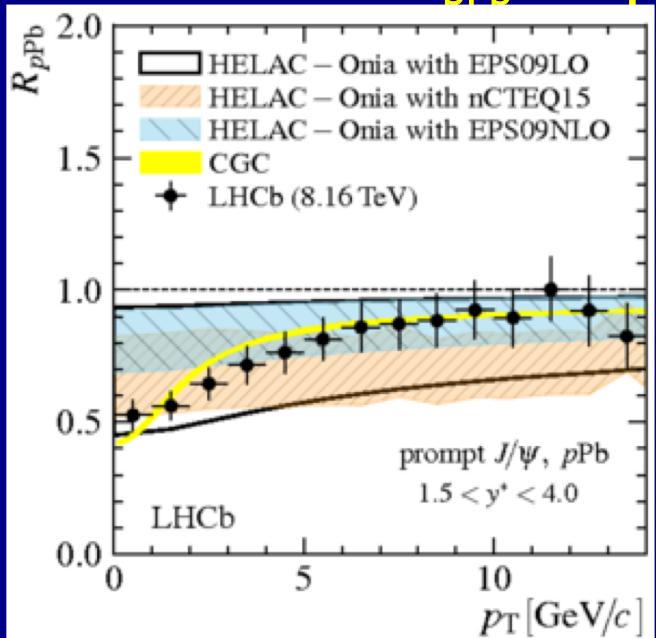
LHCb-PAPER-2017-014
PLB 774 (2017) 159

First analysis of run2 pPb sample !

Double differential in y and p_T

Prompt and non-prompt J/ψ separated through pseudoproper time distribution

Measured: $R_{p\text{Pb}}$ for prompt and non-prompt



MODELS:

HELAC: Eur. Phys. J. C77 (2017)1; Comput.Phys.Comm.184(2013) 2562, Comput. Phys. Comm.198 (2016) 238.

EPS09: JHEP 04 (2009) 065, arXiv:0902.4154.

nCTEQ15: Phys. Rev. D93 (2016) 085037.

EnergyLoss: JHEP 03 (2013) 122, arXiv:1212.0434.

CGC: Phys. Rev. D91 (2015) 114005

FONLL: JHEP 05(1998) 007, JHEP03 (2001) 006

J/ψ analysis in $p\text{Pb}$ collisions

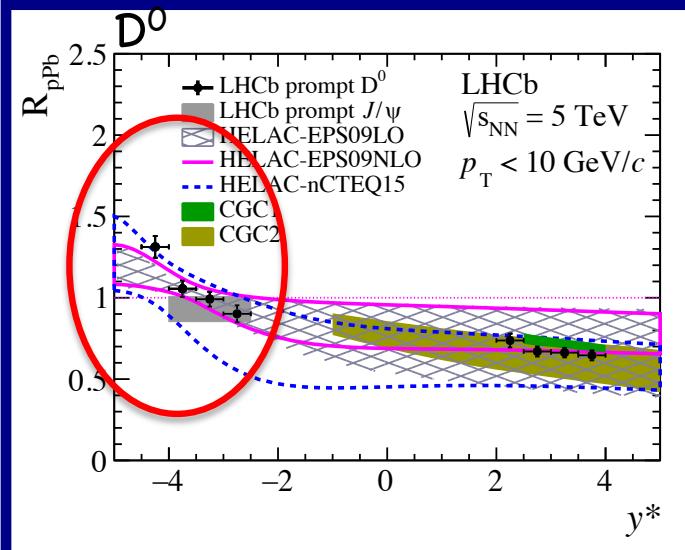
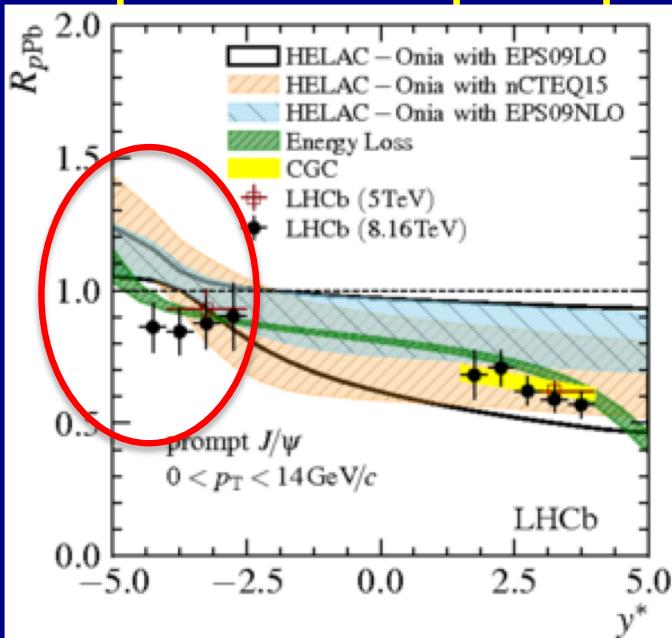
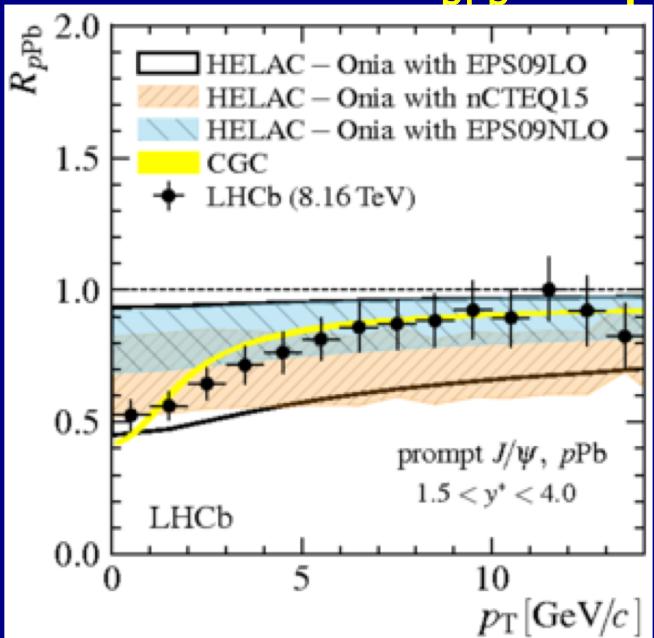
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First analysis of run2 pPb sample !

Double differential in y and p_T

Prompt and non-prompt J/ψ separated through pseudoproper time distribution

Measured: R_{pPb} for prompt and non-prompt



MODELS:

HELAC: Eur. Phys. J. C77 (2017) 1; Comput. Phys. Comm. 184 (2013) 2562, Comput. Phys. Comm. 198 (2016) 238.

EPS09: JHEP 04 (2009) 065, arXiv:0902.4154.

nCTEQ15: Phys. Rev. D93 (2016) 085037.

EnergyLoss: JHEP 03 (2013) 122, arXiv:1212.0434.

CGC: Phys. Rev. D91 (2015) 114005

FONLL: JHEP 05(1998) 007, JHEP03 (2001) 006

Summary and Outlook

LHCb successfully participated in pPb data-taking in 2016

- Collected good statistics → benefit from large data samples in 2016
- Measurement of J/ψ, Y performed, ψ(2S) and χ_c production upcoming & others ongoing
 - See also open beauty and charm results in Y.Zhang's talk on Thursday!

Results compared with several theoretical predictions, discussion with theorists ongoing

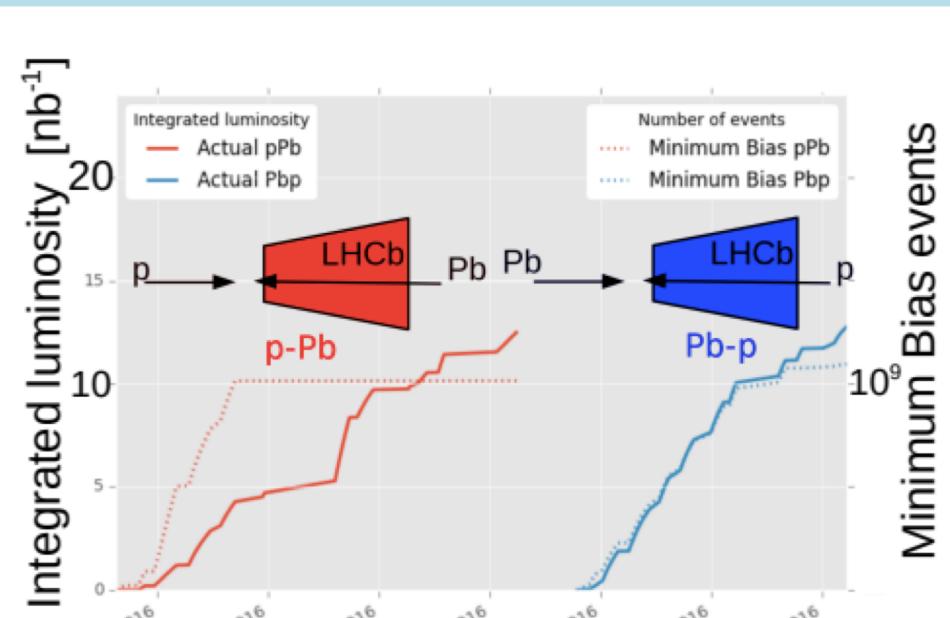
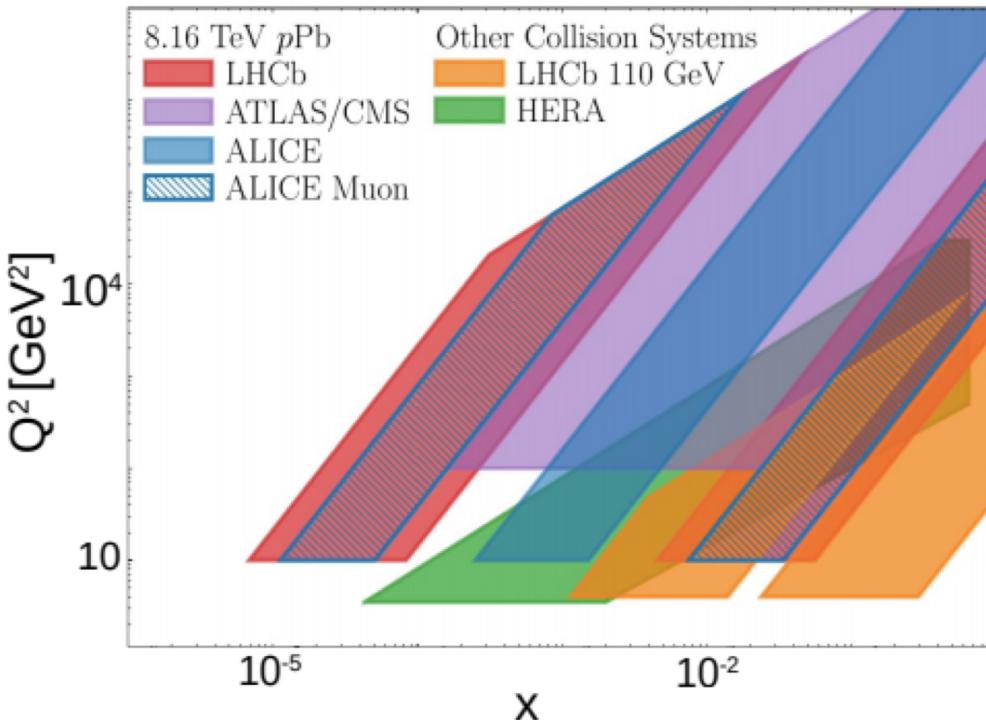
Many results also studied in view of the new detector in Run3/4

- Yellow report on the way *LHCb-TDR-12 – 17; CERN-LHCC-2018-026; LHCb-TDR-019*

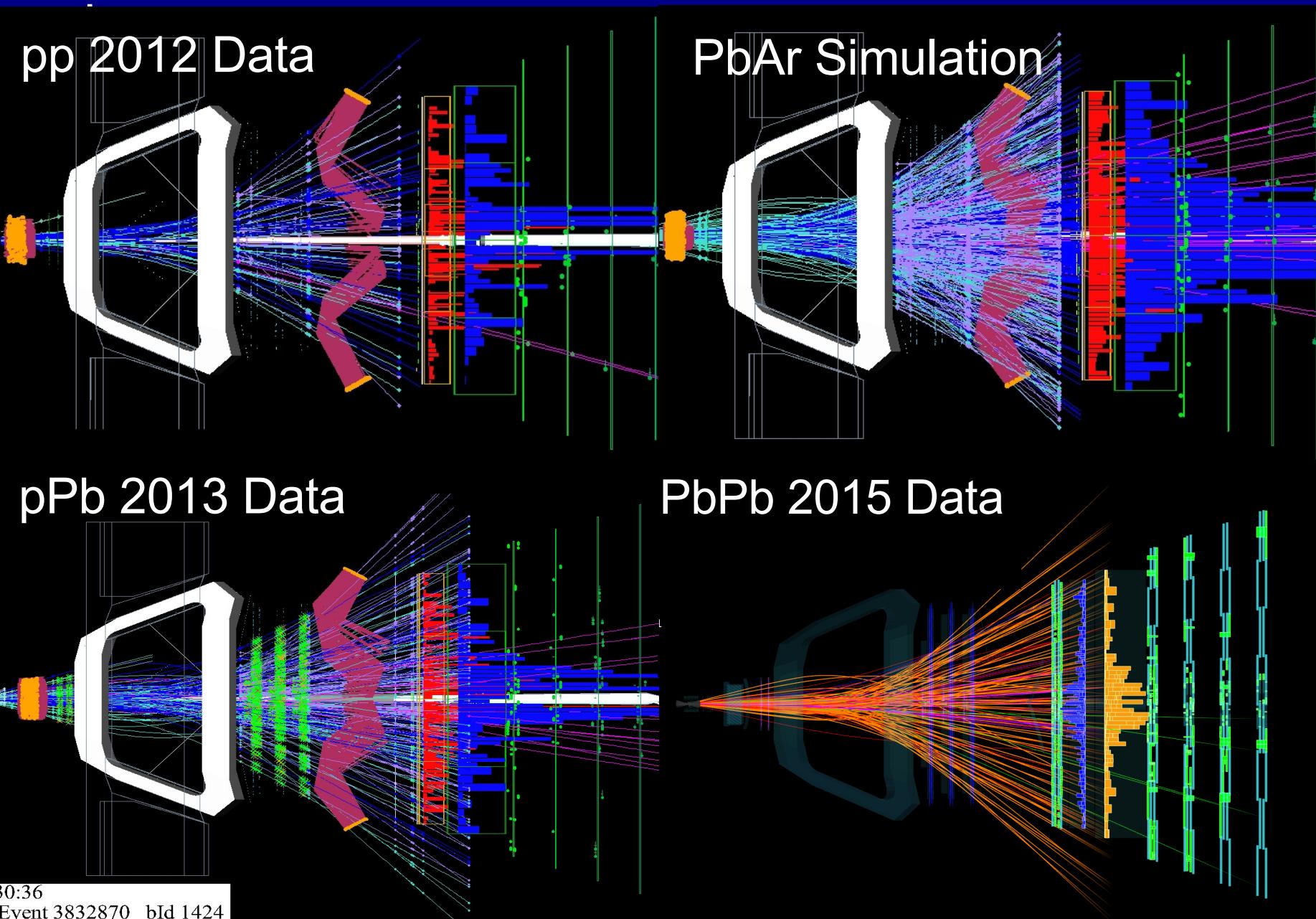


Back up

Running in pPb

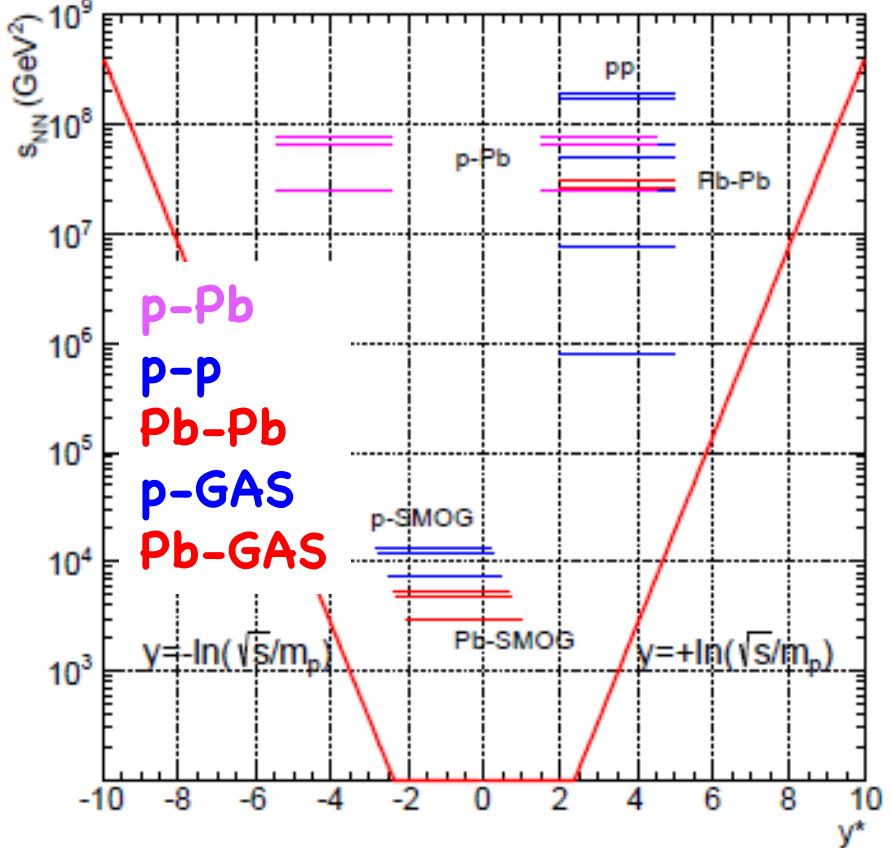


Multiplicities



Phase Space Coverage and Running Modes

Kinematic acceptance & (existing/future) beam-target combinations



y^* : rapidity in nucleon-nucleon centre-of-mass system, with forward direction (positive values) in direction of the proton/beam

$E_{\text{beam}}(p)$	pp	p-GAS	p-Pb/Pb-p	Pb-GAS	Pb-Pb
450 GeV	0.90 TeV				
1.38 TeV	2.76 TeV				
2.5 TeV	5 TeV	69 GeV			
3.5 TeV	7 TeV				
4.0 TeV	8 TeV	87 GeV	5 TeV	54 GeV	
6.5 TeV	13 TeV	110 GeV	8.2 TeV	69 GeV	5.1 TeV
7.0 TeV	14 TeV	115 GeV	8.8 TeV	72 GeV	5.5 TeV

p/Pb-GAS operation so far:

Collisions	\sqrt{s} (GeV)	Length	# p on target	Year
pHe	87	84 h	4.6×10^{22}	2016
pHe	110	18 h	3×10^{21}	2016
pNe	110	12 h	1×10^{21}	2015
pHe	110	8 h	2×10^{21}	2015
pAr	110	17 h	4×10^{22}	2015
PbAr	69	100 h	2×10^{20}	2015
pNe (pilot run)	87	30 m		2012
PbNe(pilot run)	54	30 m		2013

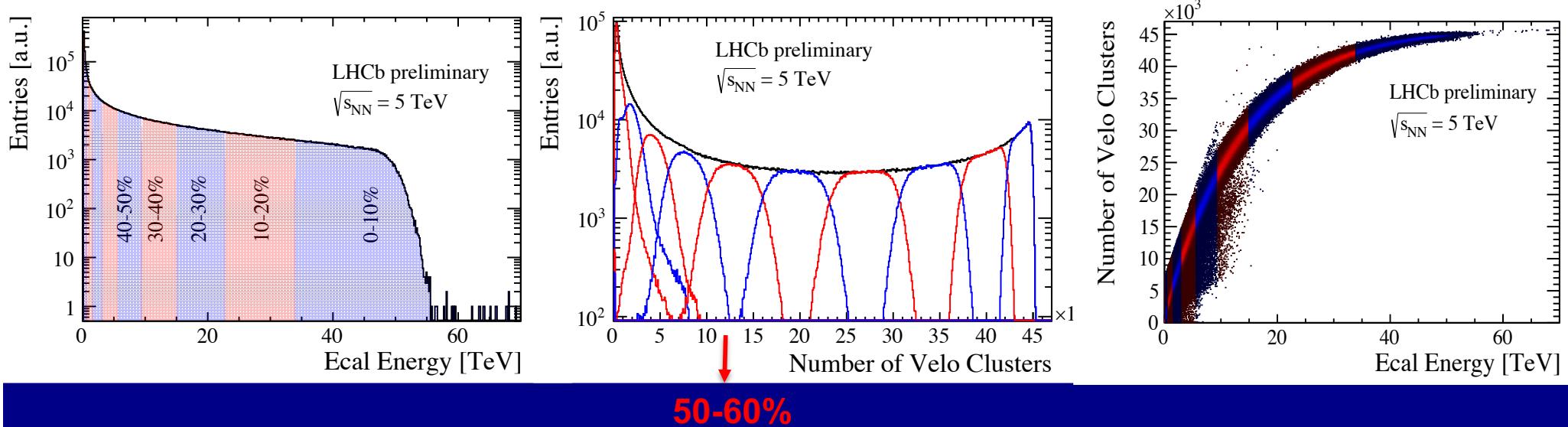
Centrality Determination in LHCb

<https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015>

Crucial variable for physics measurements

We use energy deposition in electromagnetic calorimeter (as well as number of VELO clusters)

Definition of Ecal event “activity classes” first step towards centrality determination



PbPb data studies are ongoing

Large multiplicities observed are new for LHCb and the detector response needs to be understood in detail

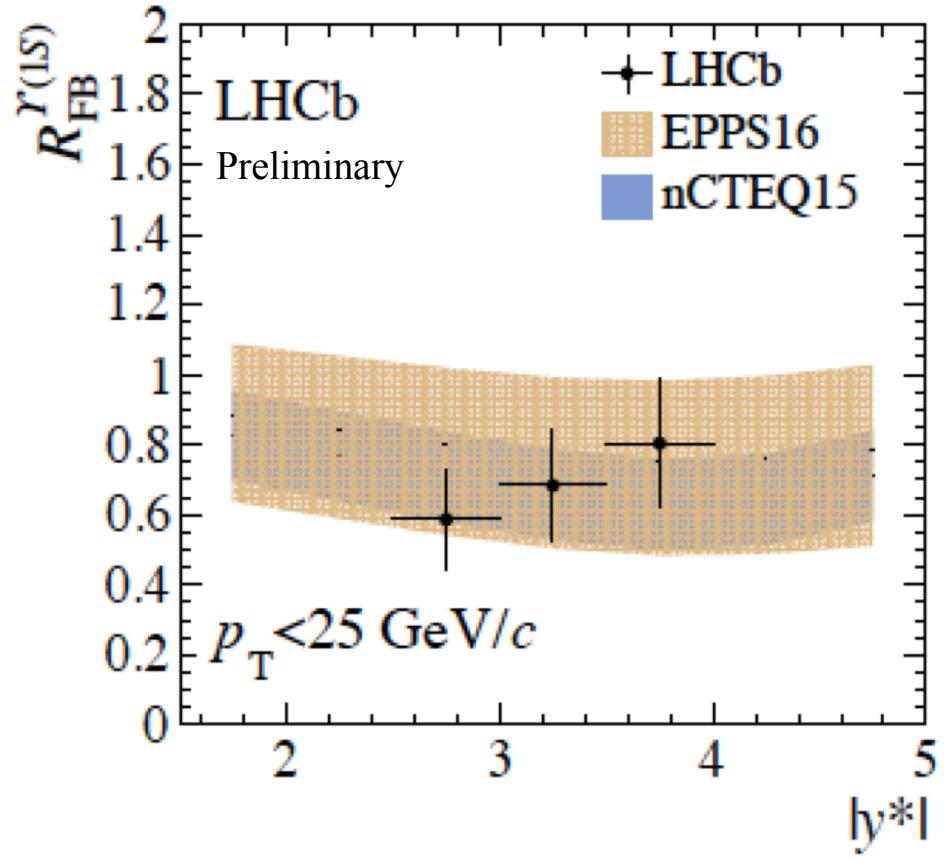
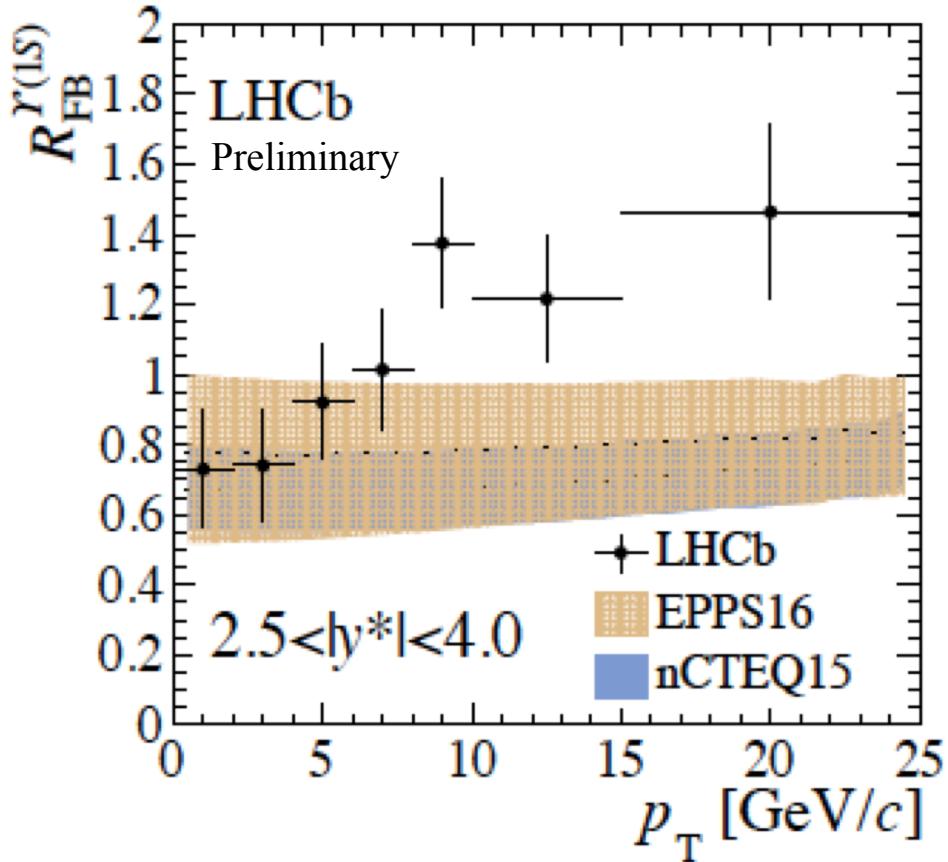
$\gamma(1S)$ Forward-Backward Asymmetry

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To be submitted to JHEP

$$R_{\text{FB}}(p_T, |y^*|) = \frac{d^2\sigma_{p\text{Pb}}(p_T, +|y^*|)/dp_T dy^*}{d^2\sigma_{\text{Pbp}}(p_T, -|y^*|)/dp_T dy^*}$$

For back-up

As a function of p_T and y^*



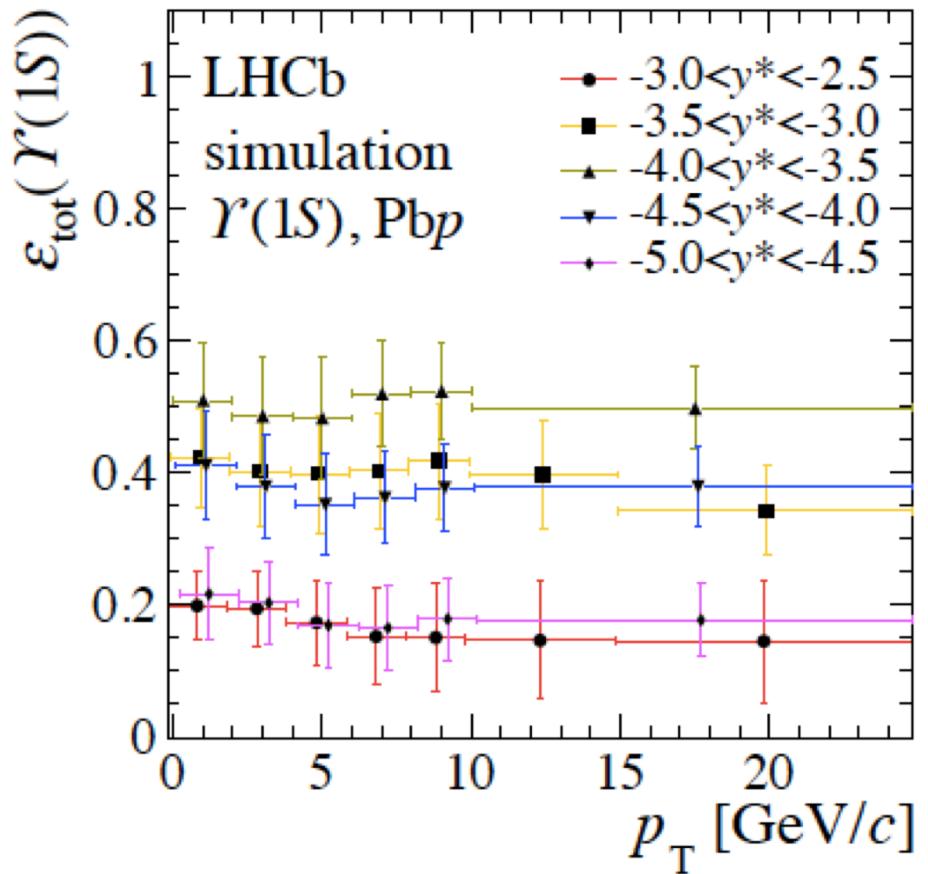
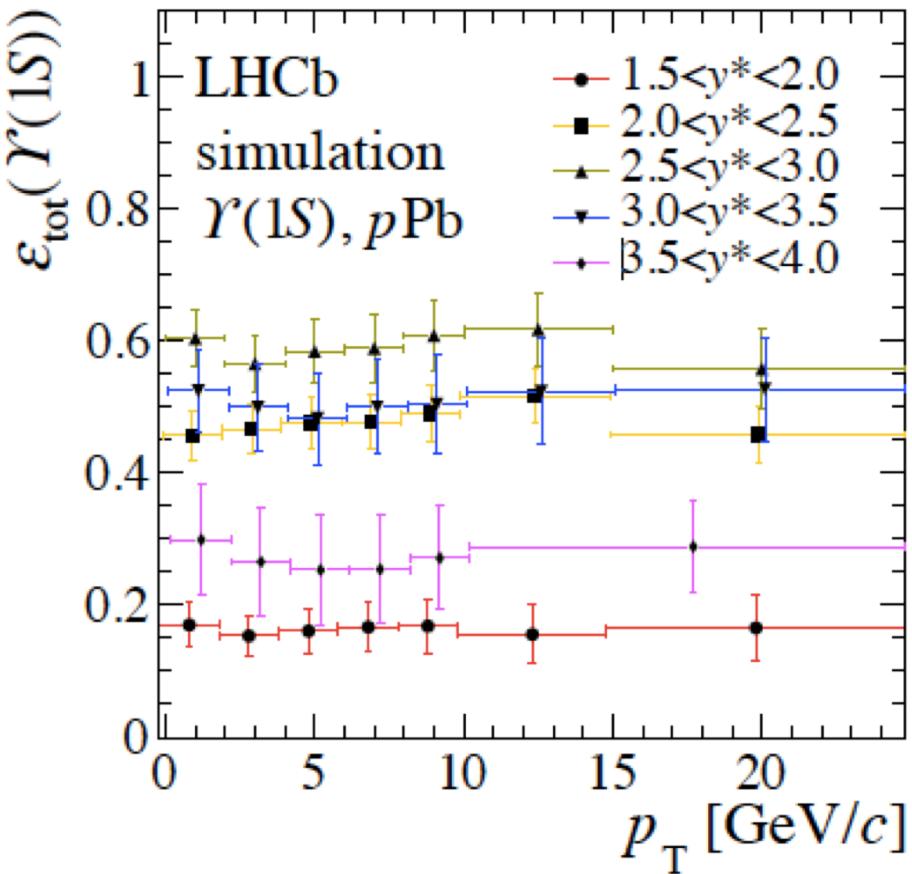
$\gamma(nS)$ analysis in $p\text{Pb}$ collisions

LHCb-PAPER-2018-035
To be submitted to JHEP

Efficiencies

- Measured with proton-lead simulation
- Factorised as

$$\varepsilon_{\text{tot}} = \varepsilon_{\text{acc}} \times \varepsilon_{\text{trk}} \times \varepsilon_{\text{sel}} \times \varepsilon_{\text{ID}} \times \varepsilon_{\text{trigger}}$$



$\Upsilon(nS)$ analysis in $p\text{Pb}$ collisions

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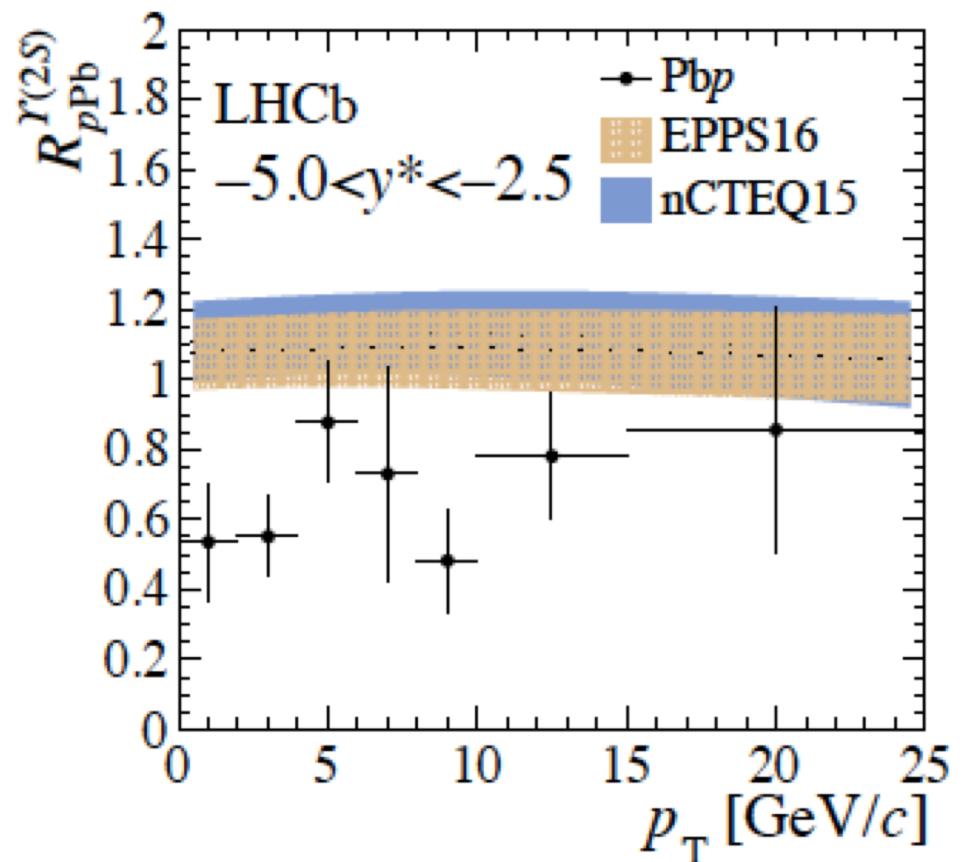
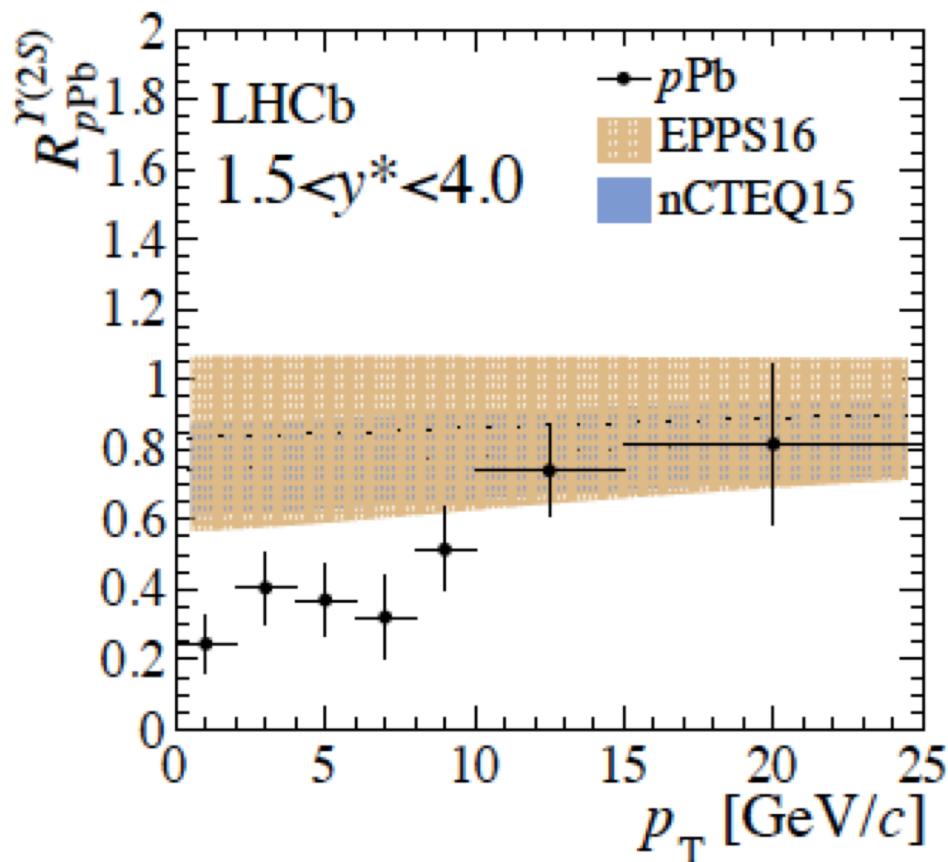
Systematic uncertainties

Table 2: Sources of the systematic uncertainty on the cross-section measurements. The range is the minimum and maximum value in different bins, for all $\Upsilon(nS)$ states.

Source	$p\text{Pb}$	Pbp
Acceptance	0.7% – 3.4%	0.5% – 3.5%
Reconstruction efficiency	2.1% – 7.9%	2.5% – 8.1%
Offline selection efficiency	0.1% – 0.8%	0.1% – 1.4%
PID efficiency	1.1% – 4.4%	1.9% – 6.0%
Trigger efficiency	2.0% – 2.8%	2.0% – 2.4%
Signal extraction	5.7%	5.7%
Branching ratio	2.0% – 9.6%	2.0% – 9.6%
Luminosity	2.6%	2.5%

$\gamma(2S)$ nuclear mod factor

Integrated over y^* as a function of p_T



J/ψ analysis in $p\text{Pb}$ collisions

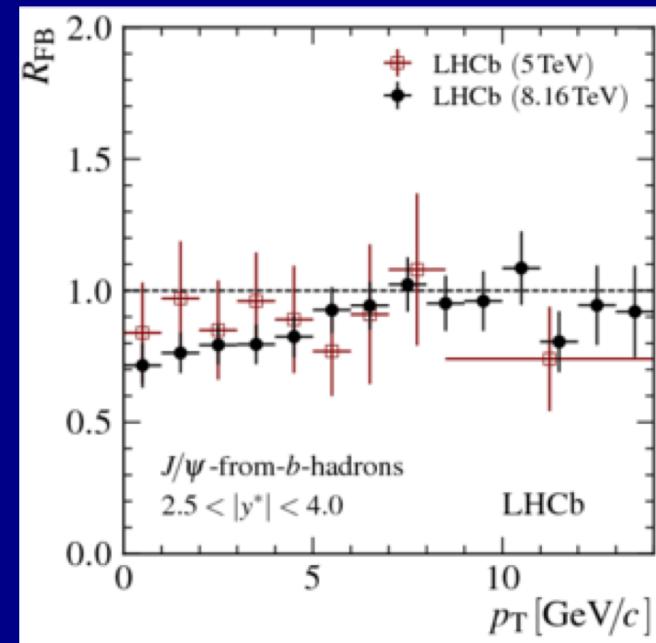
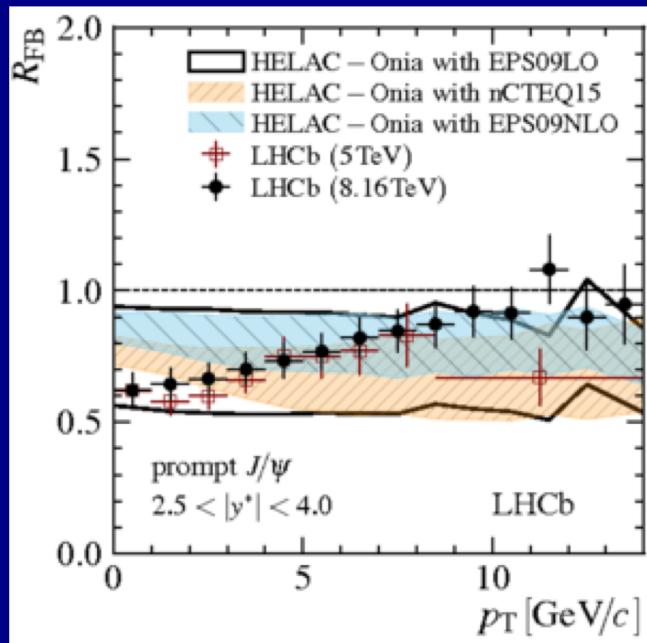
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First analysis of run2 $p\text{Pb}$ sample !

Double differential in y and p_T

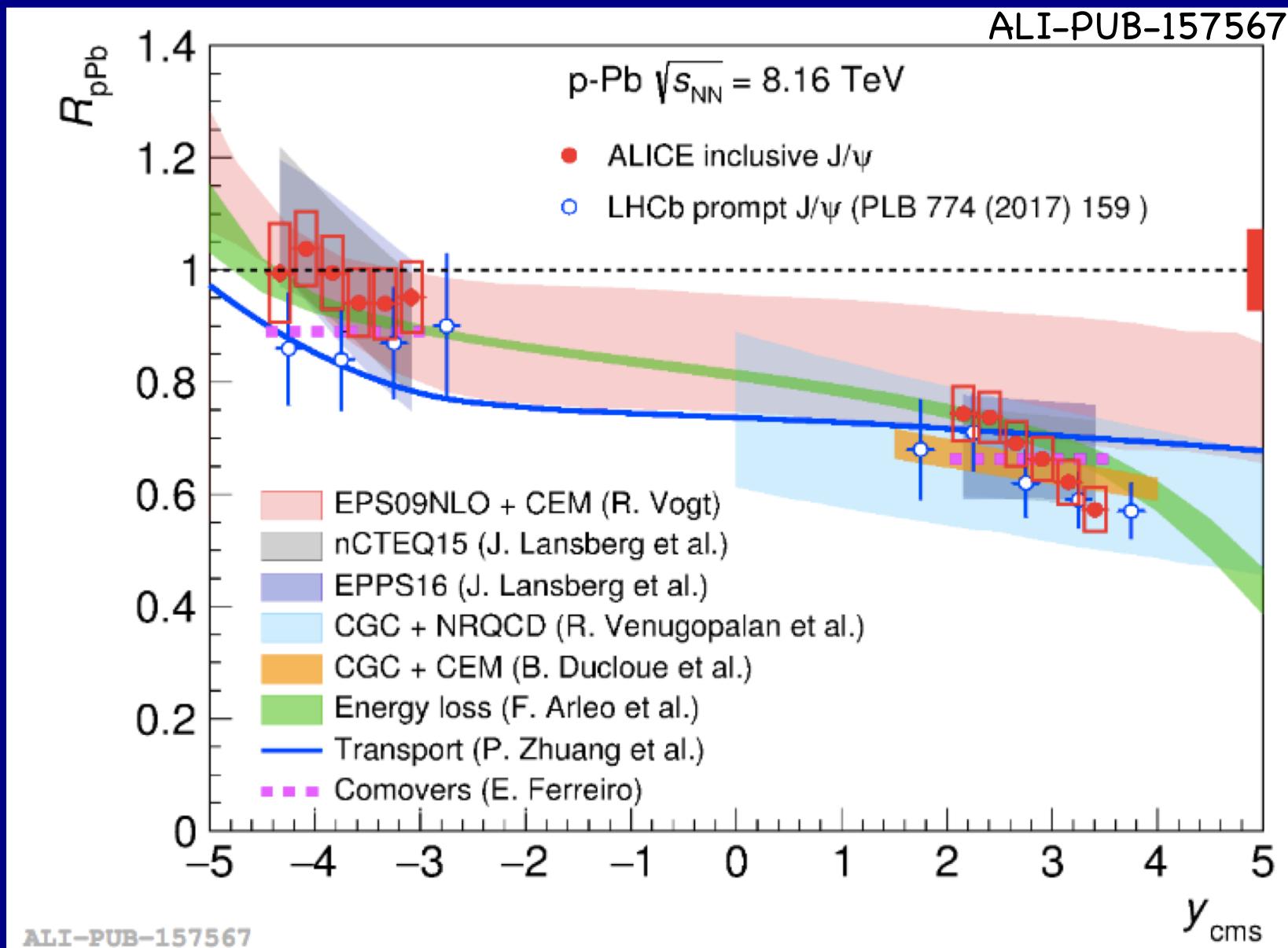
Prompt and non-prompt J/ψ separated through pseudoproper time distribution

Measured: R_{FB} for prompt and non-prompt



Overall suppression is observed at low momentum
 $\psi(2S)$ measurement in the pipeline in this sample

Comparison with ALICE



J/ψ analysis in $p\text{Pb}$ collisions

[arXiv:1706.07122](https://arxiv.org/abs/1706.07122)

First analysis of run2 pPb sample !
Double differential in y and $p\text{T}$
prompt and delayed J/ψ separated
through pseudoproper time distribution
measured R_{pPb}

