UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

ATLAS EXPERIMENT

Measurement of quarkonia production in heavy-ion collisions with the ATLAS detector

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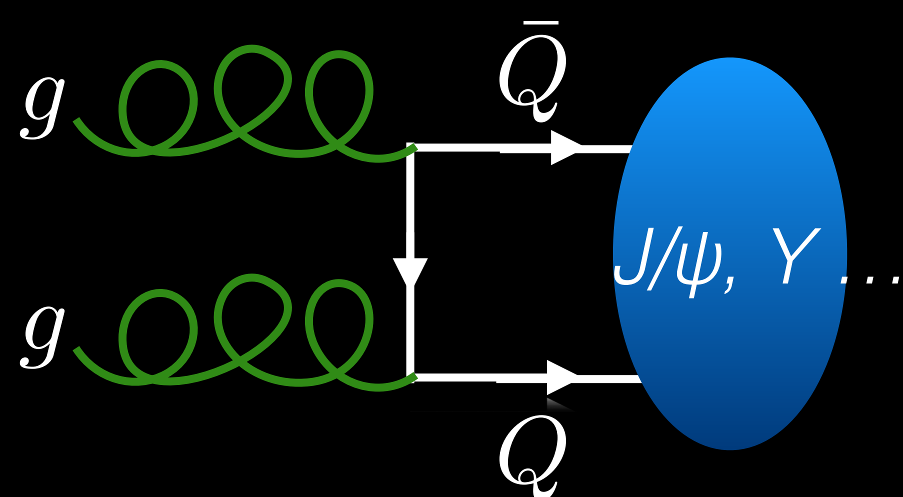
Particles and Nuclei International Conference 2017
Beijing, China

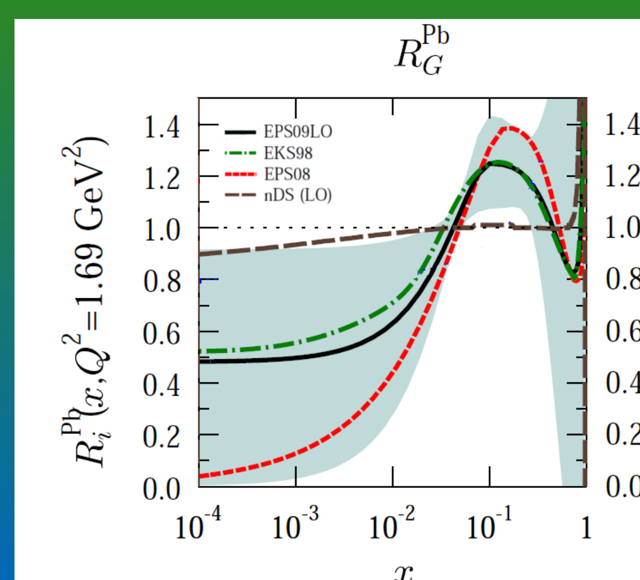
Why Quarkonia?

Quarkonia
- Bound states of quark and anti-quark
- Interact strongly with the environment
- Sensitive to hot and cold matter effects



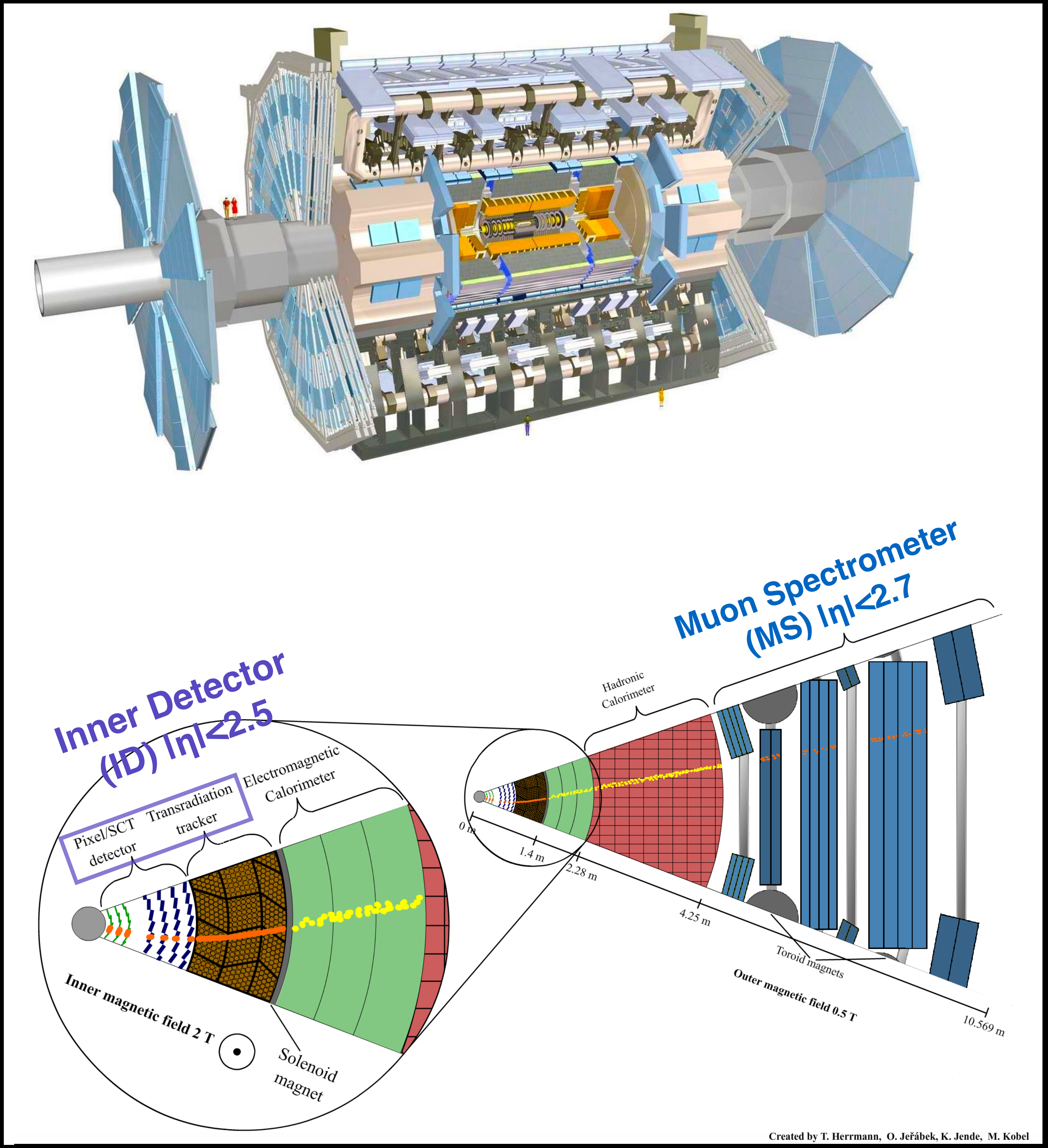
"Quarkonia as QGP thermometer",
T. Matsui and H. Satz PLB 178 (1986) 416

CNM effects
- Nuclear PDFs
- Gluon Saturation
- Parton Energy loss
- Nuclear Absorption
- Comover Breakup



QGP effects
- Debye screening
  - ☆ Sequential melting
- Regeneration
- Energy loss ?

ATLAS detector



Muon Trigger System

Barrel, |η| < 1.05, RPC
Endcaps, 1.05<|η|<2.4, TGC

Muon Tracking System

Barrel, |η| < 2.0, MDT
Endcaps, 2.0<|η|<2.7, CSC

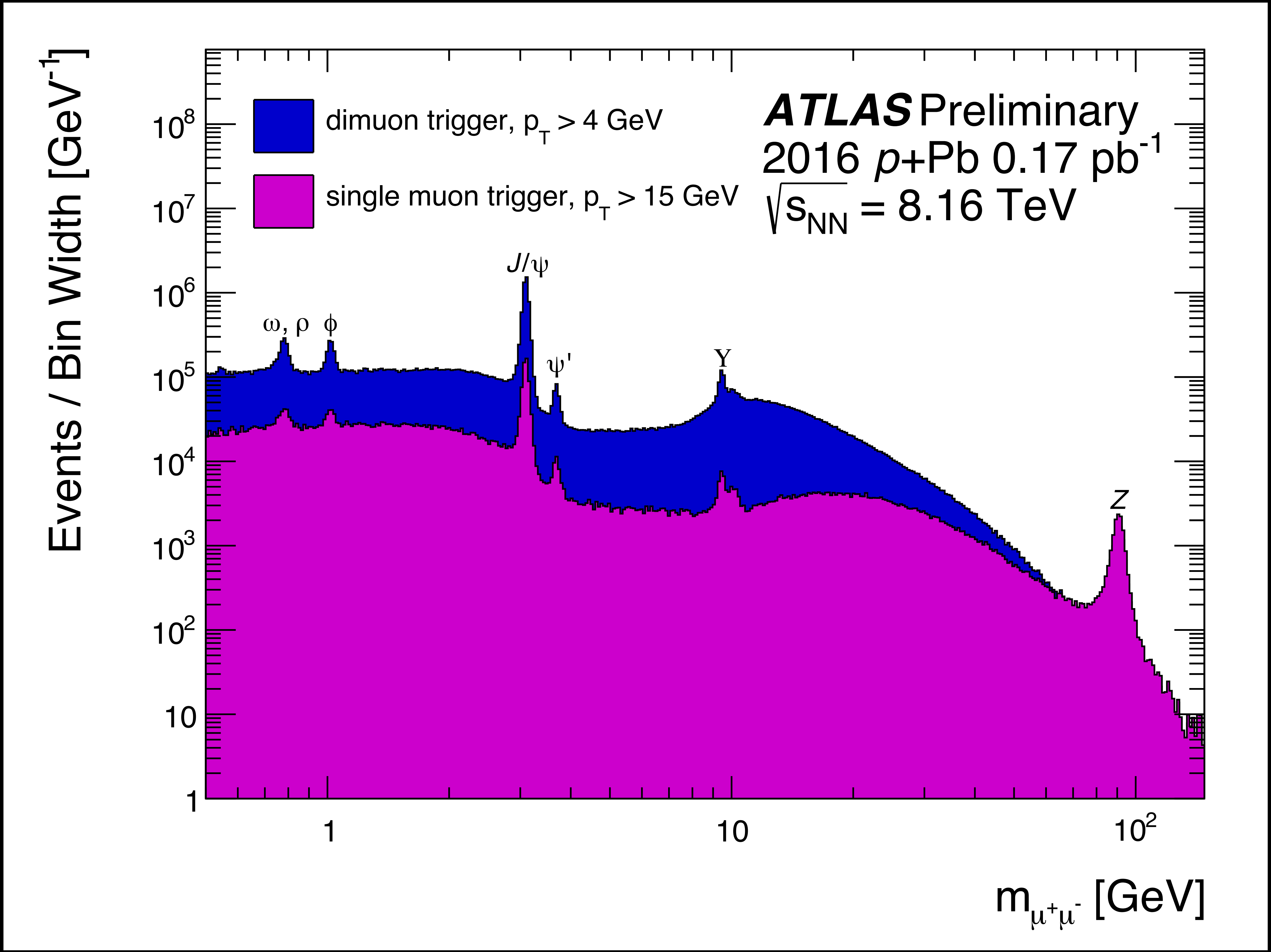
"Muons are reconstructed combining data from the MS and the ID"

Forward Calorimeter, FCal

3.1<|η|<4.9

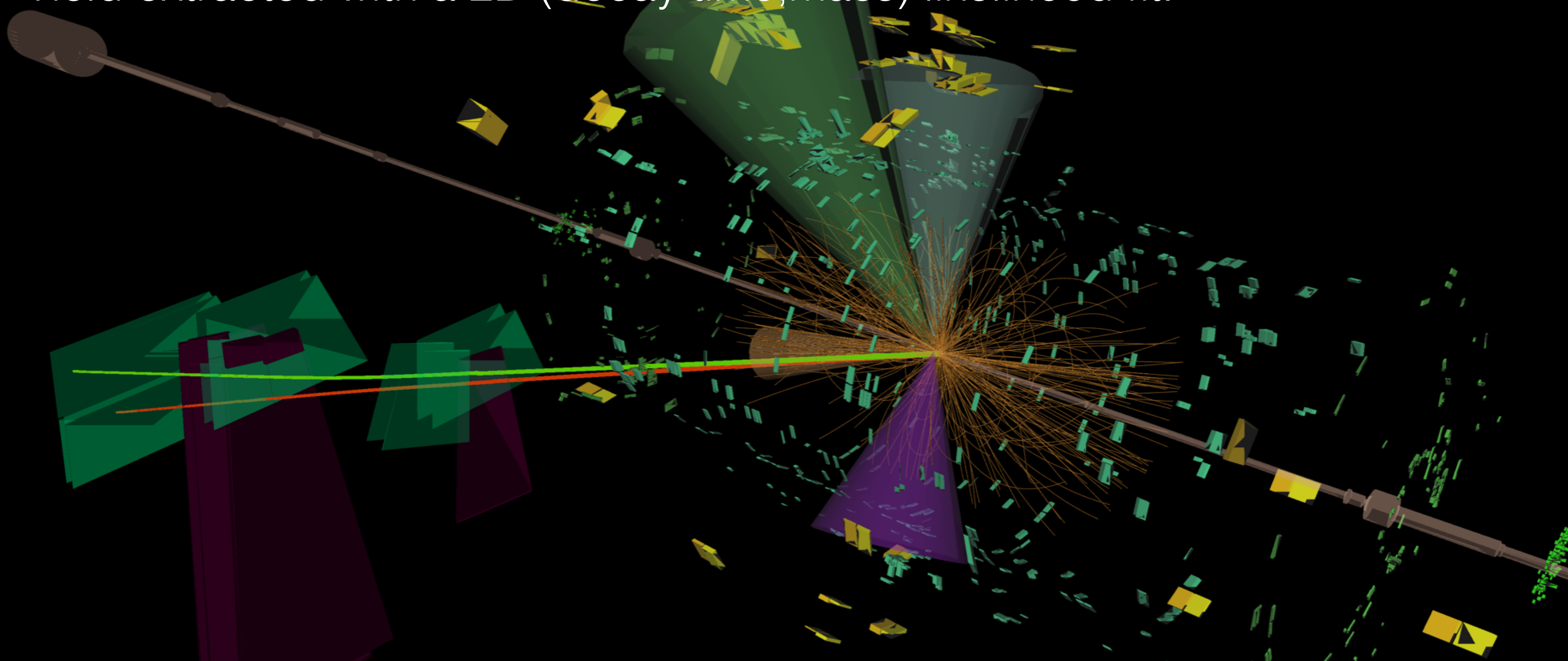
"Centrality of collision is characterized with the sum of transverse energy in both FCal modules in PbPb and the Pb side for pPb collisions"

Di-muon invariant mass spectrum



J/ψ and ψ(2S) measurements

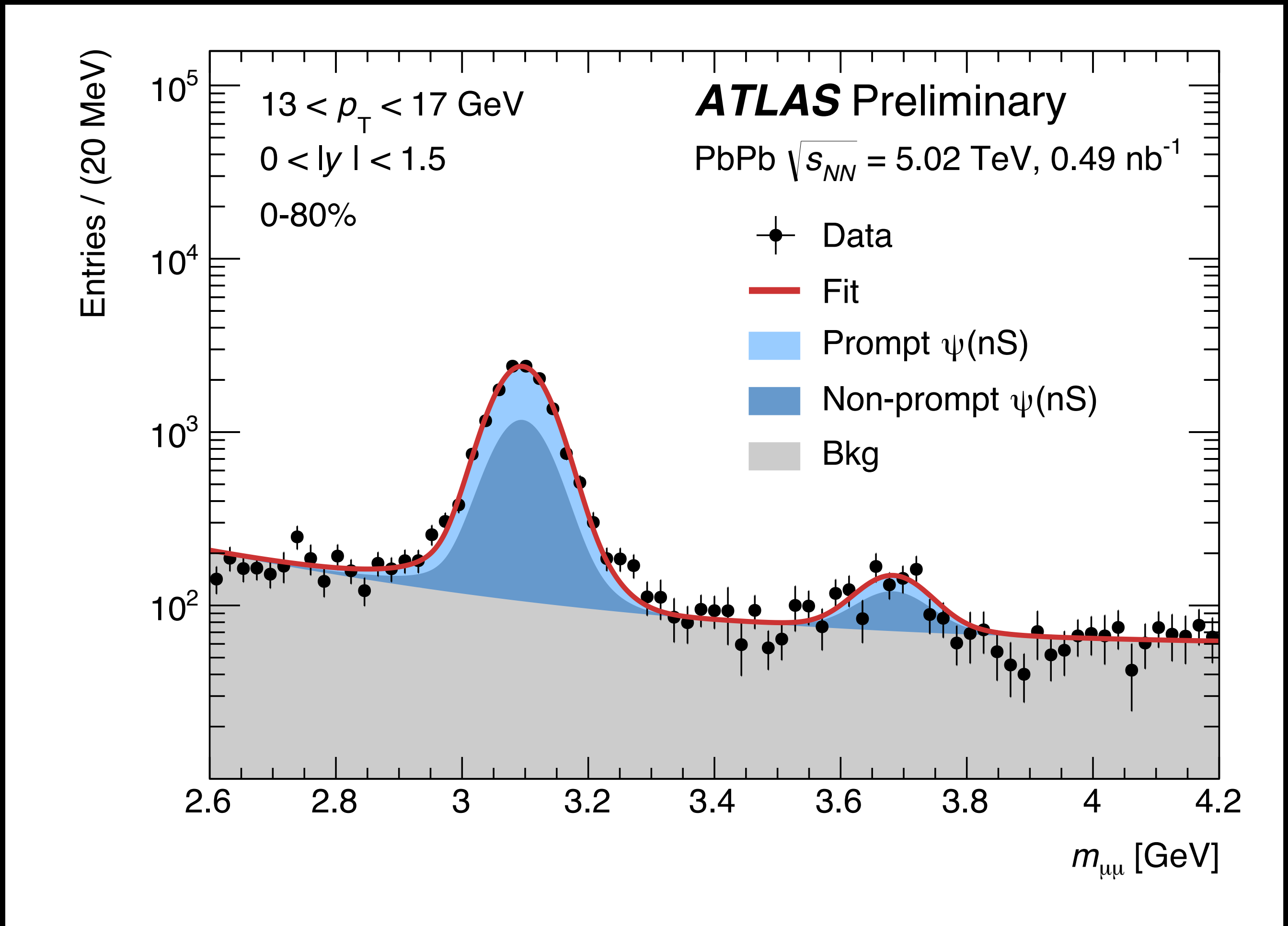
- Di-muon channel, $2.6 < m_{\mu\mu} < 4.2$ GeV
- Di-muon trigger
- Kinematic Range: $8(9) < p_T < 40$ GeV
- Yield extracted with a 2D (decay time,mass) likelihood fit.



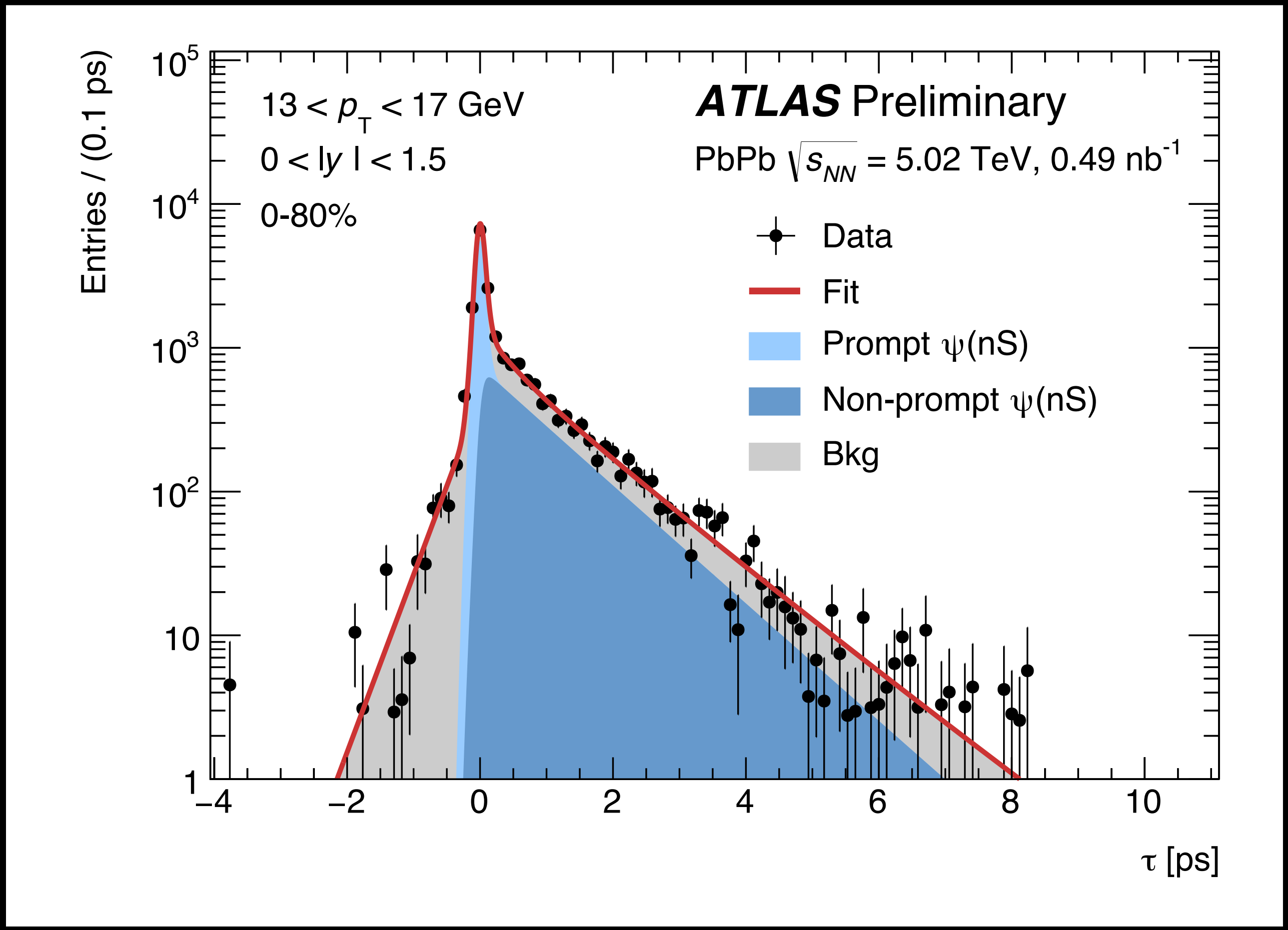
- Phys. Rev. C 92, 034904 (2015), 2013 p+Pb @ 5.02 TeV
- ATLAS-CONF-2015-023, 2013 p+Pb @ 5.02 TeV and p+p @ 2.76 TeV
- ATLAS-CONF-2016-109, 2015 Pb+Pb @ 5.02 TeV and p+p @ 5.02 TeV

Simultaneous Fit Method

Fit projections



Prompt:
produced in the direct collision
Non-prompt:
Decays from B-hadron



Pseudo-proper decay time

$$\tau = \frac{L_{xy} m_{\mu\mu}}{p_T^{\mu\mu}}$$

L_{XY} = projection of decay length on the transverse plane

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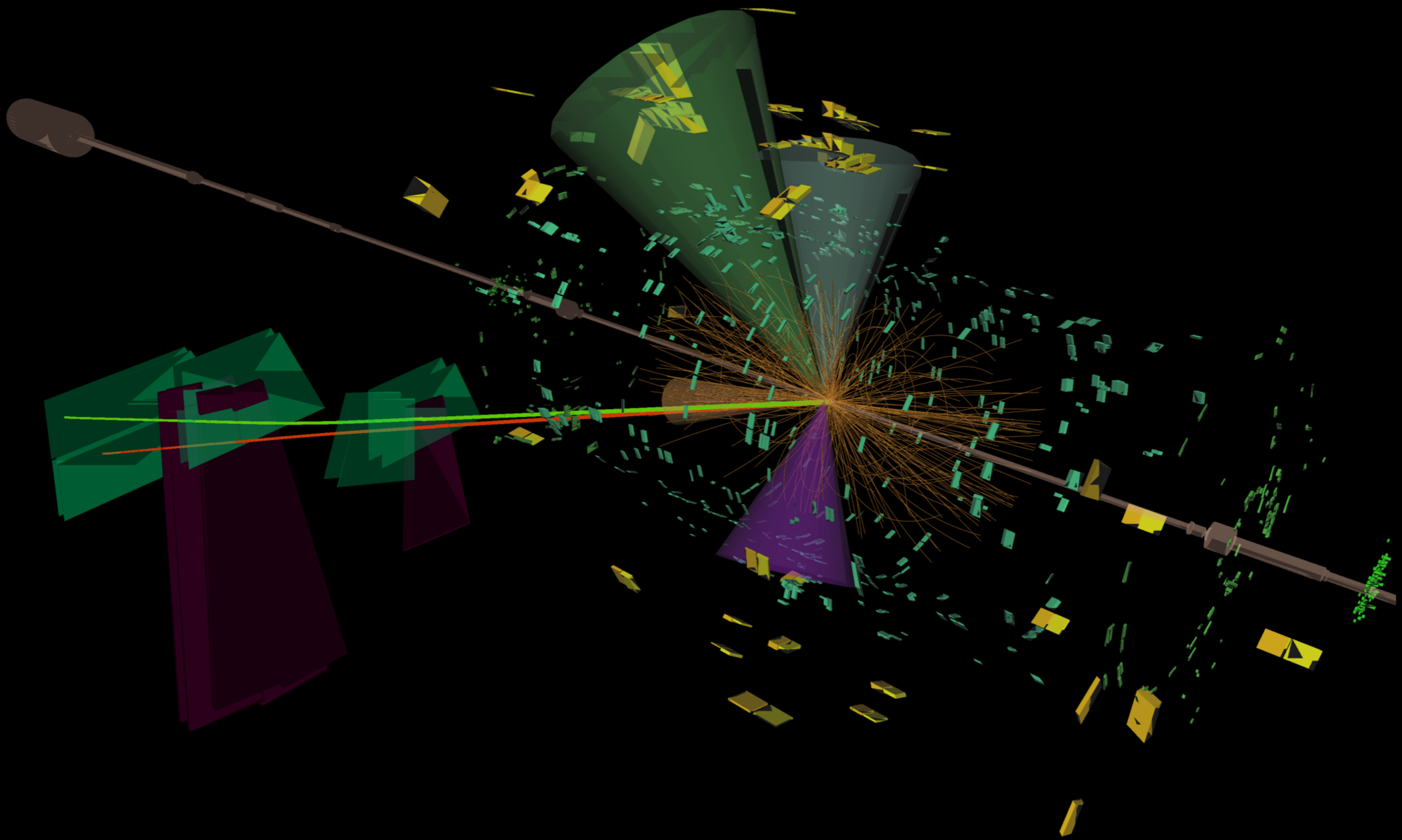
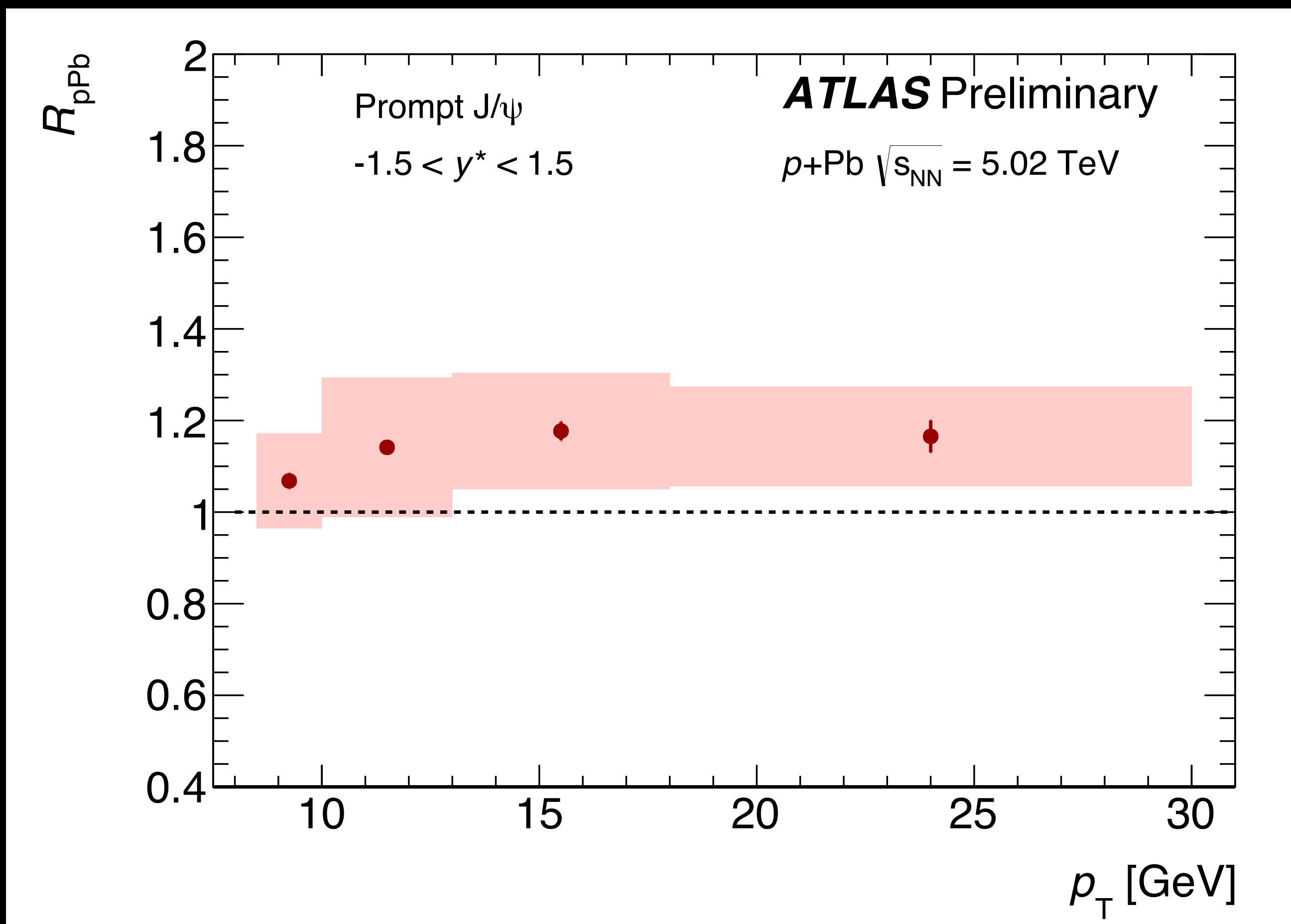
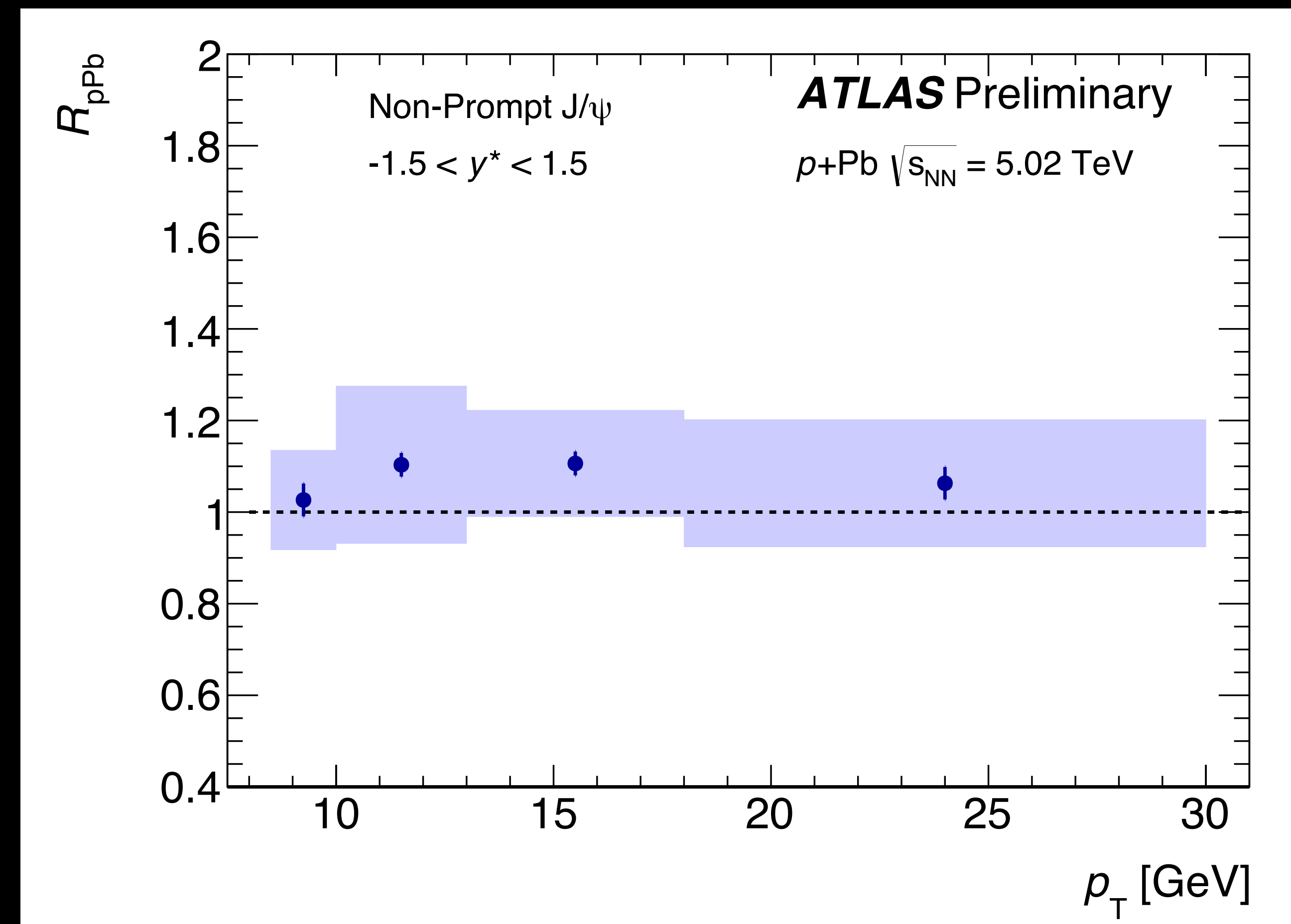
Charmonia in p+Pb collisions



R_{pPb} vs. p_T

$$R_{\mathrm{pPb}} = \frac{\sigma_{pPb}}{A * \sigma_{pp}}$$





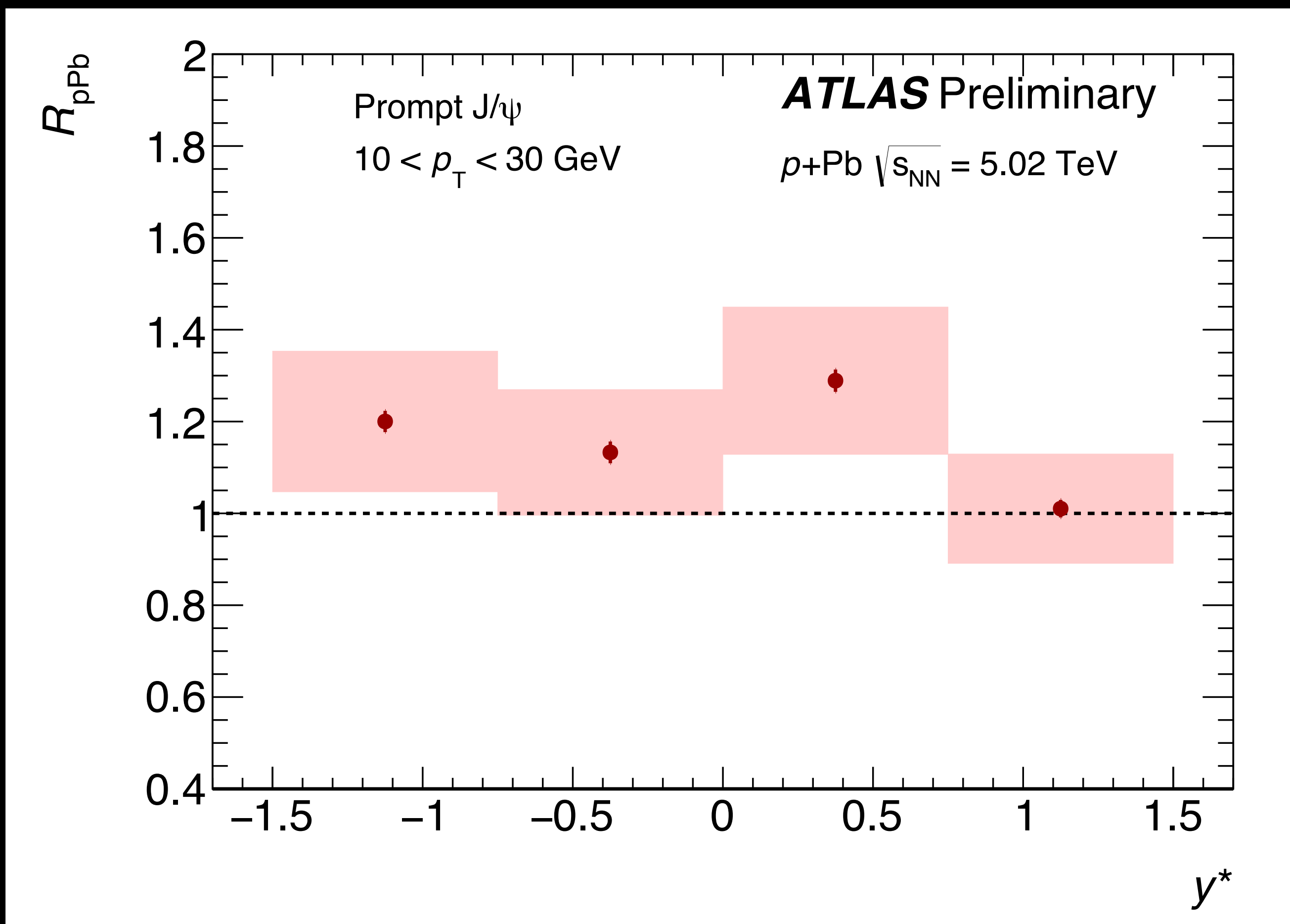
No strong modification of prompt and non-prompt production

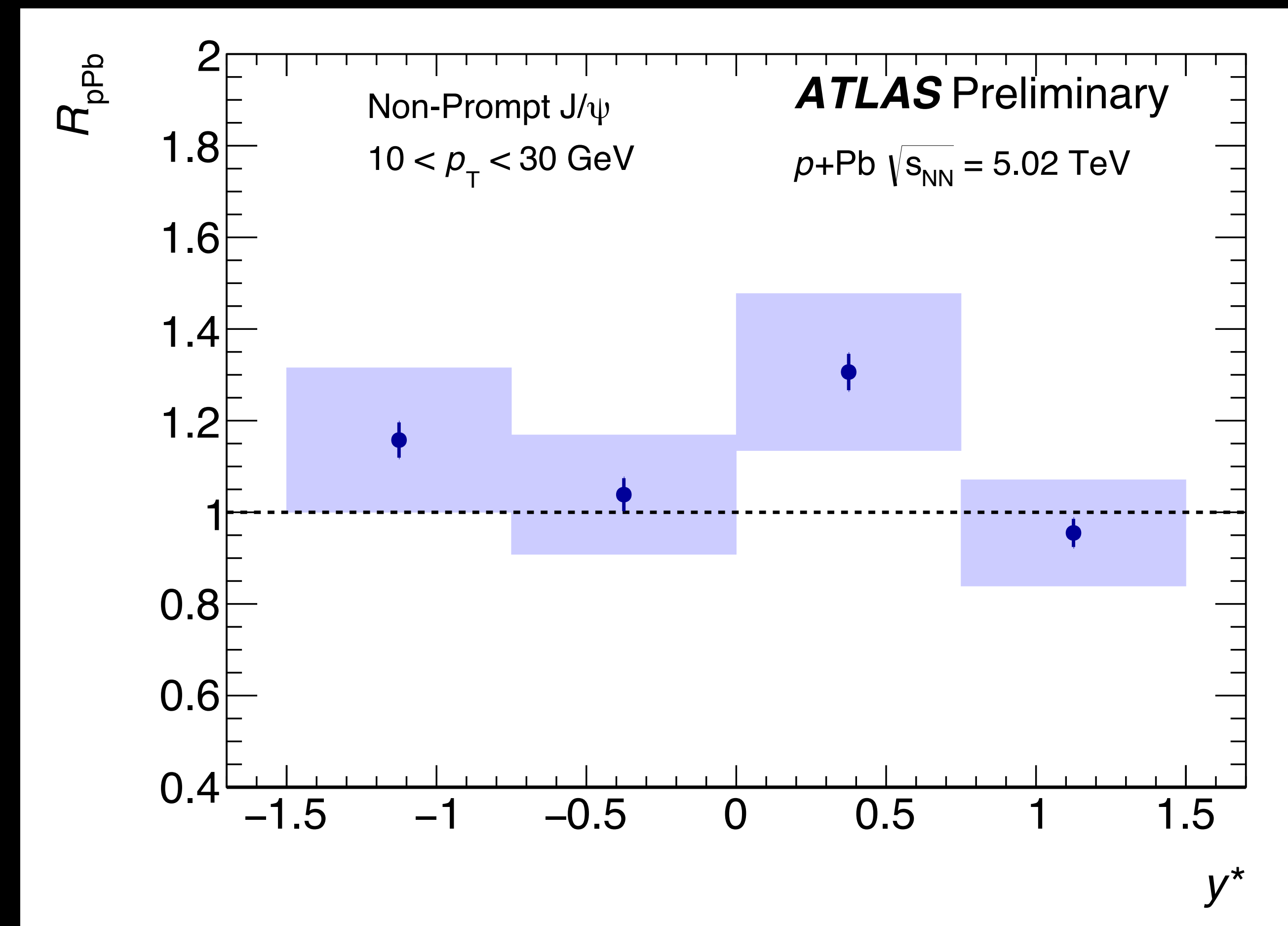
pp reference is interpolated from 2.76 TeV, 7 TeV and 8 TeV

ATLAS-CONF-2015-023

R_{pPb} vs. y*

$$R_{\mathrm{pPb}} = \frac{\sigma_{pPb}}{A * \sigma_{pp}}$$





Prompt and non-prompt nuclear modification factor consistent with unity, no clear evidence of nPDF effects

pp reference is interpolated from 2.76 TeV, 7 TeV and 8 TeV

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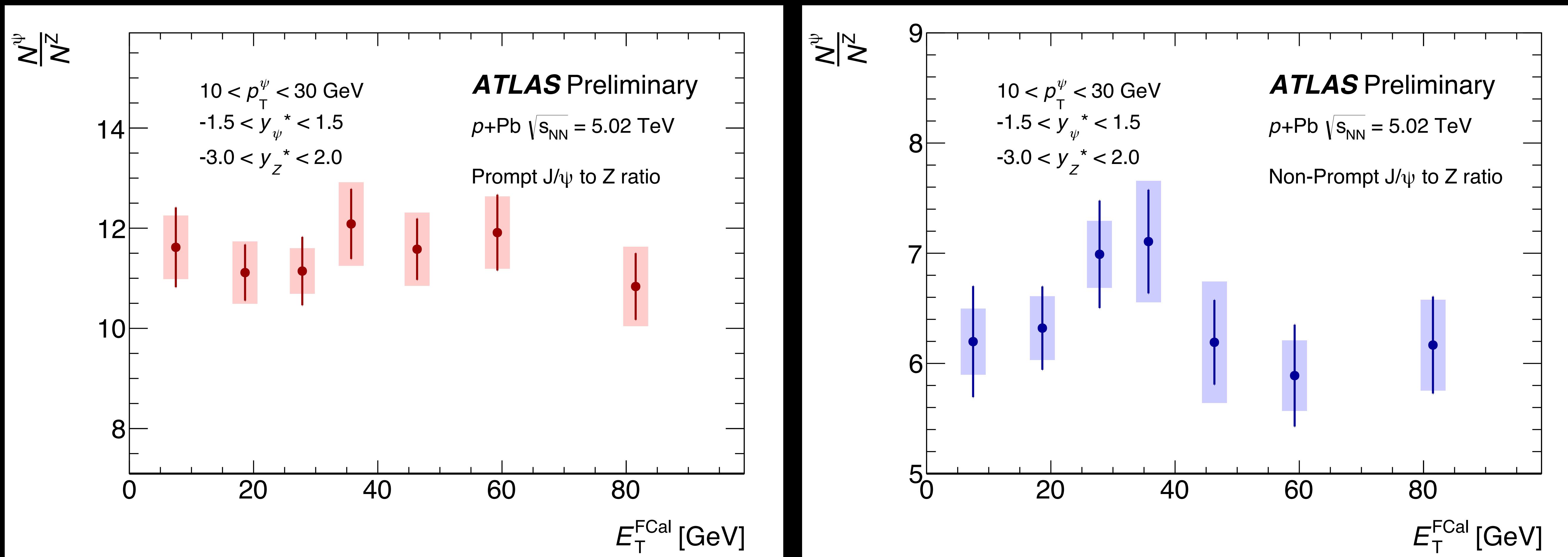
J/ψ to Z ratio

$$N^{J/\psi}/N^{Z}$$



Ratios of J/ψ and Z yields are independent on event activity, they scale with the number of interactions

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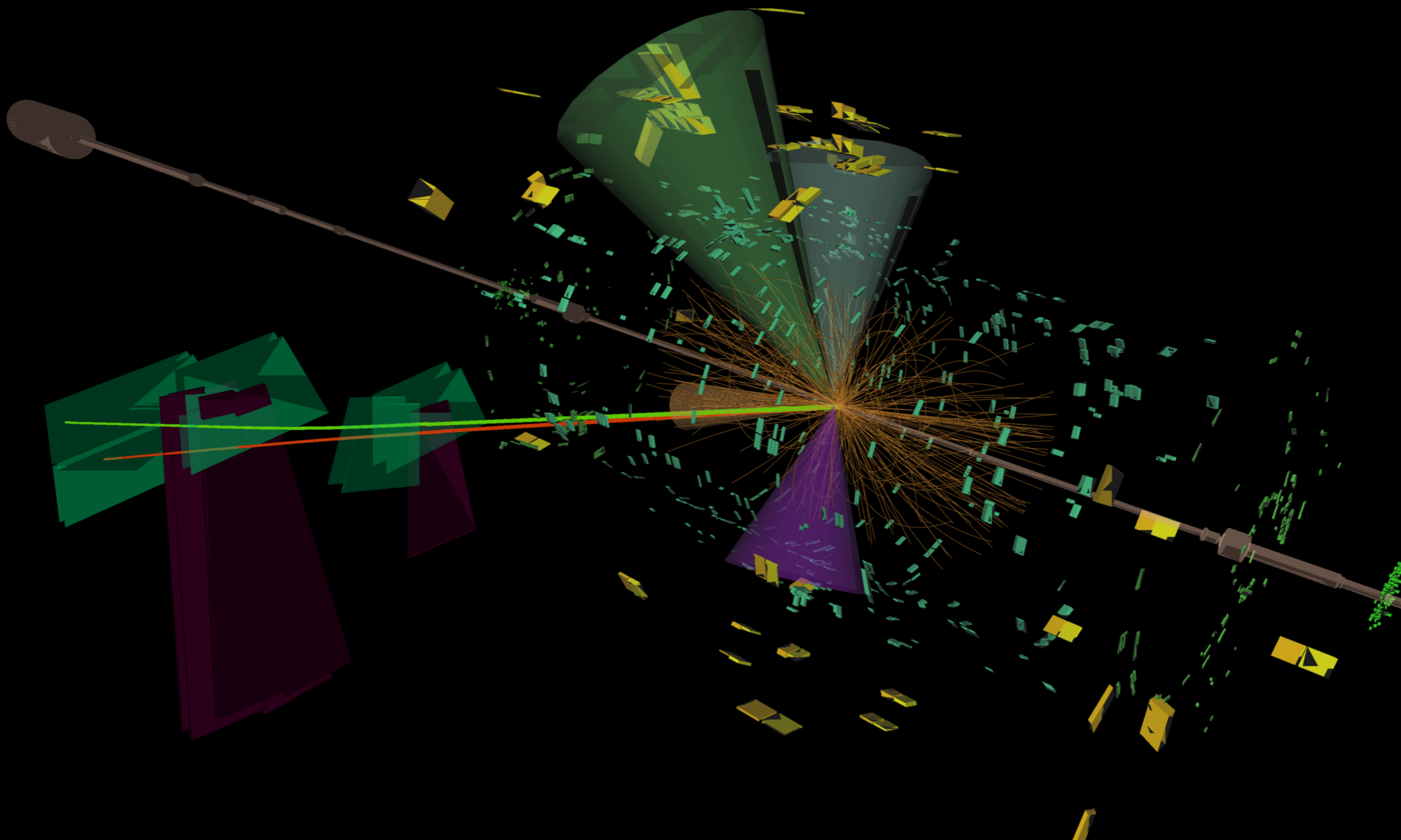
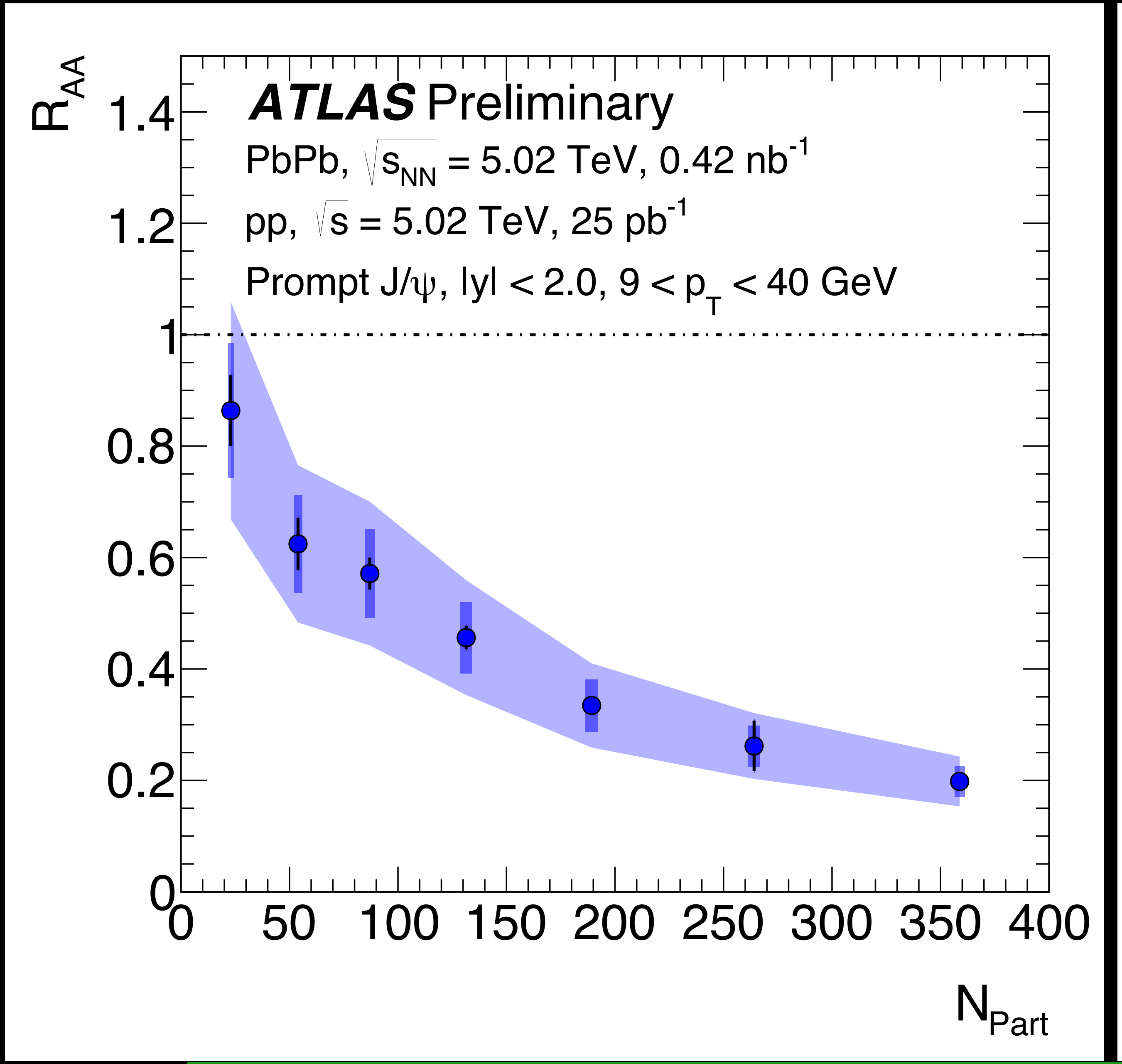
Charmonia in Pb+Pb collisions



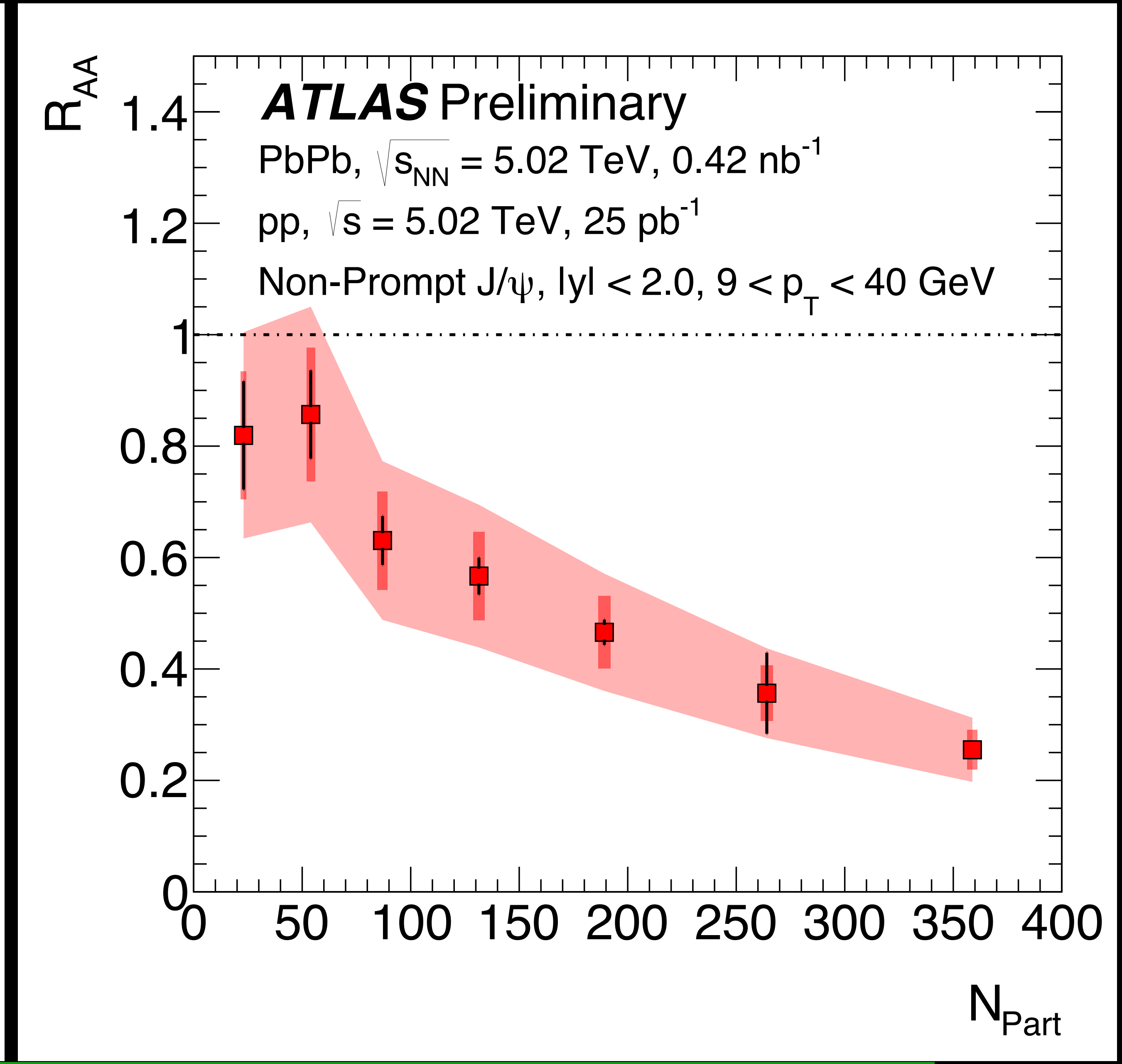
R_{AA} vs. N_{part}

N_{part}: mean number of participants

Prompt



Non-prompt



- J/ψ is strongly suppressed in most central collisions
- Prompt and non-prompt show a similar pattern

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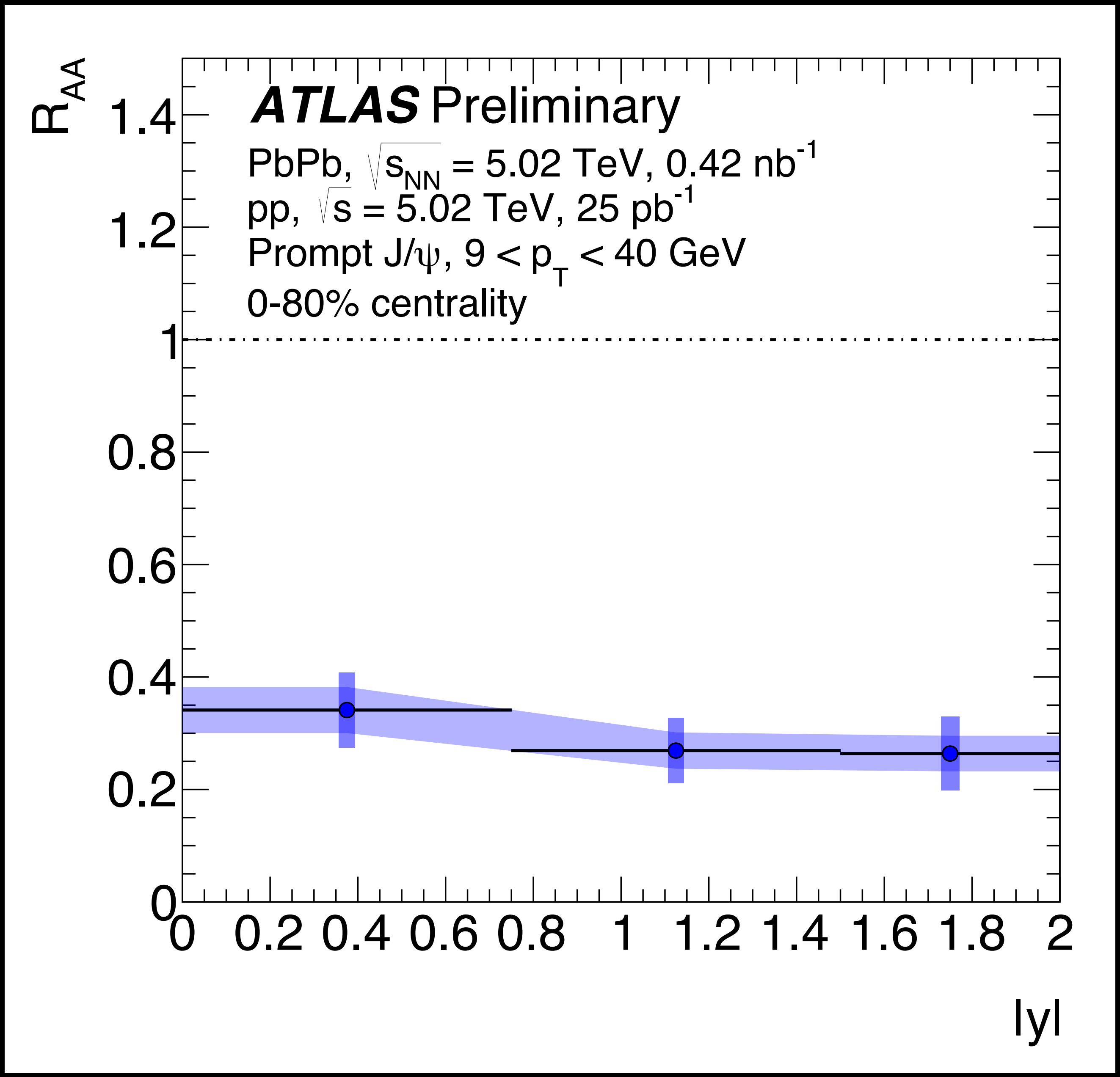
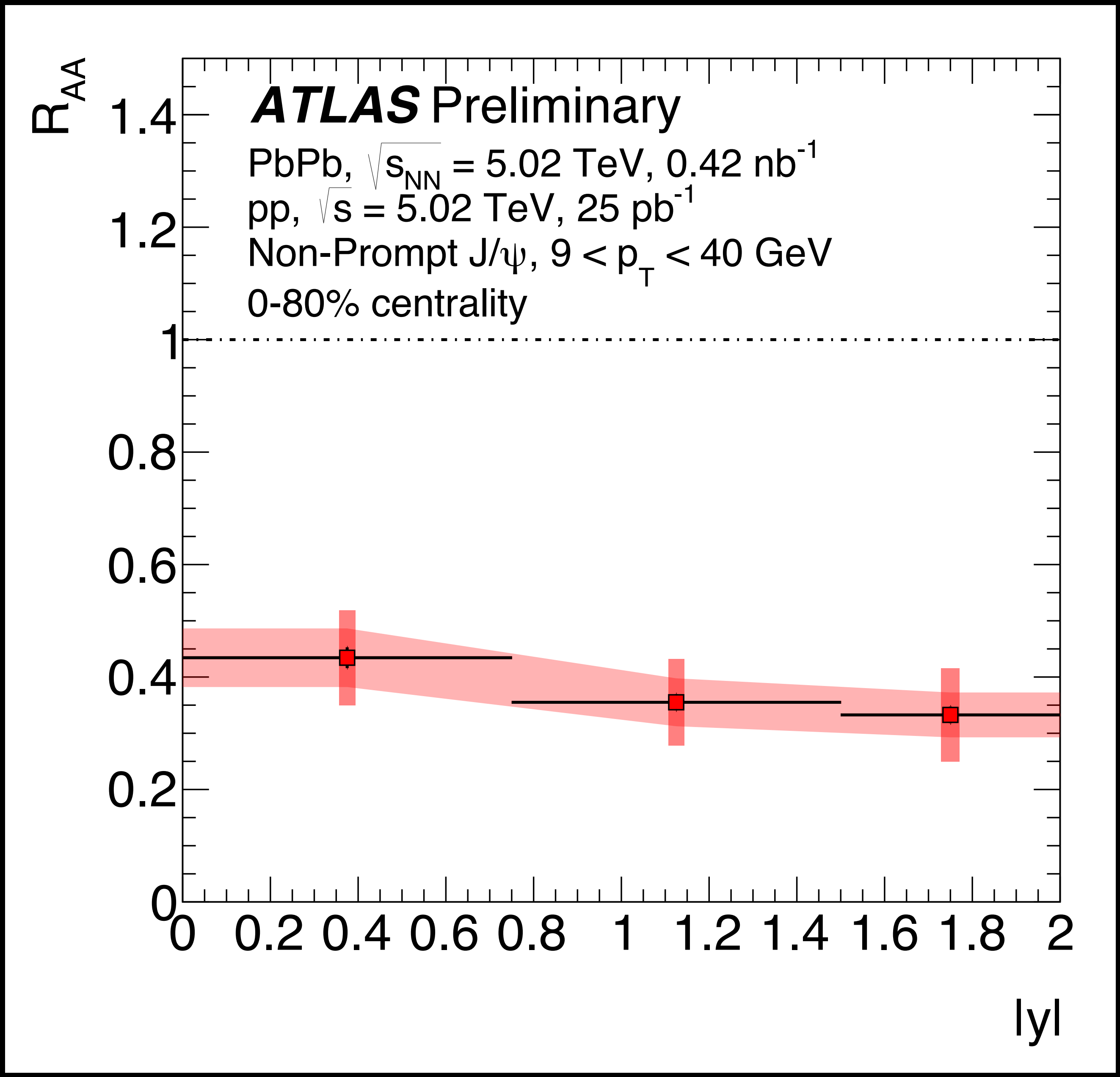
R_{AA} vs. |y|

$$R_{AA} = \frac{N_{AA}}{\langle T_{AA} \rangle \sigma^{pp}}$$

Prompt



Non-prompt



No significant |y| dependence

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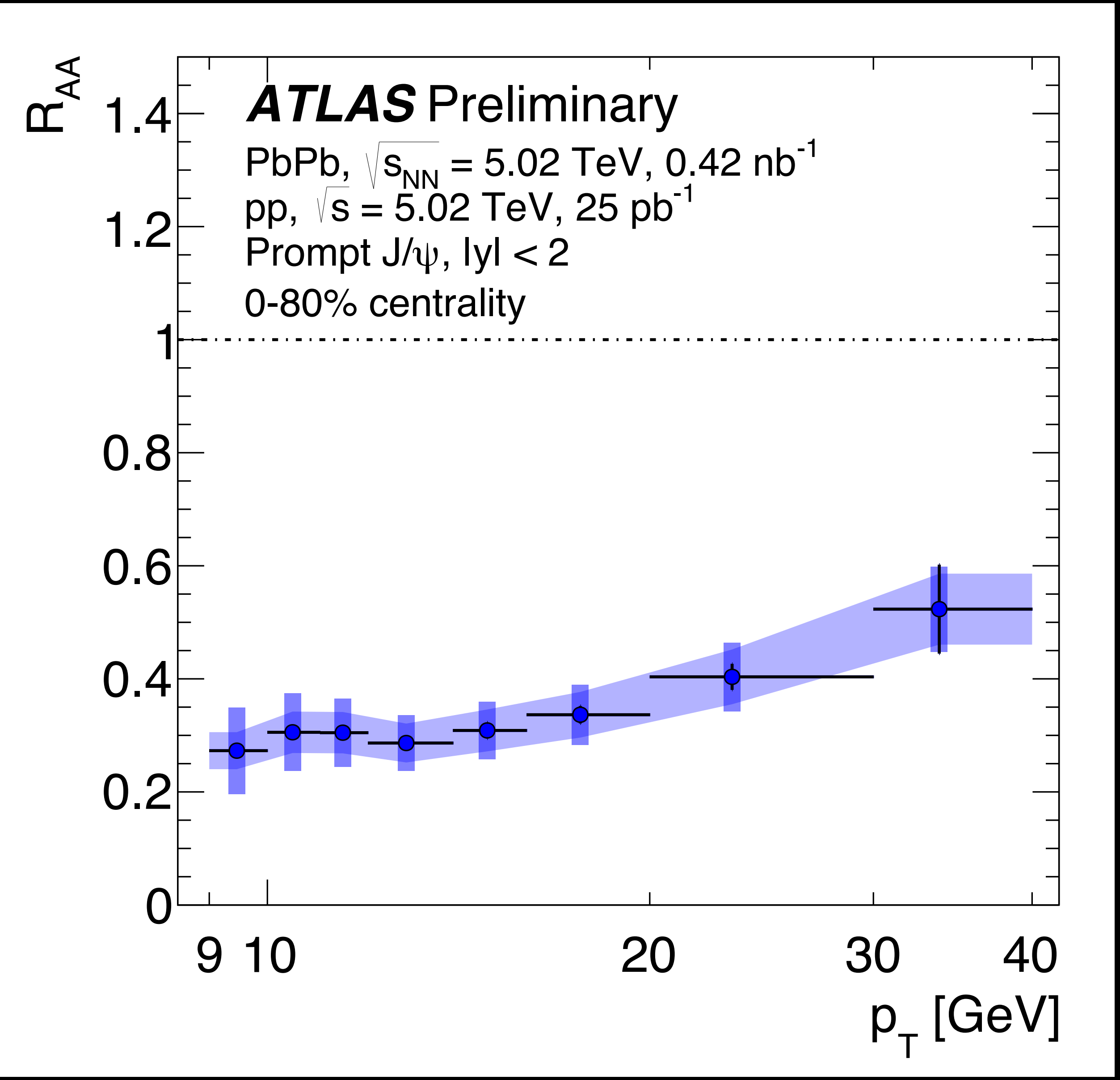
R_{AA} vs. p_T

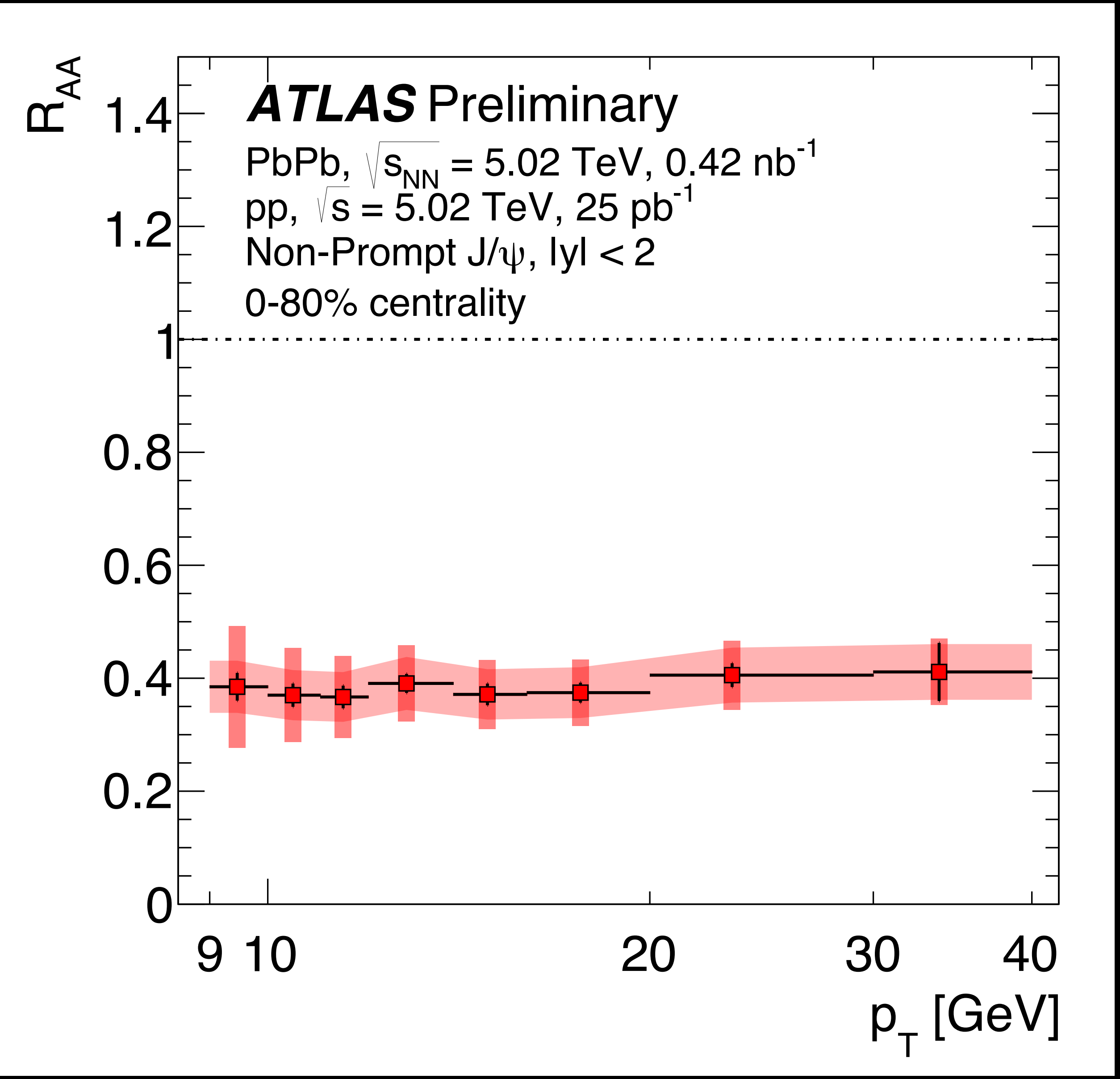
$$R_{AA} = \frac{N_{AA}}{\langle T_{AA} \rangle \sigma^{pp}}$$

Prompt



- R_{AA} increases for p_T > 20 GeV
- Related to energy loss effects, rather than dissociation?

Non-prompt



Flat in the measured p_T range

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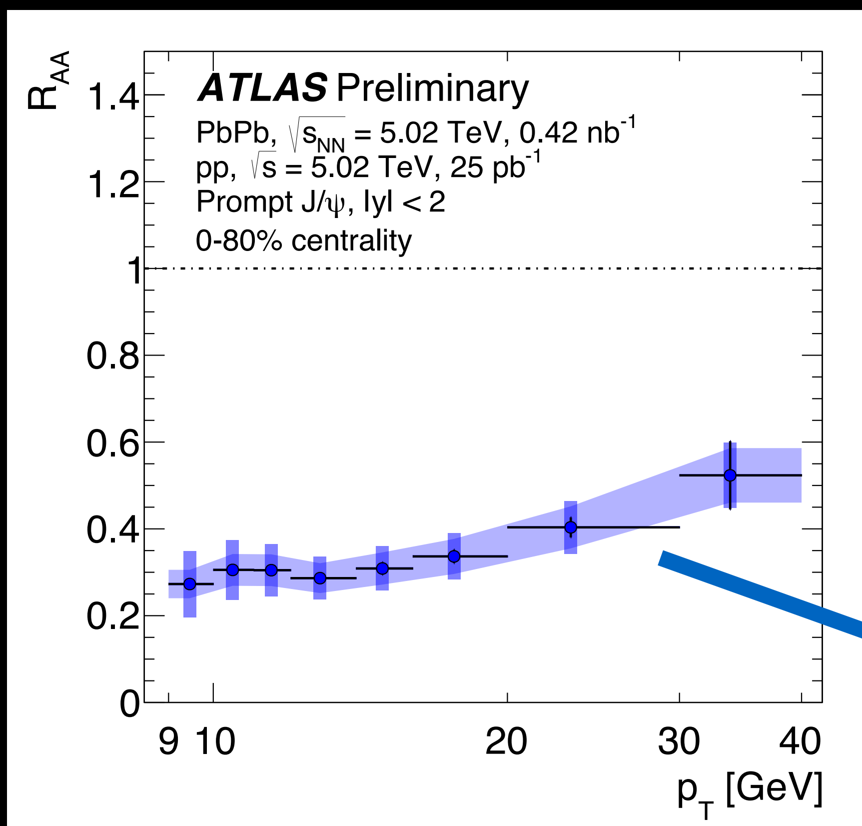
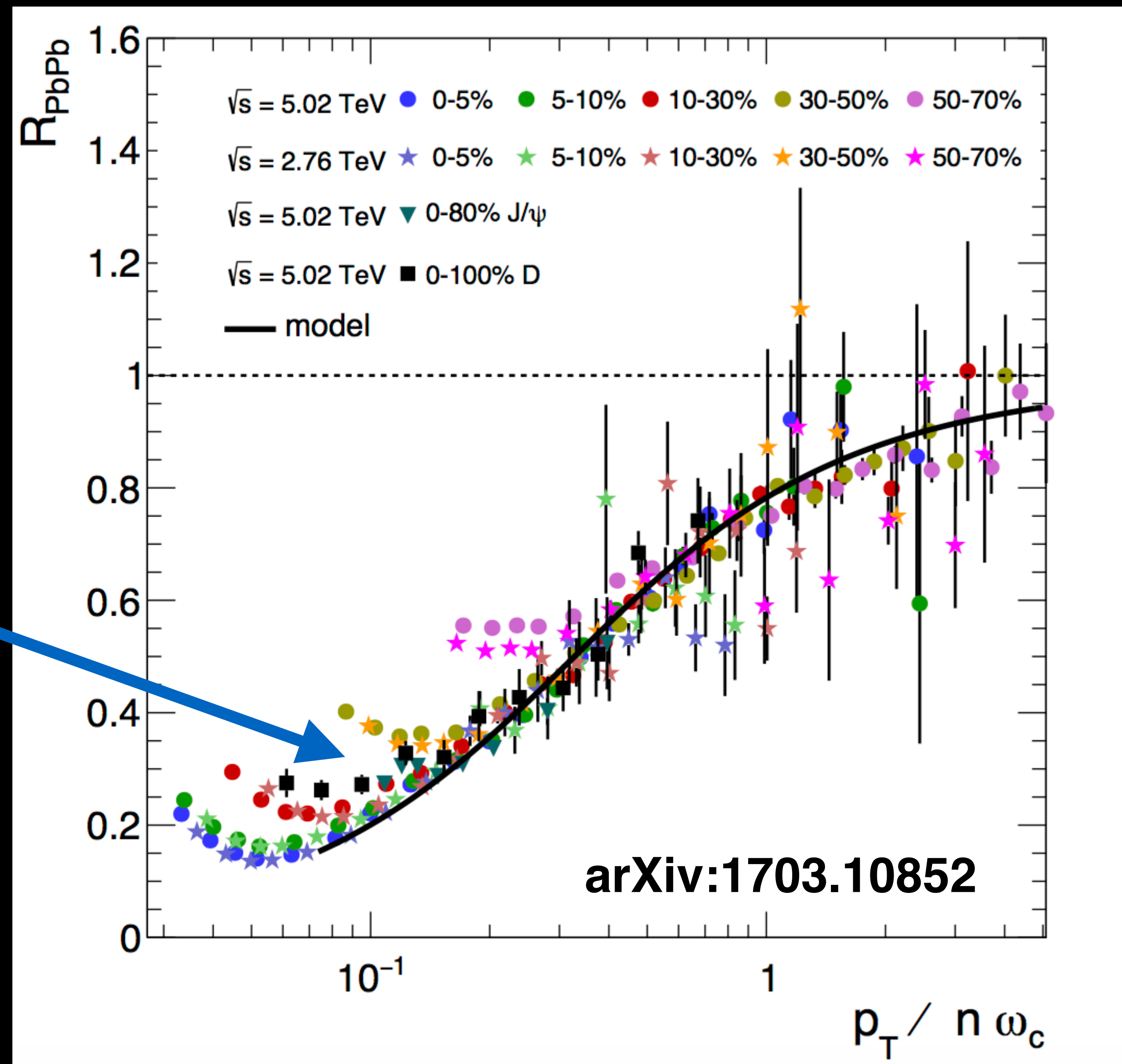
R_{AA} theory calculations

Prompt





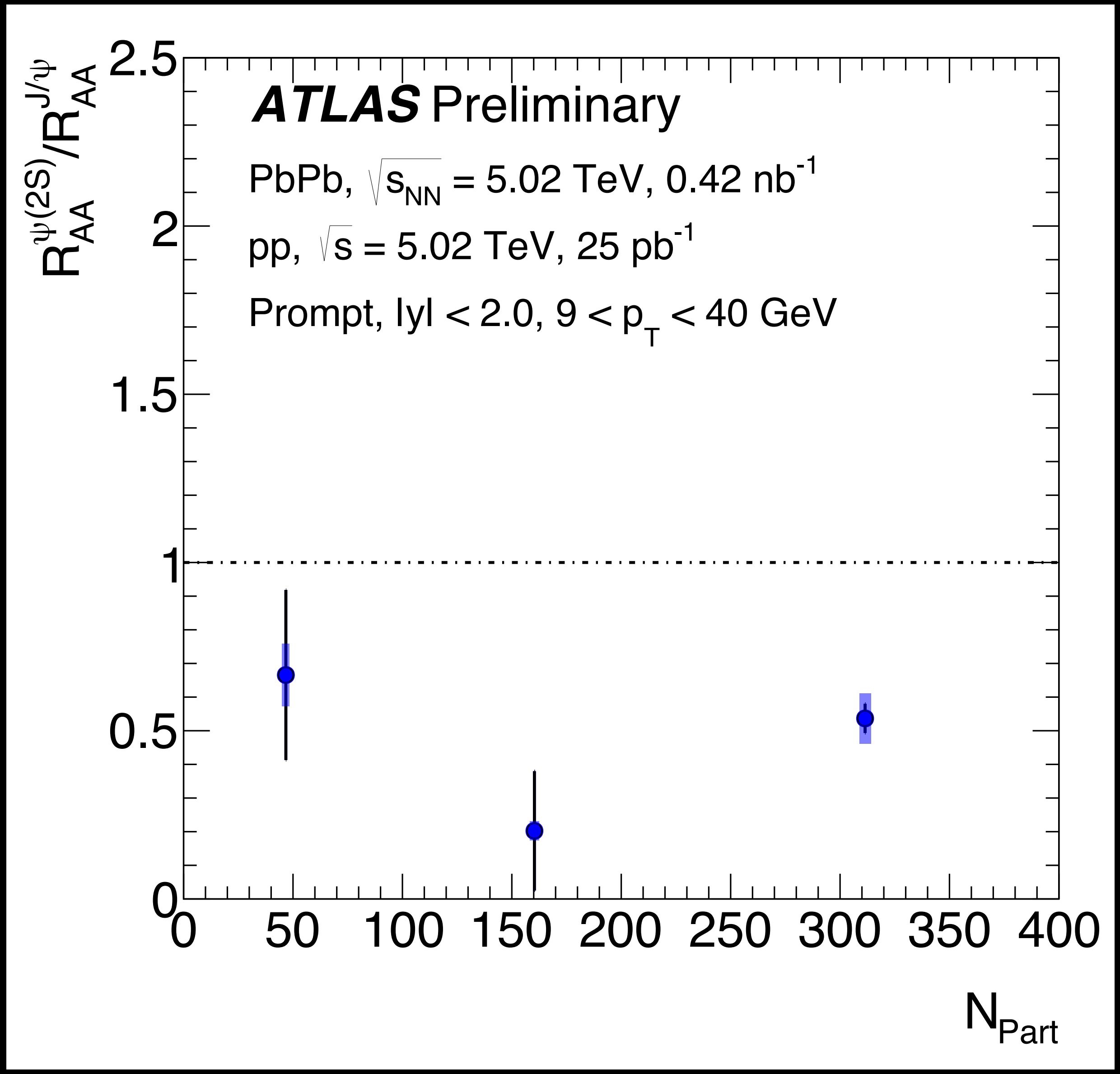
free parameter

$$\omega_c = \frac{1}{2}\hat{q}L^2$$

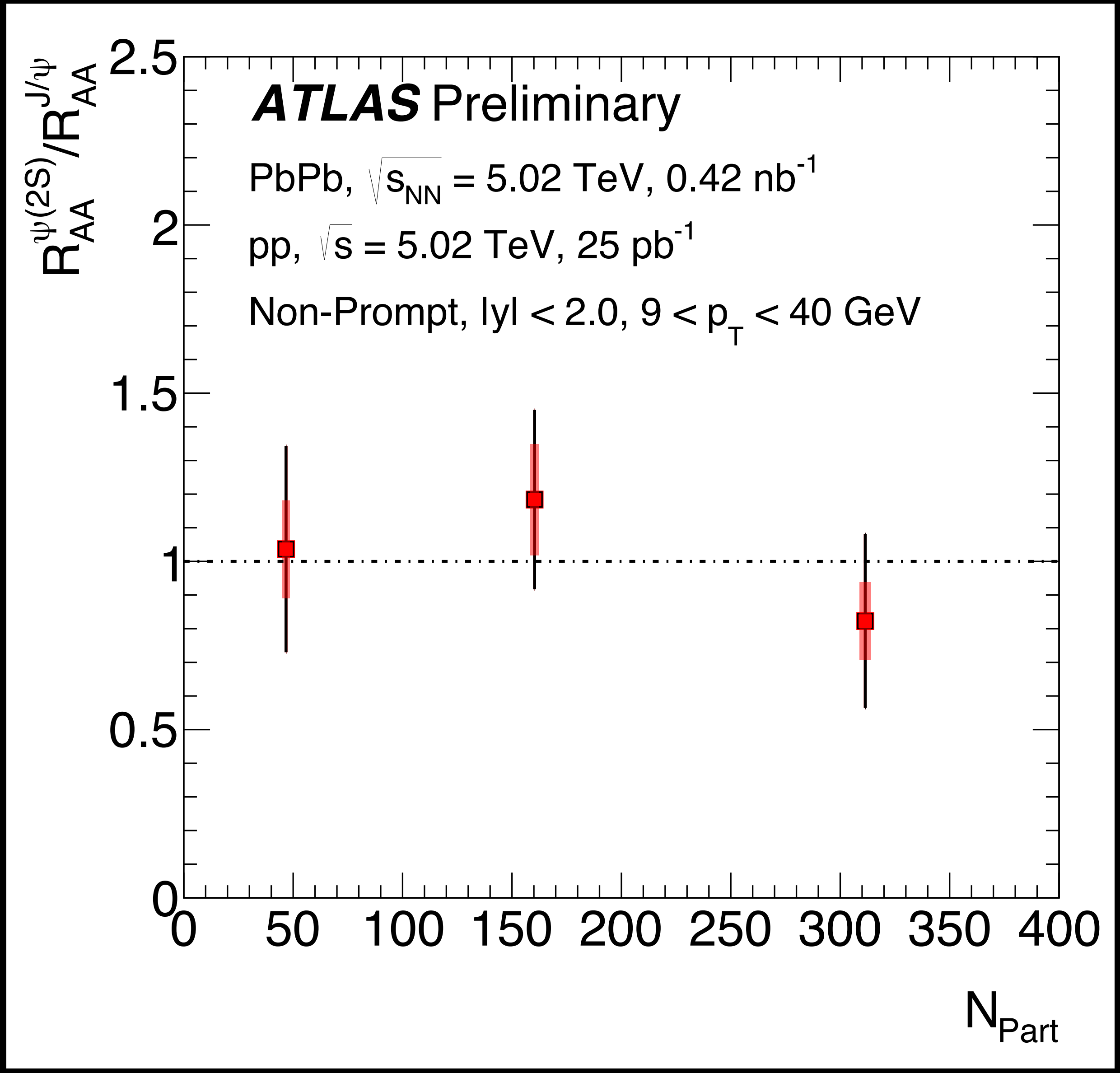
Well described by energy loss model, but still an open question.

$\psi(2S)$ to J/ψ ratio vs N_{part}

Prompt



Non-prompt



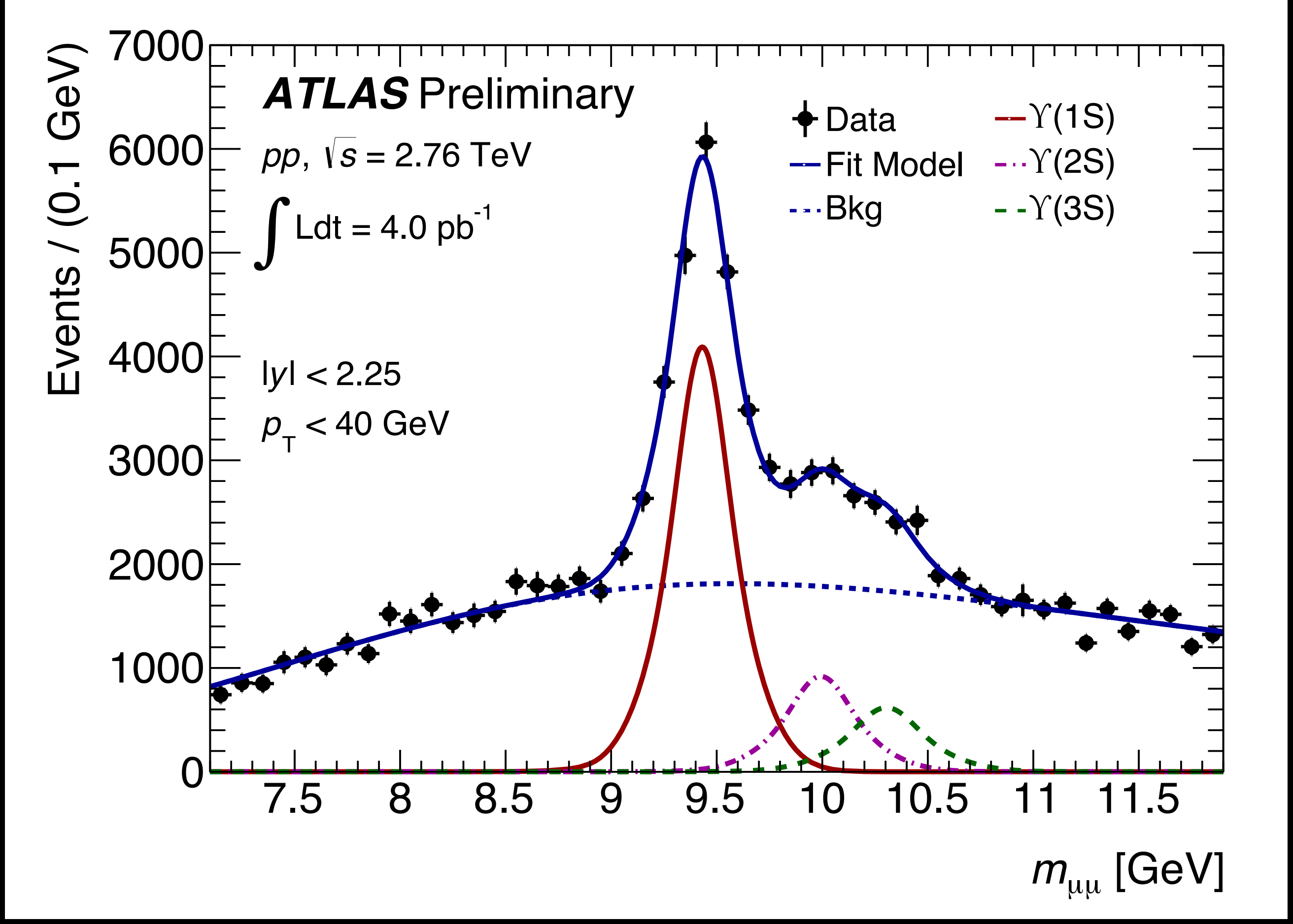
- Stronger suppression of $\psi(2S)$ with respect to the J/ψ
- Consistent with $\psi(2S)$ having a weaker binding than J/ψ but also with E. loss from color octet state.

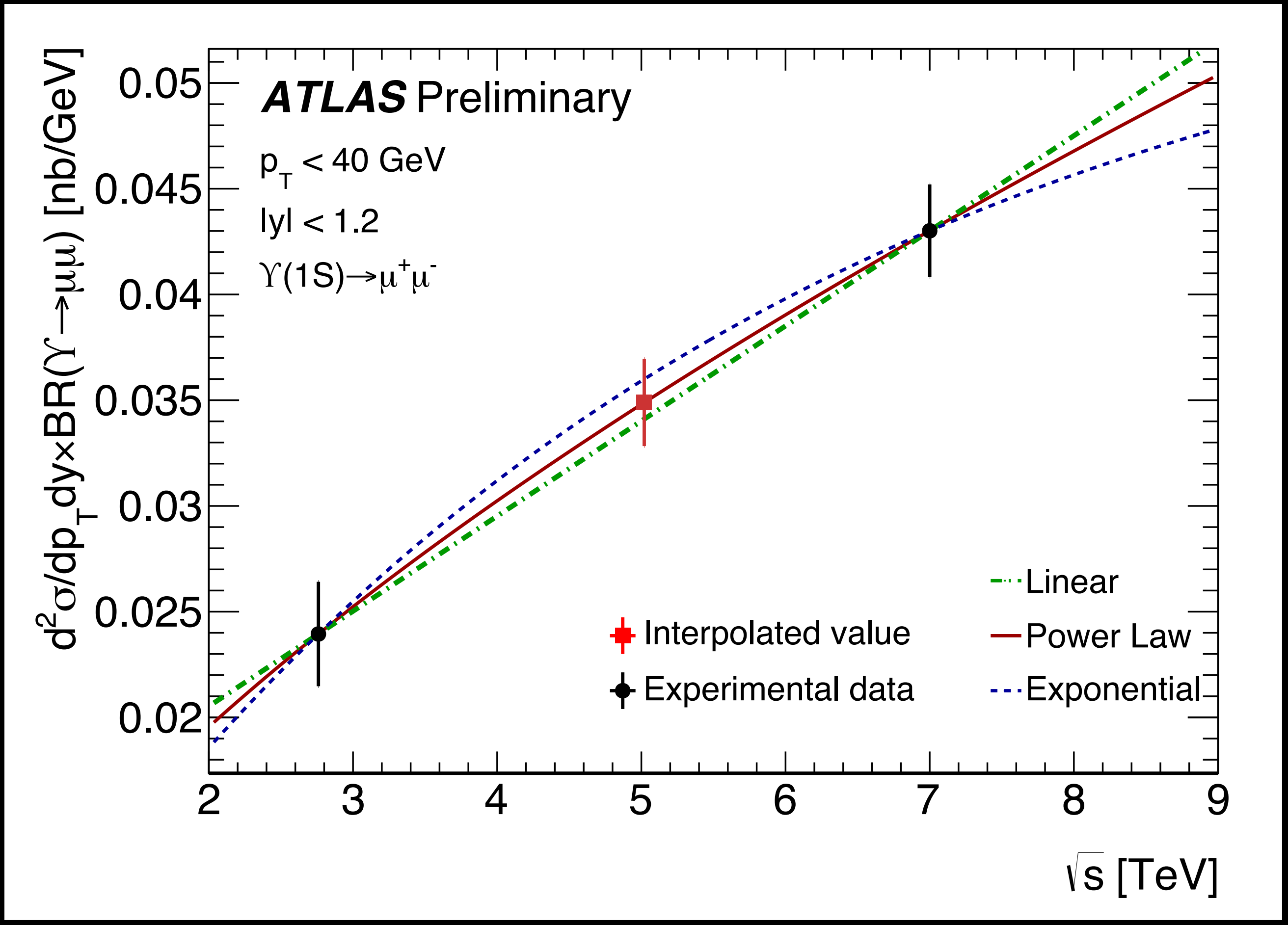
- Consistent with unity and with the picture of the B-hadron decaying outside the hot medium

ATLAS-CONF-2016-109

Upsilon measurement

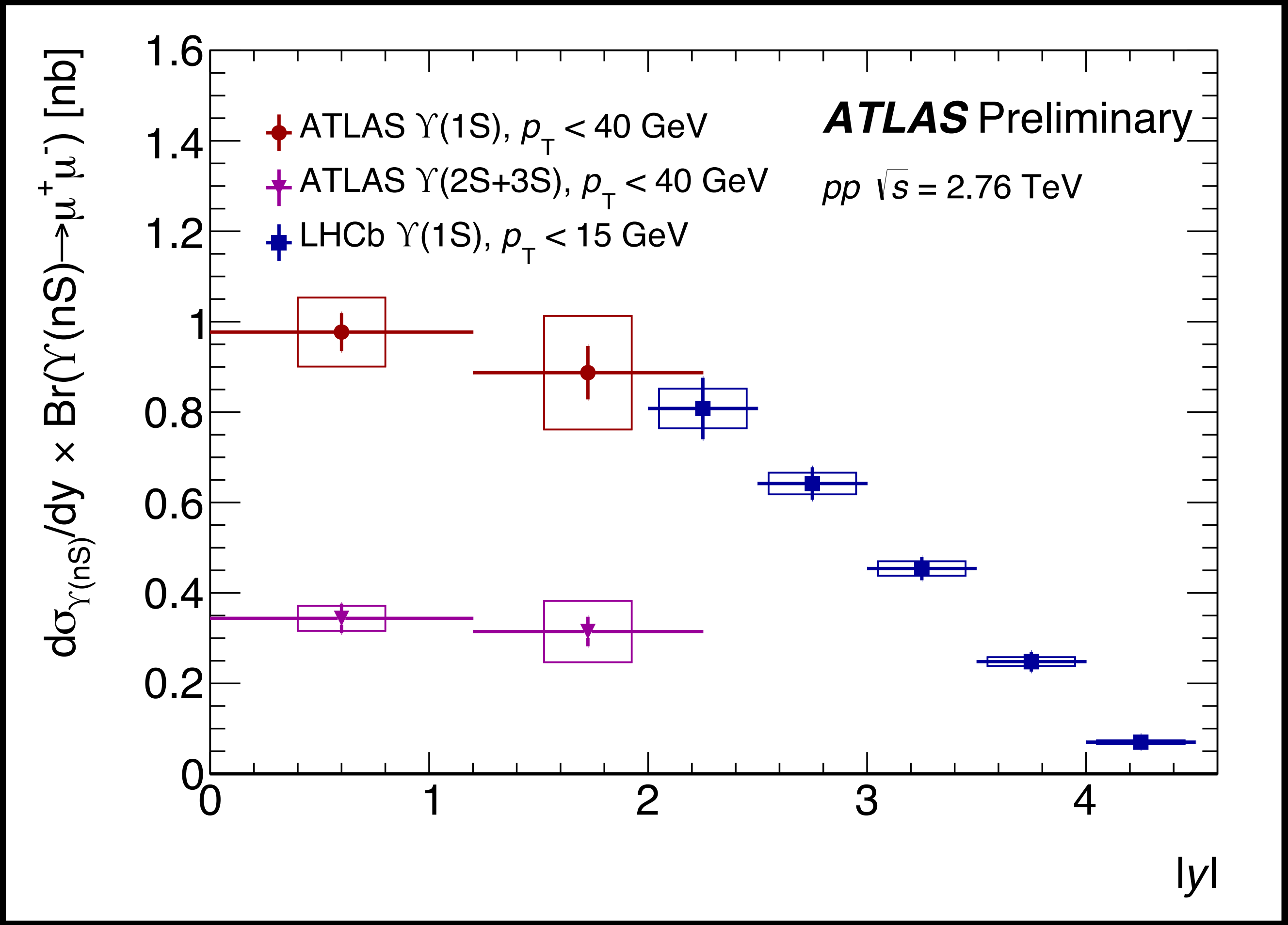
- Di-muon channel, $7.6 < m_{\mu\mu} < 12.$ GeV
- Di-muon trigger
- Kinematic range: $p_T < 40$ GeV and $-2.25 < y^* < 1.2$
- Yield extracted with a binned least squared fit.

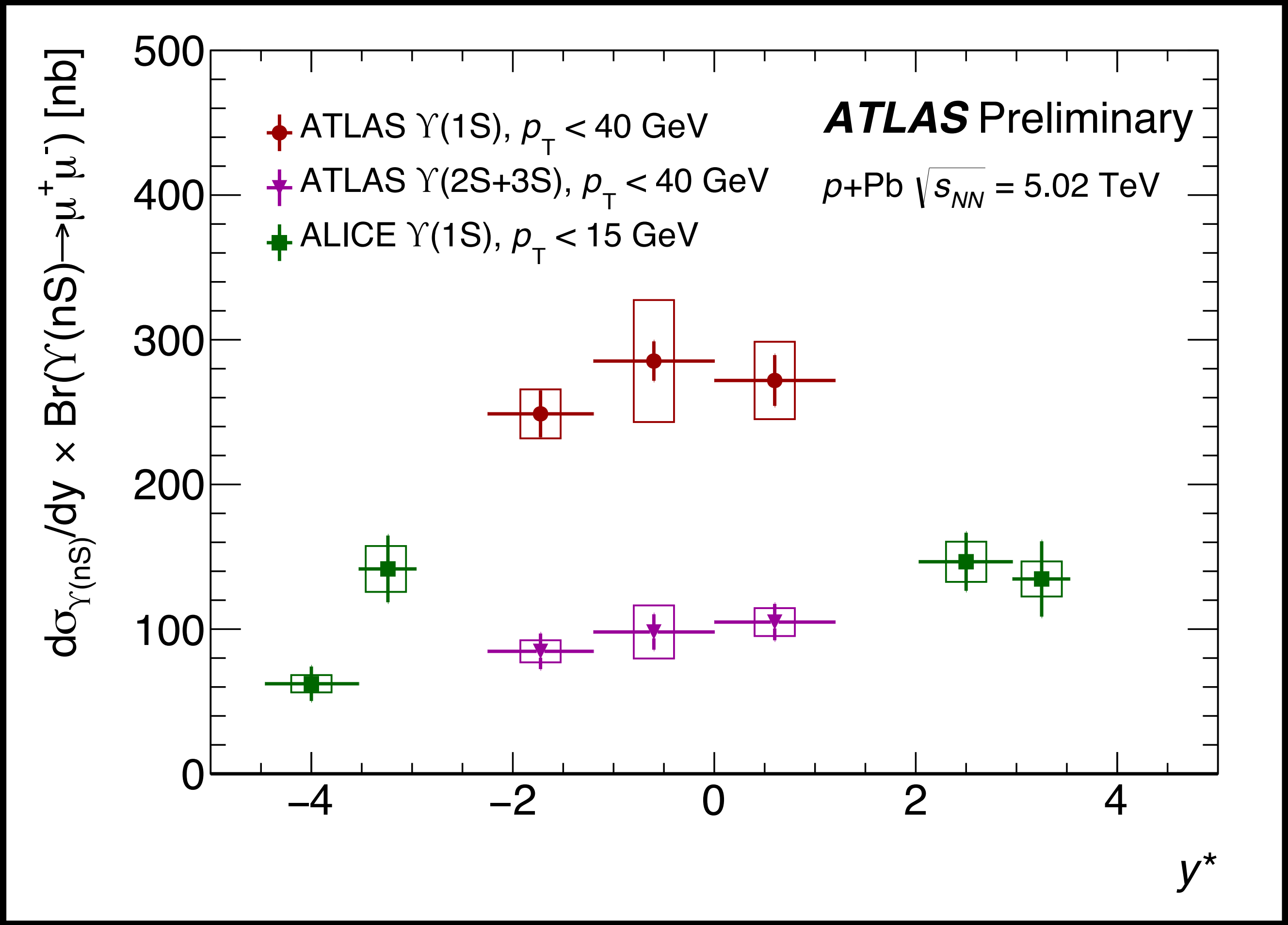




- ATLAS-CONF-2015-050, 2013 p+Pb @ 5.02 TeV and p+p @ 2.76 TeV

Cross section in p+Pb data



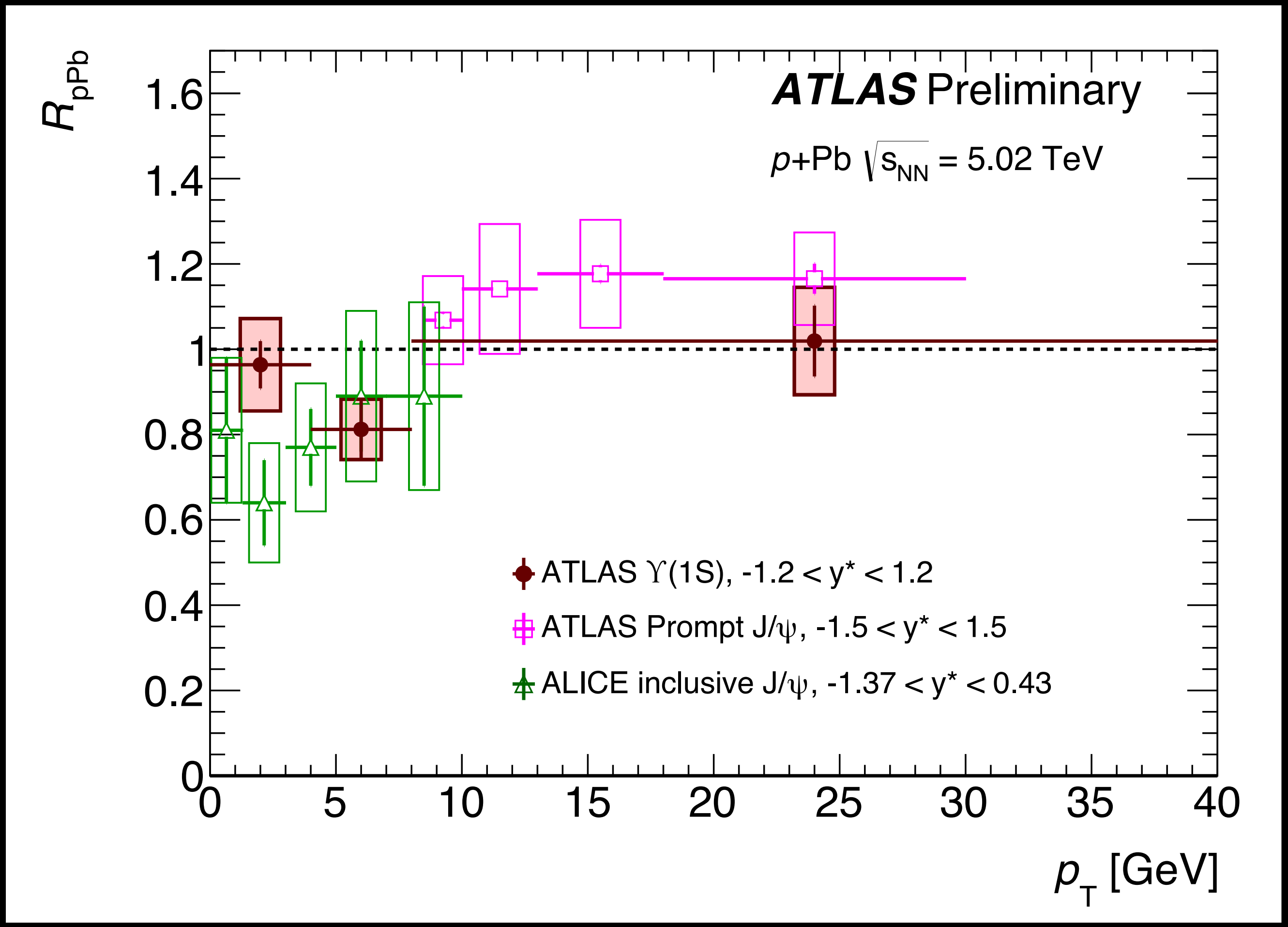


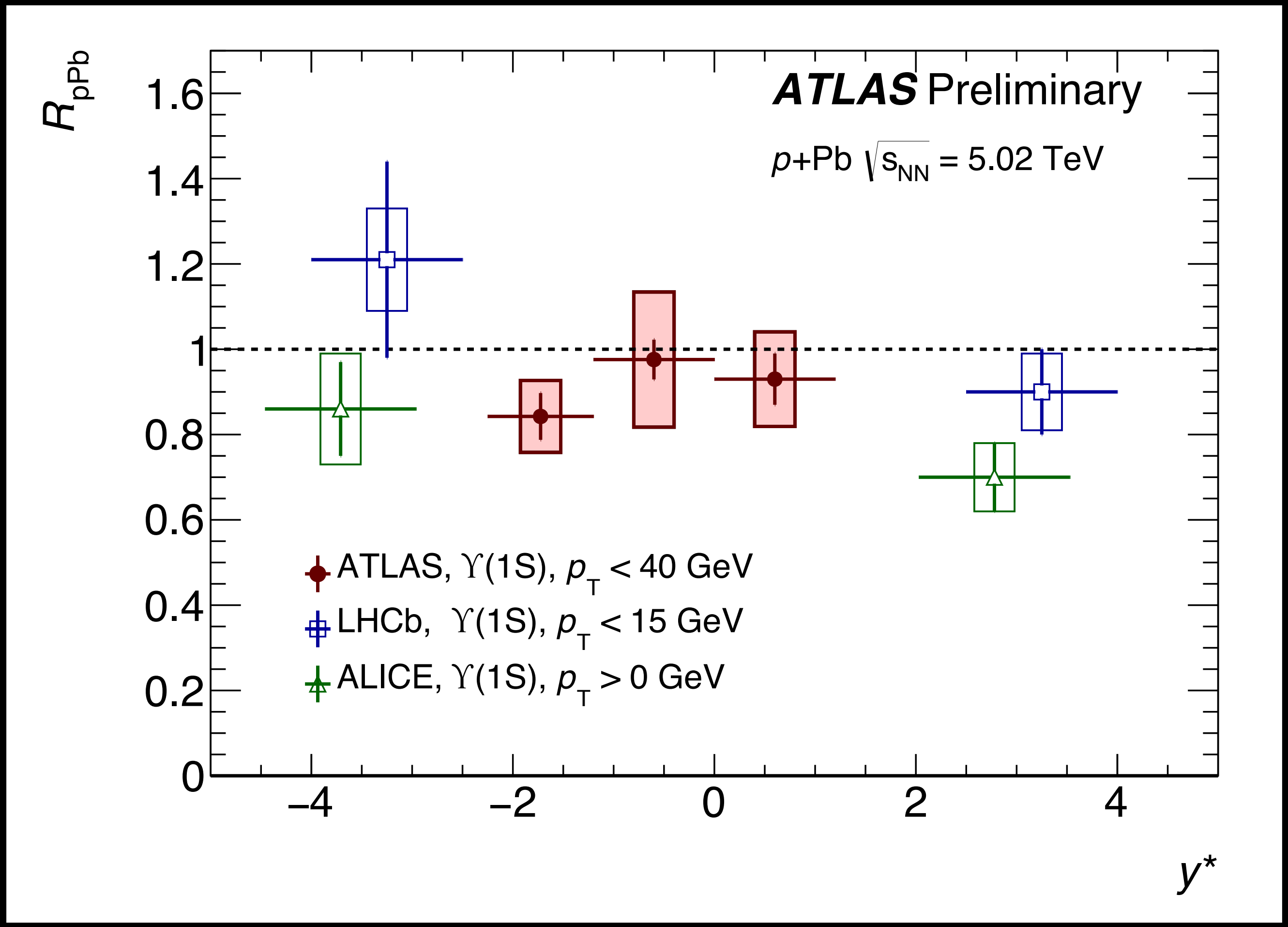
ATLAS results complement the ALICE and LHCb measurement.

ATLAS-CONF-2015-050

R_{pPb} vs. p_T and y*

$$R_{\mathrm{pPb}} = \frac{\sigma_{pPb}}{A * \sigma_{pp}}$$





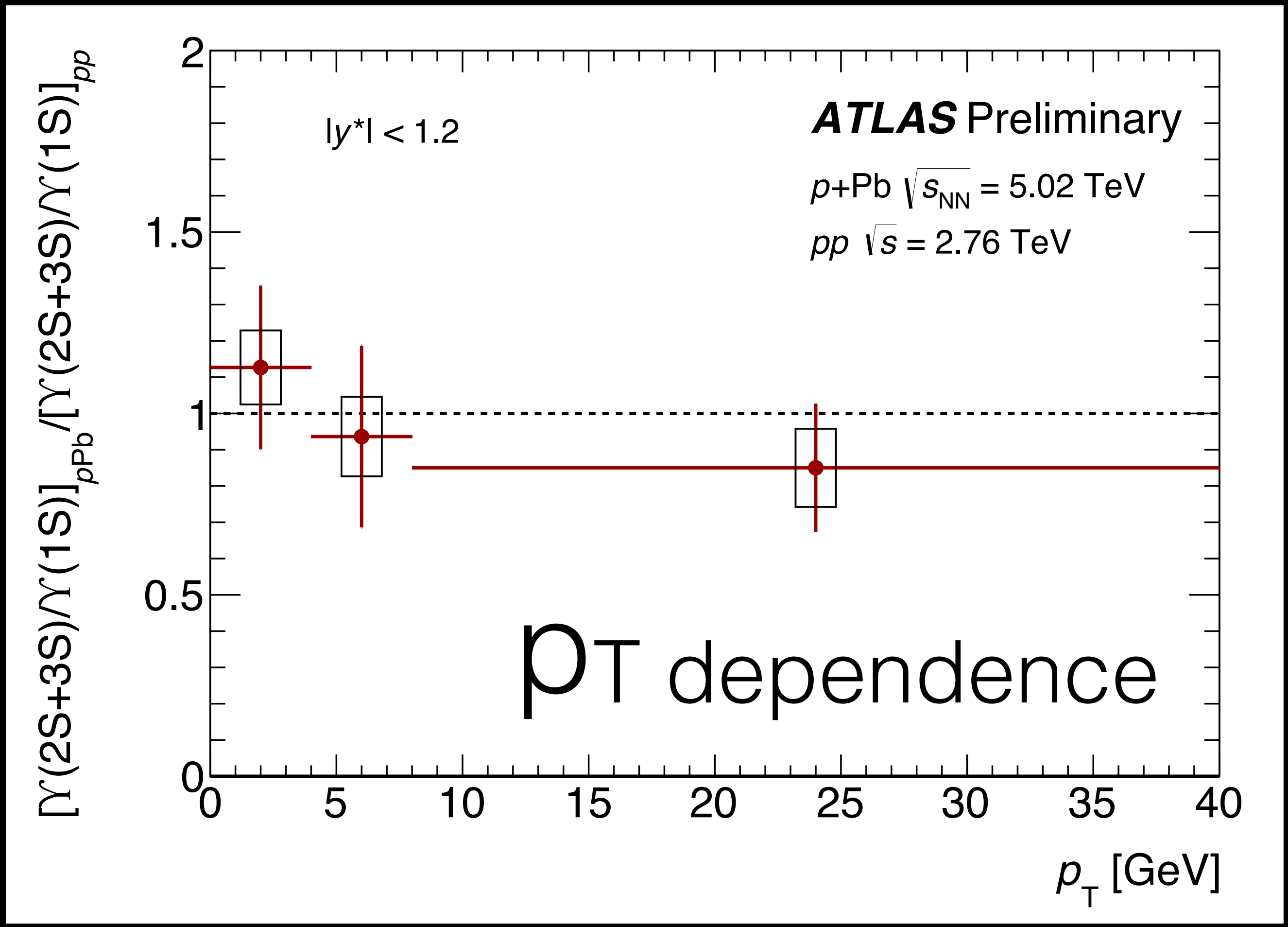
Compatible with results of J/ψ R_{pPb} from ALICE and ATLAS

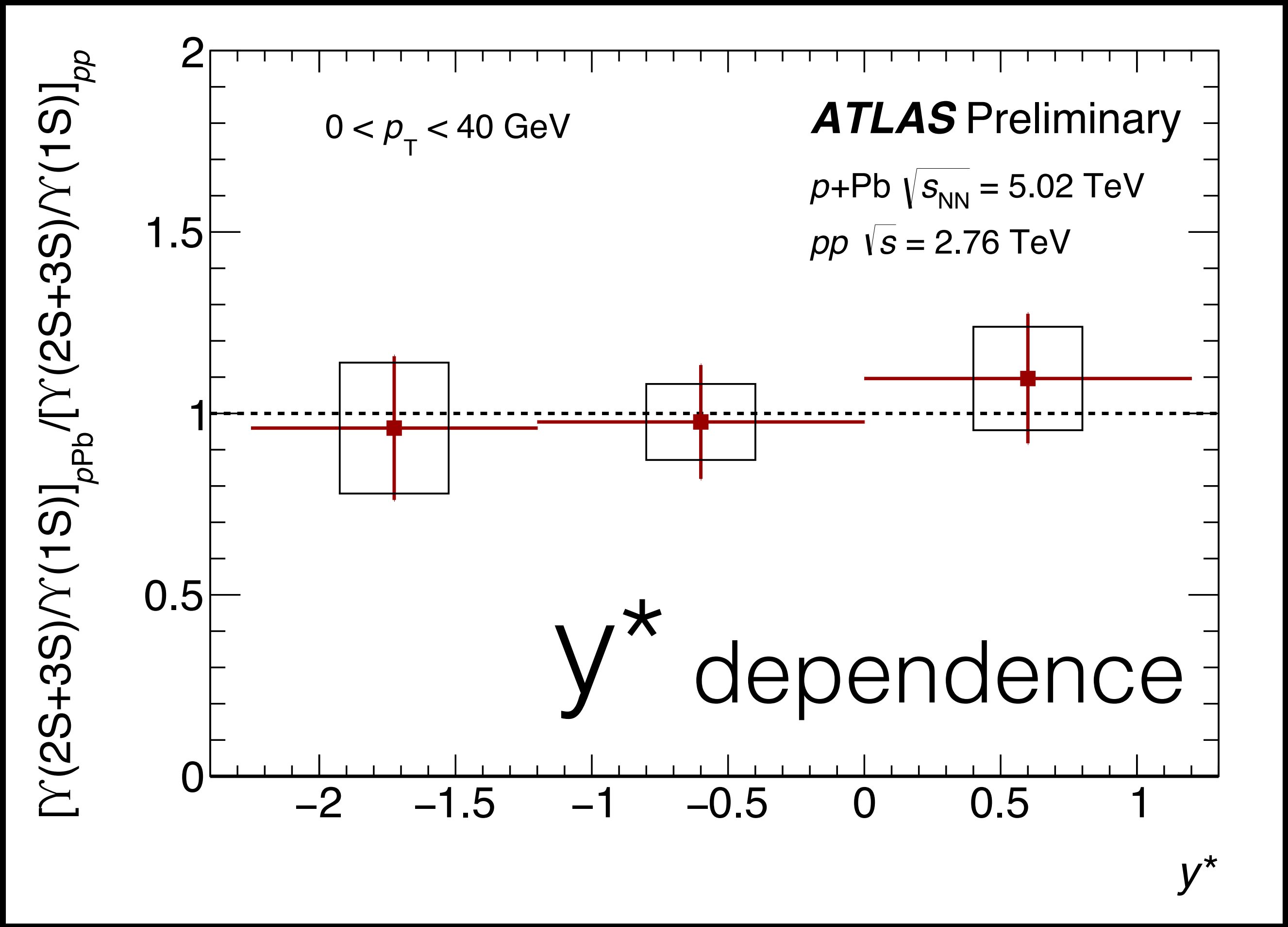
Comparison with Y(1S) results of ALICE and LHCb

pp reference is interpolated from 2.76 TeV, 7 TeV and 8 TeV

ATLAS-CONF-2015-023

Υ(2S+3S) to Υ(1S) ratio vs p_T and y*





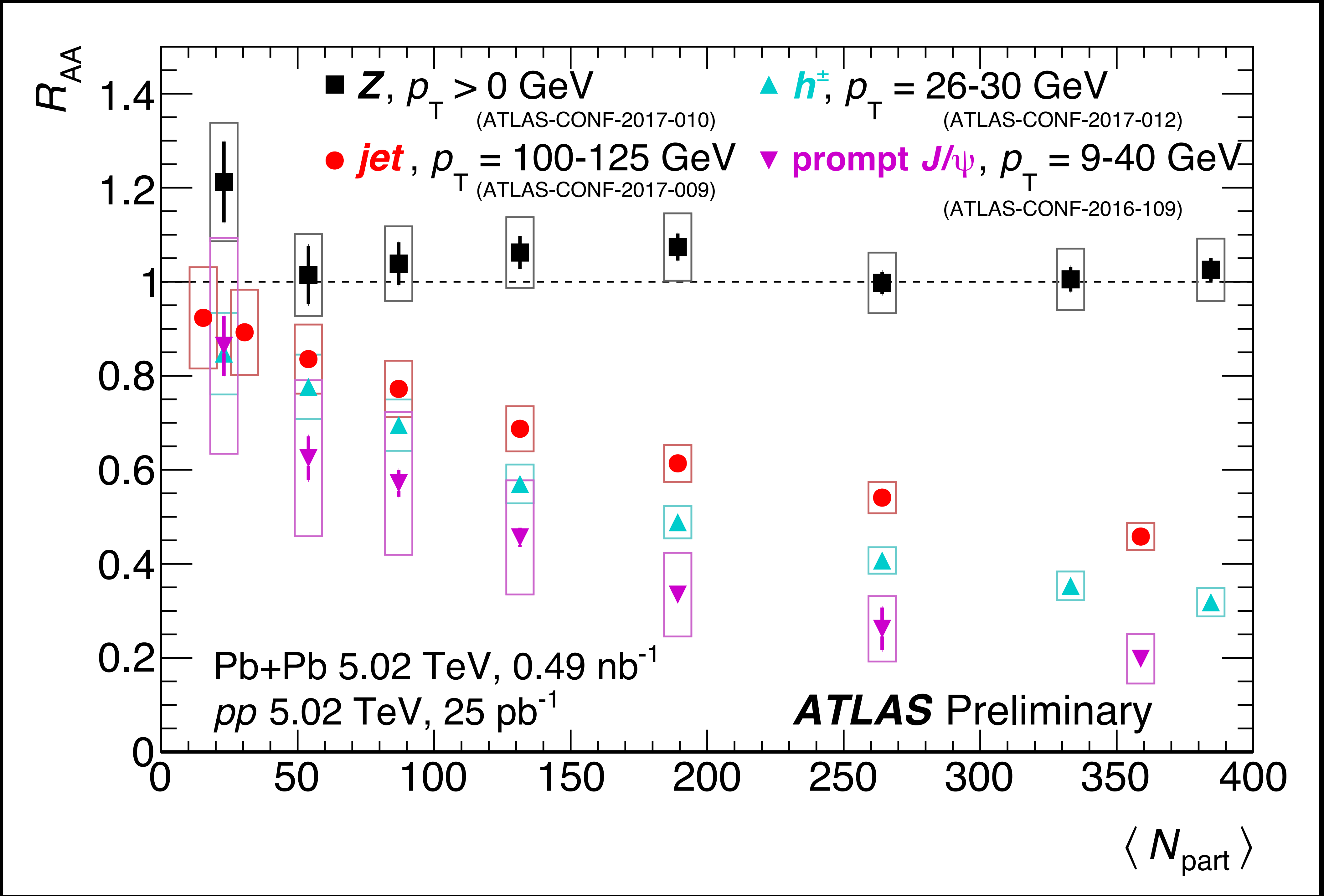
$$\frac{[\Upsilon(2S+3S)/\Upsilon(1S)]_{\mathrm{pPb}}}{[\Upsilon(2S+3S)/\Upsilon(1S)]_{\mathrm{pp}}}$$

No significant difference in production, no suppression in higher states

pp @ 2.76 TeV

ATLAS-CONF-2015-023

RAA of different probes



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

Conclusions

- Results on quarkonia production in p+Pb and Pb+Pb collisions in ATLAS have been presented.
- p+Pb:
    - Charmonia R_{pPb} show no obvious p_T or rapidity dependence.
    - Υ(1S) R_{pPb} compatible with prompt J/ψ
    - No clear evidence of CNM effects
    - Ongoing work on reducing systematic uncertainties while switching to the 5.02 TeV pp reference data, improved results soon!
- Pb+Pb:
    - A strong suppression for J/ψ and ψ(2S) is observed.
    - R_{AA} as a function of p_T shows a different trend for prompt and non-prompt components.
    - Prompt high p_T suppression well describe by E. loss models as well as screening.

Additional Slides

Definition of y*

$$y^* = y_{lab} - 0.465$$

$$y^* = -(y_{lab} + 0.465)$$

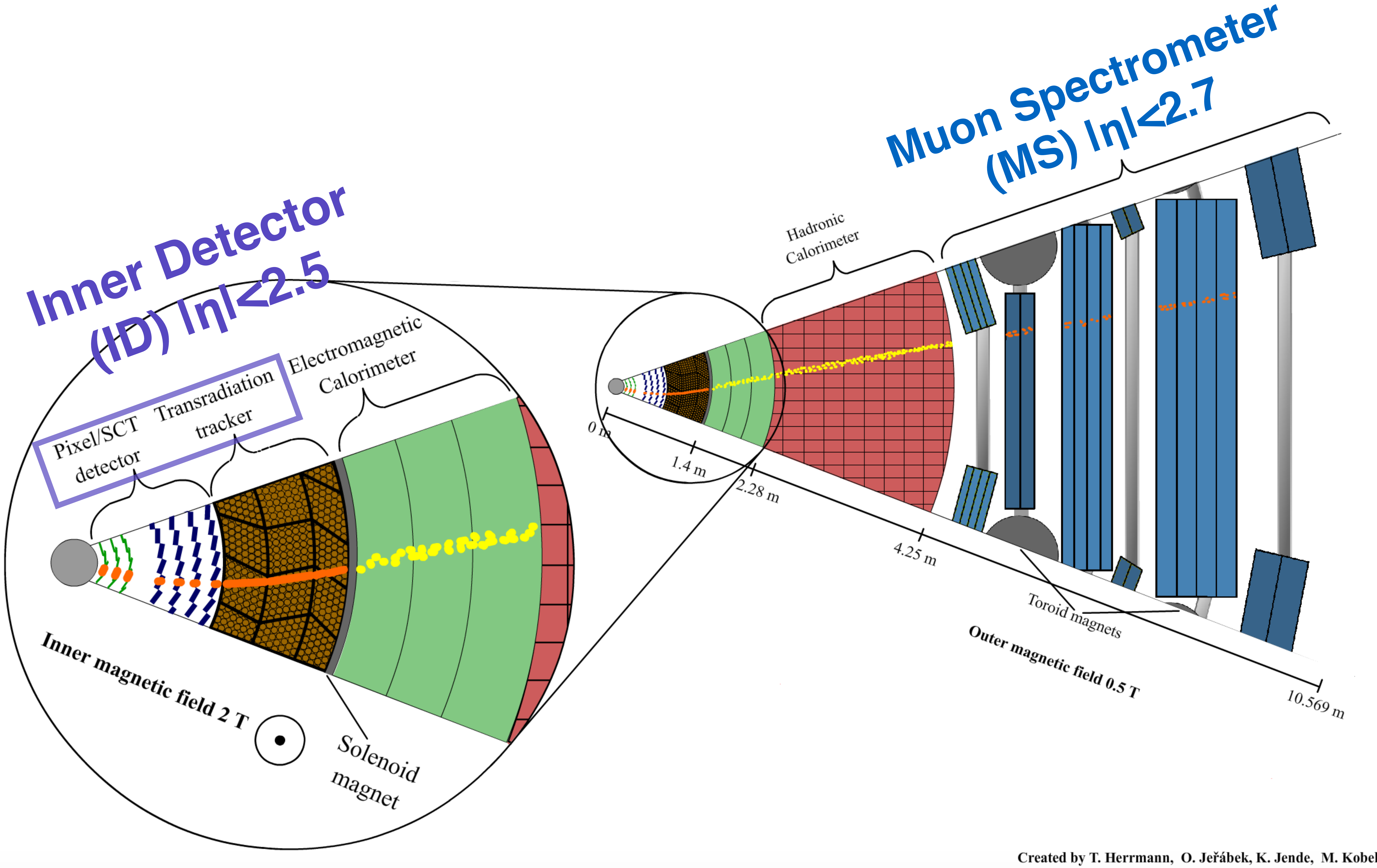
due to shift in the center mass

y* is defined positive in the proton beam direction

Nuclear modification factor R_{AA} and R_{pPb}

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

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



Inner Detector
(ID) |η|<2.5
Muon Spectrometer
(MS) |η|<2.7
Pixel/SCT
detector
Transradiation
tracker
Electromagnetic
Calorimeter
Hadronic
Calorimeter
Inner magnetic field 2 T
Solenoid
magnet
0 m
1.4 m
2.28 m
4.25 m
10.569 m
Toroid magnets
Outer magnetic field 0.5 T
Created by T. Herrmann, O. Jeřábek, K. Jende, M. Kobel

Centrality

Glauber model

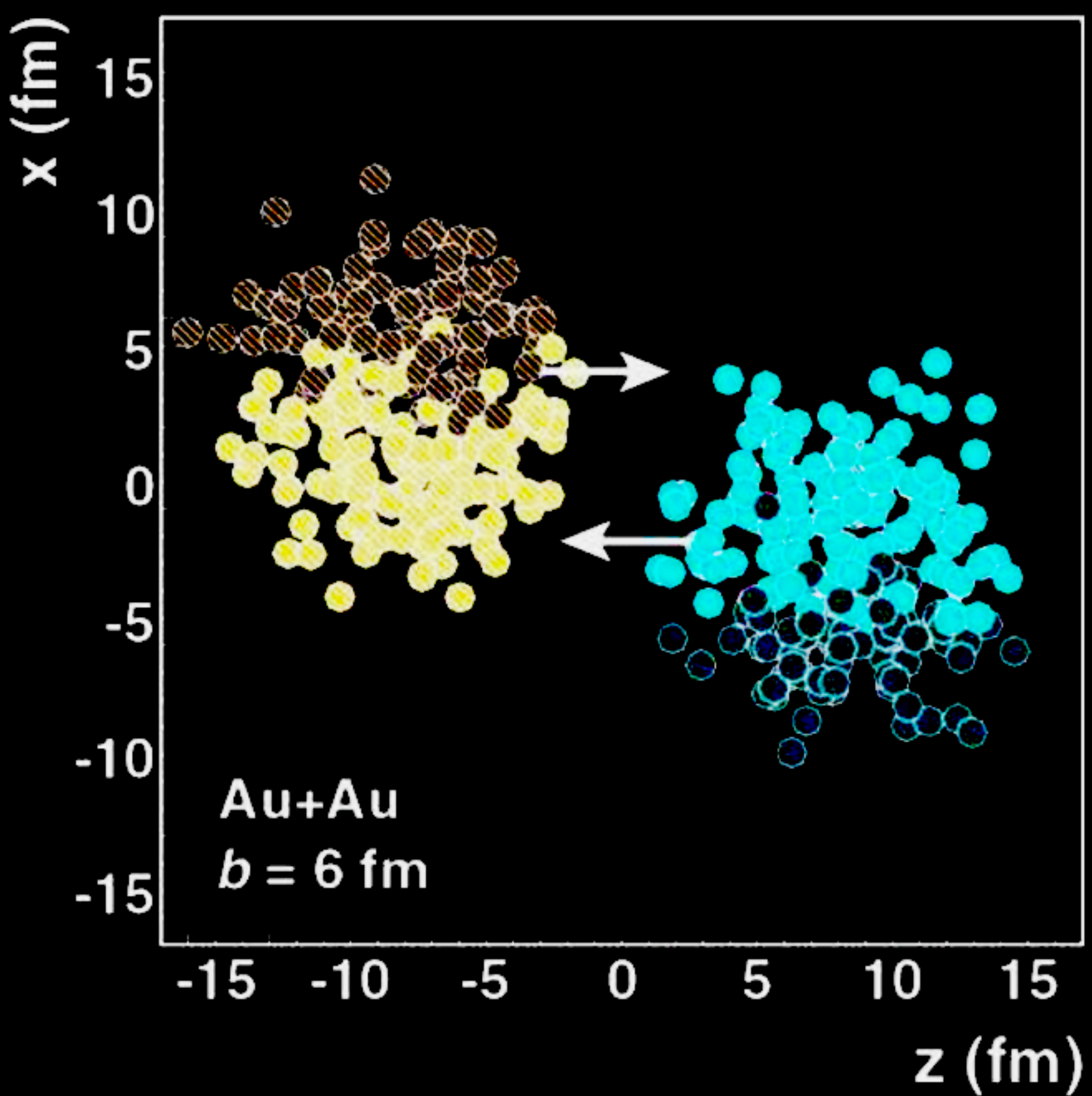
1) Generate two colliding nuclei with 3D nucleon positions chosen from measured density distributions (e^- scattering)

$$\rho(r) = \frac{\rho_0}{1 + exp([r - R]/a)}$$

2) Nucleons interact when transverse distance satisfies

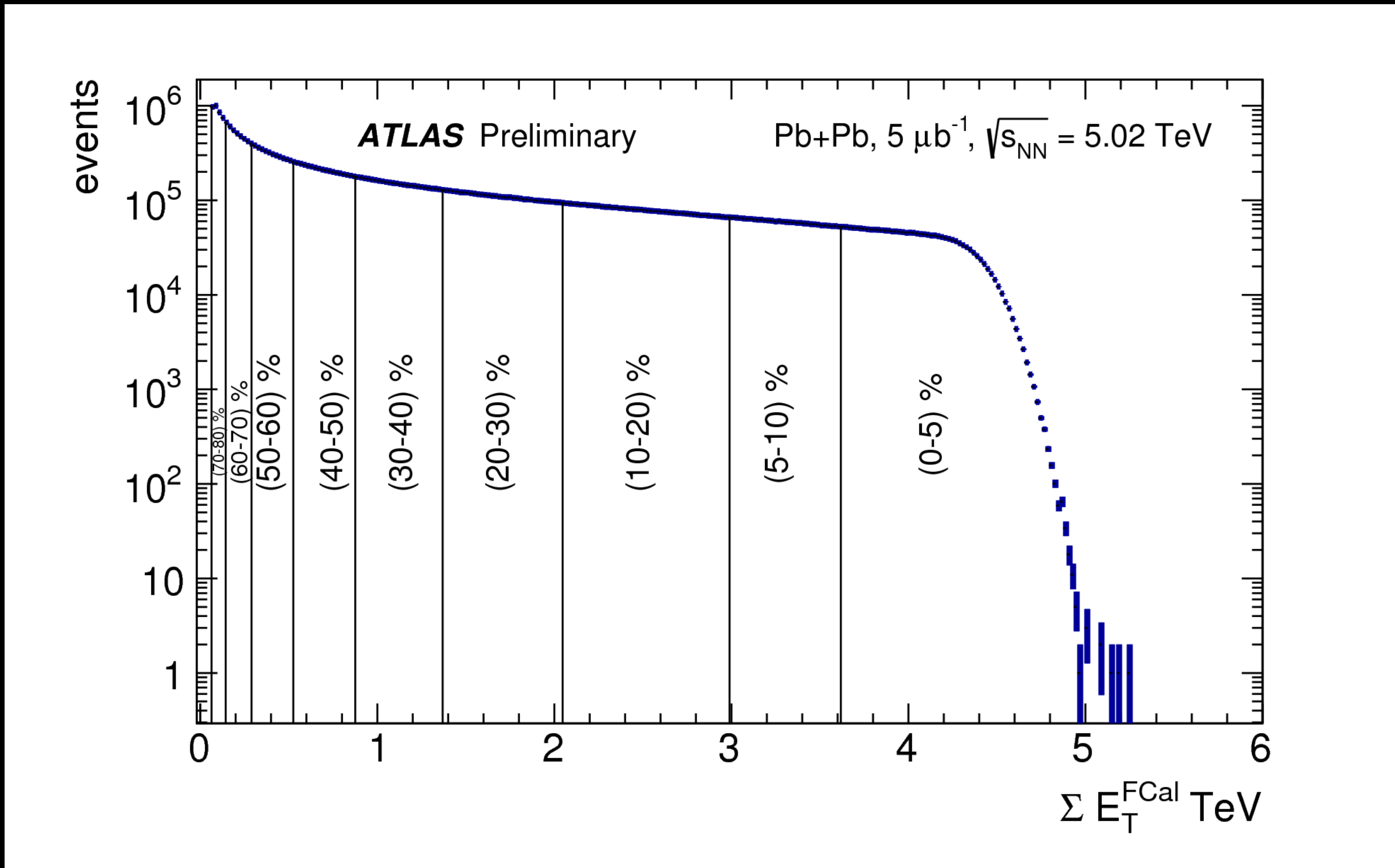
$$d < \sqrt{\sigma_{NN}/\pi}$$

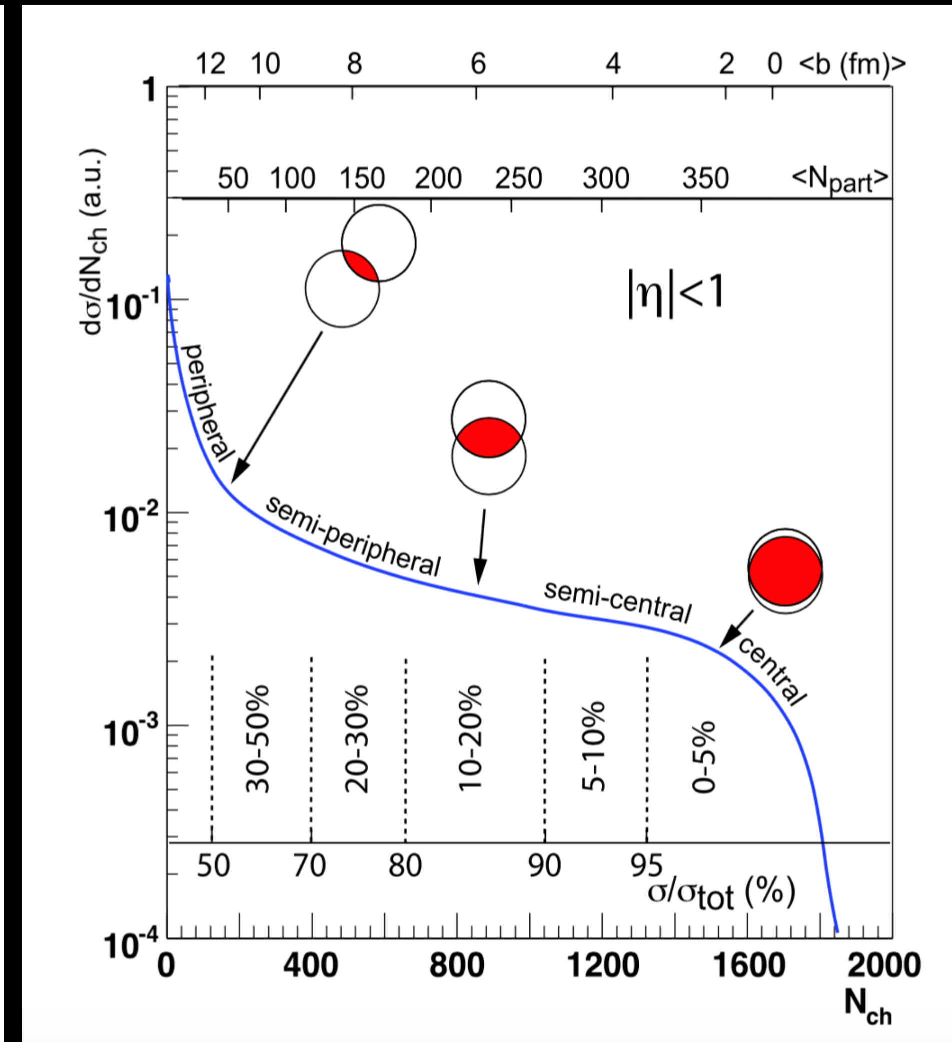
typically using the inelastic pp cross section for NN



Centrality

Energy deposited in the forward calorimeters





$\sum E_T^{FCal}$ = Sum of energy deposited in the forward calorimeters

Data is then divided into percentile bins: Models allow extraction of $\langle N_{part} \rangle$, $\langle N_{coll} \rangle$ and $\langle T_{AA} \rangle$.

Method

J/ψ and ψ(2S) reconstructed in the di-muon channel, $2.6 < m_{\mu\mu} < 4.2$ GeV

Pb-Pb Trigger

- L1 Trigger: 1 muon, $p_T > 4$ GeV
- High Level Trigger: 2 muons, $p_T > 4$ GeV

pp Trigger

- L1 Trigger: 2 muons, $p_T > 4$ GeV
- High Level Trigger: 2 muons, $p_T > 4$ GeV

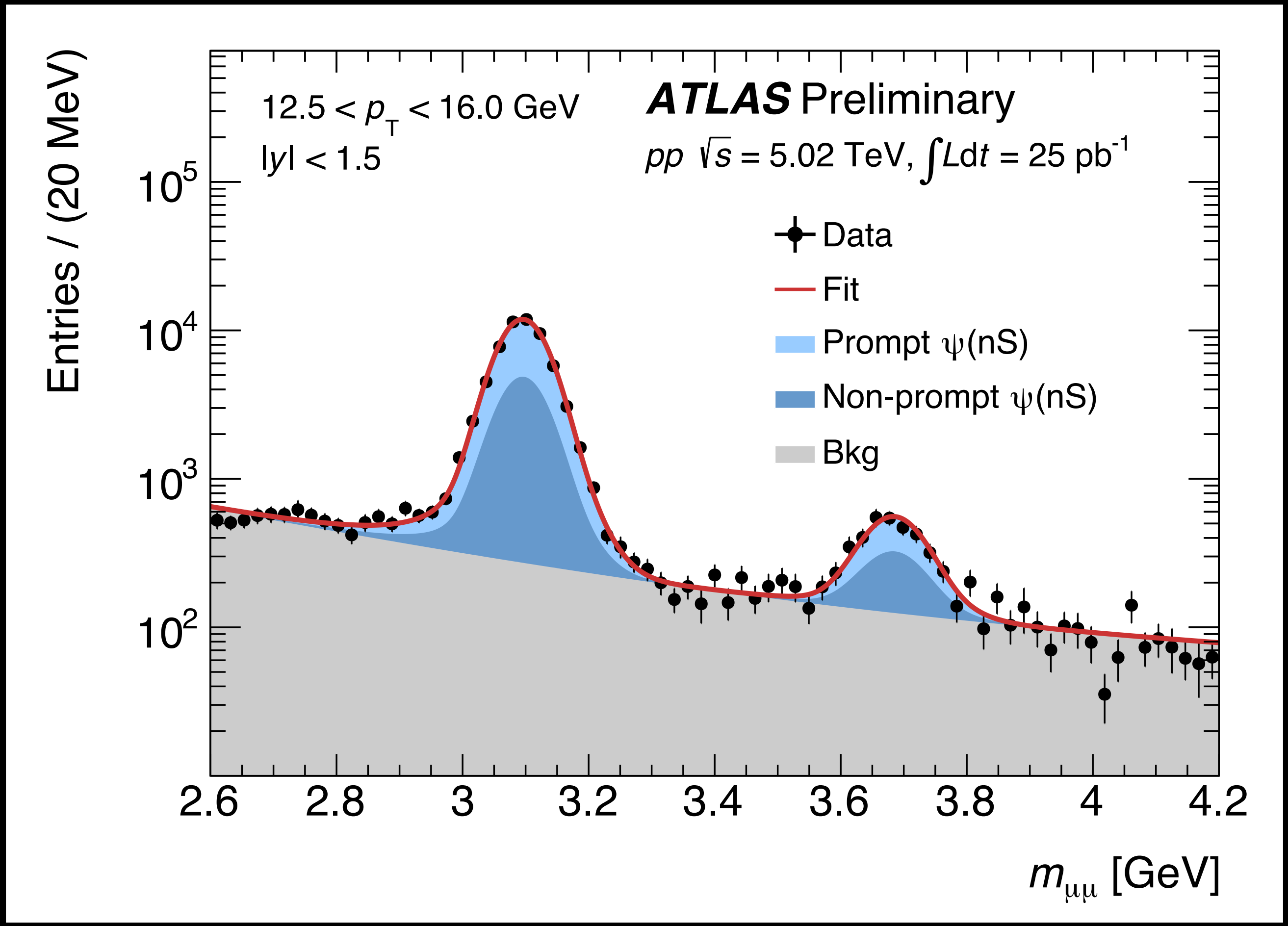
Kinematic Range: $9 < p_T < 40$ GeV and $|y| < 2$, centrality 0-80%

Perform weighted 2D unbinned maximum likelihood fit

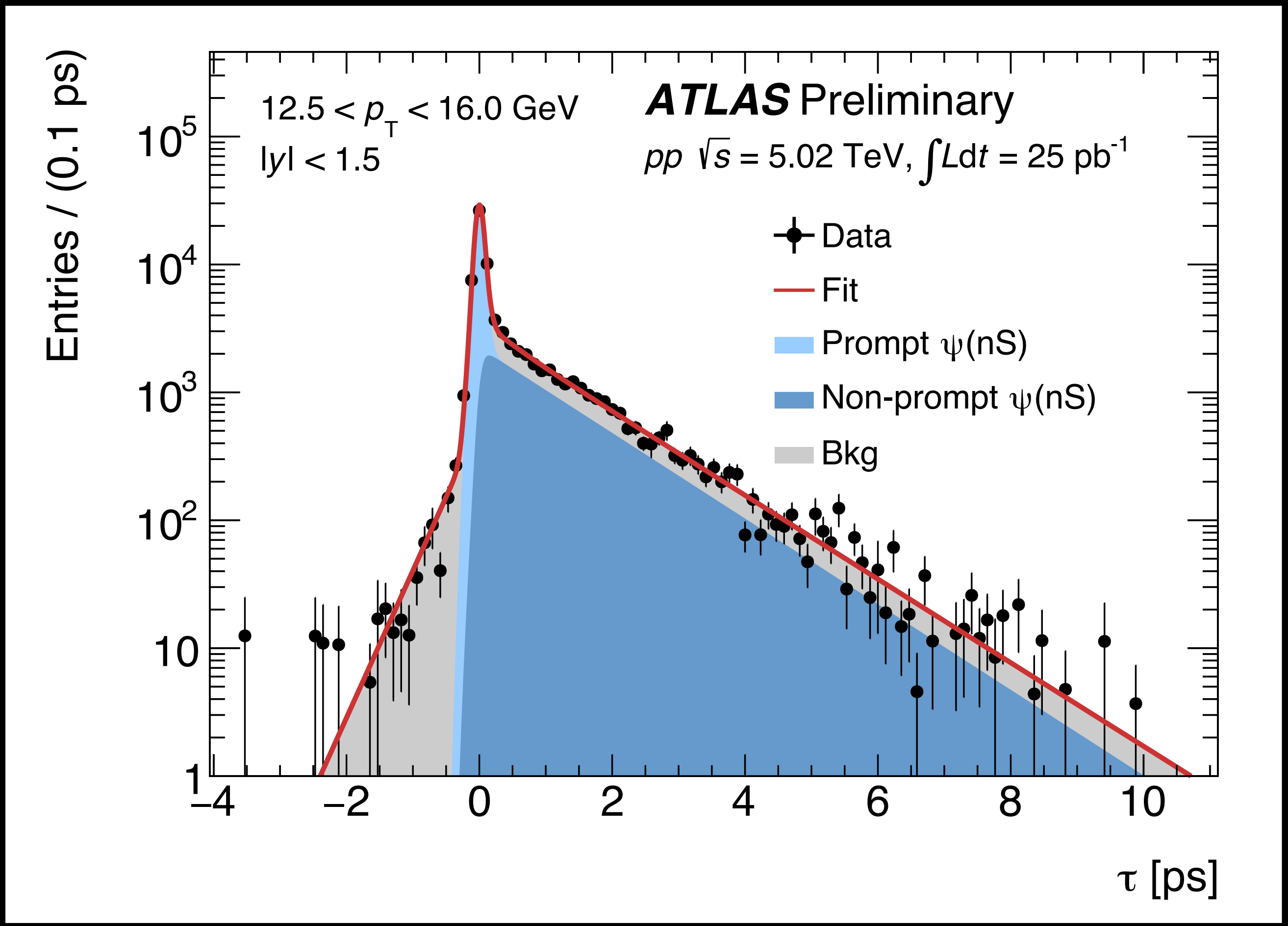
- Di-muon Invariant mass and lifetime
- Extract fraction of prompt and non-prompt J/ψ and ψ(2S)
- Per-dimuon weight: trigger, reconstruction and acceptance

Simultaneous Fit Method

PbPb projections



Invariant dimuon mass and lifetime



Weights: Acceptance, trigger and reconstruction efficiency

Simultaneous Fit Method

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

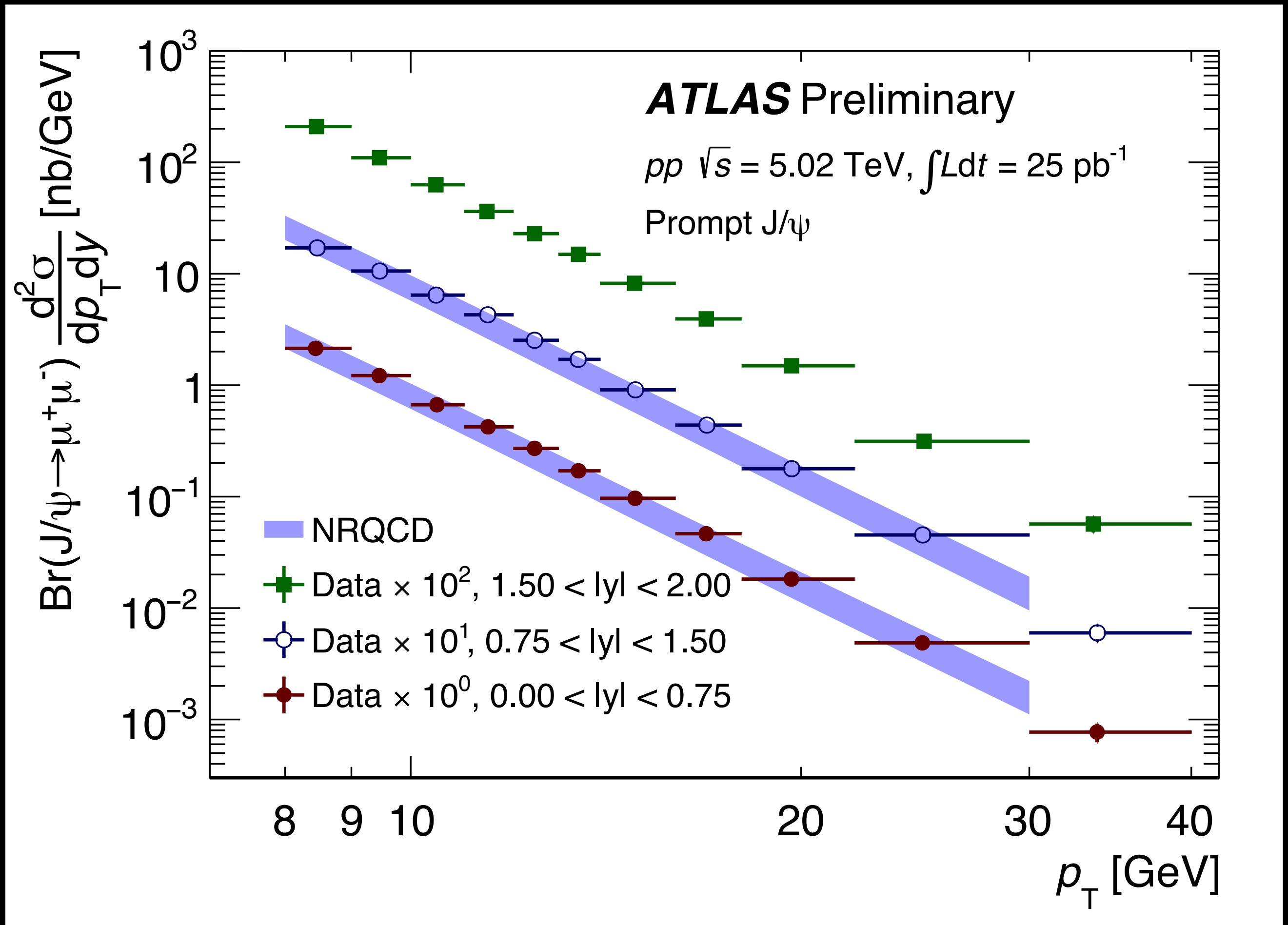
i	Type	Source	$f_i(m)$	$h_i(\tau)$
1	J/ψ S	P	$\omega_i \mathrm{CB}_1(m) + (1-\omega_i)\mathrm{G}_1(m)$	$\delta(\tau)$
2	J/ψ S	NP	$\omega_i \mathrm{CB}_1(m) + (1-\omega_i)\mathrm{G}_1(m)$	$\mathrm{E}_1(\tau)$
3	$\psi(2S)$ S	P	$\omega_i \mathrm{CB}_2(m) + (1-\omega_i)\mathrm{G}_2(m)$	$\delta(\tau)$
4	$\psi(2S)$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

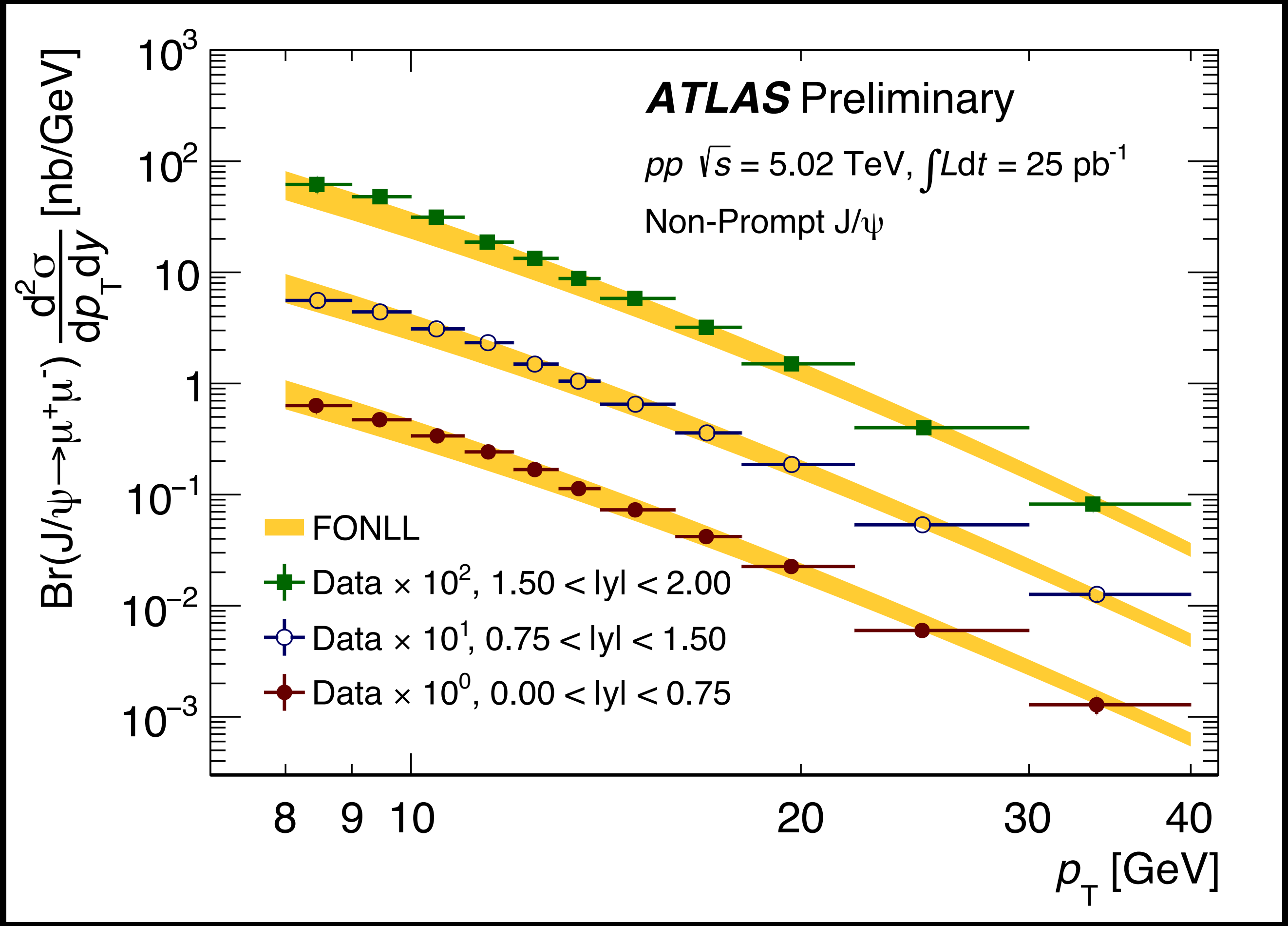
The composite PDF terms are defined as follows:

- CB - Crystal Ball;
- G - Gaussian;
- E - Exponential;
- Resolution function $g(\tau)$ is a double Gaussian function;
- δ - delta function.

Differential Cross Section

Prompt and Non-prompt J/ψ production



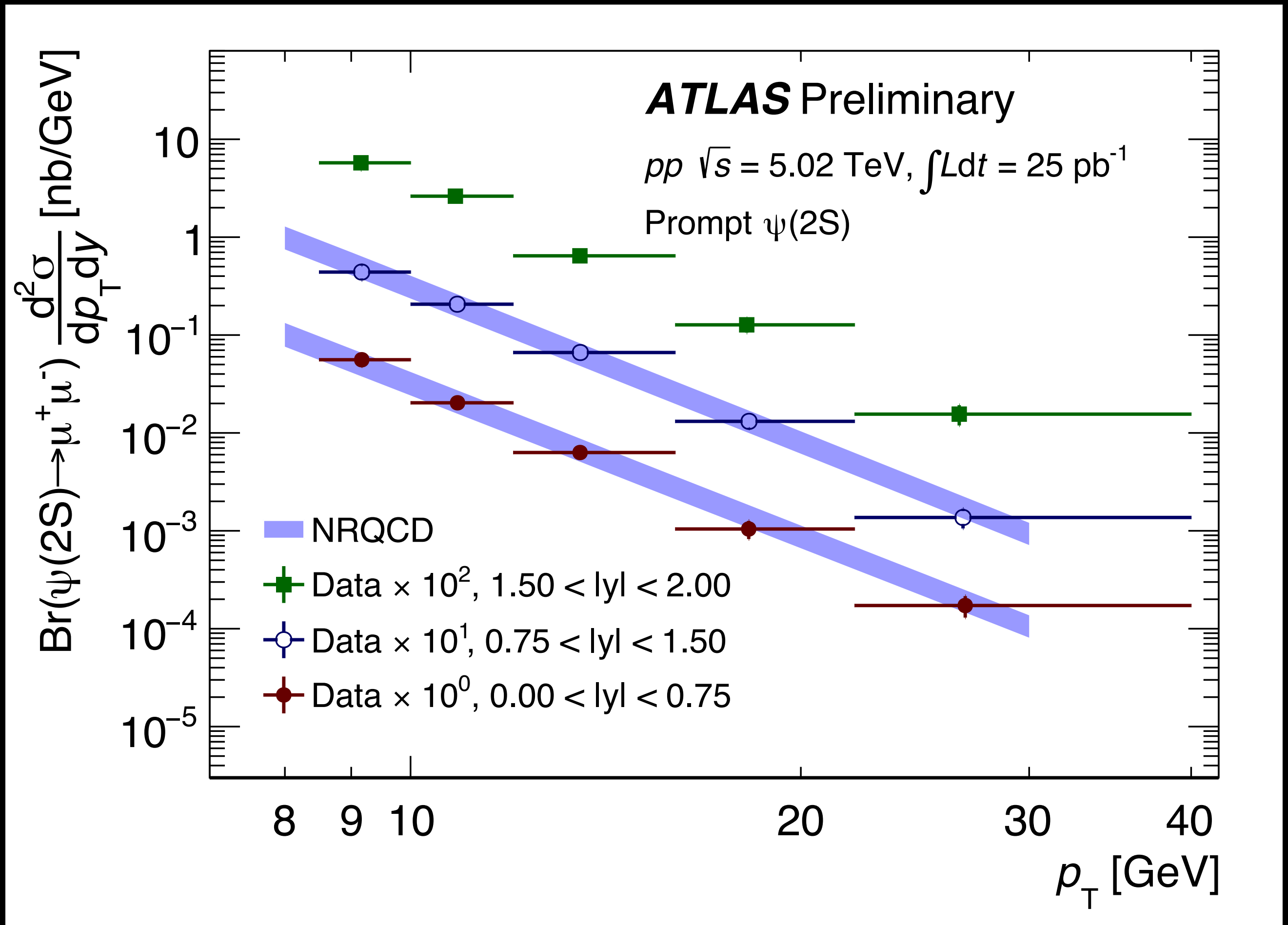


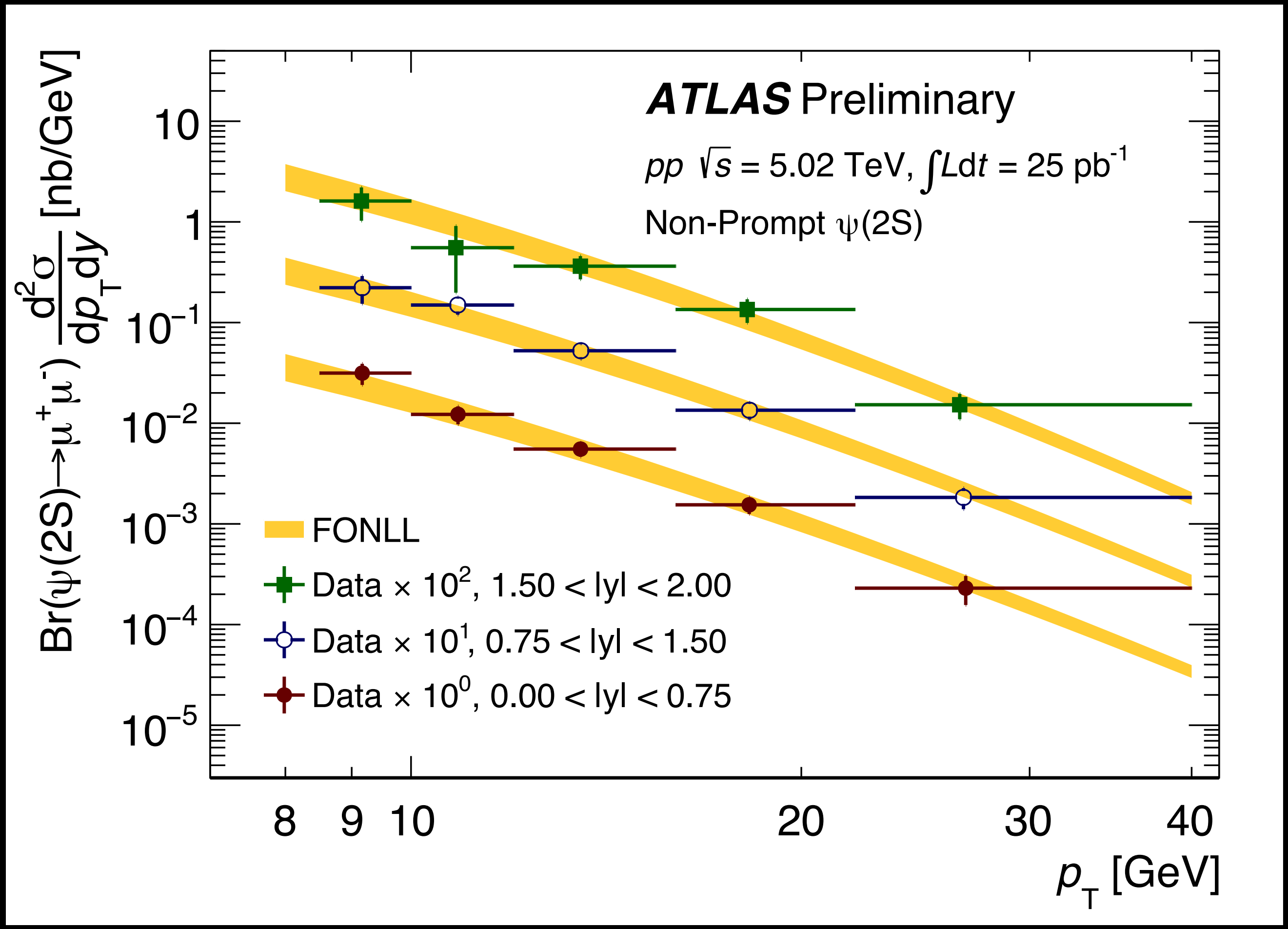
NRQCD and FONLL model the data very well, the comparison is limited by the uncertainties on the theory, not on the experiment.

ATLAS-CONF-2016-109

Differential Cross Section

Prompt and Non-prompt ψ(2S) production





The data are in very good agreement with the theoretical prediction within the uncertainties.

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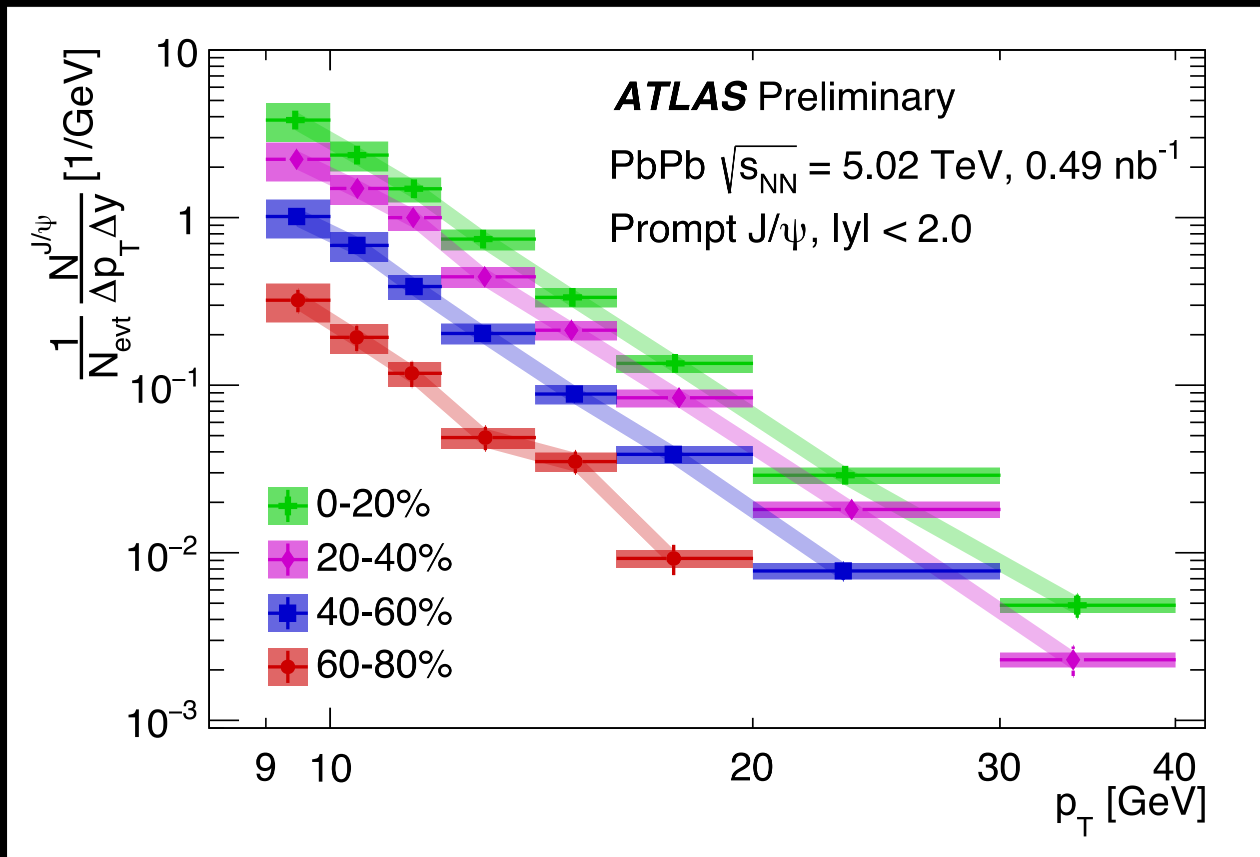
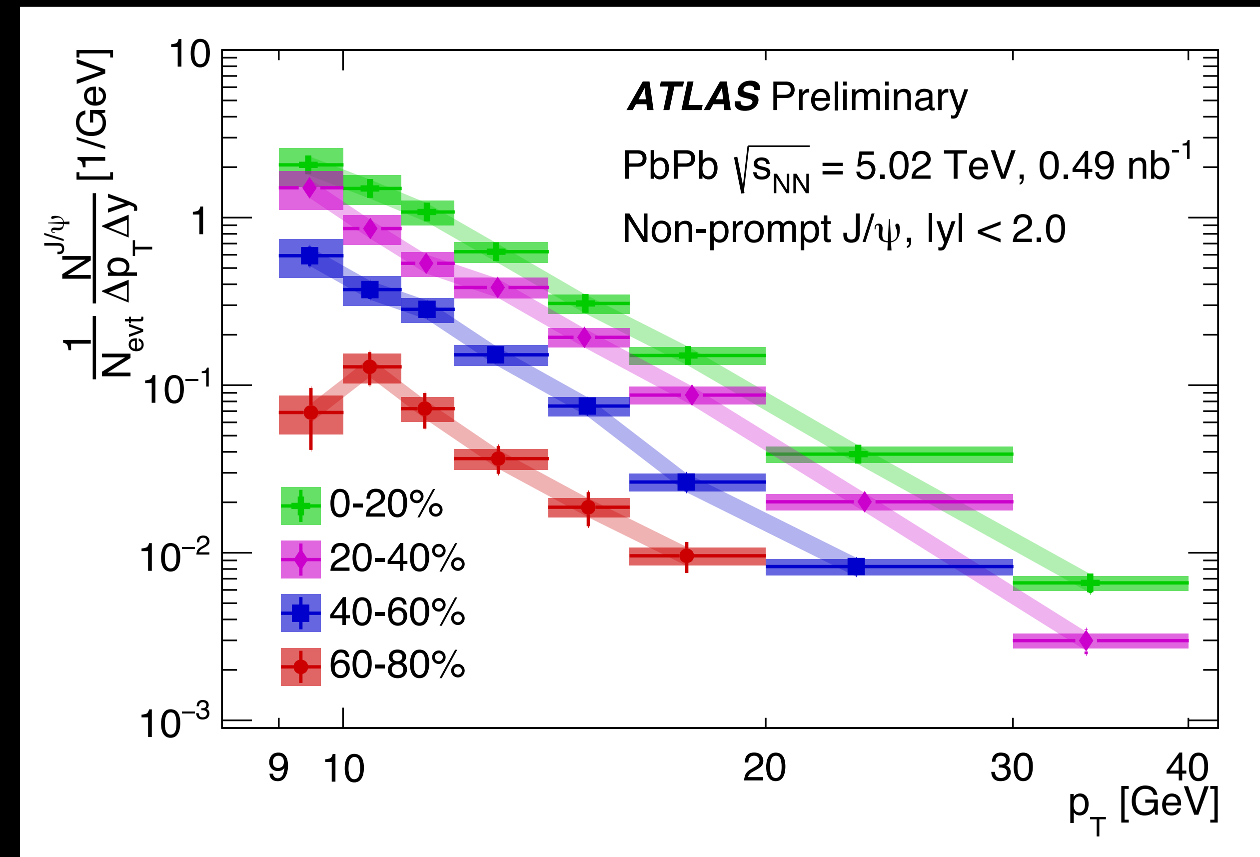
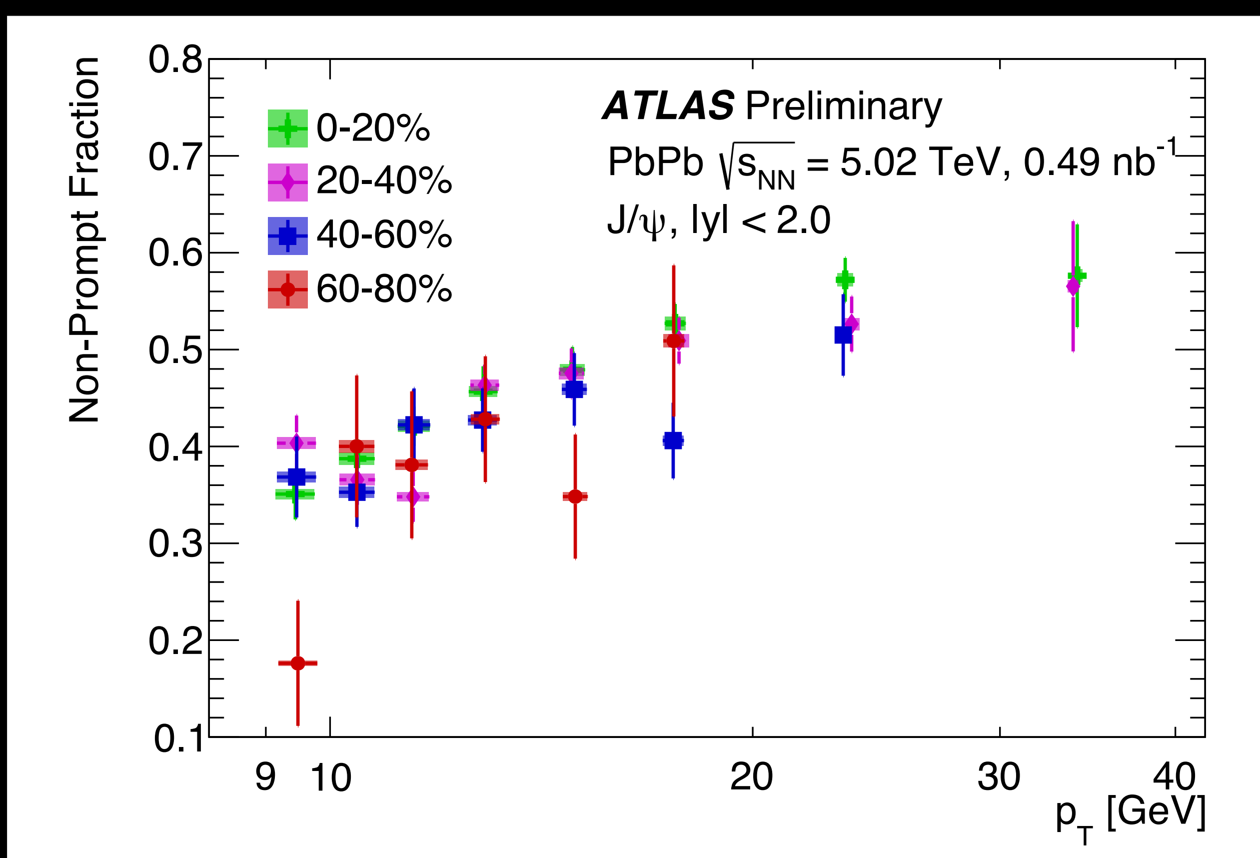
Per-event-yields prompt and non-prompt J/ψ

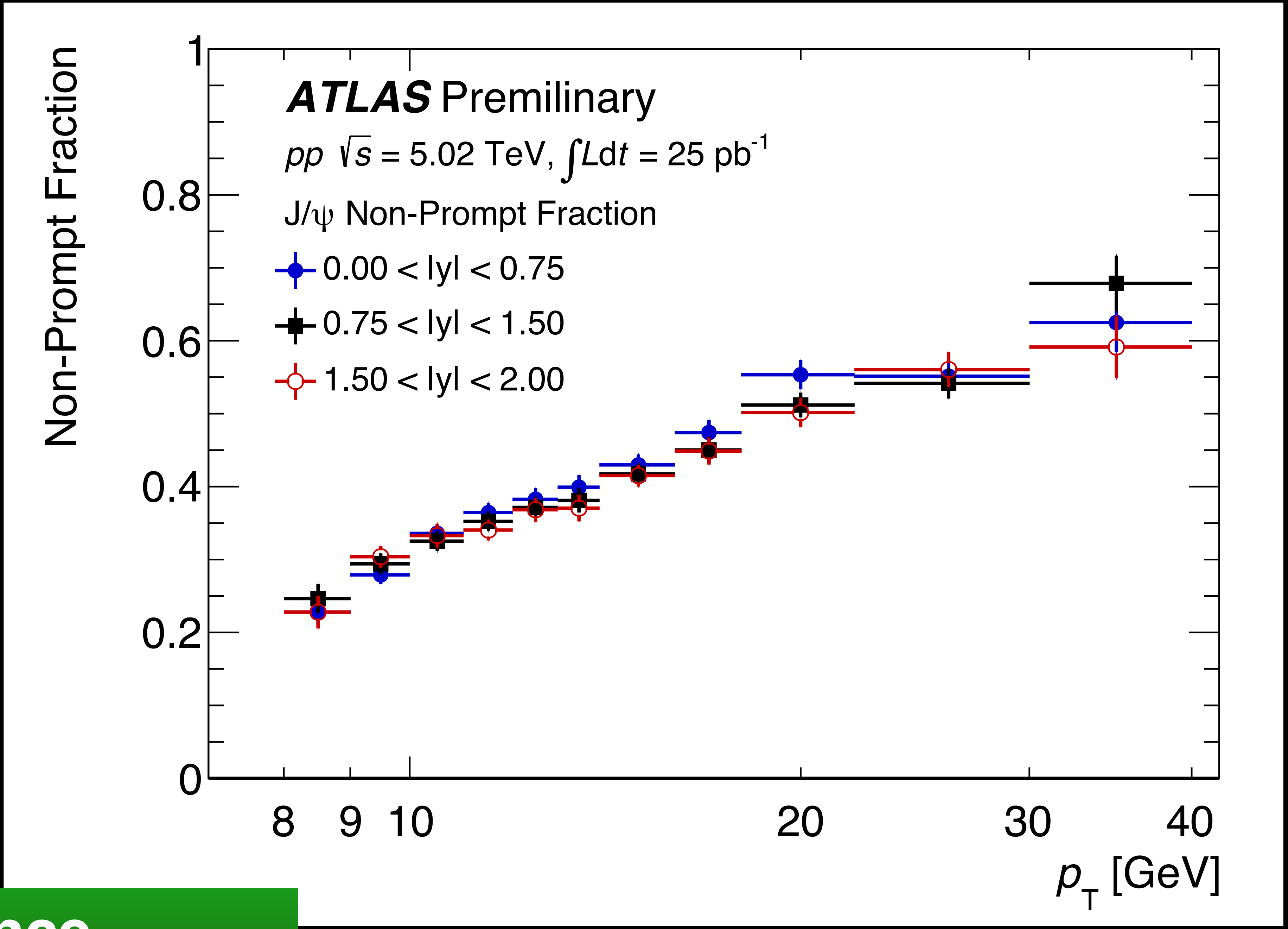






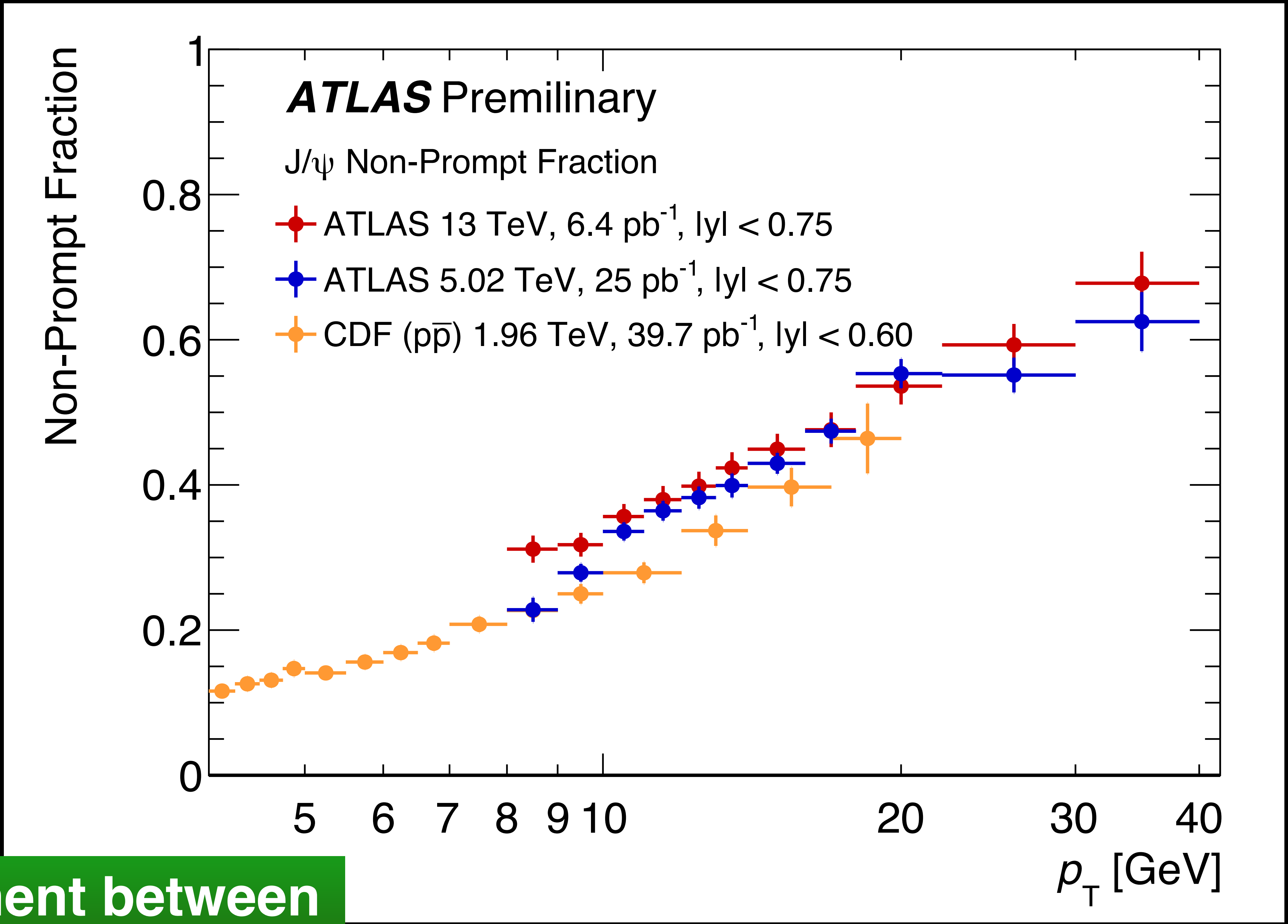
Non-prompt fraction of J/ψ in pp 5.02 TeV vs. pT for |y| slices

$$f_{\mathrm{NP}}^{\psi(nS)} = \frac{N_{\mathrm{NP}}^{\psi(nS)}}{N_{\mathrm{NP}}^{\psi(nS)} + N_{\mathrm{P}}^{\psi(nS)}}$$



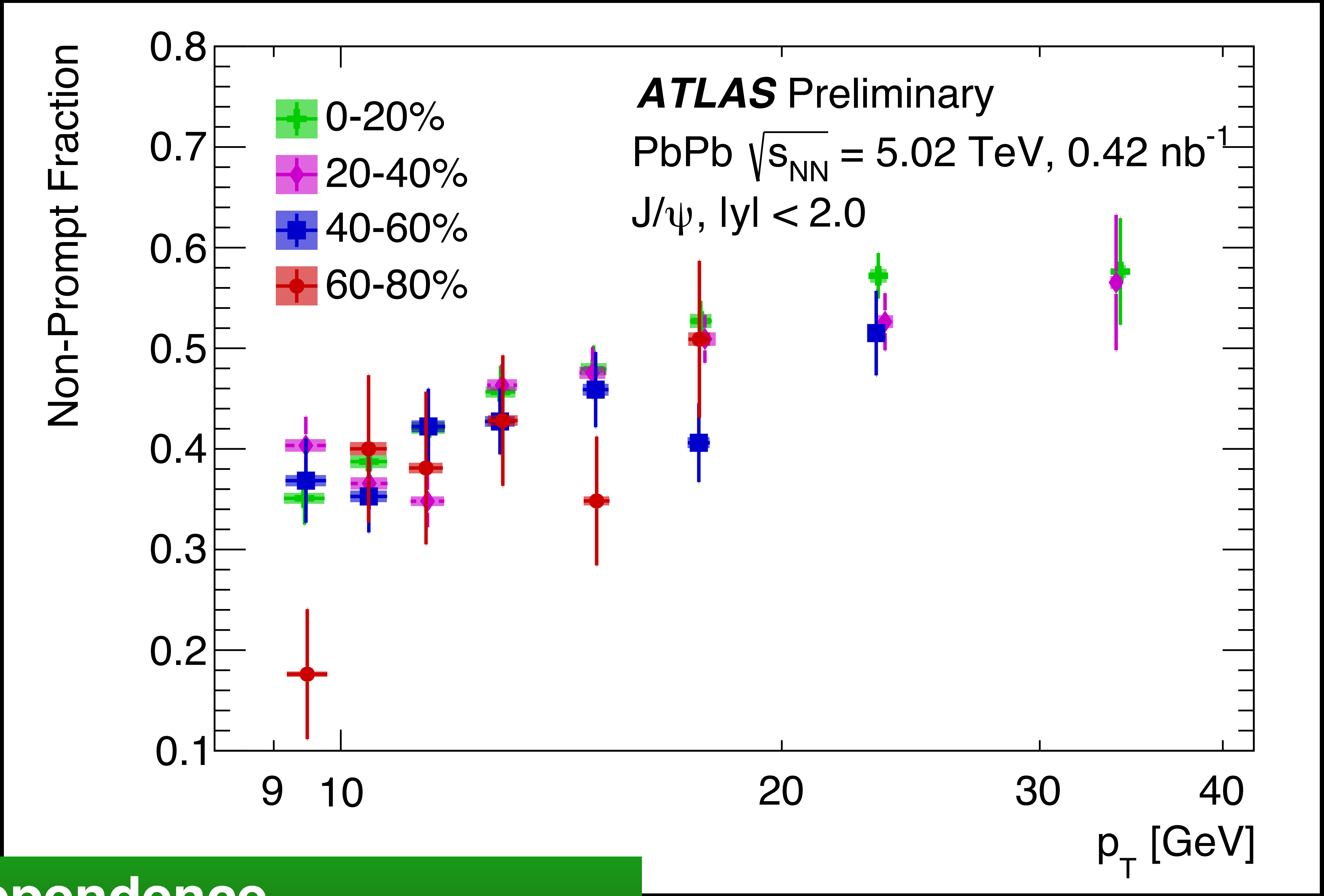
Strong pT dependence
No significant lyl dependence

Non-prompt fraction of J/ψ in pp 5.02 TeV, 13 TeV and 1.96 TeV



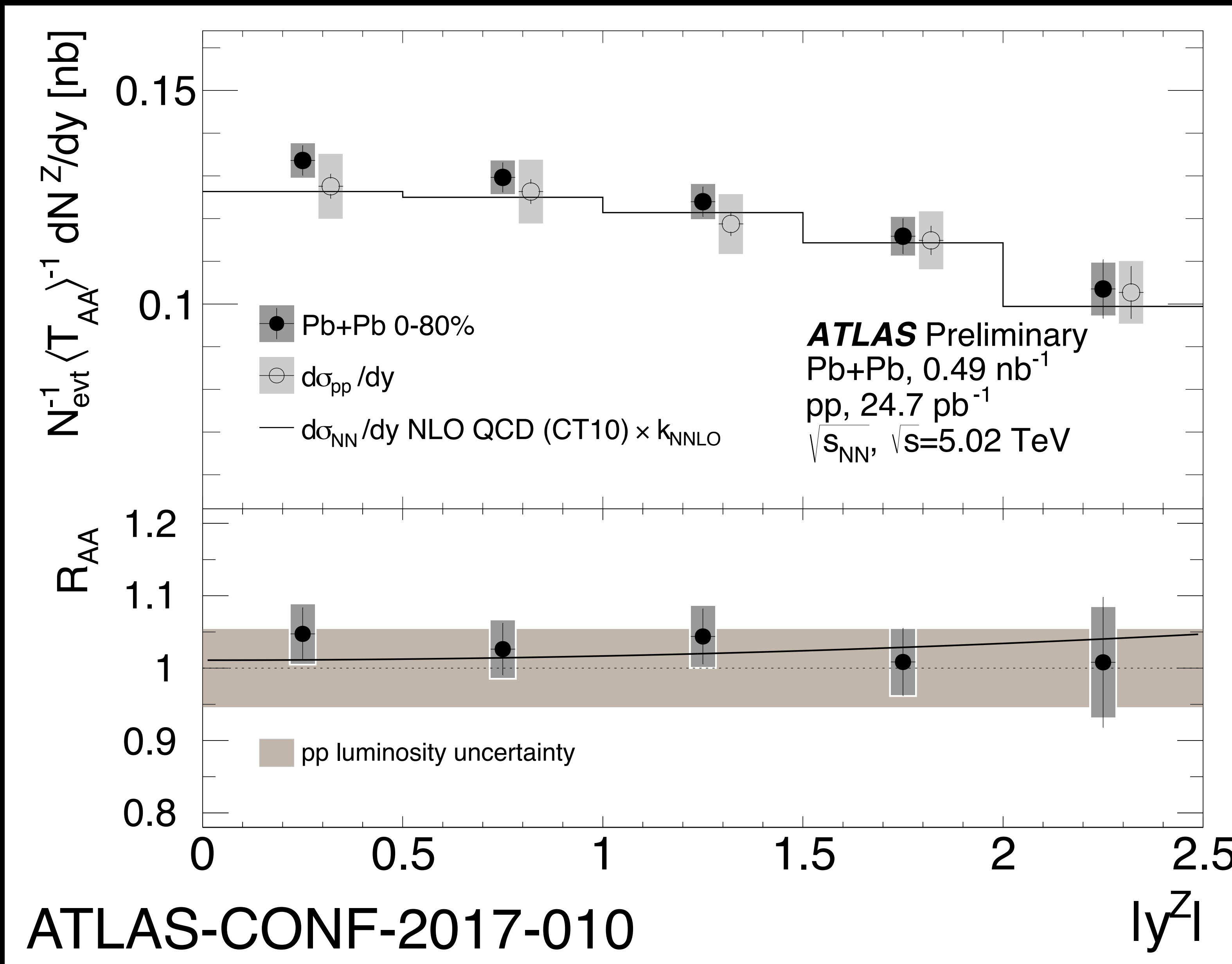
fairly agreement between the different energies

Non-prompt fraction of J/ψ in Pb+Pb 5.02 TeV



Strong pT dependence
No significant centrality dependence

PbPb Nuclear modification factor



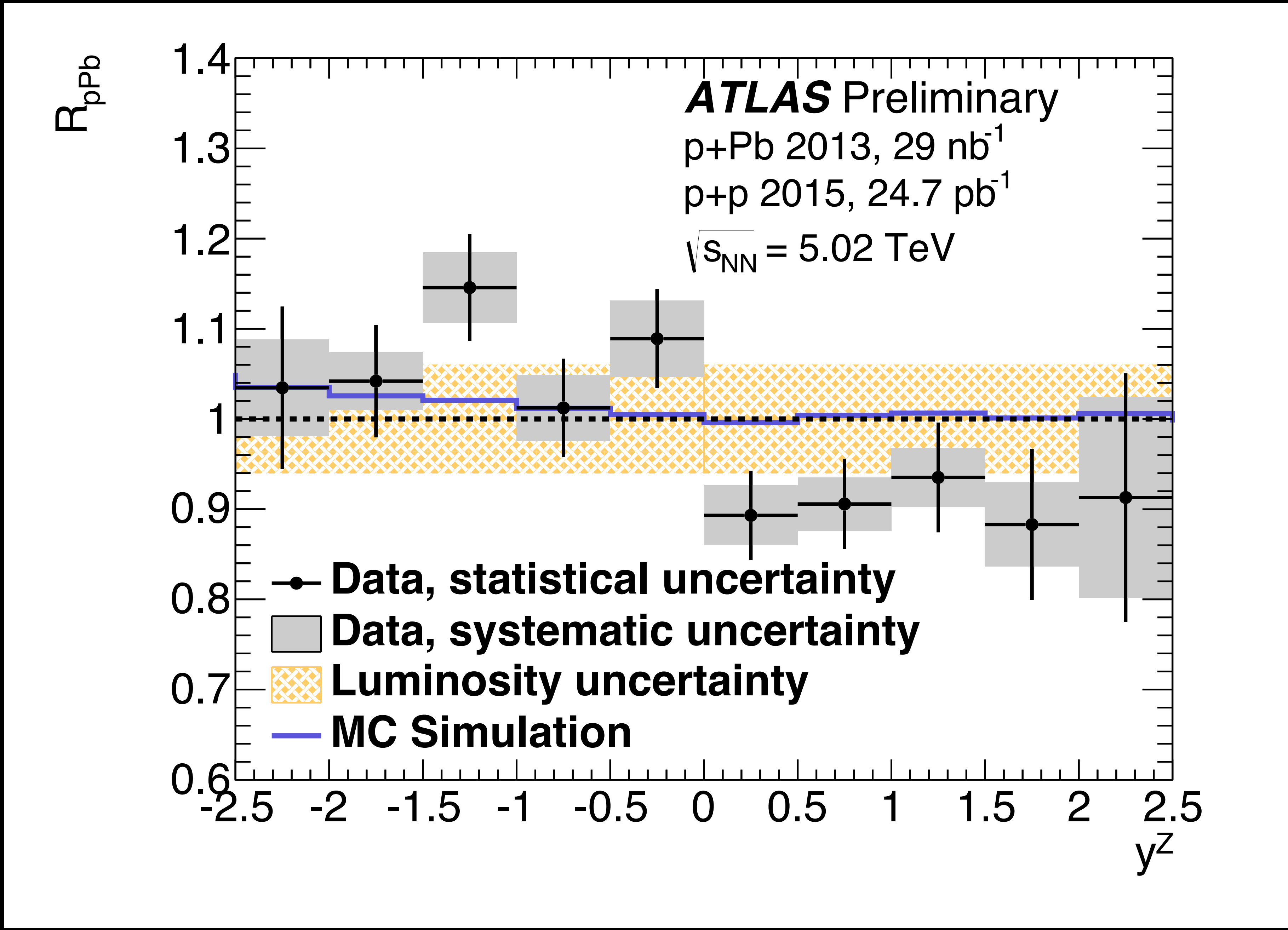
$$R_{\mathrm{AA}} = \frac{N_{\mathrm{AA}}}{\langle T_{\mathrm{AA}} \rangle \sigma^{pp}}$$

pp data agree with pQCD calculations

Good agreement between pp and PbPb after scaling

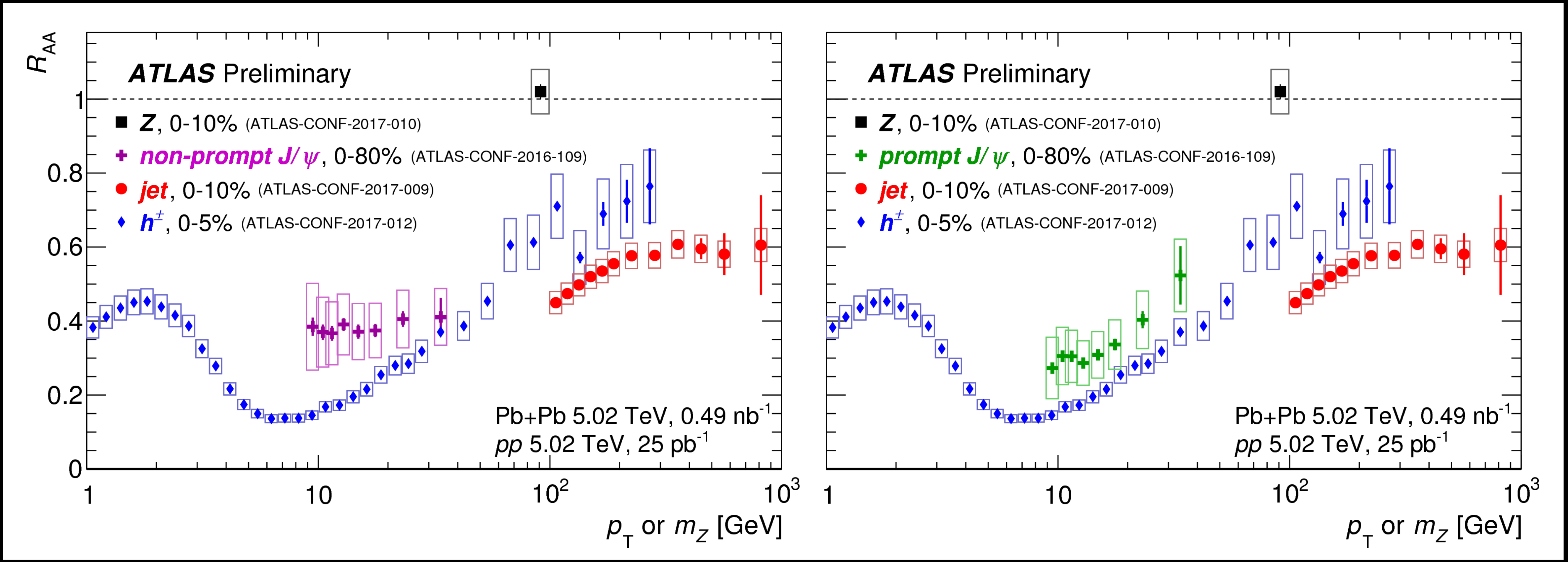
A hint of nPDF effects but not clear with the current resolution

pPb Nuclear modification factor



Suppression is observed at forward rapidity consistent with nuclear shadowing.

R_{AA} of different probes



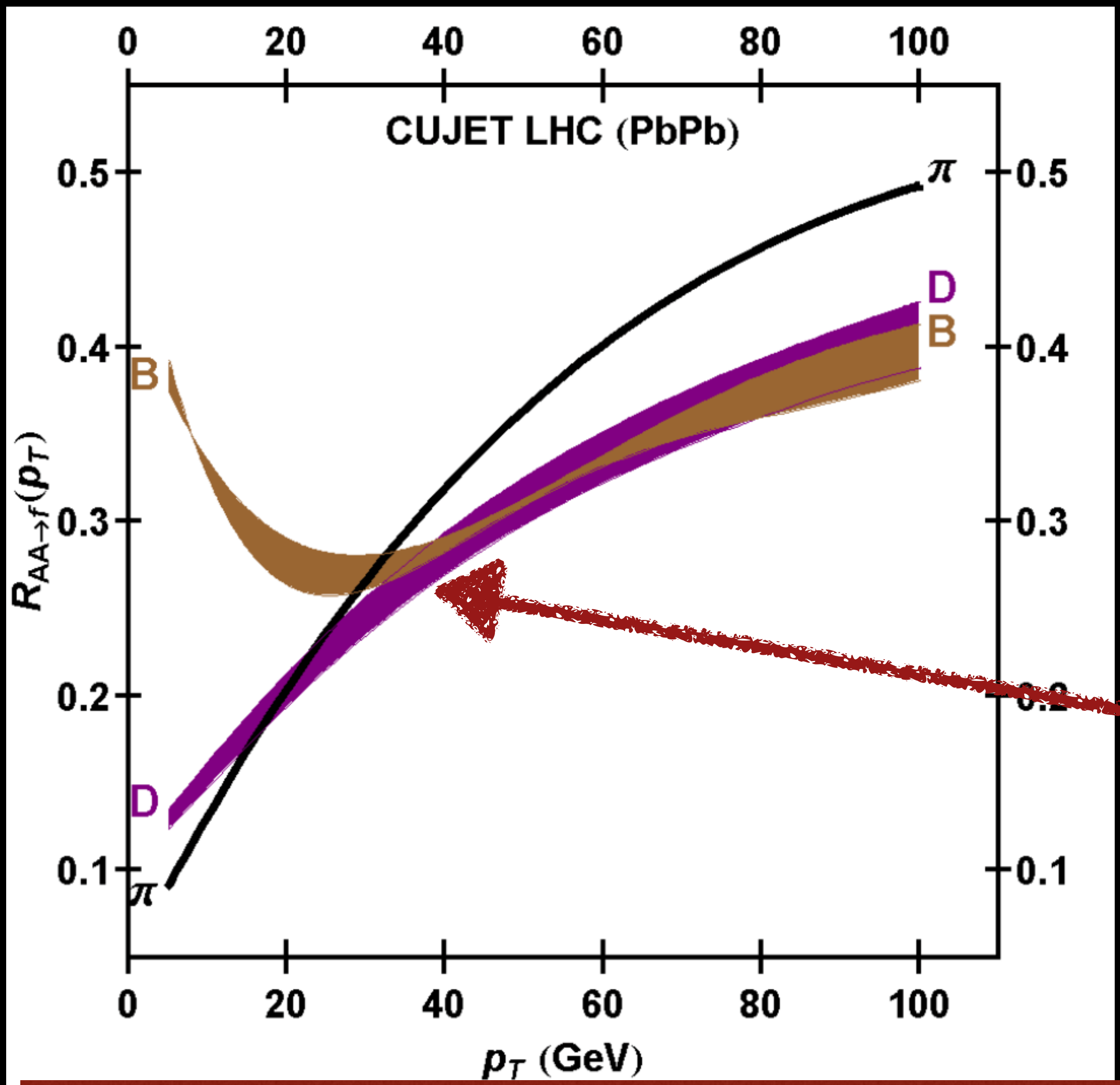
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

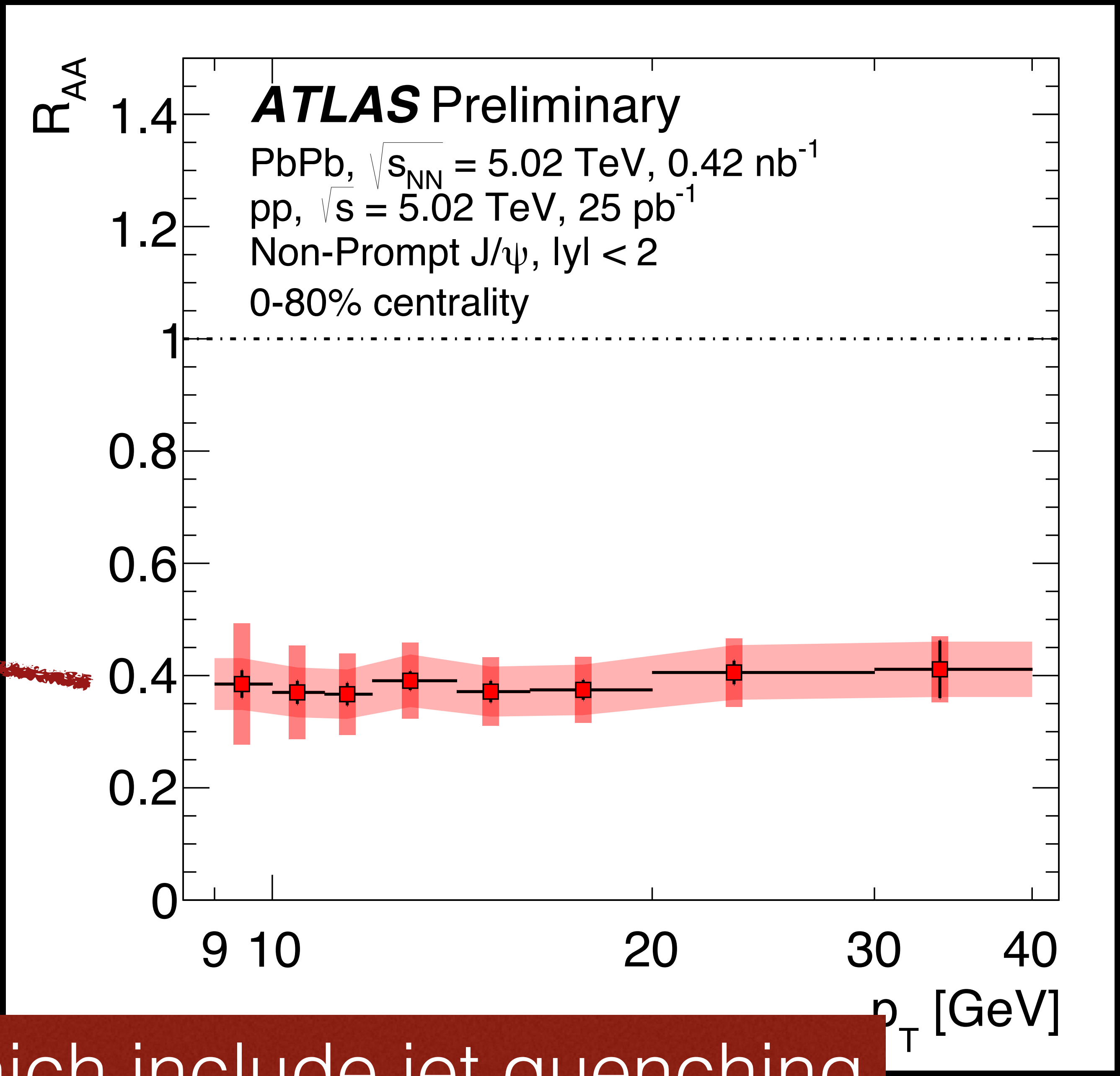
R_{AA} vs. p_T

$$R_{AA} = \frac{N_{AA}}{\langle T_{AA}\rangle \sigma^{pp}}$$

arXiv:1106.3061v2

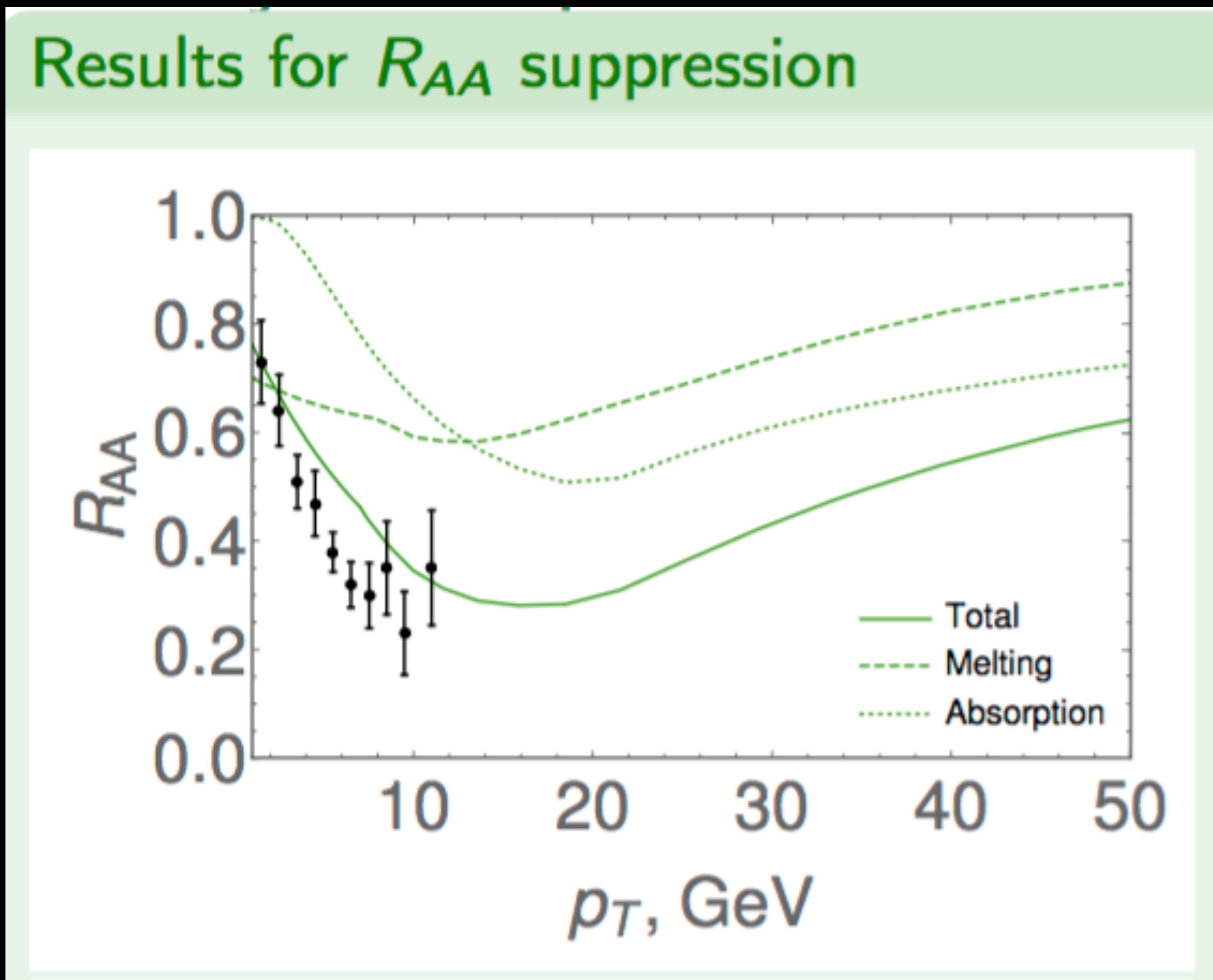
Non-prompt

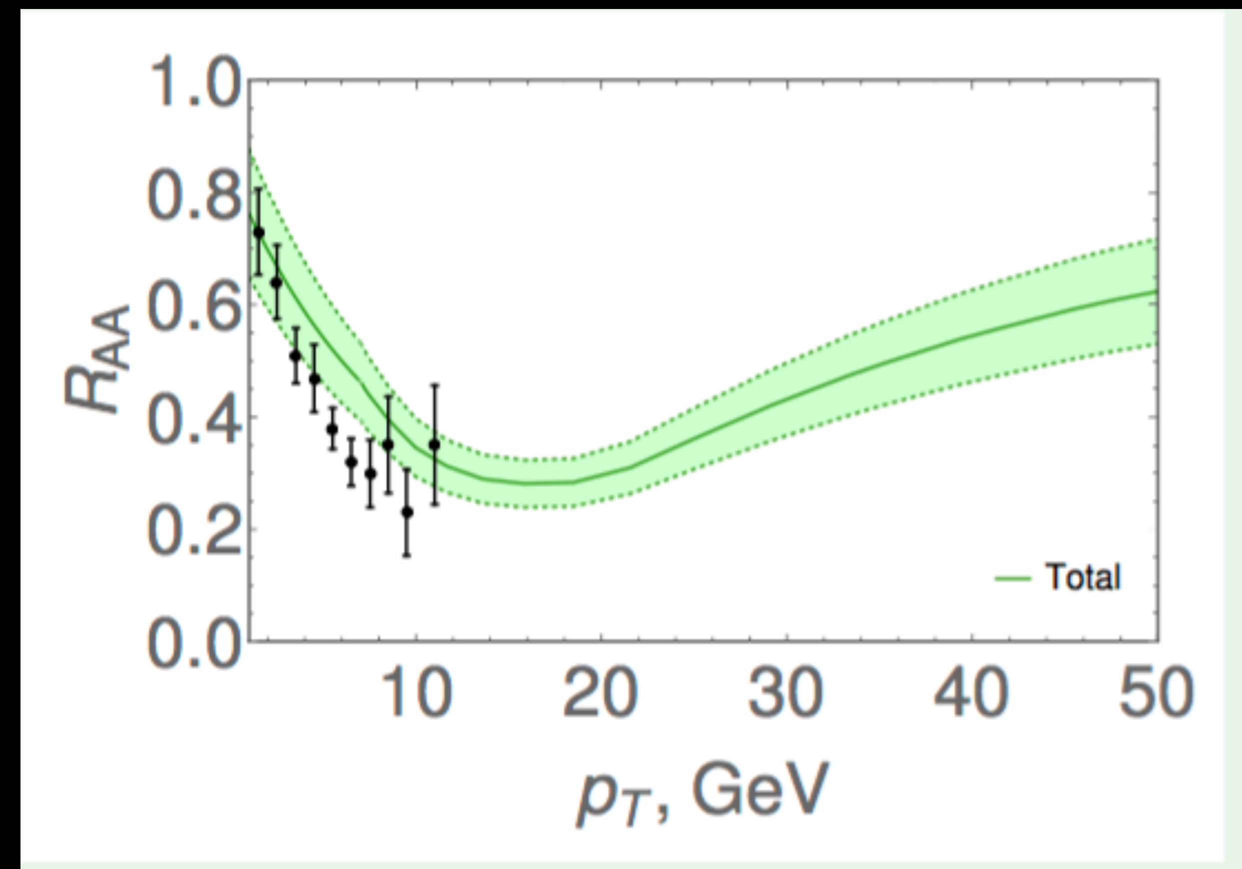




Shape predicted by models which include jet quenching

R_{AA} theory calculations



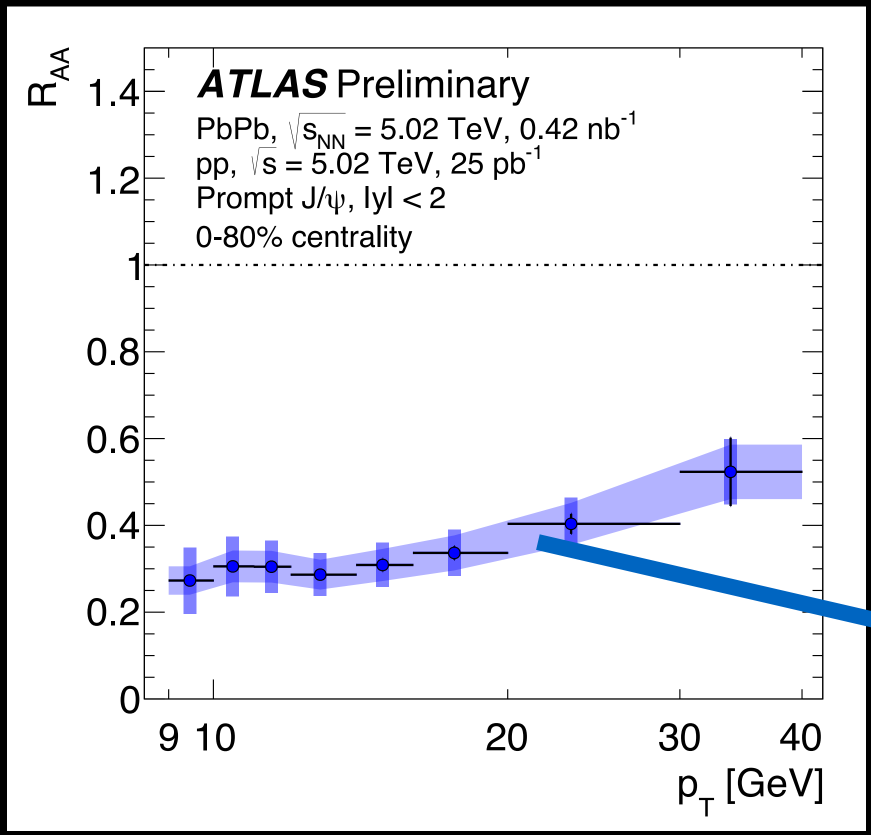


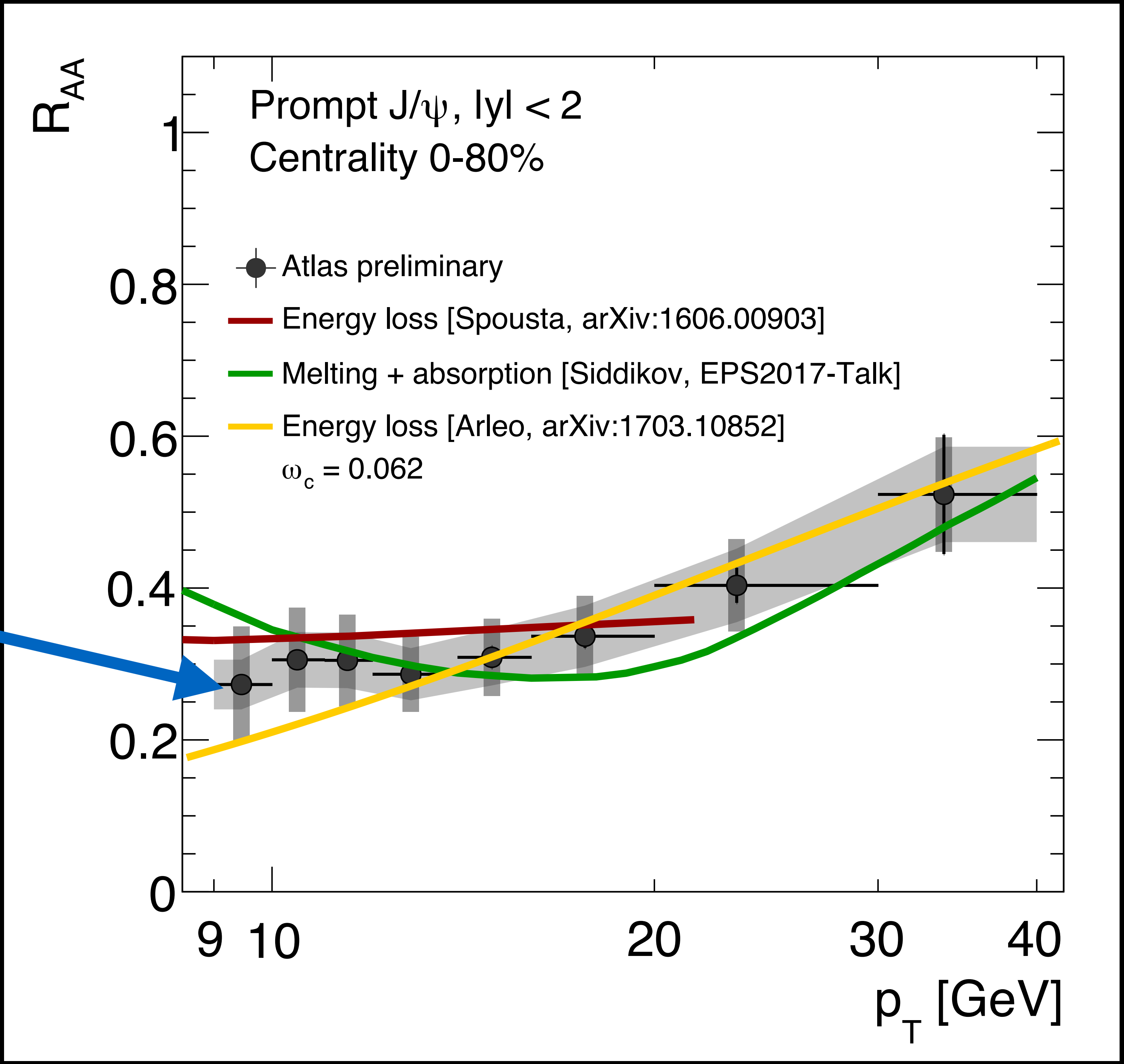
M. Siddikov, B. Kopeliovich, Ivan Schmidt

https://indico.cern.ch/event/466934/contributions/2588213/attachments/1488432/2313026/Siddikov_EPS2017_Quarkonium.pdf

R_{AA} theory calculations

Prompt





Well described by energy loss models as well as melting+absorption.