Density dependent QCD effects in pp collisions

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CERN

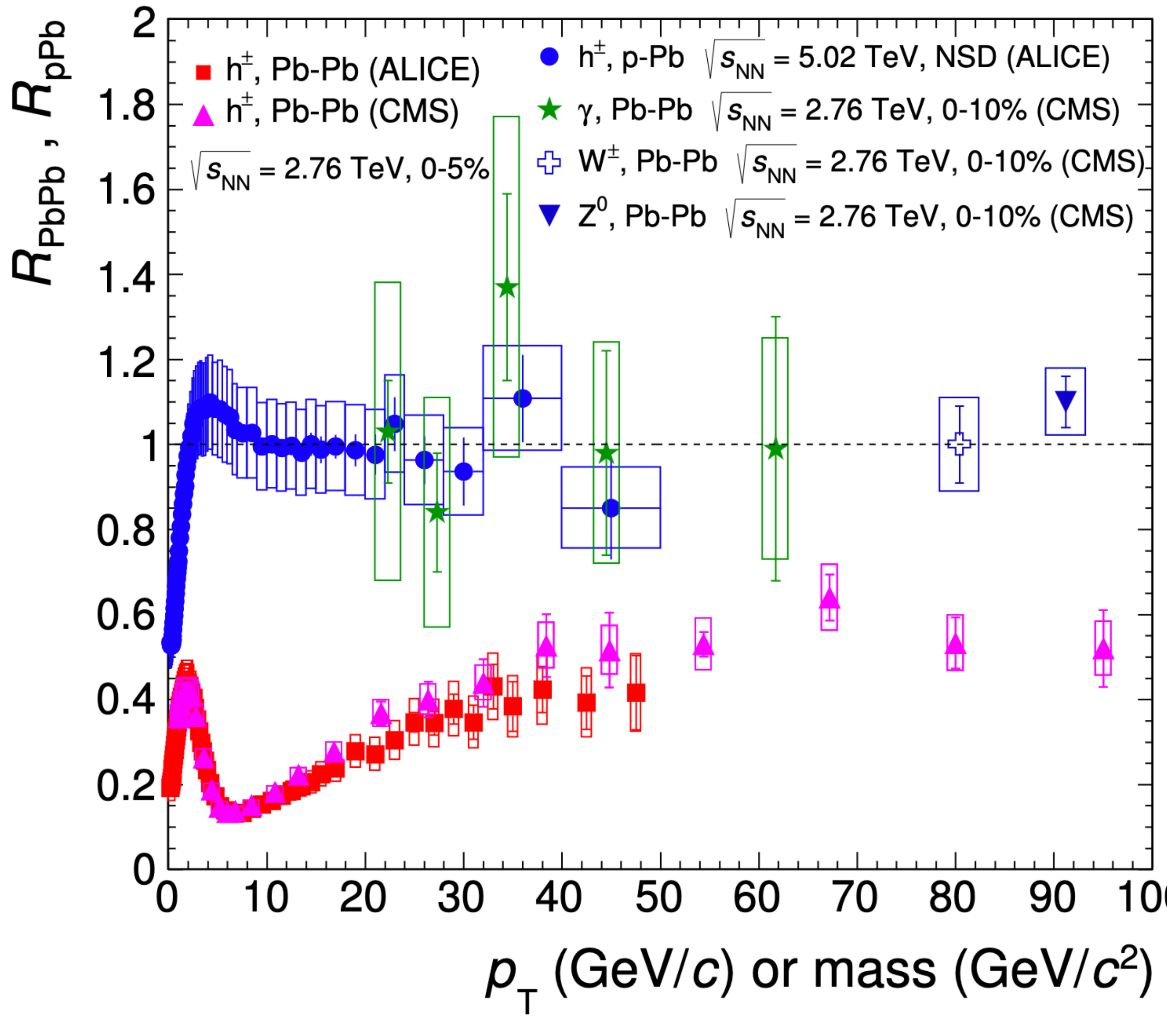
30th anniversary of China-ALICE cooperation

- … I have known Prof. Daicui Zhou even a bit longer
- Later on, pleasure to cooperate / interact with other CCNU members
    - Yaxian Mao, Xiaoming Zhang
    - Xiaowen Ren (@CERN), Lang Xu, Feng Fan, …during their PhD student time
- For the talk I concentrate on purpose on subjects that …
    - allow to expose their work in a broader context
    - and to highlight some future perspectives

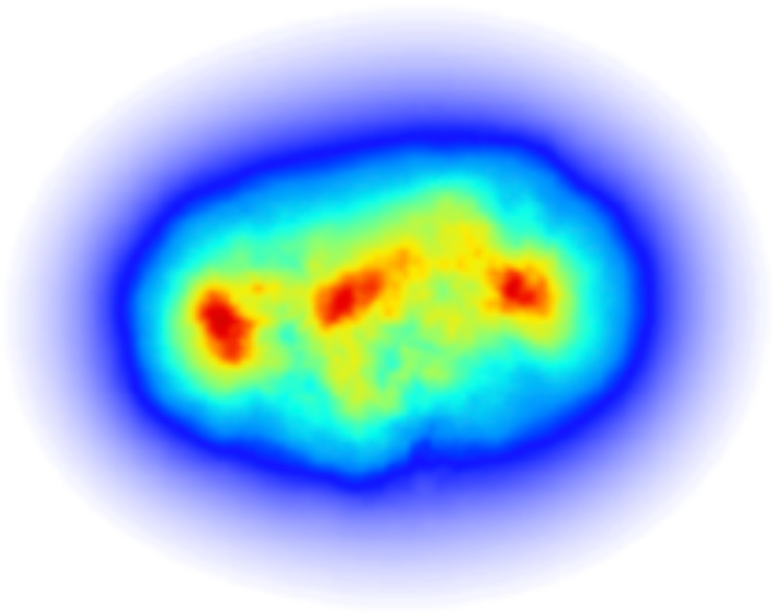
Interest in pp from Heavy Ion Physics perspective

reference system

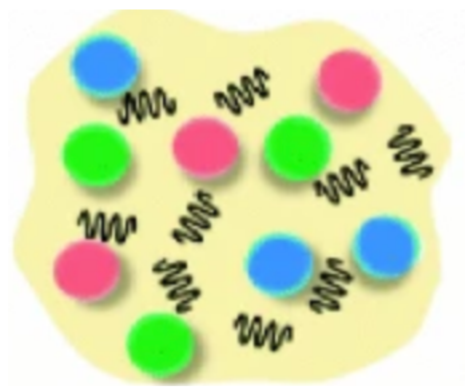
$$R_{\rm AA}(p_{\rm T}) = \frac{\frac{{\rm d}\sigma^{\rm cent}_{PbPb}}{{\rm d}p_{\rm T}}}{N_{\rm col}\frac{{\rm d}\sigma^{\rm cent}_{pp}}{{\rm d}p_{\rm T}}}$$



laboratory for sub-fm energy density fluctuations

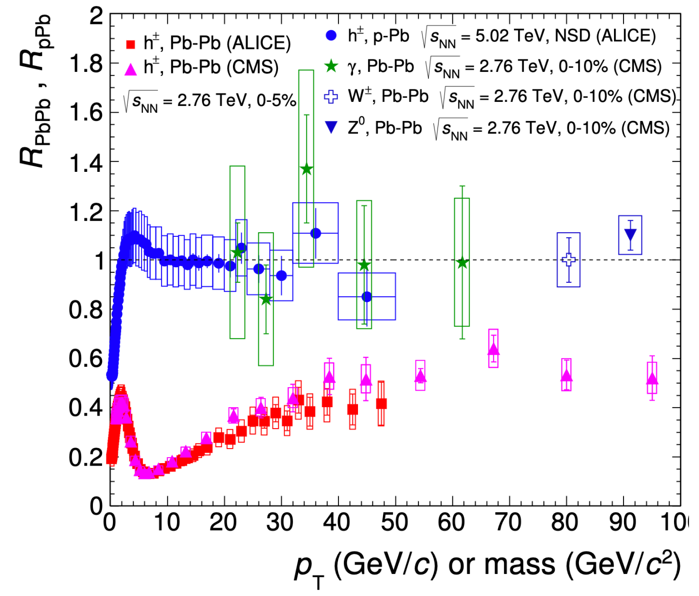


laboratory for high-density QCD



$\epsilon \approx$ 10 GeV/fm^3 for 10x mean multiplicity, similar to Pb-Pb

Heavy Ion Physics and QGP

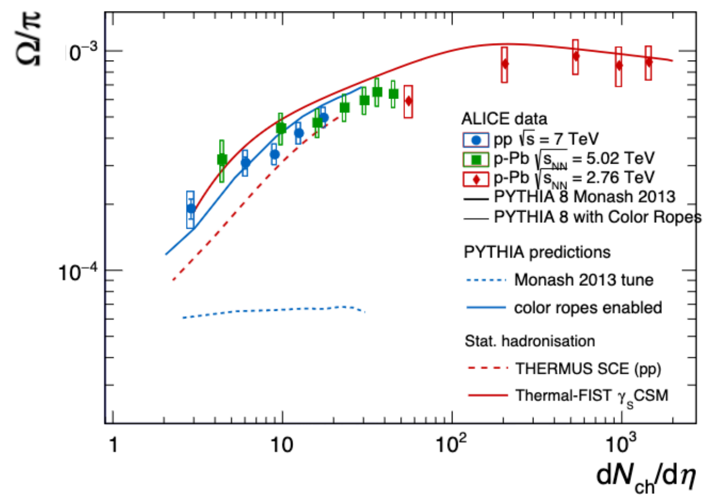


pp as a reference system

enhancements even at lowest multiplicity

strange and heavy flavor baryons

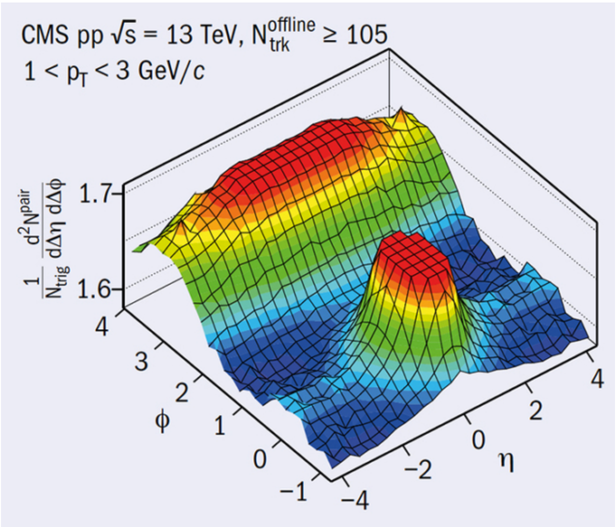
challenge: yield modifications of hard probes

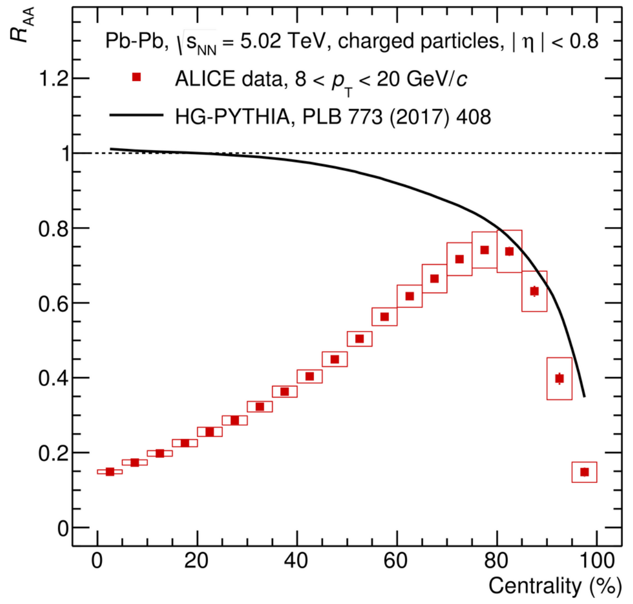


Underlying Event

hard-soft correlations

collectivity signals





insights for centrality determination (N_{coll})

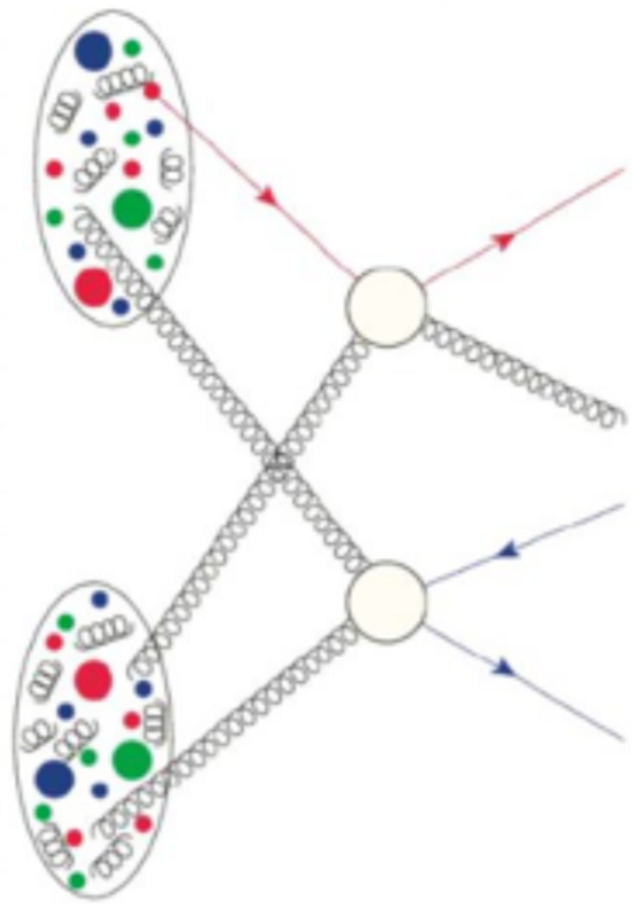
in p-Pb and Pb-Pb

High density pp at LHC from pQCD perspective

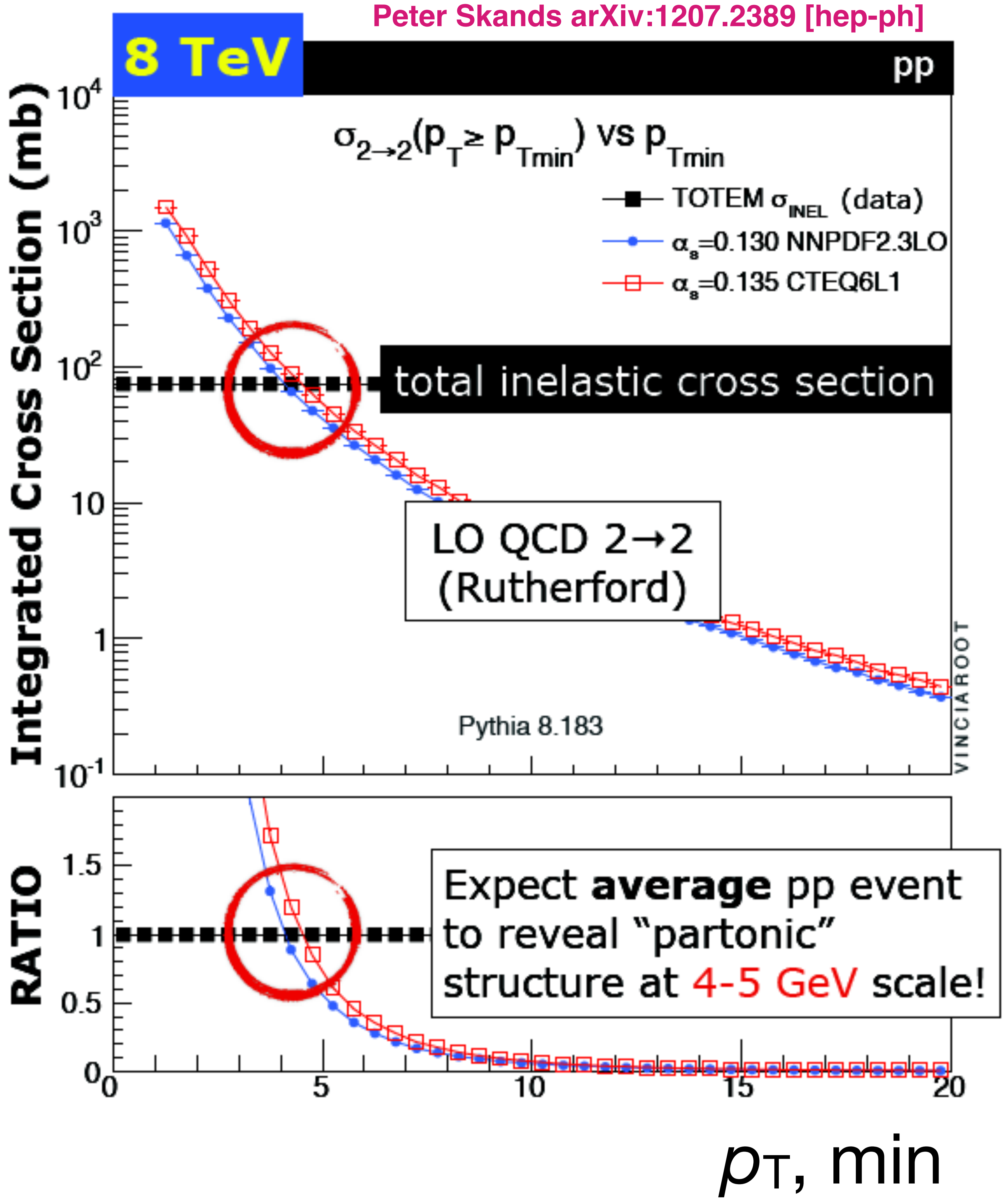
- High initial densities can be produced by **multiple parton-parton interactions (MPI)**
- Straightforward interpretation of pQCD $\sigma_{2\to 2} > \sigma_{tot}$
- Number of 2→2 scatterings per event assuming naïve **factorization**:

$$\langle n_{2\to 2}\rangle = \frac{\sigma_{2\to 2}}{\sigma_{tot}}$$

$$P_n = \frac{\langle n_{2\to 2}\rangle^n}{n!} e^{-\langle n_{2\to 2}\rangle}$$



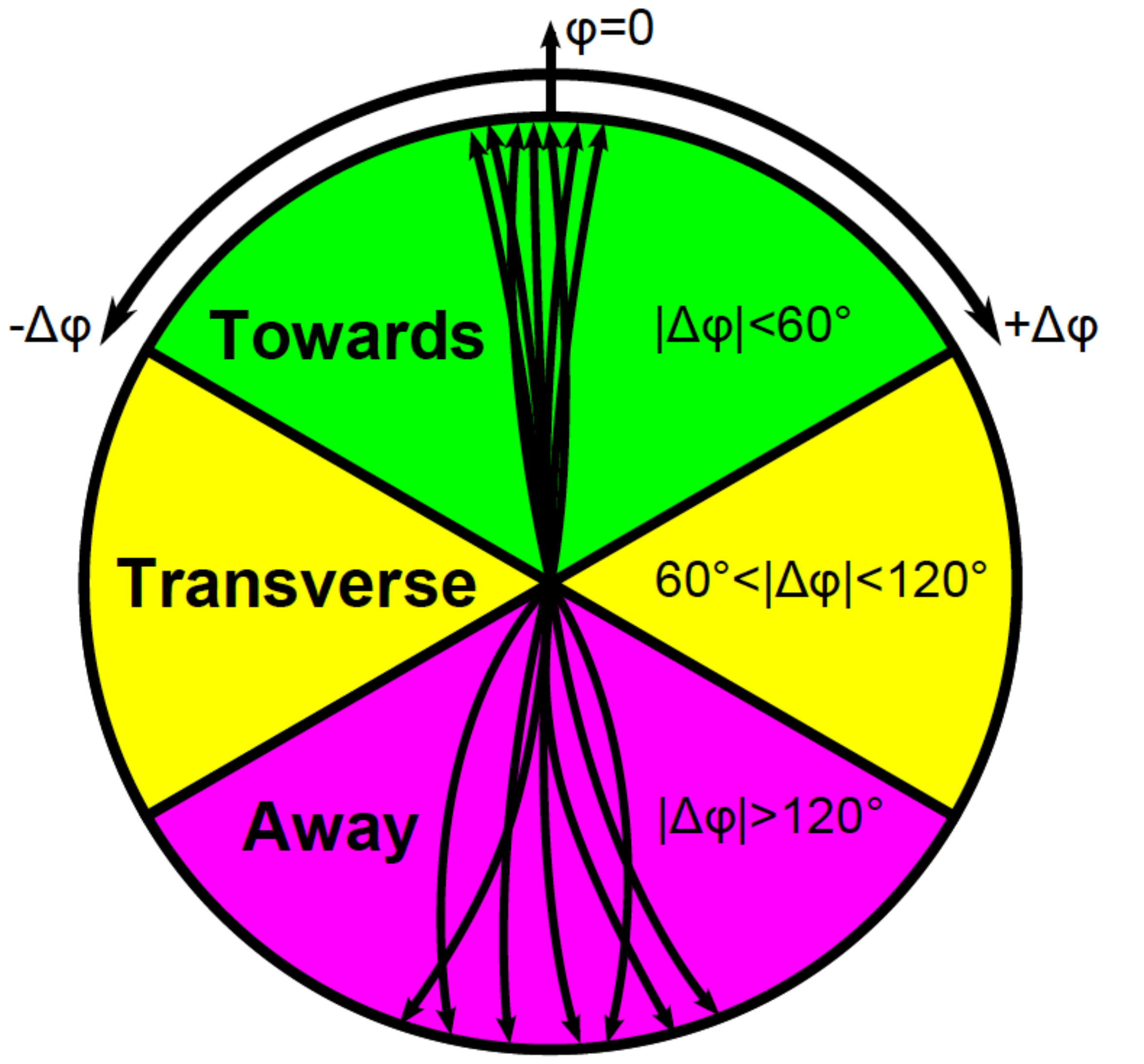
Integrated hard cross-section above cut-off p_{Tmin}



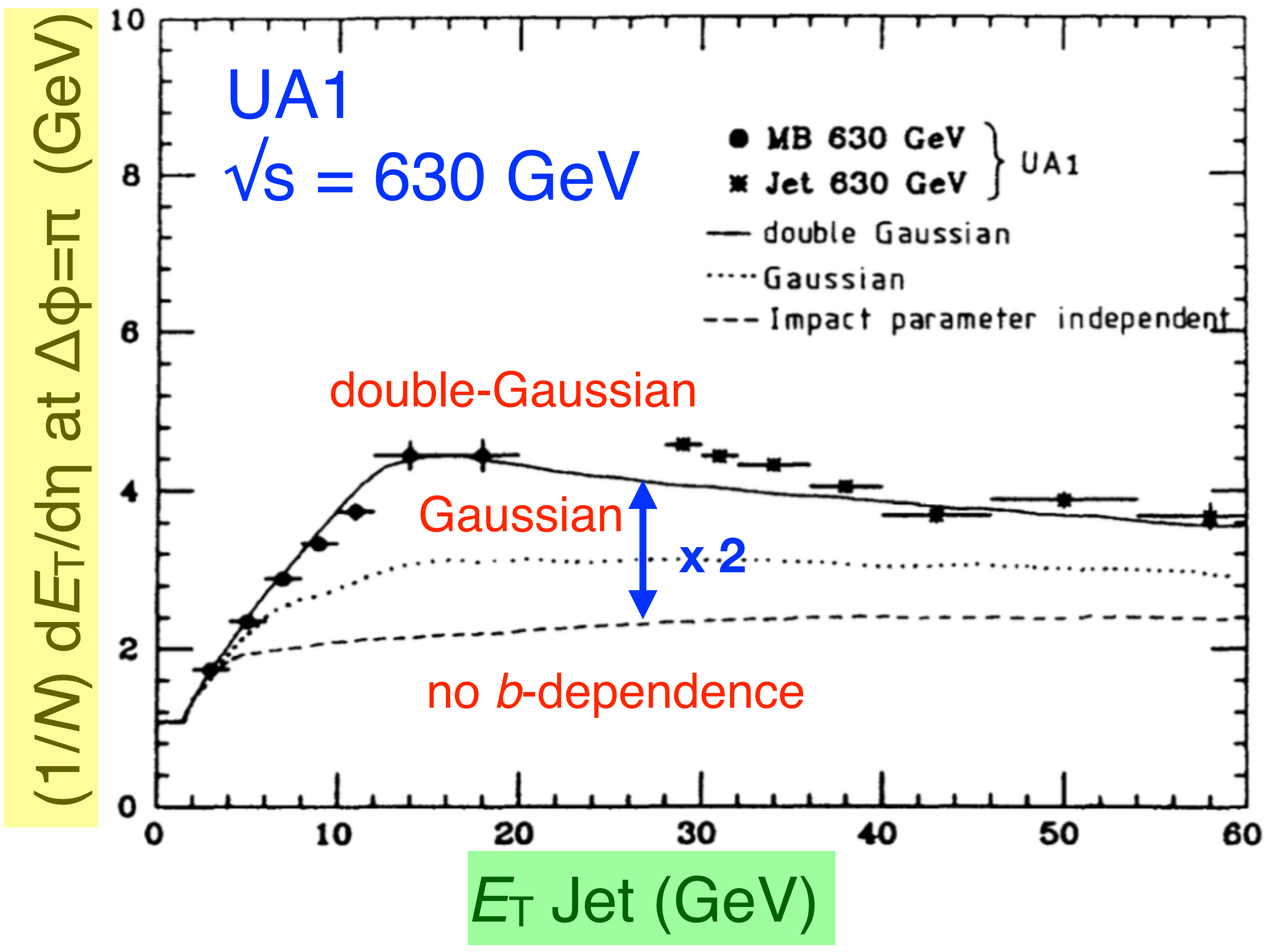
At LHC multiple hard scatterings at perturbative scales

~5 per minimum bias collision

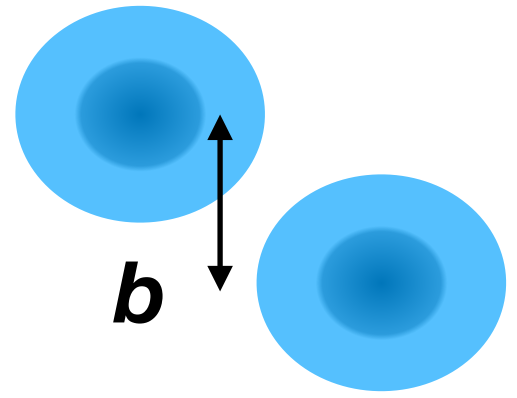
Jet Pedestal effect and pp centrality



Transverse Region Underlying Event (UE) dominated



"jet pedestal"



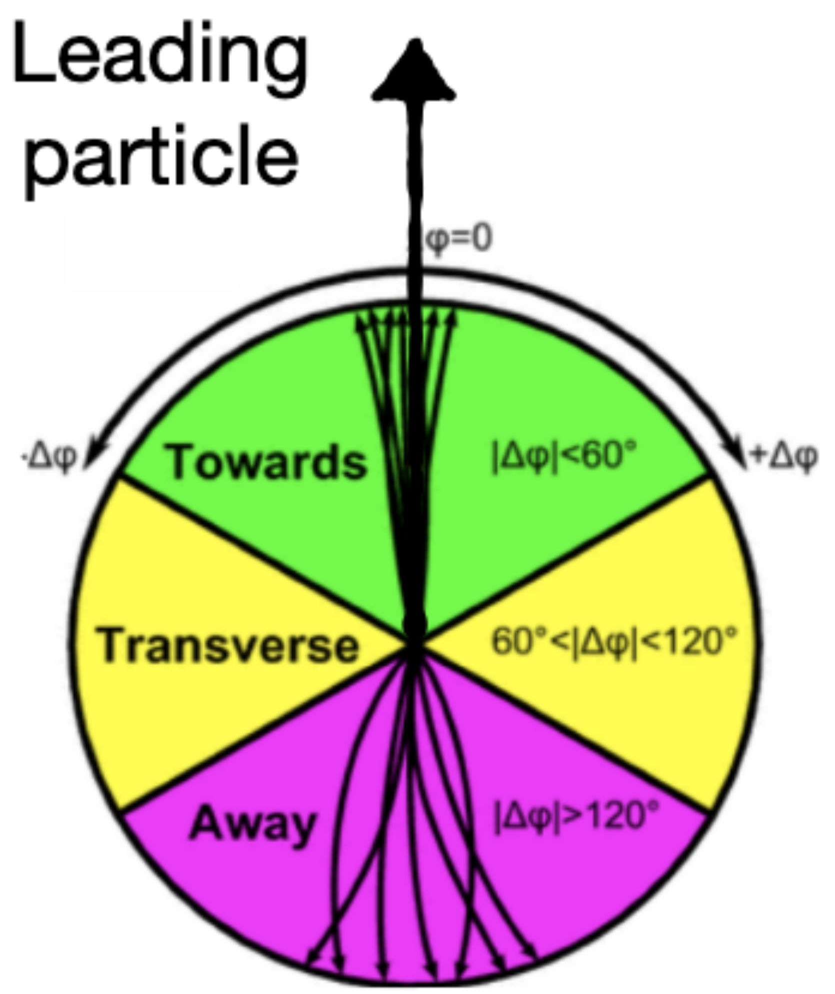
Explained by number of hard scatterings depending on matter overlap:

$$\langle n^{\text{hard}} \rangle = T_{\text{pp}}(b)\sigma_{\text{hard}}$$

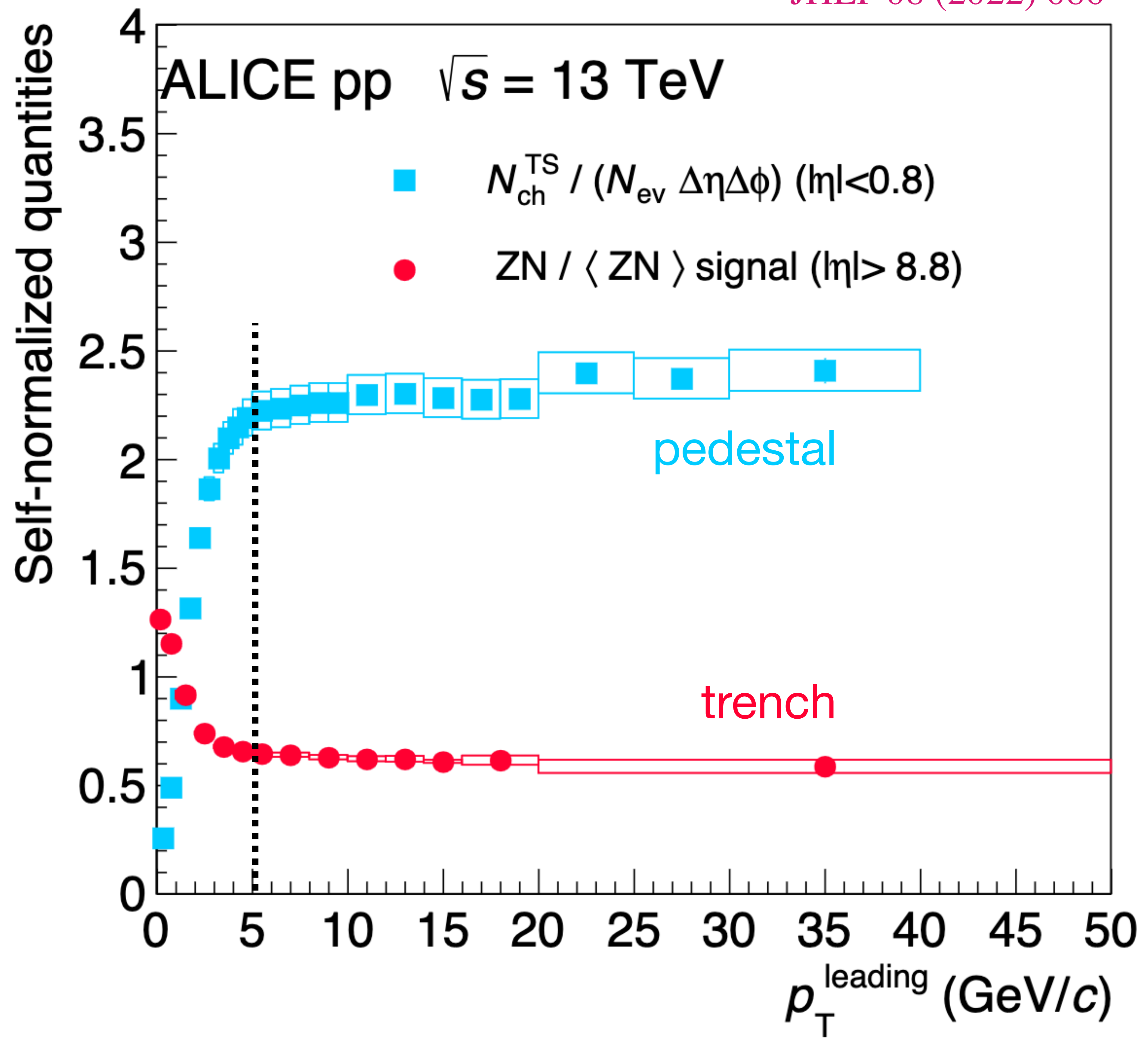
- High p_T objects bias towards smaller b where probability for additional interactions is larger → increased UE activity.
- Constrain in MPI models radial parton distribution in proton

Pedestal becomes trench for large rapidity separation

- Correlation between 0-deg energy and leading particle p_T



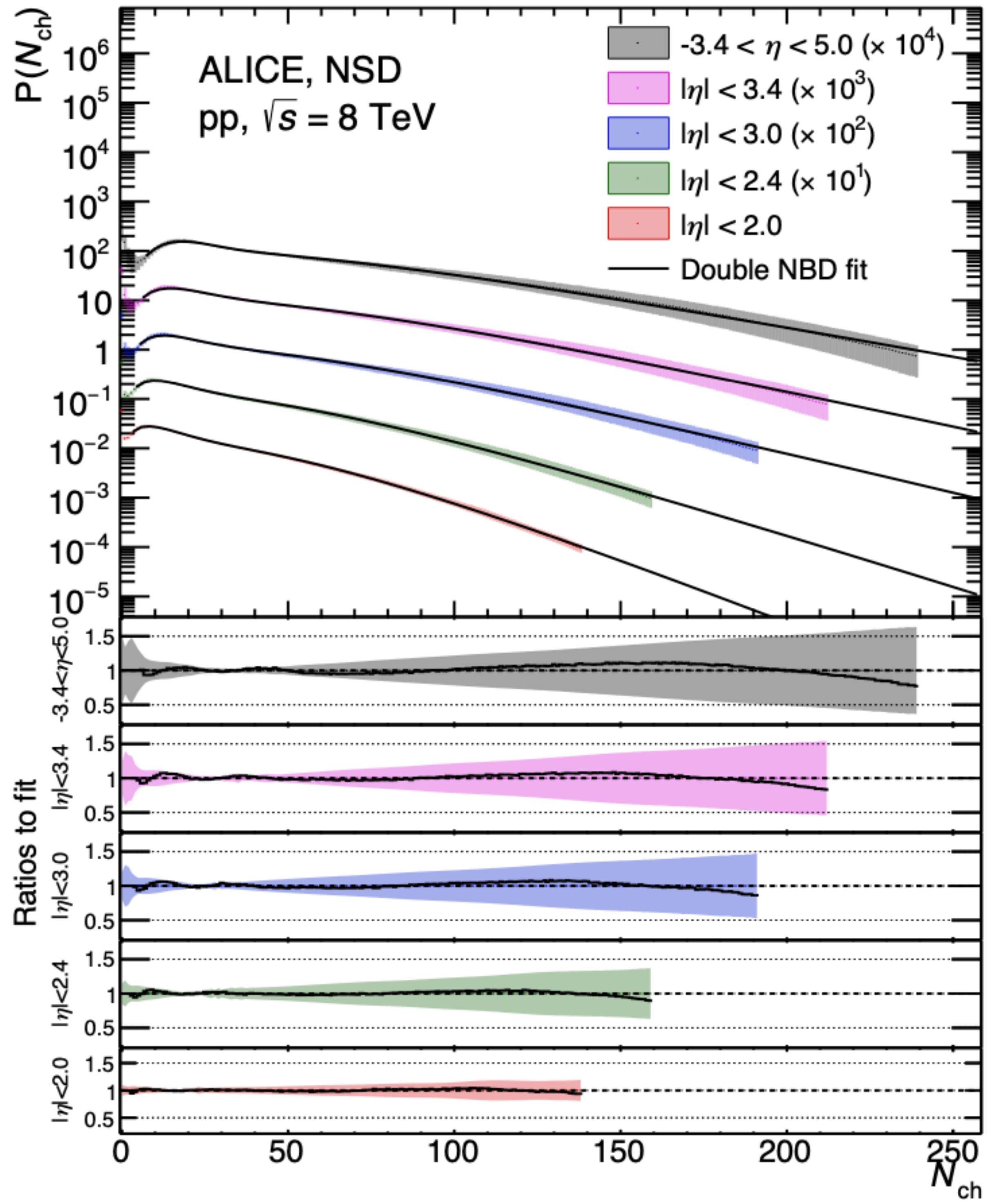
JHEP 08 (2022) 086



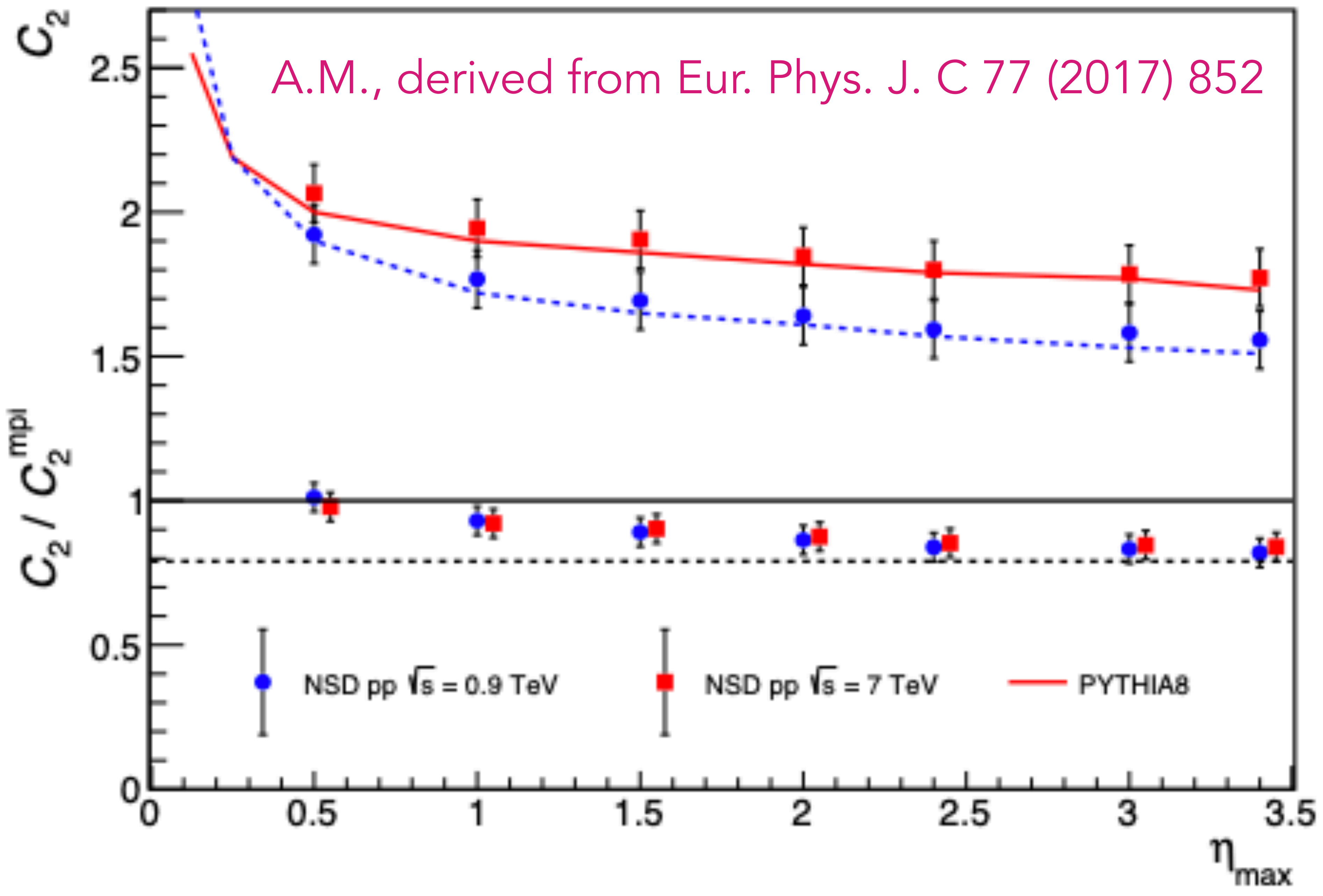
pedestal height rel. to Minimum Bias ≈ 2.4

Correlations of signals separated by 8 units of rapidity show that an initial state effect is observed

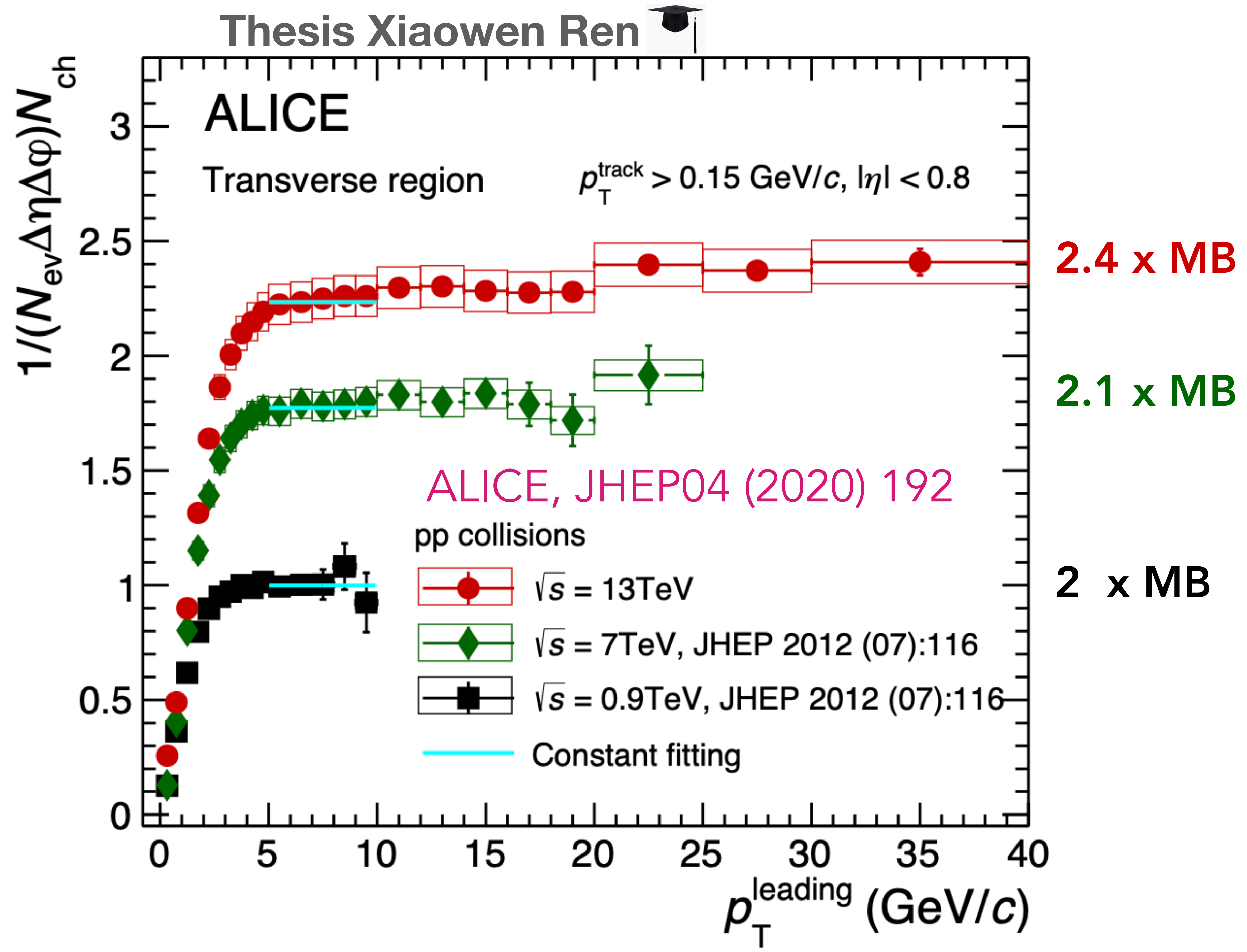
Pedestal and multiplicity fluctuations are related



normalized moments



normalized pedestal height



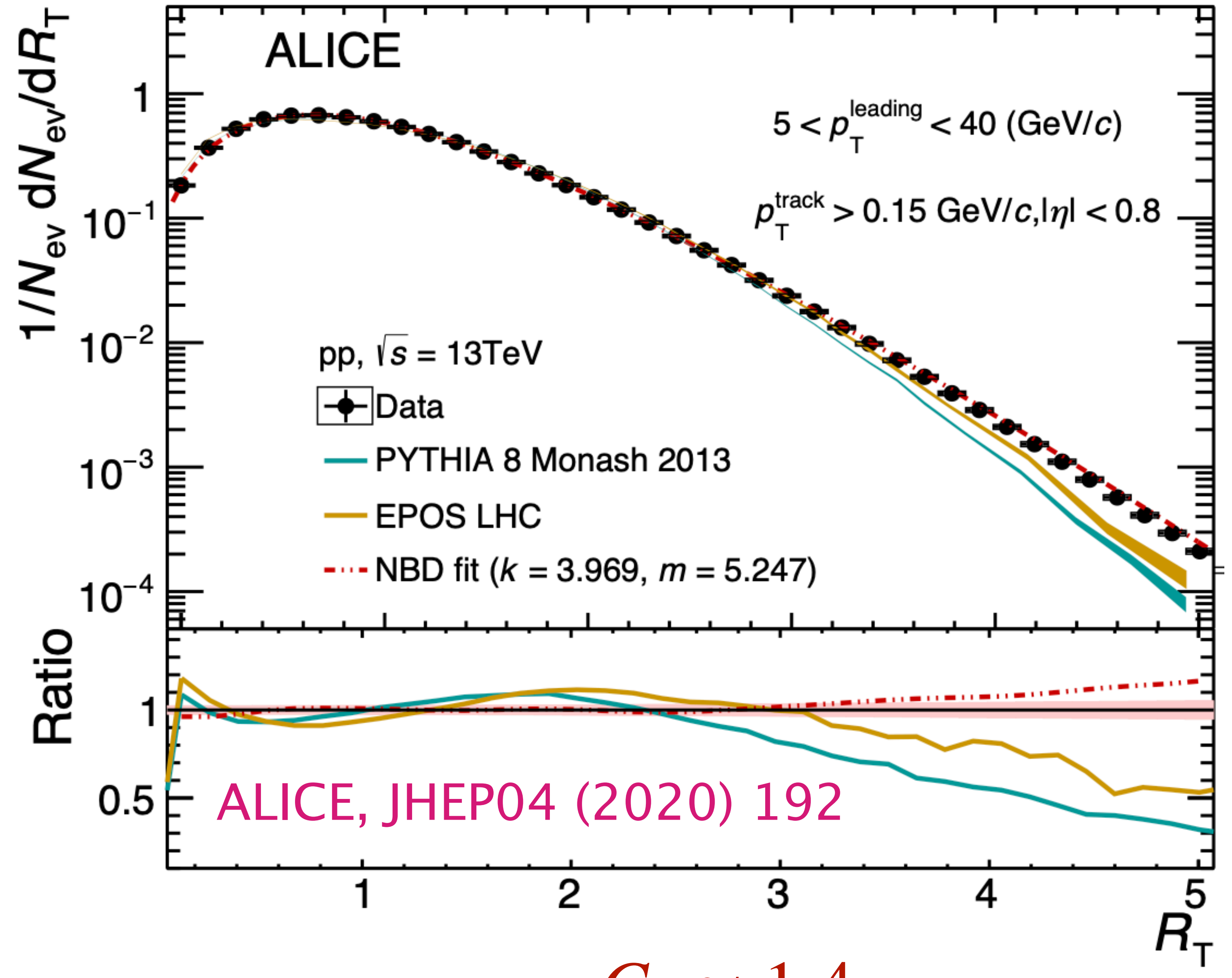
- Impact parameter variations also determine shape of multiplicity distribution (“shoulder”)
  - characterised by normalised second moment C_2
- Jet Pedestal and multiplicity fluctuations increase with $\sqrt{s}$
- They are similar in size, when properly normalised
- Relation via impact parameter fluctuations

$$C_2 = \frac{\langle N^2 \rangle}{\langle N \rangle^2} = \text{ normalized jet pedestal} \approx 2$$

Fluctuations within the transverse region

- Leading particle > 5 GeV/c restricts impact parameter variation to small values
  - => reduced multiplicity fluctuation in transverse region wrt MinBias
  - from Pythia 8: $C_2^{pedestal} \approx C_3^{MPI}/(C_2^{MPI})^2 \approx 1.4 < C_2^{MB}$

Multiplicity fluctuations inside pedestal region

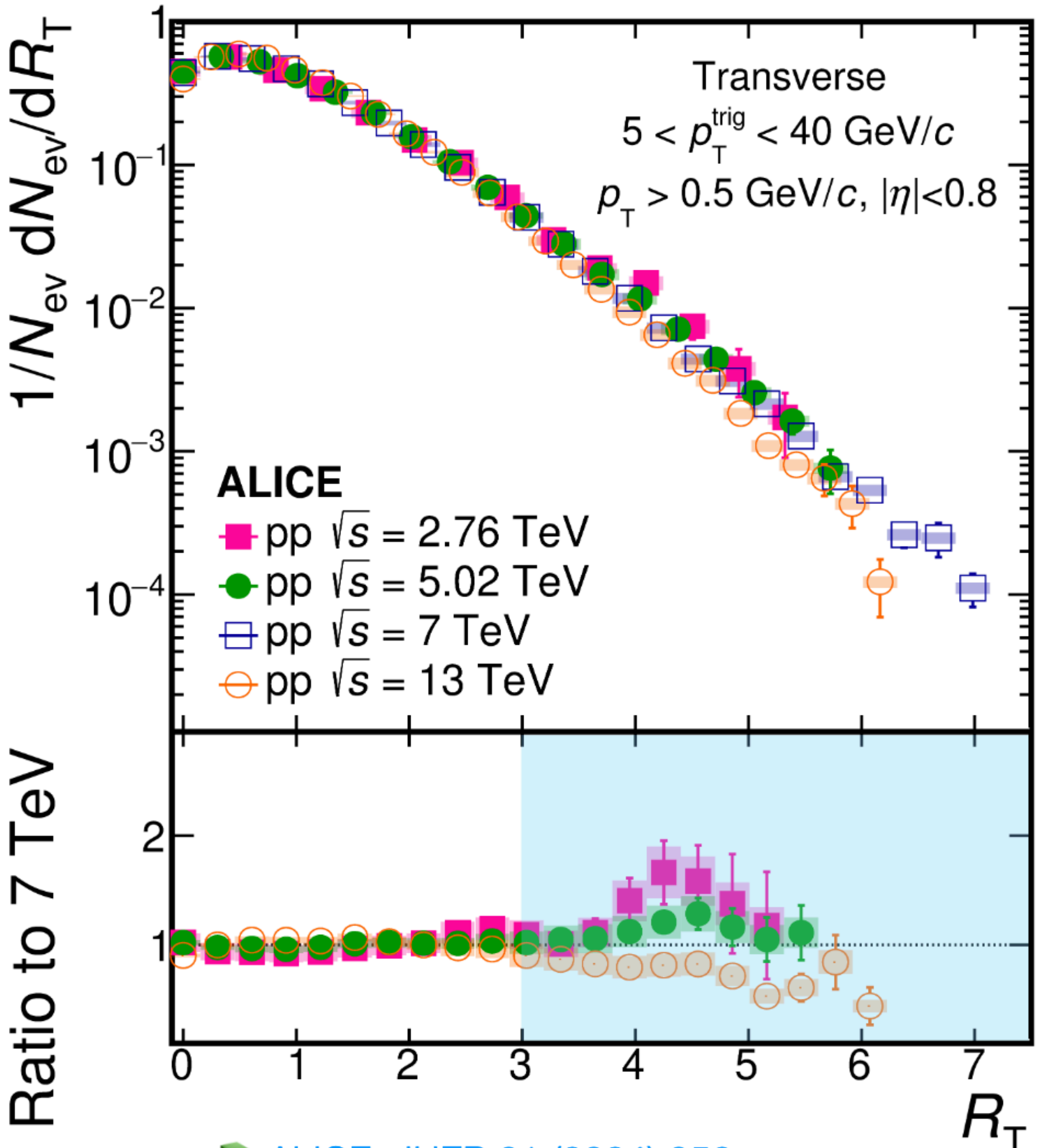


$C_2 \approx 1.4$

and well described by one NBD

Thesis Xiaowen Ren

$R_T = N_T/\langle N_T \rangle$



ALICE, JHEP 01 (2024) 056

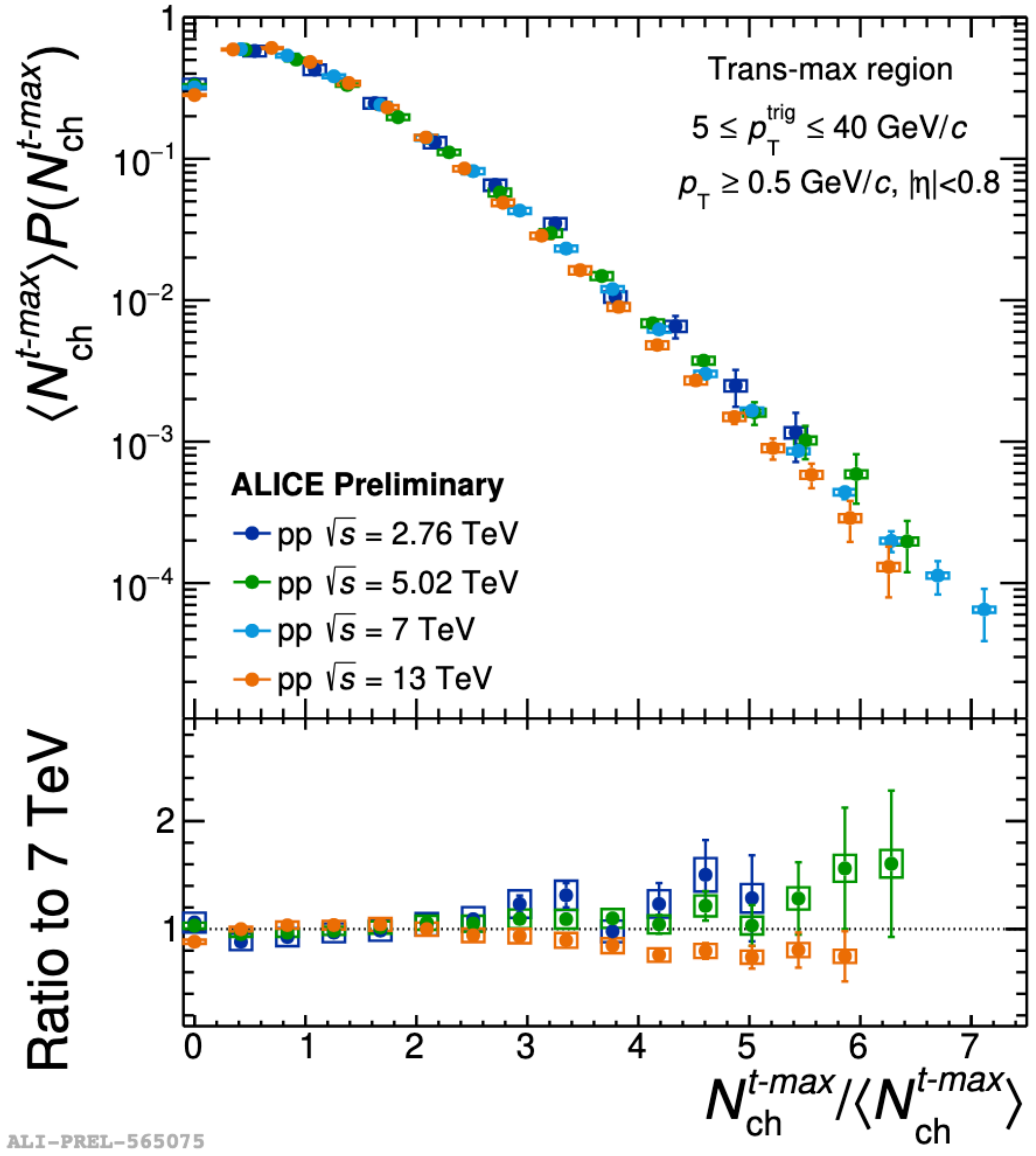
Thesis Feng Fan

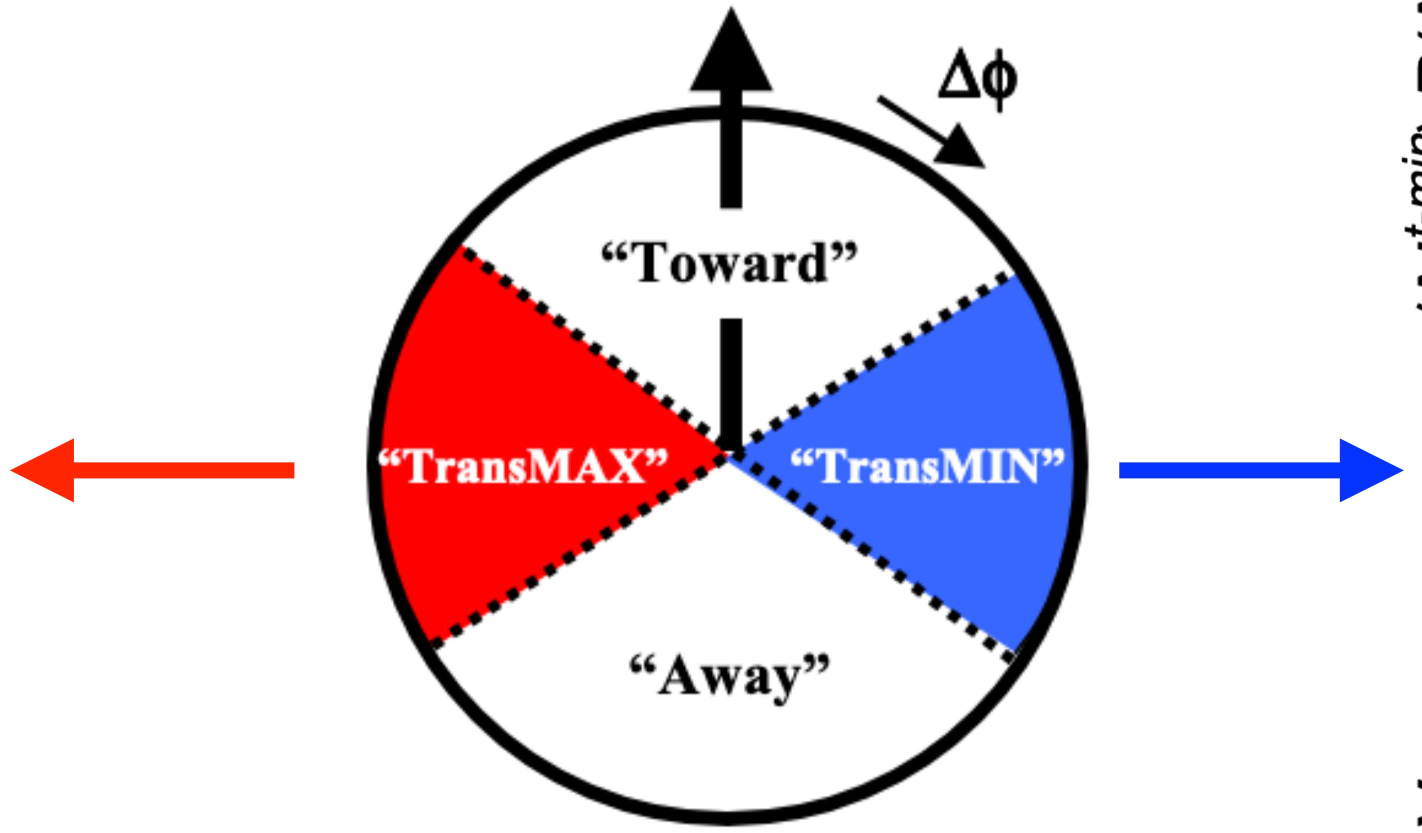
Higher sensitivity to ISR/FSR for lower $\sqrt{s}$

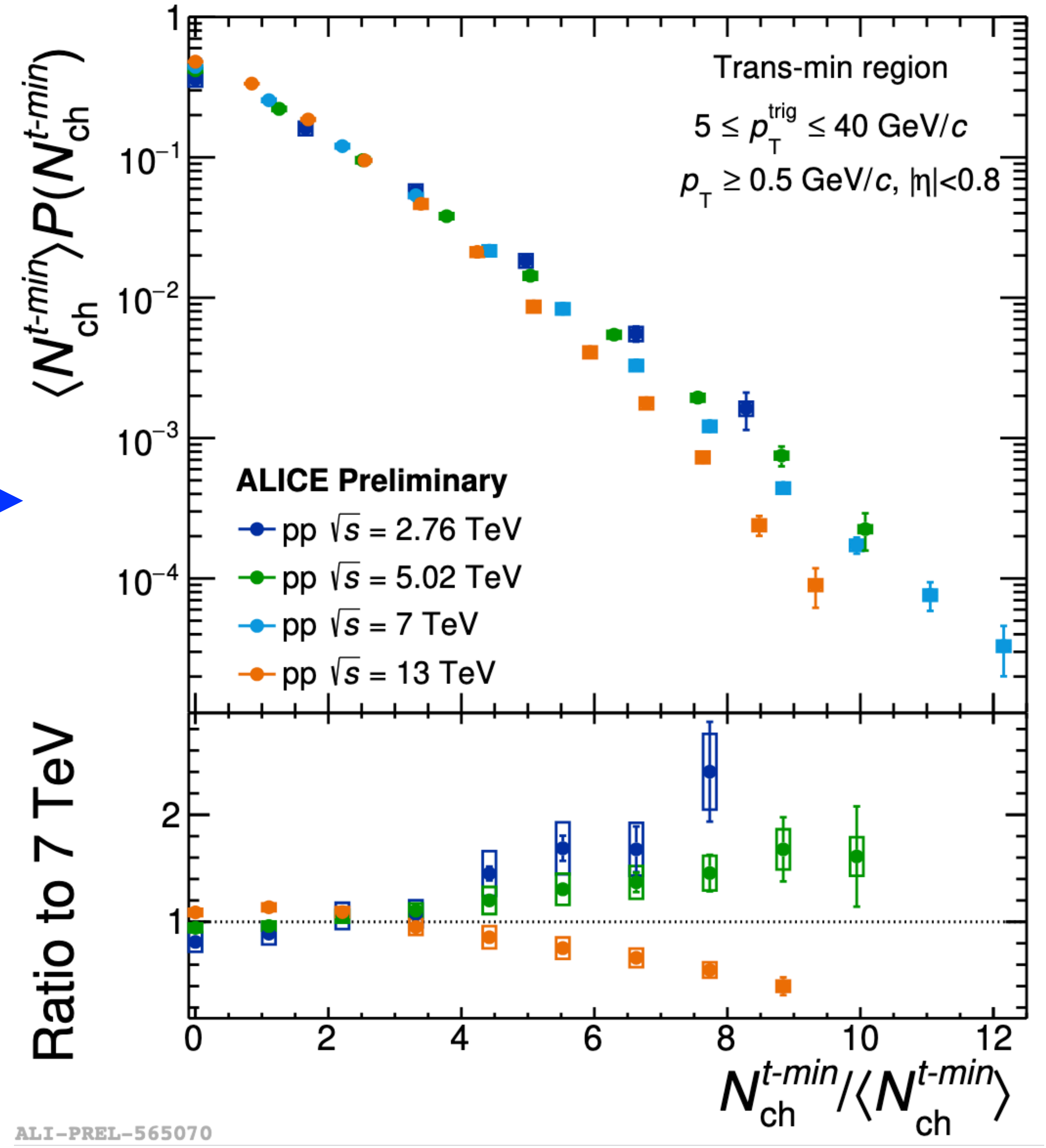
EbyE Separation into TransMIN / TransMAX Region

Thesis Feng Fan

using KNO scaling variables

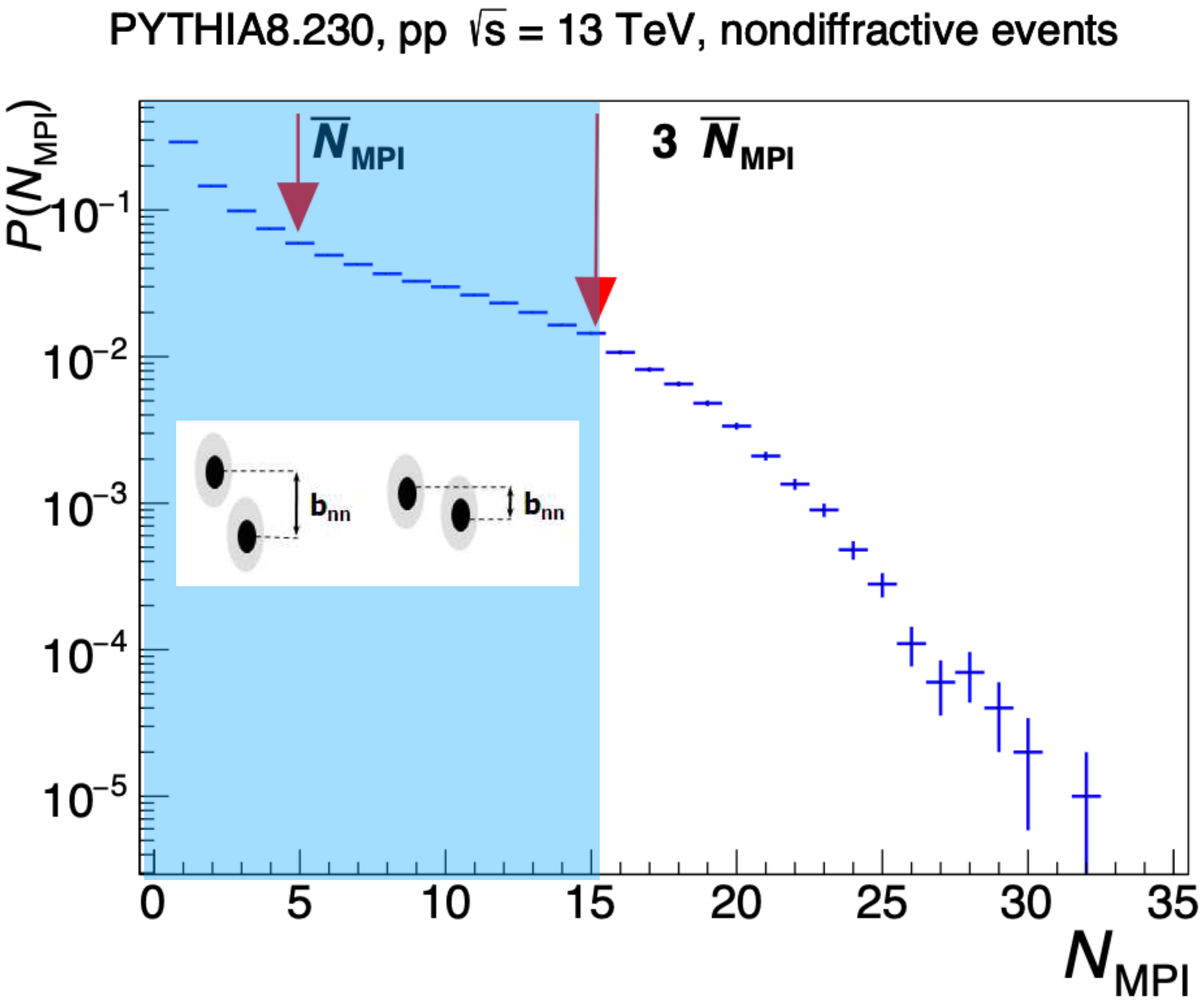






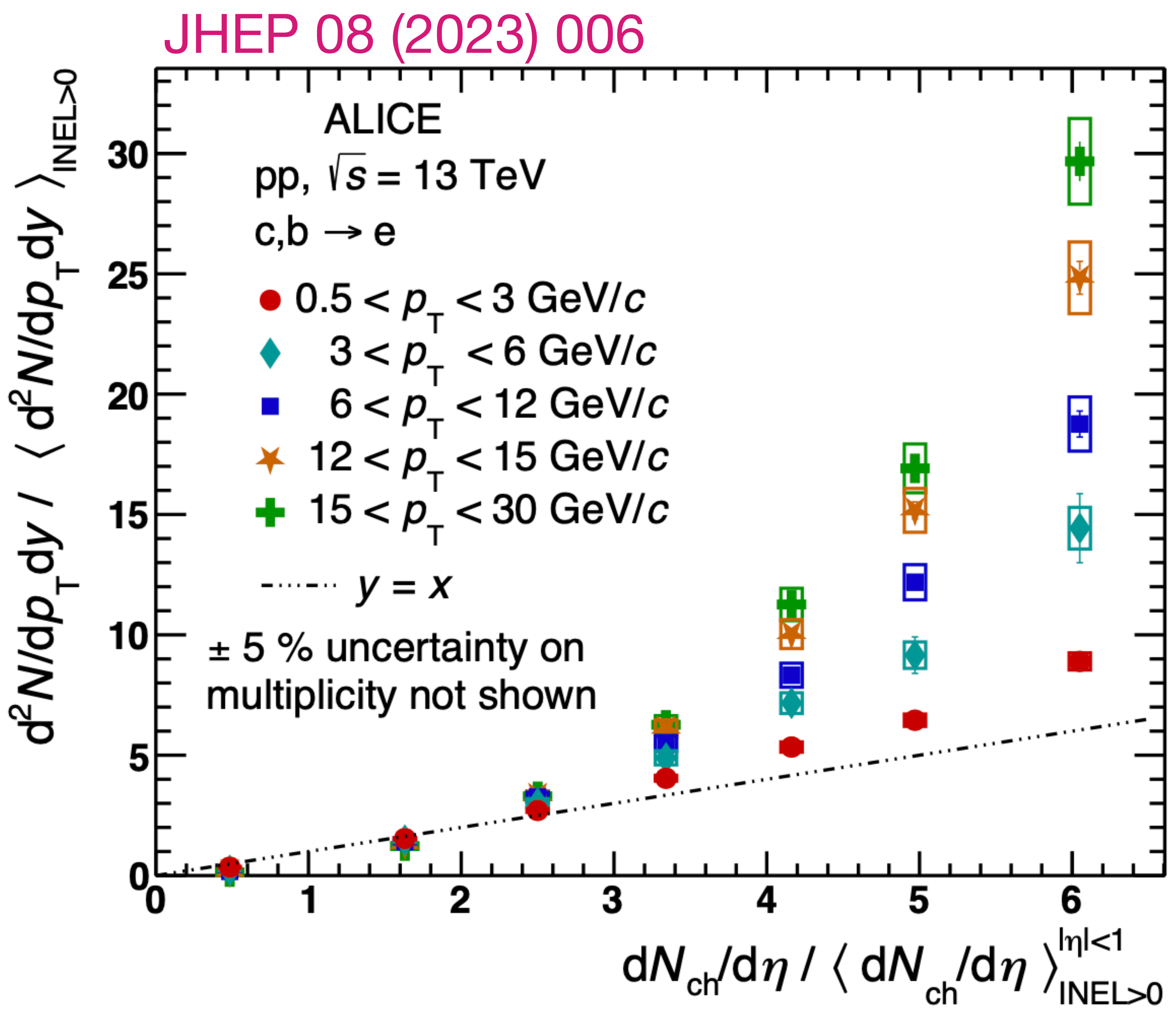
- Expect larger sensitivity to hard contribution (ISR/FRS) in the MAX region
- KNO scaling holds for both up to $N/\langle N\rangle \approx 4$

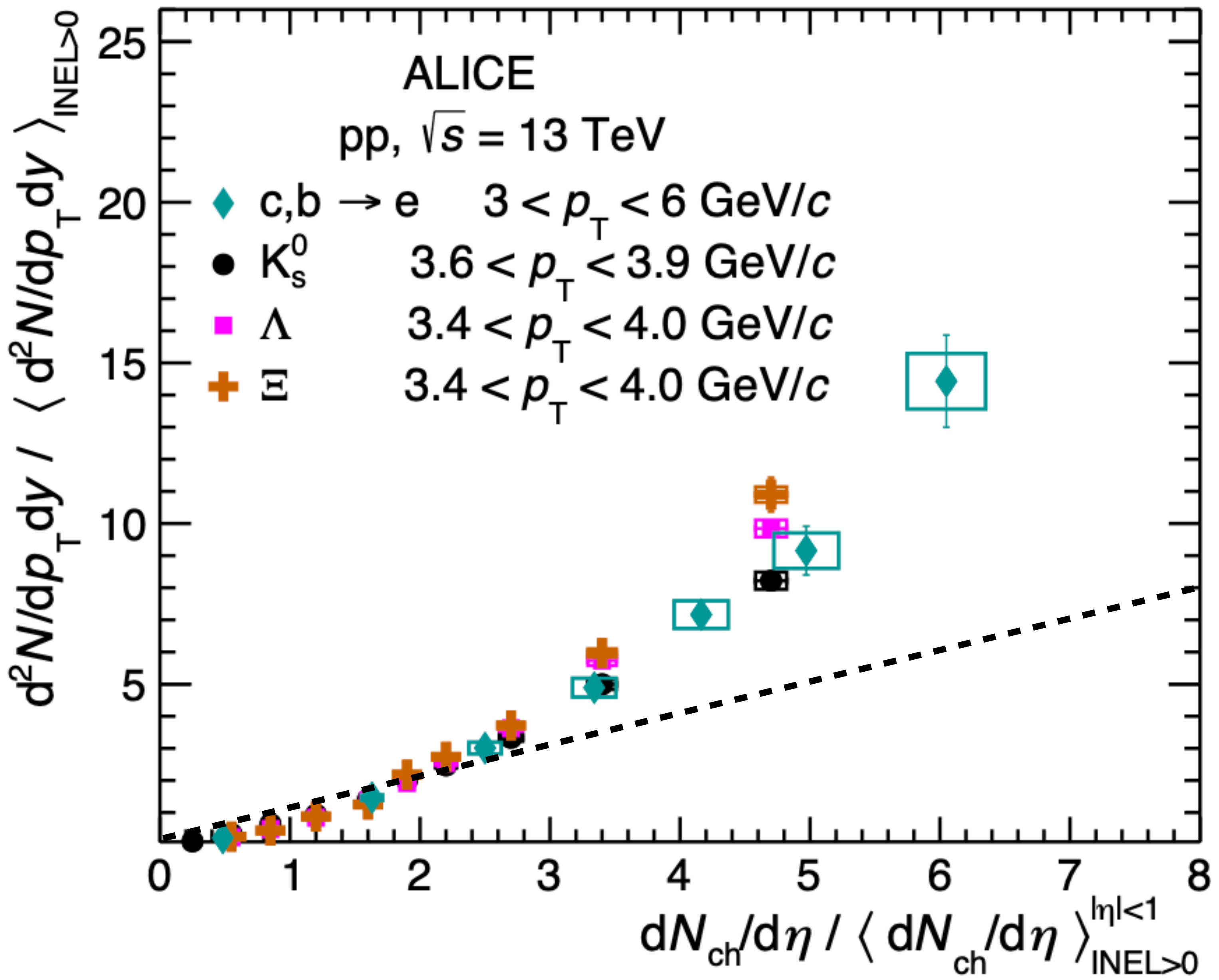
Origin of very high multiplicity events

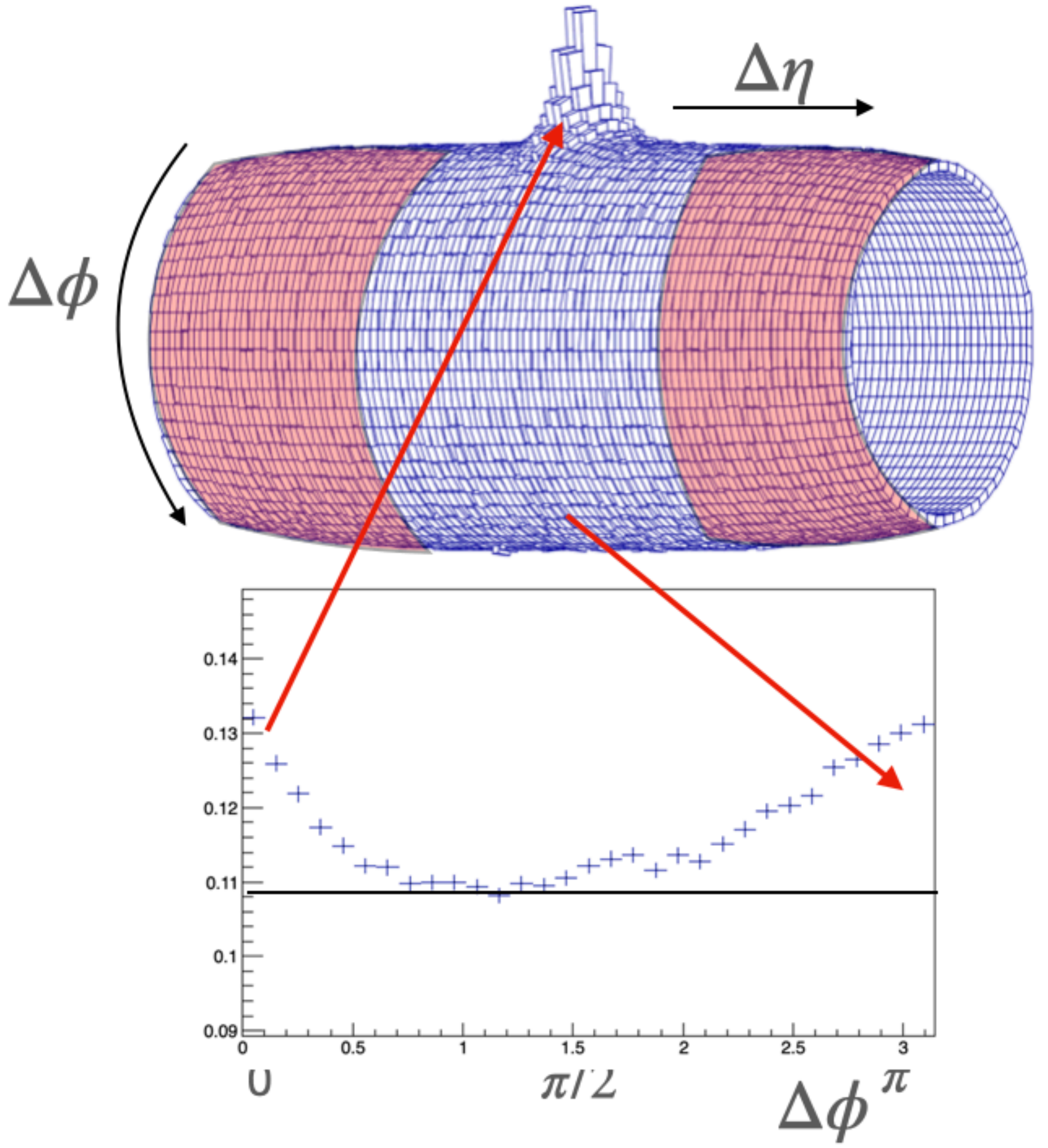


- Very high multiplicity events are not anymore explained by centrality
- Mainly statistical fluctuations.

Multiplicity dependence of particle yields







$$pp \to Y + N = (Y + N_{cor}) + N_{uncor}$$

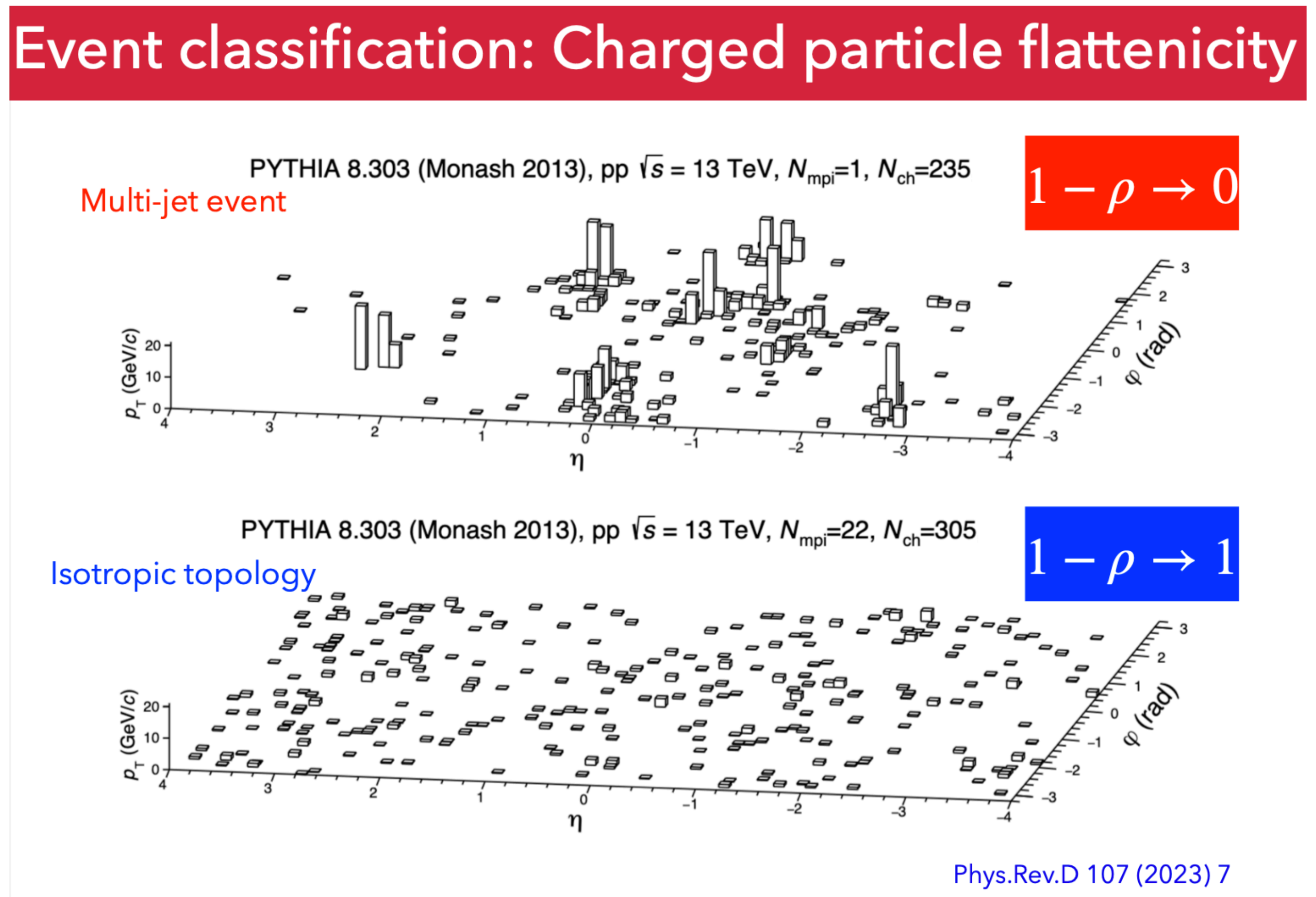
- Hard probe itself contributes always to some extent to the measured event multiplicity
- Strong deviation from linearity due to autocorrelation effects?
  - plus additional more interesting density effects?
- Clear dependence on hardness and no dependence on particle species at high p_T

How to meet the challenge

Deny

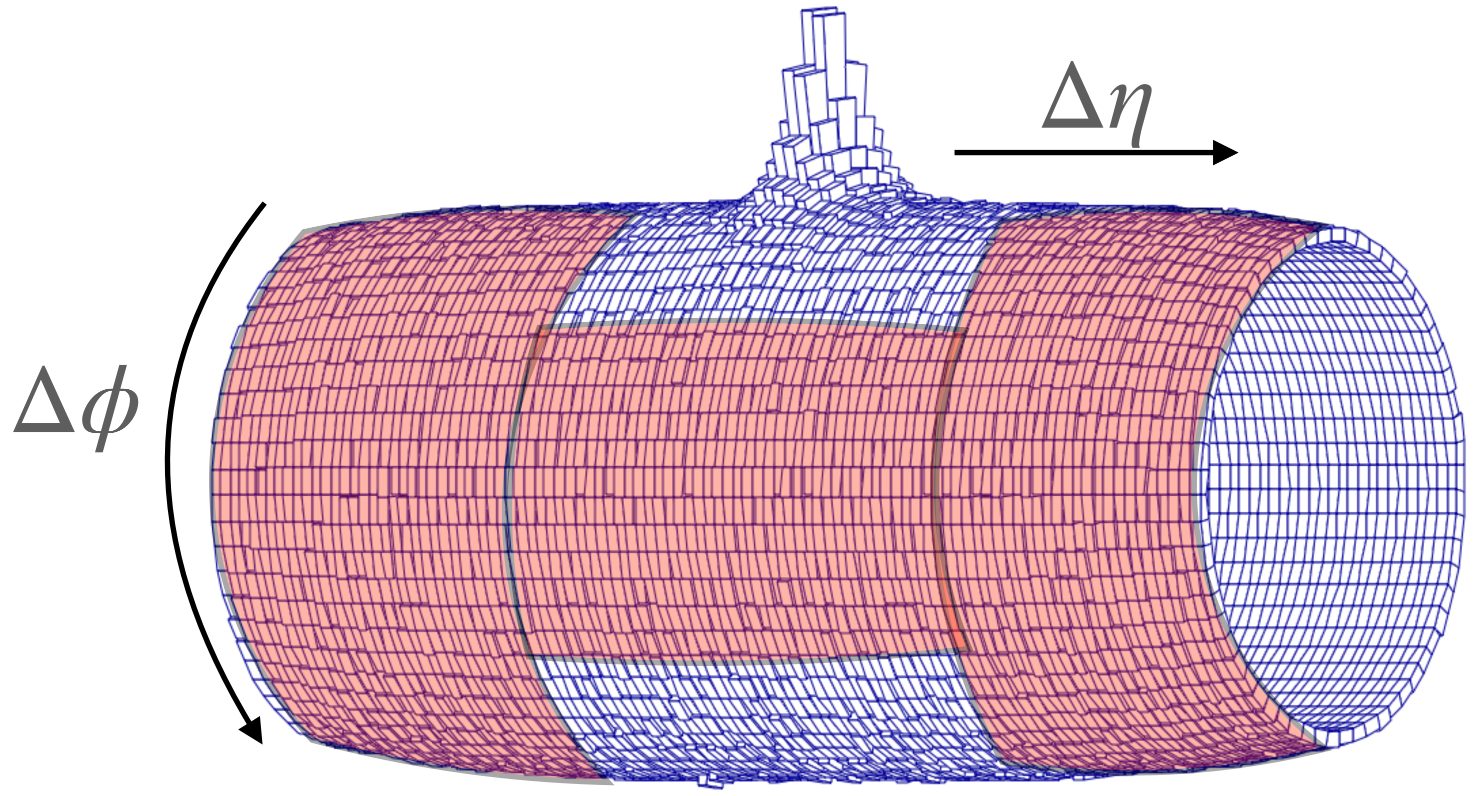
Accept

Event Classification

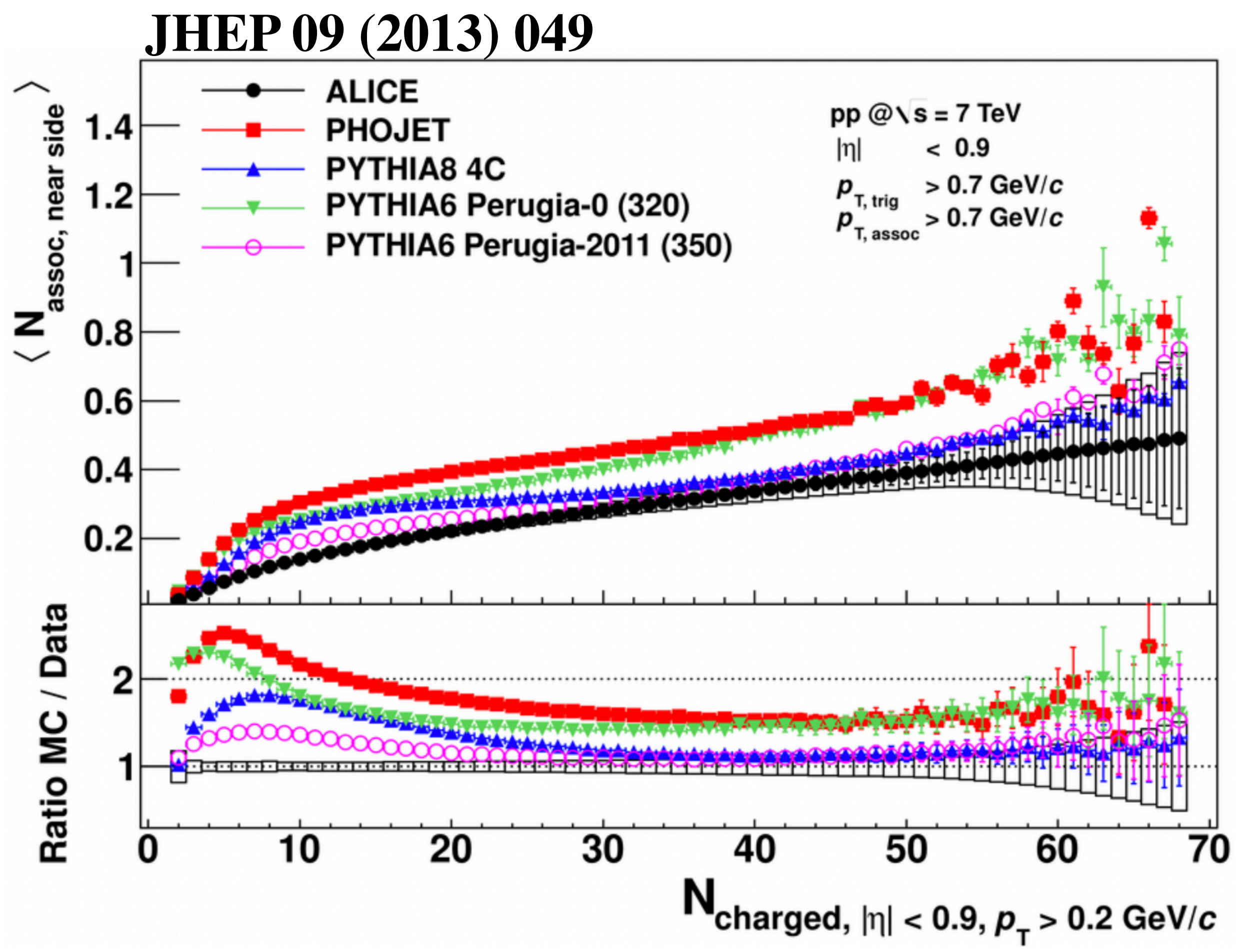


Talk by Antonio Ortiz Velasquez, Wed 23/10

Rapidity gap, Transverse Region



Embrace

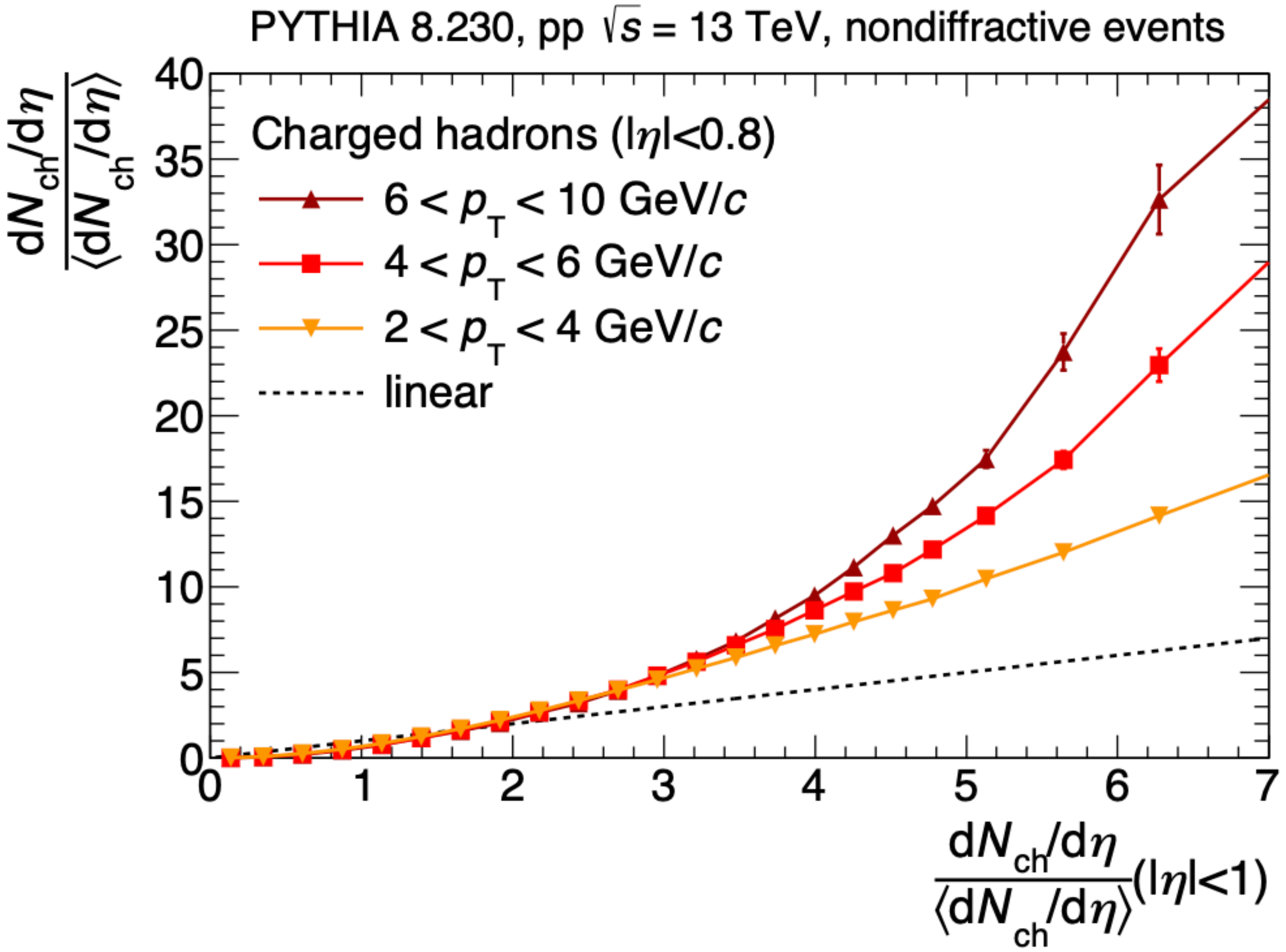


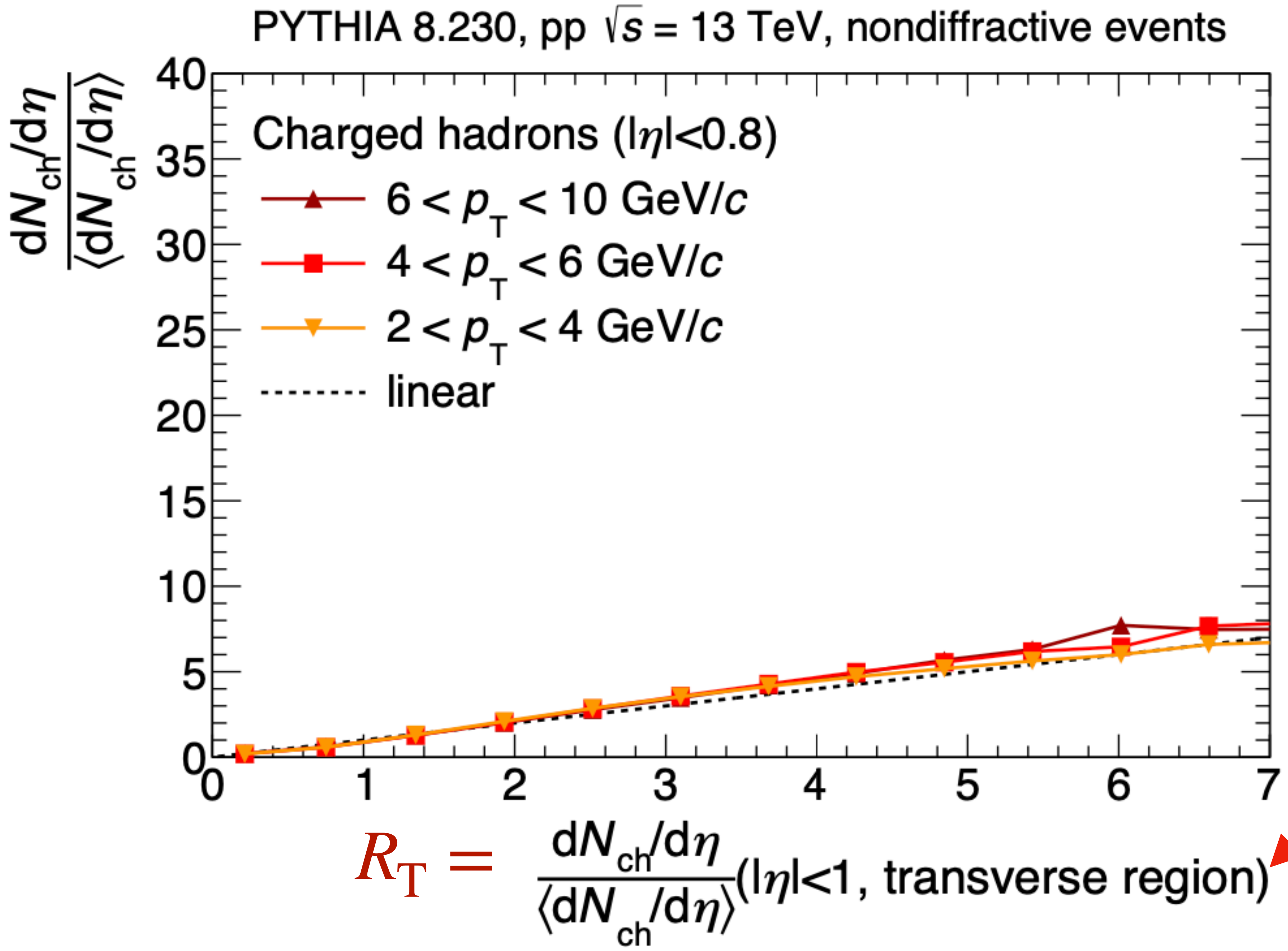
Measure multiplicity dependence and correlations for the same observable

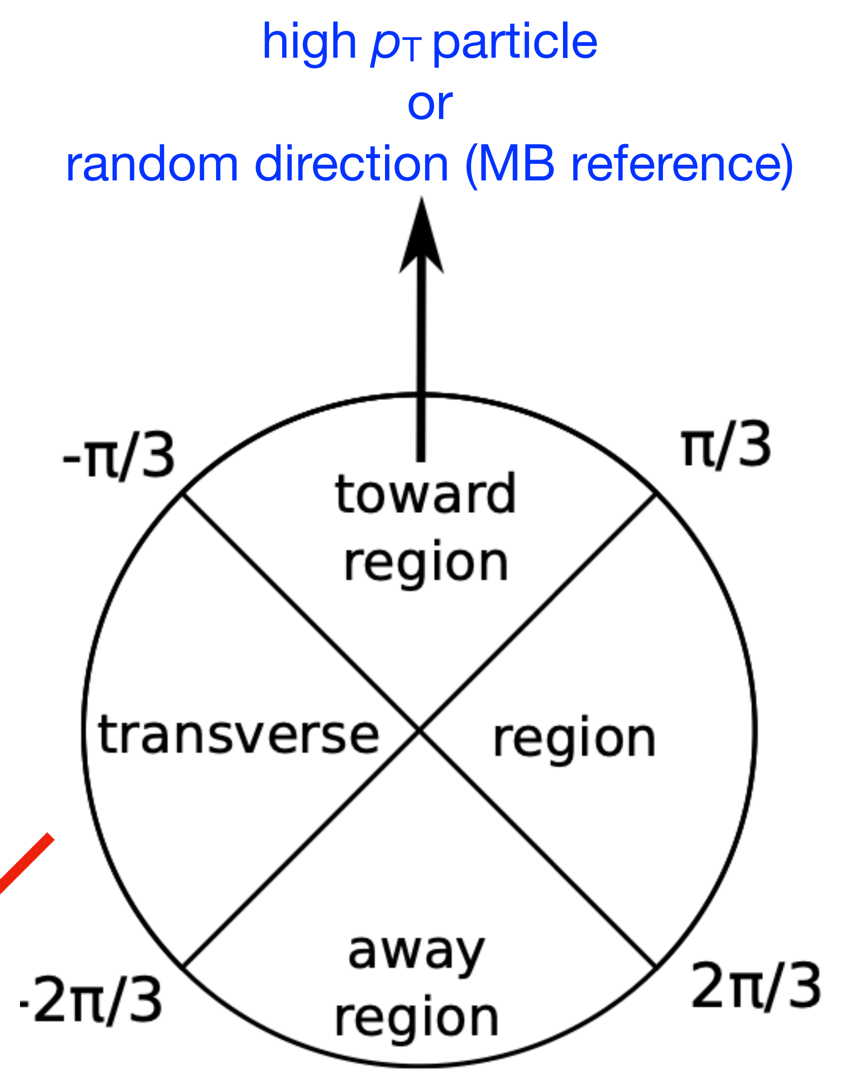
Should be focus for Run 3, if we want to continue with Yield vs Multiplicity measurements

Avoid bias by using transverse region as event activity estimator

S. Weber et al., EPJC, 79 (2019)

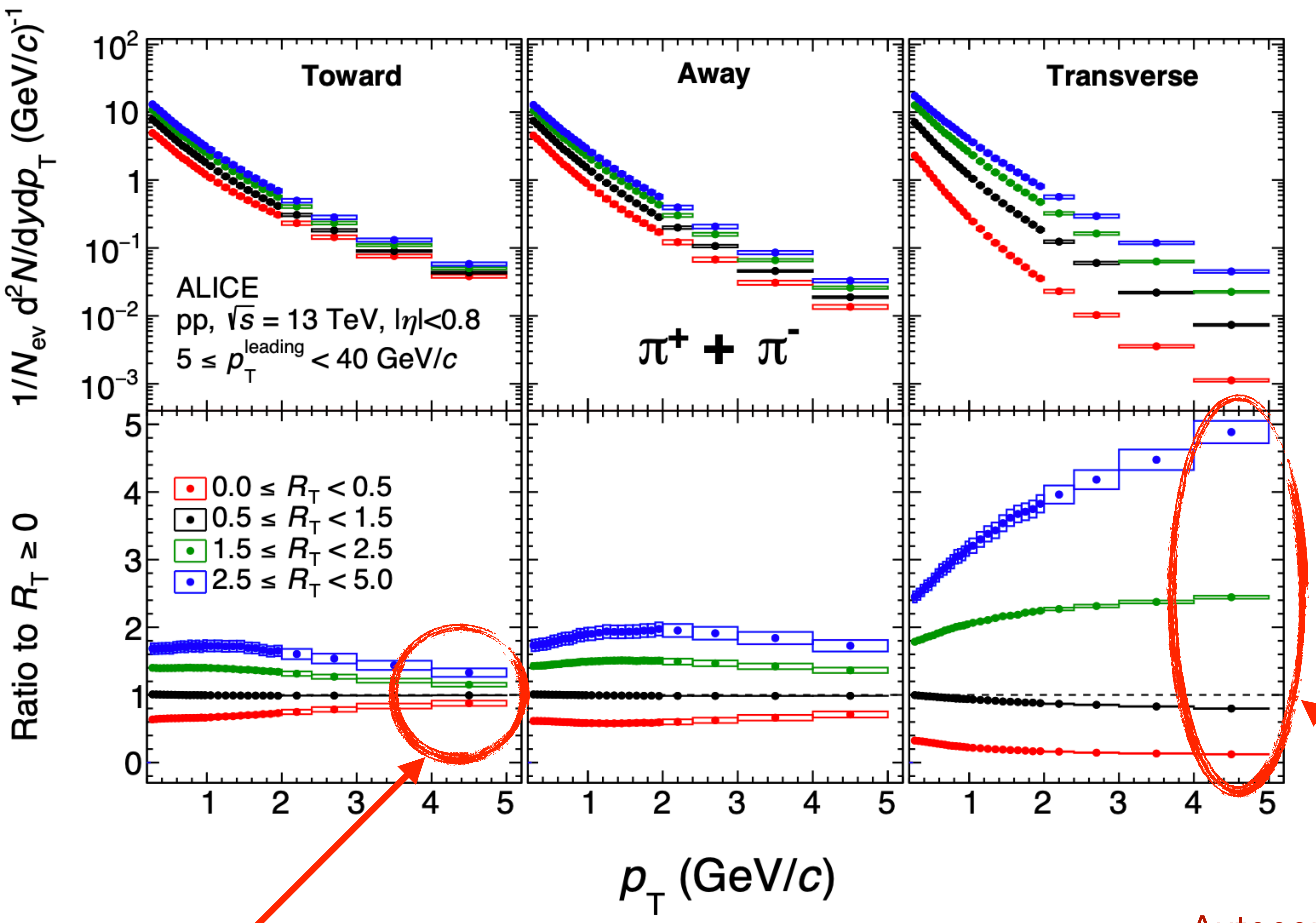


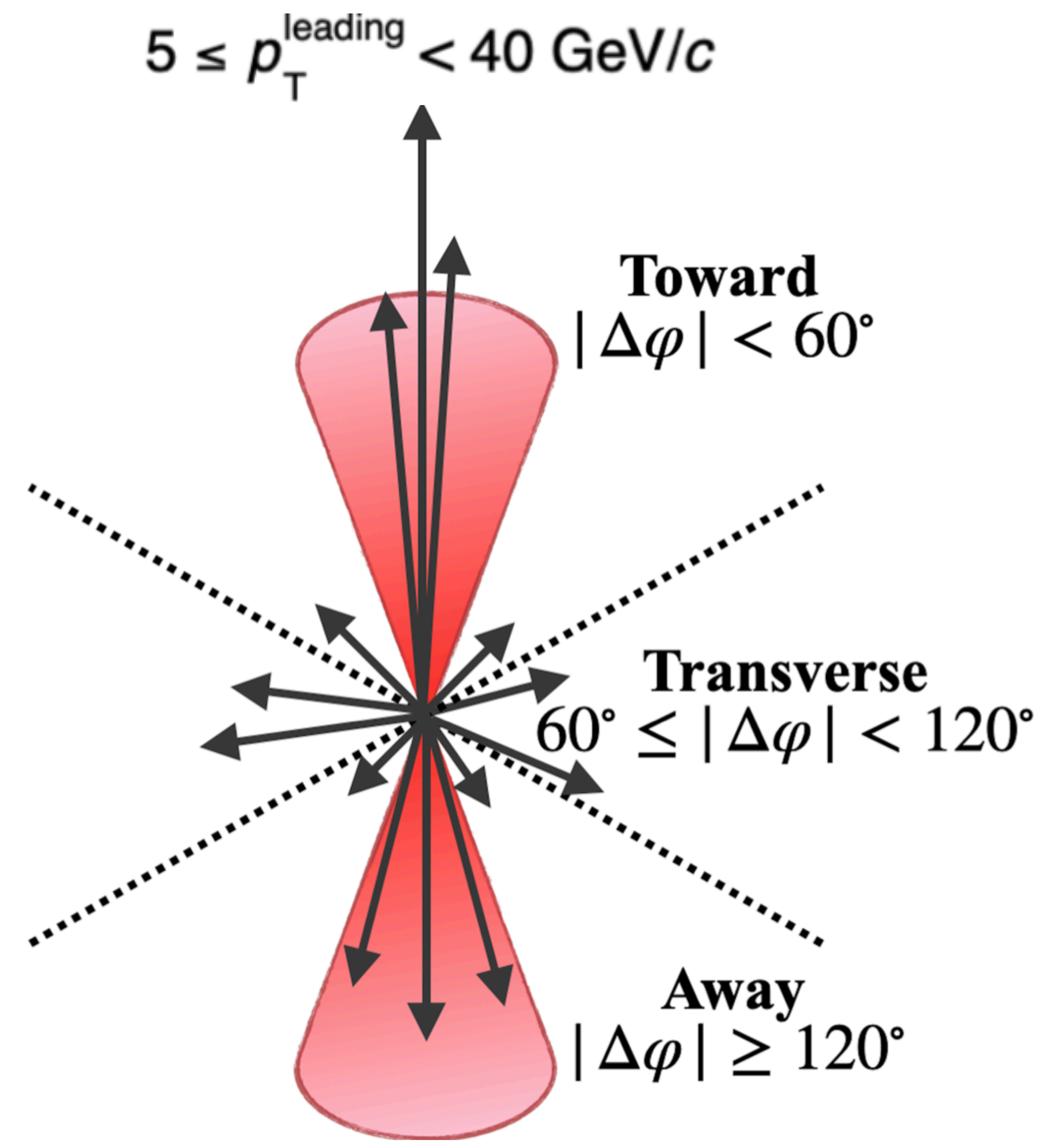




- In MC: R_T estimator removes bias for all p_T bins
- 0-bin (signal free bin) is important for the correct normalisation
  - use random azimuth direction for this bin (“random cones”)
- Has not been exploited so far

Production of π, K, p as a function of p_T and R_T



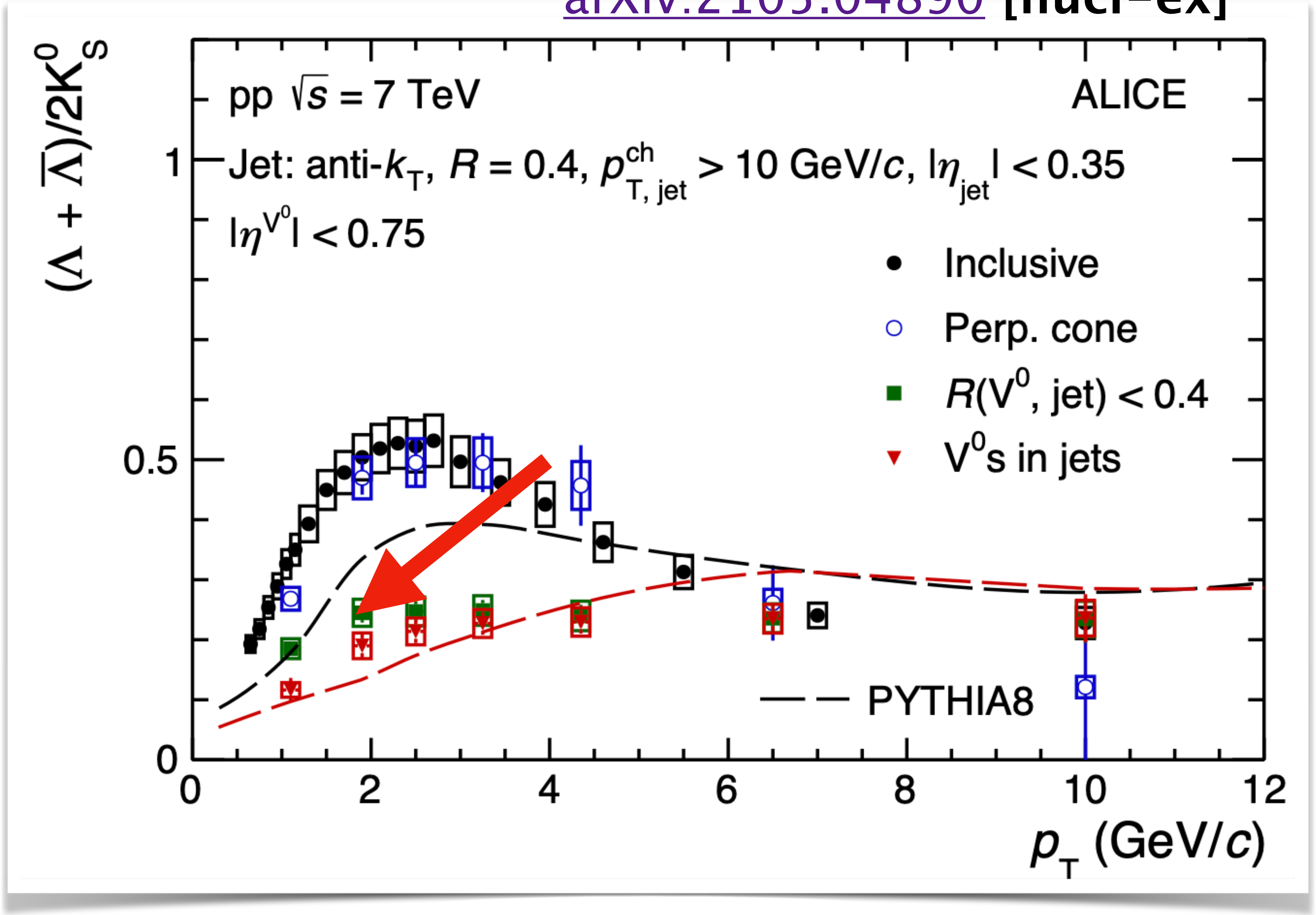


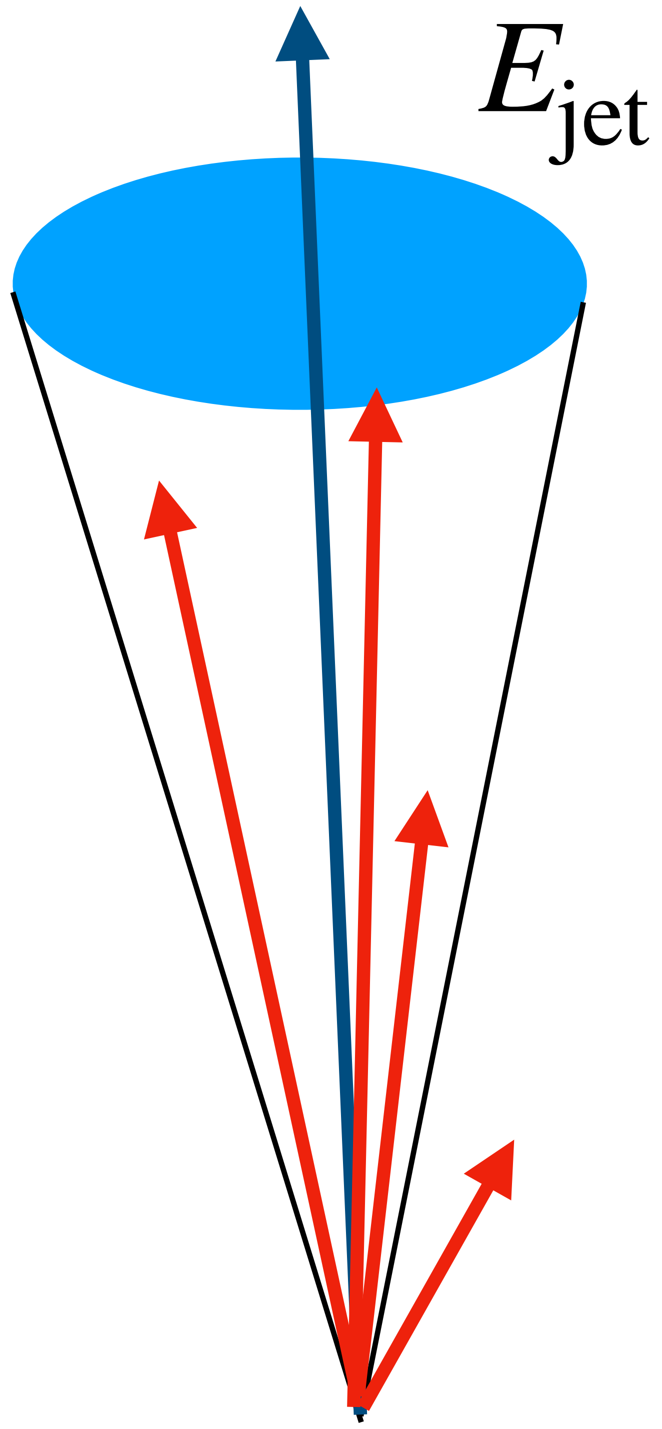
- Constrained by normalisation to events with trigger particle.
- Trigger particle as function of R_T has not been studied.

- Autocorrelation bias in the transverse direction
- UE ≈ MinBias and not a softer version of it

Particle production inside / outside jet

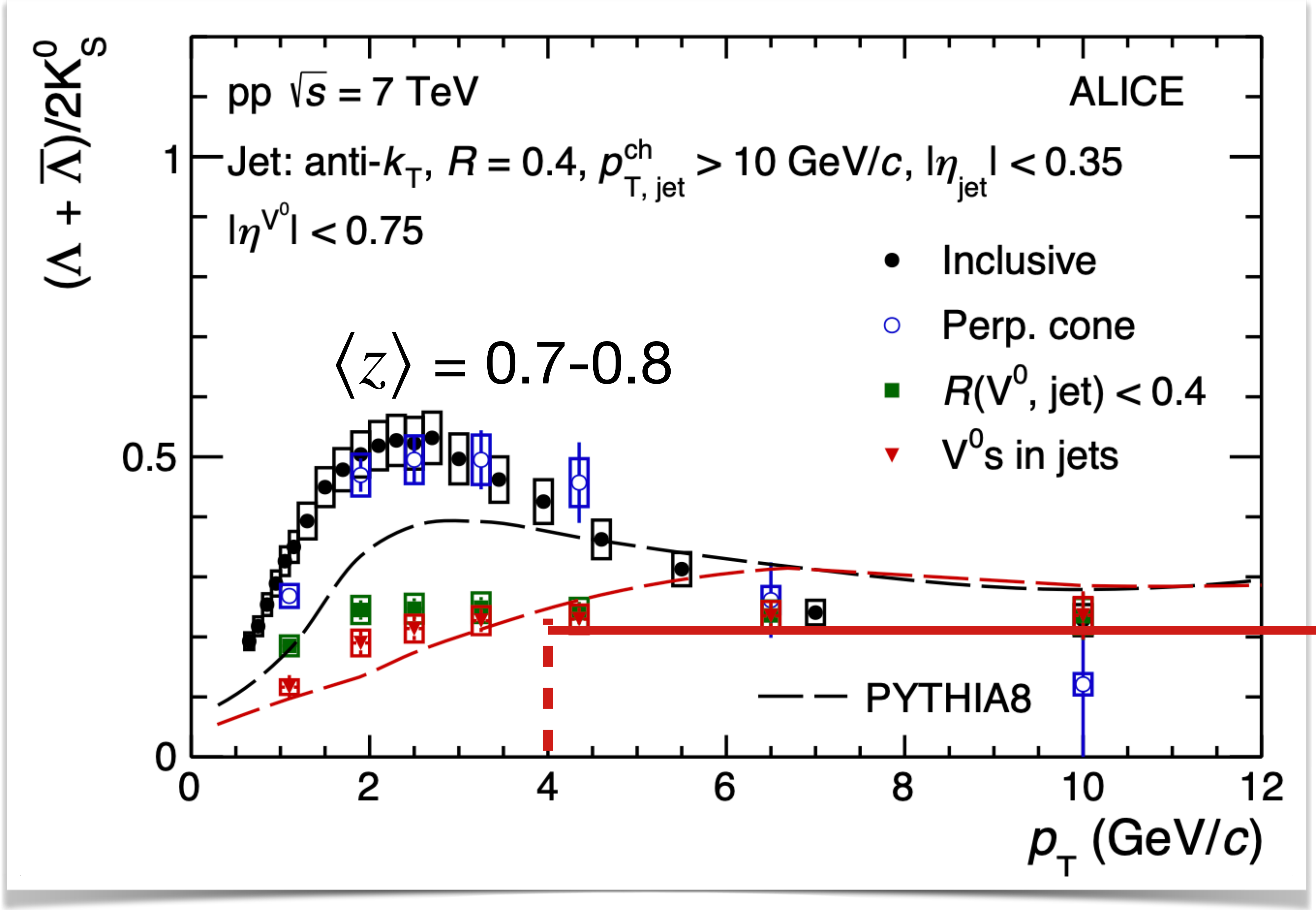
arXiv:2105.04890 [nucl-ex]

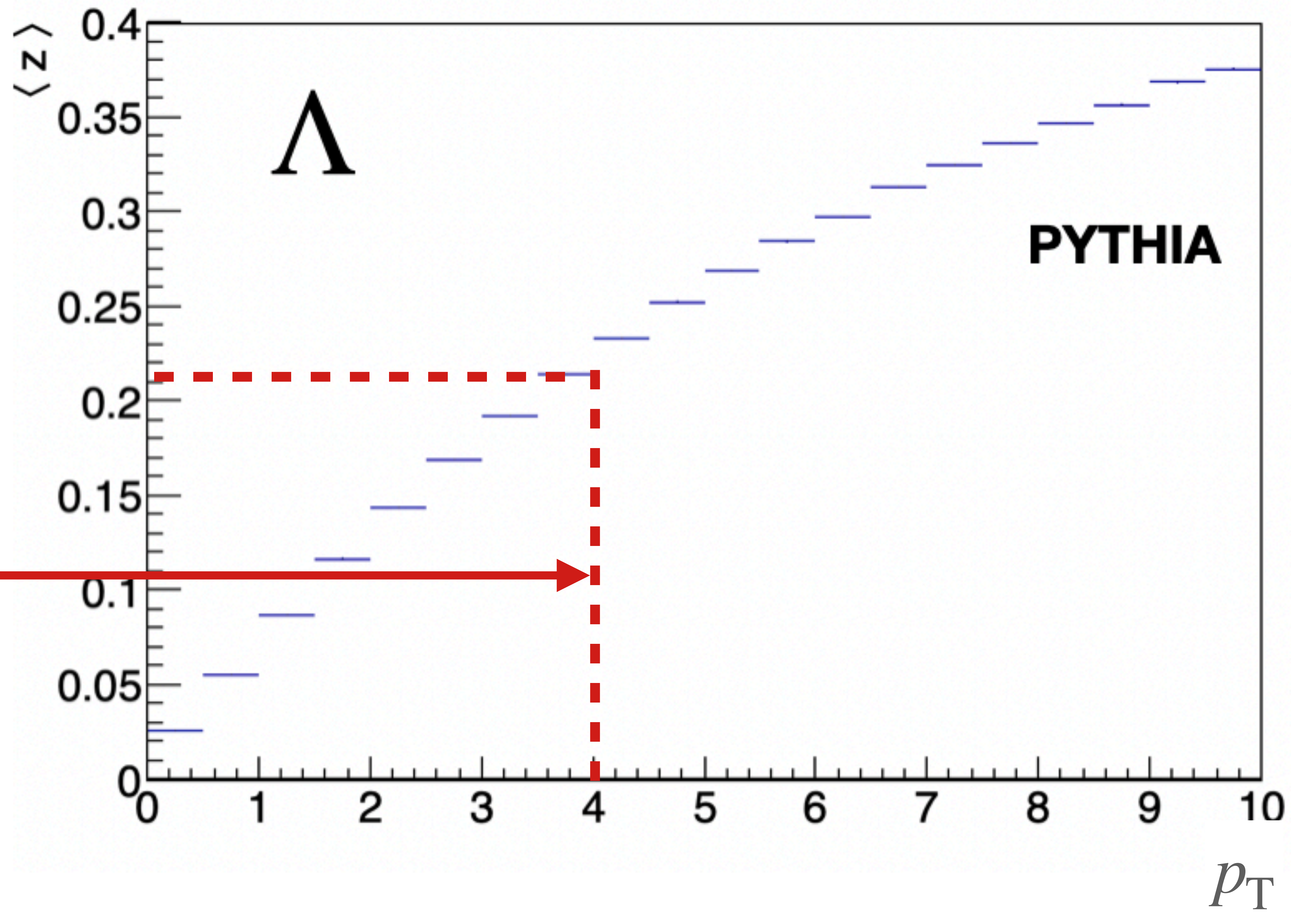




- UE ≈ MB for effects vs p_T seen in many measurements
- Expected if MPIs approximately factorise (i.e. probability of an interaction does not depend on the others)
- However, it is not necessarily the case that if an effect is not present in a jet or (towards region) that it is not related to parton fragmentation
- Reason: jet-tag introduces an additional scale not present in the inclusive measurements.
- Need refined definition of “out-of-jet production”

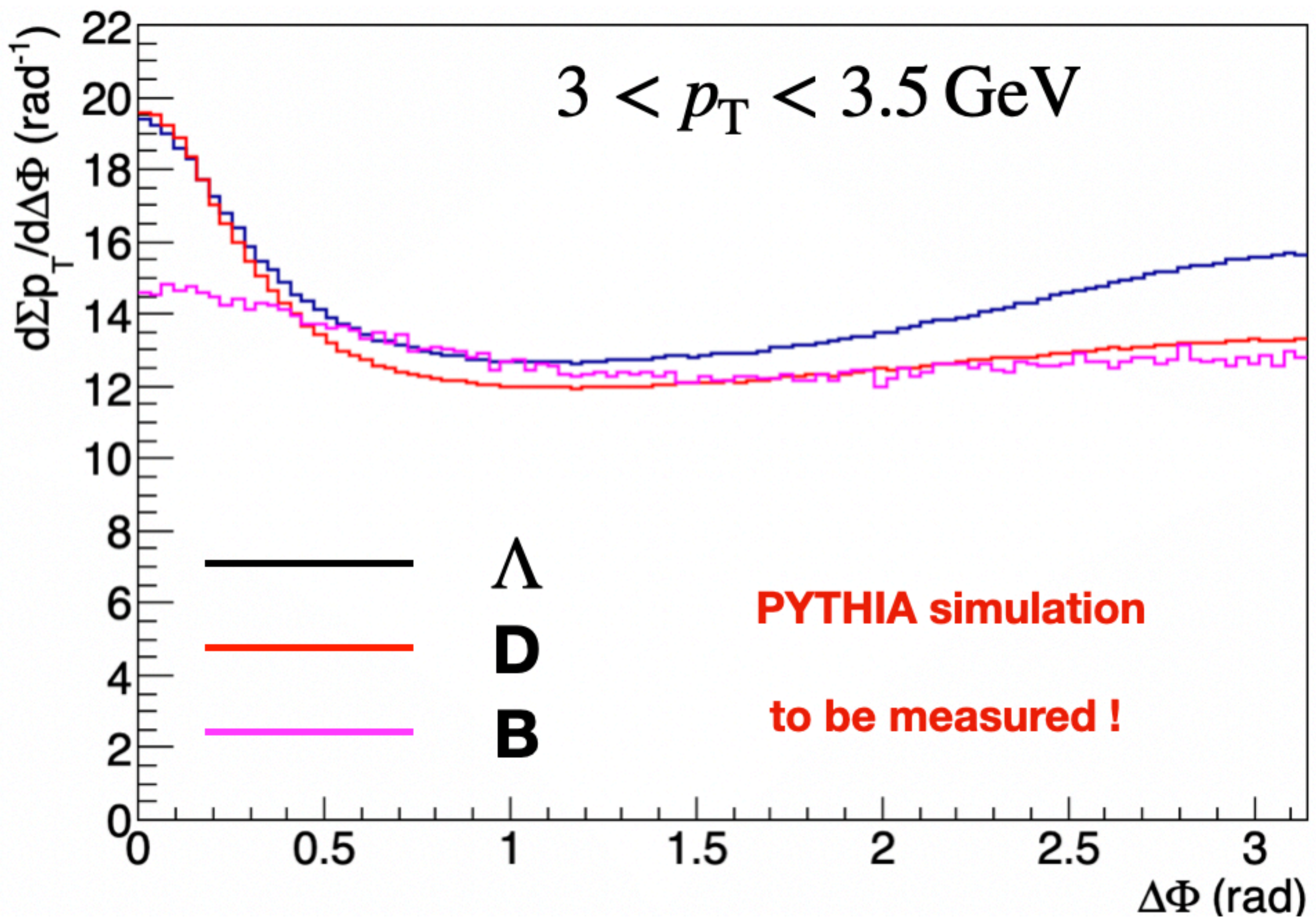
Particle production from fragmentation





- Fragmentation yield depends mainly on momentum fraction $\langle z \rangle = p_T/E_{jet}$
- For Λ inside jets (previous slide), $\langle z \rangle$ is small and increase with p_T
- It is expected to be high ($\langle z \rangle$ = 0.7-0.8) and approximately constant for the inclusive selection = fragmentation bias related to steepness of p_T spectrum

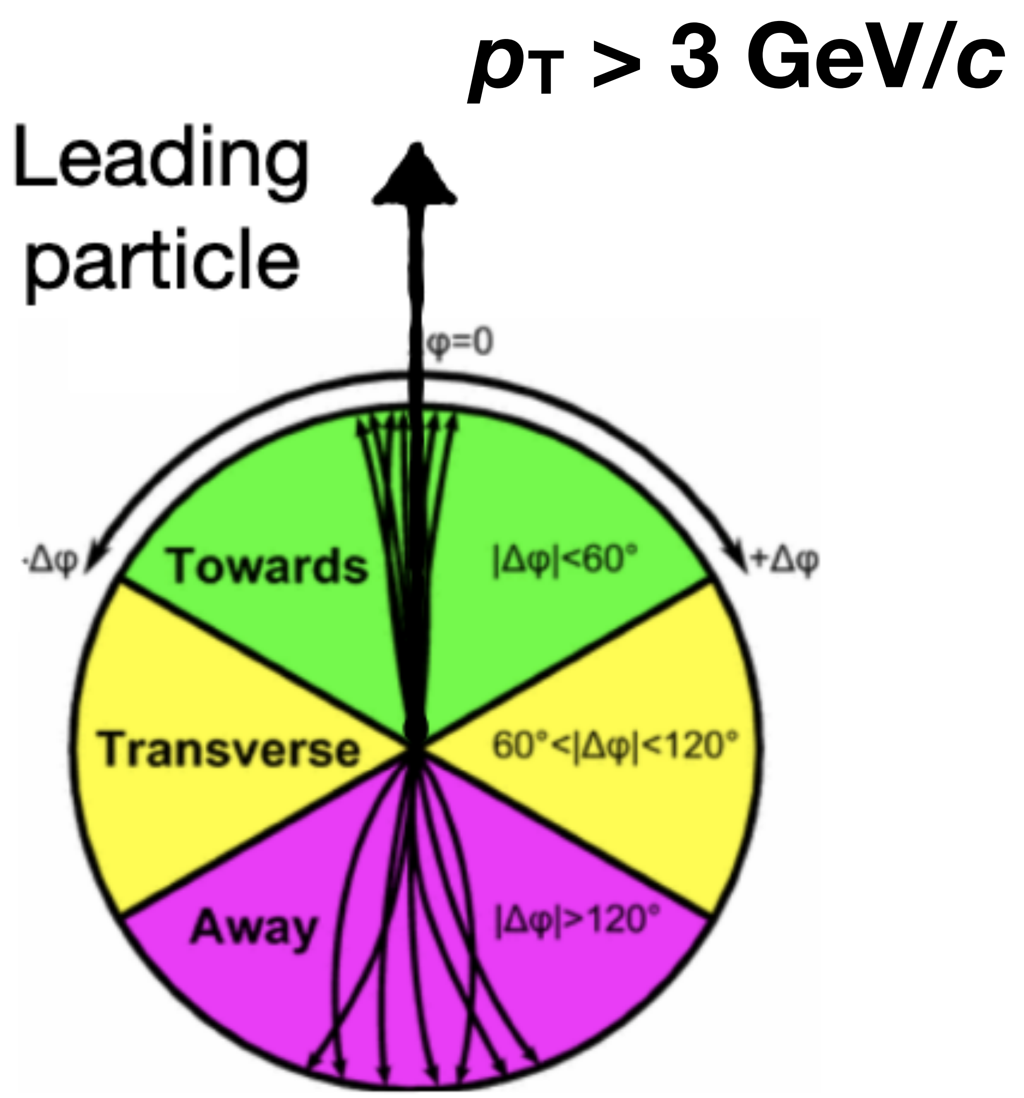
$\langle z \rangle$ from p_T weighted Di-hadron correlation

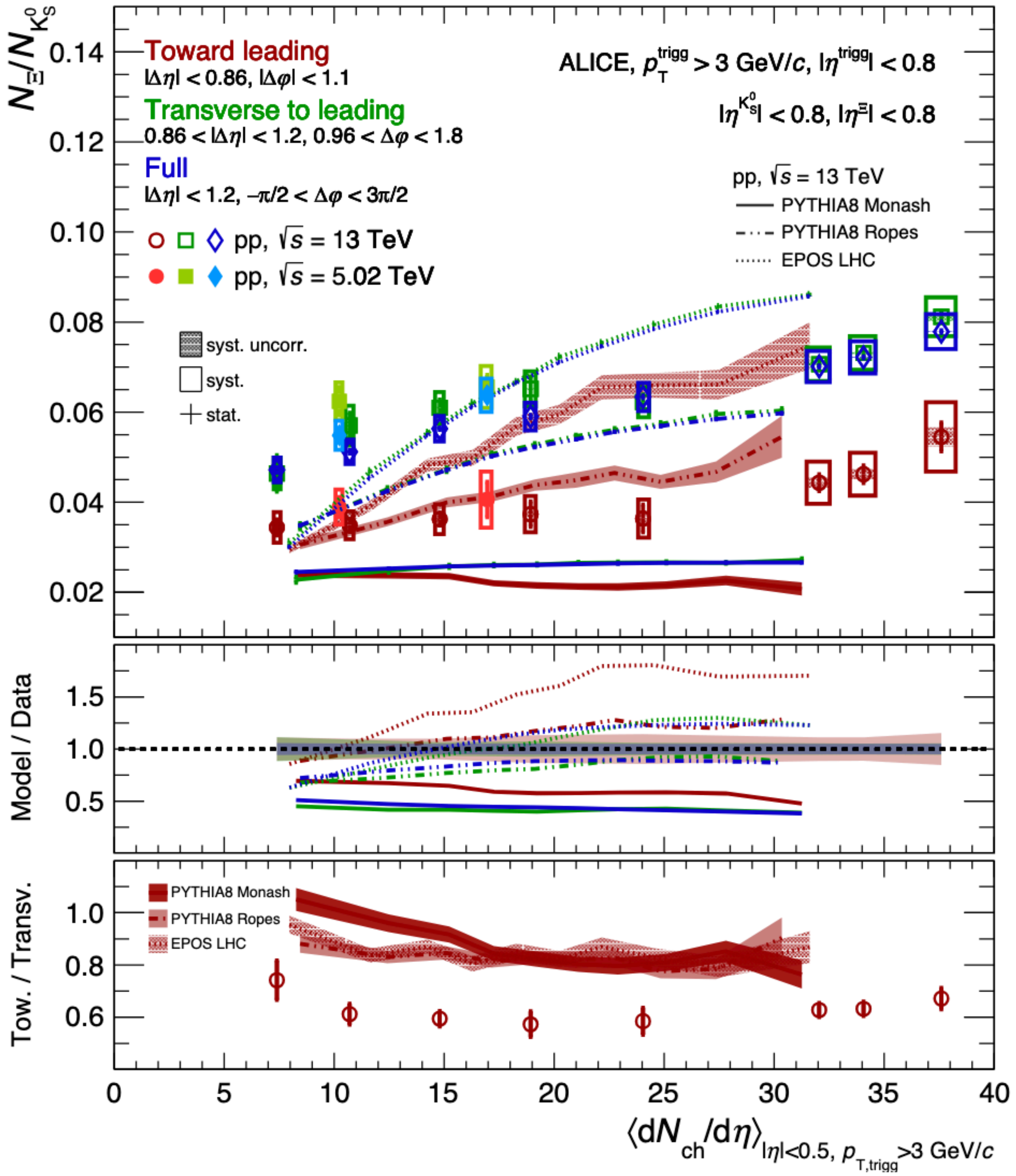


Analysis Lang Xu

- $\langle z \rangle_{DHC}$ can be only be a proxy for the real $\langle z \rangle$
- However, expected difference between inclusive and jet measurements are large
- Does also work for multiplicity dependent measurements
- Expect additional constraints on models.

Strangeness enhancement using angular correlations





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UE ≈ inclusive

Jet region

- Might also help to understand appearance of strangeness enhancement effects in the towards region when lowering the trigger cut

Summary

- Measurements of multiplicity distribution in the underlying event of hard processes help to better understand the production mechanisms of high multiplicity events in pp collisions.
  - Important contributions from CCNU members (R_T distributions)
- Prospects for improving measurements of particle yields vs multiplicity
  - Reduce auto-correlation bias
    - by combination with angular correlation measurements
    - use R_T as classifier for the trigger yield
    - … or event classification (see talk Antonio Ortiz)
  - Aim for improved sensitivity to particle production mechanisms (“bulk” vs jet)
    - complementing present “out-of-jet” definition with mean momentum fraction measurements