Upsilon - underlying event correlations in *pp* collisions

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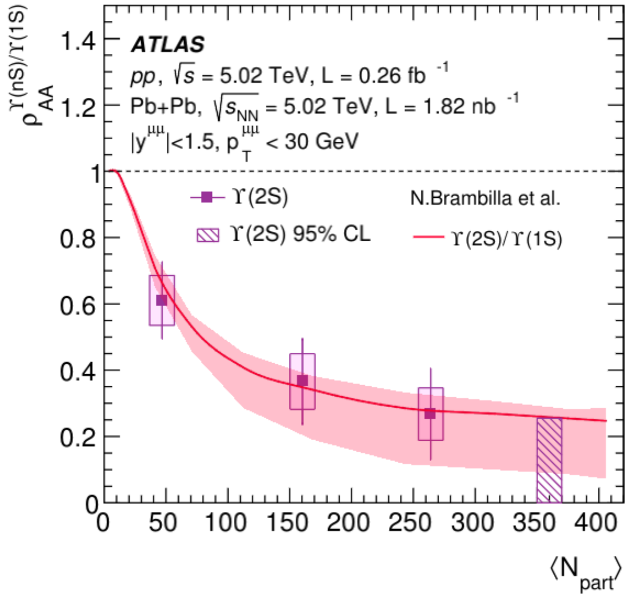
Motivation

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*

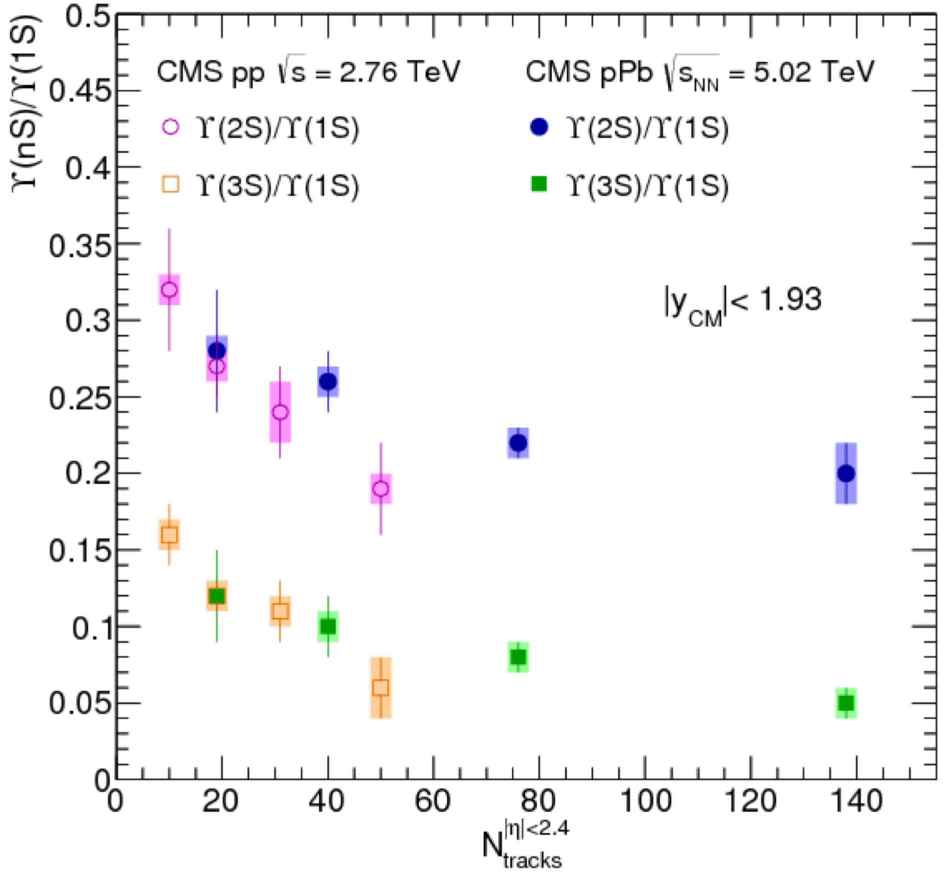
firm constraints on jet energy loss in *p*+Pb, no indication of QGP from any of the `hard' probes that require QGP scenario

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



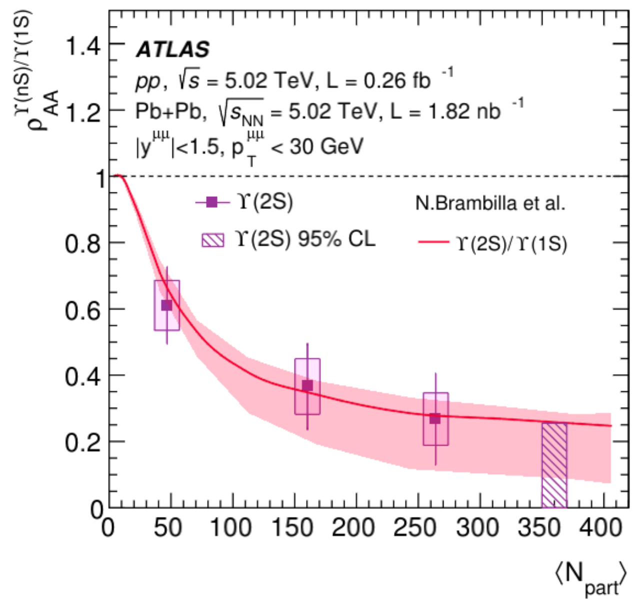
CMS results for 2.76 GeV in pp

JHEP 04 (2014) 103

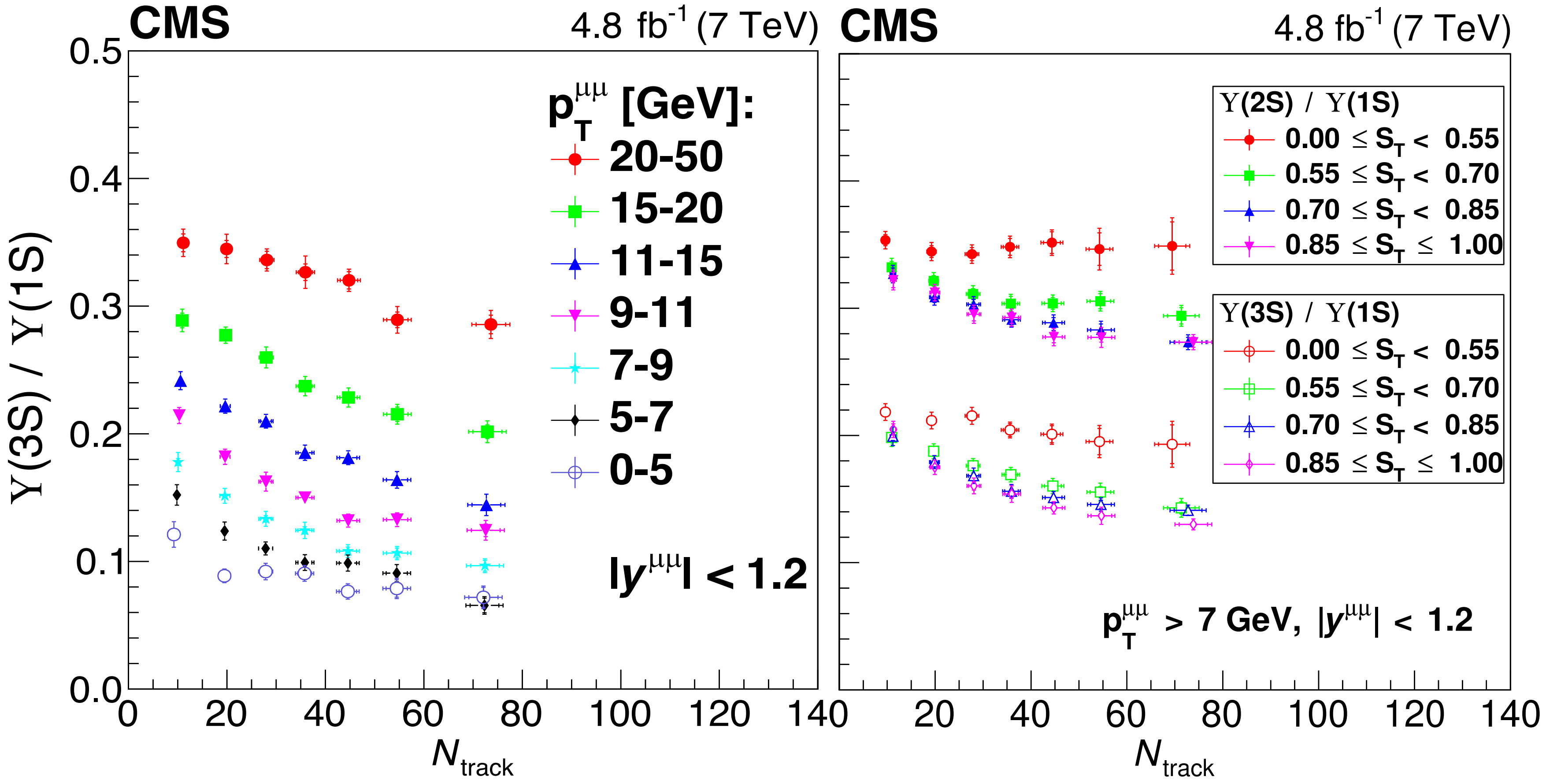


In 2014 CMS published the first result showing the multiplicity dependence of $q\bar{q}$ states in pp

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



CMS results



$$S_{\mathrm{T}} \equiv \frac{2\lambda_2}{\lambda_1 + \lambda_2},$$

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

$$\lambda_1 > \lambda_2$$

$S_T = 0$ – 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 $\Upsilon(1S)$ meson is accompanied by about one more track on average ($\langle N_{\mathrm{track}} \rangle = 33.9 \pm 0.1$) than the $\Upsilon(2S)$ ($\langle N_{\mathrm{track}} \rangle = 33.0 \pm 0.1$), and about two more than the $\Upsilon(3S)$ ($\langle N_{\mathrm{track}} \rangle = 32.0 \pm 0.1$). […] 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 $\Upsilon(\mathrm{n}S)$

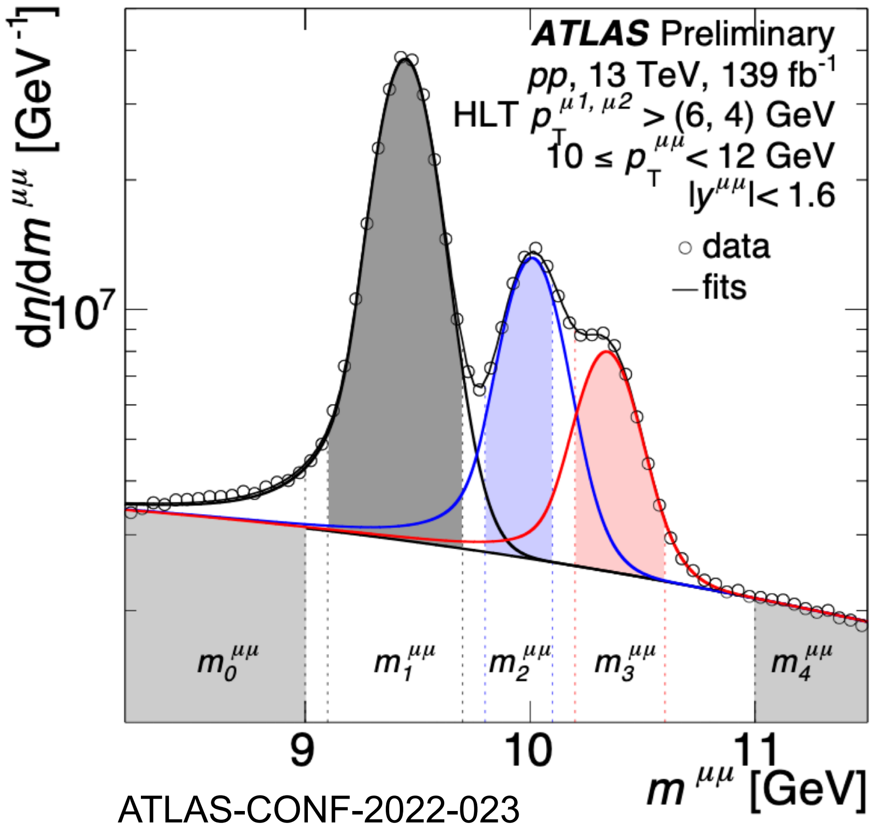
This has several technical advantages that result in clearer picture

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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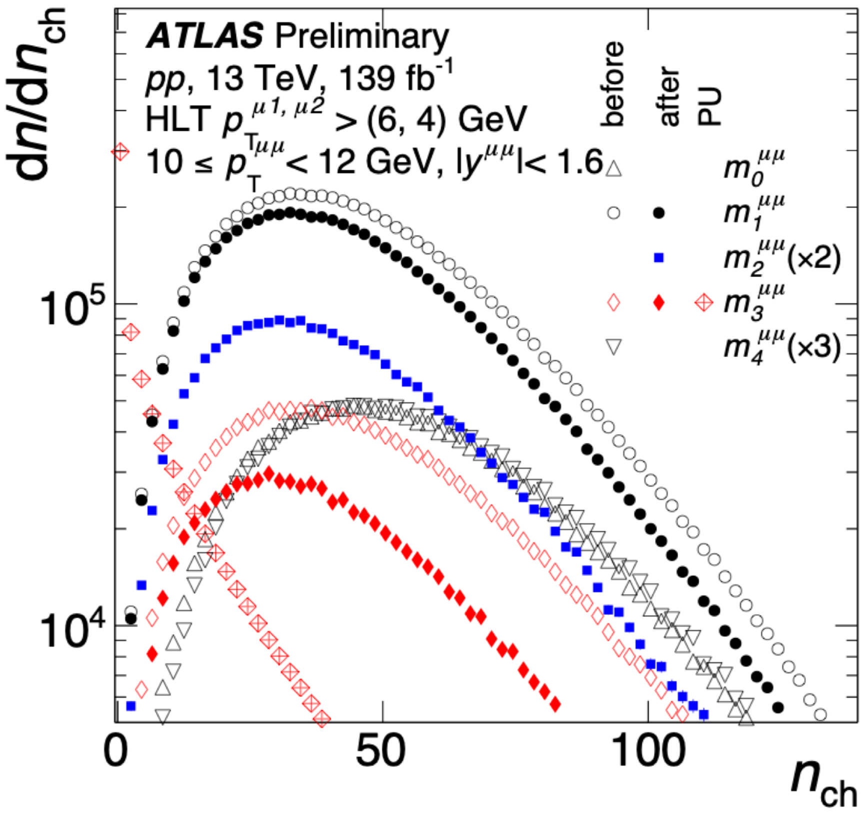


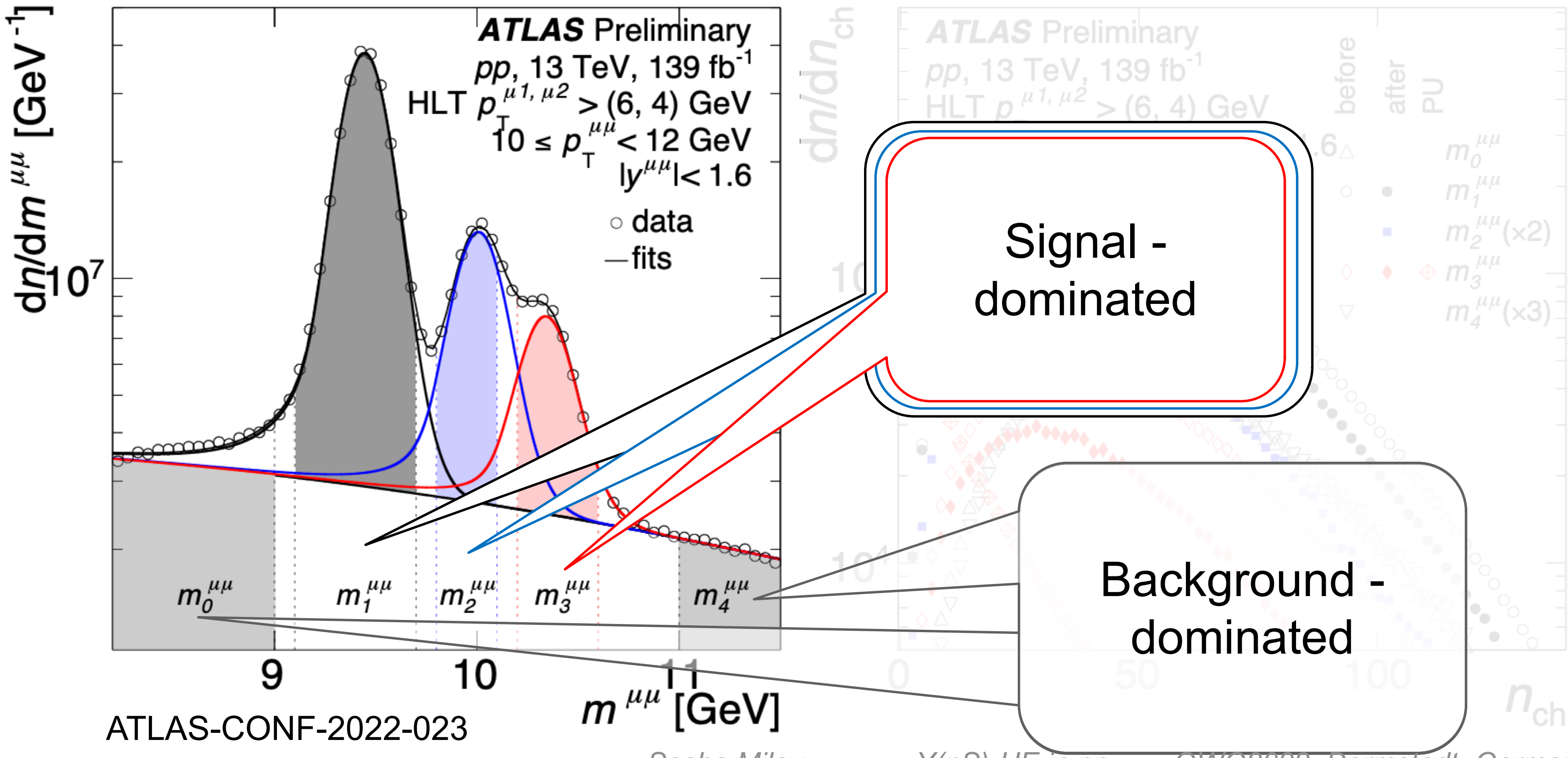
Signal extraction

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

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

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

Define 3+2 regions



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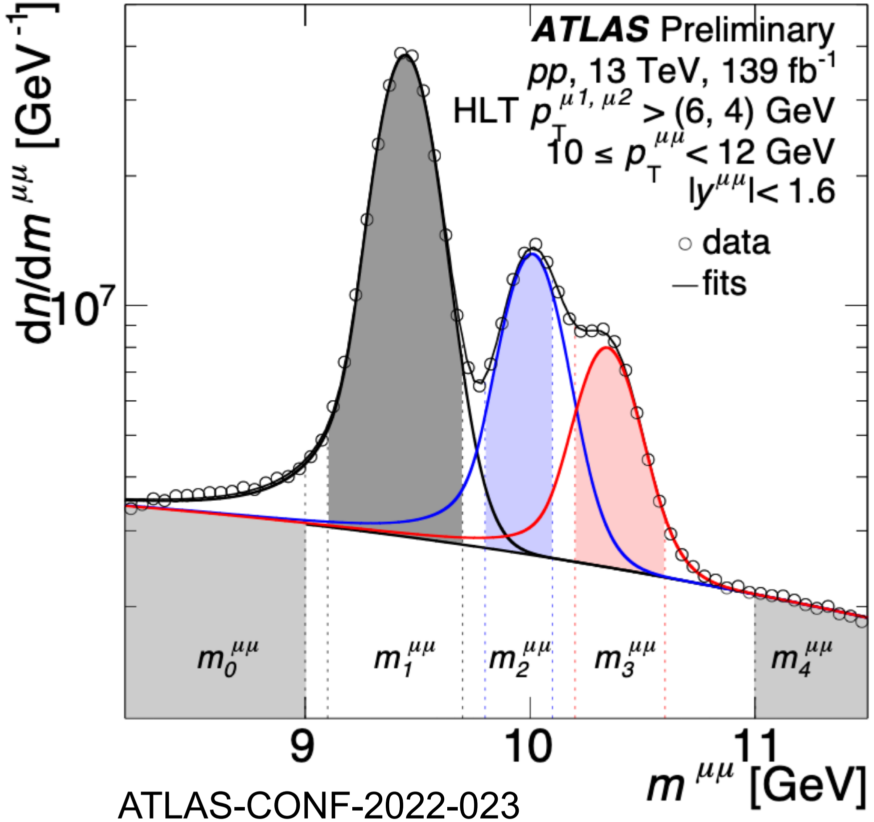
Signal extraction

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

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

Define 3+2 regions

Bkg shapes are similar – interpolate



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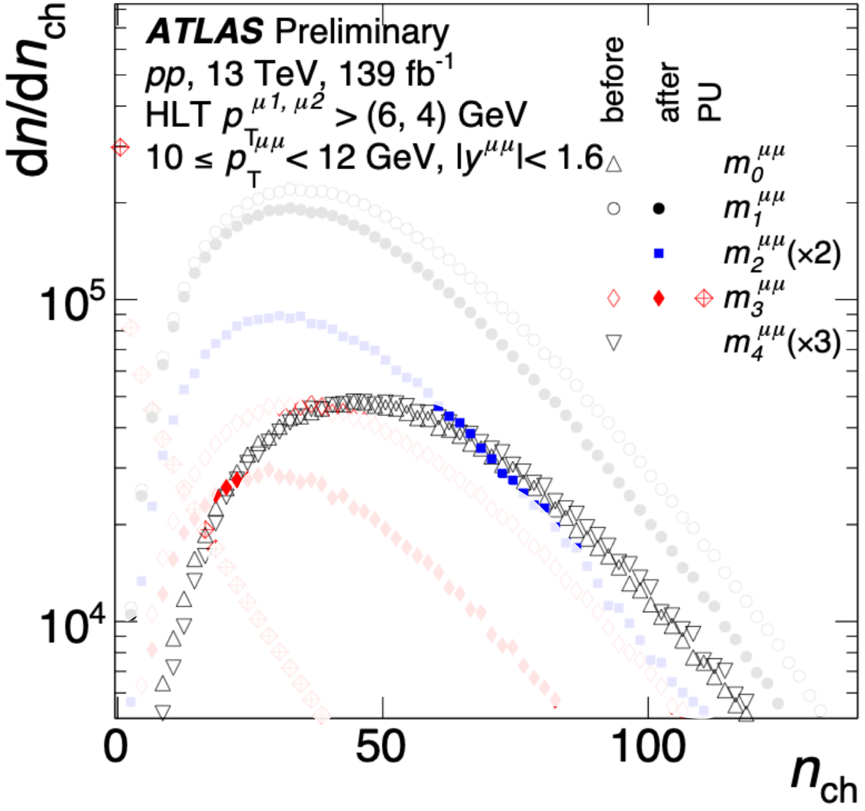


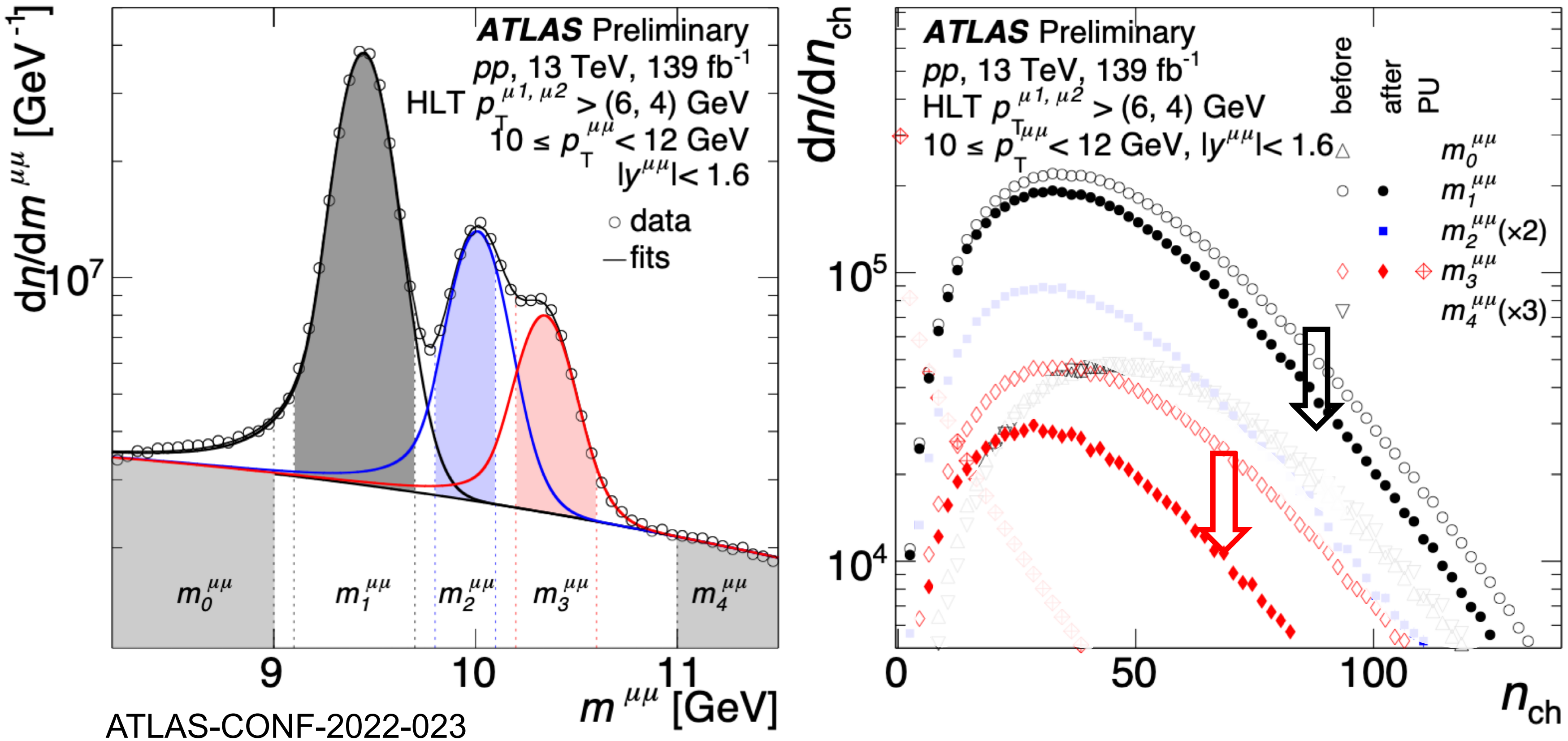
Signal extraction

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

Define 3+2 regions

Bkg shapes are similar – interpolate

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



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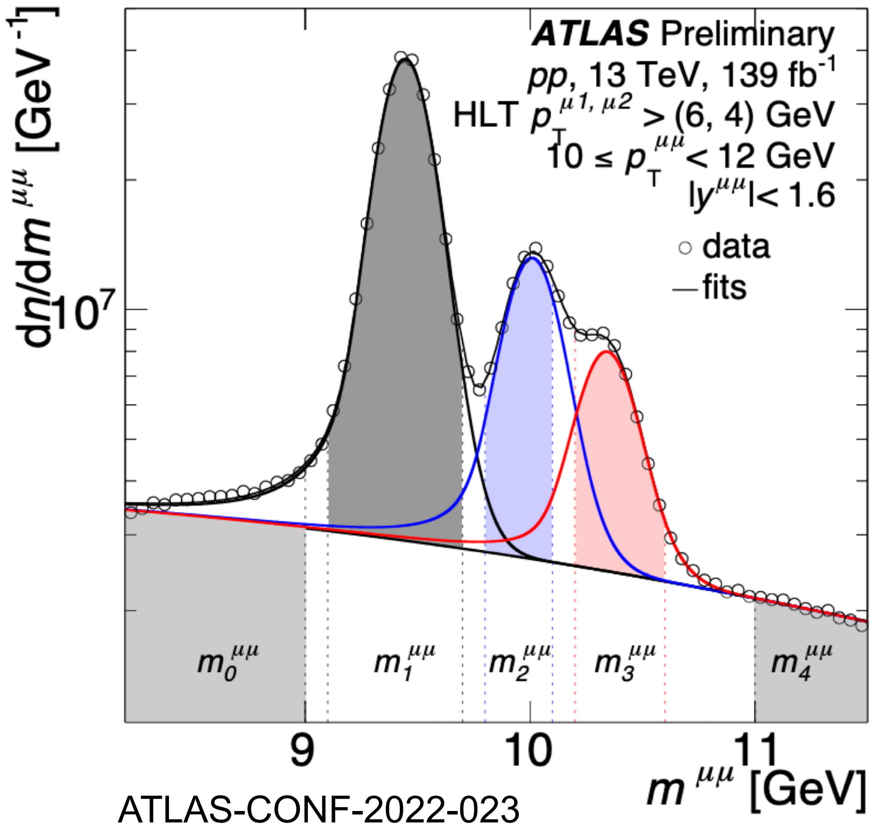
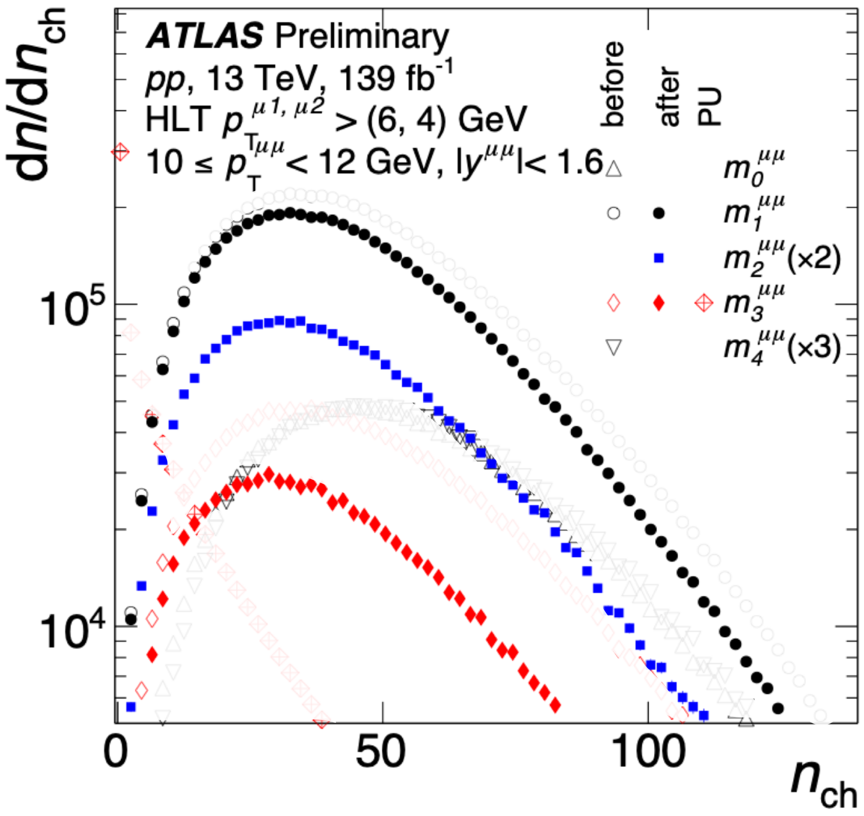
After subtraction n_{ch} look different





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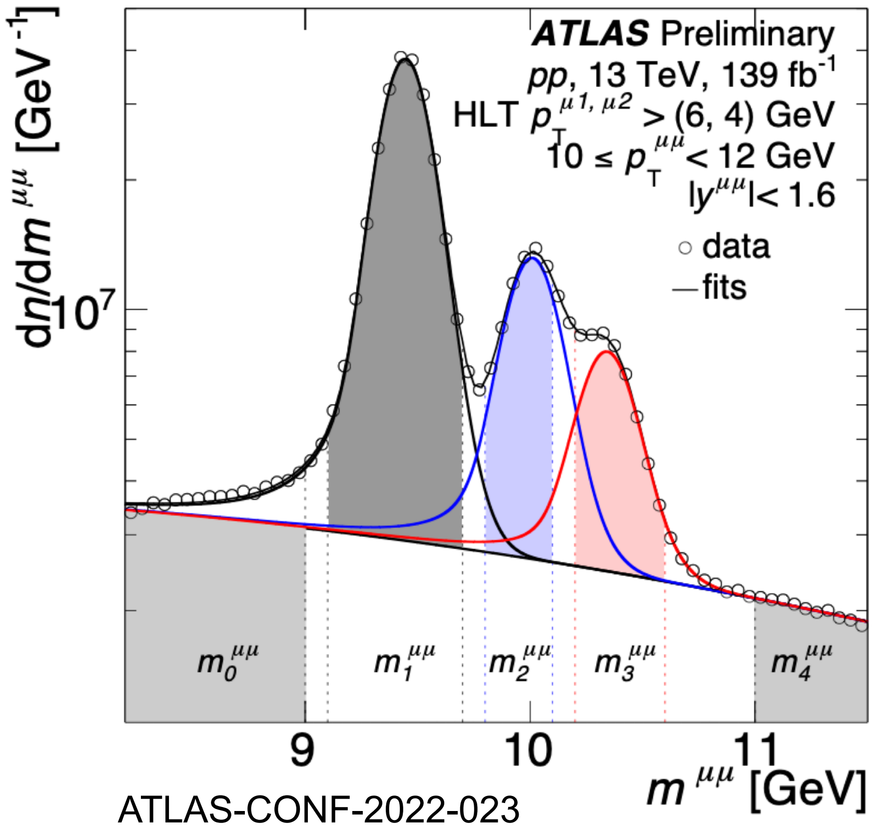
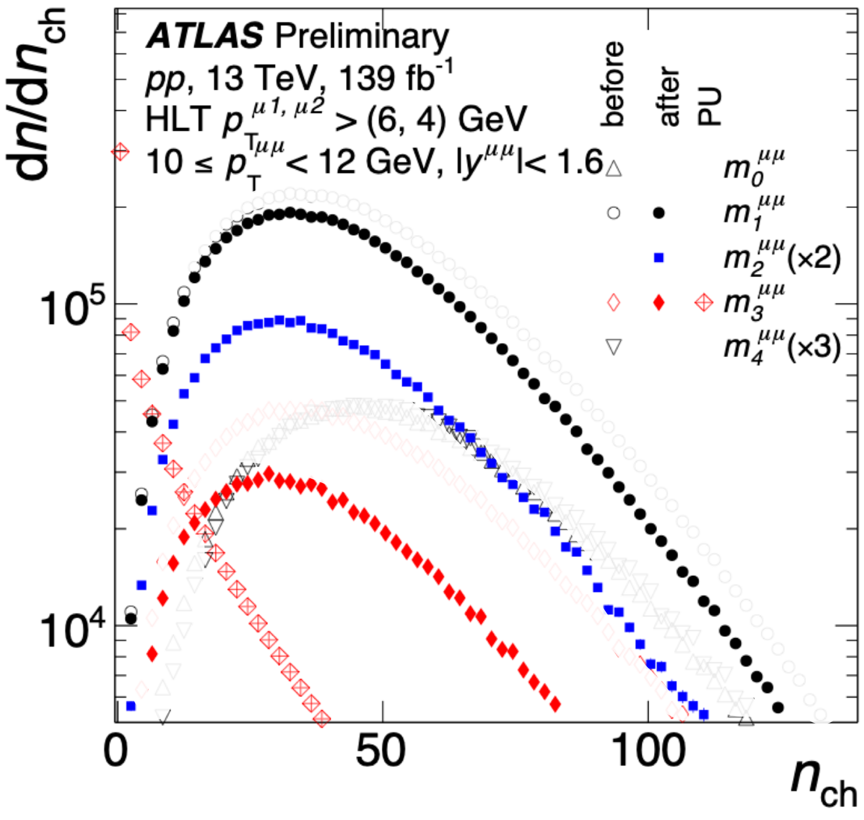
Signal extraction

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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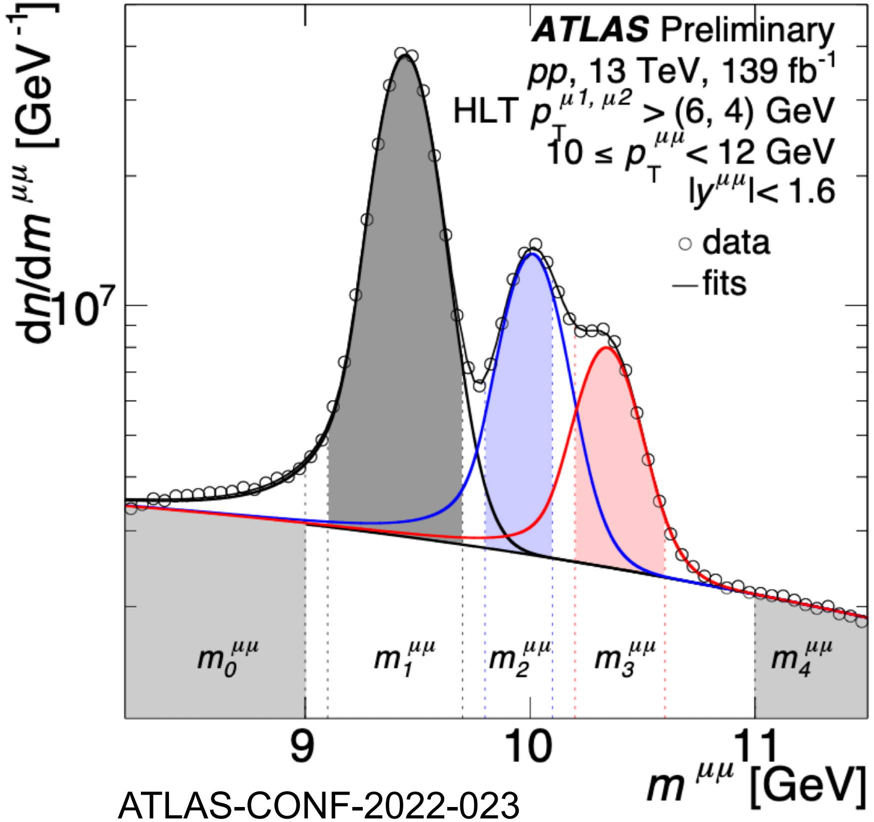
Remove pileup, same shape for all $\Upsilon(nS)$

Signal extraction

The procedure is illustrated with n_{ch},
But it also works for dn_{ch}/dp_T and dn_{ch} /dΔϕ. Δϕ=ϕ$^{\Upsilon}$−ϕ^{h}



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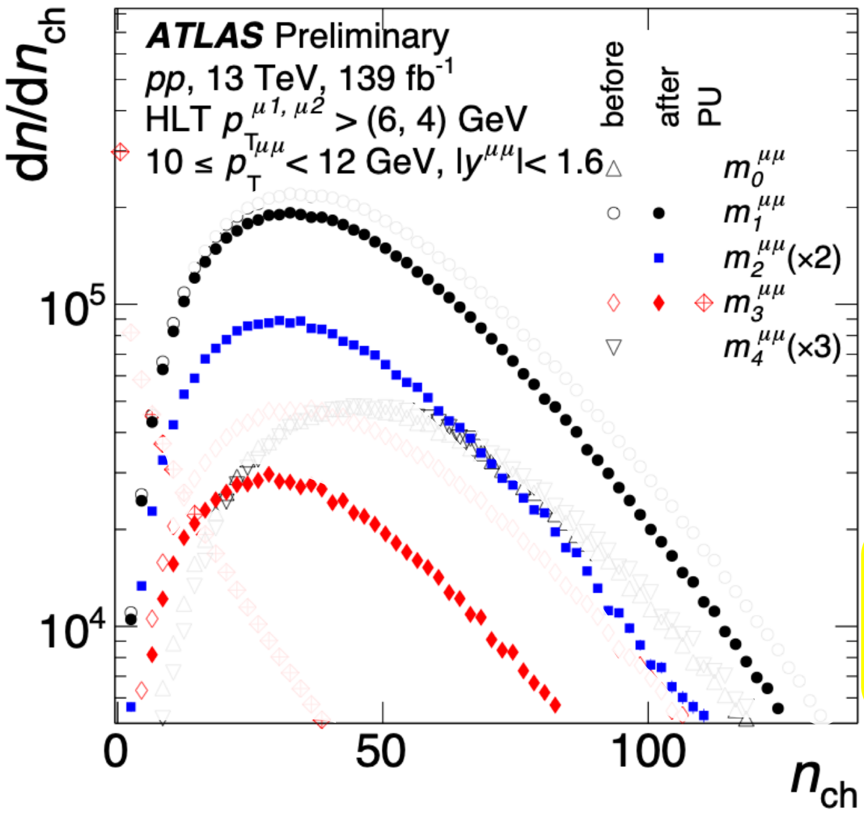

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Direct measurement of n_{ch}
dn_{ch}/dp_T dn_{ch} /d$\Delta\phi$

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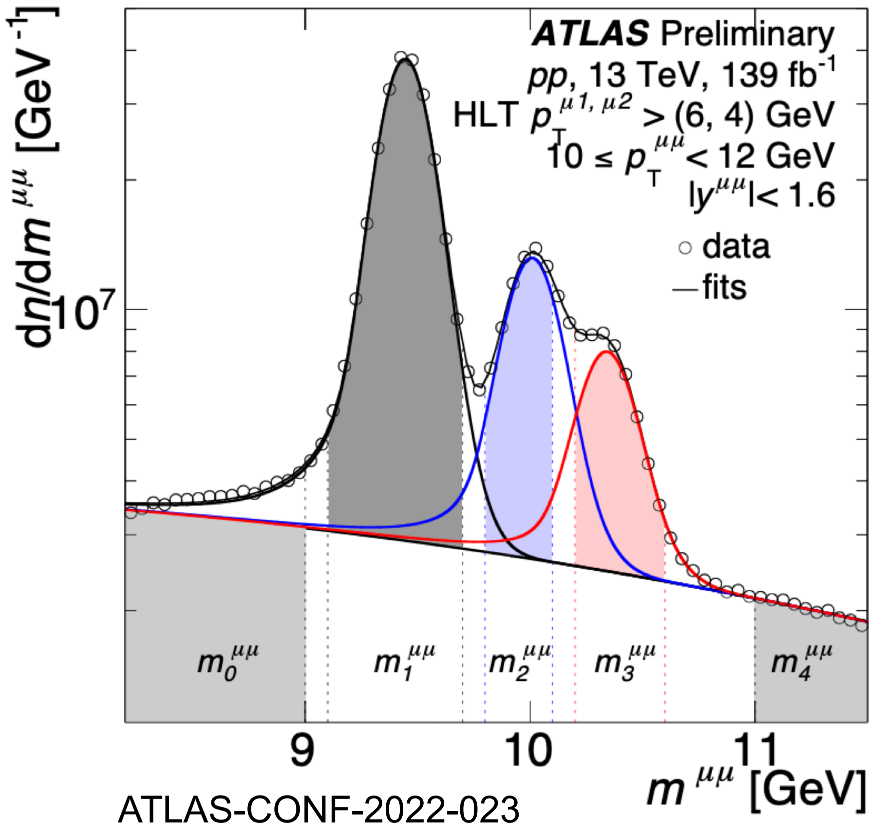

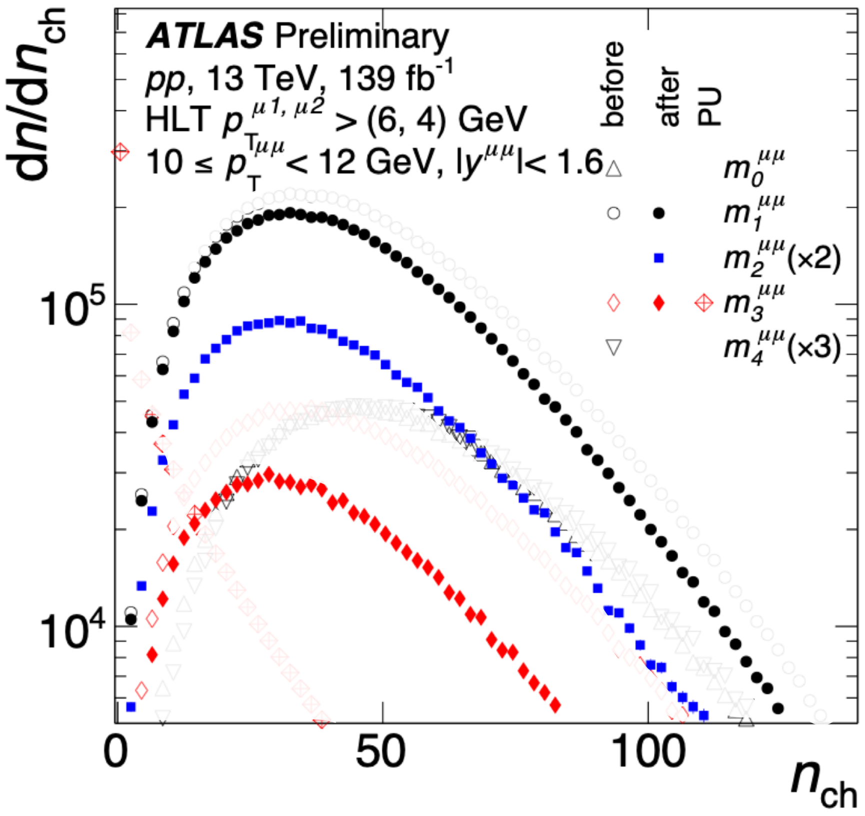

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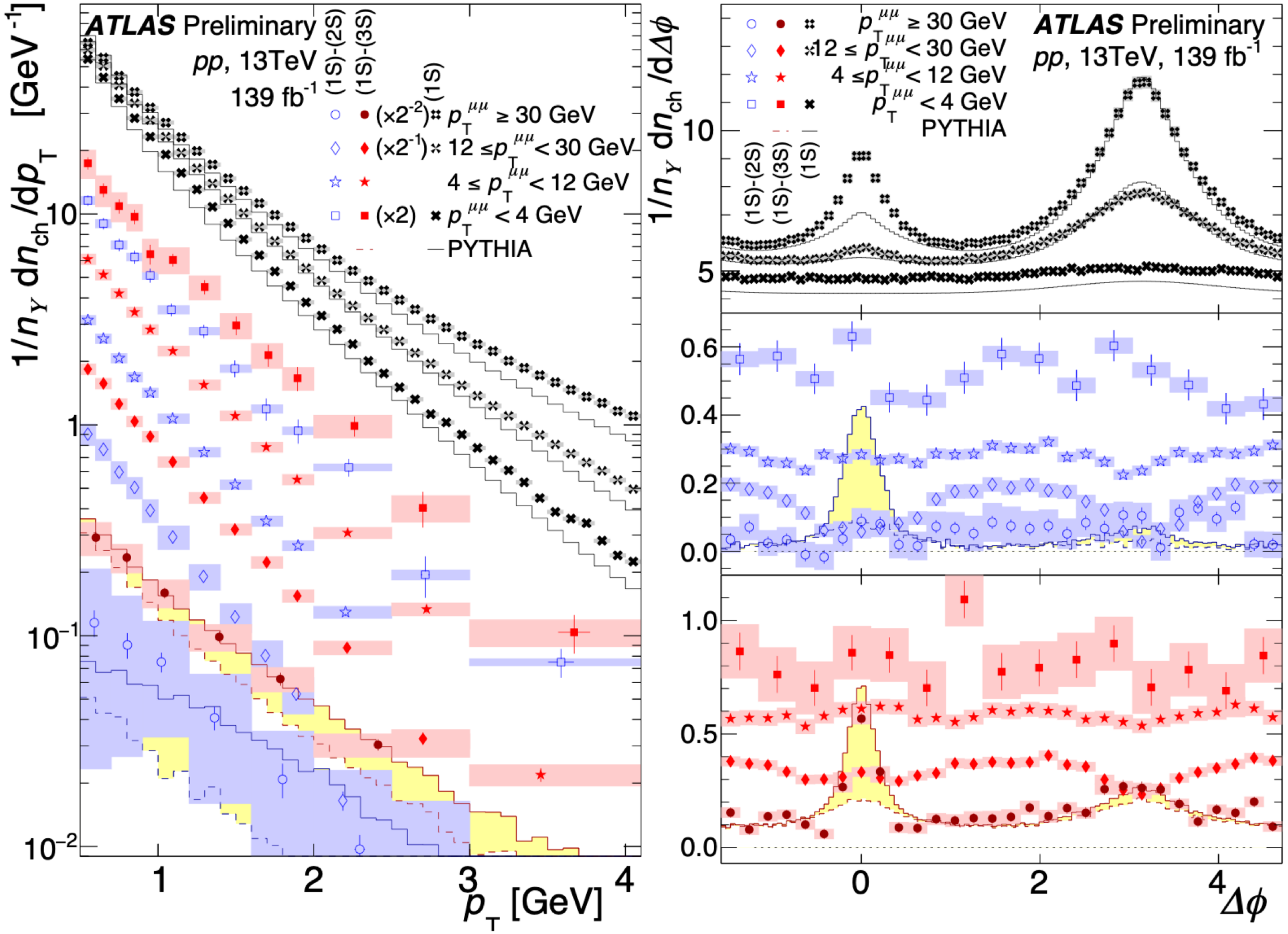
Kinematic distributions



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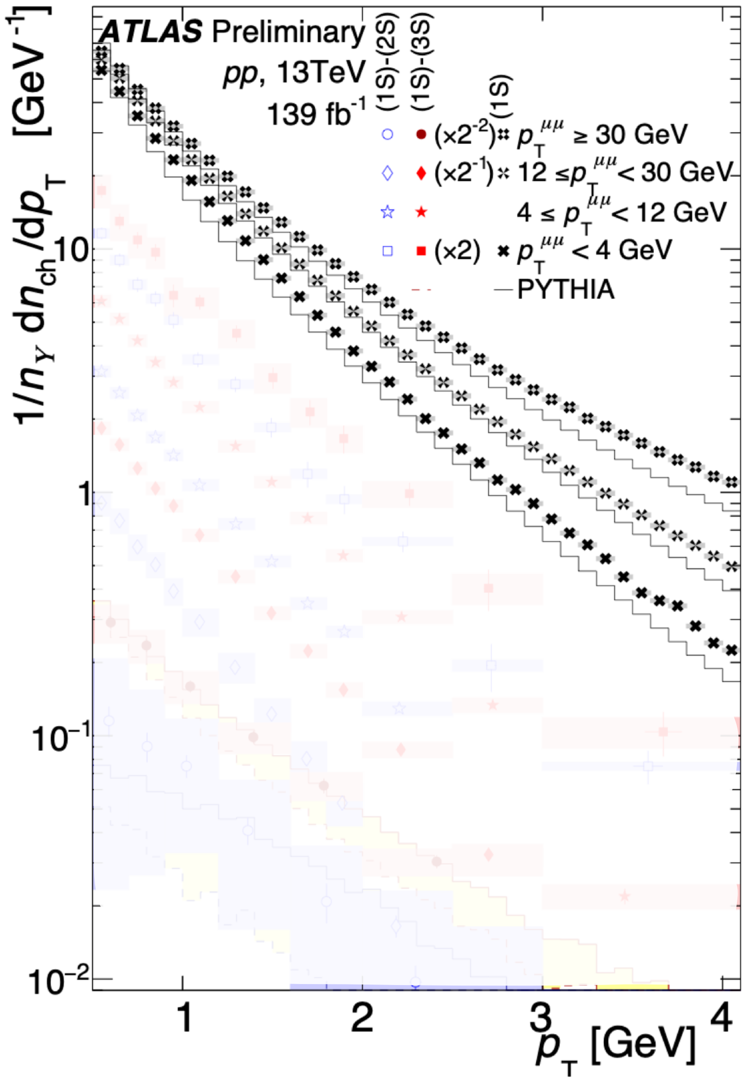

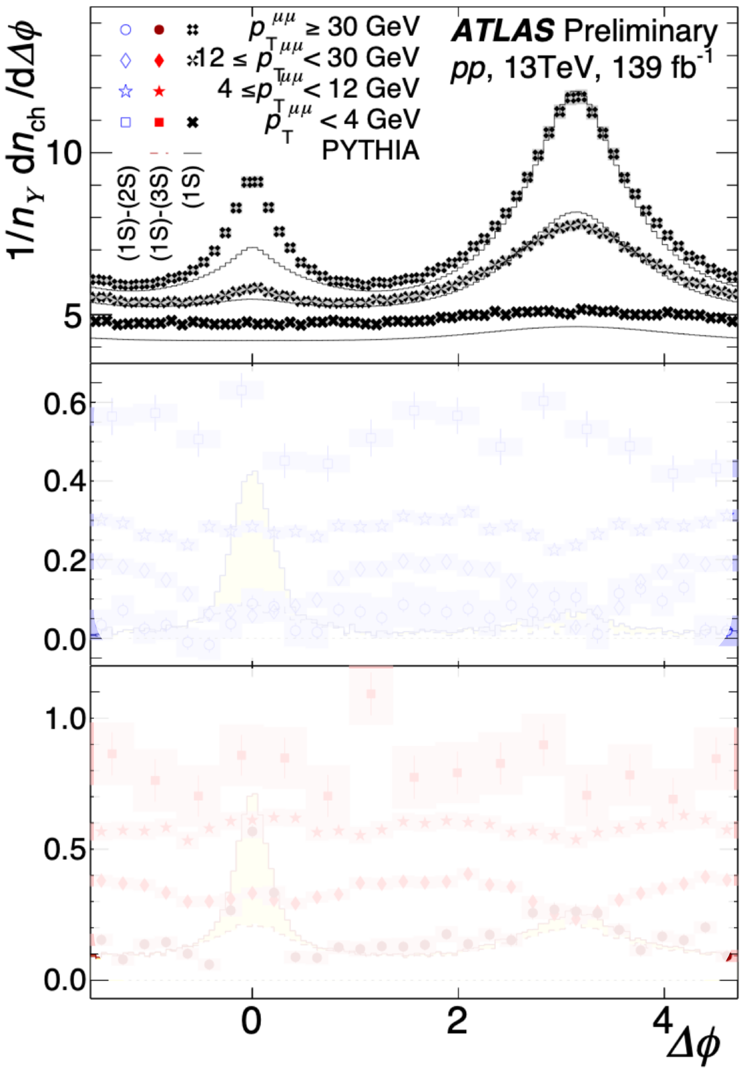

Distributions for $\Upsilon(1S)$

Pythia does not describe data well

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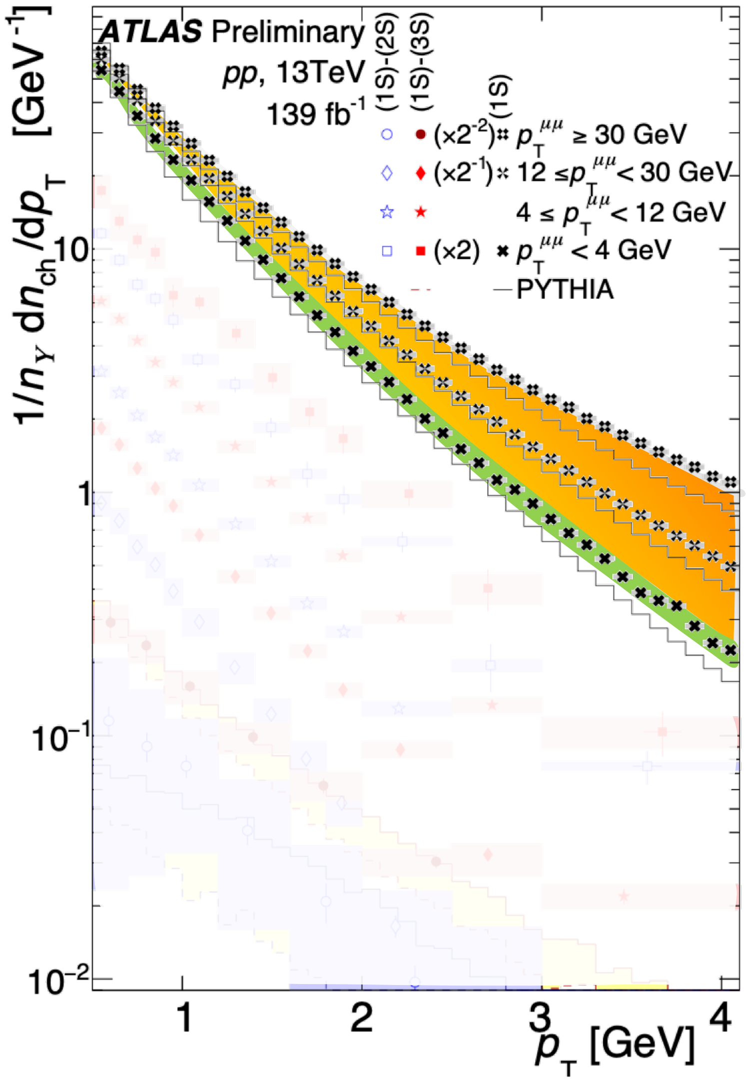
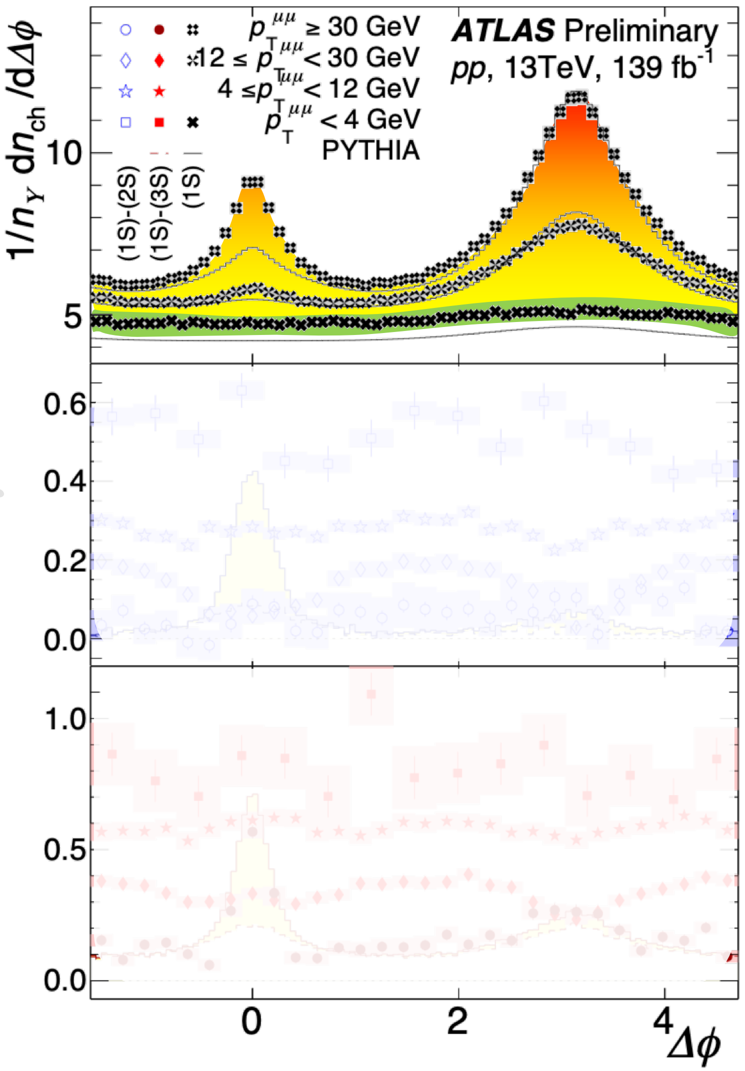
Kinematic distributions





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Distributions for $\Upsilon(1S)$

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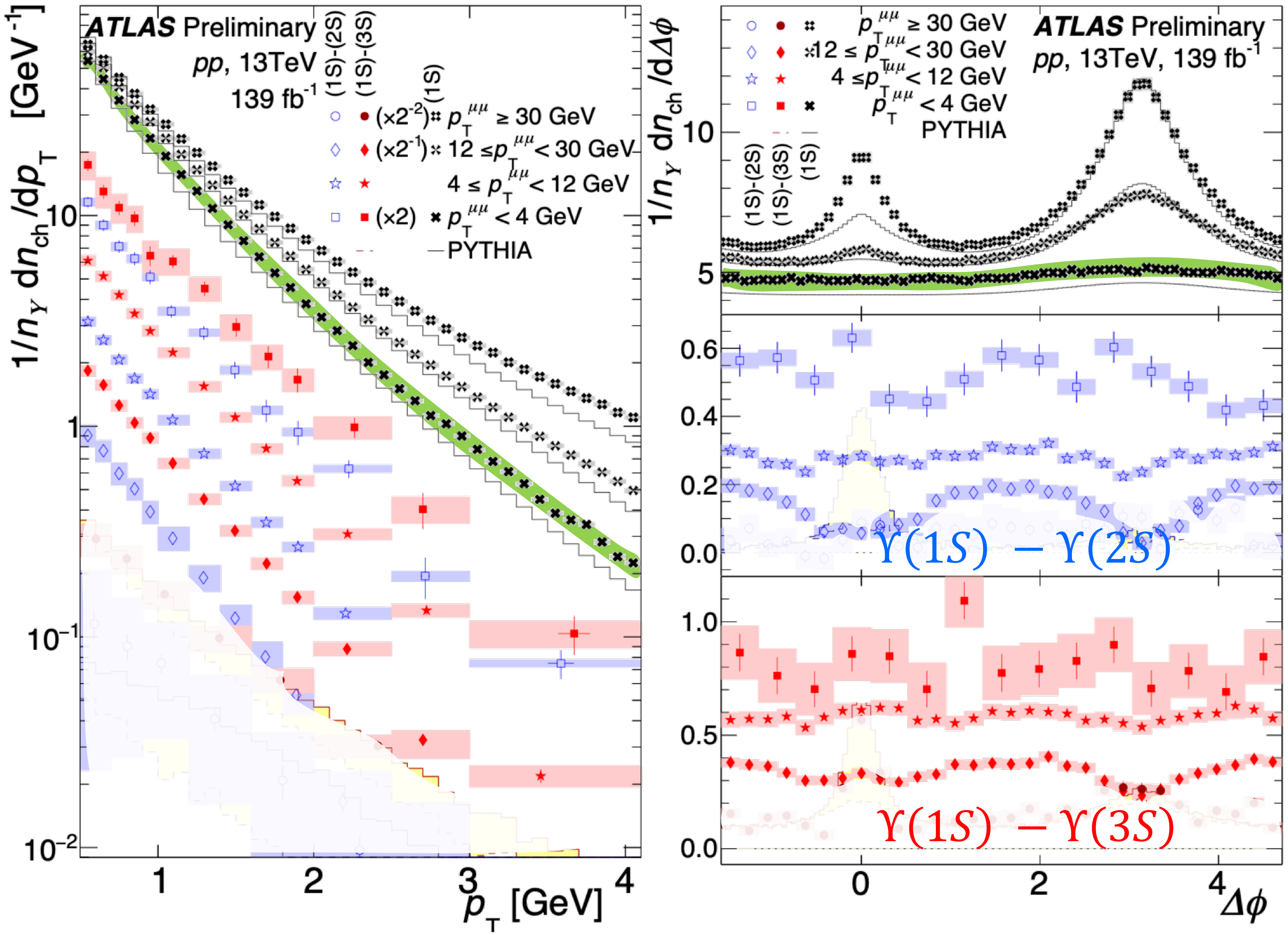
One cannot measure the UE, but p_T < 4 GeV is the closest to it, jet part that is correlated to $\Upsilon(nS)$

Kinematic distributions



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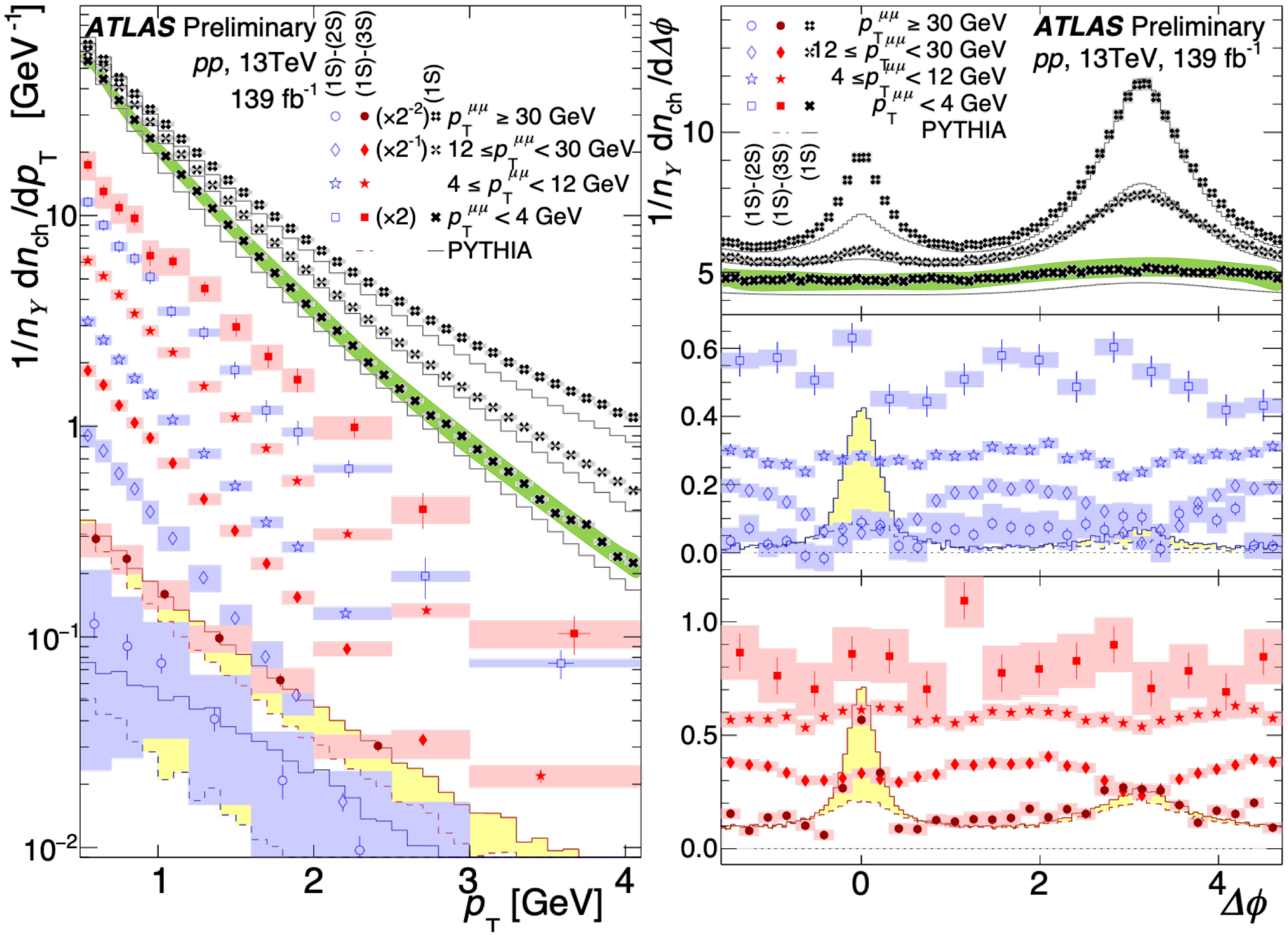
Subtracted distributions look like UE at rather high $\Upsilon(nS)$ p_T. At the highest p_T there are feed-downs

Kinematic distributions



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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

Away from jets there are regions with charged particles

This suggests that the effect is related to the UE

Multiplicity dependence on Υ–momentum

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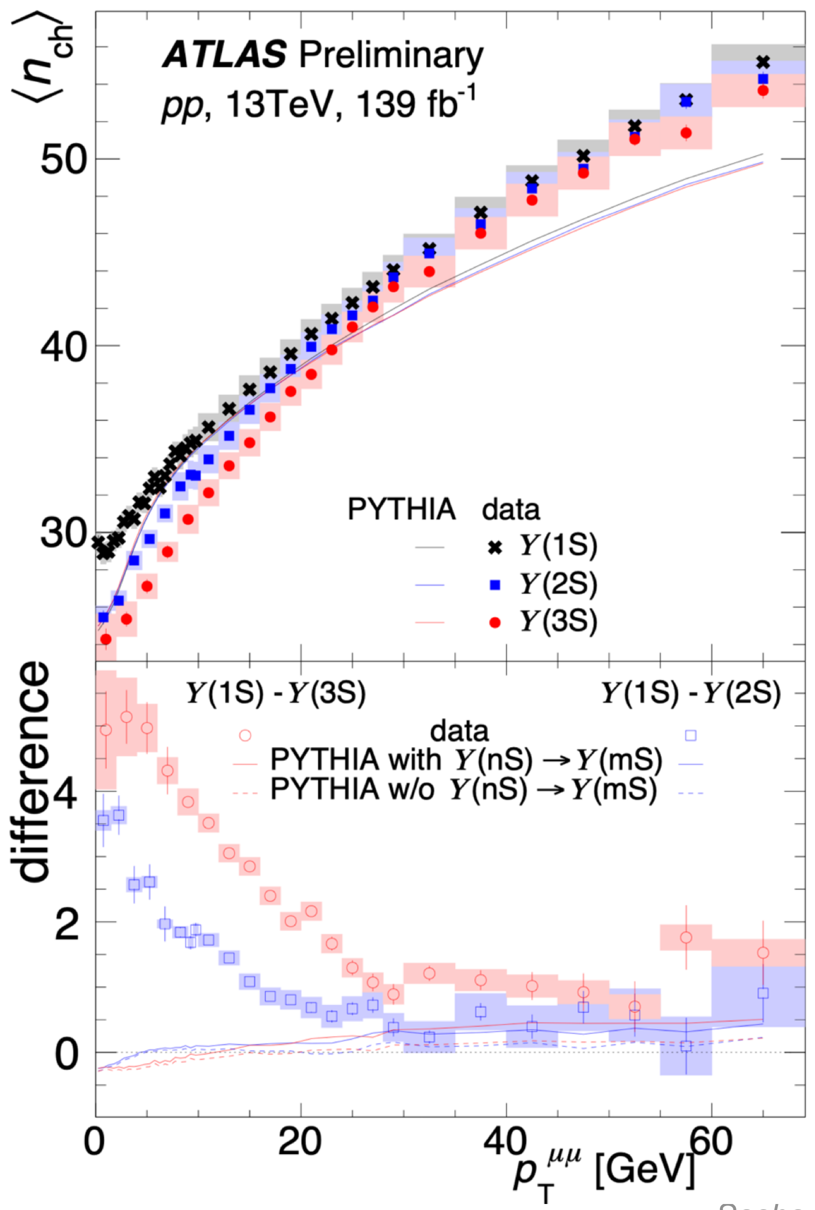


Multiplicity is different for different $\Upsilon(nS)$ states

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 $\left\langle n_{ch}^{\Upsilon(1S)} \right\rangle$

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

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

Comover interaction model

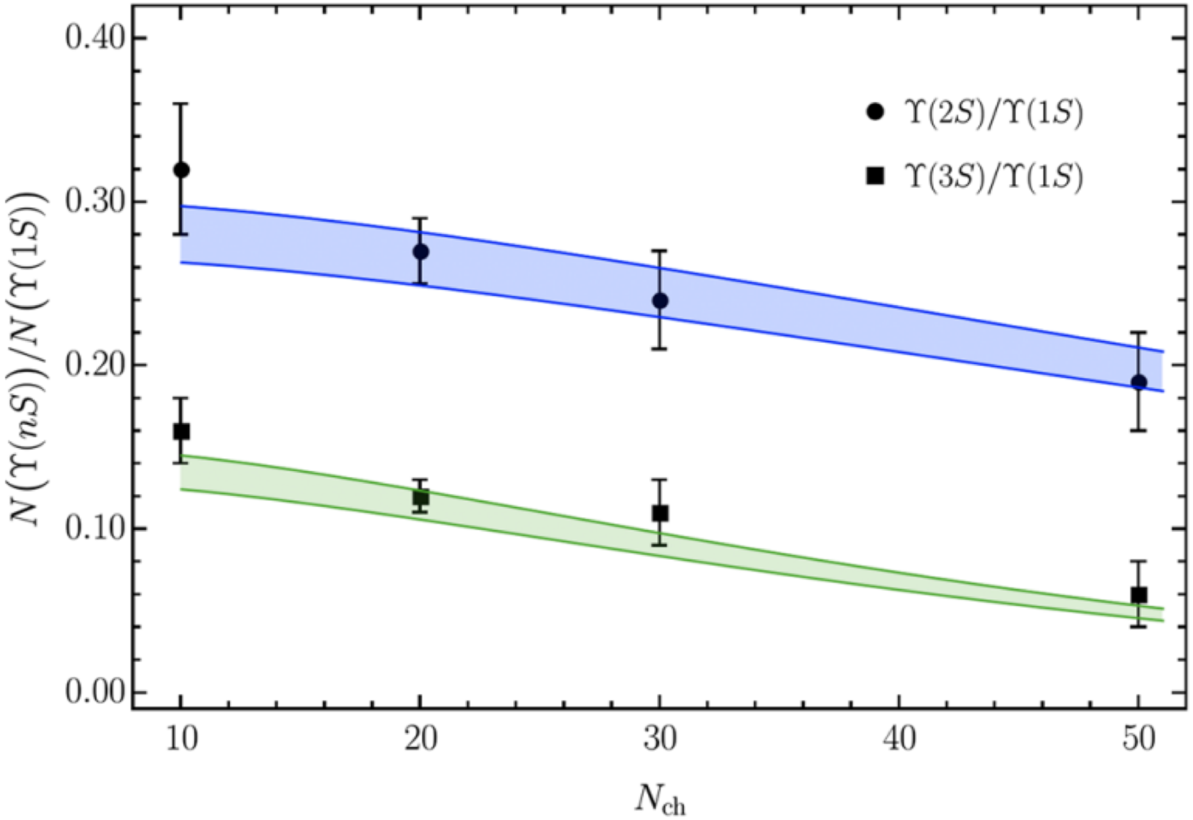
EPJC 81, 669 (2021)

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.*

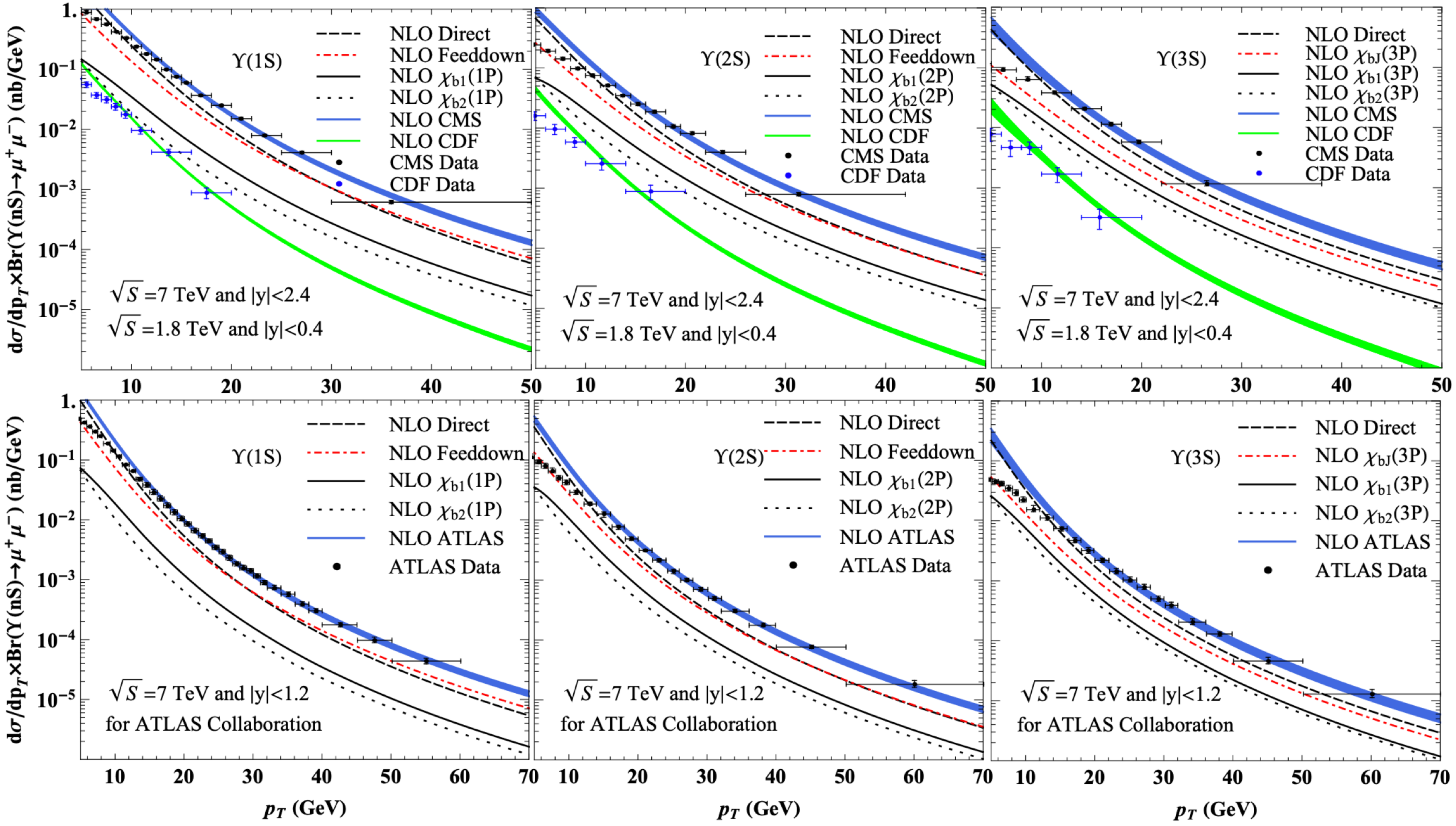
With the new data, CIM can be tested on *pp* to reproduce $\Upsilon(nS) - \Upsilon(1S)$ differences

- 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

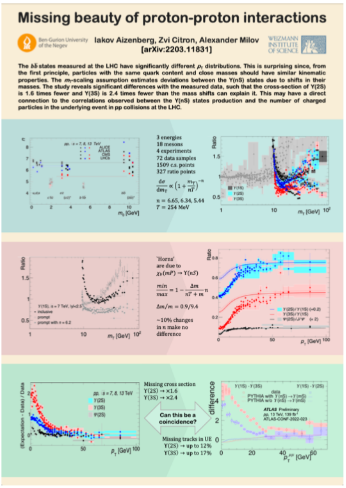
$\Upsilon(1S)$ curve overshoots the data

Global analysis

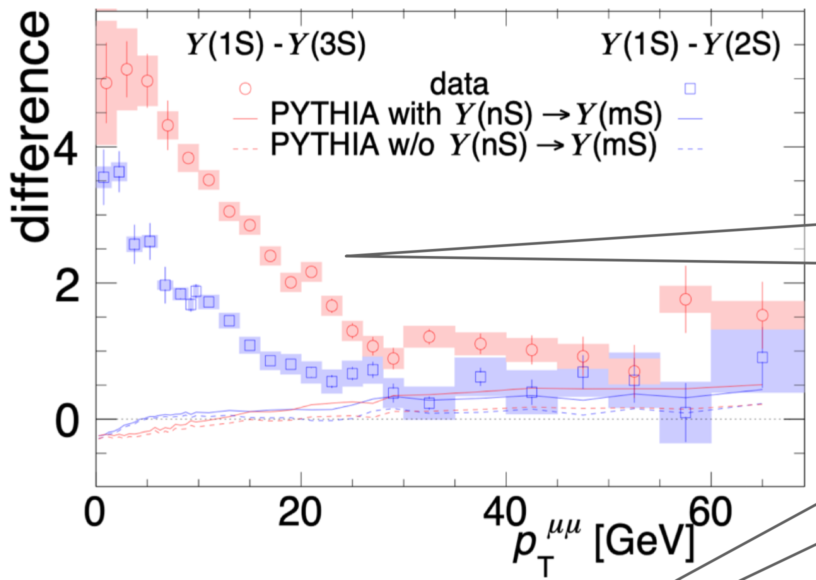
Assumption: particles with the same quark content and close masses shall have similar kinematics

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

There are obvious similarities in two independent measurements

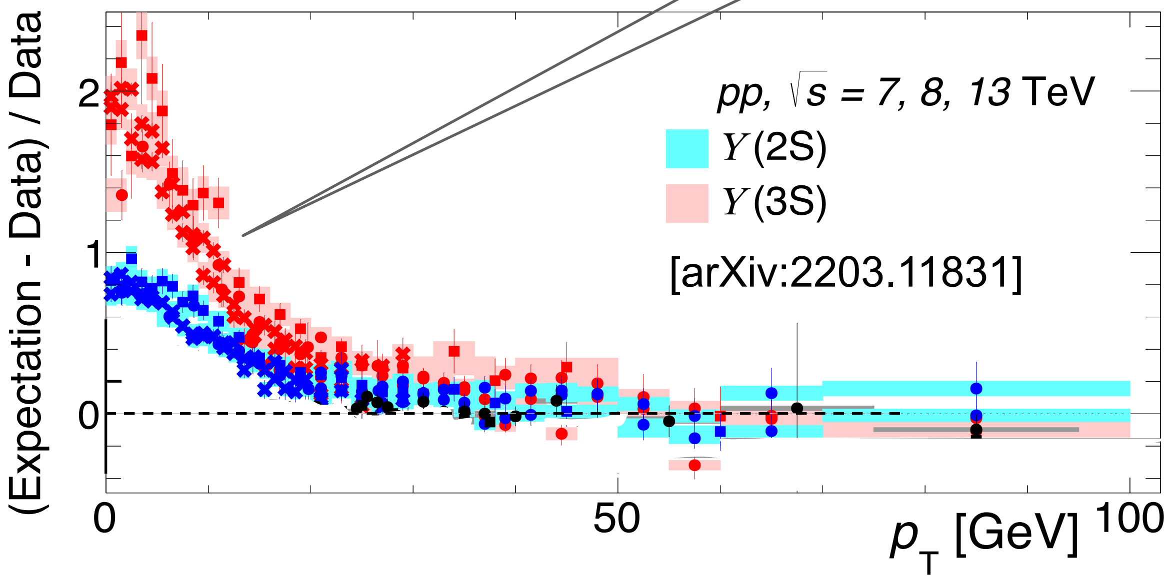


More details in the poster session



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

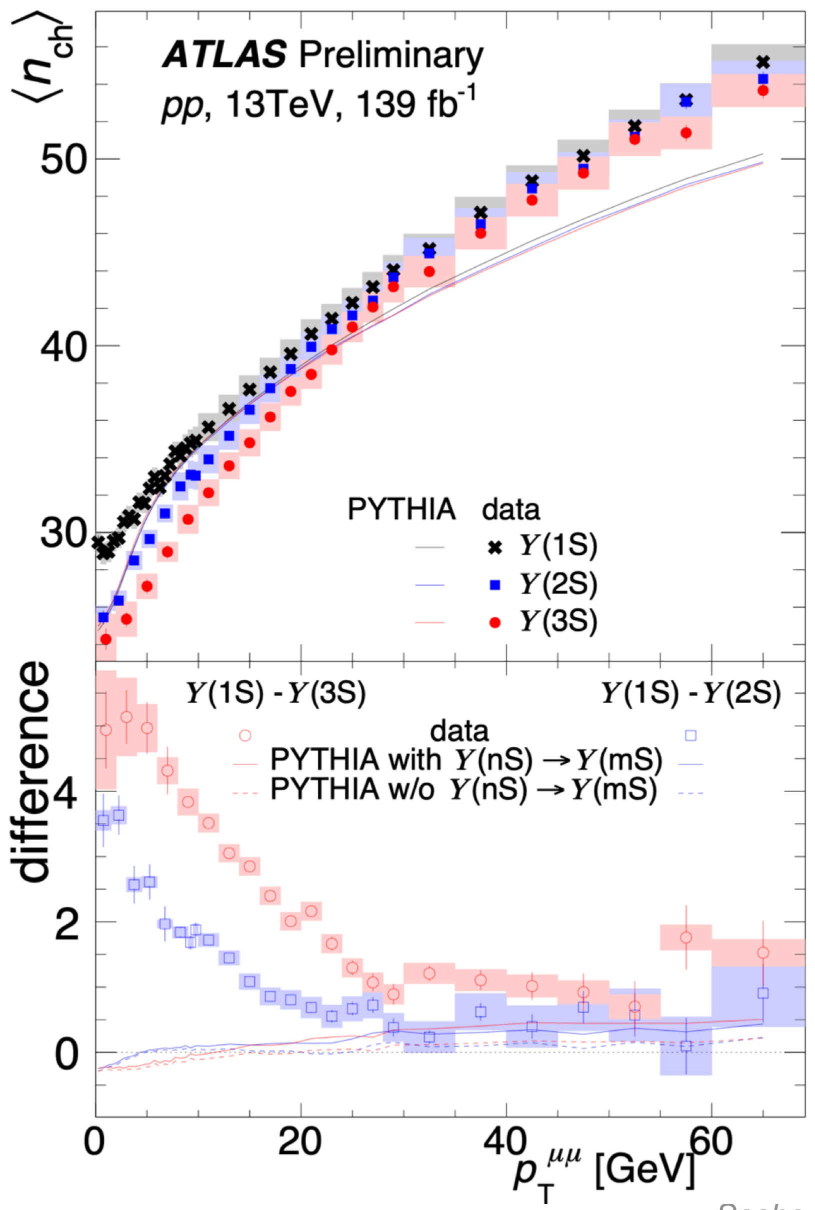
Bringing pieces together:

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

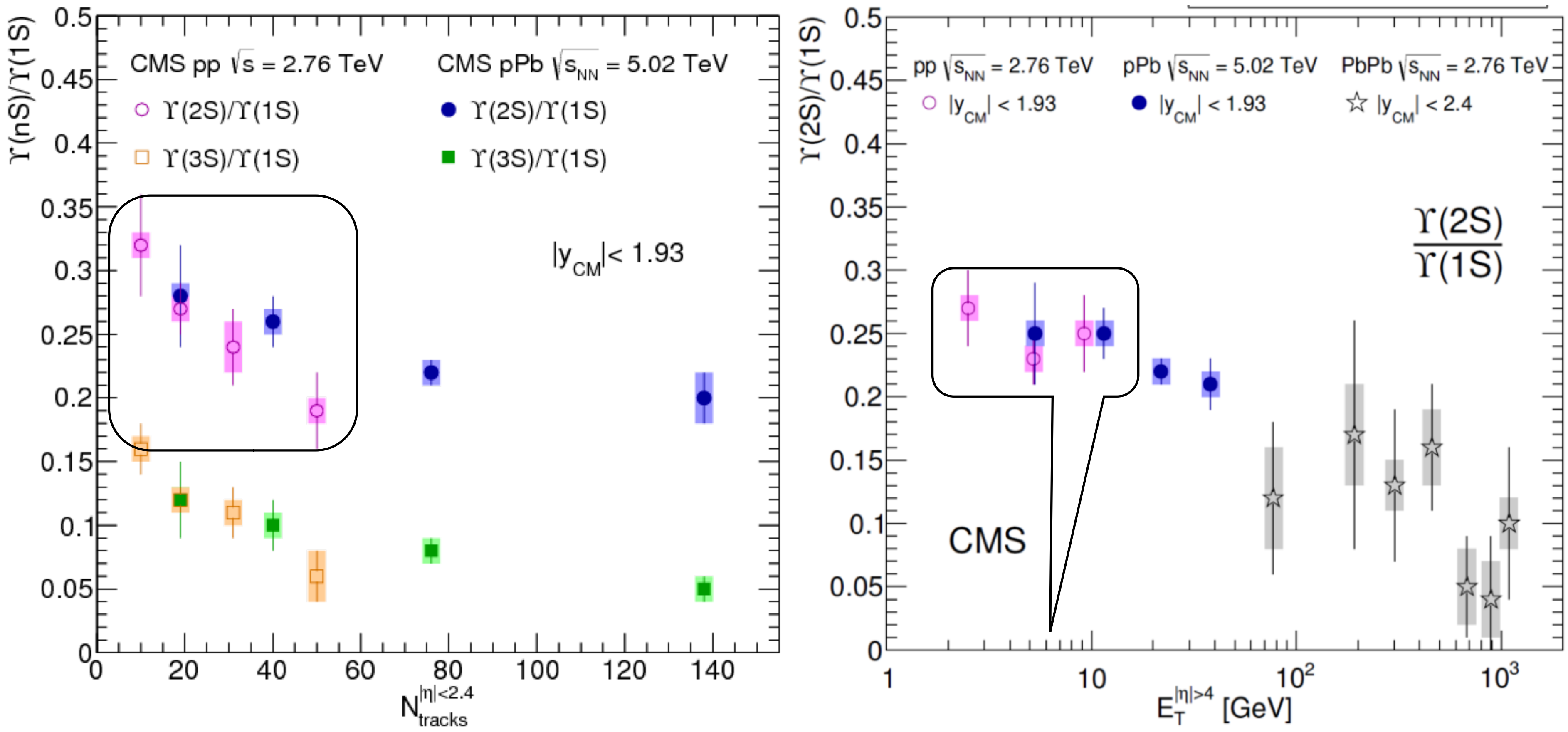
PLB 758 (2016) 67
EPJC 79 (2019) 666
JHEP 07 (2018) 032
JHEP 03 (2017) 157

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



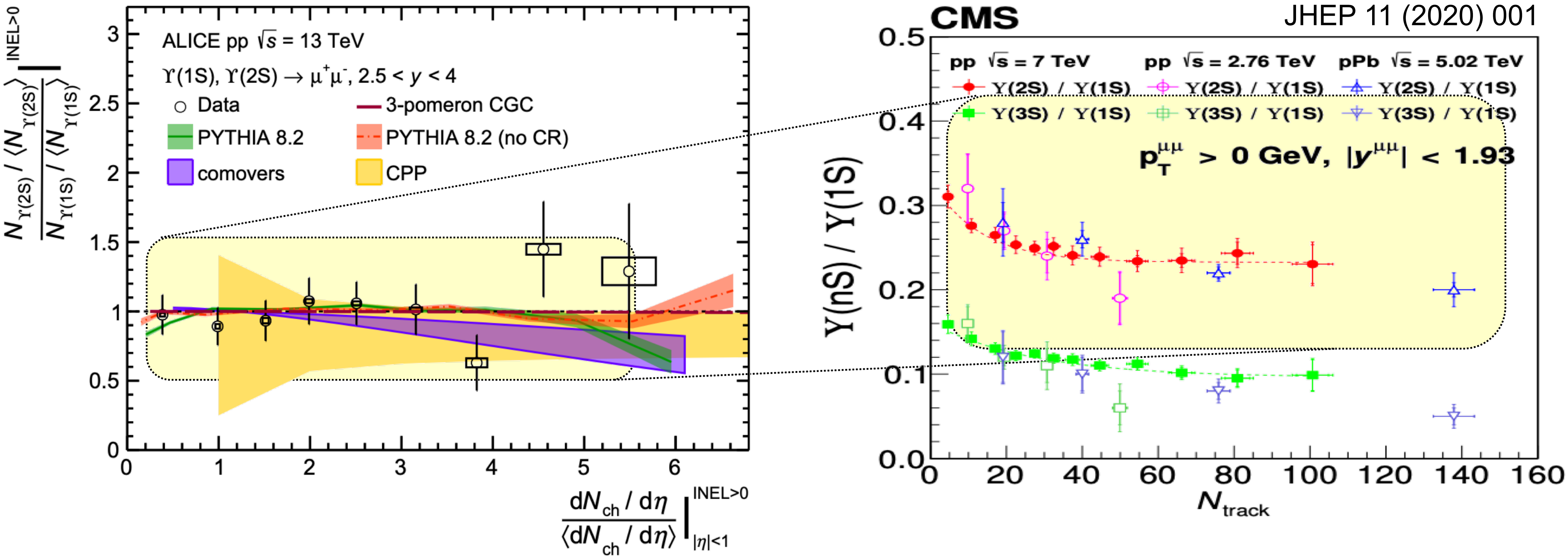
Introducing midrapidity-forward gap flattens the dependence as mentioned in HP2018 summary talk: https://indico.cern.ch/event/634426/contributions/3003672/

But it may be due to loss of resolution…

Does the rapidity matter?

arXiv:2209.04241

JHEP 11 (2020) 001



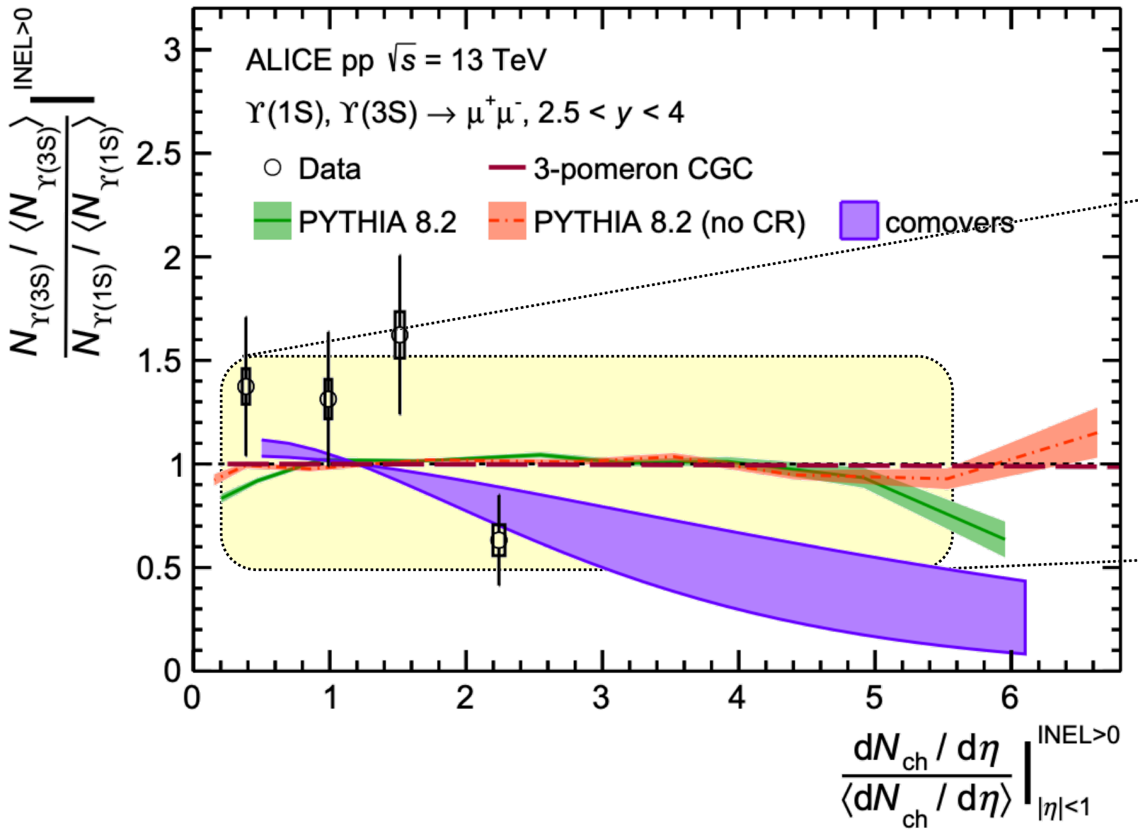
ALICE result on forward $\Upsilon(2S)/\Upsilon(1S)$ vs tracks at midrapidity

Data doesn't warrant any gap dependence

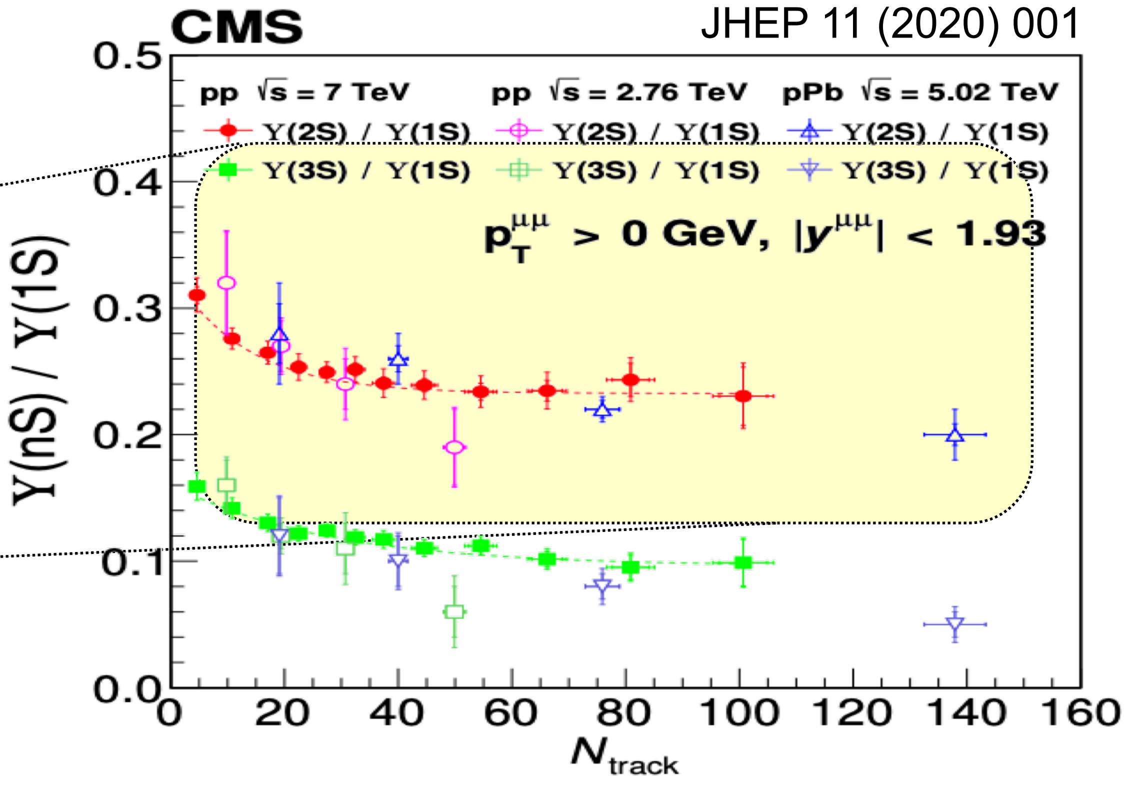
A direct answer should come from $\Delta\eta$ – analysis

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 $\Upsilon(1S)$

for example, ALICE: EPJC81 (2021) 256

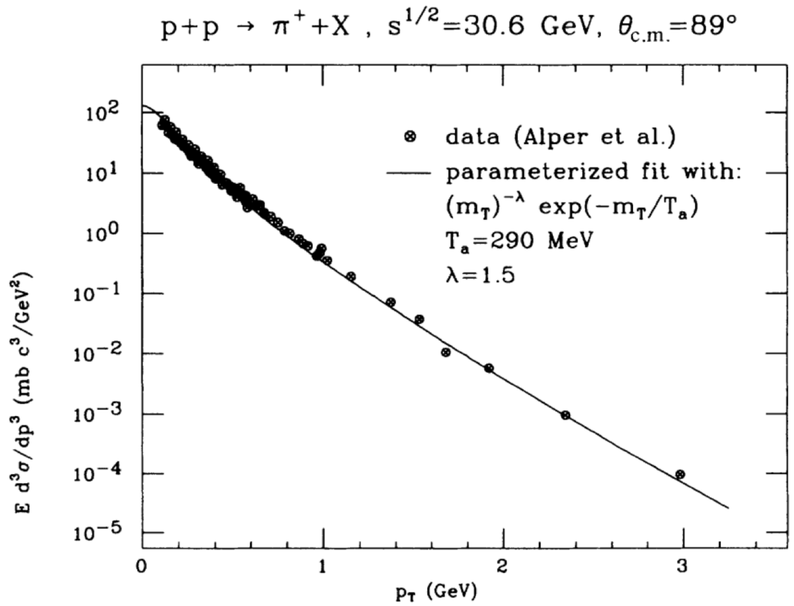
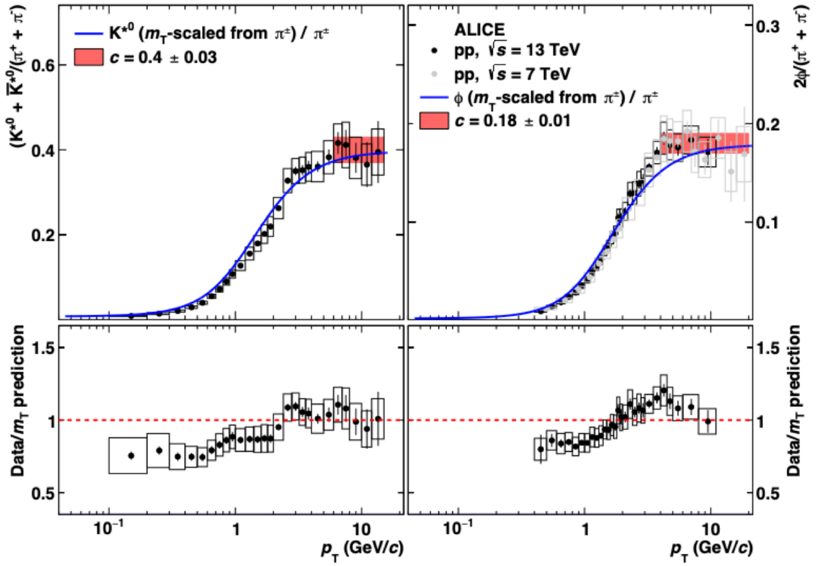
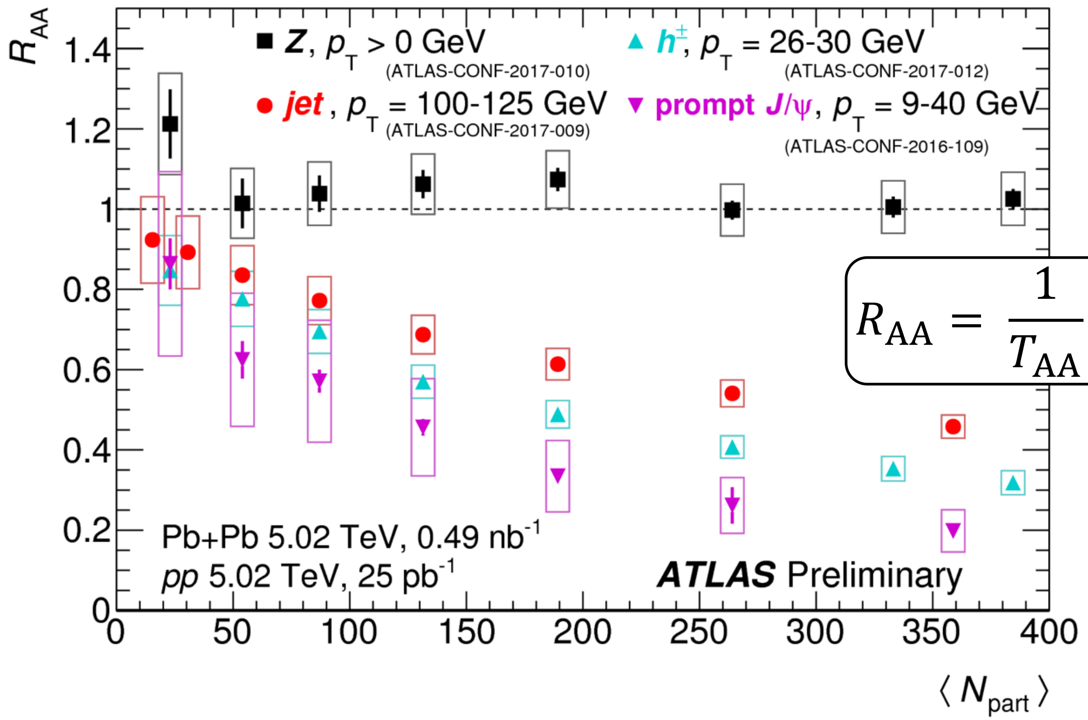


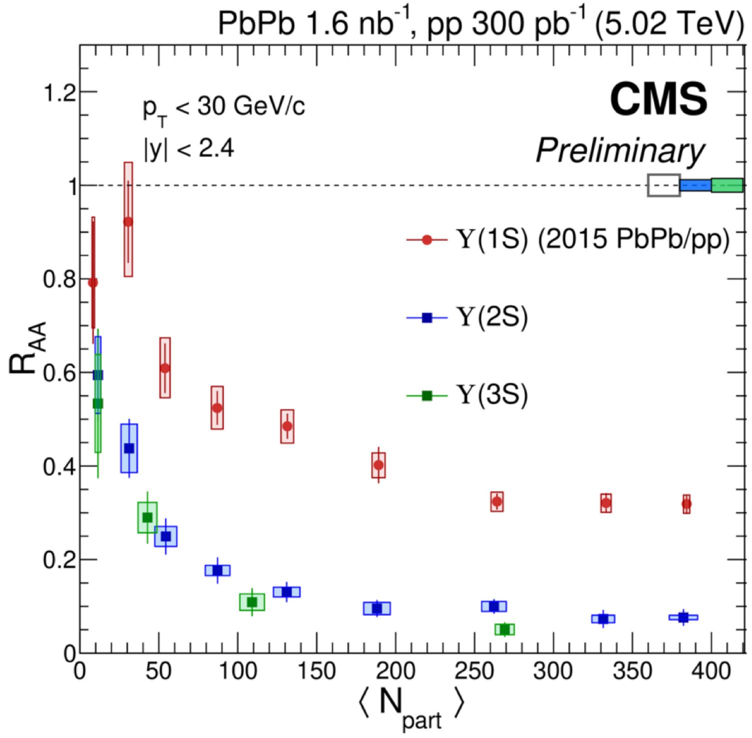
FIG. 3. *p-p* data from Alper *et al.*, fit here with $m_T^{-\lambda}\exp(-m_T/T_a)\times$const, having $T_a=200$ MeV and $\lambda=1.5$.



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

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

The pileup story

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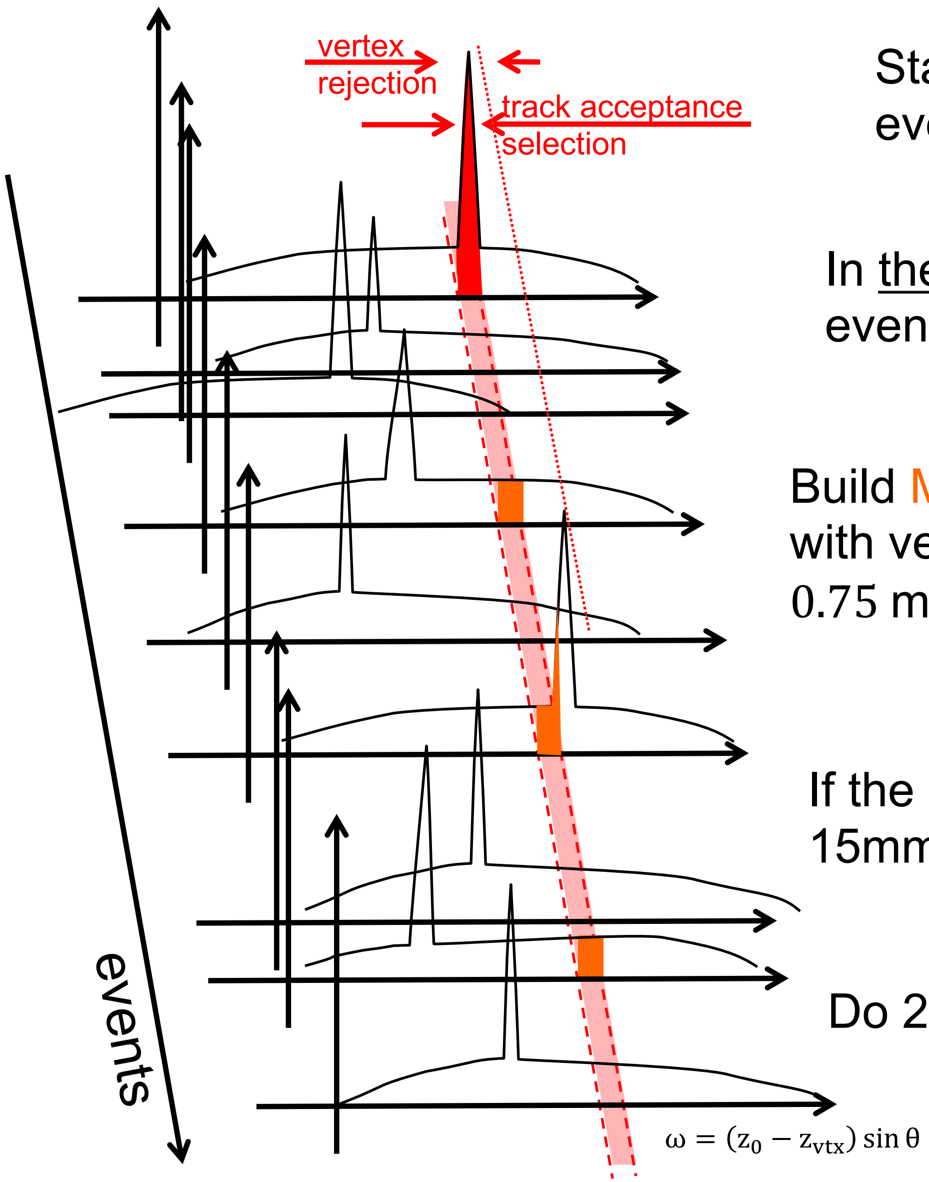


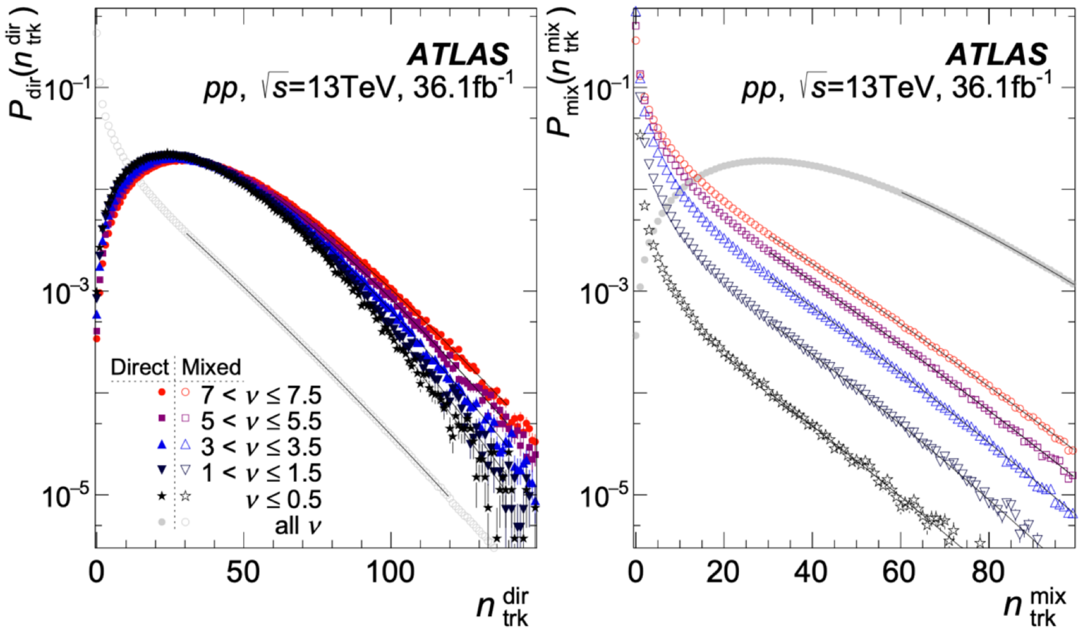
Start with the triggered event, called Direct

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) — $\frac{d^2 n_{trk}}{d\omega d\bar{\mu}}$

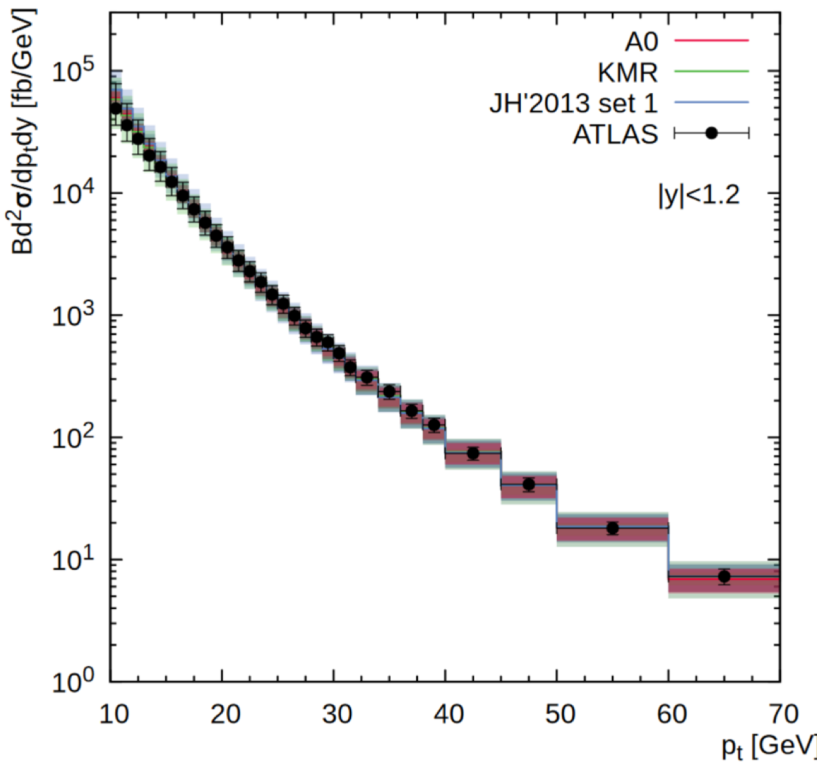
Analysis selection — ω_0

z_{vtx} distribution — $Gauss(\bar{z}_{vtx})$

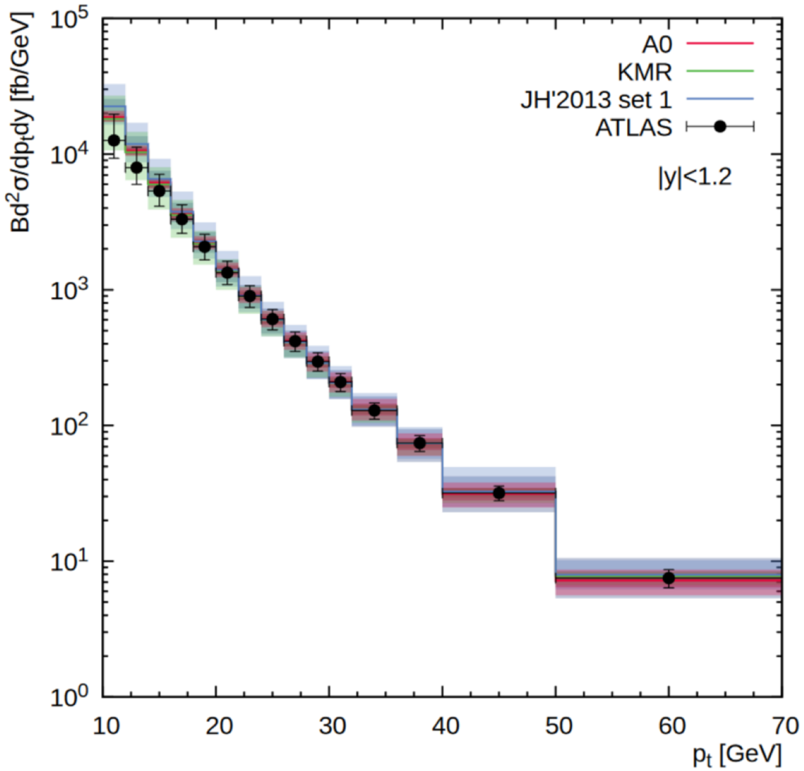
Instantaneous luminosity — $\bar{\mu}$

Theory calculation

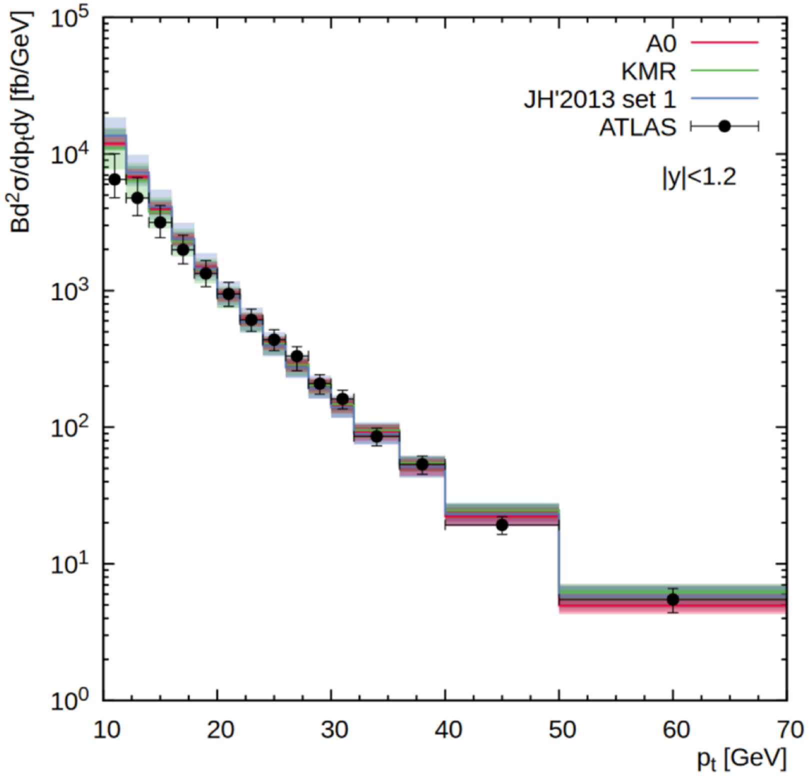
$\Upsilon(1S)$



$\Upsilon(2S)$



$\Upsilon(3S)$



[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.
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[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.