Quarkonium production in p-Pb at the LHC

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Outline

- (Short) Introduction
- Charmonia in p-Pb collisions
- Bottomonia in p-Pb collisions
- Summary

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- Charmonia in p-Pb collisions
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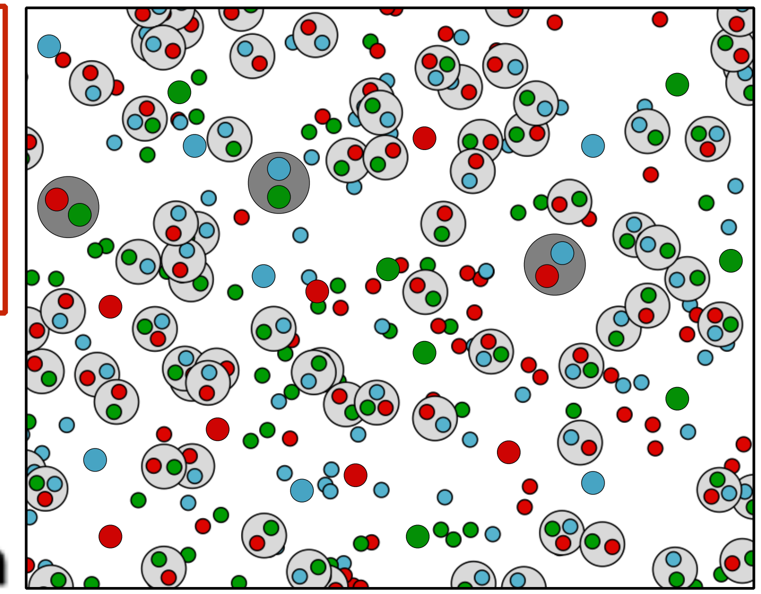
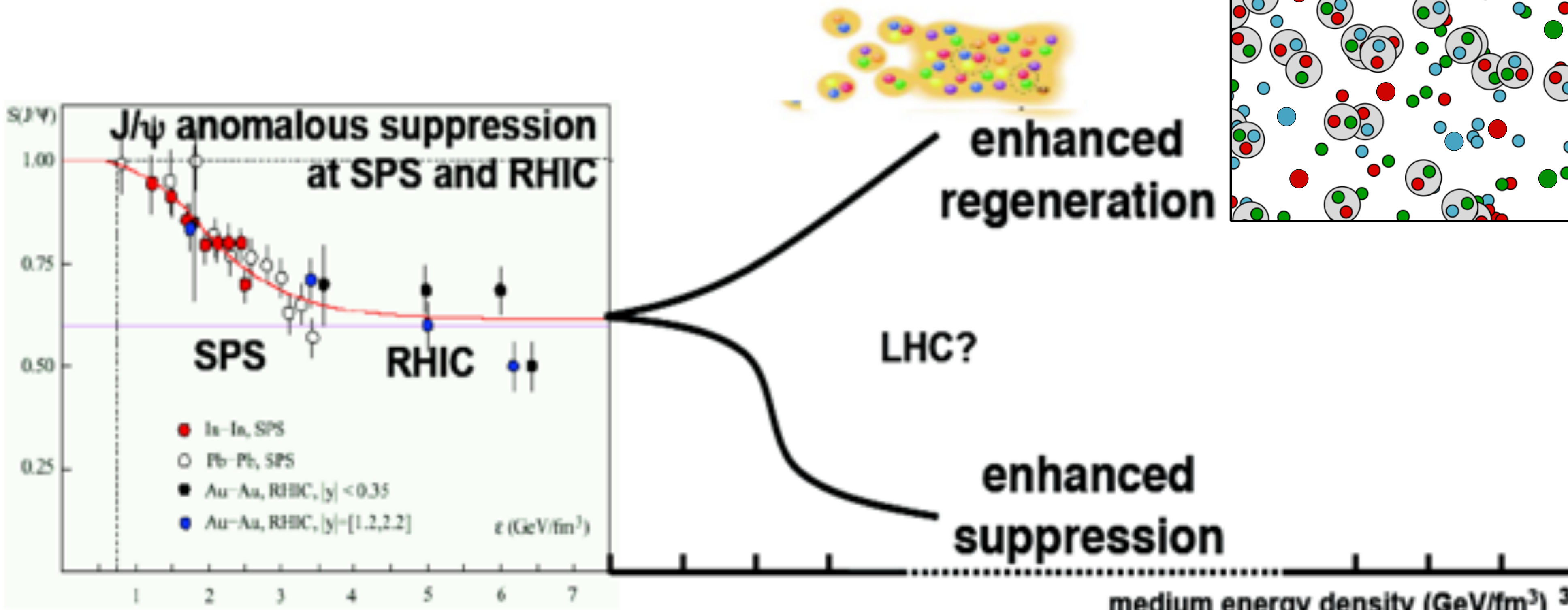
- Event activity results in Davide's talk!

Quarkonia

If c-cbar pairs are abundantly produced and thermalize with the medium, recombination could compensate or exceed colour-screening suppression

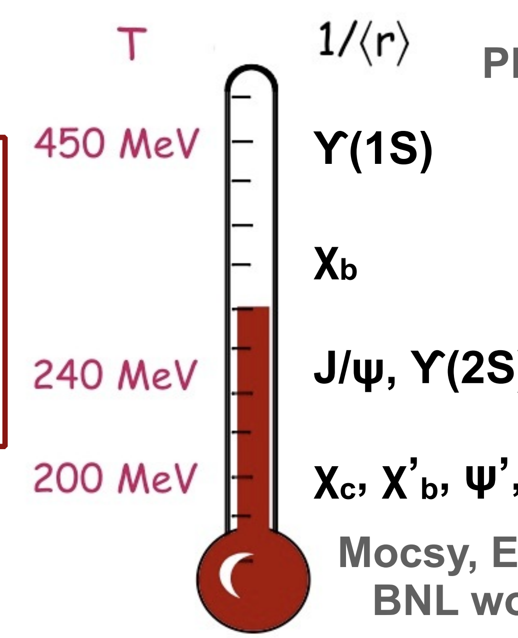




“Cold Nuclear Matter” effects could alter the quarkonium yields: nuclear absorption, gluon shadowing, …

Sequential quarkonium suppression by colour-screening could provide a measurement of the QGP initial temperature

Matsui & Satz, PLB168 (1986) 415

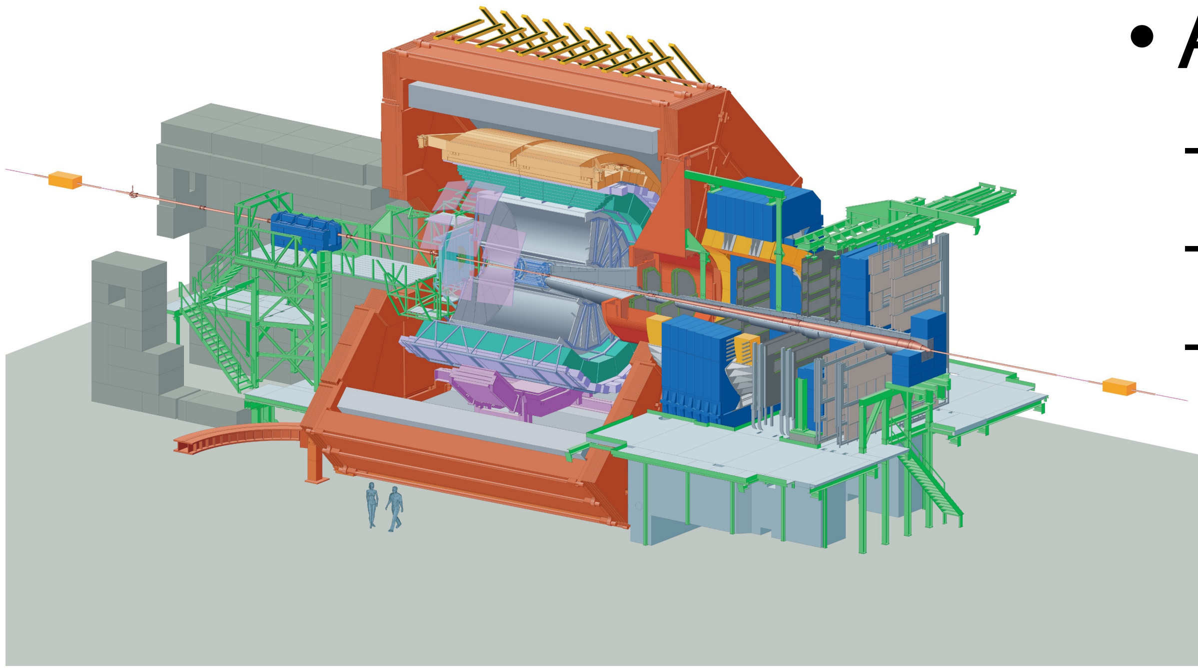


Mocsy, EPJC61 (2009) 705
BNL workshop in June

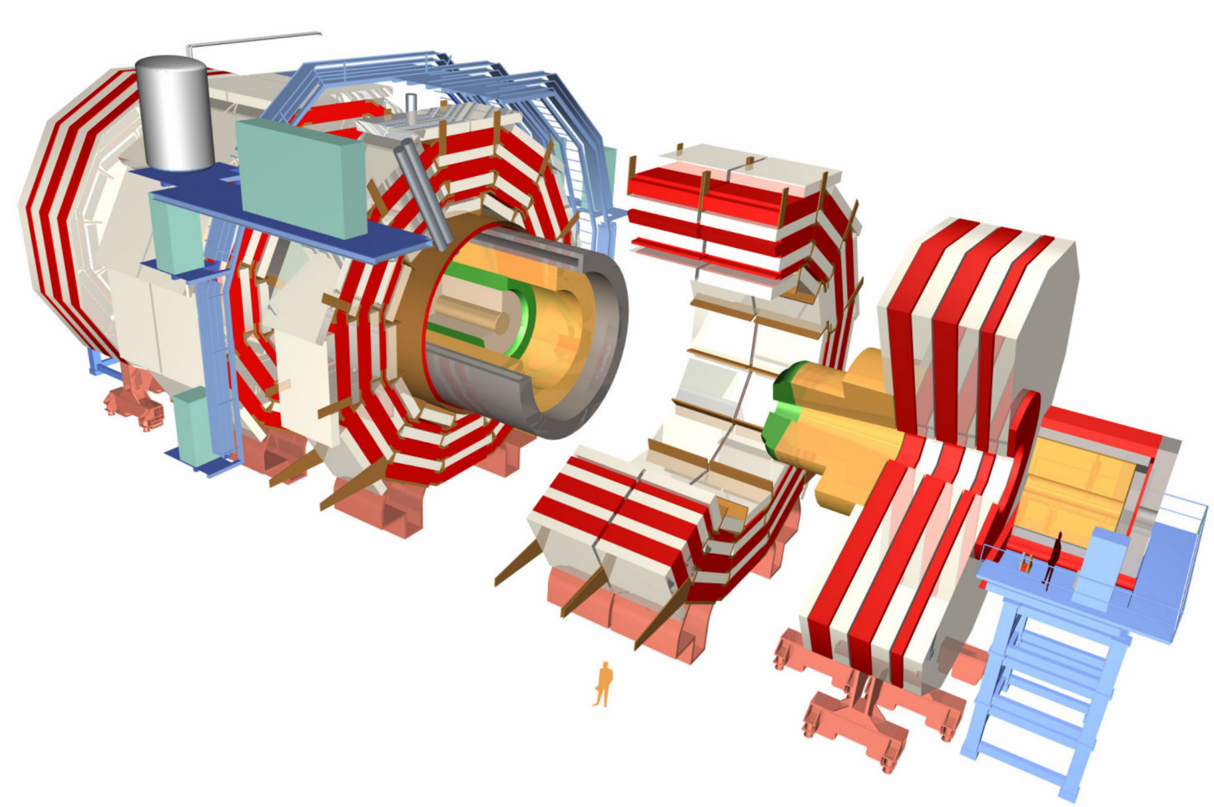
Quarkonia in p-A collisions

- In Pb-Pb collisions quarkonium production is affected by the QGP and by Cold Nuclear Matter (CNM) effects
- p-A collisions used to study CNM effects in the absence of a hot medium
- Main effects
  - Modification of the Parton Distribution Functions in the nuclei with respect to free nucleons
    - “gluon Shadowing”
  - Saturation via Colour Glass Condensate (CGC)
  - Coherent parton energy loss
  - Nuclear absorption
    - Expected to be negligible at LHC energies
- J/ψ and Υ in p-Pb collisions are complementary
  - Different mass
  - Different kinematics range (Bjorken-x) probed

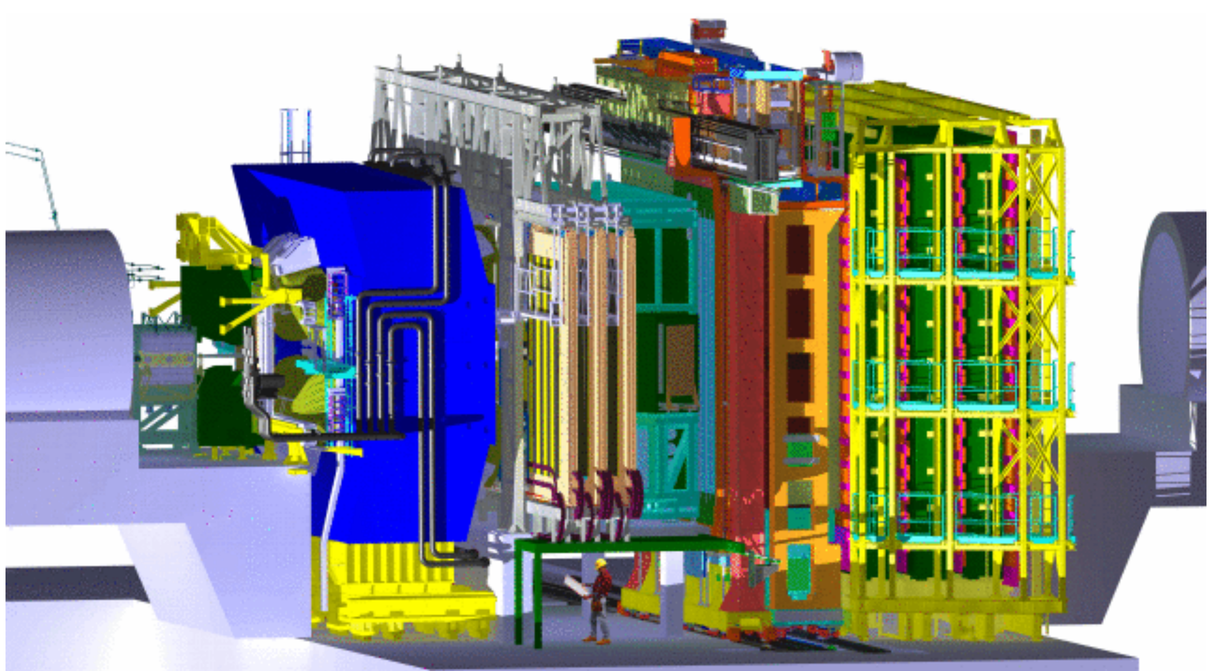
ALICE – CMS – LHCb



- ALICE
  - -4.46 < y < -2.96 (μμ, Pb-going)
  - -1.37 < y < 0.43 (ee)
  - 2.03 < y < 3.53 (μμ, p-going)

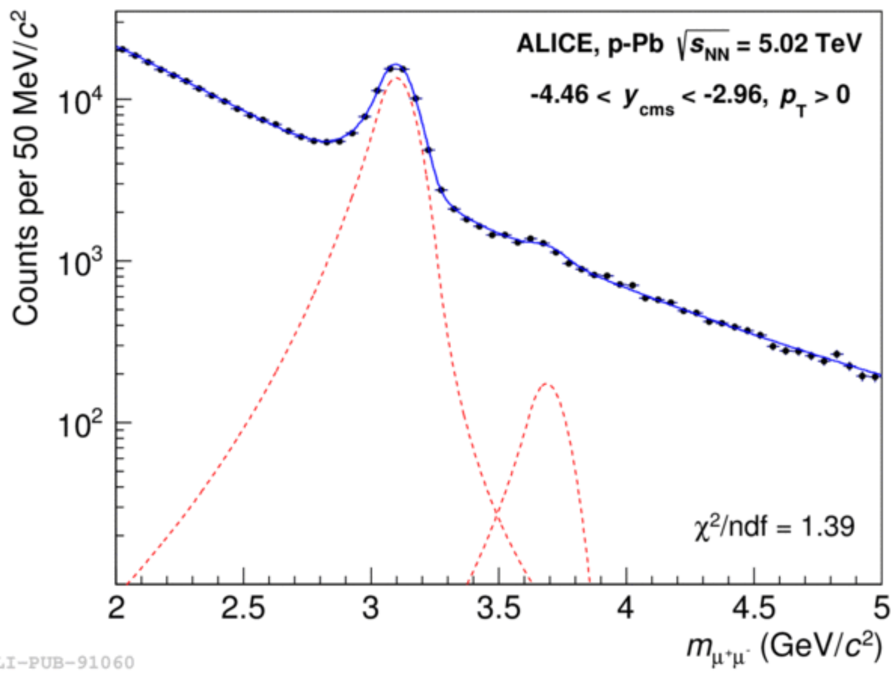


- CMS
  - -1.93 < y < 1.93 (μμ)



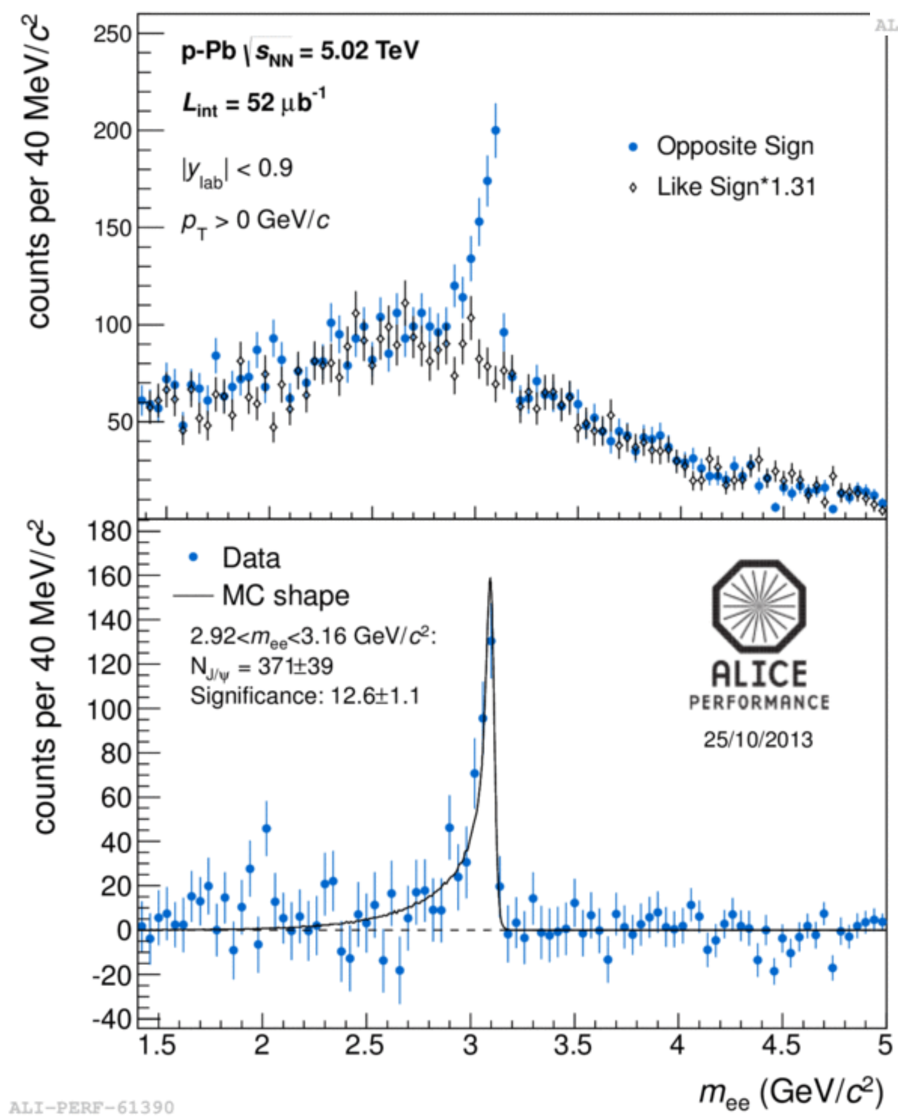
- LHCb
  - -5.00 < y < -2.50 (μμ, Pb-going)
  - 1.50 < y < 4.00 (μμ, p-going)

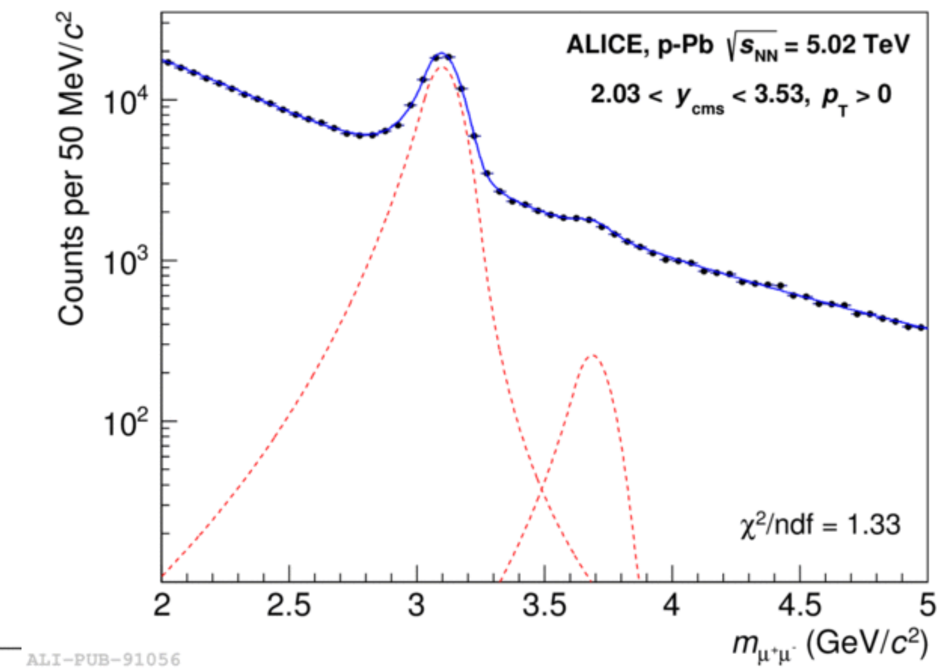
J/ψ in ALICE



- $-4.46 < y < -2.96$ (Pb-going)
  - $\mu^+\mu^-$
  - Inclusive
  - L_{int} = 5.8 nb^{-1}

- $-1.37 < y < 0.43$
  - e^+e^-
  - Inclusive
  - L_{int} = 52 μb^{-1}





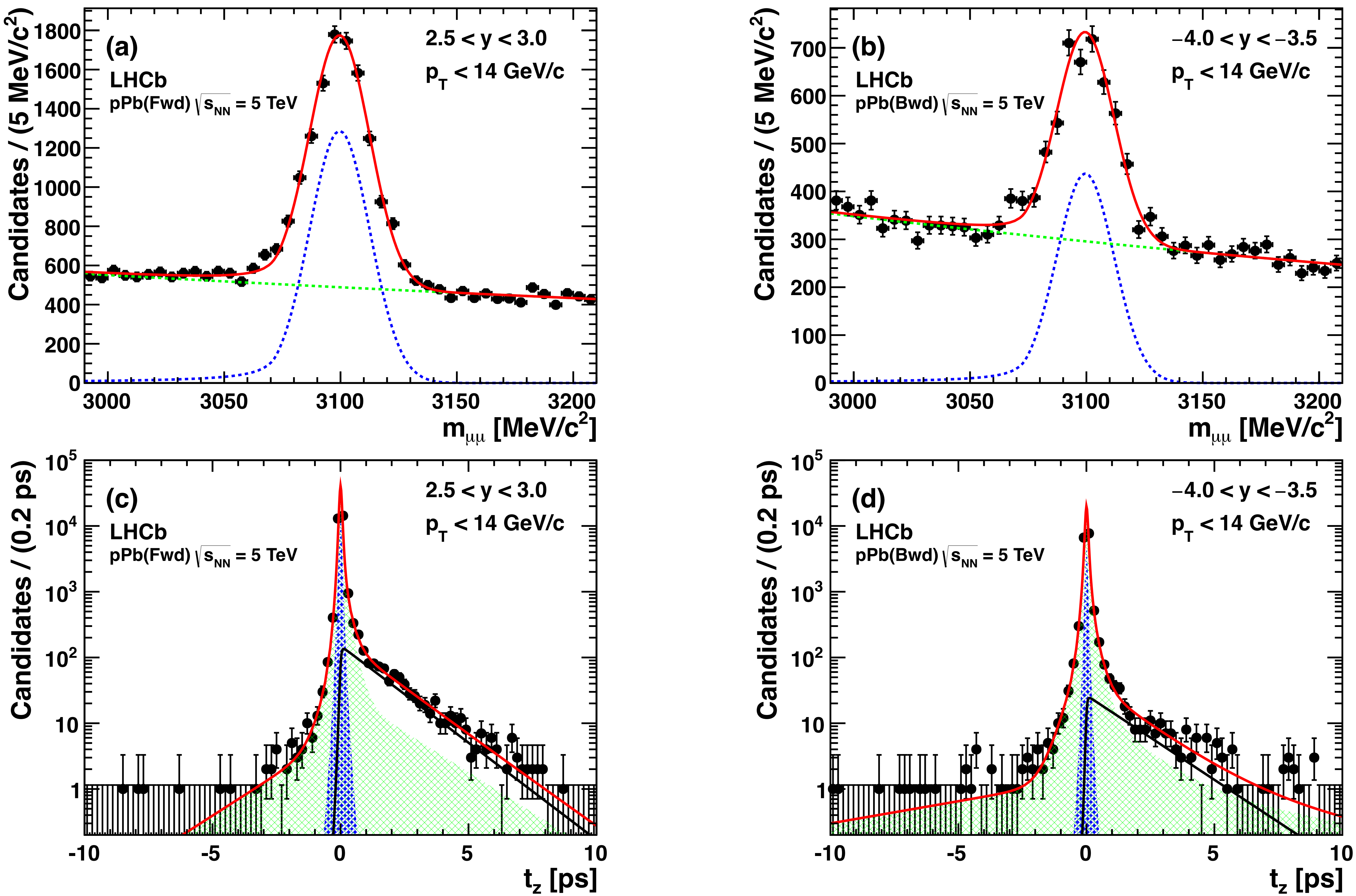
- $2.03 < y < 3.53$ (p-going)
  - $\mu^+\mu^-$
  - Inclusive
  - L_{int} = 5.0 nb^{-1}

Inclusive J/ψ measurements, include:

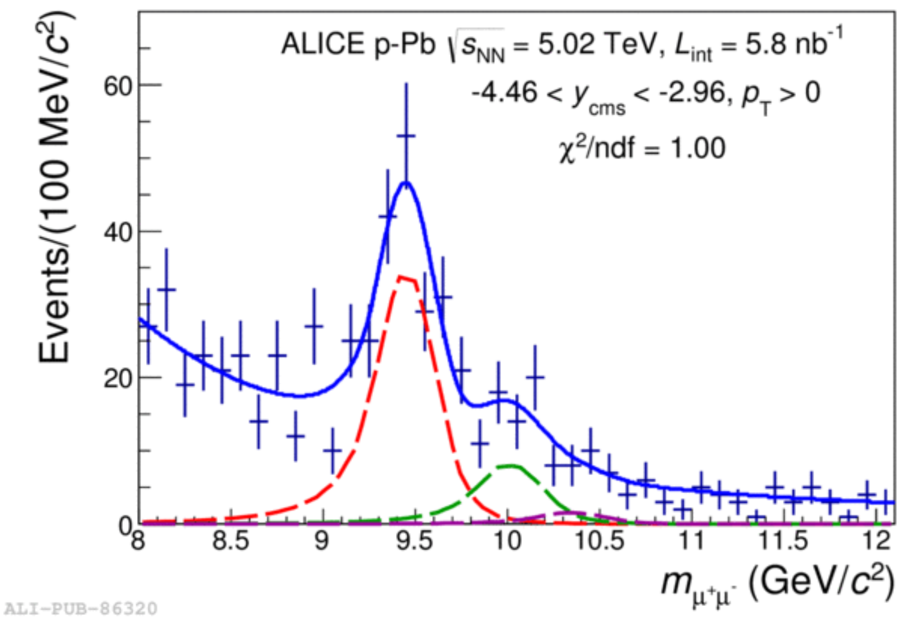
- Promp (direct J/ψ and feed down from higher mass charmonium states)
- Non-prompt (feed down from b-hadron decays)

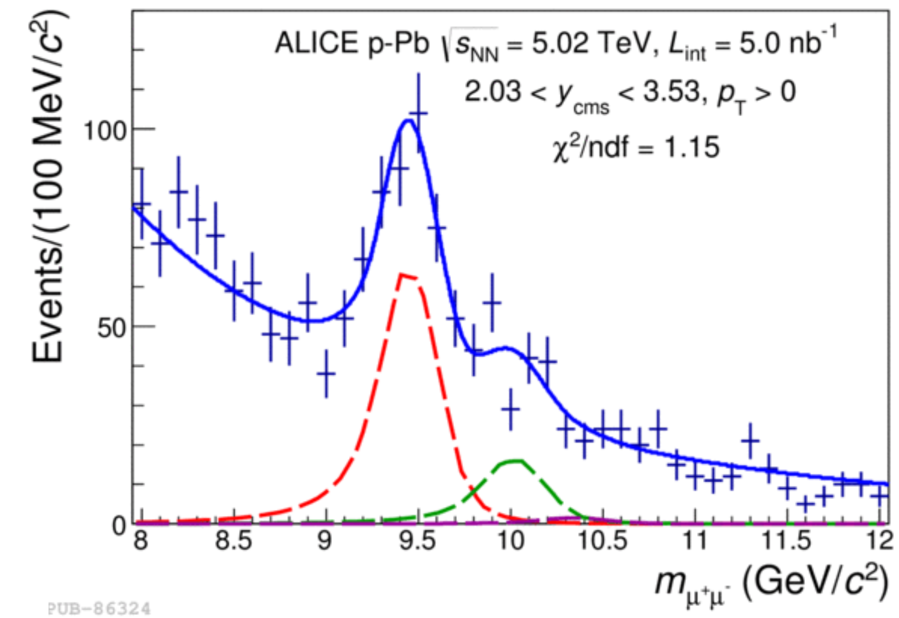
J/ψ in LHCb

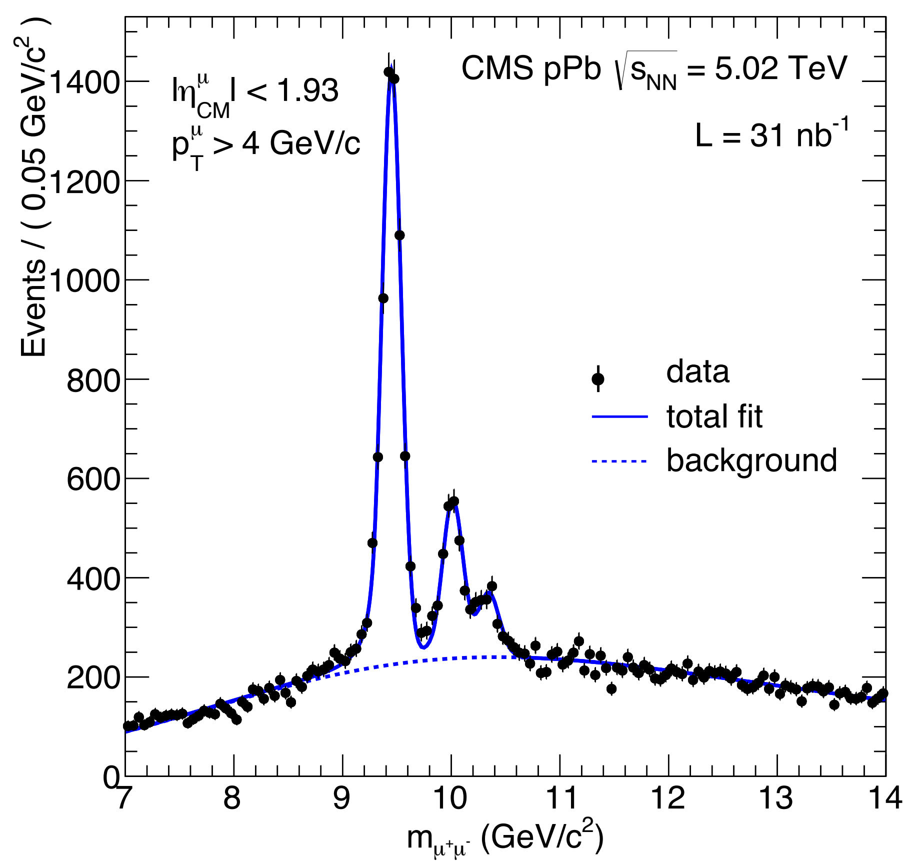
- Prompt and non-prompt separation using simultaneous fit of invariant mas and pseudo-proper decay time distributions

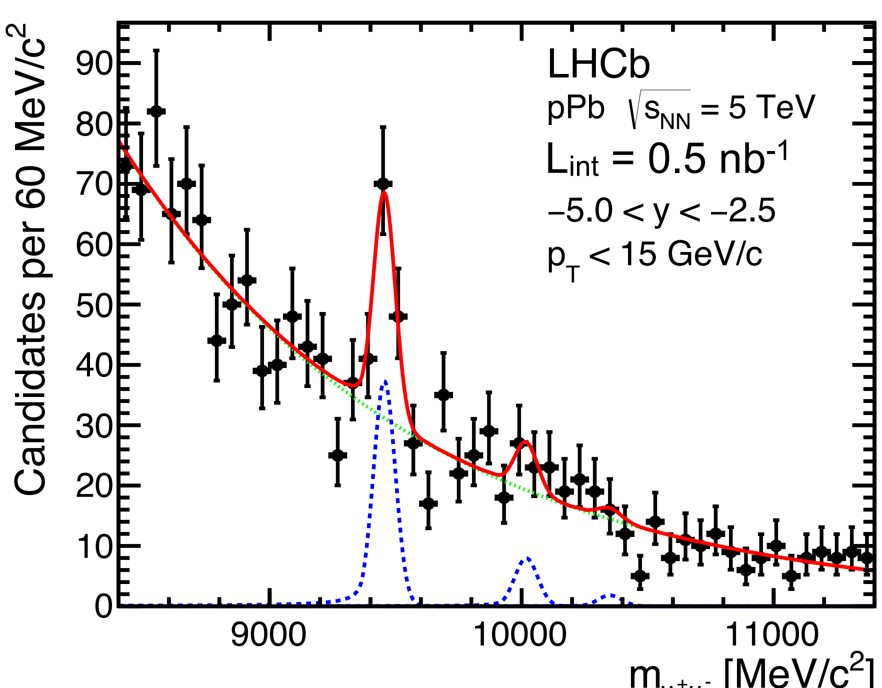


Inclusive Υ

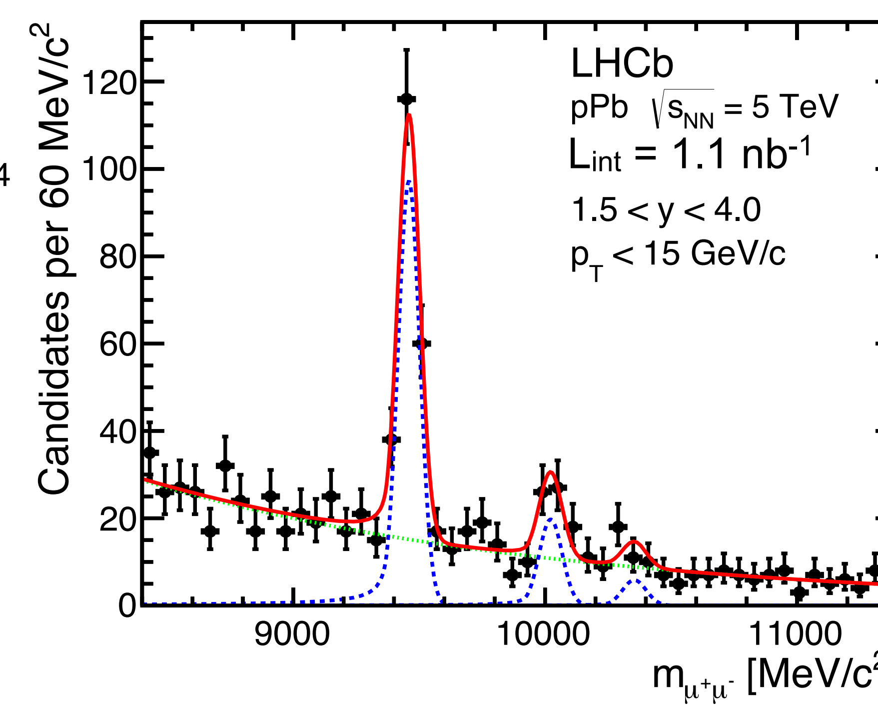








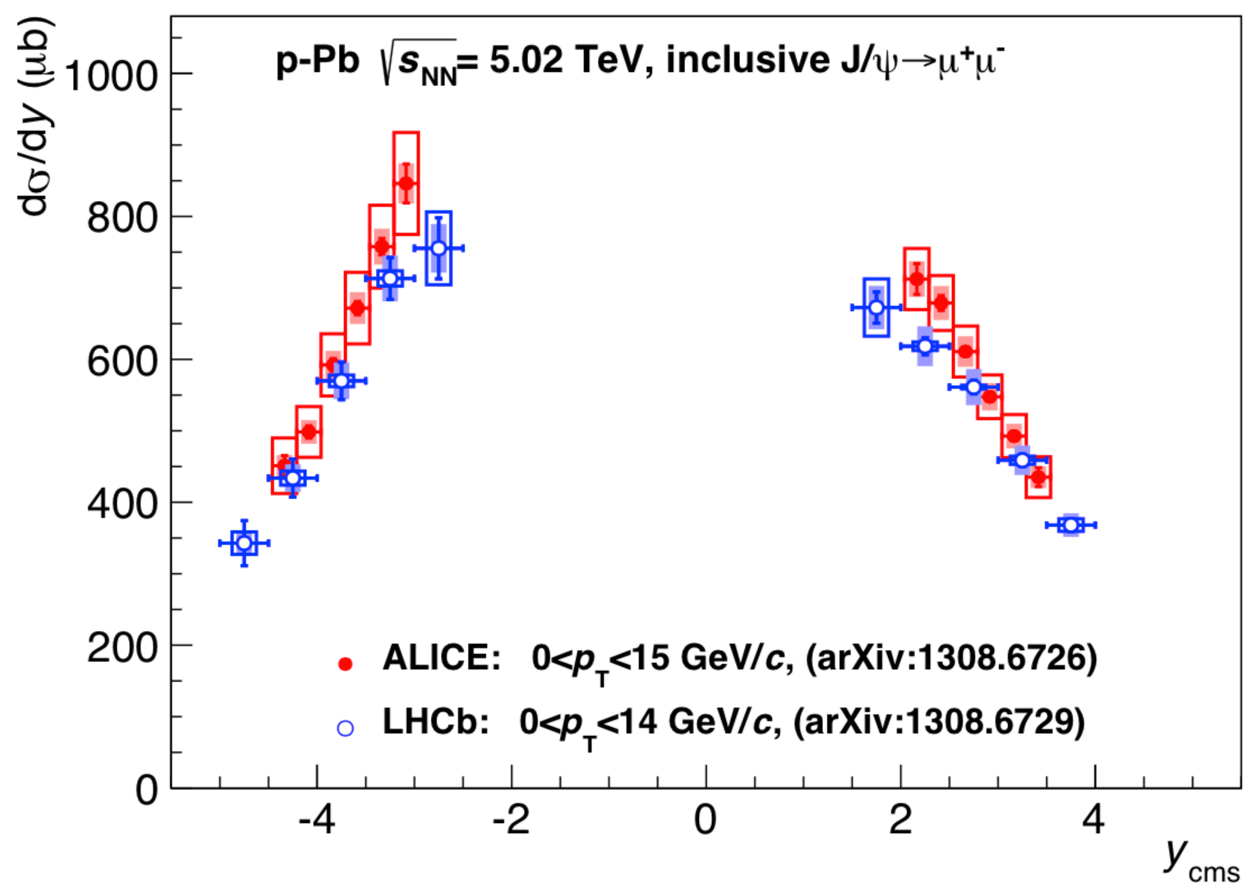
- In all cases
  - $p_T > 0$
  - $\mu^+\mu^-$
  - Υ(1S), Υ(2S) (and Υ(3S))

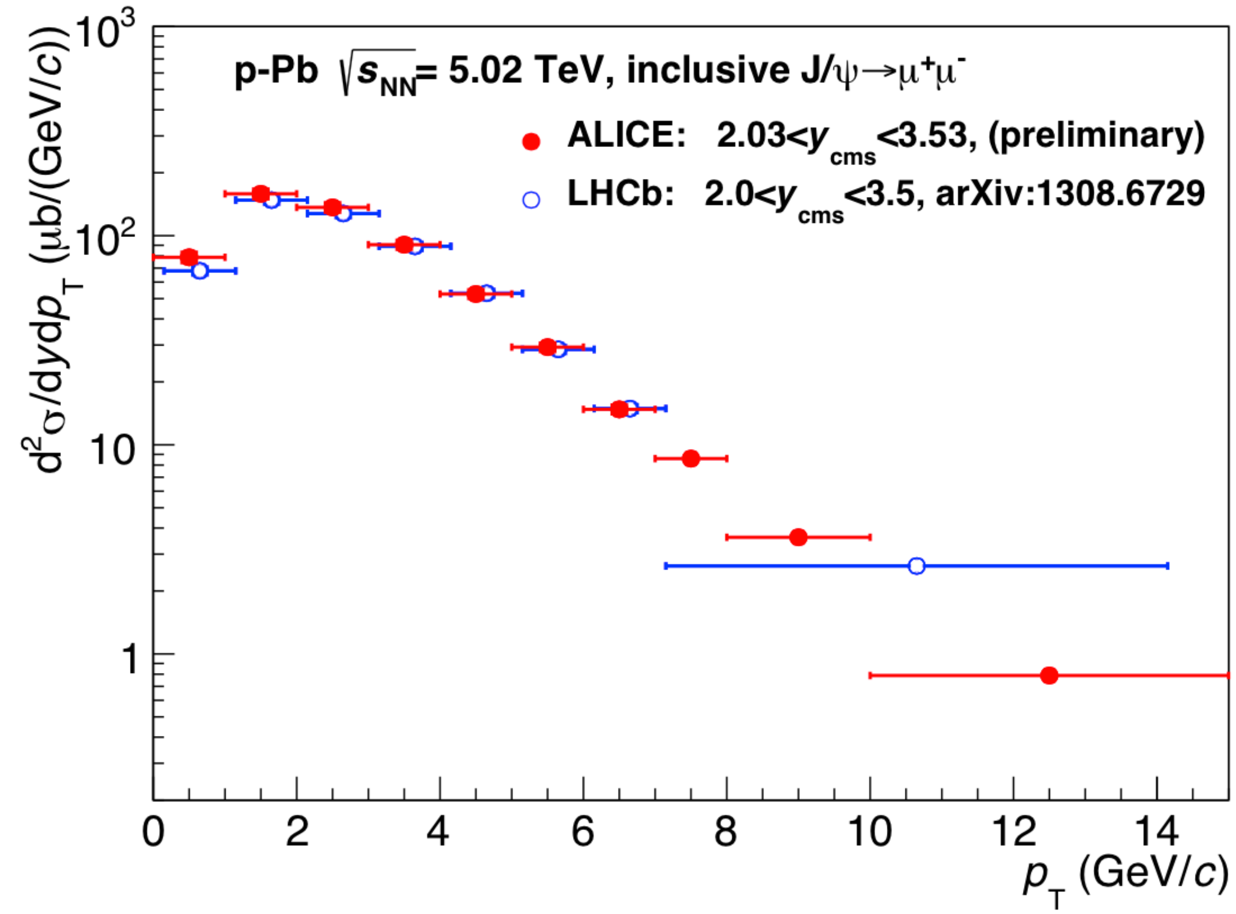


Comparison ALICE/LHCb

ALICE-PUBLIC-2013-002 – LHCb-CONF-2013-013

- Inclusive J/ψ
- Good agreement between ALICE and LHCb results

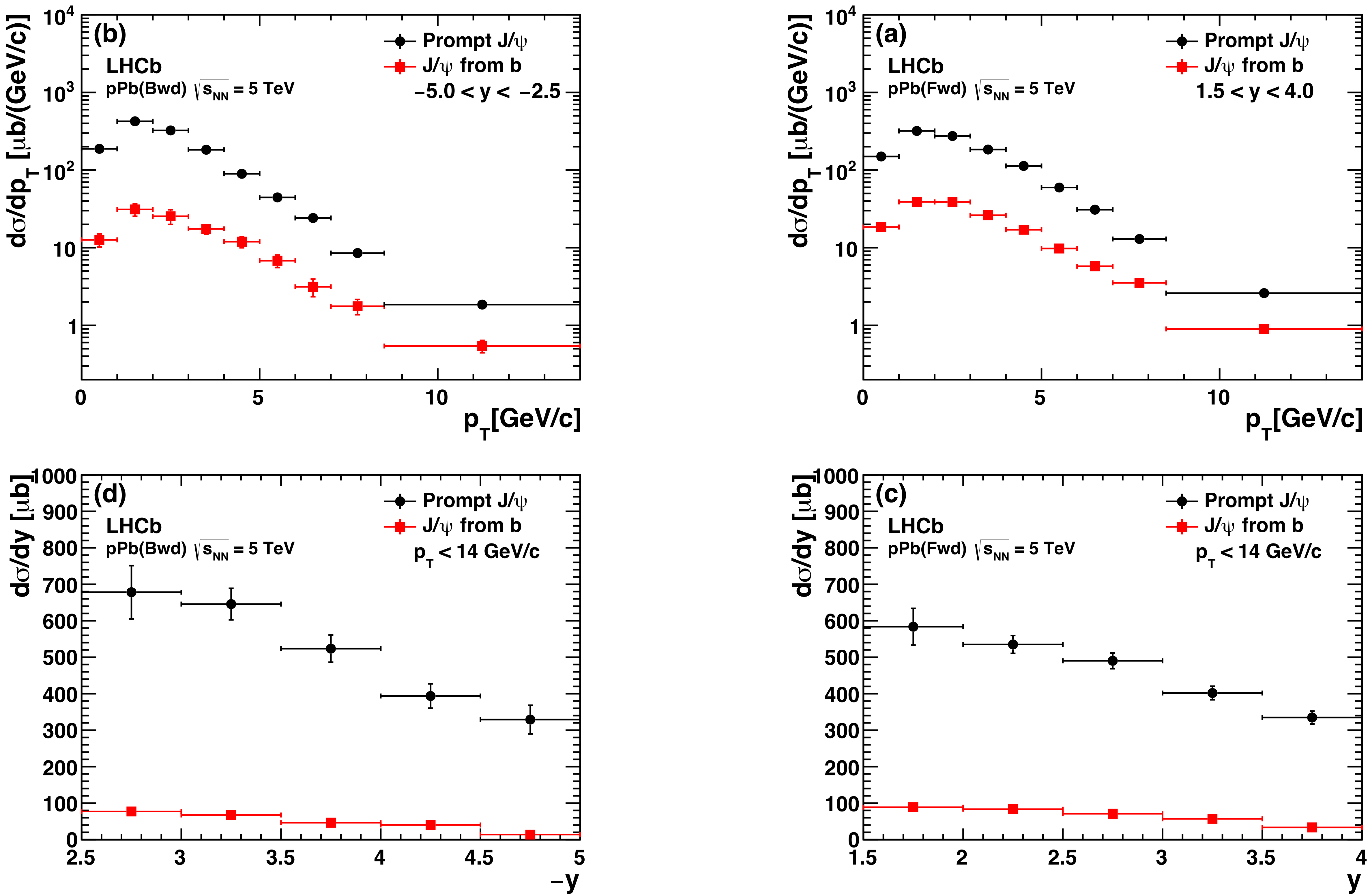




Prompt and Non-prompt J/ψ production cross section

JHEP 02 (2014) 072

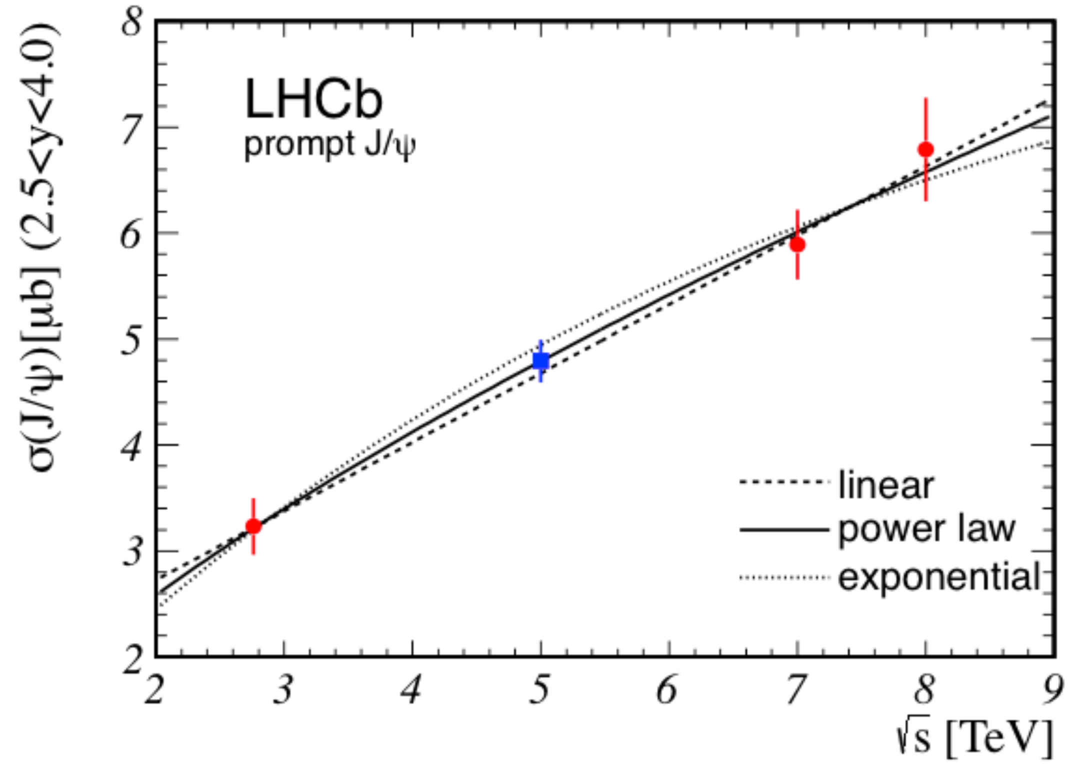
- Non-prompt J/ψ are about 10% of Prompt J/ψ

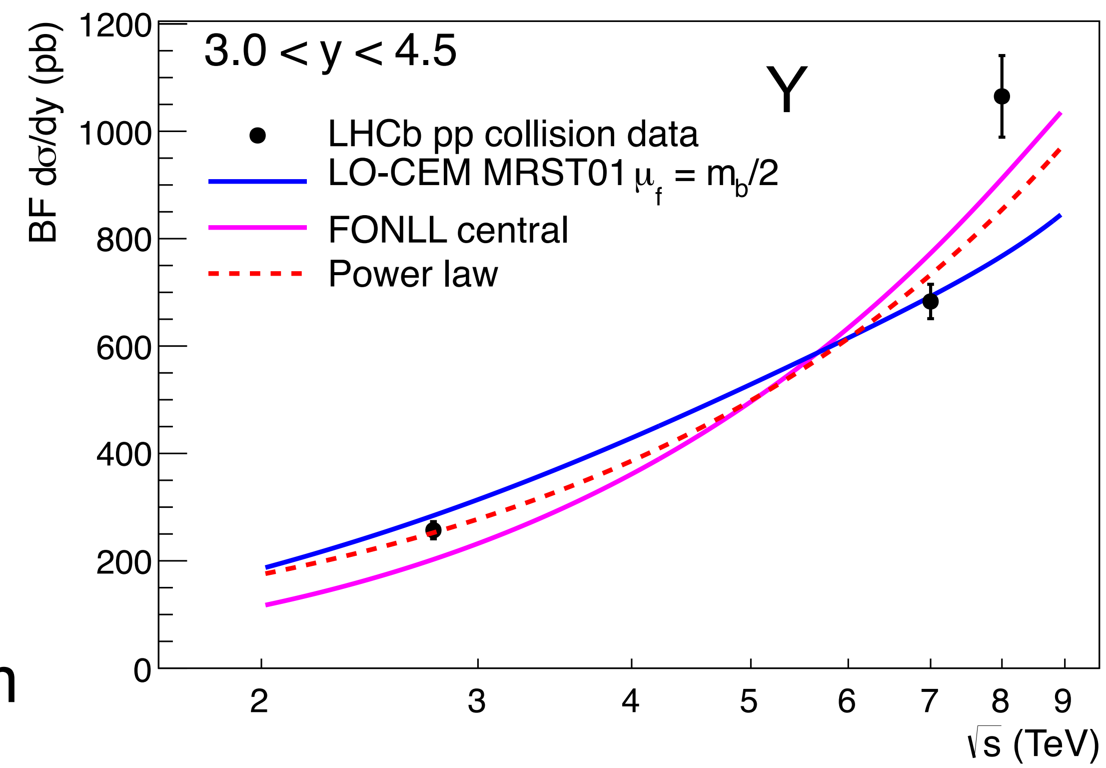


pp reference @ 5.02 TeV

ALICE-PUBLIC-2013-002 – LHCb-CONF-2013-013
ALICE-PUBLIC-2014-002 – LHCb-CONF-2014-003

- CNM effects evaluated via the nuclear modification factor R_{pPb}
- Need pp reference at same $\sqrt{s_{NN}}$
- Joint effort by the ALICE and LHCb collaborations
- Energy interpolation at forward rapidity
  - J/ψ [ALICE-PUBLIC-2013-002] [LHCb-CONF-2013-013]
    - using either ALICE data at 2.76 and 7 TeV or LHCb data at 2.76, 7 and 8 TeV
    - and several "reasonable" functional forms
    - but also pQCD FONLL calculations
    - rapidity extrapolation using gaussian, pol2 and pol4 functions (ALICE)
  - Υ [ALICE-PUBLIC-2014-002] [LHCb-CONF-2014-003]
    - using LHCb data at 2.76, 7 and 8 TeV
    - and several "reasonable" functional forms
    - but also pQCD FONLL calculations
- More details in Martino's talk, 11/12/14 @ 9 am





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    - rapidity extrapolation using gaussian, pol2 and pol4 functions (ALICE)
  - Υ [ALICE-PUBLIC-2014-002] [LHCb-CONF-2014-003]
    - using LHCb data at 2.76, 7 and 8 TeV
    - and several “reasonable” functional forms
    - but also pQCD FONLL calculations
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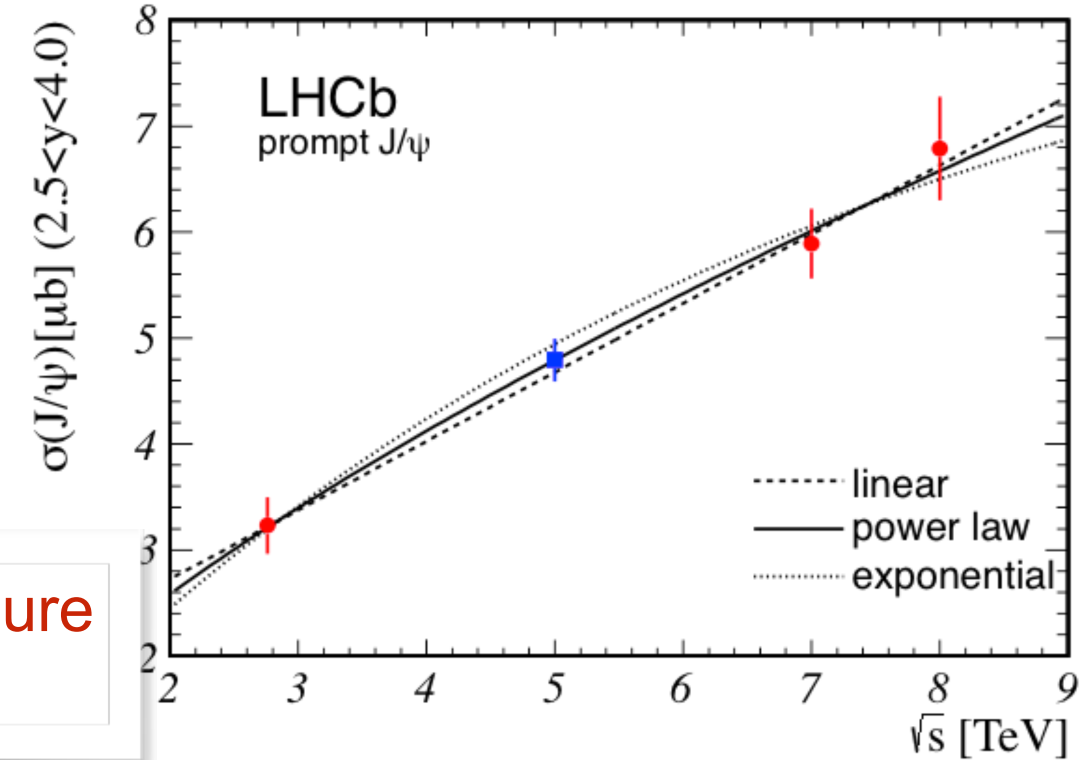
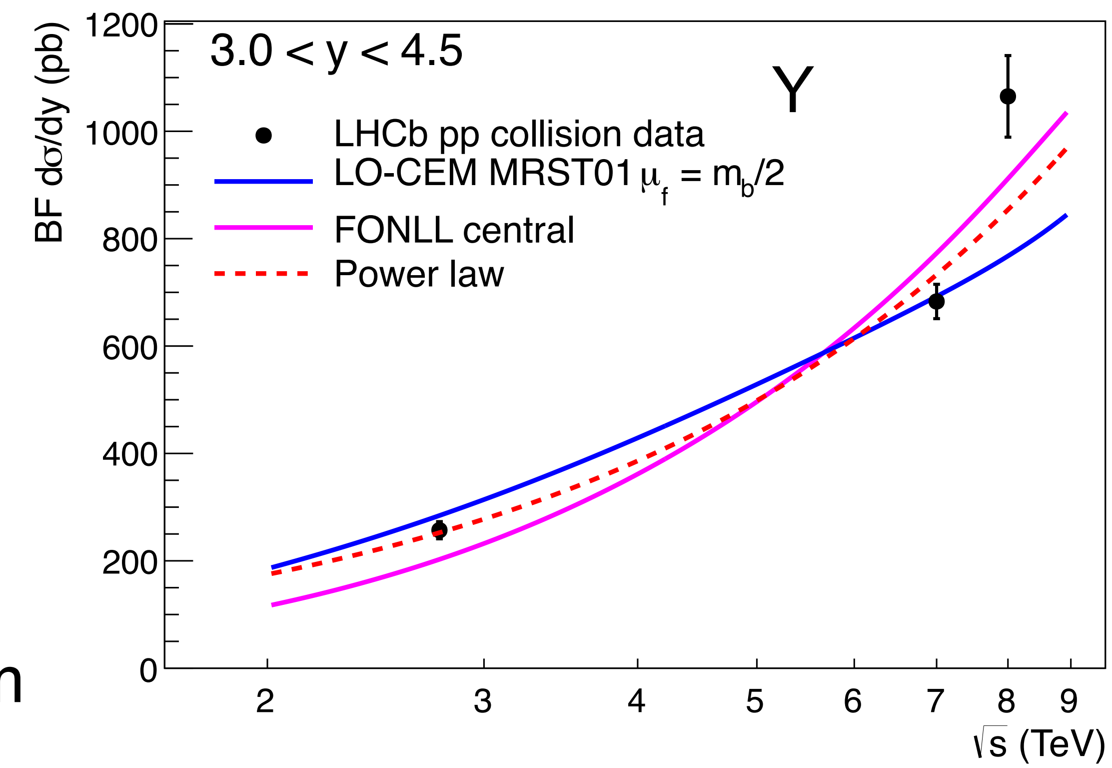
- We need to measure this references!





J/ψ nuclear modification factor R_{pPb}

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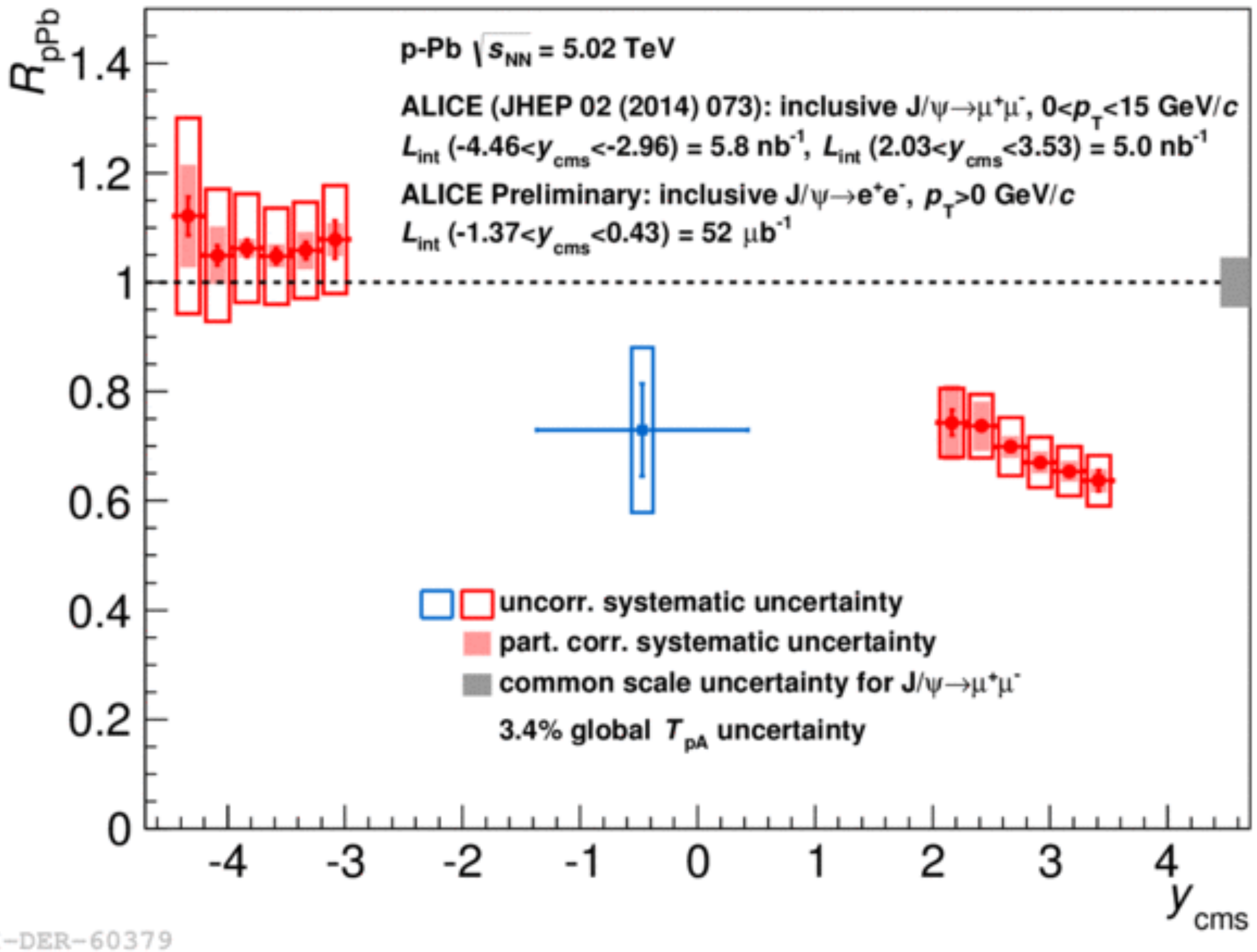
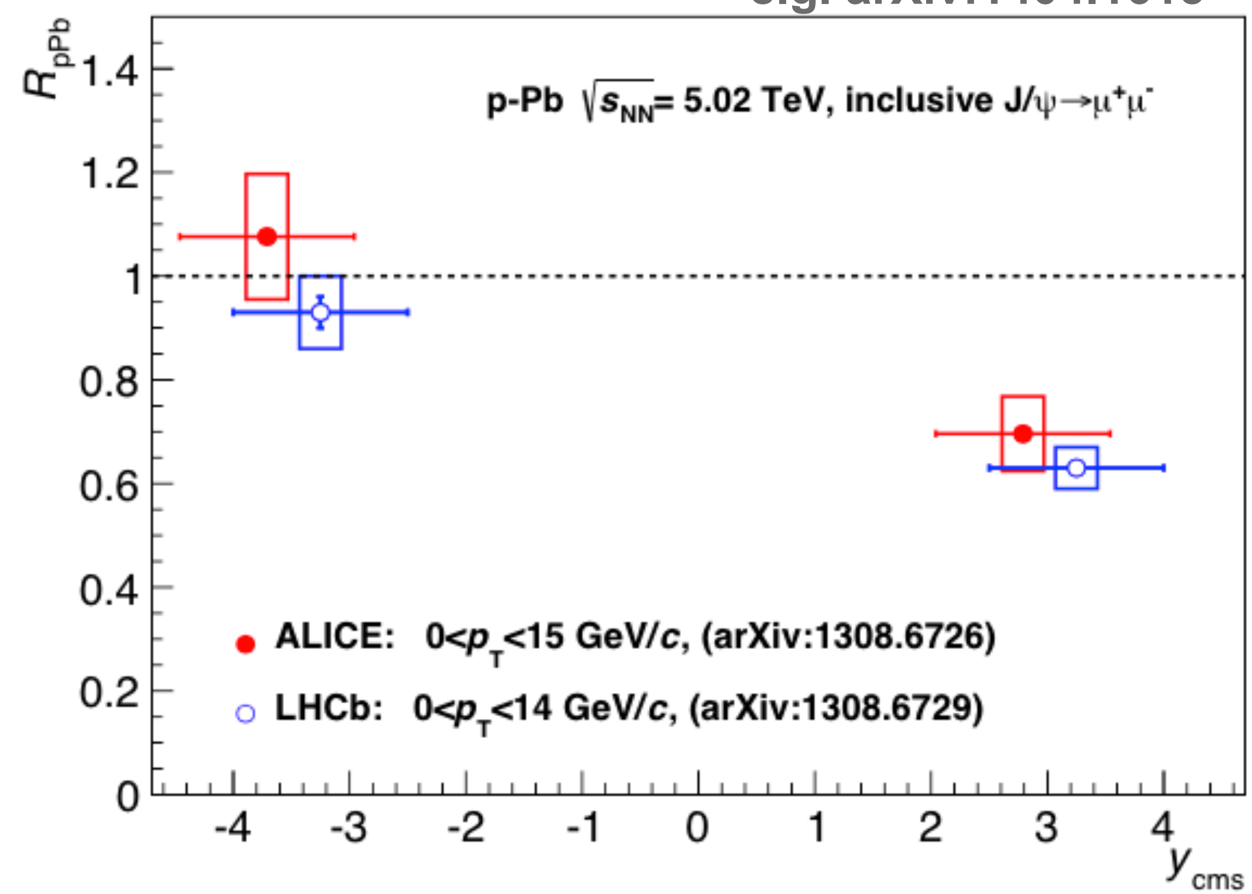
JHEP 02 (2014) 073
e.g. arXiv:1404.1615



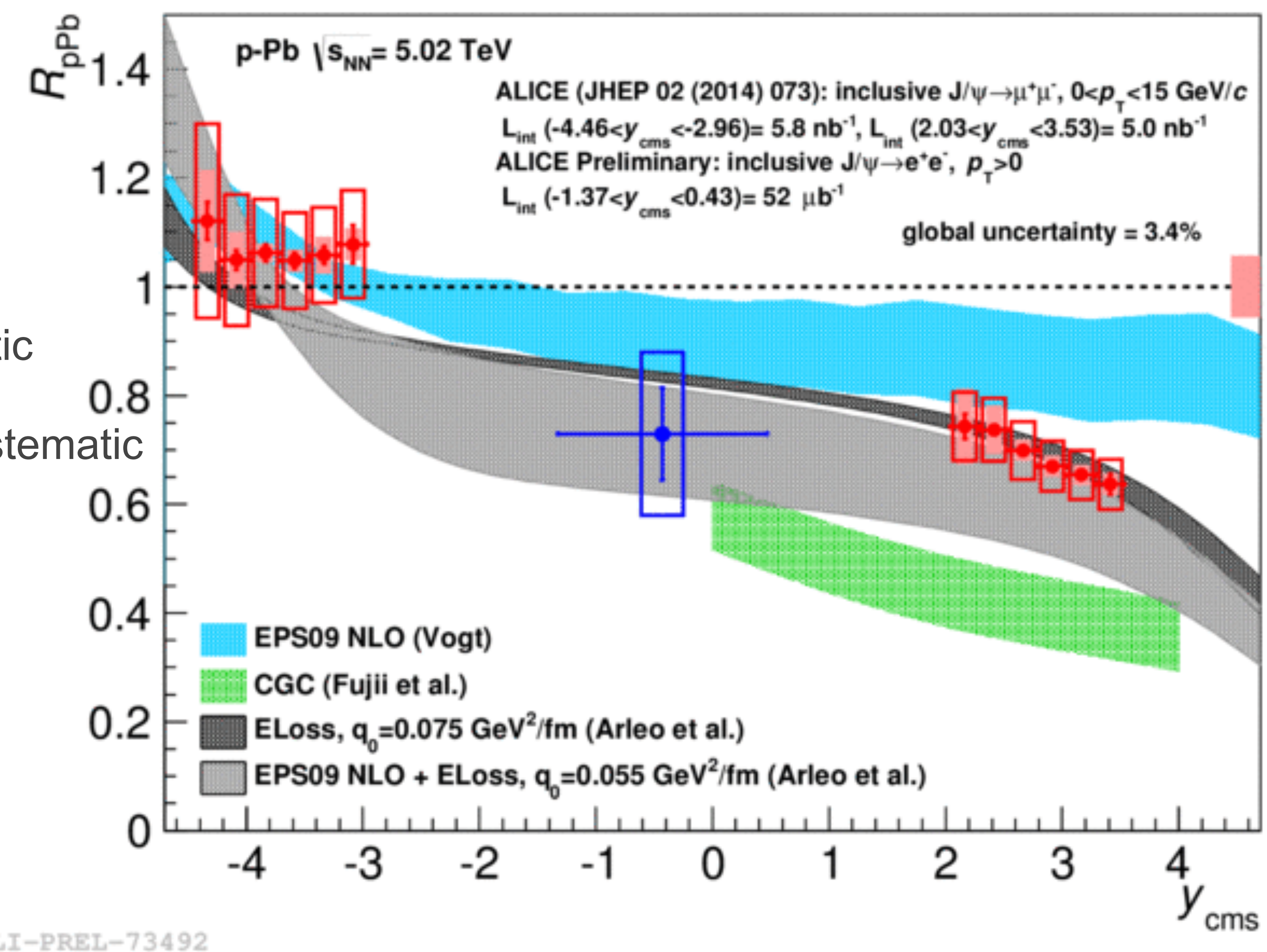


- Good agreement between ALICE and LHCb
- Strong suppression at forward rapidity
- Similar suppression a mid- than at forward rapidity
- A backward rapidity the R_{pPb} is compatible with unity

Model comparison – I

JHEP 02 (2014) 073
e.g. arXiv:1404.1615

Uncertainties:
- Bars: Statistical
- Open boxes: Uncorrelated systematic
- Shaded boxes: Partially correlated systematic
- Full box: Correlated systematic



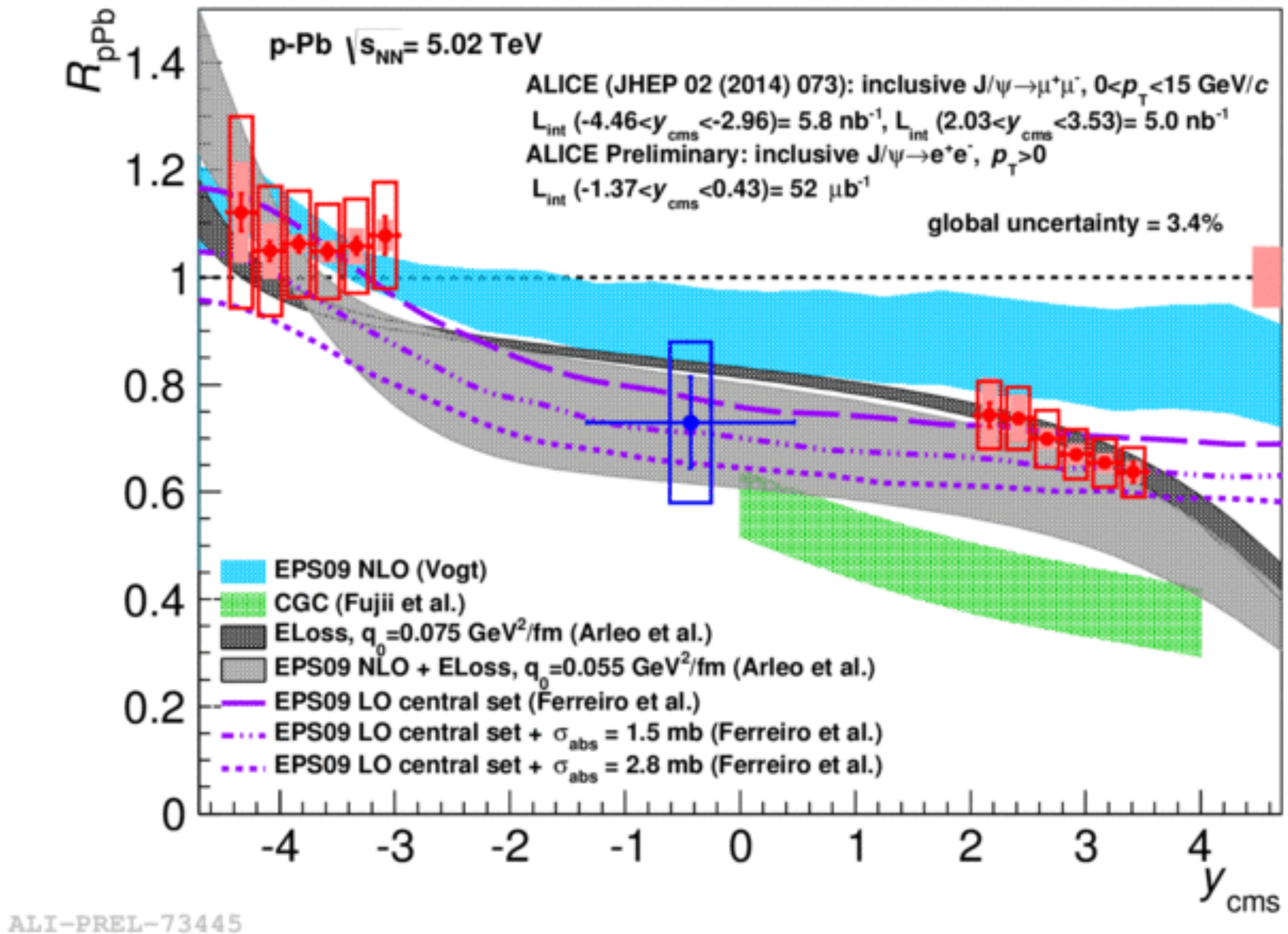
This CGC based [NPA 915 (2013) 1] calculation is clearly disfavoured

- Vogt [arXiv:1301.3395]
  - CEM production model at NLO
  - EPS09 shadowing parameterization at NLO
  - Fair agreement with measured R_{pPb} within uncertainties
    - Tendency to underestimate suppression at forward rapidity

- Arleo et al. [JHEP 1303 (2013) 122]
  - Model including a contribution from coherent parton energy loss
  - With or without shadowing (EPS09)
  - Fair agreement in both cases over the full y-range
    - Tension at backward rapidity?

Model comparison – II

JHEP 02 (2014) 073
e.g. arXiv:1404.1615

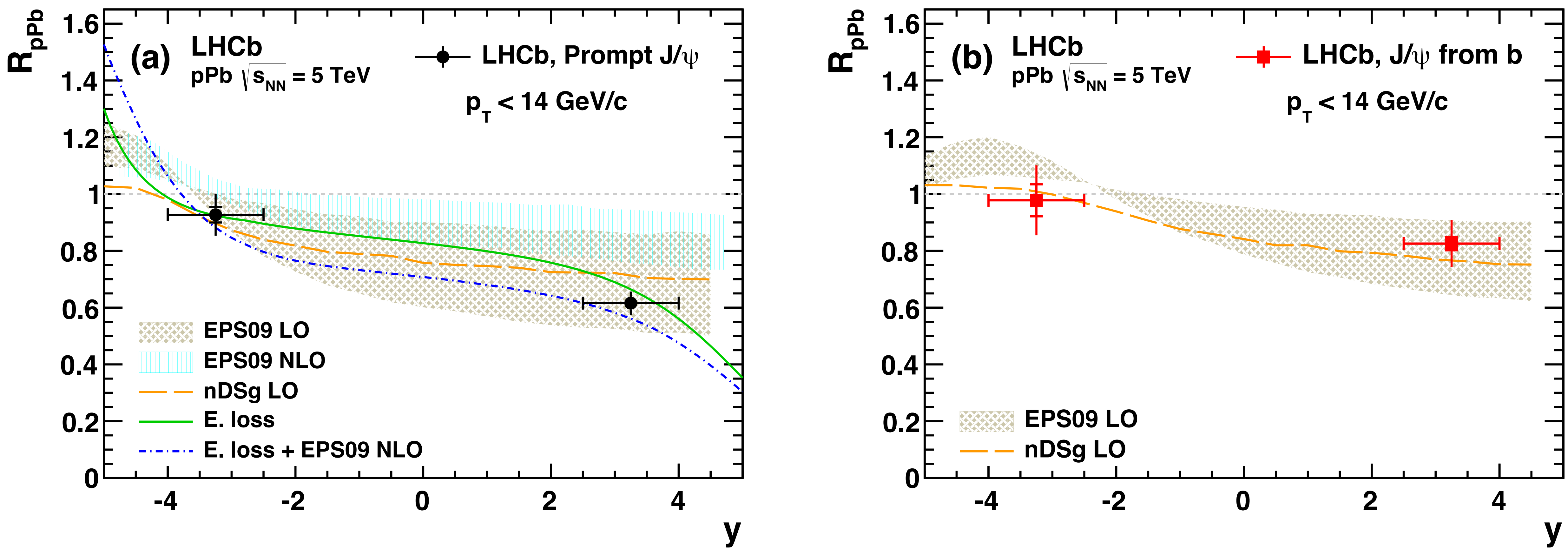


- Ferreiro et al. [PRC 88, (2013) 047901]
  - Generic 2→2 production model at LO
  - EPS09 shadowing parameterization at LO
  - Fair agreement with measured R_{pPb}
    - Here, effect of nuclear absorption highlighted, large σ_{abs} disfavoured

Model comparison – III

JHEP 02 (2014) 072

- R_{pPb} of prompt and non-prompt J/ψ
  - Conclusions unchanged

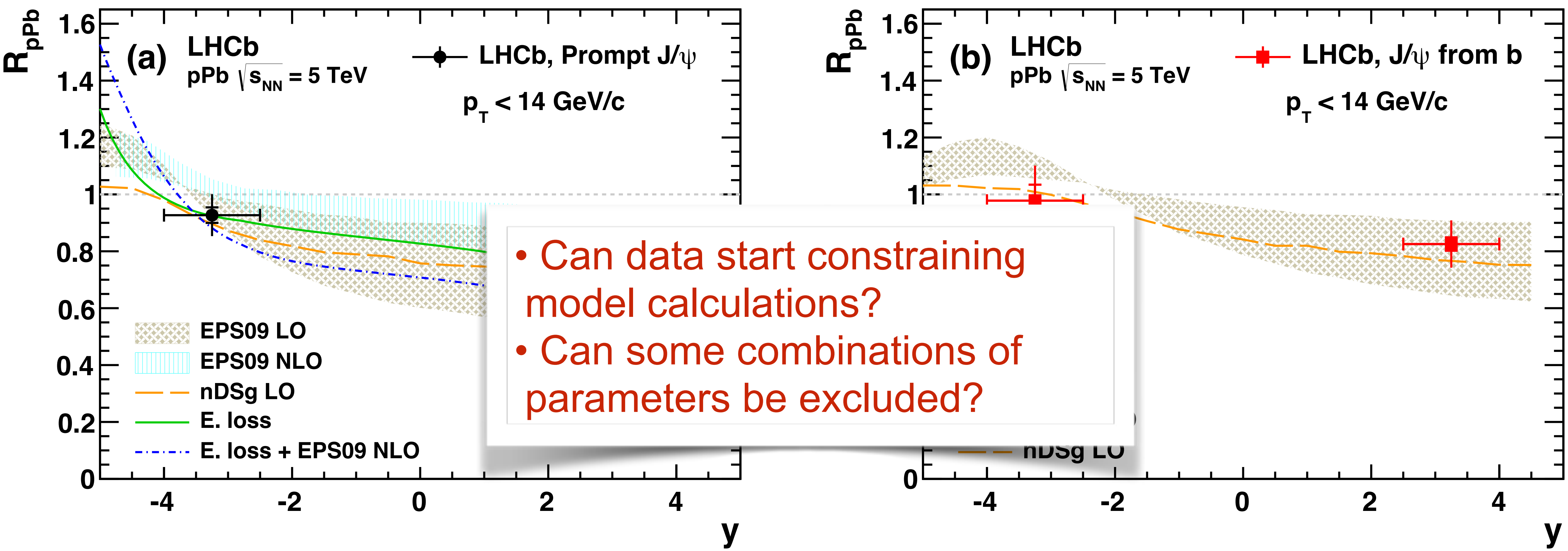


- Vogt [arXiv:1301.3395]
- Arleo et al. [JHEP 1303 (2013) 122]
- Ferreiro et al. [PRC 88, (2013) 047901]
  - Here, effect of different nPDF tested

Model comparison – III

JHEP 02 (2014) 072

- R_{pPb} of prompt and non-prompt J/ψ
  - – Conclusions unchanged



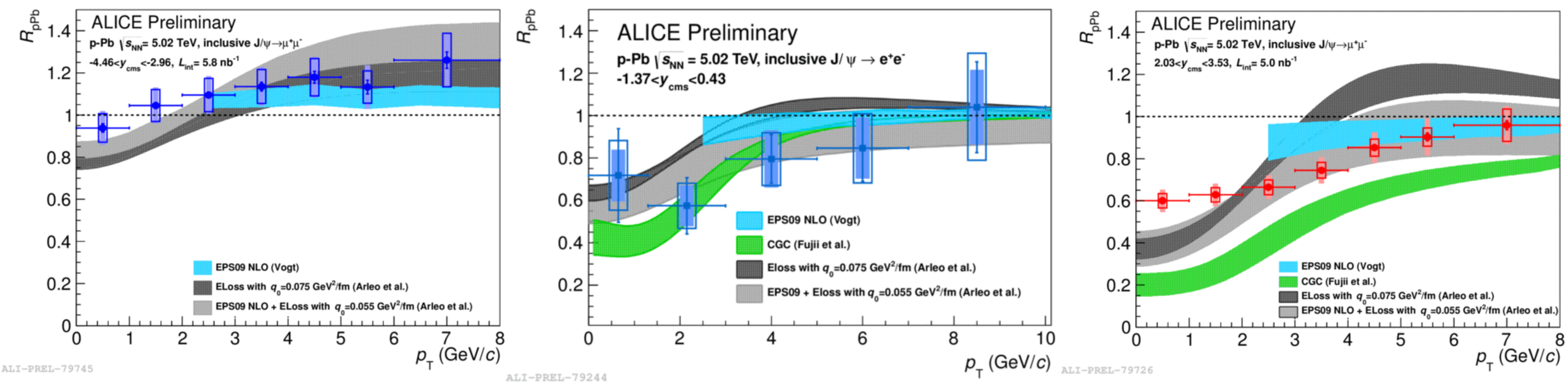
- Can data start constraining model calculations?
- Can some combinations of parameters be excluded?

- Vogt [arXiv:1301.3395]
- Arleo et al. [JHEP 1303 (2013) 122]
- Ferreiro et al. [PRC 88, (2013) 047901]
  - – Here, effect of different nPDF tested

Transverse momentum dependence

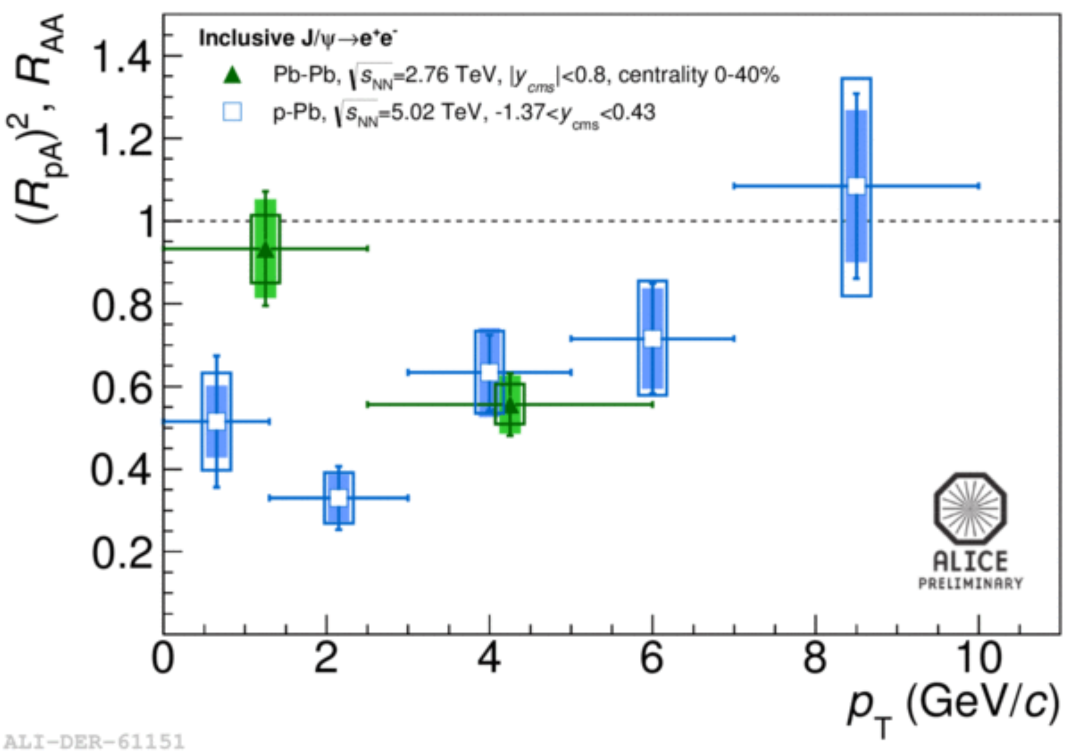
e.g. arXiv:1404.1615

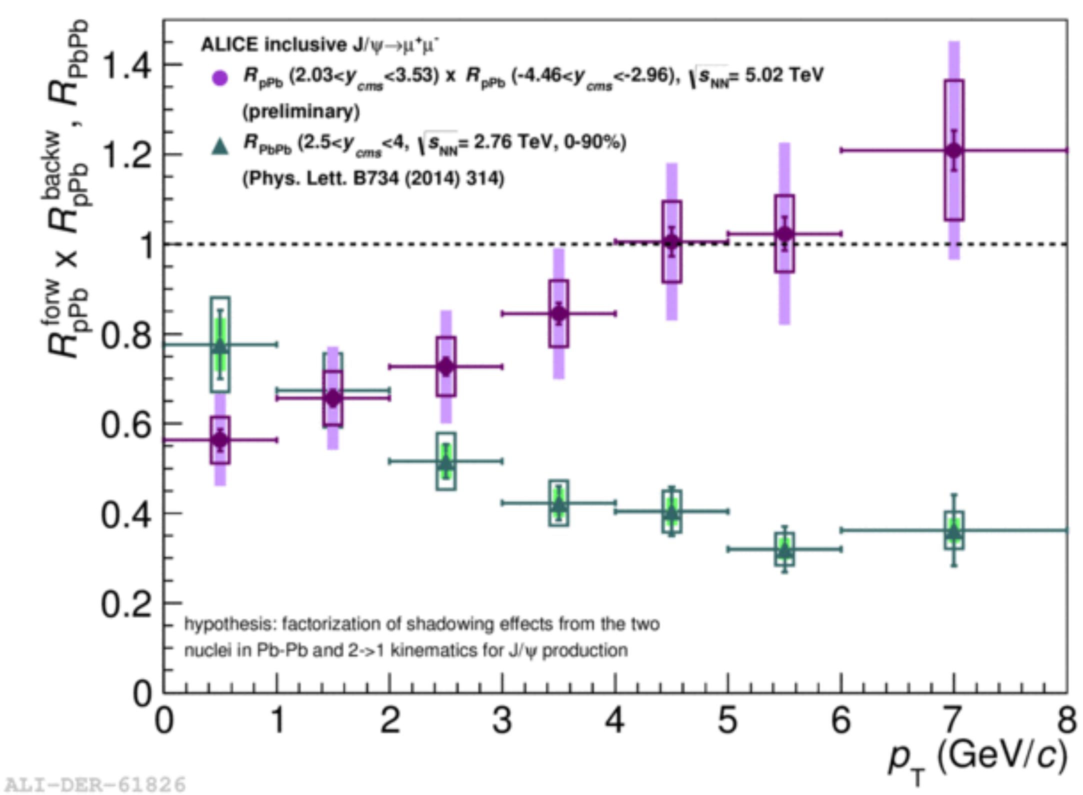
- Strong suppression at mid and forward rapidity
  - Increases with p_T, compatible with unity for $p_T \gtrsim 5$ GeV/c
- No suppression at backward rapidity
  - Small p_T dependence, compatible with unity



- Shadowing only model (calculation for $p_T > 2.5$ GeV/c) describes trend of data but underestimates suppression at forward rapidity and $2.5 < p_T < 3$ GeV/c (and below ?)
- Coherent energy loss only does not describe the measured trends
- Coherent energy loss with shadowing describes data at high p_T but overestimates suppression at forward rapidity and low p_T
- CGC overestimates suppression at forward rapidity

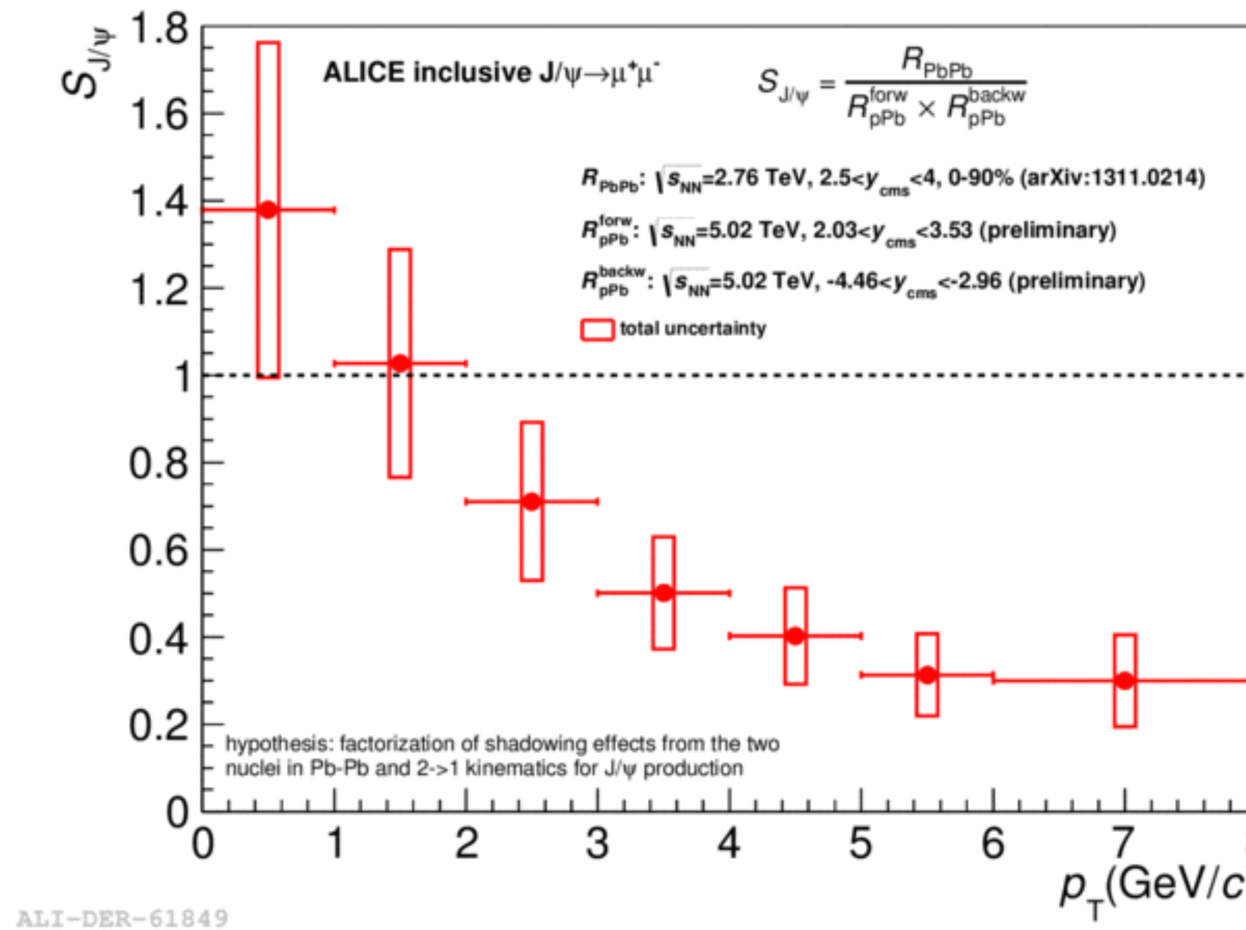
CNM from p-Pb to Pb-Pb





e.g. arXiv:1404.1615

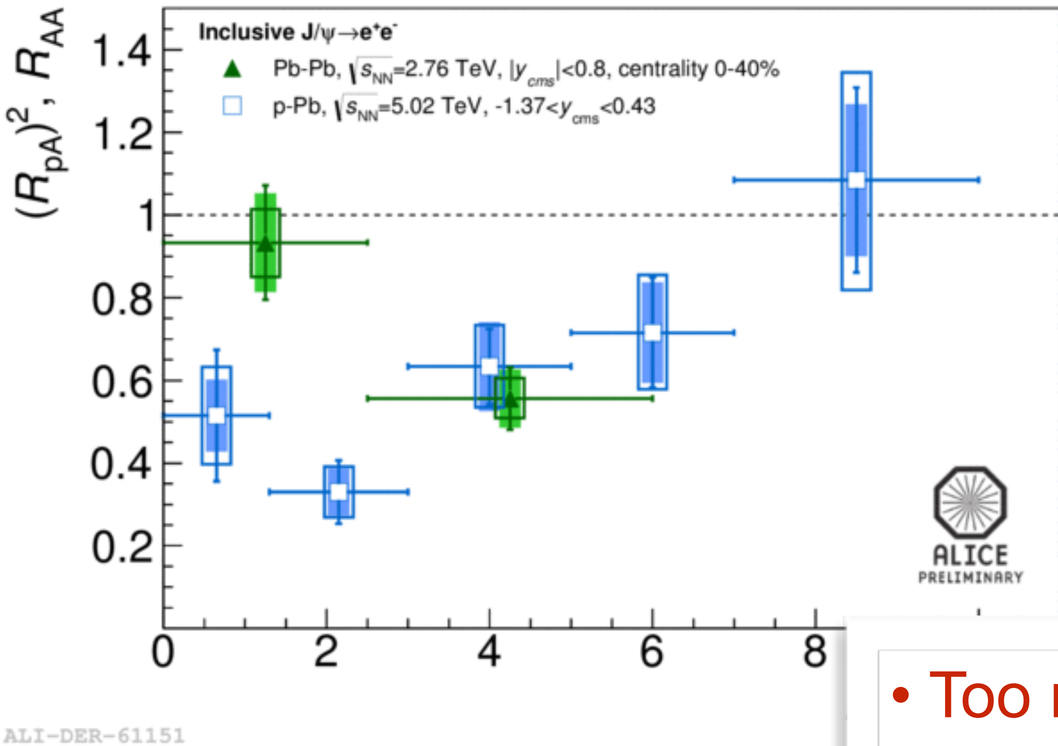
- The poor's man approach: AA = pA x Ap
- Assumptions:
  - Production mechanism: g+g → J/ψ
  - CNM effects factorize in p-nucleus and are dominated by shadowing

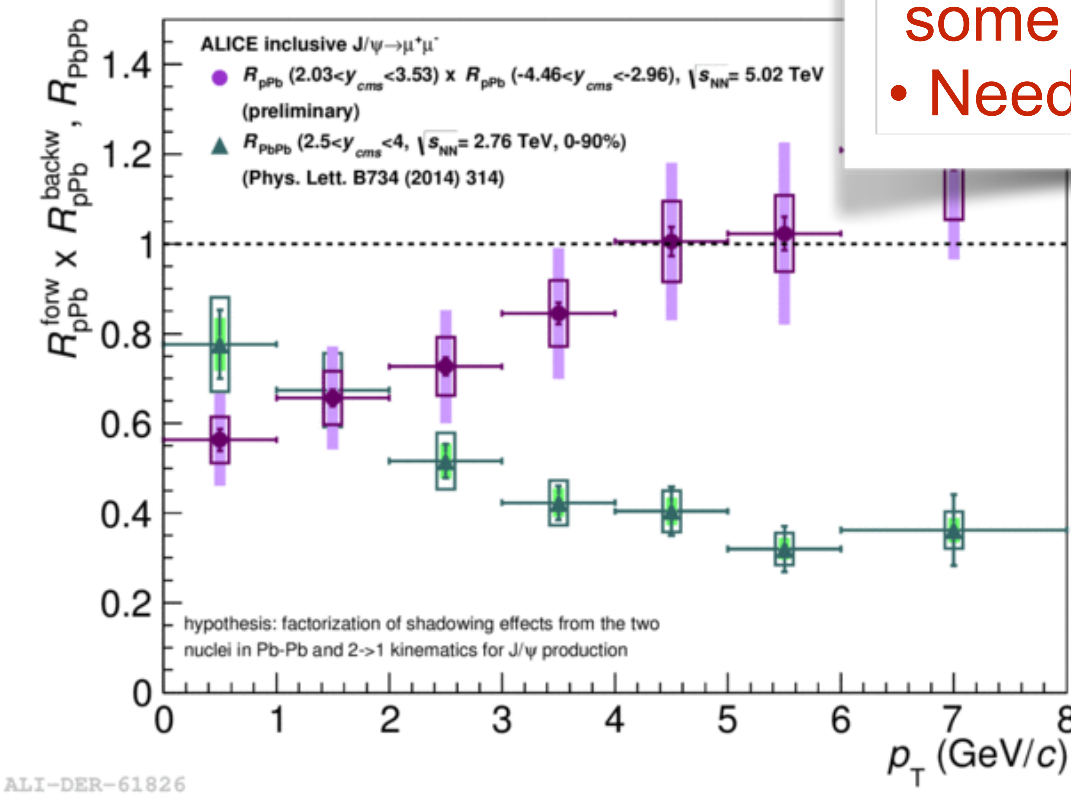


- Strong suppression at high p_T due to the hot medium
- Increase of $S_{J/\psi}$ at low p_T (observation that favours (re)combination scenario in Pb-Pb)

CNM from p-Pb to Pb-Pb

e.g. arXiv:1404.1615





- The poor's man approach: AA = pA x Ap
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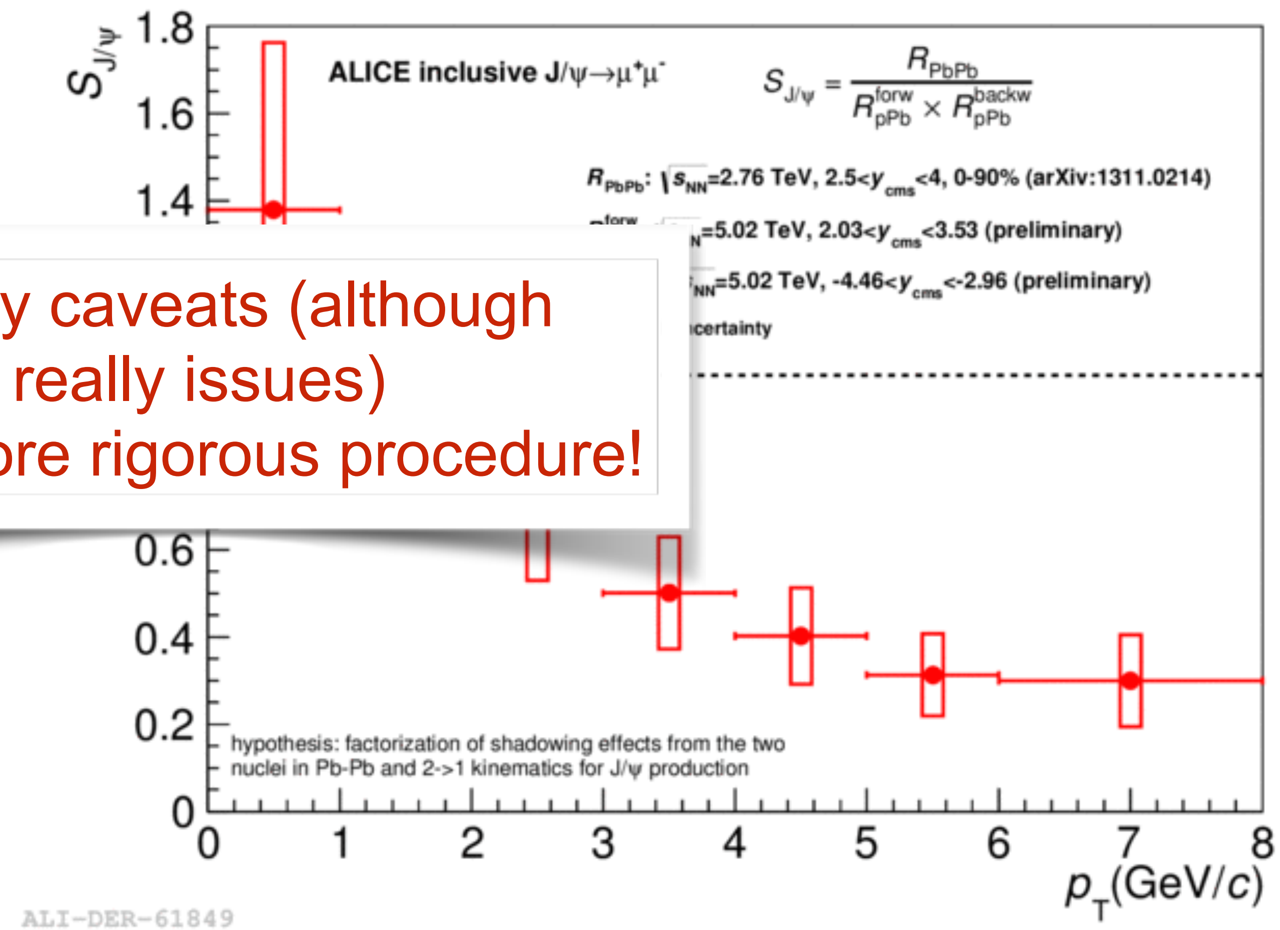


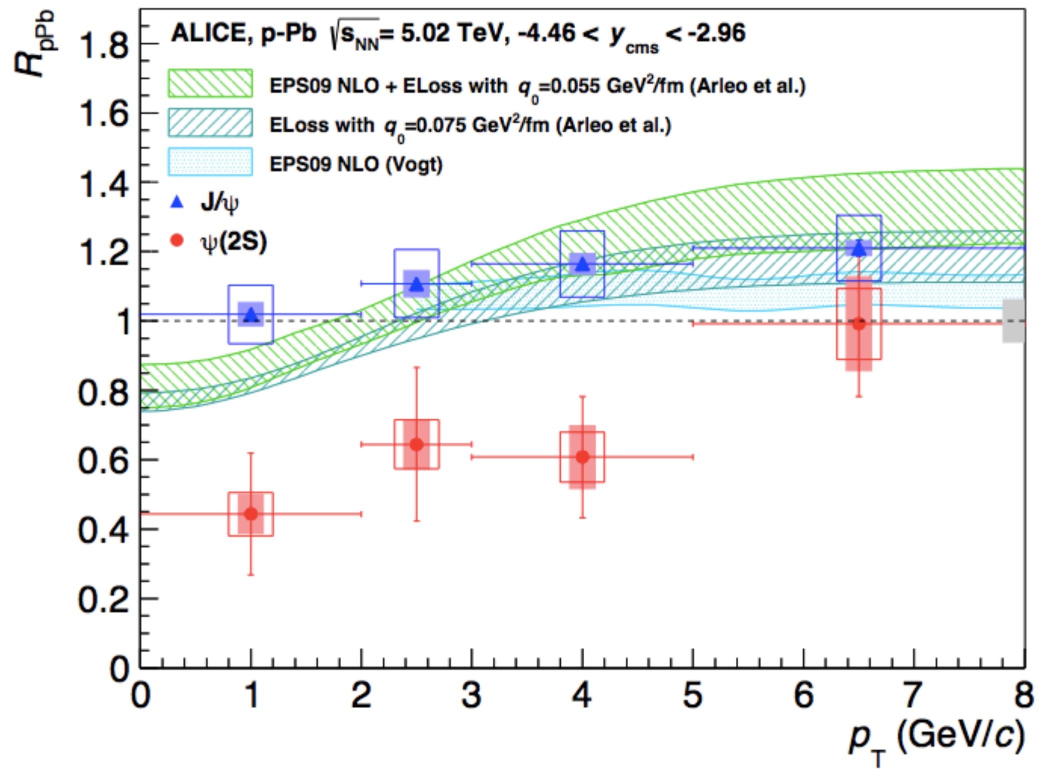
$$S_{J/\psi} = \frac{R_{PbPb}}{R_{pPb}^{forw} \times R_{pPb}^{backw}}$$

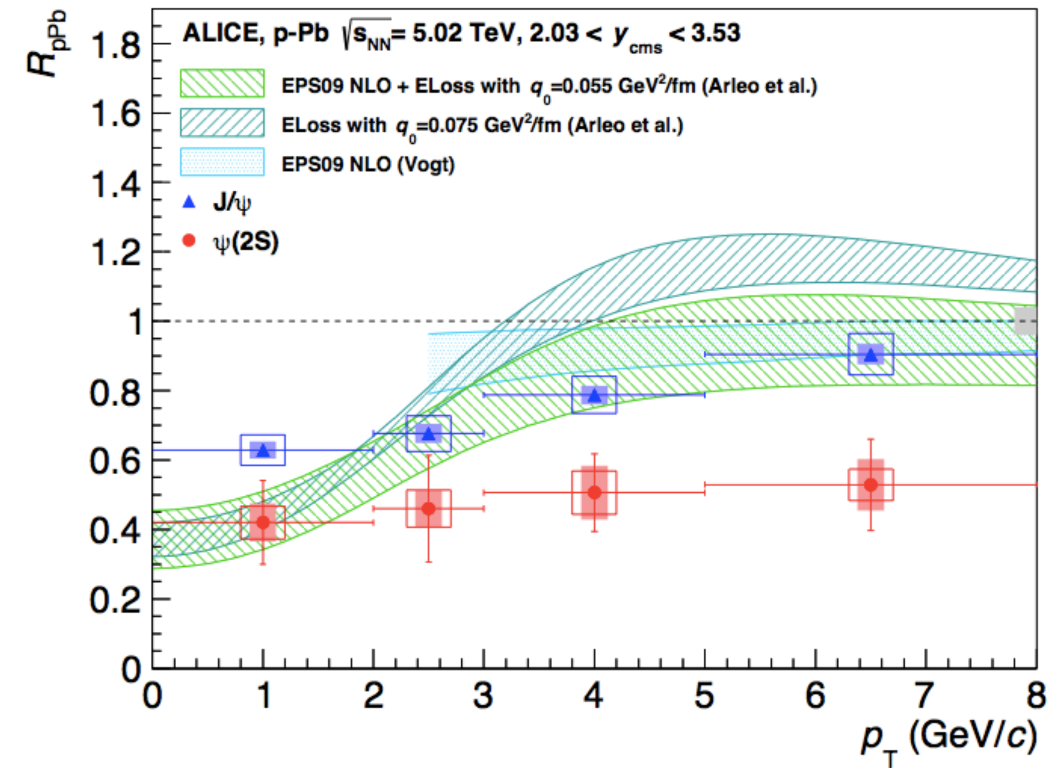
- Too many caveats (although some not really issues)
- Need more rigorous procedure!

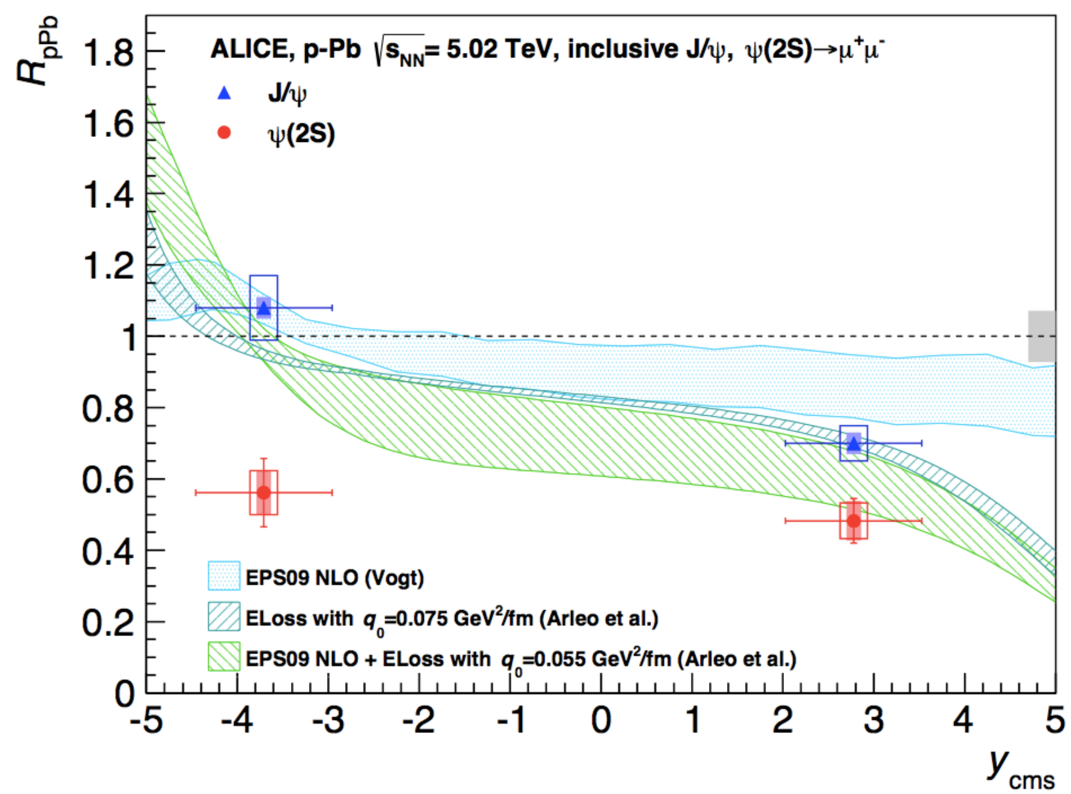
- Strong suppression at high p_T due to the hot medium
- Increase of $S_{J/\psi}$ at low p_T (observation that favours (re)combination scenario in Pb-Pb)

ψ(2S) suppression in p-Pb

arXiv:1405.3796



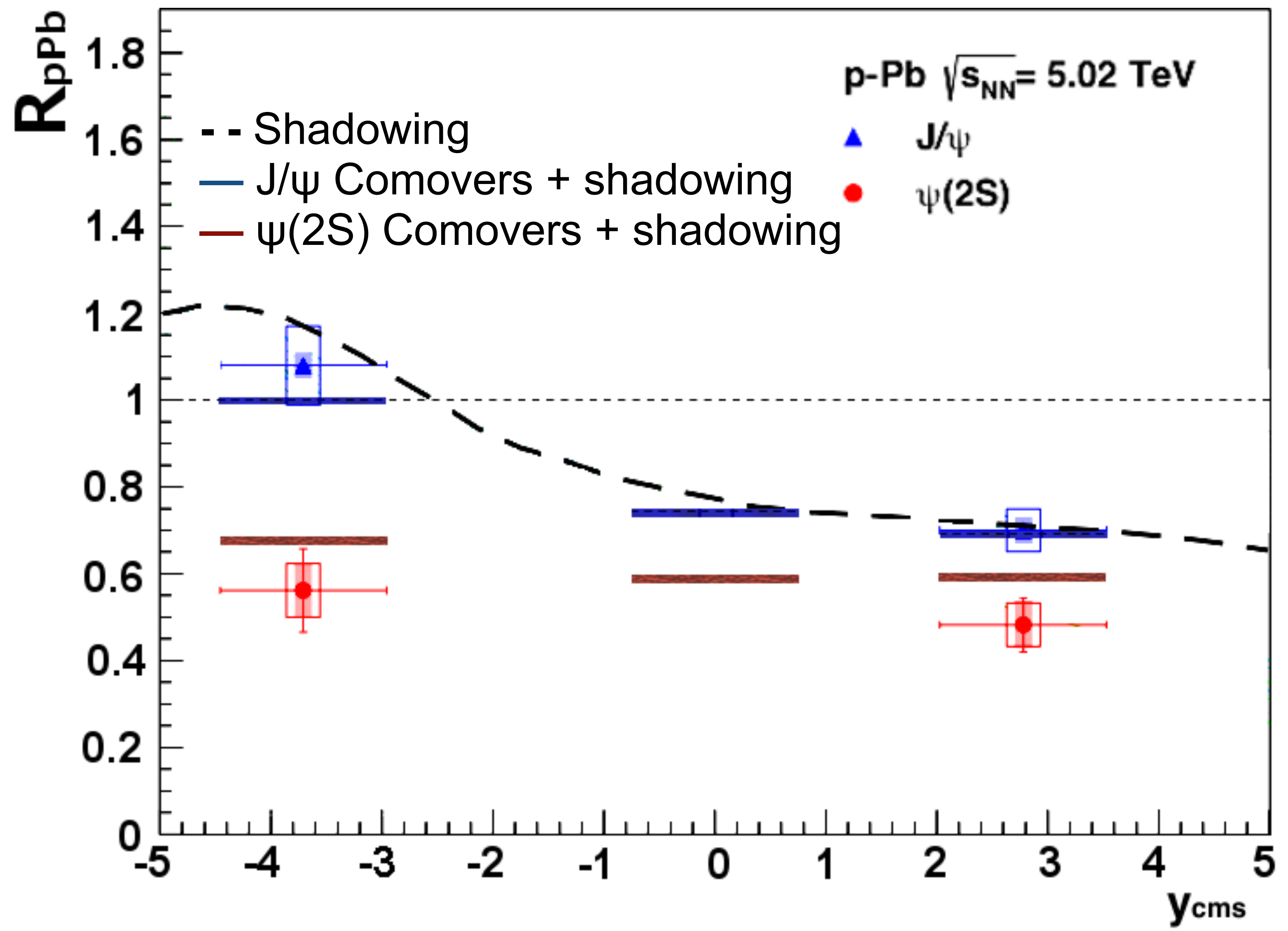




- Stronger ψ(2S) suppression than J/ψ!
- Similar observation at RHIC
- Models including shadowing or energy loss or both describe J/ψ R_{pPb} but underestimate the ψ(2S) suppression
  - Similar prediction for both states
- Break-up effects are unlikely to describe the difference
  - formation time $\tau_f \gtrsim \tau_c$ crossing time
- Other final state effects are required to describe the stronger ψ(2S) suppression

Comover Interaction

arXiv:1405.3796



- E. Ferreiro [arXiv:1411.0549]
  - Charmonium dissociation by comover interaction
  - EPS09 shadowing parameterization at LO
  - Good description of J/ψ and ψ(2S) R_{pPb} at both backward and forward rapidity

Υ(2S)/Υ(1S)

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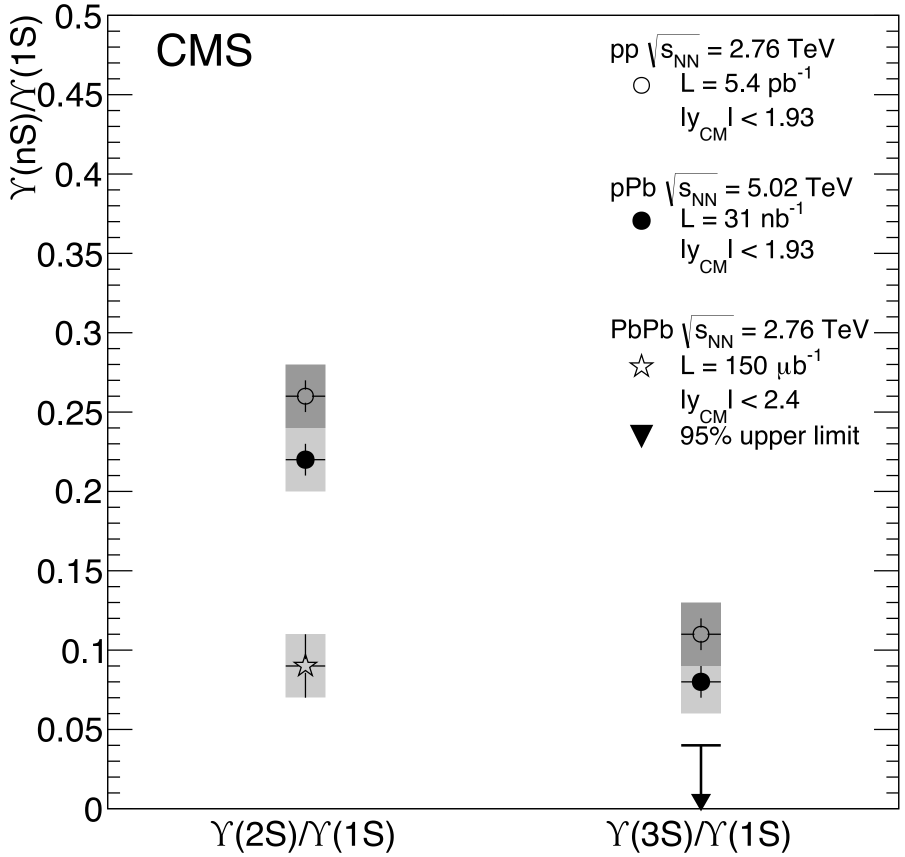
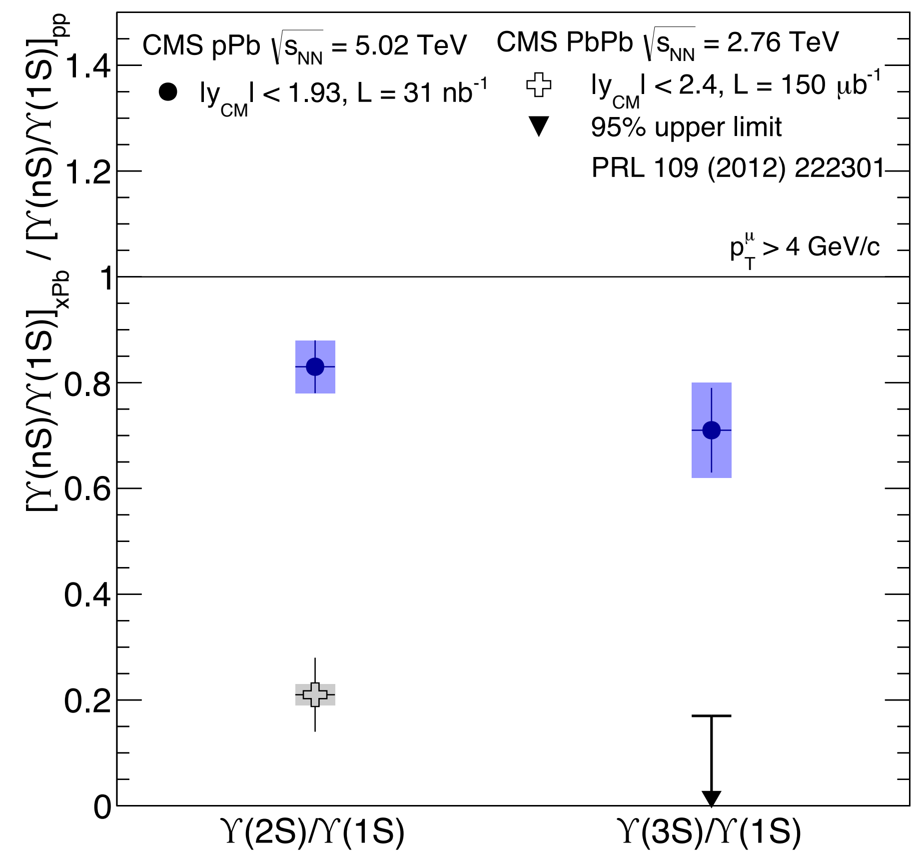
JHEP 07 (2014) 094
PLB 740 (2015) 105

- Also stronger suppression of Υ(2S) than Υ(1S) in p-Pb observed by CMS at mid-y





- Not seen (yet) at forward or backward rapidity by ALICE nor LHCb
  - p-Pb Y(2S)-to-Y(1S) cross section ratio
    - $-4.46 < y_{cms} < -2.96$: 0.26 ± 0.09 ± 0.04 (ALICE) $-5.00 < y_{cms} < -2.50$: 0.28 ± 0.14 ± 0.04 (LHCb)
    - $2.03 < y_{cms} < 3.53$: 0.27 ± 0.08 ± 0.04 (ALICE) $1.50 < y_{cms} < 4.00$: 0.20 ± 0.05 ± 0.01 (LHCb)
  - Similar values measured in pp collisions by ALICE (2.5 < y < 4.0) and LHCb (2.0 < y < 4.5)
    - ALICE 7 TeV: 0.28 ± 0.08
    - LHCb 2.76 TeV: 0.24 ± 0.03
    - LHCb 7 TeV: 0.25 ± 0.02
    - LHCb 8 TeV: 0.23 ± 0.01

Υ(2S)/Υ(1S)

- Also stronger suppression of Υ(2S) than Υ(1S) in p-Pb observed by CMS at mid-y

JHEP 04 (2014) 103
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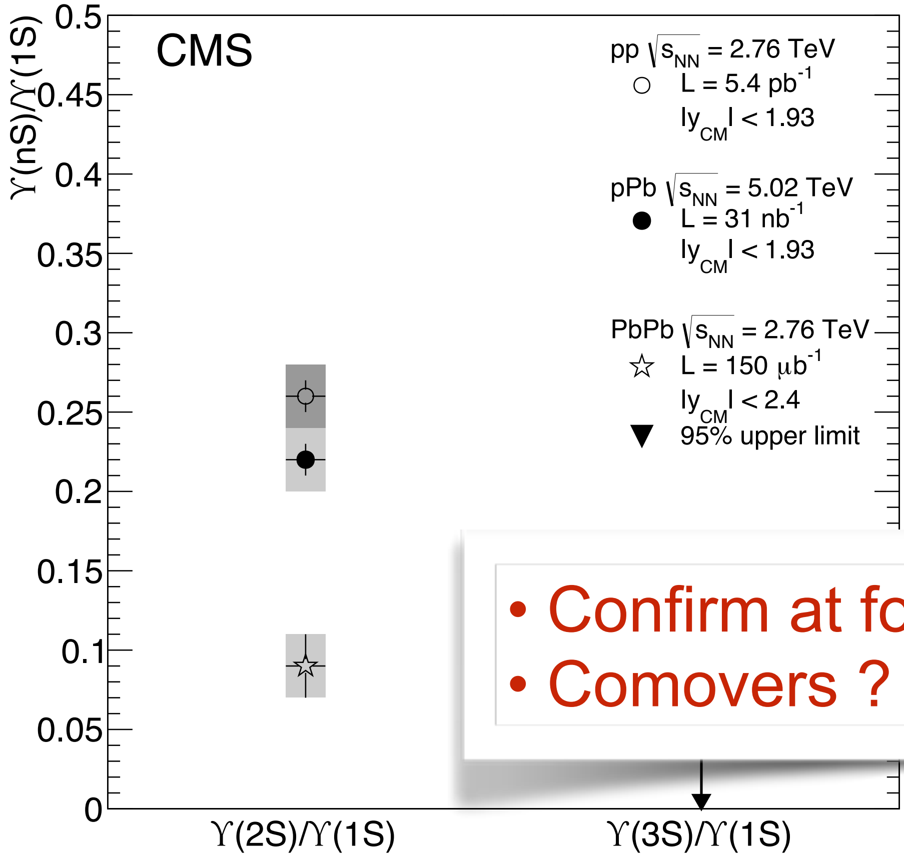
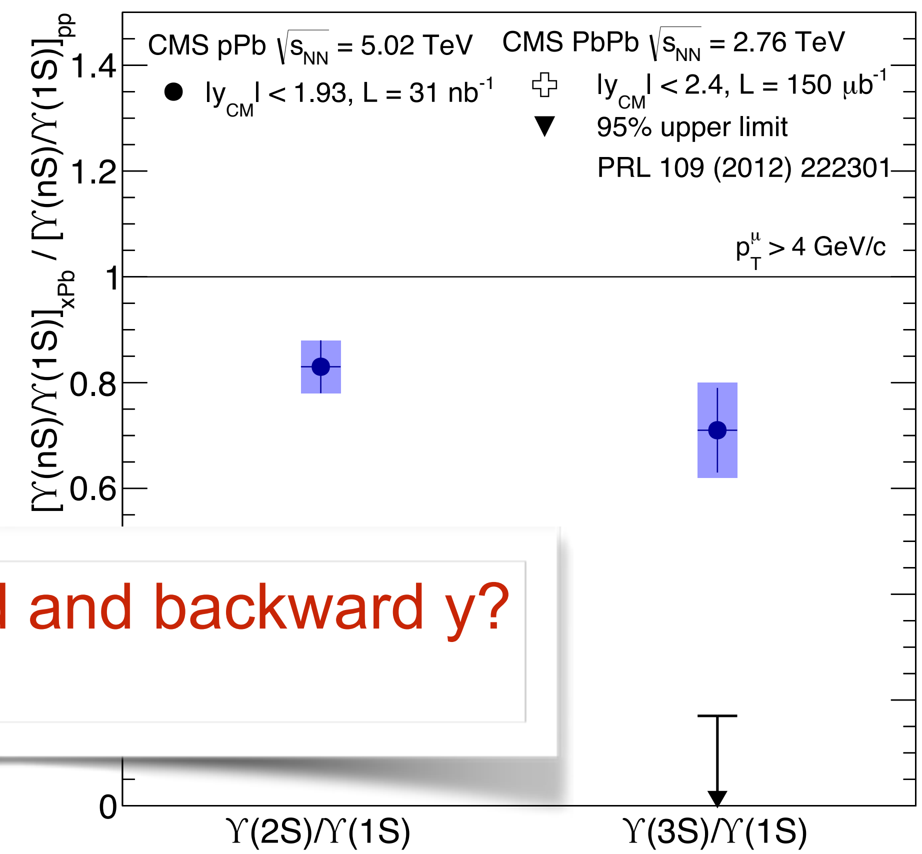
PLB 740 (2015) 105





- Confirm at forward and backward y?
- Comovers ?

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Υ nuclear modification factor in p-Pb

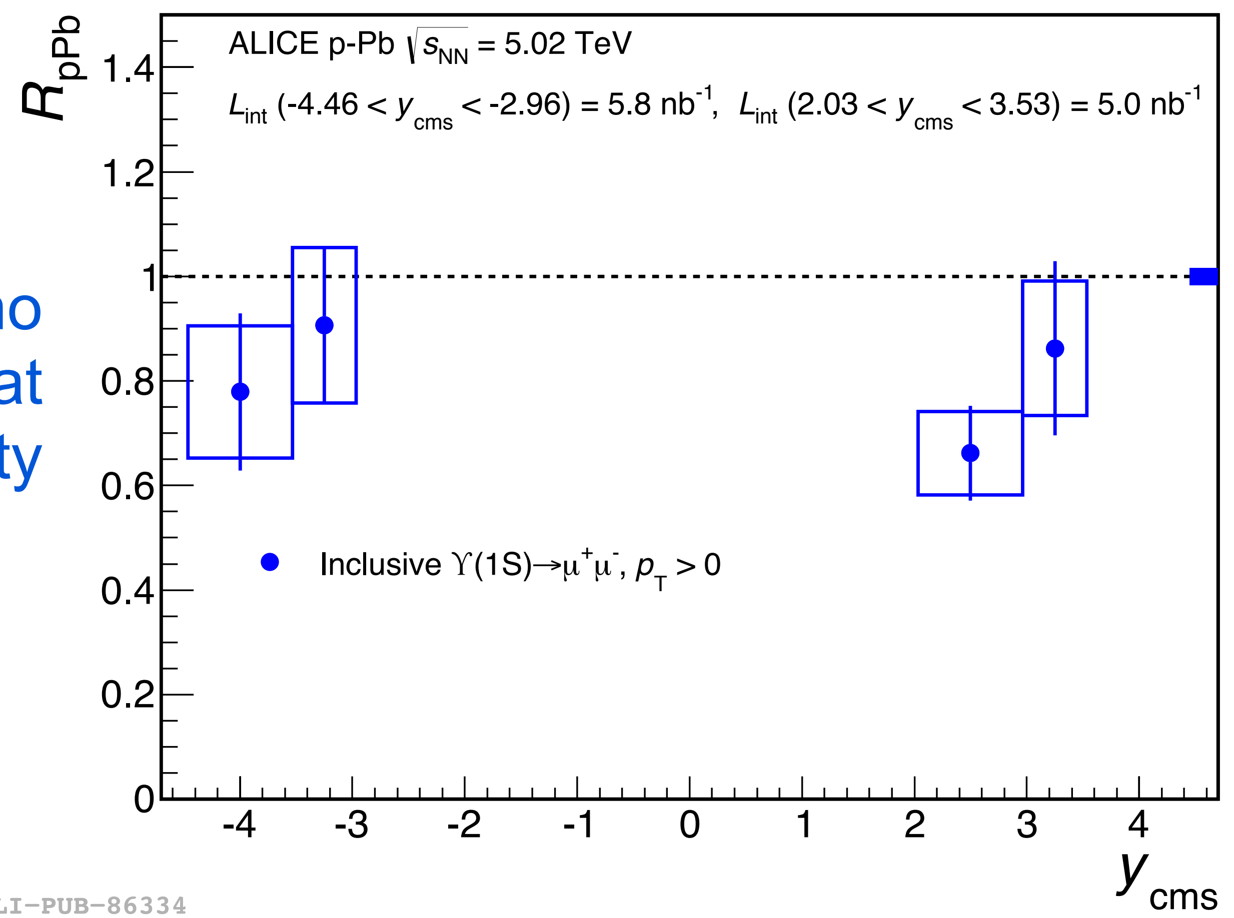
pPb @ 5.02 TeV

PLB 740 (2015) 105

- Inclusive $\Upsilon(1S)$ R_{pPb}

Uncertainties:
- Bars: Statistical
- Open boxes: Systematic
- Full box: Correlated systematic

Consistent with no suppression at backward rapidity



Indication of suppression at forward rapidity

- Assuming a 2→1 production process the tested Bjorken-*x* ranges are
  - Backward: $3.6\cdot10^{-2} < x < 1.6\cdot10^{-1}$ (antishadowing region)
  - Forward: $5.5\cdot10^{-5} < x < 2.5\cdot10^{-4}$ (shadowing region)

Υ nuclear modification factor in p-Pb

pPb @ 5.02 TeV

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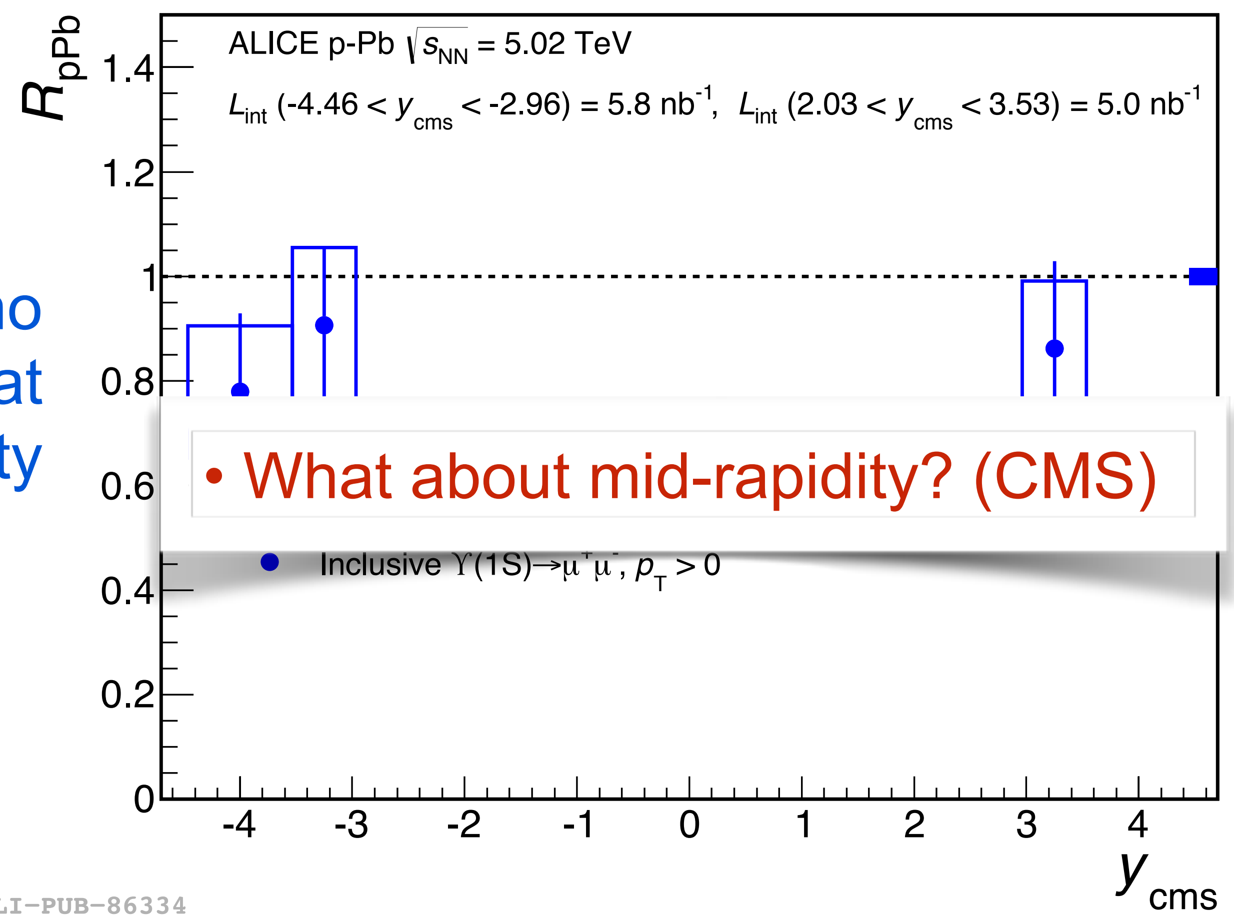
- Inclusive Υ(1S) R_{pPb}

Uncertainties:
- Bars: Statistical
- Open boxes: Systematic
- Full box: Correlated systematic

Consistent with no suppression at backward rapidity



Indication of suppression at forward rapidity

- What about mid-rapidity? (CMS)

- Assuming a 2→1 production process the tested Bjorken-*x* ranges are
  - Backward: $3.6 \cdot 10^{-2} < x < 1.6 \cdot 10^{-1}$ (antishadowing region)
  - Forward: $5.5 \cdot 10^{-5} < x < 2.5 \cdot 10^{-4}$ (shadowing region)

pPb @ 5.02 TeV

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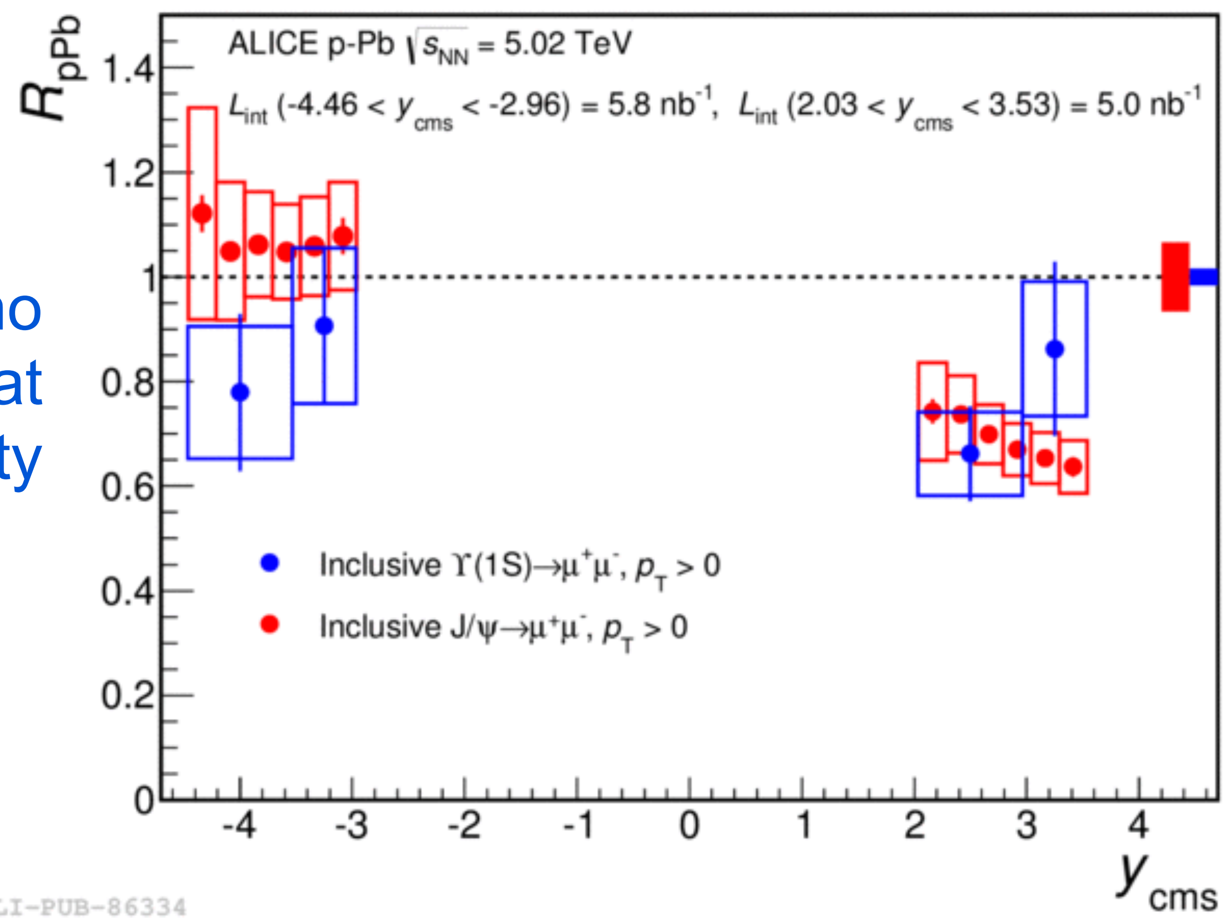
- Comparison with ALICE J/ψ R_{pPb}
  - Forward: similar suppression
  - Backward: slightly lower ϒ R_{pPb}, but compatible within uncertainties

Consistent with no suppression at backward rapidity



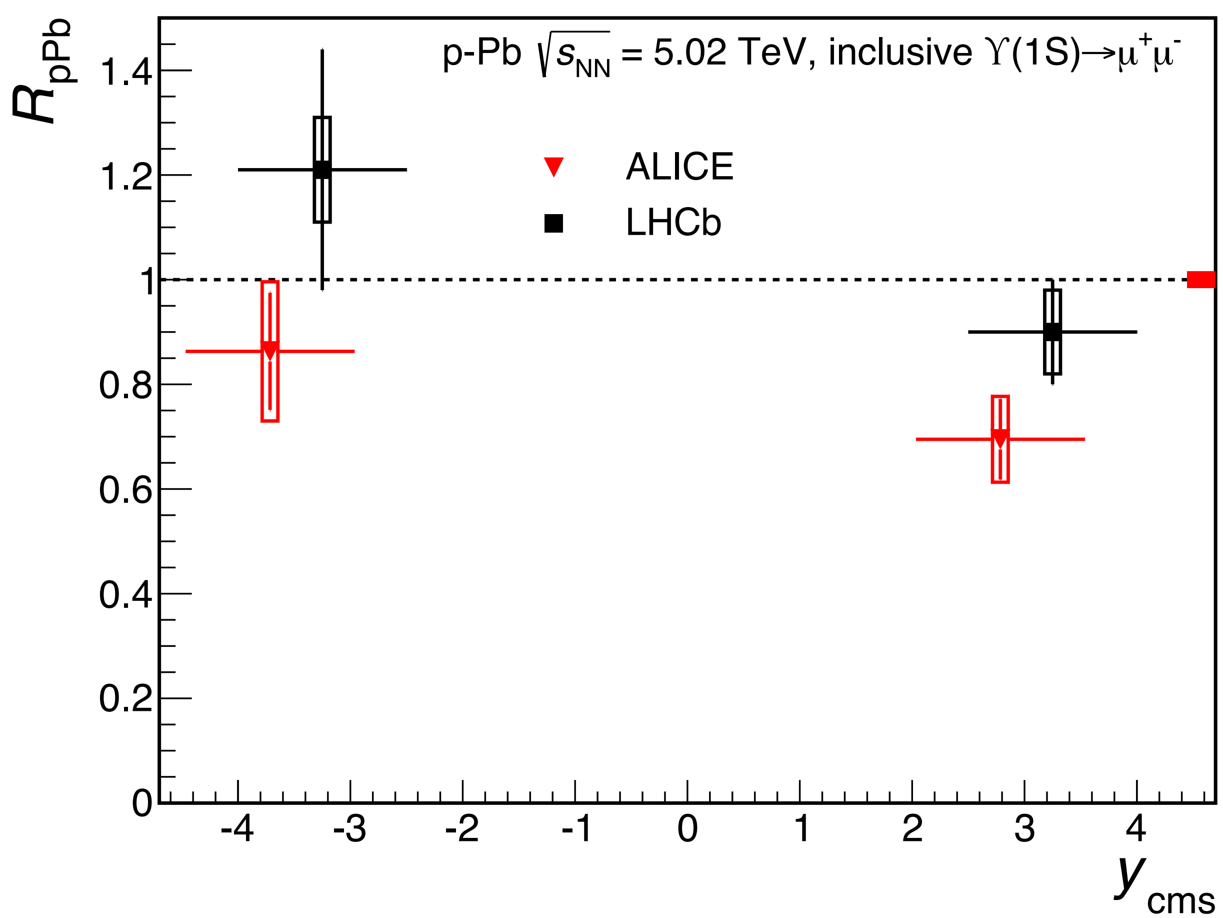
Indication of suppression at forward rapidity

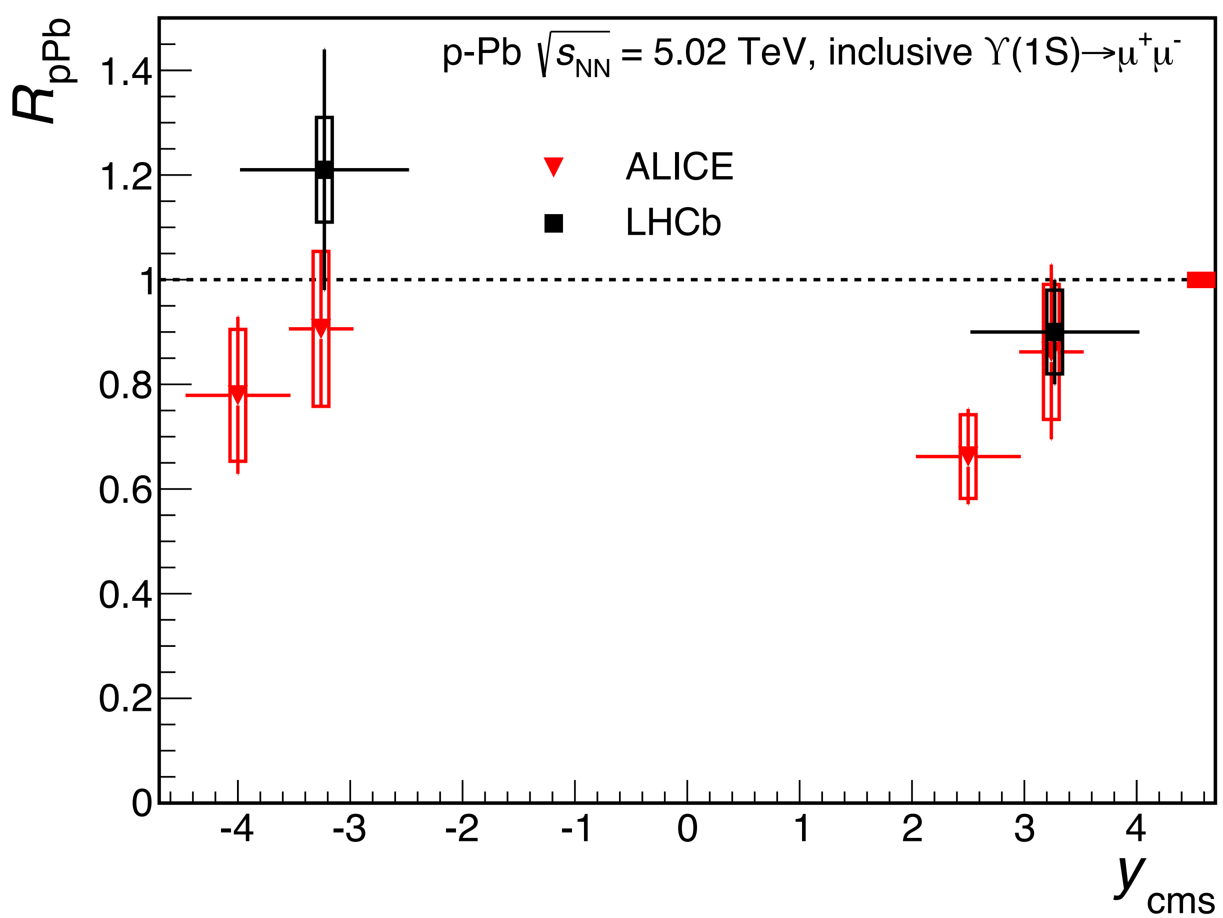
- Assuming a 2→1 production process the tested Bjorken-*x* ranges are
  - Backward: $3.6\cdot10^{-2} < x < 1.6\cdot10^{-1}$ (ϒ) and $1.2\cdot10^{-2} < x < 5.3\cdot10^{-2}$ (J/ψ)
  - Forward: $5.5\cdot10^{-5} < x < 2.5\cdot10^{-4}$ (ϒ) and $1.8\cdot10^{-5} < x < 8.1\cdot10^{-5}$ (J/ψ)

Comparison with LHCb

ALICE-PUBLIC-2014-002 – LHCb-CONF-2014-003

- Comparison with LHCb ϒ R_{pPb}
  - Both measurements are compatible
  - Systematically higher for LHCb than ALICE





Model comparisons – I

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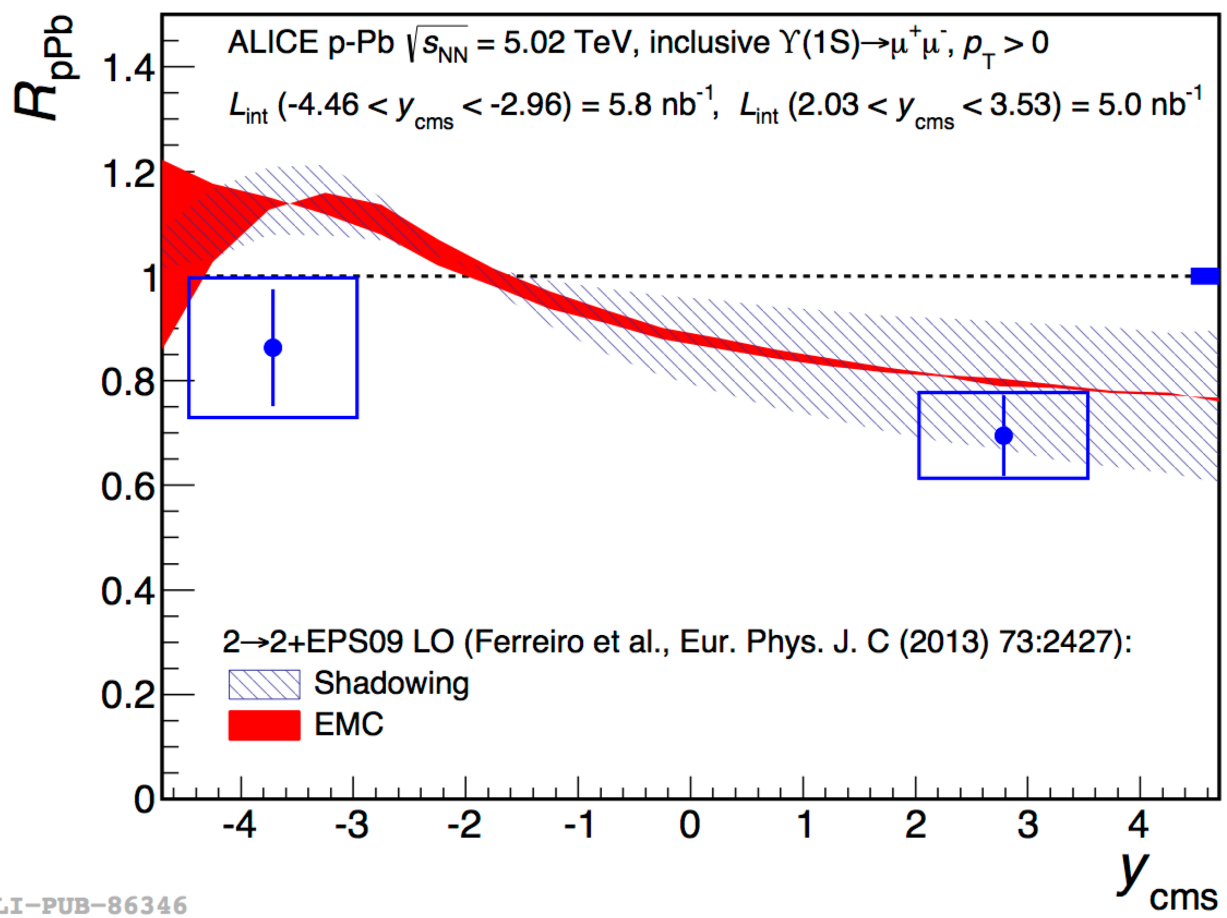

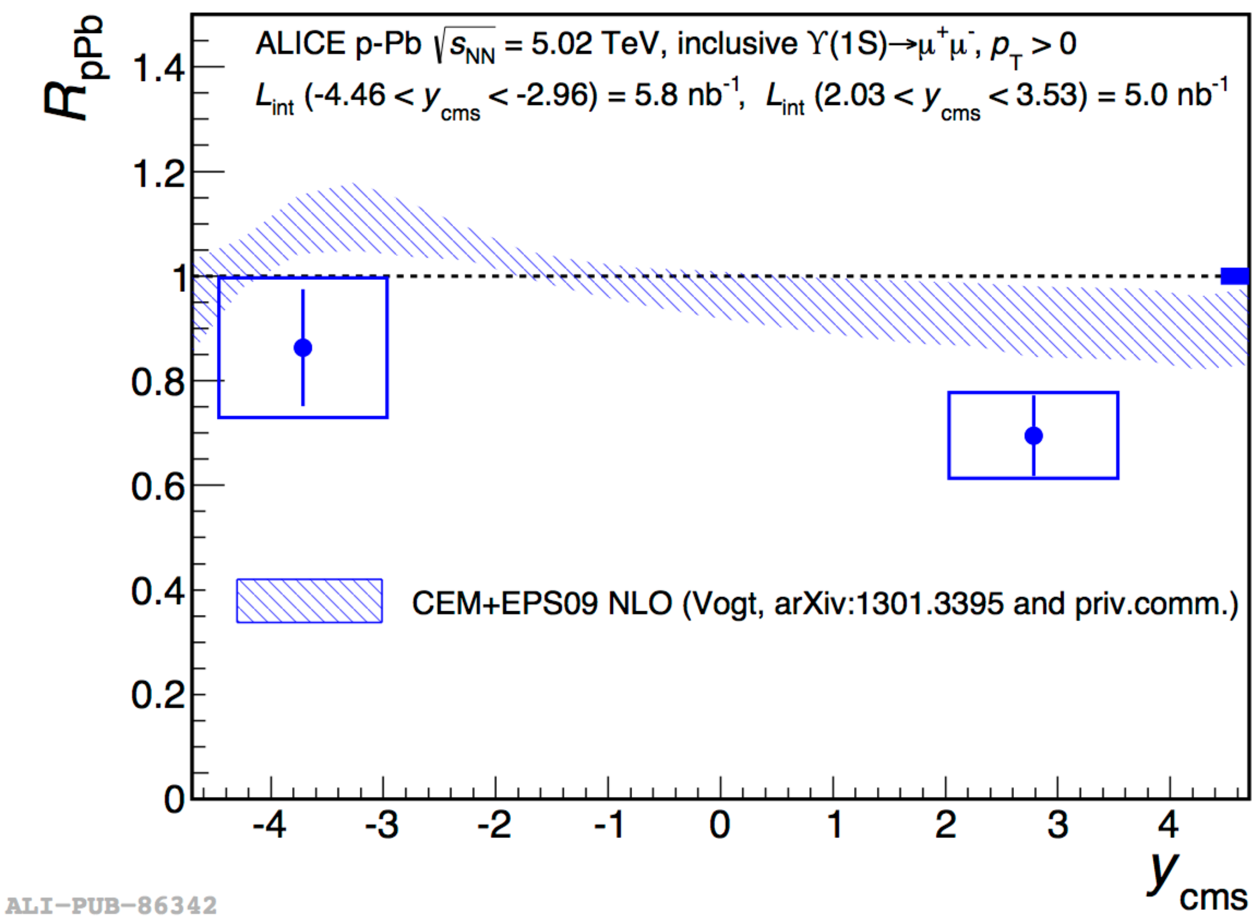

- Ferreiro et al. [EPJC 73 (2013) 2427]
  - Generic 2→2 production model at LO
  - EPS09 shadowing parameterization at LO
  - Fair agreement with measured R_{pPb}
    - Although slightly overestimates it in the antishadowing region
- Vogt [arXiv:1301.3395]
  - CEM production model at NLO
  - EPS09 shadowing parameterization at NLO
  - Fair agreement with measured R_{pPb} within uncertainties
    - Although slightly overestimates it

Model comparisons – II

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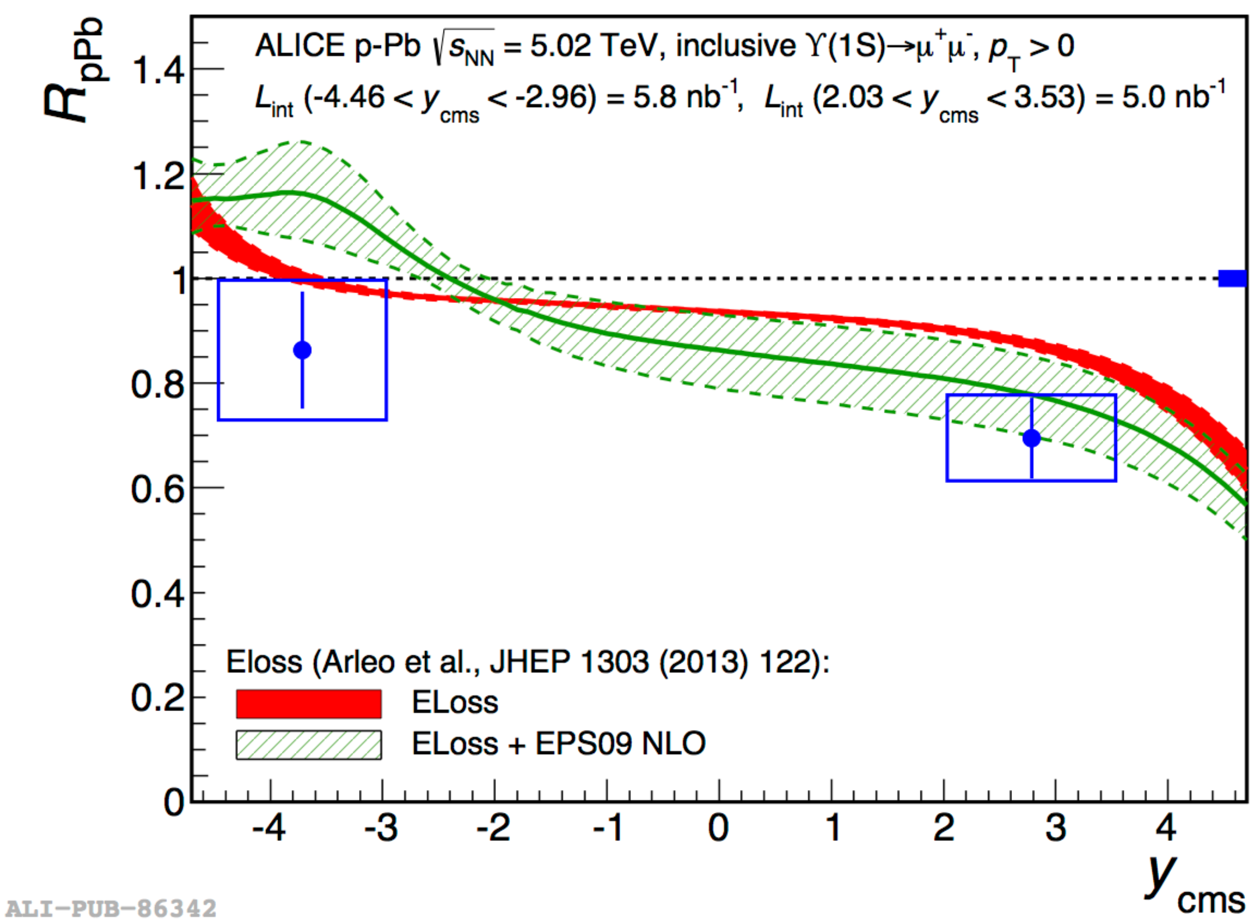
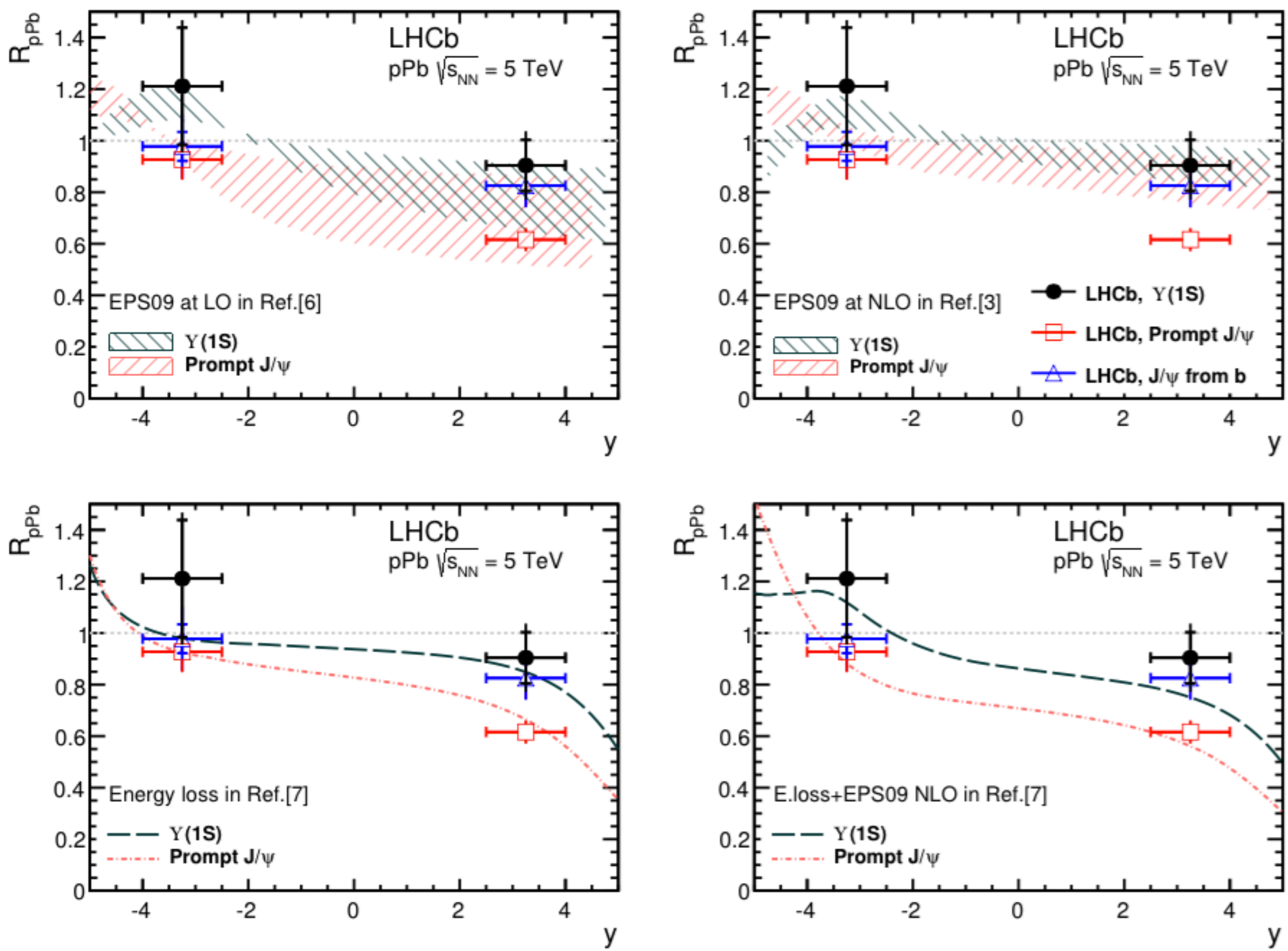


- Arleo et al. [JHEP 1303 (2013) 122]
  - Model including a contribution from coherent parton energy loss
  - With or without shadowing (EPS09)
  - Forward: Better agreement with ELoss and shadowing
  - Backward: Better agreement with ELoss only

Model comparison – III



Summary

- The production of J/ψ in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV shows
  - A strong suppression of J/ψ at forward rapidity
    - Suppression decreases with increasing p_T
  - A similar measurement at forward rapidity
  - A R_{pPb} consistent with unity at backward rapidity
    - Above unity for p_T > 4 GeV/c

- The production of inclusive ϒ(1S) in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV shows
  - A suppression of ϒ(1S) at forward rapidity (small-*x* region)
    - Similar R_{pPb} as for J/ψ
  - A R_{pPb} consistent with unity at backward rapidity (large-*x* region)
    - Model comparisons suggest smaller anti-shadowing than assumed

- Excited states are more suppressed than ground states
  - ψ(2S) R_{pPb} is well described by comovers approach
    - what about ϒ(2S)?

It's almost Christmas, here is my wish-list

- LHC Run2 is about to start …
- What can be improved from the experimental side
  - LHCb will increase their stat. in Run2
    - better J/ψ and Υ(1S) measurement
    - significant ψ(2S) and Υ(2S) measurement
    - larger y coverage
  - ALICE will increase their stat. in Run2
    - better ψ(2S) and Υ family measurements
  - Eventually CMS will join the game (with more than double ratios)
    - broad y coverage for Υ family RpPb
  - Measured pp reference is a must!
    - will improve all quarkonium R_{pPb} measurements
- What we need from theory
  - Interaction with comovers explain the ψ(2S) results, what about Υ(2S)?
  - Many statistically significant results are out there, can't we start considering them to constrain the models?
  - For some of us the goal is to extrapolate to Pb-Pb, let's get to the task!
- The question is still open, should LHC run their p-Pb collisions at 5 or 8 TeV?

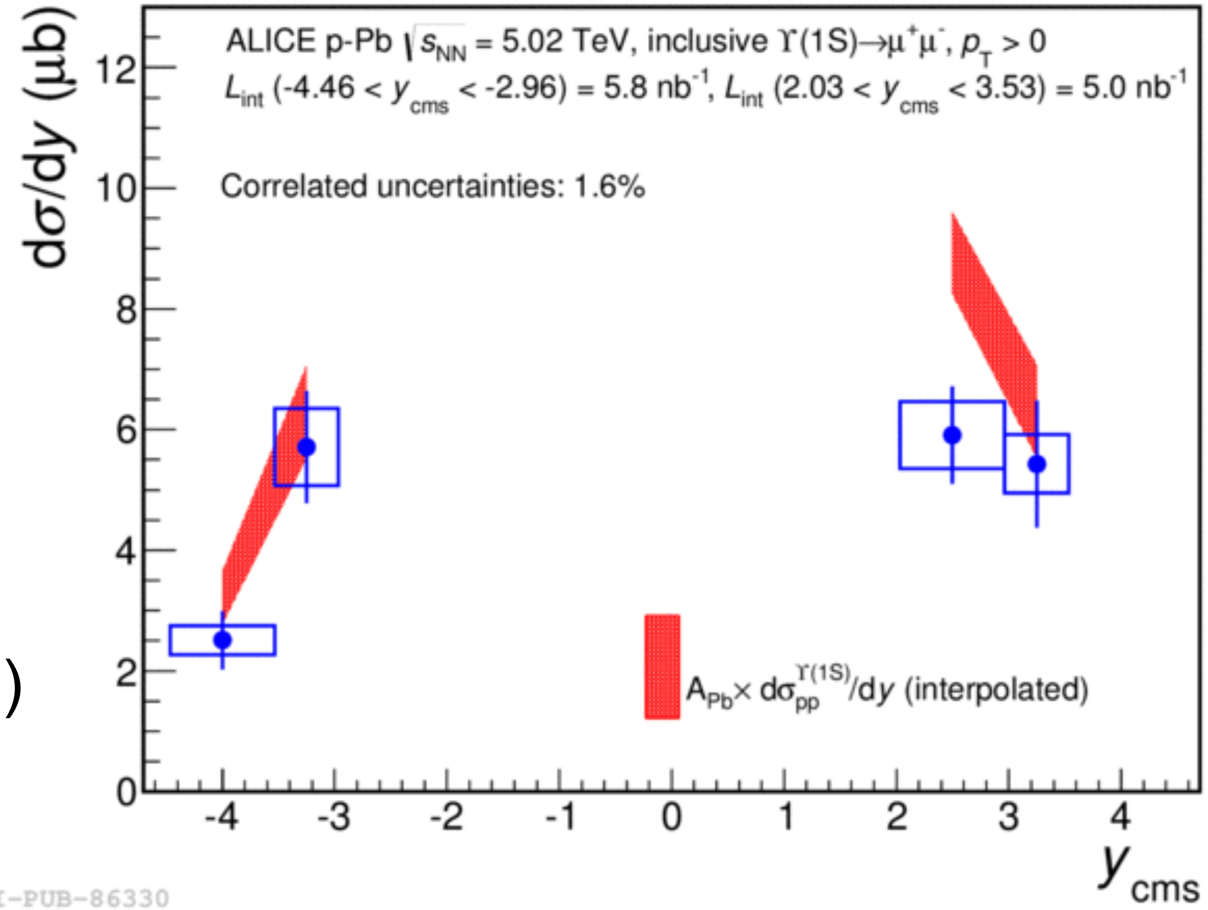
Back-up

Production cross section

pPb @ 5.02 TeV

arXiv:1410.2234

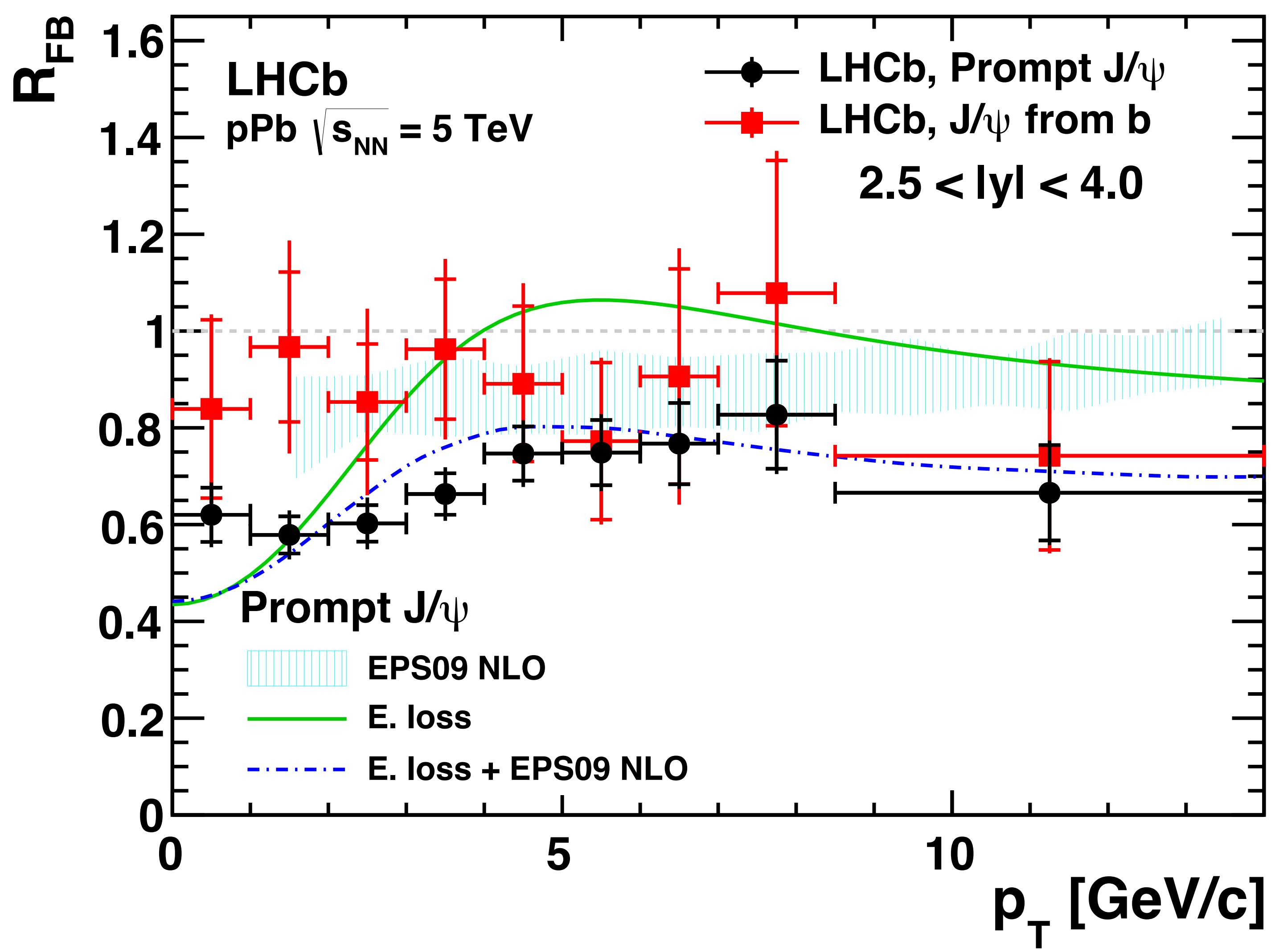
- Rapidity integrated cross sections
  - $\sigma_{\Upsilon(1S)}(-4.46 < y_{cms} < -2.96) = 5.57\pm0.72(stat)\pm0.60(syst)$ μb;
  - $\sigma_{\Upsilon(1S)}(2.03 < y_{cms} < 3.53) = 8.45\pm0.94(stat)\pm0.77(syst)$ μb.
  - $\sigma_{\Upsilon(2S)}(-4.46 < y_{cms} < -2.96) = 1.85\pm0.61(stat)\pm0.32(syst)$ μb,
  - $\sigma_{\Upsilon(2S)}(2.03 < y_{cms} < 3.53) = 2.97\pm0.82(stat)\pm0.50(syst)$ μb.



- Y(2S)-to-Y(1S) cross section ratio
  - $-4.46 < y_{cms} < -2.96$: 0.26 ± 0.09 ± 0.04
  - $2.03 < y_{cms} < 3.53$: 0.27 ± 0.08 ± 0.04

- Similar values measured in pp collisions by ALICE (2.5 < y < 4.0) and LHCb (2.0 < y < 4.5)
  - ALICE 7 TeV: 0.28 ± 0.08
  - LHCb 2.76 TeV: 0.24 ± 0.03
  - LHCb 7 TeV: 0.25 ± 0.02
  - LHCb 8 TeV: 0.23 ± 0.01

No evidence of different CNM effects on Y(2S) than on Y(1S)



LHCb
pPb $\sqrt{s_{NN}}$ = 5 TeV
LHCb, Prompt J/ψ
LHCb, J/ψ from b
2.5 < |y| < 4.0
Prompt J/ψ
EPS09 NLO
E. loss
E. loss + EPS09 NLO
R_{FB}
p_T [GeV/c]

Forward to Backward ratio

pPb @ 5.02 TeV

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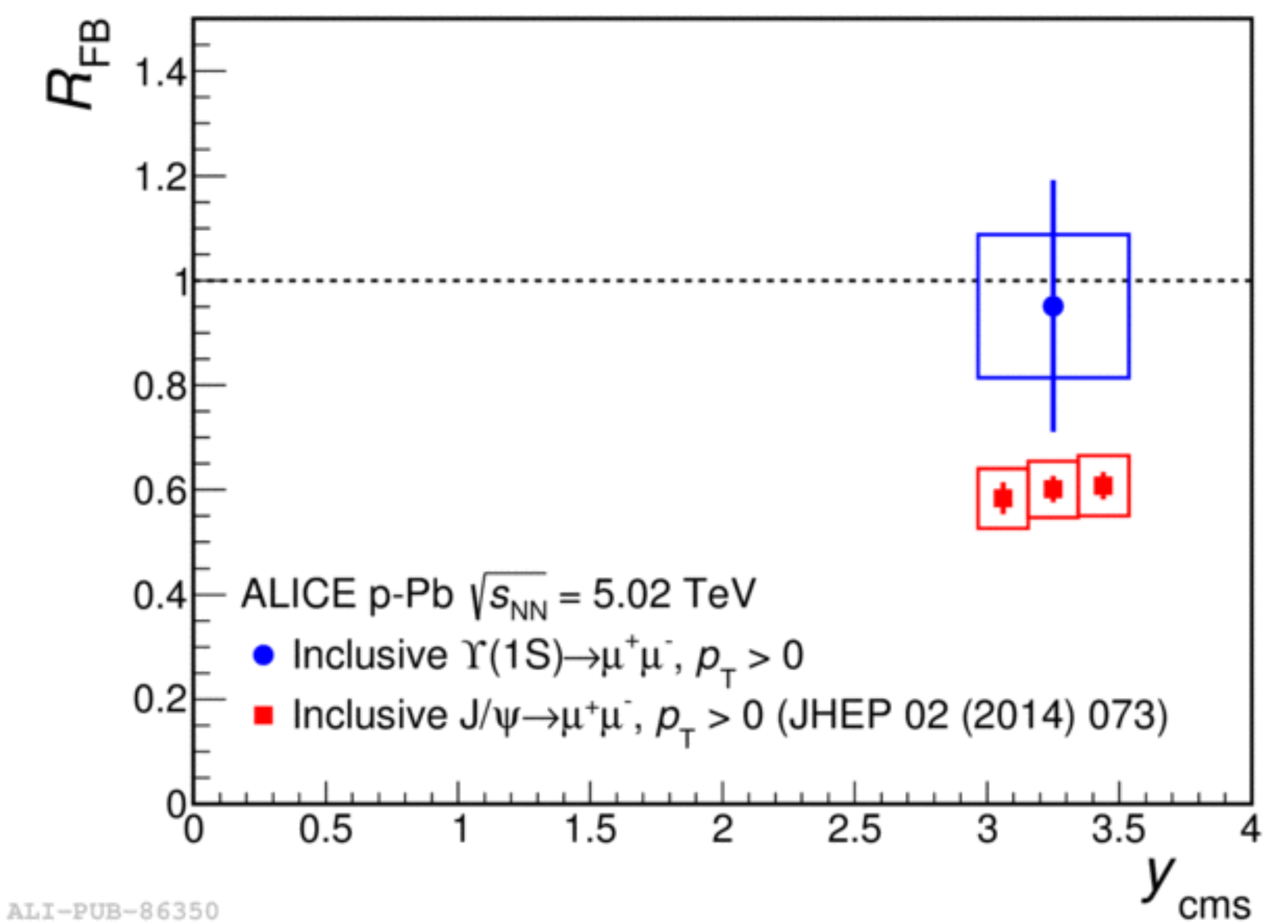
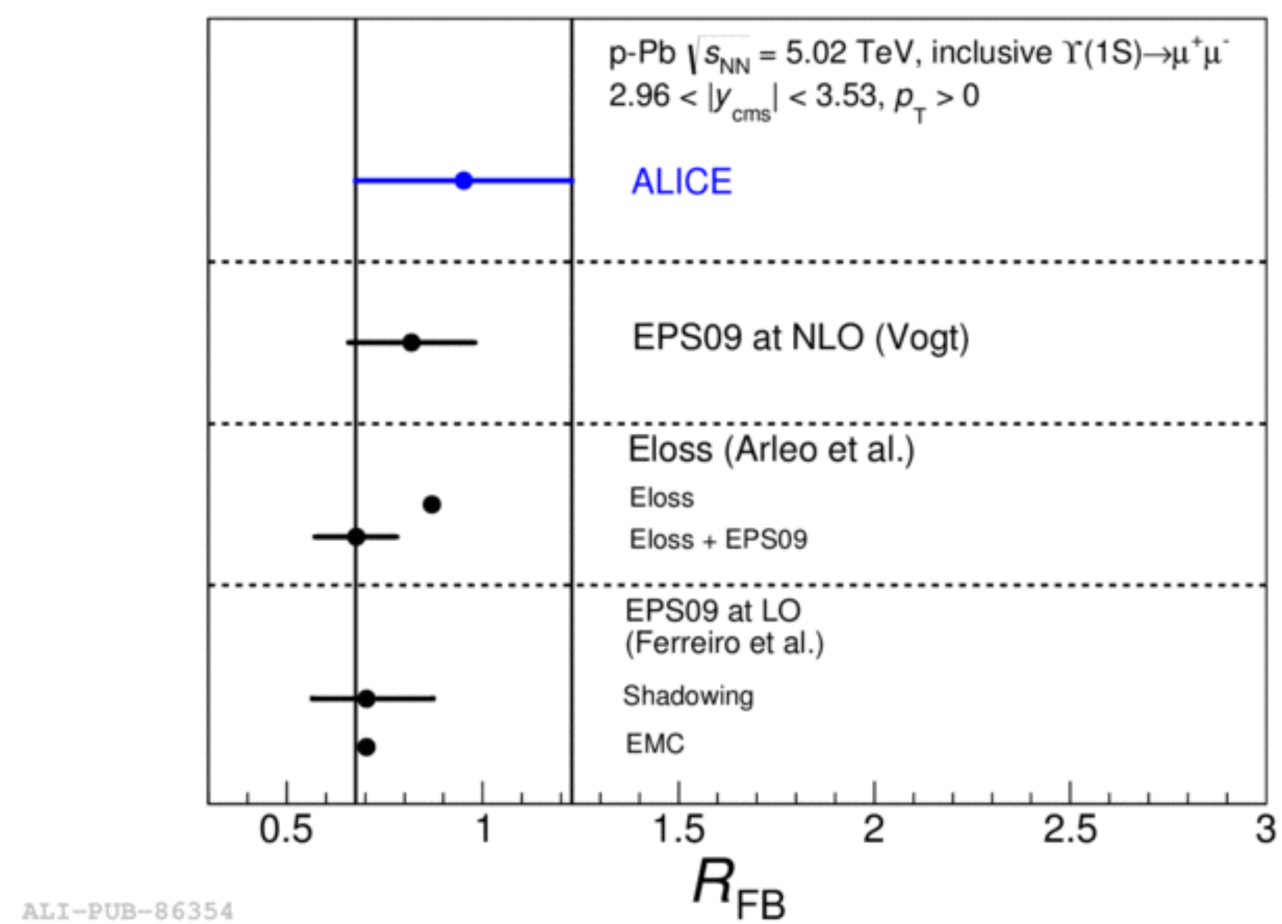
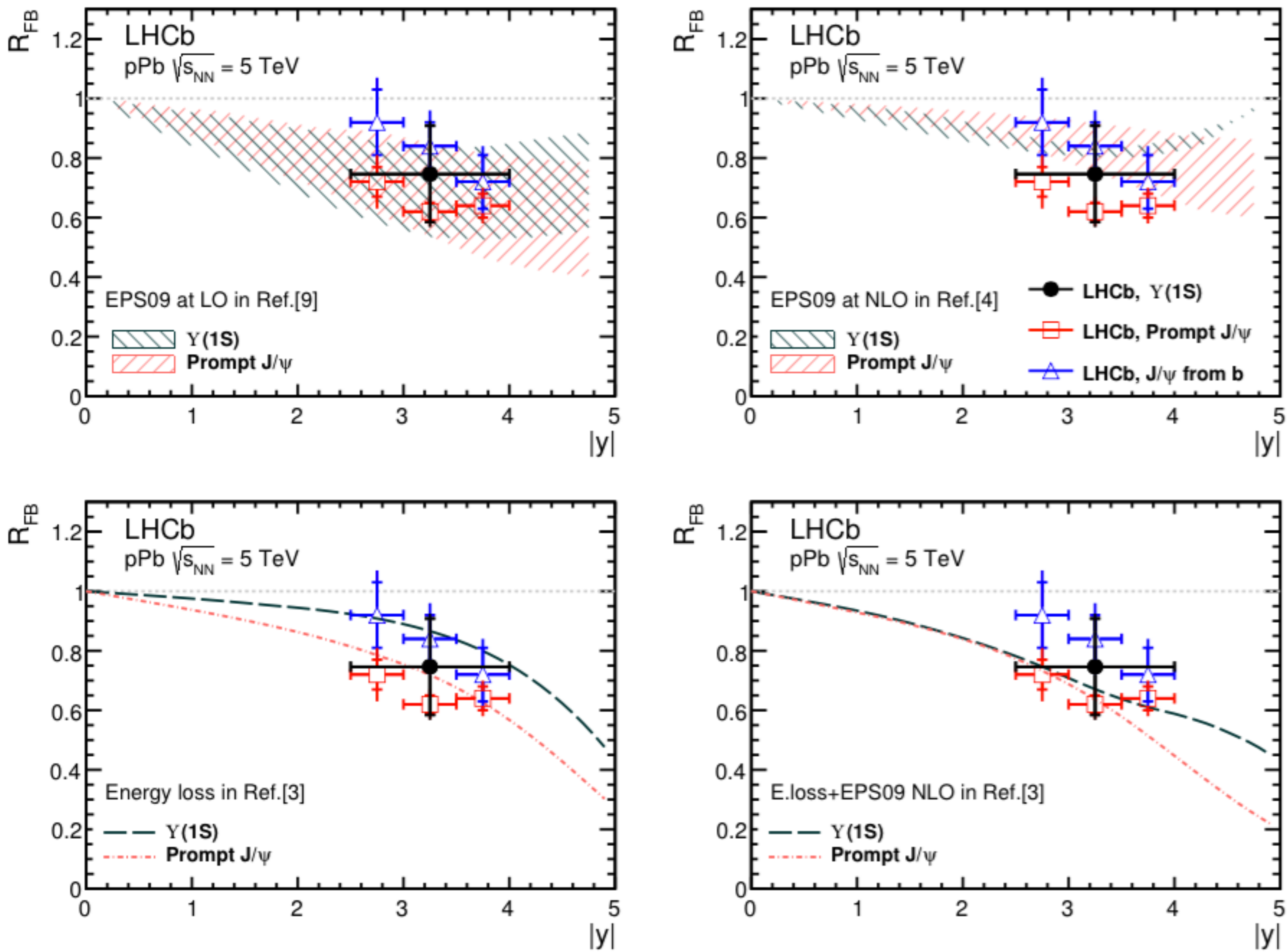
- Ratio of the Forward to Backward yields
  - Pros: No need of pp reference
  - Cons: Rapidity acceptance restricted to common region $2.96 < |y_{cms}| < 3.53$





  - All models are in agreement with our measurement within uncertainties



LHCb
pPb $\sqrt{s_{NN}}$ = 5 TeV
EPS09 at LO in Ref.[9]
Υ(1S)
Prompt J/ψ
EPS09 at NLO in Ref.[4]
LHCb, Υ(1S)
LHCb, Prompt J/ψ
LHCb, J/ψ from b
Energy loss in Ref.[3]
E.loss+EPS09 NLO in Ref.[3]
R_{FB}
|y|