Y(nS) meson production in Pb+Pb and *pp* collisions

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Physics motivation

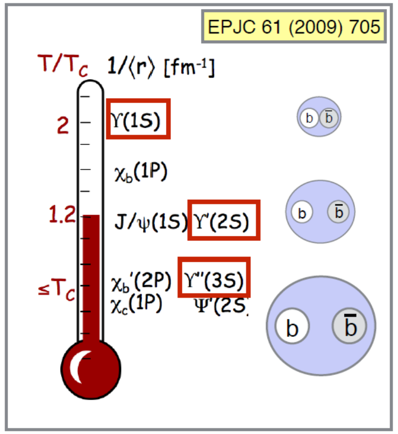
Upsilons can serve as an important tool for studying QGP

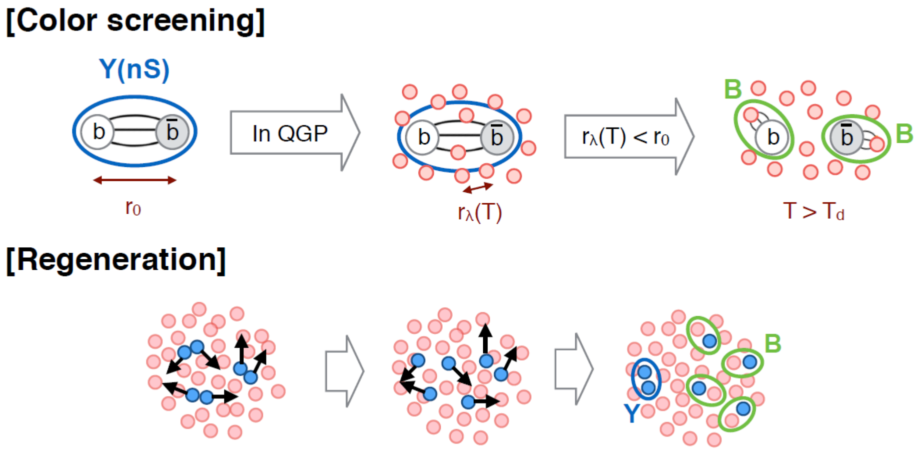
In nucleus-nucleus collisions:

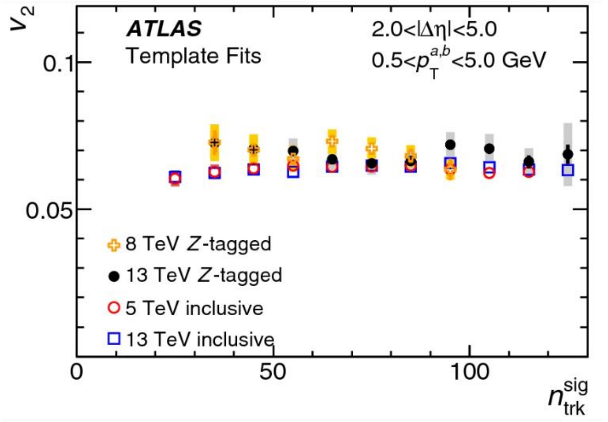
- The three Υ states have similar kinematics, but different binding energies.
  -> QGP "thermometer" (sequential melting).
- Very different non-prompt fraction and regeneration compared to charmonia.

QGP-like signatures have been observed in small systems, even in pp

- Event multiplicity dependencies







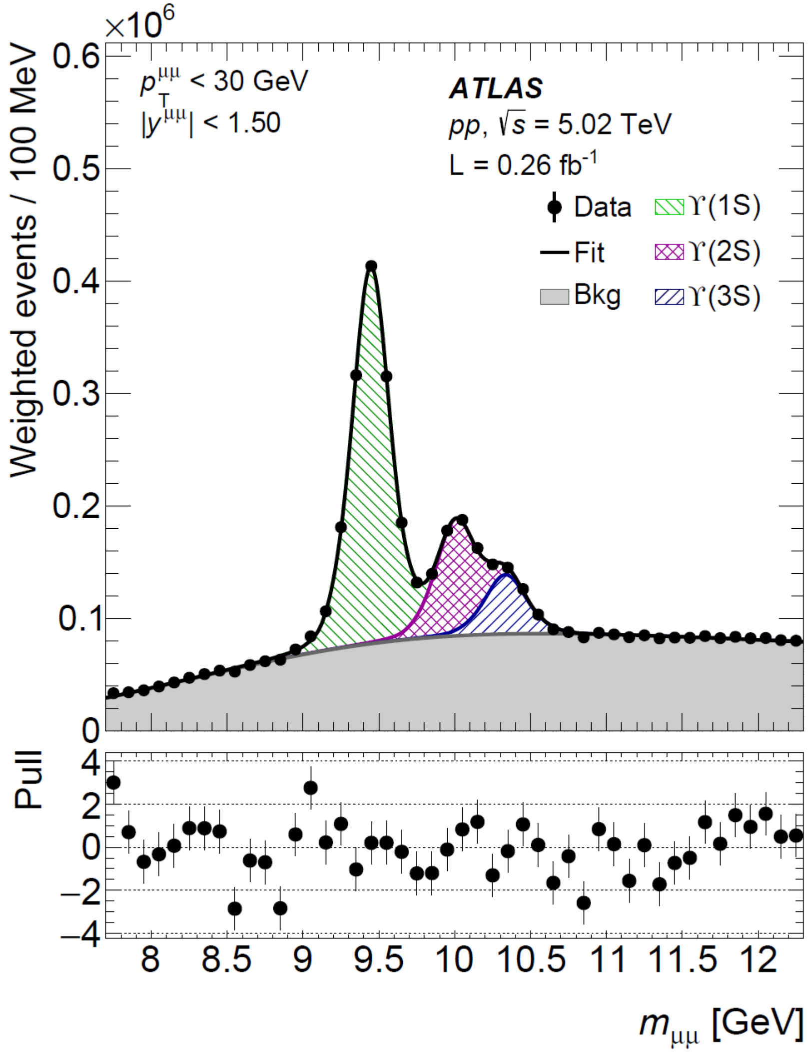
Signal Extraction in *pp* and Pb+Pb collisions

Upsilons measured in di-muon channel at midrapidity

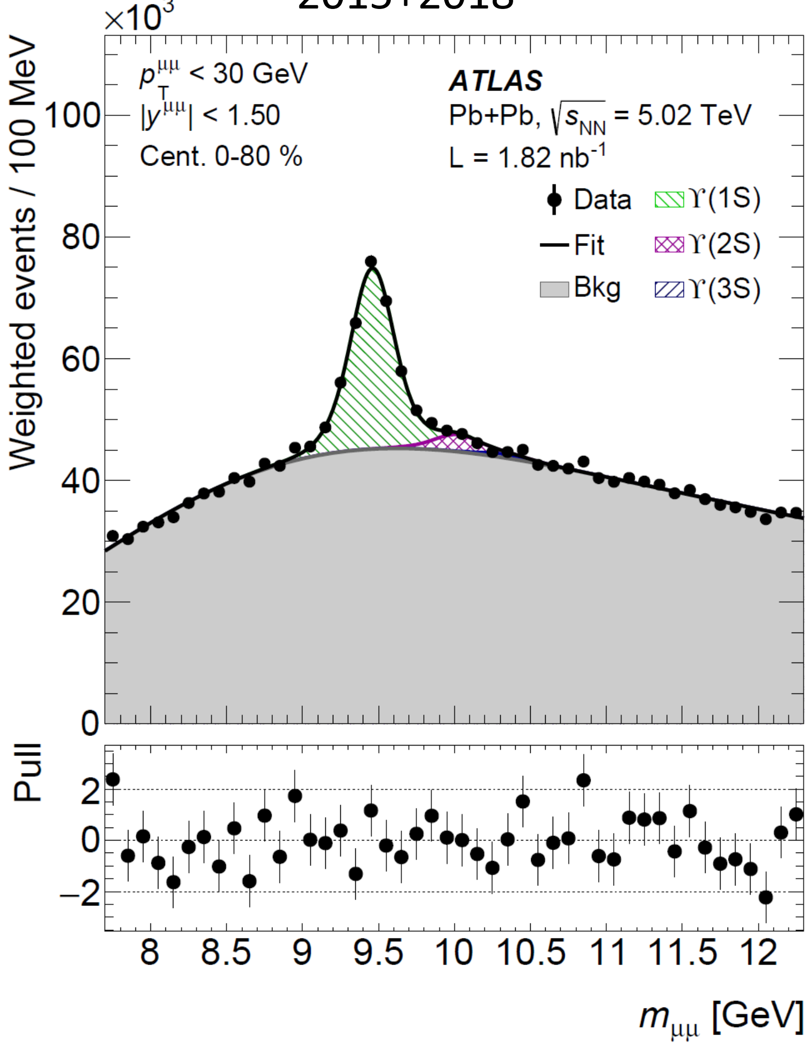
Υ kinematics:
p_T < 30 GeV
|y|<1.5
Centrality: 0-80%

Signal:
Crystal Ball + Gauss

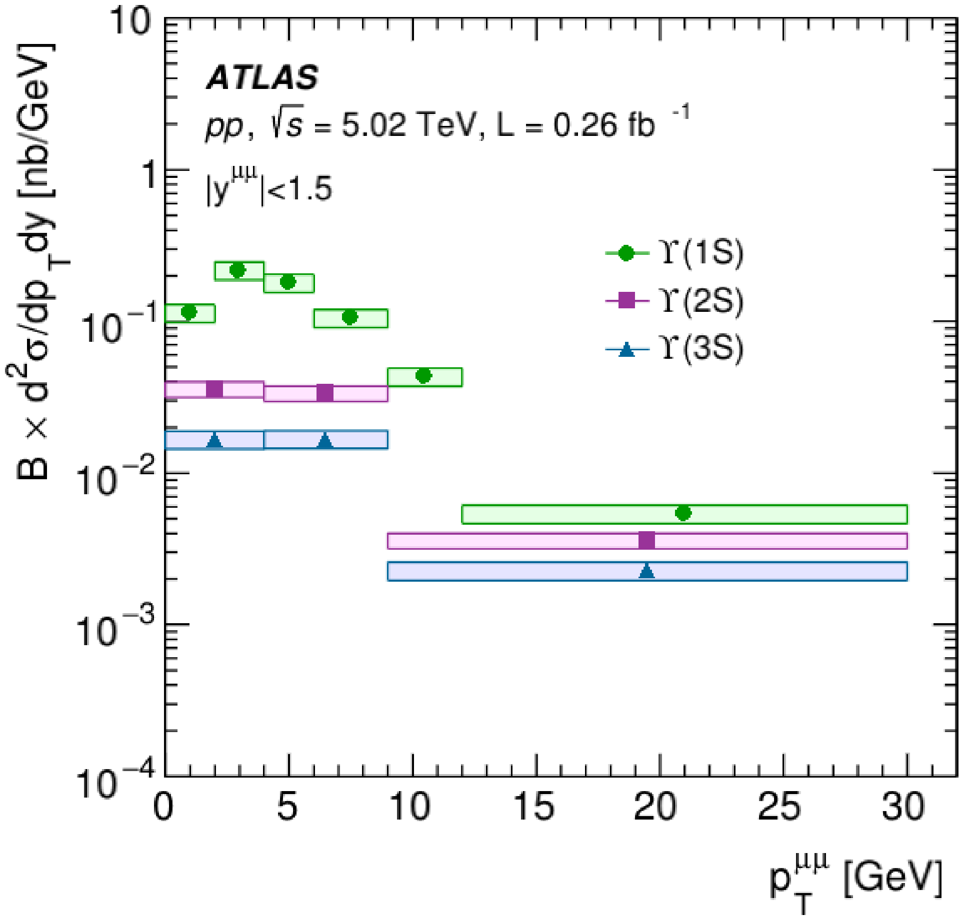
Background:
2nd order polynomial
or Erf*Exp

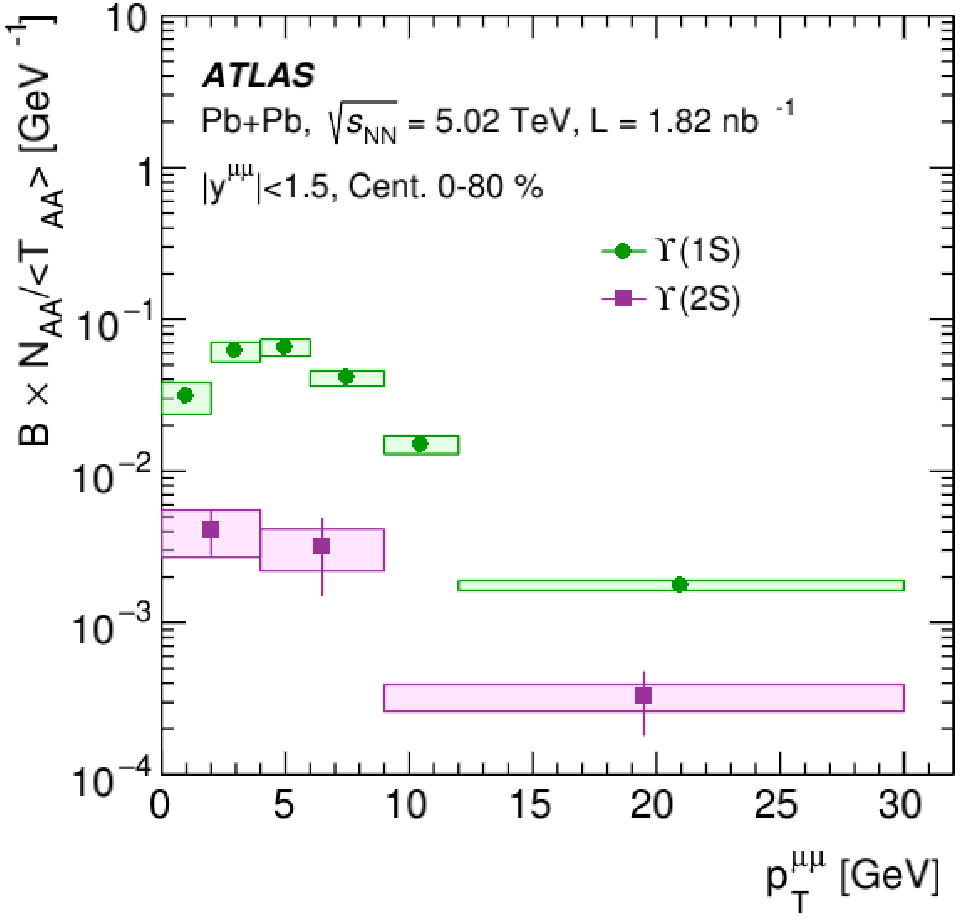


2015+2018



Cross-section in *pp* and Pb+Pb





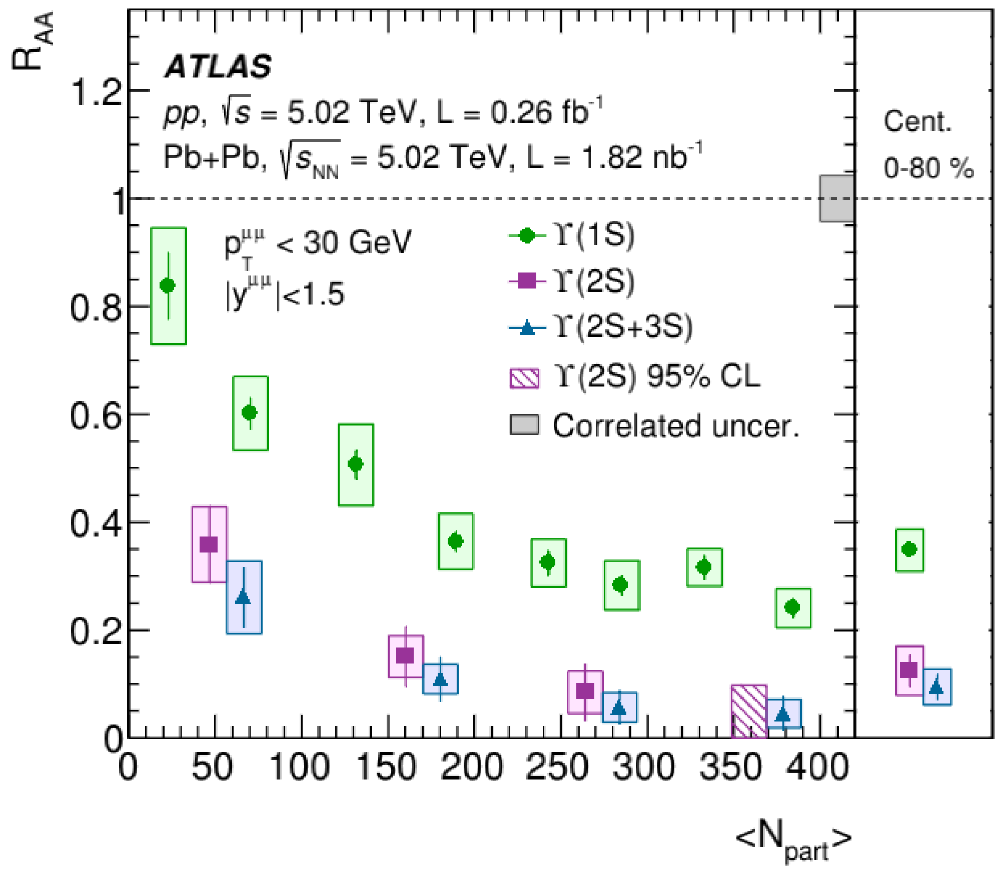
Υ(3S) not shown since peaks are not statistically significant.

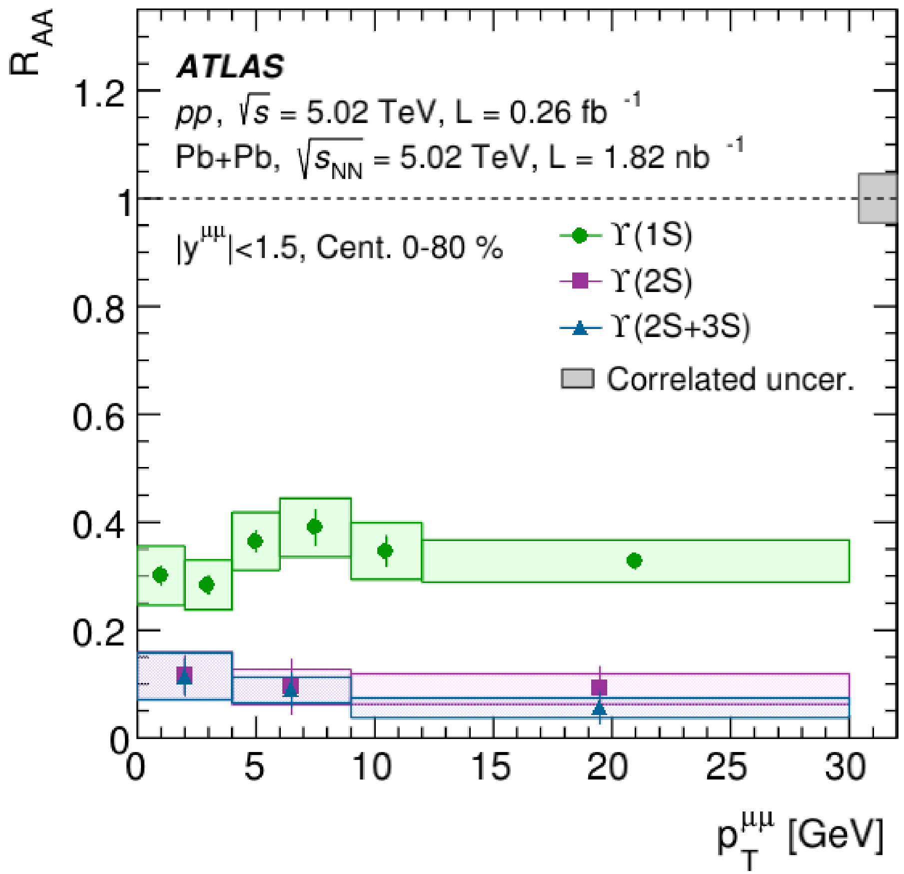
Nuclear modification factor R_{AA}

Nuclear modification factor

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

- Ordering in R_{AA}: Υ(1S) > Υ(2S) > Υ(2S+3S)
- More suppression in more central collisions
- No strong p_T dependence.
- Υ(2S+3S) is shown instead of Υ(3S)

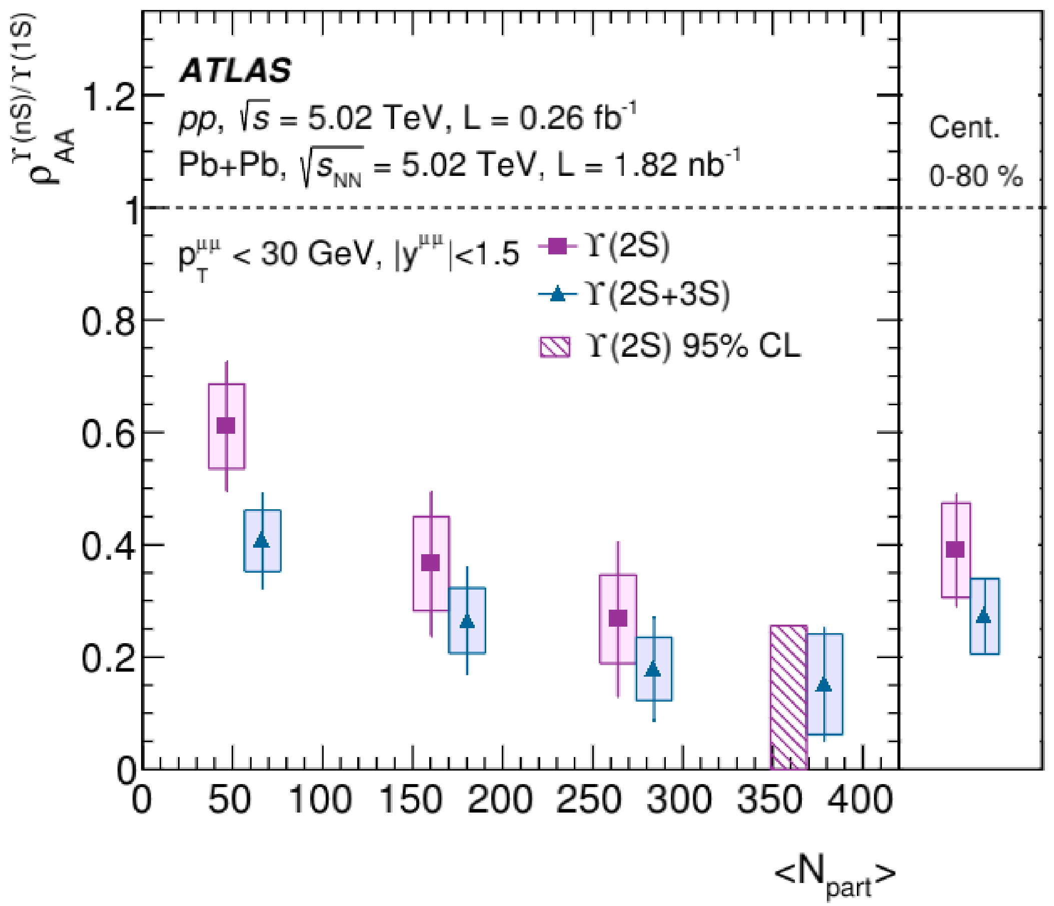


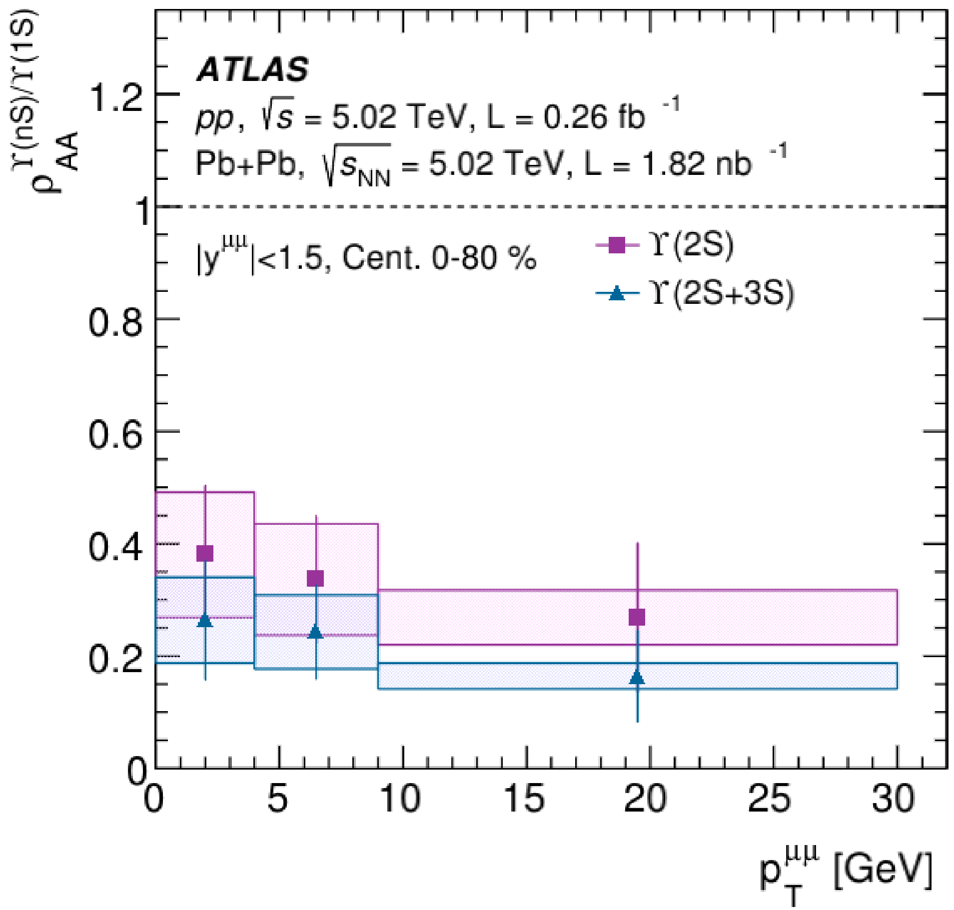


Double ratios

$$\rho_{AA}^{\Upsilon(nS)/\Upsilon(1S)} = \frac{\sigma_{AA}^{\Upsilon(nS)}/\sigma_{AA}^{\Upsilon(1S)}}{\sigma_{pp}^{\Upsilon(nS)}/\sigma_{pp}^{\Upsilon(1S)}} = \frac{R_{AA}(\Upsilon(nS))}{R_{AA}(\Upsilon(1S))}$$

- Luminosity and $\langle T_{AA}\rangle$ corrections cancel
- Acceptance and efficiency corrections partially cancel
- Consistent with sequential melting
- Y(2S+3S) systematically lower than Y(2S)





Comparison with models (R_{AA})

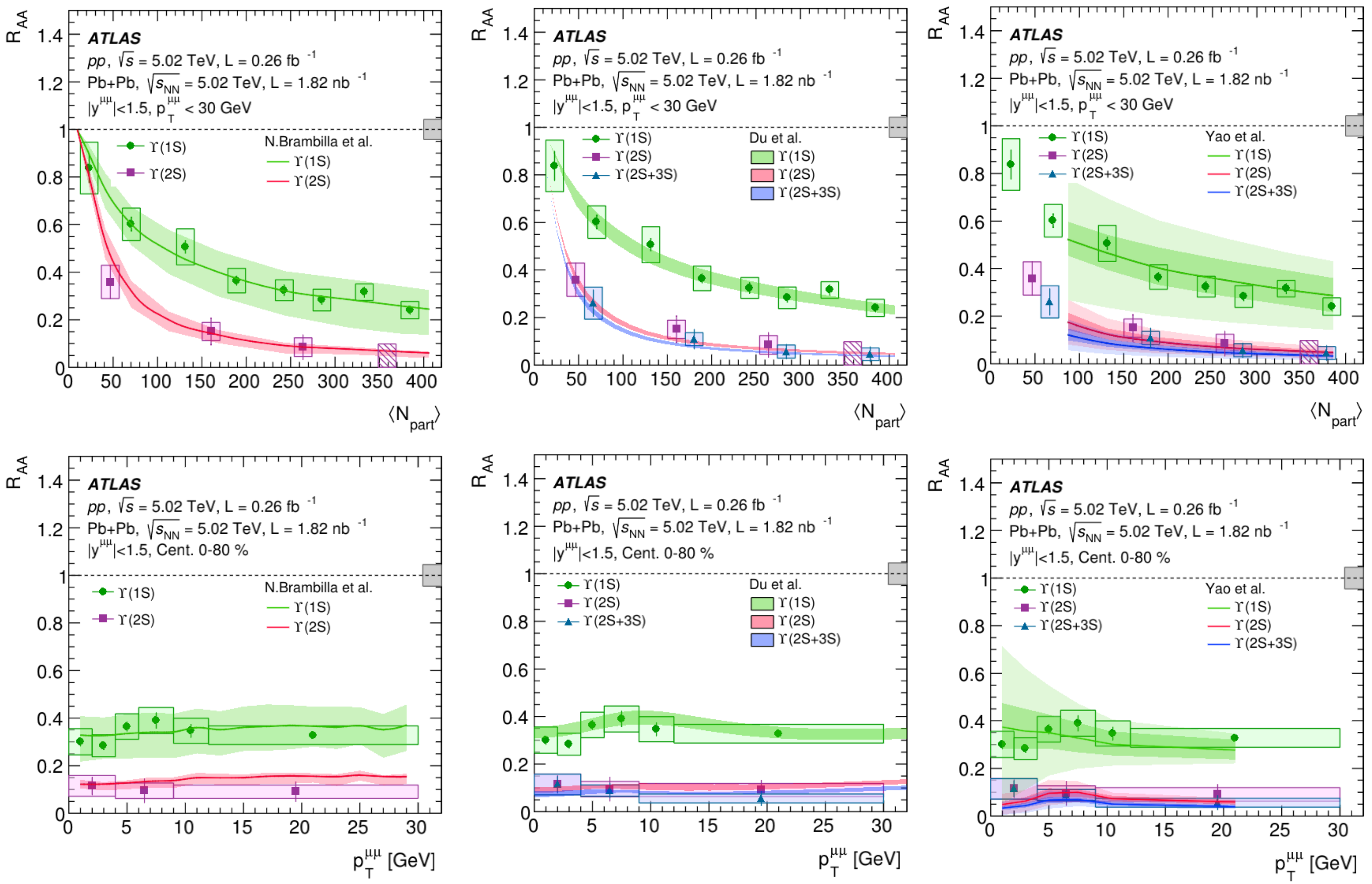
[1] N.Brambilla et al., Phys. Rev. D 104 (2021) 094049

[2] M. H. X.Du and R. Rapp, Phys. Rev. C 96 (2017) 054901

[3] X. Yao et al., JHEP 2021 (2021) 46

- Models use different approach to Υ suppression, but include deconfinement as key ingredient.
- Good agreement with the data. Previous Υ suppression data available to authors.

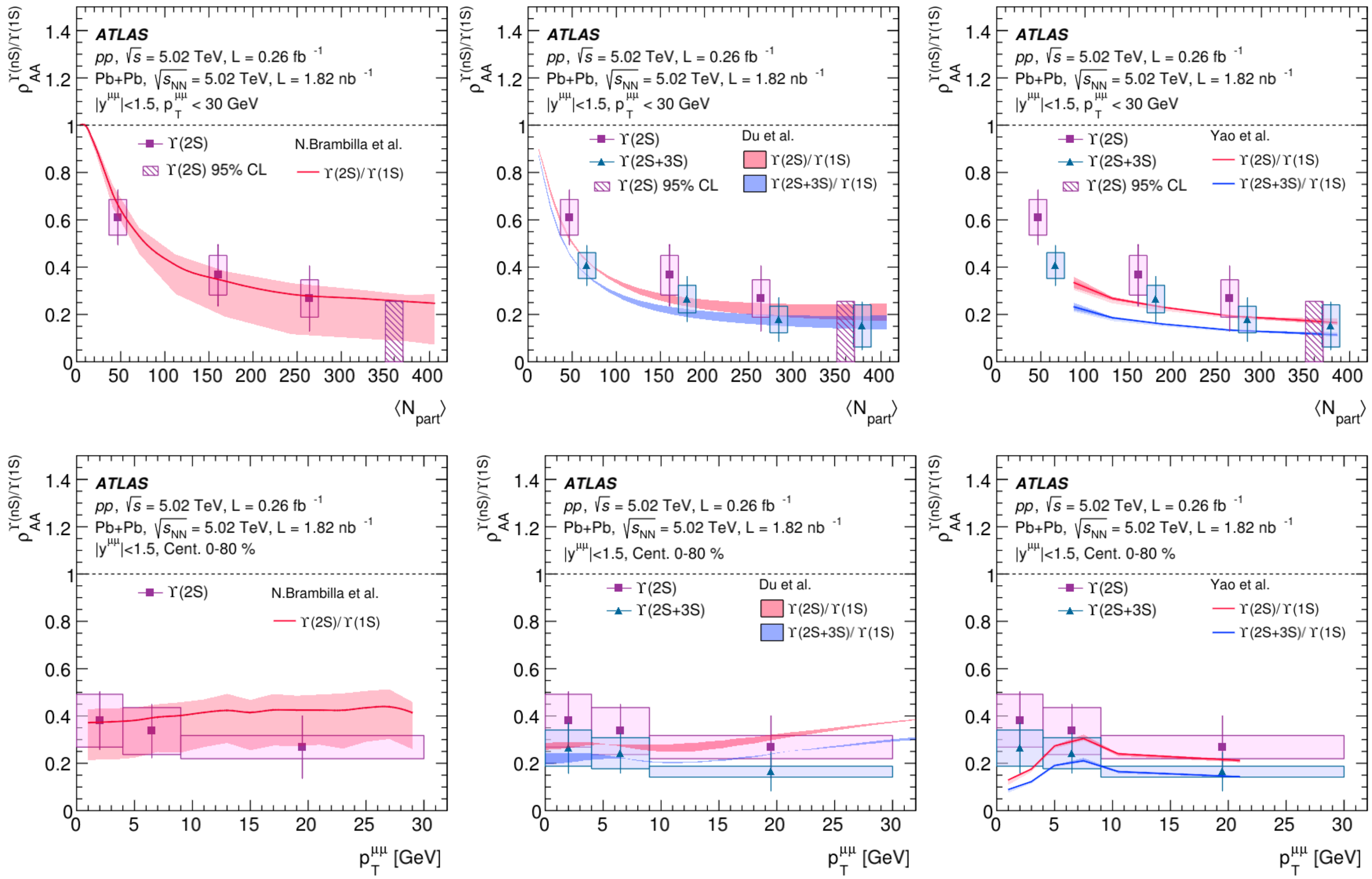
[1] [2] [3]



Comparison with models (double ratios)

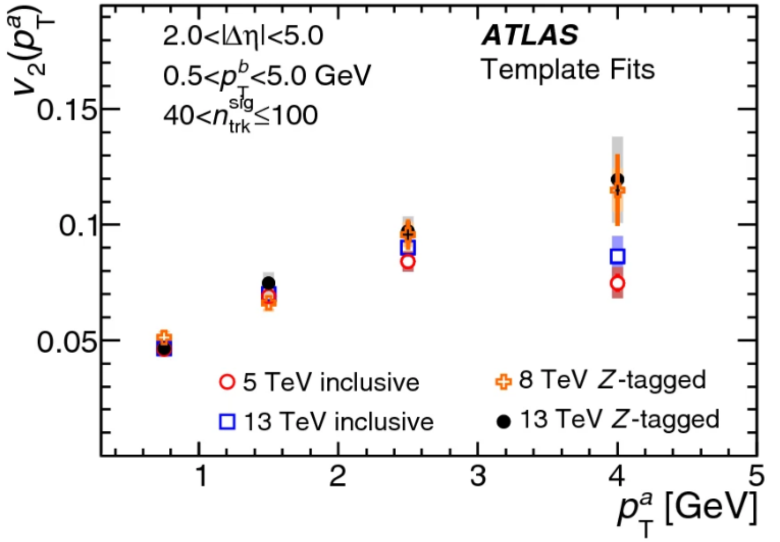
- Good agreement with the data.
- Υ(2S+3S) suppression relative to Υ(2S) in models consistent with data.
- Many model uncertainties cancel in double ratio.

[1] [2] [3]

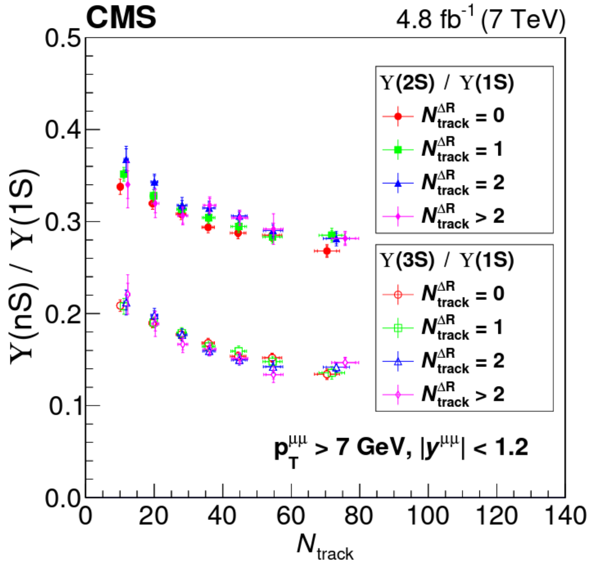


Correlation of Υ meson production with the underlying event in pp collisions

- Heavy ion features have been observed in pp
  - *Flow in Z tagged pp events by ATLAS [Eur. Phys. J* ***C80*** *(2020) 64],*
  - *Υ double ratios decreasing with multiplicity pp events by CMS [JHEP* ***2020*** *(2020) 001]*



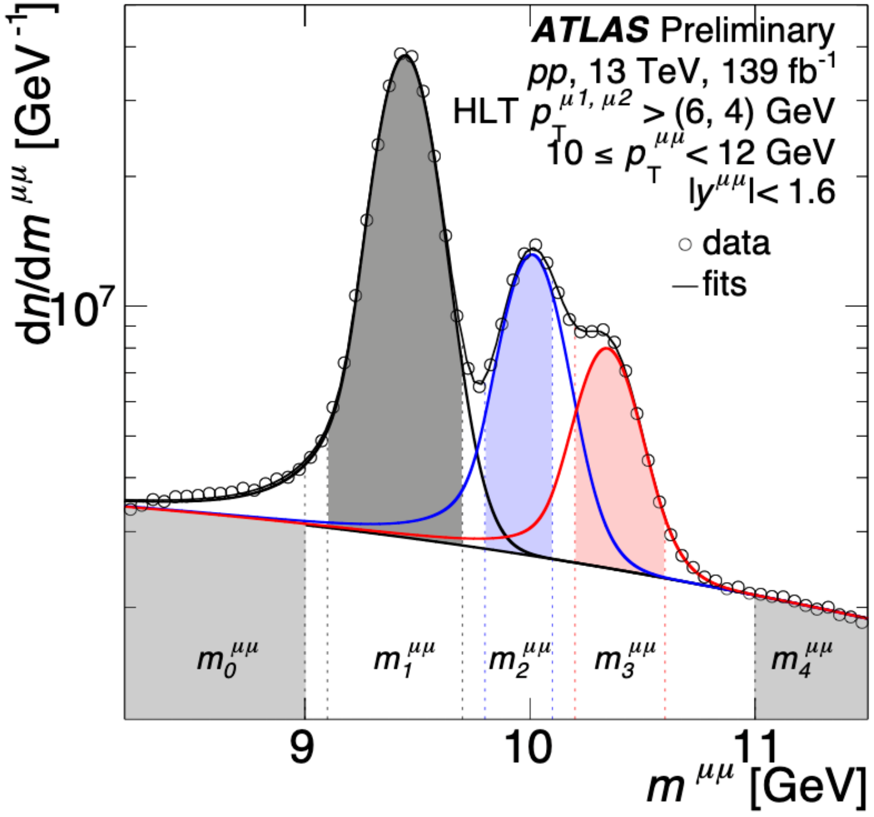
- We search for QGP-like signatures by looking at how underlying event changes in events with Upsilons
  - *Measure charged particle multiplicity, p_T and $\Delta\phi$ distributions in events with different Υ states.*

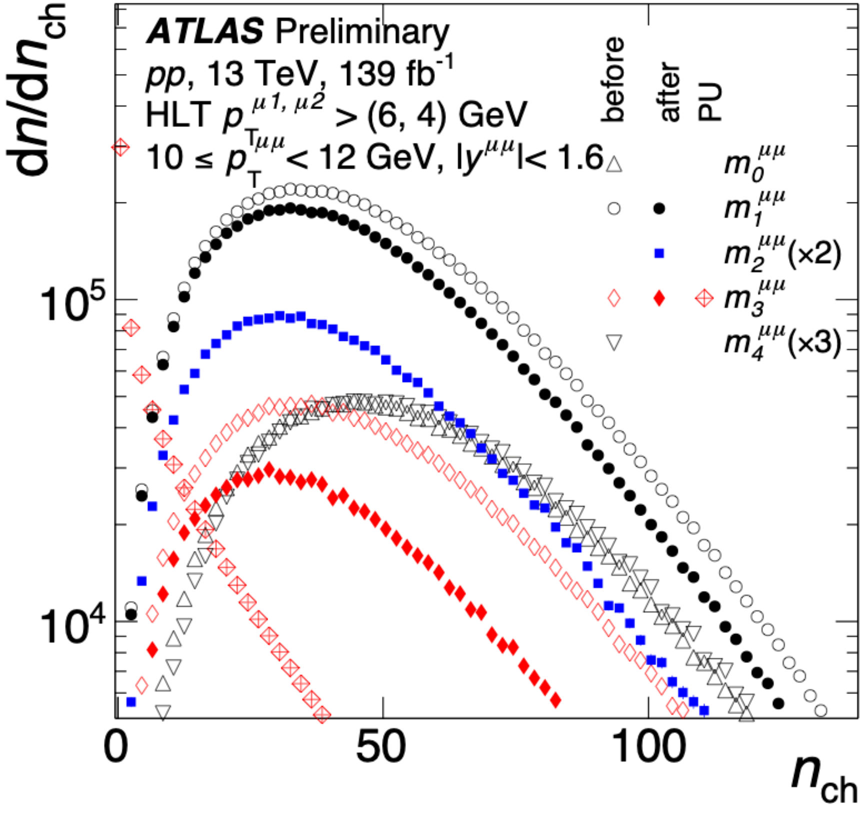


- For details see poster by Iakov Aizenberg

Analysis details

- Entire Run-2 *pp* 13 TeV collisions, 139 fb^{-1}
- Events with Υ(nS)→$\mu\mu$, $|y|$<1.6, all triggers, all p_T
- Charged hadron n_{ch}, dn_{ch}/dp_T and $dn_{ch}/d\Delta\phi$. $\Delta\phi=\phi^{\Upsilon}-\phi^{h}$
- Fully corrected, including pileup





Analysis details

- Select 5 mass regions

- Entire Run-2 *pp* 13 TeV collisions, 139 fb^{-1}
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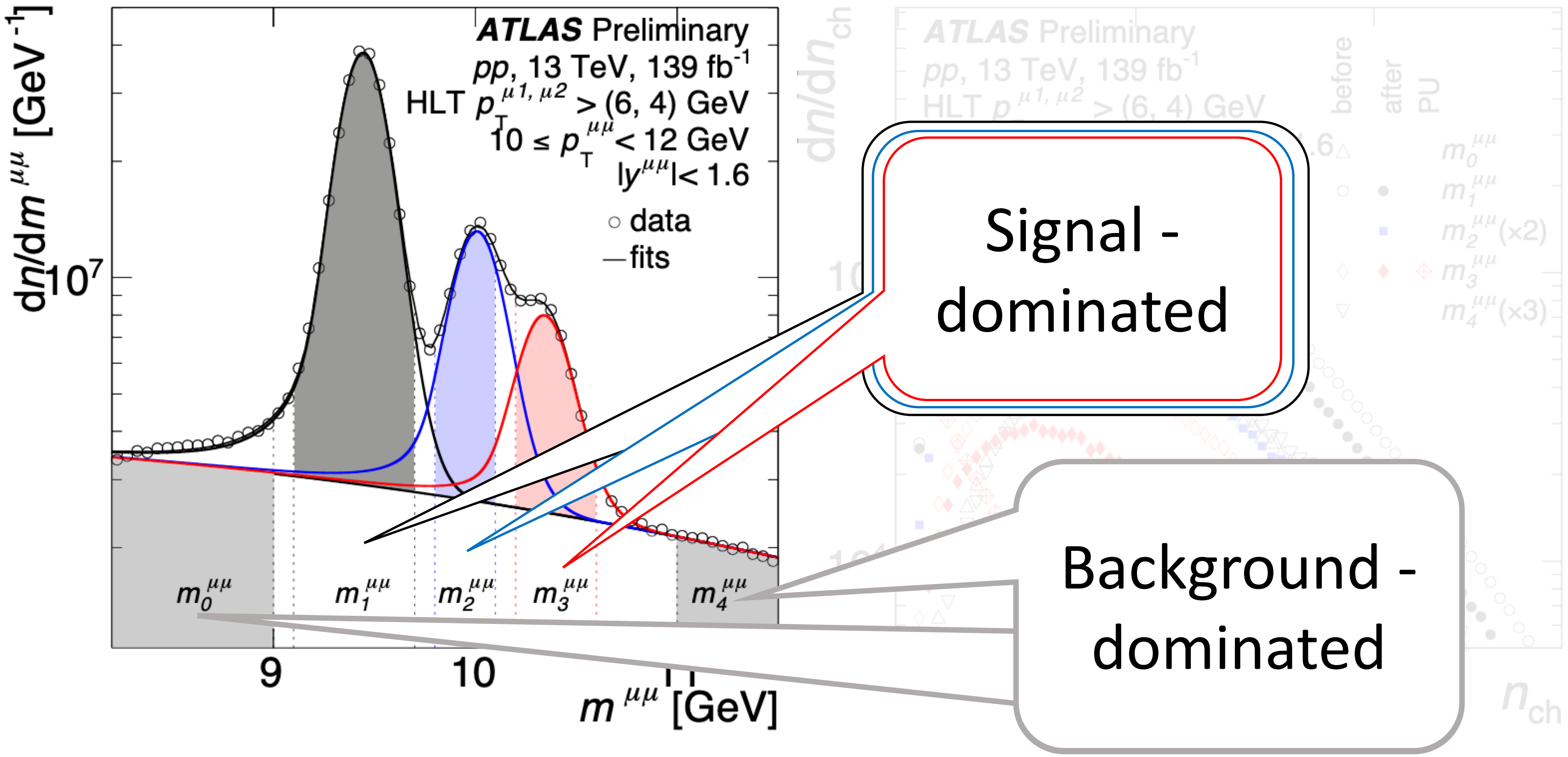

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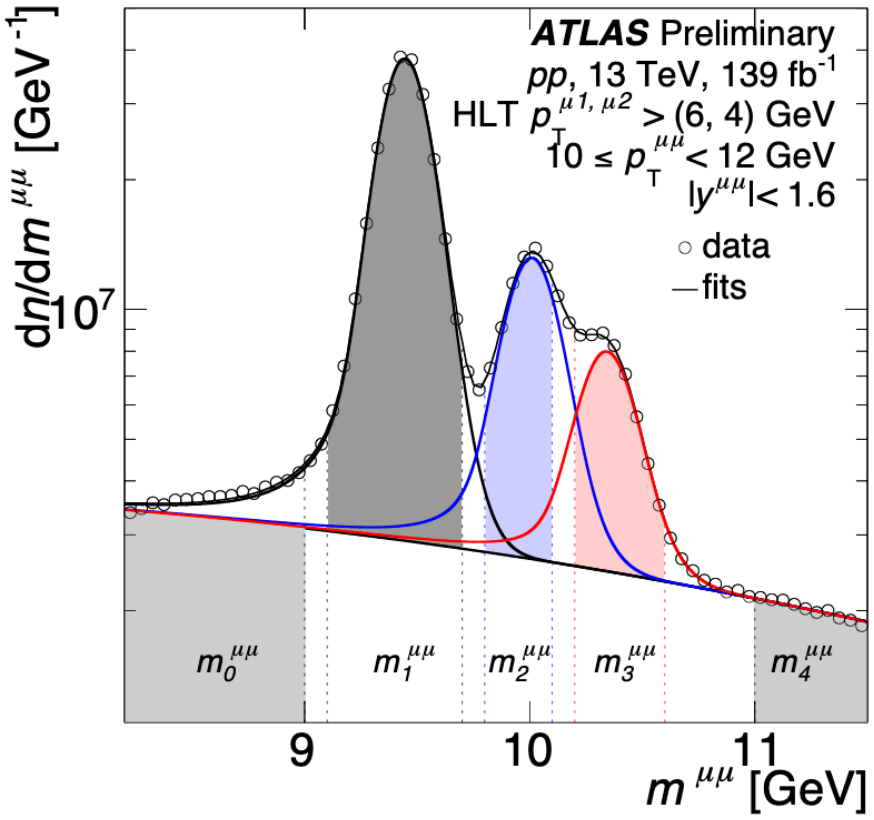

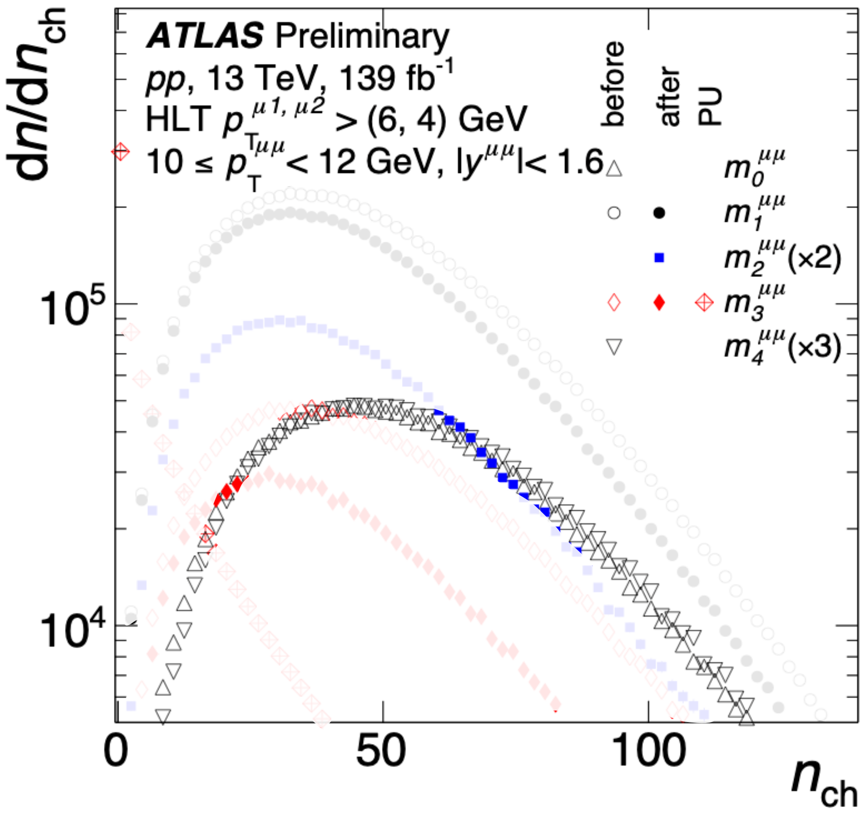

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- Bkg shapes are similar – interpolate

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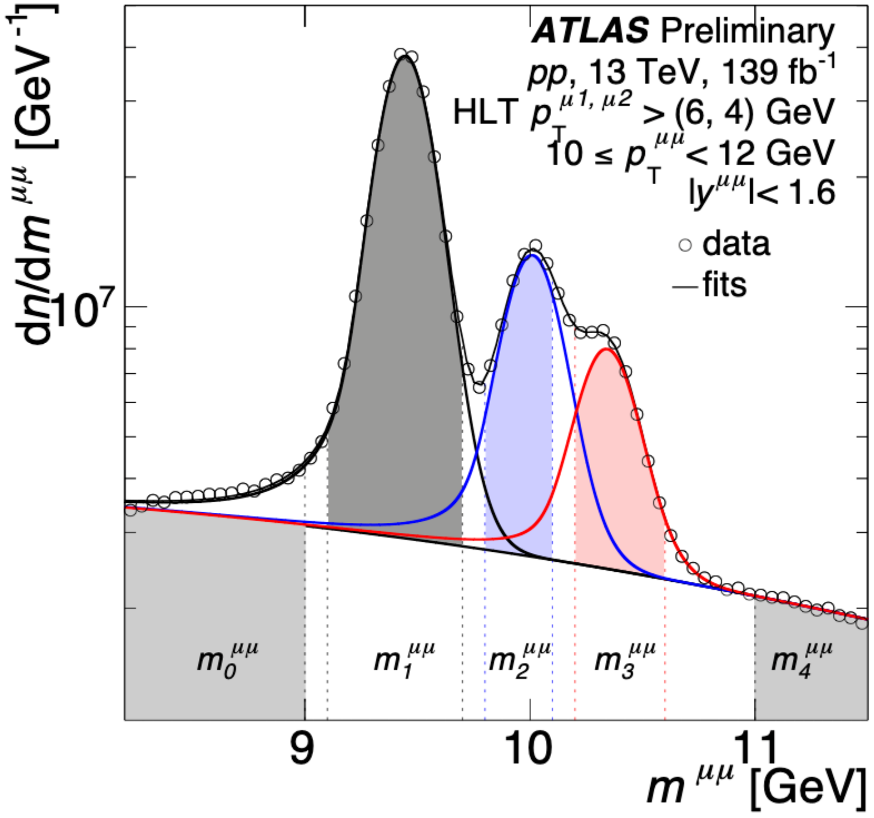

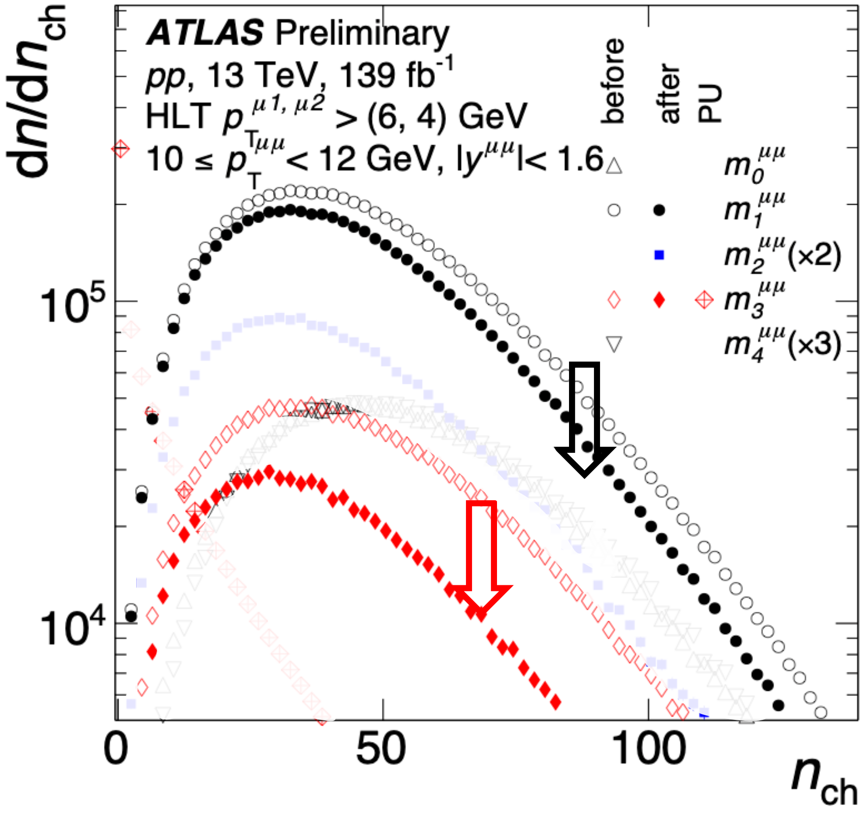

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- Bkg shapes are similar – interpolate
- Bkg subtraction for Y(1S) and Y(3S)

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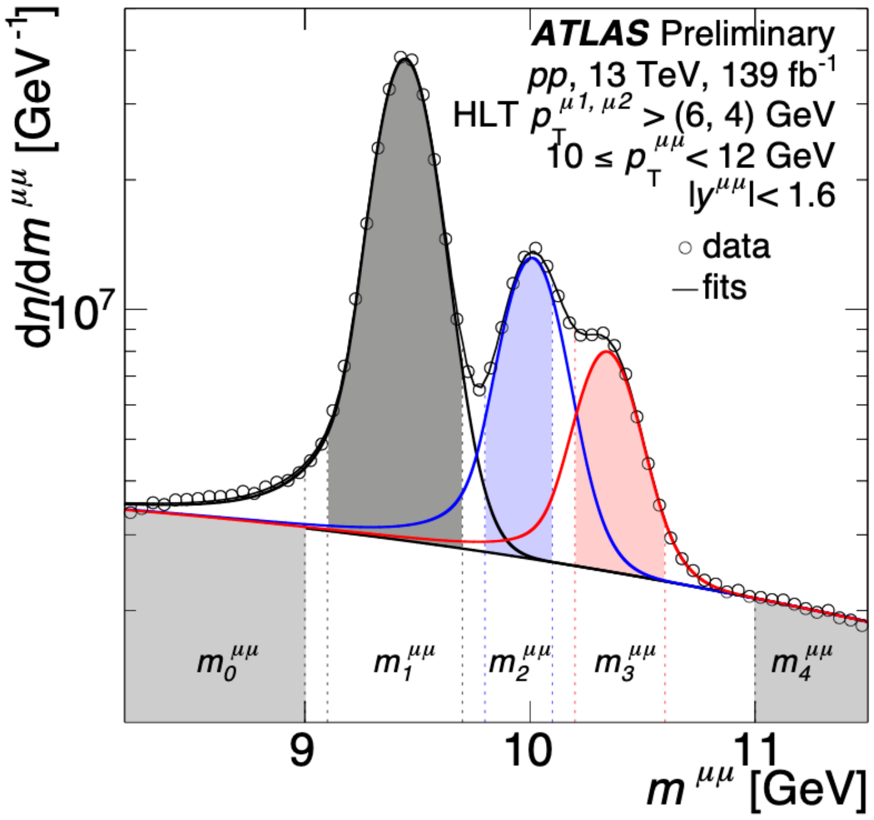

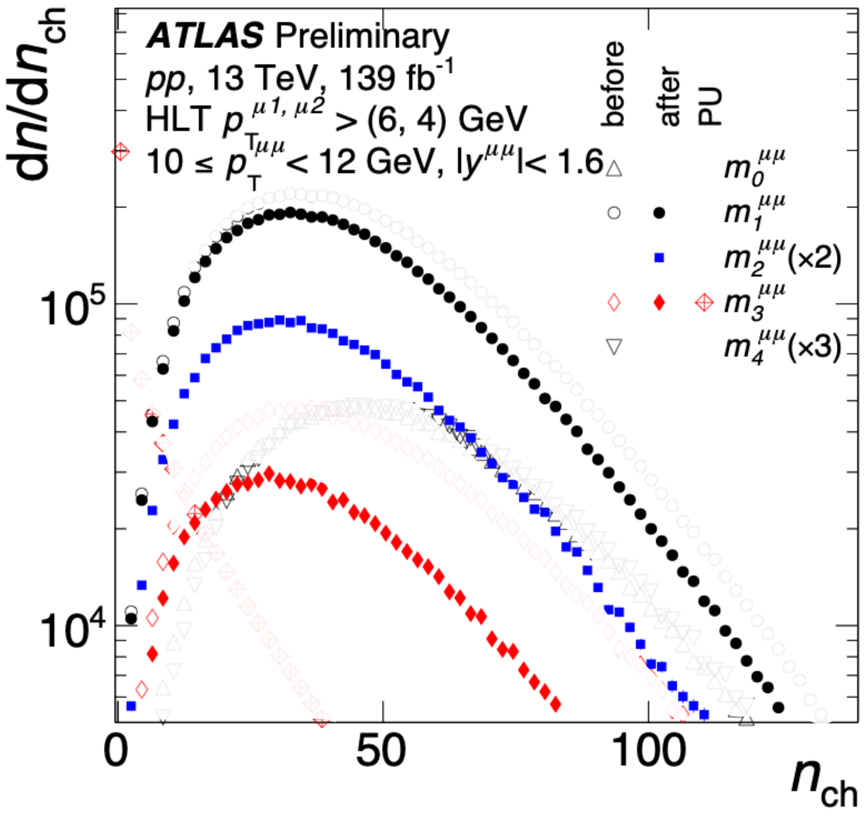

- Define 3+2 regions
- Bkg shapes are similar – interpolate
- Bkg subtraction for Y(1S) and Y(3S)
- After subtraction n_{ch} look different

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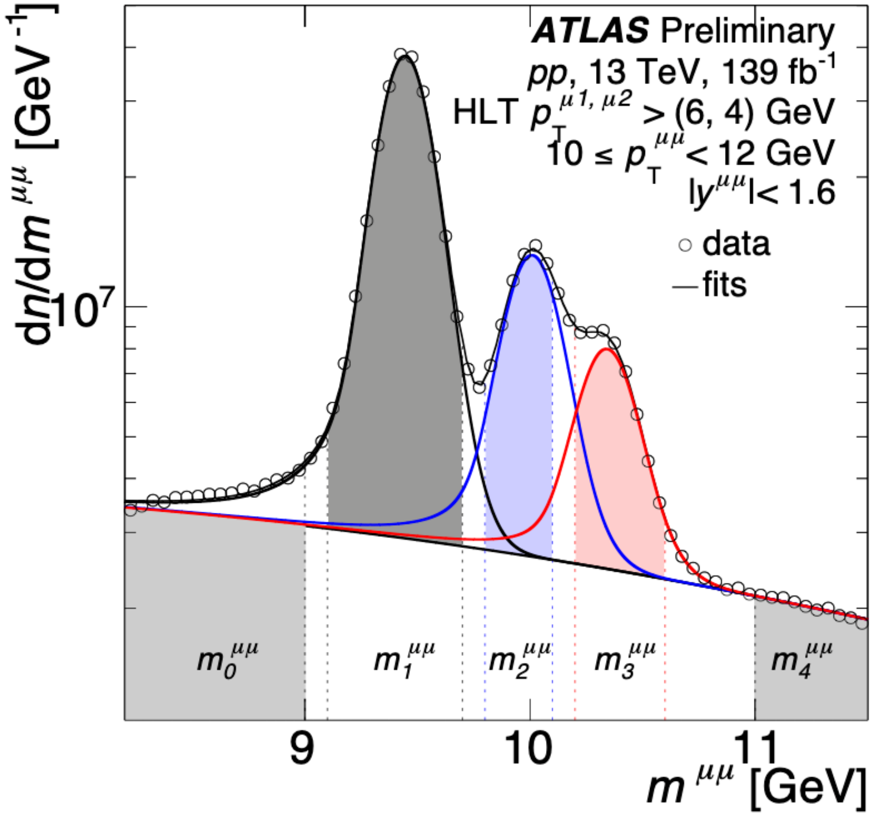

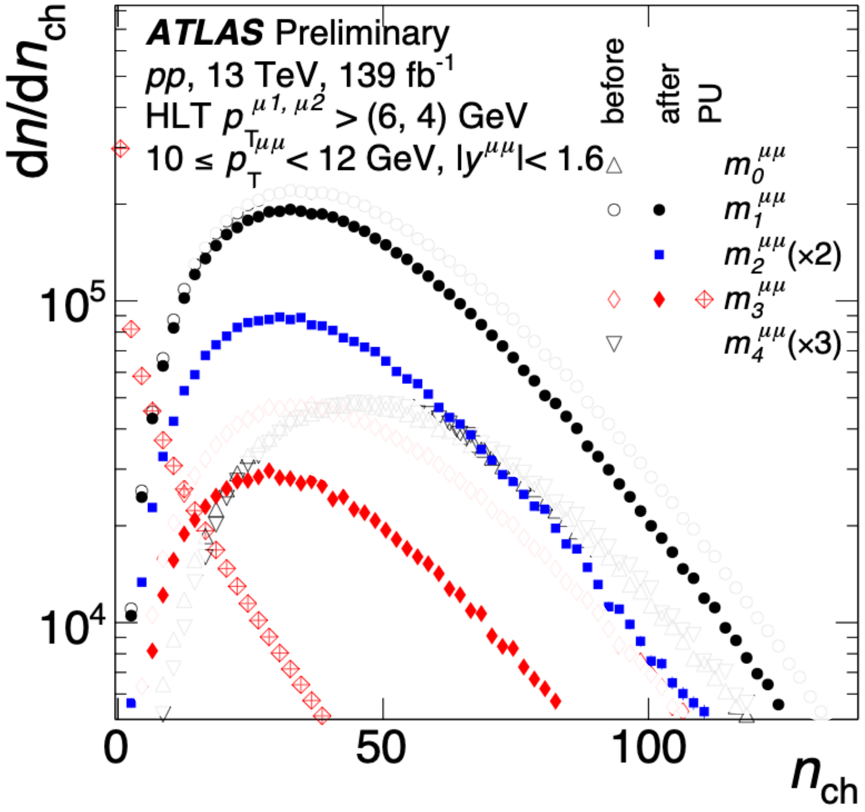

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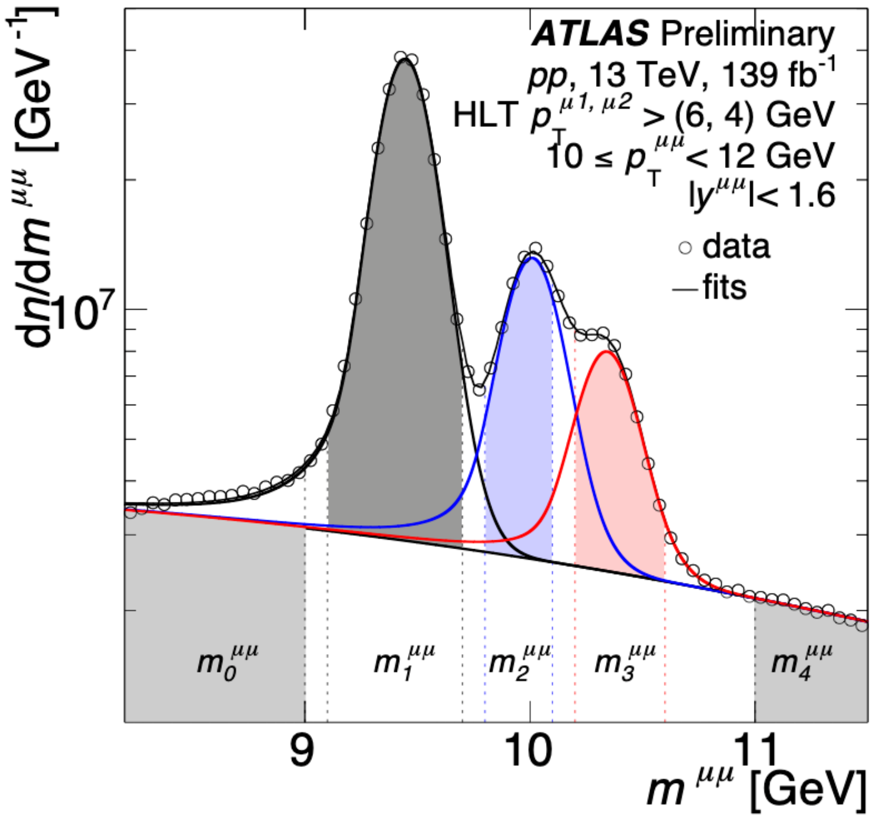
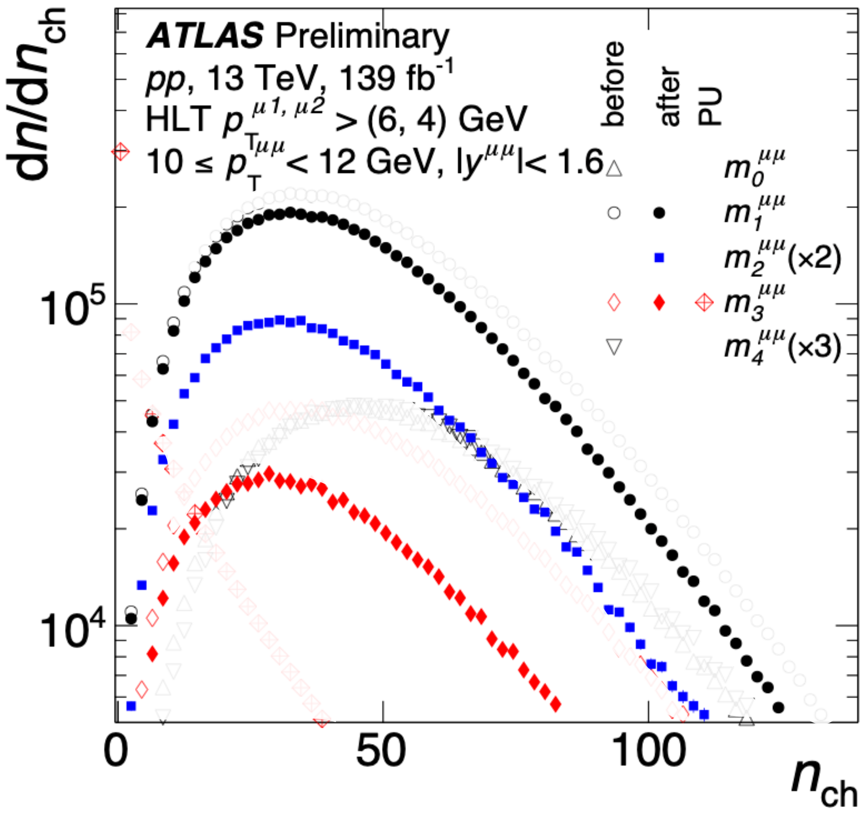
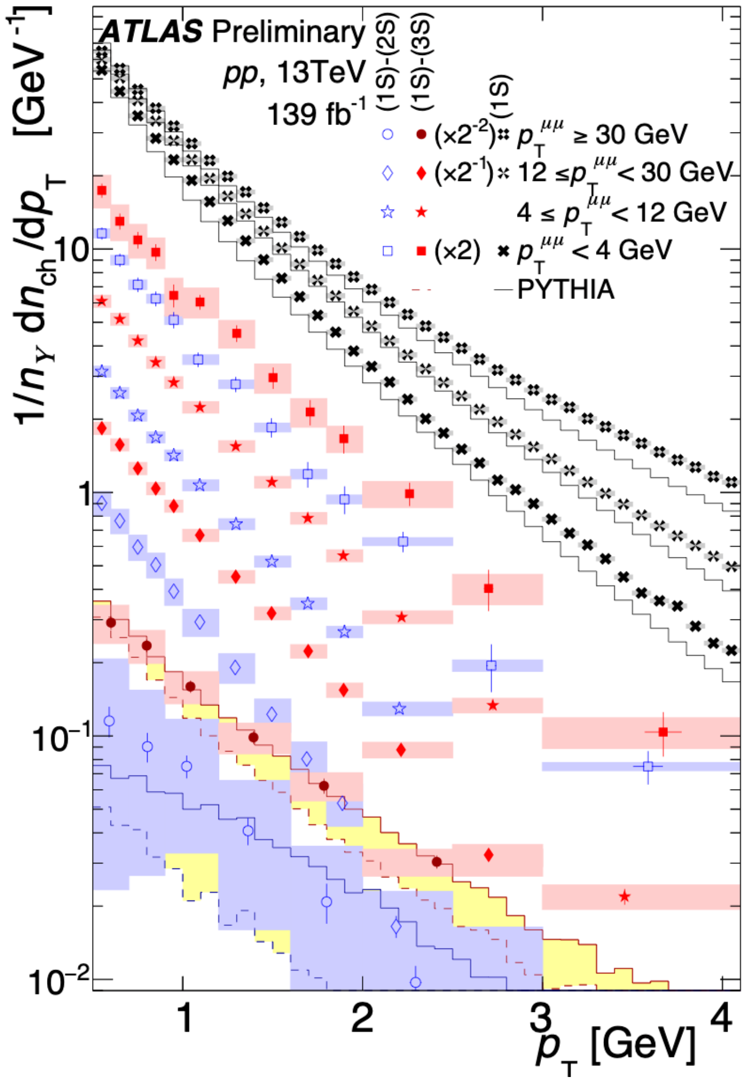
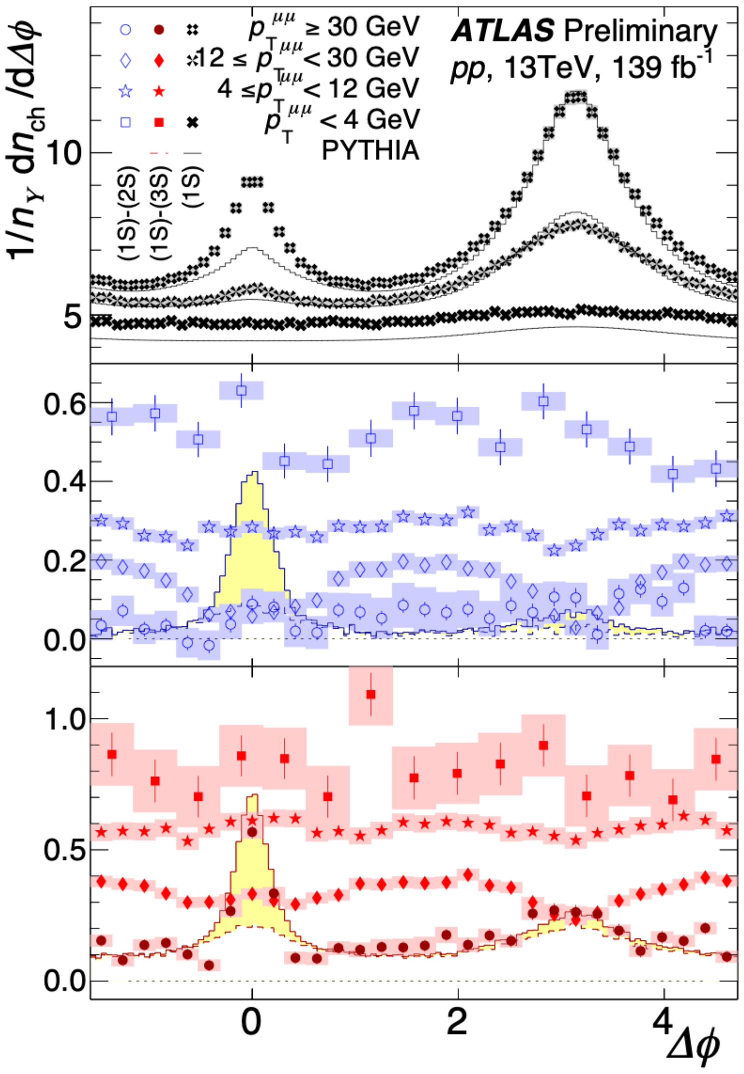




- Define 3+2 regions
- Bkg shapes are similar – interpolate
- Bkg subtraction for Y(1S) and Y(3S)
- After subtraction n_{ch} look different
- Remove PU, same shape for all Y(nS)
- Direct measurement of n_{ch} dn_{ch}/dp_T $dn_{ch}/d\Delta\phi$

Kinematic distributions





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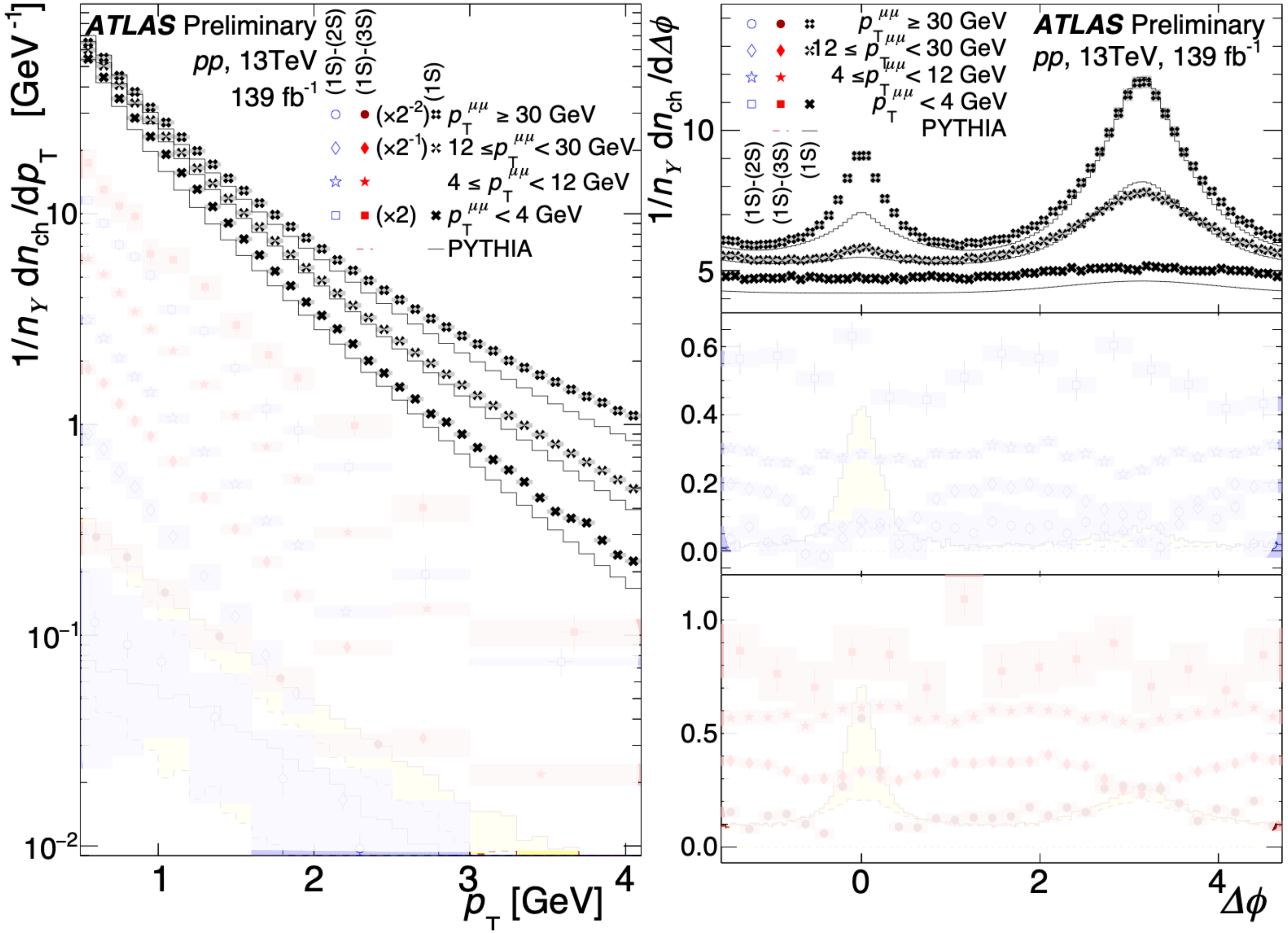
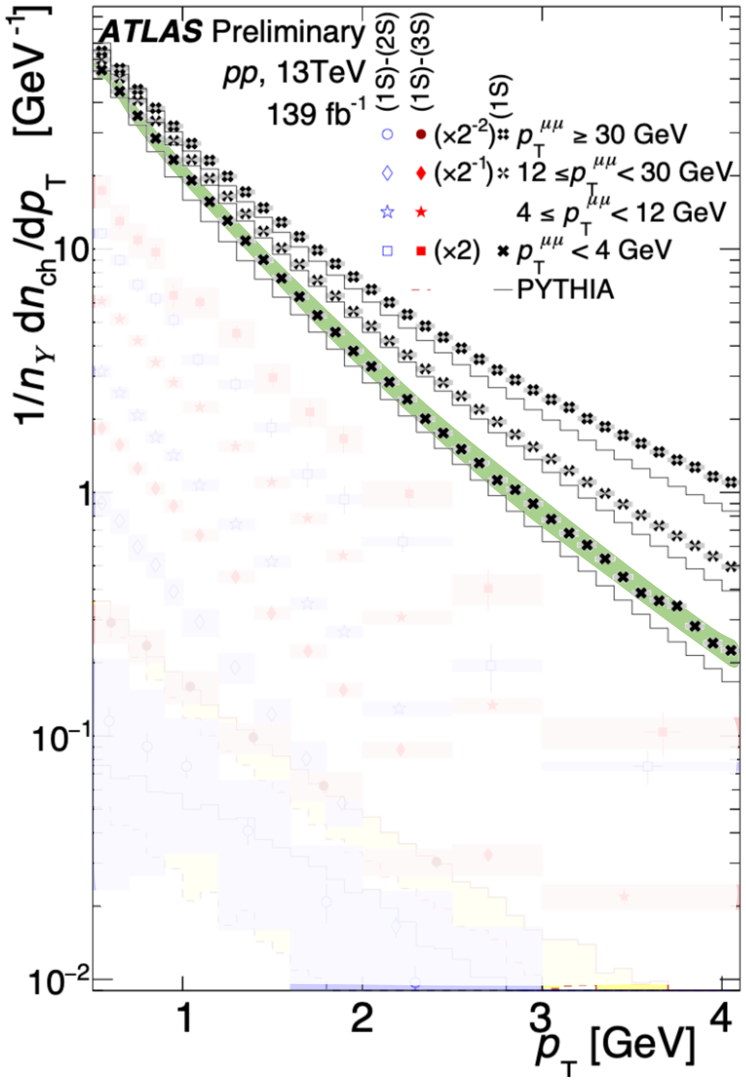
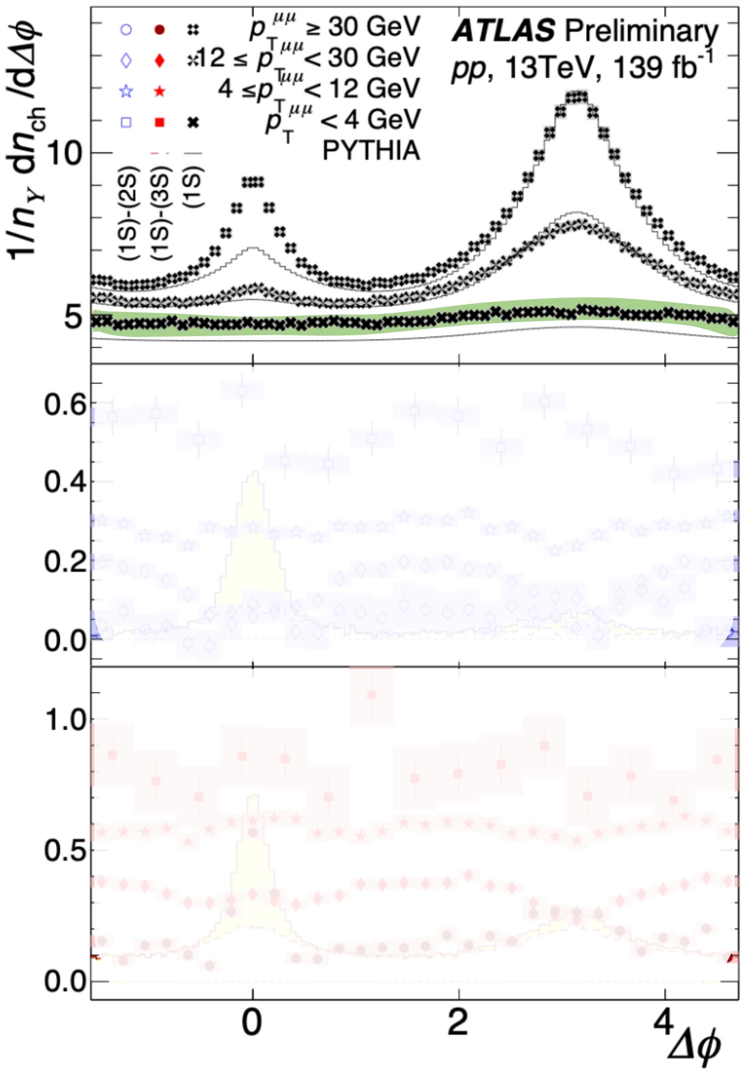


- Distributions for Υ(1S)
- Pythia does not describe well

Kinematic distributions





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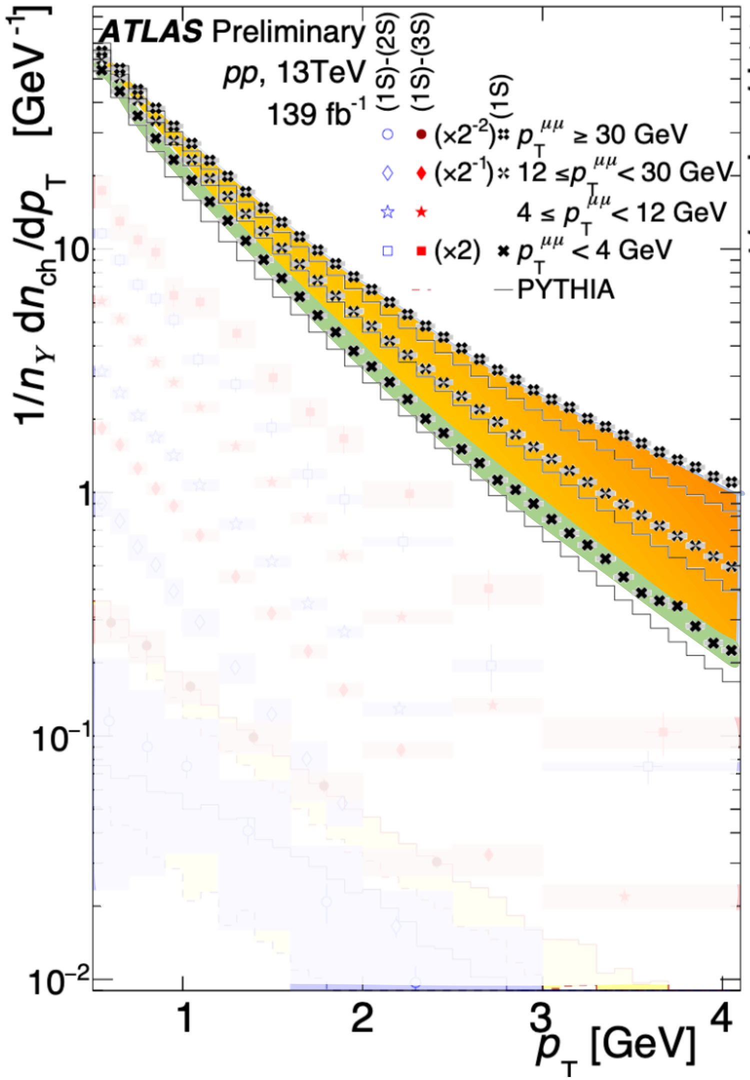
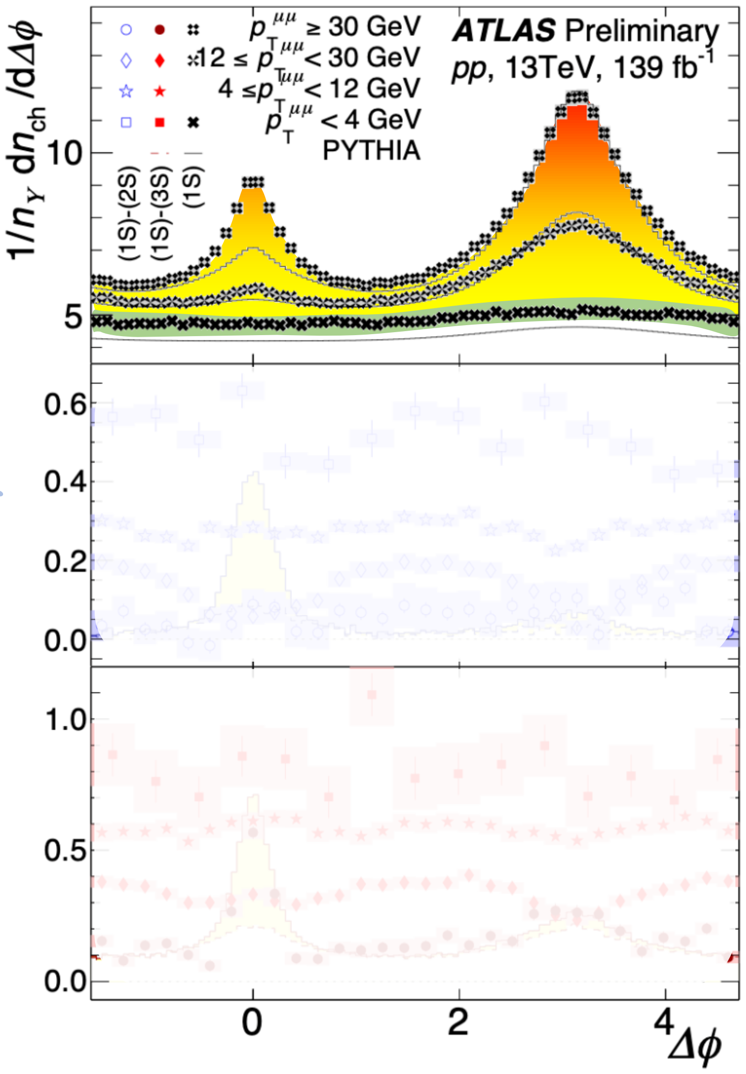
Kinematic distributions





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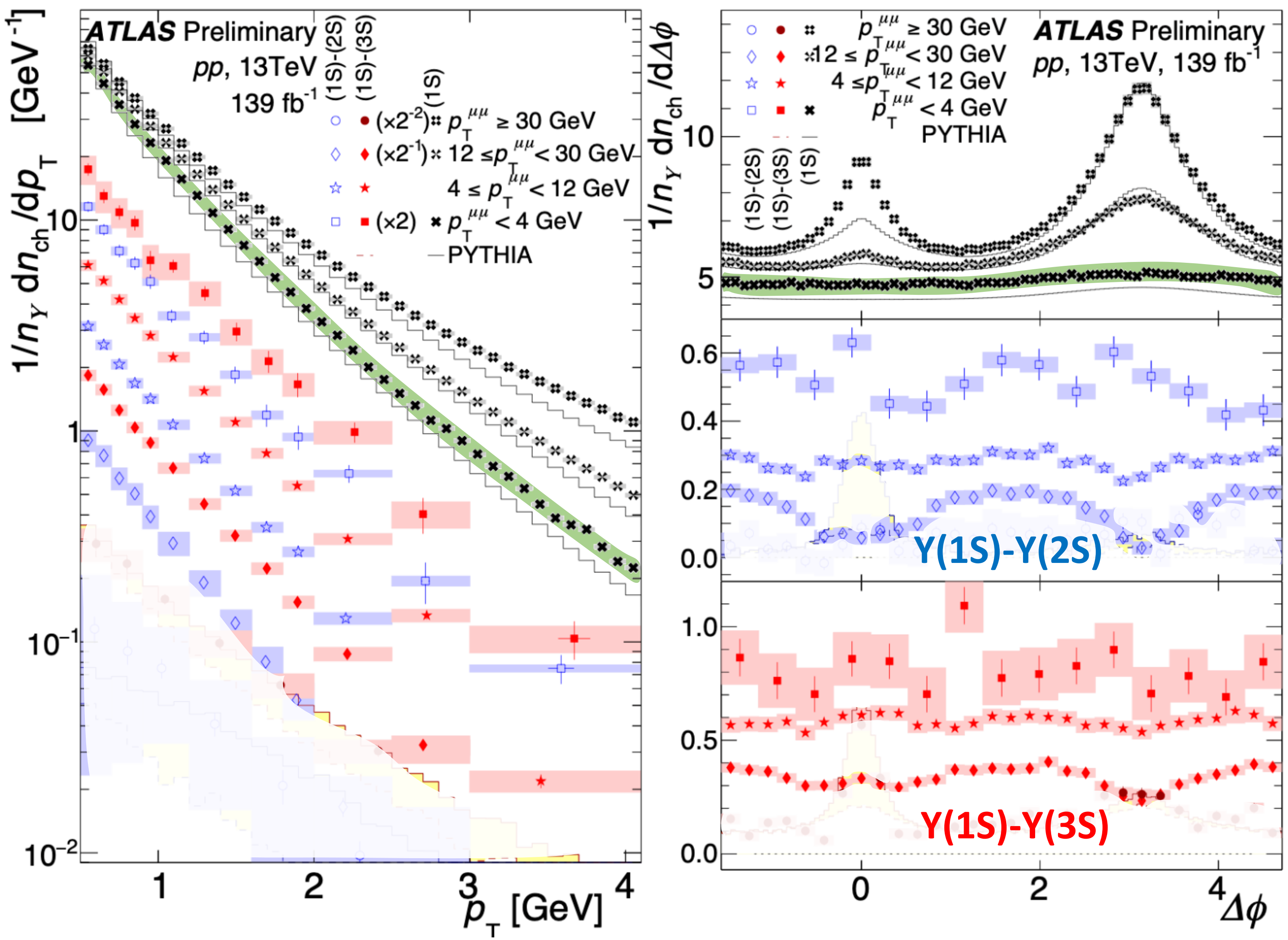

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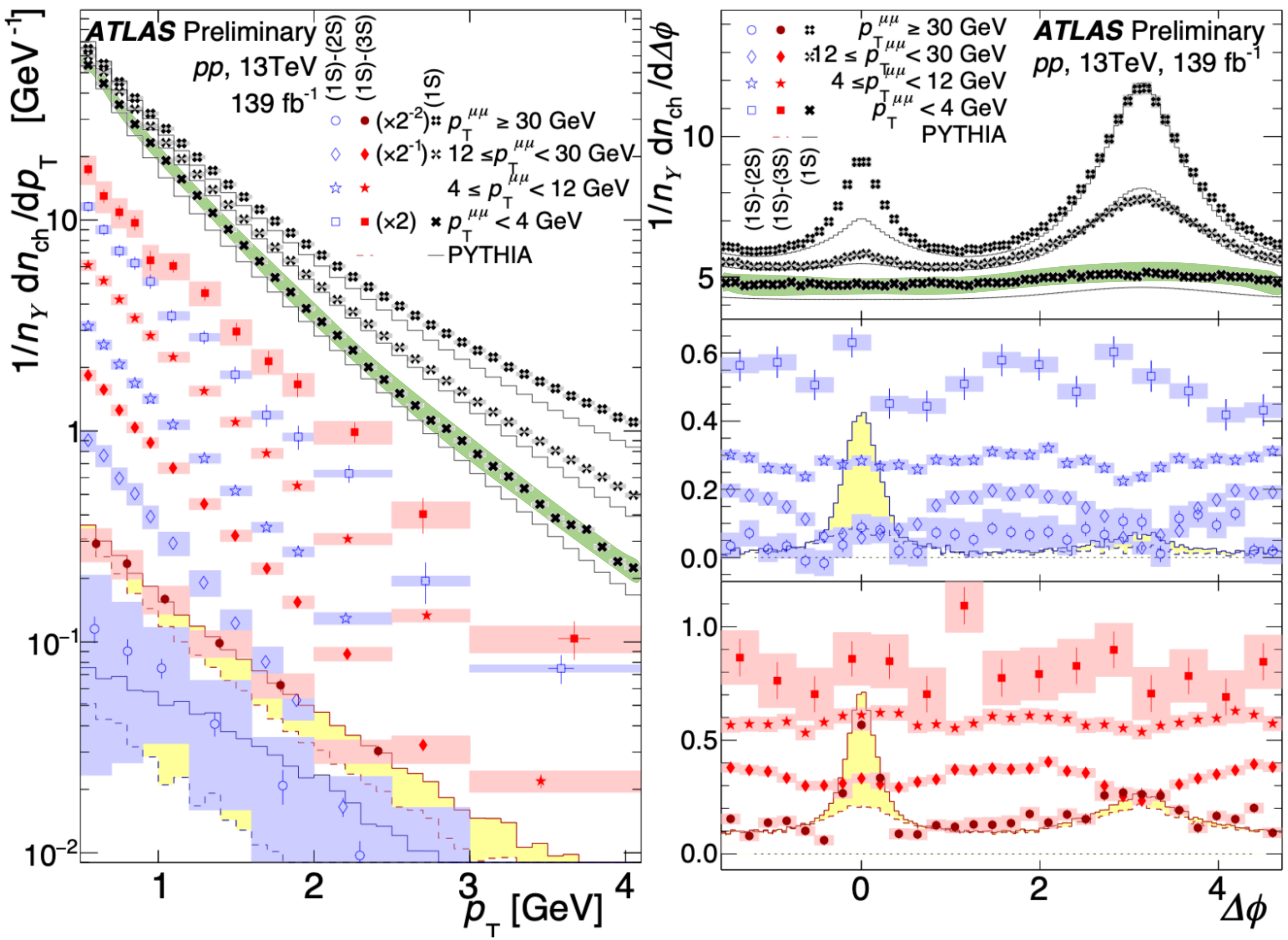
- Subtracted distributions look like UE at rather high Y(nS) p_T.

Kinematic distributions



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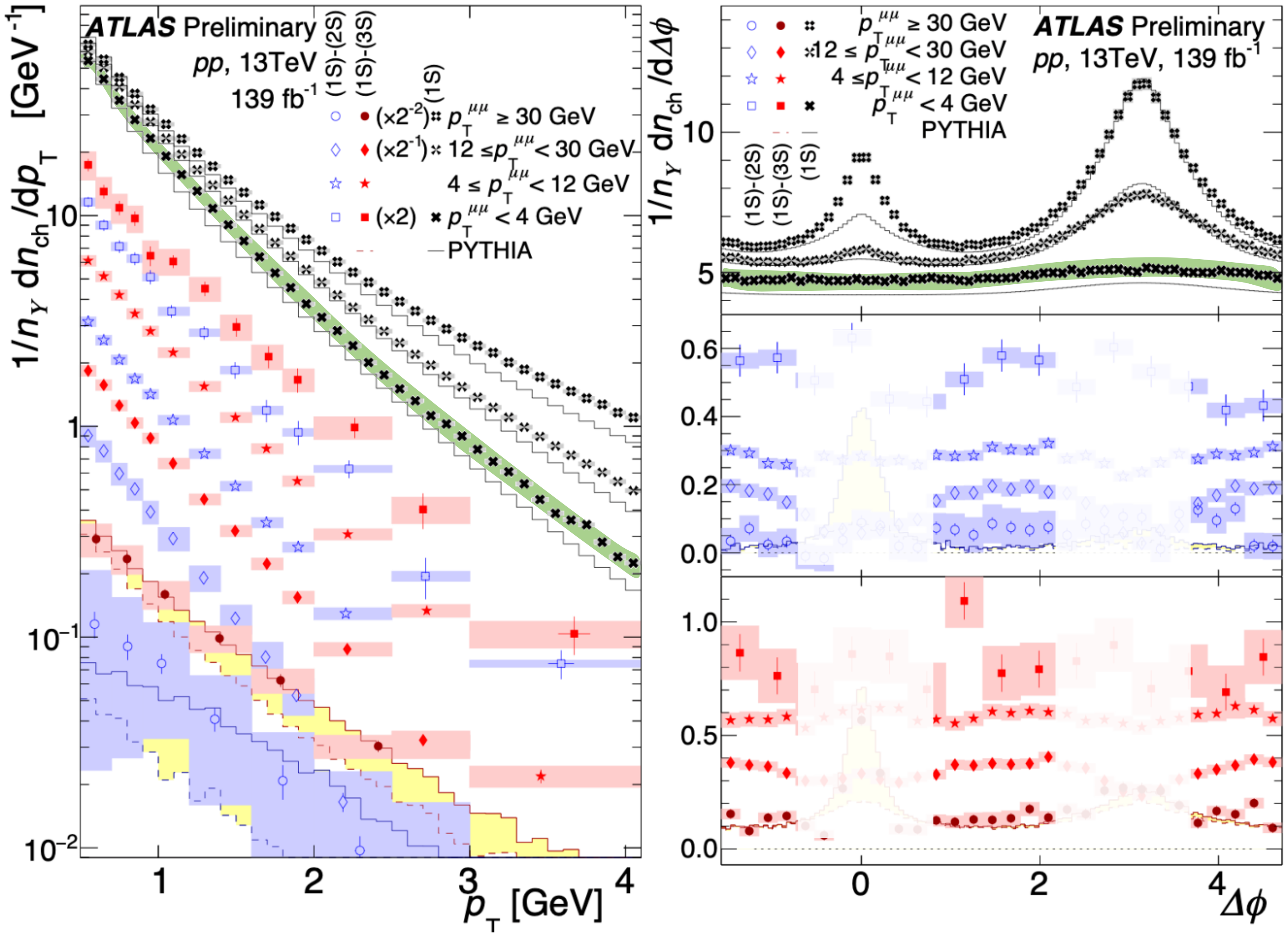
Kinematic distributions



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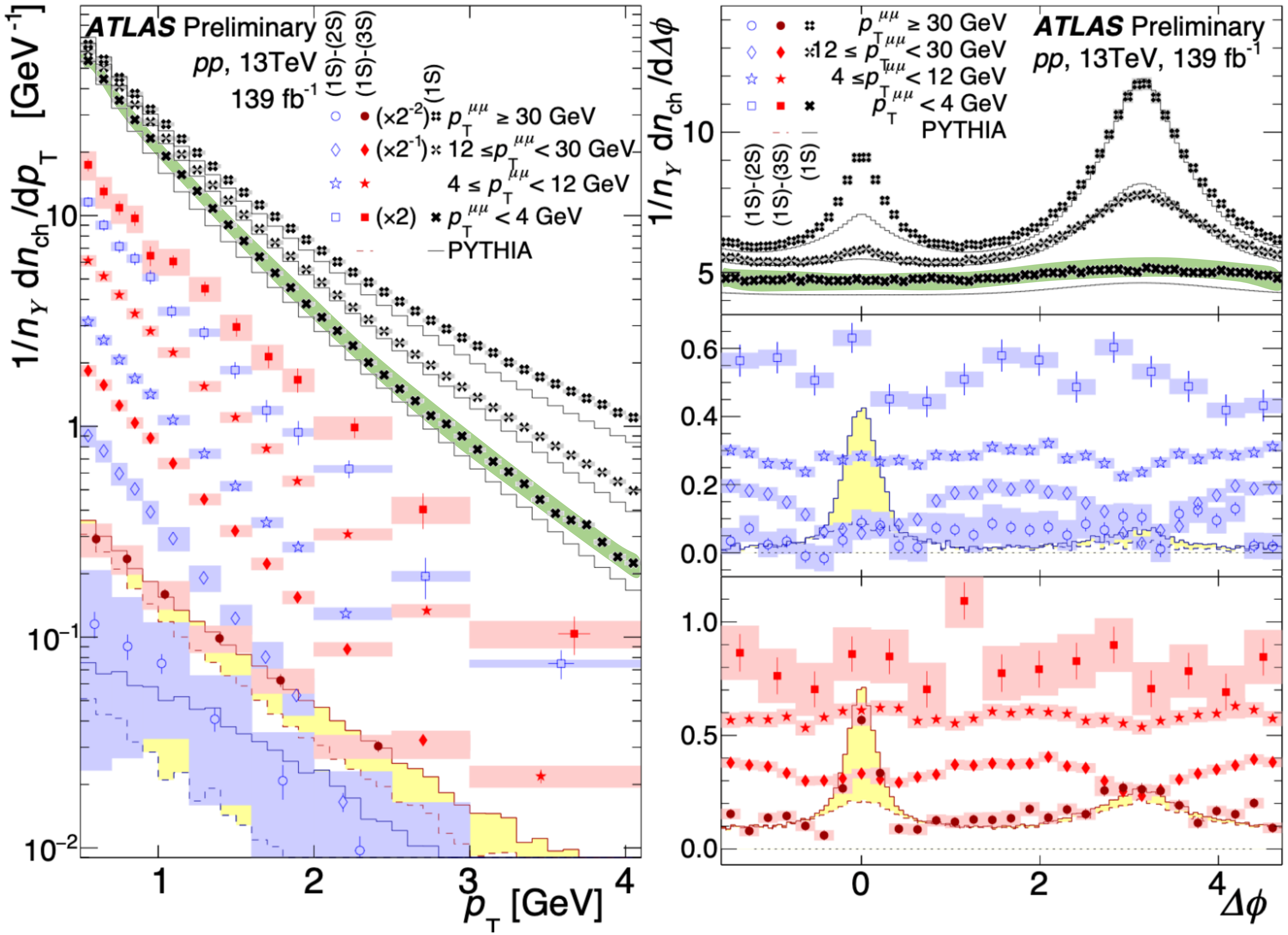
- Away from jets there are regions with charged particles.

Kinematic distributions



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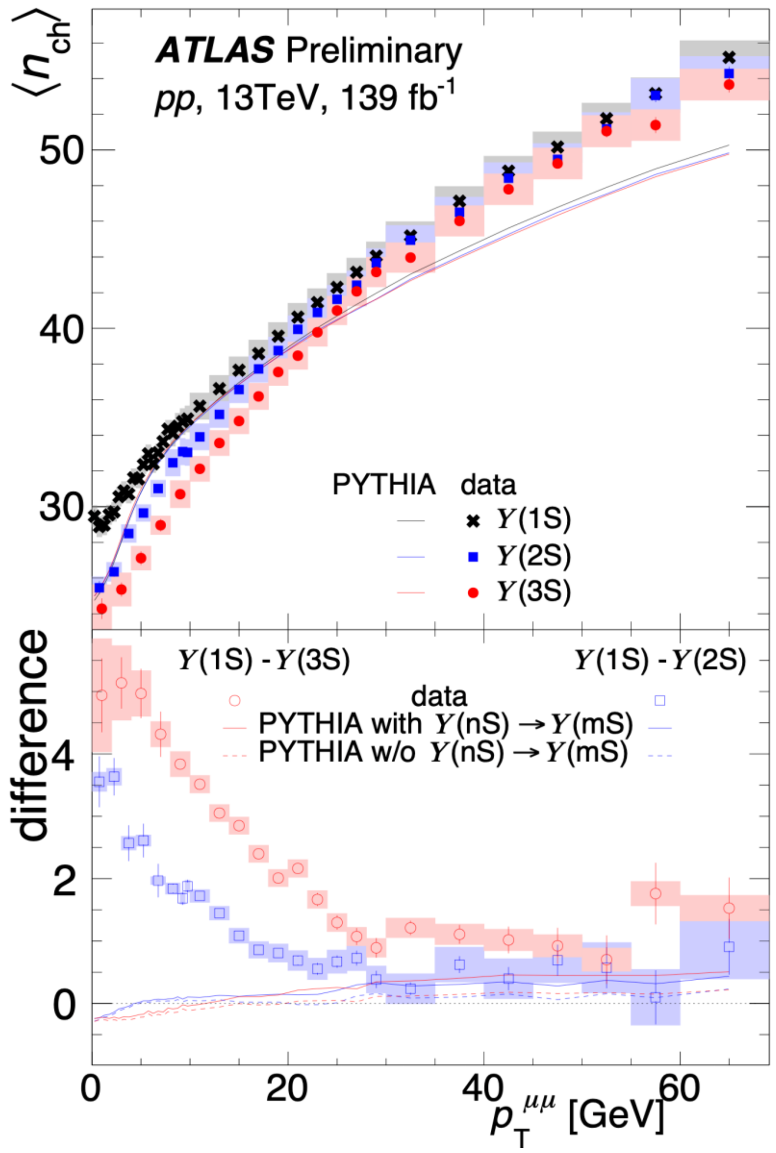
- Subtracted distributions look like UE at rather high Y(nS) p_T. At the highest p_T there are feed-downs
- Away from jets there are regions with charged particles
- This suggests that the effect is related to the UE.

Mean n_{ch} values associated with different Υ states



- Strong difference in the multiplicity of the UE for different Υ(nS) states is observed.
- It does not exist in pythia and pythia needs to be improved to better model Υ production
- The effect is strongest at $p_T = 0$ and diminishes with increasing p_T, but still visible at 20-30 GeV.
- At the lowest p_T,
  for Υ(1S)-Υ(2S) the difference is 3.6 ± 0.4
  for Υ(1S)-Υ(3S) the difference is 4.9 ± 1.1

Conclusions

- Two measurements with similar effects in very different systems.

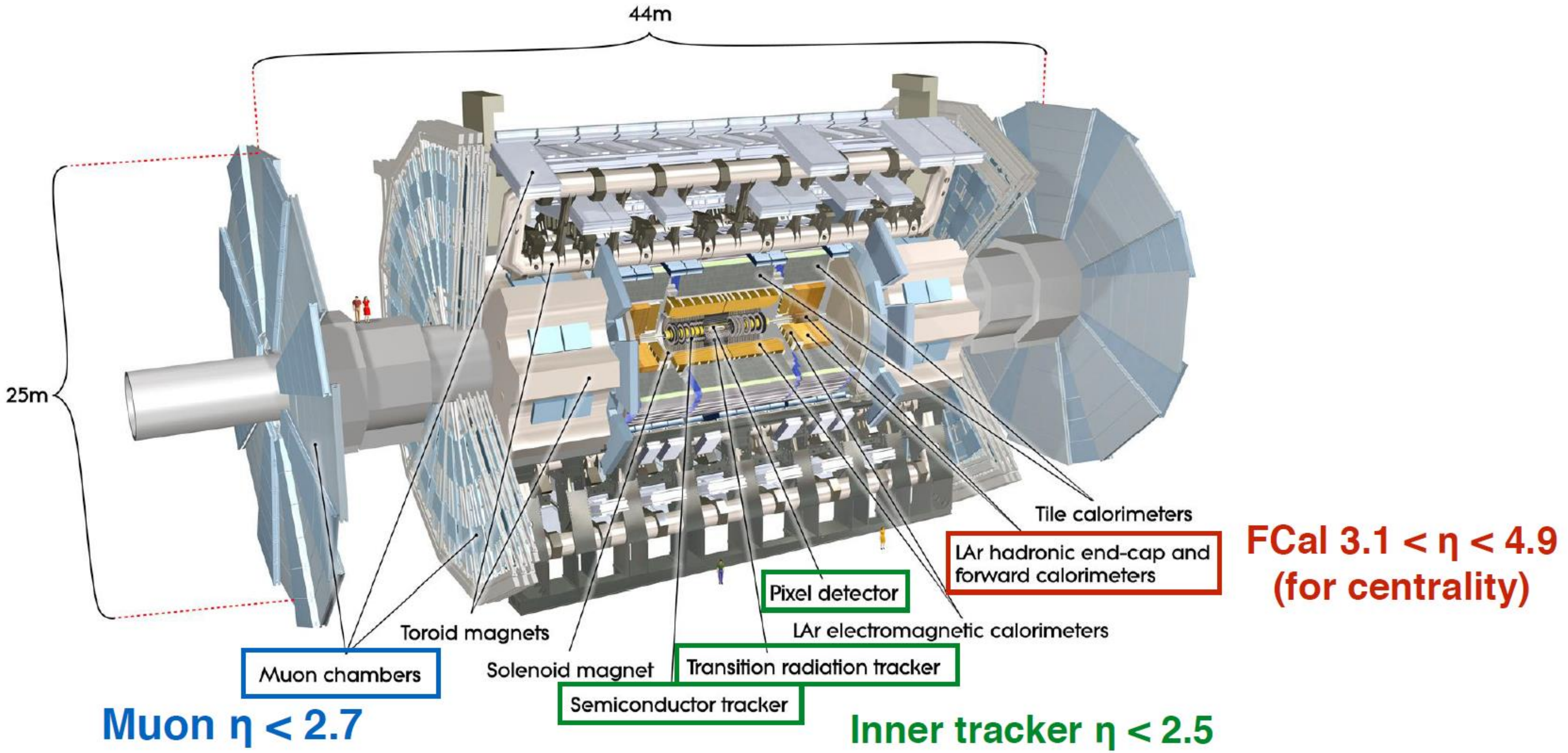
- In Pb+Pb: R_{AA} and ρ_{AA} decrease with increasing centrality, and show no strong dependence on p_T.
- More suppression for excited states supporting a sequential melting scenario.
  - Models describe the data well and incorporate deconfinement as a key ingredient in the suppression of the Y yields.

- In pp: Difference in $<n_{ch}>$ distributions in events tagged with Y is observed.
- Events with excited Upsilon states have lower $<n_{ch}>$ than with the ground state
  - The difference is largest at low p_T and almost disappears at $p_T > 30$ GeV.
- One possible explanation is higher suppression of excited Y states in high multiplicity events, consistent with sequential melting scenario.

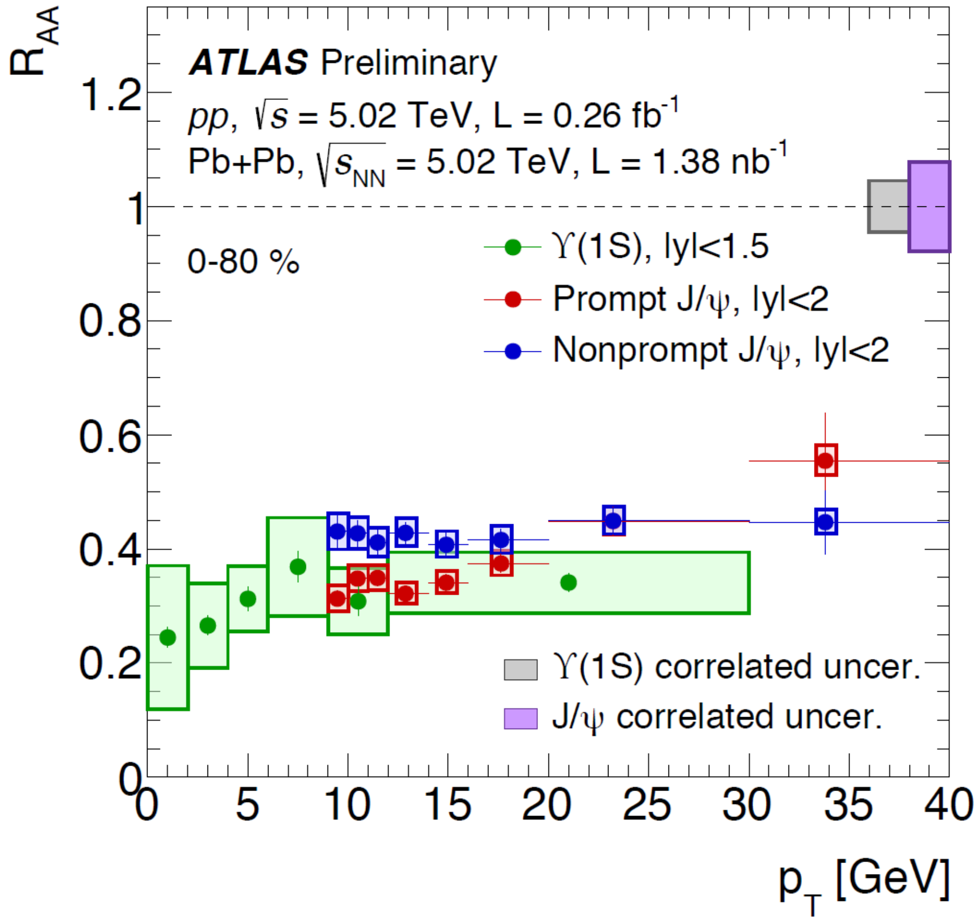
Backup Slides

ATLAS Detector

Y(nS) are measured via dimuon decay channel at midrapidity.



Bottomonium vs. Charmonium



J/ψ (EPJC 78 (2018) 762): $9 < p_T < 40$ GeV, $|y| < 2$

Similar amount of suppression for Υ(1S) and prompt J/ψ although Υ(1S) is more tightly bound

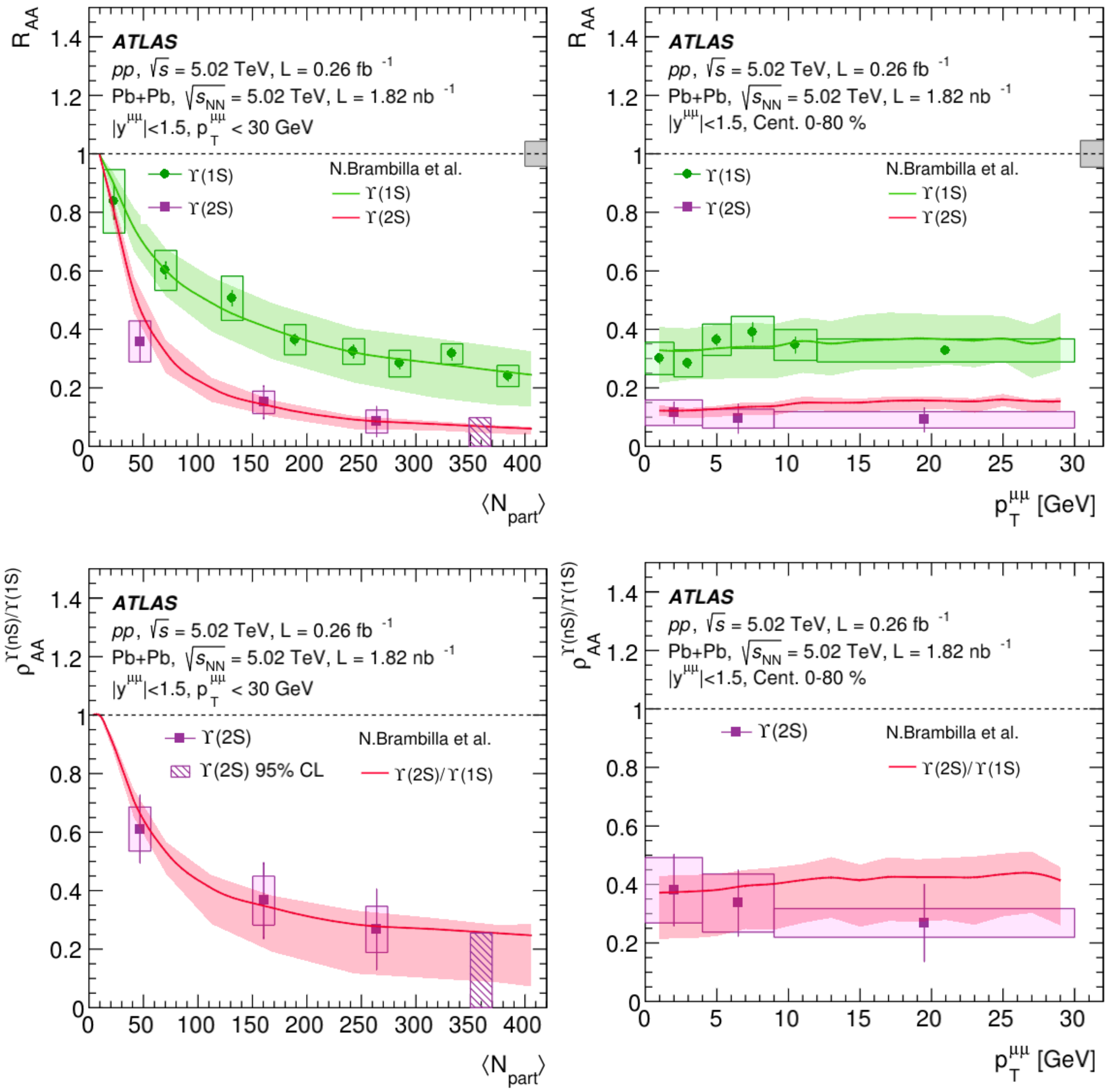
Hard to draw a firm conclusion due to different regenerations, feed-down effects, etc.

Non-prompt J/ψ RAA reflects b-quark energy loss

Theory 1

N. Brambilla et al.,
“Bottomonium production in heavy-ion collisions using quantum trajectories: Differential observables and momentum anisotropy.”
Phys. Rev. D 104 (2021) 094049,
arXiv: 2107.06222

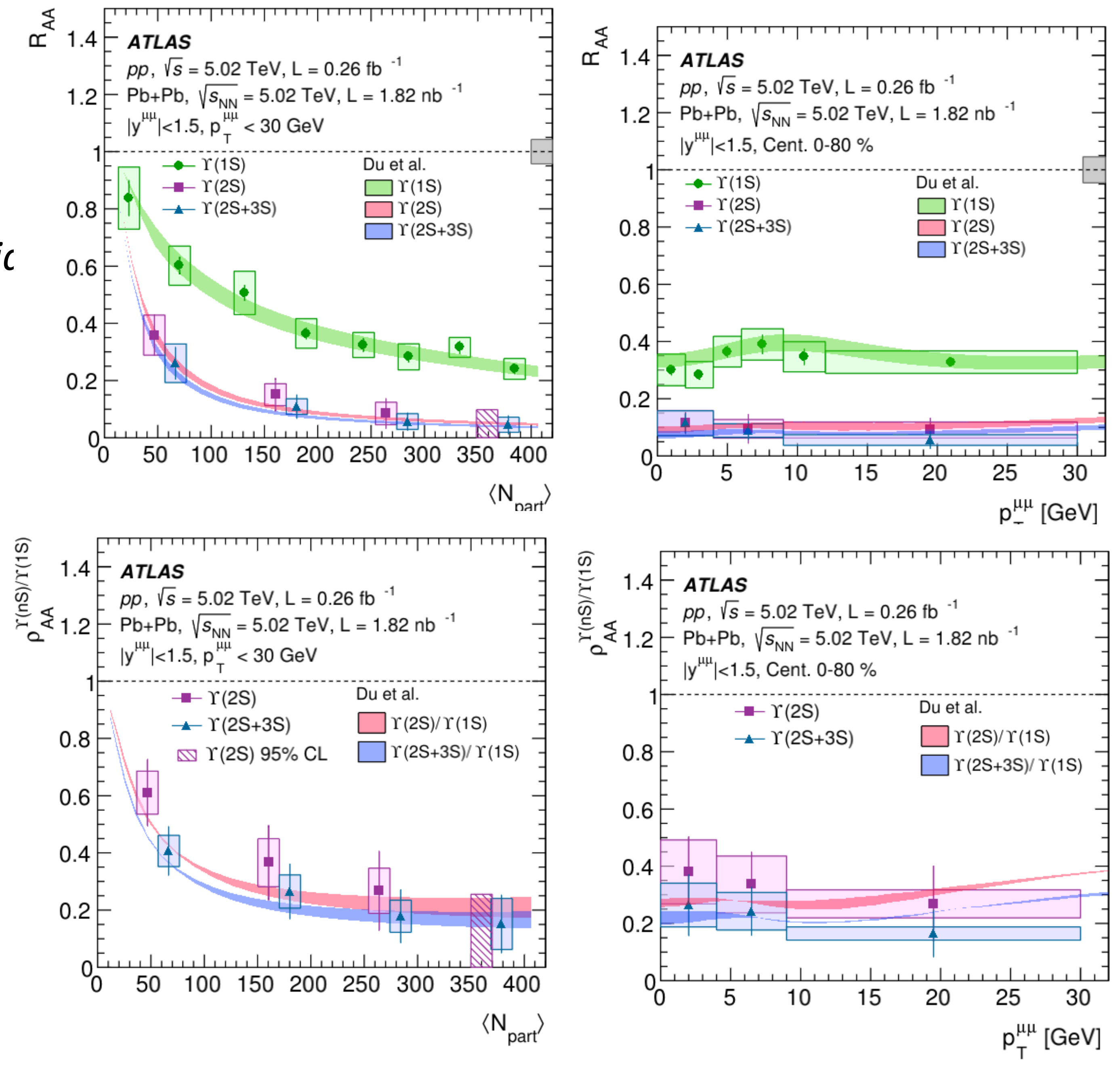
Potential NRQCD and the formalism of open quantum systems to numerically solve the Lindblad equation.
Heavy-quark interactions with the strongly coupled medium are encoded in the two nonperturbative transport coefficients: the heavy-quark momentum diffusion coefficient and its dispersive counterpart.



Theory 2

M. H. X.Du and R. Rapp,
“Color Screening and Regeneration of Bottomonia in High-Energy Heavy-Ion Collisions.”
Phys. Rev. C 96 (2017) 054901,
arXiv: 1706.08670

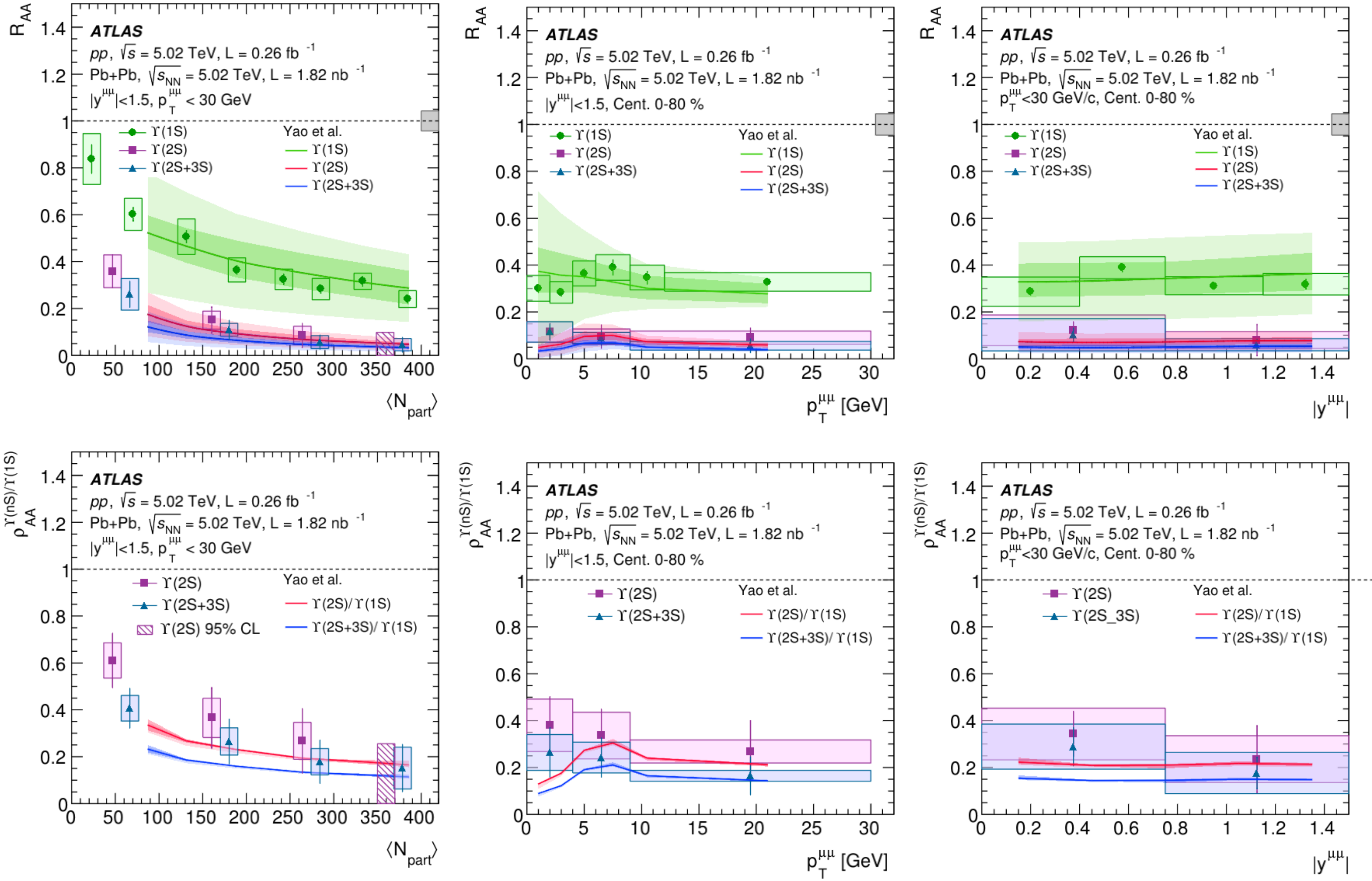
Kinetic-rate equation approach including regeneration and has four dimensionless parameters which characterize the temperature dependence of the pertinent screening masses. These parameters are extracted through the fits to the data already available at RHIC and LHC.



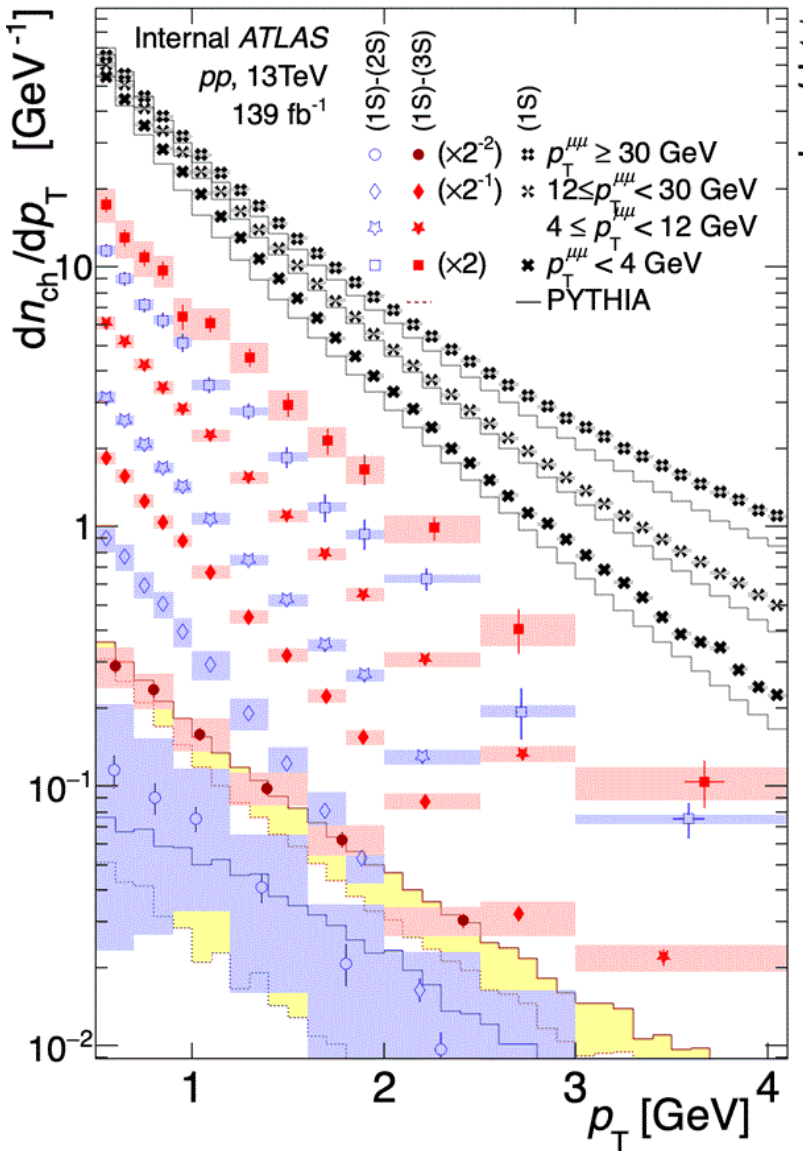
Theory 3

X. Yao et al.,
“Coupled Boltzmann Transport Equations of Heavy Quarks and Quarkonia in Quark-Gluon Plasma.”
JHEP 2021 (2021) 46,
arXiv: 2004.06746

Use of coupled transport equations for open heavy-flavor and quarkonium in order to describe their transport inside the QGP, including regeneration.
The model depends on the choice of nPDF and two coupling constant parameters.



p_T dependence of $\langle n_{ch} \rangle$ in Υ events



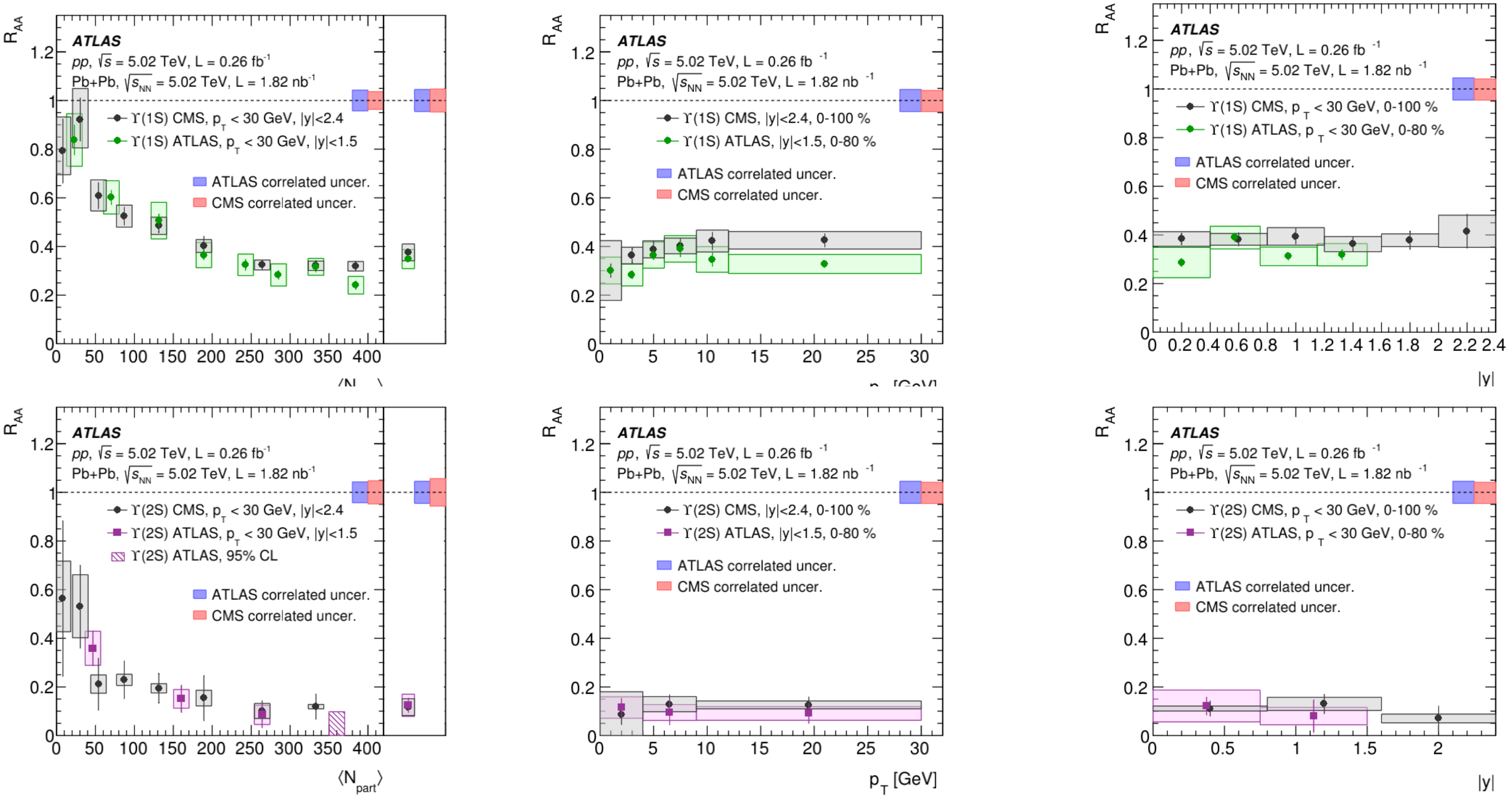
For p_T< 4 GeV, the distribution resembles particles coming from the UE.

For p_T< 30 GeV, subtracted distributions are consistent in shape with Υ(1S) distribution measured in the lowest p_T.

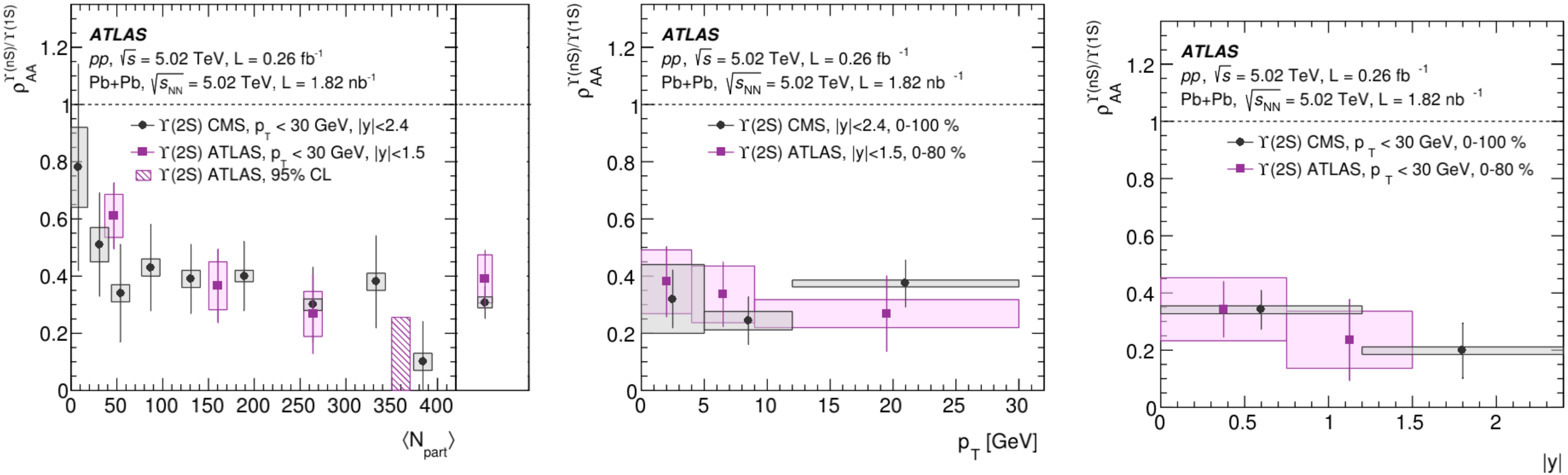
Above 30 GeV, subtracted distributions gets harder, which is explained by feed-down decay processes.

Comparison with CMS (R_{AA})

CMS: *"Measurement of nuclear modification factors of Υ(1S), Υ(2S), and Υ(3S) mesons in PbPb collisions at* $\sqrt{s_{NN}}$ *= 5.02 TeV"*, Phys. Lett. B 790 (2019) 270



Comparison with CMS (double ratio)



Miscellaneous plots