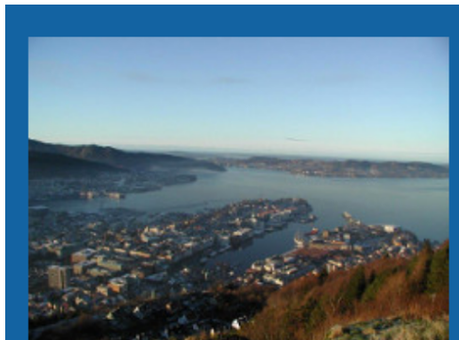
Multiple Parton Interactions - Overview

Andreas Morsch
CERN



12th International Workshop on High-pT Physics in the RHIC/LHC era

2-5 October 2017, University of Bergen

Plan for this talk …

- Raise the awareness of importance of understanding MPI in pp for interpretation of high p_T probes in heavy ion collisions

- On the way …

  - present some recent experimental and phenomenological results

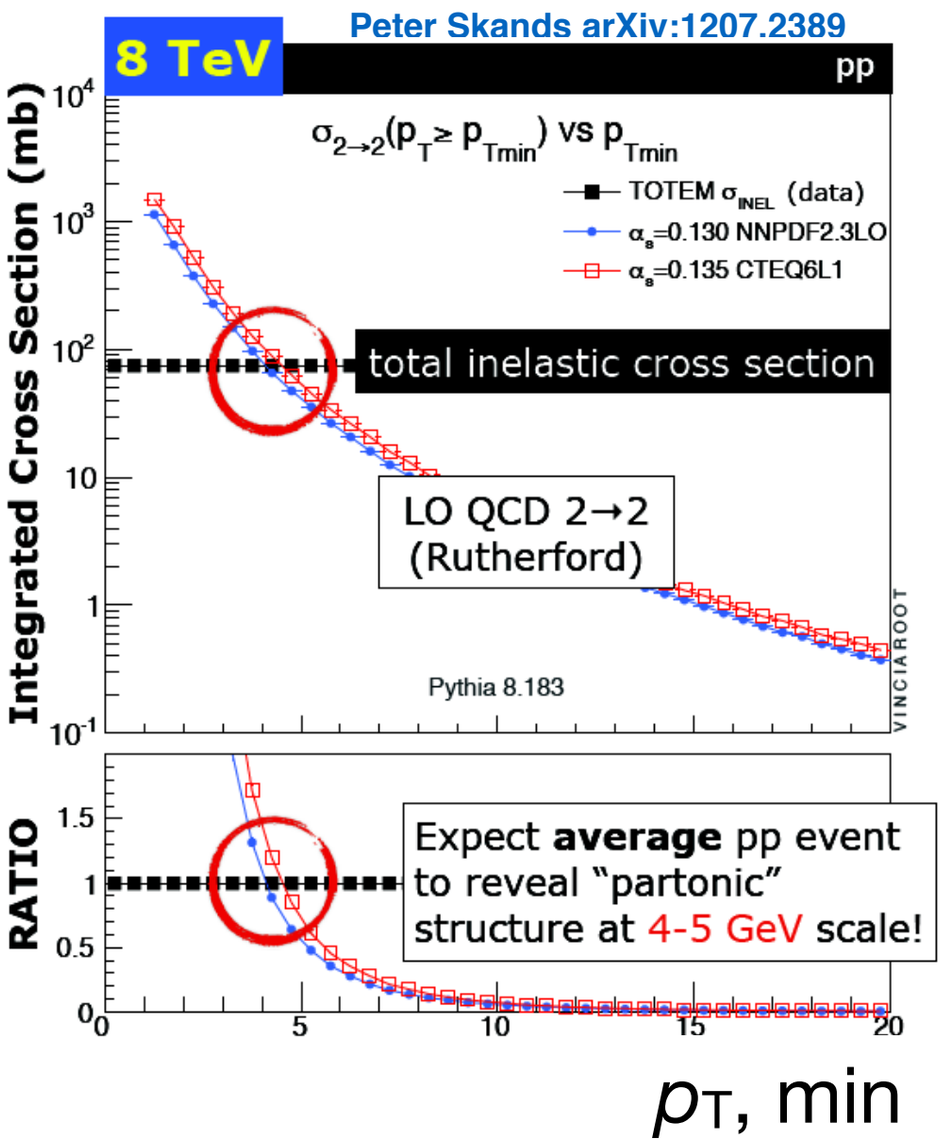
  - do not include high p_T Double Parton Scattering (DPS)

  - MPI in the low to medium p_T region where they contribute to bulk particle production

Importance of MPI in pp @LHC

Integrated hard cross-section

Peter Skands arXiv:1207.2389



- Straightforward interpretation of pQCD $\sigma_{2\to2} > \sigma_{tot}$

Number of 2→2 scatterings per event, naïve **factorization**:

$$\langle n_{2\to2} \rangle = \frac{\sigma_{2\to2}}{\sigma_{tot}}$$

$$P_n = \frac{\langle n_{2\to2} \rangle^n}{n!} e^{-\langle n_{2\to2} \rangle}$$

-$p_T \gg \Lambda_{QCD}$ for pQCD to be applicable

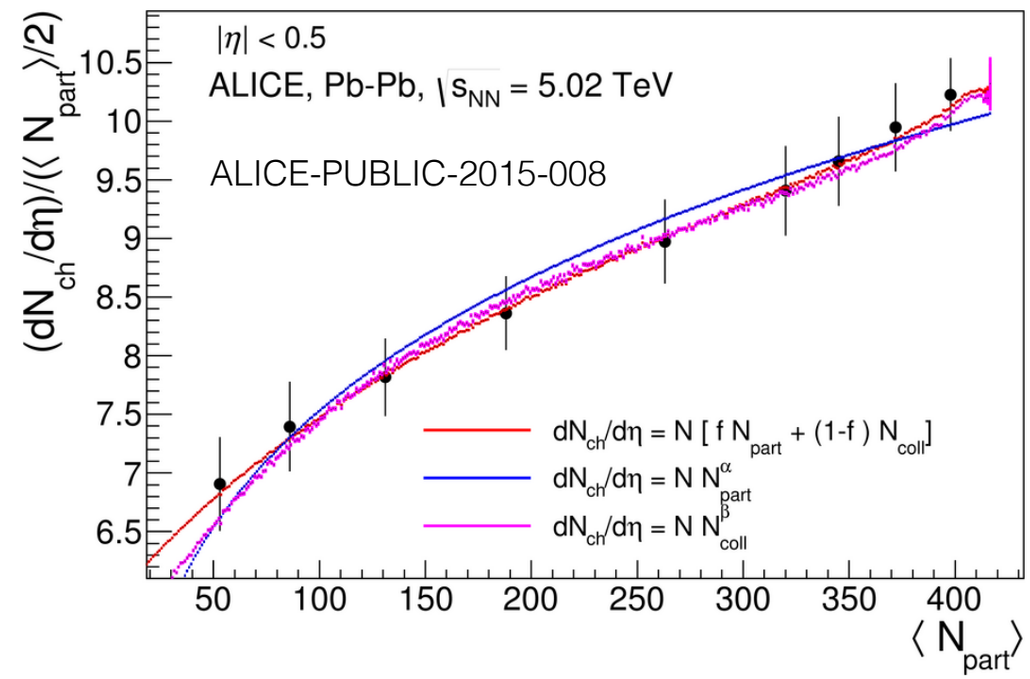
-factorisation breaks for $n_{2\to2}$ large in area $\propto \frac{1}{p_T^2}$

- Hard cross-section must "saturate" at low p_T
- Does not exclude dominance of semi-hard particle production at low p_T
- Bulk particle yields (N_{ch}) not described by pQCD

- At LHC multiple hard scatterings at perturbative scales
- Large contribution to **underlying event (UE)**

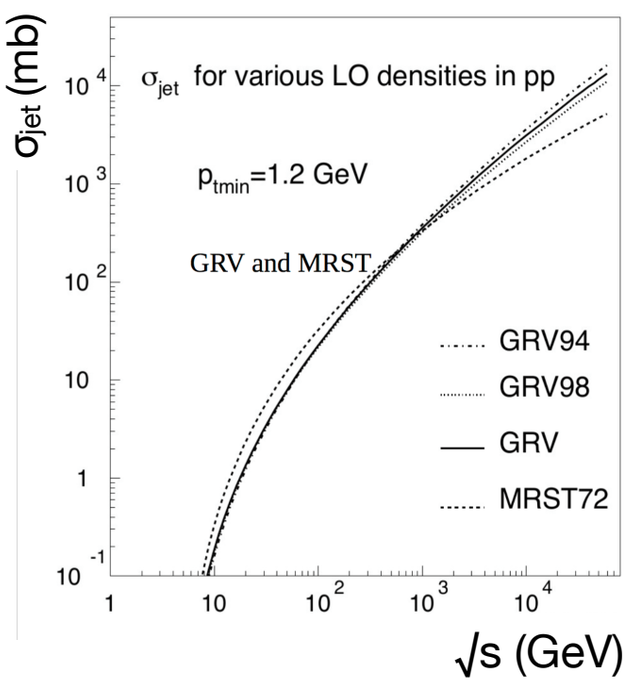
Charged Particle Multiplicity at Mid-Rapidity

- Hard cross-section
  - strong increase with √s
  - ~N_{coll} in A-A (p-A)
- MPI dominance would (naively) imply
  - corresponding increase of multiplicity
  - as a function of √s and centrality

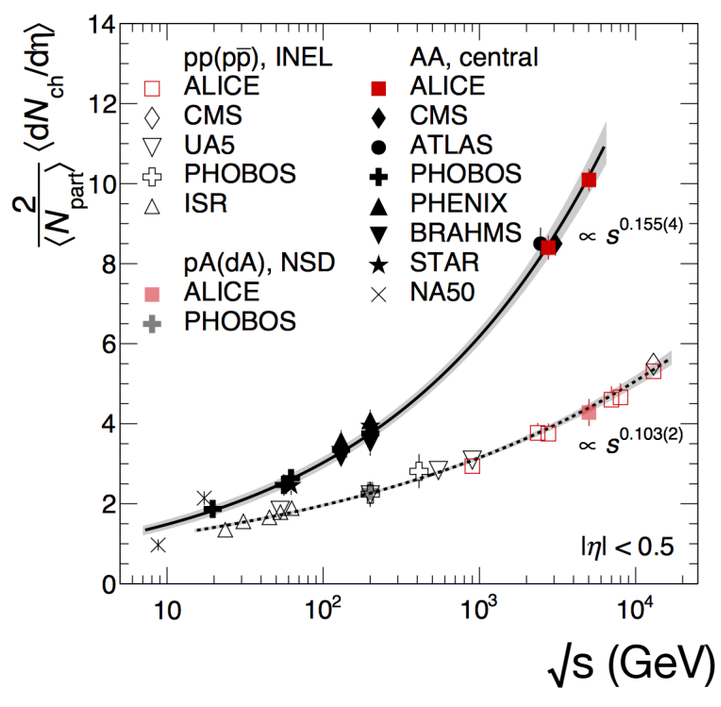


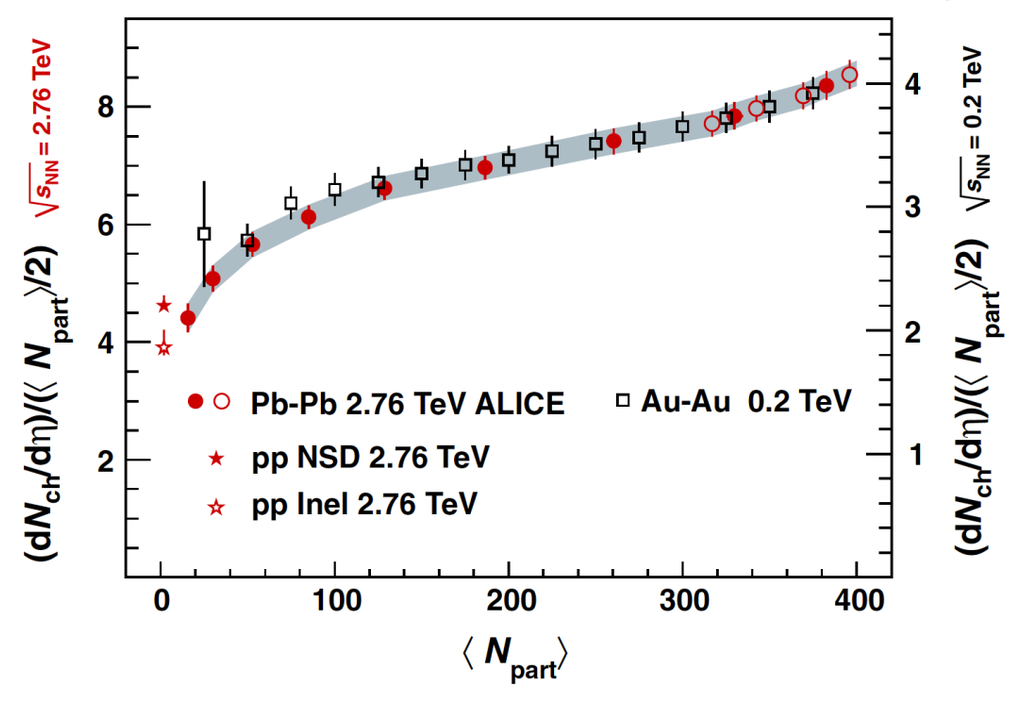
√s = 10 - 10 TeV

σ_{hard} x 10^5



pp: N_{ch} x 4 AA: x10



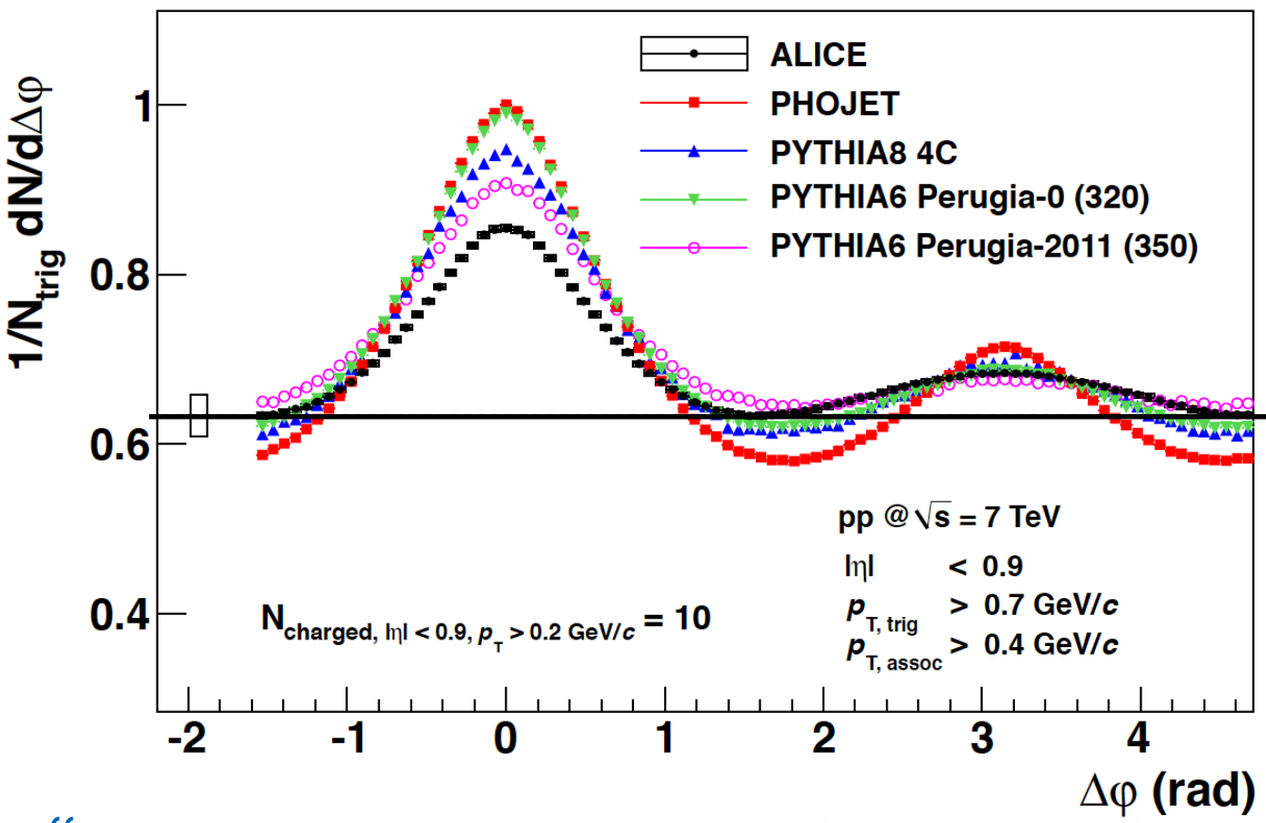


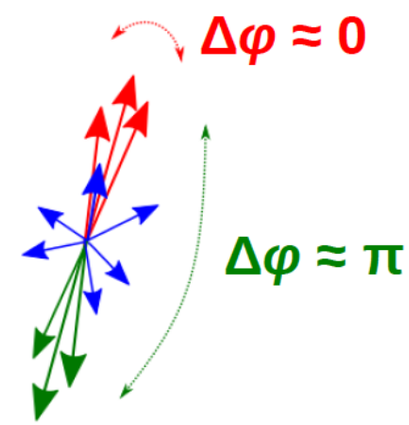
S-shape consistent with hard+soft scaling (f *N*part + (1-f)*N*coll)
But shape almost energy independent!

Topological Identification of MPI

Di-Hadron Azimuthal Correlations

2013 JHEP 1309 049





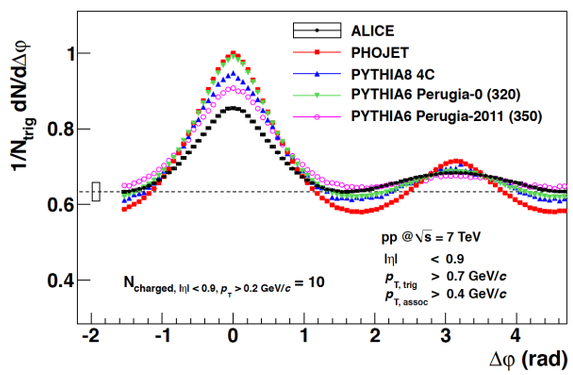
Underlying Event (UE)

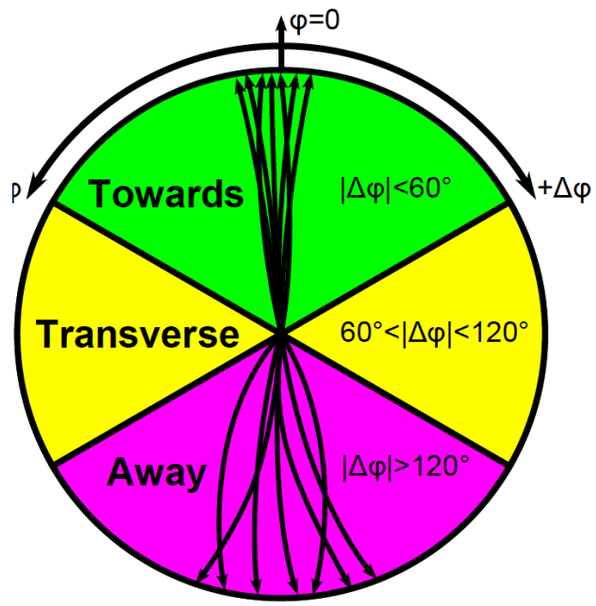
(M Varga Kofarago, Thu am)

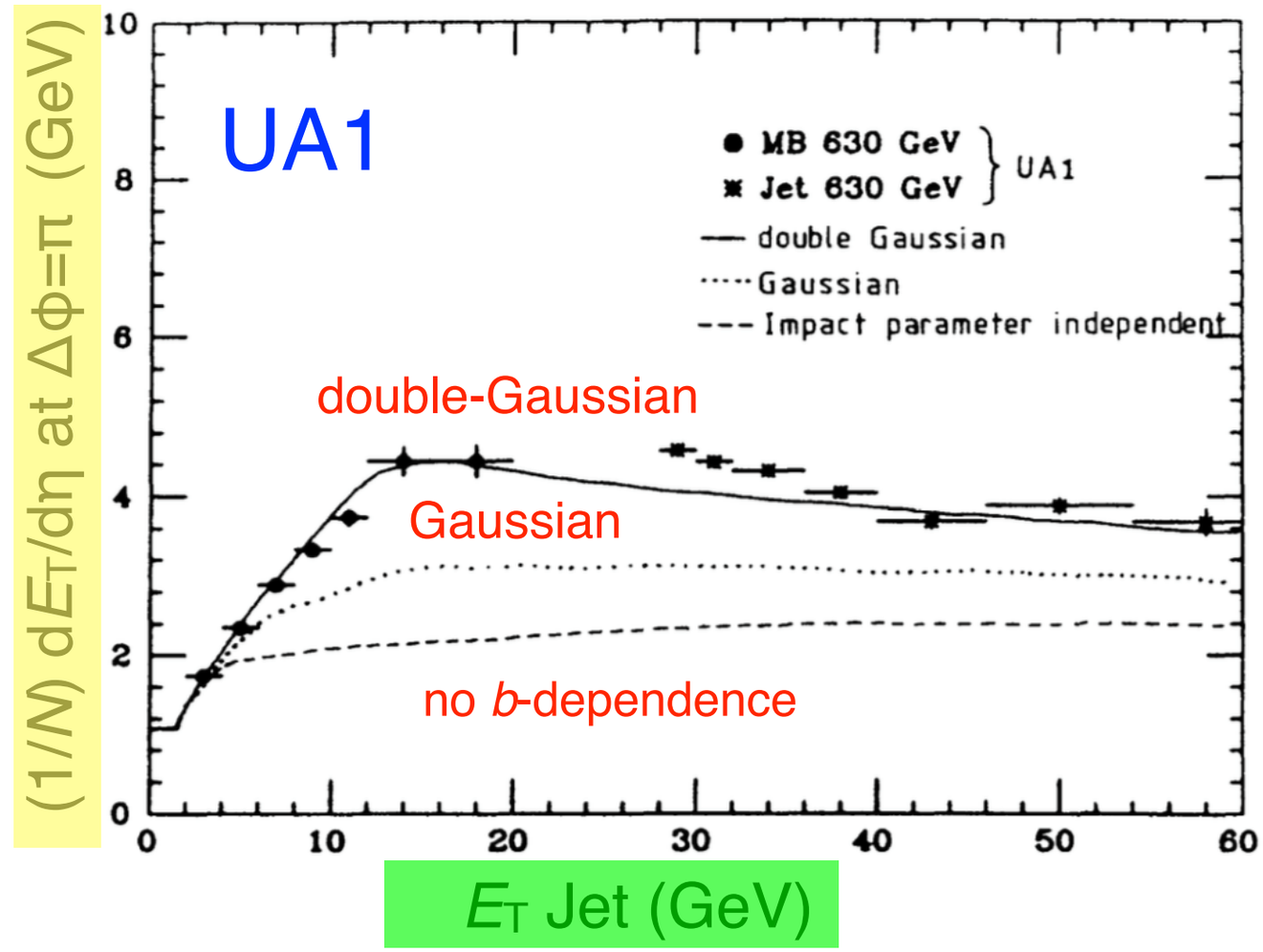
- "mini-jets" contribution to low-p_T "bulk" particle production
- Multiplicity dependence sensitive to relative contribution of hard-soft processes
- should be the Achilles heel of MPI based models

Quite well described by some of the MC tunes.

UE / Jet Pedestal Effects



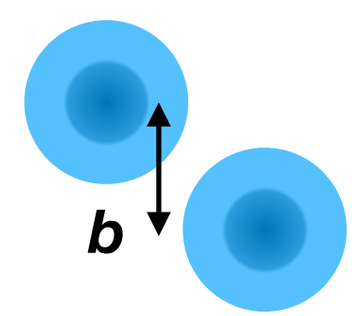




- High p_T objects bias towards smaller b where probability for additional interactions is larger increased UE activity.
- Constrain in MPI models radial parton distribution in proton

Number of hard scatterings depends on matter overlap:

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

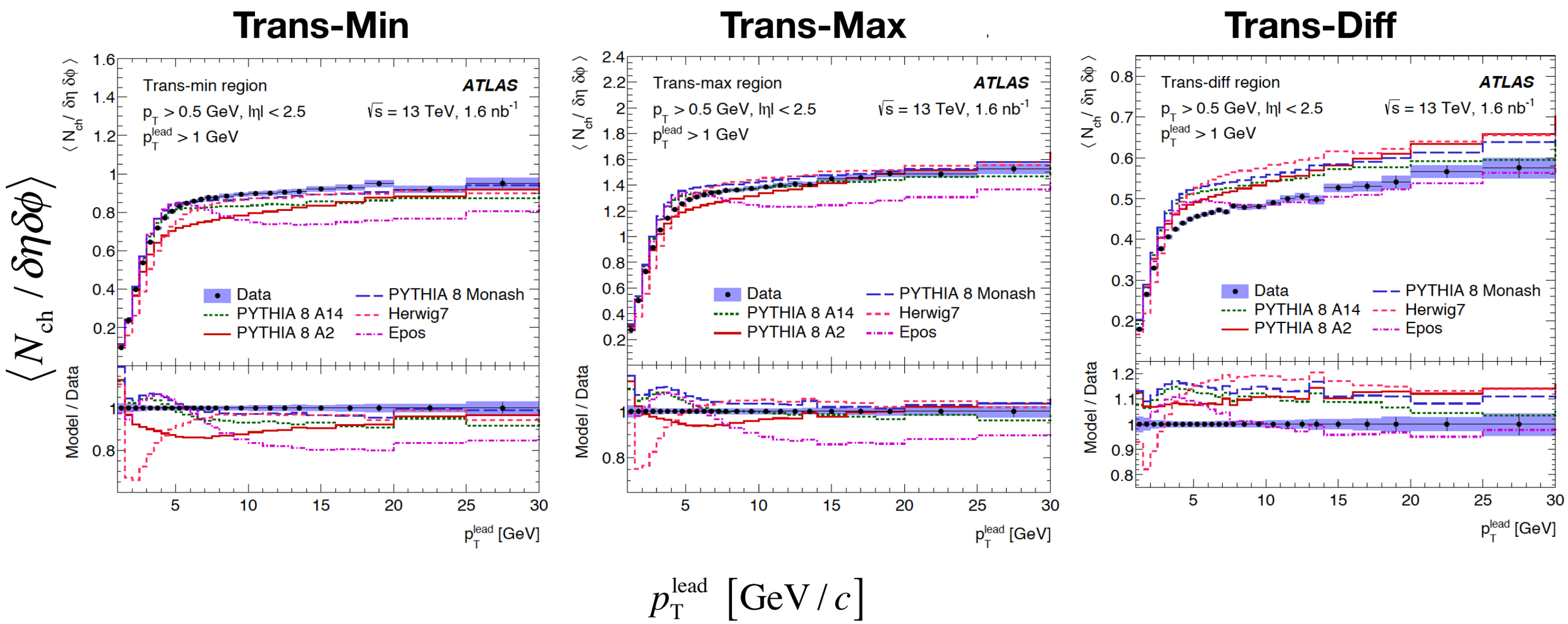


UE at the LHC

Additional observables studied:

- 2nd moment of multiplicity distribution, scalar ΣpT (Phys. Rev. D83 (2011) 112001)
- jet-multiplicity (EPJ C73 no. 12, (2013) 2674)
- dividing transverse region event-by-event into Min and Max

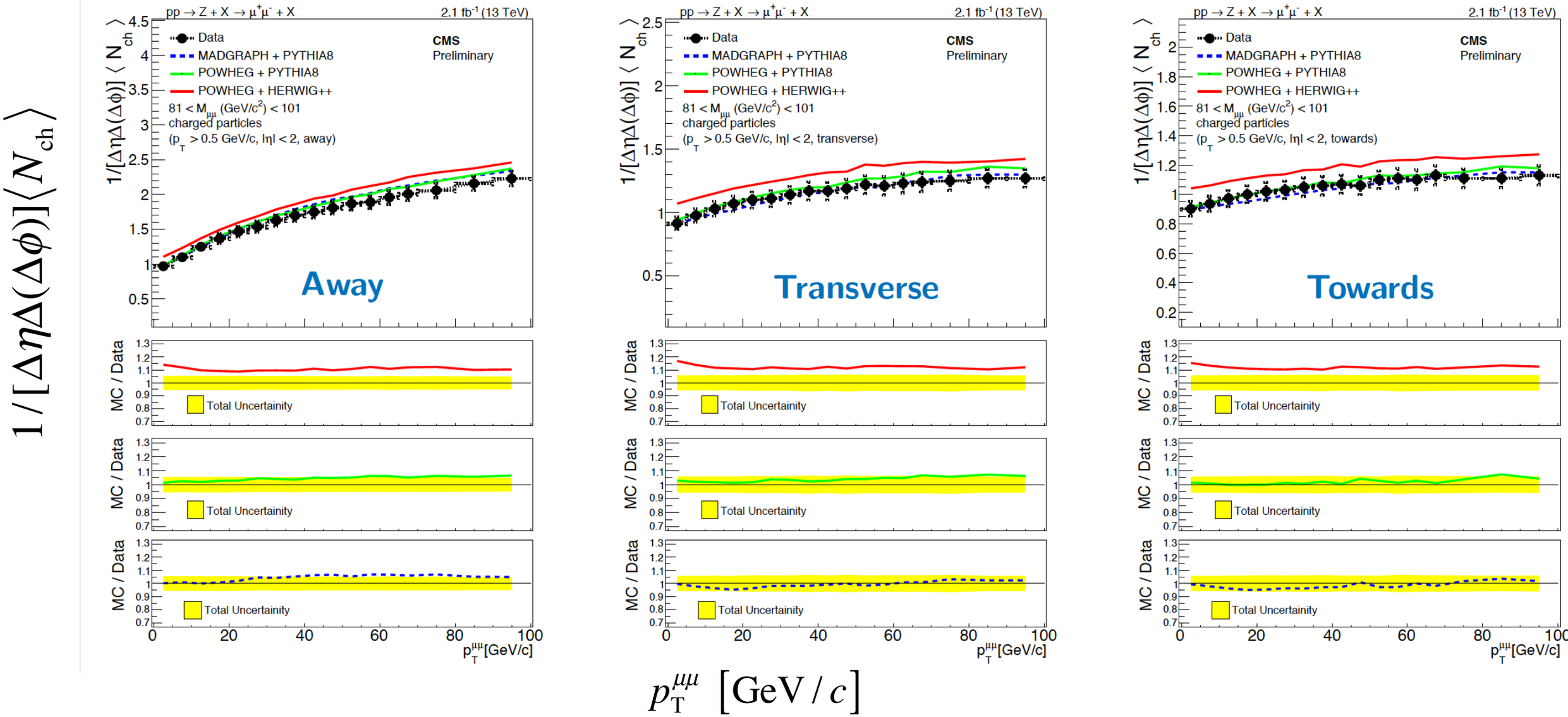
JHEP 03 (2017) 157



- Trans-Max and Trans-Diff have increased sensitivity to Initial State Radiation
- Increase as a function of hard scale

UE in pp→Z+X→μ⁺μ⁻

CMS-PAS-FSQ-16-008



- No Final state radiation: more direct access to ISR and MPI
- No sharp increase at low p_T: Z mass sets hard scale
- Increase with p_T due to ISR

p_T Spectra in Event Activity Classes

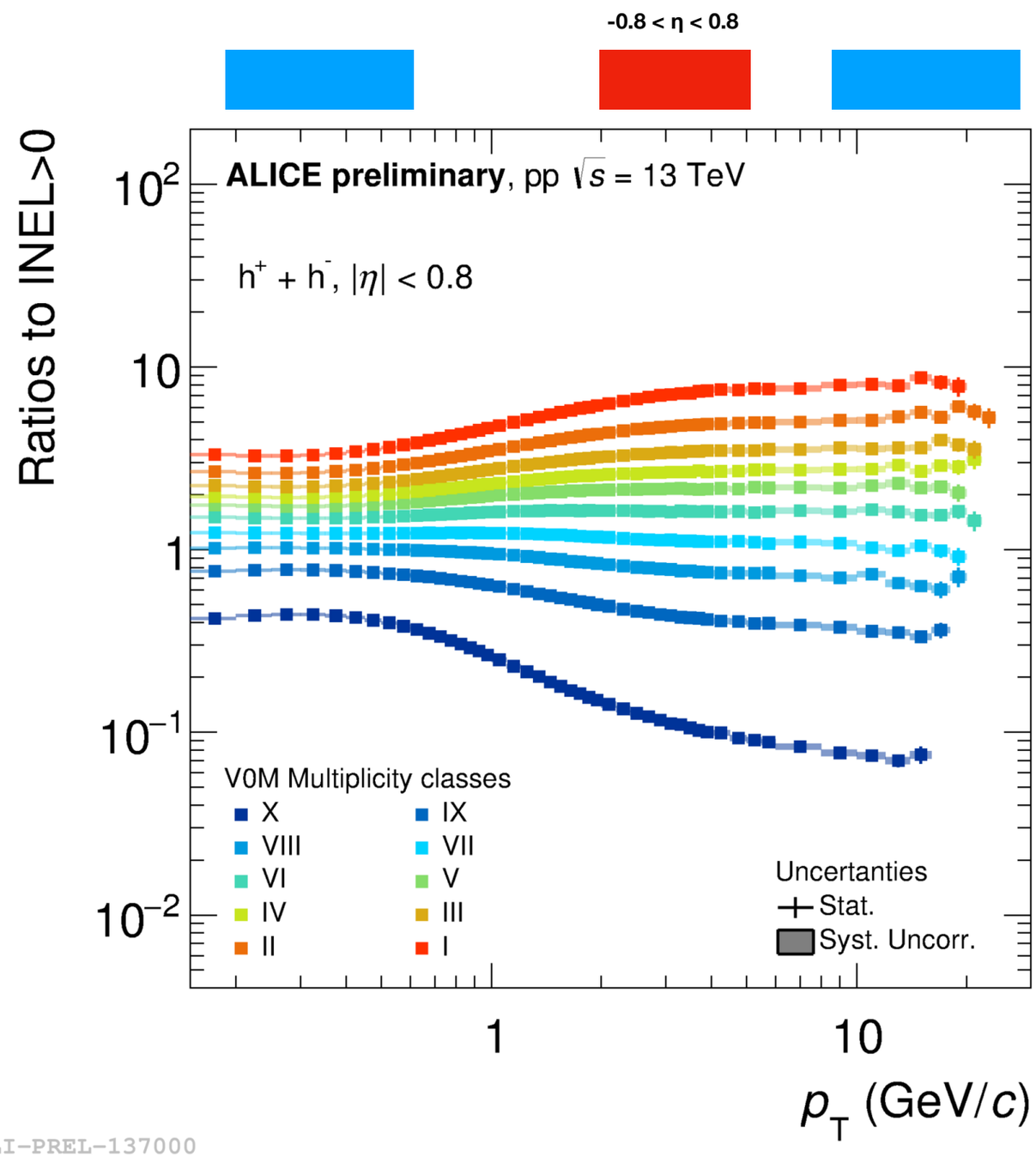
$N_{UE}(p_T)$
$\Rightarrow$
$dN/dp_T(N)$

For independent (incoherent) MPI expect:
dN/dp_T constant at sufficiently high p_T

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

- n^{hard} increases with event activity "centrality"
- ratio to Minimum Bias constant for $p_T > 5$ GeV
- Very different scaling at low and hight p_T

Event Activity Selection in Fwd Direction



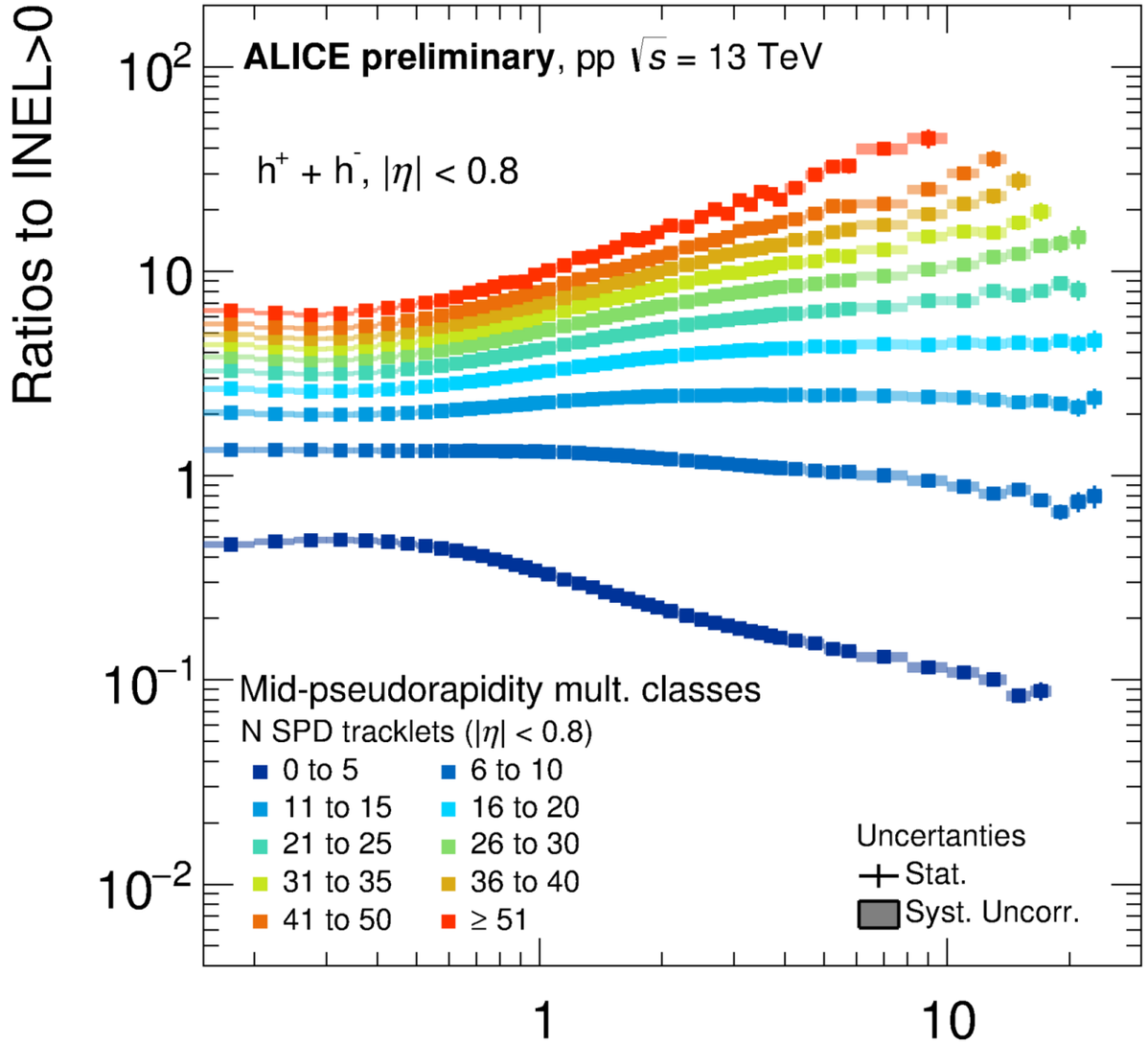
 ALI-PREL-137000

p_T Spectra in Event Activity Classes

Event Activity Selection at mid rapidity

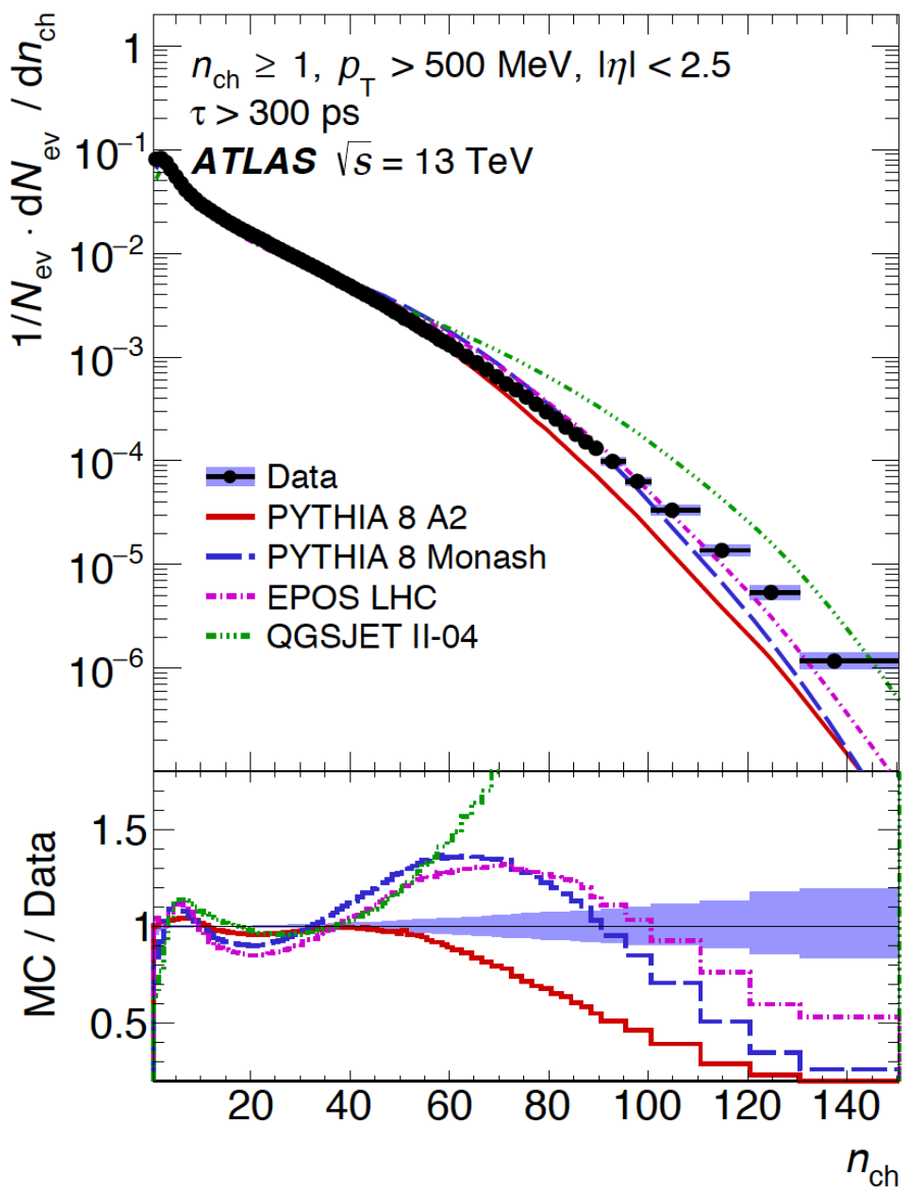
-0.8 < η < 0.8

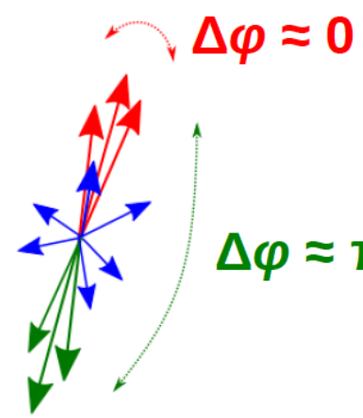
- ratio to MB increases for high event activity
  - jet bias ?
- ratio to MB decreases for low event activity
  - jet veto ?

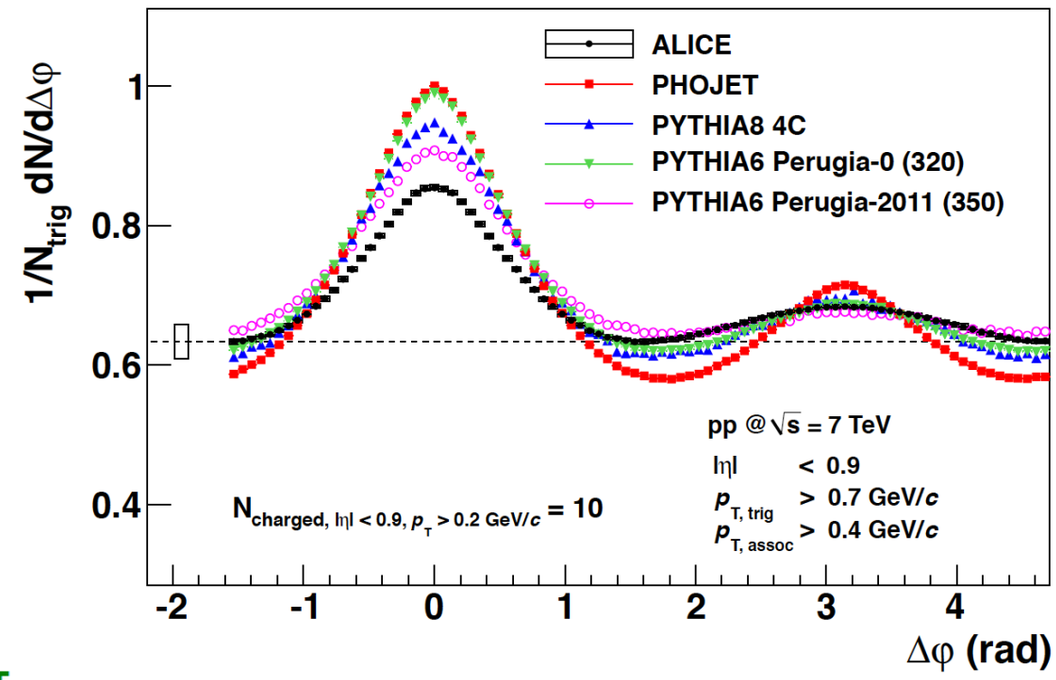


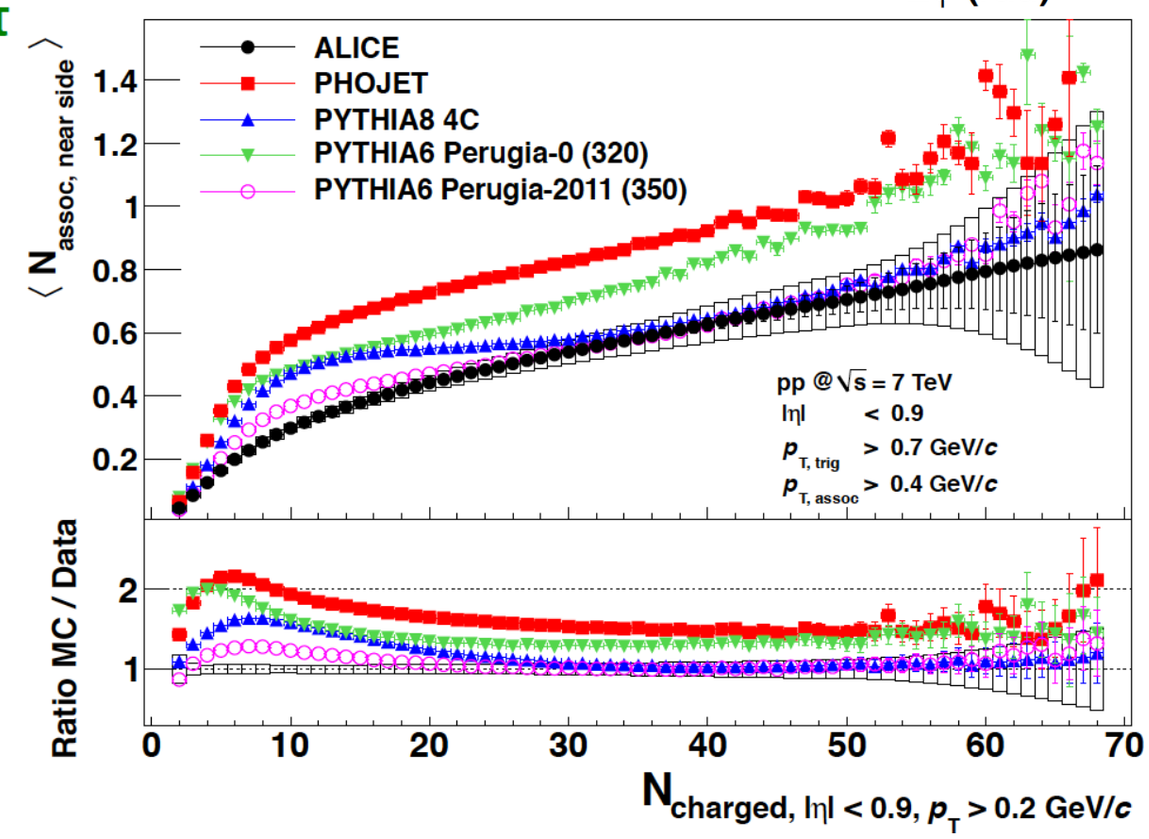
Selection Bias in pp

Events are selected from steeply falling multiplicity distribution









Strong multiplicity dependence of number of particles per mini-jet

Importance of MPI in pp for A-A and p-A

Nuclear Modification Factor R_{AA}:
Ratio of yield of hard process in AA to reference of incoherent superposition of N_{coll} pp collisions.

$$R_{AA}^{cent} = \frac{Y_{\mathrm{AA}}}{T_{AA}^{\mathrm{cent}}\sigma_{\mathrm{hard}}} = \frac{Y_{\mathrm{AA}}}{N_{\mathrm{coll}}^{\mathrm{cent}} Y_{\mathrm{pp}}}$$

Well defined for

- minimum bias: $\langle N_{coll} \rangle = A^2\, \sigma_{pp}/\sigma_{AA}$
- In general: **Yield ~ $\langle N_{coll} \rangle$ x $\langle$Yield per N-N collisions$\rangle$**
  - N-N degrees of freedom integrate out in Minimum Bias

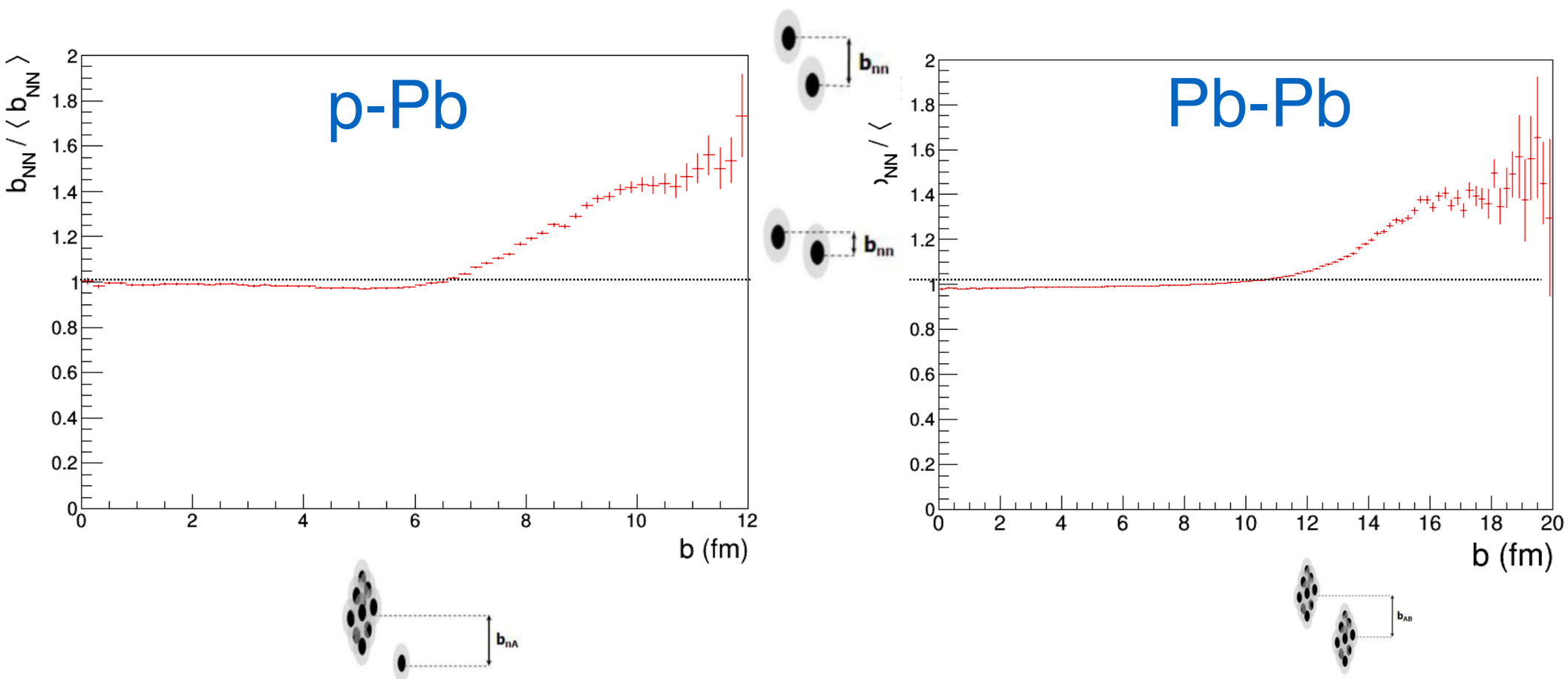
In all other cases (centrality selection) one needs to take into account

- Impact parameter dependent geometrical biases: Jiang Yong Jia, PLB 681 320-325 (2009)
  - Phase space distribution of nucleons in nucleon ≠ protons in bunches
- Correlation between centrality estimator and hard processes
  - via initial and final state of the collision

Geometrical Bias

Unlike bunches of free protons (reference), for p in nuclei
$d\sigma \sim b\, db$ and strong b dependence of nuclear overlap
$\Rightarrow$

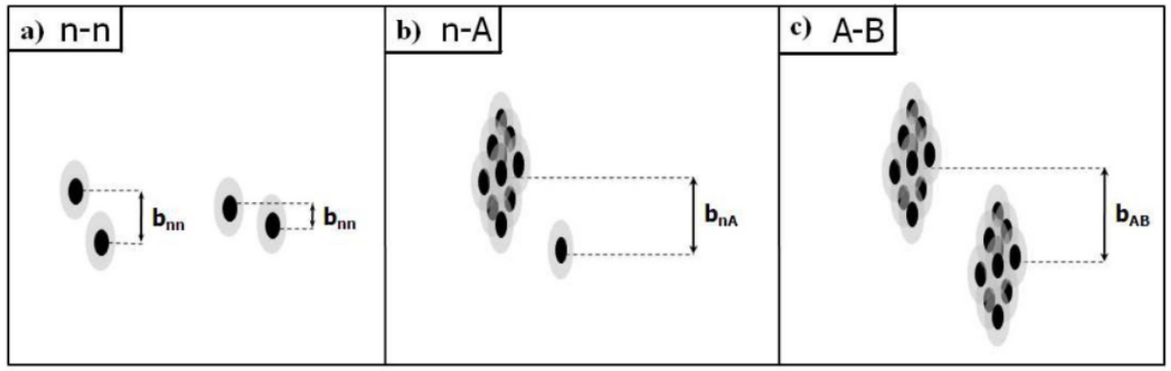
at high b:
increased probability for large N-N impact parameter b_{NN}



Jiang Yong Jia, PLB 681 320-325 (2009)

Geometry Bias in modified Optical Glauber

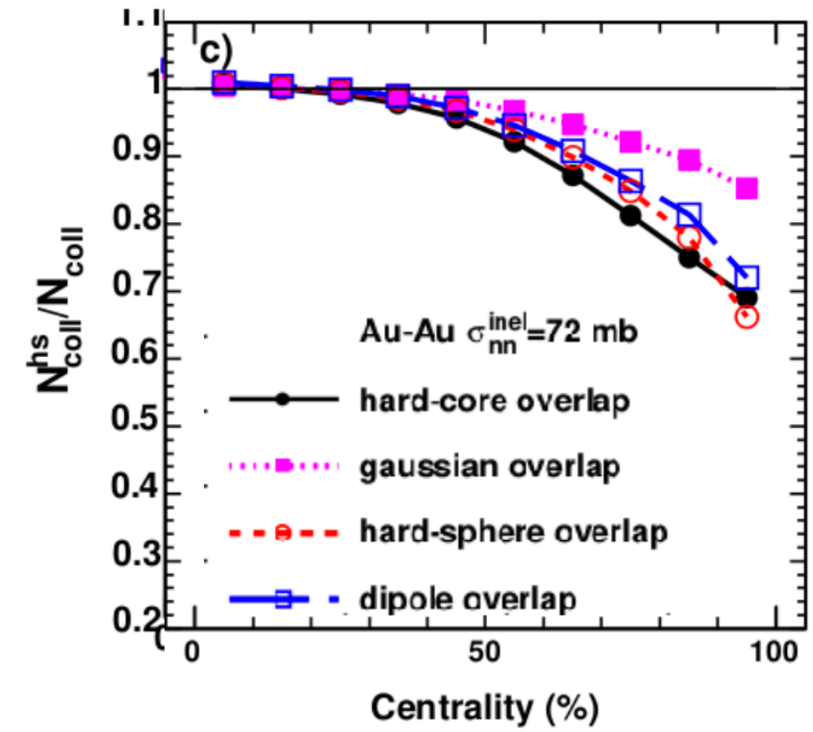
Jiang Yong Jia, PLB 681 320-325 (2009)

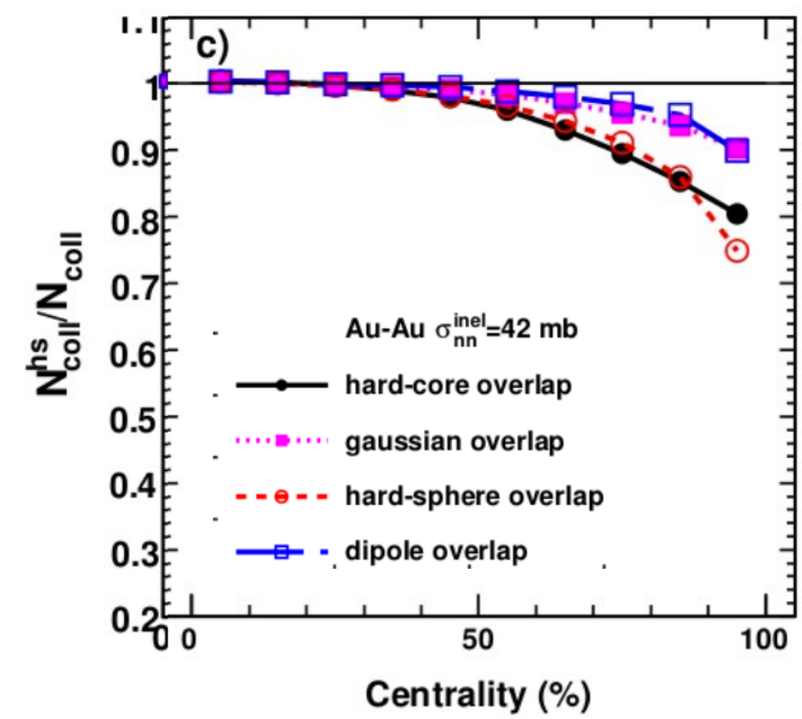


$$T_{\rm AB}(\vec{b}_{AB}) = \int d\vec{b}_A d\vec{b}_B \; T_A(\vec{b}_A) T_B(\vec{b}_B) t(\vec{b}_{AB} - \vec{b}_A + \vec{b}_B)$$

$$= \int d\vec{s} d\vec{b}_{nn} \; T_A(\vec{s}) T_B(\vec{s} - \vec{b}_{AB} + \vec{b}_{nn}) t(\vec{b}_{nn}).$$

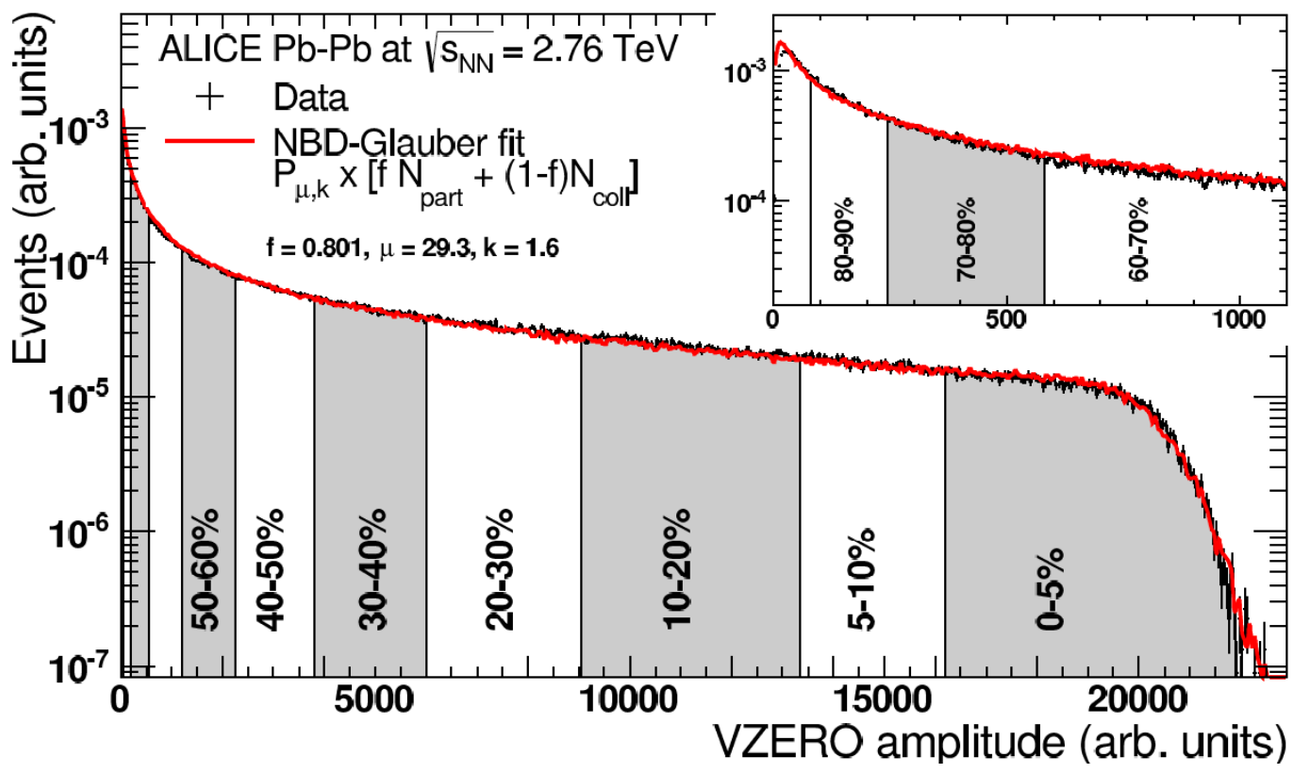
$$N_{\rm coll} = T_{\rm AB}\, \sigma_{\rm NN}$$





Including an impact parameter dependent nucleon-nucleon overlap function can lead to 10-20% variation of $N_{\rm coll}$ for peripheral collisions.

N_{coll} (N_{part}) from Glauber Fit



Model centrality estimator as

$$sources \otimes particle\ production$$

$$P_{N_{\text{ancestor}}} \otimes NBD$$

$$N_{\text{ancestor}} = f(N_{\text{part}}, N_{\text{coll}})$$

$$P_{\text{NBD}}(n;\mu,k) = \frac{\Gamma(n+k)}{\Gamma(n+1)\Gamma(k)} \frac{\left(\mu/k\right)^n}{\left(1+\mu/k\right)^{n+k}}$$

$$\frac{\sigma}{\mu} = \sqrt{\frac{1}{\mu} + \frac{1}{k}}$$

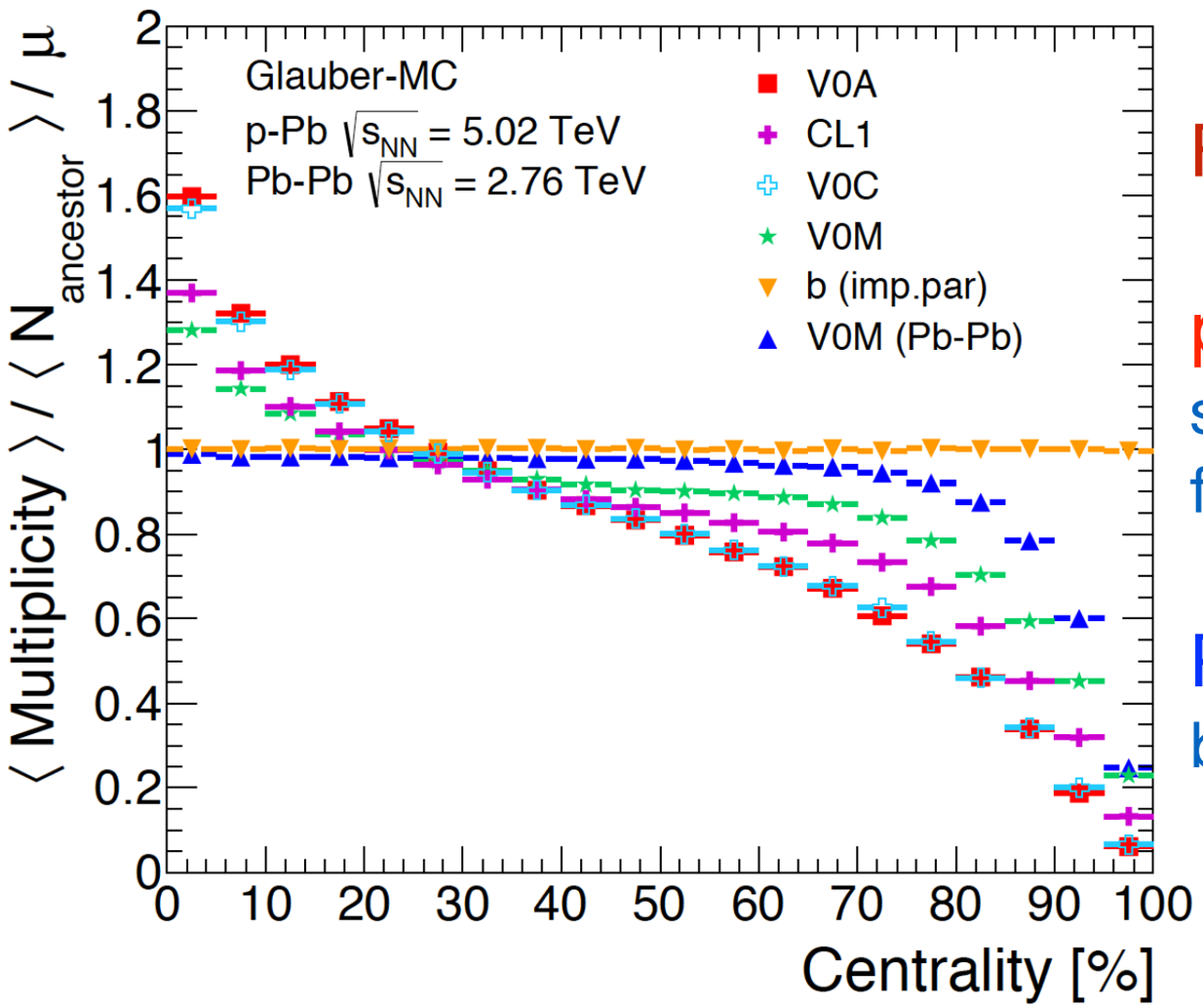
Includes fluctuations of number of particles per ancestor (soft particle production)

- not important for large $N_{ancestor}$
  - central limit theorem
- significant effects when $N_{ancestor}$ small
  - p-A
  - peripheral A-A

Fluctuations are raison d'être of Glauber Fit

Consequence for centrality classes:
multiplicity per ancestor deviates from fit value μ

Bias on Soft Particle Production



From ALICE Glauber Fit

p-Pb

strong bias

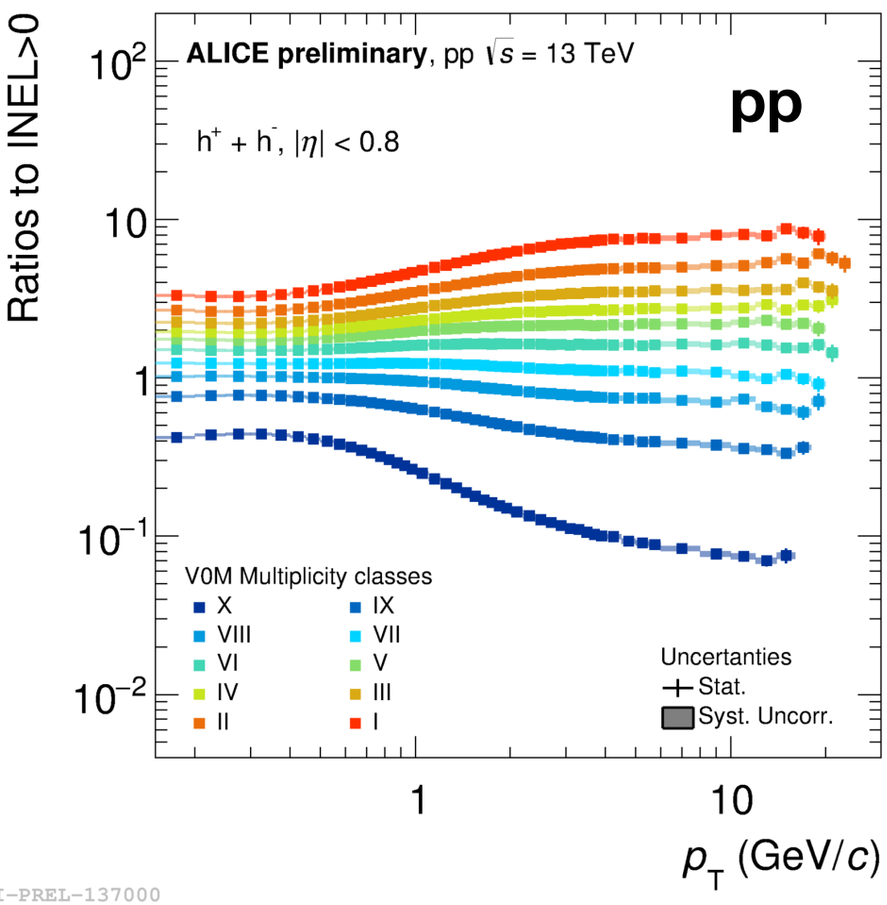
fwd n-energy used as centrality estimator

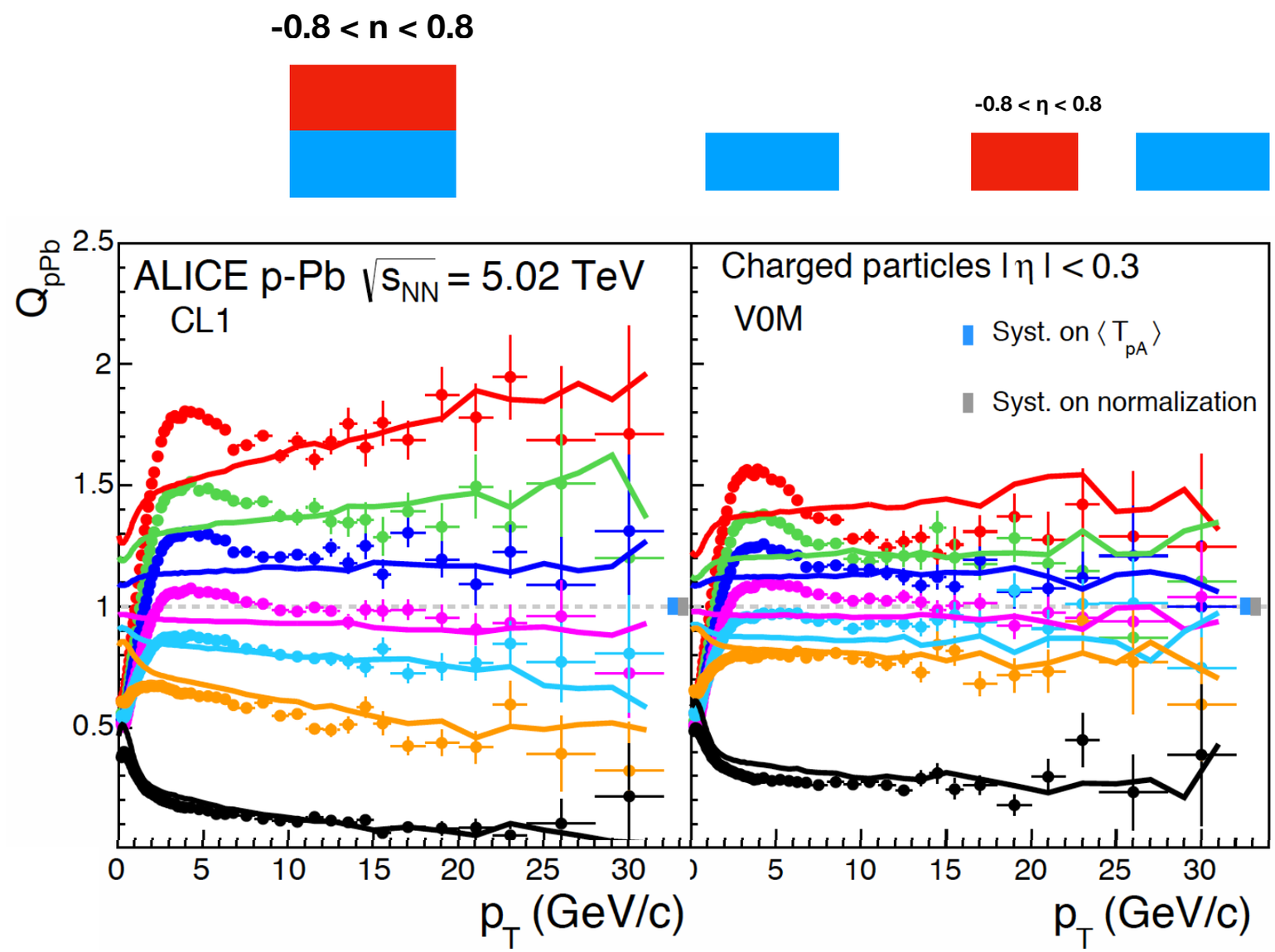
Pb-Pb

biased for peripheral collisions

- Will affect hard production if hard and soft processes are correlated
- In standard Glauber-Fit Approach no correlation between soft particle fluctuations and initial state fluctuations.

Multiplicity Bias in p-Pb

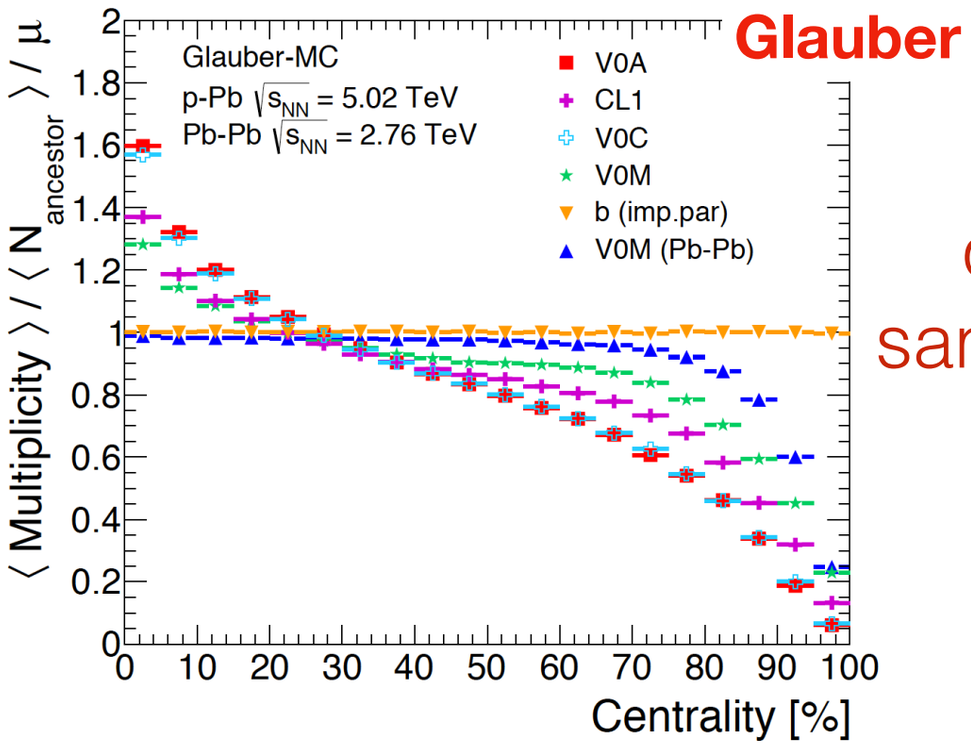




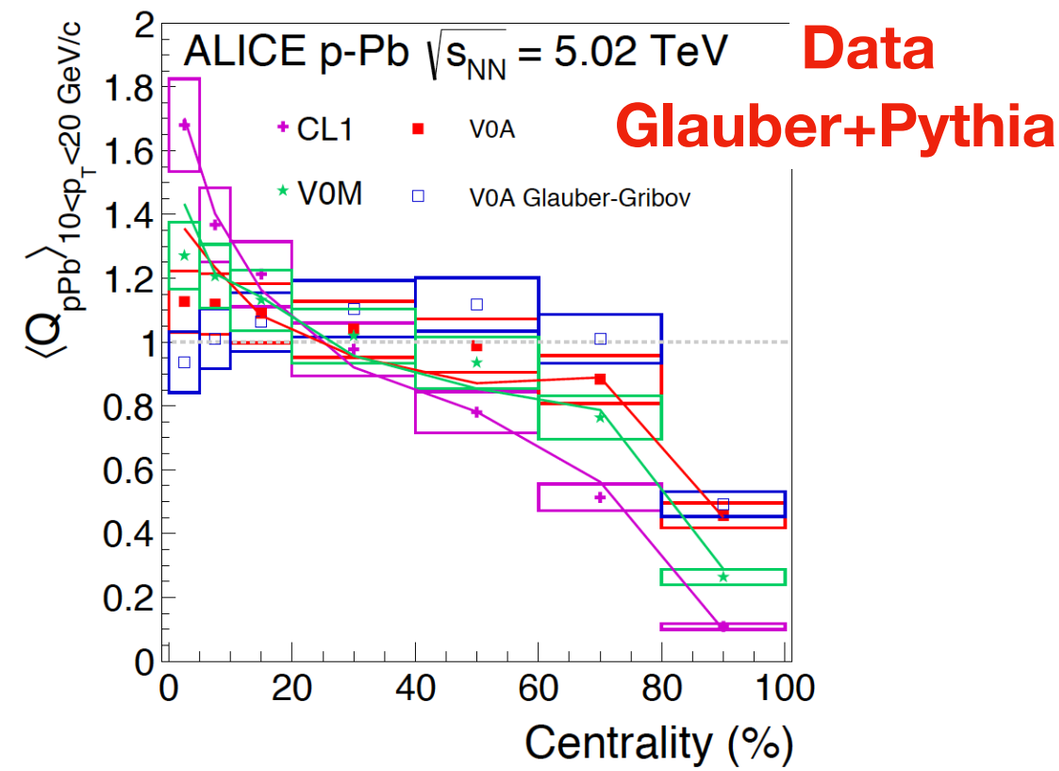
Phys. Rev. C 91 (2015) 064905

Modelling of the Multiplicity Bias

bias on soft particle production

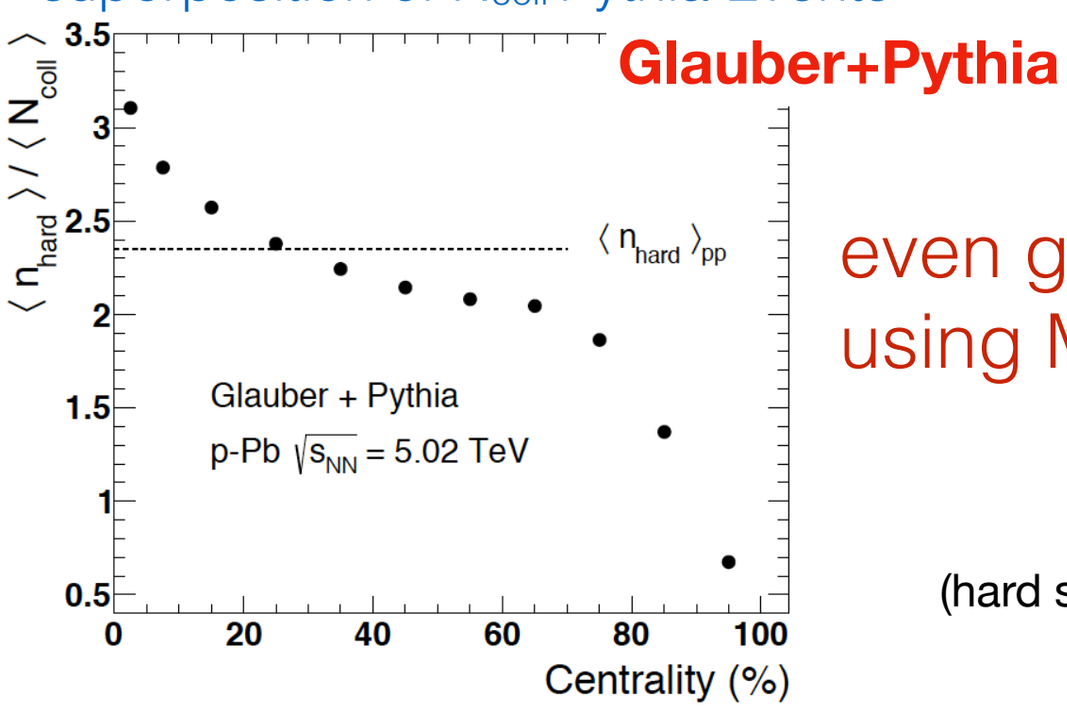


bias on hard particle production



qualitatively same behaviour!

superposition of N_{coll} Pythia Events

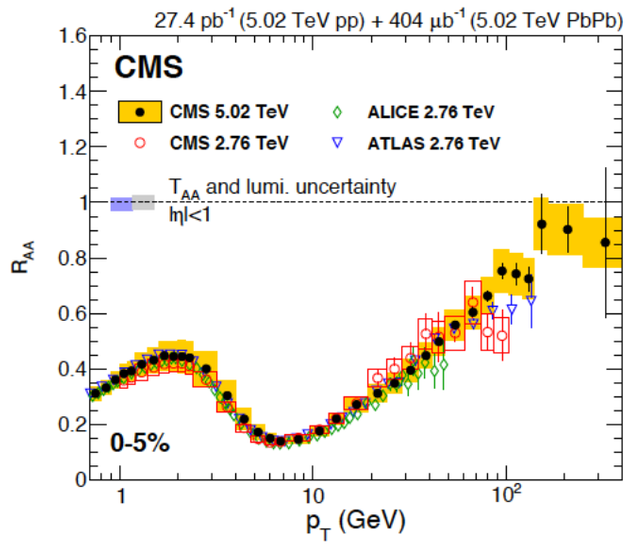


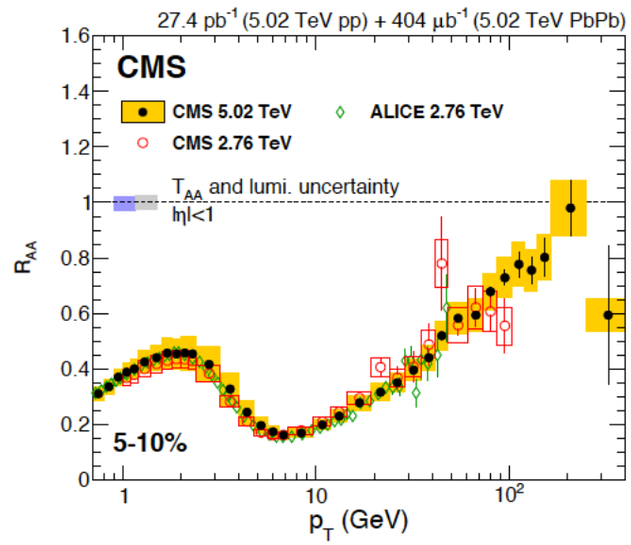
even good quantitative understanding using MPI model (Pythia)

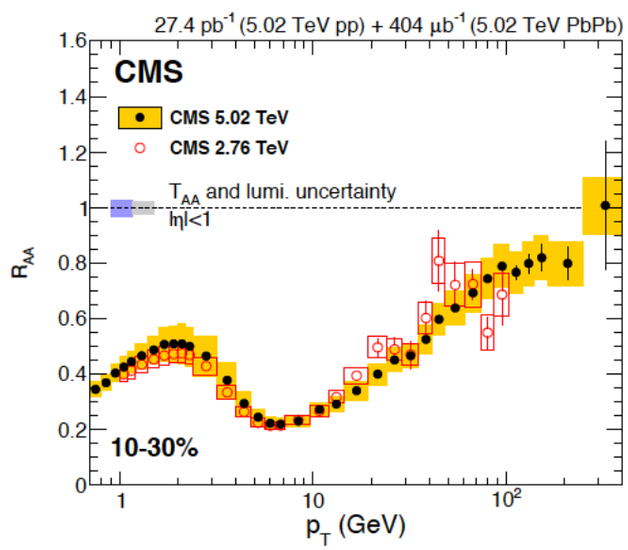
(hard soft correlation: see also DV Perepelitsa, PA Steinberg arXiv:1412.0974)

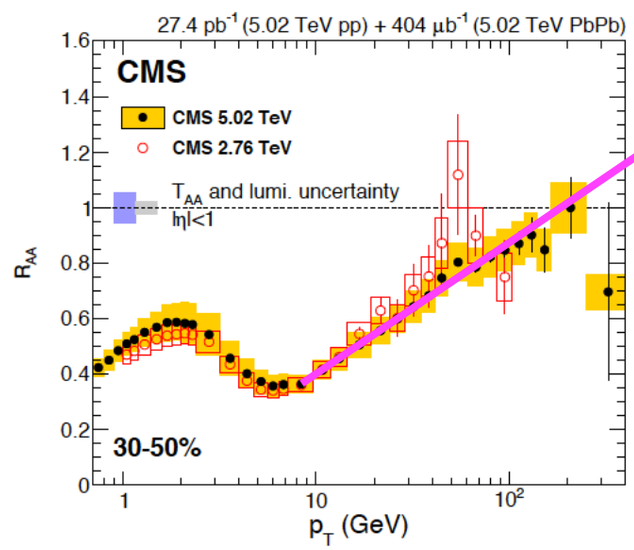
Inclusive Hadron R_{AA} in Pb-Pb

JHEP 04 (2017) 039

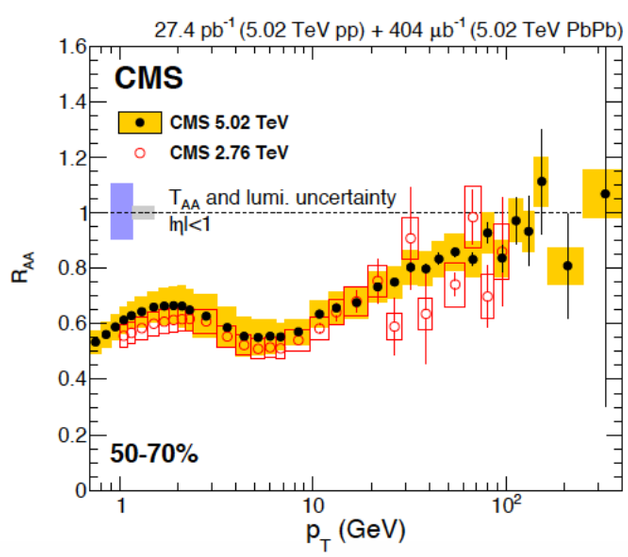


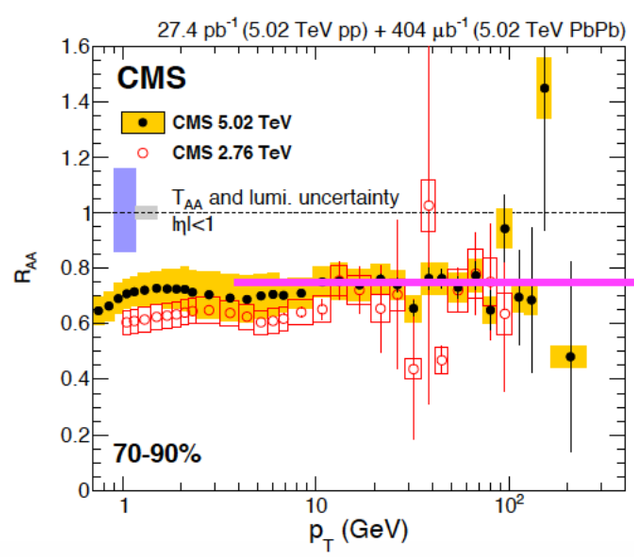






Rising and approaching 1



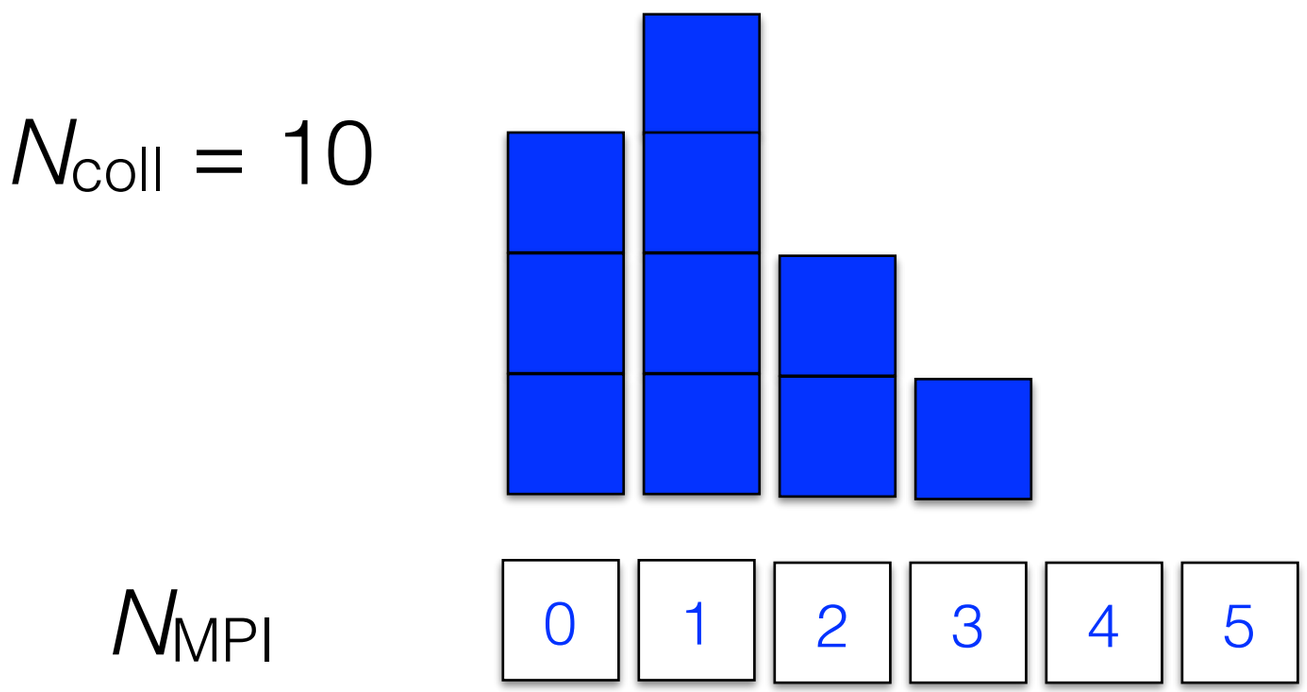


constant around 0.8

Selection bias ?

HG-Pythia

C Loizides, AM, arXiv:1705.08856



- Generate N_{MPI} distribution using HIJING Glauber
- Generate, select and overlap Pythia Events such that the N_{MPI} distribution is reproduced.
- Analyse in bins of forward multiplicity

RAA for peripher Au-Au and Pb-Pb

C Loizides, AM, arXiv:1705.08856

HIJING

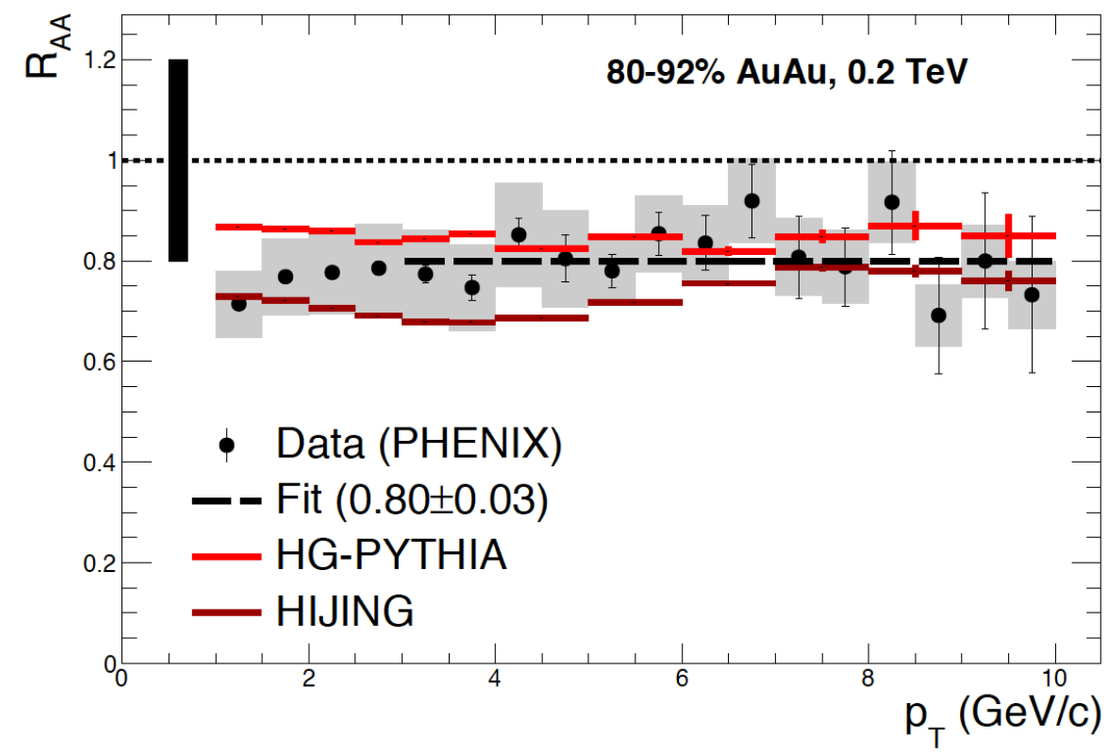
- No quenching, no shadowing but
  - ad-hoc momentum conservation
  - multiple scattering
- Does not give $R_{AA} \rightarrow 1$ at high p_T for central collisions

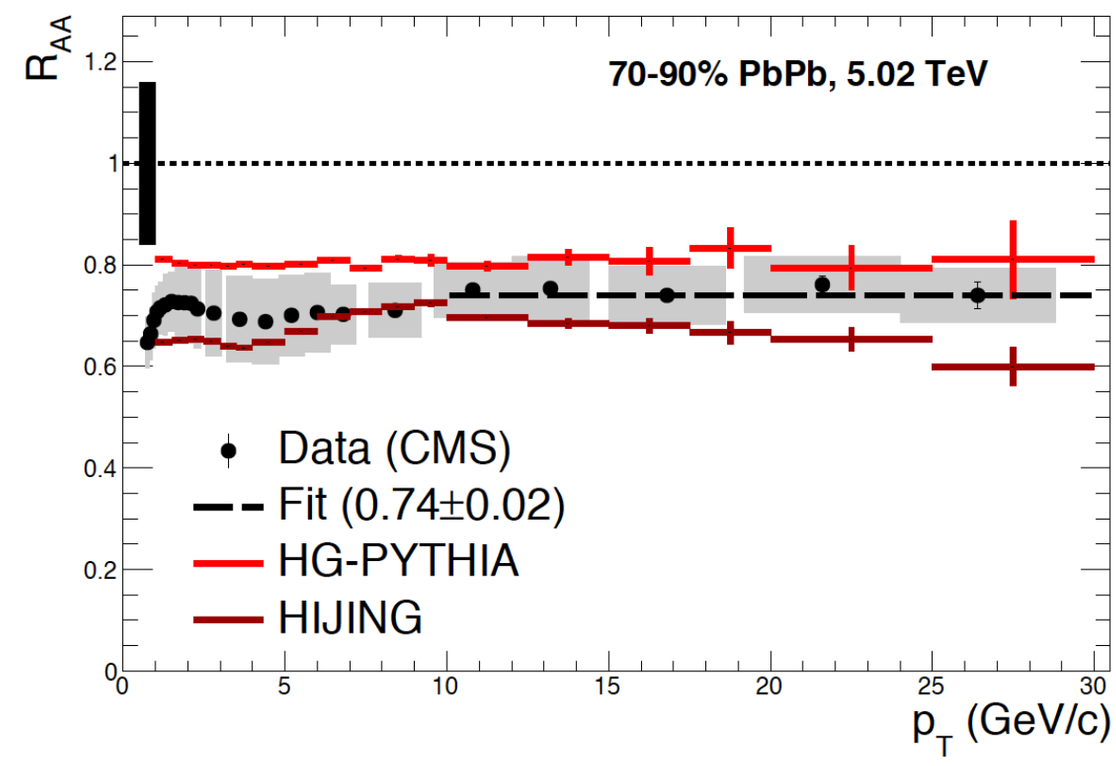
HG-Pythia:

- use as HIJING n_{hard}
- superimpose PYTHIA (Perugia 2011) events
- does not reproduce multiplicity

- Results obtained using event ordering (slicing) for forward multiplicity (2.5<|η|<5)

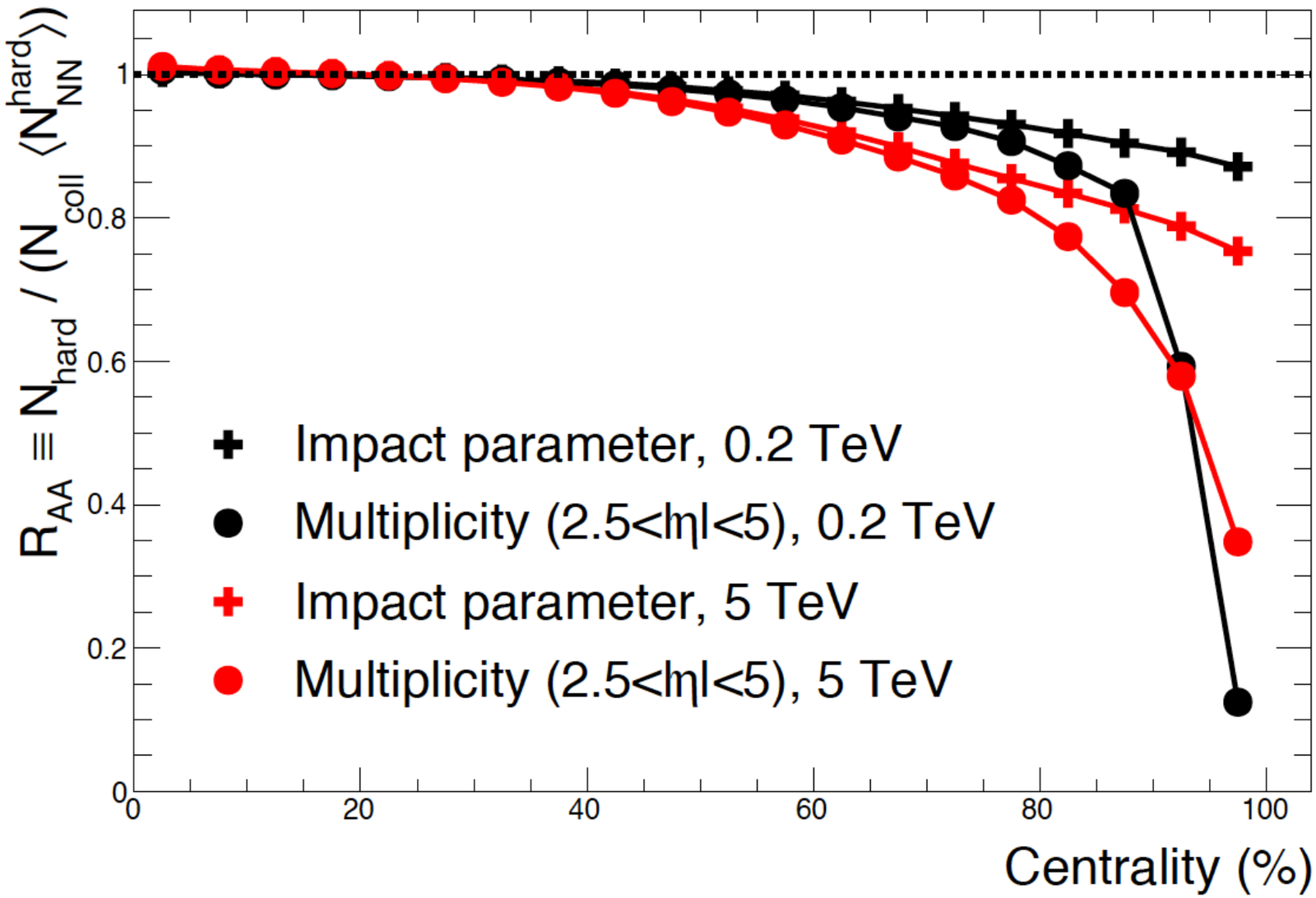
Multiplicity bias can cause apparent suppression!





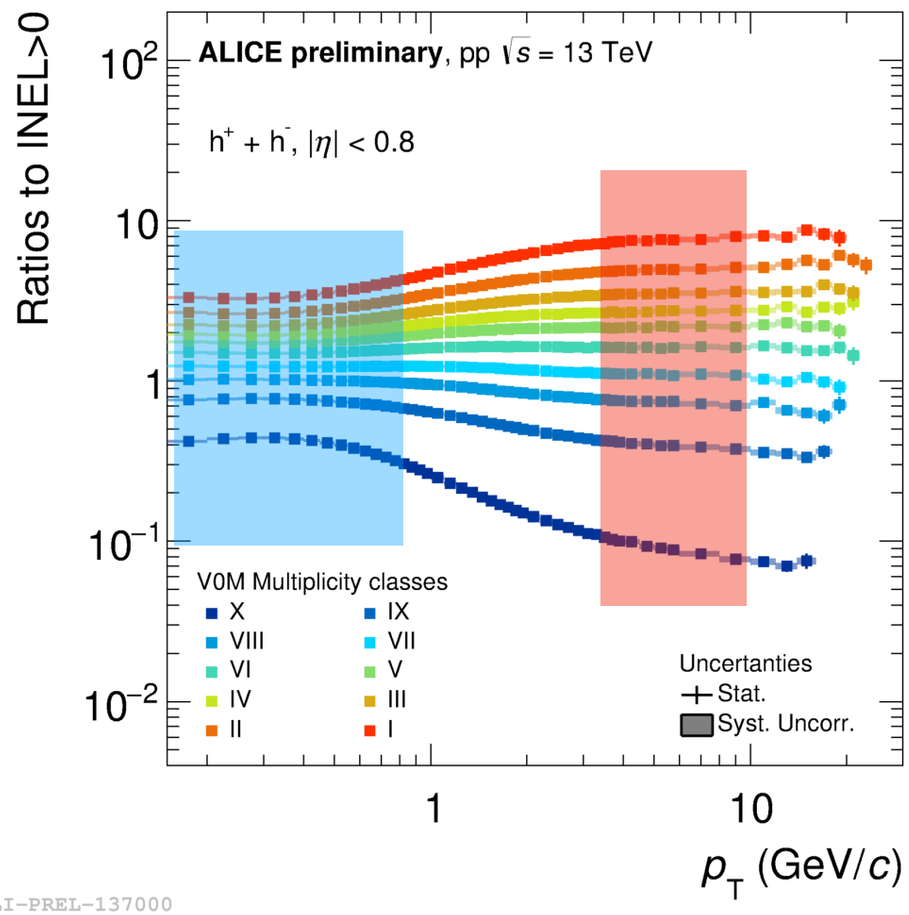
Geometrical and Multiplicity Bias

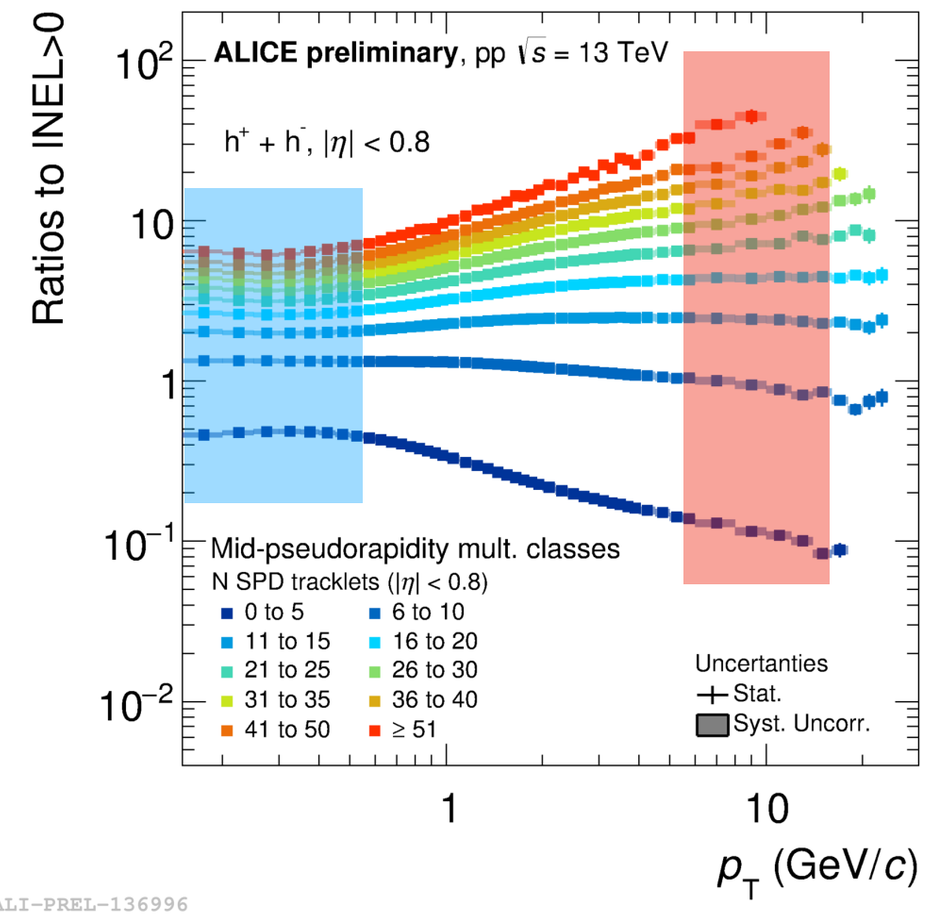
C Loizides, AM, arXiv:1705.08856

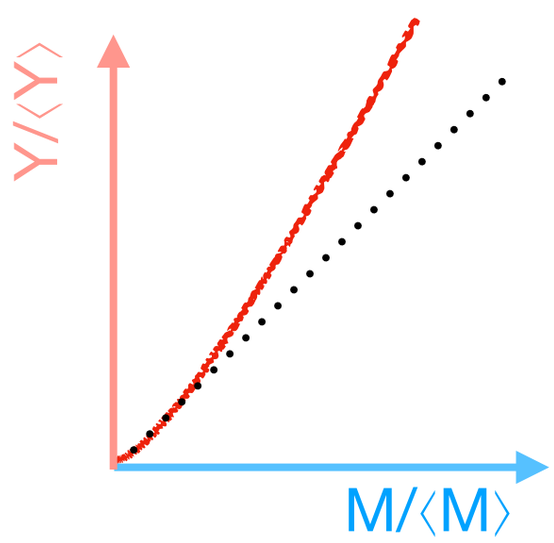


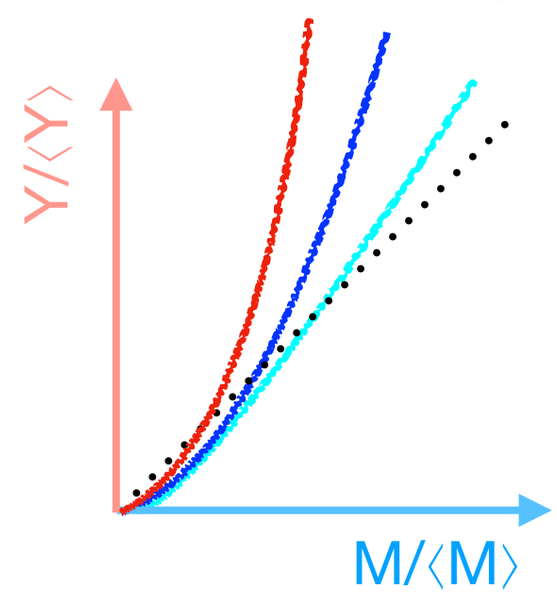
Peripheral collisions strongly affected by multiplicity bias.

Multiplicity Dependence of Hard Processes in pp

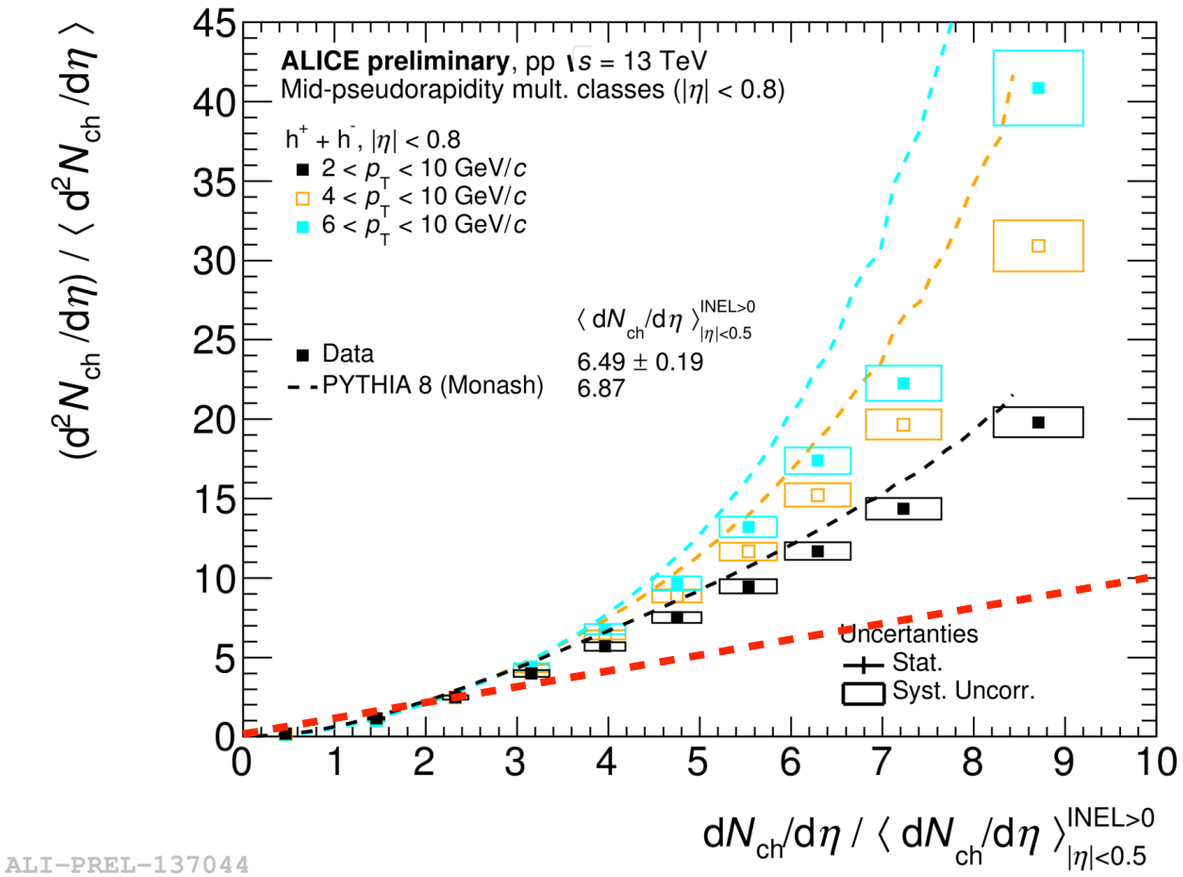


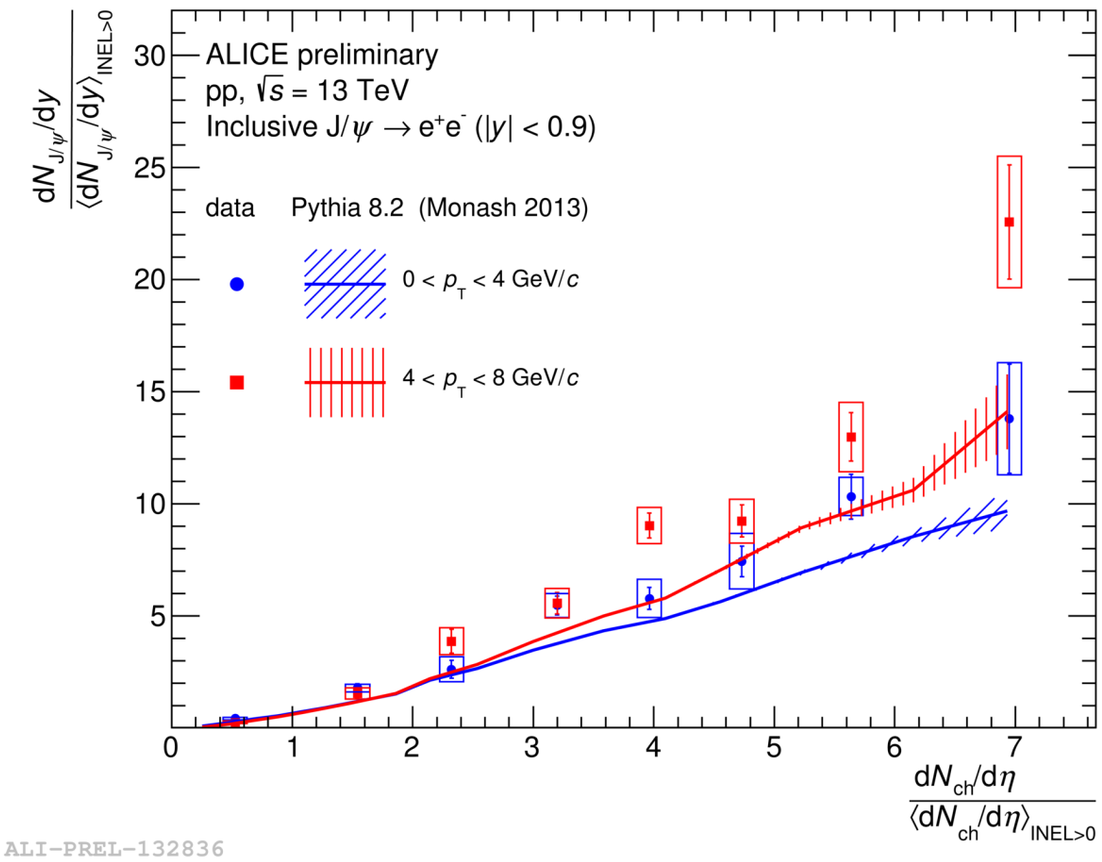






Universality of Hard-Soft Correlations?



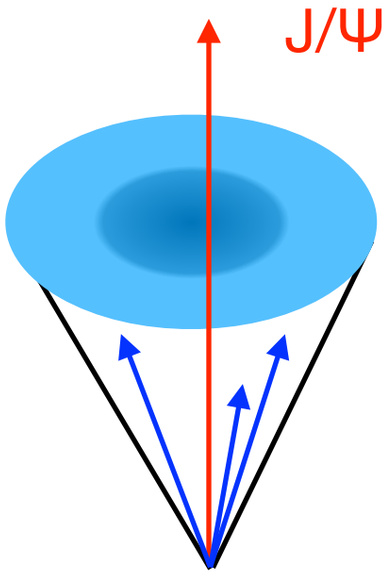


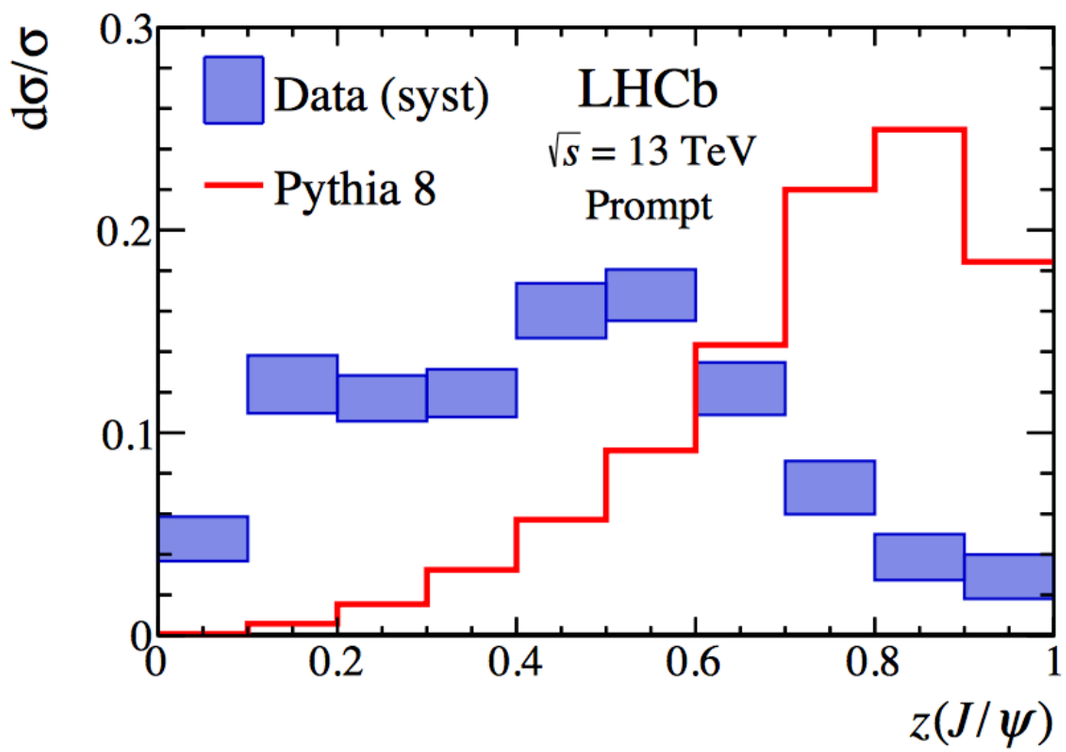
Universality can be broken by differences in the particle distribution in final state.

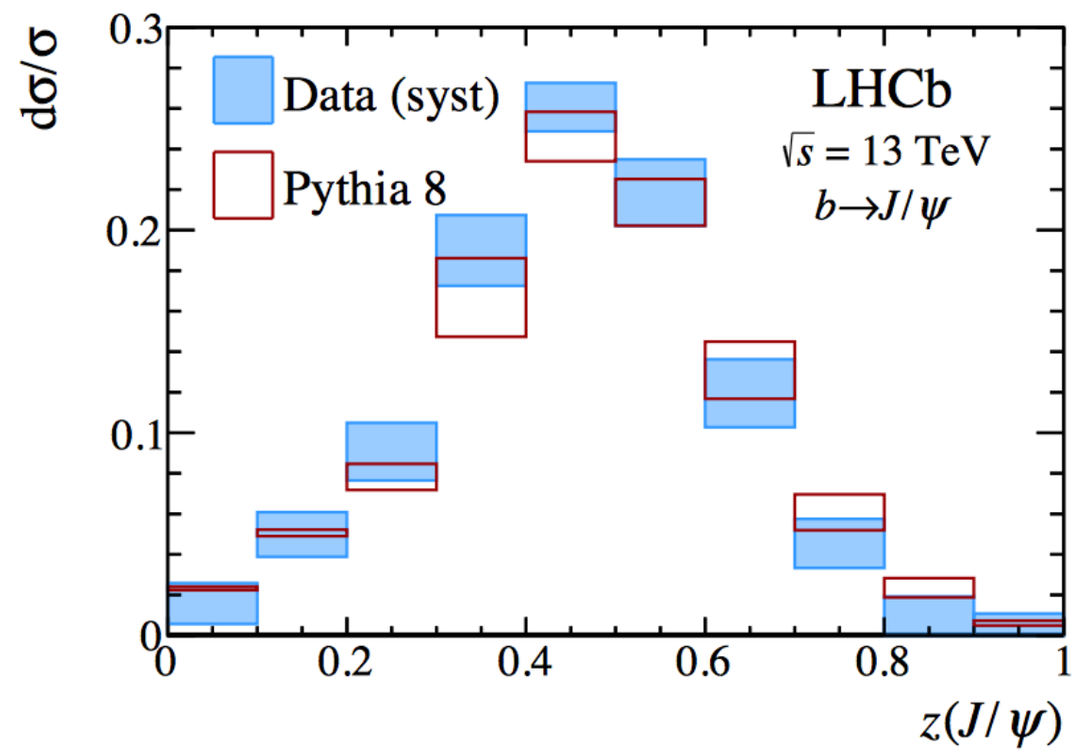
F. Fionda Thu pm

Prompt J/Ψ Production in Jets

PRL 118, 192001 (2017), arXiv:1701.0511





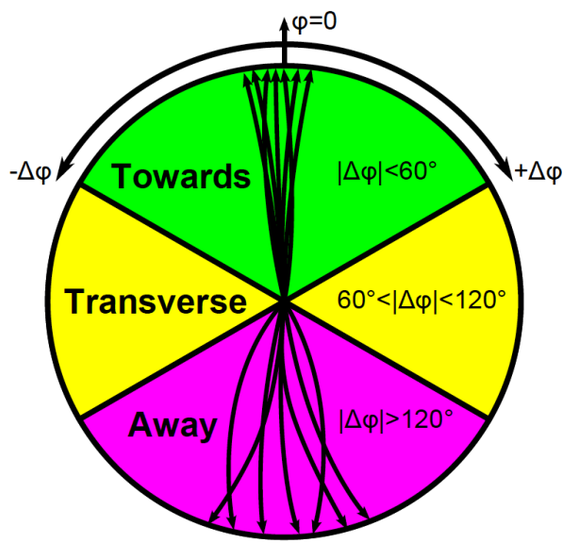


- Only fraction of jet energy carried by J/Ψ
- Implies non-isolation of prompt J/Ψ
- Not reproduced by Pythia8

M Schmelling Tue pm

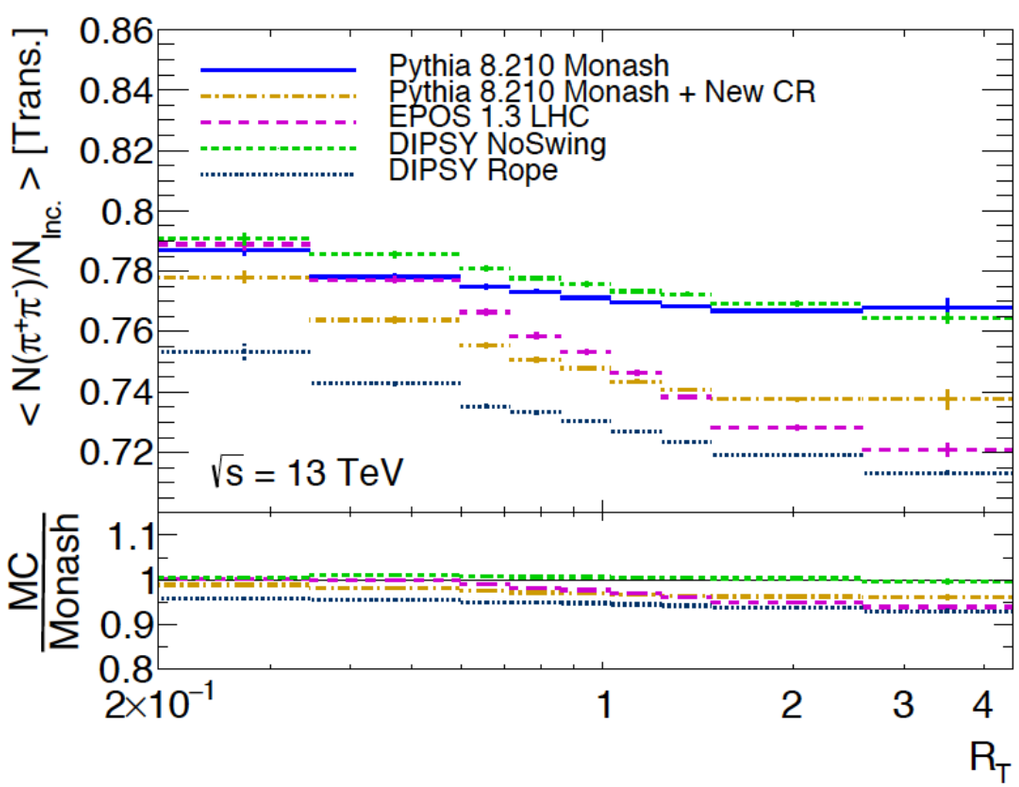
Relative Transverse Activity Classifier

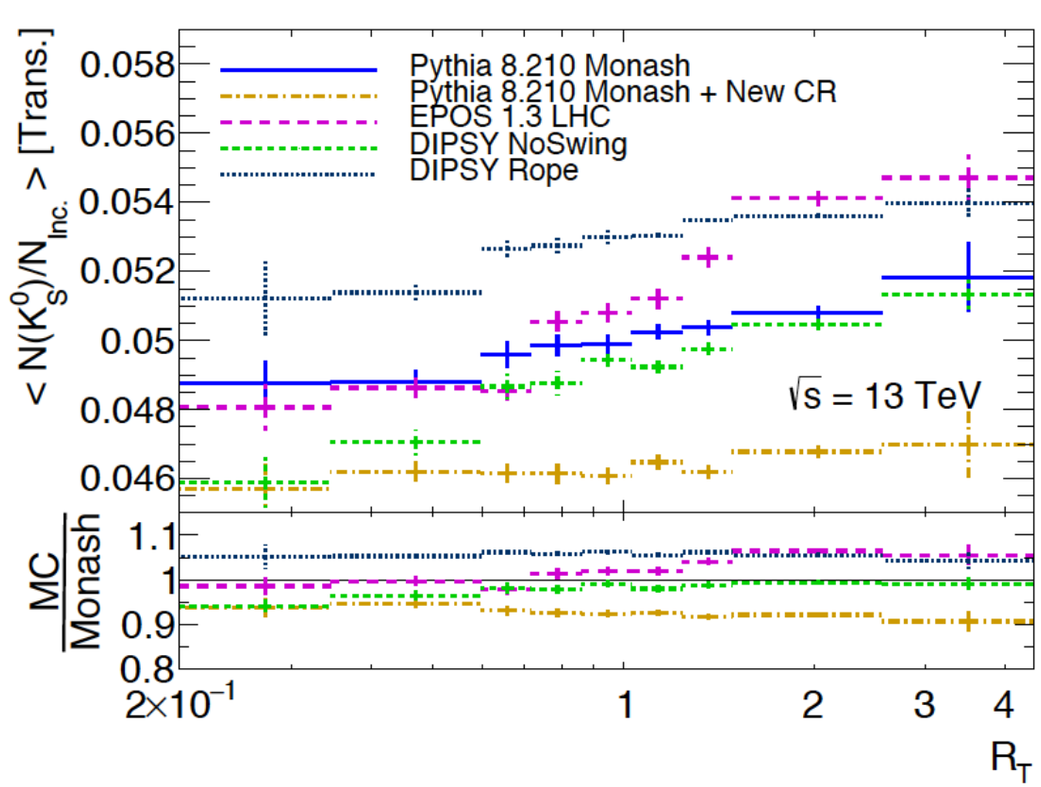
T Martin, P Skands, S Farrington, EPJ C 2016, 76(5), 1-12



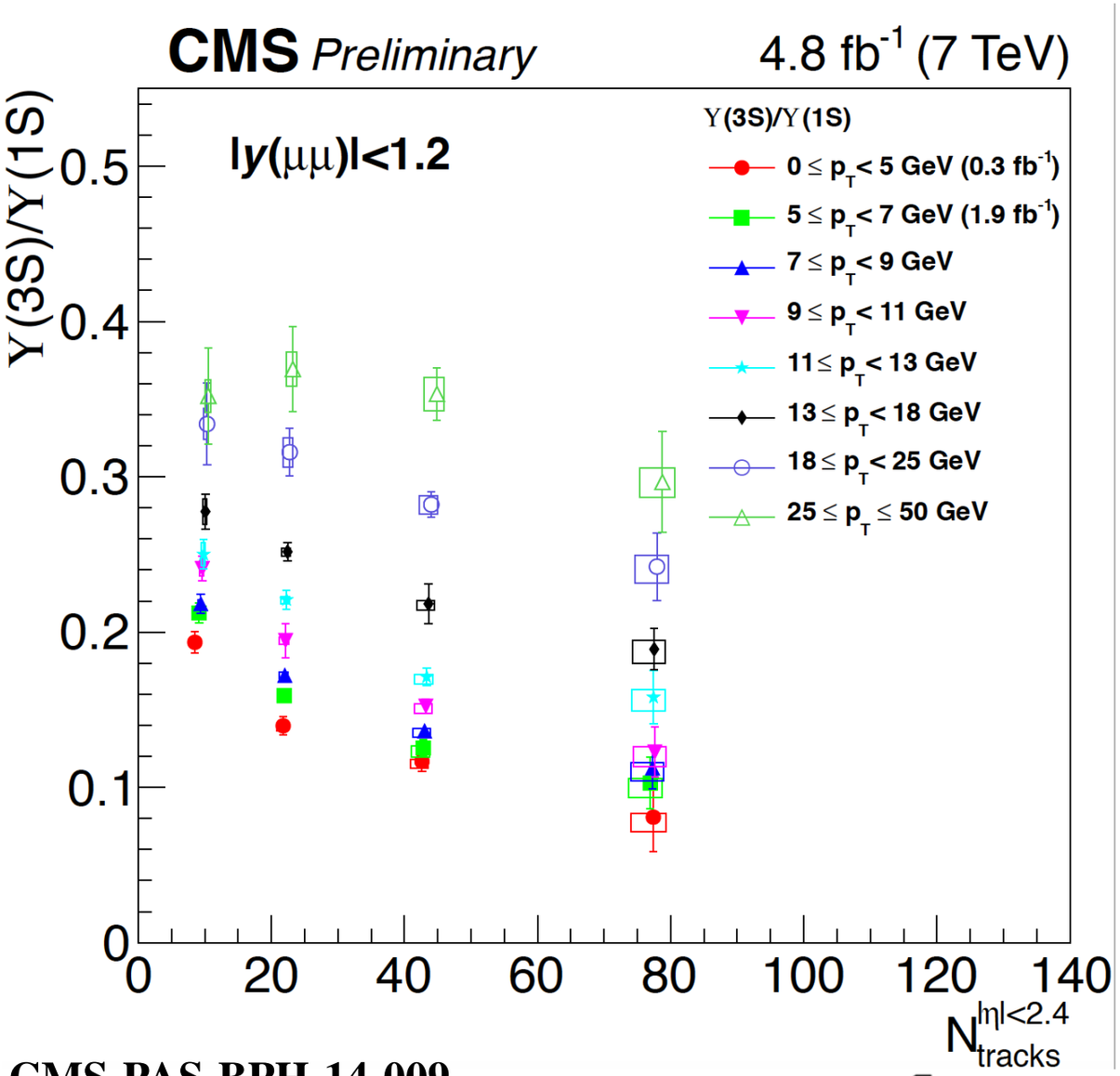
$$R_T = \frac{N_T}{\langle N_T \rangle}$$

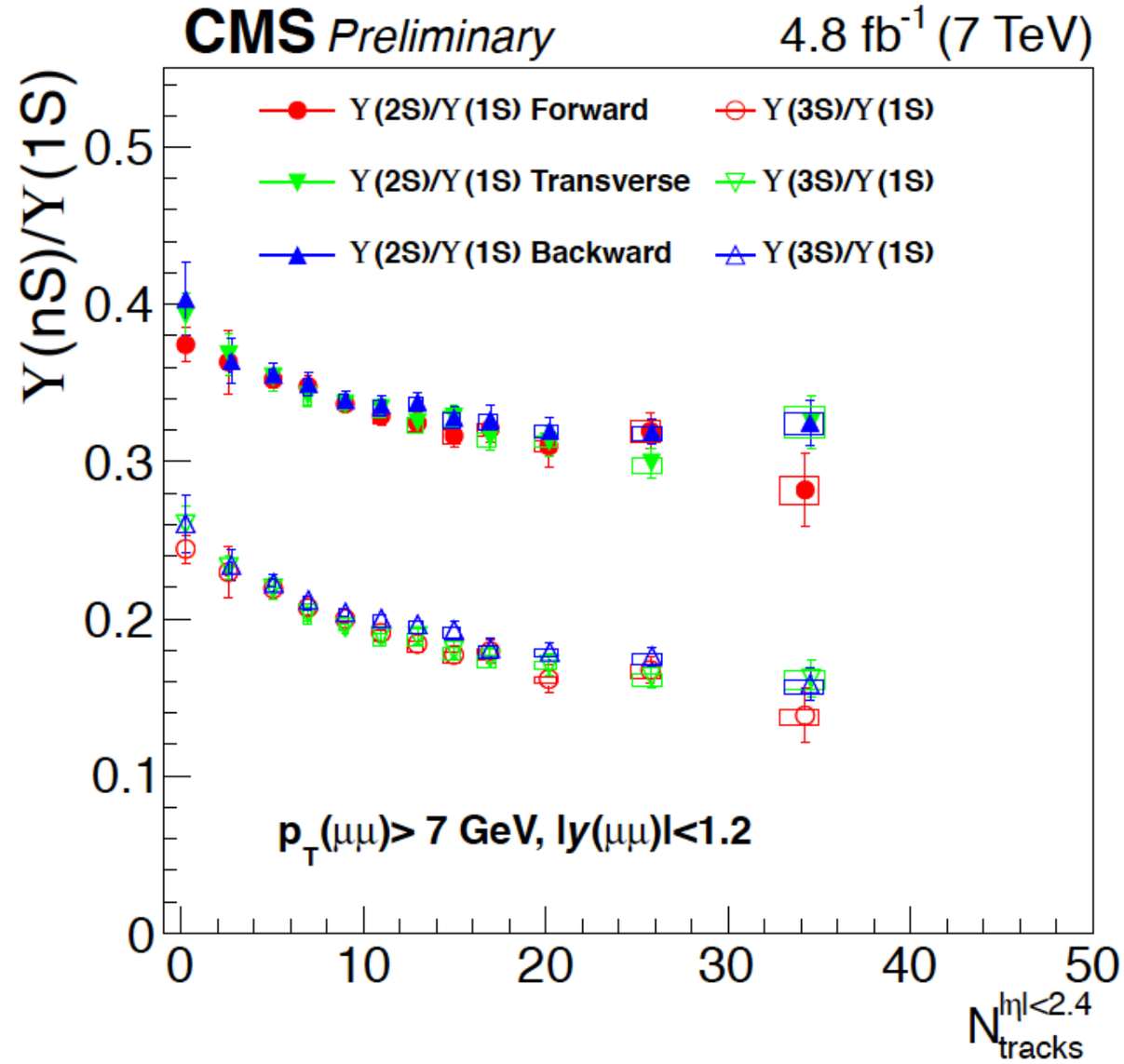
Multiplicity dependence excluding leading jet



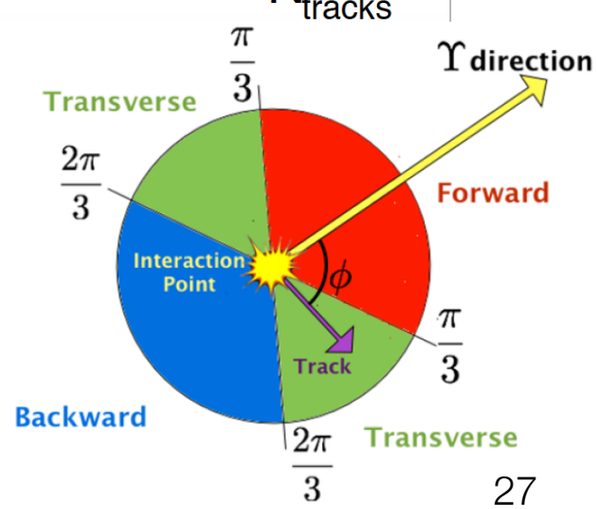


Υ(ns) Production Ratios vs Multiplicity





CMS-PAS-BPH-14-009



***N*-dependence in diff. regions rel to Υ**
⇒ exclusion of trivial bias

Summary

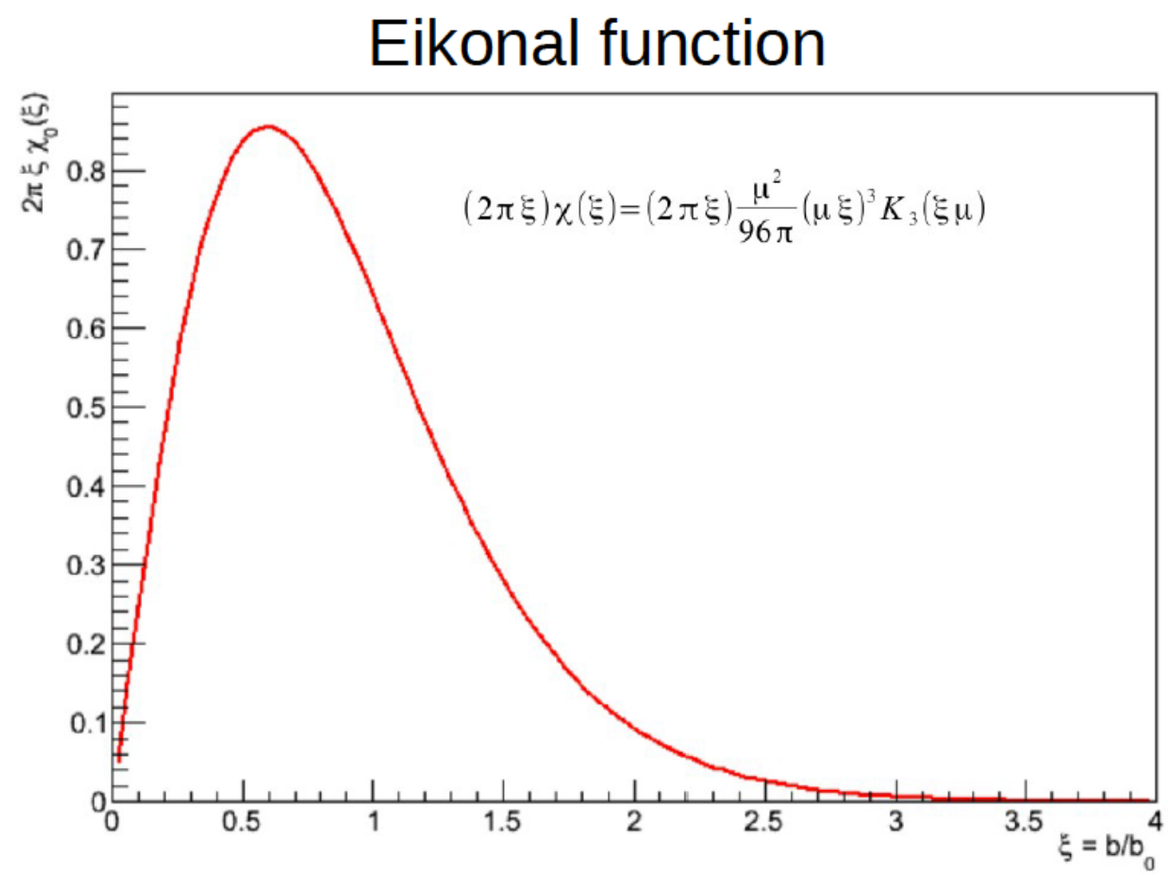
- Understanding MPI in pp is important for interpretation of high p_T probes in heavy ion collisions
- Toy model studies based on MPI suggest that apparent suppression in very peripheral AA originates from biases. Relevant for
  - all hard probes
  - at all energies

MPI in Pb-Pb: HIJING Glauber (HG)

$$\mathrm{d}\sigma_{inel} = 2\pi b_{NN}\mathrm{d}b_{NN}\left[1-\mathrm{e}^{-(\sigma_{\mathrm{soft}}+\sigma_{\mathrm{soft}})T_{\mathrm{NN}}(b_{\mathrm{NN}})}\right]$$

$$P\left(n^{\mathrm{hard}}\right) = \frac{\left\langle n^{\mathrm{hard}}\right\rangle^{n^{\mathrm{hard}}}}{n^{\mathrm{hard}}!}\mathrm{e}^{-\left\langle n^{\mathrm{hard}}\right\rangle}$$

$$\left\langle n^{\mathrm{hard}}\right\rangle = T_{\mathrm{NN}}(b)\sigma_{\mathrm{hard}}$$



Initial state correlation between hard and soft particle production through N-N impact parameter.