Absence of jet quenching in peripheral nucleus-nucleus collisions ?

… and how this is related to modelling of underlying event physics and multi-parton interactions in pp, pA and AA

Andreas Morsch
CERN

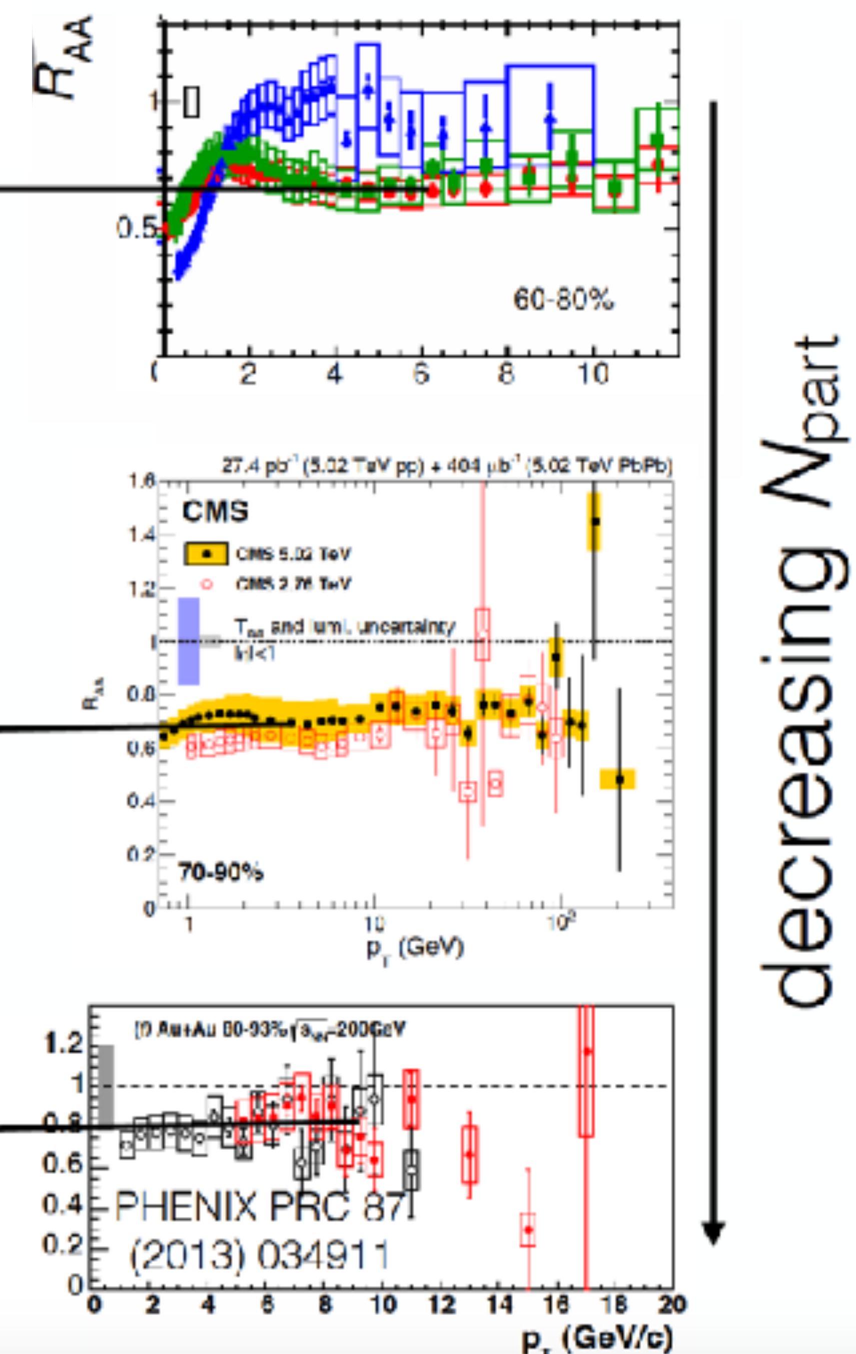
GDR QCD “Partons and Nuclei”, Orsay 1-2 June 2017

What is the smallest system exhibiting jet quenching ?

60-80% Pb+Pb, R_{AA} = 0.65
<N_{part}> = 23 (ATLAS similar)
<1% *p*+Pb (0-5% in Glauber-Gribov!)

70-90% Pb+Pb, R_{AA} = 0.7
<N_{part}> = 11
~20-30% *p*+Pb

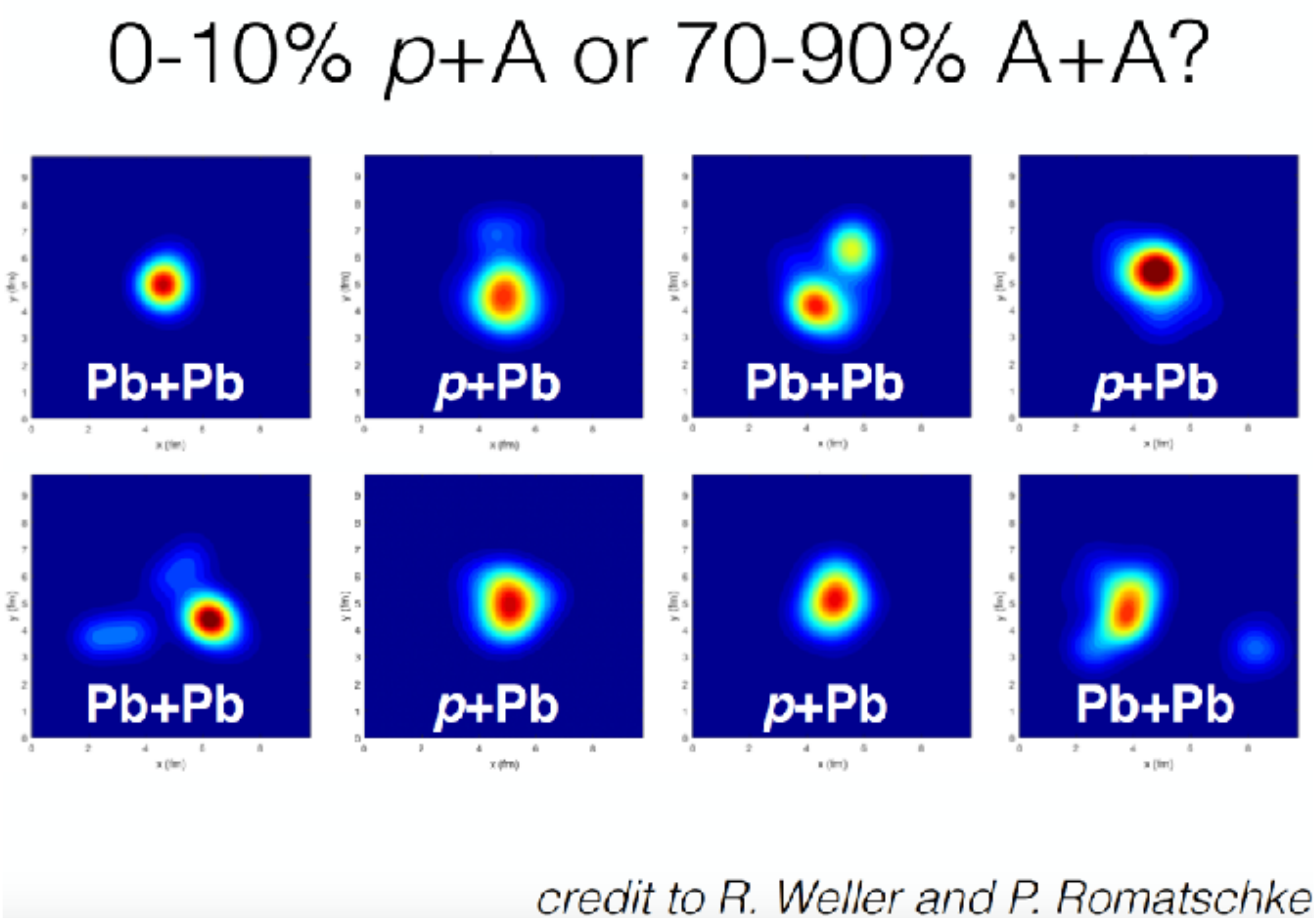
80-93% Au+Au, R_{AA} = 0.8
<N_{part}> = 5
~50-70% *p*+Pb



N_{part} in peripheral A-A similar to p-A

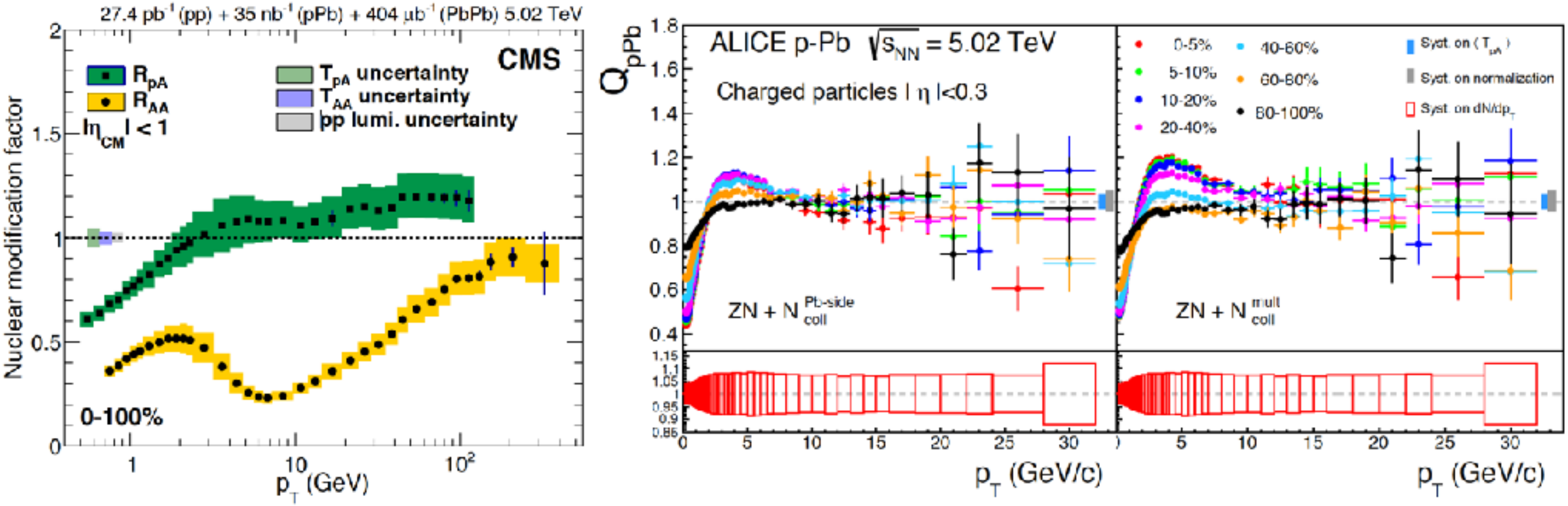
Centrality based on fwd multiplicity or summed energy measurements.

What is the smallest system exhibiting jet quenching ?



Also similar initial geometry

R_{AA} in p-Pb

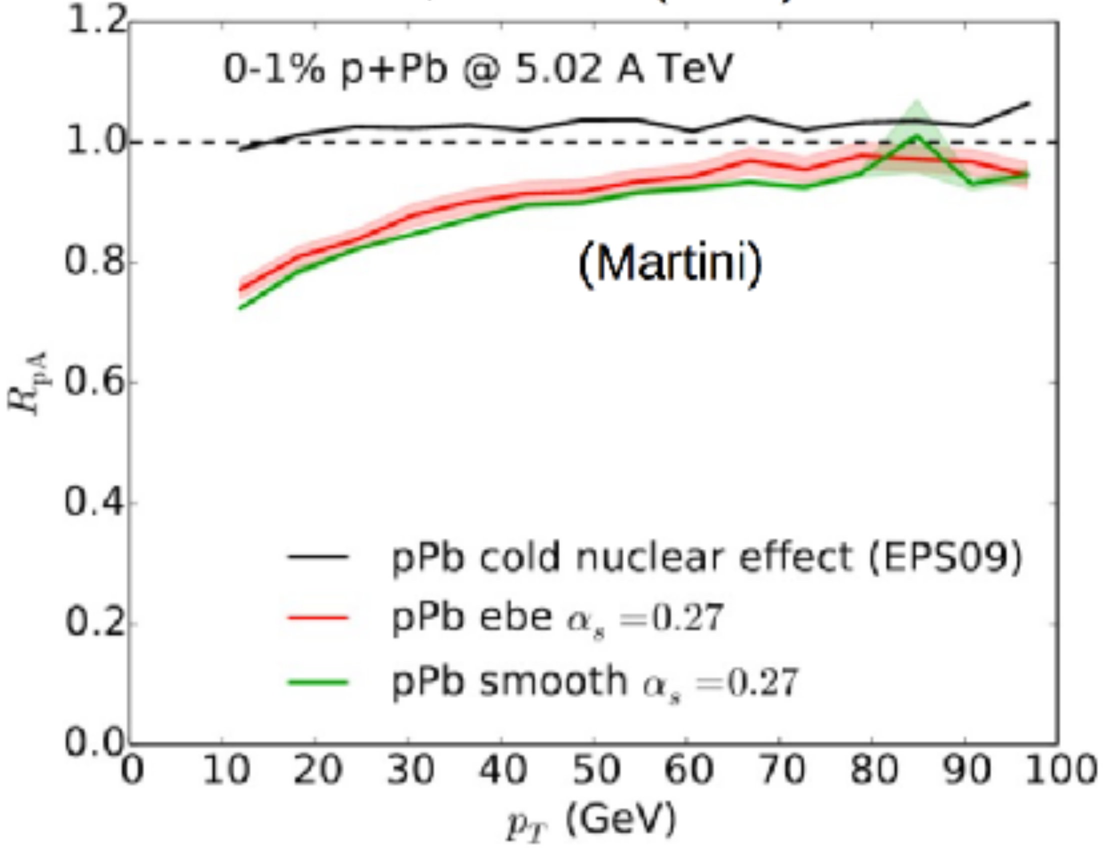


No significant modification at high p_T
for N_{part} comparable to peripheral Pb-Pb.

Model predictions

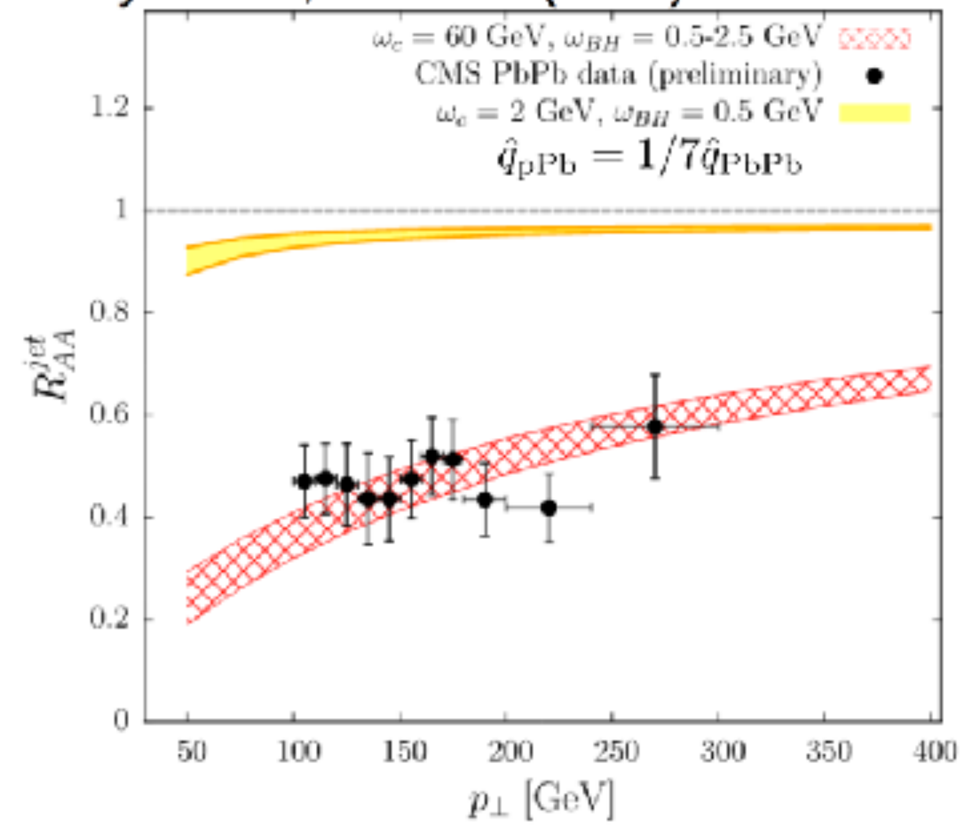
p-Pb

C.Shen et al., NPA956 (2016) 741

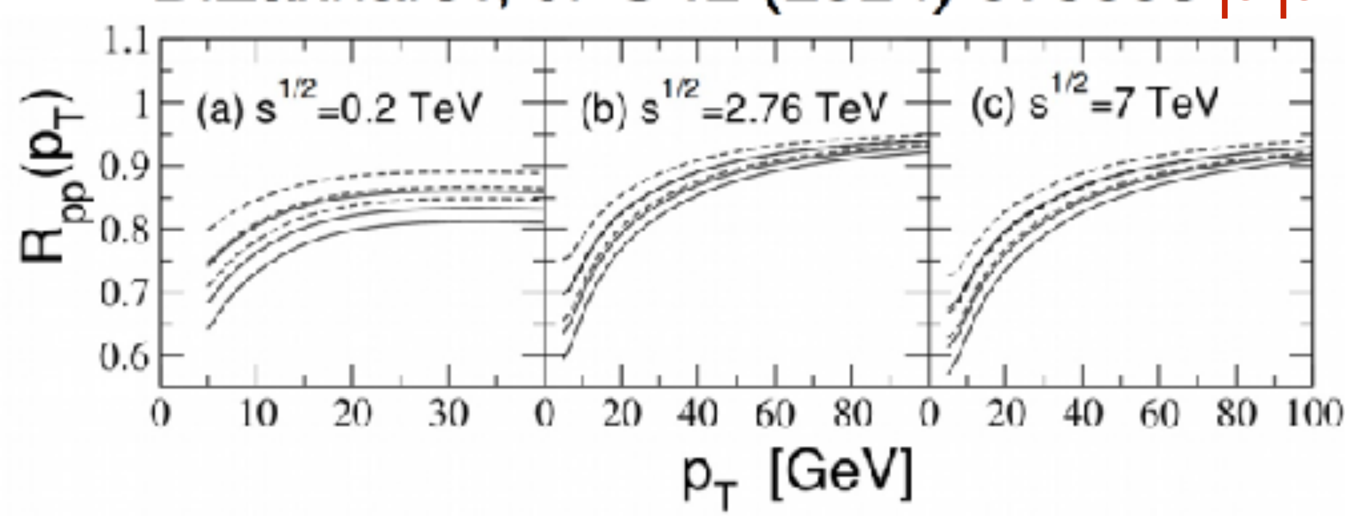


p-Pb

K. Tywoniuk, NPA 926 (2014) 85



B.Zakharov, JPG41 (2014) 075008 pp



Calculations expect sizeable (10-20%) suppression for "central" p-Pb and even pp

Nuclear Modification Factor

Definition: Ratio of yield of hard process in AA to reference of incoherent superposition of $N_{\rm coll}$ pp collisions.

$$R_{AA}^{cent} = \frac{Y_{\rm AA}}{T_{AA}^{\rm cent}\sigma_{\rm hard}} = \frac{Y_{\rm AA}}{N_{\rm coll}^{\rm cent} Y_{\rm pp}} \qquad R_{AA}^{cent,\,\rm modelA} \quad c.t. \quad \frac{Y_{\rm AA}^{\rm data}}{N_{\rm coll}^{\rm cent,\,modelB(data)} Y_{\rm pp}^{\rm data}}$$

Well defined for

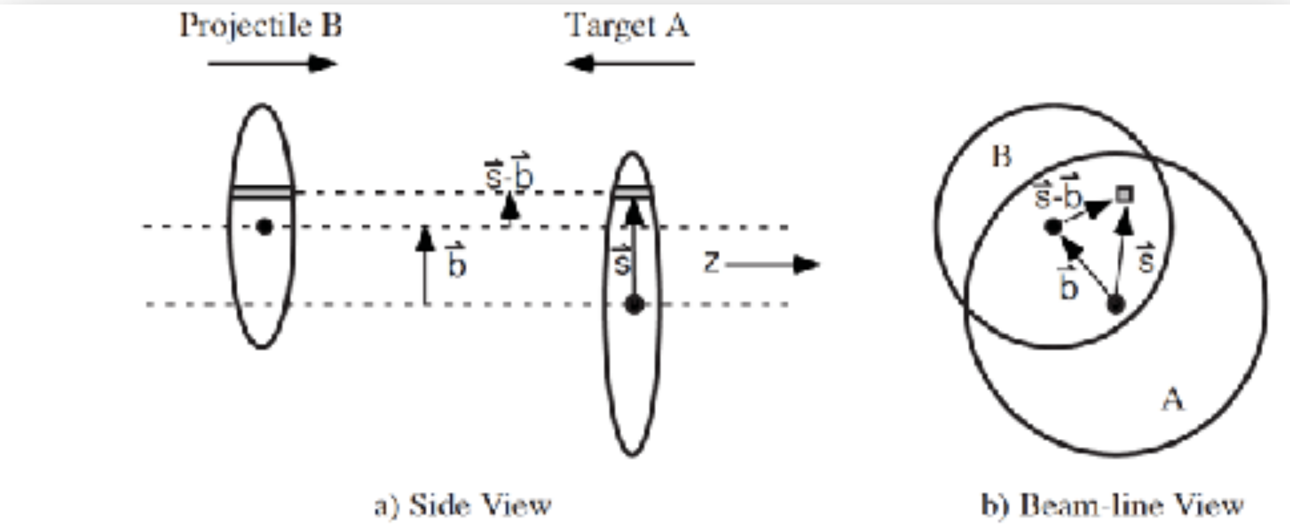
- minimum bias: $\langle N_{\rm coll}\rangle = A^2\, \sigma_{\rm pp}/\sigma_{\rm AA}$
- measurement of spectators: $N_{\rm spec} = 2A - N_{\rm part}$

- **"nuisance" factors**
  - **nucleon vs parton dof**
  - **density fluctuations**
  - **hard soft correlations**

In all other cases one needs to take into account

- Geometrical biases:
  - Phase space distribution of nucleons in nucleon ≠ protons in bunches
- Correlation between centrality estimator and hard processes (initial and final state)

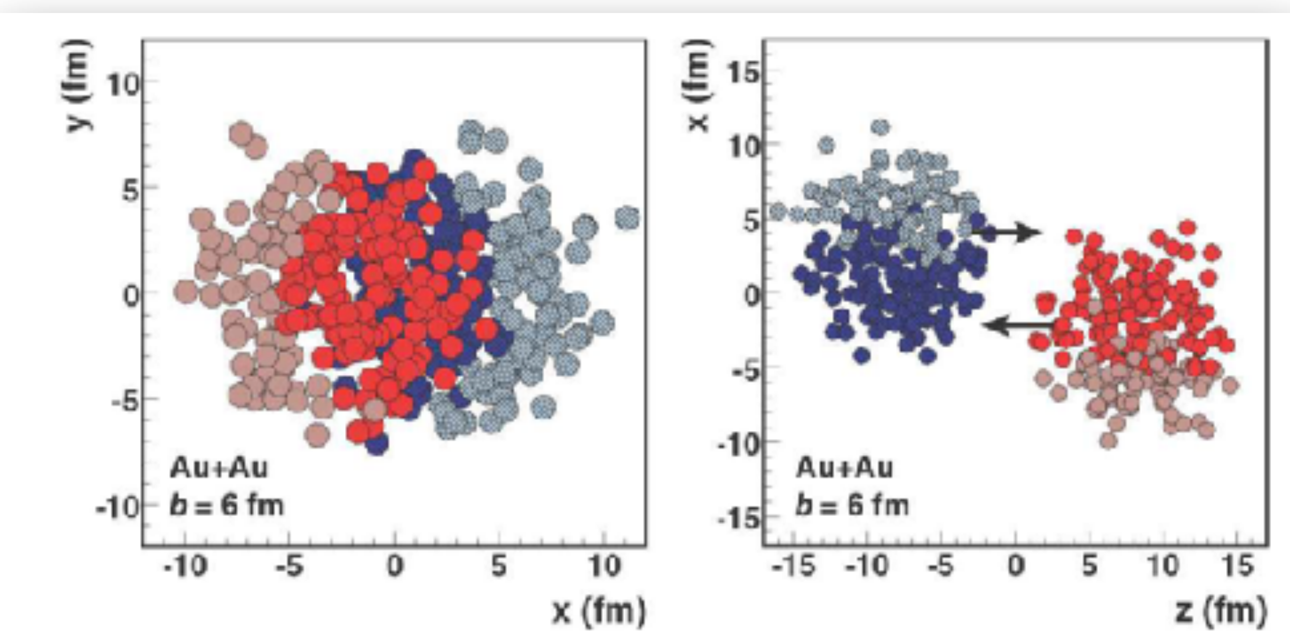
Glauber Modelling



Optical Glauber

- Interaction probability
- Overlap of thickness functions

$$\mathrm{d}T_{\mathrm{AB}}\left(\vec{b}\right) = \mathrm{d}T_{\mathrm{A}}\left(\vec{s}\right)\mathrm{d}T_{\mathrm{B}}\left(\vec{s}-\vec{b}\right)\mathrm{d}^2\vec{s}$$

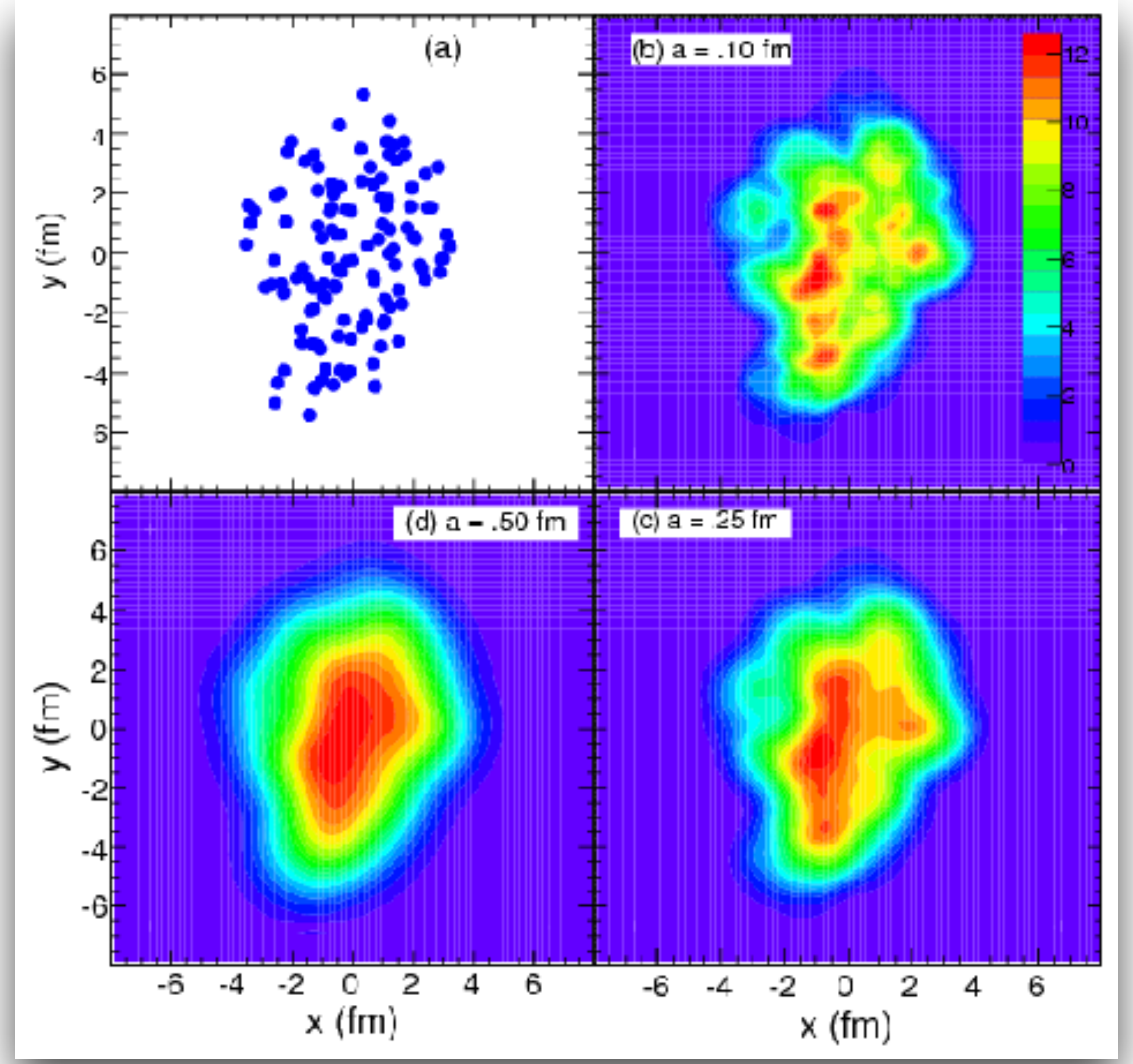


Monte Carlo Glauber

- Random distribution of nucleons
- Interaction probability: Hit or miss
- Additional information
  - Initial state fluctuations
    - nucleon positions
  - N-N impact parameter
    - alignment of fluctuations

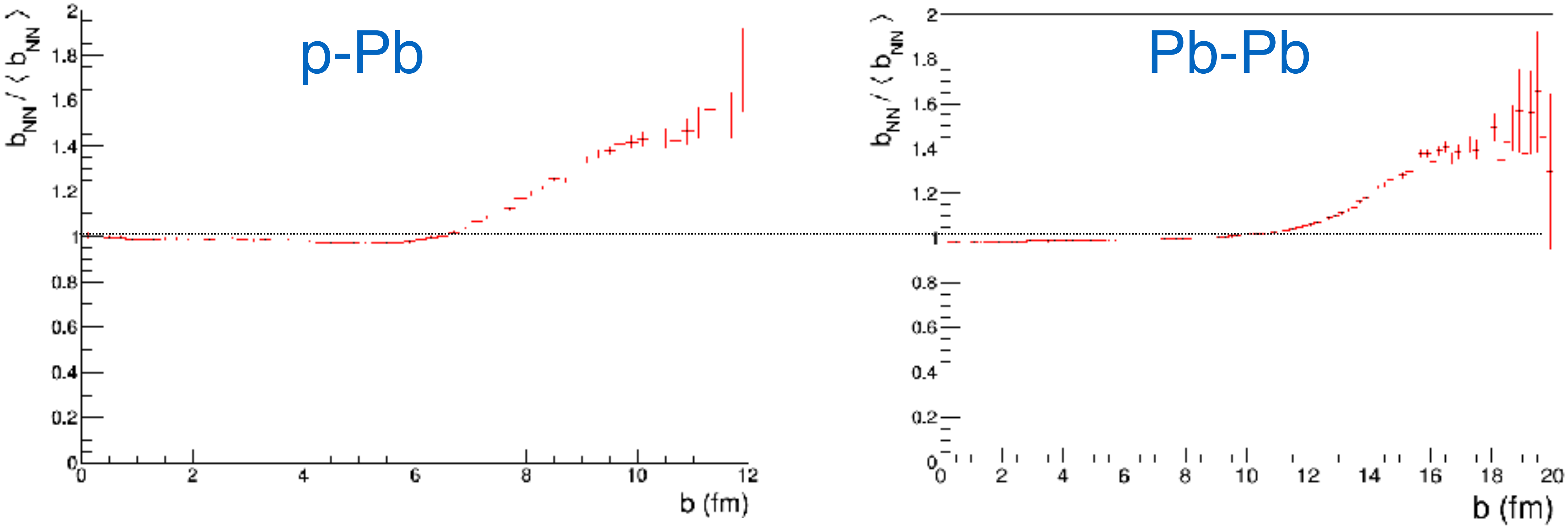
Fluctuating Initial Conditions

- wounded nuclei



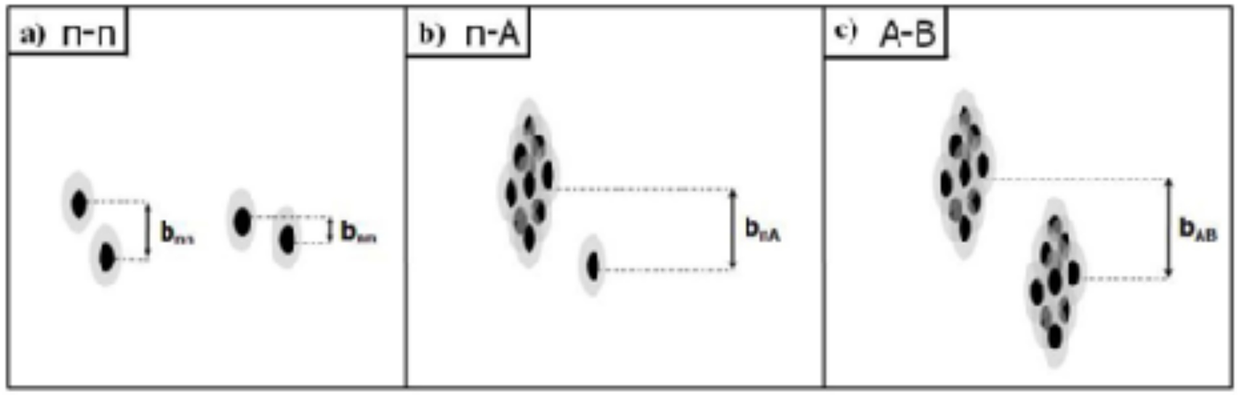
Rihan Haque, Md. *et al*. Phys.Rev. C86 (2012) 037901 arXiv:1204.2986

Geometric Bias



$d\sigma \sim b\, db$
at high b:
increased probability for large N-N impact parameter b_{NN}

Geometry Bias in modified Optical Glauber

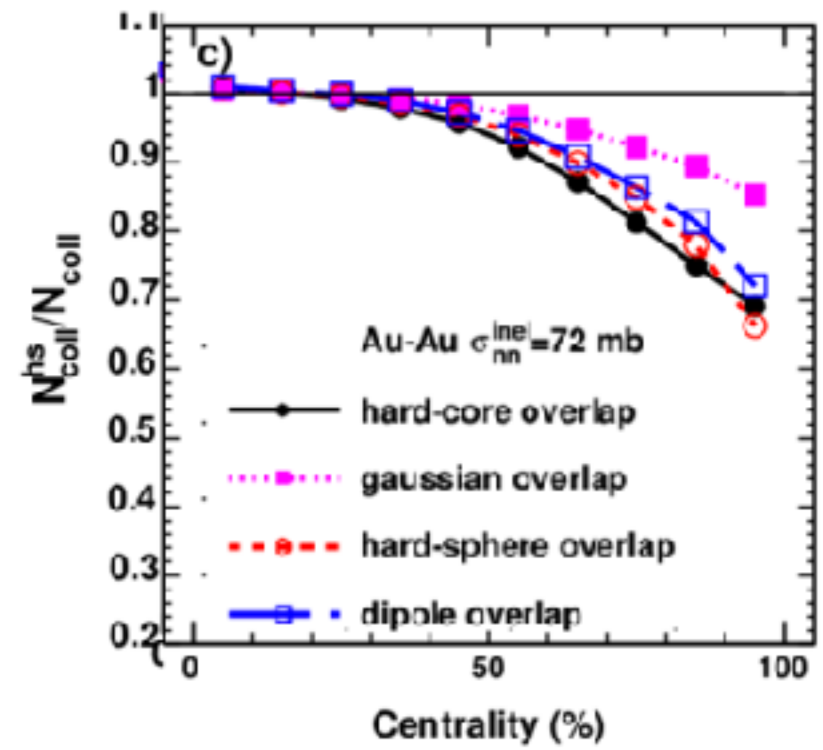


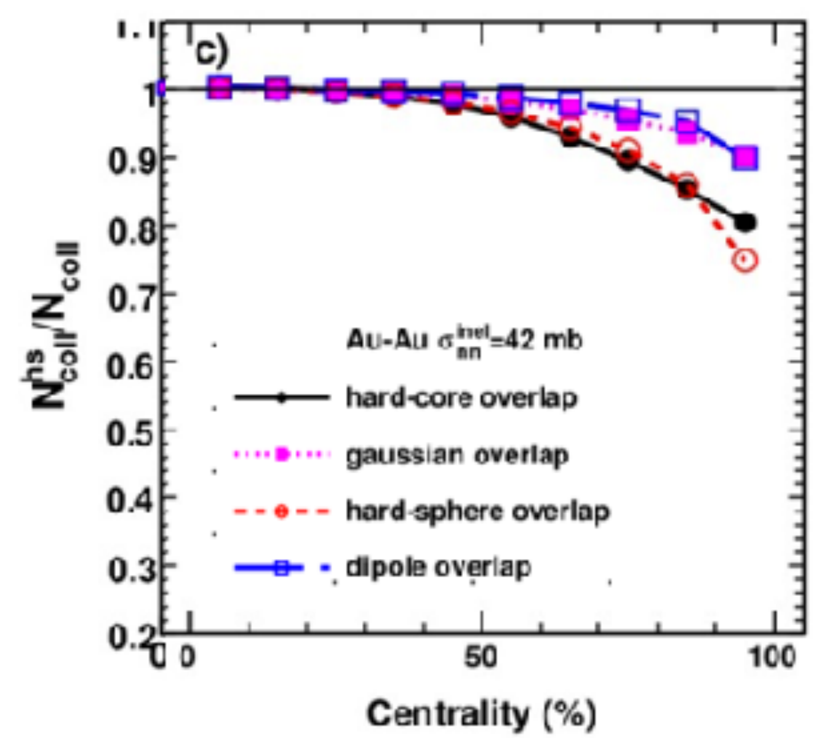
$$T_{AB}(\vec{b}_{AB}) = \int d\vec{b}_A d\vec{b}_B\, T_A(\vec{b}_A) T_B(\vec{b}_B) t(\vec{b}_{AB} - \vec{b}_A + \vec{b}_B)$$
$$= \int d\vec{s} d\vec{b}_{nn}\, T_A(\vec{s}) T_B(\vec{s} - \vec{b}_{AB} + \vec{b}_{nn}) t(\vec{b}_{nn}).$$

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

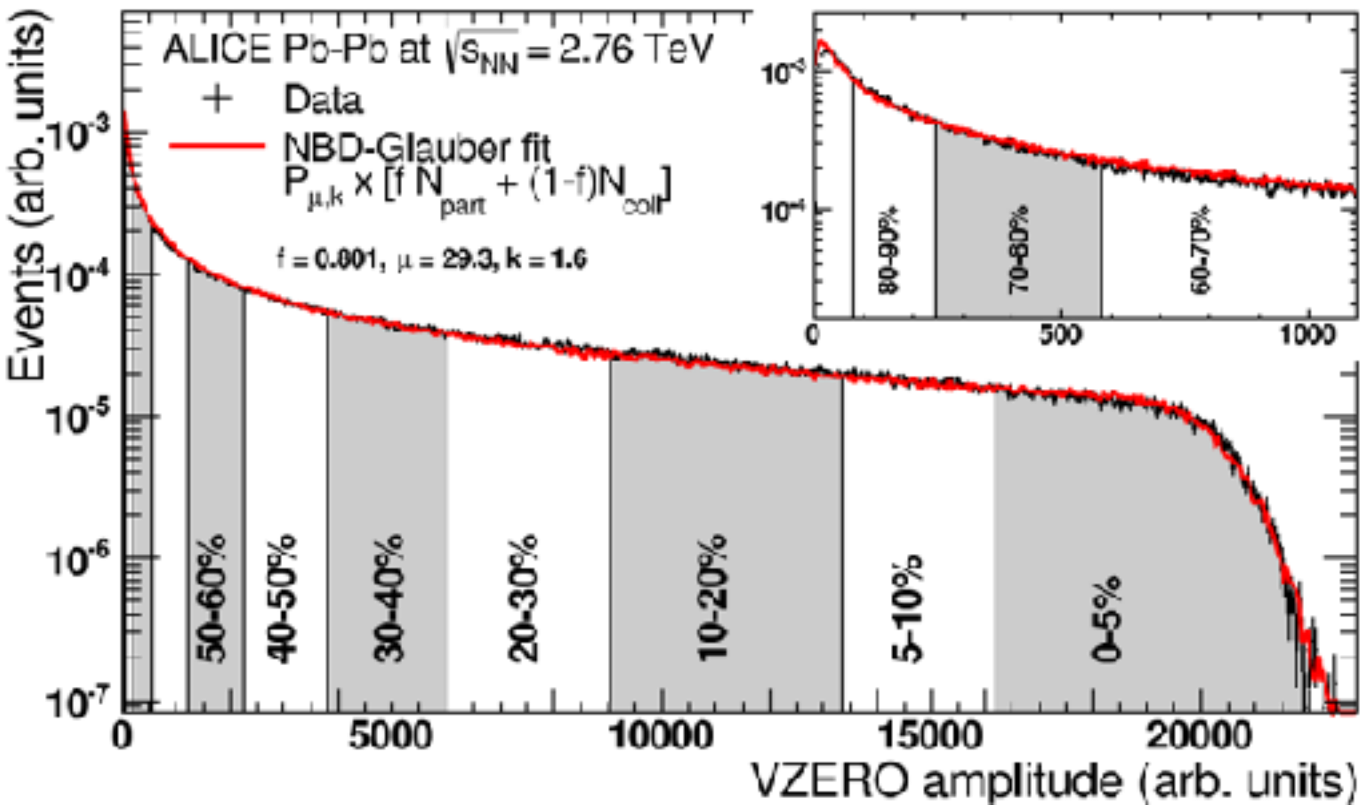
Including an impact parameter dependent nucleon-nucleon overlap function can lead to 20% variation of $N_{\rm coll}$ for peripheral collisions.

J.Jia, PLB 681 (2009) 320





Connection to Data
N_{part} N_{coll} from Glauber Fit



Model centrality estimator as

$$sources \otimes particle\ production$$

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

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

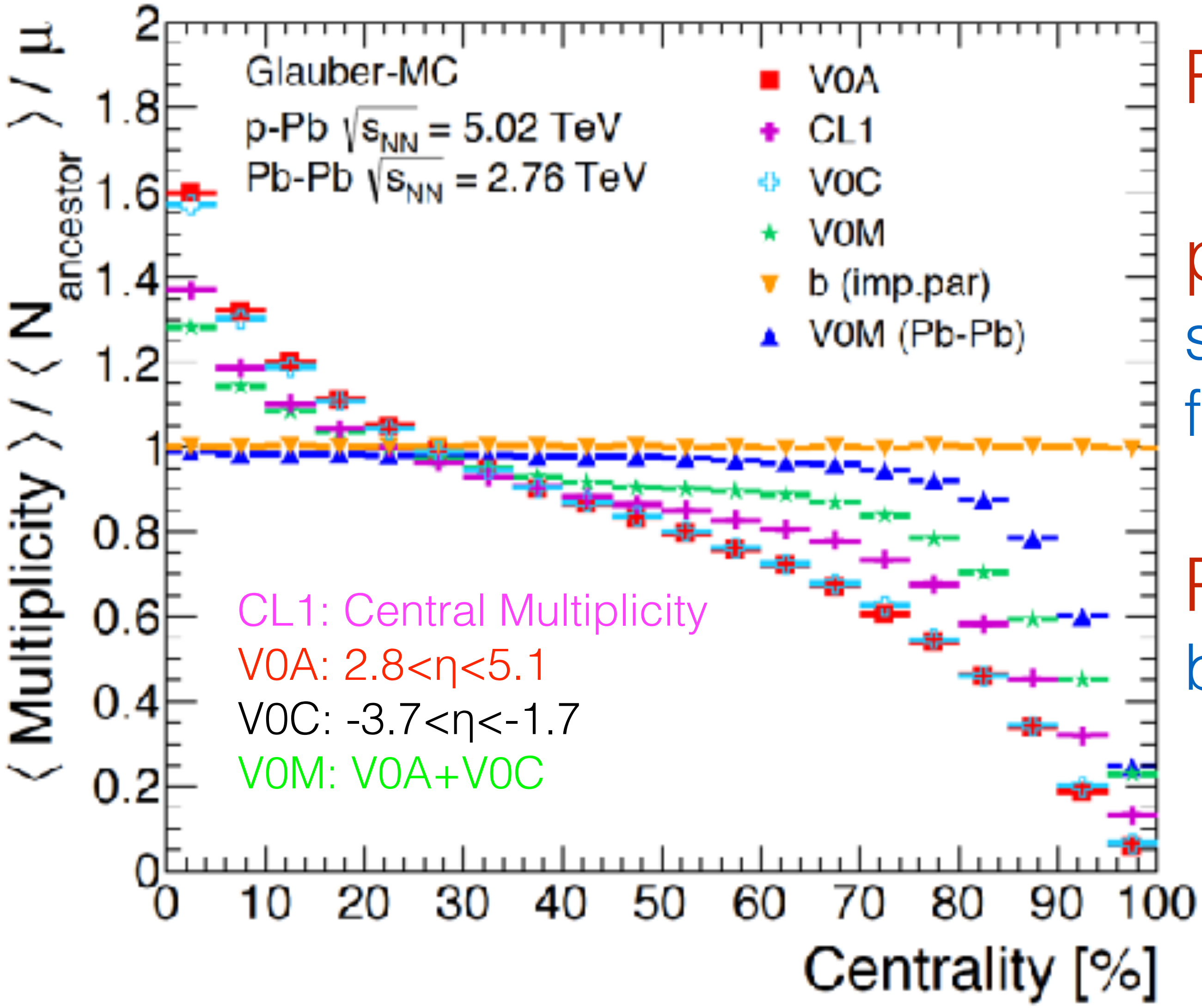
$$P_{\text{NBD}}(n;\mu,k) = \frac{\Gamma(n+k)}{\Gamma(n+1)\Gamma(k)} \frac{\left(\mu/k\right)^n}{\left(1+\mu/k\right)^{n+k}}$$

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

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

Bias on Soft Particle Production



From ALICE Glauber Fit

p-Pb

strong bias

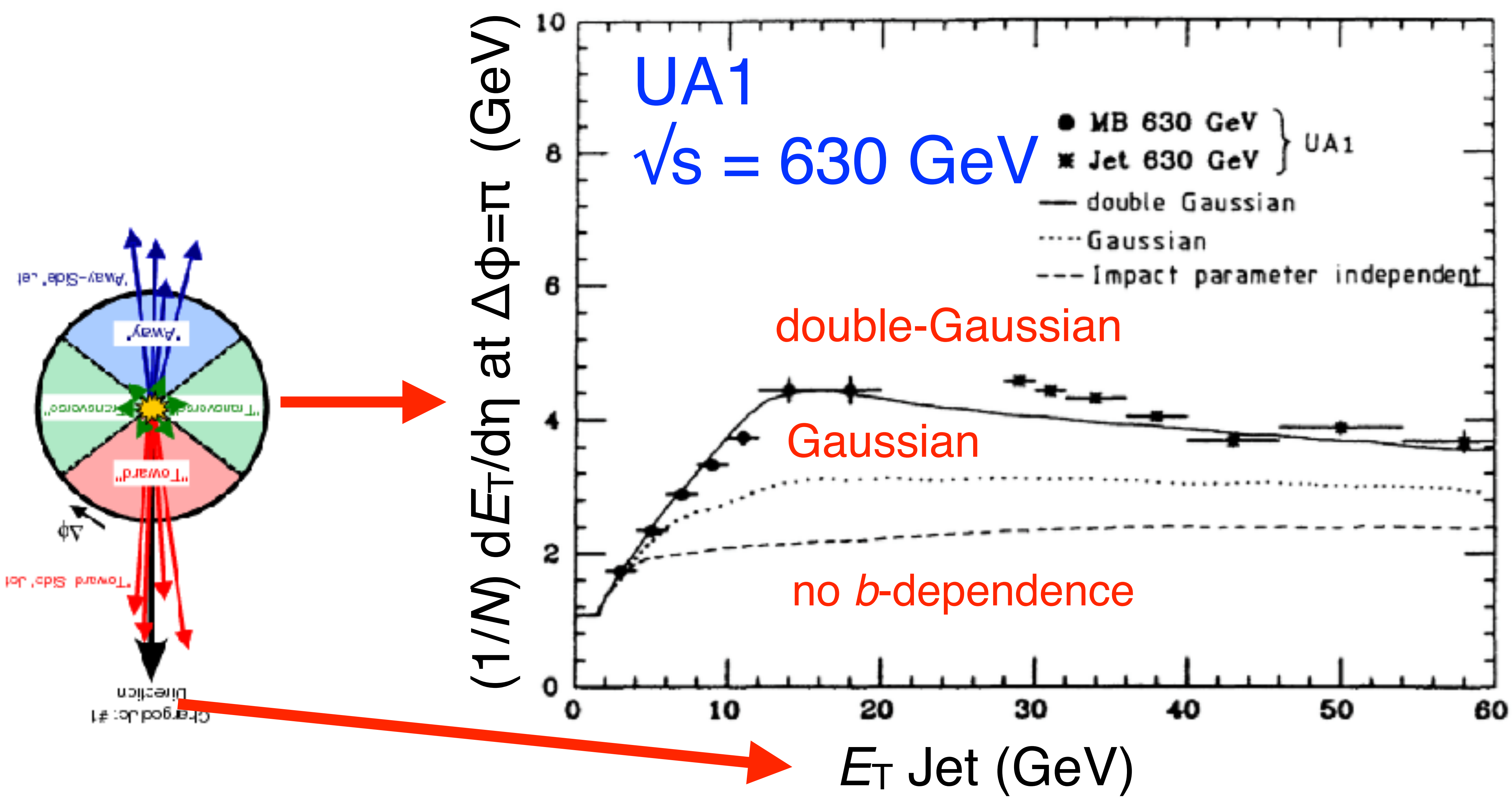
fwd n-energy used as centrality estimator

Pb-Pb

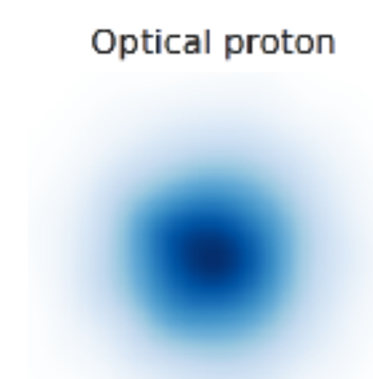
biased for peripheral collisions

- Deviations of mean multiplicity per ancestor from μ indicate possible biases.
- 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.

Jet Pedestal Effect



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



Importance of MPI in pp (at LHC)

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

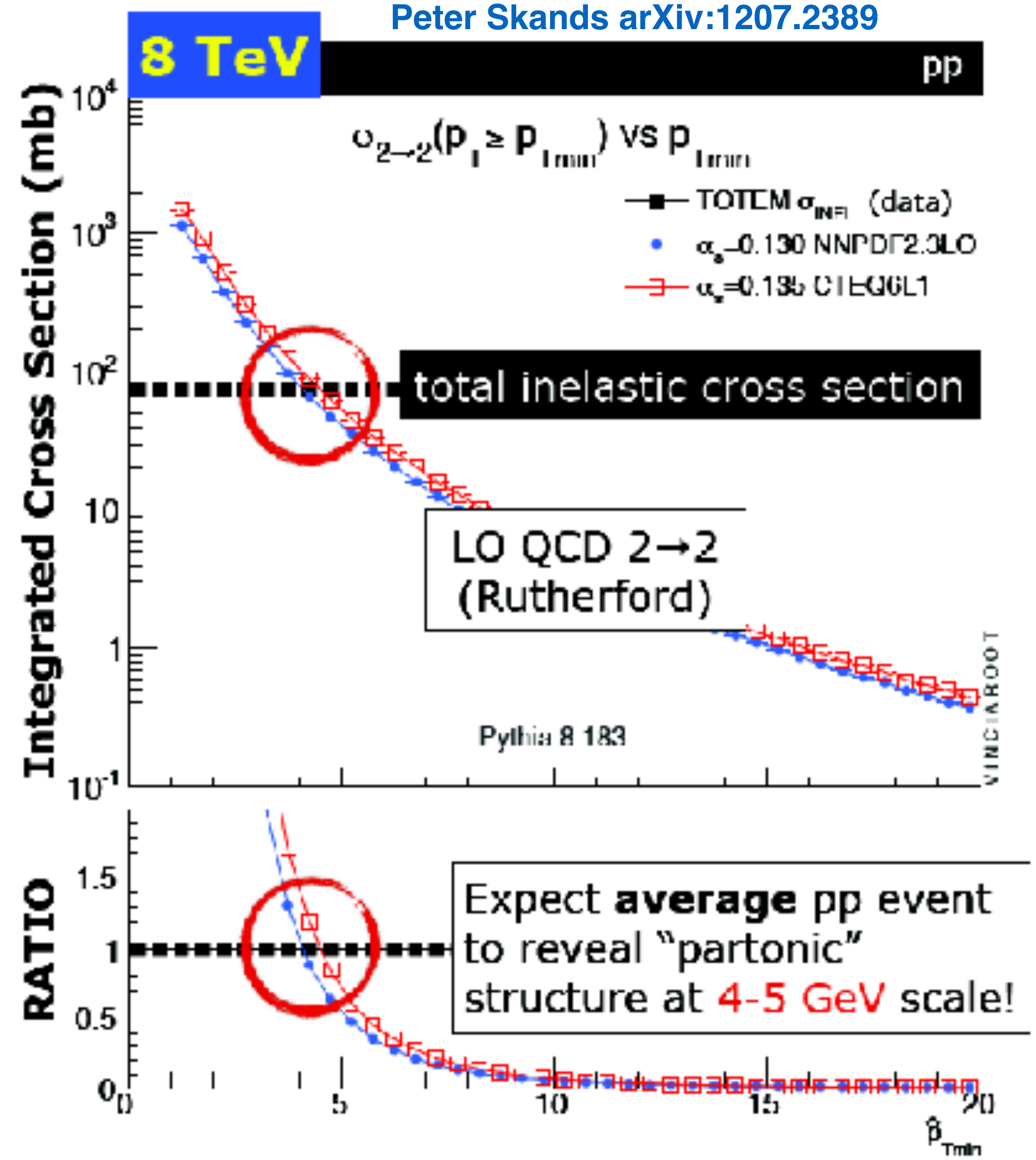
Number of 2→2 scatterings per event, naïve factorization:

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

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

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

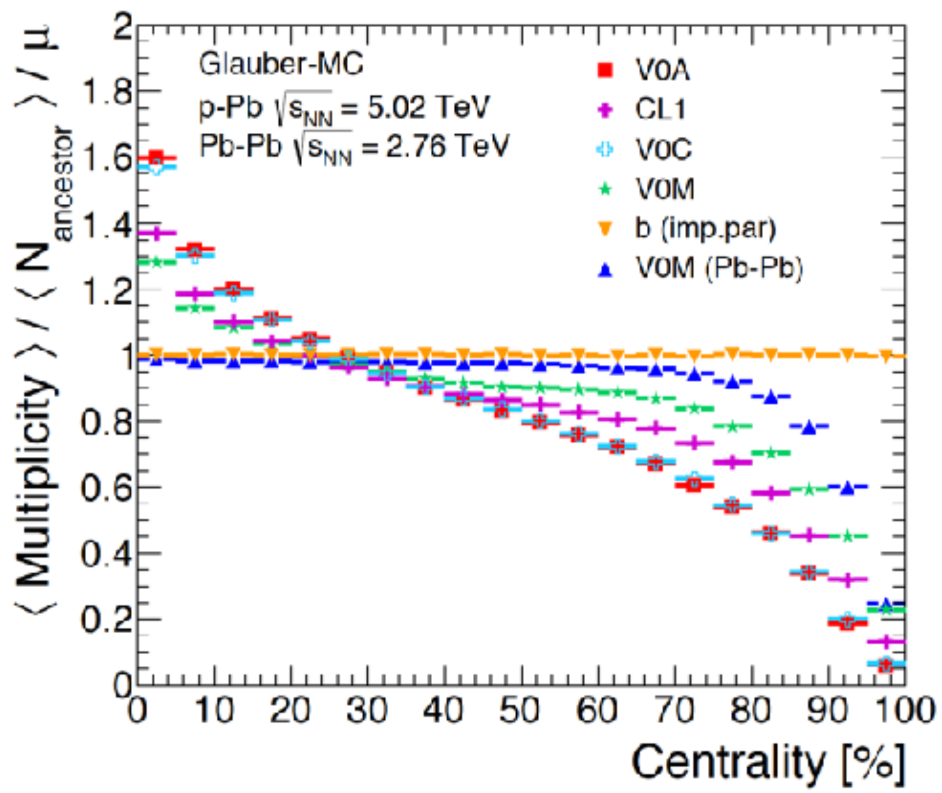
factorisation breaks for $n_{2\to2}$ large in area $\frac{1}{p_T^2}$



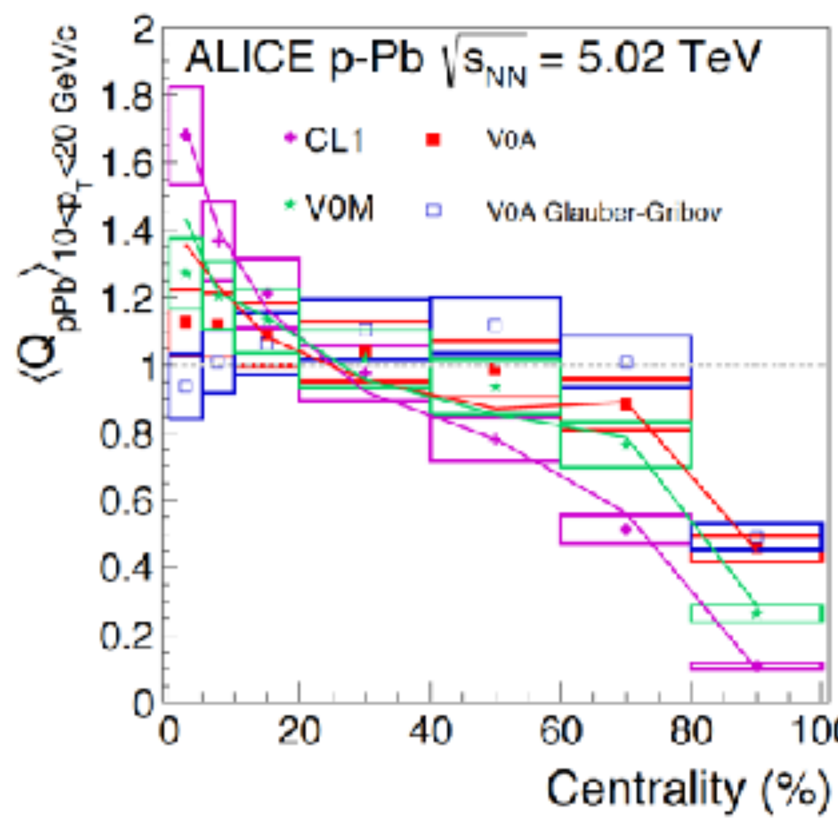
- At LHC multiple hard scatterings at perturbative scales
- Large contribution to underlying event

Modelling of Multiplicity Bias

bias on soft particle production

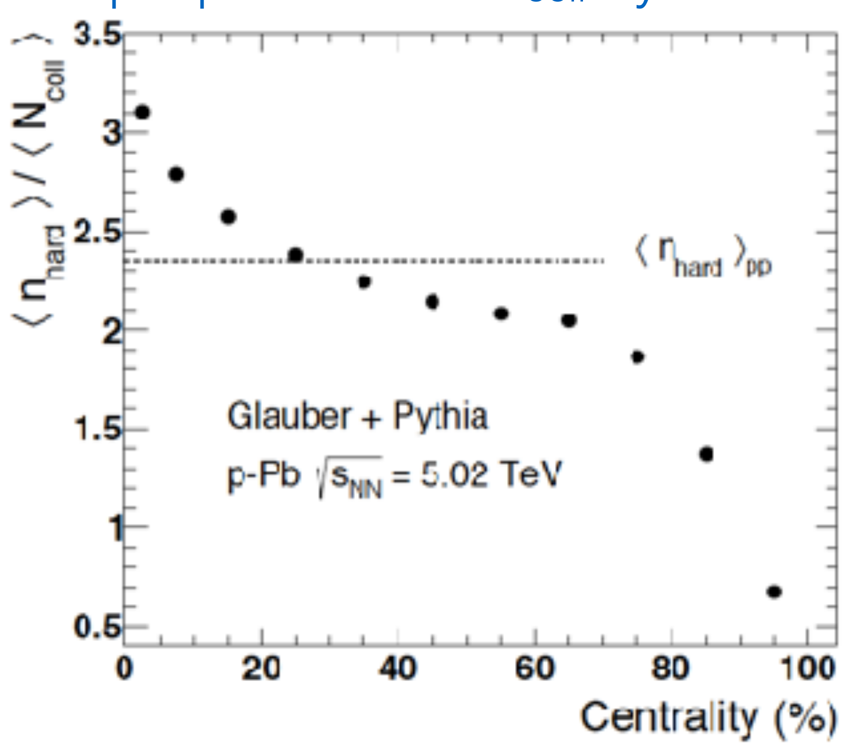


bias on hard particle production



qualitatively same behaviour!

superposition of N_{coll} Pythia Events



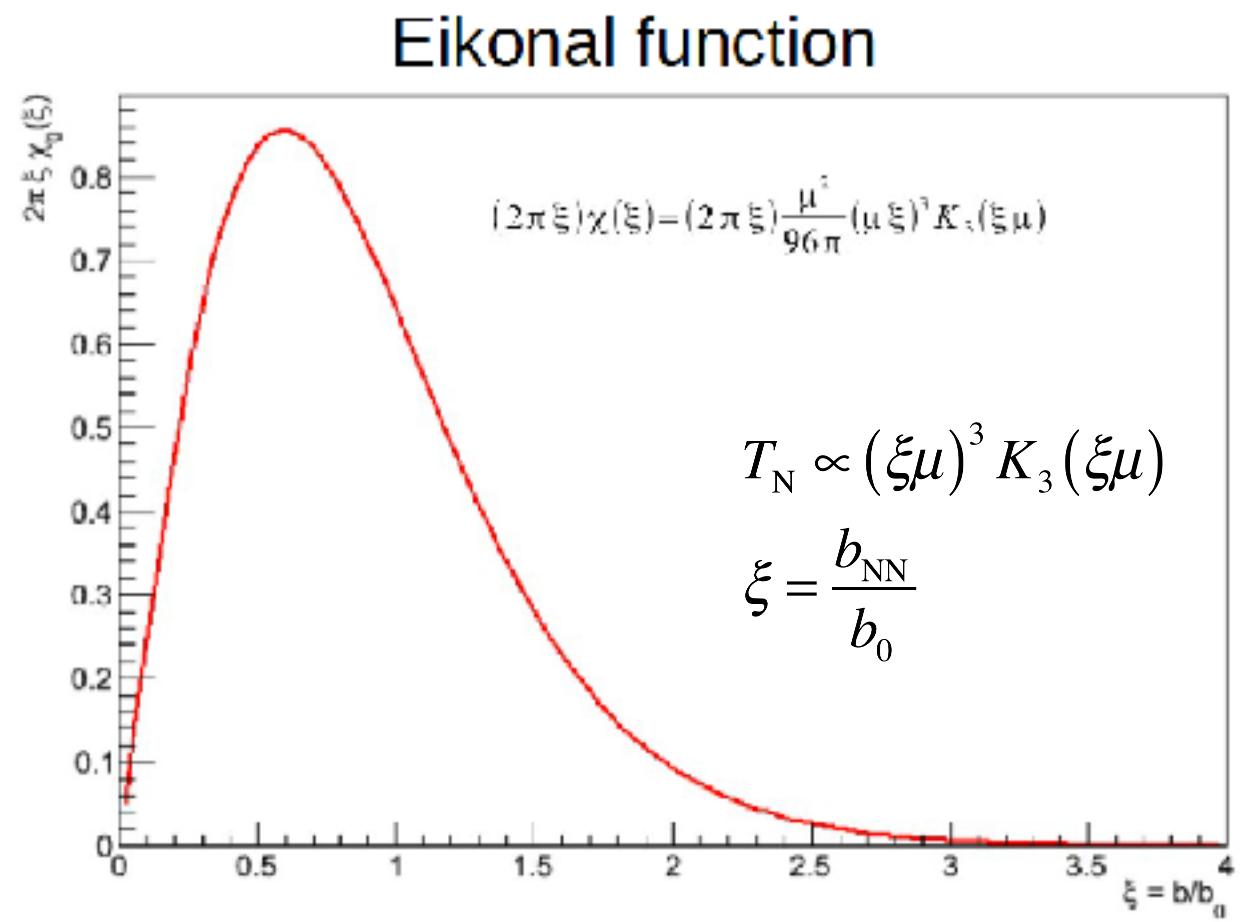
even good quantitative understanding using MPI model (Pythia)

HIJING Glauber (HG)

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

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

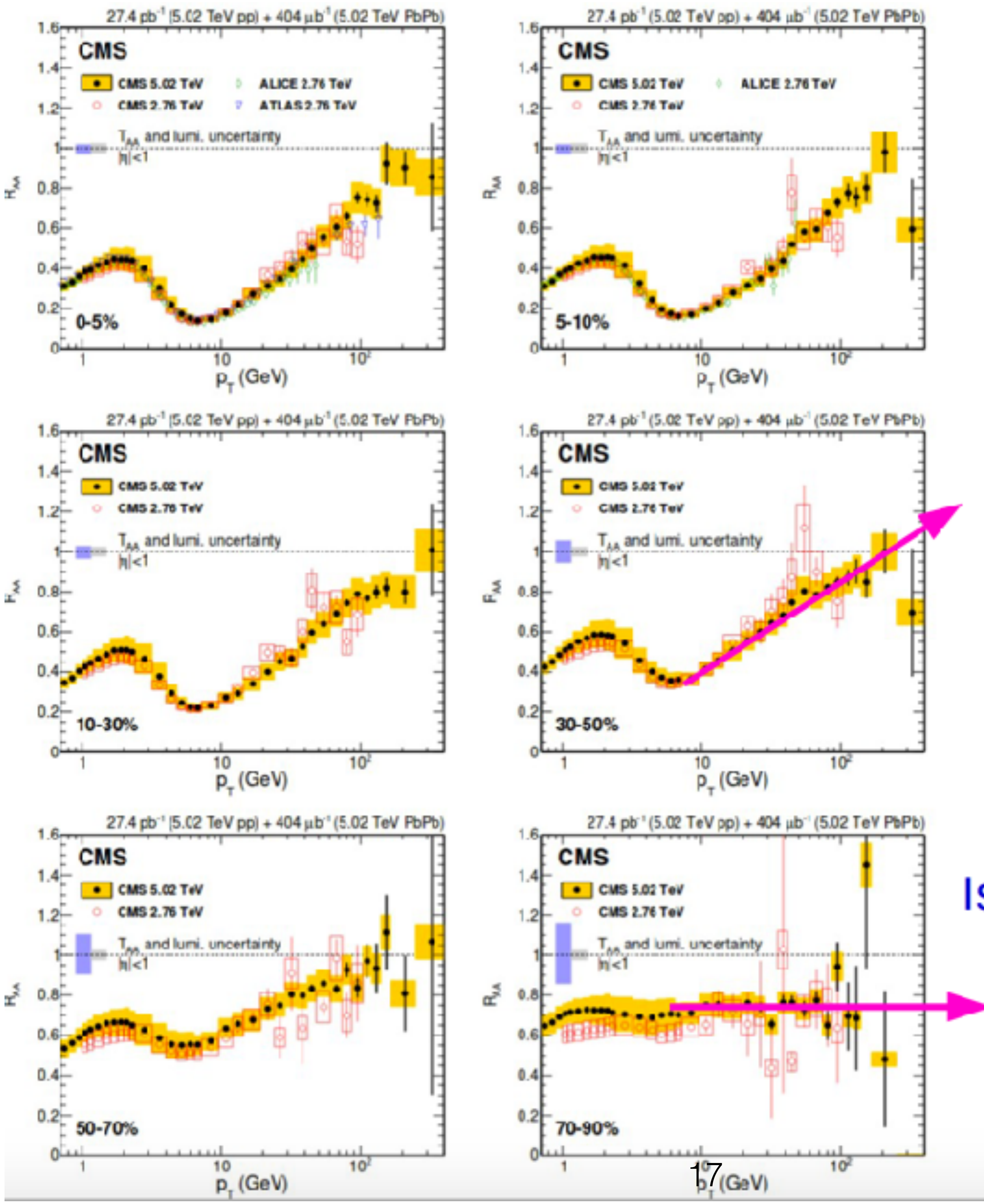
$$\left\langle n^{\mathrm{hard}}\right\rangle = T_{\mathrm{NN}}(b)\sigma_{\mathrm{hard}}$$



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

Inclusive Hadron R_{AA} in Pb-Pb

JHEP 04 (2017) 039



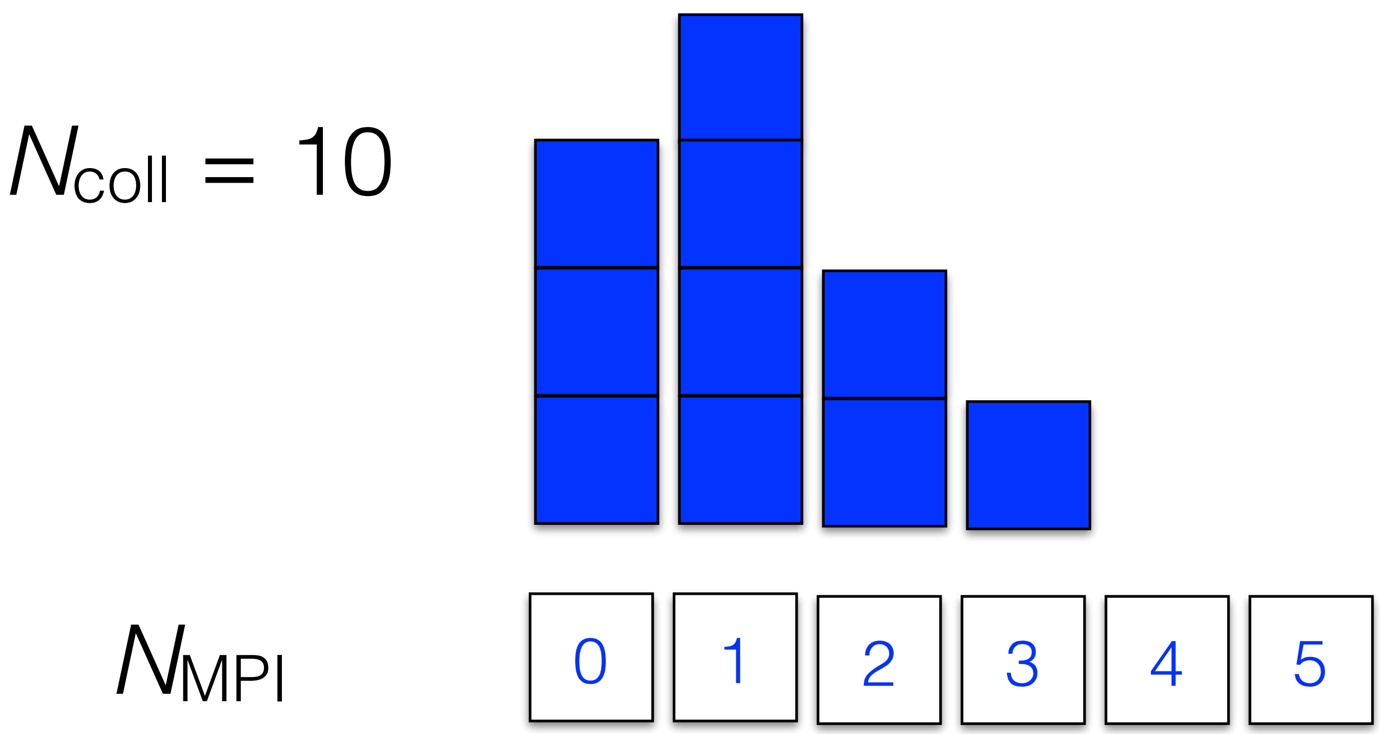
Rising and approaching R~1!

Is it a multiplicity bias?

Seemingly constant at around R~0.8

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

Model Comparison

C Loizides, AM, arXiv:1705.08856

HIJING

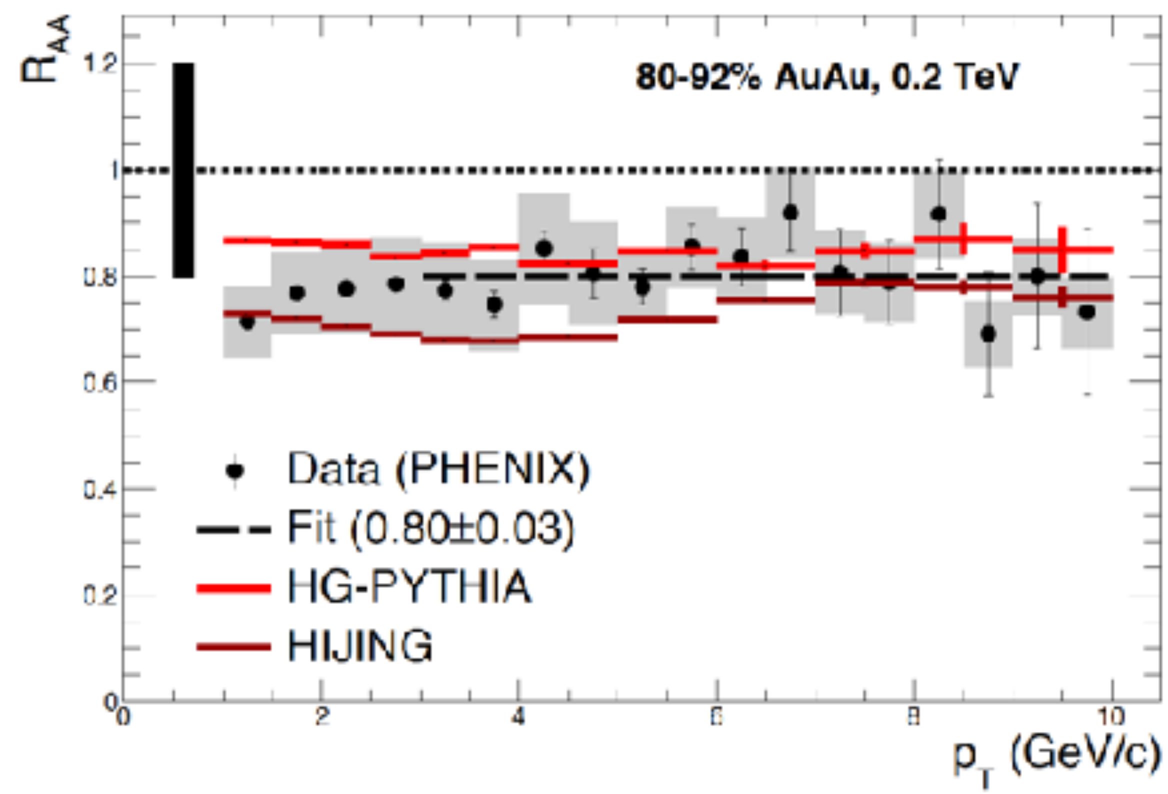
- No quenching, no shadowing but
  - ad-hoc momentum conservation
  - multiple scattering
- Does not give $R_{AA} \to 1$ at high p_T for central collisions

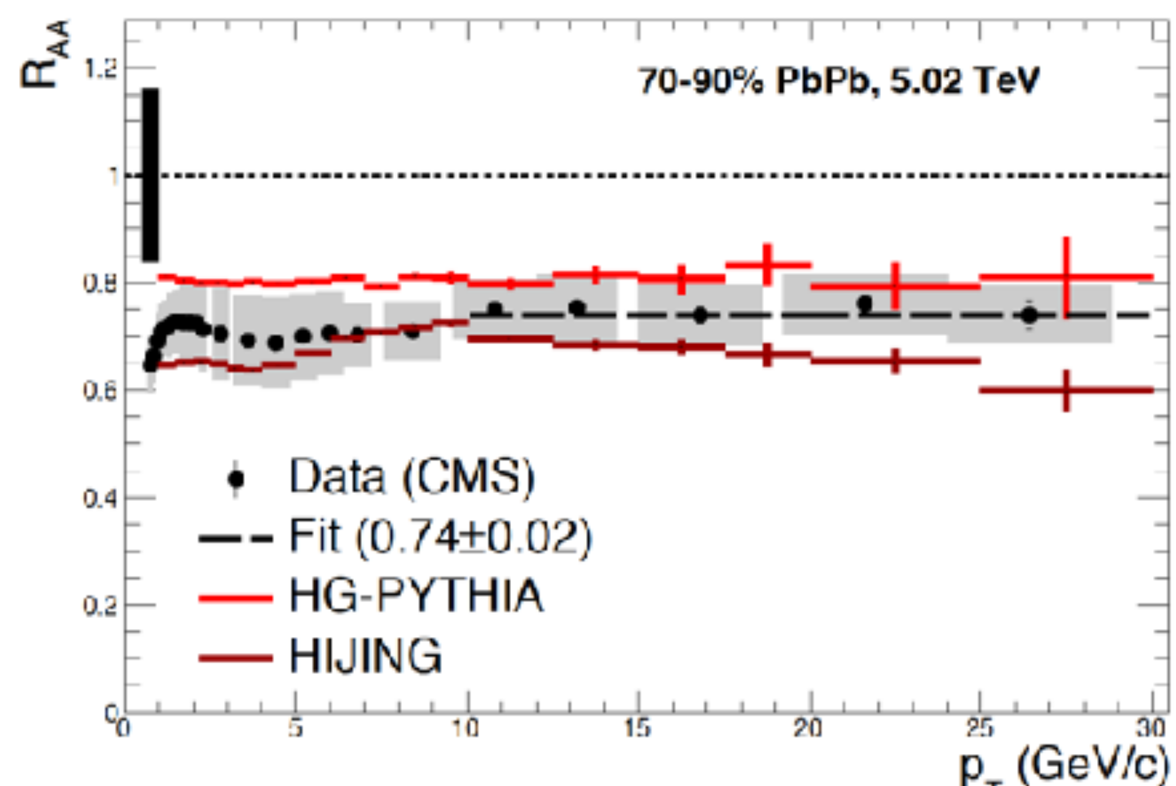
HG-Pythia:

- 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)

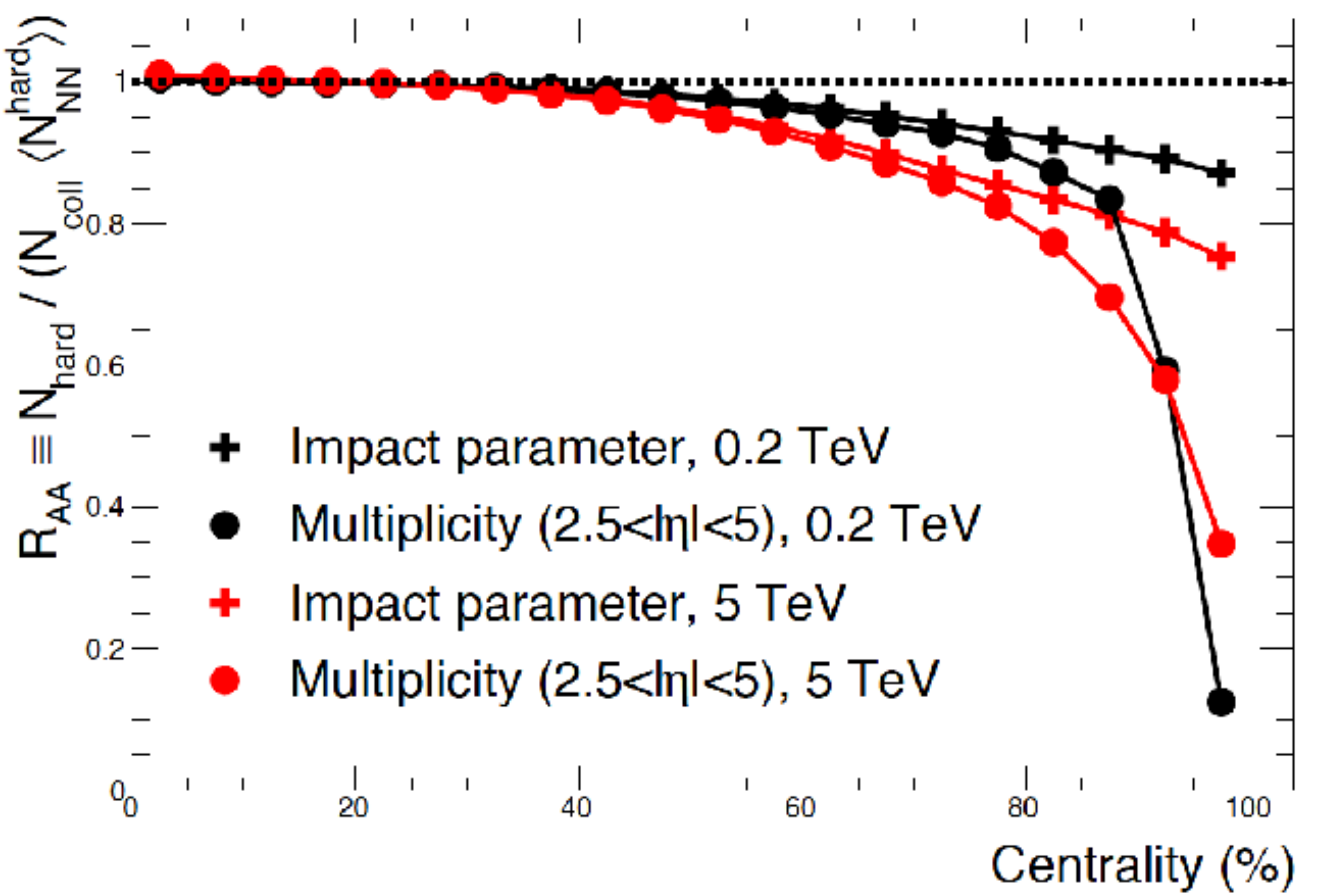
Multiplicity bias can cause the apparent suppression!





Geometrical and Multiplicity Bias

C Loizides, AM, arXiv:1705.08856



Peripheral collisions strongly affected by multiplicity bias.

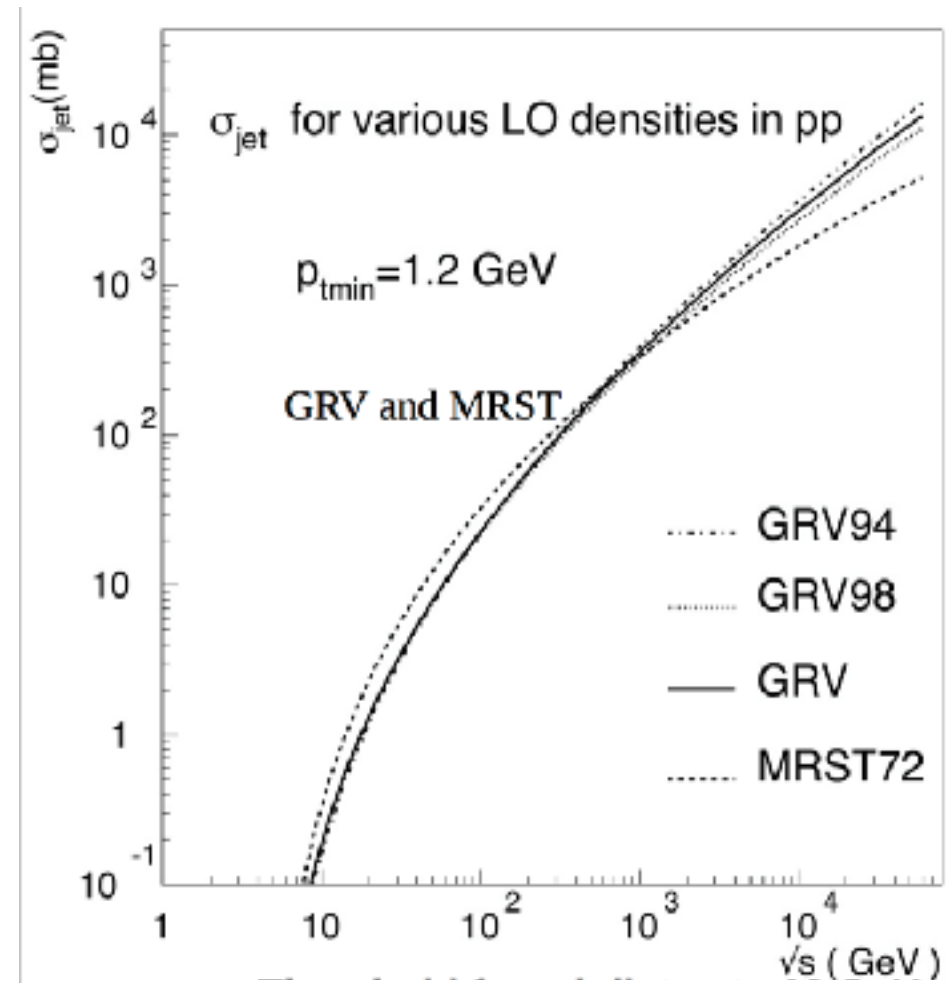
Centrality in Small Systems

- Needs good understanding / MC modelling of interplay between hard and soft particle production.
- What other experimental constraints do we have?

Naive two Component Model

- between 10 GeV and 10 TeV hard cross-section increases by factor 10^5

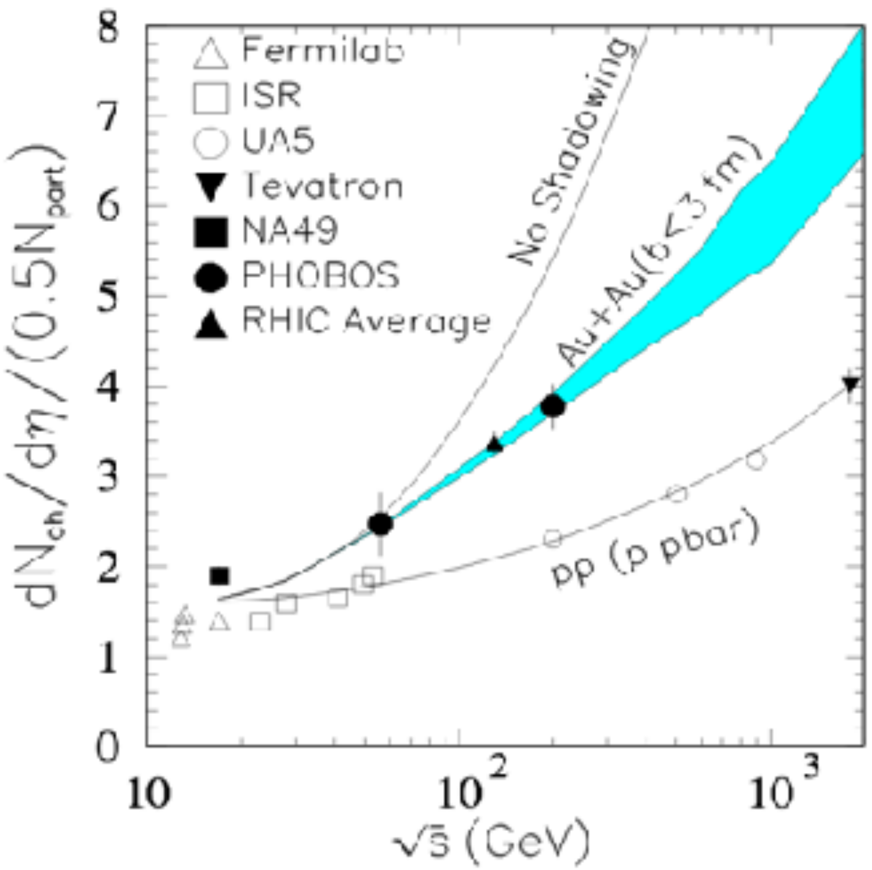
$$\frac{dN_{ch}}{d\eta} = \frac{1}{2}\langle N_{part}\rangle\langle n_{soft}\rangle + \langle N_{coll}\rangle\langle n_{soft}\rangle\frac{\sigma_{jet}\left(\sqrt{s}\right)}{\sigma_{inel}\left(\sqrt{s}\right)}$$



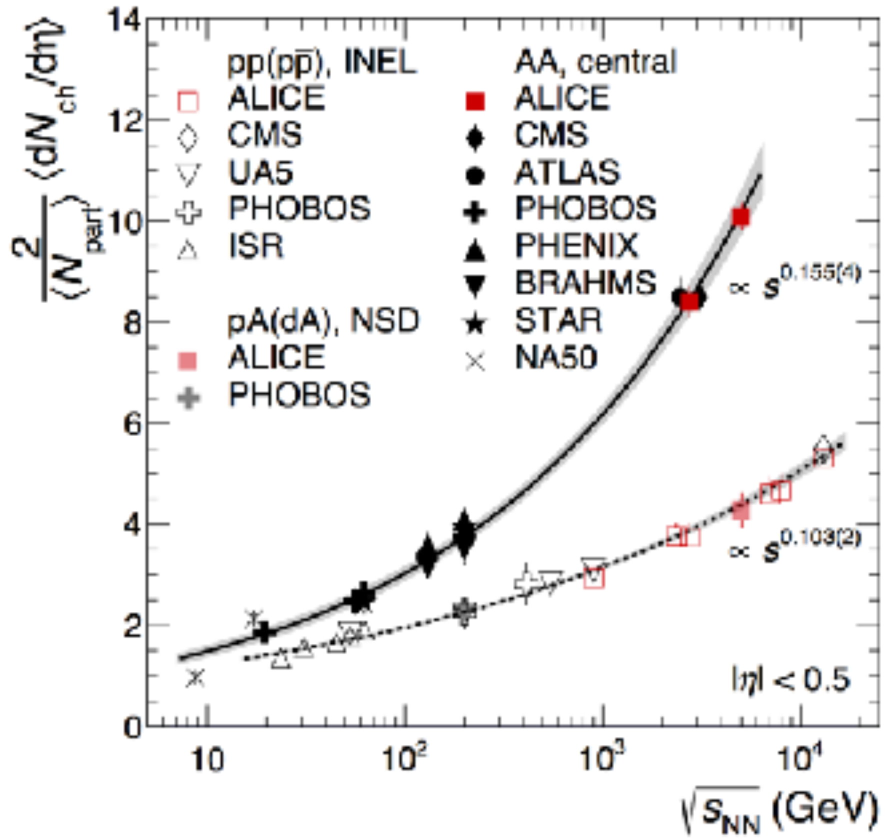
- Do hard processes dominate particle production at high √s ?
- Further increase in A-A due to N_{coll} scaling ($\sim A^2$)
- However factorisation not guarantied if many scatterings happen in the same transverse area.

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

Charged particle multiplicity at mid-rapidity



$dN_{ch}/d\eta$ = 1943±56

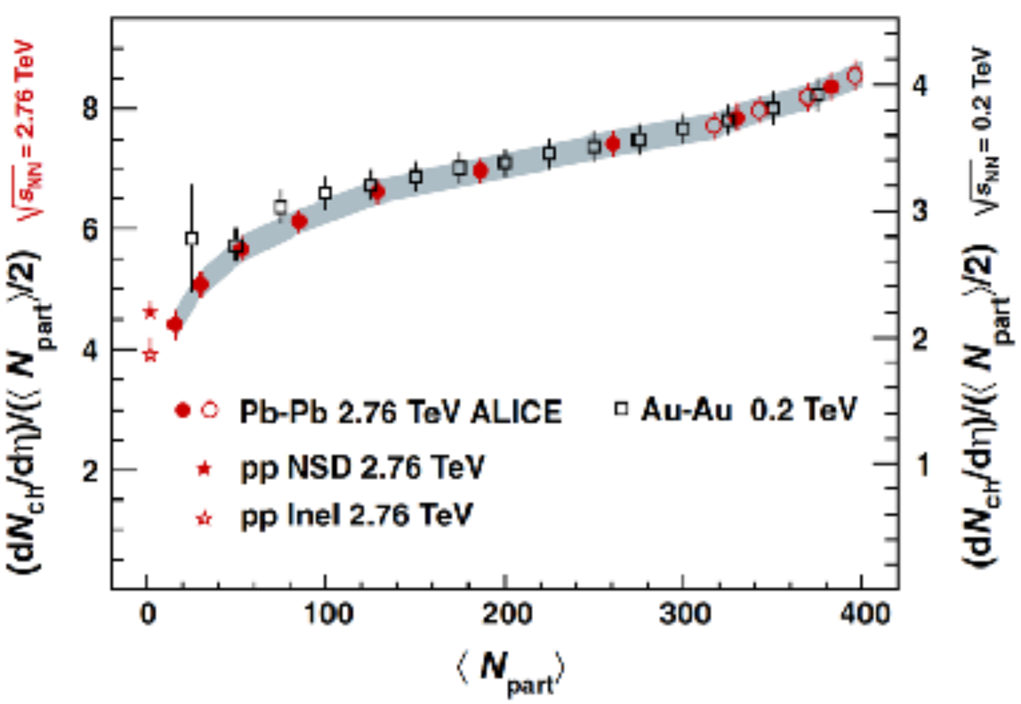


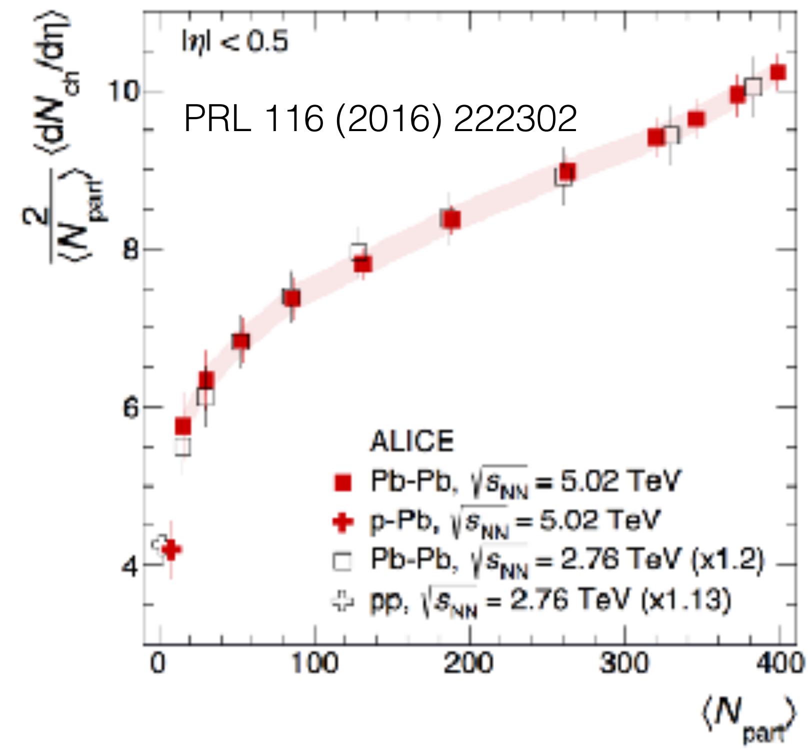
PRL 116 (2016) 222302

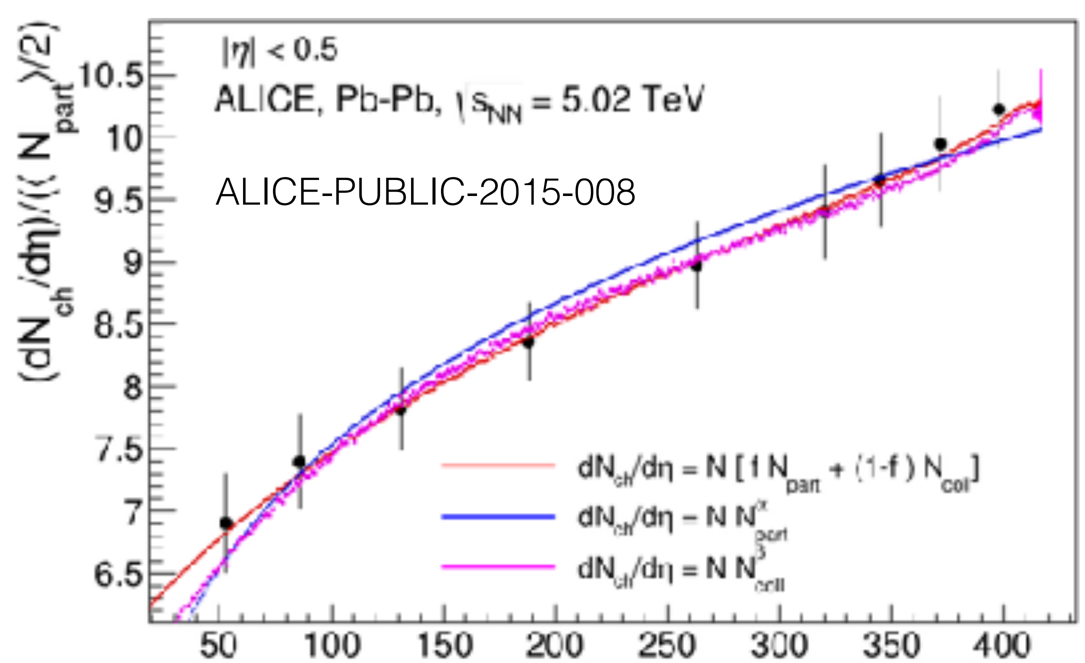
Trend established at lower energy confirmed at LHC!
Considerably steeper rise of A-A multiplicity wrt pp.

Centrality Dependence

Although S-shape consistent with hard+soft scaling (f N_{part} + (1-f) N_{coll})
Shape almost energy independent!

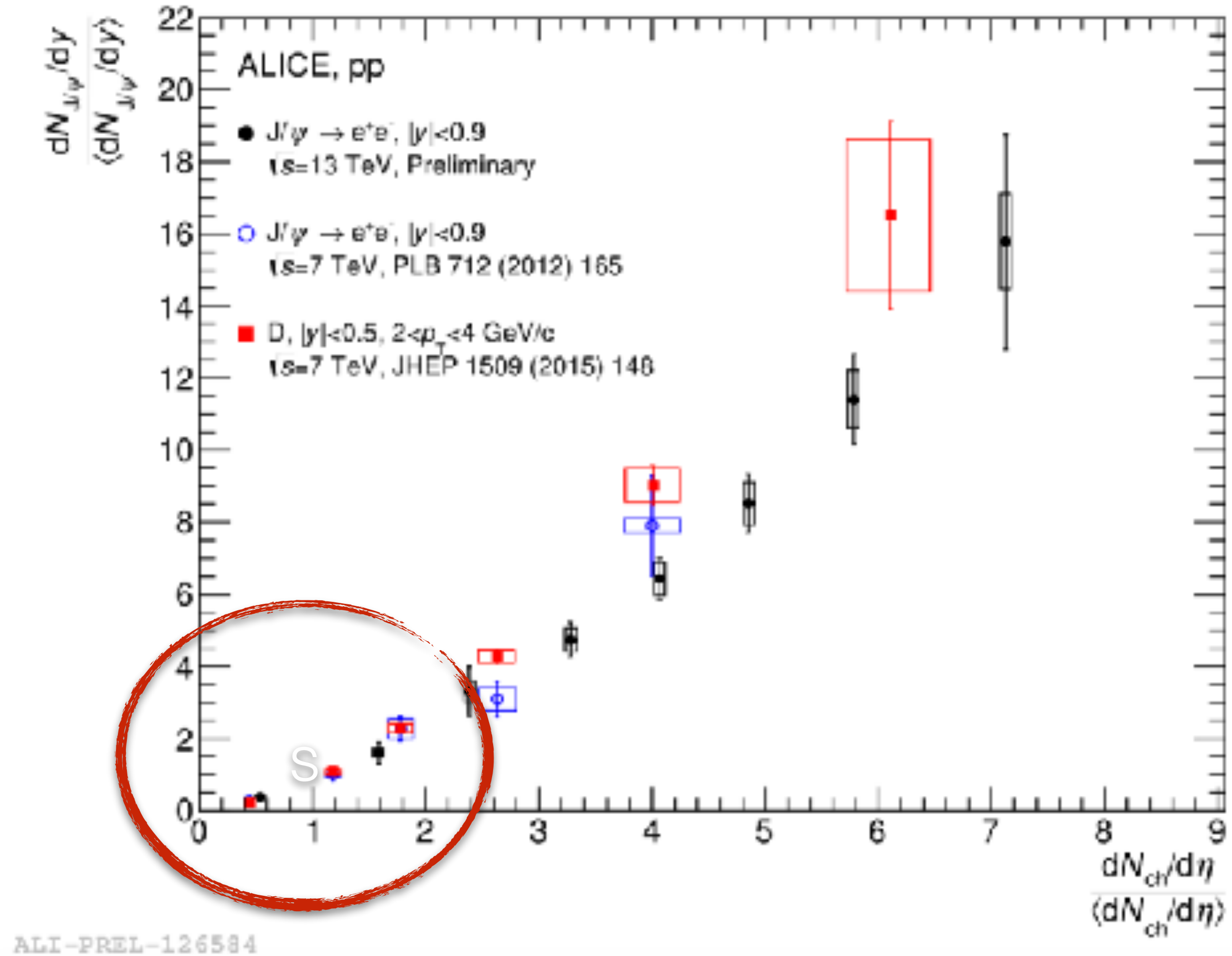






“Centrality” Dependence in pp

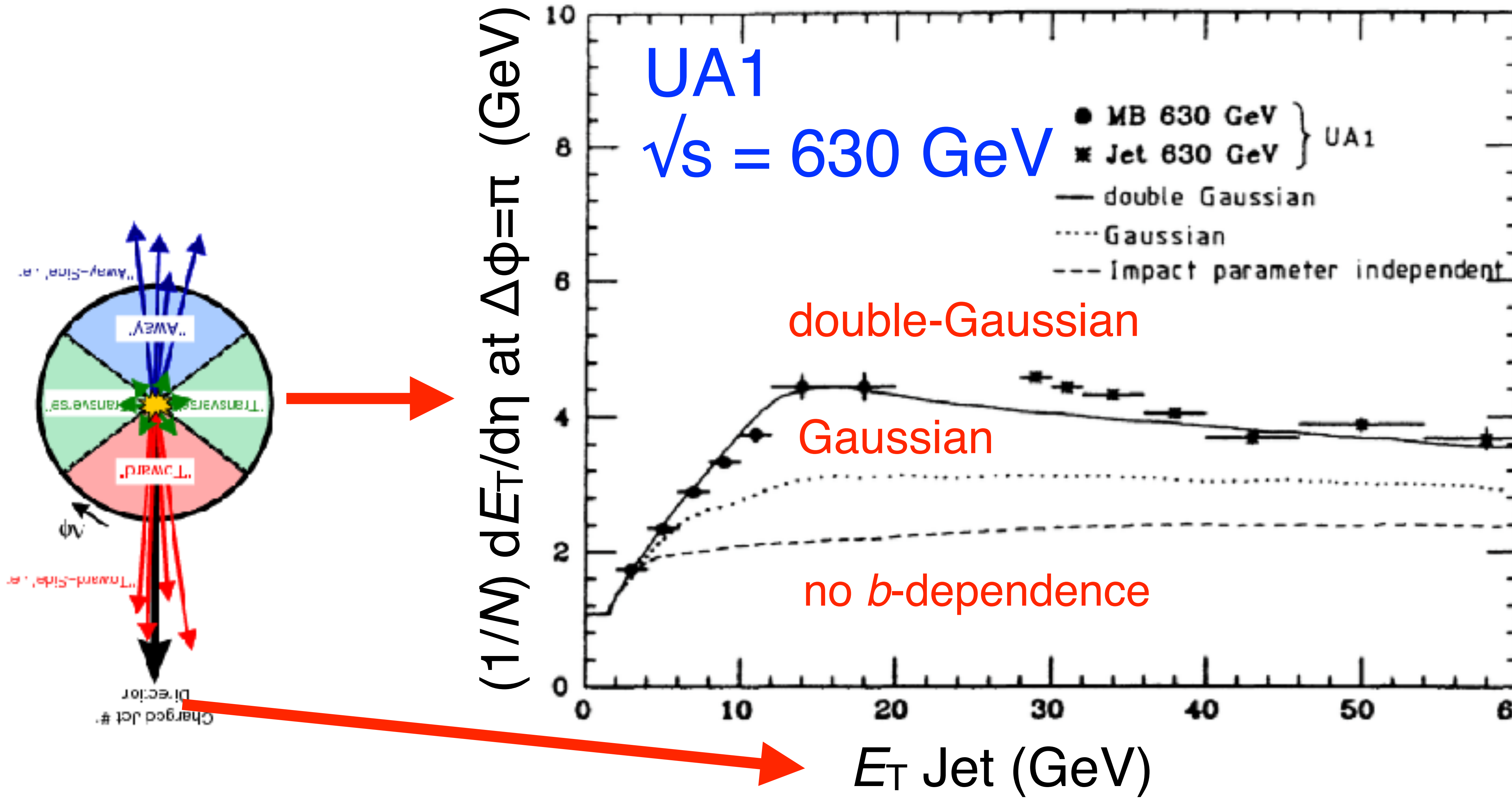
Heavy Flavour



As in Pb-Pb

Transition region soft→hard dominated seems to scale with √s

Proton Structure

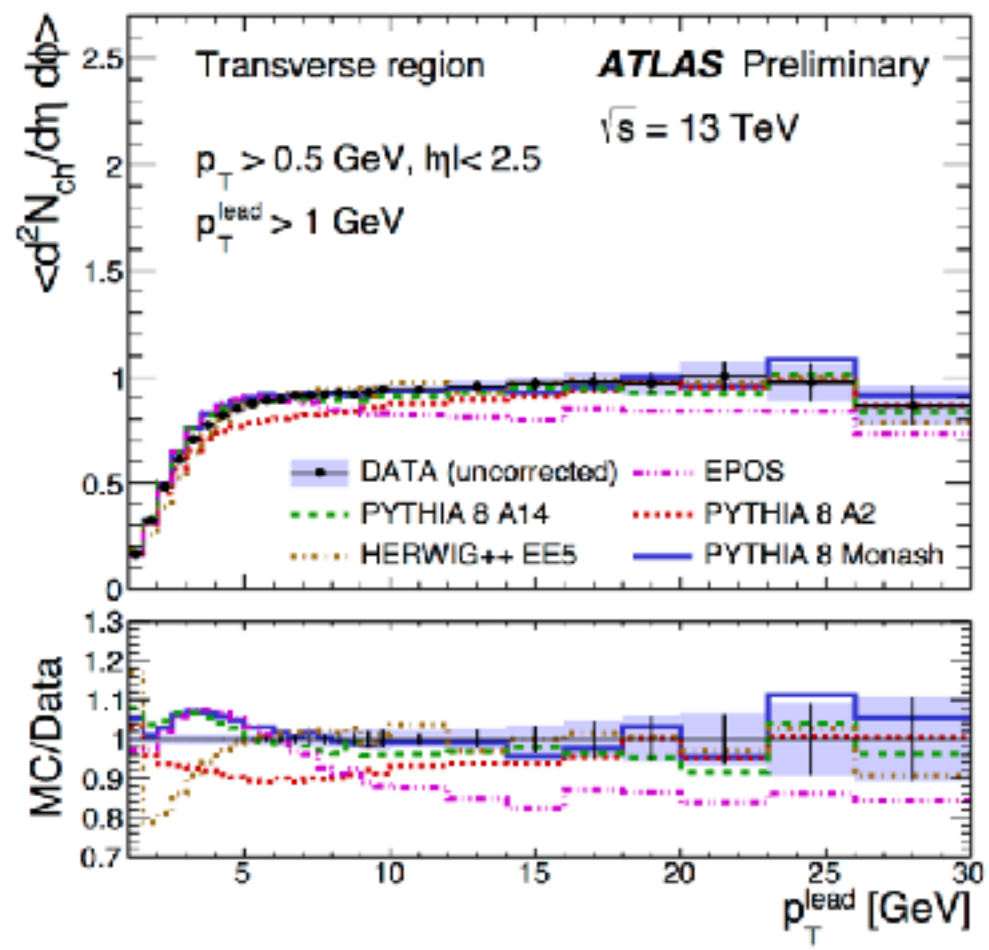


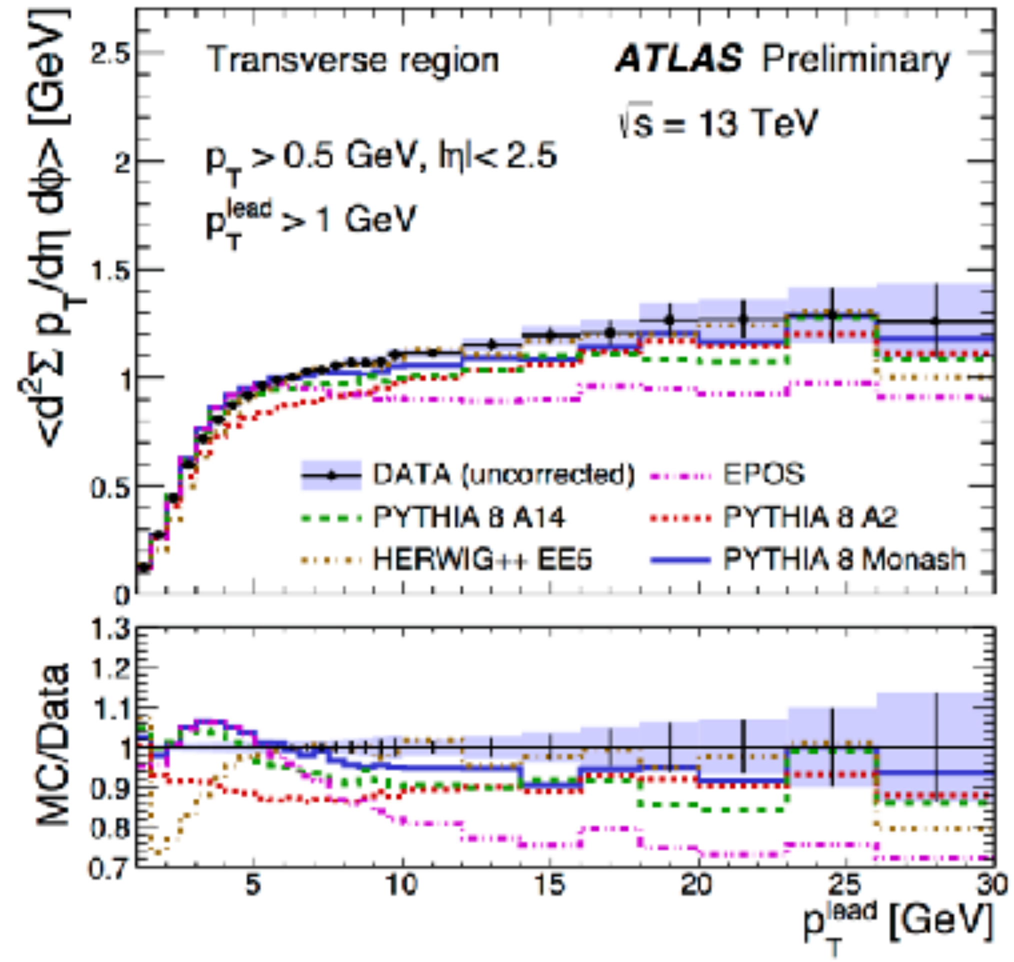
Optical proton

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

UE in pp @ √s =13 TeV

ATL-PHYS-PUB-2015-019





- Clear discriminating power between different models (tunes)

- However, to which extent can we constrain individual mode components:
  - exact impact parameter dependence of hard/soft scattering ?
  - modelling of soft processes ?
  - confidence intervals for the parameters ?

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

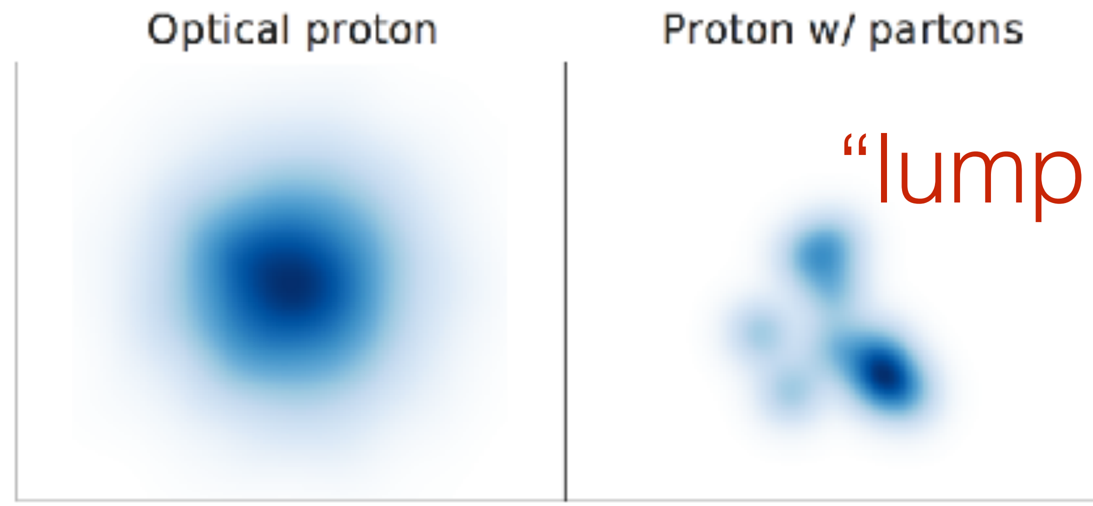
$$a(x) = a_0\left(1 + a_1 \ln\frac{1}{x}\right)$$

- In principle proton density function could be *x*-dependent
  - Which measurement would be sensitive to this ?

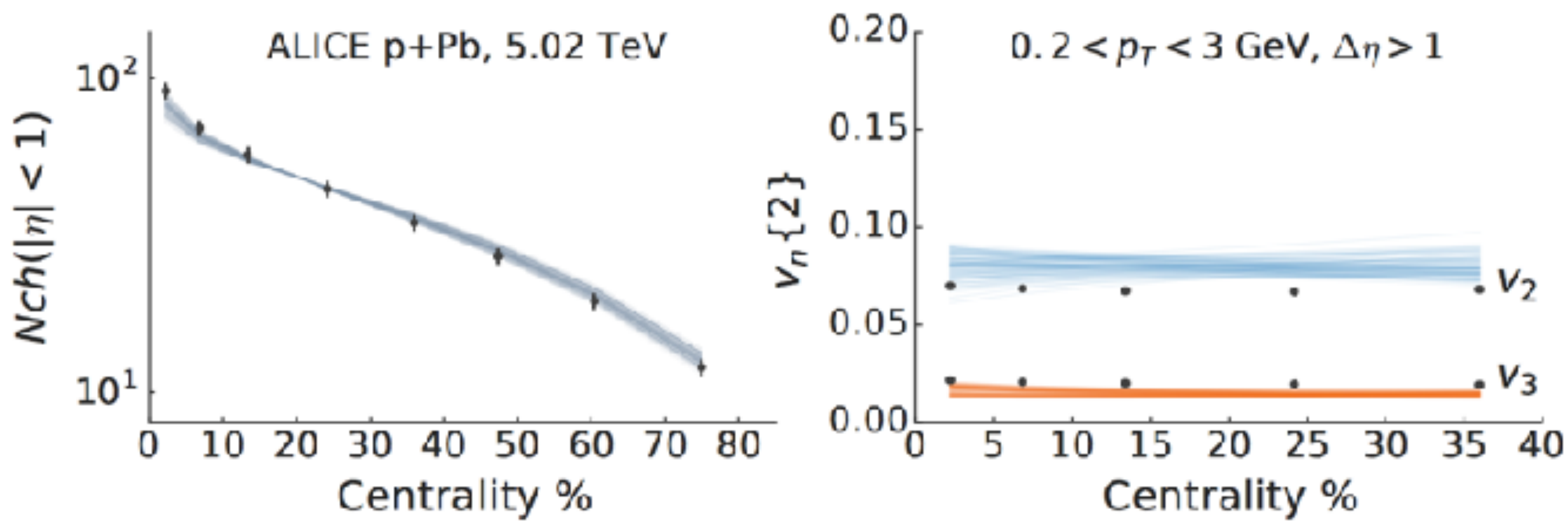
Initial State for Hydro Calculations

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

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



JS Moreleland, QM'17

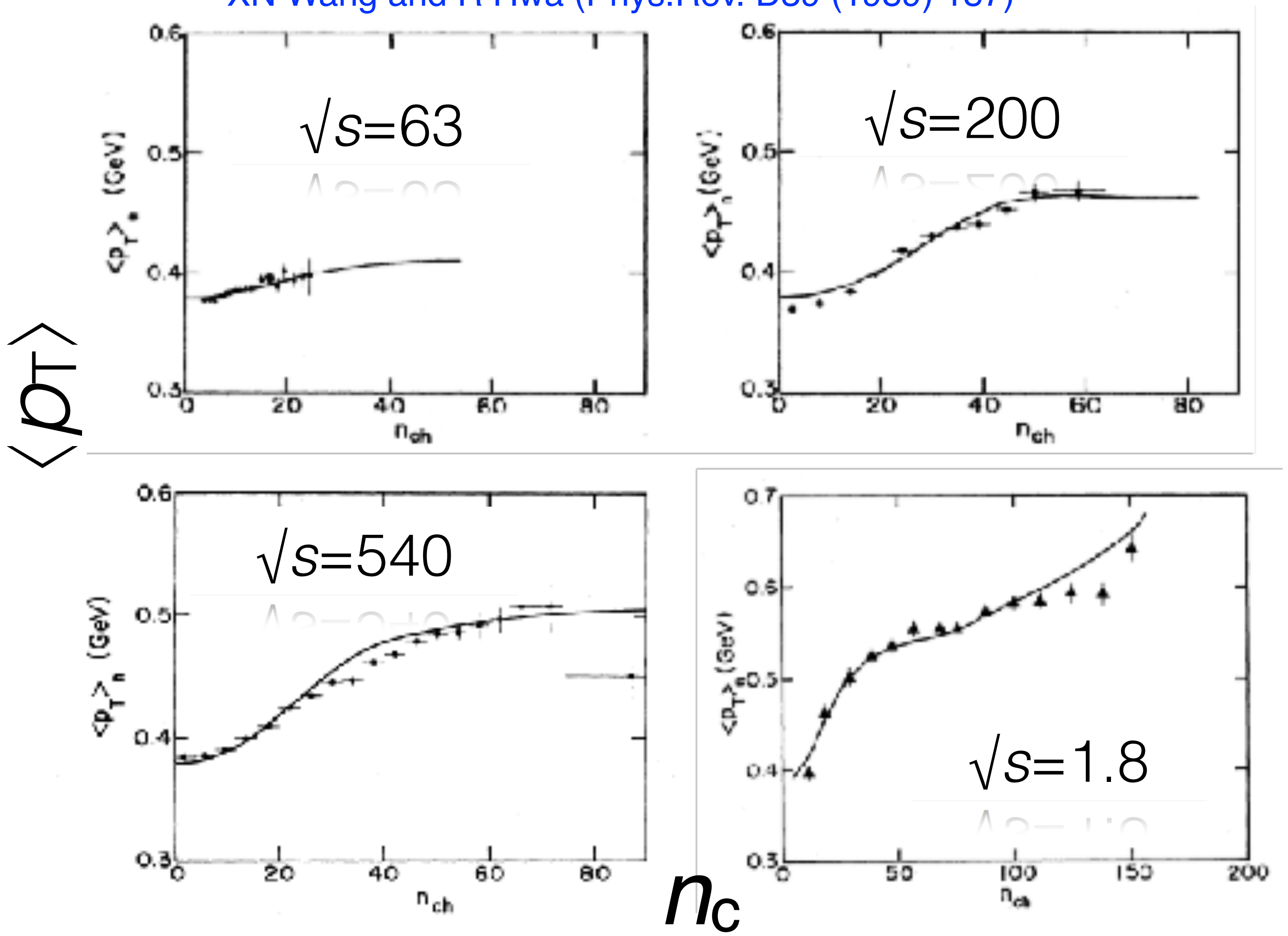


Data: ALICE, PRC 90, 054901 [1406.2474]

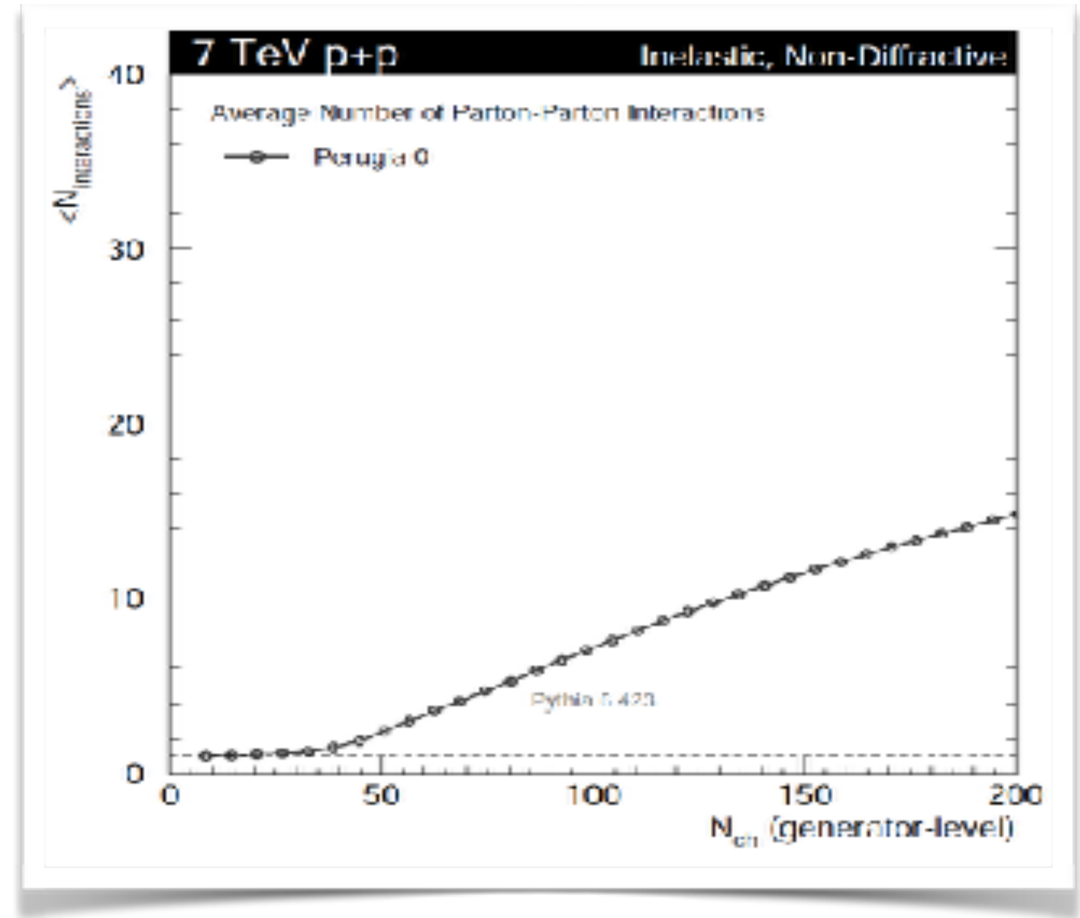
- Also consistent with UE measurements ?
- Are there other measurements (UE fluctuations) that can constrain the model ?

Probing Coherence Effects

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



P. Skands



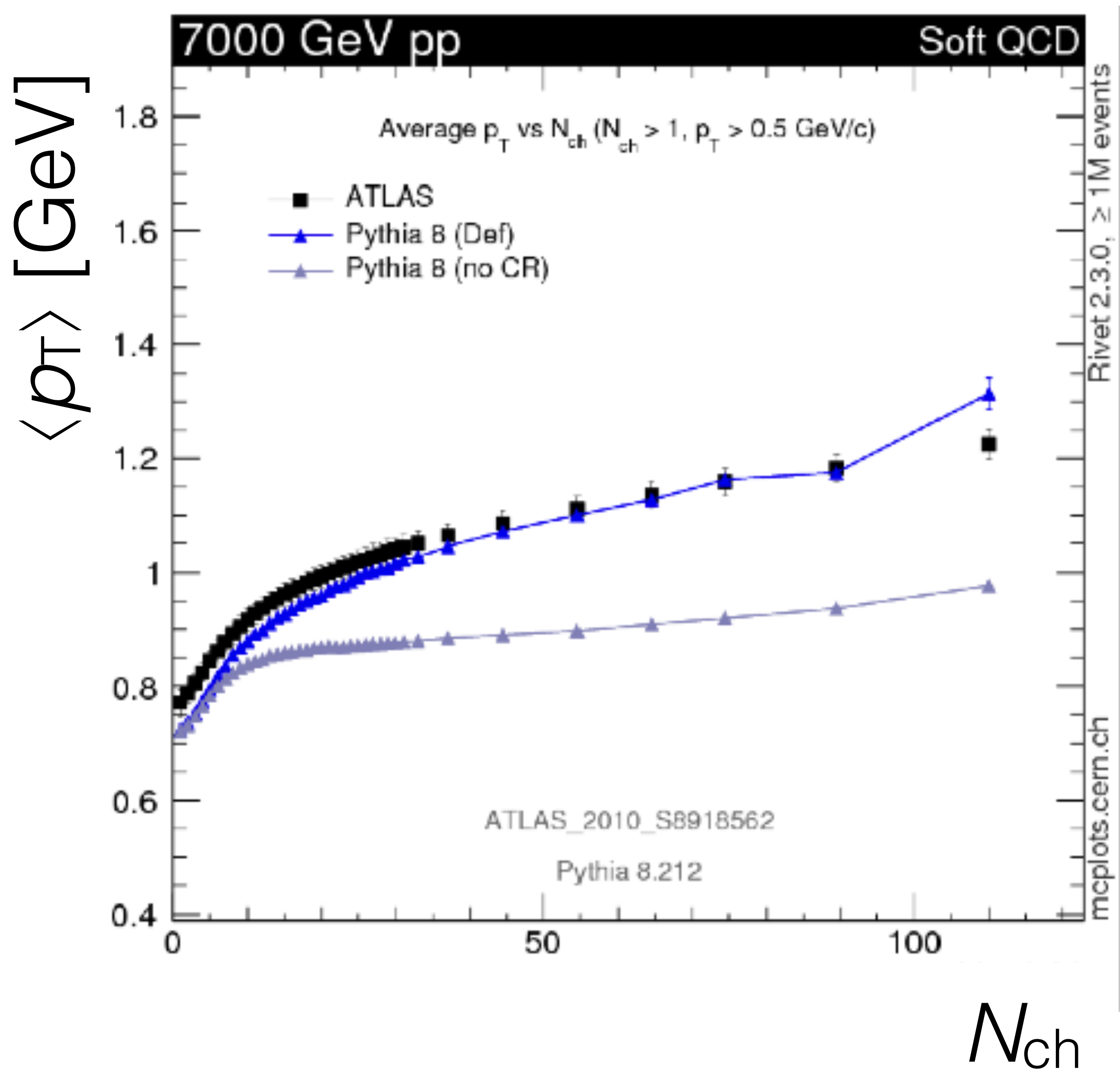
Two component model

➠Ledge Effect: rise – plateau – rise

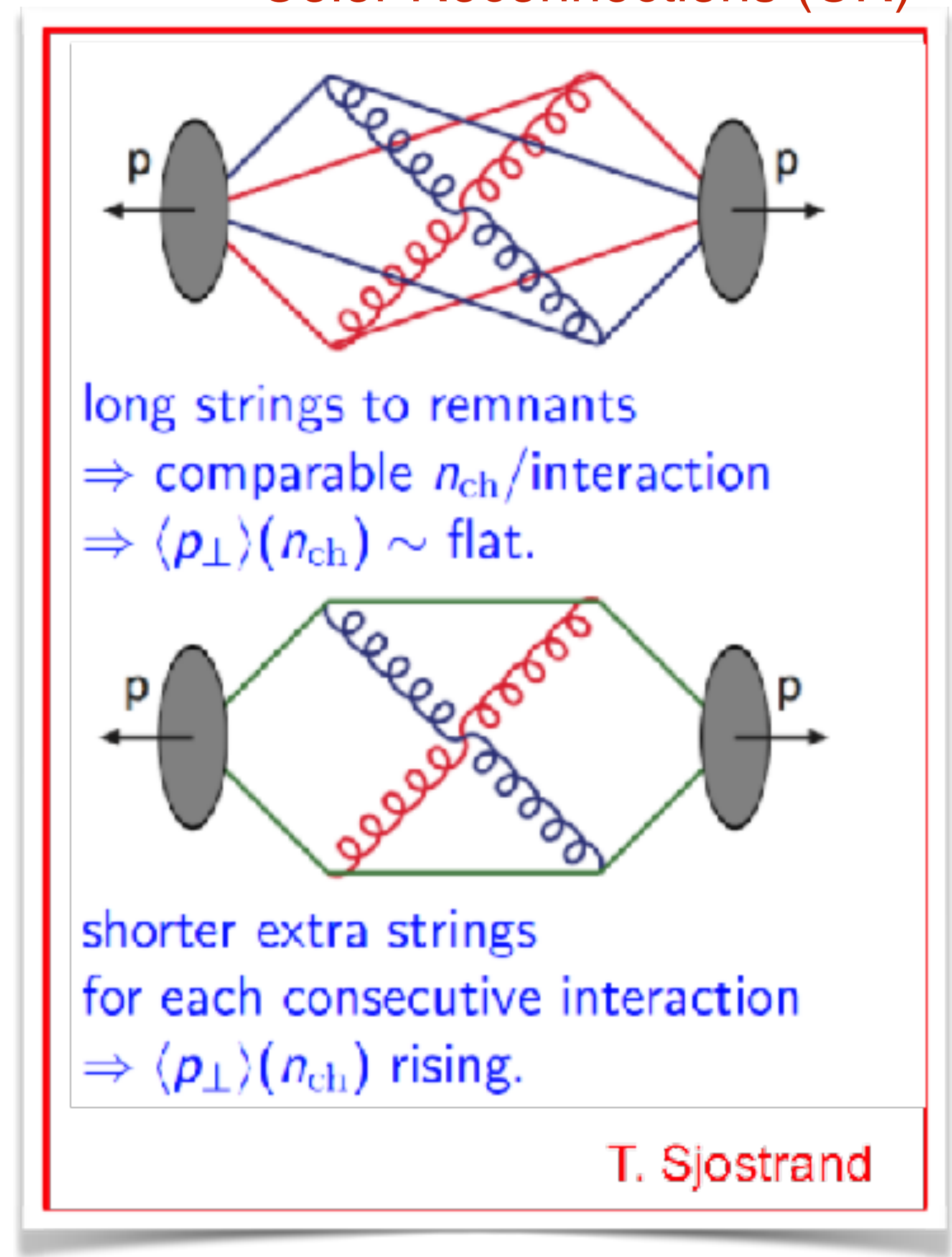
1st rise: increased dominance of hard over soft interactions

2nd rise: jet bias (jets contribute to soft particle production ~ ln E_{jet})

Pythia: Color Reconnections

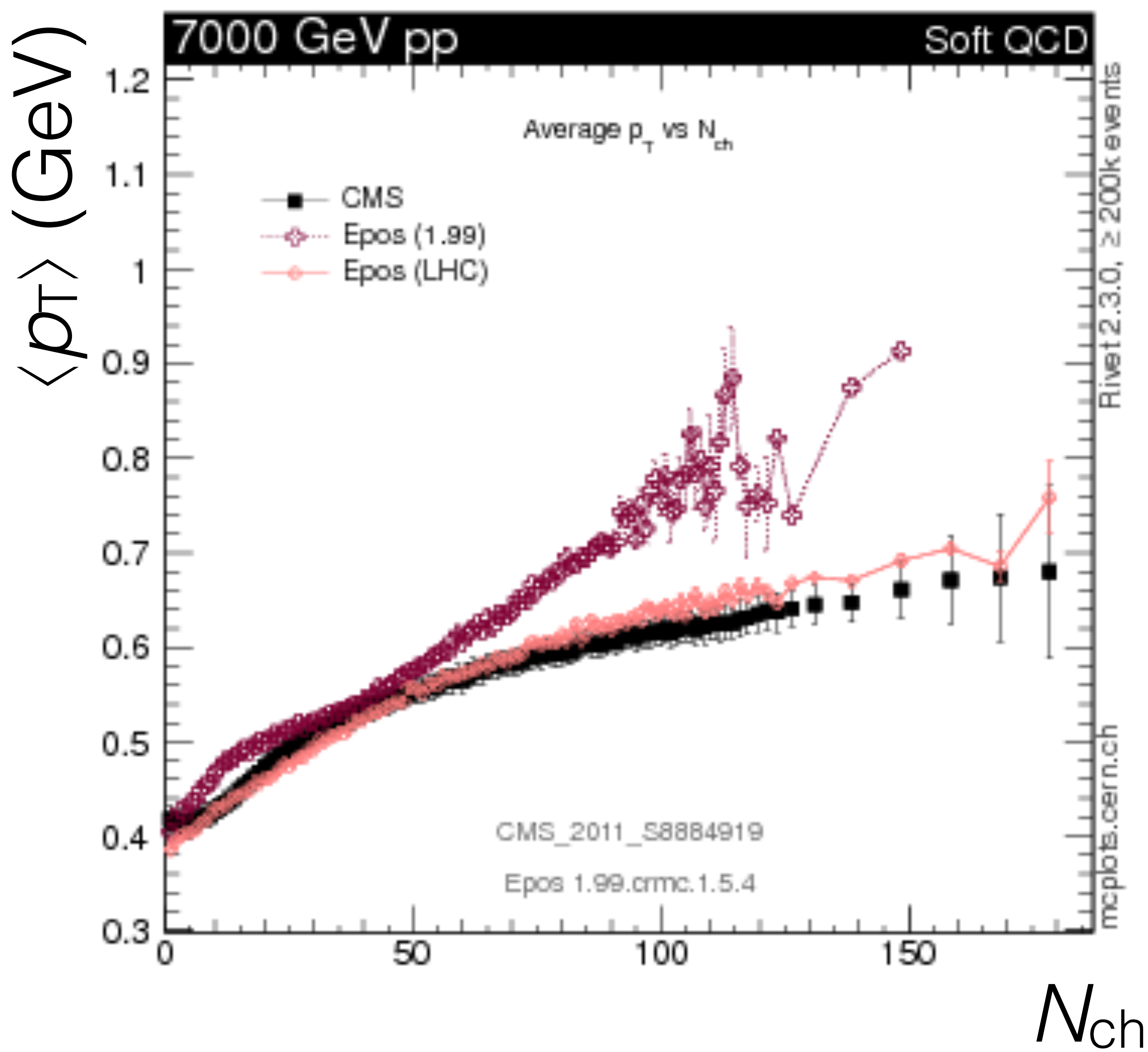


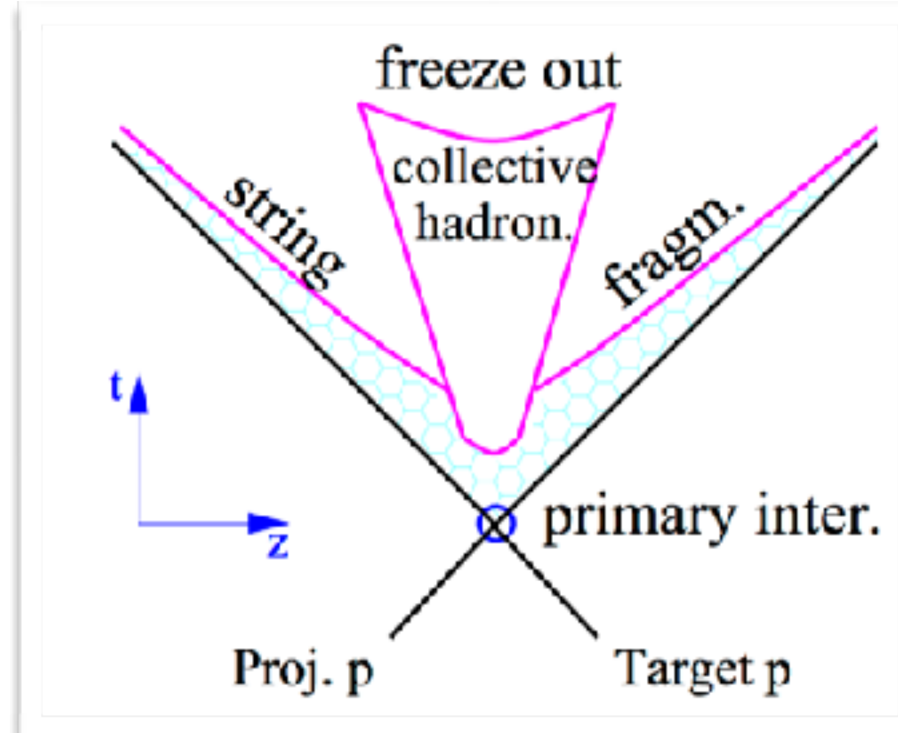
Color Reconnections (CR)

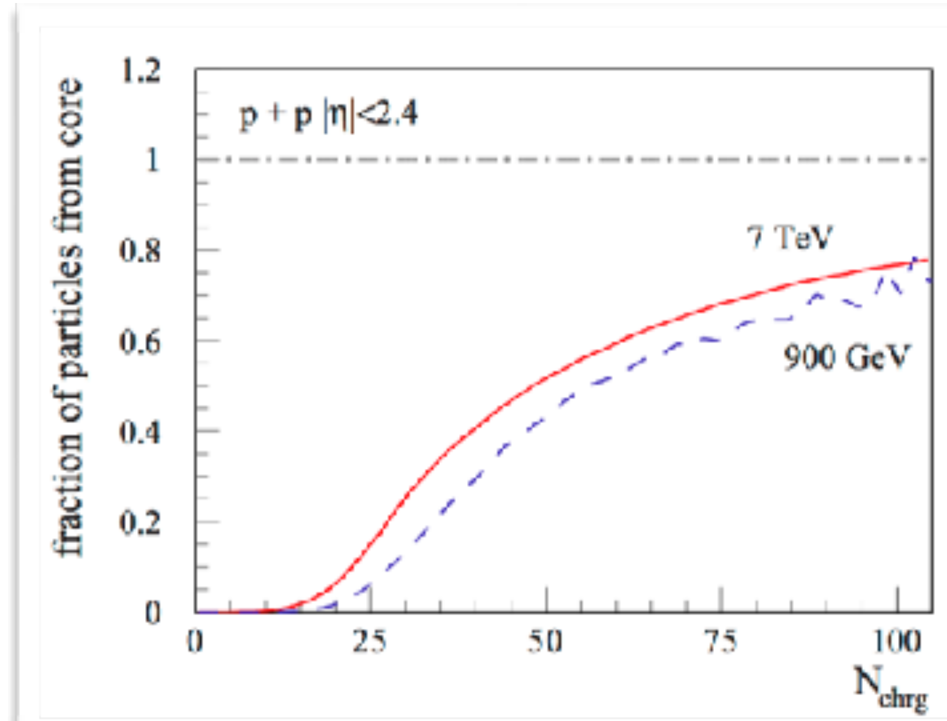


Pythia:
Interplay between hard and soft not enough to describe rise

EPOS: Collective Hadronization



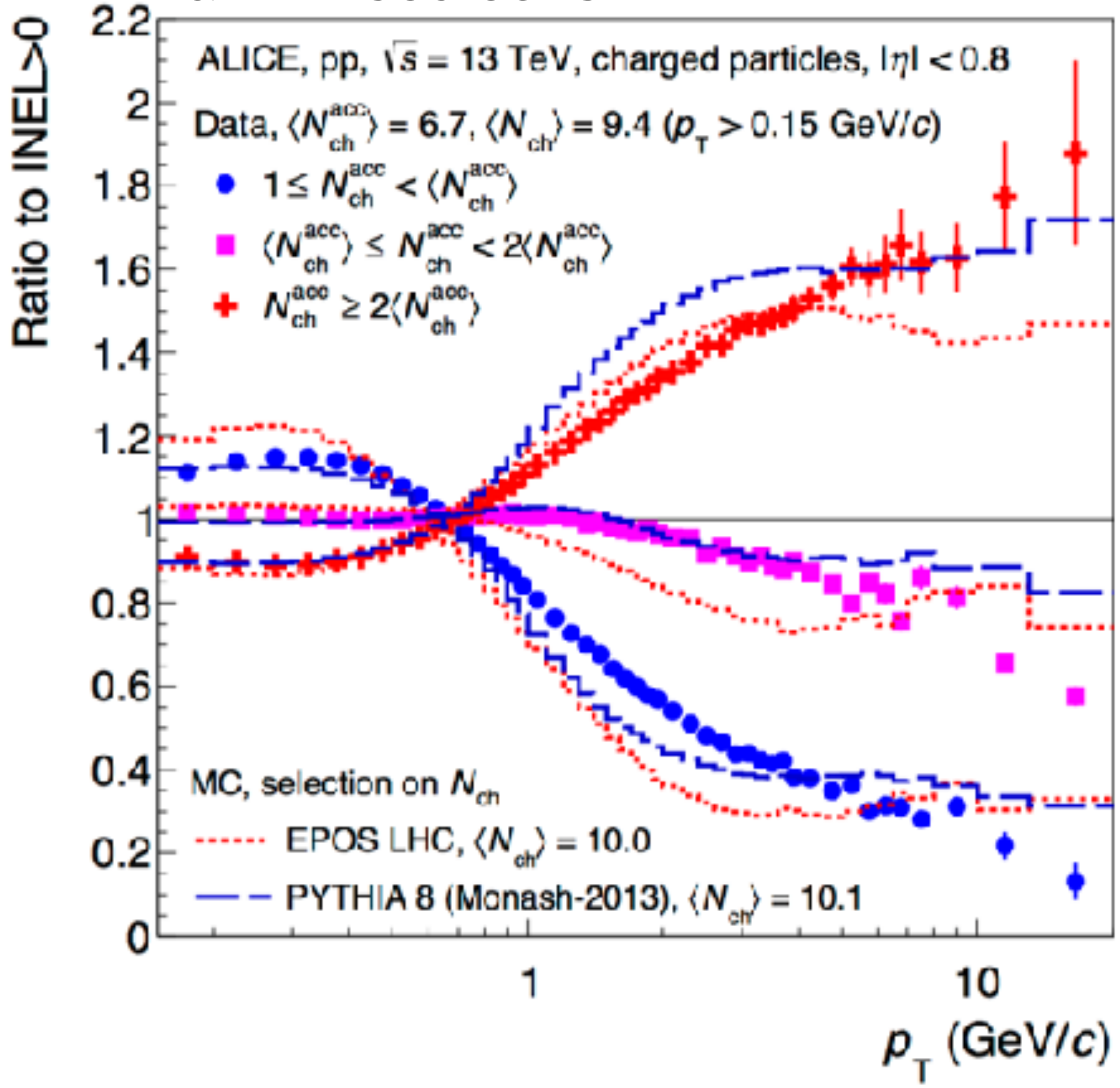




Ledge Effect Re-visited

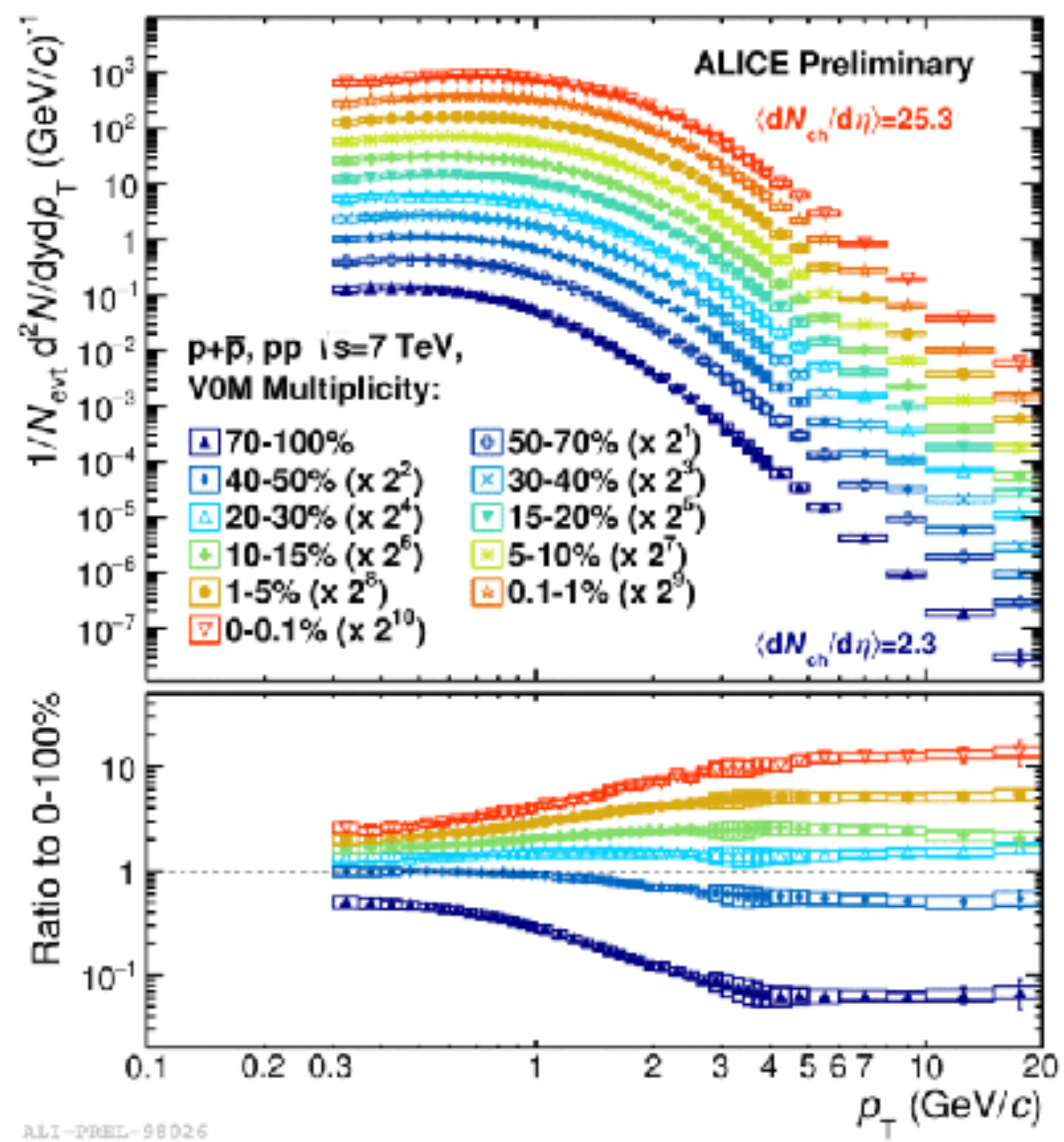
Multiplicity measured in: $|\eta|<0.9$

arXiv:1509.08734v1



- Spectra measured at mid-rapidity,
- hardness multiplicity dependent

$2.8 < \eta < 4.1 \cup -3.7 < \eta < -1.7$



- Scaling at high p_T, reminiscent of R_{pA}
- Informs about N_{MPI}
- “Some kind of centrality measure”

Summary

- Toy model study suggests that apparent suppression in very peripheral AA originates from biases. Relevant for
  - all hard probes
  - at all energies
- Consistent with $R_{\mathrm{pA}} = 1$ for similar N_{part}
- Understanding of centrality estimators based on multiplicity or summed energy in small systems pp, p-A, per. A-A hinges on knowledge and modelling of correlations between soft and hard particle production.