Particle Production and Binary Scaling in p-Pb Collisions with ALICE

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on behalf of the ALICE Collaboration

CERN LHC Seminar
November 12, 2013

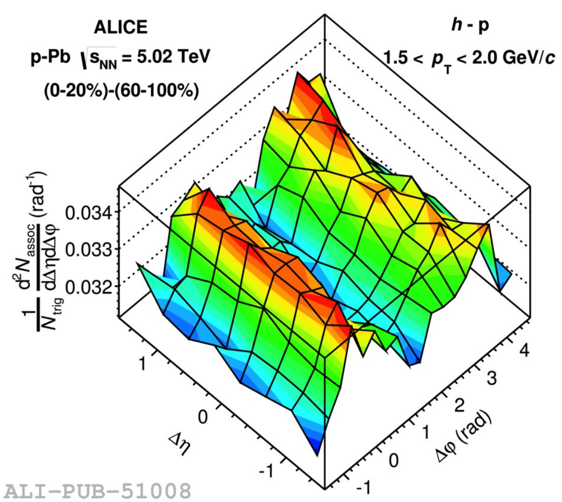
Outline

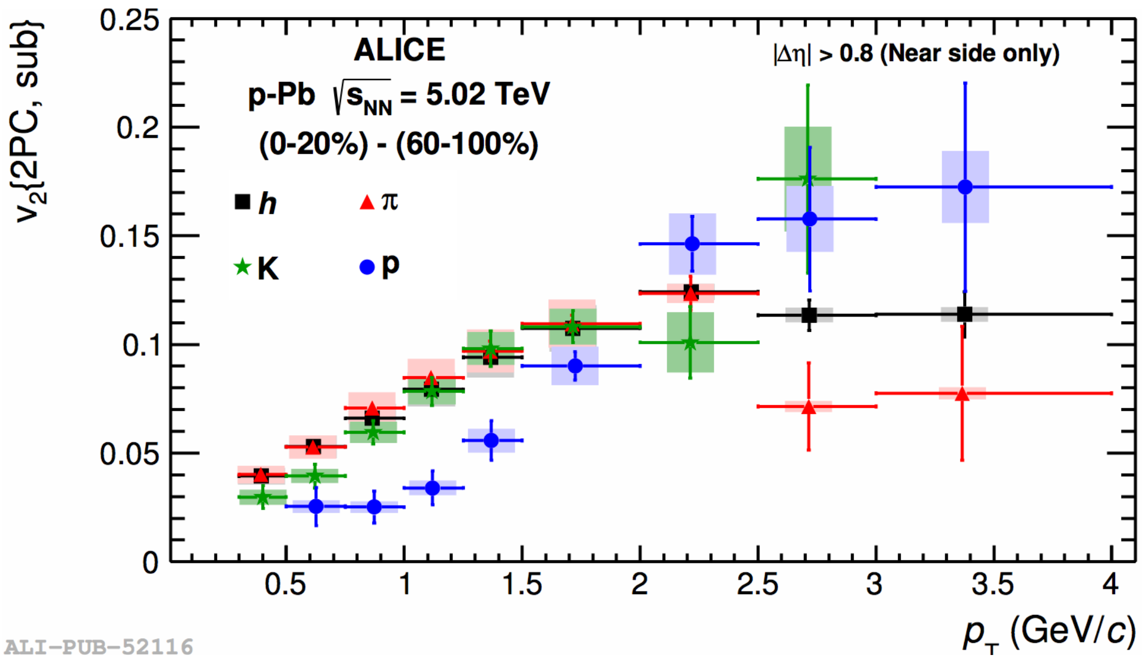
- Introduction
- Nuclear modification factors in minimum bias p-Pb collisions measured by ALICE
  - Need for centrality dependent measurements
- Centrality determination with ALICE
- Possible biases on binary scaling
  - Study of correlation of bulk particle production and semi-hard scattering in p-Pb using di-hadron correlations
  - Bias inclusive charged hadron production
- Conclusions

Study of p-A Collisions ...

- Field developed from
  - crucial control-experiment to study cold nuclear effects and to establish a baseline for Pb-Pb
  - to an area where on could see some interesting effects
    - ex. suppression of away-side correlations (RHIC)
      - saturation ?
  - Groundbreaking discoveries ... but also new challenges

"Double-Ridge"

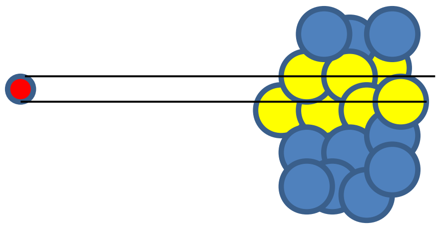




Nuclear modification factor

$$R_{\mathrm{pA}}^{\mathrm{X}}(p_{\mathrm{T}}) = \frac{\mathrm{d}N_{\mathrm{X}}^{\mathrm{pA}}/\mathrm{d}p_{\mathrm{T}}}{\langle N_{\mathrm{coll}}\rangle \mathrm{d}N_{\mathrm{X}}^{\mathrm{pp}}/\mathrm{d}p_{T}}$$

"binary scaling" in Glauber model
$\langle N_{\mathrm{coll}} \rangle$ number of binary collisions
("nucleons hit in the nucleus")



$$\frac{\mathrm{d}\sigma^{pA\rightarrow X}}{\mathrm{d}p_{\mathrm{T}}} \propto f_i^p(x_1, Q^2) \circ f_j^A(x_2, Q^2) \circ \sigma^{ij\rightarrow k}(x_1, x_2, p_{\mathrm{T}}/z, Q^2) \circ D_{k\rightarrow X}(z, Q^2) \circ FS\ effects$$

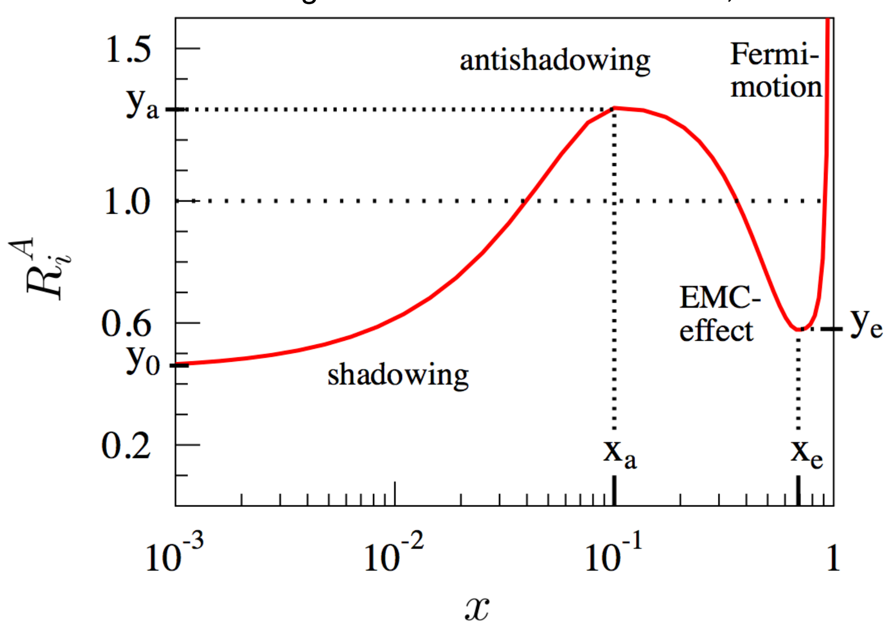
- In absence of strong final state effects, R_{pA} provides information about nuclear modifications of *the parton density function*

Write

$$f_i^A(x, Q^2) \equiv R_i^A(x, Q^2) f_i^{\mathrm{CTEQ6.1M}}(x, Q^2)$$

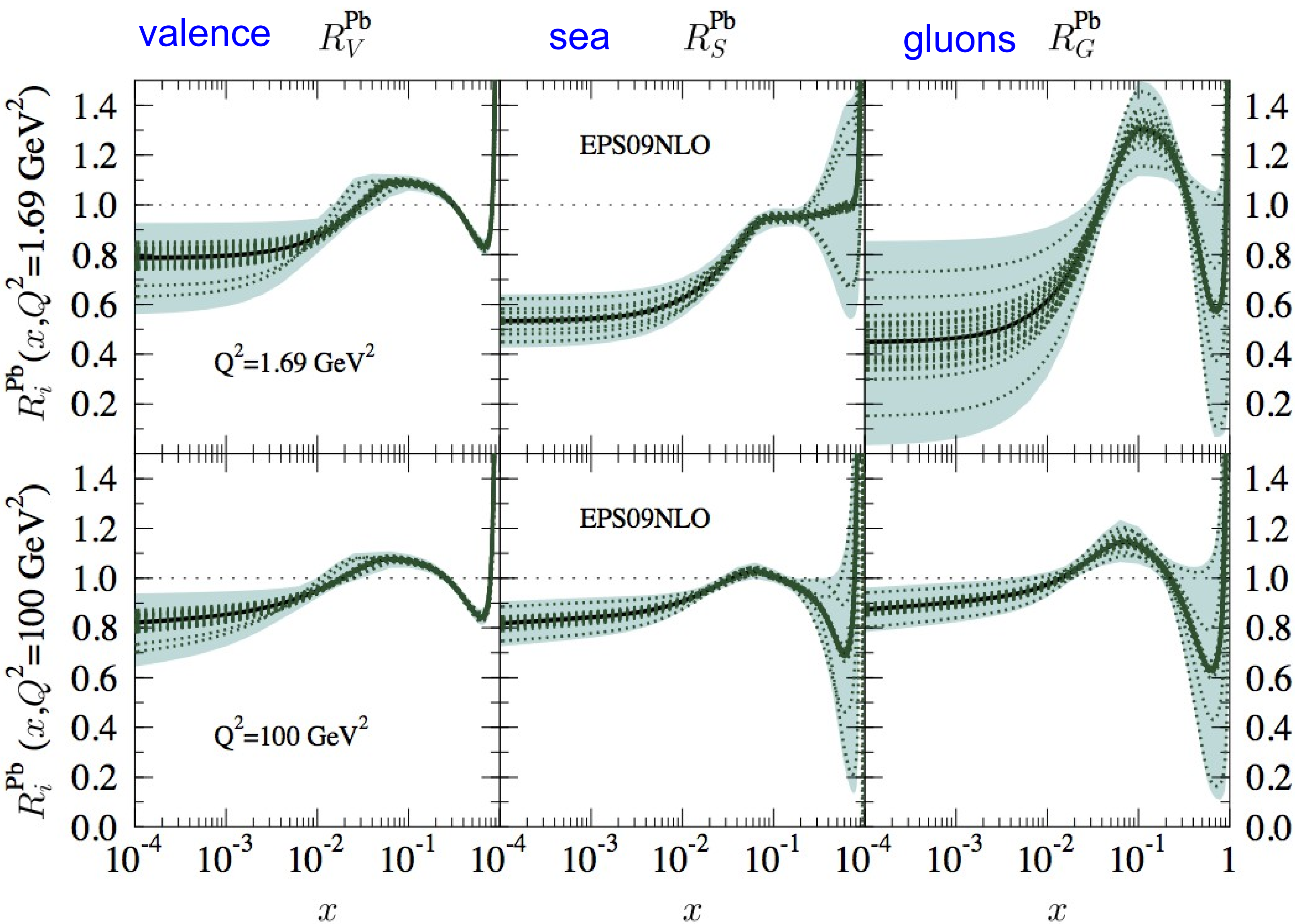
Two regions important at the LHC
- shadowing
- anti-shadowing

C. Salgado et al. JHEP 0904:065,2009

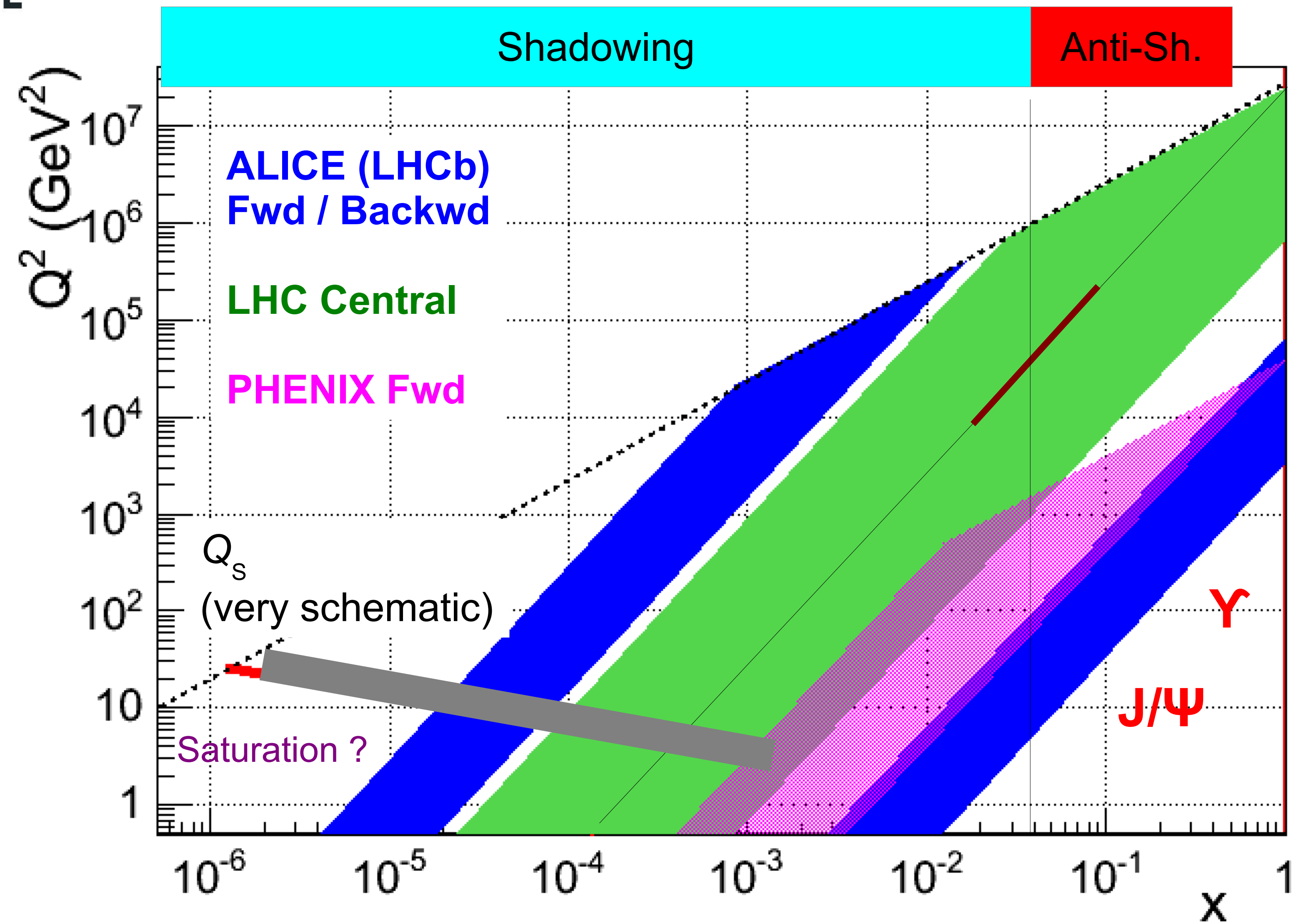


EPS09

C. Salgado et al. JHEP 0904:065,2009



Where are we ?



Possibility to approach saturation scale in perturbative region.
Most of measurement performed in shadowing region.

Multiple-(Hard) Collisions

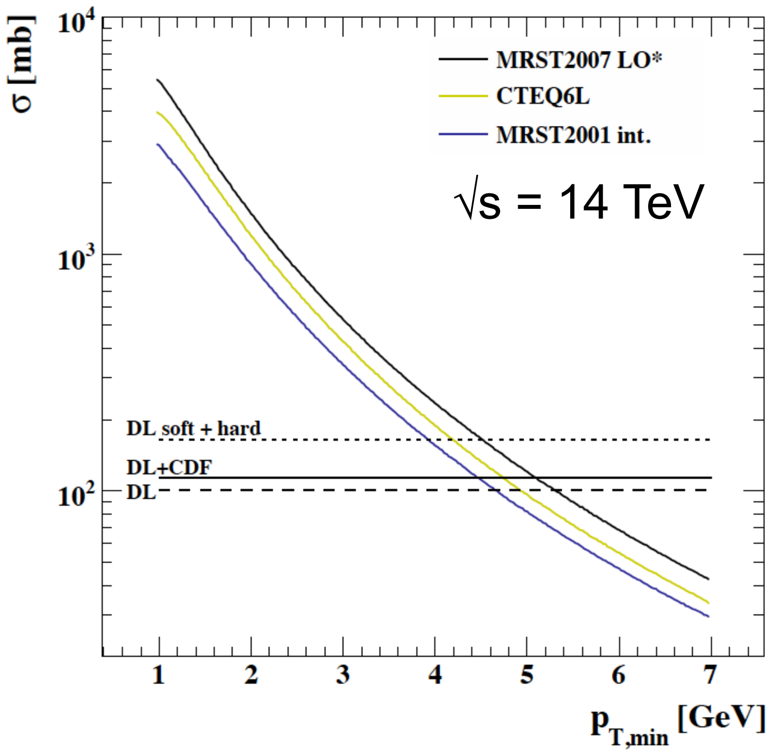


Figure 1: The inclusive hard cross section for three different proton PDFs, compared to various extrapolations of the non-perturbative fits to the total *pp* cross section at 14 TeV centre-of-mass energy.

M. Bahr, J.M. Butterworth and M.H. Seymour, The underlying event and the total cross section from Tevatron to the LHC , JHEP 01 (2009) 065 [arXiv:0806.2949] [INSPIRE].

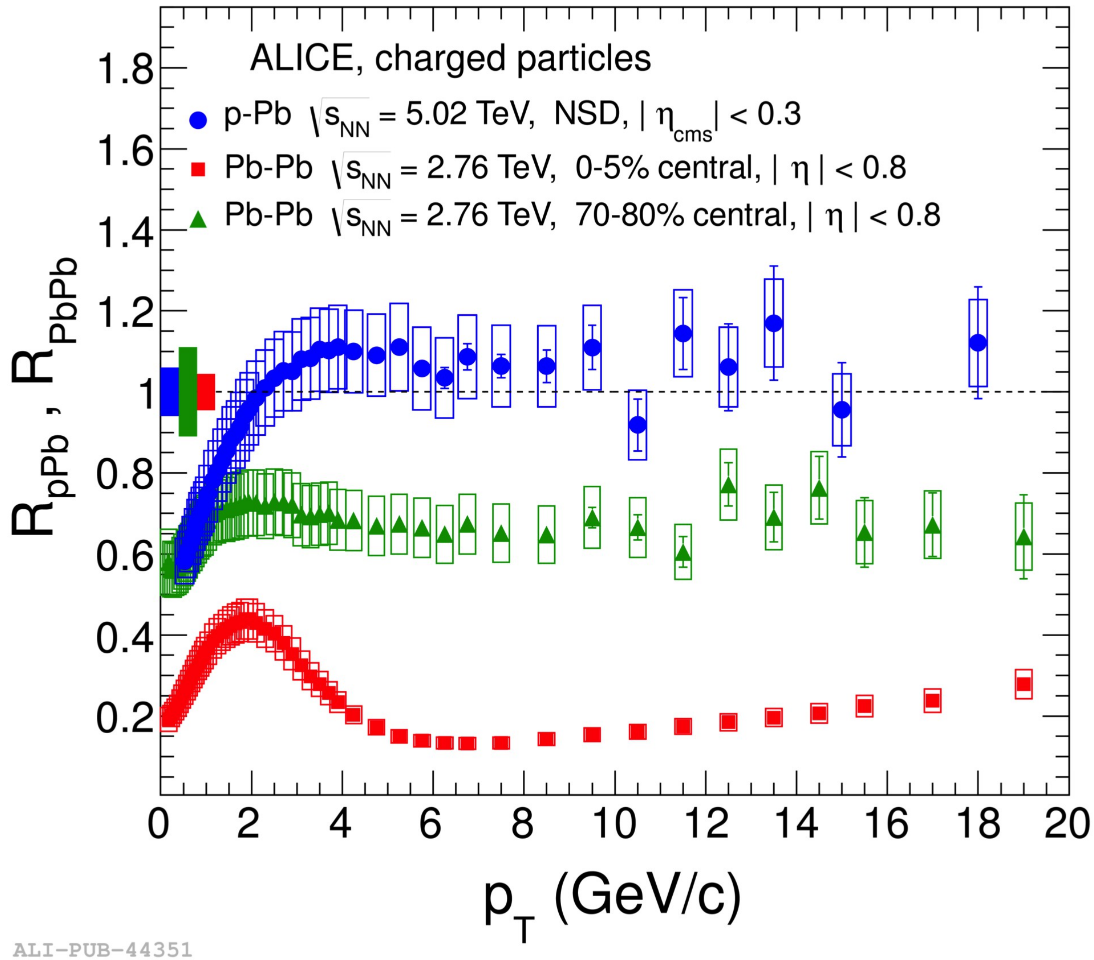
- In pp hard cross-section exceeds the total cross-section, strongly indicating that there are multiple semi-hard (perturbative collisions per event)
- N_{coll} binary collisions implies >> N_{coll} semi-hard-scatterings in addition to the hard process studied
- Correlations between hard process and bulk of particle production ?
- Possible consequences for centrality determination (to be discussed later ...)

$$f_i^p(x_1, Q^2; x_{1,1}, Q_1^2, x_{1,2} Q_2^2, ...)$$

Results for nuclear modification factors in minimum bias p-Pb collisions ($\sqrt{s_{NN}}$ = 5.02 TeV)

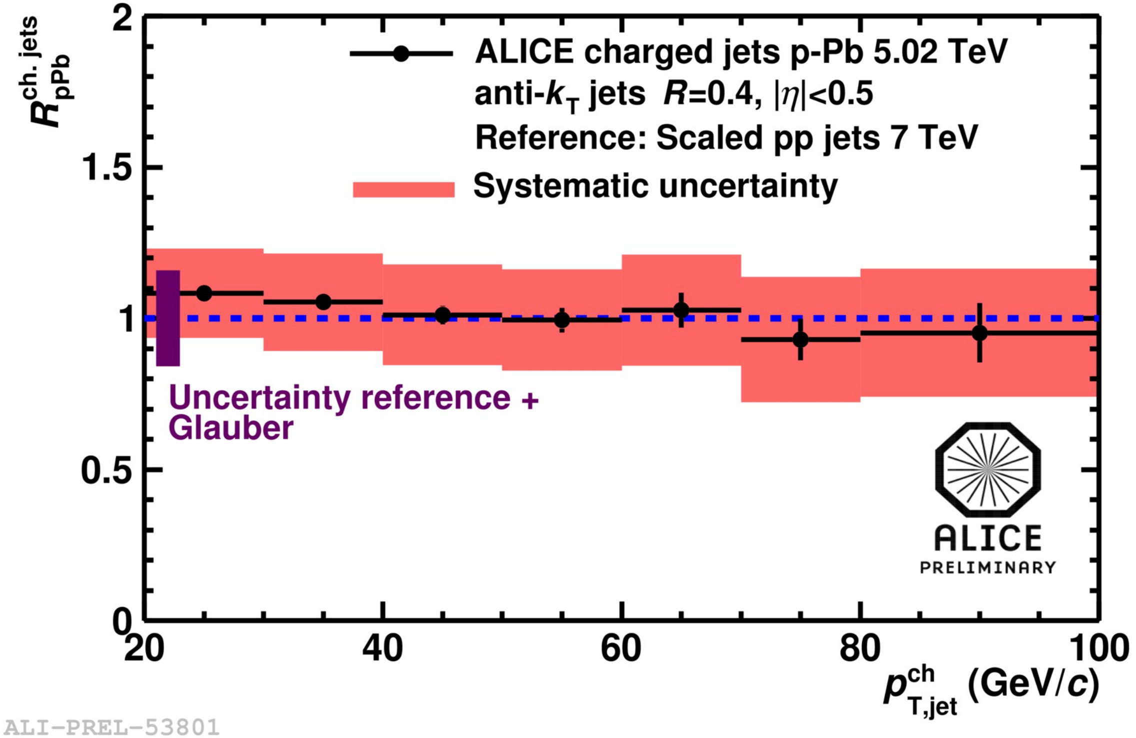
Inclusive Charged Hadrons

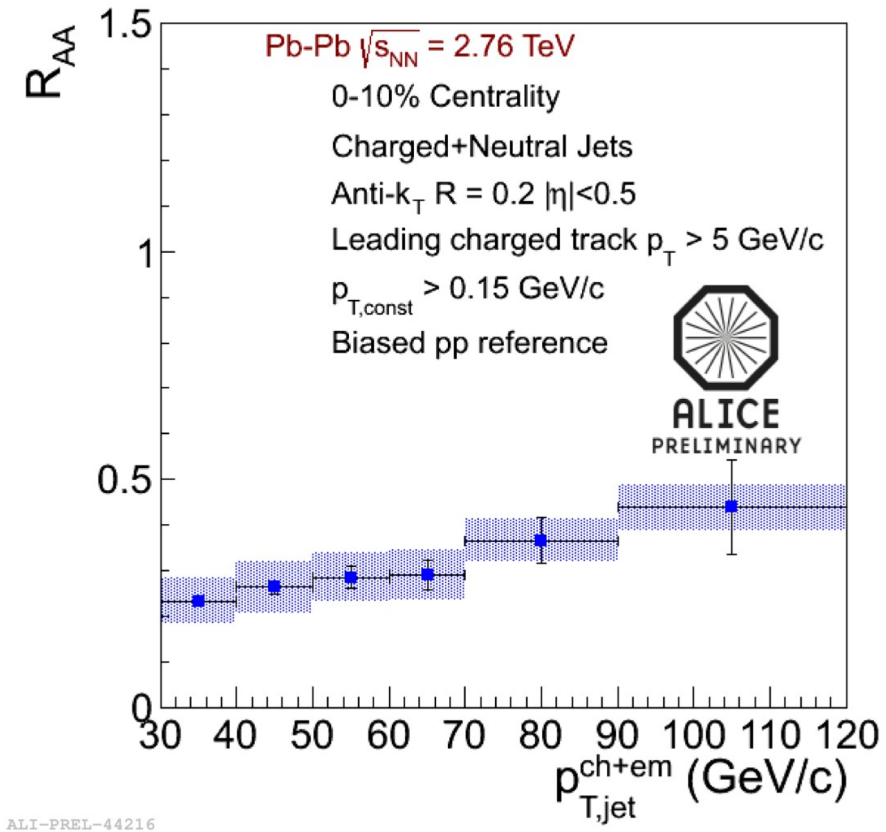
ALICE, **Phys.Rev.Lett. 110 (2013) 082302** arXiv:1210.4520



Suppression at high p_T seen in Pb-Pb is final state effect.

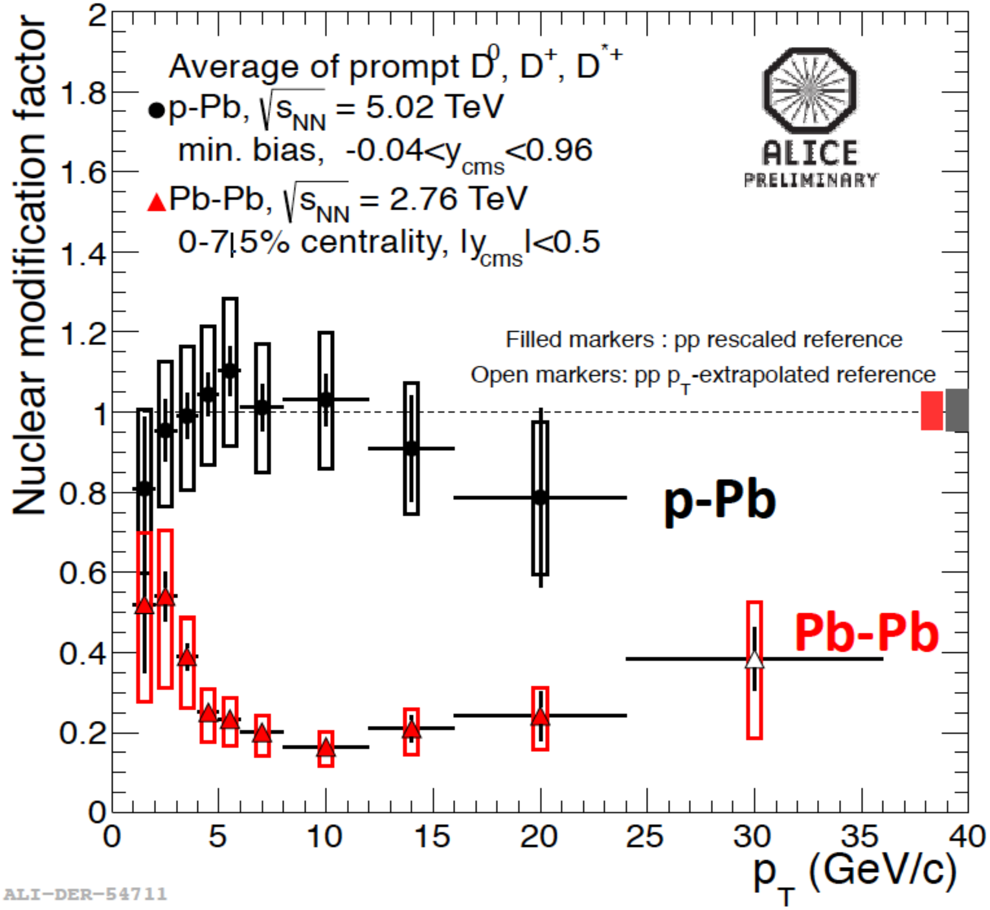
Jets

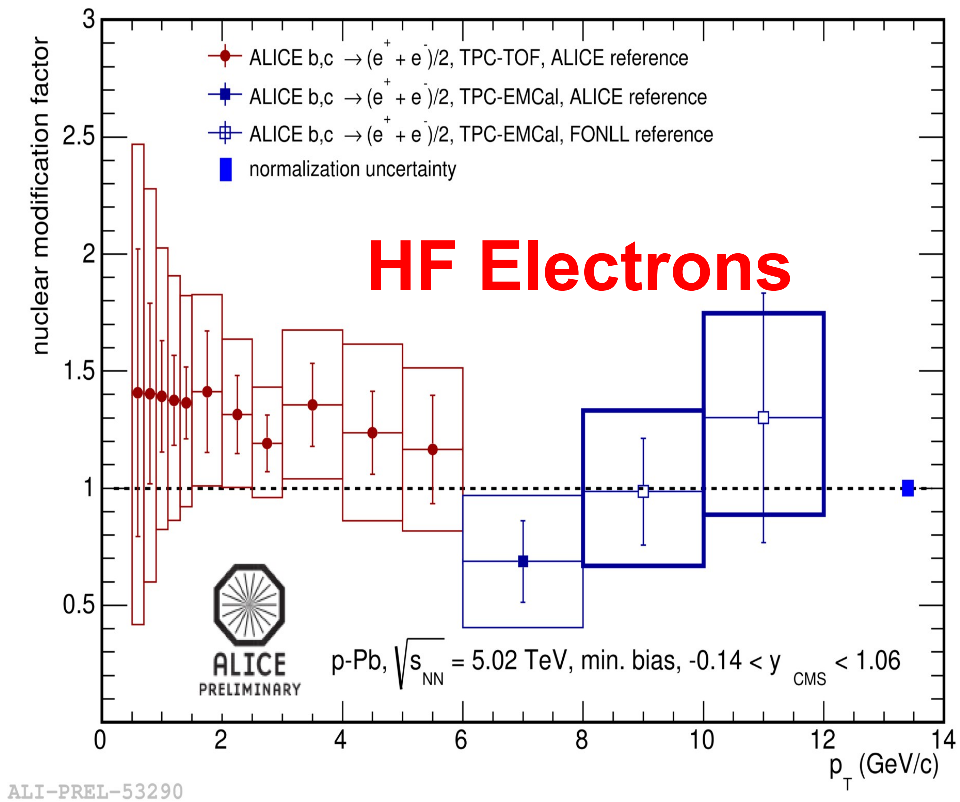




Suppression seen in central Pb-Pb is final state effect.

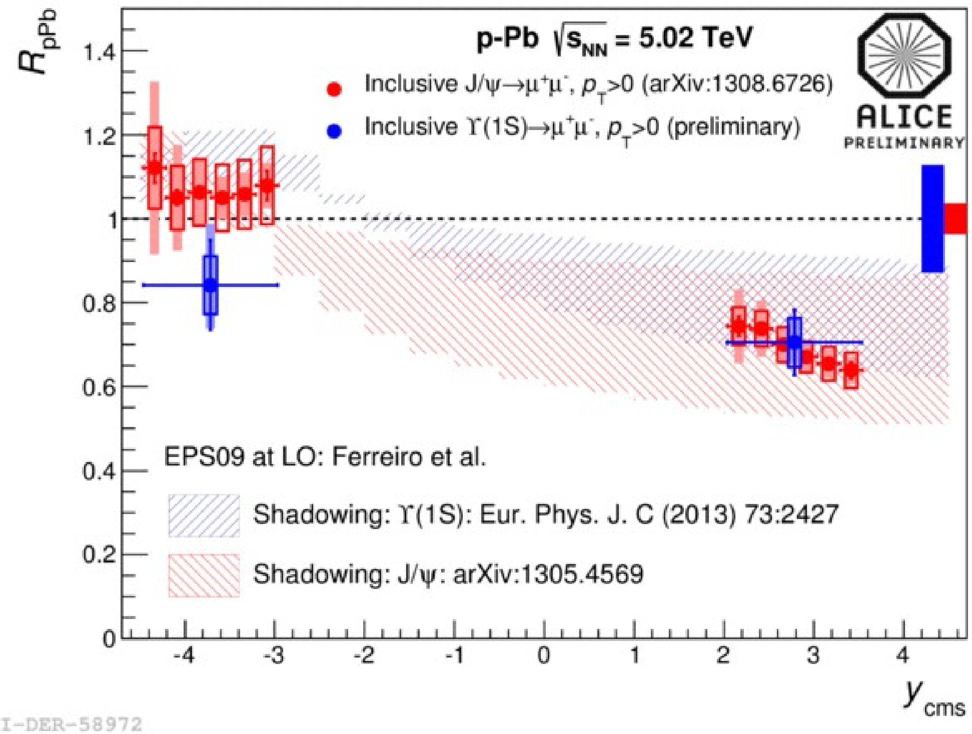
Open Heavy Flavor

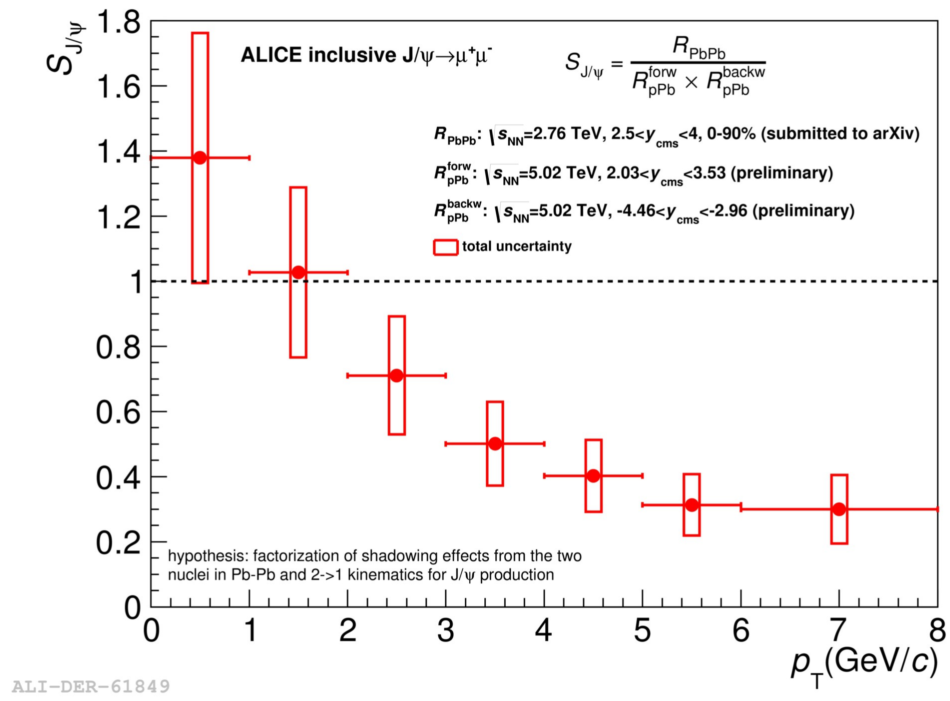




Strong suppression seen in Pb-Pb is final state effect.

Quarkonia

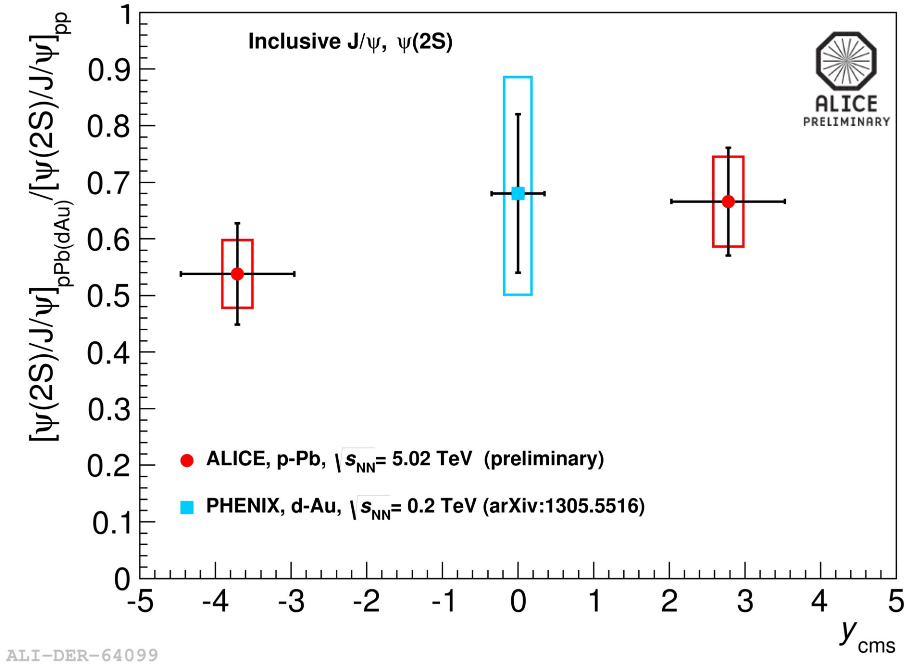




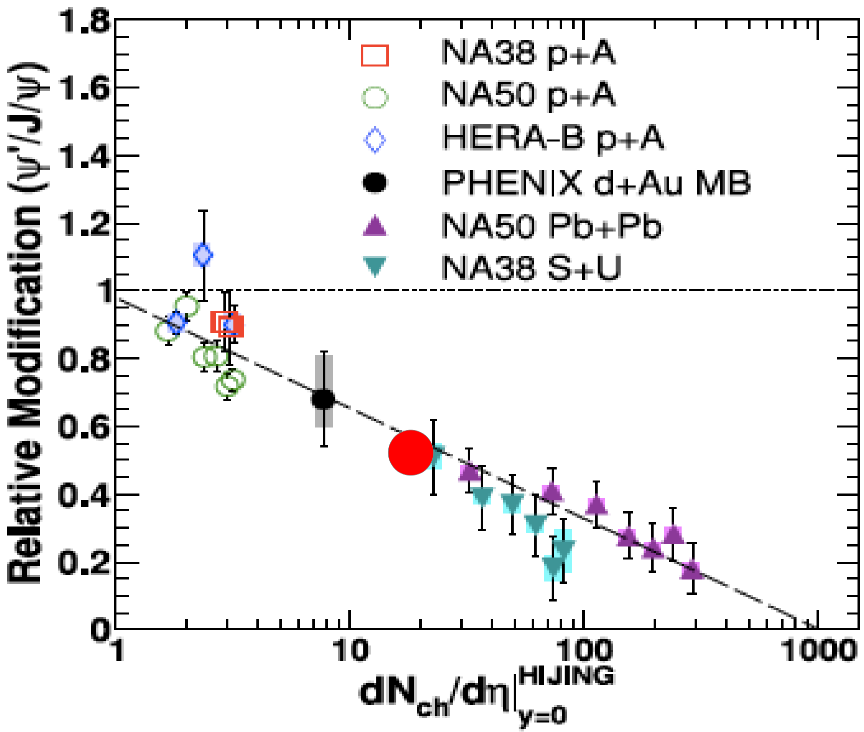
- Shadowing seen in the forward direction
- Direct consequences for suppression seen in Pb-Pb
  - Expected to enhance J/ψ recombination effect at low p_T
- Important to check N_{coll} dependence !

Ψ' same Q^2 but stronger suppression

backward
(highest co-moving density) forward

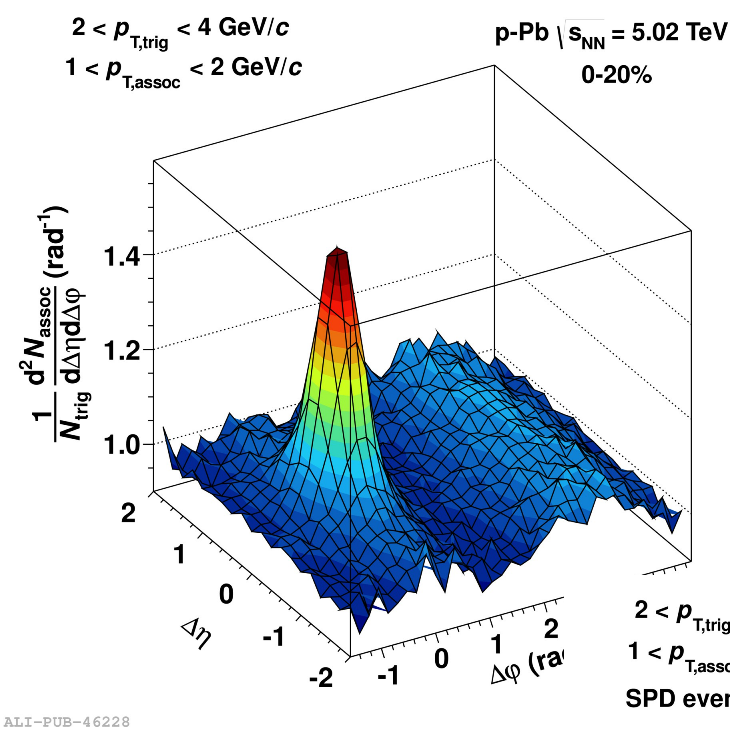


PHENIX arXiv:1305.5515, to be publ PRL



- 20% difference between forward and backward suppression
- Qualitatively consistent with break-up by co-moving medium
  - But also large effect in the forward direction.
- In trend with multiplicity dependence observed p(d)-A and A-A at lower √s
  - Important to check N_{coll} dependence.

Multiplicity dependent studies: Double ridge



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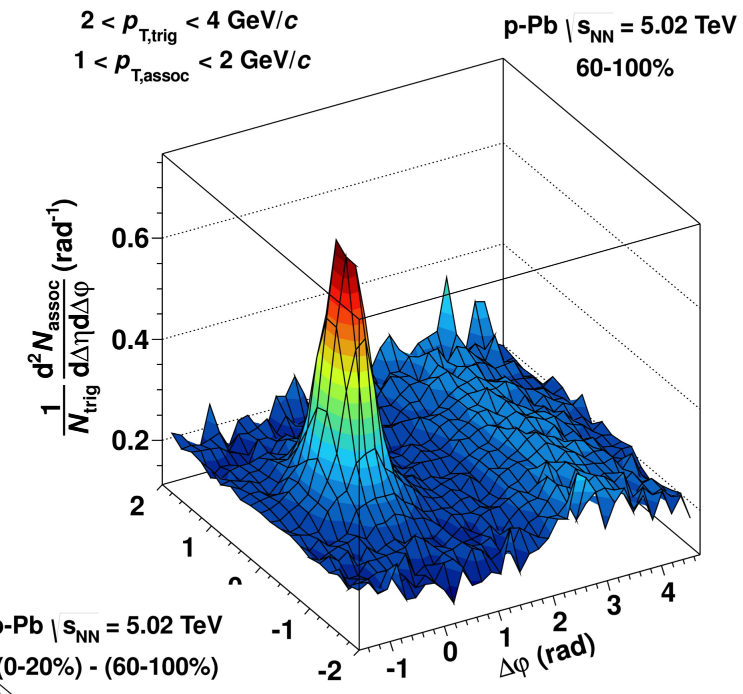

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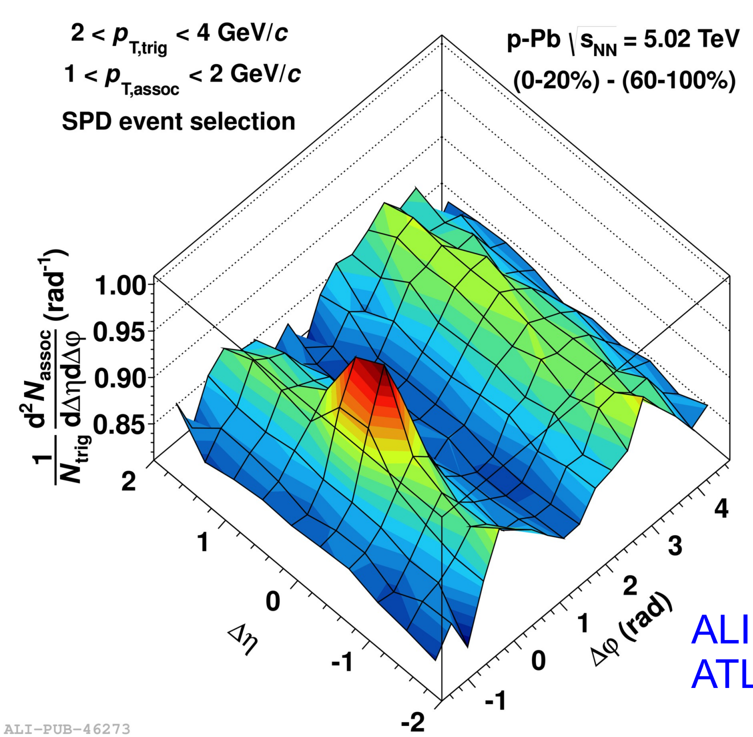
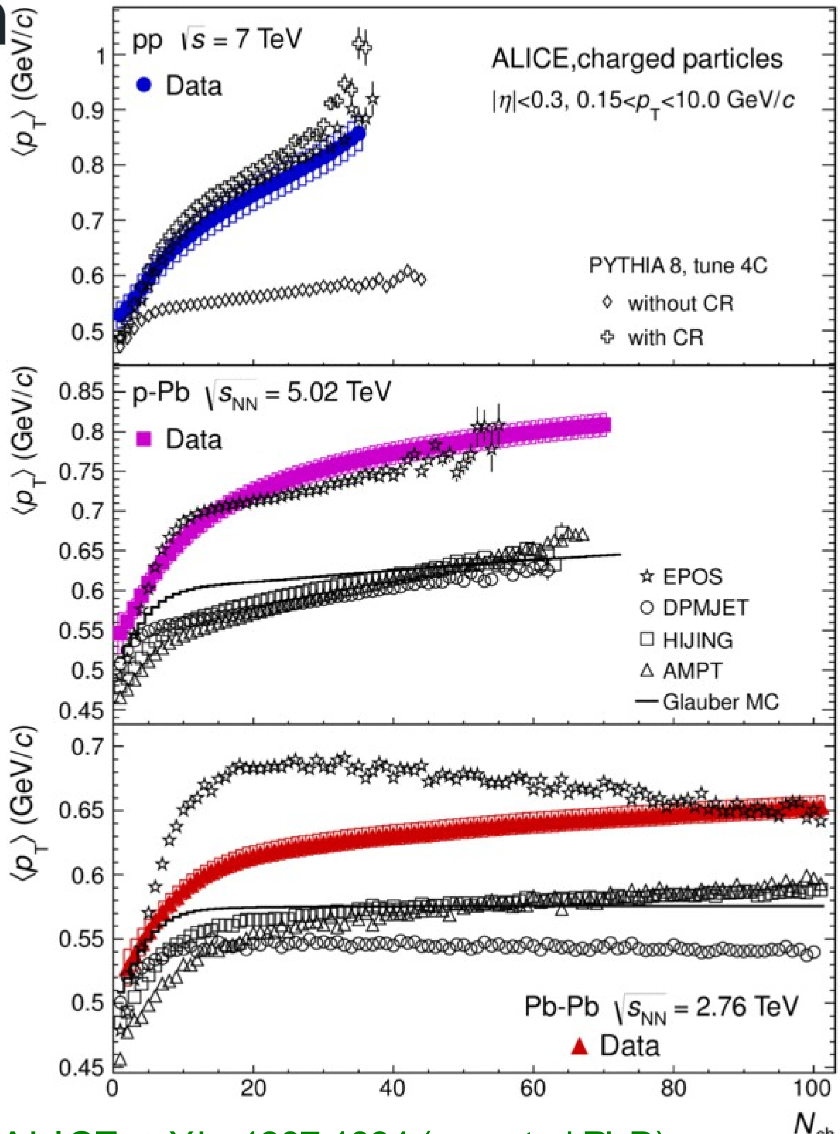


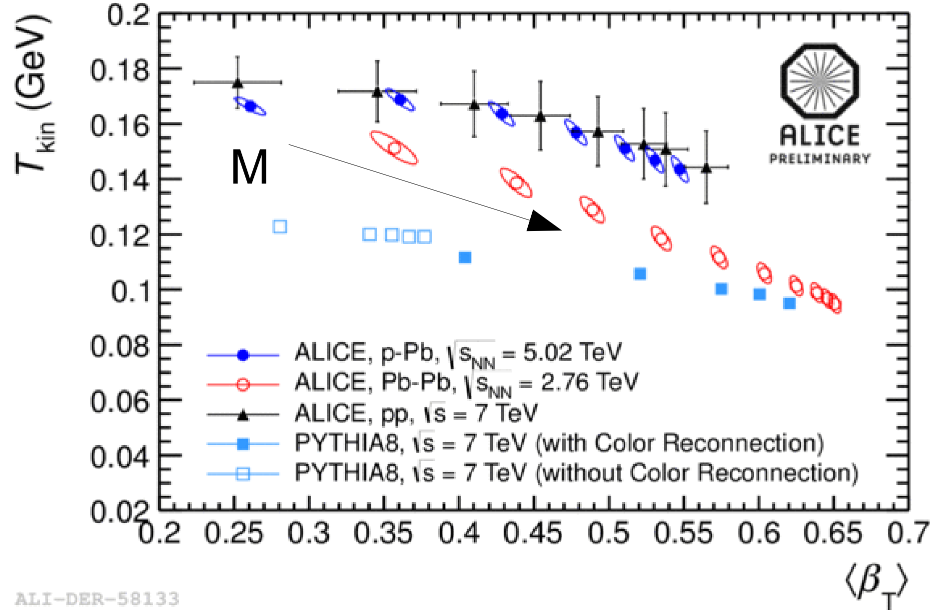
Symmetric
Near-side Away-side ridges !

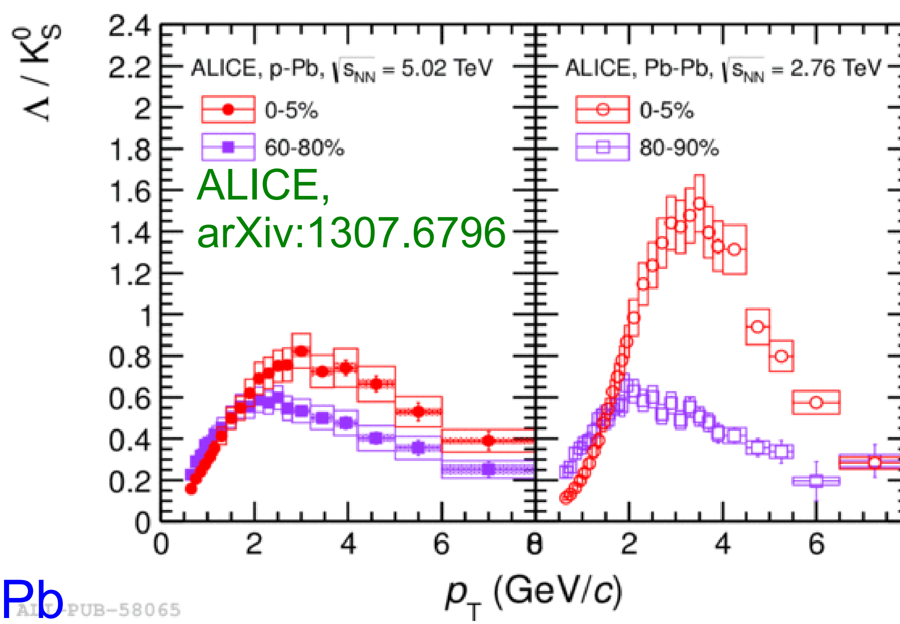
ALICE PLB719 (2013) 29
ATLAS Phys. Rev. Lett. 110, 182302 (2013)

Multiplicity dependent studies



ALICE, arXiv:1307.1094 (accepted PLB)



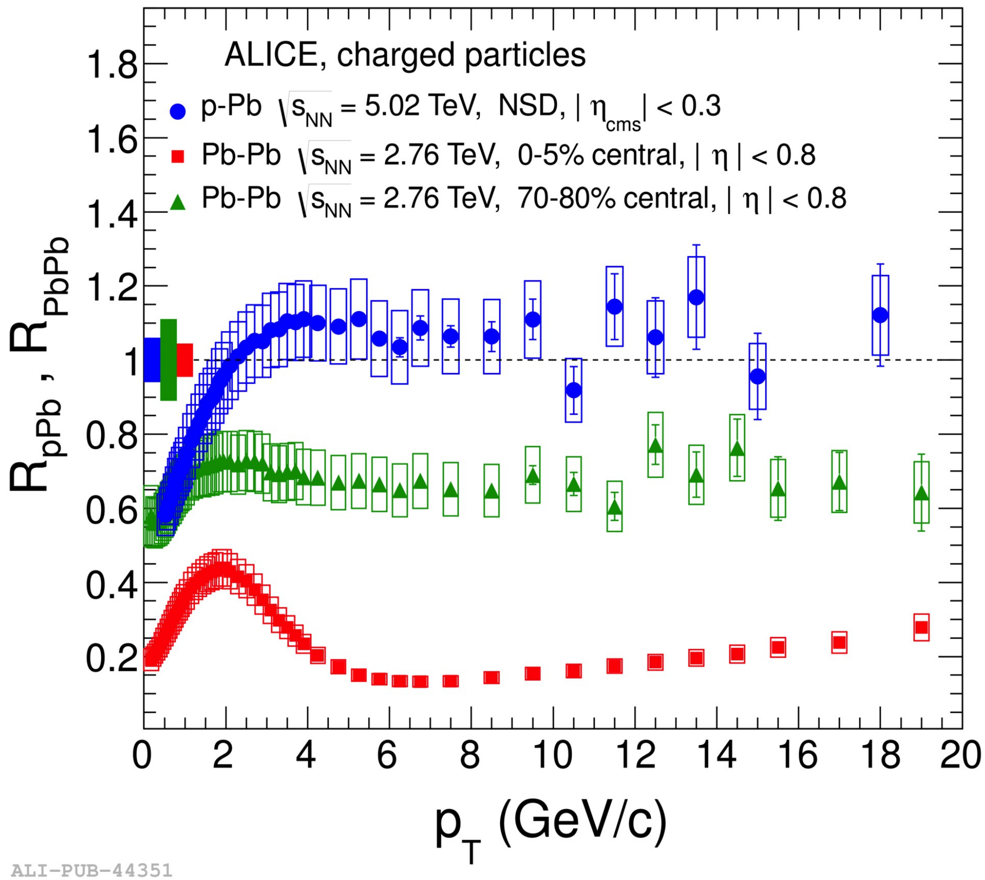


Indication collective flow in high multiplicity p-Pb
or Color reconnections = coherent effects between strings = some form of collectivity

How to obtain multiplicity dependent R_{pA} ?

Nuclear Modification Factor for p-Pb

ALICE, **Phys.Rev.Lett. 110 (2013) 082302** arXiv:1210.4520



Minimum Bias:

$$R_{pA}^{MB}(p_T) = \frac{dN^{pA}/dp_T}{\langle T_{pA}\rangle d\sigma^{pp}/dp_T} = \frac{dN^{pA}/dp_T}{\langle N_{coll}\rangle dN^{pp}/dp_T}$$

Average p-Pb overlap function <T_{pA}> determined by total (geometric) p-A cross-section:

$$\langle N_{coll}\rangle = 208\,\sigma_{pN}/\sigma_{pA} = 6.9 \text{ with}$$

$$\sigma_{pN} = 70\text{ mb}$$

$$\sigma_{pPb} = 2100\text{ mb}$$

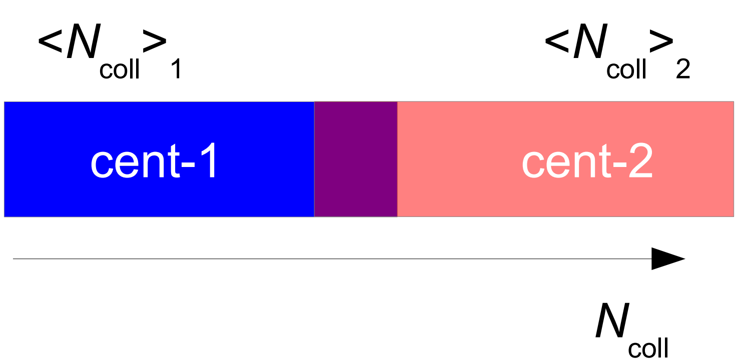
$$\langle T_{pPb}\rangle = \langle N_{coll}\rangle/\sigma_{pN} = 208/2100\text{ mb}^{-1} = 0.098\text{ mb}^{-1}$$

How can we make this measurement centrality/multiplicity dependent ?

$$R_{pA}^{cent}(p_T) = \frac{dN^{pA}/dp_T}{\langle T_{pA}^{cent}\rangle d\sigma^{pp}/dp_T} = \frac{dN^{pA}/dp_T}{\langle N_{coll}^{cent}\rangle dN^{pp}/dp_T}$$

$\langle N_{coll} \rangle$ for centrality classes

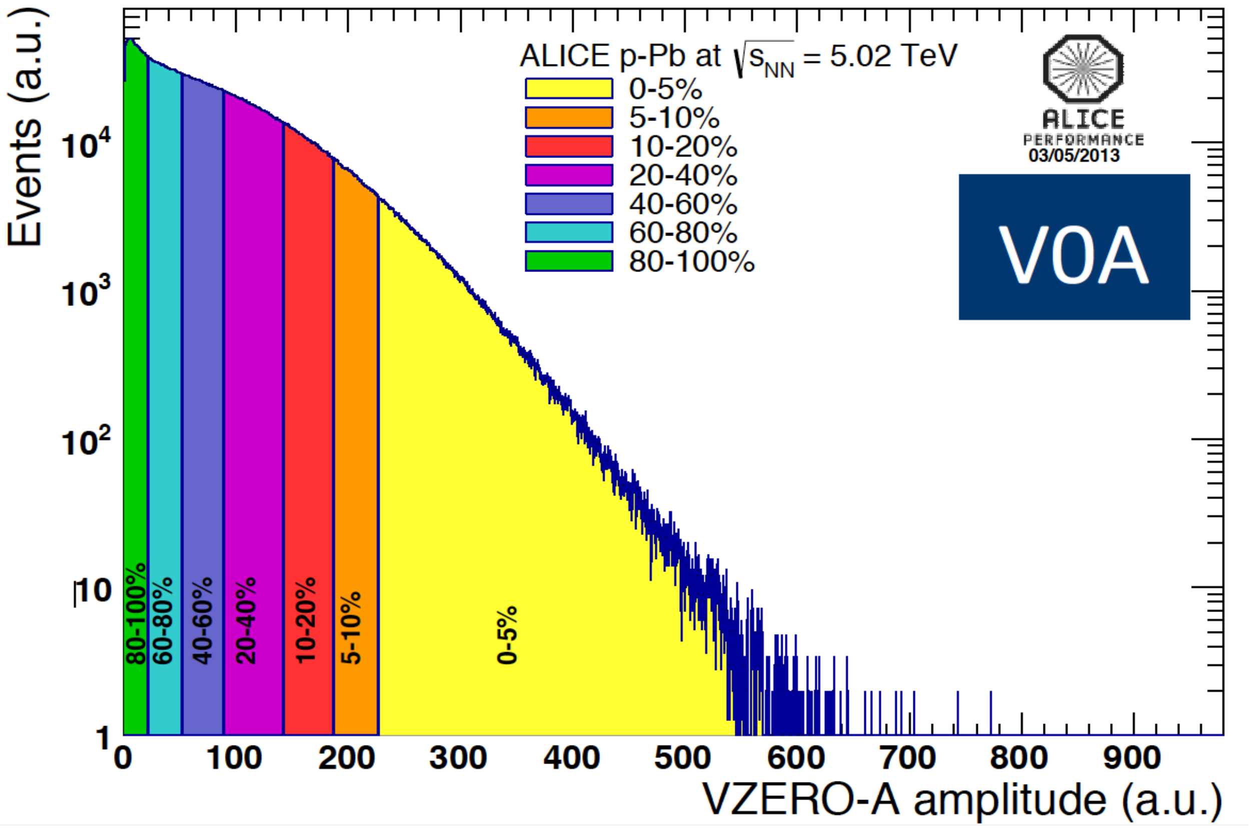
- Centrality event classes defined using centrality estimators
  - Particle multiplicity or summed energy in given pseudo-rapidity region
  - Centrality defined as percentiles of the multiplicity distribution
- For each centrality class, two independent questions
  - Q1 How many collisions: N_{part}, N_{coll} ?
    - These are relative small numbers in p-Pb
    - Fluctuations are important.
  - Q2 How unbiased are the nucleon-nucleon collisions ?



What distinguishes cent-1 from cent-2 for the same N_{coll} ?
Is it relevant for other physics observables ?

Let's start with Q1 ...

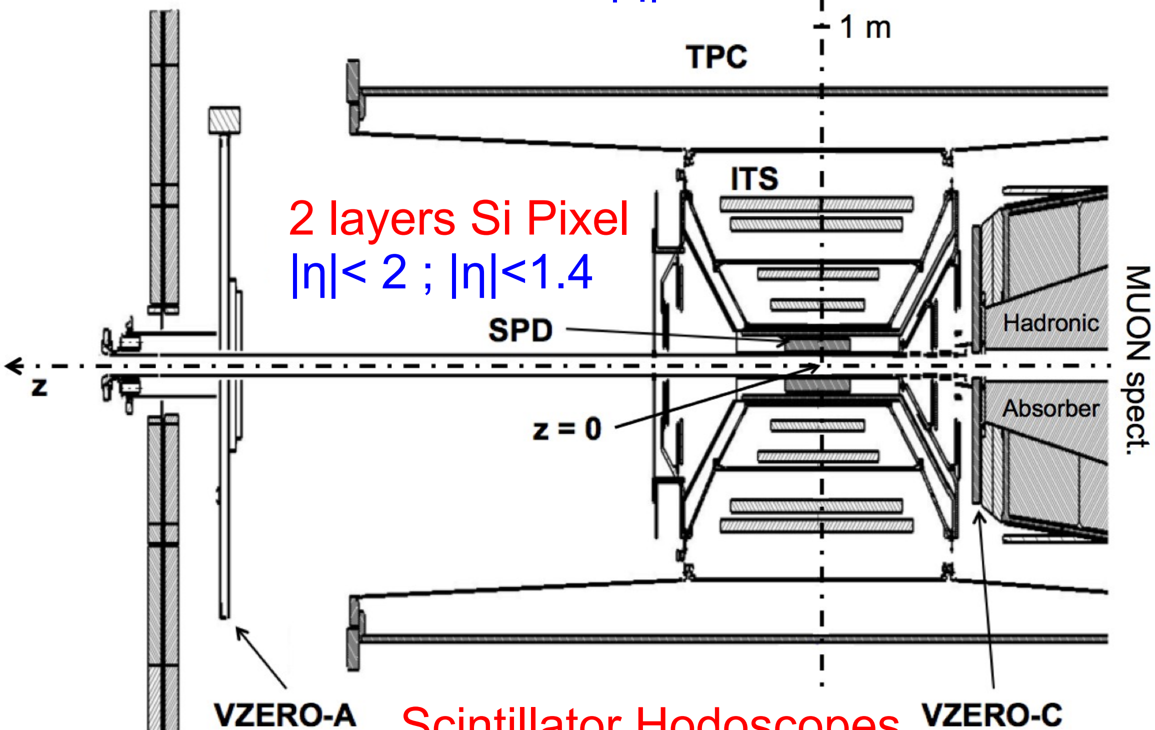
Percentiles example



Detectors for Centrality Estimation

p → ← Pb

TPC+ITS
Tracks |η| < 0.9



2 layers Si Pixel
|η|< 2 ; |η|<1.4

Scintillator Hodoscopes

z = 340 cm
2.8 < η < 5.1

z = -90 cm
-3.7 < η < -1.7

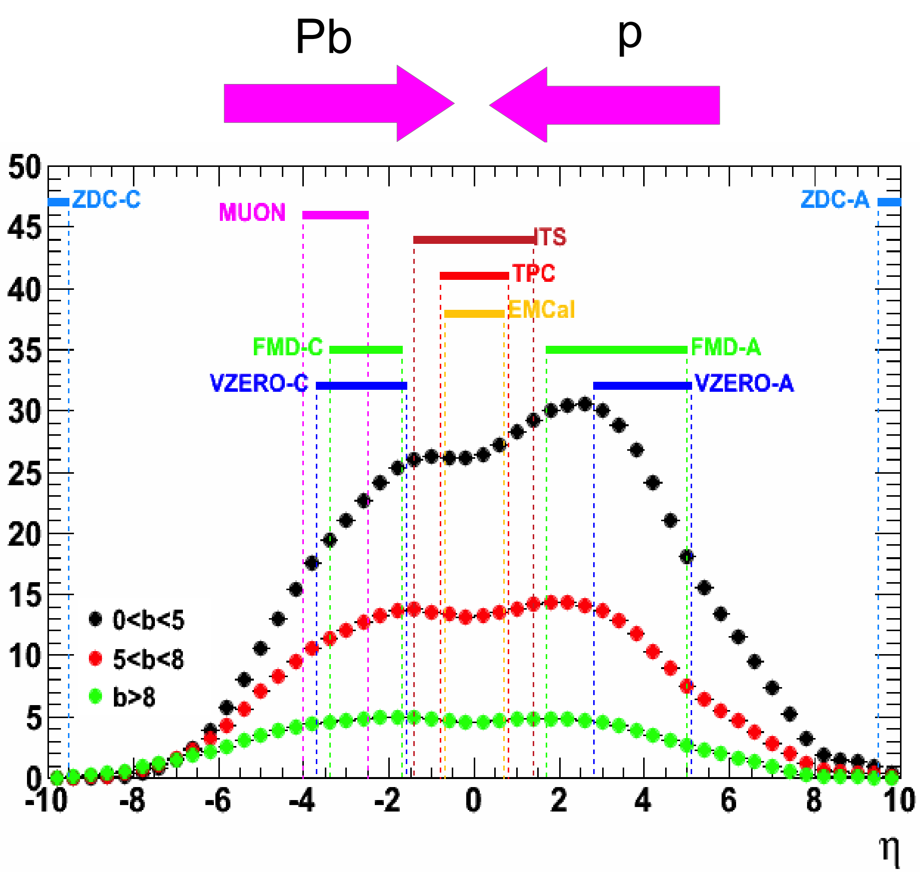
Quartz-Fiber "Spaghetti"
Zero Degree Calorimeters

z = ·± 112.5 m

Centrality Estimators discussed here:

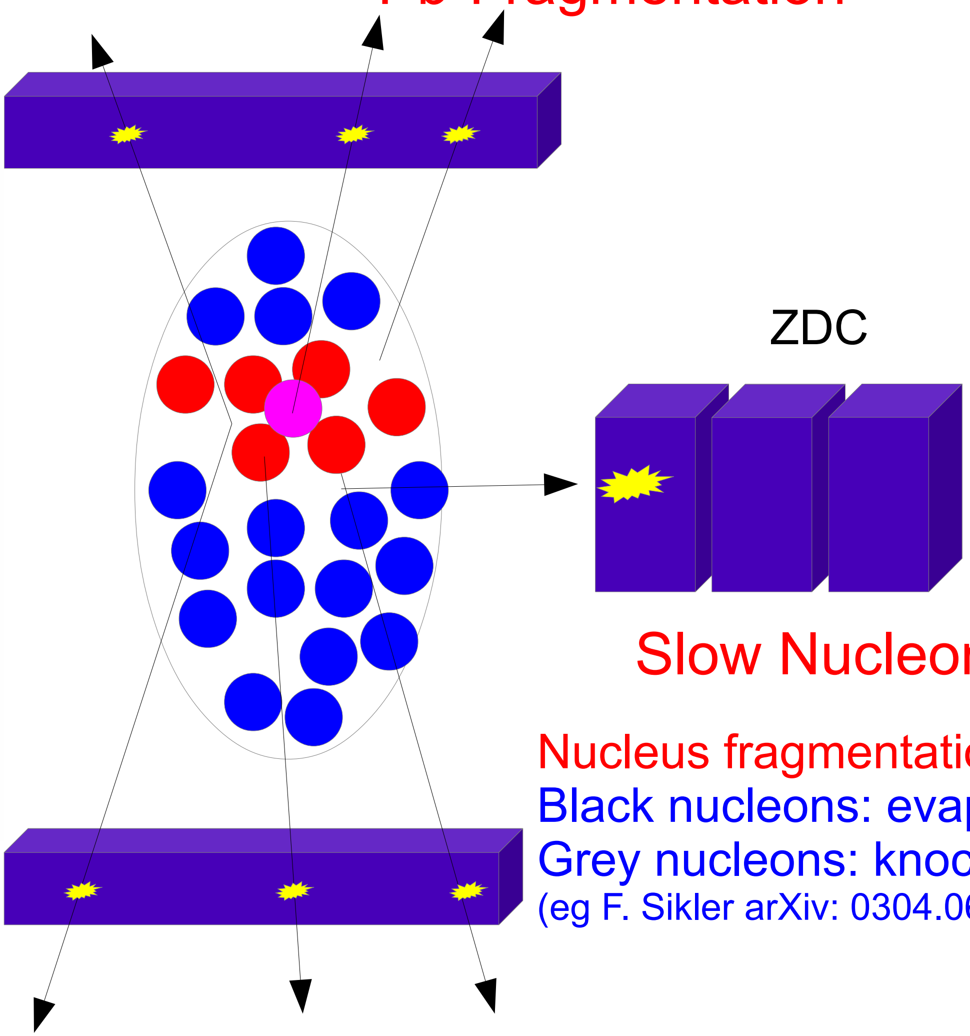
CL1:	Clusters in 2nd Pixel Layer
V0A:	V0A Multiplicity
V0M:	V0A+V0C Multiplicity
ZNA:	ZNA Energy

Estimators sensitive to ..



Binary p-N collisions

$$N_{coll} = N_{part} - 1$$



Slow Nucleons

Nucleus fragmentation model:
Black nucleons: evaporation
Grey nucleons: knock-out
(eg F. Sikler arXiv: 0304.065)

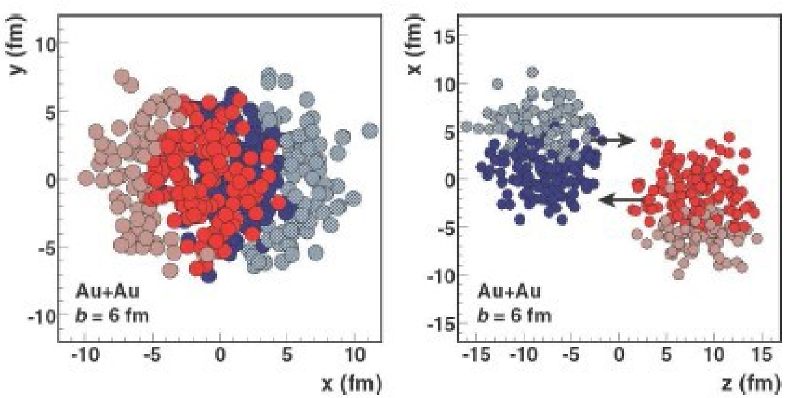
Particle production modeled by Negative Binomial Distribution (NBD)

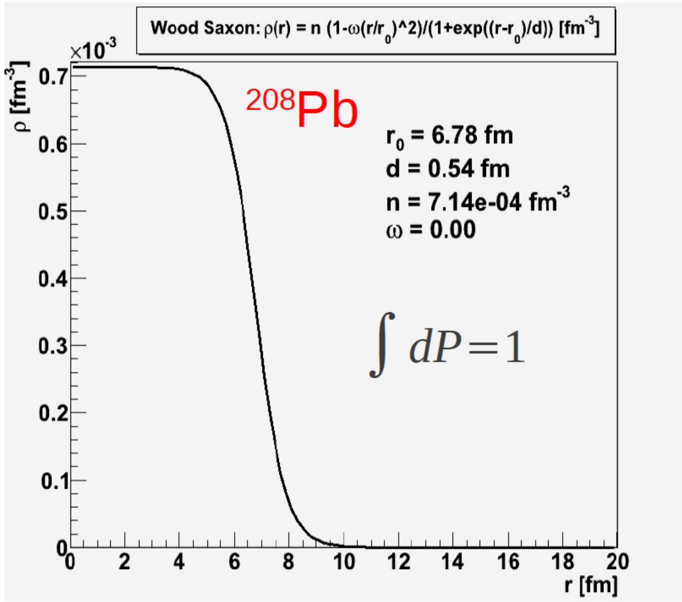
Excursion: N_{coll} from Glauber Monte Carlo

- The two colliding nuclei are represented by randomly distributing the A nucleons of nucleus A and the B nucleons from nucleus B in three spatial dimensions according to the respective density functions (Wood-Saxon)
  - a minimum distance between nucleons can be imposed
- A random impact parameter is drawn from dσ/db = 2π b
- A nucleus-nucleus collision is treated as a sequence of independent binary nucleon-nucleon collisions
  - nucleons travel in straight lines
  - collision takes place if the distance d

$$d \leq \sqrt{\frac{\sigma_{inel}^{NN}}{\pi}}$$

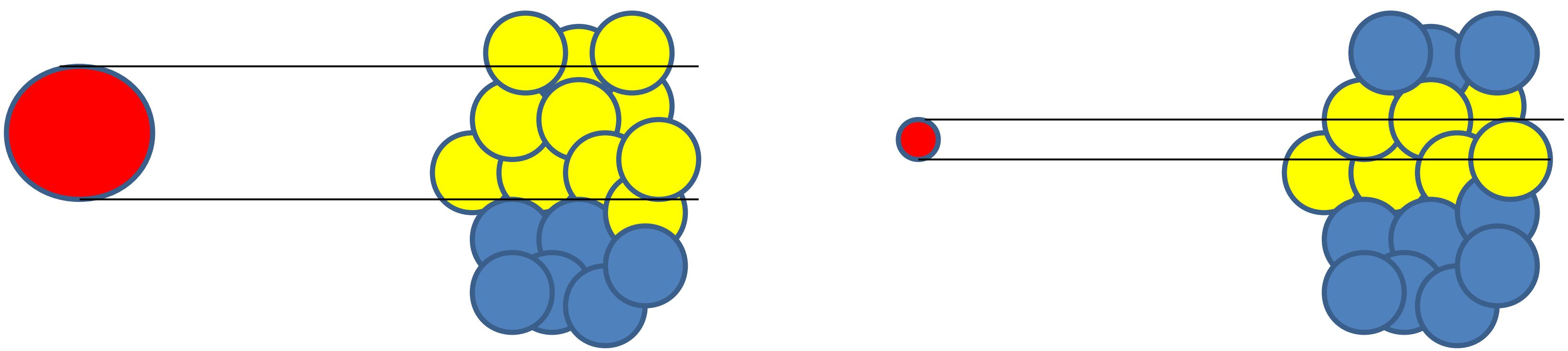
$$dP = 4\pi r^2 \rho(r)\, dr$$





Possible extensions of the “black-disc” MC

- Smear p-N impact parameter according with exp. distribution to take into account matter distribution inside p (ALICE)
- p-Eikonal (HIJING, Pythia, ALICE)
  - interaction probability depends on p-N overlap
- Glauber-Gribov (ATLAS, CONF-2013-96)
  - fluctuating p-N cross-section (fluctuating proton configurations)



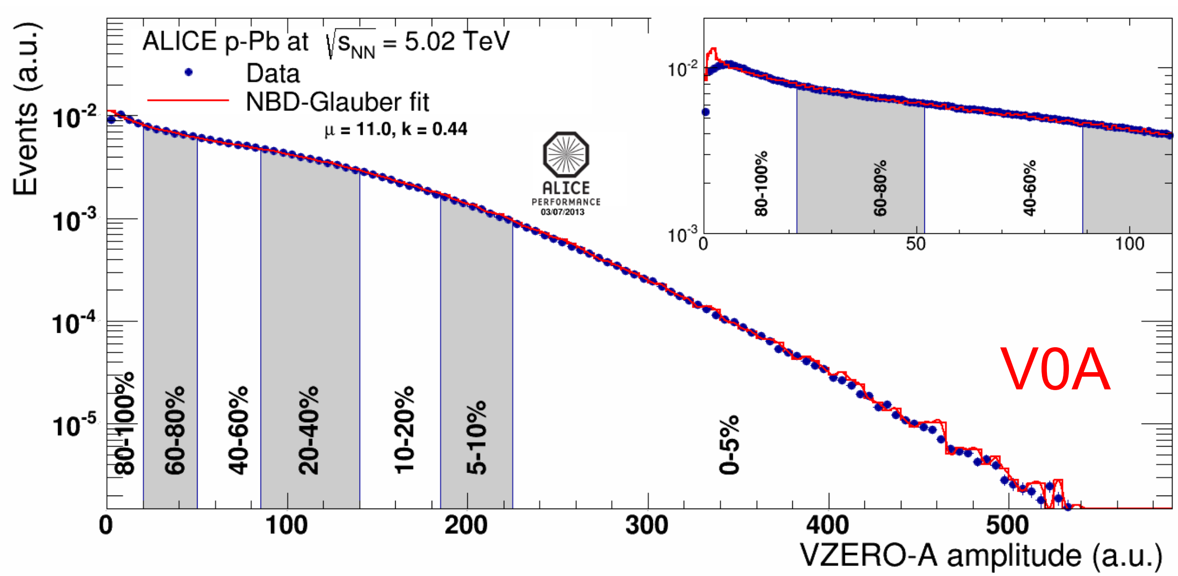
Unclear how to relate N_{coll} to fluctuations for the hard cross-section at high Q^2 and low x

Glauber Fit with NBD in p-Pb

- Same procedure as for Pb-Pb (ALICE, arXiv:1301.4361)
- Centrality classes: Multiplicity distribution sliced into percentiles of cross-section
  - Starting with the highest multiplicity = most central collisions
- Obtain $P(N_{part})$ from Glauber Monte Carlo
  - N_{part} is equal to number of ancestors

$$N_{coll} = N_{part} - 1$$

- For each ancestor obtain multiplicity form Negative Binomial Distribution (NBD) and iterated to fit NBD parameters
- Obtain $\langle N_{coll} \rangle$ from MC for each centrality class



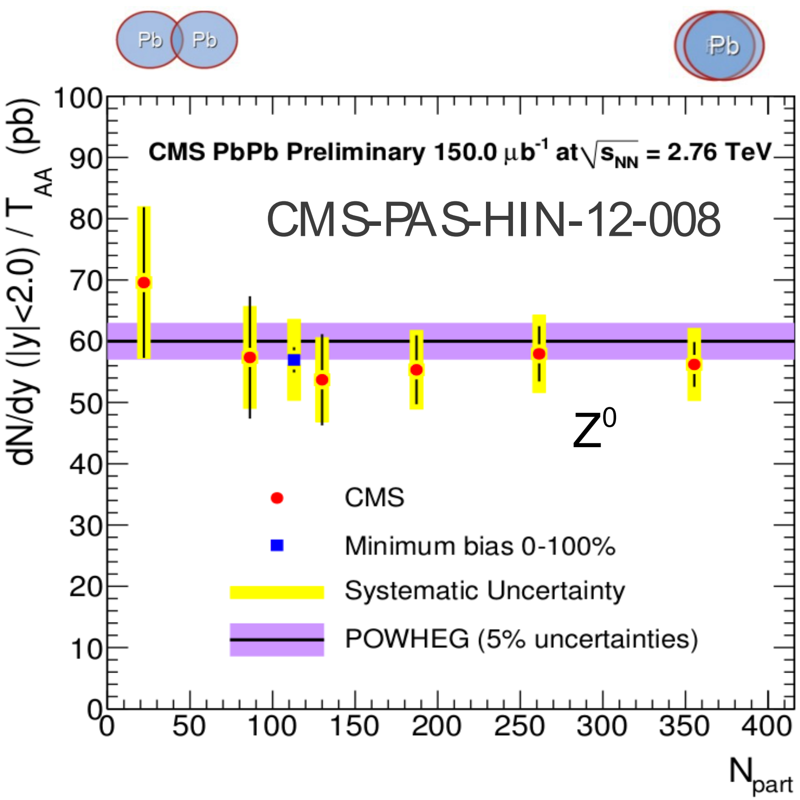
Negative Binomial Distribution:

$$f(n;k,p) = \binom{n+k-1}{n} (1-p)^k p^n$$

$$\text{Mean}: \mu = \frac{pk}{1-p}$$

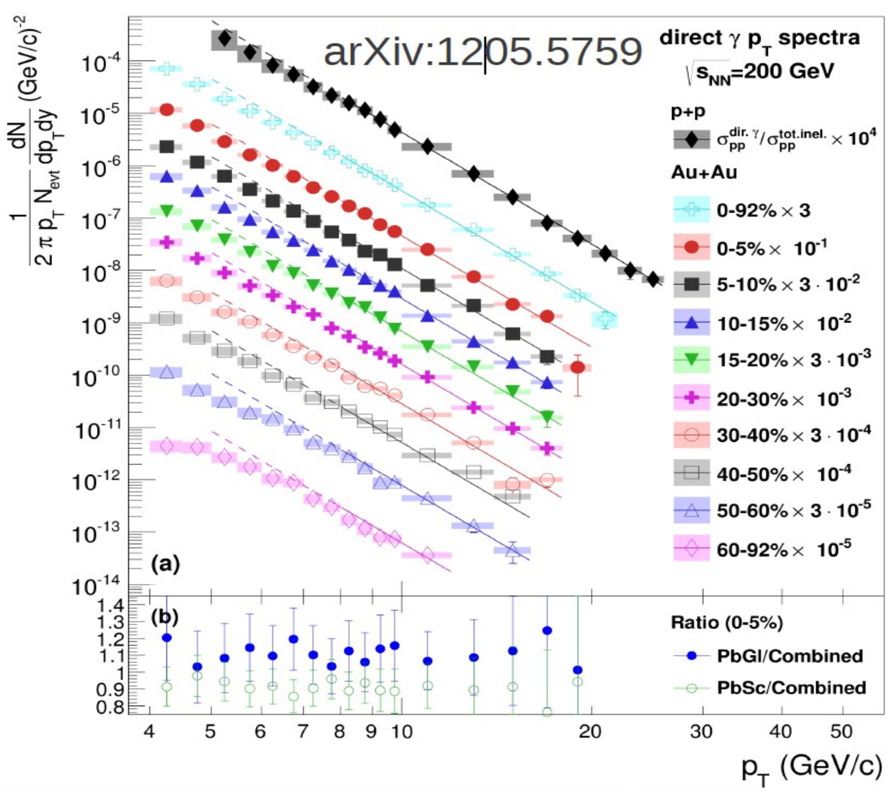
$$\text{Variance}: \sigma^2 = \mu + \frac{\mu^2}{k}$$

Binary Scaling in A-A



direct gamma

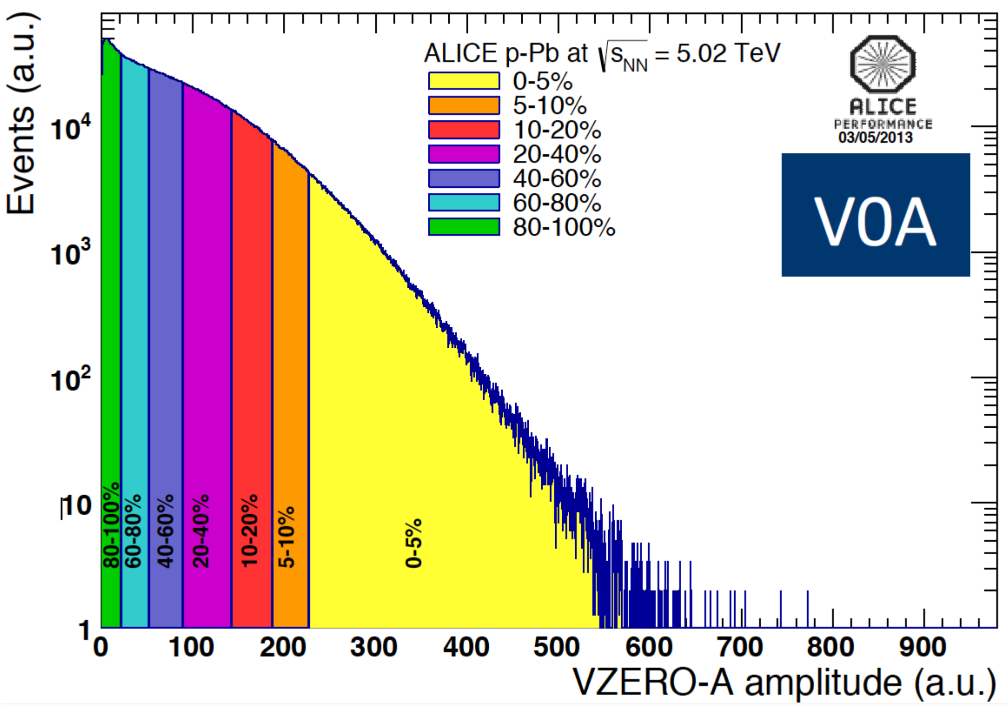
PHENIX



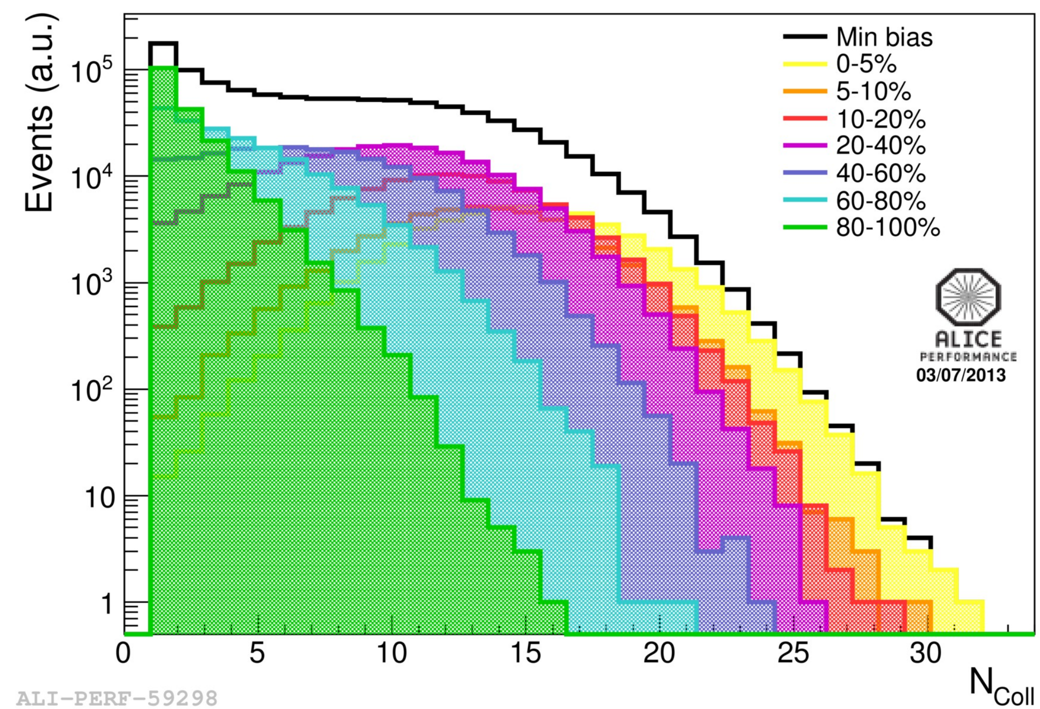
Comparison to binary scaled pp pQCD prediction.

N_{coll} from V0A

Slicing (percentiles)



Correspondence in Glauber MC



N_{coll} fluctuations within the same class are large !

Glauber Fit Results

Glauber MC Parameters

$$\rho(r)=\rho_0 \frac{1}{1+\exp\left(\frac{r-R}{a}\right)}$$

R = 6.62 ± 0.06 fm

a = 0.546 ± 0.01fm

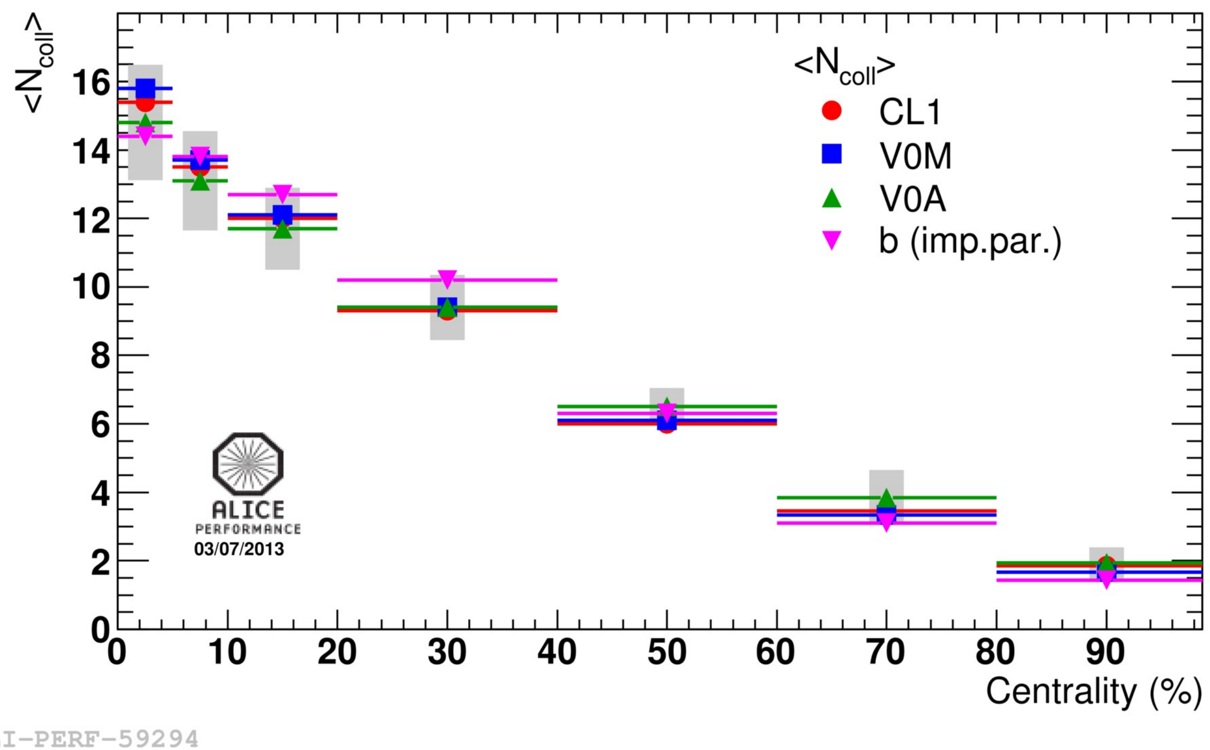
Minimum NN distance:
0.4±0.4 fm

pN Cross-section

σ_{pN} = 70 ± 5 mb

Proton radius

R_p = 0.6 ± 0.2 fm



- N_{coll} similar for different estimators

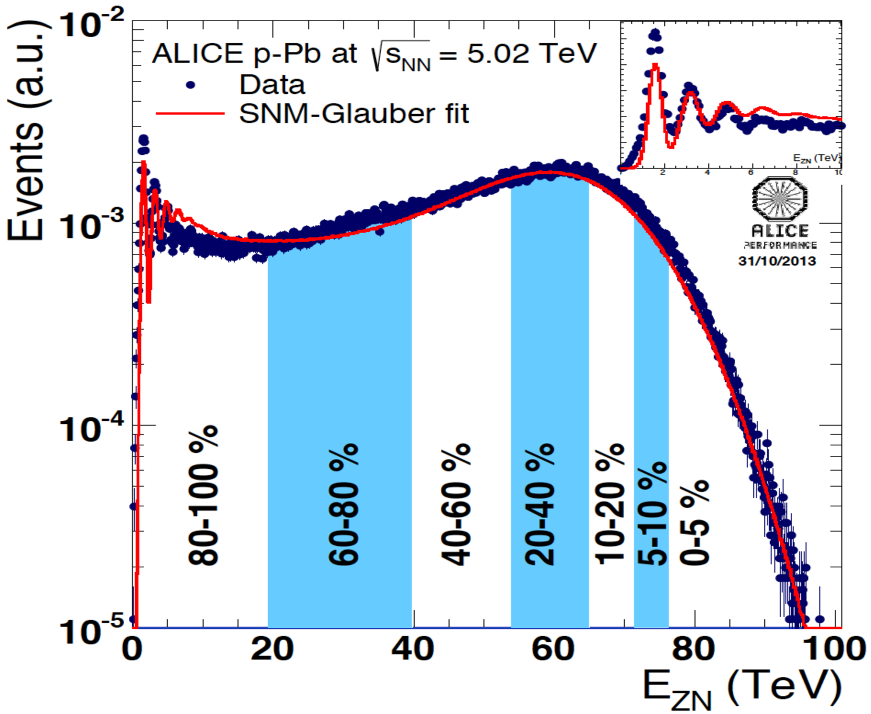
- Similar to MC closure and Glauber MC systematic error.

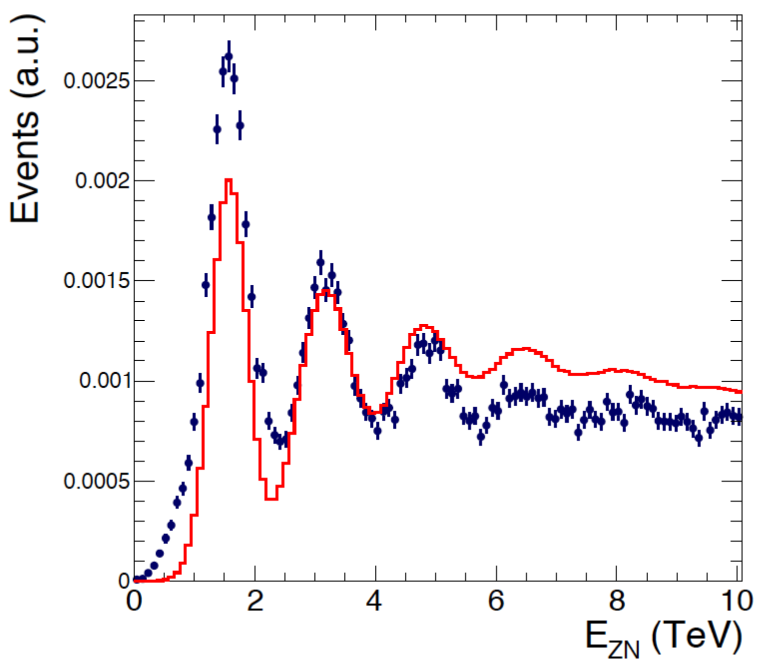
- Systematic error estimated by varying Glauber MC parameters.
- MC closure test performed with HIJING.

Glauber Fit for Slow Nucleons

- Same procedure, however, particle production coupled to to model for slow nucleon emission.
  - Properties of emitted nucleons expected to only weakly depend on energy.
  - Phenomenological model based on data at low energies
  - Able to reproduce main features of ZNA spectrum

F. Sikler arXiv: 0304.065





Work in progress !

Biases on p-N Collisions ?

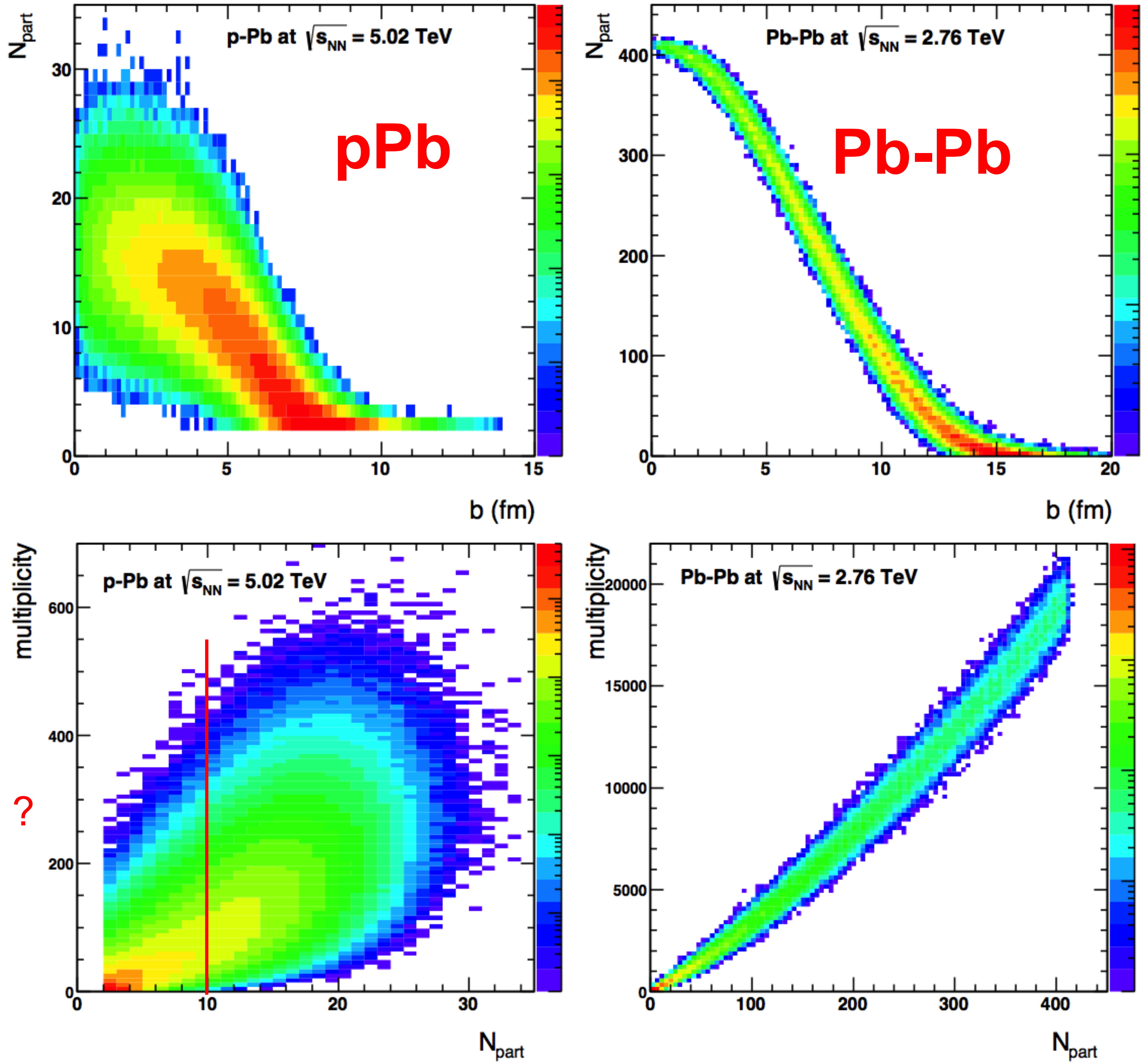
Compared to Pb-Pb

- Looser correlation between N_{part} and impact parameter (b)

- Looser correlation between N_{part} and Multiplicity

What distinguishes cent1 from cent2 for the same N_{coll} ?

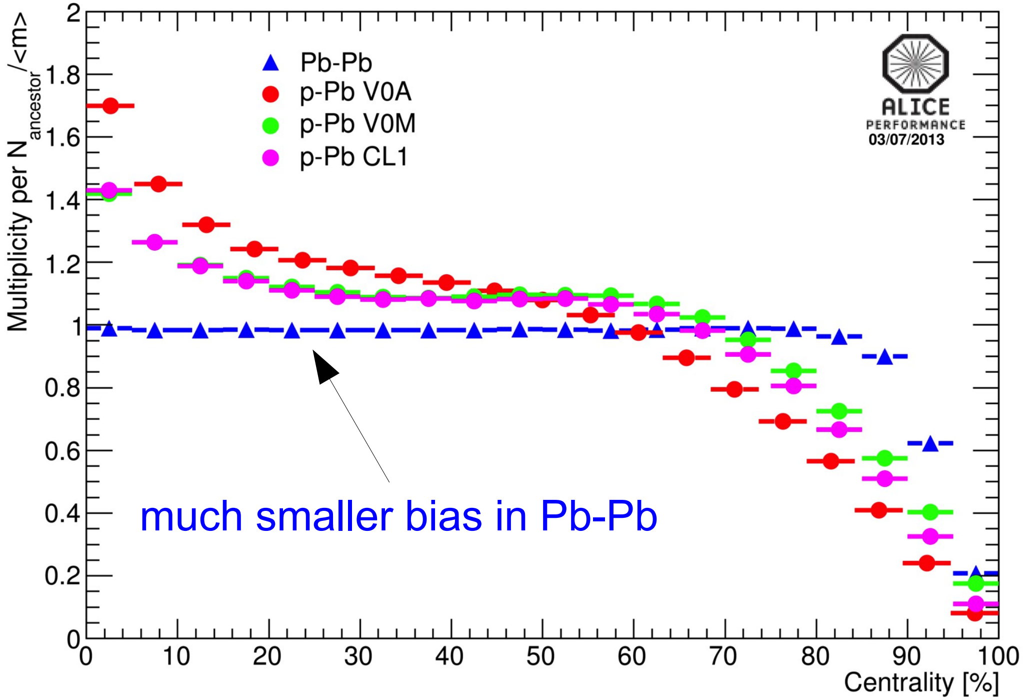
Is it relevant for other physics observables ?



More Information from Glauber MC

Multiplicity / N_{part} strongly biased for peripheral and central collisions.

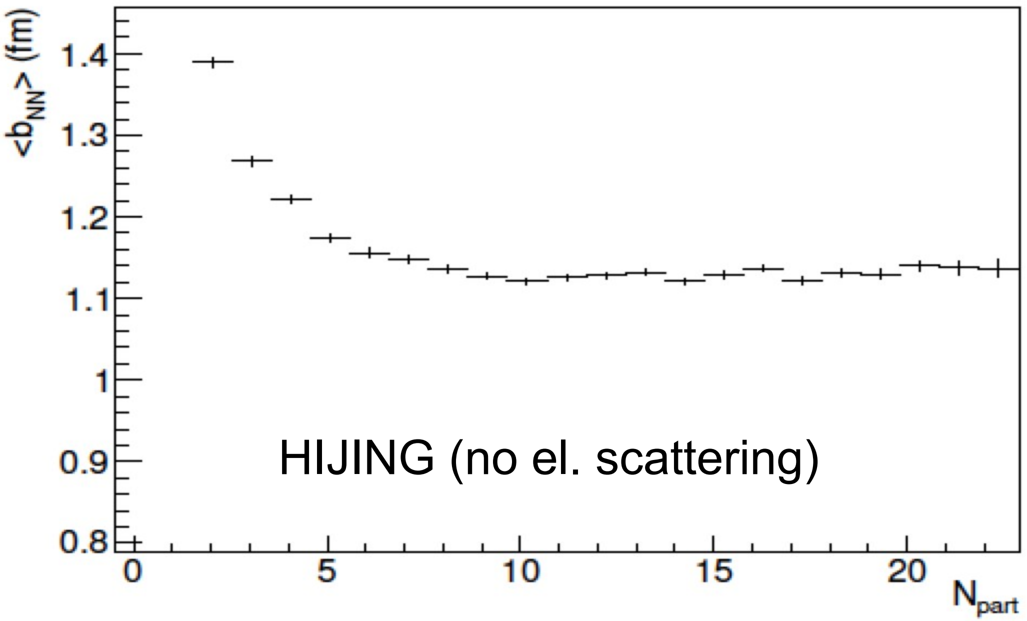
(This is a qualitatively a general result. All systems with fluctuations and dynamical limits will show this.)



Mean p-nucleon impact parameter increases in peripheral collisions.

Also softer than average collisions ?

Is there any dynamic interpretation of these fluctuations ?



Biases and Binary Scaling

- Models based on multi-parton interaction (MPI) include intrinsically a fluctuating number of particles sources (hard scatterings). For example HIJING (X.N. Wang and M. Gyulassy, nucl-th/9502021)

Mean number of scatterings per event obtained from impact parameter b_{NN} dependent proton-nucleon overlap function $T_N(b_{NN})$

$$\langle n_{\mathrm{hard}} \rangle (b_{\mathrm{NN}}) = \sigma_{\mathrm{hard}} T_{\mathrm{N}} (b_{\mathrm{NN}})$$

Poissonian probability for multiple hard interaction

$$p_i(b_{\mathrm{NN}}) = \frac{\langle n_{\mathrm{hard}} \rangle^i}{i!} \exp(-\langle n_{\mathrm{hard}} \rangle)$$

Link between multiplicity fluctuations (bias) and number of hard scatterings !

Qualitatively Two New Elements

$$R_{\mathrm{pA}}(p_{\mathrm{T}}) = \frac{\mathrm{d}N^{\mathrm{pA}}/\mathrm{d}p_{\mathrm{T}}}{\boxed{N_{\mathrm{coll}}^{?}}\,\mathrm{d}N^{\mathrm{pp}}/\mathrm{d}p_{T}}$$

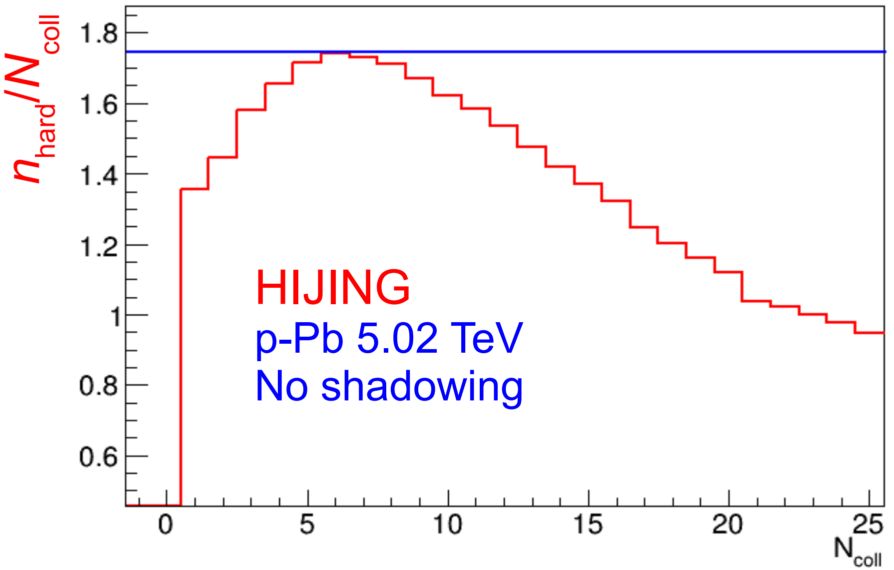
- For a given centrality percentile hard processes scale with

$$N_{\mathrm{coll}}^{\mathrm{Glauber}}\langle n_{\mathrm{hard}}\rangle_{\mathrm{cent}}/\langle n_{\mathrm{hard}}\rangle_{\mathrm{pp}}$$

- For a given p-Pb impact parameter *b*, $\langle n_{\mathrm{hard}}\rangle$ depends on the average pN impact parameter $\langle b_{\mathrm{NN}}\rangle$
  - Mainly important for peripheral collisions
  - Here multiplicity cut acts also as a veto for hard processes.

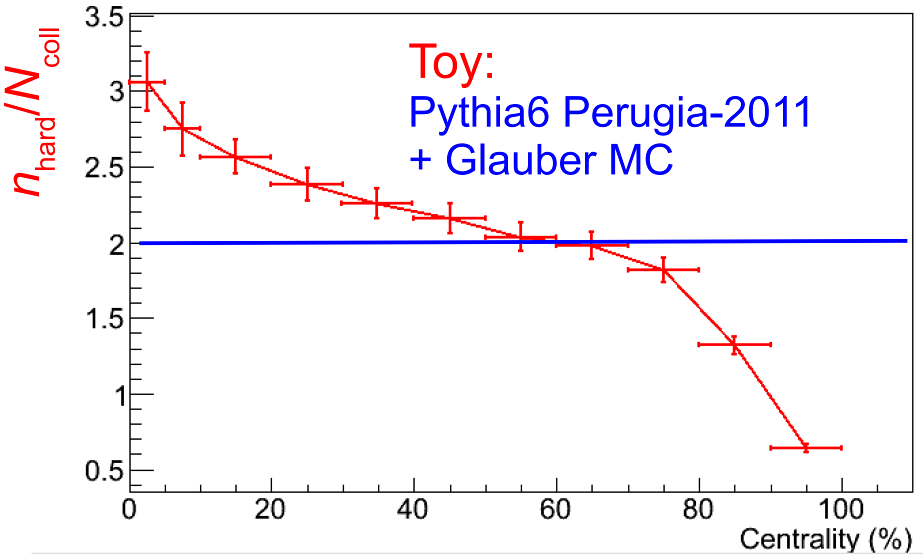
Insights from Monte Carlo

N_{coll} scaling: n_{hard}/N_{coll} = const.



Number of hard scatterings per p-N collision

- vs N_{coll} (no multiplicity bias here !)
- Deviation from N_{coll} scaling
  - at low N_{coll} : geometry b_{NN}
  - at high N_{coll} : energy conservation (break down of factorization)



p-Pb collisions described as incoherent superposition of nucleon-nucleon

- vs centrality from multiplicity $|\eta| < 1.4$
- only multiplicity bias
- strong deviation from N_{coll} -scaling at low and high centralities.

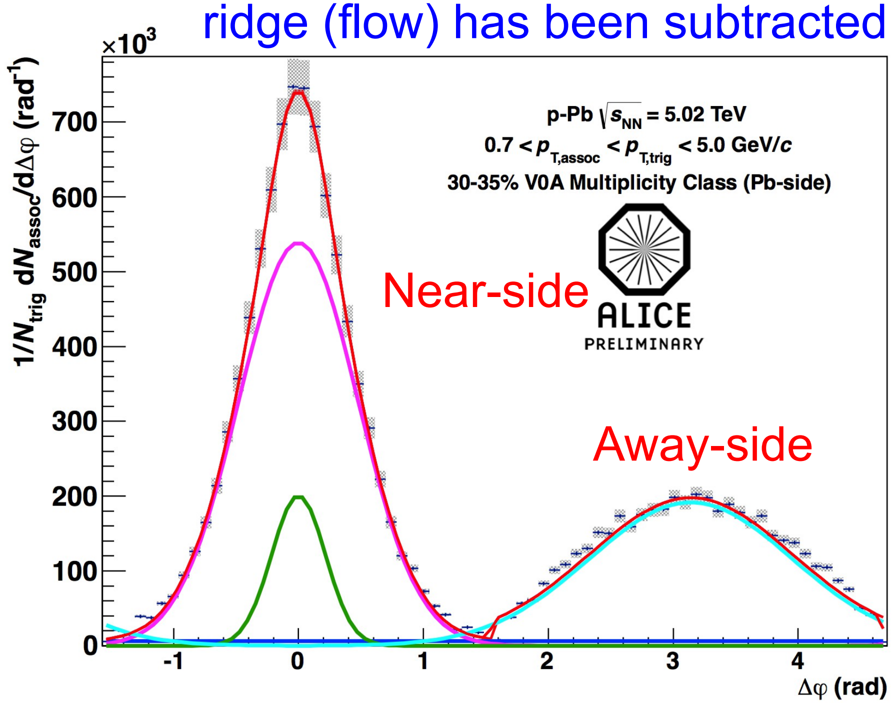
Excursion:
What can data tell about multiple low-p_T scatterings in p-Pb

- Important to get more insight into bulk particle production and hard scatterings in a kinematic region where they overlap (low-p_T)
- Triggered di-hadron angular ($\Delta\varphi$) correlations are an ideal tool to study mini-jets.
  - separates overlapping particle sources on a statistical basis
  - sensitivity to fragmentation properties and number of particle sources

ridge (flow) has been subtracted

Chose p_T cuts large enough to be insensitive to string breaking ($> \Lambda_{QCD}$) and low enough to be able to get information about particle production where multiple parton interactions are important.

$p_T > 0.7$ GeV

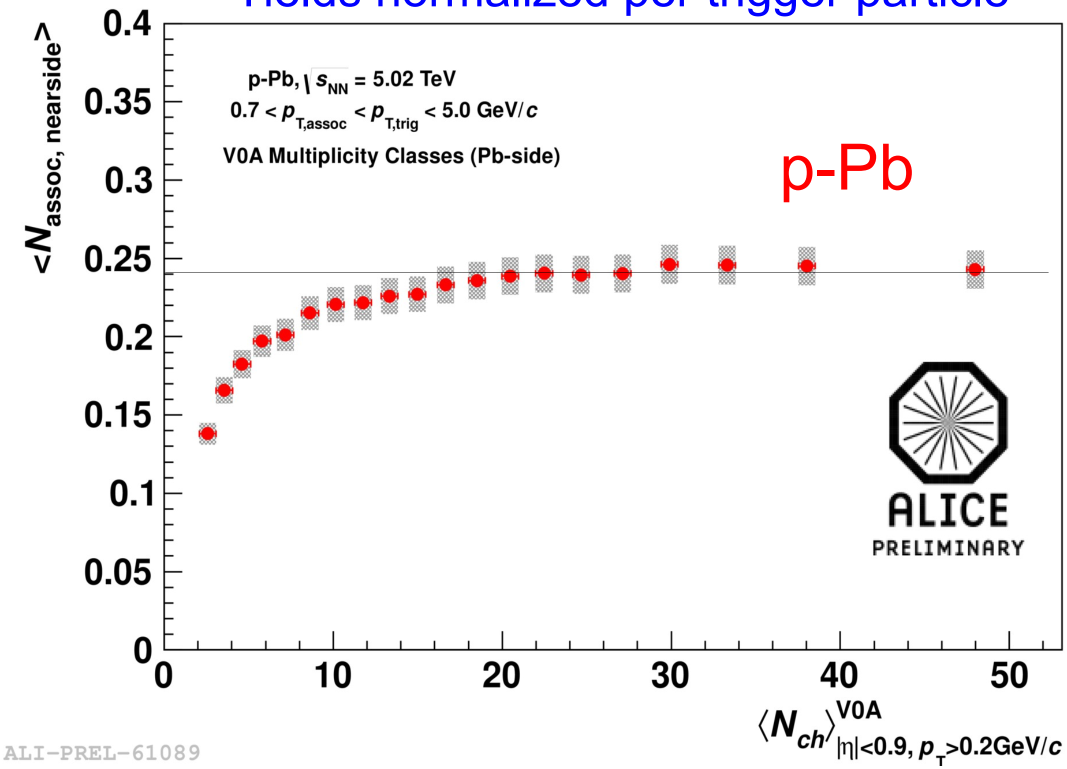


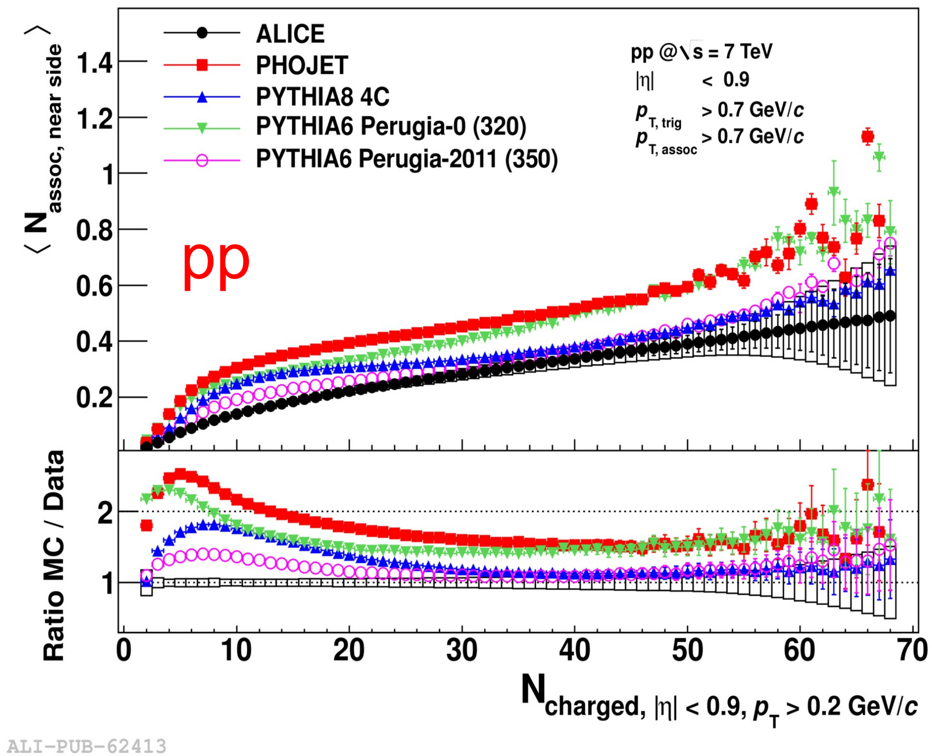
Lines: Double Gaussian Fit

Near-side Yield

Yields normalized per trigger particle

ALICE, JHEP 09 (2013) 049

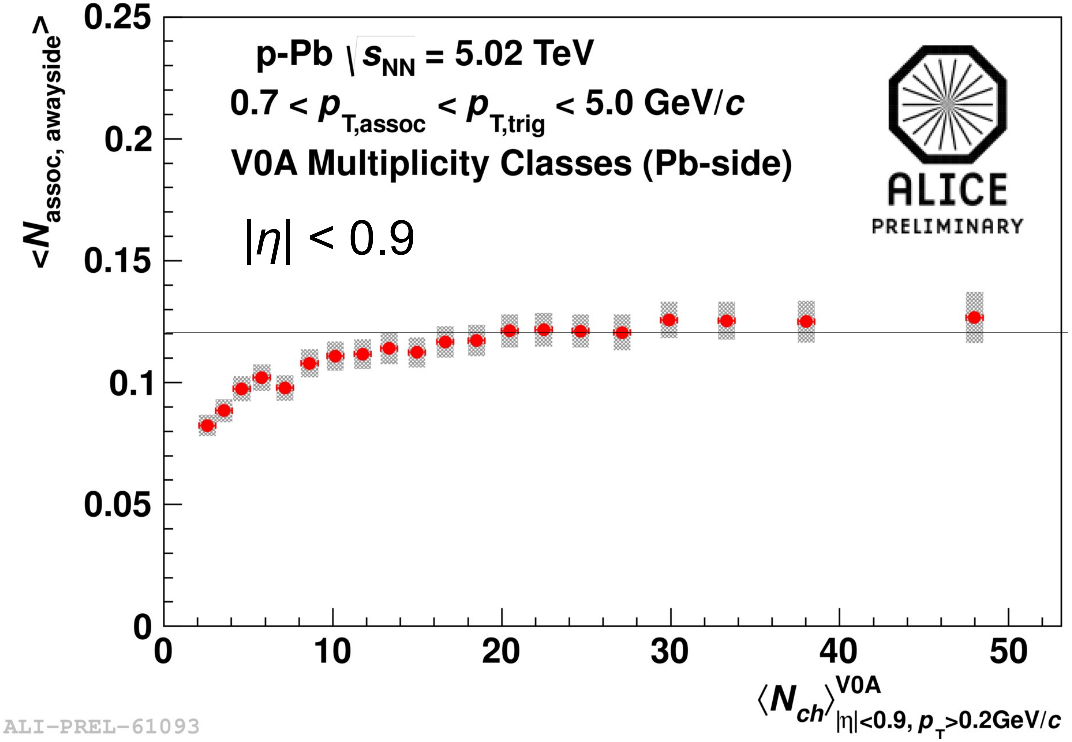




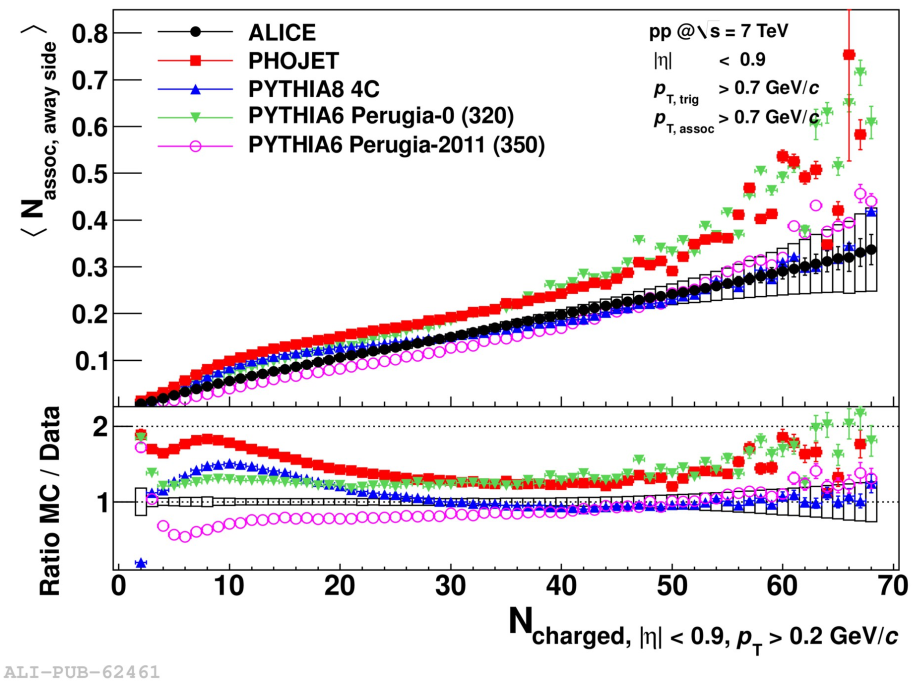
central multiplicity for 20 V0A percentiles

No bias on near-side yield except for low multiplicities.
Bias to softer than average p-N collisions.

Away-side Yield



ALICE, JHEP 09 (2013) 049

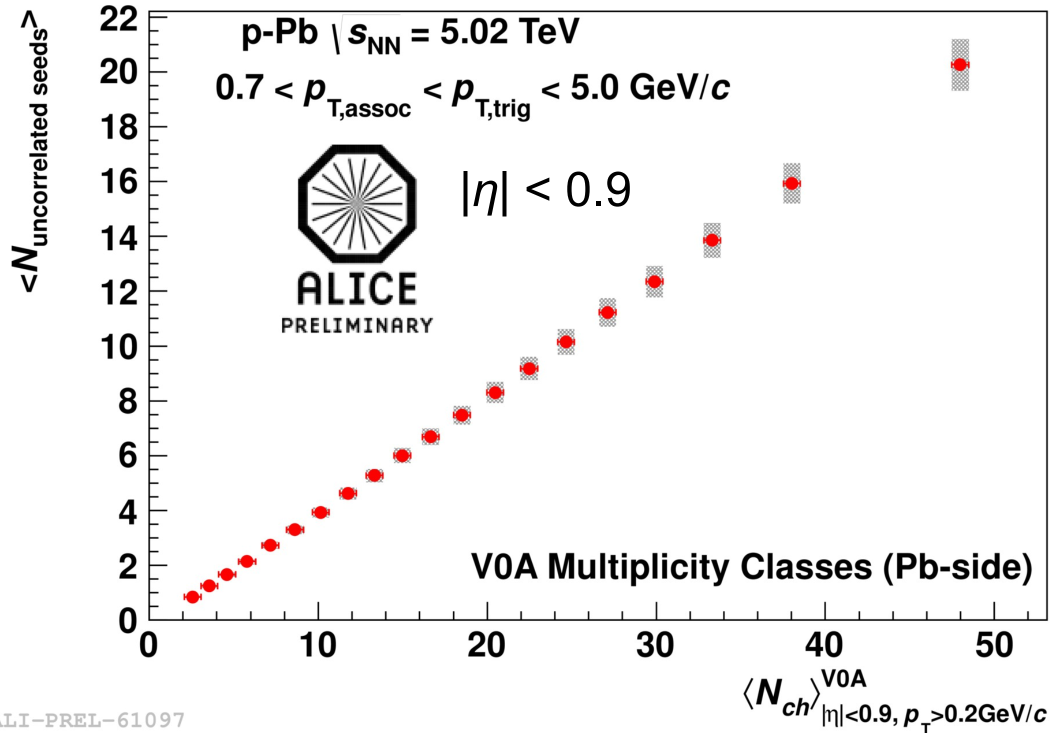


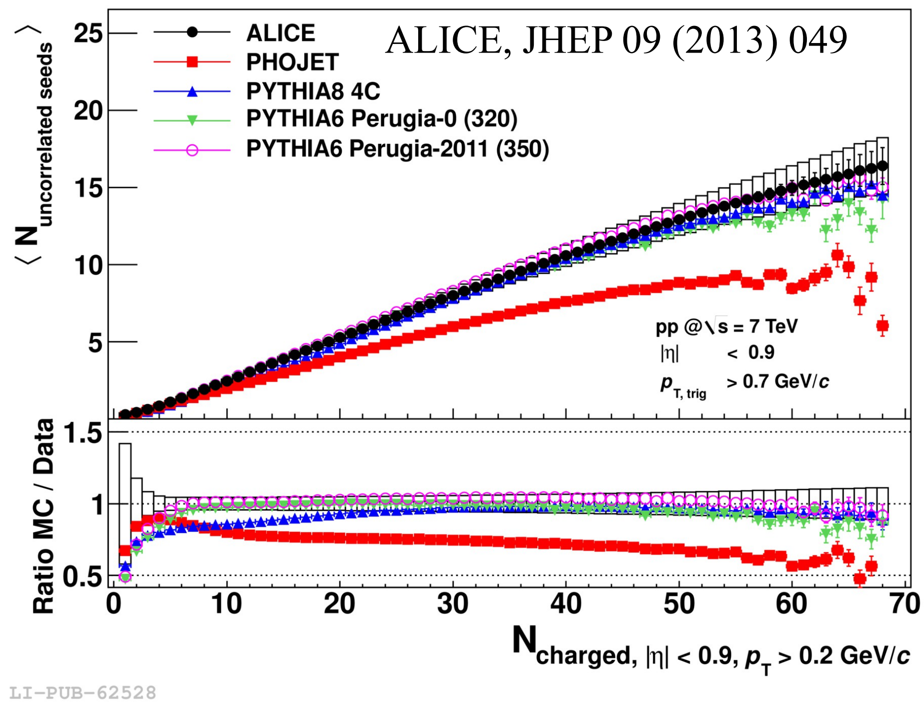
Same behavior for the back-to-back correlations (away-side)

Quite surprising result, since at the same time v_2 and $<p_T>$ strongly increase.

One degree of complexity less !

Number of uncorrelated seeds





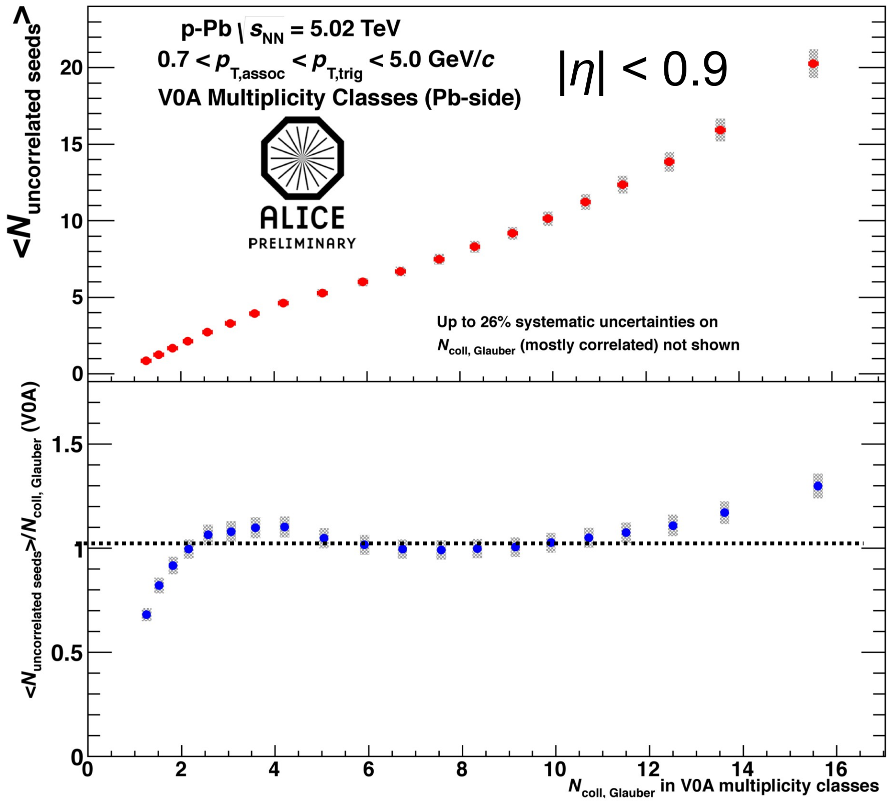
To reduce sensitivity to fragmentation properties we define:

$$< M_{\mathrm{uncorrelated\,seeds}} > = \frac{< N_{\mathrm{trigger}} >}{< 1 + N_{\mathrm{assoc,near+away}} >}$$

(In pp, more important for shape in pp)

Corroborates picture of linear increase of number of parton scatterings with V0A estimator. No additional fragmentation bias at high multiplicity.

$N_{\text{coll, Glauber}}$ scaling ?



- Approximate scaling within (10%) from $N_{\text{coll, Glauber}}$ = 3-13
- Important deviations for low and high N_{coll} => less / more semi-hard scatterings per p-N collision ?

Di-hadron correlation analysis as a function of multiplicity provides framework in which models for correlation between hard processes and bulk particle production can be tested.

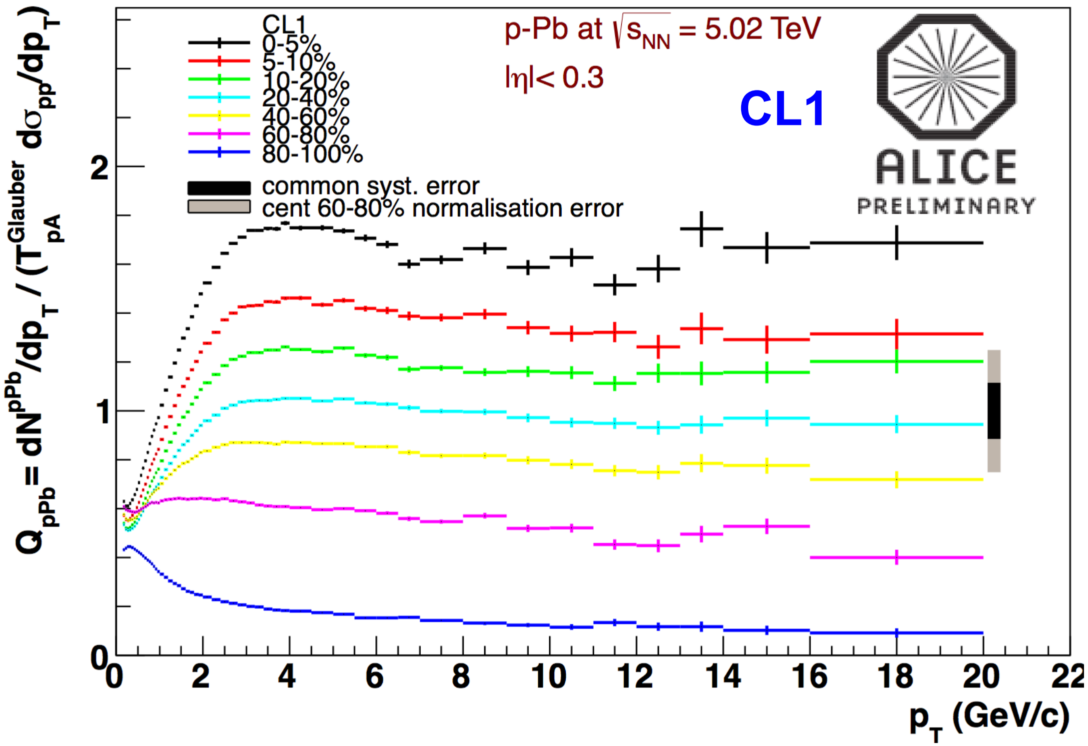
Bias from Different Estimators

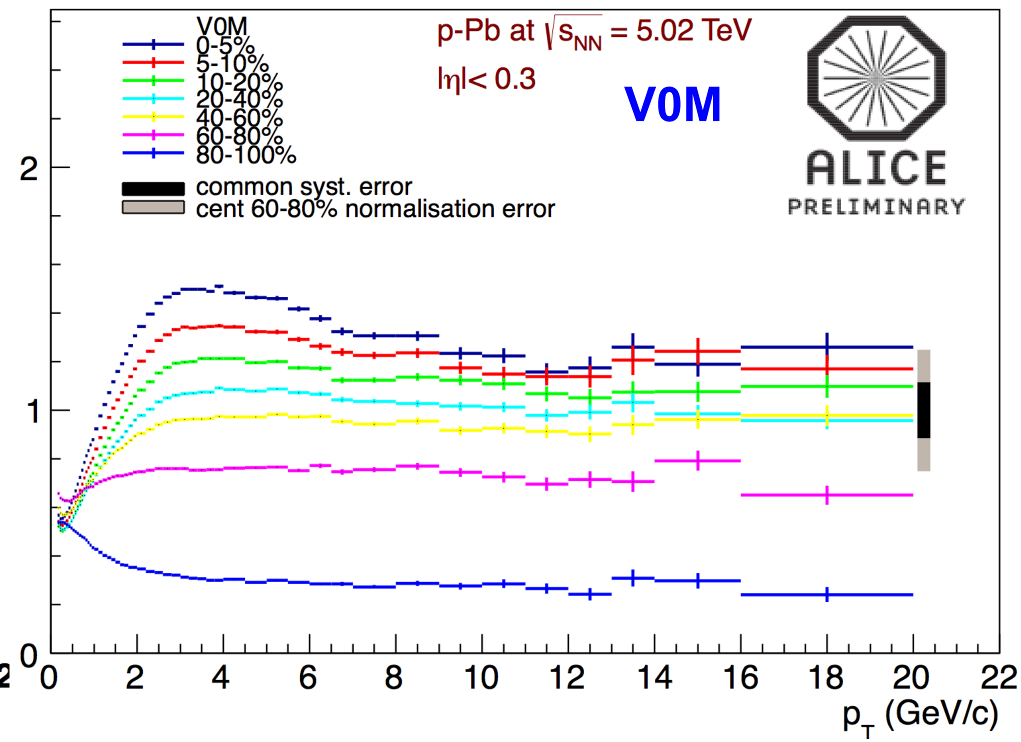
- Different centrality estimators expected to show different deviations from N_{coll} scaling
  - CL1 (Clusters Pixel Layer 2): strong bias due to full overlap with tracking region.
    - Additional bias in peripheral event from “Jet veto effect”
    - Jets contribute to the multiplicity and shift events to higher centralities (p_{T} dependent)
  - V0M (V0A+V0C Multiplicity): reduced bias since outside tracking region
  - V0A Multiplicity: reduced bias because of important contribution from Pb fragmentation region.
  - ZNA: small bias slow nucleon production independent of hard processes

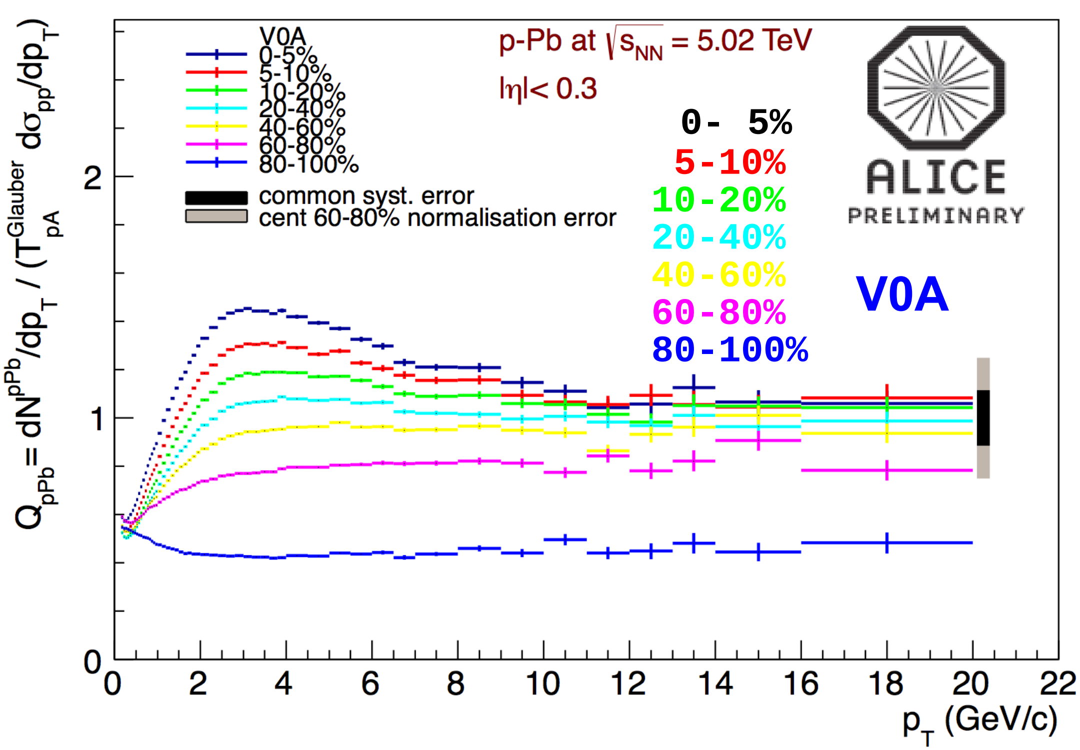
At high p_{T}

$$Q_{\text{pA}}(p_{\text{T}};cent)=\frac{\mathrm{d}N^{\text{pA}}/\mathrm{d}p_{\text{T}}}{N_{\text{coll}}^{\text{Glauber}}\,\mathrm{d}N^{\text{pp}}/\mathrm{d}p_{T}}=\frac{\mathrm{d}N^{\text{pA}}/\mathrm{d}p_{\text{T}}}{T_{\text{pA}}^{\text{Glauber}}\,\mathrm{d}\sigma^{\text{pp}}/\mathrm{d}p_{T}}\neq 1$$

In general N_{coll} for a given centrality class can not be used to scale the pp cross-section !





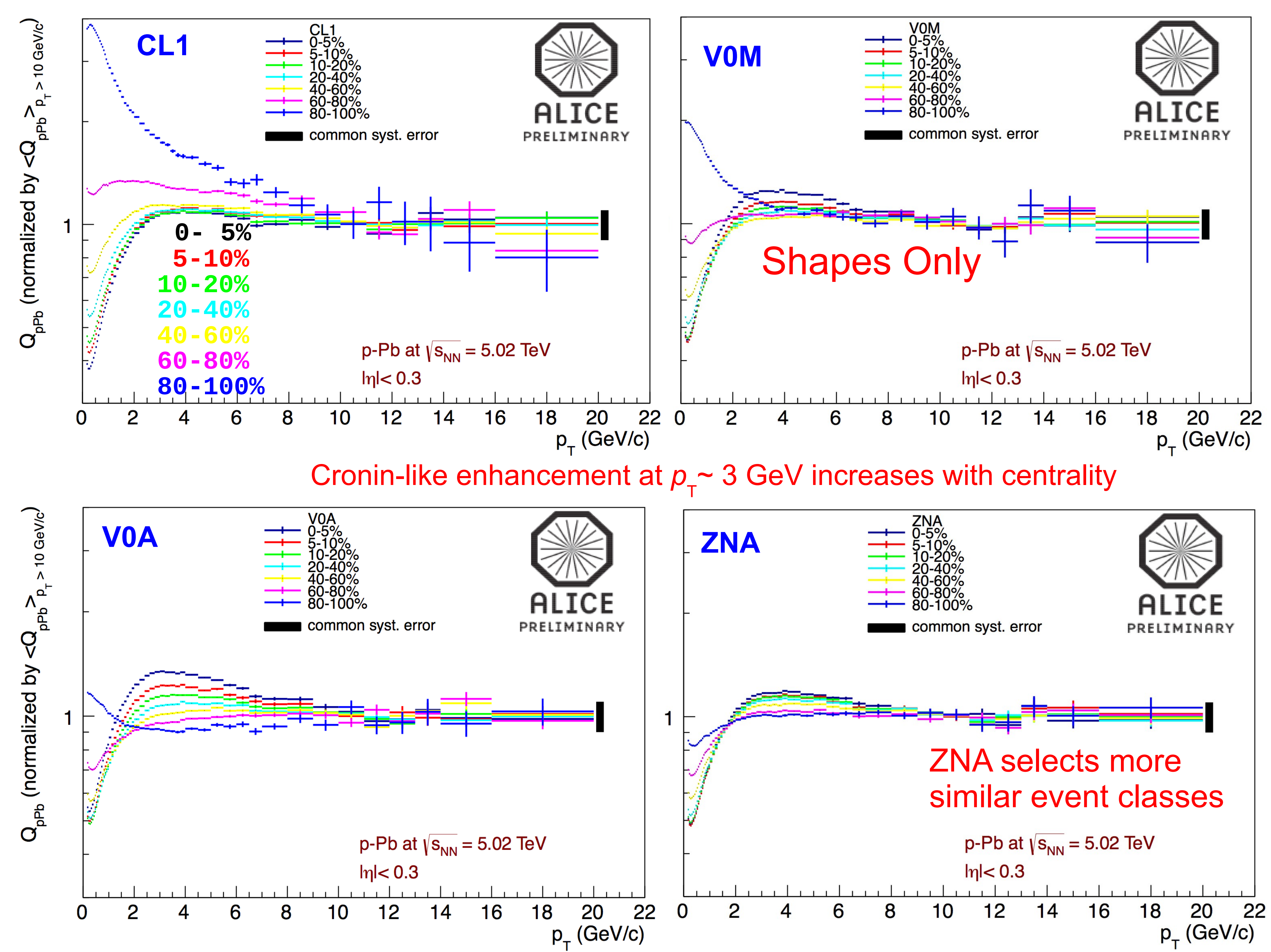


Not an R_{pPb} Measurement !

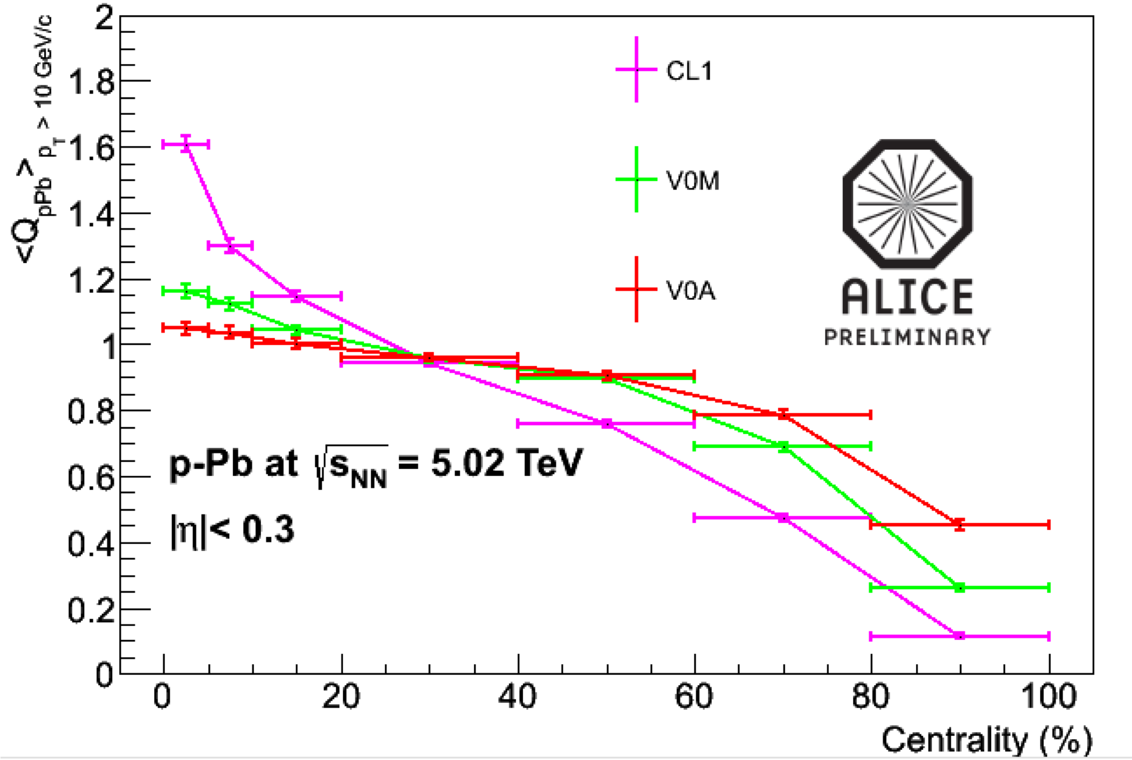
- Q_{pPb} spread between centrality classes reduces CL1→V0M→V0A

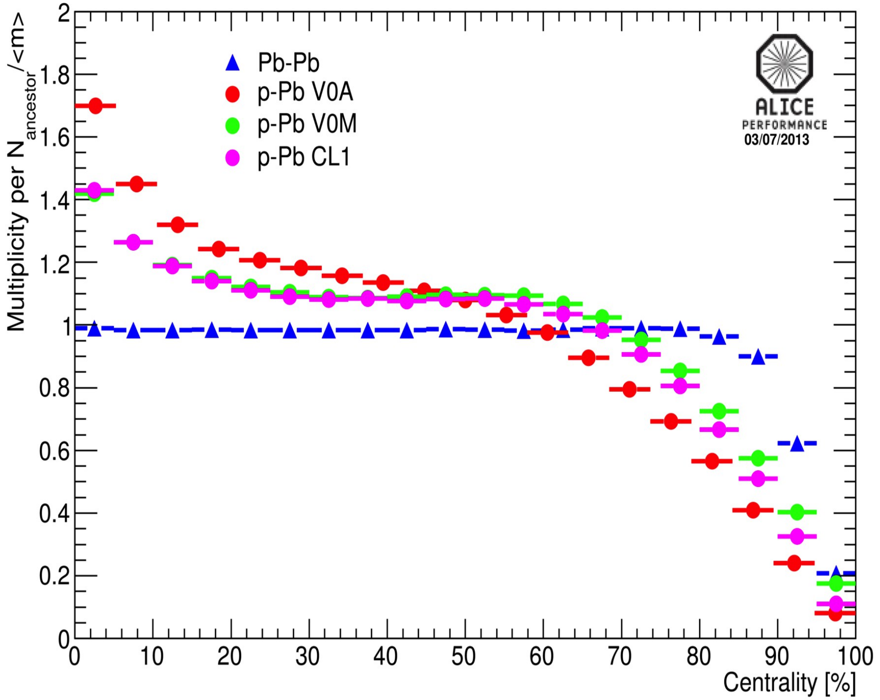
- Clear "jet veto bias" in CL1 80-100%

- No "jet veto" bias in V0A 80-100% but $Q_{pPb} < 1$


CL1
CL1
0-5%
5-10%
10-20%
20-40%
40-60%
60-80%
80-100%
common syst. error
ALICE
PRELIMINARY
0- 5%
5-10%
10-20%
20-40%
40-60%
60-80%
80-100%
p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV
$|\eta|$< 0.3
Q_{pPb} (normalized by $\langle Q_{pPb} \rangle_{p_T > 10\ GeV/c}$)
p_T (GeV/c)
V0M
V0M
0-5%
5-10%
10-20%
20-40%
40-60%
60-80%
80-100%
common syst. error
ALICE
PRELIMINARY
Shapes Only
p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV
$|\eta|$< 0.3
p_T (GeV/c)
Cronin-like enhancement at p_T~ 3 GeV increases with centrality
V0A
V0A
0-5%
5-10%
10-20%
20-40%
40-60%
60-80%
80-100%
common syst. error
ALICE
PRELIMINARY
p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV
$|\eta|$< 0.3
Q_{pPb} (normalized by $\langle Q_{pPb} \rangle_{p_T > 10\ GeV/c}$)
p_T (GeV/c)
ZNA
ZNA
0-5%
5-10%
10-20%
20-40%
40-60%
60-80%
80-100%
common syst. error
ALICE
PRELIMINARY
ZNA selects more
similar event classes
p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV
$|\eta|$< 0.3
p_T (GeV/c)

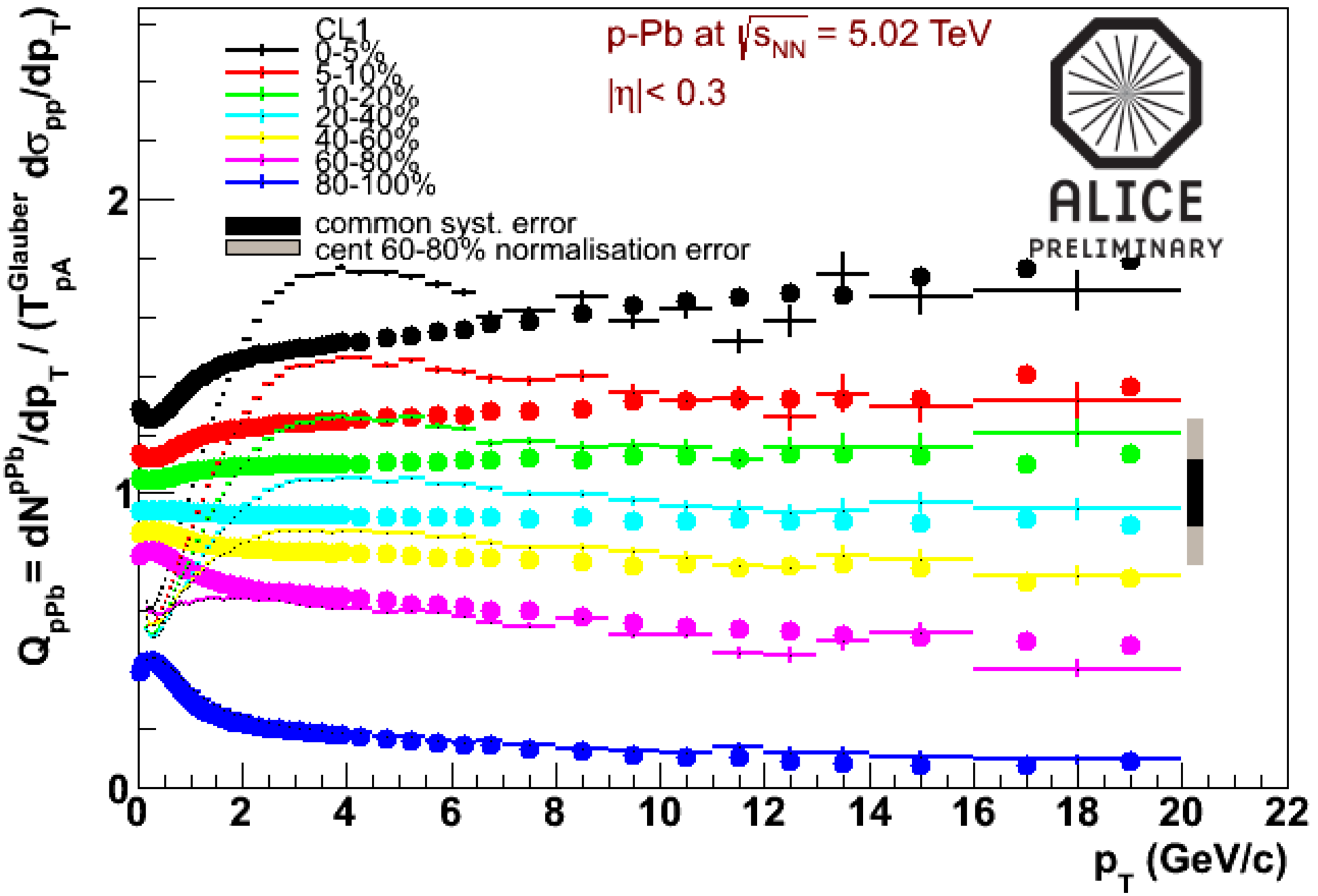
Mean Q_{pPb} at High p_T





"S-shape" dependence as seen from multiplicity bias (Glauber + NBD fit),
Shape flattens CL1→V0M→V0A

Comparison with Glauber+Pythia



Symbols ● MC

- Bias at high p_T described by incoherent superposition of pp collisions.
- For most peripheral p-Pb, good agreement also in low- and intermediate p_T region.
- Strong deviations for all other centrality bins !

Conclusions

- In p-Pb, centrality estimators based on multiplicity measured in $|\eta| < 5$ induce biases on the average multiplicity per p-nucleon collision.
  - due to the relatively large fluctuations of the p-N multiplicity.
  - dynamical models of these fluctuations can relate this bias to a bias on the binary scaling of hard processes.
  - Such a relation is provided by multiple parton interactions as used in Monte Carlo generators.
  - The biases decreases by increasing the η-gap between centrality estimator and momentum measurement.
- Measurements of multiplicity dependent di-hadron correlations provide a framework to test models for correlation between hard probes and bulk particle productions in kinematic regions where they overlap
  - Our measurements at low p_T show that there is no additional fragmentation bias at high N_{coll} and we observe biases on binary scaling similar to the one at high p_T.

X.N. Wang and M. Gyulassy, nucl-th/9502021

Some more details

- Interaction probability calculated from nucleon-nucleon (pp) overlap function.

$$T_N(b) = 2\frac{\chi_0(b,s)}{\sigma_{soft}}$$

$$\chi_0(\xi) = \frac{\mu_0^2}{96}(\mu_0\xi)^3 K_3(\mu_0\xi), \xi = b/b_0(s)$$

- Inelastic cross-section (1 – probability for no interaction)

$$d\sigma_{inelastic} = \pi\, db^2[1 - \exp(-2\chi(b,s))] = \pi\, db^2[1 - \exp(-(\sigma_{soft} + \sigma_{hard}) T_N(b,s))]$$

- Centrality integrated

$$\langle N_{col}\rangle = A\frac{\sigma_{pp}}{\sigma_{pA}}; \langle n_{hard}\rangle = \frac{\sigma_{hard}}{\sigma_{soft}}\langle N_{col}\rangle$$