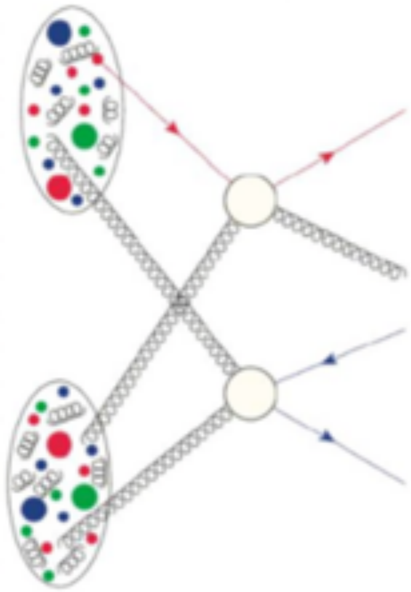
Multiple **P**arton-Parton **I**nteractions: from pp to A-A

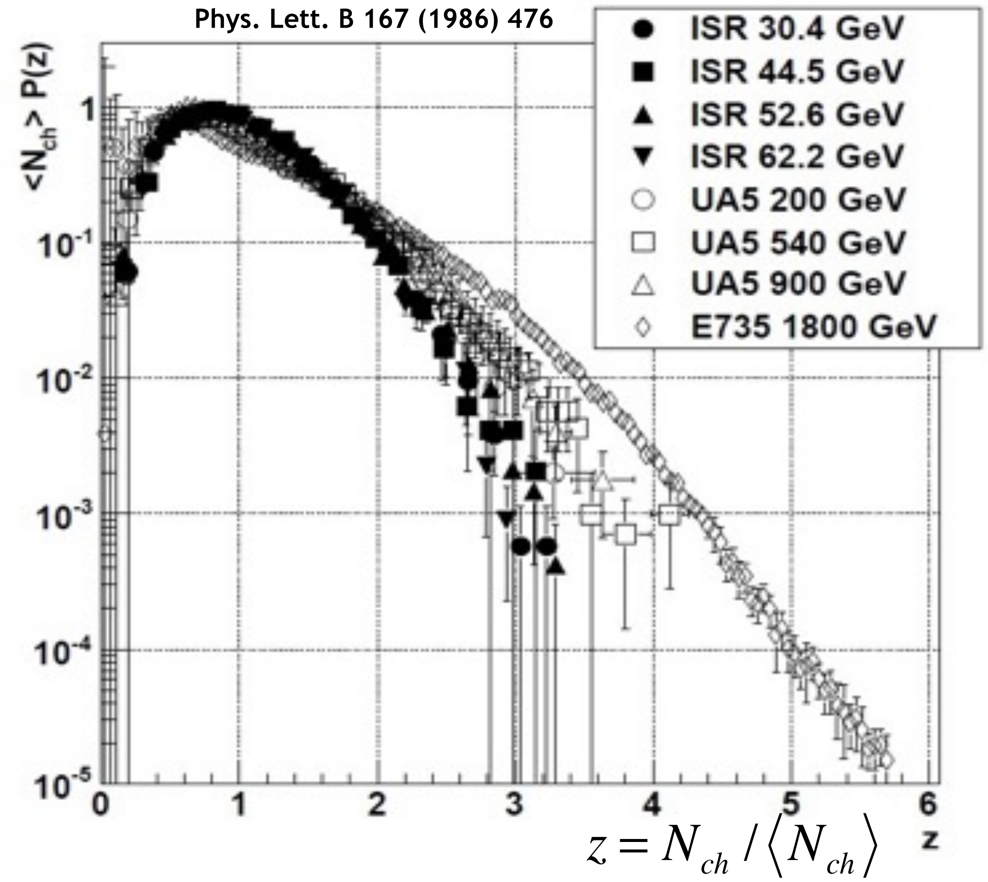
Andreas Morsch
CERN

QCD Challenges at LHC
Taxco, Mexico, Jan 18-22 (2016)

Multiple Parton-Parton Interactions



$$Q_i^2 \gg \Lambda_{QCD}^2$$



"self normalised"

- Theoretical basis to understand
  - Global event properties of non-diffractive pp collisions
    - Multiplicity distribution
      - deviation from KNO scaling for $\sqrt{s} > 200$ GeV
    - Underlying event of hard processes
    - Forward-Backward Correlation
    - Increase of mean p_T with multiplicity
- Implemented in many event generators (Pythia, Herwig, Sherpa …)

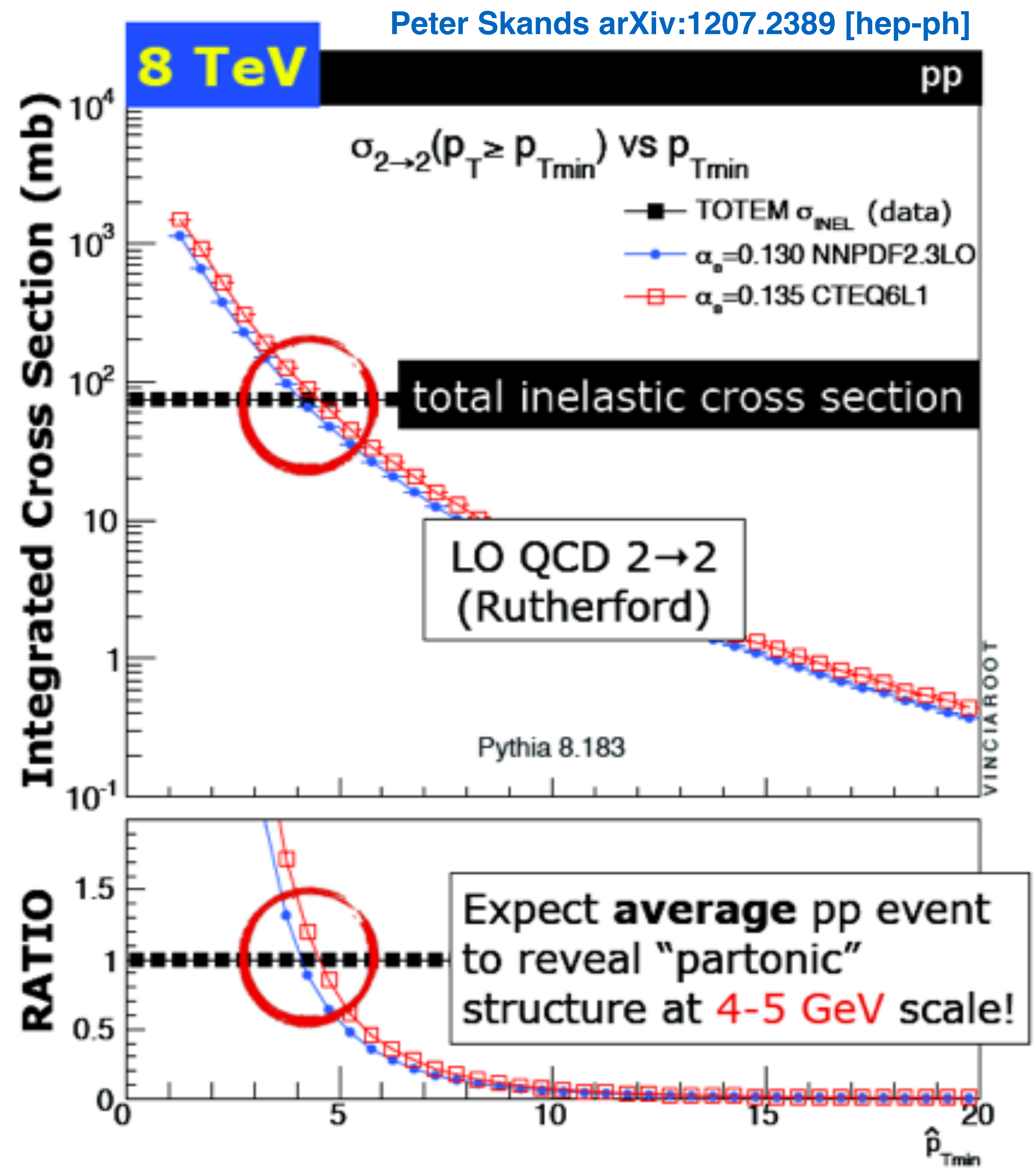
- Straightforward interpretation of pQCD $\sigma_{2\to2} > \sigma_{tot}$

Hard and Total Cross-Section

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

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

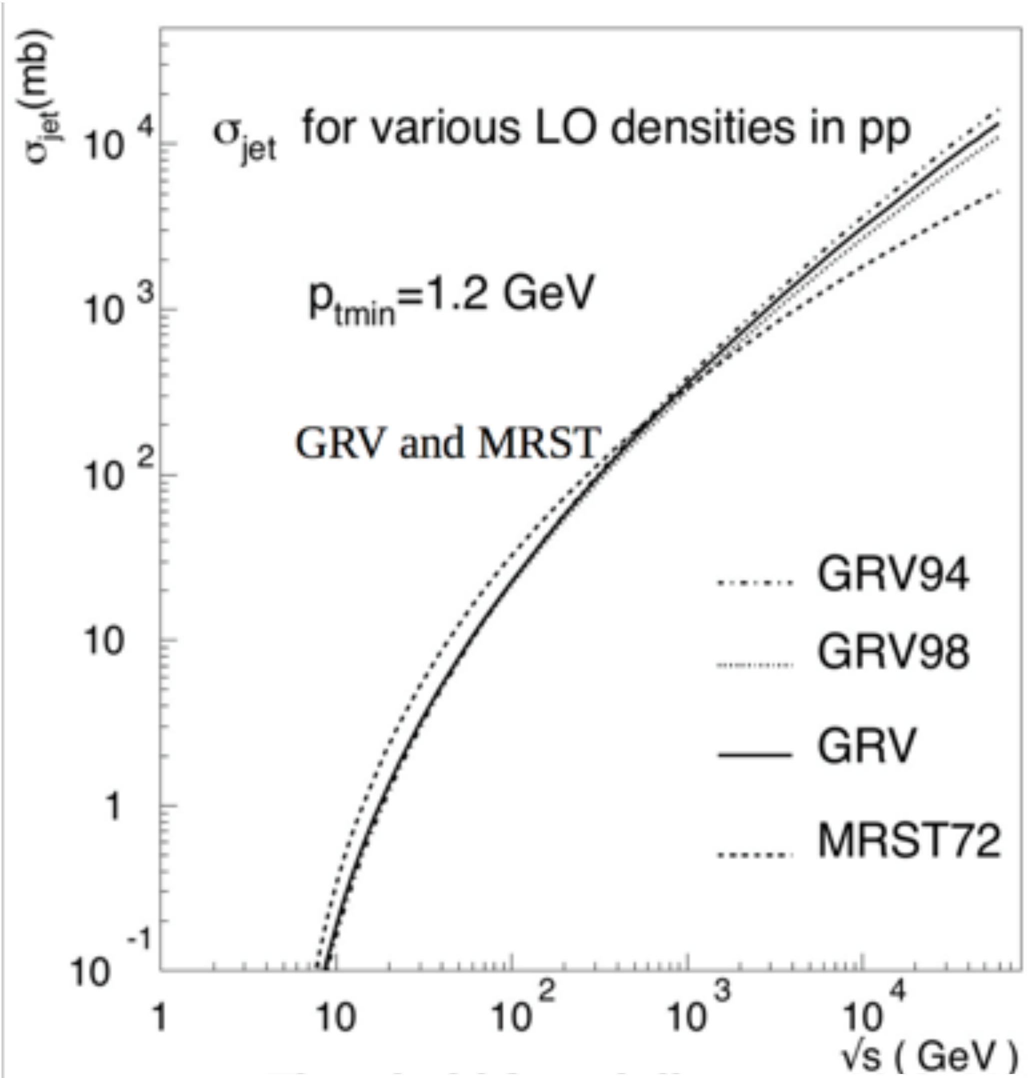
$$P_n = \frac{\langle n \rangle^n}{n!} \exp - \langle n \rangle$$

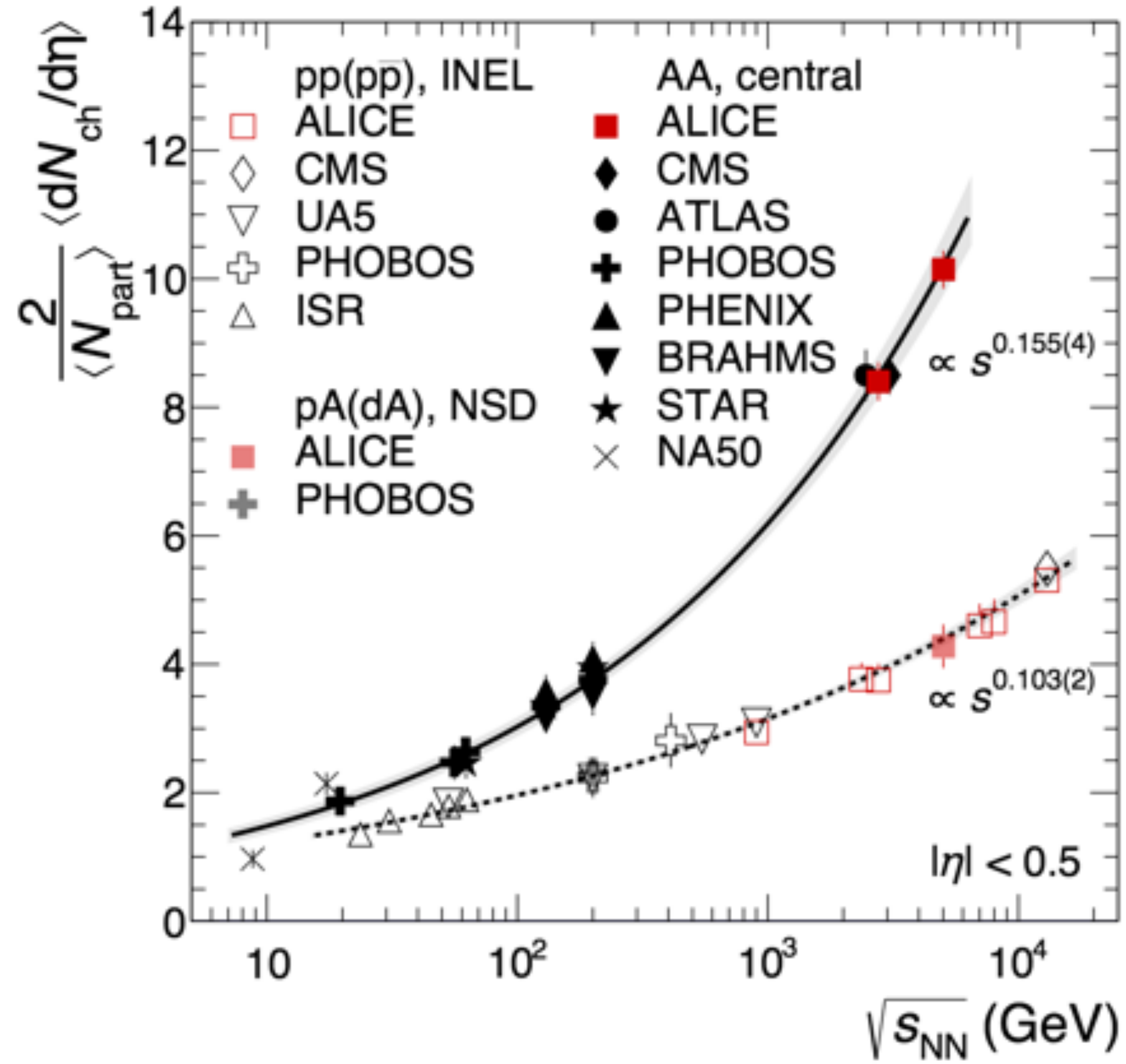


- Approach only very approximate for several theoretical reasons
- Also experimentally impossible to select event samples that are pure (unbiased) superpositions.

Damping of Hard Cross-Section at Low p_T

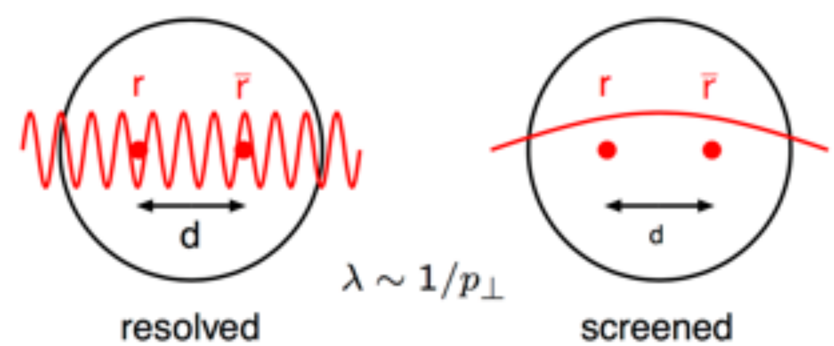
- pQCD x-section diverge for $p_T \to 0$ + strong √s-dependence





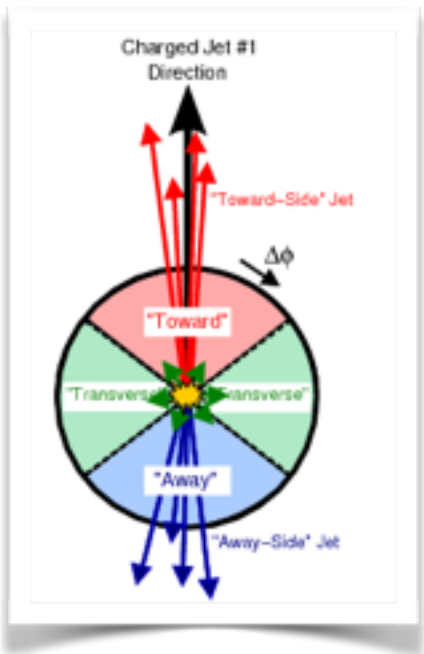
Hard cross-section has to be damped below certain momentum scale (color screening, saturation)

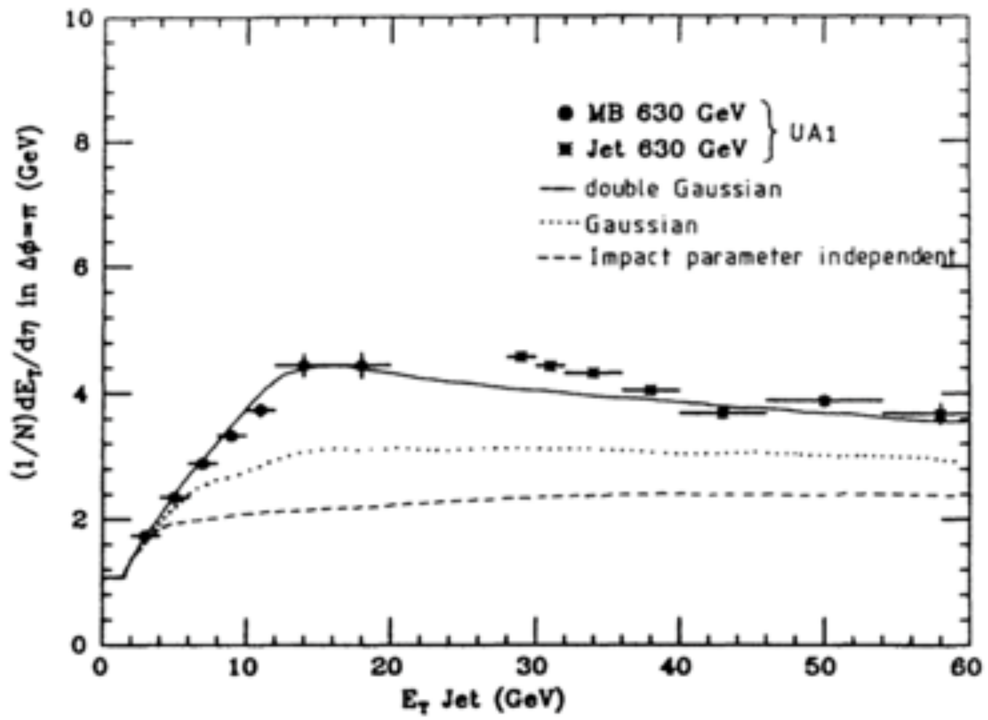
$$\sigma\left(\hat{p}_T\right) \to \sigma\left(\hat{p}_T\right)\frac{\hat{p}_T^{\,4}}{\left(\hat{p}_{T0}^{\,2}+\hat{p}_T^{\,2}\right)^2};\ \hat{p}_{T0} \approx 1.5-2\ \text{GeV}$$

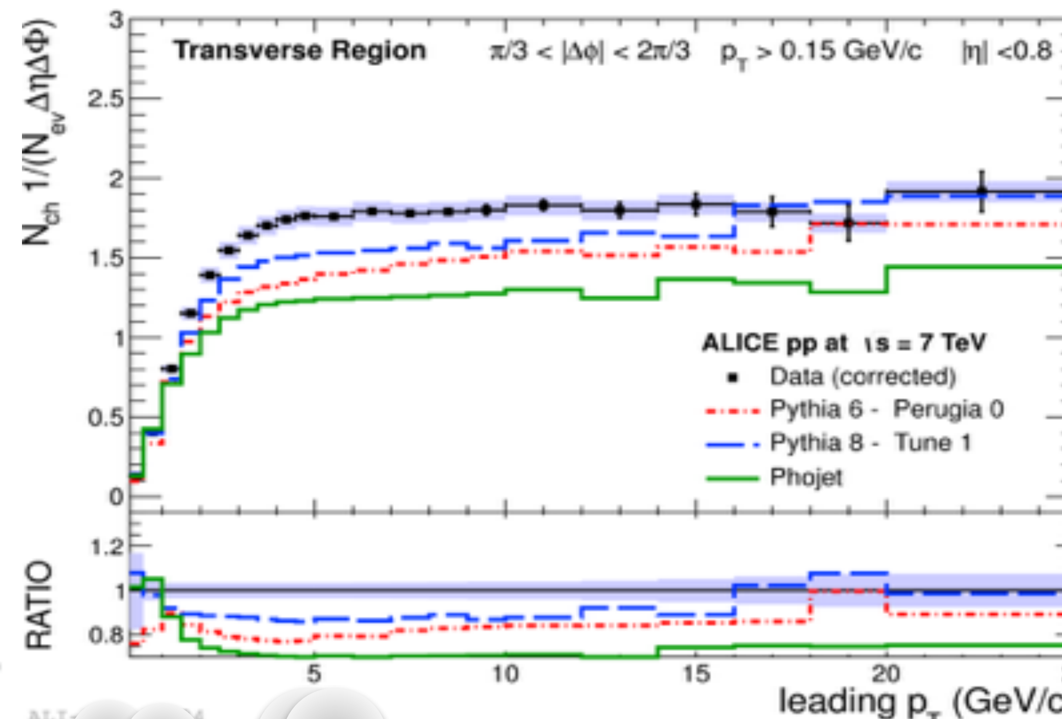


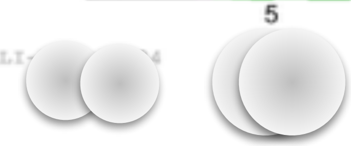
Jet Pedestal Effect

JHEP 2012, 7 (2012), 116







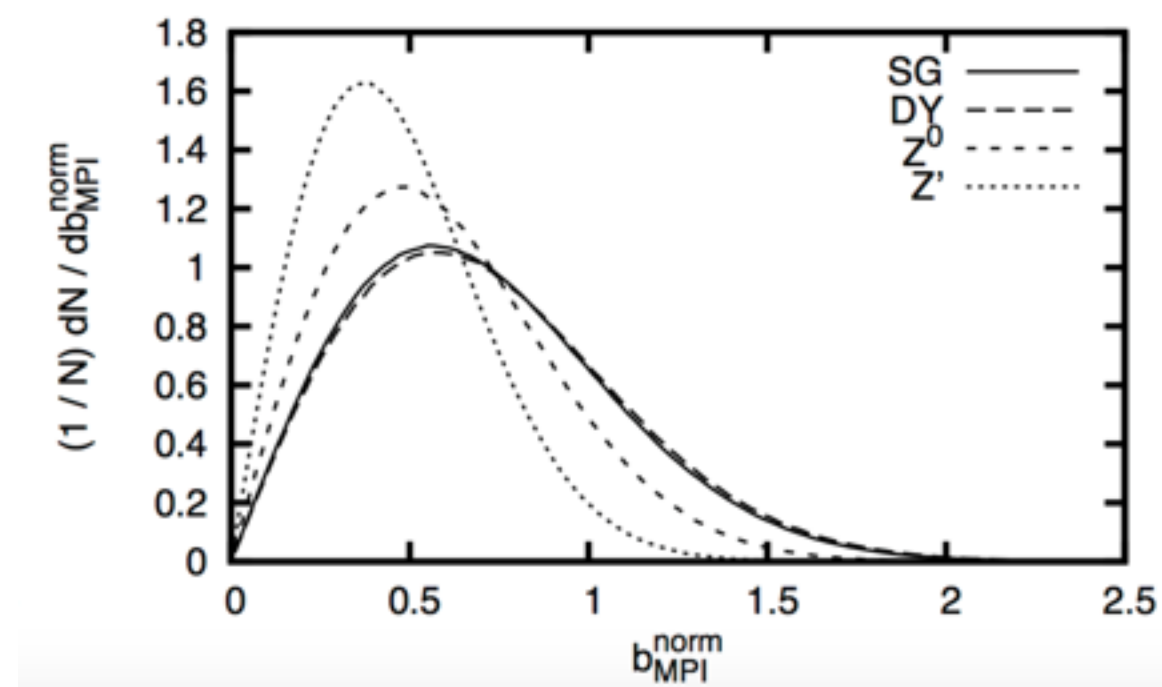


Effect described by impact parameter dependence
hard and soft processes

$$d\sigma_{2\to 2} = db^2 T_p(b_{pp}, ..)$$

$$\rho(r,x) \propto \frac{1}{a^3(x)} \exp\left(-\frac{r^2}{a^2(x)}\right)$$

$$a(x) = a_0\left(1 + a_1 \ln\frac{1}{x}\right)$$

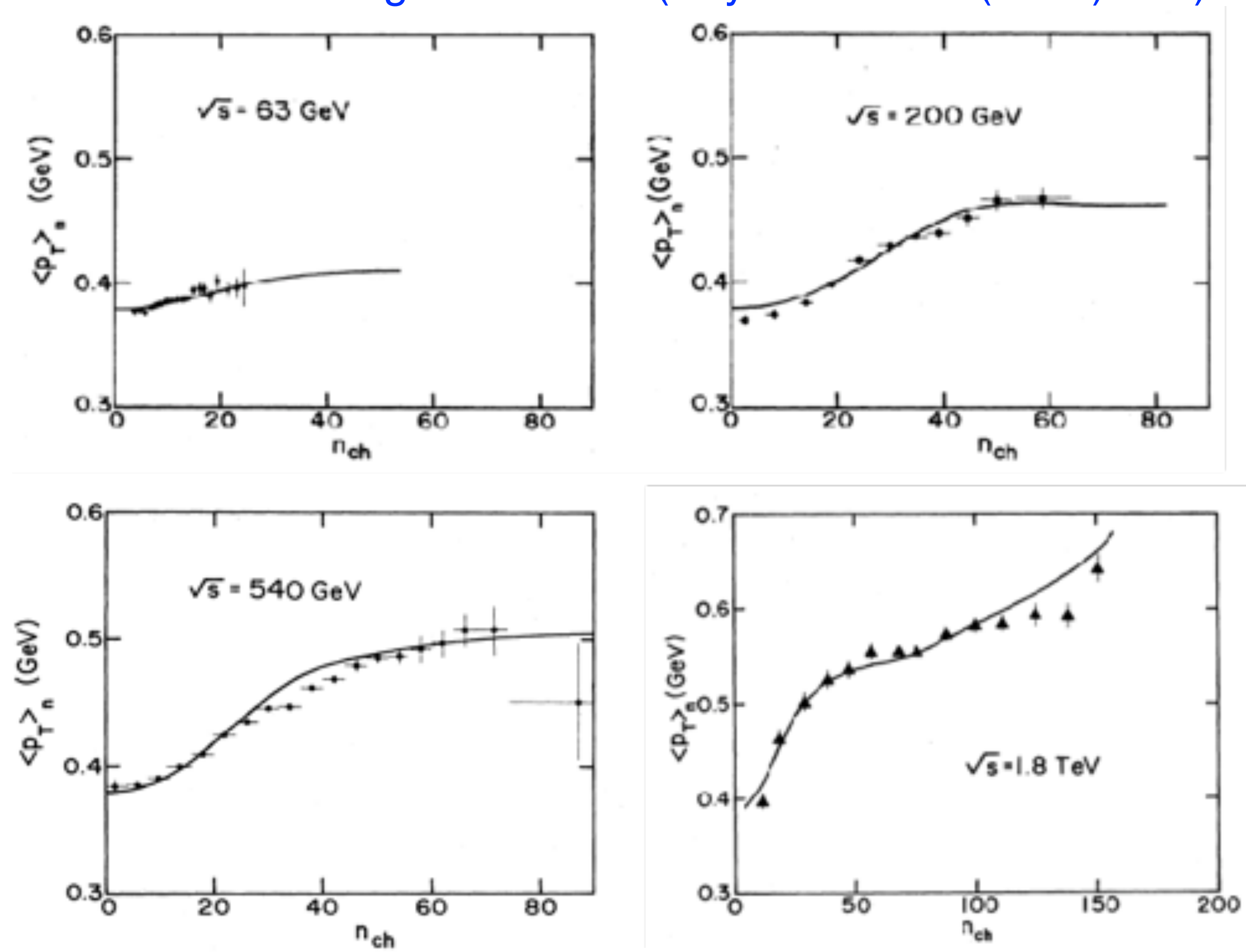


Ledge Effect

XN Wang and R Hwa (Phys.Rev. D39 (1989) 187)

Geometrical Branching Model.

- two component model
- hard and soft process impact parameter dependent



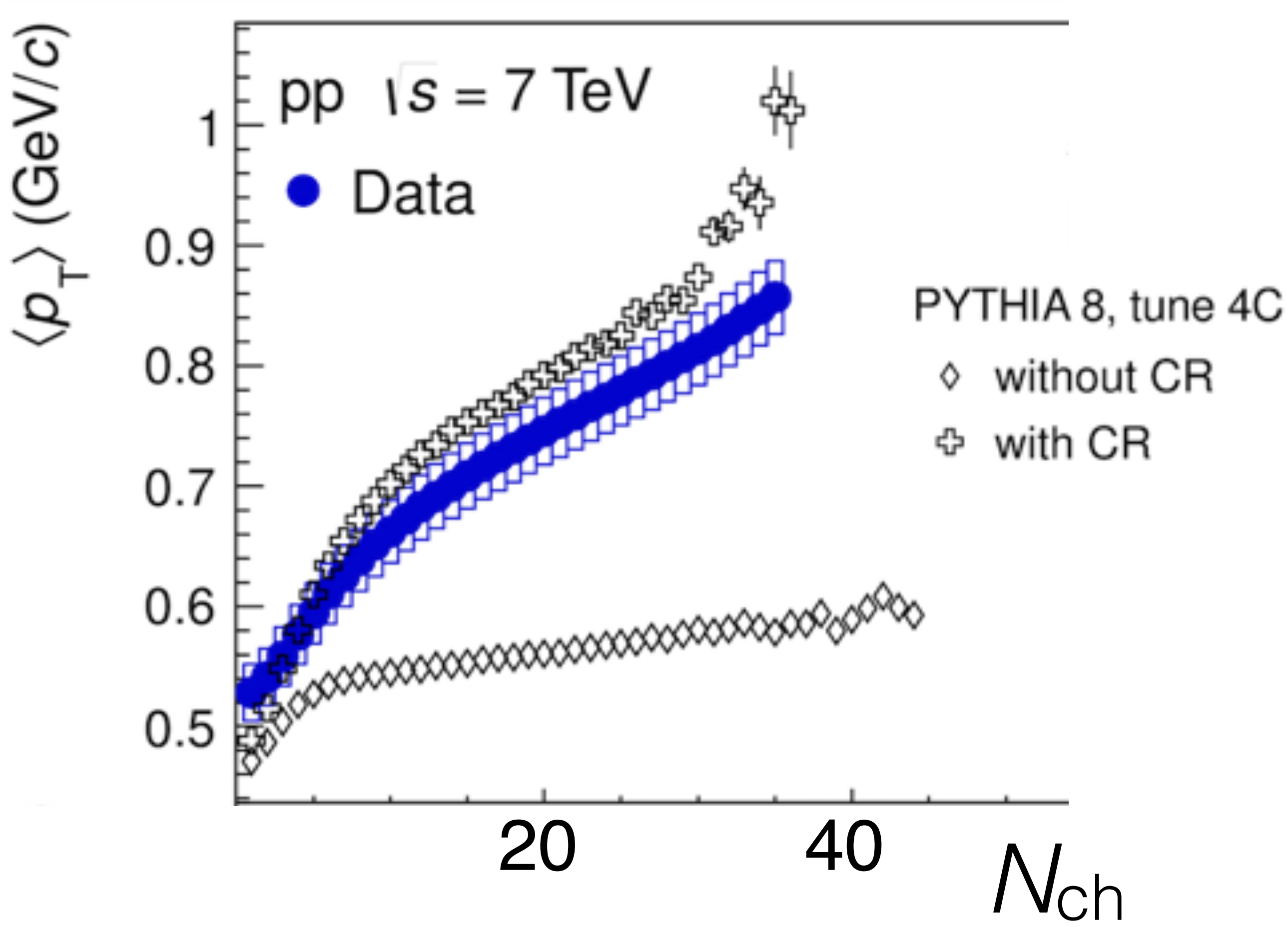
Ledge: rise – plateau – rise

1st rise: increased dominance of hard over soft interactions

2nd rise: jet fragmentation bias

Coherence Effects

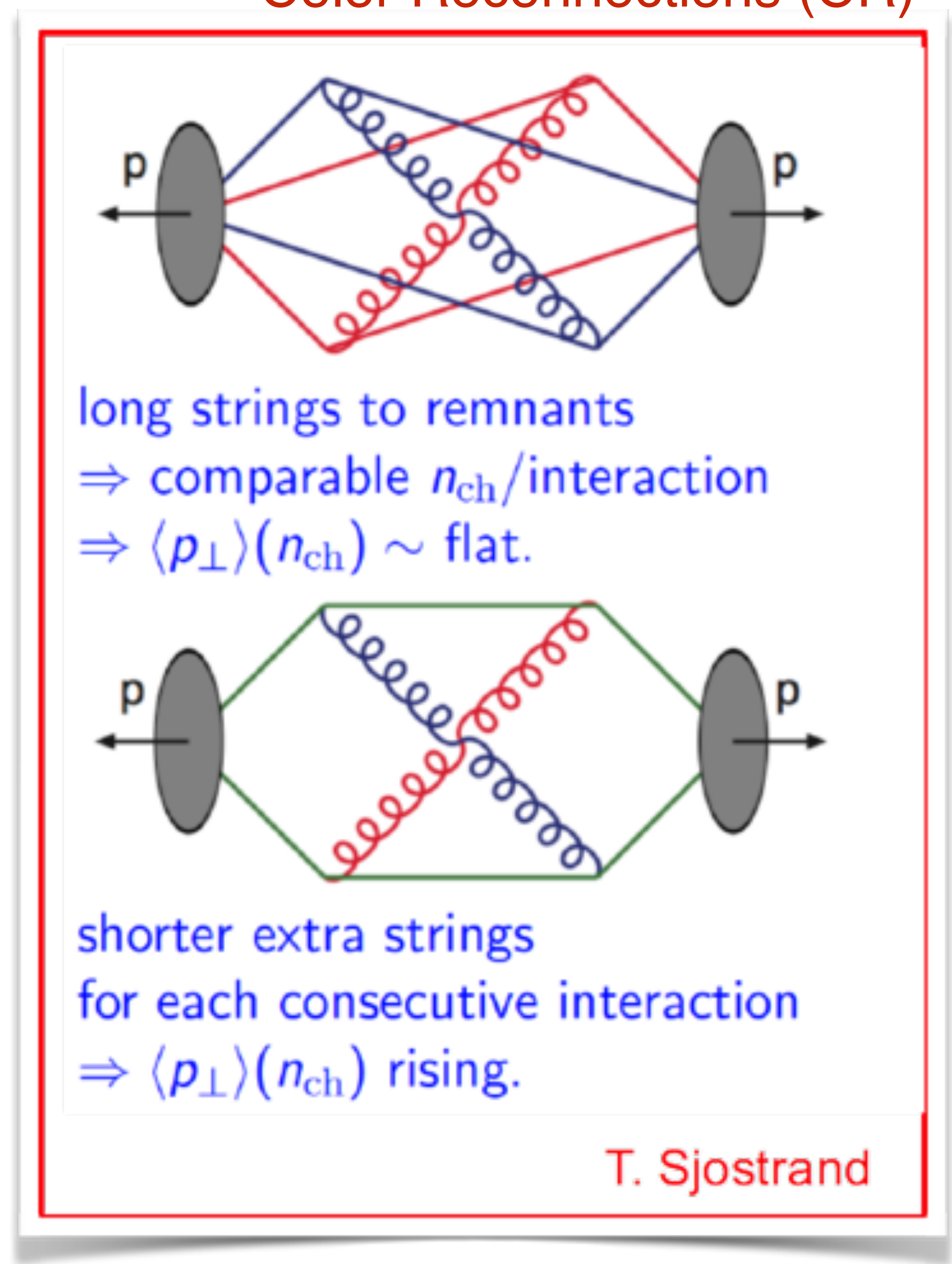
ALICE Phys.Lett. B727 (2013) 371-380



ALICE,charged particles

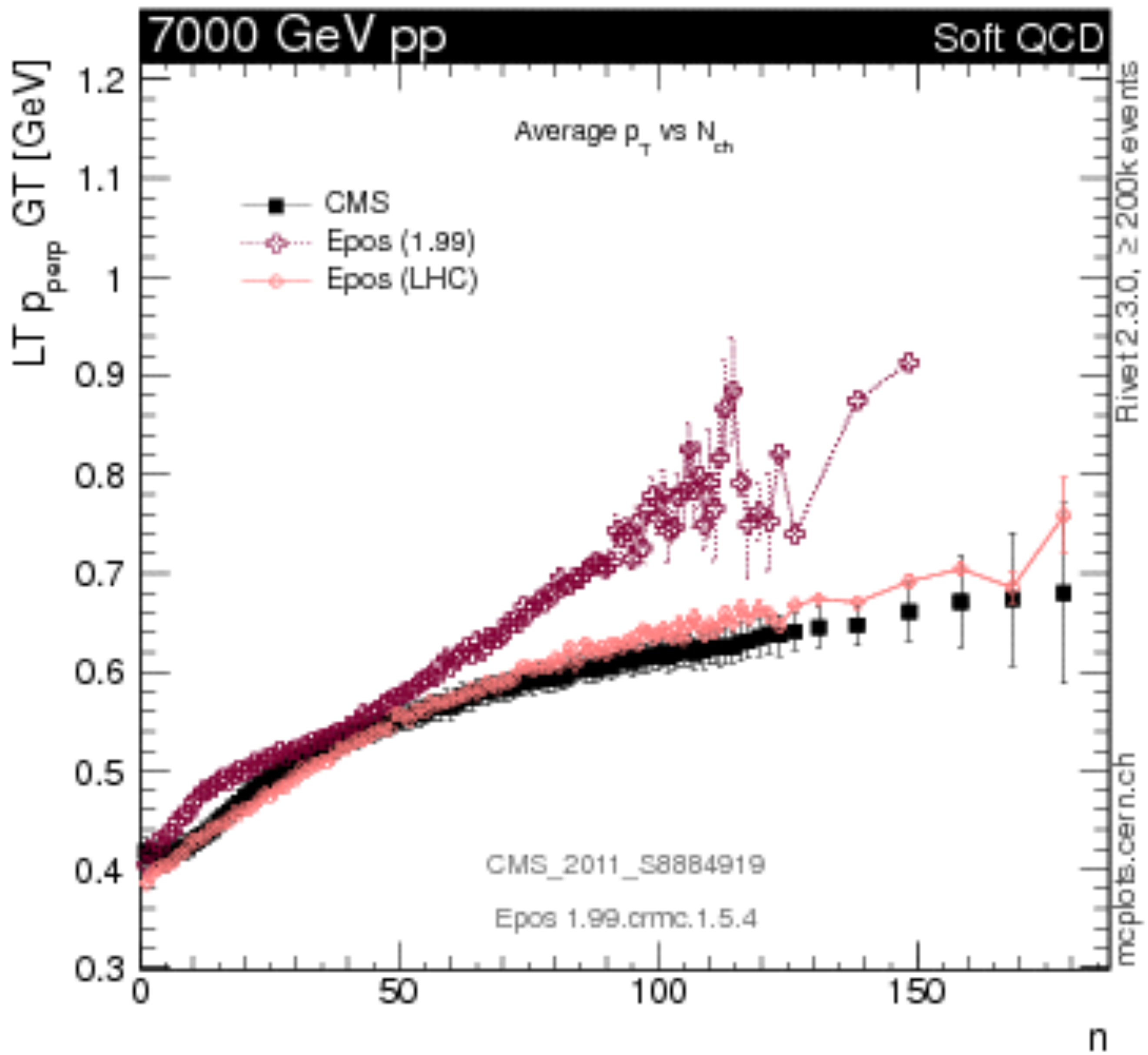
$|\eta|<0.3$, $0.15<p_T<10.0$ GeV/c

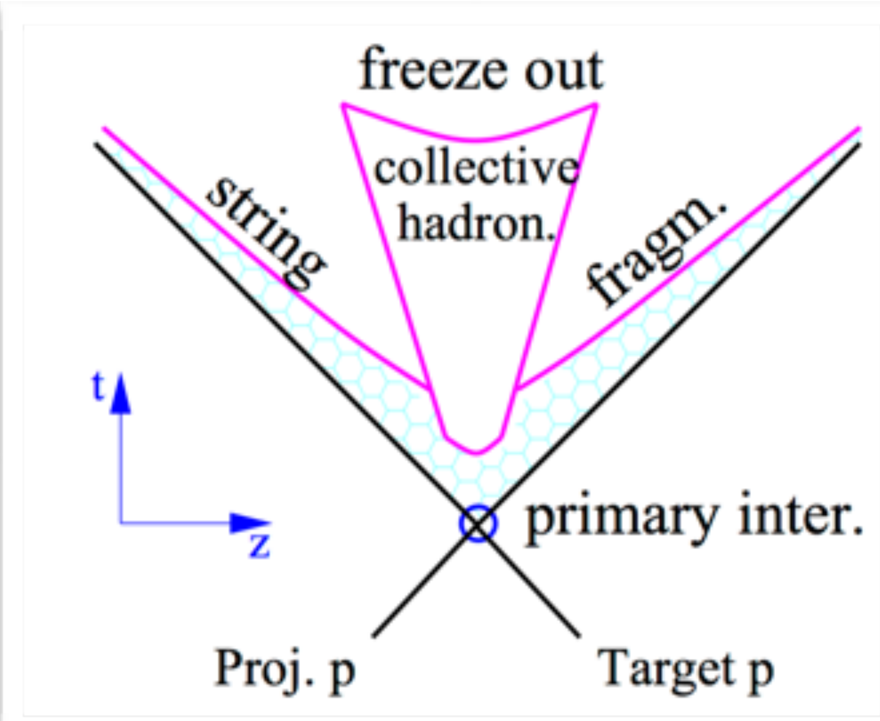
Color Reconnections (CR)

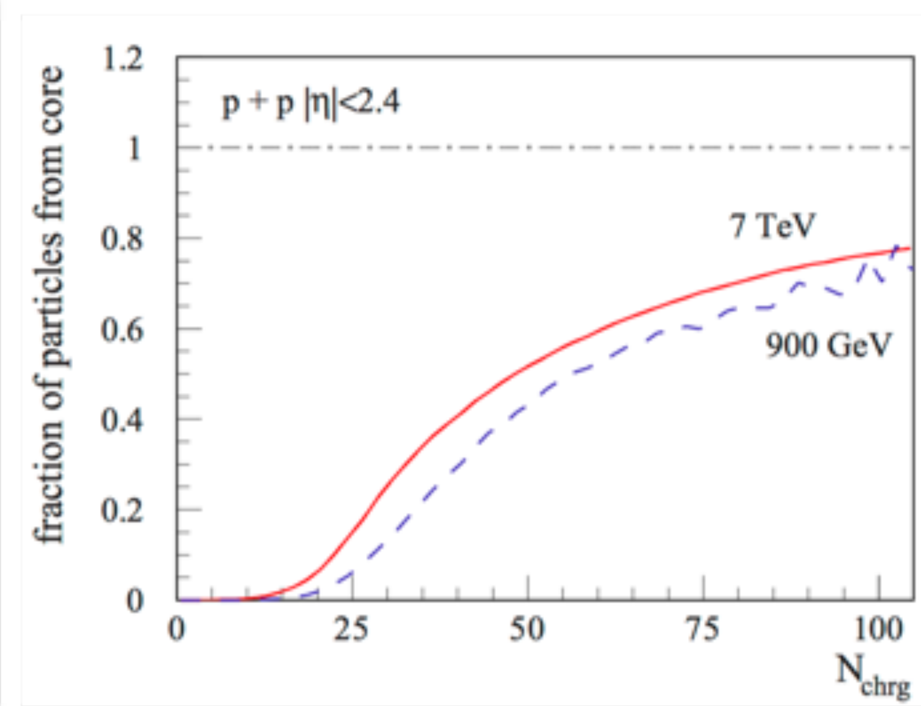


Collective Hadronization

http://mcplots.cern.ch/

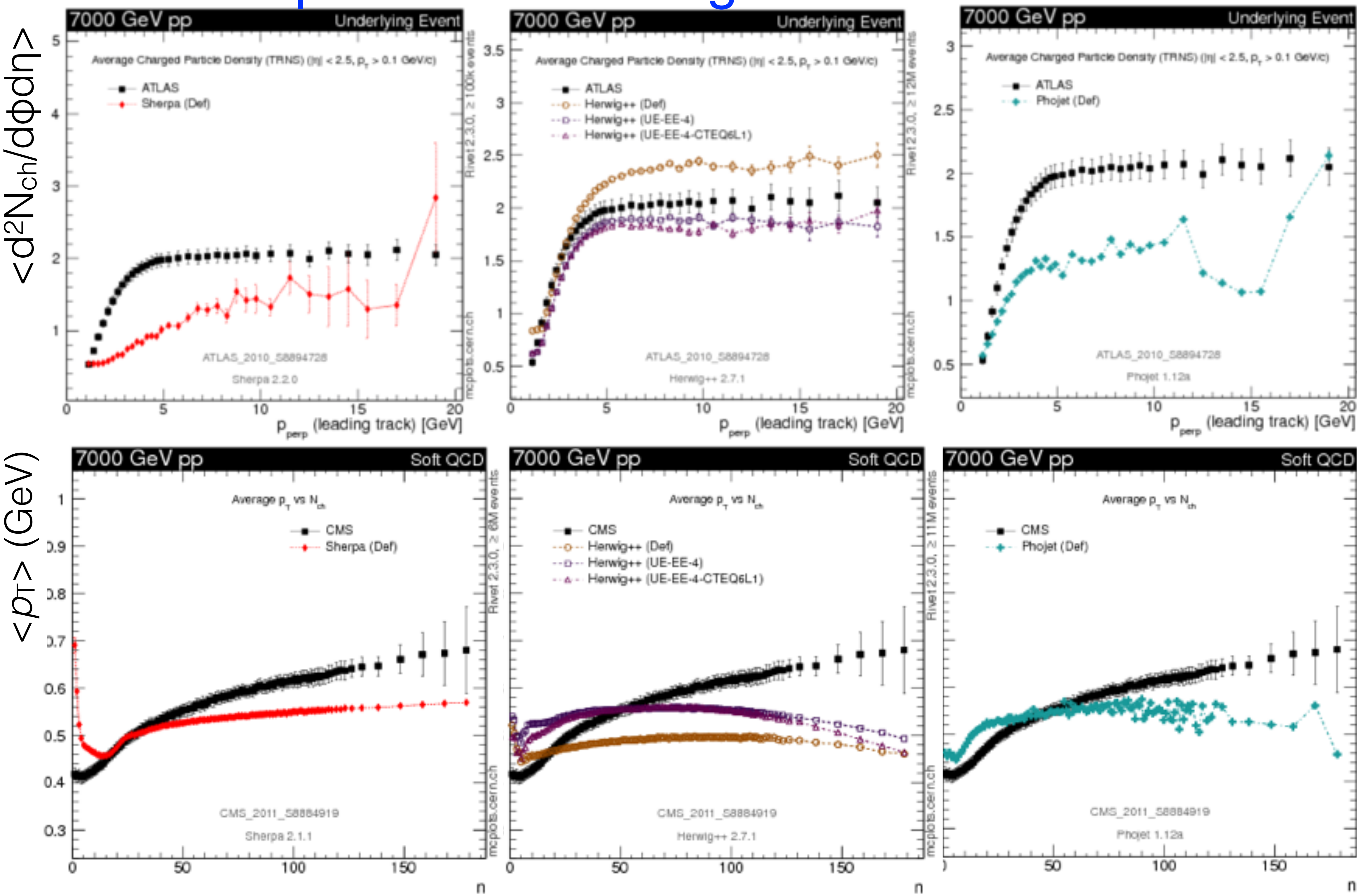






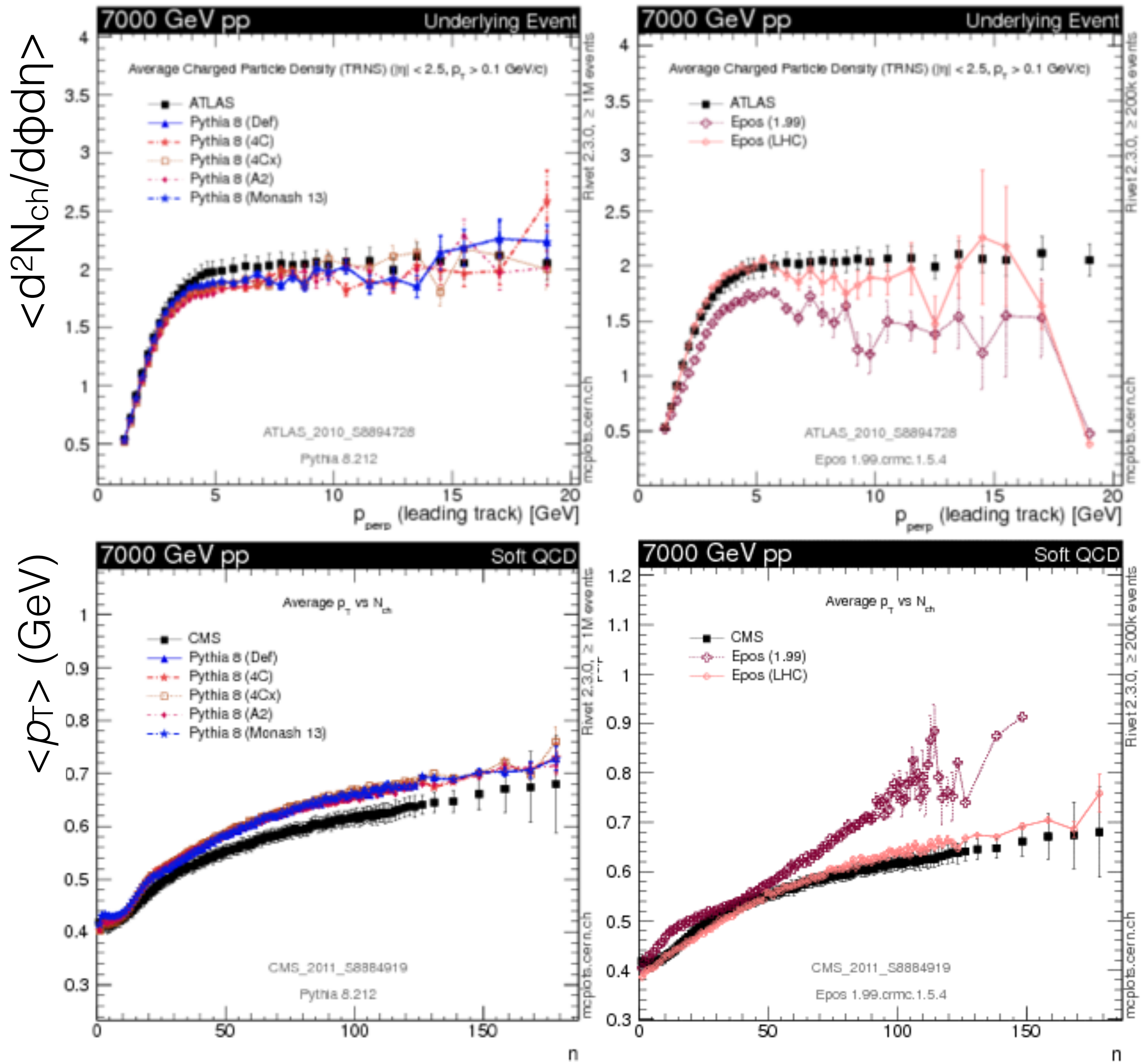
Model Constraints

Sherpa | Herwig++ | PHOJET++



Model Constraints

Pythia8 EPOS



Better Tuning ?

Correlations between MPIs via PDF

- Naive factorisation:

$$\frac{d\sigma^{AA\to X}}{dp_T} \propto \sum_{n}^{N_{\rm MPI}} f_i\left(x_i^n, Q_n^{\,2}\right) \circ f_j\left(x_j^n, Q_n^{\,2}\right) \circ \sigma^{ii\to k}\left(x_i^n, x_j^n, p_T / z, Q_n^{\,2}\right) \circ D_{k\to X}(z, Q_n^{\,2})$$

- More realistic:

$$\frac{d\sigma^{AA\to X}}{dp_T} \propto f_i\left(x_i^1, x_i^2, x_i^3, \ldots; Q_1^{\,2}, Q_2^{\,2}, \ldots\right) \circ f_j\left(x_j^1, x_j^2, x_j^3, \ldots; Q_1^{\,2}, Q_2^{\,2}, \ldots\right) \circ \sum_{n}^{N_{\rm MPI}} \sigma^{ii\to k}\left(x_i^n, x_j^n, p_T / z, Q_n^{\,2}\right) \circ D_{k\to X}(z, Q_n^{\,2})$$

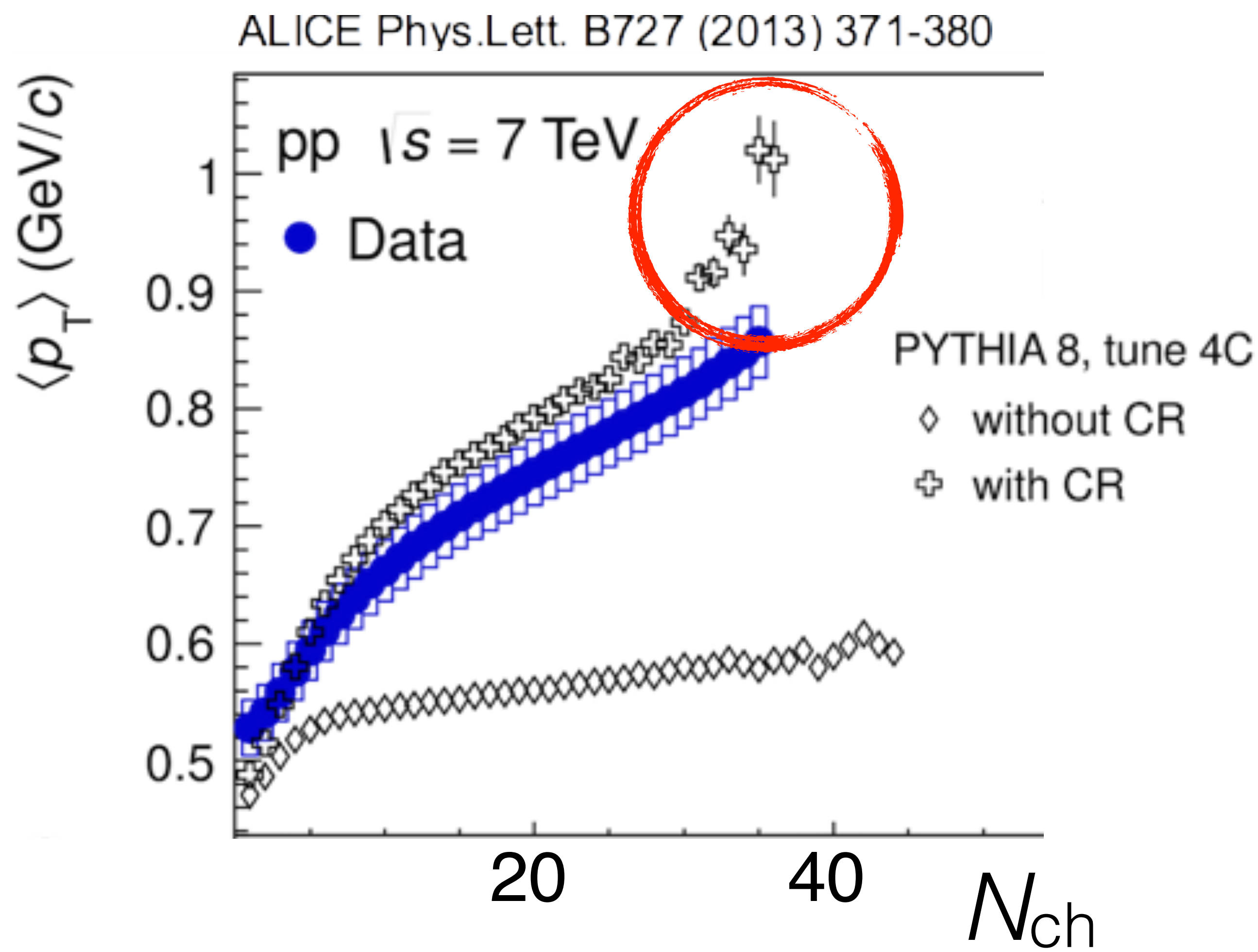
- Ex. Pythia: rescaling prescription:

$$0 < x < 1 \Rightarrow 0 < x < 1 - \sum x_i$$

- HIJING: Limit on $N_{\rm MPI}$ to enforce energy conservation

Introduces correlation between hard and soft particle production at high rapidity / multiplicity (measurement ?)

Ledge Effect Revisited



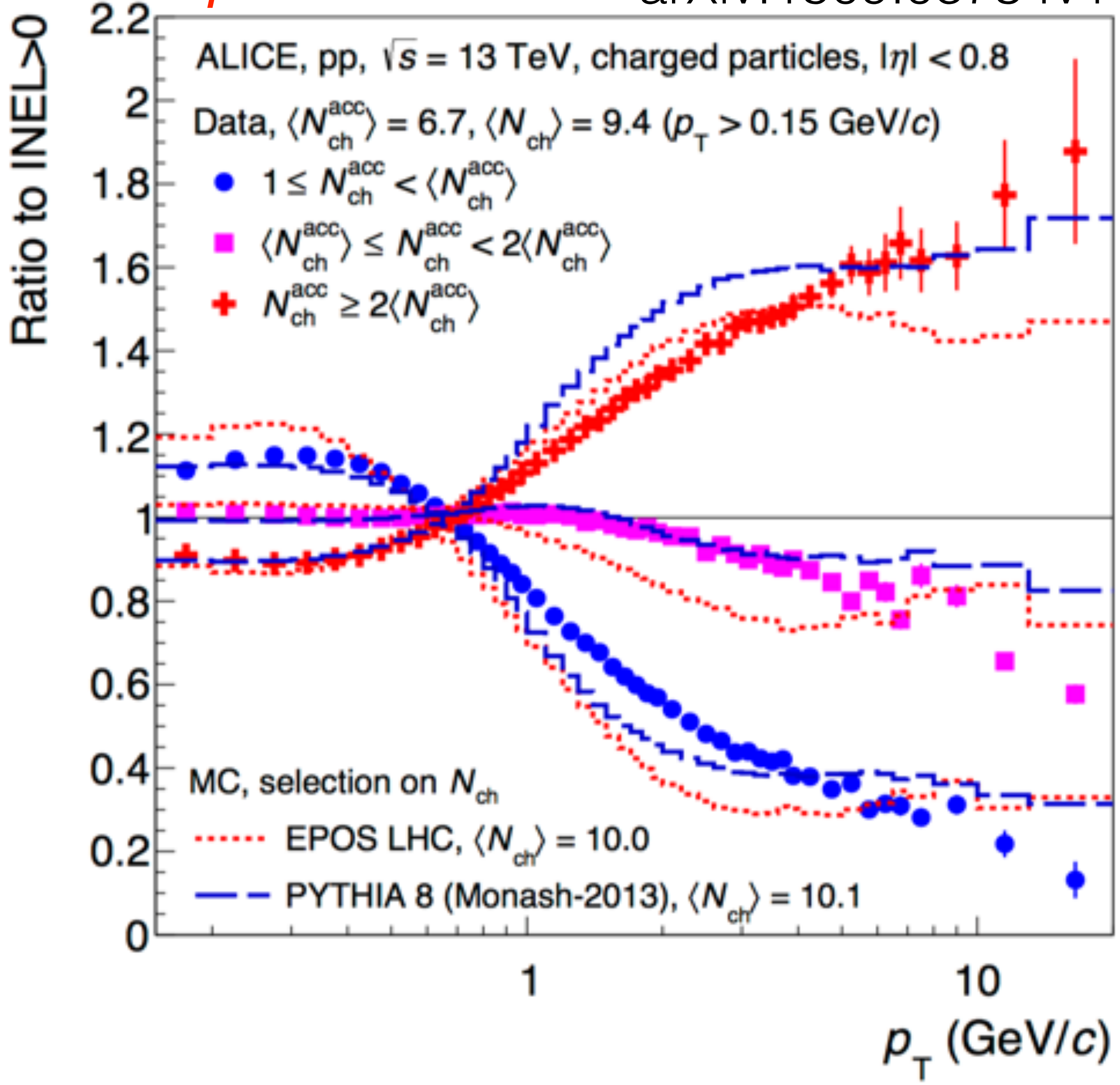
ALICE,charged particles

$|\eta|<0.3$, $0.15<p_T<10.0$ GeV/c

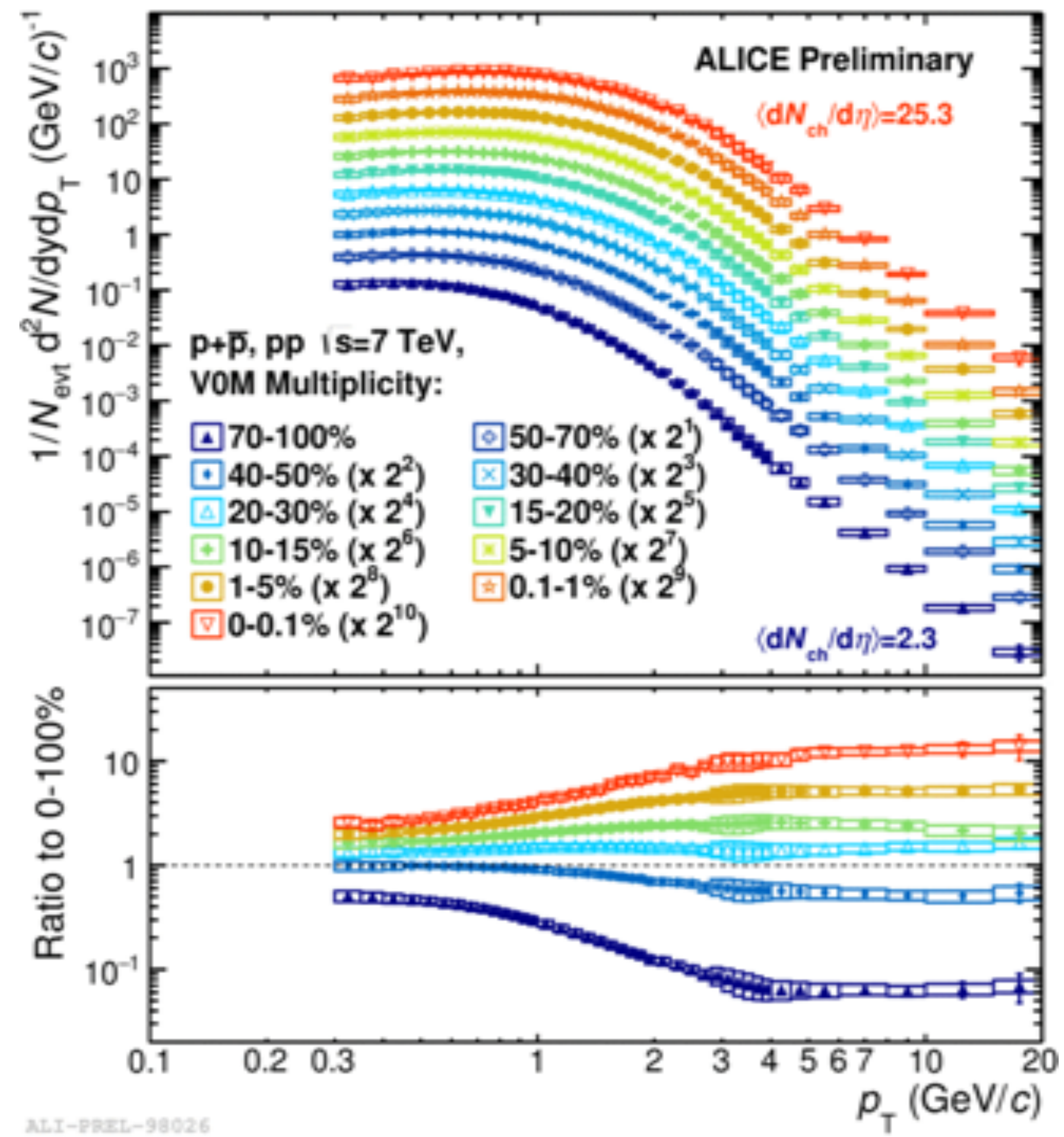
Ledge Effect Re-visited

Multiplicity measured in:

|η|<0.9 arXiv:1509.08734v1

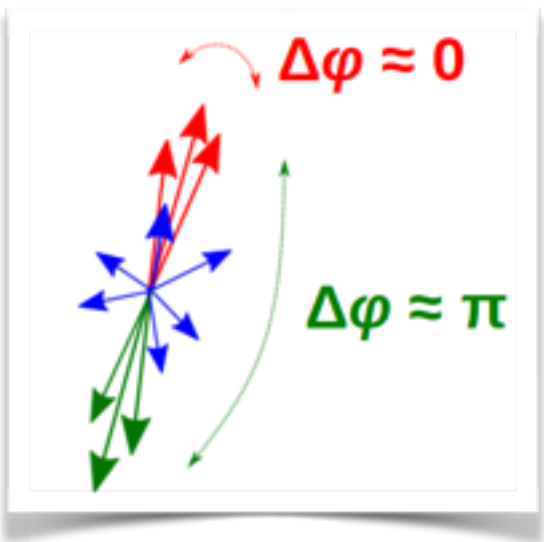


2.8 < η < 4.1 ∪ -3.7 < η < -1.7

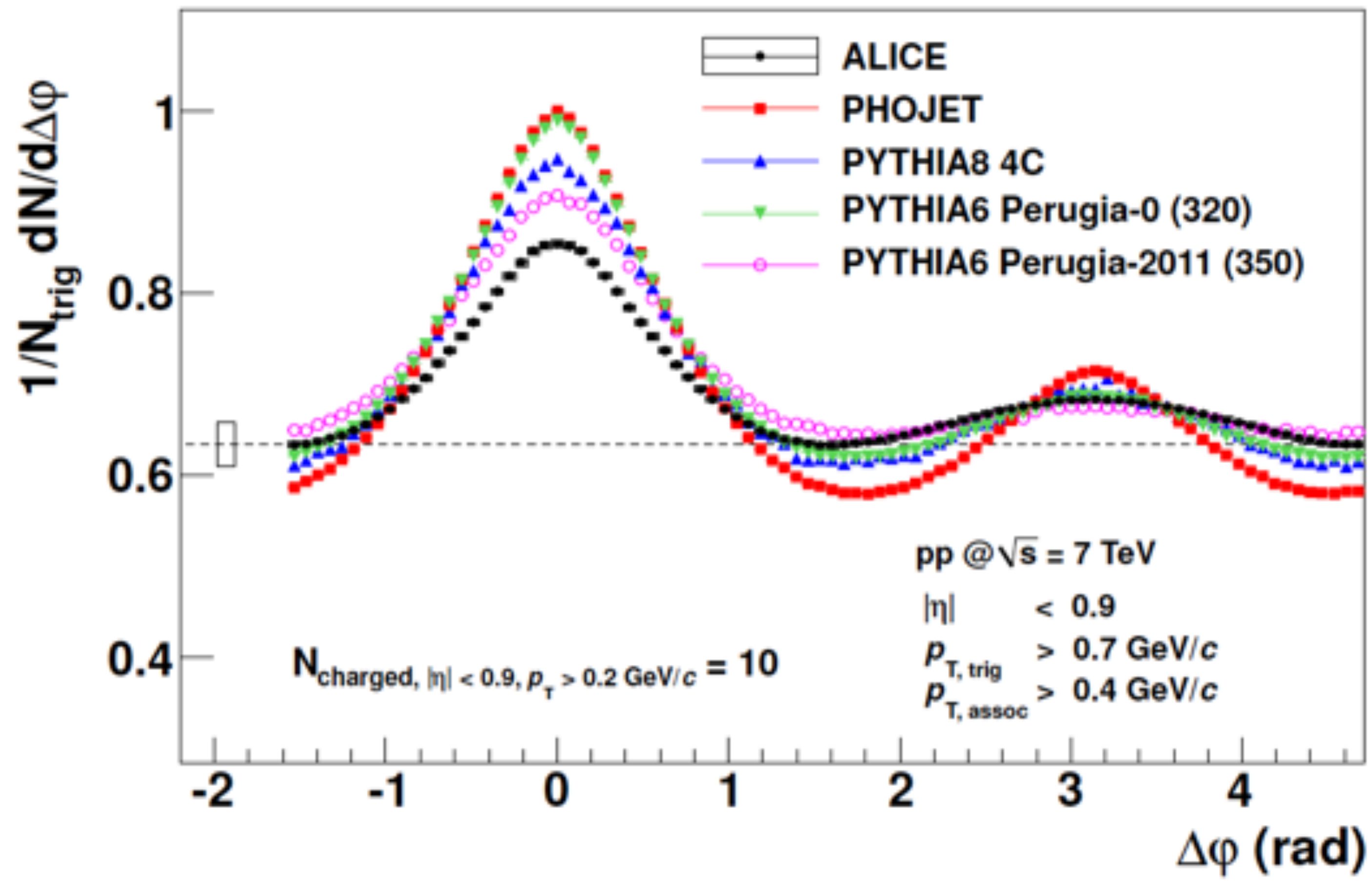


- Spectra measured at mid-rapidity, hardness multiplicity dependent
- Reduced bias with “centrality estimator” from forward region
- Decomposition of effects in the intermediate p_T region less obvious

MPI at the Boundary Between Hard and Soft

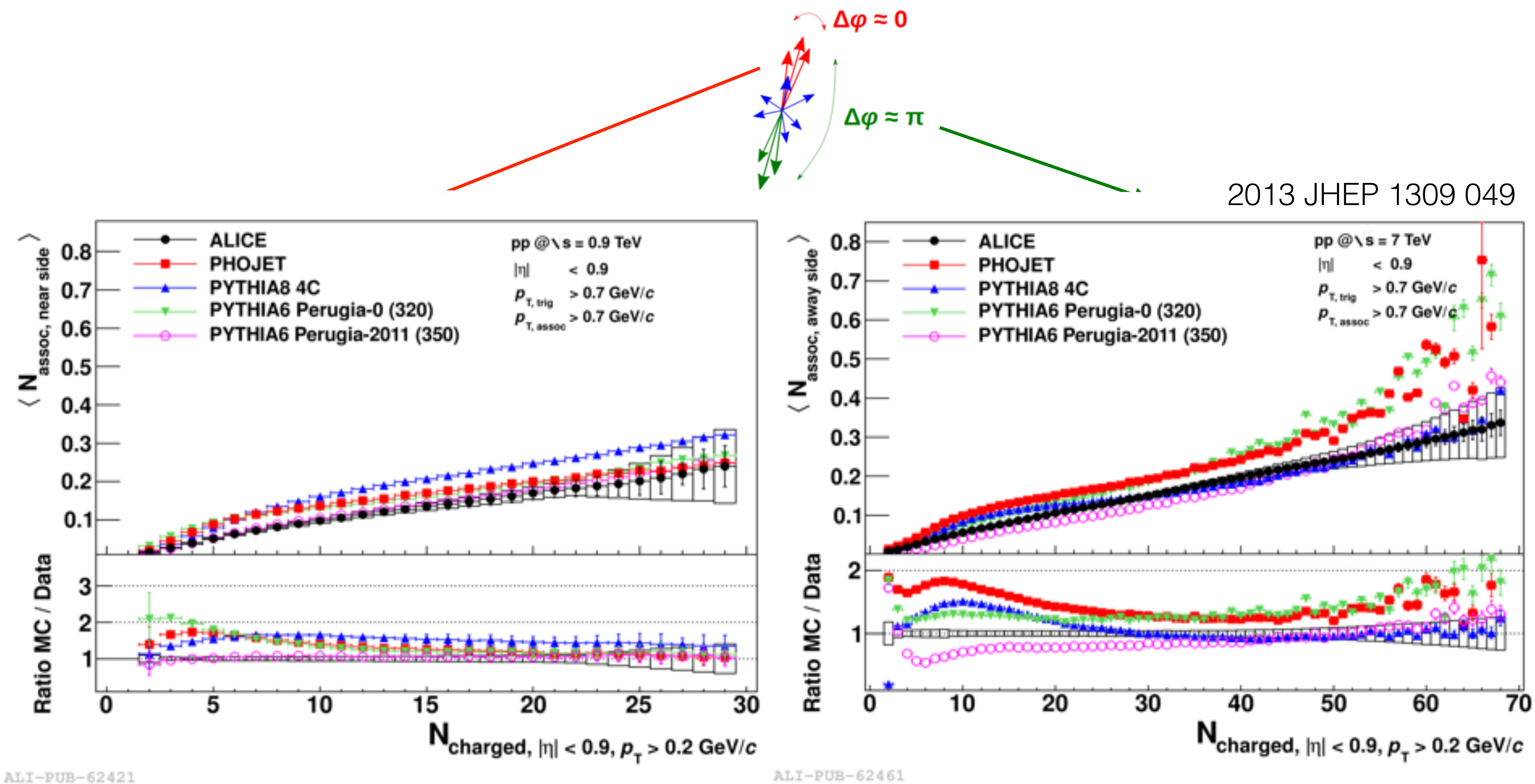


2013 JHEP 1309 049



- More direct way to study contribution of hard processes and fragmentation biases at low p_T
- Study 2→2 scatterings with azimuthal di-hadron correlations
  - decomposition
    - trigger particles $p_T > p_{T,trig}$
    - correlated associated particles $p_T > p_{T,assoc}$
- At low p_T, but $p_T \gg \Lambda_{QCD}$

Yield per Trigger vs Multiplicity



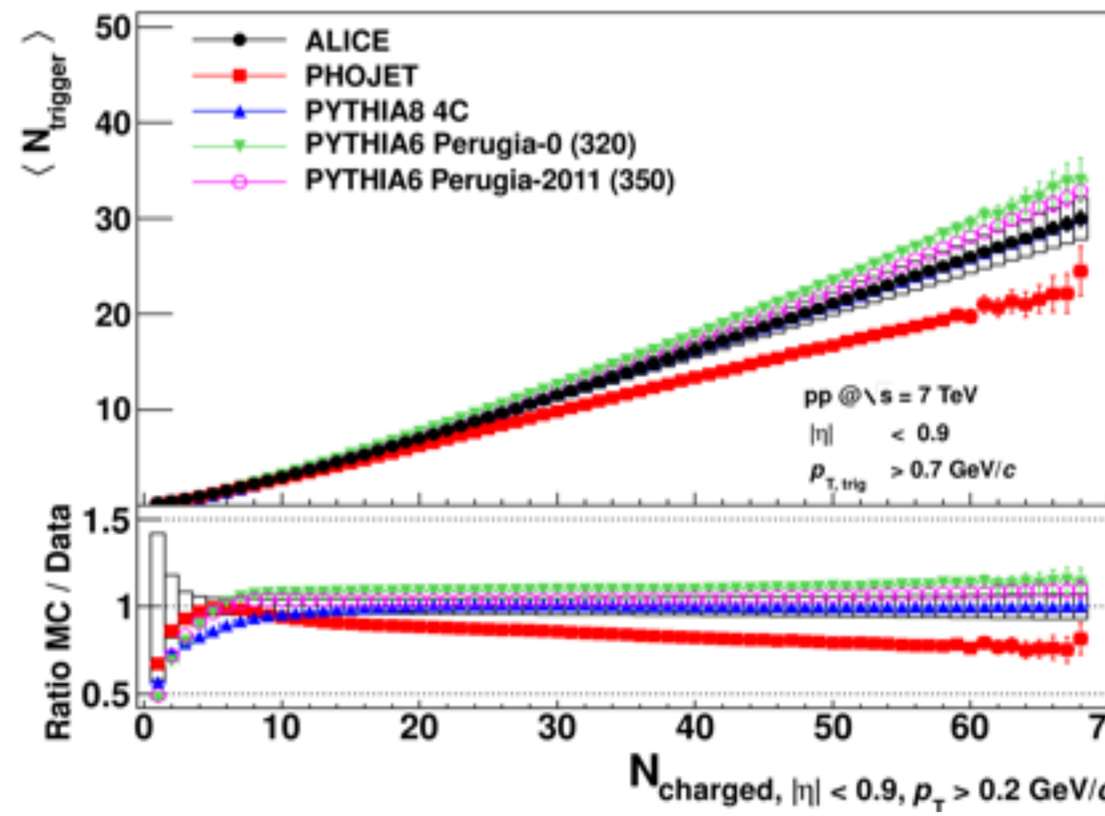
- Number of associated particles increases with multiplicity
- Non-linearity between N_{MPI} and semi-hard particle production

Uncorrelated Seeds

2013 JHEP 1309 049

Fragmentation bias results in non-linear increase of number of trigger particles.

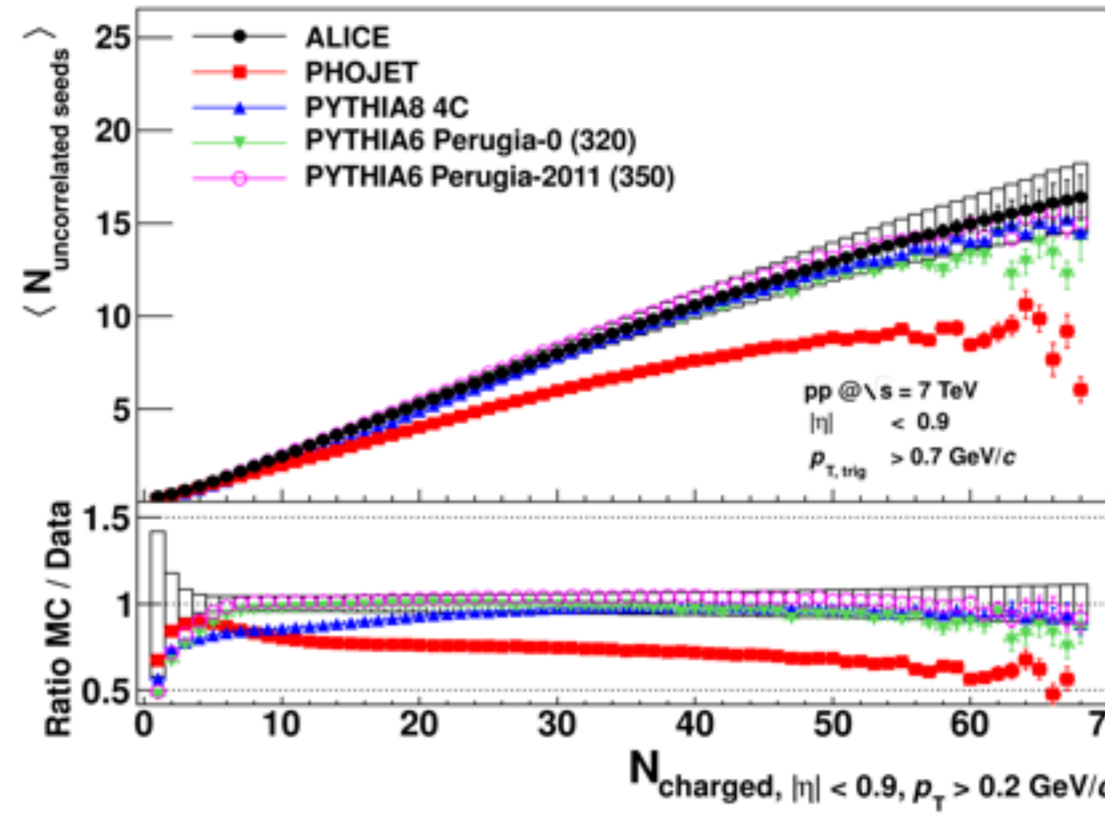
$$\frac{\langle N_{\mathrm{trig}}\rangle}{\langle N_{\mathrm{trig}}\rangle_{\mathrm{MB}}} > \frac{\langle N_{\mathrm{ch}}\rangle}{\langle N_{\mathrm{ch}}\rangle_{\mathrm{MB}}}$$



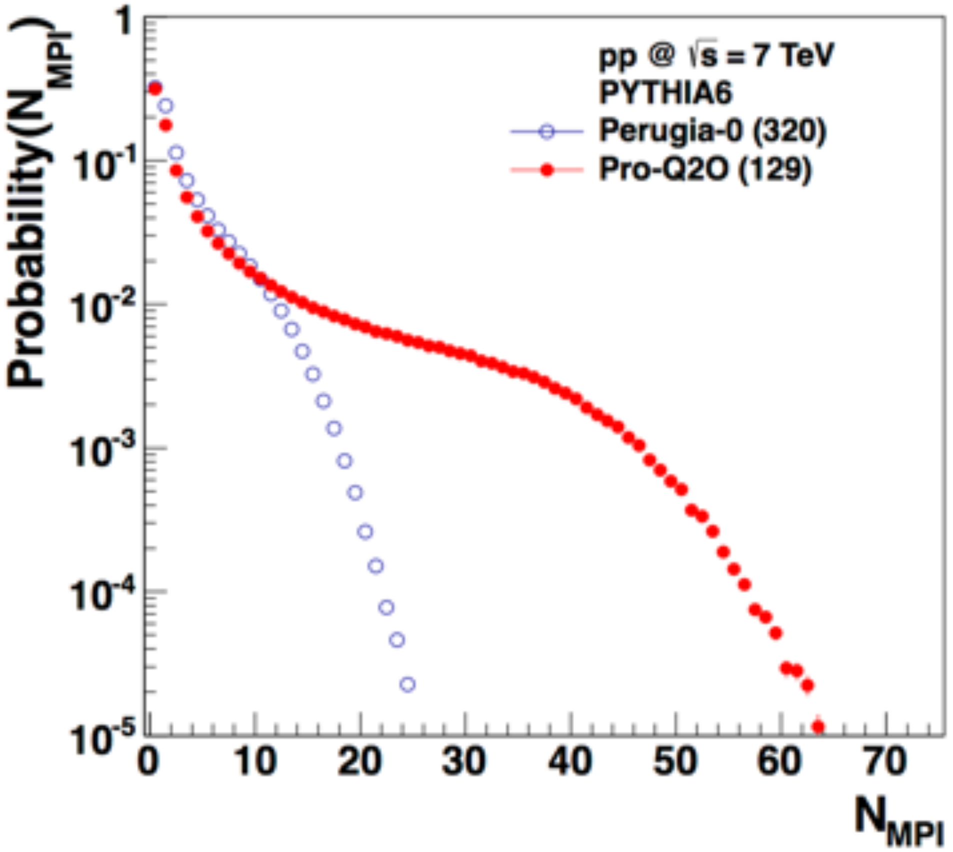
Reduced number of trigger particles

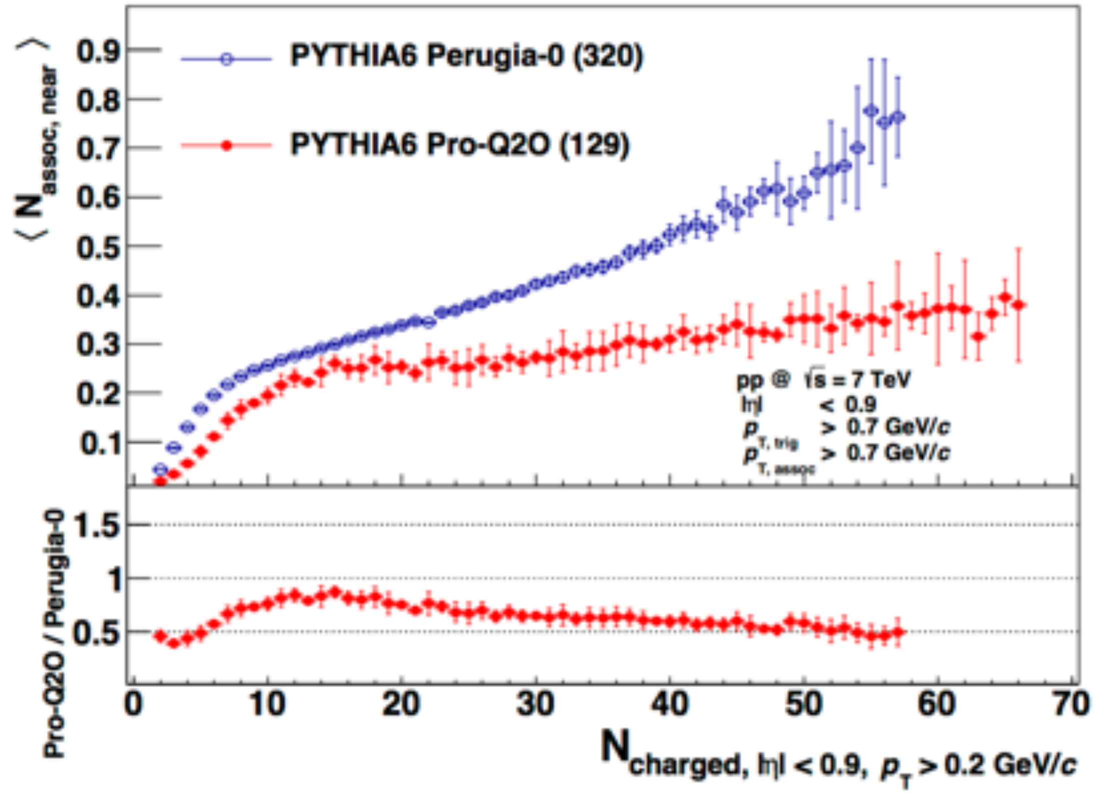
$$N_{\text{uncorrelated seeds}} = \frac{N_{\text{trig}}}{1 + N_{\text{assoc}}}$$

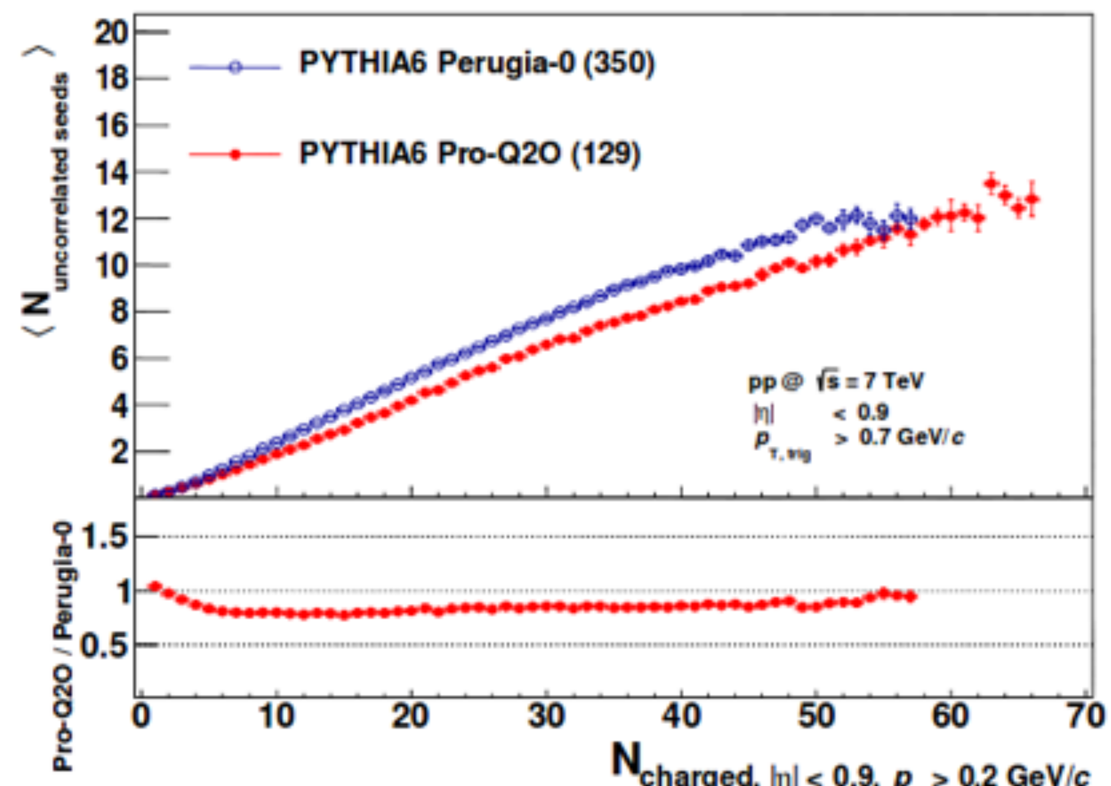
$$\frac{\langle N_{\text{tunc seeds}}\rangle}{\langle N_{\text{unc seeds}}\rangle_{\mathrm{MB}}} \simeq \frac{\langle N_{\mathrm{ch}}\rangle}{\langle N_{\mathrm{ch}}\rangle_{\mathrm{MB}}}$$



Sensitivity to MPI Distribution







Multiplicity Evolution of Global Event Shape

Transverse Sphericity:

$$S_{xy}^{L} = \frac{1}{\sum_i p_T^i} \sum_i \frac{1}{p_T^i} \begin{pmatrix} p_x^{i\,2} & p_x^i p_y^i \\ p_x^i p_y^i & p_y^{i\,2} \end{pmatrix}$$

$$S_T = \frac{2\lambda_2}{\lambda_1 + \lambda_2}; \quad \lambda_{1,2} : \text{Eigenvalues}$$

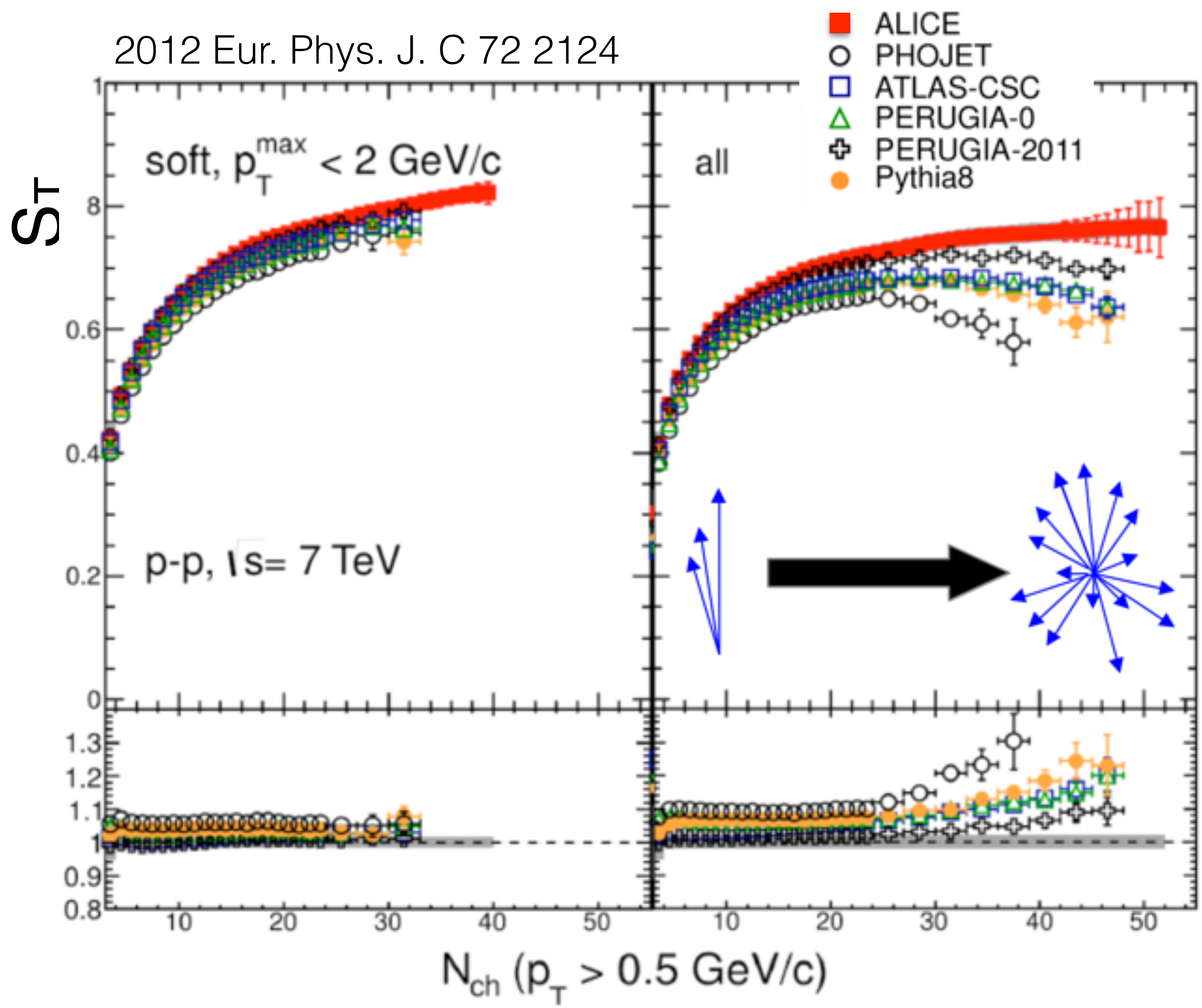
- Evolution towards isotropic independent mini-jet production

  $S_T \rightarrow 1$

- Single jet dominance

  S_T decreases

2012 Eur. Phys. J. C 72 2124



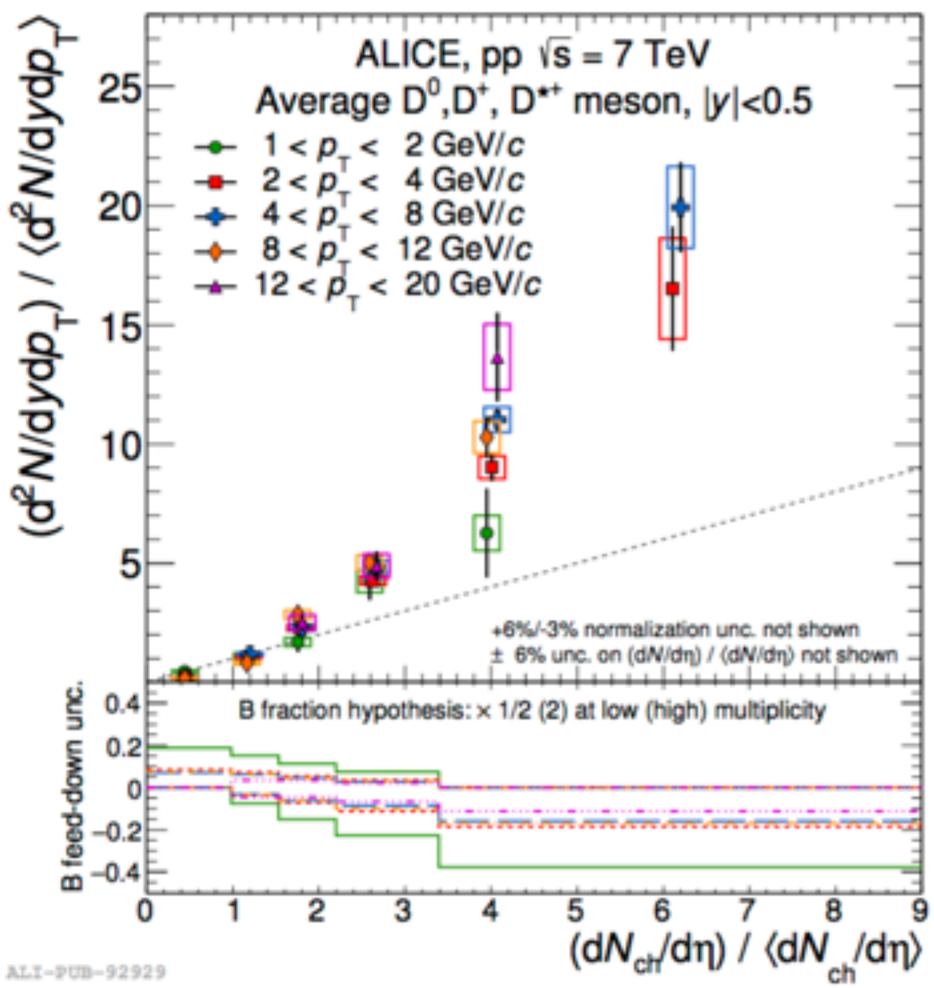
In general, MC predict "jettier" events at high N_{ch}

Open Charm Yield vs Multiplicity

Heavy Flavor
= Tag for hard interaction even at low p_T

Multiplicity from:

|η|<0.9 JHEP 09 (2015) 148



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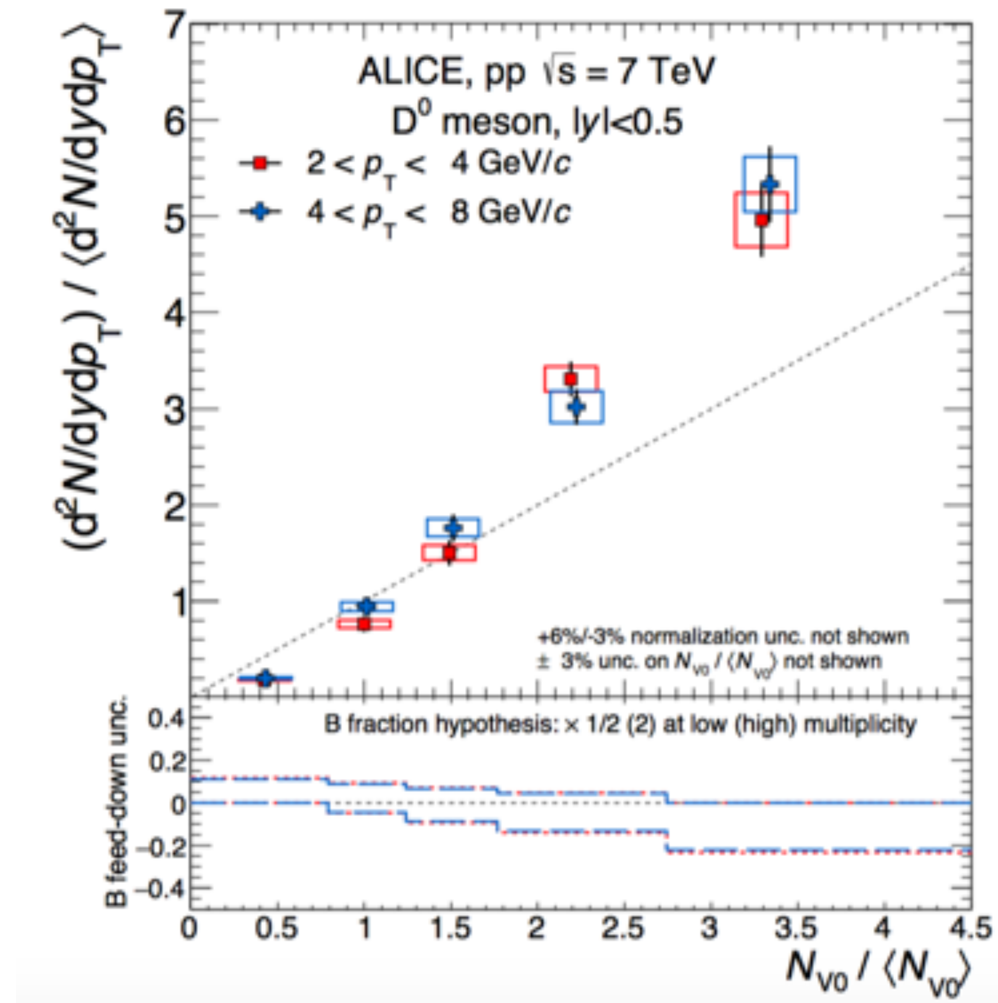
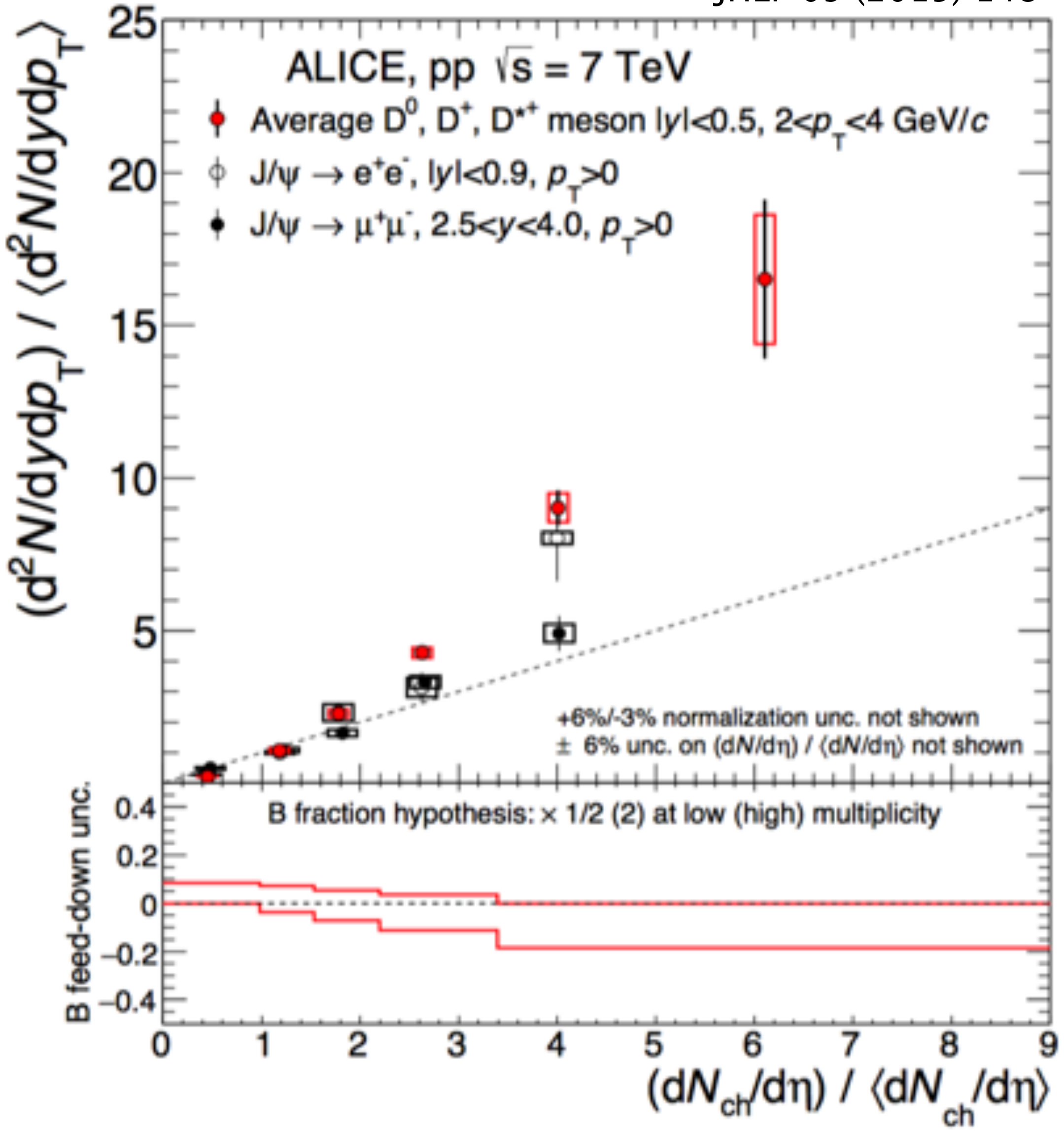
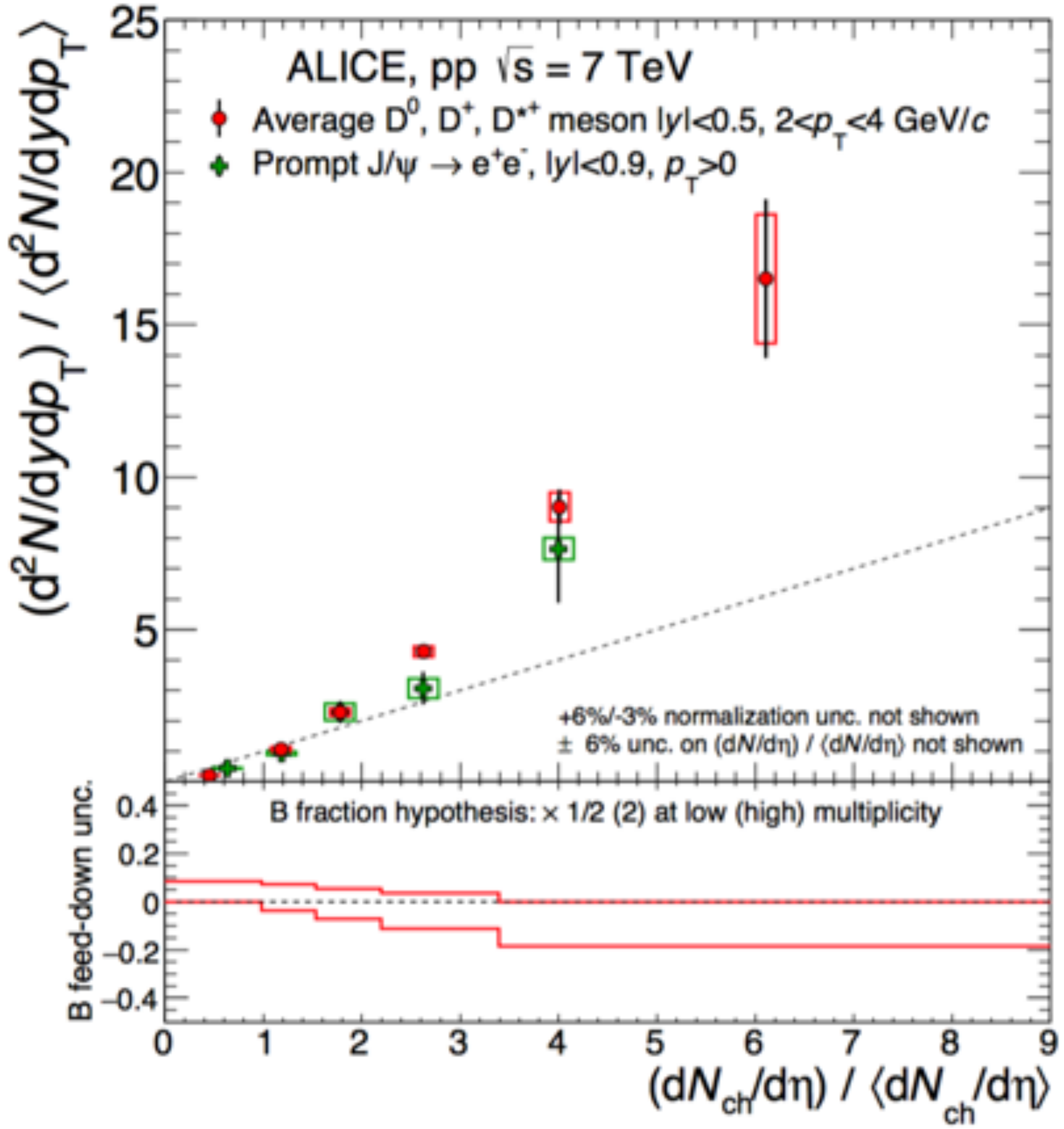


- Non-linear increase at high multiplicity.
- Or linear increase + threshold effect
- No p_T dependence (= no bias) ?

Charmonia

JHEP 09 (2015) 148



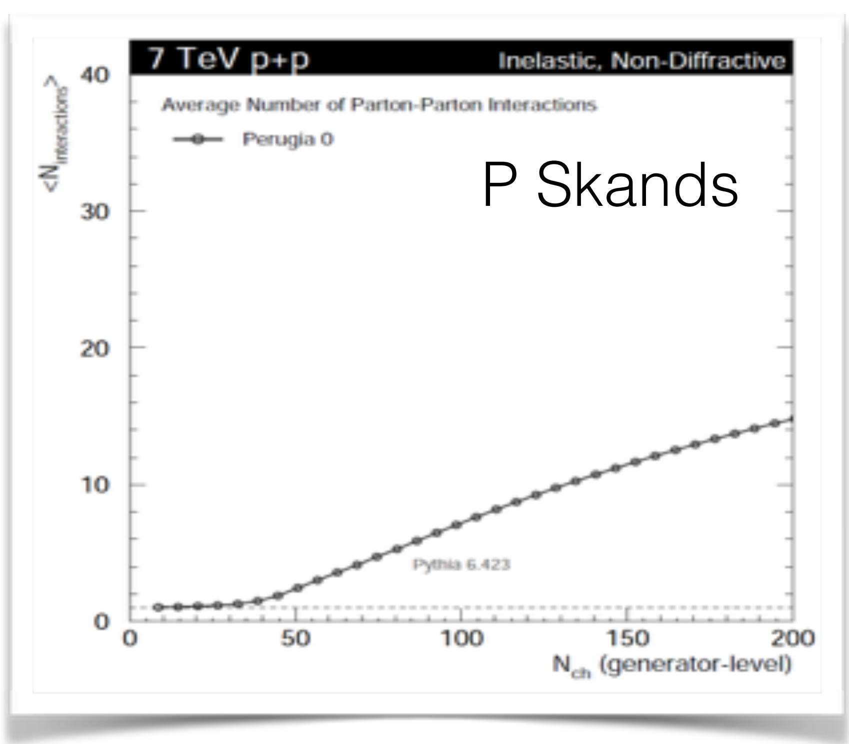


Similar behaviour for J/ψ at mid-rapidity

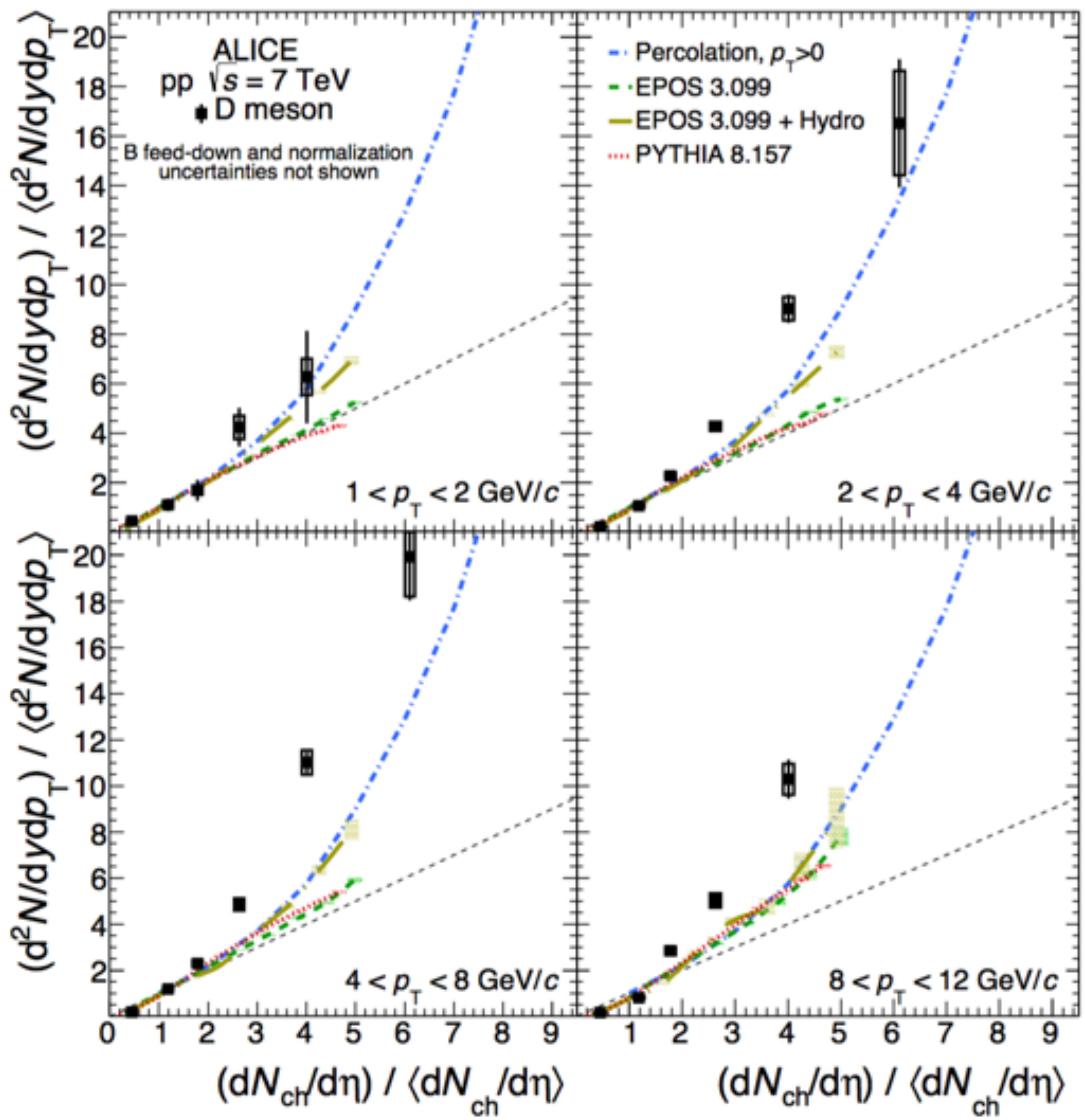
Linear for forward J/ψ ?

Model Comparison

- So far only percolation model shows qualitative agreement.
- Should try other Pythia option, for example *x*-dependent proton geometry
  - Role of diffraction at low N_{ch}



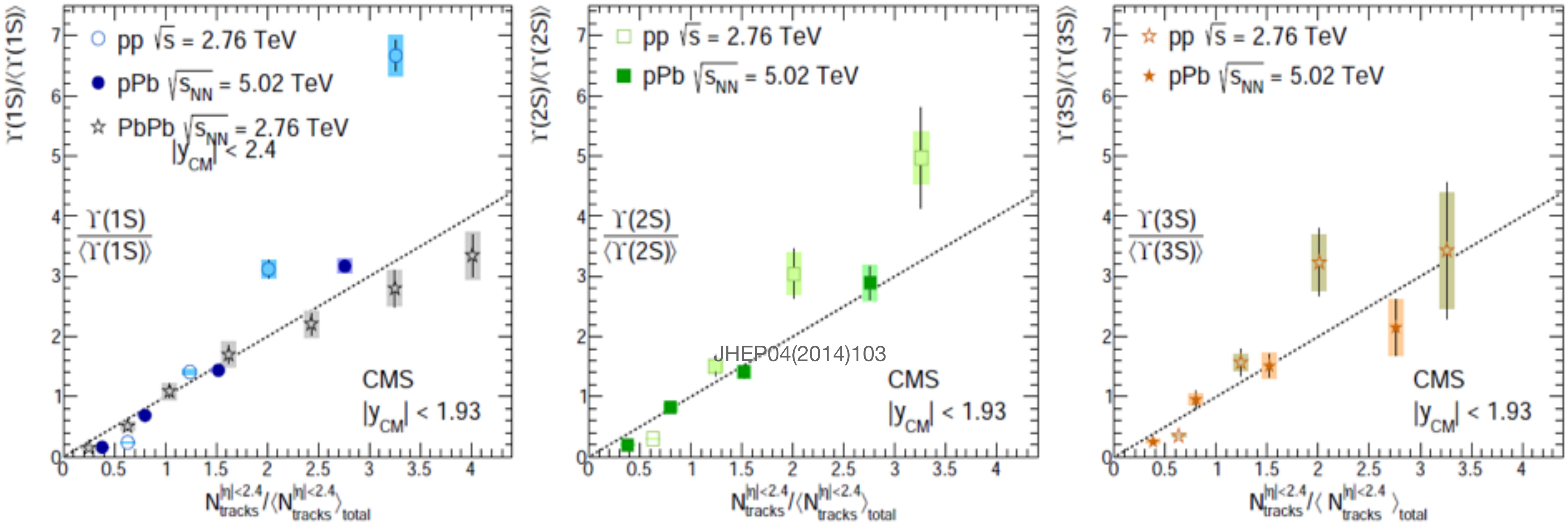
JHEP 09 (2015) 148



No simple $N_{MPI}/\langle N_{MPI} \rangle_{MB}$ expected

Upsilon Production vs Multiplicity

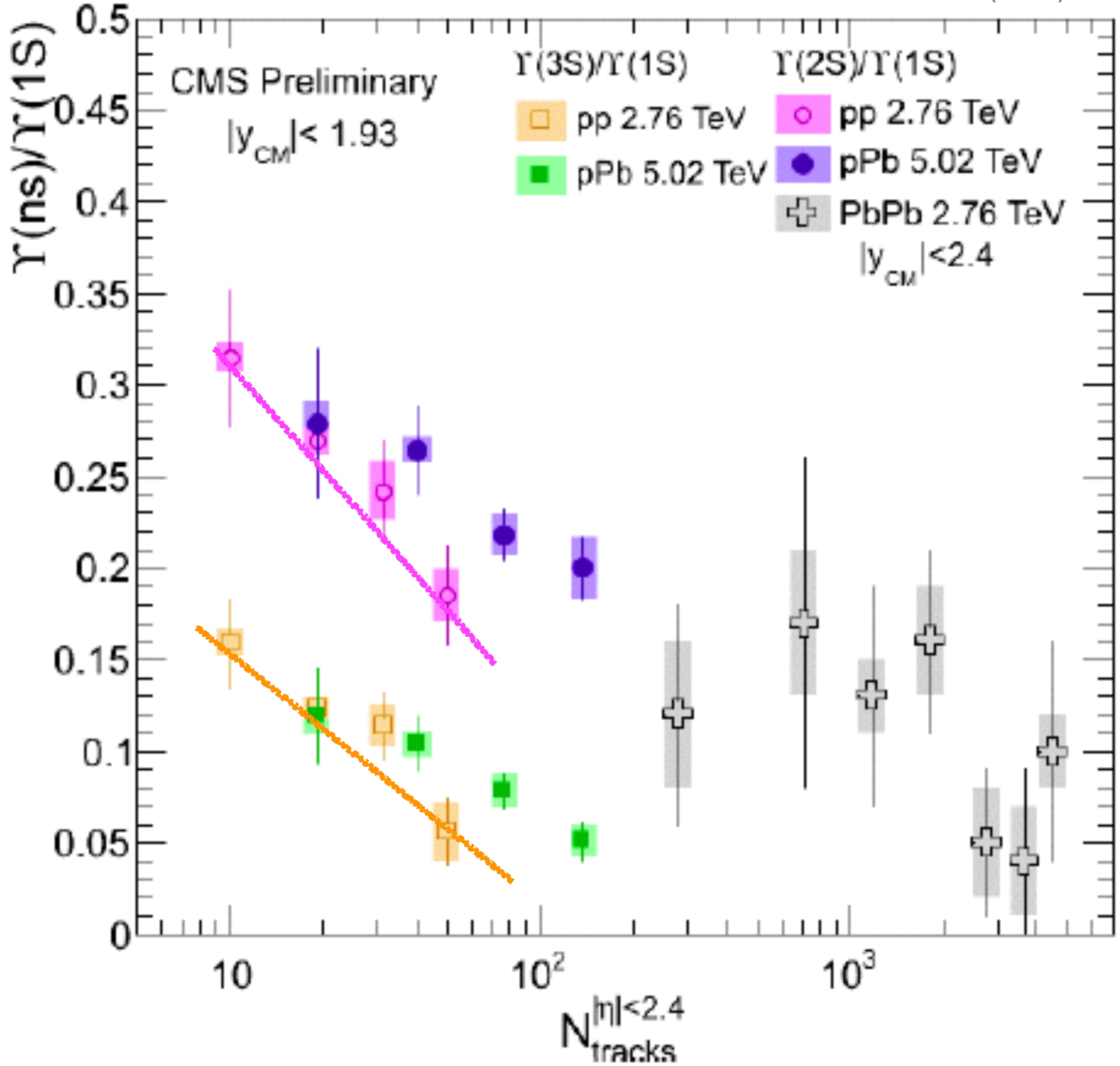
JHEP04(2014)103



Puzzling: Non linear-increase strongest for Y(1S)

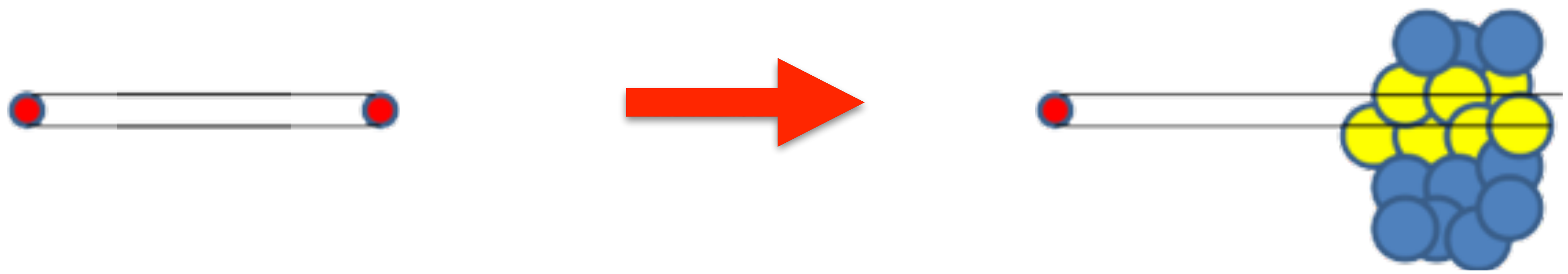
Y(2S), Y(3S)-Suppression in pp …

JHEP04(2014)103



… or rather an Y(1S) enhancement
Needs analysis of h-Y angular correlations

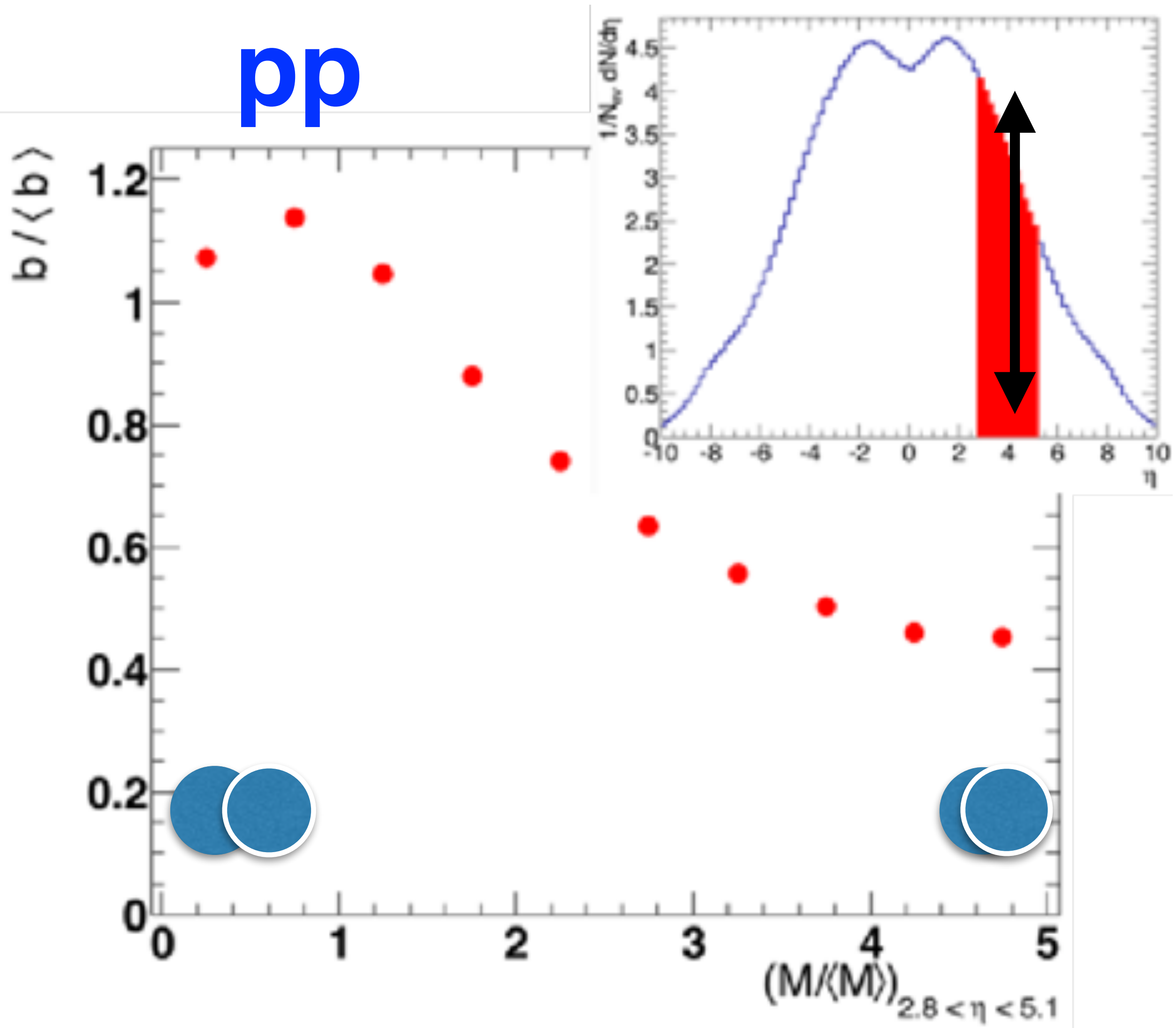
From pp to p-A



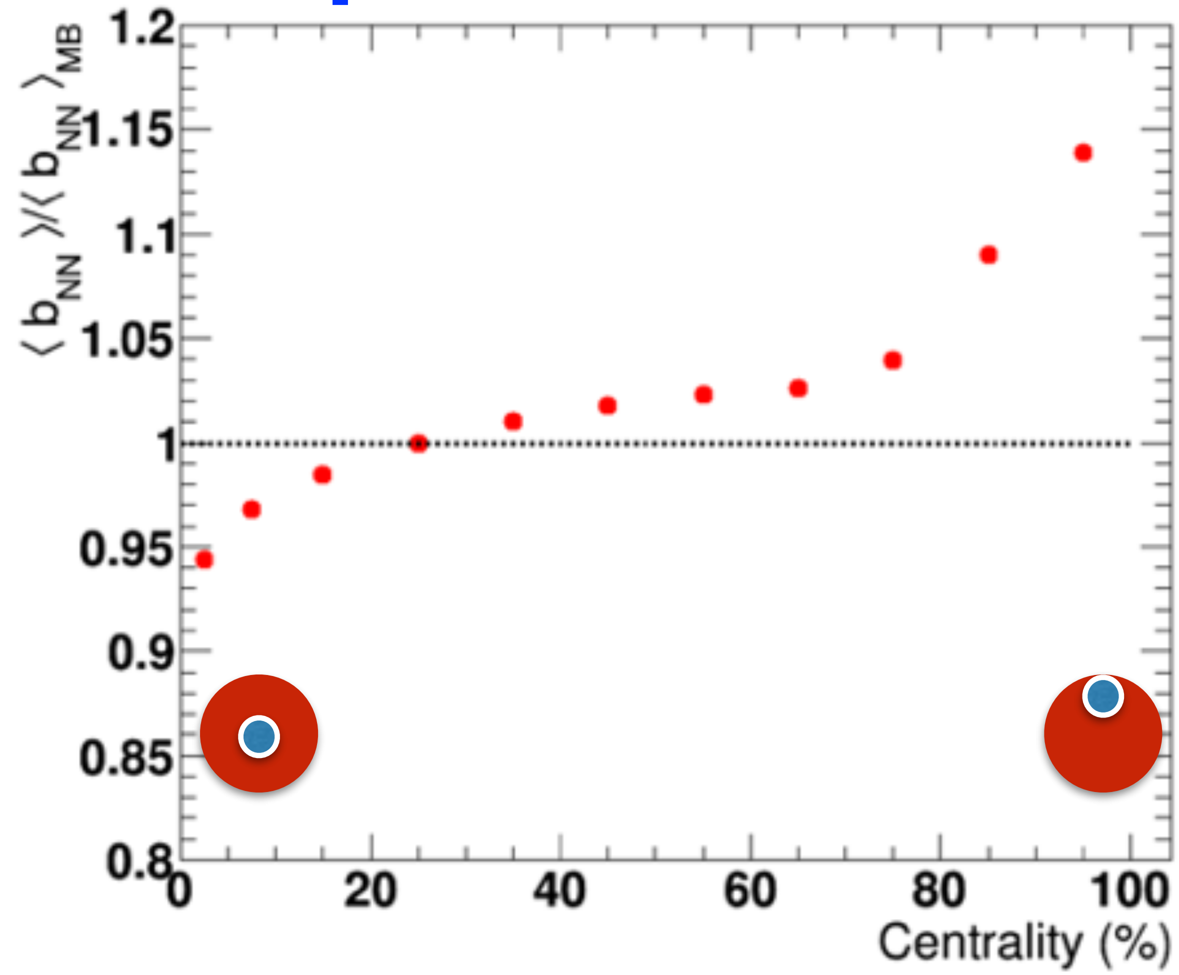
- Transverse size of interaction region similar to pp
  - increases initial energy density and overlap of strings
  - Increases coherence (collective) effects ?
- Number of parton-parton interactions $\sim N_{coll} \,.\, n_{hard}$
  - Expect stronger effects from energy conservation
- Interplay between multiplicity and MPI ?
  - Important for centrality selection (N_{coll} determination)
  - Extrapolate from knowledge on pp

Bias on initial state from centrality estimators

pp



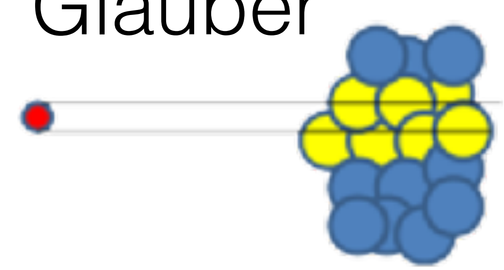
p-Pb



Slicing of Multiplicity in 2.8 < η< 5.1

Multiplicity selects on N_{coll}
and
local p-N overlap
and
minijet fragmentation

Glauber



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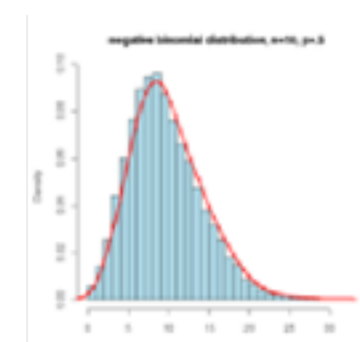
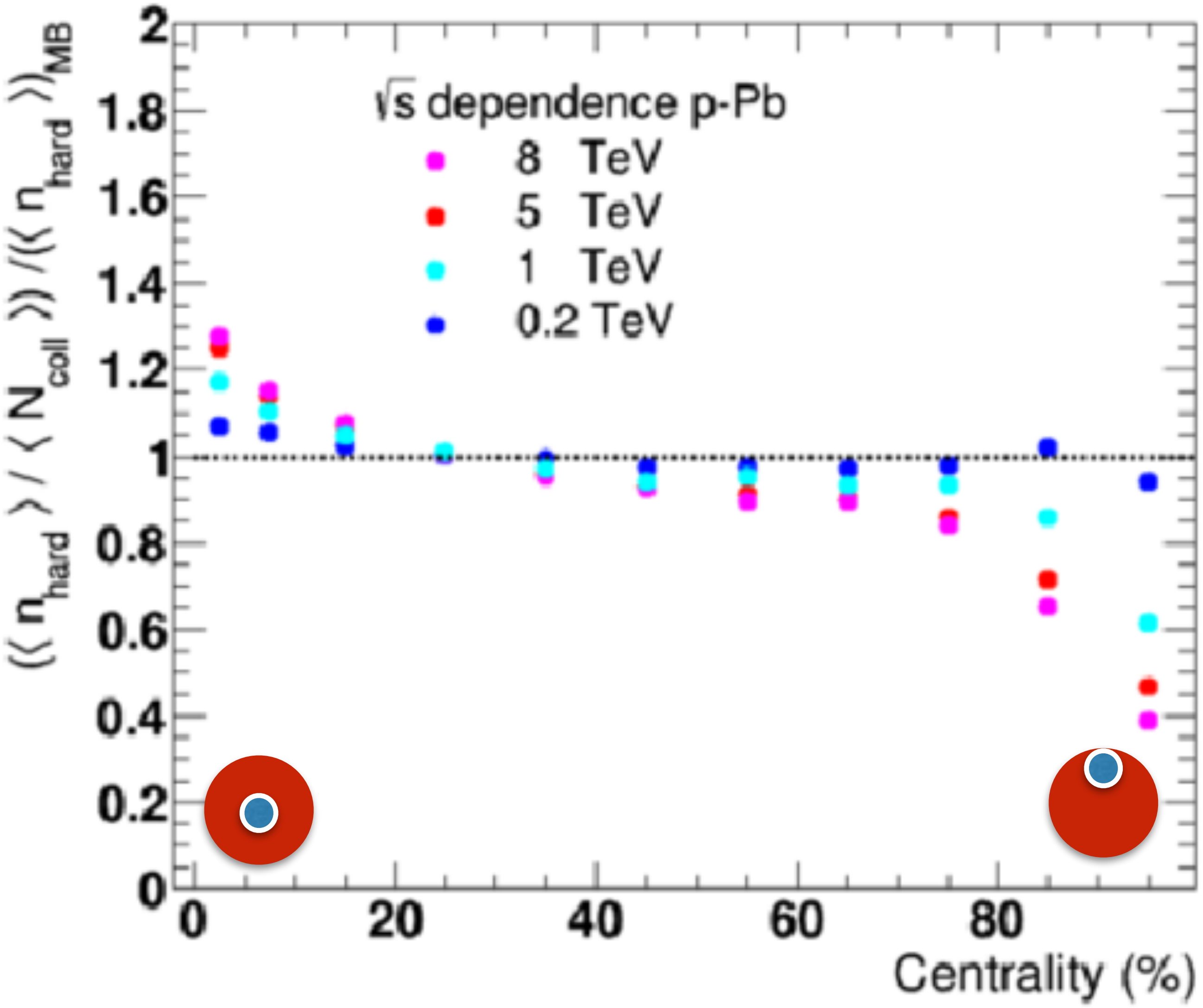
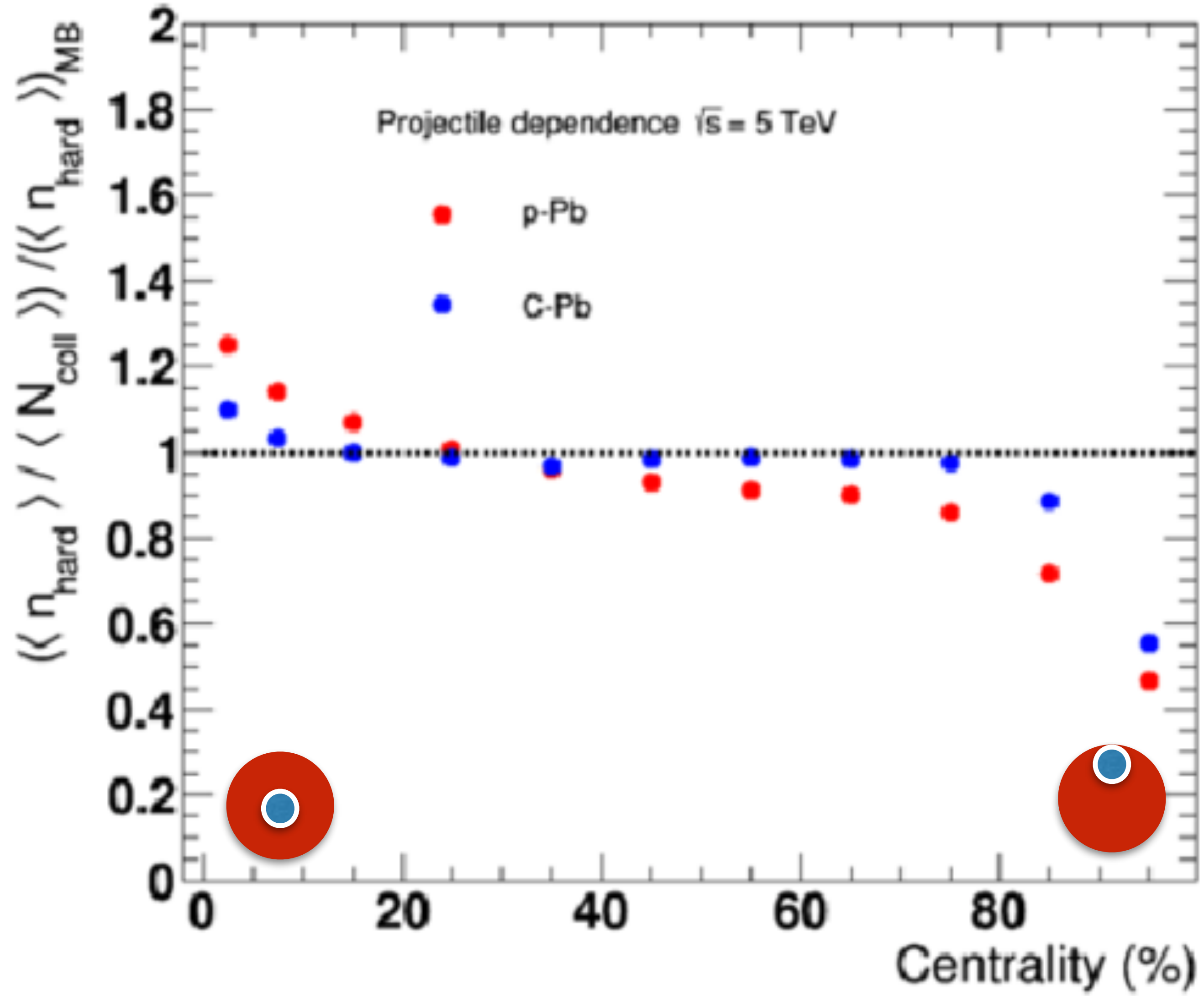


Pythia

Collisions Energy and System Size Dependence

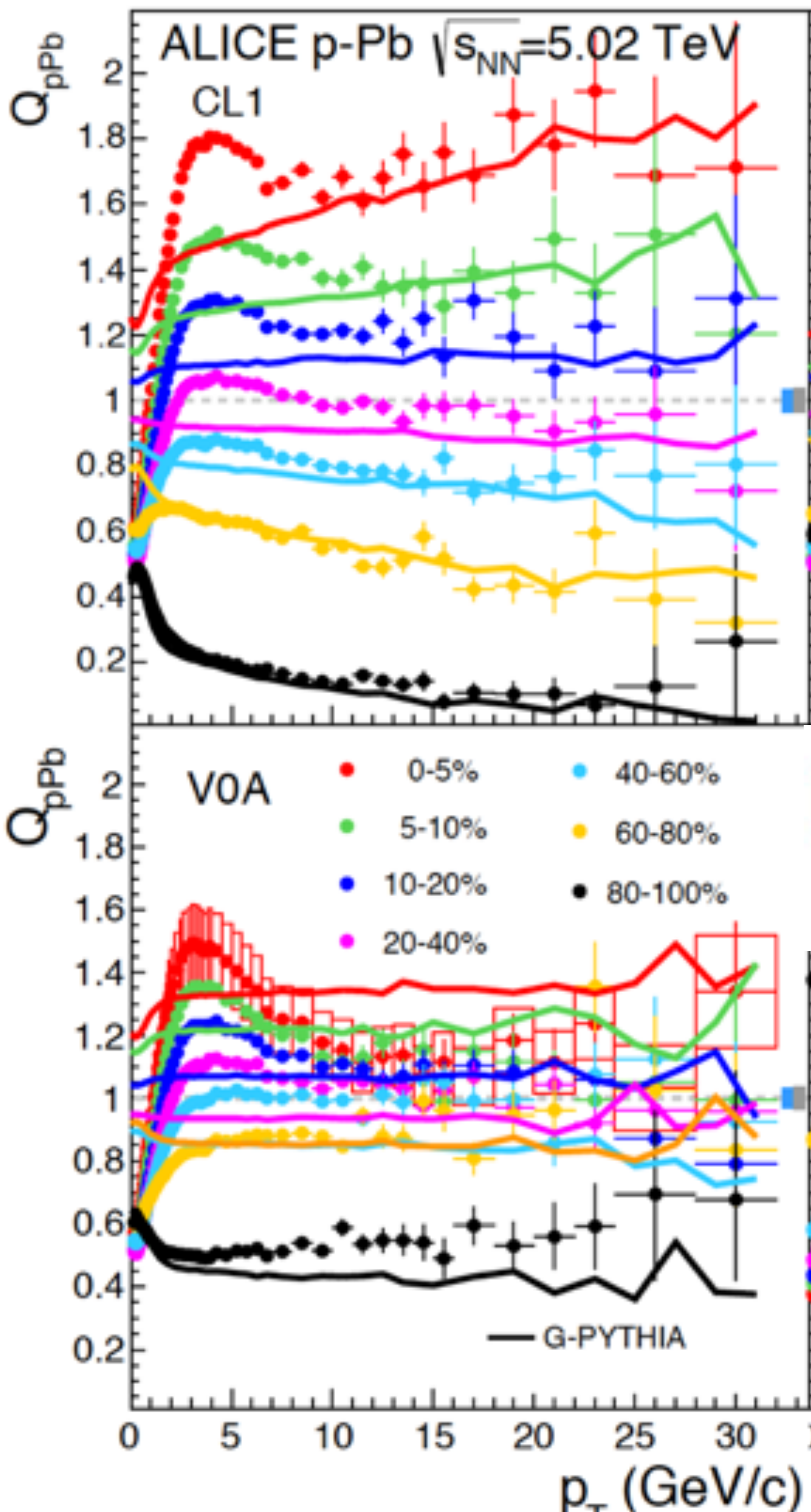


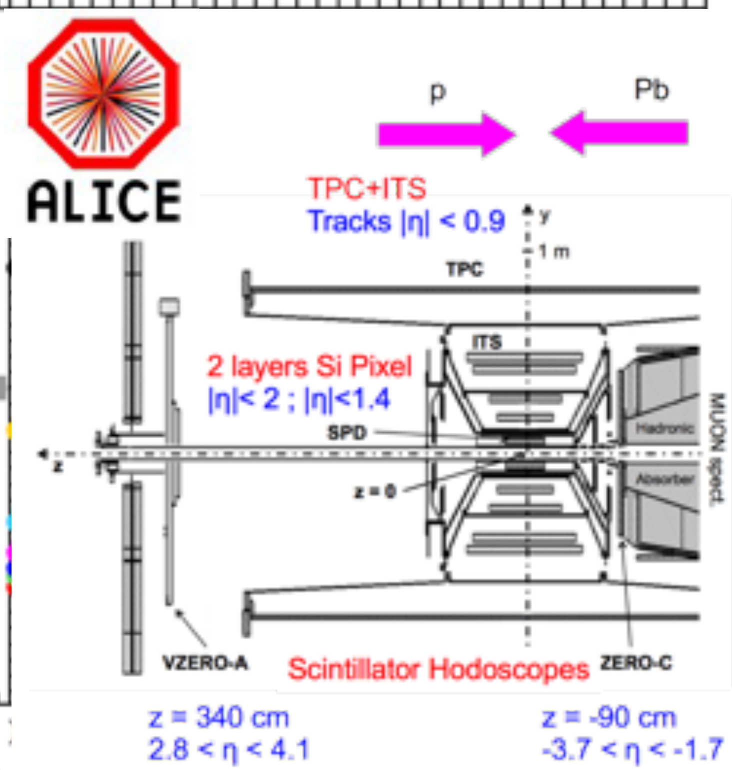


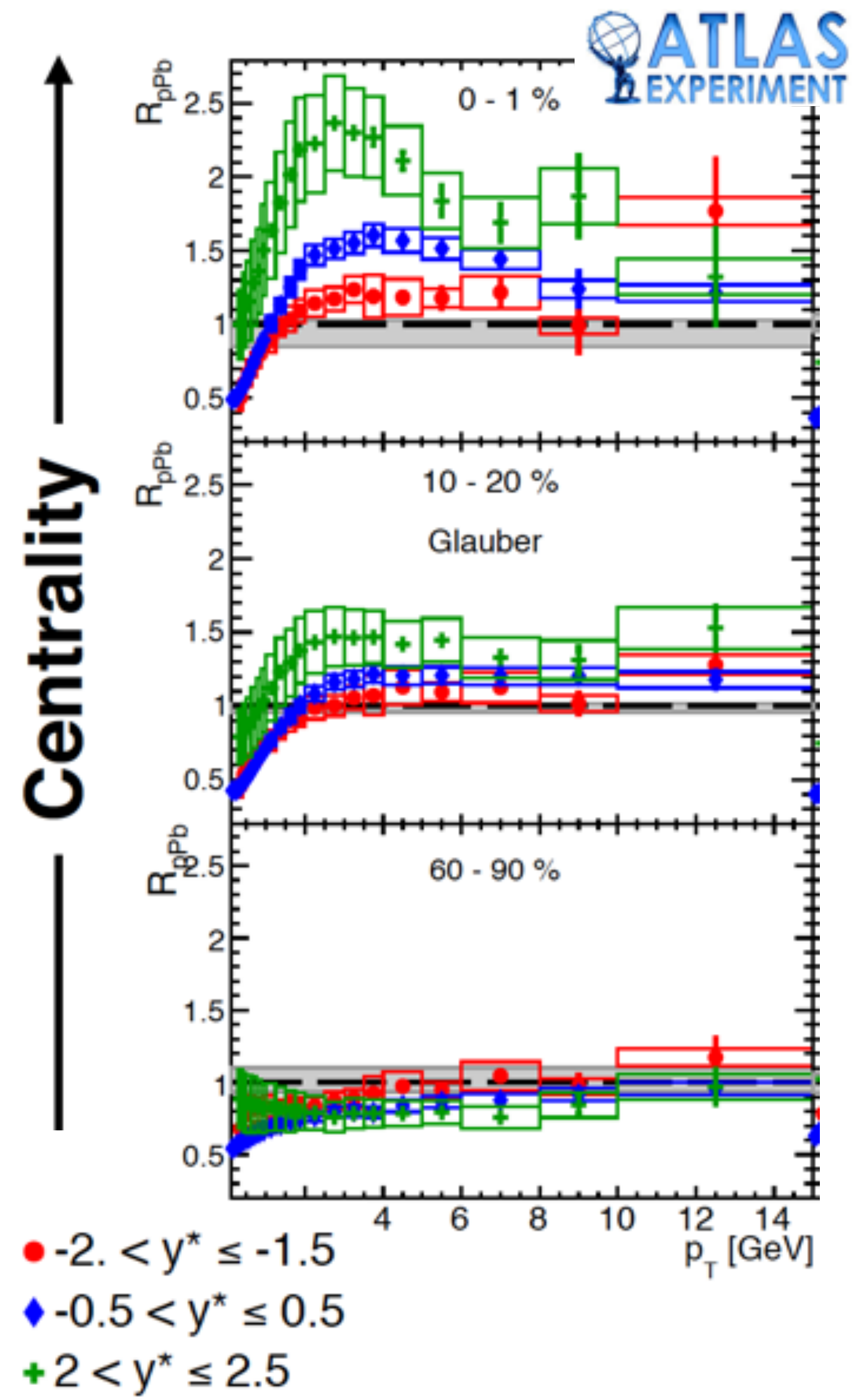
- No significant p-N bias at 200 GeV (RHIC)
- Decreasing effect with increasing target size

Consequences for R_{pA}

Phys. Rev. C 91, 064905 (2015)

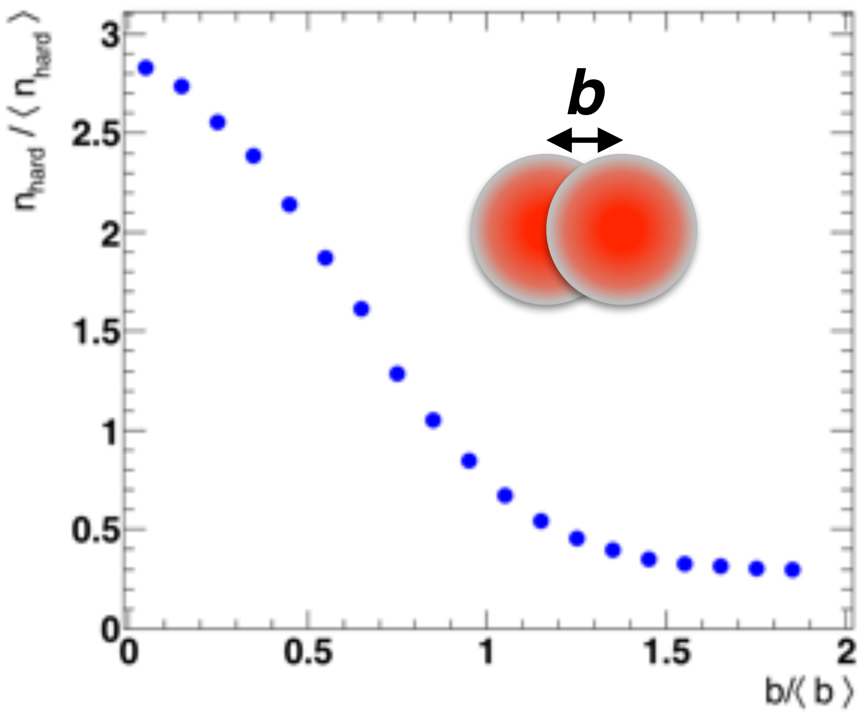


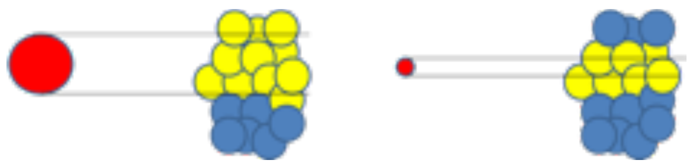


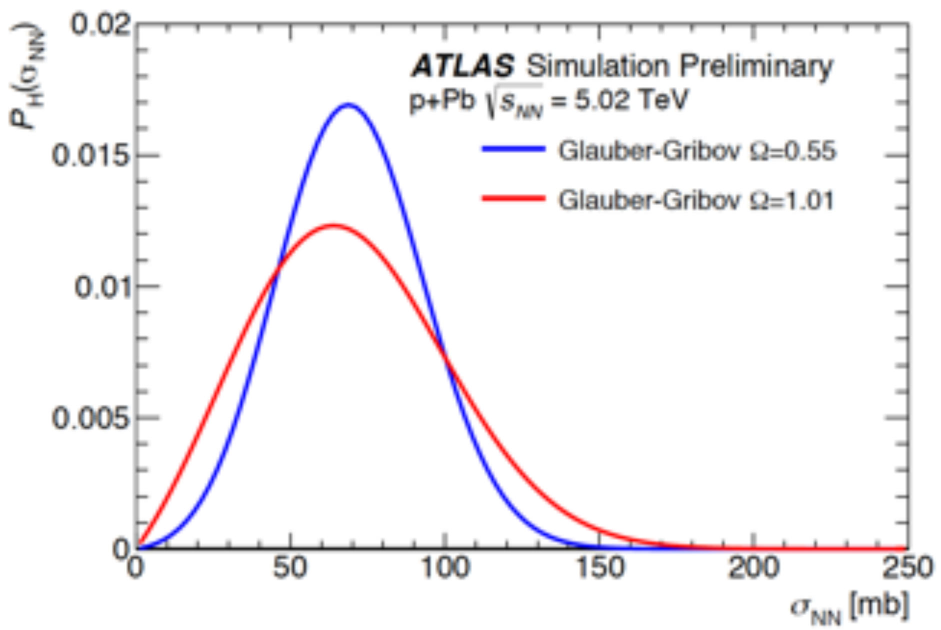


Non-Trivial Glauber Extensions

- HIJING Glauber
  - Mean number of pQCD 2→2 scatterings (n_{hard}) depends on p-A overlap $T_{pA}(b_{pN})$
  - Poissonian fluctuations of n_{hard}
- Glauber-Gribov Color Fluctuations
  - Size of proton changes event by event
  - Configuration frozen for a single p-A collision
  - Parameter Ω=width of Gaussian Fluctuations

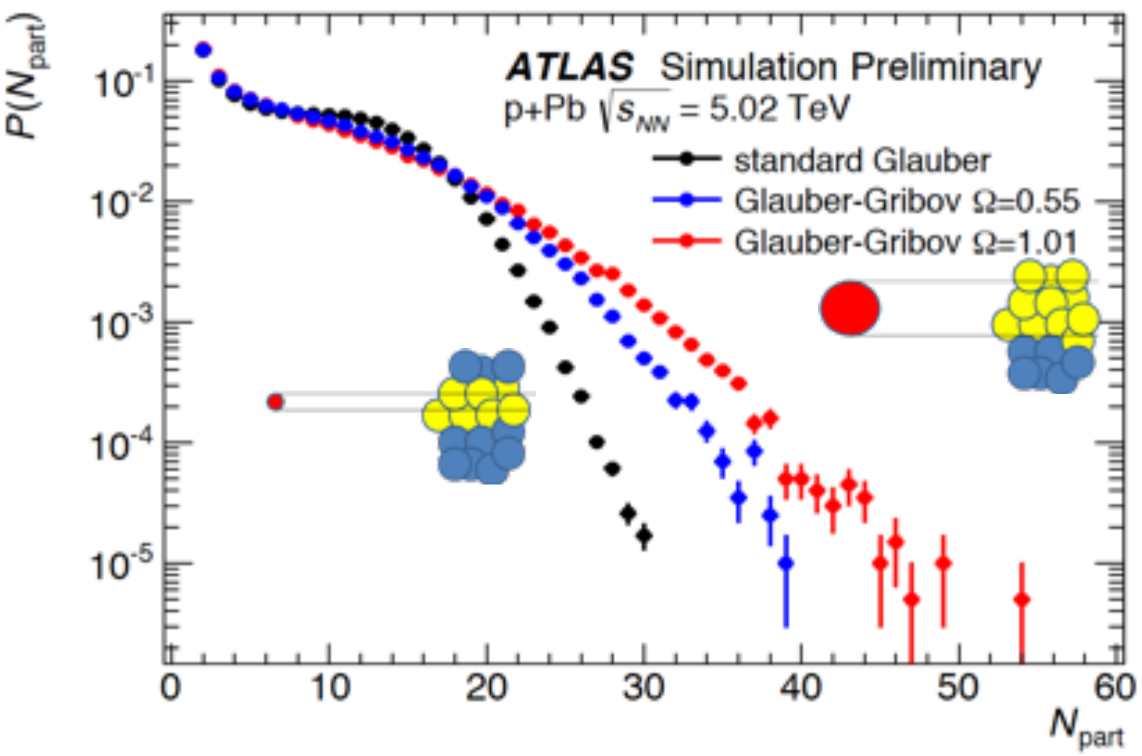


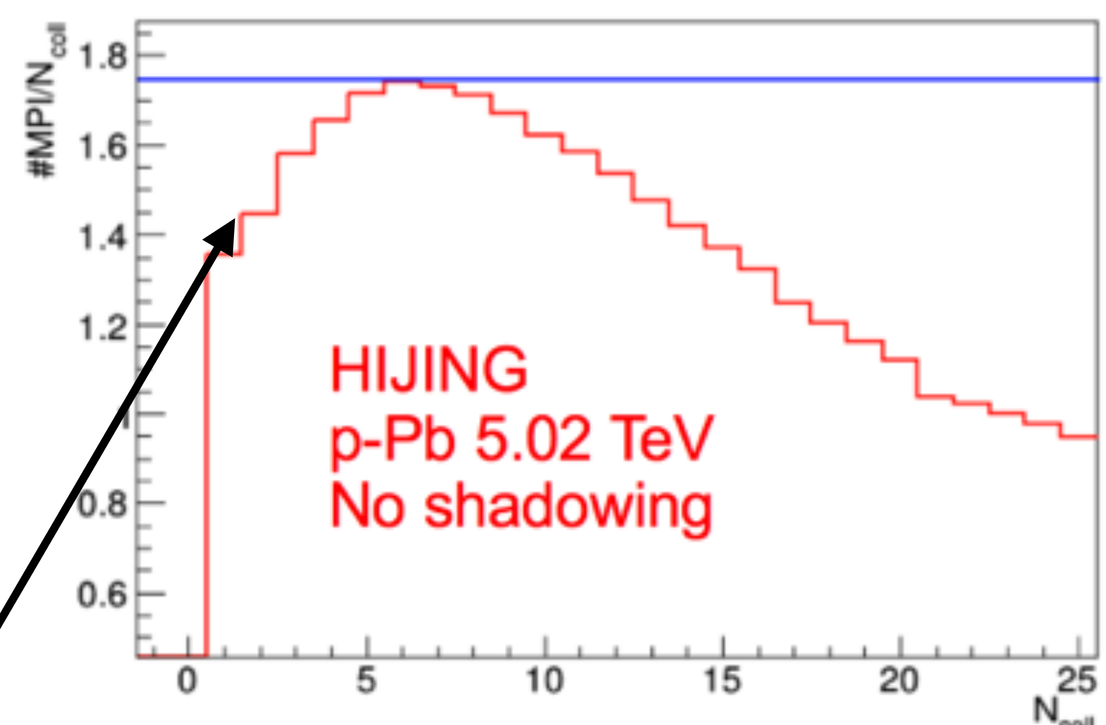




Non-Trivial Glauber Extensions

- Glauber-Gribov Color Fluctuations
  - Changes $P(N_{coll})$
- HIJING Glauber
  - Does not change $P(N_{coll})$
  - Provides correlation between hard and soft particle production
  - Caveat: high values of hard suppresses by energy conservation

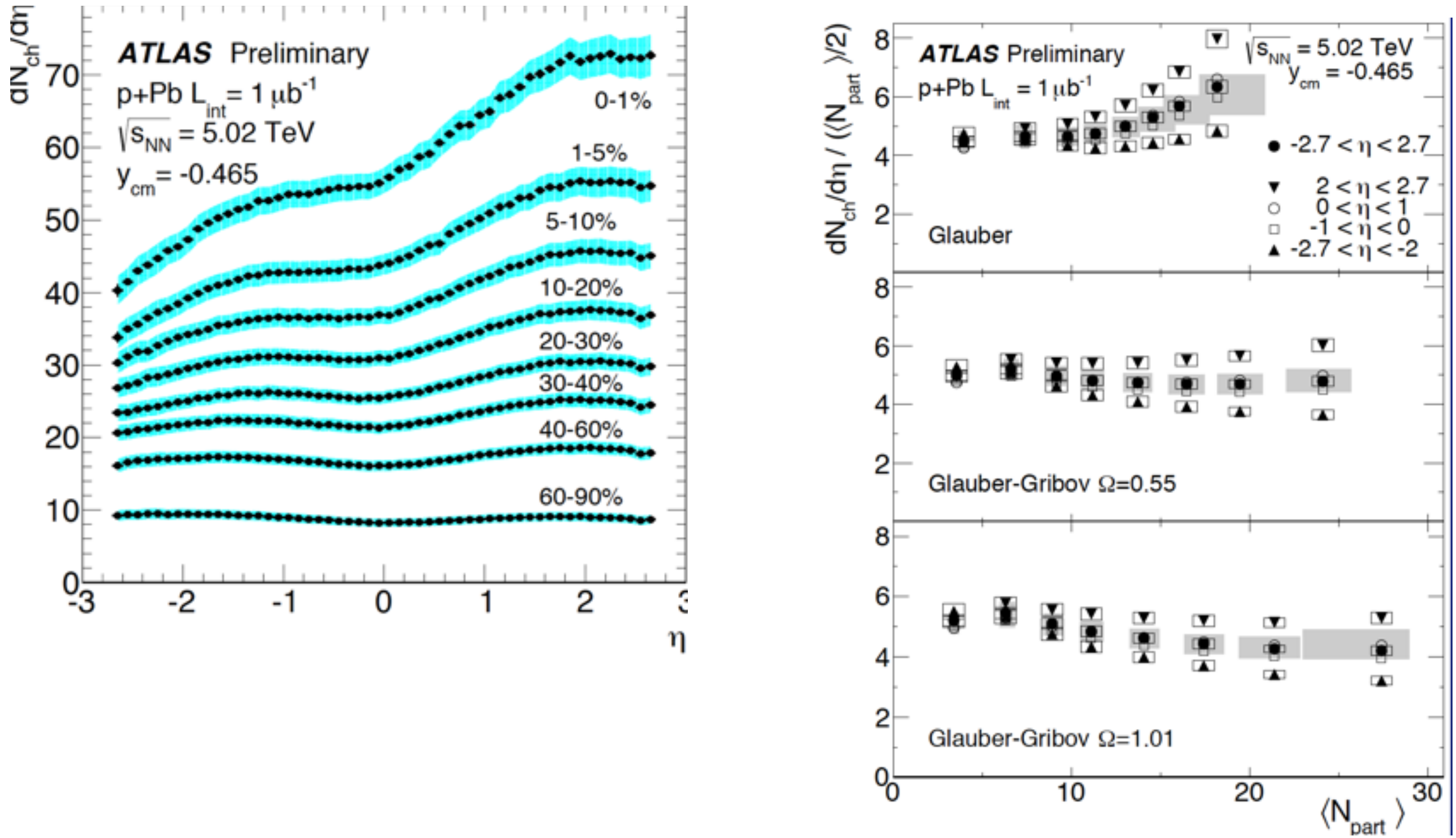




No pA generator implementing known basic effects exists !

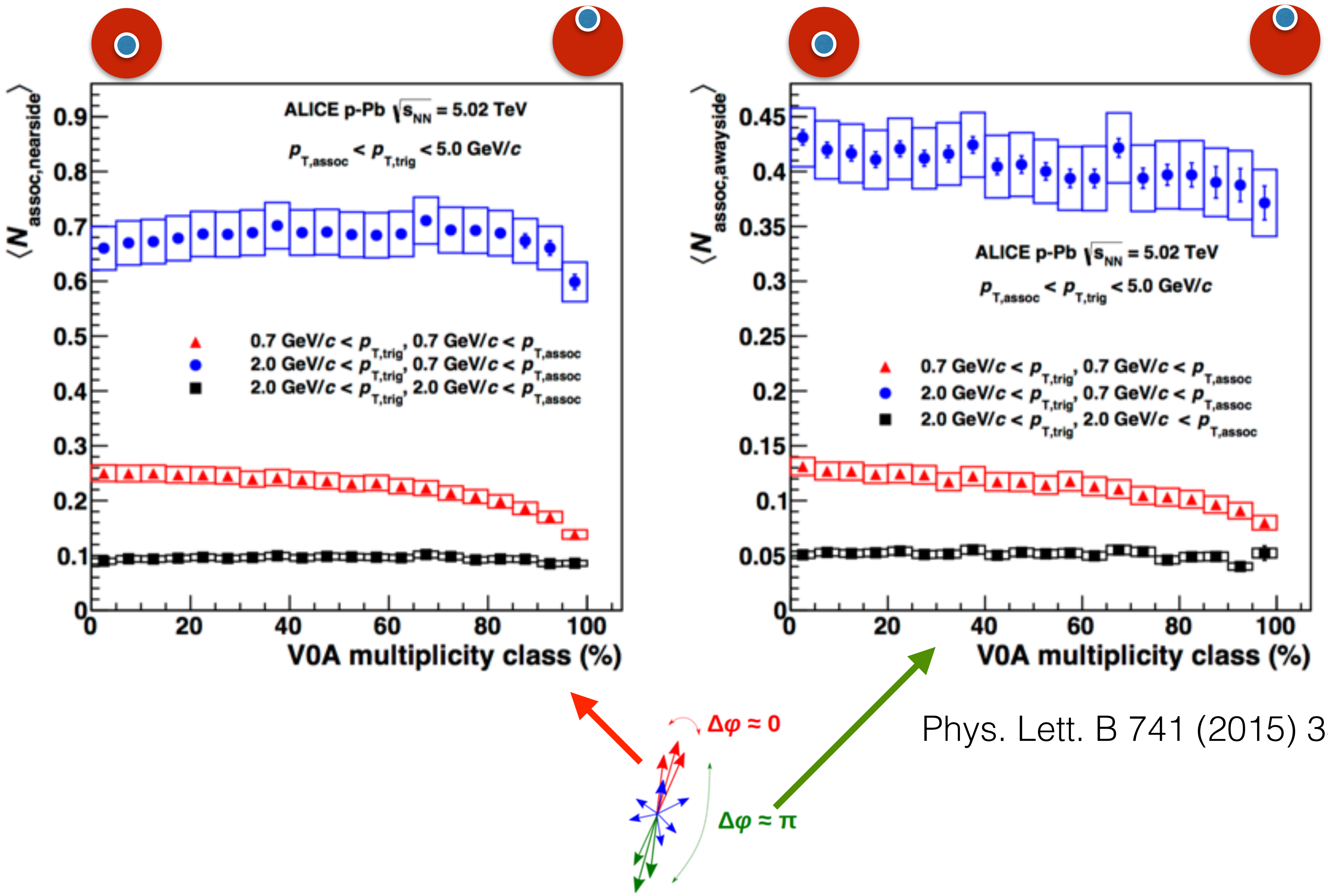
Geometry bias, see also J.Jia arXiv:0907.4175

Centrality dependent dN/dη



Interpretation depends on parameter Ω

MPI at low-p_T from di-hadron correlations



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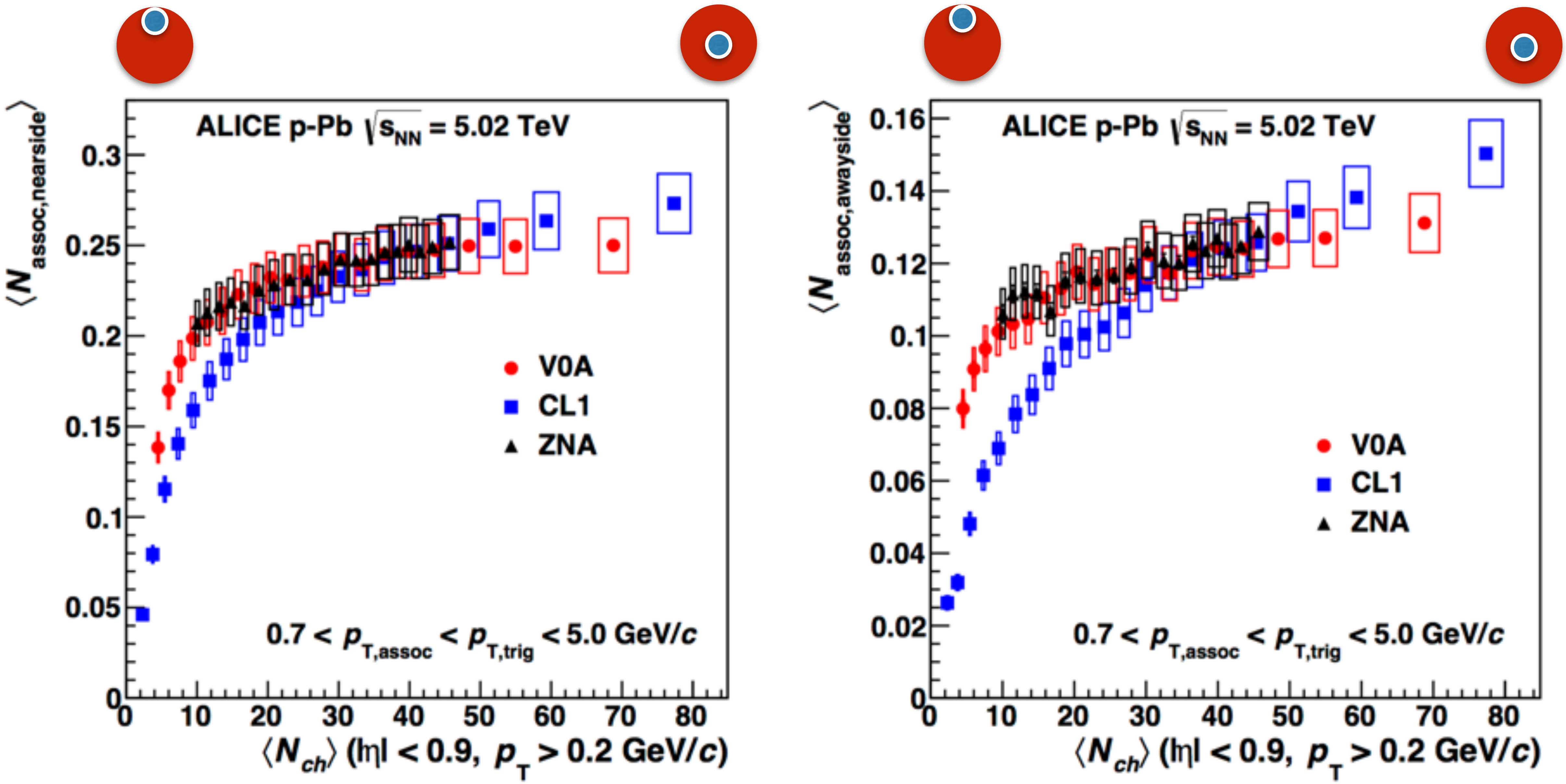
Small bias for peripheral collisions
Increased fraction of soft events?

Centrality Estimator Dependence



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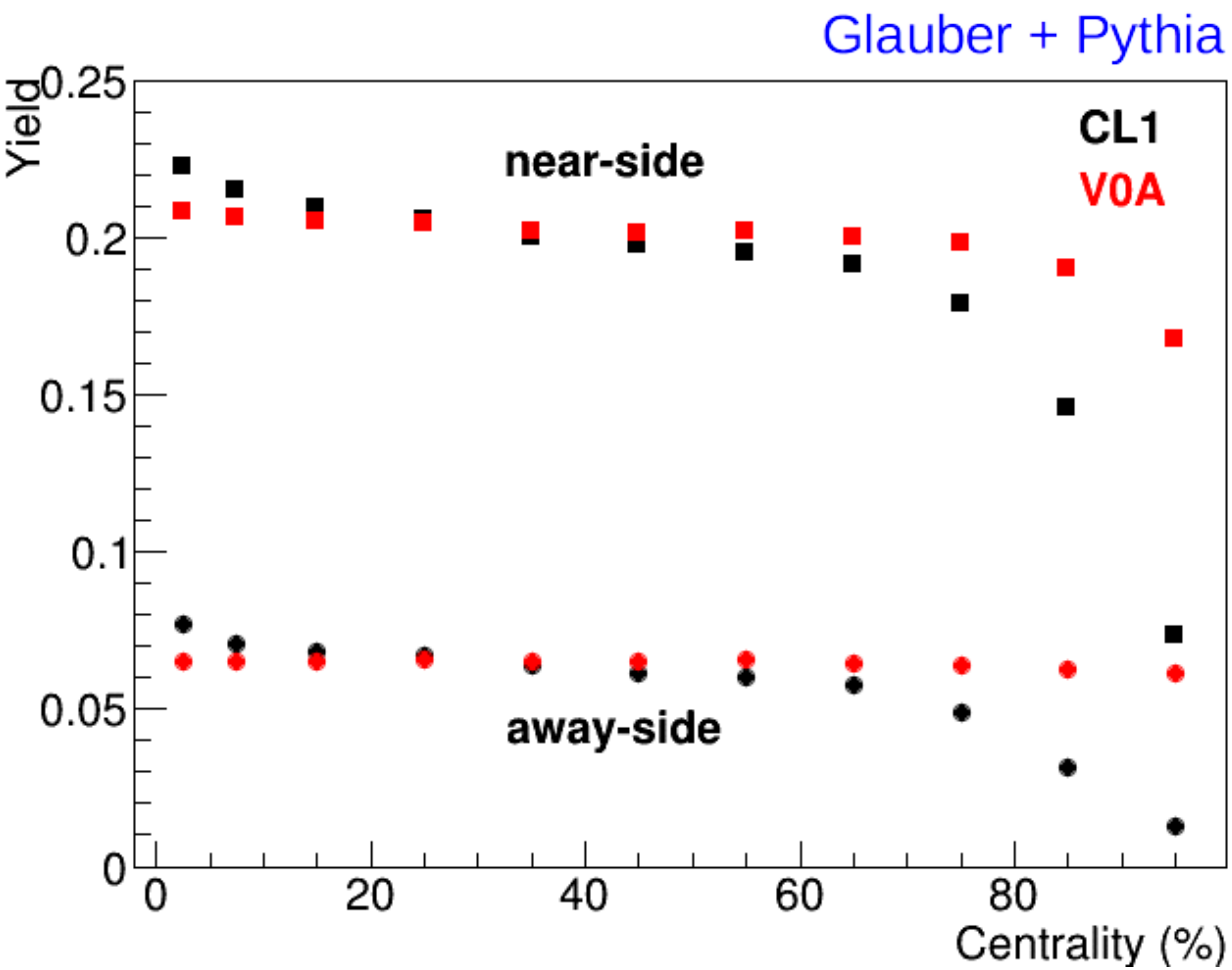
Strong bias if multiplicity measured in central region.

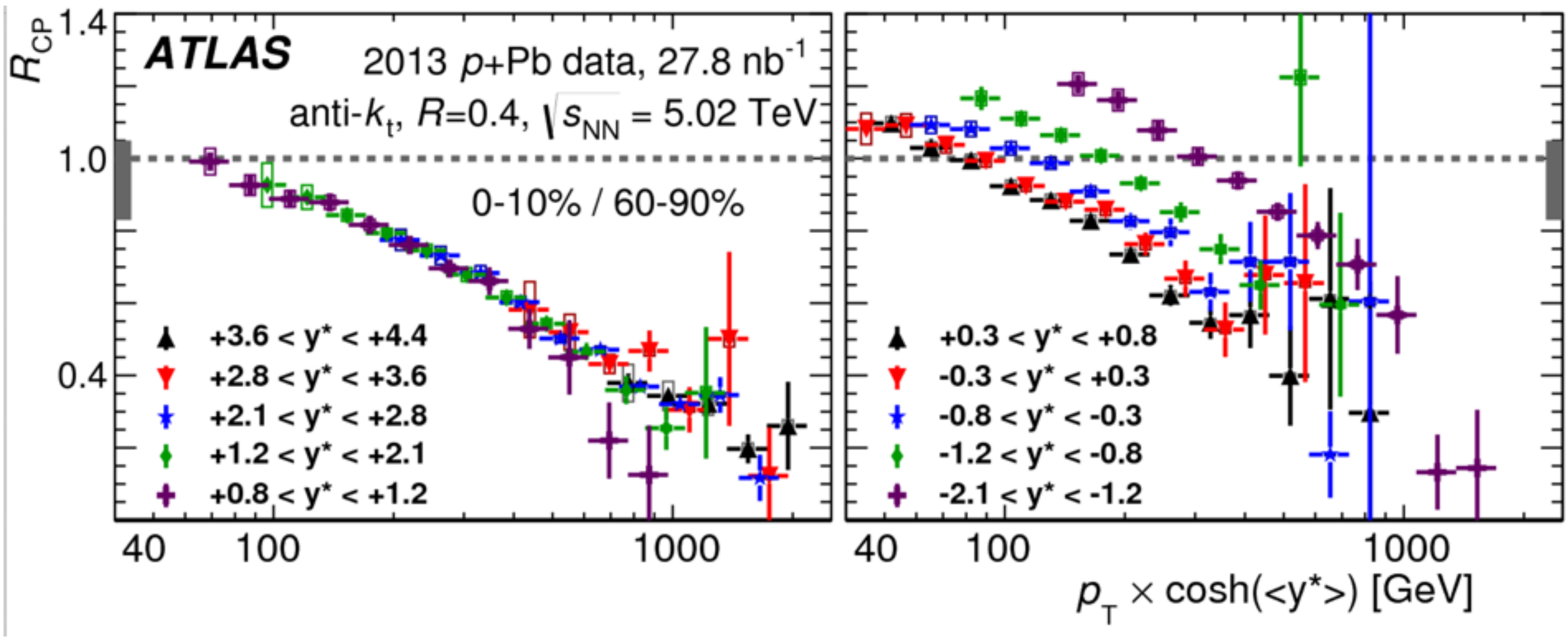
Model Comparison



Good qualitative agreement with data !

Centrality Dependence of Jet Production

Centrality classes from total transverse energy
in $-4.9 < \eta < -3.2$



Correlation between Hard and Soft

$$0 < x < 1 \Rightarrow 0 < x < 1 - \sum x_i$$

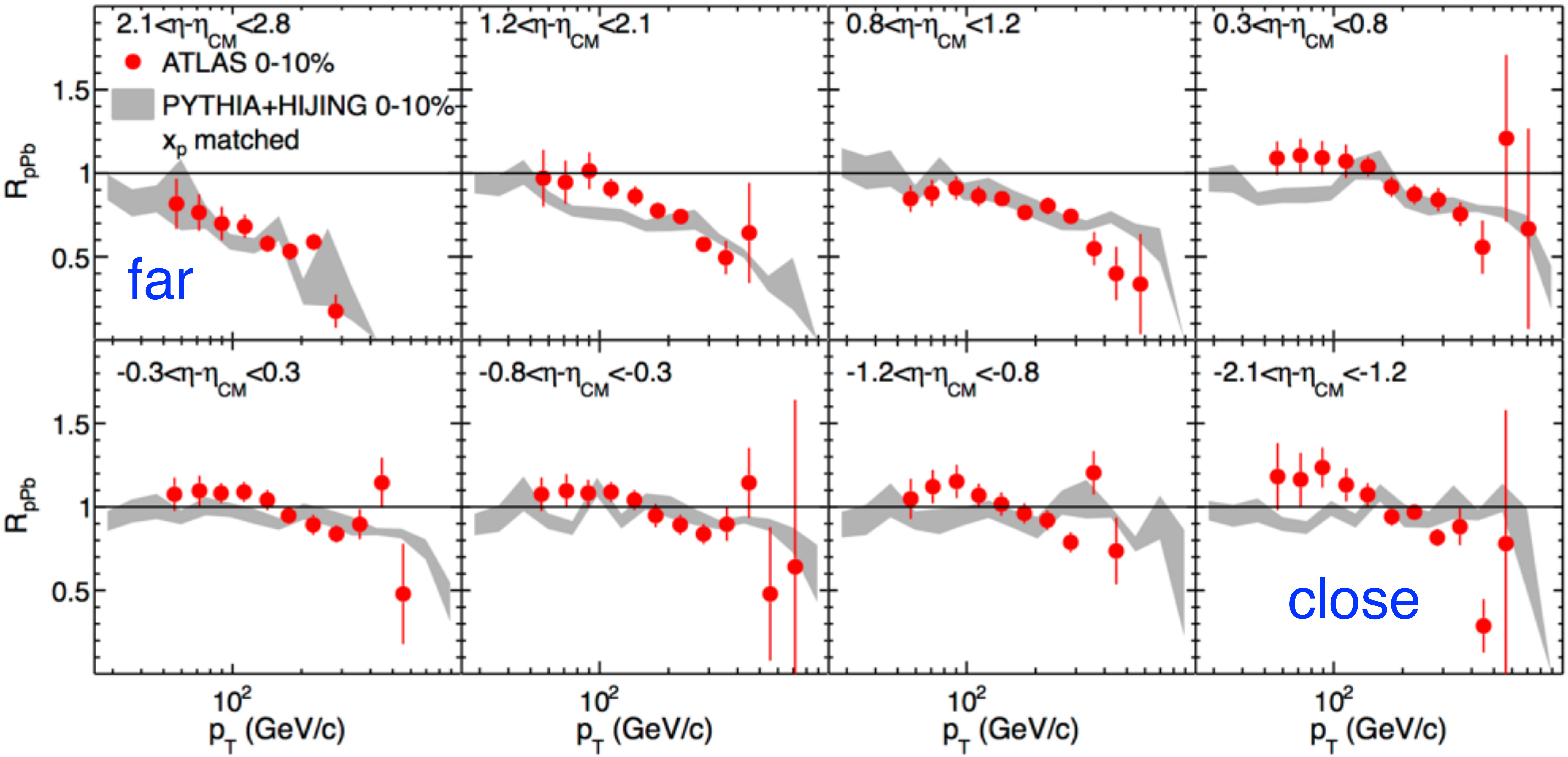
Can lead to large effects if one of the x is large, e.g. jets at large rapidity

- Simple model [N. Armesto et al. arXiv1502.02986]
  - Simulate hard scattering with Pythia
  - Subtract from each proton energy of parton participating in the hard scattering
  - Simulate underlying event from p-Pb collision with reduced energy (HIJING)

Model Comparison

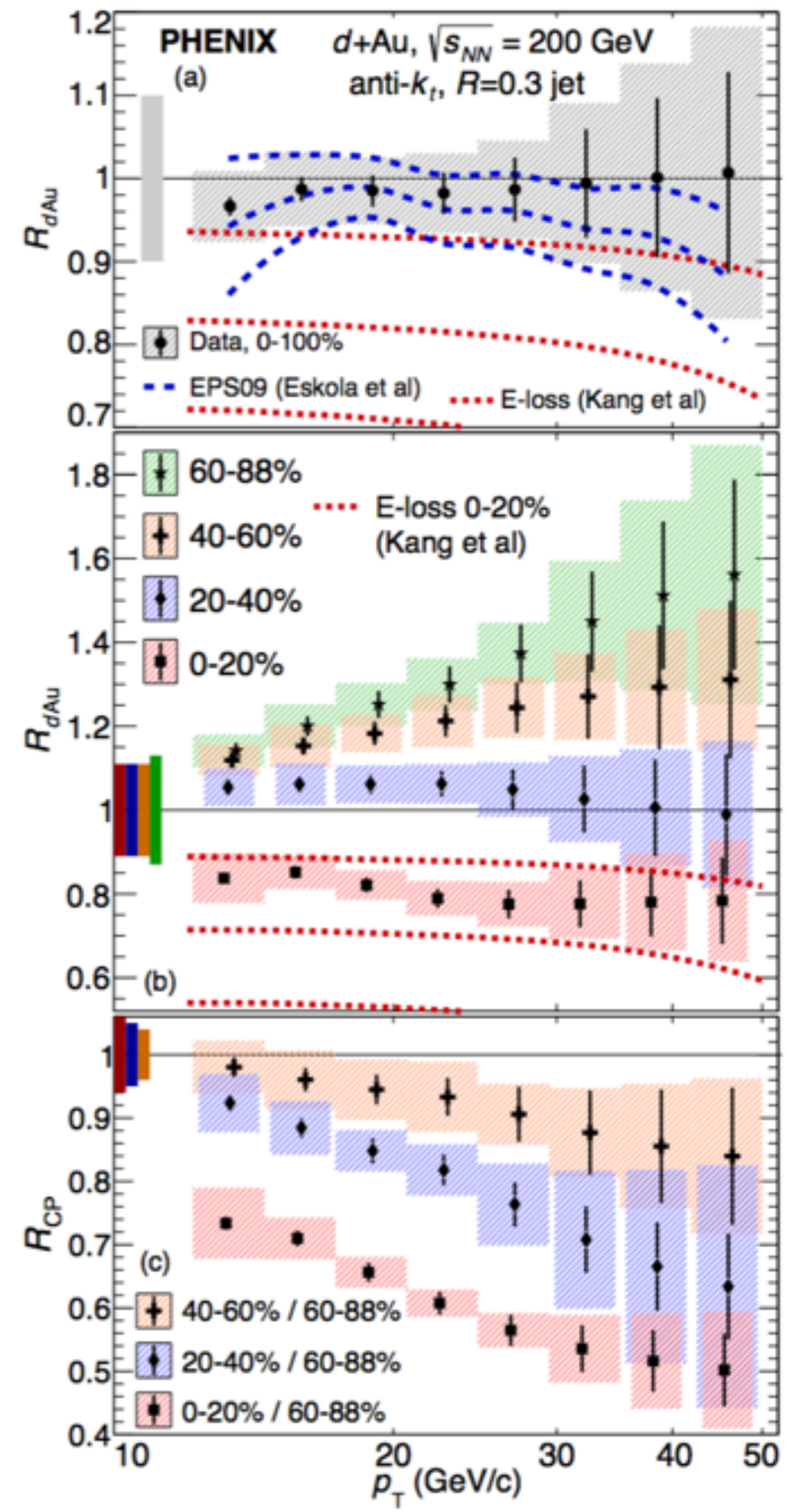
Centrality classes from total transverse energy
in $-4.9 < \eta < -3.2$

- N. Armresto et al. arXiv1502.02986



Jets at mid-rapidity in d-Au @ 200 GeV

- Jet production
  - enhancement in central collisions
  - suppression in peripheral collisions
- Red Flags for Centrality Bias
  - effects vanishes when averaged over centrality classes
  - peripheral collisions inconsistent with pp expectation.



From pp to AA

- Naively (factorisation) one expects the cross-section from semi-hard scatterings to increase $\sim A^2$
  - Would mean that these are the dominant source of particle production in central collisions
- The interaction area increases $\sim A^{2/3}$ and scattering density $\sim A^{4/3}$

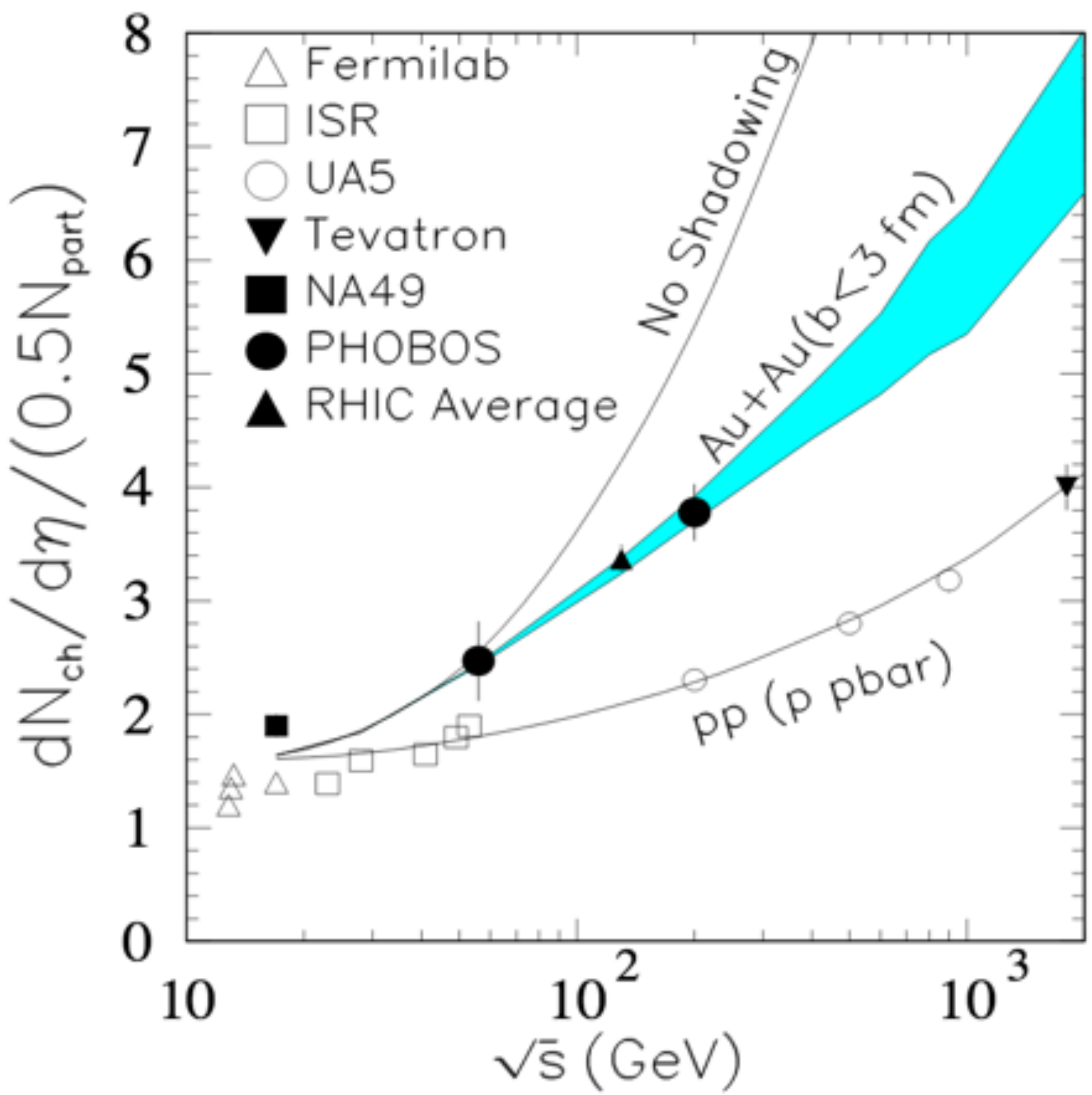
$$\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta} = \frac{1}{2}\langle N_{\mathrm{part}}\rangle\langle n_{\mathrm{soft}}\rangle + \langle N_{\mathrm{part}}\rangle\langle n_{\mathrm{soft}}\rangle \frac{\sigma_{\mathrm{jet}}\left(\sqrt{s}\right)}{\sigma_{\mathrm{inel}}\left(\sqrt{s}\right)}$$

Charged Particle Density in AA

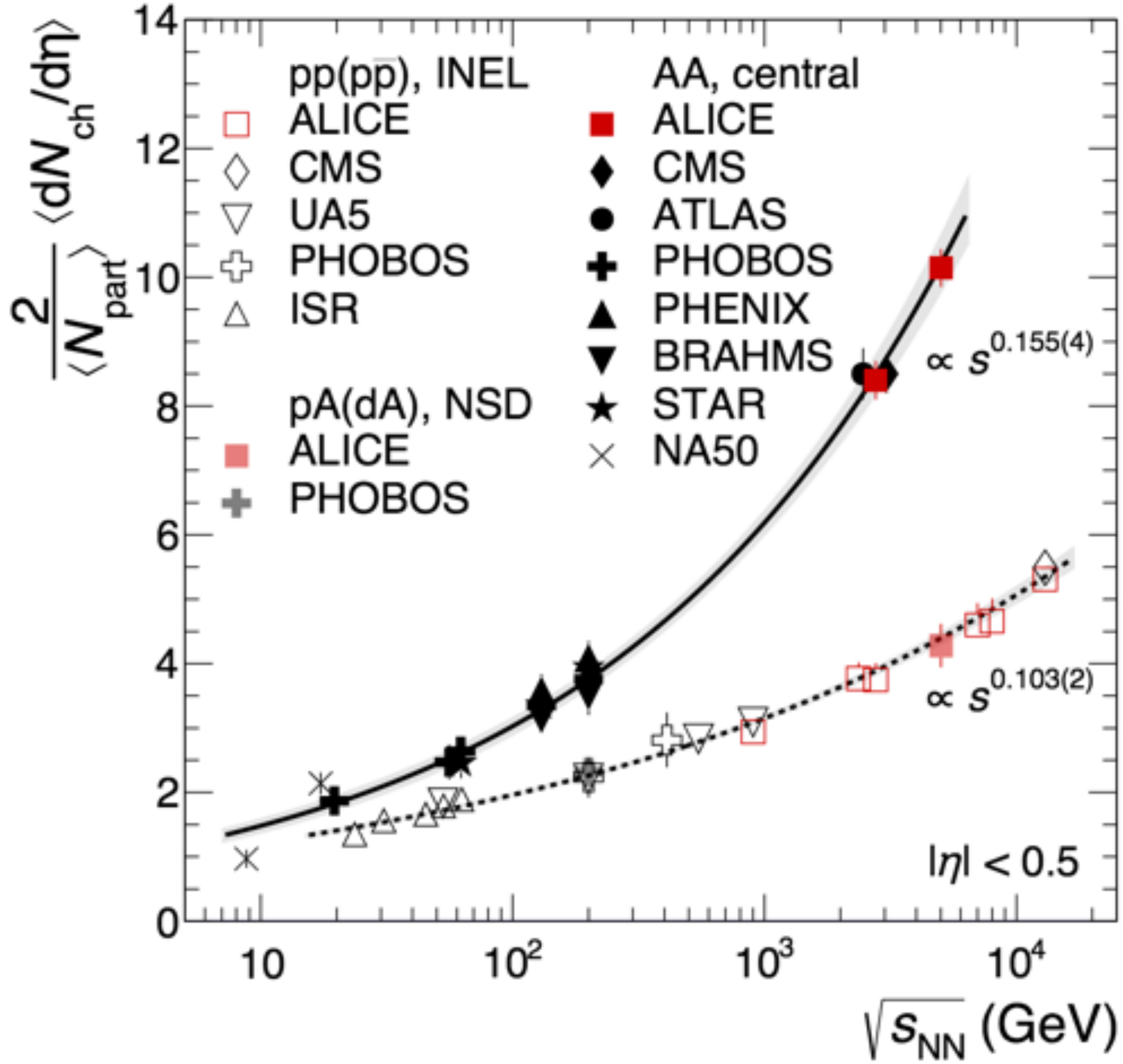
- Naive 2-component model fails
- Factorisation breaks
- Several interactions per area of hard scattering

$$a_{\text{hard}} \propto \frac{1}{p_{\text{T0}}^{2}}$$

- Scattering are not independent anymore



New data from Run II



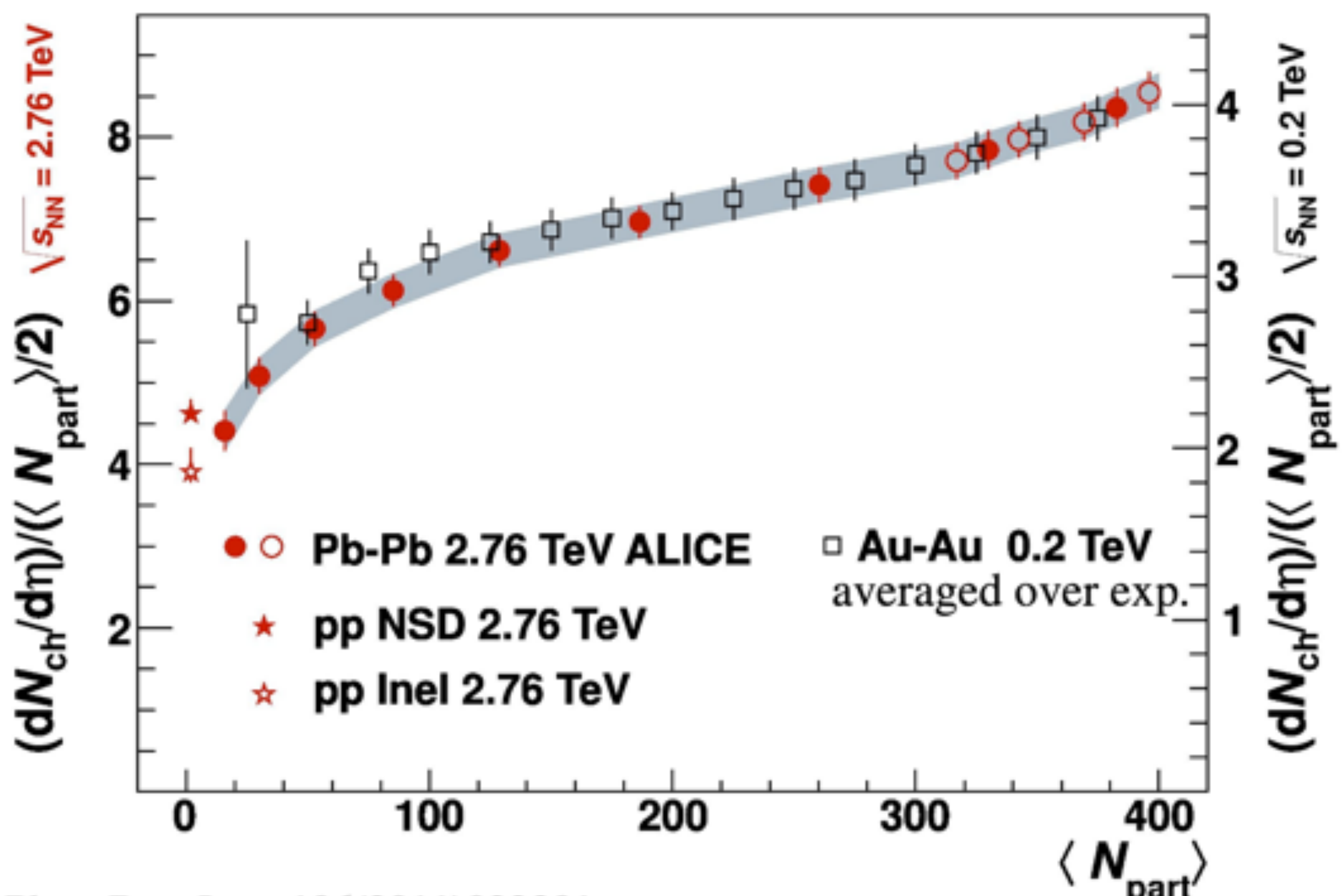
Trend established at lower $\sqrt{s}$ confirmed
Considerably steeper rise of AA multiplicity wrt pp.

arXiv:1512.06104

Centrality Dependence

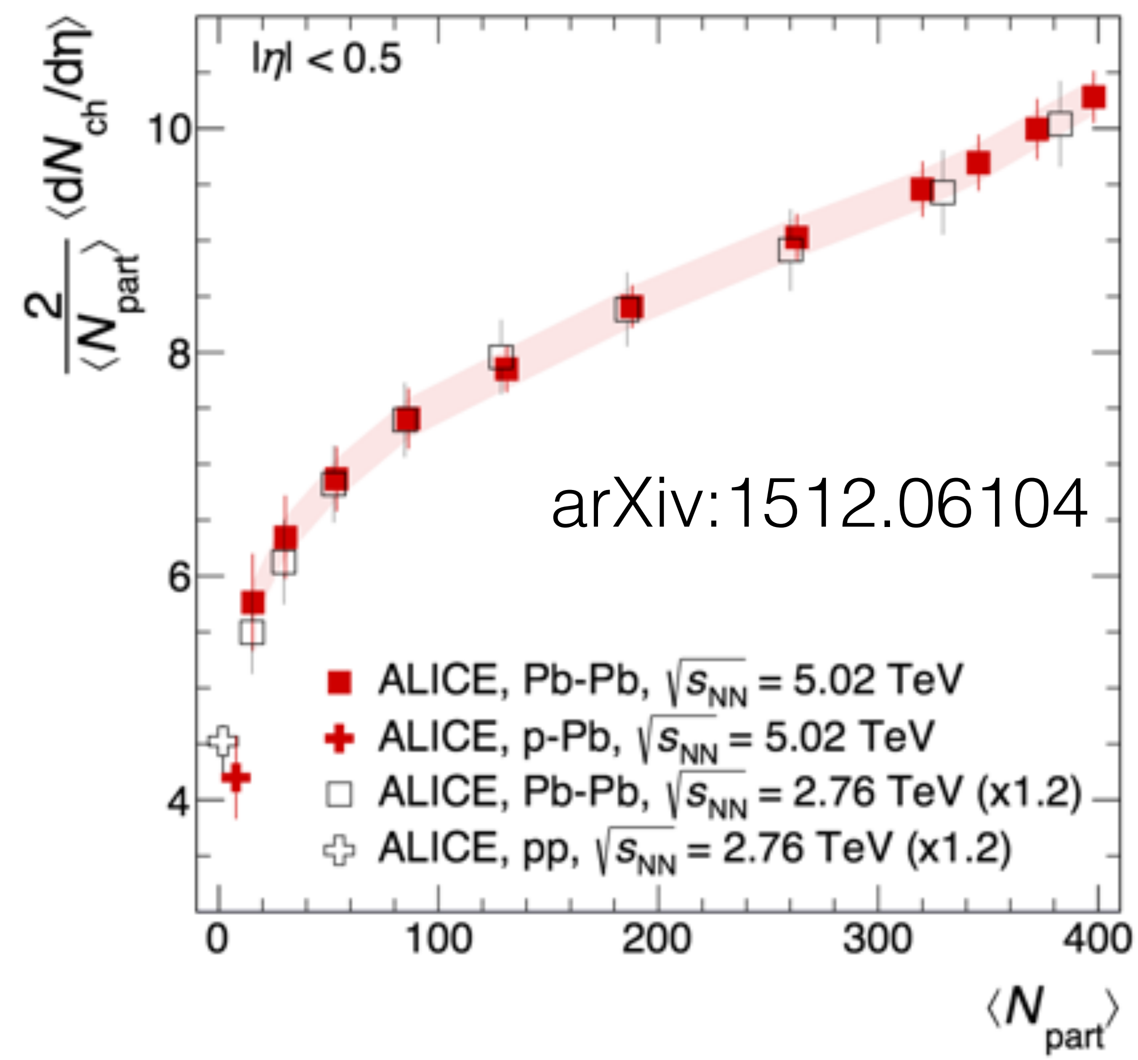
- S-shape reflects hard+soft scaling ($f\, N_{part}$ + (1-f) N_{coll})
- But shape almost energy independent.
  - Strong $\sqrt{s}$ dependence of the hard component expected

0.2 and 2.76 TeV



Phys. Rev. Lett. 106(2011)032301

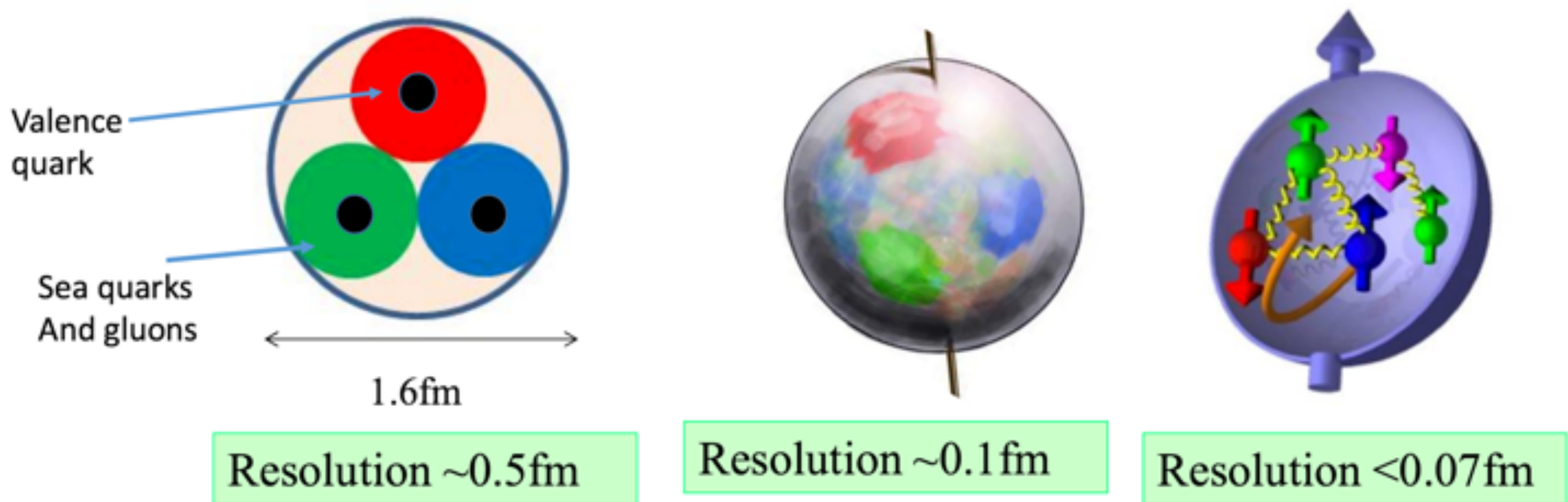
2.76 and 5.02 TeV



Participant Quark Scaling

Constituent quarks are Gell-Mann's quarks from Phys. Lett. 8 (1964)214, proton=uud. These are relevant for static properties and soft physics, low $Q^2<2$ GeV^2 ; resolution> 0.14fm

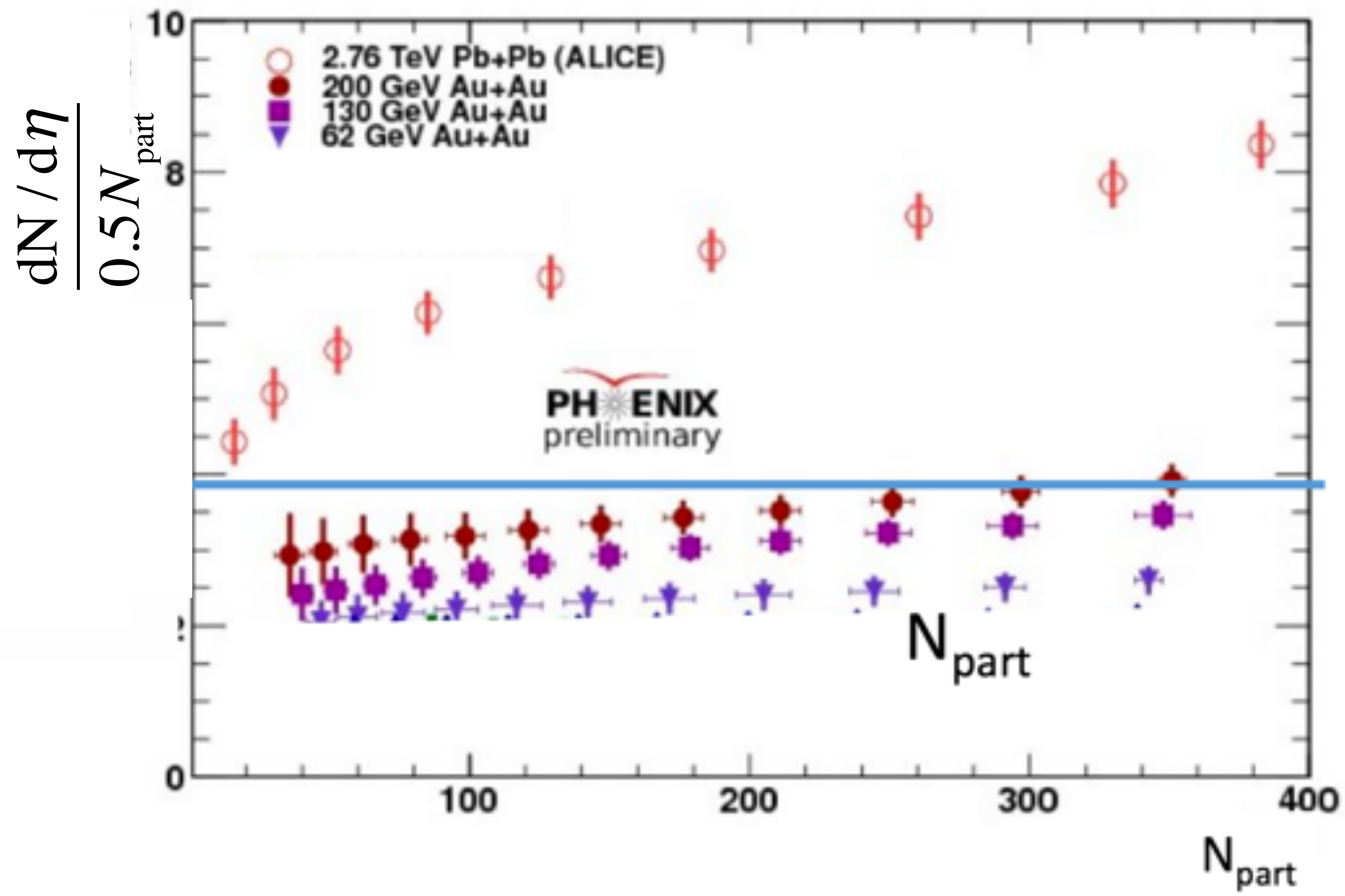
For hard-scattering, $p_T>2$ GeV/c, $Q^2=2p_T^2>8$ GeV^2, the partons (~massless current quarks, gluons and sea quarks) become visible

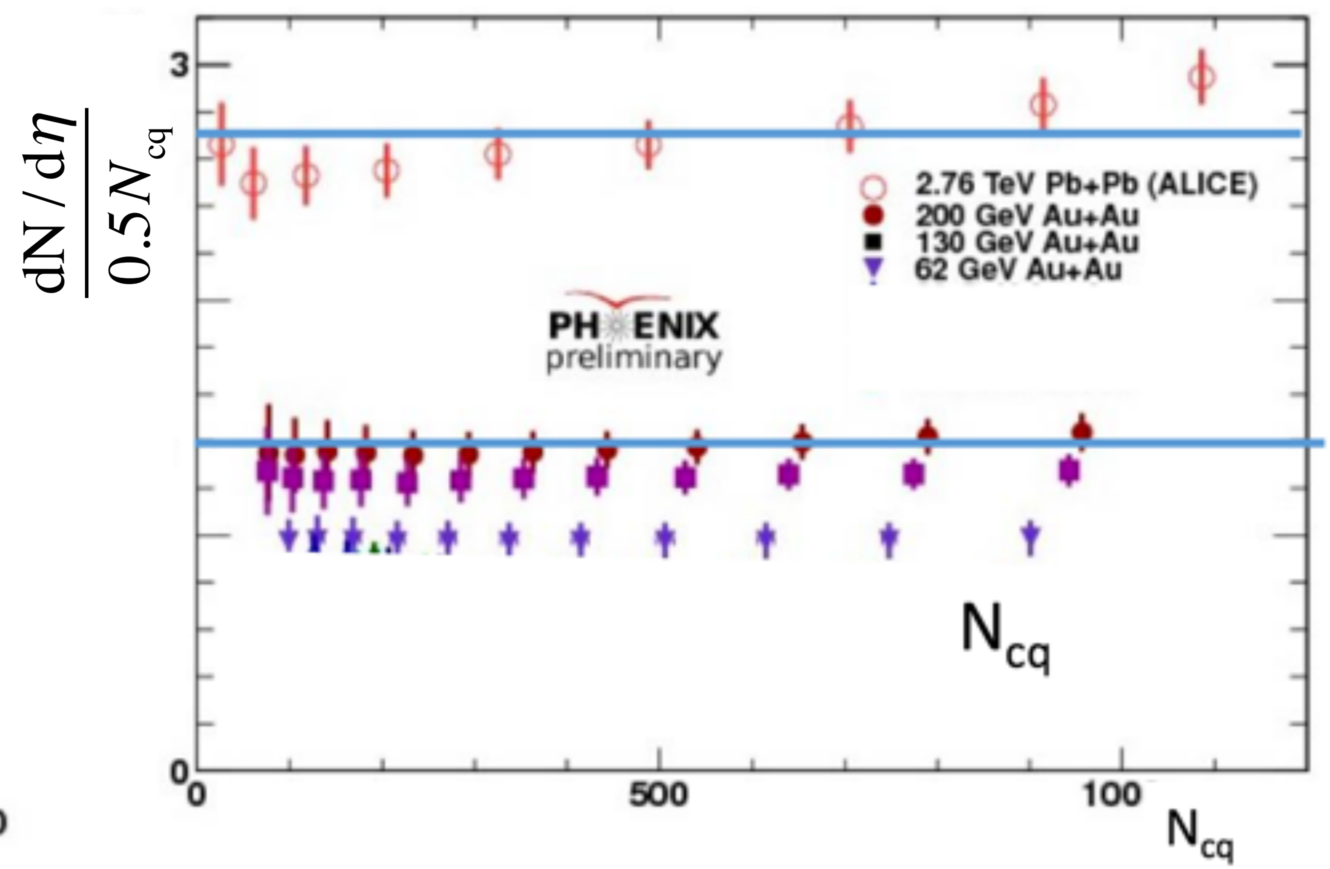


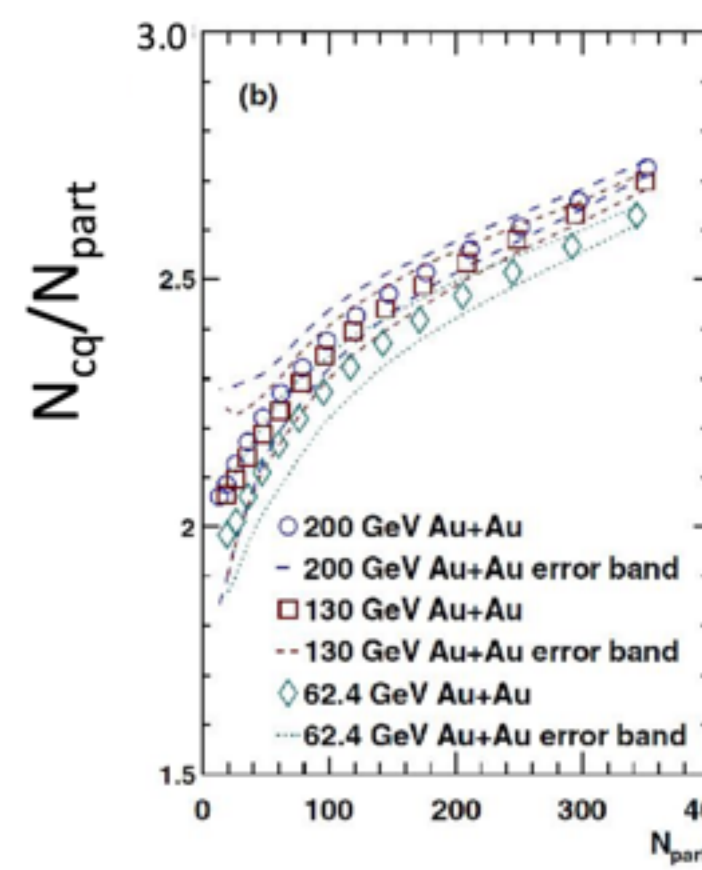
Slide from M. J. Tannenbaum

- Seems to imply that only quarks are involved contrary to what one expects from the increase of the gluon density at low *x*.
- Maybe better: Regions of size $1/p_0^2$ interact coherently
- Two limits:
  - $N_q = 1$: N_{part} scaling
  - $N_q = \infty$: N_{coll} scaling
- Constituent quark scaling naturally interpolates between the two.

Participant Quark Scaling ?



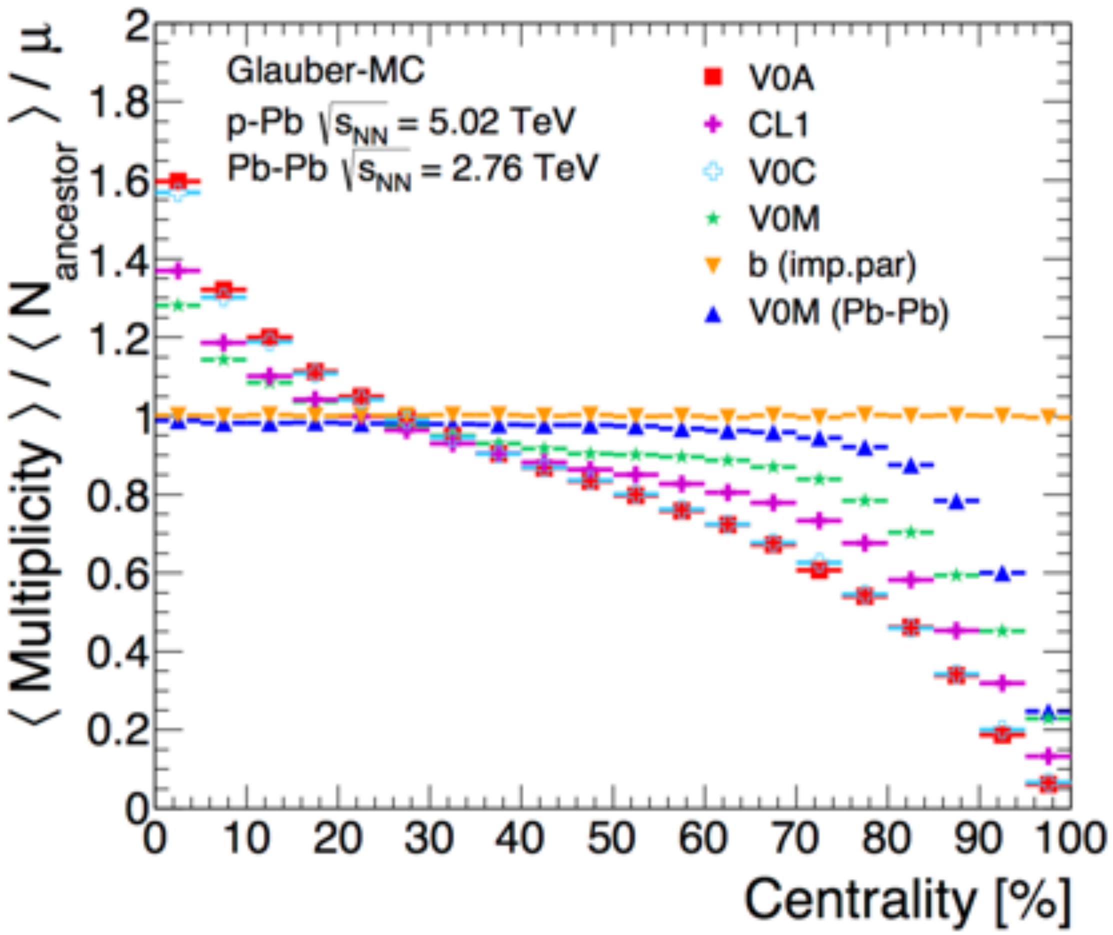




Works pretty well !

Other Aspects of MPI in AA

- Role of coherence effects in pp MPI for AA
  - How does coherence in individual collisions extend to the whole interaction area?
- Centrality in peripheral Pb-Pb Collisions
  - Event selection biases similar to p-Pb can be expected for centralities > 80%



Summary

- In pp, rich systematics from measurements of observables as a function of multiplicity from
  - Interplay between particle production from soft and multiple hard processes
    - coherent fragmentation / collective hadronisation
    - correlation via parton density function (momentum conservation)
    - biases on the mini-jet fragmentation

Summary

- In pA
  - fragmentation biases decrease
  - all other effects are expected to increase due to the multiple interactions of the proton (or overlap with more dense matter)
    - In particular fwd hard and bkwd soft correlations
- In AA
  - Role of coherence effects in smaller systems ?
    - initial state parton density
    - final state correlations