ATLAS Quarkonia Measurements

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for the ATLAS Collaboration

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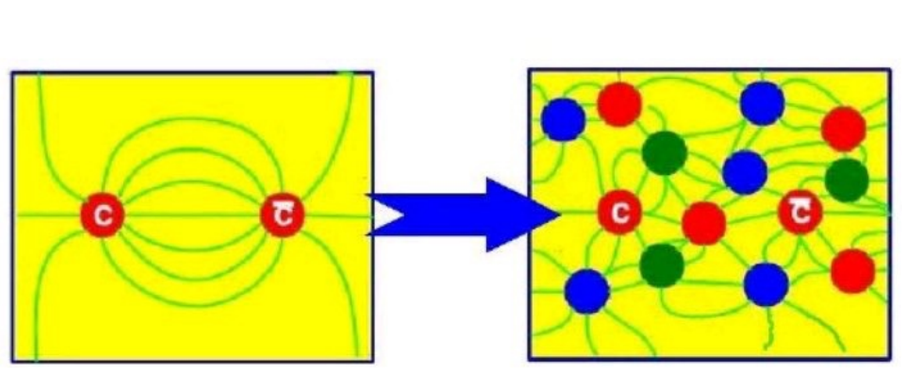
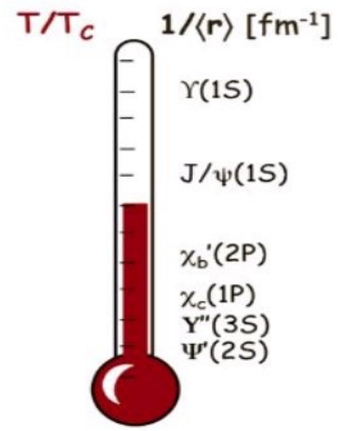
Why measure quarkonia?

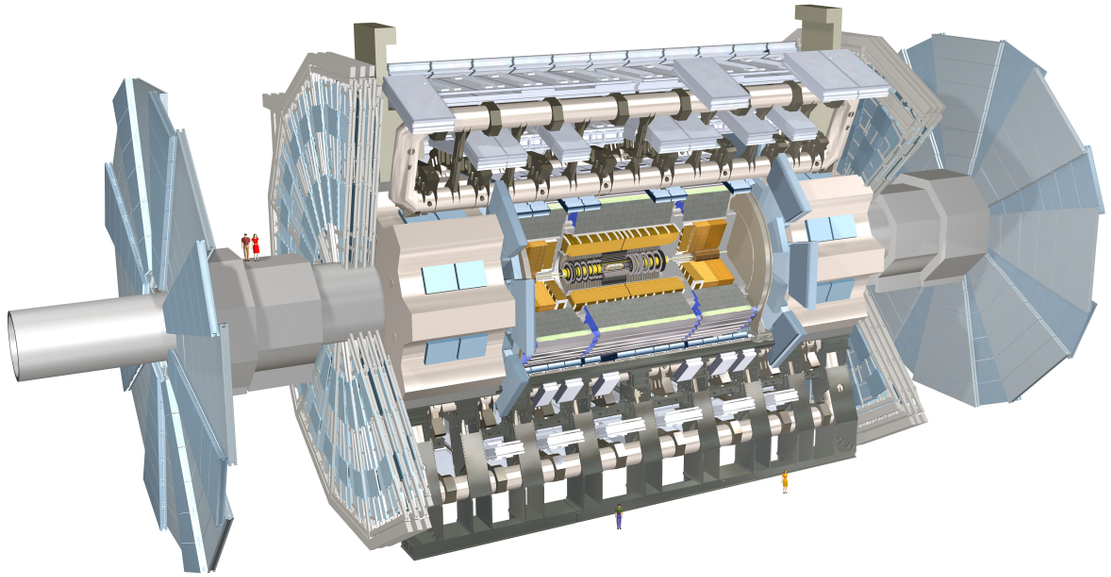
- *Charmonia*: bound states of charm and anti-charm quarks: *J/ψ* and *ψ(2S)* mesons.
  - Two production mechanisms:
    - **Prompt** production from hard-scattering and very short time decays.
    - **Non-Prompt** production dominated by b-hadron decays.
- *Bottomonia*: bound states of bottom and anti-bottom quarks: *Υ(1S), Υ(2S), Υ(3S).*
- *Many related issues:*
  - **Cold nuclear matter** effects:
    - PDF modification within nucleus
    - Initial stage energy loss
    - Nuclear absorption/dissociation
  - **Hot nuclear matter** effects**:**
    - Suppression by color screening
    - Regeneration via statistical recombination
    - Medium induced energy loss
  - Feed down of excited states of charmonium and B-hadrons to *J/ψ* and *ψ(2S)*





- *Unique probes to study the hot, dense system created in heavy ion collisions.*

The ATLAS Experiment at the LHC



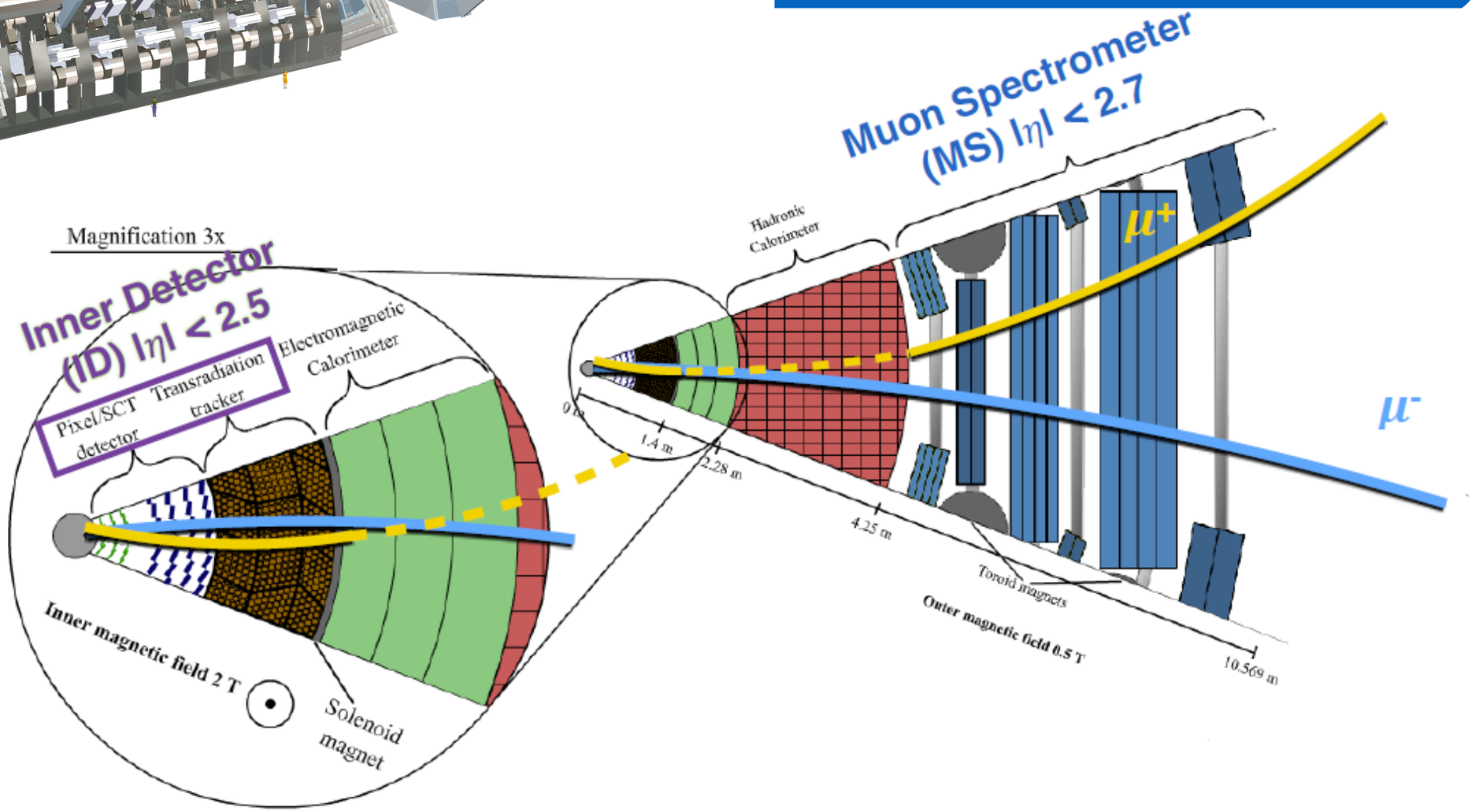
2013 **p+Pb** 5.02 TeV, 28 nb^{-1}

2013 **pp** 2.76 TeV, 4 pb^{-1}

2015 **Pb+Pb** 5.02 TeV, 0.42 nb^{-1}

2015 **pp** 5.02 TeV, 25 pb^{-1}

2016 **p+Pb** 8.16 TeV, 0.17 pb^{-1}



Forward Calorimeters (FCal) at $3.1 < |\eta| < 4.9$: Centrality determination.

ATLAS *J/ψ, ψ(2S), Υ(*nS) measurements

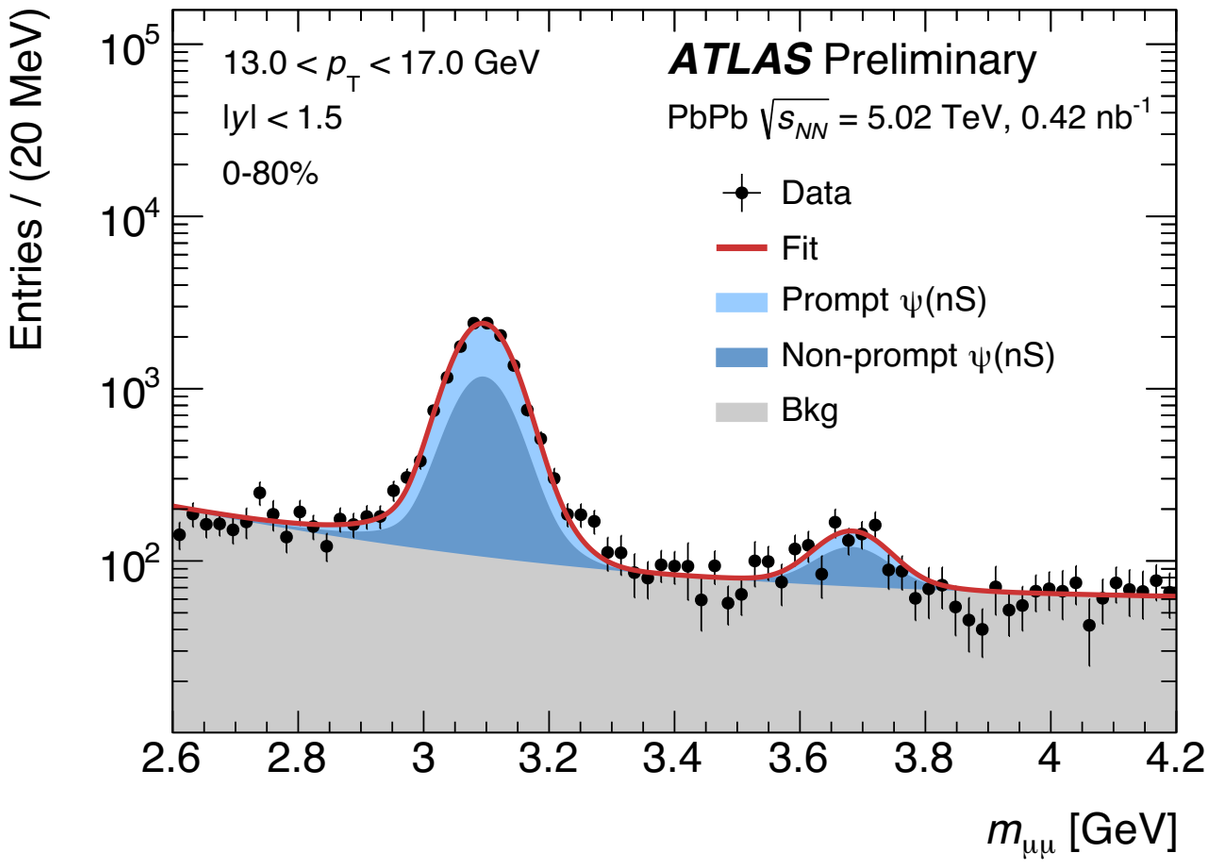
- May 2015, *J/ψ* paper
  - ATLAS Collaboration, Phys. Rev. C **92**, 034904
  - **p+Pb** 5.02 TeV
- June 2015, *J/ψ* and *ψ(2S)*
  - ATLAS-CONF-2015-023
  - **p+Pb** 5.02 TeV and **pp** 2.76 TeV, 7 TeV, 8 TeV
- September 2016, *J/ψ* and *ψ(2S)*
  - ATLAS-CONF-2016-109 (updated)
  - **Pb+Pb** 5.02 TeV and **pp** 5.02 TeV
- September 2017, *J/ψ, ψ(2S), Υ(*nS)
  - https://arxiv.org/abs/1709.03089
  - **p+Pb** 5.02 TeV and **pp** 5.02 TeV

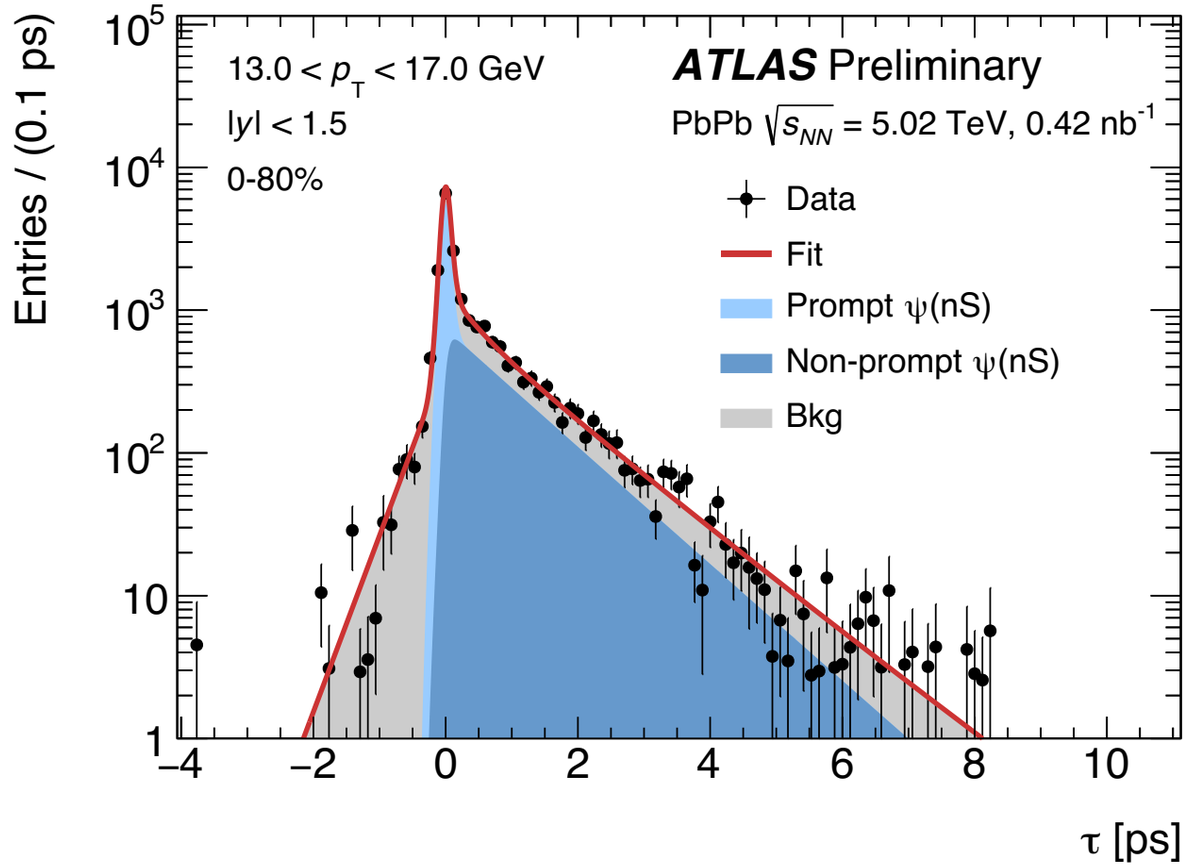
Published paper compatible with new analysis for *J/ψ* and *ψ(2S)* in p+Pb

Data Analysis Method

- Charmonia and bottomonia production studied via $\mu\mu$ decay channel.
- Trigger:
  - p+Pb: 2 muons with $p_T > 2$ GeV, at least one muon from L1.
  - Pb+Pb: 2 muons with $p_T > 4$ GeV, at least one muon from L1.
- Kinematic range:
  - p+Pb: $8 < p_{T(dimuon)} < 40$ GeV, $-2.0 < y^* < 1.5$, Centrality 0 - 90%, $\boldsymbol{\psi}$
  - p+Pb: $0 < p_{T(dimuon)} < 40$ GeV, $-2.0 < y^* < 1.5$, Centrality 0 - 90%, $\boldsymbol{\Upsilon}$
  - Pb+Pb: $9 < p_{T(dimuon)} < 40$ GeV, $|y| < 2$, Centrality 0 - 80%, $\boldsymbol{\psi}$
- Observable determination:
  - Two dimensional weighted unbinned, maximum likelihood fits
  - Dimuons weighted to correct for trigger, reconstruction and acceptance.
  - Extraction of prompt and non-prompt fraction of measured yields.

Simultaneous fit method





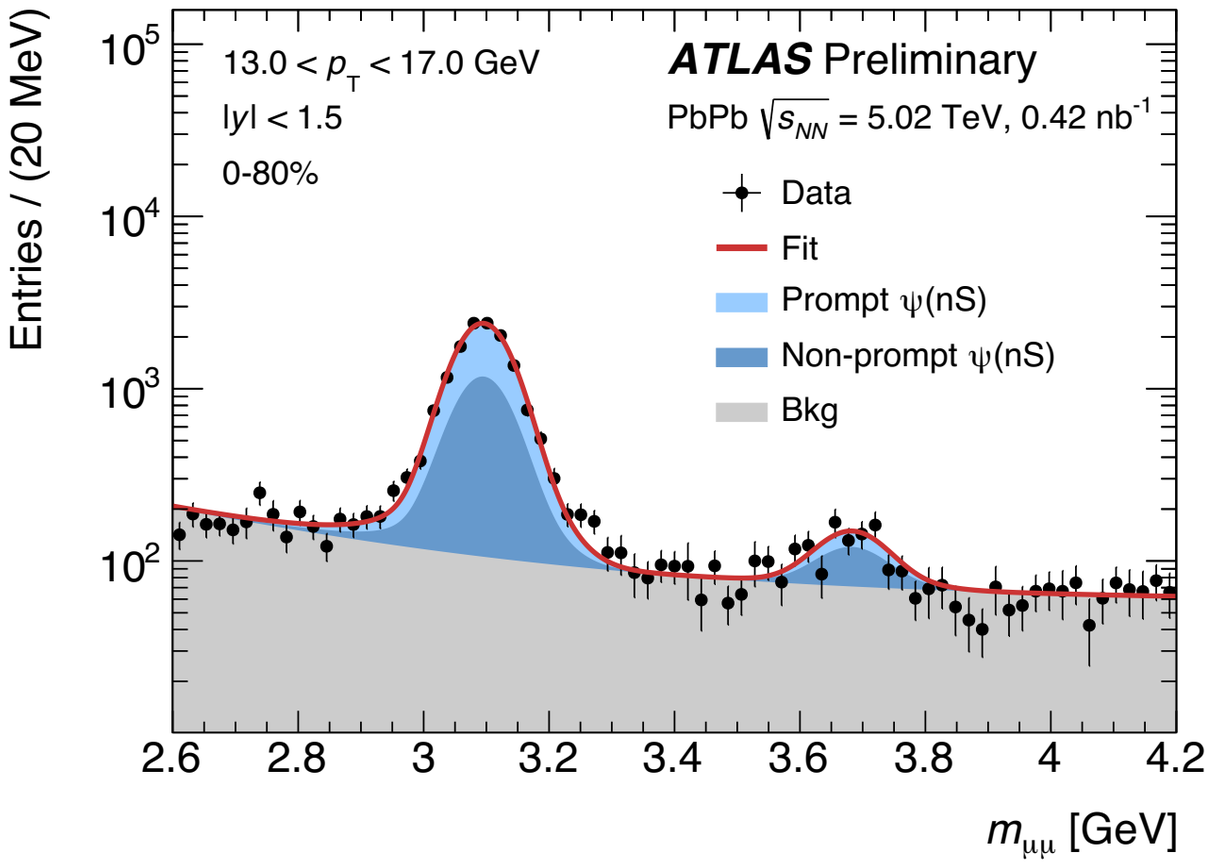
$$\mathrm{PDF}(m,\tau) = \sum_{i=1}^{7} \kappa_i f_i(m) \cdot h_i(\tau) \otimes g(\tau),$$

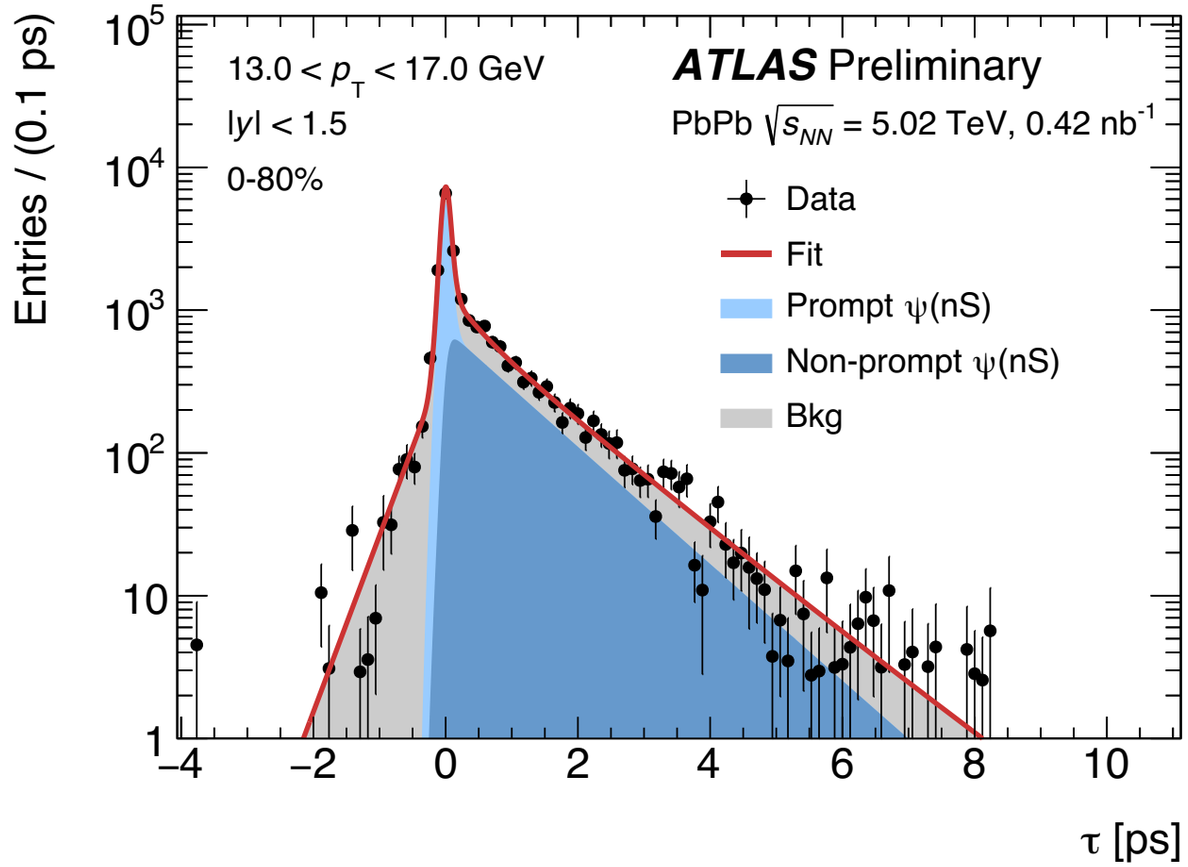
mass pdf

time resolution

time pdf

Simultaneous fit method





i	Type	Source	$f_i(m)$	$h_i(\tau)$
1	J/ψ	P	$\omega_i \mathrm{CB}_1(m) + (1-\omega_i)\mathrm{G}_1(m)$	$\delta(\tau)$
2	J/ψ	NP	$\omega_i \mathrm{CB}_1(m) + (1-\omega_i)\mathrm{G}_1(m)$	$\mathrm{E}_1(\tau)$
3	$\psi(2S)$	P	$\omega_i \mathrm{CB}_2(m) + (1-\omega_i)\mathrm{G}_2(m)$	$\delta(\tau)$
4	$\psi(2S)$	NP	$\omega_i \mathrm{CB}_2(m) + (1-\omega_i)\mathrm{G}_2(m)$	$\mathrm{E}_2(\tau)$
5	Bkg	P	flat	$\delta(\tau)$
6	Bkg	NP	$\mathrm{E}_3(m)$	$\mathrm{E}_4(\tau)$
7	Bkg	NP	$\mathrm{E}_5(m)$	$\mathrm{E}_6(\lvert\tau\rvert)$

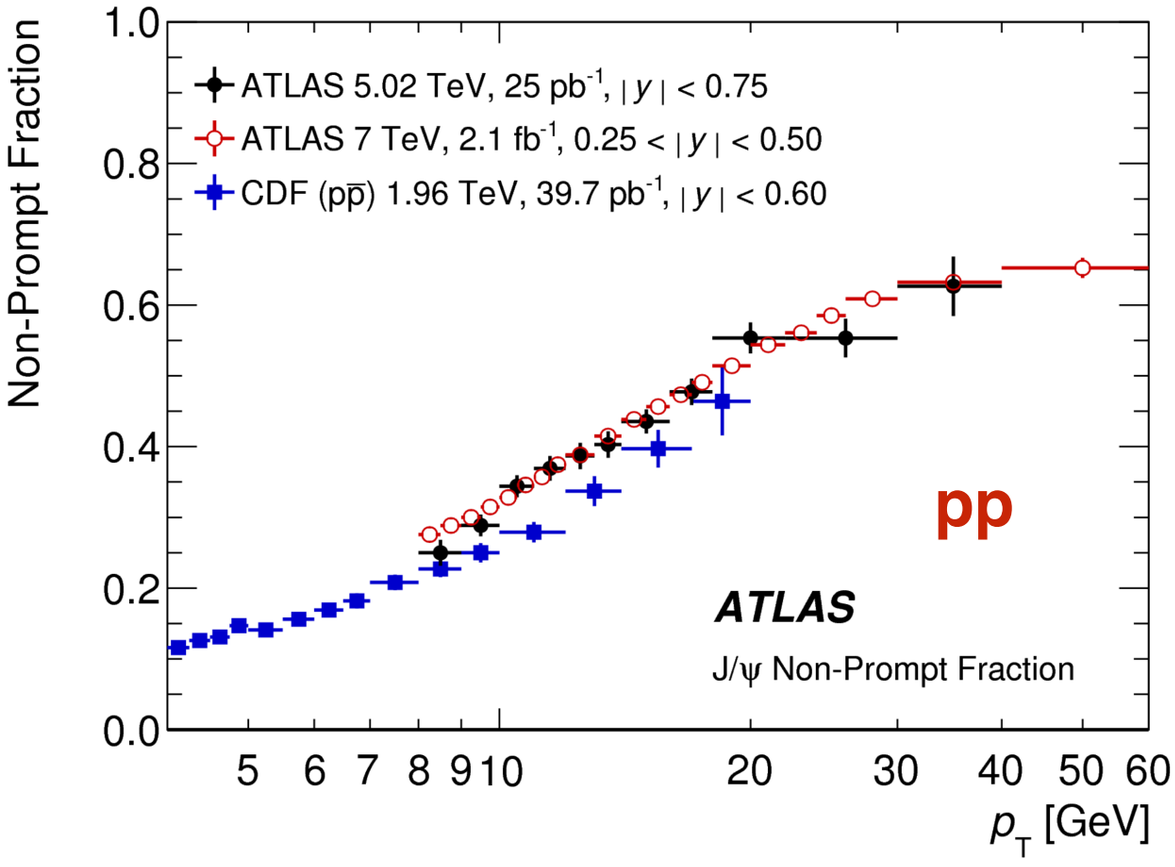
Pseudo-proper decay time

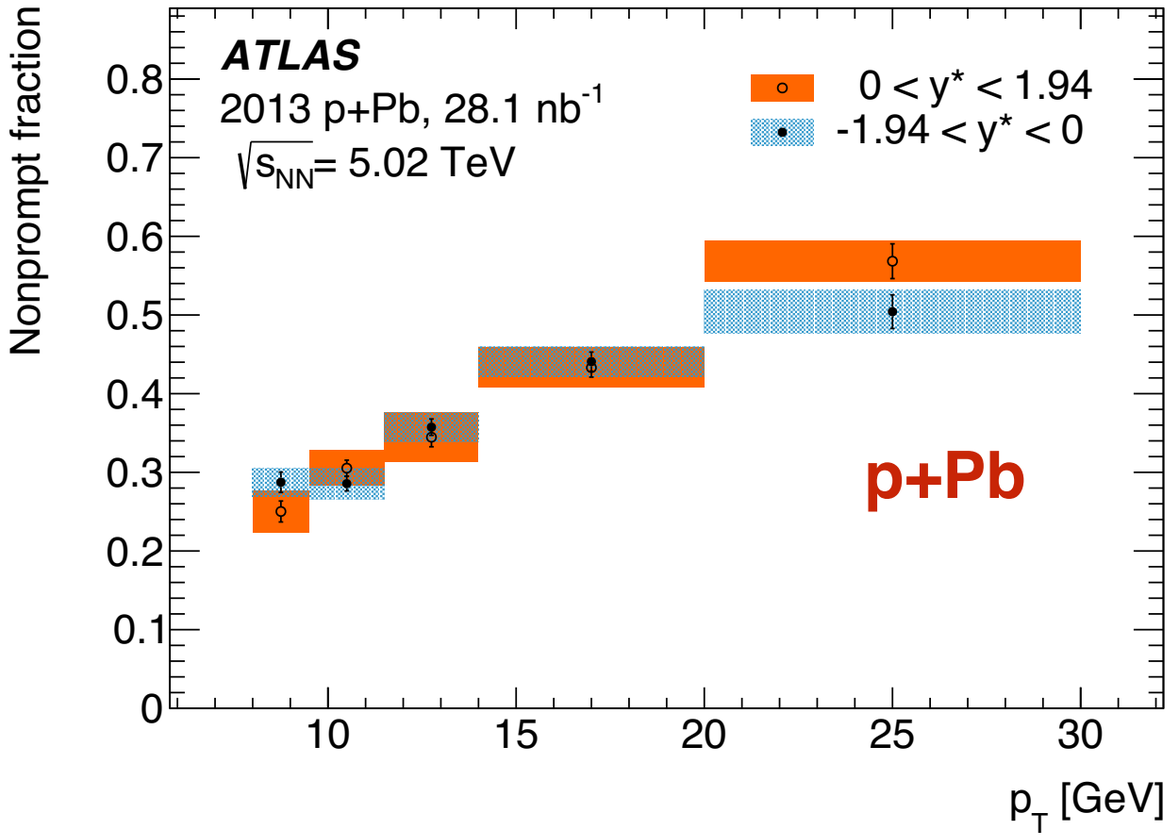
$$\tau = \frac{L_{xy} m_{\mu\mu}}{p_{\mathrm{T}}^{\mu\mu}}$$

$$\mathrm{PDF}(m,\tau) = \sum_{i=1}^{7} \kappa_i f_i(m) \cdot h_i(\tau) \otimes g(\tau),$$

J/ψ non-prompt fraction vs p_T

$$\text{Non-Prompt Fraction} = \frac{N^{\text{Non-Prompt } J/\psi}(p_T, y)}{N^{\text{Total } J/\psi}(p_T, y)}$$





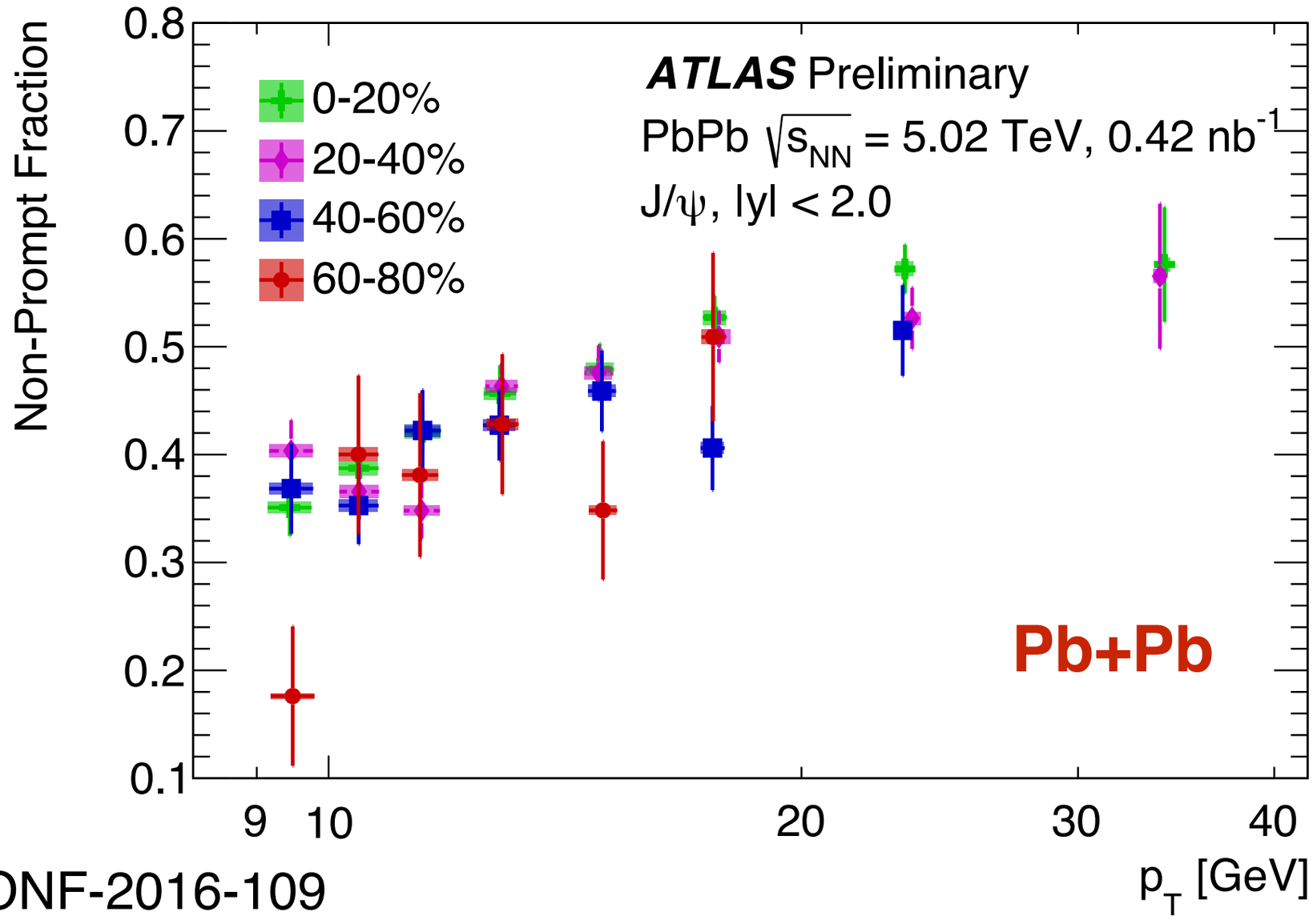
https://arxiv.org/abs/1709.03089

Phys. Rev. C 92, 034904

~No rapidity dependence, pp and p+Pb are compatible

J/ψ non-prompt fraction vs p_T

Non-prompt fraction for several centrality slices in **Pb+Pb**



ATLAS-CONF-2016-109

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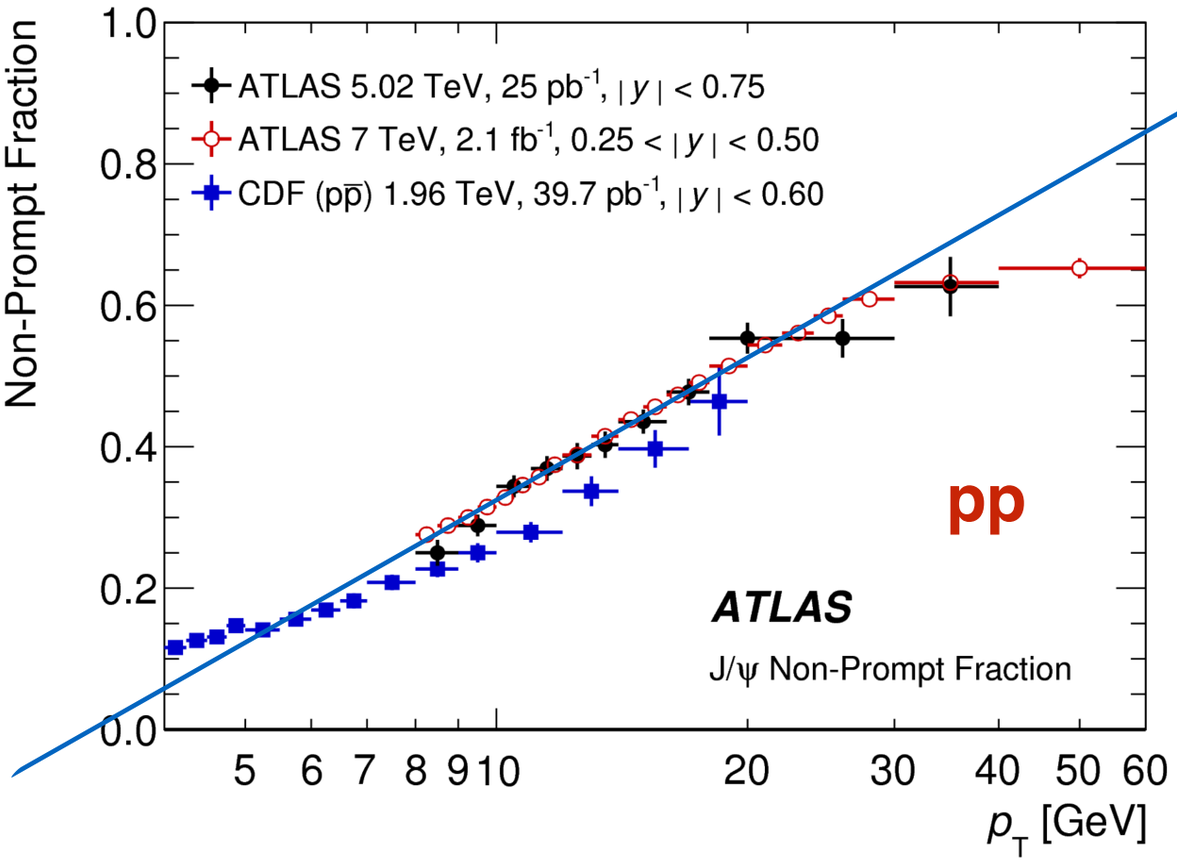

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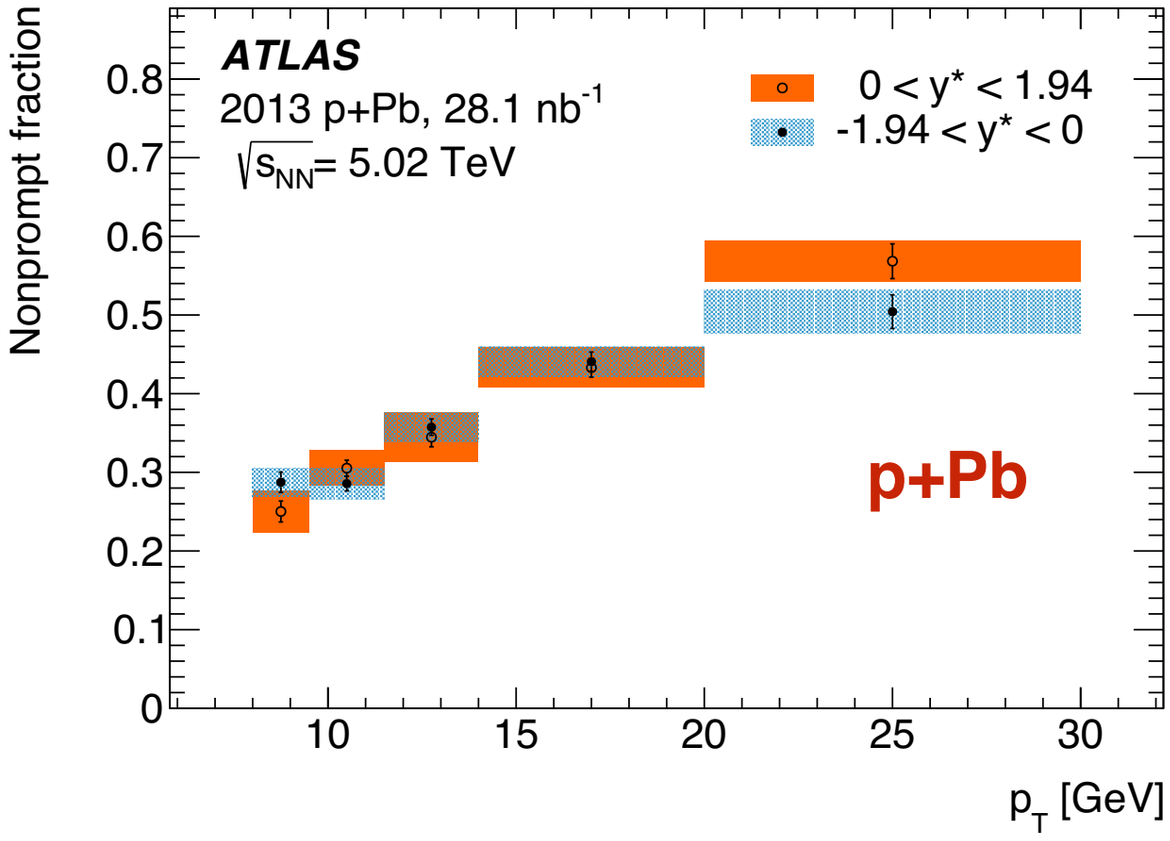

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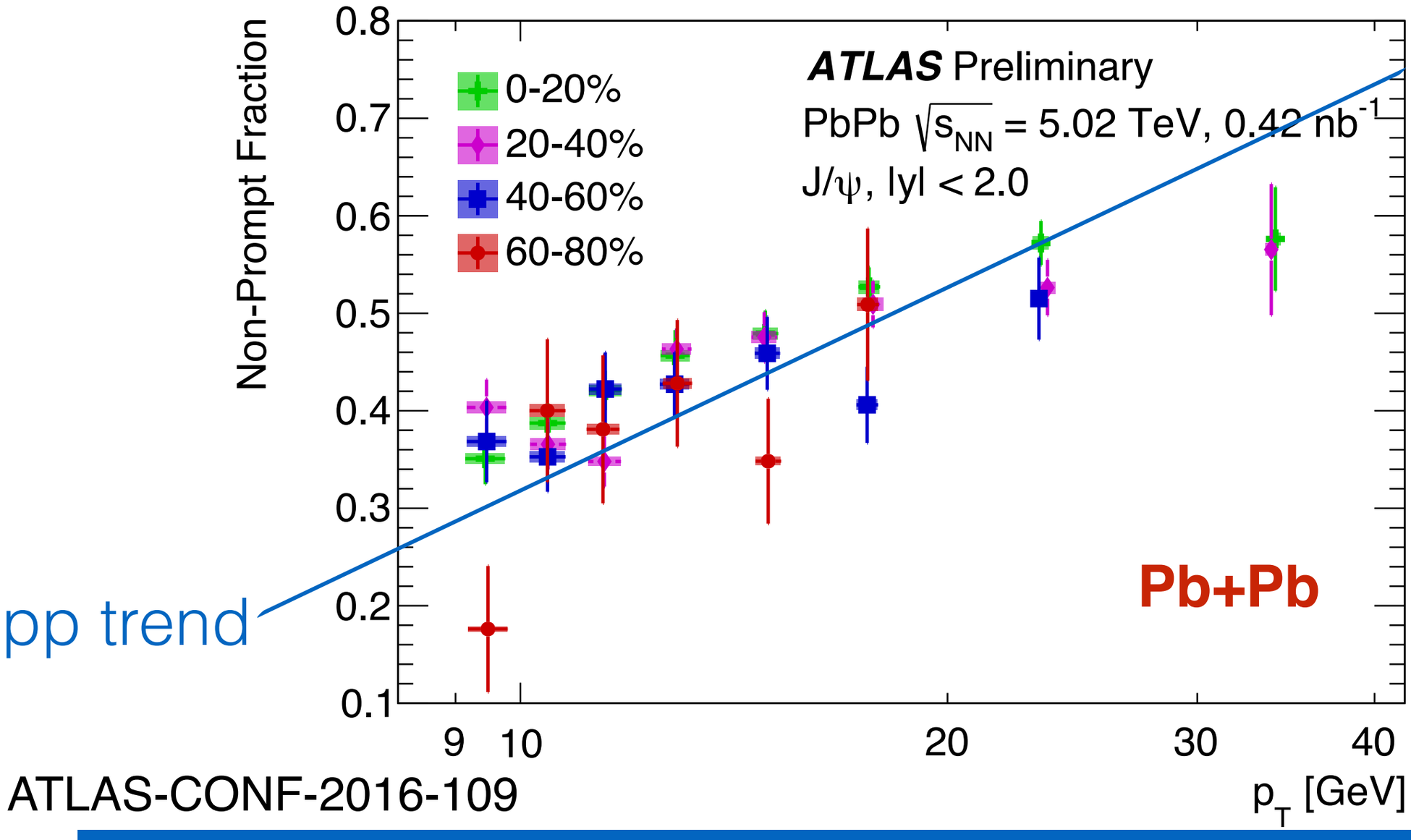
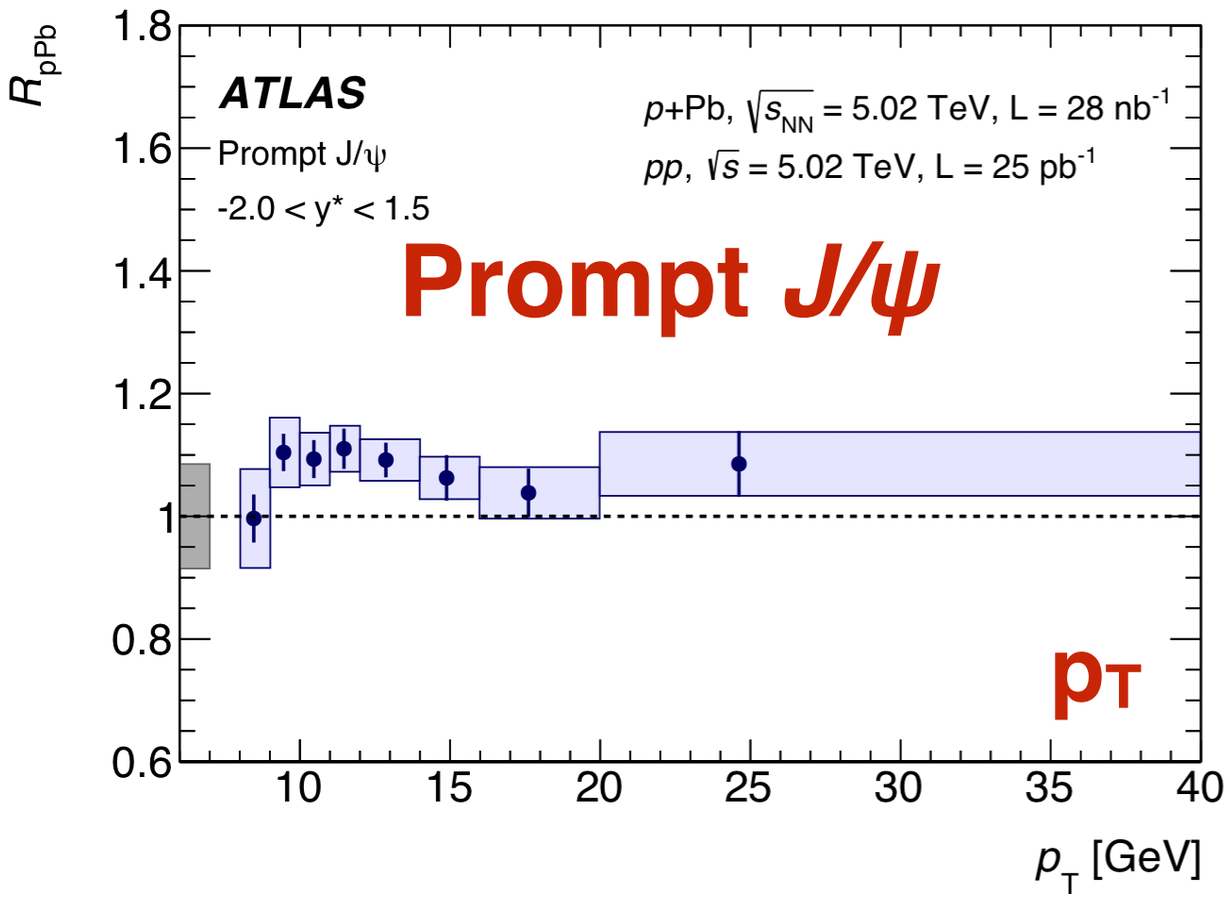


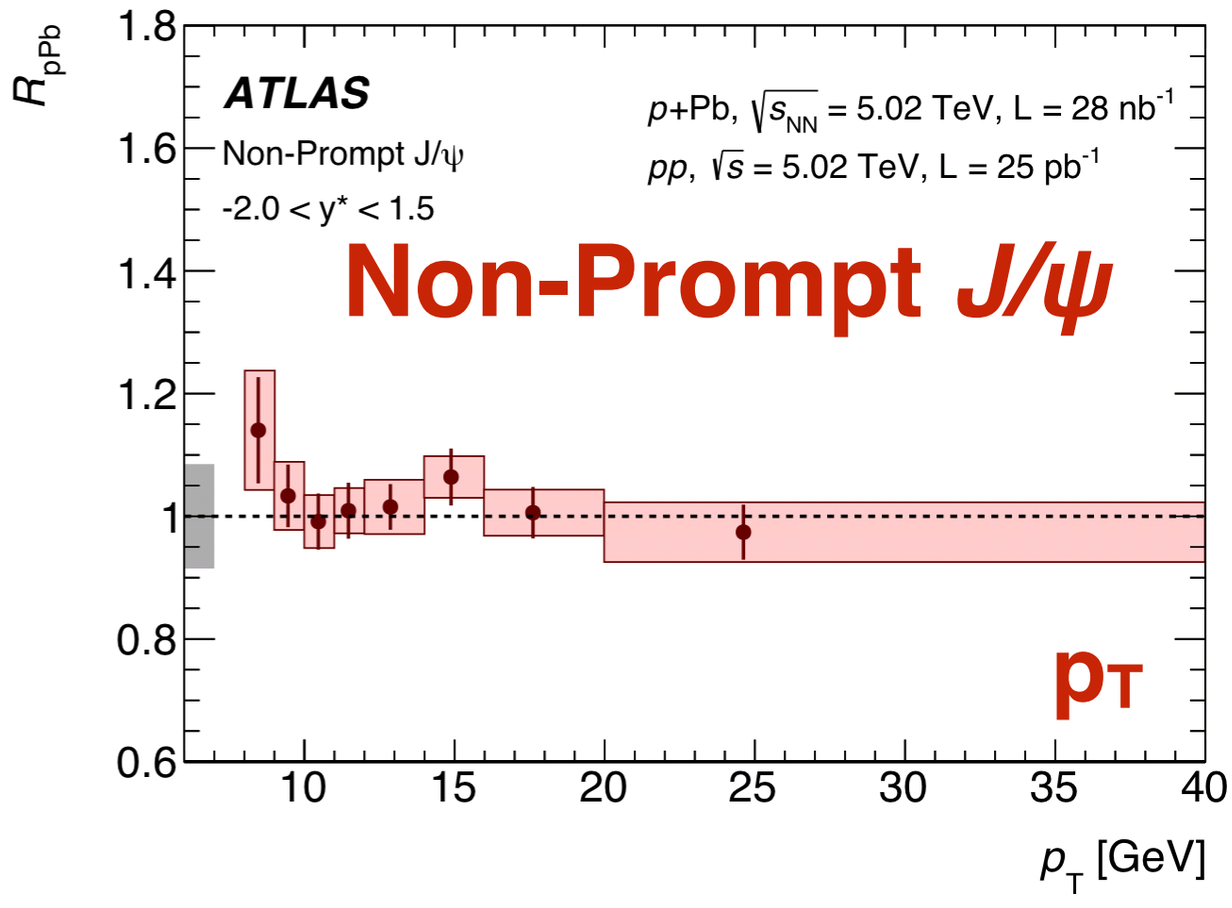
ATLAS-CONF-2016-109

Slightly different from pp at low and high p_T.
Different suppression for prompt than non-prompt in those limits .

Nuclear modification factor R_{pPb}

$$R_{p\mathrm{Pb}} = \frac{1}{A^{\mathrm{Pb}}} \frac{d^2\sigma_{\psi}^{p+\mathrm{Pb}}/dy^* dp_{\mathrm{T}}}{d^2\sigma_{\psi}^{pp}/dy dp_{\mathrm{T}}}$$





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~No p_T dependence observed. R_{pPb} is consistent with unity.

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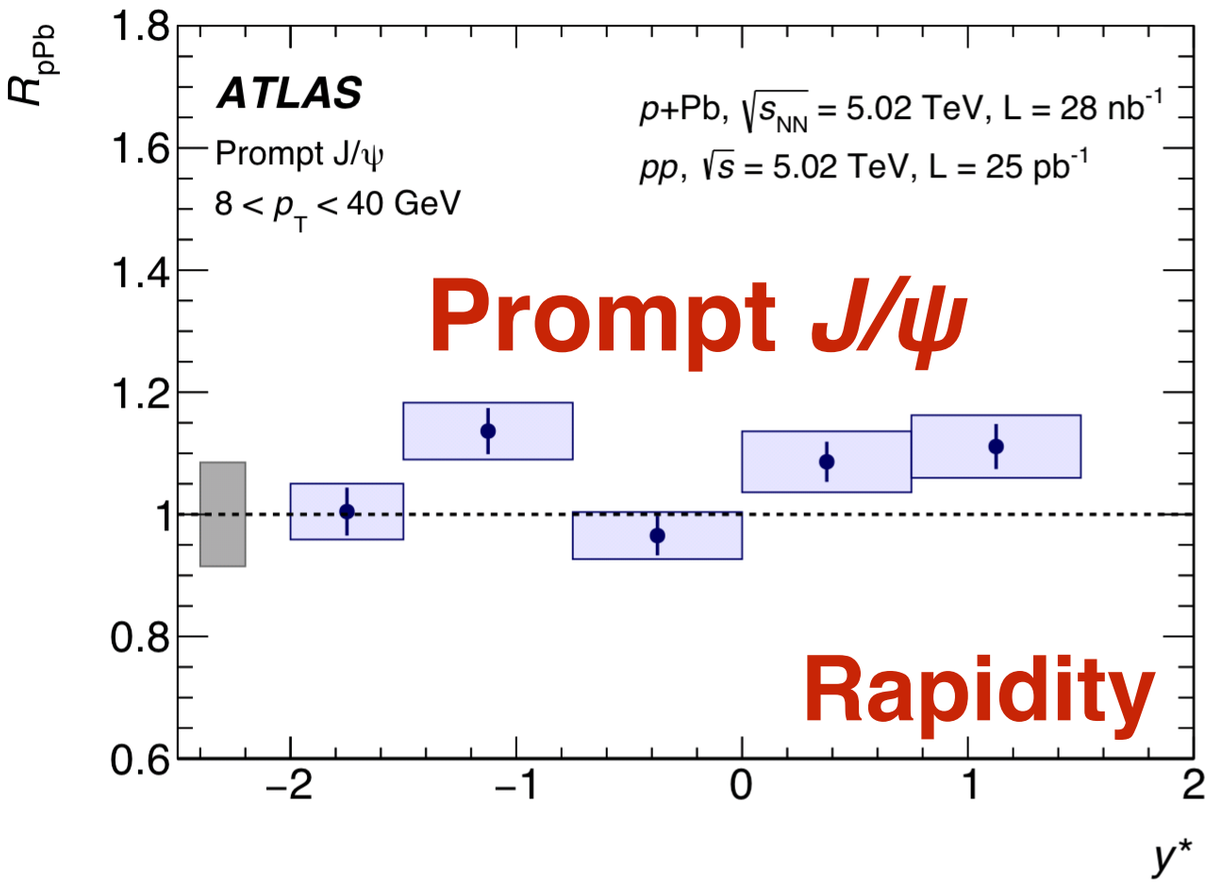

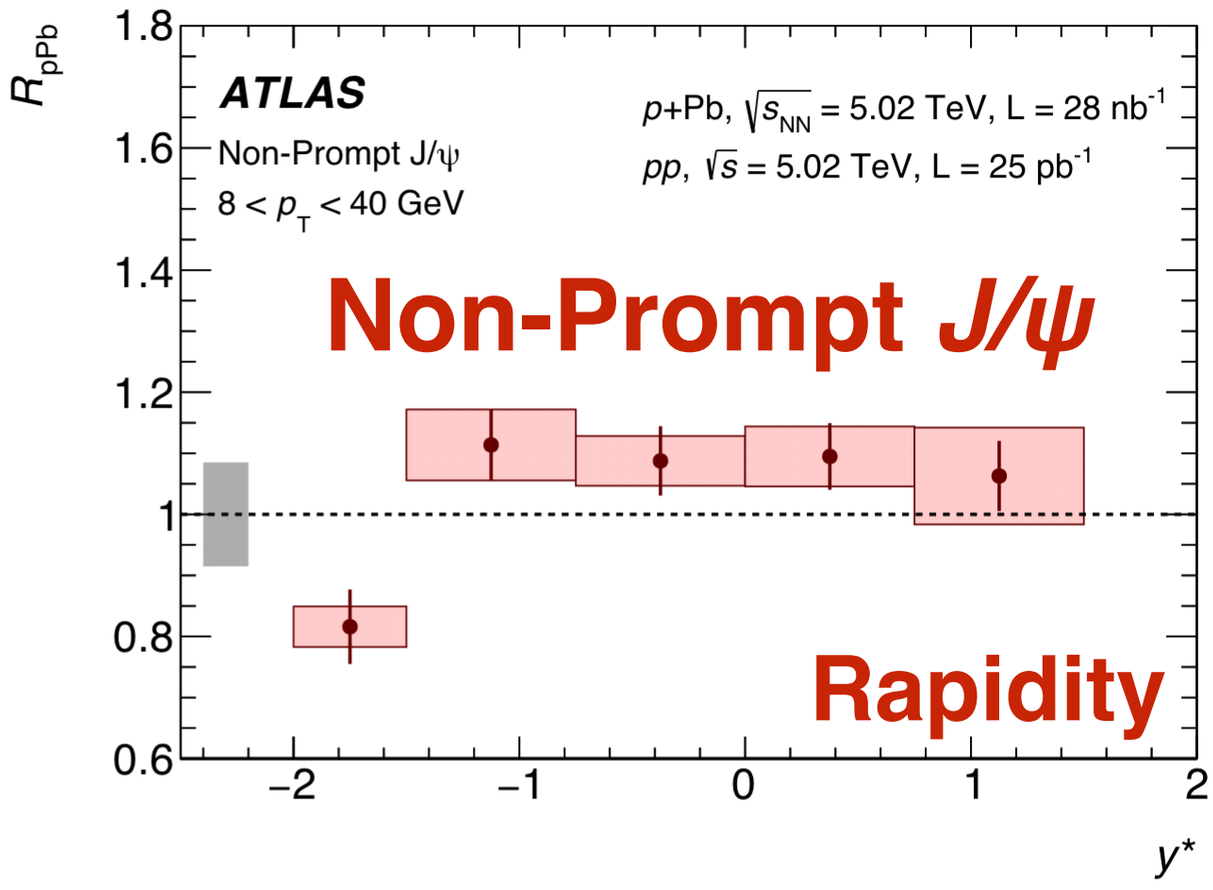

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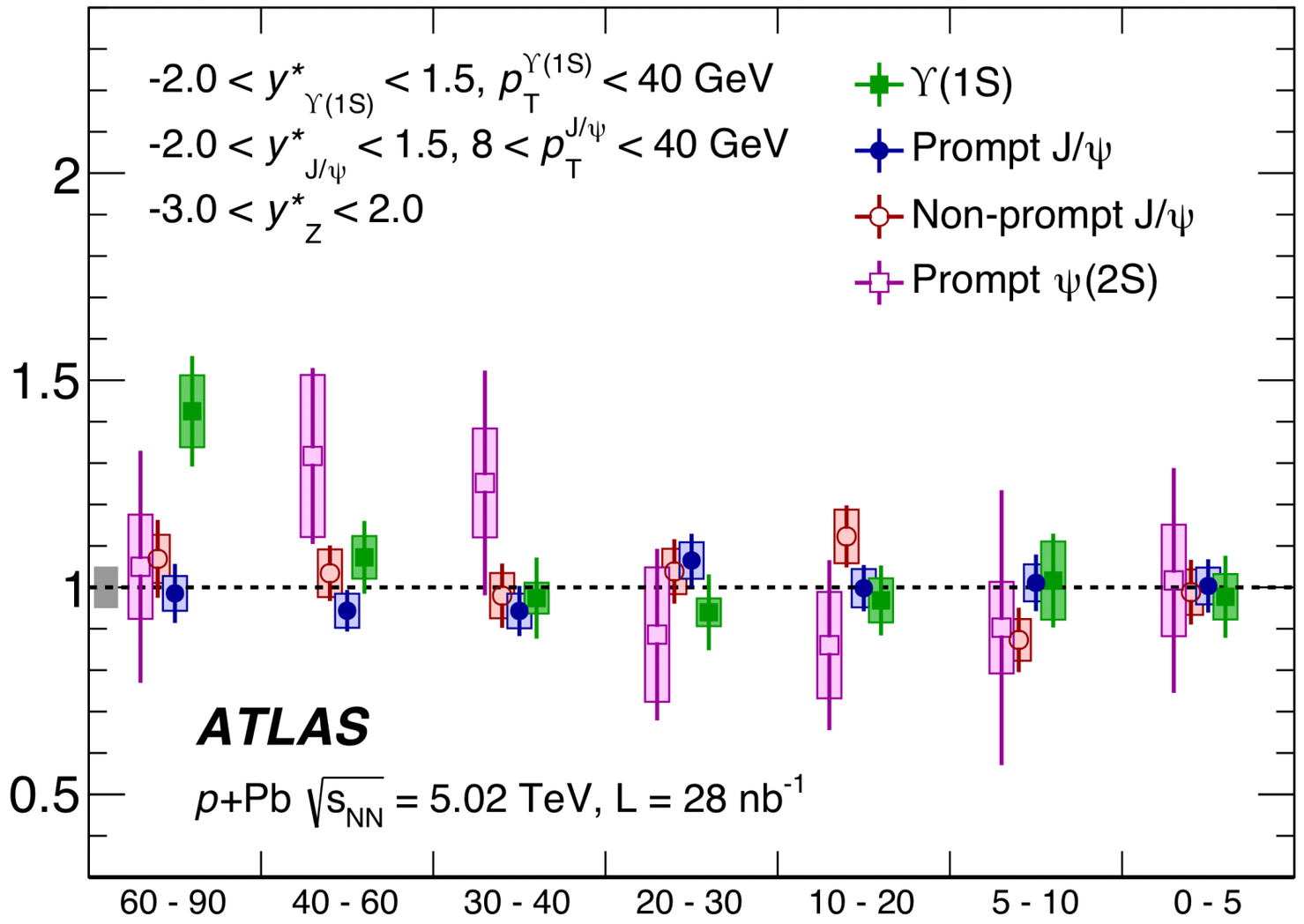
~No rapidity dependence observed. R_{pPb} is consistent with unity.

J/ψ to Z yield ratio vs. Centrality

$$R^{Z}_{p\mathrm{Pb}}(\mathcal{O}(n\mathrm{S})) = \frac{N^{\mathrm{cent}}_{\mathcal{O}(n\mathrm{S})}/N^{\mathrm{cent}}_{Z}}{N^{0-90\%}_{\mathcal{O}(n\mathrm{S})}/N^{0-90\%}_{Z}}$$

- Number of Z bosons scales with number of NN interactions.
- Ratio of yields provides a test of production scaling independent of geometric models.



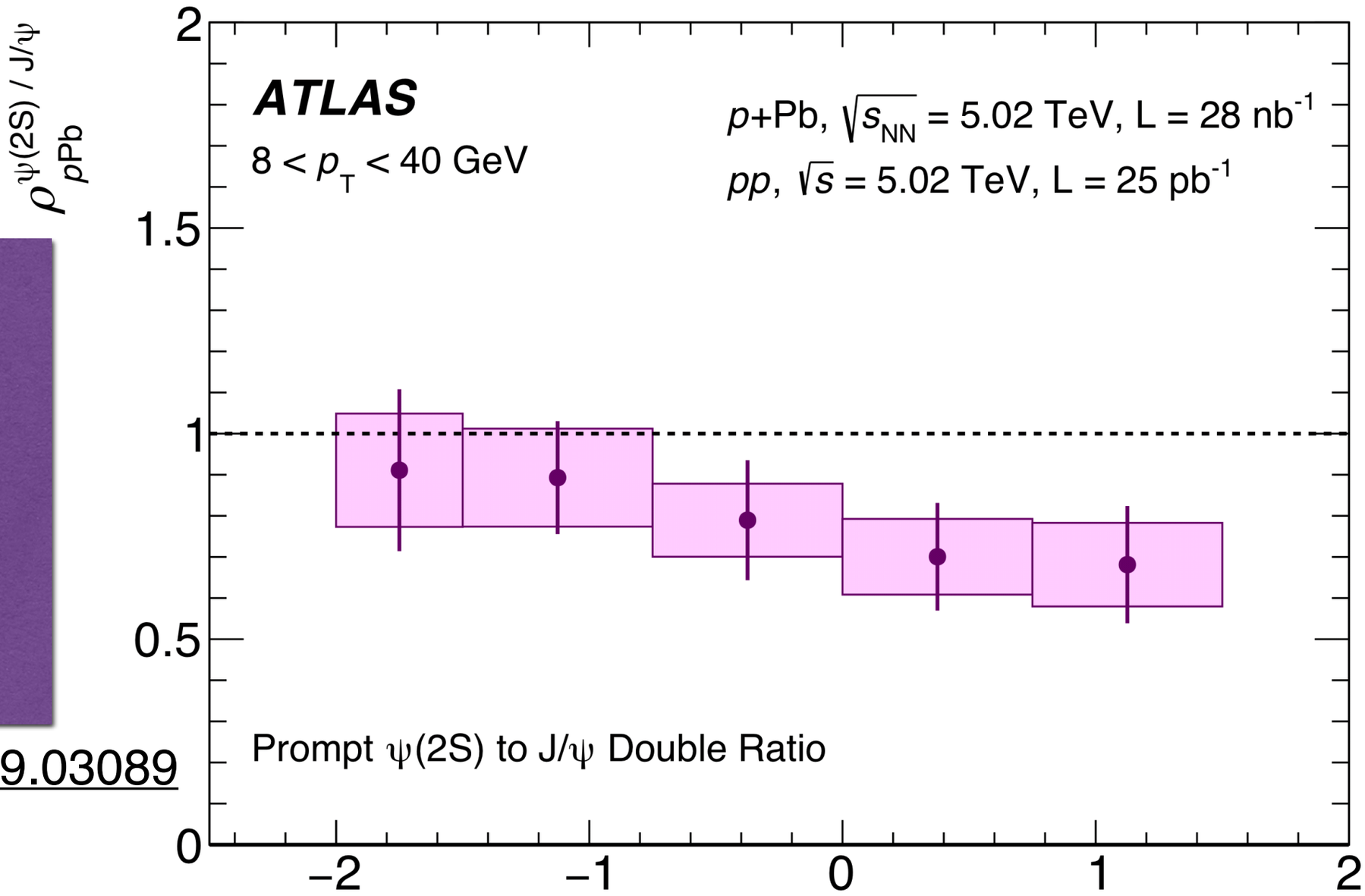
https://arxiv.org/abs/1709.03089

- Check of the centrality dependence by normalizing to the number of Z bosons

$\psi(2S)$ to J/ψ production in **p+Pb**

Evidence for a rapidity dependence; $\psi(2S)$ more suppressed in proton direction

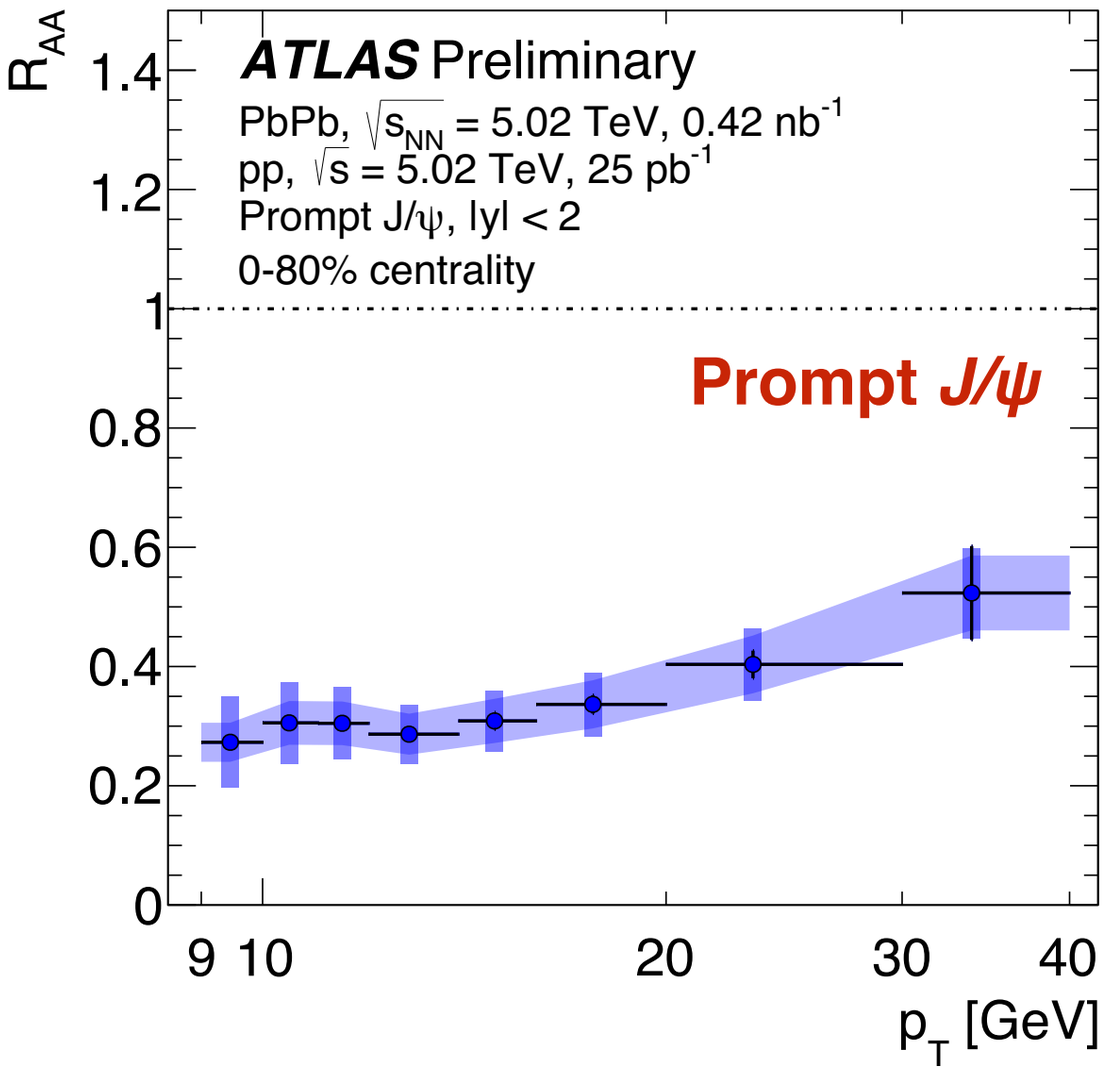
https://arxiv.org/abs/1709.03089

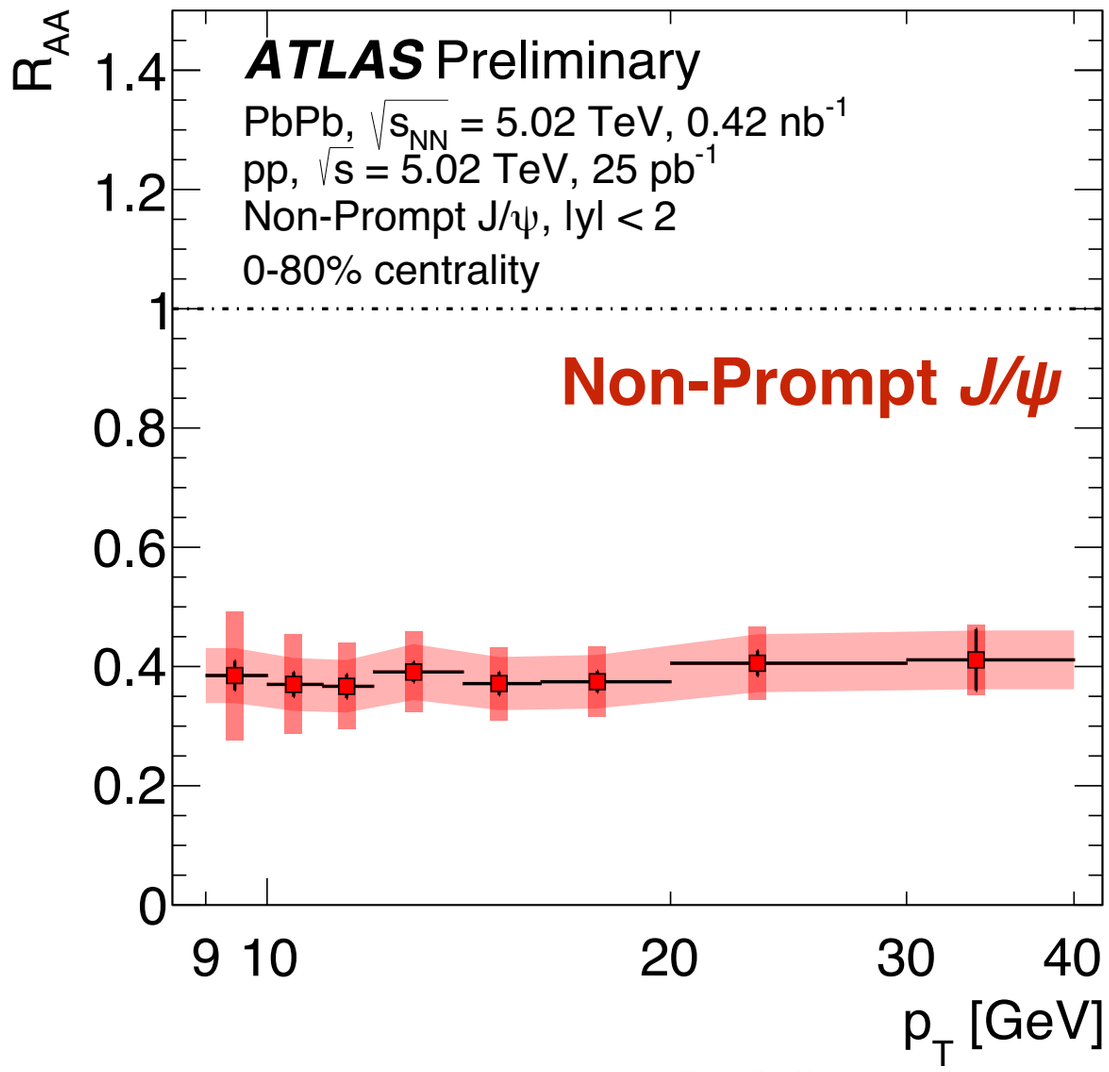


$$\rho^{O(nS)/O(1S)}_{p\mathrm{Pb}} = \frac{R_{p\mathrm{Pb}}(O(n\mathrm{S}))}{R_{p\mathrm{Pb}}(O(1\mathrm{S}))} = \frac{\sigma^{O(n\mathrm{S})}_{p+\mathrm{Pb}}}{\sigma^{O(1\mathrm{S})}_{p+\mathrm{Pb}}} \Big/ \frac{\sigma^{O(n\mathrm{S})}_{pp}}{\sigma^{O(1\mathrm{S})}_{pp}}$$

J/ψ nuclear modification factor $\mathbf{R_{AA}}$

$$R_{\mathrm{AA}} = \frac{N^{\mathrm{AA}}}{\langle T_{\mathrm{AA}} \rangle \times \sigma^{pp}}$$

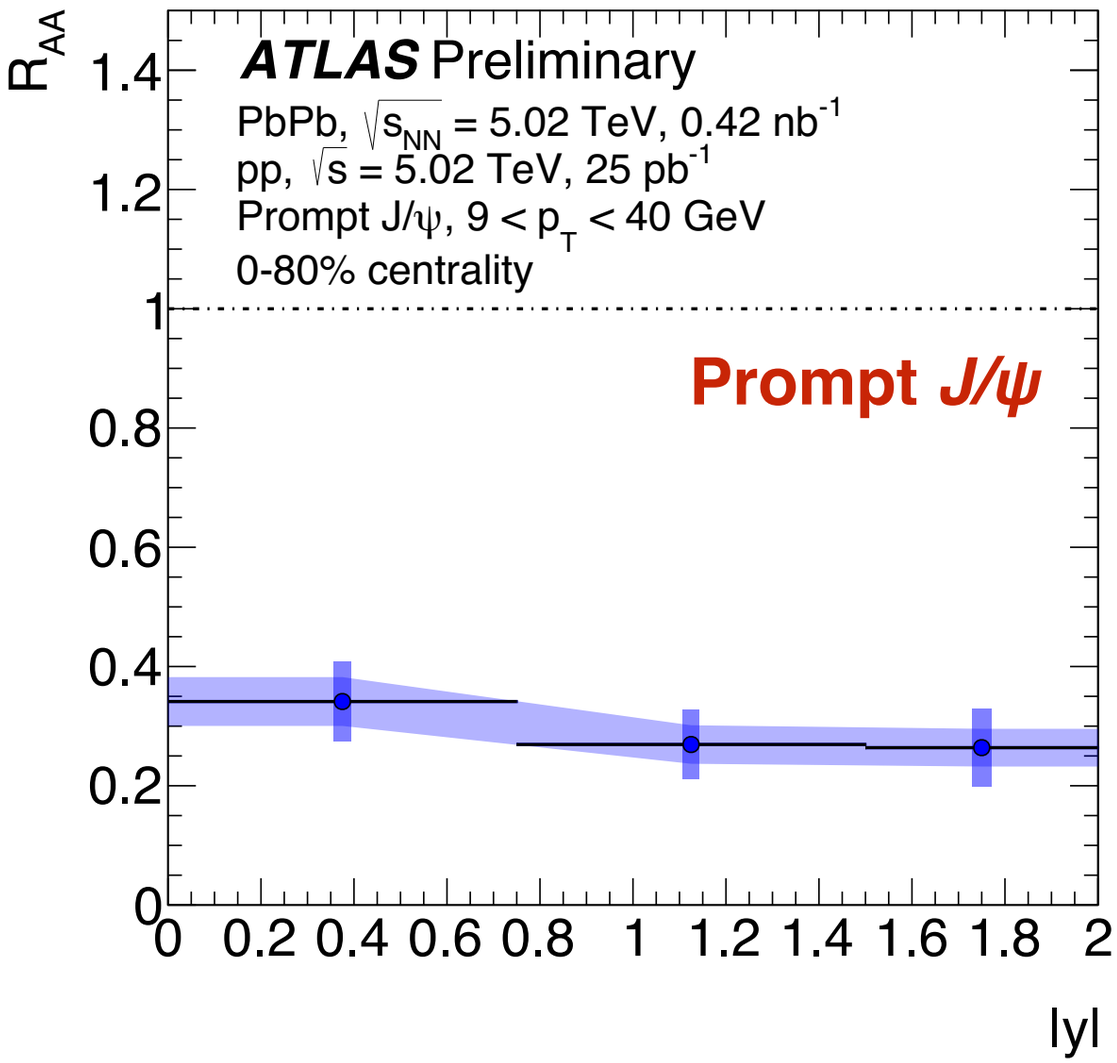


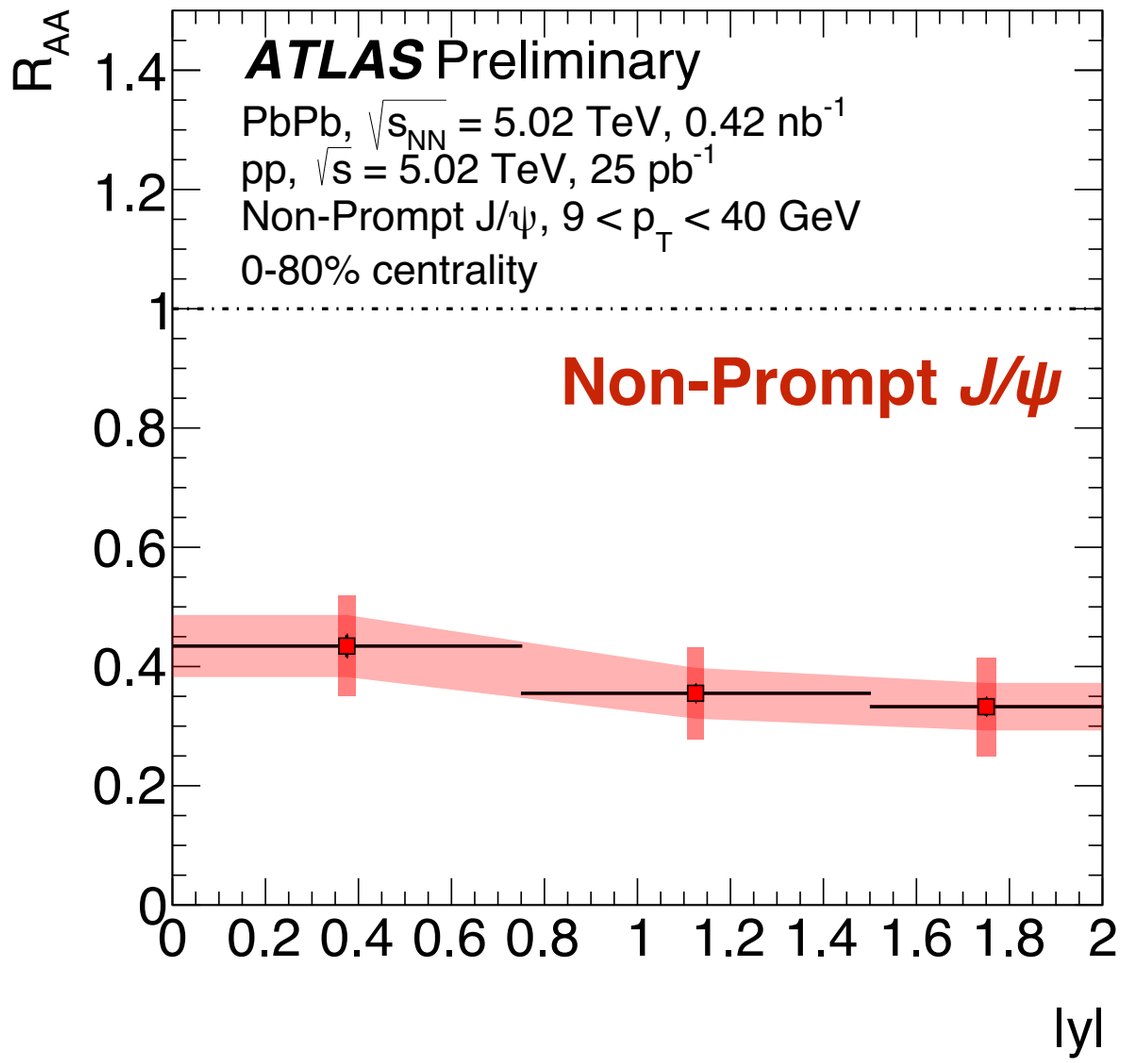


ATLAS-CONF-2016-109

Suppression shows p_T dependence only for prompt *J/ψ*

J/ψ nuclear modification factor R_{AA}





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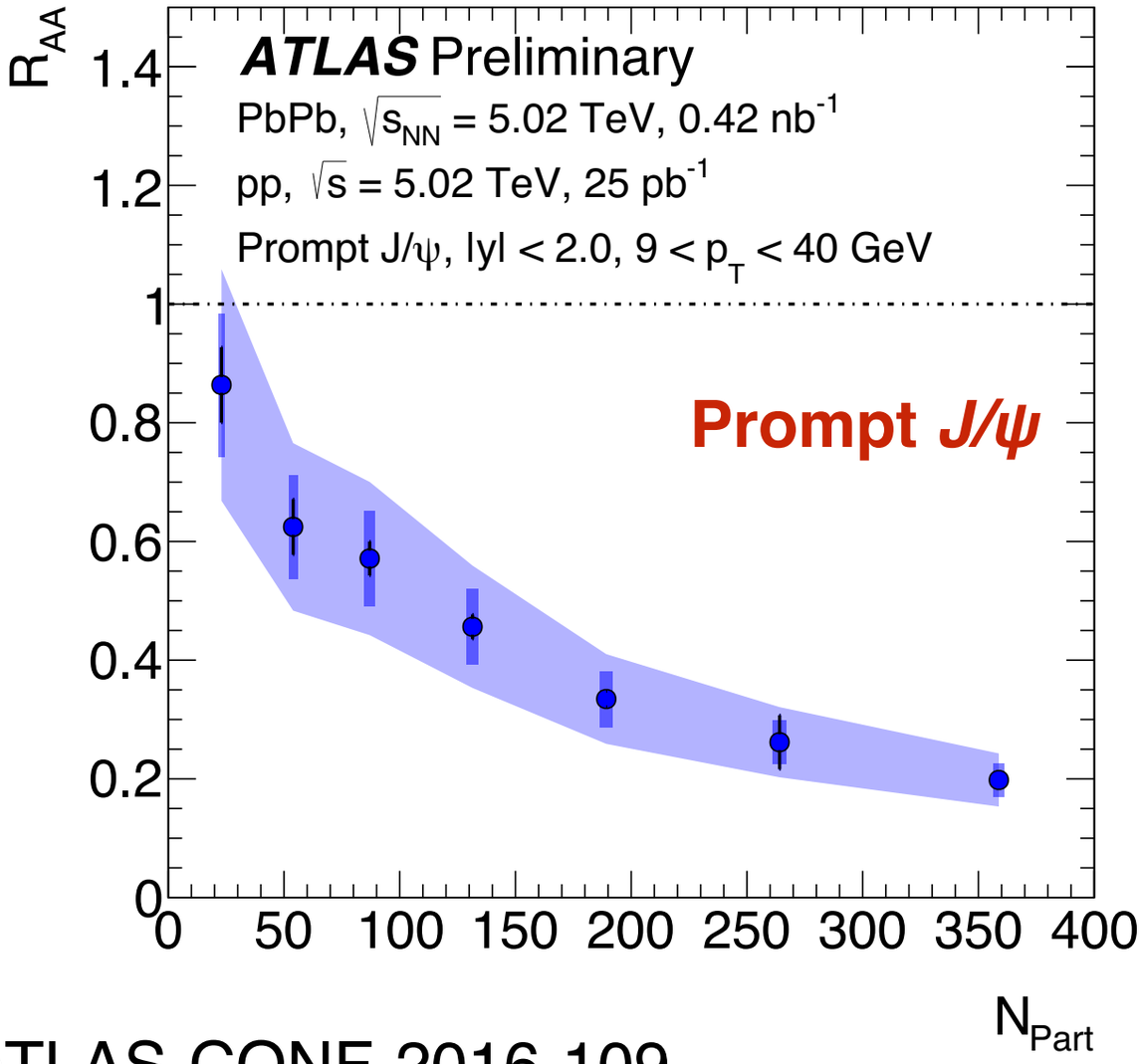
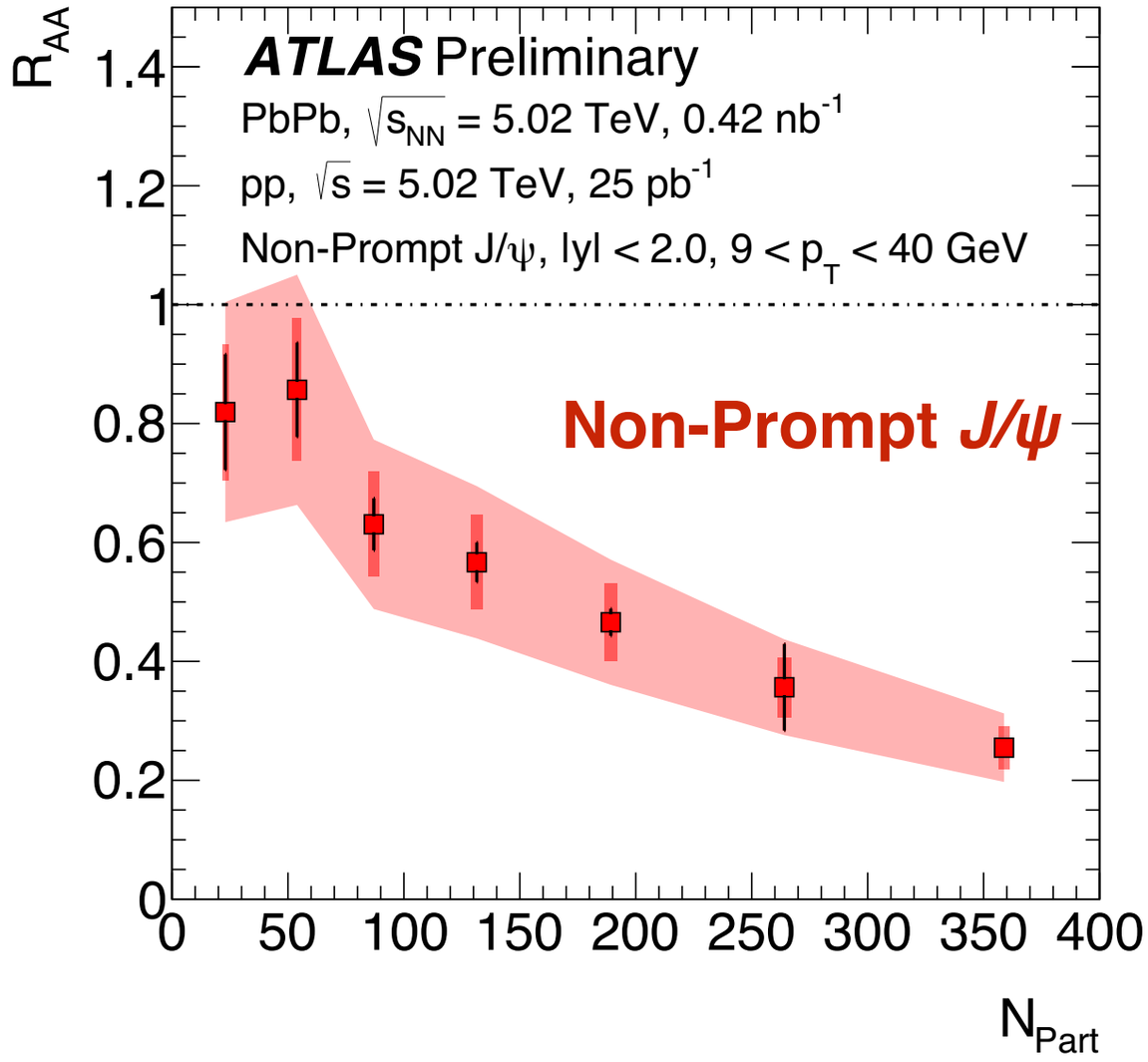
No significant rapidity dependence

J/ψ nuclear modification factor R_{AA}





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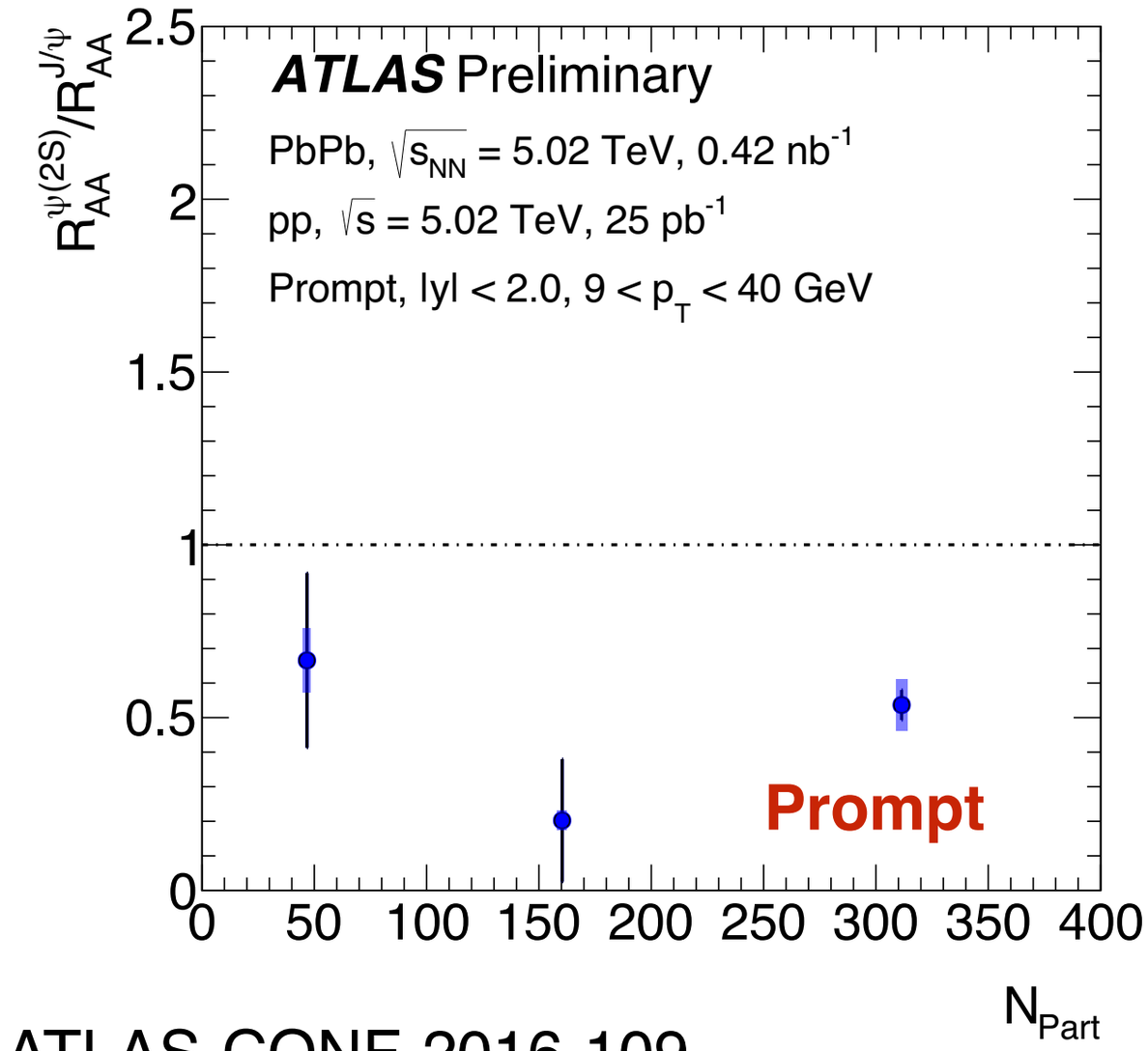
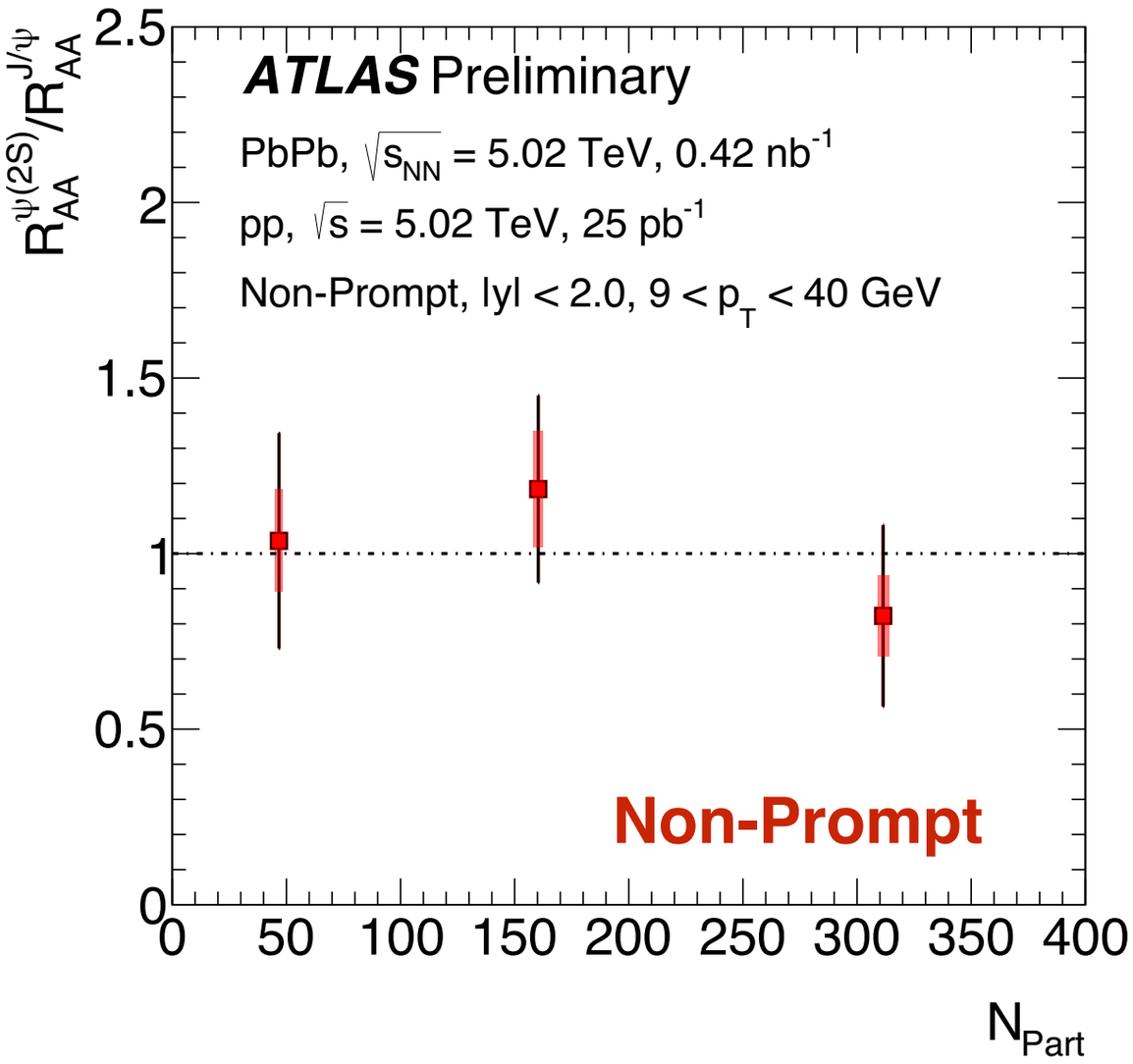
- **R_{AA} strongly dependent on collision centrality.**
- **Suppression pattern and magnitude are very similar for both production mechanisms.**

$\psi(2S)$ to J/ψ double ratio in **Pb+Pb**





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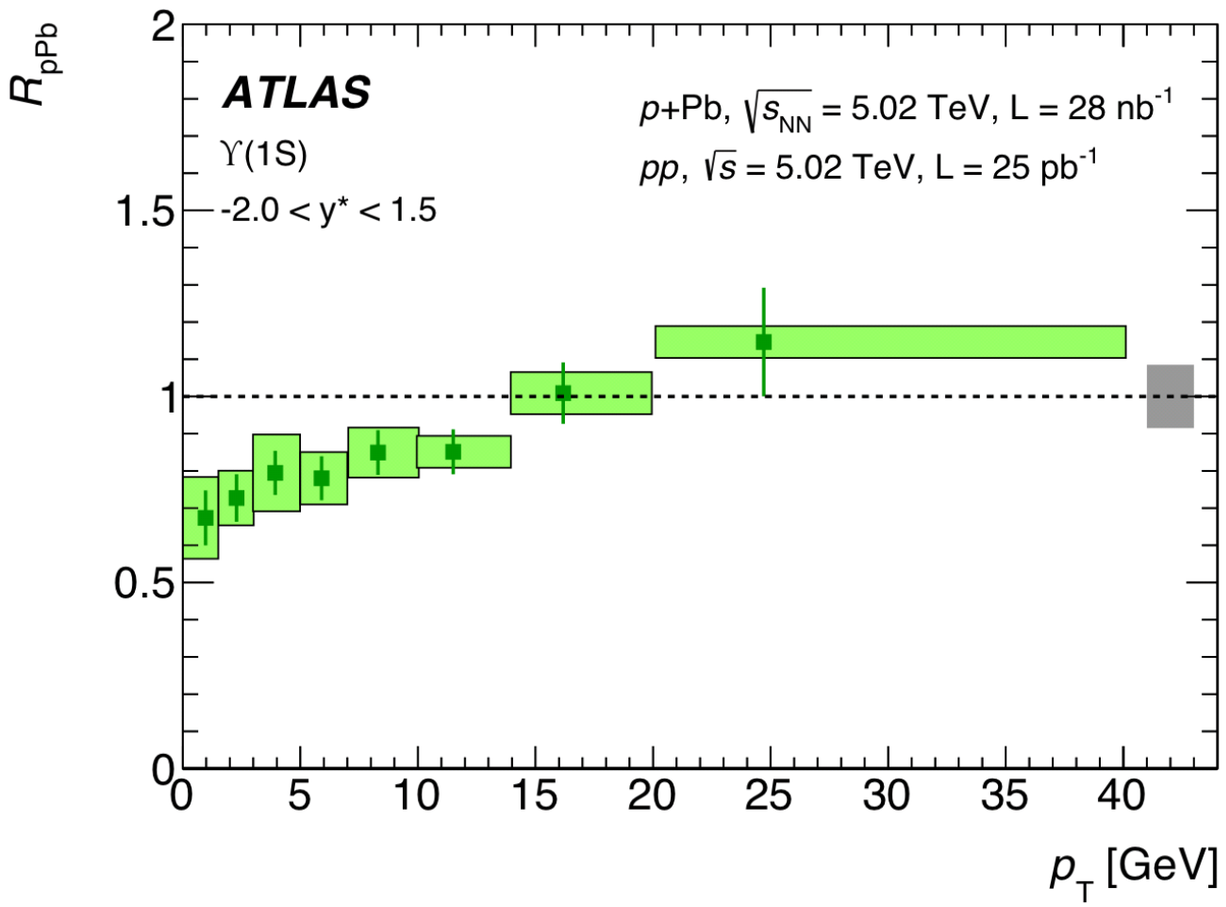
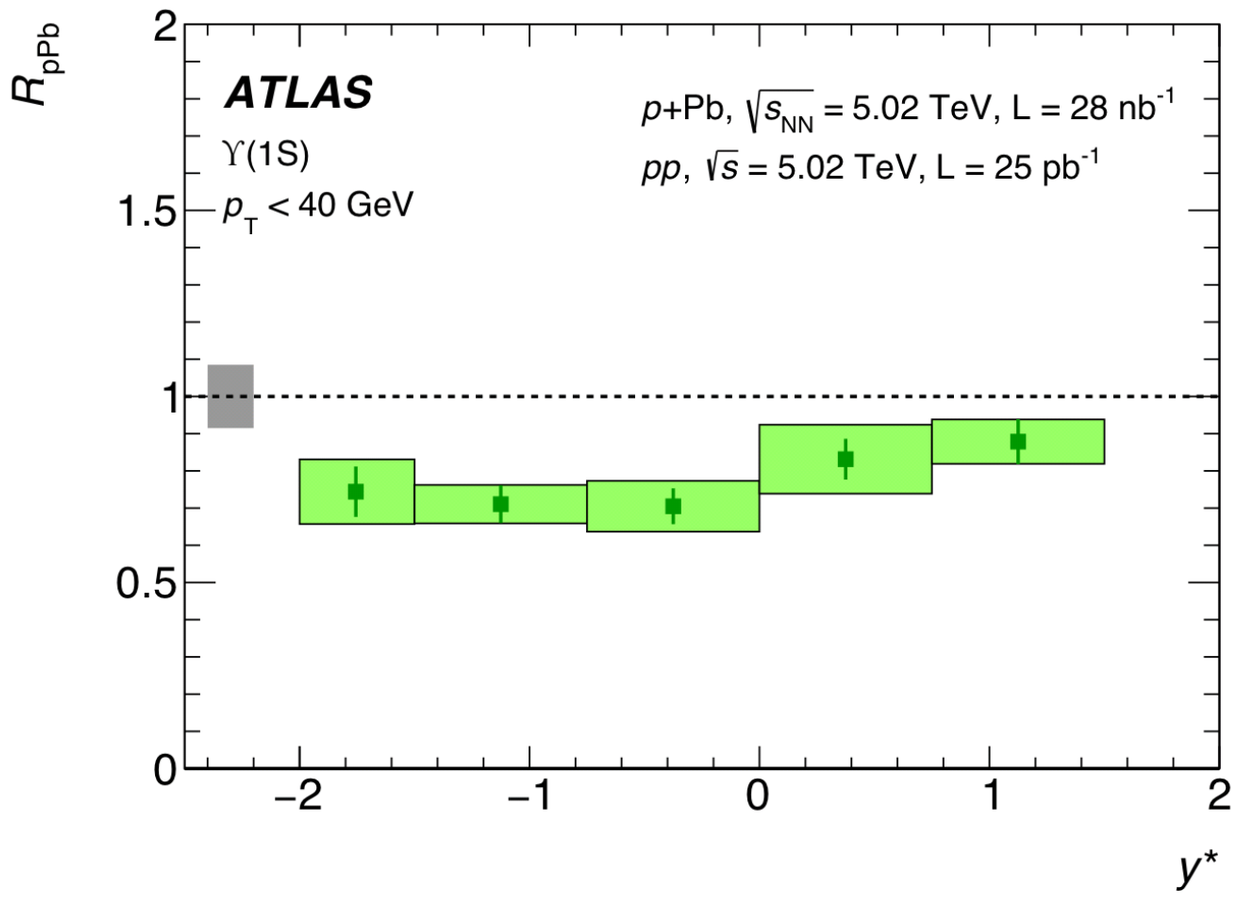
- **Stronger suppression of prompt $\psi(2S)$ with respect to J/ψ.**
- **Non-prompt double ratio consistent with unity. Consistent with *B*-mesons decaying outside the nuclear medium.**

Suppression of Υ(1S) in *p*+Pb

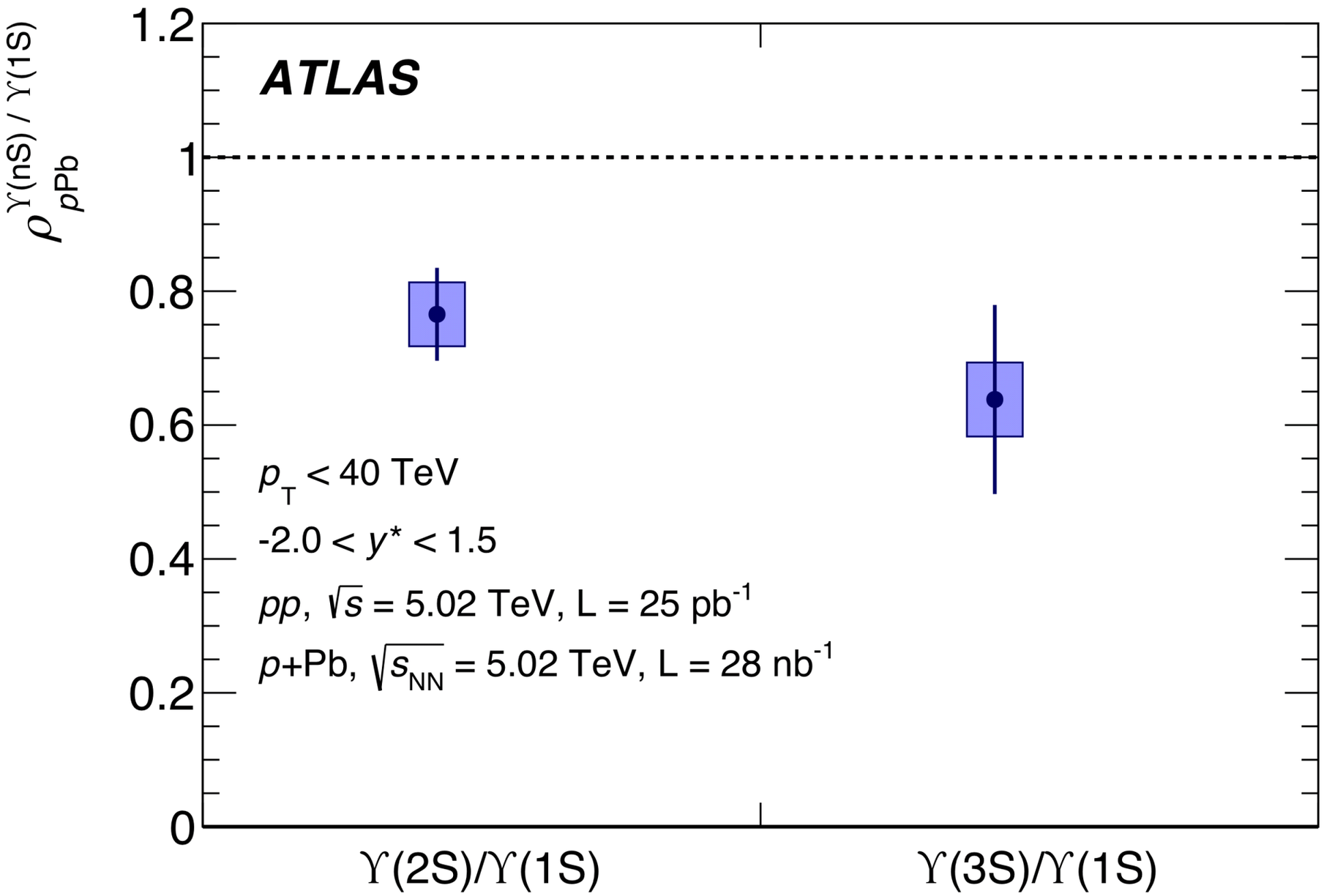




Quite a strong cold matter effect!

https://arxiv.org/abs/1709.03089

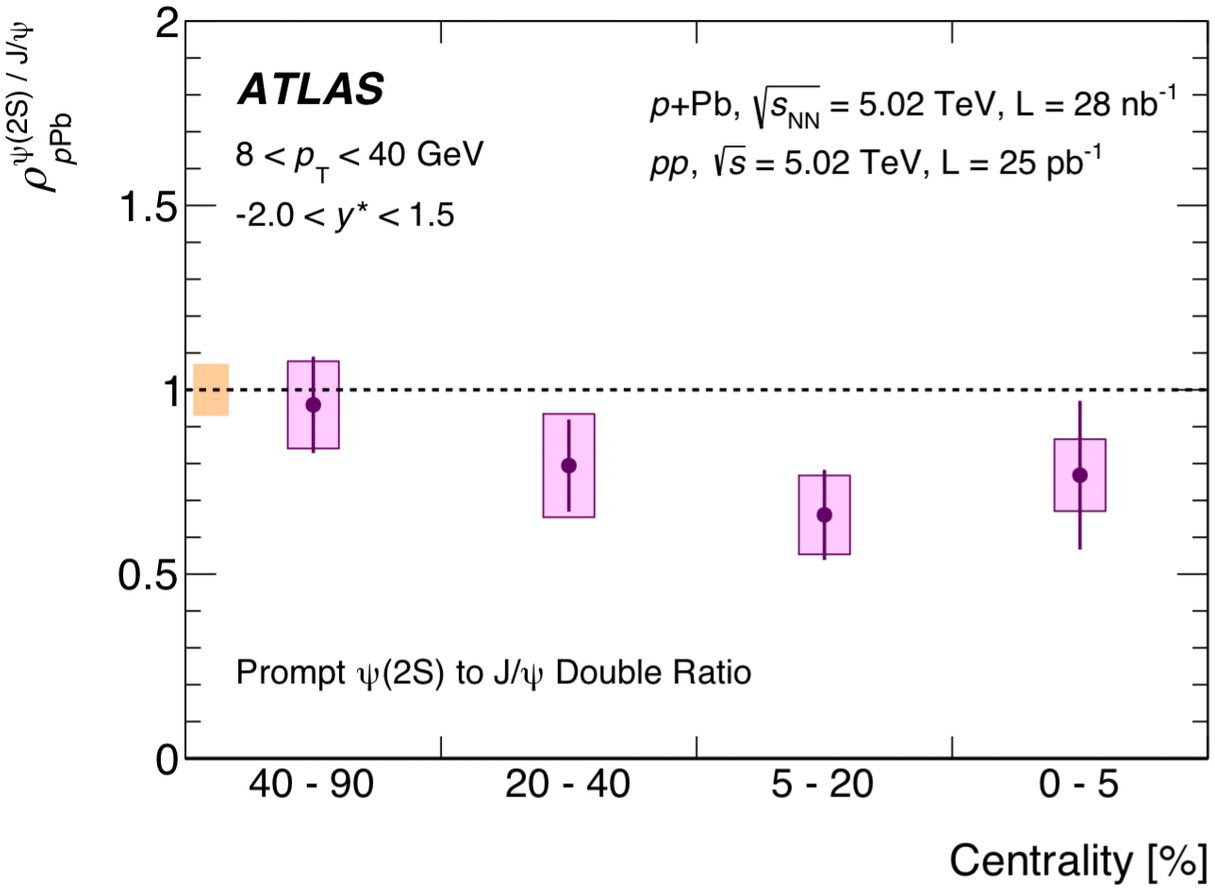
Suppression of *Y* excited states in *p*+Pb

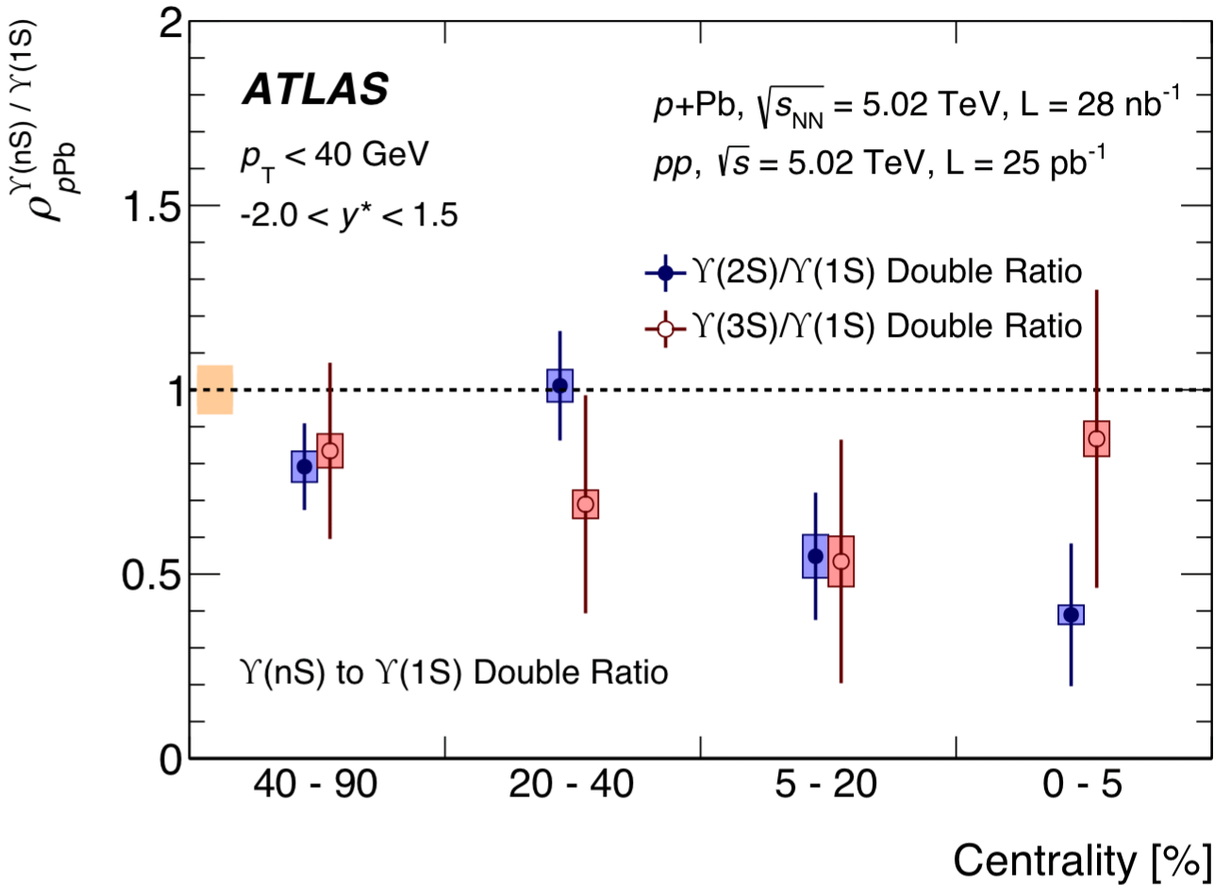


Same pattern as seen in the *ψ* system.

https://arxiv.org/abs/1709.03089

Suppression of excited states in *p*+Pb

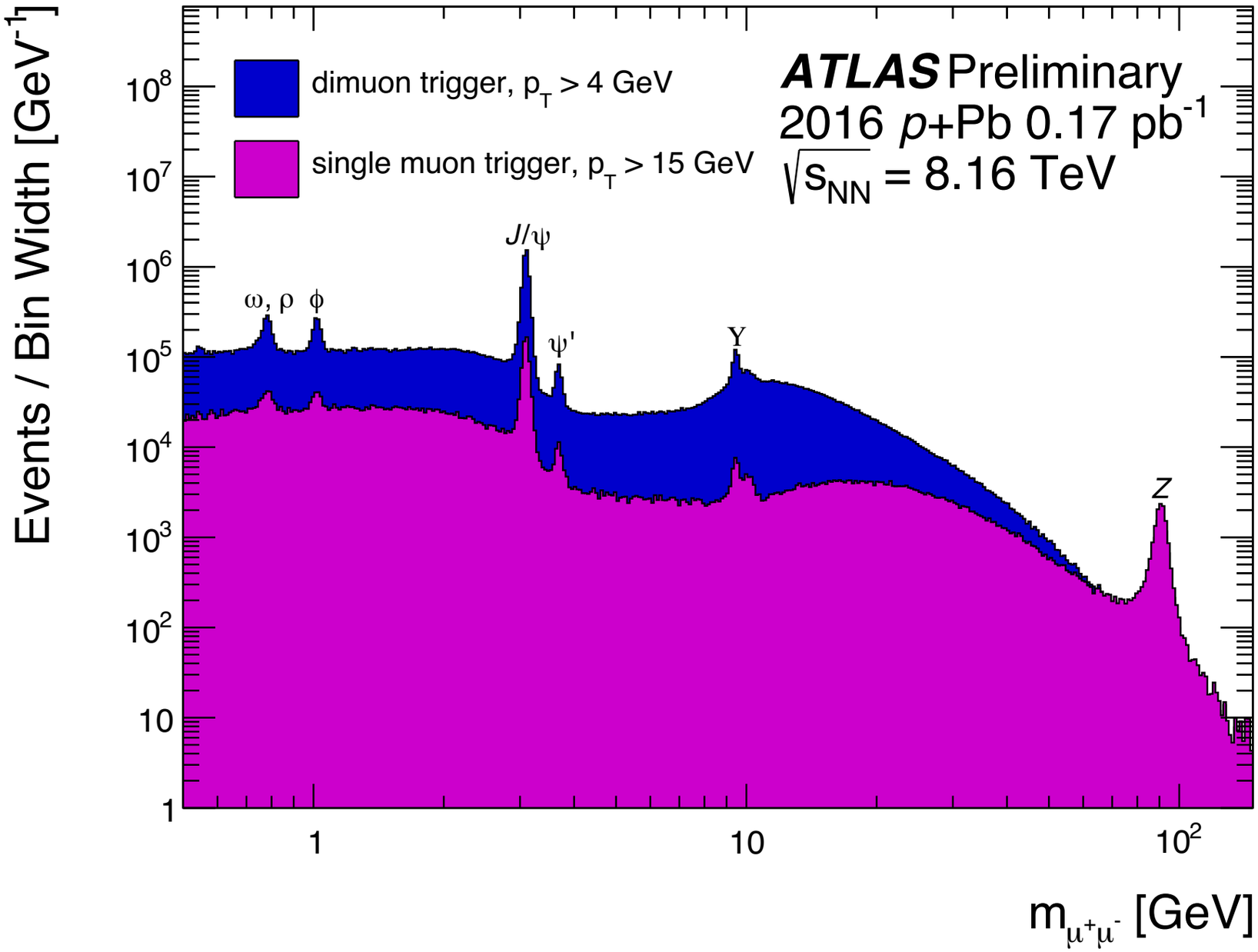




Centrality behavior ~similar for charmonium, bottomonium

https://arxiv.org/abs/1709.03089

2016 p+Pb run dimuon spectrum



8.16 TeV collisions

Summary

- For *J/ψ* and *ψ(2S), p+Pb and Pb+Pb:*
  - R_{pPb} and R_{AA} show no significant rapidity dependence.
  - R_{AA} for prompt and non-prompt components have different behavior as a function of p_T.
  - R_{pPb} has no significant dependence on centrality.
  - Prompt and non-prompt R_{AA} strongly depend on centrality.
  - Prompt *ψ(2S)/J/ψ* is suppressed in Pb+Pb and *p*+Pb.
  - Non-prompt: no suppression of *ψ(2S)/J/ψ,* Pb+Pb.
- *Y* production in p+Pb:
  - R_{pPb} for *Y(1S)* shows clear suppression!
  - Excited states suppressed: *Y(2S)/Y(1S) and Y(3S)/Y(1S) <1*
- Factor of six more pPb data at 8.16 TeV collected in 2016!