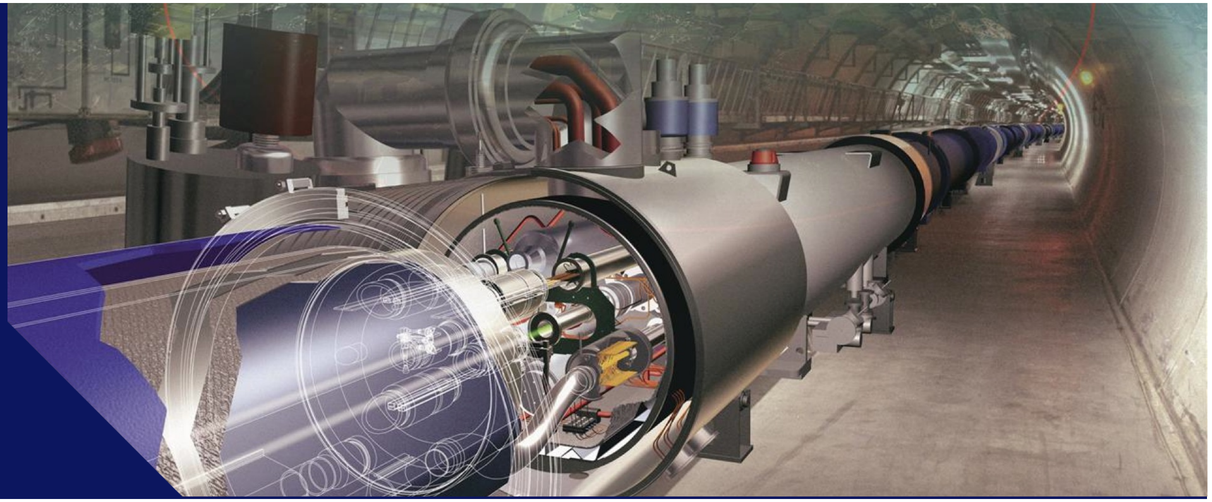
DIS 2023

Michigan State University

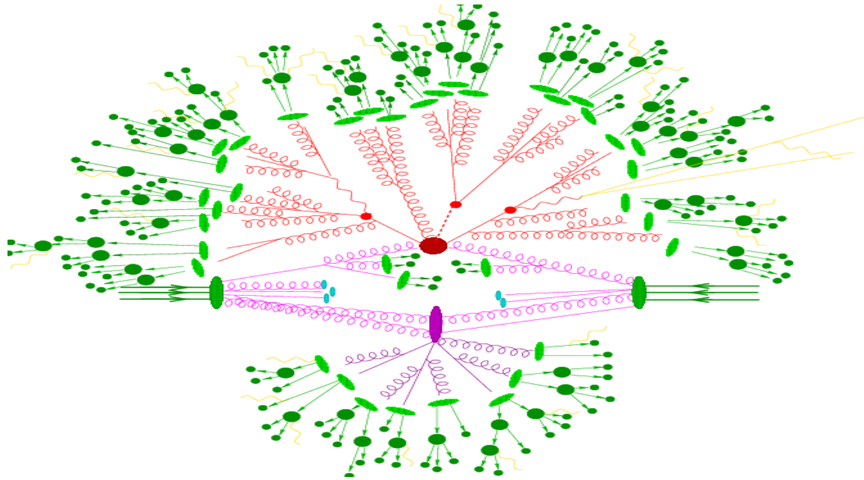
27 – 31 March 2023



# Underlying Event Measurements at ATLAS

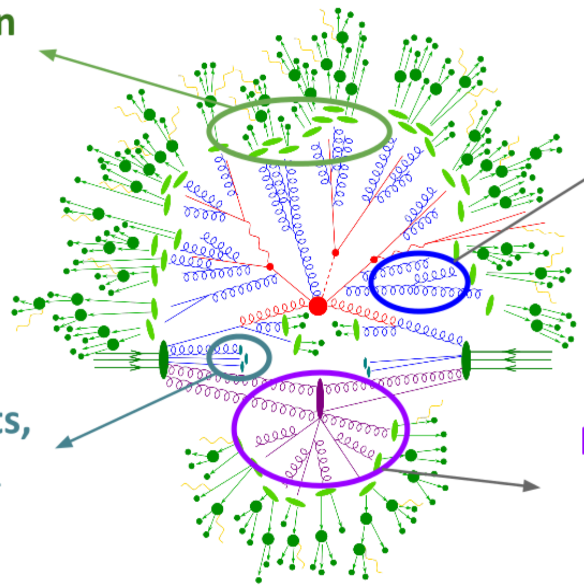

Claire Gwenlan, Oxford

on behalf of the ATLAS collaboration

- *Observables sensitive to colour reconnection in ttbar events* ( arXiv:2209.07874 )
- *Correlation of $\Upsilon$ meson production with the underlying event* ( ATLAS-CONF-2022-23 )

# Underlying Event at the LHC



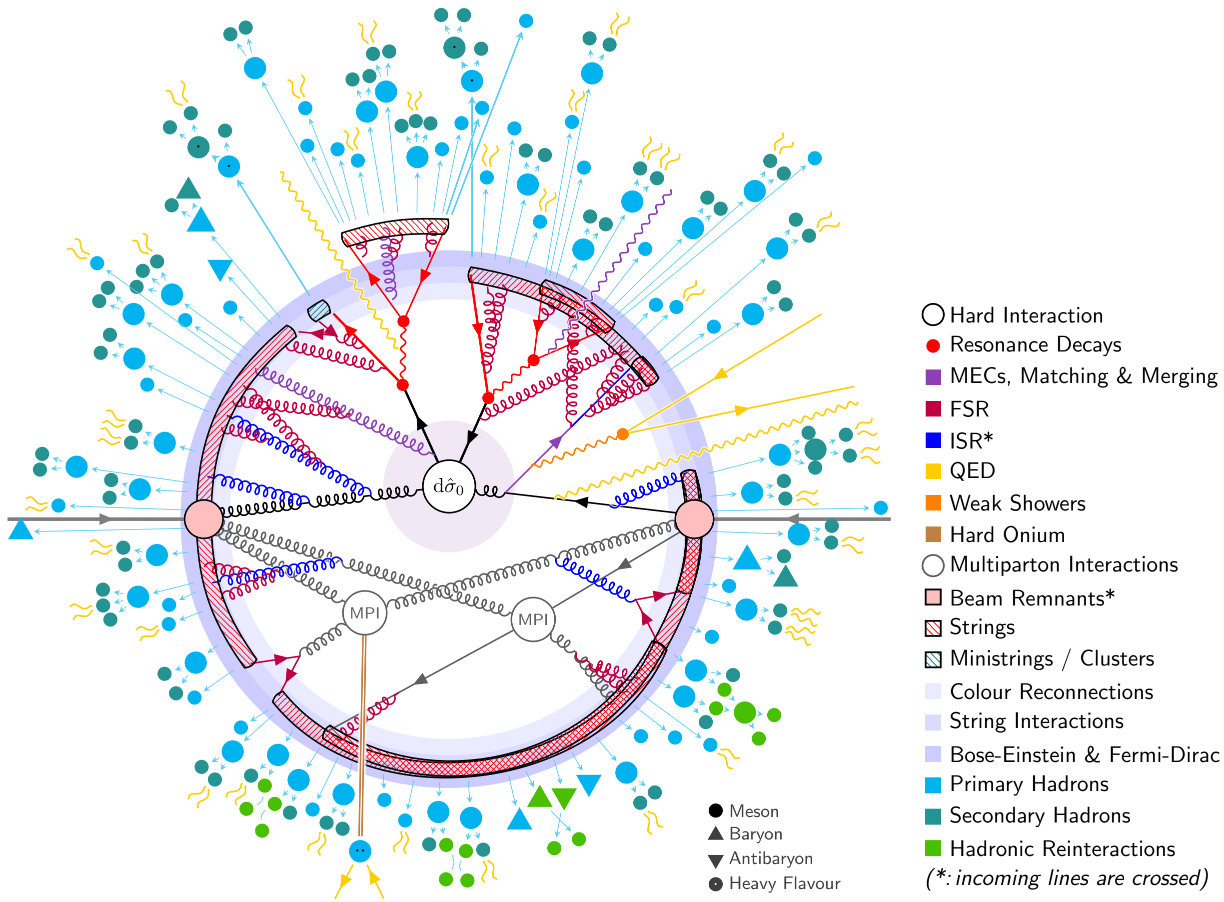

Credit: Frank Siegert

- **underlying event** : any hadronic activity not associated with hard scattering process
- contributions not always calculable in perturbative QCD → phenomenological models in **MC**, which must be tuned to data
- typically modelled with :
  - **multiple parton interactions**
  - **initial and final state radiation**
  - **colour reconnection (CR) with beam remnants**

CR refers to the way in which colour fields rearrange themselves after collision

# Measurements of observables sensitive to colour reconnection in $t\bar{t}$ events with the ATLAS detector

**arXiv:2209.07874, accepted by EPJ**




structure of a $pp \to t\bar{t}$ event, as modelled by PYTHIA.

# Motivation

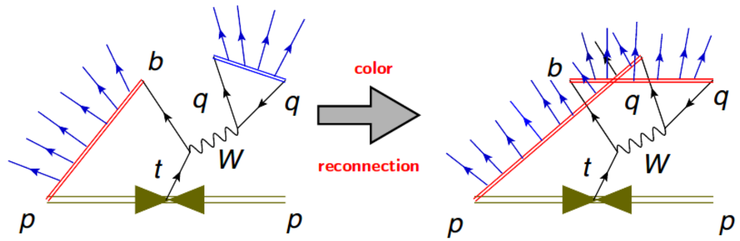
- **CR experimentally motivated** → first introduced in MC to describe rise of ⟨$p_T$⟩ vs $n_{ch}$
- **CR** intimately connected to **MPI**
- new constraints on **CR** and **MPI**,
  will provide improved description everywhere

- **specifically in context of top**, modelling of **CR** is a **dominant systematic uncertainty** on top mass determination

| | $m_{top}$ [GeV] |
|---|---|
| Result | 172.21 |
| Statistics | 0.20 |
| Method | 0.05 ± 0.04 |
| Matrix-element matching | 0.40 ± 0.06 |
| Parton shower and hadronisation | 0.05 ± 0.05 |
| Initial- and final-state QCD radiation | 0.17 ± 0.02 |
| Underlying event | 0.02 ± 0.10 |
| Colour reconnection | 0.27 ± 0.07 |
| Parton distribution function | 0.03 ± 0.00 |
| Single top modelling | 0.01 ± 0.01 |
| Background normalisation | 0.03 ± 0.02 |
| Jet energy scale | 0.37 ± 0.02 |
| $b$-jet energy scale | 0.12 ± 0.02 |
| Jet energy resolution | 0.13 ± 0.02 |
| Jet vertex tagging | 0.01 ± 0.01 |
| $b$-tagging | 0.04 ± 0.01 |
| Leptons | 0.11 ± 0.02 |
| Pile-up | 0.06 ± 0.01 |
| Recoil effect | 0.39 ± 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) | 0.80 ± 0.06 |

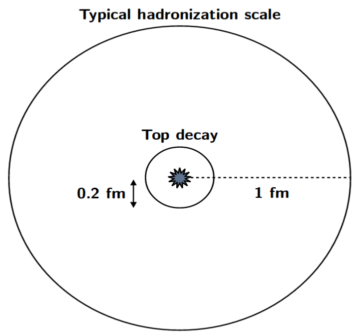
ATLAS-CONF-2022-058

**Color reconnection affects the reconstruction of the top system**




Ambiguity in the definition of the top mass: $m_{\text{top}}^2 \neq (p_{\text{b}} + p_{\text{j1}} + p_{\text{j2}})^2$

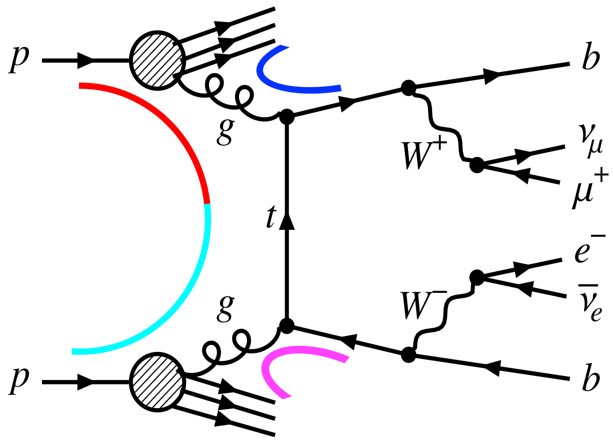
**Credit: S Argyropoulos** JHEP11 (2014) 043




- **interesting unresolved question** regarding involvement of top quark versus its decay products in **CR**

# ATLAS measurement of top quarks and CR

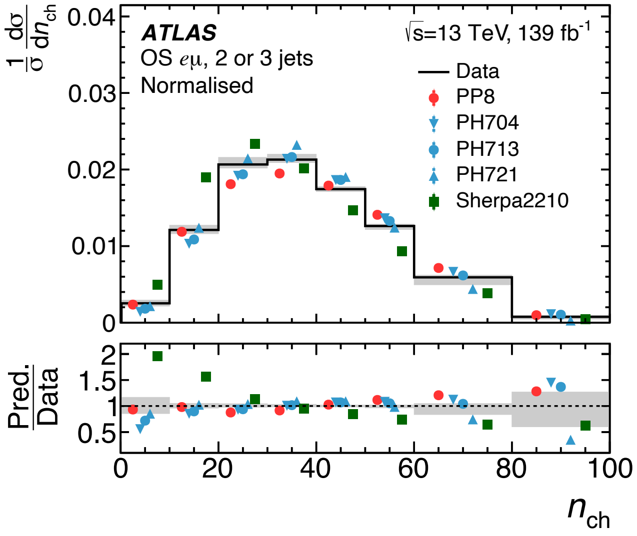
- select $t\bar{t}$ events in di-leptonic **eμ** channel
  (exactly **1 e**, **1 μ** and **2 or 3 jets**, 2 of which **b-tagged**)
- measure inclusive† charged particle properties:
  † excluding leptons or jet tracks, $p_T > 0.5$ GeV, $|\eta| < 2.5$
  - multiplicity $n_{ch}$
  - scalar sum of charged particle transverse momentum, $\Sigma_{n_{ch}}\, p_T$
  - **$\Sigma_{n_{ch}}\, p_T$ in bins of $n_{ch}$**

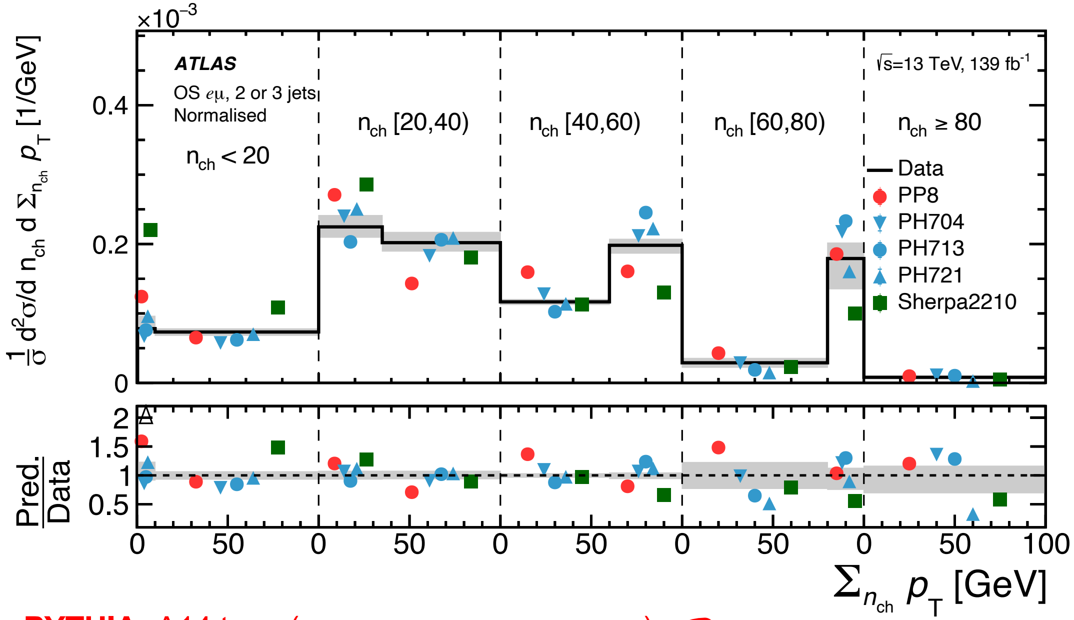


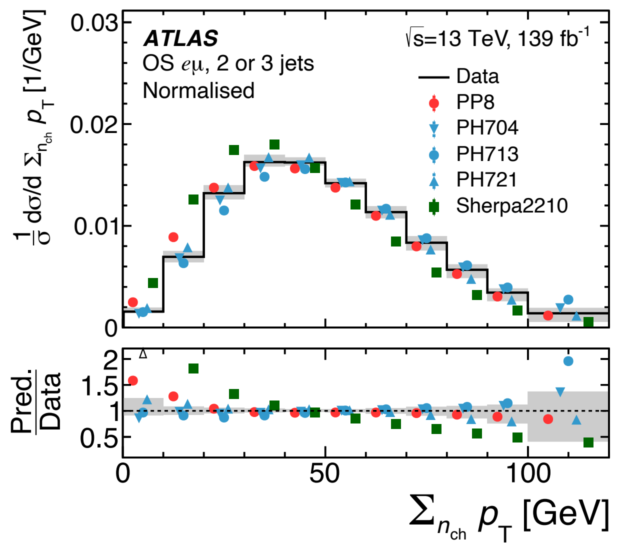

Credit: Z Citron for ATLAS, MPI@LHC

- pileup and fake-lepton contribution subtracted with MC templates
- **compare MC with unfolded normalised differential cross sections:**
- **PYTHIA8** : Lund string model for hadronisation – several CR models
- **HERWIG7** : cluster hadronisation – several CR models
- many tuneable parameters

# cf. different MC Generators



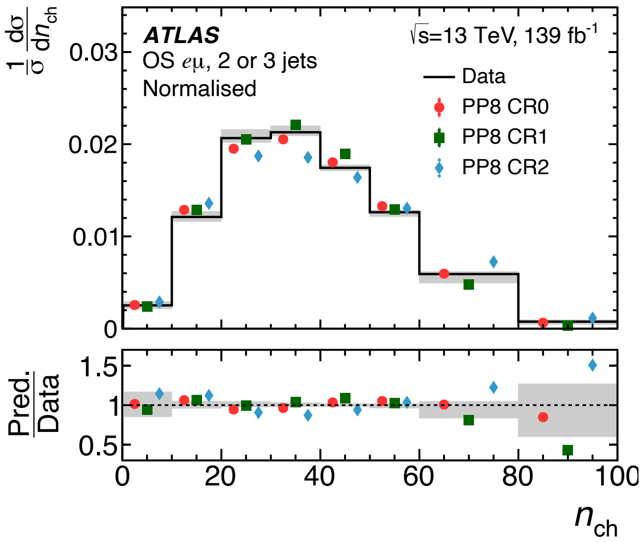

**PYTHIA:** A14 tune (CR based on same model as CR0)

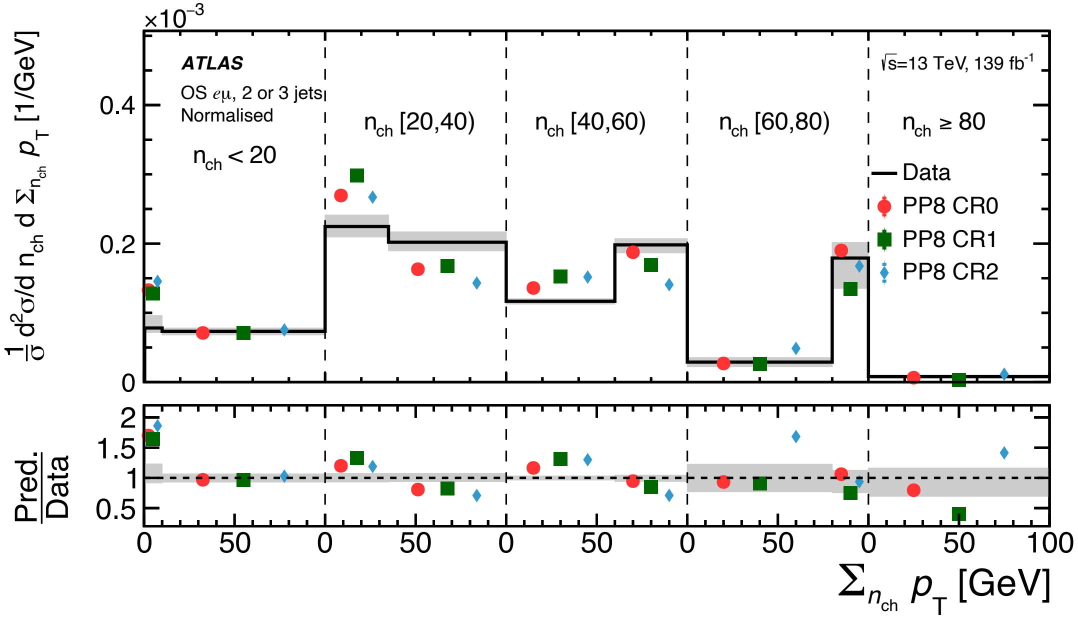
| Observable | $n_{ch}$ | $\Sigma_{n_{ch}} p_T$ | $\Sigma_{n_{ch}} p_T$ in bins of $n_{ch}$ |
|---|---|---|---|
| NDF | 7 | 10 | 8 |
| Generator set-up | | $\chi^2$ | |
| Powheg+Pythia 8.230 | 62 | 106 | 224 |
| CR0 | 55 | 113 | 129 |
| CR1 | 98 | 60 | 158 |
| CR2 | 58 | 179 | 238 |
| Powheg+Herwig 7.0.4 | 39 | 16 | 29 |
| Powheg+Herwig 7.1.3 | 53 | 42 | 41 |
| Powheg+Herwig 7.2.1 | 78 | 25 | 87 |
| Powheg+Herwig Baryonic CR | 75 | 20 | 29 |
| Powheg+Herwig Stat CR | 23 | 40 | 39 |
| Sherpa 2.2.10 | 77 | 211 | 124 |

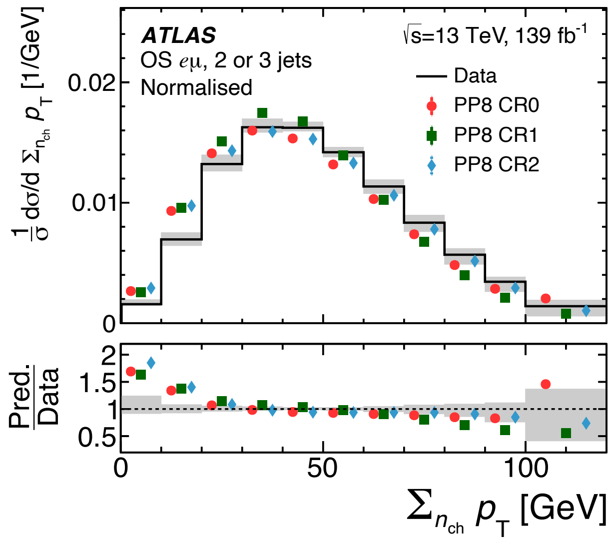
**SHERPA:** PYTHIA-like MPI model, **NO CR**

**HERWIG:** MPI/CR tunes from MC authors

# cf. PYTHIA8 CR Models



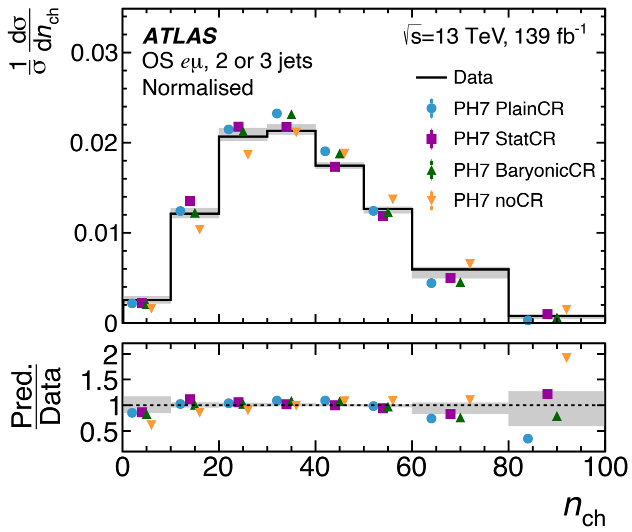



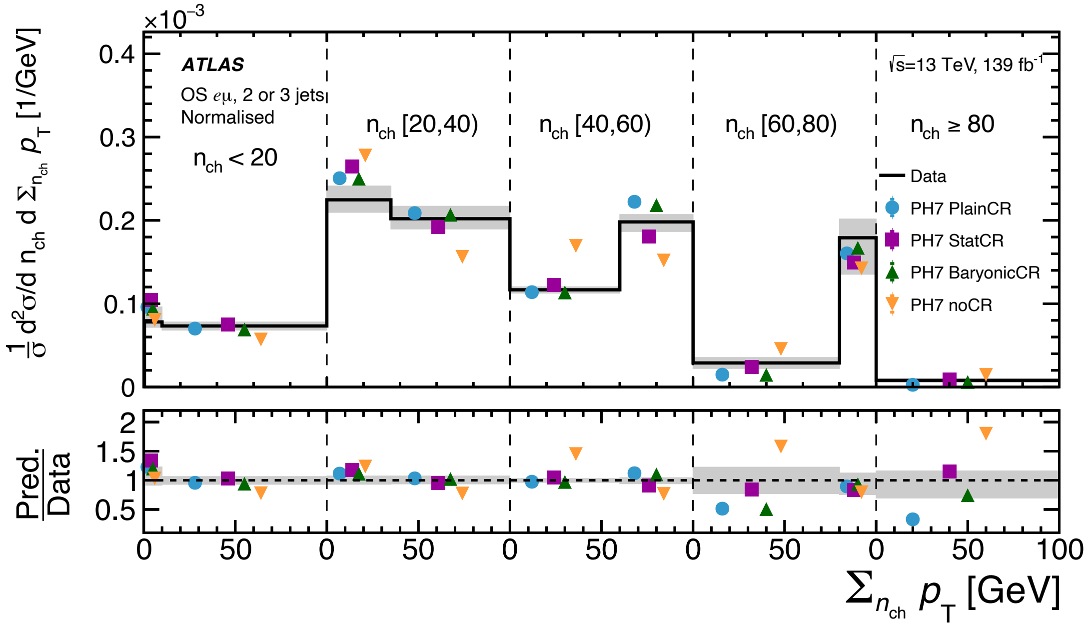

- PYTHIA CR models, previously tuned to **ATLAS UE measurements** ( ATLAS-PHYS-PUB-2017-008 )

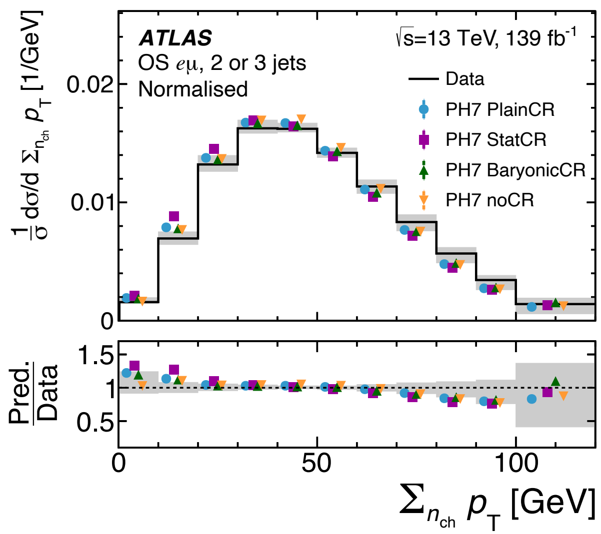
1. *MPI-based* (CR0), simplest model with only 1 tuneable parameter; default in PYTHIA and in ATLAS
2. *QCD-inspired* (CR1), nominally improved scheme, full QCD colour configuration in beam remnant taken into account
3. *Gluon Move* (CR2), simple model, but with only gluons considered for reconnection

(NB, in all 3 models here, top quark lifetime sufficiently long that only it, and not its decay products, is involved in CR process)

# cf. HERWIG7 CR Models



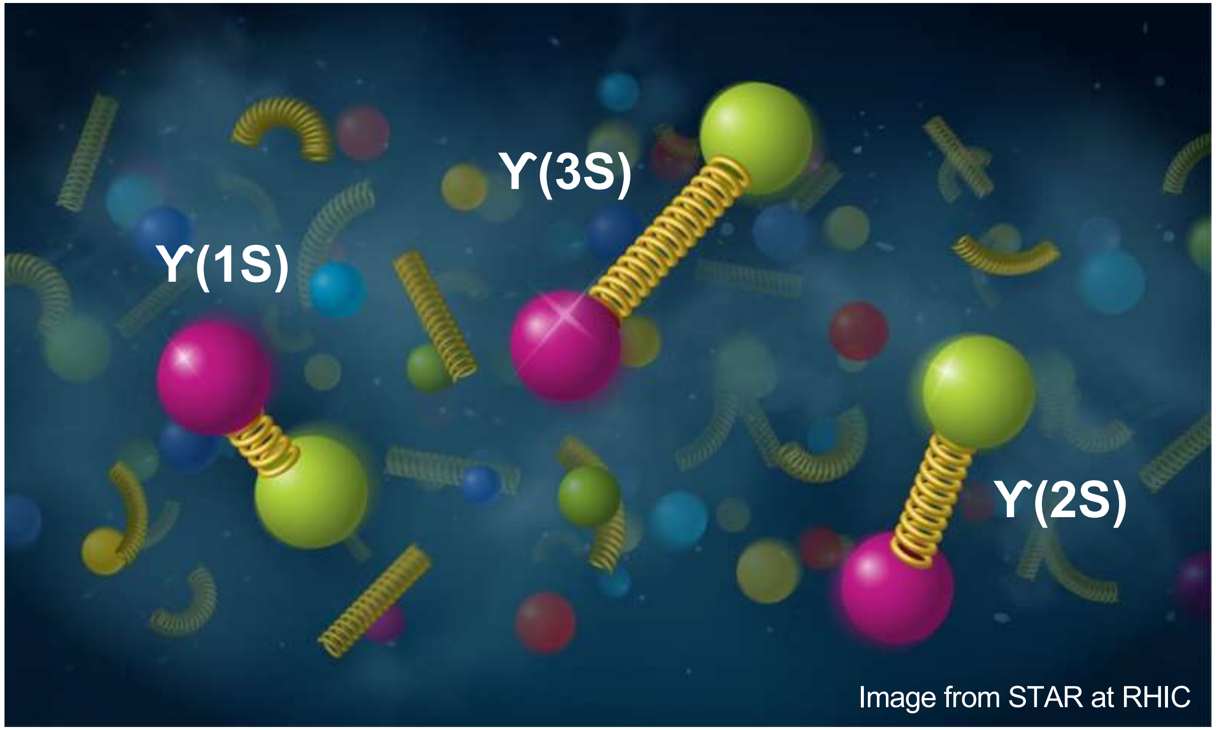

- HERWIG CR models, using tunes from MC authors

1. ***Plain CR***, quarks rearranged between clusters, typically leads to clusters with smaller invariant mass and so less overall UE activity; default used in ATLAS
2. ***Statistical CR***, more sophisticated version, uses Statistical Annealing algorithm to find optimal cluster configuration
3. ***Baryonic CR***, simple geometric picture of nearest neighbour combinations

- **overall best description is by the HERWIG CR models, though no panacea**

# Correlation of ϒ meson production with the underlying event in pp collisions measured by the ATLAS experiment

## ATLAS-CONF-2022-23



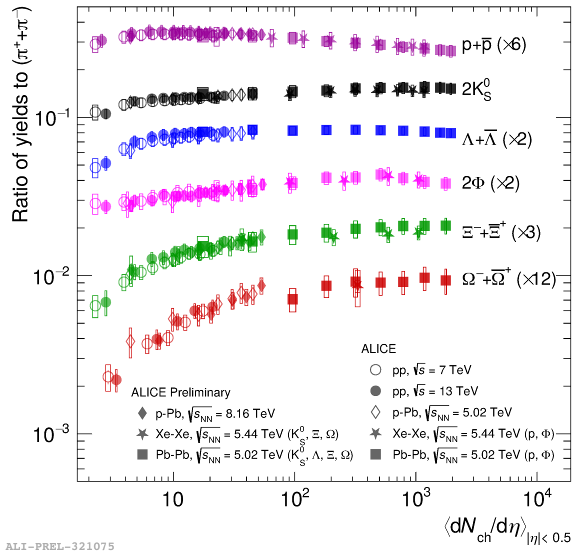
# Motivation

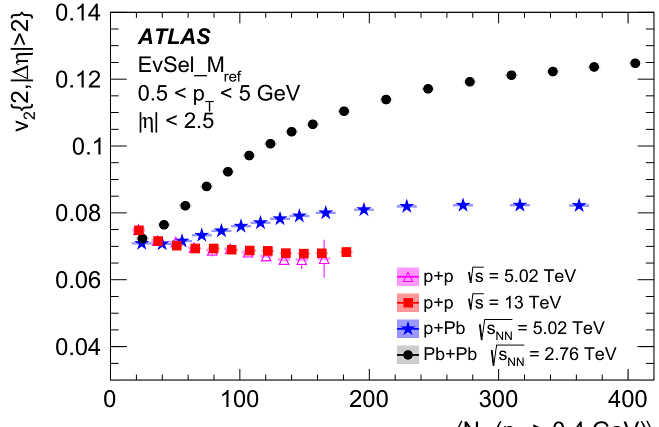
- **Quark Gluon Plasma (QGP)** in **A+A** well established, but smaller collision systems controversial
- → naively do not expect QGP formation in small systems
- → experimental observations of **QGP-like behaviour** in **p+A** and **p+p** calls this into question

- many studies of small systems demonstrating QGP-like phenomena in soft physics, EG. **strangeness enhancement**, **multi-particle correlations** in peripheral **A+A**, **p+A**, and also **p+p**
- → **not many studies using hard probes**

- **ATLAS measurement** ([ATLAS-CONF-2022-23])
- study correlations between **upsilon meson** (ϒ) production and **inclusive charged particles** to bridge **soft-hard** gap

ALI-PREL-321075

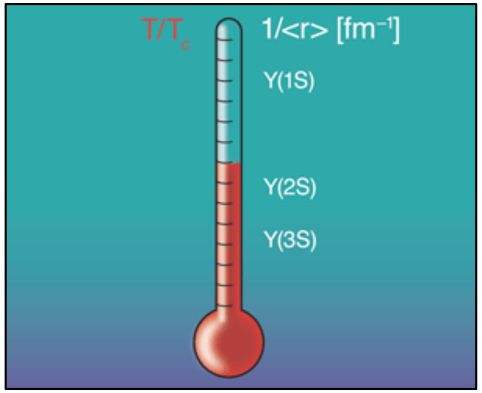



EPJ C77 (2017) 428

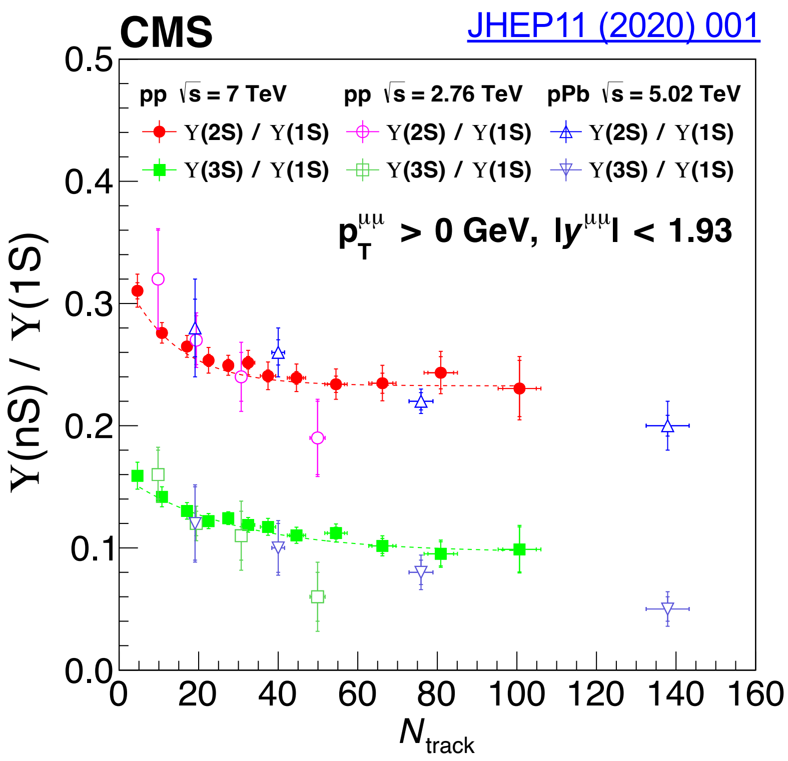
# Why ϒ mesons ?

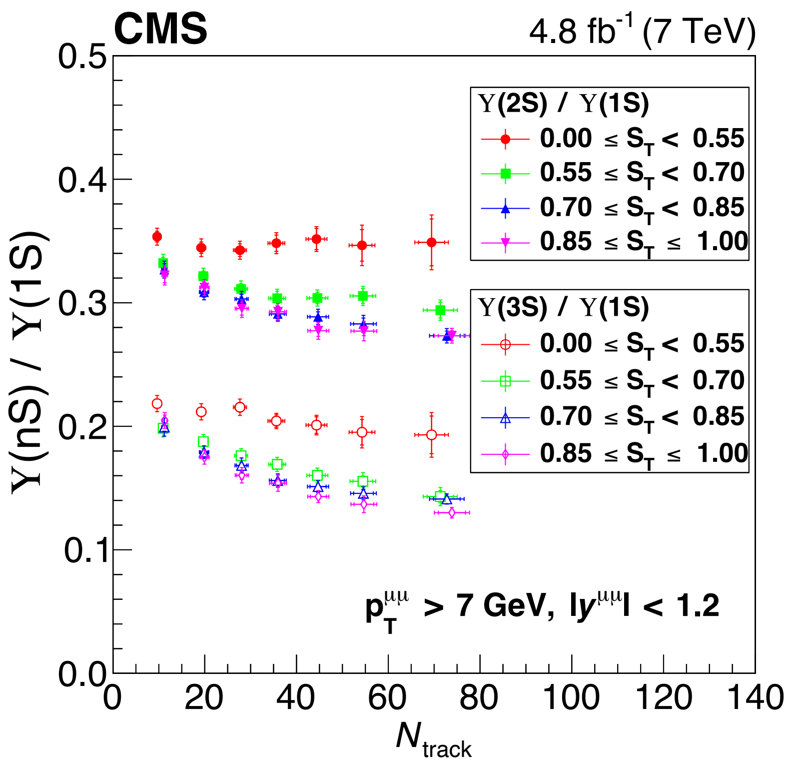
- HI perspective: heavy quarkonia produced early in collision → experience full evolution
- measuring **ϒ(nS)** state suppression can be a thermometer for a QGP :
- 3 distinct **ϒ** ($b\bar{b}$) states: **ϒ(1S) ϒ(2S) ϒ(3S)**
- **sequentially "dissolve"** or dissociate when potential between constituent quarks screened by colour charges of q, g in QGP
- → the more loosely bound the state, the more easily it dissolves: **ϒ(3S)** is more suppressed than **ϒ(2S)** is more suppressed than **ϒ(1S)**
- **ϒ** less affected by recombination effects than $c\bar{c}$ states, given small probability for b quarks
- **→ ϒ ideal probe to study QGP**


Adapted from EPJ C61 (2009) 705

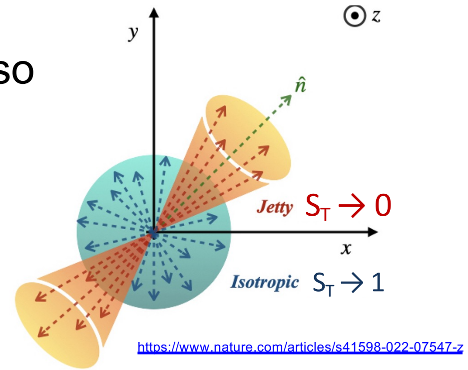
# CMS measurements of ϒ(nS) and multiplicity




- CMS results from 2014 (JHEP04 (2014) 103) and confirmed with more detail in 2020:
- **ϒ(nS)/ϒ(1S)** ratio decreases as a function of charged particle multiplicity

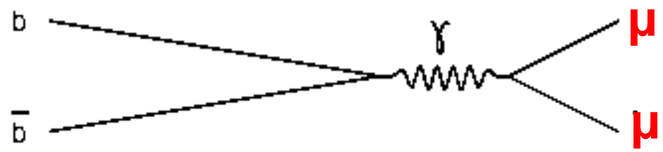
- … measured also as a function of event topology (**sphericity**)




- → suggests effect correlated with UE and not jets

# ATLAS approach to study Υ(nS) correlation with UE

- **ATLAS** analysis is an “inversion” of CMS approach:
- instead of measuring “conventional” variables such as **Υ(nS)** yields vs $n_{ch}$ ,
  **ATLAS measures $n_{ch}$ for different Υ(nS)**

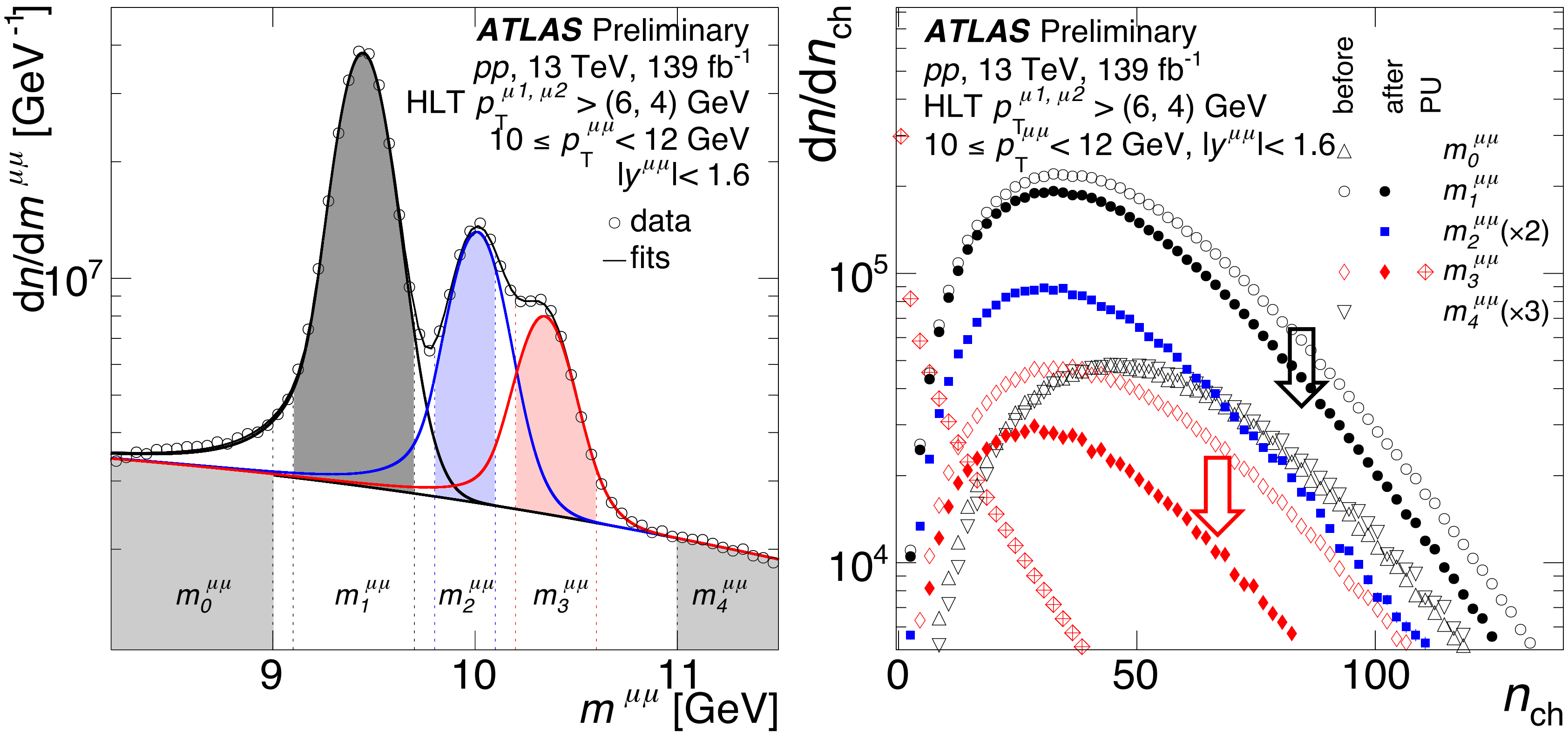



- ATLAS full Run-2 $\sqrt{s}$=13 TeV pp dataset
- **Υ(nS) → μμ** events with:
  - $8.2 \leq m^{\mu\mu} < 11.8$ GeV
  - $|y^{\mu\mu}| < 1.6$
- charged particle tracks
- not directly involved in formation of **Υ**
  - $0.5 < p_T < 10$ GeV
  - $|\eta| < 2.5$

- search for modification of **underlying event** (soft) for **different Υ states** (hard) in **pp** events – measure:
- multiplicity $n_{ch}$
- kinematic distributions: $dn_{ch}/dp_T$ and $dn_{ch}/d\Delta\varphi$, where $\Delta\varphi = \varphi^{\Upsilon} - \varphi^{h}$

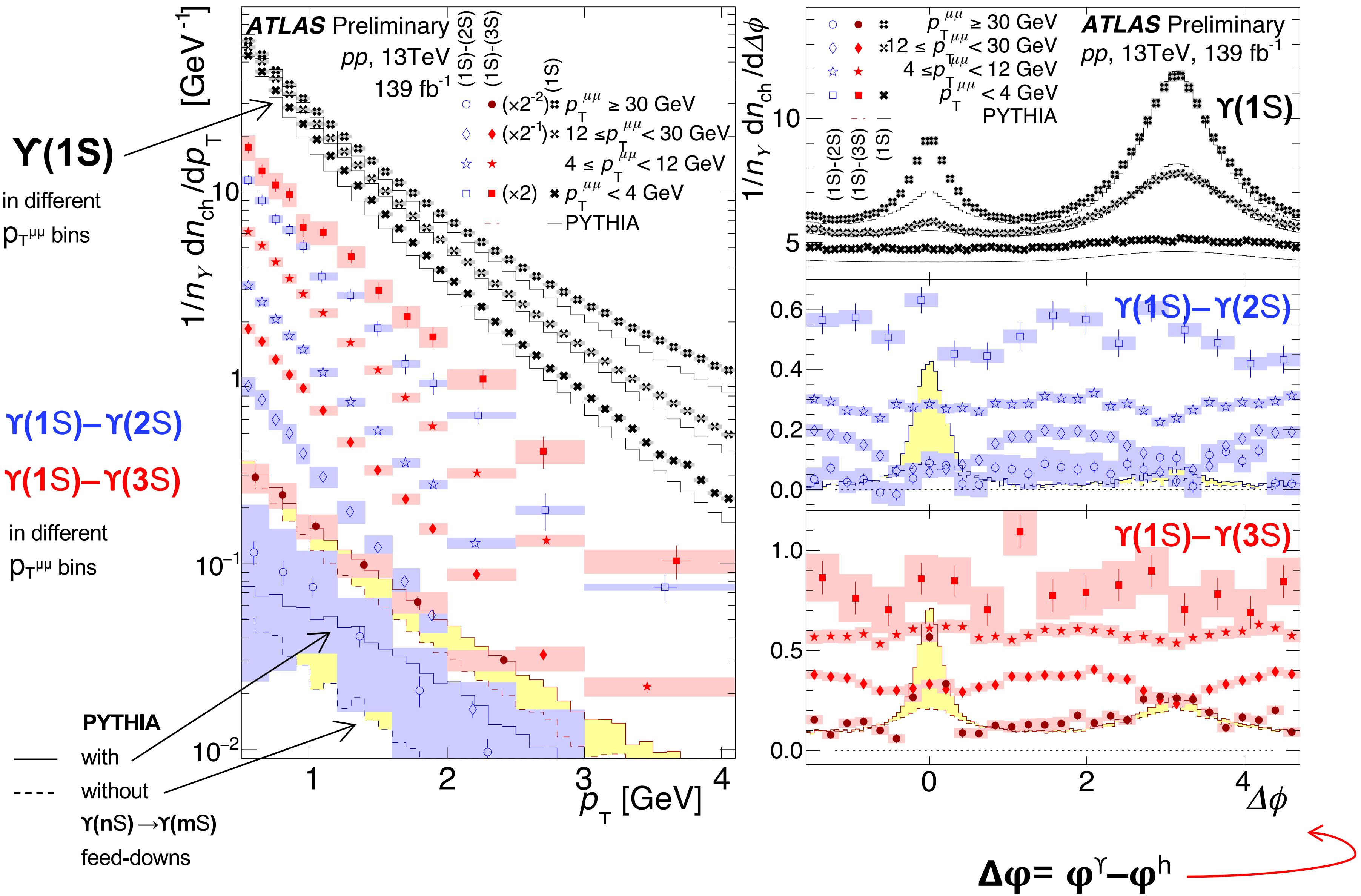
- analysis performed in $p_T^{\mu\mu}$ intervals and **observables corrected for pileup**

# ATLAS measurement of ϒ(nS) and underlying event



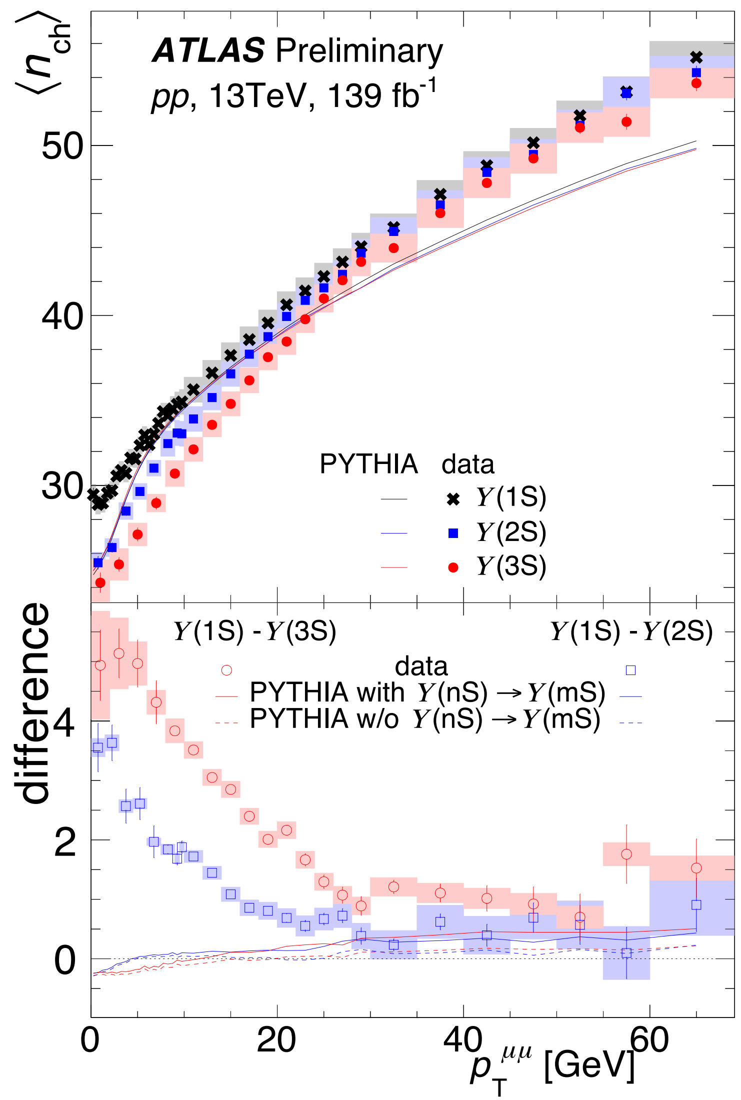

- well controlled background – **ϒ** candidates in 5 mass regions → signal+BG fits and sideband subtraction
- pileup corrected on a statistical basis using event mixing technique, developed for EPJC 80 (2020) 64 (illustrated here with $\boldsymbol{n_{ch}}$, but works also for d$\boldsymbol{n_{ch}}$/d$\boldsymbol{p_T}$ and d$\boldsymbol{n_{ch}}$/d$\boldsymbol{\Delta\varphi}$)

# Kinematic distributions of ϒ(1S) – ϒ(nS)



# Mean values of $n_{ch}$ distribution

- significant differences observed for different **ϒ(nS)** states
- PYTHIA mismodels **ϒ** production
  no ⟨*n*ch⟩ dependence of different states
- effect largest at $p_T^{\mu\mu} = 0$ :
- **ϒ(1S) – ϒ(2S) Δ⟨*n*ch⟩** = 3.6 ±0.4
- **ϒ(1S) – ϒ(3S) Δ⟨*n*ch⟩** = 4.9 ±0.4
- observations cannot be explained by **mass differences**, **feed-down of states**, or **systematic uncertainties**



# summary

***Observables sensitive to CR in ttbar events*** ( [arXiv:2209.07874](arXiv:2209.07874) ):

ATLAS measurement of CR sensitive observables in top quark events gives detailed handle on CR and MPI

***Correlation of ϒ meson production with the underlying event***

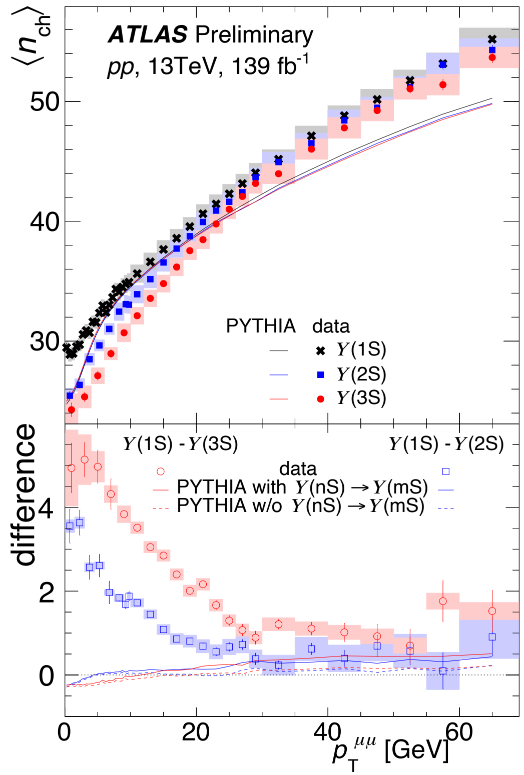
( [ATLAS-CONF-2022-23](ATLAS-CONF-2022-23) ):

significant differences in charged particle multiplicity observed

- **ϒ(1S):** $\langle n_{ch} \rangle$ = 29.5 ±0.7
- **ϒ(2S):** 12% less
- **ϒ(3S):** 17% less

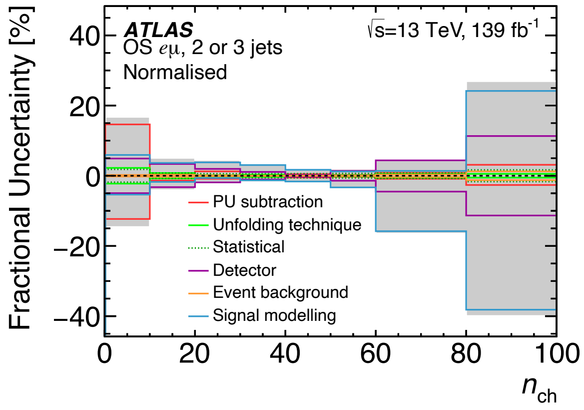
can be interpreted as suppression of excited states at higher multiplicity

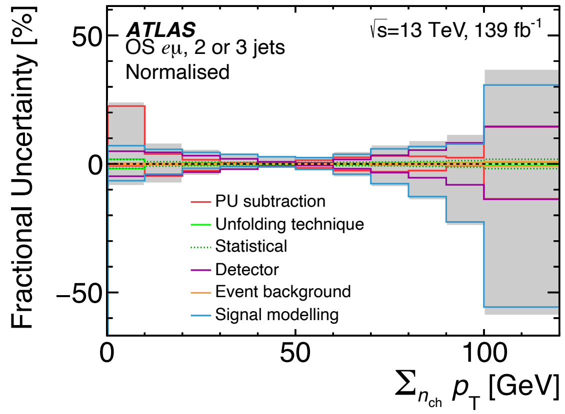
**➜ something interesting going on in pp that must be further explored**

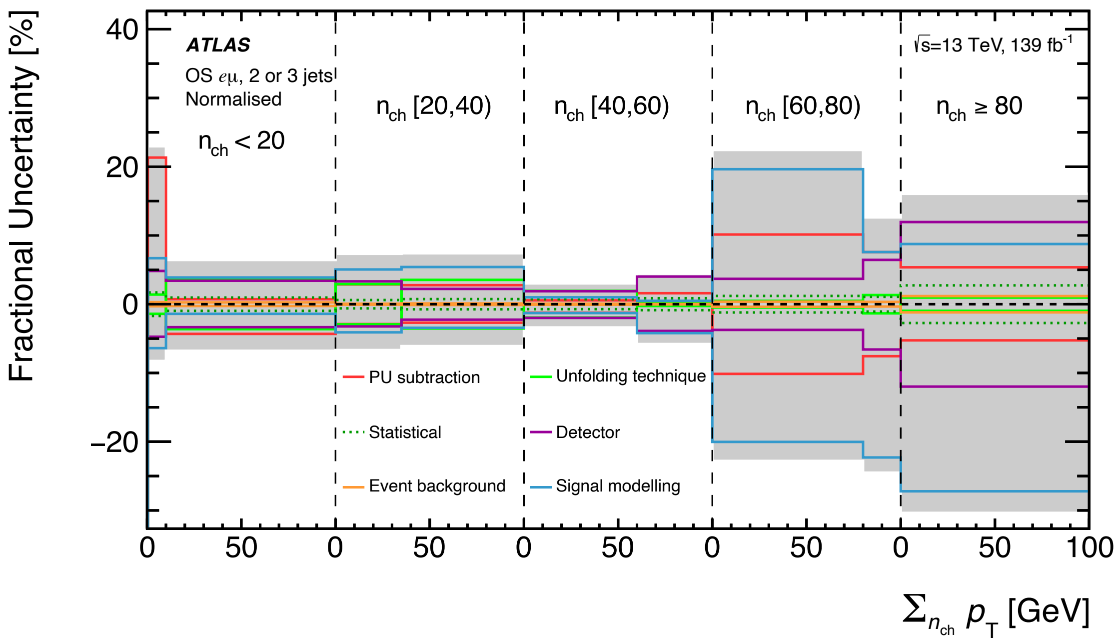


# extras

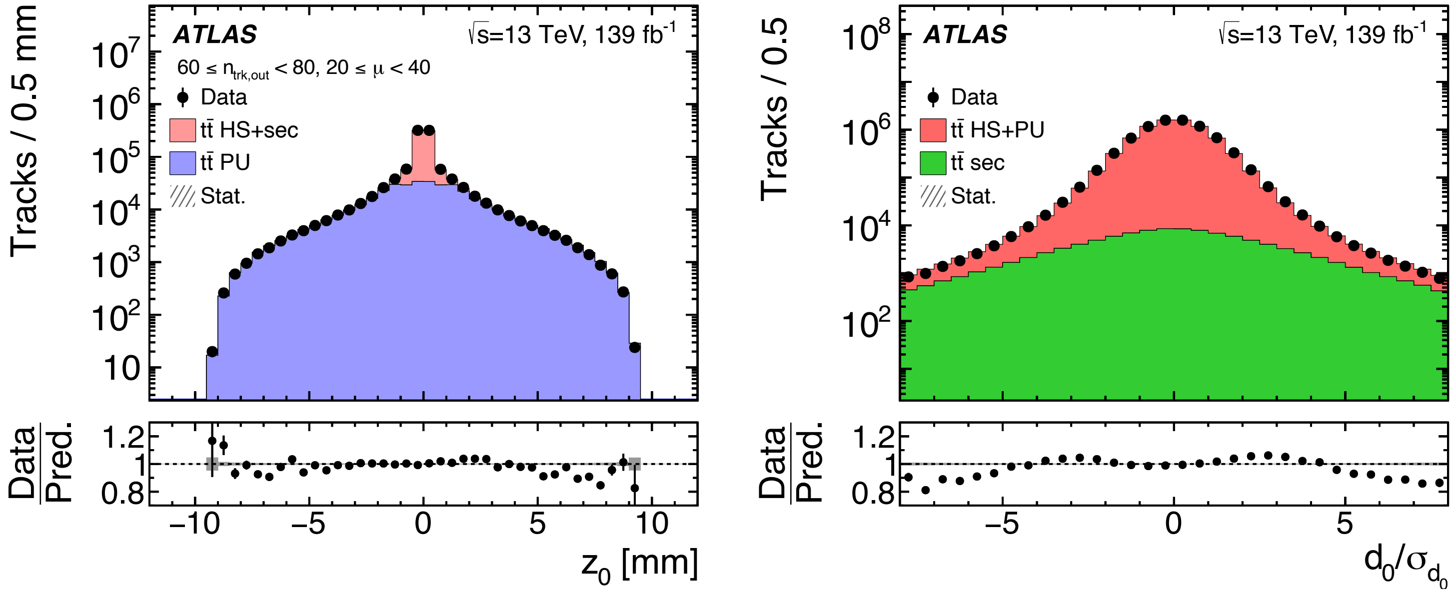
# ATLAS measurement of top quarks and CR



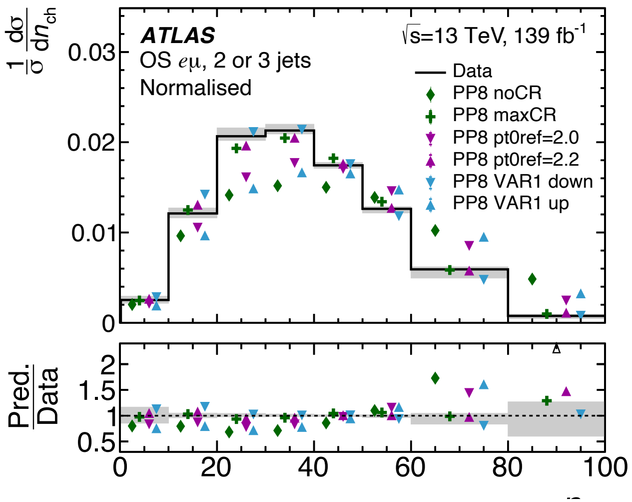
# Track-based BG

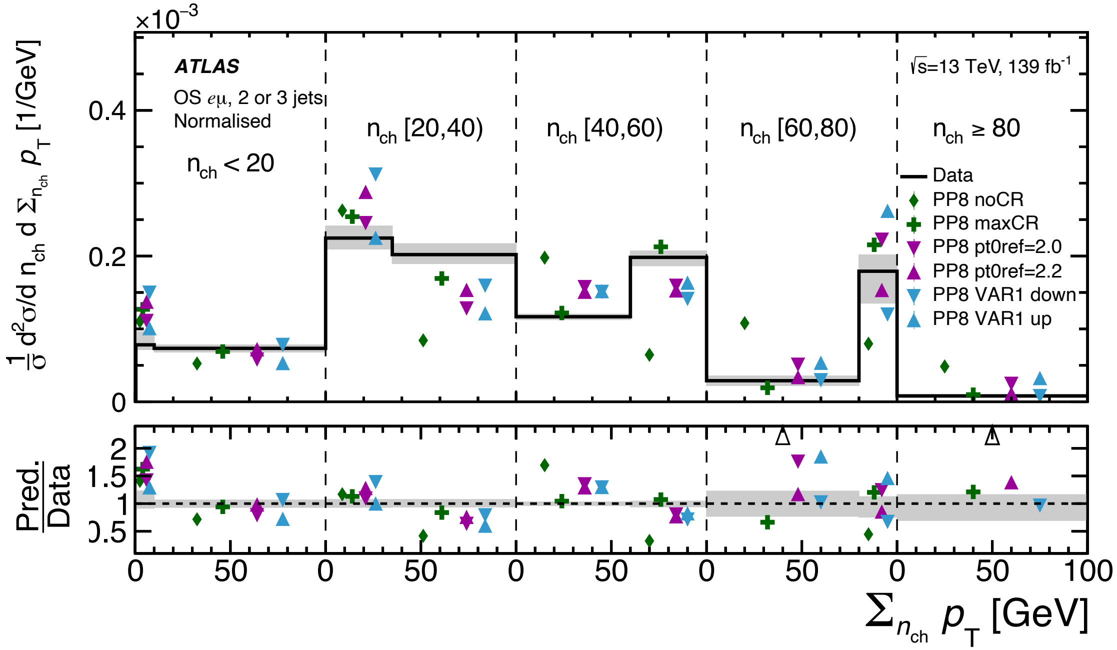


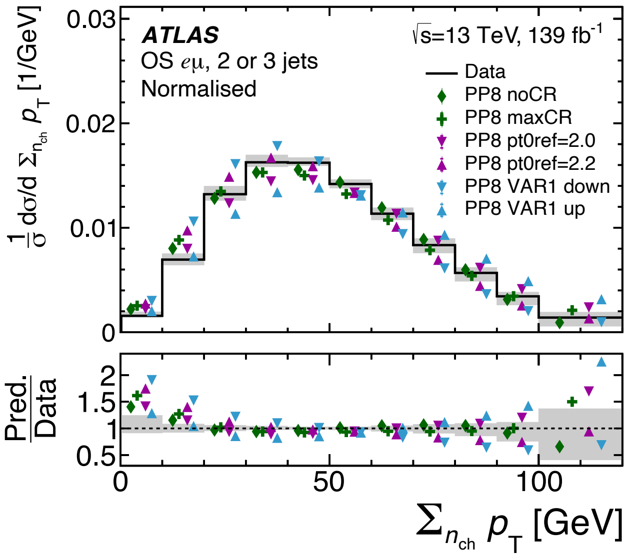

## pileup scale factors $c_{PU}$

| Region | $n_{\mathrm{trk,out}} < 20$ | $20 \leq n_{\mathrm{trk,out}} < 40$ | $40 \leq n_{\mathrm{trk,out}} < 60$ | $60 \leq n_{\mathrm{trk,out}} < 80$ | $80 \leq n_{\mathrm{trk,out}} \leq 100$ |
|---|---|---|---|---|---|
| $\mu < 20$ | 0.91 | 1.04 | 0.97 | 1.05 | 1.08 |
| $20 \leq \mu < 40$ | 0.91 | 1.08 | 1.08 | 1.07 | 1.11 |
| $\mu \geq 40$ | 0.95 | 1.15 | 1.23 | 1.27 | 1.36 |

# cf. PYTHIA8 – parameter variations

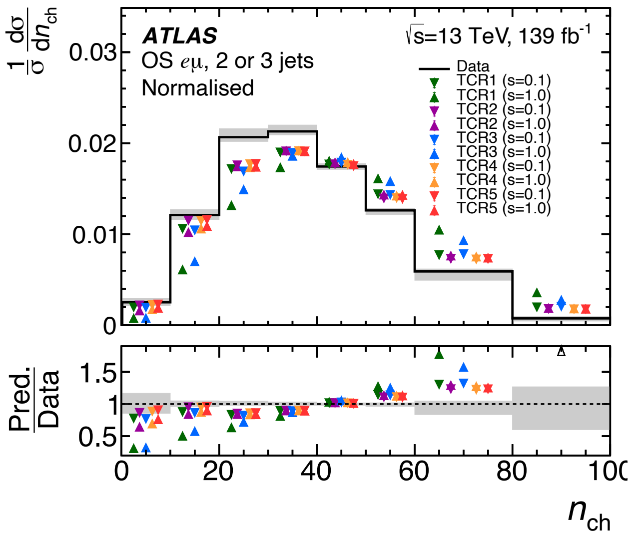


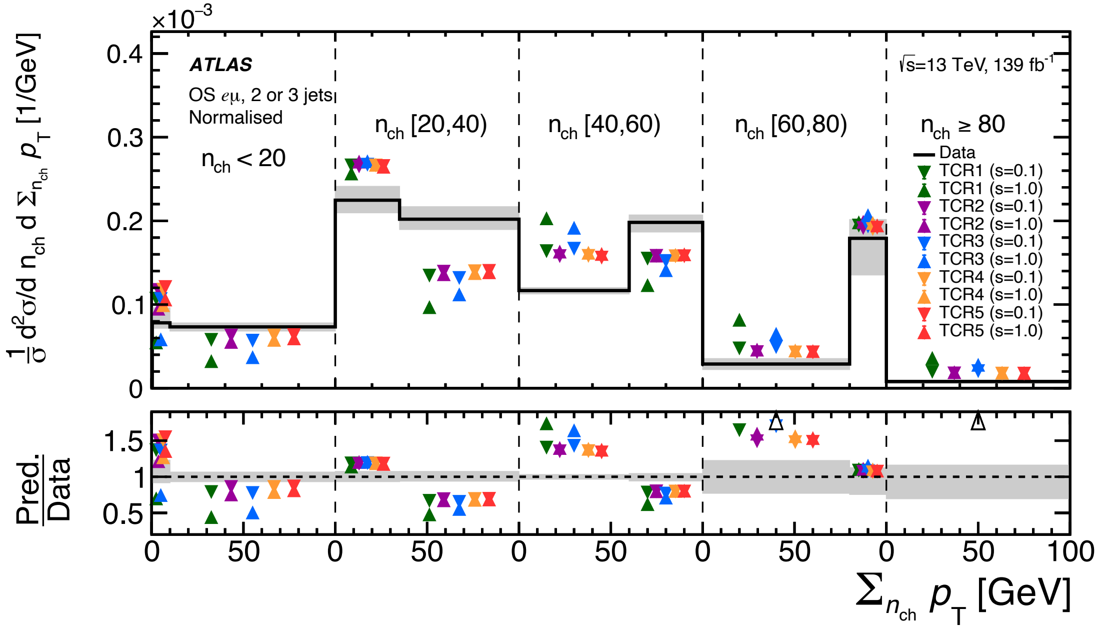



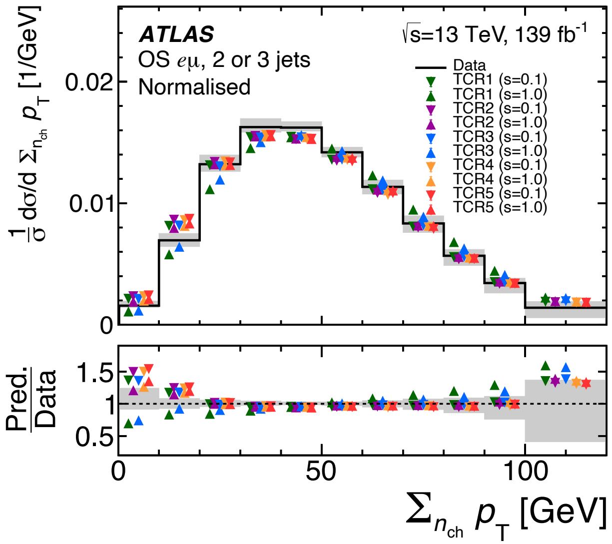




- CR range parameter $R_{\rm rec}$ is set to its maximal value of $R_{\rm rec} = 10$, such that the reconnection probability reaches saturation (maxCR). The default is 1.71.
- CR is switched off, i.e. $R_{\rm rec} = 0$ (noCR).
- MPI parameter $p_{\rm T0}^{\rm ref}$, by default set to 2.09, is lowered to 2.0 and raised to 2.2.
- UE activity is varied by using the Var1 eigentune of the A14 tune [21]. This eigentune includes variations of $\alpha_{\rm s}$ and variations of $R_{\rm rec}$.

# cf. PYTHIA8 – top quark specific CR Models



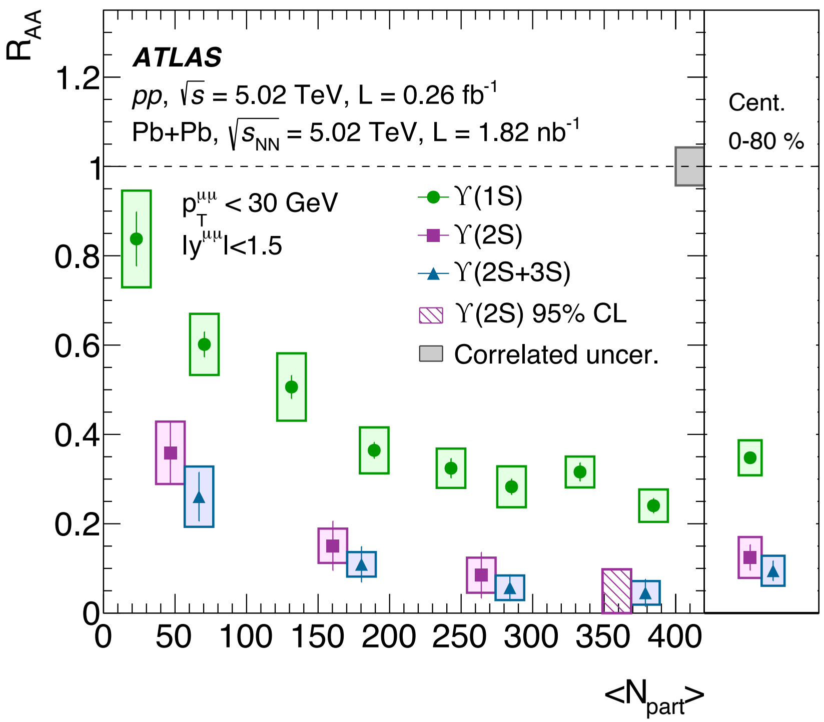




- CR models designed to affect top-quark decay products also considered (further details in: JHEP11 (2014) 043 )

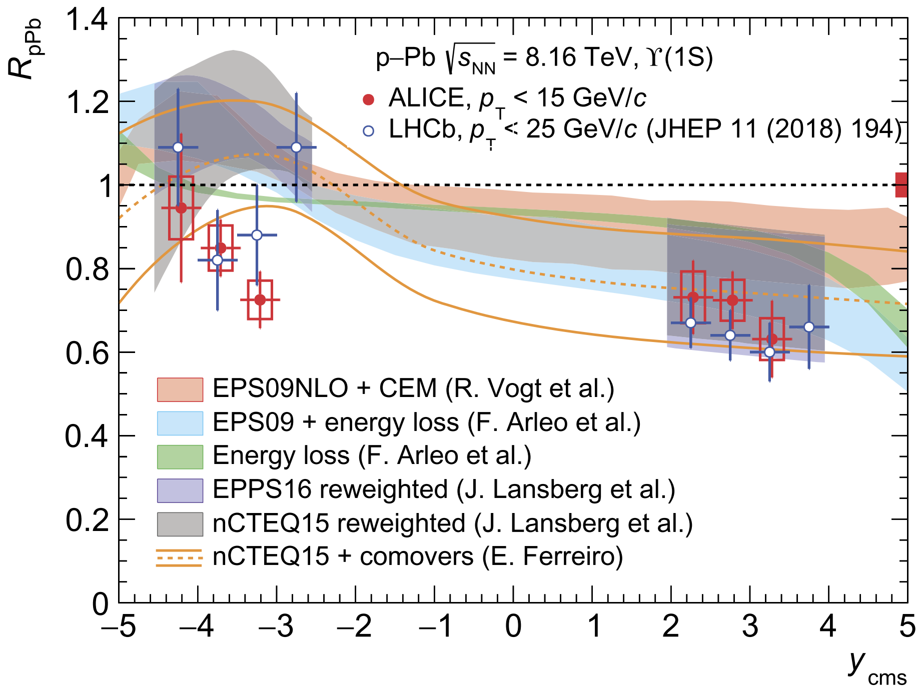
1. **Forced random (TCR1)**
   A gluon from $\{g_t\}$ is forced to exchange colours with a random gluon from the other set, $\{g_r\}$.
2. **Forced nearest (TCR2)**
   A gluon from $\{g_t\}$ is forced to exchange colours with the gluon from $\{g_r\}$ that minimises $m^2(g_t, g_r)$.
3. **Forced farthest (TCR3)**
   A gluon from $\{g_t\}$ is forced to exchange colours with the gluon from $\{g_r\}$ that maximises $m^2(g_t, g_r)$.
4. **Forced smallest $\Delta\lambda$ (TCR4)**
   A gluon from $\{g_t\}$ is forced to exchange colours with the gluon from $\{g_r\}$ for which the change in $\lambda$ (available rapidity range of particle production) is smallest.
5. **Smallest $\Delta\lambda$ (TCR5)**
   This is the same as the previous model, except that gluons exchange colours only if $\Delta\lambda < 0$.

# what is known about Υ production and collectivity at the LHC?

arXiv:2205.03042




PLB 806 (2020) 135486



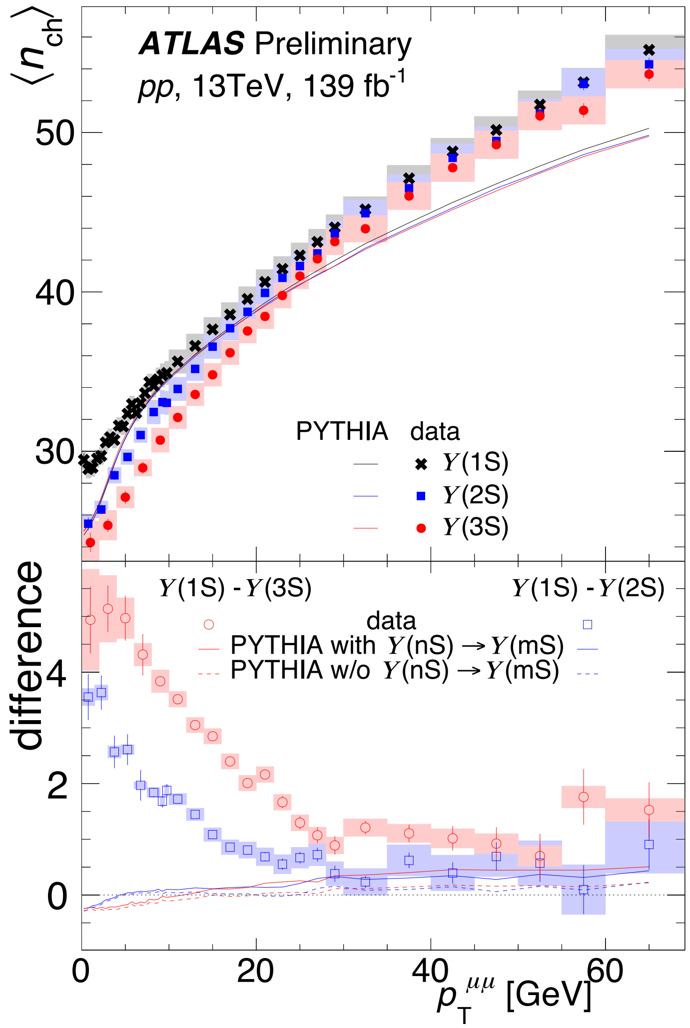

$$R_{AA} = \frac{N_{\Upsilon;AA}}{\langle T_{AA}\rangle \times \sigma^{pp\to\Upsilon}}$$

$T_{AA}$ is the nuclear overlap function

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

- $R_{AA}$: nuclear modification factor compares **AA** to **pp**
- **pA** could give sense of influence of cold nuclear effects

# naïve question



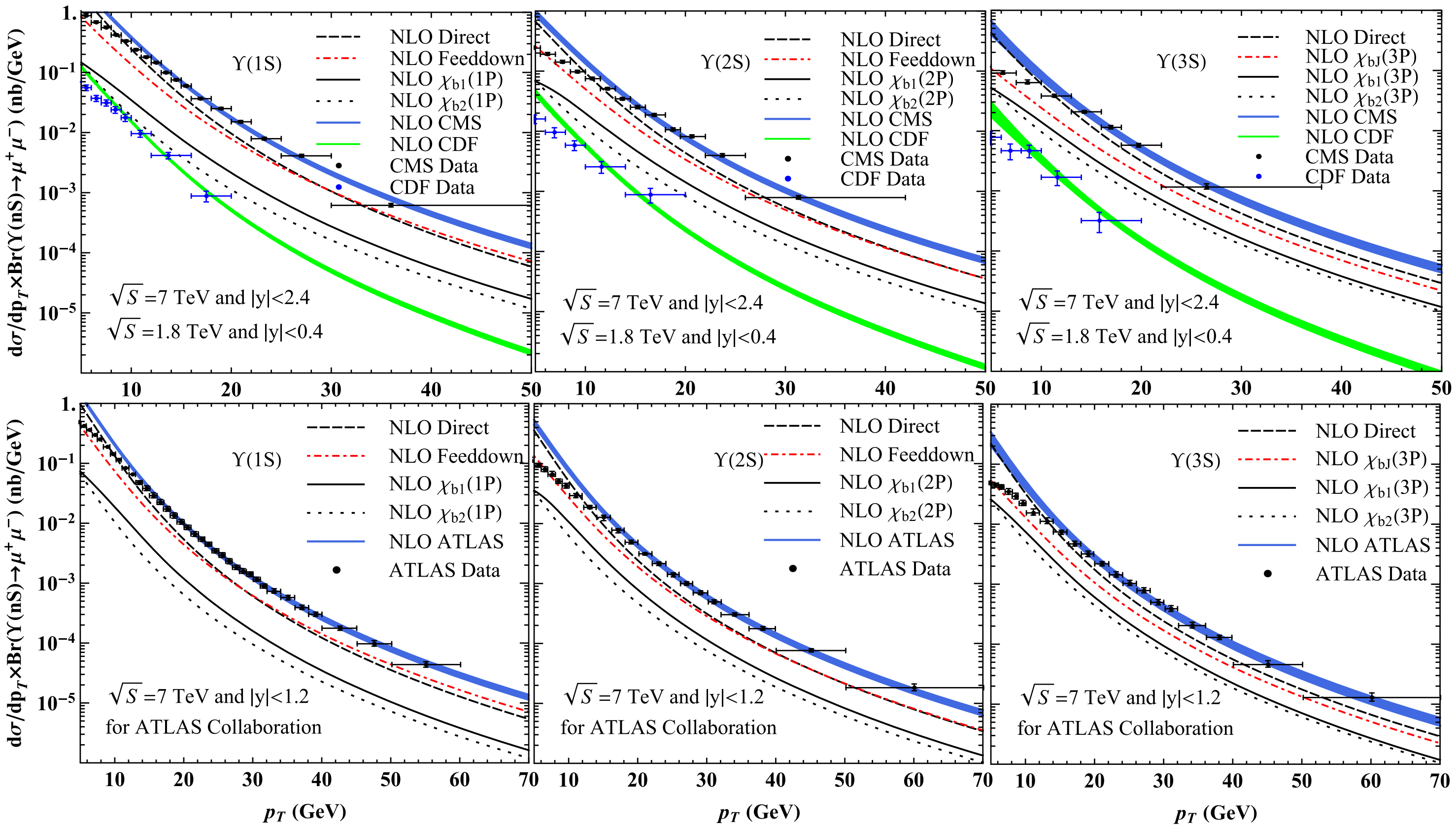

- could the observations correspond to an enhancement of ***n*ch** for the **ϒ(1**S**)** ground state, rather than a suppression for the excited states?

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

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

- **ϒ(1**S**)** appears consistent with these numbers, while **ϒ(2**S**), ϒ(3**S**)** lower, **i.e. suppression of excited states**

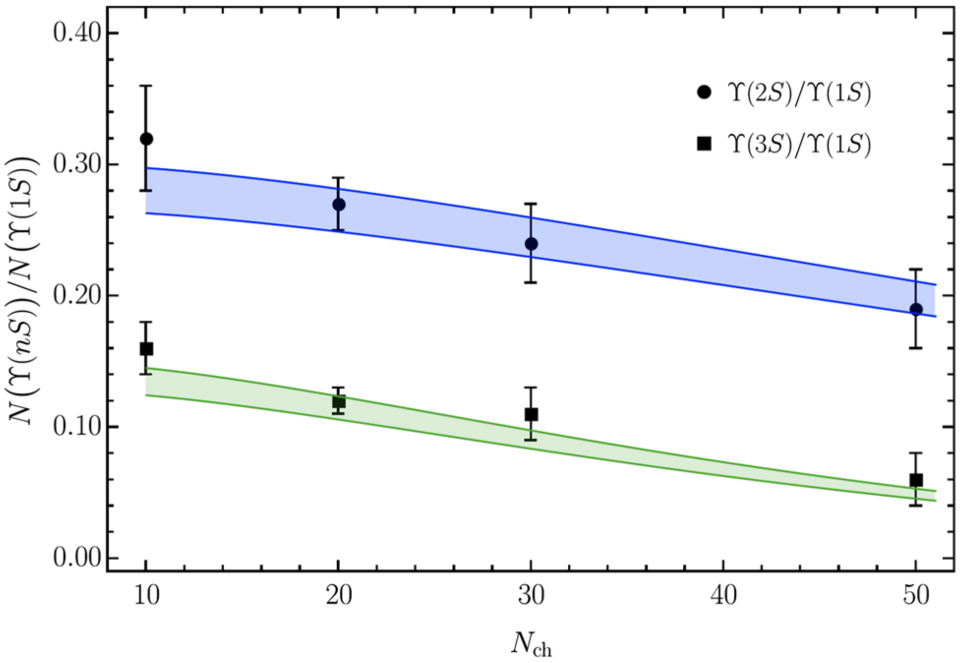
# QCD cross section calculations




- calculations show discrepancies with data, largest for higher **ϒ(n**S**)** and lower pT

# Co-mover Interaction Model (CIM)

- **CIM**: quarkonia are broken by collisions with co-movers, i.e. final state particles with similar rapidities
- **CIM** typically used to explain **p+A** and **A+A** systems – matches CMS **ϒ** data



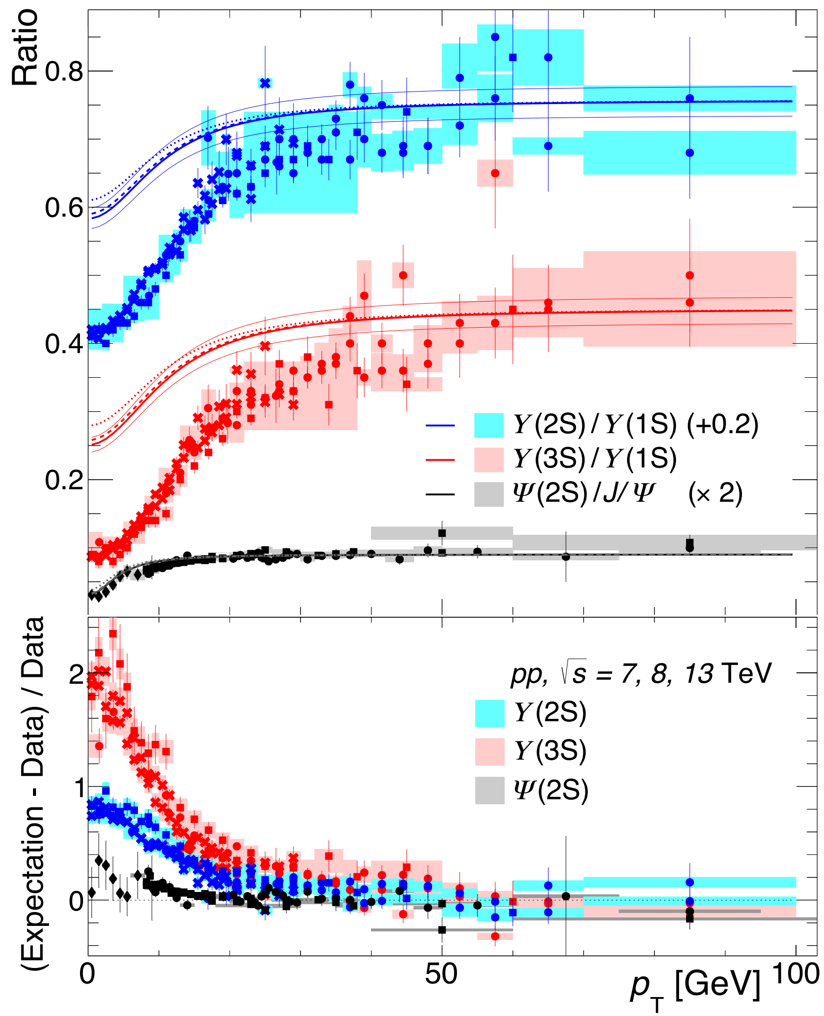

- **CIM** can be tested on new pp measurements to test if it can reproduce **ϒ(nS)–ϒ(1S)**
- cross sections
- multiplicity $n_{ch}$
- kinematic distributions $p_T$, $\Delta\varphi$, $\Delta\eta$

# Quarkonia rations expected from mT−scaling

- **mT-scaling** allows one to define an expectation for the excited states relative to the ground states

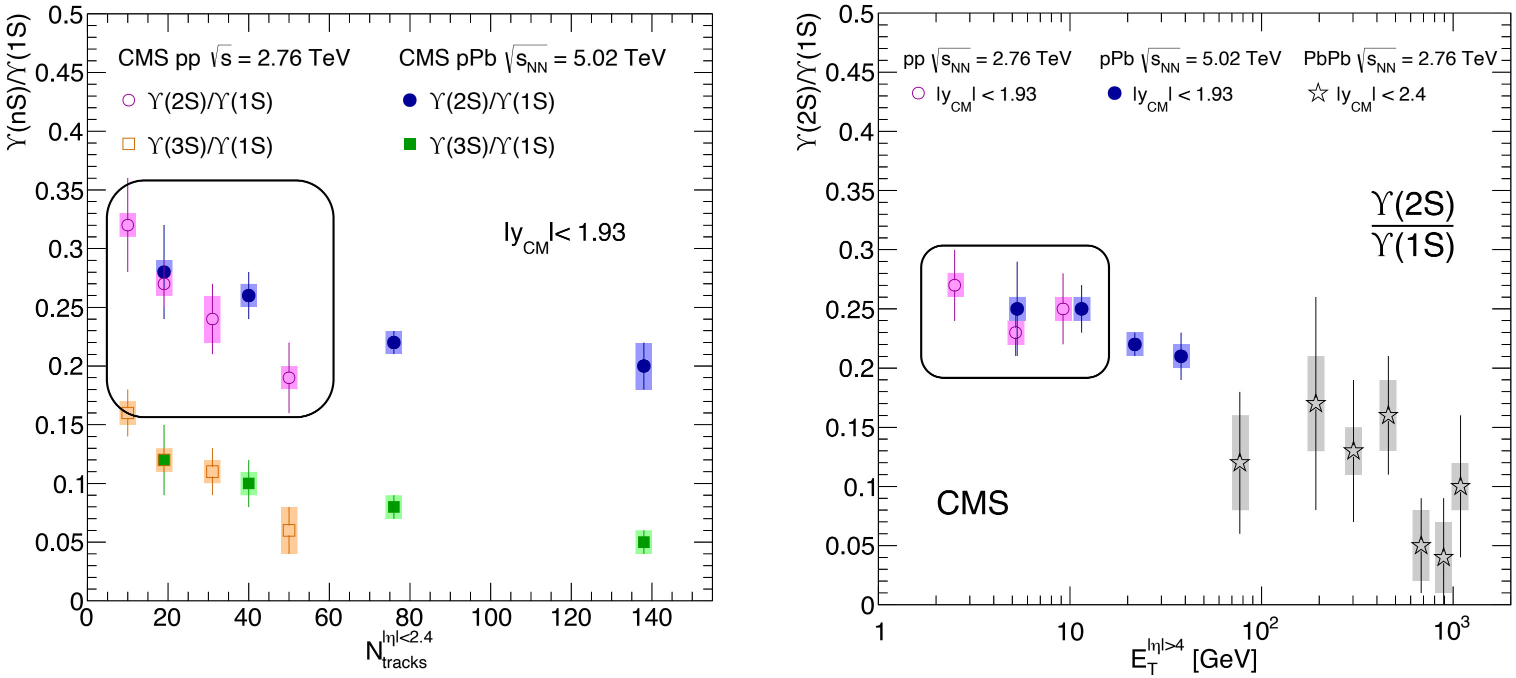
$$\frac{d^2\sigma}{dy\,dm_T} \propto \left(1 + \frac{m_T}{nT}\right)^{-n}$$

- works well for light mesons at the LHC
- application to **ϒ** meson cross sections shows missing excited states at low pT
- **ϒ(2S)** : missing factor of **1.6**
- **ϒ(3S) :** factor of **2.4**



# is there rapidity dependence?

[JHEP04 (2014) 103]



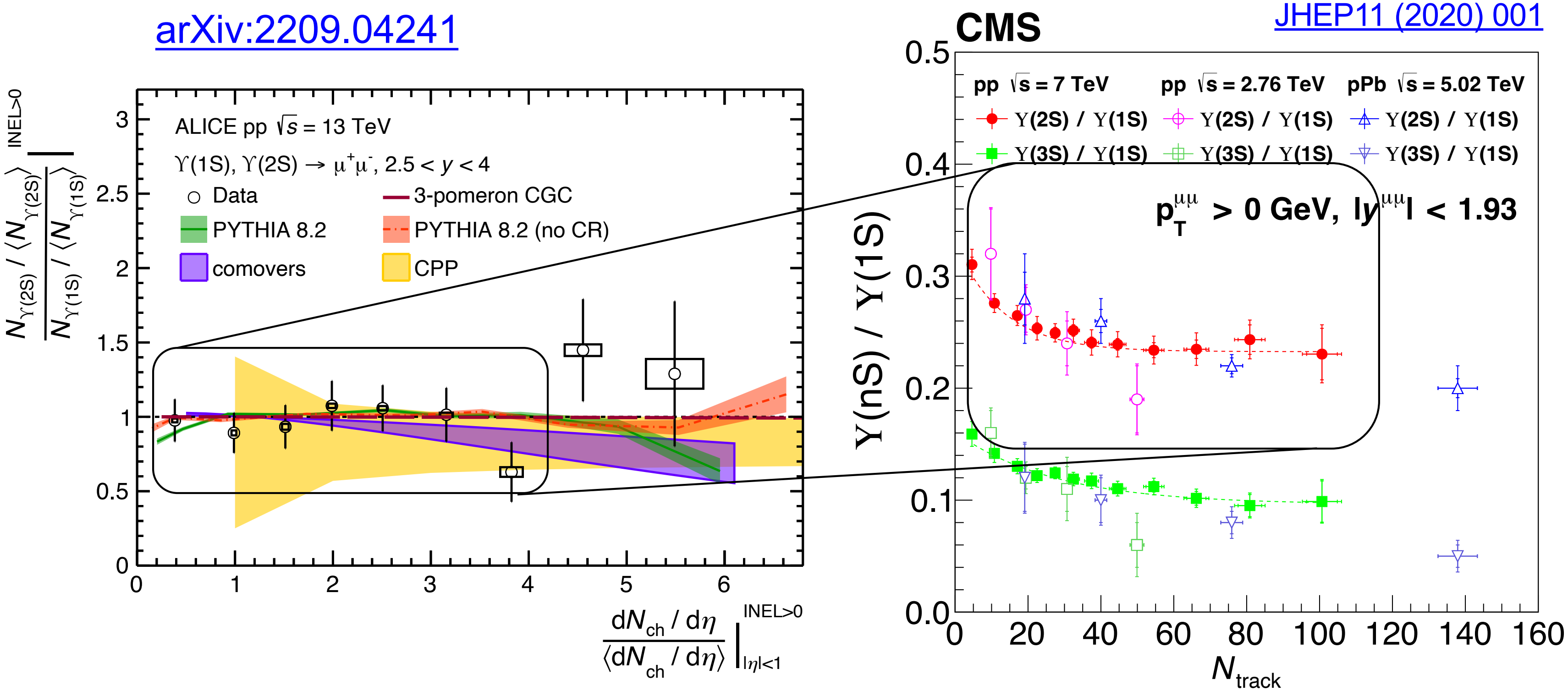

- CMS : dependence flattened when forward-midrapidity gap introduced
- (as noted in HP2018 summary: https://indico.cern.ch/event/634426/contributions/3003672/ )

- could be due to loss of resolution ... ?

# is there rapidity dependence?

arXiv:2209.04241

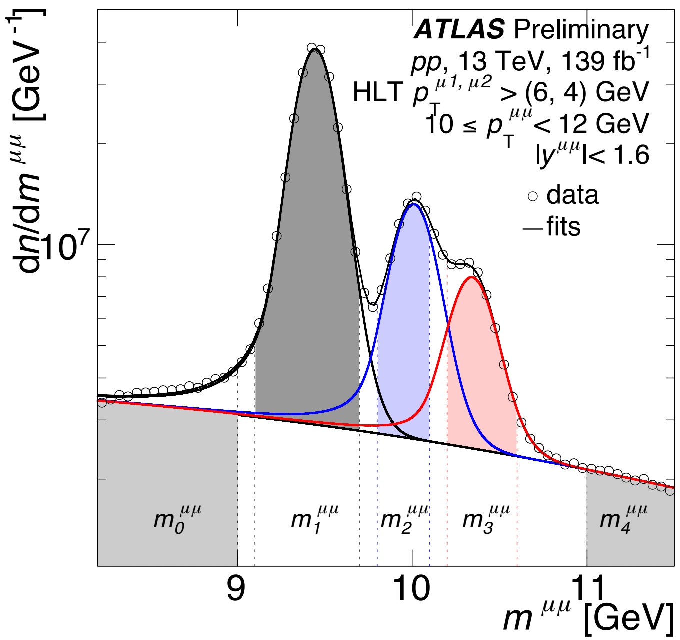
JHEP11 (2020) 001




- ALICE : forward **ϒ(2**S**)/ ϒ(1**S**)** vs tracks at midrapidity
- measurements do not clearly indicate rapidity dependence

**→ Δη analysis should provide direct answer**

# $\Upsilon(nS)$ and UE correlations – BG fit details




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

Crystal Ball + Gaussian

Polynomial

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

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

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

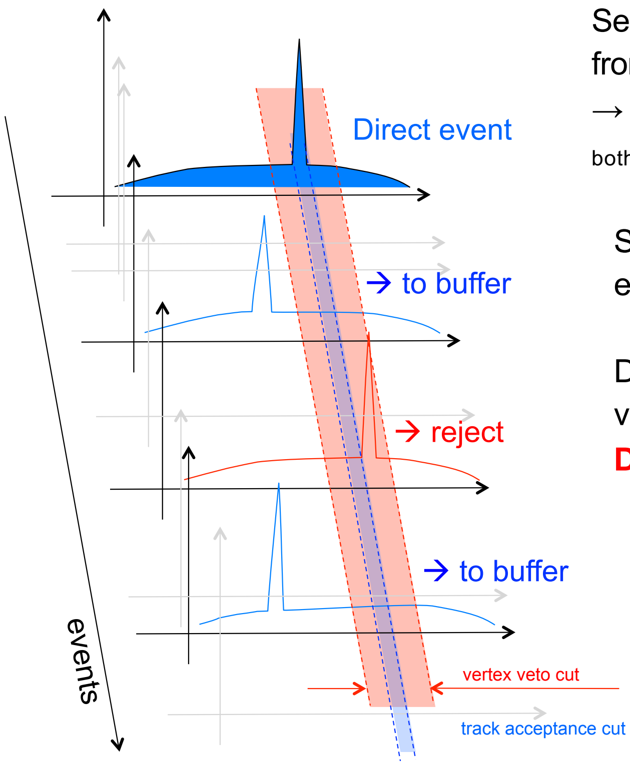
$$
\begin{pmatrix} P(m_0^{\mu\mu}) \\ P(m_1^{\mu\mu}) \\ P(m_2^{\mu\mu}) \\ P(m_3^{\mu\mu}) \\ P(m_4^{\mu\mu}) \end{pmatrix}
=
\begin{pmatrix}
1-f_{01} & f_{01} & 0 & 0 & 0 \\
k_1(1-s_1) & s_1 & 0 & 0 & (1-k_1)(1-s_1) \\
k_2(1-s_2-f_{21}-f_{23}) & f_{21} & s_2 & f_{23} & (1-k_2)(1-s_2-f_{21}-f_{23})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

$P(m_n^{\mu\mu})$ : measured distribution in mass interval $m_n^{\mu\mu}$

- invert matrix to determine contributions coming from $\Upsilon(nS)$ and from **BG** in the low (0) and high mass (4) BG intervals

# correction for pileup

- subtraction of pileup using **event mixing technique** [EPJC 80 (2020) 64]

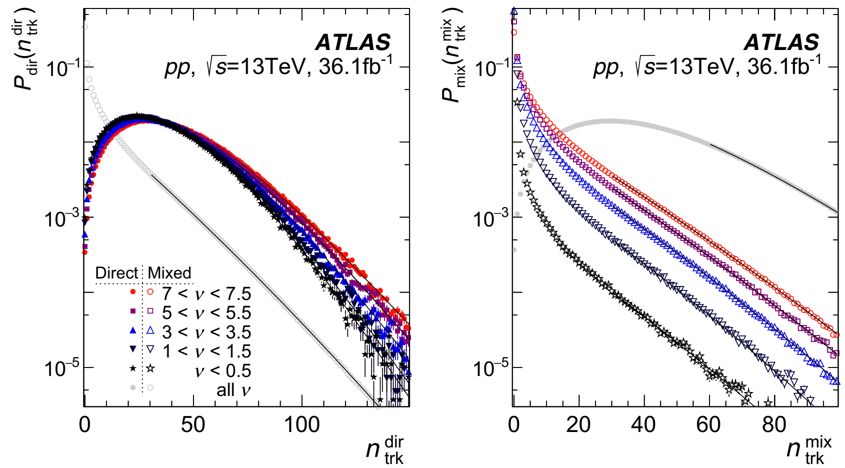



**Credit: Y Aizenberg**

Select an event from main sample → **Direct event** (with both signal and pileup)

Same run: search for events with same μ

Discard events where vertex within **15mm** of **Direct event**




**Mixed event** sample built from tracks with vertex pointing **$|\omega|=|(z_0-z_{vtx})\sin\theta| < 0.75$mm** to Direct event

Procedure repeated 20 times to suppress statistical fluctuations in **Mixed** sample

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

Track production (physics)

$z_{vtx}$ distribution

Analysis selection

Instantaneous luminosity

- BKG ≡ Mixed → average number of pileup tracks:

# $\Upsilon(nS)$ and UE correlations – systematics summary

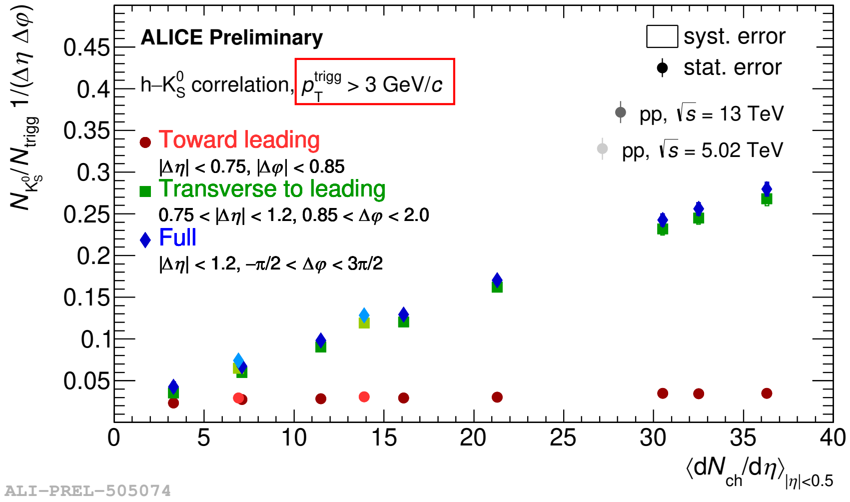
| | $p_T^{\mu\mu} \leq 4$ GeV | $4 < p_T^{\mu\mu} \leq 12$ GeV | $12 < p_T^{\mu\mu} \leq 30$ GeV | $p_T^{\mu\mu} > 30$ GeV |
|---|---|---|---|---|
| $\Upsilon(1S)$ | 0.5 – 0.6 | 0.5 – 0.7 | 0.7 – 0.8 | 0.8 – 0.9 |
| $\Upsilon(2S)$ | 0.6 – 0.6 | 0.5 – 0.7 | 0.7 – 0.8 | 0.8 – 1.0 |
| $\Upsilon(3S)$ | 0.9 – 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 $|\eta| < 2.5$.

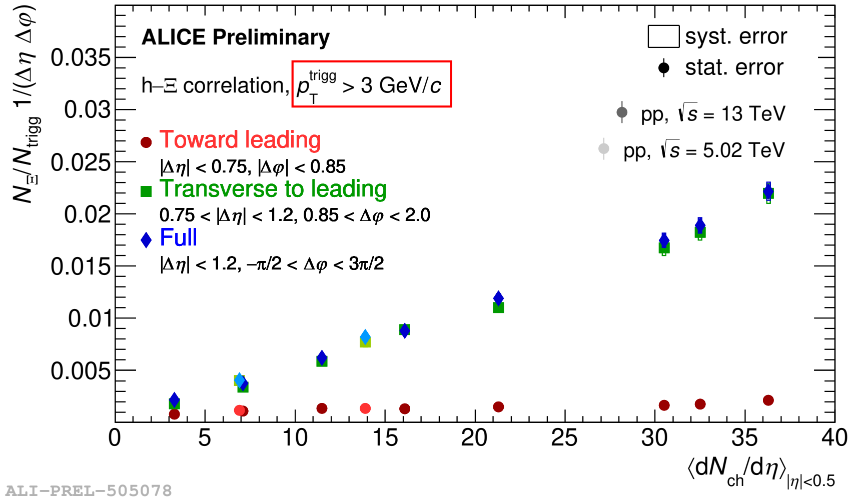
- shown for $\boldsymbol{n}_{ch}$ but propagated to all quantities

# strange enhancement

$K^0_S$




$\Xi^{\pm}$




- enhancement of strange hadrons is one of the **signature pp collectivity** results
- ALICE measurement (ALI-PREL-505074) shows strange hadron yields from **out-of-jet** and **full** samples increases with multiplicity and are consistent with each other
- **toward jet** yields do not depend on multiplicity

**➜ could suggest that it is an underlying event effect**