Experimental Summary

Hyperlinks in this color

Int. Conference on the Initial Stages of High-Energy Nuclear Collisions

Constantin Loizides
(LBNL/EMMI)

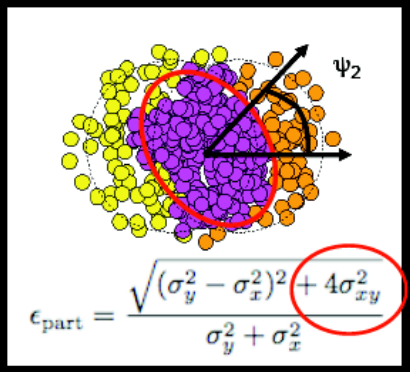
14 Sep 2013

Disclaimer: Not everything can be covered in a summary talk. Apologize to those not mentioned!

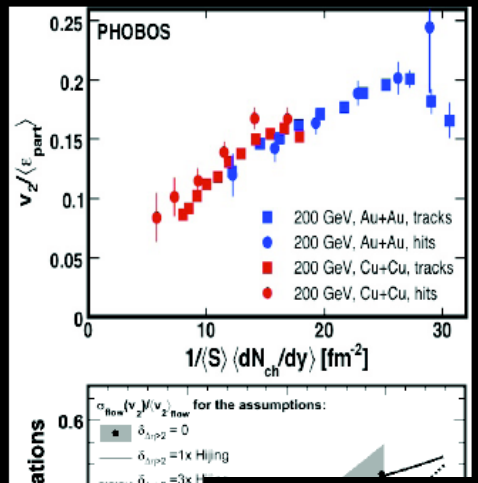
Thermalization and Higher Harmonics

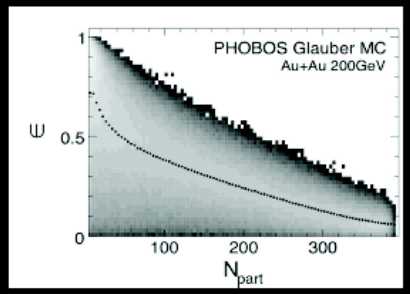
Geometry Fluctuations and Participant Eccentricity

Participant Eccentricity

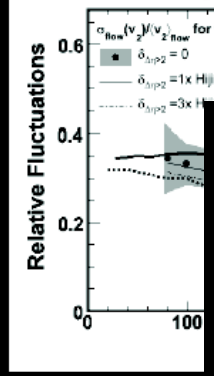


PHOBOS
QM2005
PRL 98, 242302 (2007)





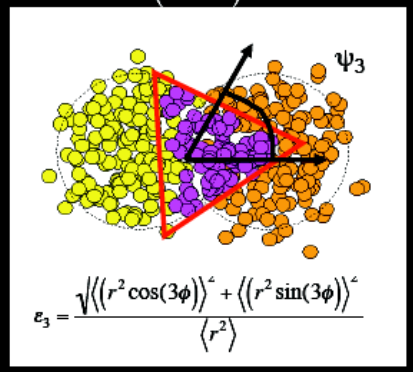
PHOBOS
PRL 104, 142301 (2010)
PHOBOS
PRC81, 034915 (2010)



Iconoclast
(see Gunther's talk)

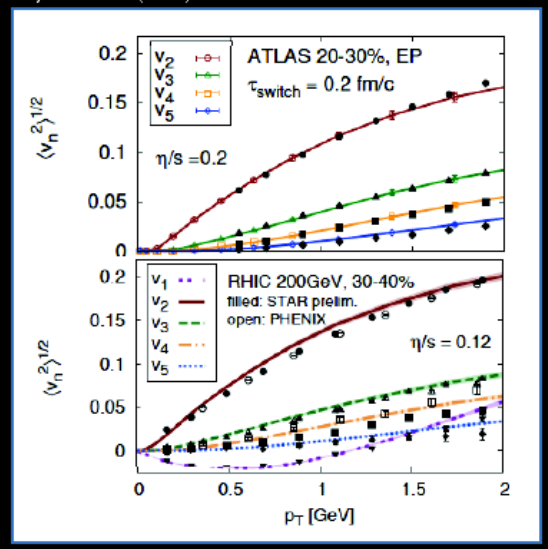
Geometry Fluctuations and Higher Order Harmonics

Participant Triangularity
(2010)



Alver, Roland
Phys.Rev.C81:054905,2010

Bjoern Schenke et al
Phys.Rev. C85 (2012) 024901



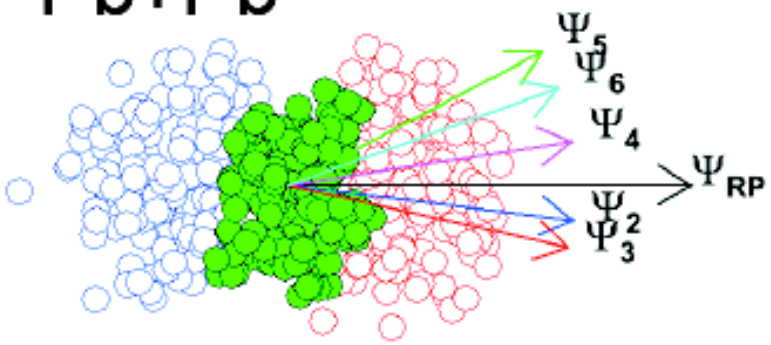
Just like elliptic flow reflects event-by-event eccentricity, "triangular flow" (v_3) reflects event-by-event "triangularity" (ε_3)

Single calculation describes Fourier coefficients at RHIC and LHC (2012) (small change in η/s from RHIC to LHC)

Glauber: Correlations with Participant Plane

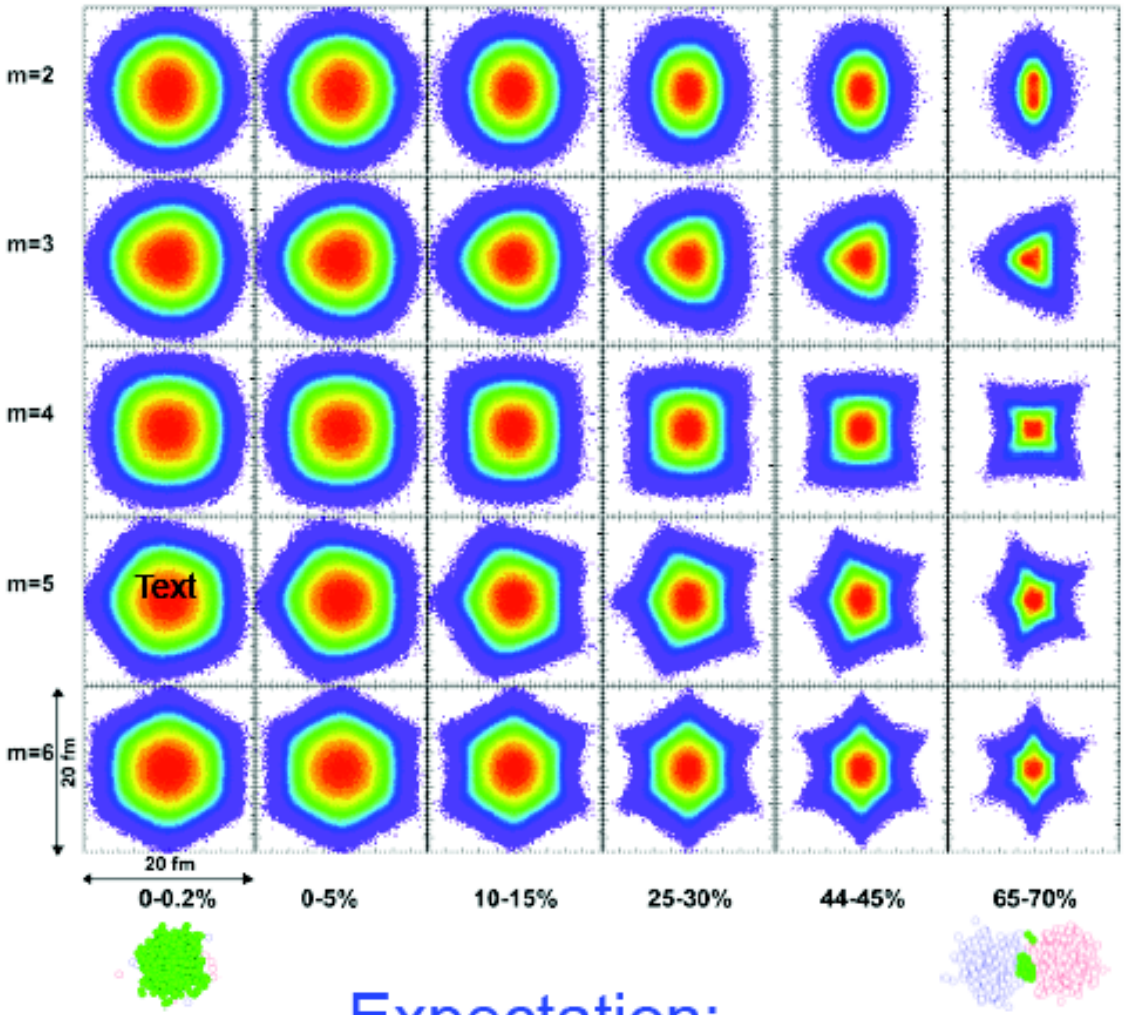
Participant densities with respect to participant plane:

Pb+Pb



Centrality ~35%

$$\Psi_m^{pp} = \frac{1}{m}\tan^{-1}\left\{\frac{\sum_{i=1}^{N_{part}}\left(r_i'\right)^m \sin\left(m\phi_i'\right)}{\sum_{i=1}^{N_{part}}\left(r_i'\right)^m \cos\left(m\phi_i'\right)}\right\} - \frac{\pi}{m}$$



Measure:

$$\frac{dN}{d\left(\phi - \Psi_m\right)} \propto 1 + \sum_{n\geq m}^{\infty} 2v_n^{obs}\left\{\Psi_m\right\}\cos\left[n\left(\phi - \Psi_m\right)\right]$$

Expectation:

v_n=(medium evolution)×ε_n

$$\Psi_m \approx \Psi_m^{pp}$$

Harmonic Order Dependence

$$\frac{v_n}{\sqrt{\langle \varepsilon_n^2 \rangle}} \sim \exp\left[-\beta n^{\alpha}\right]$$

with

$$\alpha \geq 1$$

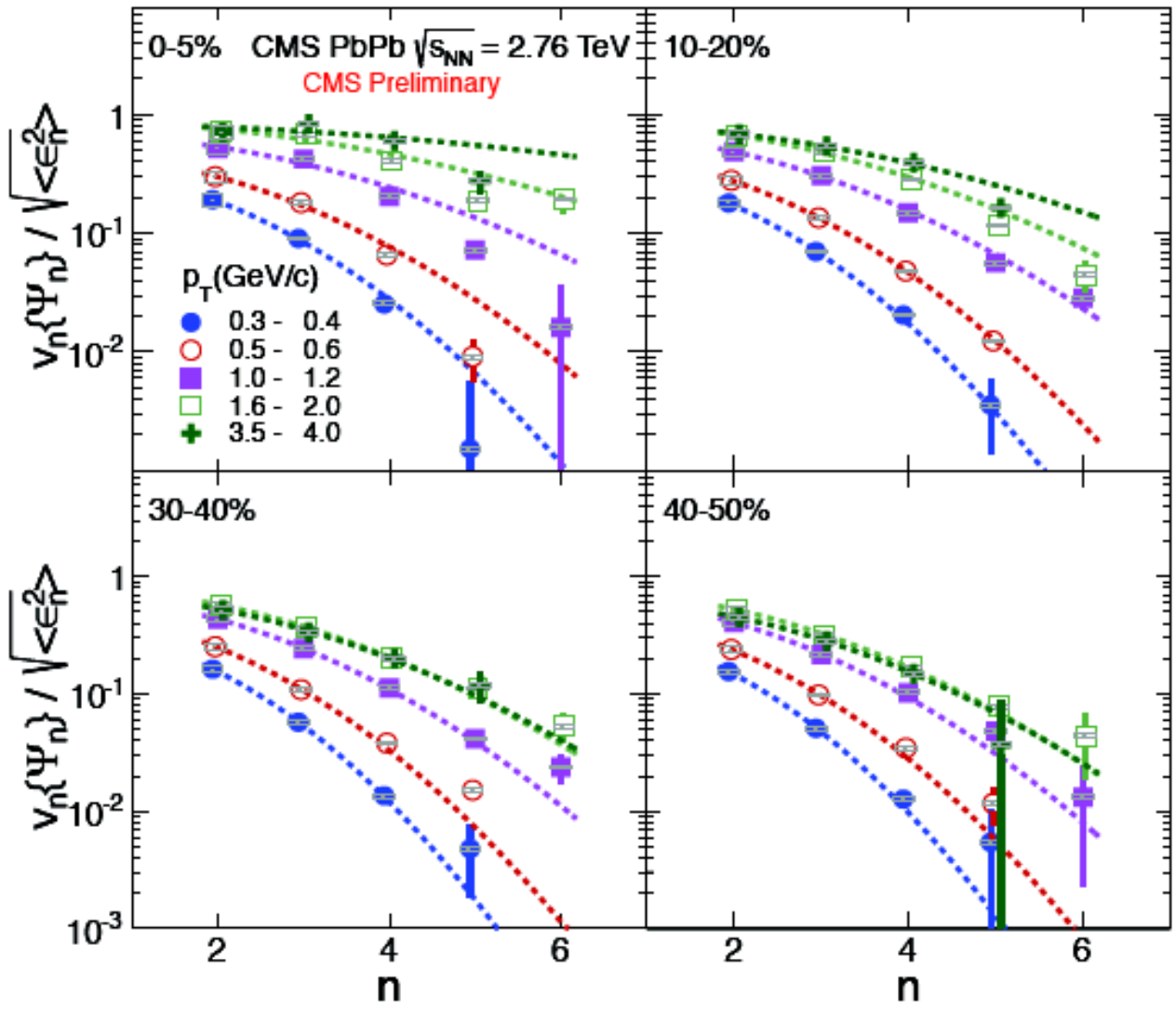
For acoustic flow

(Lacey et al.,arXiv:1301.0165)

$$\alpha = 2$$

$$\beta \propto \frac{\eta}{s}$$

$\exp\left[-\beta n^2\right]$ fits

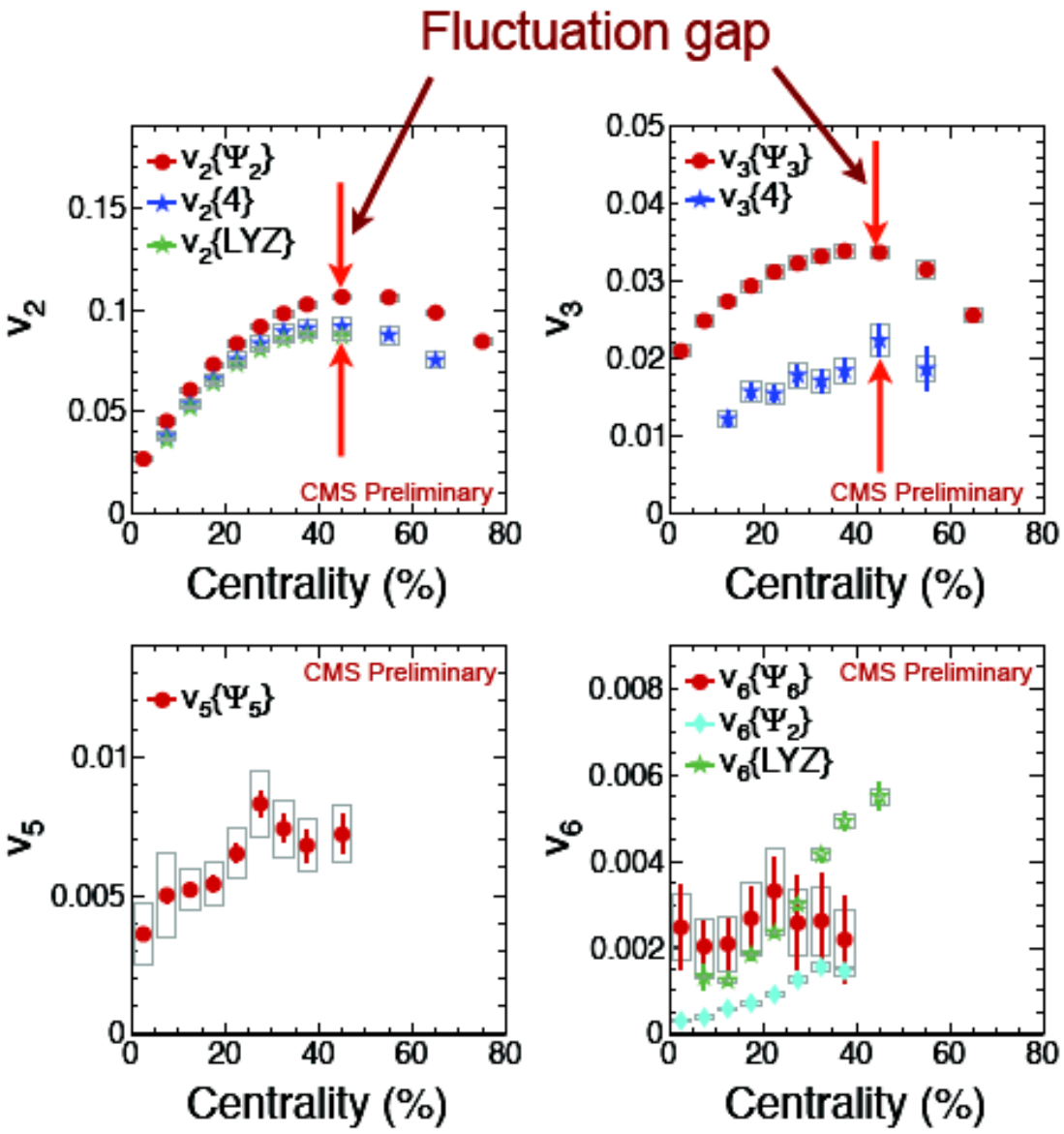


v_n ($0.3 \le p_T < 3.0$ GeV/c)

m=2 reference distribution

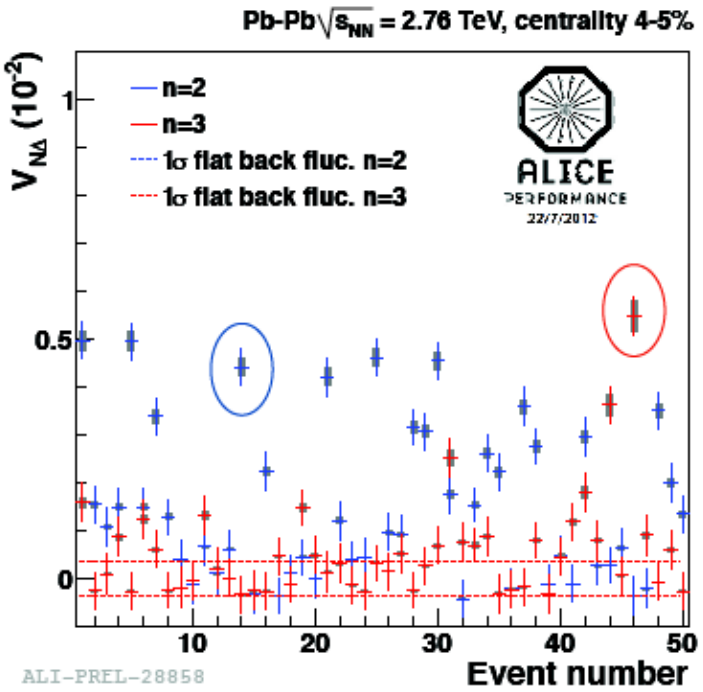
⇒Strong centrality dependence

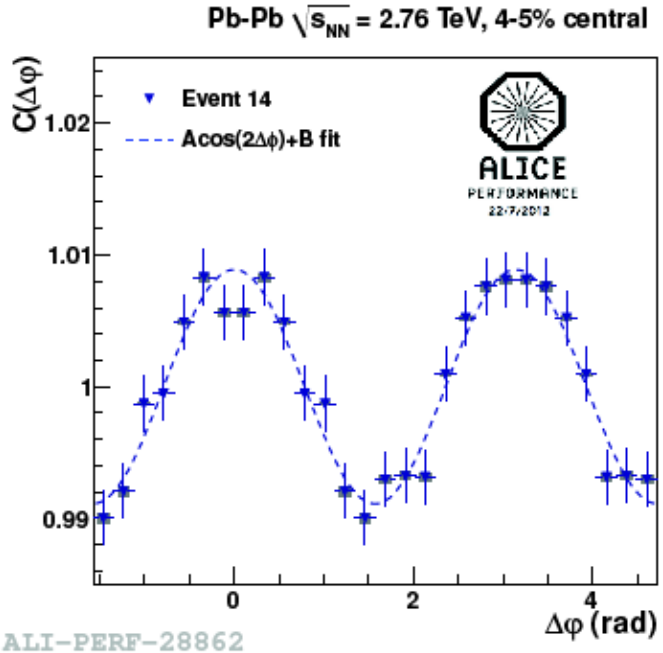
CMS PbPb $\sqrt{s_{NN}} = 2.76$TeV

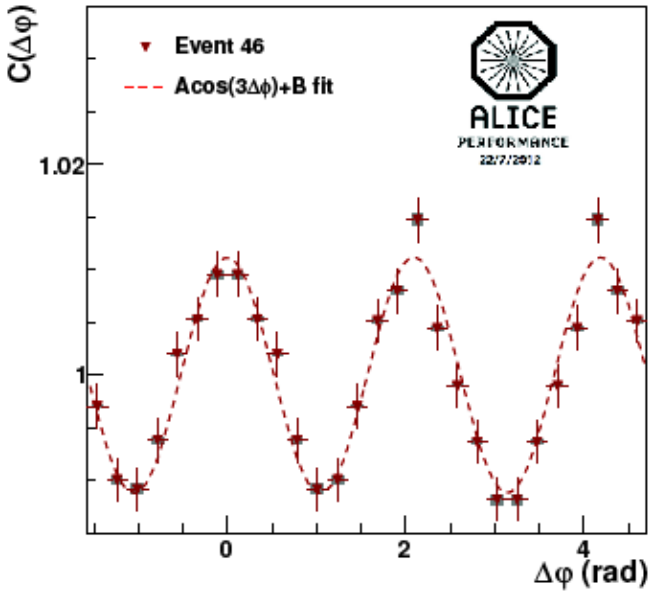


v_2 and v_3 fluctuations

- **Large fluctuations in v_2^2 and v_3^2** observed event by event
  - ✓ Appear largely independent
- 2 particle correlations in circled events dominated by v_2 and v_3
  - ✓ Allows v_n distributions to be obtained…





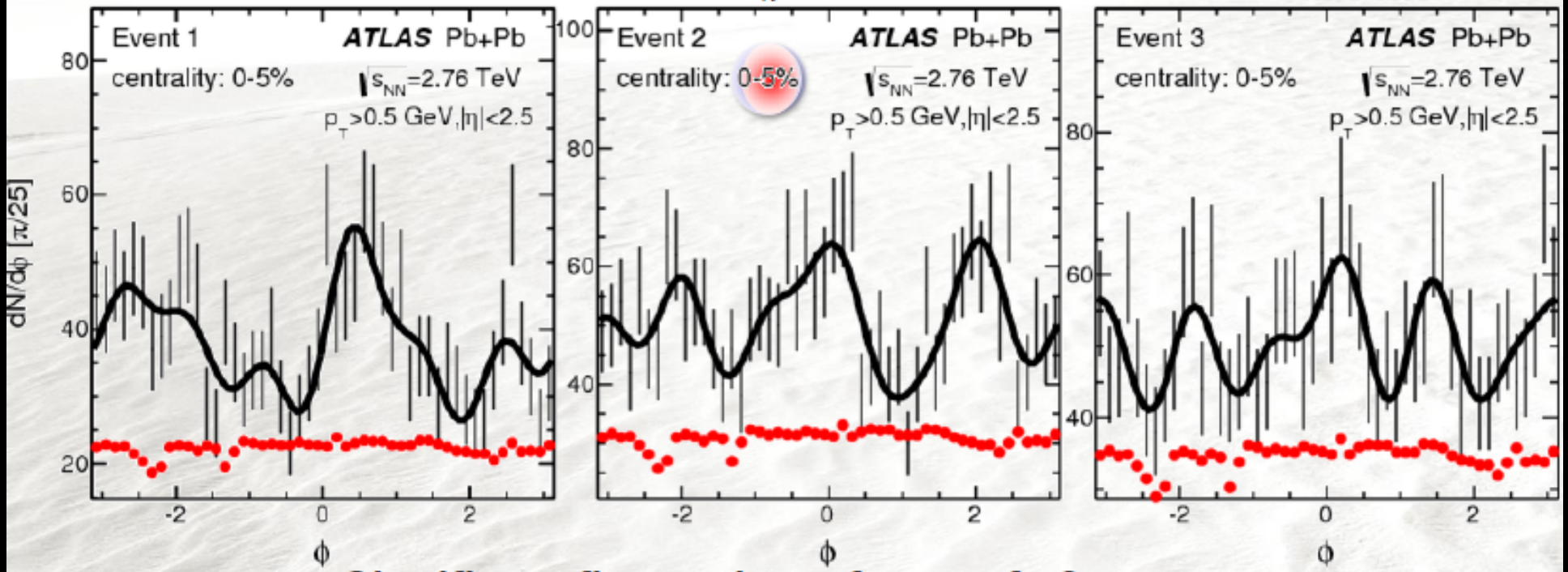


$$V_{n\Delta} = v_n^2$$

Fluctuations event-by-event

$$\frac{dN}{d\phi} \mu 1 + 2 \sum_n v_n \cos n\left(\phi - \Phi_n\right)$$

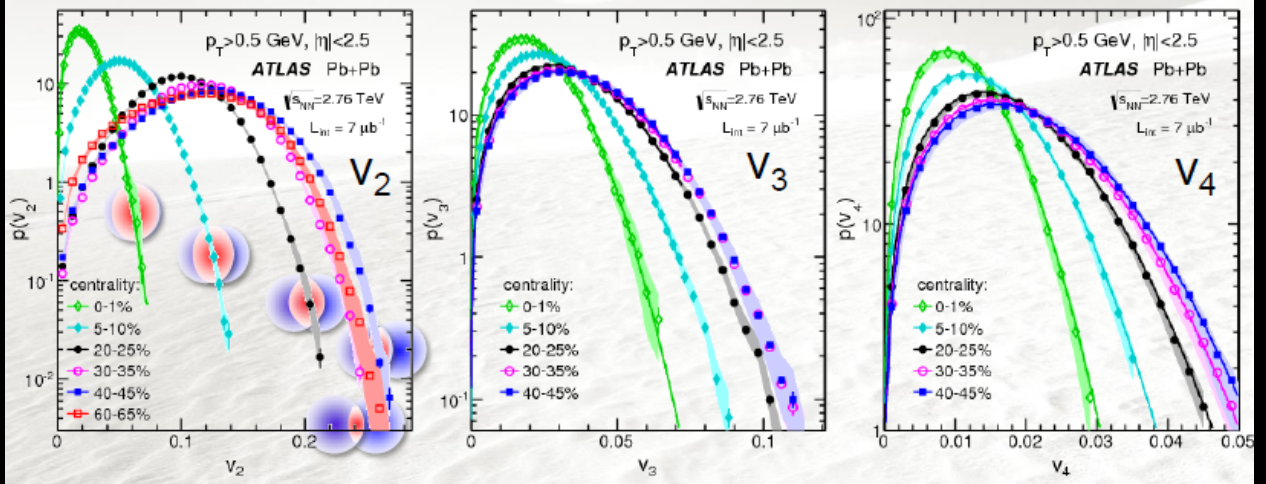
arXiv:1305.2942



Significant fluctuations, factor of ~2
Cannot be explained by detector effects
Shall be corrected for:
- **efficiency**
- **acceptance**
- **limited statistics**

Sasha Milov (ATLAS)

Flow probability distributions



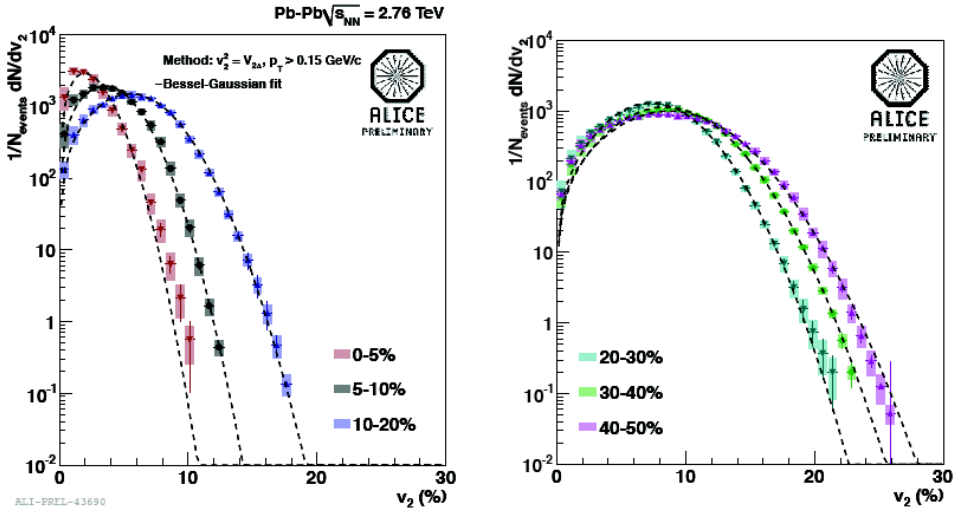
arXiv:1305.2942

v_n distributions in p_T and centrality

Fully corrected for detector effects an unfolded for limited statistics

Anthony Timmins (ALICE)

Unfolded v_2 distributions

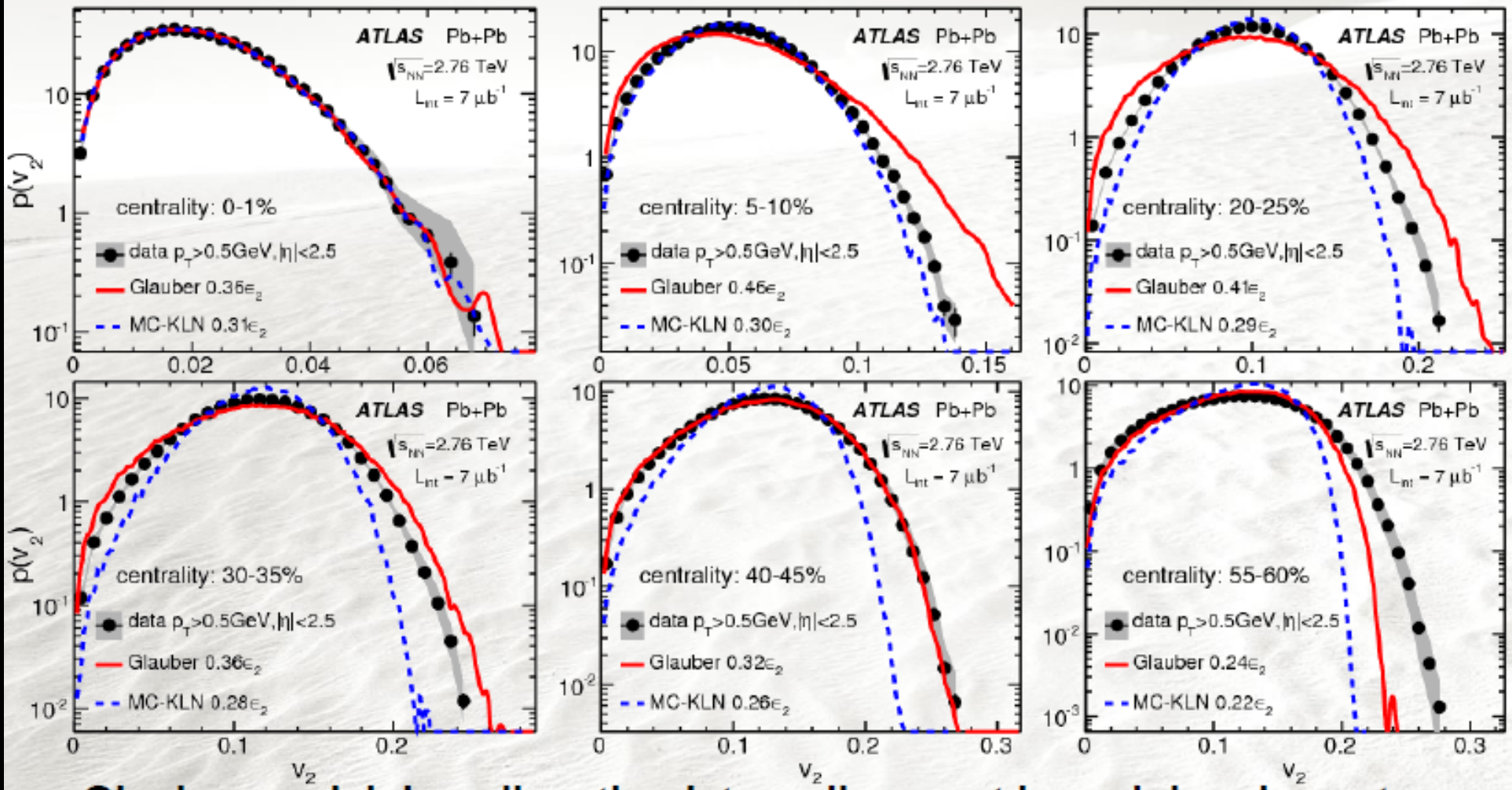


- Unfolding removes effects of finite statistics
  - ✓ Expected to reflect eccentricity fluctuations of initial state (arix:1212.1008)
  - ✓ Bessel Gaussian fits work nearly always.

ALICE

Comparison to models

arXiv:1305.2942

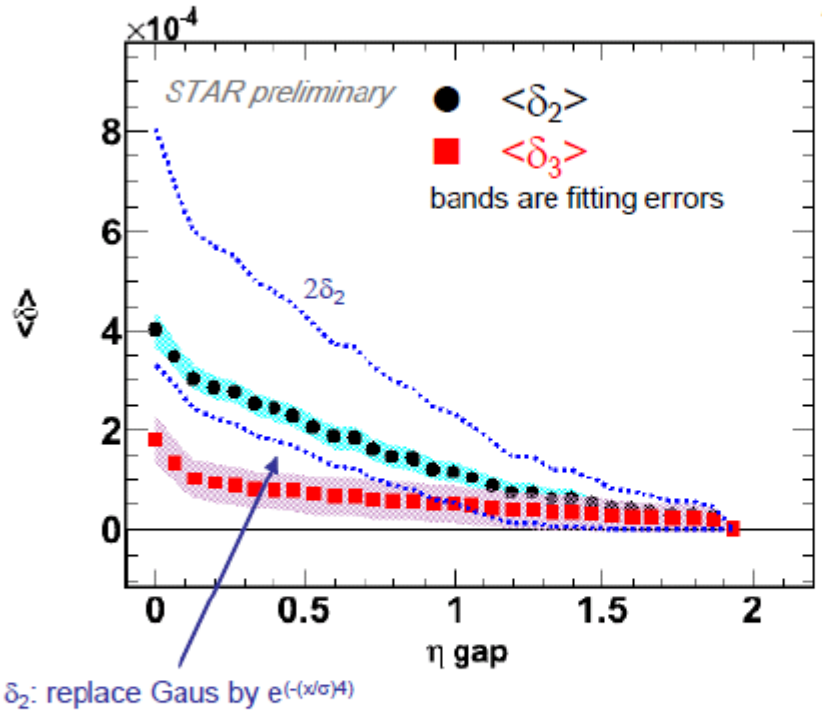


Glauber model describes the data well, except in peripheral events

MC-KLN is less accurate even in mid-central collisions

Nonflow δ_n

AuAu@200GeV 20-30%



- δ_n drops as η gap increases.

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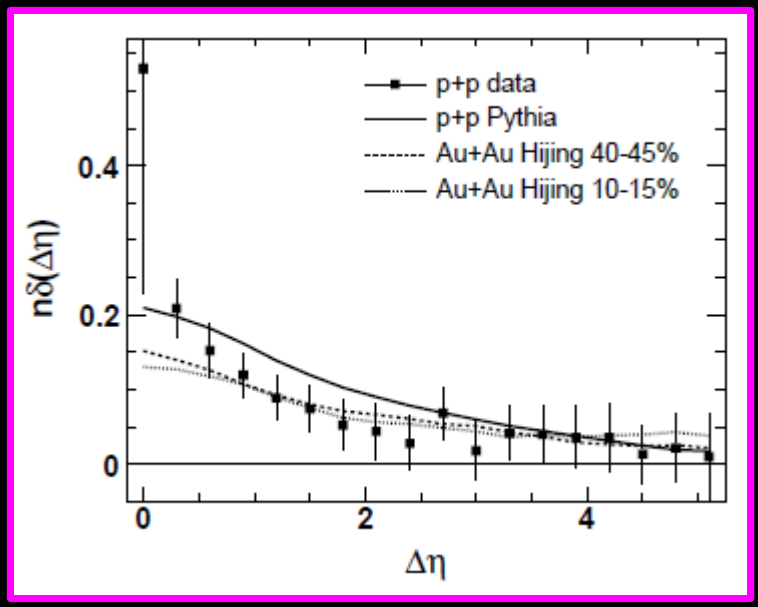
Li YI, IS2013, Spain

PHOBOS, PRC 81 (2010) 034915



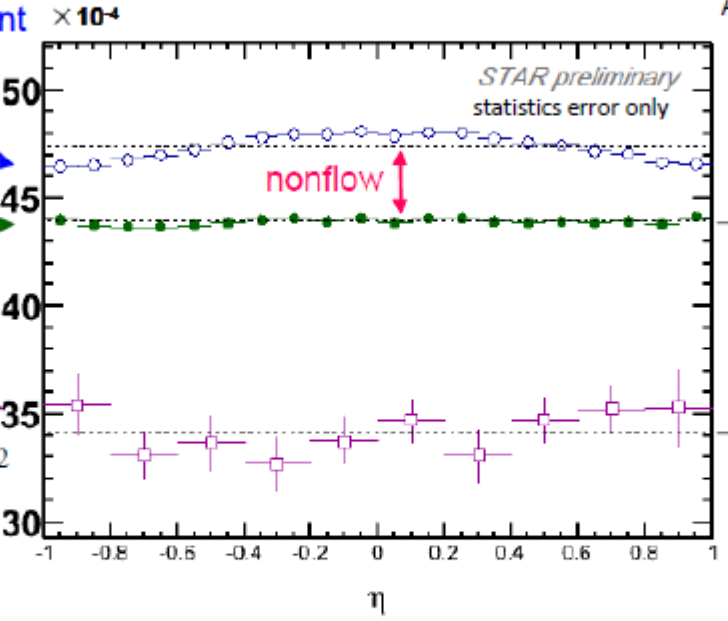
Indicates that HIJING roughly describes the non-flow (Caveat phase-space difference?)

'Flow' vs η

raw 2-particle cumulant $v_2\{2\}^2 = \delta_2 + \langle v_2^2 \rangle$

$\langle v_2^2 \rangle$ decomposed flow

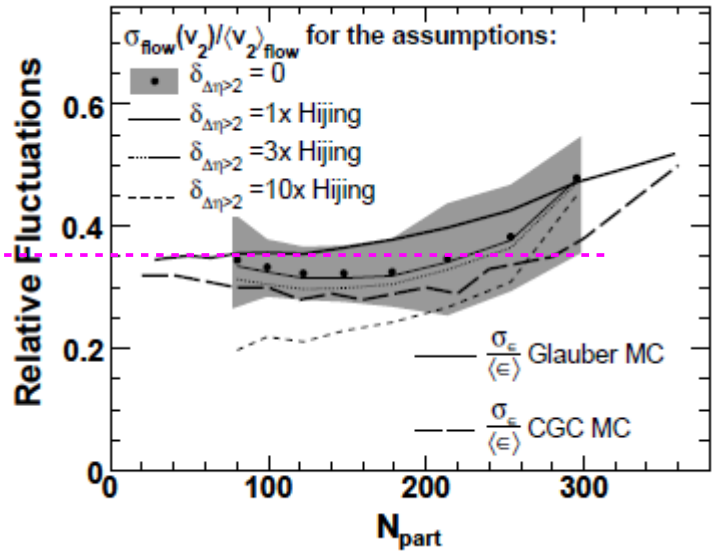
$v_2\{4\}^2 \approx \langle v_2^2 \rangle - 2\sigma_2^2$ raw 4-particle cumulant



$$\frac{\sigma_2^2}{\langle v_2 \rangle^2} \sim \frac{\langle v_2^2 \rangle - v_2\{4\}^2}{\langle v_2^2 \rangle + v_2\{4\}^2} \sim 12.6\% + 0.7\% - 4.0\%$$

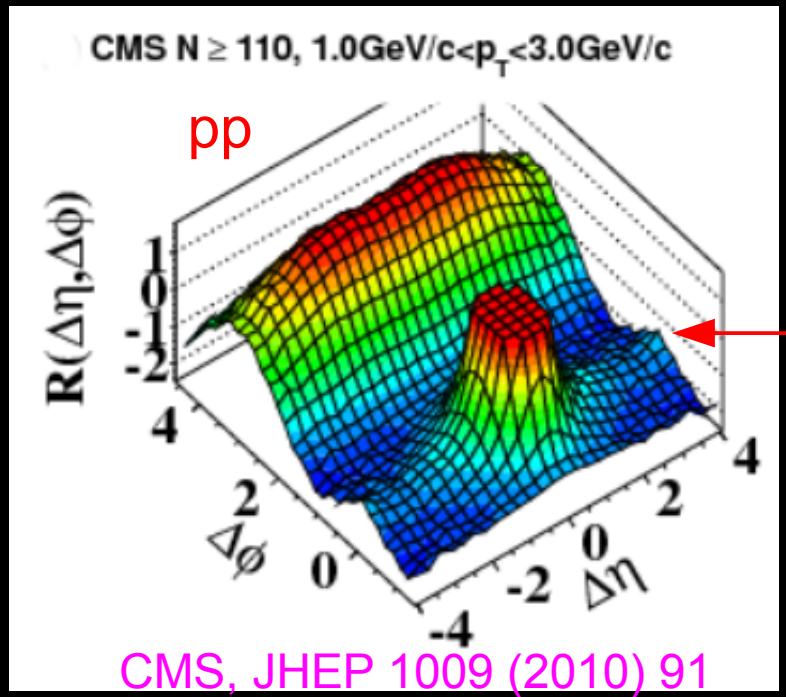
- v_2 flow seems independent of η.
- (Fluctuation/flow)^2 for v_2 ~ 13%

PHOBOS, PRC 81 (2010) 034915



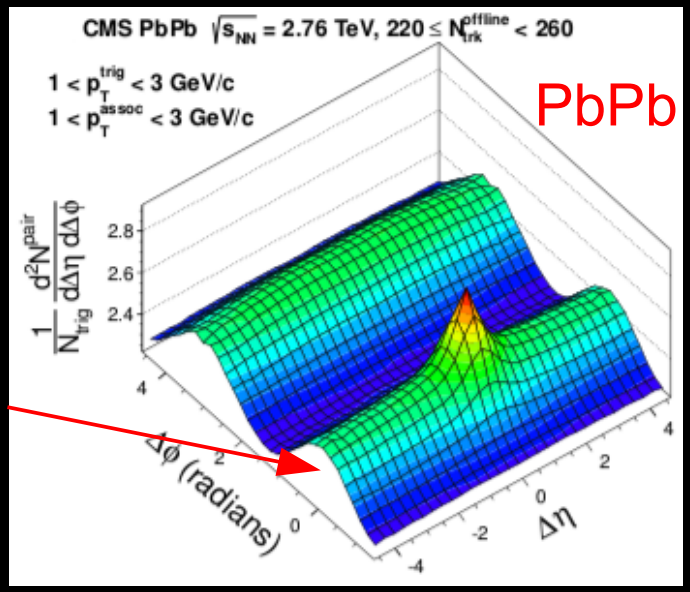
Consistent with PHOBOS
(with 0 or 1x HIJING subtraction)

Ridge in pPb (dAu)

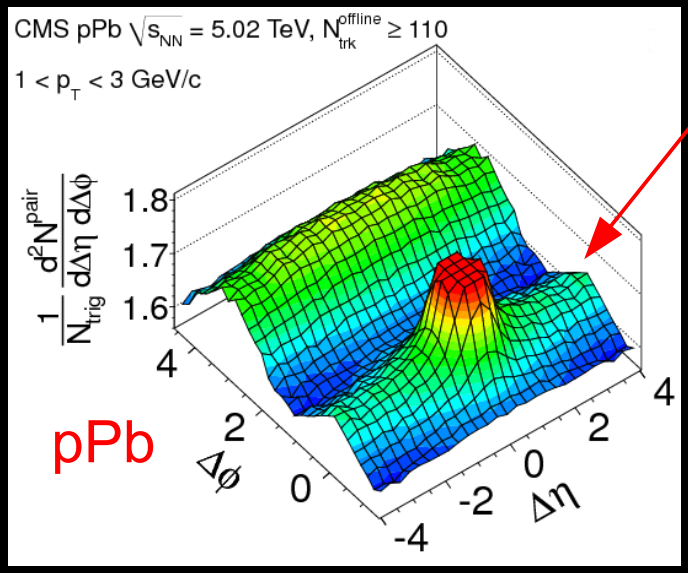


CMS, JHEP 1009 (2010) 91

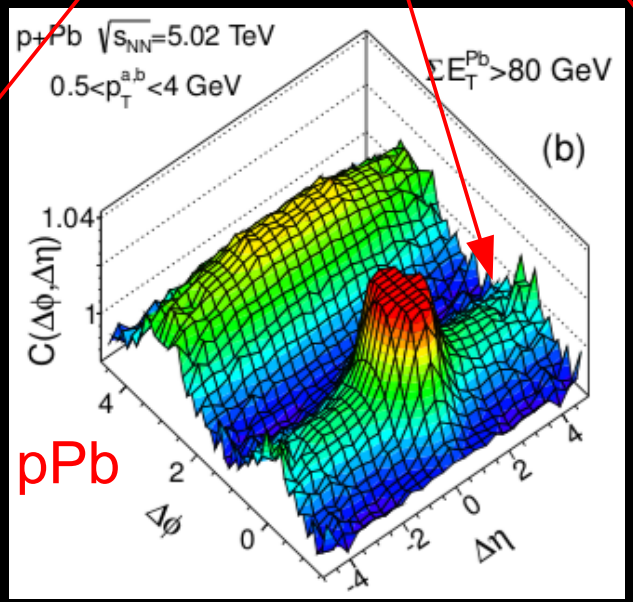
Near-side ridges apparent in high multiplicity events at LHC energies



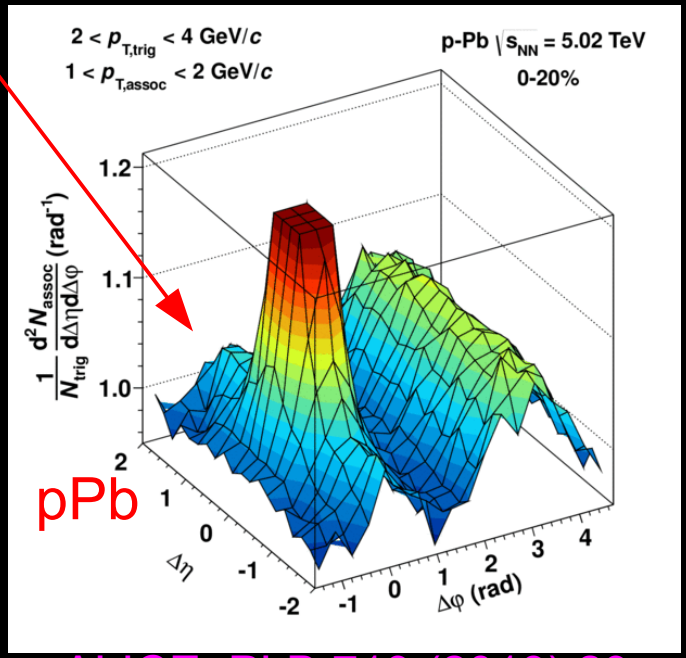
CMS, PLB 724 (2013) 213



CMS, PLB 718 (2012) 795



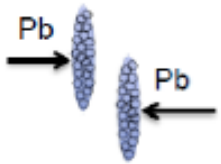
ATLAS, PRL 110 (2013) 182302

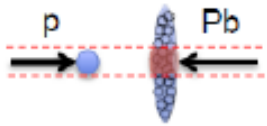


ALICE, PLB 719 (2013) 29

p_T dependence of v_n : PbPb vs pPb

Dashed-dotted curves
N<20 subtracted
Important for high-p_T

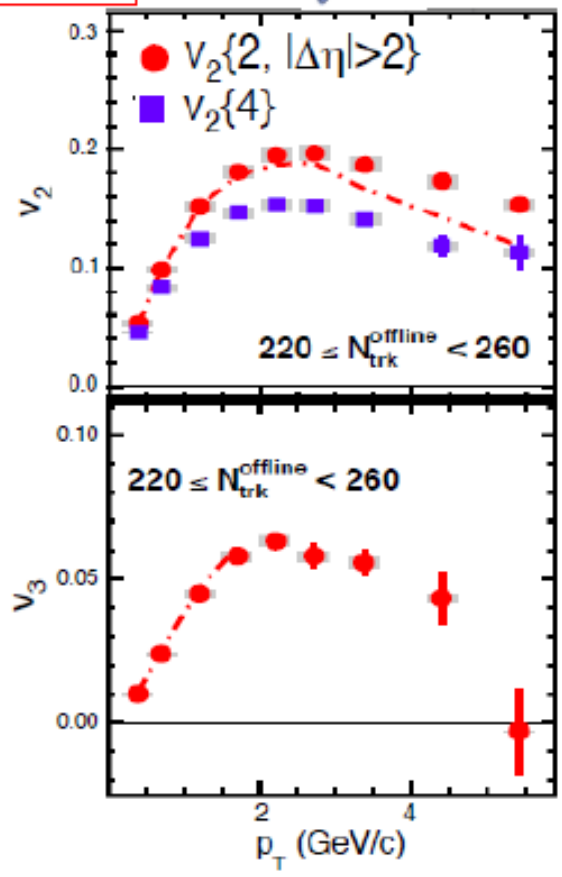


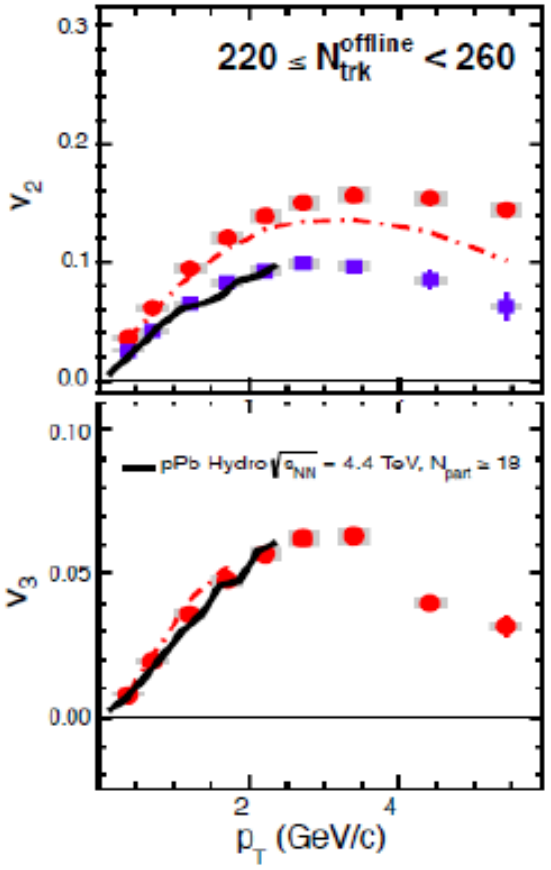


PLB 724 (2013) 213

n = 2

n = 3

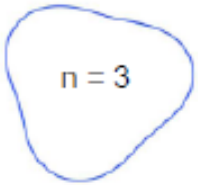


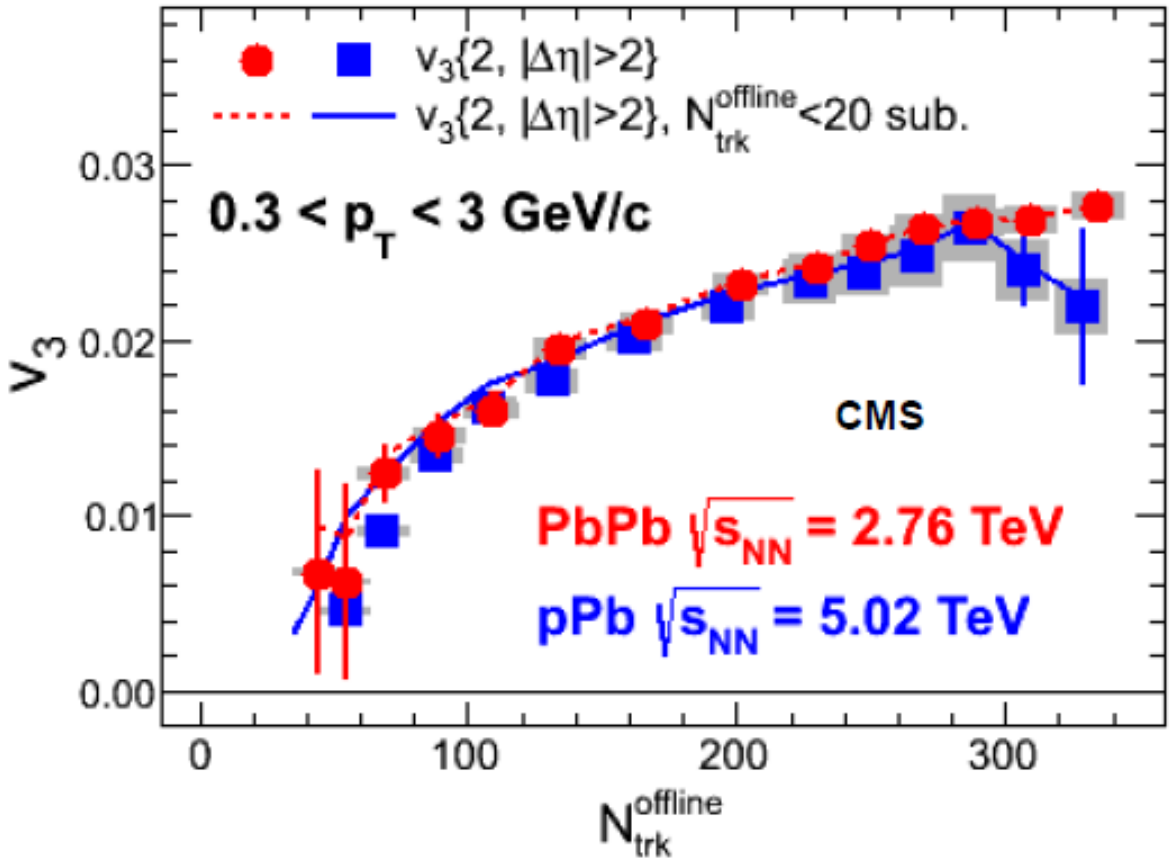


Remarkable similarity in PbPb and pPb for same multiplicity

Multiplicity dependence of v_3

PLB 724 (2013) 213

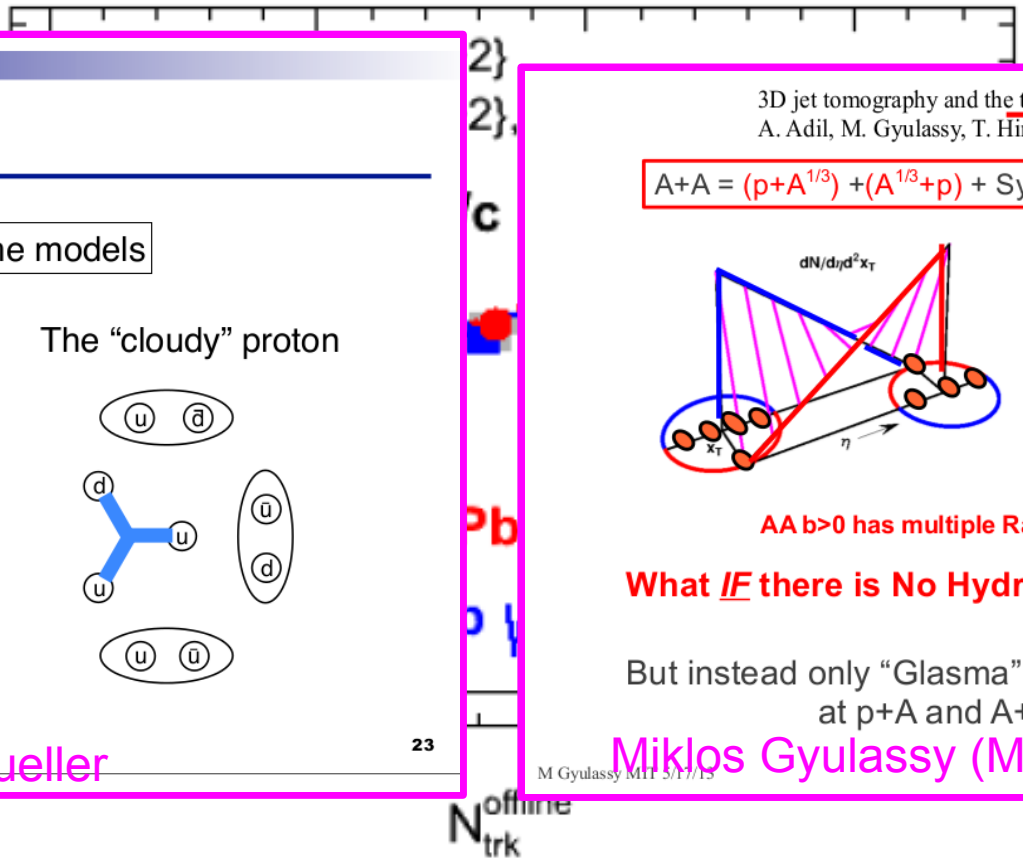




- Independent of system size
- Does not extrapolate to 0

Multiplicity dependence of v_3

PLB 724 (2013) 213

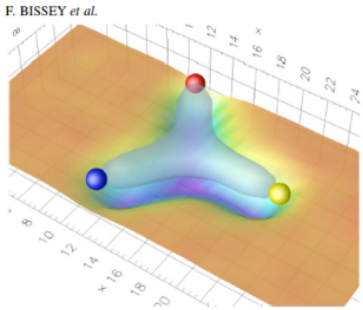


DUKE Theory

"Obese" protons

Two extreme models

The "stringy" proton



The "cloudy" proton

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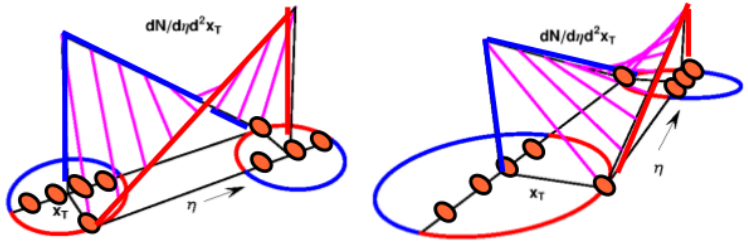
Wednesday, September 11, 13

Berndt Mueller

3D jet tomography and the twisted color glass condensate
A. Adil, M. Gyulassy, T. Hirano , Nucl.Phys. A774 (2006) 593

$A+A = (p+A^{1/3}) + (A^{1/3}+p) + \text{Symmetric Stuff}(A\text{-}A^{1/3} + A\text{-}A^{1/3})$



AA b>0 has multiple Rapidity Triangle p+A edges

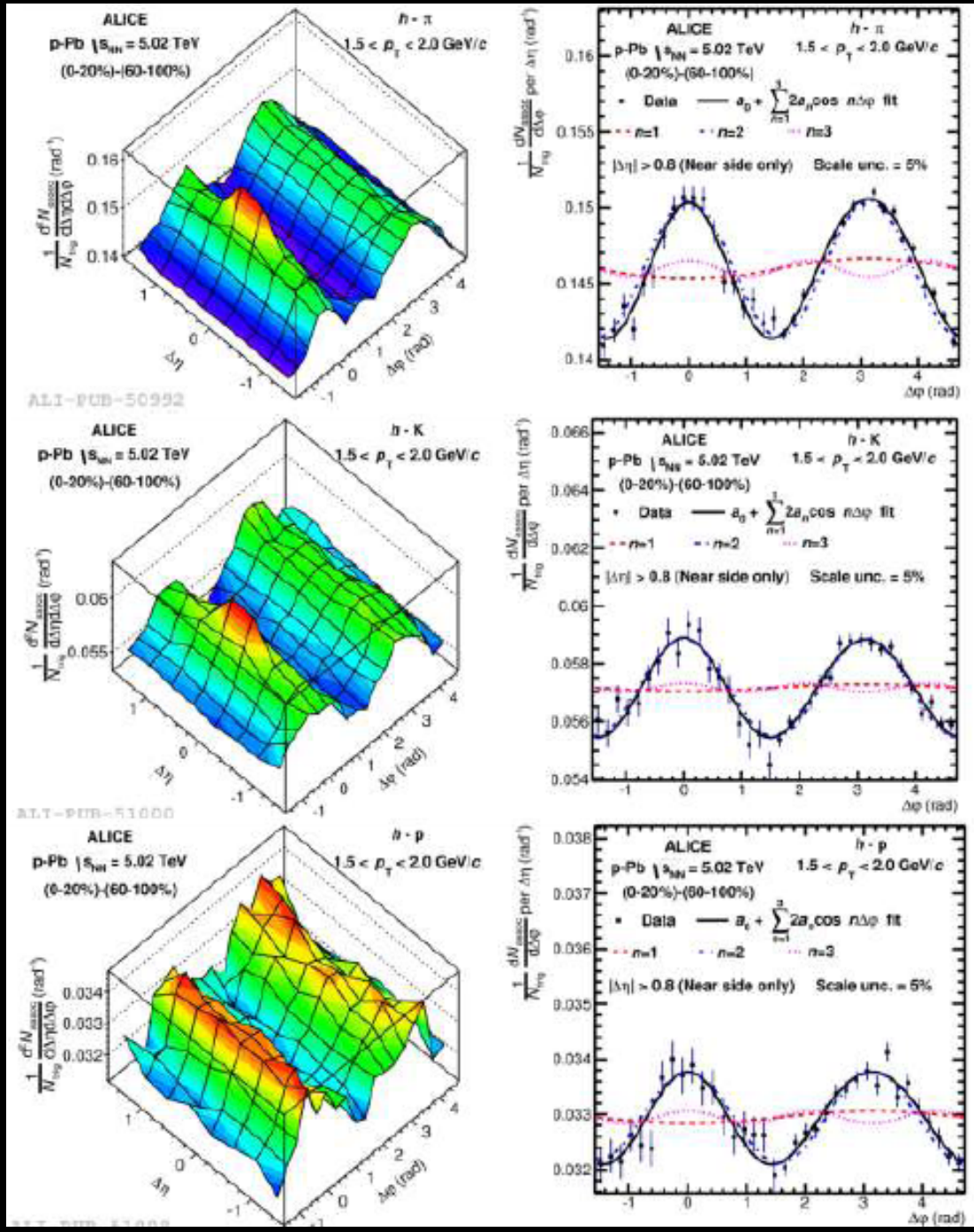
What *IF* there is No Hydro , No v_n Flow from bulk ??

But instead only "Glasma" Interference Phenomena
at p+A and A+p edges ???

M Gyulassy MIT 5/17/13 31

Miklos Gyulassy (MIT workshop, 2013)

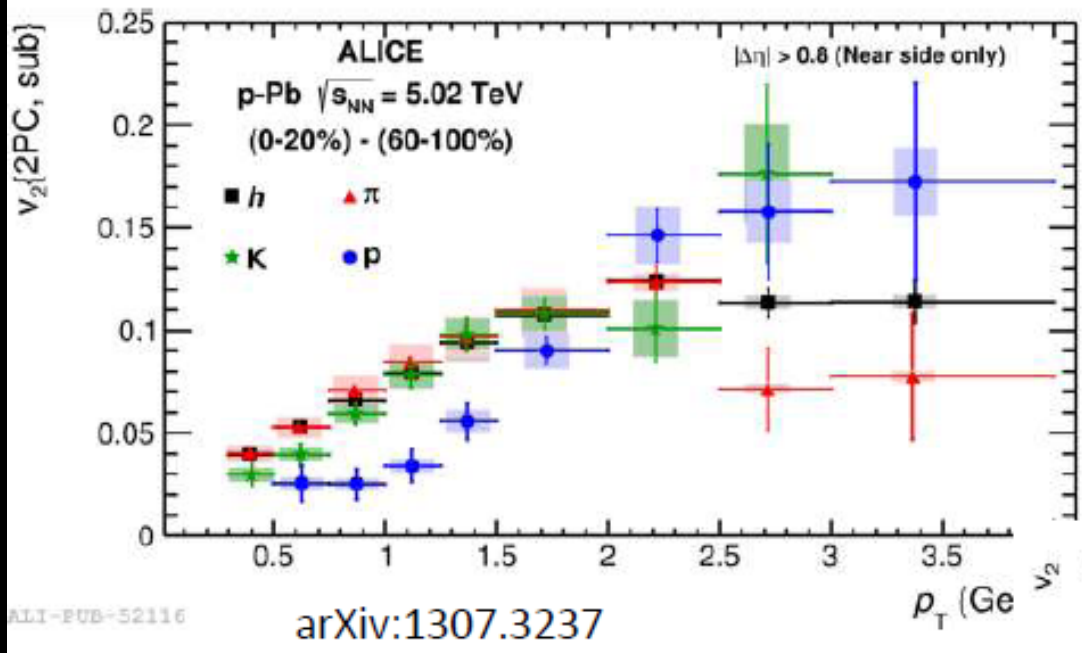
- Independent of system size
- Does not extrapolate to 0



Identified particles

Same subtraction procedure for identified particle correlations

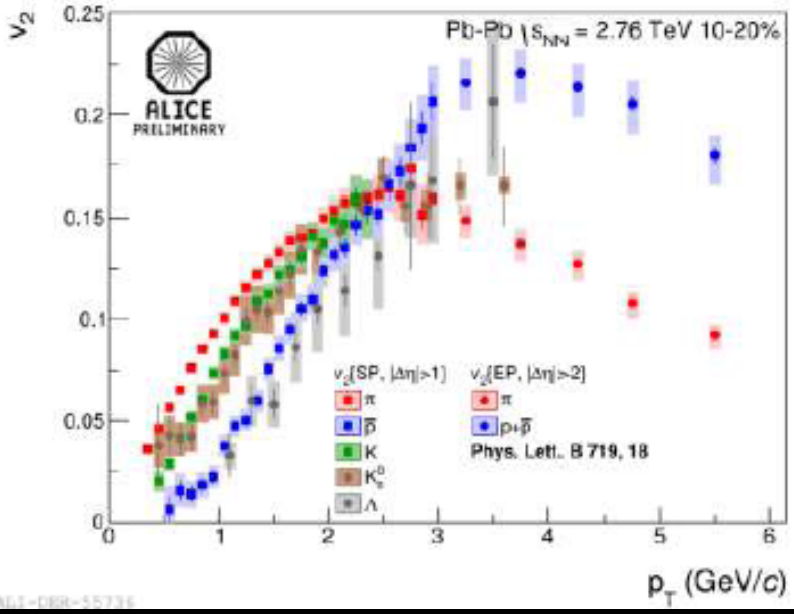
Identified particle v_2 vs p_T



arXiv:1307.3237

Mass ordering similar to Pb-Pb

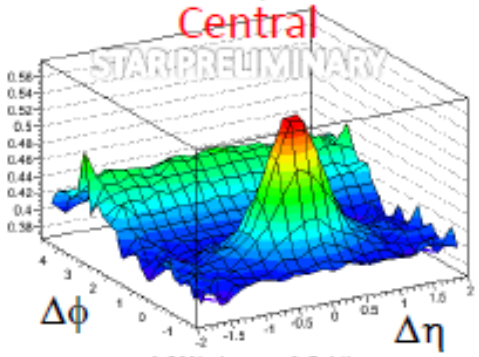
Proton v_2 crossing π v_2 near 2 GeV/C
Kaons probably below pions



2D TPC-TPC correlation functions

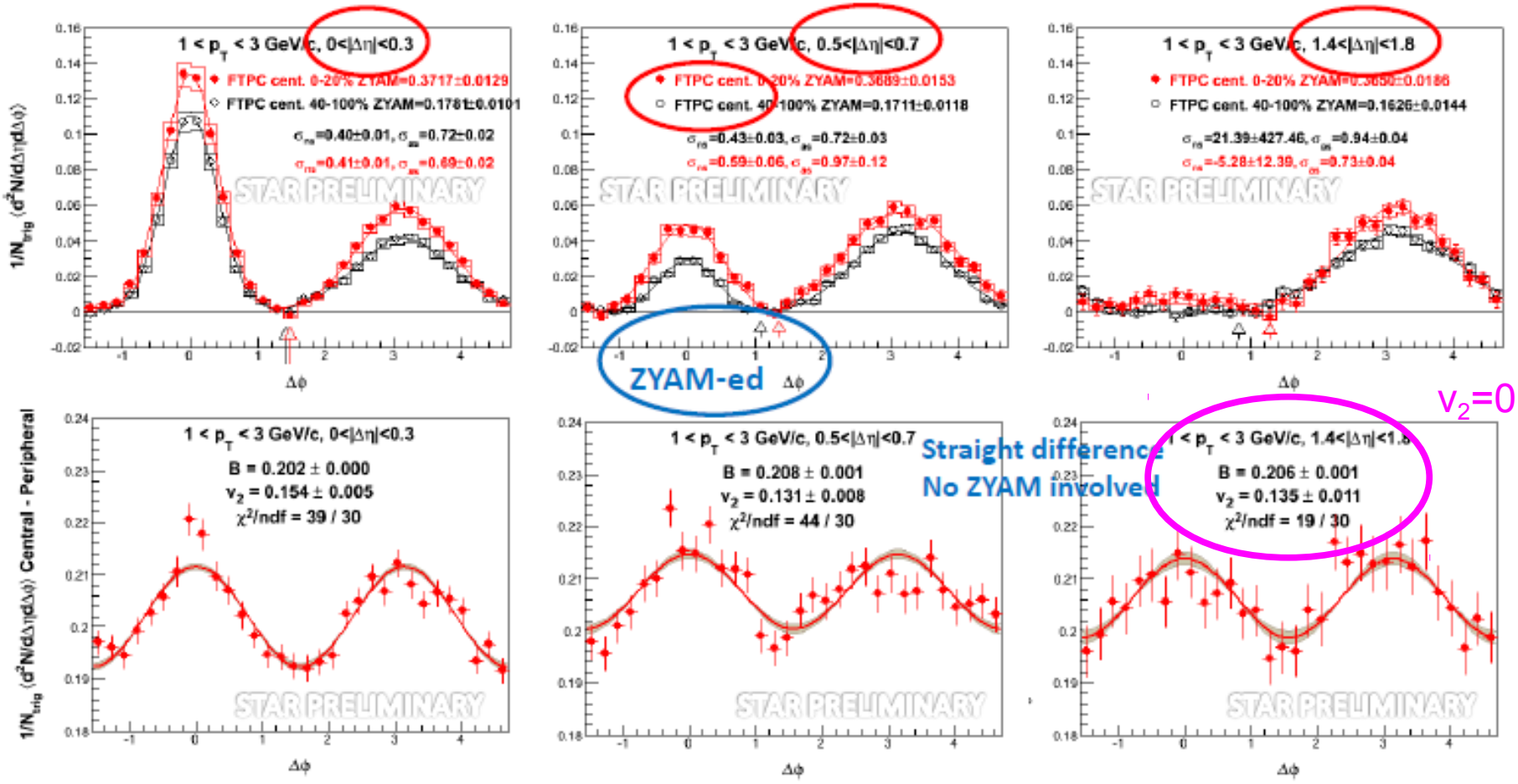
$1 < p_T^{trig}, p_T^{assoc} < 3$ GeV/c

Centrality def.	Central	Peripheral	Central – Peripheral
TPC mult. $\lvert\eta\rvert<1$	0-20%, $1 < p_T < 3$ GeV/c	50-80%, $1 < p_T < 3$ GeV/c	
FTPC-E (Au-side) $-3.8<\eta<-2.8$	0-20%, $1 < p_T < 3$ GeV/c	40-100%, $1 < p_T < 3$ GeV/c	
ZDC-E (Au-side)	0-20%, $1 < p_T < 3$ GeV/c	40-100%, $1 < p_T < 3$ GeV/c	?



$\Delta\phi$ projections vs $\Delta\eta$ (FTPC as centrality)

$1 < p_T^{trig}, p_T^{assoc} < 3$ GeV/c

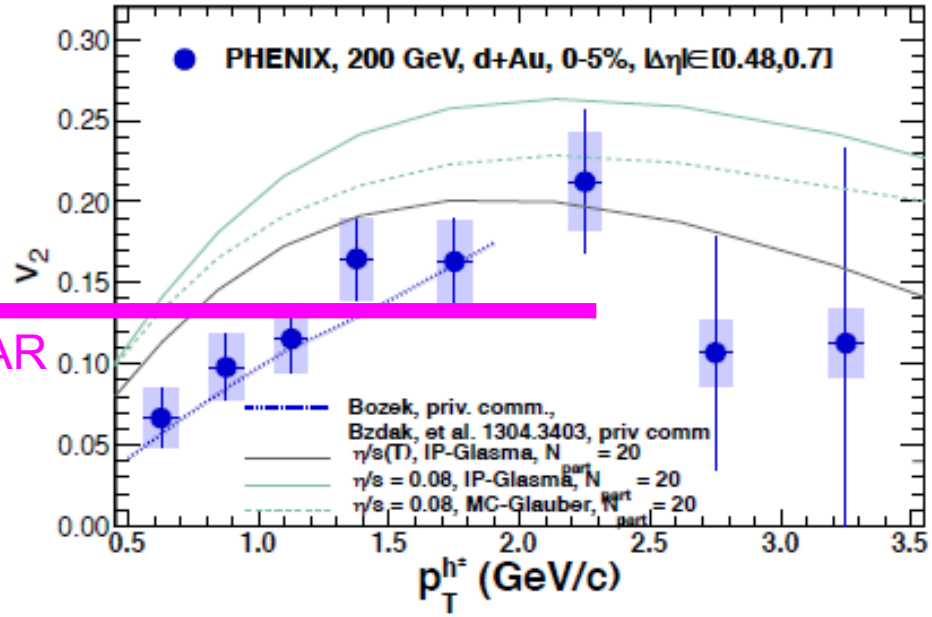


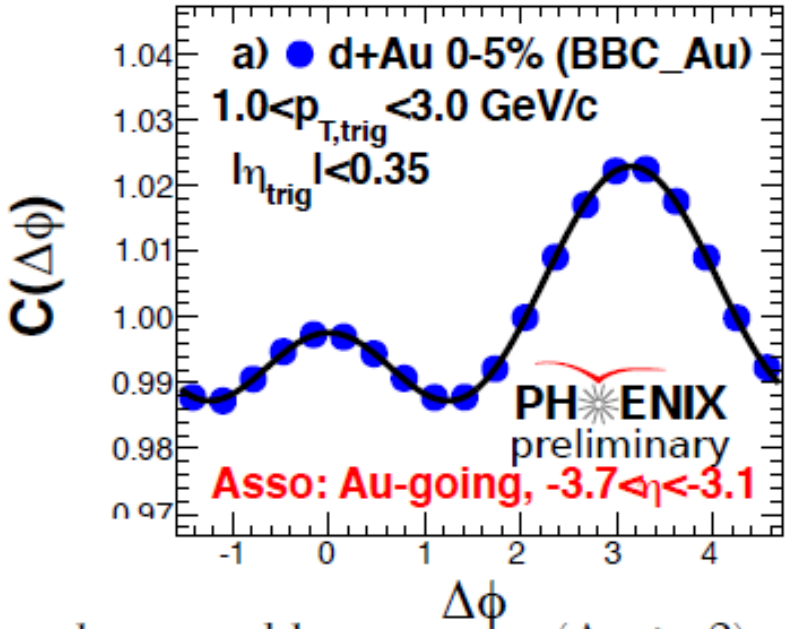
- ZYAM syst. error from different sizes of $\Delta\phi$ region for ZYAM.
- Efficiency corrected: 85 ± 5% .

- Multiplicity biases jets.
- Remaining back-to-back structure at large $\Delta\eta$.

conclusions

STAR

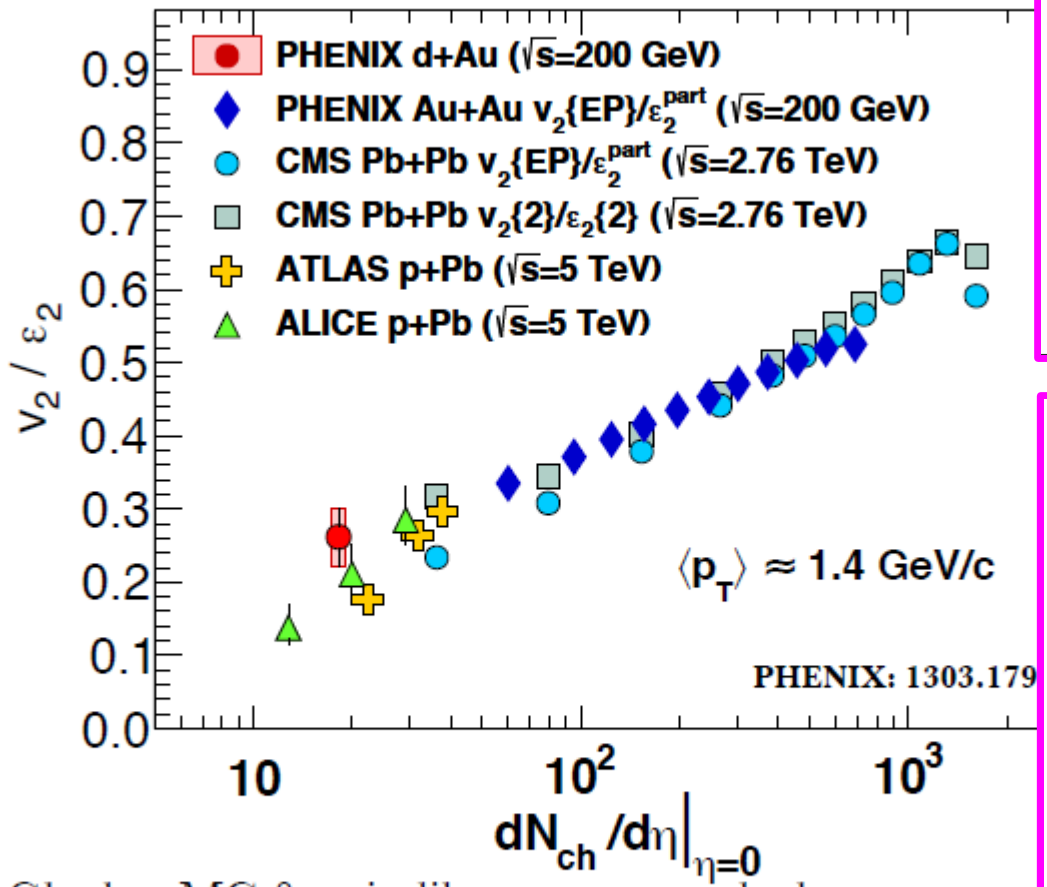


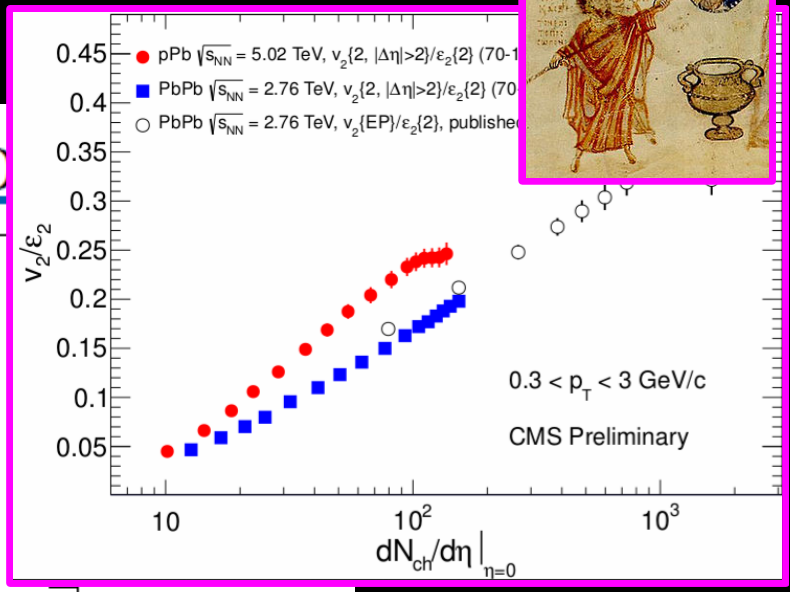


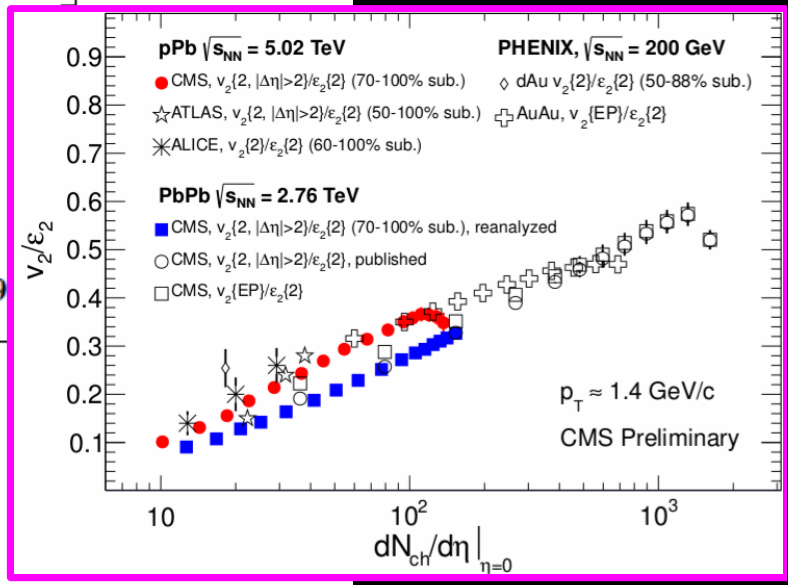
- ridge-like behavior seen at PHENIX at short and long range ($\Delta\eta > 3$) with large v_2 at midrapidity
- we're working to extend these measurements:
  - yields, $v_N(\eta)$, different collision systems (pA, dA, He^3A, peripheral heavy ions, asymmetric collisions...)
  - ...in order to understand what's going on in very small systems

more on d+Au: John Chen 9/12 parallel session

v_2/ε_2 vs multip







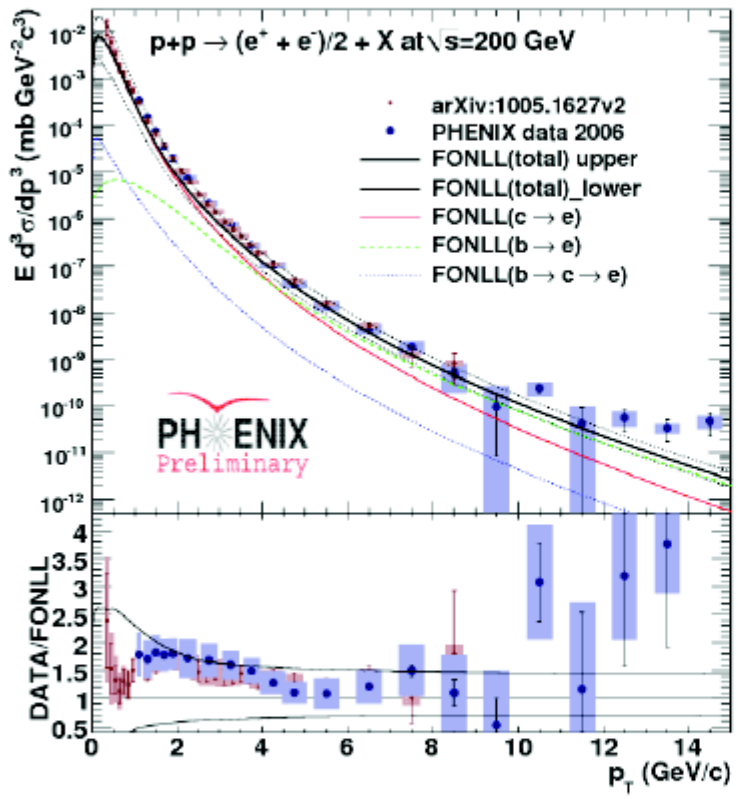
- Glauber MC & pointlike centers to calculate ε_2
- → approximate scaling of v_2/ε_2 with $dN/d\eta$

a common relationship between geometry and v_2?

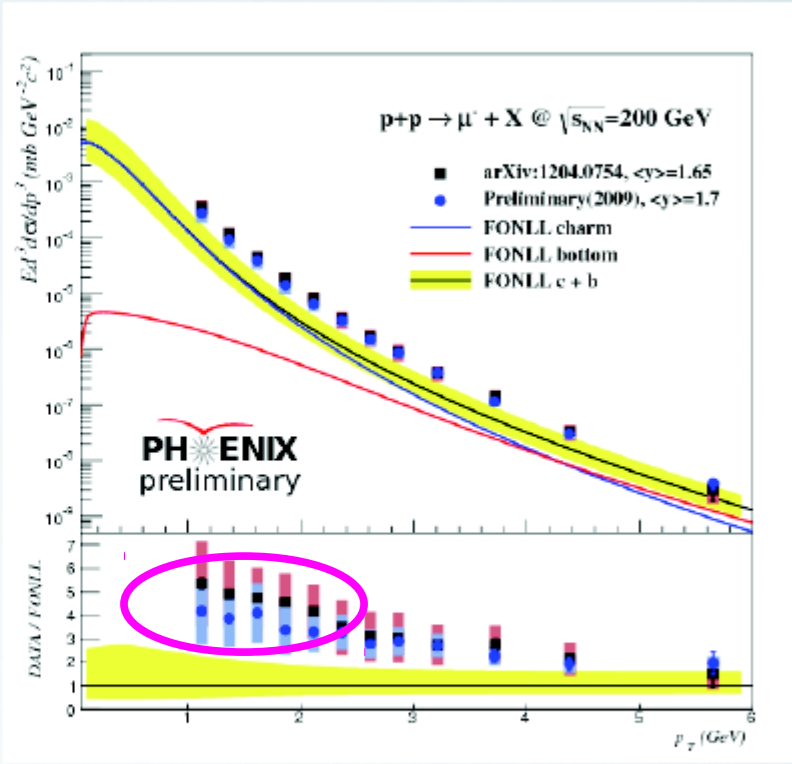
Heavy-flavor and Quarkonia

Heavy flavor in p+p collisions

mid-rapidity

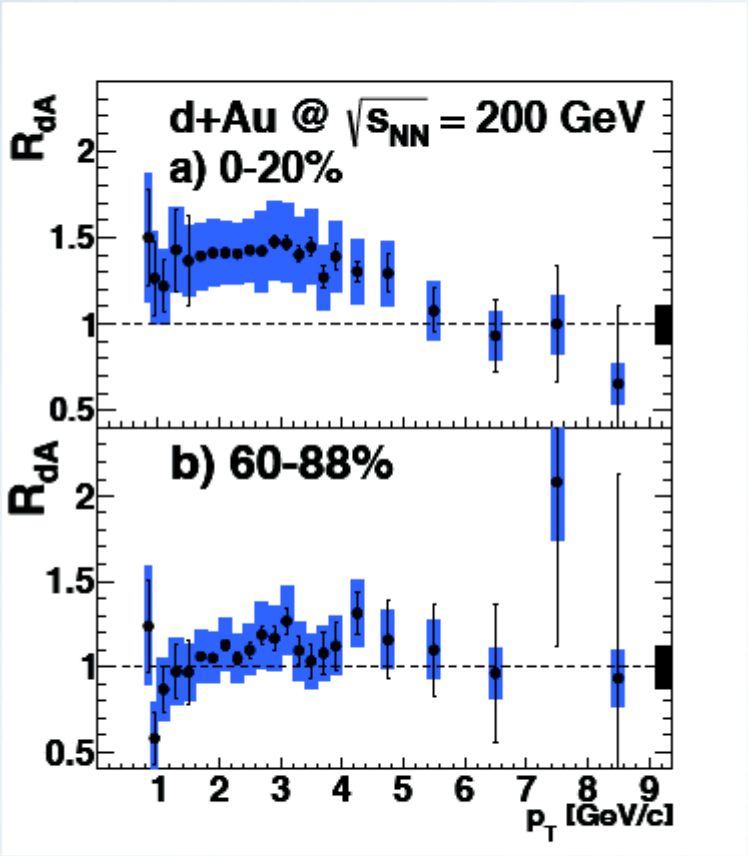


forward rapidity



- Extend kinematic range and reduce uncertainties with enhanced statistics and improved analysis techniques

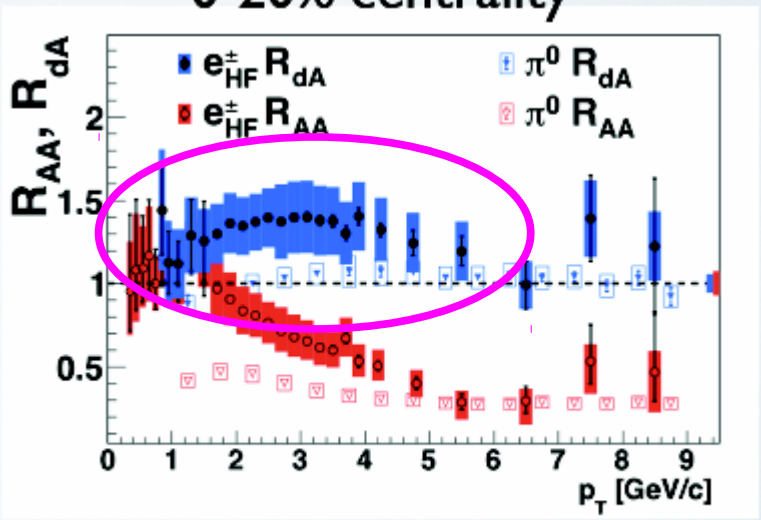
HF electrons @ mid-rapidity



Phys. Rev. Lett. 109, 242301 (2012)

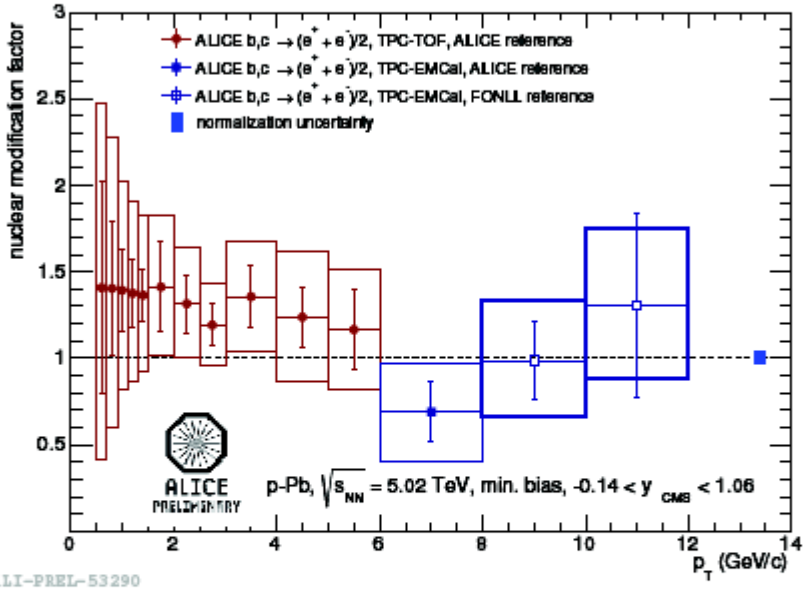
- R_{dA} ~ 1 in the peripheral collisions
- Large enhancement in the central collision
  - HF R_{dA} is larger than π^0 R_{dA}
  - HF suppression in Au+Au is due to the HNM effects

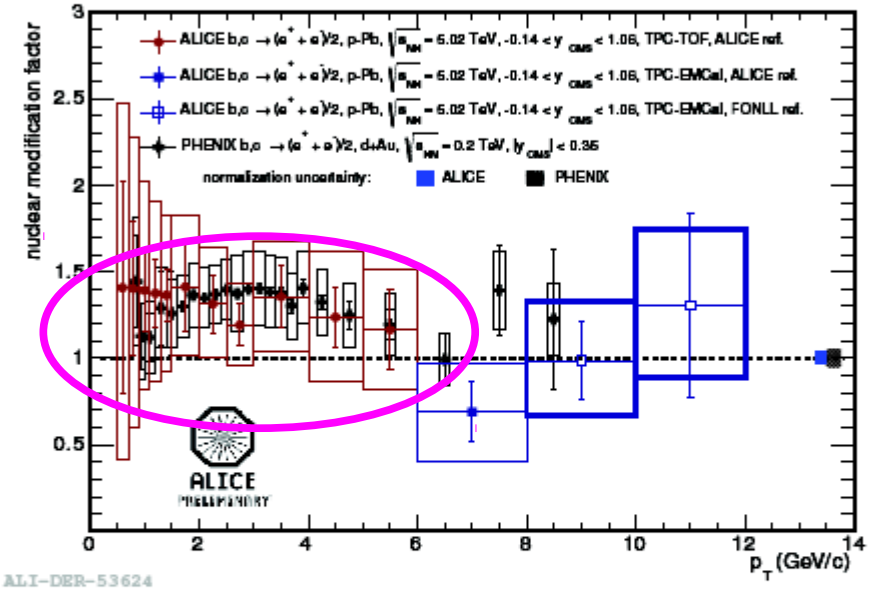
0-20% centrality



PHENIX

R_{pPb} of HFE

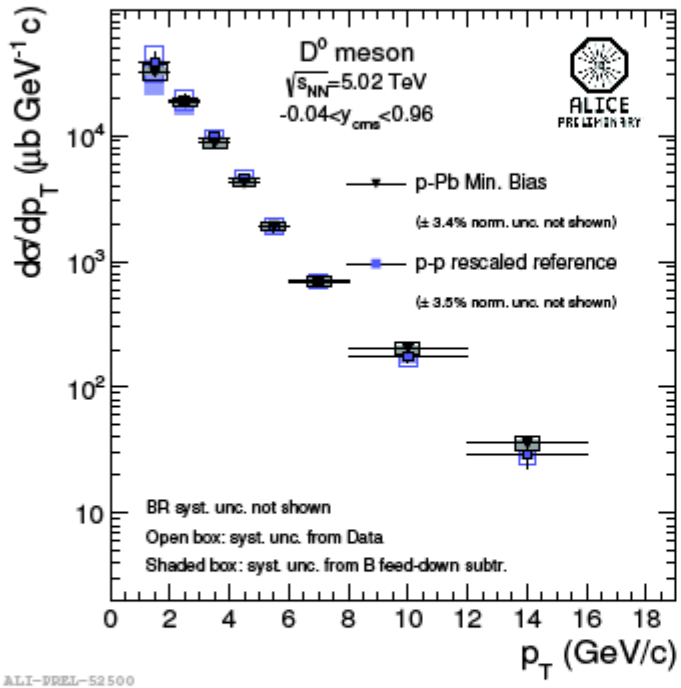


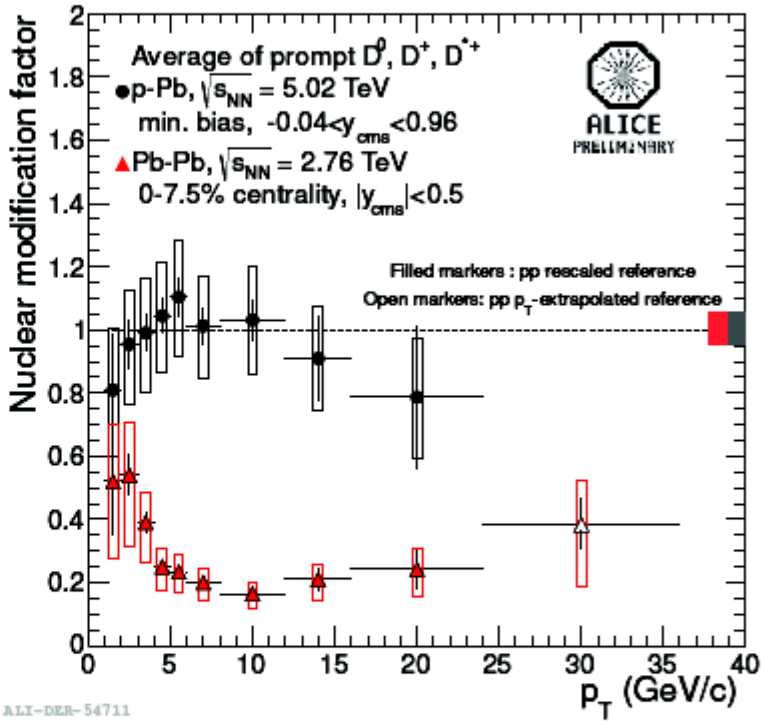


Phenix: Phys. Rev. Lett. 109 (2012) 242301

- R_{pPb} of HFE (charm + beauty)
  - compatible with unity within uncertainties
  - similar behaviour observed at PHENIX for d-Au at $\sqrt{s_{NN}}$ = 0.2 TeV

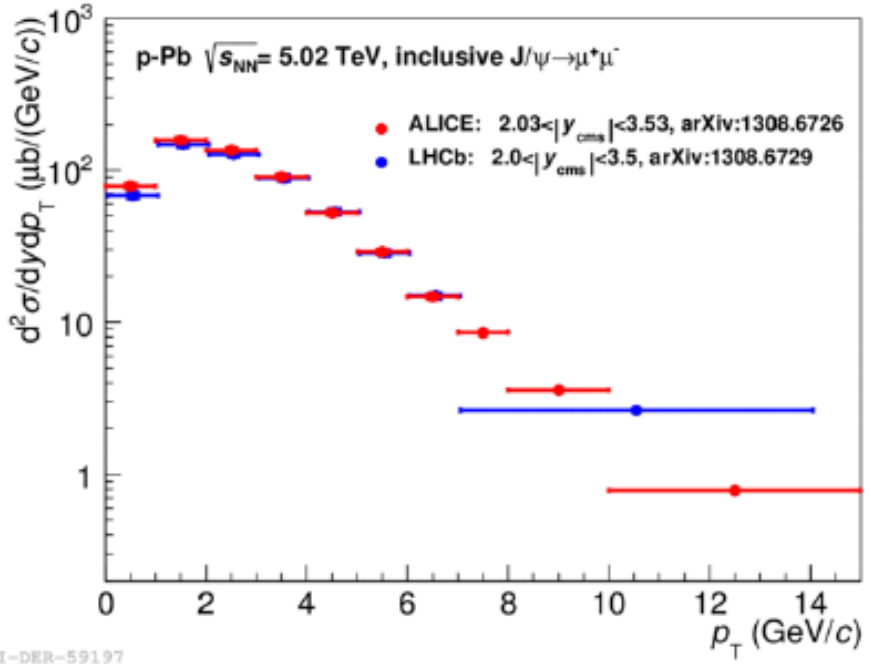
R_{pPb} of D mesons

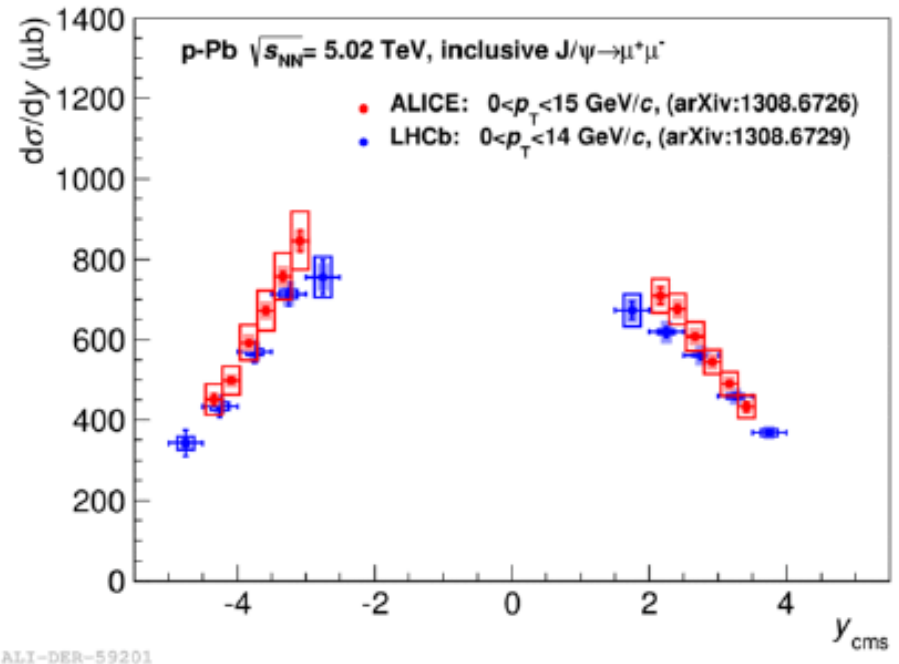




- pA collisions: no hot medium effects
  - separate initial state (cold nuclear matter) effects on HF R_{AA} in Pb-Pb collisions
- R_{pPb} of D meson is compatible with unity within uncertainties
- Small initial state effects
  - the strong suppression in Pb-Pb is a hot medium effects

J/ψ cross section in p-Pb, comparison to LHCb





Excellent agreement between the two experiments

Hugo Pereira (ALICE)

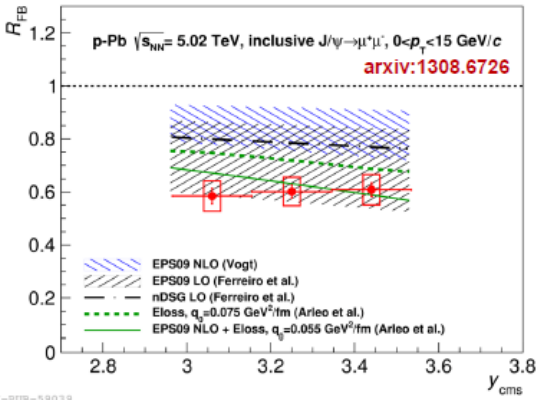
J/ψ Forward/Backward ratio R_{FB}

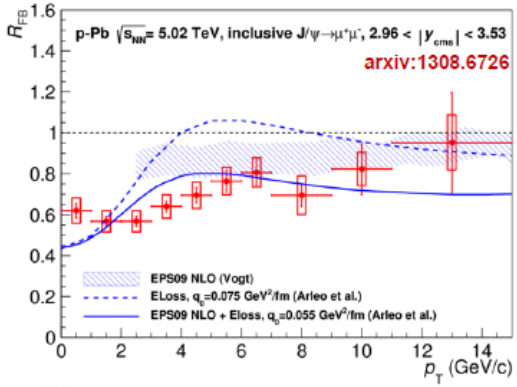
$$R_{FB}^{J/\Psi} = \frac{Y^{J/\Psi}_{\text{p-Pb (y>0)}}}{Y^{J/\Psi}_{\text{Pb-p (y<0)}}}$$

Several systematic uncertainties cancel in the ratio and there is no need for pp reference

Statistic is decreased because one has to match the rapidity range between the two data sets

Comparison to theory is less stringent than R_{pPb}





Little to no dependence of R_{FB} on y, qualitatively consistent with models

More suppression at low p_T than at high p_T, but less dependence than energy loss models. R_{FB} is well reproduced for p_T>5 GeV

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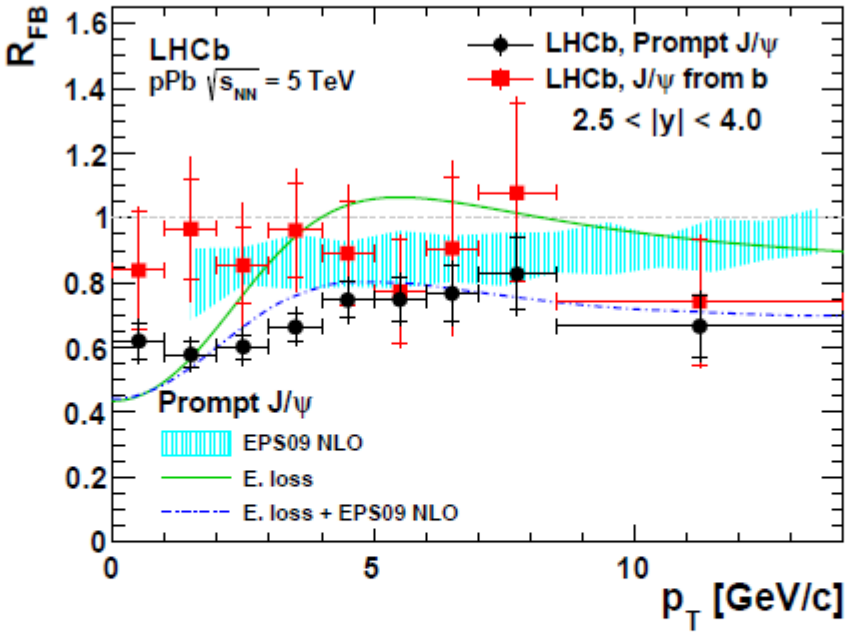
Johan Blouw (LHCb)

R_{FB} *vs* transverse momenta

Forward-backward asymmetry *vs.* transverse momentum:



Results from arXiv:1308.6729,

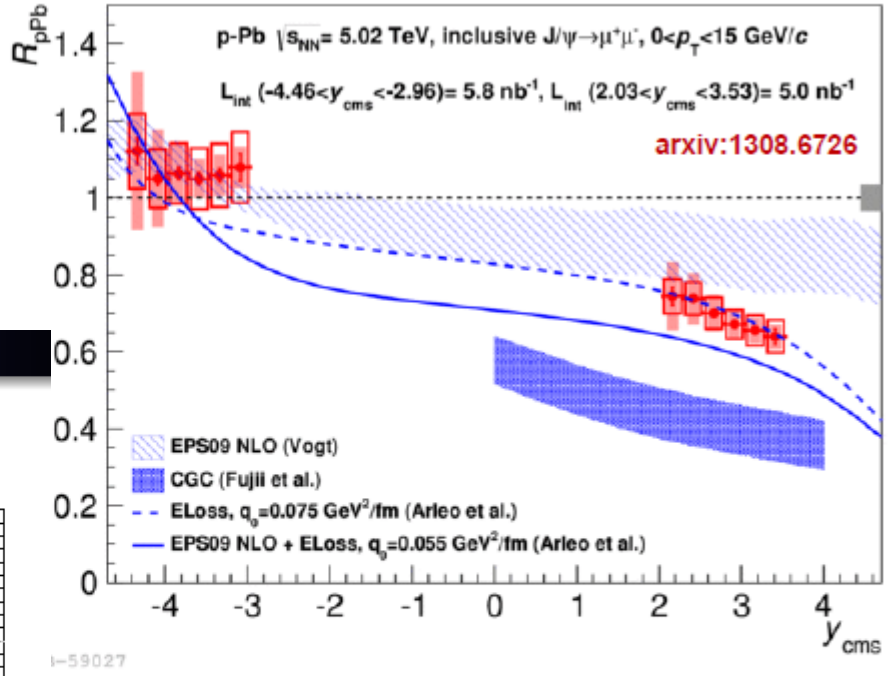
predictions from arXiv:1305.4569, IJM Phys E22 (2013) 1330007, JHEP 03 (2

Hugo Pereira (ALICE)

J/ψ R_{pPb} vs rapidity

$$R_{\mathrm{pPb}}^{J/\Psi} = \frac{Y_{\mathrm{pPb}}^{J/\Psi}}{T_{\mathrm{pPb}} . \sigma_{\mathrm{pp}}^{J/\Psi}}$$

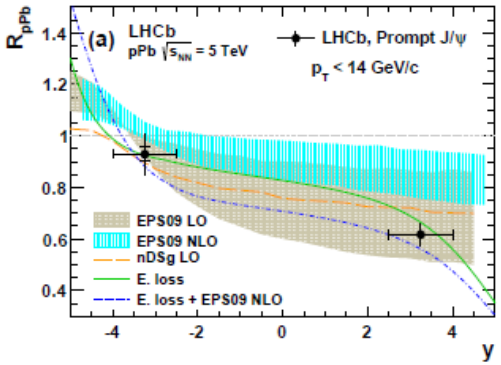
J/ψ cross section in pp is



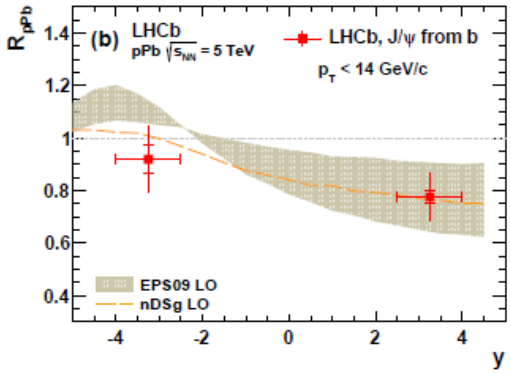
Johan Blouw (LHCb)

Nuclear modification

Nuclear modification *vs.* rapidity for prompt J/Ψ's:



and for J/Ψ from b-quarks:



$$R_{pA}(y,\sqrt{s}) = \frac{1}{A}\frac{\frac{d\sigma_{pA}(y,\sqrt{s})}{dy}}{\frac{d\sigma_{pp}(y,\sqrt{s})}{dy}}$$

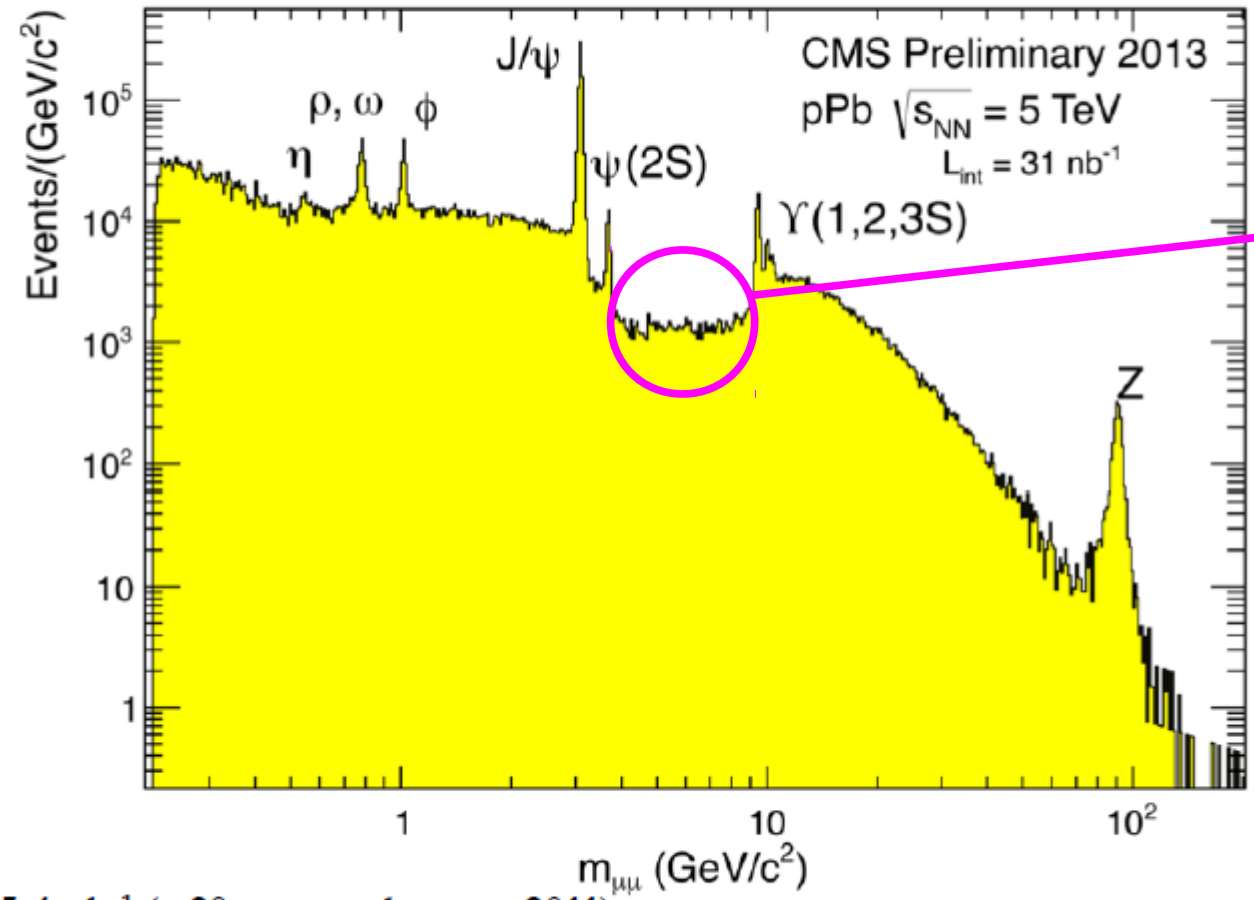
Theory confirmed by data; but more needed to separate saturation from energy loss

Results from arXiv:1308.6729,
predictions from arXiv:1305.4569, IJM Phys E22 (2013) 1330007, JHEP 03 (2013) 122

…nsistent with shadowing and energy loss,
…reakup
…e suppression
…re well within systematic uncertainties,

12

pPb 2013, pp 2013



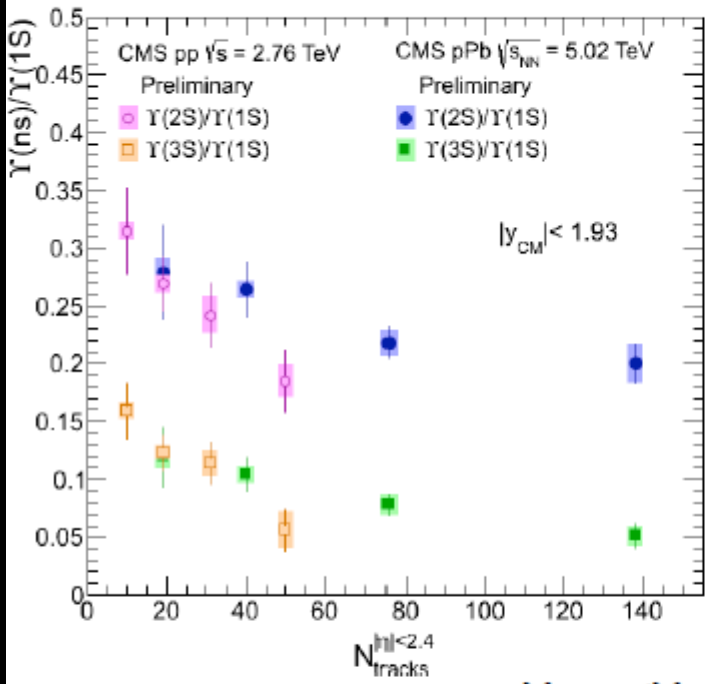
Due to mix of different single muon cuts and triggers

- pp: 5.4 pb^{-1} (~20x more than pp 2011)
- pPb: 31 nb^{-1}

15

Tuesday, September 10, 13

Υ(nS)/Υ(1S) vs N_{track} $|\eta|<2.4$



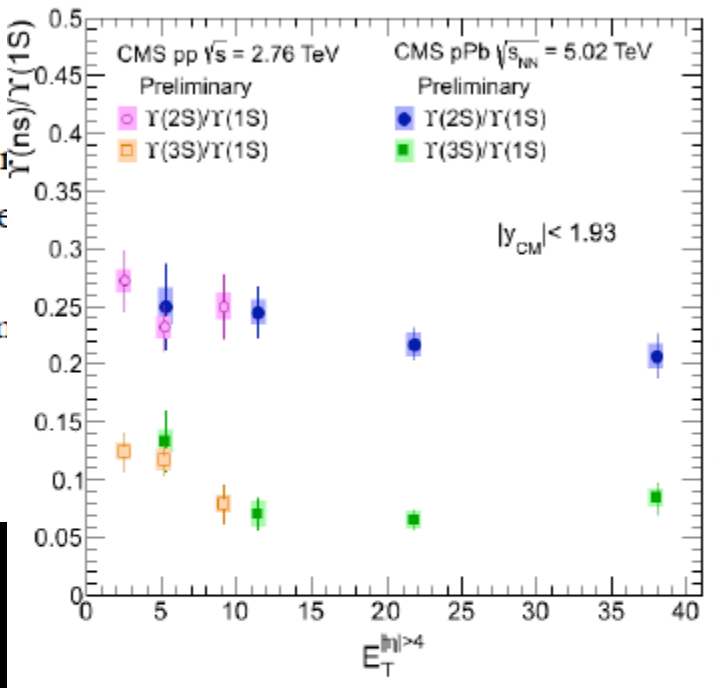
$$\left[\frac{\Upsilon(nS)}{\Upsilon(1S)}\right]_{pp,pPb}$$

- Ratios corrected for acceptance and efficiency
- Systematic uncertainties: from signal extraction
  - ➡ additional 7-9% global uncer
- Abscissae are the bin-average i sample

- **Significant decrease of Υ(nS)/Υ(1S) with increasing multiplicity, i**
- Can think at 2 ways to produce this dependence, at play alone or togethe
  - ➡ Υ 'affects' the multiplicity
    - in both pp and pPb ~2 extra tracks in 1S events compared to 2S and 3S even
  - ➡ the multiplicity 'affects' the Υ
    - activity around the Υ breaks the states

Tuesday, September 10, 13

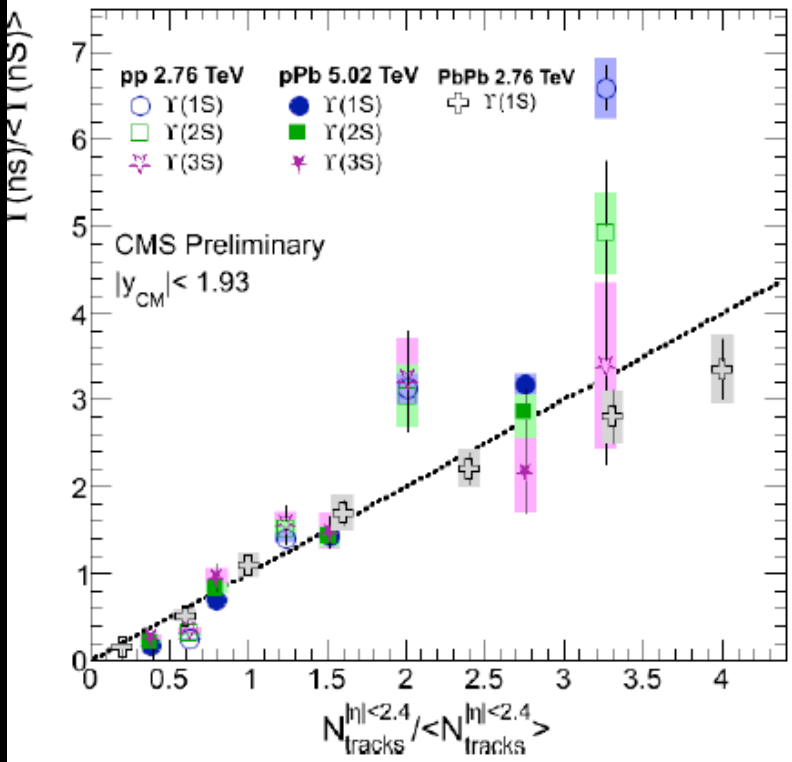
Υ(nS)/Υ(1S) vs E_T $|\eta|>4$



Self-normalized ratios: $\Upsilon(nS)/\langle\Upsilon(nS)\rangle_{\eta}$

Υ [-1.9,1.9]

N_{tracks} [-2.4, 2.4]

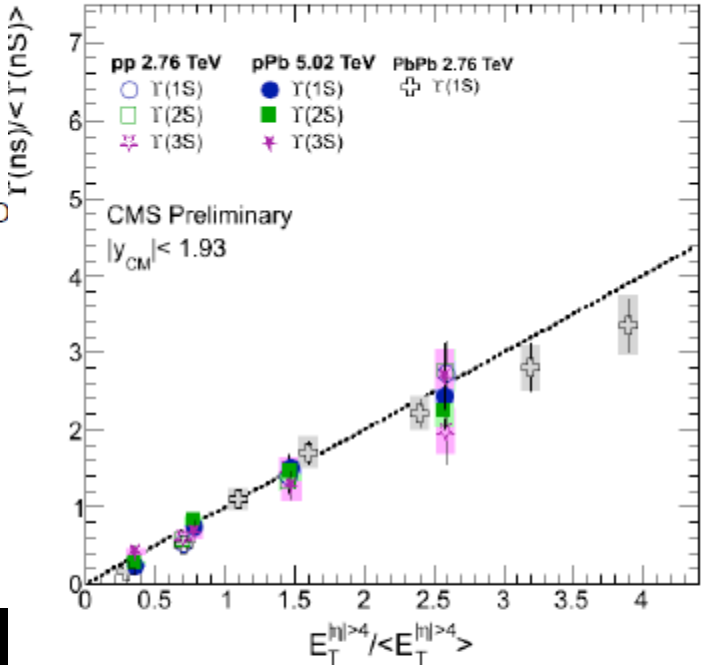


$$\frac{\Upsilon(nS)}{\langle\Upsilon(nS)\rangle}$$

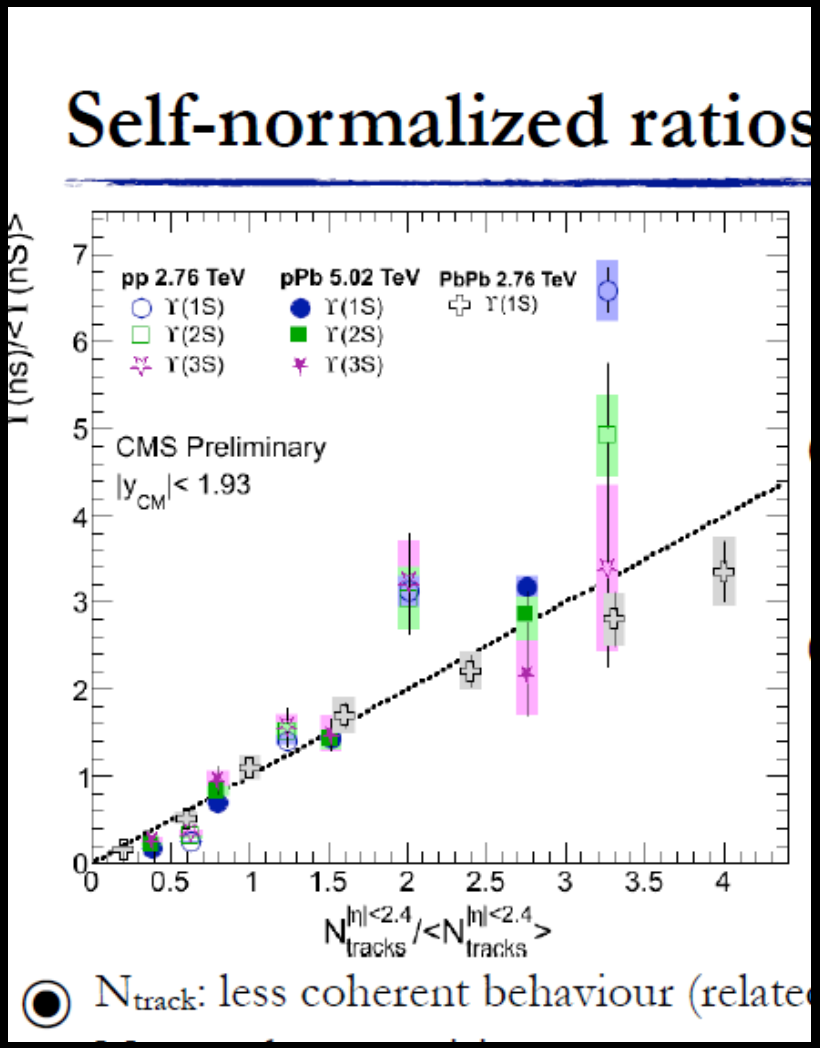
- Yield versus event-activity, both normalized to average
  - ➡ more upsilons in events with higher-event activity
- Corrected ratios (multiplic reconstruction efficiency)

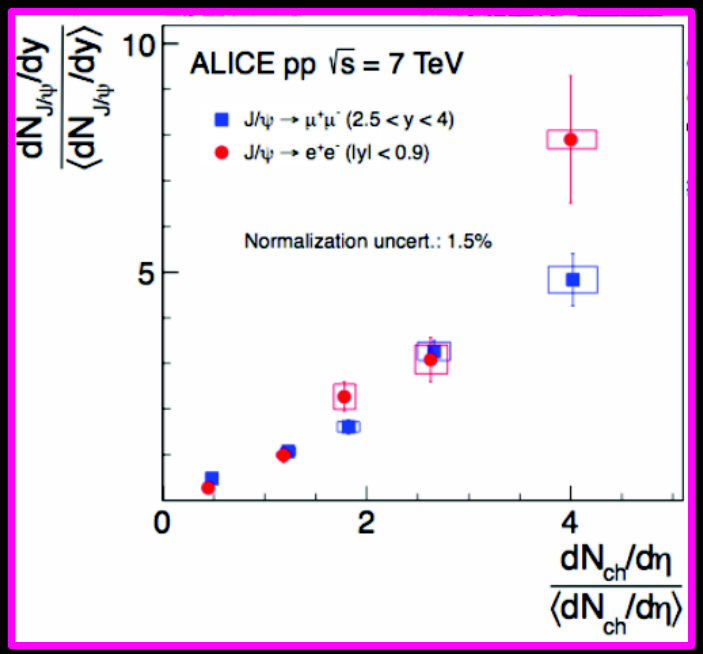
- N_{track}: less coherent behaviour (related to the $\Upsilon(nS)/\Upsilon(1S)$ variatio
- More or less surprising:
  - ➡ pPb and PbPb: N_{coll} scaling
  - ➡ pp: multi parton interaction
    - should have the same effect on 1S, 2S and 3S
    - 'most central' pp shows differences ... need more data (7, 8TeV ?)

Self-normalized ratios

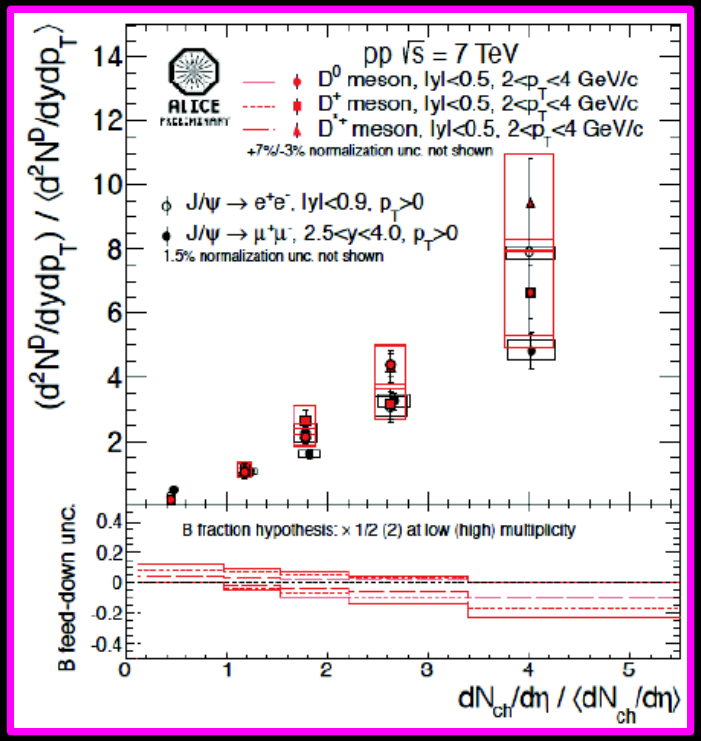


Camilia Mironov (CMS)





Similar dependence also seen in related ALICE results in pp

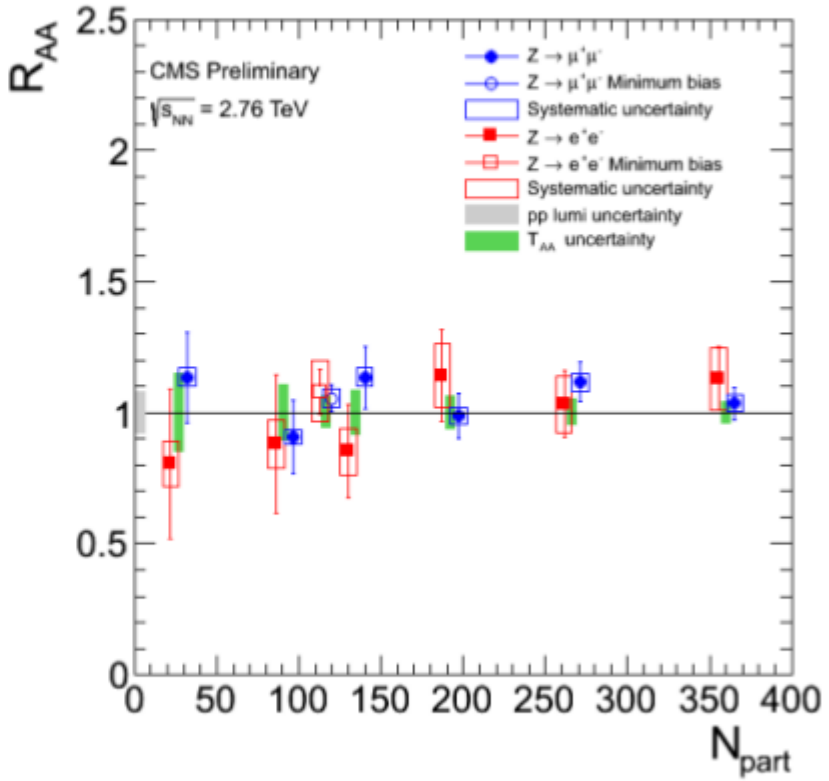


High-p_T and centrality in pPb

Nuclear modification factor

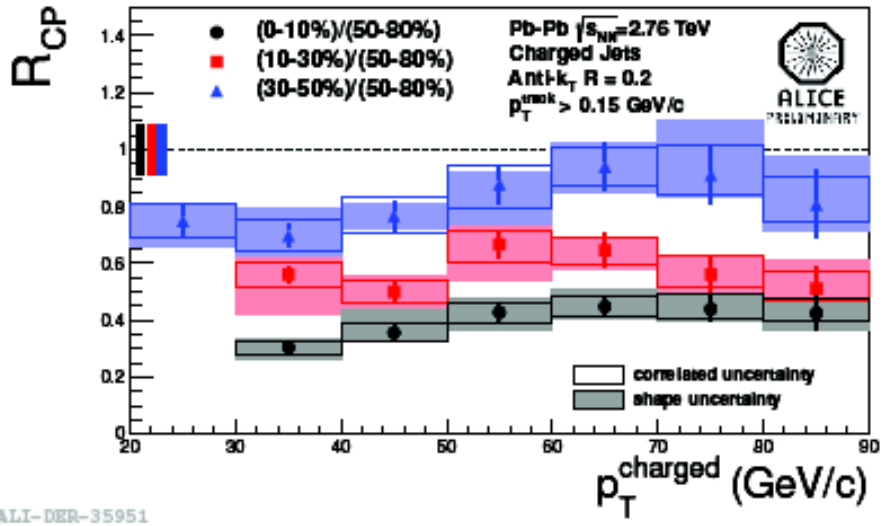
CMS-PAS-HIN-13-004

- $dN_{AA} / T_{AA} = d\sigma^{pp} \times R_{AA}$
- T_{AA}: nuclear overlap function from Glauber-model calculations
- R_{AA} (muon) = 1.06 ± 0.05 ± 0.11
- R_{AA} (electron) = 1.08 ± 0.09 ± 0.14
- The two leptonic decay channels are in agreement
- Z production (as expected) scales with T_{AA}

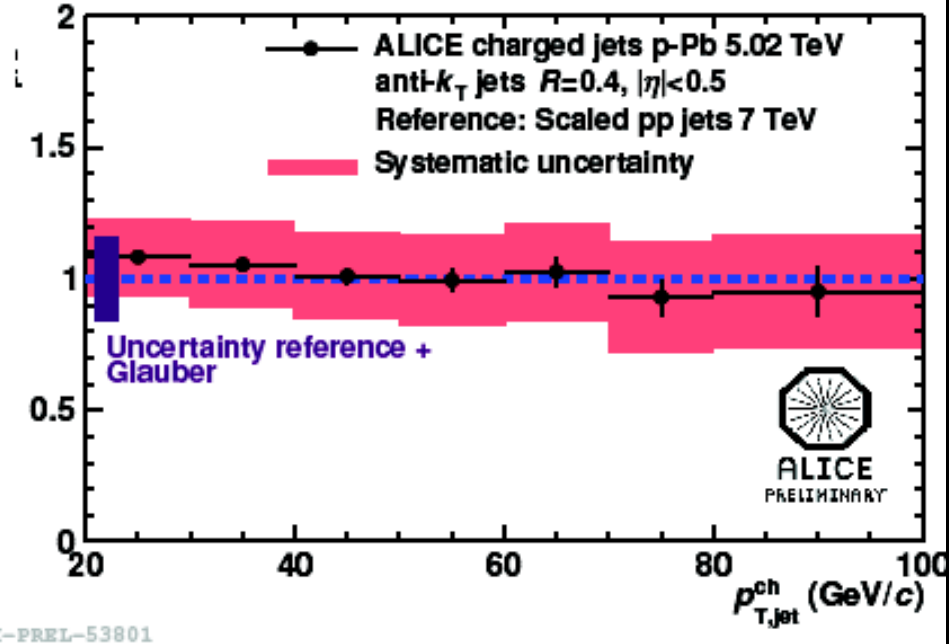


Jet R_{AA} and R_{pPb}

Charged particle jet R_{CP}
(R=0.2; Similar conclusion for R=0.3)



R_{pPb} of charged particle jets (R=0.4)



Pb-Pb:

- R_{AA}: Strong suppression in most central collisions R~0.4
- R_{CP}(50-80%): Similar suppression for jet radii R=0.2 (shown) and R=0.3
- Moderate p_T dependence (plateau at R_{AA}=0.4? similar to hadron R_{AA})

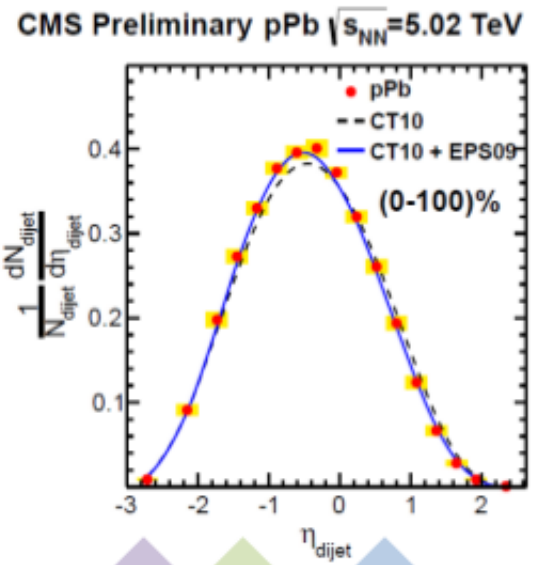
p-Pb:

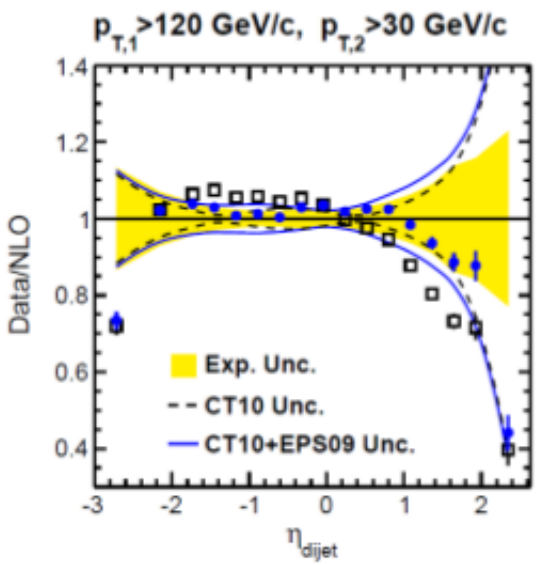
- R_{pPb} in minimum bias collisions consistent with unity

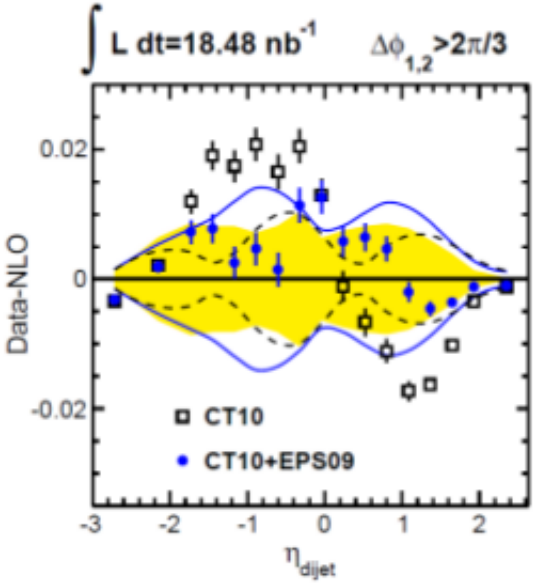
Comparison to EPS09 predictions

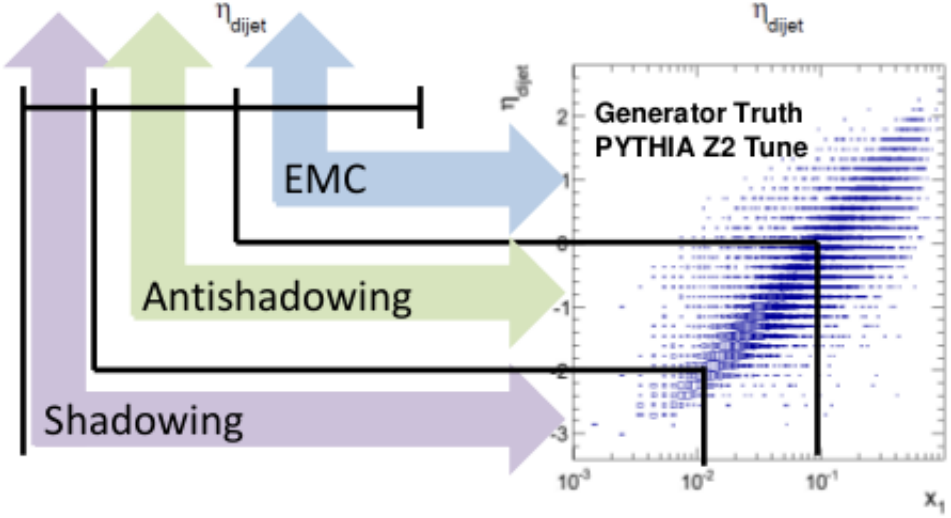
Escola, Paukkunen, Salgado. arxiv:1308.6733

CMS PAS HIN-13-001







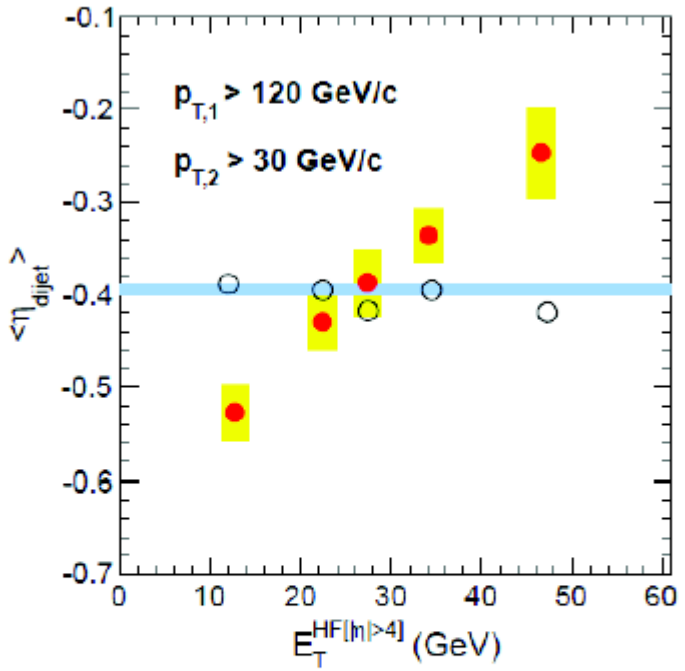


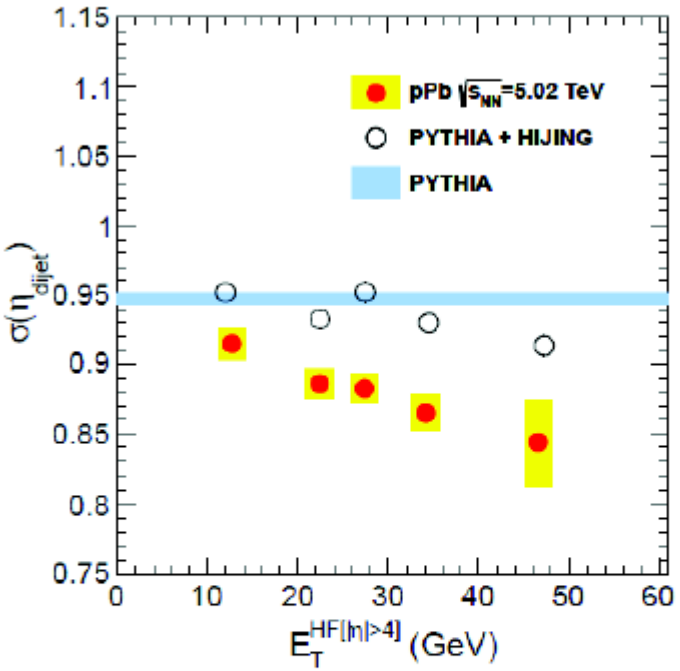
- Agreement between data with EPS09 within systematics.
- Data has slightly larger. modification in anti-shadowing and EMC regions compared to CT10+EPS09. (DSSZ agreement would be worse)
- Large uncertainties in forward region.

Yaxian Mao (CMS) Doga Gulhan (parallel)

Summary from dijet η

CMS PAS HIN-13-001





$$\eta_{dijet} = \frac{\eta_1+\eta_2}{2}$$

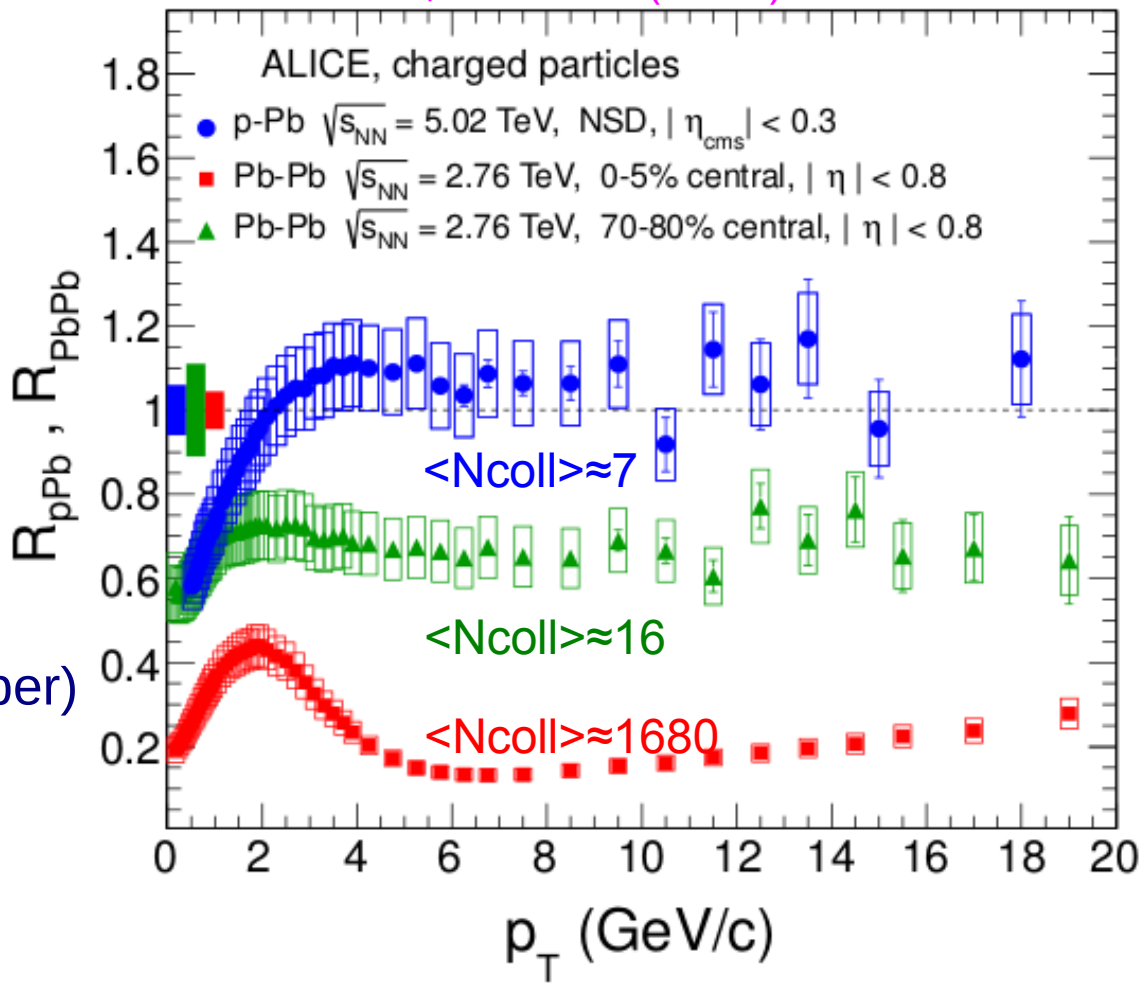
- Mean of η_{dijet} increases v.s. forward calorimeter energy
- Width of η_{dijet} decreases v.s. forward calorimeter energy

Effects are much stronger than expected from nPDFs

$$R_{AB} = \frac{\mathrm{d}N_{AB}/\mathrm{d}p_{\mathrm{T}}}{\langle N_{\mathrm{coll}}\rangle \mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

- $\langle N_{coll}\rangle = A\,\sigma_{pp}/\sigma_{pA} \approx 7$ with
  - σ_{pp} = 70 mb from interpolation of existing data
  - σ_{pA} = 2090 ± 120 mb from LHCb-CONF-2012-034 (or Glauber)
- Note: $\langle N_{coll}\rangle \approx 15$ is reached in "0-5% central" pPb collisions

ALICE, PRL 110 (2013) 082302

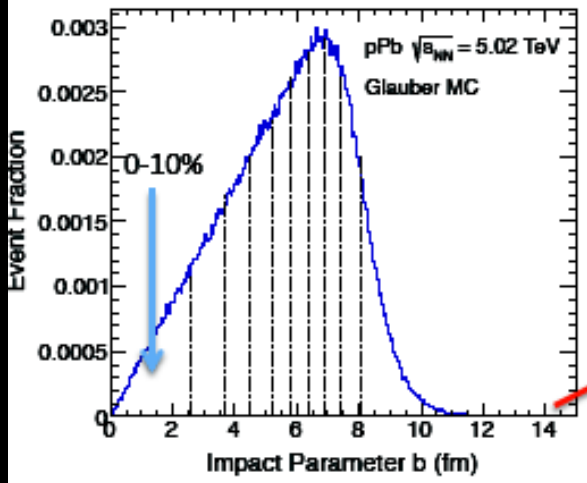


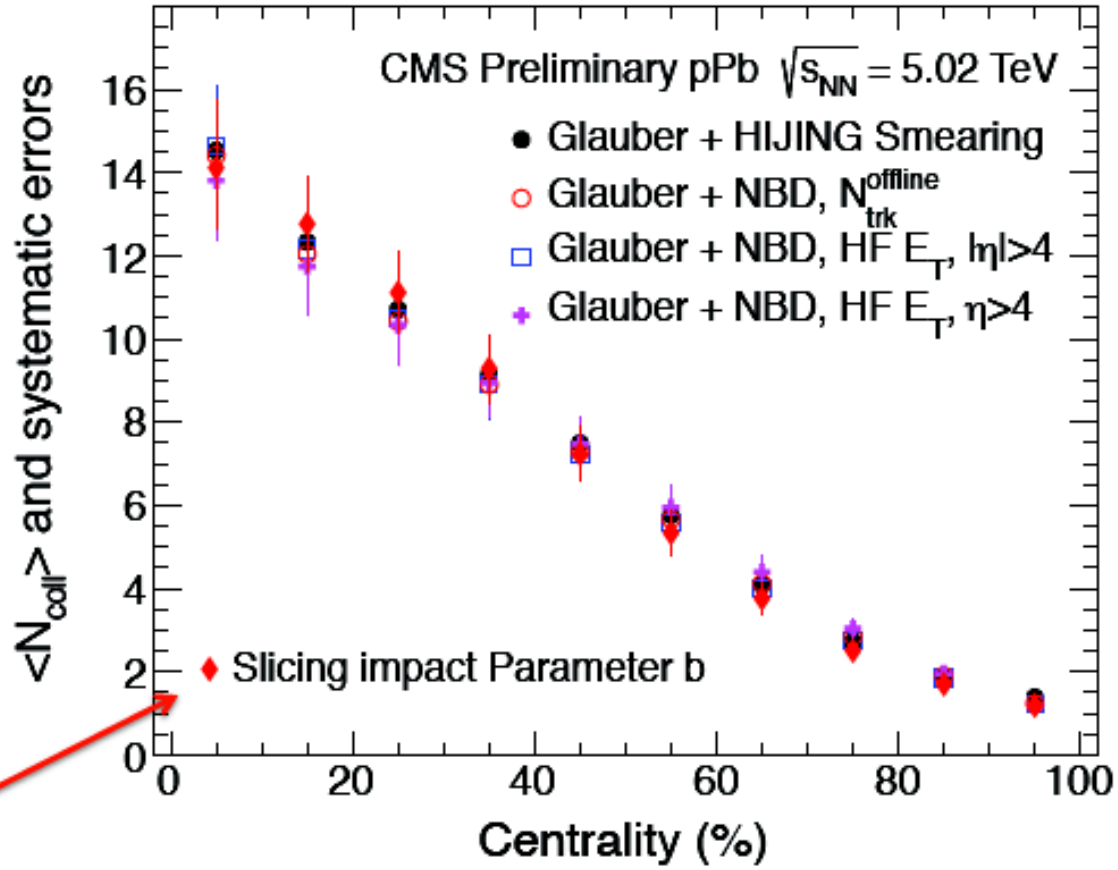
How to make measurement centrality dependent?

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

Key: R=1 in absence of nuclear effects!

$\langle N_{coll} \rangle$ from different methods agree well



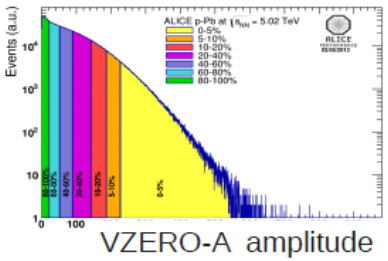


- Glauber + Smearing and Glauber + NBD show small difference
- Different detector η ranges agree well (HF in forward and multiplicity in mid-η)

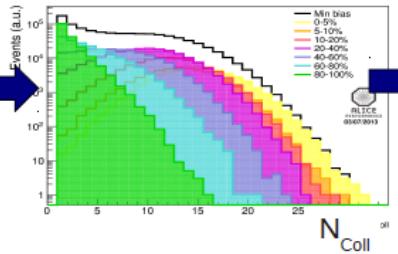
6

1.a Results from Glauber+NBD

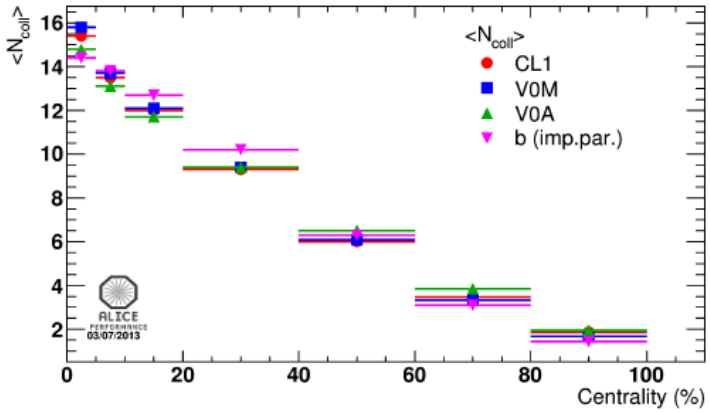
Slice in fitted MULT



Classes of N_{coll}



$\rightarrow \langle N_{coll} \rangle$



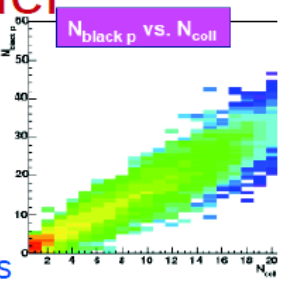
- $\langle N_{coll} \rangle$ similar for different estimators
- Systematic error estimated by varying Glauber MC parameters.
- MC closure test performed with HIJING

7

b Slow Nucleon Model

independent of $E_{projectile}$ (1GeV → 1 TeV)

emission dictated by collision geometry
mann (independent statistical emission)
nulsion experiments

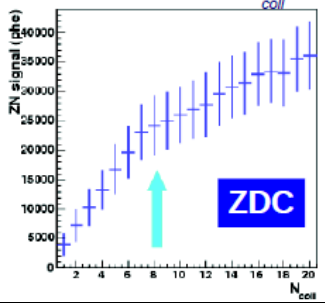


- Gray: soft nucleons knocked out by wounded nucleons
- Black: low energy target fragments from de-excitation, evaporation

- 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

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

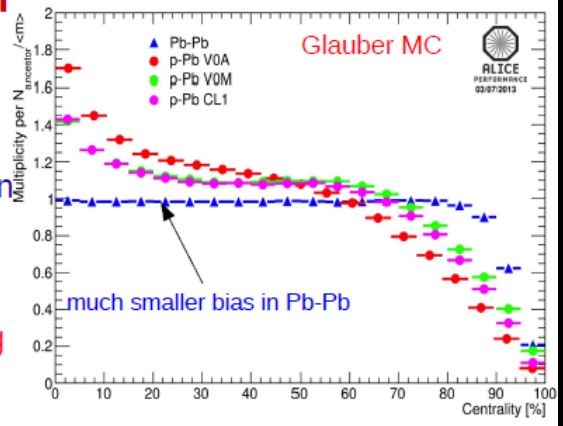
saturation in N_{black} vs N_{gray}
→ also in ZDC vs N_{coll}

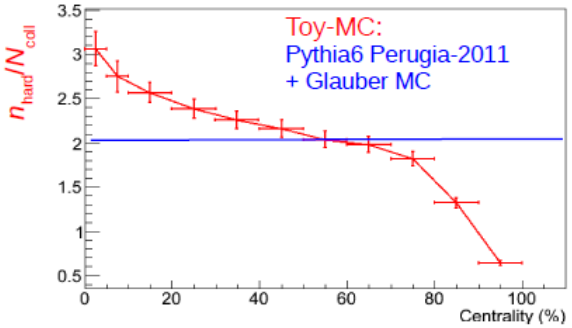


2.a Bias in pA

- **2.a** Multiplicity 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



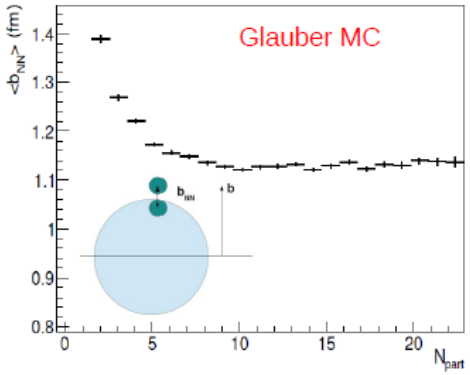


Toy-MC (Glauber+Pythia)

- build a Toy-MC by adding a Pythia (pp) event N_{coll} (from Glauber pPb calculation) times
- slice it in multiplicity as the real data → centrality classes

2.b,c Bias in pA --peripheral

nucleon-nucleon impact (b_{NN}) increases in peripheral

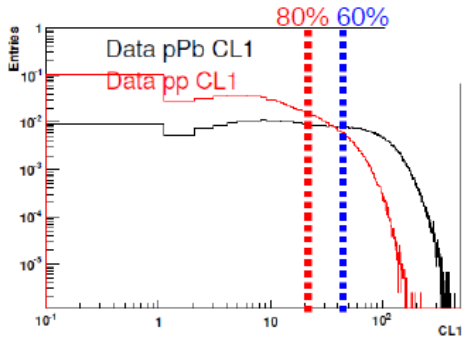


MPI mult. fluctuations depend on fluctuations in particle sources (hard scatterings)

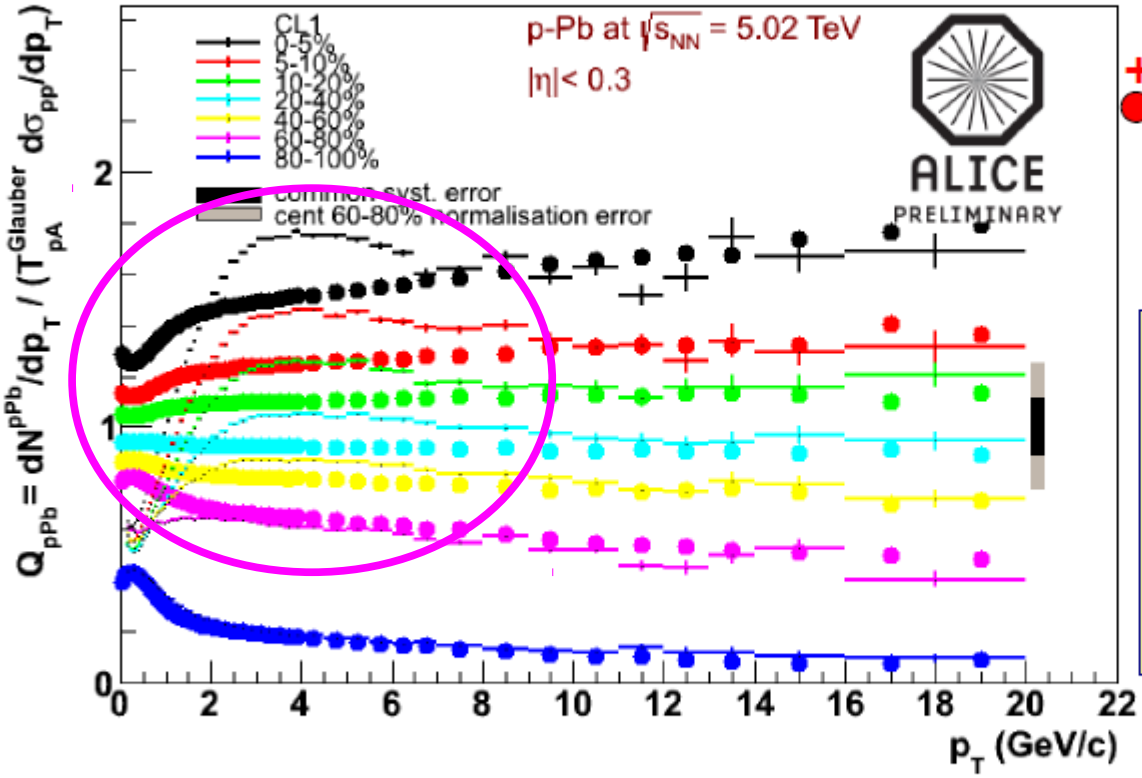
- Mean number of scatterings per event obtained from impact parameter (b_{NN})-dependent proton-nucleon overlap function $T_N(b_{NN})$

→ bias in mult ~ bias in hard scattering emphasized at peripheral

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



Comparison with Glauber+Pythia



Centrality Estimator: CL1

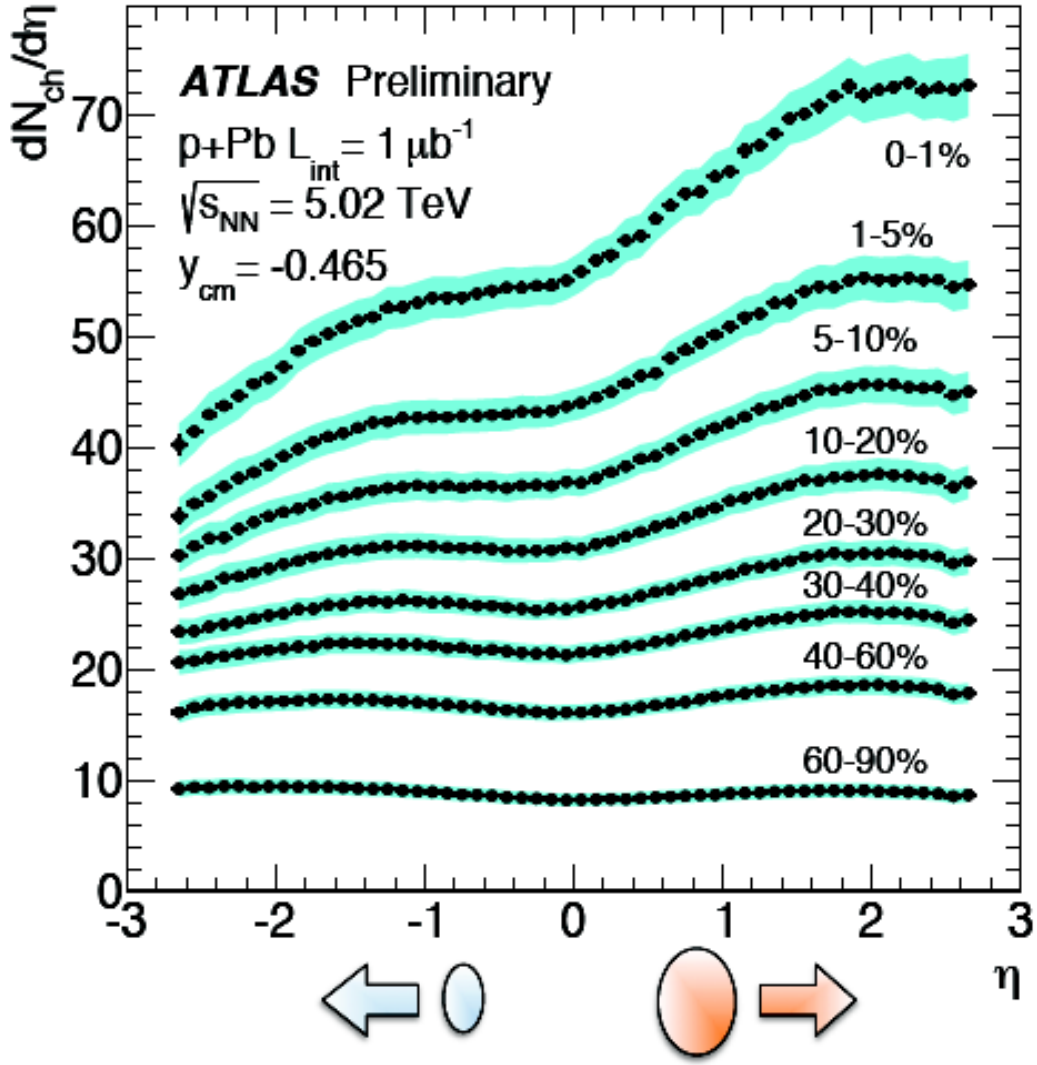
+ data
● MC (Glauber + Pythia)

Toy-MC (Glauber+Pythia)

- build a Toy-MC by adding a Pythia (pp) event N_{coll} (from Glauber pPb calculation) times
- slice it in multiplicity as the real data

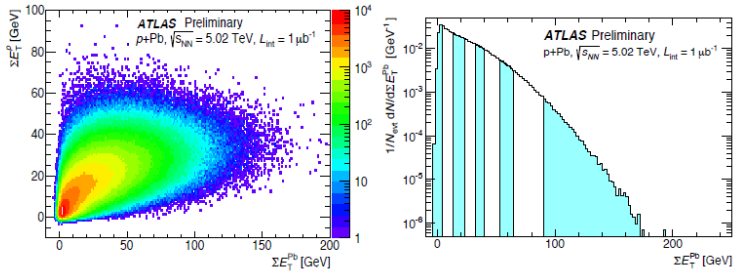
- Bias at high p_T described by incoherent superposition of pp collisions.
- For most peripheral, good agreement also in low- and intermediate p_T region.
- Strong deviations for all other centrality bins !

dN/dη for different centralities



- $dN_{ch}/d\eta$ is measured for $|\eta| < 2.7$ in eight centrality intervals
- 60-90% - double-peak structure similar to pp
- Forward backward asymmetry between p and Pb going directions grows with cer

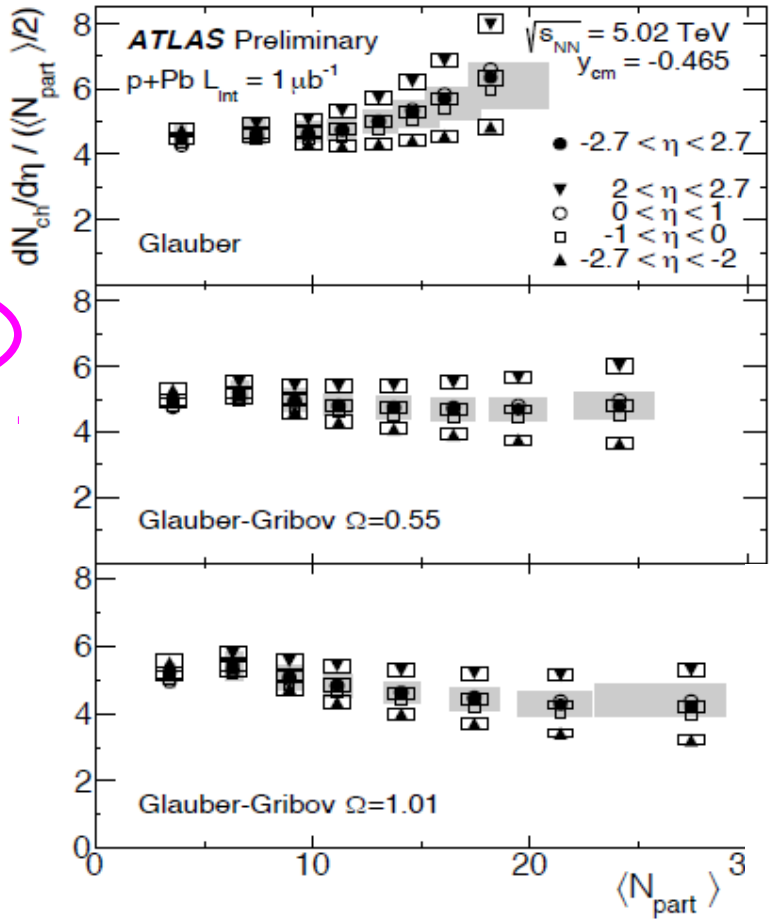
Centrality definition



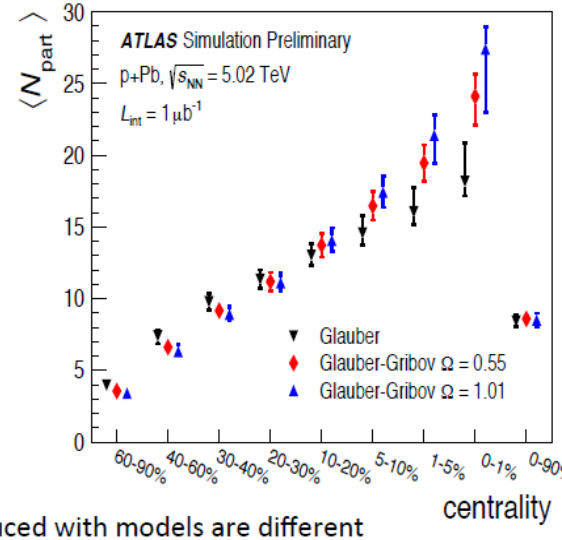
- Pb-going FCal (side "A") is used to characterize event centrality, it is more sensitive to nuclear geometry
- FCal ΣE^{Pb}_T is divided into centrality intervals: 0-1%, 1-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-60%, 60-90%
- 90-100% is excluded due to larger systematic uncertainties on event composition and reconstruction efficiency

Centrality dependence of $\langle dN_{ch}/d\eta \rangle$

- $\langle dN_{ch}/d\eta \rangle$ per pair of participants vs N_{part} for five η intervals
- Results are dependent on Glauber implementation
- Standard Glauber, used up to now shows increase with $\langle N_{part} \rangle$
- Glauber-Gribov with Ω=0.55 is almost flat with Ω=1.01 even decreases

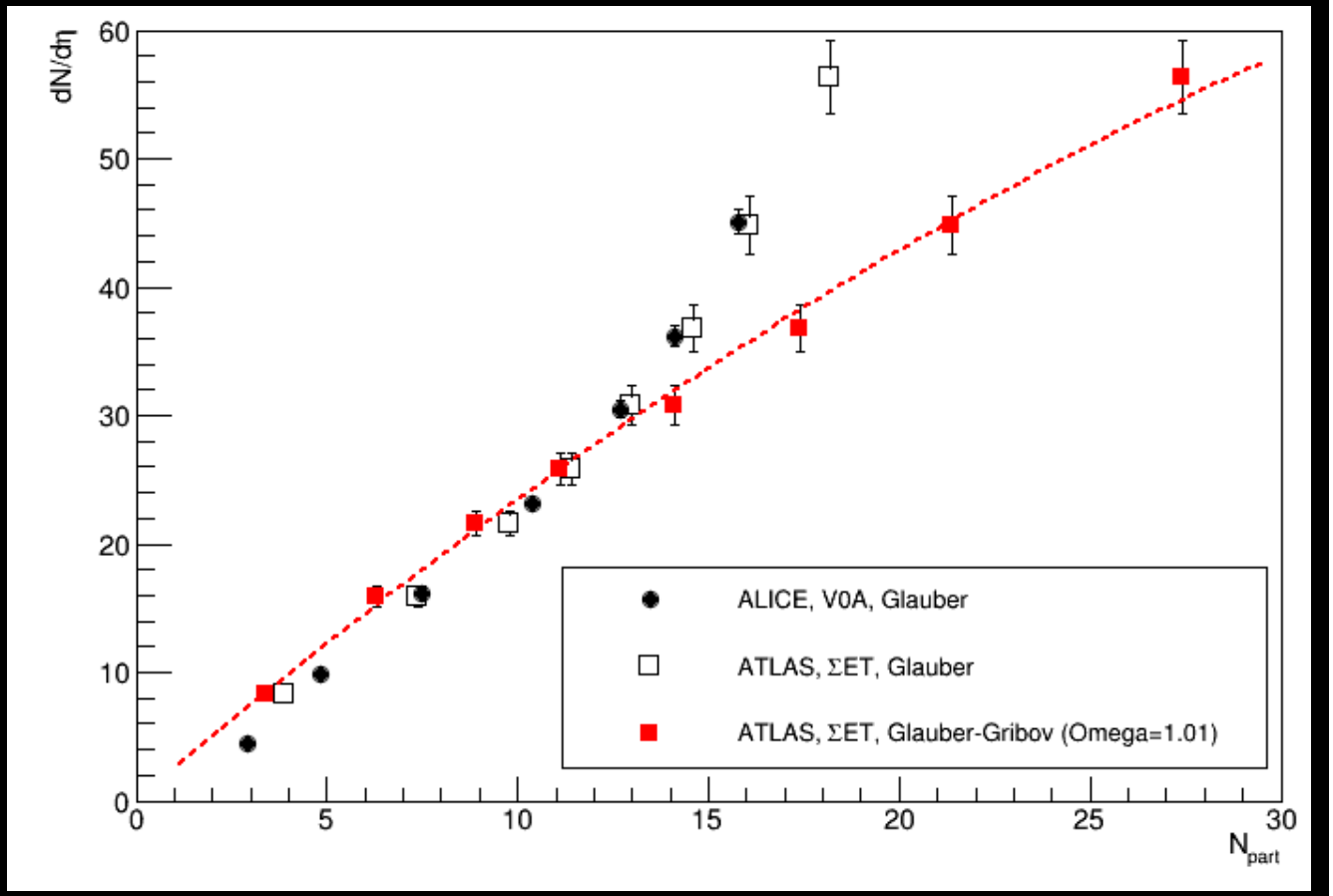


N_{part} for different Glauber mod

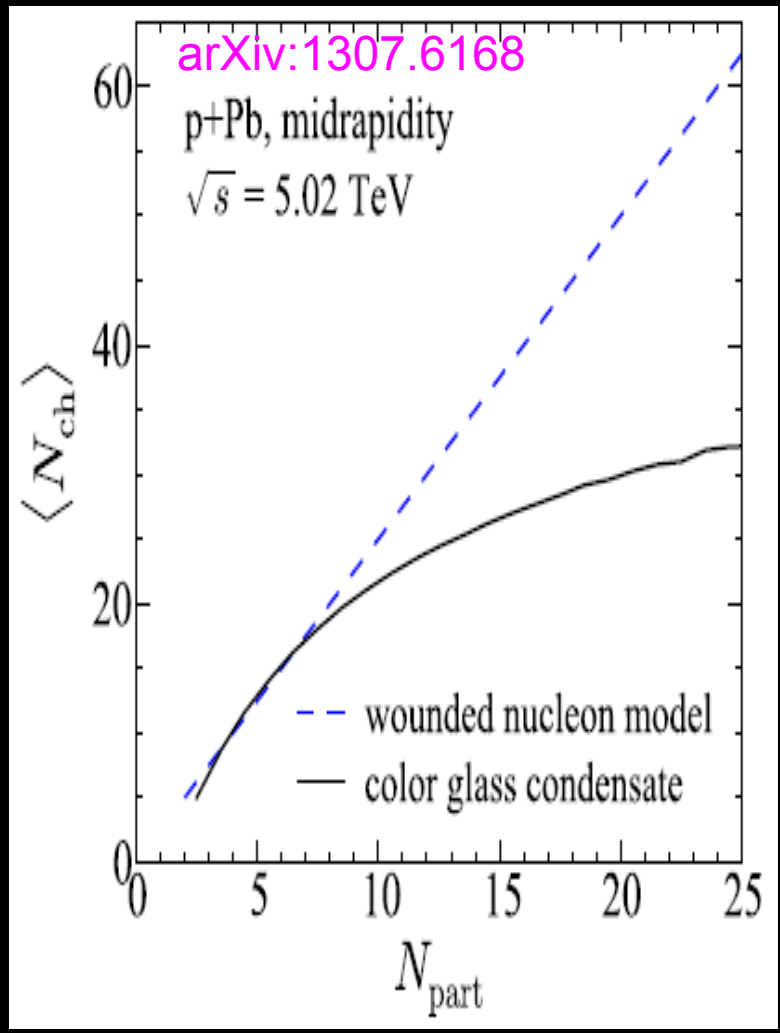


produced with models are different
rd Glauber has highest fluctuations of produced E_T pe
r-Gribov Ω=1.01 has less E_T fluctuation and therefore

Quo vadis, CGC?



Decisive test:

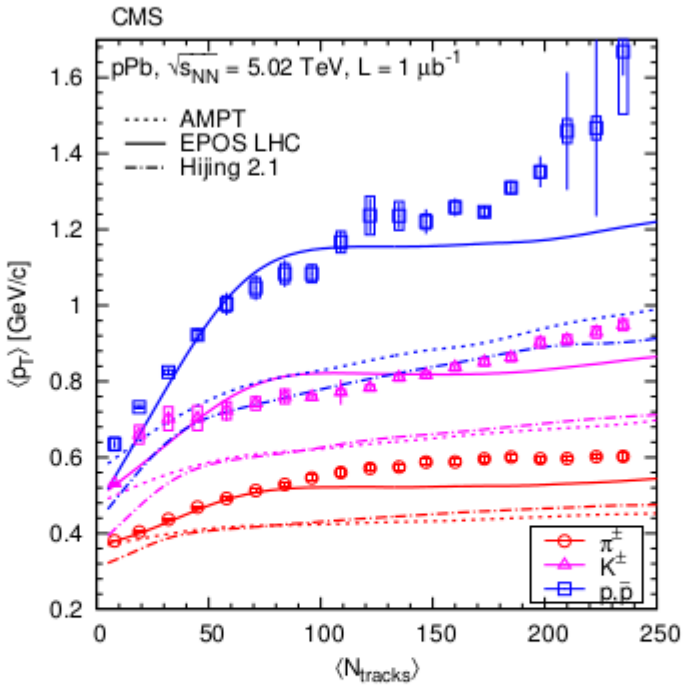


- ATLAS and ALICE measurements (black symbols) consistent (similar bias induced by V0A and ΣET)
  - ALICE points from arXiv:1307.6796
  - ATLAS points read of at dN/dη=0 (Glauber values from ATLAS-CONF-2013-96)

Dynamical biases need to be understood before decisive test can be made!

Identified particle spectra

Results – $\langle p_T \rangle$ – multiplicity dependence



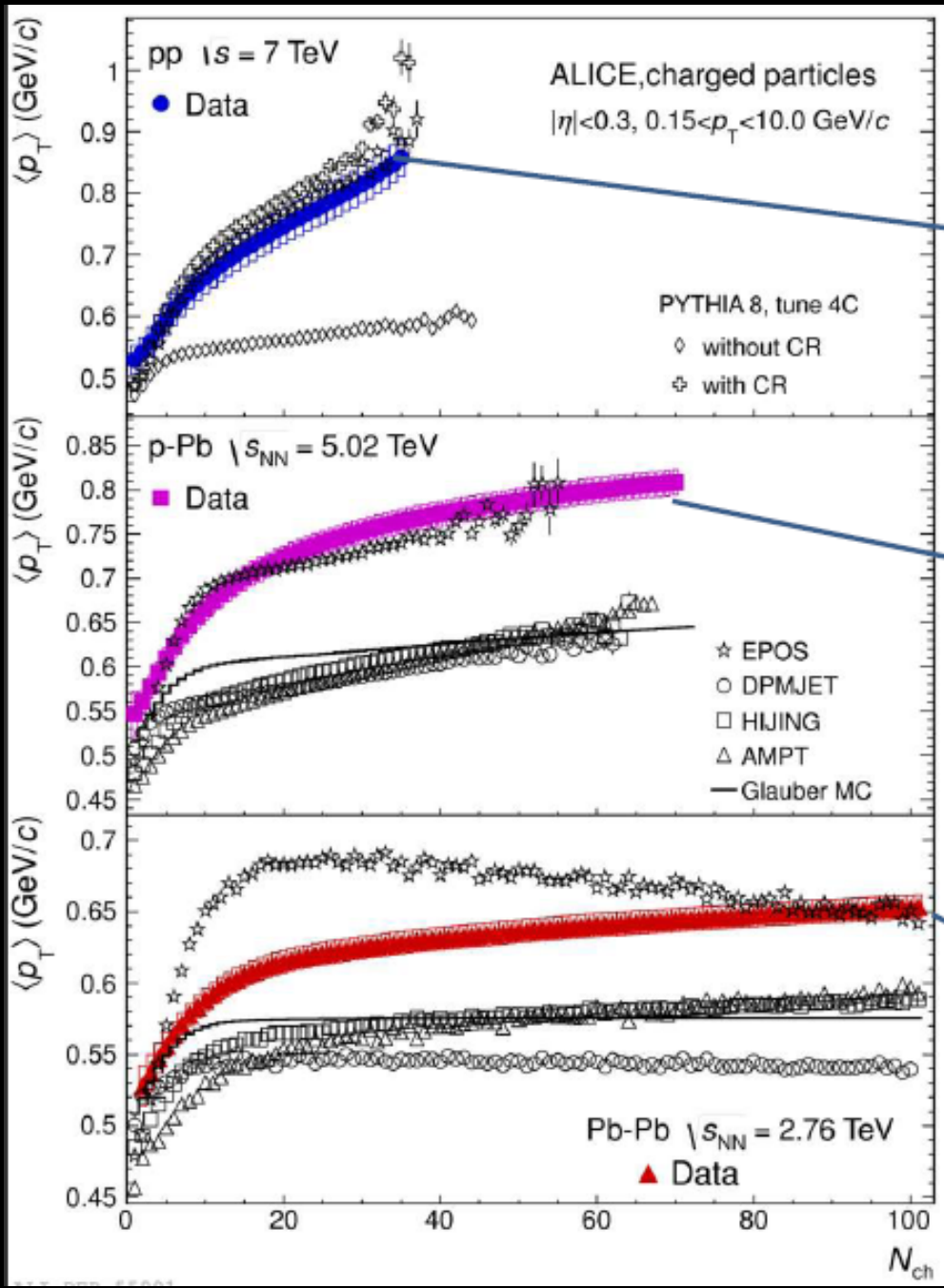
Calculated using MC technique followed by numerical integration

Error bars show the combined $\sqrt{\text{stat}^2 + \text{syst}^2}$ errors, boxes give systematic only

AMPT and Hijing 2.1 underpredict the measured values

Good description by EPOS LHC: includes explicit hydrodynamic treatment

Models



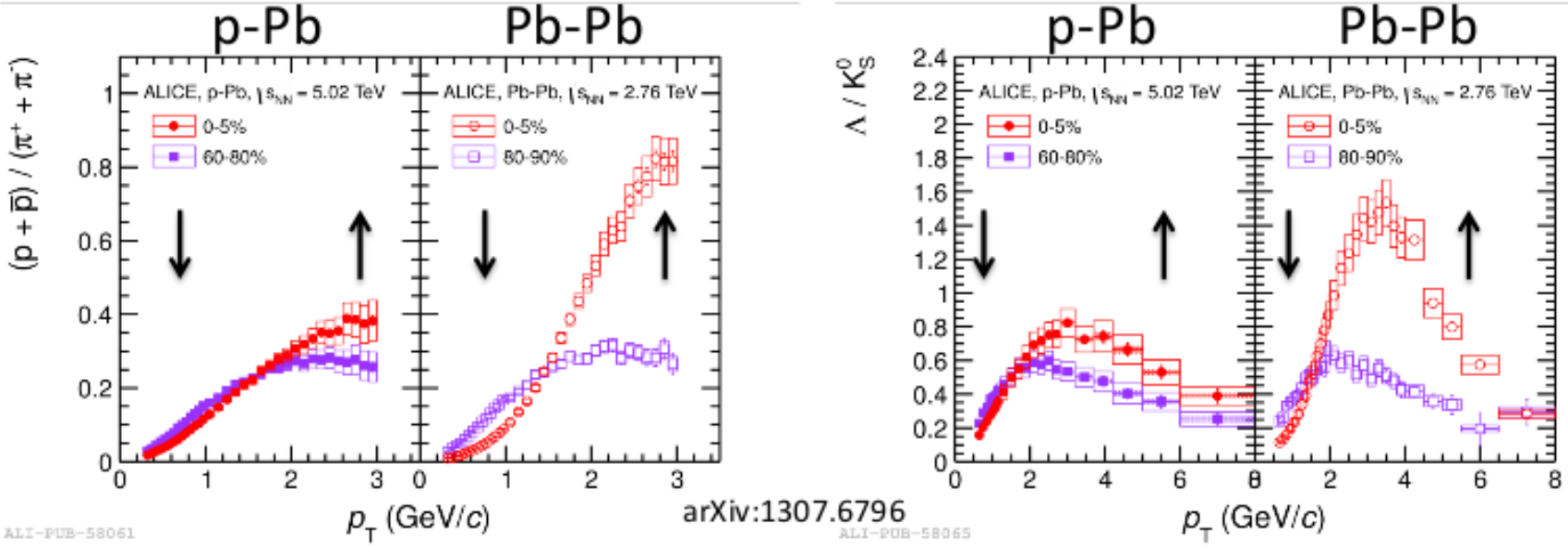
PYTHIA 8 tune4C needs *Colour Reconnection* to describe the data in pp

EPOS includes *collective effects* to describe the data in p-Pb
Hijing, DPMJET, AMPT, Glauber do not use colour reconnection here

EPOS (with collective effects) fails to describe shape, no quantitative description in any of these models

arXiV:1307.1094

Features of the data

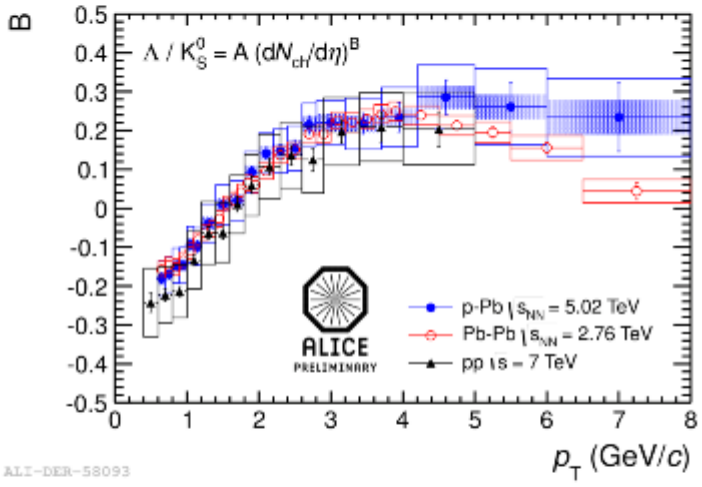


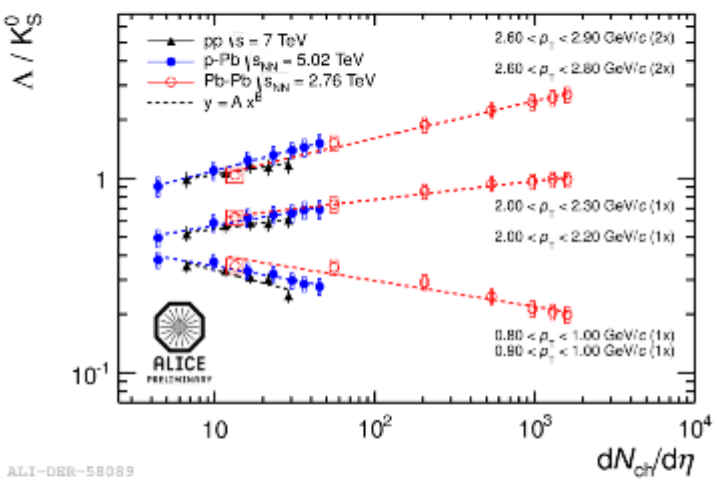
arXiv:1307.6796

- Characteristic evolution of p/π and Λ/ K^0_S with multiplicity is reminiscent of Pb-Pb where it is believed to be due to radial flow
- NB! The solid boxes for p-Pb ratios indicate the uncorrelated systematic error
  ⇒ the relative trend can be measured rather precisely

Integrated particle ratios and $\langle p_T \rangle$ will be covered by Francesco Barile

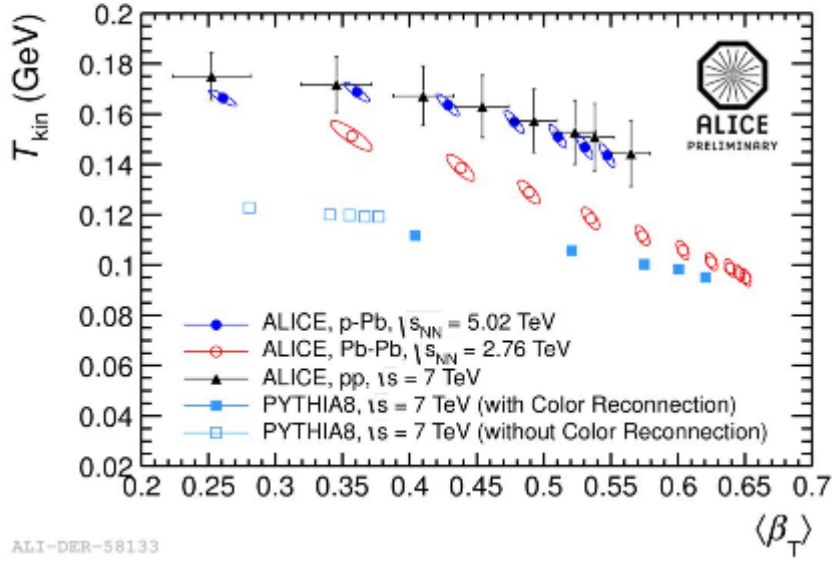
Similar studies with Λ/K^0_S: adding pp





- The way the multiplicity is defined i (significantly more than the Λ/K^0_S)
- The evolution of Λ/K^0_S (p/π) with dN systems
  ⇒ surprising suggestive pattern tha the ratios for all systems and for all onset in dN/dη) ....

the blast-wave studies



Suggests common origin for observed effects

simulated PYTHIA8 pp events follow a qualitati

Summary

Great meeting at a great place. Thanks for your valuable contribution, and to the organizers and sponsors for making this meeting possible!