Soft-hard correlations in small systems

SoftJet2024

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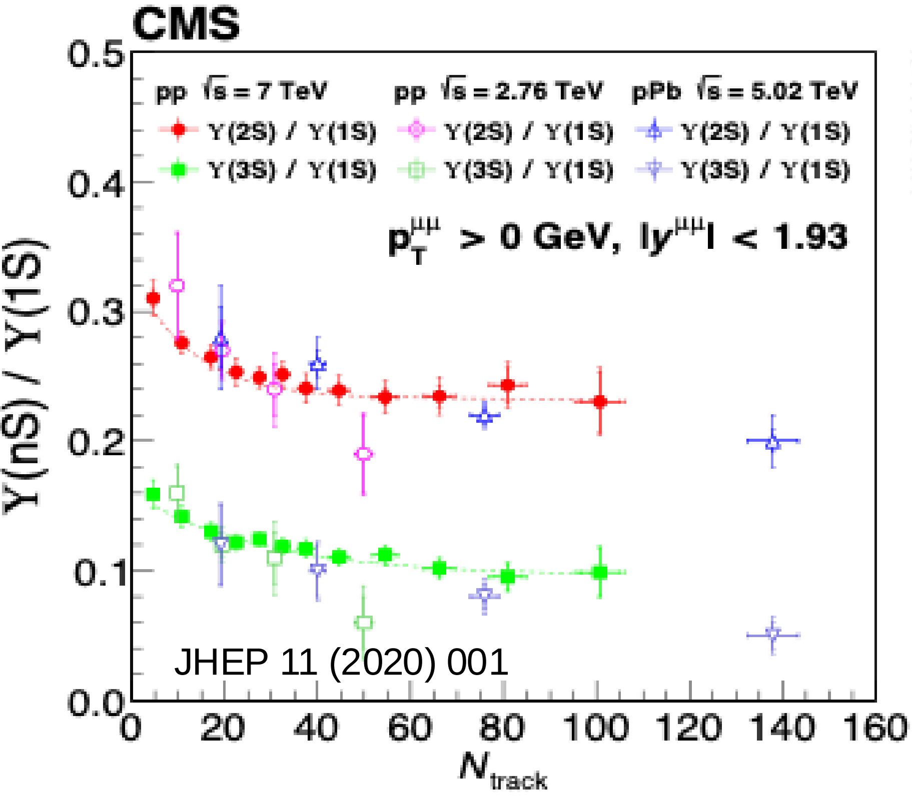
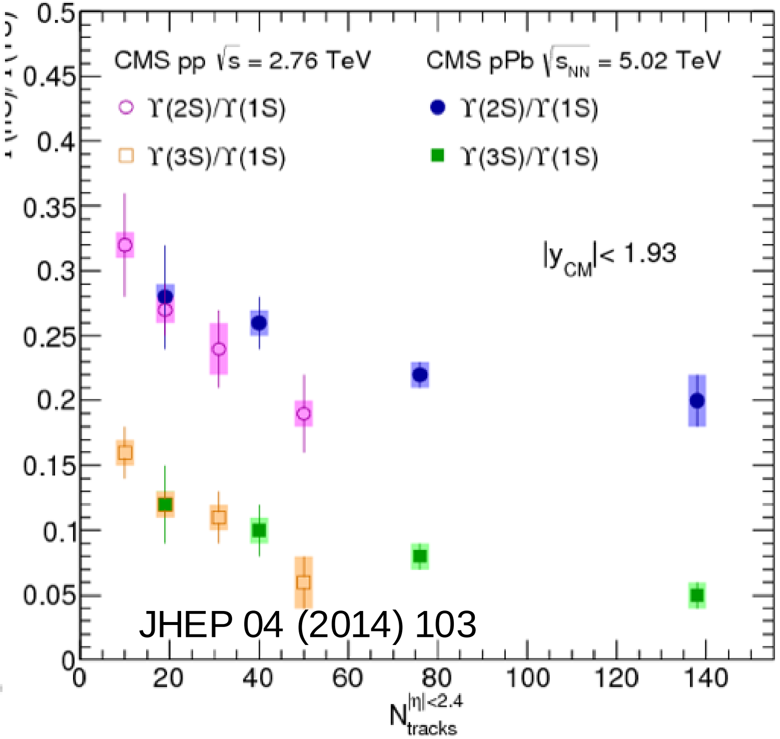
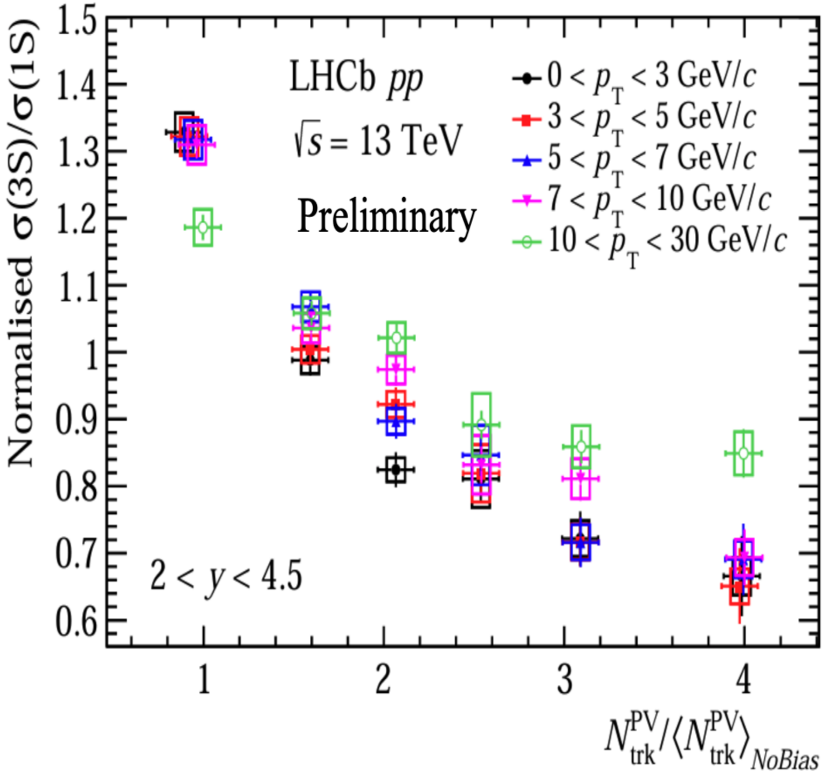
CMS results with $\Upsilon(nS)$ suppression



JHEP 11 (2020) 001



JHEP 04 (2014) 103

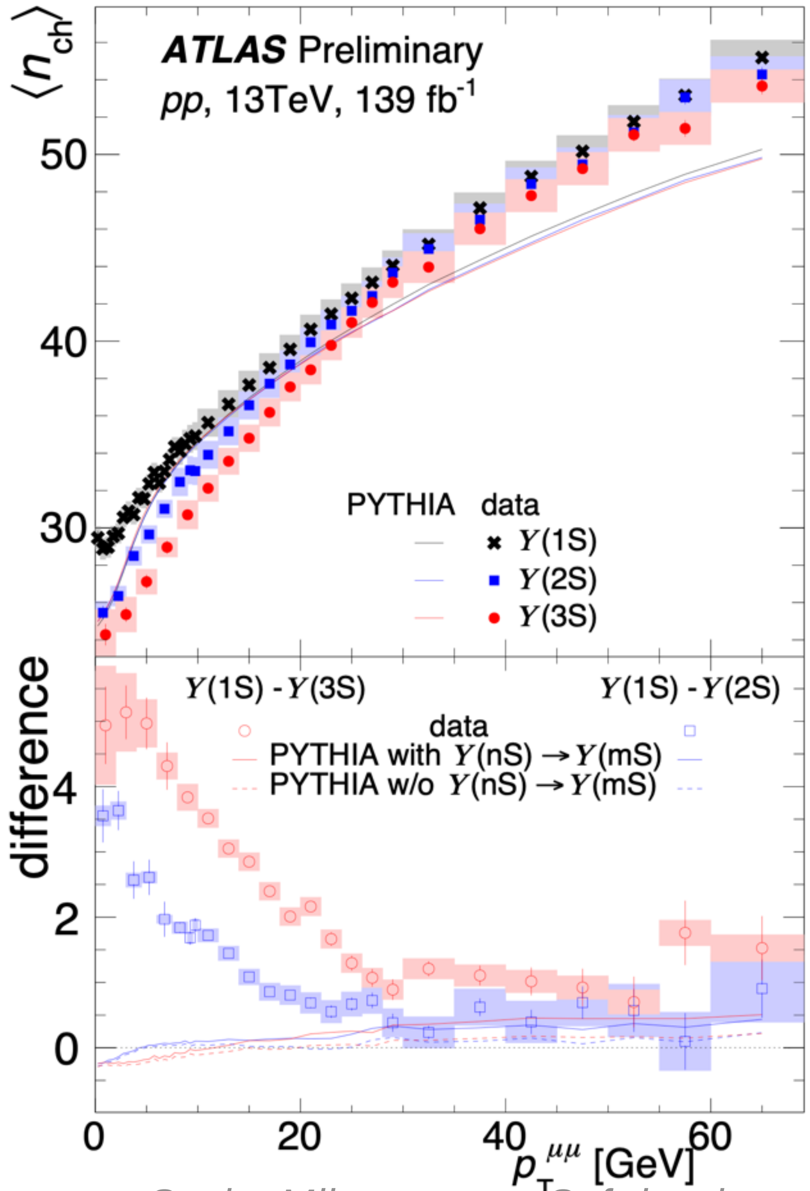


Using n_{trk} the CMS and now LHCb measured suppression of the $\Upsilon(nS)/\Upsilon(1S)$ ratios
There are also complimentary ALICE results, w/o obvious suppression at high rapidity, but with much lower statistics.

ATLAS used another approach to look at the data

Multiplicity dependence on Υ–momentum

ATLAS-CONF-2022-023



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

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

Pythia has no effect like this

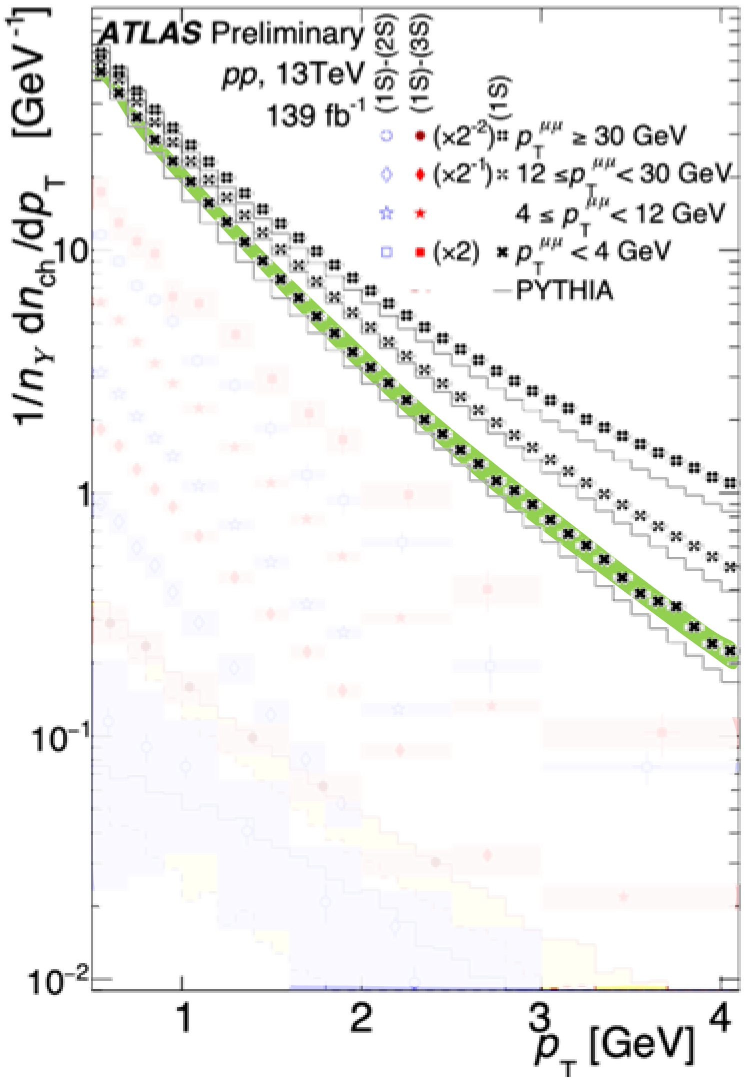
At the lowest p_T, where the effect is the strongest:

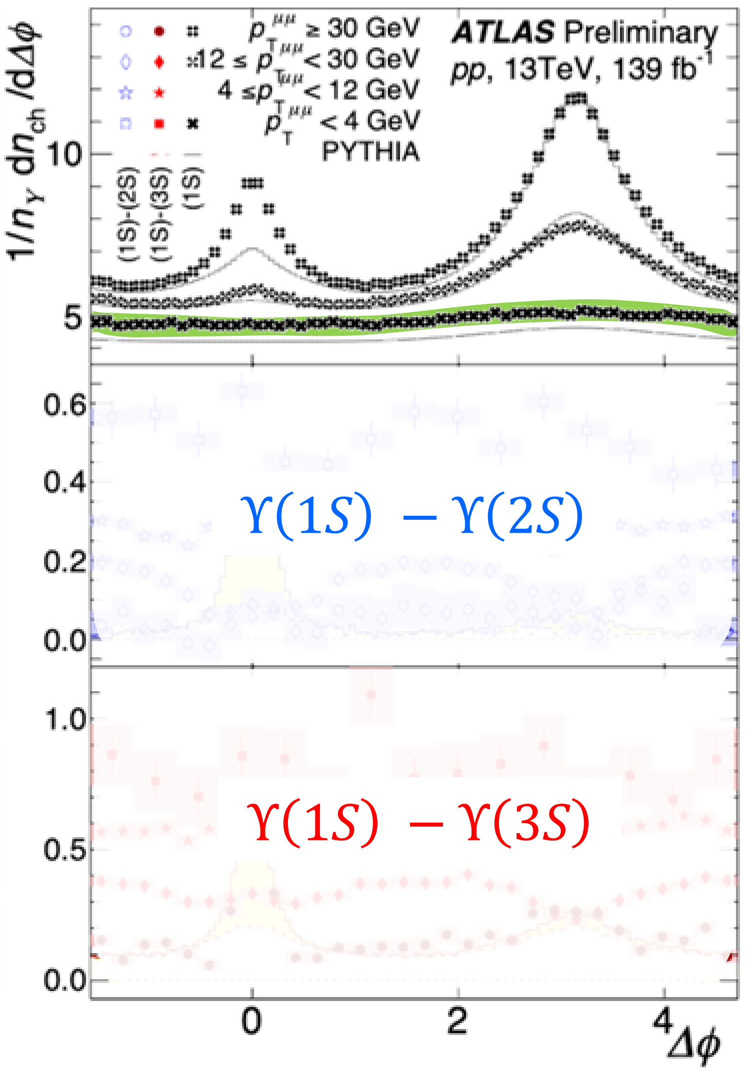
$\Upsilon(1S) - \Upsilon(2S)\ \Delta\langle n_{ch}\rangle =$ 3.6 ± 0.4 12% of $\left\langle n_{ch}^{\Upsilon(1S)} \right\rangle$

$\Upsilon(1S) - \Upsilon(3S)\ \Delta\langle n_{ch}\rangle =$ 4.9 ± 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

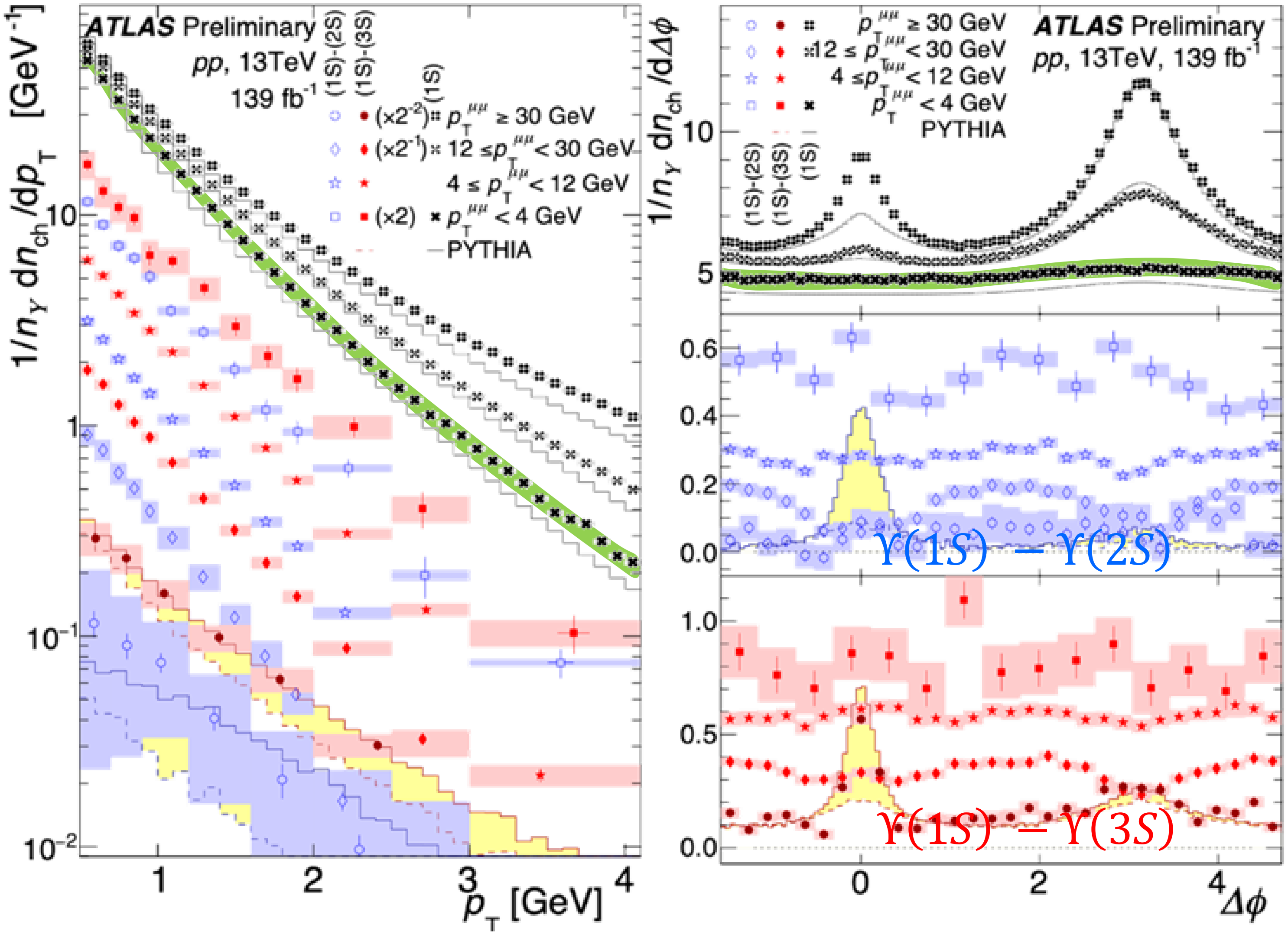
Kinematic distributions of $\Upsilon(1S)$





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 of the differences



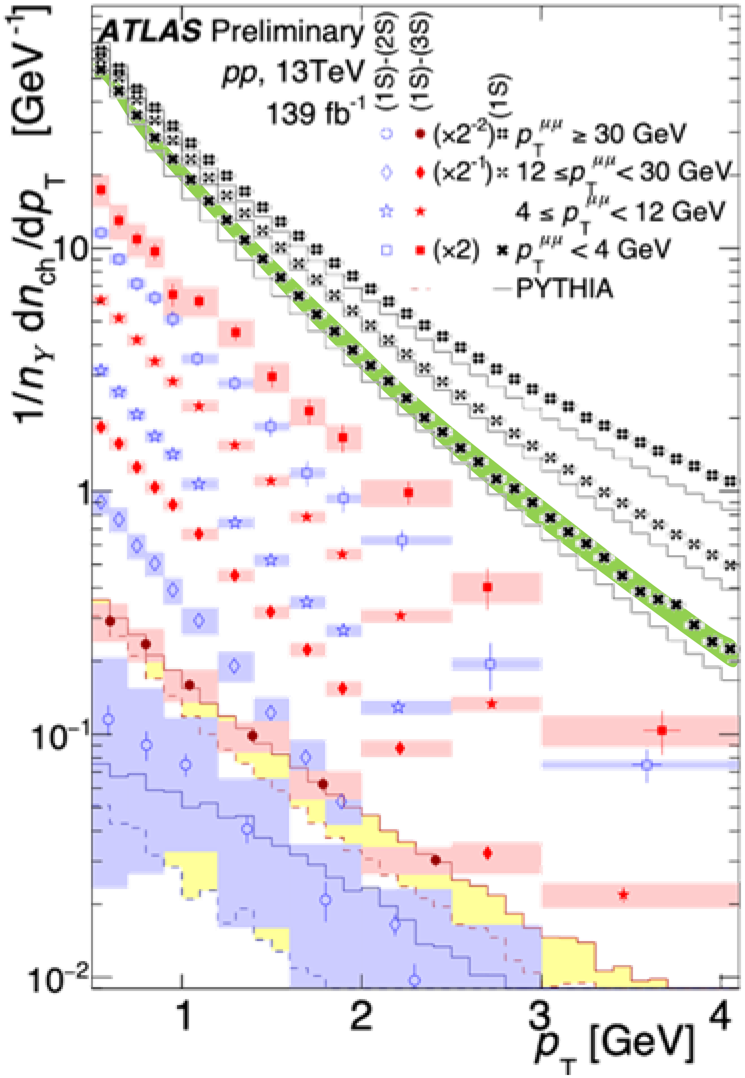
One cannot measure the UE, but $p_T < 4$ GeV is the closest to it, jet part that is correlated to $\Upsilon(nS)$

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

The effect is related to the UE

Where are the differences coming from?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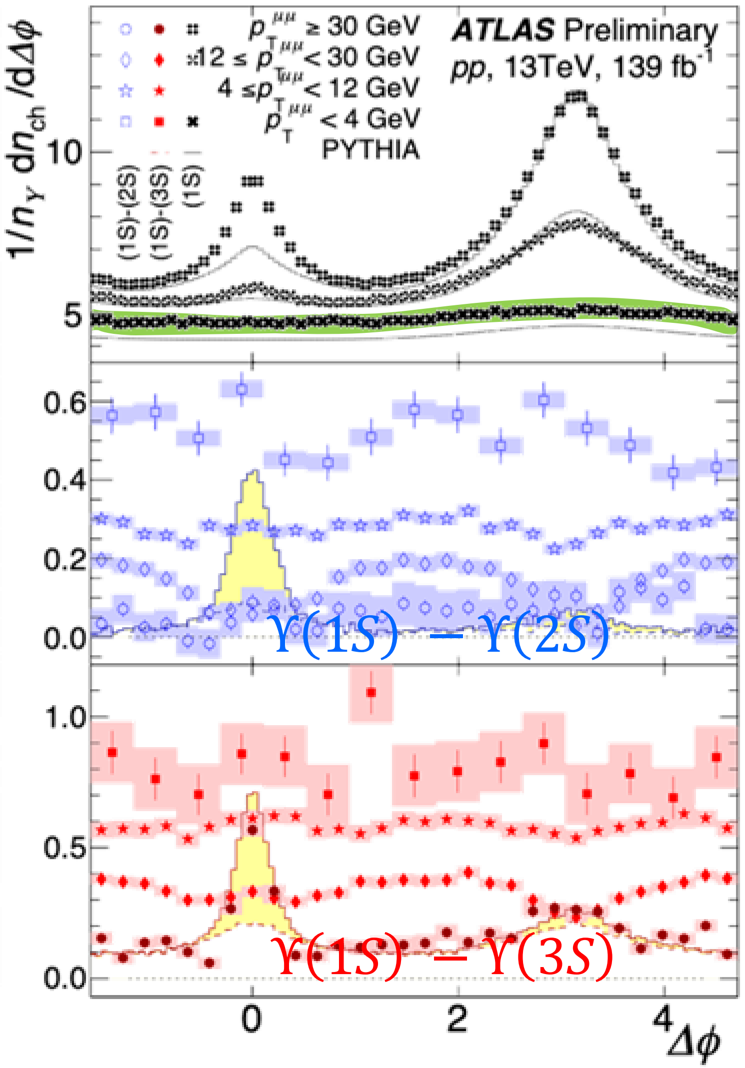
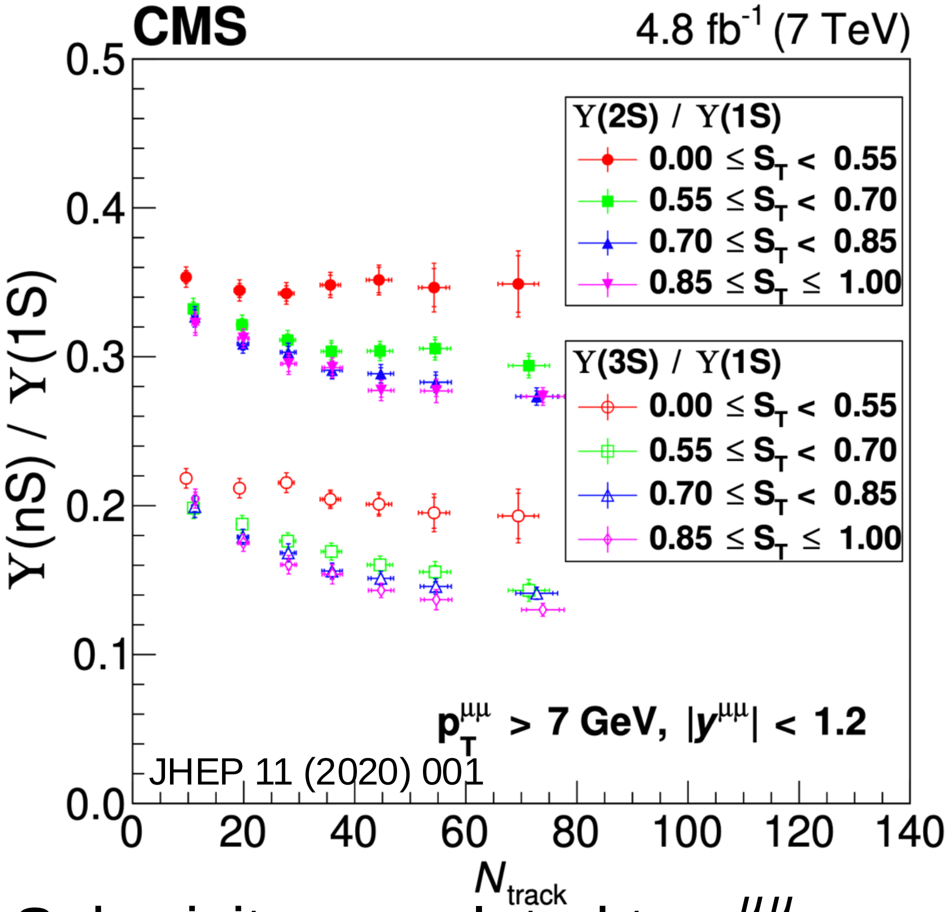




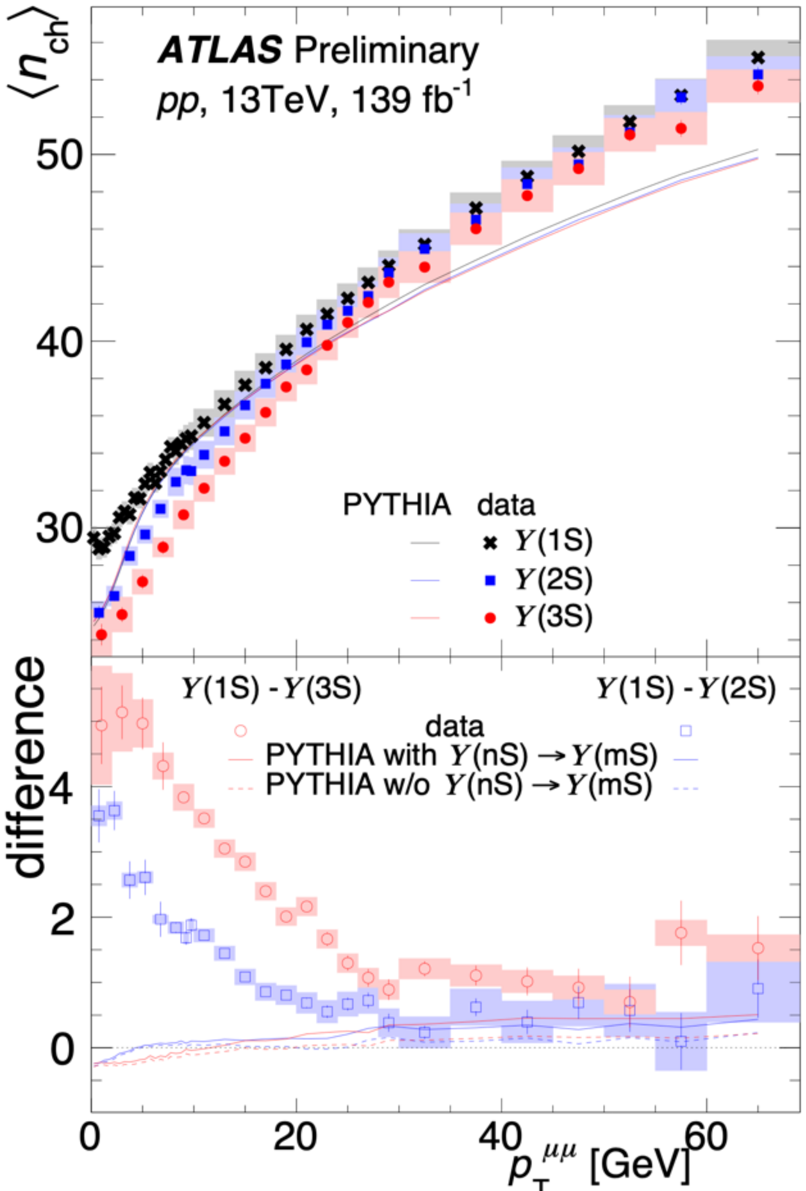
Spherisity, correlated to $p_T^{\mu\mu}$

$S_T < 1$ jet-like

$S_T \sim 1$ no jet ← stronger effect

Is it a deficit for $\Upsilon(nS)$ or an excess for $\Upsilon(1S)$?

ATLAS-CONF-2022-023/



How large is the UE in the presence of $\Upsilon(nS)$?

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

On the other hand, a p_T – dependence of the $\Delta\langle n_{ch} \rangle$ points to the modification of p_T spectrum. What shall be the p_T spectrum of $\Upsilon(nS)$?

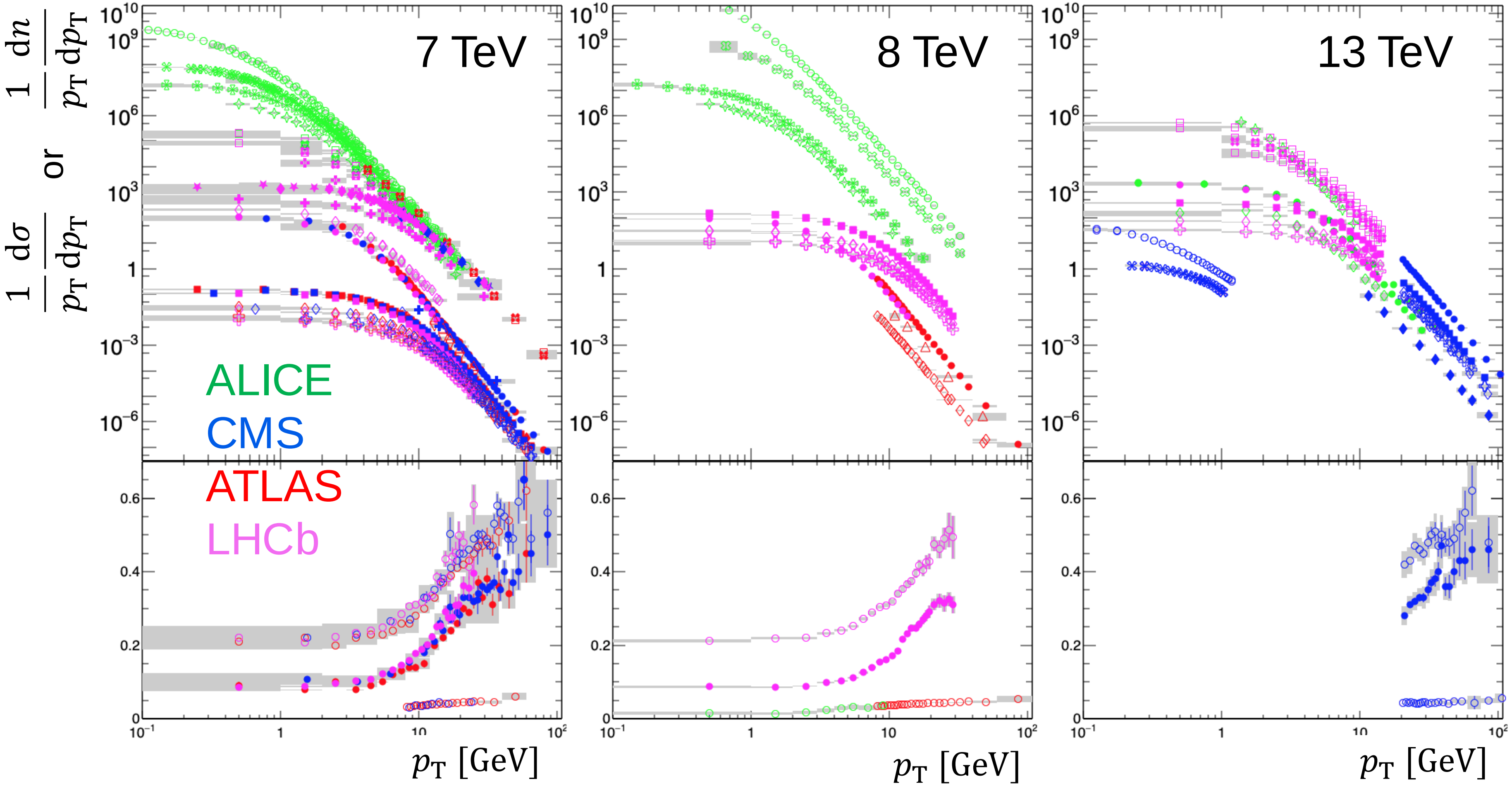
Basic assumption:

If particles have the same quark content and the same mass, they must have the same kinematics.

For small Δm between particles one can use m_T – scaling

LHC data for m_T - scaling

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



Only mesons

4 LHC experiments

$\sqrt{s} = 7, 8, 13$ TeV

18 species + iso-partners

72 data samples with 1509 data points

15 quarkonia ratios with 327 data points

T is fixed to 254 MeV

Spectra at high p_T

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_\mathrm{T}} \propto \left[1+\frac{m_\mathrm{T}}{nT}\right]^{-n}$$

n

Open flavor mesons ($c||\bar{c}$ and $b||\bar{b}$) has harder spectra (lower *n*)

LHCb data (high-rapidity) are typically higher than midrapidity data

Excited quarkonia ($(c\bar{c})^*$ and $\left(b\bar{b}\right)^*$) have lower *n*

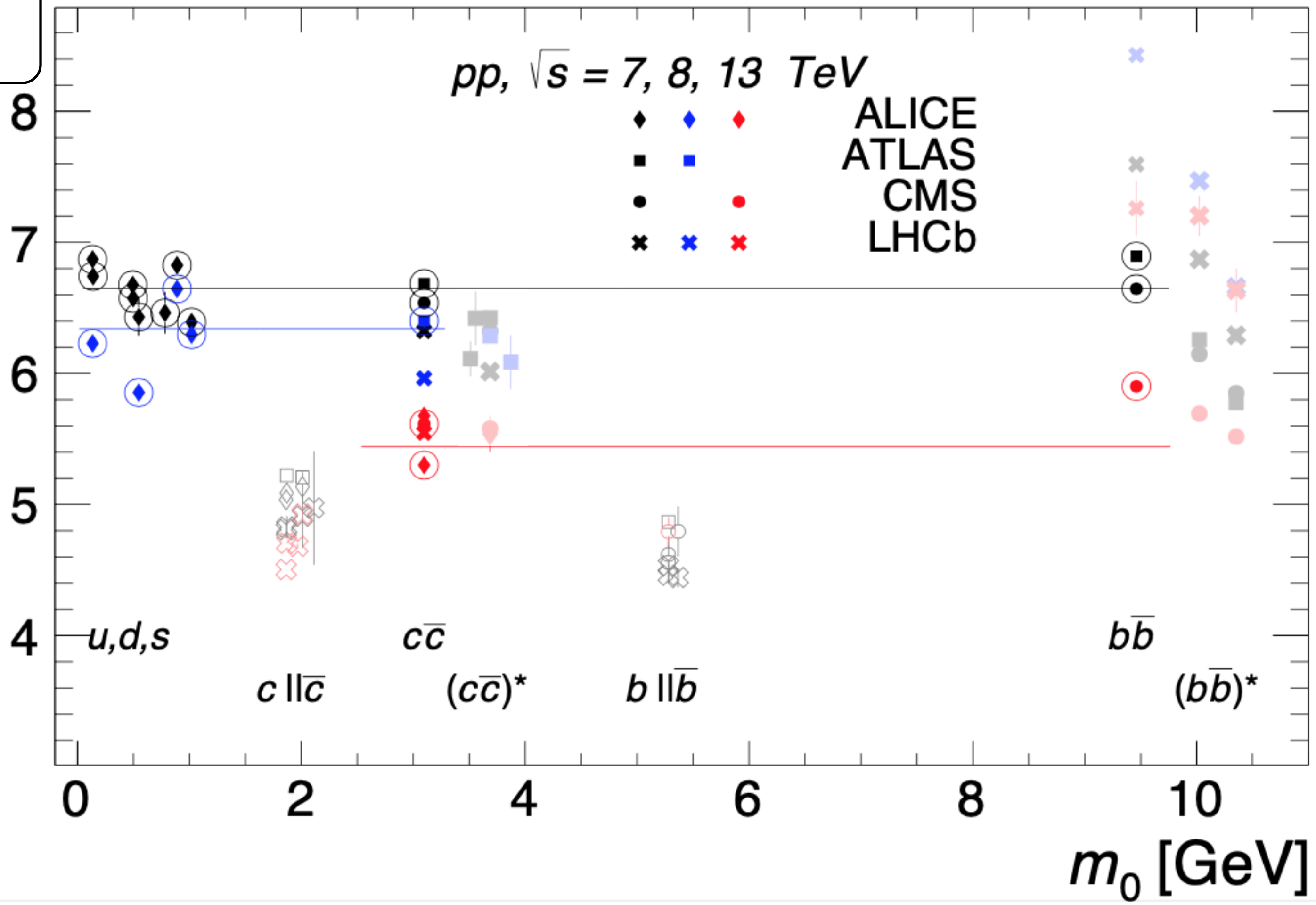
u,d,s & $q\bar{q}$ are fit simultaneously

n = 6.65 $\sqrt{s} = 7$ TeV

n = 6.34 $\sqrt{s} = 8$ TeV

n = 5.44 $\sqrt{s} = 13$ TeV

PRD **107**, 014012 (2023)



T is fixed to 254 MeV

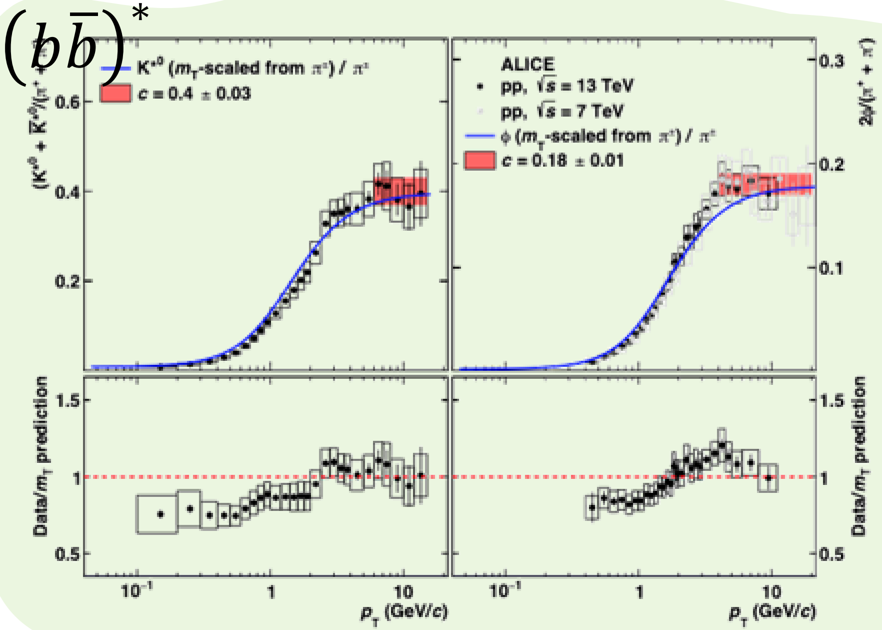
Quarkonia ratios: expected & measured

Normalized at $p_{\mathrm{T}} > 50$ GeV

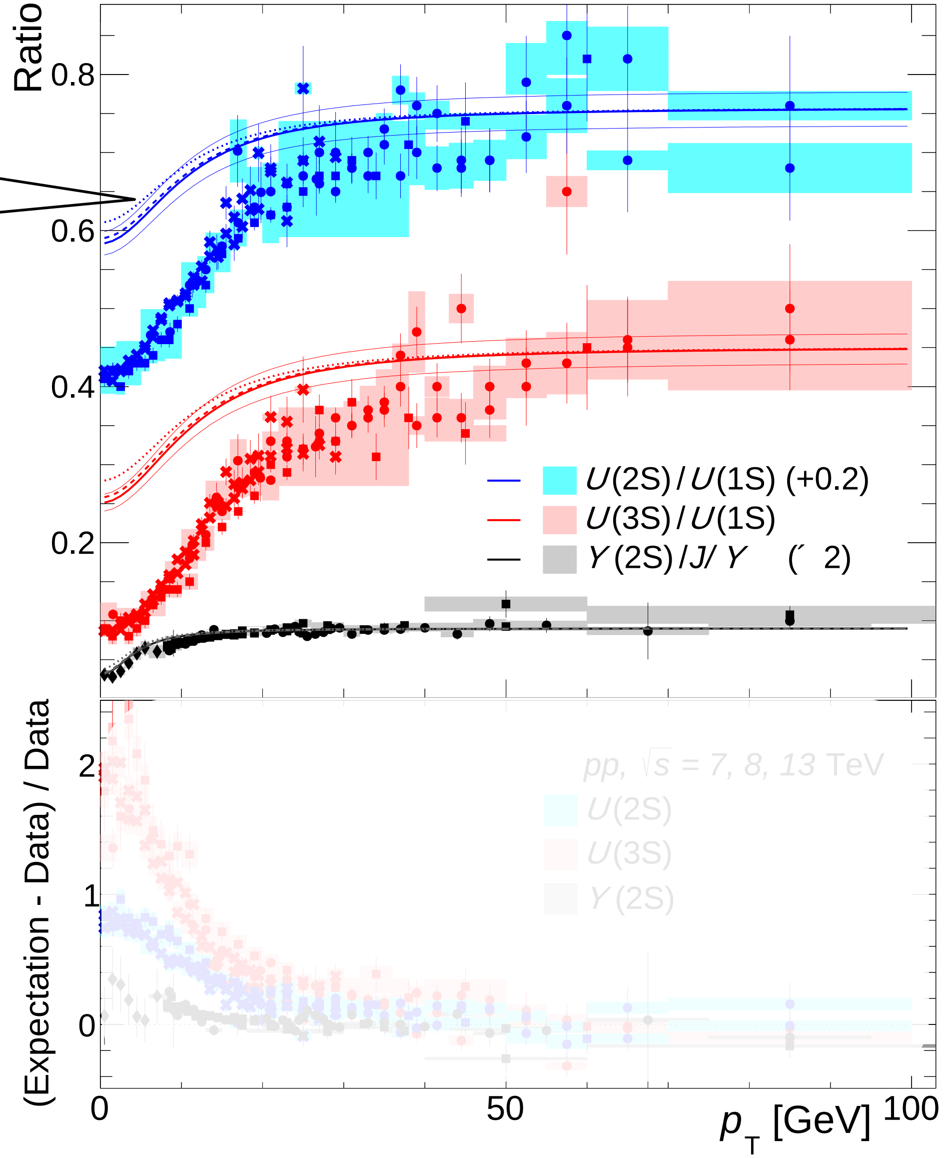
$$\lim_{\Delta m, p_T \ll m_{q\bar{q}}} \left[\frac{nT + \sqrt{p_{\mathrm{T}}^2 + \left(m_{q\bar{q}} + \Delta m\right)^2}}{nT + \sqrt{p_{\mathrm{T}}^2 + m_{q\bar{q}}^2}}\right]^{-n} = 1 - \frac{n\Delta m}{nT + m_{q\bar{q}}}$$

Measured $\Upsilon(nS)/\Upsilon(1S)$ are not as derived

No known effects can bridge differences for $(b\bar{b})^*$



An example
EPJC81 (2021) 256



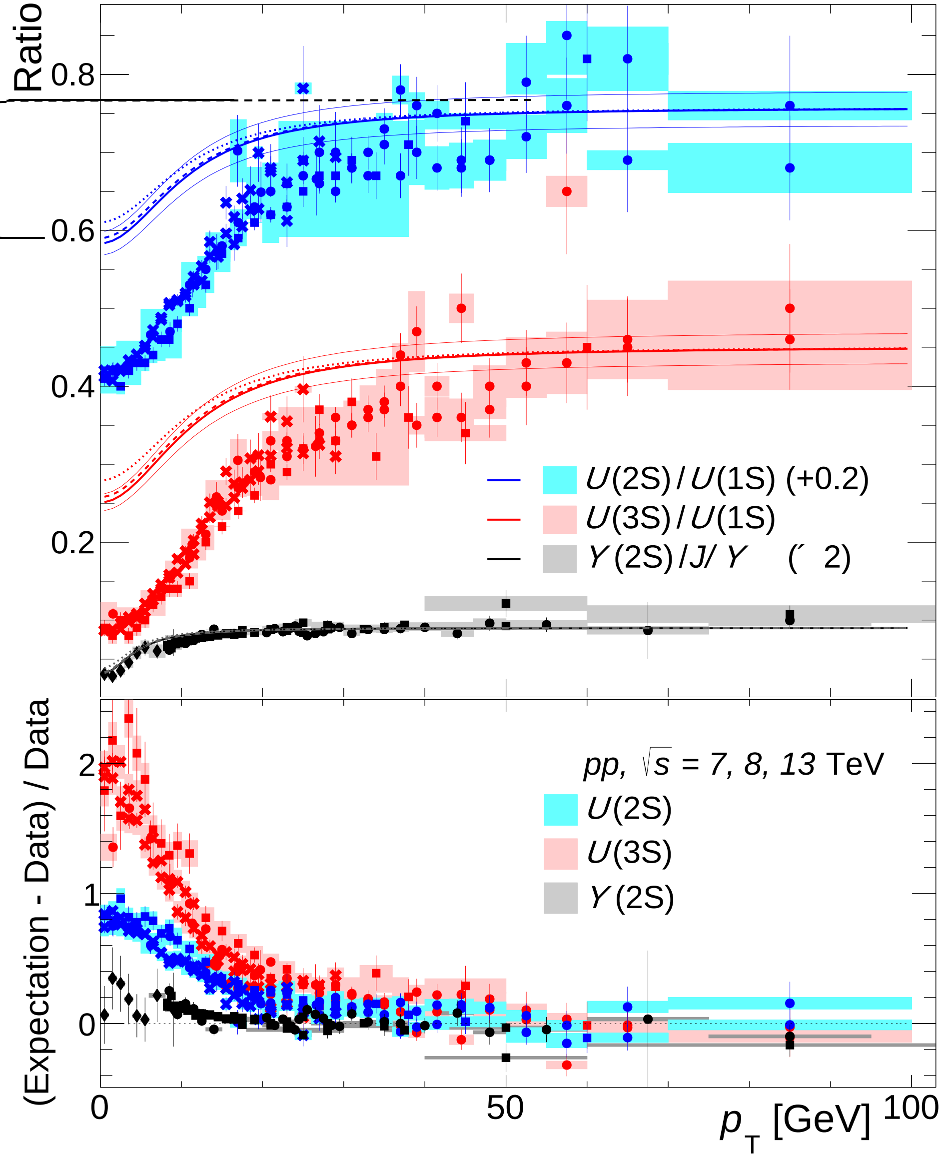
Quarkonia ratios: expected & measured

Normalized at $p_{\mathrm{T}} > 50$ GeV

Measured ratios are not as derived $1 - \dfrac{n\Delta m}{nT + m_{q\bar{q}}}$

No known effects can bridge differences for $\left(b\bar{b}\right)^*$

$$\text{Missing beauty} = \frac{\text{Expected}}{\text{Measured}} - 1$$



Quarkonia ratios: expected & measured

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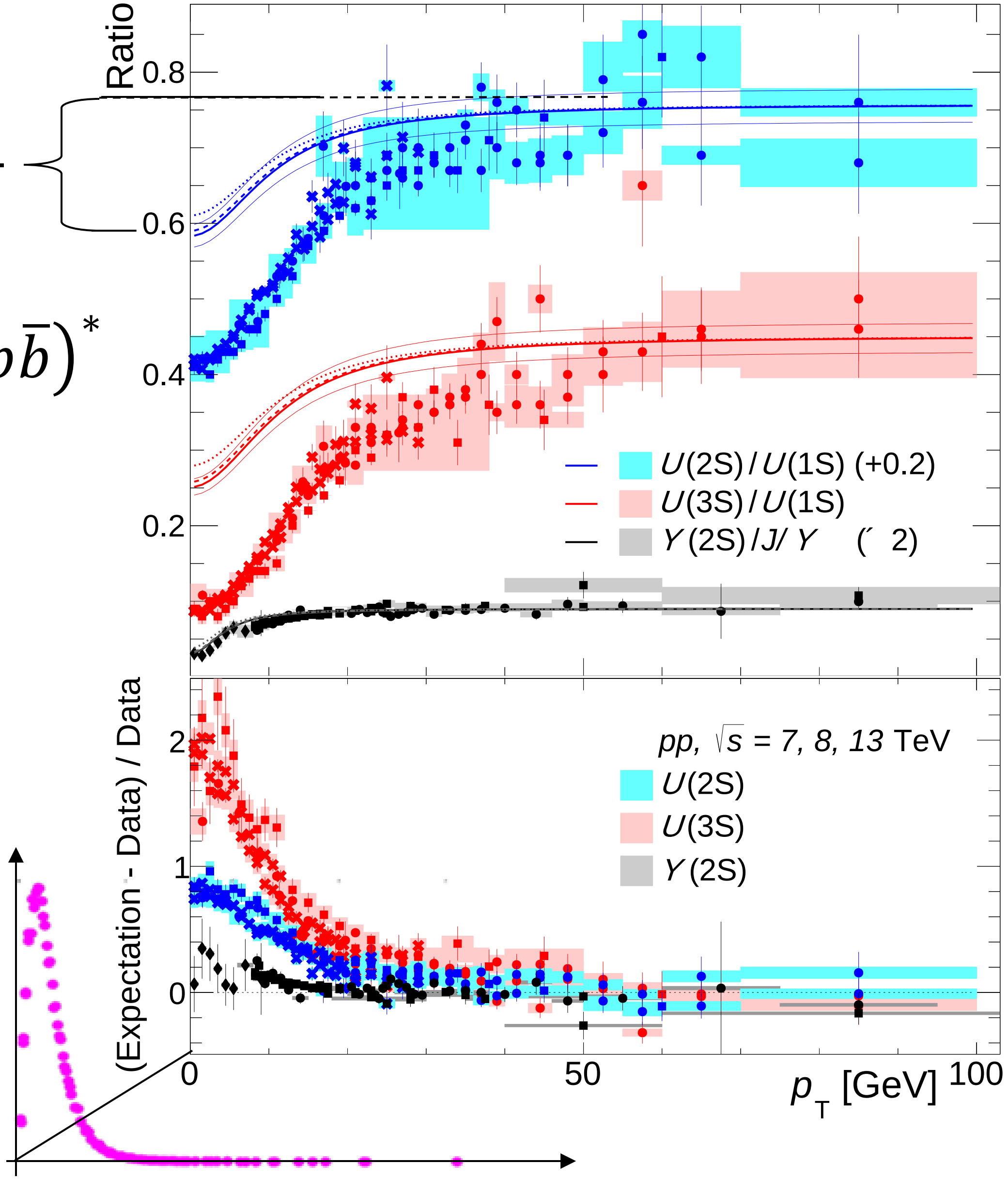
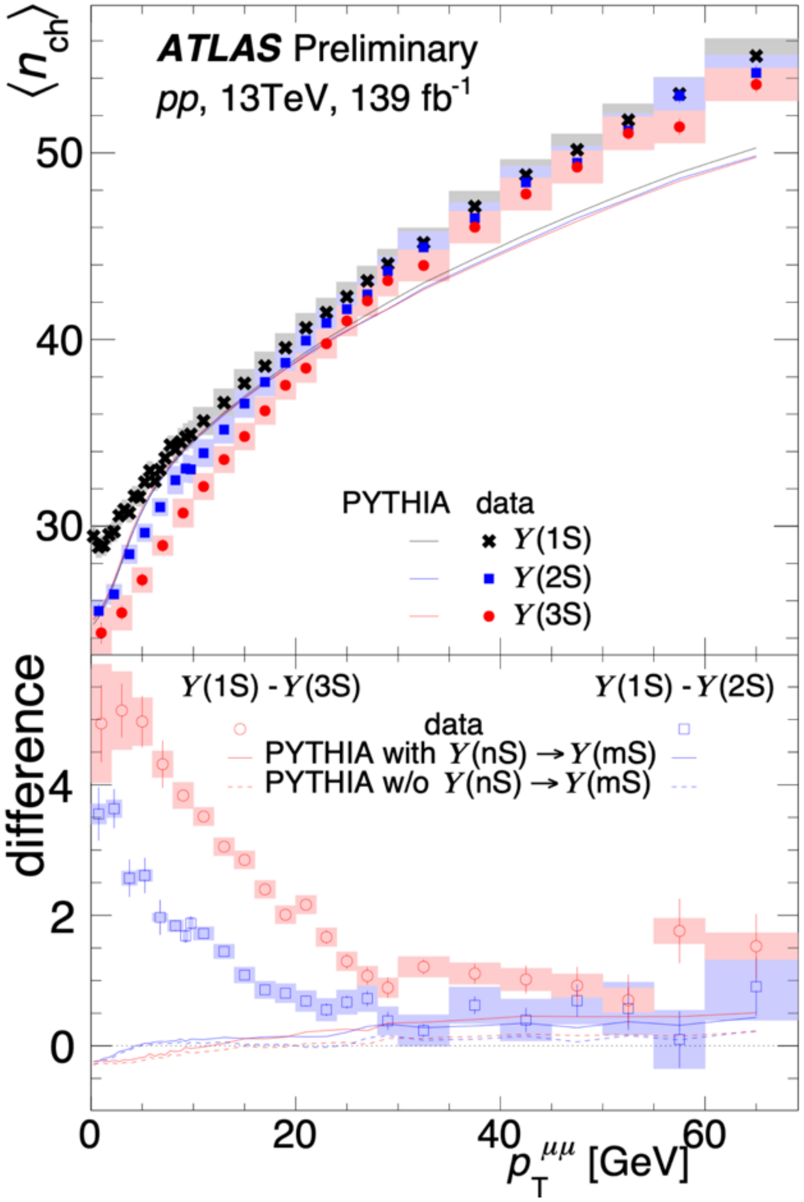
No known effects can bridge differences for $(b\bar{b})^*$

$$\text{Missing beauty} = \frac{\text{Expected}}{\text{Measured}} - 1$$

Multiplying by experimental spectra
- $\Upsilon(2S)$ should be factor 1.6 larger!
- $\Upsilon(3S)$ factor 2.4!



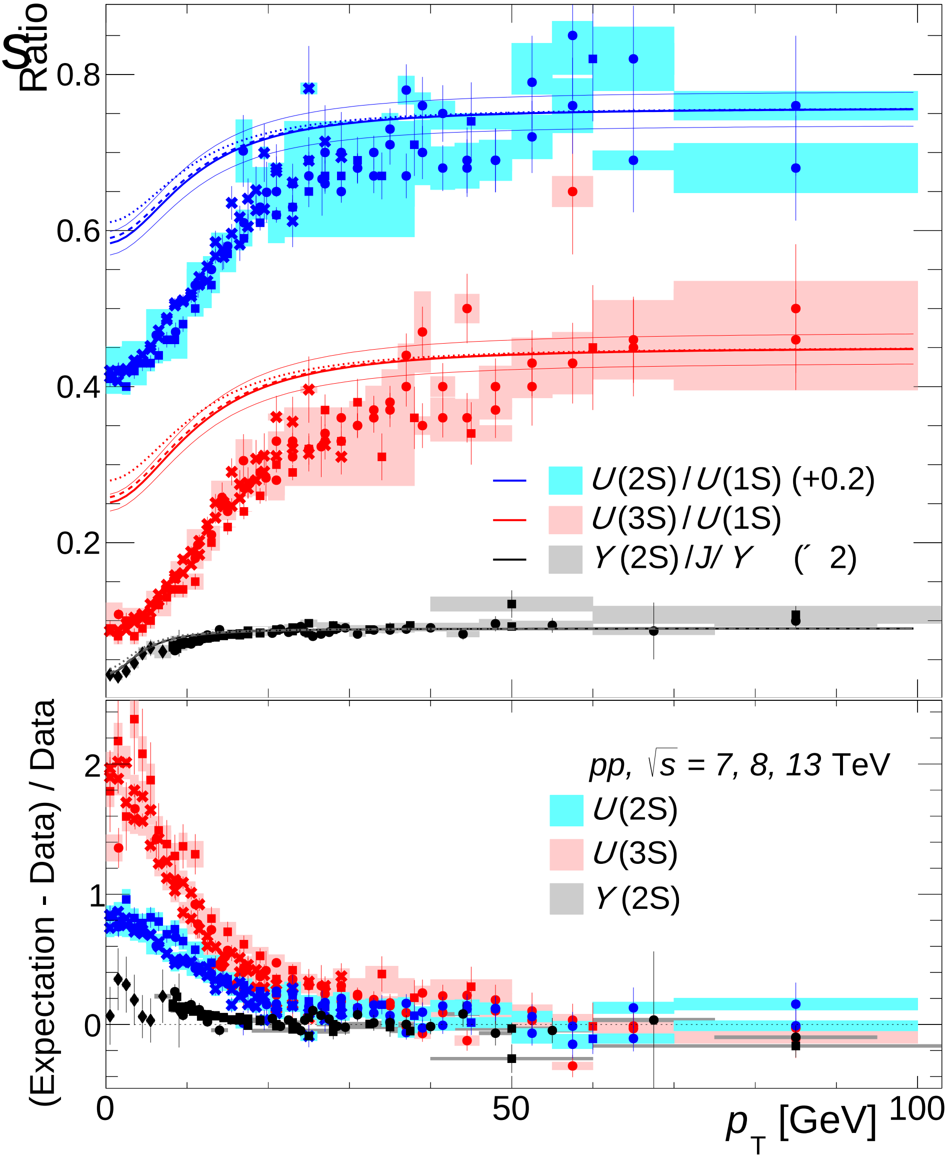
Bringing pieces together



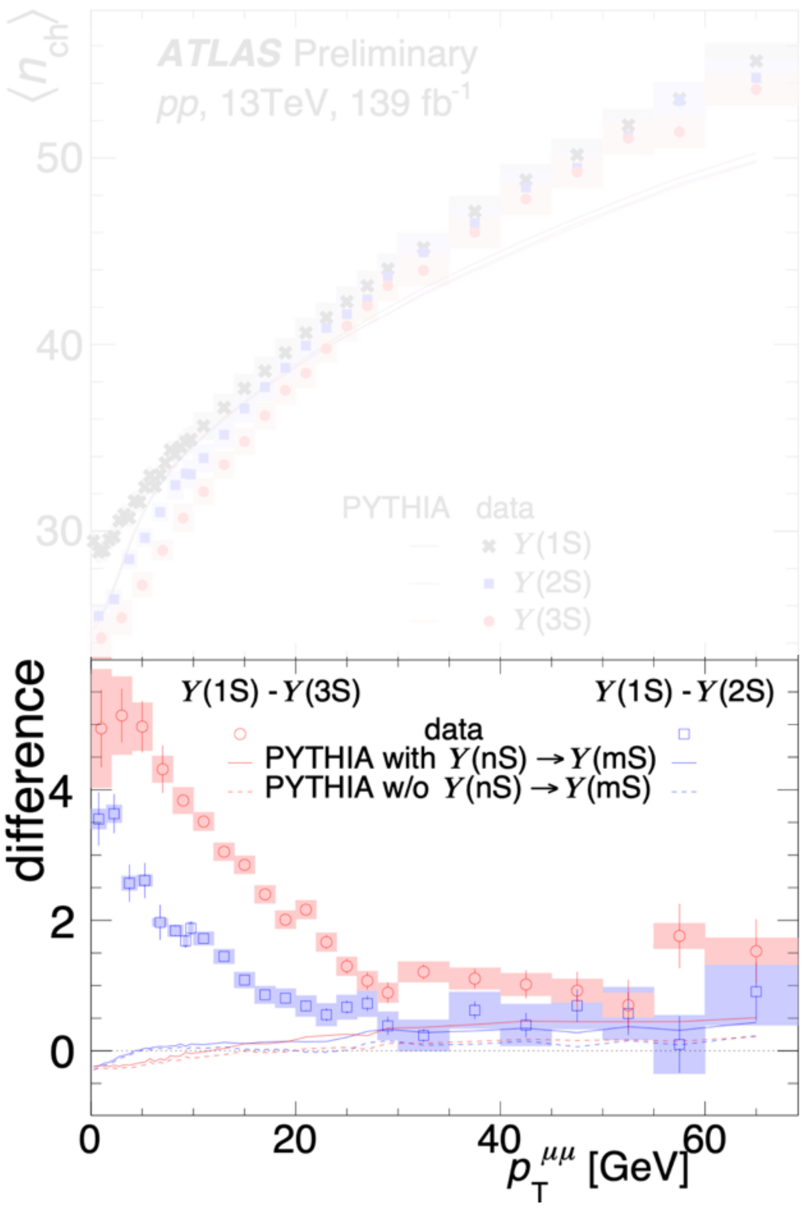
Independent analyses by three experiments

Link the $\Upsilon(nS)$ production to the UE
 -- ATLAS by kinematics
 -- CMS by sphericity

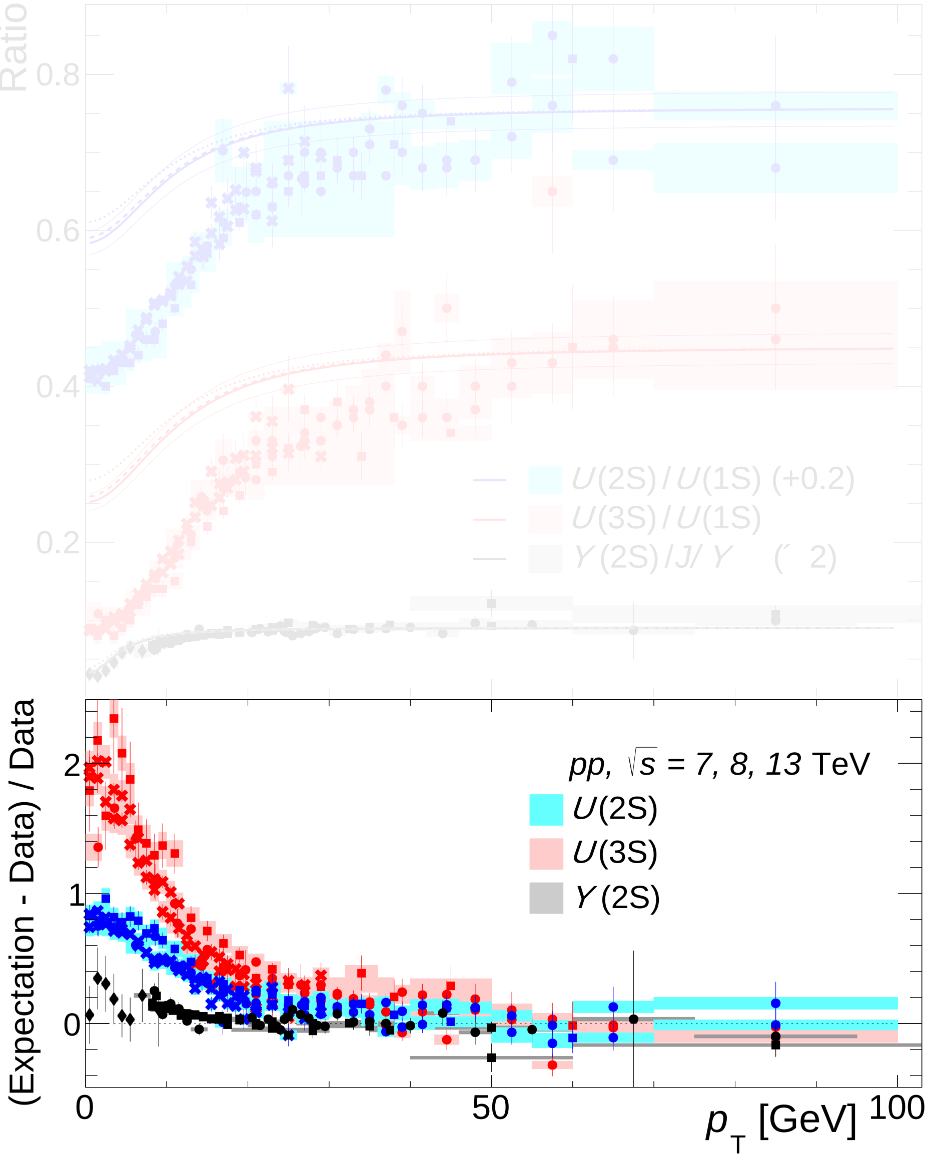
Deficit of the excited $\Upsilon(nS)$ with similar
 -- p_T dependence
 -- specie ordering



Final state interaction in *pp*



$\Upsilon(nS)$ production in *pp* is suppressed by the UE



Charmonia suppression *pp*

LHCb measured $\Psi(2S)/\ J/\Psi$

For prompt and no form non-prompt

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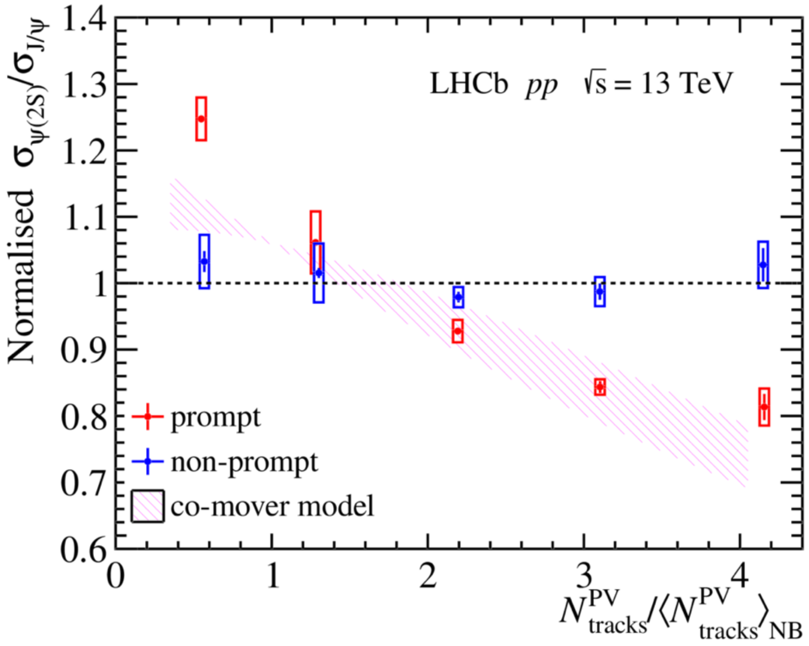
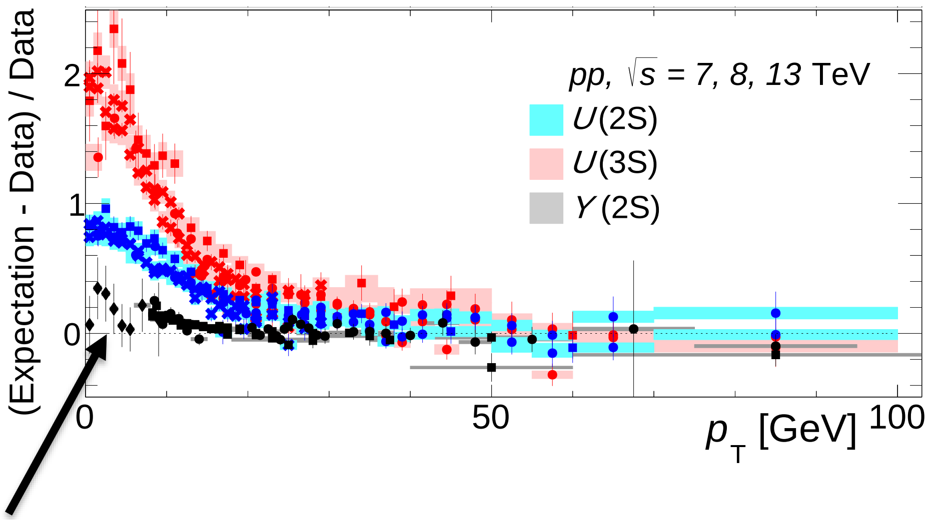
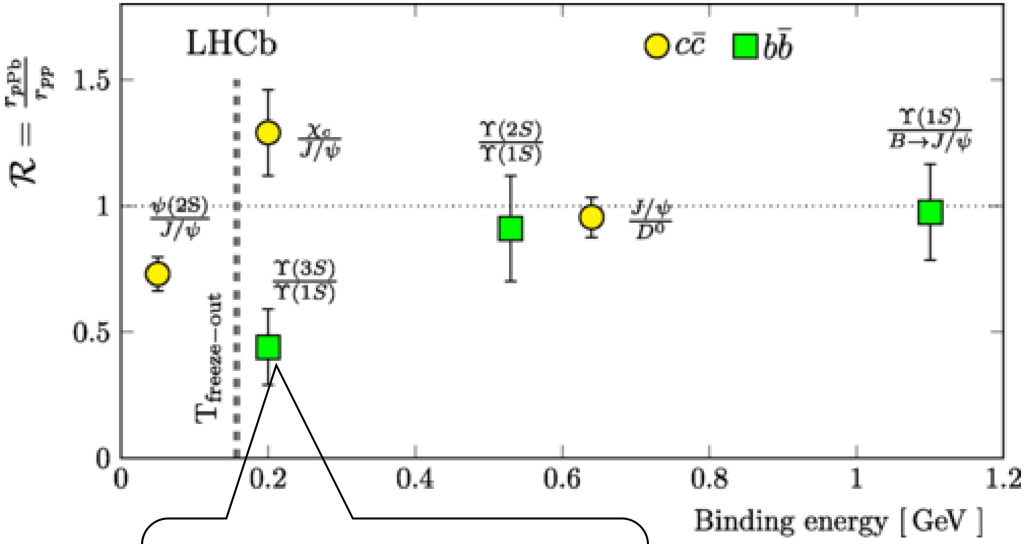


Clear suppression of prompt charmonia



Charmonia suppression in *pp* vs *p*+Pb

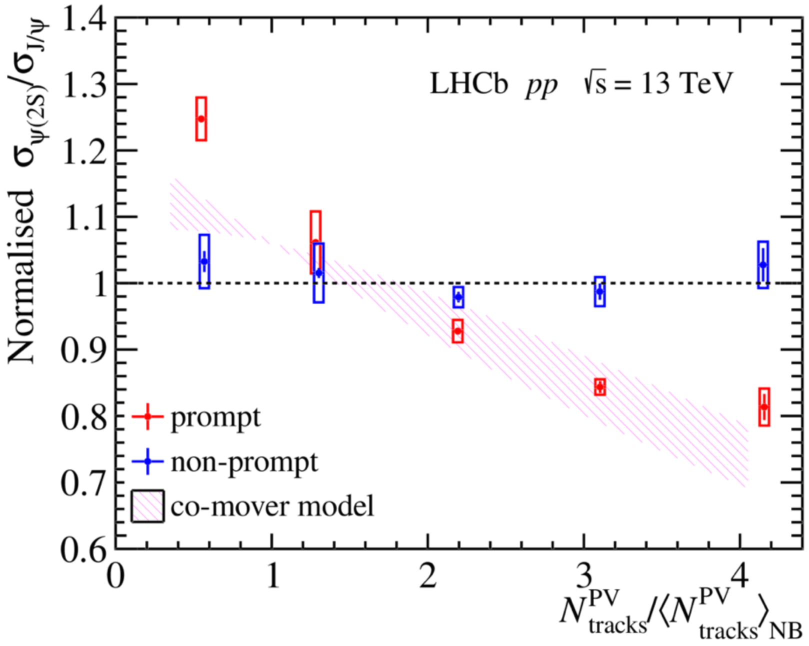
$\Upsilon(3S)$ relative suppression consistent with the dissociation of the feed-down source from $\chi_b(3P)$ decays.



Heavier → slower → dissociates stronger

PRL 132 (2024) 102302

JHEP 05 (2024) 243



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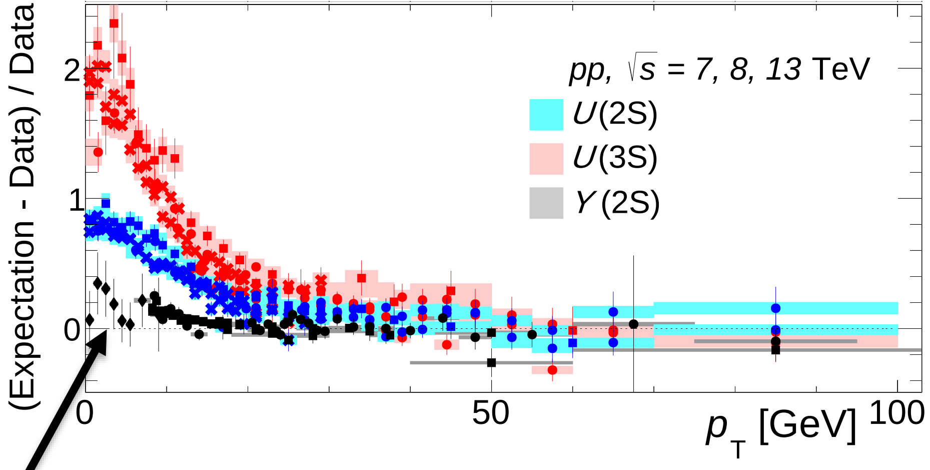
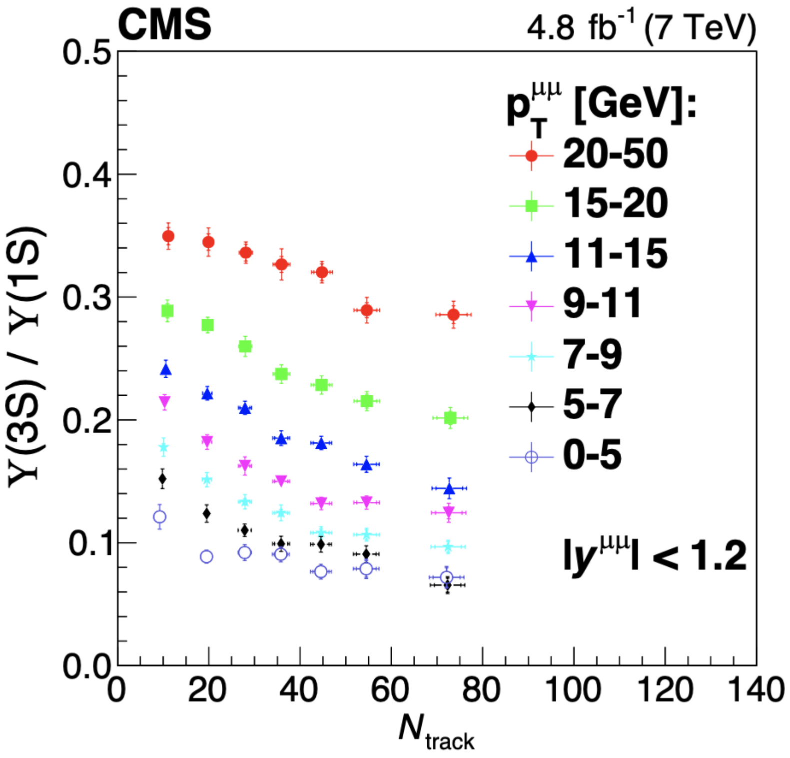
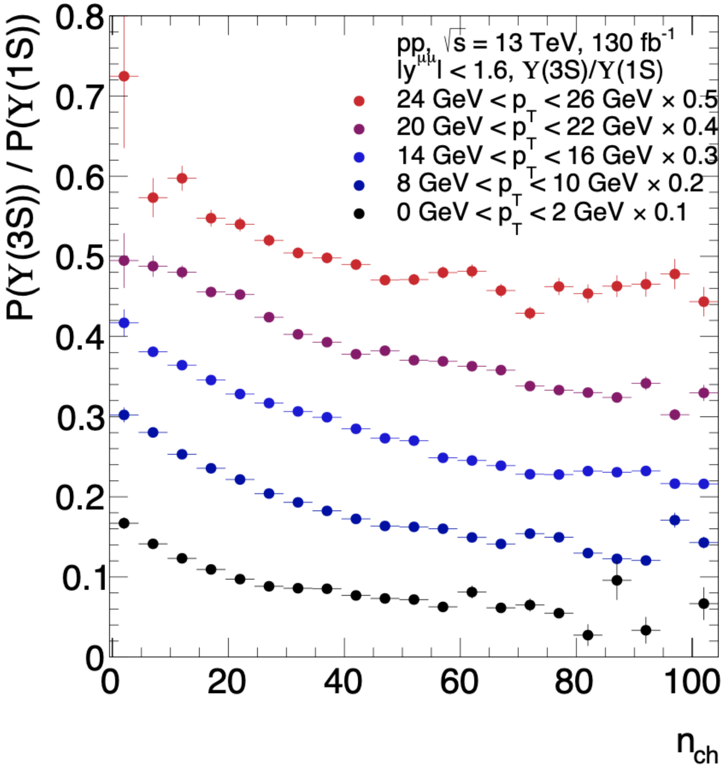
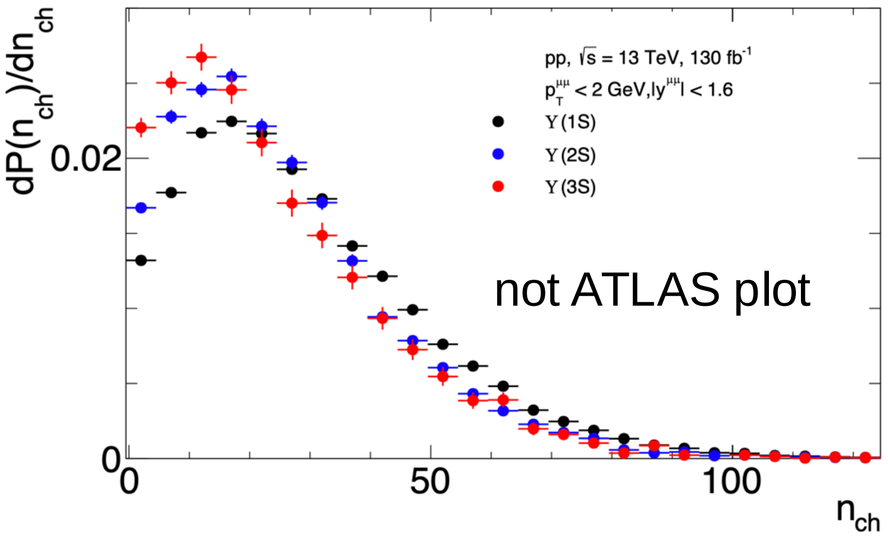


The right variable

$$\mathcal{R}^{\Upsilon(nS)}_{\Upsilon(1S)} = \mathcal{R}^{\Upsilon(nS)}_{\Upsilon(1S)}(\sigma) \times \mathcal{R}^{\Upsilon(nS)}_{\Upsilon(1S)}(\frac{dP(n_{ch})}{dn_{ch}})$$



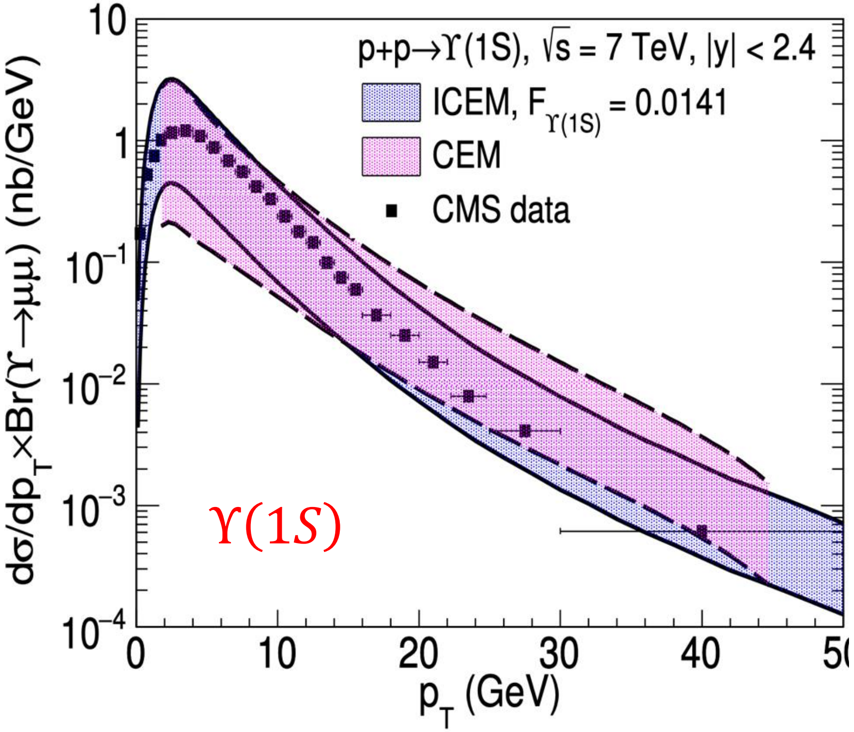


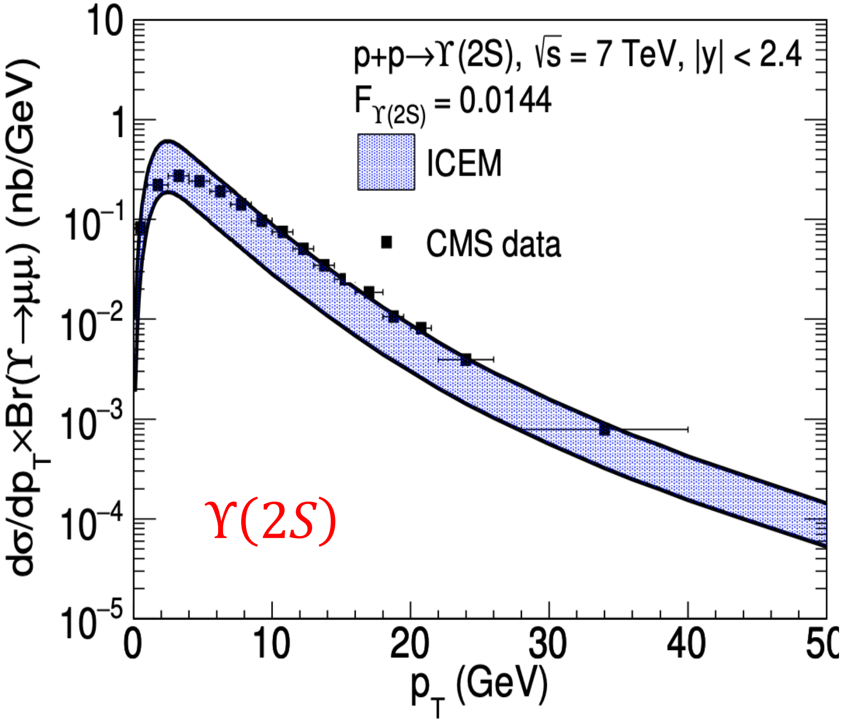


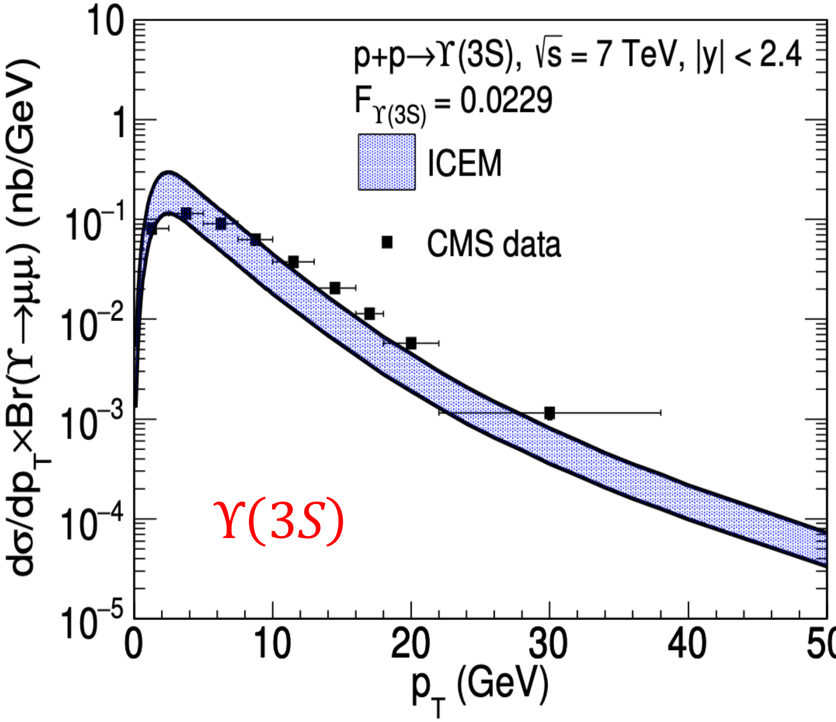
not ATLAS plot

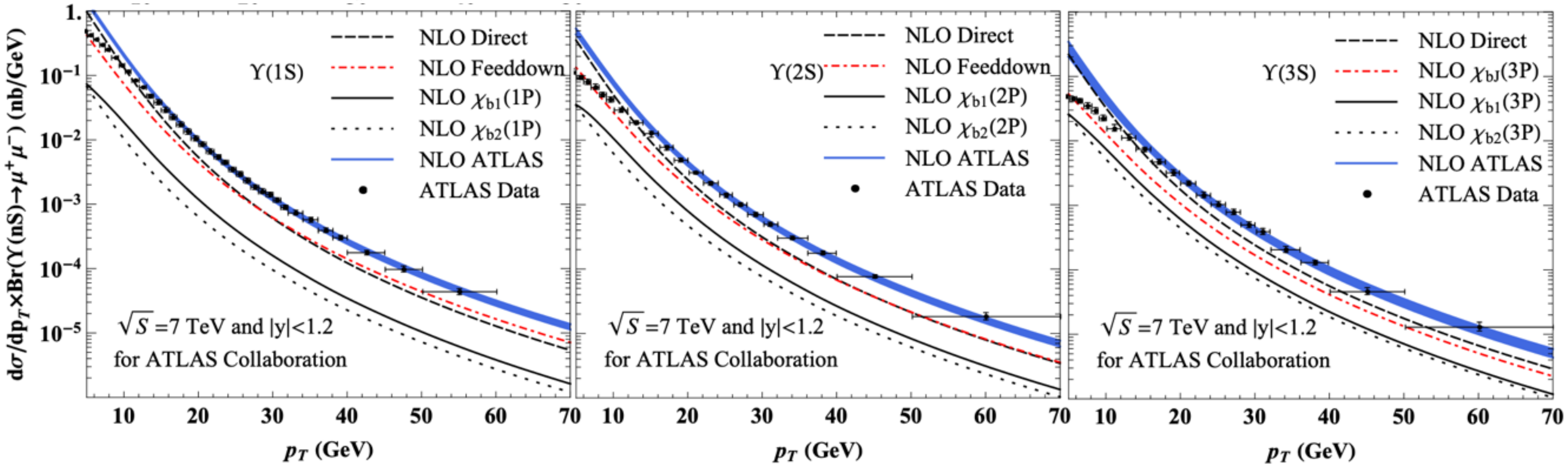
CERN-THESIS-2022-345

Cross-section calculations





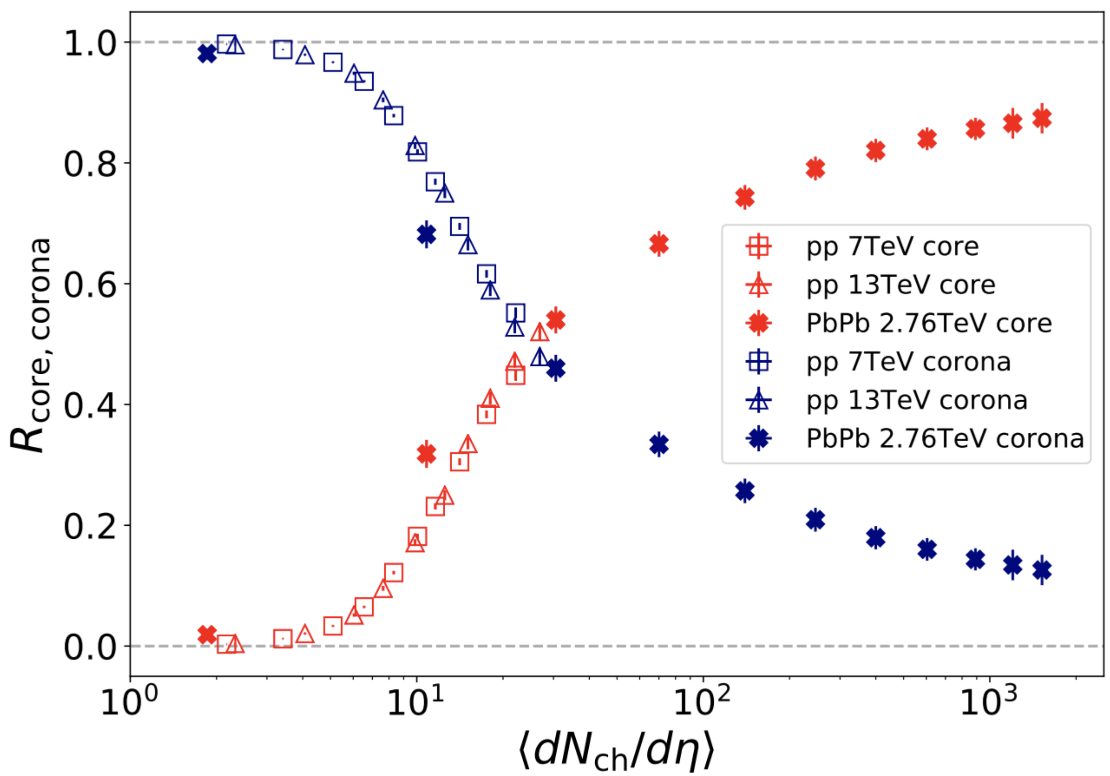




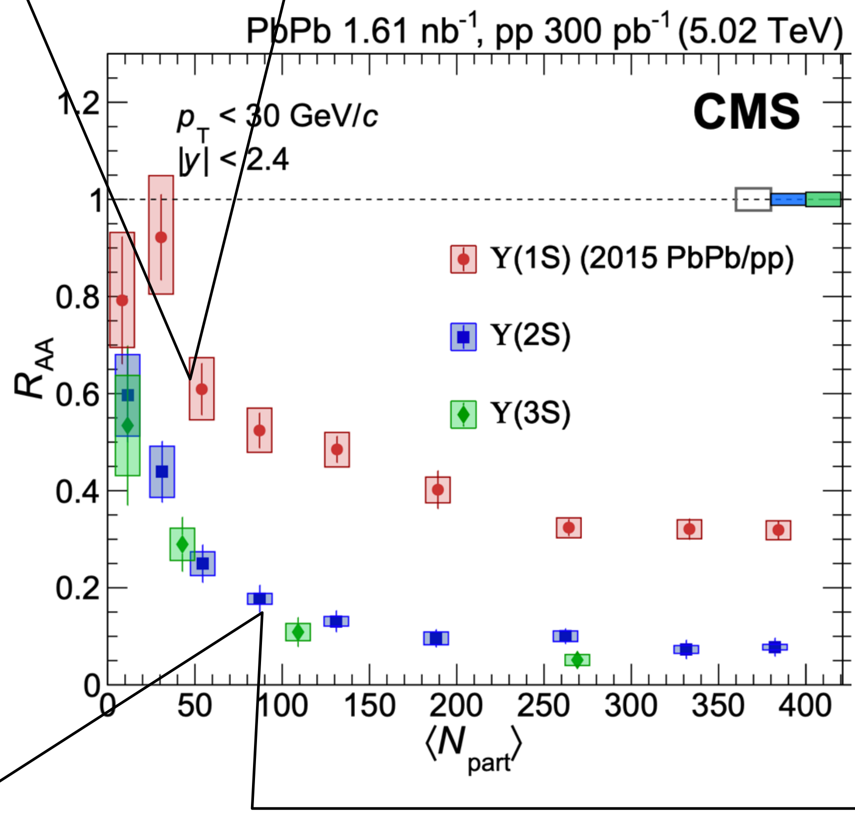
PRD94, 014028 (2016)
PPNP 131, (2023), 104044
arXiv:2305.13177

How it can look like in larger systems

EPJ Web Conf. 276 (2023) 01017

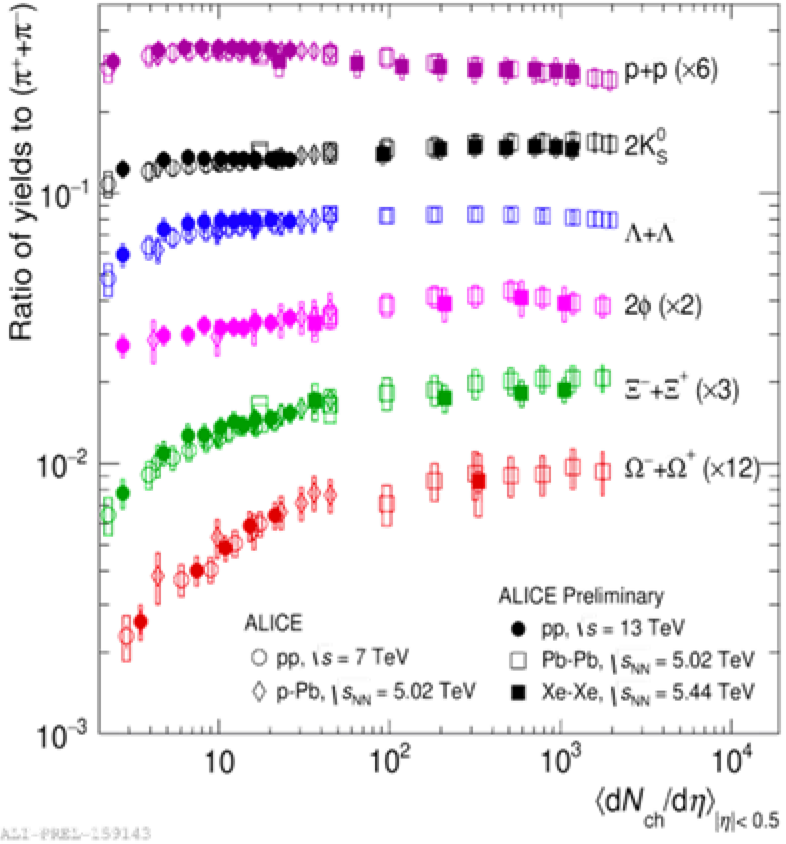


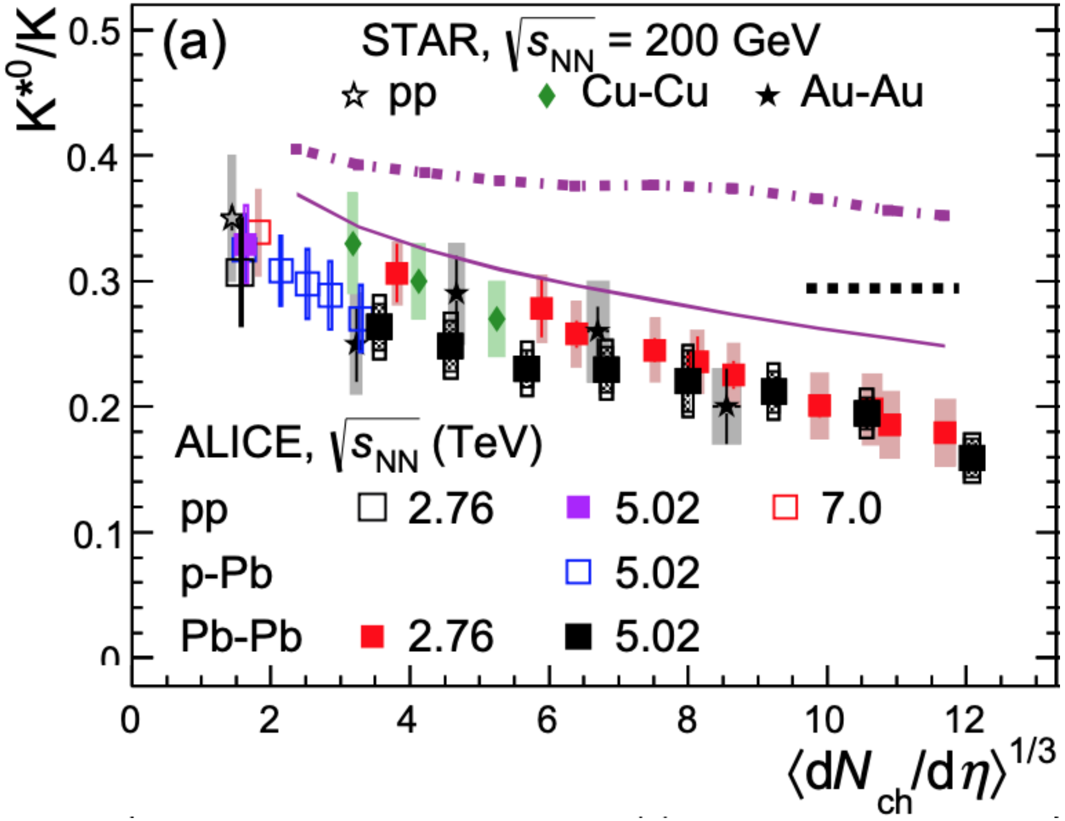
Core + corona: $\Upsilon(1S)$ resembles other particles, or we can't say better



Pure corona: medium is nearly opaque to $\Upsilon(2S)$ and $\Upsilon(3S)$) even in *pp*

QGP signatures in small systems





All strange-to-non-strange particle ratios go up

And K*/K ratio goes down…

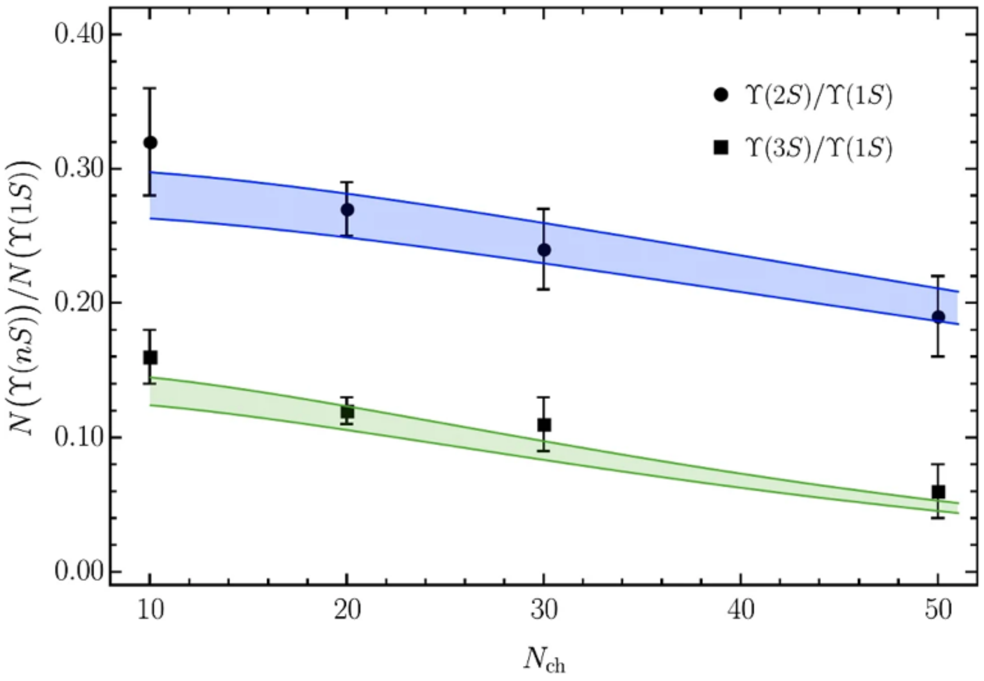
It might be that the effect is wider than just quarkonia

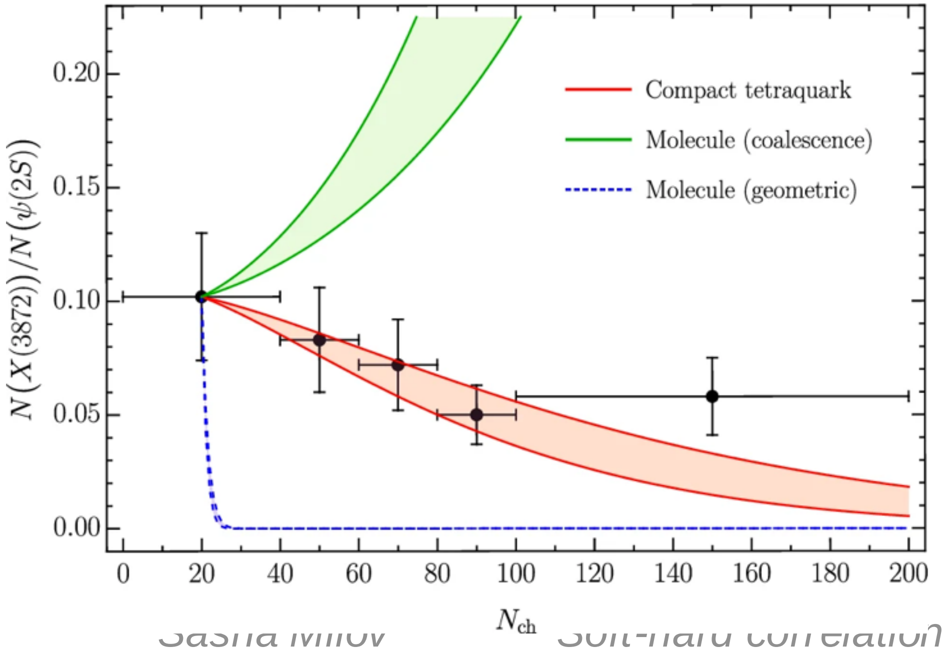
Comover interaction model

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.*





It looks like the effect isn't limited to only $\Upsilon(nS)$, at least χ_c can be affected as well, and possibly $\Psi(2S)$

Summary

Excited$(q\bar{q})^*$states are destroyed in *pp* collisions by interactions with the UE

Only ~60% of $\Upsilon(2S)$ and only ~40% of $\Upsilon(3S)$ emerge from the *pp* collisions at the LHC energies, based on what should be there from measured $\Upsilon(1S)$

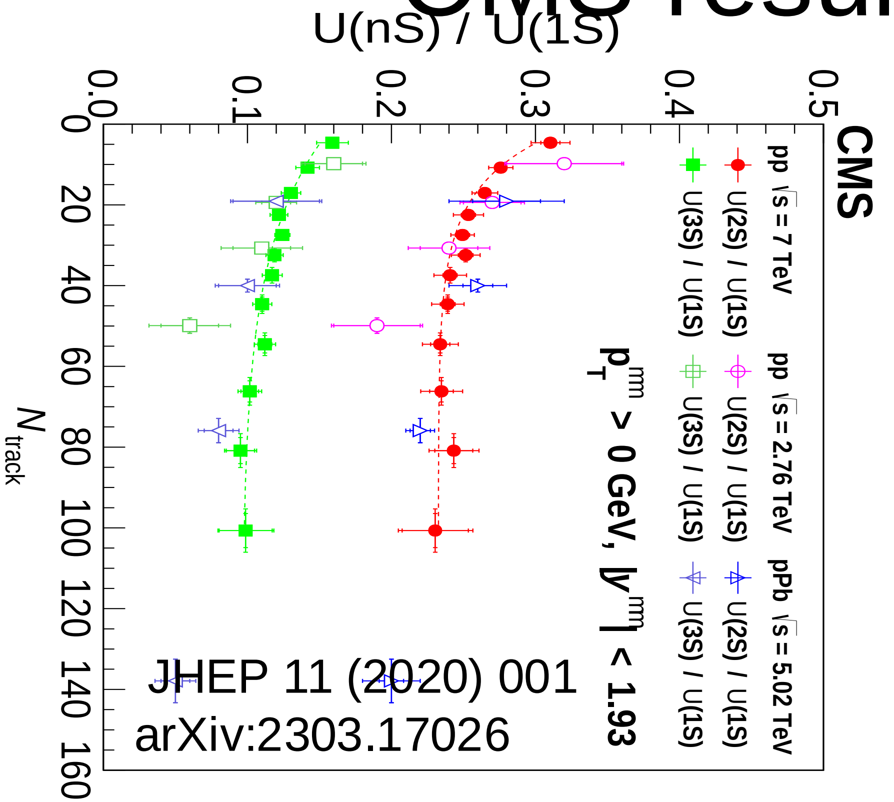
m_T scaling analysis hinted at suppression of $\Psi(2S)$, recently observed by LHCb. Other particles can be affected as well, ground states, or even even K*

At the moment we do not know much about the observed phenomenon, but many signatures can be measured and not only at the LHC

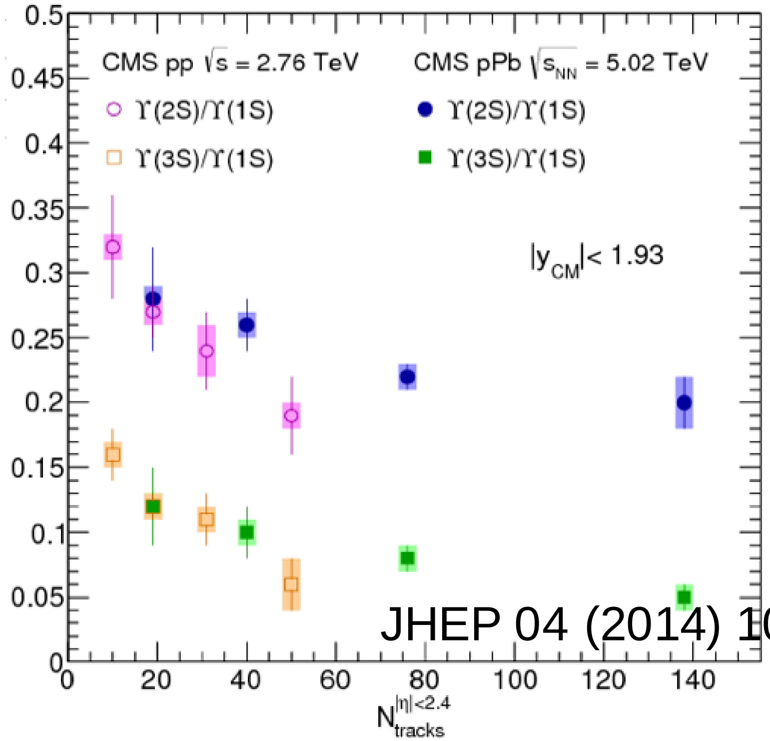
Comover model explains it, but to validate its correctness one needs to (at least) measure 2PC. More theoretical guidance is badly needed

backups

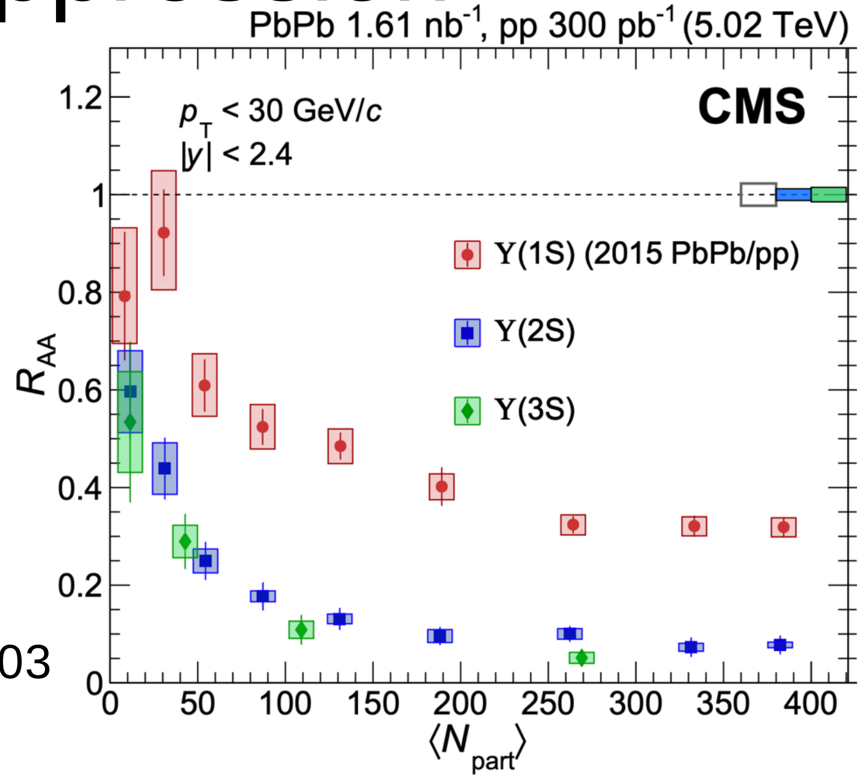
CMS results with $\Upsilon(nS)$ suppression



JHEP 11 (2020) 001
arXiv:2303.17026

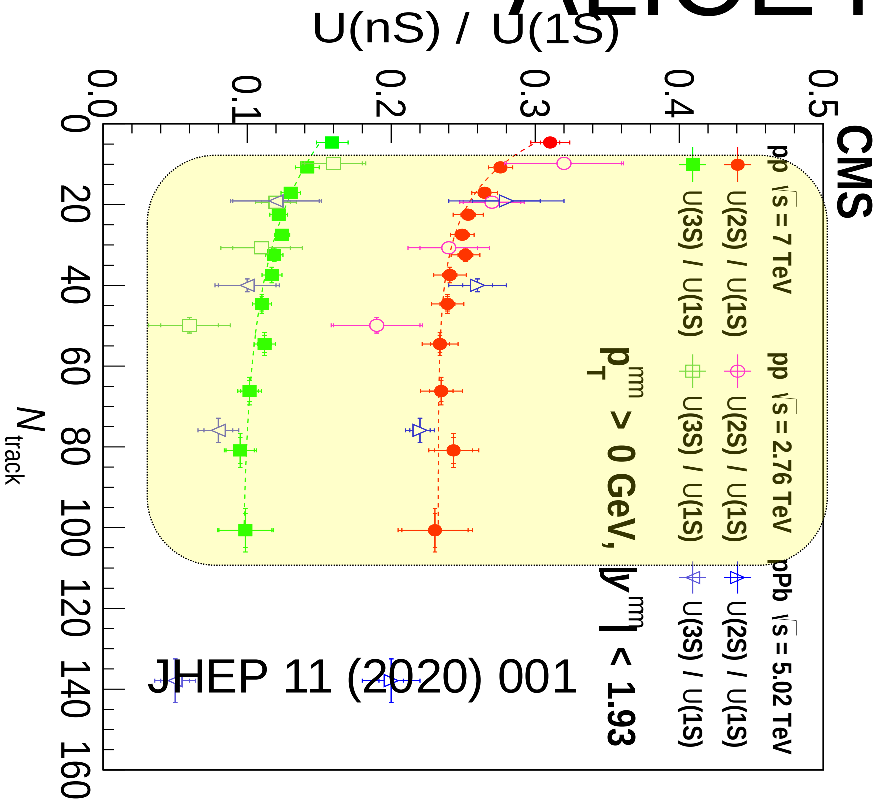


JHEP 04 (2014) 103

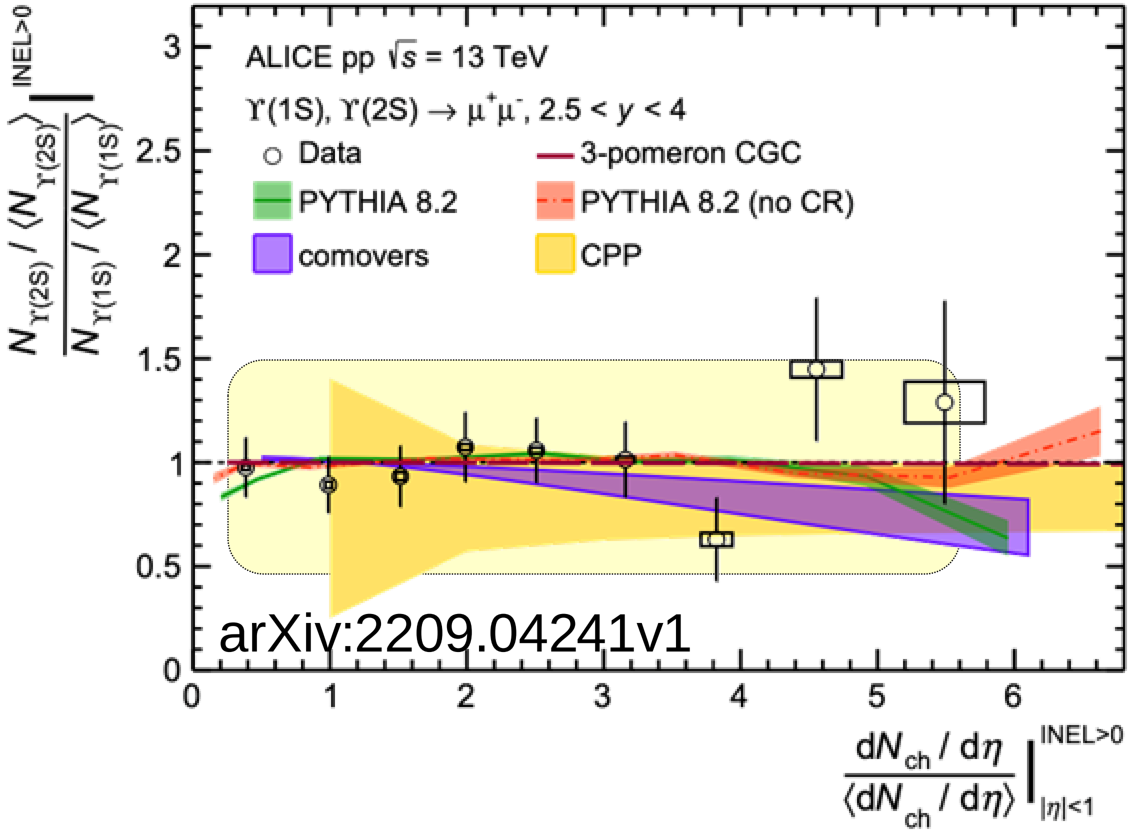


CMS: "It was concluded that the feed-down contributions cannot solely account for this feature. This is also seen in the present analysis, where the $\Upsilon(1S)$ meson is accompanied by about one more track on average ($\langle N_{\rm track}\rangle = 33.9 \pm 0.1$) than the $\Upsilon(2S)$ ($\langle N_{\rm track}\rangle = 33.0 \pm 0.1$), and about two more than the $\Upsilon(3S)$ ($\langle N_{\rm track}\rangle = 32.0 \pm 0.1$). […] 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)."

ALICE result with a rapidity gap



JHEP 11 (2020) 001



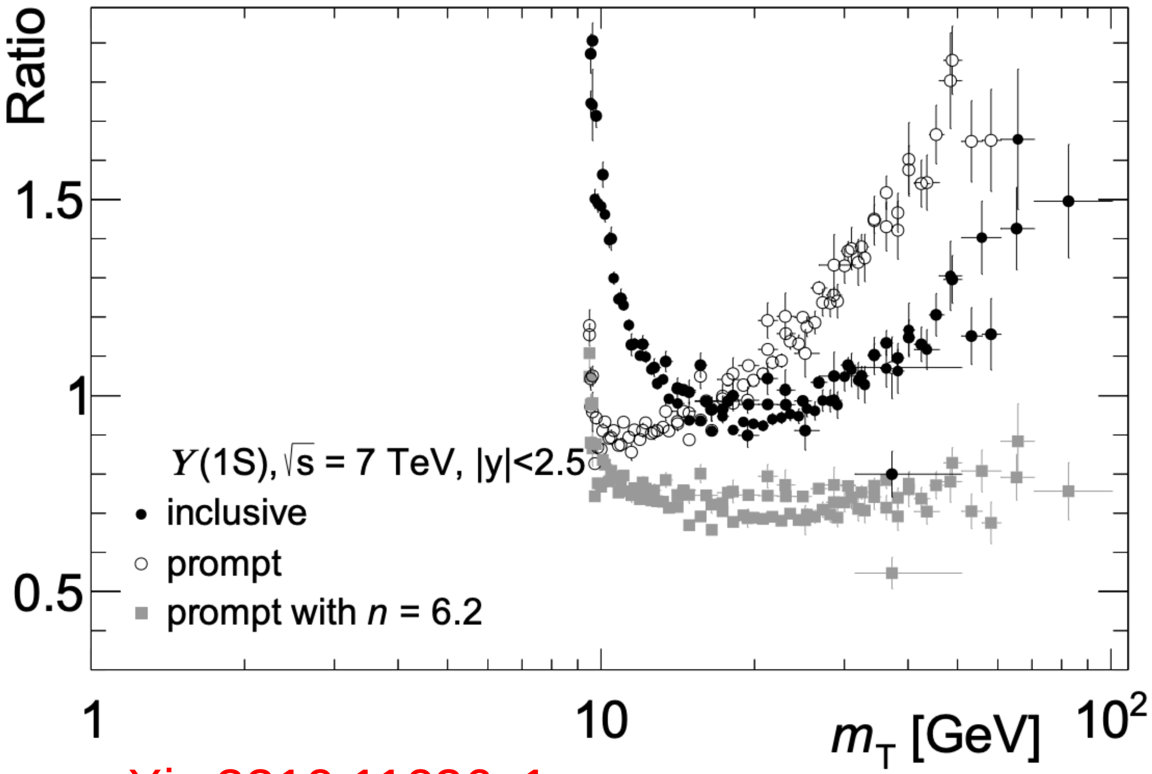
arXiv:2209.04241v1

ALICE result on forward $\Upsilon(2S)/\Upsilon(1S)$ vs. tracks at midrapidity shows rather different behavior when quarkonia and multiplicity measured at different rapidities

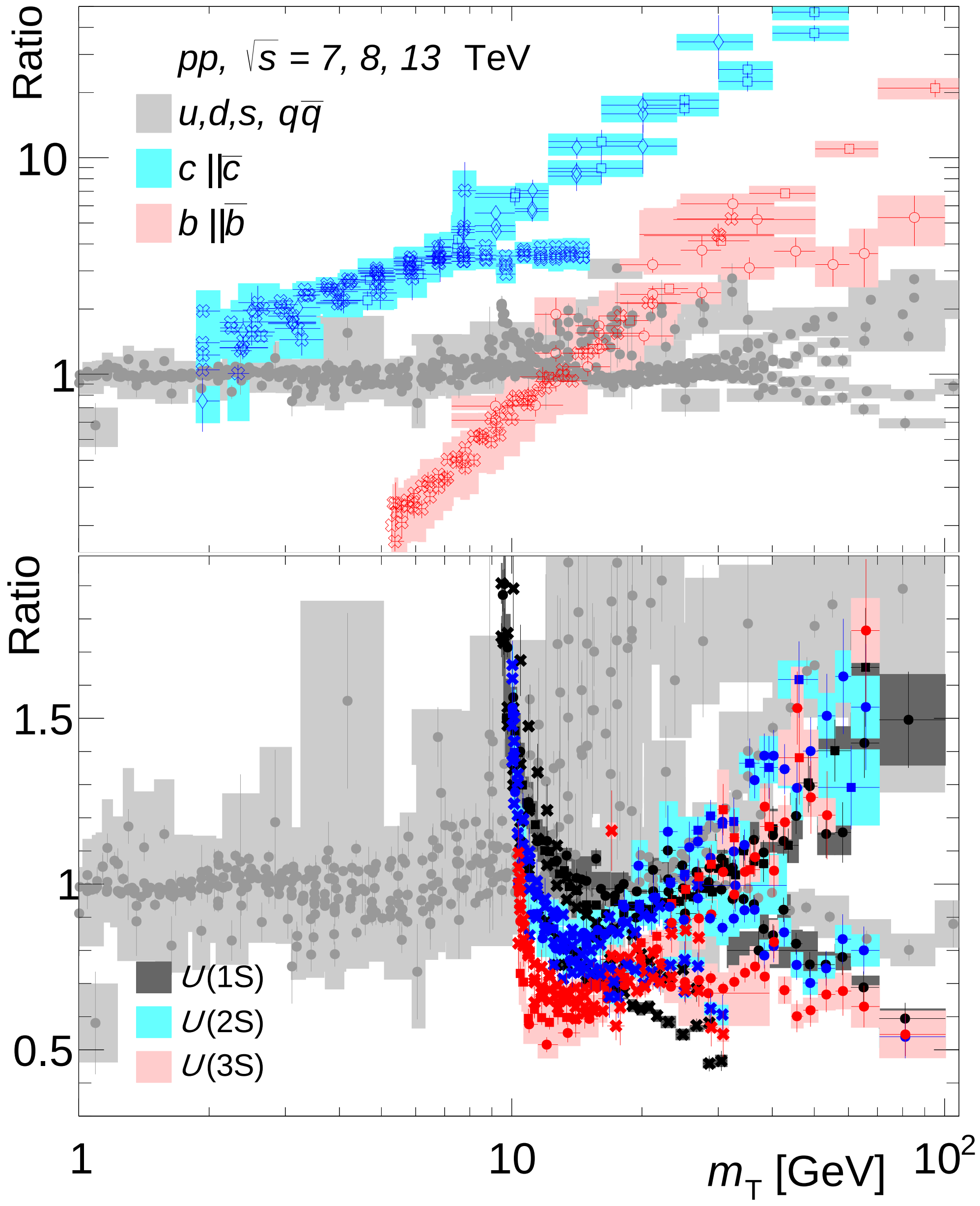
Statistics is too low to warrant any gap dependence

Common fit

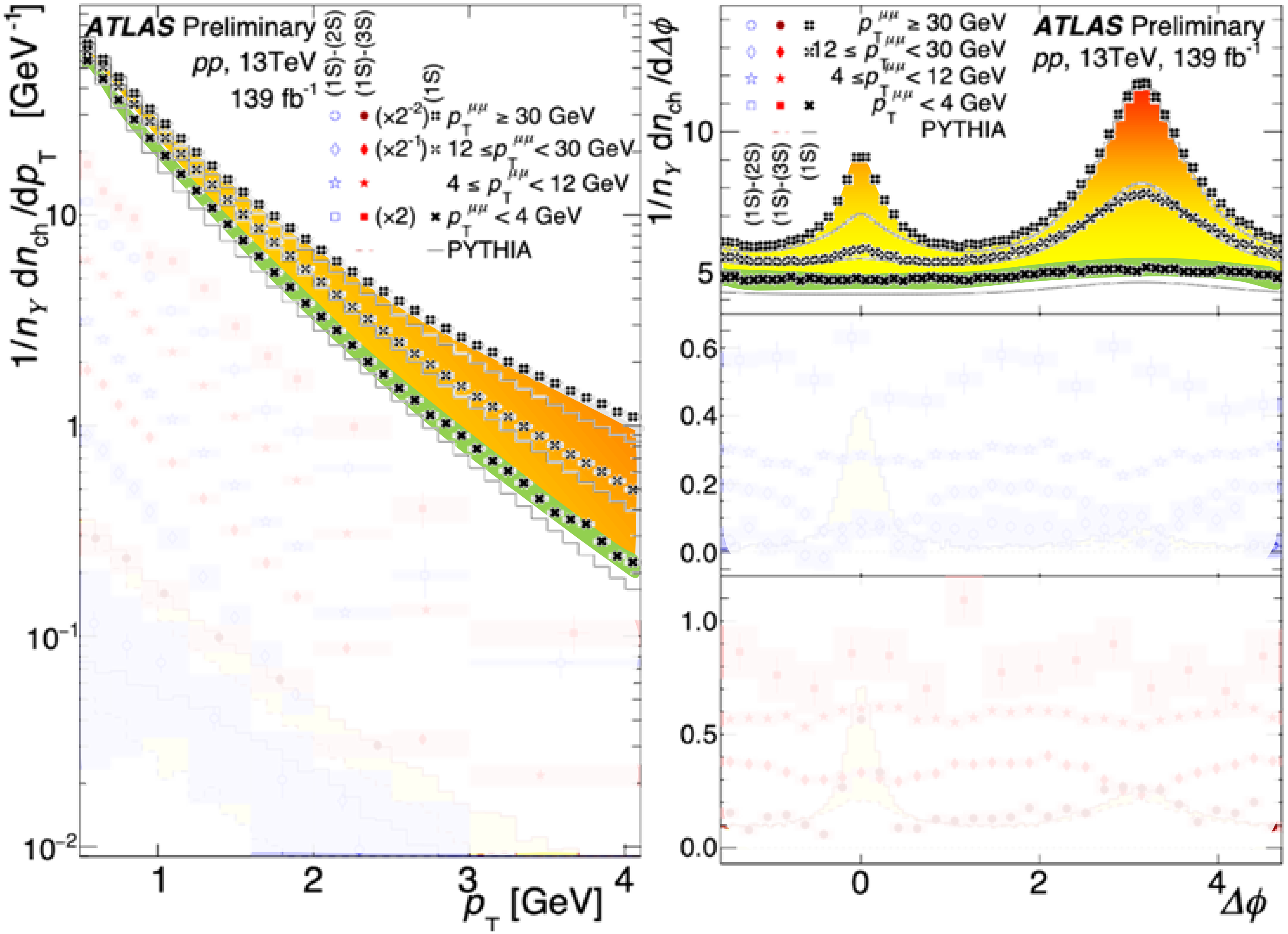
$$\lim_{\Delta m, p_T \ll m_{q\bar{q}}} \left[\frac{nT + \sqrt{p_{\mathrm{T}}^2 + \left(m_{q\bar{q}} + \Delta m\right)^2}}{nT + \sqrt{p_{\mathrm{T}}^2 + m_{q\bar{q}}^2}}\right]^{-n} = 1 - \frac{n\Delta m}{nT + m_{q\bar{q}}}$$



arXiv:2210.11026v1



Kinematic distributions



- Distributions for $\Upsilon(1S)$
- Pythia does not describe well
- One cannot measure the UE, but $p_T < 4$ GeV is the closest to it, jet part that is correlated to $\Upsilon(nS)$

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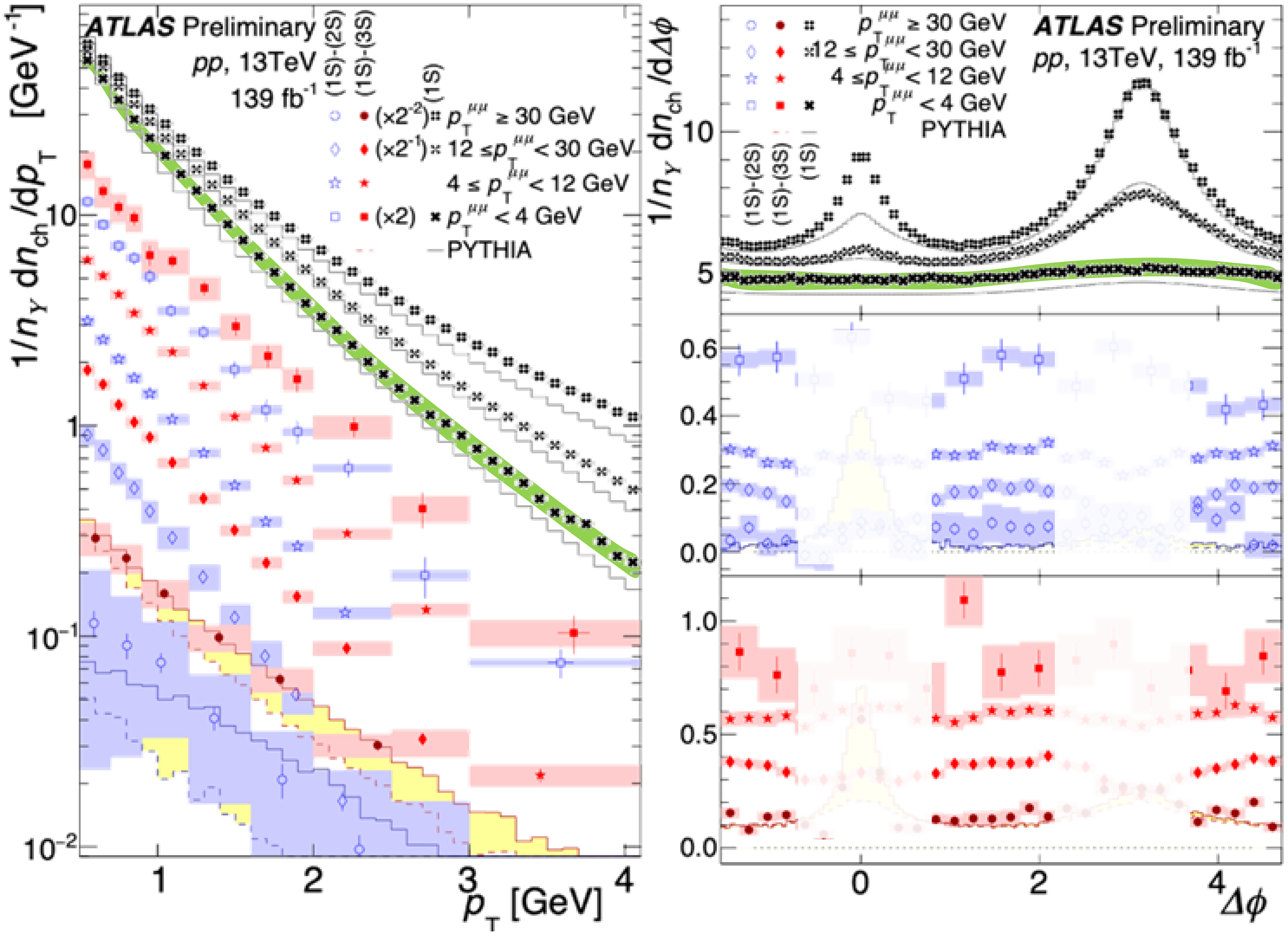


- Distributions for $\Upsilon(1S)$
- Pythia does not describe well
- One cannot measure the UE, but $p_T < 4$ GeV is the closest to it, jet part that is correlated to $\Upsilon(nS)$
- Subtracted distributions look like UE at rather high $\Upsilon(nS)$ p_T. At the highest p_T there are feed-downs
- Away from jets there are regions with charged particles

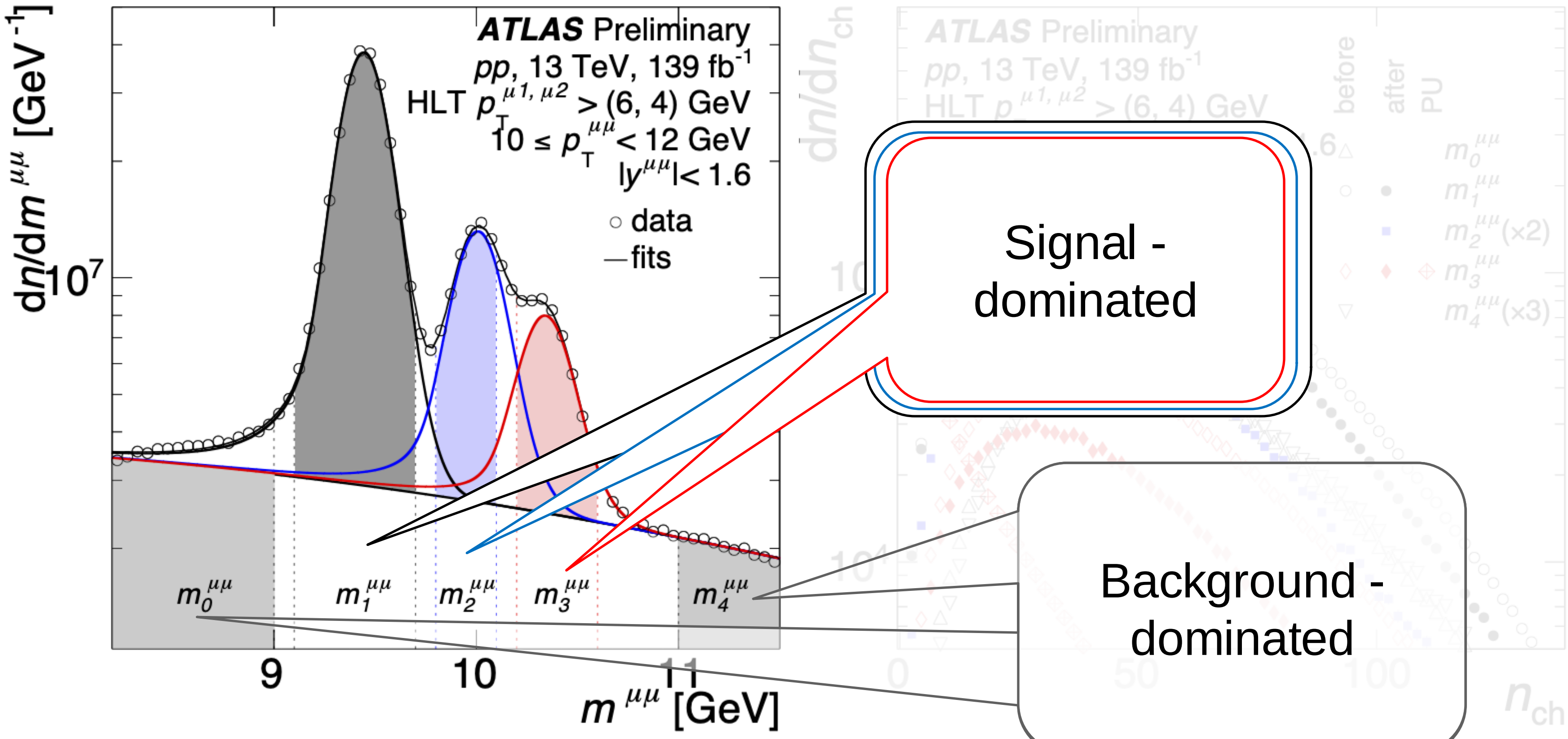
Signal extraction

$$\mathrm{fit}\,(m) = \sum_{n\mathrm{S}} N_{\Upsilon(n\mathrm{S})} F_n(m) + N_{\mathrm{bkg}} F_{\mathrm{bkg}}(m)$$

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

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

- Define 3+2 regions



Signal - dominated

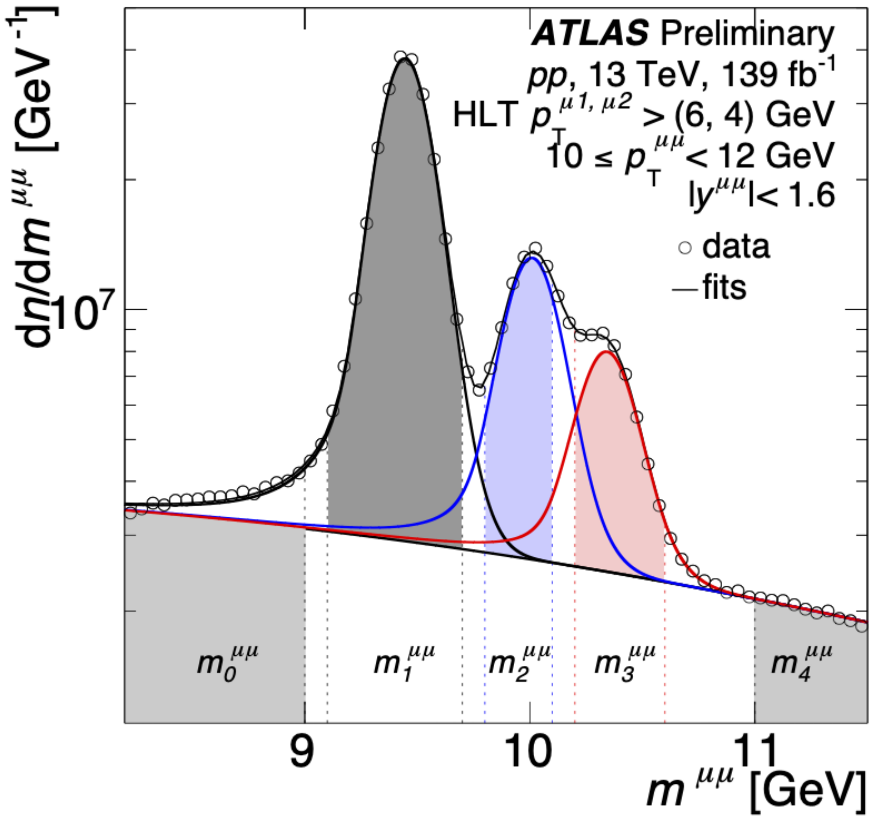
Background - dominated

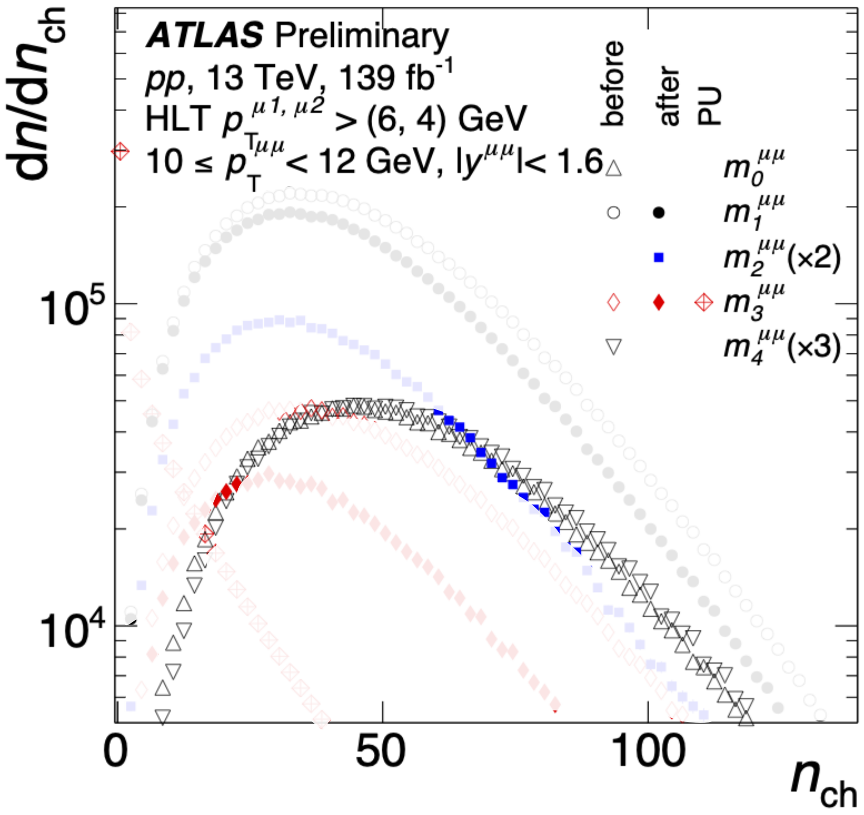
Signal extraction

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

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

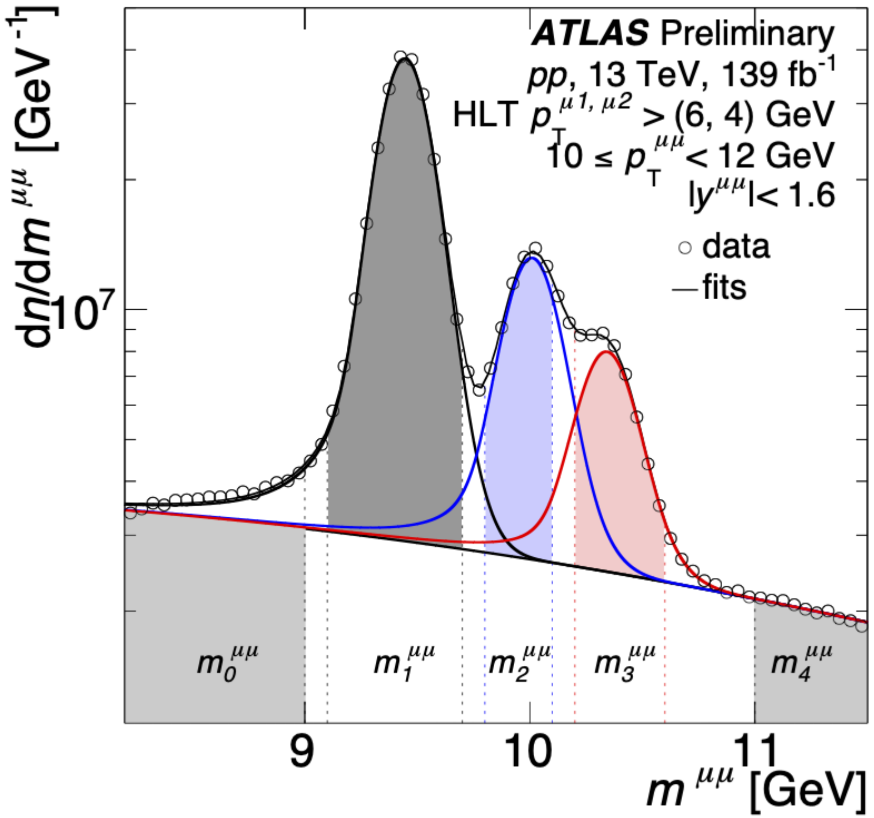
- Define 3+2 regions
- Bkg shapes are similar – interpolate

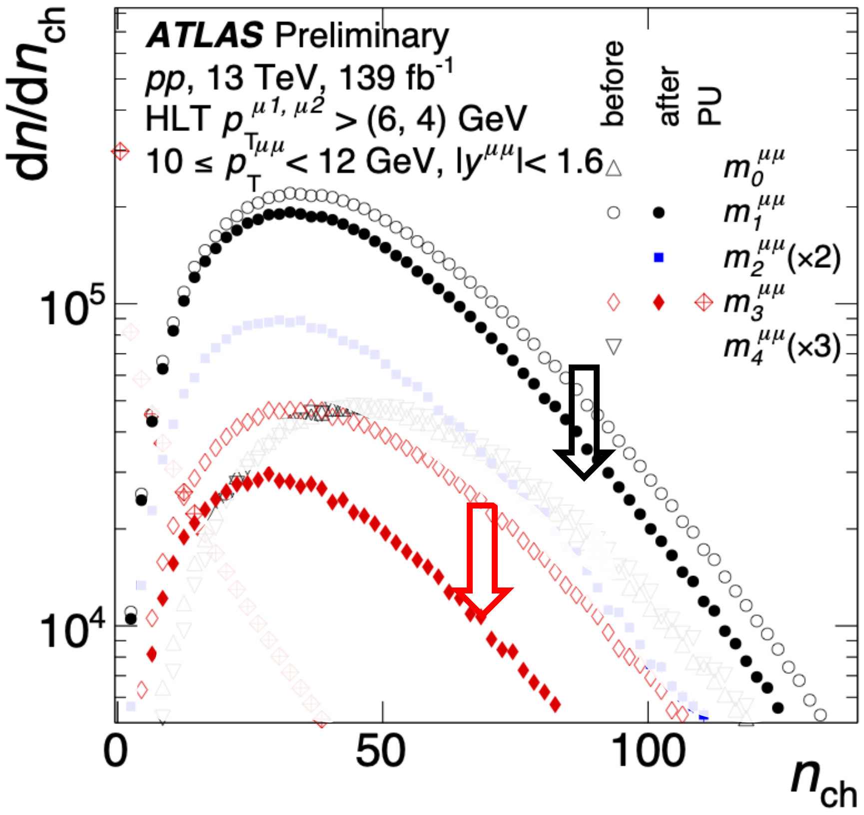




Signal extraction

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

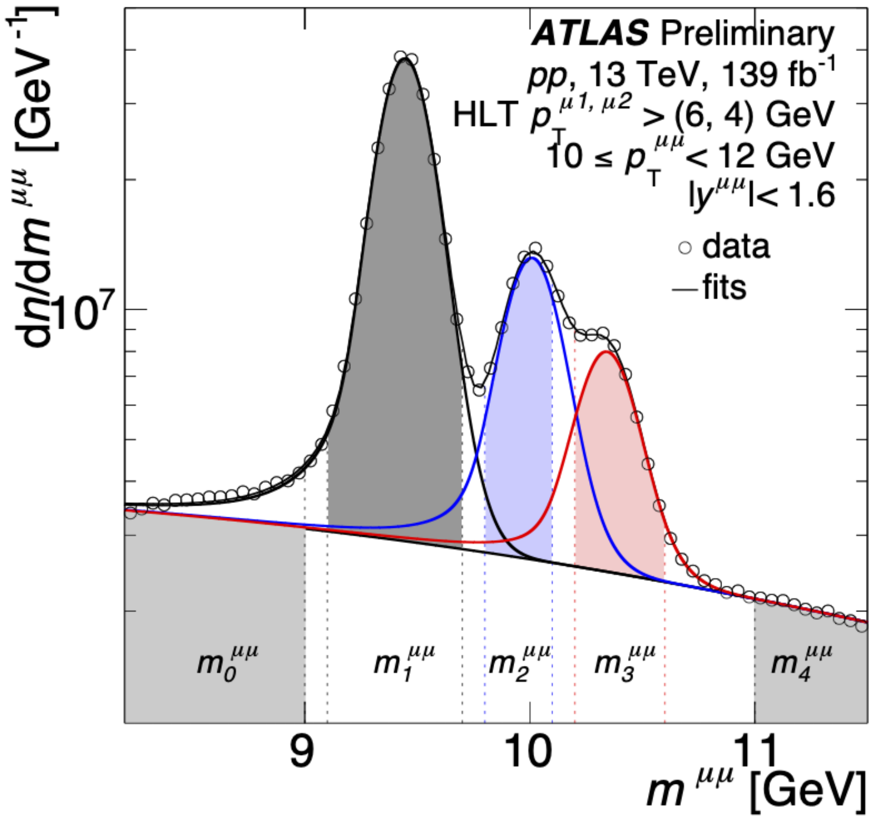


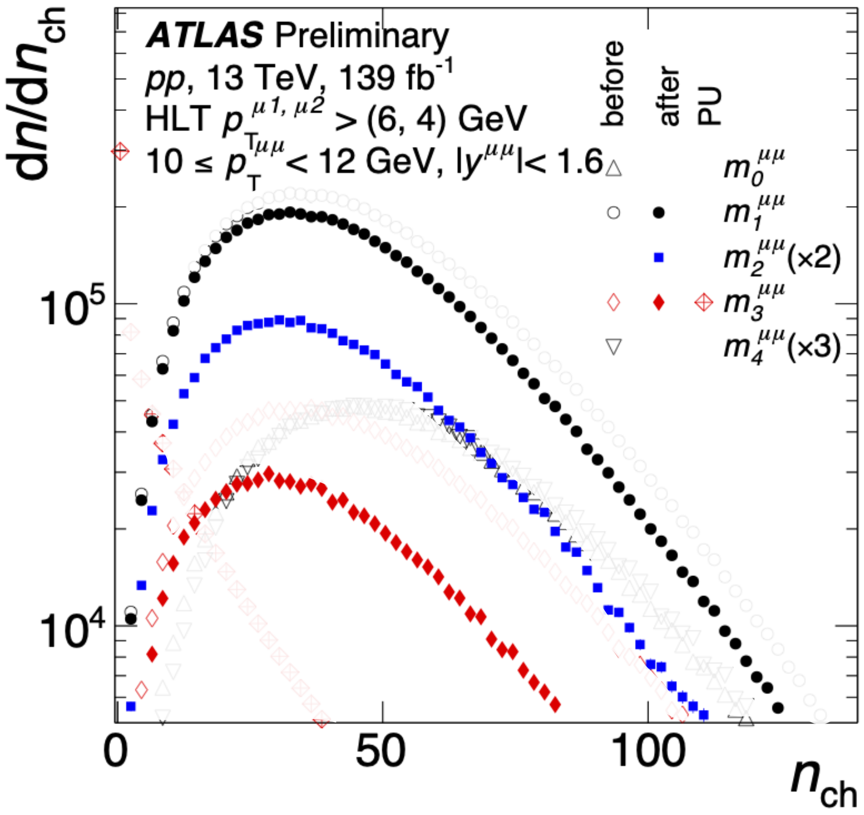


- Define 3+2 regions
- Bkg shapes are similar – interpolate
- Bkg subtraction for $\Upsilon(1S)$ and $\Upsilon(3S)$

Signal extraction

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

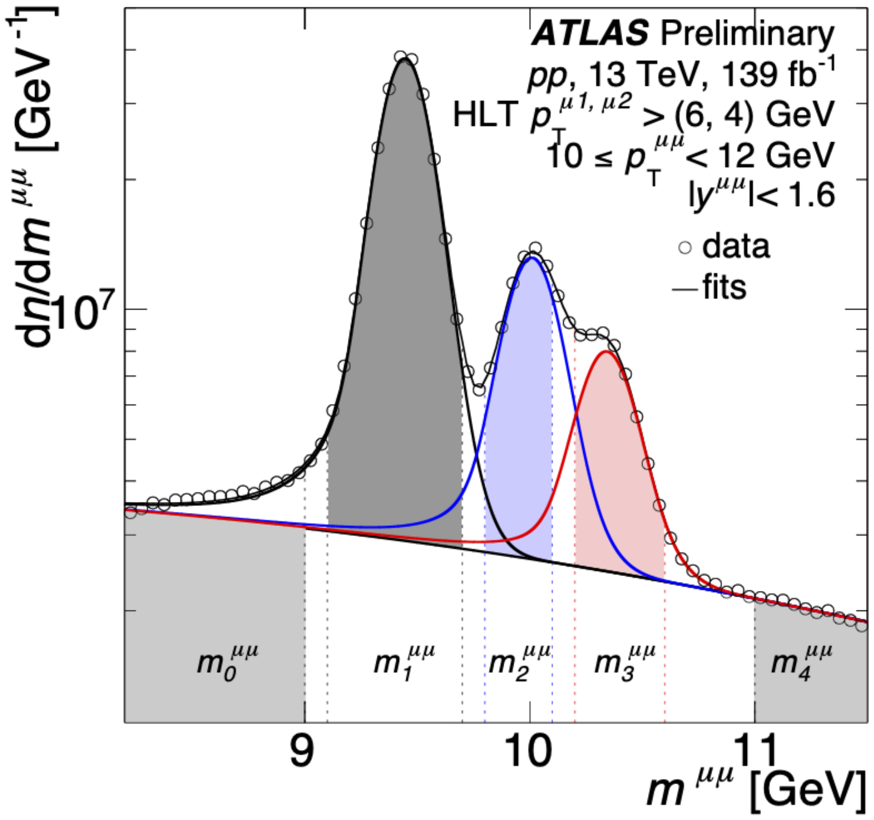


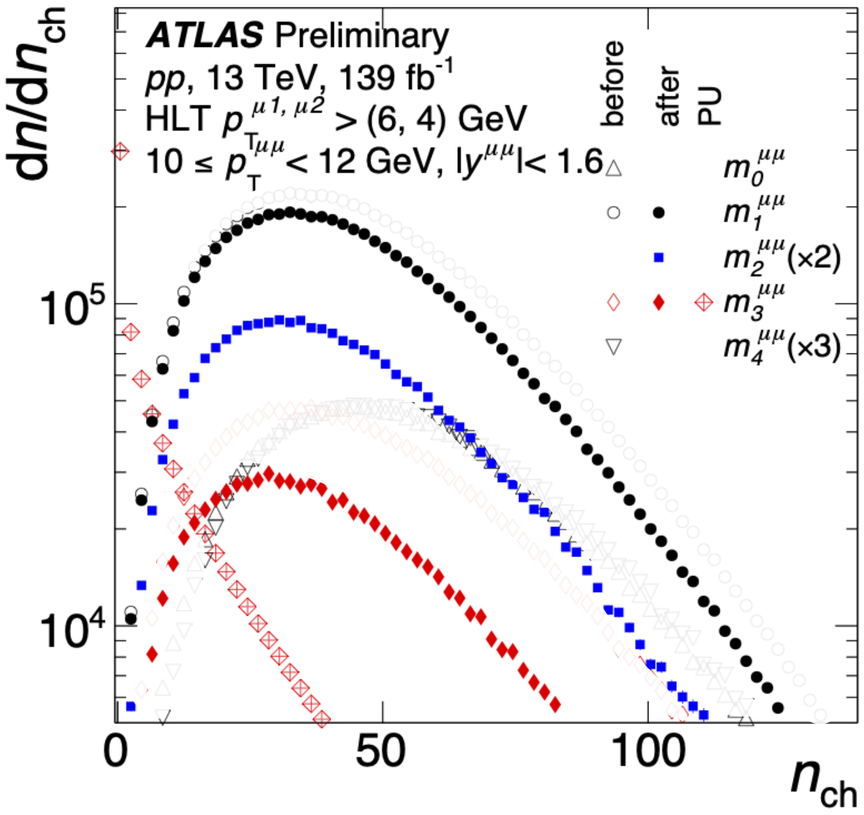


- Define 3+2 regions
- Bkg shapes are similar – interpolate
- Bkg subtraction for $\Upsilon(1S)$ and $\Upsilon(3S)$
- After subtraction n_{ch} look different

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





- Define 3+2 regions
- Bkg shapes are similar – interpolate
- Bkg subtraction for $\Upsilon(1S)$ and $\Upsilon(3S)$
- After subtraction n_{ch} look different
- Remove pileup, same shape for all $\Upsilon(nS)$

The pileup story

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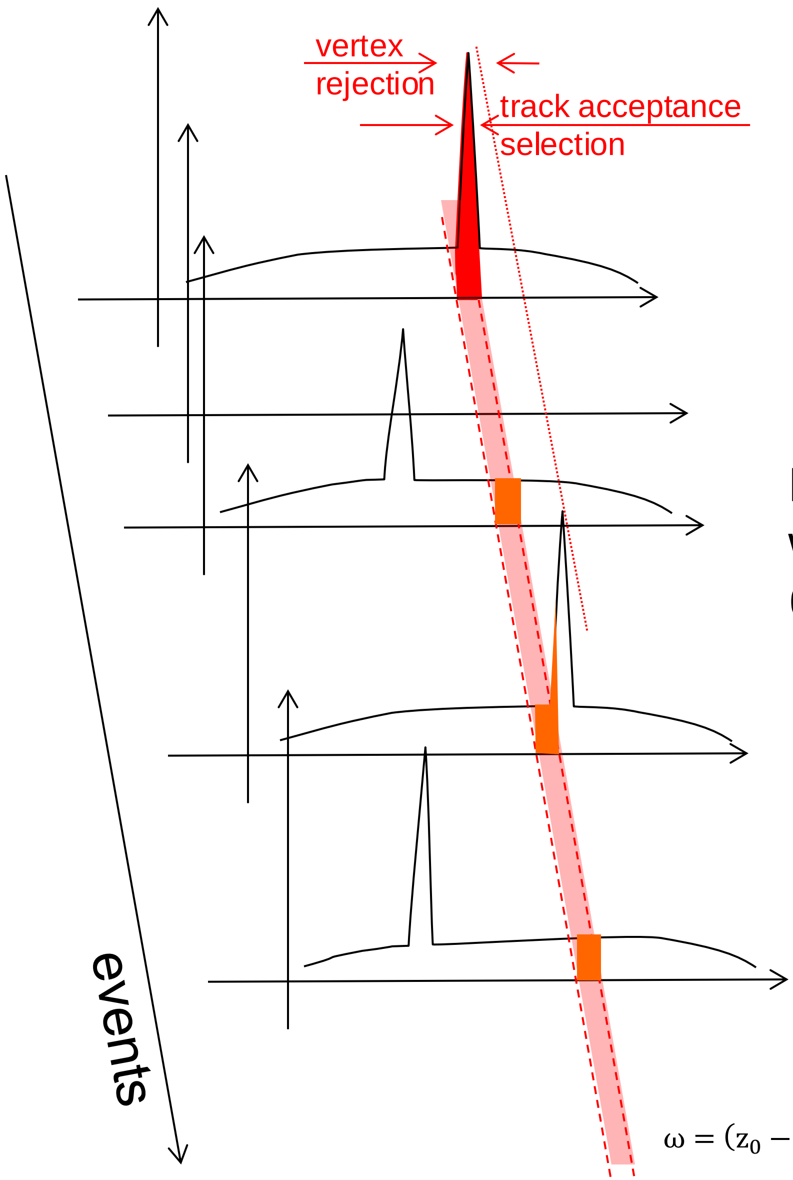


$\omega = (z_0 - z_{vtx}) \sin\theta$

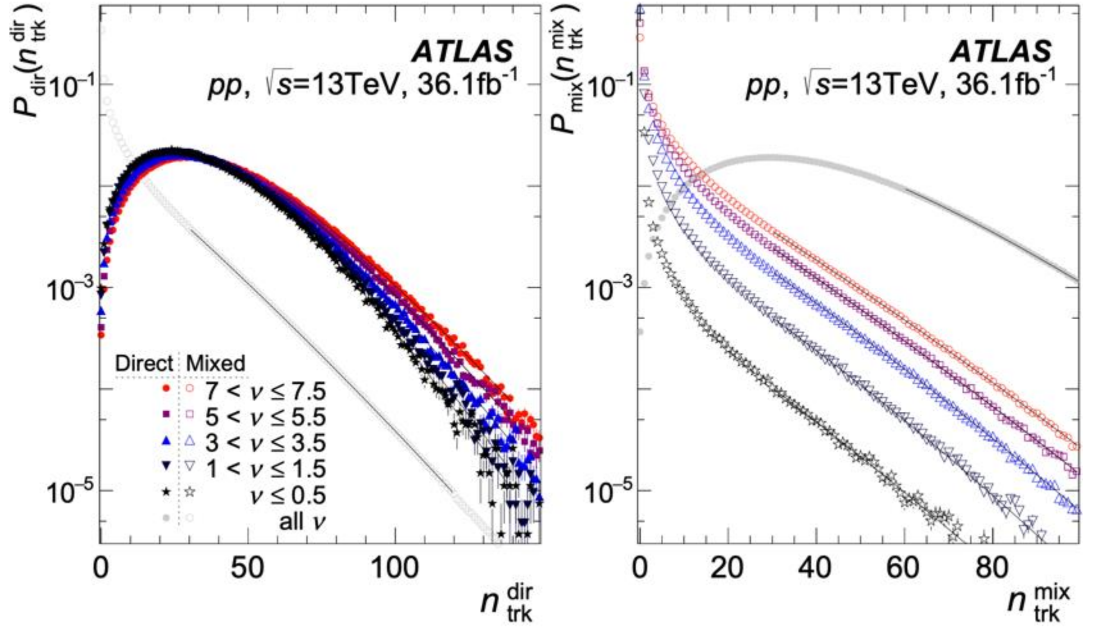
Start with the triggered event, called Direct

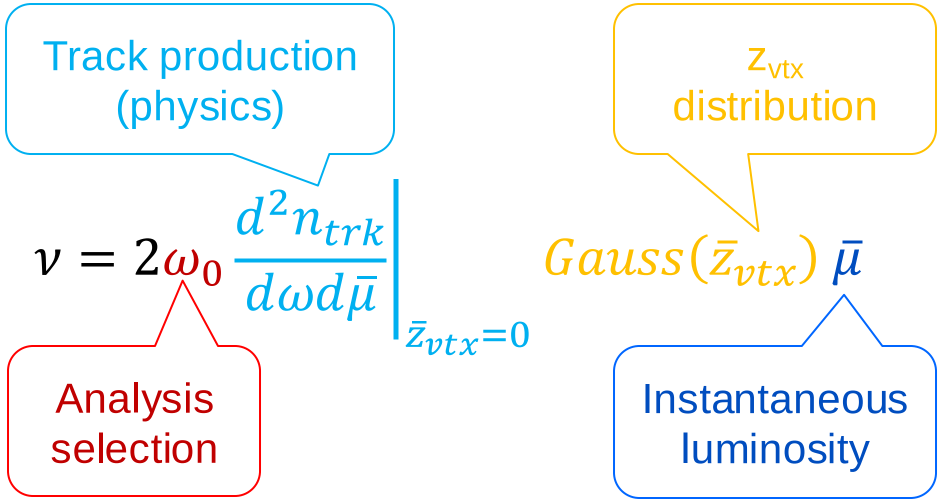
In the same run search for events with at the same μ

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





Track production (physics)

z_{vtx} distribution

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

Analysis selection

Instantaneous luminosity

Analysis in brief

Entire ATLAS Run-2 data: 2015 – 2018, √s = 13 TeV, 139 fb^{-1}

Full luminosity data constrained at $\mu < 50$ (fake production) and then at $\nu < 20$ in 40 intervals

$\Upsilon(nS)$ are reconstructed as di-muons

6 different di-muon triggers with muon p_T from 4 to 11 GeV

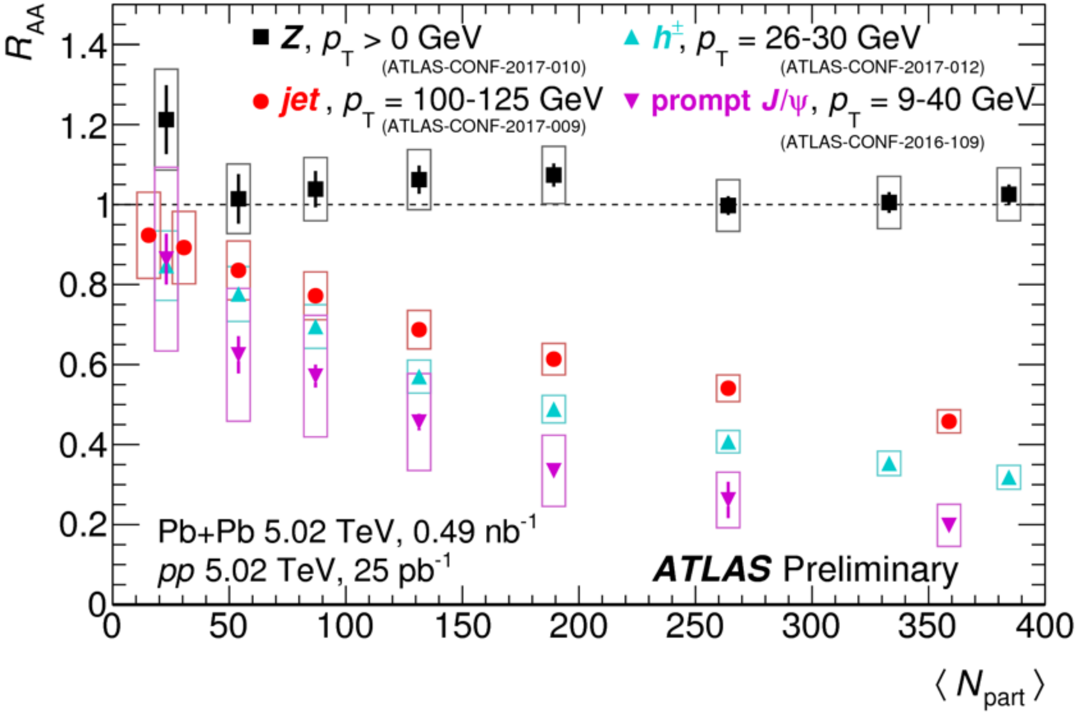
$\Upsilon(nS)$ kinematics $|y| < 1.6$, $0 < p_T < 70$ GeV where we ran out of statistics

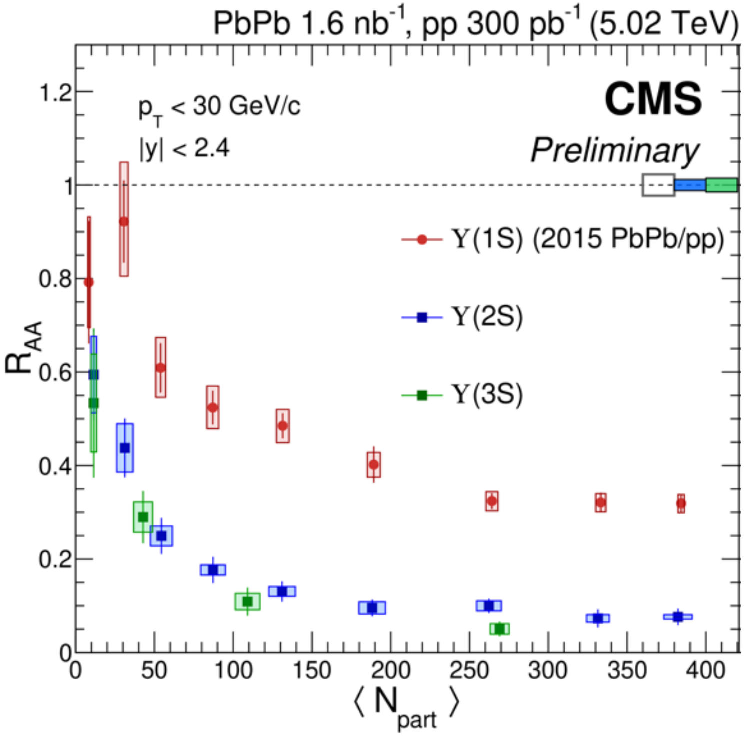
All together after cuts: $\sim 5 \times 10^7 \Upsilon(1S)$, $\sim 10^7 \Upsilon(2S)$, $\sim 7 \times 10^6 \Upsilon(3S)$

Charged hadrons kinematics $|\eta| < 2.5$, $0.5 < p_T < 10$ GeV, fully corrected

Dimuon invariant mass distributions are fitted to functions with 24 parameters

Back to heavy ions



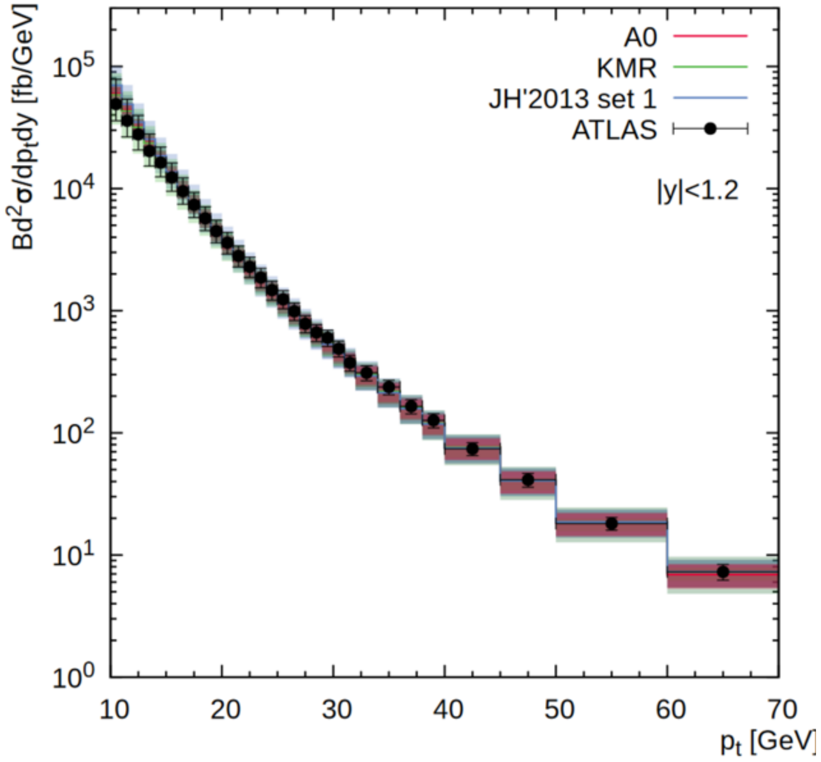


Similarity in the suppression of $\Upsilon(1S)$ and other species and the difference to higher $\Upsilon(nS)$ can be an indication of the regime change

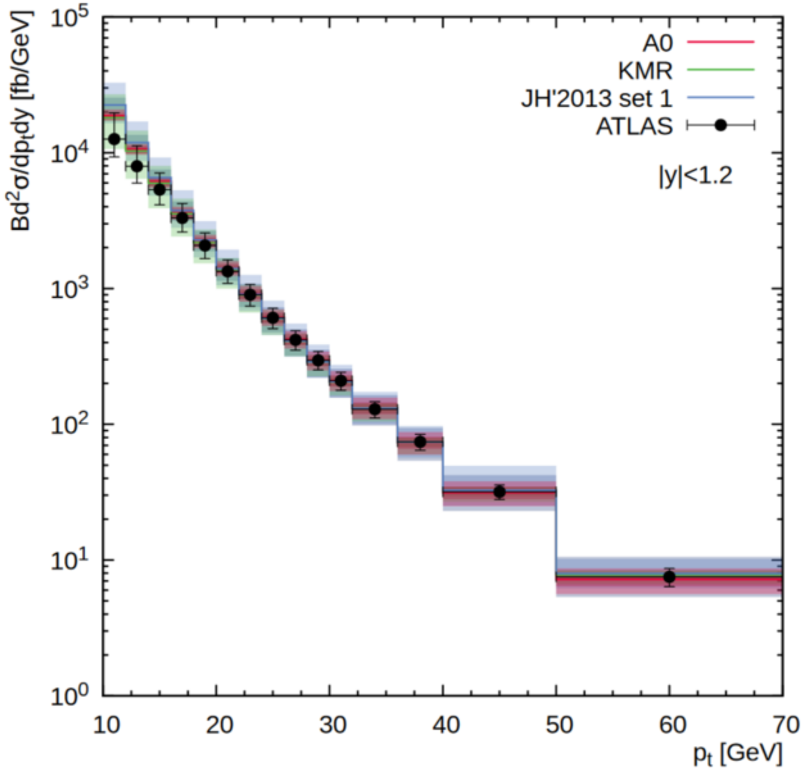
Most particles, including $\Upsilon(1S)$	$L \geq \sqrt[3]{N_{\text{part}}} \times r_p$	volume emission
$\Upsilon(2S)$, $\Upsilon(3S)$	$L \ll \sqrt[3]{N_{\text{part}}} \times r_p$	surface emission

Theory calculation

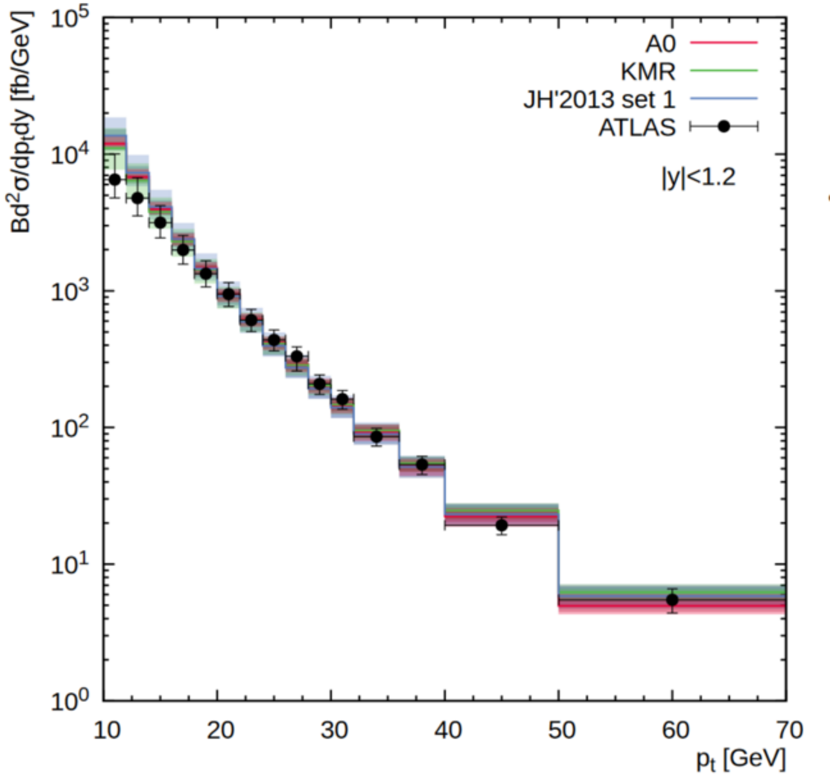
$\Upsilon(1S)$



$\Upsilon(2S)$



$\Upsilon(3S)$



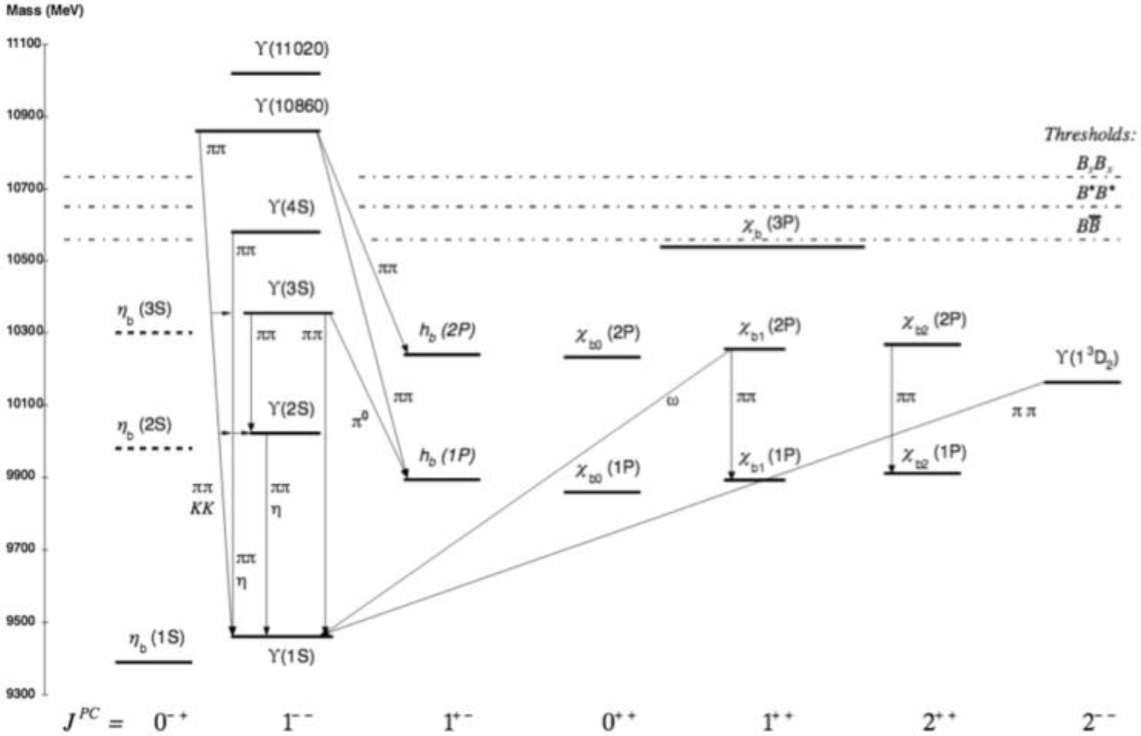
[61] N. A. Abdulov and A. V. Lipatov, Bottomonium production and polarization in the NRQCD with kT - factorization. III: Υ(1S) and χb(1P) mesons, Eur. Phys. J. C 81, 1085 (2021), arXiv:2011.13401.
[62] N. A. Abdulov and A. V. Lipatov, Bottomonia production and polarization in the NRQCD with kT - factorization.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

Global analysis

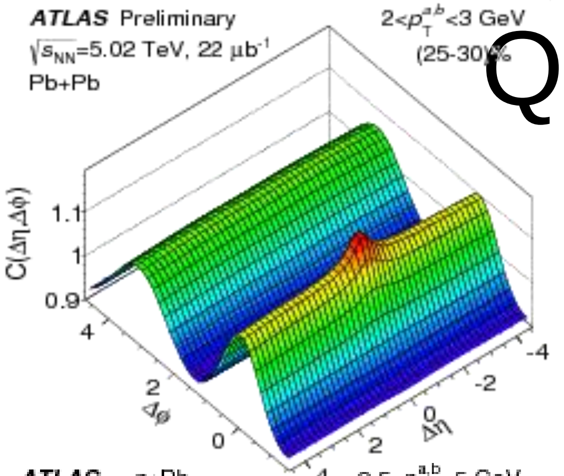
Basic principle:

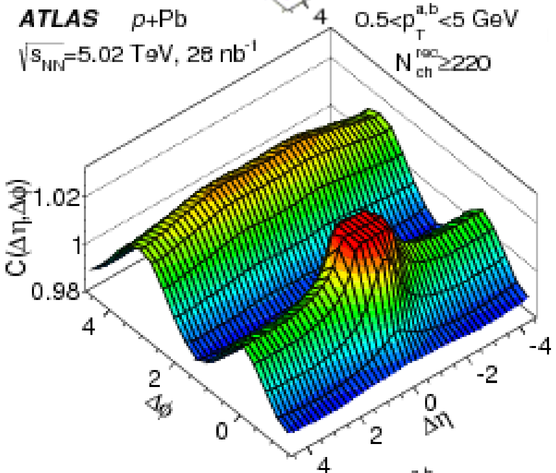
Particles with the same quark content and same masses shall have the same kinematics

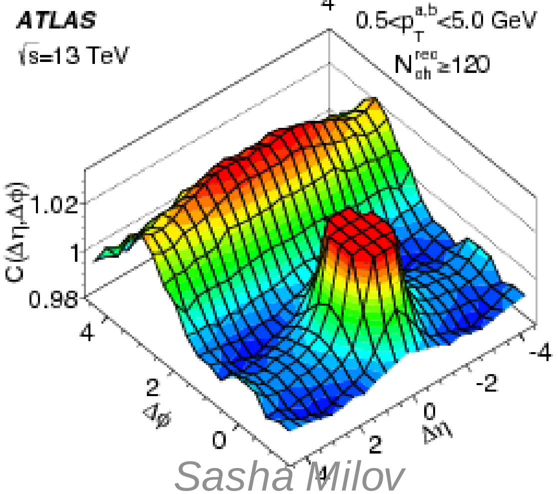
The extent of deviation due to a 10% difference in masses can be tested with the m_T – scaling

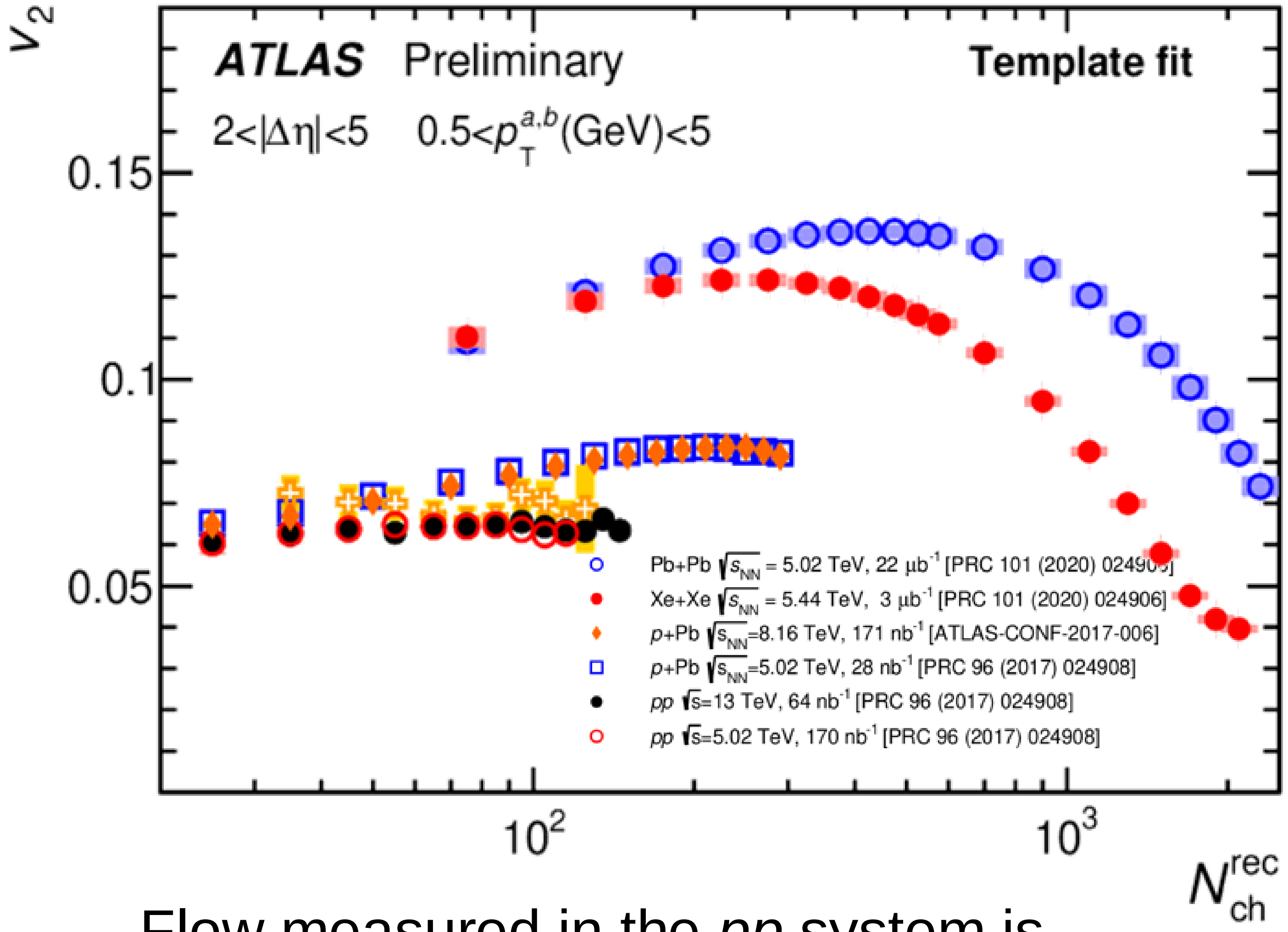


QGP signatures in small systems





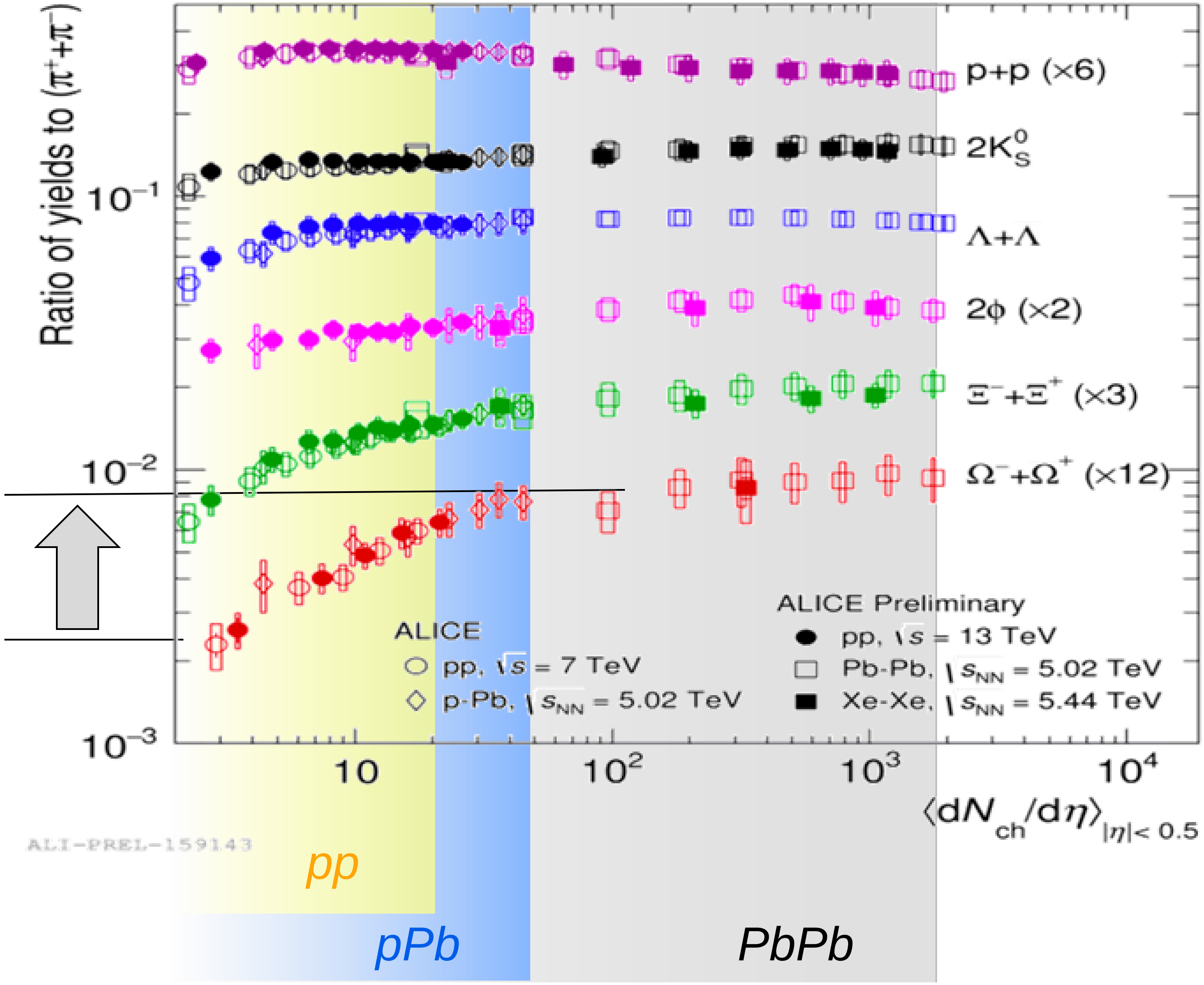




Flow measured in the *pp* system is comparable to much larger systems

QGP signatures in small systems

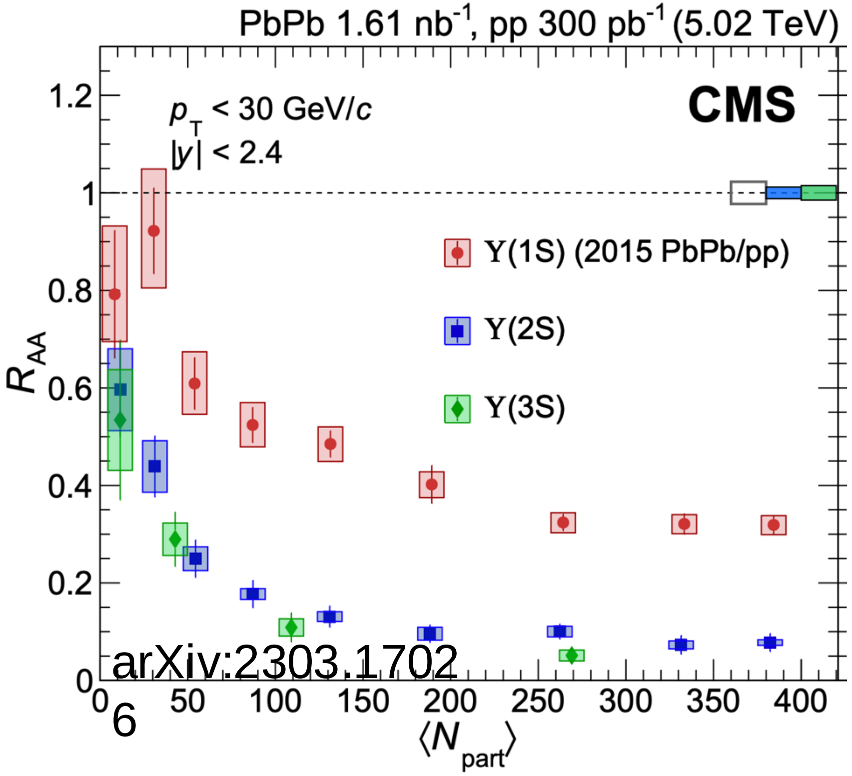
see NP **13**, 535–539 (2017)



Strangeness enhancement happens in the range pf multiplicities of small systems

What about hard probes?

If we are to look for the most sensitive QGP hard probe the obvious suspect would be the $\Upsilon(nS)$ family…

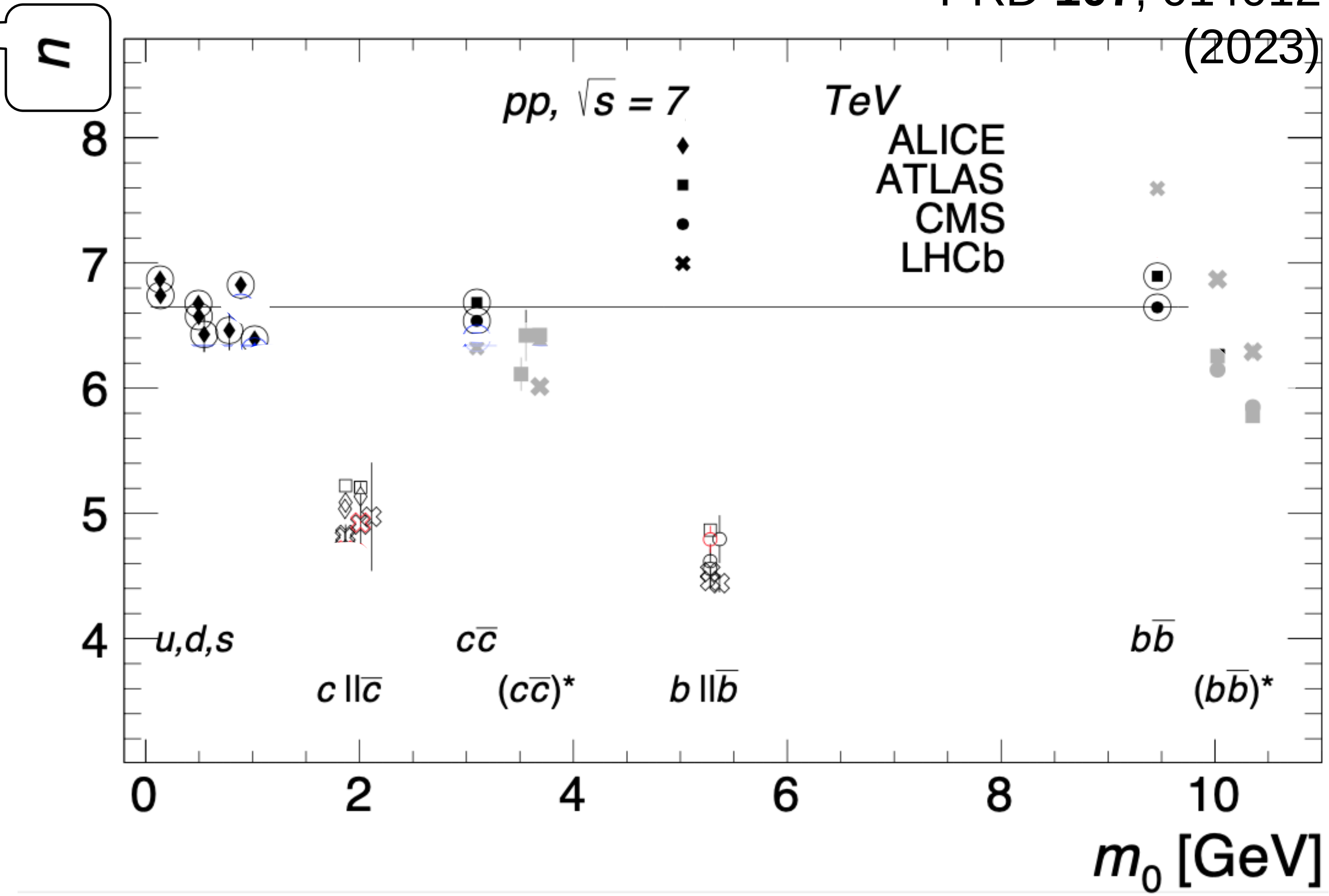


arXiv:2303.17026

Spectra at high p_T

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

PRD **107**, 014012 (2023)



T is fixed to 254 MeV

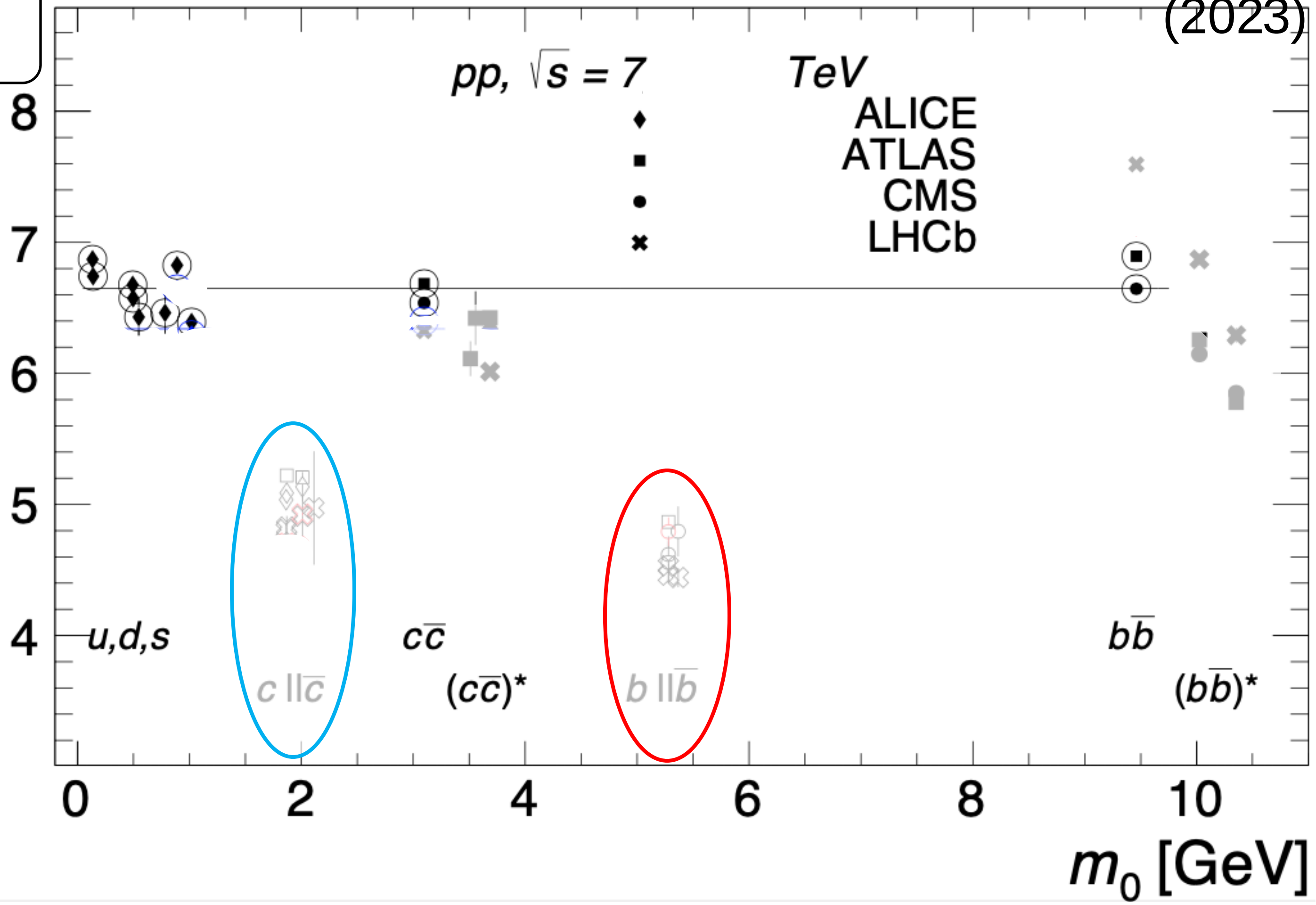
Spectra at high p_T

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

n

Open flavor mesons ($c||\bar{c}$ and $b||\bar{b}$)
has harder spectra (lower *n*)

PRD **107**, 014012 (2023)



T is fixed to 254 MeV

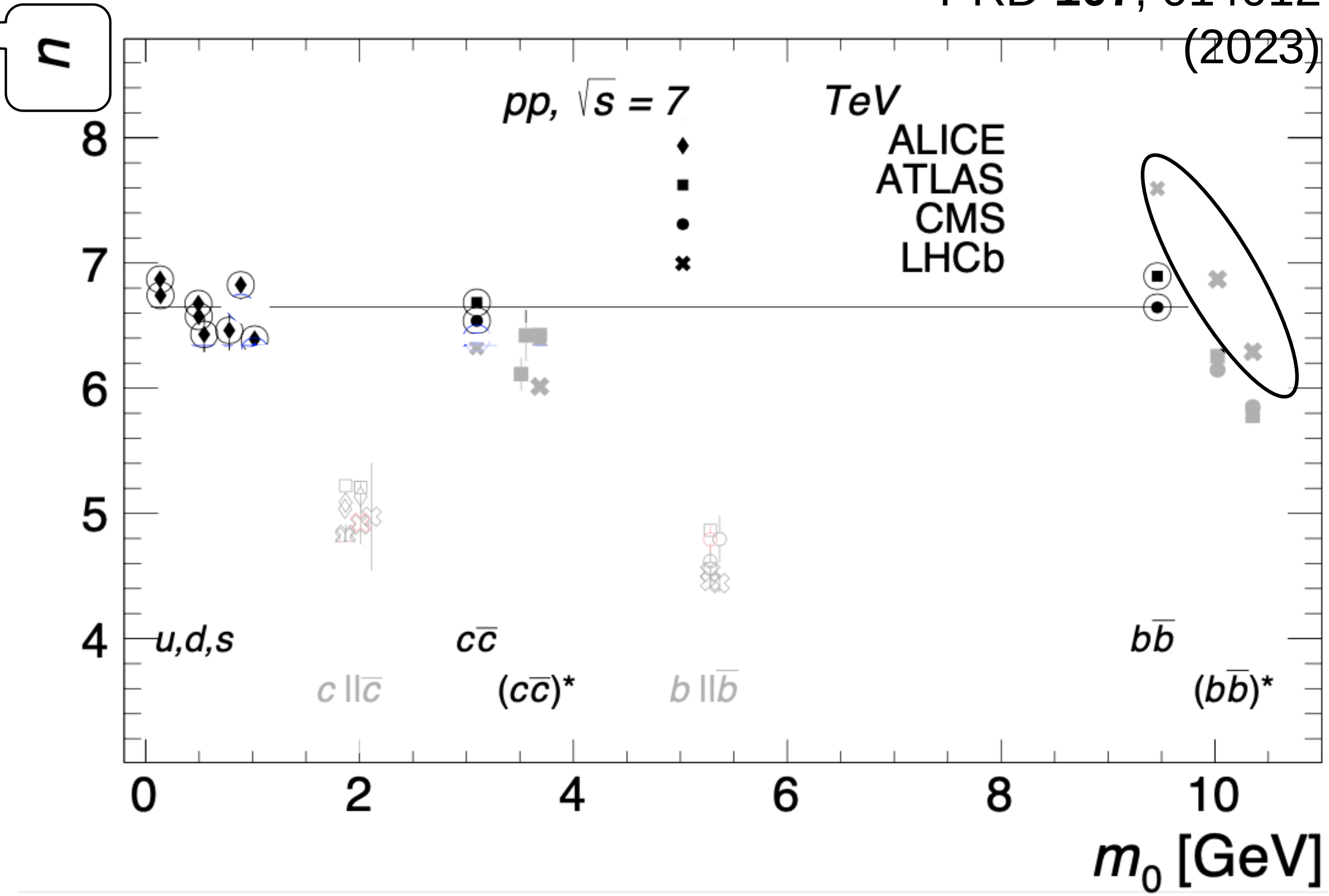
Spectra at high p_T

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_\mathrm{T}} \propto \left[1 + \frac{m_\mathrm{T}}{nT}\right]^{-n}$$

Open flavor mesons ($c||\bar{c}$ and $b||\bar{b}$)
has harder spectra (lower *n*)

LHCb data (high-rapidity) are typically higher than midrapidity data

PRD **107**, 014012 (2023)

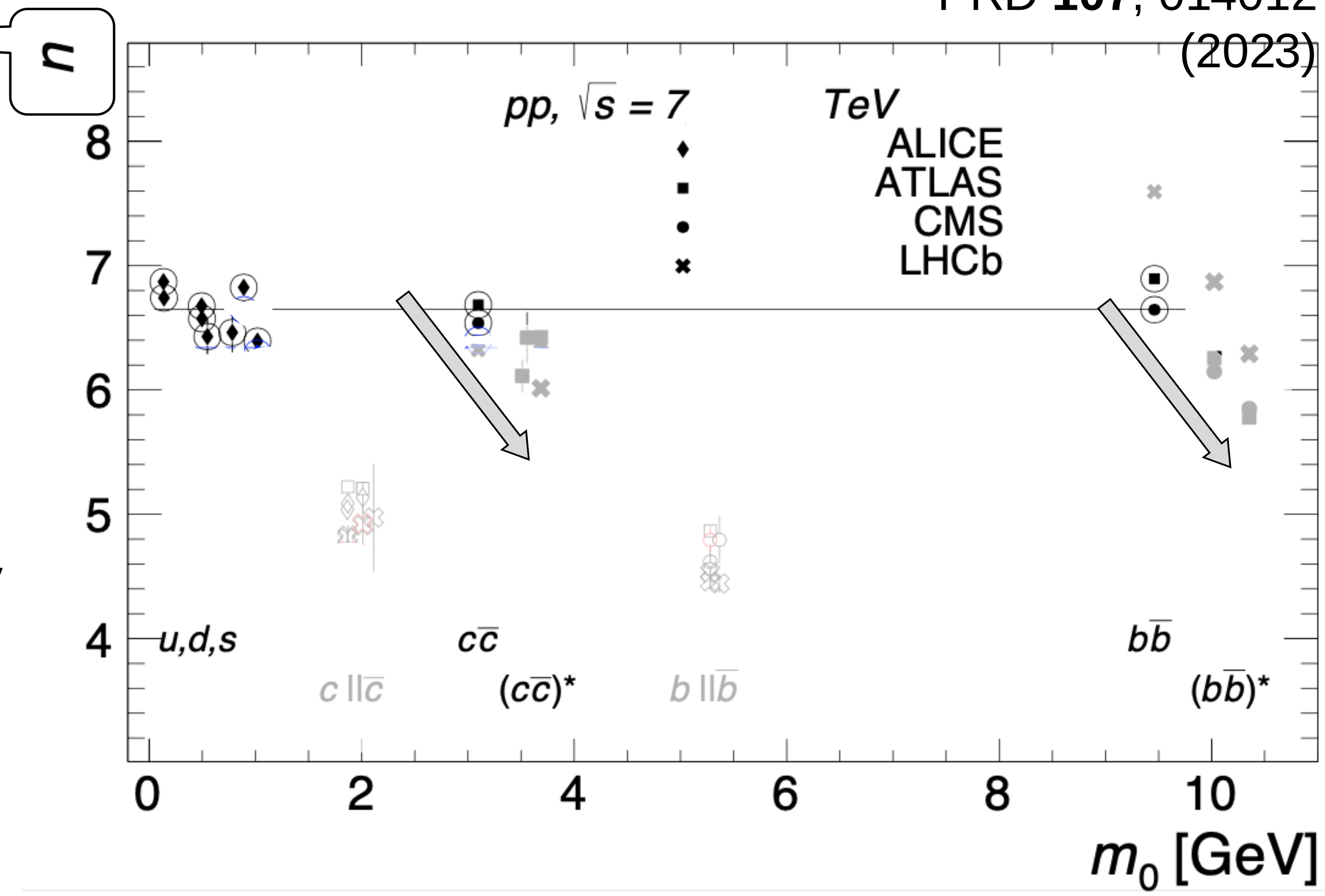


T is fixed to 254 MeV

Spectra at high p_T

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

PRD **107**, 014012 (2023)



Open flavor mesons ($c||\bar{c}$ and $b||\bar{b}$)
has harder spectra (lower *n*)

LHCb data (high-rapidity) are typically higher than midrapidity data

Excited quarkonia ($(c\bar{c})^*$ and $(b\bar{b})^*$)
have lower *n*

u,d,s & $q\bar{q}$ are fit simultaneously
$n = 6.65$ $\sqrt{s} = 7$ TeV

T is fixed to 254 MeV