Quarkonium Production in *pp* and *p*+Pb Collisions with ATLAS at the LHC

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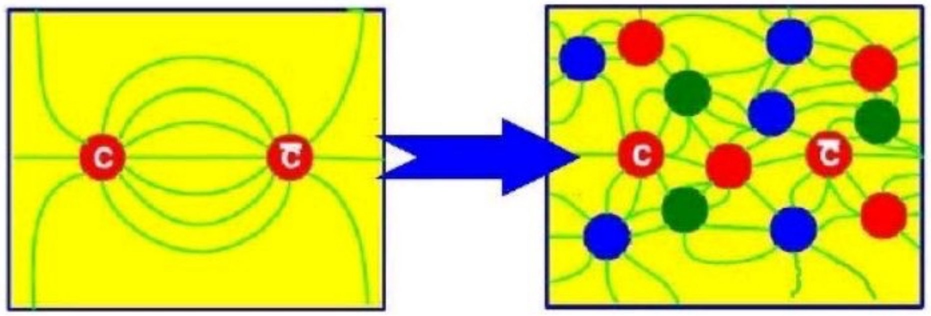
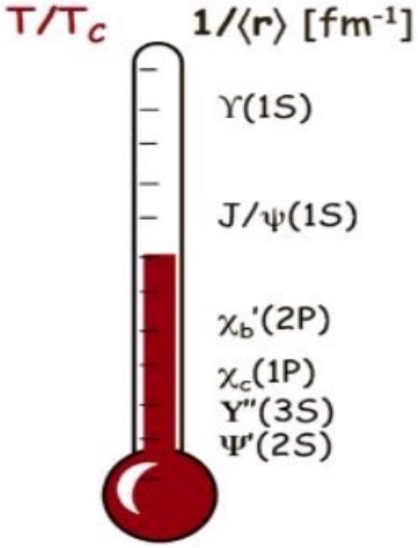
Physics Motivation

Quarkonium suppression in A-A collisions due to color screening provides signature of formation of deconfined QGP





Quarkonium suppression is also observed in p-A collisions due to **Cold Nuclear Matter** (CNM) effects. The CNM effects must be understood before suppression in A-A collisions can be fully understood.

CNM effects:

- Shadowing + other gluon PDF modification
- Medium-induced gluon radiation
- Absorption of the $Q\bar{Q}$ pair

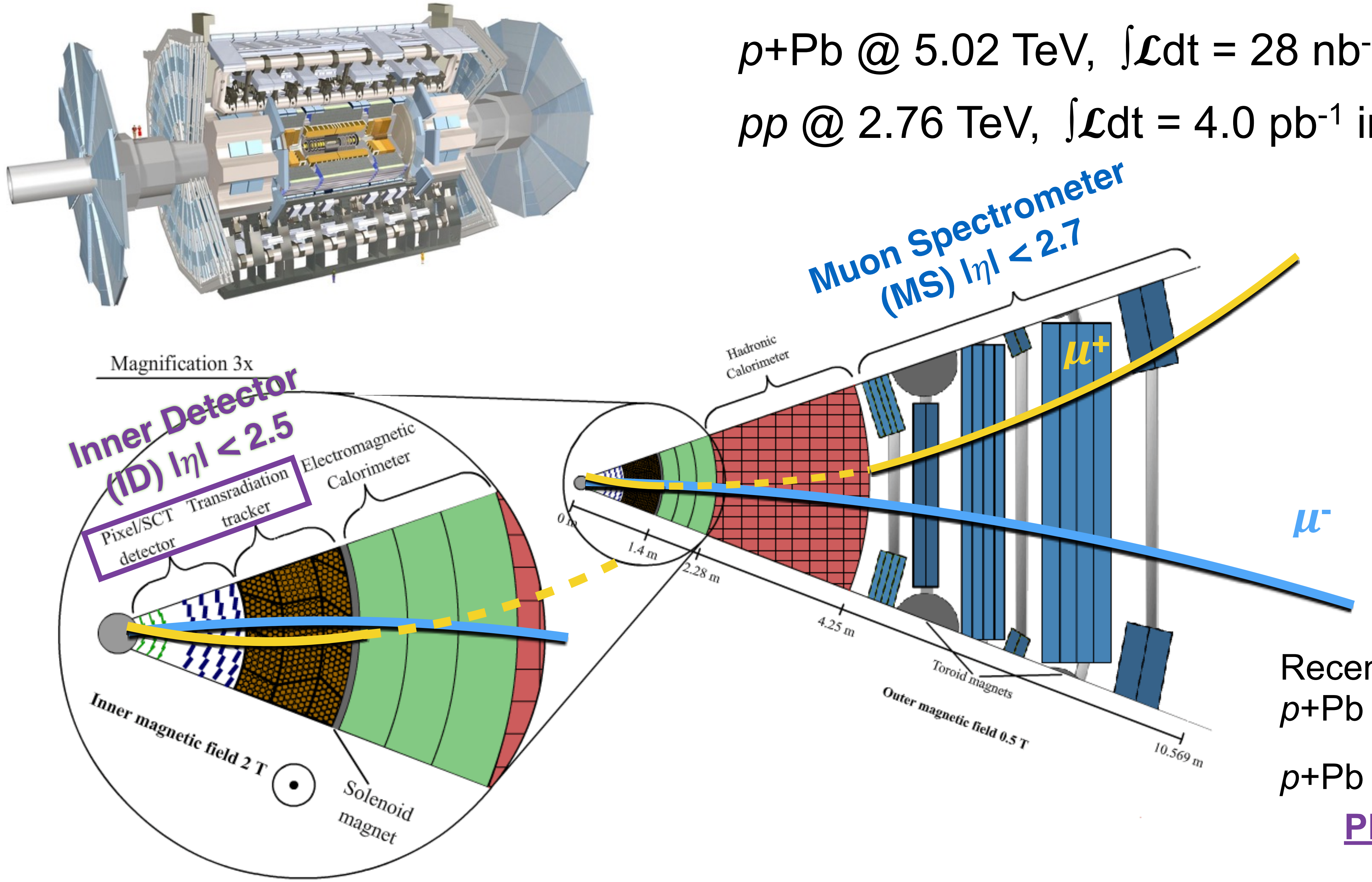
Initial state effects

Final state effects

The ATLAS Detector

p+Pb @ 5.02 TeV, $\int\mathcal{L}dt$ = 28 nb^{-1} in 2013

pp @ 2.76 TeV, $\int\mathcal{L}dt$ = 4.0 pb^{-1} in 2013



ψ(nS)→$\mu^+\mu^-$

Υ(nS)→$\mu^+\mu^-$

Recent ATLAS Heavy Ion *p*+Pb quarkonium results:

p+Pb J/ψ

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p+Pb and *pp* J/ψ vs. ψ(2S)

Revised ATLAS-CONF-2015-023

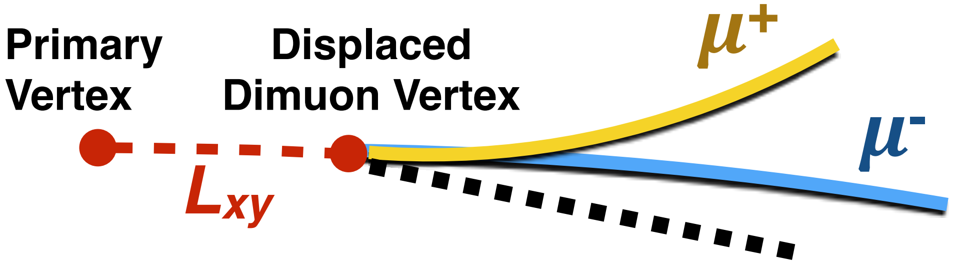
p+Pb and *pp* Υ(nS)

New ATLAS-CONF-2015-050

Event trigger: di-muon trigger with 2 GeV p_T threshold

Muon candidates:
Successful combinations of ID and MS tracks.

Quarkonium Signal Extraction



Correct every event for acceptance and efficiencies.

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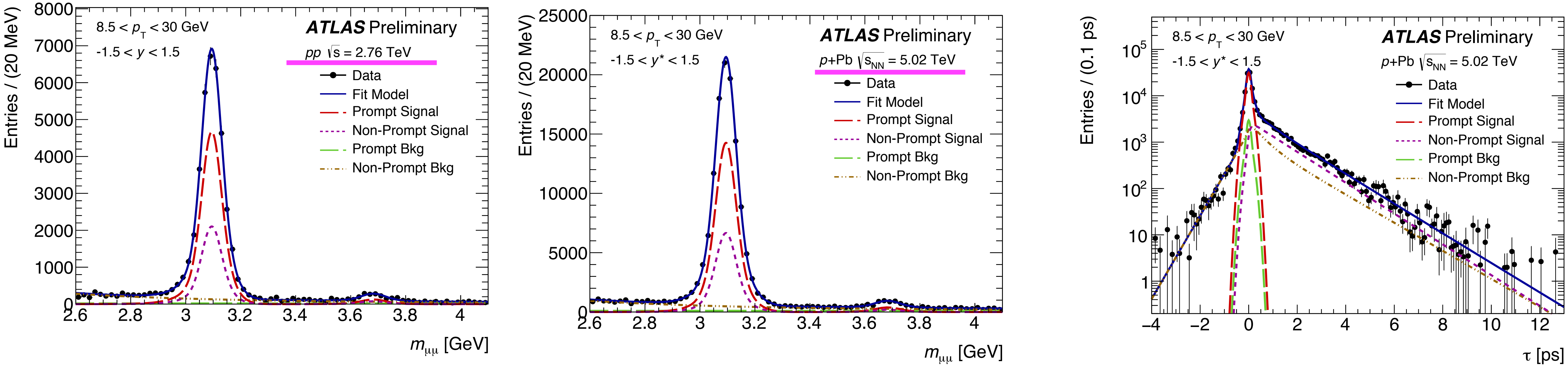

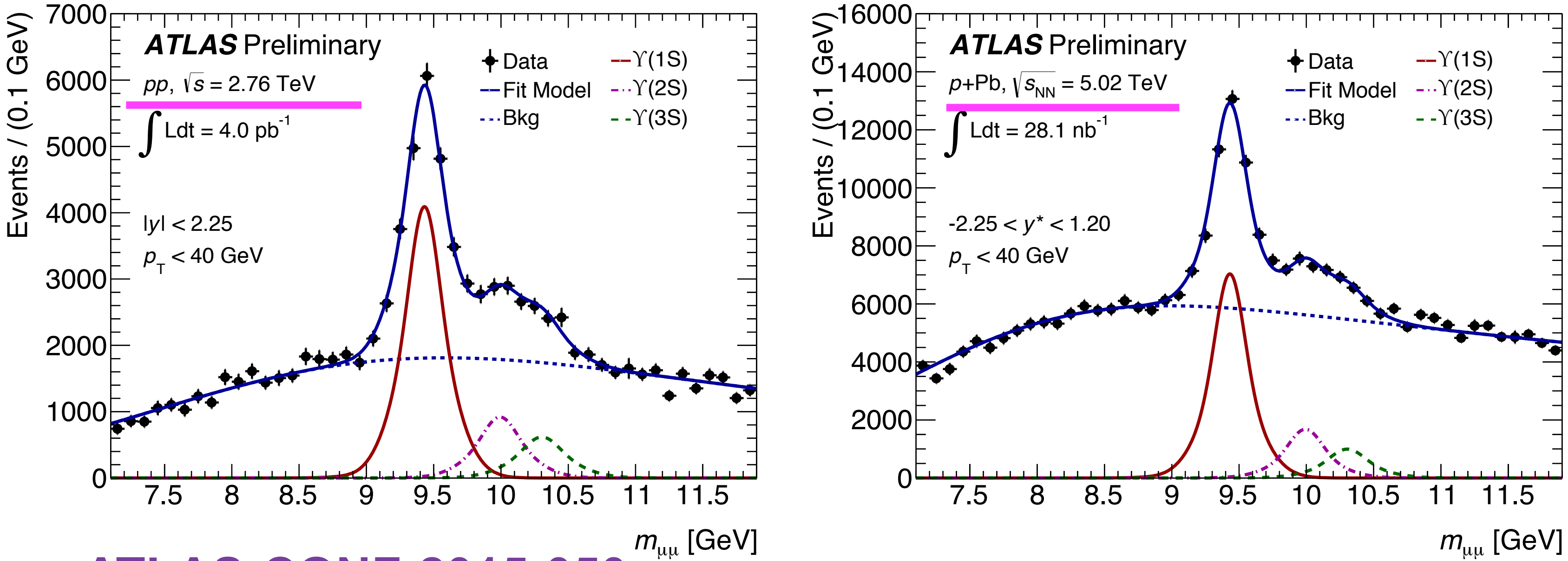

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Prompt ψ(nS):

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

- Direct production
- Feed-down contribution

Non-prompt ψ(nS):

- Decays from B hadrons

Υ(2S) and Υ(3S) are combined as Υ(2S+3S).

Forward to Backward Ratio

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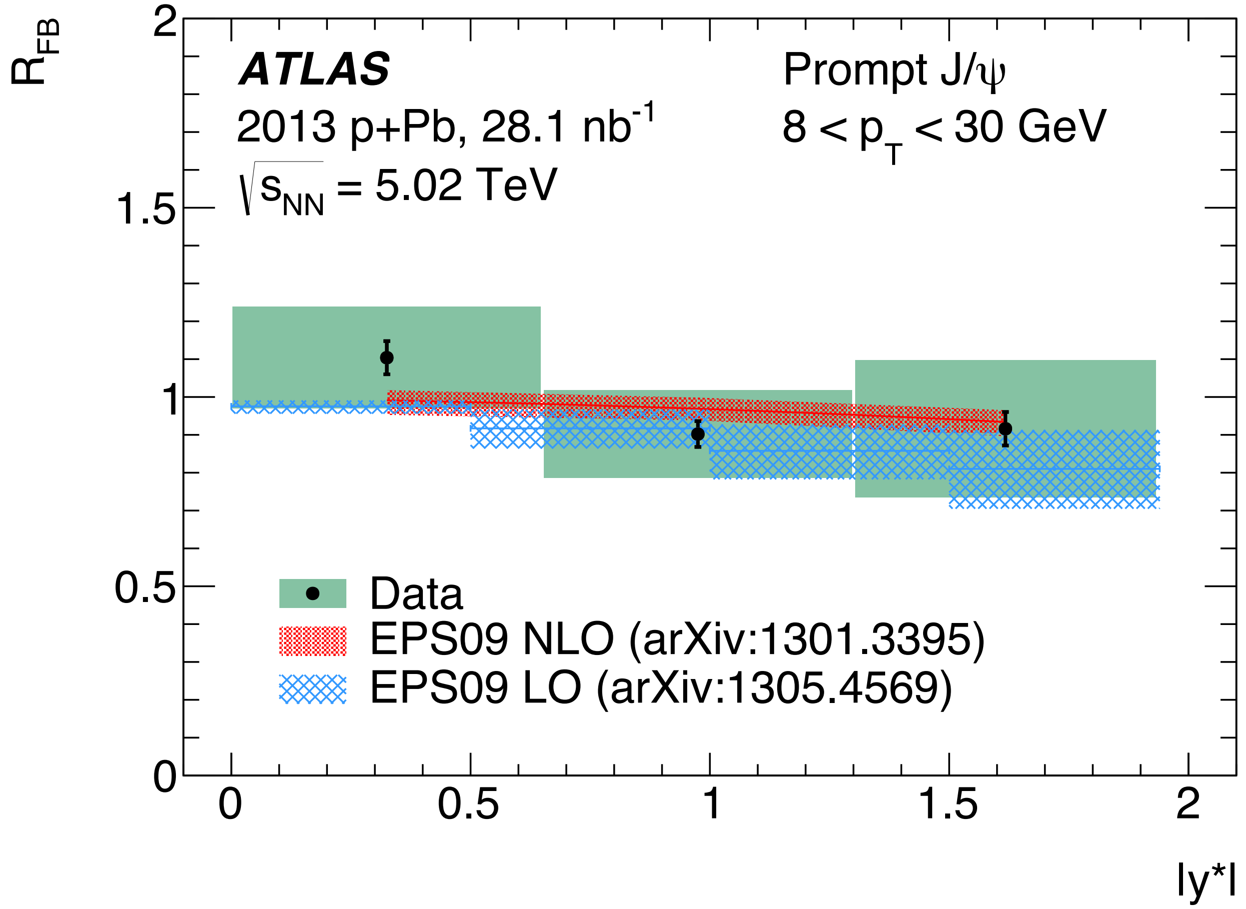

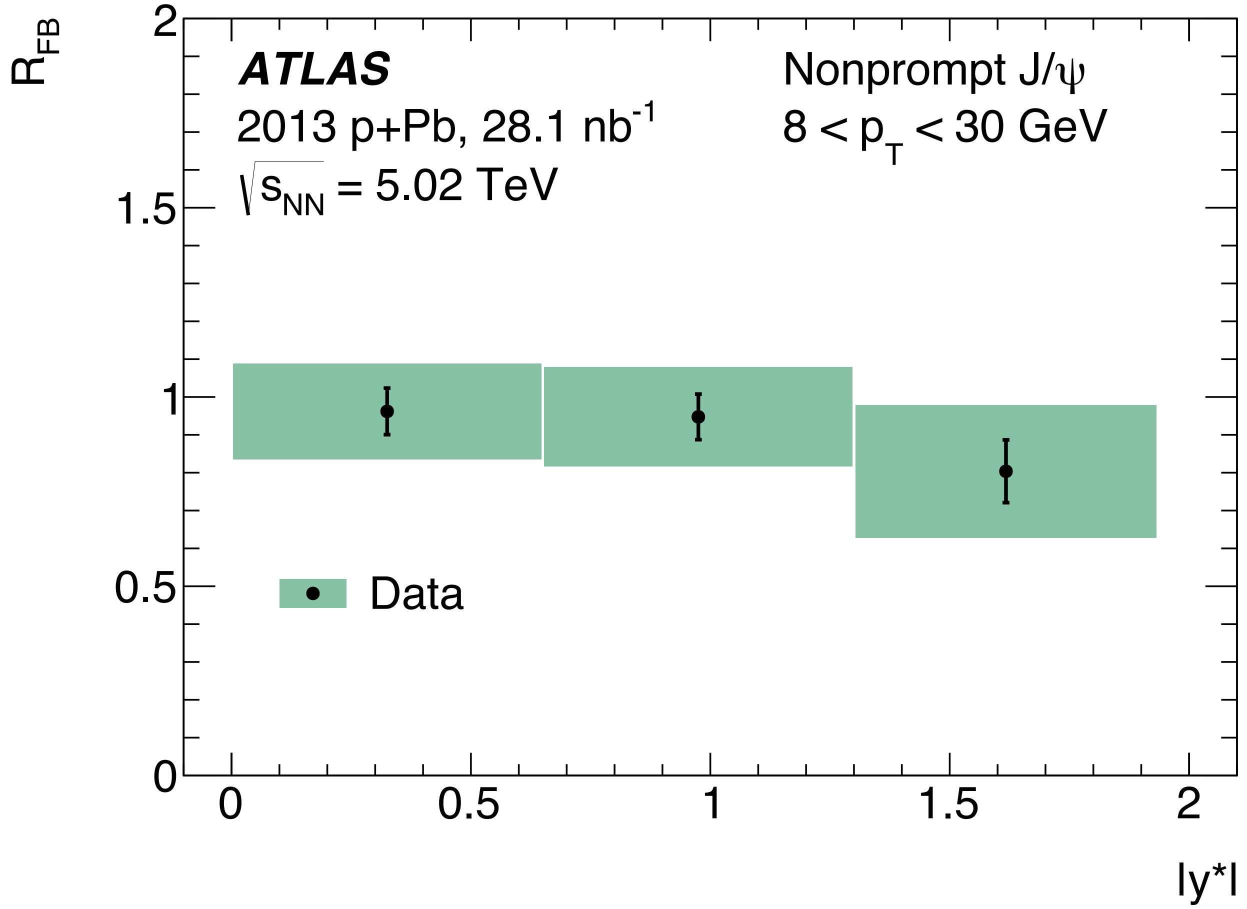

- *(Left)* Prompt J/ψ R_{FB}
- *(Right)* Non-prompt J/ψ R_{FB}

$$R_{\mathrm{FB}}(p_{\mathrm{T}}, y^{*}) \equiv \frac{d^{2}\sigma(p_{\mathrm{T}}, y^{*} > 0)/dp_{\mathrm{T}}dy^{*}}{d^{2}\sigma(p_{\mathrm{T}}, y^{*} < 0)/dp_{\mathrm{T}}dy^{*}}.$$

Prompt J/ψ R_{FB} is compatible with both EPS09 models.

y^*: CM rapidity being positive in forward (proton beam direction)

Nuclear Modification Factor — ψ(nS)

$$R_{pPb} = \frac{1}{A^{Pb}} \frac{d^2\sigma_{\psi}^{p+Pb}/dy^* dp_T}{\boxed{d^2\sigma_{\psi}^{pp}/dy dp_T}},$$

pp reference is constructed using interpolations

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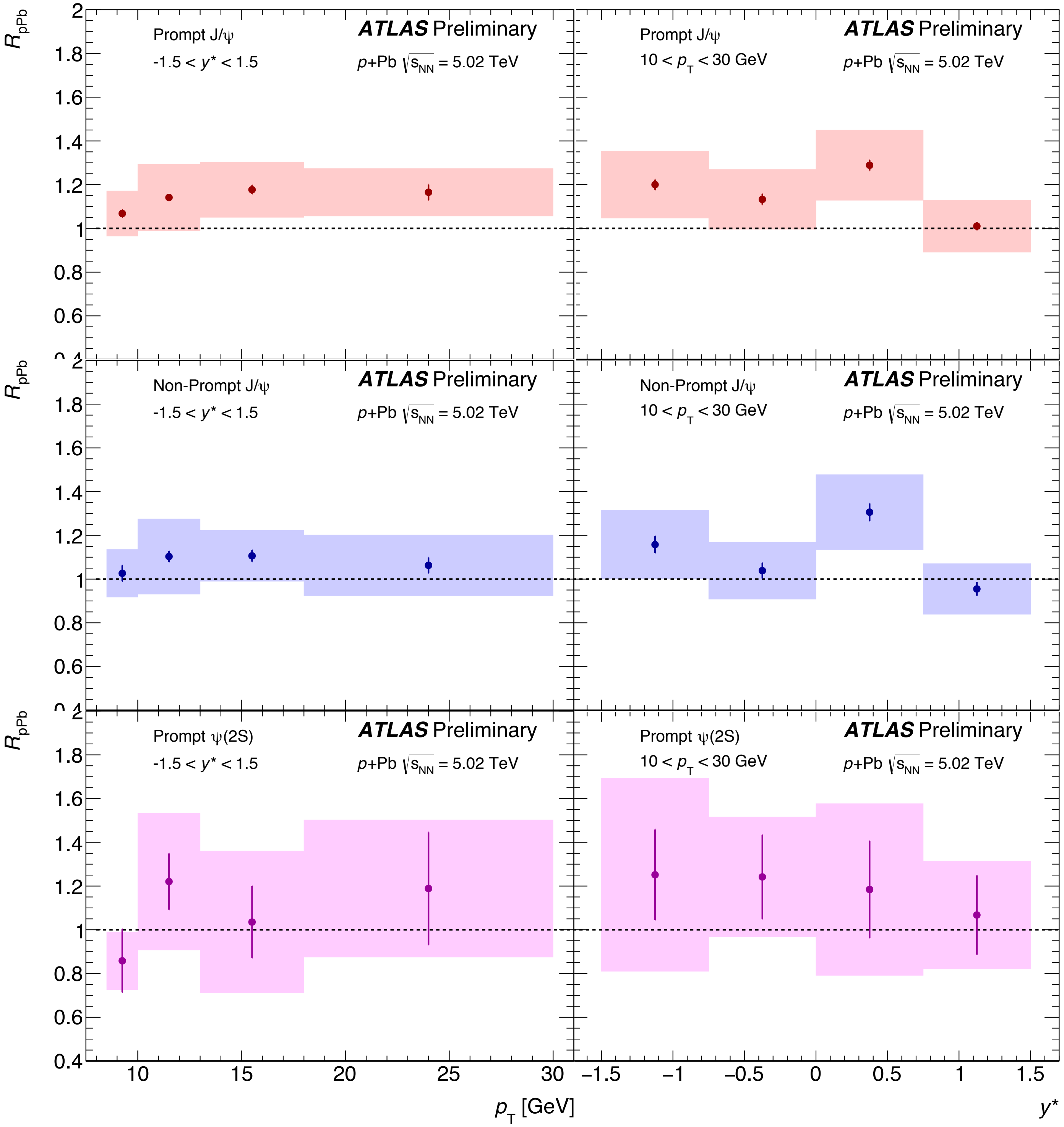

- *(Top)* Prompt J/ψ
- *(Middle)* Non-Prompt J/ψ
- *(Bottom)* Prompt ψ(2S)

No significant suppression or enhancement for the kinematics range of |y*| < 1.5 and 10 < p_T < 30 GeV

Nuclear Modification Factor — Υ(1S)

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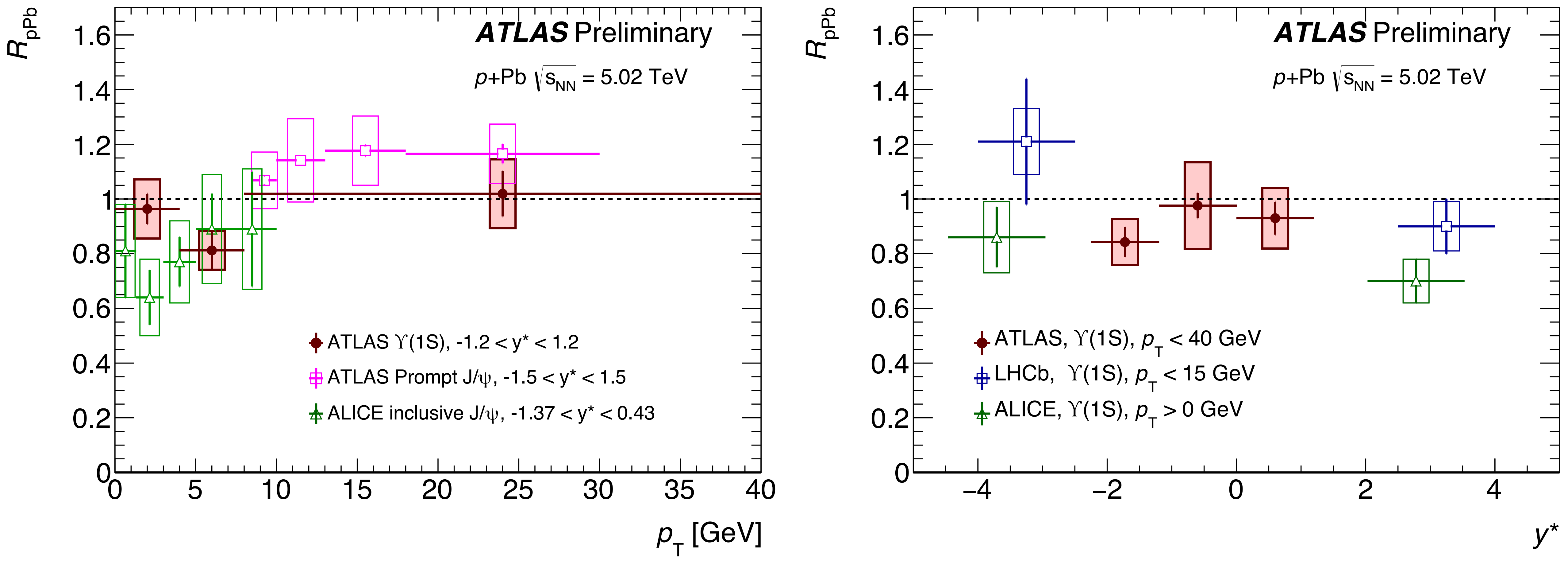

- *(Left)* Υ(1S) R_{pPb} vs. p_{T}.

  Compatible with inclusive J/ψ R_{pPb} at low p_{T} (***ALICE***) and prompt J/ψ R_{pPb} at higher p_{T} (***ATLAS***)

- *(Right)* Υ(1S) R_{pPb} vs. y*

  In comparison with ***ALICE*** and ***LHCb*** results. Provide constrains for models at central rapidity.

Double Ratio

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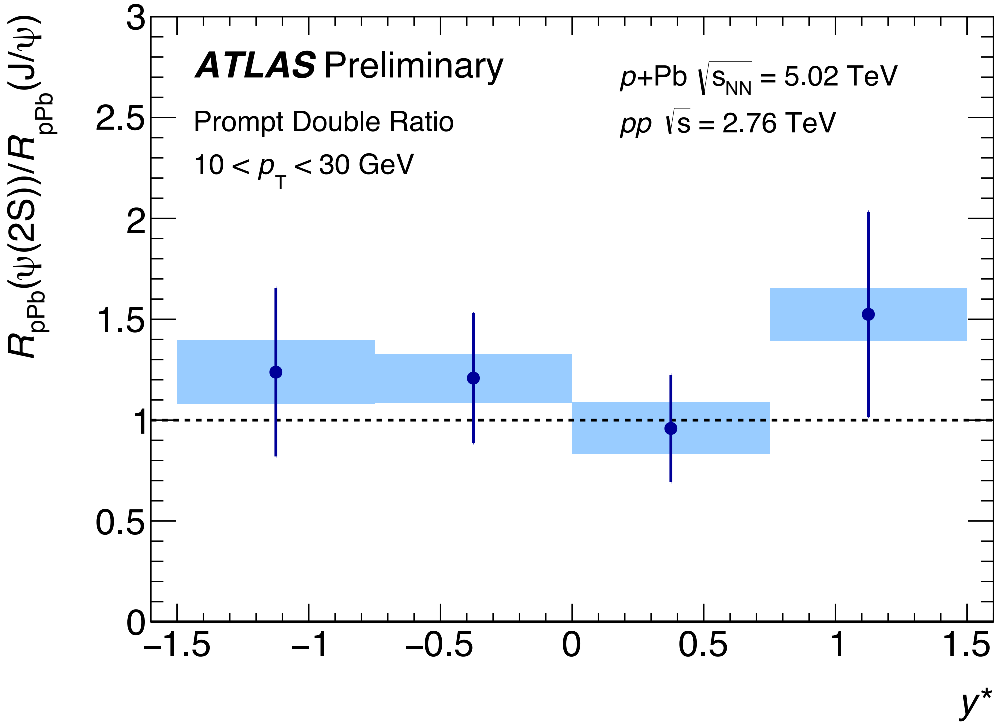

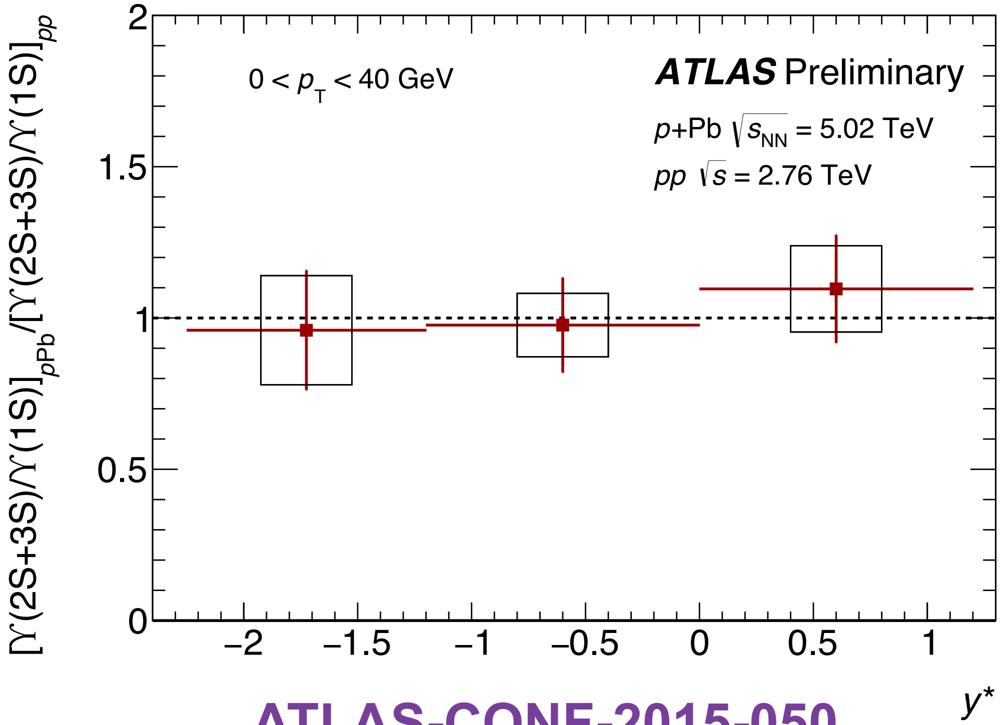

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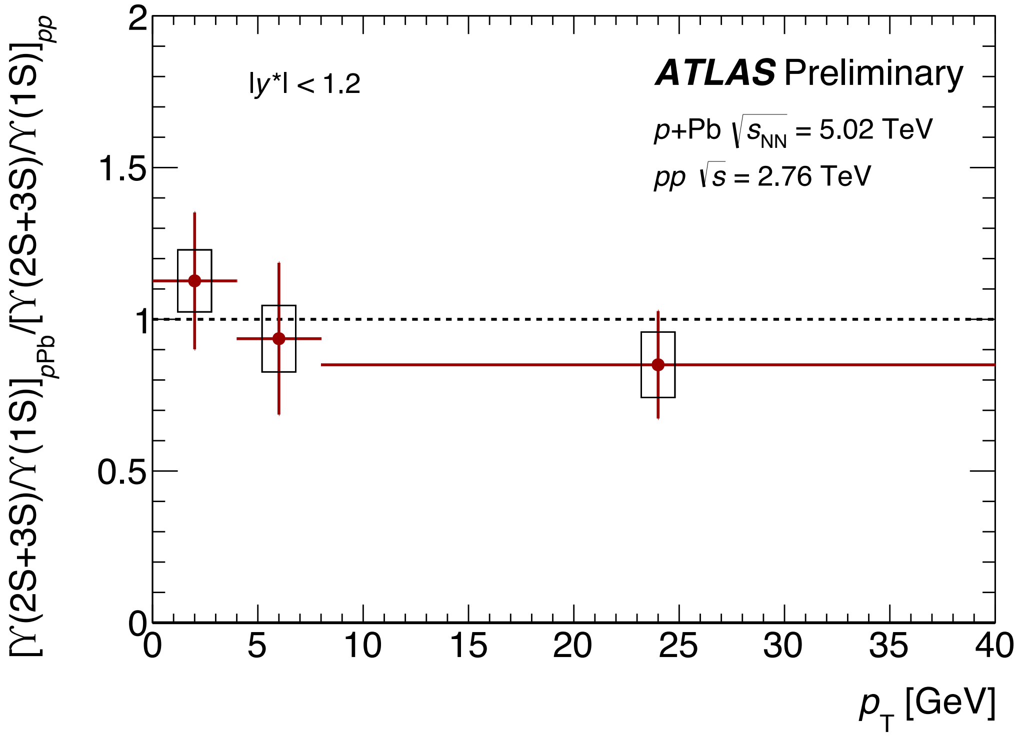


- *(Left)* Prompt charmonium double ratio
- *(Right)* Bottomonium double ratio

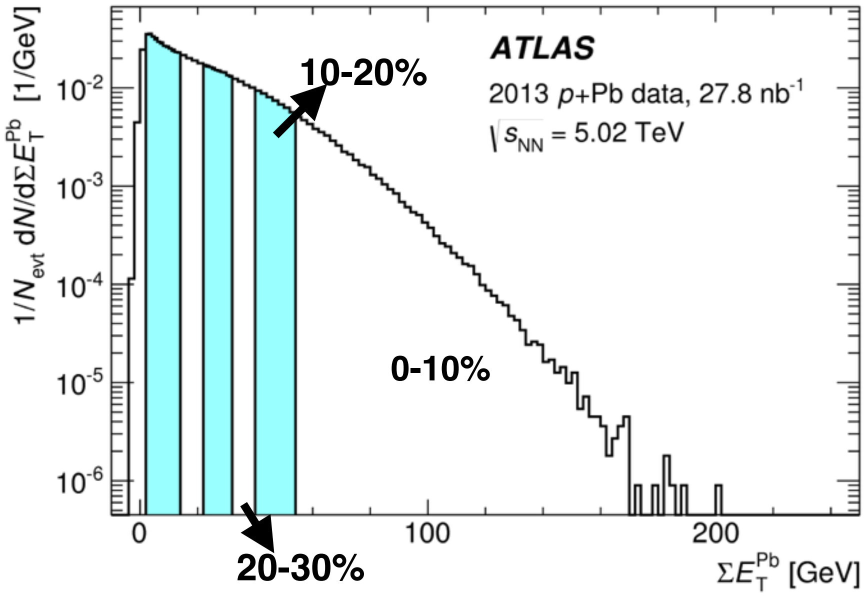
No obvious p_T and rapidity dependence

$$\frac{[\Upsilon(2S+3S)/\Upsilon(1S)]_{pPb}}{[\Upsilon(2S+3S)/\Upsilon(1S)]_{pp}}$$

pp @ 2.76 TeV

Centrality in p+Pb

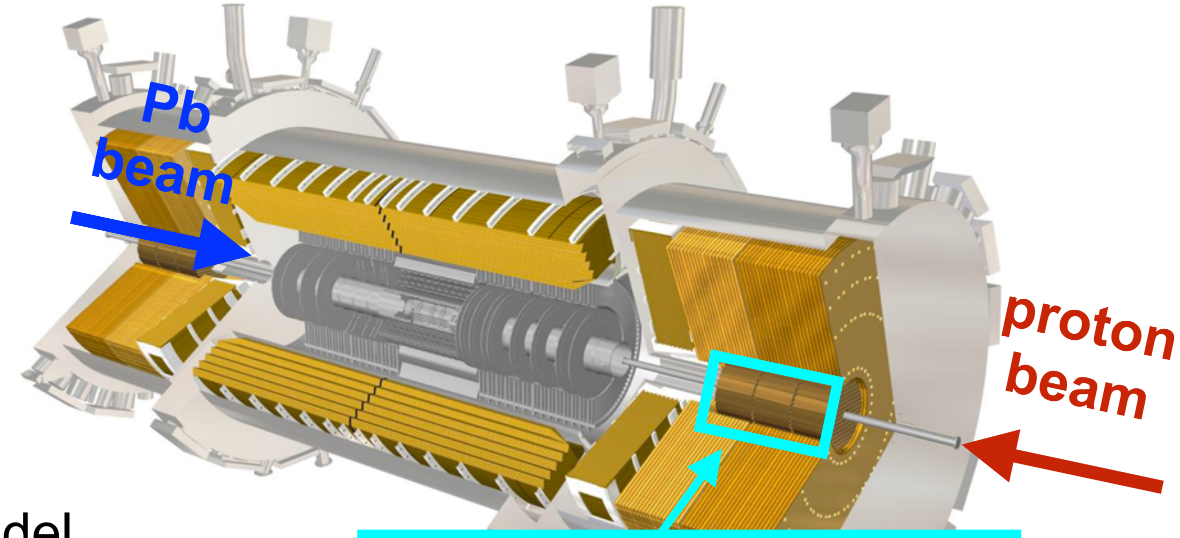
FCal sum E_T in Pb beam direction ⇒ Centrality ⇒ $\langle N_{part} \rangle$



Two models:

- Glauber Model
- Glauber-Gribov Color fluctuation (GGCF) Model

Only focus on the Glauber model in this talk.

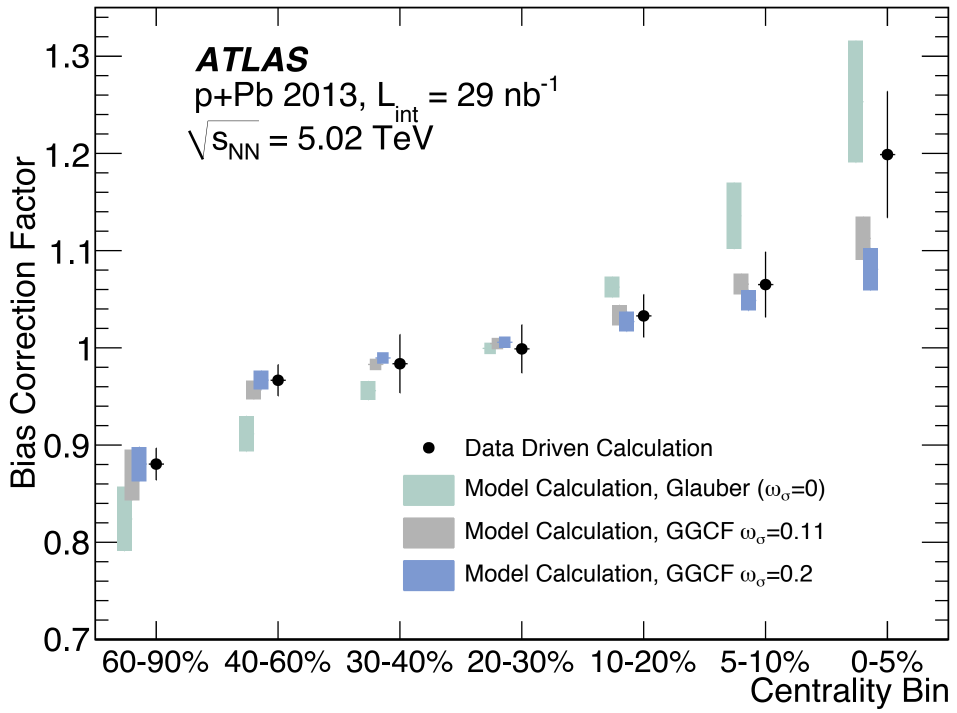


Forward Calorimeters (FCal) $3.2 < \eta < 4.9$

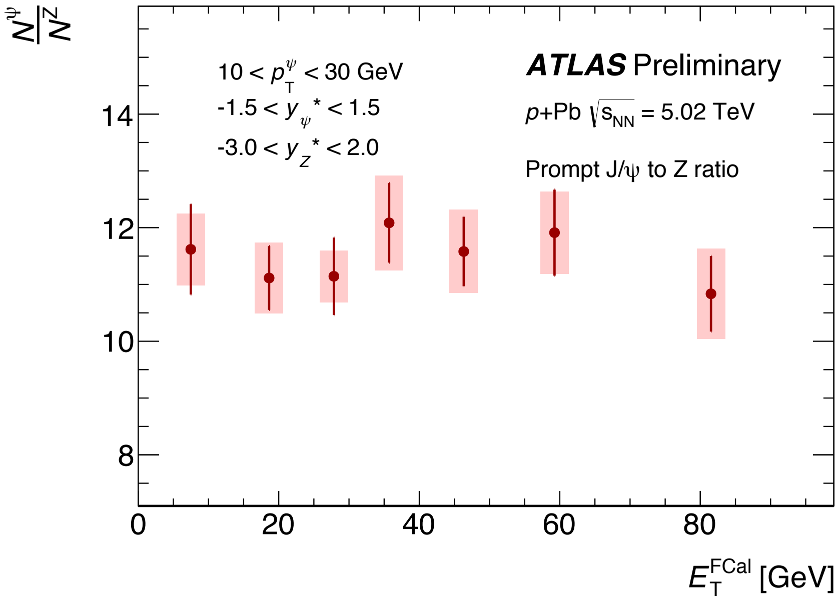
Centrality Bias: hard scatterings are often correlated with a larger transverse energy of the underlying event.

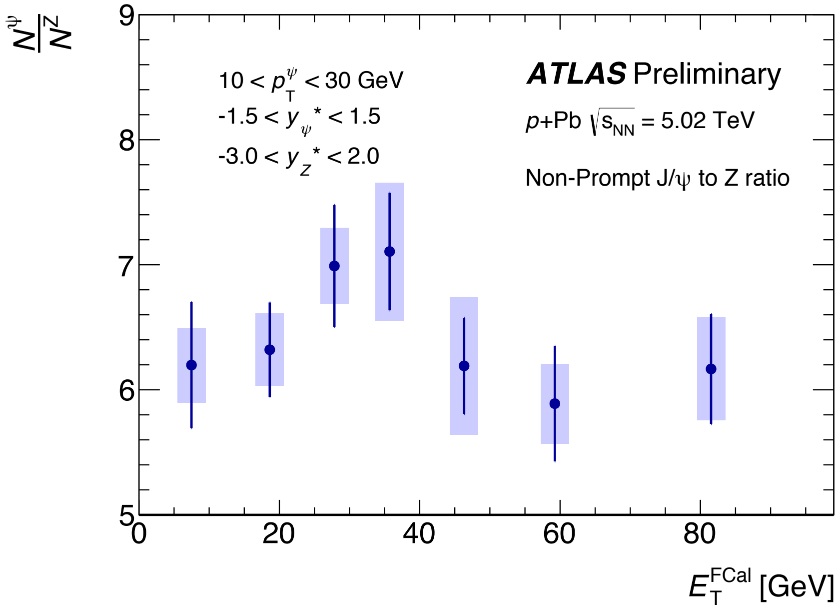
Process independent centrality bias correction factor from model calculation (arXiv:1412.0976) double-checked by data-driven calculation (arXiv:1507.06232).

How would the bias correction factor work for quarkonium production?



J/ψ R_{pPb} vs. $\langle N_{\mathrm{part}}\rangle$





J/ψ to Z boson yield ratio can serve as a baseline.

No obvious centrality dependence of J/ψ production.

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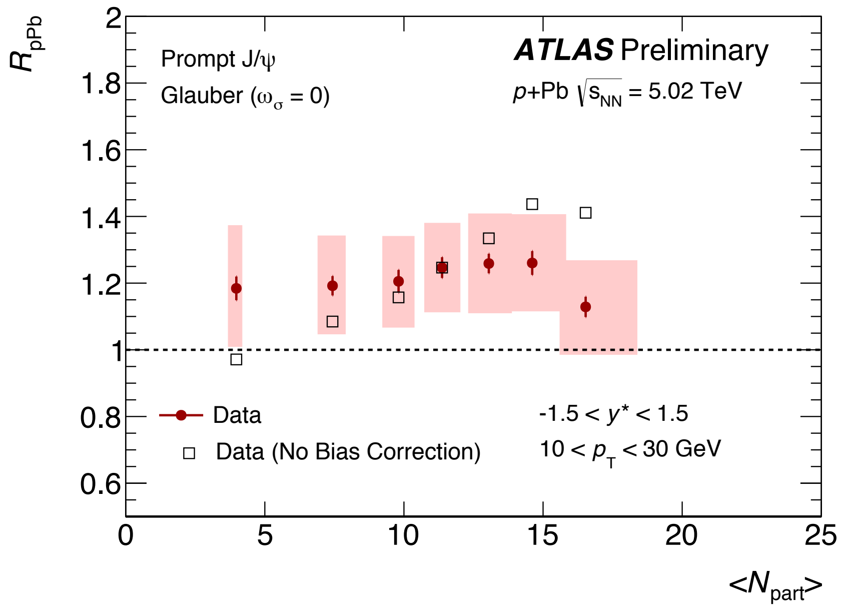
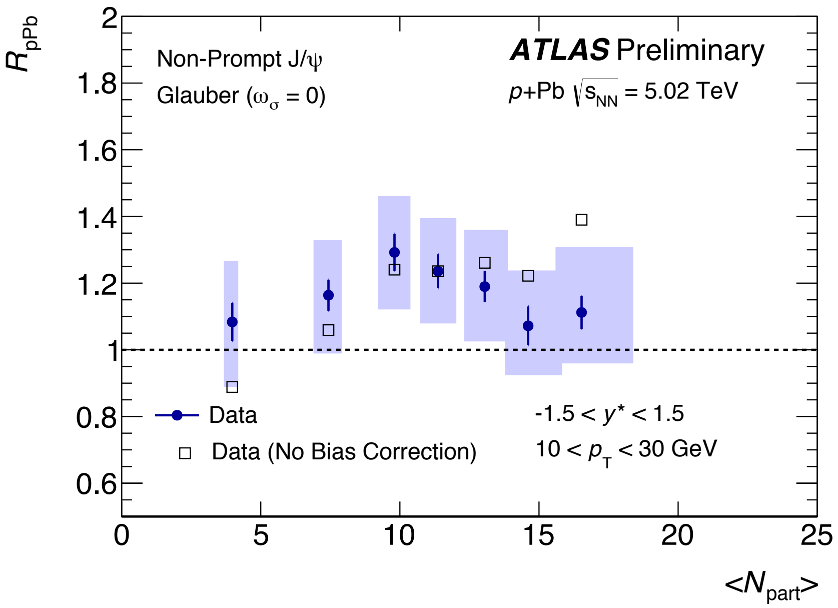
$$R_{pPb} = \frac{1}{\langle T_{pPb}\rangle_{\mathrm{cent}}} \frac{1/N_{\mathrm{evt}}\, d^2N_{\psi}^{p+\mathrm{Pb}}/dy^*dp_{\mathrm{T}}\big|_{\mathrm{cent}}}{d^2\sigma_{\psi}^{pp}/dy\,dp_{\mathrm{T}}},$$





Biased corrected R_{pPb} gives expected trend.

The bias correction works for quarkonium.

$\psi(2S)$ and $\Upsilon(1S)$ R_{pPb} vs. $\langle N_{\mathrm{part}} \rangle$

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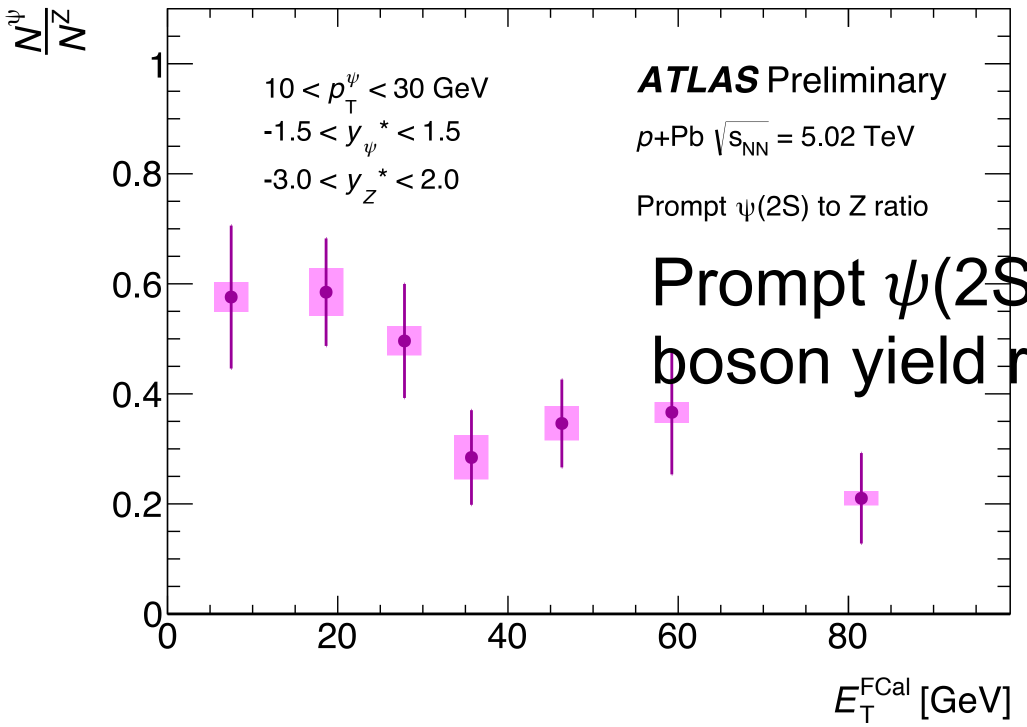
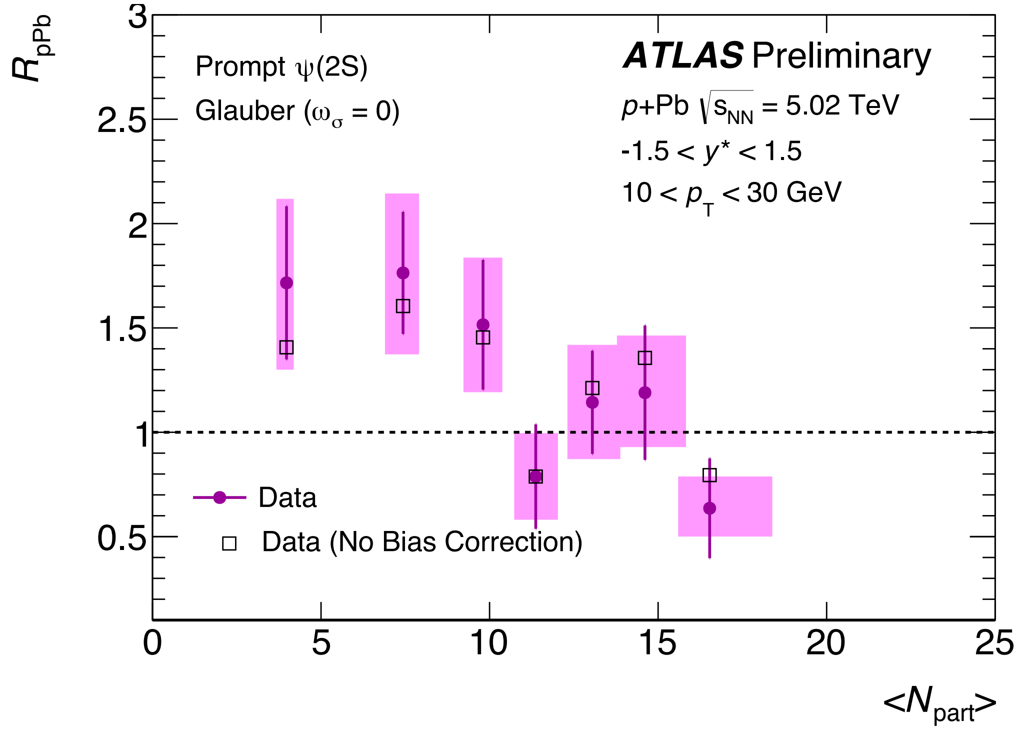


Prompt $\psi(2S)$ to Z boson yield ratio



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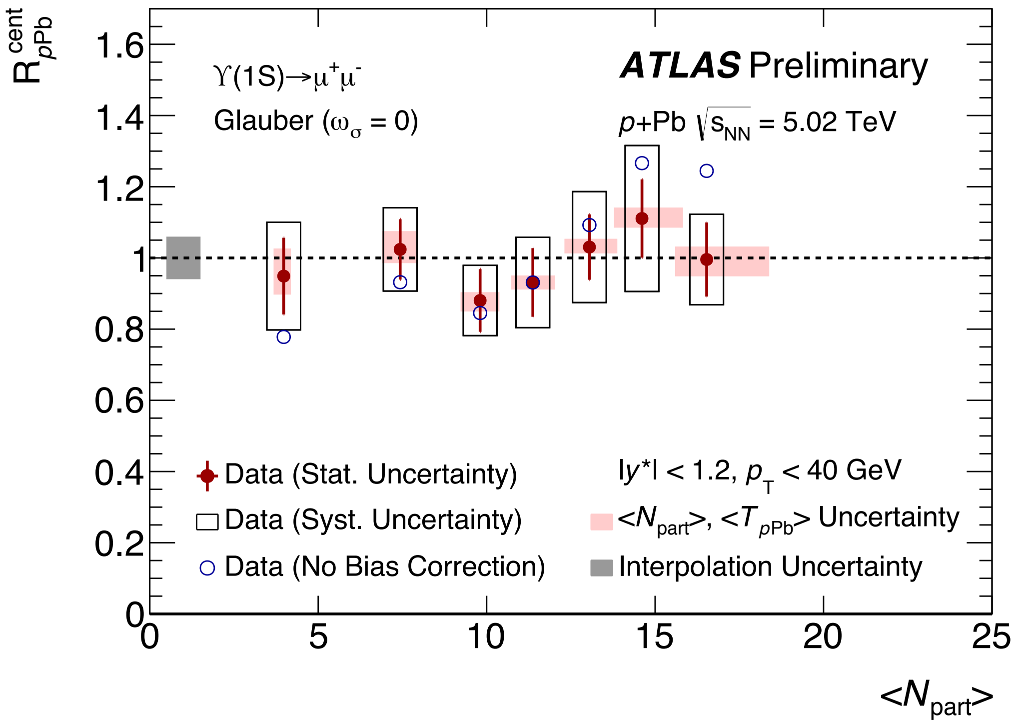

Bias corrected $\Upsilon(1S)$ R_{pPb} is consistent with being constant.

Evident decrease trend as $\langle N_{\mathrm{part}} \rangle$ or ΣE_T increases for prompt $\psi(2S)$ production.

Suppressed in more central collisions wrt. more peripheral collisions.

Double Ratio vs. FCal ΣE_T

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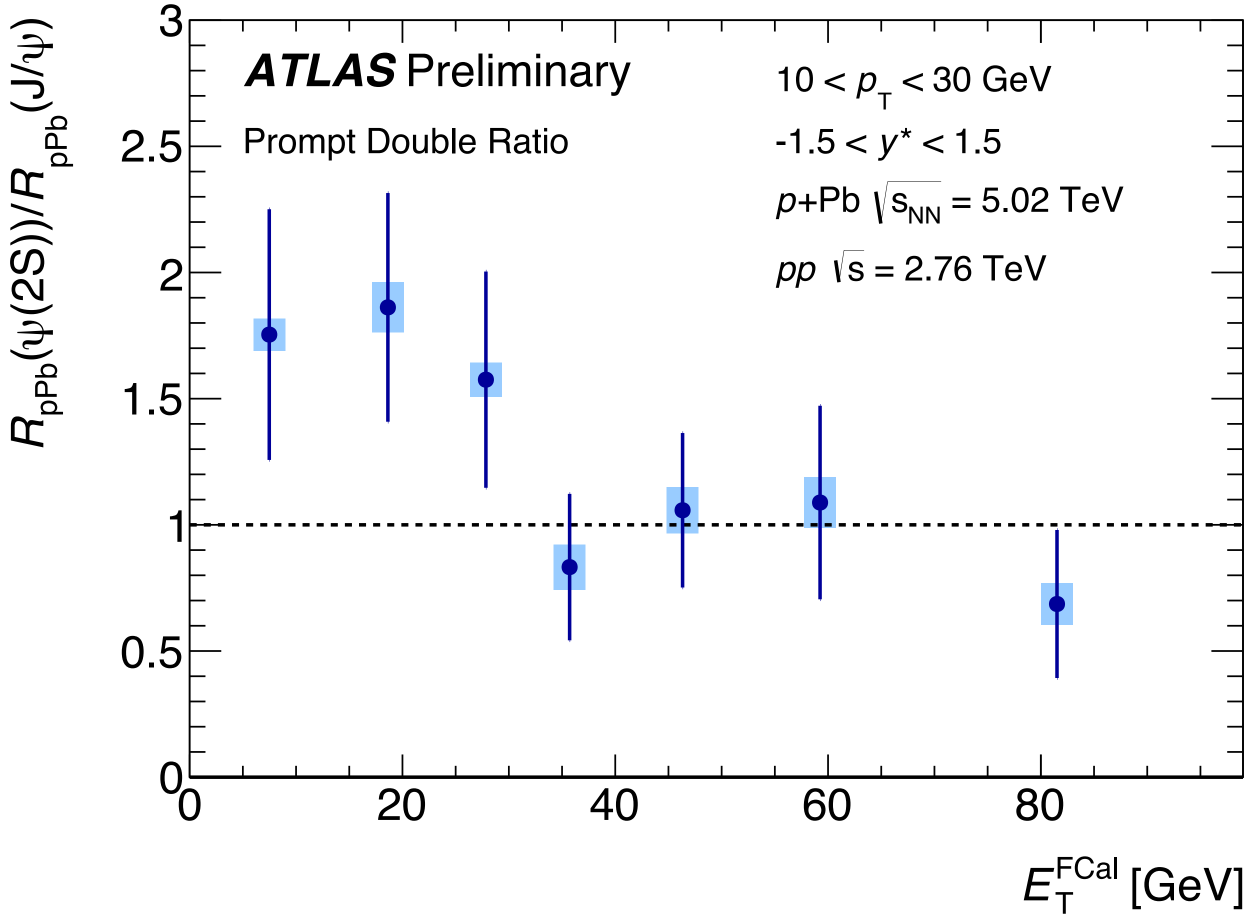

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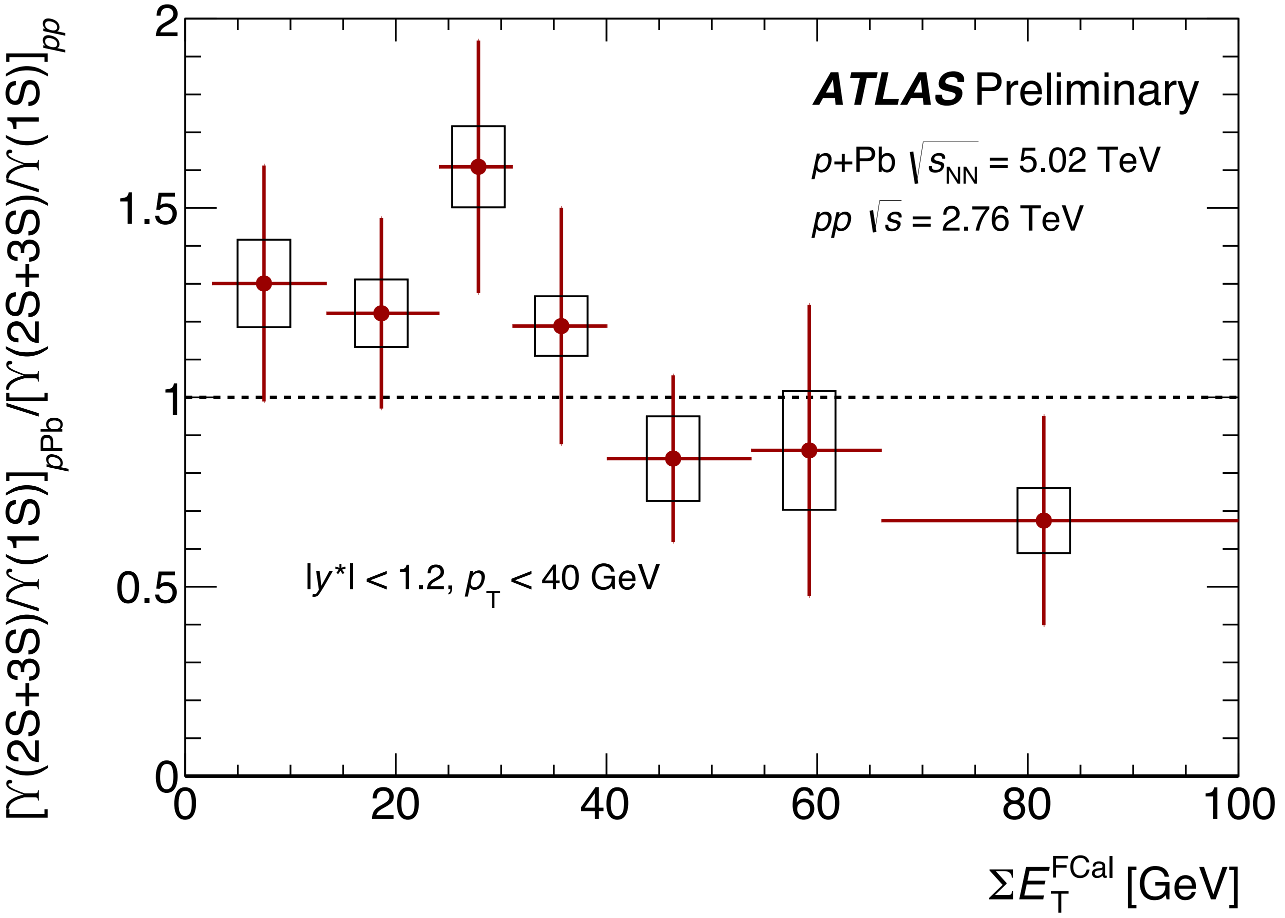

- *(Left)* Prompt charmonium double ratio
- *(Right)* Bottomonium double ratio

Both show sizable ΣE_T dependence. Excited states (ψ(2S) and Υ(2S+3S)) are more suppressed wrt. ground states in more central collisions in a similar way.

Self-normalized Ratio (I)

ϒ yields are binned in centrality according to E_T of ϒ events.

$$\frac{\Upsilon}{\langle\Upsilon\rangle} = \frac{N_{\Upsilon}^{cen}/N_{\mathrm{evt}}^{cen}}{N_{\Upsilon}^{0-90\%}/N_{\mathrm{evt}}^{0-90\%}}$$

$$\frac{\Sigma E_{\mathrm{T}}^{\mathrm{FCal},cen}}{\langle\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}\rangle^{0-90\%}}$$

Obtained from MinBias events

Obtained from MinBias events

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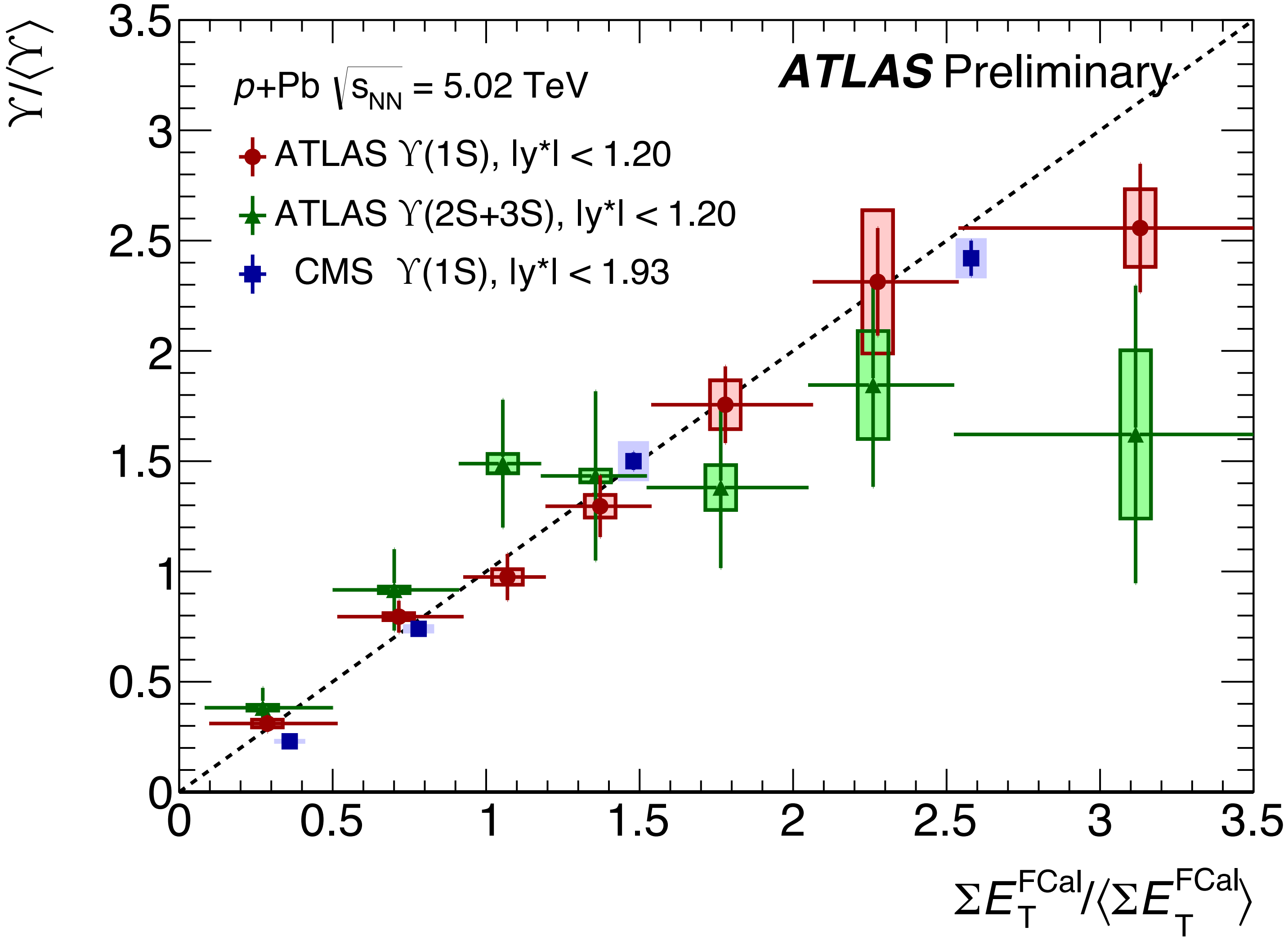

$(\Sigma E_{\mathrm{T}}^{\mathrm{HF}}/\langle\Sigma E_{\mathrm{T}}^{\mathrm{HF}}\rangle$ for CMS)

$\Sigma E_T/\langle\Sigma E_T\rangle < 2.3$

Self-normalized ϒ yields are consistent with the unitarily sloped line. Compatible with ***CMS***.

$\Sigma E_T/\langle\Sigma E_T\rangle = 3.1$

2σ deviated from line at for both ϒ(1S) and ϒ(2S+3S).

Self-normalized Ratio (II)

$$\frac{\Upsilon}{\langle\Upsilon\rangle} = \frac{N_{\Upsilon}^{cen}/N_{\mathrm{evt}}^{cen}}{N_{\Upsilon}^{0-90\%}/N_{\mathrm{evt}}^{0-90\%}}$$

Self-normalized ratio still suffers centrality bias by definition.

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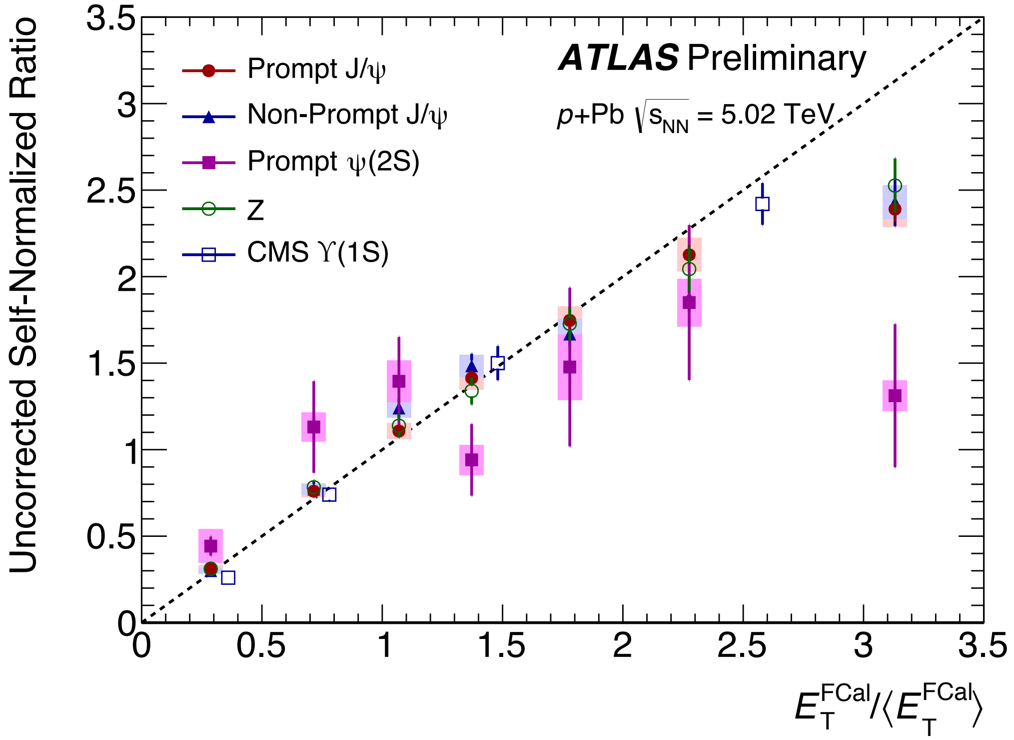
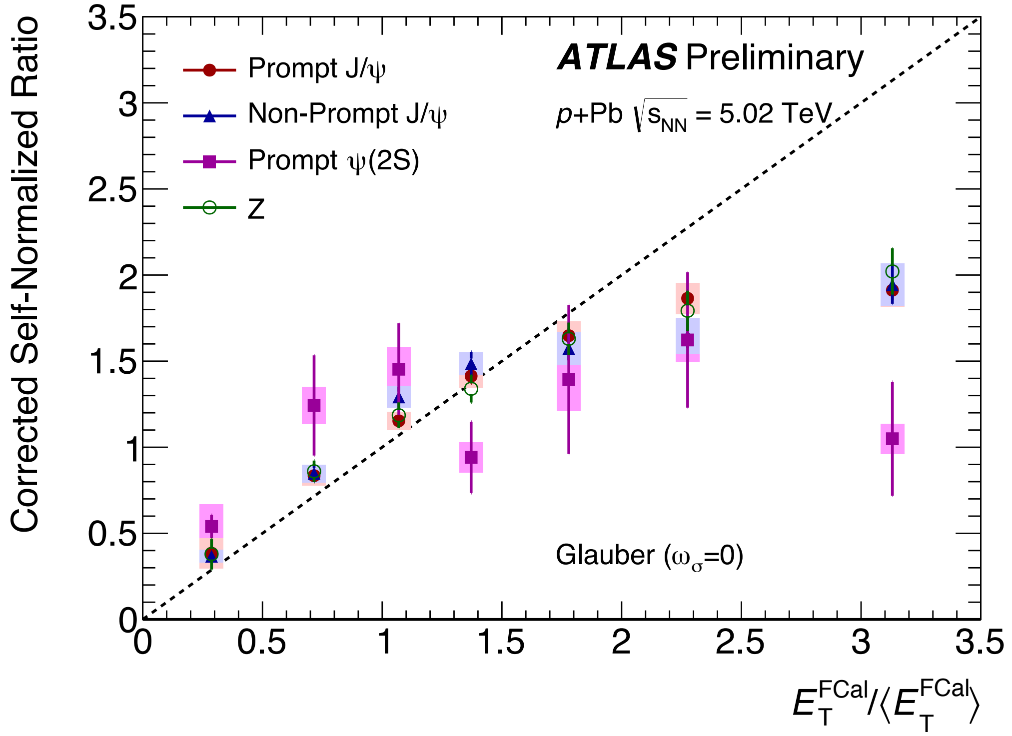




- *(Left)* Uncorrected self-normalized ratio for charmonium and *Z*.
  Consistent with line when $\Sigma E_T / \langle \Sigma E_T \rangle < 2.3$, more than **3$\sigma$** deviated from line at $\Sigma E_T / \langle \Sigma E_T \rangle = 3.1$.
- *(Right)* Bias corrected ratios. More significant deviations.

Summary

- Charmonia and bottomonia production in *pp* and *p*+Pb collisions are presented.
- **Charmonia (J/ψ and ψ(2S)):**
  - Charmonia R_{pPb} shows no obvious p_T and rapidity dependence.
  - J/ψ R_{pPb} shows no centrality dependence.
  - Prompt ψ(2S) is more suppressed in more central collisions wrt. more peripheral collisions.
- **Bottomonia (ϒ(1S) and ϒ(2S+3S)):**
  - ϒ(1S) R_{pPb} is compatible with prompt J/ψ R_{pPb}.
  - ϒ(1S) R_{pPb} shows no centrality dependence.
  - ϒ(2S+3S) states are more suppressed in more central collisions.

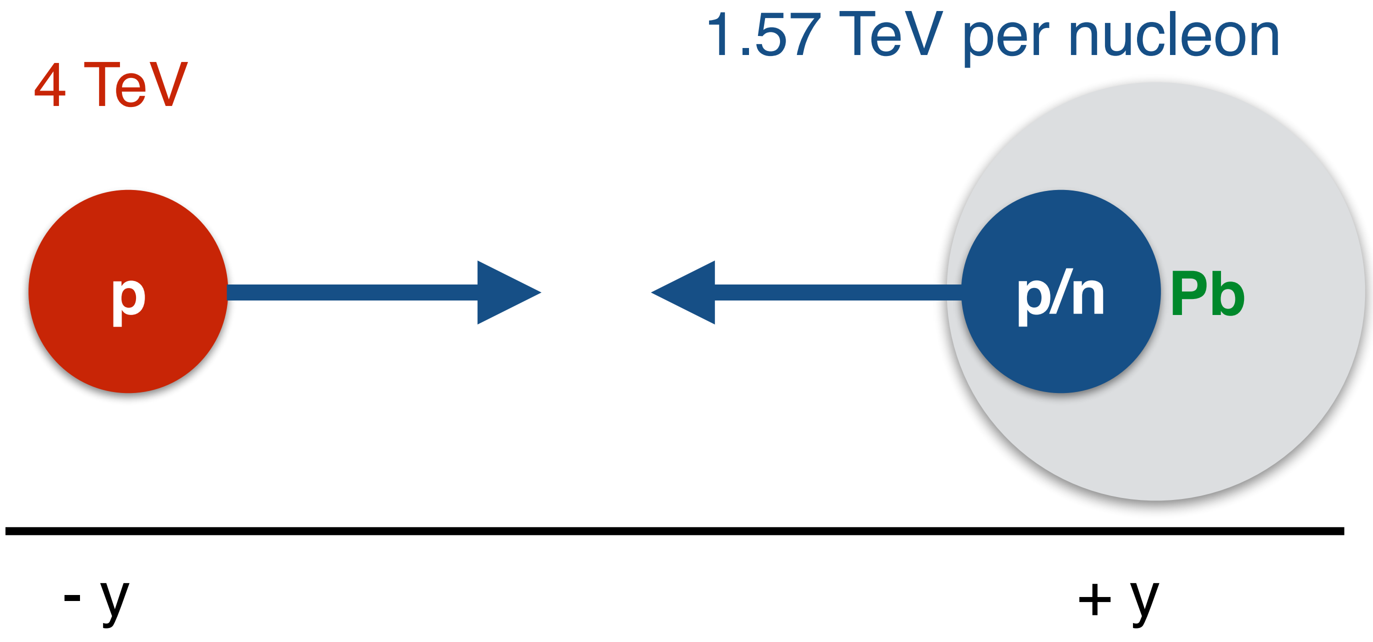
Thank you！
ありがとう

Backup

pPb Beam Configuration

The proton-nucleon center of mass (CM) frame has a shift of 0.465 in rapidity in the proton beam direction.

*y**: CM rapidity being positive in forward (proton beam direction).

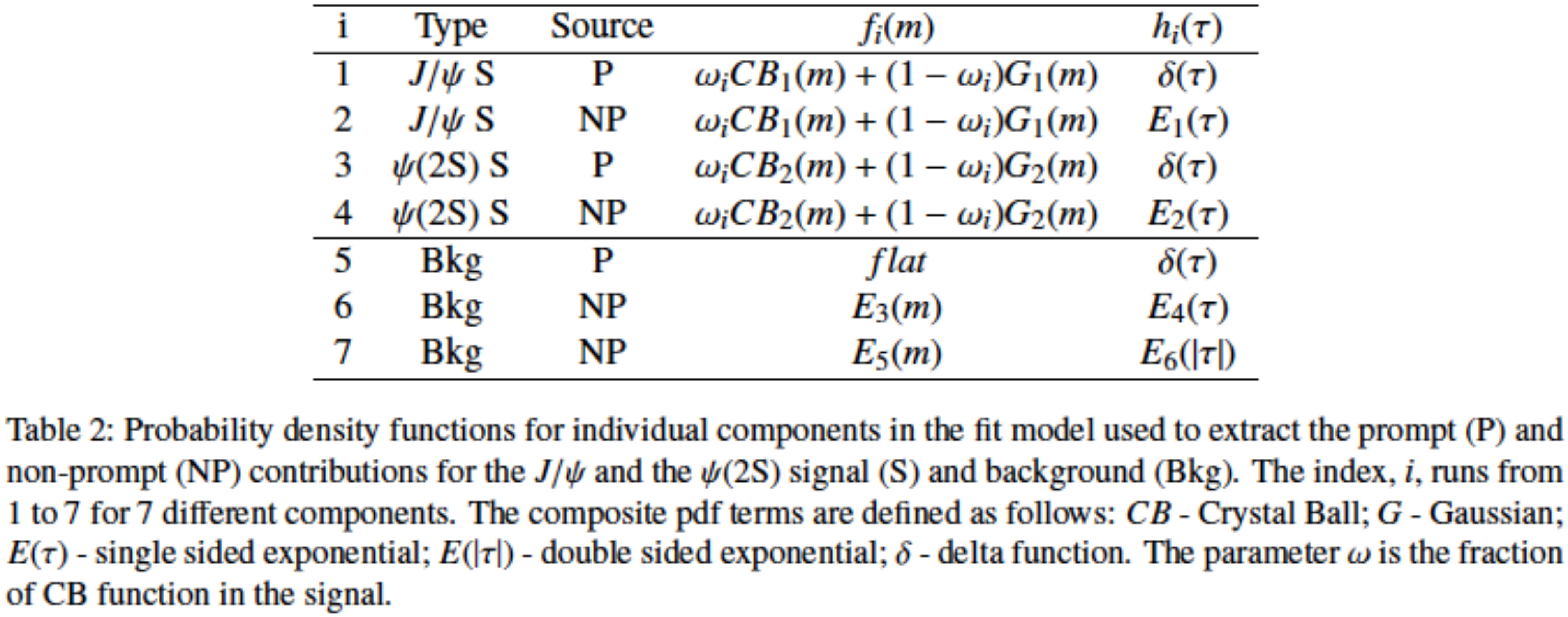


p+Pb collision beam configuration

$y^* = -(y_{lab} + 0.465)$ p+Pb run period A

$y^* = y_{lab} - 0.465)$ p+Pb run period B

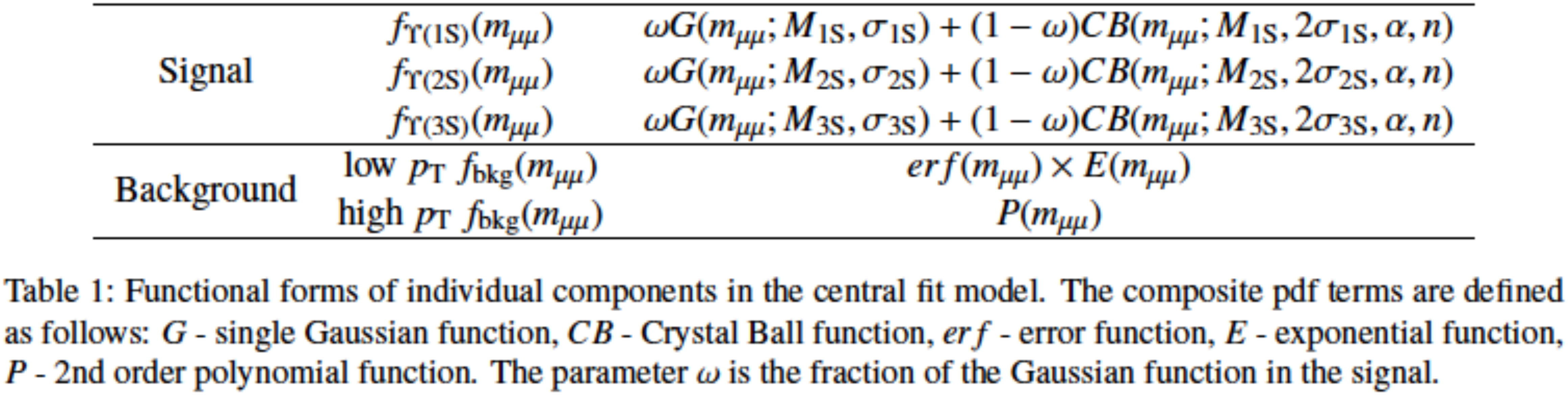
Charmonium Fit Model



i	Type	Source	$f_i(m)$	$h_i(\tau)$
1	J/ψ S	P	$\omega_i CB_1(m) + (1-\omega_i)G_1(m)$	$\delta(\tau)$
2	J/ψ S	NP	$\omega_i CB_1(m) + (1-\omega_i)G_1(m)$	$E_1(\tau)$
3	$\psi(2S)$ S	P	$\omega_i CB_2(m) + (1-\omega_i)G_2(m)$	$\delta(\tau)$
4	$\psi(2S)$ S	NP	$\omega_i CB_2(m) + (1-\omega_i)G_2(m)$	$E_2(\tau)$
5	Bkg	P	$flat$	$\delta(\tau)$
6	Bkg	NP	$E_3(m)$	$E_4(\tau)$
7	Bkg	NP	$E_5(m)$	$E_6(\|\tau\|)$

Table 2: Probability density functions for individual components in the fit model used to extract the prompt (P) and non-prompt (NP) contributions for the J/ψ and the $\psi(2S)$ signal (S) and background (Bkg). The index, i, runs from 1 to 7 for 7 different components. The composite pdf terms are defined as follows: CB - Crystal Ball; G - Gaussian; $E(\tau)$ - single sided exponential; $E(|\tau|)$ - double sided exponential; δ - delta function. The parameter ω is the fraction of CB function in the signal.

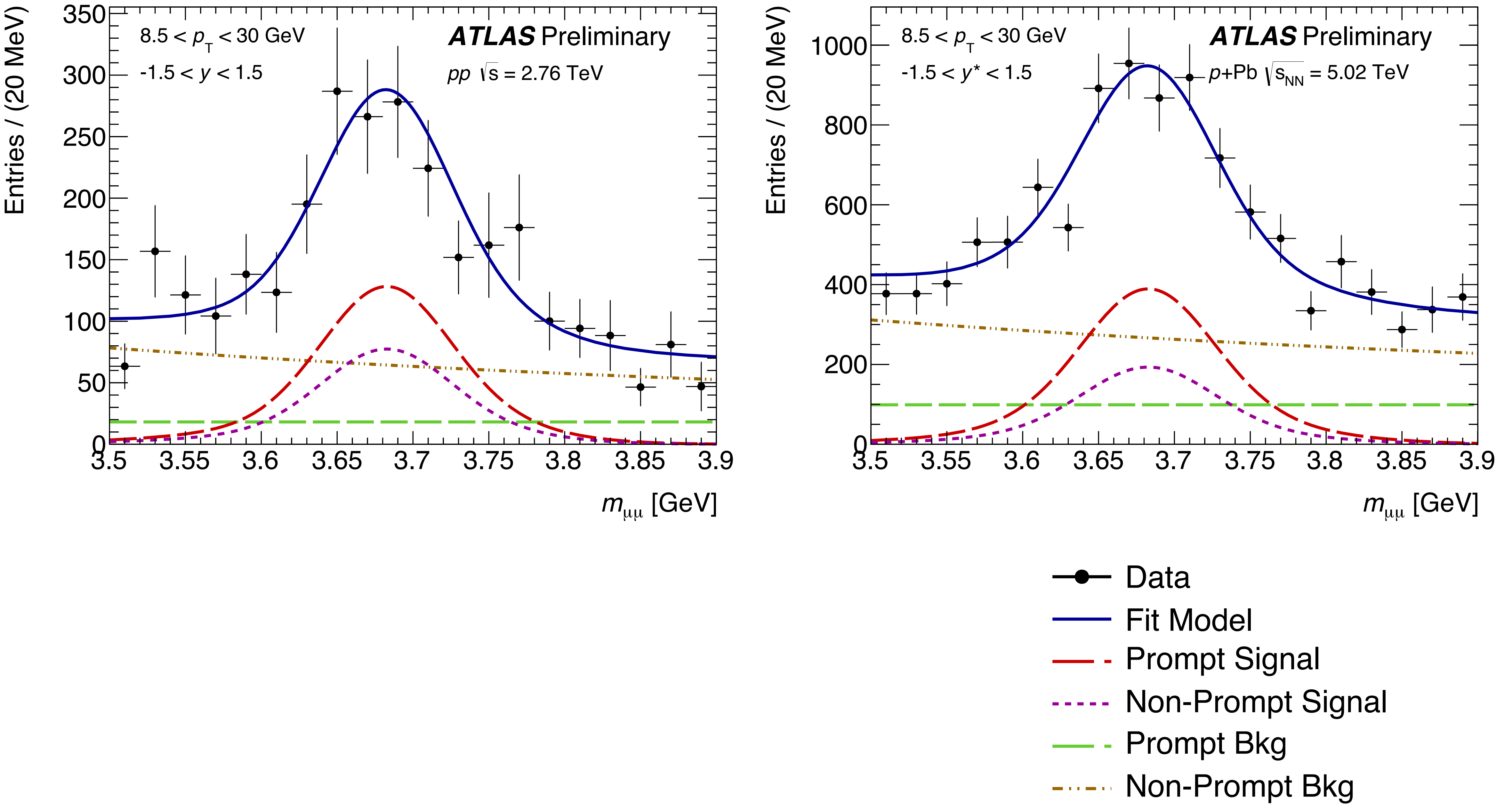
Bottomonium Fit Model



Signal	$f_{\Upsilon(1S)}(m_{\mu\mu})$	$\omega G(m_{\mu\mu}; M_{1S}, \sigma_{1S}) + (1-\omega) CB(m_{\mu\mu}; M_{1S}, 2\sigma_{1S}, \alpha, n)$
	$f_{\Upsilon(2S)}(m_{\mu\mu})$	$\omega G(m_{\mu\mu}; M_{2S}, \sigma_{2S}) + (1-\omega) CB(m_{\mu\mu}; M_{2S}, 2\sigma_{2S}, \alpha, n)$
	$f_{\Upsilon(3S)}(m_{\mu\mu})$	$\omega G(m_{\mu\mu}; M_{3S}, \sigma_{3S}) + (1-\omega) CB(m_{\mu\mu}; M_{3S}, 2\sigma_{3S}, \alpha, n)$
Background	low p_T $f_{\mathrm{bkg}}(m_{\mu\mu})$	$erf(m_{\mu\mu}) \times E(m_{\mu\mu})$
	high p_T $f_{\mathrm{bkg}}(m_{\mu\mu})$	$P(m_{\mu\mu})$

Table 1: Functional forms of individual components in the central fit model. The composite pdf terms are defined as follows: G - single Gaussian function, CB - Crystal Ball function, erf - error function, E - exponential function, P - 2nd order polynomial function. The parameter ω is the fraction of the Gaussian function in the signal.

Selected ψ(2S) fits



pp Reference at 5 TeV

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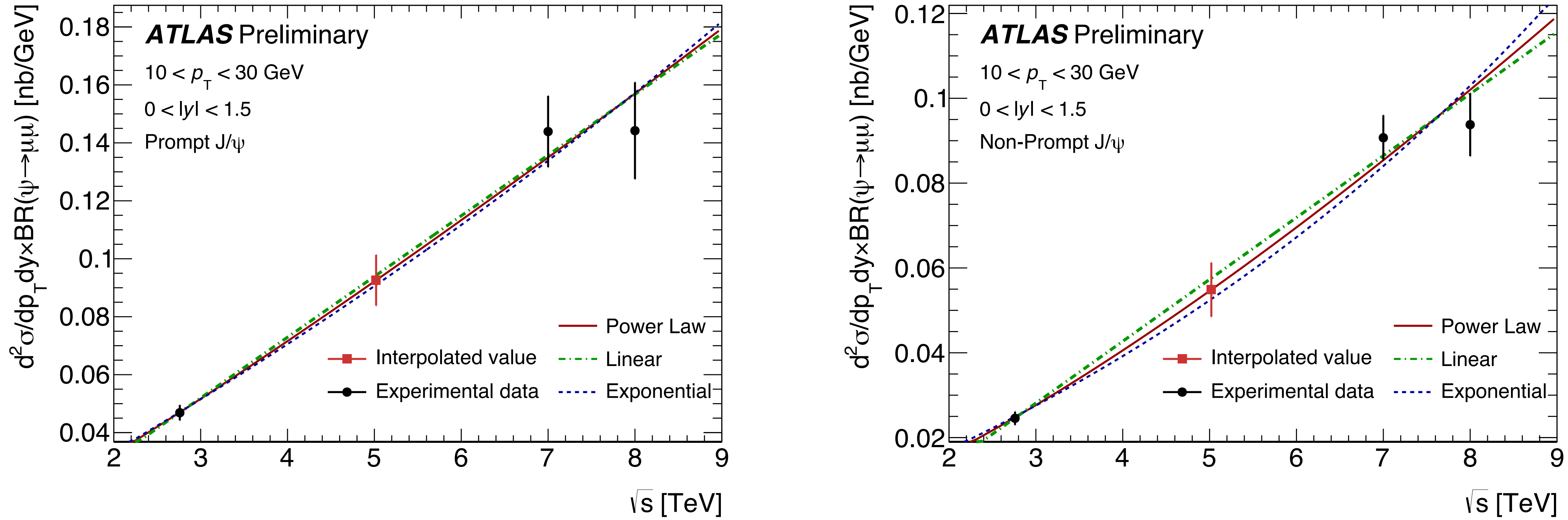

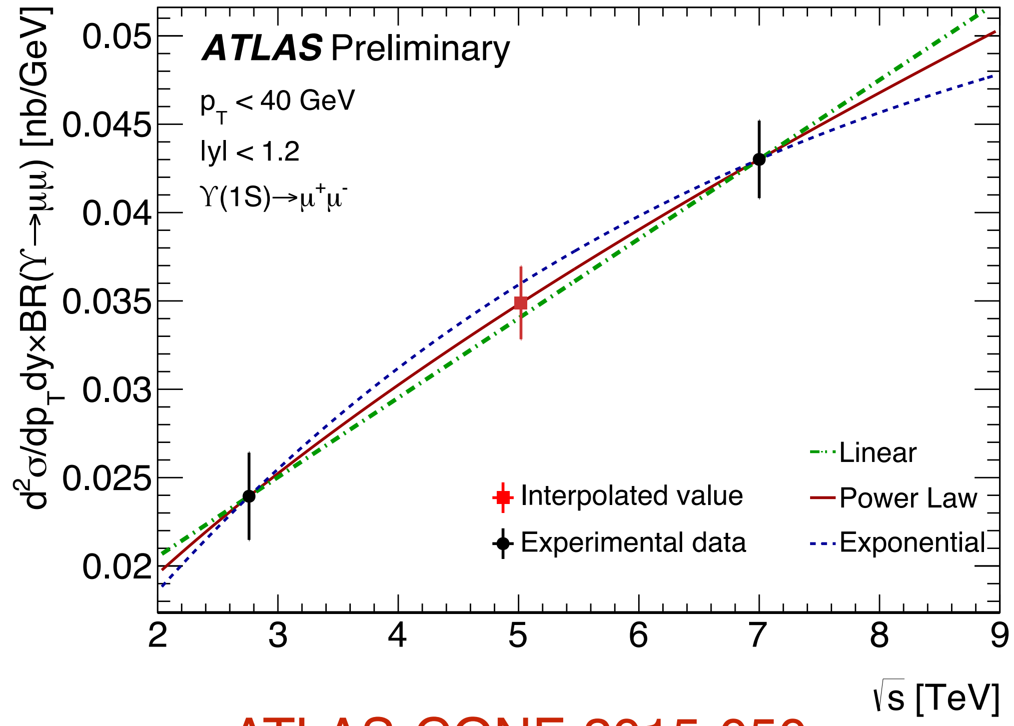

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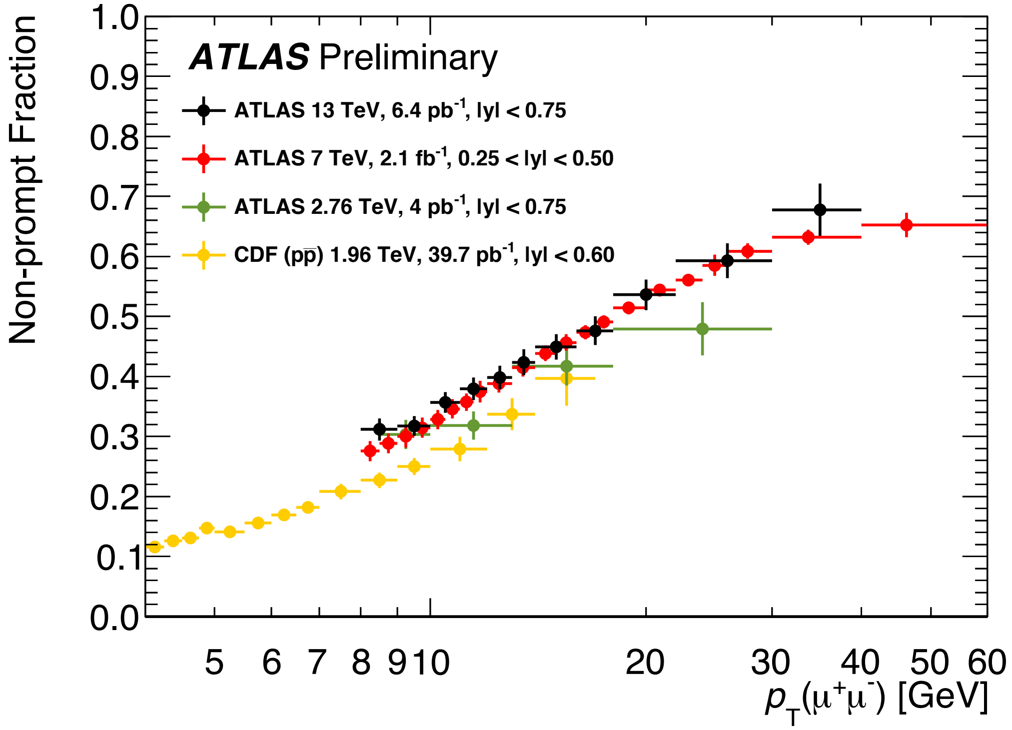
Three interpolation functions used to calculate pp reference at 5.02 TeV, central values obtained from power law function.

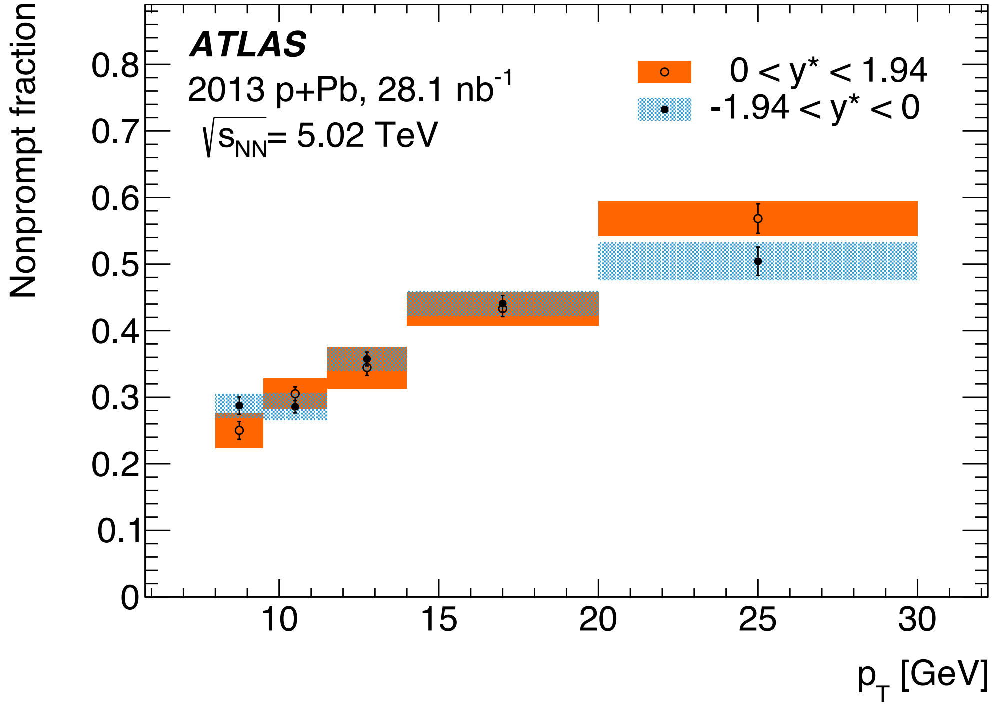
$$\sigma(\sqrt{s}) = \begin{cases} p_0 + \sqrt{s}p_1 & \text{linear} \\ (\sqrt{s}/p_0)^{p_1} & \text{power law} \\ p_0(1-\exp(-\sqrt{s}/p_1)) & \text{exponential} \end{cases}$$

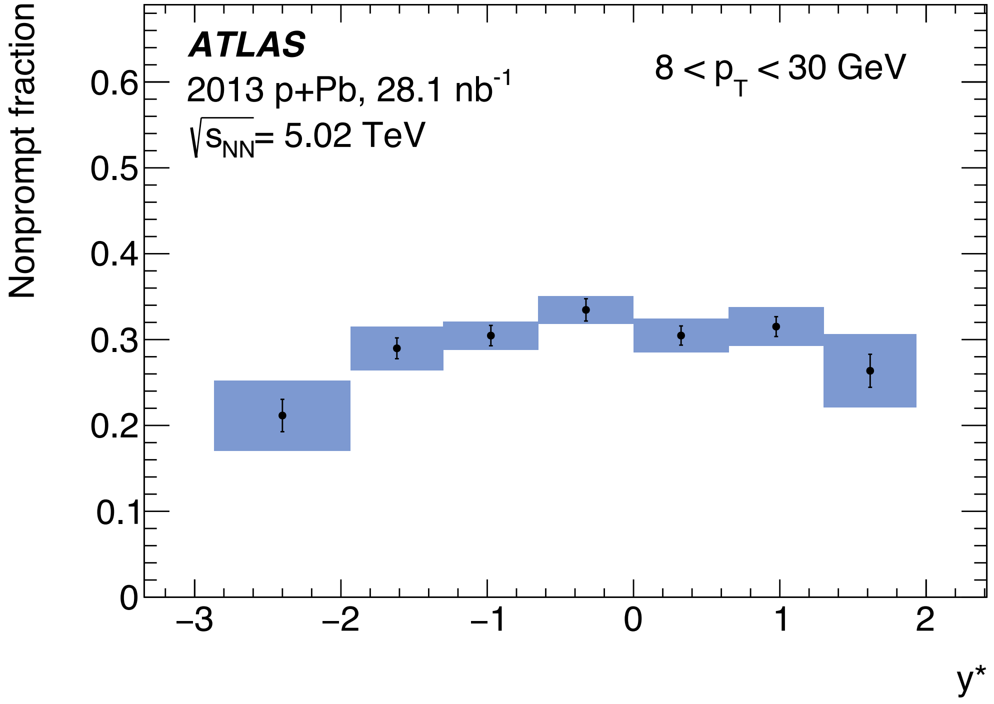
Three points for charmoina interpolation

Two points for bottomoina interpolation

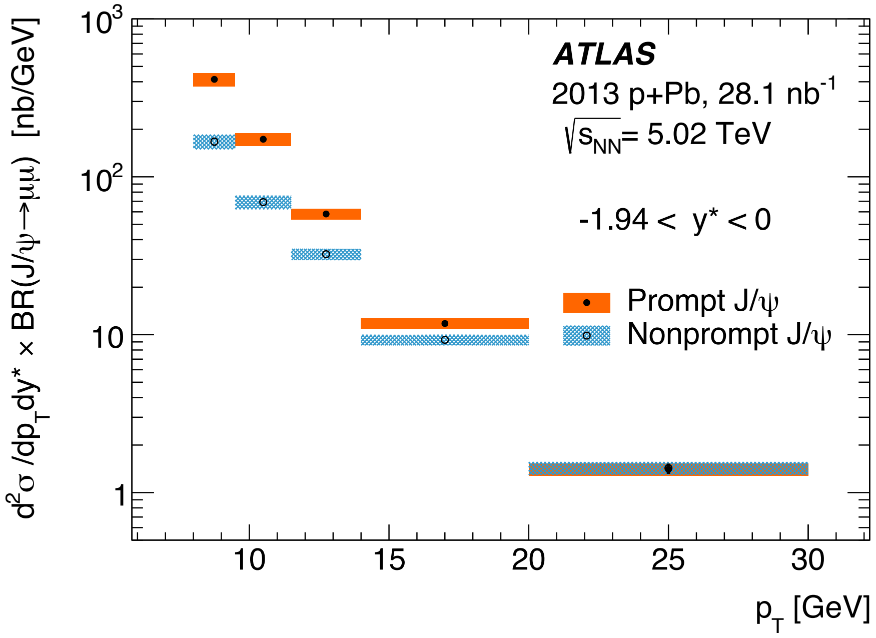
Non-prompt fraction

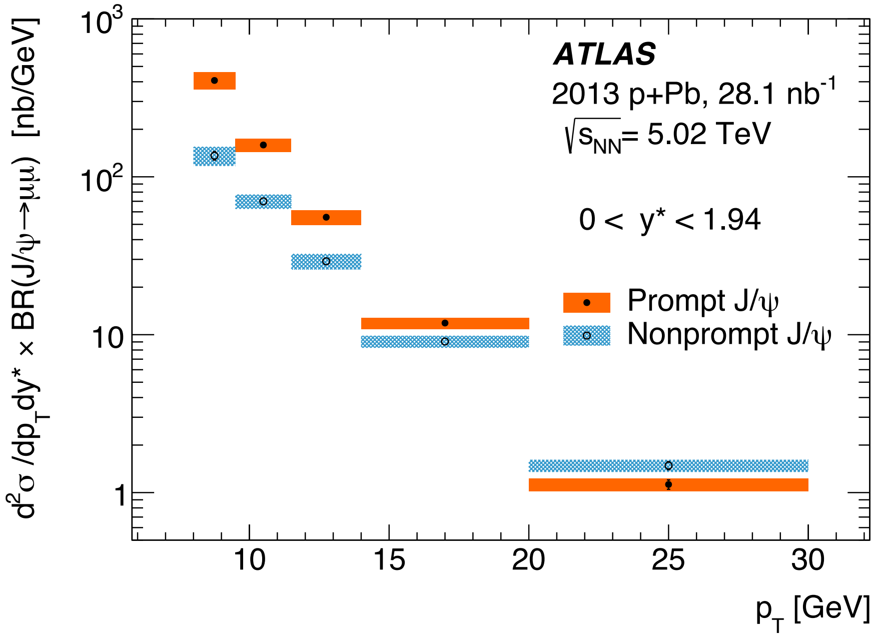


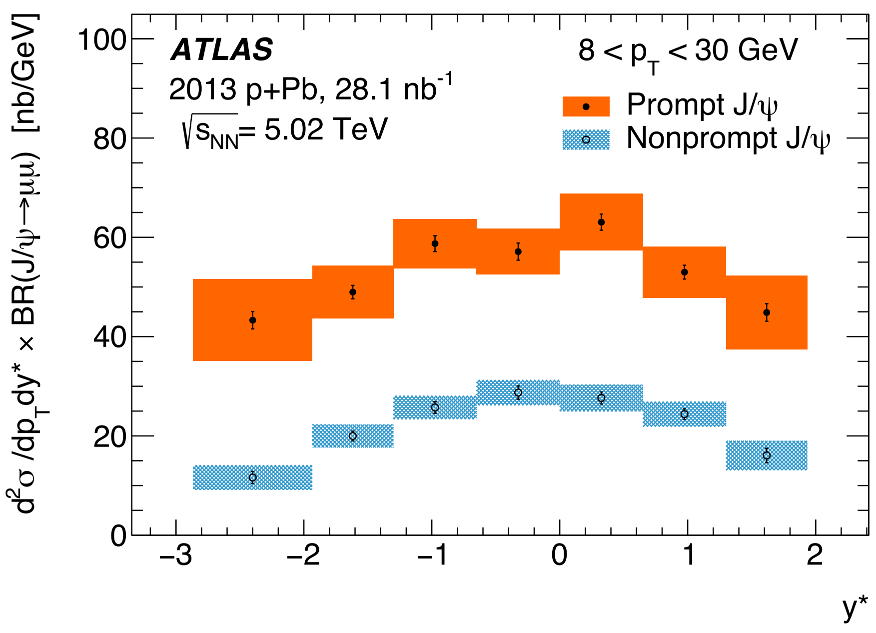


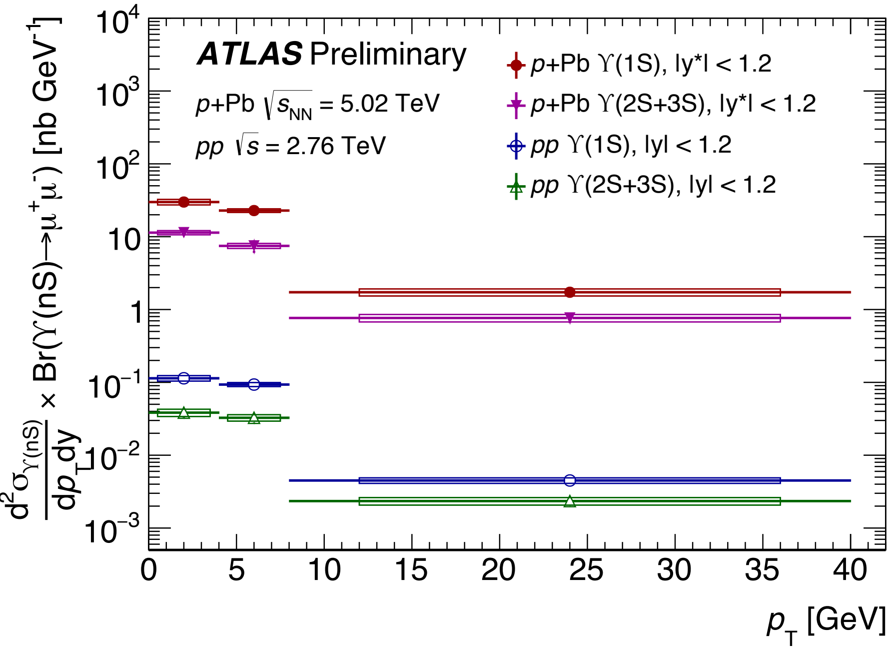


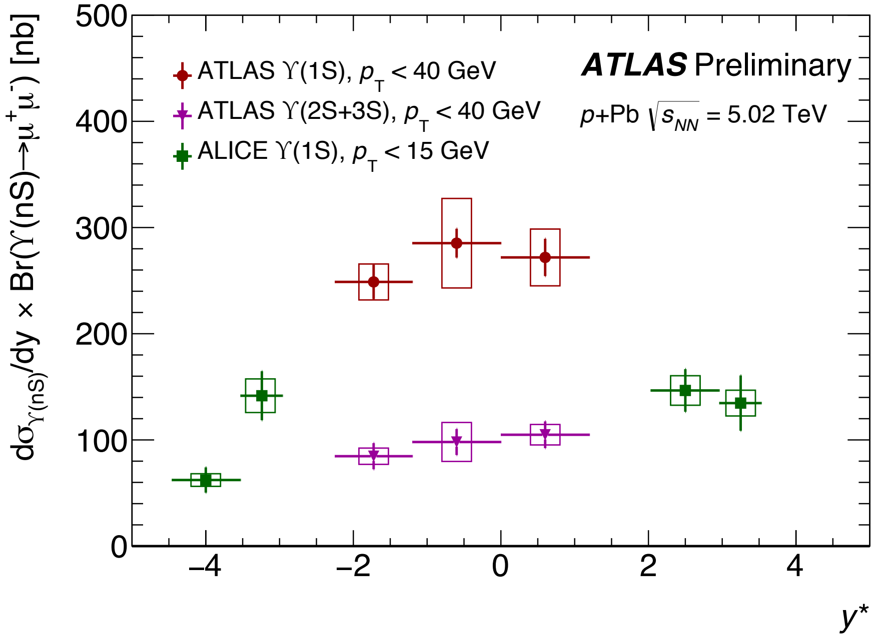
Cross Sections

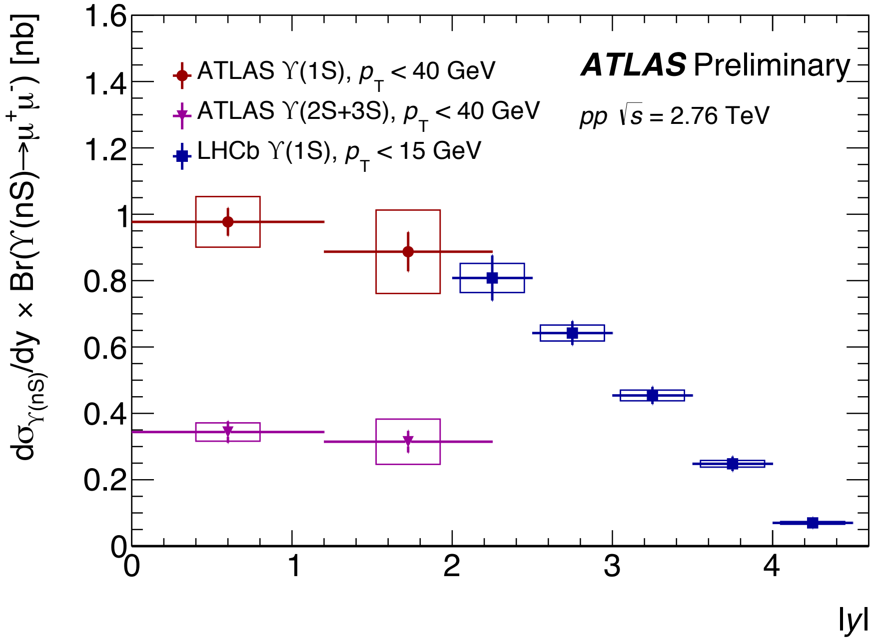












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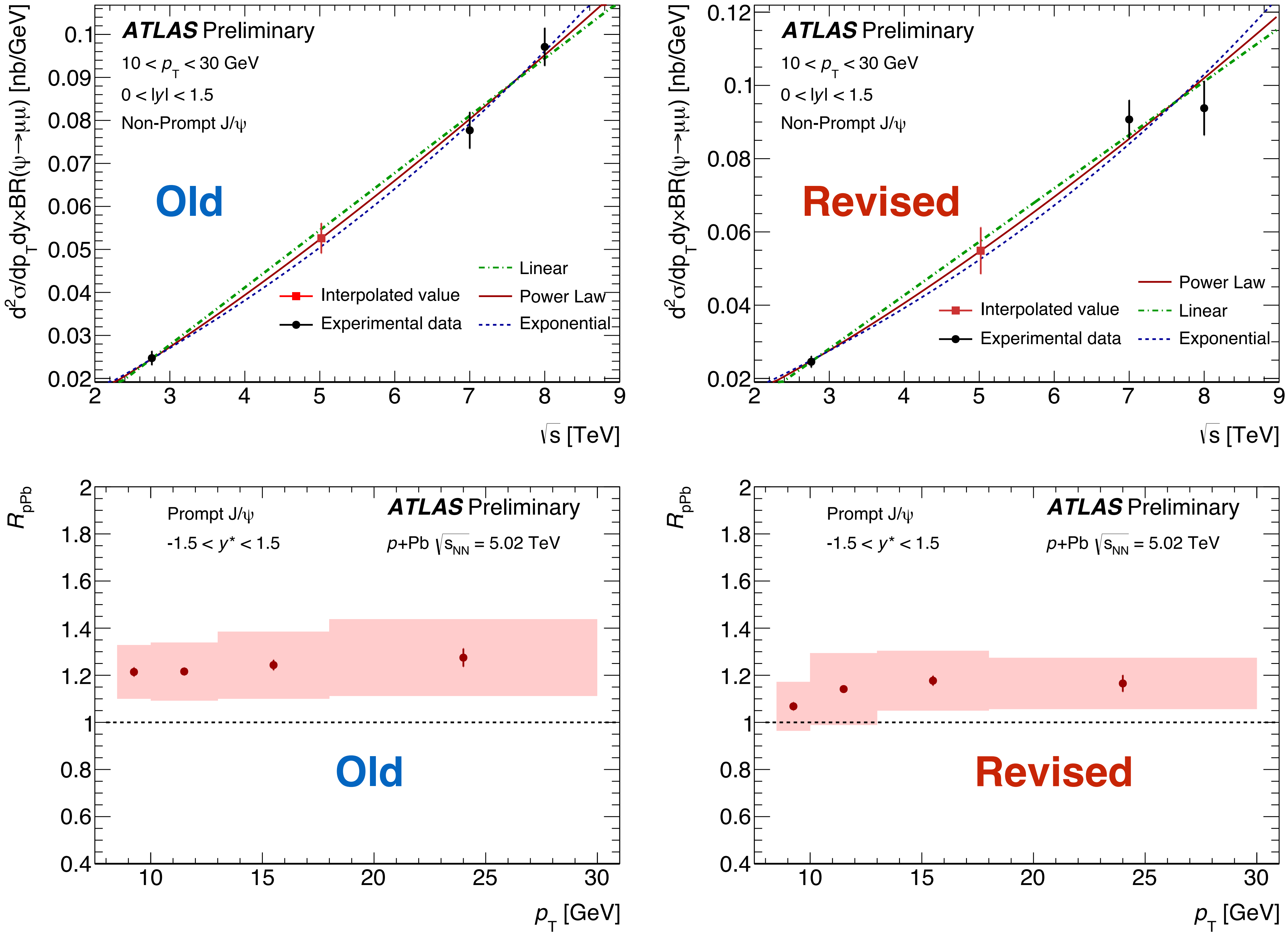

Update 7 and 8 TeV results used in the interpolation

E_T / $\langle E_T \rangle$ Scale Factor

ATLAS defintion:

$$\frac{\Sigma E_{\mathrm{T}}^{\mathrm{FCal},cen}}{\langle \Sigma E_{\mathrm{T}}^{\mathrm{FCal}} \rangle 0-90\%}$$

Obtained from MinBias events

Obtained from MinBias events

CMS proposed defintion:

$$\frac{\Sigma E_{\mathrm{T}}^{\mathrm{FCal},cen}}{\langle \Sigma E_{\mathrm{T}}^{\mathrm{FCal}} \rangle 0-90\%}$$

Obtained from Dimuon events

Obtained from MinBias events