CENTRALITY DEPENDENCE OF PARTICLE PRODUCTION IN p-Pb COLLISIONS WITH ALICE AT THE LHC

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on behalf of the ALICE Collaboration

OUTLINE

- Motivation
- Standard tools for geometry
- ALICE approach
- Results:
multiplicity
nuclear modification factors

Strangeness in Quark Matter 2015

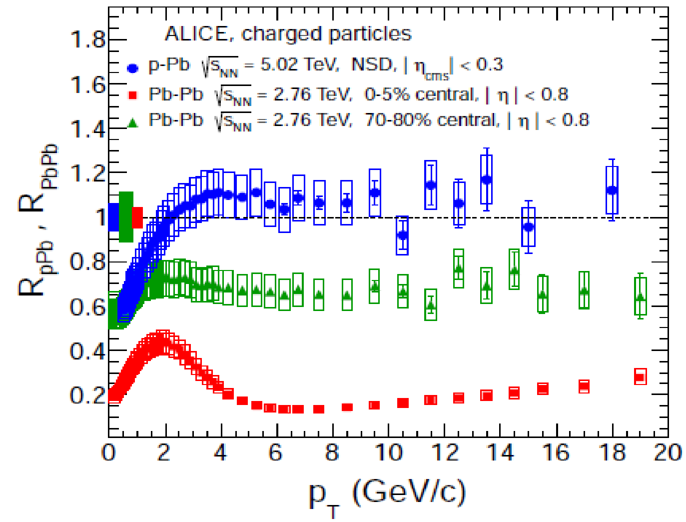
Dubna (Russia)

MOTIVATION

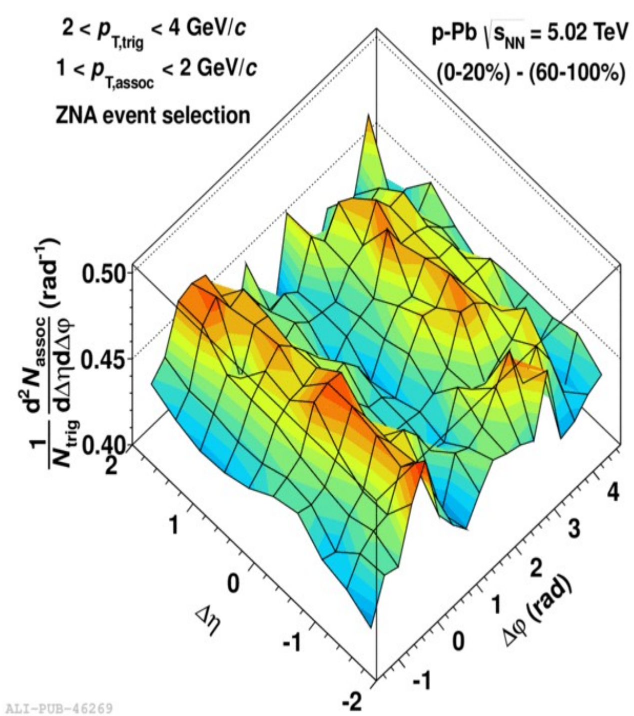
R_{pPb} (N_{ch})

Benchmark measurements **R_{pPb} ~1**

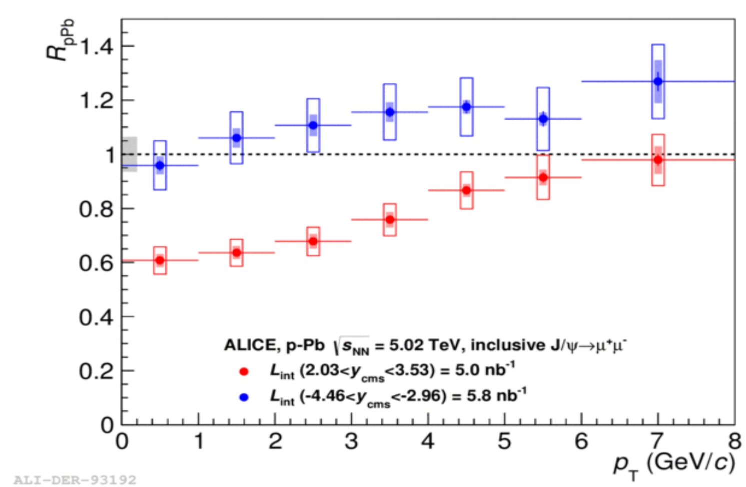
no nuclear effects in p-Pb
→ suppression in Pb-Pb
is a final state effect



DOUBLE RIDGE



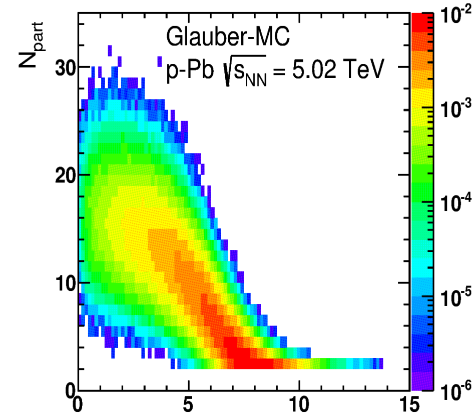
Measurements at low-p_T
not explained with Ncoll x pp
→ **coherent/collective** effects?
Strength increase with mult.
→ **geometry** dependence



R_{pPb} (J/ψ)

Importance of
cold nuclear matter
effects to interpret J/ψ
suppression in Pb-Pb

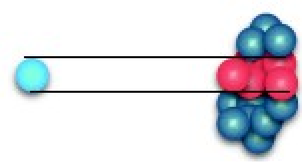
Geometry dependence: centrality

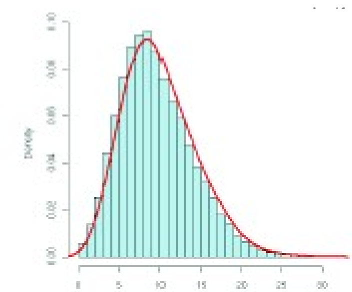


- Centrality: classification of collision geometry based on a measured observable
- Impact parameter b controls <Ncoll>
  - for small systems b weakly correlated with Npart

Centrality estimator related via a **Glauber model** to Ncoll

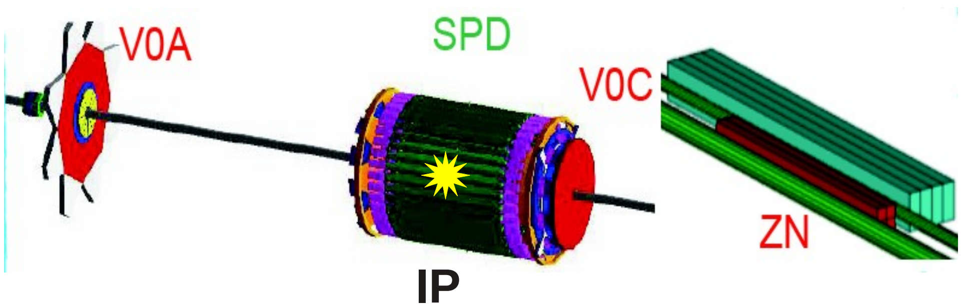
- description of the observable through a model
- conditional probability **P(M | Ncoll)**
- classify events as % of cross-section
- <Ncoll> in each centrality bin





Glauber MC: $P(N_{coll})$ ⊗ Model: $P(M|N_{coll})$

Centrality detectors in ALICE



- **Mid-rapidity**: ITS $|\eta|<2$, $|\eta|<1.4$
- **Forward**: V0A $2<\eta<5.1$
  V0C $-3.7<\eta<-2.7$
- **Beam-rapidity**: neutron ZDC (ZN) $|\eta|<8.7$

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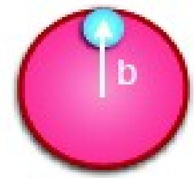
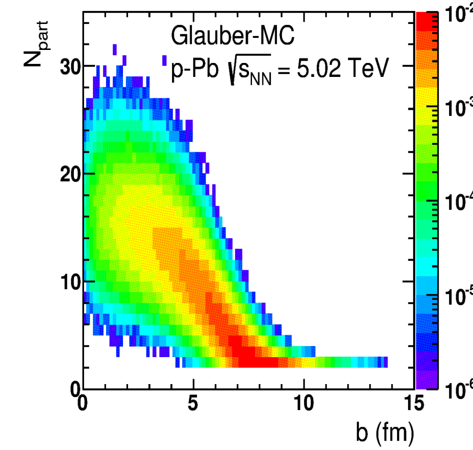
GEOMETRY DEPENDENCE: CENTRALITY

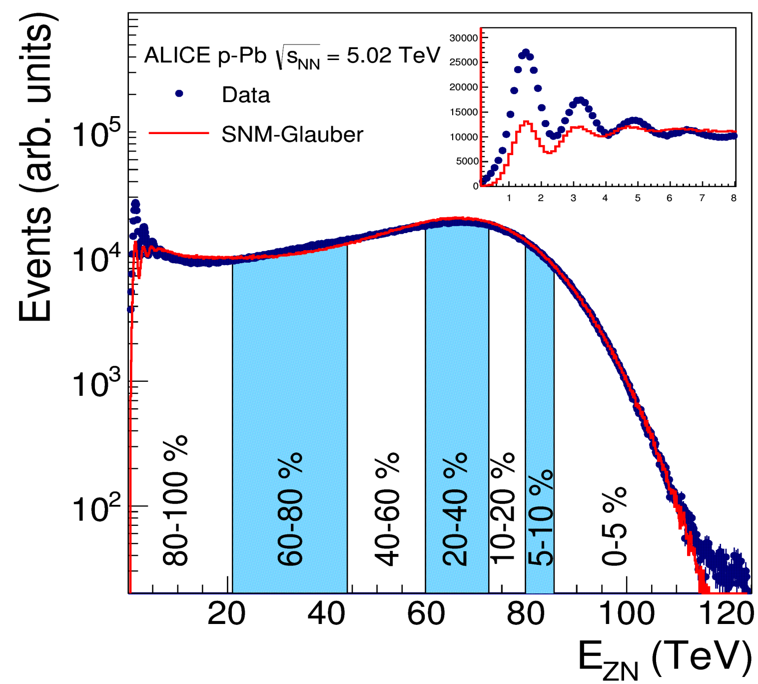
- Centrality: classification of collision geometry based on a measured observable
- Impact parameter b controls <Ncoll>
  - for small systems b weakly correlated with Npart



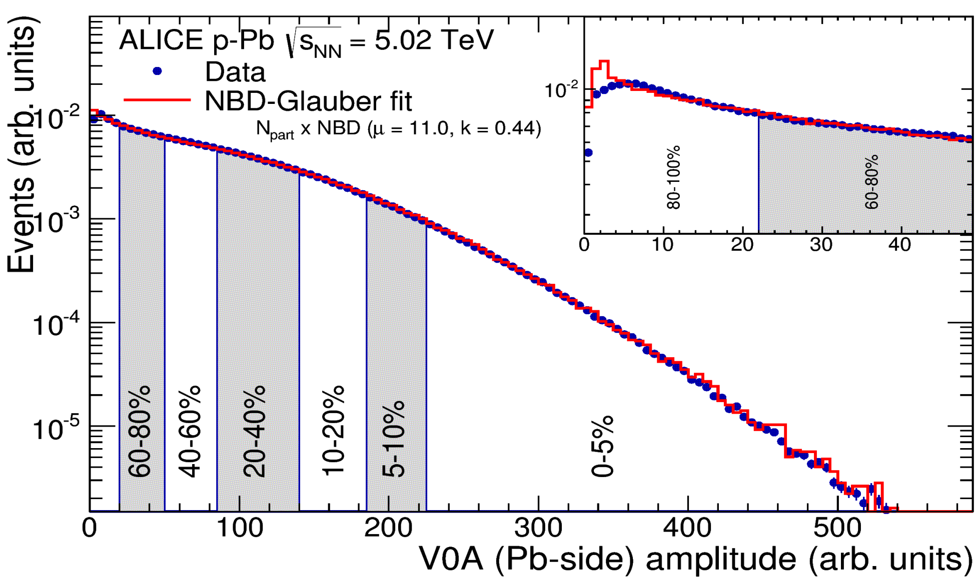


Centrality estimator related via a Glauber model to Ncoll
- description of the observable through a model
- conditional probability P(M | Ncoll)
- classify events as % of cross-section
- <Ncoll> in each centrality bin

Glauber + **Slow Nucleon Model**



Glauber + **Negative Binomial Distribution**



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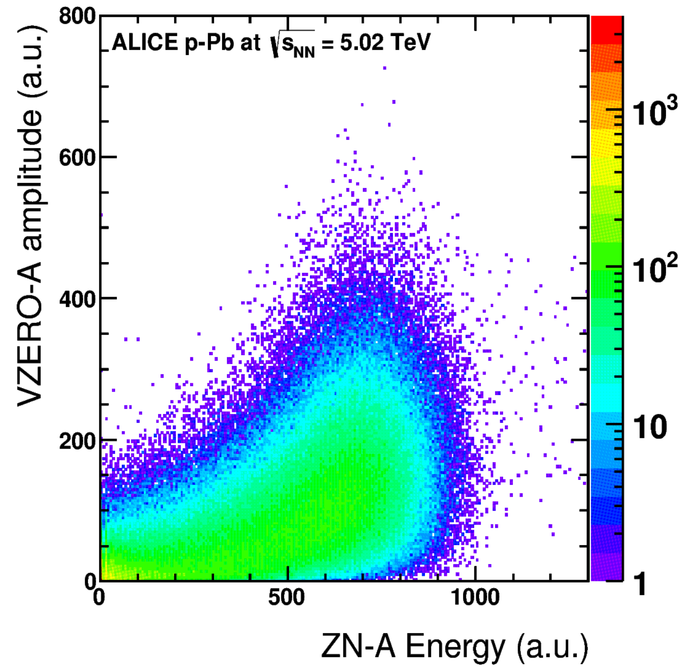
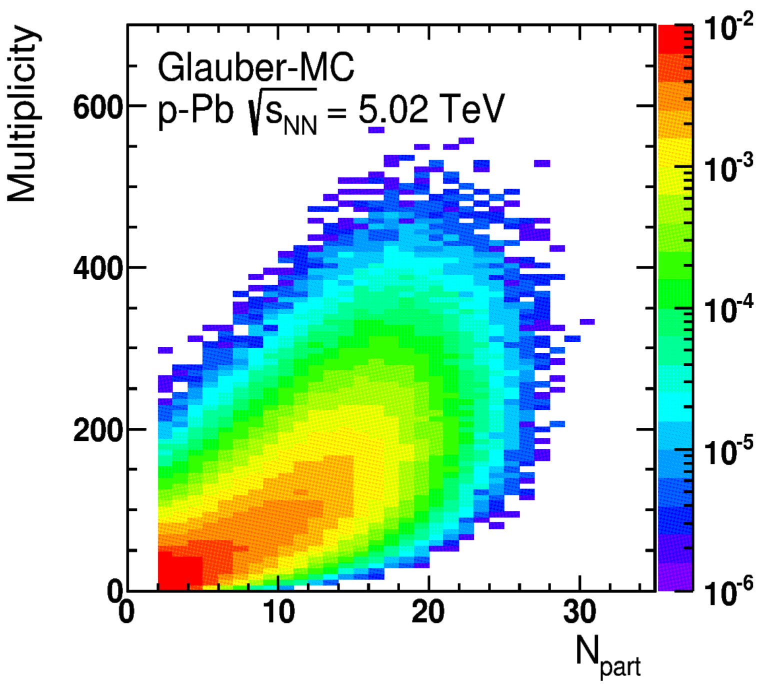
GEOMETRY DEPENDENCE: CENTRALITY

1) Verify the **connection** of the measurement **to the collision geometry**:
- correlating observables from **kinematic** regions **casually disconnected** after collision
- comparing Glauber MC and data for a **known process**





2) Demonstrate the **consistency** of the approach:
- check if the centrality selection could induce a **bias in the geometry parameters**
  - → selection in a system with large relative **fluctuations** can induce a bias
- need to identify the **physics origin** of the bias to correct centrality dependent measurements

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BIASES IN pA

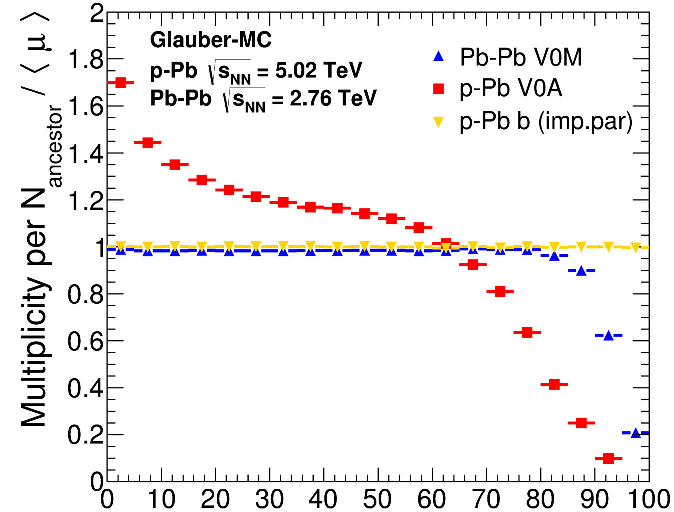
- **Multiplicity bias:** fluctuations sizable
  → centrality selection based on multiplicity may select a sample on NN collisions biased w.r.t. a sample defined by cuts on b

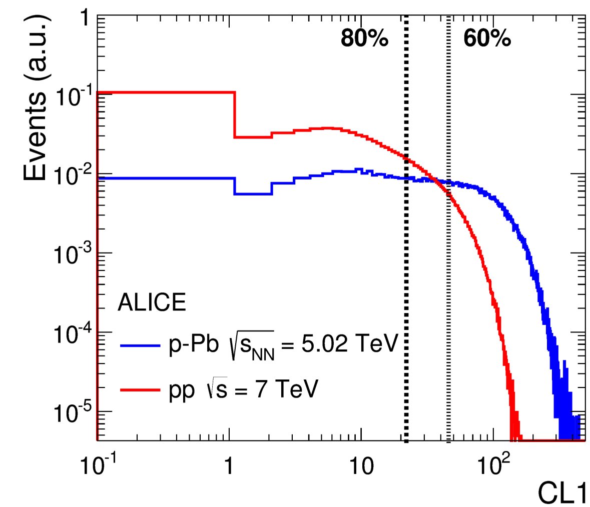
- MC generators: multiplicity fluctuations are due to fluctuations in MPIs
  → bias in mult ~ bias in hard scattering

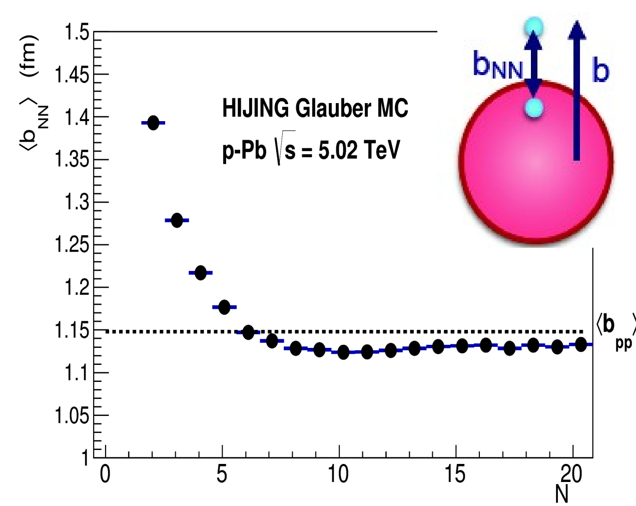
- **Jet-veto:** multiplicity range in peripheral events represent an effective veto on hard processes

- **Geometry bias:**
  Mean nucleon-nucleon impact parameter (b_{NN}) increases in peripheral collisions
  → reduced number of MPI for peripheral events

→ $Q_{pPb} = R_{pPb}$ INCLUDING POSSIBLE BIASES







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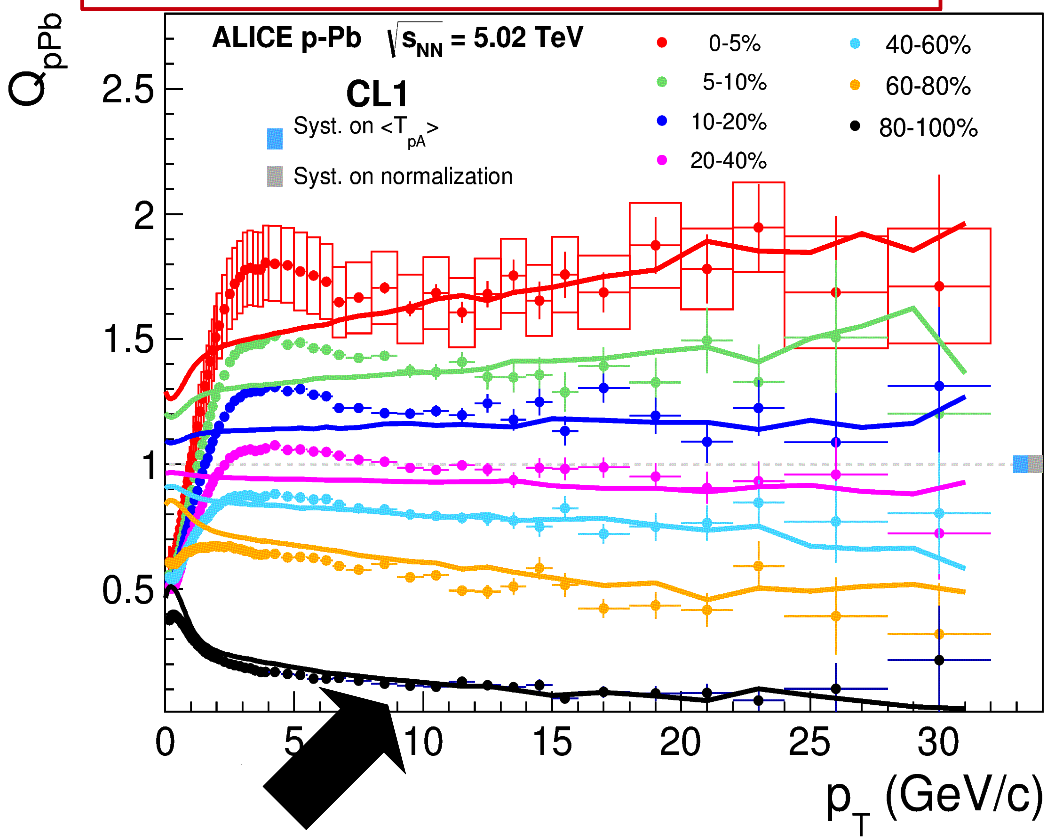
DEVIATIONS FROM BINARY SCALING

Selecting events according to **multiplicity leads to a bias**
→ Expected deviations from binary scaling at high p_T

Q_{pPb} (NCH) CENTRALITY: SPD |η| < 1.4



- **Central:**
  higher <mult/source> → R_{pPb}>1
- **Peripheral**:
  lower <mult/source> → R_{pPb}<1

→ large spread **NOT** related to nuclear effects!

Jet-veto effect in most peripheral bin with a significant negative slope vs p_T

G-PYTHIA: Incoherent superposition of N-N PYTHIA collisions reproduces data

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THE ALICE APPROACH

1) assumption: an event selection based on **Zero Degree Energy** does not induce bias on bulk particle production at midrapidity

2) assumption: mechanism of **particle production**

$\langle N_{coll} \rangle = 208\,\sigma_{pN}/\sigma_{pA} = 6.9$ with
$\sigma_{pN} = 70$ mb
$\sigma_{pPb} = 2100$ mb

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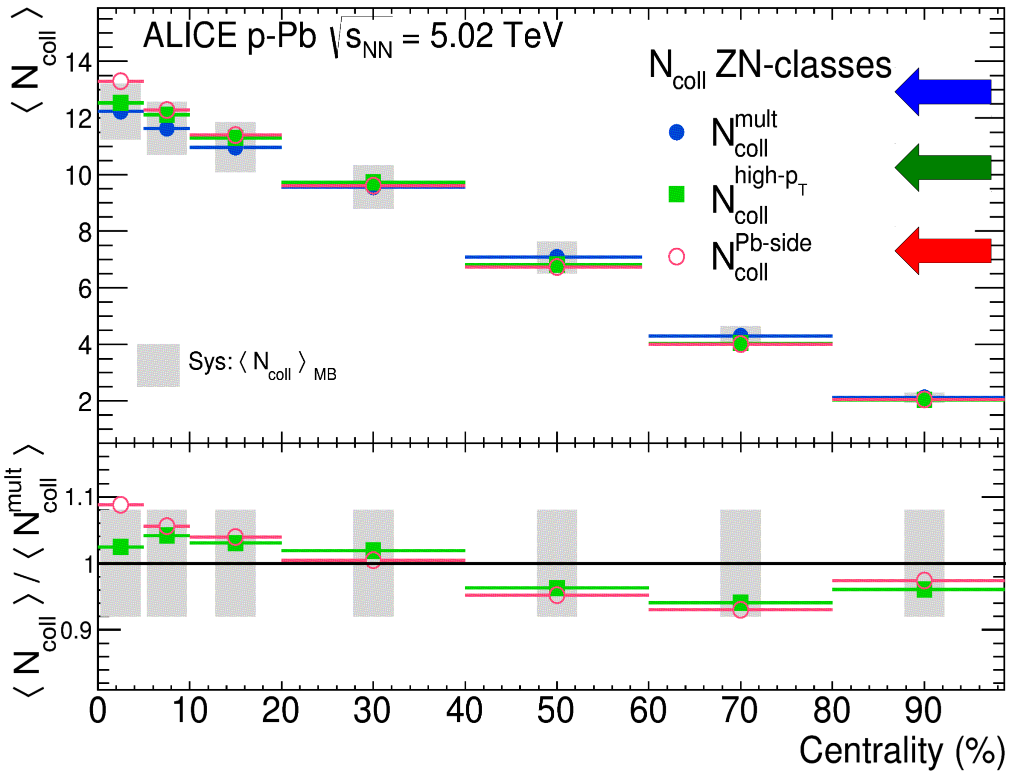
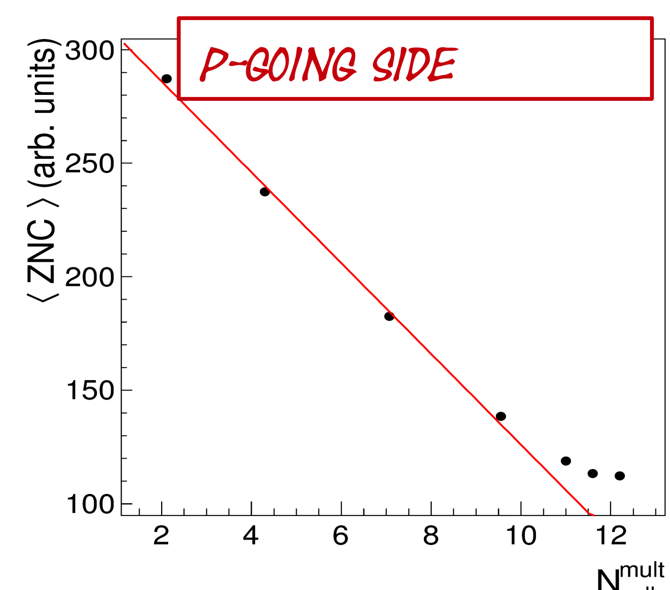


a) **Mid-rap** $dN/d\eta \sim$ **N_{part}**

b) Yield at **high-p_T** $\sim$ **N_{coll}**

c) **Pb-side** $dN/d\eta \sim$ **N_{part}^{target}** (= N_{coll} in pA)

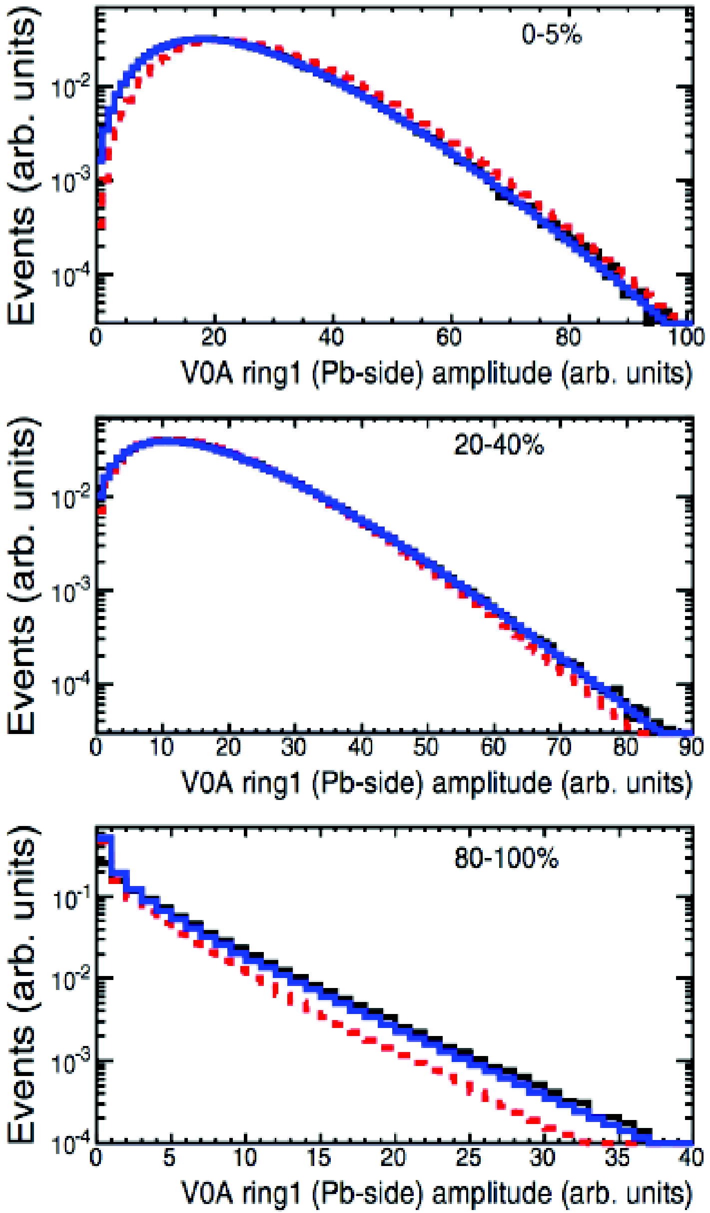


consistent with a longitudinal energy transfer of the proton proportional to the number of binary collisions.

- All values within at most 10%
→ consistency of assumptions
- This does not yet prove the validity of any (or all) of these assumptions

CONSISTENCY CHECK

ZNA: Zero Degree Energy
V0A: Forward Multiplicity



- ZNA and V0A: establish their relation to centrality ➧ P(Ncoll)
  - P(Ncoll) distributions in ZNA bins ⊗ NBD from Glauber fitto MB V0A multiplicity ➧ P(Ncoll)
  - unfolding: P(Ncoll) distributions ⊗ NBD from Glauber fits V0A data in ZNA centrality bins ➧ P(Ncoll)

does not work for biased centrality selection (CL1)

→ energy measured by ZN is connected to the collision geometry
→ ZNA unbiased centrality selection

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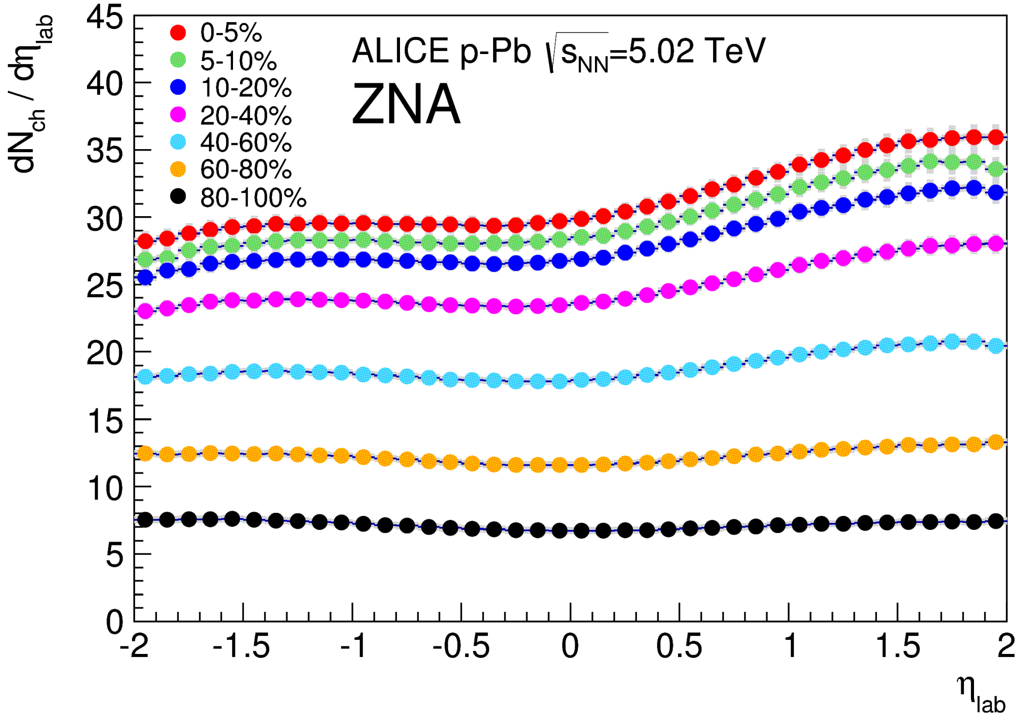
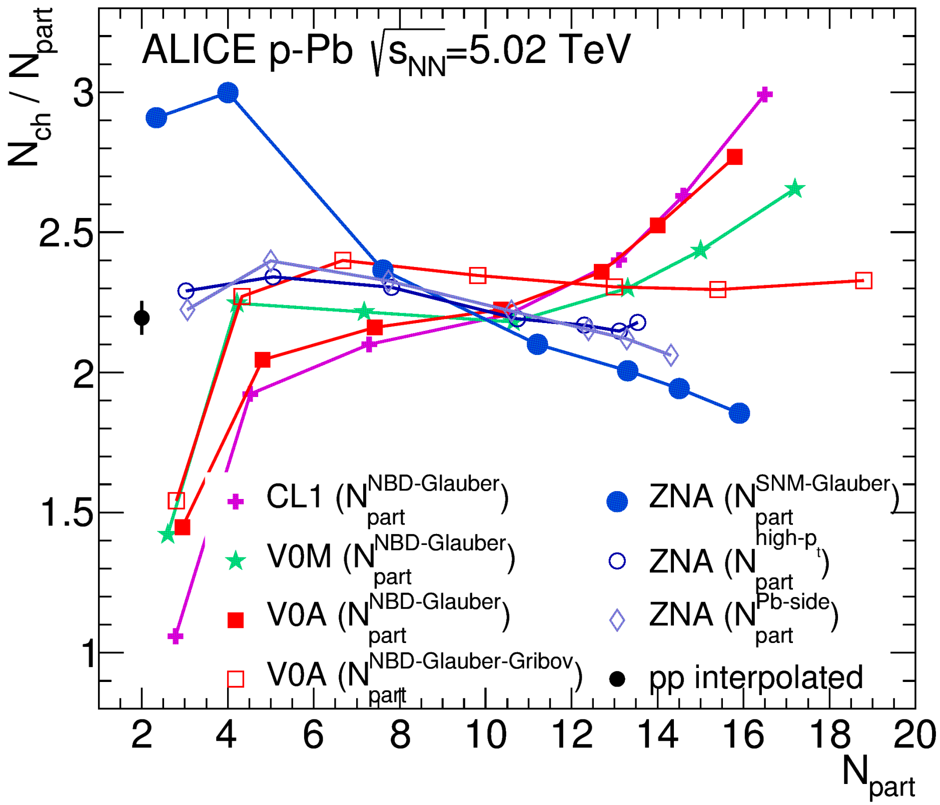
DN/Dη AT MIDRAPIDITY





- **V0A (Glauber)** steeper than linear increase in Npart
- **V0A (Glauber-Gribov)** linear scaling with Npart apart from the peripheral point
- **ZN centrality** + assumptions on scaling for high-p_T and Pb-fragmentation side yields show linear scaling with Npart within 10% and the peripheral bin agrees with pp data

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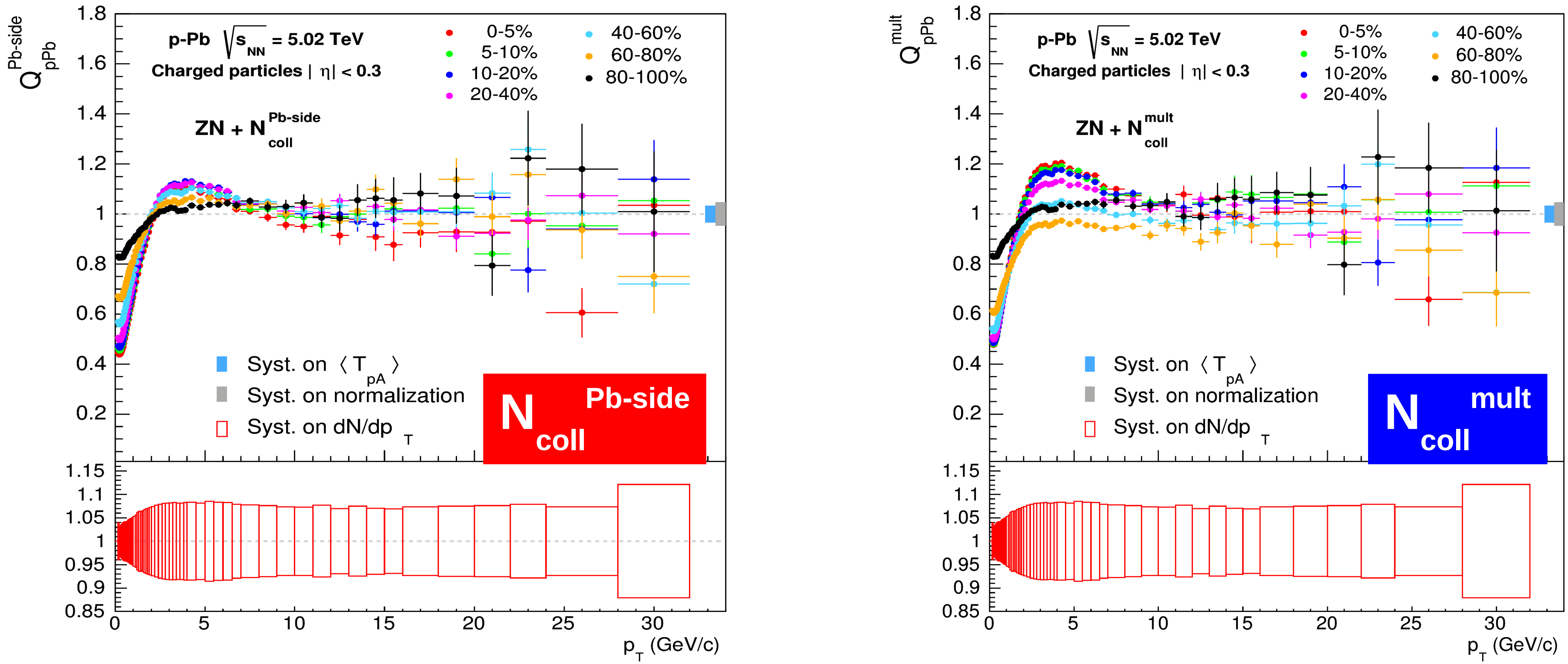
NUCLEAR MODIFICATION FACTOR

Q_{pPb} (NCH) CENTRALITY: ZERO DEGREE ENERGY



- Nuclear modification factors **consistent with unity** at high p_T for whole centrality range
- intermediate-p_T enhancement (**“Cronin”**) increases with centrality
- Results from the 2 assumptions used here are in agreement within uncertainties
- The geometry bias effect is still present in the most peripheral bin

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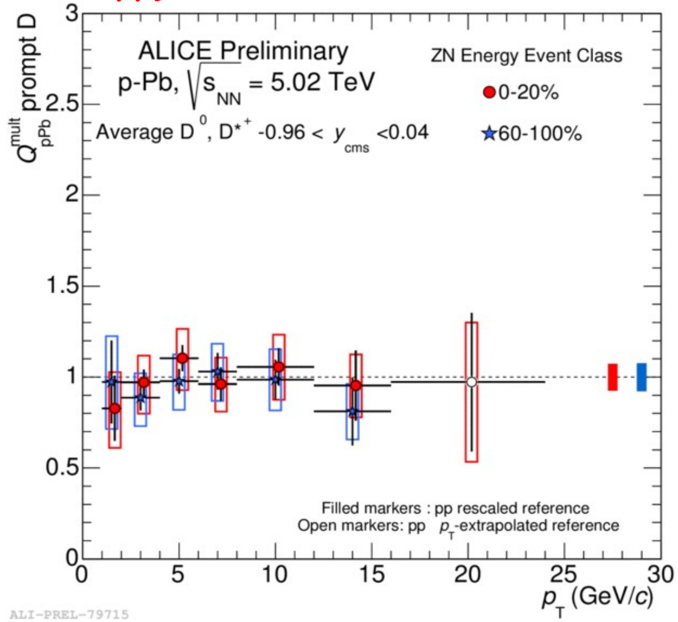
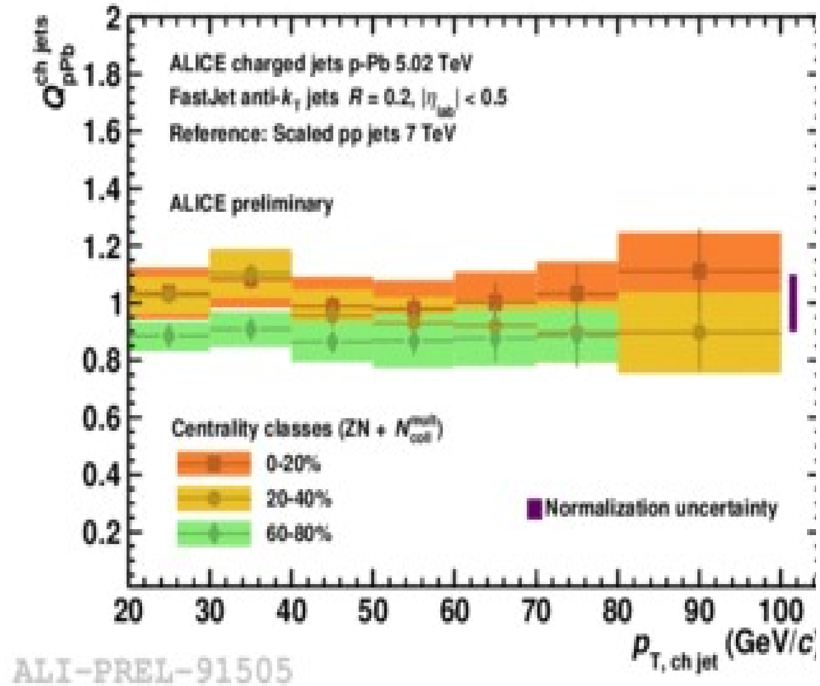
… and many more pA results vs. centrality…

R. Bailhache, Thu 10:00
A. Festanti, Thu 17:00
A. Barbano, Thu 15:40

Q_{pPb} (D-mesons)

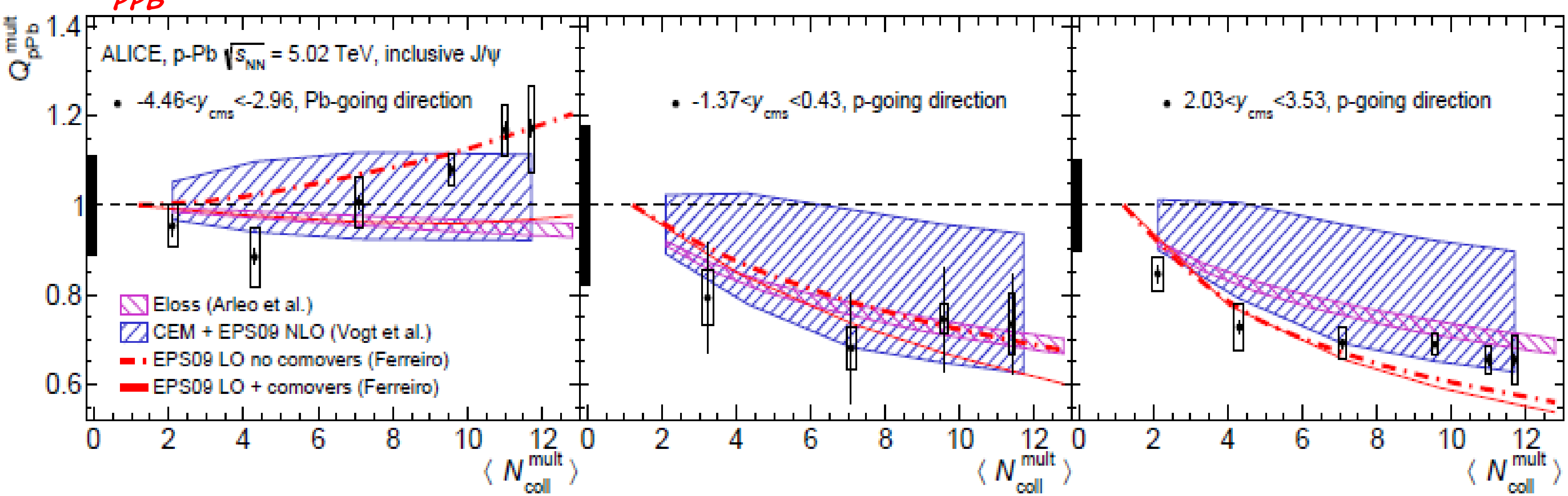


Q_{pPb} (jets)



F. Krizek, Fri 12:00

Q_{pPb} (J/ψ) forward / mid / backward



I. Arsene Thu 11:30
S. Weber, Thu 16:00
A. Camejo, Thu 16:20
ArXiv: 1506.08808

CONCLUSIONS

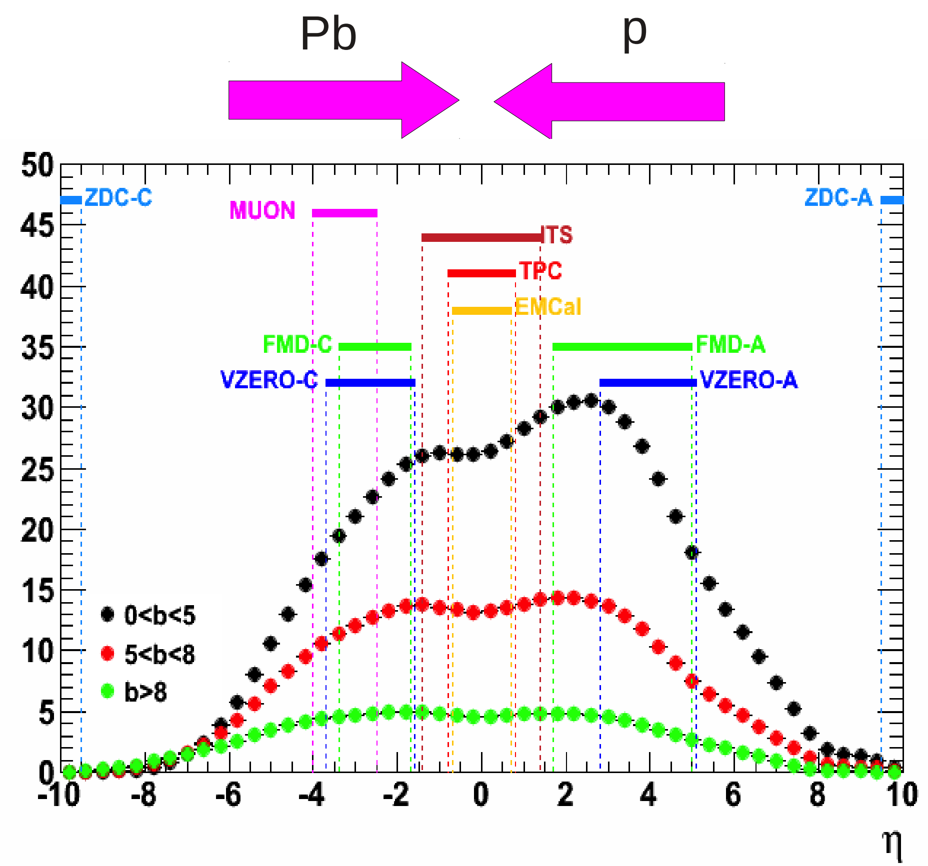
- p-Pb physics program: As control experiment baseline measurements provide clear proof that effects in Pb-Pb collisions are genuine hot deconfined QCD matter effects
- Study centrality dependence: is hard probes connection to collision geometry the same as for MB?
  centrality selection → different sources of bias
- ALICE approach:
  forward energy from nucleus fragmentation → unbiased selection
  + assumptions for particle scaling
- Centrality dependence of particle production:
  - dN/dη at midrapidity scales with Npart
  - high-p_T particle production follows binary scaling

  but also: cold nuclear matter effects for J/ψ absorption
  ...

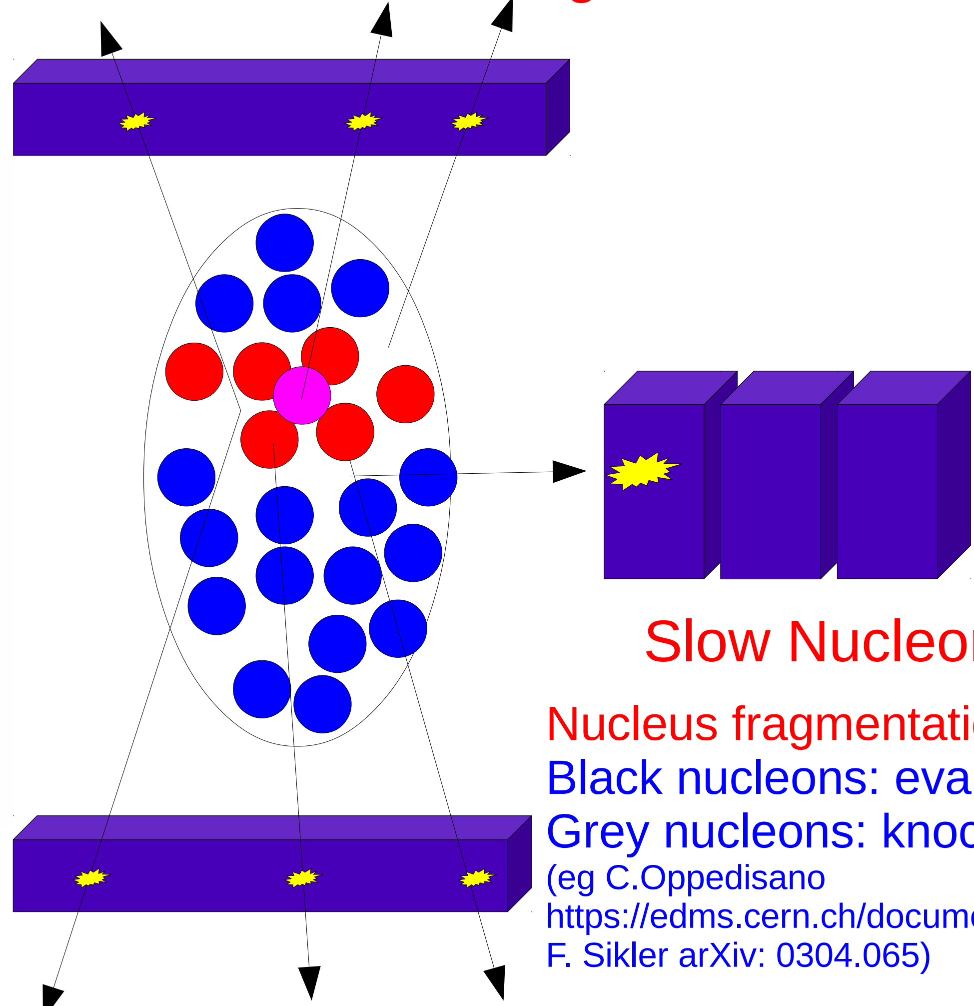
Night wraps the sky in tribute from the stars.
(Vladimir Mayakovsky, 1930)

BACKUP

DETECTORS USED FOR CENTRALITY



Pb-Fragmentation



Slow Nucleons

Nucleus fragmentation model:
Black nucleons: evaporation
Grey nucleons: knock-out
(eg C.Oppedisano
https://edms.cern.ch/document/682801/1
F. Sikler arXiv: 0304.065)

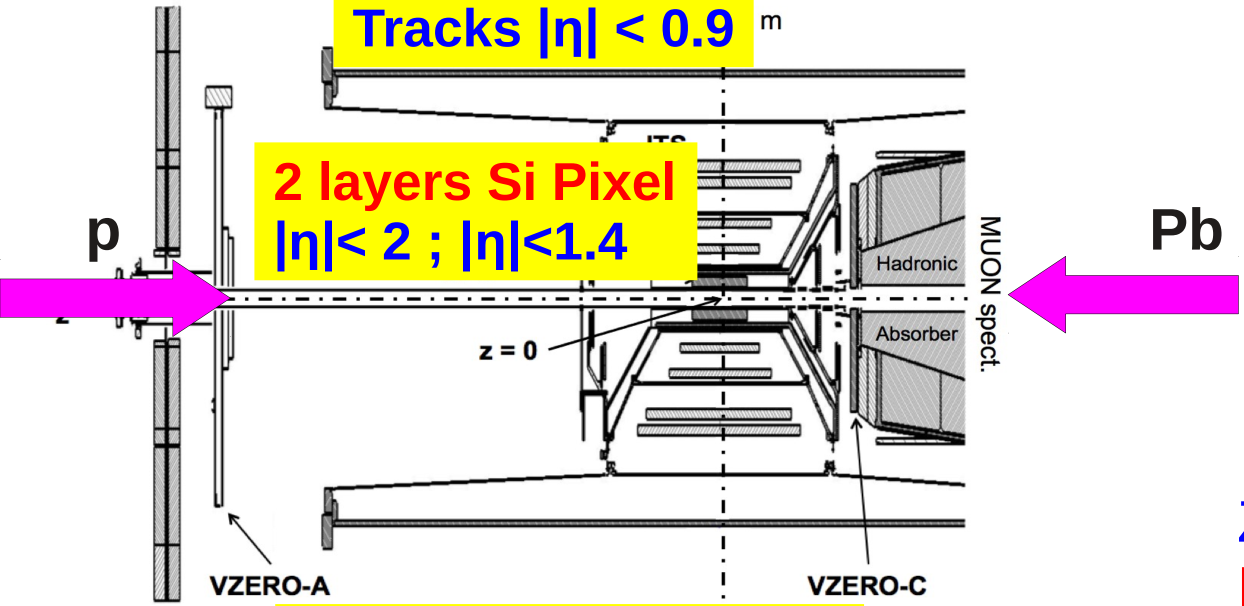
Particle production modeled by Negative Binomial Distribution (NBD)

DETECTORS USED FOR CENTRALITY

MID-RAPIDITY

TPC+ITS
Tracks |η| < 0.9

2 layers Si Pixel
|η|< 2 ; |η|<1.4



VZERO Scintillators

z = 340 cm
2.8 < η < 5.1

z = -90 cm
-3.7 < η < -1.7

Particle production modeled by Negative Binomial Distribution
Pb-fragmentation more relevant at forward rapidity

ZERO-DEGREE

Quartz-Fiber “Spaghetti”
Zero Degree Calorimeters

ZDC sensitive to slow nucleons
Nucleus fragmentation model:
Black nucleons: evaporation
Grey nucleons: knock-out

Centrality Estimators:
CL1: Clusters in 2nd Pixel Layer
V0M: VZERO-A+C Multiplicity
V0A: VZERO-A Multiplicity
ZNA: ZDC-A Neutron Energy

GLAUBER FIT

Glauber MC Parameters

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

R = 6.62 ± 0.06 fm

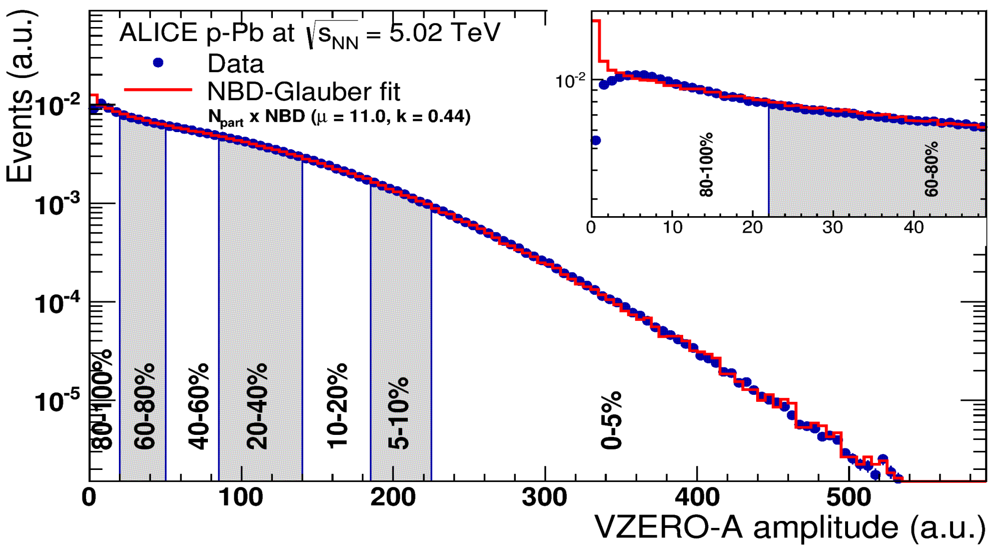
a = 0.546 ± 0.01fm

Minimum NN distance: 0.4±0.4 fm

pN Cross-section: σ_{pN} = 70 ± 5 mb

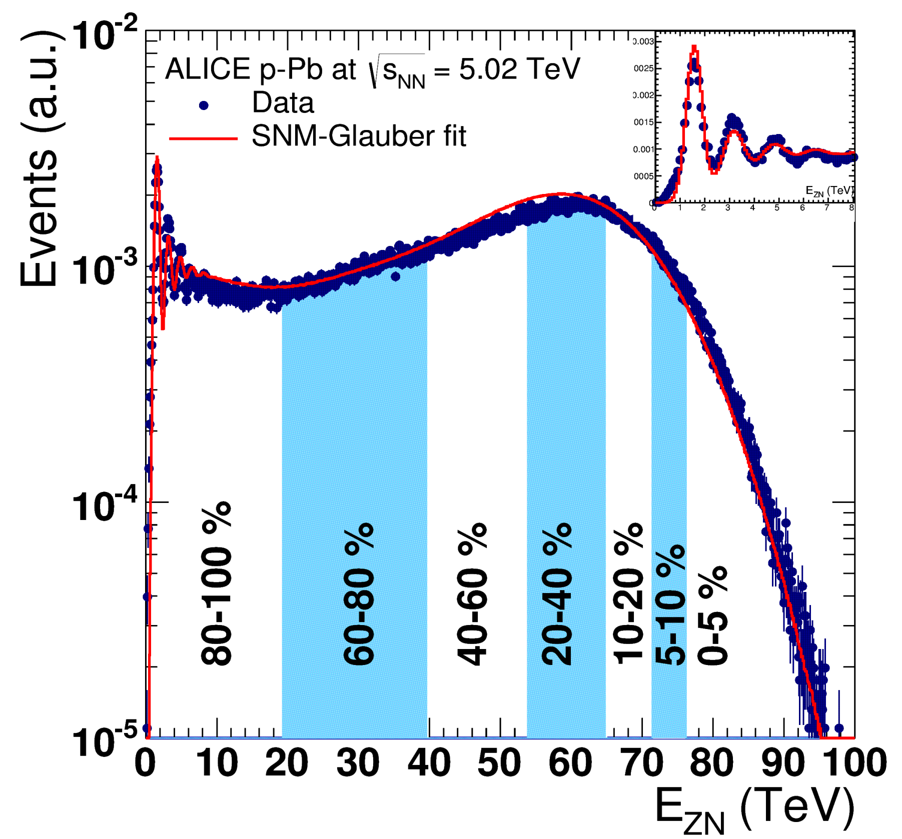
Proton radius: R_p = 0.6 ± 0.2 fm

Glauber + **Negative Binomial Distribution**

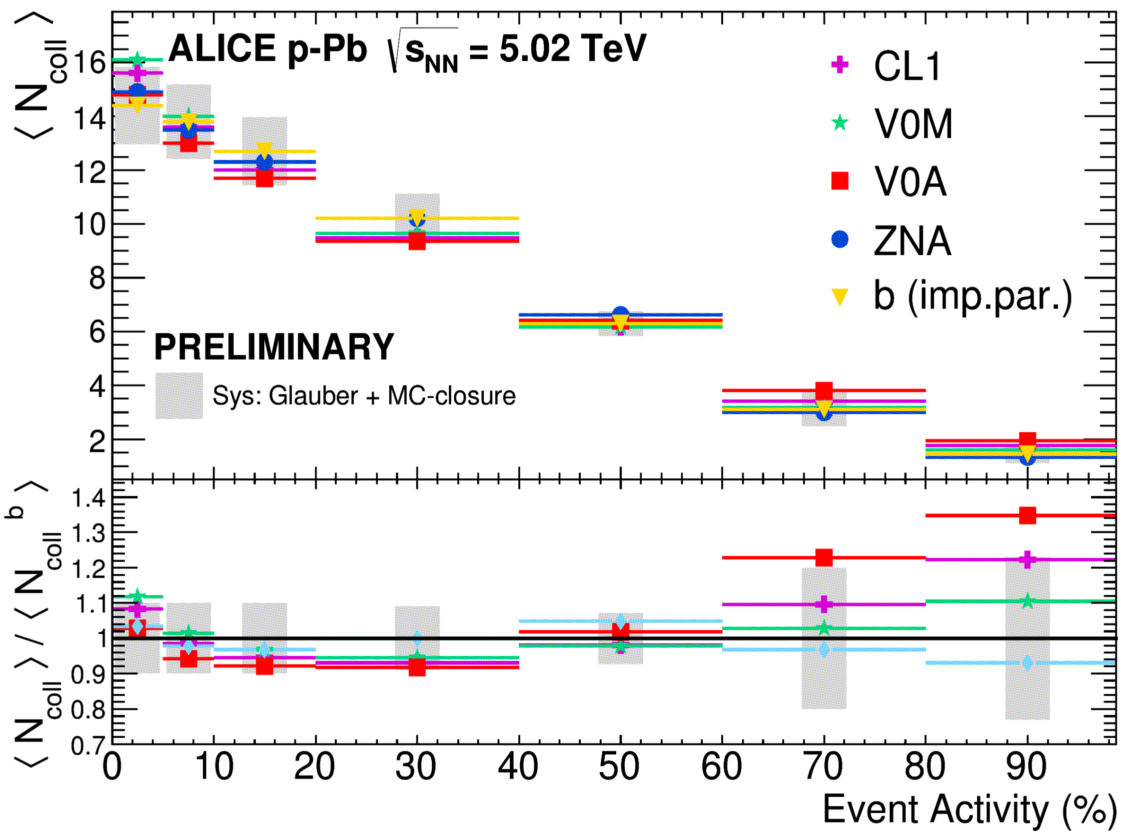


- Centrality classes: Multiplicity distribution sliced into percentiles of cross-section
- Obtain P(N_{coll}) from Glauber MC
- For each N_{coll} obtain
  - Multiplicity from NBD
  - Slow nucleons from SNM
- Obtain <N_{coll}> for each centrality class

Glauber + **Slow Nucleon Model**



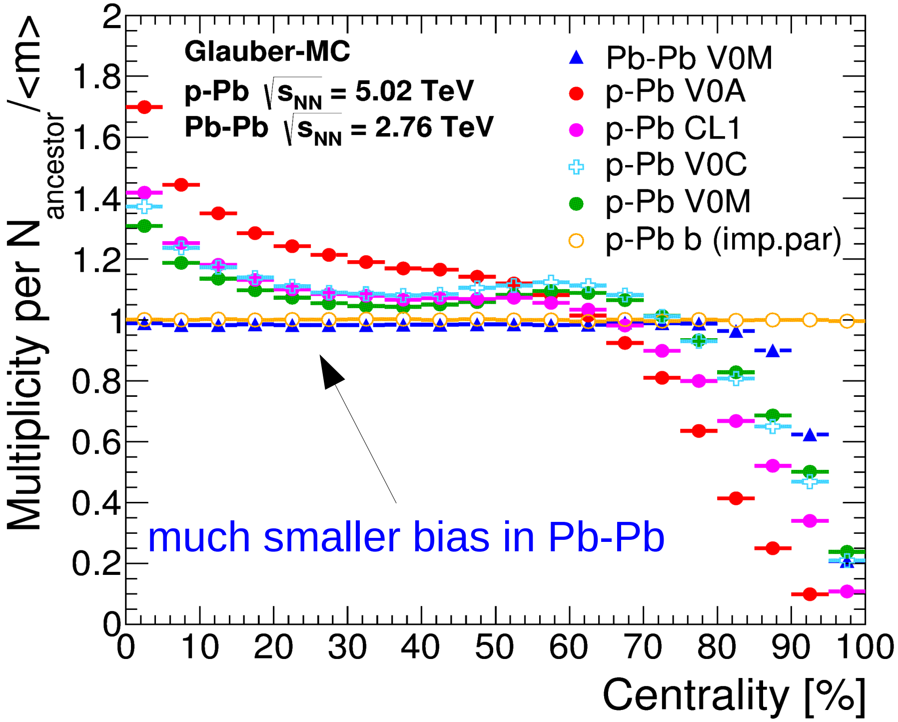
NCOLL FROM GLAUBER FITS

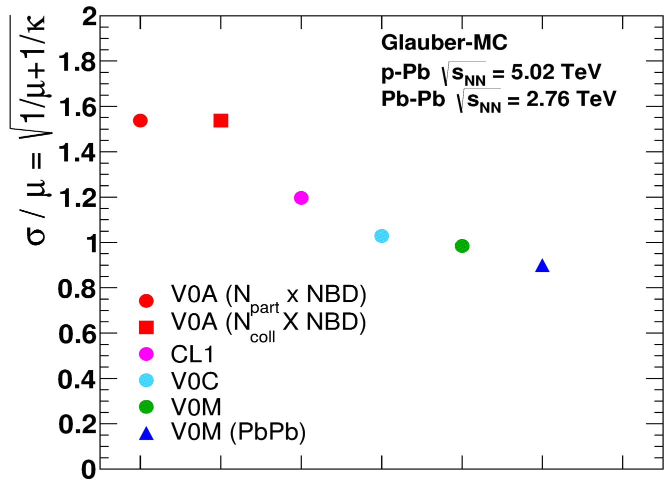


- **$<N_{coll}^{Glauber}>$** similar for different estimators
- Except for peripheral events, also similar to b-slicing
- Systematic error estimated by varying Glauber MC parameters.
- MC closure test performed with HIJING

Centrality (%)	N^{b}_{coll}	N^{CL1}_{coll}	N^{V0M}_{coll}	N^{V0A}_{coll}	Sys. Glauber	Sys. MC	Sys.Tot	N^{ZNA}_{coll}	Sys. SNM
0 - 5	14.4	15.6	15.7	14.8	10% (3.7%)	3%	10%	14.9	10%
5 - 10	13.8	13.6	13.7	13.0	10% (3.5%)	1%	10%	13.5	20%
10 - 20	12.7	12.0	12.1	11.7	10% (3.2%)	2%	10%	12.3	20%
20 - 40	10.2	9.49	9.55	9.36	8.8% (3.1%)	2%	9%	10.2	20%
40 - 60	6.30	6.18	6.26	6.42	6.6% (4.3%)	3%	7.2%	6.61	30%
60 - 80	3.10	3.40	3.40	3.81	4.3% (6.7%)	20%	20%	3.00	40%
80 -100	1.44	1.76	1.72	1.94	2.0% (9.3%)	23%	23%	1.34	10%
0 -100	6.90	6.82	6.87	6.87	10% (3.4%)	-	10%	6.90	-

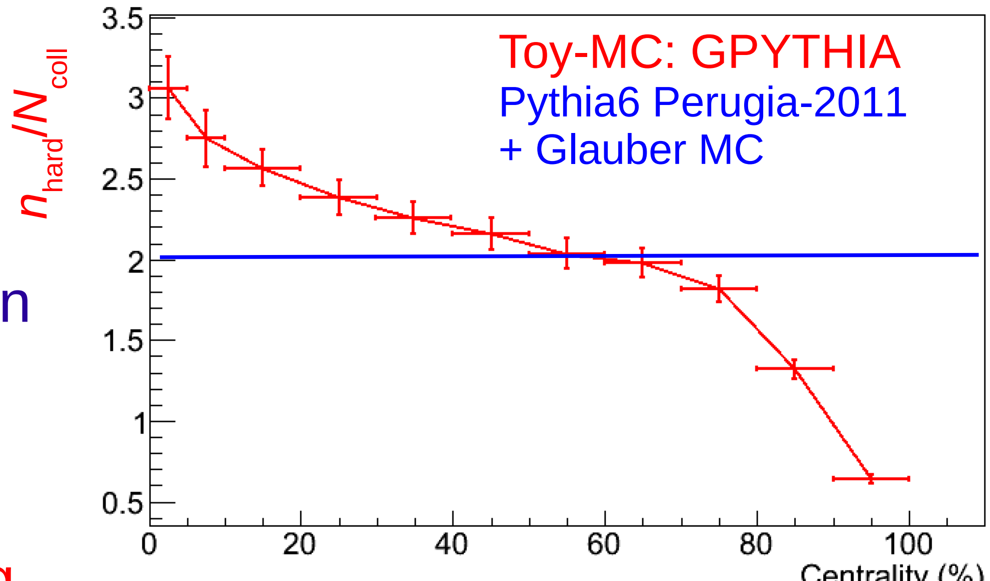
MULTIPLICITY BIAS IN PA





- **Multiplicity bias**: fluctuations sizable
  → Bias on Mult/N_{part} at central and peripheral collisions

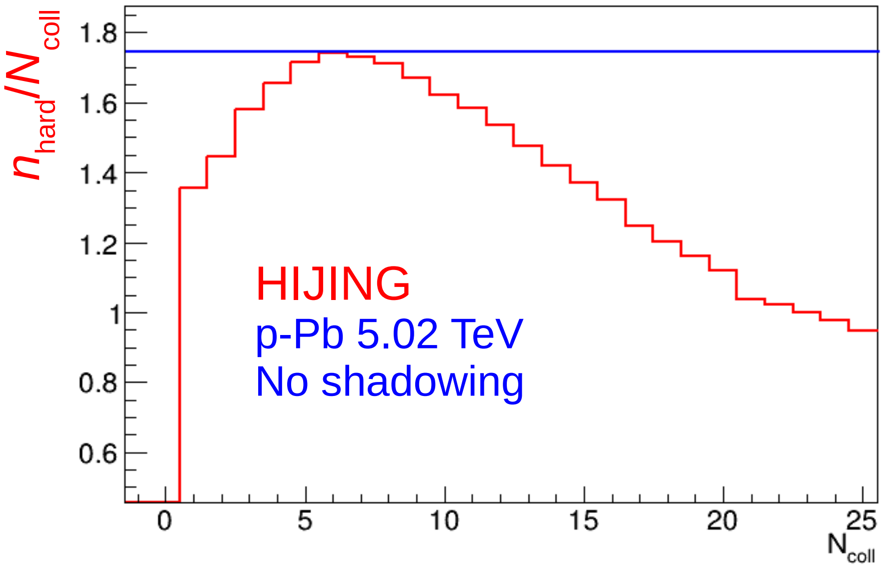
- MC models with multi-parton interaction (MPI) include fluctuations of particle sources (hard scatterings)
  HIJING (X.N. Wang, M. Gyulassy, nucl-th/9502021)



→ bias in mult ~ bias in hard scattering

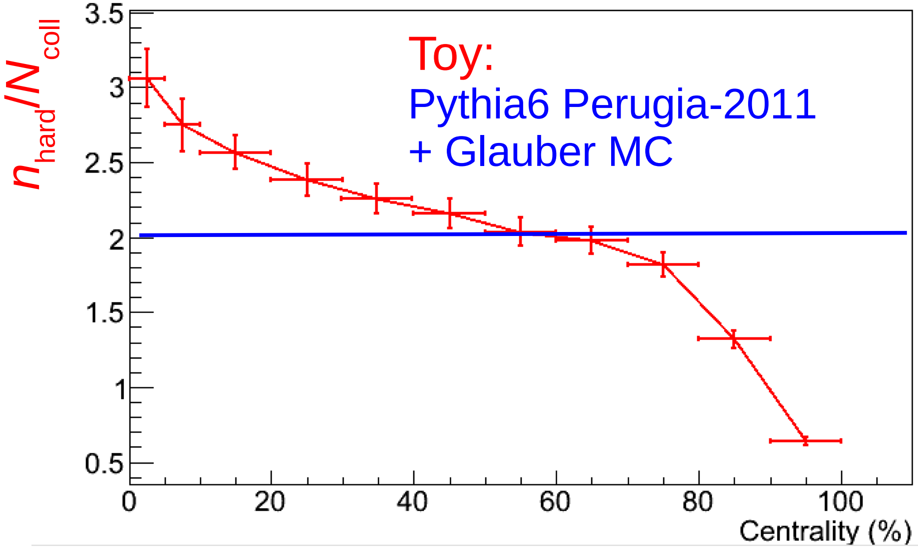
Insights from Monte Carlo

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)

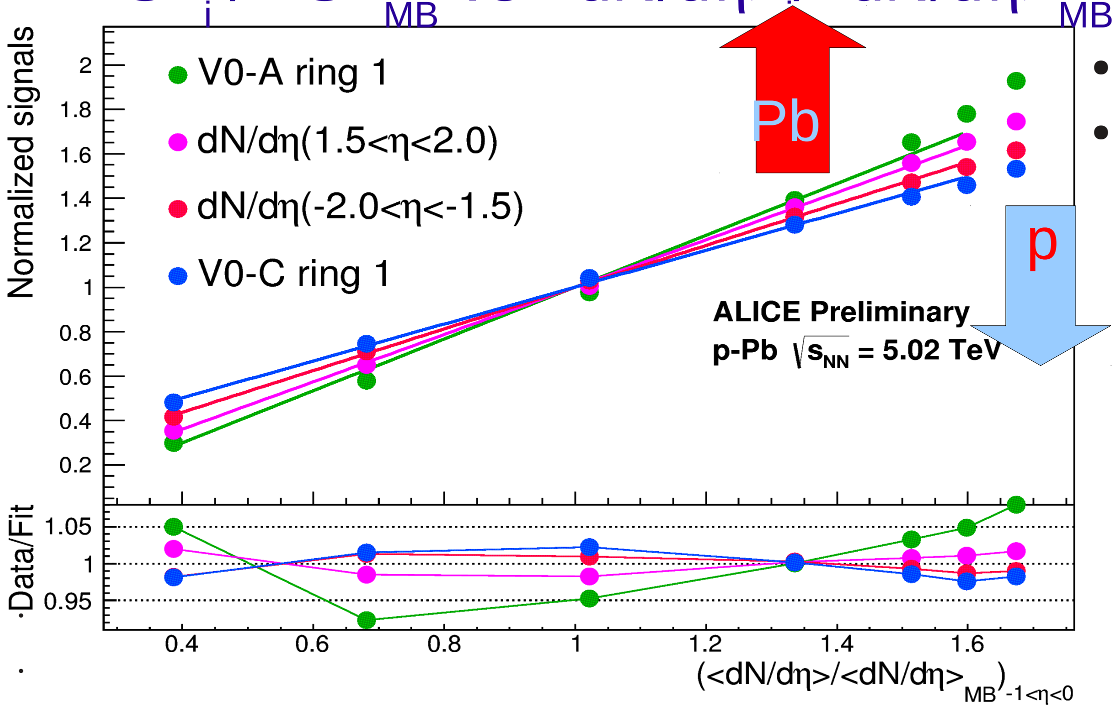


p-Pb collisions described as incoherent superposition of nucleon-nucleon

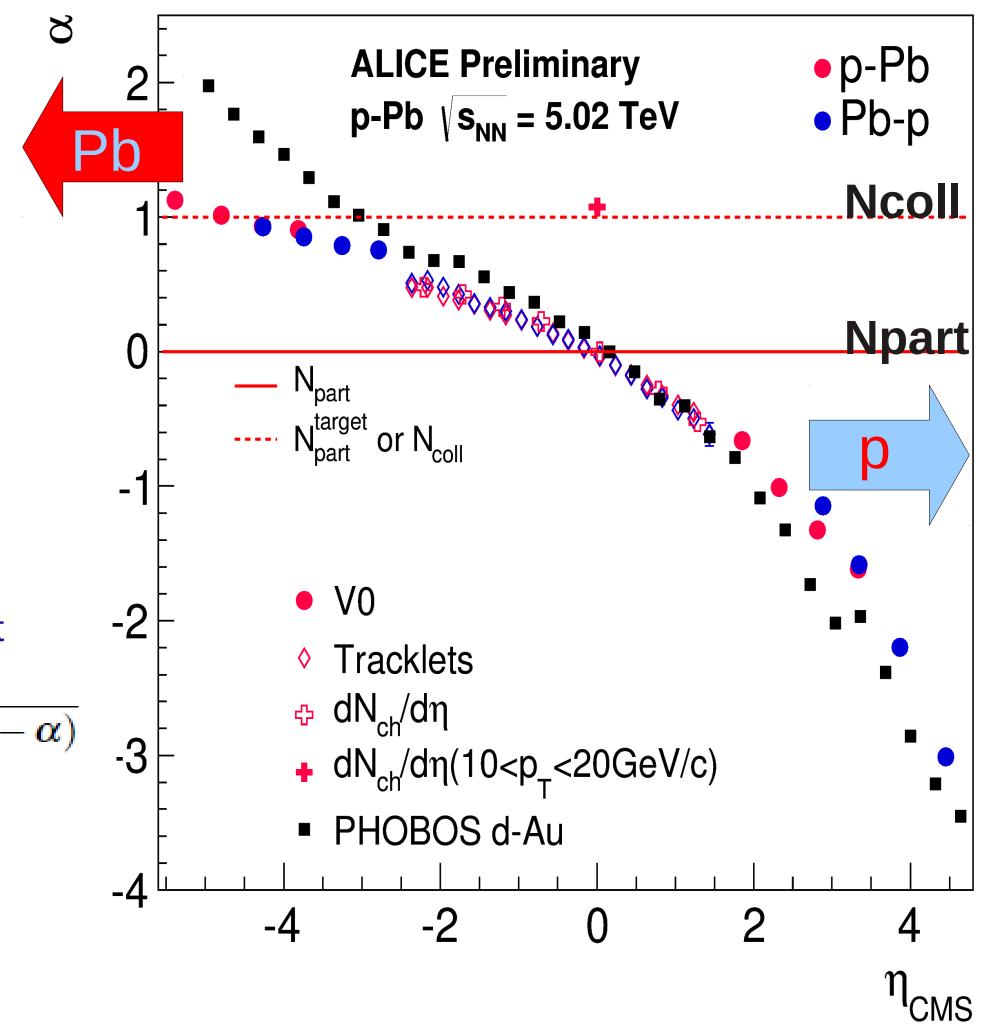
- vs centrality from multiplicity $|\eta| < 1.4$
- only multiplicity bias
- strong deviation from N_{coll} -scaling at low and high centralities.

SCALING OF PARTICLE PRODUCTION

- $\langle S \rangle_i$ / $\langle S \rangle_{MB}$ vs $\langle dN/d\eta \rangle$/$\langle dN/d\eta \rangle_{MB}$ $(-1<\eta_{lab}<0)$



- PHOBOS d-Au: η → 1.6*η (beam rapidity)
- Similar dependence except A-going dir.



- Fit: assuming dN/dη scales with N_{part}

$$\frac{\langle S\rangle_i}{\langle S\rangle_{MB}} = \frac{\langle N_{part}\rangle_{MB}}{(\langle N_{part}\rangle_{MB}-\alpha)} \cdot \left(\frac{\langle dN/d\eta\rangle_i}{\langle dN/d\eta\rangle_{MB}}\right)_{-1<\eta<0} - \frac{\alpha}{(\langle N_{part}\rangle_{MB}-\alpha)}$$

α = 0 – perfect N_{part} scaling

α = 1 – perfect N_{coll} (or N_{part}^{target}) scaling

α has clear meaning (N_{part} vs N_{coll} scaling)

correlation between causally disconnected observables (eg: slow neutrons - multiplicity)

→ **connection to geometry.**

SLOW NUCLEON MODEL

PROTONS

- E910 (p-Au @ 18 GeV/c) fit to N_{gray} vs. N_{coll} to determine the average number of gray protons [I. Chemakin *et al.*, Phys. Rev. C **60** 024902 (1999)]

  $<N_{gray\ p}> = (c_0 + c_1\ N_{coll} + c_2\ N_{coll})\ (A_{Pb}/A_{Au})^{2/3}$

- COSY (p-Au @ 2.5 GeV) measured the fraction of black over gray protons for the average number of black protons [A. Letourneau, Nucl. Phys. A 712 (2002) 133]

  $<N_{black\ p}> = f_{blackovergray} * <Ngray\ p>$ ➡ $f_{blackovergray} = 0.65$

- $N_{gray\ p}$, $N_{black\ p}$ extracted from binomial distributions

NEUTRONS

- from COSY: Light Charged Particle (Z<=7)

  $LCP = (<N_{gray\ p}> + <N_{black\ p}>)/\alpha$ ➡ $\alpha = 0.585$ (COSY) is left free

  $<N_{slow\ n}> = <N_{black\ n}> + <N_{gray\ n}> = a + b/(c\text{-}LCP)$ ➡ a (b, c) can be finely tuned

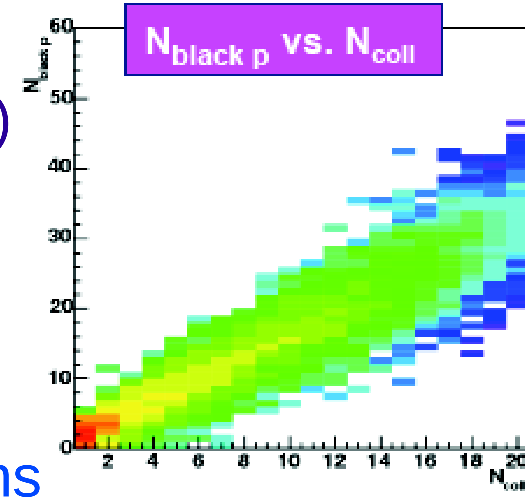
- results from p induced spallation reactions (0.1-10 GeV) for the fraction of black/gray neutrons

  $<N_{black\ n}> = 0.9 * (<N_{slow\ n}>)$

- $N_{gray\ n}$, $N_{black\ n}$ extracted from binomial distributions

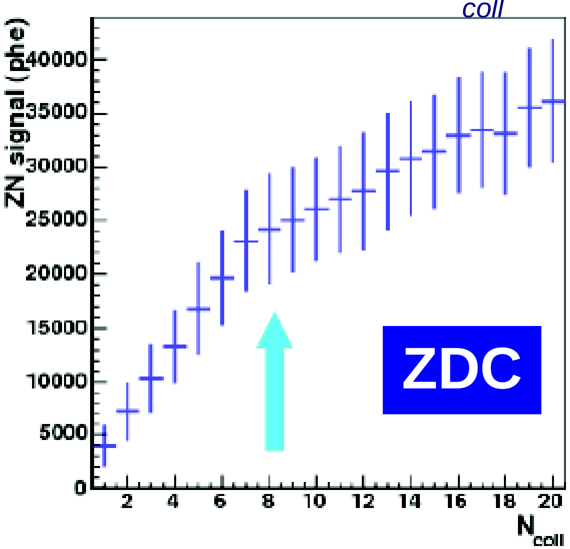
15

Slow Nucleon Model



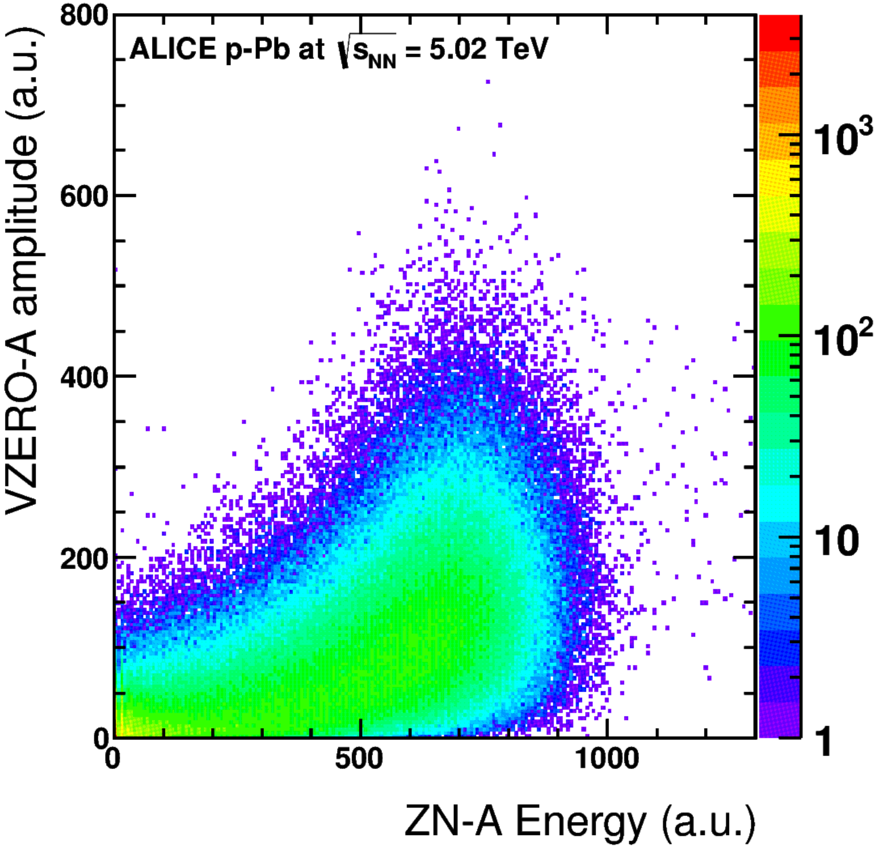
- Features of N_{ch} ~ independent of $E_{projectile}$ (1GeV → 1 TeV)
- **Slow nucleons** emission dictated by collision geometry → Maxwell-Boltzmann (independent statistical emission) classified from emulsion experiments
  - Gray: soft nucleons knocked out by wounded nucleons
  - Black: low energy target fragments from de-excitation, evaporation
- Glauber model → distribution of N_{coll}
- implemented model used a parameterization of results from low energy experiments
  C.Oppedisano https://edms.cern.ch/document/682801/1
  F. Sikler, hep-ph/0304065

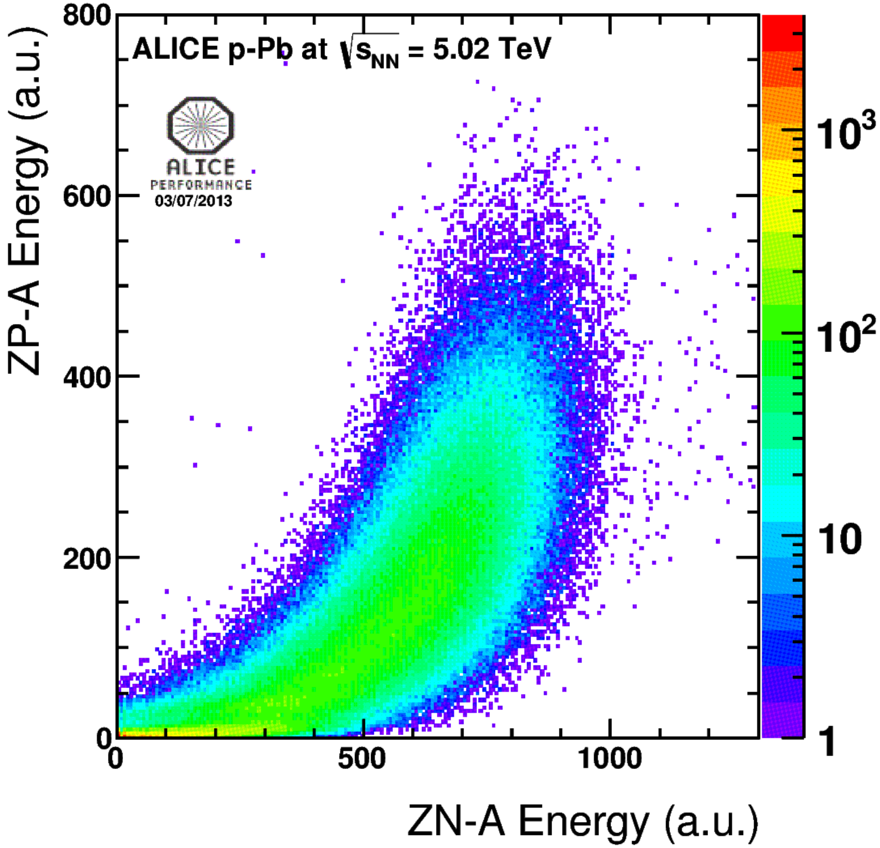
saturation in N_{black} vs N_{gray}
→ also in ZDC vs N_{coll}



SLOW NUCLEONS	β [c units]	p [MeV/c]	E_{kin} [MeV]
Black	0 ÷ 0.25	0 ÷ 250	0 ÷ 30
Gray	0.25 ÷ 0.70	250 ÷ 1000	30 ÷ 400

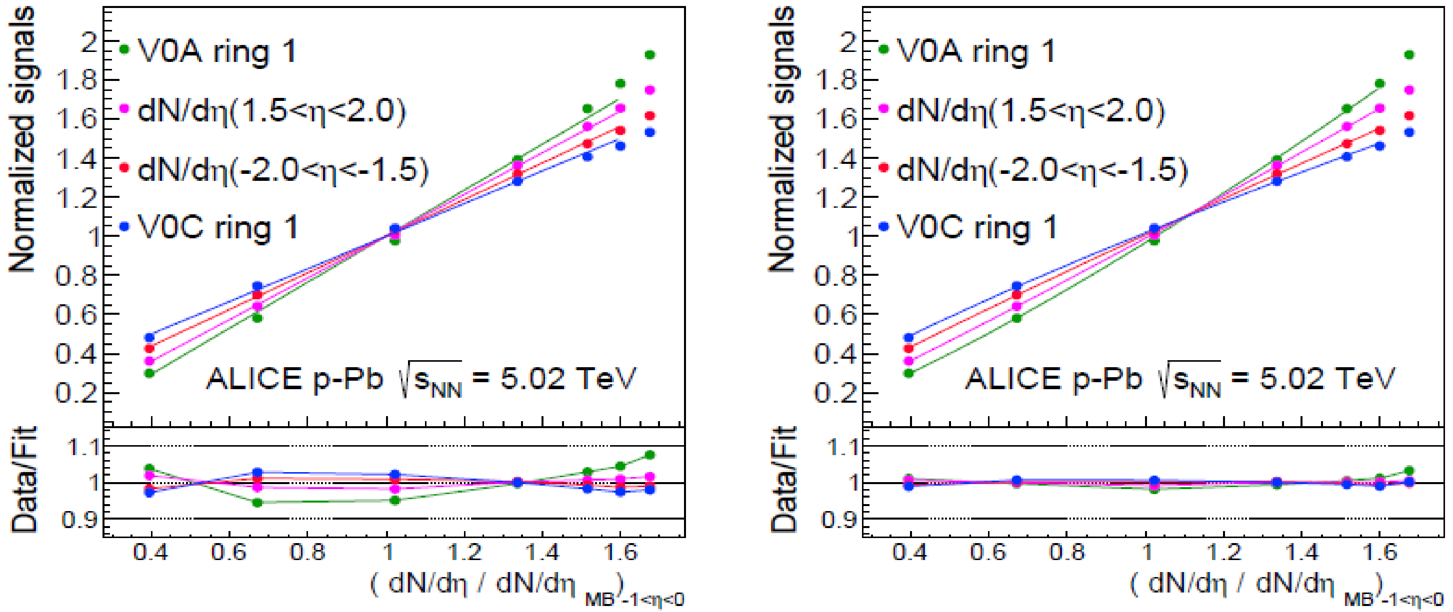
ZNA correlations





SCALING OF PARTICLE PRODUCTION

- Scaling studied by defining so called self-normalized signals <S>i / <S>MB vs self-normalized mid-rapidity dNdeta(-1<eta_lab<0)



- Fit: assuming mid-rapidity dNdeta scales with Npart

LINEAR

$$\frac{\langle S\rangle_i}{\langle S\rangle_{MB}} = \frac{\langle N_{part}\rangle_{MB}}{(\langle N_{part}\rangle_{MB}-\alpha)} \cdot \left(\frac{\langle \mathrm{d}N/\mathrm{d}\eta\rangle_i}{\langle \mathrm{d}N/\mathrm{d}\eta\rangle_{MB}}\right)_{-1<\eta<0} - \frac{\alpha}{(\langle N_{part}\rangle_{MB}-\alpha)}$$

POWER-LAW

$$\frac{\langle S\rangle_i}{\langle S\rangle_{MB}} = \frac{\langle N_{\mathrm{part}}\rangle^{\beta}_{MB}}{\langle N^{\beta}_{\mathrm{part}}\rangle_{MB}} \cdot \left(\frac{\langle \mathrm{d}N/\mathrm{d}\eta\rangle_i}{\langle \mathrm{d}N/\mathrm{d}\eta\rangle_{MB}}\right)^{\beta}_{-1<\eta<0}$$

α = 0 – perfect Npart scaling

α = 1 – perfect Ncoll (or Ntarget_part) scaling

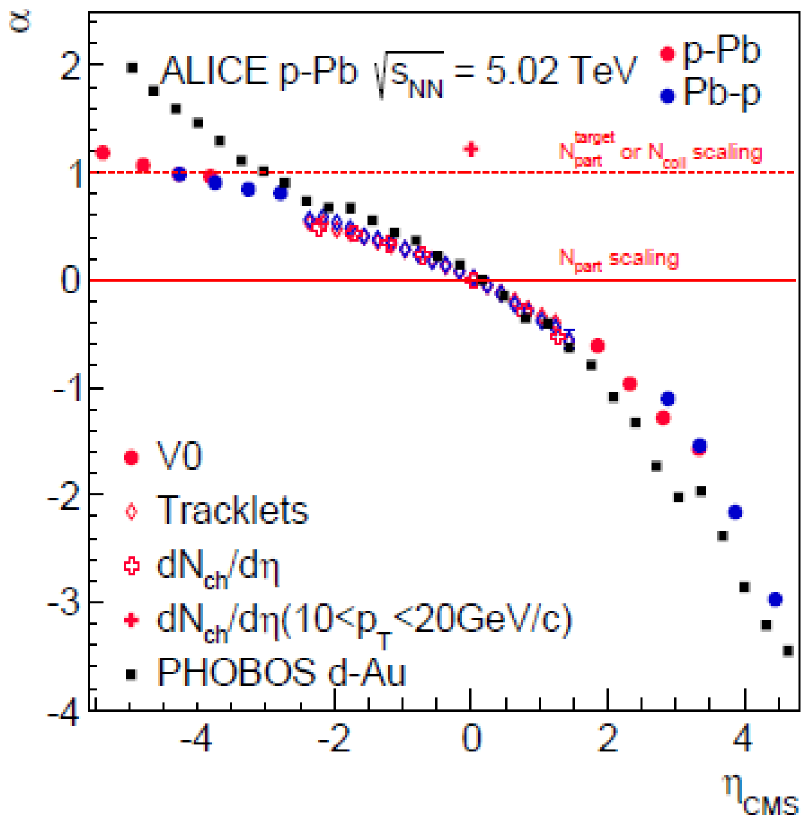
α has clear meaning (Npart vs Ncoll scaling)

β = 0 – perfect Npart scaling

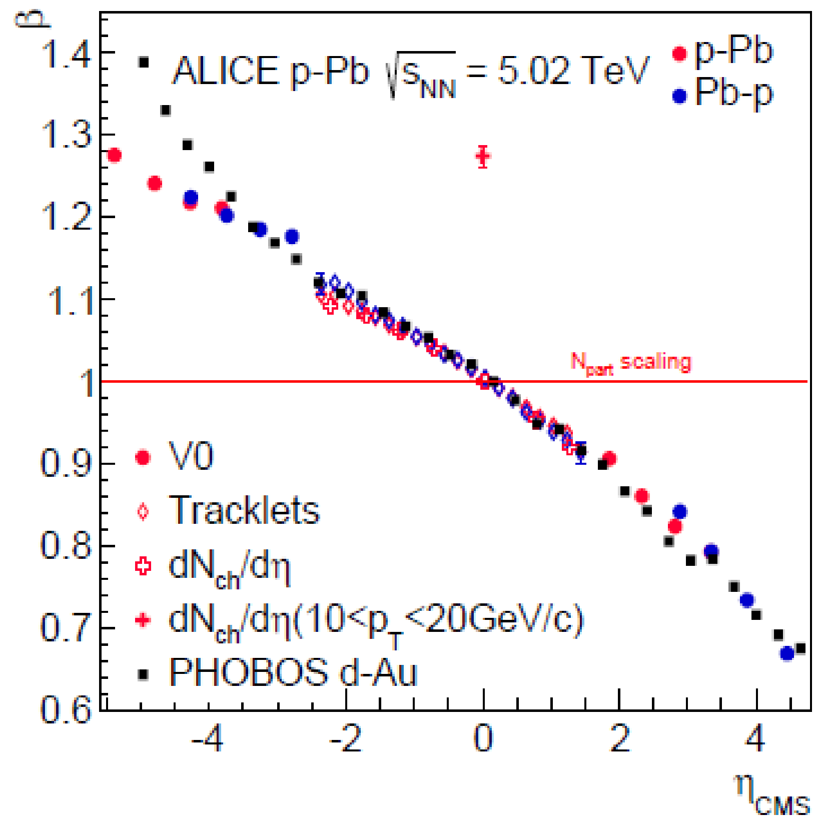
SCALING VS η_{CMS}

Ring	$\langle\eta_{CMS}\rangle$ (p-Pb)	$\langle\eta_{CMS}\rangle$ (Pb-p)
VZERO-A ring 1	-5.39	4.45
VZERO-A ring 2	-4.80	3.87
VZERO-A ring 3	-4.28	3.35
VZERO-A ring 4	-3.82	2.89
VZERO-C ring 1	3.34	-4.26
VZERO-C ring 2	2.82	-3.74
VZERO-C ring 3	2.33	-3.25
VZERO-C ring 4	1.86	-2.78

LINEAR

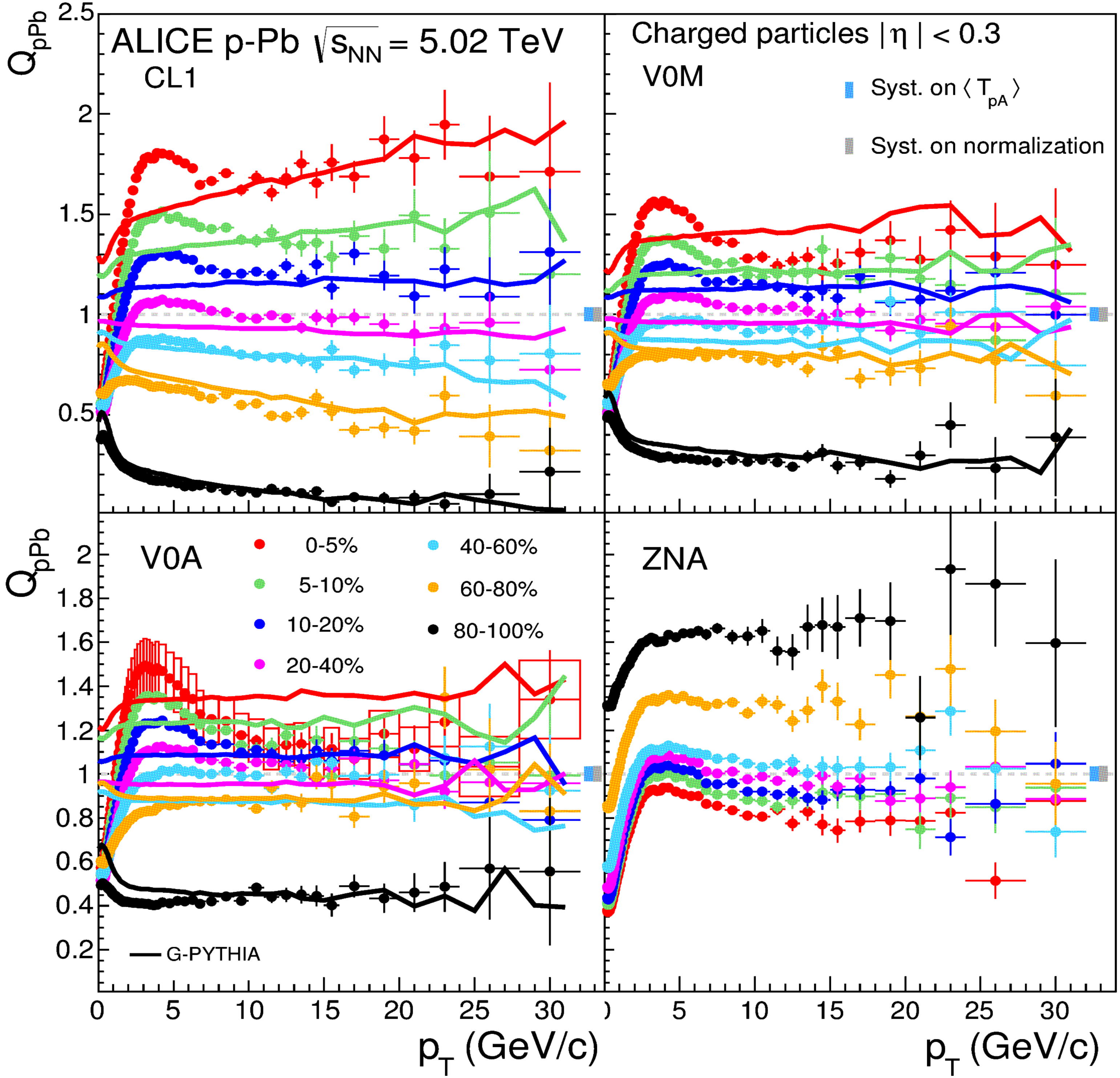


POWER-LAW



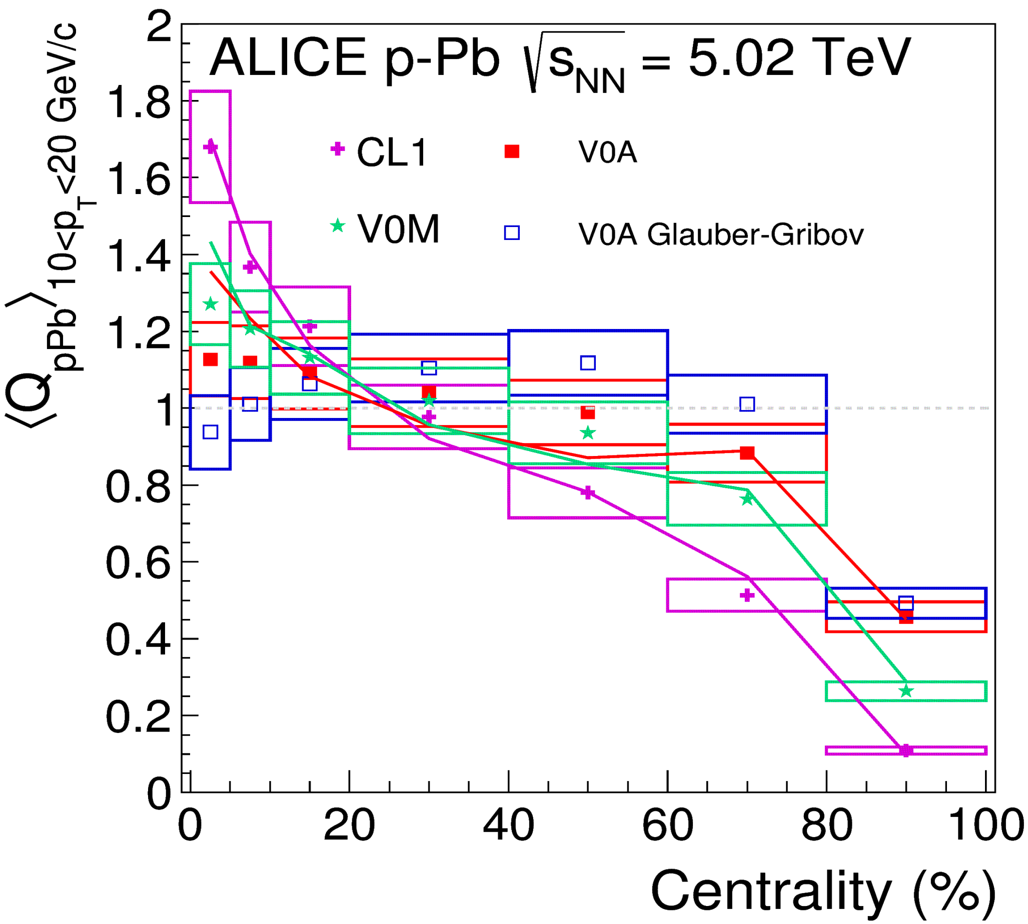
- PHOBOS d-Au dNdeta(eta) data, eta → 1.6*eta (beam rapidity RHIC → LHC)
- Similar dependence between our and PHOBOS data, except forward nucleus-going direction
- High-pT and inner VZERO-A ring quite similar, delta(alpha)~0.2
- Mid-rapidity vs inner VZERO-A is not perfect Npart vs Ncoll scaling, delta(alpha)~1.2

Q_{PPB}



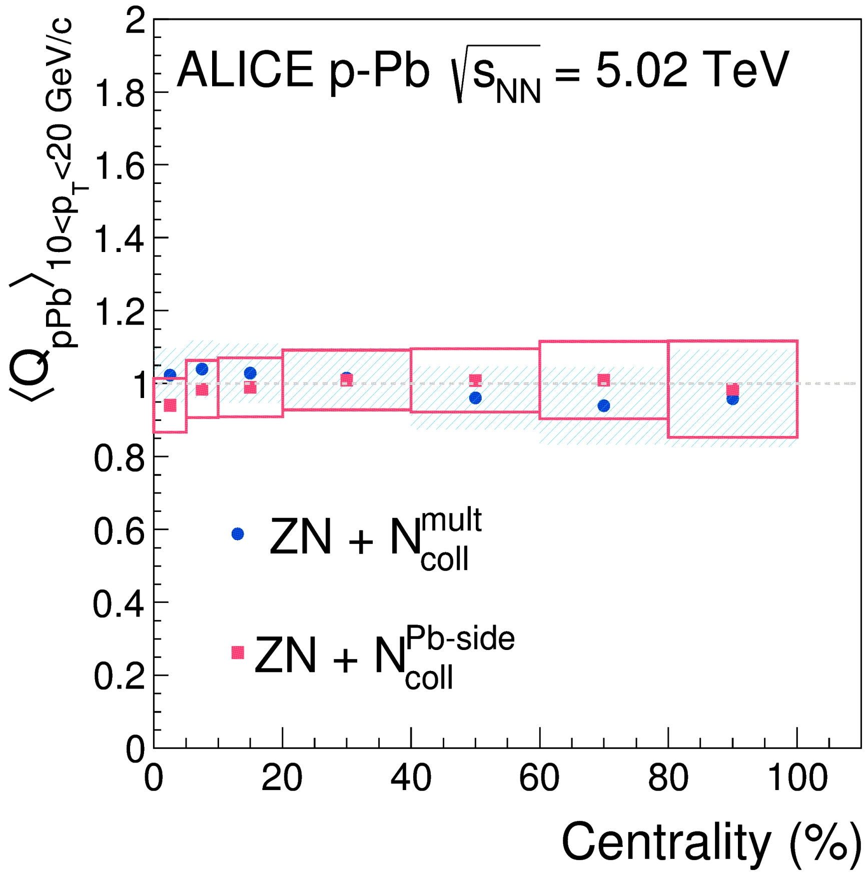
ALICE p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
CL1
Charged particles |η| < 0.3
V0M
Syst. on ⟨T_{pA}⟩
Syst. on normalization
V0A
ZNA
0-5%
5-10%
10-20%
20-40%
40-60%
60-80%
80-100%
G-PYTHIA
Q_{pPb}
p_T (GeV/c)

MEAN Q_{pPb} AT p_T > 10 GEV



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.

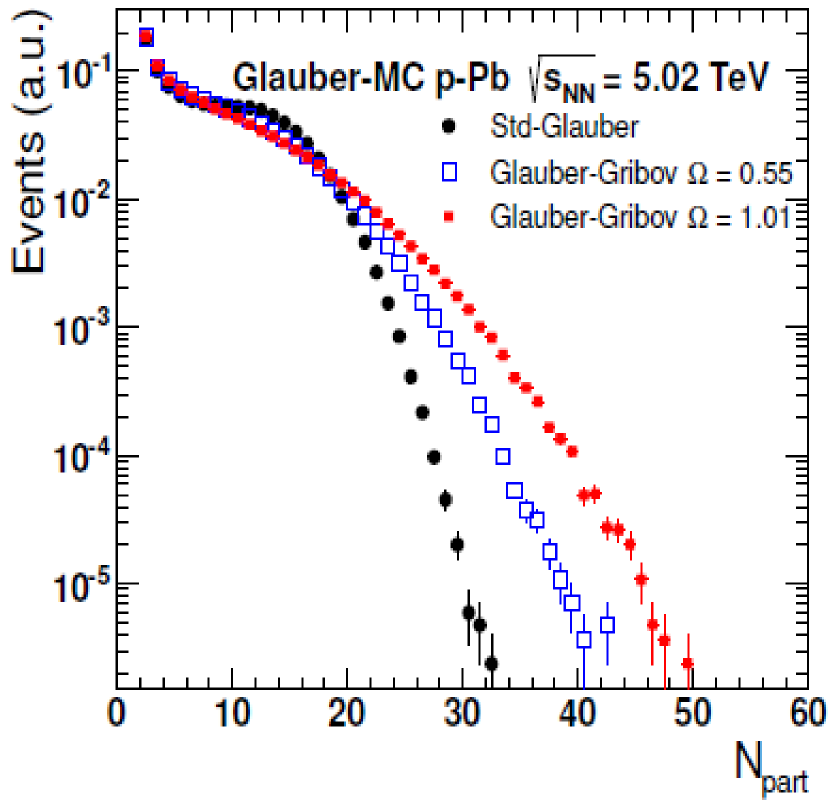


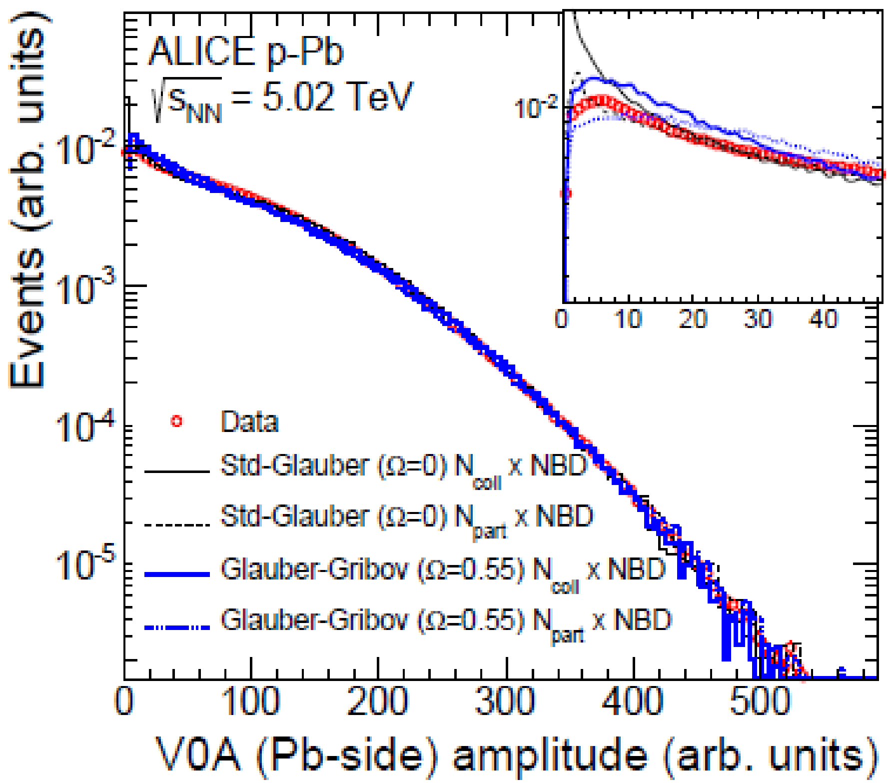
Same "S-shape" dependence as seen
- from multiplicity bias (Glauber + NBD fit)
- from Toy-MC (Glauber + Pythia)

Shape flattens with increasing rapidity gap: CL1→V0M→V0A

QpA flat for hybrids

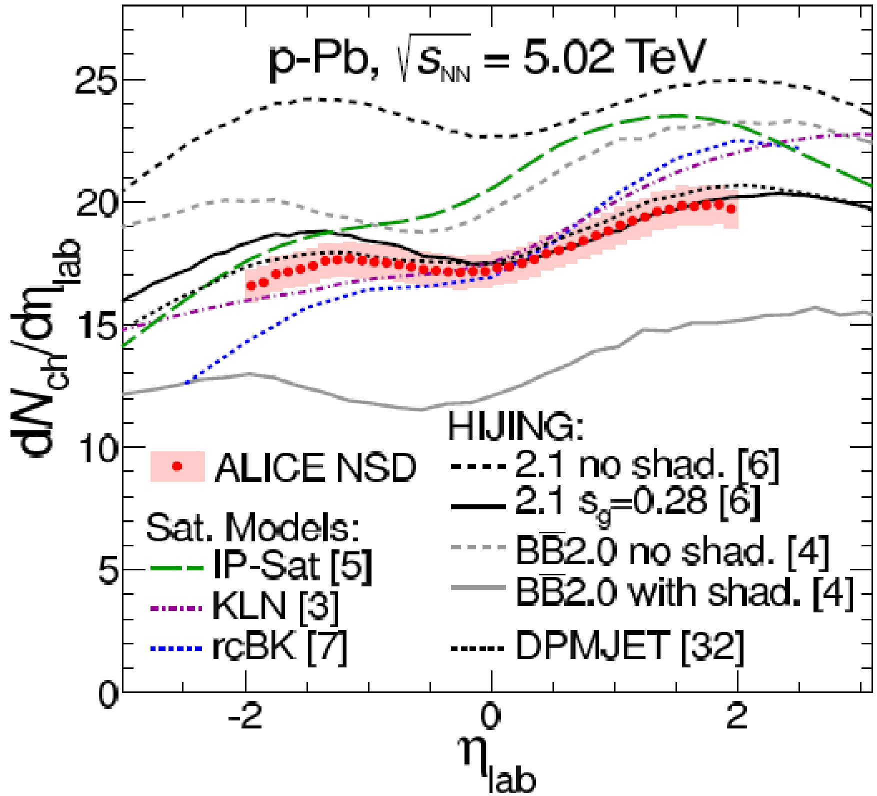
Glauber-Gribov





	Glauber		Glauber-Gribov	
Centrality (%)	N_{part} x NBD	N_{coll}x NBD	N_{part} x NBD	N_{coll}x NBD
0 - 5	14.8	14.9	17.8	19.2
5 - 10	13.0	13.2	14.4	15.2
10 - 20	11.7	11.8	12.0	12.5
20 - 40	9.36	9.49	8.82	9.04
40 - 60	6.42	6.49	5.68	5.56
60 - 80	3.81	3.59	3.33	2.89
80 -100	1.94	1.85	1.80	1.43
0 -100	6.87	6.87	6.73	6.75

MULTIPLICITY IN PA



RAPIDITY DISTRIBUTION

- Data favors models that incorporate shadowing
- Saturation models predict much steeper η-dependence which is no seen in the data

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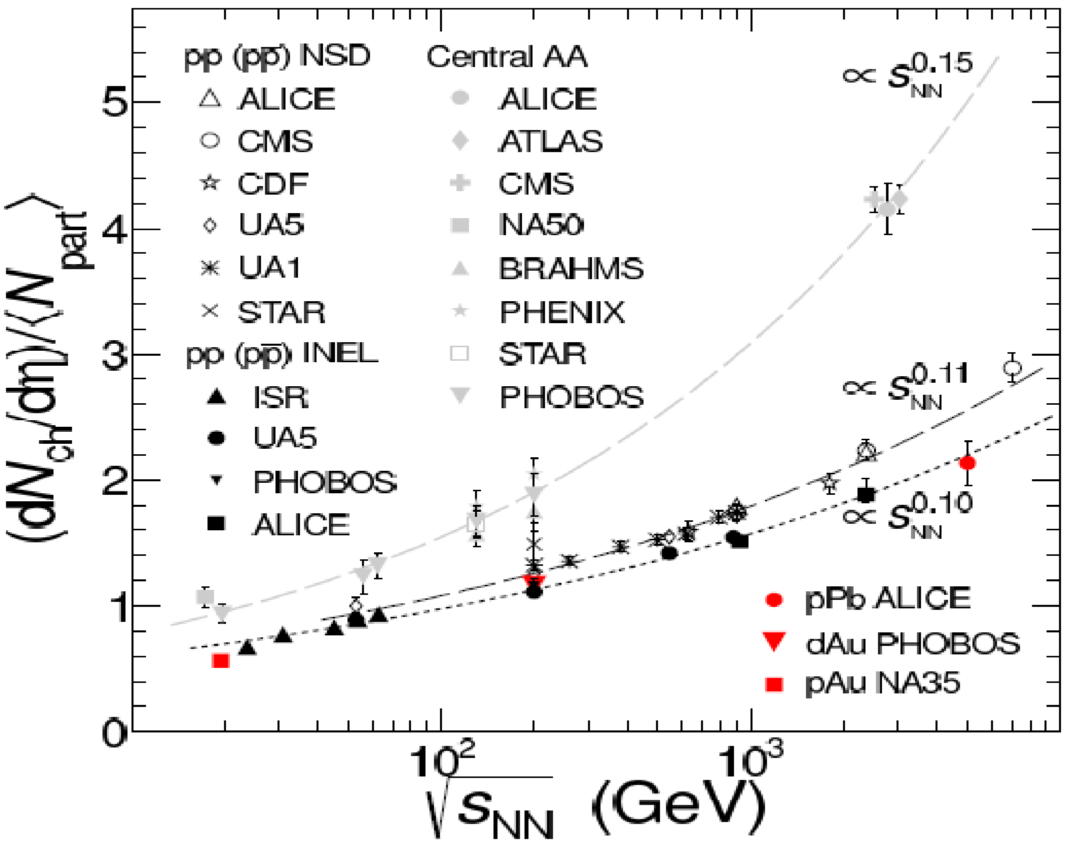
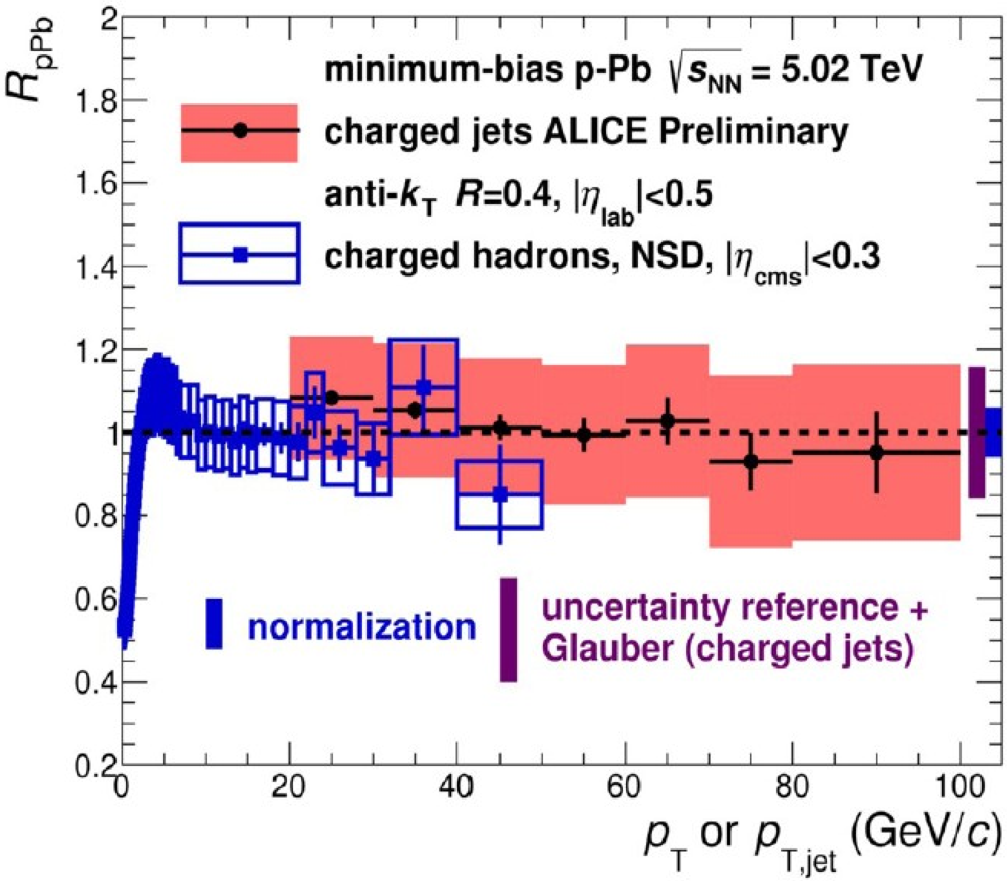
ENERGY DEPENDENCE

- ~15%below NSD pp collisions
- Similar to inelastic pp collisions
- 84% higher than in d–Au collisions at $\sqrt{s_{NN}}$ = 0.2 TeV.

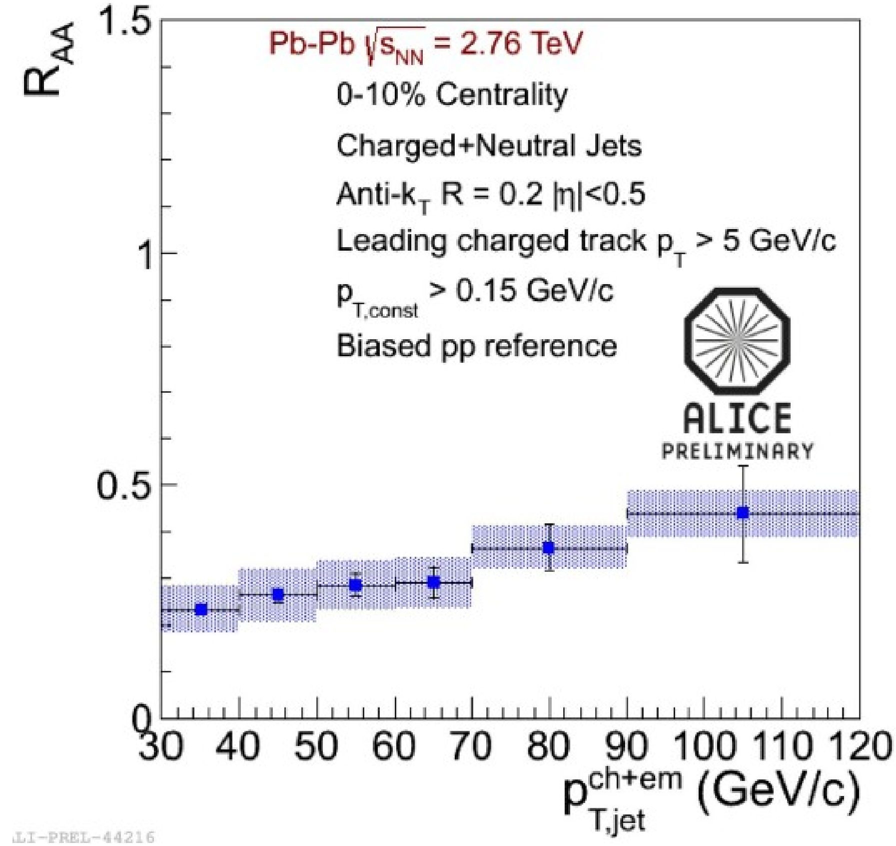


JETS R_{PA}

p-Pb (minimum bias)



Pb-Pb (central)

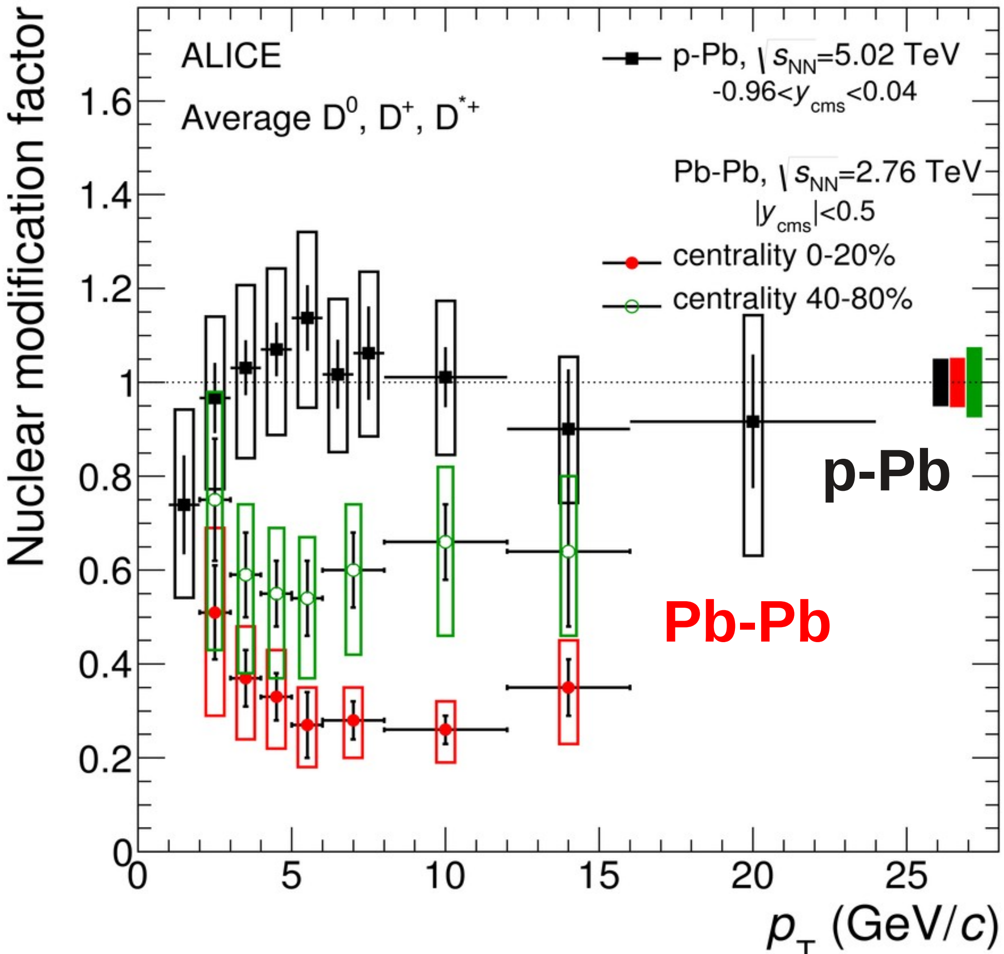


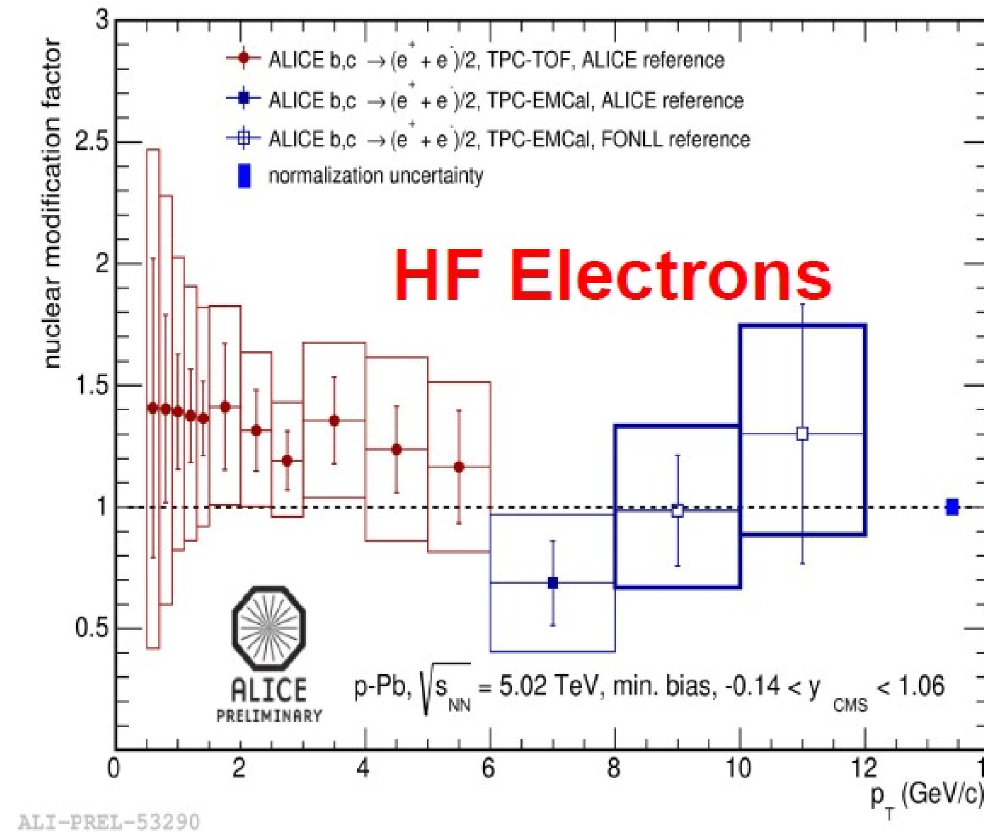
- R_{pPb} **~1** → no nuclear effects in pPb

→ suppression in PbPb is a final state effect

ALICEColl. Phys. Lett. B 741 (2015) 38-50

HEAVY FLAVOR R_{PA}



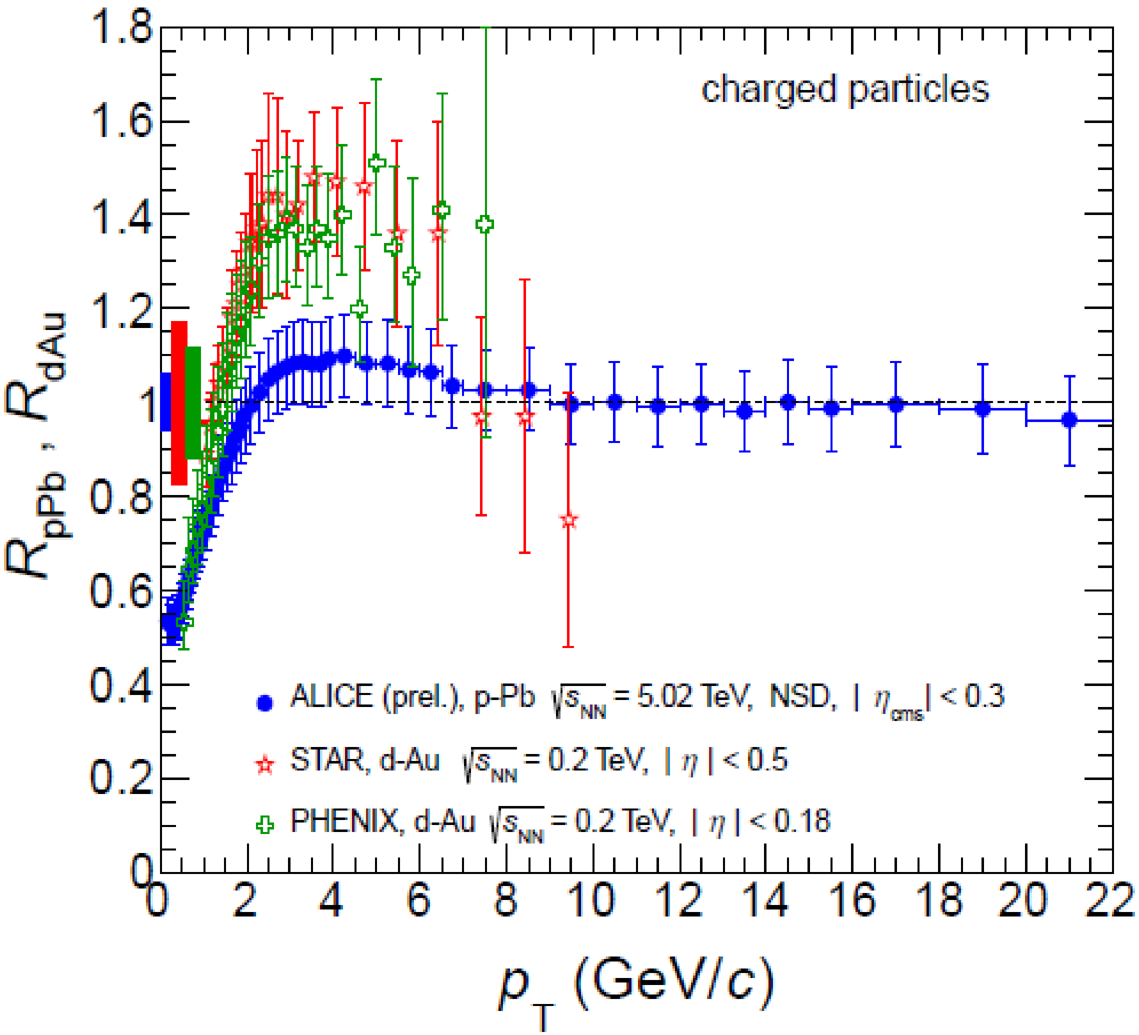


- R_{pPb} **~1** → no nuclear effects in pPb

→ suppression in PbPb is a final state effect

ALICE Coll. Phys. Rev. Lett. 113 (2014) 232301

FLOW, CRONIN OR SATURATION?



To distinguish scenarios
look differentially!

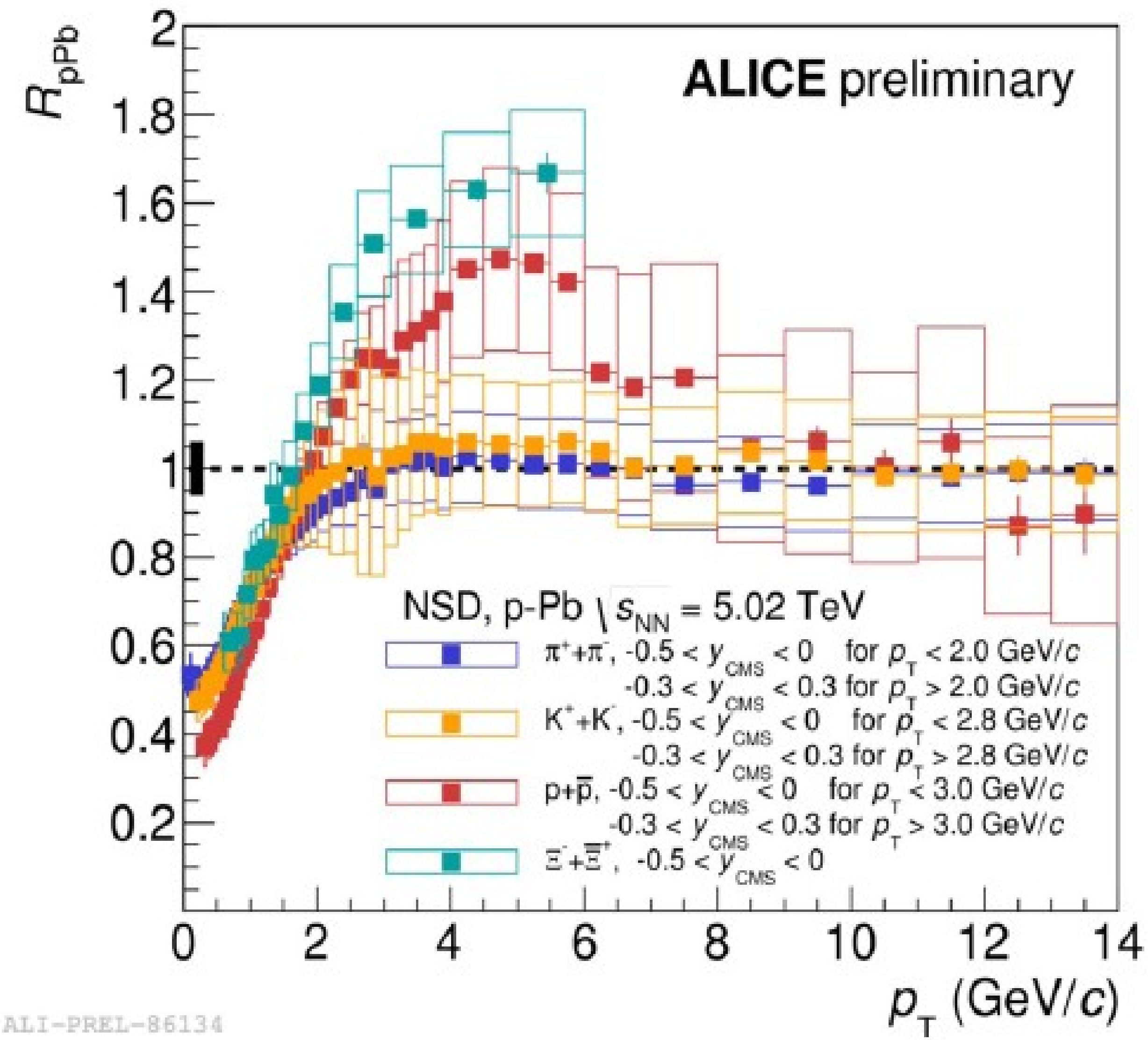
LHC vs. RHIC data

- Cronin effect: "re-distribution" of low-pT hadrons at higher pT due to multiple (parton) scattering larger at RHIC
First observed by Cronin in PRD 11 (1975) 3105
→ Multiple soft scatterings in IS prior to hard scatter (arXiv:hep-ph/0212148)

- flow: blue-shift of spectra larger at LHC

- saturation: depletion of spectra at low pT larger at LHC

R_{pA} for particle species



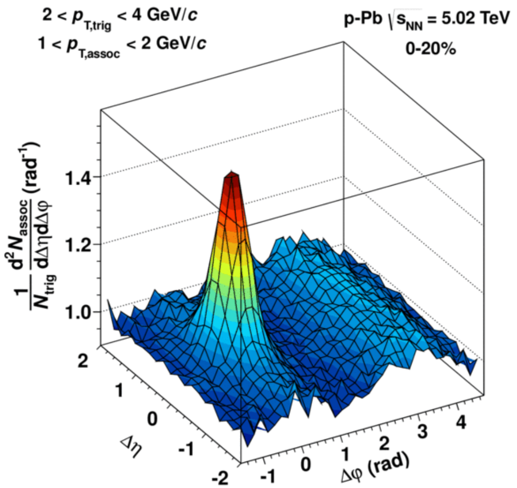
At intermediate pT (Cronin region): Indication of mass ordering

- No enhancement for pions and kaons
- **Pronounced peak for protons**
- Even stronger for cascades

Particle species dependence points to relevance of final state effects

DOUBLE RIDGE

0-20% **60-100%**



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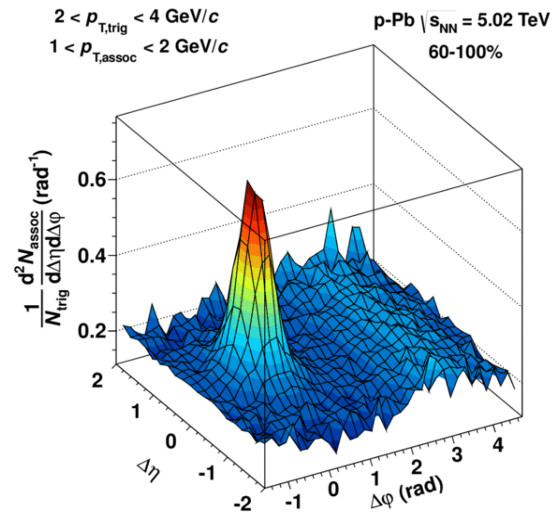

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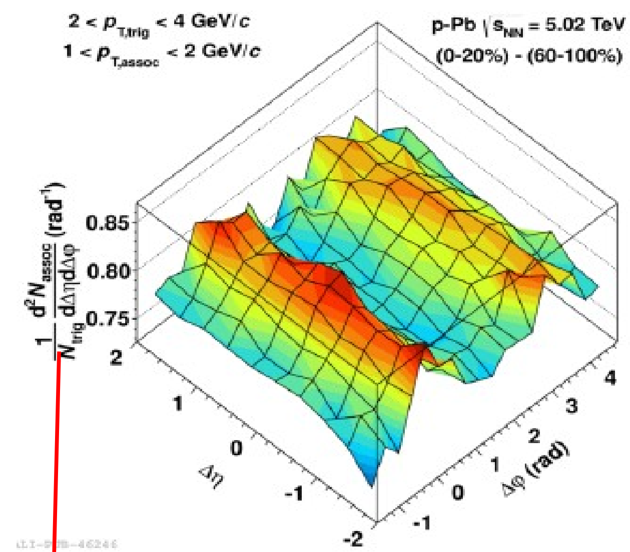
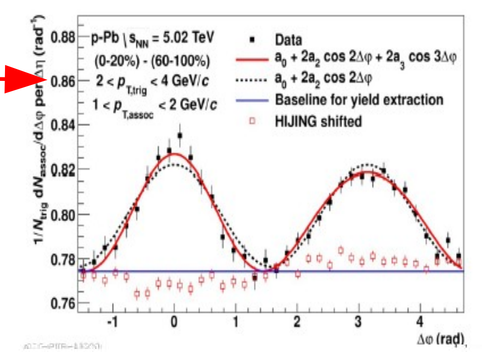


PLB 719 (2013),29-41

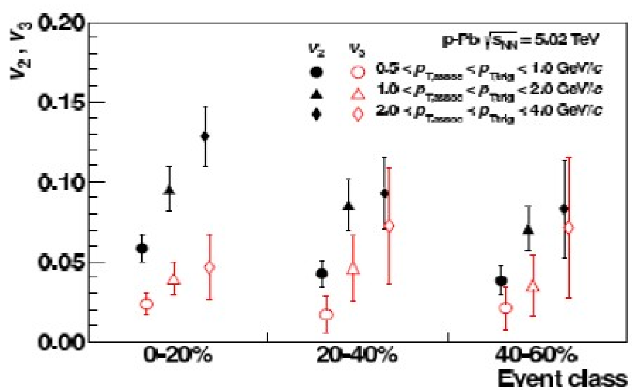


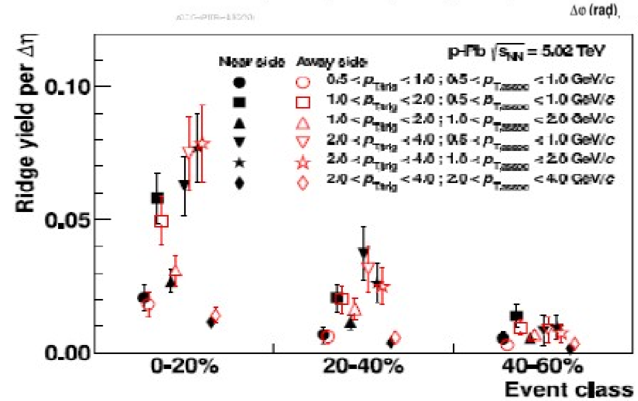
long range correlation:

Double (near+away side) ridge structure emerging when subtracting per-trigger yield of low (60-100%) from high-multiplicity (0-20%) events.

Near and away side nearly identical independent of mult.

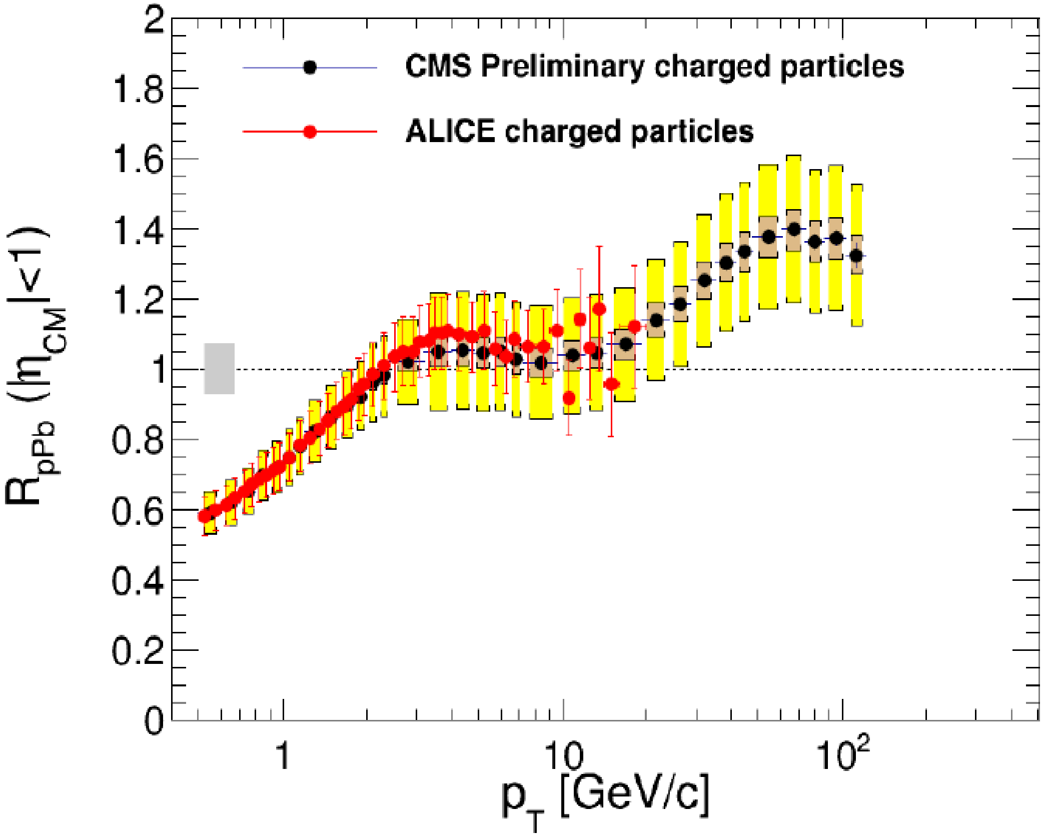
→ common underlying physics?

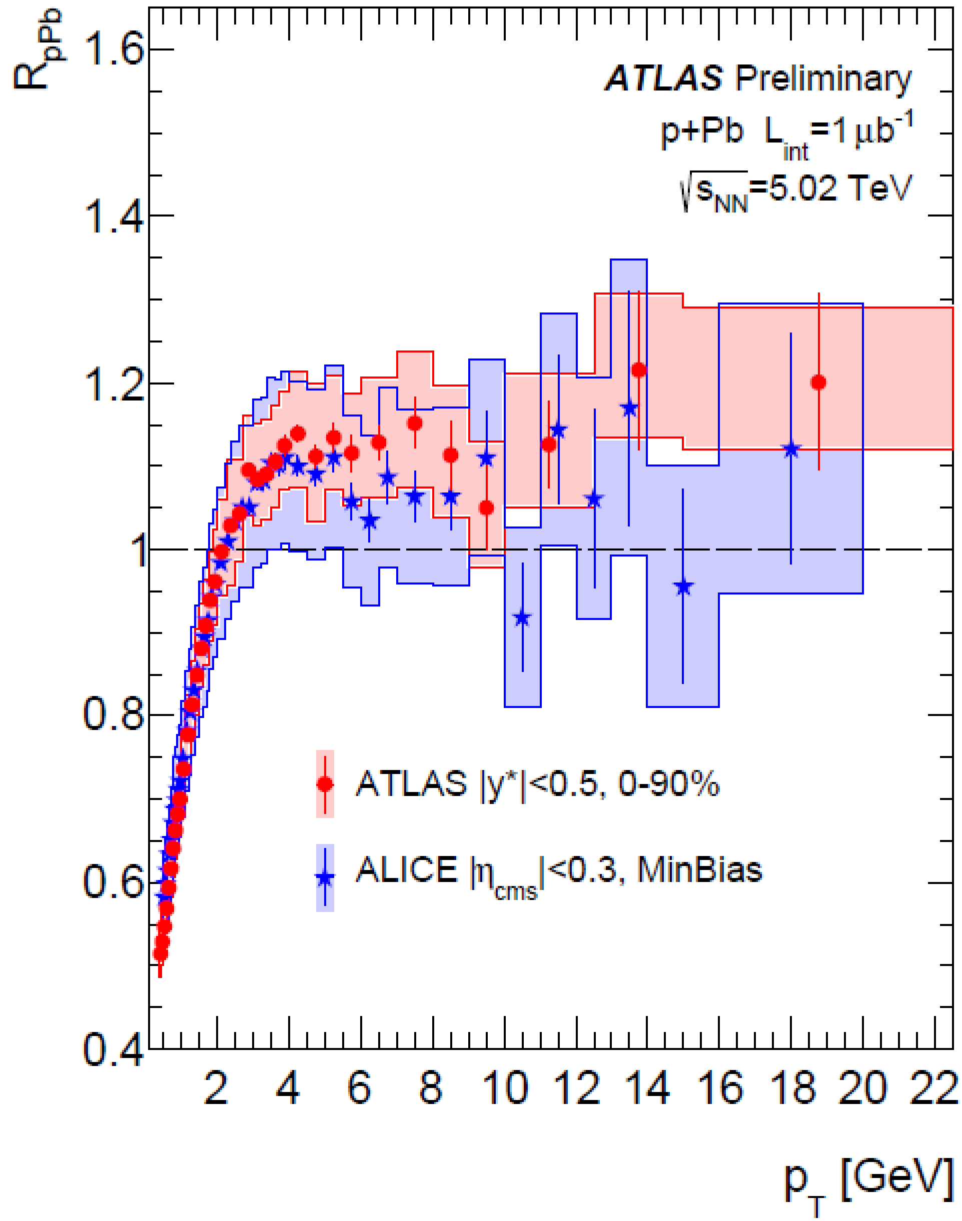




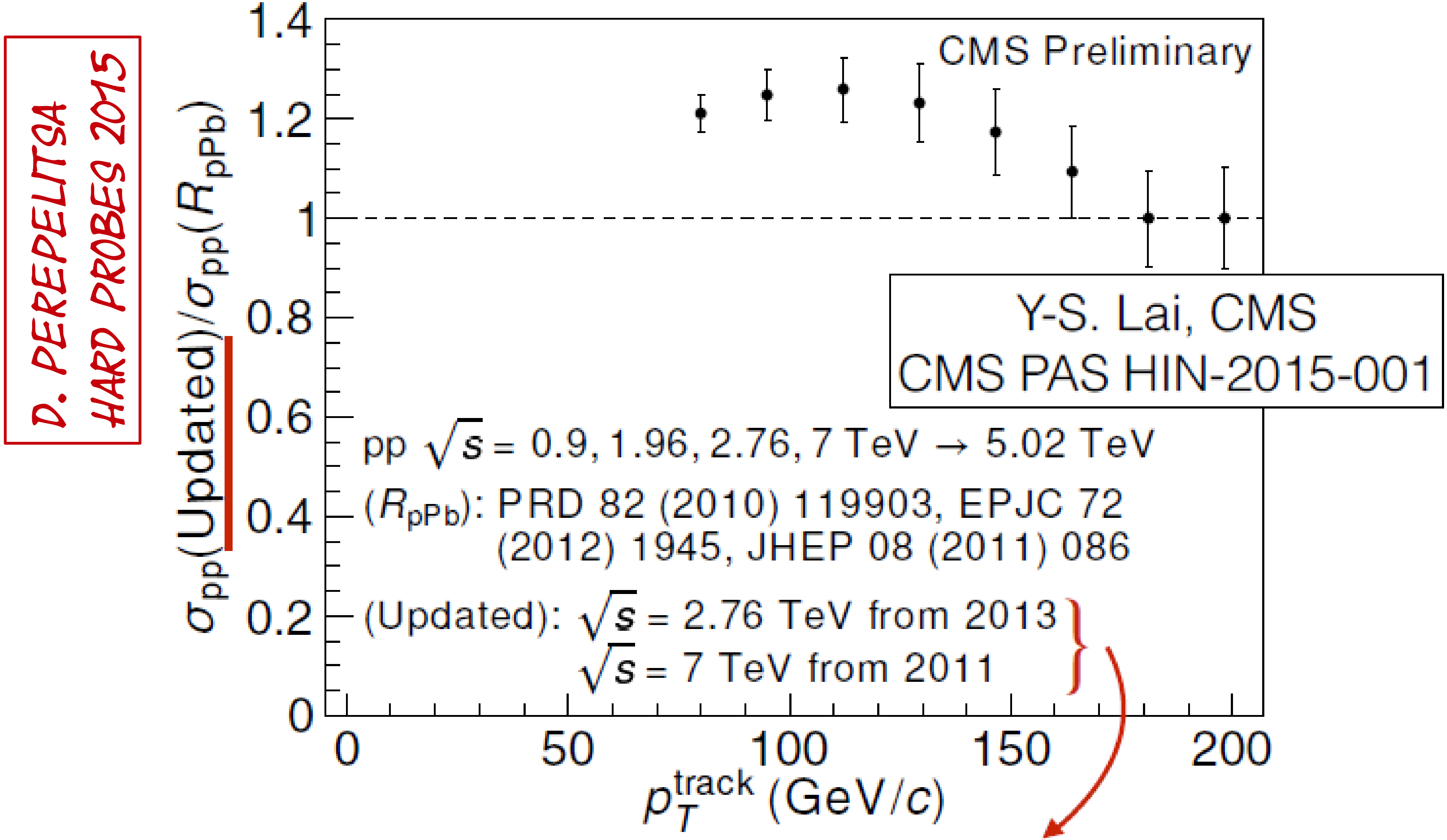
ALICEColl. PLB 719 (2013), pp. 29-41

RPA ALICE VS ATLAS VS CMS





pp @ 5 TeV reference for CMS

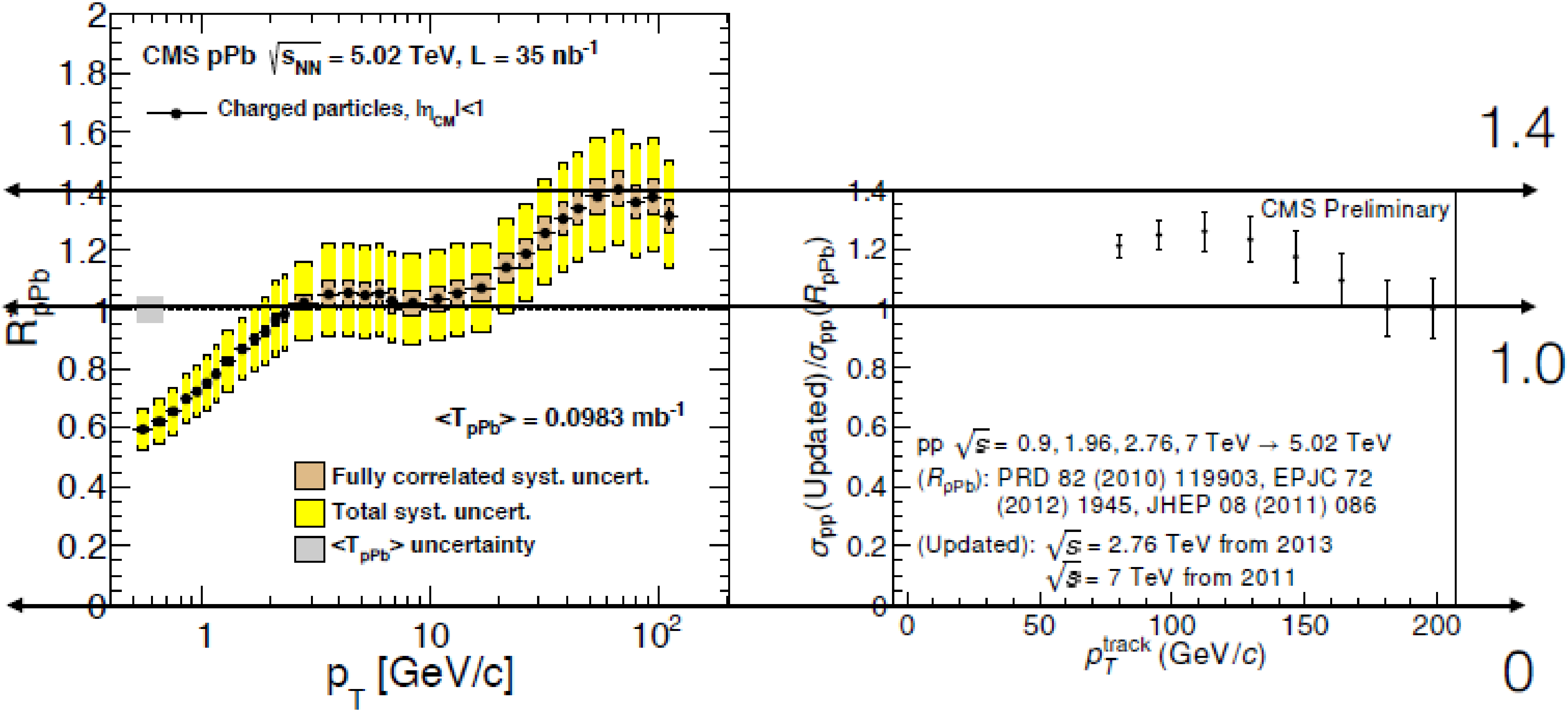


using *updated* 2.76 TeV and 7 TeV measurements

⇒ what would the effect on the R_{pPb} be?

D. PEREPELITSA
HARD PROBES 2015

line these up vertically…



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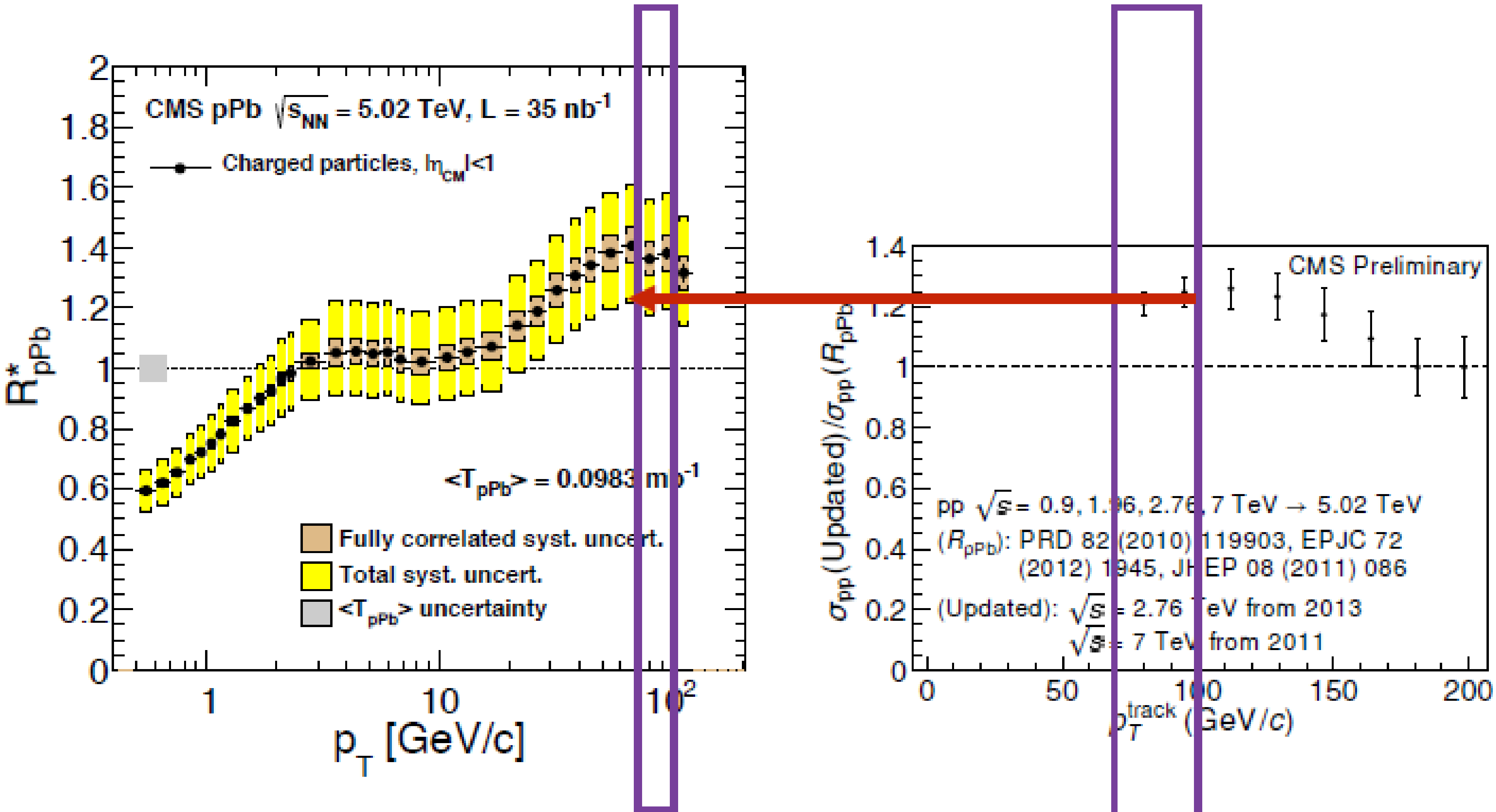
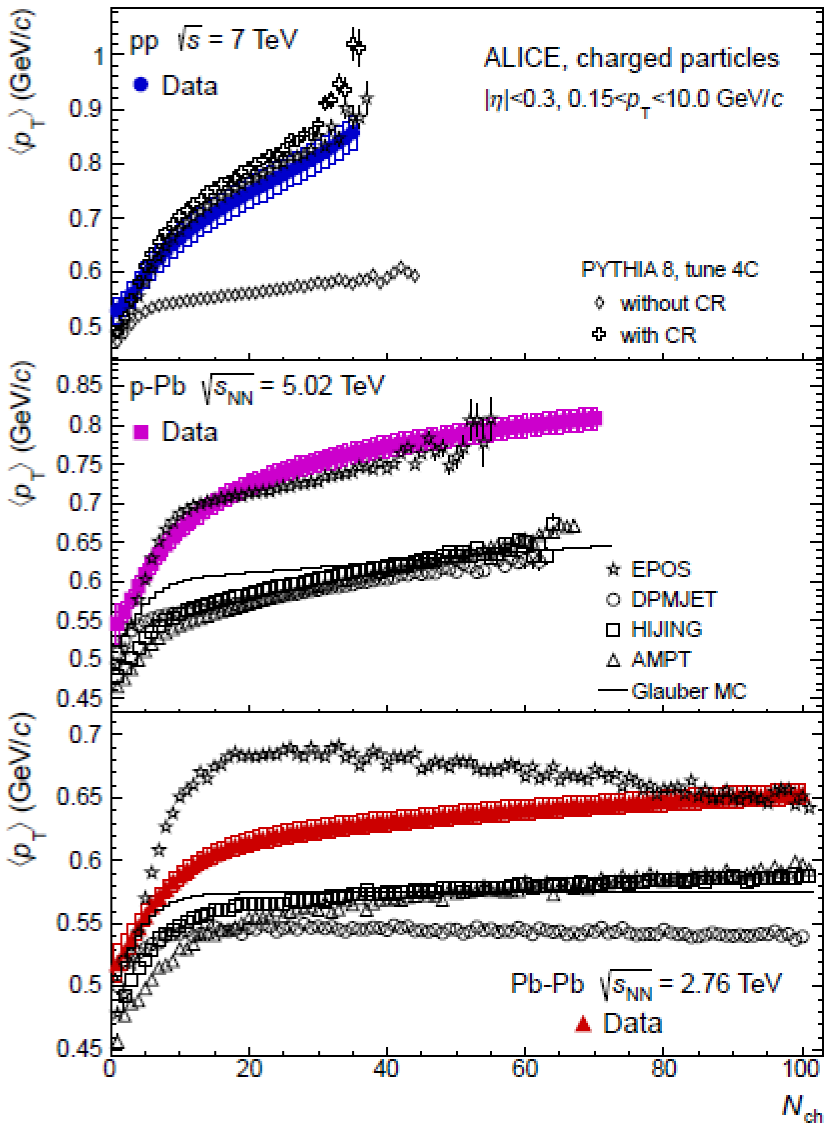
new reference would **eliminate** most of the enhancement



70-100 GeV (log scale)

70-100 GeV (linear scale)

MEAN P_T

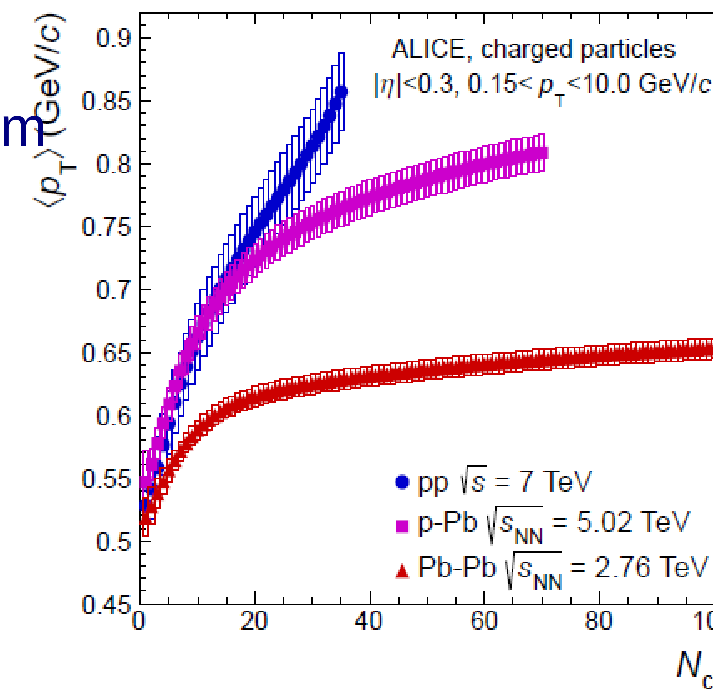


ALICE Coll. PLB 727 (2013) 371

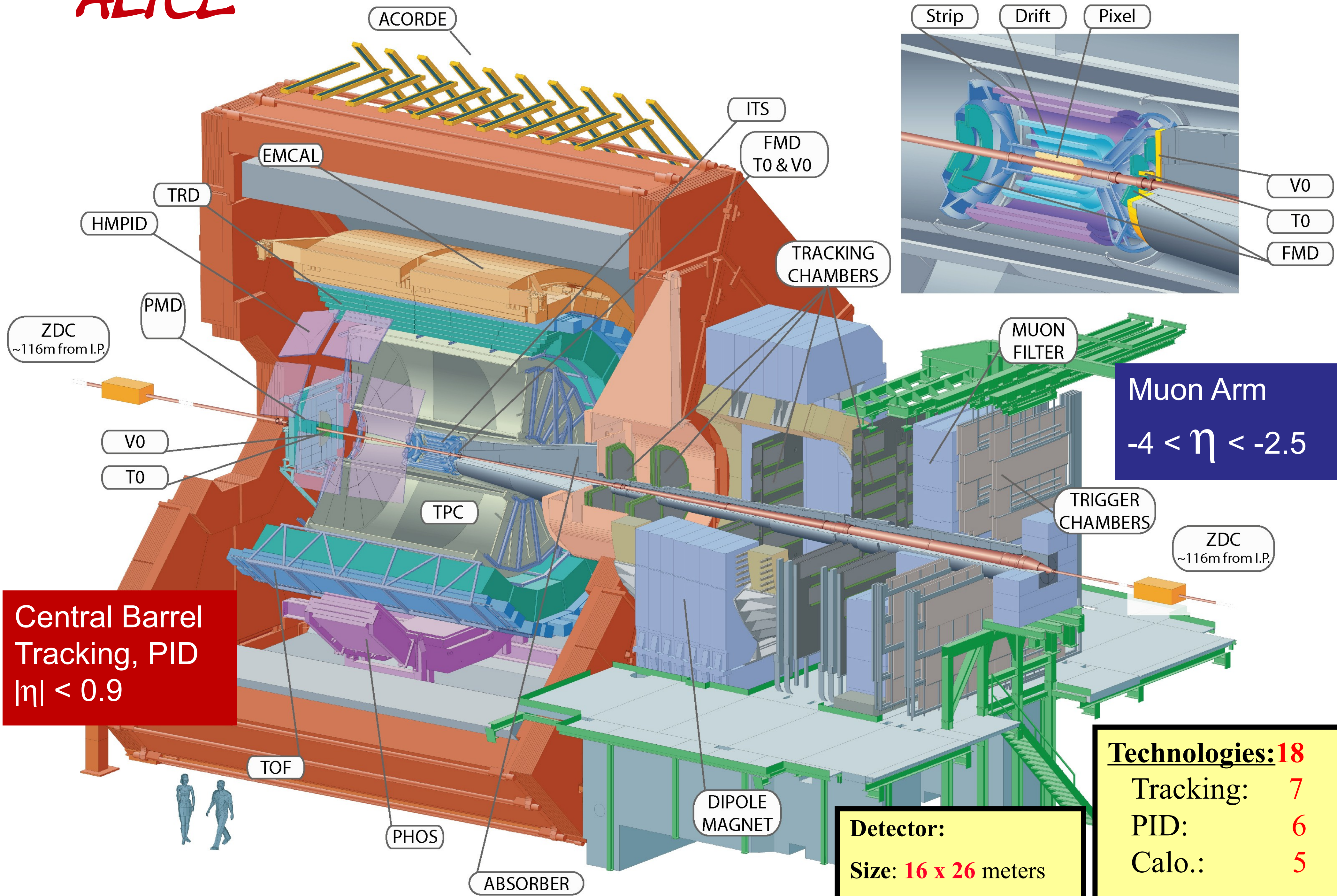
pp: high-mult through multiple parton interactions BUT incoherent production → same <pt>
→ Color reconnection: strings from independent parton interactions do not independently produce hadrons, but fuse before hadronization
→ fewer, but more energetic, hadrons
Sign of collectivity?

pPb: features of both
less saturation than in PbPb → higher <pt>
Sign of collectivity?

PbPb: high-mult from superposition of parton interactions, collective flow
→ moderate increase of <pt>



ALICE



Central Barrel
Tracking, PID
$|\eta| < 0.9$

Muon Arm
$-4 < \eta < -2.5$

Detector:

Size: 16 x 26 meters

Weight: 10,000 tons

<u>Technologies:</u>18

Tracking: 7
PID: 6
Calo.: 5