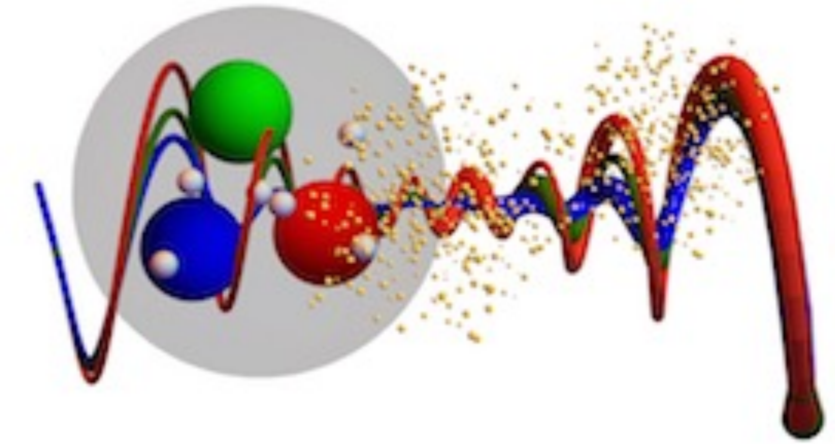
בס"ד

Underlying Event Measurements at ATLAS

Zvi Citron for ATLAS

MPI@LHC



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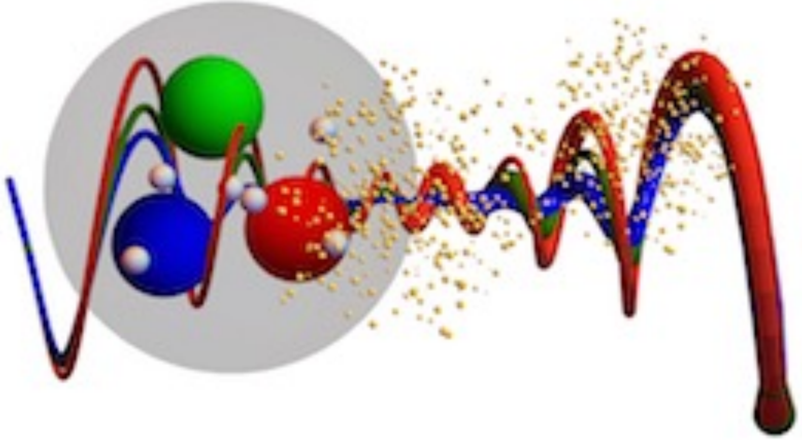
בס"ד

Underlying Event Measurements at ATLAS

Zvi Citron for ATLAS

MPI@LHC

- **Charged Particles in $t\bar{t}$ events**
  → Constrain color reconnection in MC
- **Charged Particles in Υ(nS) events**
  → Color effect not in MC (?)(!)



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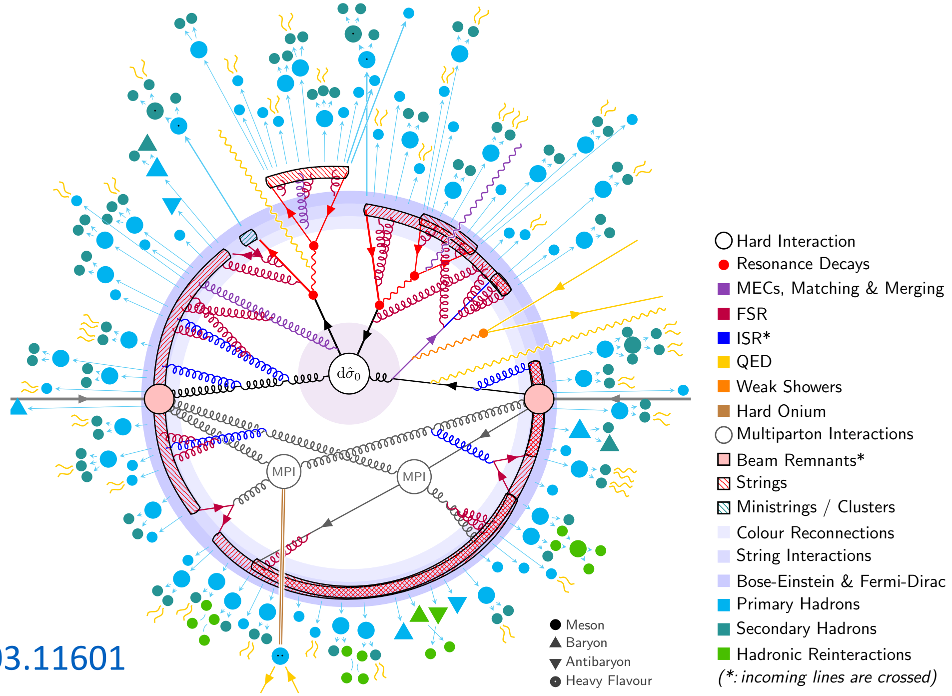
Big Picture: Why look at top quarks and CR?

- Good for top quarks
  - Color reconnection (CR) modeling is a leading uncertainty in top mass measurements
- Good for generators models
  - Better constraints on CR (MPI) should help everywhere else

	m_{top} [GeV]
Result	172.63
Statistics	0.20
Method	0.05 ± 0.04
Matrix-element matching	0.35 ± 0.07
Parton shower and hadronisation	0.08 ± 0.05
Initial- and final-state QCD radiation	0.20 ± 0.02
Underlying event	0.06 ± 0.10
Colour reconnection	0.29 ± 0.07
Parton distribution function	0.02 ± 0.00
Single top modelling	0.03 ± 0.01
Background normalisation	0.01 ± 0.02
Jet energy scale	0.38 ± 0.02
b-jet energy scale	0.14 ± 0.02
Jet energy resolution	0.05 ± 0.02
Jet vertex tagging	0.01 ± 0.01
b-tagging	0.04 ± 0.01
Leptons	0.12 ± 0.02
Pile-up	0.06 ± 0.01
Recoil effect	0.37 ± 0.09
Total systematic uncertainty (without recoil)	0.67 ± 0.05
Total systematic uncertainty (with recoil)	0.77 ± 0.06
Total uncertainty (without recoil)	0.70 ± 0.05
Total uncertainty (with recoil)	0.79 ± 0.06

ATLAS-CONF-2022-058



arXiv:2203.11601

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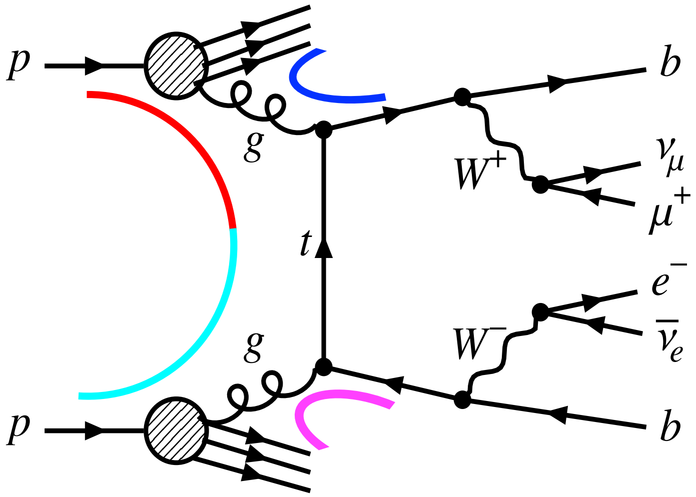
How do we look at top quarks and CR?

- Select $t\bar{t}$ events using di-leptonic $e\mu$ channel
- Look at inclusive* charged particles as:
  - [*Not including the leptons or jet tracks]
  - Multiplicity n_{ch}
  - Scalar sum of charged particle p_T, $\sum_{n_{ch}} p_T$
  - $\sum_{n_{ch}} p_T$ in bins of n_{ch}
- Pileup and fake contribution subtracted with MC templates
- Compare data to MC
  - Pythia8 hadronizes with Lund strings … several CR models
  - Herwig7 hadronizes with clusters … several CR models
  - Many parameters!



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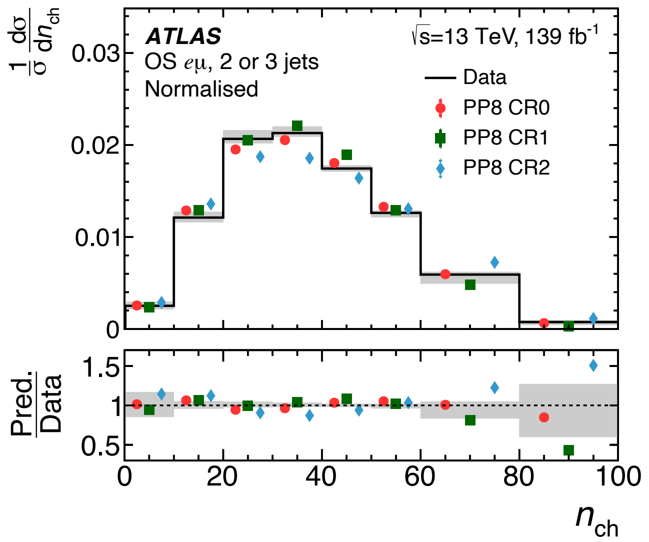
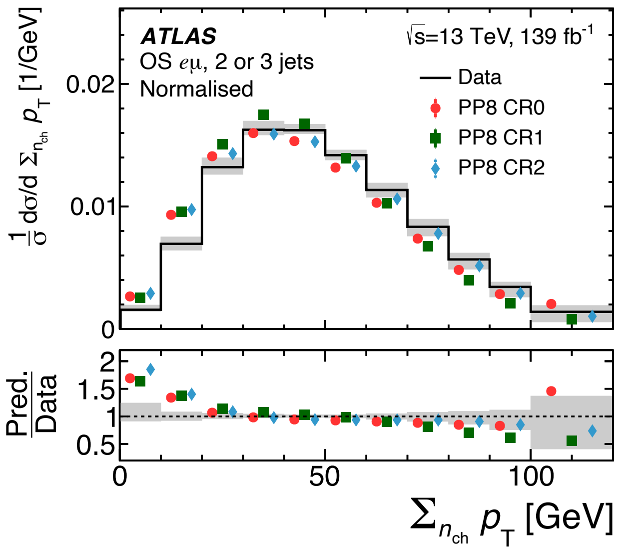
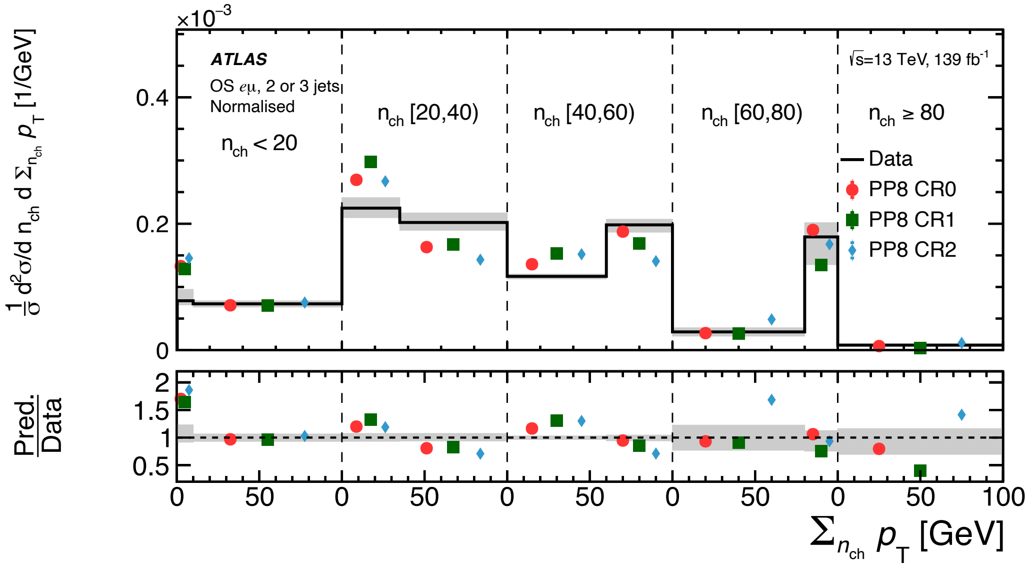
How Does Pythia8 Do?

arXiv:2209.07874



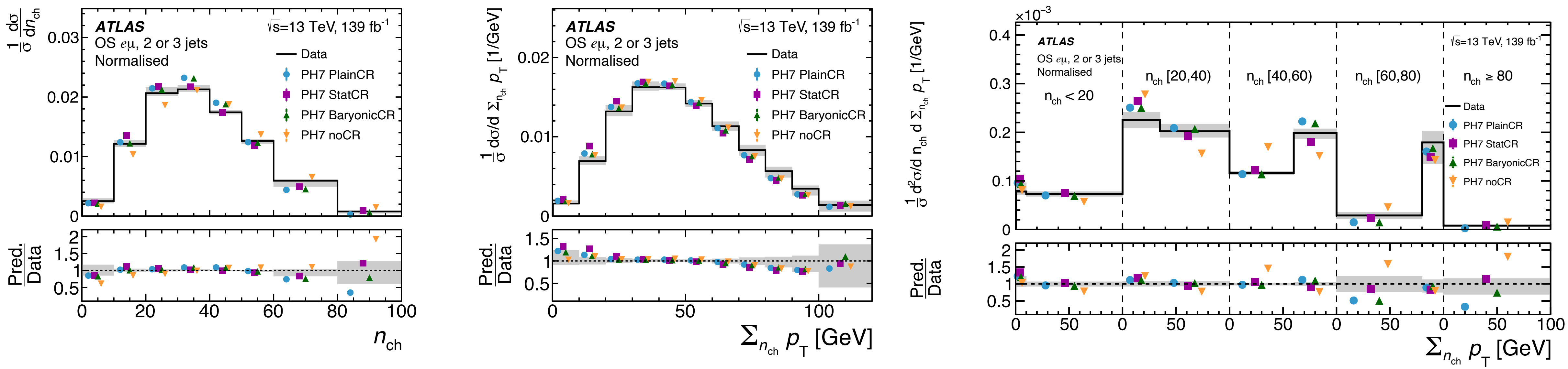




- Misses features of the data
- CR0, “MPI based” minimize color string lengths - baseline for Pythia& ATLAS
- CR1,“QCD based”, nominally improved version of CR0 is same~worse
- CR2, “gluon move”, only gluons for reconnection (partially top mass motivated)

How Does Herwig7 Do?

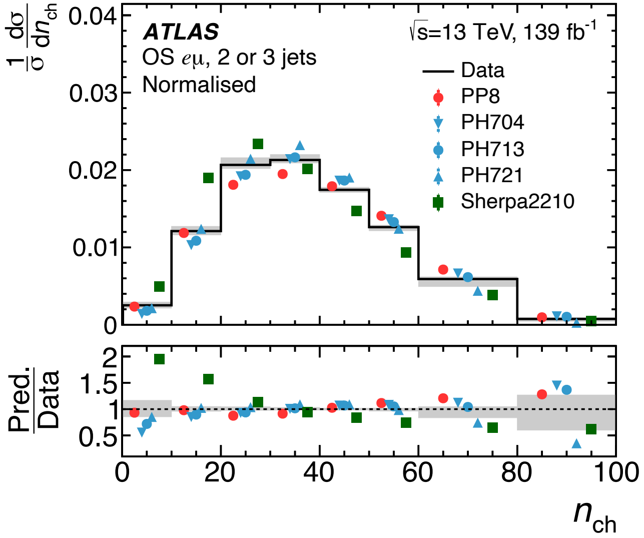
arXiv:2209.07874

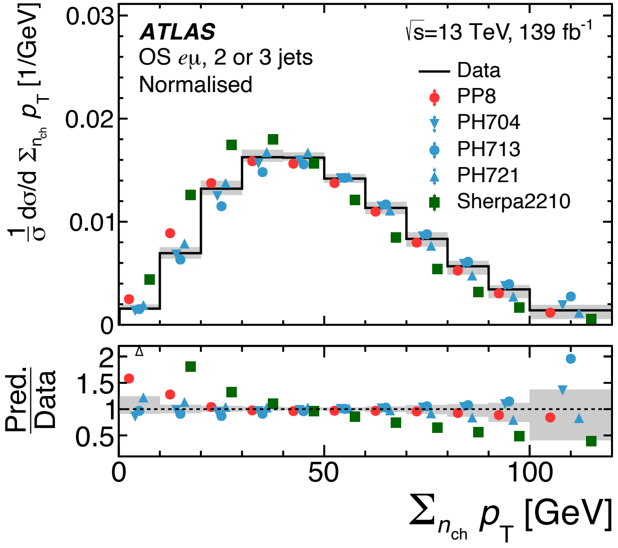


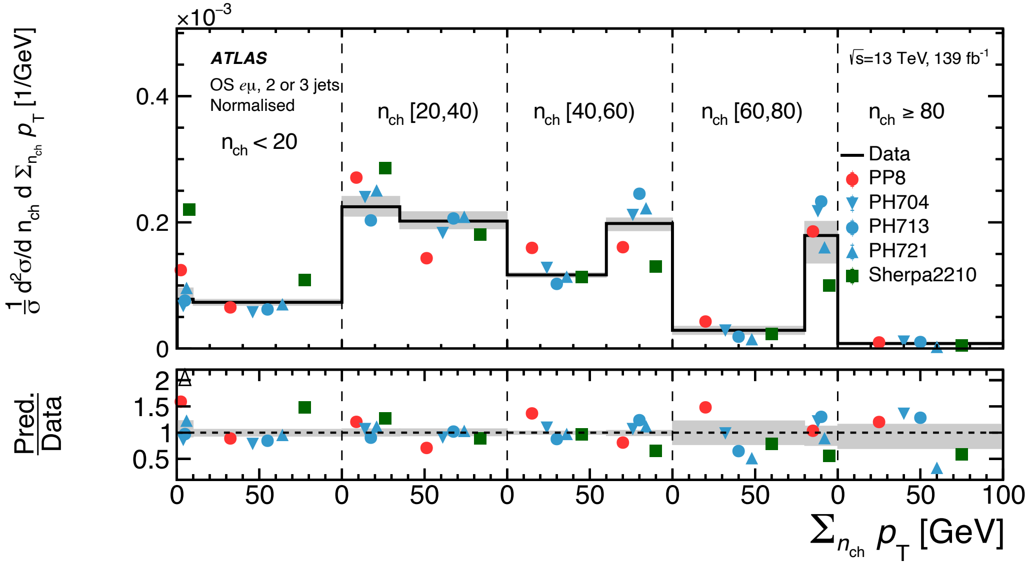
- Somewhat better
- Plain & Stat CR: quarks can be rearranged from cluster to cluster
- Baryonic CR: geometric (nearest neighbor) combinations
- No CR model silver bullet

Model to Model

arXiv:2209.07874







- Herwig probably best
- Data is ahead of models

Observable	n_{ch}	$\Sigma_{n_{ch}} p_T$	Global(n_{ch},$\Sigma_{n_{ch}} p_T$)	$\Sigma_{n_{ch}} p_T$ in bins of n_{ch}
NDF	7	10	17	8
Generator set-up			χ^2	
Powheg+Pythia 8.230	62	106	434	224
CR0	55	113	629	129
CR1	98	60	581	158
CR2	58	179	402	238
Powheg+Herwig 7.0.4	39	16	145	29
Powheg+Herwig 7.1.3	53	42	188	41
Powheg+Herwig 7.2.1	78	25	313	87
Powheg+Herwig Baryonic CR	75	20	241	29
Powheg+Herwig Stat CR	23	40	121	39
Sherpa 2.2.10	77	211	263	124

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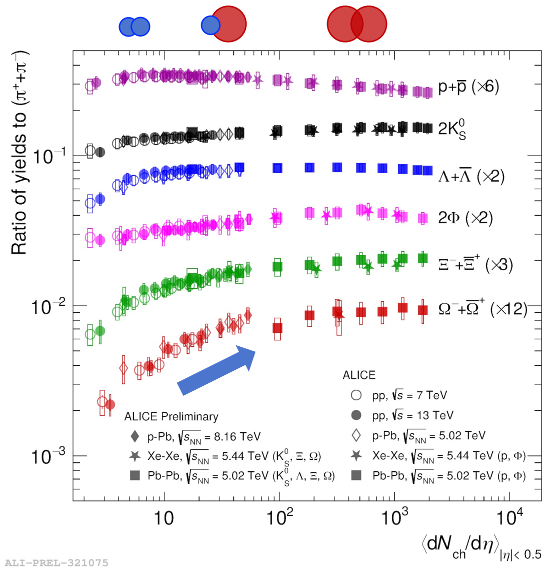
Big Picture: Why look at *Υ*-UE correlations?

- Soft sector observables that were once (uniquely) associated with a QGP have been measured in pp collisions
  - Most prominently “flow” which persists to low multiplicity pp & even photo-nuclear interactions
  - Strangeness enhancement
- It’s more difficult to tell this story with hard sector observables
- Here we look at **Upsilon meson correlations with inclusive charged particles** to try to bridge the soft-hard gap
  - Analyze charged particles kinematics to focus on Underlying Event (UE)



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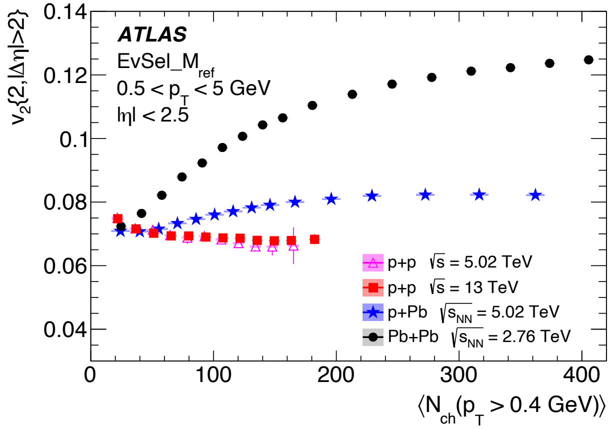

Eur. Phys. J. C 77 (2017) 428

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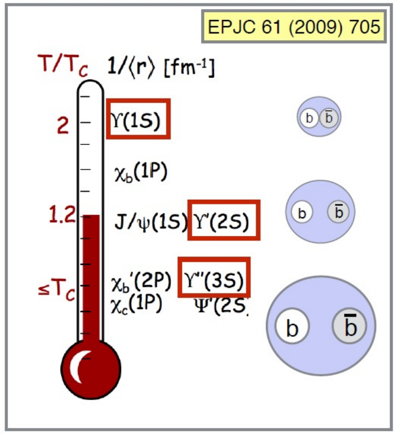
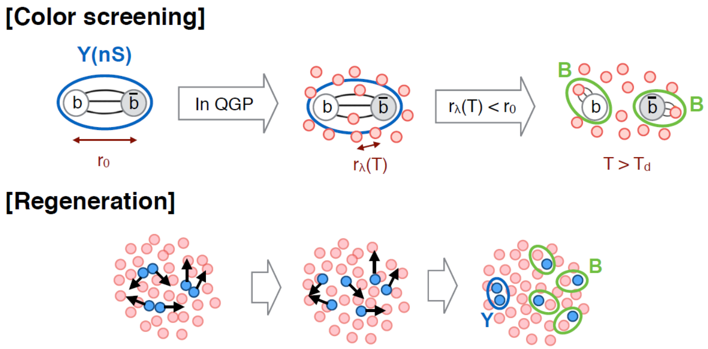
What Do We Know about Upsilon Production *and collectivity* at the LHC?

- From a heavy-ion perspective Υ(nS) states could be a thermometer for a QGP

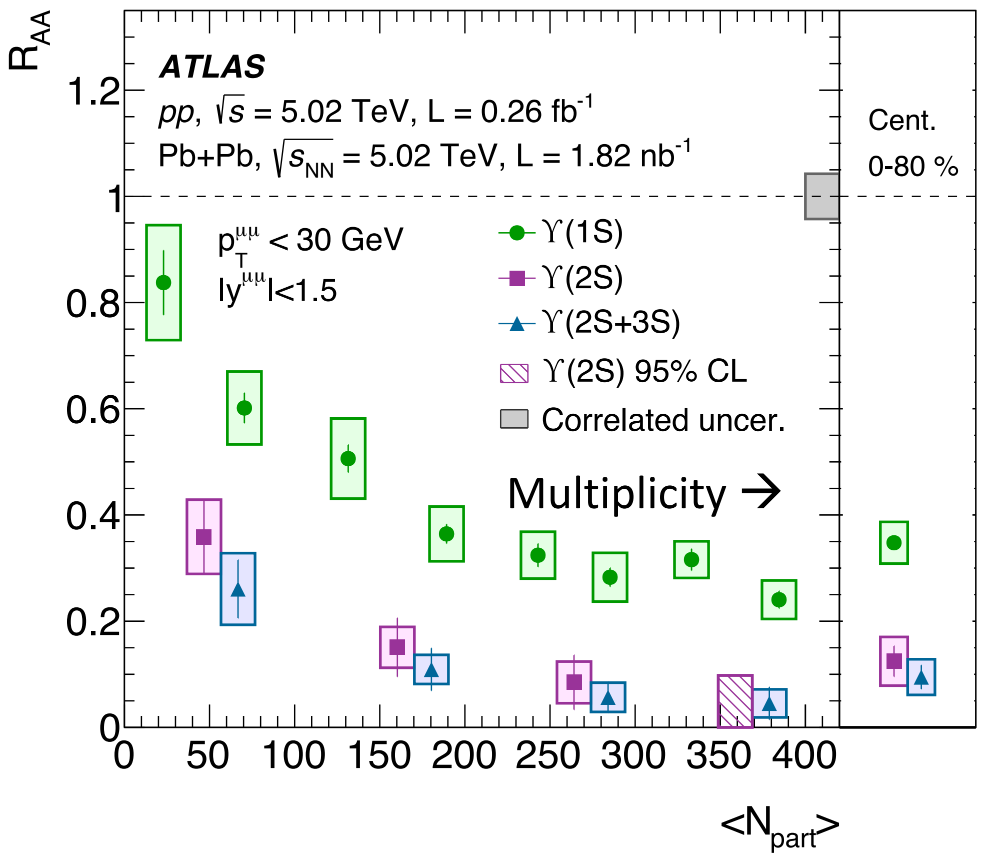




What Do We Know about Upsilon Production *and collectivity* at the LHC?

arXiv:2205.03042

- From a heavy-ion perspective Υ(nS) states could be a thermometer for a QGP
- We can measure the nuclear modification factor in heavy-ion collisions to compare AA to pp production



$$R_{AA} = \frac{N_{\Upsilon;AA}}{\langle T_{AA}\rangle \times \sigma^{pp\to\Upsilon}}$$

T_{AA} is the nuclear overlap function

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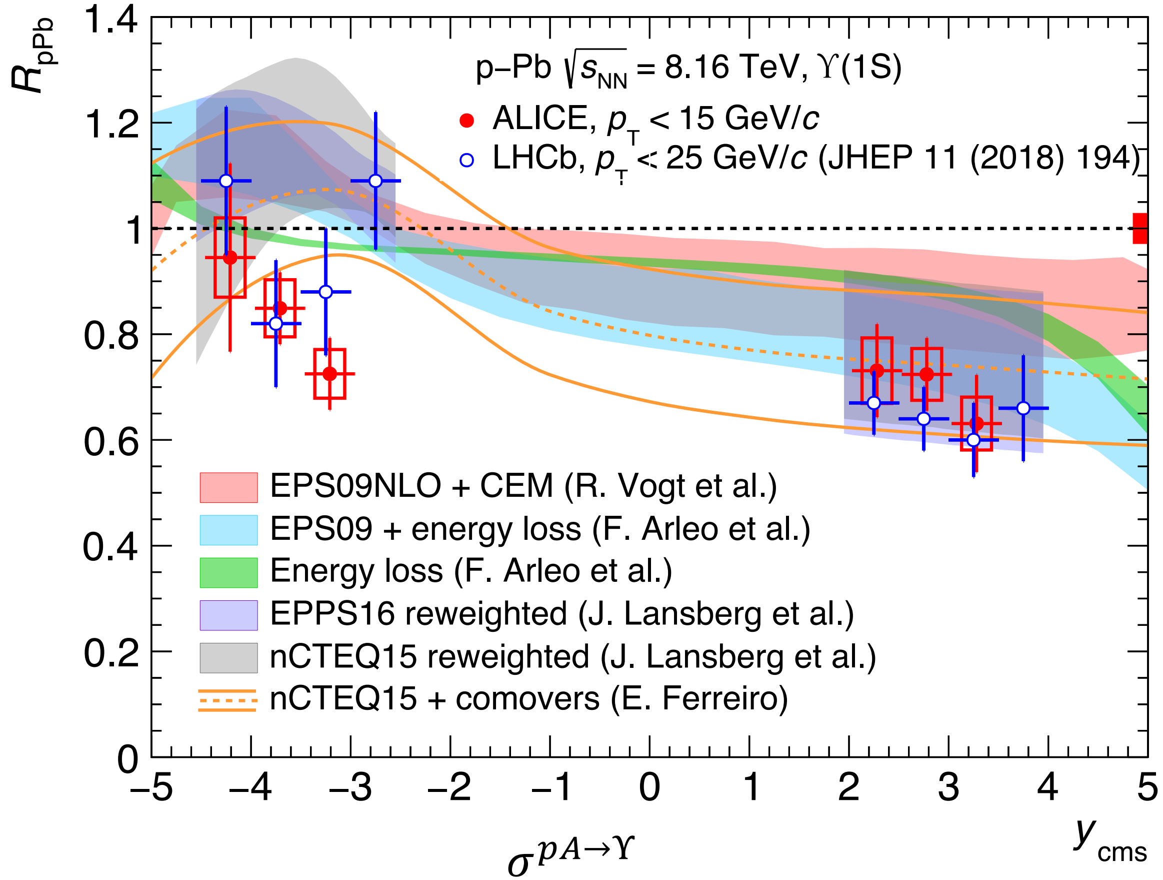
What Do We Know about Upsilon Production *and collectivity* at the LHC?

PLB 806 (2020) 135486

- From a heavy-ion perspective Υ(nS) states could be a thermometer for a QGP
- We can measure the nuclear modification factor in heavy-ion collisions to compare AA to pp production
    - pA could give us some sense of the influence of “cold nuclear effects”



$$R_{pA} = \frac{\sigma^{pA\to\Upsilon}}{A\times\sigma^{pp\to\Upsilon}}$$

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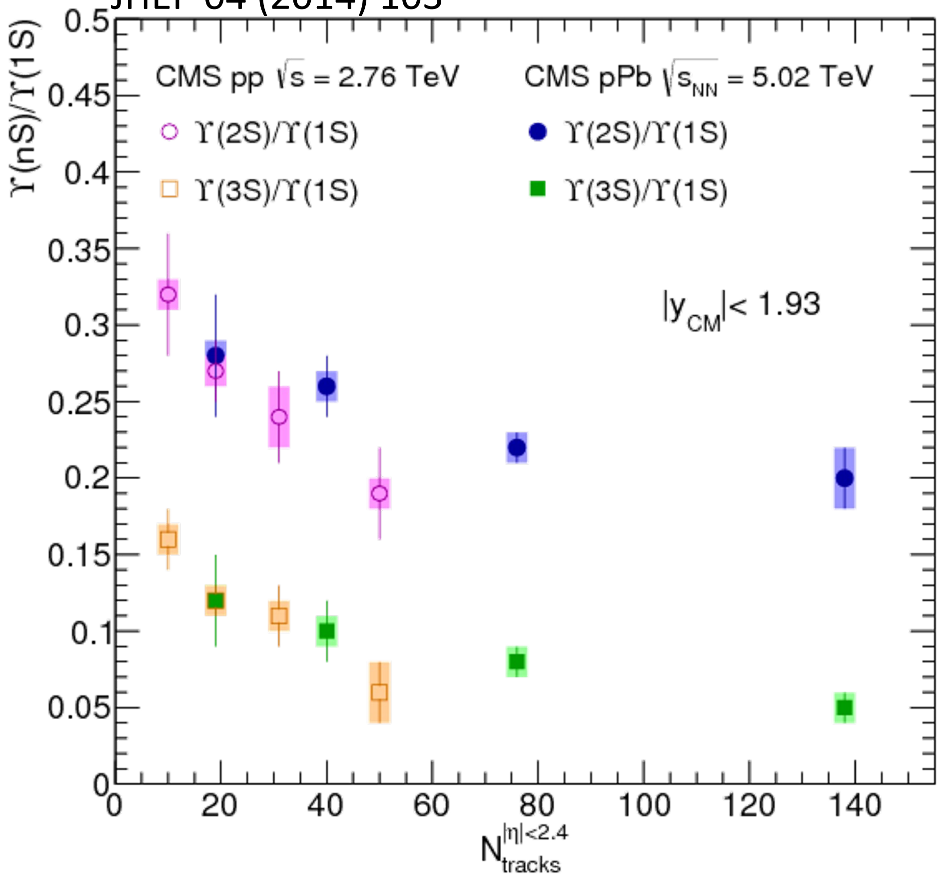
CMS Measurement of Y(nS) and pp Multiplicity

- CMS results all the way back in 2014 challenge Y suppression as a nuclear effect by showing a decrease in excited Y states compared to the ground state vs pp multiplicity

JHEP 04 (2014) 103



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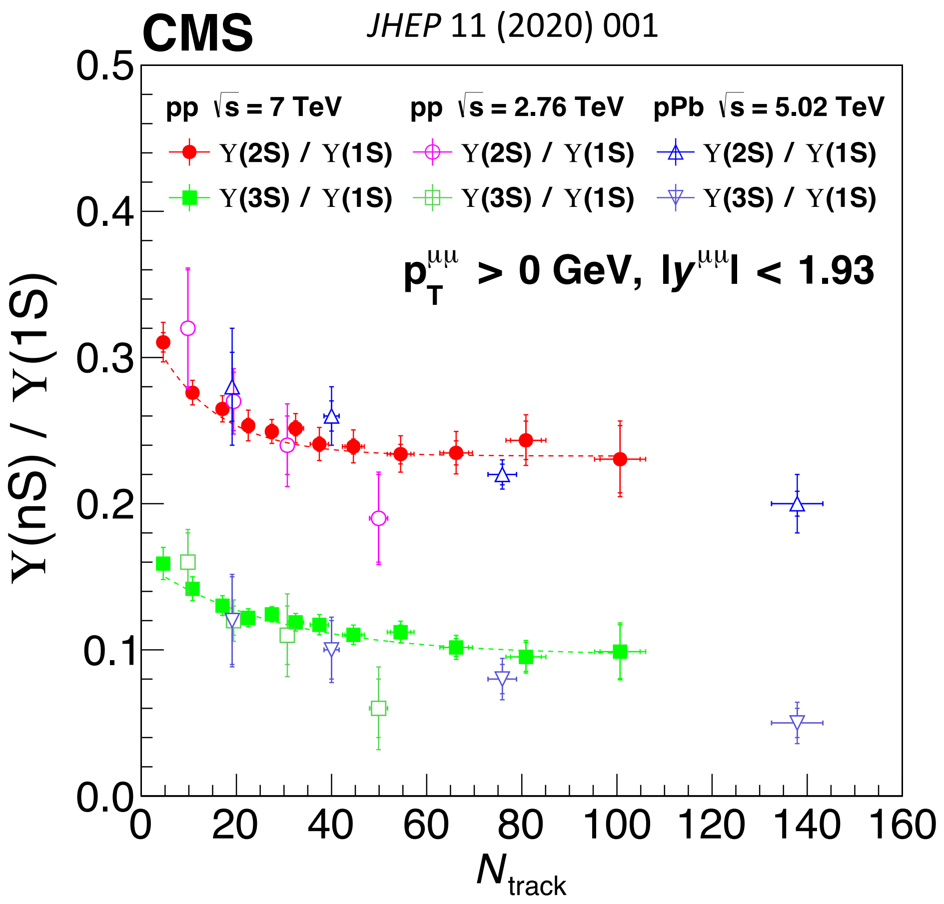
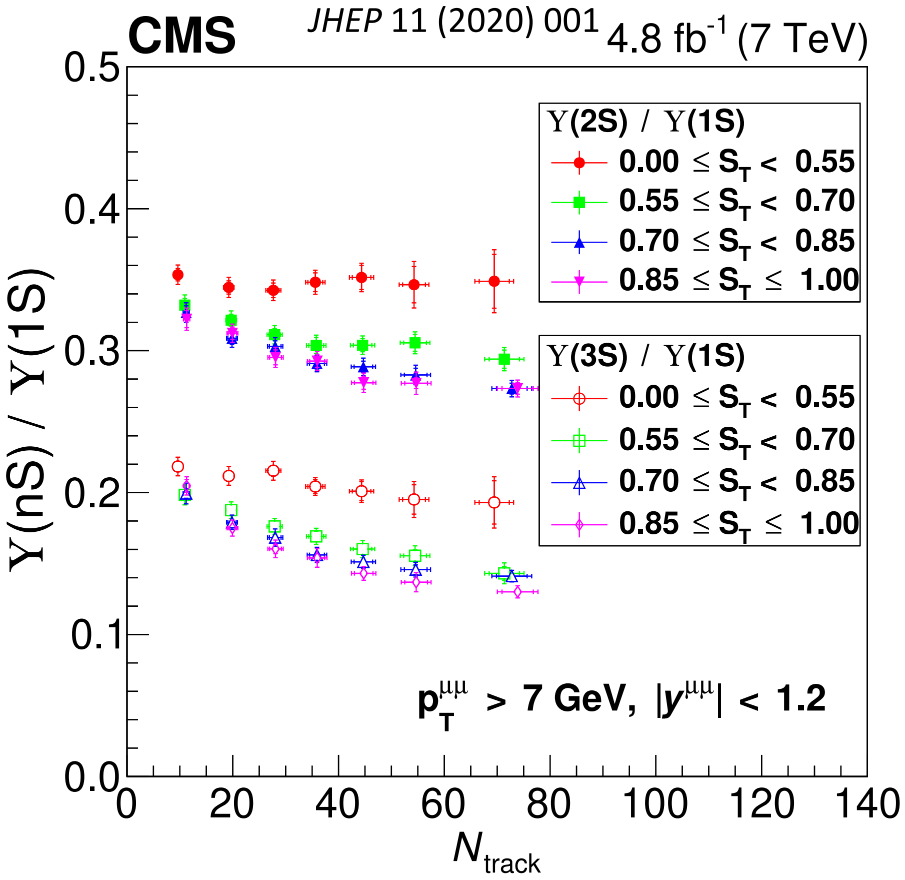
- More detailed measurements in 2020



CMS Measurement of Υ(nS) and pp Multiplicity

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

- CMS results all the way back in 2014 challenge Υ suppression as a nuclear effect by showing a decrease in excited Υ states compared to the ground state vs pp multiplicity
- More detailed measurements in 2020
  - Including analysis of event geometry via spherocity, which suggests effect **is connected with UE not jets**



$S_T = 0$ → jet-like

$S_T = 1$ → not jet-like

ATLAS Measurement of Υ(nS) and UE

ATLAS-CONF-2022-023

- Measure the total multiplicity in the event (and particle kinematics) for each Upsilon state
- Precise control of background and pile-up
- Use differential particle kinematics to reach for the UE
- Compare excited to ground states

- “Inversion” of CMS approach, study same physics with emphasis on the UE itself

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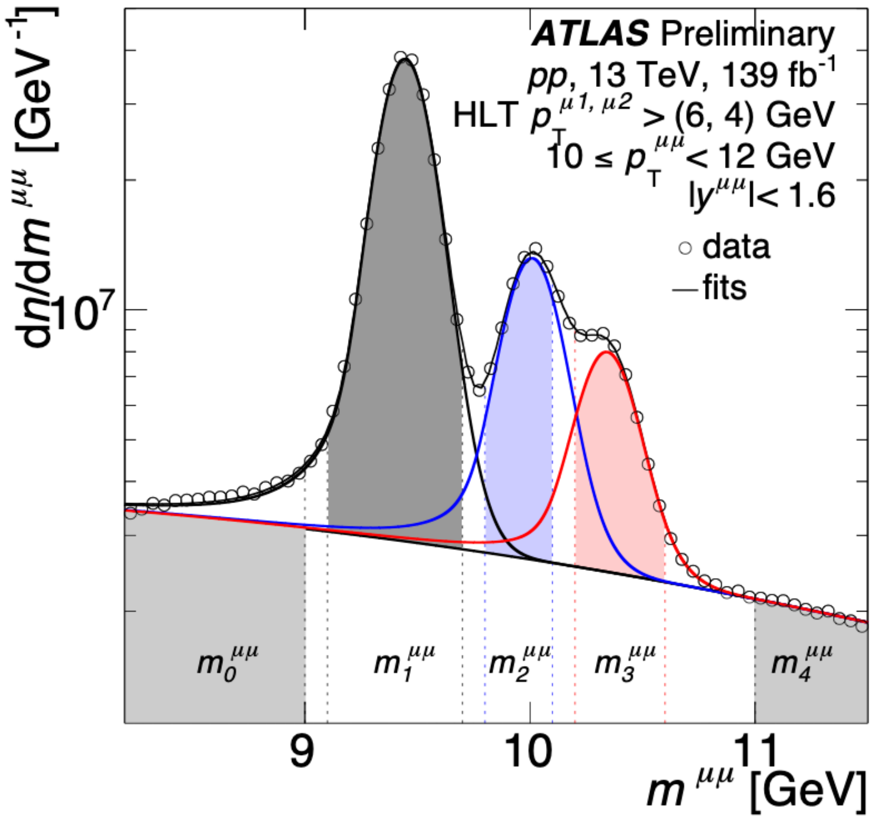

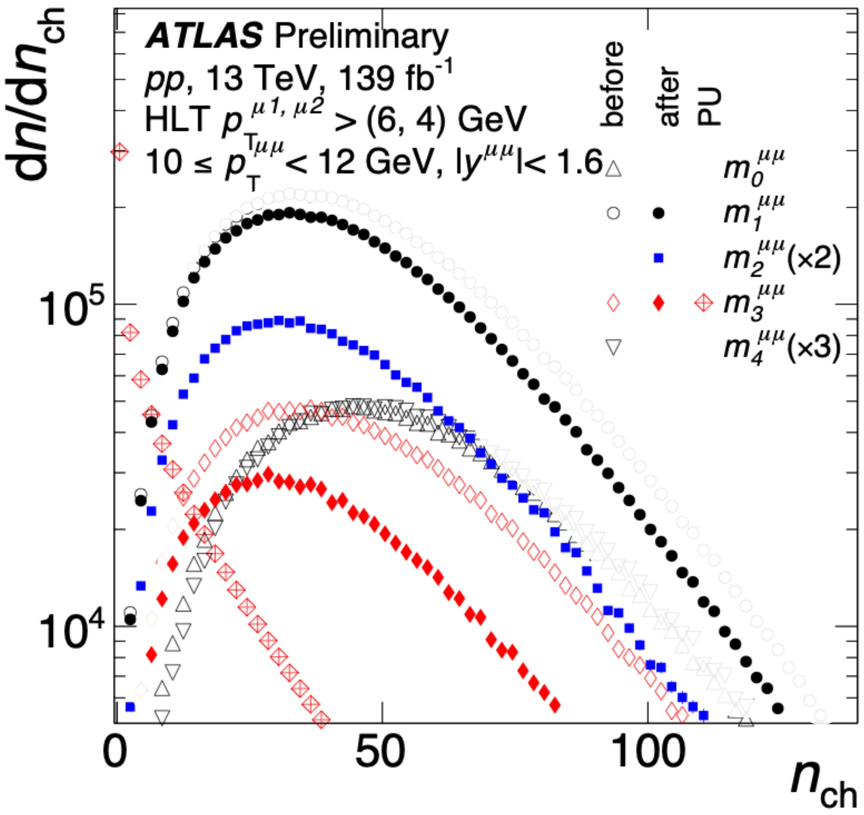

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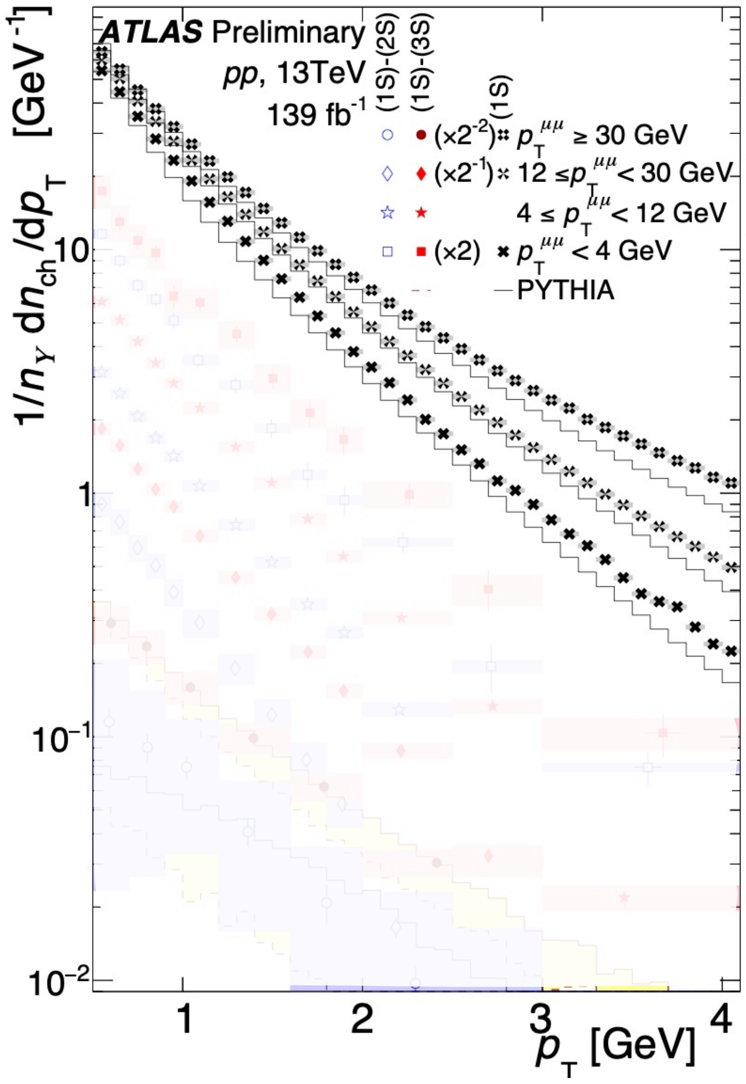

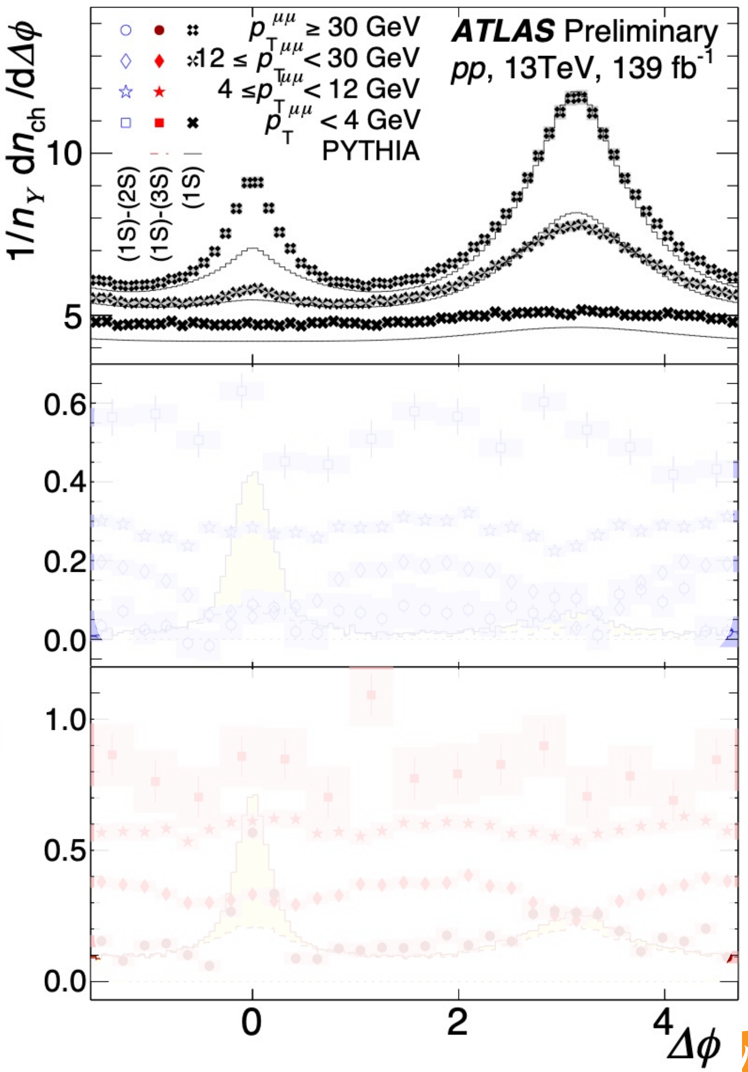

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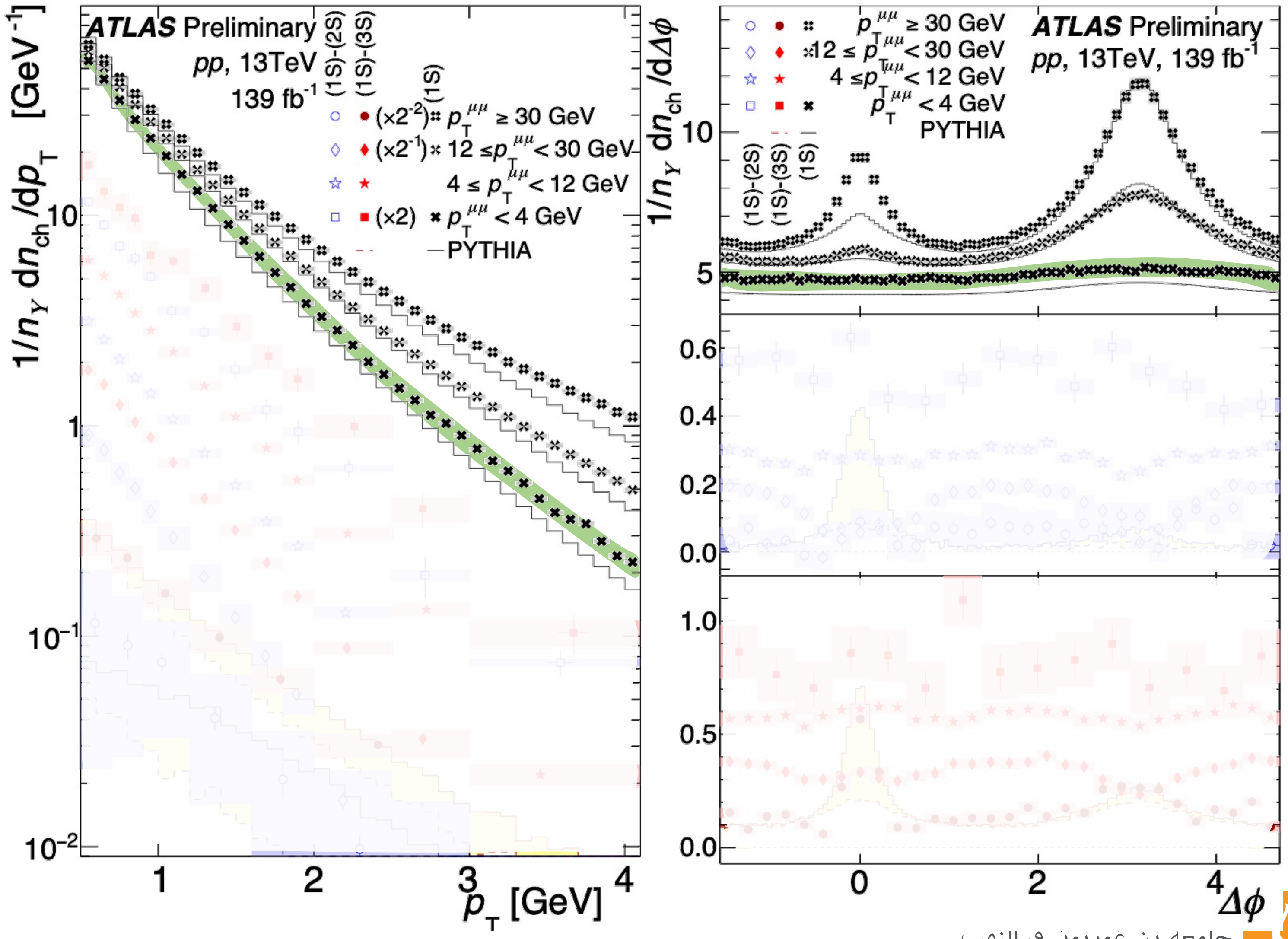

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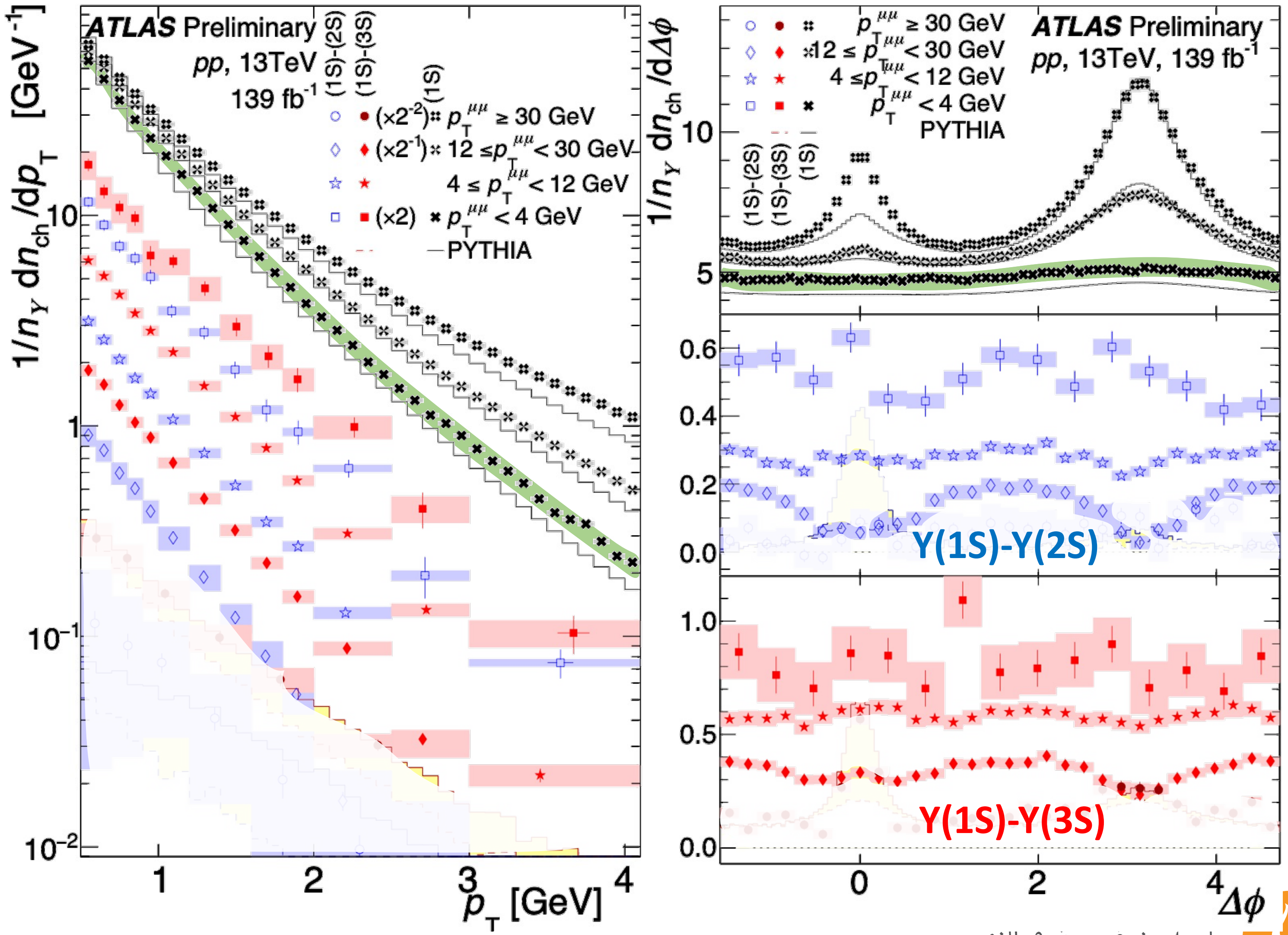

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ATLAS Measurement of Y(nS) and UE

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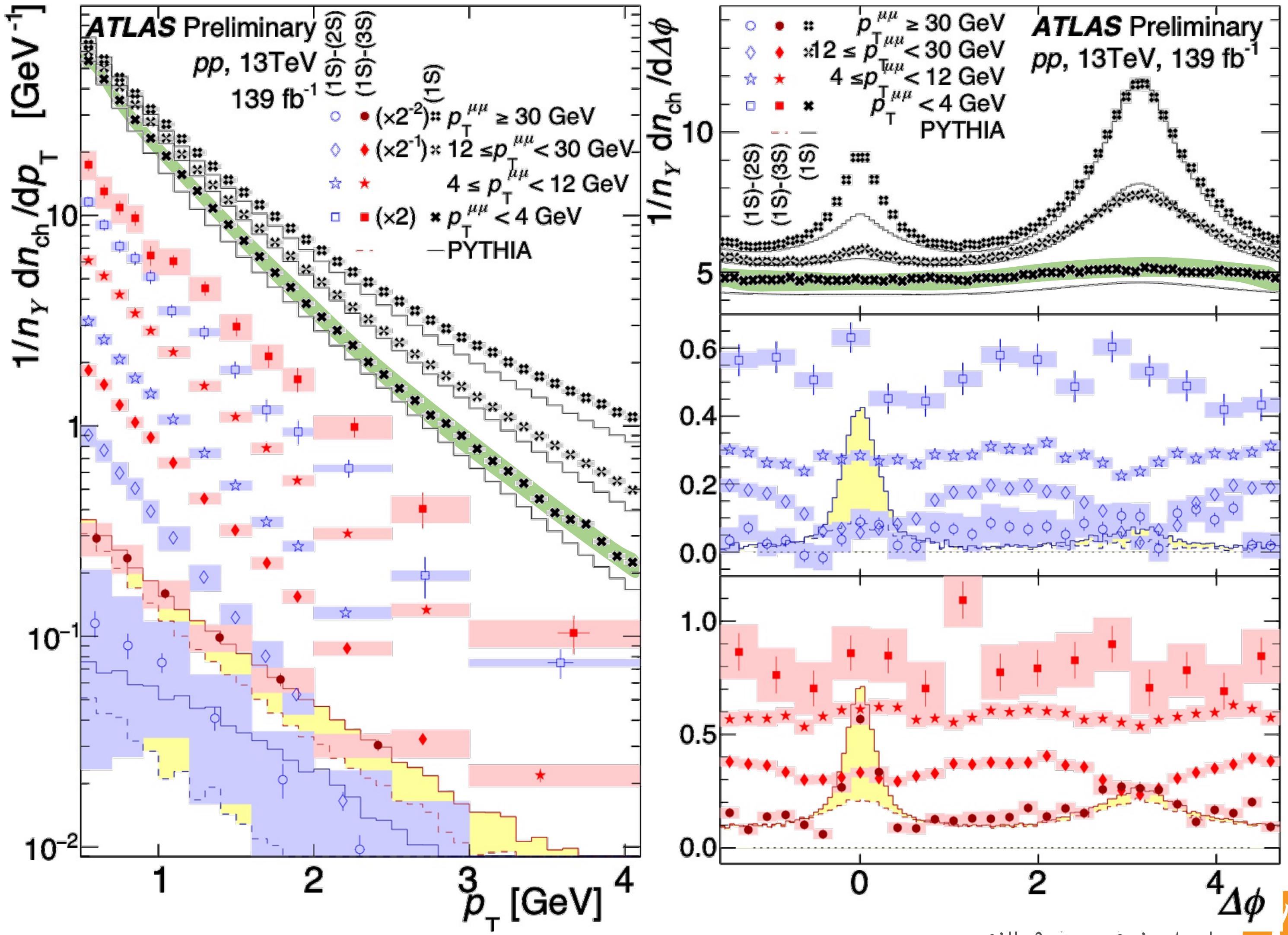

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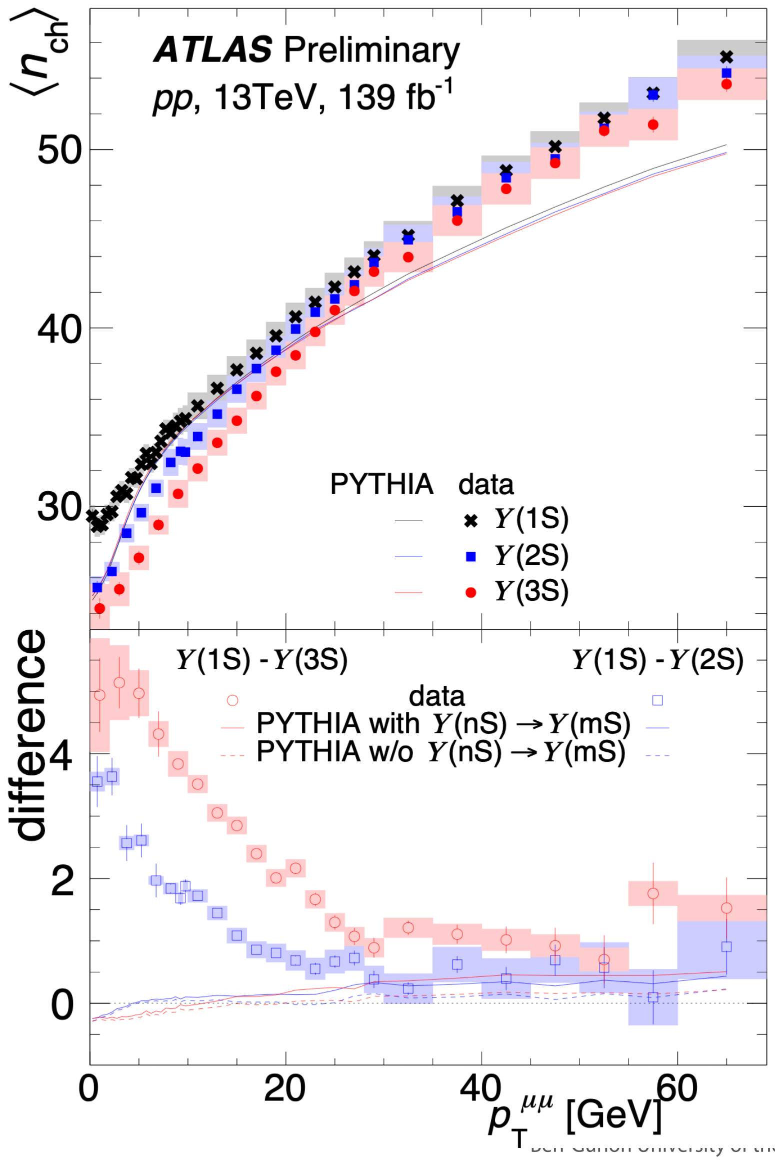

ATLAS Measurement of Y(nS) and UE

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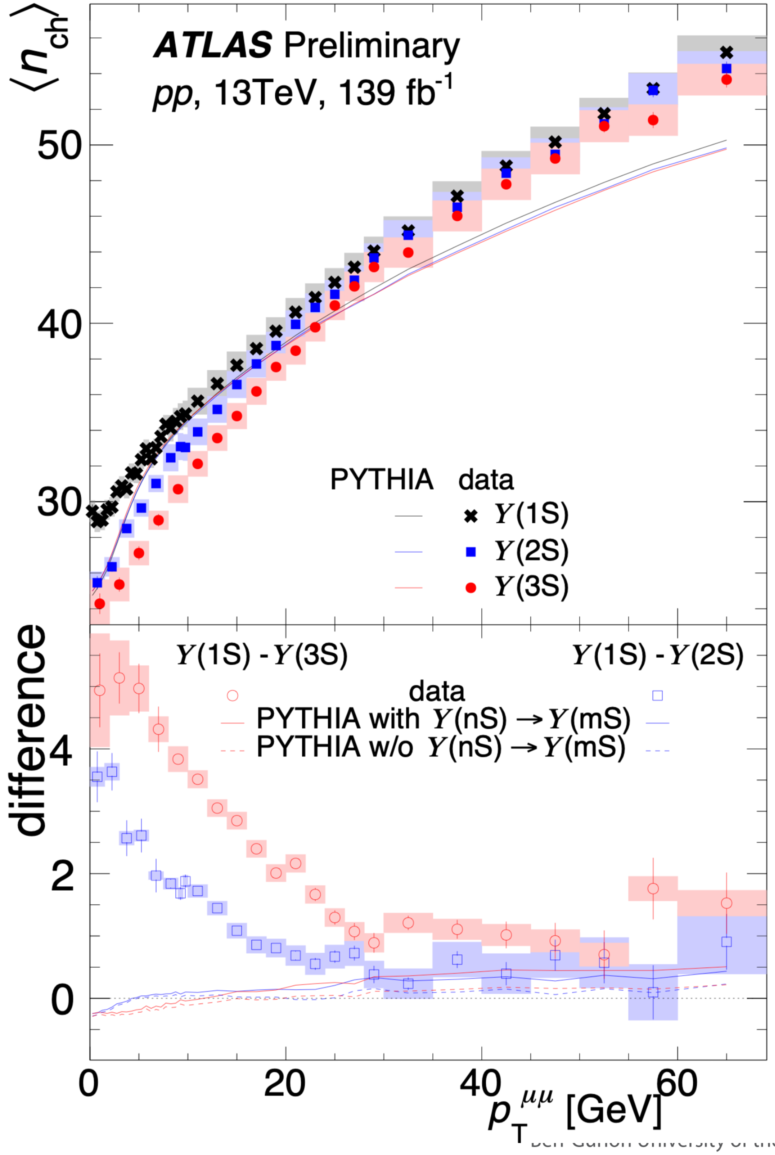
- Shift in UE multiplicity across different excitation states can be understood as suppression of excited states at higher multiplicity



Is there Υ(nS) Suppression in pp Collisions?

- As event multiplicity (should be UE) grows larger, excited Υ states are, compared to the ground state, relatively less likely to be found
- Do the CMS and ATLAS results show some “QGP-like” quarkonium “melting”?
- Is it even suppression? (yes) Maybe ground state enhancement? (no) →**In any case seems to be a hard – UE correlated phenomenon beyond CR/MPI tunings**

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Summary

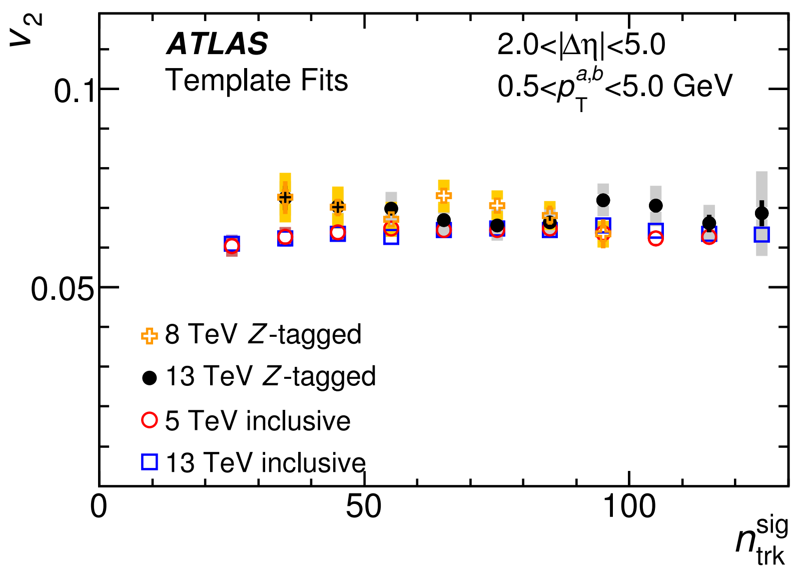
- Measuring CR sensitive observables in top quark events, gives us a detailed handle on CR/MPI
- Strong evidence from Upsilon mesons that there is some non-trivial interaction between the “UE” and a hard scattering
  - ATLAS & CMS have independent approaches that both point to UE driven modification of relative abundance of ground state vs excited state Upsilon mesons
  - Modification appearst to be a suppression of excited states
  - ***Seems we don’t understand Upsilon meson production in pp***

Extra Slides

A Previous Hard-Soft Study: Two-particle correlations in Z Boson Tagged pp Collisions

- In a previous study we asked: Does the presence of a hard scattering in the collision change "*something-like-geometry*" and consequently the observed "*flow*"?
- To answer we studied v_2 via 2-particle correlations in pp collisions 'tagged' by a Z boson
- The answer to above question is not really

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



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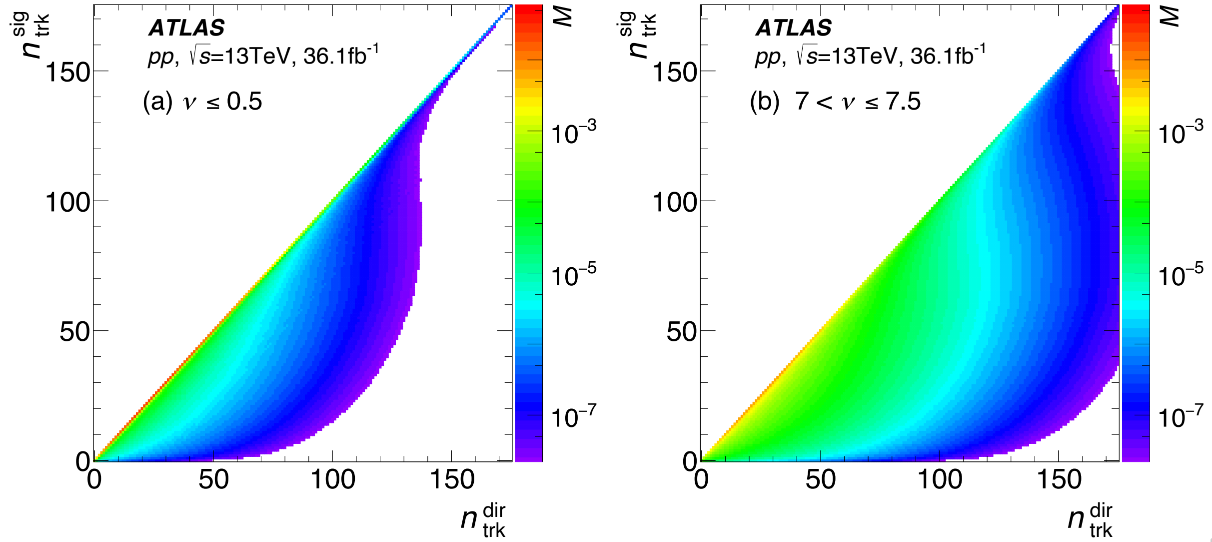
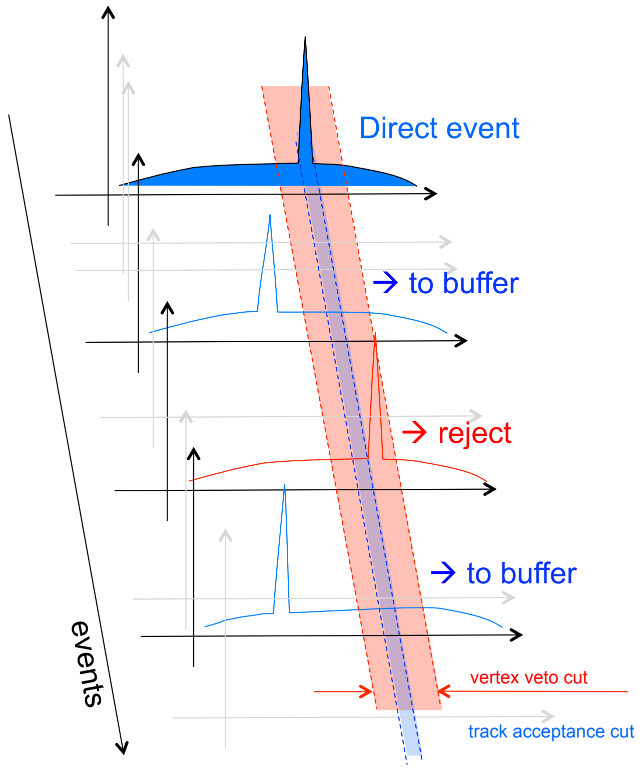
A Previous Hard-Soft Study: Two-particle correlations in Z Boson Tagged pp Collisions

- Developed techniques for HI-style analysis in high-luminosity pp collisions
  - We learned how to look at all tracks in the event even with high pile-up conditions
  - Starting thinking about where else this could be used … **Upsilon mesons**!



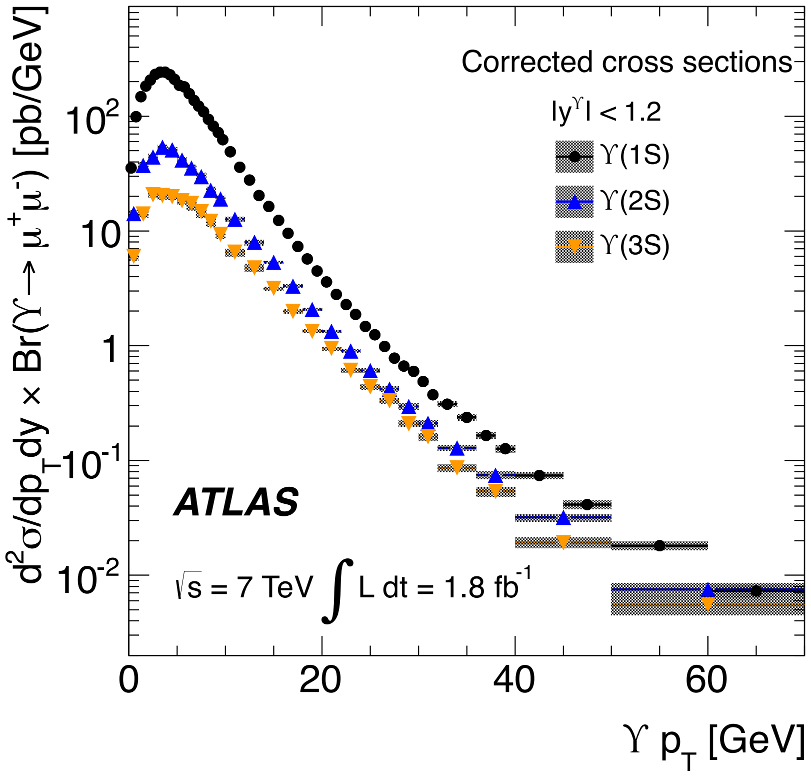


Eur. Phys. J. C **80,** 64 (2020)

What Do We Know about Upsilon Production at the LHC?

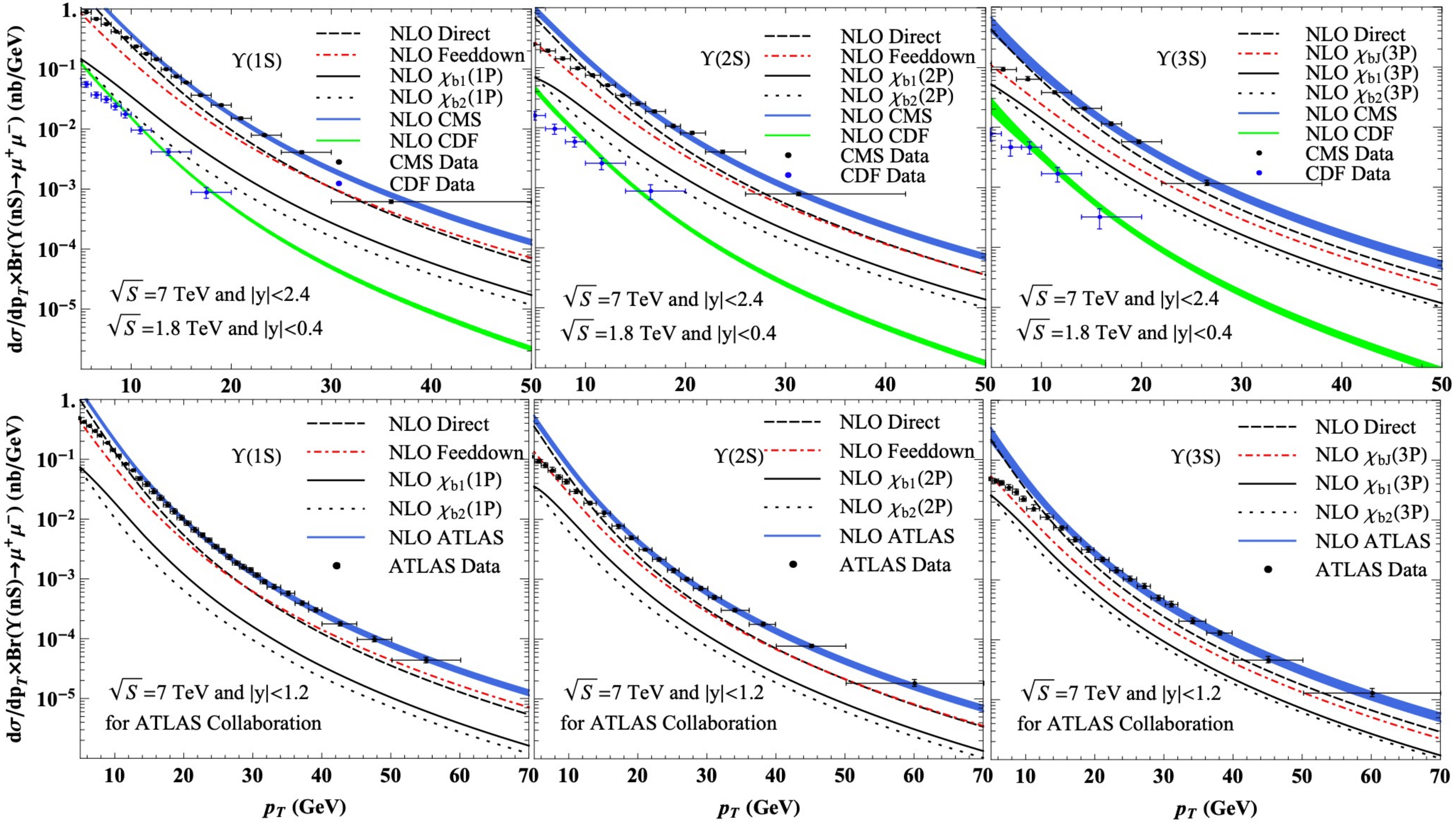
- Production cross-section seems well measured in pp collisions
- Some questions remain regarding polarization, importance of χ_b feed-down etc

Phys.Rev.D 87 (2013) 5, 052004



pQCD Calculations of Cross-Sections

PRD94, 014028 (2016)



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

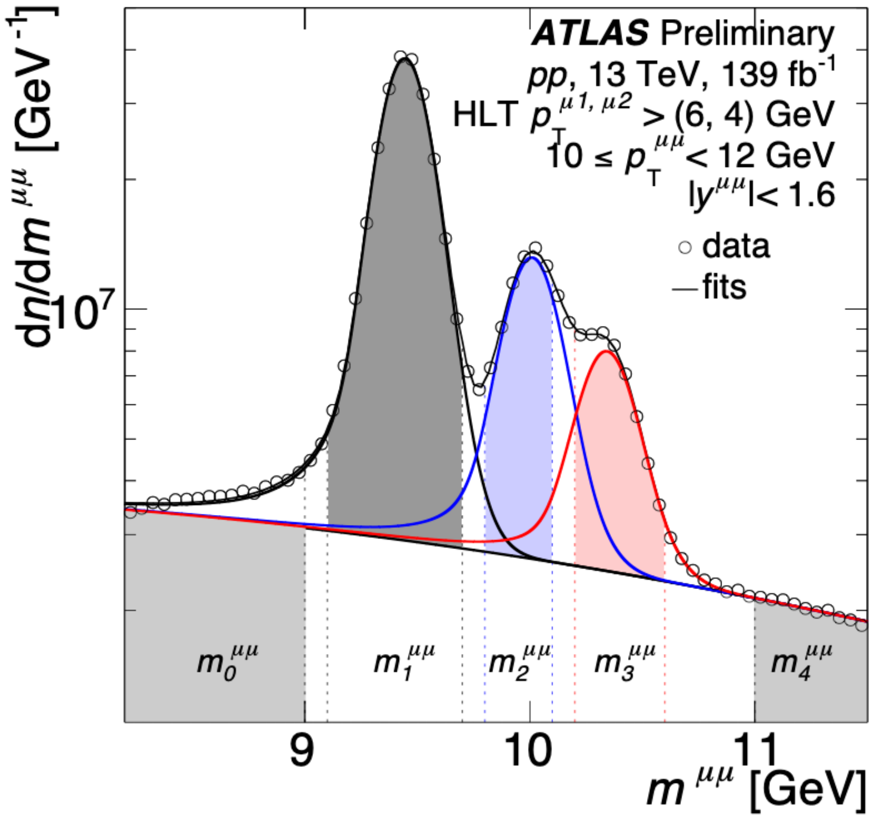
Calculations and the data show clear differences

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

Technical Fit Things



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

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

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

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

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

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

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

Systematics Summary

	$p_T^{\mu\mu} \leq 4$ GeV	$4 < p_T^{\mu\mu} \leq 12$ GeV	$12 < p_T^{\mu\mu} \leq 30$ GeV	$p_T^{\mu\mu} > 30$ GeV
$\Upsilon(1S)$	0.5 – 0.6	0.5 – 0.7	0.7 – 0.8	0.8 – 0.9
$\Upsilon(2S)$	0.6 – 0.6	0.5 – 0.7	0.7 – 0.8	0.8 – 1.0
$\Upsilon(3S)$	0.9 – 1.3	0.5 – 0.8	0.7 – 0.8	0.8 – 0.9
$\Upsilon(1S) - \Upsilon(2S)$	0.11 – 0.15	0.06 – 0.10	0.12 – 0.21	0.2 – 0.5
$\Upsilon(1S) - \Upsilon(3S)$	0.6 – 0.9	0.14 – 0.36	0.14 – 0.15	0.16 – 0.19

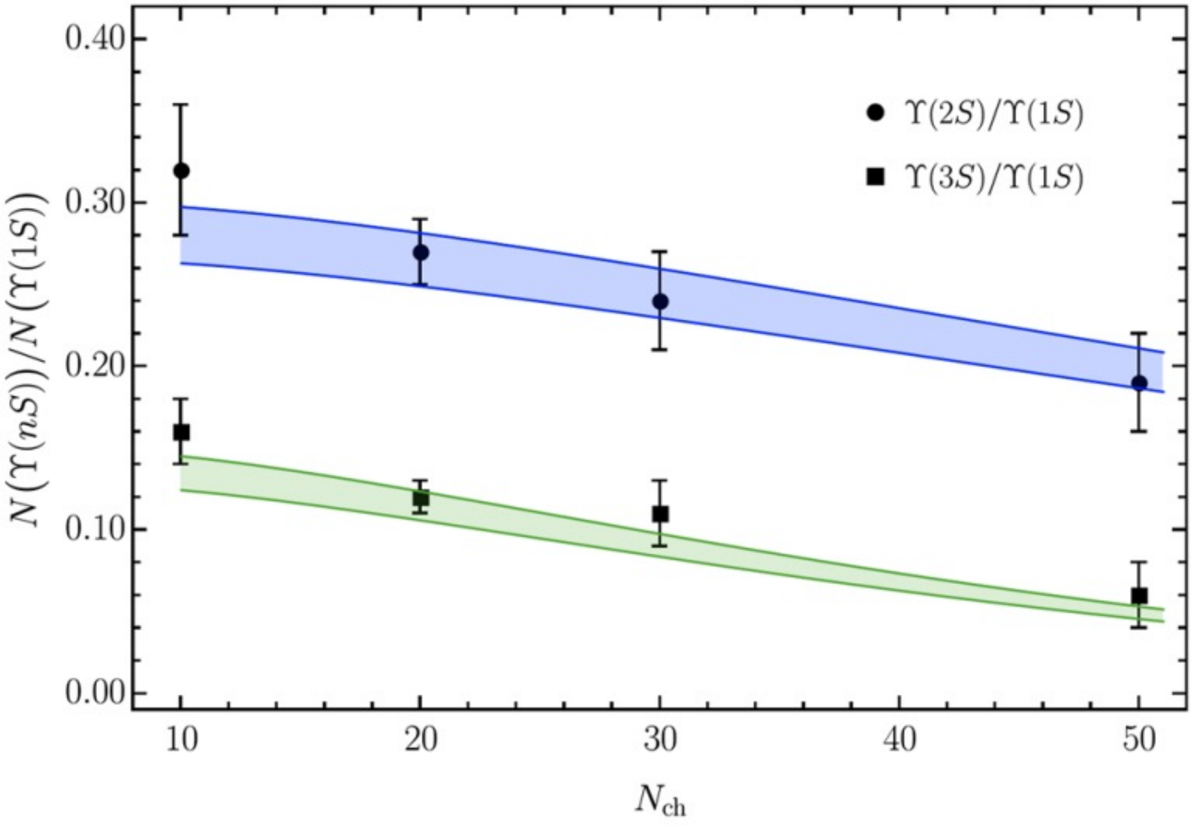
Table 1: Systematic uncertainties for measurements of $\langle n_{ch} \rangle$ and their differences for different $\Upsilon(nS)$ states and for the difference between $\langle n_{ch} \rangle$ measured for $\Upsilon(1S) - \Upsilon(nS)$. The values are the number of charged particles with $0.5 \leq p_T < 10$ GeV and $|\eta| < 2.5$.

Shown here in "units" of n_{ch} but propagated to all quantities

Co-mover Interaction Model (CIM)

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, matches CMS Upsilon pp data.
- 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}, $\Delta\varphi$ $\Delta\eta$

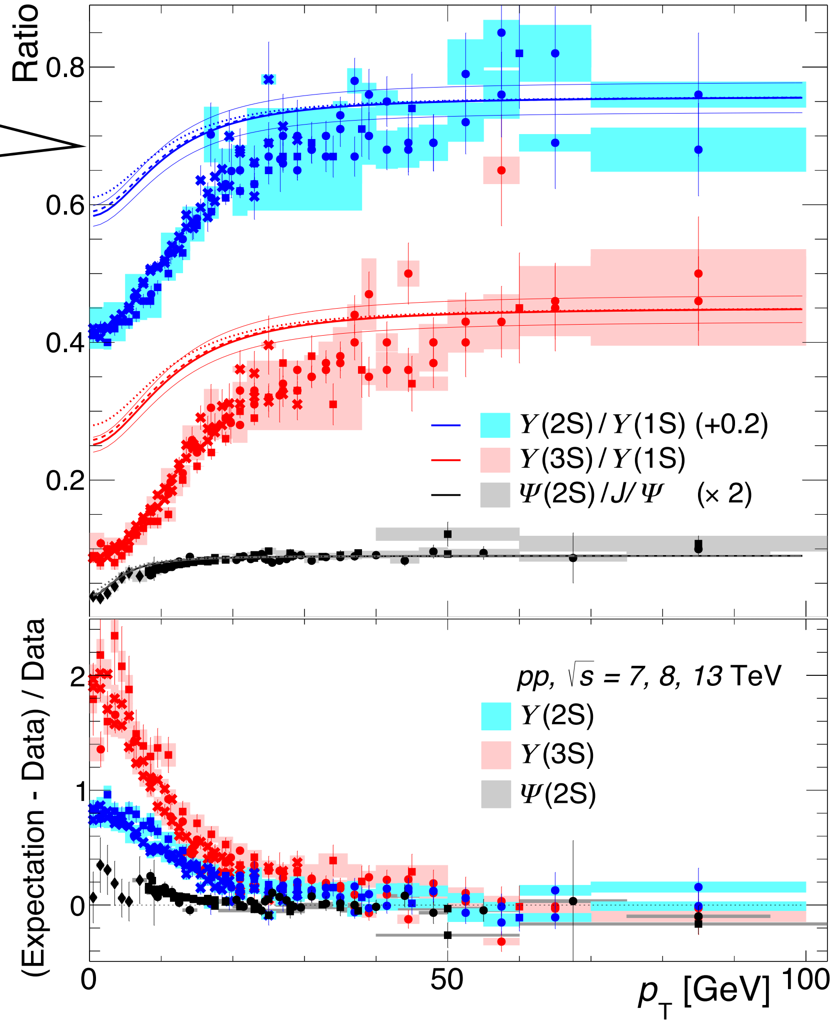


Quarkonia Ratios Expected From m_T Scaling

arXiv:2203.11831

- Transverse mass scaling lets one define an expectation for the excited states relative to the ground states
- Works well ~universally for light mesons at LHC energies
- Looking at Upsilon meson cross-sections shows missing excited states at low p_T
  for $\Upsilon(2S)$ factor of 1.6 are missing
  for $\Upsilon(3S)$ factor of 2.4!

$$1 - \frac{n\Delta m}{nT + m_{q\bar{q}}}$$



ATLAS EXPERIMENT

אוניברסיטת בן-גוריון בנגב
جامعة بن غوريون في النقب
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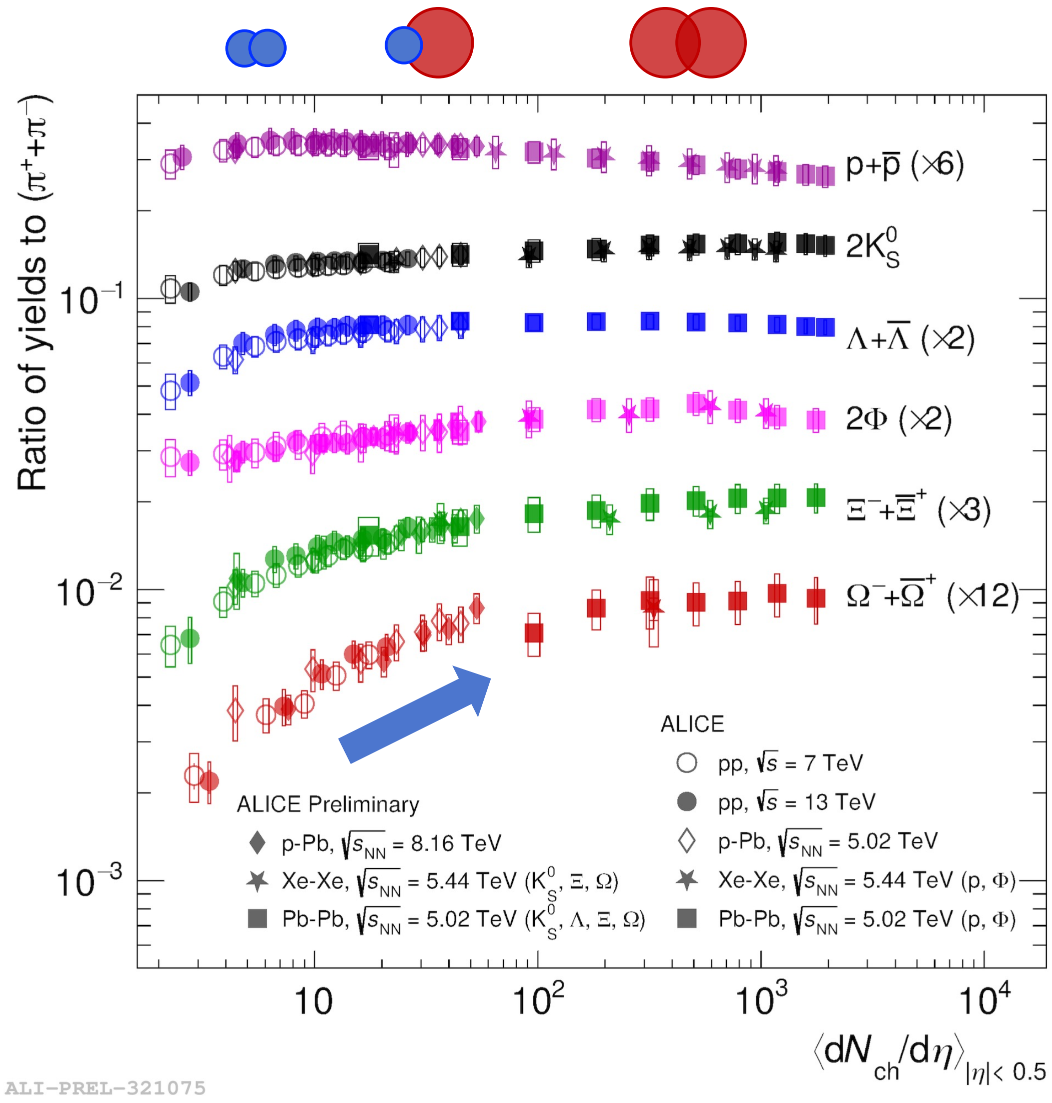
A Strange Digression

- Enhancement of strange hadrons is one of the signature pp collectivity results
- Recent ALICE analyses seek to understand its nature …



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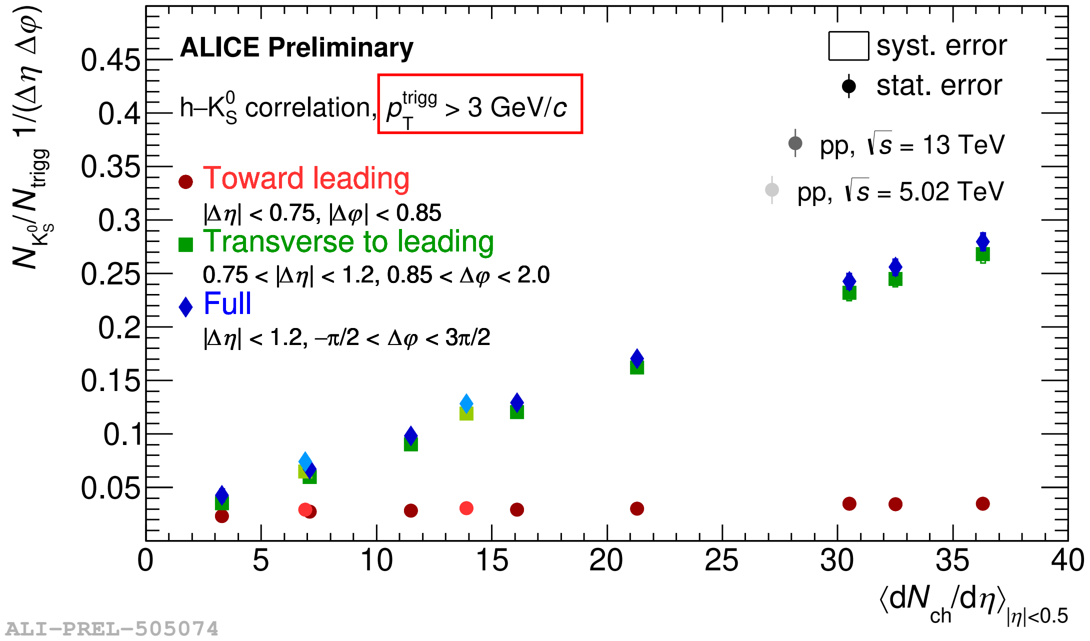
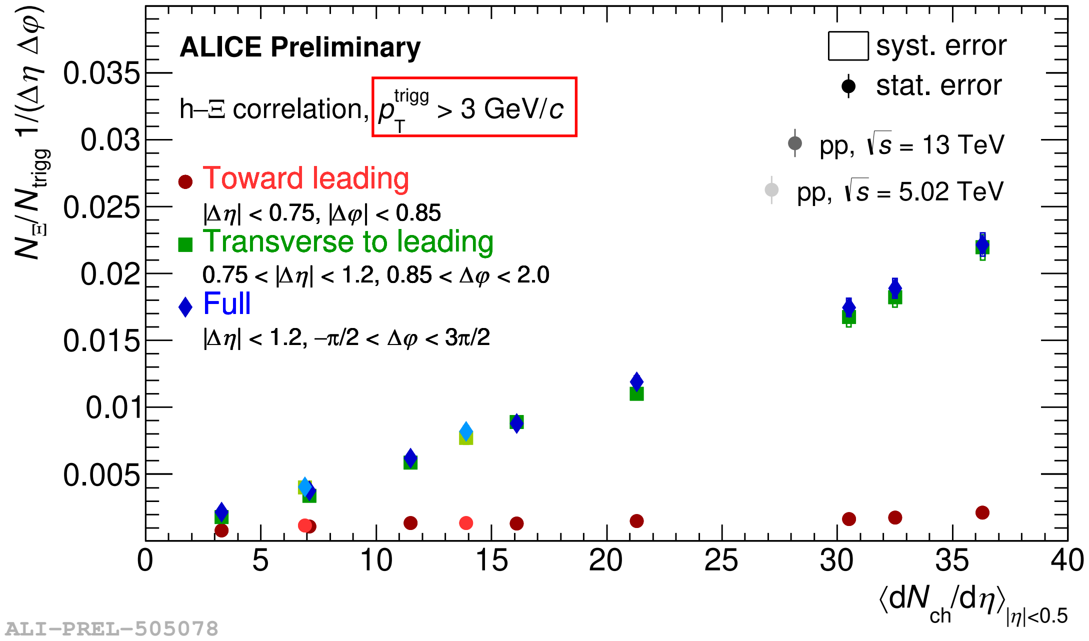
A Strange Digression

- Enhanced strange hadrons are transverse to leading particle in event
- Strangeness enhancement is occurring outside of jets, perhaps implying that it's a UE effect …

K^0_S

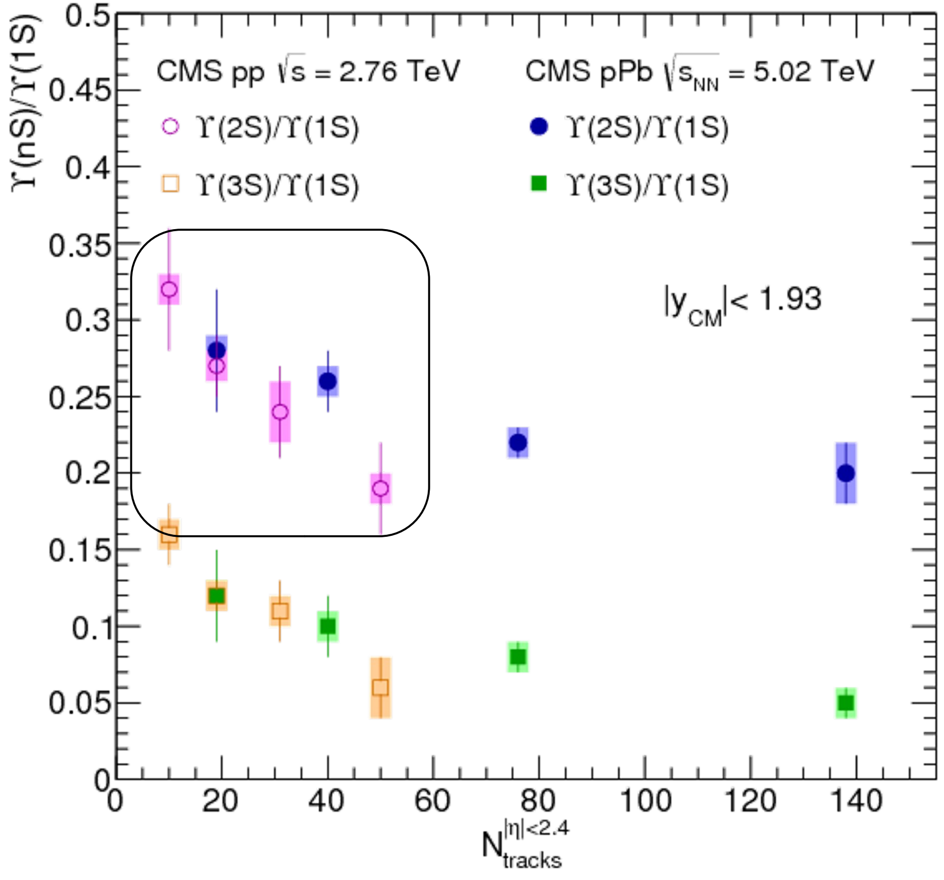


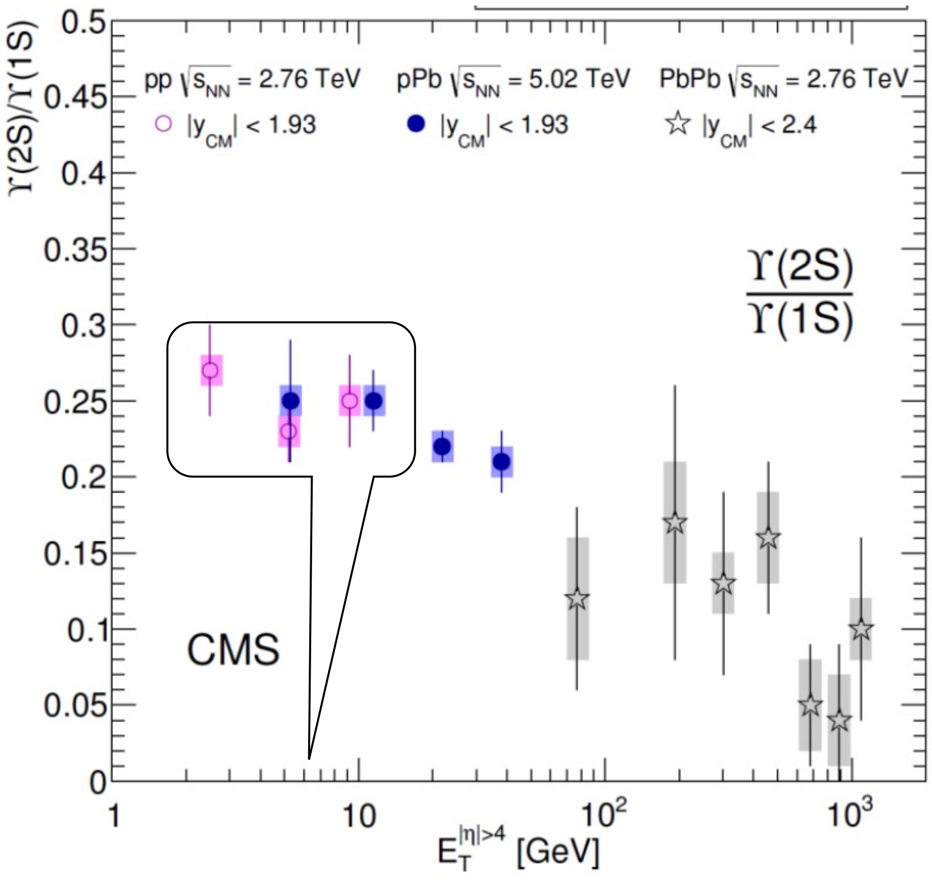
$\Xi^{\pm}$



Does the rapidity matter?

JHEP 04 (2014) 103





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

But it may be due to loss of resolution…

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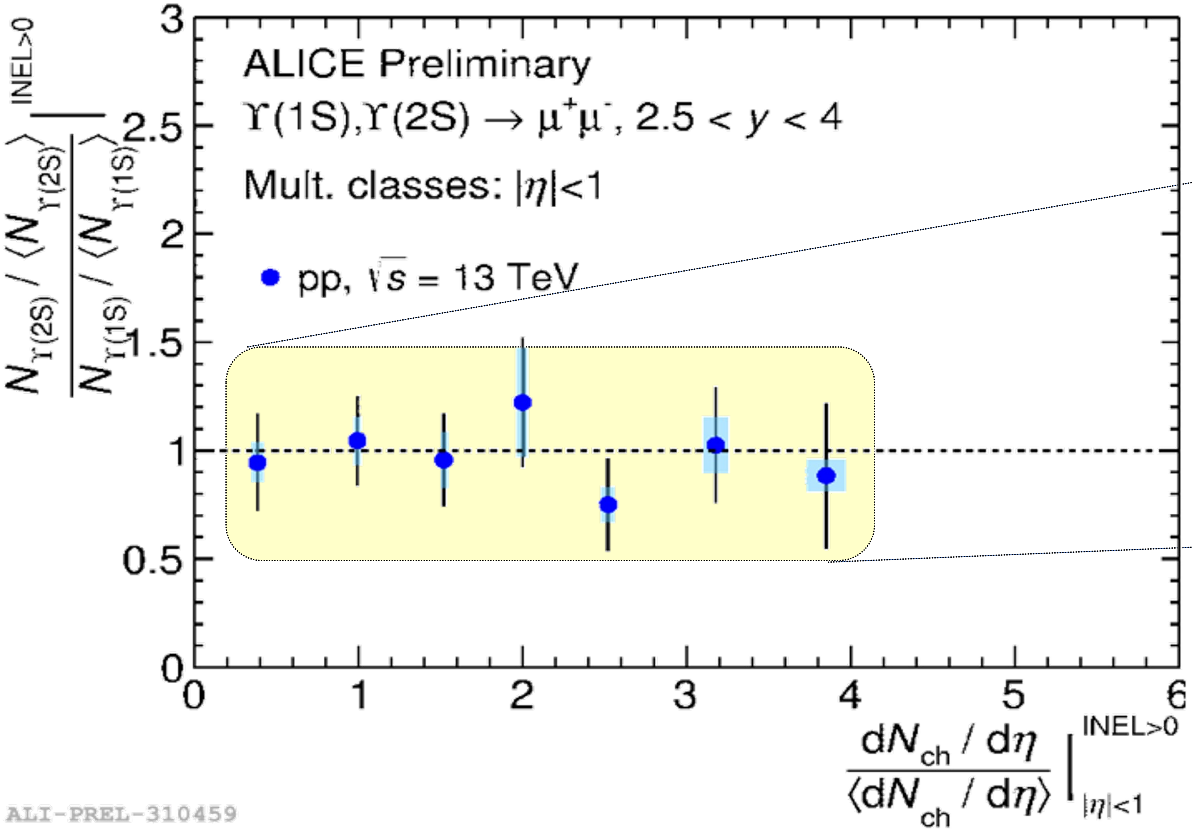
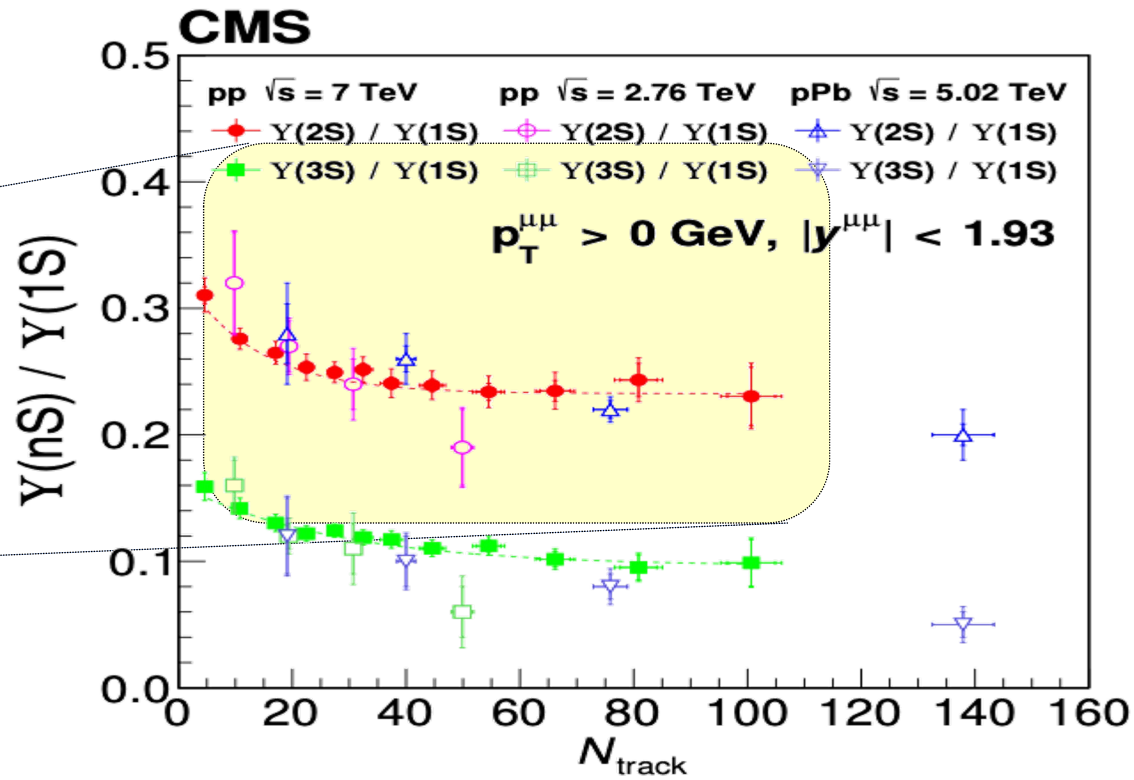
Does the rapidity matter?





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