J/ψ production in p-Pb collisions with ALICE at the LHC

Igor Lakomov*, IPN Orsay

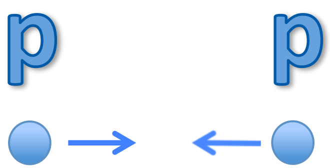
*on behalf of the ALICE collaboration

Strangeness in Quark Matter 2013, Birmingham, 21-27.07.2013

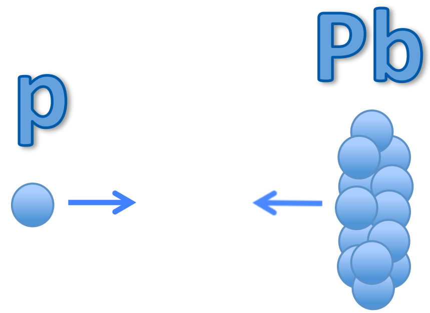
Outline

- ✧ Physics motivation
- ✧ Analysis
- ✧ Results
  - ❖ Forward to Backward ratio $R_{FB}^{J/\psi}$ integrated and vs p_T, vs y_{cms}
  - ❖ Nuclear modification factor $R_{pPb}^{J/\psi}$ integrated and vs y
- ✧ Summary and outlook

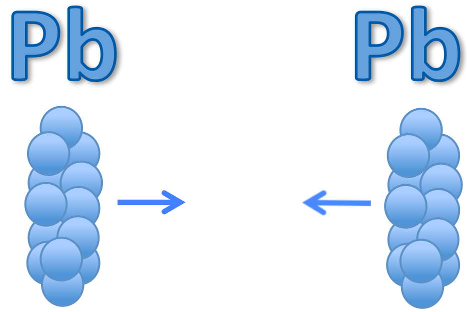
Physics motivation



Elementary collision
No nuclear matter effects



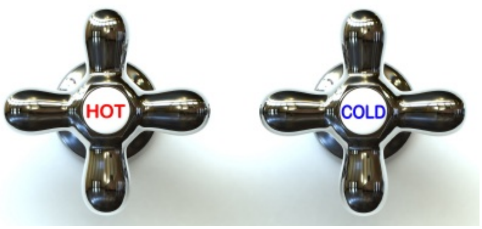
Cold nuclear matter effects – without Quark-Gluon Plasma (QGP)



Cold nuclear matter effects – without QGP
+
Hot nuclear matter effects – related to QGP formation

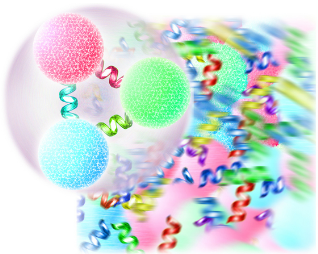
*See the talk of
Lizardo Valencia Palomo

- ➢ To disentangle hot and cold nuclear matter (CNM) p-Pb measurements are needed as an intermediate step between Pb-Pb and benchmark pp collisions.



Cold nuclear matter effects

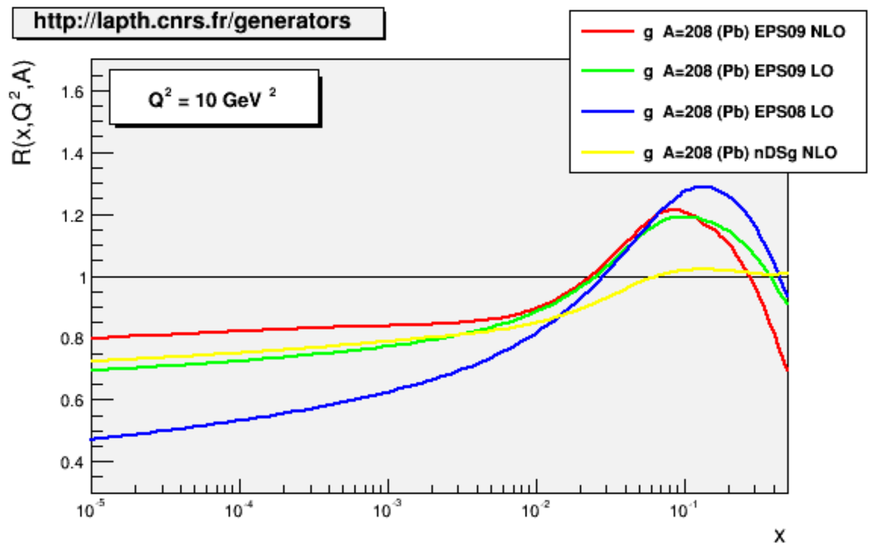
In p-Pb different kinds of nuclear matter effects can be considered:



① **Initial-state**

✓ gluon shadowing[1] (or saturation[2]): at high energies gluons start shadowing each other (or recombining).

➢ At LHC energies large shadowing is expected.



② **Coherent energy loss** [4]: gluon radiates a soft gluon.

➢ The amount of medium-induced gluon radiation defines the strength of the J/ψ suppression.

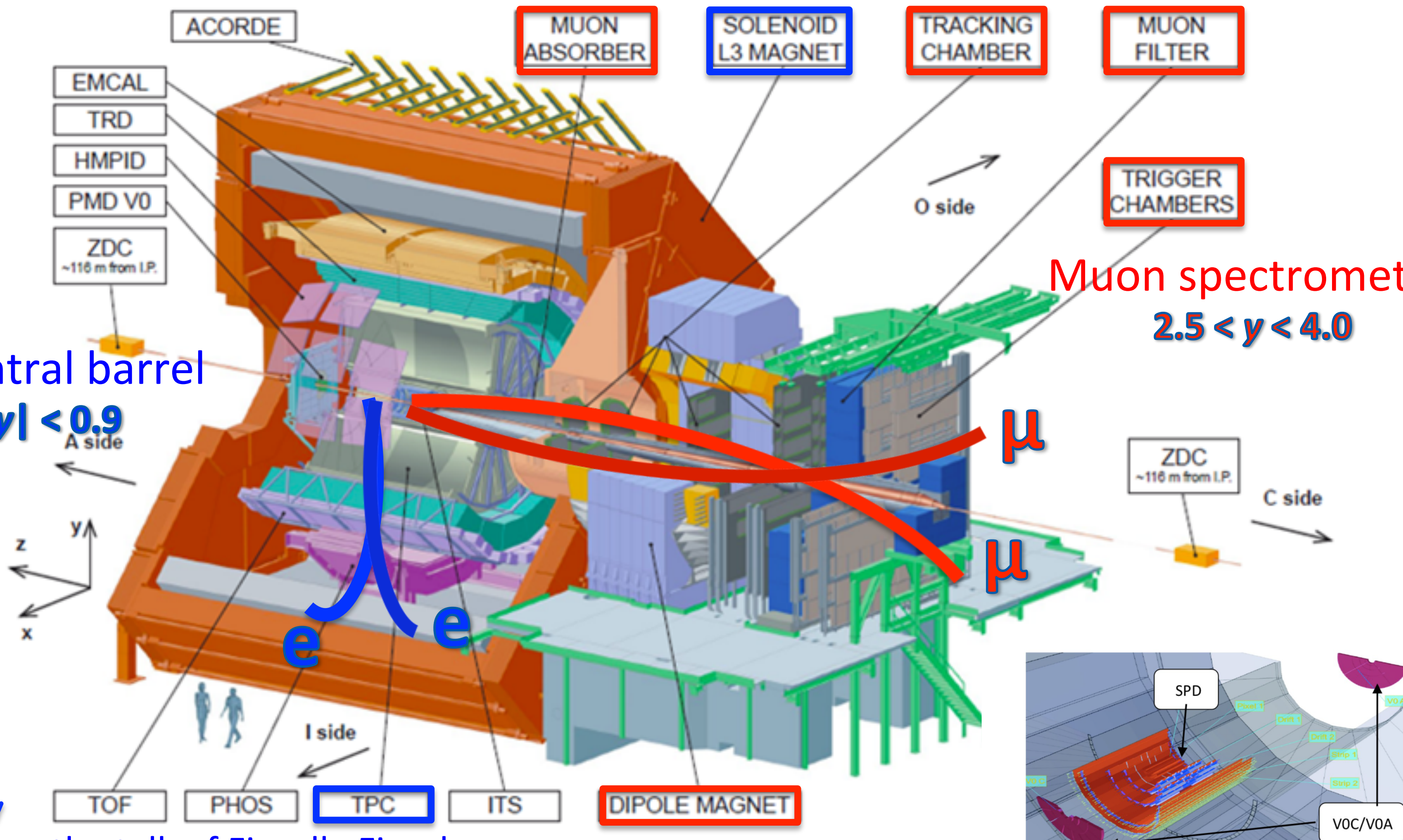
③ **Final-state**

✓ nuclear absorption: J/ψ pre-resonant state destruction by colliding nucleons.

➢ At the LHC at mid- and forward rapidity in p-Pb the ccbar pair spends a very short time within cold nuclear matter, due to the large Lorentz gamma of the colliding nuclei. Consequently, nuclear absorption is then expected to be negligible [5].

[1] K. Eskola et al., JHEP 0904:065 (2009)
[2] D. E. Kharzeev et al., arXiv:1205.1554 (2012); F. Dominguez et al. arXiv:1109.1250 (2012)
[3] R. Vogt Phys.Rev. C81 (2010) 044903
[4] F. Arleo, S. Peigne, arXiv1204.4609 (2012)
[5] Lourenco et al., JHEP 0902:014, 2009

ALICE detector



Central barrel

$|y| < 0.9$

Muon spectrometer

$2.5 < y < 4.0$

See the talk of Fiorella Fionda

Event selection and analysis cuts

- Event selection
  - ✓ MB trigger: Coincidence of the two sides of VZERO: $2.8 < \eta < 5.1$, $-3.7 < \eta < -1.7$
  - ✓ MB trigger efficiency ~99% for NSD events
  - ✓ Rejection of beam-gas and electromagnetic interactions
  - ✓ SPD used for vertex determination

- Dimuon trigger
  - ✓ Coincidence of minimum bias (MB) interaction with two opposite sign muon tracks detected in the trigger chambers of the Muon spectrometer

- The following cuts (standard for J/ψ analysis) were also applied:
  - ✓ Muon trigger matching
  - ✓ $-4 < \eta_{\mu} < -2.5$
  - ✓ 17.6 cm < R_{abs} < 89.5 cm, where R_{abs} – track radial position at the absorber end
  - ✓ Unlike sign dimuon
  - ✓ $2.5 < y_{\mu\mu}^{lab} < 4$

Main observables (R_{pPb}, R_{Pbp})

➢ Nuclear modification factor R_{pPb} and R_{Pbp}

$$R_{pPb}^{J/\psi} = \frac{Y_{pPb}}{\langle T_{pPb} \rangle \sigma_{pp}^{J/\psi \to \mu^+\mu^-}}, \qquad Y_{pPb} = \frac{N_{J/\psi \to \mu^+\mu^-}}{(A \times \varepsilon) N_{MB}}$$

R_{pPb} and R_{Pbp} are computed in the range $2.5 < y_{lab} < 4$

$T_{pPb} = 0.0983 \pm 0.0034\ \text{mb}^{-1}$ – nuclear overlap function

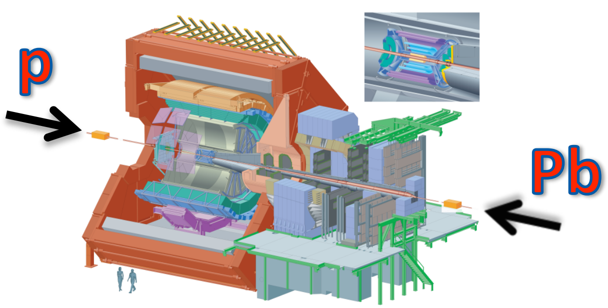
See talk of Andreas Morsch

➢ Shift in y_{cms} and rapidity coverage

LHC beam asymmetry (E_{Pb}=1.58•A TeV, E_p=4 TeV) => $|\Delta y|_{cms} = 0.5\ \text{Log}(Z_{Pb}A_p/Z_pA_{Pb}) = 0.465$

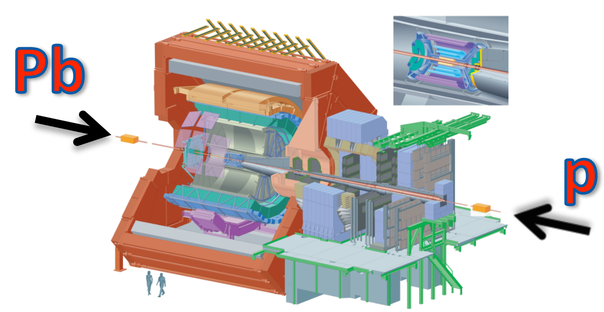
p-Pb: $2.03 < y_{cms} < 3.53$

$8.1 \cdot 10^{-5} > x_{Bjorken} > 1.8 \cdot 10^{-5}$



Pb-p: $-4.46 < y_{cms} < -2.96$

$5.3 \cdot 10^{-2} > x_{Bjorken} > 1.2 \cdot 10^{-2}$



Main observables (R_{FB})

➢ Forward to Backward ratio R_{FB}

$$R_{FB}^{J/\psi} = \frac{R_{pPb}}{R_{Pbp}}$$

✧ R_{FB} is computed in the y_{cms} **range common to both p-Pb and Pb-p**: $2.96 < y_{cms} < 3.53$ which corresponds to the following range in lab.system:

p-Pb: $3.43 < y_{lab} < 4$
$3.2 \cdot 10^{-5} > x_{Bjorken} > 1.8 \cdot 10^{-5}$

Pb-p: $-3.07 < y_{lab} < -2.5$
$2.1 \cdot 10^{-2} > x_{Bjorken} > 1.2 \cdot 10^{-2}$

In that case T_{pPb} and the pp cross-section cancel out in the ratio:

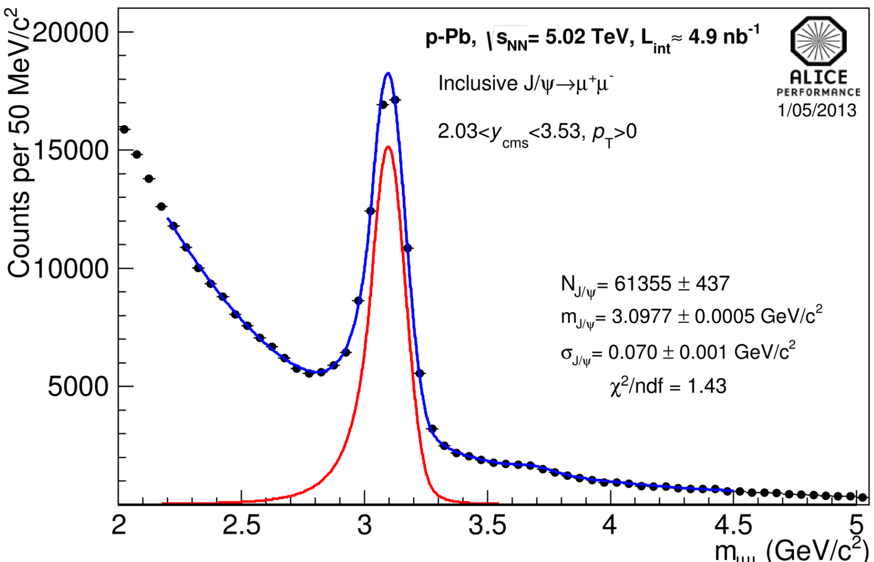
$$R_{FB}^{J/\psi} = \frac{Y_{pPb}^{Forward}}{Y_{pPb}^{Backward}} = \frac{N_{J/\psi\to\mu^+\mu^-}^{Forward}}{(Acc\times\varepsilon)^{Forward}\, N_{MB}^{Forward}} \times \frac{(Acc\times\varepsilon)^{Backward}\, N_{MB}^{Backward}}{N_{J/\psi\to\mu^+\mu^-}^{Backward}}$$

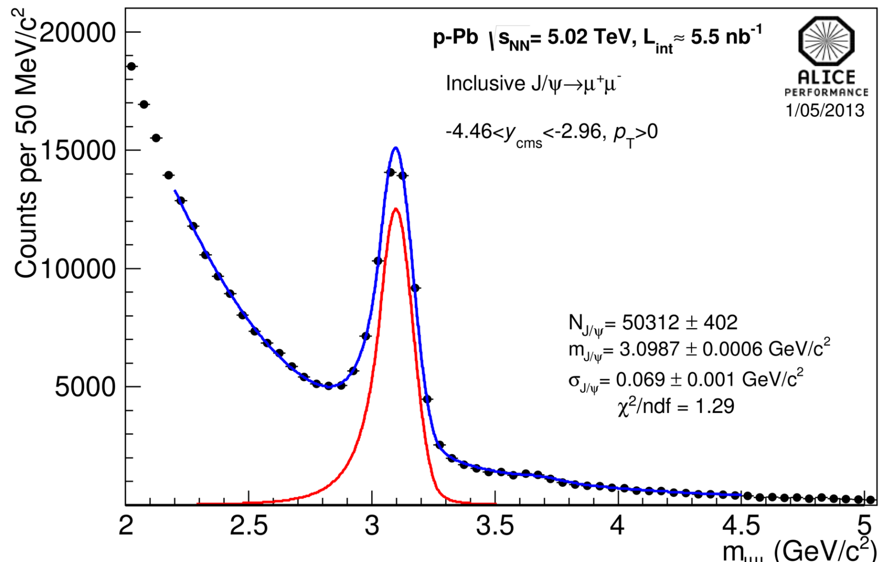
BIRMINGHAM SQM 2013

Signal extraction

Signal extraction (and its syst. unc.) is based on fits of dimuon inv.mass distribution by varying:

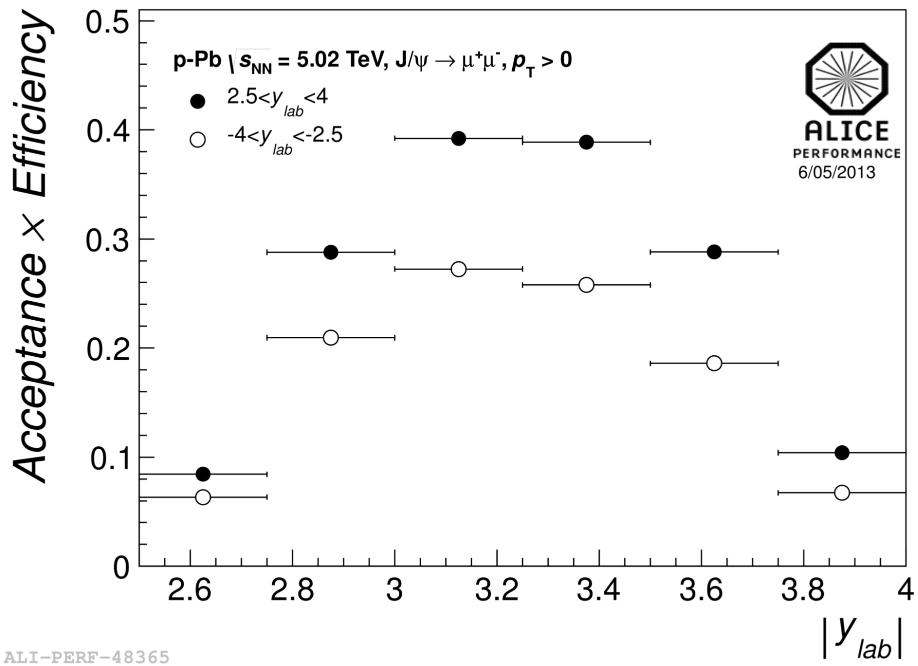
1. **Signal shape:** Extended Crystal Ball (CB2) or other pseudo-Gaussian functions (tails tuned on the corresponding Monte Carlo (MC))
2. **Background shape:** Variable Width Gaussian (VWG) or Pol2*Exp (or Pol4*Exp)
3. **Fitting range**

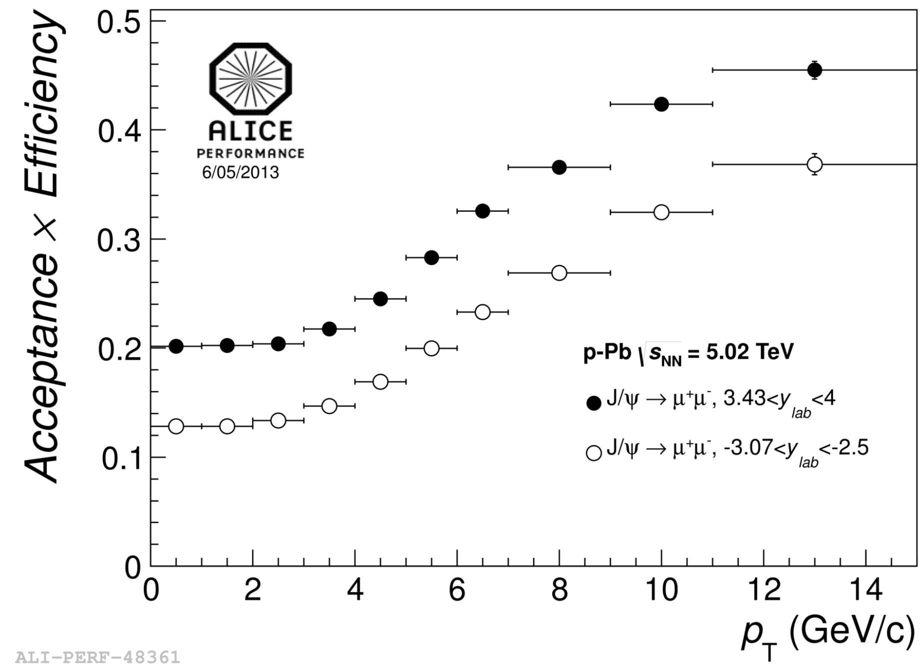




These plots are examples of the fit with **CB2+VWG**.

Acceptance x Efficiency





- Average J/ψ acceptance x efficiency:

  p-Pb: ~25% in 2.03<y_{cms}<3.53 Pb-p: ~17% in -4.46<y_{cms}<-2.96

  - Difference in AccxEff between p-Pb and Pb-p is due to different efficiency of detector in two periods of data-taking

- Systematic uncertainties on acceptance inputs uncorrelated vs p_T, y and collision system (different physics)

Summary on the syst. uncertainties

Source of systematic uncertainty:	Systematic uncertainty
Signal extraction	1-4%
Nuclear thickness function T_{pPb}	3.4%
Acceptance inputs	1-3.5%
Tracking efficiency	4-6%
Trigger efficiency	3%
Matching efficiency	1%
Normalization dimuon-MB trigger	1%
Total syst. uncertainty	**7-12%**

*(ranges correspond to values obtained in y or p_T bins)

$d^2\sigma_{J/\psi}/dydp_T$

$$\sigma^{pPb}_{J/\psi\to\mu^+\mu^-} = \frac{N_{J/\psi\to\mu^+\mu^-}}{L_{int}\times Acc\times\varepsilon\times BR_{J/\psi\to\mu^+\mu^-}}$$

$$L_{int} = \frac{N_{MB}}{\sigma_{MB}}$$

✓ σ_{MB} obtained using VdM scans:

✓ σ_{MB}: MB condition related to signal in VZERO

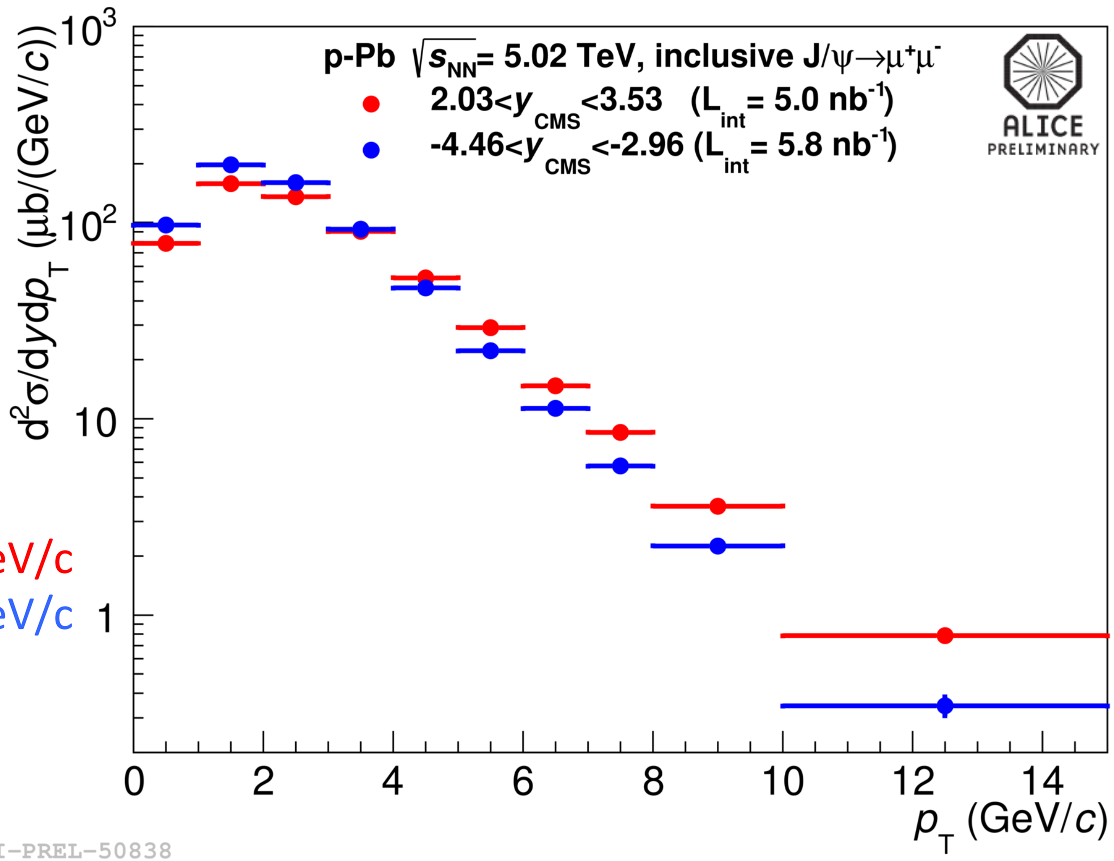
2.08 b ± 3.4% for p-Pb period

2.12 b ± 3.2% for Pb-p period

L_{int}^{pPb} = 5.0 nb^{-1}; L_{int}^{Pbp} = 5.8 nb^{-1}

One can calculate $\langle p_T\rangle|_{0\text{-}15\ GeV/c}$:

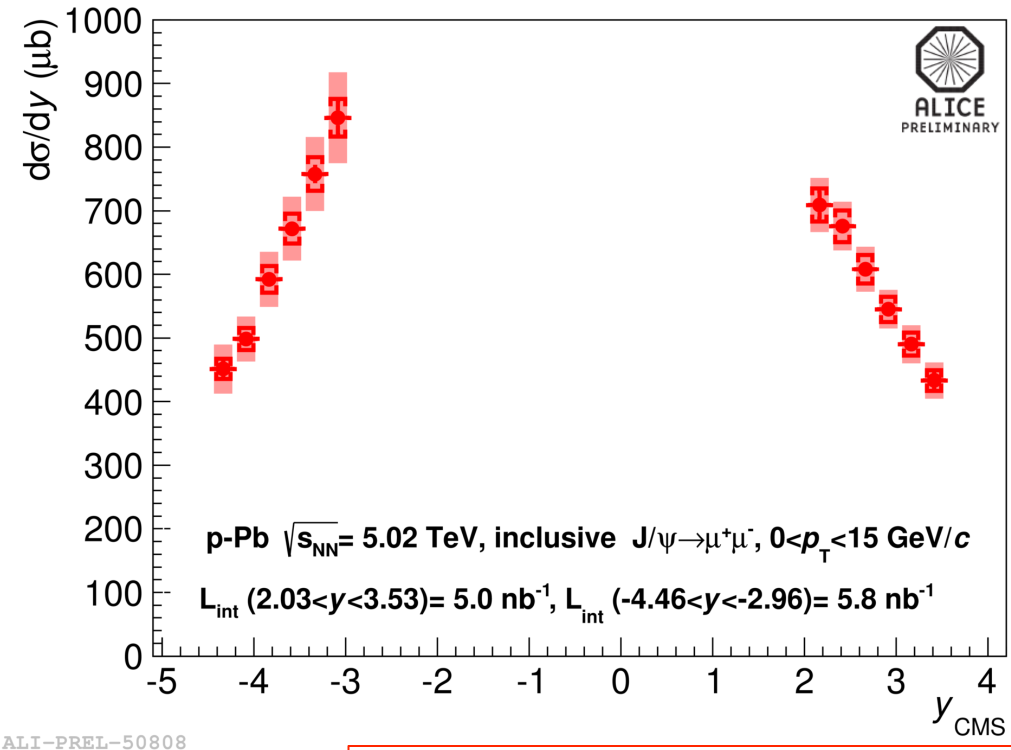
- $\langle p_T\rangle$ = 2.77 ± $0.01^{stat.}$ ± $0.02^{syst.}$ GeV/c
- $\langle p_T\rangle$ = 2.47 ± $0.01^{stat.}$ ± $0.02^{syst.}$ GeV/c



ALI-PREL-50838

BIRMINGHAM SQM 2013

$d\sigma_{J/\psi}/dy$



- ✓ **Correlated uncertainties** (brackets): luminosity, normalization factor, BR
- ❖ Luminosity is correlated within p-Pb or Pb-p, but not within the two systems
- ✓ **Uncorrelated uncertainties** (filled boxes): matching, trigger efficiency, tracking, acc. inputs, signal extraction
- ✓ **Statistical uncertainties** (line)

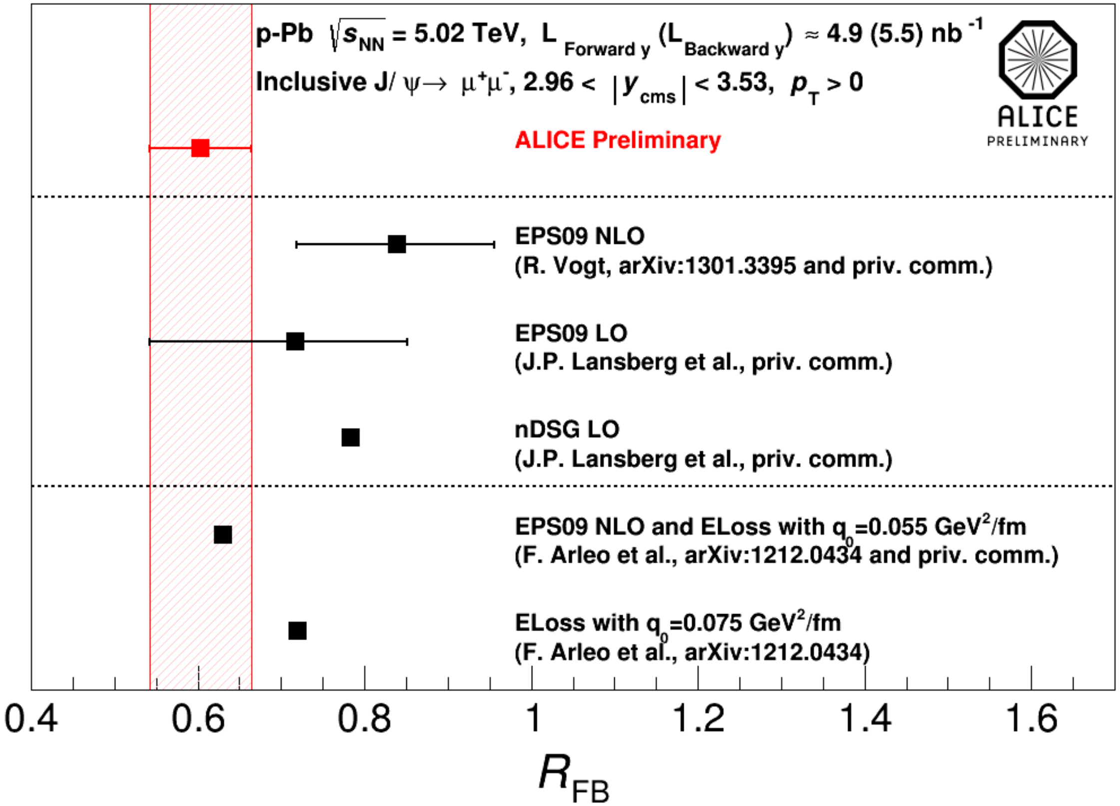
$$\frac{d\sigma_{pPb}}{dy} = 588 \pm 4\ (stat.) \pm 38\ (syst.)\ \mu b$$

$$\frac{d\sigma_{Pbp}}{dy} = 644 \pm 5\ (stat.) \pm 51\ (syst.)\ \mu b$$

➢ Cross-sections are higher in the backward rapidity region (Pb-p).

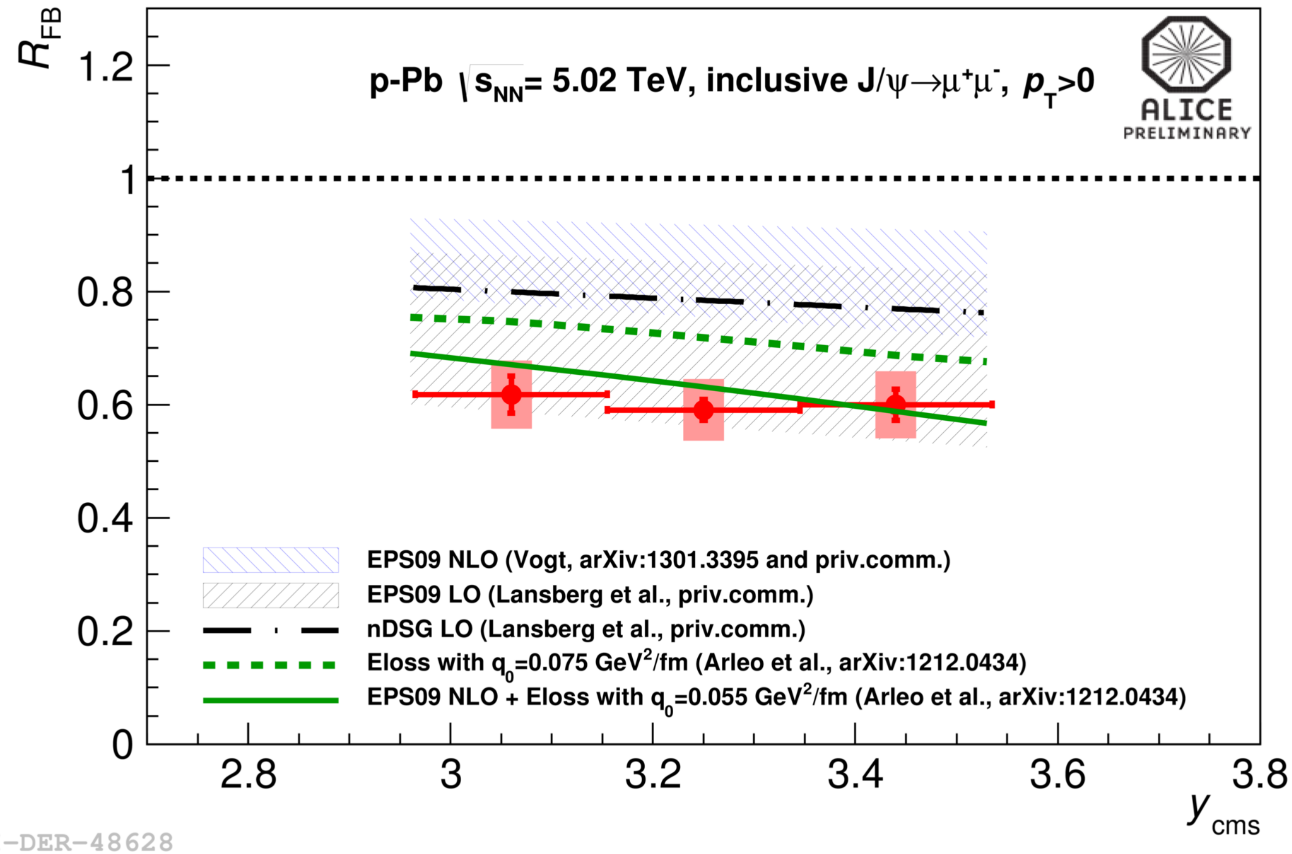
Integrated R_{FB}

R_{FB} = 0.60 ± 0.01 (stat.) ± 0.06 (syst.)



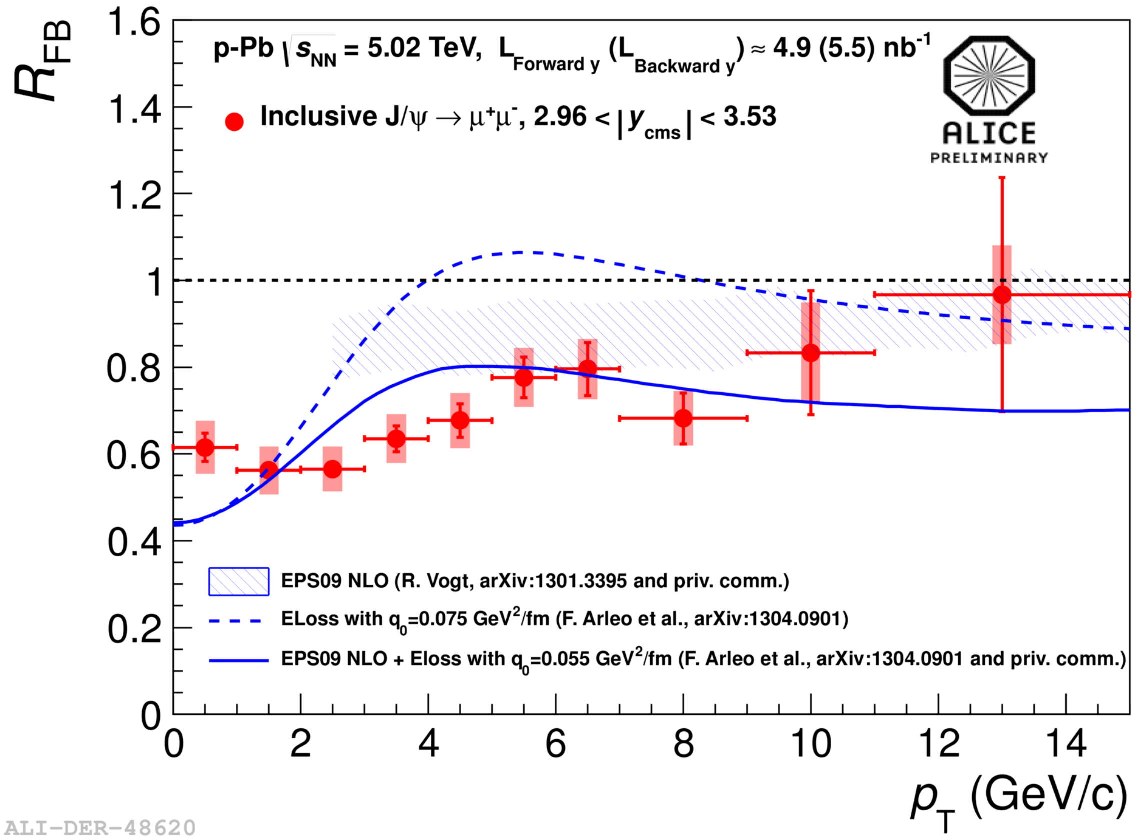
- The uncertainty is small
- Pure shadowing slightly overestimates the data
- Model including energy loss contribution is rather good

R_{FB} vs rapidity



- Comparison with theoretical models confirms previous observations done on the *y*-integrated results.
- Calculations including both shadowing and energy loss seems consistent with the data

R_{FB} vs p_T



- A sizeable p_T-dependence of R_{FB} is seen.
- Stronger suppression is found at low p_T.
- Theoretical models including energy loss show strong nuclear matter effects at low p_T in fair agreement with the data
- The observed p_T-dependence is smoother than expected in coherent energy loss models

pp-reference

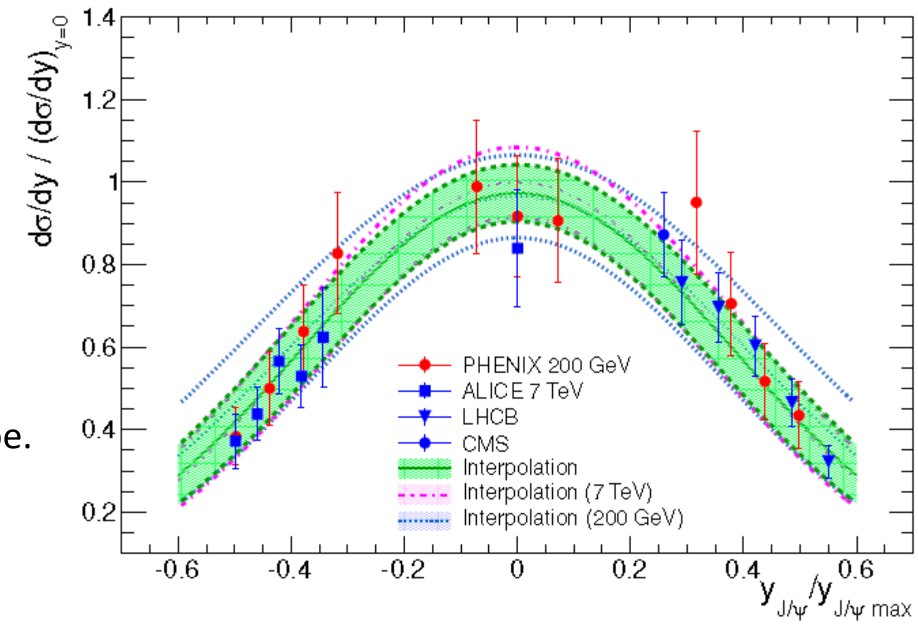
Phenomenological interpolation of the inclusive J/ψ x-section to pp collisions at $\sqrt{s_{NN}}$=5.02 TeV from CDF, RHIC and LHC (2.76 and 7 TeV) based on the paper from arXiv:1103.2394v3.

① Energy dependence: pp cross-section at mid-rapidity

Calculations performed using a Monte Carlo toy.

Parametrization with a power-law shape.

$$\left.\frac{d\sigma^{pp}_{J/\psi\to\mu^+\mu^-}}{dy}\right|_{y=0} = 362 \pm 6(stat.)^{+55(syst.)}_{-37(syst.)} nb$$



② Rapidity dependence

Based on a universal, energy independent gaussian shape.

③ Systematic uncertainties

Evaluated within 2.5σ in order to include most of the uncertainties from FONLL and CEM LO interpolation.

$$d\sigma^{pp}_{J/\psi\to\mu^+\mu^-}/dy\,(2.03 < y_{cms} < 3.53) = 231^{+41(syst.)}_{-32(syst.)} nb$$

$$d\sigma^{pp}_{J/\psi\to\mu^+\mu^-}/dy\,(-4.46 < y_{cms} < -2.96) = 159^{+40(syst.)}_{-27(syst.)} nb$$

Summary on the systematics

Source of systematic uncertainty:	Systematic Uncertainty
Signal extraction	1-4%
Nuclear thickness function T_{pPb}	3.4%
Acceptance inputs	1-3.5%
Tracking efficiency	4-6%
Trigger efficiency	3%
Matching efficiency	1%
Normalization dimuon-MB trigger	1%
pp reference @ y=0, $\sqrt{s}$ = 5.02 TeV	10-15%
y-dependence of pp interpolation @ $\sqrt{s_{NN}}$ = 5.02 TeV	10-20%
Total syst. uncertainty (excluding pp interpol.)	**7-12%**

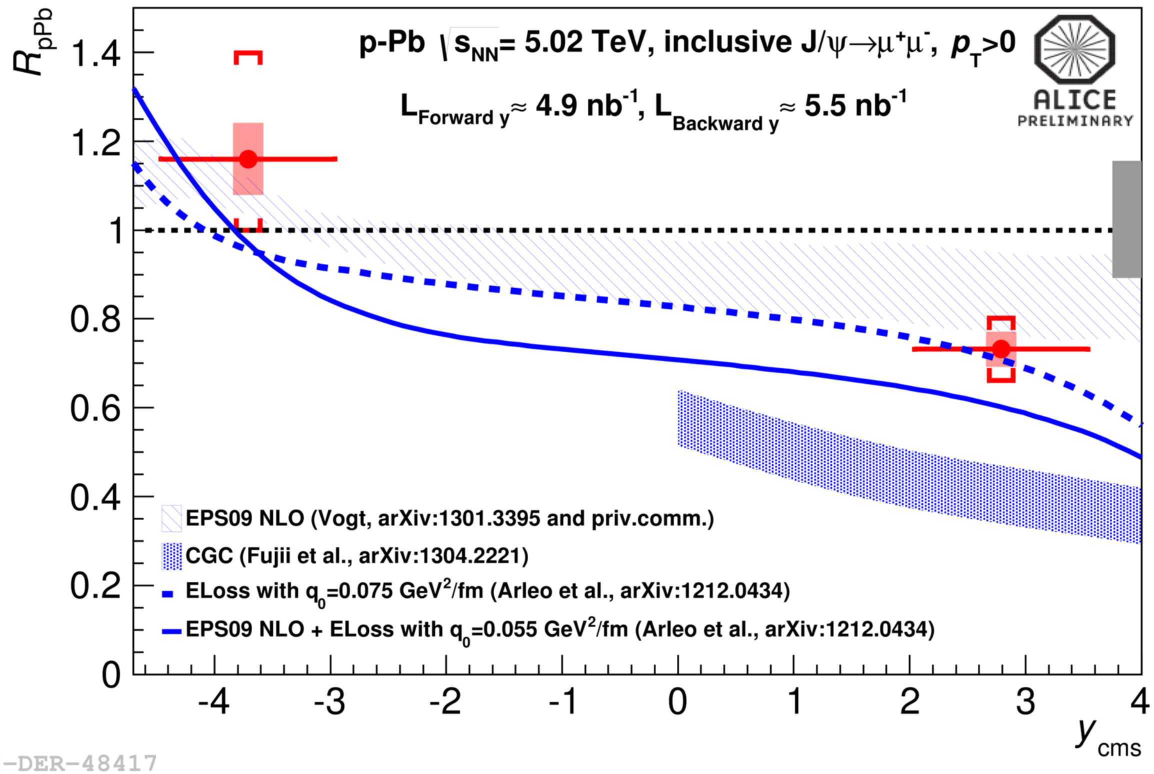
*(ranges correspond to values obtained in y or p_T bins)

BIRMINGHAM SQM 2013

R_{pPb} and R_{Pbp} integrated

R_{pPb} (2.03<y_{cms}<3.53) = 0.732 ± 0.005(stat) ± 0.059(syst) + 0.131(syst. ref) – 0.101(syst.ref)

R_{pPb} (-4.46<y_{cms}<-2.96) = 1.160 ± 0.010 (stat) ± 0.096(syst) + 0.296(syst. ref) – 0.198(syst.ref)

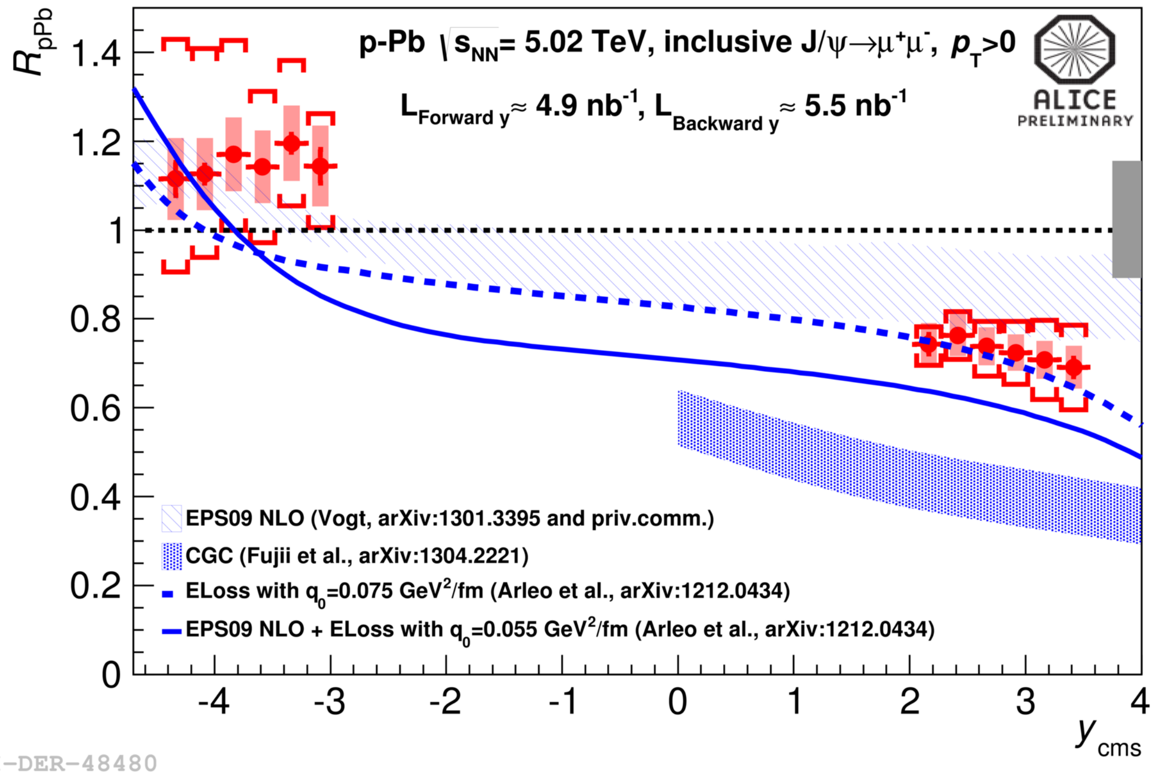


Error bars:

- ✓ boxes around the points: uncorrelated
- ✓ [ ]: partially correlated
- ✓ grey box around unity: fully correlated

- ➢ Large uncertainty (correlated and uncorrelated) from pp interpolation
- ➢ At forward rapidity, data in-between shadowing and energy loss models
- ➢ Color Glass Condensate (CGC) model underestimates the data

R_{pPb} and R_{Pbp} vs rapidity



Error bars:

- ✓ boxes around the points: uncorrelated
- ✓ [ ]: partially correlated
- ✓ grey box around unity: fully correlated

- ➢ At backward rapidity, models including coherent parton energy loss show a slightly steeper pattern than the one observed in data
- ➢ Results dominated by a large uncertainty from pp interpolation

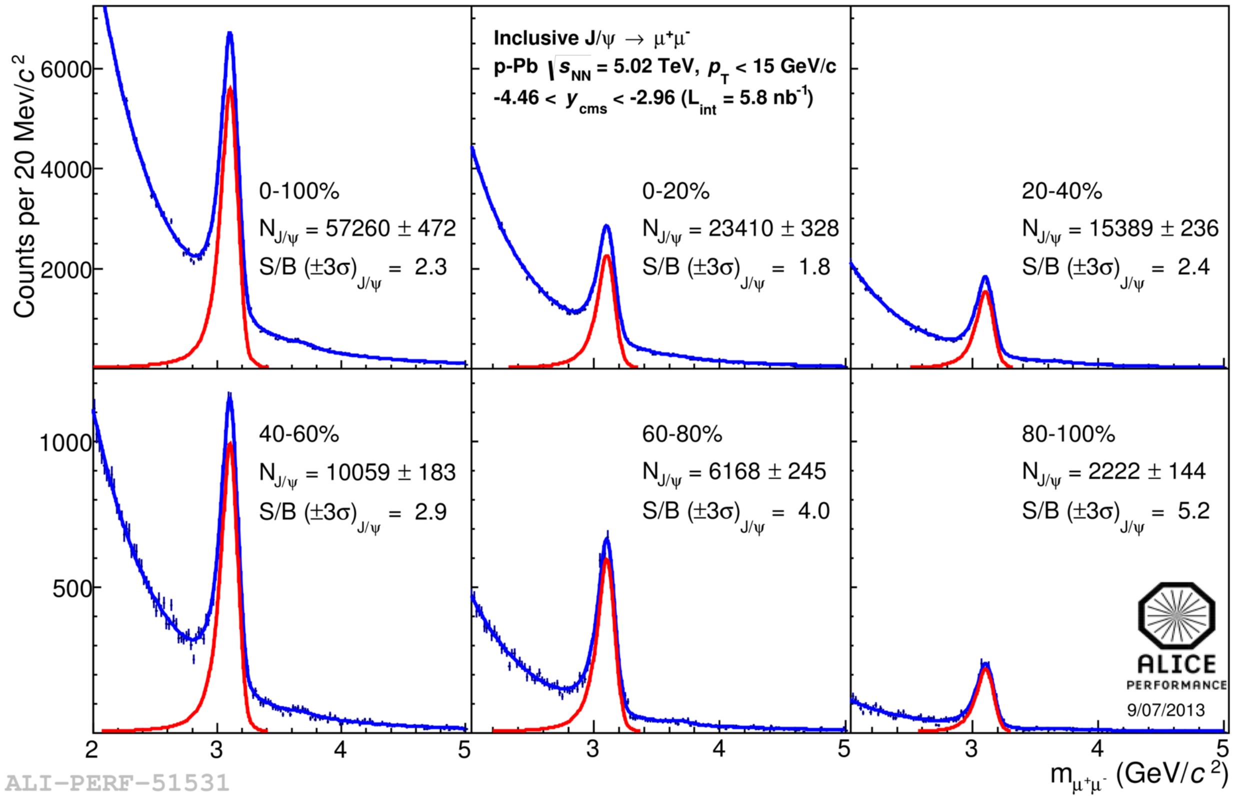
Summary…

ALICE has measured **inclusive J/ψ production in p-Pb run in backward and forward rapidity regions at $\sqrt{s_{NN}}$ = 5.02 TeV**. Many interesting results are obtained:

- Measured **strong p_T dependence of R_{FB} with a decrease at low p_T** is in a fair agreement with models including coherent energy loss contribution.
- **R_{pPb} and R_{Pbp} show an increase of suppression towards forward rapidity** in agreement with energy loss model and/or shadowing model EPS09 NLO.
- pure nuclear shadowing and/or energy loss seem to reasonably describe the data, indicating that **final state absorption may indeed be negligible at LHC energies**

…and outlook

- Many other interesting results are under study: R_{pPb} vs centrality, Ψ(2S) yield…

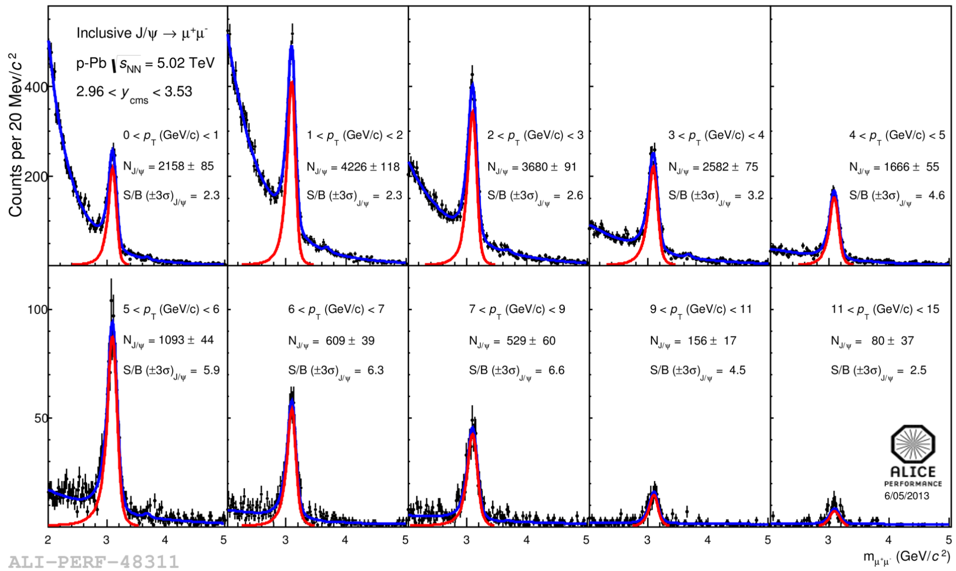


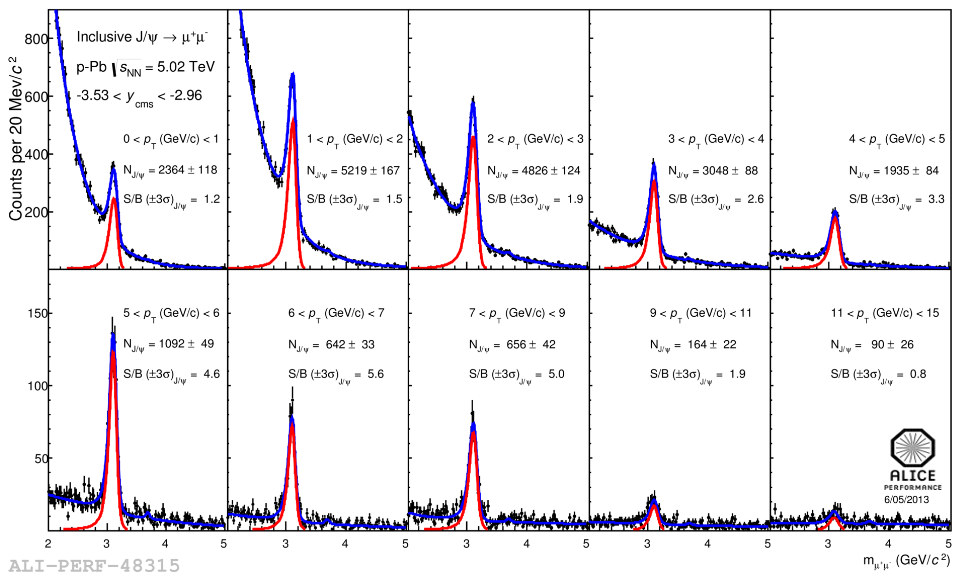
Stay tuned…

➢ Thank you for your attention!

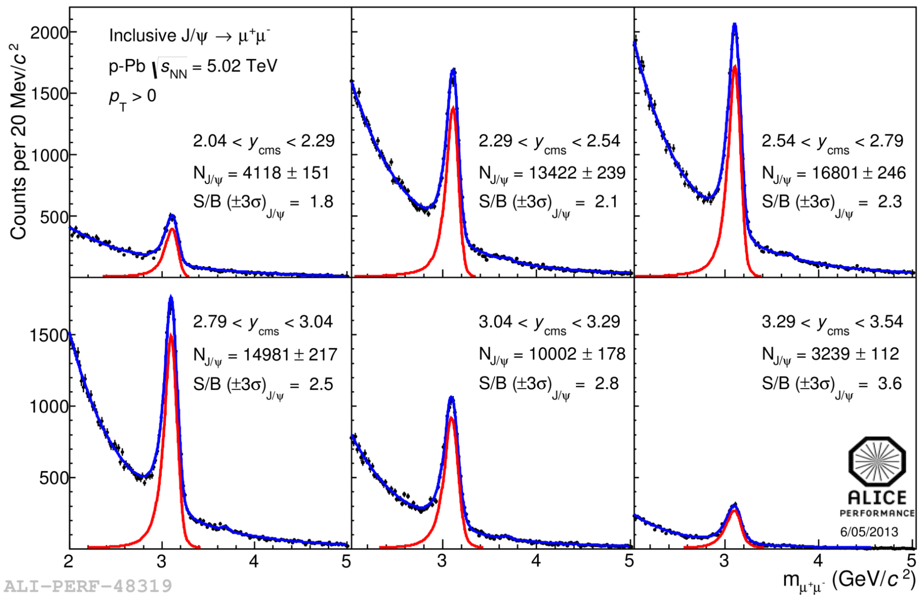
Backup slides

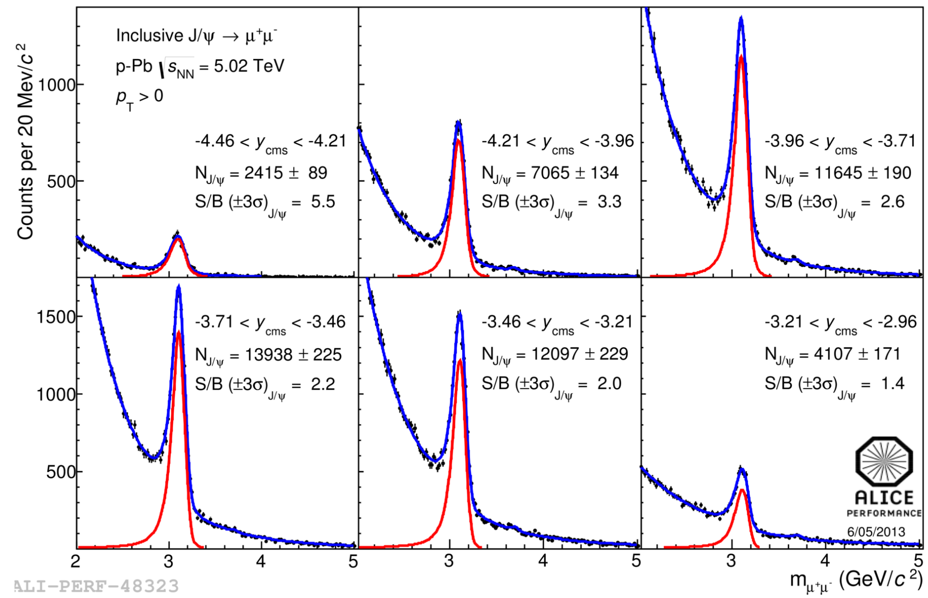
Signal extraction in p_T bins





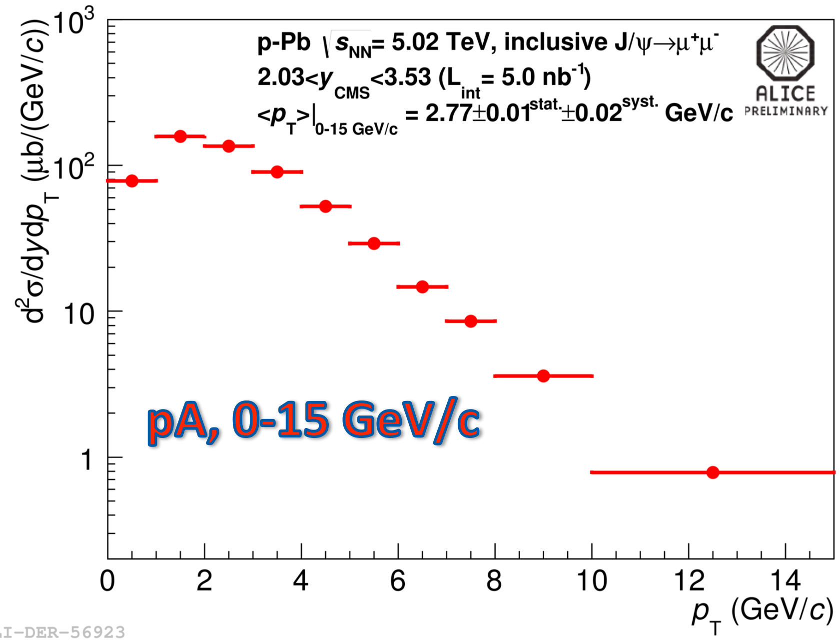
Signal extraction in *y* bins

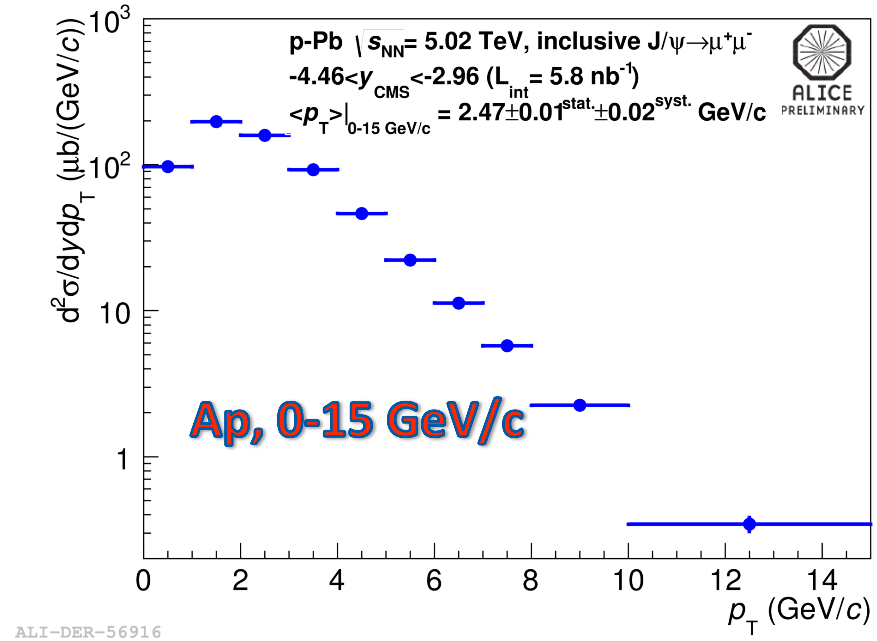




$d^2\sigma_{J/\psi}/dp_T dy$ and $<p_T>$ in full y-range

From the $d^2\sigma/dydp_T$ distributions one can calculate the mean p_T in the full y-range





pp, 0-8 GeV/c

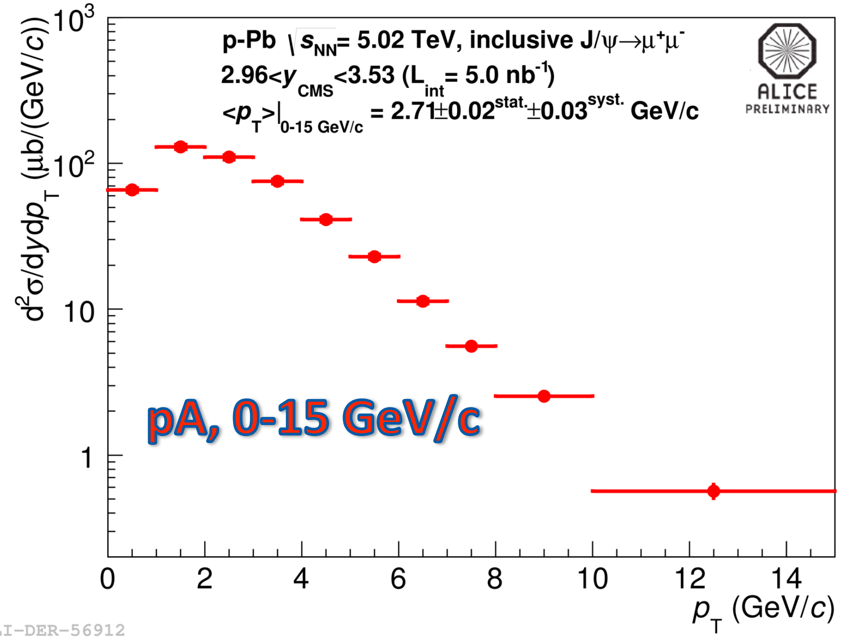
	$\langle p_t \rangle$ (GeV/c)	$\langle p_t^2 \rangle$ (GeV/c
$\sqrt{s} = 2.76$ TeV, $2.5 < y < 4$	$2.28 \pm 0.07 \pm 0.04$	7.06 ± 0.40
$\sqrt{s} = 7$ TeV, $\lvert y \rvert < 0.9$	$2.72 \pm 0.21 \pm 0.28$	10.02 ± 1.4
$\sqrt{s} = 7$ TeV, $2.5 < y < 4$	$2.44 \pm 0.09 \pm 0.06$	8.32 ± 0.50

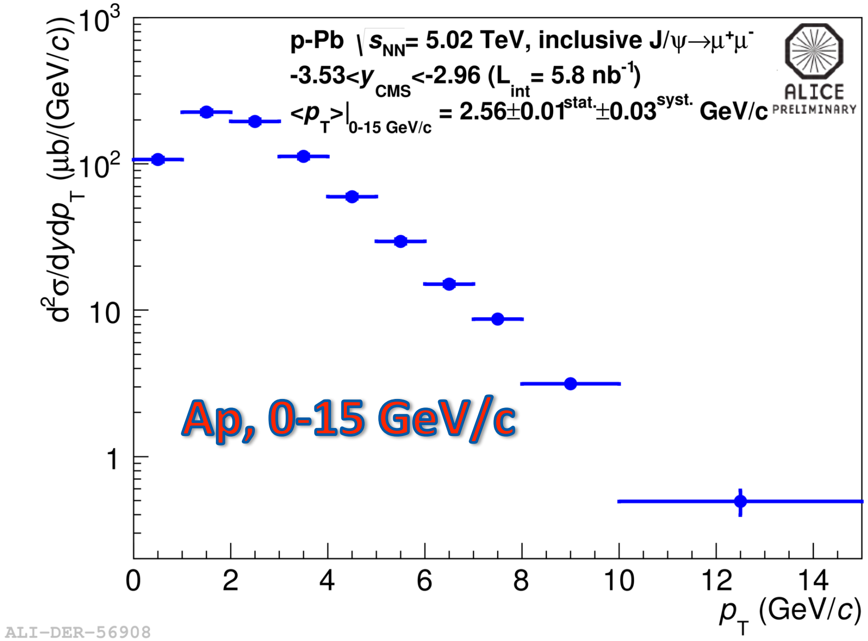
- $<p_T>|_{0\text{-}15\ GeV/c} = 2.77 \pm 0.01^{stat.} \pm 0.02^{syst.}$ GeV/c in p-Pb
- $<p_T>|_{0\text{-}15\ GeV/c} = 2.47 \pm 0.01^{stat.} \pm 0.02^{syst.}$ GeV/c in Pb-p

- $<p_T>$ is higher in p-Pb than in pp at $\sqrt{s_{NN}}$=7 TeV
- $<p_T>$ in Pb-p is close to the one in pp at $\sqrt{s_{NN}}$=7 TeV

$d^2\sigma_{J/\psi}/dp_T dy$ and $\langle p_T \rangle$ in common y-range

From the $d^2\sigma/dydp_T$ distributions one can calculate the mean p_T in the common y-range



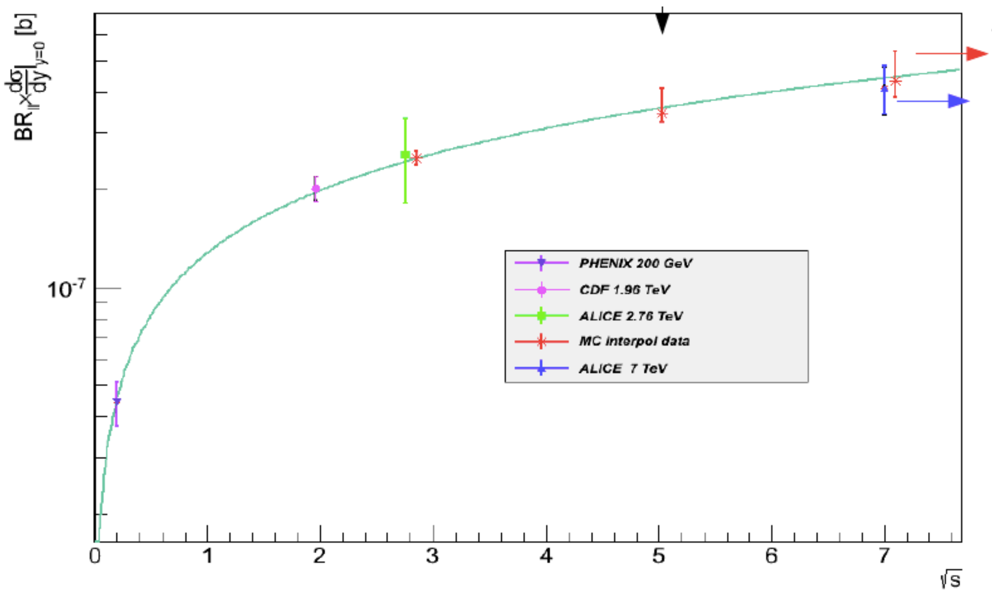


- **$\langle p_T \rangle|_{0\text{-}15\ GeV/c} = 2.71 \pm 0.02^{stat.} \pm 0.03^{syst.}$ GeV/c in p-Pb**
  – > compare to $\langle p_T \rangle|_{0\text{-}15\ GeV/c}$ = **2.77** $\pm 0.01^{stat.} \pm 0.02^{syst.}$ GeV/c in the full y-range

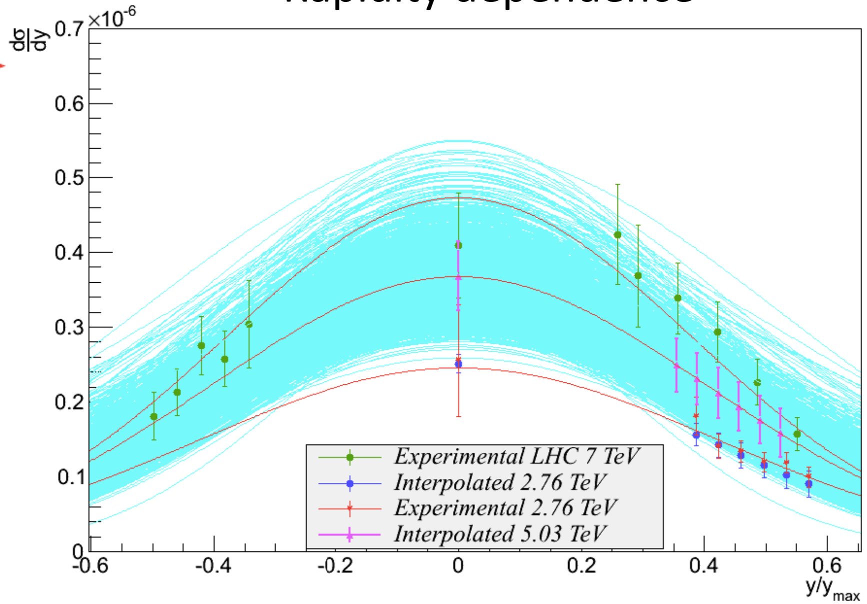
- **$\langle p_T \rangle|_{0\text{-}15\ GeV/c} = 2.56 \pm 0.01^{stat.} \pm 0.03^{syst.}$ GeV/c in Pb-p**
  – > compare to $\langle p_T \rangle|_{0\text{-}15\ GeV/c}$ = **2.47** $\pm 0.01^{stat.} \pm 0.02^{syst.}$ GeV/c in the full y-range

Interpolation of $\sigma_{J/\psi}^{pp}$ at $\sqrt{s_{NN}}$=5.02 TeV

Energy dependence



Rapidity dependence



Signal shapes functions

CB extended

$$f(x;N,\bar{x},\sigma,\alpha,n,\alpha',n') = N\cdot\begin{cases}\exp\left(-\frac{(x-\bar{x})^2}{2\sigma^2}\right), & for\ \frac{(x-\bar{x})}{\sigma} > -\alpha \\ A\cdot\left(B-\frac{x-\bar{x}}{\sigma}\right)^{-n}, & for\ \frac{(x-\bar{x})}{\sigma} \le -\alpha \\ C\cdot\left(D+\frac{x-\bar{x}}{\sigma}\right)^{-n'}, & for\ \frac{(x-\bar{x})}{\sigma} \ge \alpha'\end{cases}$$

$$A = \left(\frac{n}{|\alpha|}\right)^n \cdot \exp\left(-\frac{|\alpha|^2}{2}\right)$$

$$B = \frac{n}{|\alpha|} - |\alpha|$$

$$C = \left(\frac{n'}{|\alpha'|}\right)^{n'} \cdot \exp\left(-\frac{|\alpha'|^2}{2}\right)$$

$$D = \frac{n'}{|\alpha'|} - |\alpha'|$$

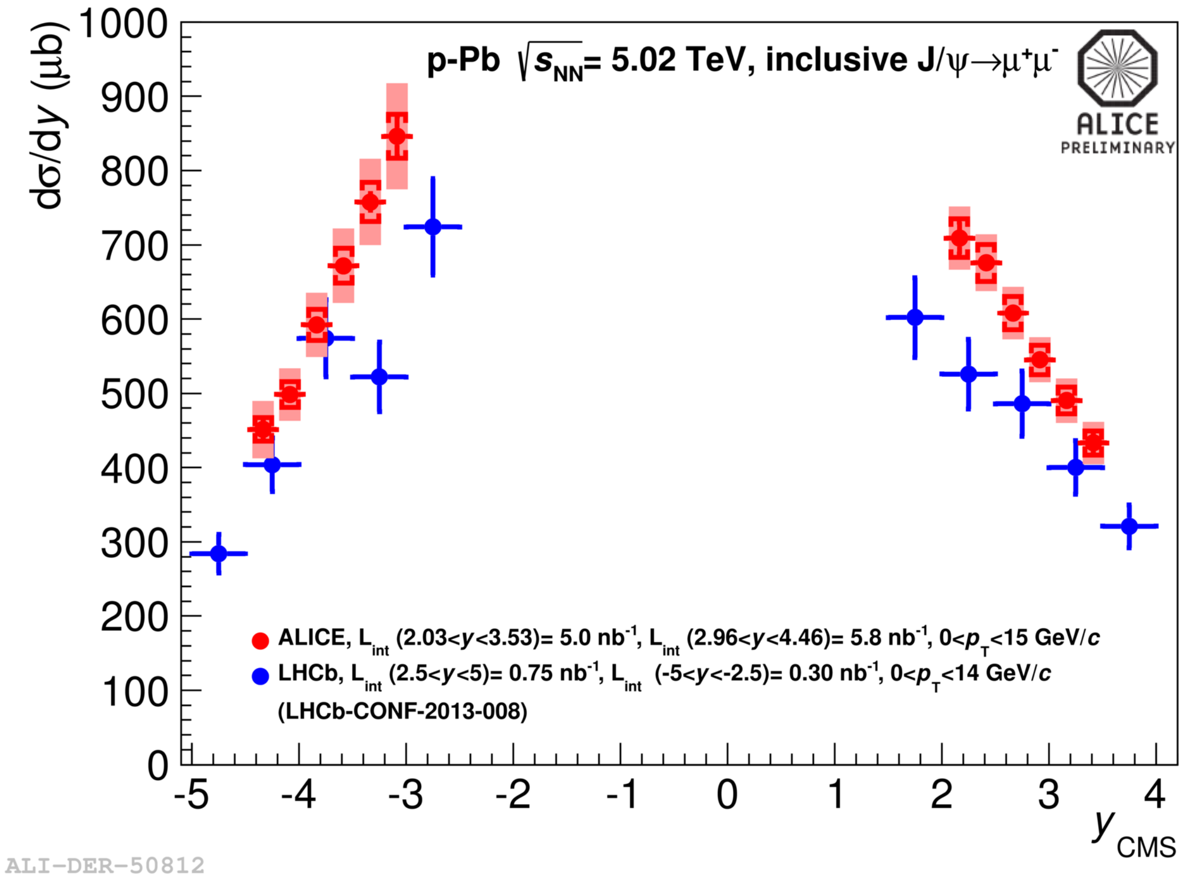
NA60 function

$$f(x;N,\bar{x},\sigma,x_1,x_2,p_1,\ldots,p_6) = N\cdot\exp\left(-\frac{(x-\bar{x})^2}{2\sigma_{NA60}^2}\right)$$

$$\sigma_{NA60} = \begin{cases}\sigma\cdot\left(1+p_1(x_1-x)^{p_2-p_3\sqrt{x_1-x}}\right), & for\ x < x_1 \\ \sigma, & for\ x_1 \le x < x_2 \\ \sigma\cdot\left(1+p_4(x-x_2)^{p_5-p_6\sqrt{x-x_2}}\right), & for\ x \ge x_2\end{cases}$$

- ✓ Parameters *N*, *σ*, *x* are left free in the data
- ✓ All the other parameters are fixed on the tuned MC

Comparison of ALICE results with LHCb - 1



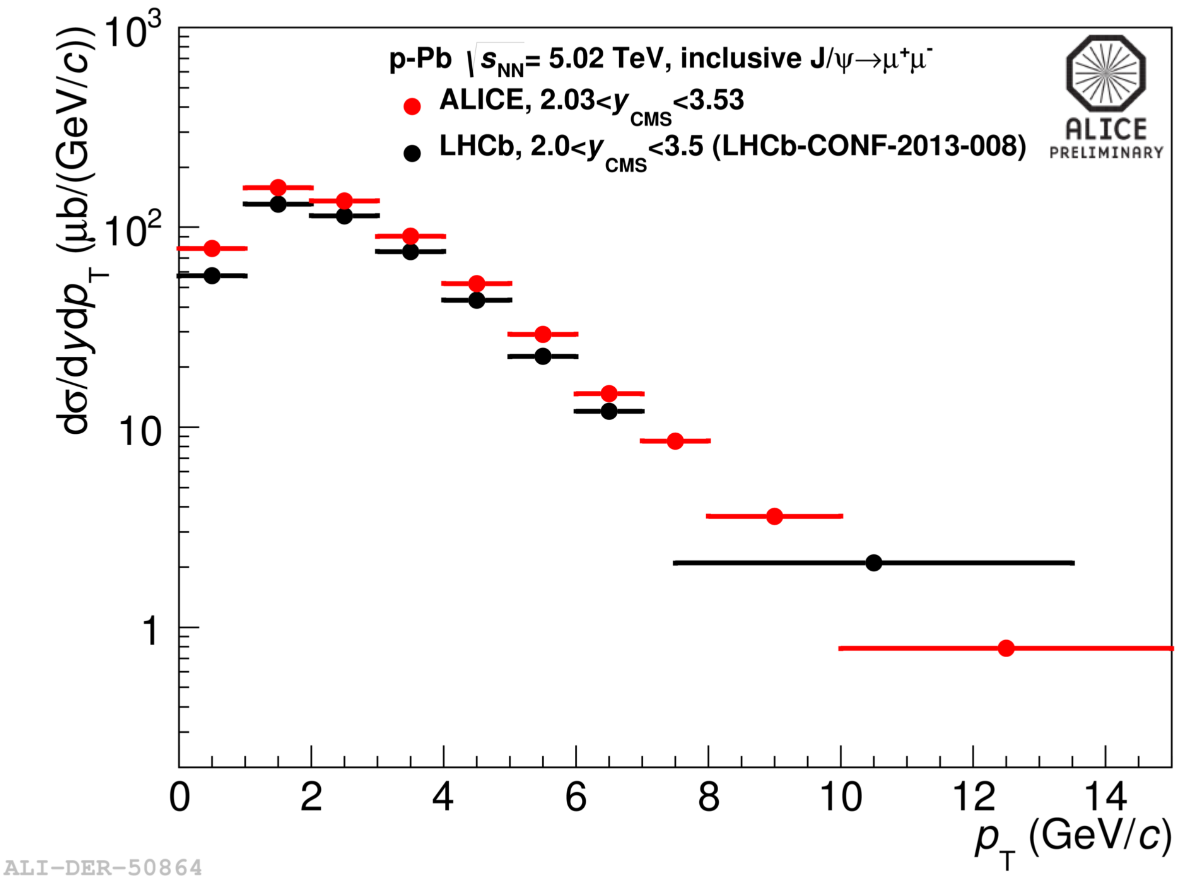
ALICE uncertainties:

- ✧ **Statistical uncertainties** (line)
- ✧ **Systematic uncertainties:**

Corr. uncertainties (brackets): luminosity, normalization factor, BR
(Luminosity is correlated within p-Pb or Pb-p, but not within the two systems)
Uncorr. uncertainties (filled boxes): matching, trigger, tracking, acc. inputs, signal extraction

- ➢ Visible disagreement in results.
- ➢ Only half of statistics analyzed by LHCb.
- ➢ Difference in cross-sections seems to be the main source of the discrepancy.
- ➢ Work in progress on understanding the discrepancy between experiments.

Comparison of ALICE results with LHCb - 2



ALICE uncertainties:

✧ **Statistical uncertainties** (line)

✧ **Systematic uncertainties:**

Corr. uncertainties (brackets): luminosity, normalization factor, BR (Luminosity is correlated within p-Pb or Pb-p, but not within the two systems)

Uncorr. uncertainties (filled boxes): matching, trigger, tracking, acc. inputs, signal extraction

- Visible disagreement in results.
- Same conclusions as in the previous slide.
- Work in progress on understanding the discrepancy between experiments.