LHCb results from proton-ion collisions

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Outline

- ❑ **The LHCb detector**
- ❑ **The p-Pb and Pb-p data taking**
- ❑ **Physics motivations for proton-nucleus studies**
- ❑ **Results from the pPb and Pbp data taking of 2013**
    - J/ψ production
    - $\psi(2S)$ production
    - $\Upsilon(nS)$ production
    - Z production
    - Two particle angular correlations
- ❑ **Conclusions and prospects for heavy ion studies**

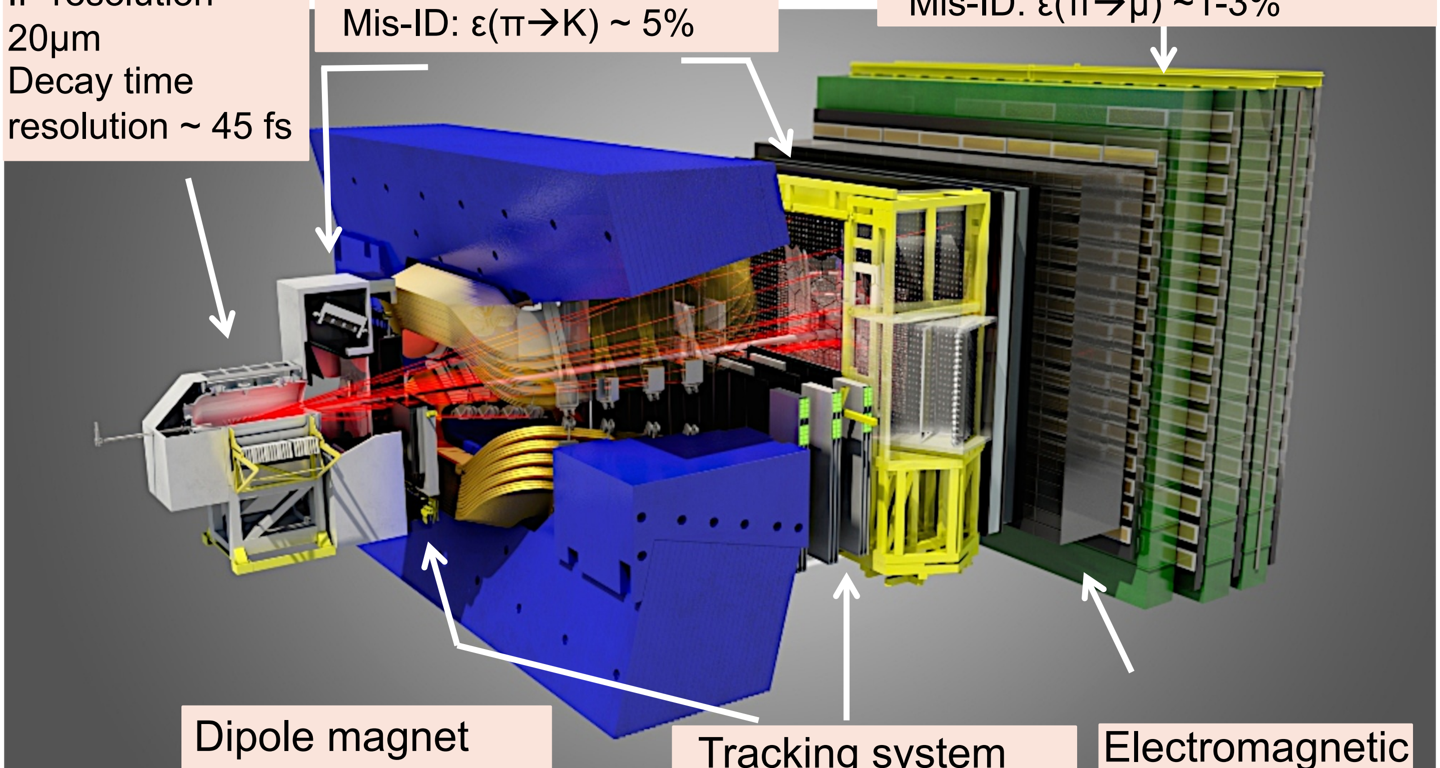
The LHCb detector

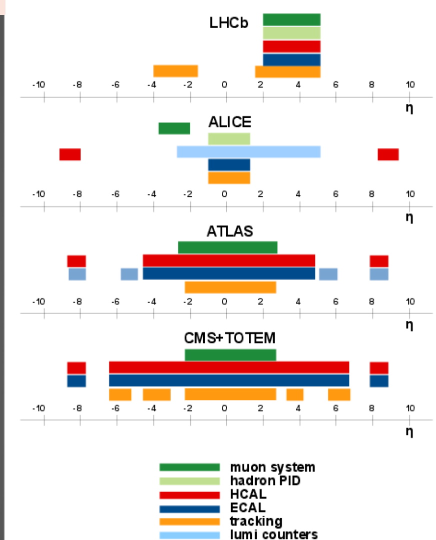
- Single arm spectrometer in the forward region
- Fully instrumented in its angular acceptance
- Pseudorapidity coverage $2 < \eta < 5$
- Designed initially for b-physics but general purpose detector (fixed target collisions, heavy ion physics program…)

Vertex detector
IP resolution ~ 20μm
Decay time resolution ~ 45 fs

RHIC: K/π/p separation
ε(K→K) ~ 95%
Mis-ID: ε(π→K) ~ 5%

Muon system
μ identification: ε(μ→μ) ~ 97%
Mis-ID: ε(π→μ) ~1-3%





Dipole magnet
Bending power 4 Tm

Tracking system
Δp/p = 0.4% - 0.8%
(5 GeV/c – 100 GeV/c)

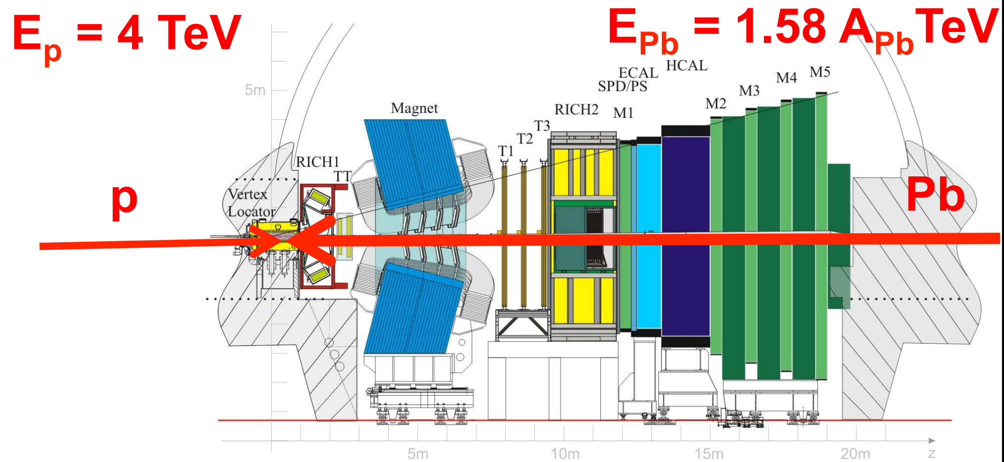
Electromagnetic + hadronic calorimeters

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

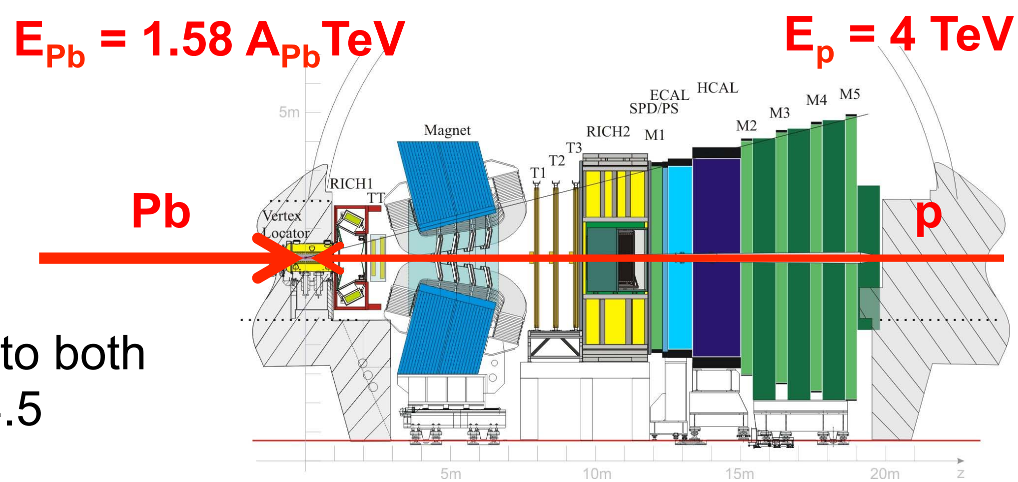
The p-Pb and Pb-p data taking

- p-Pb and Pb-p data collected at a nucleon-nucleon center of mass energy $\sqrt{s_{NN}}$ = 5 TeV
- Asymmetric beams: nucleon-nucleon center-of-mass system shifted by Δy = 0.47 in the direction of the p beam

p + Pb collisions (forward)
Rapidity coverage: $1.5 < y_{CMS} < 4.5$
2013 data sample: $L_{int} = 1.1\ nb^{-1}$
→ Applies to all analyses unless specified



Pb + p collisions (backward)
Rapidity coverage: $-5.5 < y_{CMS} < -2.5$
2013 data sample: $L_{int} = 0.5\ nb^{-1}$
→ Applies to all analyses unless specified



Rapidity coverage in common to both configurations: $2.5 < |y_{CMS}| < 4.5$

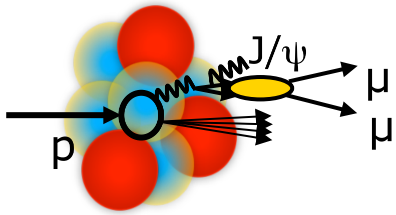
Physics motivation for proton-nucleus studies

Proton-nucleus collisions are interesting by themselves but also provide reference for heavy ion studies

Heavy flavours and Quarkonia as tools to study cold nuclear matter effect (CNM)
→ Necessary reference to disentangle QGP effects from CNM effects in AA collisions

Initial state effects

- **Nuclear shadowing = gluon shadowing at LHC [1]**
- **Parton saturation / CGC [2]**
- **Radiative energy loss [3]**
- **Cronin effects [4]**



Final state effects

- **Nuclear absorption [6]:Expected to be small at LHC [7]**
- **Radiative energy loss [8]**
- **Comovers [9]**

Neither initial nor final

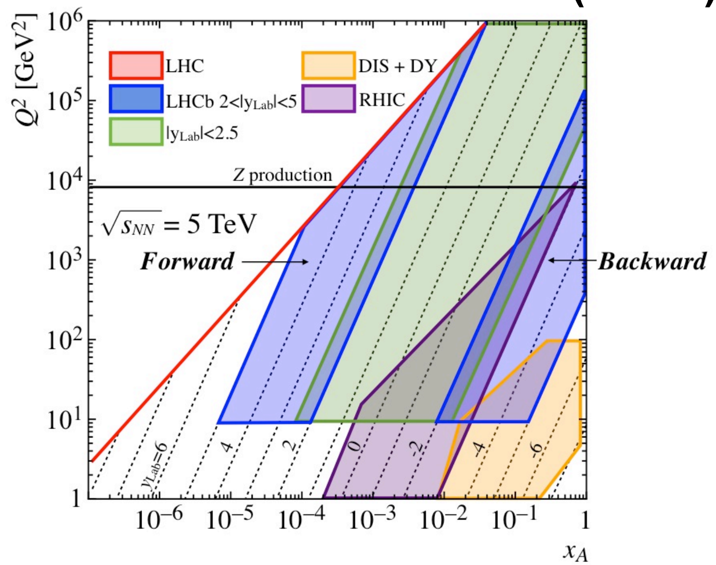
- **Coherent energy loss[5]**

[1] K.J. Eskola et al., JHEP 0904 (2009) 065.
[2] D. Kharzeev et al., Nucl. Phys. A770 (2006) 40.
[3] S. Gavin et al., Phys. Rev. Lett. 68 (1992) 1834.
[4] J. W. Cronin et al., Phys. Rev. D, 11:3105, 1975.
[5] F. Arleo et al., Phys. Rev. Lett. 109 (2012) 122301.
[6] R. Vogt, Nucl. Phys. A700 (2002) 539.
[7] C. Lourenco et al., JHEP 0902.014, 2009.
[8] R. Vogt, Phys. Rev. C61 (2000) 035203
[9] E. Ferreiro, arXiv:1411.0549v2

Physics motivation for proton-nucleus studies

Z boson production to constrain the nuclear parton distribution functions (nPDF)

LHCb in p+Pb and Pb+p probes two different regions in x-Q^2
Complementary measurement to ATLAS/CMS



Sensitivity to nuclear PDF at large x_A (10^{-1}), and low x_A (10^{-4})

Two-particle correlations to probe collective effects in the dense environment of high energy collisions

Highest particle density and multiplicities reached in pp and pA at LHC of similar size to that of non central AA collisions

LHCb can investigate at forward rapidity the long-range correlation on the near side («the ridge») which was observed in pp, pPb (and PbPb) at mid-rapidity $|\eta|< 2.5$

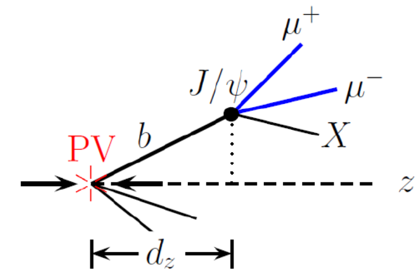
Results from the p-Pb and Pb-p data taking of 2013

J/ψ production in p-Pb and Pb-p

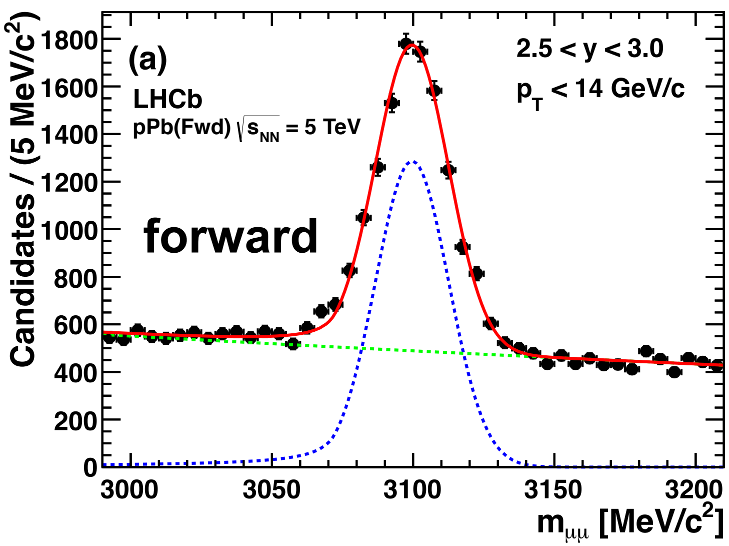
JHEP 02 (2014) 072

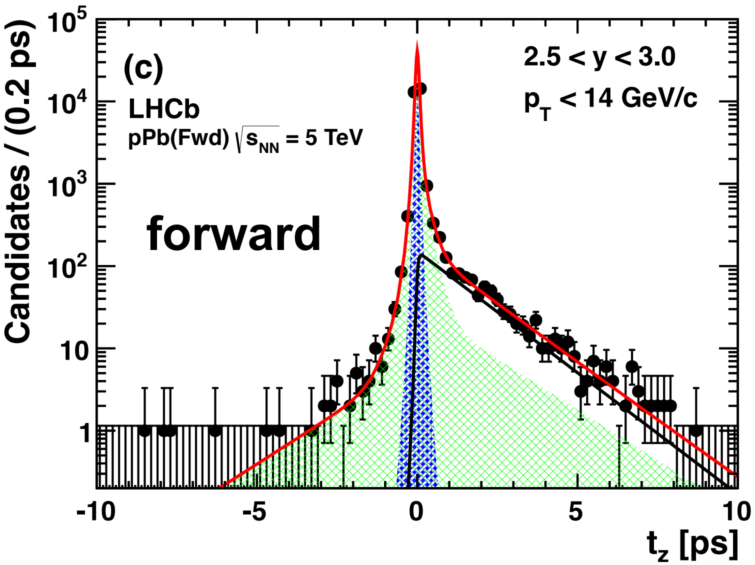
- J/ψ are reconstructed from two well identified muons
- Disentangle prompt J/ψ from J/ψ from b using pseudo-proper time:

$$t_Z = \frac{(Z_{J/\Psi} - Z_{PV}) \times M_{J/\Psi}}{p_z}$$



- Yields of prompt J/ψ and J/ψ from b extracted from simultaneous fit of mass and pseudo-proper time





Mass distribution:

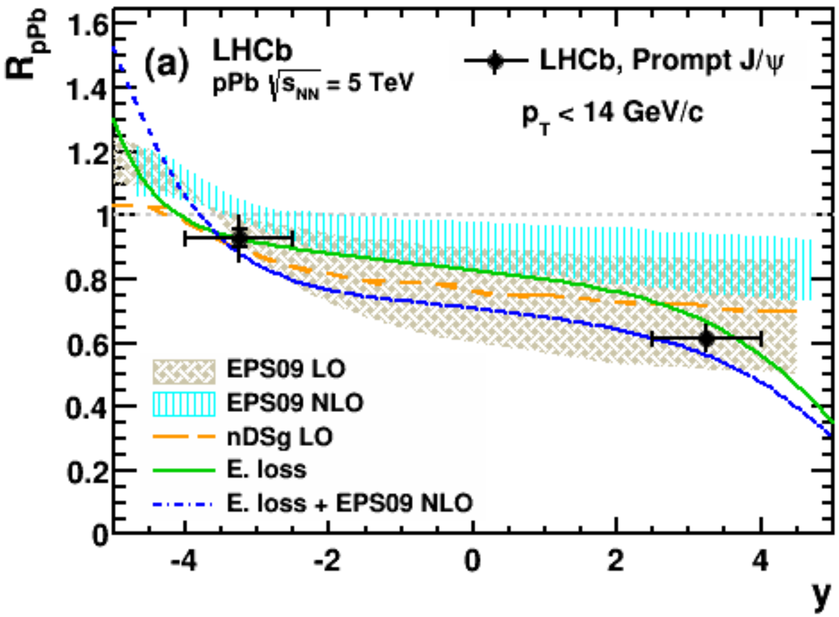
- Signal: Crystal-Ball function
- Background: Exponential

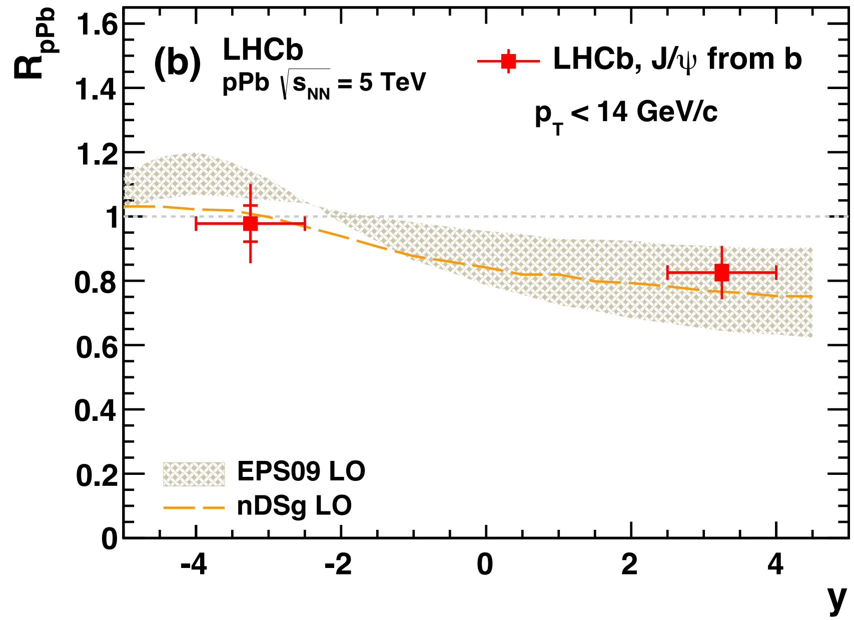
t_Z distribution:

- Signal: - $\delta(t_z)$ for prompts J/ψ (blue curve)
  - Exponential for J/ψ from b (black line)
- Background: Empirical function from sideband (green hatched)

J/ψ nuclear modification factor (R_{pPb}) JHEP 02 (2014) 072

- $R_{pPb}(y) = (1/A) \times (d\sigma_{pA}/dy)/(d\sigma_{pp}/dy)$ in the common range $2.5 < |y_{CMS}| < 4.0$





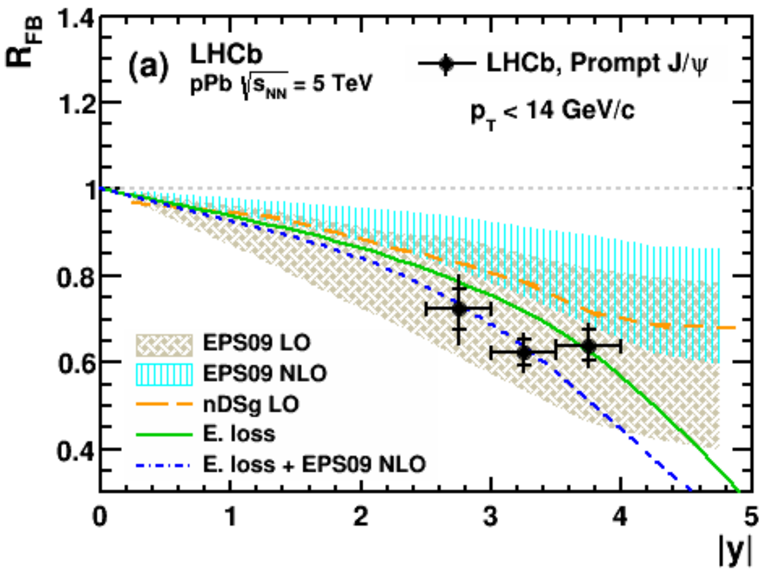
Prompt J/ψ: strong suppression at forward y (strong CNM effect)
→ Data well described by coherent energy loss models (w and w/o shadowing)
J/ψ from b: small suppression in the forward region
→ first indication of suppression of b hadron production

Models: EPS09LO (CSM): PRC88 (2013) 047901; NPA 926 (2014) 236
EPS09LNO (shadowing + CEM): IJMP E22 (2013) 1330007
Energy Loss: JHEP 03 (2013) 122; JHEP 05 (2013) 155
nDSg LO: PRC88 (2013) 047901

J/ψ forward to backward ratio (R_{FB})

JHEP 02 (2014) 072

- $R_{\mathrm{FB}}(y) = (\mathrm{d}\sigma_{\mathrm{pA}}/\mathrm{d}y)/(\mathrm{d}\sigma_{\mathrm{Ap}}/\mathrm{d}y)$ in common range $2.5 < |y_{CMS}| < 4.0$



Rapidity dependence:

Prompt J/ψ: Clear forward-backward asymmetry

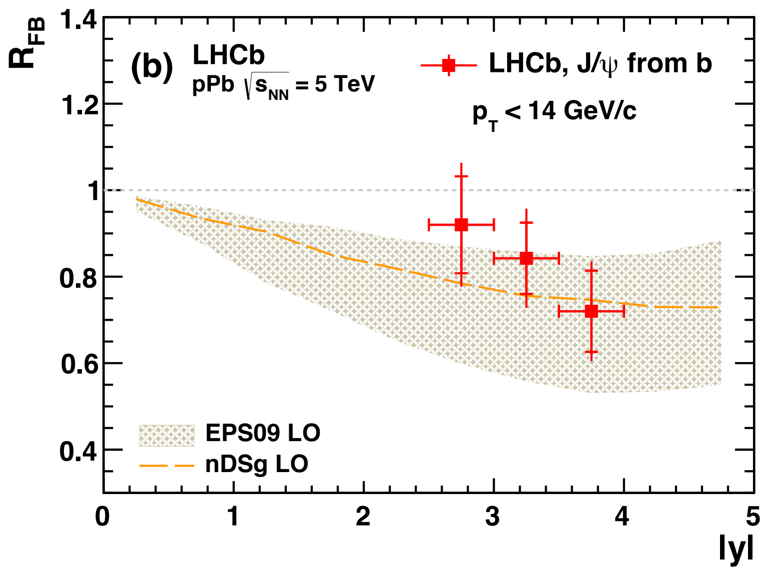
→ More statistics needed to distinguish between models

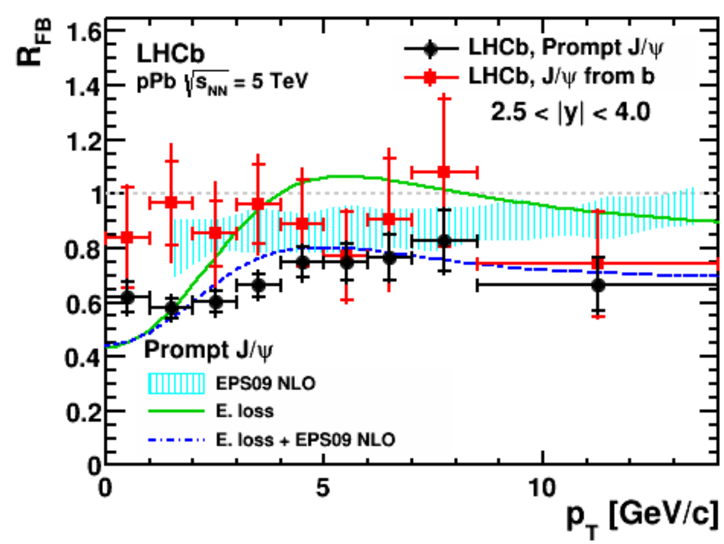
J/ψ from b: Small forward-backward asymmetry

p_T dependence:

Prompt J/ψ : forward backward asymmetry agrees best with eloss + shadowing (except at low p_T)

J/ψ from b: R_{FB} close to 1



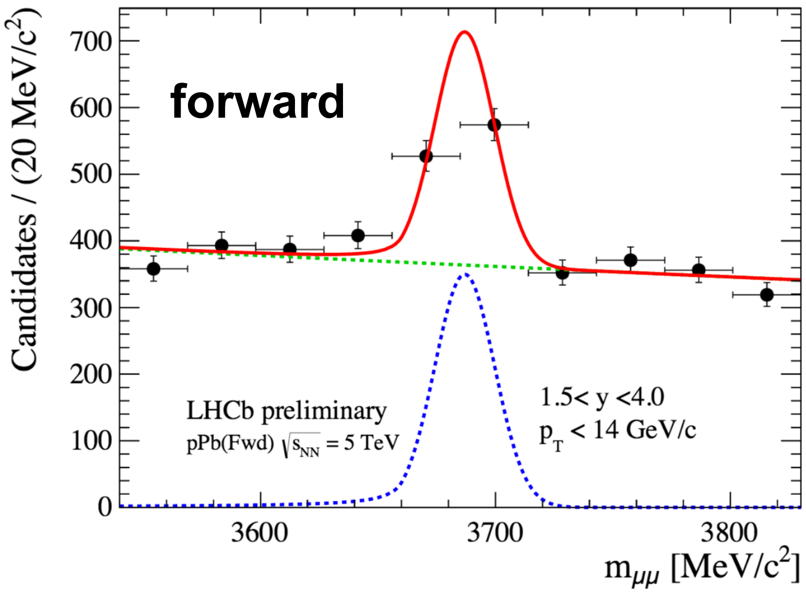


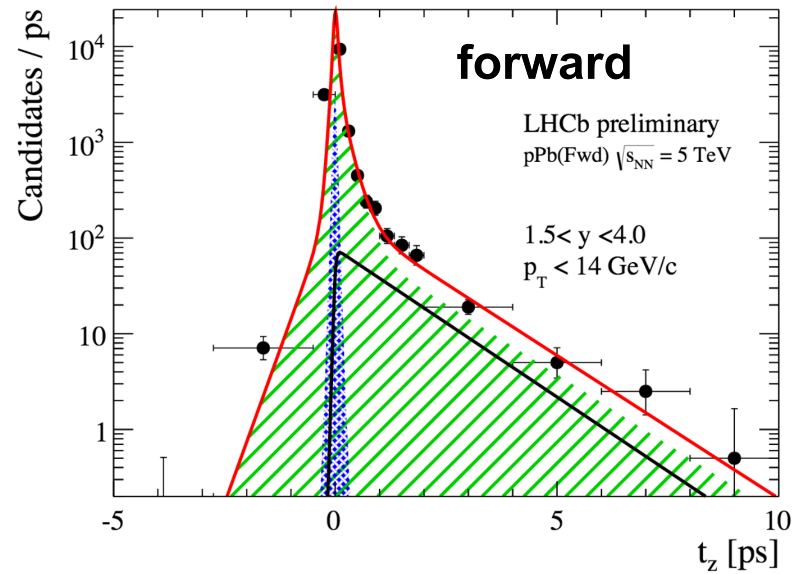
Ψ(2S) production in p-Pb and Pb-p

NEW

LHCb-CONF-2015-005

- Similar analysis strategy as for the J/ψ
- Yields of prompt ψ(2S) and ψ(2S) from b extracted from simultaneous fit of mass and pseudo-proper time





Mass distribution:

- Signal: Crystal-Ball function
- Background: Exponential

t_z distribution:

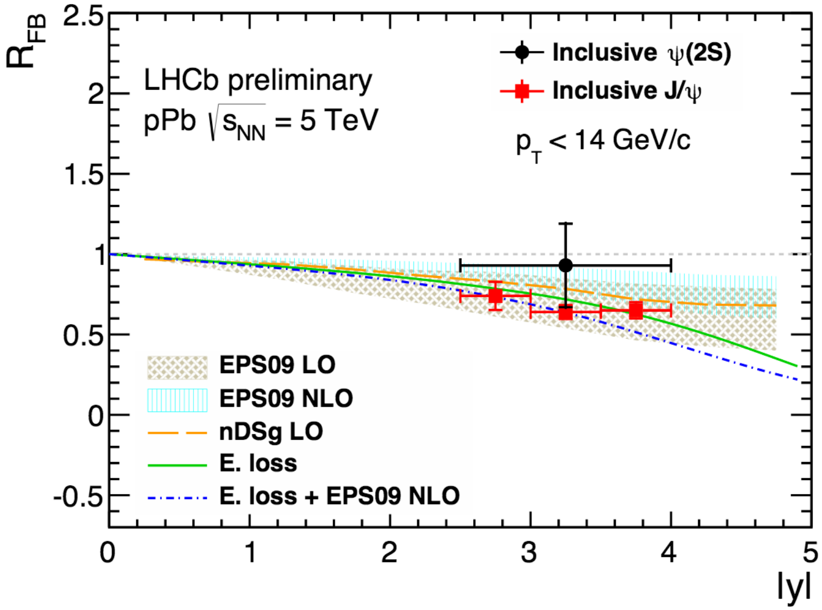
- Signal: - $\delta(t_z)$ for prompts ψ(2S) (blue curve)
  - Exponential for ψ(2S) from b (black line)
- Background: Empirical function from sideband (green hatched)

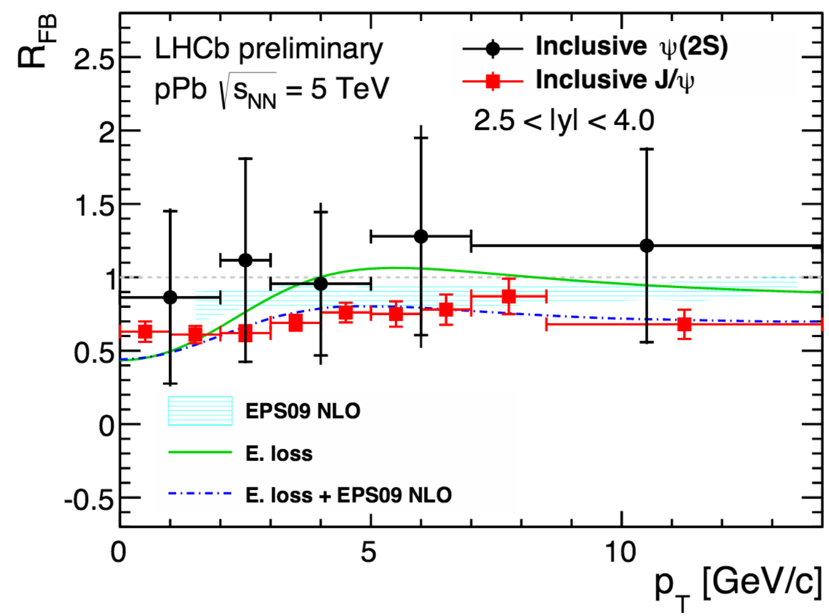
Ψ(2S) forward to backward ratio

NEW

LHCb-CONF-2015-005

- R_{FB} as a function of p_T and rapidity in common range $2.5 < |y_{CMS}| < 4.0$
- No need of pp refence cross section, part of experimental and theoretical uncertainties cancel





Large experimental uncertainties → more statistics needed to get a trend (R_{FB} of inclusive ψ(2S) compatible both with unity and with suppression of inclusive J/ψ)

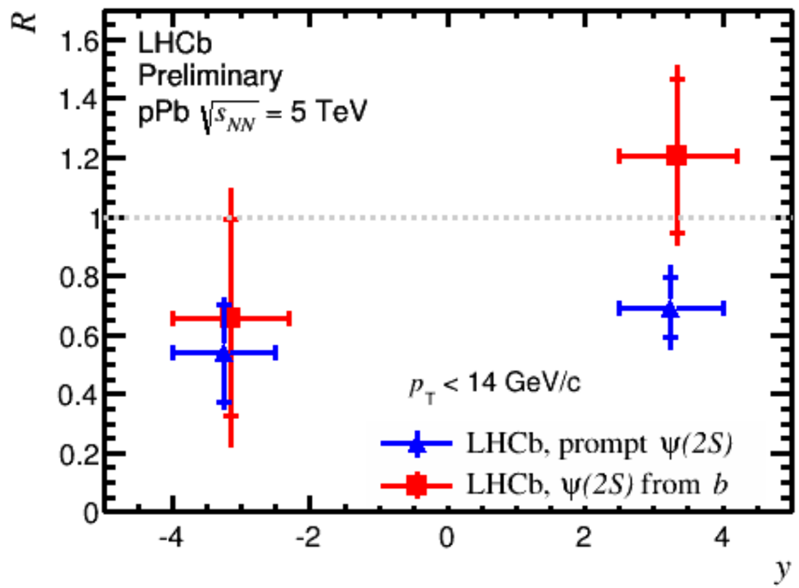
Ψ(2S) relative suppression wrt J/ψ

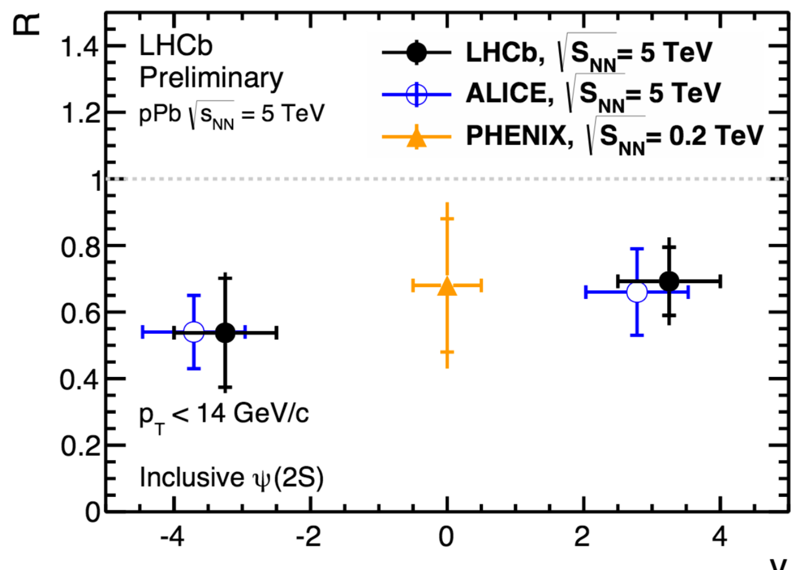
NEW

LHCb-CONF-2015-005

- Relative suppression is calculated as:

$$R = \frac{R_{pPb}^{\psi(2S)}}{R_{pPb}^{J/\Psi}} = \frac{\sigma_{pPb}^{\psi(2S)}(5\text{TeV})}{\sigma_{pPb}^{J/\Psi}(5\text{ TeV})}\frac{\sigma_{pp}^{J/\Psi}(5\text{ TeV})}{\sigma_{pp}^{\Psi(2S)}(5\text{ TeV})} \approx \frac{\sigma_{pPb}^{\psi(2S)}(5\text{TeV})}{\sigma_{pPb}^{J/\Psi}(5\text{ TeV})}\frac{\sigma_{pp}^{J/\Psi}(7\text{ TeV})}{\sigma_{pp}^{\Psi(2S)}(7\text{ TeV})}$$





ALICE: JHEP 12 (2014) 073
PHENIX: Phys. Rev. Lett. 111 (2013), no. 20 (202301)

Intriguing stronger suppression of prompt ψ(2S) than that of prompt J/ψ
Similar suppression for ψ(2S) from b and J/ψ from b
→ R compatible with 1 within large uncertainties
Results for inclusive ψ(2S) compatible with ALICE measurement

Ψ(2S) nuclear modification factor

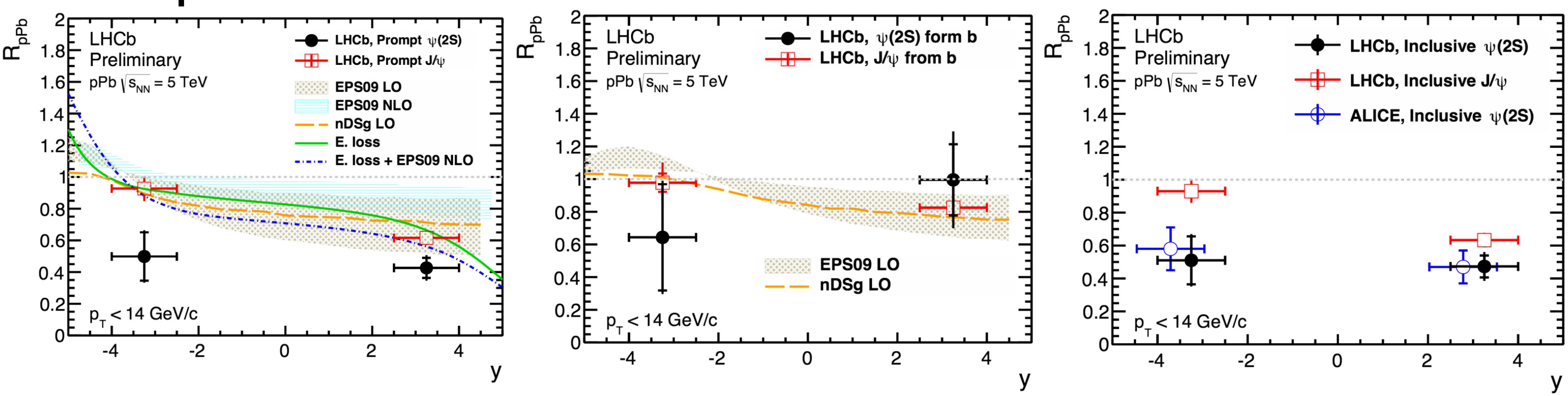
NEW

LHCb-CONF-2015-005

- Ψ(2S) nuclear modification factor is calculated from J/Ψ nuclear modification factor

$$R_{pPb}^{\Psi(2S)} \approx R_{pPb}^{J/\Psi} \times R \quad \text{Assuming} \quad \frac{\sigma_{pp}^{J/\Psi}(5\ \text{TeV})}{\sigma_{pp}^{\Psi(2S)}(5\ \text{TeV})} \approx \frac{\sigma_{pp}^{J/\Psi}(7\ \text{TeV})}{\sigma_{pp}^{\Psi(2S)}(7\ \text{TeV})}$$

Prompt **From b** **Inclusive**



ALICE: JHEP 12 (2014) 073

Prompt ψ(2S) more suppressed than prompt J/ψ
Eloss + shadowing don't explain the ψ(2S) suppression in the backward region (other mechanism at play?)
Suppression of ψ(2S) from b consistent with that of J/ψ from b
Suppresion of inclusive ψ(2S) consistent with ALICE results

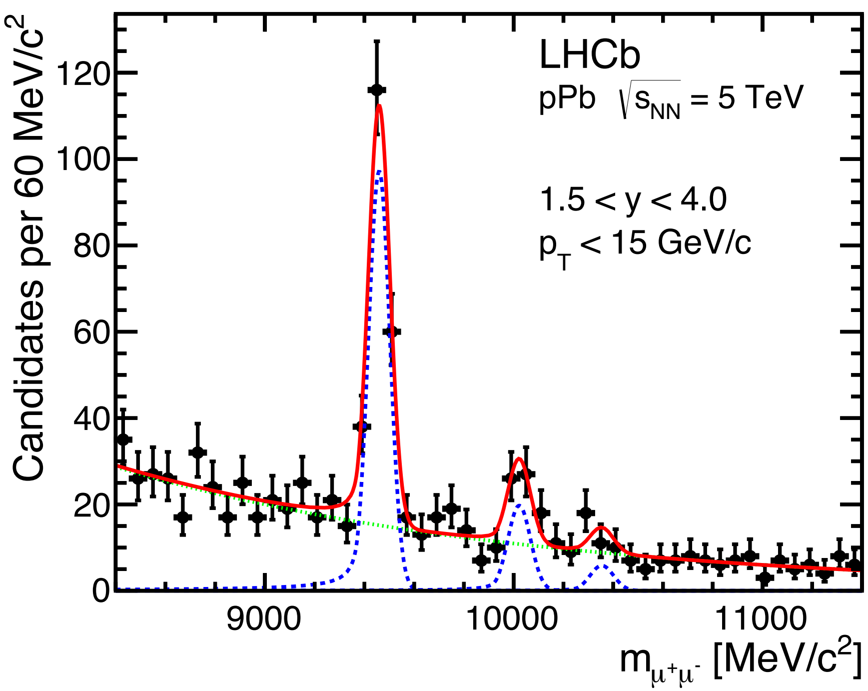
Υ(nS) production in p-Pb and Pb-p

JHEP 07 (2014) 094

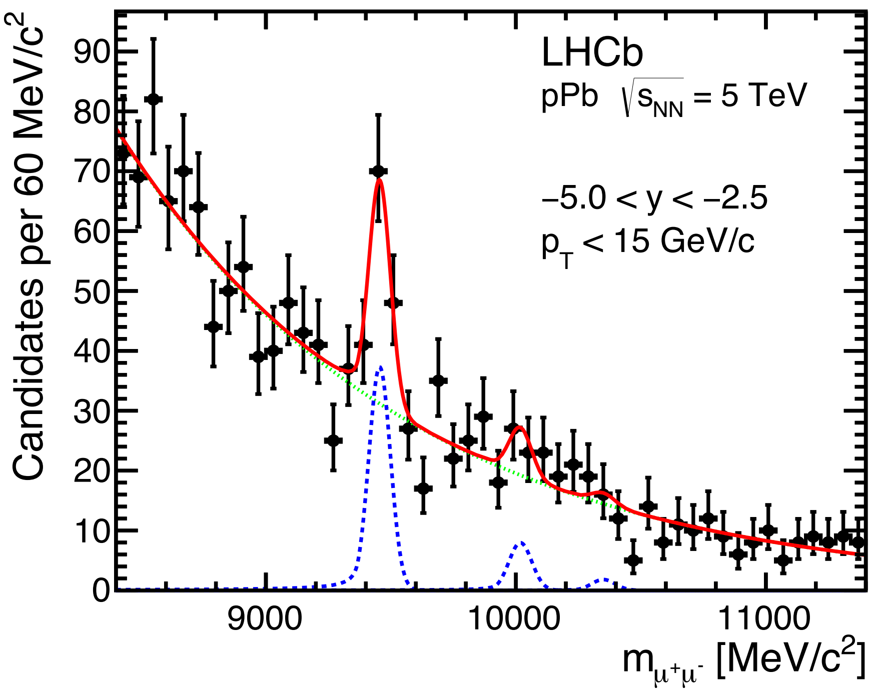
- ❑ Υ states in the dimuon decay channel
- ❑ Forward: $1.5 < y_{CMS} < 4.0$, backward: $-5.0 < y_{CMS} < -2.5$; $p_T < 15$ GeV/c
- ❑ Fit performed with 3 Crystal Balls for signal and an exponential for background

➡ Limited statistics do not permit to do a differential measurement

Forward production



Backward production

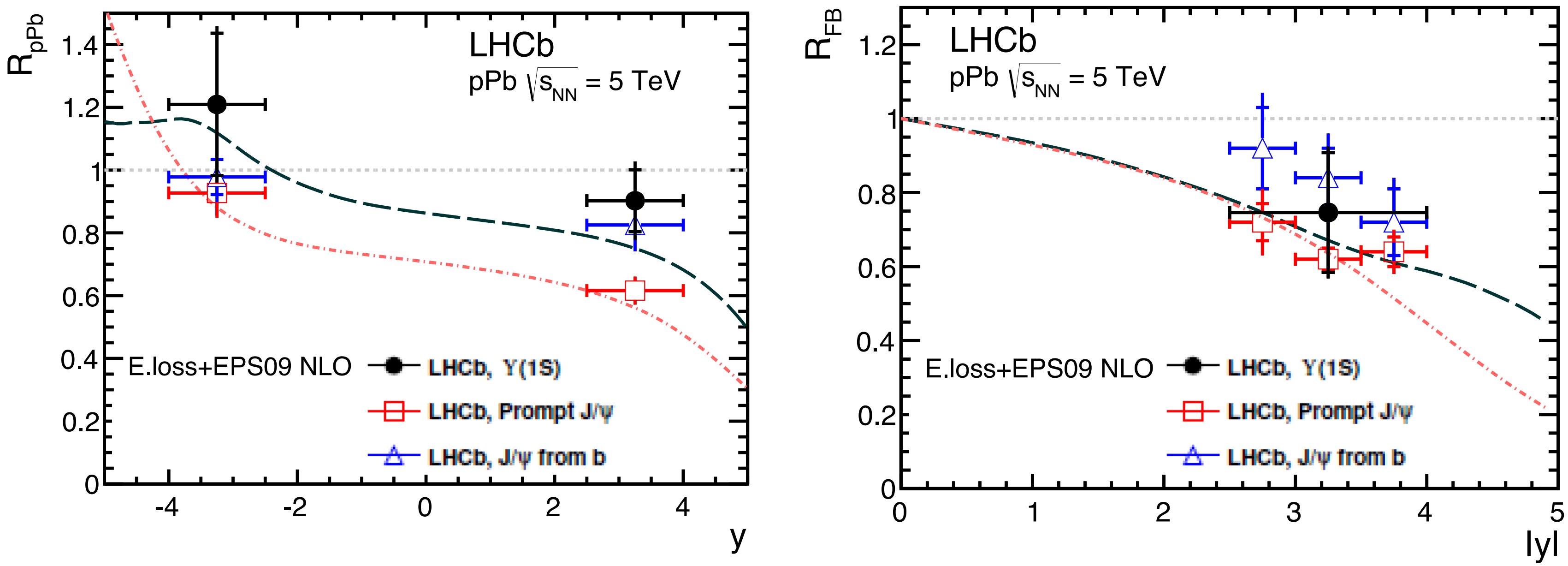


Υ(1S) R_{pA} and R_{FB}

JHEP 07 (2014) 094

- In common range $2.5 < |y_{CMS}| < 4.0$
- Measurement of Υ(1S) R_{pPb} and R_{FB} is complementary to the one of J/ψ

➡ Probing different x_A



Υ(1S) is also sensitive to CNM effets

R_{pPb} versus rapidity:

Suppression in forward region is smaller than for J/ψ

Central value in forward region close to that of J/ψ from b → CNM effects on b hadrons

Indication of enhancement in the backward region → could be attributed to anti-shadowing

R_{FB} versus rapidity:

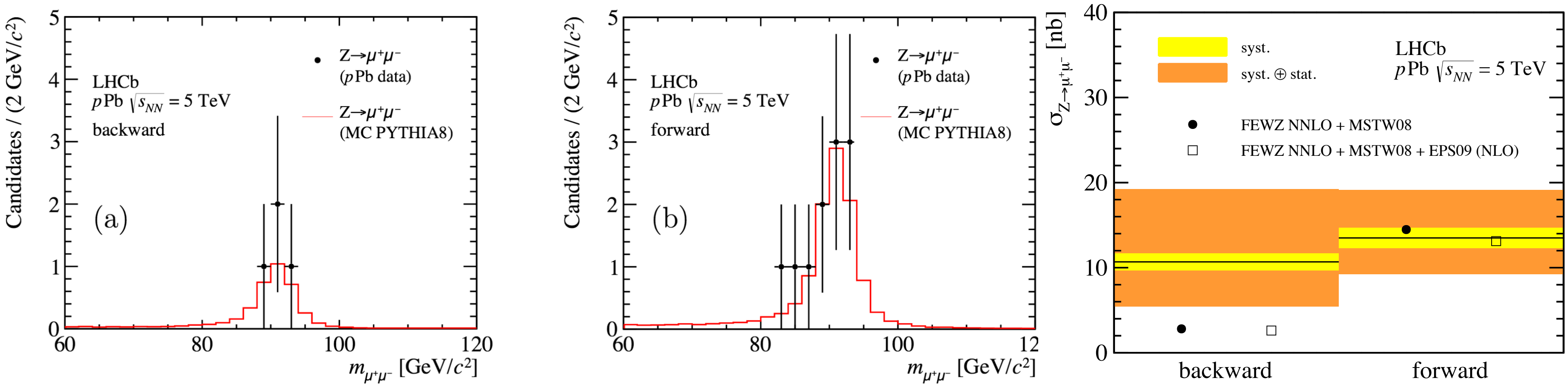
Ratio in agreement with predictions of energy loss + shadowing (EPSO9 NLO)

Z production in p-Pb and Pb-p

JHEP 09 (2014) 030

Muon selection: p_T > 20 GeV/c, 2.0 < η < 4.5, 60 < M(μ⁺μ⁻) < 120 GeV/c²
Backgrounds: very small, purity > 99% determined from data

→ Clean signal: 11 forward candidates, 4 backward candidates



Cross sections in agreement with predictions, although the production of Z in the backward region appears slightly higher than prediction

R_{FB} calculated in the common rapidity range is lower than expectations

→ deviation of 2.2σ from R_{FB} = 1

Statistical precision of measured cross sections prevents conclusions on the presence of CNM

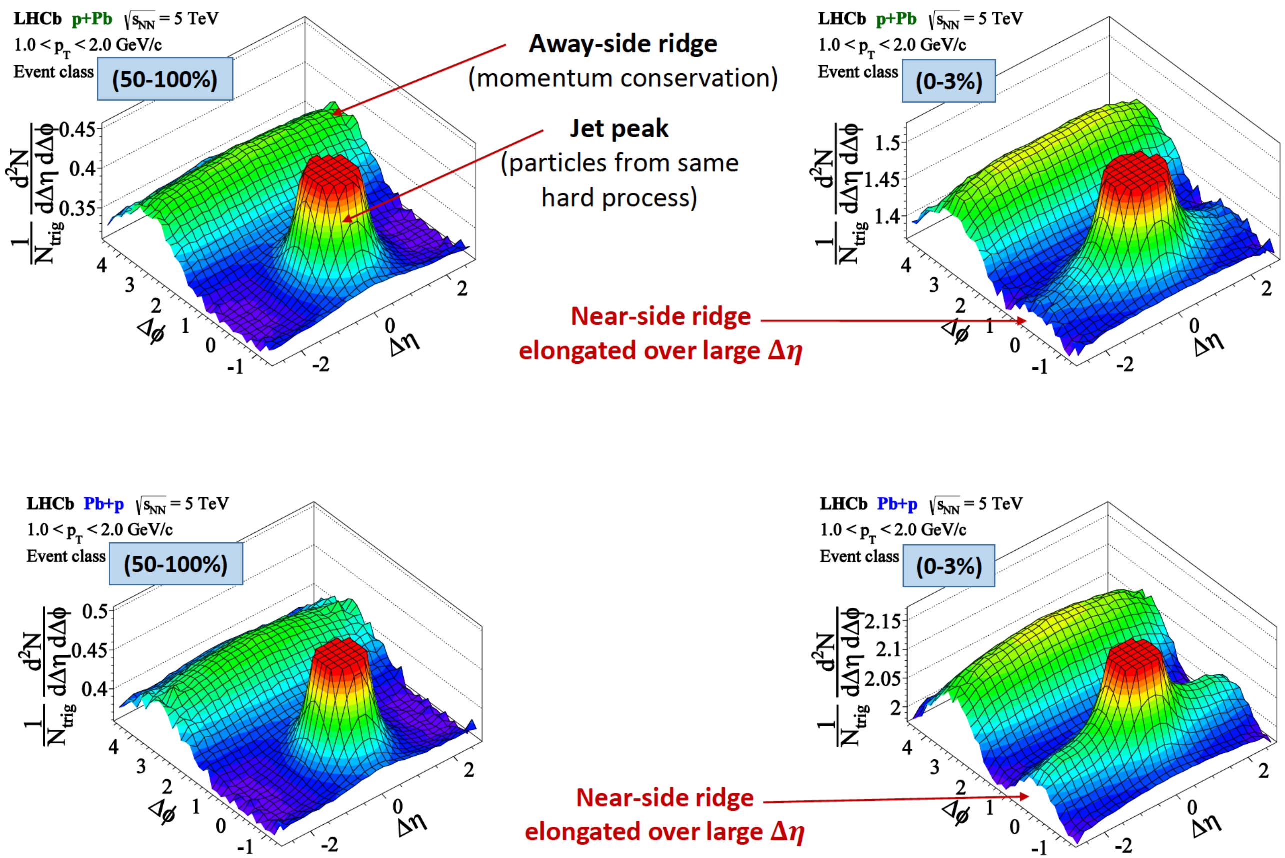
Looking forward to take more data during run II

Two particle correlations in p-Pb and Pb-p

LHCB-CONF-2015-004

- Measurement of angular (Δη,Δϕ)-correlations of prompt charged particles
- Both beam configurations analyzed separately: L_{int} = 0.46nb^{-1} (p+Pb), L_{int} = 0.30nb^{-1} (Pb-p)
- Rapidity range 1.5 < y_{CMS} < 4.4 (forward), -5.4 < y < -2.5 (backward)
- Correlation function is decribed as a per-trigger particle associated yield:

$$\frac{1}{N_{trig}}\frac{d^2N_{pair}}{d\Delta\eta d\Delta\varphi} = \frac{S(\Delta\eta,\Delta\varphi)}{B(\Delta\eta,\Delta\varphi)} \times B(0,0)$$



p-Pb configuration
Δϕ=0 near-side ridge clearly visible **in high event activity class** (however not very pronounced)

Pb-p configuration
Δϕ=0 very pronounced near-side ridge in Pb-p in **high activity event class**

Two particle correlations in p-Pb and Pb-p

LHCB-CONF-2015-004

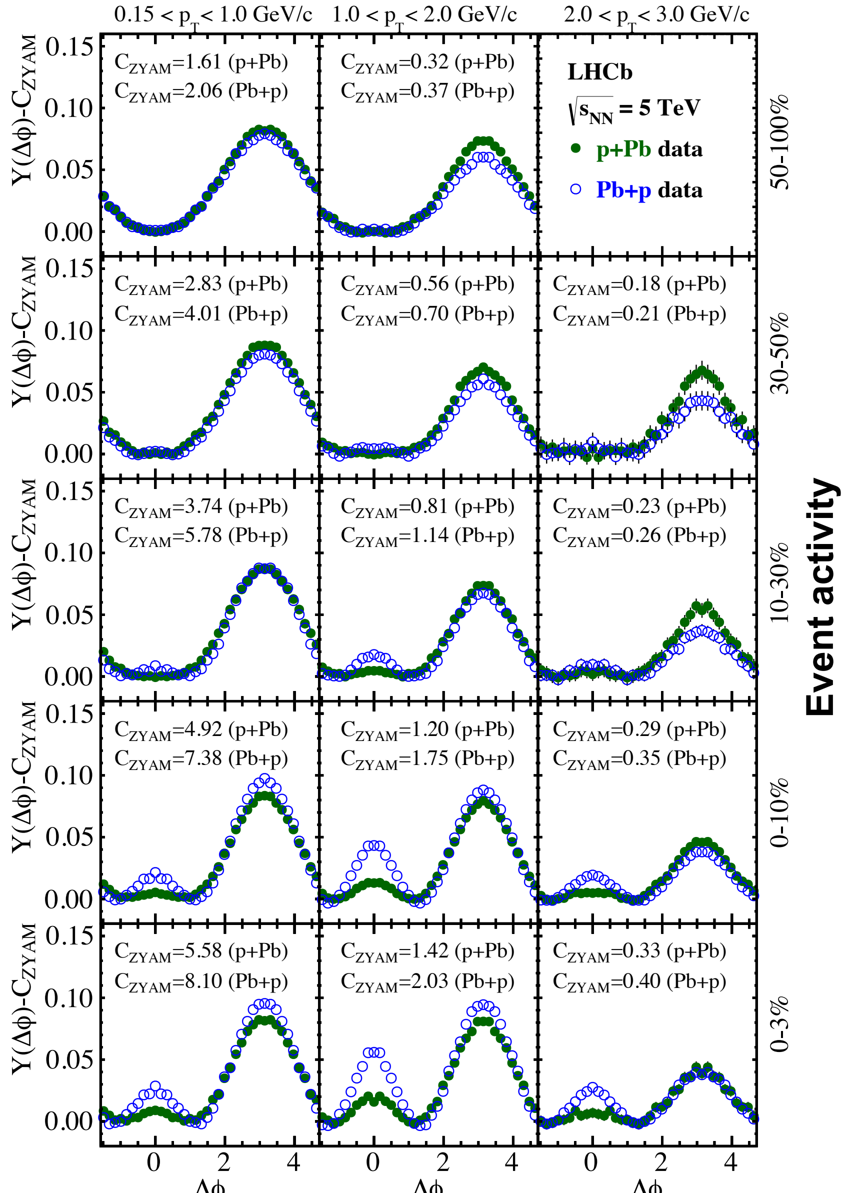
- To study the evolution of the long-range correlations on the near and away sides in more details, correlation function on $\Delta\phi$ are calculated:

$$Y(\Delta\phi) \equiv \frac{1}{N_{trig}} \frac{dN_{pair}}{d\Delta\phi} = \frac{1}{\Delta\eta_b - \Delta\eta_a} \int_{\Delta\eta_a}^{\Delta\eta_b} \frac{1}{N_{trig}} \frac{d^2N_{pair}}{d\Delta\eta d\Delta\phi} d\Delta\eta$$

- 2D-yield averaged in the range $2.0 < \eta < 2.9$ to exclude short range correlations (jet peak)

- Subtraction of the zero yield at minimum (ZYAM)

Correlation yield increases with event activity
Away-side ridge decreases towards higher p_T
On the near side the ridge emerges (from 10-30% event activity class in Pb-p, from 0-10% event activity class in p-Pb) with a maximum in $1 < p_T < 2$ GeV/c
Near-side ridge is more pronounce in Pb-p than in p-Pb



Conclusions and prospects for heavy ion studies

- **LHCb succesfully participated in the proton-Pb data taking in 2013**
  - Measurement of J/ψ, ψ(2S) and ϒ production
    - → Cold nuclear matter effects visible in J/ψ, ψ(2S) and ϒ(1S) production
  - First observation of forward Z production in proton-nucleus collisions
    - → Analysis will benefit from larger statistics data sample in Run 2
  - New results on « two-particle» correlations
    - → Near side ridge also observed in the forward region

LHCb is more than a pp heavy flavour experiment

- **LHCb detector will also collect PbPb data at the end of this year**
  - Rich program in heavy flavour physics, EW, (soft) QCD and QGP studied
  - Expected to collect 50-80 μb^{-1} this year

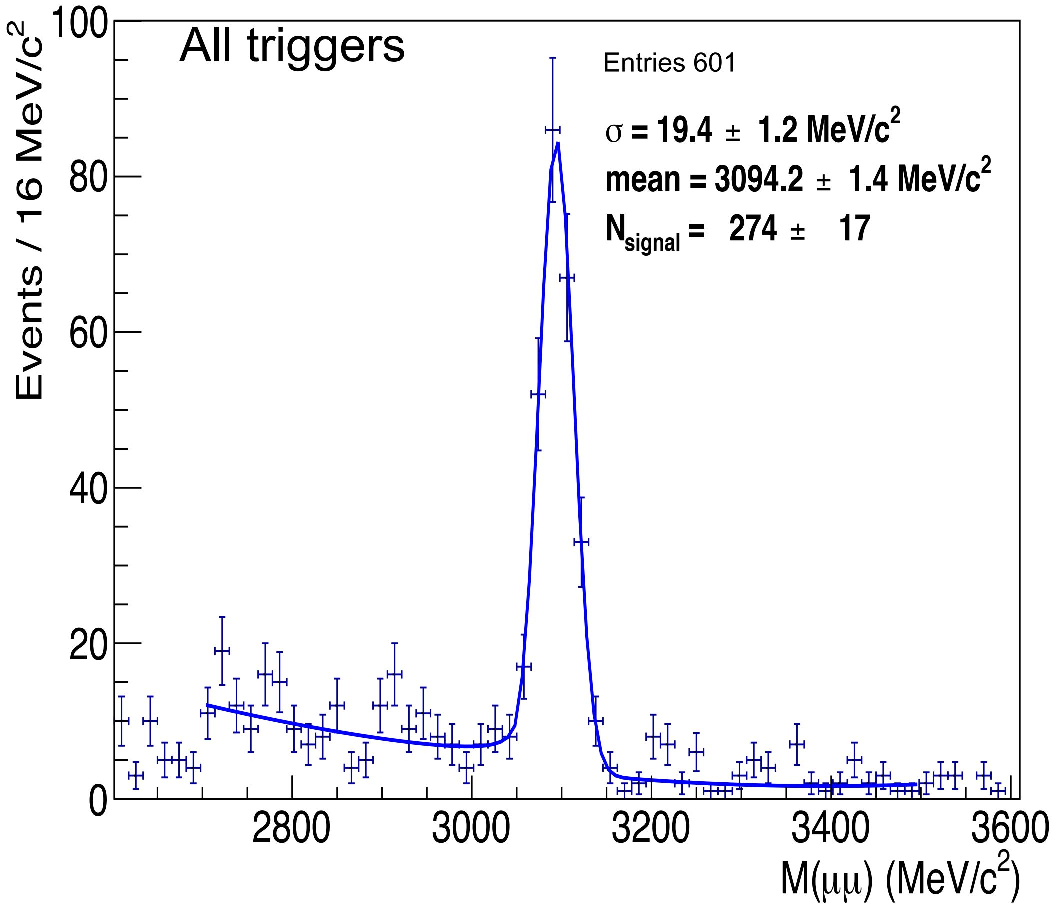
- **In addition LHCb is in the unique position to do fixed target physics**
  - Exploit the SMOG system with different noble gases (p-Ne, p-He already collected, p-Ar and Pb-Ar runs to come)
  - Bridge the gap from SPS to LHC physics with a single experiment

LHCb is a truly general purpose detector in the forward region

Back up

J/ψ signal in p-Ne collisions in 2015 with SMOG

- ❑ $\sqrt{s_{NN}}$ = 110 GeV
- ❑ ~12h of data taking
- ❑ Pressure of the Ne gas ~ 1.5 x 10^{-7} mbar



Physics motivation for proton-nucleus studies

➡ Proton-nucleus collisions are interesting by themselves but also provide reference for heavy ion studies

Heavy flavours and Quarkonia as tools to study cold nuclear matter effect (CNM)
→ Necessary reference to disentangle QGP effects from CNM effects in AA collisions

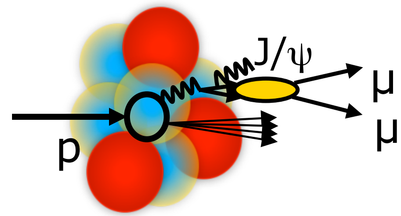
Initial state effects

Nuclear shadowing = gluon shadowing at LHC [1]
Gluon distribution functions are modified by the nuclear environnement. PDF in nuclei ≠ superposition of the individual nucleon PDFs

Parton saturation / CGC [2]
At small x, density of gluons > density of quarks. Saturation of gluon distributions

Radiative energy loss [3]: incoming partons radiate gluons as it traverses the medium

Cronin effects [4]: increase of $<p_T^2>$ from pp to pA . Broadening of the intrinsic p_T distribution → from multiple scattering experienced by the initial gluon from proton as it goes through the nucleus



p-A collisions

coherent energy loss [5]: neither initial nor final state effect. Amount of medium-induced gluon radiation defines strength of J/ψ suppression

Final state effects

Nuclear absorption [6]: break-up of pre-resonant cc pairs due to successives interaction with spectator nucleons
Expected to be small at LHC [7]

Radiative energy loss [8]: outgoing particle radiates energy while traversing the medium

Comovers [9]: interaction of the quarkonium with the produced medium

[1] K.J. Eskola et al., JHEP 0904 (2009) 065.
[2] D. Kharzeev et al., Nucl. Phys. A770 (2006) 40.
[3] S. Gavin et al., Phys. Rev. Lett. 68 (1992) 1834.
[4] J. W. Cronin et al., Phys. Rev. D, 11:3105, 1975.
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[9] E. Ferreiro, arXiv:1411.0549v2