p-Pb with ALICE

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on behalf of the ALICE Collaboration

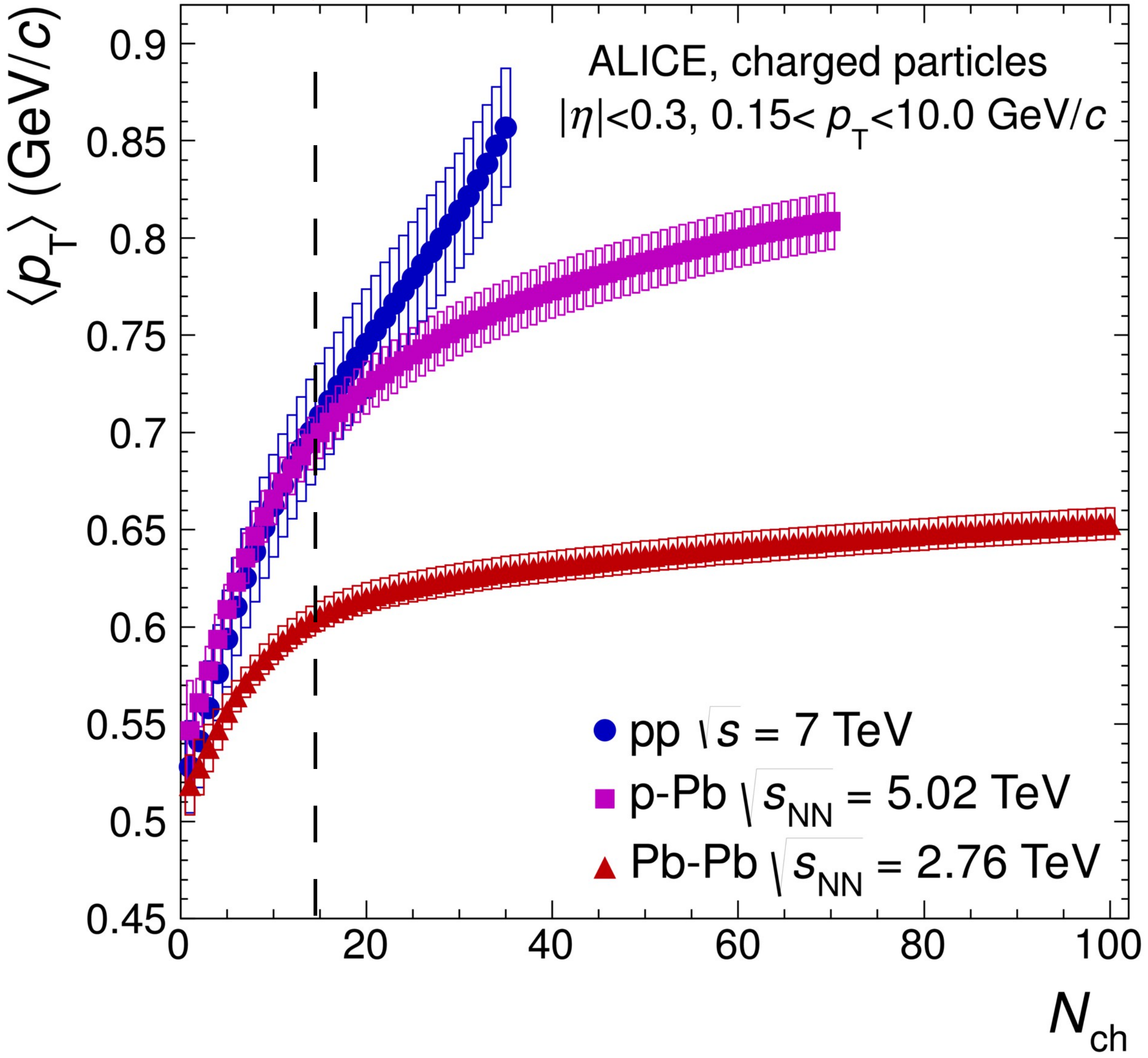
Strangeness in Quark Matter
Birmingham, July 25 2013

Outline

- Interesting new results from the low- and intermediate p_T region
  - Mean p_T *vs* multiplicity
  - v_2 of identified particles from 2-particle correlations
- Not explained by an incoherent superposition of proton-nucleon (pN) collisions.
  - Indication for collective effects in p-Pb
- To assess nuclear modifications at high p_T
  - Test binary collisions (N_{coll}) scaling
  - Important results concerning biases on the scaling
  - Emphasis on centrality in p-Pb

Mean p_T in pp, p-Pb and Pb-Pb

ALICE, arXiv:1307.1094



ALI-PUB-55941

- Three different $\sqrt{s}$, but $\sqrt{s}$ dependence expected to be weak (known from pp)
- Much stronger increase wrt Pb-Pb
- p-Pb $<p_T>$ follows pp in region up to $N_{ch} \approx 14$

$N_{ch} > 14$ corresponds to

10% of pp x-section:

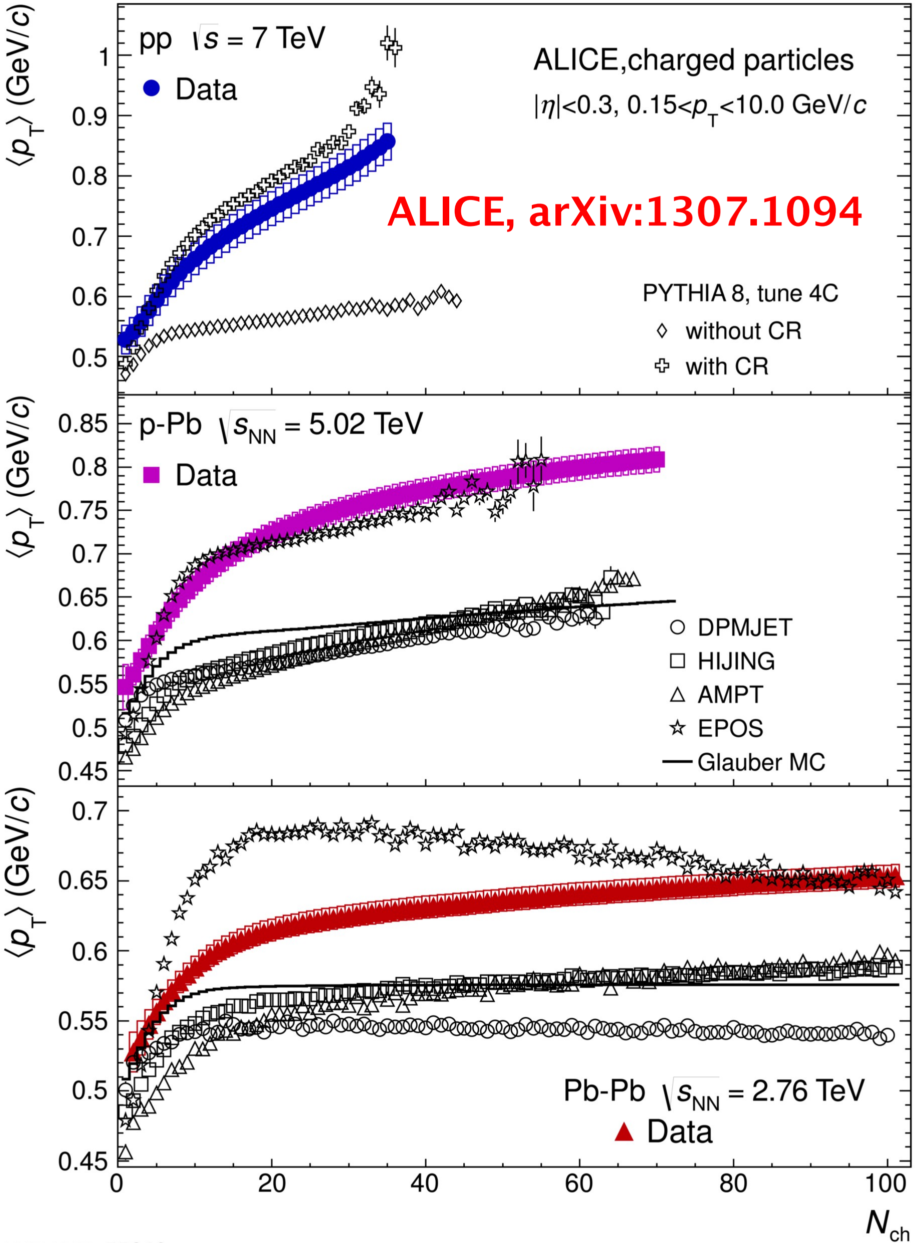
- pp already highly biased

50% of pPb x-section

- only centrality bias

Scaling with multiplicity
~ number of parton-parton interactions
(number of initial strings) ?

Comparison with Models



pp

- Within PYTHIA model strong increase with N_{ch} attributed to Color Reconnections between hadronizing strings.

- Can be seen as a collective final state effect.

pPb

- Glauber MC of incoherent superposition of pN collisions but including measured $<p_T>$ dependence in pp cannot reproduce p-Pb data !

- Situation like in pp ?

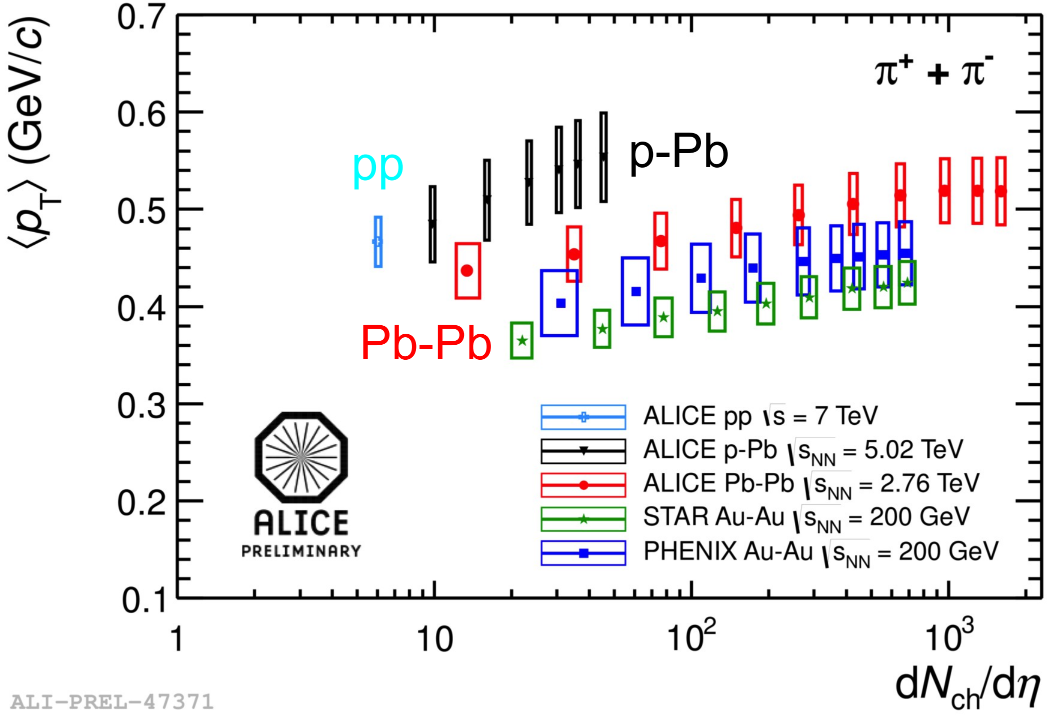
- Do we need coherent effects between strings formed by different pN collisions ?

- EPOS includes collective effects and reproduces the data,

PbPb

- HIJING, AMPT get trend right. EPOS has different shape for very peripheral collisions.

$\langle p_T \rangle$ vs Charged Multiplicity for Identified Particles



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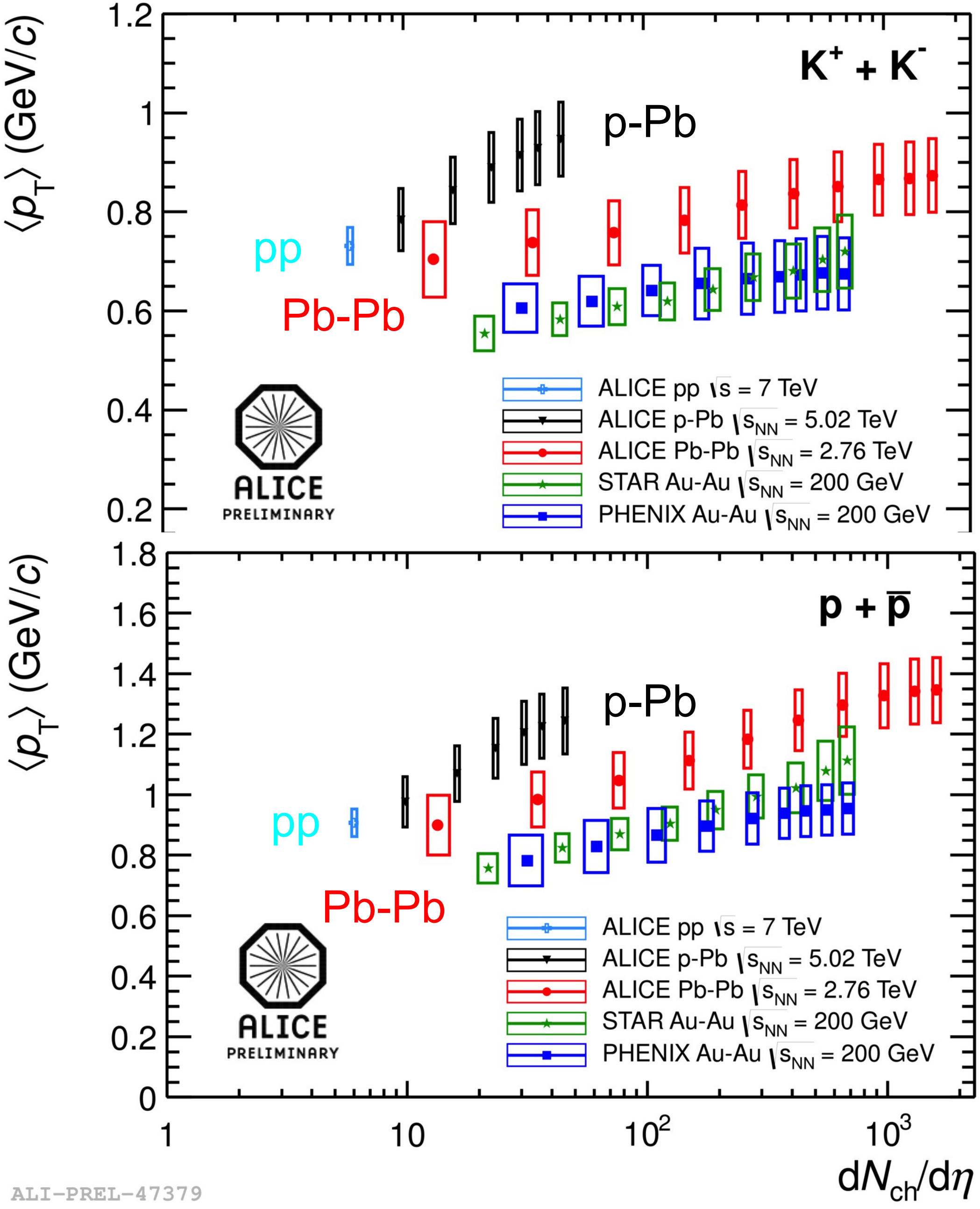


ALI-PREL-47379

- Clear mass ordering:

$\langle p_T \rangle_p > \langle p_T \rangle_K > \langle p_T \rangle_\pi$

- pp MB in trend with p-Pb

- At same multiplicity:

$\langle p_T \rangle$ in p-Pb higher than in Pb-Pb

Flow Pattern in Δη-Δφ Correlations

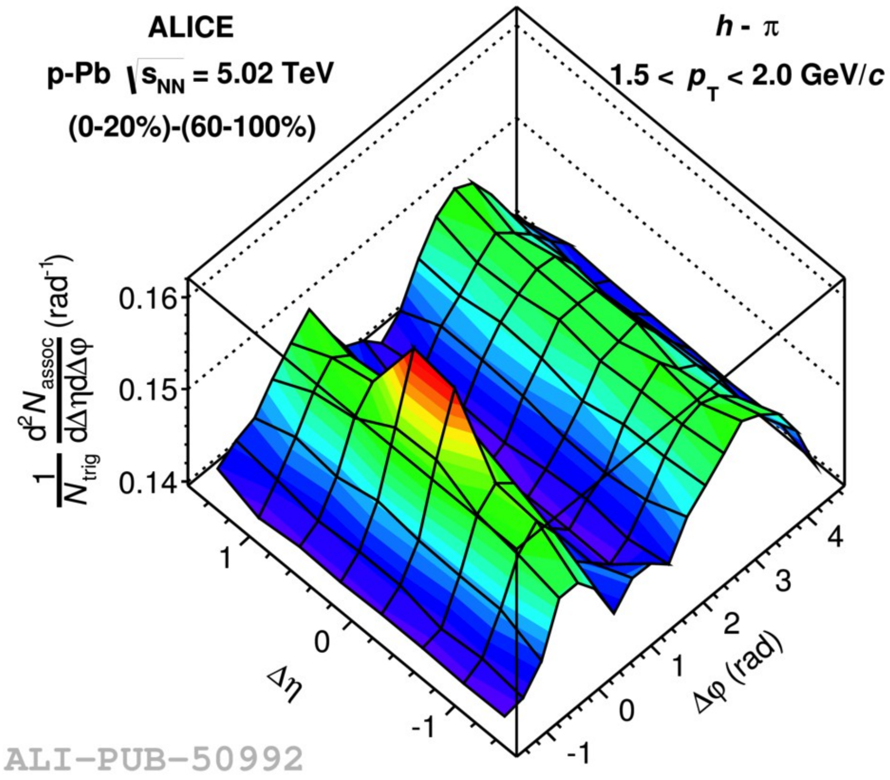
See also L. Milano
PS pA collisions 26/7

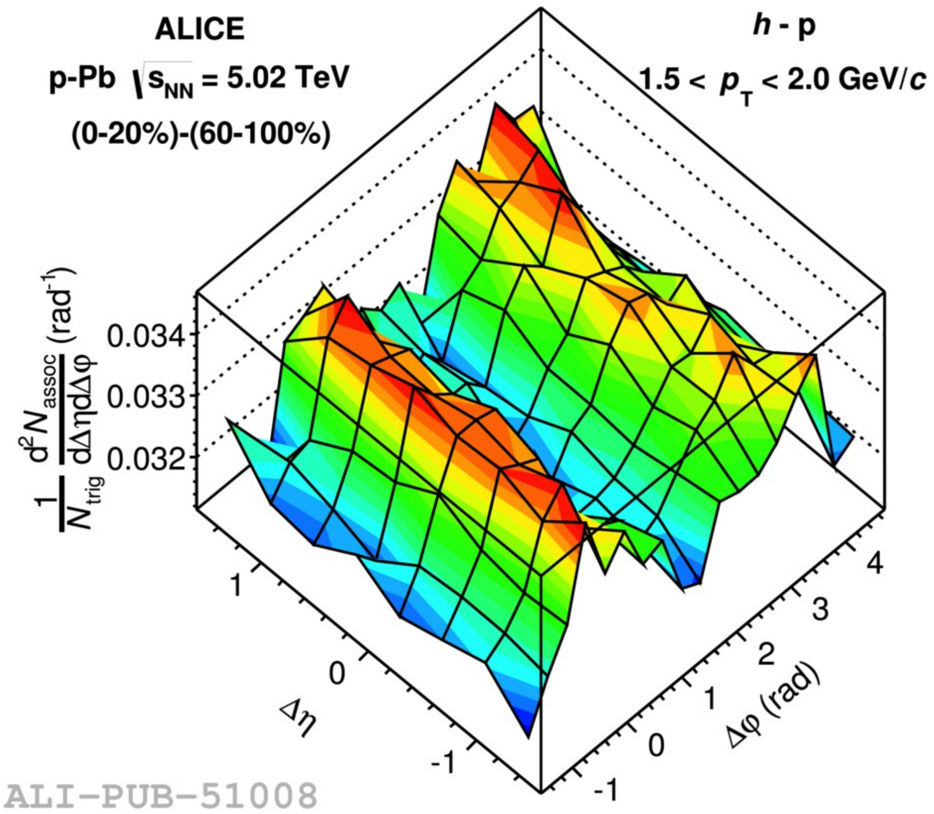
New results with identified particles ...

h-π

(0-20%) - (60-100%)

h-p



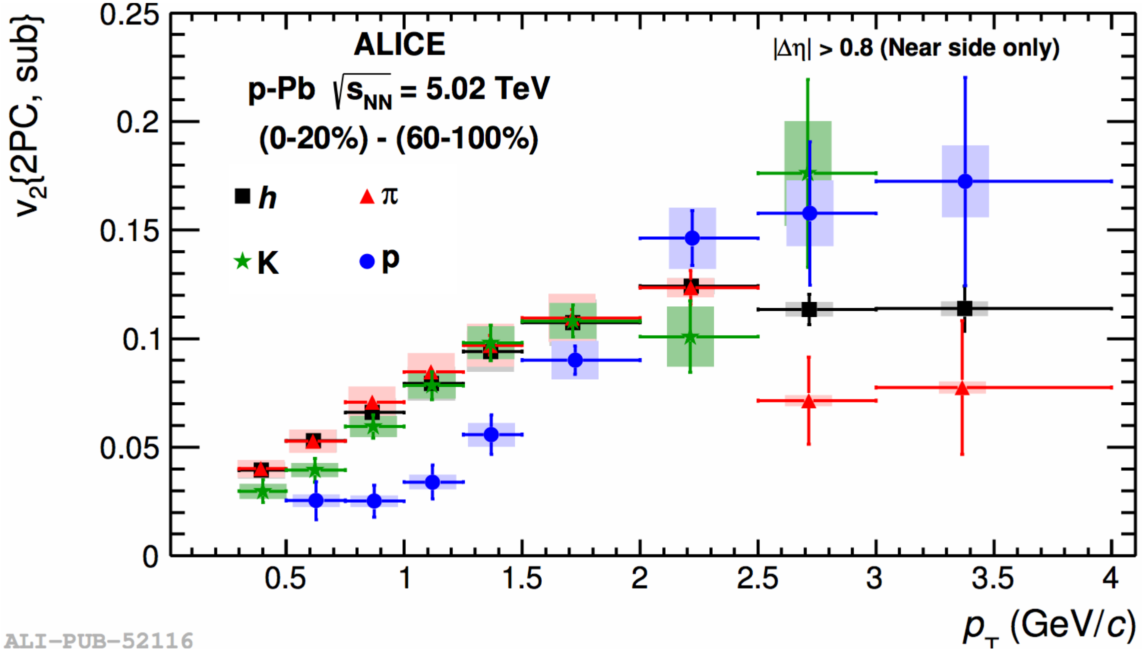


v_2 from Fourier decomposition of Δφ- projection

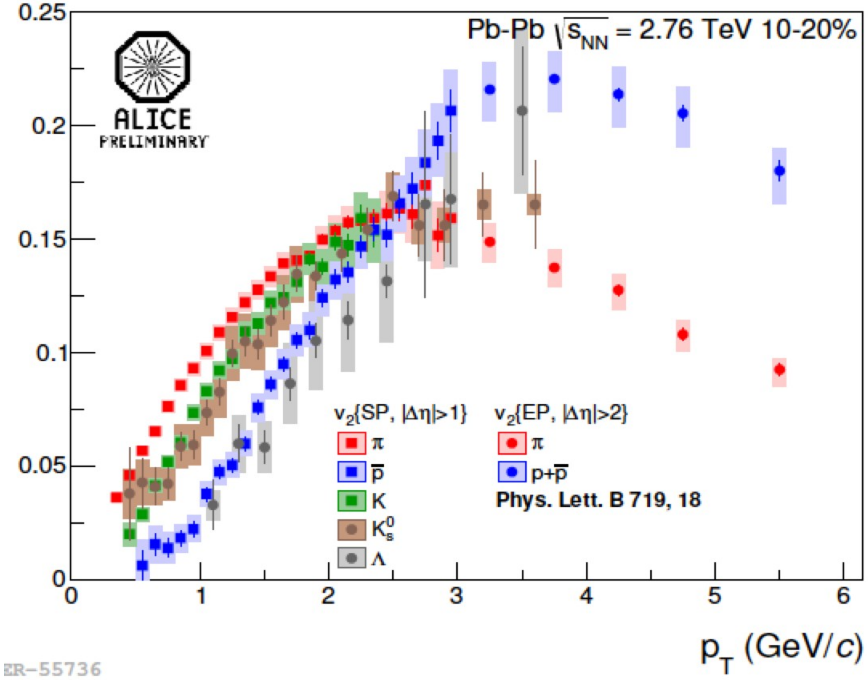
ALICE, arXiv:1307.3237

v_2 from h-(π, K, p) Correlations

p-Pb



Pb-Pb 10-20%



Mass ordering like in Pb-Pb !

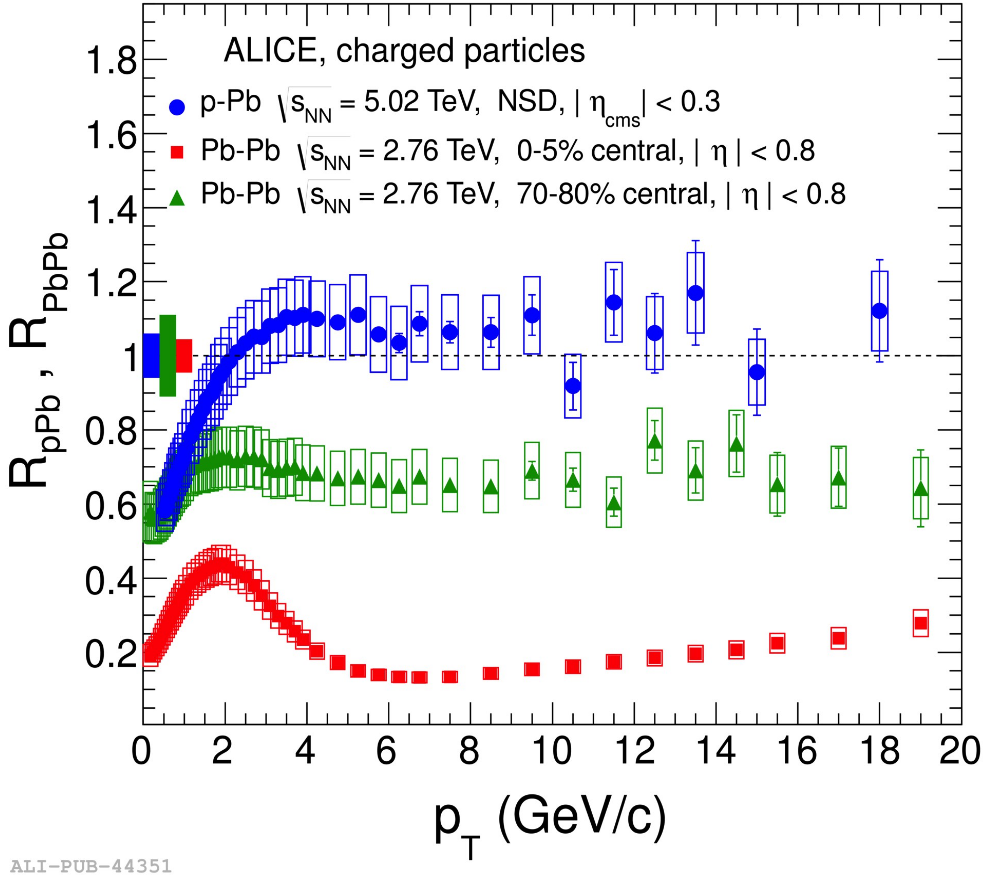
ALICE, arXiv:1307.3237

See also L. Milano
PS pA collisions 26/7

Centrality in p-Pb and Binary Collision Scaling

Nuclear Modification Factor for p-Pb MB

ALICE, arXiv:1210.4520



ALI-PUB-44351

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

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

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

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

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

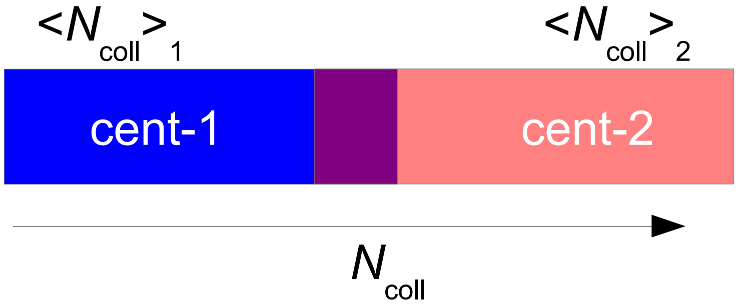
$$\langle T_{pPb}\rangle = \langle N_{coll}\rangle/\sigma_{pN} = 208/2100\text{ mb}^{-1} = 0.098\text{ mb}^{-1}$$

How can we make this measurement centrality dependent ?

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

p-Pb Nuclear Effects ...

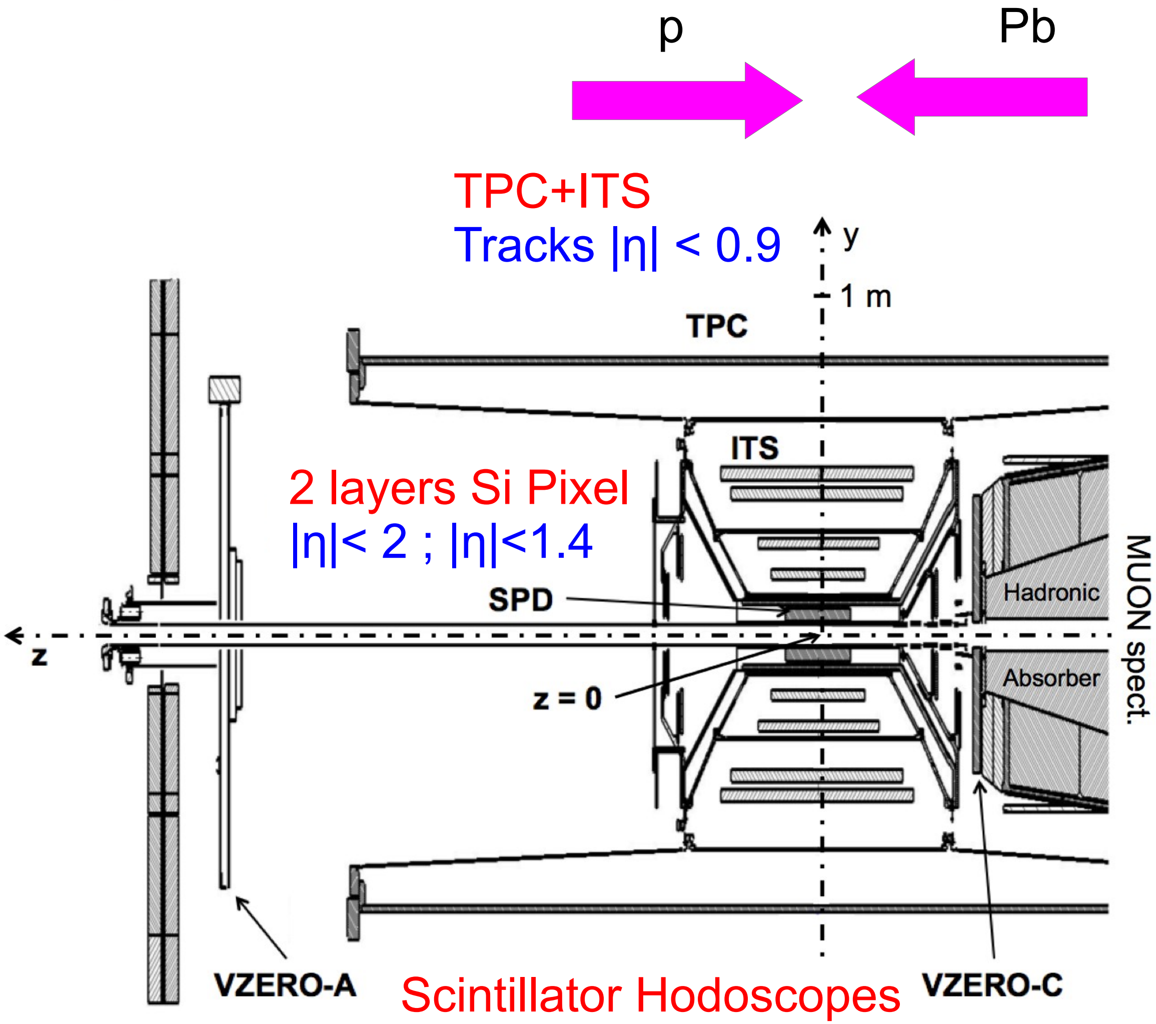
- ... can be quantified by comparison to incoherent superposition of p-nucleon collisions
- Centrality event classes defined using centrality estimators
  - Particle multiplicity or summed energy in given pseudo-rapidity region
- For each centrality class, two independent questions
  - Q1 How many collisions: 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 ...

Detectors for Centrality Estimation



TPC+ITS
Tracks $|\eta| < 0.9$

2 layers Si Pixel
$|\eta| < 2$; $|\eta| < 1.4$

Scintillator Hodoscopes

z = 340 cm
$2.8 < \eta < 5.1$

z = -90 cm
$-3.7 < \eta < -1.7$

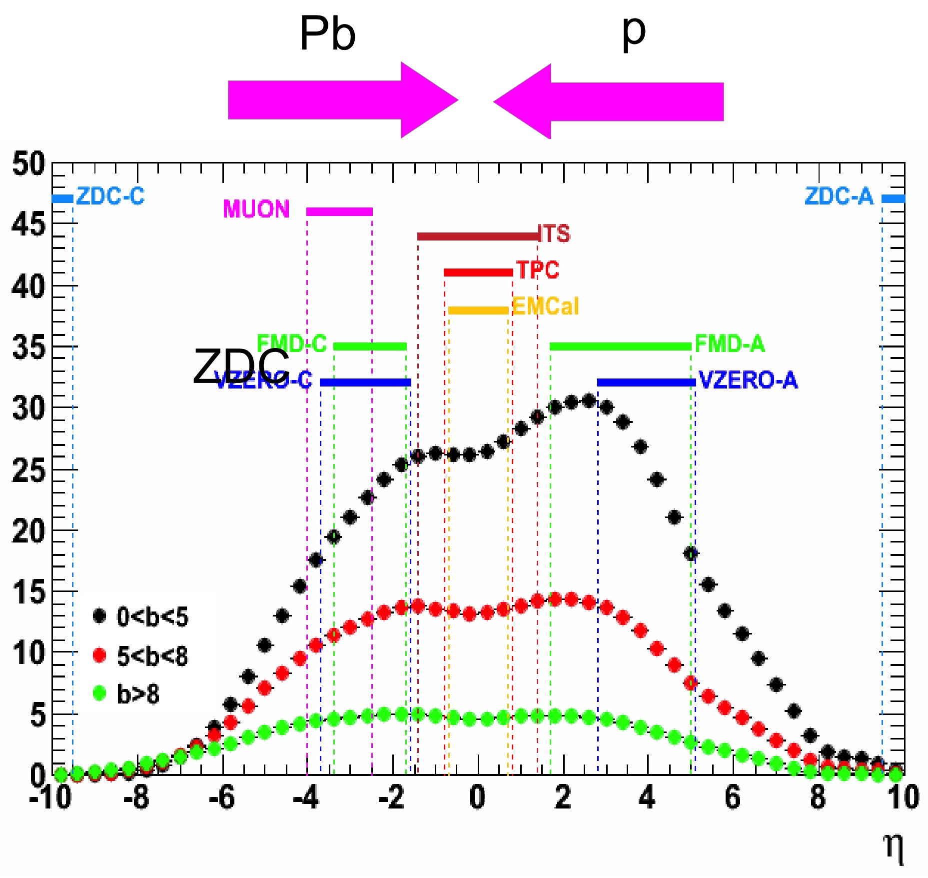
Quartz-Fiber “Spaghetti”
Zero Degree Calorimeters

z = ·± 112.5 m

Centrality Estimators discussed here:

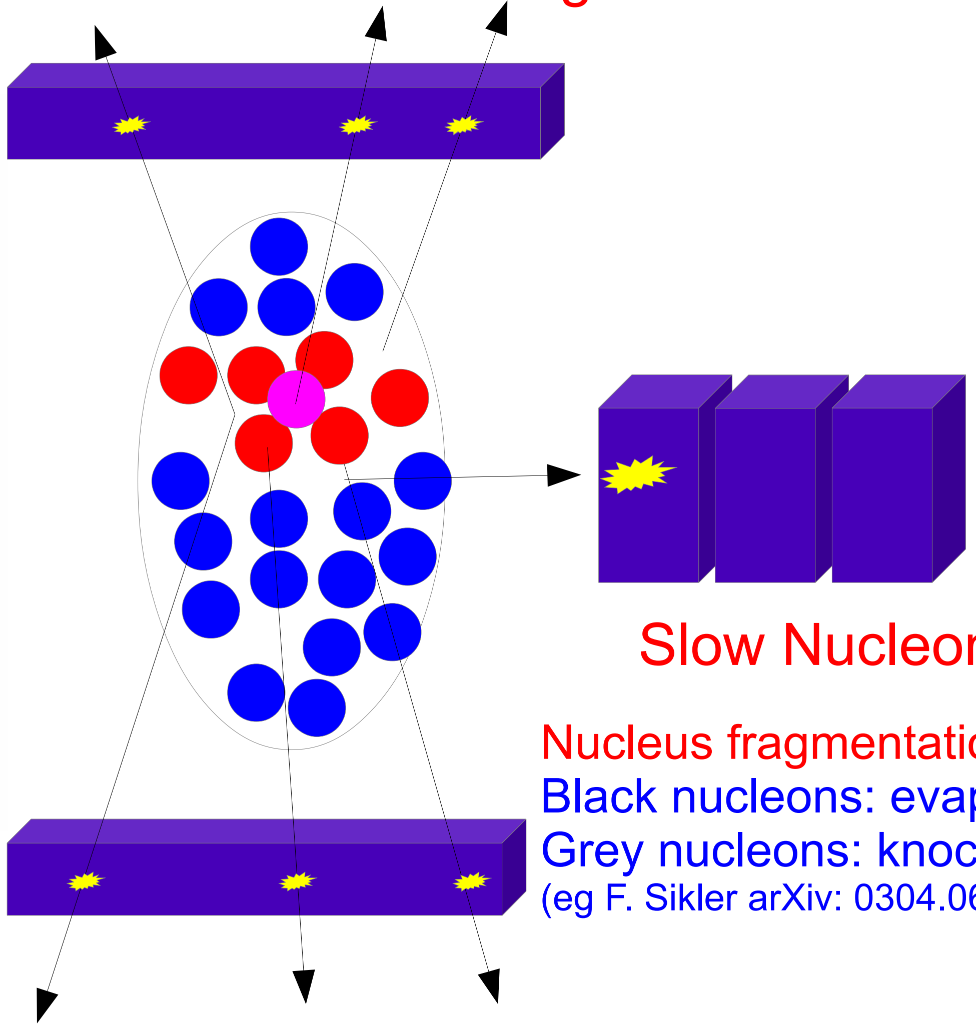
CL1:	Clusters in 2nd Pixel Layer
V0A:	V0A Multiplicity
V0M:	V0A+V0C Multiplicity
ZNA:	ZNA Energy

Estimators sensitive to ..



Binary pN collisions

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



Pb-Fragmentation

Slow Nucleons

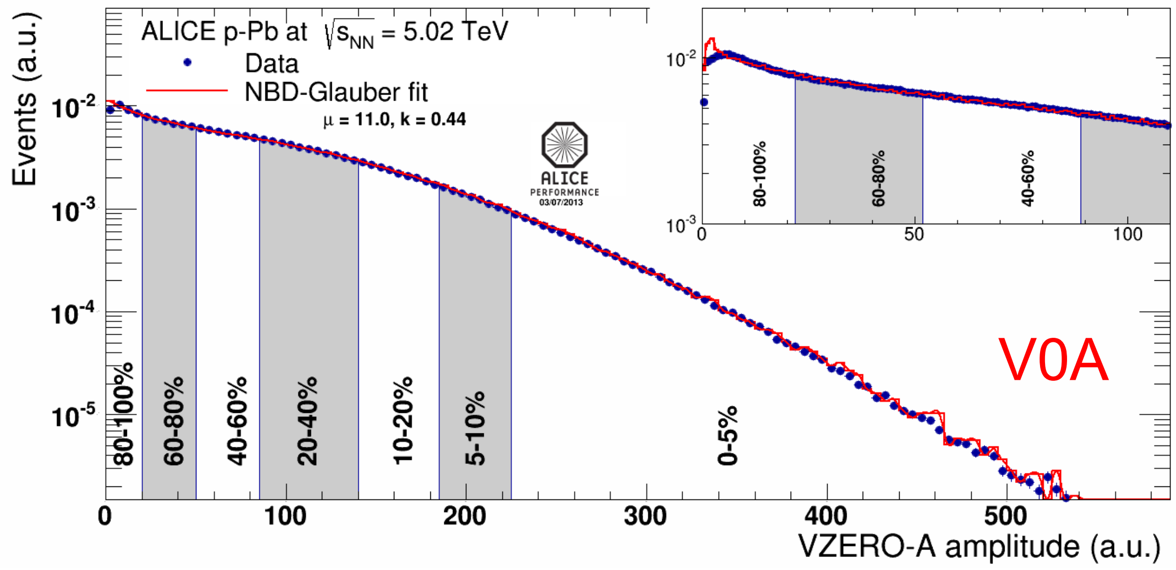
Nucleus fragmentation model:
Black nucleons: evaporation
Grey nucleons: knock-out
(eg F. Sikler arXiv: 0304.065)

Particle production modeled by Negative Binomial Distribution (NBD)

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

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



Negative Binomial Distribution:

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

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

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

Glauber Fit Results

Glauber MC Parameters

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

$R = 6.62 \pm 0.06$ fm

$a = 0.546 \pm 0.01$fm

Minimum NN distance:
0.4±0.4 fm

pN Cross-section

$\sigma_{pN} = 70 \pm 5$ mb

Proton radius

$R_p = 0.6 \pm 0.2$ fm

Centrality	$\langle N_{coll} \rangle$ CL1	$\langle N_{coll} \rangle$ V0M	$\langle N_{coll} \rangle$ V0A	Max Diff.	*Impact Parameter* Slicing
0 - 5%	15.4	15.8	14.8	6.8%	14.4
5 - 10%	13.5	13.7	13.1	4.5%	13.8
10 - 20%	12.0	12.1	11.7	3.4%	12.7
20 - 40%	9.3	9.4	9.4	1.1%	10.2
40 - 60%	6.0	6.1	6.5	6.6%	6.3
60 - 80%	3.46	3.33	3.85	16%	3.1
80 -100%	1.86	1.67	1.94	16%	1.44

- N_{coll} similar for different estimators

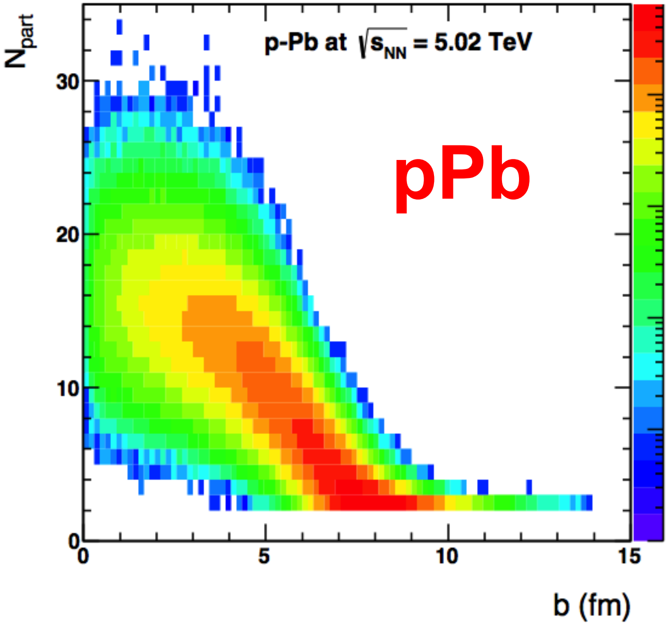
- Similar to MC closure and Glauber MC systematic error.

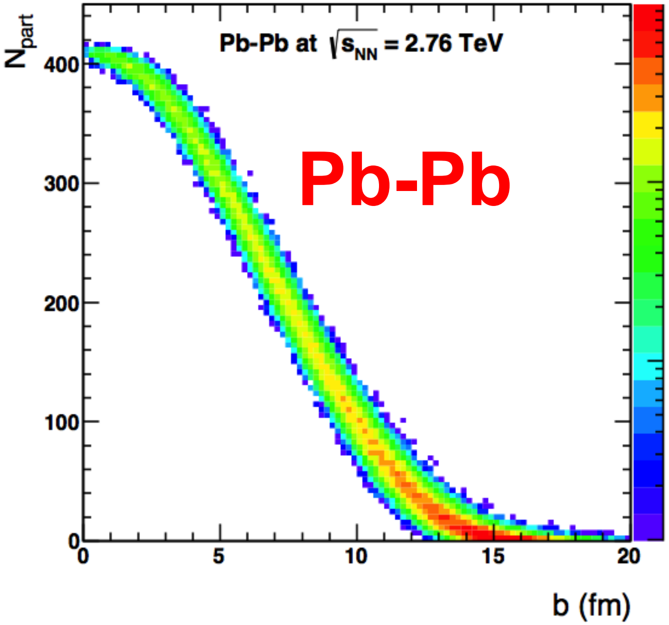
- Systematic error estimated by varying Glauber MC parameters.
- MC closure test performed with HIJING.

Biases on pN Collisions ?

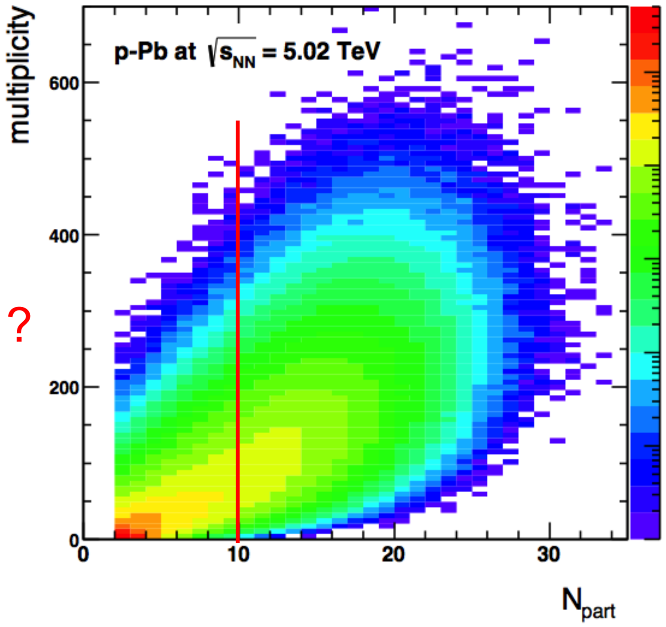
Compared to Pb-Pb

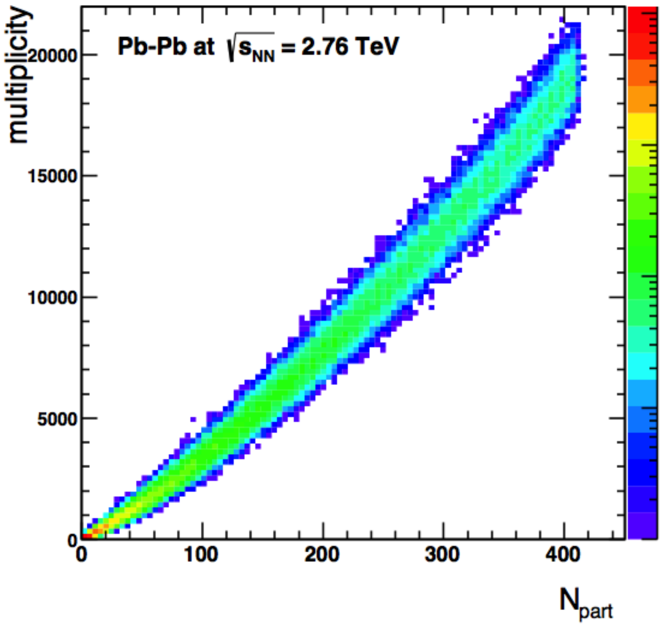
- Looser correlation between N_{part} and impact parameter (b)





- Looser correlation between N_{part} and Multiplicity



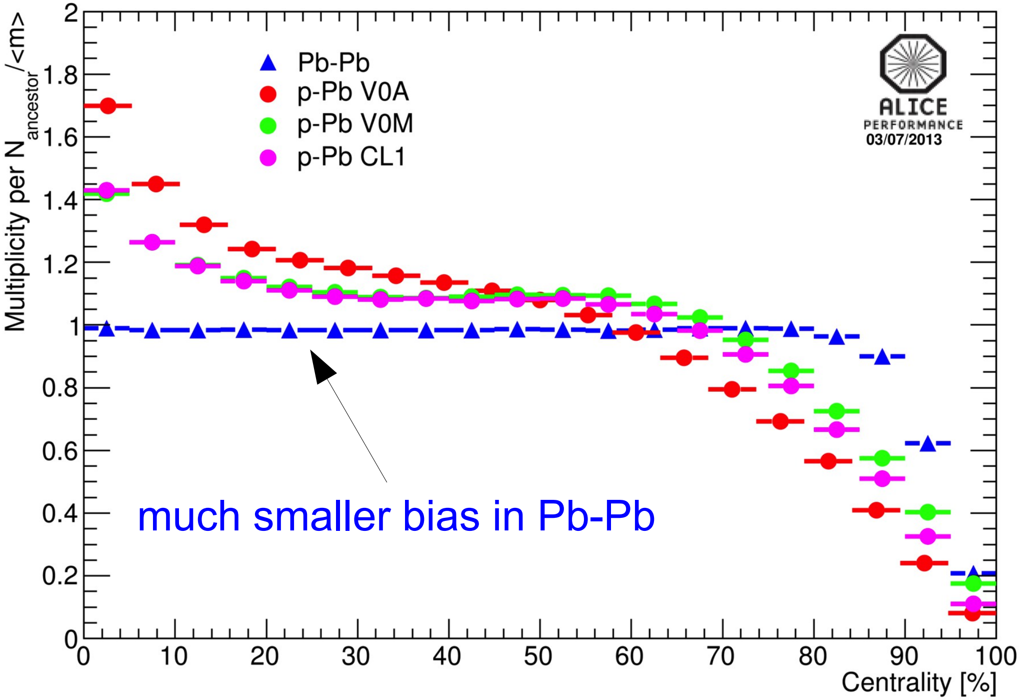


What distinguishes cent1 from cent2 for the same N_{coll} ?

Is it relevant for other physics observables ?

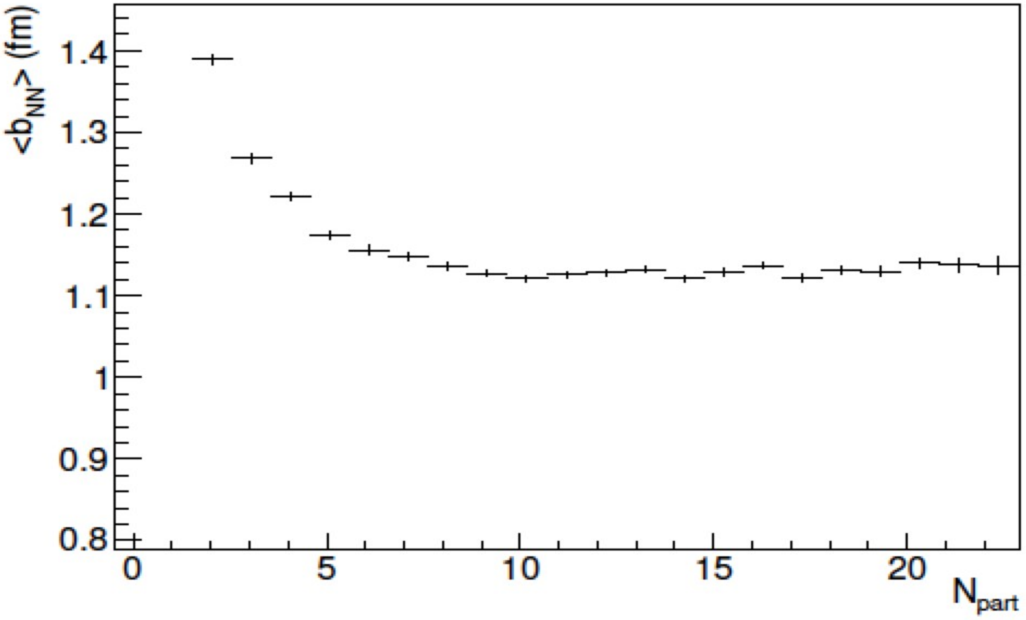
More Information from Glauber MC

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



much smaller bias in Pb-Pb

Mean nucleon-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

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

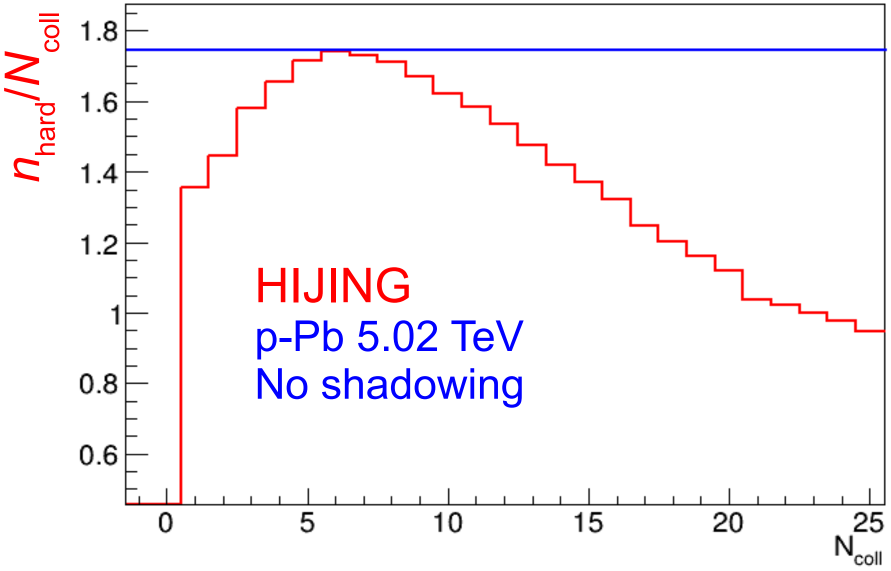
- For a given centrality percentile hard processes scale with

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

- 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.

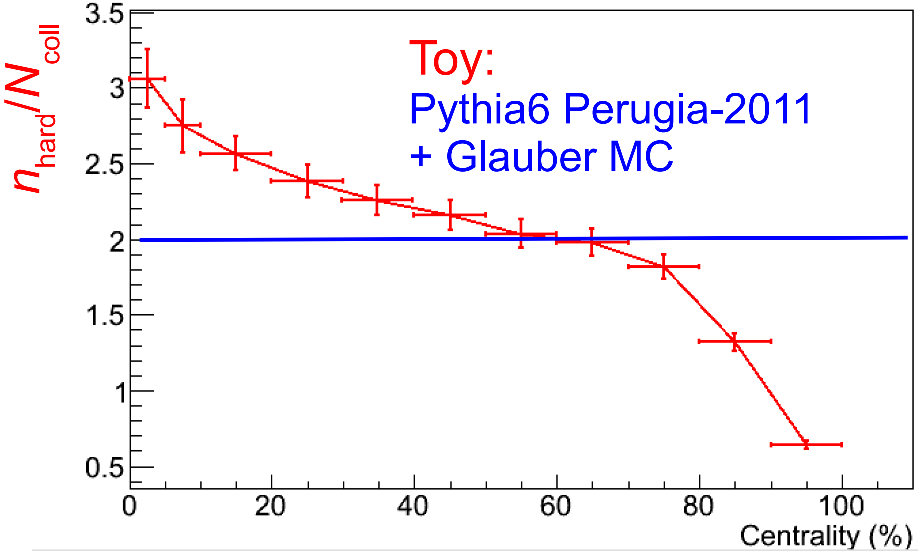
Insights from Monte Carlo

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.

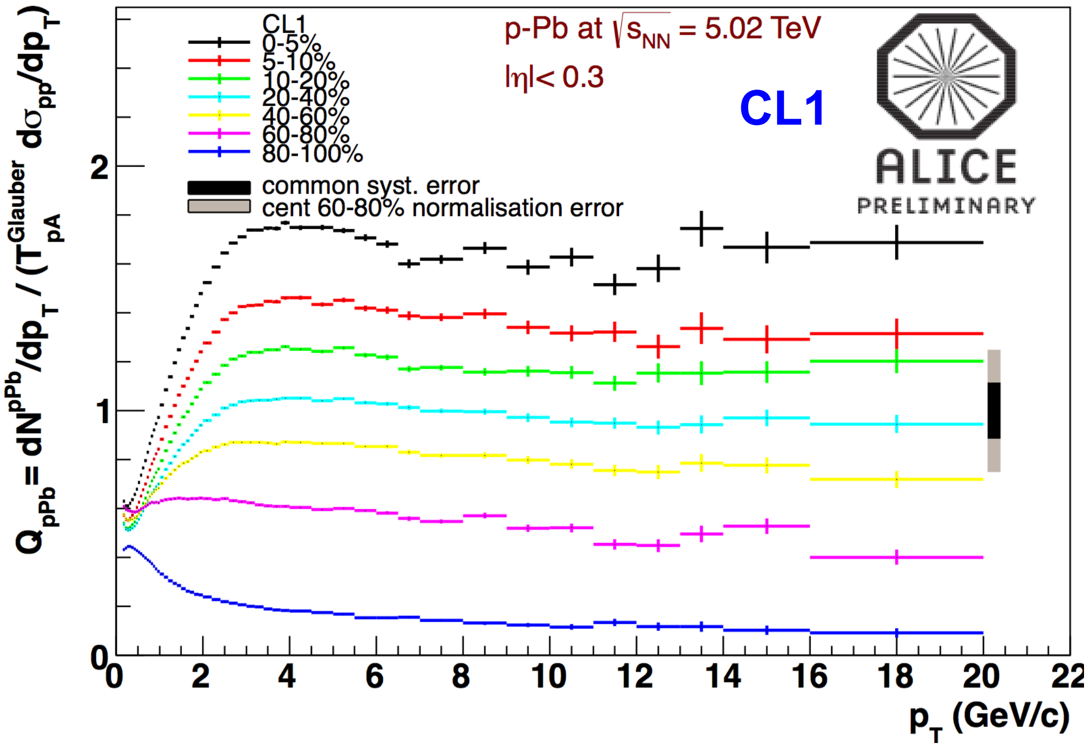
Bias from Different Estimators

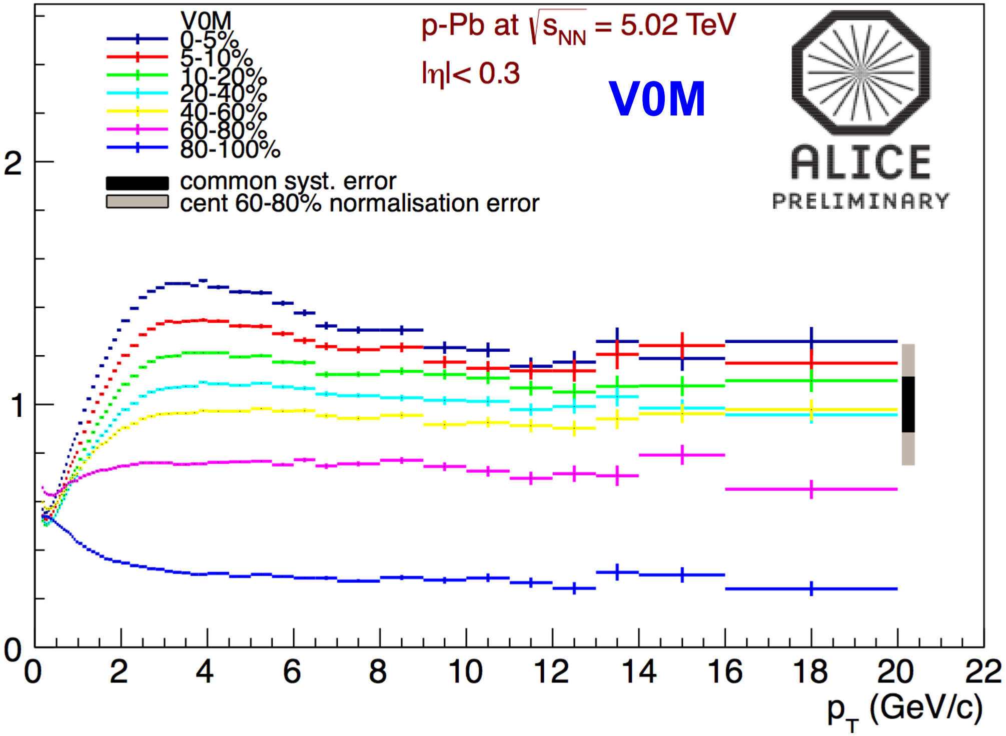
- Different centrality estimators expected to show different deviations from N_{coll} scaling
  - – CL1 (Clusters Pixel Layer 2): strong bias due to full overlap with tracking region.
    - Additional bias in peripheral event from “Jet veto effect”
    - Jets contribute to the multiplicity and shift 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

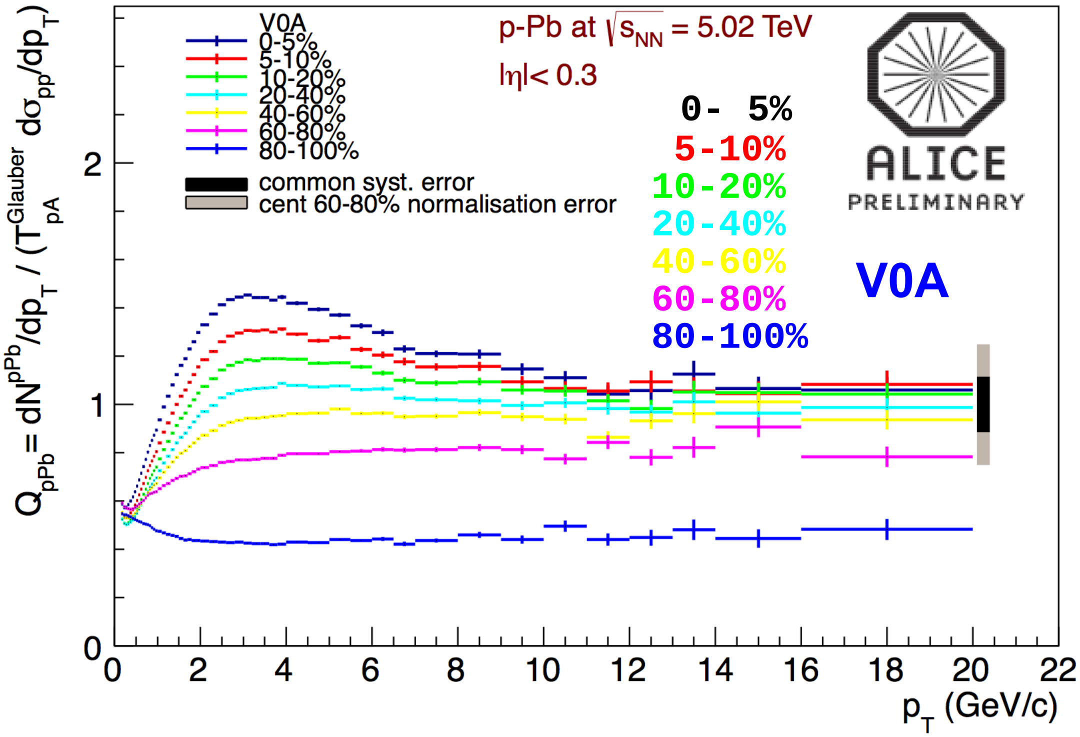
At high p_{T}

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

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





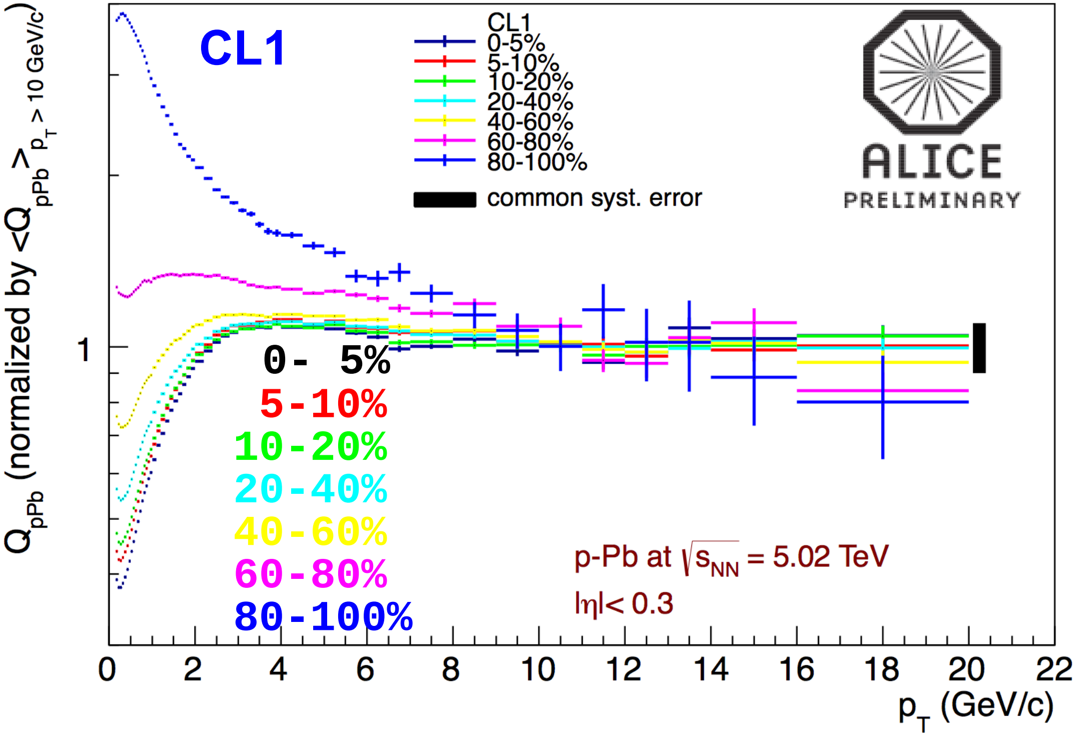


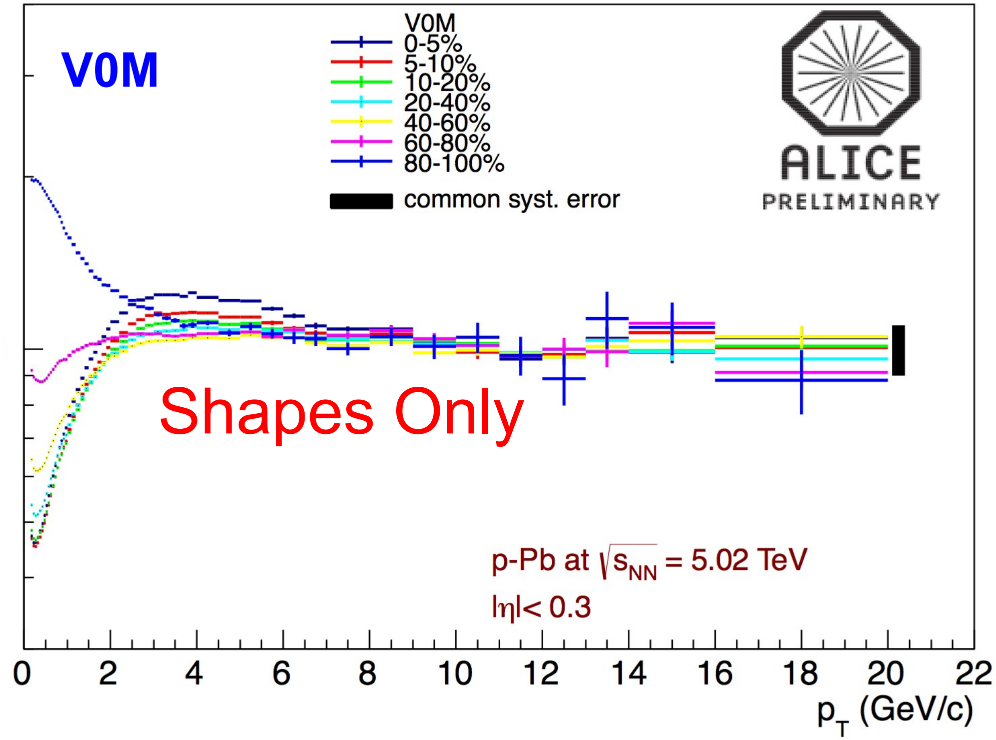
Not an R_{pPb} Measurement !

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

- Clear “jet veto bias” in CL1 80-100%

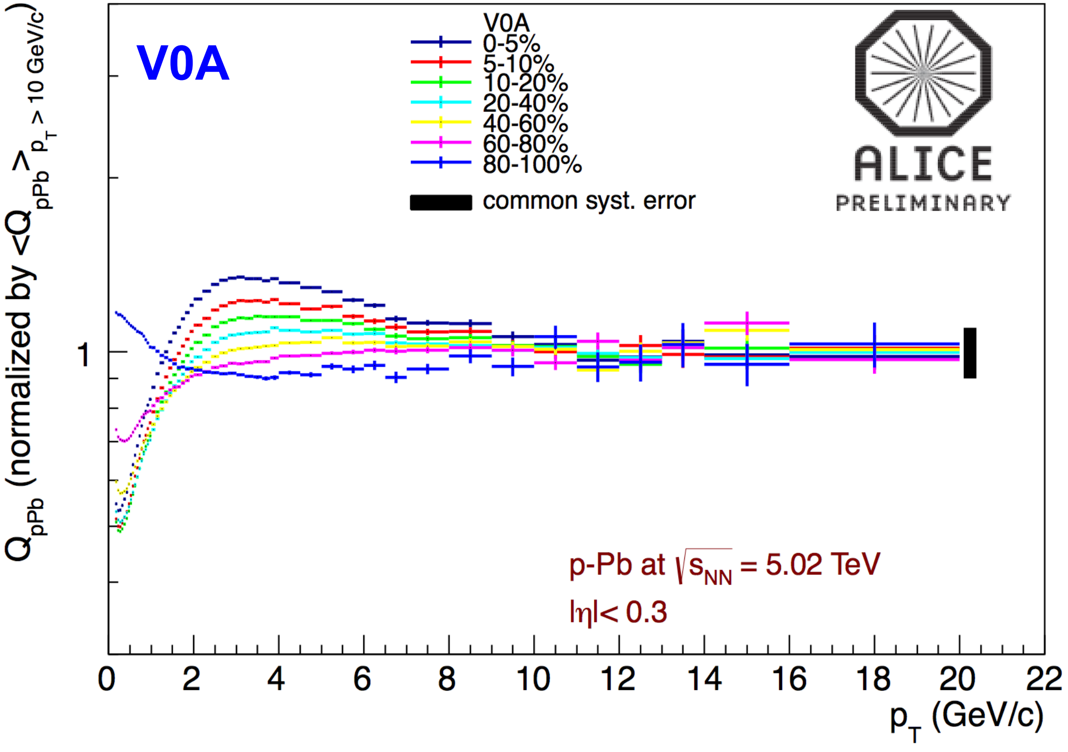
- No “jet veto” bias in V0A 80-100% but $Q_{pPb} < 1$

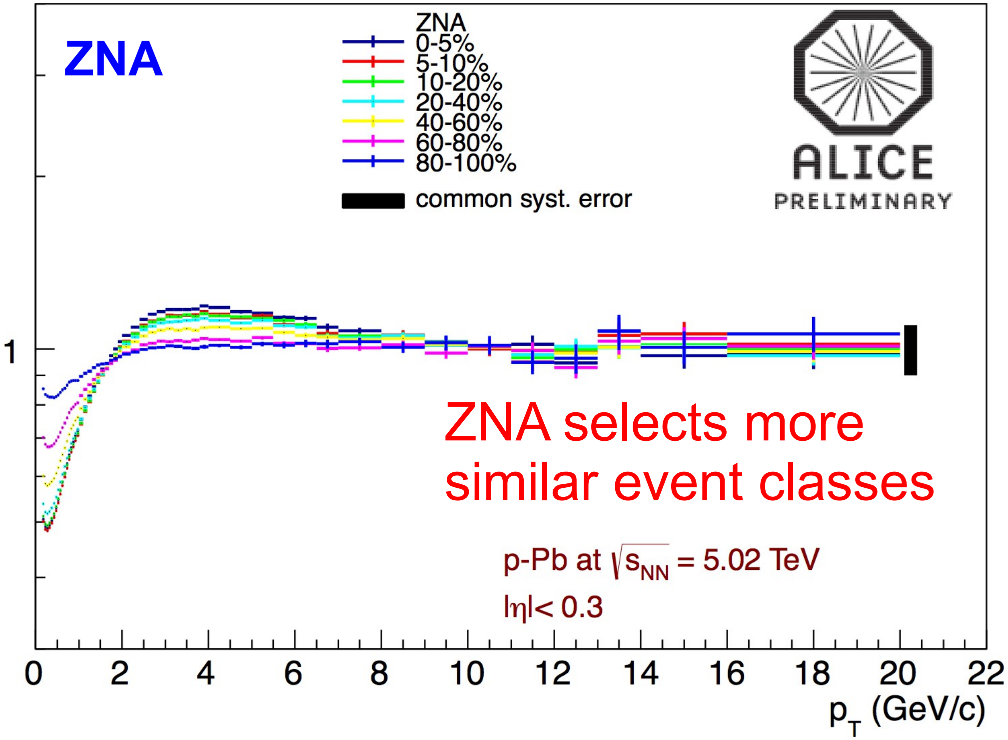




Shapes Only

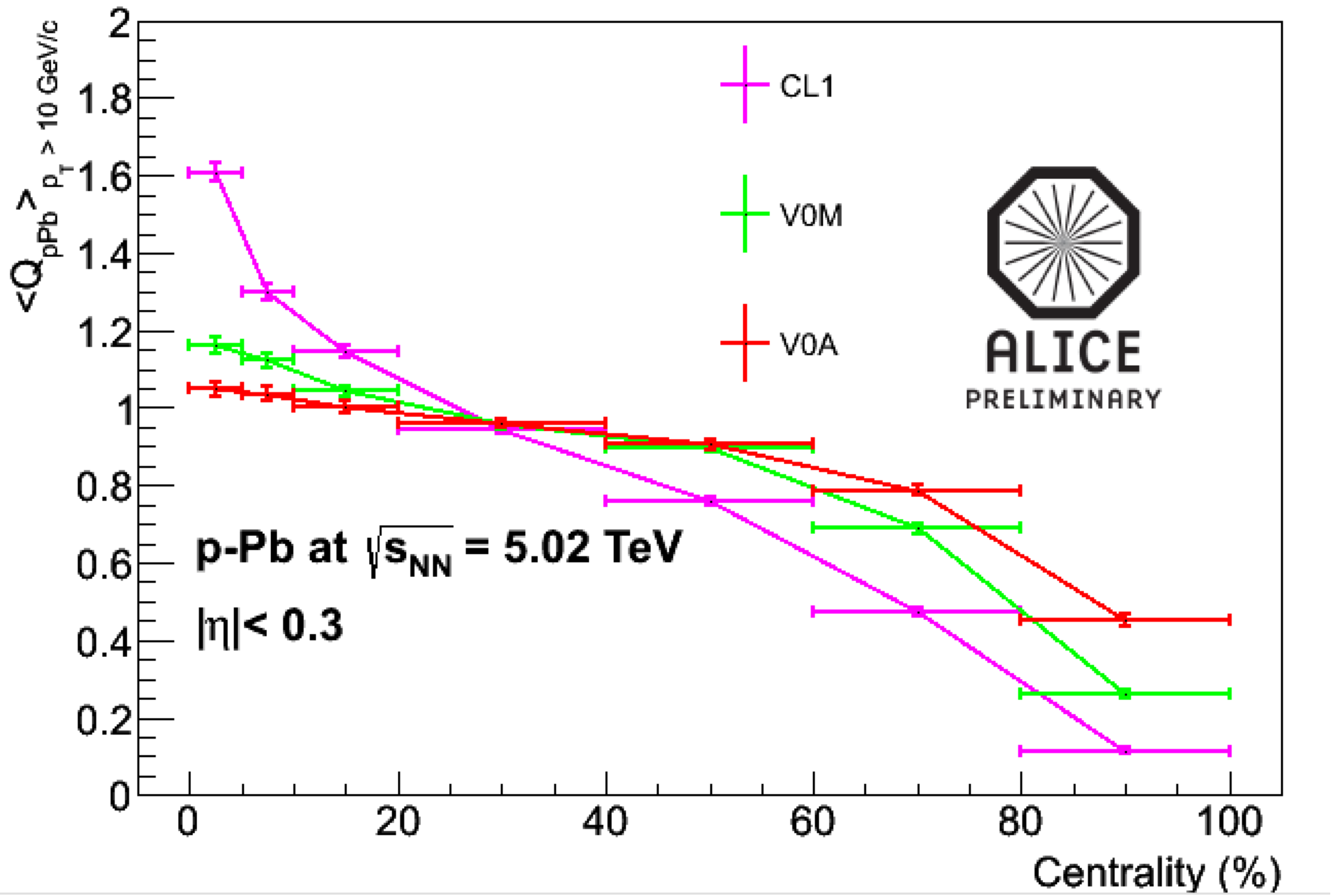
Cronin-like enhancement at p_T~ 3 GeV increases with centrality





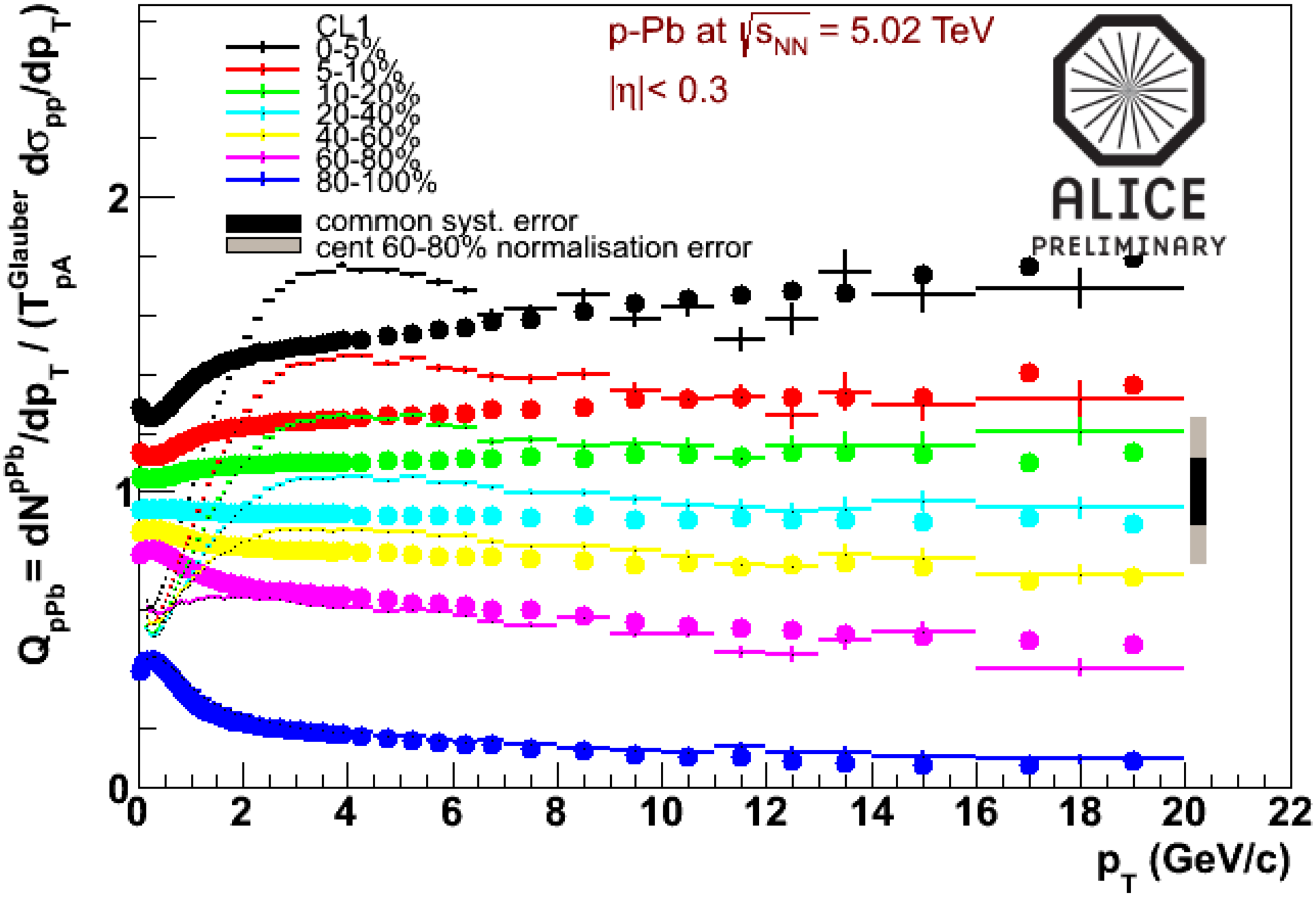
ZNA selects more similar event classes

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 (1)

- In pp and p-Pb a strong increase in $<p_T>$ with multiplicity is observed
  - In models for pp understood as consequence of color reconnections between strings produced in multi parton interactions
  - Similar effects in p-Pb ? collective flow (EPOS) ? Initial state effects ?
- v_2 coefficients of “jet”-subtracted identified particles show mass ordering and crossing of v_2 of protons and pions.
  - Pattern reminiscent of Pb-Pb collisions
  - Mass ordering also obtained in hydrodynamic calculations

Conclusions (2)

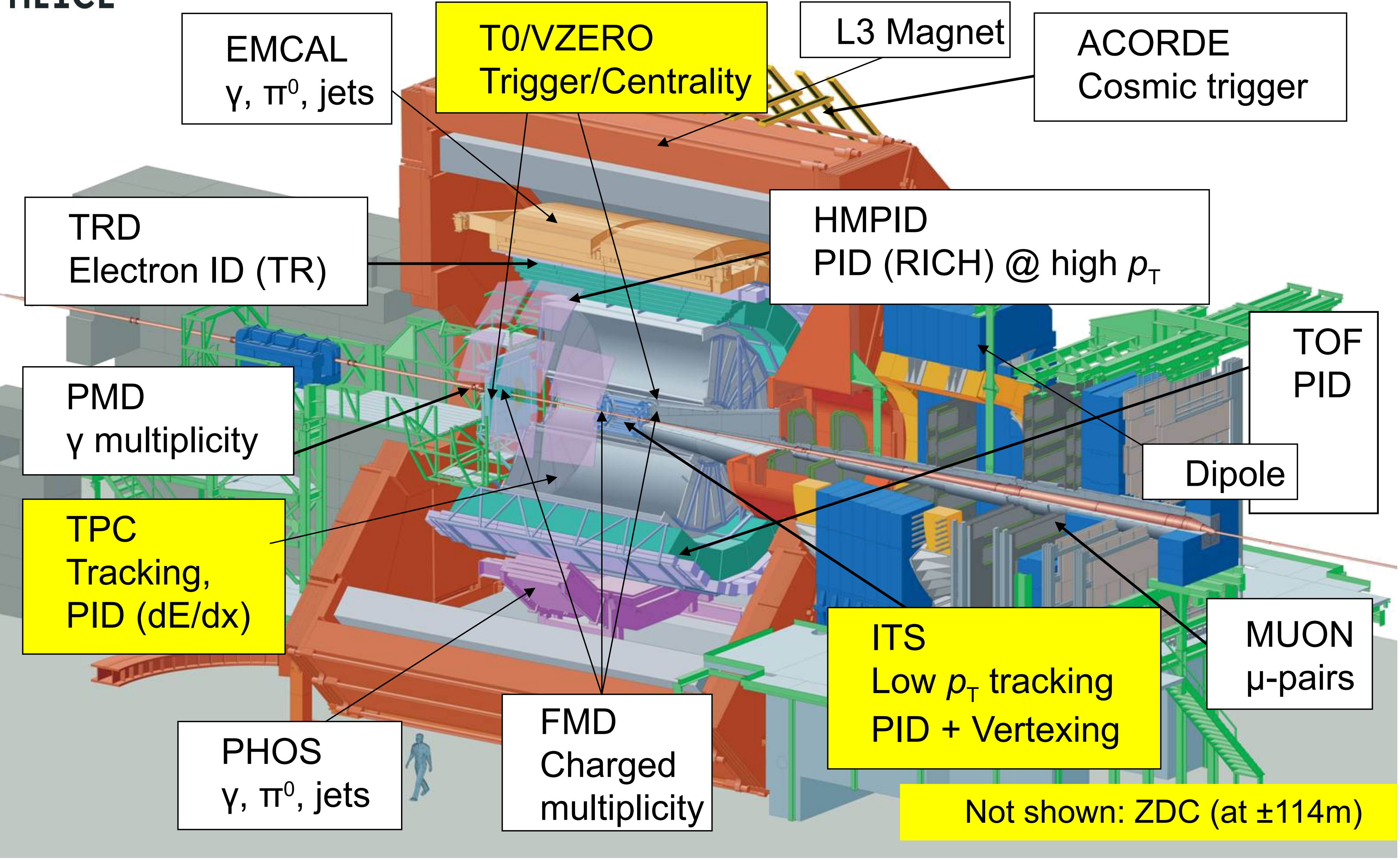
- Centrality estimators based on multiplicity measurements in $|\eta| < 5$ induce a bias on the hardness of the pN collisions that can be quantified by the number of hard scatterings per pN collision.
  - Low (high) – multiplicity p-Pb → lower (higher) than average number of hard scatterings.
  - Comparisons to incoherent superposition of pN collisions have to be performed including this bias.

Parallel Session p-Pb Talks

- D meson-hadron correlations in pp and p-Pb, F. Colomaria (26/7)
- J/Ψ production in p-Pb, I. Lakomov (26/7)
- Jet production and structure in pp, p-Pb and Pb-Pb, M. Verweij (25/7)
- Low mass vector meson production in pp, p-Pb and Pb-Pb, A. de Falco (25/7)
- D-meson production in p-Pb, G. Luperello (26/7)
- Electrons from heavy flavor hadron decays, M. Heide (26/7)
- Identified hadrons in p-Pb collisions, J. Anielski (26/7)
- Two-particle correlations in p-Pb collisions, L. Milano (26/7)

Back-Up

A Large Ion Collider Experiment



EMCAL
γ, π^0, jets

T0/VZERO
Trigger/Centrality

L3 Magnet

ACORDE
Cosmic trigger

TRD
Electron ID (TR)

HMPID
PID (RICH) @ high p_T

TOF
PID

PMD
γ multiplicity

Dipole

TPC
Tracking,
PID (dE/dx)

ITS
Low p_T tracking
PID + Vertexing

MUON
μ-pairs

PHOS
γ, π^0, jets

FMD
Charged
multiplicity

Not shown: ZDC (at ±114m)

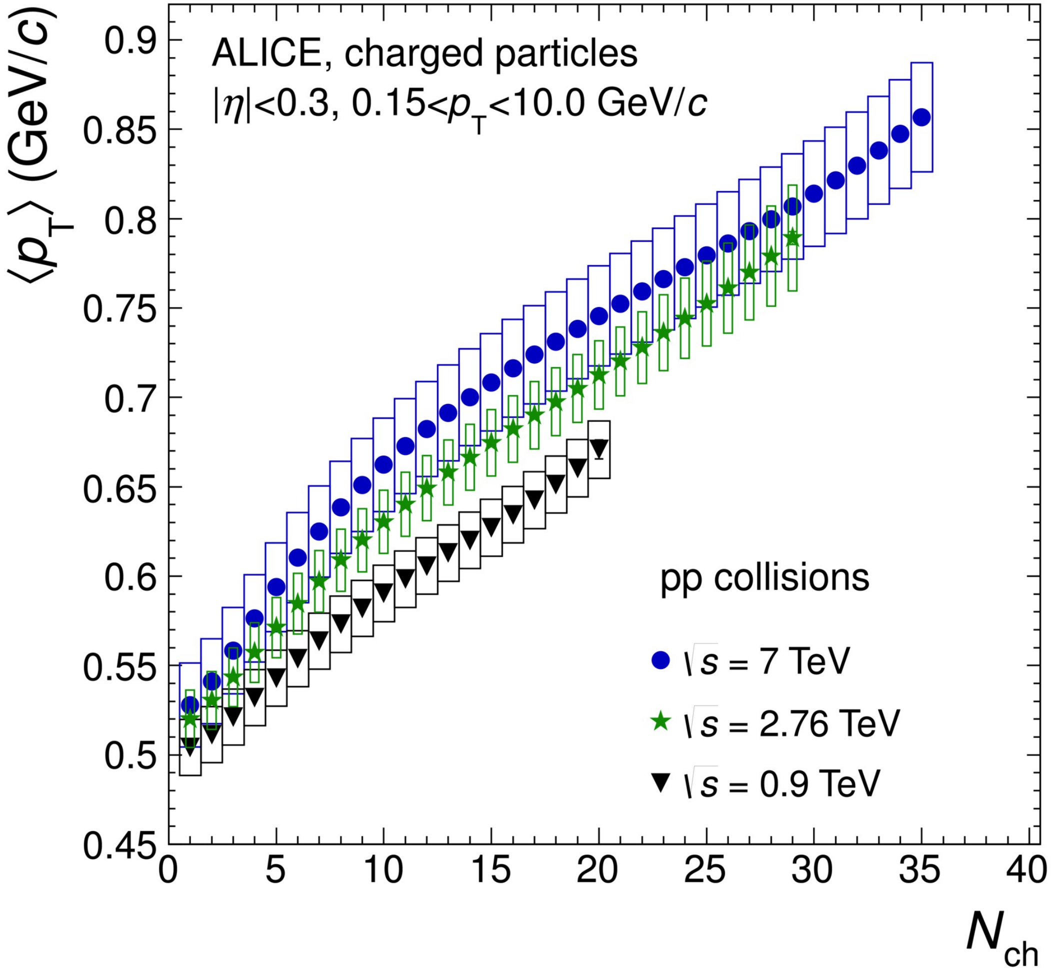
2013 LHC p-Pb Run

- 4 weeks in January and February 2013 at $\sqrt{s_{NN}} = 5.02$ TeV
  - p (8 TeV) + Pb (3.15 TeV)
  - Rapidity shift $\Delta y = -0.46$ in p-direction
- Maximum luminosity 4 x 10^{27} $cm^{-2}s^{-1}$
  - 10 kHz hadronic interactions
- ALICE collected
  - 10^8 minimum bias events
  - 30 nb^{-1} integrated luminosity

Excellent performance of the LHC !

$<p_T>$ in pp Collisions

ALICE, arXiv:1307.1094

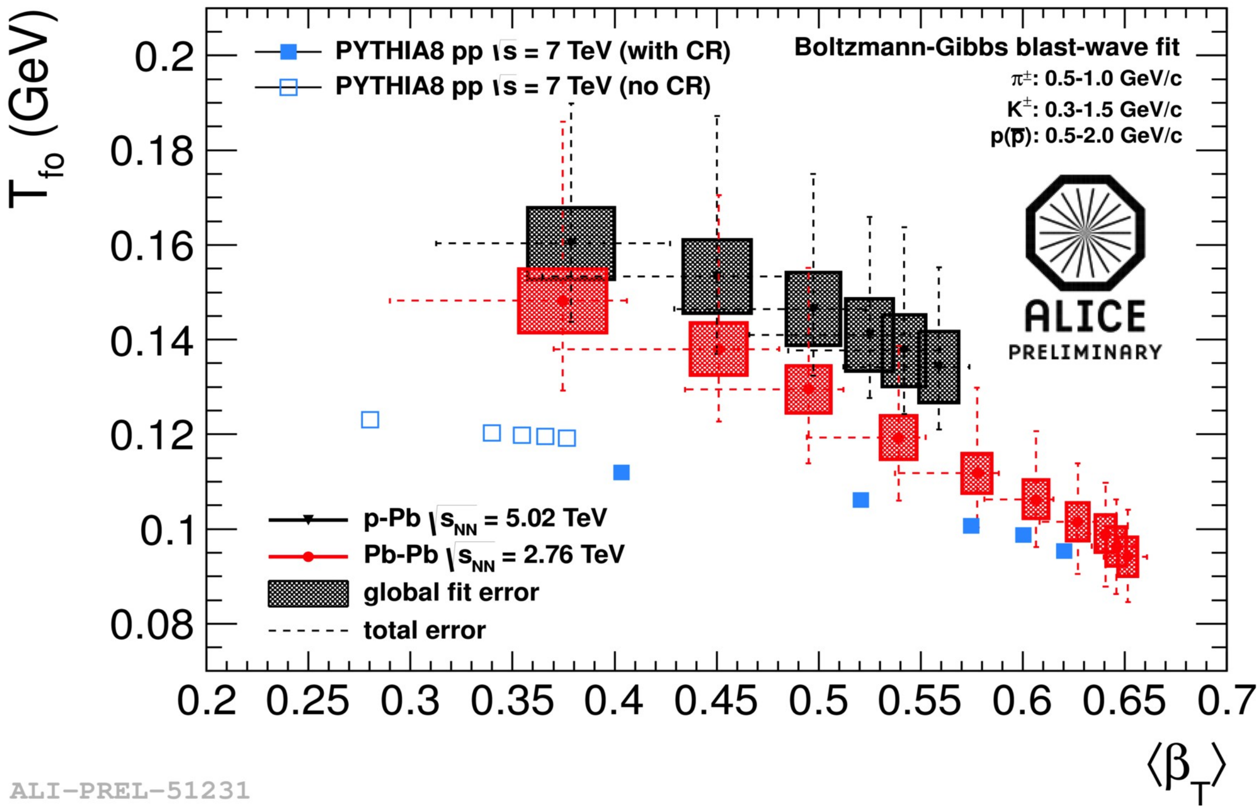


ALI-PUB-55936

- Strong increase of $<p_T>$ with Multiplicity
- At the same multiplicity, relatively mild increase between $\sqrt{s}$ = 2.76 TeV and $\sqrt{s}$ = 7 TeV
- $<p_T>$ at $\sqrt{s}$ = 7 TeV can be expected to be close to $\sqrt{s}$ = 5.02 TeV (p-Pb)
- Valid reference for p-Pb

Blast Wave Fit

- Mass ordering indication for common radial velocity
- Blast-Wave Fit tool to describe common features of spectra of all identified particles
  - Mean radial flow velocity: $<\beta_T>$
  - Freeze-out temperature: T_{fo}
  - Velocity profile: n



ALI-PREL-51231

Similar evolution of T_{fo} vs $<\beta_T>$ in p-Pb and Pb-Pb

At similar multiplicity T_{fo} similar in p-Pb and Pb-Pb but larger $<\beta_T>$in p-Pb

Caveat:

Pythia spectra also described by Blast-Wave Fit but no radial flow in Pythia

Color Reconnections increase $<\beta_T>$

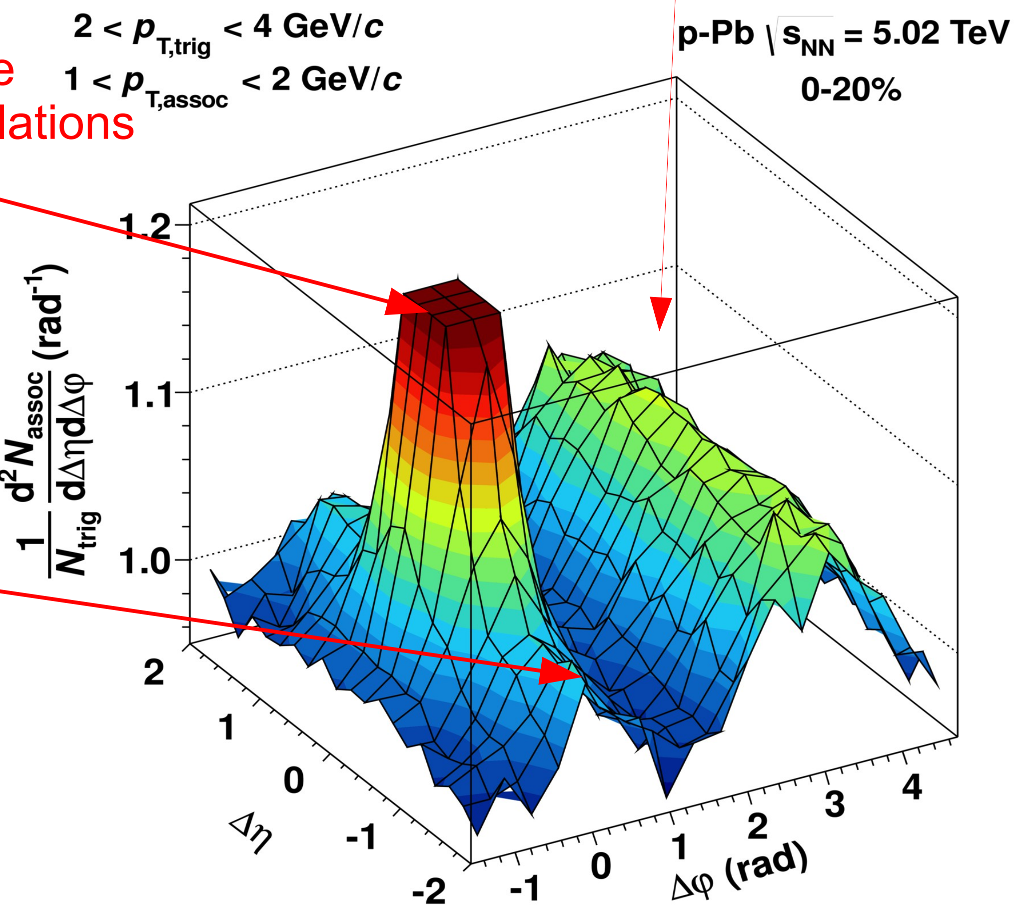
Δφ-Δη Correlations with Unidentified Particle

See also L. Milano
PS p-A collisions 26/7

Correlations between trigger and associated particles in p_T intervals $p_{T,\mathrm{assoc}} < p_{T,\mathrm{trig}}$

$$\frac{1}{N_{\mathrm{trig}}}\frac{d^2 N_{\mathrm{assoc}}}{d\Delta\varphi\, d\Delta\eta} = \frac{S(\Delta\varphi, \Delta\eta)}{B(\Delta\varphi, \Delta\eta)}$$

Pairs from
S: same event
B: mixed event



Away-side
Jet correlation + ridge ?

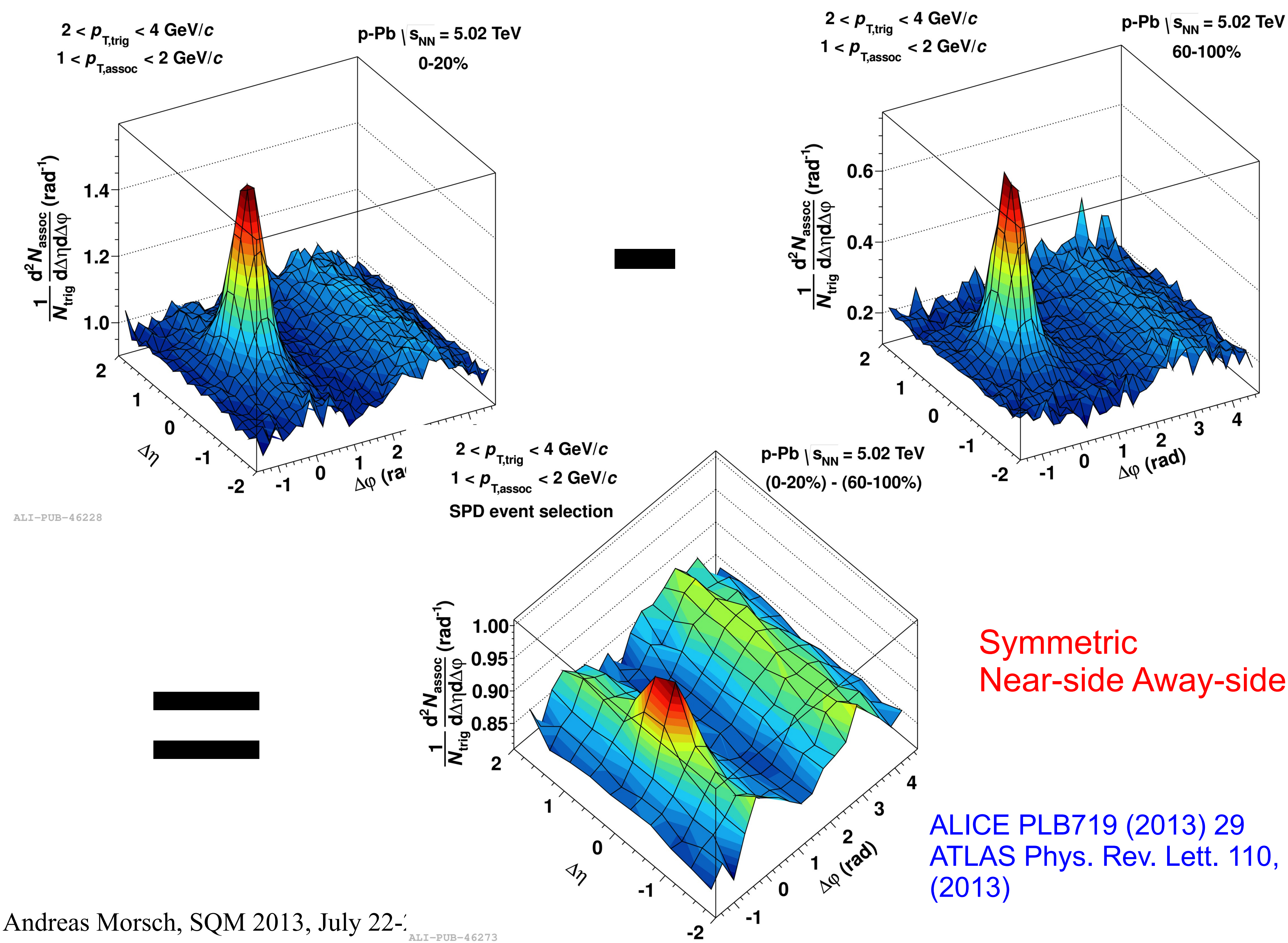
Near-side
Jet-correlations

Near-side
ridge

CMS Phys. Lett. B 718 (2013)795
ALICE PLB719 (2013) 29

Subtraction Method

See also L. Milano
PS p-A collisions 26/7

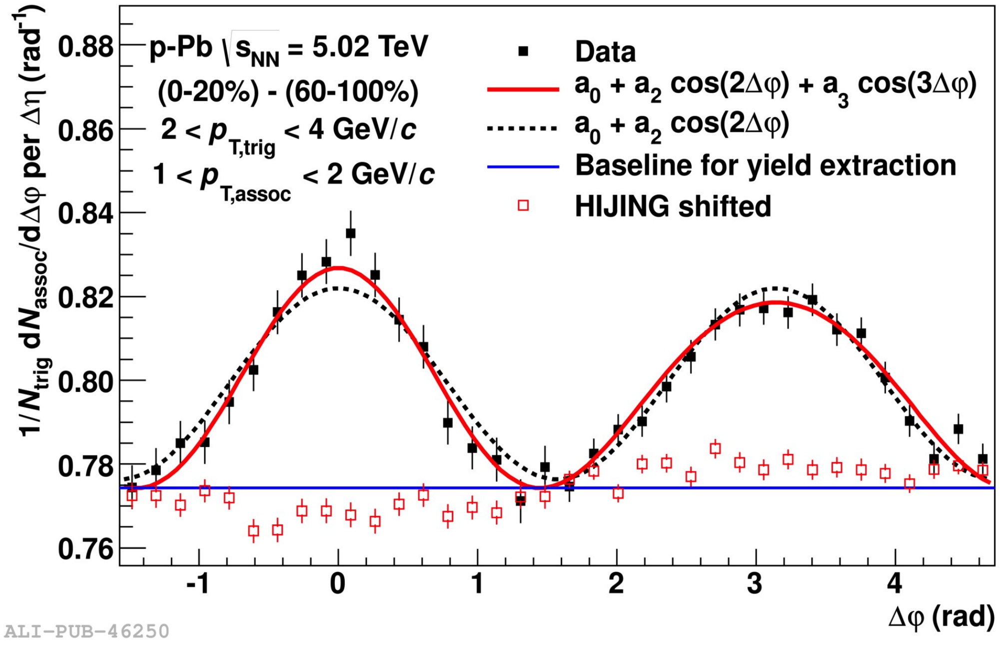


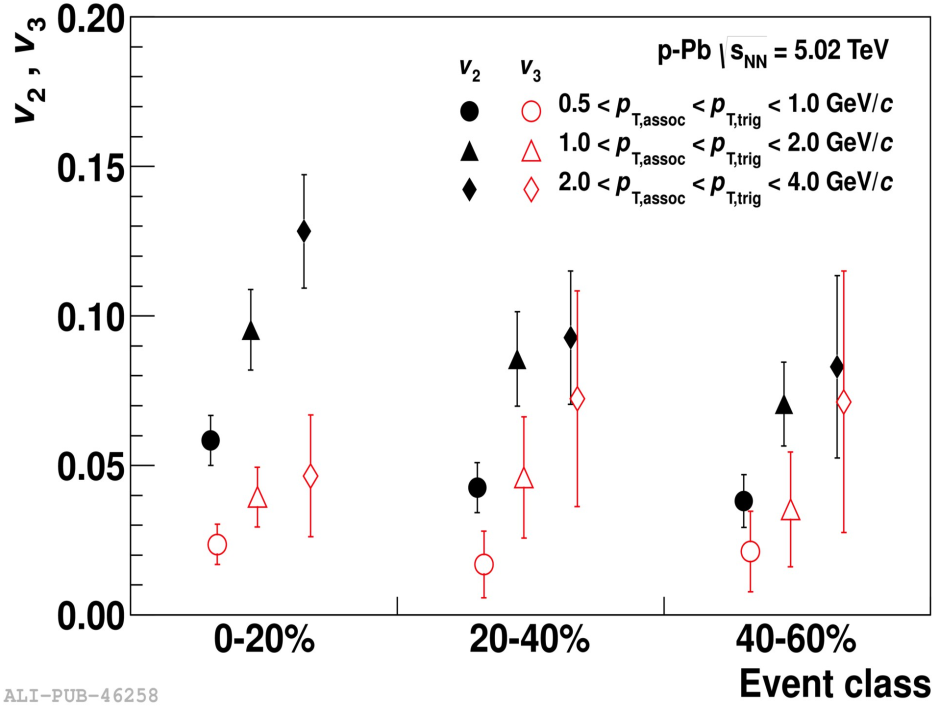
Symmetric
Near-side Away-side ridges !

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

Elliptic Flow in p-Pb ?

See also L. Milano
PS p-A collisions 26/7





Is it flow ?
Study identified particle correlations !

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

Glauber Extension in HIJING

- 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)

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

- (Poissonian) Probability for multiple hard collisions

$$p_i(b) = \frac{(\sigma_{hard} T_N(b))^j}{j!}\exp(-\sigma_{hard} T_N(b))$$

- Sum rules for Minimum Bias:

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

Centrality Estimators

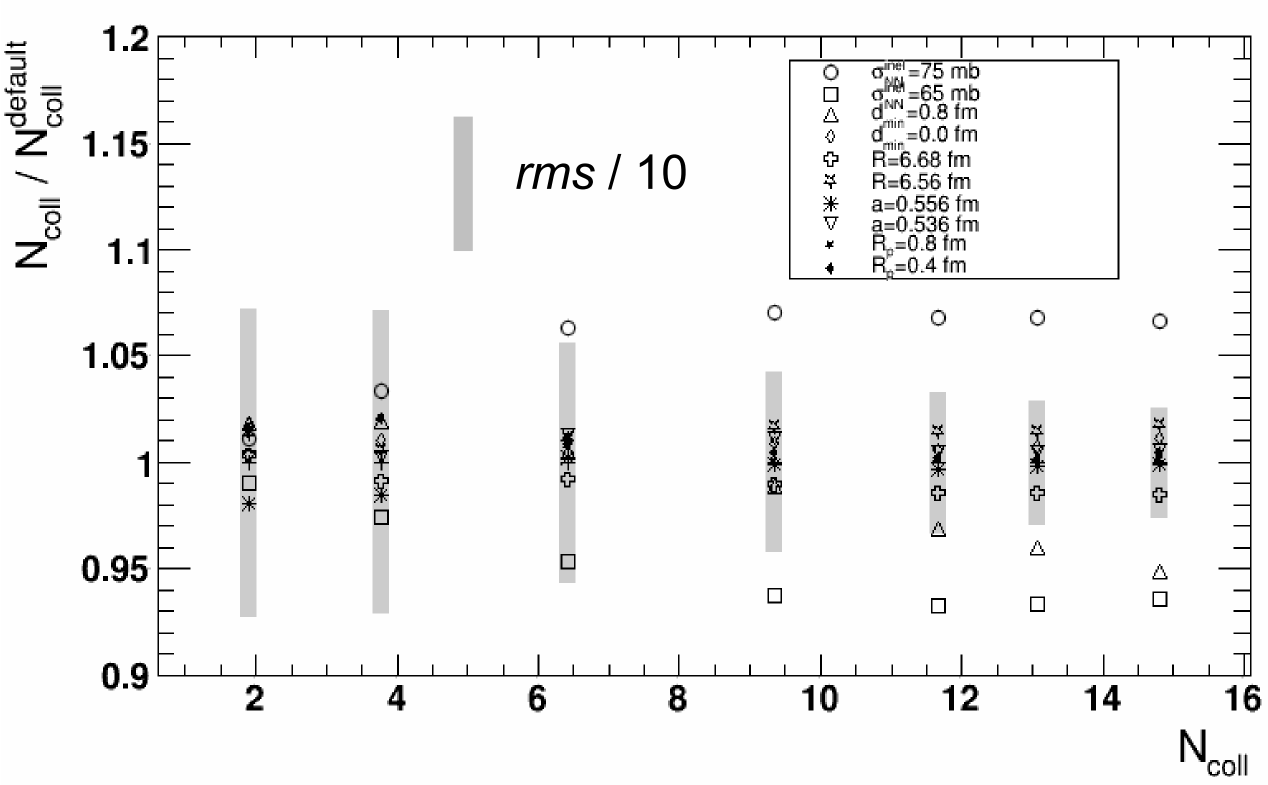
- Tracking Detectors
  - Full overlap with tracking region
    - TRK: Number of tracks
    - CL1: Clusters in 2nd Pixel Layer
- VZER0
  - Forward multiplicity
    - V0A: VZERO-A Multiplicity
      - (in pPb within Pb fragmentation region)
    - V0C: VZERO-C Multiplicity
    - V0M: V0A+V0C

Particle production modeled by Negative Binomial Distribution (NBD)

- ZDC
  - Slow nucleons
    - ZNA: neutrons
    - ZPA: protons

Nucleus fragmentation model:
Black nucleons: evaporation
Grey nucleons: knock-out

Systematic Error and MC Closure



Centrality (%)	HIJING	Glauber +NBD	Diff
0- 5	14.9	15.3	+2.7%
5- 10	13.6	13.5	-0.7%
10- 20	12.1	11.9	+2.7%
20- 40	9.7	9.5	-1.7%
40- 60	6.2	6.4	+3.4%
60- 80	2.97	3.56	+20%
80-100	1.45	1.79	+23%
MB	6.69	6.90	+3%

7% variation of σ_{pN} dominates since $\langle N_{coll} \rangle_{MB} = 208\ \sigma_{pN}/\sigma_{pPb}$

MC Closure:
Small absolute differences in 0-60% translate to large relative differences in 60-100%.

Large variance of N_{coll} within a centrality class.

Glauber Monte Carlo

- Glauber model: geometrical picture of p-A collision
  - Nucleons move on straight lines
  - p-N cross-section independent of the number of collisions the proton has undergone before
  - Nuclear density profile Wood-Saxon
    - Radius R = 6.62 ± 0.06 fm
    - Skin depth a = 0.546 ± 0.01fm
    - Imposed intra-nucleon distance 0.4 ± 0.4 fm
  - p-N inelastic cross-section
    - σ_{NN}=70 ± 5 mb at $\sqrt{s_{NN}}$ = 5.02 TeV
    - Proton radius R_p = 0.6 ± 0.2 fm
  - Uncertainties estimated by varying model parameters

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

Biases and Binary Scaling

- Fluctuations described by NBD have no stringent dynamic interpretation.
  - Except clan model: NBD describes a number of clans with a Poissonian probability distribution and the particle distribution for each clan is a log-series

$$Poisson(k\,; r\ln(1-p)) \circ \frac{-p^n}{n\ln(1-p)}$$

- 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 $T_N(b_{NN})$

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

Poissonian probability for multi hard interaction

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

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