ATLAS EXPERIMENT

measurement of correlations between Y mesons and inclusive charged particles

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מכון ויצמן למדע
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Physics Motivation

- Heavy Ion Collisions is a tool to create hot and dense QCD medium (QGP)

- How small can the system be to form QGP?

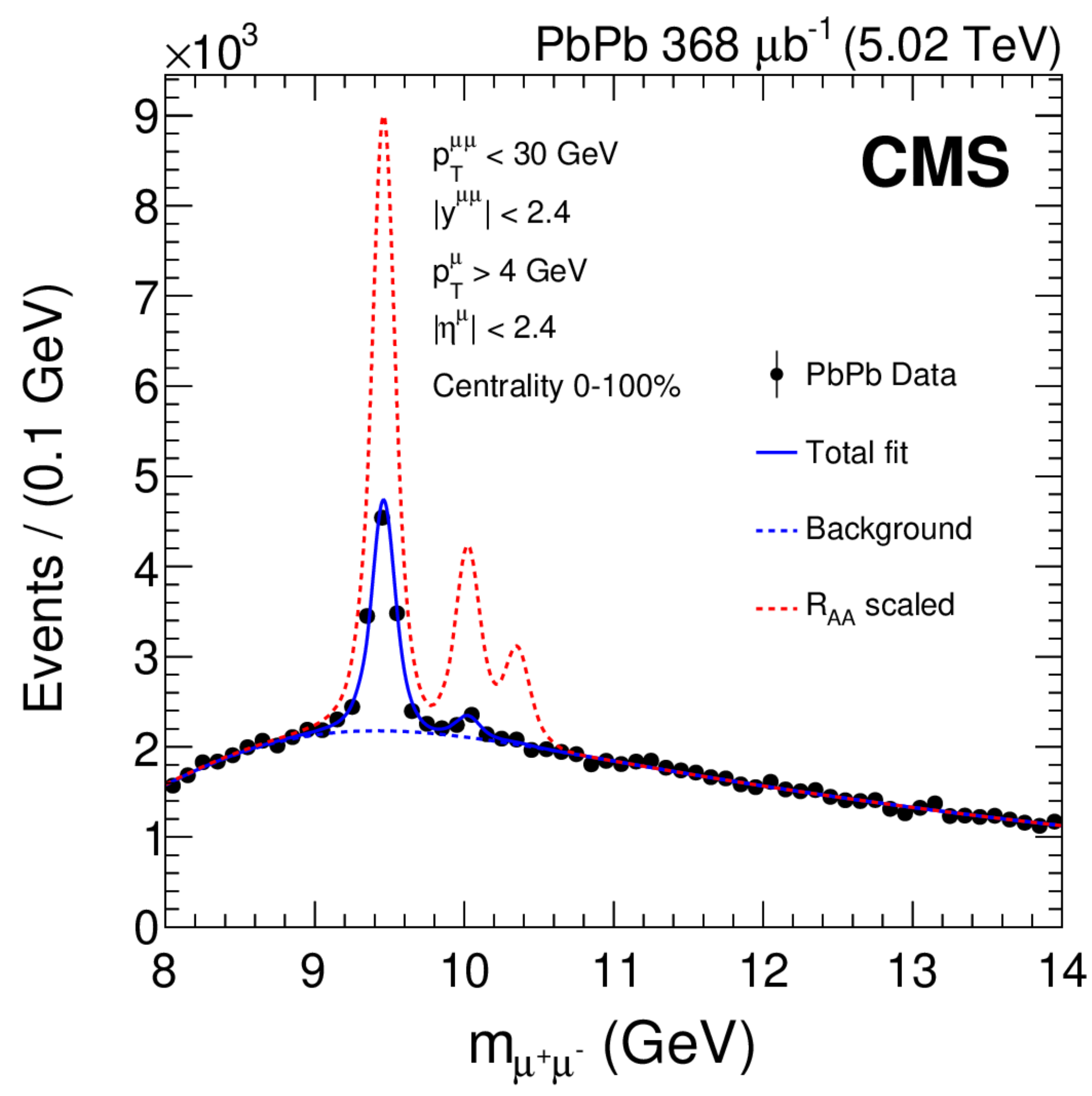
- Observables:
  Global (kinematic distribution, particle composition)
  Correlations & Fluctuations (multiparticle correlations, etc.)
  Heavy Flavor & Quarkonia (J/Psi, Y, D, etc)
  High-p_T Probes (jets, EW bosons)

- Currently there are not many measurements in hard probe class of signatures that point to QGP in small systems

- However, *pp* demonstrates QGP-like signatures that belong to **soft** physics

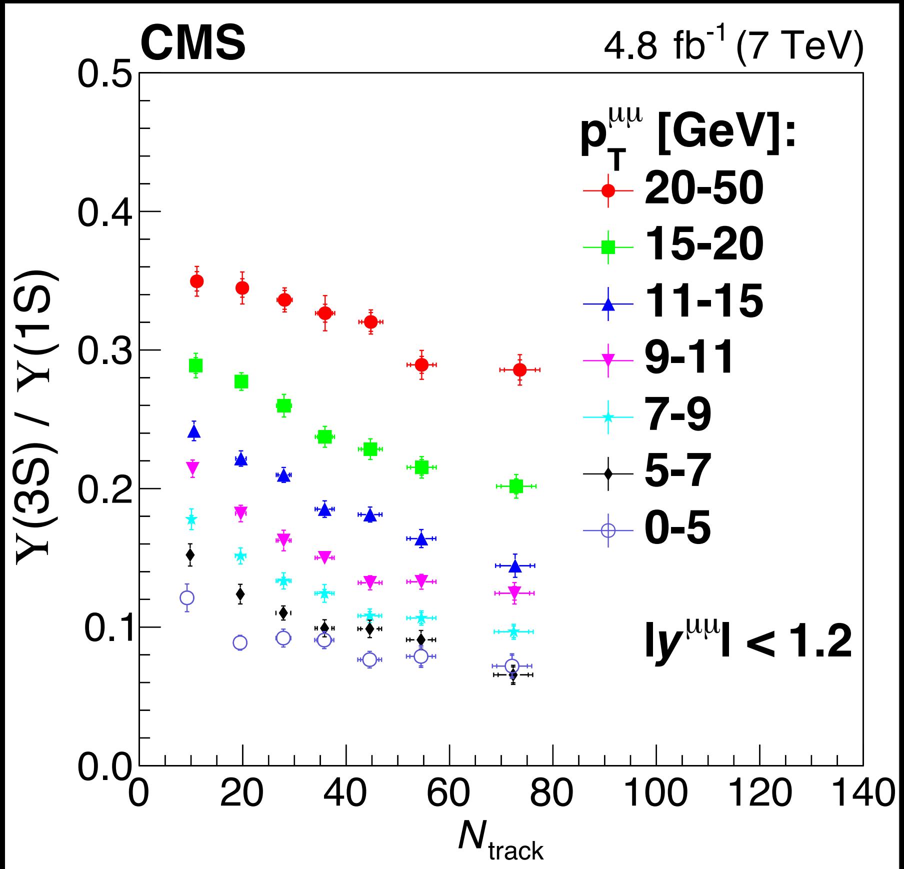
Why Upsilons?

Phys. Lett. B 790 (2019) 270



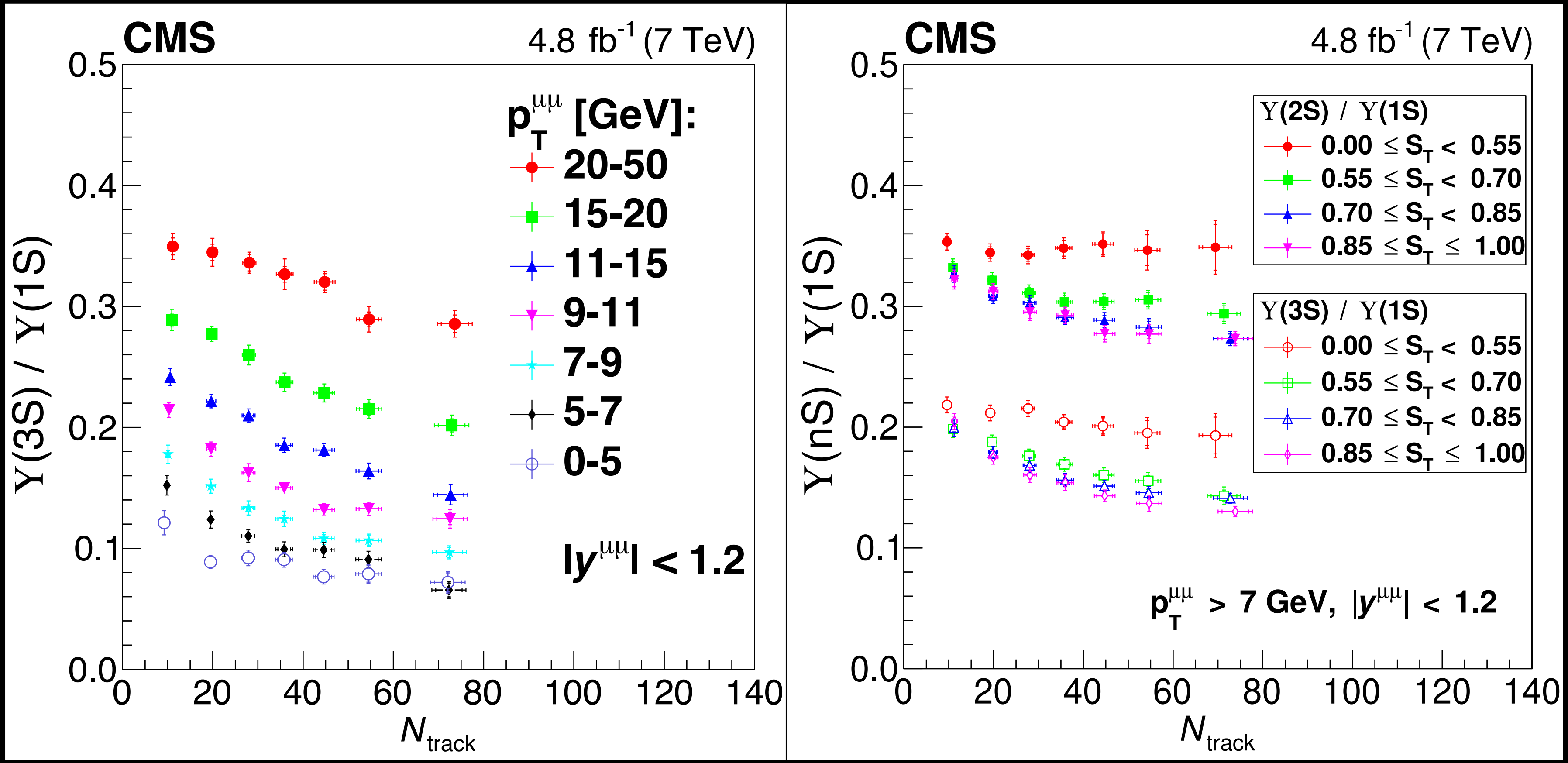
- Among hard probes, Upsilon states are most sensitive to QGP in A+A systems
- Sequential suppression of Upsilon states
- QGP explanation: size of the excited Upsilon states are larger → easier to melt inside the hot and dense matter compared to lower states

CMS Results



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

CMS Results



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

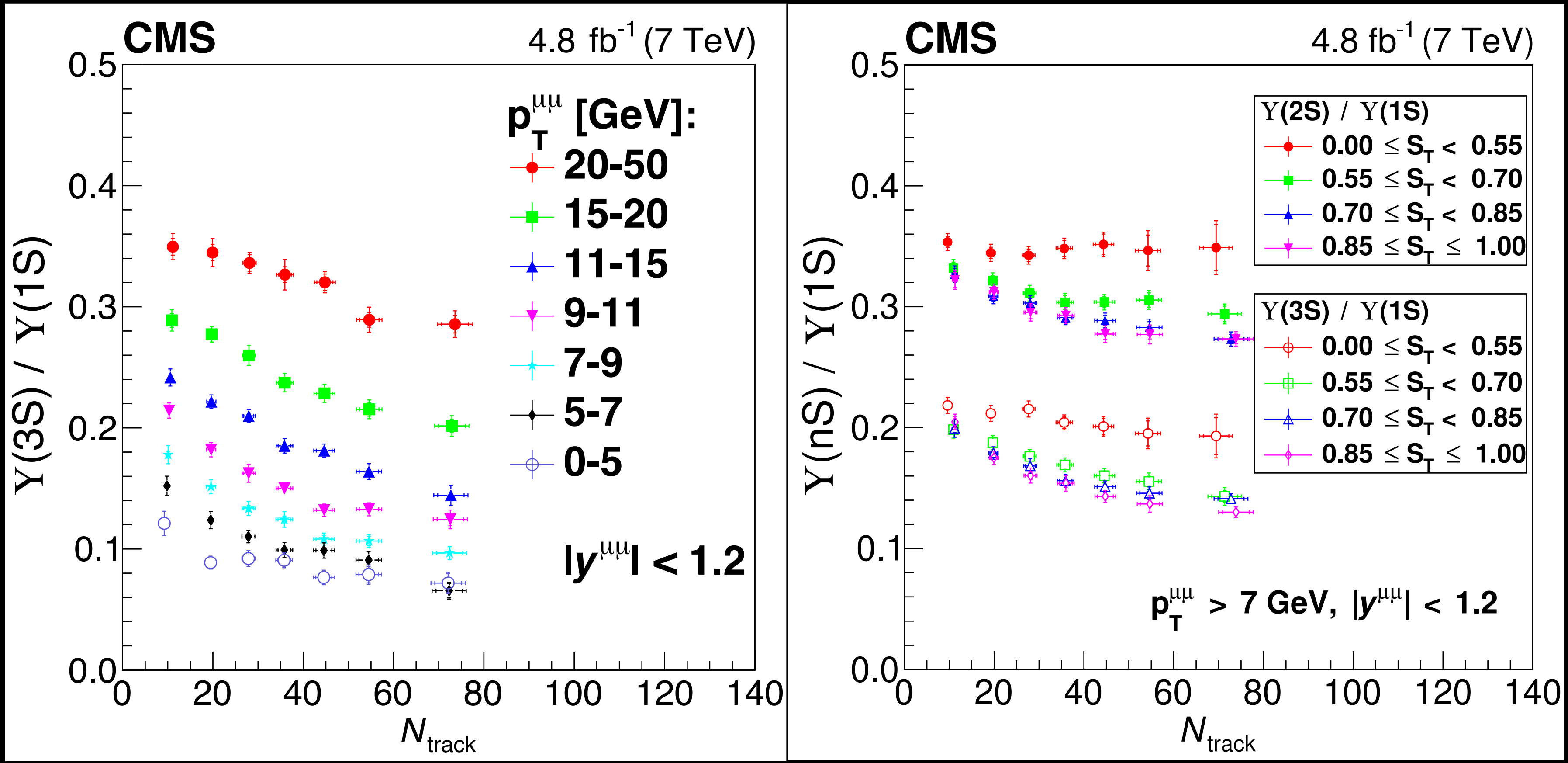
Transverse sphericity- momentum space variable, commonly classified as an event shape observable.

$S_T = 0$ – jets

$S_T = 1$ - Underlying Event

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

CMS Results



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

Approach

- Search for modification of the Underlying Event (UE) for different Upsilon states in pp collisions.

- UE is characterized by the collection of charged particles not directly involved in the formation of the Upsilon state produced in the collision.

- How: measurement of the multiplicity of the charged hadrons in the UE where the Upsilon is observed

- Data: Run-2 13 TeV pp data at full luminosity

Event & Track Selection

Event Selection:

- Selected by dimuon Upsilon trigger
- $\Upsilon \rightarrow \mu\mu$:
  - $p_T^{\mu} > 4\ GeV, |\eta^{\mu}| < 2.4$
  - Selected muons should point to the event vertex
- $8.2\ GeV < \ m_{\mu\mu} < 11.8\ GeV$
- $|y^{\mu\mu}| < 1.6$
- $\mu < 50$

Track Selection:

- $0.5 < p_T < 10\ GeV, |\eta| < 2.5$
- Track should point to the event vertex
- Muons from Upsilon decays are excluded

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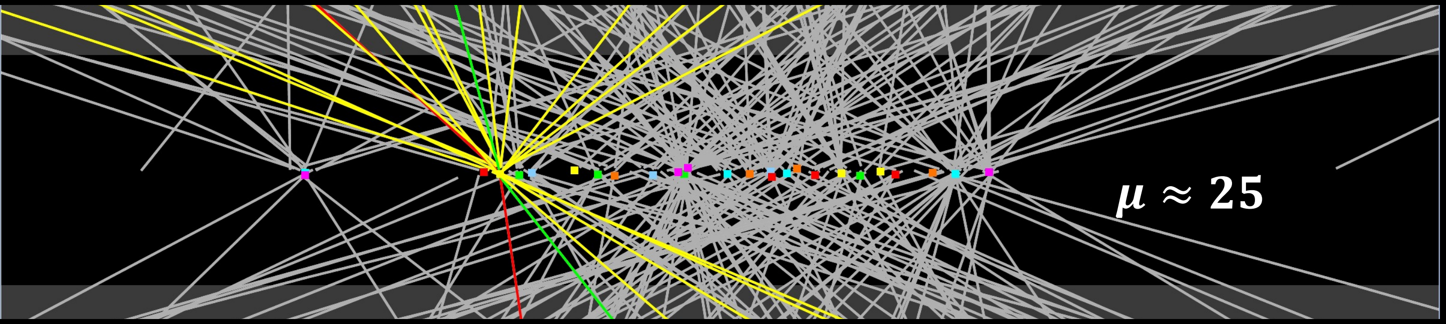
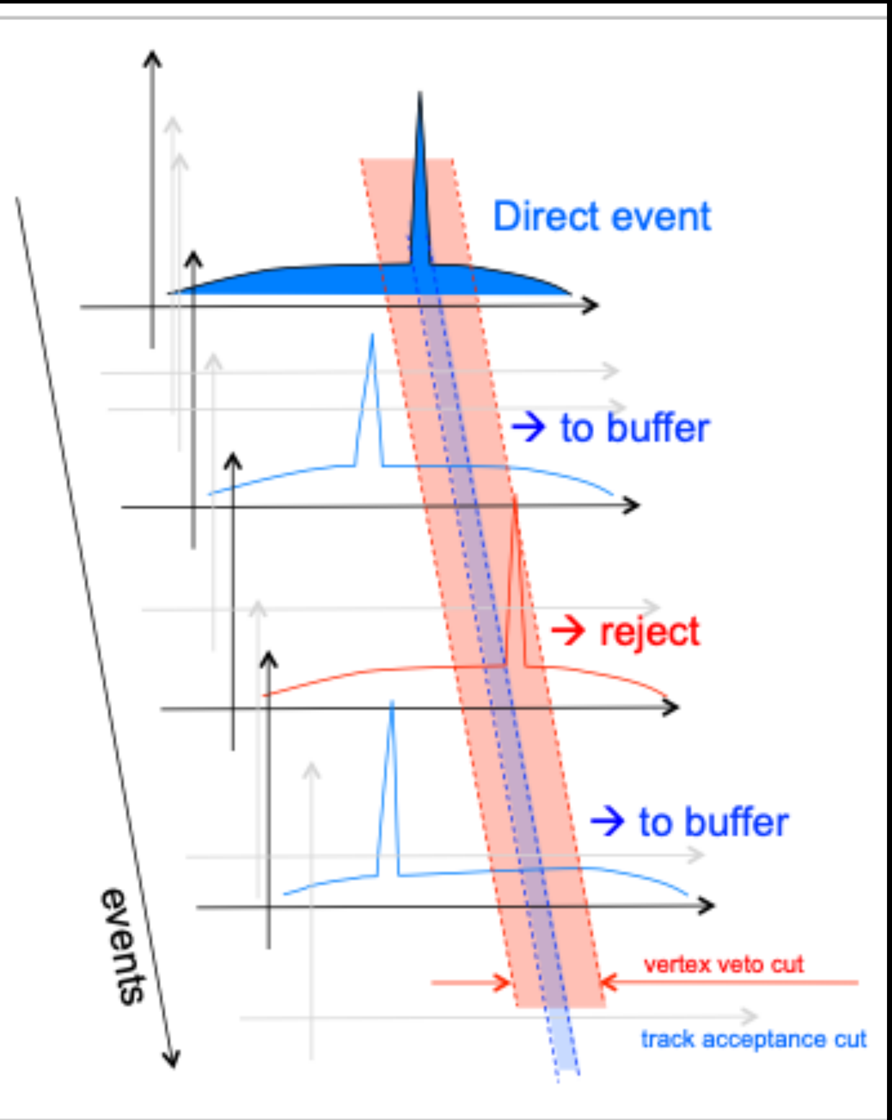


Pile-Up Evaluation

Eur. Phys. J. C **80,** 64 (2020)

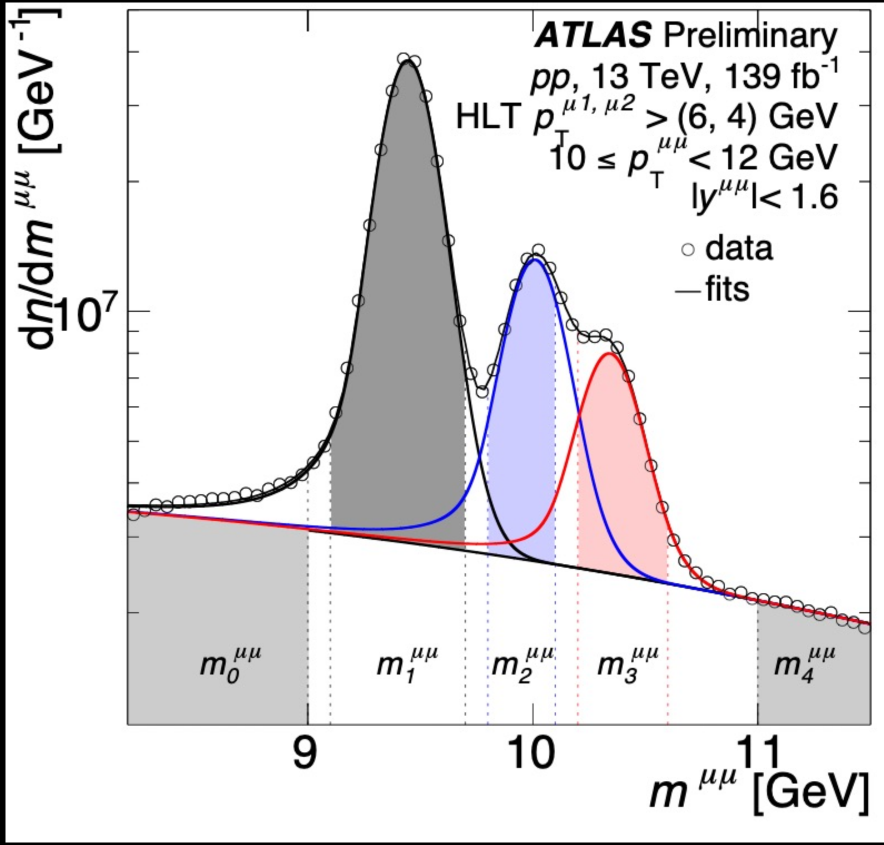


- Pile-Up (PU) is the collision that occur in addition to the process of interest.
- Selected tracks still contain a fraction that is coming from the PU. They cannot be rejected, but their contribution can be measured by the mixed event technique. Mixed event technique constructs the PU contribution of the event from other events present in the data.
- We start with the events sample and isolate one event (***Direct***)
- In the same run we search for events taken at the same instantaneous luminosity.
- If the vertex in the other events is within 15mm of the ***Direct***, it's not considered.
- Tracks are selected to ***Mixed*** event, if they satisfy vertex pointing in longitudinal plane w.r.t. vertex of the ***Direct*** event.
- Procedure repeats N=20 times for each ***Direct*** event to increase statistics.
- Properties of ***Mixed*** event distributions depend on the average number of PU tracks in an event ν.
- $\nu < 20$ in 40 intervals!!!

Fitting Procedure

- Fit MC simulated distributions independently for each Y(nS) and constrain or fix parameters responsible for the shape of the peaks
- Parametrize $p_T^{\mu\mu}$ dependence of the fit parameters responsible for the shape
- Use parametrizations to fit the data, keeping peak amplitudes and background free
    - Background ~ Jets + DY
- Relax shape parameters in the data one at a time and adjust $p_T^{\mu\mu}$ dependencies for those parameters that can be reliably exctracted from the data
- Parametrize background as a function of $p_T^{\mu\mu}$

$$\begin{aligned}
\mathrm{fit}\,(m) &= \sum_{\mathrm{nS}} N_{\Upsilon(\mathrm{nS})} F_{\mathrm{nS}}(m) + N_{\mathrm{bkg}} F_{\mathrm{bkg}}(m) \\
F_{\mathrm{nS}}(m) &= (1-\omega_{\mathrm{nS}}) CB(m, \mathrm{nS}) + \omega_{\mathrm{nS}} G(m, \mathrm{nS}) \\
F_{\mathrm{bkg}}(m) &= P_3(m) = \sum_{n=0}^{3} a_n (m - M_0)^n ; a_0 = 1
\end{aligned}$$



Extraction of n_{ch} distribution

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

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

$$
f_{nk} = \frac{\int_{m_n^{\mu\mu}} N_{\Upsilon(kS)} F_k(m)\,dm}{\int_{m_n^{\mu\mu}} \mathrm{fit}(m)\,dm}
$$

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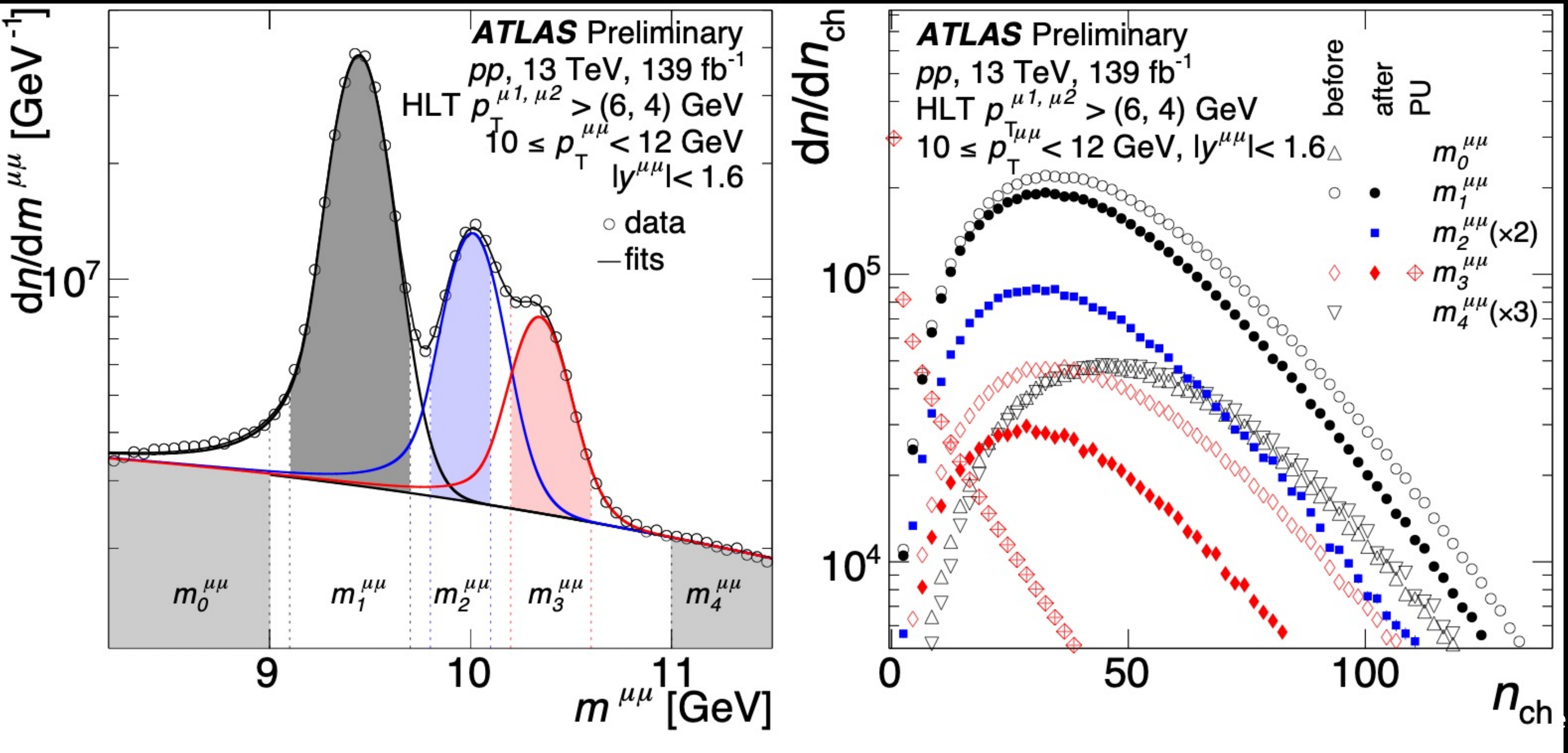
k_n = \frac{\langle F_{\mathrm{bkg}}(m)\rangle|_{m_4^{\mu\mu}} - \langle F_{\mathrm{bkg}}(m)\rangle|_{m_n^{\mu\mu}}}{\langle F_{\mathrm{bkg}}(m)\rangle|_{m_4^{\mu\mu}} - \langle F_{\mathrm{bkg}}(m)\rangle|_{m_0^{\mu\mu}}}
$$



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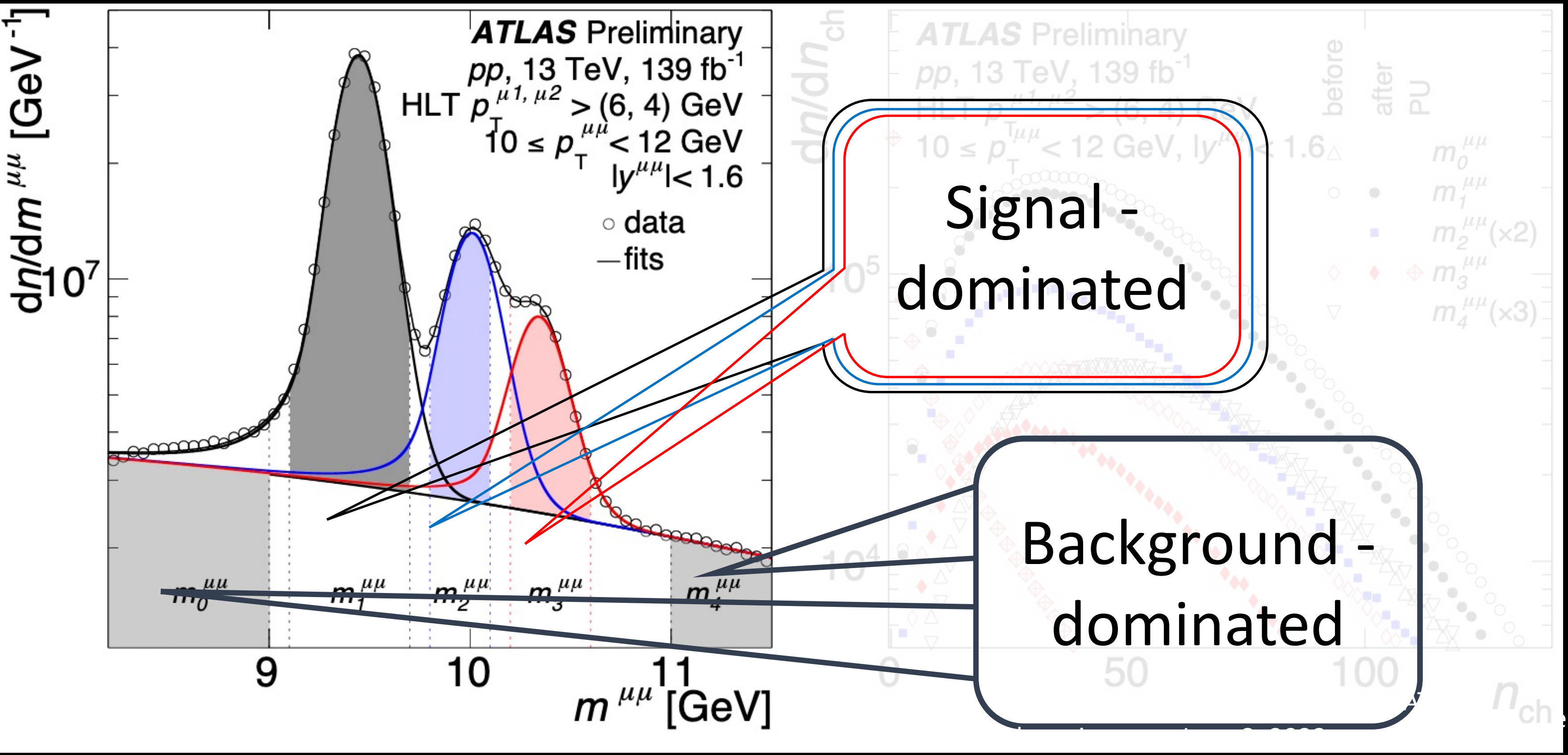
k_n = \frac{\langle F_{\mathrm{bkg}}(m)\rangle|_{m_4^{\mu\mu}} - \langle F_{\mathrm{bkg}}(m)\rangle|_{m_n^{\mu\mu}}}{\langle F_{\mathrm{bkg}}(m)\rangle|_{m_4^{\mu\mu}} - \langle F_{\mathrm{bkg}}(m)\rangle|_{m_0^{\mu\mu}}}
$$



- Introduce five mass regions – three for Upsilons and two for the background
- Selecting events in those mass regions one can measure UE multiplicity and kinematic distributions

Extraction of n_{ch} distribution

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

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

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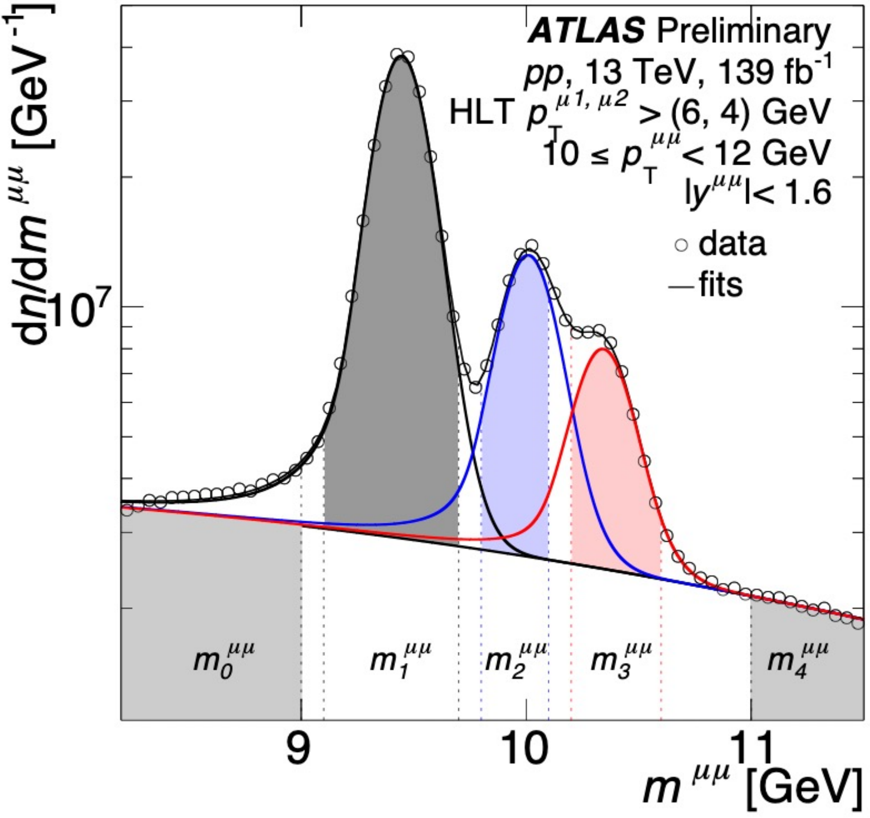

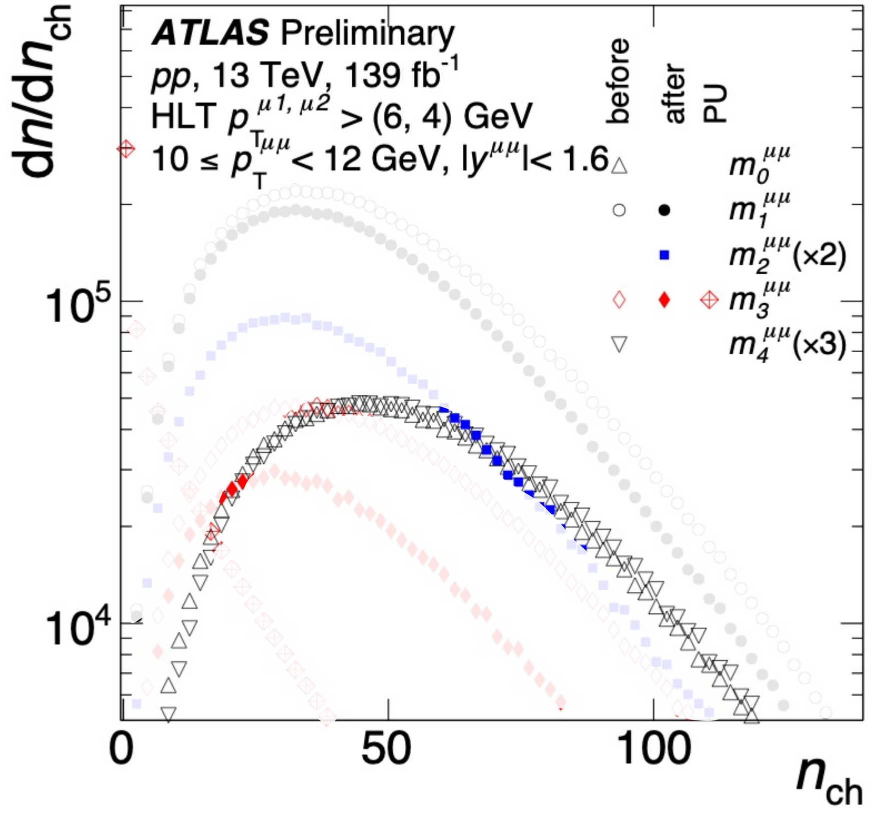

Extracting n_{ch} distributions for background dominated mass regions, one can see that the background in the ‘upper-mass’ and ‘lower-mass’ regions are quite similar in shape → side-band subtraction works well!

Extraction of n_{ch} distribution

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

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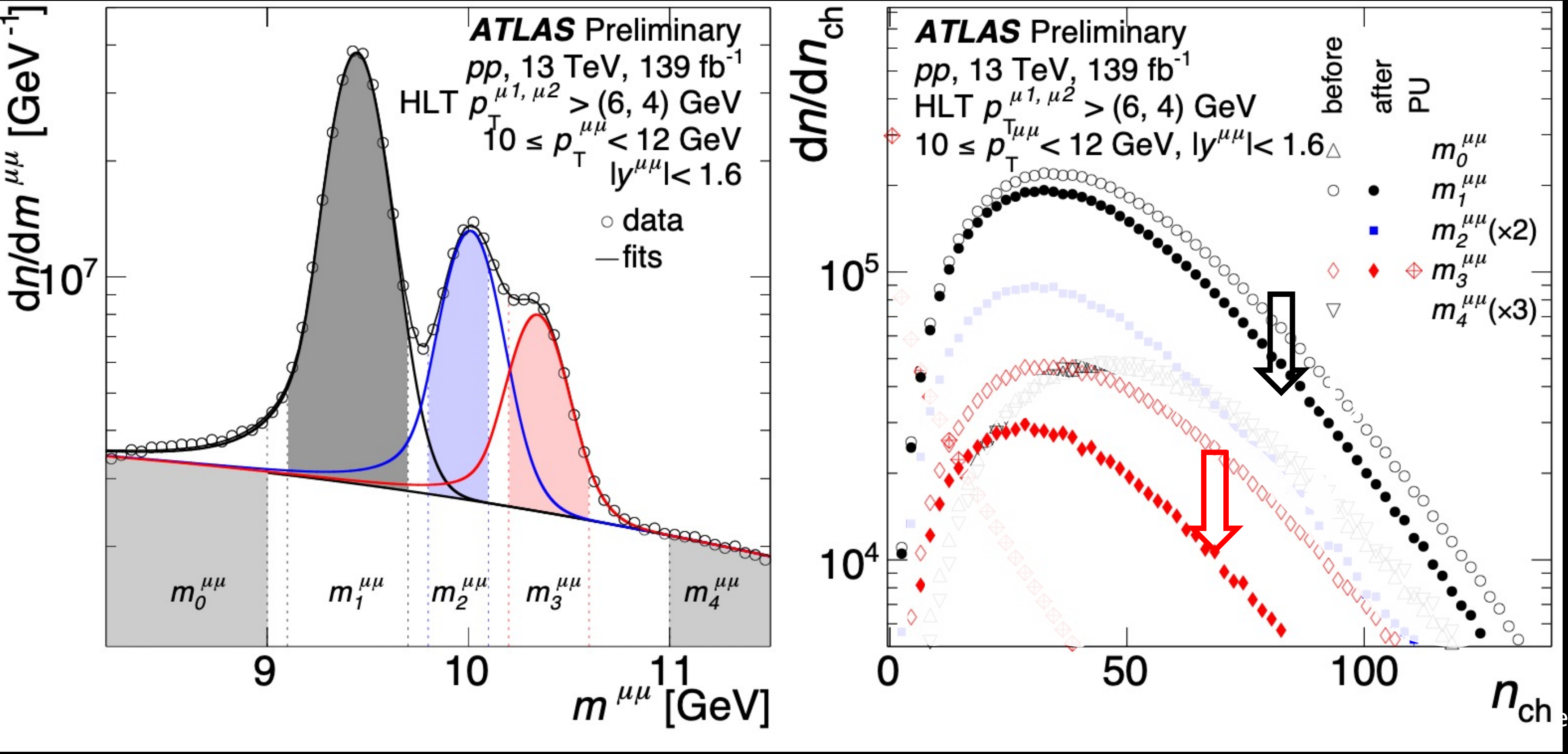

Subtraction works as a transition from open markers to close markers.

Extraction of n_{ch} distribution

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

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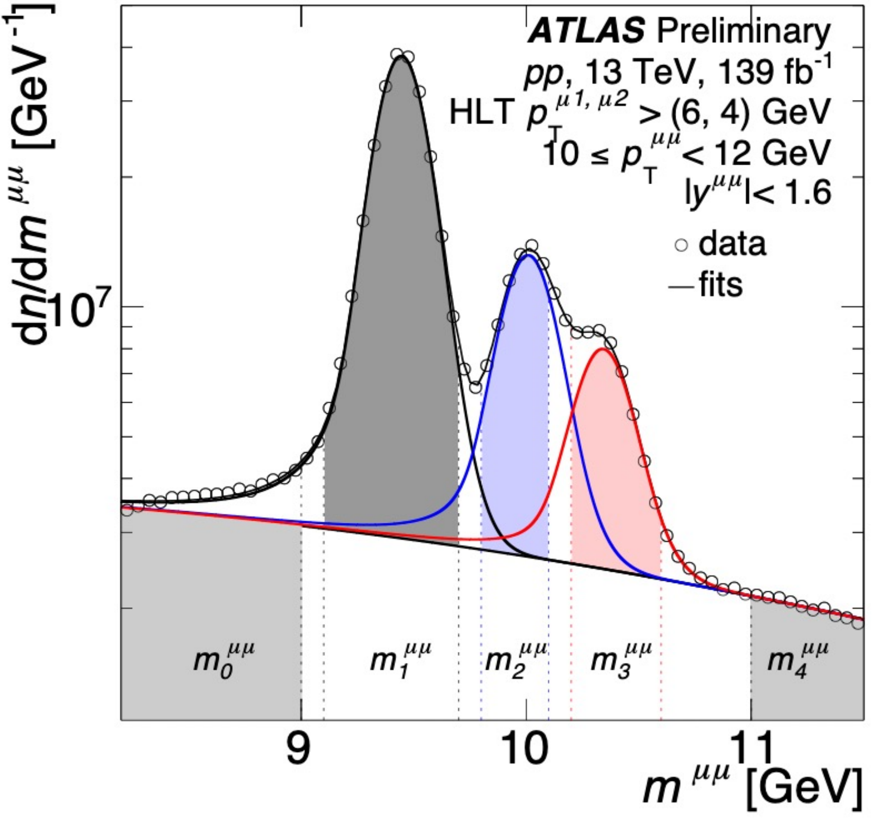

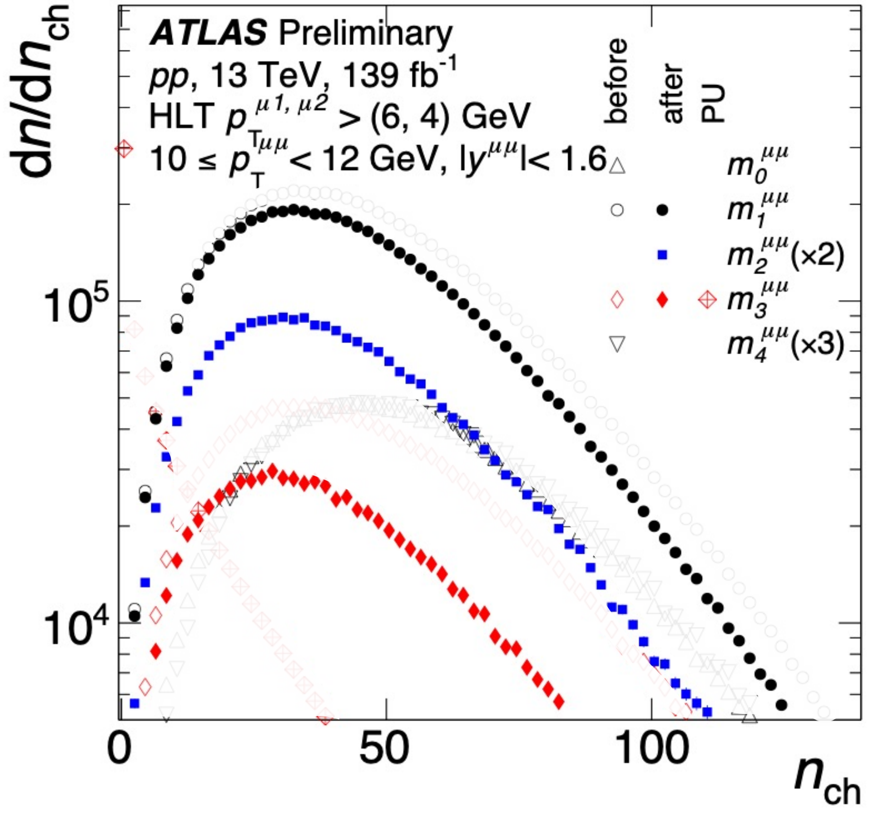

After background removal one can see with bare eye that distributions have different means.

Extraction of n_{ch} distribution

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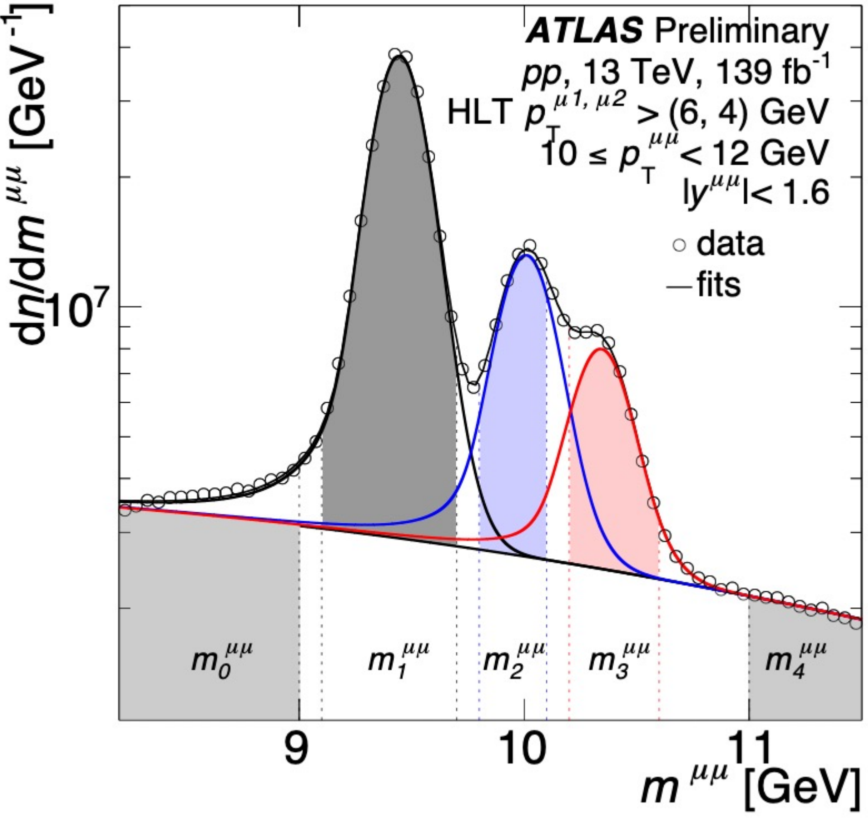
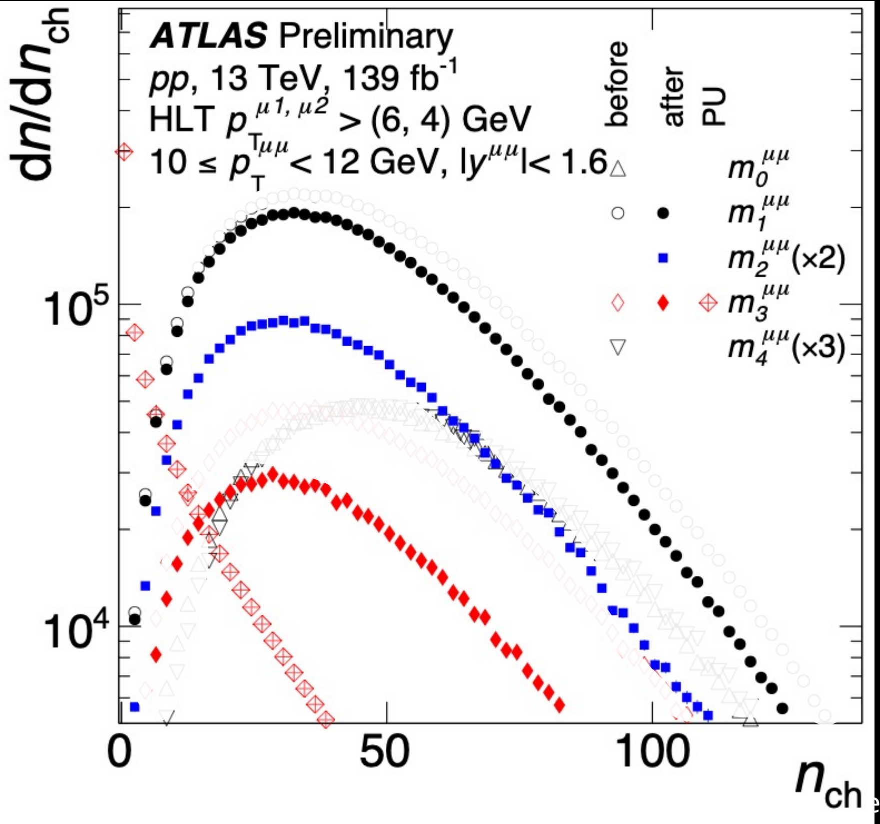
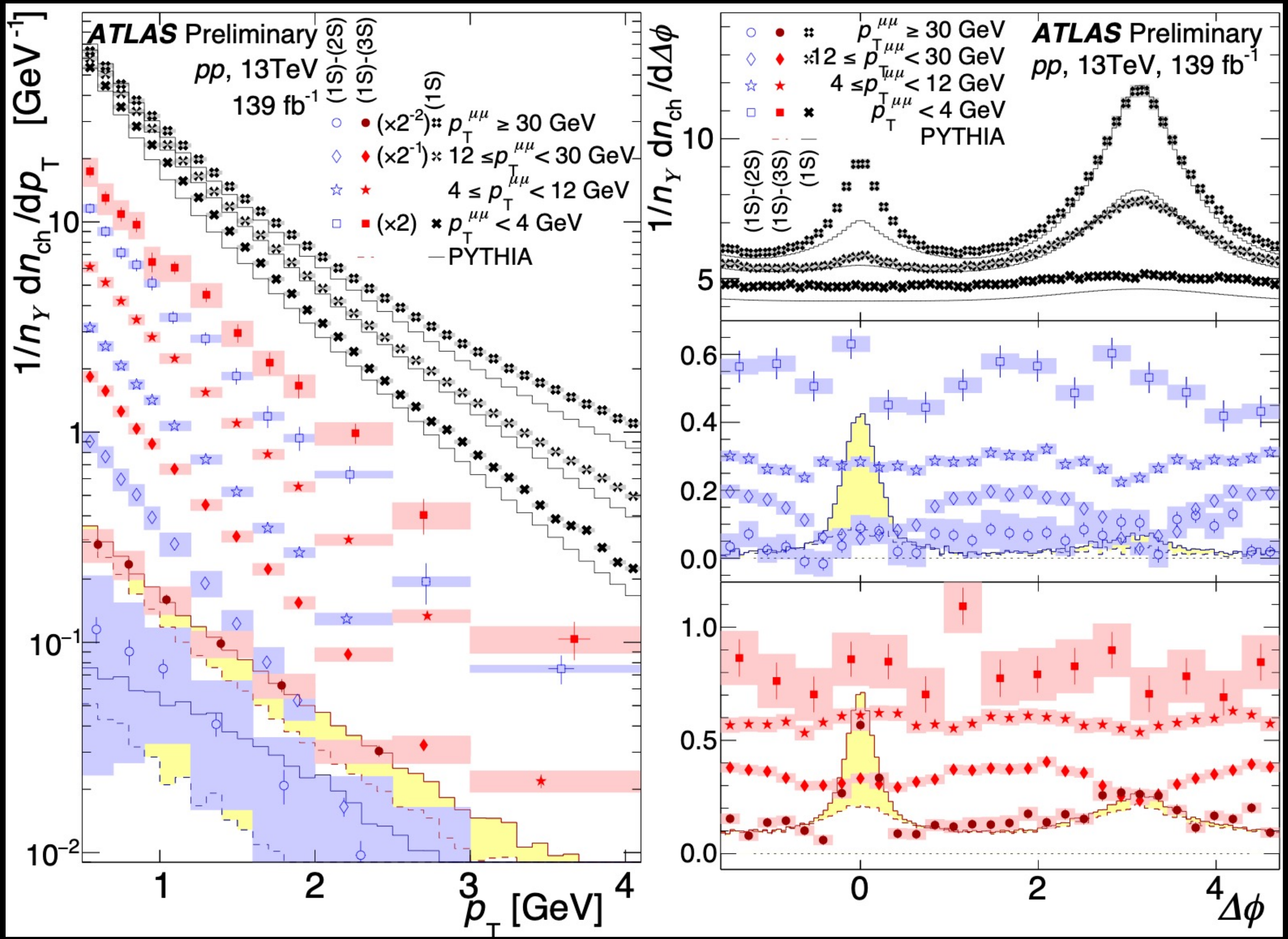




Still all distributions has PU in them

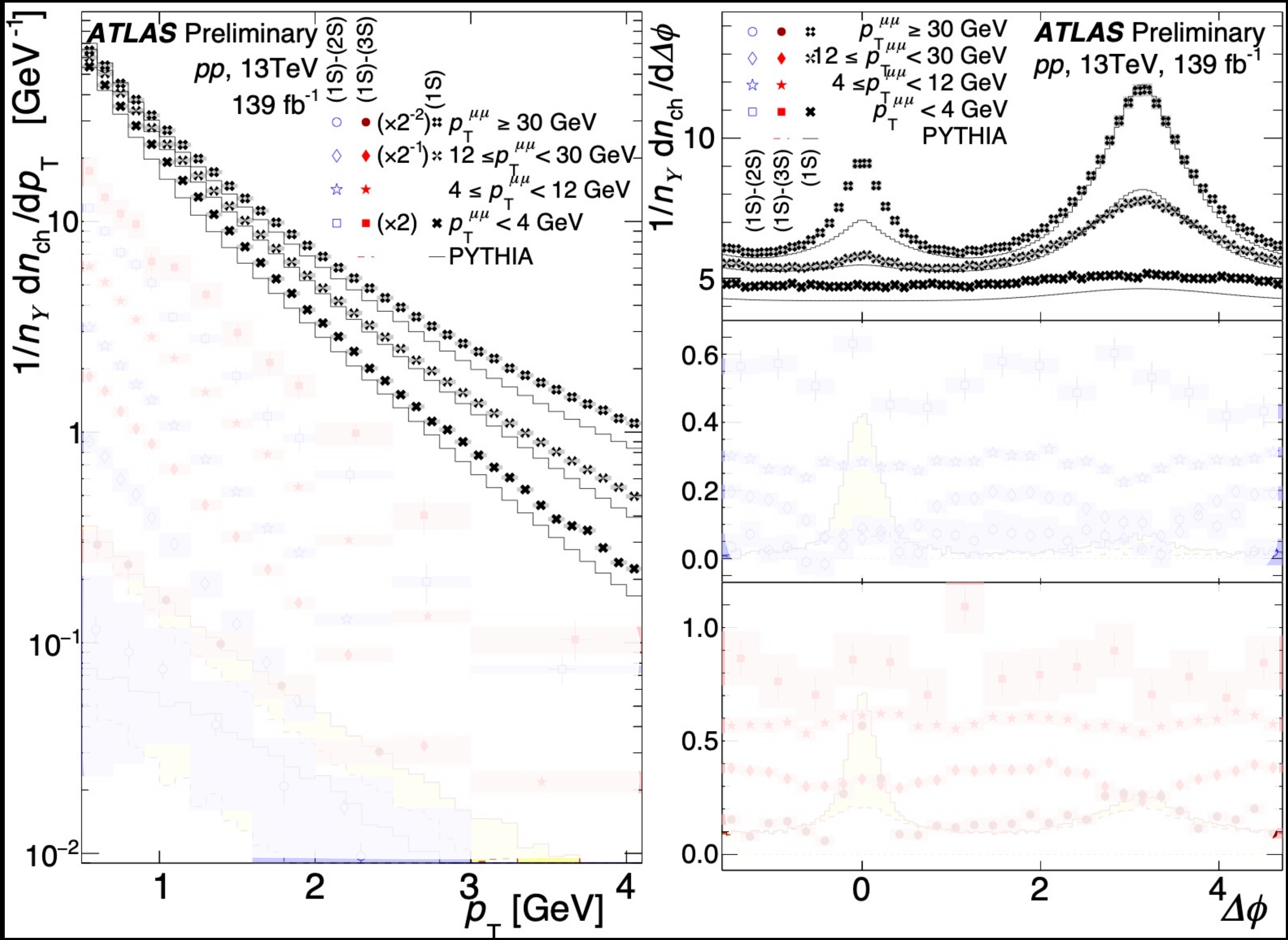
Results

Kinematic Distributions



$\Delta\phi$ – azimuthal angle between the directions of the particle and the Υ-meson

Kinematic Distributions



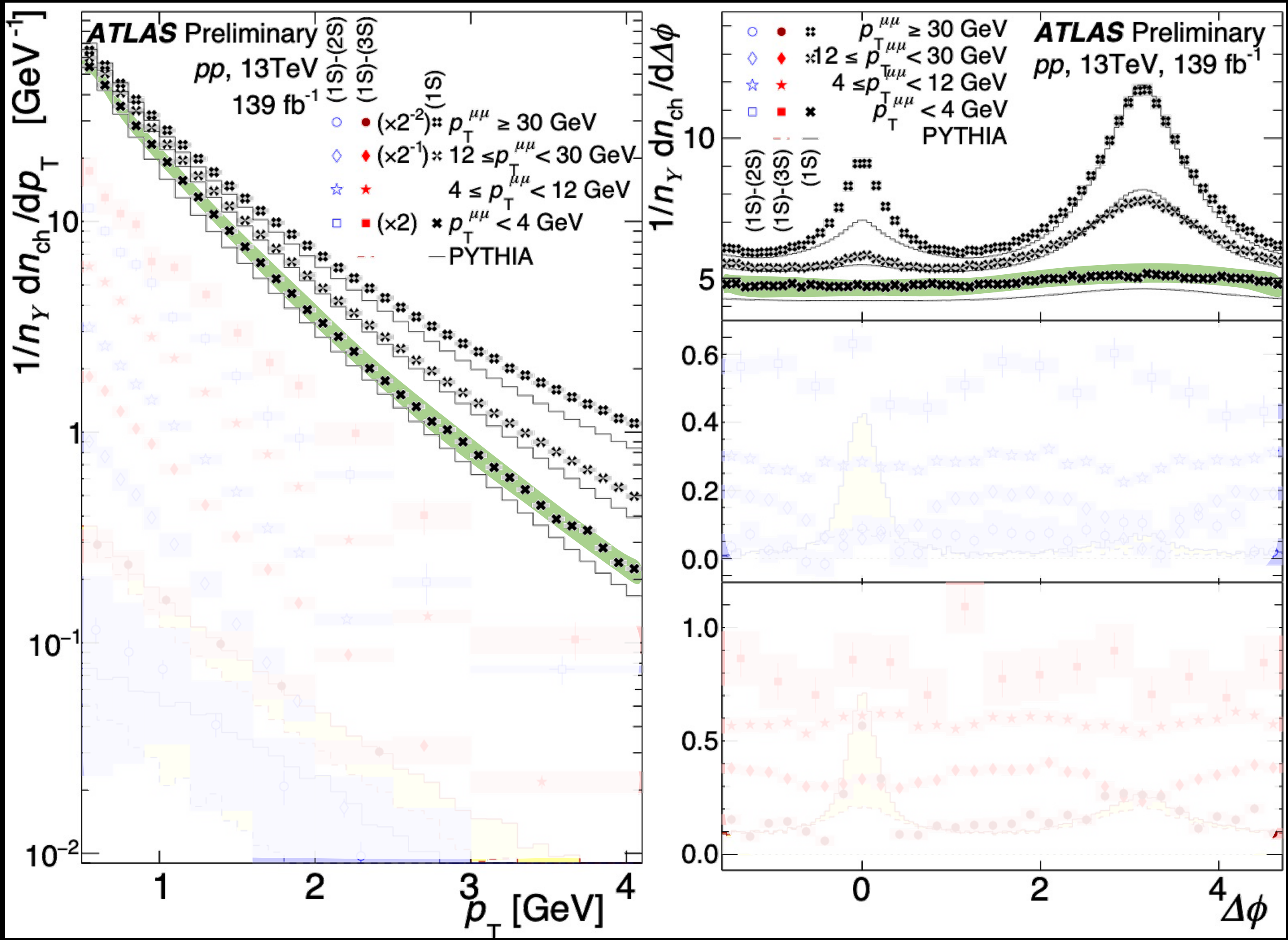
Distributions measured for Y(1S) for three different $p_T^{\mu\mu}$ intervals of Y (1S) :

- the lowest - up to 4 GeV
- the highest - above 30 GeV
- and the one in between

Lines are Pythia, and it generally does not do very well

- it has smaller UE
- underestimate the low-$\Delta\phi$ region

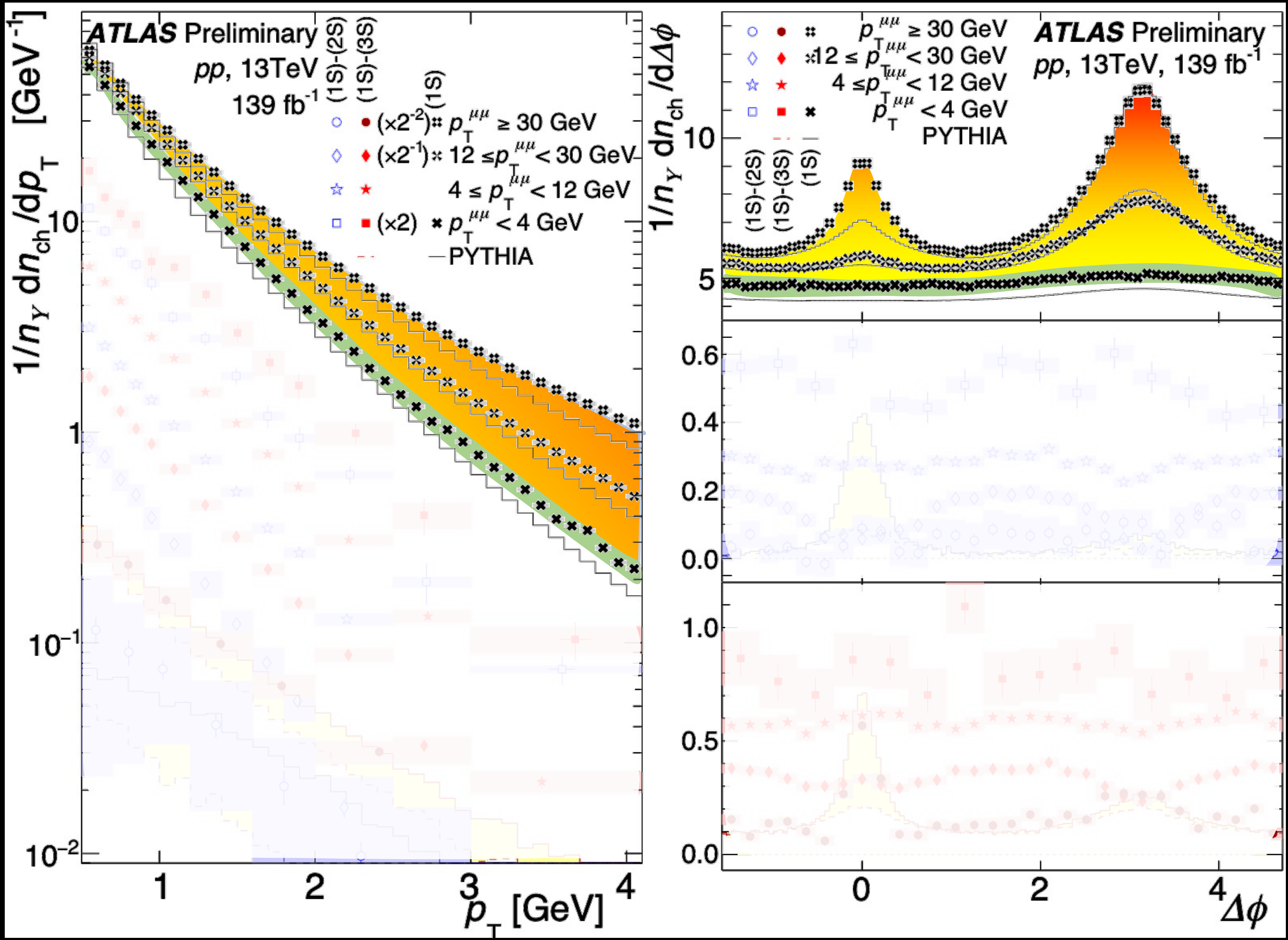
Kinematic Distributions



We are interested to understand where the effect comes from, from UE, or from the jet part of the event.

Because one cannot really draw a line between them, we can assume that the UE is more like lower p_T distributions highlighted in green.

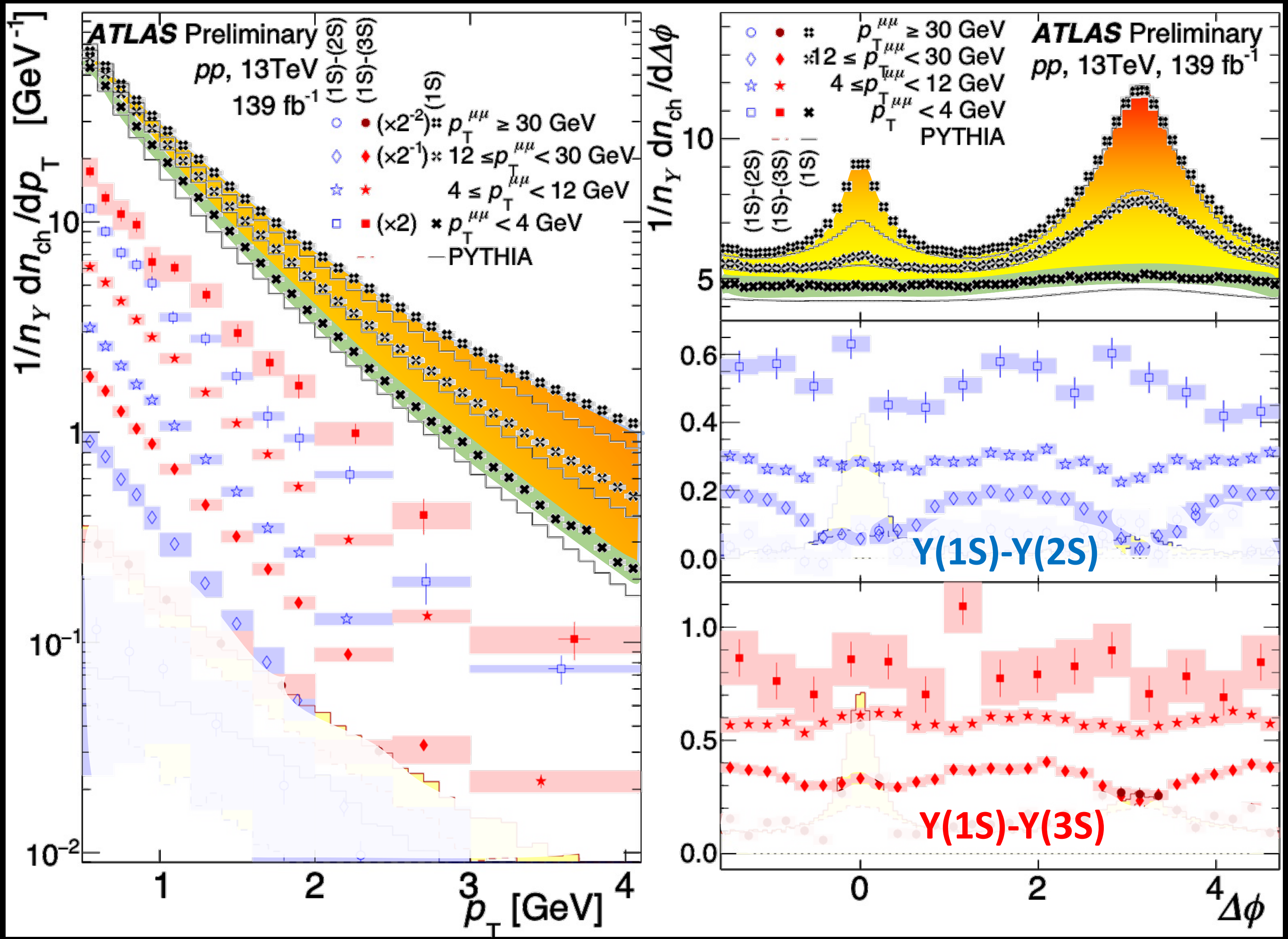
Kinematic Distributions



And the part which is the jet associated with the hard scattering where Y was produced is the difference between high-$p_T^{\mu\mu}$ and low-$p_T^{\mu\mu}$.

Let's focus on the UE part, which is close to green curves

Kinematic Distributions



Let's look at the subtracted curves:

- Y(1S)-Y(2S) blue color
- Y(1S)-Y(3S) red color

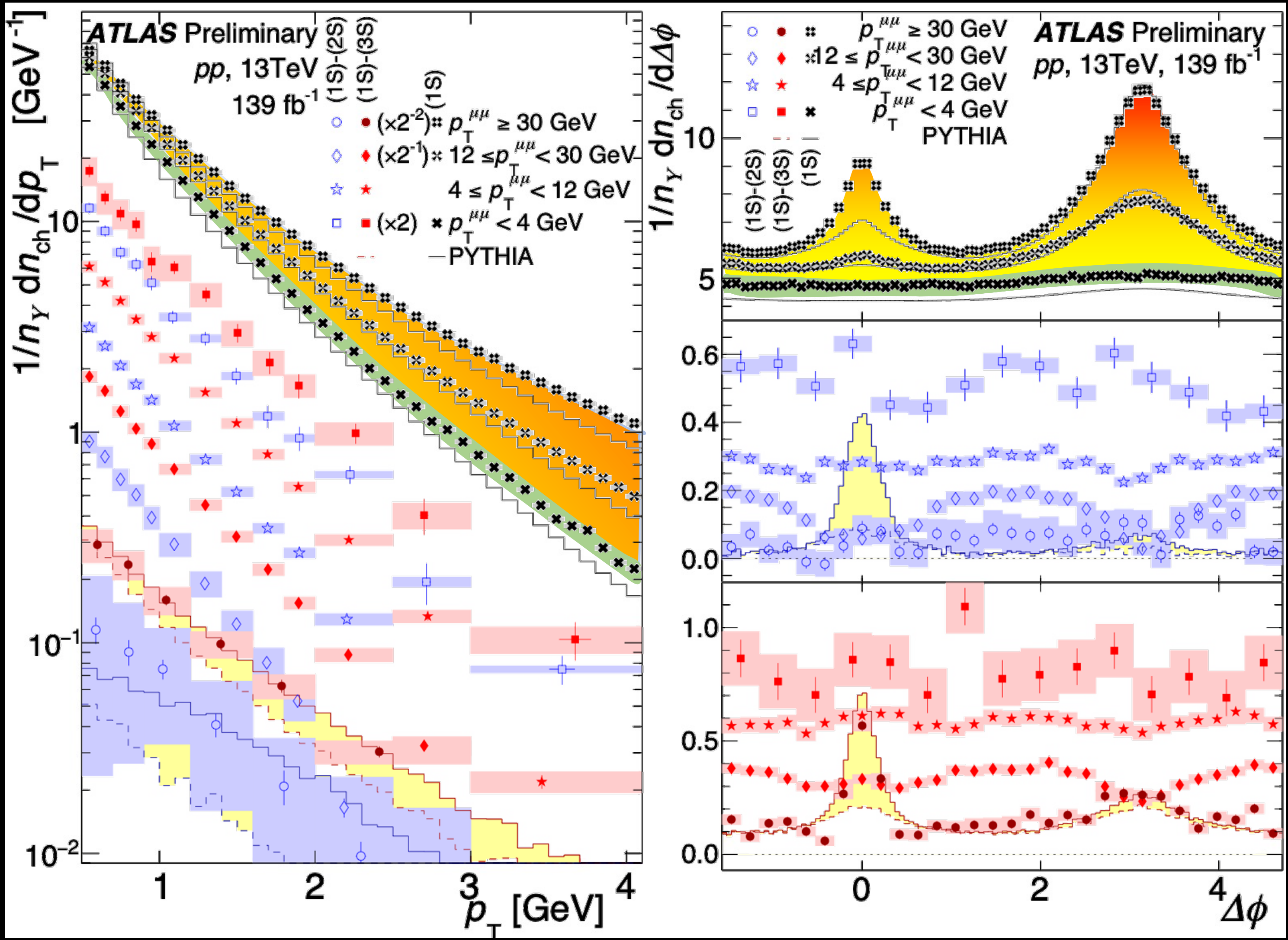
Curves, shown here, are for $p_T^{\mu\mu}$ up to 30 GeV.

The differences are parallel to the curve representing the UE

There are some modulations at higher $p_T^{\mu\mu}$ which we do not fully understand

Pythia does not have accurate mechanisms for Y production and does not have differences between Y-states on a scale of what we observe in data → we cannot effectively use it.

Kinematic Distributions

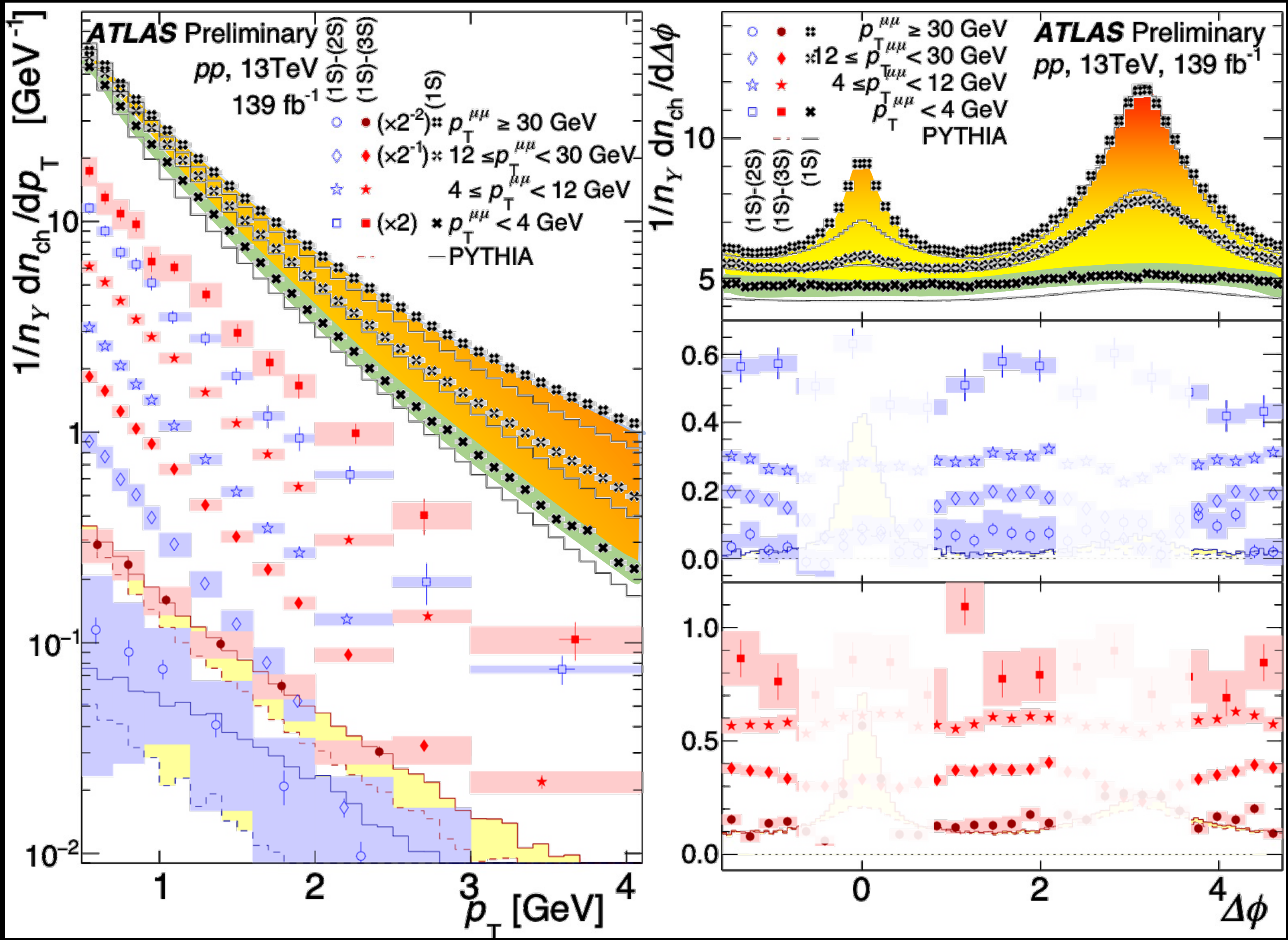


Going to the highest measured $p_T^{\mu\mu}$, spectra becomes harder and develop peaks in $\Delta\phi$.

Guidance from Pythia – peaks can be due to feed downs (yellow bands/regions) of higher Y(nS) into Y(1S), which Pythia has mechanisms to model.

χ_b->Y(nS) decays are not fully implemented in Pythia and not even measured by experiments with good precision

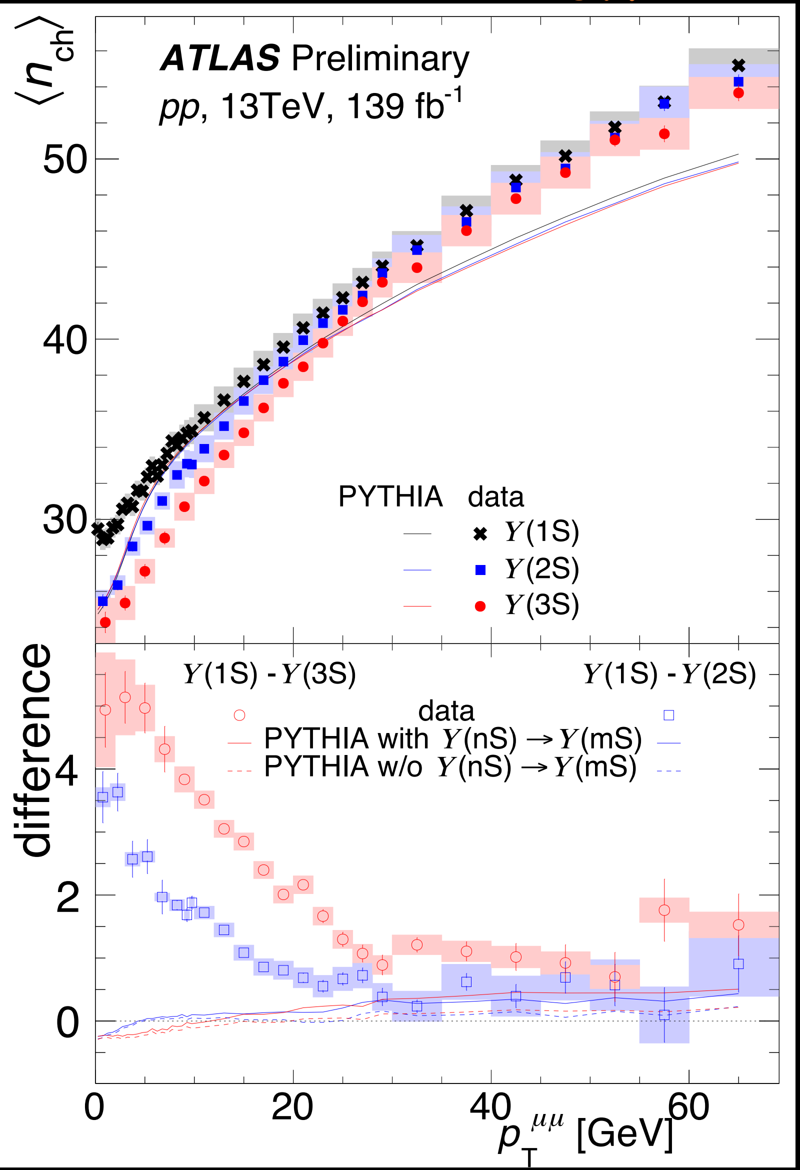
Kinematic Distributions



If we focus on the regions orthogonal to Y direction we always find charged particles there in subtracted distribution, even at highest $p_T^{\mu\mu}$.

To sum up, one can suggest that ***the effect is related to the UE.***

Mean of n_{ch} vs Dimuon p_T



Strong difference in the multiplicity of the UE for different Υ(nS) states is observed.

The effect is strongest at $p_T^{\mu\mu} = 0$ and diminishes with increasing $p_T^{\mu\mu}$, but still visible at 20-30 GeV.

Feed-down of Υ(nS) states, mass differences, systematic uncertainties cannot explain the effect.

At the lowest measured $p_T^{\mu\mu}$:

$\Upsilon(1S) - \Upsilon(2S)$	$\Delta\langle n_{\mathrm{ch}}\rangle = 3.6 \pm 0.4$	12% of $\langle n_{\mathrm{ch}}^{\Upsilon(1S)}\rangle$
$\Upsilon(1S) - \Upsilon(3S)$	$\Delta\langle n_{\mathrm{ch}}\rangle = 4.9 \pm 1.1$	17% of $\langle n_{\mathrm{ch}}^{\Upsilon(1S)}\rangle$

Conclusions

- We see significant difference in charged particle production in collisions with different Upsilon states.

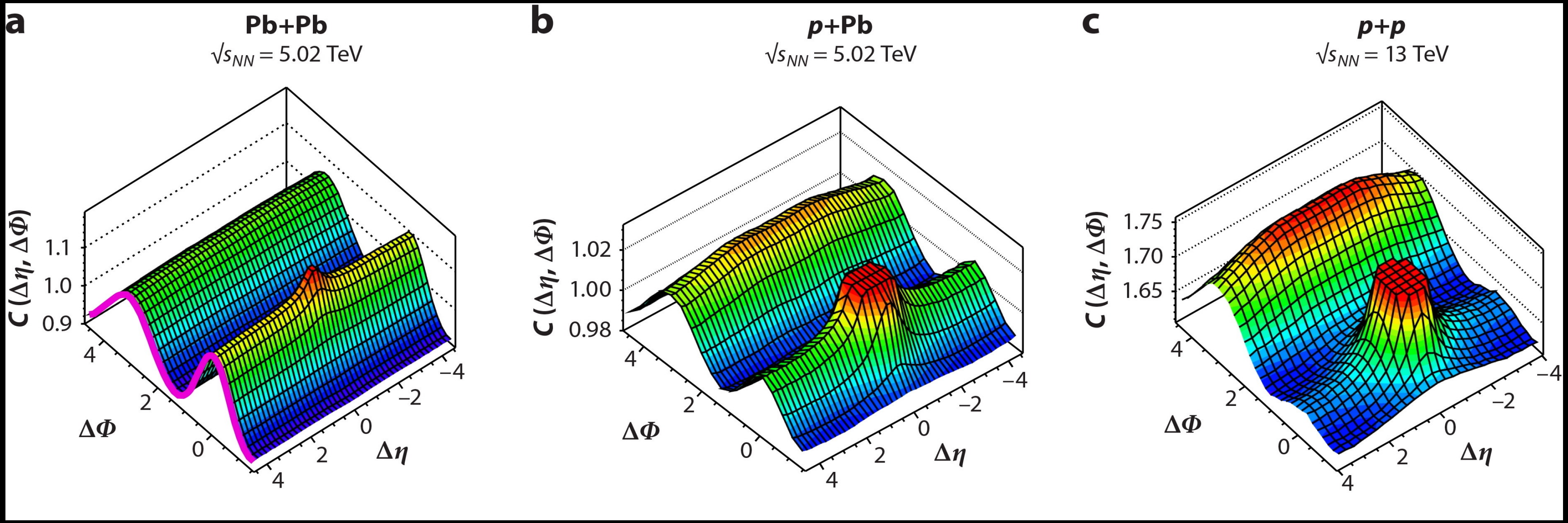
- Subtracted charged particle kinematic distributions suggest that observed differences are mainly in the UE and not in the part associated with the Upsilon production

- Differences are strongest at low Upsilon $p_T^{\mu\mu}$ and remain significant up to high- $p_T^{\mu\mu}$

- Consistent with the CMS results, but
  - Emphasis on different observables
    - Dependence of $\langle n_{ch} \rangle$ on $p_T^{\mu\mu}$
    - Charged particle p_T and $\Delta\phi$ distributions
  - The effect is demonstrated in a more significant way with
    - Better precision
    - $p_T^{\mu\mu}$ dependence of the effect is observed

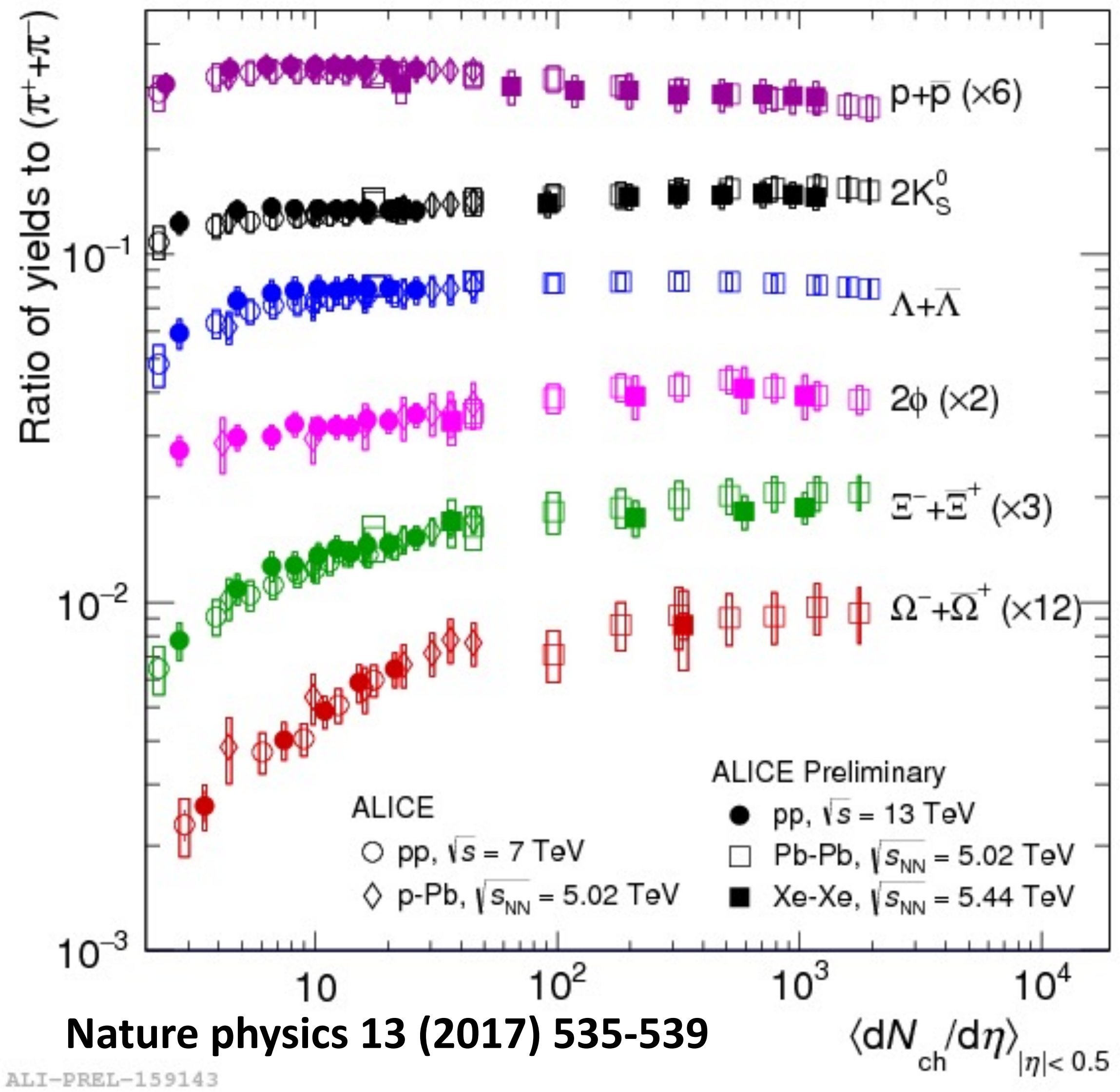
Thank you for your attention!!!

Two-particle correlations (2PC)



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.

Strangeness enhancement



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