Recent results on bottomonium production in Pb+Pb collisions from ATLAS

SASHA MILOV

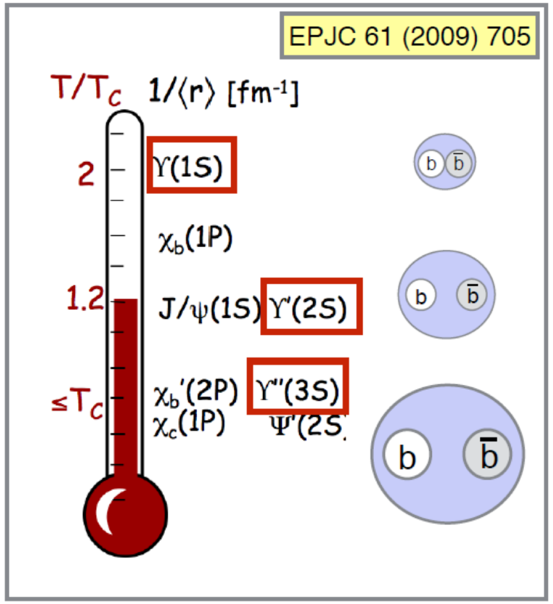
מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

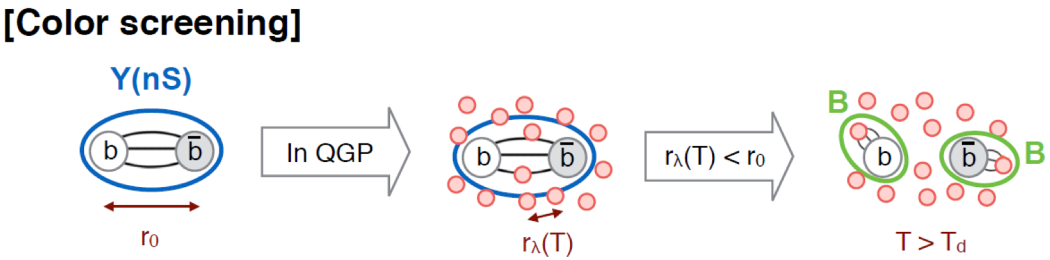
Physics motivation

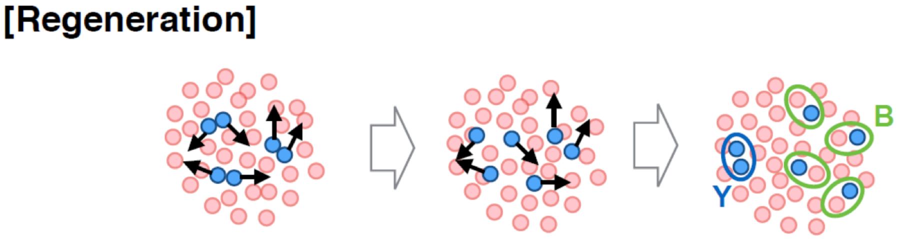
Upsilons can serve as an important tool for studying QGP

In nucleus-nucleus collisions:

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







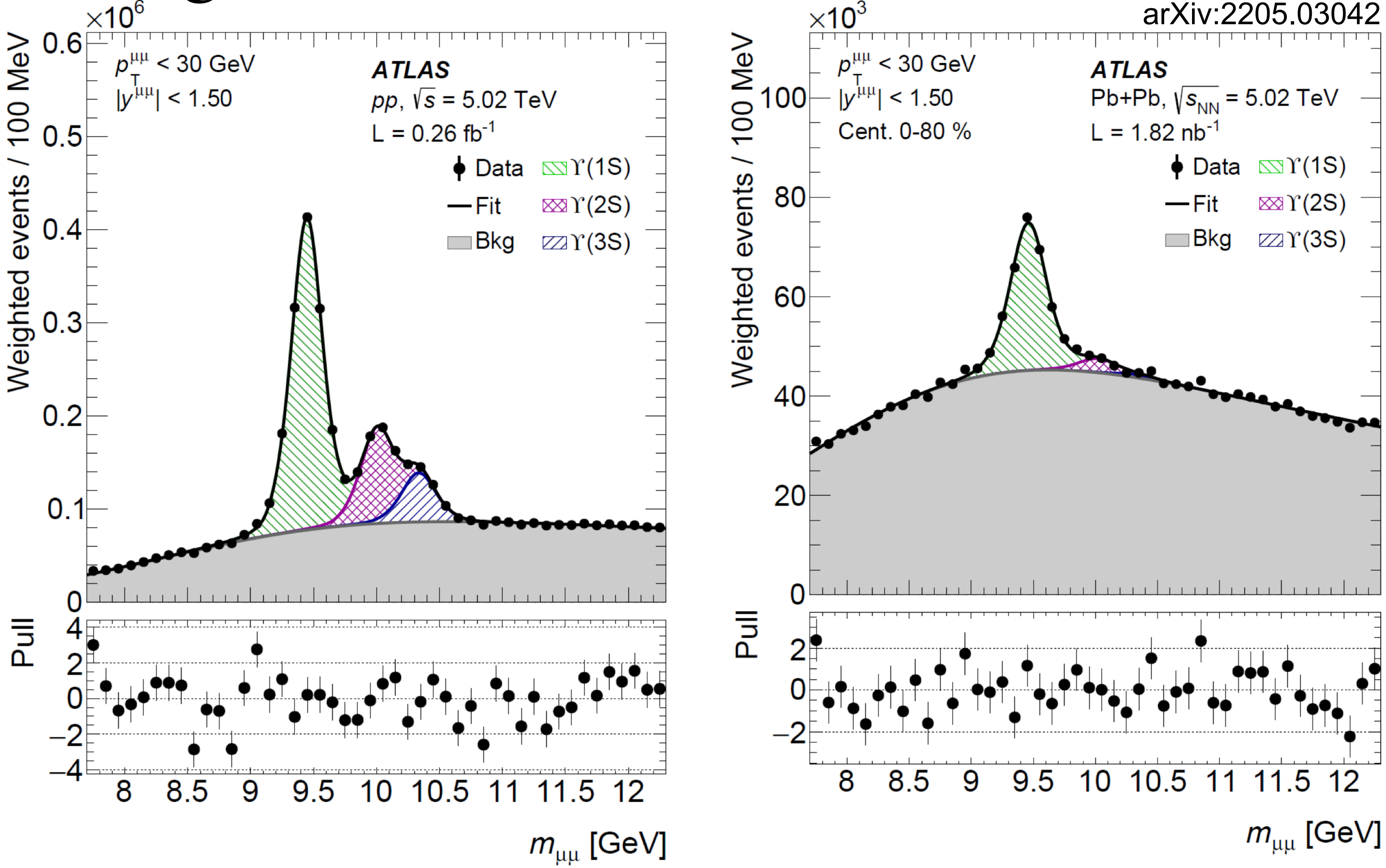
Signal extraction

Selection:
$\Upsilon(nS) \rightarrow \mu\mu$
p_T < 30 GeV
|y|<1.5
Centrality: 0-80%

Signal:
Crystal Ball + Gauss

Background:
2nd order polynomial
or $erf() \times exp()$

arXiv:2205.03042



Clear evolution of higher Υ – states in Pb+Pb, visible in raw data

Systematic uncertainties

arXiv:2205.03042

Signal extraction dominates the uncertainties

Next-in-line is the efficiency, coming from combining data samples

Both can be improved with more statistics

$\langle T_{\mathrm{AA}} \rangle$ is the centrality association

Collision type	Sources	Υ(1S) [%]	Υ(nS) [%]	Υ(nS)/Υ(1S) [%]
pp collisions	Luminosity	1.6	1.6	-
	Acceptance	0.3–9.3	0.2–4.1	-
	Efficiency	2.7–7.0	2.8–4.0	3.0–7.1
	Signal extraction	3.1–10.2	4.3–11.9	4.5–12.2
	Bin migration	<1	<1	-
	Primary-vertex association	2.0	2.0	-
Pb+Pb collisions	$\langle T_{\mathrm{AA}} \rangle$	0.8–8.2	0.8–8.2	-
	Acceptance	0.3–9.3	0.2–4.1	-
	Efficiency	4.0–15.0	3.9–25.3	4.4–28.8
	Signal extraction	3.8–16.3	14.6–28.7	16.6–31.5
	Bin migration	<2	<2	-
	Primary-vertex association	3.4	3.4	-

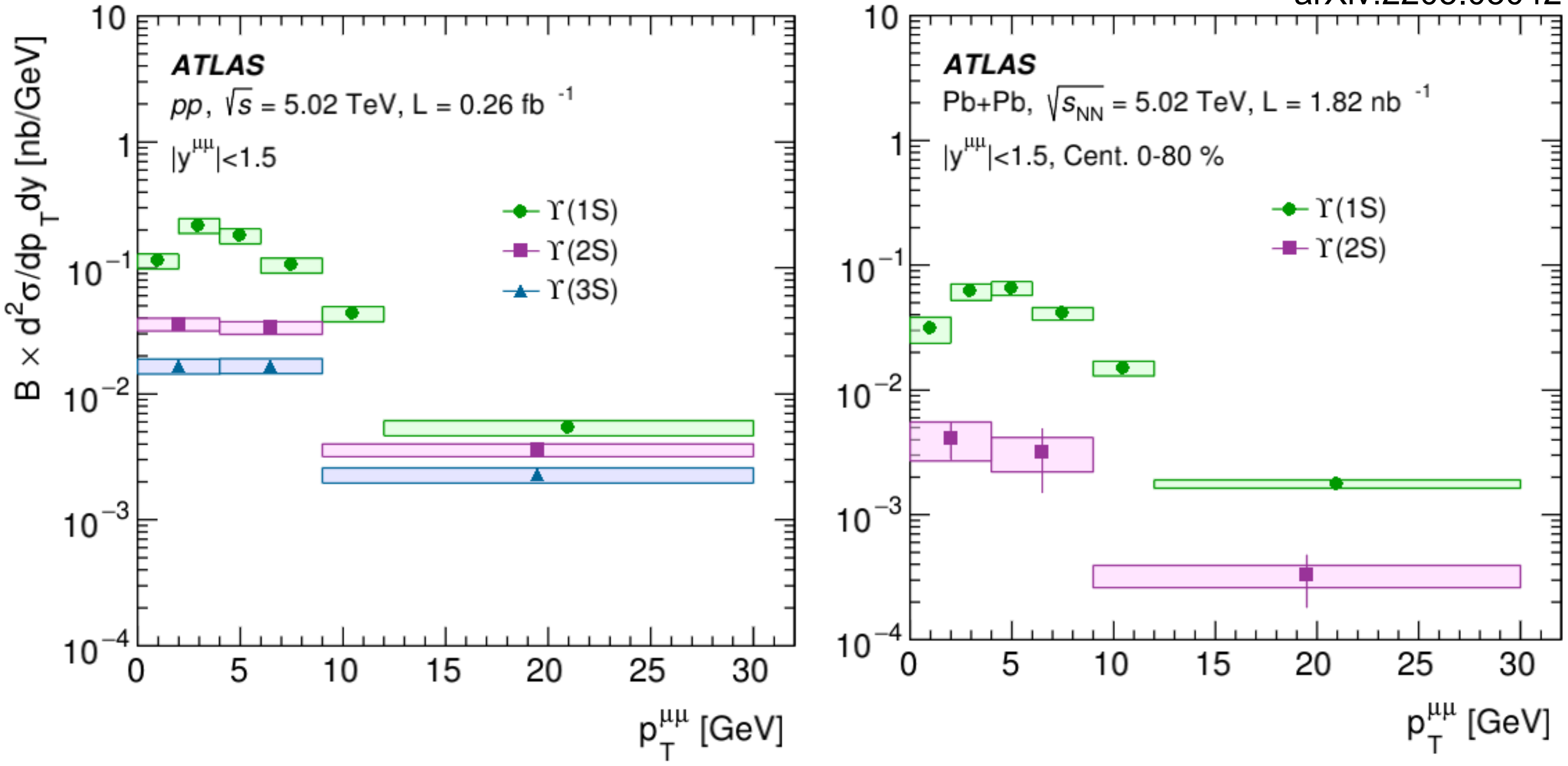
Some systematic uncertainties cancel in ratios

Signal extraction

In *pp* all $\Upsilon(nS)$ states can be measured independently

In Pb+Pb $\Upsilon(3S)$ has low statistical significance and therefore can't be isolated

arXiv:2205.03042



Nuclear modification factor R_{AA}

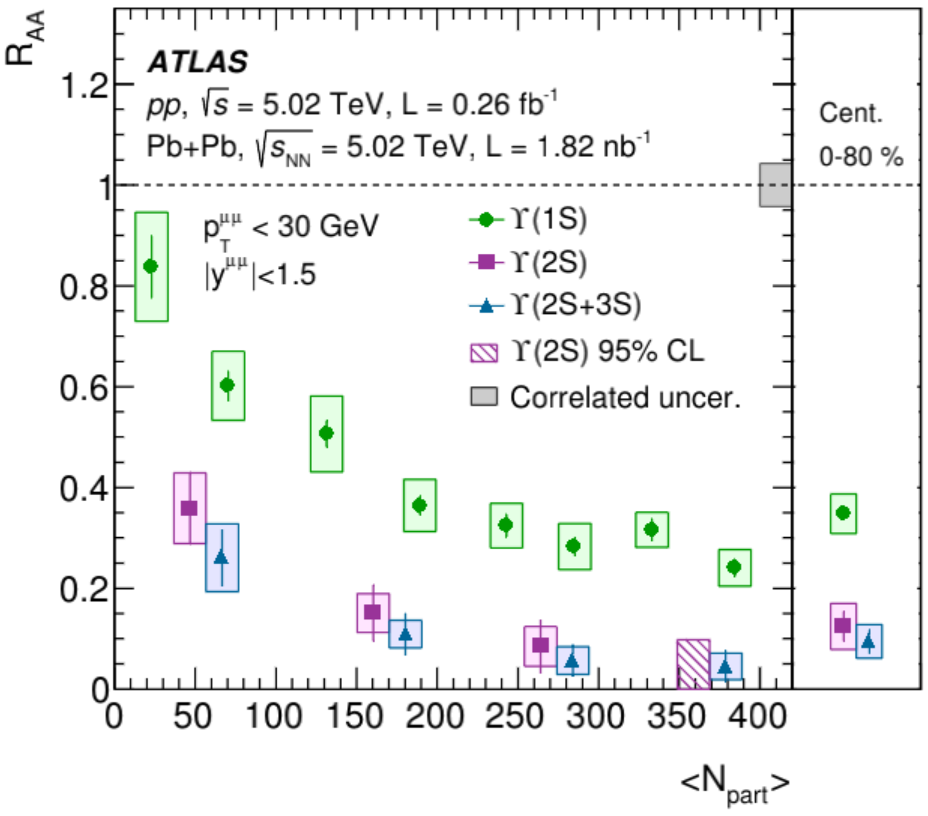
arXiv:2205.03042

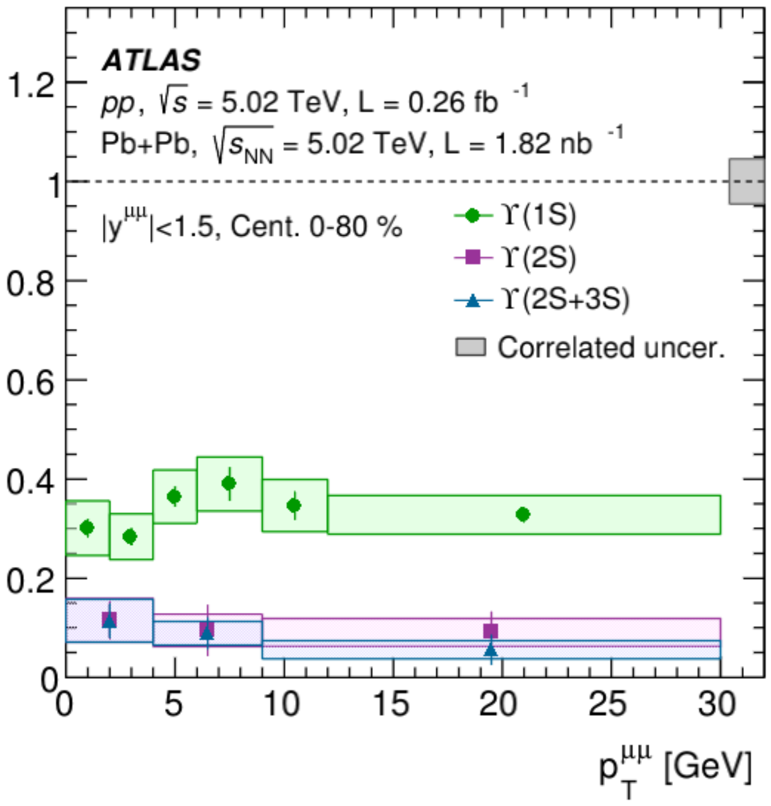
Ordering in R_{AA}:
$\Upsilon(1S) > \Upsilon(2S) > \Upsilon(2S+3S)$

$\Upsilon(2S+3S)$ is shown instead of $\Upsilon(3S)$

No strong p_T dependence

More suppression in more central collisions





Nuclear modification factor: $R_{AA} = \frac{N_{AA}}{T_{AA} \times \sigma_{pp}} = \frac{\text{rate in A+A}}{(\text{per collision luminosity}) \times (pp \text{ cross-section})}$

$R_{AA} = 1$: A+A is many times *pp*

$R_{AA} < 1$: footprint of the QGP

Double ratio

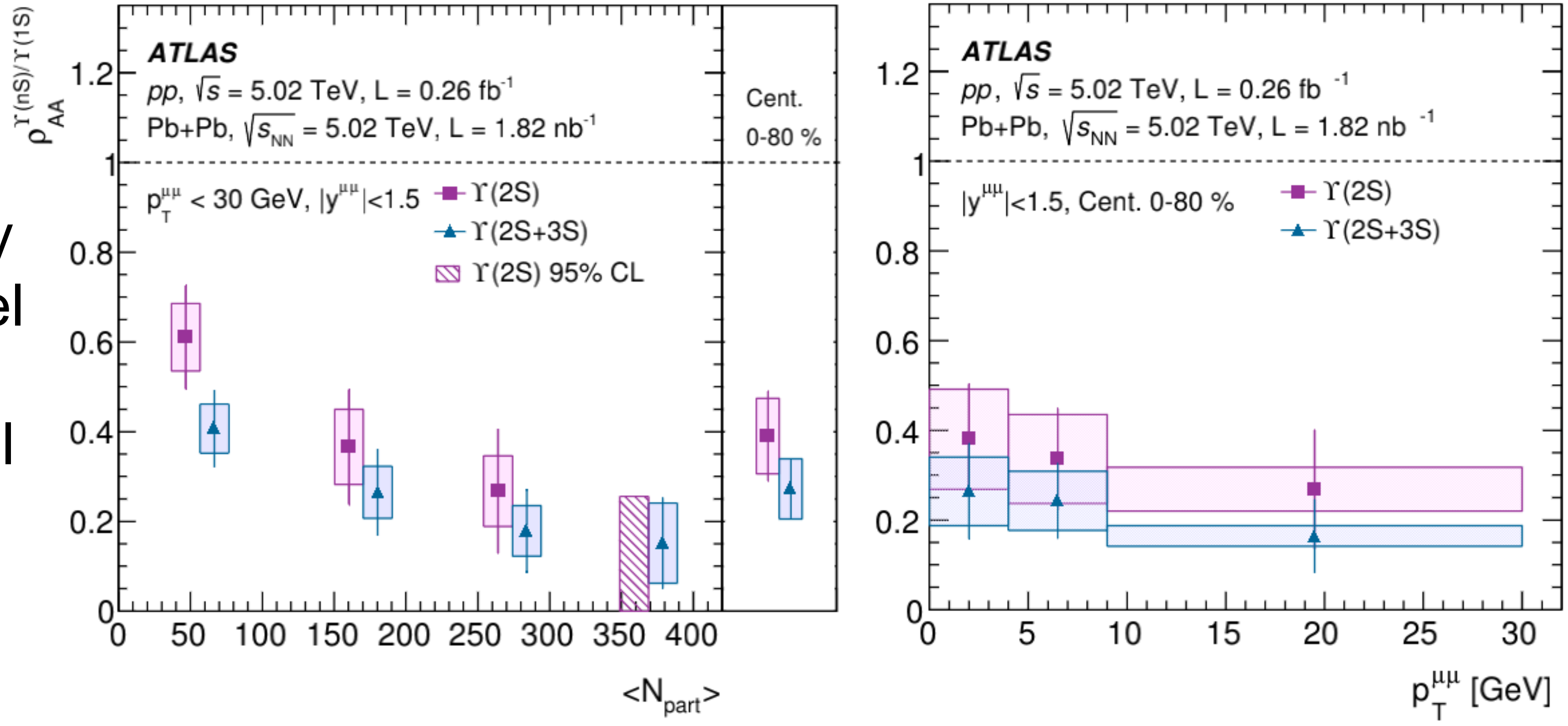
Luminosity and T_{AA} corrections cancel out

Acceptance and efficiency corrections partially cancel

Consistent with sequential melting

$\Upsilon(2S+3S)$ systematically lower than $\Upsilon(2S)$

arXiv:2205.03042



Double ratio: $$\rho_{\mathrm{AA}}^{\Upsilon(\mathrm{nS})/\Upsilon(1\mathrm{S})} = \frac{N_{\mathrm{AA}}^{\Upsilon(\mathrm{nS})}}{N_{\mathrm{AA}}^{\Upsilon(1\mathrm{S})}} \times \frac{\sigma_{pp}^{\Upsilon(1\mathrm{S})}}{\sigma_{pp}^{\Upsilon(\mathrm{nS})}} = \frac{R_{\mathrm{AA}}^{\Upsilon(\mathrm{nS})}}{R_{\mathrm{AA}}^{\Upsilon(1\mathrm{S})}}$$

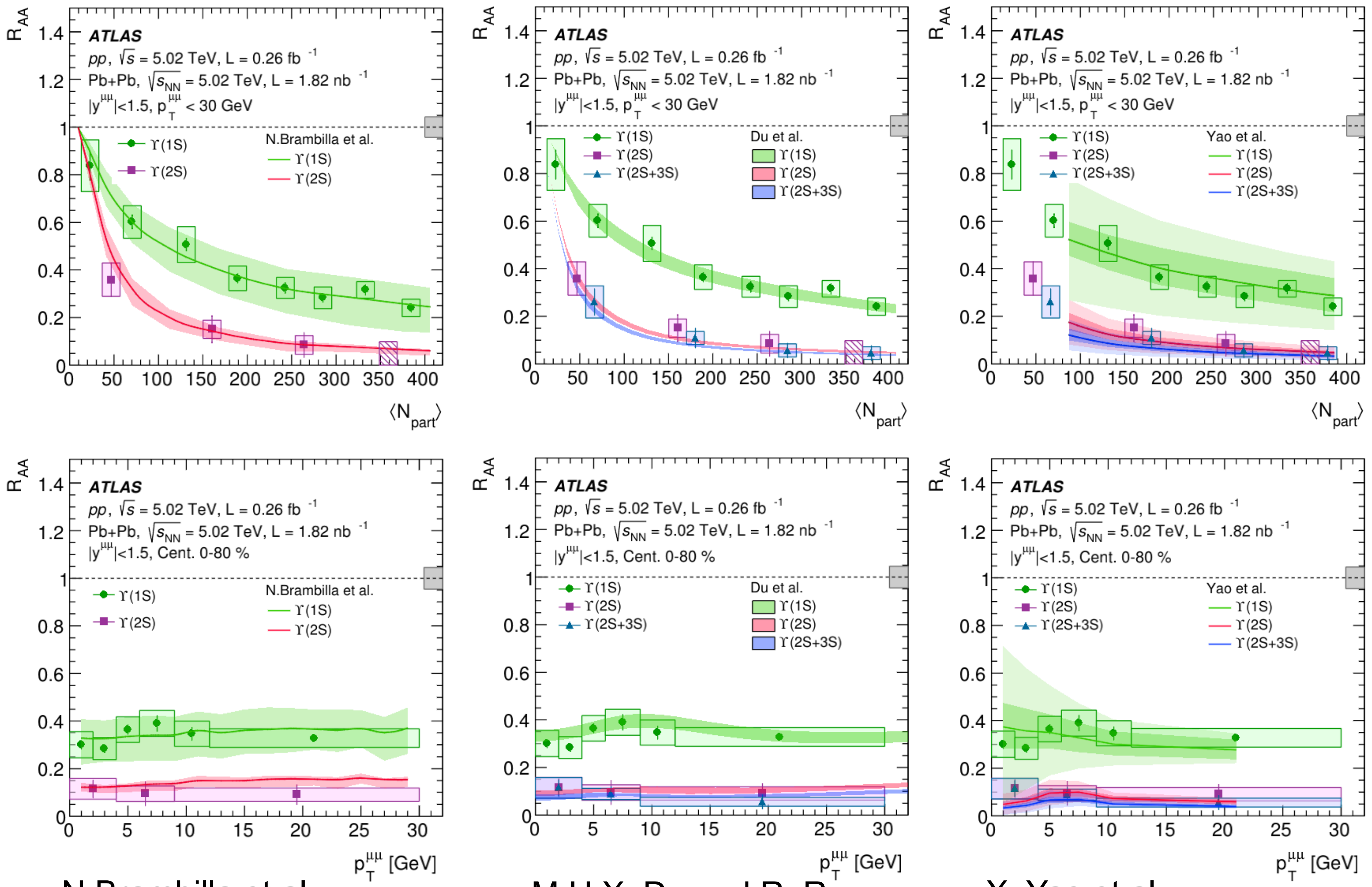
Comparison with models (R_{AA})

arXiv:2205.03042

Models use different approach to $\Upsilon(2S)$ suppression

All models include deconfinement as a key ingredient

Good agreement with the data



N.Brambilla et al., PRD 104 (2021) 094049

M.H.X. Du and R. Rapp, PRC 96 (2017) 054901

X. Yao et al., JHEP 2021 (2021) 46

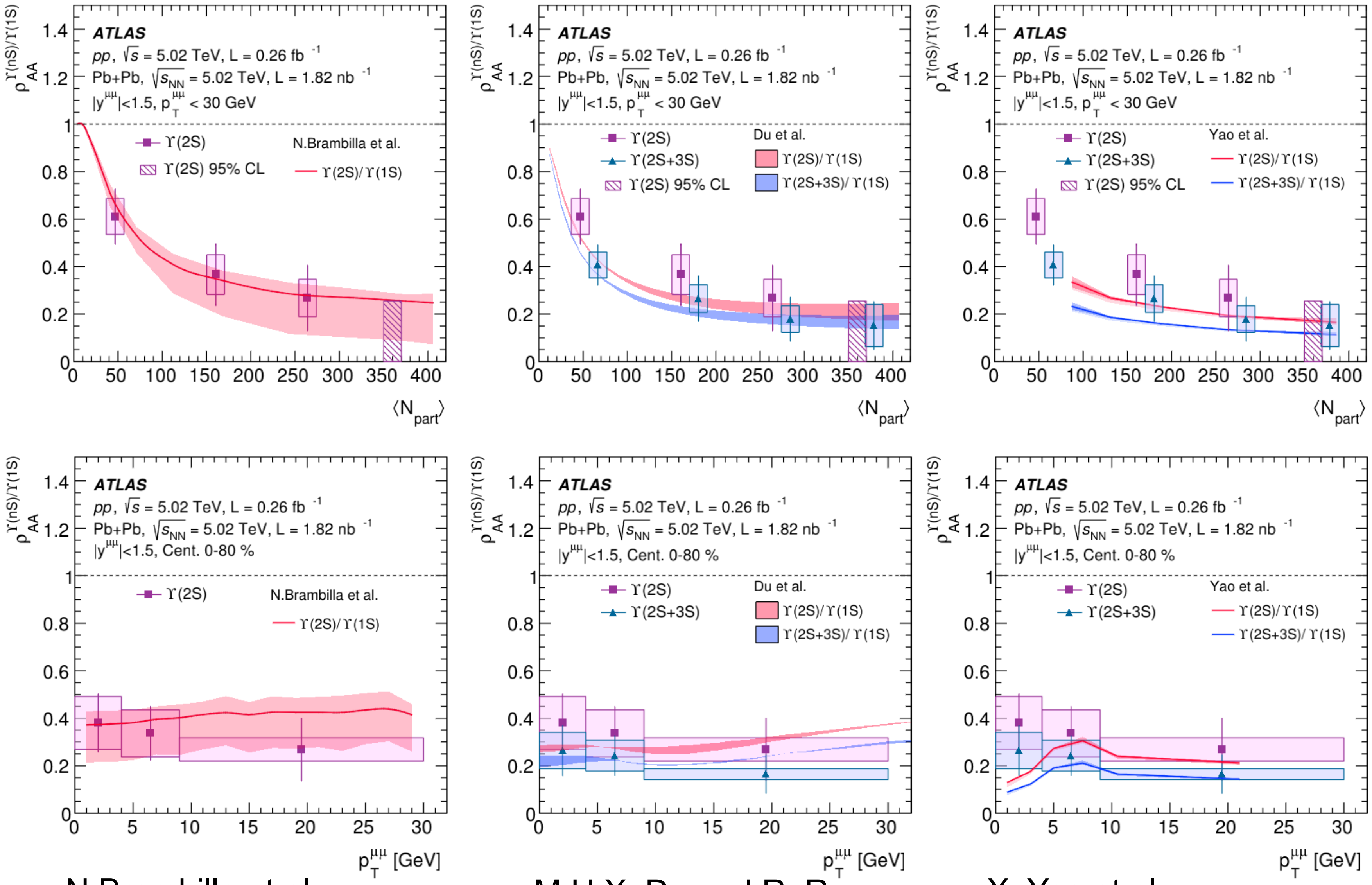
Comparison with models (double ratio)

arXiv:2205.03042

Many model uncertainties cancel in the double ratio

Good agreement with the data for $\Upsilon(2S)$

$\Upsilon(2S+3S)$ suppression relative to $\Upsilon(2S)$ is also reproduced by the models



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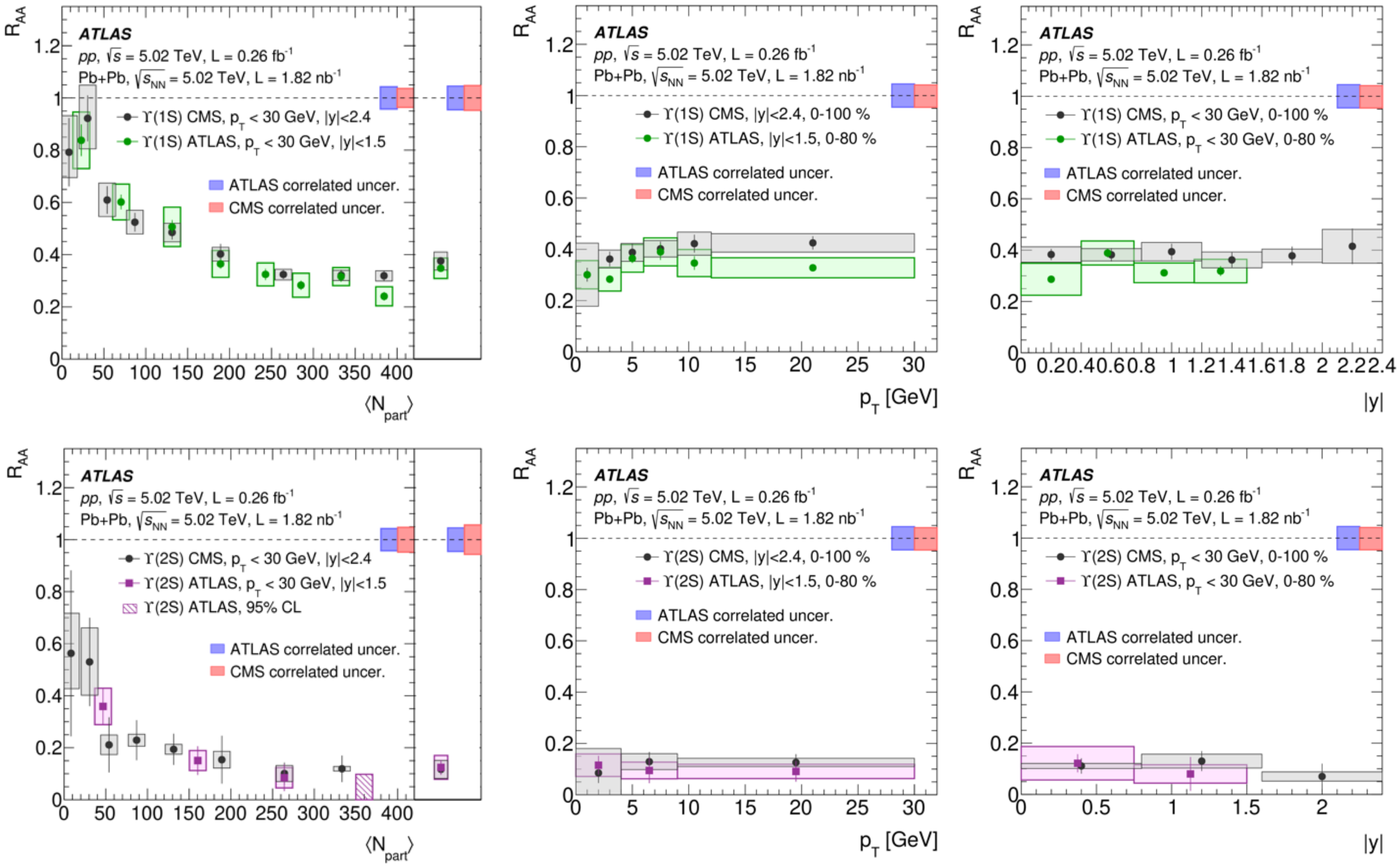
Comparison with CMS (R_{AA})

PLB 790 (2019) 270
arXiv:2205.03042

Good agreement between ATLAS and CMS vs. all measured parameters



Centrality

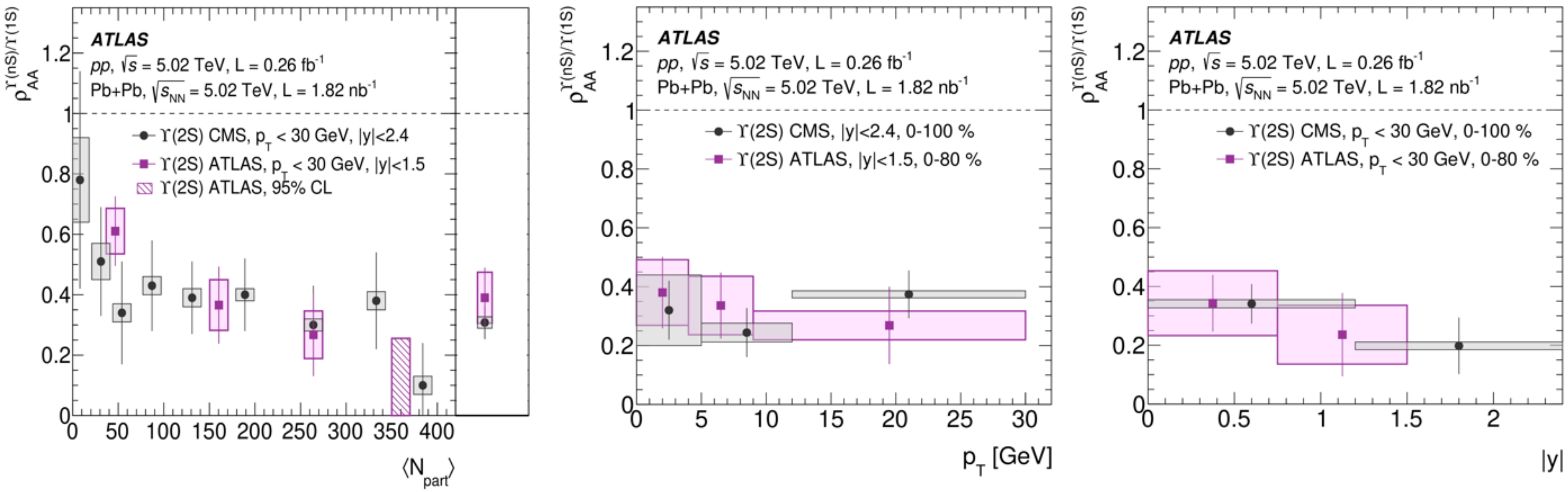
Momentum

Rapidity

Comparison with CMS (ρ)

PLB 790 (2019) 270
arXiv:2205.03042

And also for double ratio



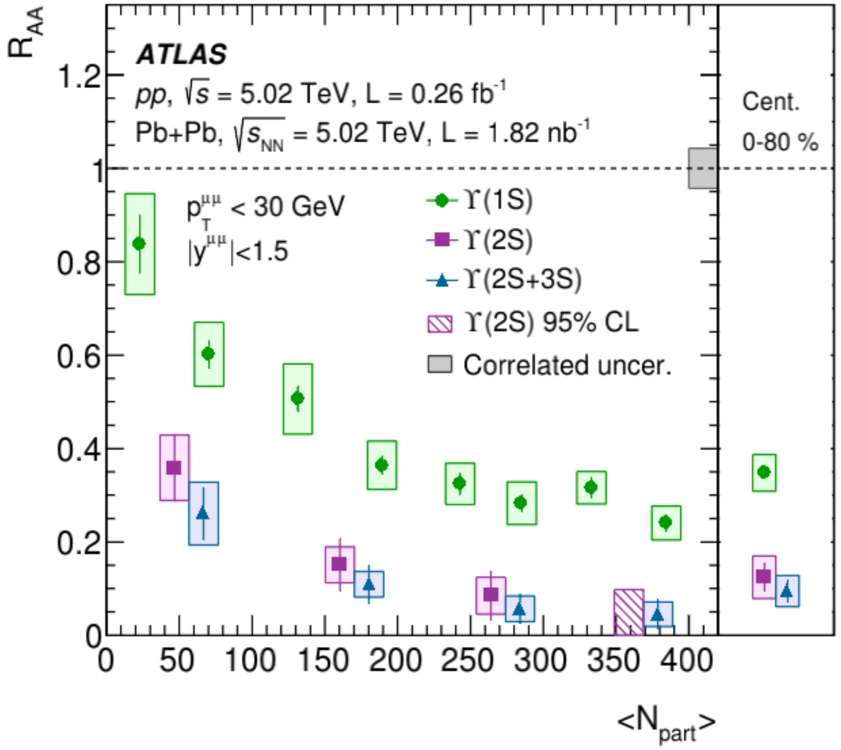
Centrality Momentum Rapidity

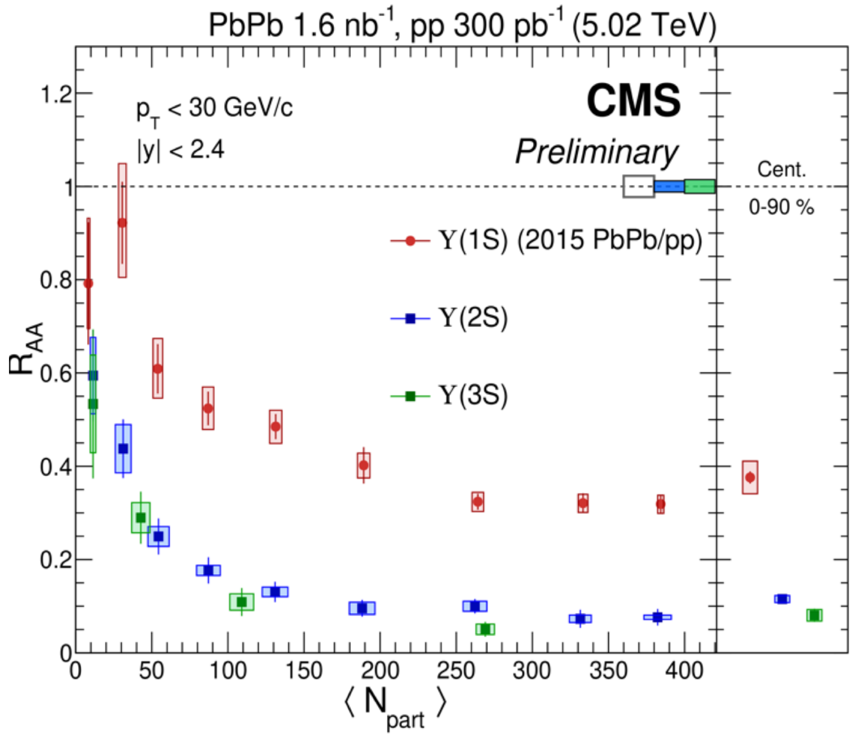
Comparison with models (new data)

CMS-PAS-HIN-21-007
arXiv:2205.03042

New preliminary results from CMS shown at QM2022

First time $\Upsilon(3S)$ is measured in Pb+Pb above the most peripheral centralities





Conclusions

R_{AA} and $\rho_{\mathrm{AA}}^{\Upsilon(\mathrm{nS})/\Upsilon(1S)}$ decrease with increasing centrality, and show rather weak dependence on p_{T}

More suppression for excited states supporting a sequential melting scenario

Models that use deconfinement as a key ingredient in the suppression of the $\Upsilon(2S)$ yields describe the data well

Good agreement between ATLAS and CMS

Upsilon - underlying event correlations in *pp* collisions

ATLAS EXPERIMENT

SASHA MILOV

מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

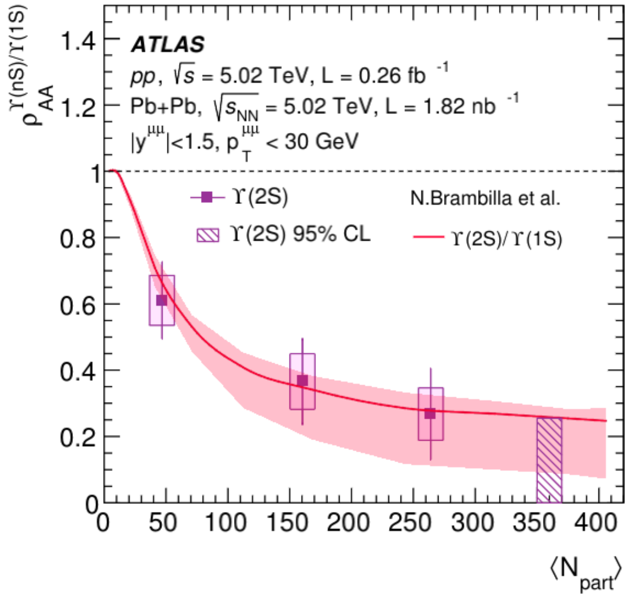
Motivation

QGP in A+A systems is well-established, but small systems are controversial:

characteristic QGP-like behavior in `soft' sector: strangeness enhancement, two-particle correlations in peripheral A+A, in *p*+A and even in *pp*

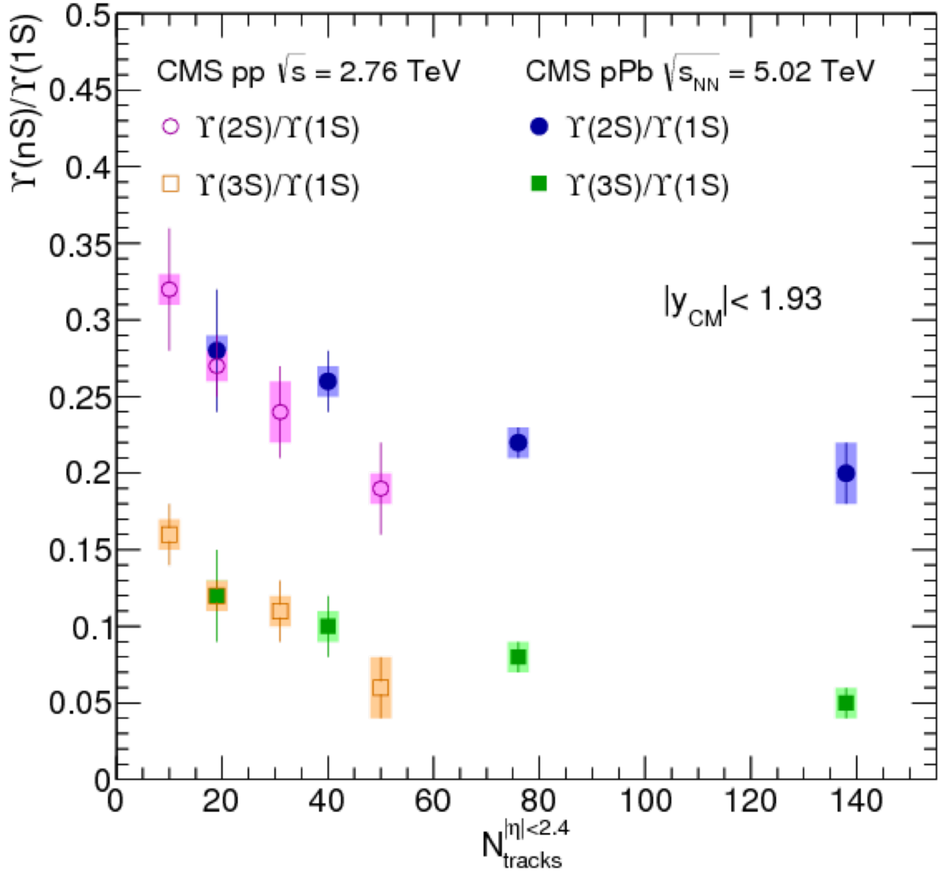
firm constraints on jet energy loss in *p*+Pb, no indication of QGP from any of the `hard' probes that require QGP scenario

Quarkonia production, shows quite unusual behavior both in A+A and in *pp*



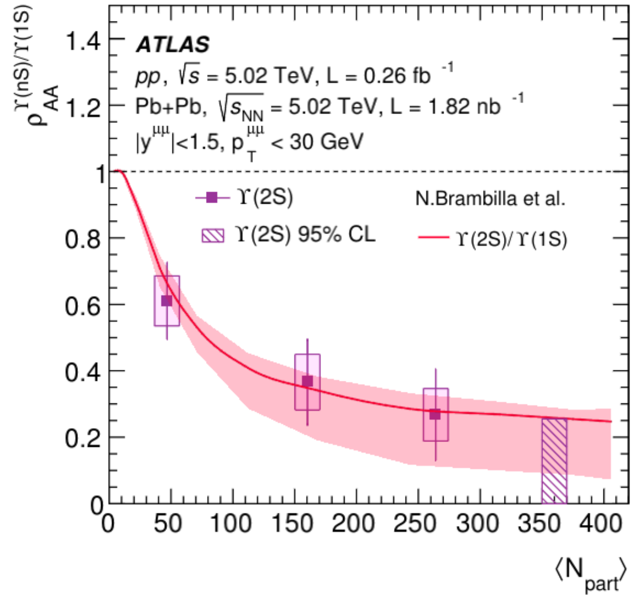
CMS results for 2.76 GeV in *pp*

JHEP 04 (2014) 103

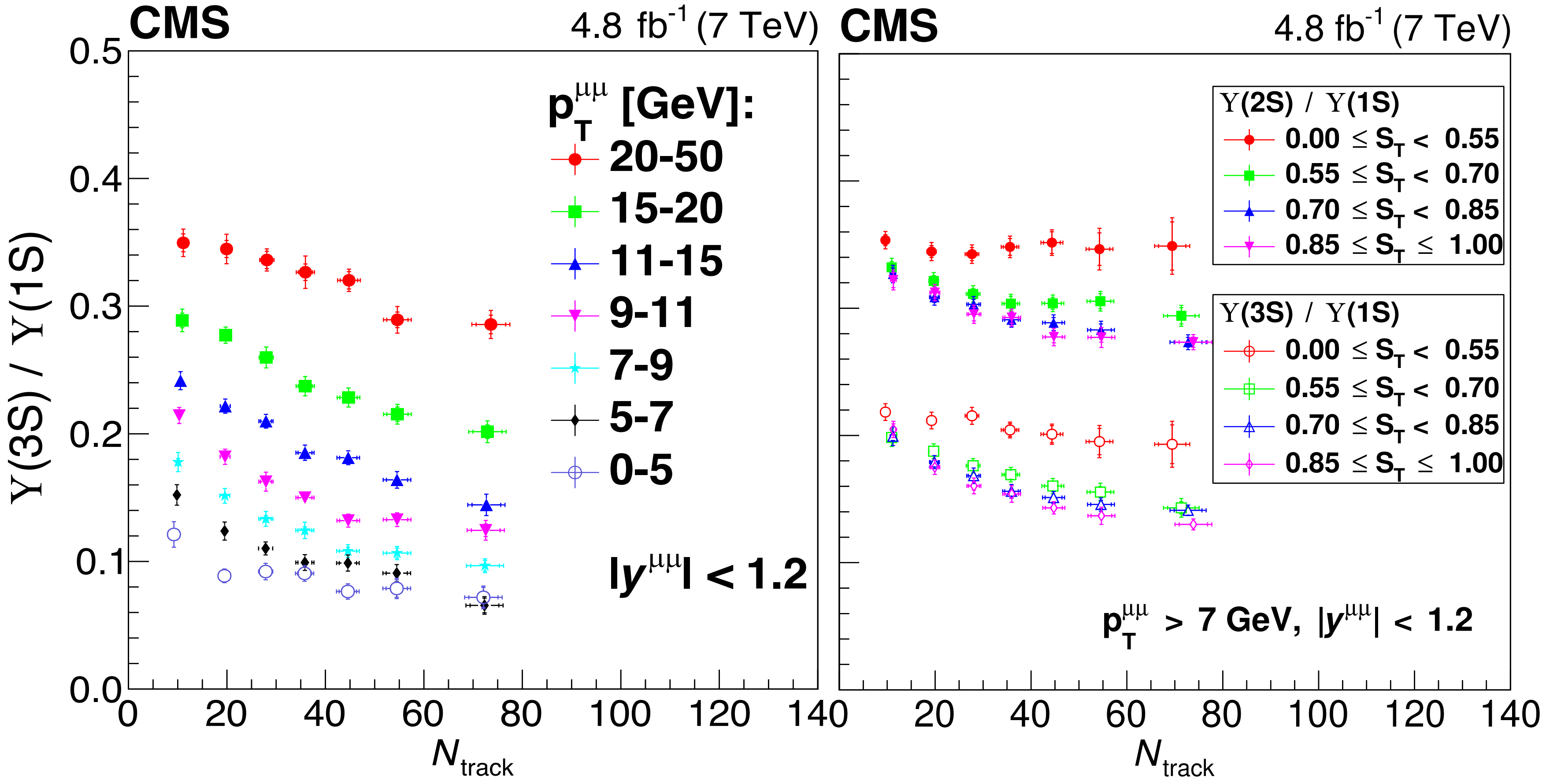


In 2014 CMS published the first result showing the multiplicity dependence of $q\bar{q}$ states in *pp*

This paper has about 100 citations, mainly due to *p*Pb and this seems really unfair :)



CMS results



$$S_T \equiv \frac{2\lambda_2}{\lambda_1 + \lambda_2},$$

$$S_{xy}^T = \frac{1}{\sum_i p_{Ti}} \sum_i \frac{1}{p_{Ti}} \begin{pmatrix} p_{xi}^2 & p_{xi}p_{yi} \\ p_{xi}p_{yi} & p_{yi}^2 \end{pmatrix}$$

$$\lambda_1 > \lambda_2$$

$S_T = 0$ – jets

$S_T = 1$ – Underlying Event

JHEP 11 (2020) 001

"It was concluded that the feed-down contributions cannot solely account for this feature. This is also seen in the present analysis, where the Υ(1*S*) meson is accompanied by about one more track on average ($\langle N_{track} \rangle = 33.9 \pm 0.1$) than the Υ(2*S*) ($\langle N_{track} \rangle = 33.0 \pm 0.1$), and about two more than the Υ(3*S*) ($\langle N_{track} \rangle = 32.0 \pm 0.1$). […] On the other hand, it is also true that, if we expect a suppression of the excited states at high multiplicity, it would also appear as a shift in the mean number of particles for that state (because events at higher multiplicities would be missing)."

The approach

Instead of measuring `conventional' variables like $\Upsilon(\mathrm{n}S)$ yields vs n_{ch}
ATLAS measured n_{ch} for different $\Upsilon(\mathrm{n}S)$

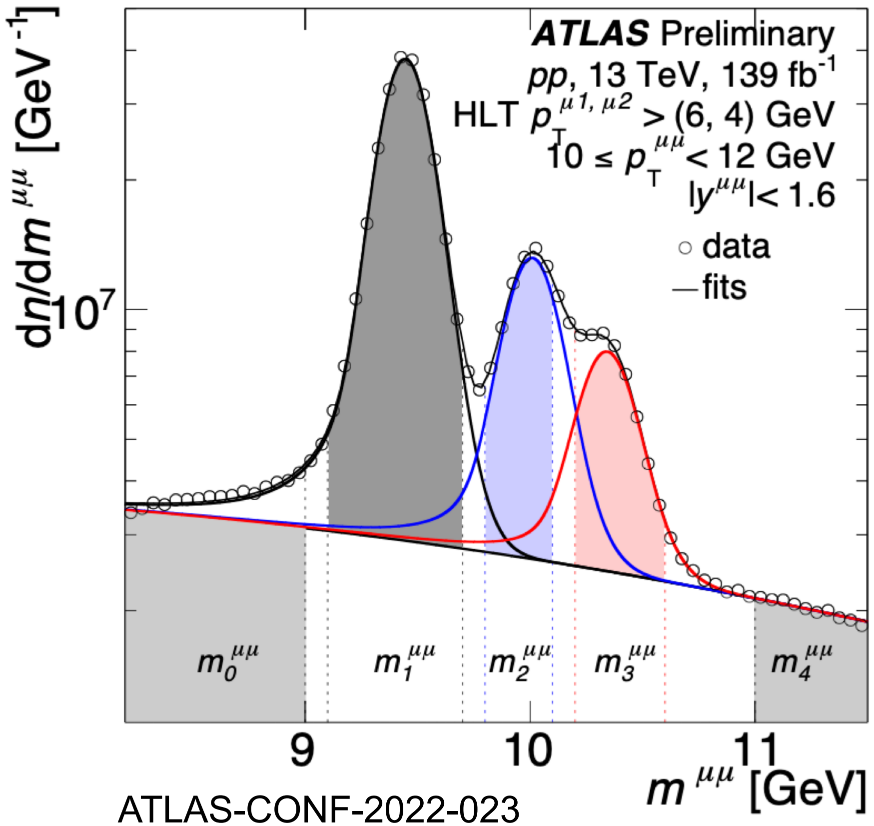
This has several technical advantages that result in clearer picture

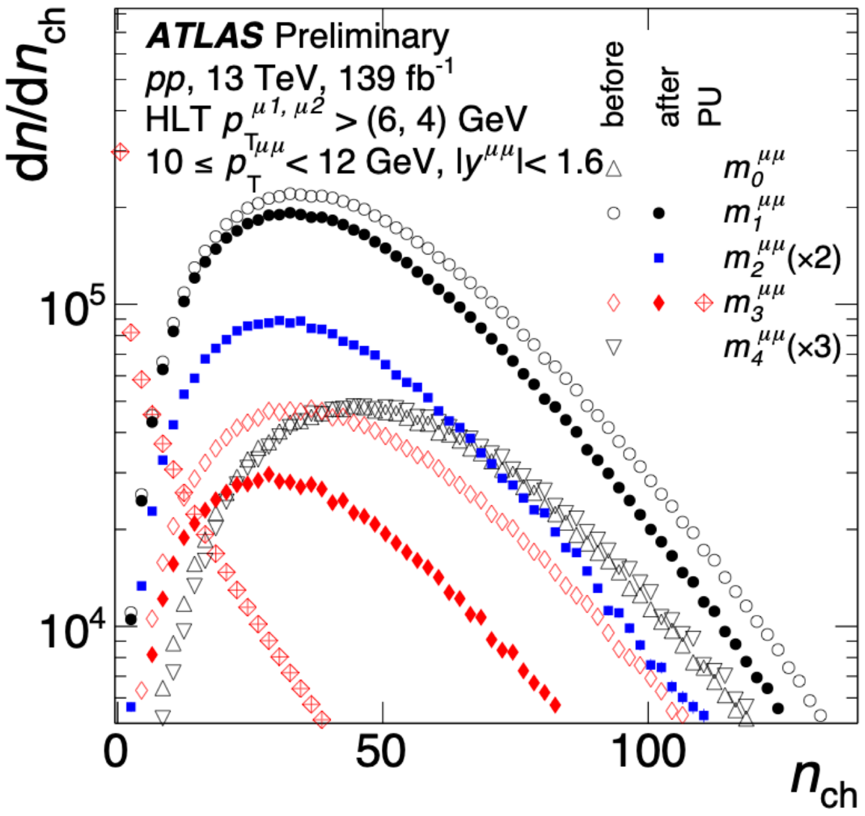
In addition, by solving the pileup problem [EPJC 80 (2020) 64] ATLAS used the entire Run-2 data up to the highest instantaneous luminosities

Signal extraction

This analysis used the entire Run-2 data and operates with about $50, 10$ & 7×10^6 millions of $\Upsilon(1S)$, $\Upsilon(2S)$, & $\Upsilon(3S)$

The procedure is illustrated with n_{ch},
But it also works for dn_{ch}/dp_T and dn_{ch} /d$\Delta\phi$. $\Delta\phi=\phi^{\Upsilon}-\phi^{h}$





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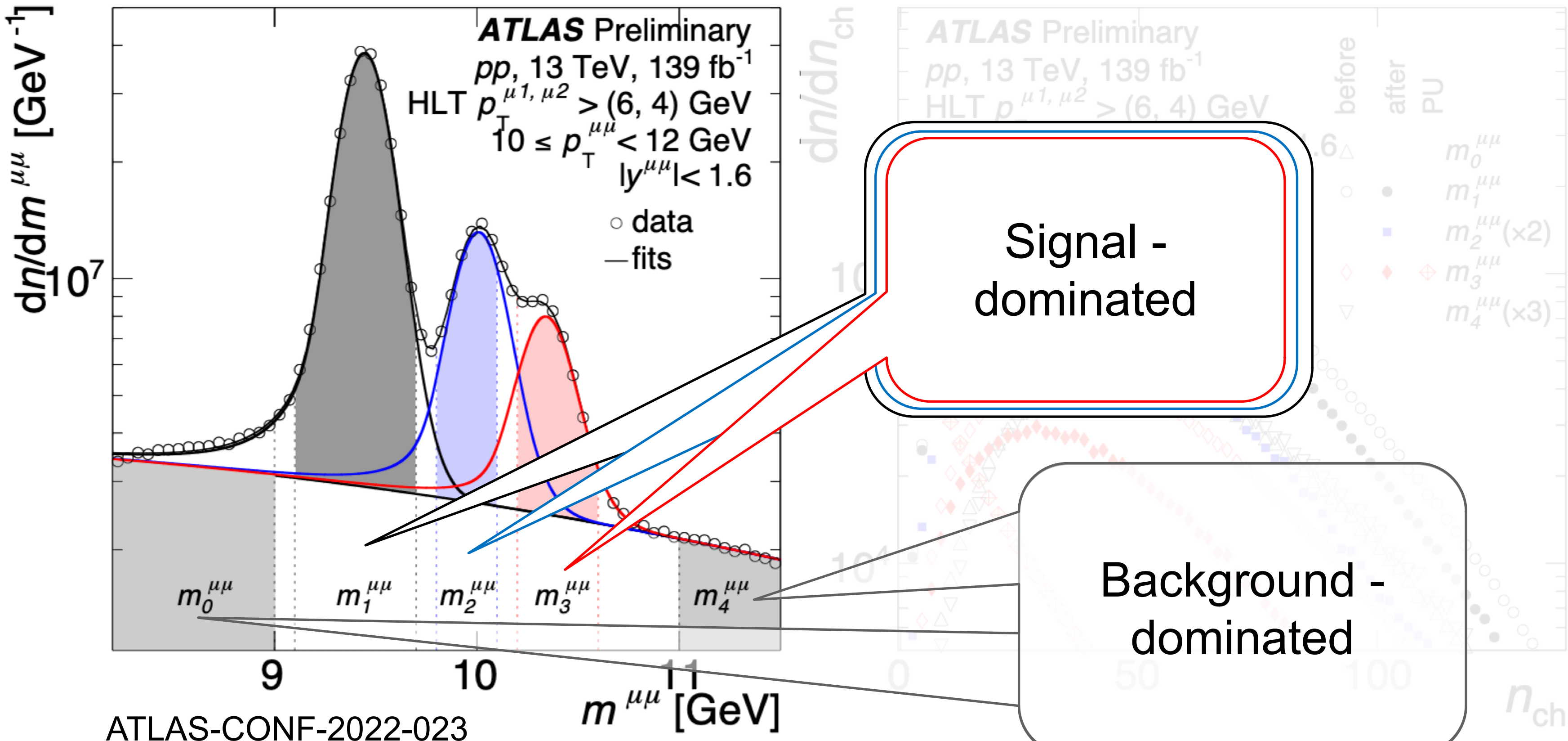
Signal extraction

$$\text{fit}(m) = \sum_{nS} N_{\Upsilon(nS)} F_n(m) + N_{\text{bkg}} F_{\text{bkg}}(m)$$

$$F_n(m) = (1-\omega_n) CB_n(m) + \omega_n G_n(m)$$

$$F_{\text{bkg}}(m) = \sum_{i=0}^{3} a_i (m - m_0)^i ; a_0 = 1$$

Define 3+2 regions



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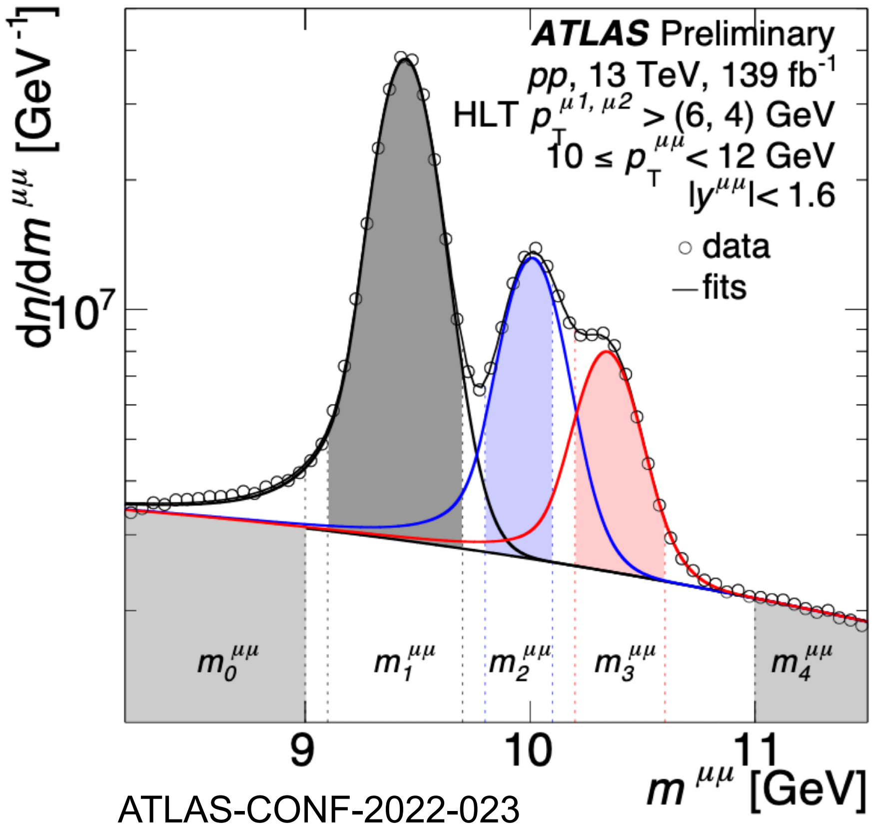
Signal extraction

$$s_n = \frac{\int_{m_n^{\mu\mu}} N_{\Upsilon(nS)} F_n(m)\, dm}{\int_{m_n^{\mu\mu}} \mathrm{fit}(m)\, dm}$$

$$f_{nk} = \frac{\int_{m_n^{\mu\mu}} N_{\Upsilon(kS)} F_k(m)\, dm}{\int_{m_n^{\mu\mu}} \mathrm{fit}(m)\, dm} \qquad k_n = \frac{\langle F_{\mathrm{bkg}}(m)\rangle|_{m_4^{\mu\mu}} - \langle F_{\mathrm{bkg}}(m)\rangle|_{m_n^{\mu\mu}}}{\langle F_{\mathrm{bkg}}(m)\rangle|_{m_4^{\mu\mu}} - \langle F_{\mathrm{bkg}}(m)\rangle|_{m_0^{\mu\mu}}}$$

Define 3+2 regions

Bkg shapes are similar – interpolate



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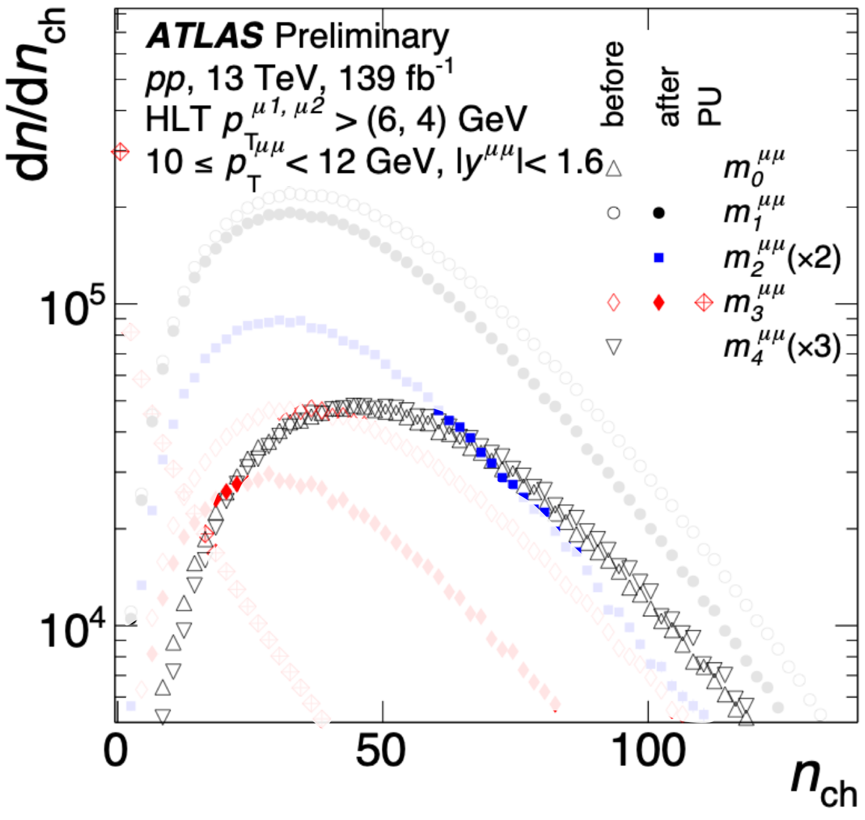

Signal extraction

$$\begin{pmatrix} P(m_0^{\mu\mu}) \\ P(m_1^{\mu\mu}) \\ P(m_2^{\mu\mu}) \\ P(m_3^{\mu\mu}) \\ P(m_4^{\mu\mu}) \end{pmatrix} = \begin{pmatrix} 1-f_{01} & f_{01} & 0 & 0 & 0 \\ k_1(1-s_1) & s_1 & 0 & 0 & (1-k_1)(1-s_1) \\ k_2(1-s_2-f_{21}-f_{23}) & f_{21} & s_2 & f_{23} & (1-k_2)(1-s_2-f_{21}-f_{23}) \\ k_3(1-s_3-f_{32}) & 0 & f_{32} & s_3 & (1-k_3)(1-s_3-f_{32}) \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} P_0 \\ P(\Upsilon(1S)) \\ P(\Upsilon(2S)) \\ P(\Upsilon(3S)) \\ P_4 \end{pmatrix}$$

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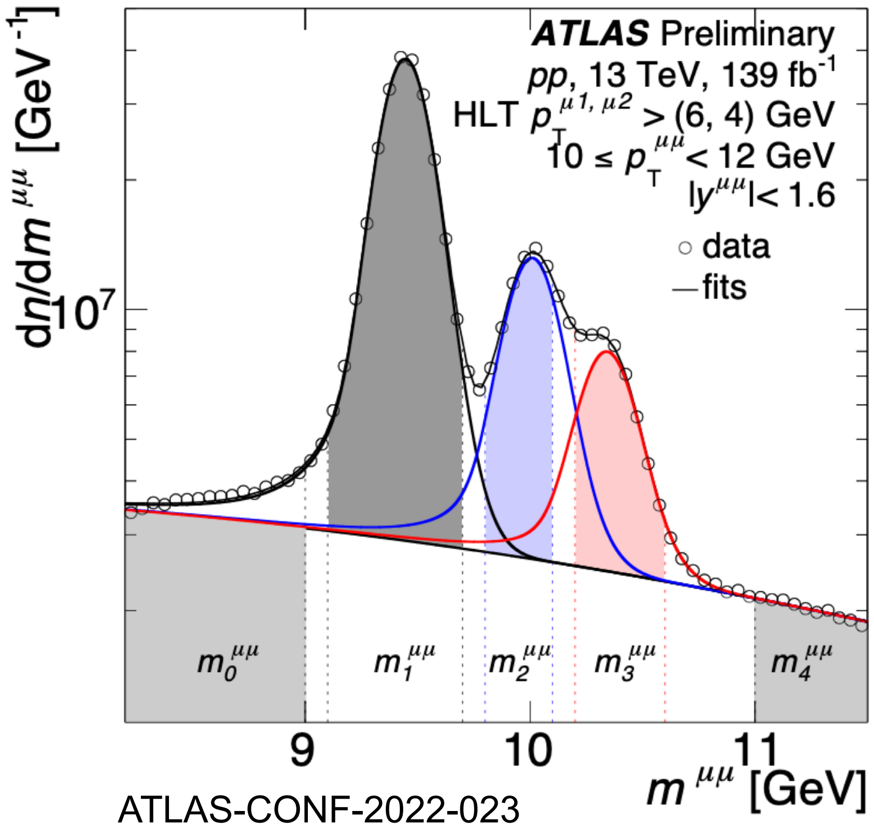
Bkg subtraction for $\Upsilon(1S)$ and $\Upsilon(3S)$



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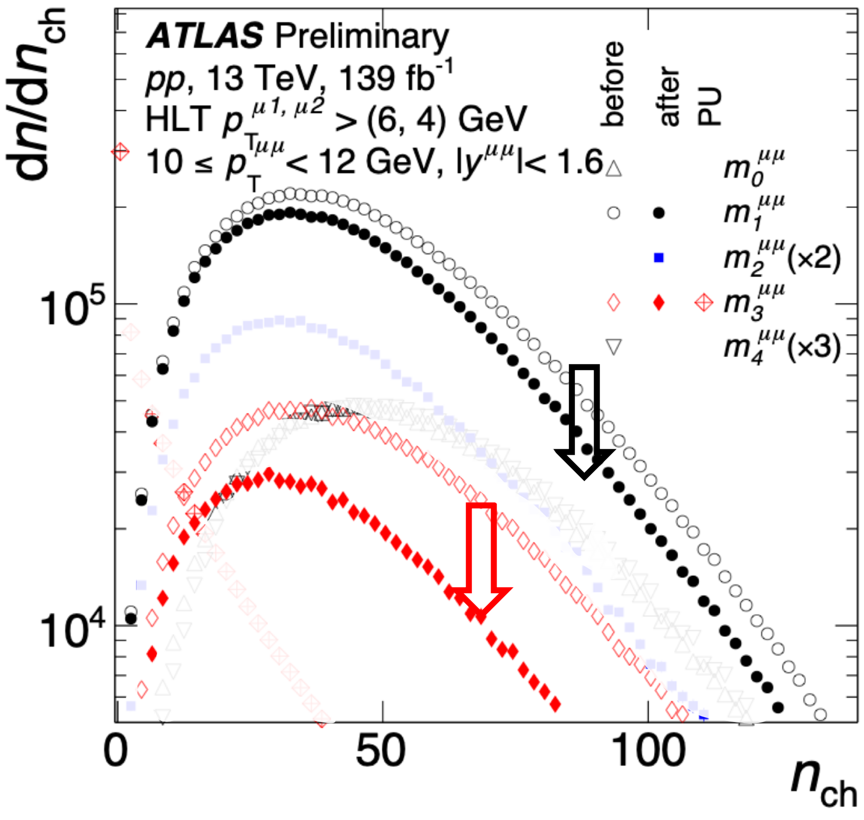

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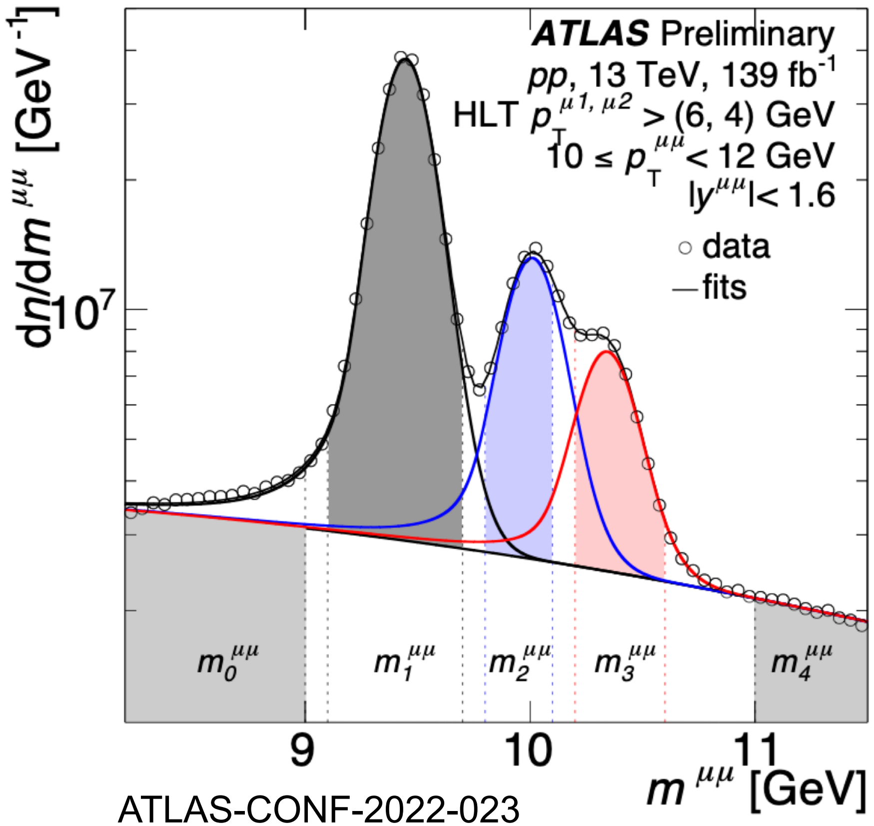
After subtraction n_{ch} look different



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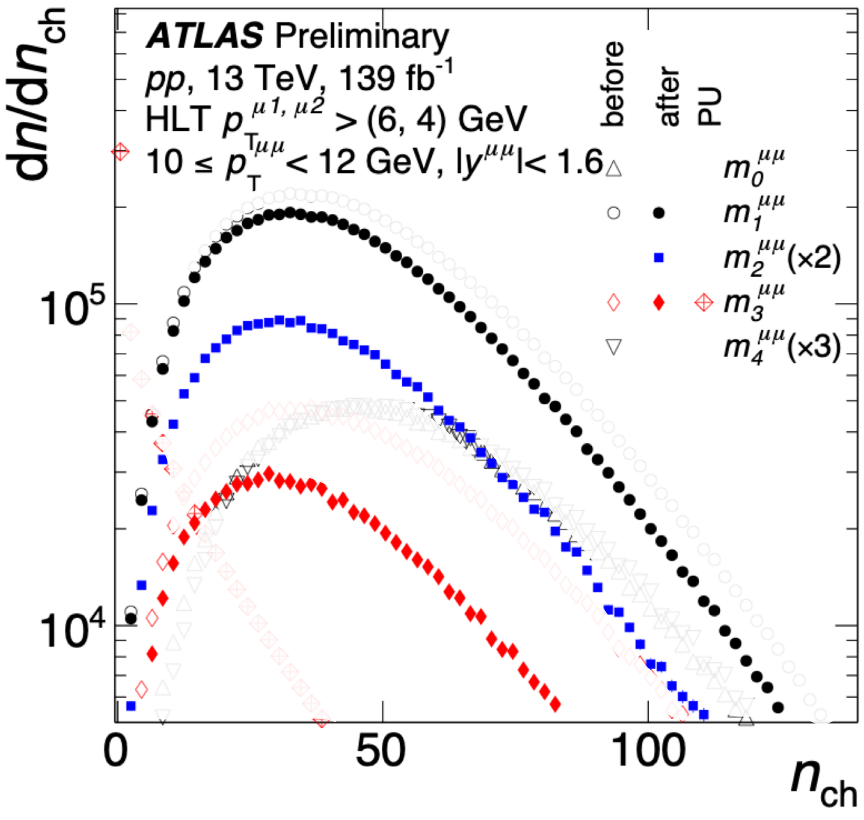
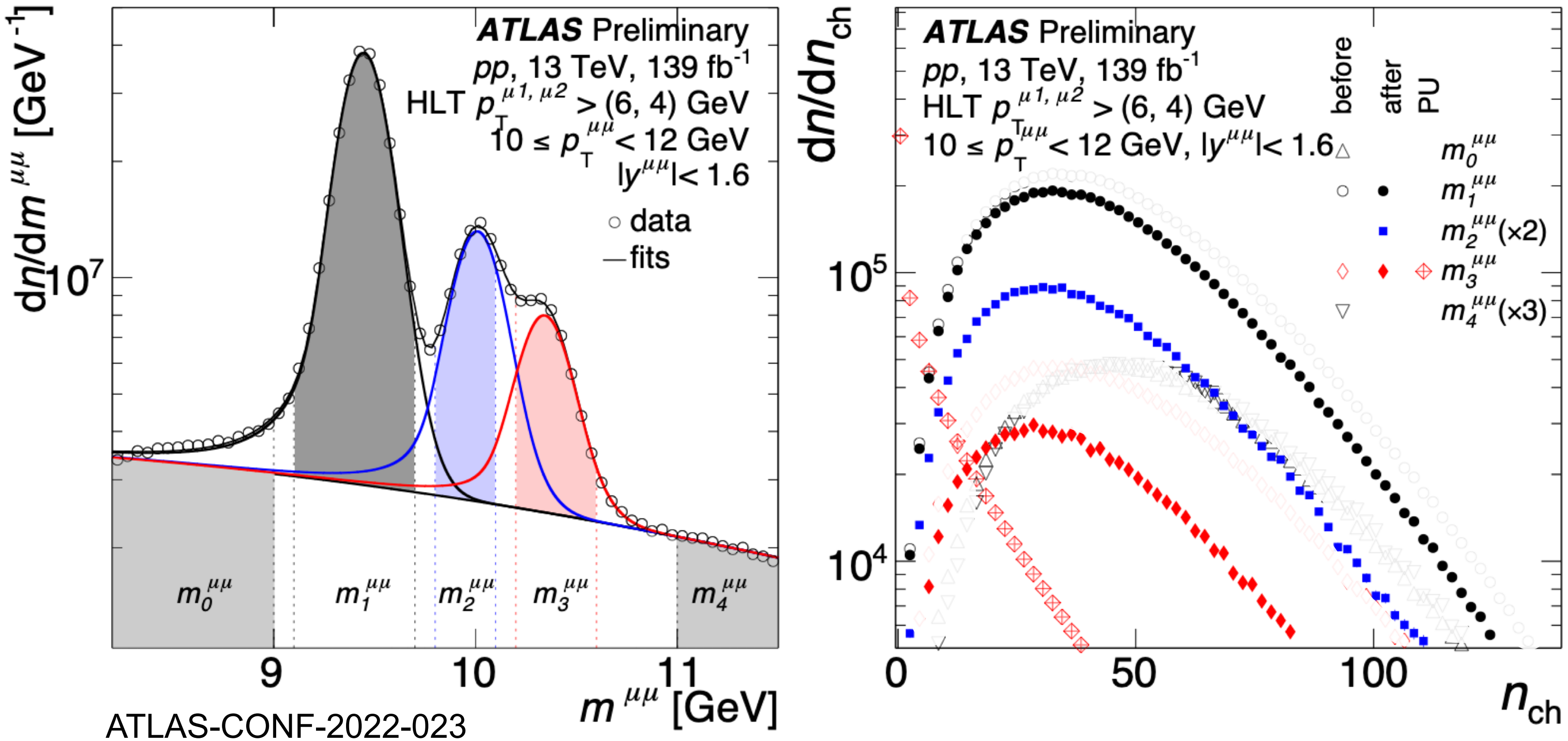


Signal extraction

Triggers are all combined together
Pileup is constructed from mixed events and is either directly subtracted or unfolded
Non-linear effects are also accounted for



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The procedure is illustrated with n_{ch},
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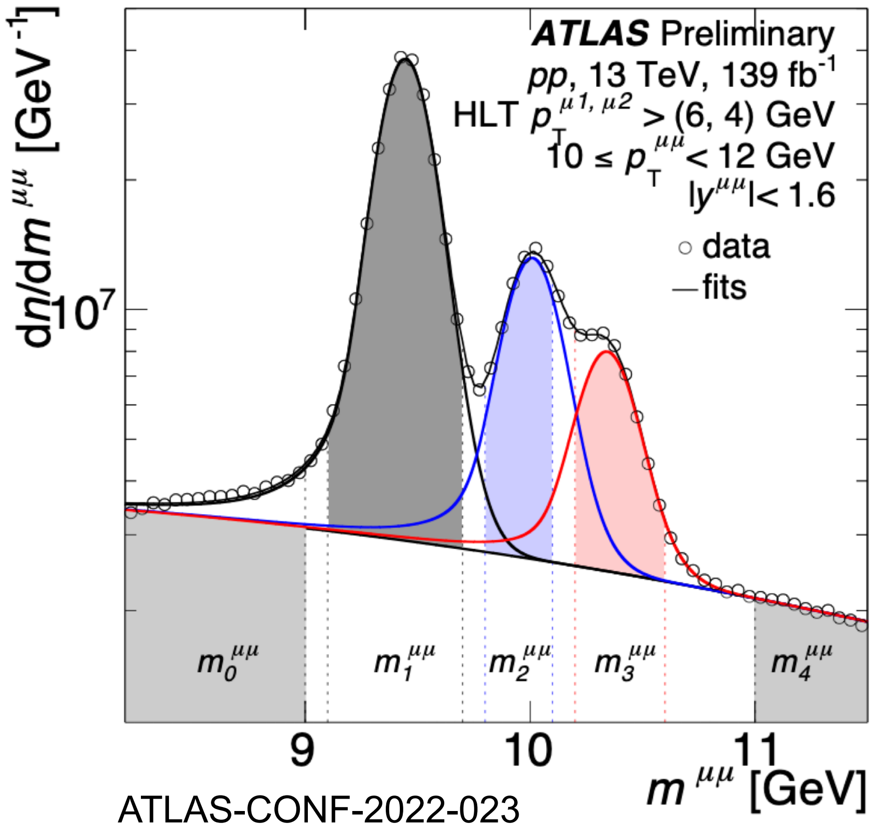

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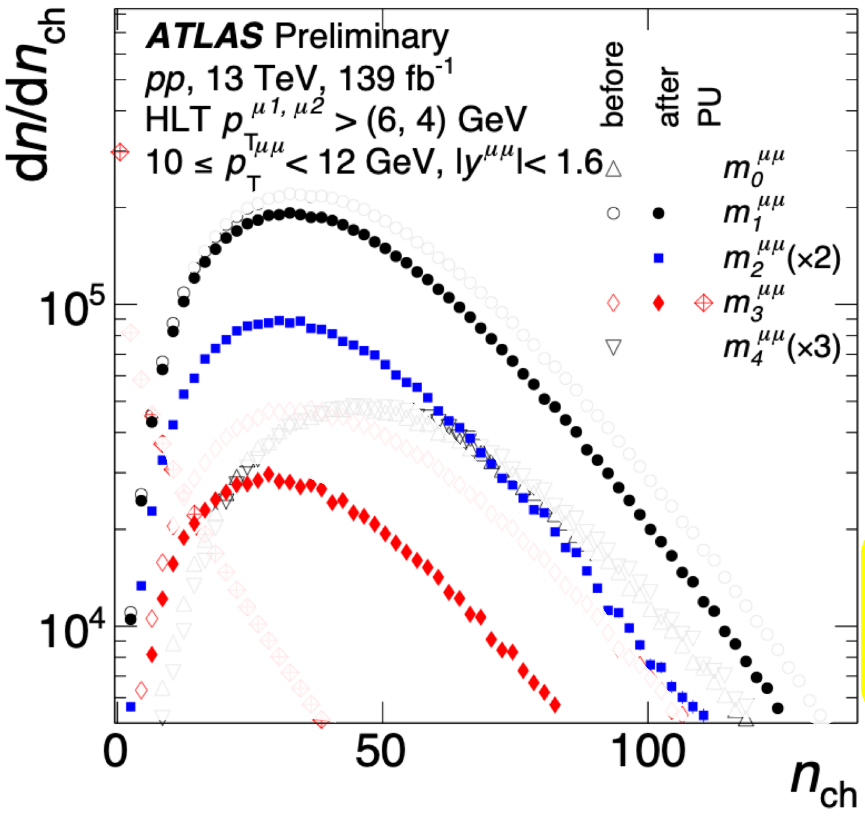

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Direct measurement of n_{ch}
dn_{ch}/dp_T $dn_{ch}/d\Delta\phi$

Signal extraction

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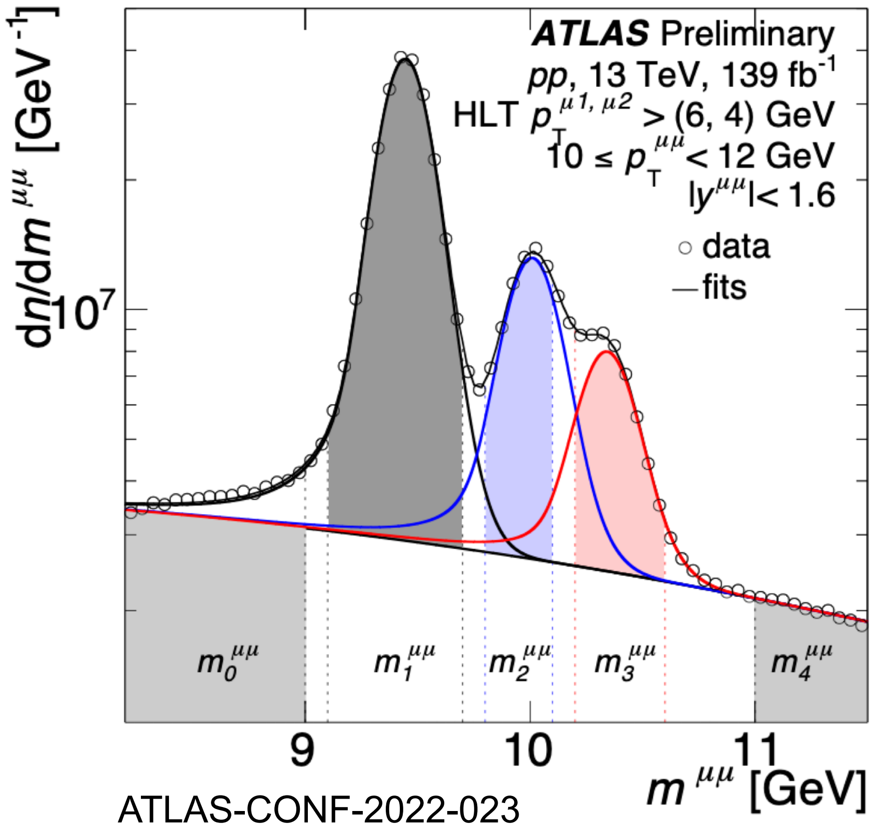

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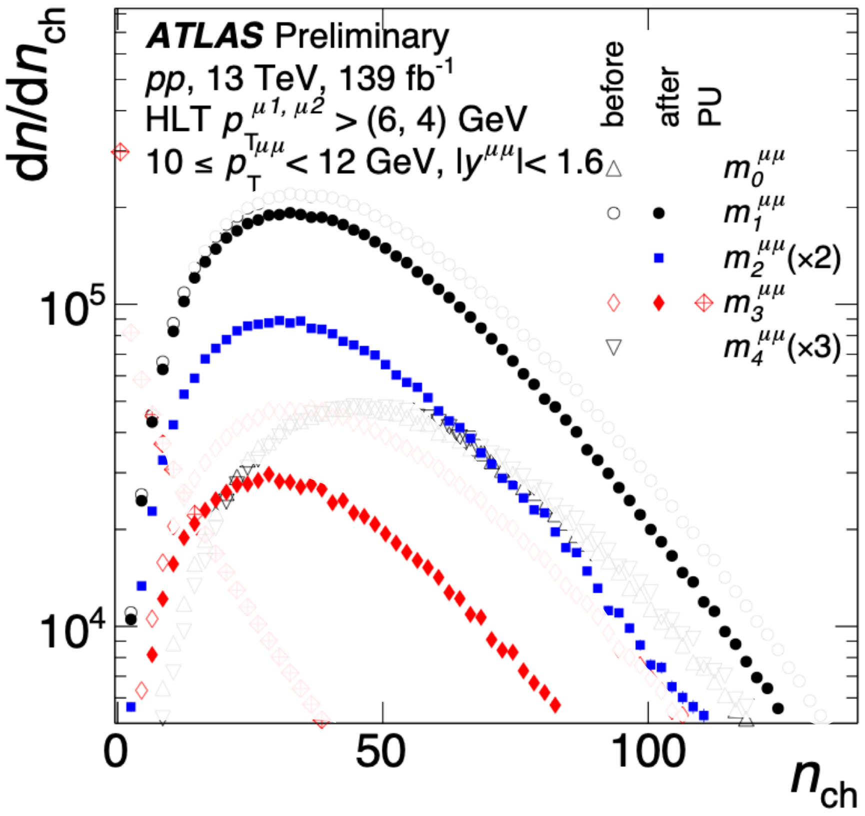

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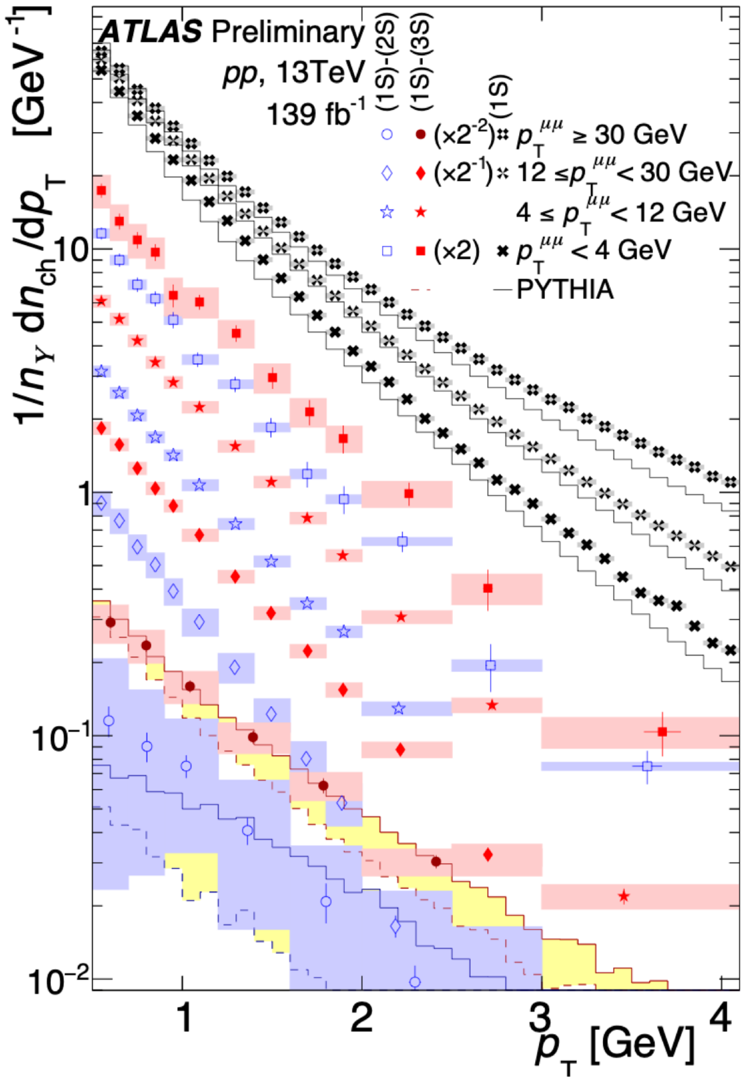
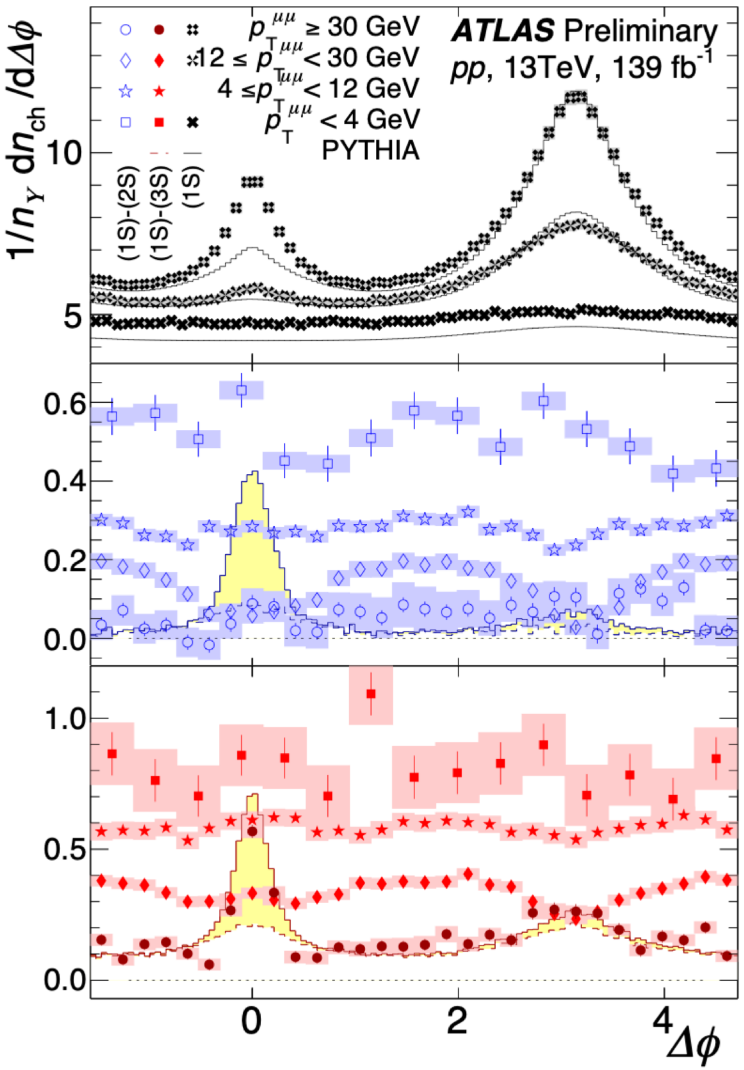
Kinematic distributions





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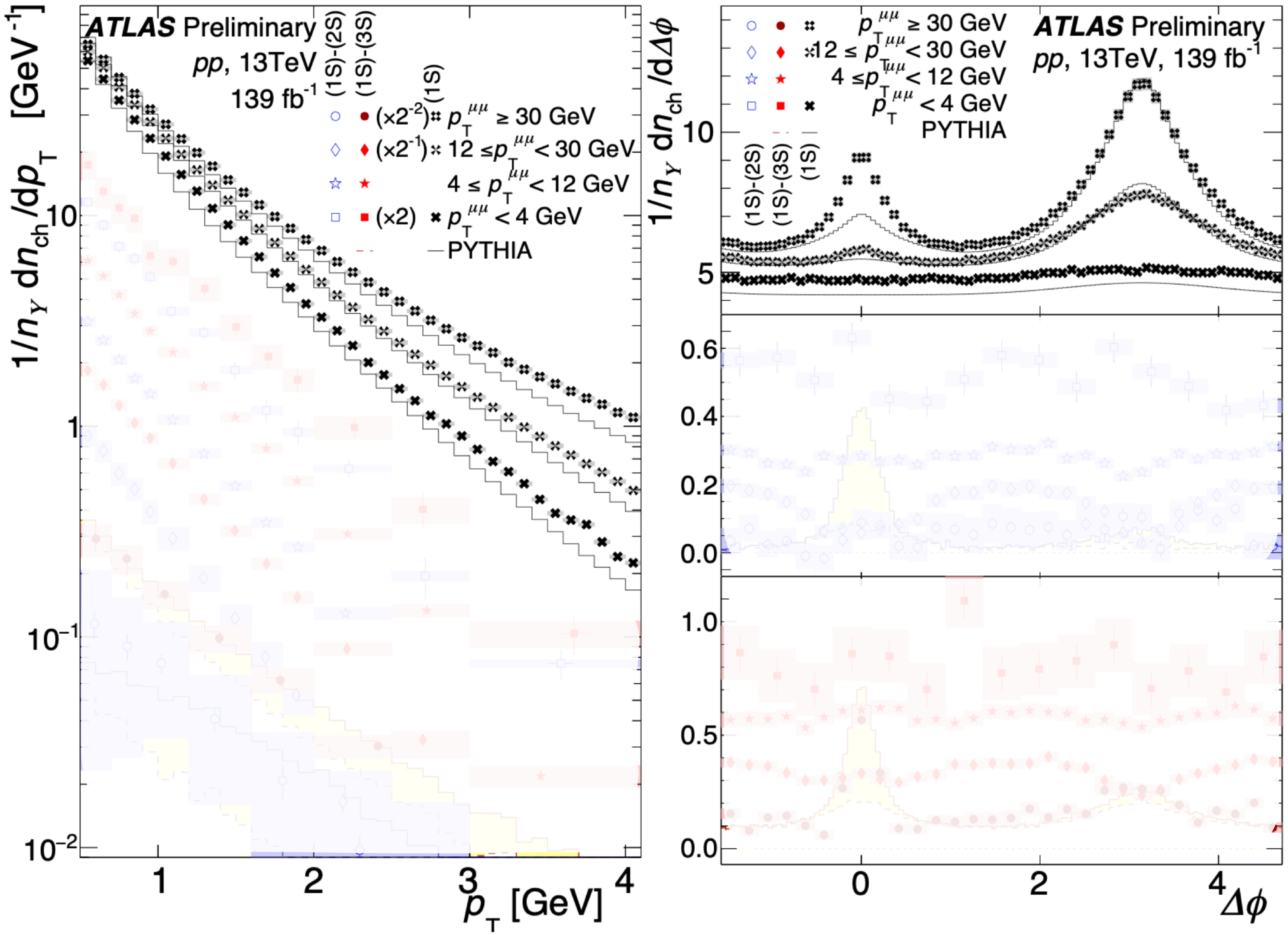

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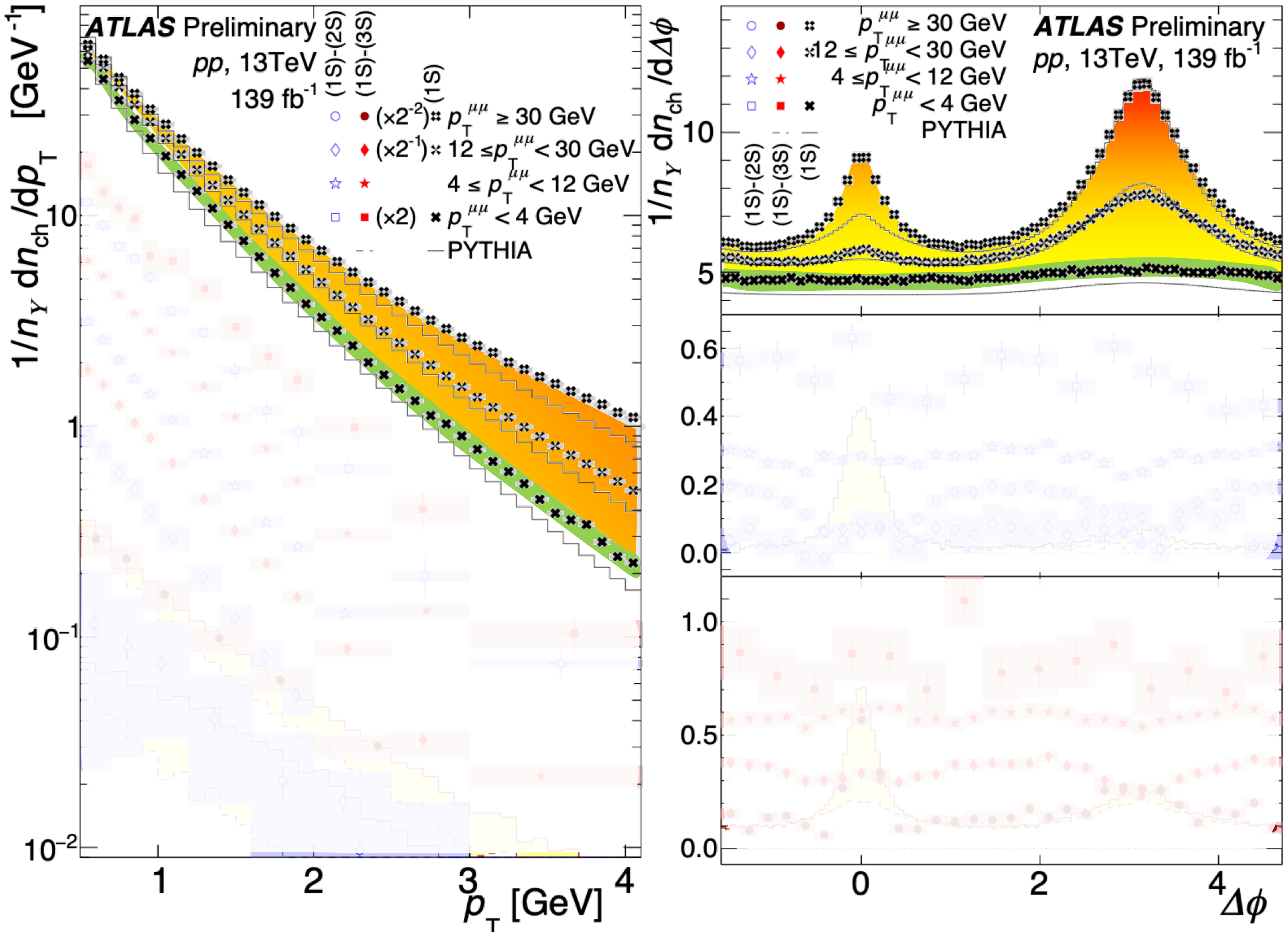
Distributions for $\Upsilon(1S)$

Pythia does not describe data well

Kinematic distributions



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Distributions for $\Upsilon(1S)$

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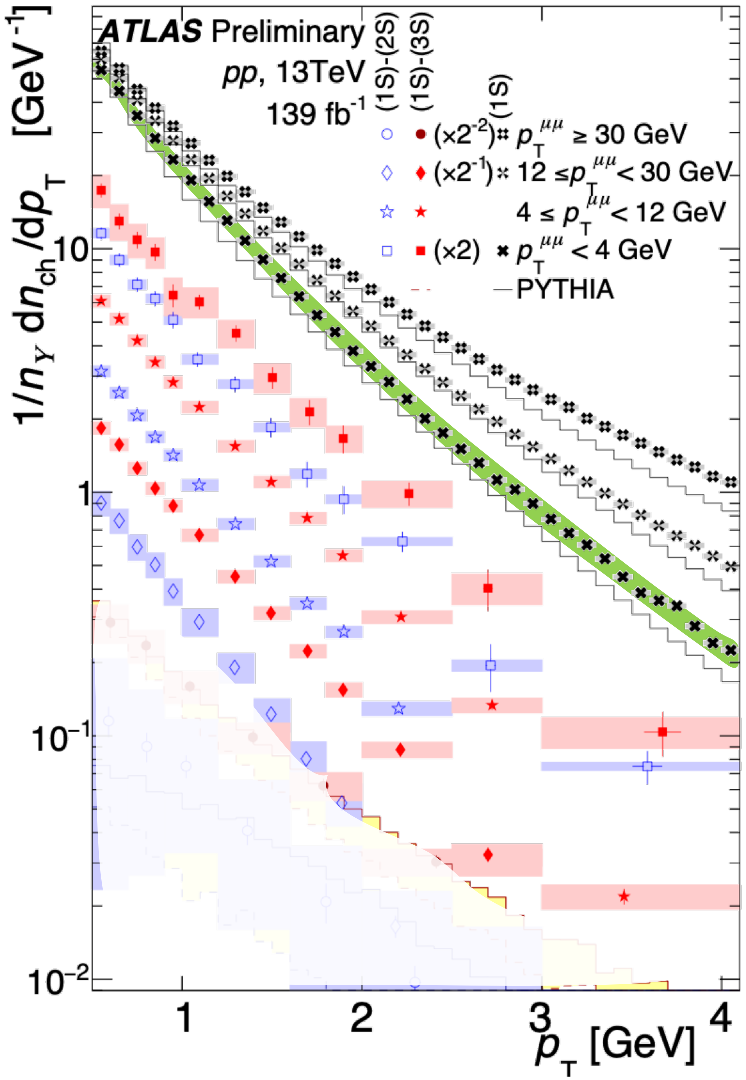
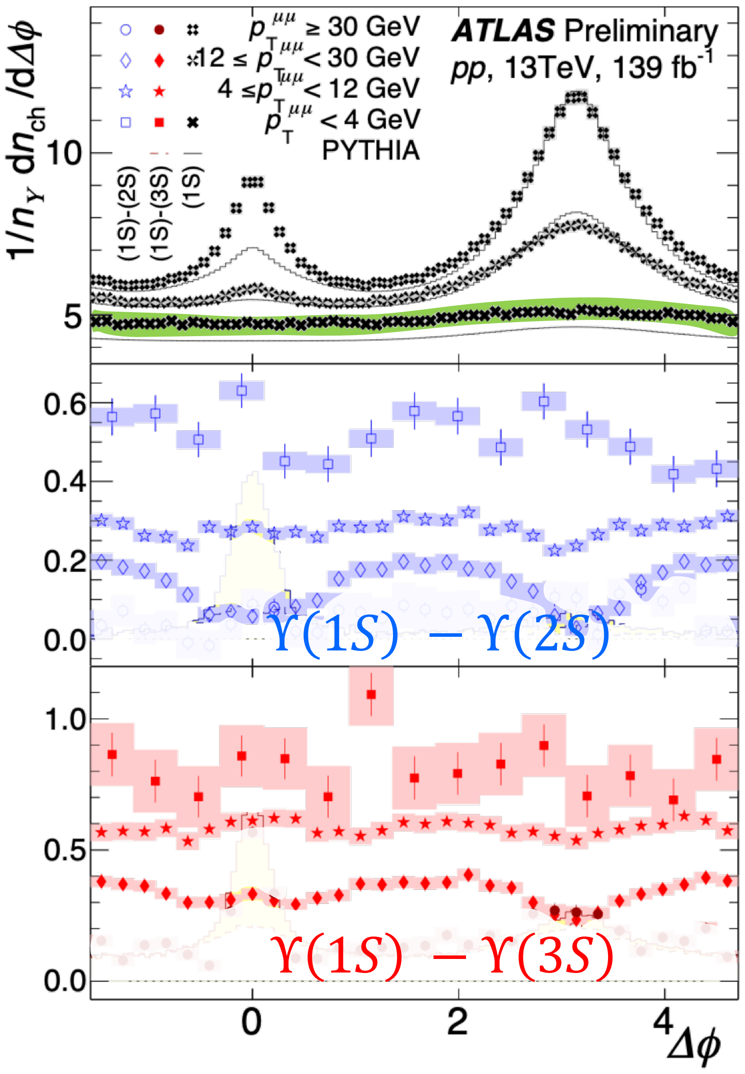
One cannot measure the UE, but $p_T < 4$ GeV is the closest to it, jet part that is correlated to $\Upsilon(nS)$

Kinematic distributions





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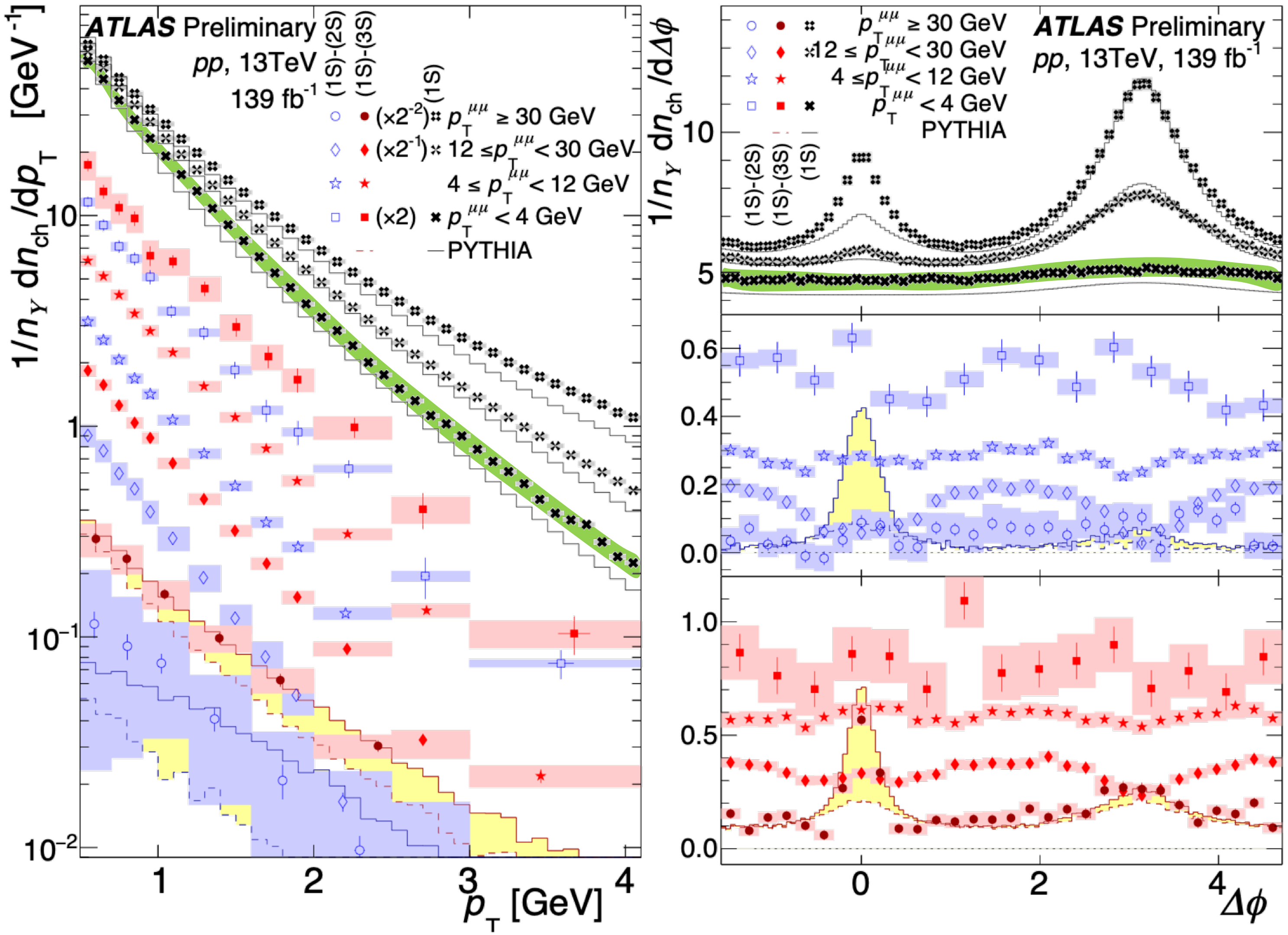
Subtracted distributions look like UE at rather high $\Upsilon(nS)$ p_T. At the highest p_T there are feed-downs

Kinematic distributions



ATLAS-CONF-2022-023

Distributions for $\Upsilon(1S)$

Pythia does not describe data well

One cannot measure the UE, but p_T < 4 GeV is the closest to it, jet part that is correlated to $\Upsilon(nS)$

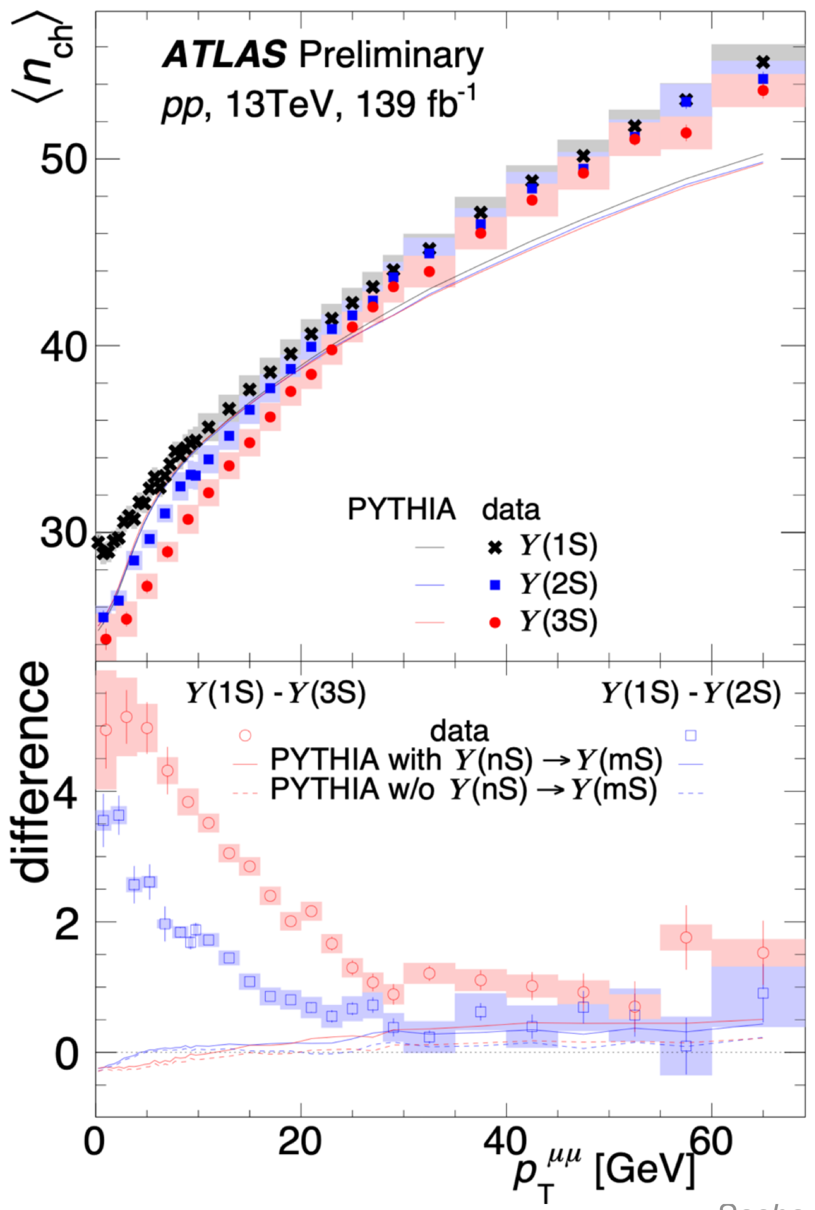
Subtracted distributions look like UE at rather high $\Upsilon(nS)$ p_T. At the highest p_T there are feed-downs

Away from jets there are regions with charged particles

This suggests that the effect is related to the UE

Multiplicity dependence on Υ–momentum

ATLAS-CONF-2022-023



Multiplicity is different for different $\Upsilon(nS)$ states

The effect is related to the UE, not to the Υ production

Can't be explained by feed downs or p_T, conservation

Pythia mismodels Υ production, and has no effect at all

At the lowest p_T, where the effect is the strongest:

$\Upsilon(1S) - \Upsilon(2S)\ \Delta\langle n_{ch}\rangle = 3.6 \pm 0.4$ 12% of $\langle n_{ch}^{\Upsilon(1S)}\rangle$

$\Upsilon(1S) - \Upsilon(3S)\ \Delta\langle n_{ch}\rangle = 4.9 \pm 1.1$ 17% of $\langle n_{ch}^{\Upsilon(1S)}\rangle$

It diminishes with p_T, but remains visible at 20–30 GeV
And actually above that as well

Comover interaction model

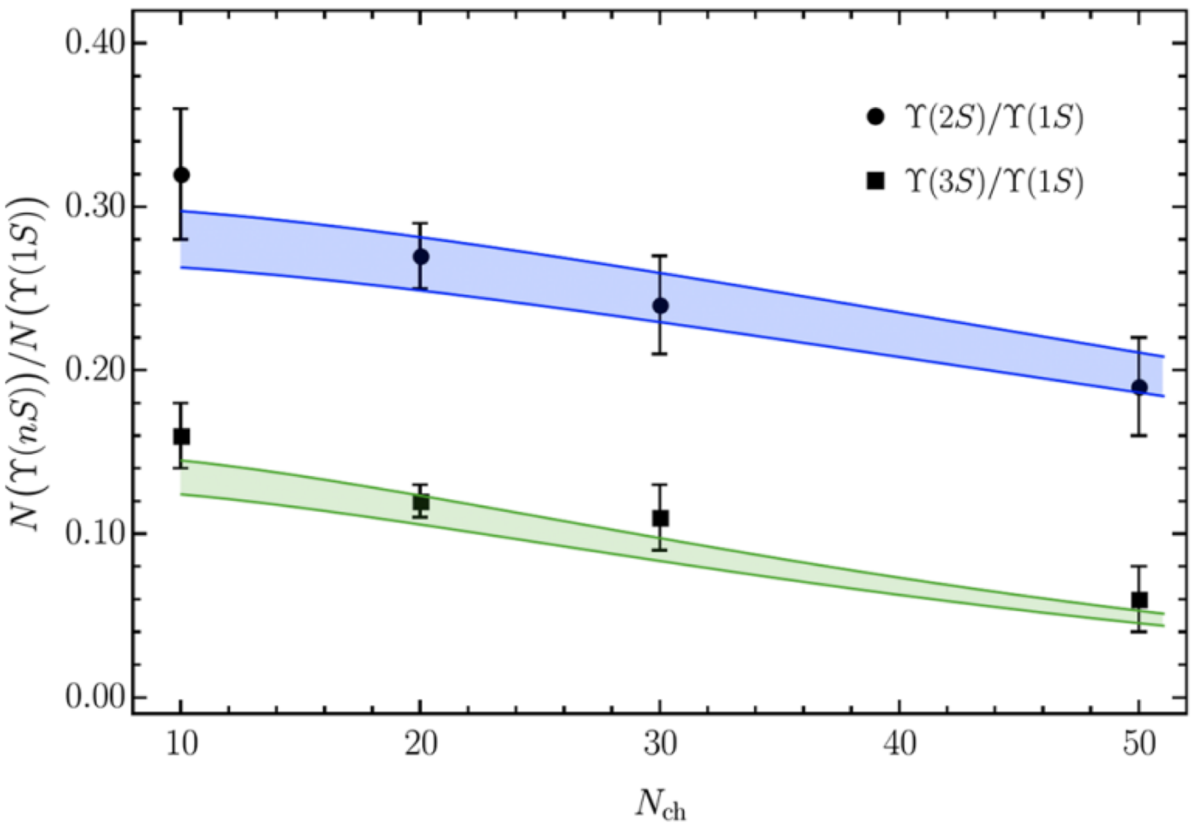
EPJC 81, 669 (2021)

Within CIM, quarkonia are broken by collisions with comovers – i.e. final state particles with similar rapidities.

CIM is typically used to explain *p*+A and A+A systems, although recently it was successfully applied to *pp.*

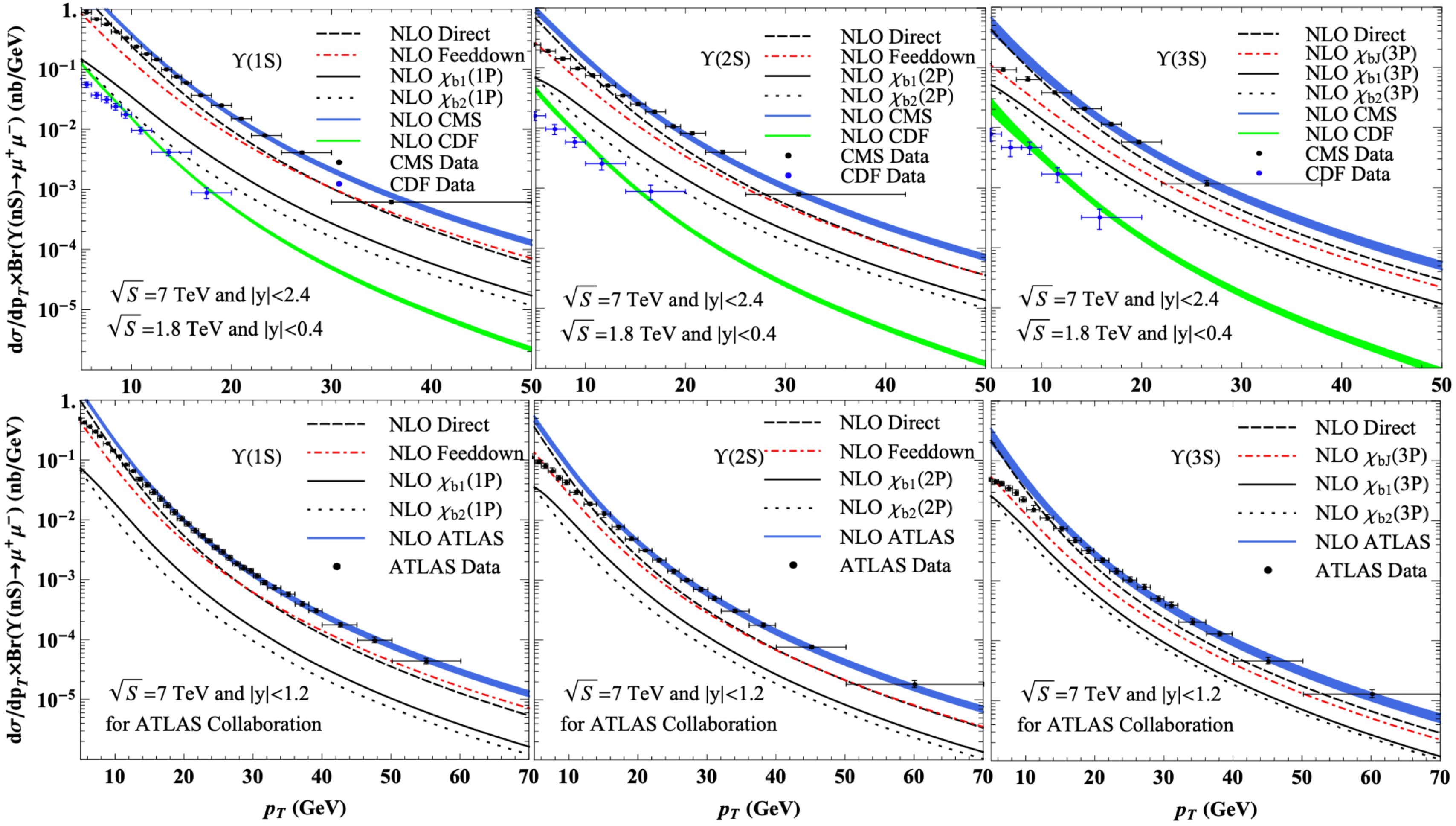
With the new data, CIM can be tested on *pp* to reproduce $\Upsilon(nS) - \Upsilon(1S)$ differences

- in cross section
- in n_{ch}
- in hadron kinematic distributions: p_T, $\Delta\varphi$ $\Delta\eta$



Cross-section calculations

PRD94, 014028 (2016)



χ_b feed-downs into $\Upsilon(nS)$ are similar for different species.

Calculations and the data show clear differences

Discrepancies are larger for higher $\Upsilon(nS)$ and lower p_{T}

It looks like the ratios would rather follow m_{T} – scaling cures rather than the data

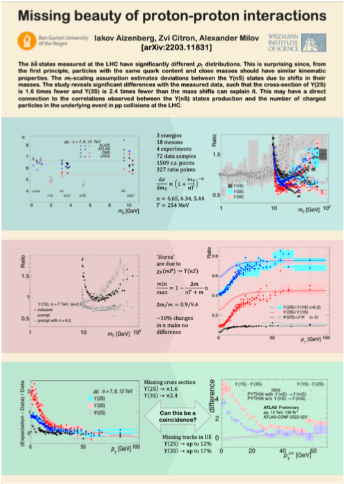
$\Upsilon(1S)$ curve overshoots the data

Global analysis

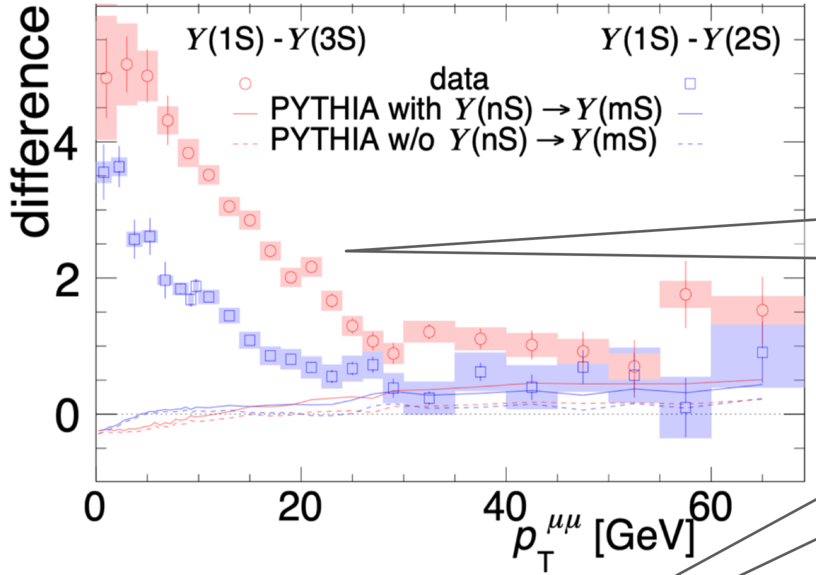
Assumption: particles with the same quark content and close masses shall have similar kinematics

The extent of similarity can be tested with the m_T – scaling

There are obvious similarities in two independent measurements

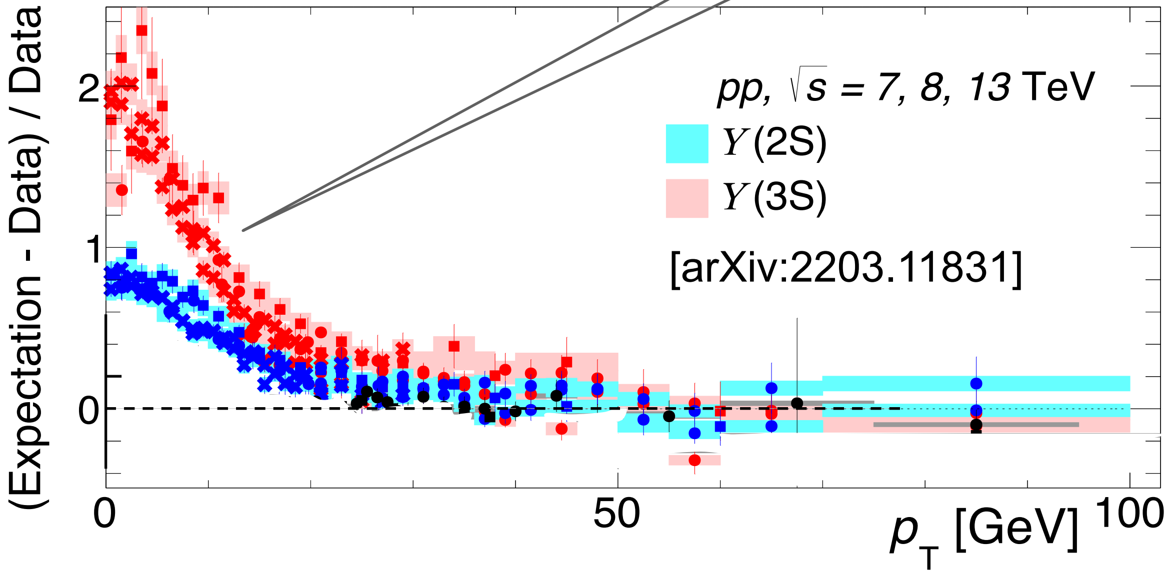


More details in the poster session



Difference in UE tracks

Deficit in cross-section



Summary

ATLAS show that higher $\Upsilon(nS)$ states reside in events with smaller n_{ch}. The magnitude of the effect reaches 17%

ATLAS relates the effect to the underlying event, not to particles produced in the same hard scattering as the $\Upsilon(nS)$

The effect is absent in Pythia

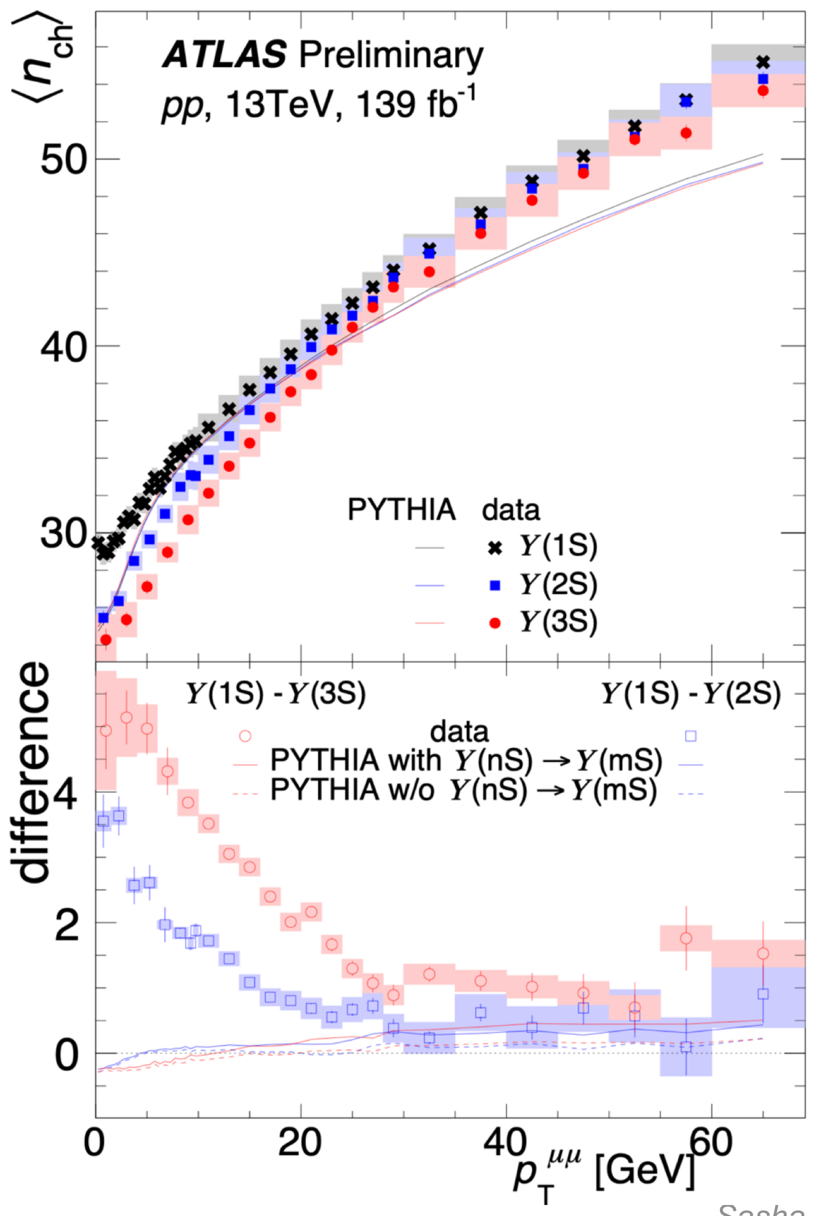
Bringing pieces together:

- different number of tracks (ATLAS, CMS)
- n_{ch} dependent $\Upsilon(\mathrm{n}S)/\Upsilon(1S)$ ratios (CMS, LHCb)
- discrepancies with models, especially at low p_{T}
- Similarities with the m_{T} – scaling analysis results

Something interesting is going on in *pp* that must be further explored!

backups

A naïve question



Is the n_{ch} for $\Upsilon(1S)$ larger than it should be or is it smaller than it should be for higher $\Upsilon(nS)$?

Inclusive *pp* collisions:	$\langle n_{\mathrm{ch}} \rangle \approx 14$
Drell-Yan with $40\ \mathrm{GeV} < m \leq m_Z$	$\langle n_{\mathrm{ch}} \rangle = 24 - 28$
Jets with leading particles $m < \frac{1}{2} m_\Upsilon$	$\langle n_{\mathrm{ch}} \rangle \approx 27$

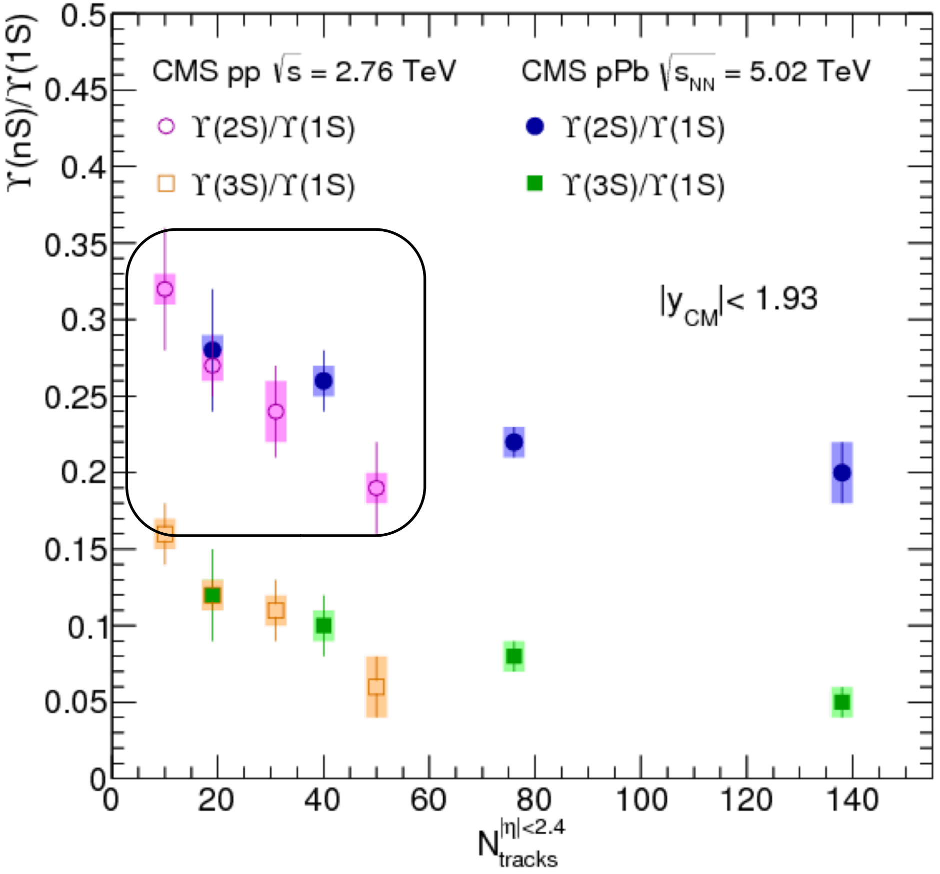
PLB 758 (2016) 67
EPJC 79 (2019) 666
JHEP 07 (2018) 032
JHEP 03 (2017) 157

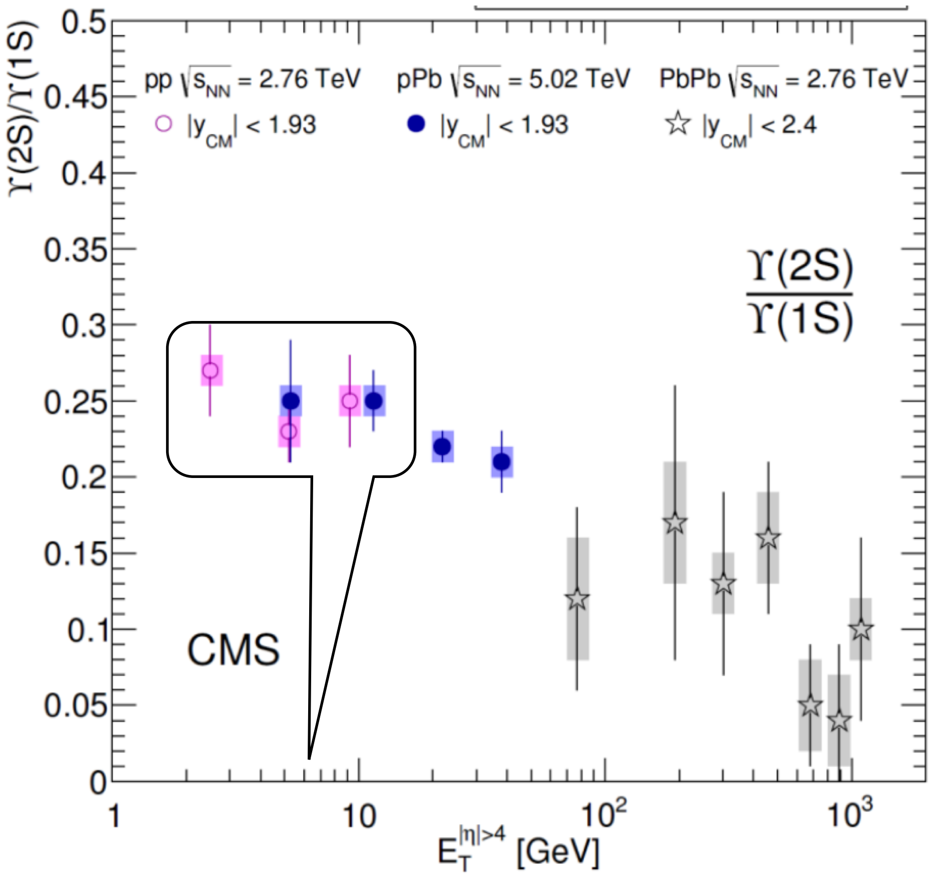
Looks like $\Upsilon(1S)$ is consistent with these numbers, and $\Upsilon(nS)$ are lower i.e. there is a deficit of higher $\Upsilon(nS)$

If $\Upsilon(1S)$ has no n_{ch} excess, then $\Upsilon(nS)$ are suppressed and one shall be able to measure it!

Does the rapidity matter?

JHEP 04 (2014) 103



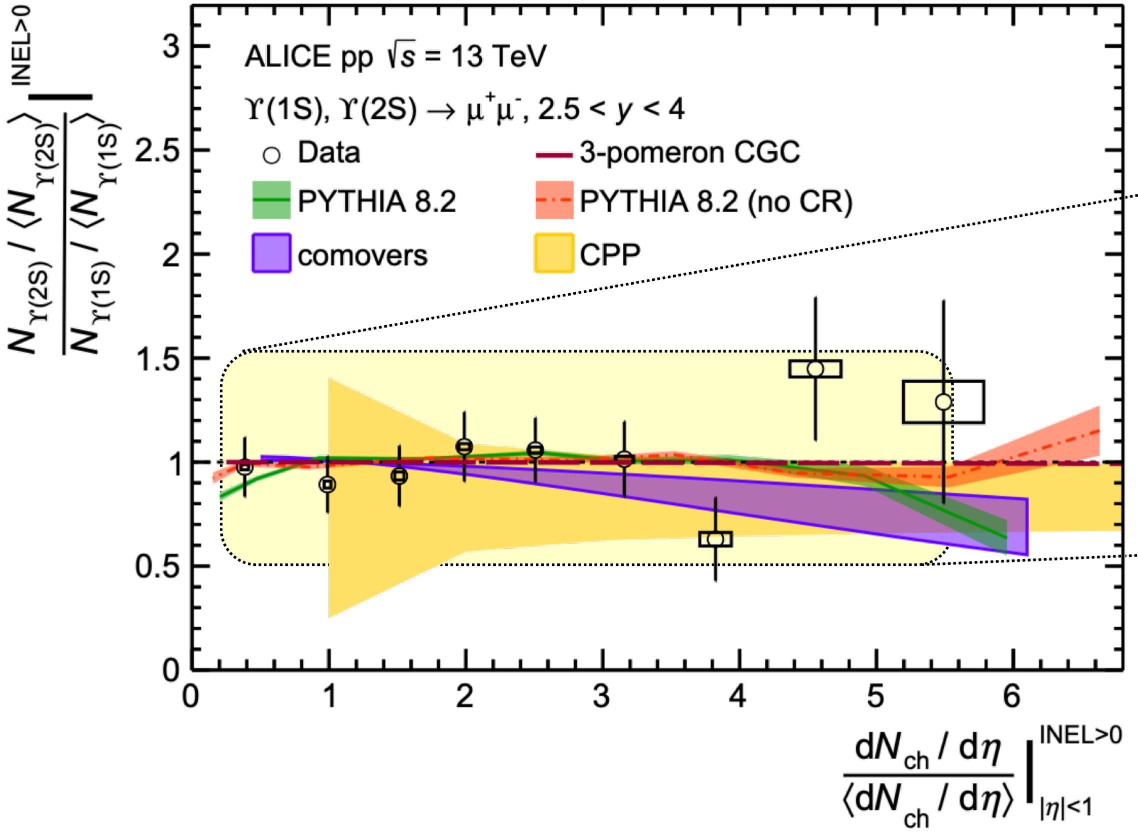


Introducing midrapidity-forward gap flattens the dependence as mentioned in HP2018 summary talk: https://indico.cern.ch/event/634426/contributions/3003672/

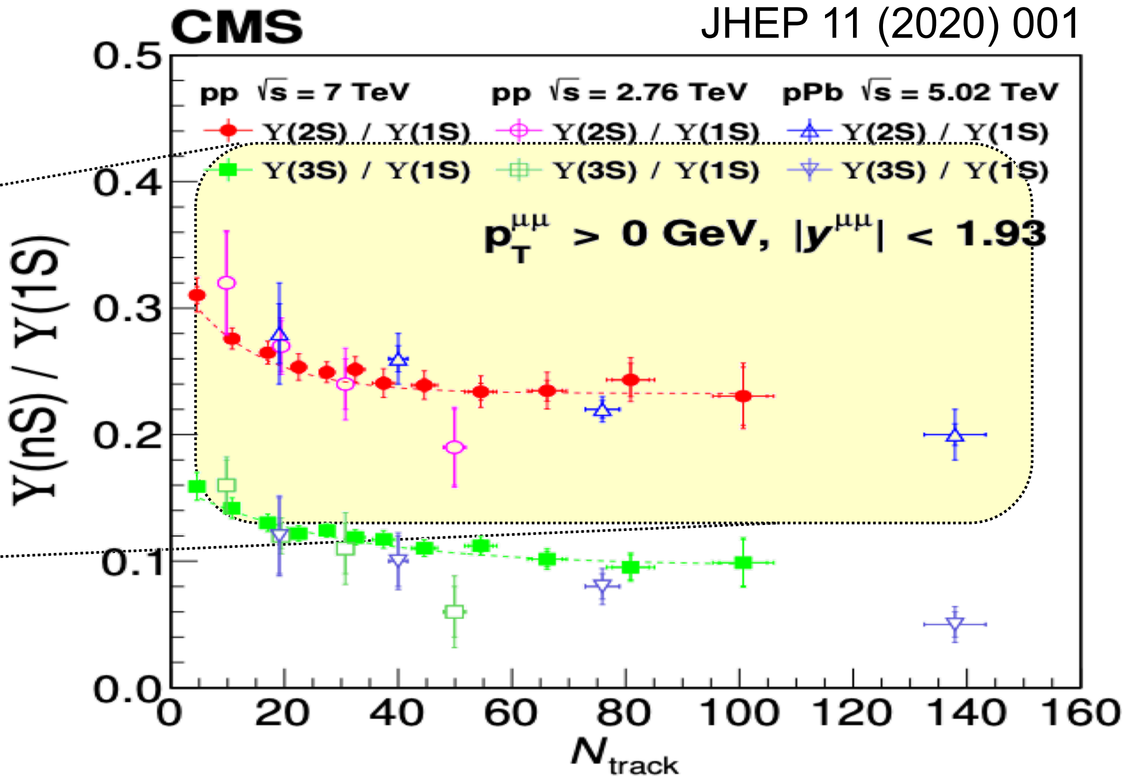
But it may be due to loss of resolution…

Does the rapidity matter?

arXiv:2209.04241



JHEP 11 (2020) 001



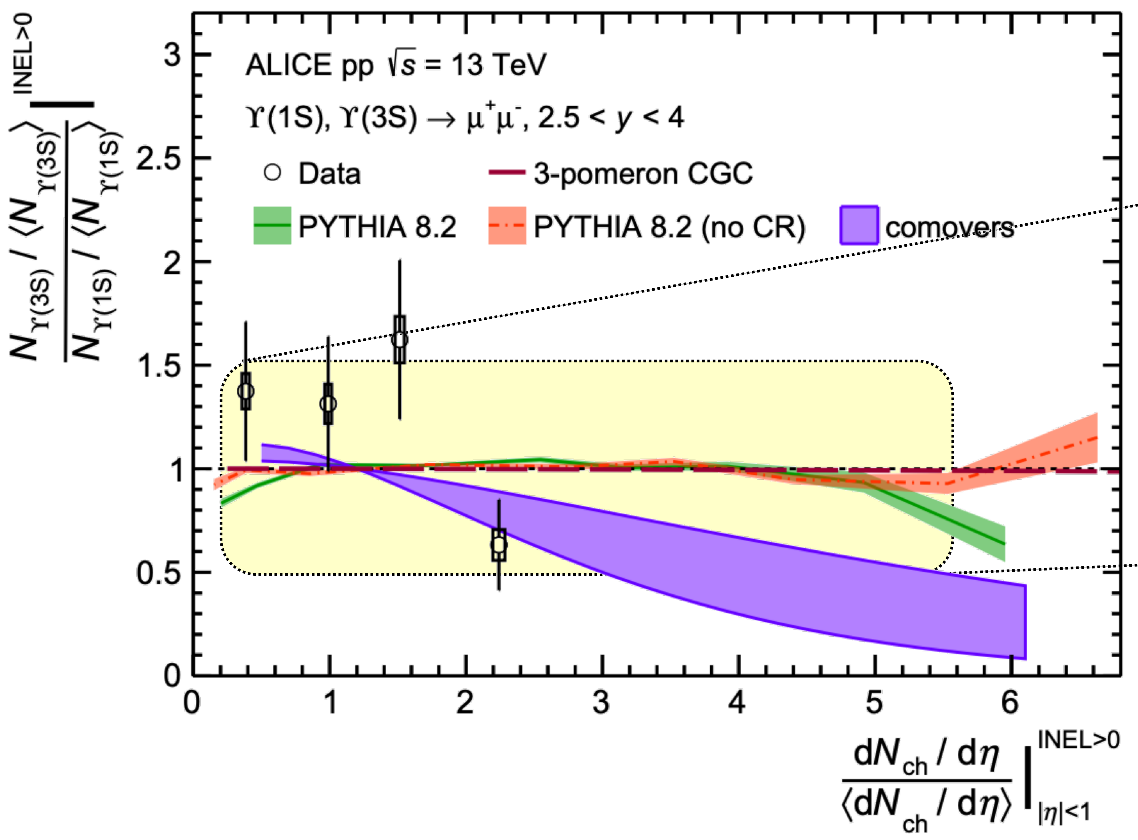
ALICE result on forward $\Upsilon(2S)/\Upsilon(1S)$ vs tracks at midrapidity

Data doesn't warrant any gap dependence

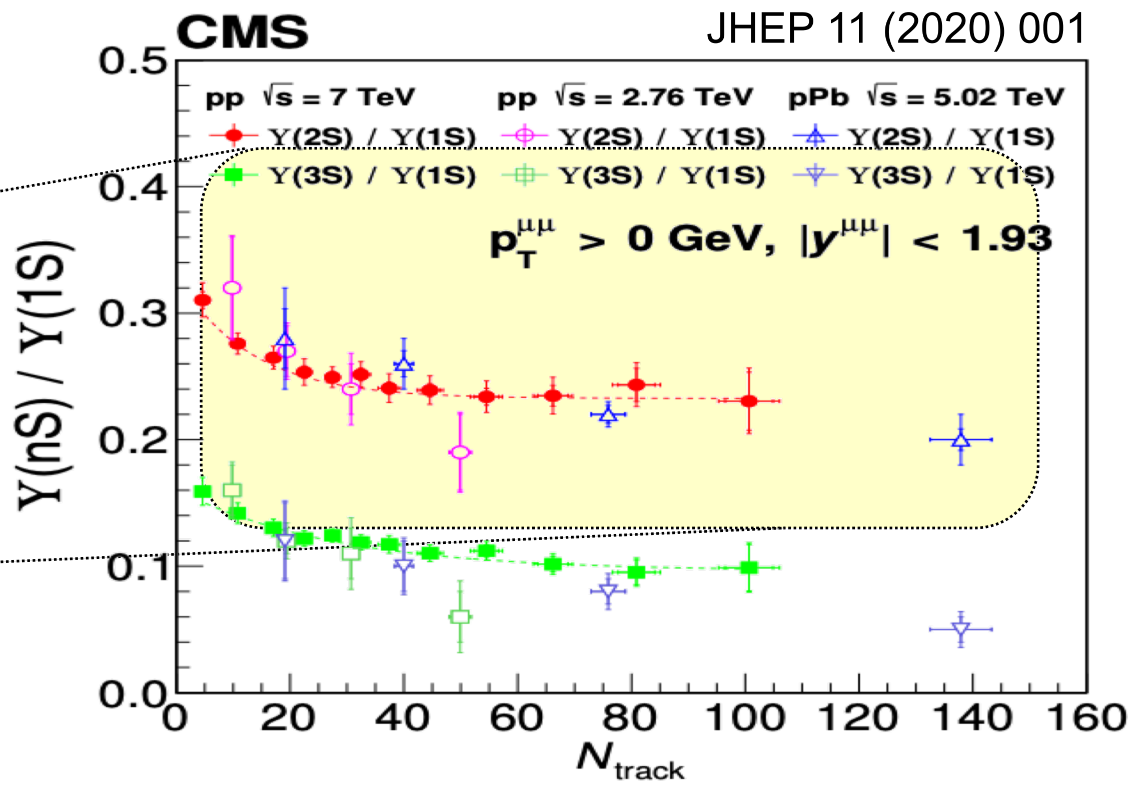
A direct answer should come from $\Delta\eta$ – analysis

Does the rapidity matter?

arXiv:2209.04241



JHEP 11 (2020) 001



ALICE result on forward $\Upsilon(3S)/\Upsilon(1S)$ vs tracks at midrapidity

Data doesn't warrant any gap dependence

A direct answer should come from $\Delta\eta$ – analysis

The m_T scaling

Proposed by R. Hagedorn [*N.Cim.Sup.*3 (1965) 147-186] and observed by the ISR [PLB **47**, 75 (1973)]

$$P(p_T) \propto \frac{1}{(m_T)^{\lambda}} \exp\left[-\frac{m_T}{T_a}\right] \qquad m_T = \sqrt{p_T^2 + m_0^2}$$

Today is more commonly used in Tsallis form

$$\frac{d\sigma}{dm_T} \propto \left[1 + \frac{m_T}{nT}\right]^{-n}$$

m_T scaling is useless to measure cross sections, but it can link spectral shapes of different particles, for example $\Upsilon(nS)$ to $\Upsilon(1S)$

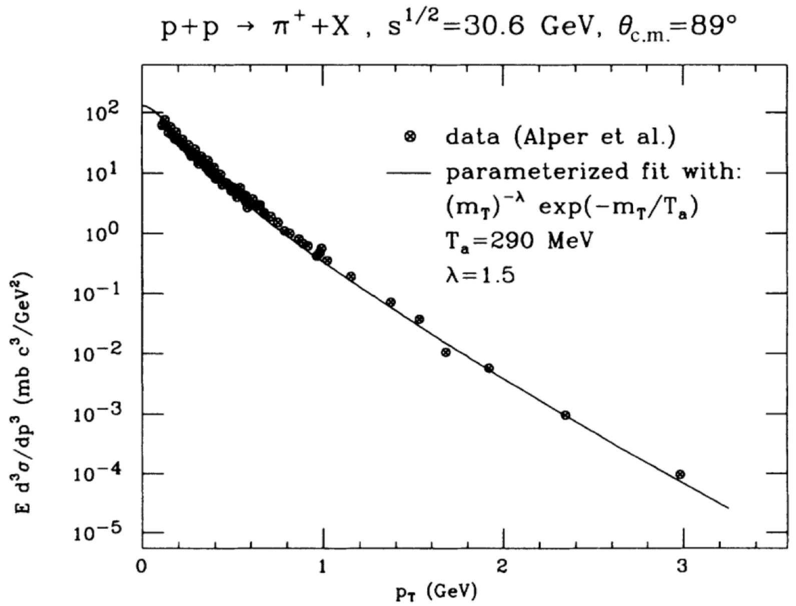
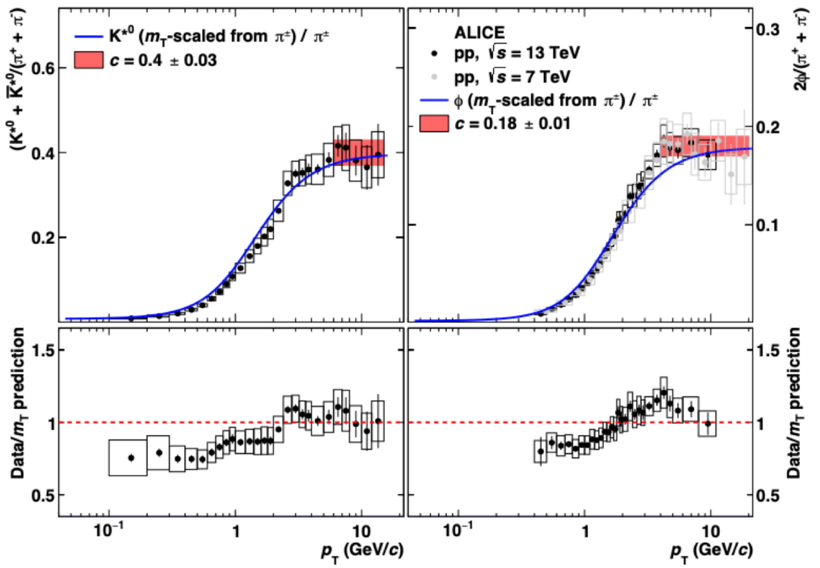
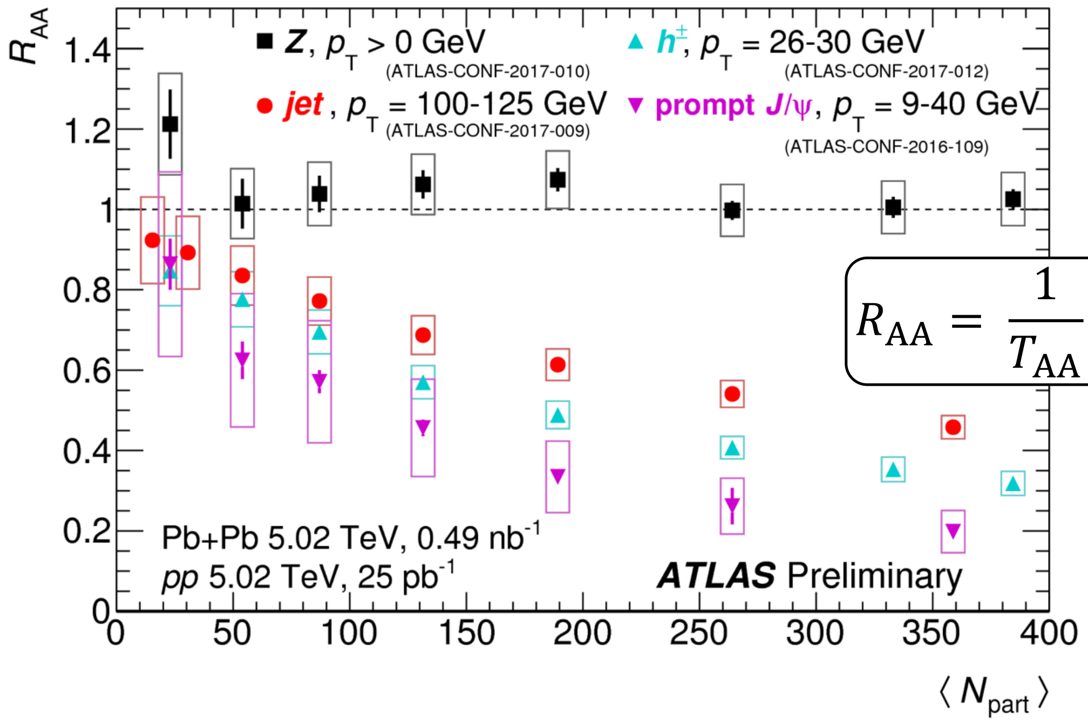


FIG. 3. *p-p* data from Alper *et al.*, fit here with $m_T^{-\lambda}\exp(-m_T/T_a)\times$const, having T_a=200 MeV and λ=1.5.

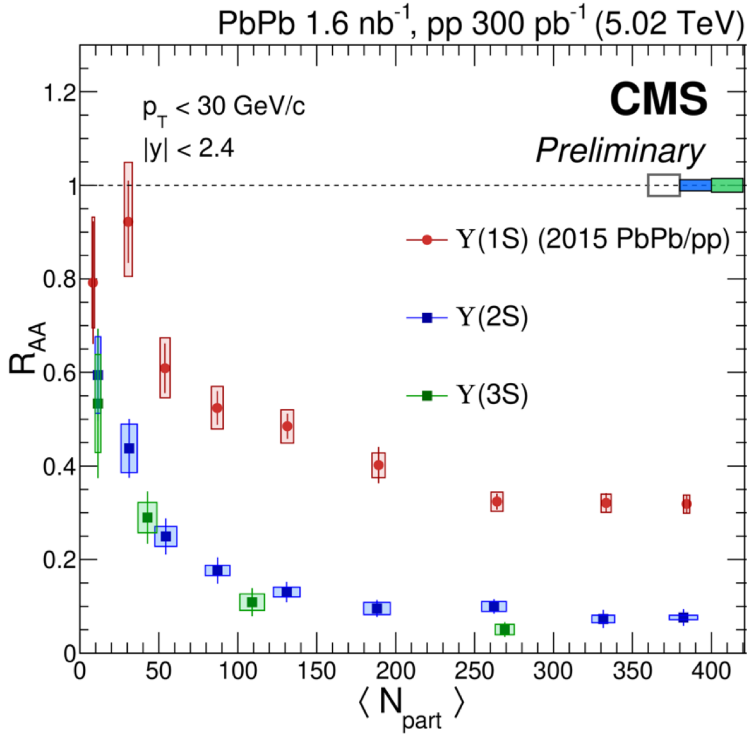
for example, ALICE: EPJC81 (2021) 256



Back to heavy ions



$$R_{AA} = \frac{1}{T_{AA}} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$



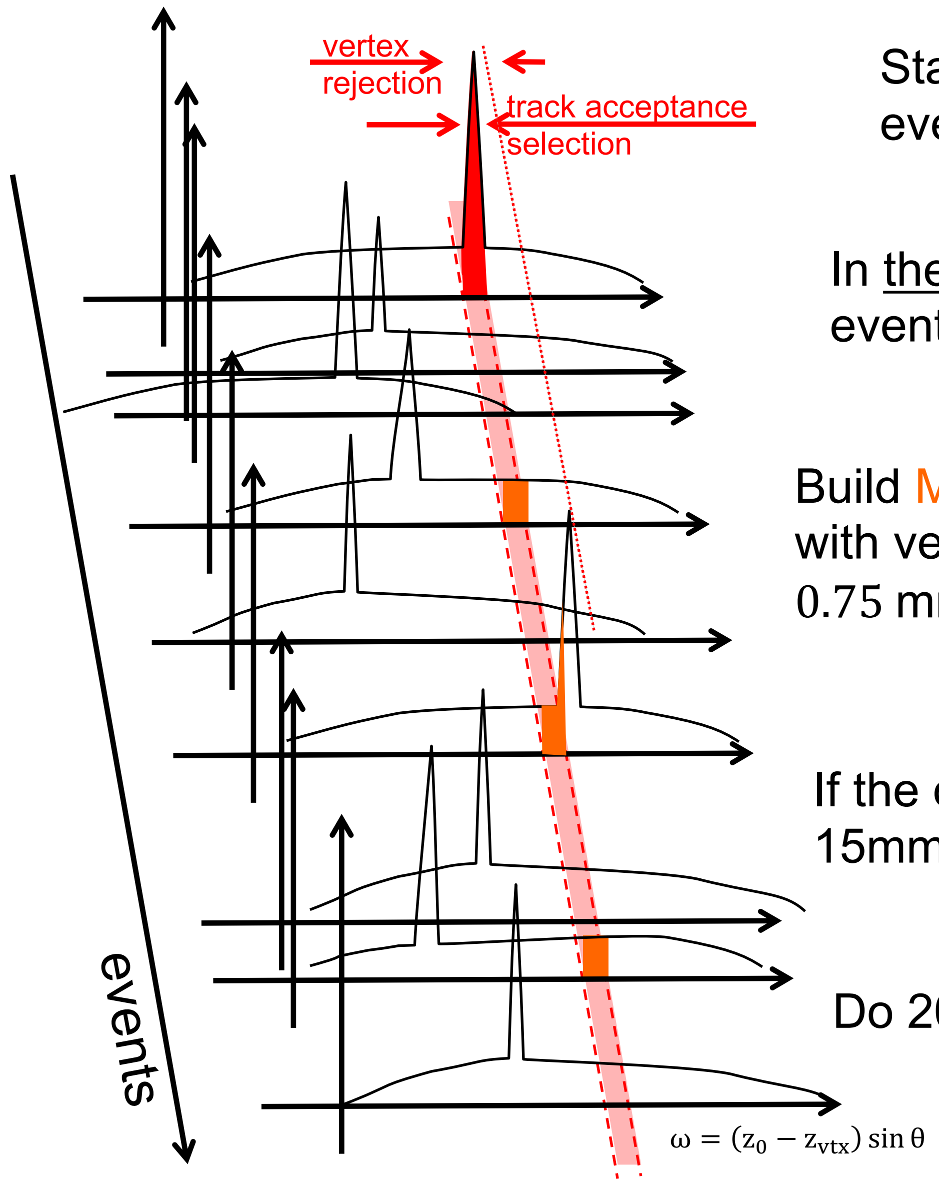
Similarity in the suppression of $\Upsilon(1S)$ and other species and the difference to higher $\Upsilon(nS)$ can be an indication of the regime change

Most particles, including $\Upsilon(1S)$ $\quad L \geq \sqrt[3]{N_{\text{part}}} \times r_p$ $\quad$ volume emission

$\Upsilon(2S)$, $\Upsilon(3S)$ $\quad L \ll \sqrt[3]{N_{\text{part}}} \times r_p$ $\quad$ surface emission

The pileup story

EPJC 80 (2020) 64



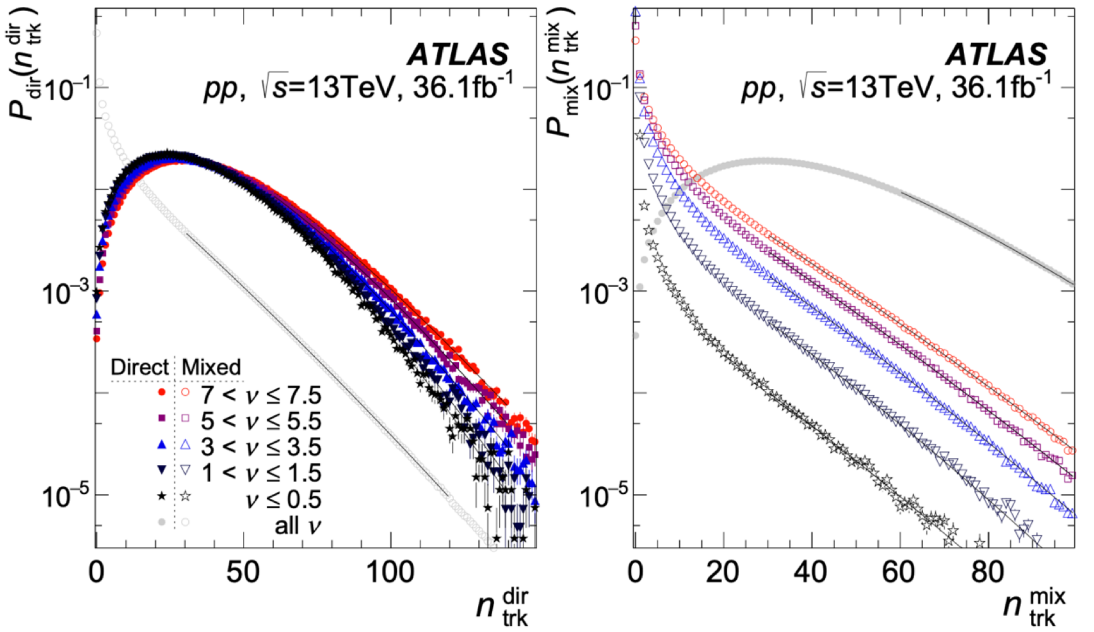
Start with the triggered event, called Direct

In the same run search for events with at the same μ

Build Mixed event from tracks with vertex pointing $|\omega| < 0.75$ mm to the Direct event

If the other vertex is within 15mm of the Direct, discard it

Do 20 times to get statistics



$$\nu = 2\omega_0 \left.\frac{d^2 n_{trk}}{d\omega d\bar{\mu}}\right|_{\bar{z}_{vtx}=0} Gauss(\bar{z}_{vtx})\,\bar{\mu}$$

Track production (physics)

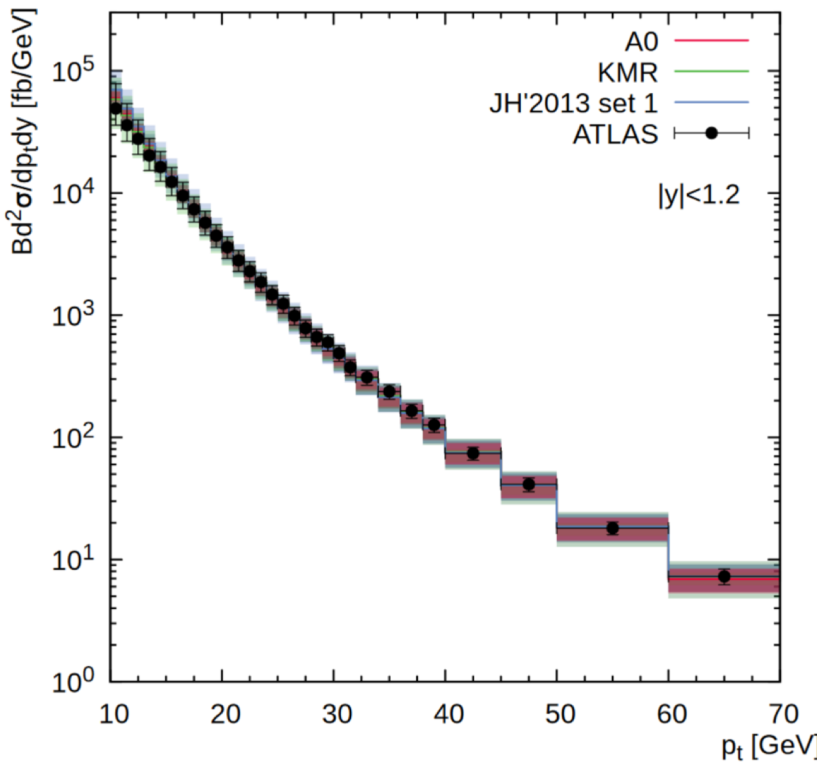
z_{vtx} distribution

Analysis selection

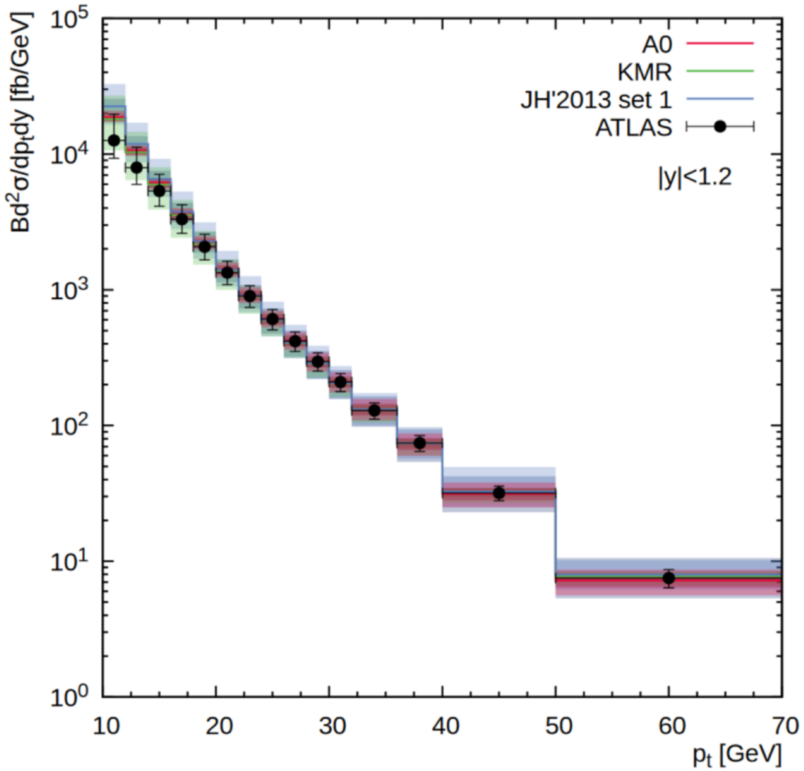
Instantaneous luminosity

Theory calculation

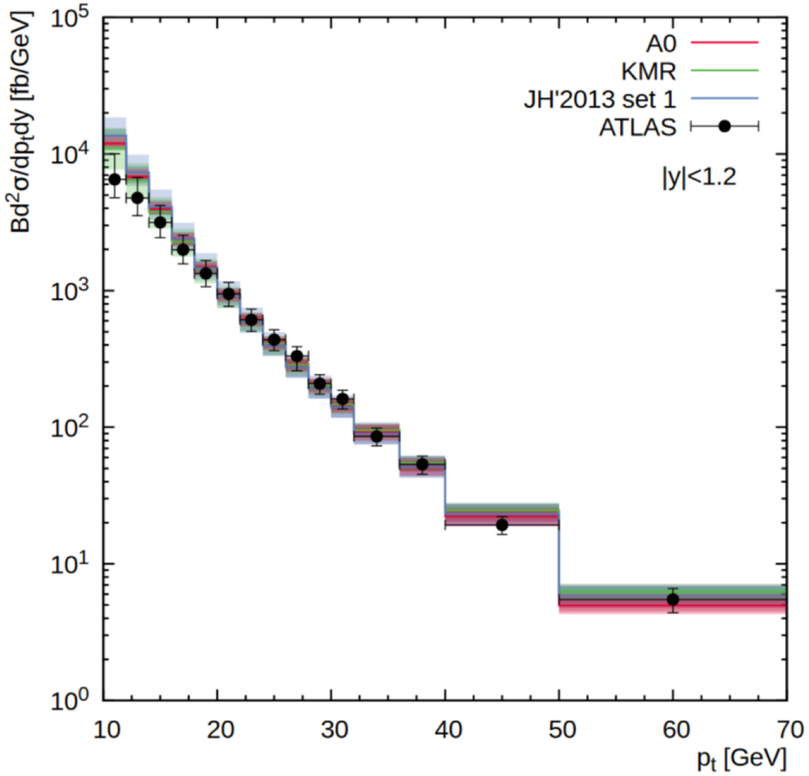
$\Upsilon(1S)$



$\Upsilon(2S)$



$\Upsilon(3S)$



[61] N. A. Abdulov and A. V. Lipatov, Bottomonium production and polarization in the NRQCD with kT - factorization. III: Y(1S) and χb(1P) mesons, Eur. Phys. J. C 81, 1085 (2021), arXiv:2011.13401.
[62] N. A. Abdulov and A. V. Lipatov, Bottomonia production and polarization in the NRQCD with kT - factorization. II: Y(2S) and χb(2P) mesons, Eur. Phys. J. C 80, 486 (2020), arXiv:2003.06201.
[63] N. A. Abdulov and A. V. Lipatov, Bottomonia production and polarization in the NRQCD with kT - factorization. I: Y(3S) and χb(3P) mesons, Eur. Phys. J. C 79, 830 (2019), arXiv:1909.05141.