Missing beauty of *pp* interactions

YASHA AIZENBERG

מכון ויצמן למדע

WEIZMANN INSTITUTE OF SCIENCE

What is this talk about

This work is motivated by Heavy Ion physics, but it is not really about it

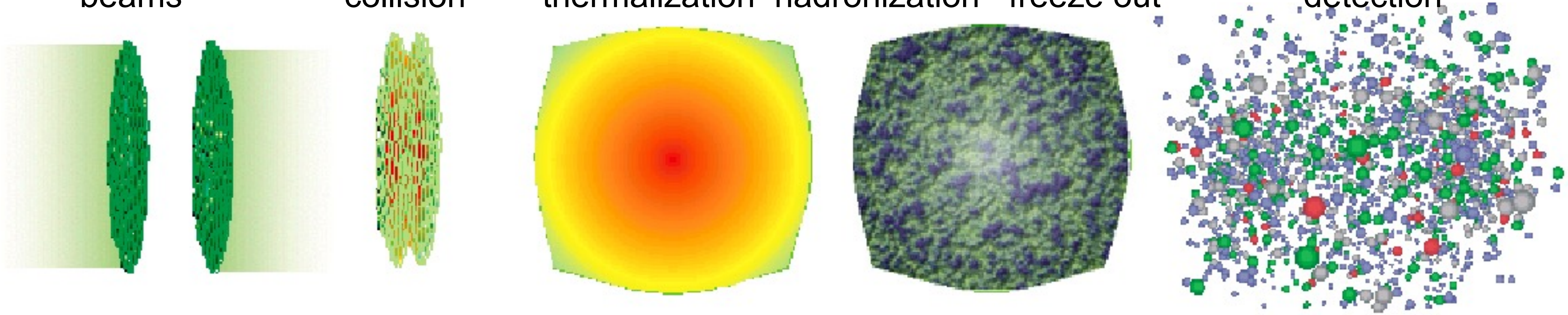
We(*) want to show you two measurements

One from ATLAS: ATLAS-CONF-2022-023
One of our own: arXiv:2203.11831

which, as we hope, would let you look differently at the *pp* interaction at high energies.

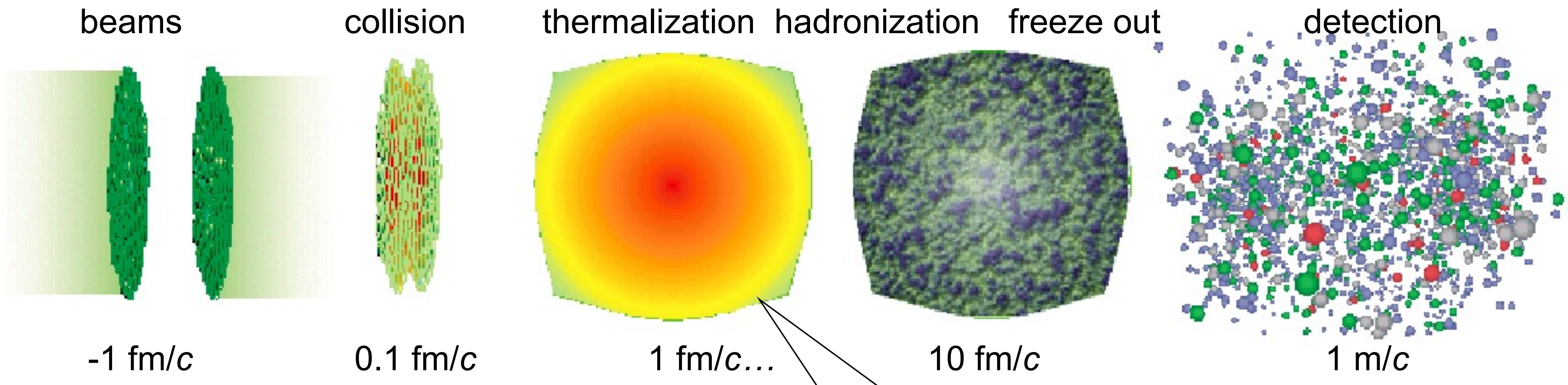
(*) Iakov Aizenberg, Alexander Milov, Zvi Citron

Stages of HI collisions



When talking about HI, system evolution and QGP are closely related.

Probes of HI collisions

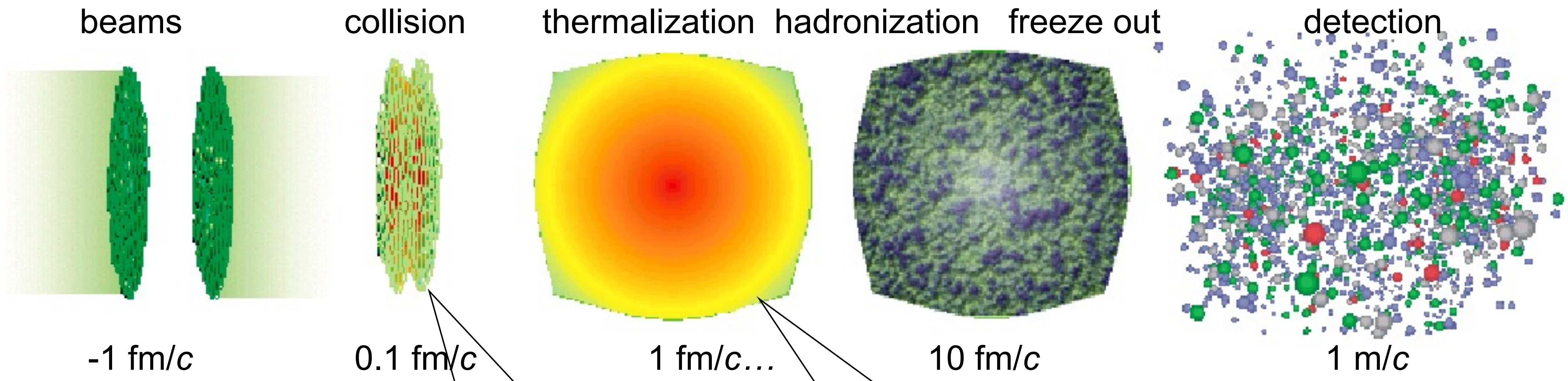


Soft probes

characteristic
$E \gtrsim T$

Event baryochemistry
Collective motion
Anisotropies

Probes of HI collisions



Hard probes

characteristic
$E \gg T$

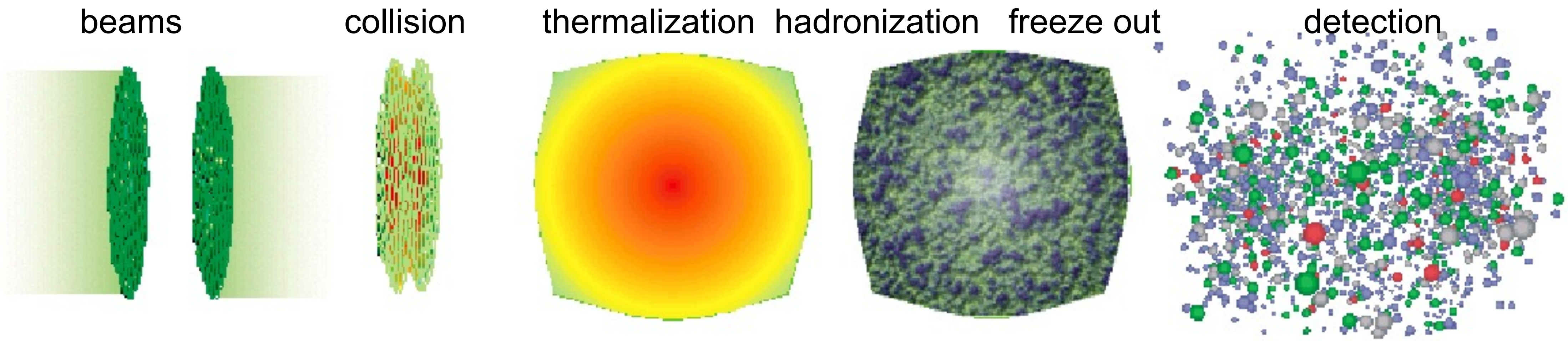
Soft probes

characteristic
$E \gtrsim T$

Jets
Heavy flavor
Electroweak bosons

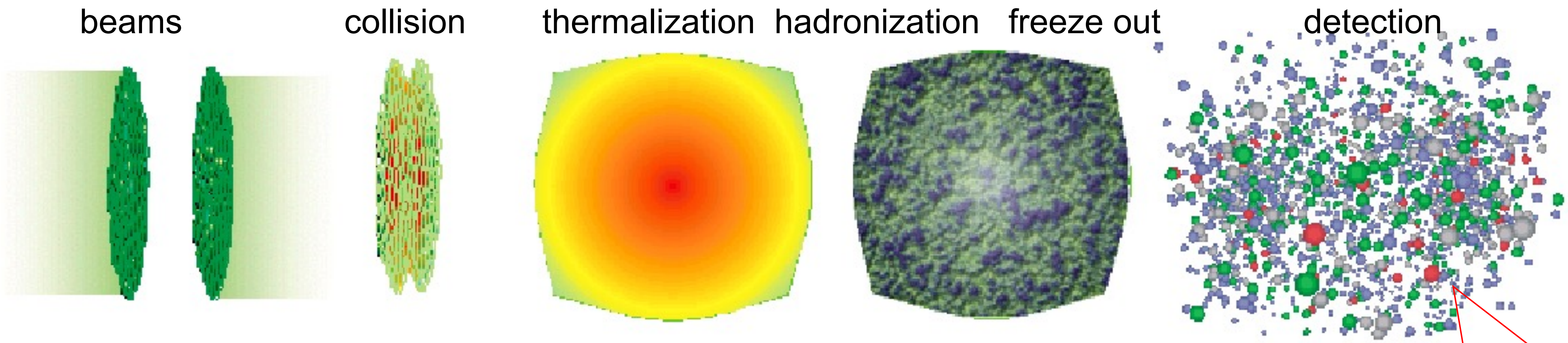
Event baryochemistry
Collective motion
Anisotropies

Observables of HI collisions

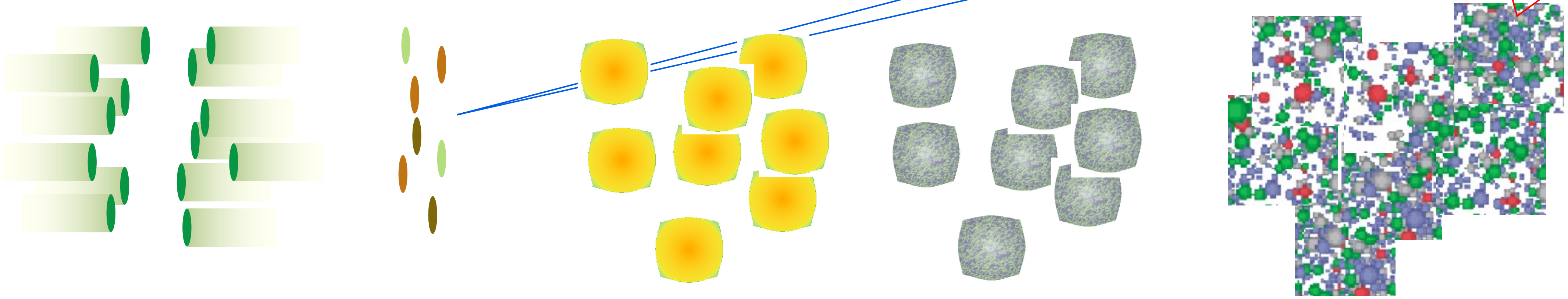


$$R_{\mathrm{AA}} = \frac{1}{T_{\mathrm{AA}}} \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{pp}/\mathrm{d}p_{\mathrm{T}}}$$

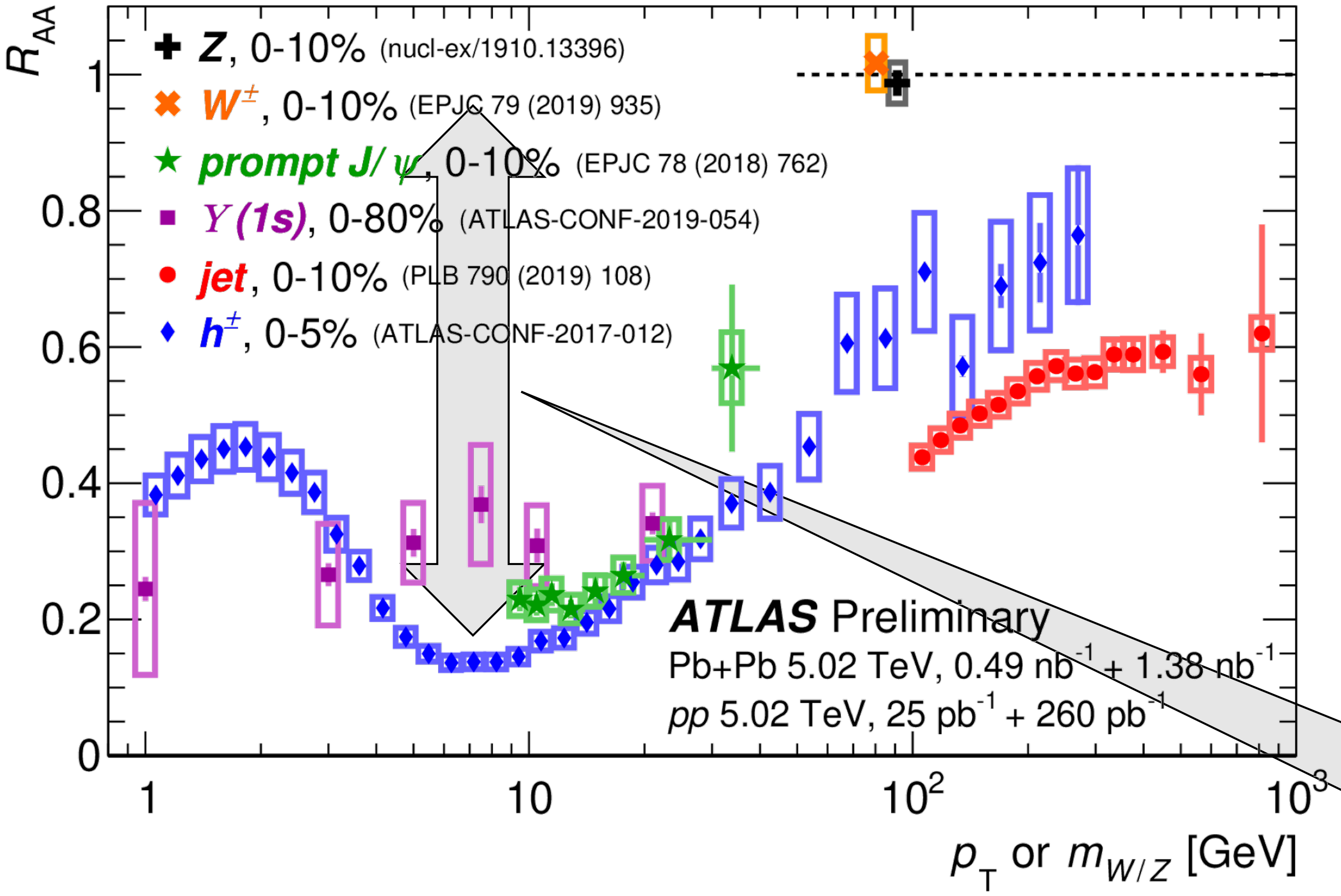
Observables of HI collisions

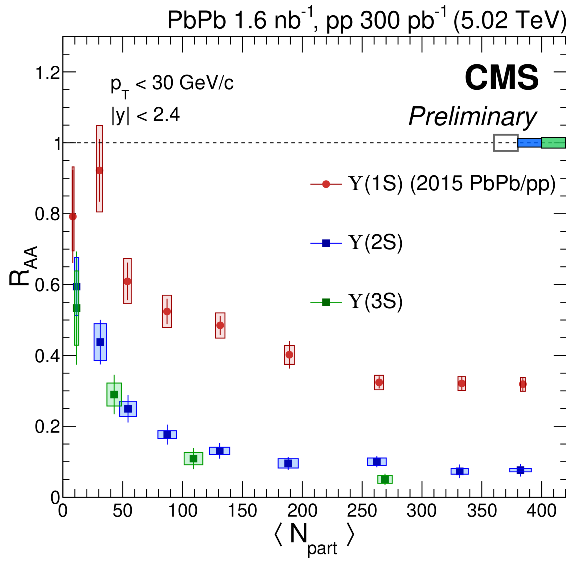


$$R_{\mathrm{AA}} = \frac{1}{T_{\mathrm{AA}}} \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{pp}/\mathrm{d}p_{\mathrm{T}}}$$



Signatures of QGP in HI collisions





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

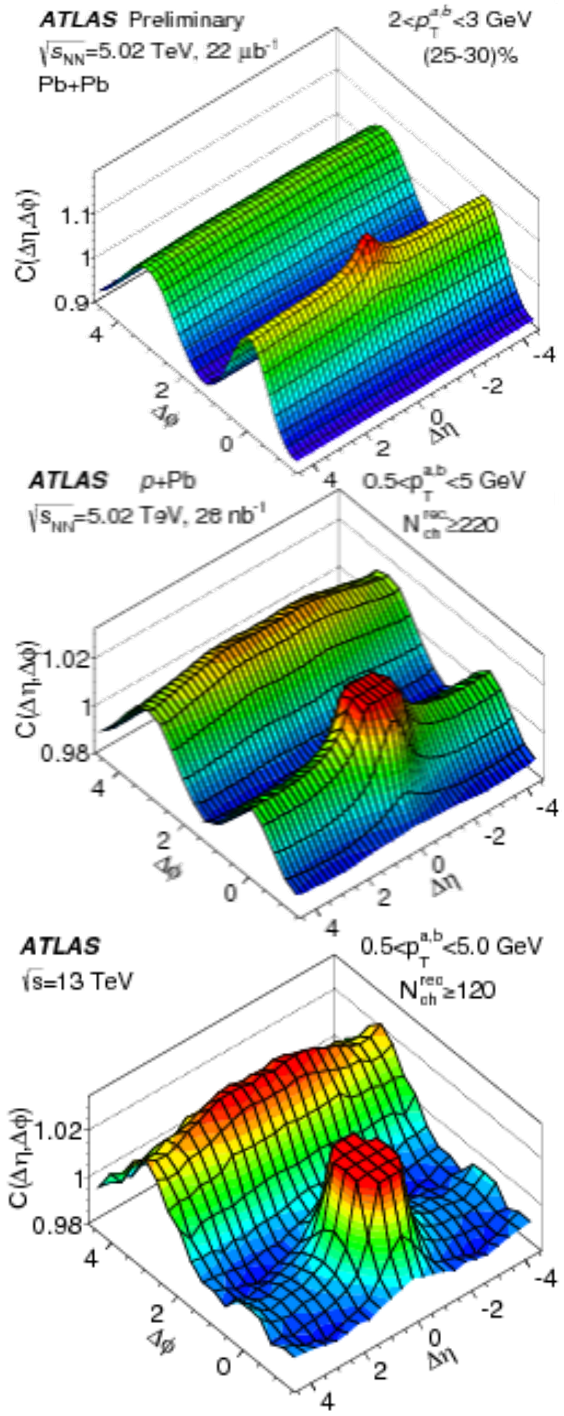
$R_{AA} = 1 \rightarrow$ A + A is "a big *pp*"

$R_{AA} < 1 \rightarrow$ system response

$R_{AA} > 1 \rightarrow$? !

How small is the system where QGP can be formed?

QGP signatures in small systems

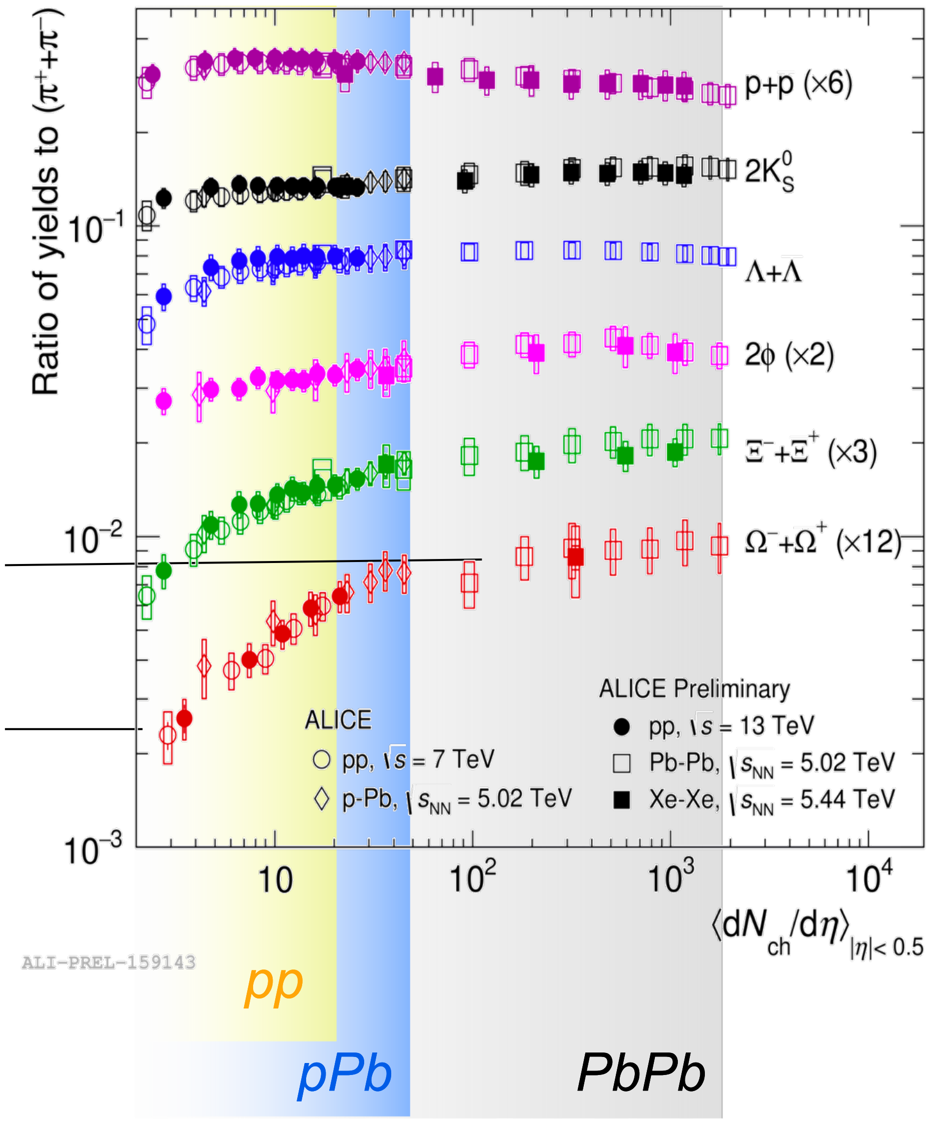


The two QGP signatures observed in *pp* belong to soft probes.

2PC are clearly seen in the hadronic collision system of any size – an elevation at $\Delta\phi = 0$ spans over the $\Delta\eta$ demonstrating the correlation between particle directions even for the particles separated by huge rapidity gaps.

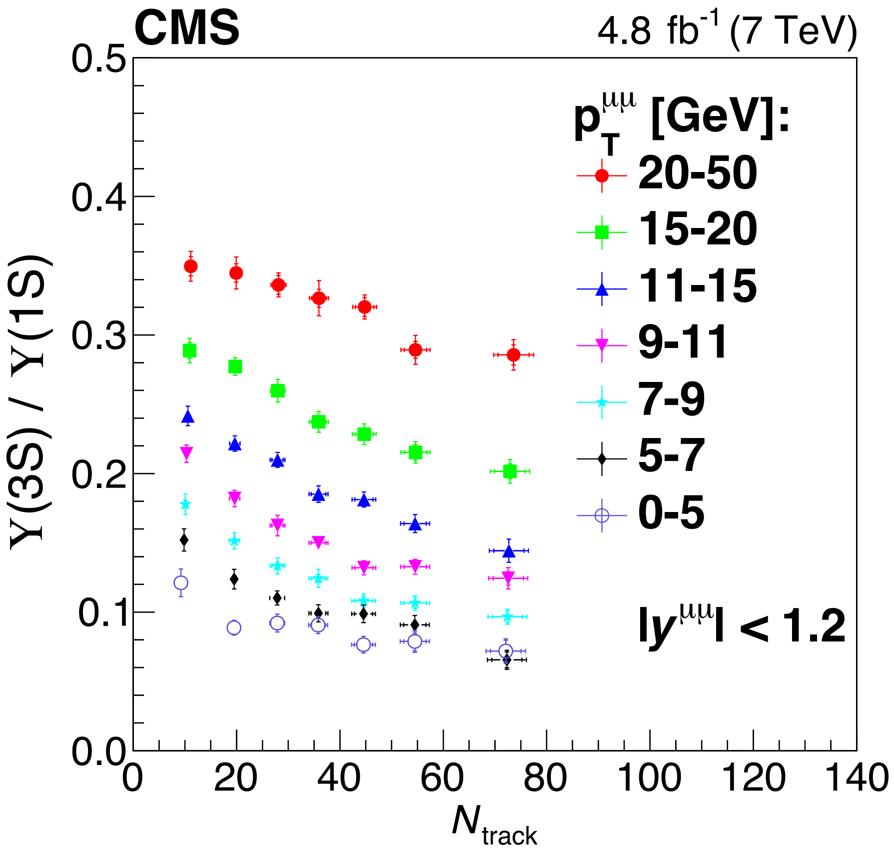
The measurements of strangeness enhancement demonstrates that the evolution of the observed effects in *pp* smoothly matches the magnitude of the effects observed in *p*Pb and PbPb(XeXe) collisions

They carry an intrinsic difficulty of distinguishing initial state from system response



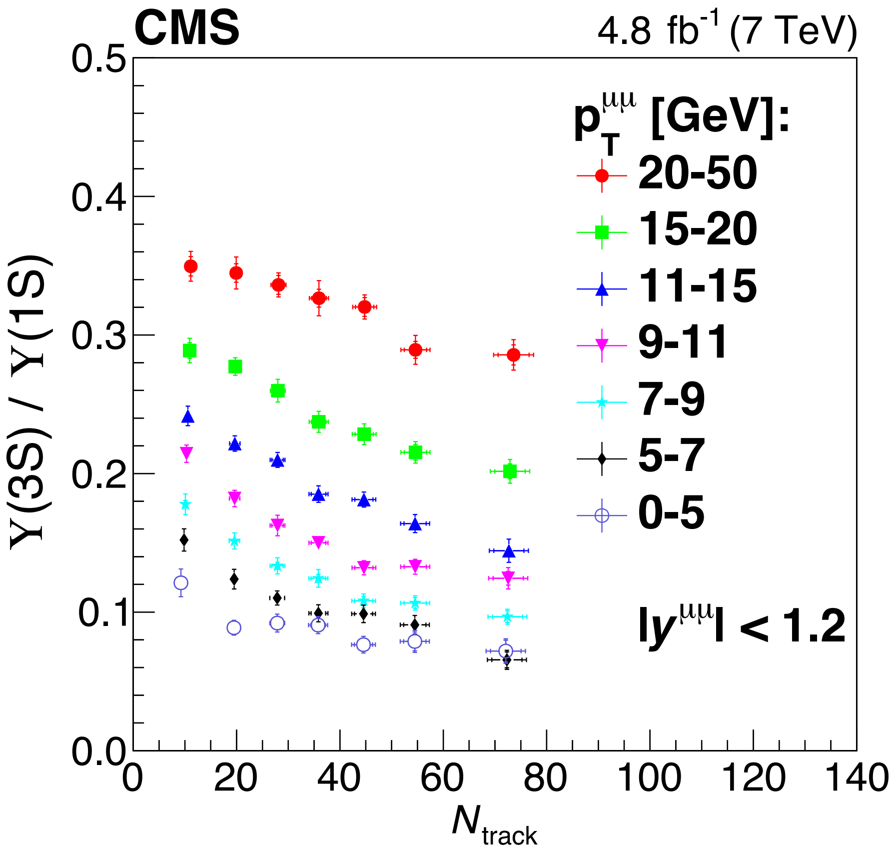
What about the hard probes?

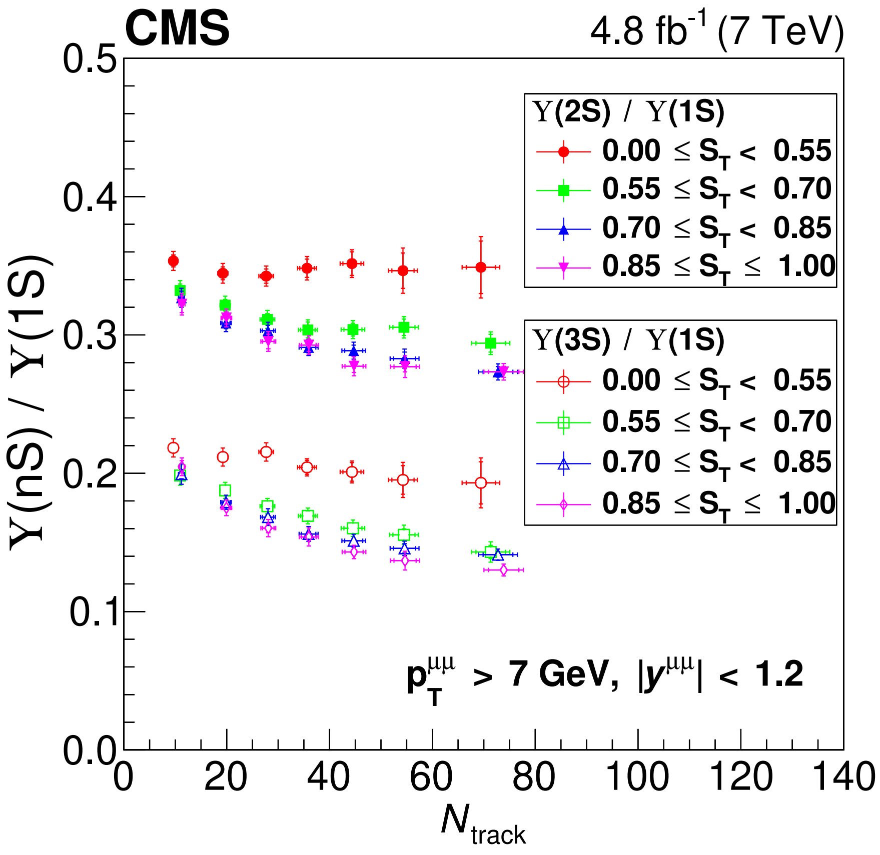
Hard probe modifications in small systems



CMS experiment showed [***JHEP11 (2020) 001***] that in pp collisions the yields of excited Υ(nS) states diminish w.r.t. lighter states when the event multiplicity grows.

Hard probe modifications in small systems





This observation suggests that the decrease in the ratios is the Underlying Event (UE) effect

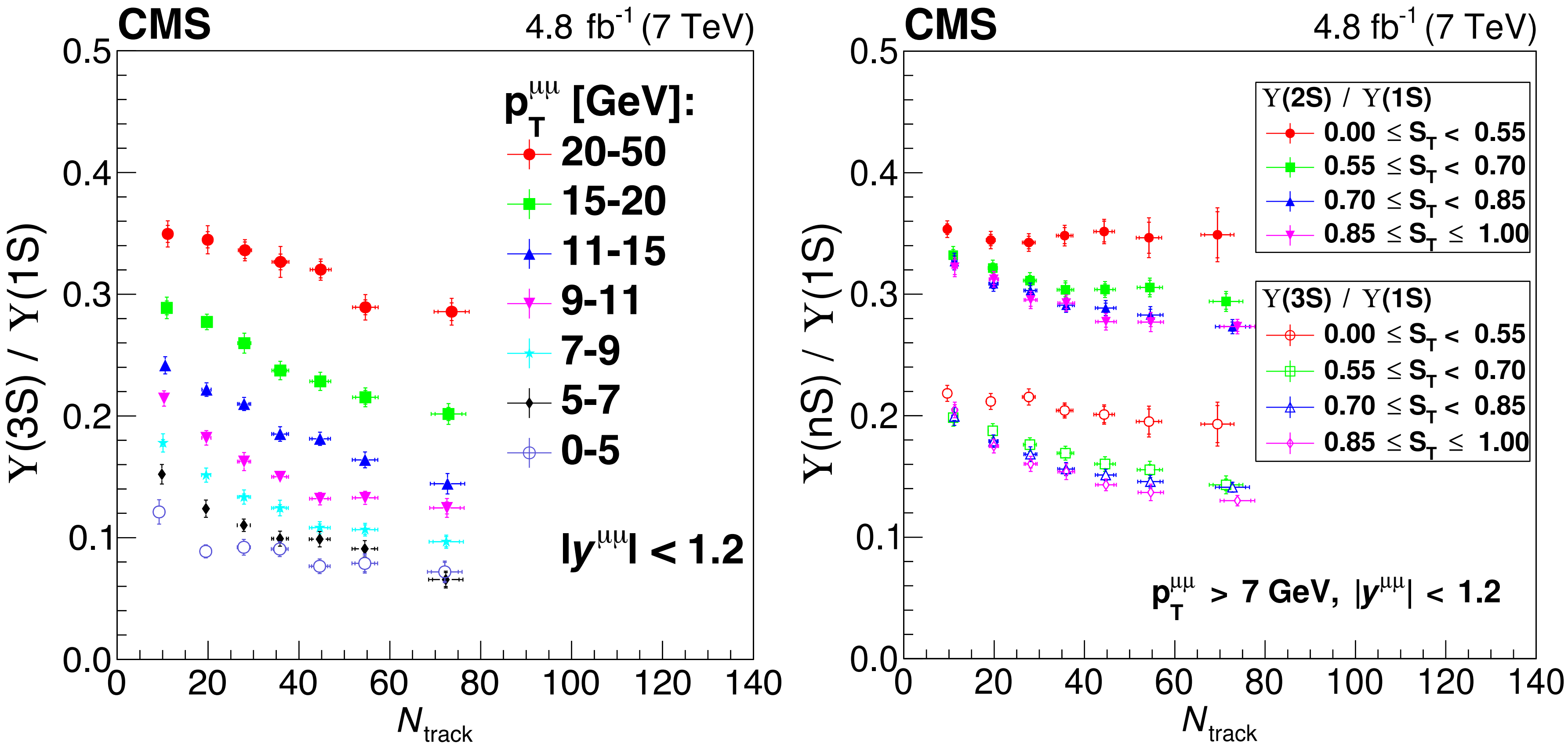
Transverse sphericity - momentum space variable, commonly classified as an event shape observable.

$S_T = 0$ – jets

$S_T = 1$ - Underlying Event

$$S_{\mathrm{T}} \equiv \frac{2\lambda_2}{\lambda_1 + \lambda_2}, \quad S_{xy}^T = \frac{1}{\sum_i p_{\mathrm{T}i}} \sum_i \frac{1}{p_{\mathrm{T}i}} \begin{pmatrix} p_{xi}^2 & p_{xi}p_{yi} \\ p_{xi}p_{yi} & p_{yi}^2 \end{pmatrix} \qquad \lambda_1 > \lambda_2$$

Hard probe modifications in small systems

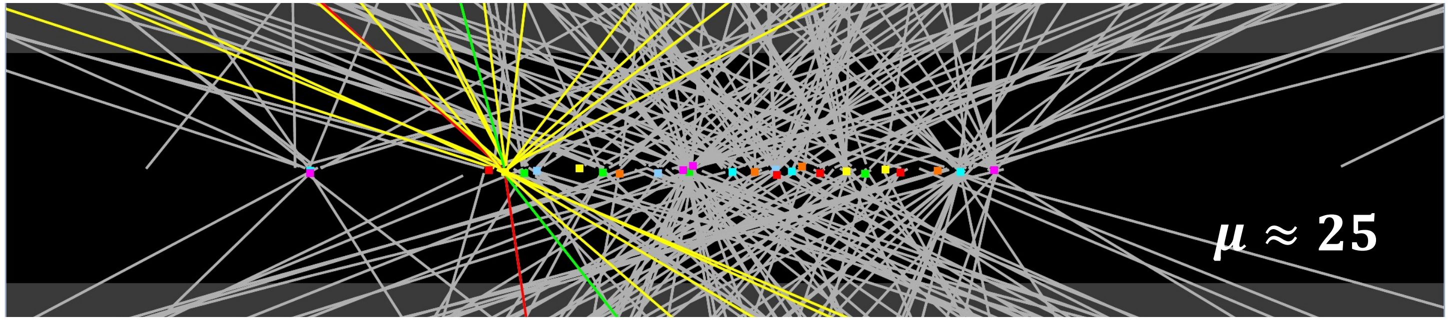


for the production of accompanying particles. On the other hand, it is also true that, if we expect a suppression of the excited states at high multiplicity, it would also appear as a shift in the mean number of particles for that state (because events at higher multiplicities would be missing). Furthermore, if we consider only the events with $0 < S_T < 0.55$, where

Some experimental practicalities…

One cannot do R_{AA} in *pp,* therefore $\Upsilon(nS)/\Upsilon(1S)$ seems like a good idea
One cannot do geometry in *pp* -- we shall stay with $N_{\mathrm{track}} \to n_{\mathrm{ch}}$

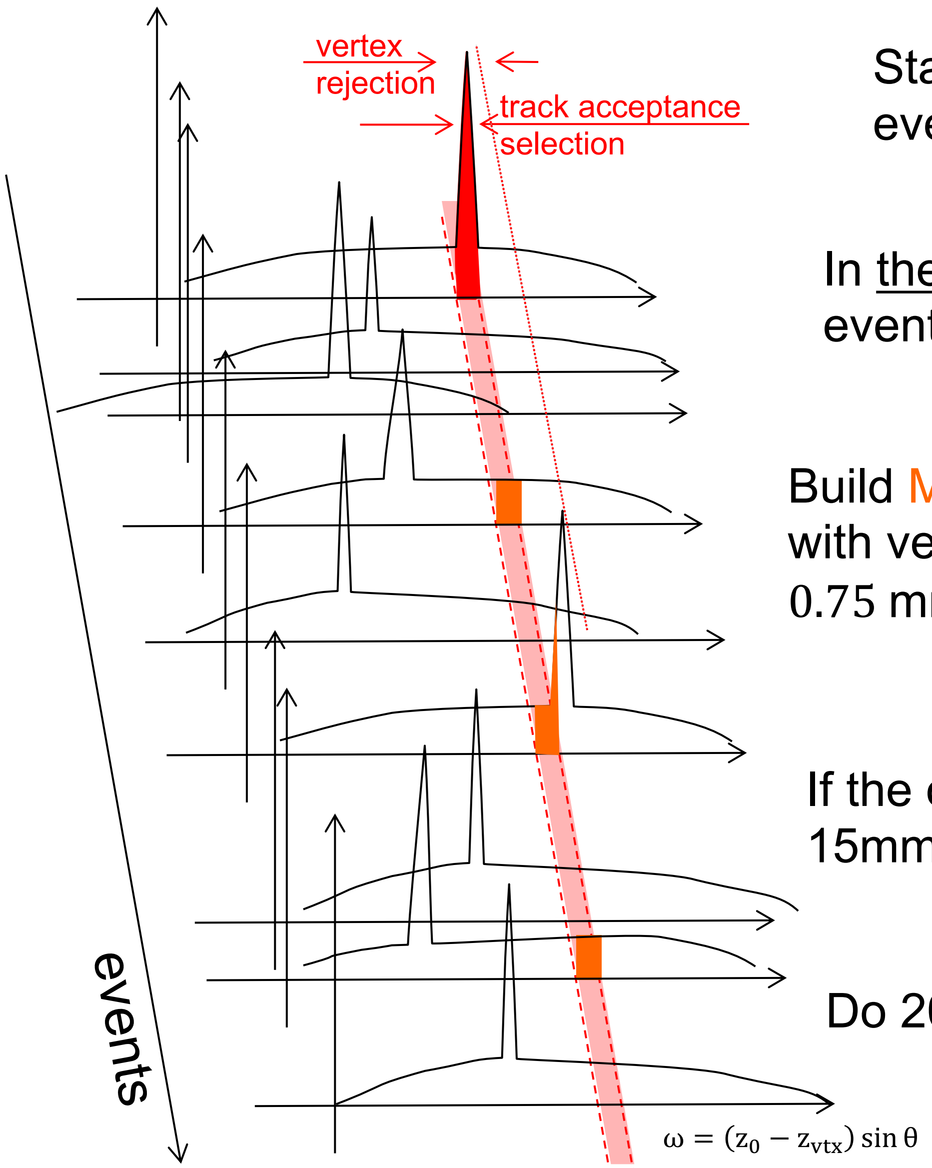
$\Upsilon(nS)$ are rare probes
- We need high statistics
  - High statistics is available, but it was obtained at $\mu < 80$
    - μ = pileup
      - Pileup doesn't allow to measure n_{ch}



"Okay, Houston, we've had a problem here!"

The pileup story

EPJC 80 (2020) 64



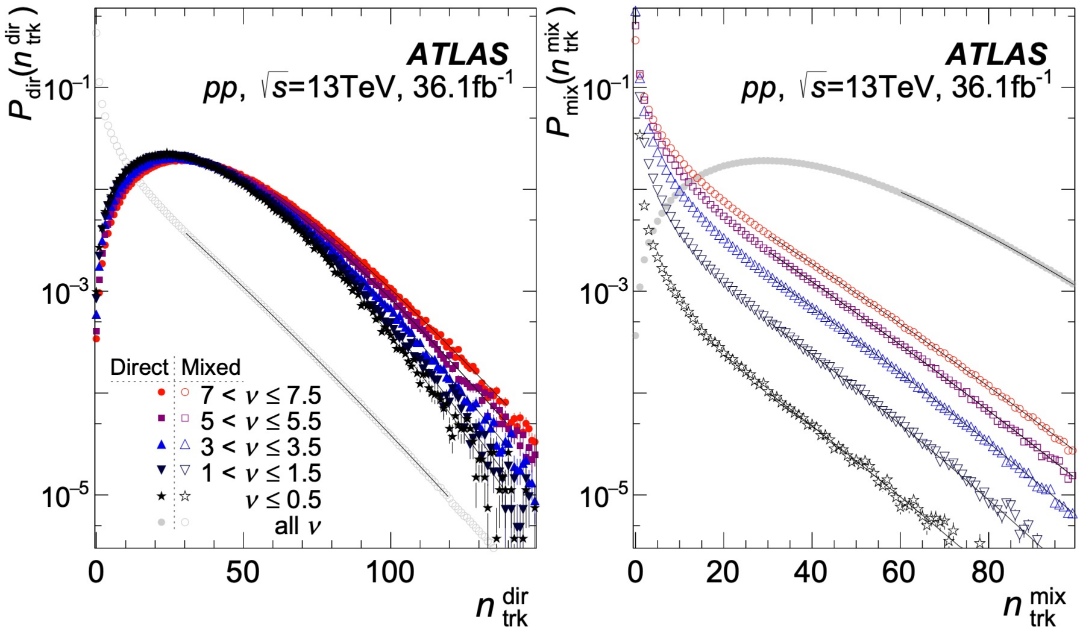
Start with the triggered event, called Direct

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



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, $\sqrt{s}$ = 13 TeV, 139 fb^{-1}

Full luminosity data constrained at μ < 50 (fake production) and then at ν < 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

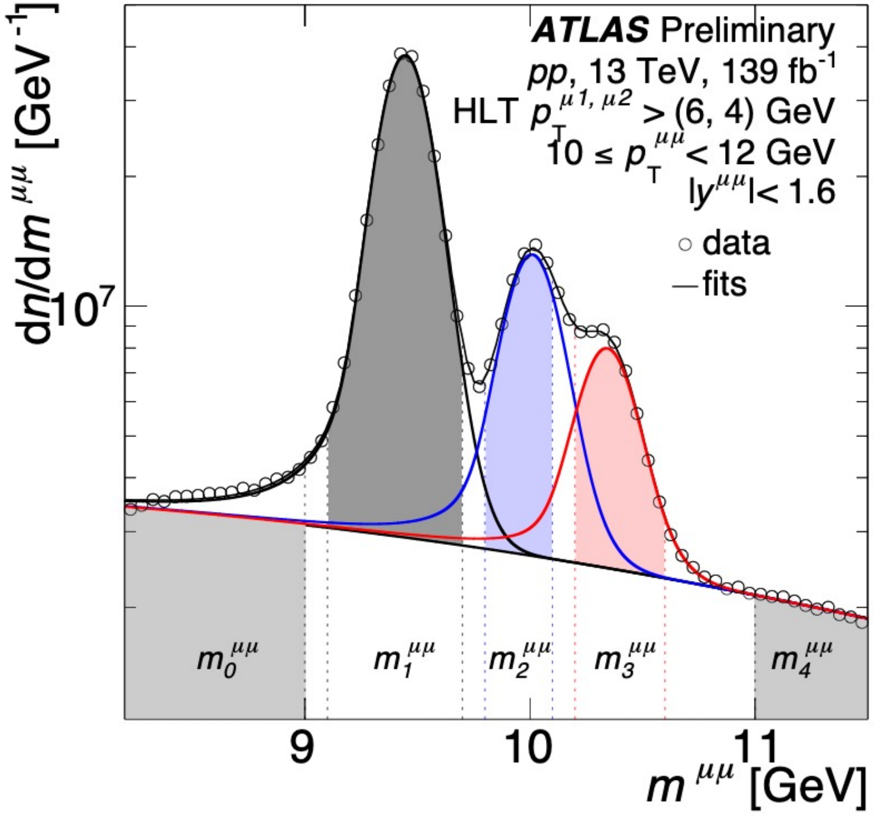
$\Upsilon(nS)$ kinematics $|y| < 1.6$, $0 < p_T < 70$ GeV where we ran out of statistics

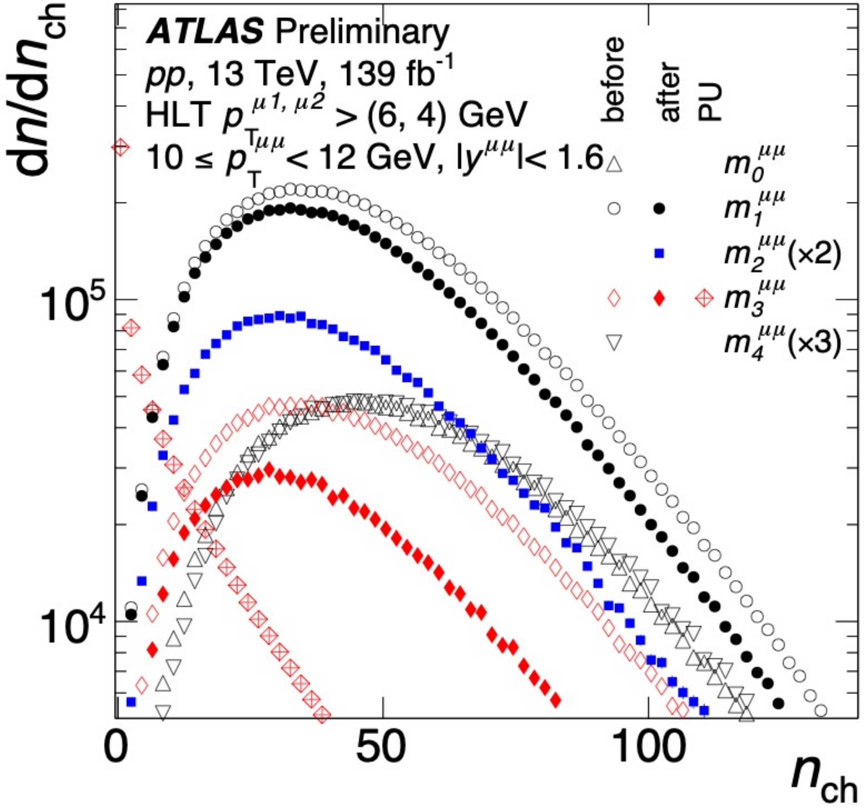
All together after cuts: $\sim 5\times 10^7 \Upsilon(1S)$, $\sim 10^7 \Upsilon(2S)$, $\sim 7\times 10^6 \Upsilon(3S)$

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

Signal extraction

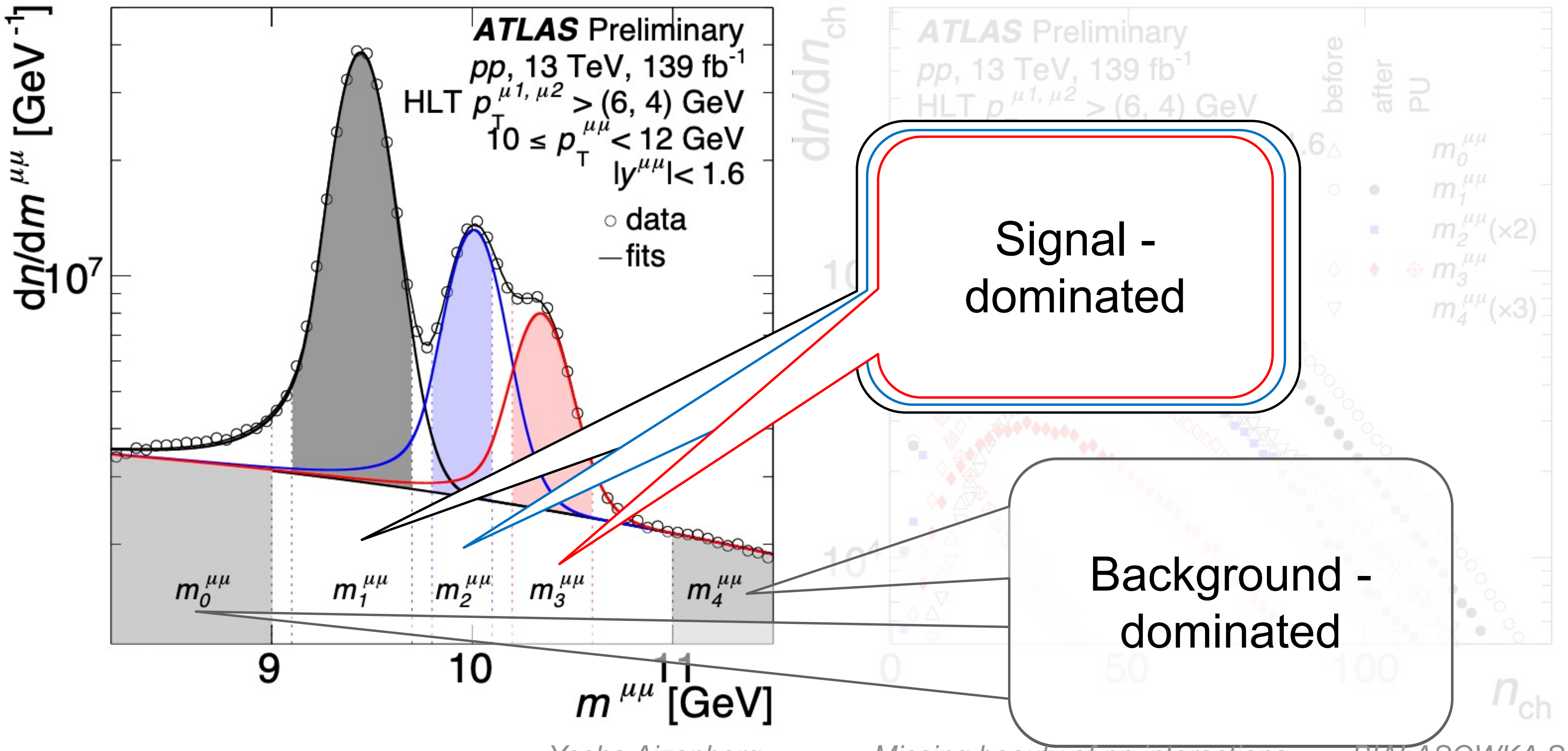




Signal extraction

$$
\begin{aligned}
\text{fit}(m) &= \sum_{nS} N_{\Upsilon(nS)} F_n(m) + N_{\text{bkg}} F_{\text{bkg}}(m) \\
F_n(m) &= (1-\omega_n) CB_n(m) + \omega_n G_n(m) \\
F_{\text{bkg}}(m) &= \sum_{i=0}^{3} a_i (m - m_0)^i;\ a_0 = 1
\end{aligned}
$$

- Define 3+2 regions

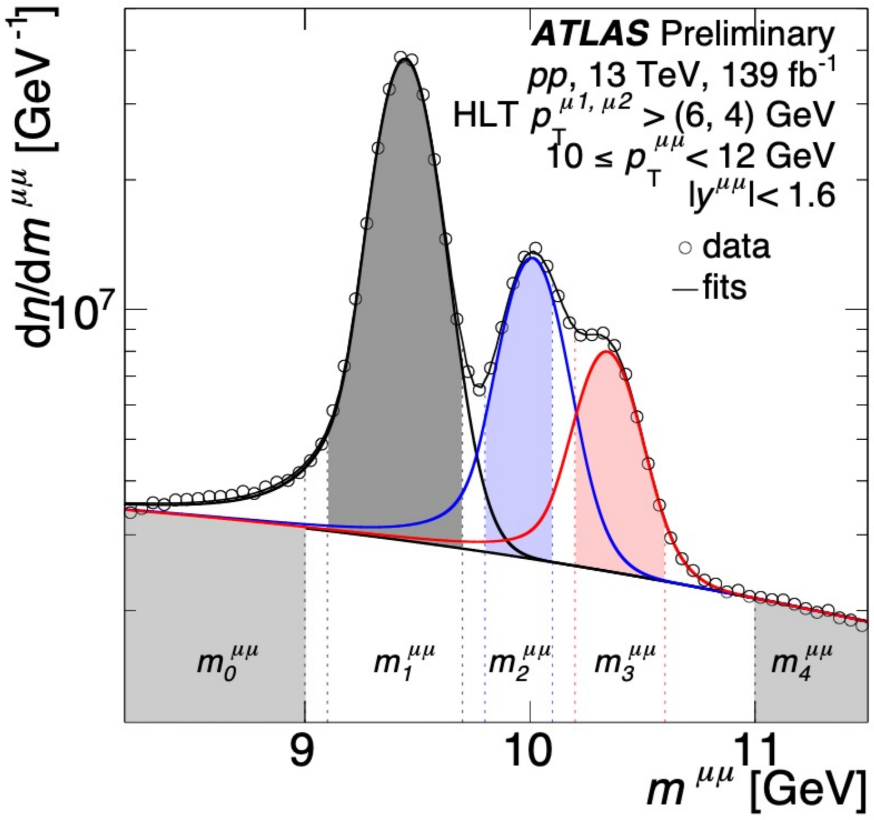


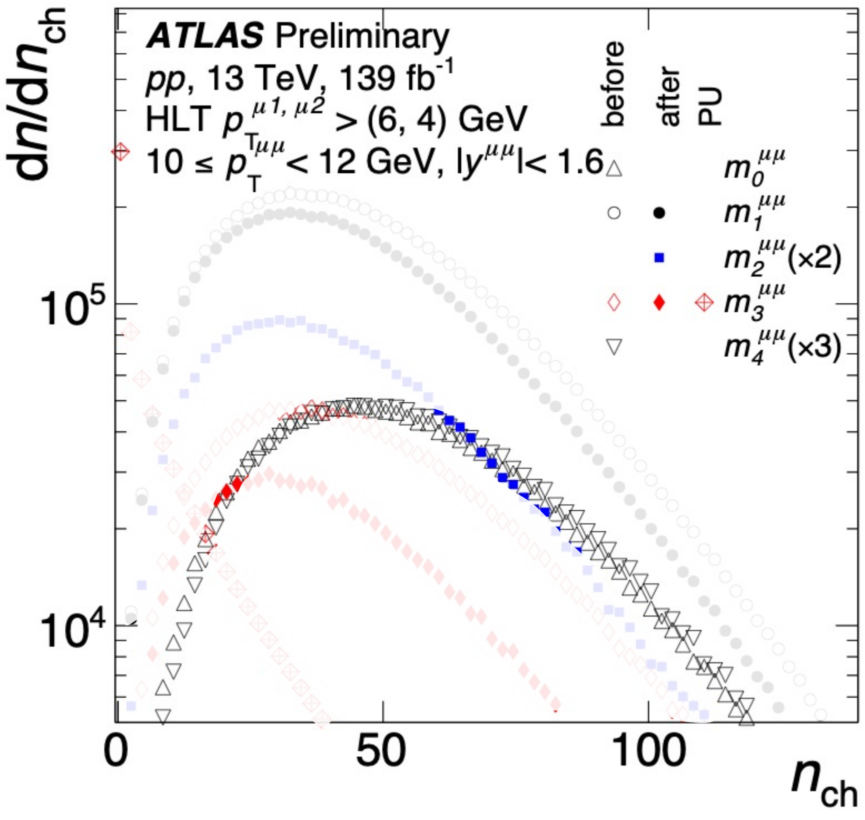
Signal extraction

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

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

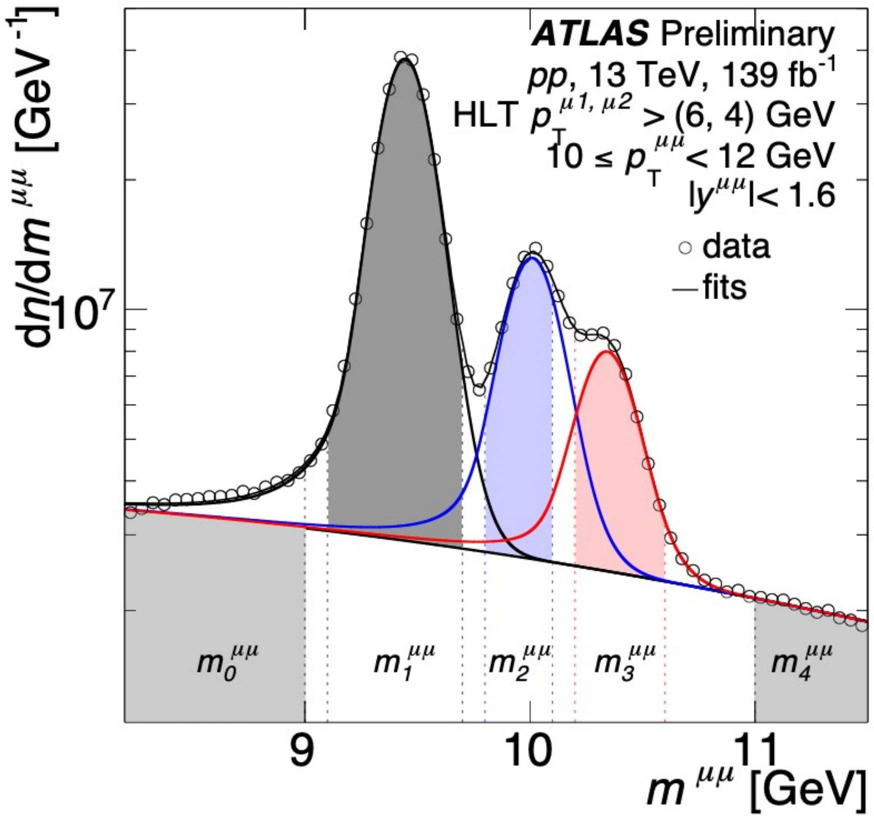
- Define 3+2 regions
- Bkg shapes are similar – interpolate

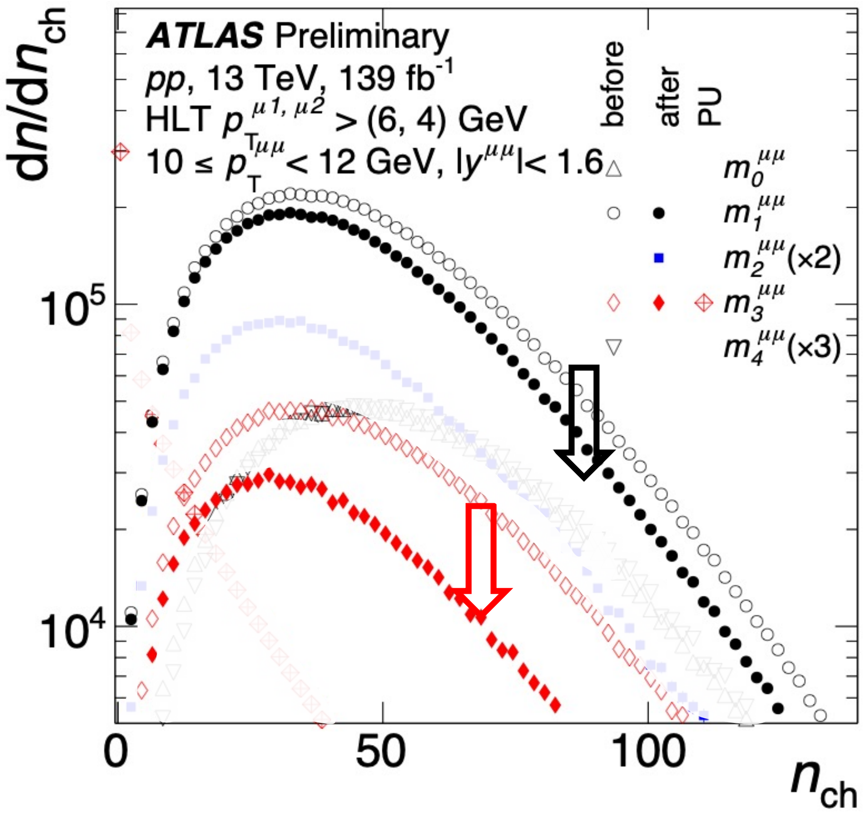




Signal extraction

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

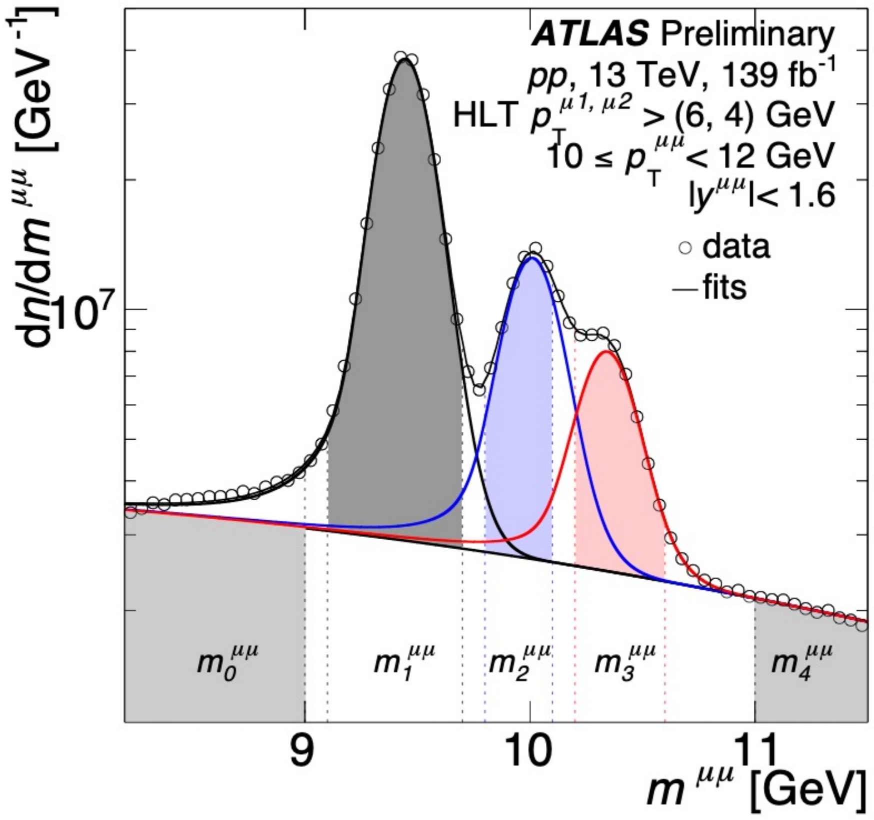


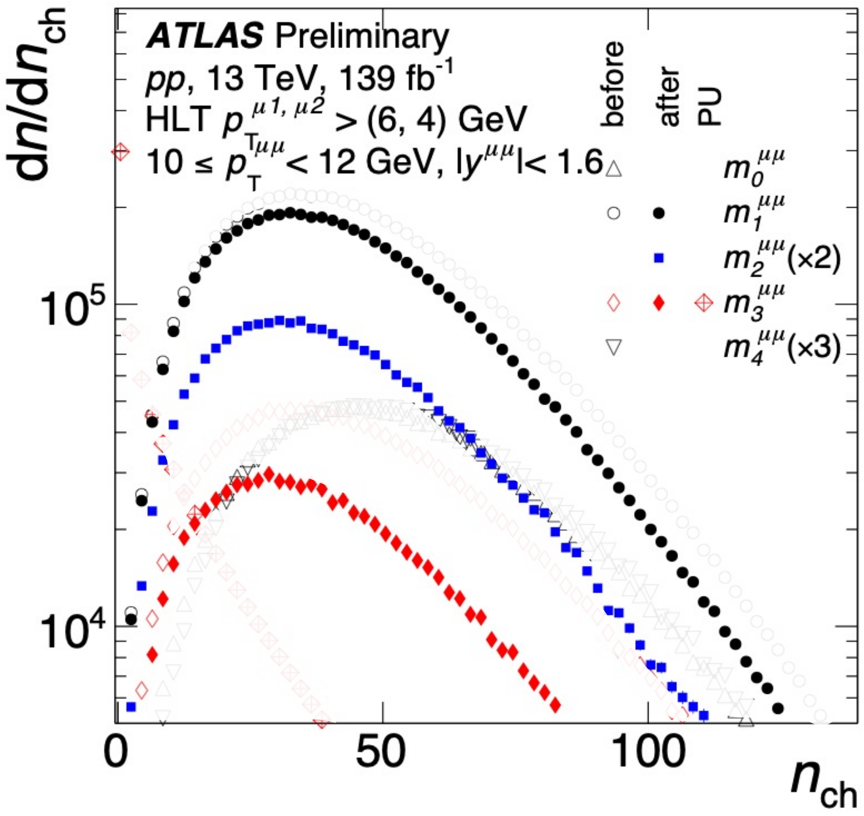


- Define 3+2 regions
- Bkg shapes are similar – interpolate
- Bkg subtraction for $\Upsilon(1S)$ and $\Upsilon(3S)$

Signal extraction

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

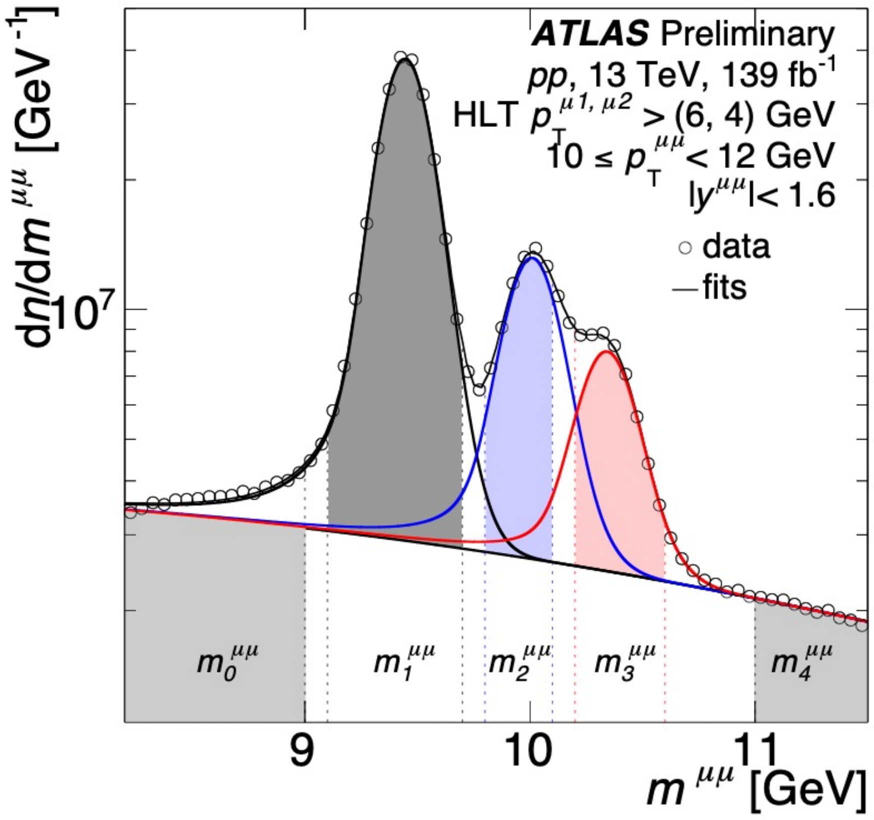


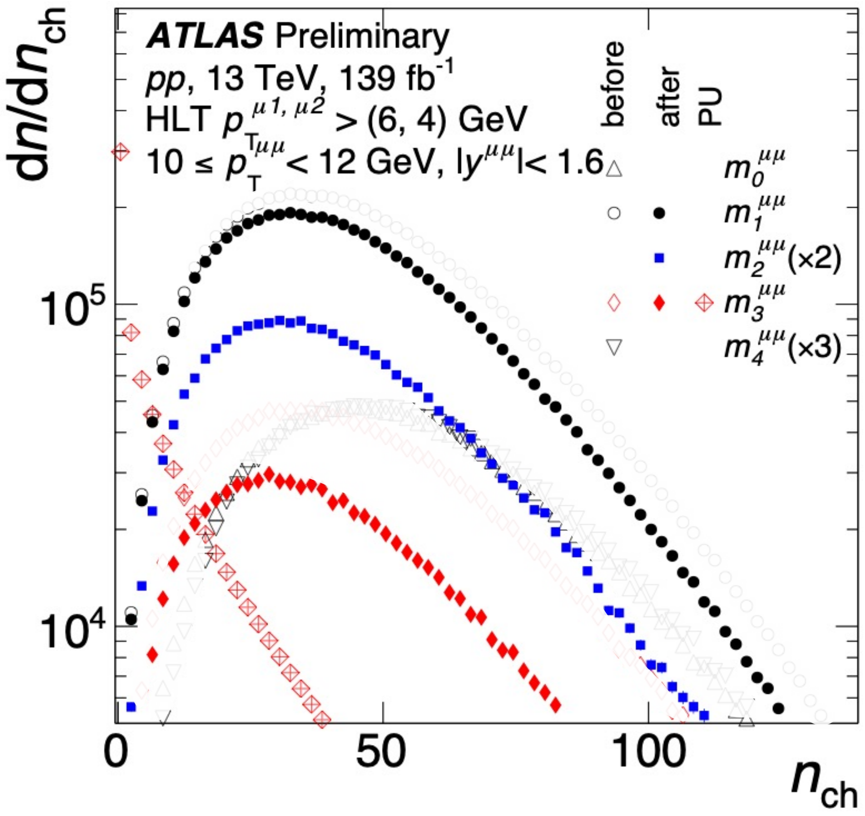


- Define 3+2 regions
- Bkg shapes are similar – interpolate
- Bkg subtraction for $\Upsilon(1S)$ and $\Upsilon(3S)$
- After subtraction n_{ch} look different

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

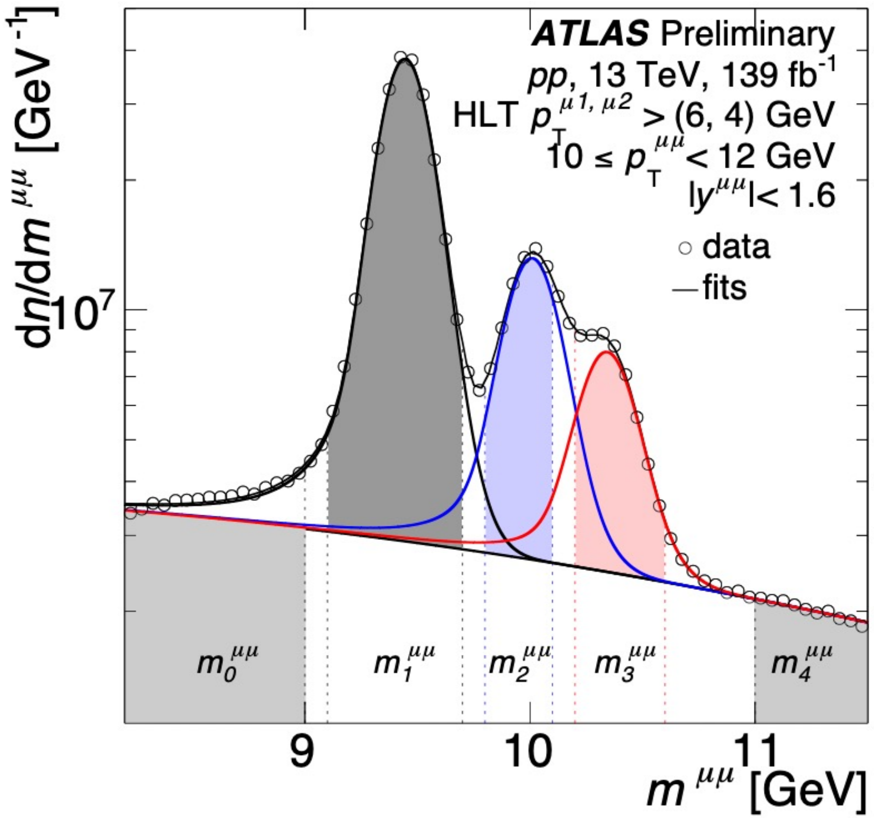


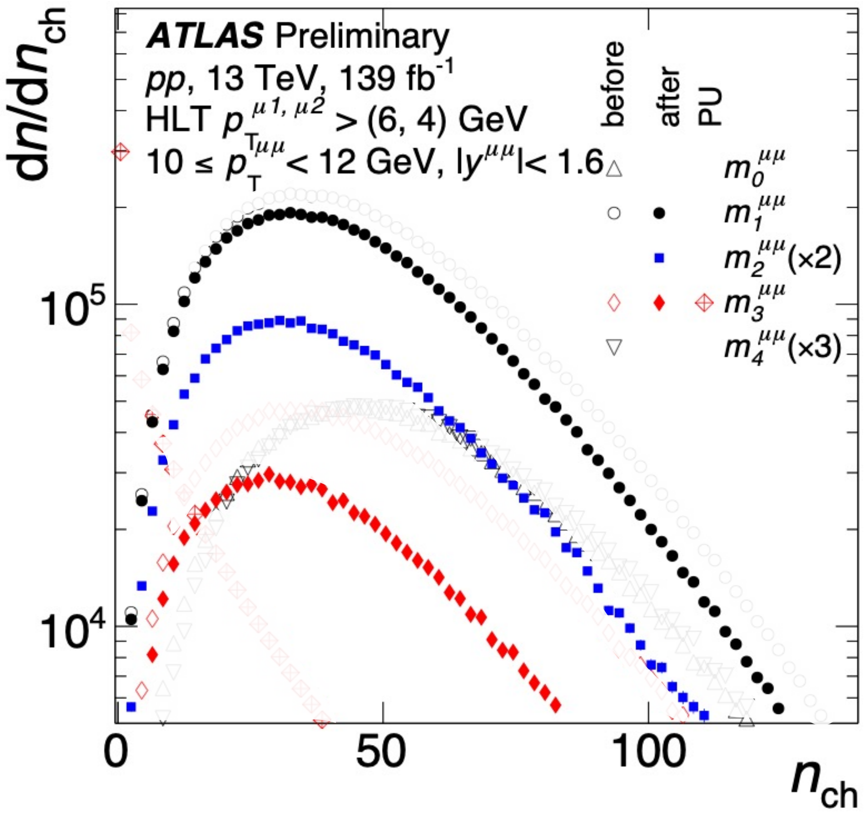


- Define 3+2 regions
- Bkg shapes are similar – interpolate
- Bkg subtraction for $\Upsilon(1S)$ and $\Upsilon(3S)$
- After subtraction n_{ch} look different
- Remove pileup, same shape for all $\Upsilon(nS)$

Signal extraction

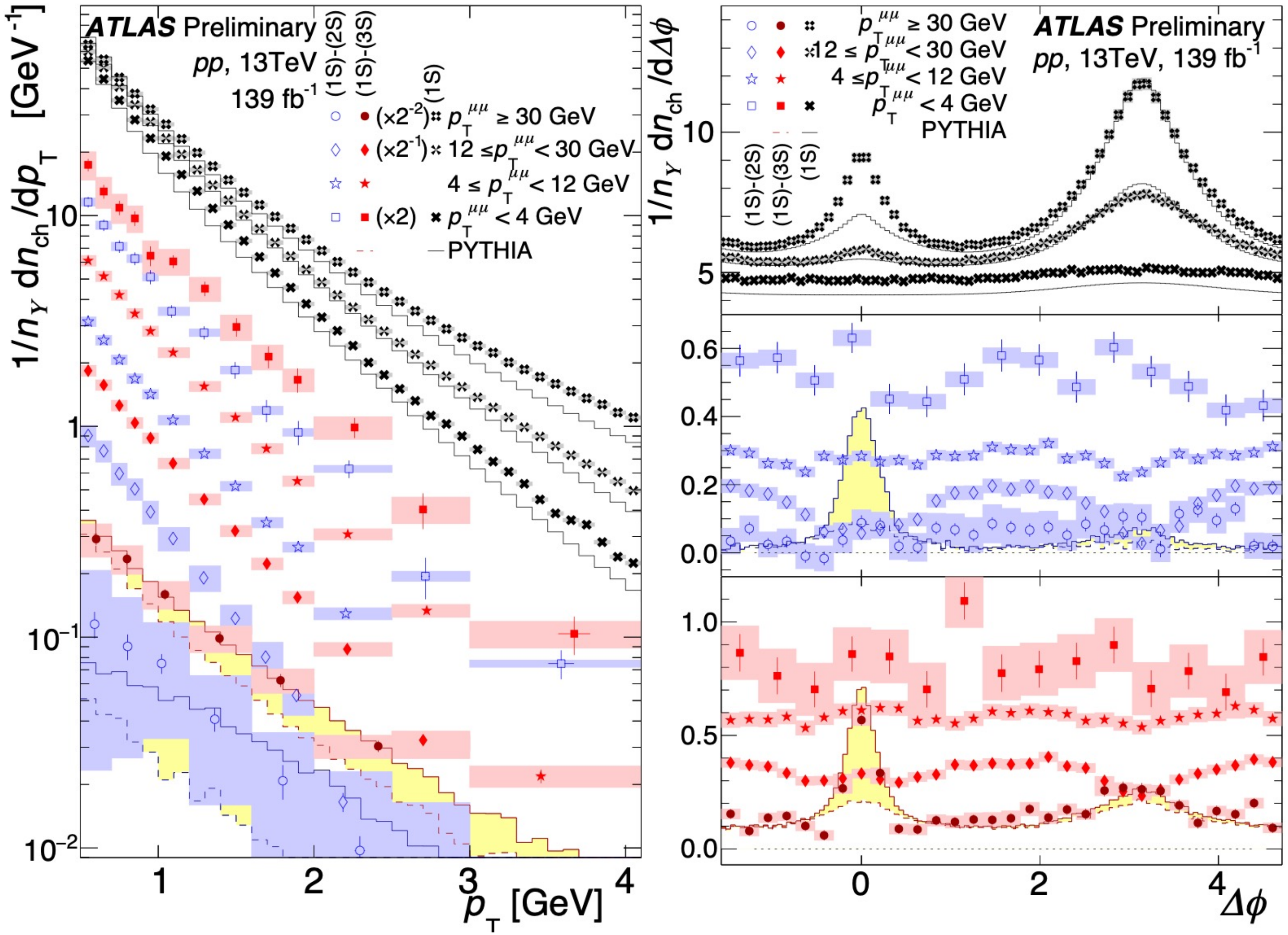
The procedure is illustrated with n_{ch},
But it also works for dn_{ch}/dp_T and $dn_{ch}/d\Delta\phi$. $\Delta\phi=\phi^{\Upsilon}-\phi^{h}$



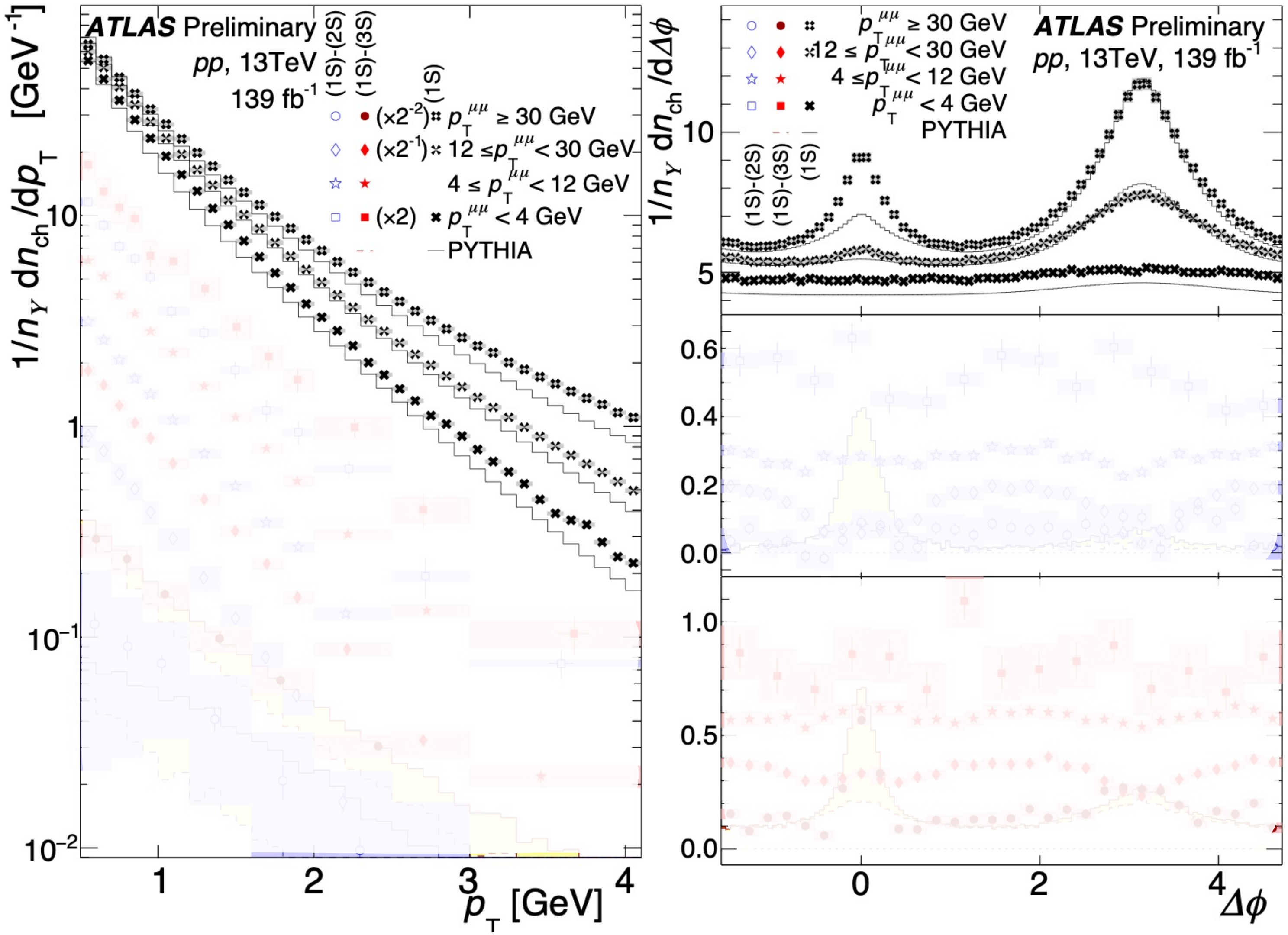


- Define 3+2 regions
- Bkg shapes are similar – interpolate
- Bkg subtraction for $\Upsilon(1S)$ and $\Upsilon(3S)$
- After subtraction n_{ch} look different
- Remove pileup, same shape for all $\Upsilon(nS)$
- Direct measurement of n_{ch} dn_{ch}/dp_T $dn_{ch}/d\Delta\phi$

Kinematic distributions

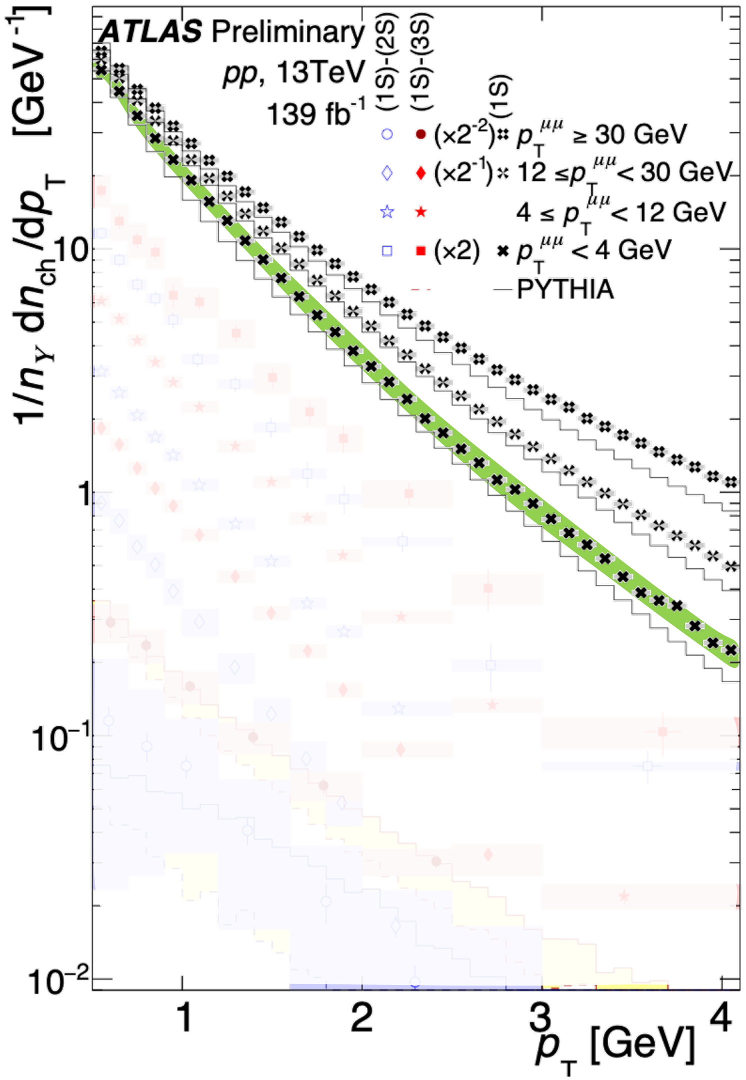


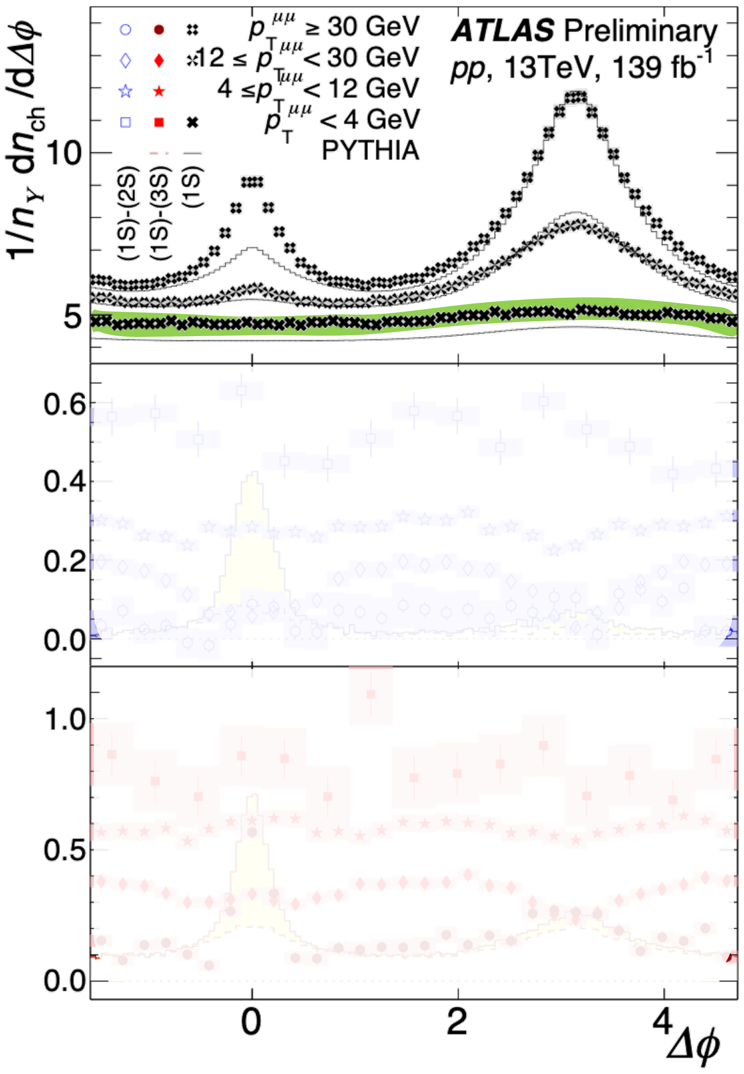
Kinematic distributions



- Distributions for $\Upsilon(1S)$
- Pythia does not describe well

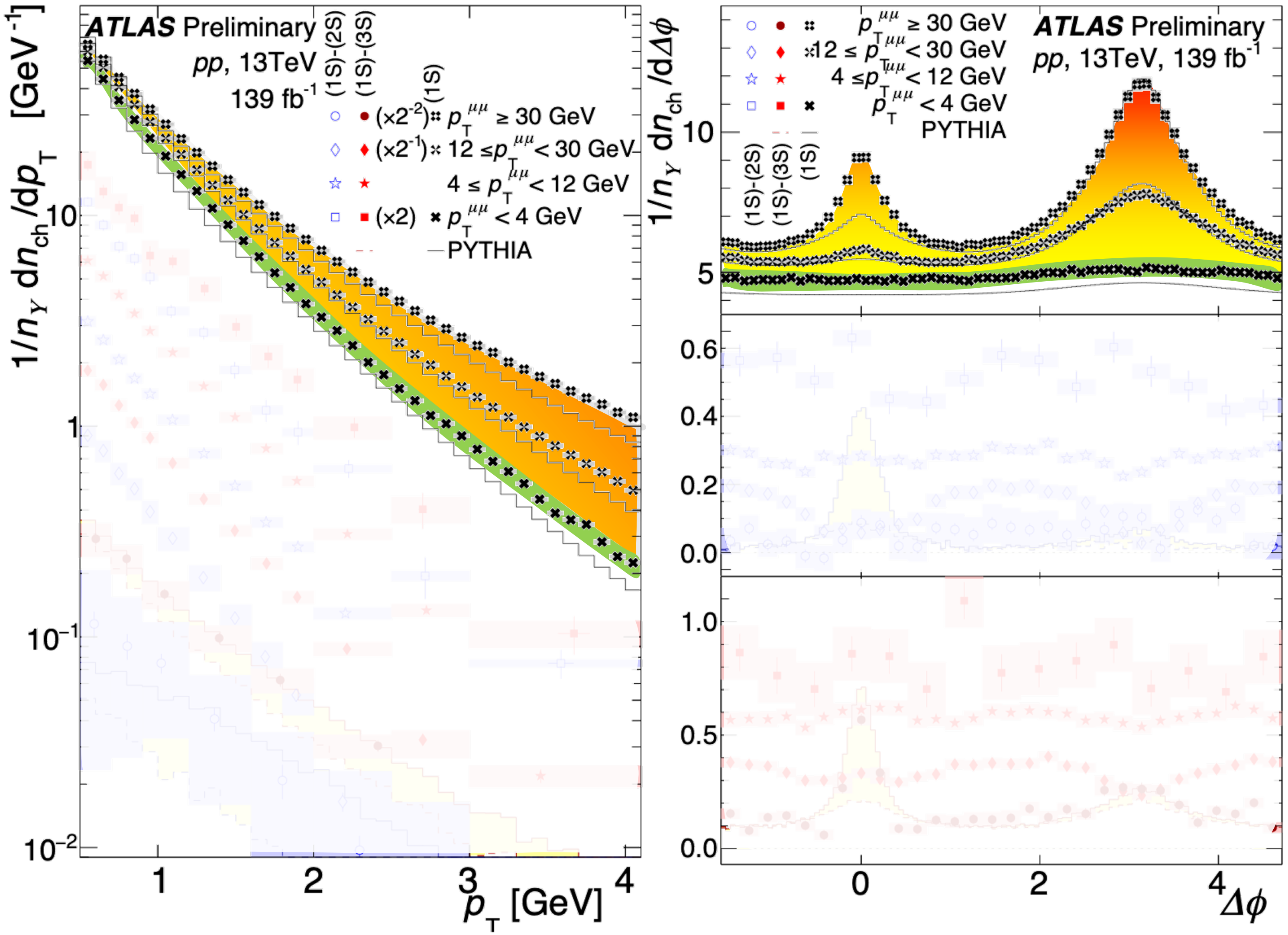
Kinematic distributions





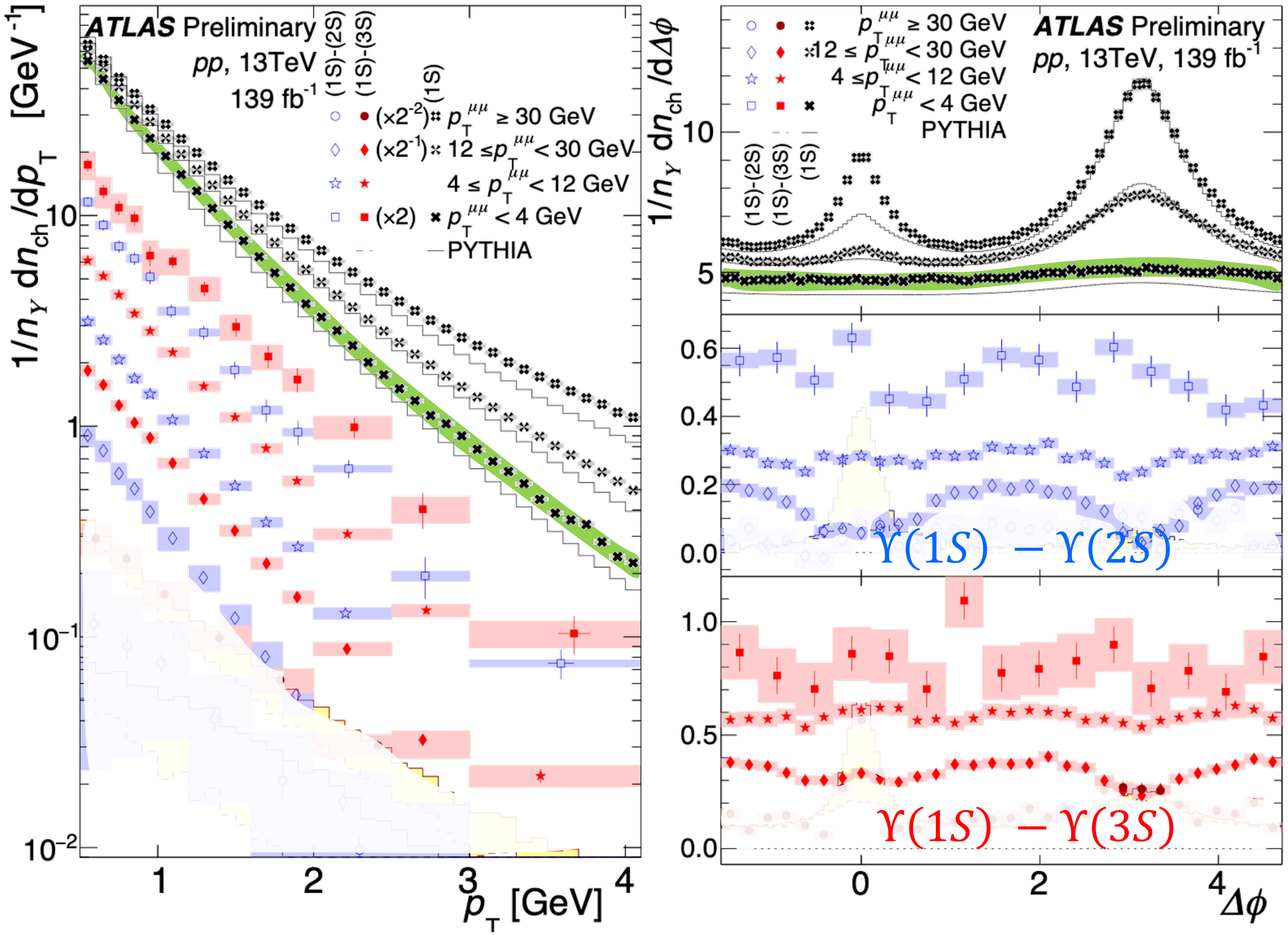
- Distributions for $\Upsilon(1S)$
- Pythia does not describe well
- One cannot measure the UE, but p_T < 4 GeV is the closest to it, jet part that is correlated to $\Upsilon(nS)$

Kinematic distributions



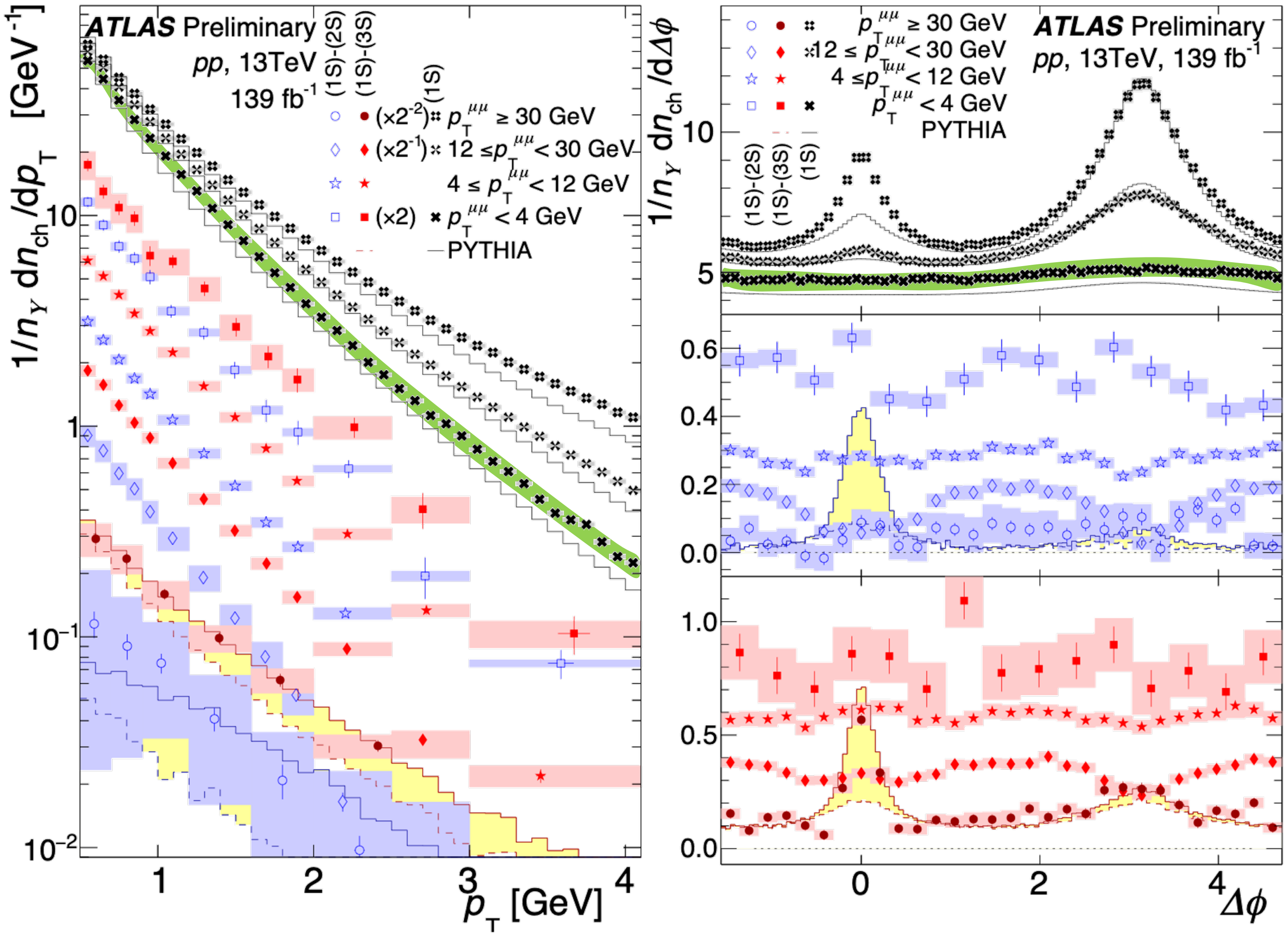
- Distributions for $\Upsilon(1S)$
- Pythia does not describe well
- One cannot measure the UE, but $p_T < 4$ GeV is the closest to it, jet part that is correlated to $\Upsilon(nS)$

Kinematic distributions



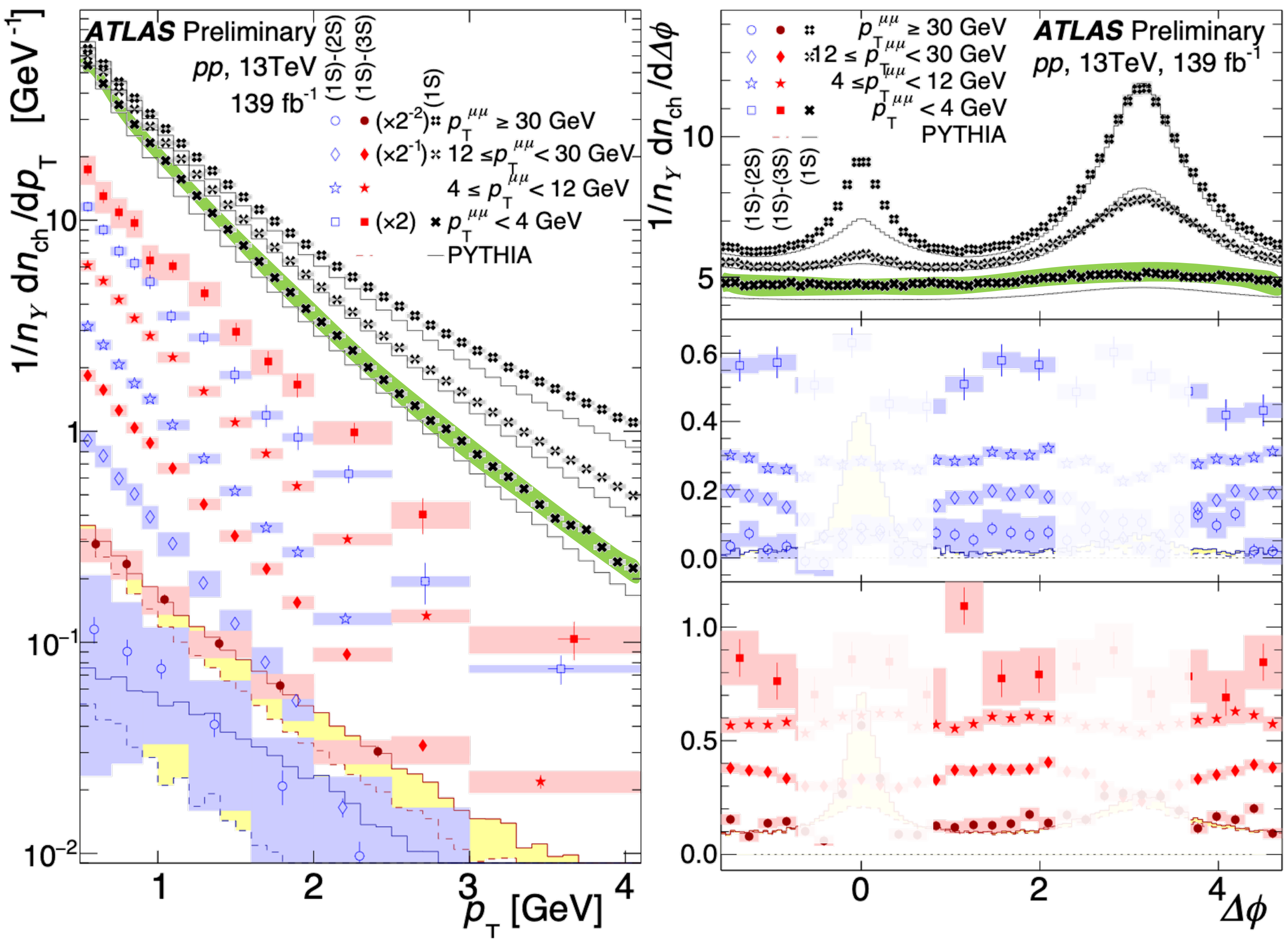
- Distributions for $\Upsilon(1S)$
- Pythia does not describe well
- One cannot measure the UE, but p_T < 4 GeV is the closest to it, jet part that is correlated to $\Upsilon(nS)$

Kinematic distributions



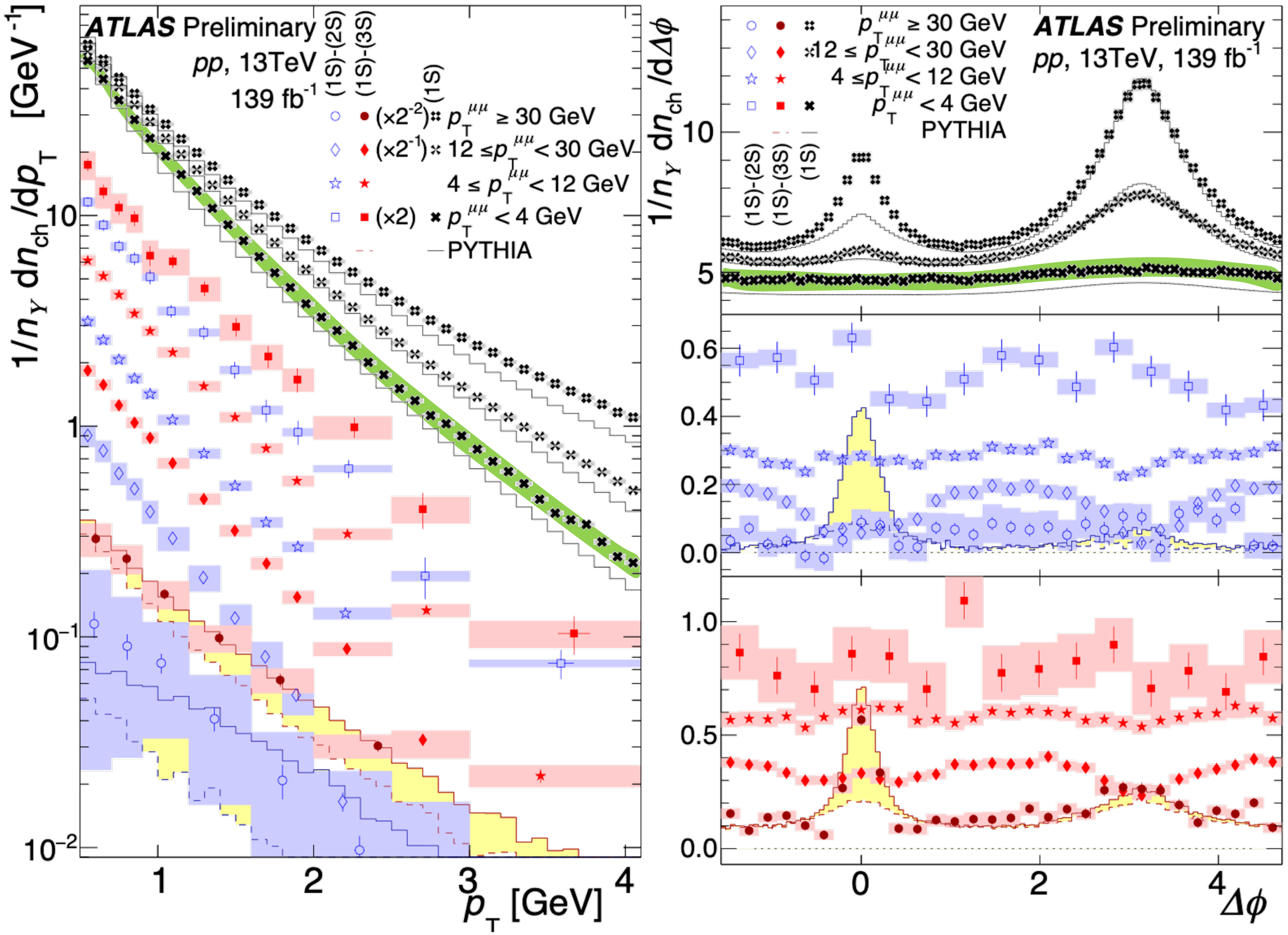
- Distributions for $\Upsilon(1S)$
- Pythia does not describe well
- One cannot measure the UE, but $p_{\mathrm{T}} < 4$ GeV is the closest to it, jet part that is correlated to $\Upsilon(nS)$
- Subtracted distributions look like UE at rather high $\Upsilon(nS)$ p_{T}. At the highest p_{T} there are feed-downs

Kinematic distributions



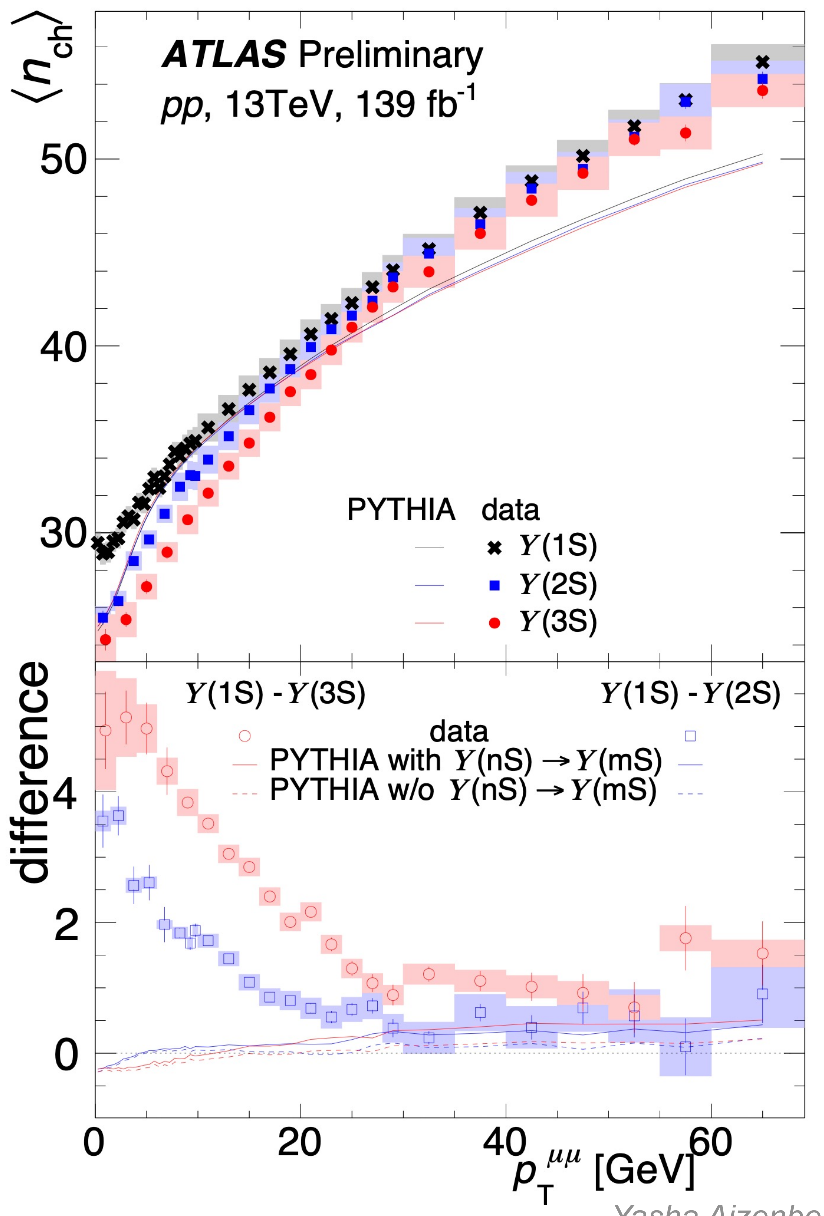
- Distributions for $\Upsilon(1S)$
- Pythia does not describe well
- One cannot measure the UE, but $p_T < 4$ GeV is the closest to it, jet part that is correlated to $\Upsilon(nS)$
- Subtracted distributions look like UE at rather high $\Upsilon(nS)$ p_T. At the highest p_T there are feed-downs
- Away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

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 $\Upsilon(nS)$
- 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



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

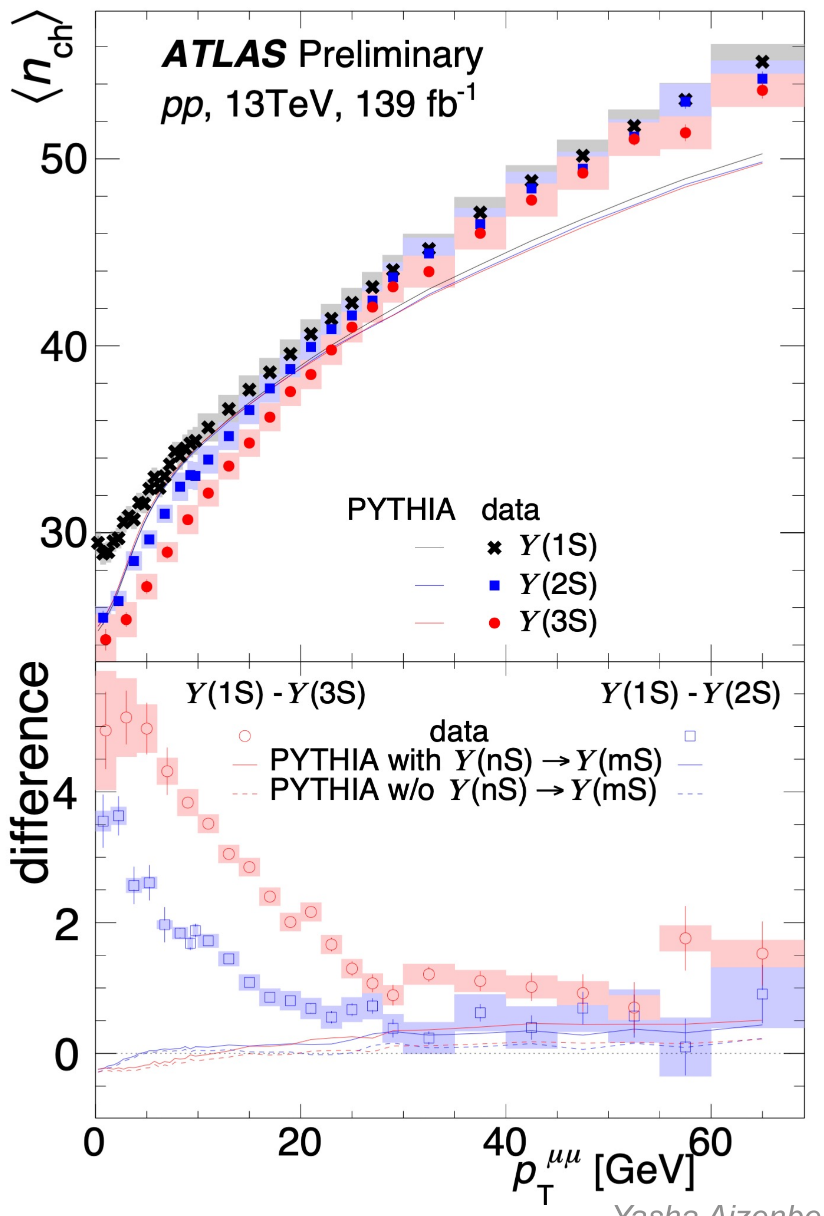
At the lowest p_T, where the effect is the strongest:

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

A naïve question



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

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

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

Let's find them!

The $m_{\rm T}$ scaling

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

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

Today is more commonly used in Tsallis form

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

$m_{\rm T}$ 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

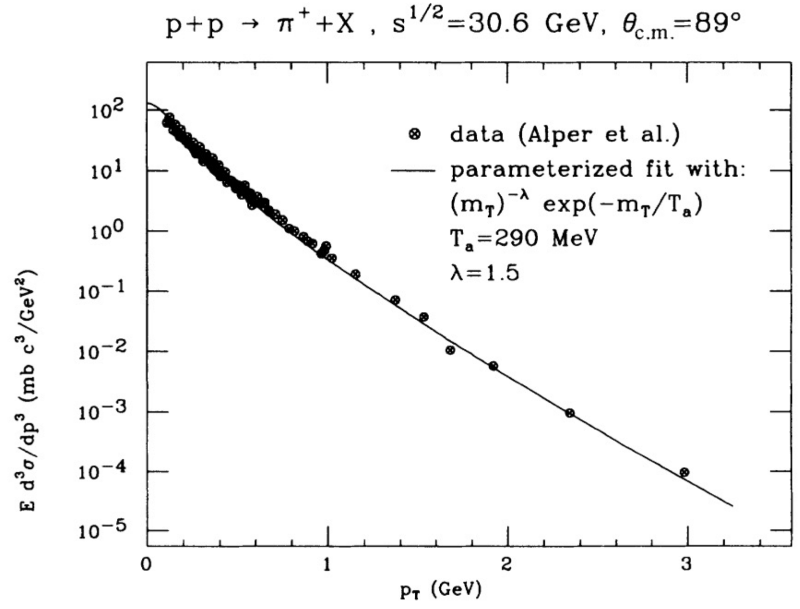
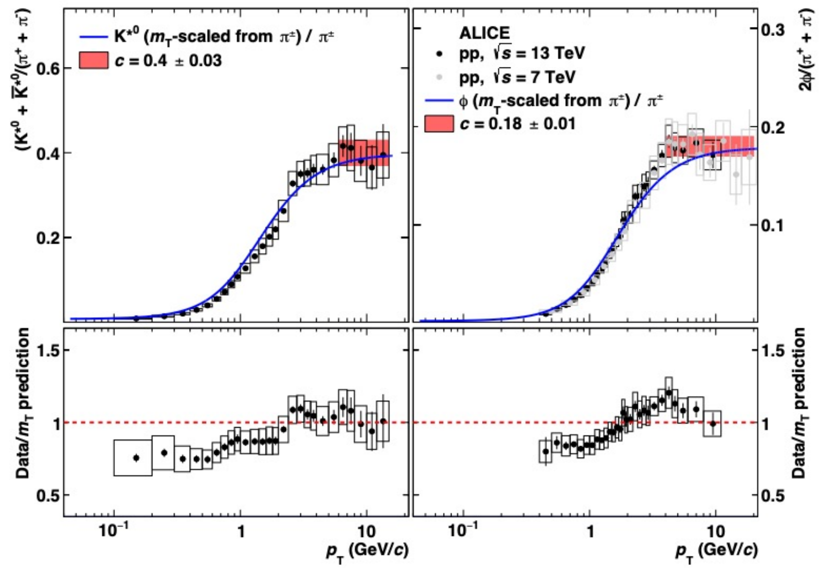
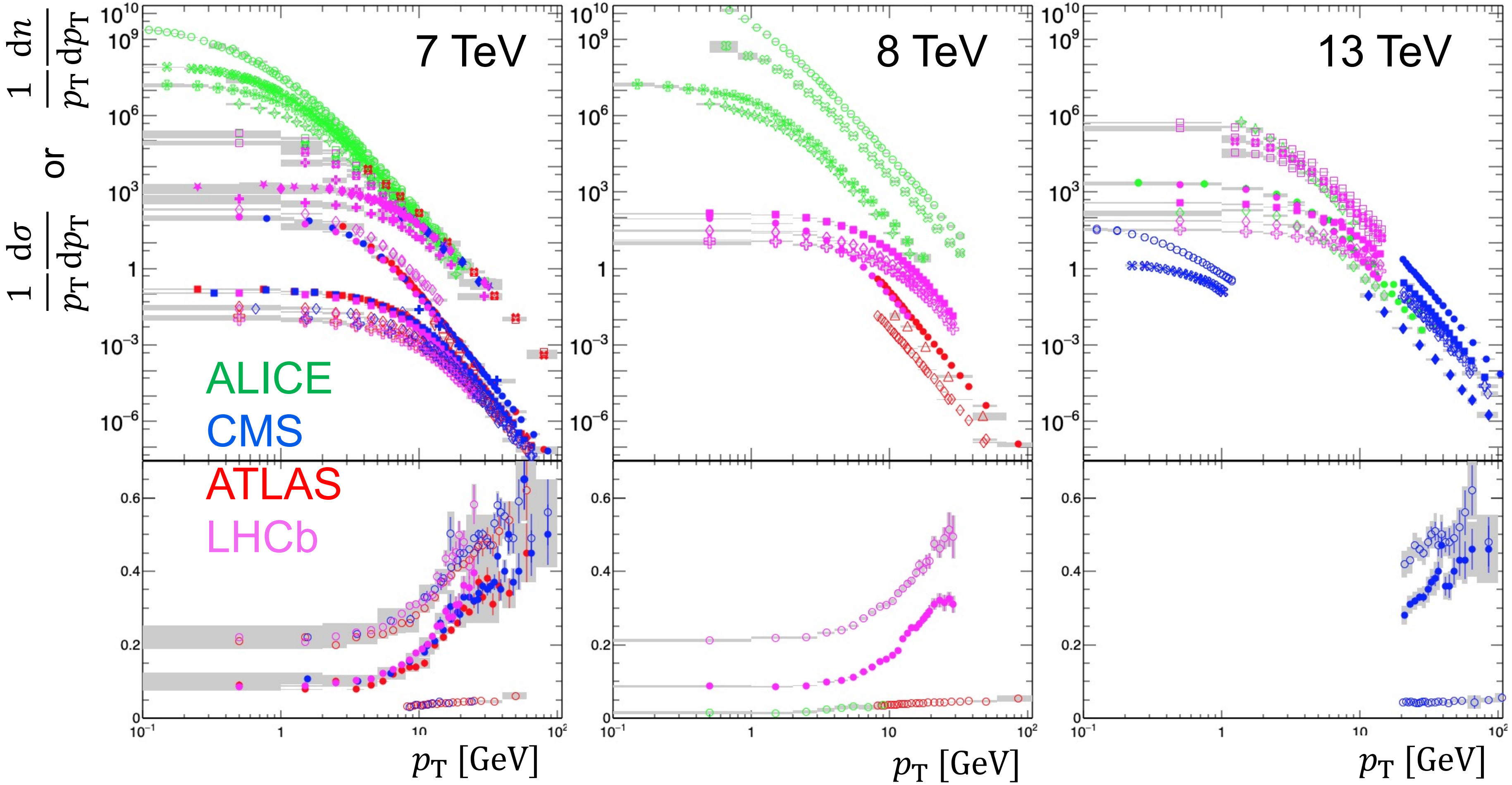


FIG. 3. *p-p* data from Alper *et al.*, fit here with $m_T^{-\lambda}\exp(-m_T/T_a)\times$const, having $T_a=200$ MeV and $\lambda=1.5$.



Let's look at the LHC data



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

Fit to

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

T is fixed to 254 MeV

Spectra at high p_T

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

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*

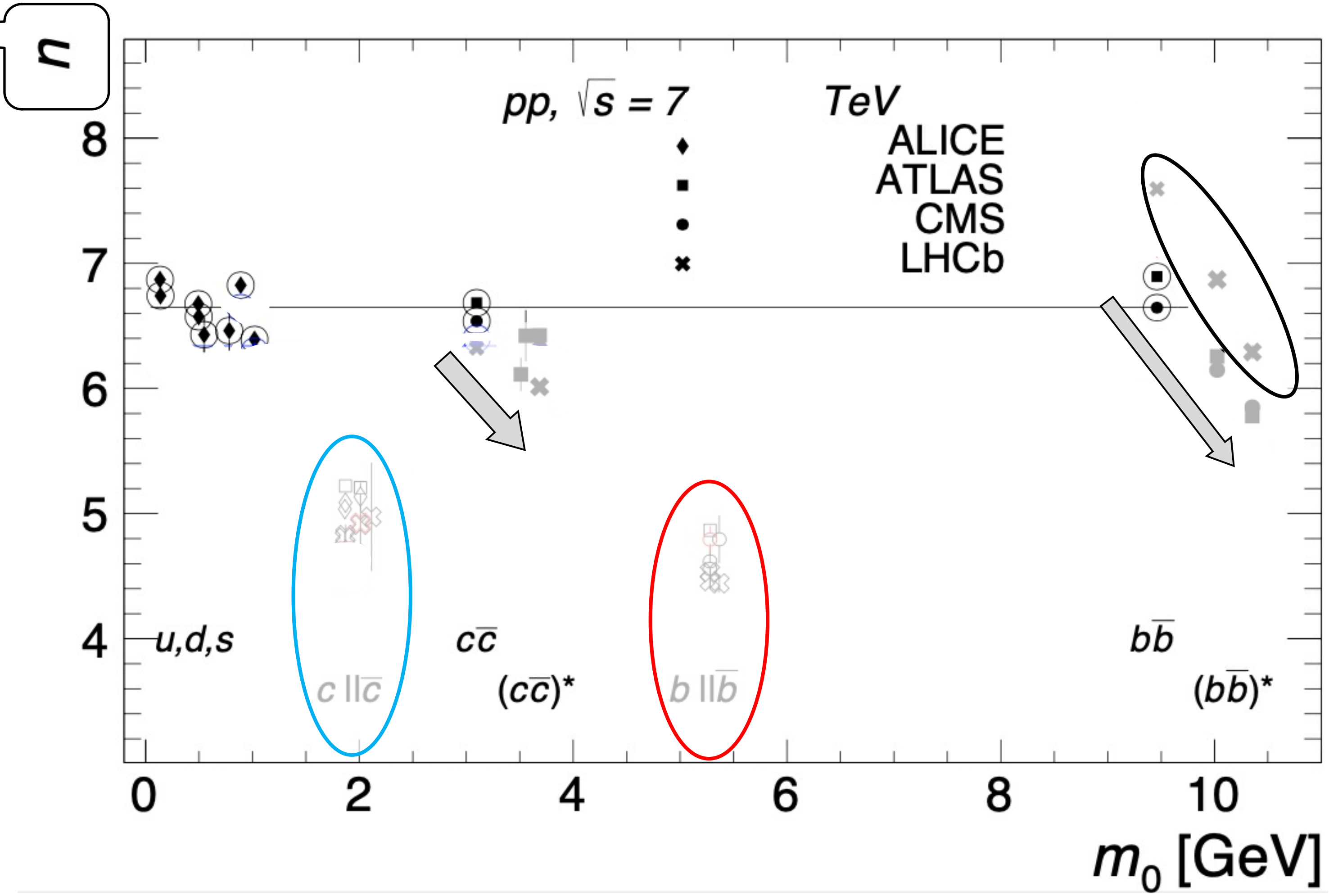
u,d,s & $q\bar{q}$ are fit simultaneously

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

and higher energies as well

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

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



T is fixed to 254 MeV

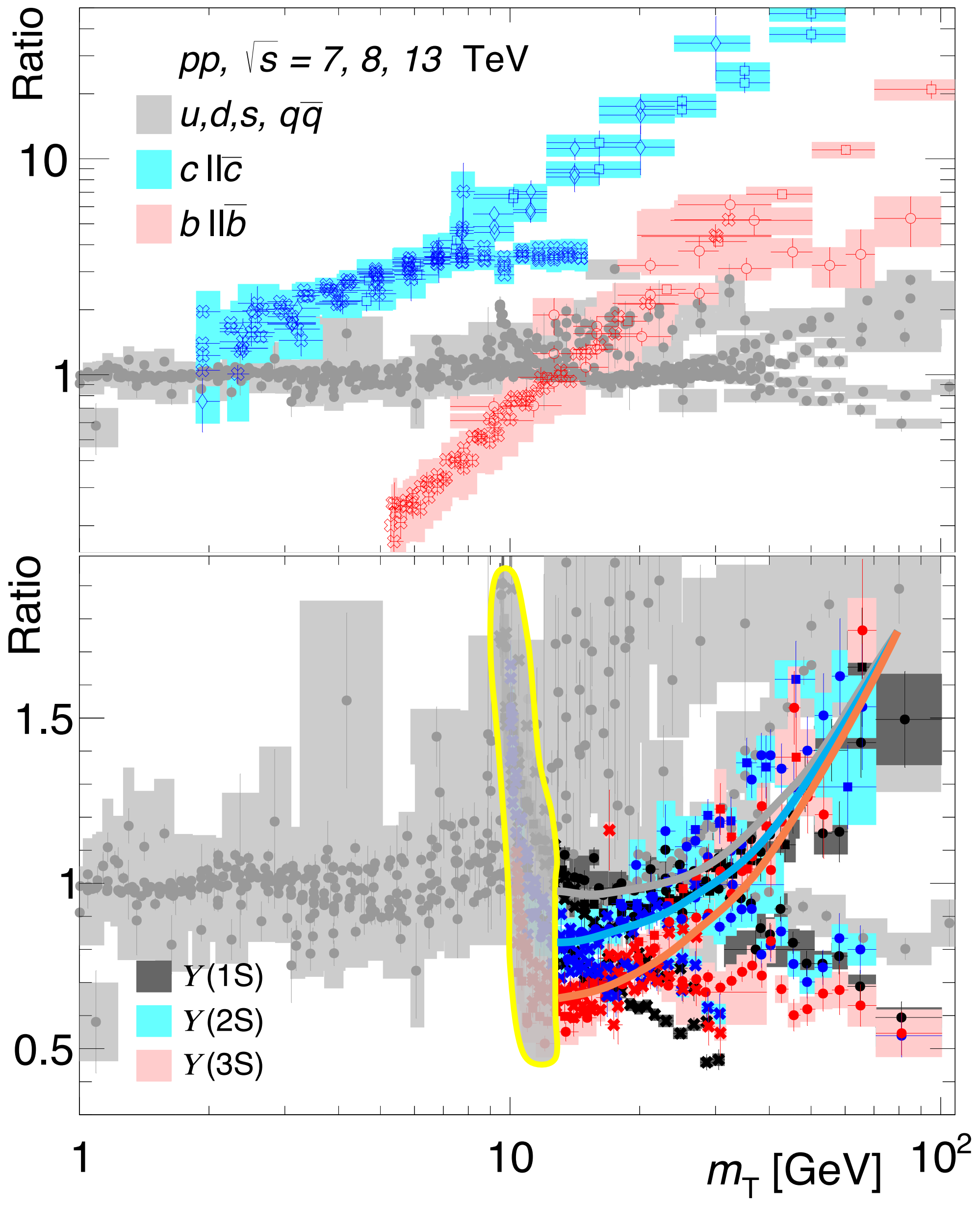
Common fit

Common fit is not perfect (small experimental differences across measurements) but works

$b||\bar{b}$ is harder than $c||\bar{c}$

Spike at low p_T of $\Upsilon(nS)$ likely due to non-prompt component from χ_b decays
χ_b feed-downs are ~same into all $\Upsilon(nS)$

Lower n for $(b\bar{b})^*$ is not a harder spectrum, but a deficit at low and intermediate p_T



Quarkonia ratios: expected & measured

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

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

$\Upsilon(nS)/\Upsilon(1S)$ expected and measured are not the same!

$\sqrt{s}$ dependence is weak, but it is still much stronger than the fitting uncertainties, *i.e.* curves are very robust

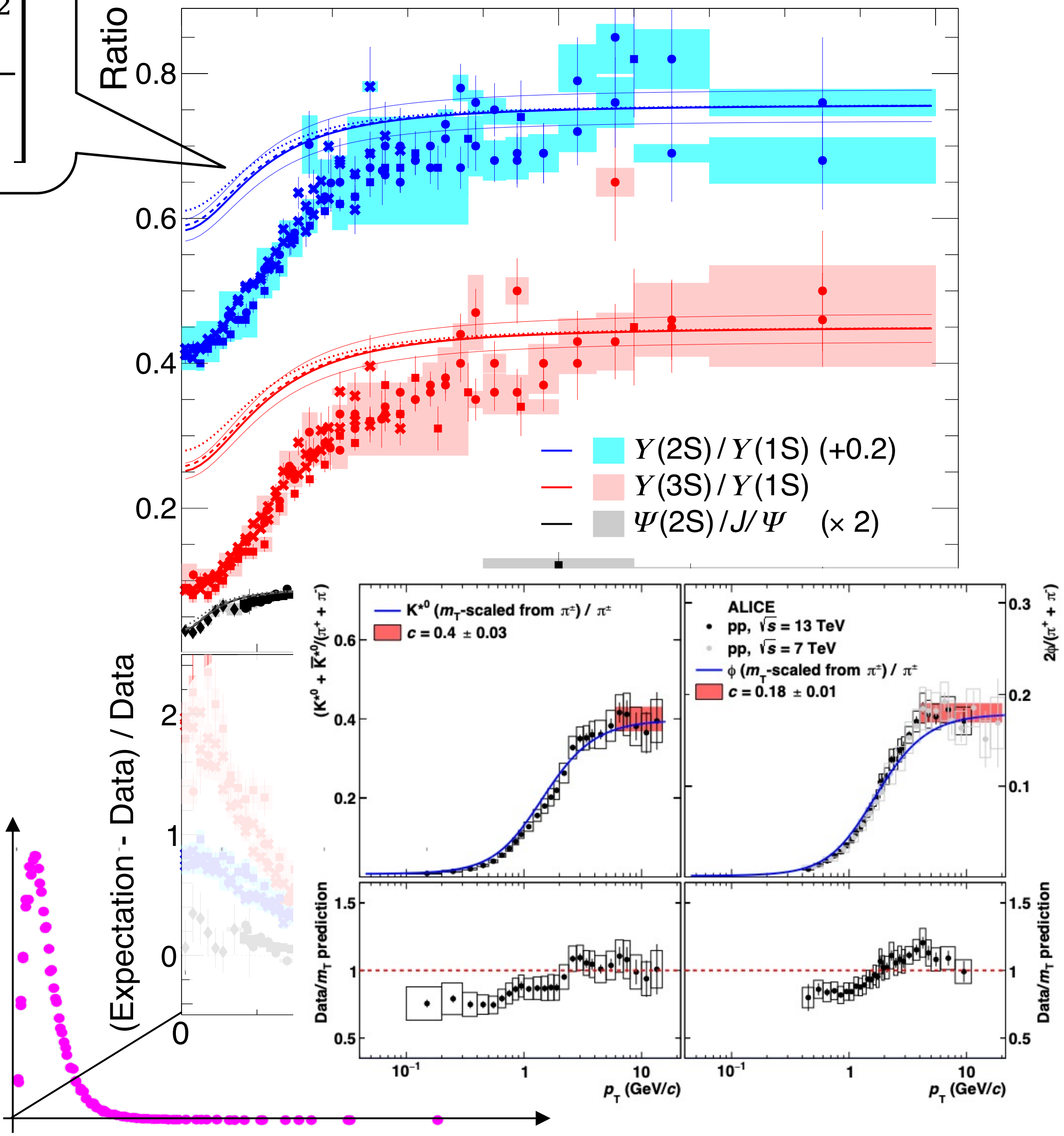
Now one can estimate how many $(q\bar{q})^*$ are missing:

Missing beauty/charm = $\dfrac{Expected}{Measured} - 1$

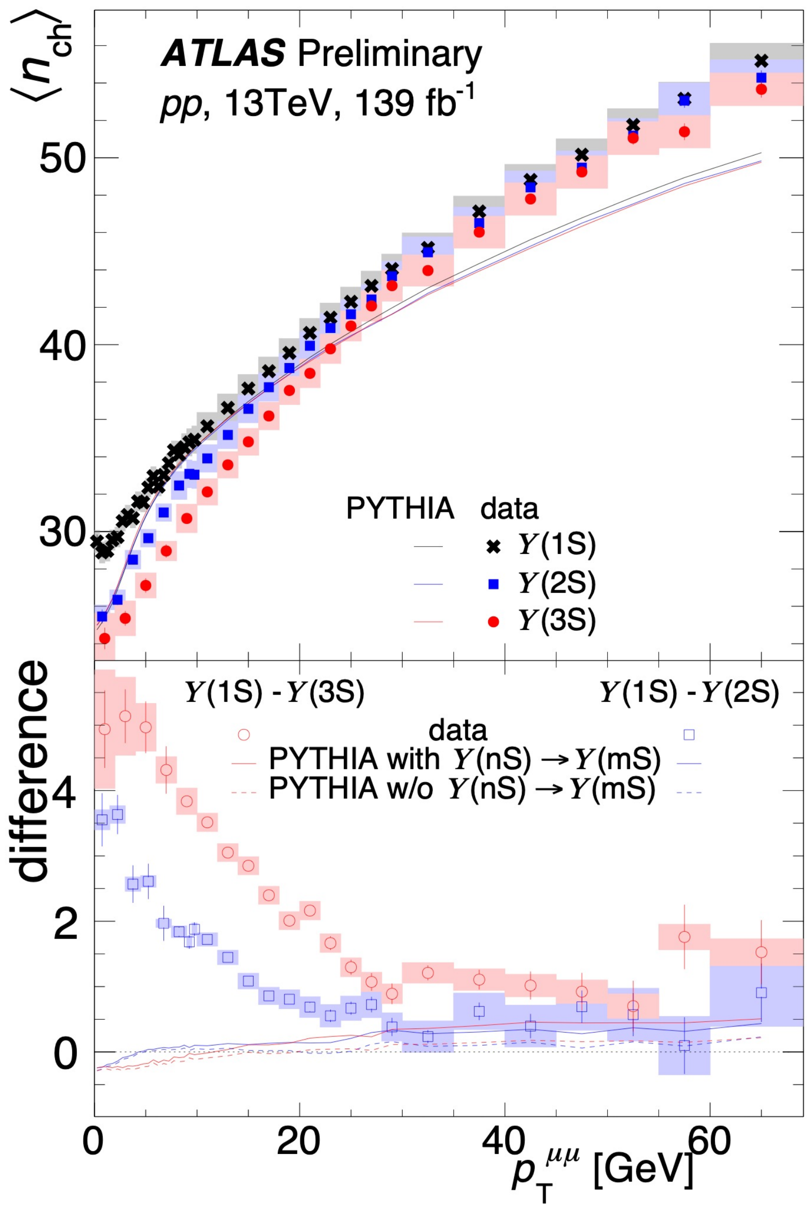
Multiplying by experimental spectra

for $\Upsilon(2S)$ ×1.6 is missing

for $\Upsilon(3S)$ ×2.4!



Let's put pieces together



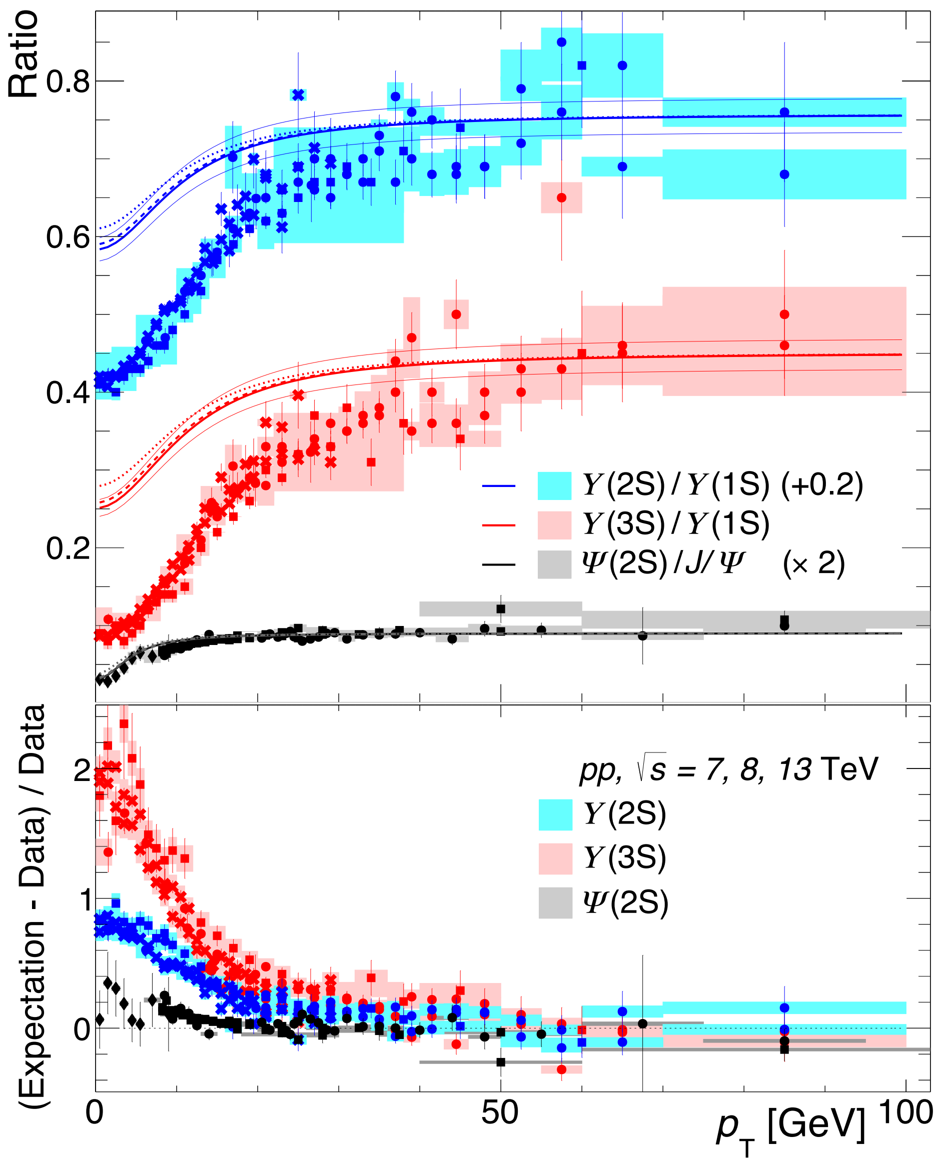
Two different analysis:
- -- particle ratios
- -- n_{ch}

n_{ch} by two experiments:
- -- CMS
- -- ATLAS

Linking effect to the UE:
- -- ATLAS by kinematics
- -- CMS by sphericity

Show analog features:
- -- pT dependence
- -- specie ordering

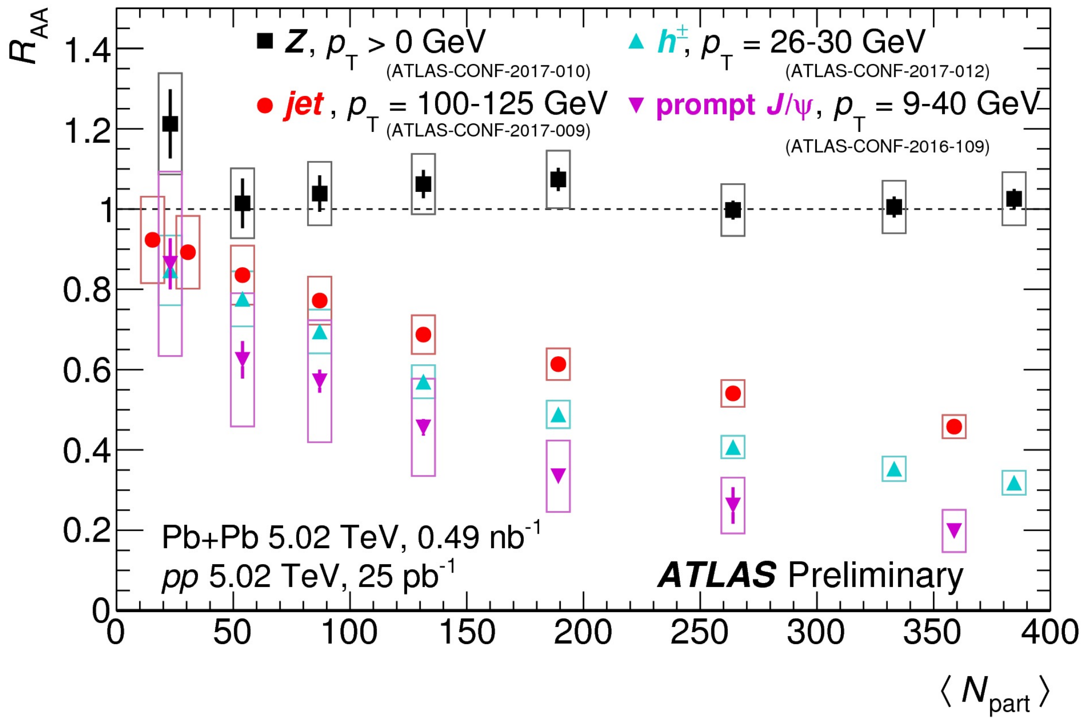
Two manifestations of the same effect:
- -- UE suppresses $\Upsilon(nS)$

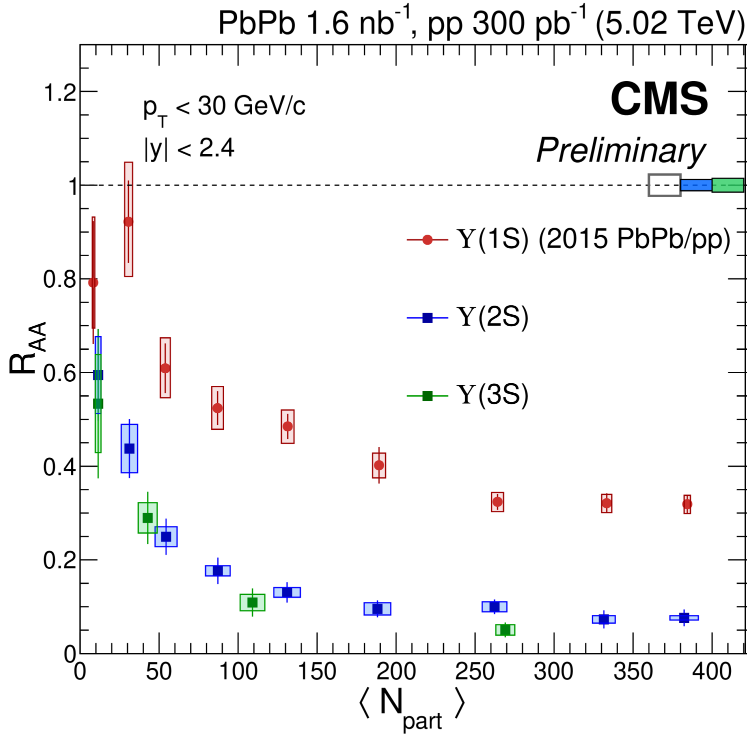


What does it mean

In *pp* collisions there exists a mechanism by which particles produced in a scattering of two energetic partons are affected by the particles produced in other parton scatterings

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

It may not be that simple

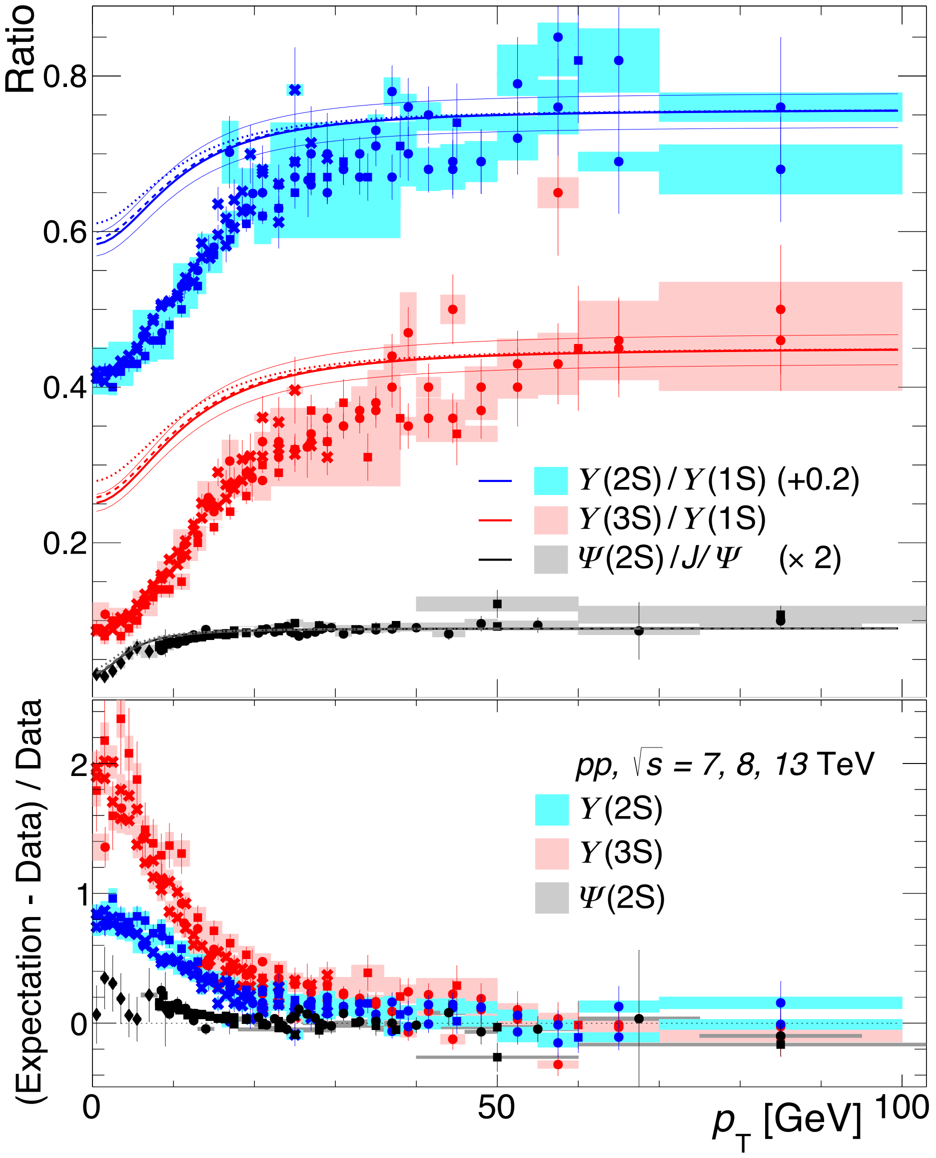
It would be logical to assume that the effect is related to the $q\bar{q}$ binging energy, but then $\psi(2S)$ must show a lot more suppression.

n_{ch} for $\psi(2S)$ shall be measured

EPJC (2018) 78:731

Table 1 Binding energies of the quarkonia shown in Fig. 3

Quarkonium	E_b (MeV)	Quarkonium	E_b (MeV)
$\chi_{b2}(3P)$	36	χ_{c0}	315
$\psi(2S)$	44	$\chi_{b0}(3P)$	326
$\chi_{b1}(3P)$	47	$\Upsilon(2S)$	536
$\chi_{b0}(3P)$	62	J/ψ	633
χ_{c2}	174	$\chi_{b2}(1P)$	647
$\Upsilon(3S)$	204	$\chi_{b1}(1P)$	666
χ_{c1}	219	$\chi_{b0}(1P)$	700
$\chi_{b2}(2P)$	290	$\Upsilon(1S)$	1099
$\chi_{b1}(3P)$	304		



What's next?

n_{ch} for $\psi(2S)$ to J/ψ – what is going on?

Does it hold at lower energies? Strong $\sqrt{s}$ dependence isn't anticipated, but...

In principle CDF data shall be sufficient to measure $\Upsilon(nS)$ at 1.96 TeV

RHIC data is probably too small, but RICH-II and the detectors are coming up

SPS may do $\psi(2S)$

EIC as a very different (and smaller) system shall be interesting

Above all, we need theoretical support for understanding the nature of the effect

Instead of a summary

In *pp* collisions there exists a mechanism by which particles produced in a scattering of two energetic partons are affected by the particles produced in other parton scatterings

Thank you for your attention!!!