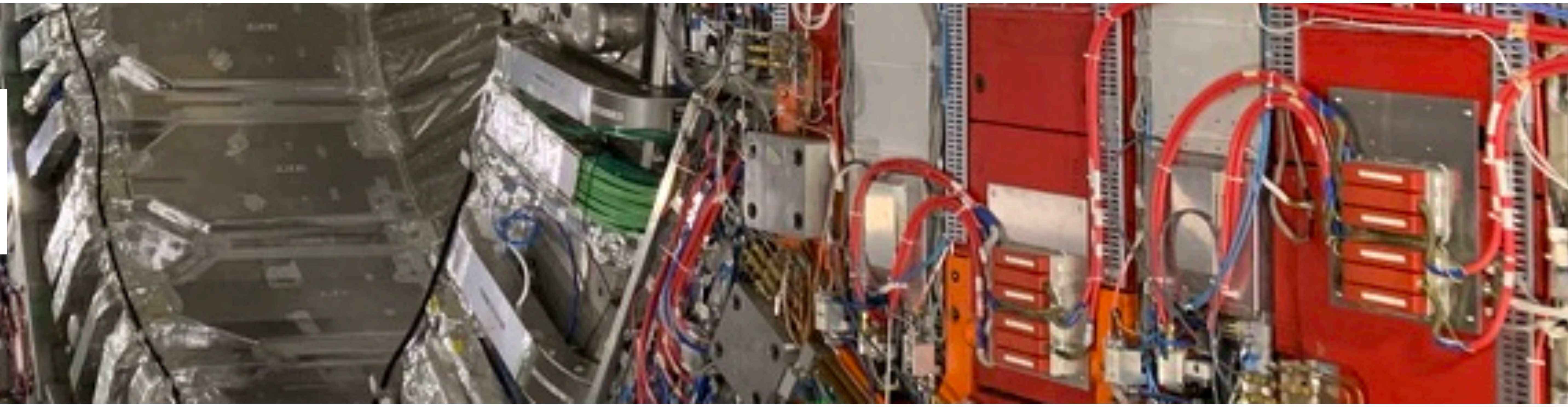
J/ψ and Y(nS) production vs. event activity

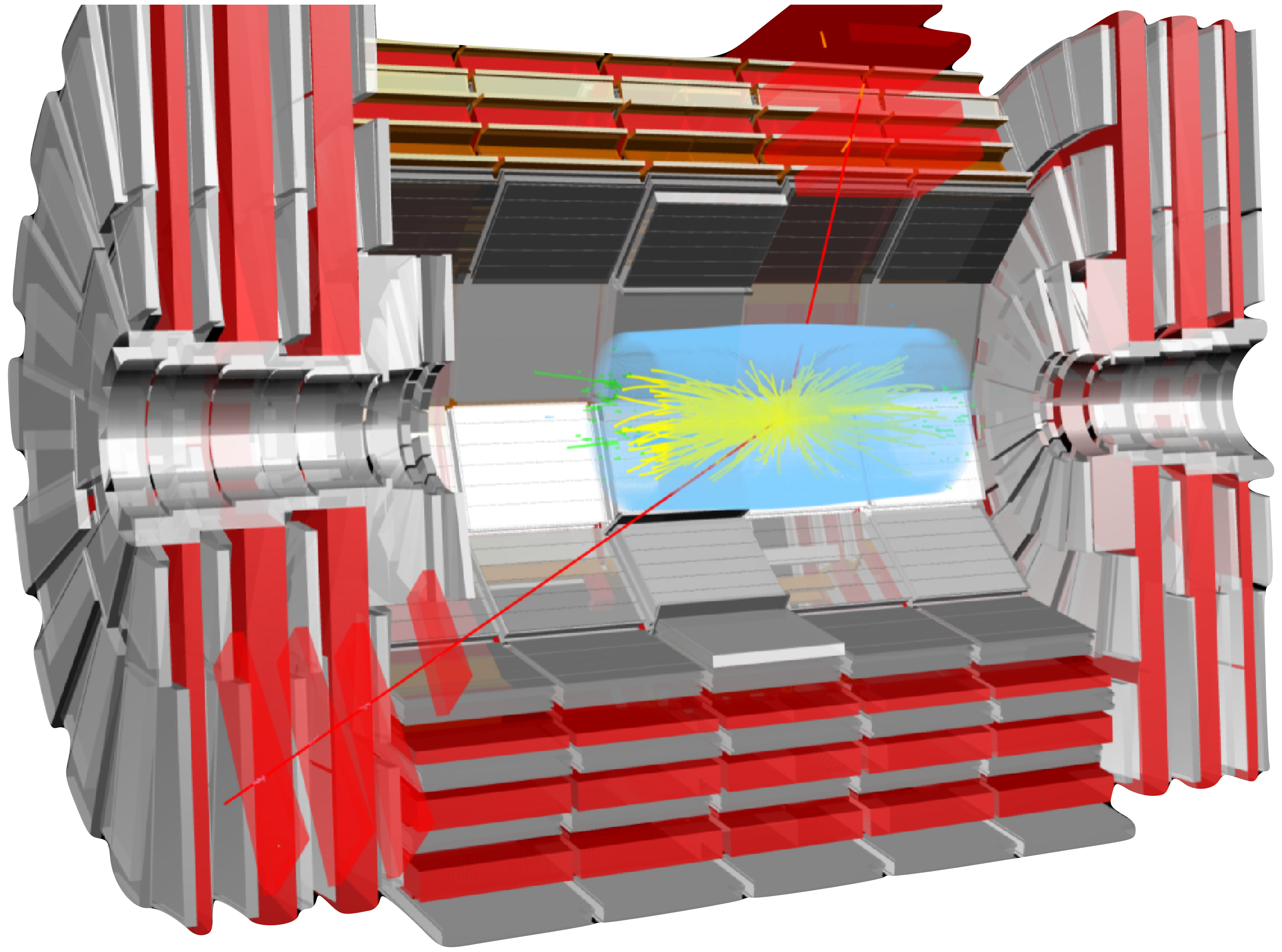
Daniele Fasanella (ATOMKI)
on behalf of the CMS Collaboration

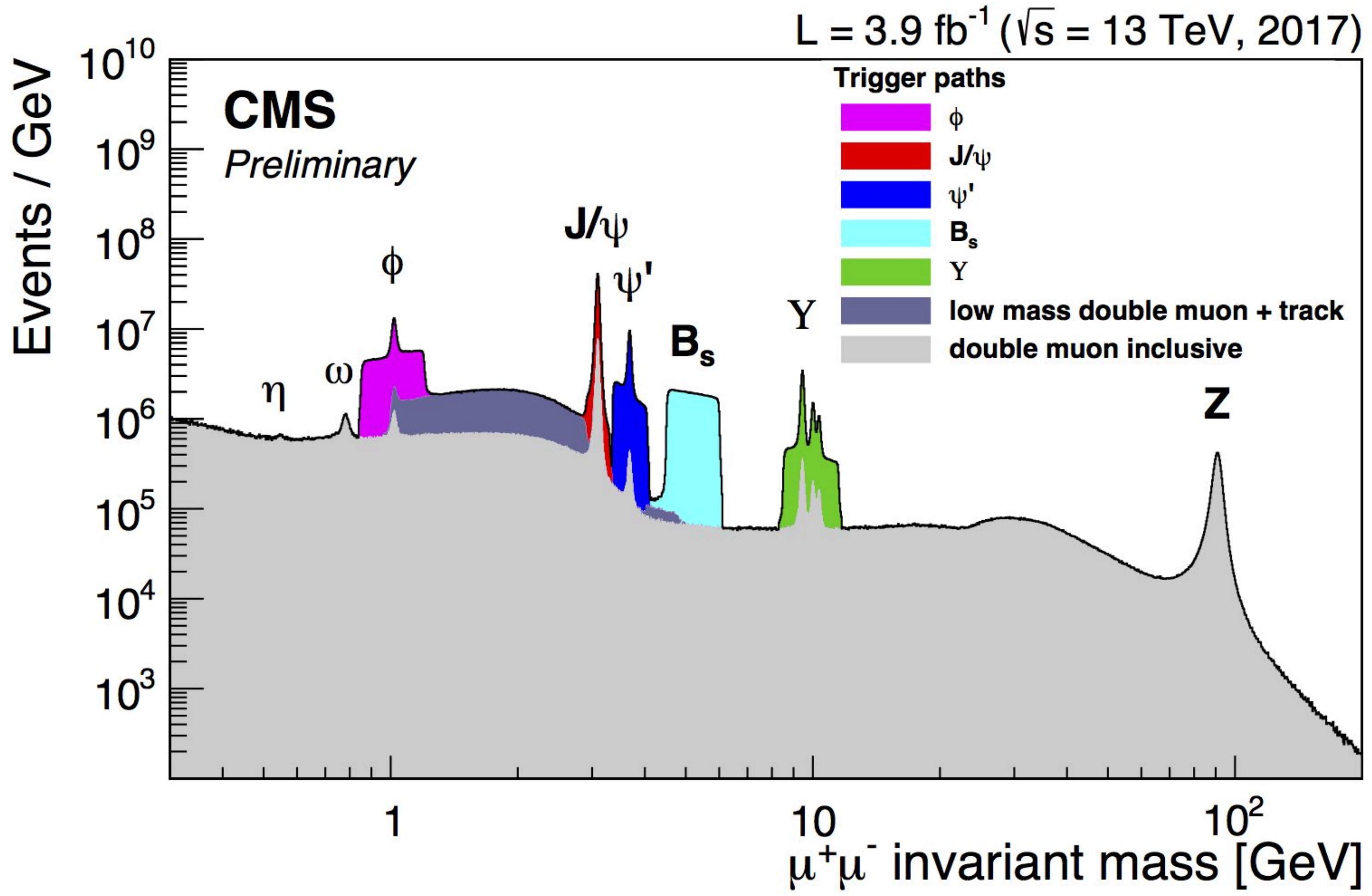


QWG 2021: The 14th International Workshop on Heavy Quarkonium, 15-19 Mar 2021, Davis, CA (United States)

Quarkonium production at CMS

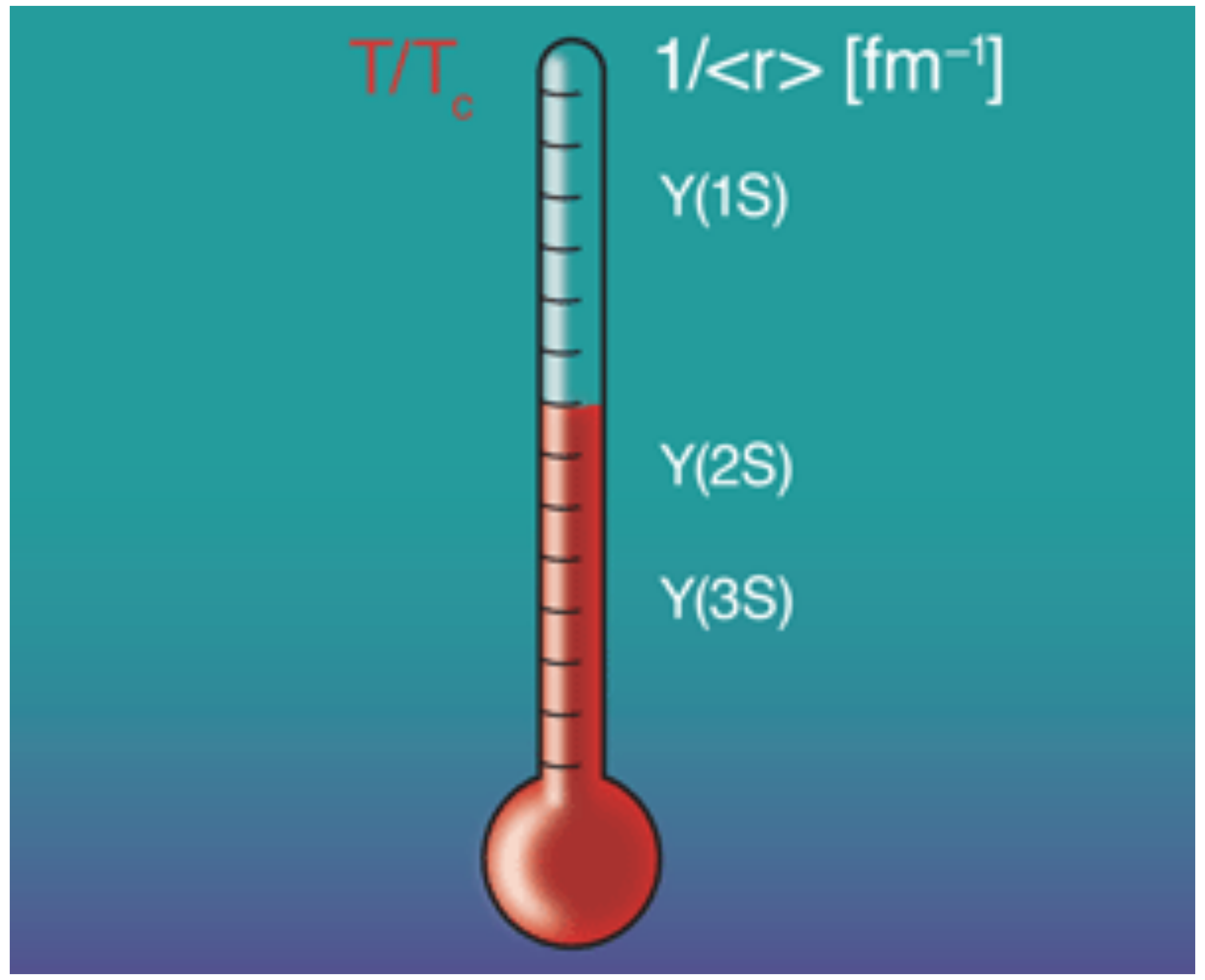
- The understanding of Quarkonia production can give an unique insight into QCD
- **CMS is a general purpose experiment ideal for its studies**
  - **Large sample of Quarkonia** collected in their $\mu^+\mu^-$decays an highly flexible High Level Trigger
    - paths dedicated to specific analyses
    - Many Quarkonia production results for LHC Run 1 and Run2
  - Full picture of the event with high precision tracking and calorimetry
    - study of the connection between quarkonia and event activity
- **In this talk highlight on two recent results:**
  - Study of J/ψ meson production from jet fragmentation in pp collisions at $\sqrt{s} = 8$ TeV **[Phys. Lett. B 804 (2020) 135409]**
  - Investigation into the event-activity dependence of Υ(nS) relative production in proton-proton collisions at $\sqrt{s} = 7$ TeV **[JHEP 11 (2020) 001]**

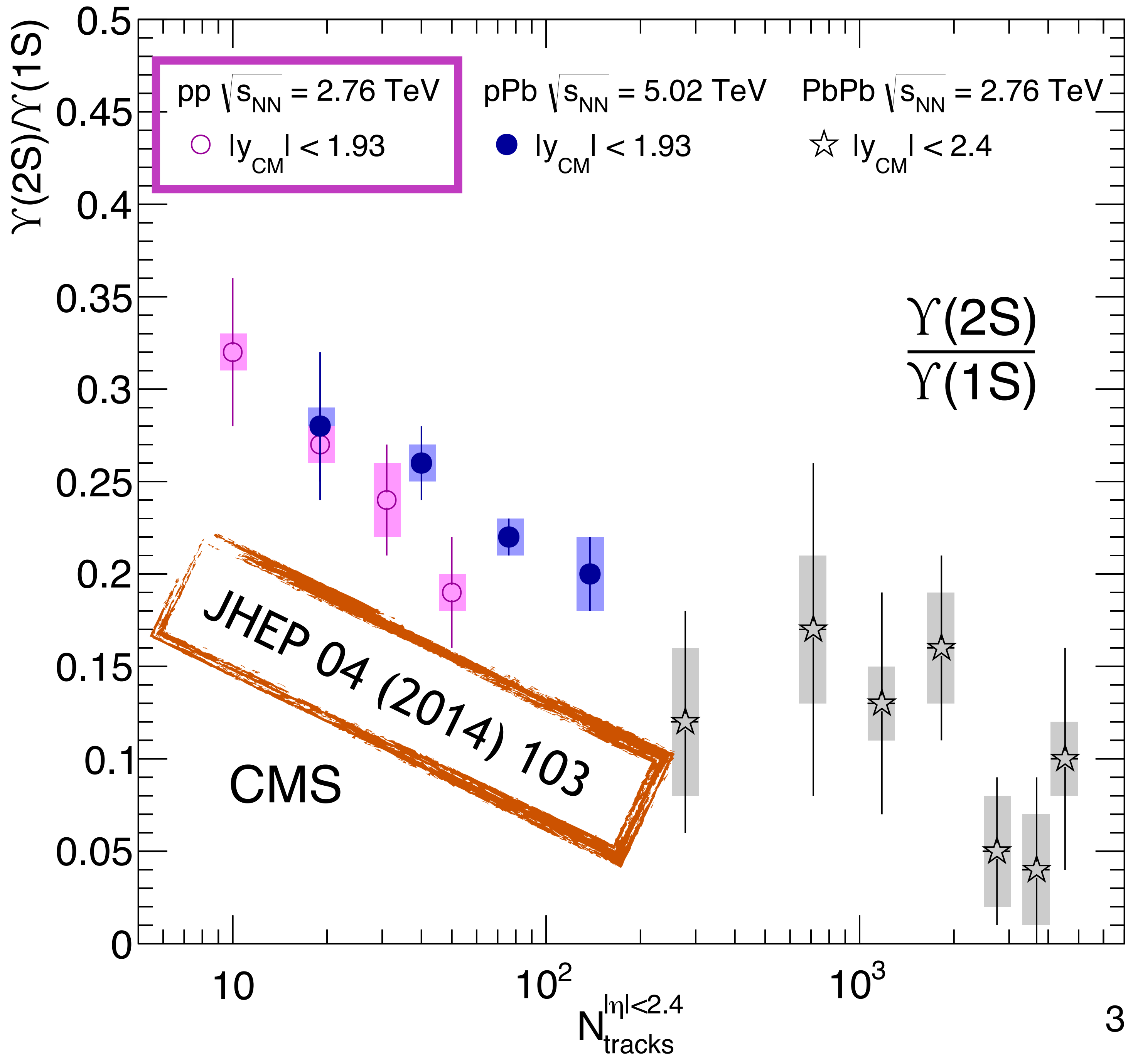




Υ(ns) ratio vs Multiplicity

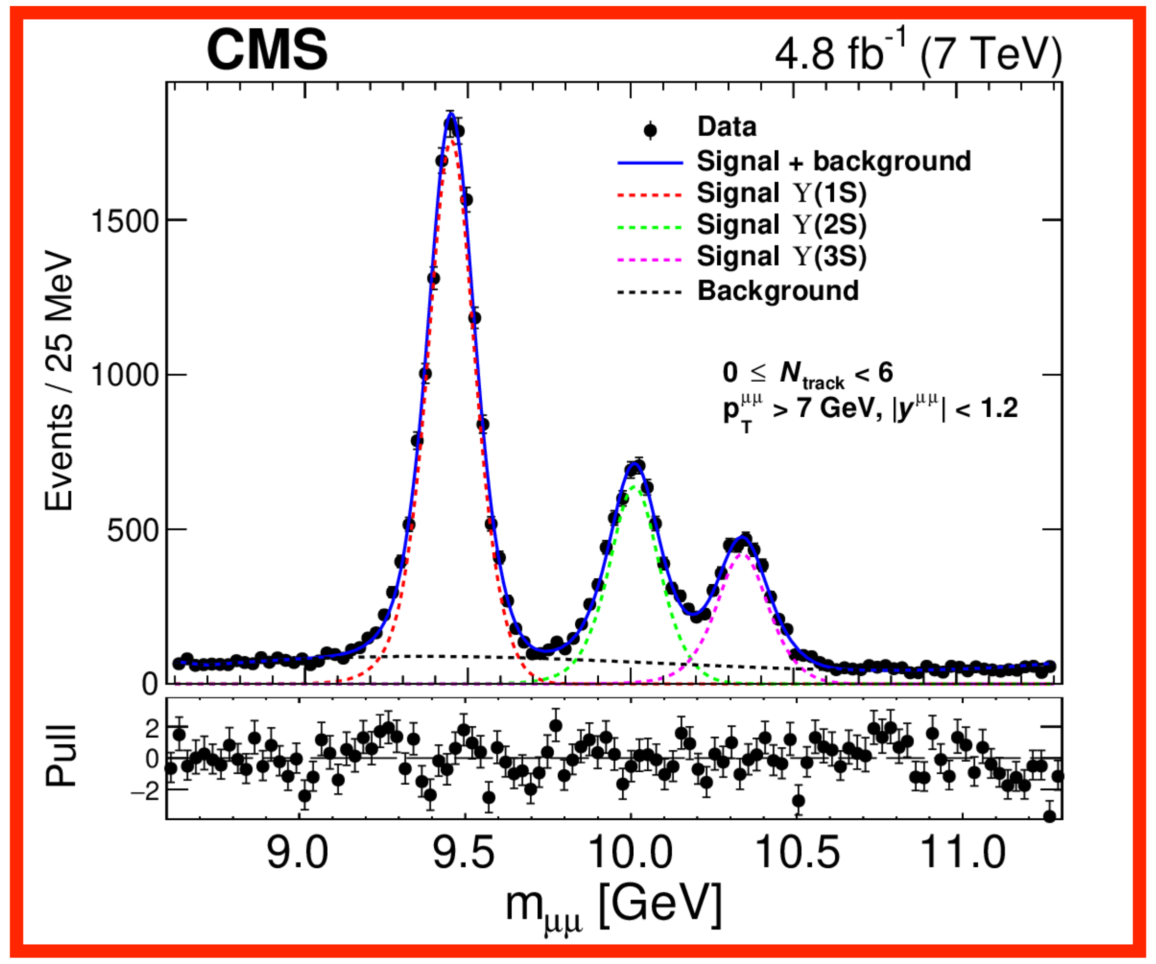
- Υ(nS) production extensively studied in Heavy Ions collision as a probe for studying the Quark Gluon Plasma (QCD)
  - Colour Screening and thermal broadening of spectral functions:
    - Sequential suppression of Υ(nS) states
    - Υ(nS) as a probe of QGP temperature
  - Colour recombination of uncorrelated quark negligible in bottomonium w.r.t. charmonium
- CMS studied Υ(nS) production in PbPb, pPb collisions, founding evidence of suppression
  - In the small pp collision (2.76 TeV) reference sample the ratio showed a decrease with the number of charged particles produced in the collision
  - **Extended studies performed using the full 7 TeV data sample (Pile-Up ~7).**

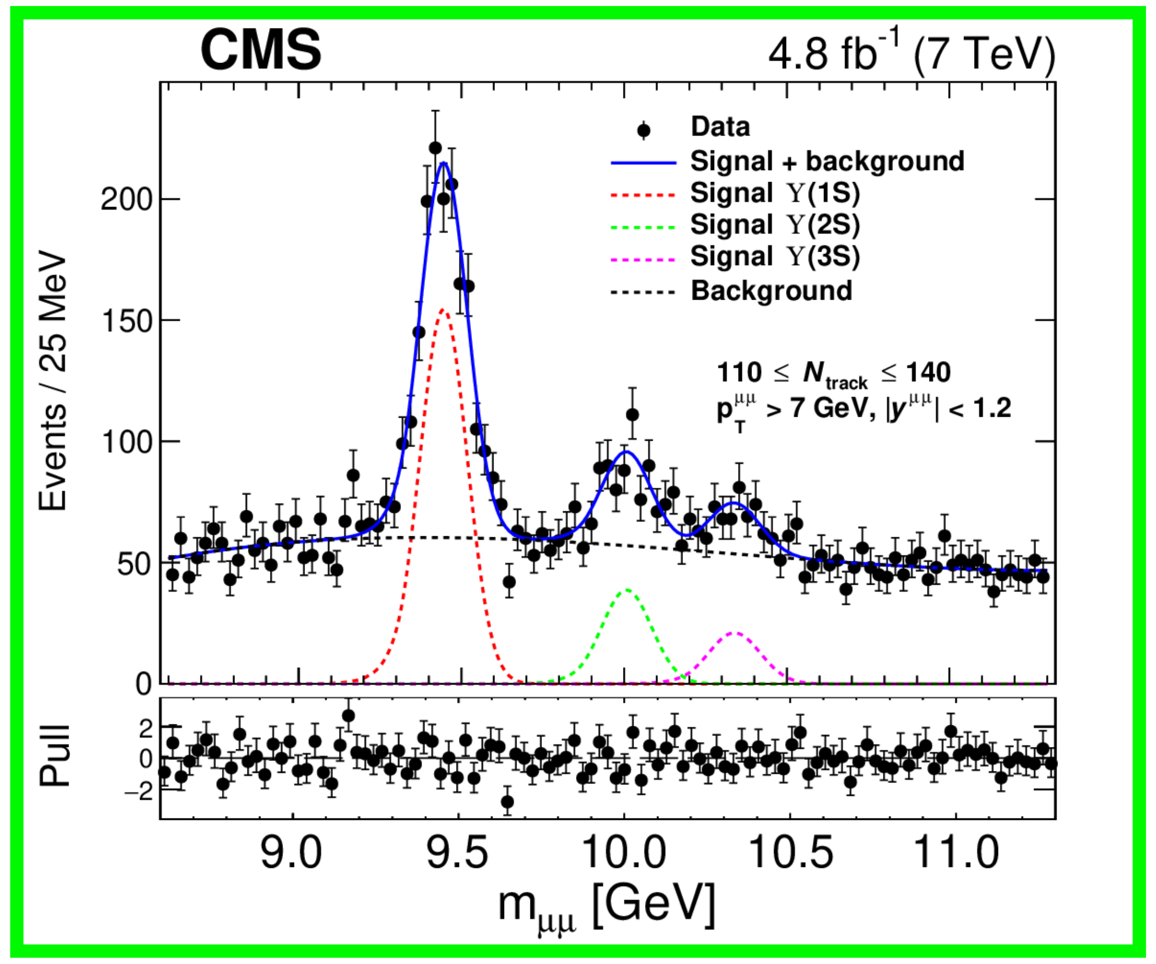




Yields and Multiplicity definitions

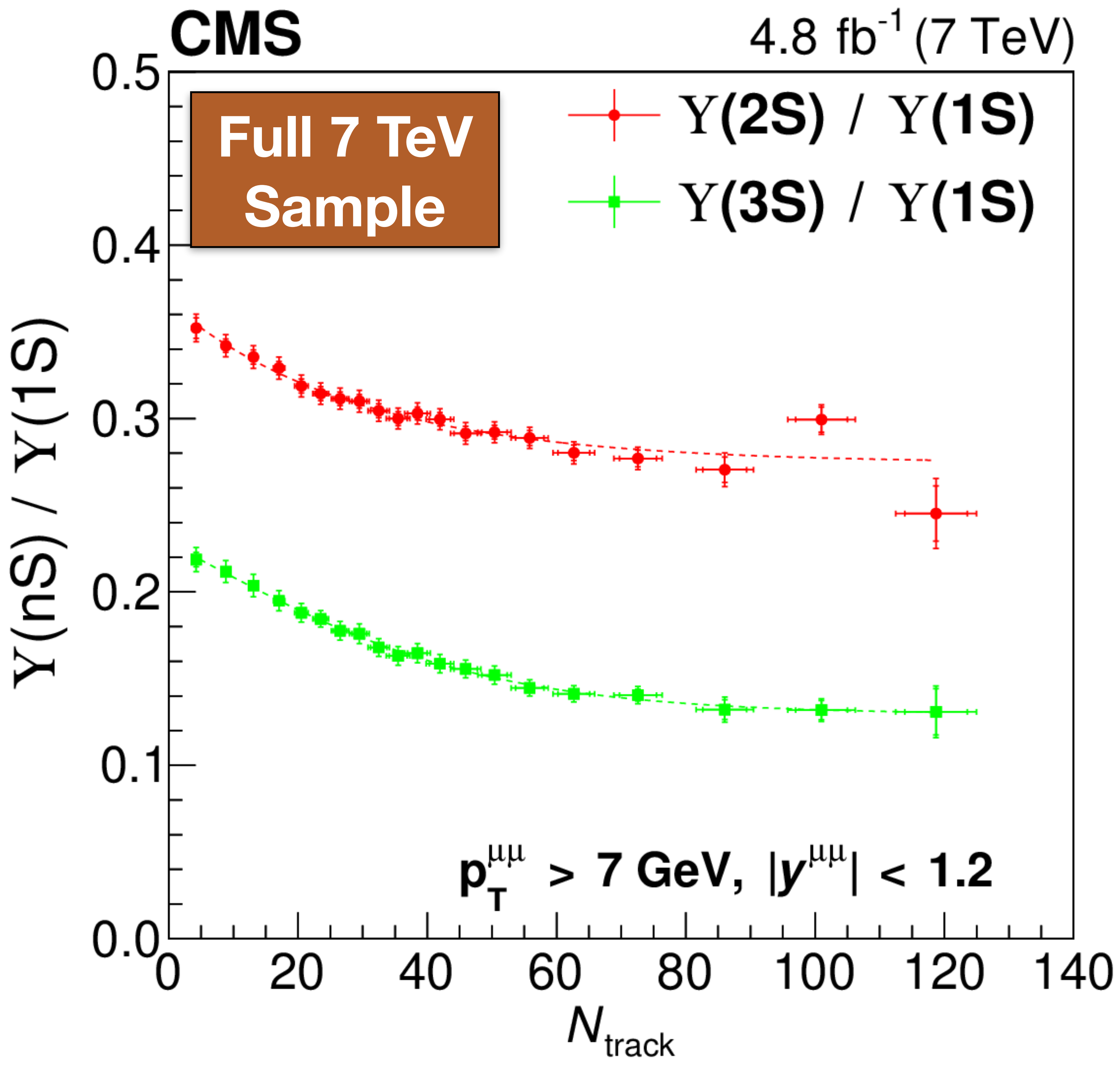
- **Υ(nS) kinematic region: |y|< 1.2 and p_T>7(0) GeV**
  - Yields from extended binned maximum likelihood fit
  - Event-by-event efficiency correction based on Tag&Probe on data
  - Acceptance correction considering unpolarised hypothesis
- **Charged Track Selection: |y|<2.4 and p_T>0.4 GeV**
  - ***Multiplicity*** of the production vertex associated to the Υ(nS)
  - Unfolded using MC taking into account
    - tracker detector efficiency
    - effect bin migration due to merging of Pile-Up vertices
  - Evaluated corresponding fraction in Minimum Bias events to facilitate comparisons.



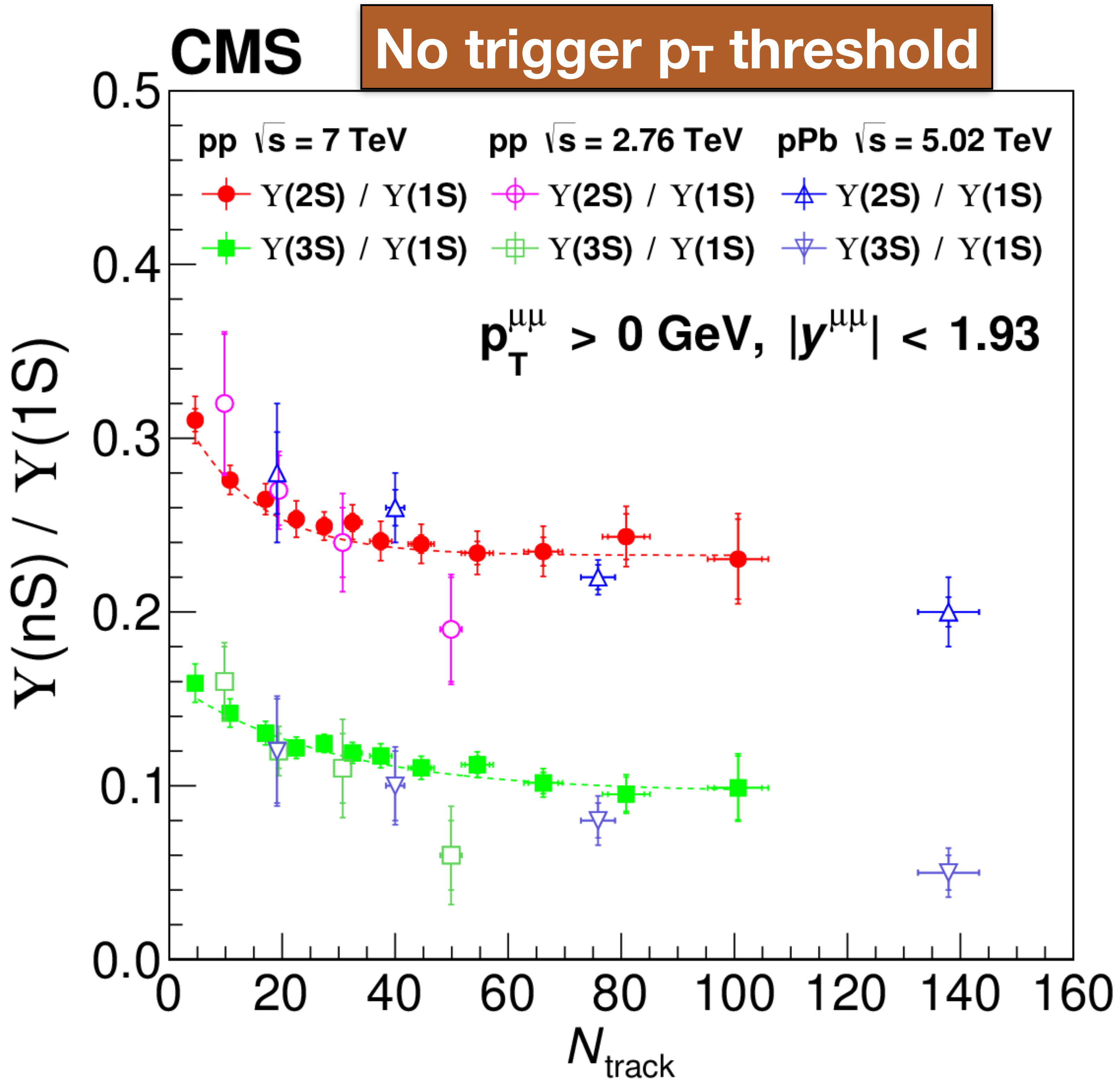


N_{track}	$\langle N_{track} \rangle$	N_{track}^{true} ($p_T^{track} > 0.4$ GeV)	N_{track}^{true} ($p_T^{track} > 0$ GeV)	MB (%)
0–6	$4.2 \pm 0.2 \pm 0.1$	4.2 ± 0.3	6.6 ± 0.6	26.94 ± 0.03
6–11	$8.8 \pm 0.4 \pm 0.3$	8.9 ± 0.4	14.9 ± 0.9	16.73 ± 0.03
11–15	$13.1 \pm 0.5 \pm 0.4$	13.4 ± 0.4	22.7 ± 0.9	10.21 ± 0.02
15–19	$17.1 \pm 0.7 \pm 0.6$	17.1 ± 0.4	28.5 ± 0.9	8.39 ± 0.02
19–22	$20.5 \pm 0.8 \pm 0.7$	20.7 ± 0.4	35.4 ± 1.0	5.36 ± 0.02
22–25	$23.5 \pm 0.9 \pm 0.8$	23.5 ± 0.4	40.3 ± 1.0	4.70 ± 0.02
25–28	$26.5 \pm 1.0 \pm 0.9$	26.4 ± 0.4	43.6 ± 1.0	4.12 ± 0.01
28–31	$29.5 \pm 1.2 \pm 1.0$	29.3 ± 0.5	48.5 ± 1.0	3.61 ± 0.01
31–34	$32.5 \pm 1.3 \pm 1.1$	32.2 ± 0.5	53.0 ± 1.0	3.12 ± 0.01
34–37	$35.5 \pm 1.4 \pm 1.2$	35.1 ± 0.5	57.6 ± 1.0	2.72 ± 0.01
37–40	$38.5 \pm 1.5 \pm 1.3$	38.0 ± 0.5	62.1 ± 1.1	2.60 ± 0.01
40–44	$42.0 \pm 1.6 \pm 1.4$	41.3 ± 0.5	67.2 ± 1.1	2.36 ± 0.01
44–48	$45.9 \pm 1.8 \pm 1.5$	45.1 ± 0.6	72.8 ± 1.2	2.21 ± 0.01
48–53	$50.4 \pm 2.0 \pm 1.7$	49.4 ± 0.6	79.1 ± 1.2	2.01 ± 0.01
53–59	$55.8 \pm 2.2 \pm 1.9$	54.4 ± 0.6	86.6 ± 1.2	1.75 ± 0.01
59–67	$62.7 \pm 2.5 \pm 2.1$	60.8 ± 0.6	95.8 ± 1.3	1.41 ± 0.01
67–80	$72.6 \pm 2.9 \pm 2.4$	69.6 ± 0.6	109.2 ± 1.3	1.12 ± 0.01
80–95	$86.0 \pm 3.4 \pm 2.9$	81.9 ± 0.6	126.4 ± 1.4	0.459 ± 0.005
95–110	$100.1 \pm 4.0 \pm 3.3$	95.8 ± 0.9	145.0 ± 1.6	0.121 ± 0.002
110–140	$118.7 \pm 4.9 \pm 3.9$	109.4 ± 1.2	164.5 ± 2.0	0.0038 ± 0.0001

Υ(ns) ratio vs Multiplicity

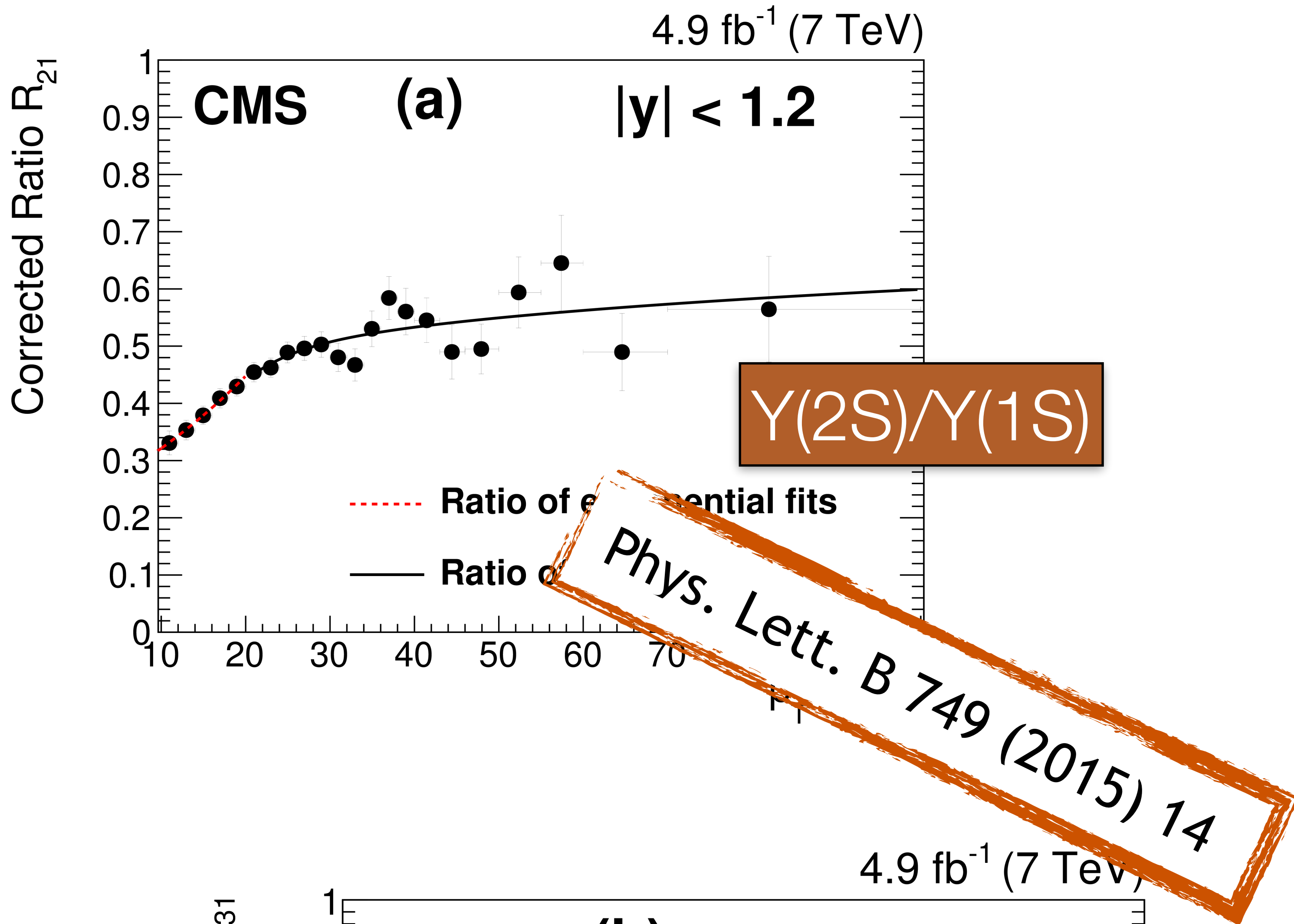


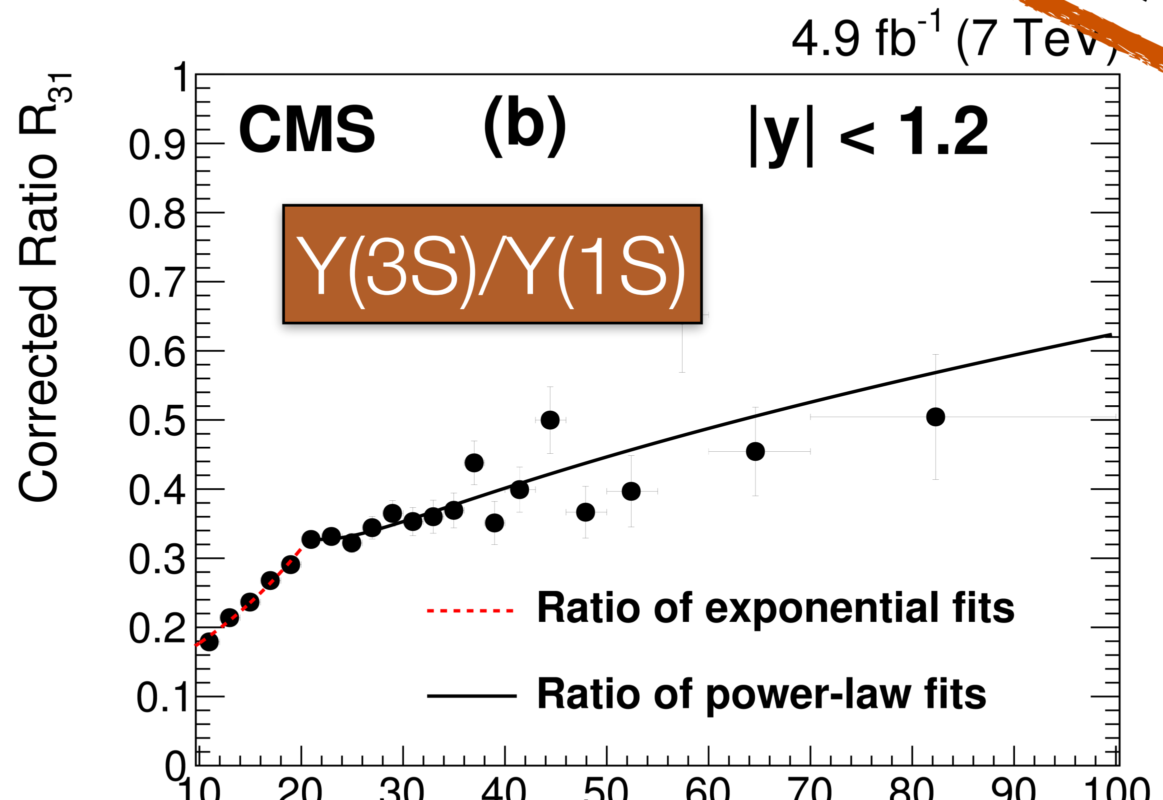
- Decrease in the ratios from low- to high-***Multiplicity*** bins.
- Fitted with an exponential function:
  - **(-22 ± 3)%** for Υ(2S)/Υ(1S)
  - **(-42±4)%** for Υ(3S)/Υ(1S)



- Comparison with previous results
  - pp collision at 2.76 TeV
  - pPb collision at 5.02 TeV
  - Observed a compatible behaviour

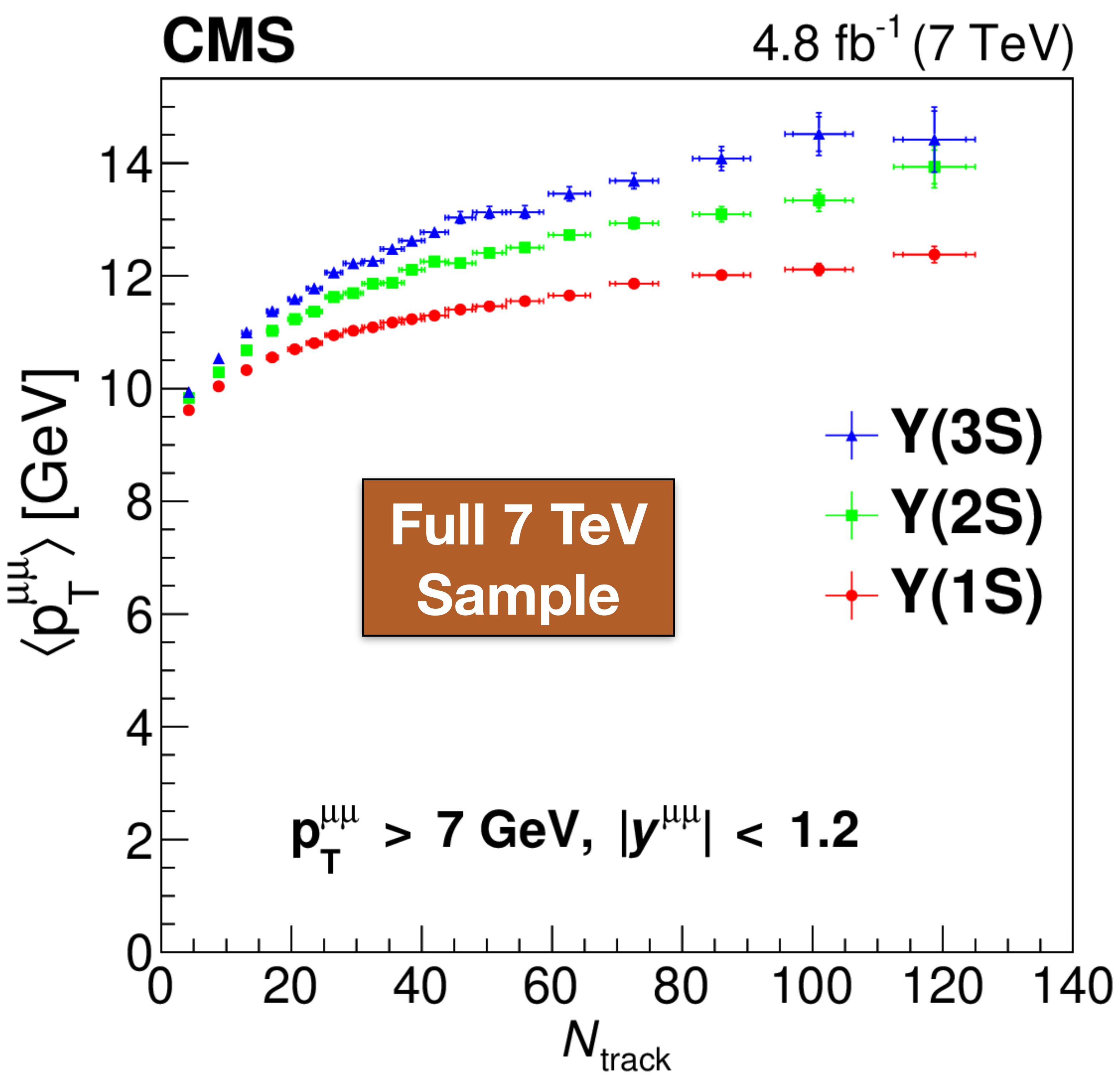
- Absolute values of the ratios are smaller at lower p_T
- Ratios increase with p_T as already measured also in CMS

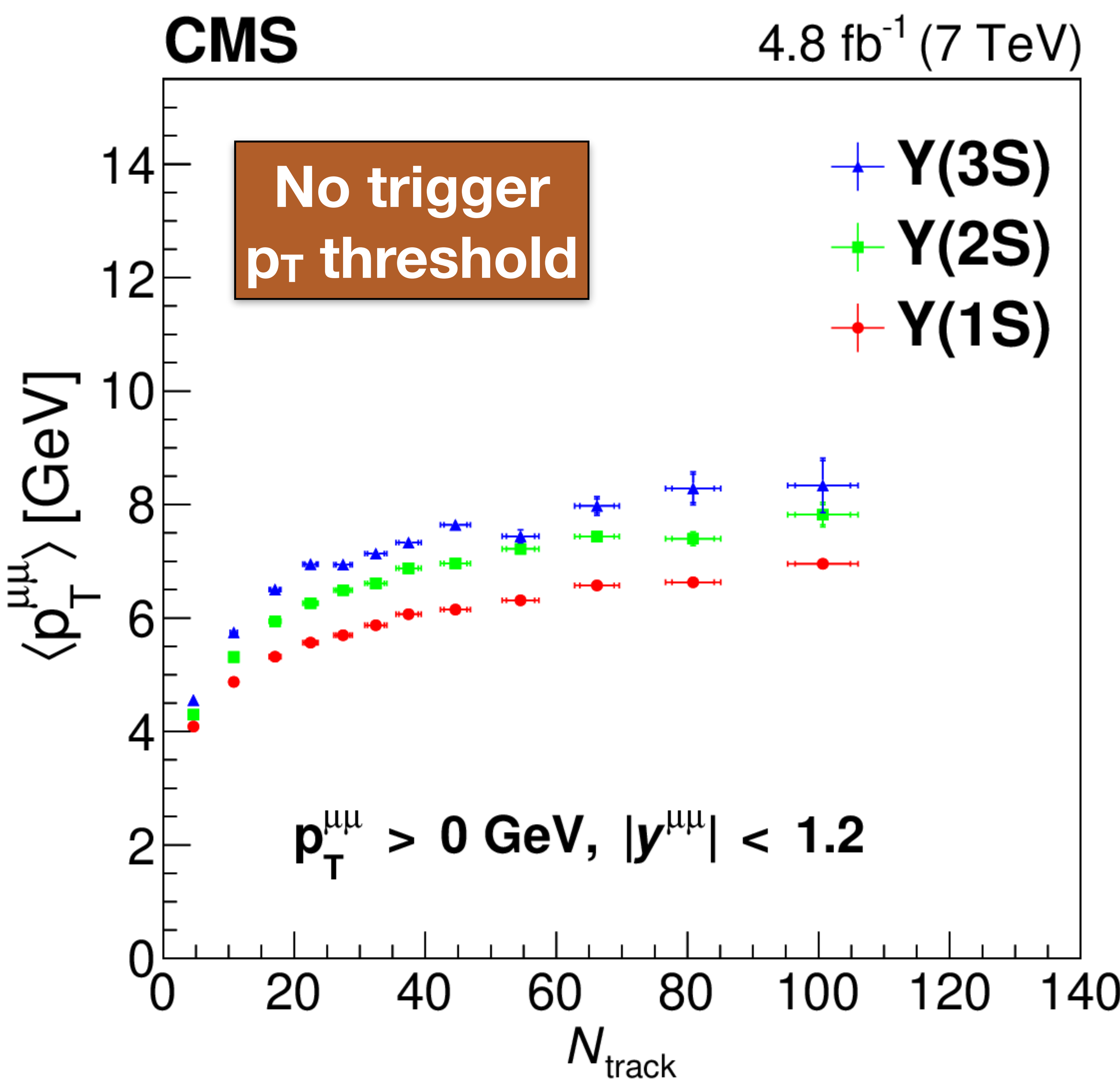




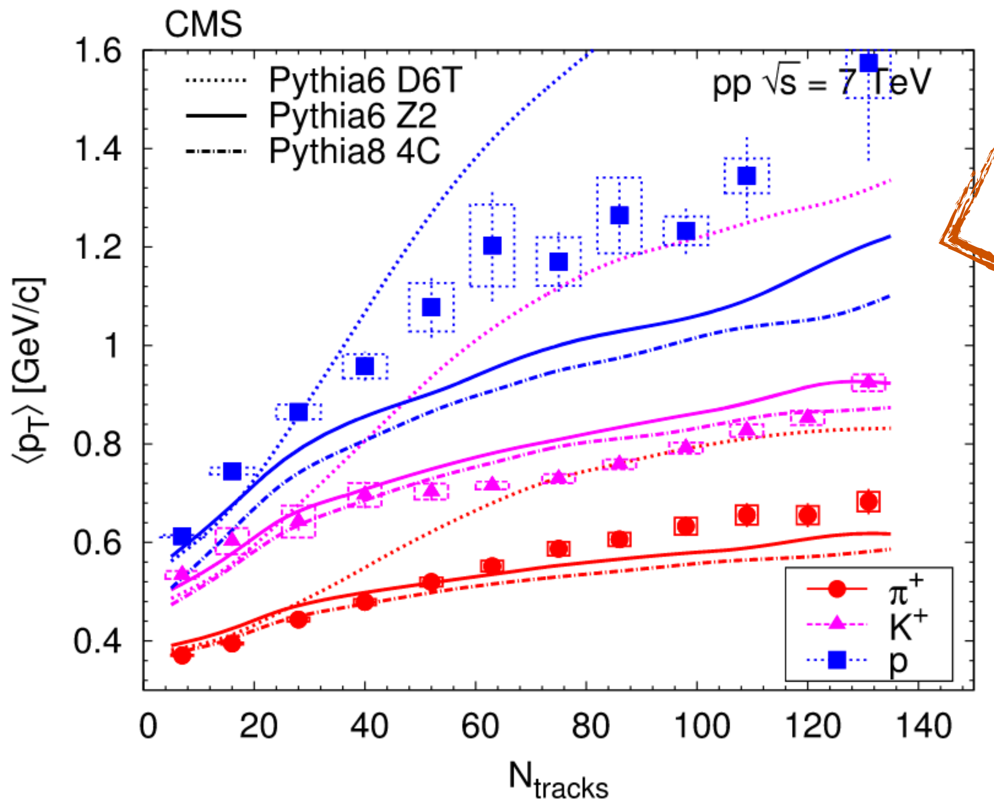
Mean p_T vs Multiplicity

- p_T spectra of the Dimuon candidates are obtained using sPlot technique
  - rescaled for efficiency and acceptance
- We observe a **hierarchical structure:**
  - transverse momentum increases more rapidly with ***Multiplicity*** as the mass of the corresponding Υ(nS) increases.



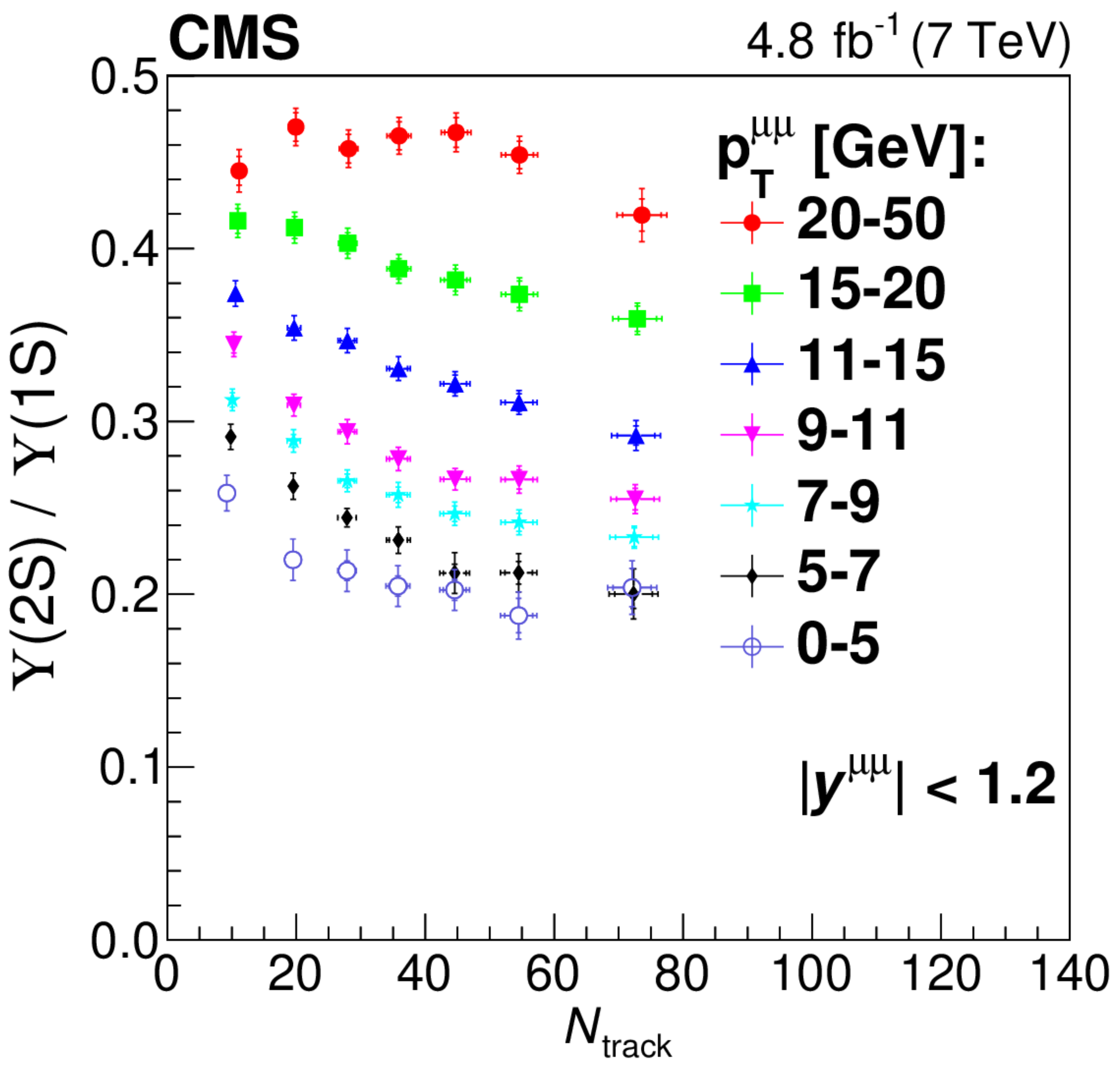


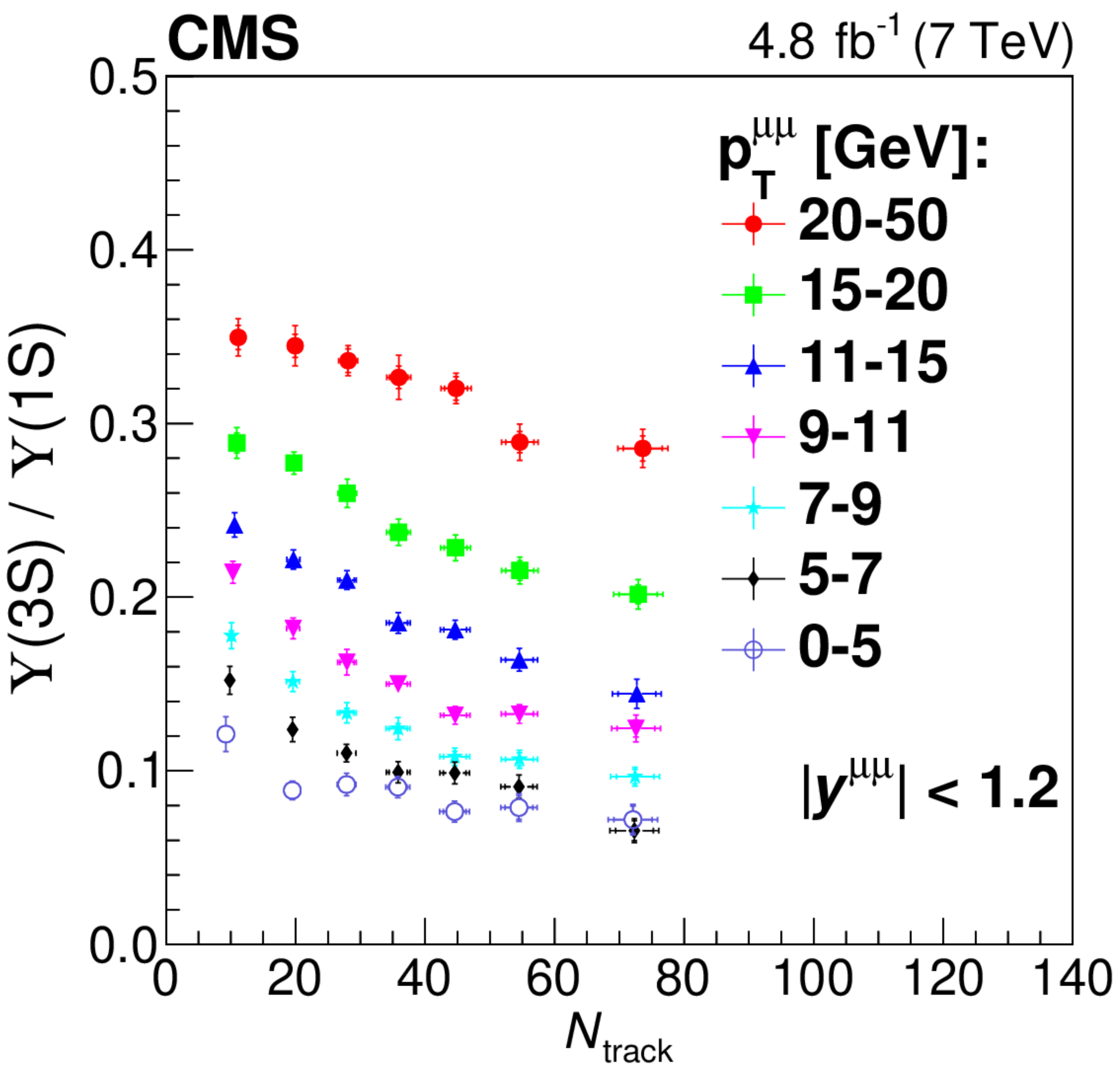
An increase with particle mass was also observed in pp collisions at the LHC for pions, kaons, and protons.



EPJC 72 (2012) 2164

Dependence on p_T

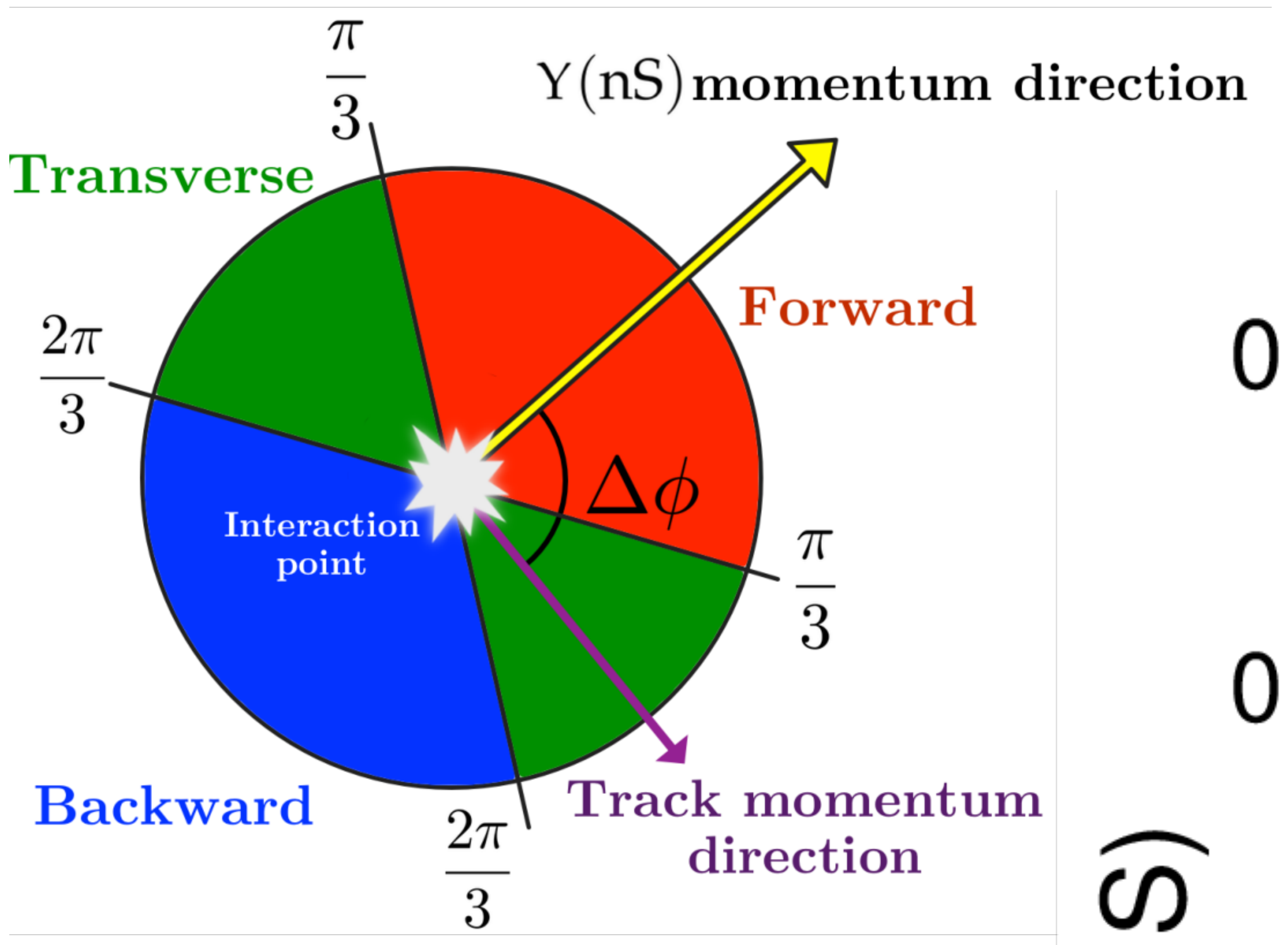


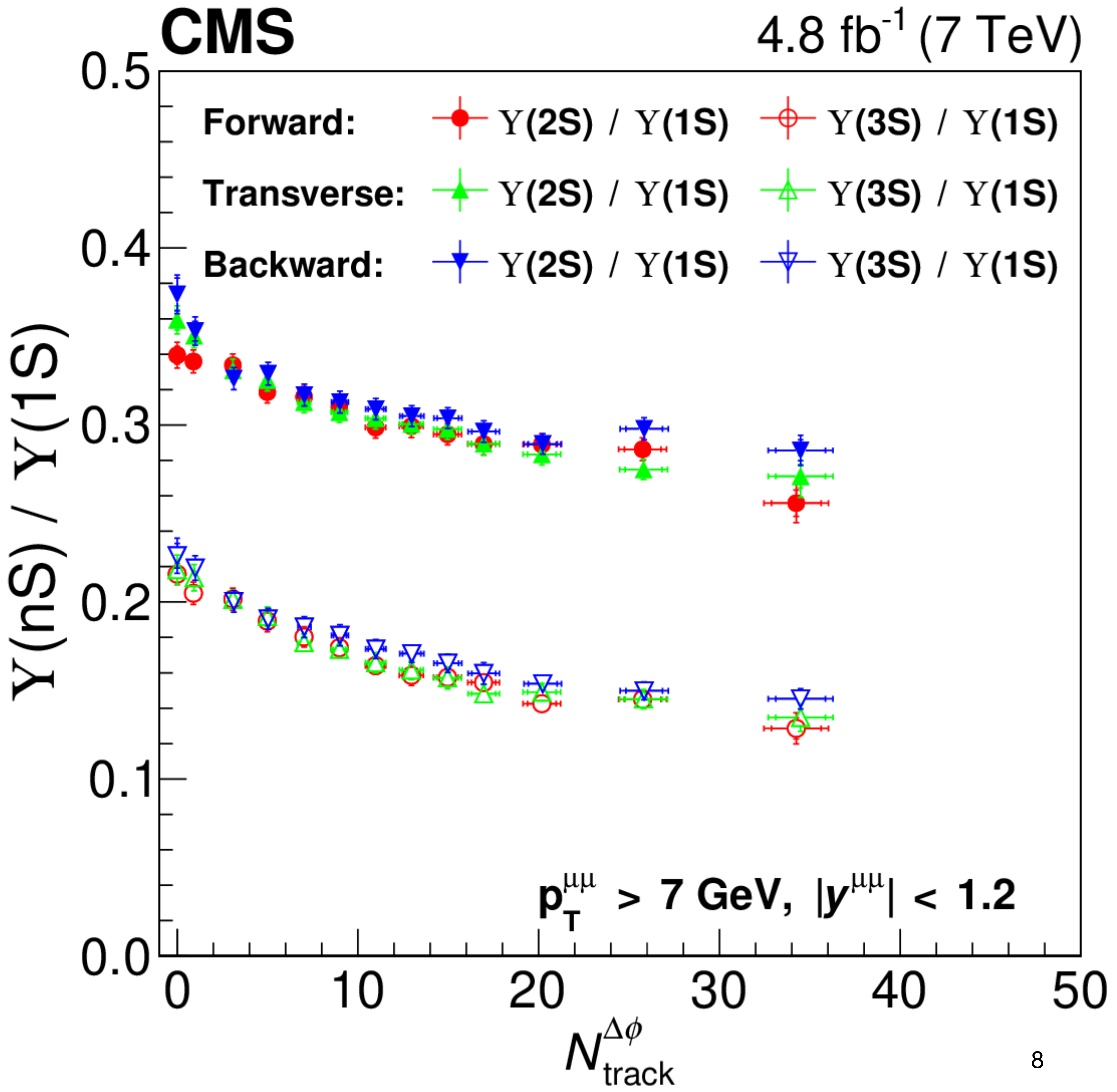


- Doubly differential study: ratios vs multiplicity in different Dimuon p_T regions
- In all the p_T ranges the decrease with increase ***Multiplicity*** is observed
  - Strongest decrease in the 5-7 GeV bin
- **Slower decrees at higher p_T**
  - The Υ(2S)/Υ(1S) ratio in the 20-50 GeV range is compatible to be constant

Local multiplicity dependence

- Ratios measured as a function of the number of particles in 3 different Δϕ regions with respect to the Dimuon direction
  - Test of the UE connection
- On average, there are ~3 less tracks in the transverse interval (11.90±0.05)



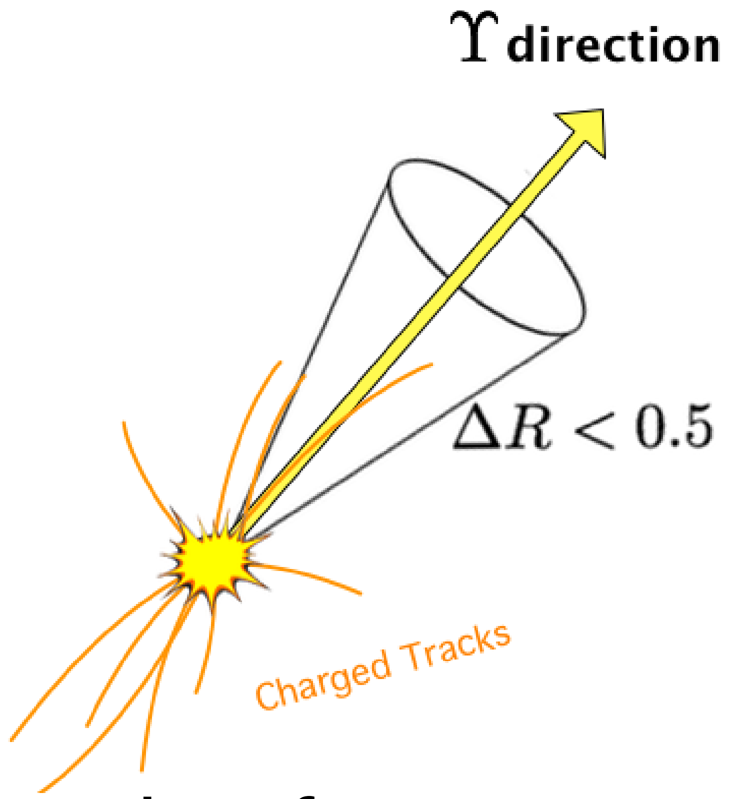


- Similar trends are obtained in the 3 angular regions.
- **Decrease in the Transverse region suggests its connection with the UE itself**
  - particles activity along the Y(nS) direction would effect only the Forward region.

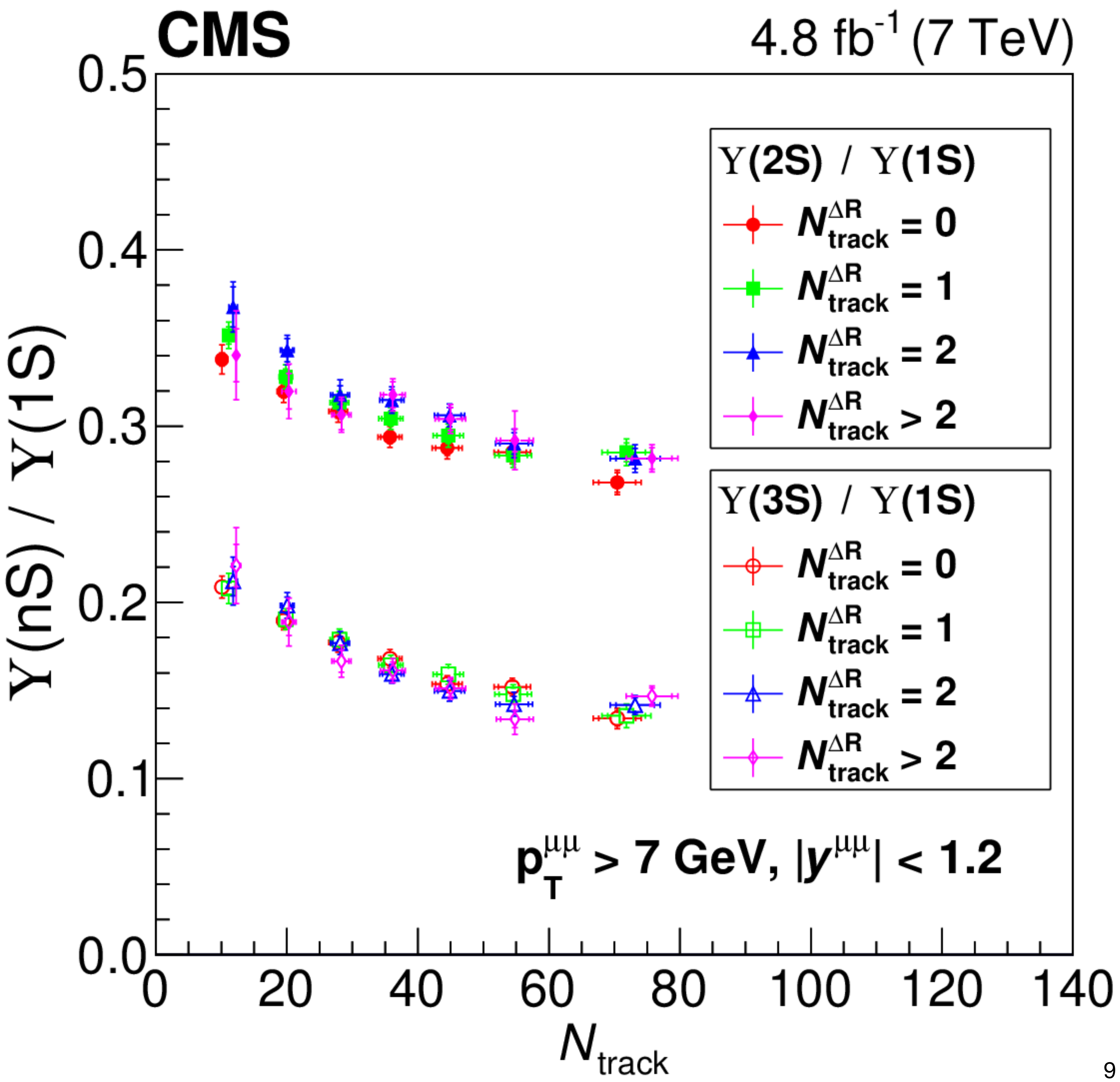
Looking for comovers effect

- Ratios vs ***Multiplicity*** are evaluated in different condition of isolation
- Isolation is defined as the number of tracks in a cone:

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.5$$



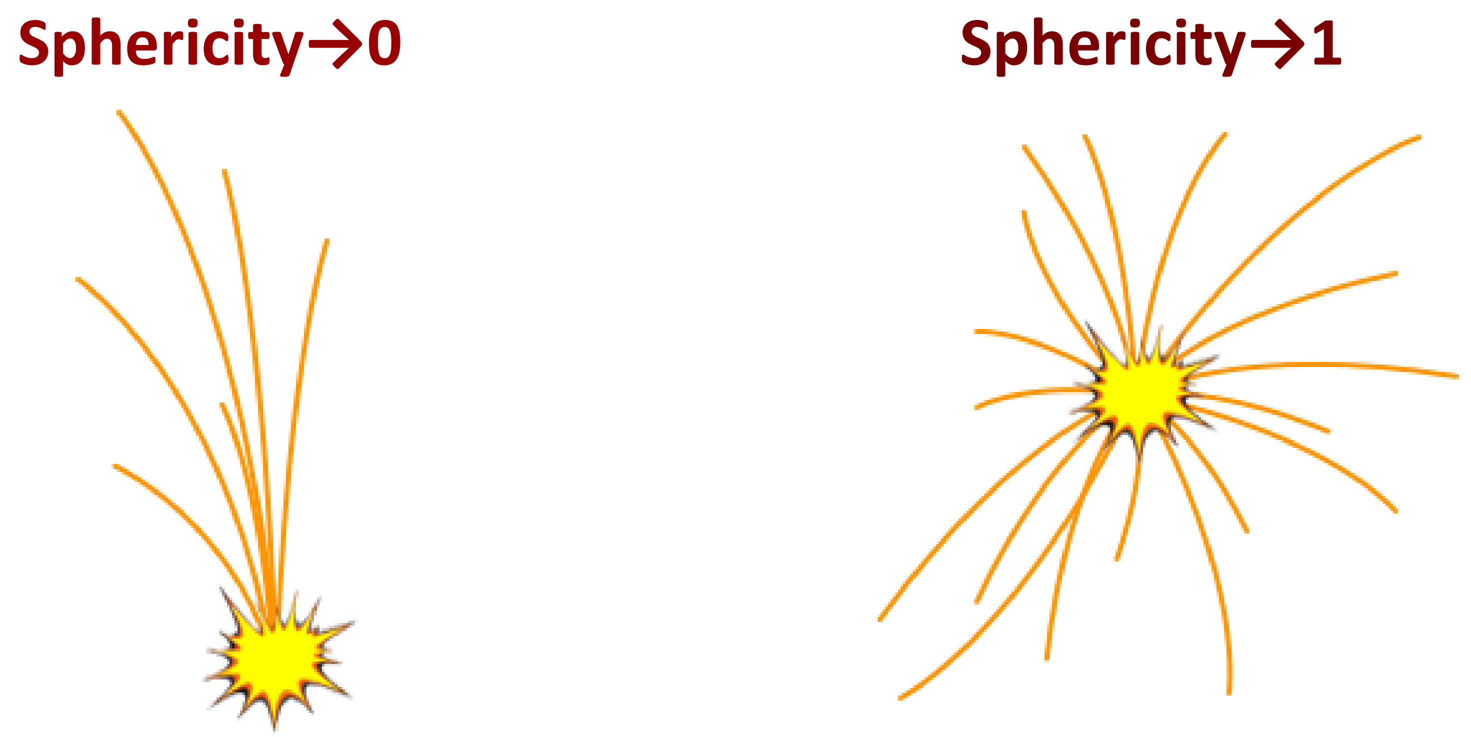
- We are looking for effect on the ratios coming from charged tracks produced along the Y momentum direction(”comovers” in [Phys. Lett. B731(2014) 57])
- A data driven correction has been needed to take into account the effect of the feed down
  - This is particularly sizeable for Y(2S)/Y(1S) due to the $Y(2S) \rightarrow Y(1S)\pi\pi$ decay
- **The dependence on the charged particle multiplicity is similar in all the categories**
  - flattening in the $N^{\Delta R}_{track}$>2 category, opposite to what would be expected in the comover picture.

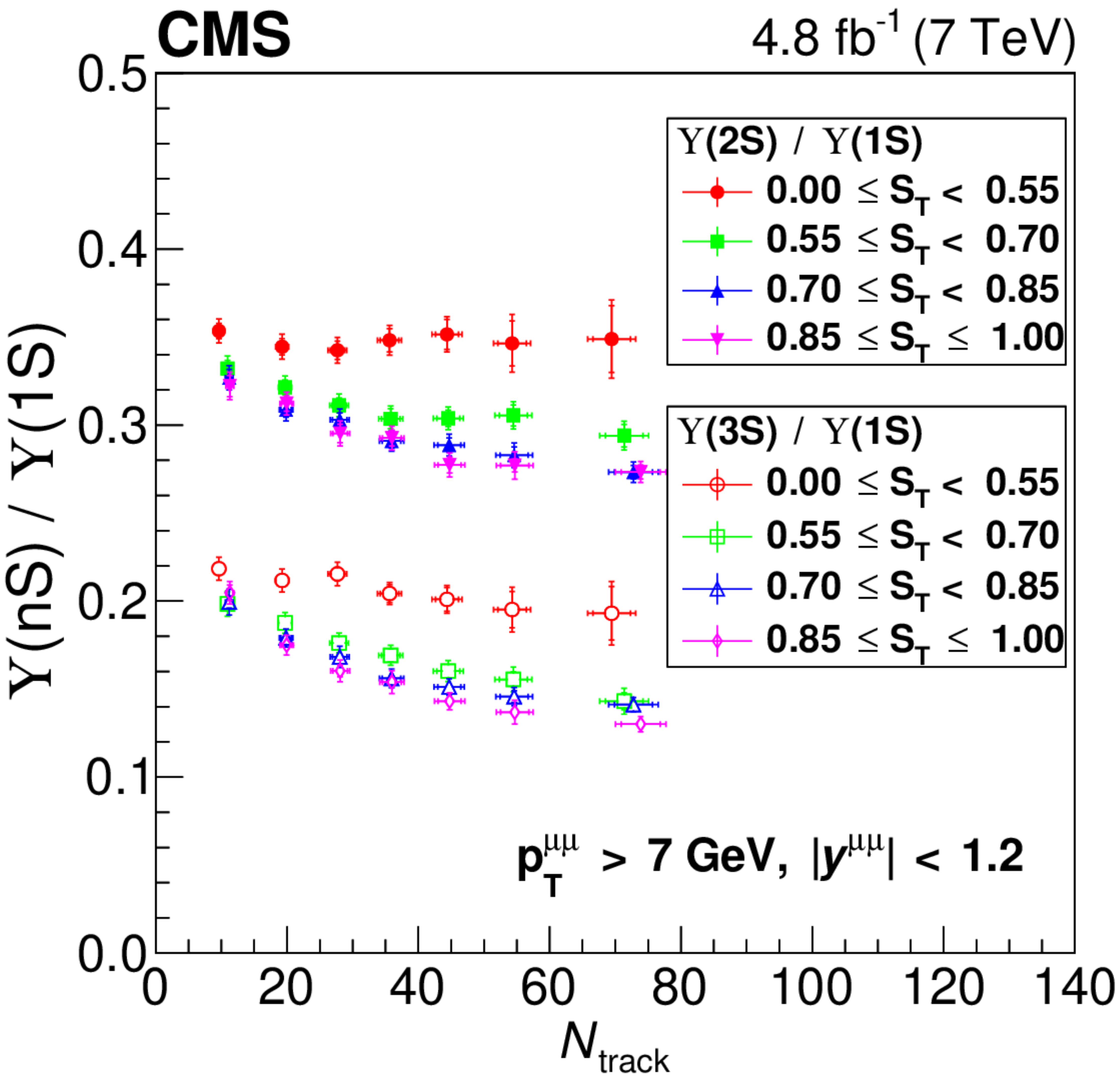


Ratios vs Sphericity

- Finally, ratios were studied as a function of the event sphericity

$$S_T \equiv \frac{2\lambda_2}{\lambda_1 + \lambda_2} \qquad S^T_{xy} = \frac{1}{\sum_i p_{Ti}} \sum_i \frac{1}{p_{Ti}} \begin{pmatrix} p^2_{xi} & p_{xi}p_{yi} \\ p_{xi}p_{yi} & p^2_{yi} \end{pmatrix}$$





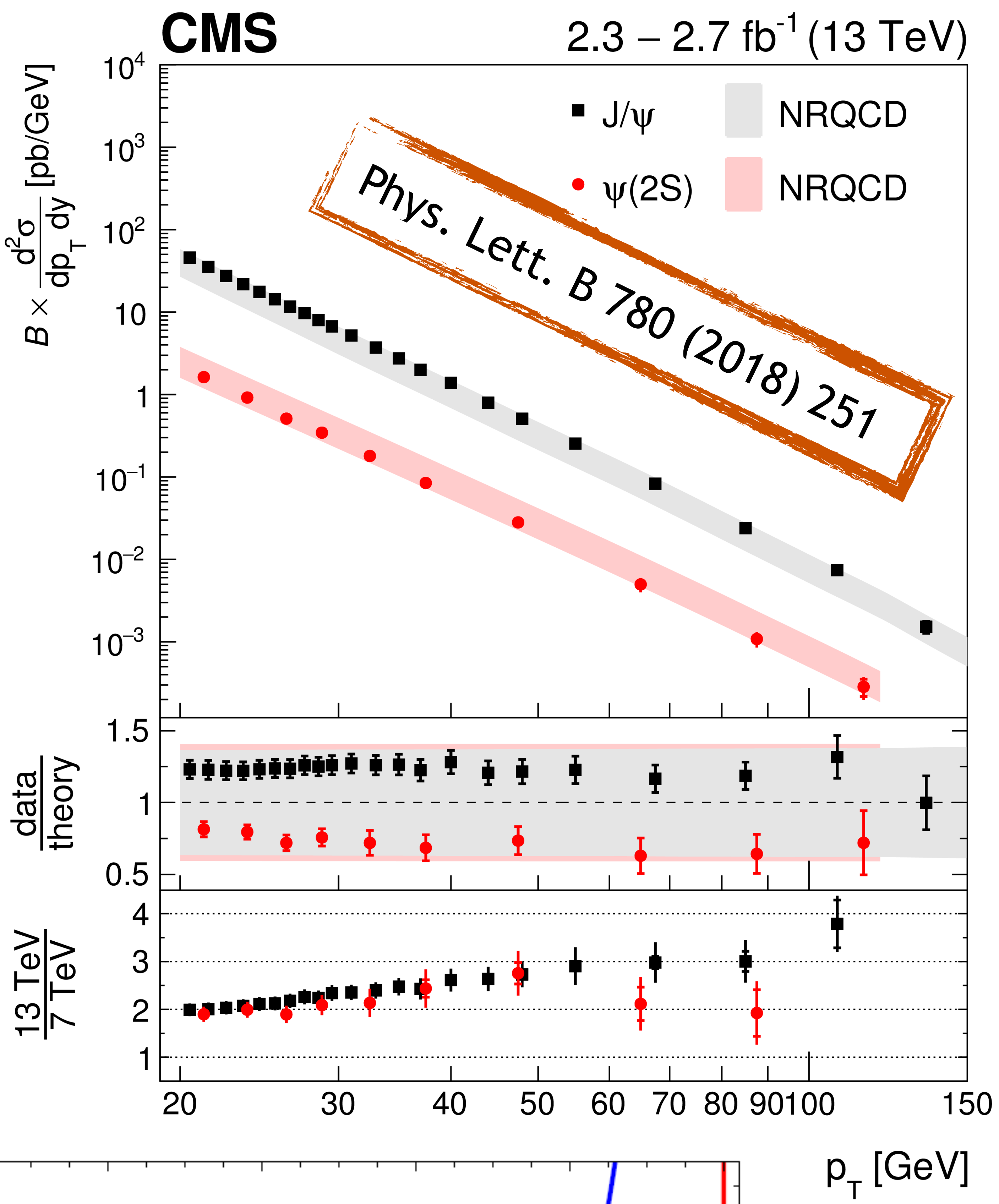
- Decrease appears linked to the UE event:
  - not present in the low-sphericity region (high multiplicity due to jets)
  - appears in a similar way when S_T>0.55

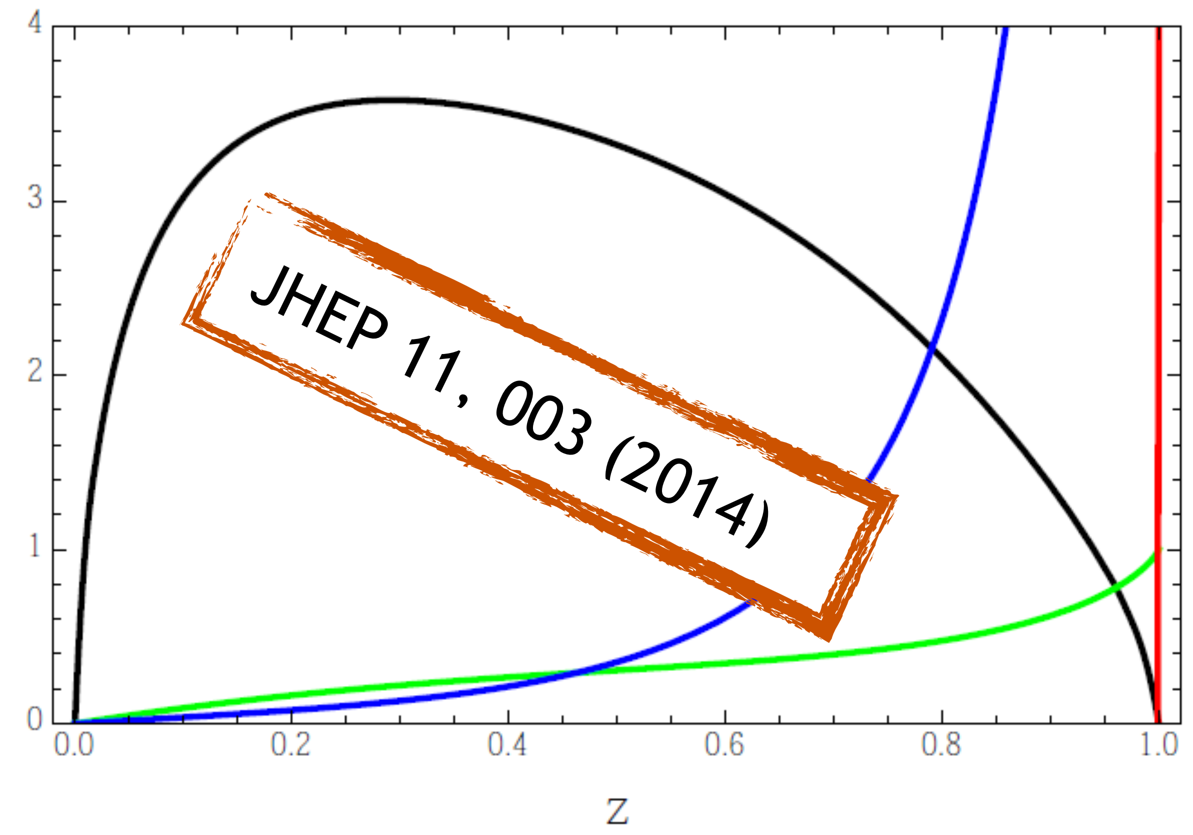
Measurement of the J/ψ-jet association

- The mechanism to go from a coloured $Q\bar{Q}$ state to a colourless $c\bar{c}$ state from hadronic collision is of great theoretical interest
  - Early Colour singlet model (CSM), underestimated Tevatron J/ψ and ψ(2S) production cross section by factors of 10-50.
- **NRQCD approach (color-singlet+color-octet amplitudes) described Tevatron data and production at LHC**
  - Uses non-perturbative long-distance matrix elements (LDMEs). Adjusting LDMEs fits p_T -dependent J/ψ and ψ(2S) differential cross sections from different data sets.
- **Theoretical interest in jet source of heavy quarks**
  - Testing role of jet fragmentation in quarkonium production
  - Described in Fragmenting-Jet Function (FJF) approach.

$$\frac{d\sigma(E_{jet},z)}{dE_{jet}dz} = H \times \Sigma_{a,b} f_{a/p} \otimes f_{b/p} \Sigma_i J_i \otimes \ \mathcal{G}^{\psi}(E_{jet}, z|R,\mu)$$

  - $G^{J/\psi}$ (containing all the **$z = E_{J/\psi}/E$** dependence) can be decomposed using LDMEs leading contribution from c and g partons
    - **CMS: gluon-dominated mid-rapidity region**
    - relevant g LDMEs: $^3S_1^{(1)}$, $^3S_1^{(8)}$, $^1S_0^{(1)}$, $^3P_J^{(8)}$



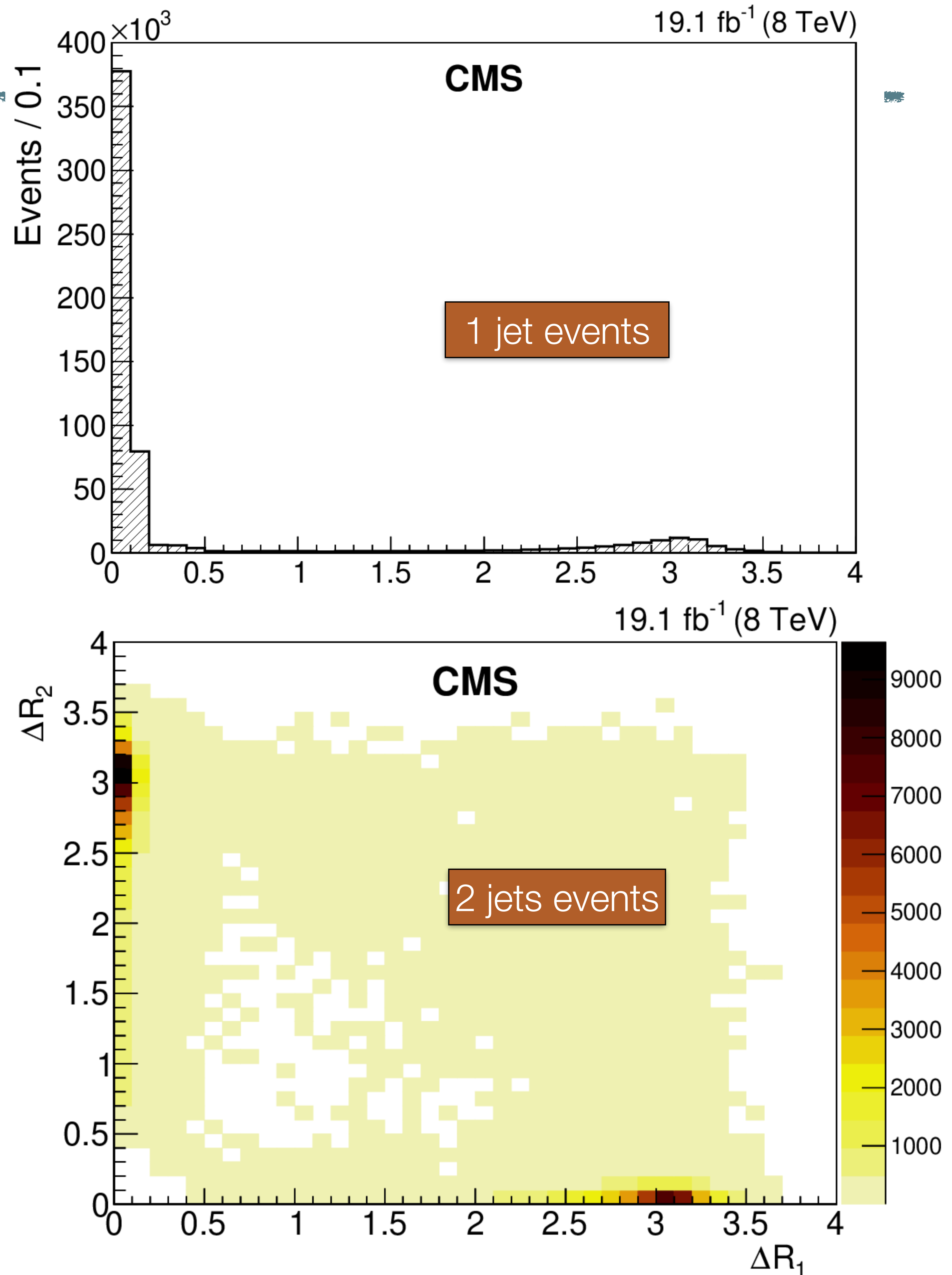


Events Selection

- 8 TeV data, 19.1 fb^{-1}
- **J/ψ: $E_{J/\psi}$ > 15 GeV, $|y_{J/\psi}| < 1$**
  - combinatorial background removed by sideband subtraction
  - Selection of only promo event with with $I_{J/\psi}$ selection
  - «Tag-and-probe» efficiencies used as event weights
- **Jets: Anti-kT jets with R = 0.5**
  - standard CMS jet energy and pileup corrections
  - $p_{T,jet}$ > 25 GeV, $|h_{jet}| < 1$
- Reconstructed J/ψ compared with all the jet in the event using a ΔR test

$$\Delta R = \sqrt{(\eta_{J/\psi} - \eta_{jet})^2 + (\phi_{J/\psi} - \phi_{jet})^2}$$

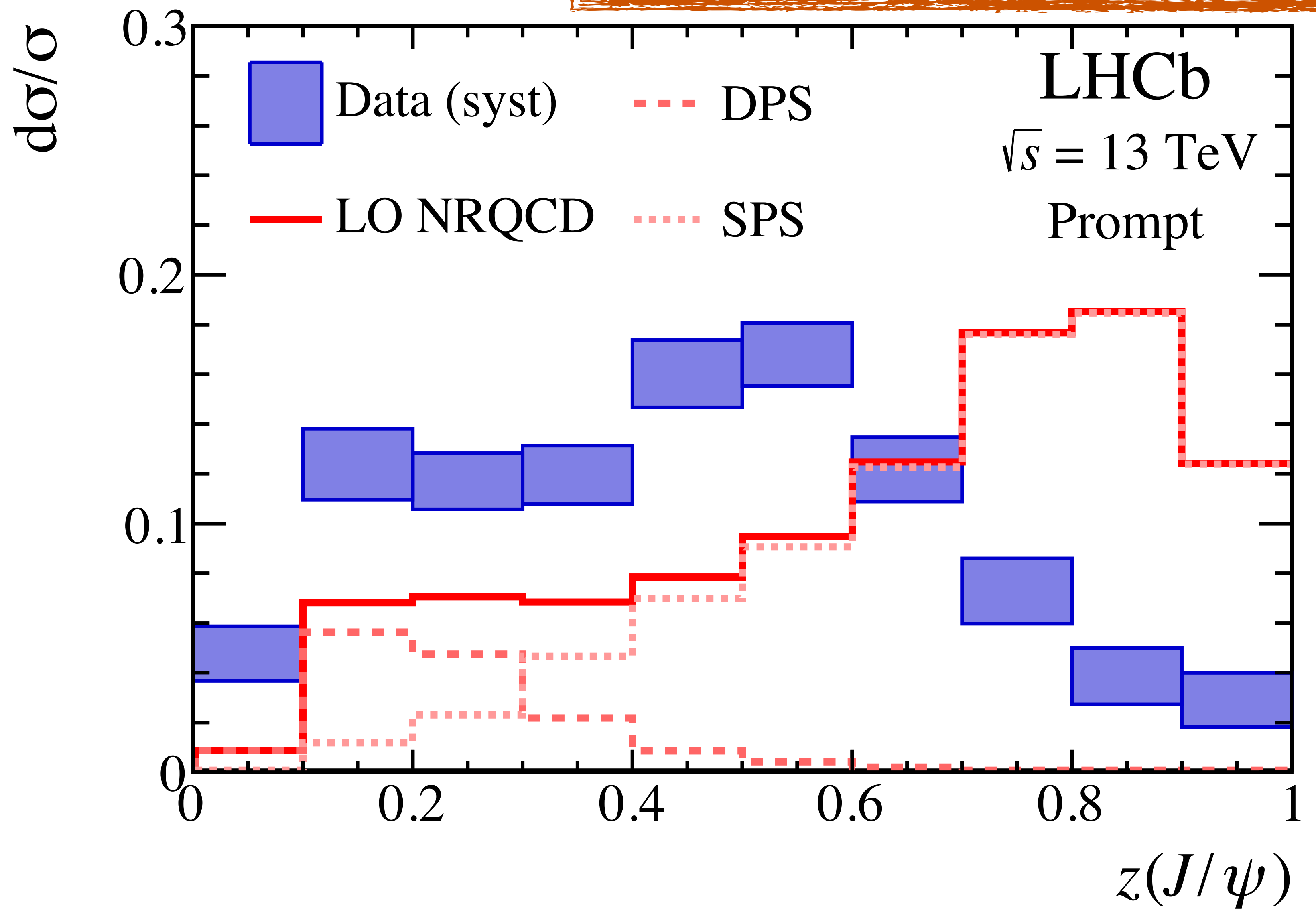
- Considering J/ψ associated when ΔR<0.5 :
- P(J/y associated | 1 jet) ~ 84%
  - P(J/y associated | 2 jets) ~ 94%
  - **When unobserved jets (p_T< 25 GeV) are taken into account → jet fragmentation is a source of ~85% of J/ψ mesons**



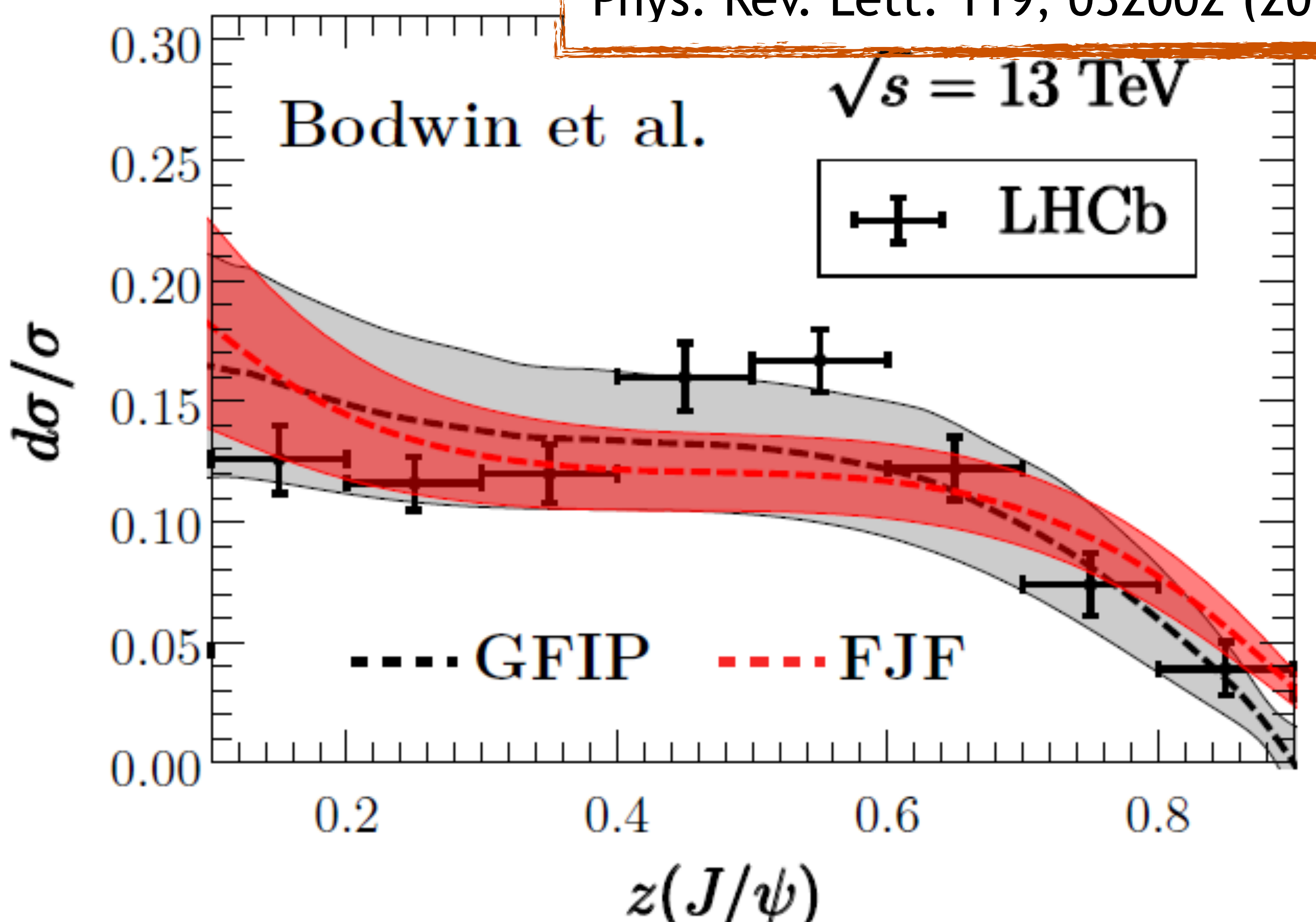
Measurement of the J/ψ-jet association

- LHCb measured the z distribution in events with a jet associated to J/ψ in high-rapidity region
  - Integrated in E_{jet}
  - Pythia8 (implementing CS+CO factorisation) does not describe data
  - FJF using LDME extraction by Bodwin et al. gives fairly good agreement
- Goal in CMS:
  - measure the experimental equivalent of normalized $d^2\sigma/dE_{jet}\,dz$ to have the sensitivity to different LDME parameter sets

Phys. Rev. Lett. 118, 192001 (2017)



Phys. Rev. Lett. 119, 032002 (2017)

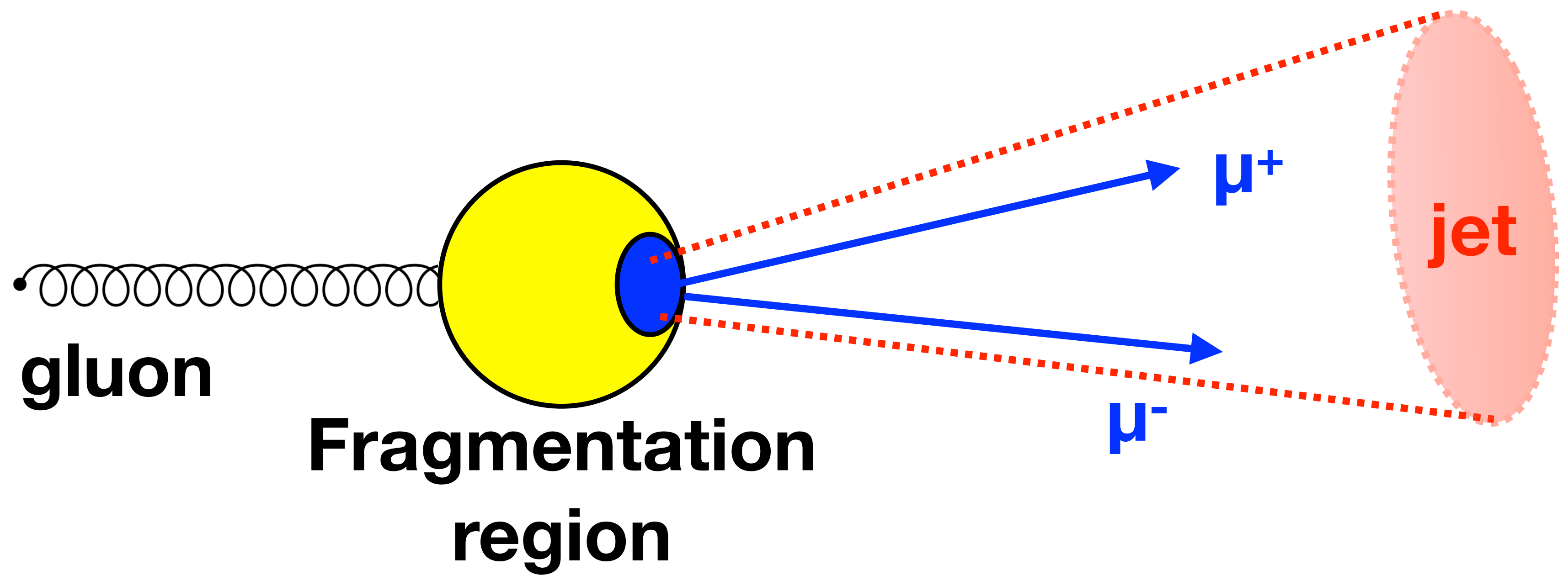


The Ξ Observable in J/ψ-jet event

- We considered the experimental quantity:

$$\Xi(E_c; z_1) \equiv \frac{N(E_c; z_1)}{\int_{0.3}^{0.8} N(E_c; z)\,\mathrm{d}z}$$

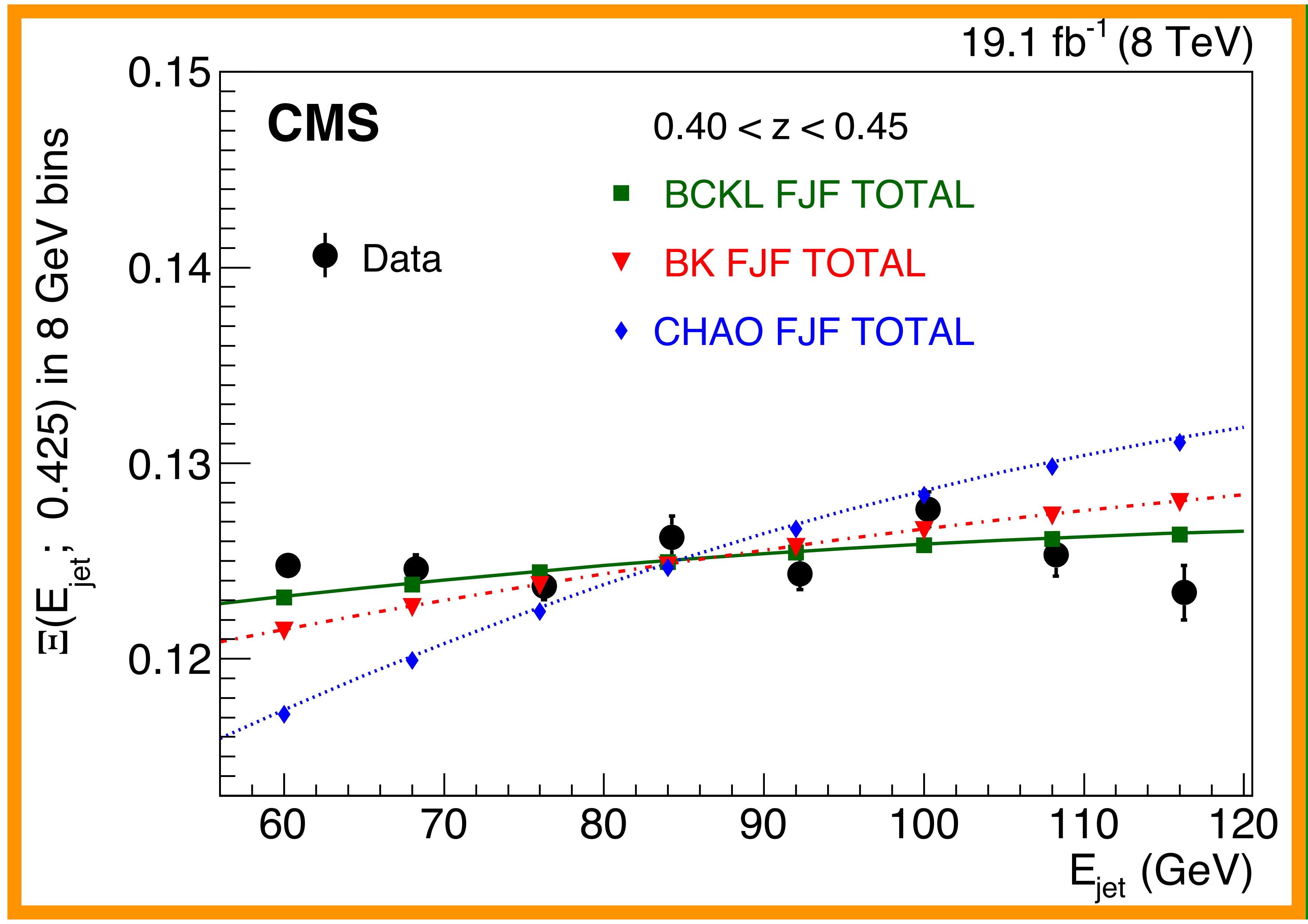
where $N(E_c,z)$ = events in a $[E_{jet},z]$ bin

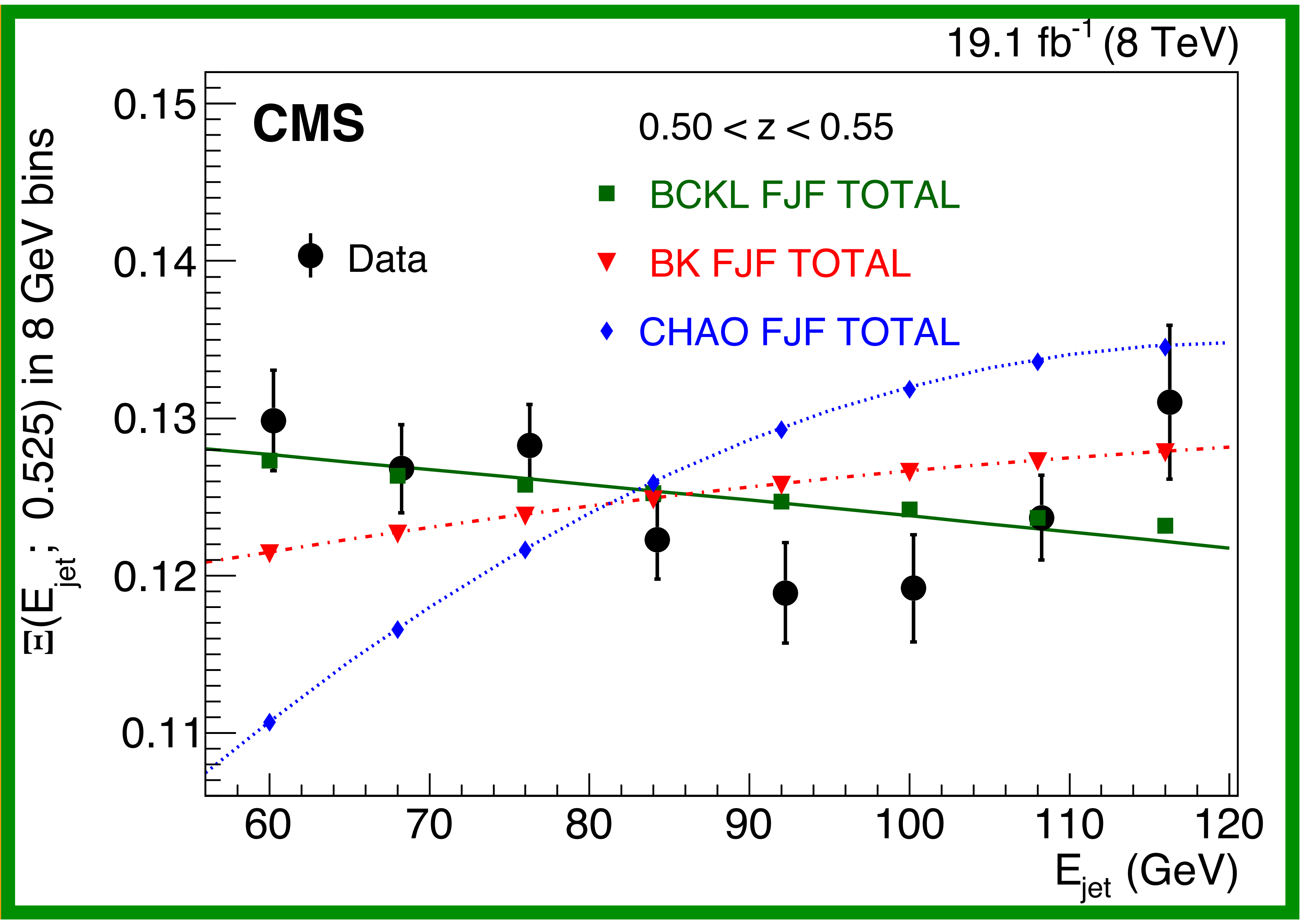


- Compare with 3 LDME parameter sets:
  - Bodwin, Chung, Kim, and Lee (BCKL) [Phys. Rev. Lett. 113 (2014) 022001]
  - Butenschoen and Kniehl (BK) [Mod. Phys. Lett. A 28 (2013) 1350027]
  - Chao, et al. (Chao) [Phys. Rev. Lett. 108 (2012) 242004]
- To look for dominance of a specific LDME in a certain z region, compare each LDME term to data shape for three z slices
- **The $N(E_c,z)$ need to be unfolded**, considering jet energy resolution
  - Restricting in the range $56 < E_{jet} < 120$ GeV (basically constant A · ε)
  - D'Agostini unfolding method **[G. d'Agostini, arXiv:1010.0632]** is used
    - Four unfolding iterations gave stable matches to the MC and no sensitivity on the input distribution
  - There is no evidence that having a J/ψ meson as a constituent affects the jet energy distribution

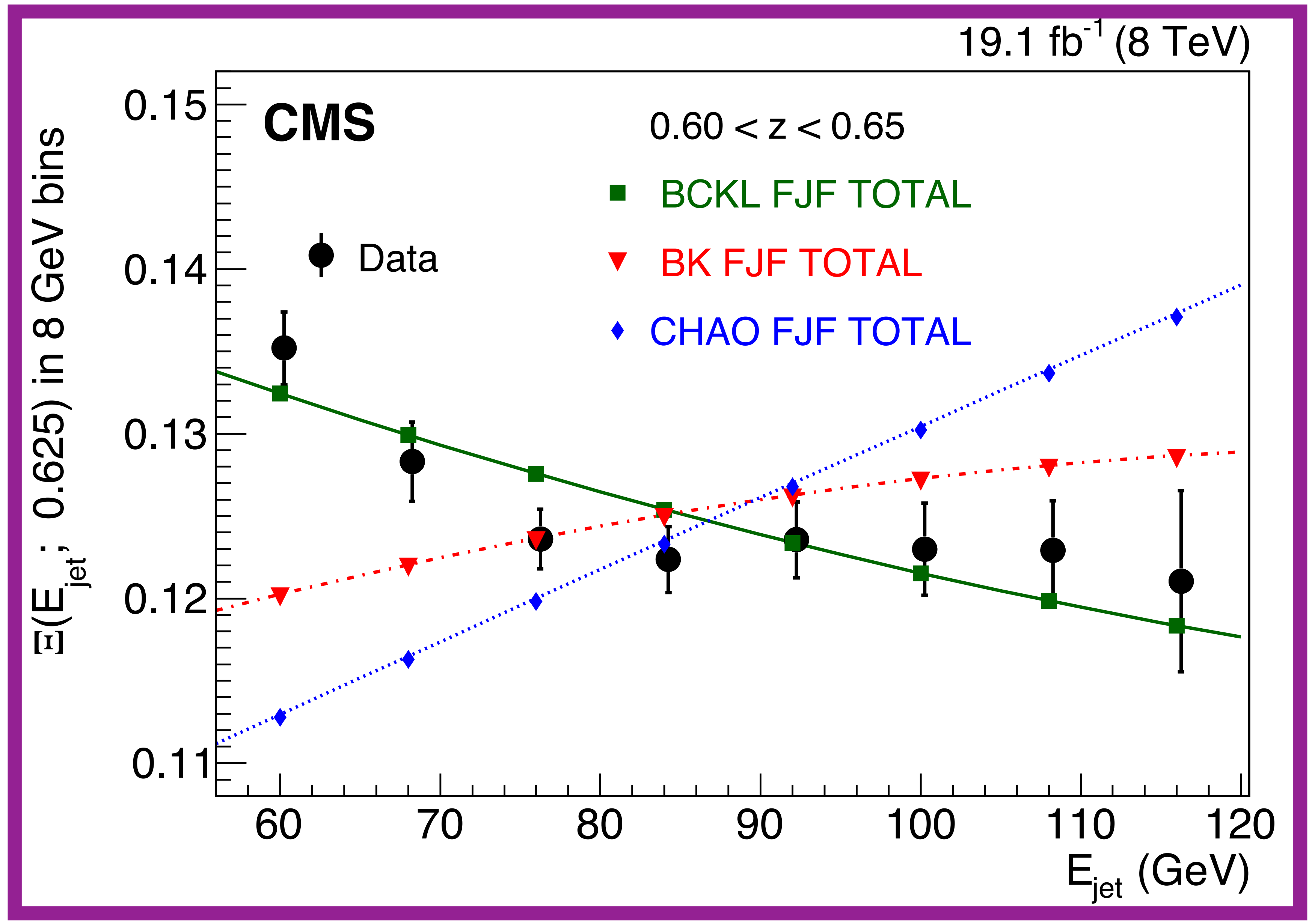
Data vs FJF total cross section predictions

- **Considered 3 z_1 values,** centres of z subregions with Δz = 0.05 from the measurement region 0.3 < z < 0.8.:
  - 0.425, 0.525, and 0.625
  - in these subregions FJF terms have different jet energy distributions for a given LDME parameter set.





- The data uncertainties include the statistical and systematic components added in quadrature.
- The normalisation theoretical uncertainty is negligible compared to the experimental uncertainty



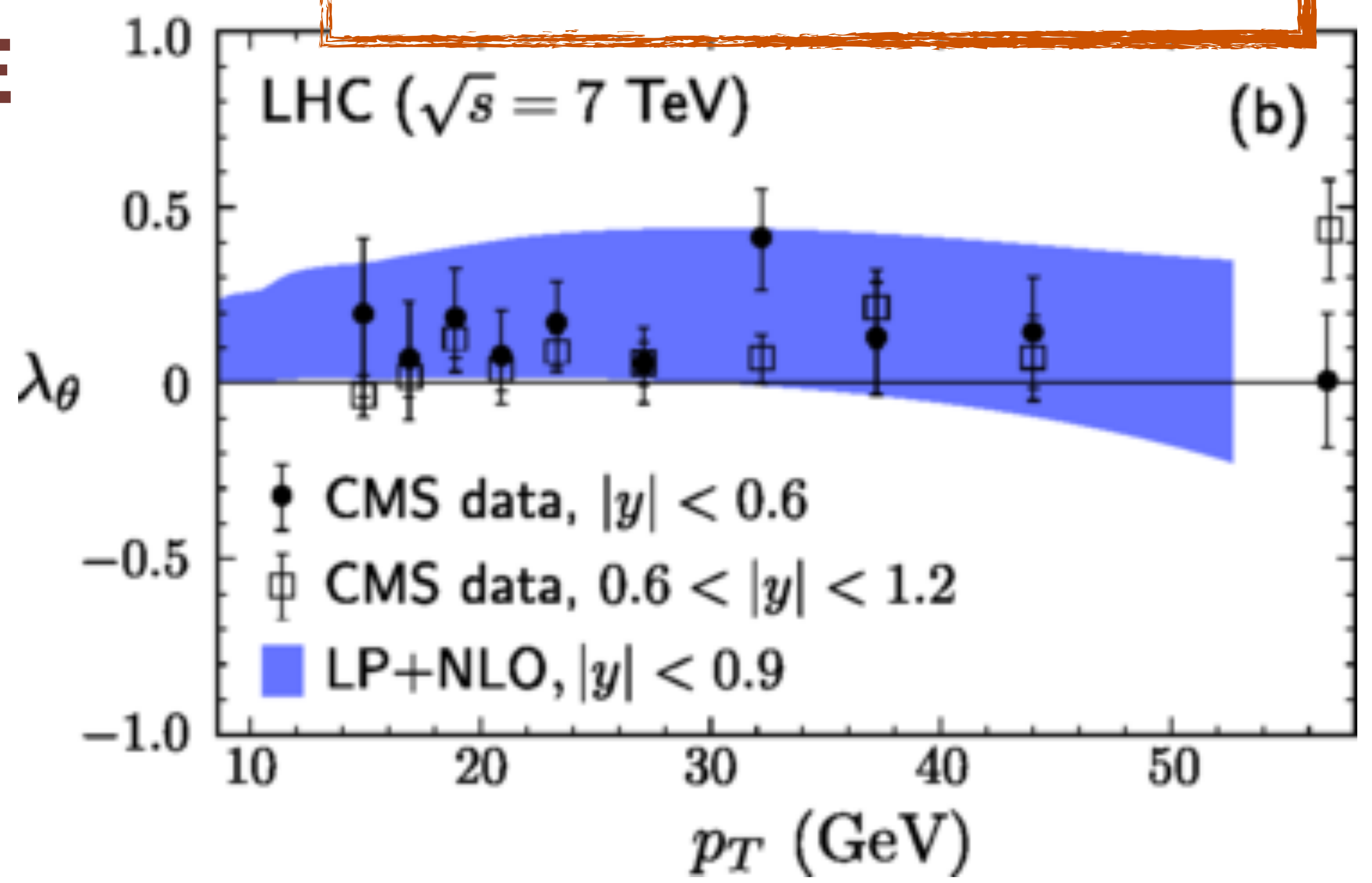
Comparison of results

- χ^2 values calculated to match data and theory.
  - a priori decision of considering an acceptable match for χ^2 p-value > 0.1 %

	0.425	0.525	0.625
BCKL	22.2 (0.23%)	11.0 (14%)	10.7 (15%)
BK	59.6 (<0.001%)	60.1 (<0.001%)	64.0 (<0.001%)
Chao	267 (<0.001%)	96 (<0.001%)	164 (<0.001%)

- **In all three z_1 ranges, only the FJF predictions with BCKL LDME parameters match data.**
  - developed from a completely different data set (inclusive hadronic production data with $p_{J/\psi}$ > 10 GeV)
  - known to predict small J/ψ polarisation, in agreement with experiments

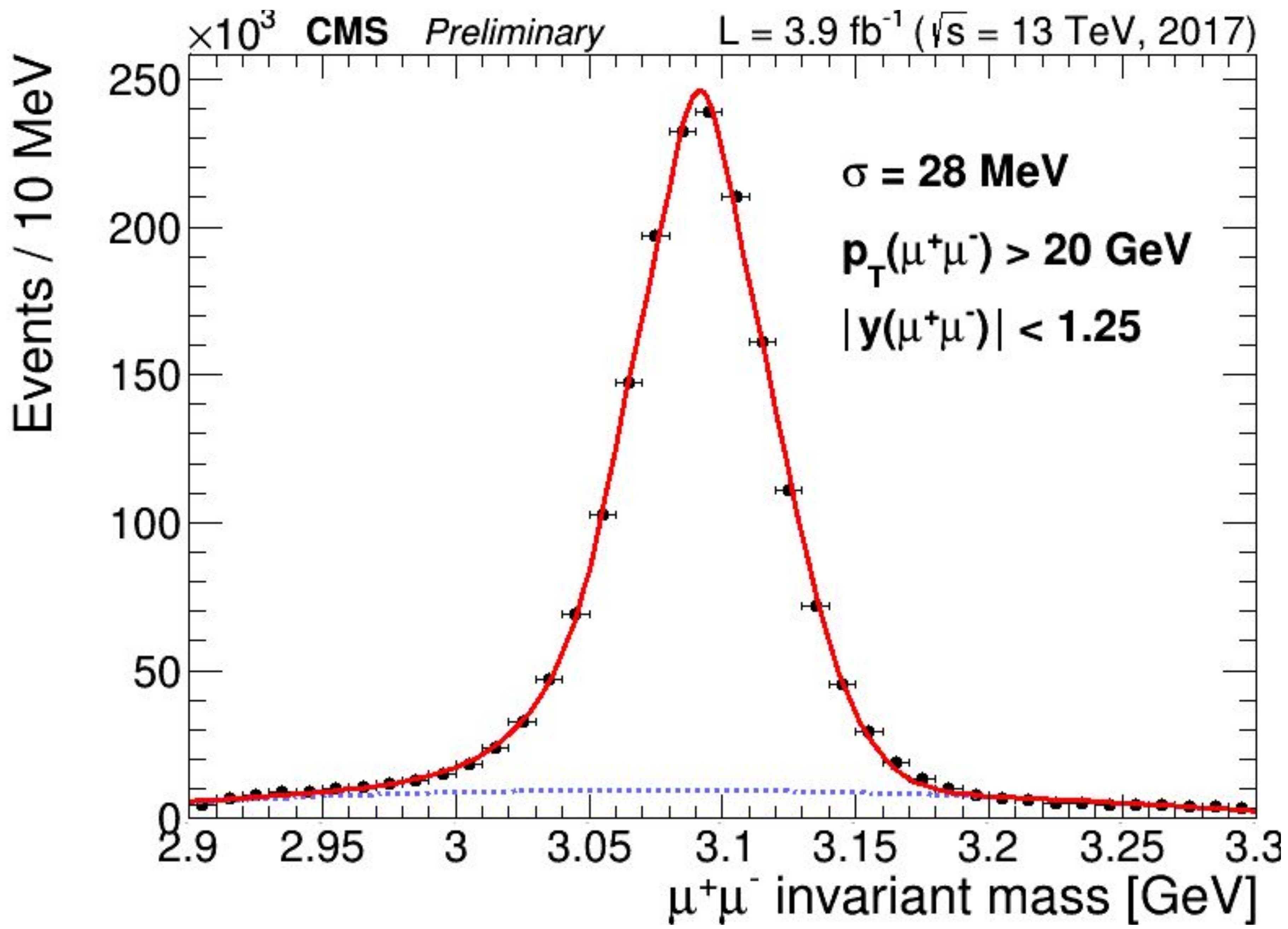
Phys. Rev. Lett. 113 (2014) 022001



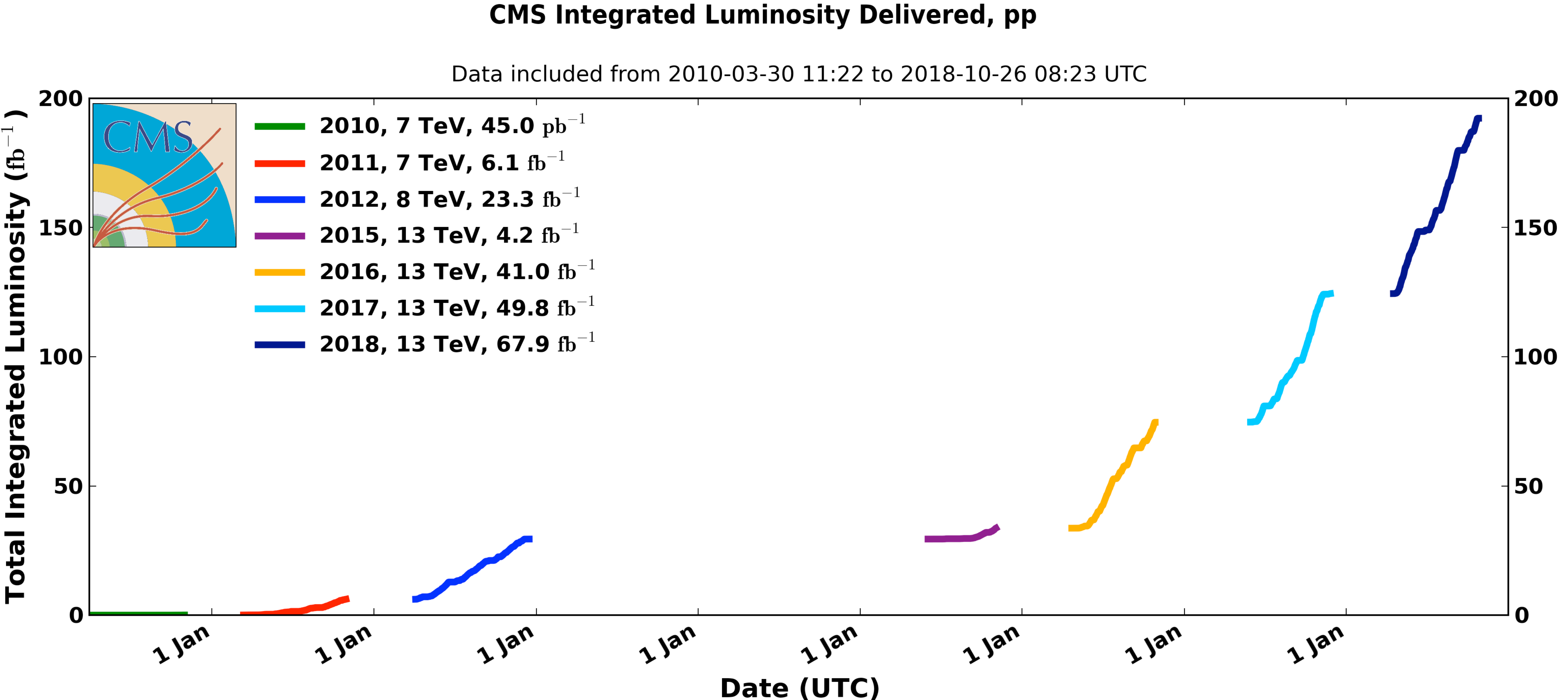
Summary

- **CMS has produced important results correlating Quarkonia with event activity in pp collisions**
  - **For Y(nS) production vs *Multiplicity***
    - A significant decrease of the exited over ground state ratio for Bottomonium was observed in pp with 2011 CMS data.
    - The decrease is stronger at lower Y(nS) p_T
    - The decrease is linked to the UE
      - No effect found from Y(nS) isolation
      - Decrease disappears for jetty events
  - **For J/ψ production in jets**
    - jets found to be source of (85 ± 3 (stat) ± 7 (syst))% of the J/ψ in $E_{J/\psi} > 15$ GeV, $|y_{J/\psi}| < 1$
    - shown that FJF analysis describe J/ψ meson production from central gluonic jets and the ability to distinguish among different sets of LDME parameters
    - Data found consistent with an NRQCD treatment of the FJF process using the BCKL parameter set.

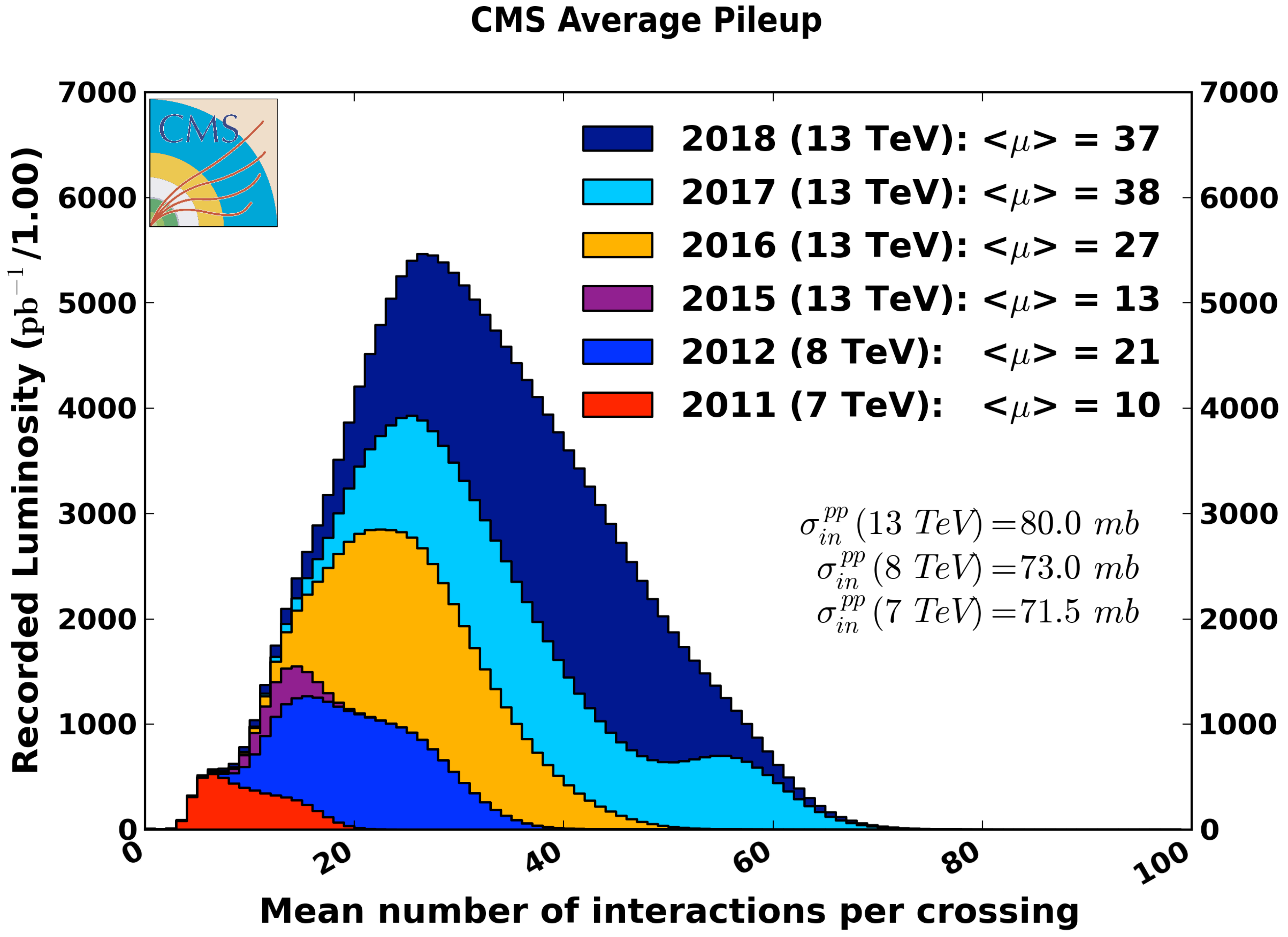
BACKUP



×10³ CMS Preliminary L = 3.9 fb⁻¹ (√s = 13 TeV, 2017)
σ = 28 MeV
p_T(μ⁺μ⁻) > 20 GeV
|y(μ⁺μ⁻)| < 1.25
Events / 10 MeV
μ⁺μ⁻ invariant mass [GeV]



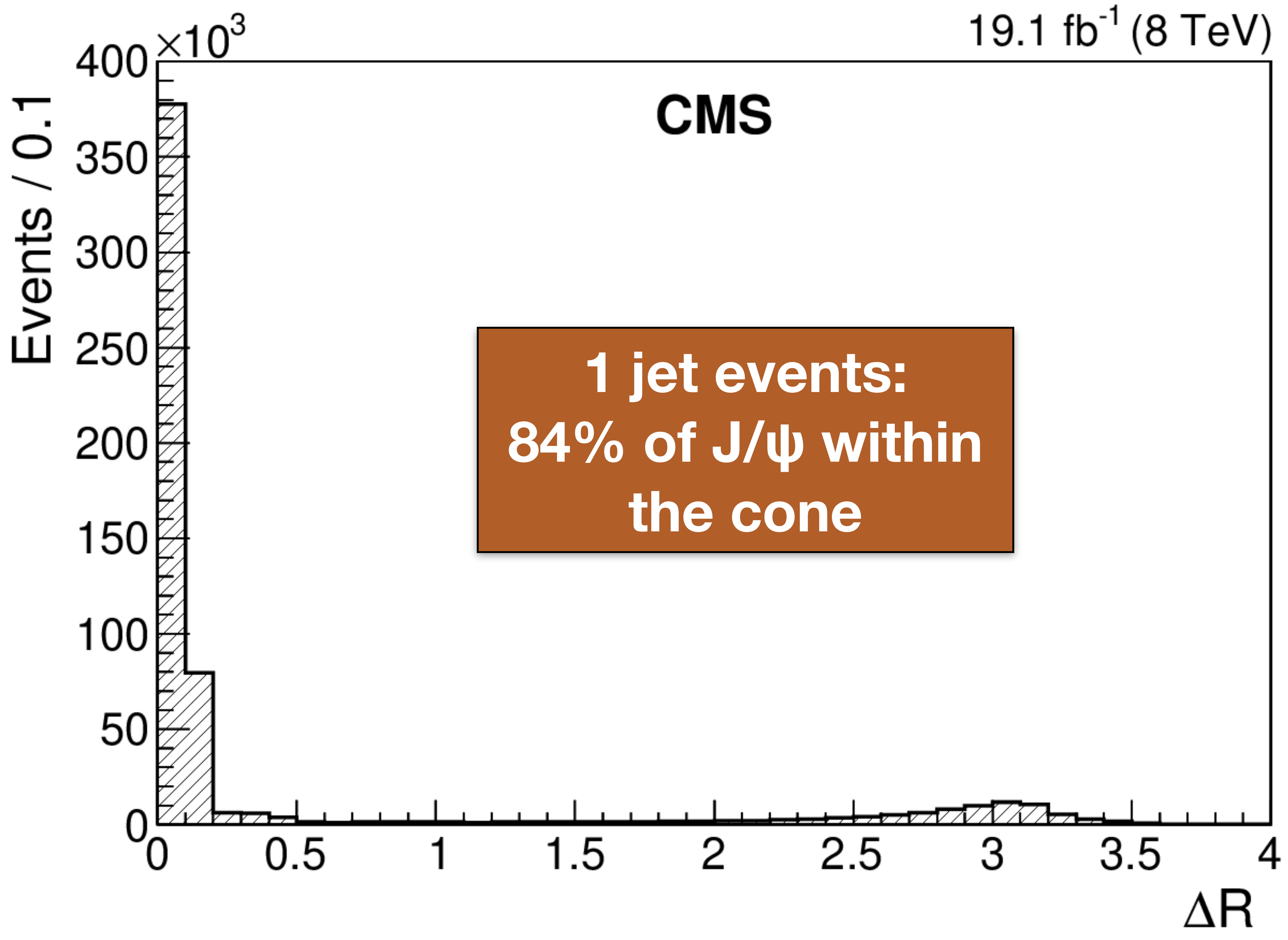
CMS Integrated Luminosity Delivered, pp
Data included from 2010-03-30 11:22 to 2018-10-26 08:23 UTC
2010, 7 TeV, 45.0 pb⁻¹
2011, 7 TeV, 6.1 fb⁻¹
2012, 8 TeV, 23.3 fb⁻¹
2015, 13 TeV, 4.2 fb⁻¹
2016, 13 TeV, 41.0 fb⁻¹
2017, 13 TeV, 49.8 fb⁻¹
2018, 13 TeV, 67.9 fb⁻¹
Total Integrated Luminosity (fb⁻¹)
Date (UTC)



CMS Average Pileup
2018 (13 TeV): <μ> = 37
2017 (13 TeV): <μ> = 38
2016 (13 TeV): <μ> = 27
2015 (13 TeV): <μ> = 13
2012 (8 TeV): <μ> = 21
2011 (7 TeV): <μ> = 10
σ_in^pp (13 TeV) = 80.0 mb
σ_in^pp (8 TeV) = 73.0 mb
σ_in^pp (7 TeV) = 71.5 mb
Recorded Luminosity (pb⁻¹/1.00)
Mean number of interactions per crossing

Absolute fraction of J/ψ in jets

- Events with >0 jets ($p_{T,jet}$>25 GeV) and observed J/ψ account for **45%** of the sample
  - Is an acceptance effect?
  - Raise $p_{T,jet}$ selection from 25 to 30 GeV
    - P(> 0 jets | J/yψ) ~ **35% but unvaried** P(J/ψ associated | 1 jet) ~ 84%
- Simple model to account for this effect:
  - The jet energy spectrum can be fit with a double-exponential function in the **constant A · ε (high-energy)** region and extrapolated to low energies
  - The **J/ψ z-probability,** when being a product of an unobserved jet fragmentation, **is described by the gluon FJFs**



$$A_i = N_i \sum_{j=1}^{55} p_j\, w(z_{ij})$$

- $\mathbf{N_i}$ = Extrapolated number of unobserved jets in E_{jet} bin i
- $\mathbf{p_j}$ = Probability to fragment into J/ψ in acceptance for each $E_{J/\psi}$ bin j (1-GeV bins from 15 to 70 GeV, taken from data)
- $\mathbf{w(z_{ij})}$ = z-probability from theory
- $\mathbf{A_i}$ = Estimated number of unobserved jets in E_{jet} bin i fragmenting into J/ψ

- **Estimated fraction of J/ψ from unobserved jets: f_{un} = (43 ± 3 stat ± 7 syst)%**
- **Estimated fraction of J/ψ from jet fragmentation: $f_{tot} = f_{obs} \cdot P + f_{un}$ = (85 ± 3 stat ± 7 syst)%**

Prompt fraction measurement

- Fit on dimuon invariant mass and pseudo-proper decay length
    - to measure prompt and non-prompt yields simultaneously
    - to disentangle the two contributions
- Pseudo-proper time measured thanks to precision tracking

$$\ell_{J/\psi} = L_{xy} \cdot m_{J/\psi} / p_T$$