Recent Results from Heavy Ion Collisions at RHIC and LHC

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31 May 2011

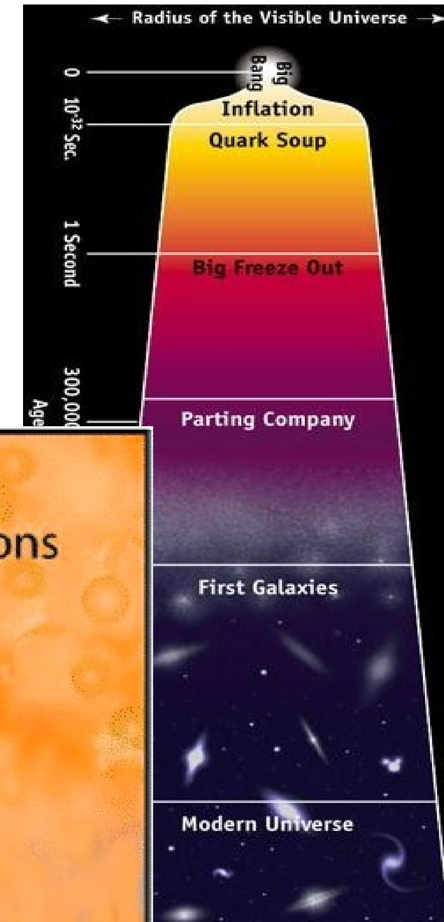
23 Rencontres de Blois
Particle physics and cosmology

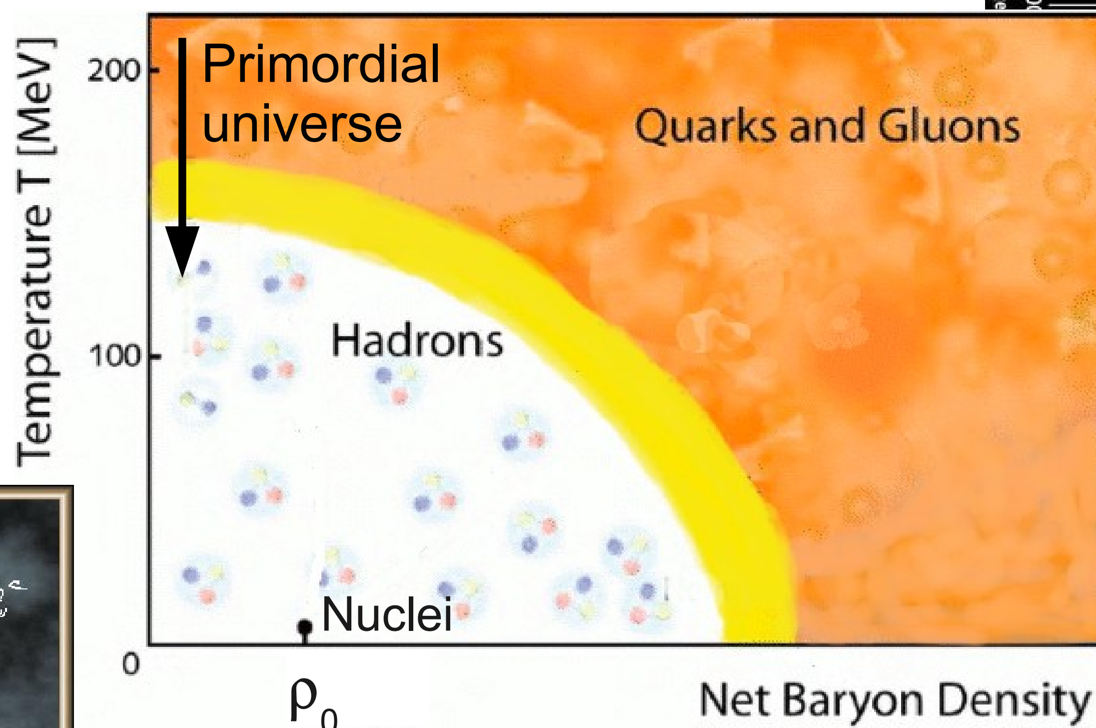
1975: Why study QCD matter

In high energy physics we have concentrated on experiments, in which we distribute a higher and higher amount of energy into a region with smaller and smaller dimensions. In order to study the question of “vacuum”, we must turn to a different direction; we should investigate some “bulk” phenomena by distributing high energy over a relatively large volume.

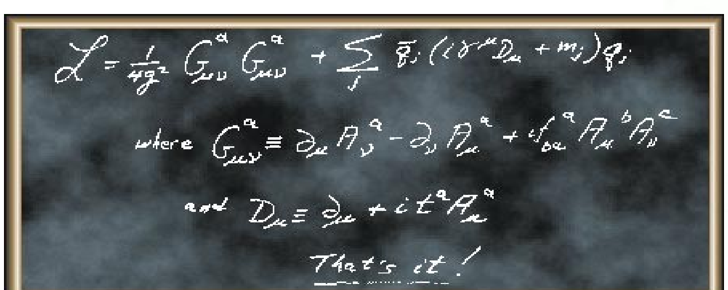
T.D.Lee,
Rev.Mod.Phys.47(1975)267

Quark-hadron phase transition in the primordial universe

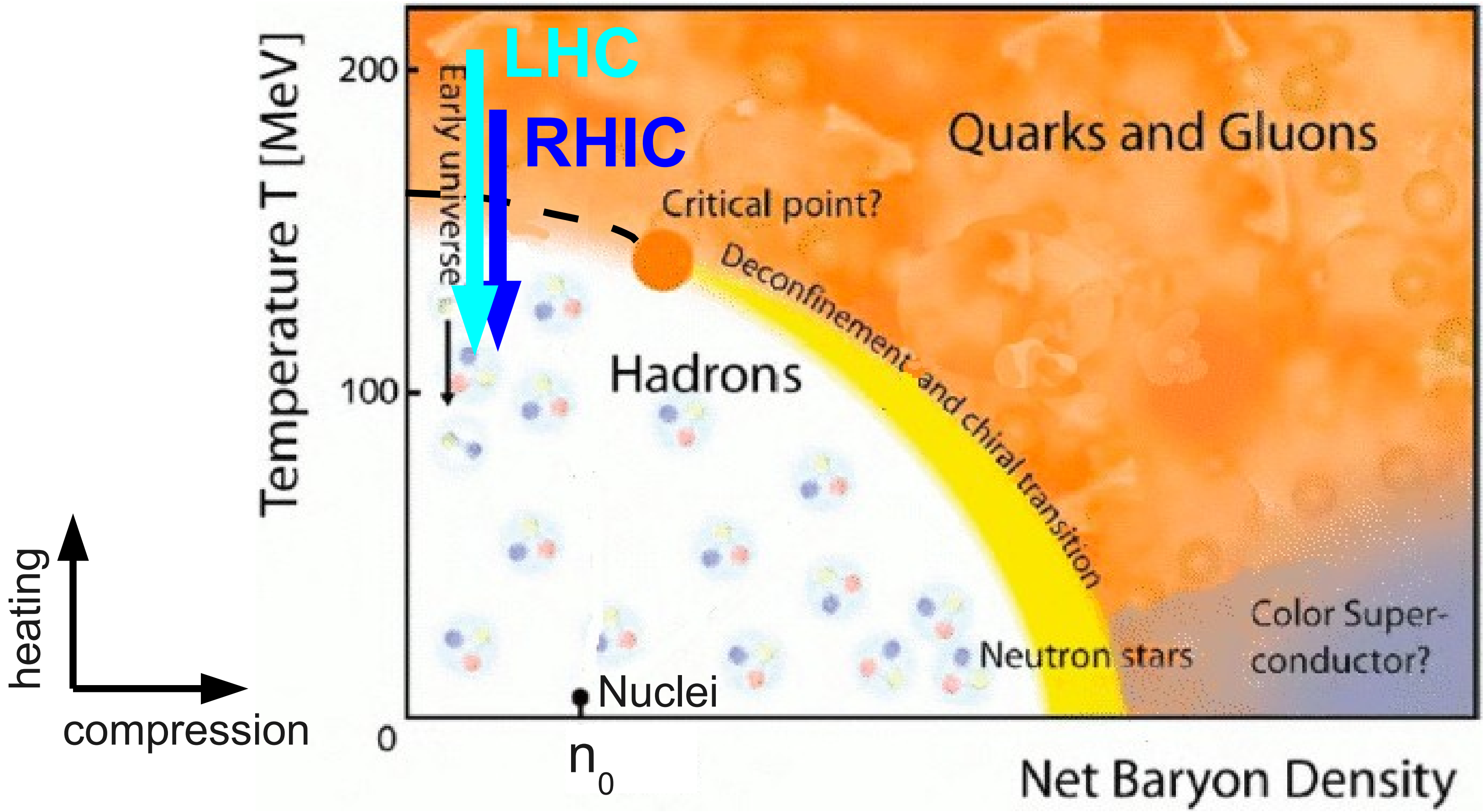




Confinement + chiral symmetry breaking (1973)

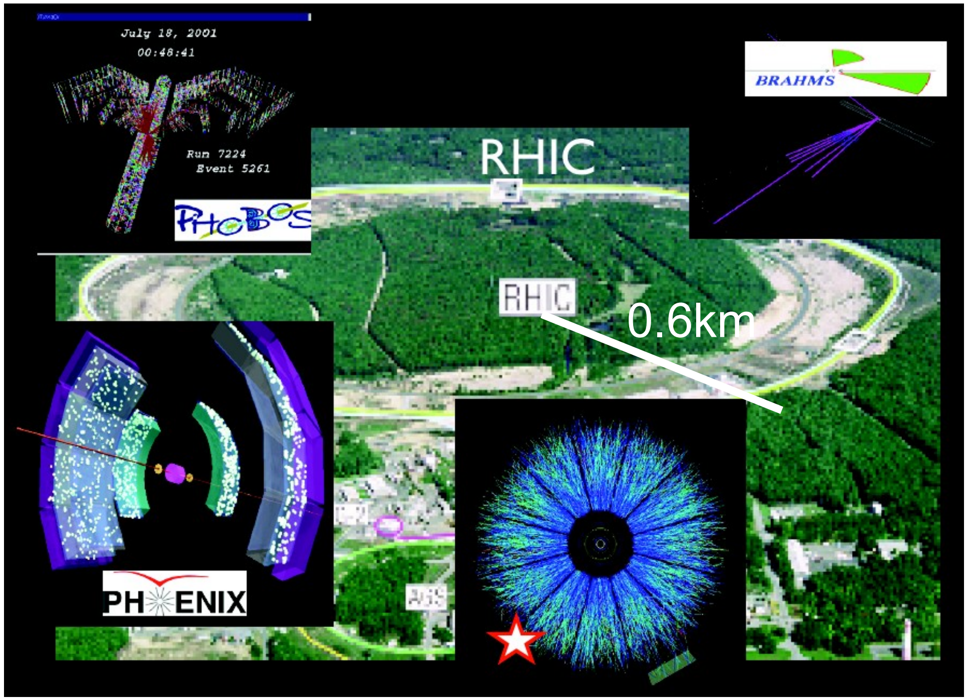


About 35 years later ...



LHC/RHIC events (at mid-rapidity) are net-baryon̄ free:
LHC/RHIC explore cross-over region of QCD phase diagram

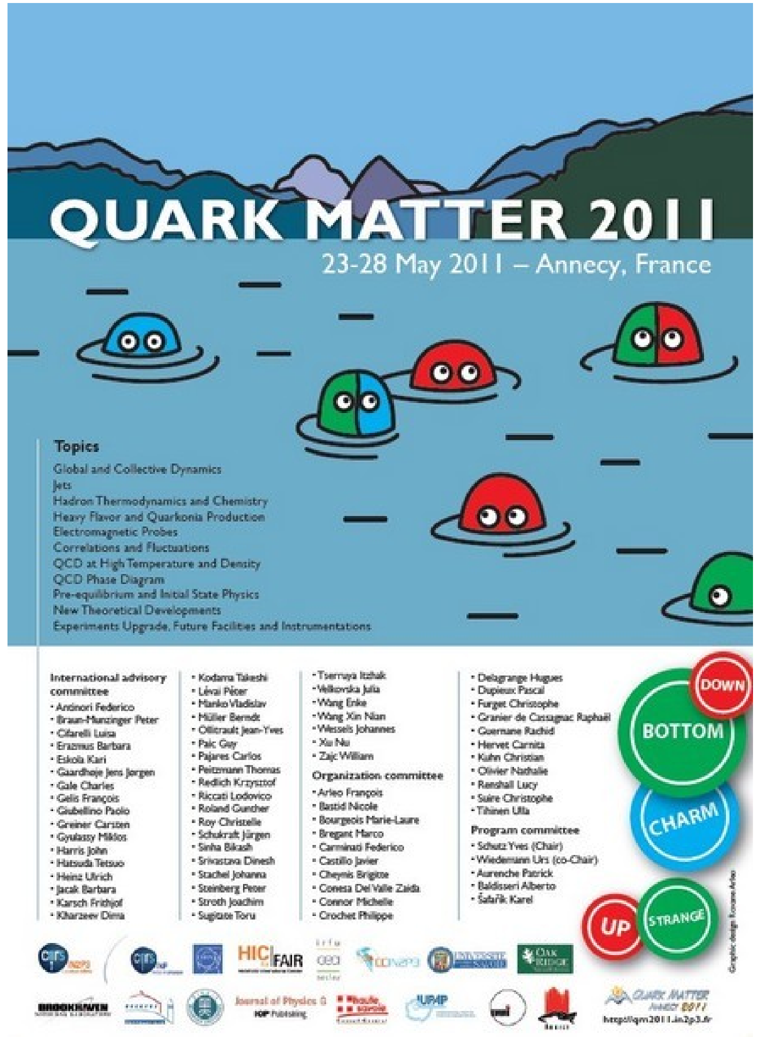
Heavy ion experiments at RHIC/LHC



- RHIC: First beams June 2000
  - p+p, d+Au, Cu+Cu, Au+Au (~20, 62.4, 130, 200 AgeV)
- 4 experiments
  - Since 2005, only STAR + PHENIX
- Beam energy scan (2010/11)

- LHC: First beams in Nov 2009
  - p+p (900, 2.36, 2.76, 7 TeV)
  - Pb+Pb at 2.76 ATeV in Nov 2010
    - Delivered up to ~10μb^{-1}
- 1 dedicated HI experiment
  - Mid-rapidity, low mass, PID
- 2 large HEP experiments
  - Large acceptance, full calorimetry

First Quark Matter conference with results from the LHC



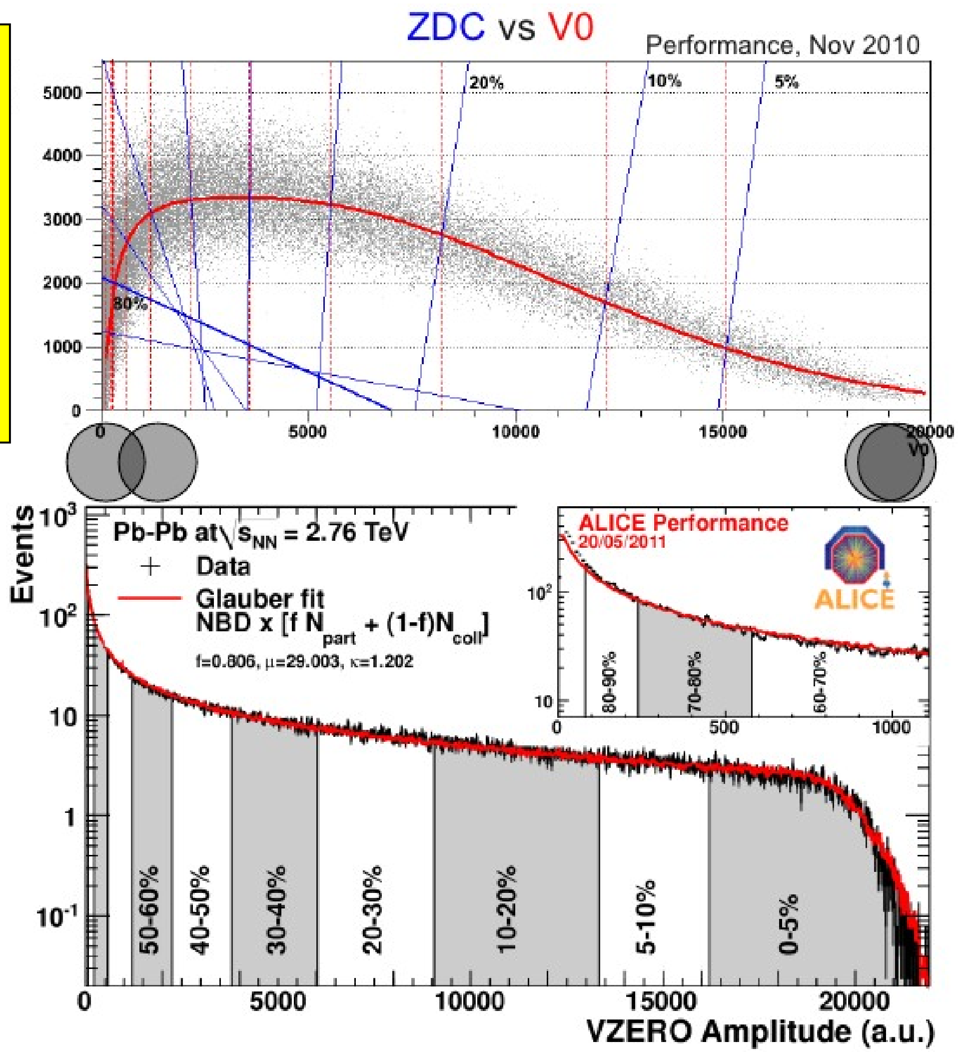
Even though, there are very interesting new results from RHIC, the focus in this talk is on LHC!

Reference given in this talk can be looked up at
https://indico.cern.ch/conferenceTimeTable.py?confId=30248#all.detailed

HI jargon: Centrality

Nuclei are “macroscopic”: Characterize collisions by impact parameter

Forward neutrons

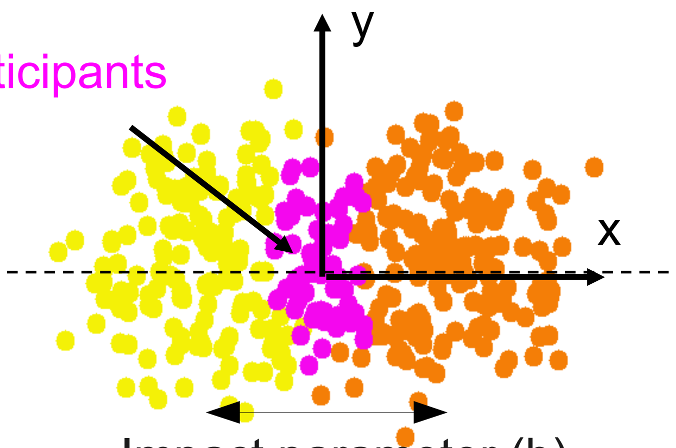


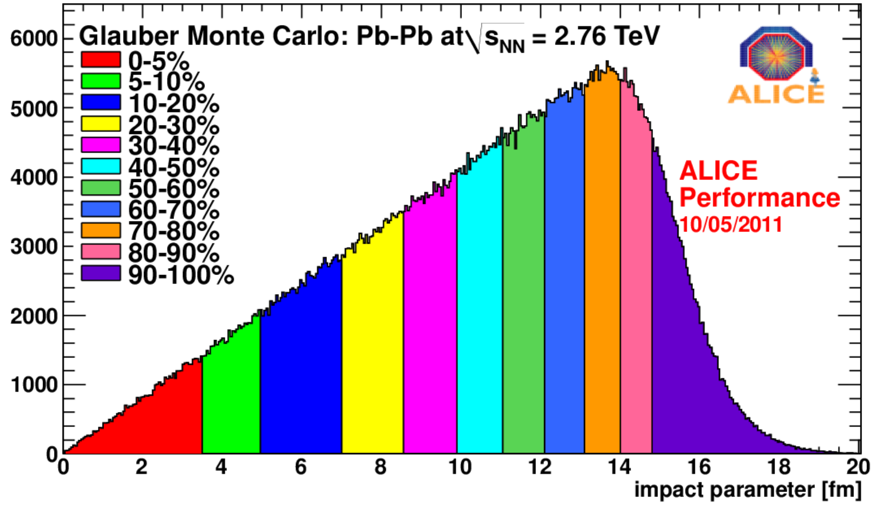
Charged hadrons η~3

- Correlate particle yields from disconnected parts of phase space
  - Correlation arises from common dependence on collision impact parameter
- Order events by centrality metric
  - Typically, classify them as “ordered” fraction of total cross section
  - eg. 0-5% most central

HI jargon: Glauber model

- Geometrical picture of inelastic nucleus+nucleus collision
  - Nucleons distributed by Woods-Saxon
    - Radius (6.62 ± 6fm)
    - Skin depth (0.546 ± 0.02 fm)
    - Inter-nucleon distance (0.4 ± 0.4 fm)
  - Straight-line nucleon trajectories
  - Interaction radius given by σ_{NN}
    - Subsequent scatters equally probably

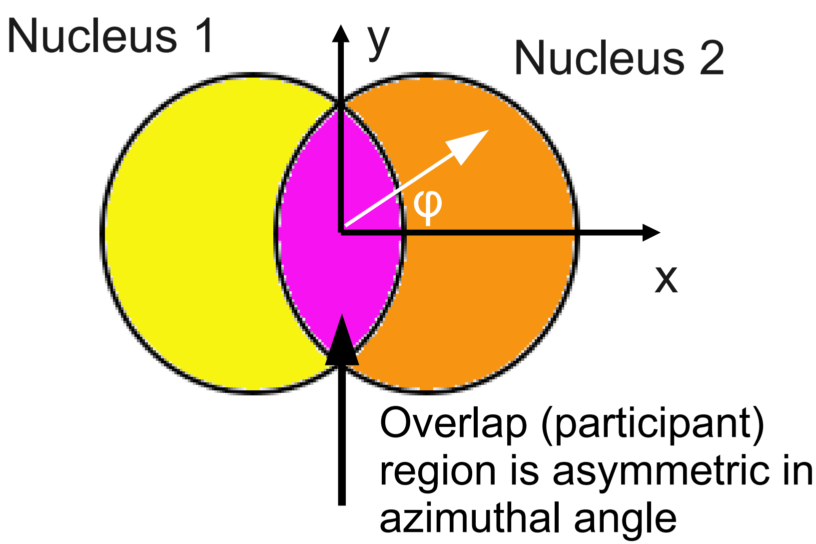




- Relate centrality to Glauber
  - Impact parameter (<b>)
  - #Participants ($\langle N_{part} \rangle$)
    - Nucleons struck at least once
  - #NN-collisions ($\langle N_{coll} \rangle$)
    - Total number of collisions

Collective flow of QCD matter

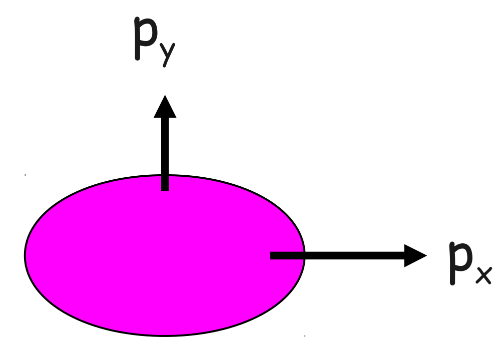
Initial spatial anisotropy



$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

Interaction of constituents

Final momentum anisotropy



$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

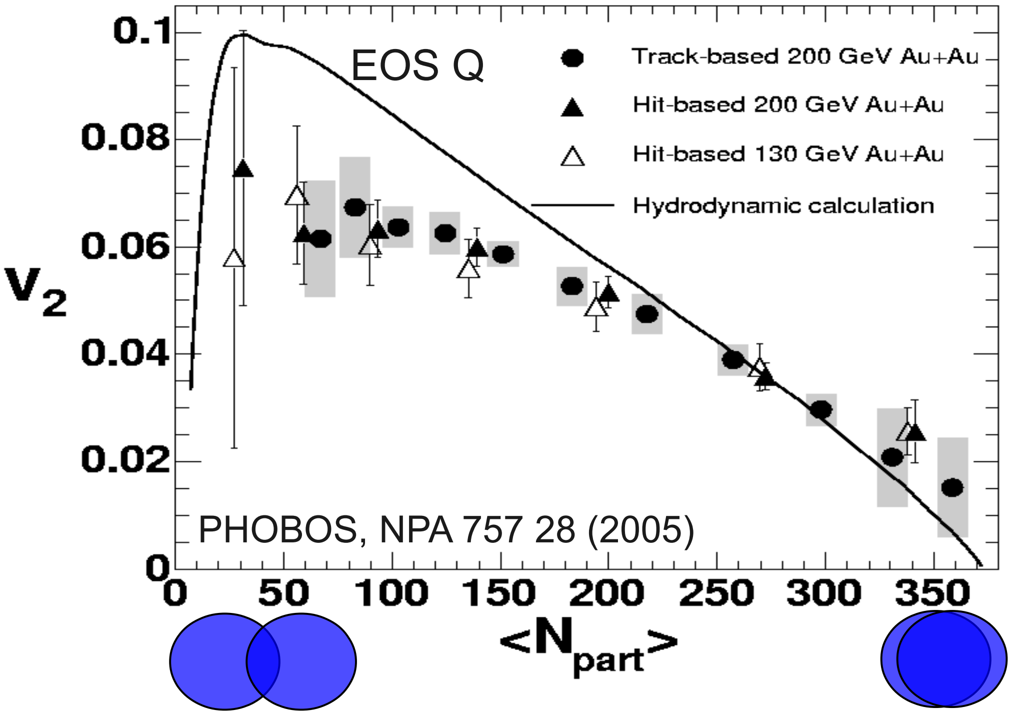
Elliptic flow

$$\frac{dN}{d\phi} \sim 1 + 2 v_2 \cos[2(\phi - \psi_R)] + \dots$$

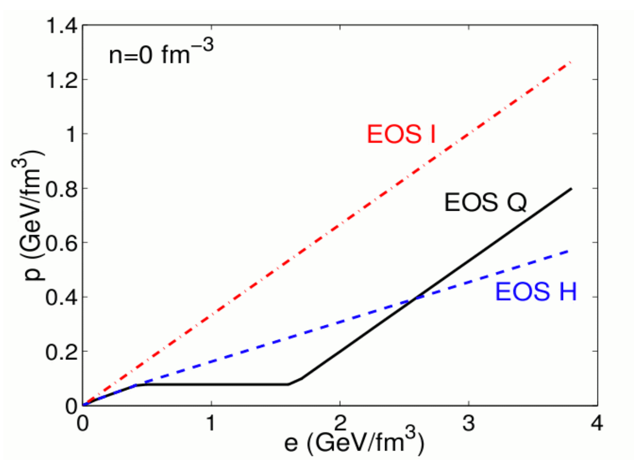
Elliptic flow and ideal hydrodynamics

Ideal relativistic hydrodynamics

$$T^{\mu\nu} = (e+p)u^{\mu}u^{\nu} - p g^{\mu\nu}$$
$$\delta_{\mu} T^{\mu\nu} = 0$$
$$\delta_{\mu} N_i^{\mu} = 0,\ i = B, S, \ldots$$
$$p = p(e, n)$$ Closure with EoS



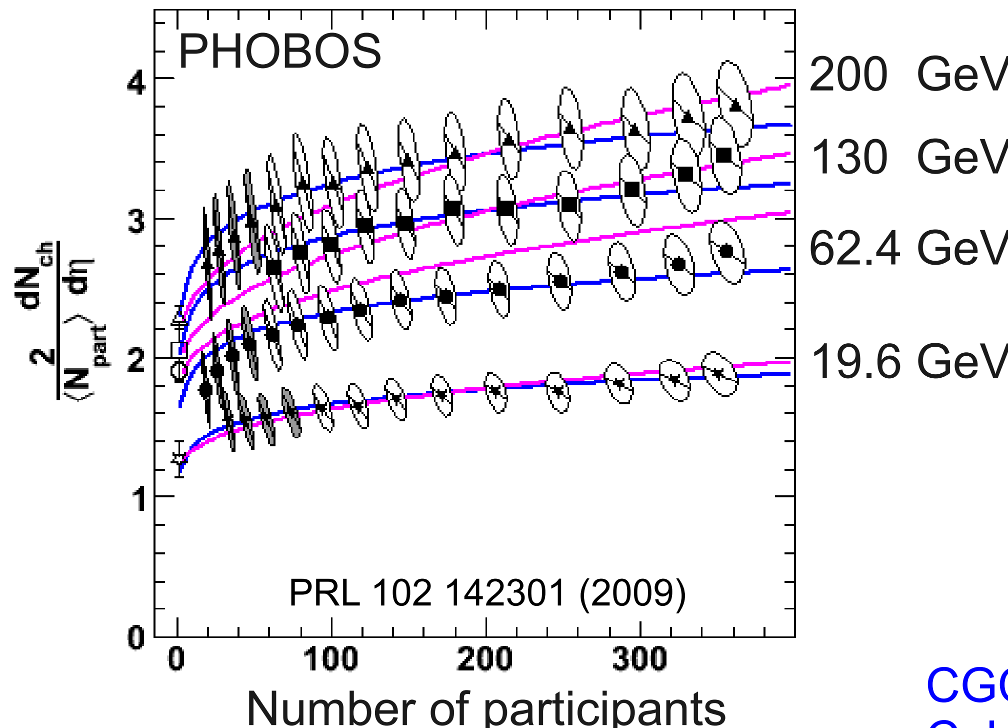
Assumption:
After a short thermalization time (≤1fm/c) a system in local equilibrium with zero mean free path and zero viscosity is created

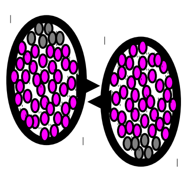


Initial conditions (IC) → Equation of state (EOS) → Freeze-out cond. (FO) → **Hydro** → Observables

Description of initial state?

Mid-rapidity density

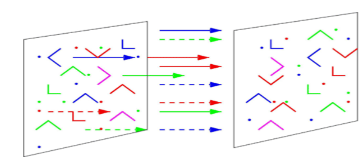




Glauber IC
Two-component model

$$\frac{dN}{d\eta} = \frac{dN}{d\eta^{pp}}((1-x)N_{coll} + x\,N_{part}/2)$$

PRC 70 021902 (2004)



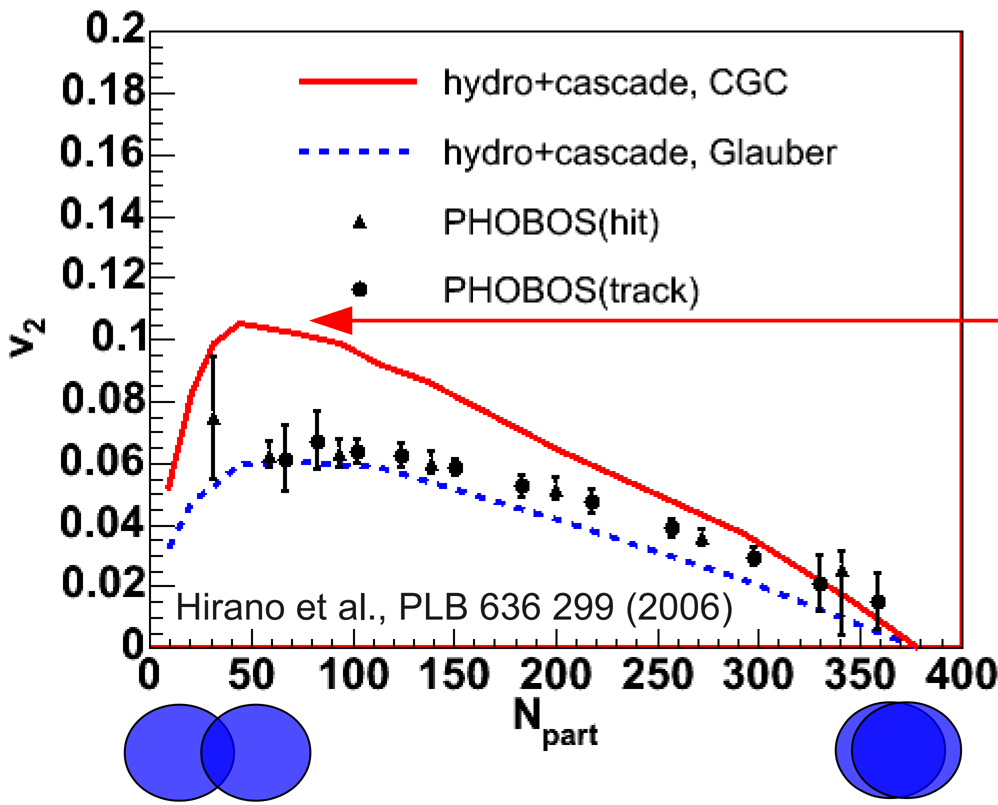
CGC IC
Color glass condensate

$$\frac{dN}{d\eta} \propto N_{part}^{\alpha} \sqrt{s}^{\lambda}$$

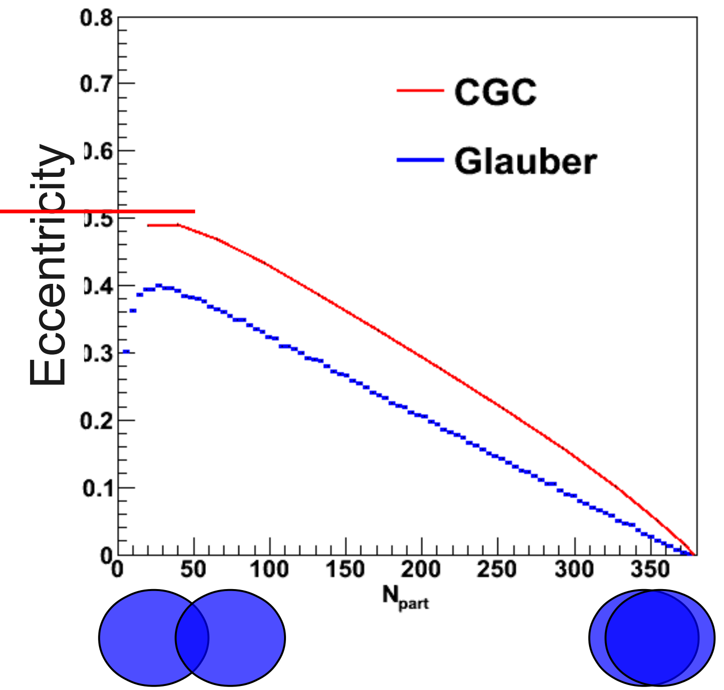
PRL 94 022002 (2005)

Two classes of models describe the multiplicity equally well

Ambiguity translates into conclusions



Higher eccentricity leads to higher flow

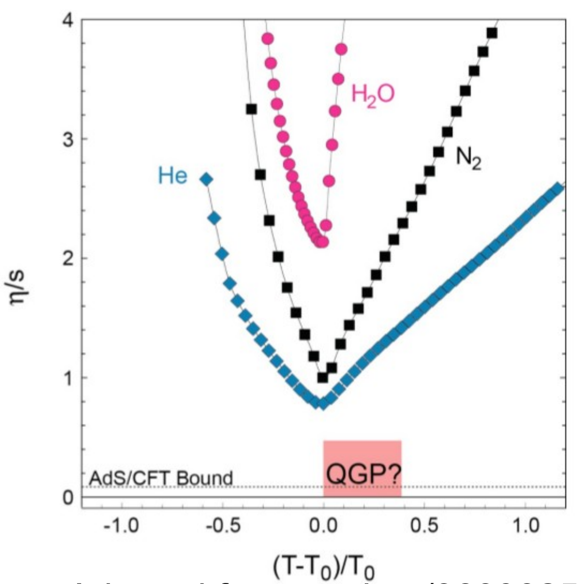


Ambiguity in description of initial state allows for various models:
Size of viscous corrections and/or soft equation of state?

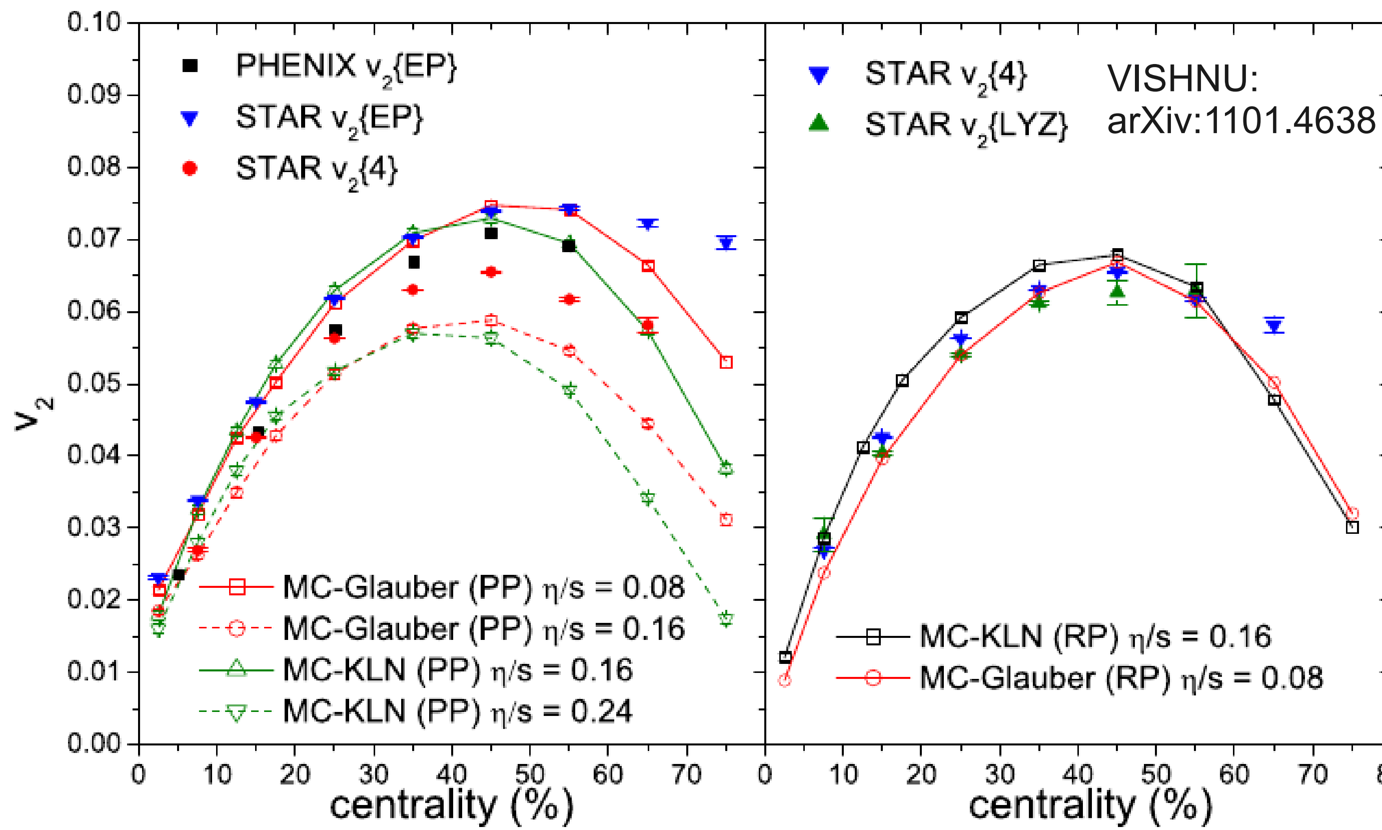
Viscosity characterizes the efficiency
of momentum transport (η~1/σ quasi-p.)

The QGP is a very low viscous fluid

B.Schenke, QM11



Adapted from nucl-ex/0609025



Combination of many calculations, including state-of-art results from Israel-Stewart theory for a conformal fluid (2+1D), hint to a low shear viscosity to entropy ratio:

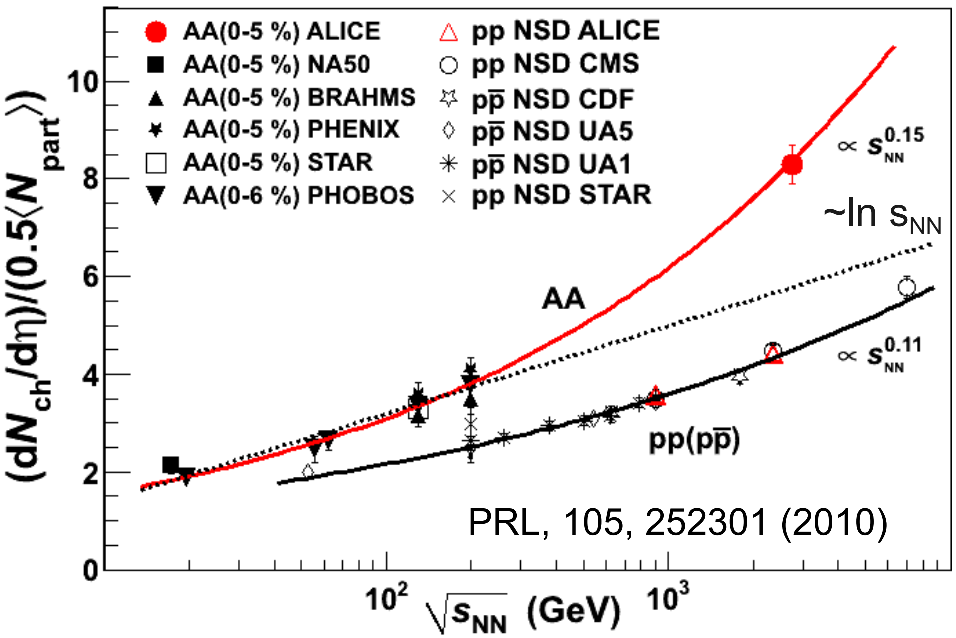
$$\frac{\eta}{s} < 4 \times \frac{1}{4\pi}$$

Large part of uncertainties still from the ambiguity in the description of initial state.

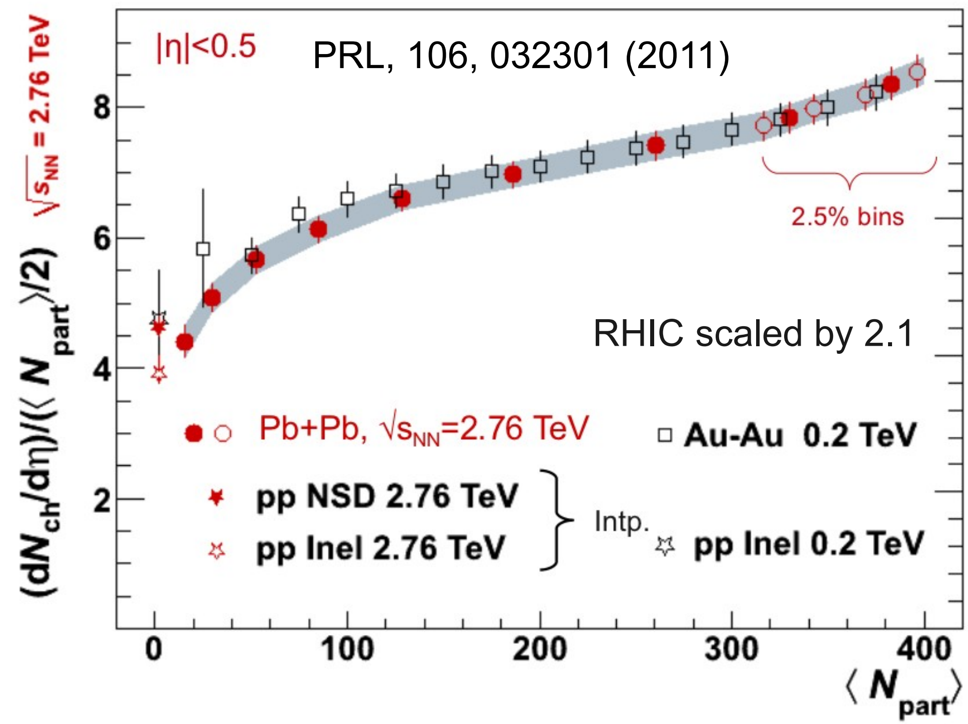
1/4π “units” motivated by ADS/CFT, see D.Mateos, QM11

LHC "first day": Multiplicity

Collision energy dependence



Centrality dependence



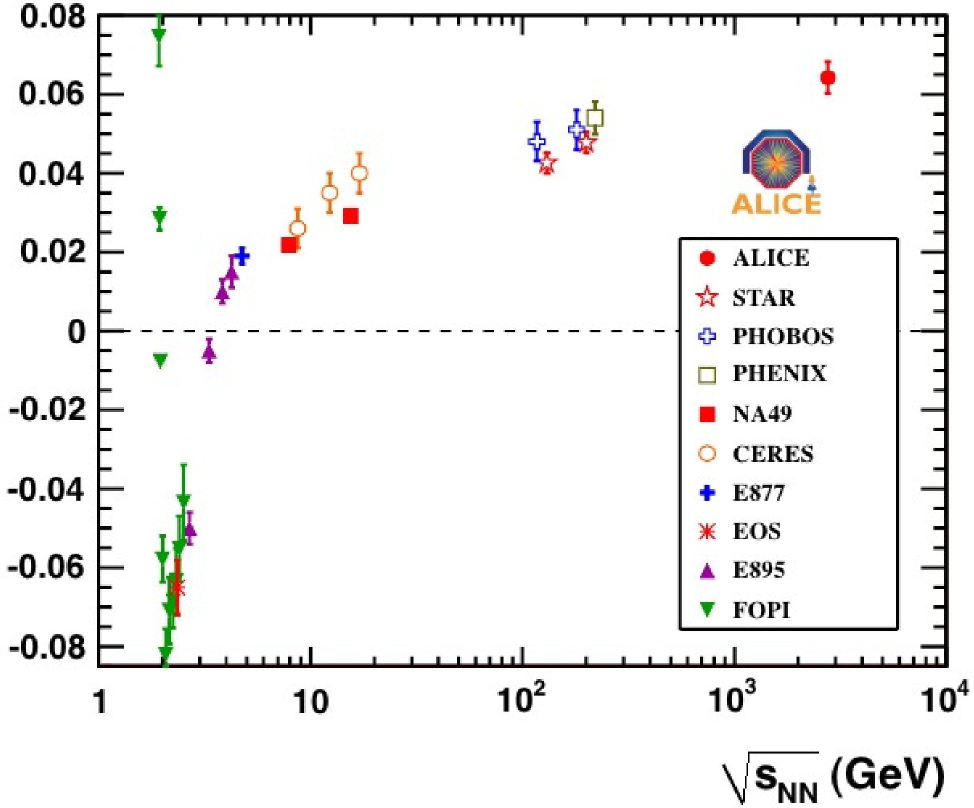
Rise with collision energy faster than expected. Challenge to most models. (Rules out existing data-driven extrapolations).

LHC centrality evolution similar to RHIC

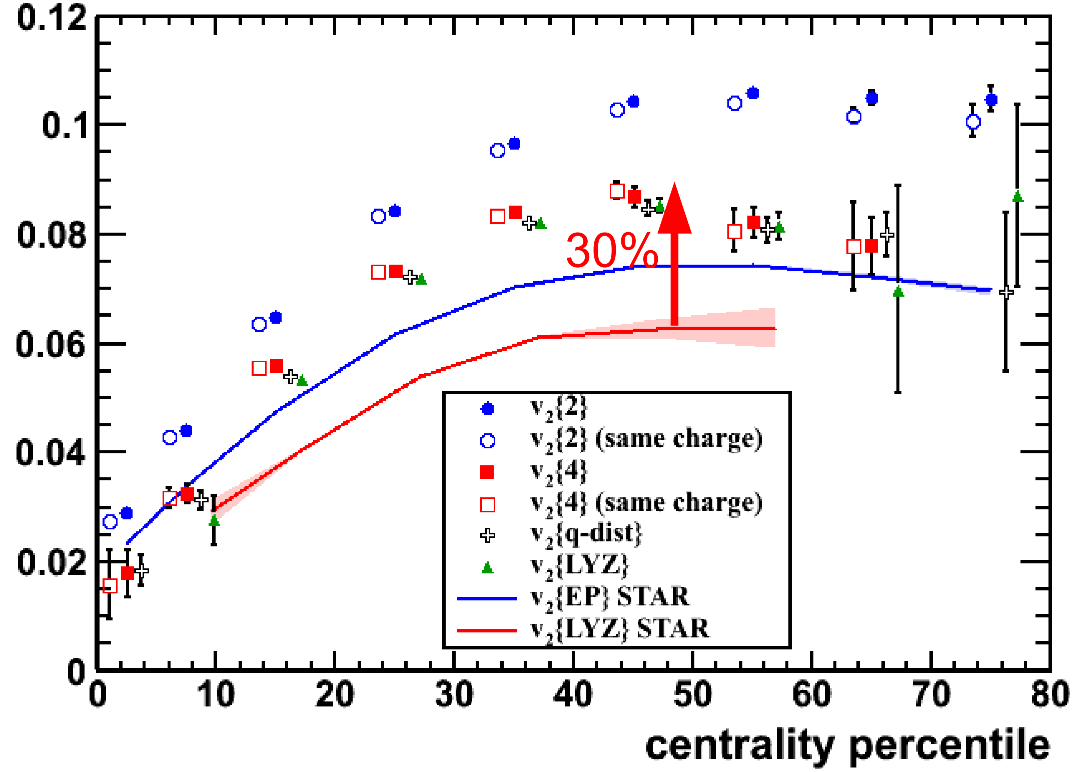
As at RHIC, particle production needs a "coherence" mechanism to reduce the effective number of sources for particle production.

LHC "first day": Elliptic flow

Collision energy dependence



Centrality dependence



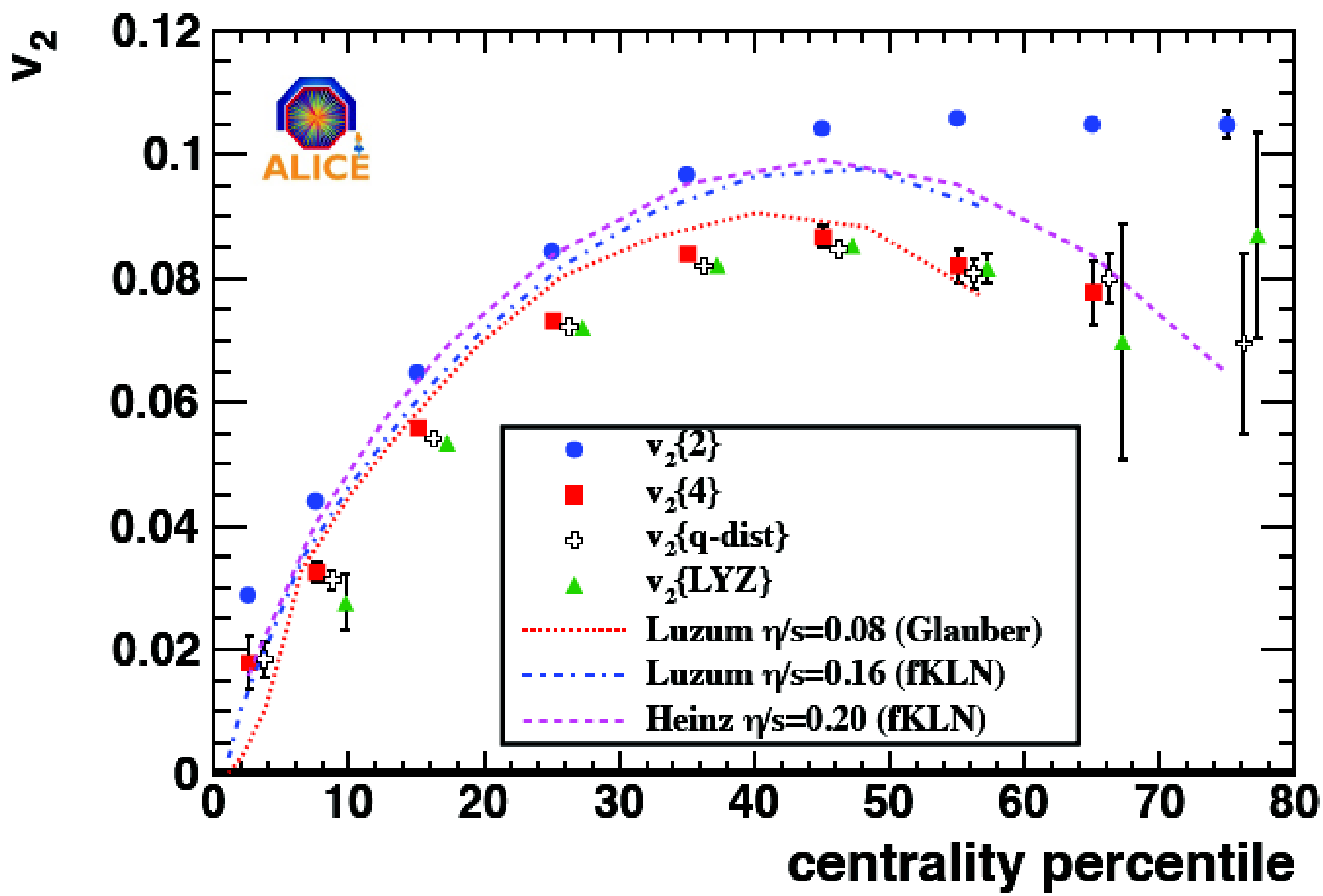
Integrated v_2: 30% increase from 0.2 TeV (STAR) to 2.76 TeV (ALICE)

Over all centrality classes, due to the increase of $<p_T>$

The system created at the LHC behaves like a very low viscosity fluid

PRL, 105, 252302 (2010), arXiv:1011.3914

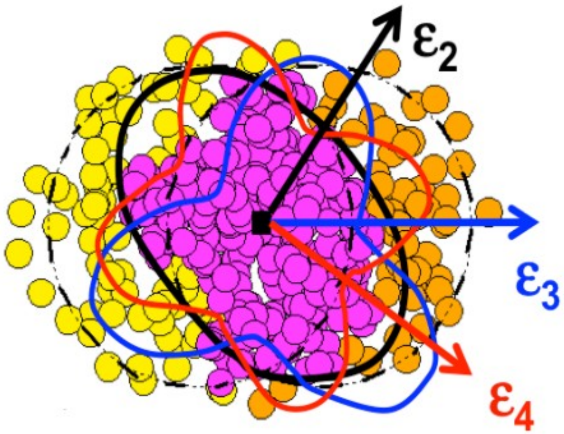
Low viscosity fluid also at LHC



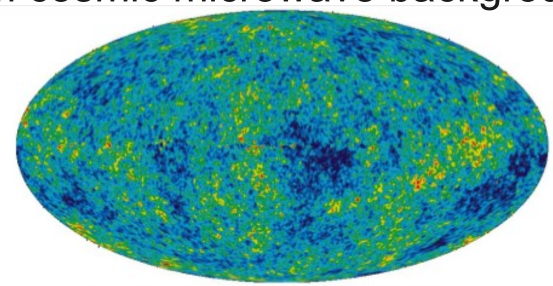
Calculation:
M.Luzum,
arXiv:1011.5173

Increase well within the range of viscous hydro predictions

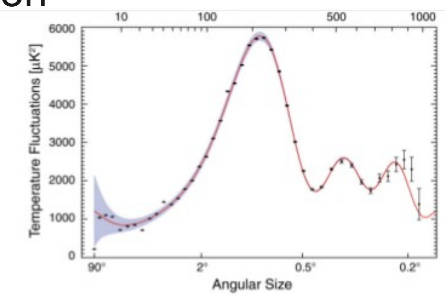
Higher azimuthal harmonics



Analogous to power spectrum extracted
from cosmic microwave background radiation

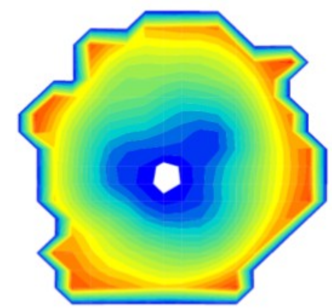


WMAP, Astrophys.J.Suppl.170:288,2007

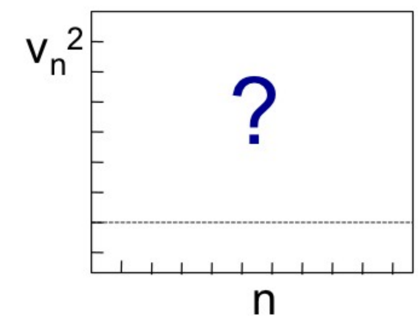


$$N_{pairs} \propto 1 + 2v_1^2 \cos\Delta\varphi + 2v_2^2 \cos 2\Delta\varphi + 2v_3^2 \cos 3\Delta\varphi + 2v_4^2 \cos 4\Delta\varphi + \ldots$$

Kowalski, Lappi and Venugopalan,
Phys.Rev.Lett. 100:022303



K. Werner, Iu. Karpenko, K.
Mikhailov, T. Pierog, arXiv:11043269

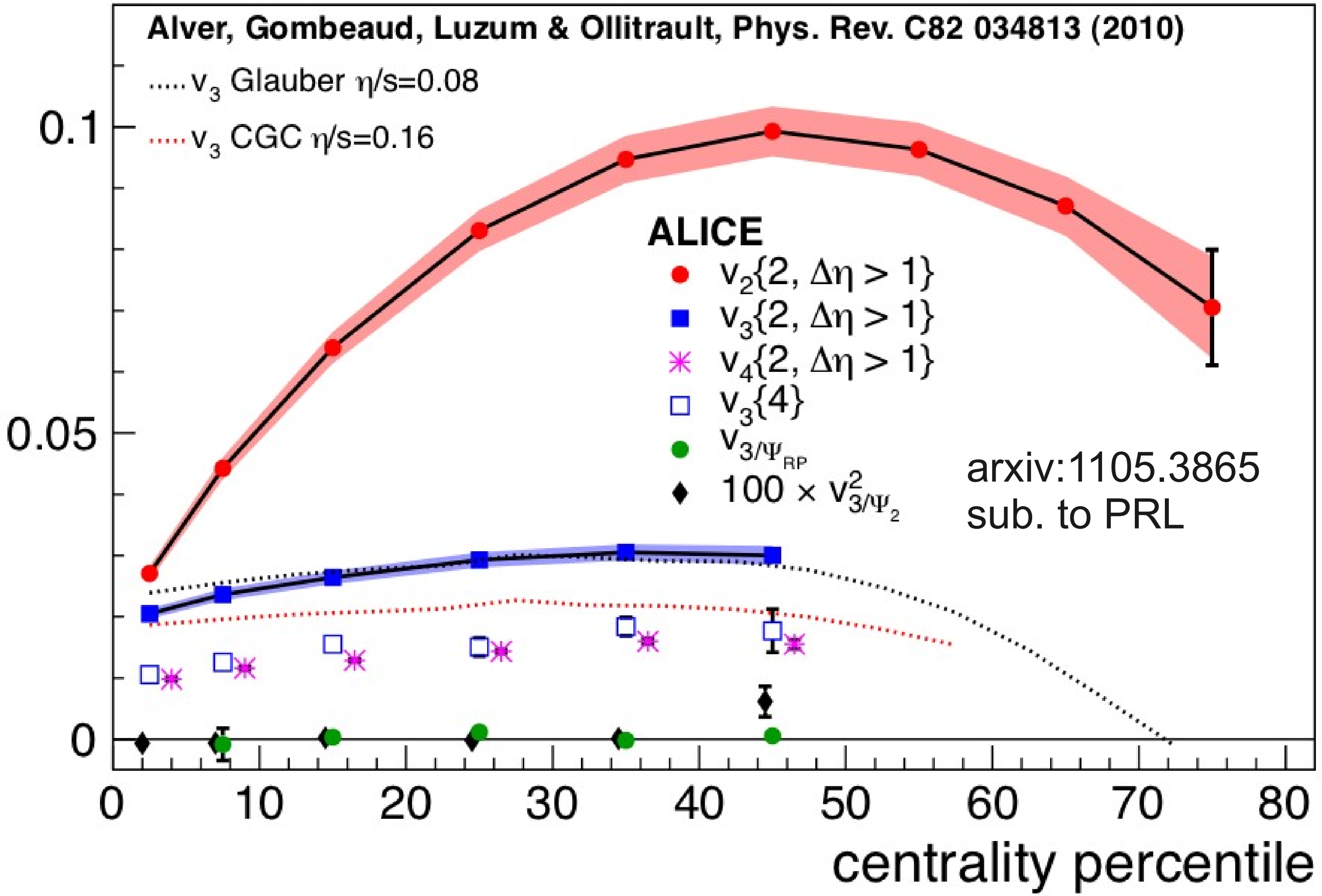


Initial spatial anisotropy not an almond, may lead to higher harmonic anisotropies in the final state

$$\frac{dN}{d\phi} \sim 1 + 2v_2 \cos[2(\phi-\psi_2)] + 2v_3 \cos[3(\phi-\psi_3)] + 2v_4 \cos[4(\phi-\psi_4)] + 2v_5 \cos[5(\phi-\psi_5)] + \ldots$$

<u>QM 11 plenary talks</u>
S.Esumi (PHENIX)
P.Sorenson (STAR)
R.Snellings (ALICE)
J.Oetringhaus (ALICE)
J.Jianyong (ATLAS)
J.Velkovska (CMS)
W.Li (CMS)

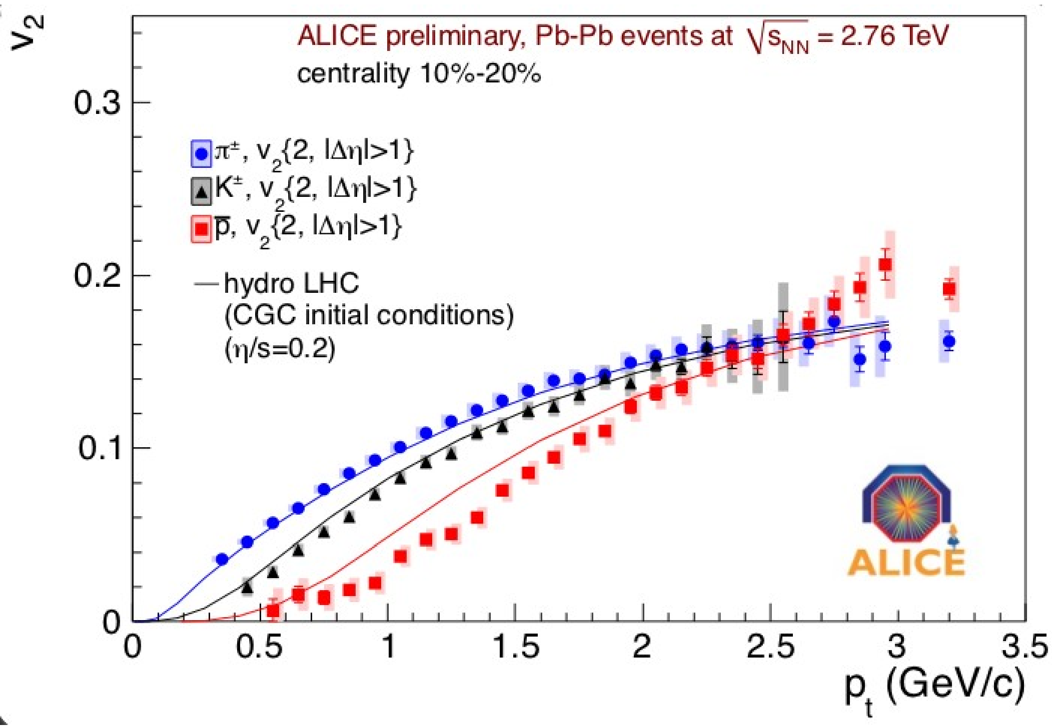
Triangular flow



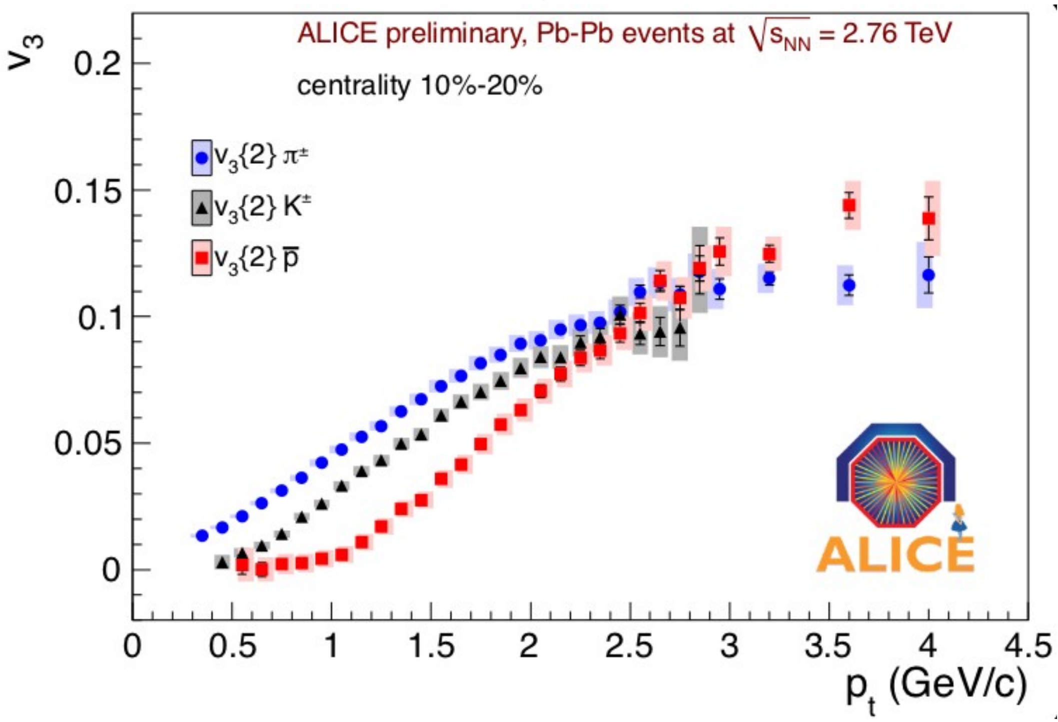
Significant triangular flow observed. Centrality dependence is different to that of elliptic flow. Measurements vs reaction planes yield zero as expected if it arises from fluctuations.

Common origin interpreted by hydro

Elliptic flow



Triangular flow



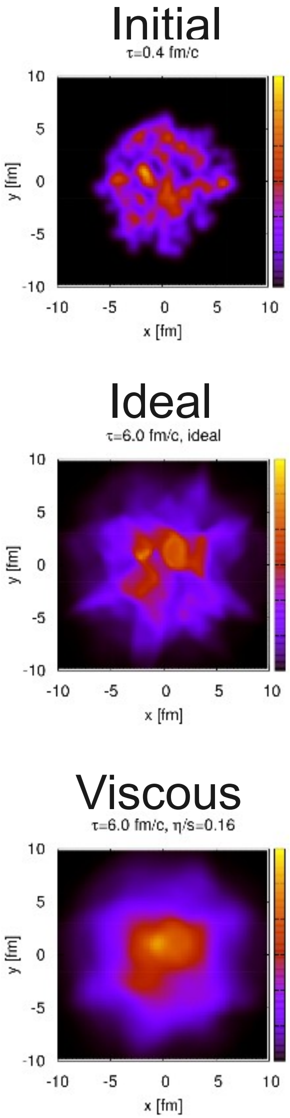
We observe the same mass splitting for v3 as predicted for v2 by hdyro.

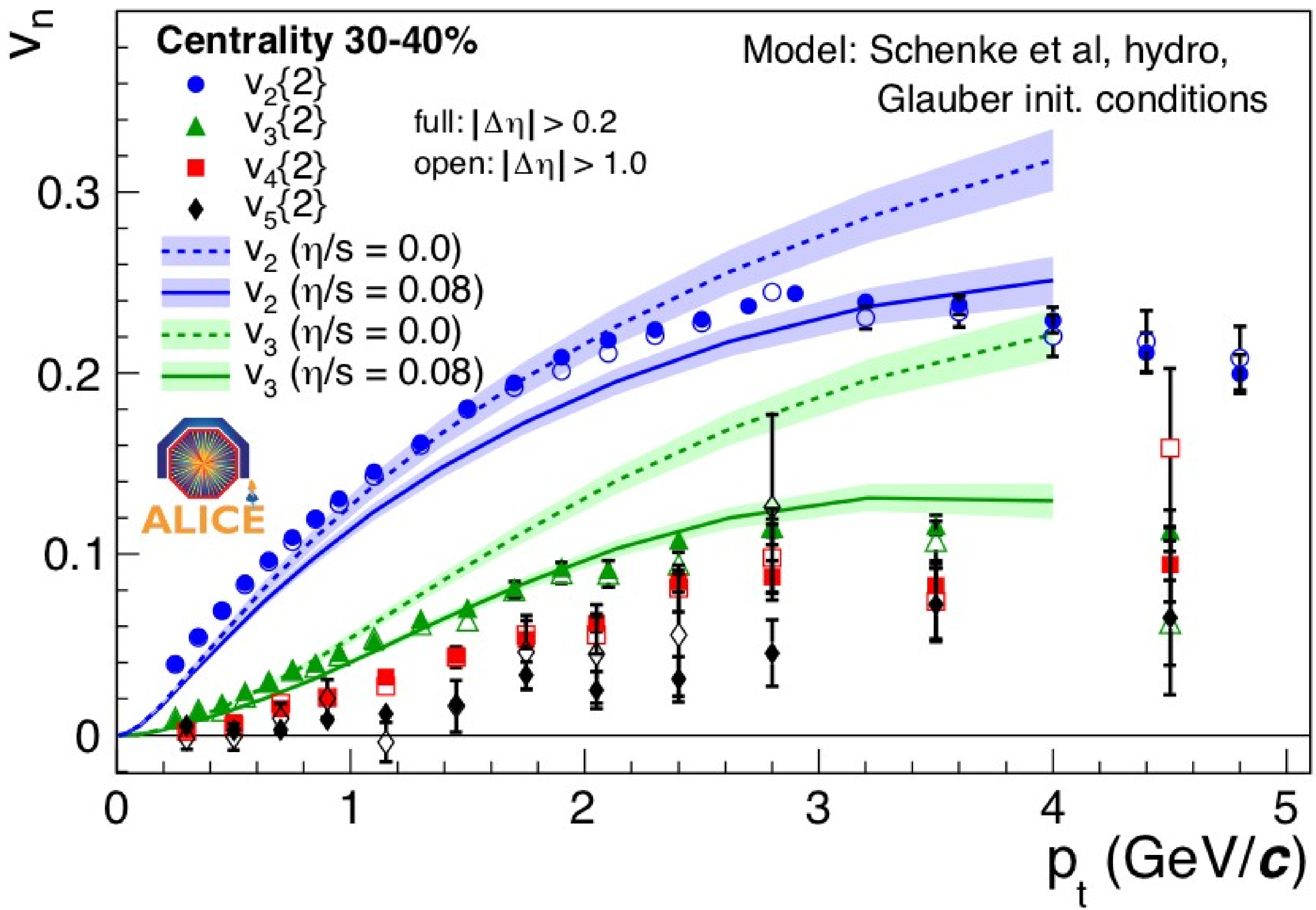
(Note also that the crossing between (anti-) protons and pions happens at the same p_T which for v2 was considered a sign of recombination.)

Hydro: Shen et al., arxiv:1105.3226

R.Snellings (ALICE) QM11

Fluctuations, viscosity and e-by-e hydro

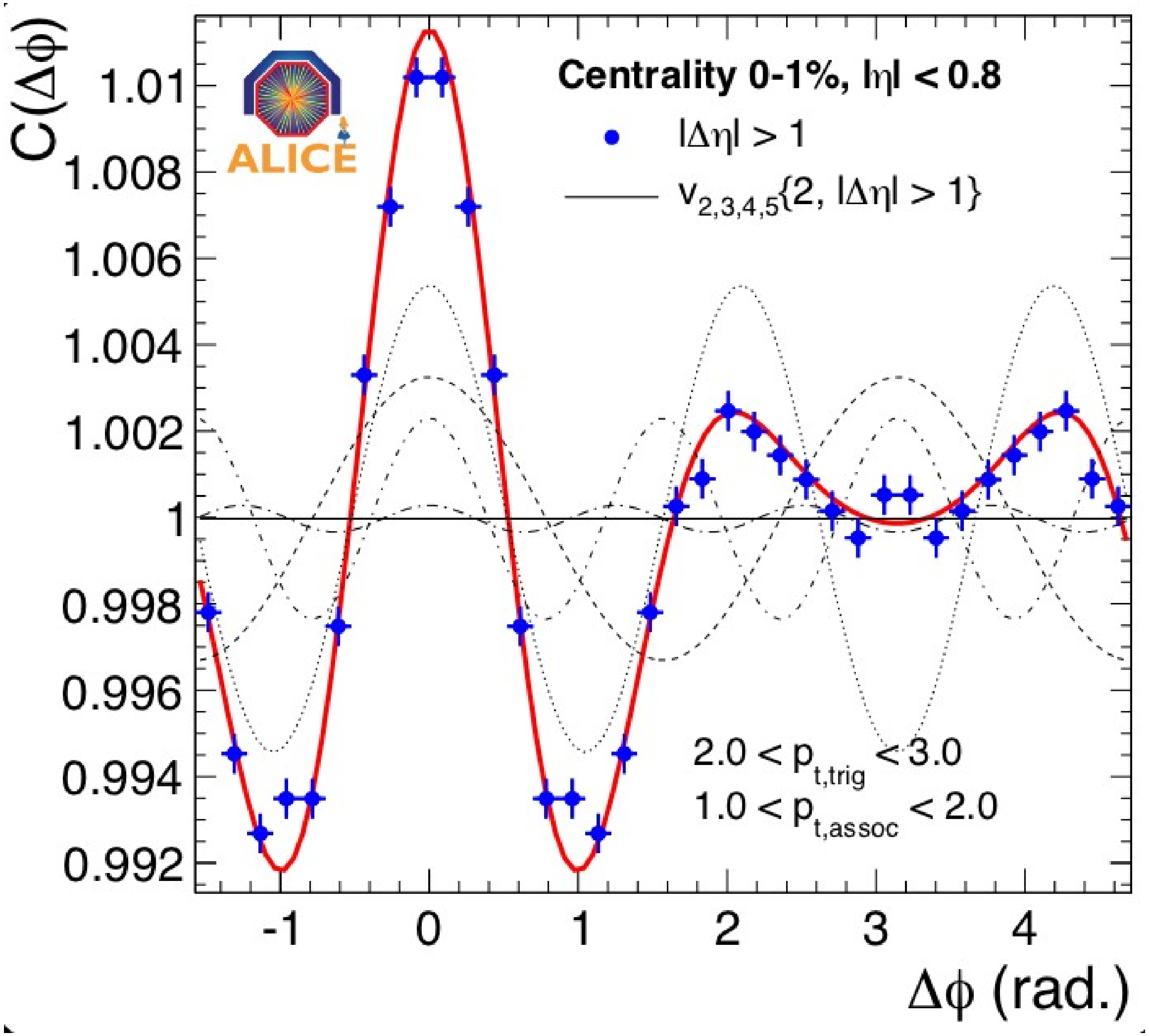


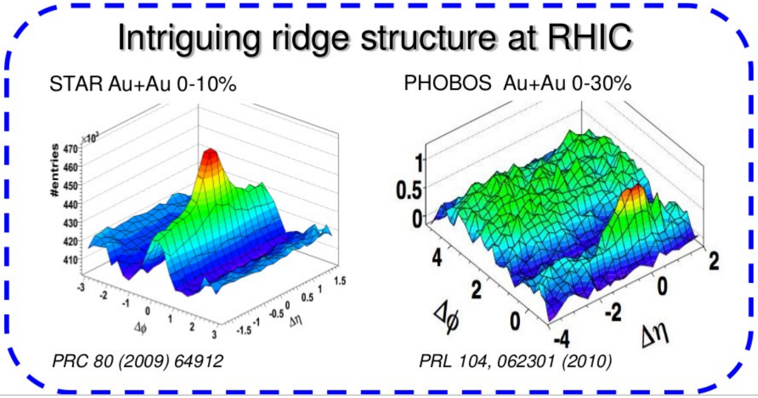


The overall dependence of v_2 and v_3 is described. However, not yet for a single η/s value. More constraints on initial conditions provided by v_3 and higher harmonics.

R.Snellings (ALICE) QM11

Two particle angular correlations





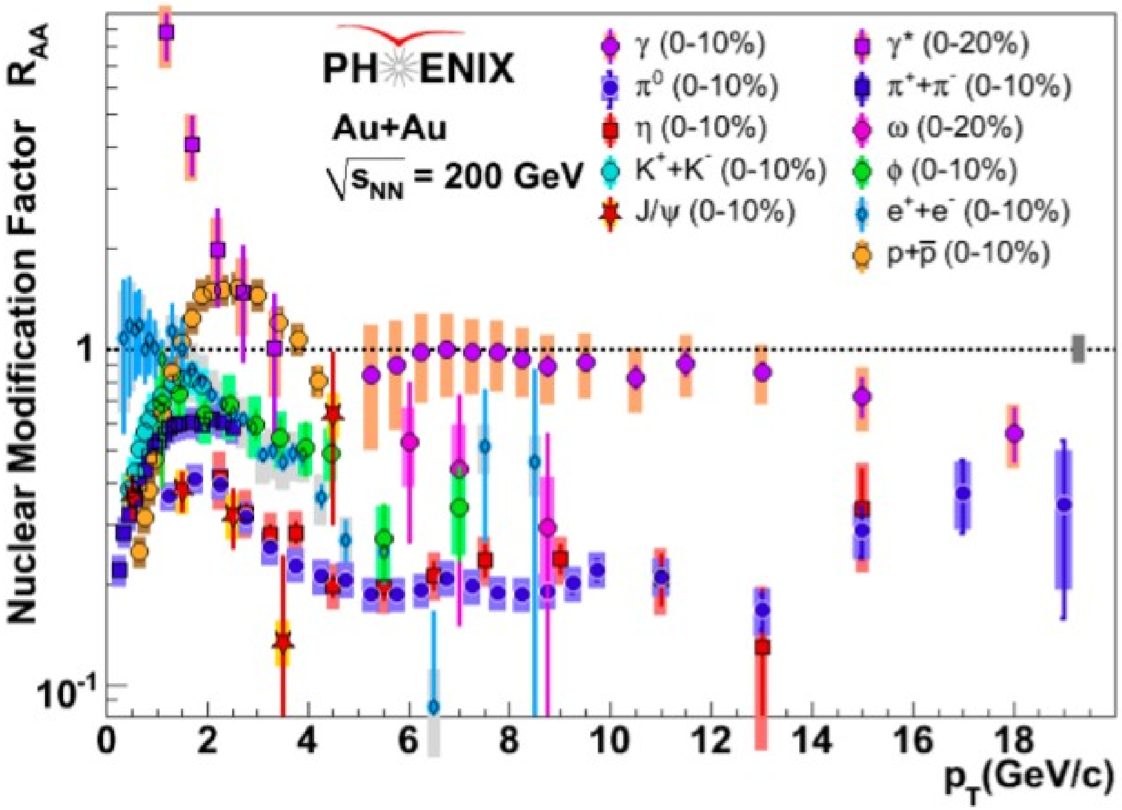
Structures seen in two particle correlations can naturally be explained by measured anisotropic flow coefficients.

$$C(\Delta\Phi) = \frac{N_{mixed}\, dN_{same}/d\Delta\Phi}{N_{same}\, dN_{mixed}/d\Delta\Phi}$$

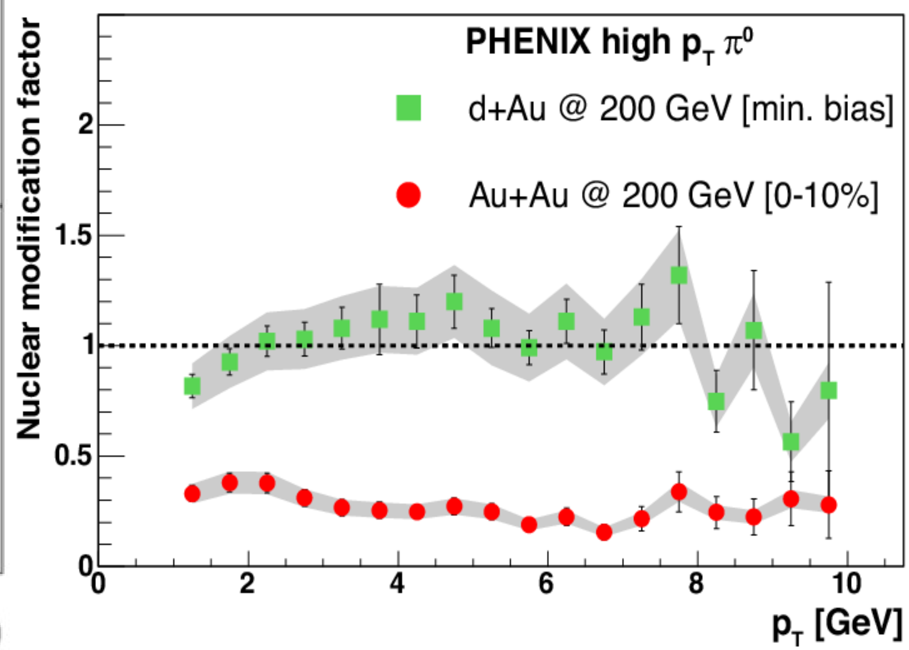
arxiv:1105.3865, sub. to PRL

Nuclear modification factor at RHIC

$$R_{AA}(,p_T) = \frac{1}{N_{coll}} \times \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$



Control measurement in dAu



Jet quenching very well established as a strong final-state effect.

Confronting R_{AA} with models

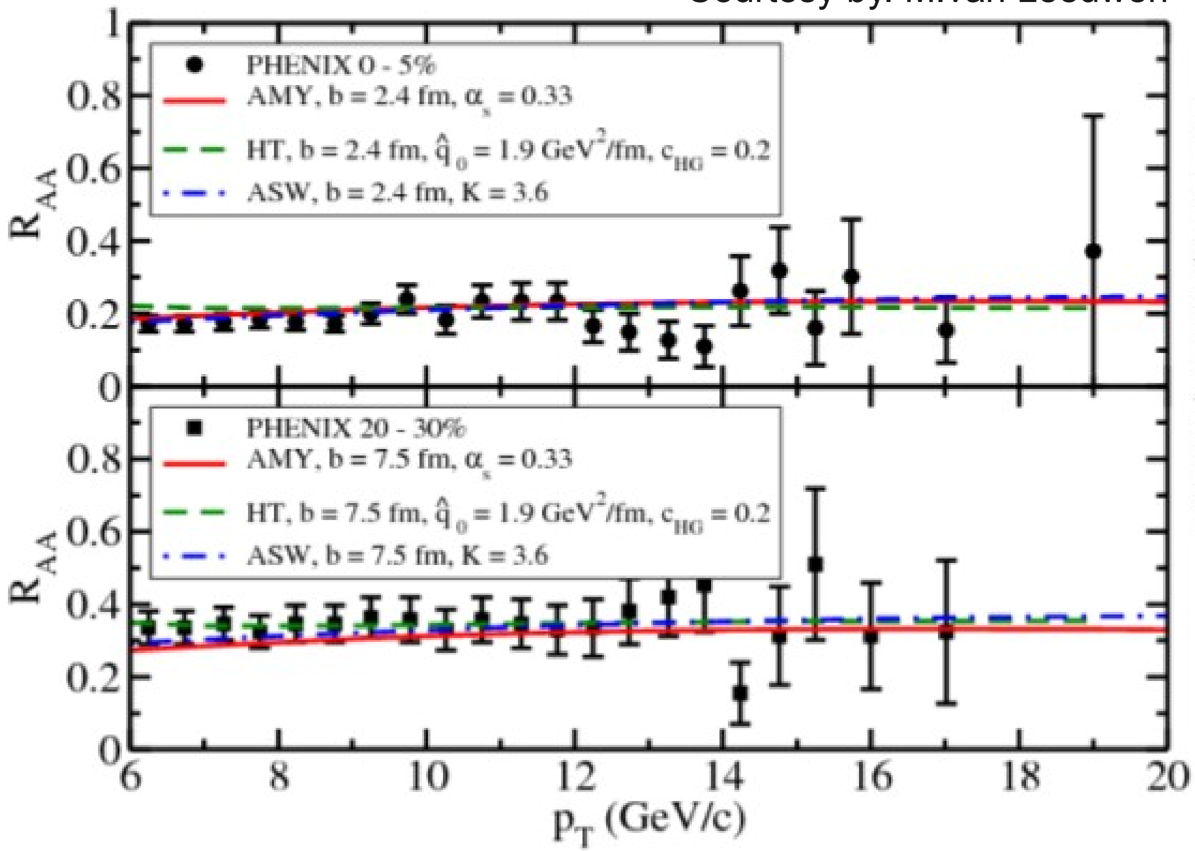
Courtesy by. M.van Leeuwen

ASW: $\hat{q} = 10 - 20\ \mathrm{GeV}^2/\mathrm{fm}$

HT: $\hat{q} = 2.3 - 4.5\ \mathrm{GeV}^2/\mathrm{fm}$

AMY: $\hat{q} \approx 4\ \mathrm{GeV}^2/\mathrm{fm}$

Large density:
AMY: T ~ 400 MeV
Transverse kick: qL ~ 10-20 GeV



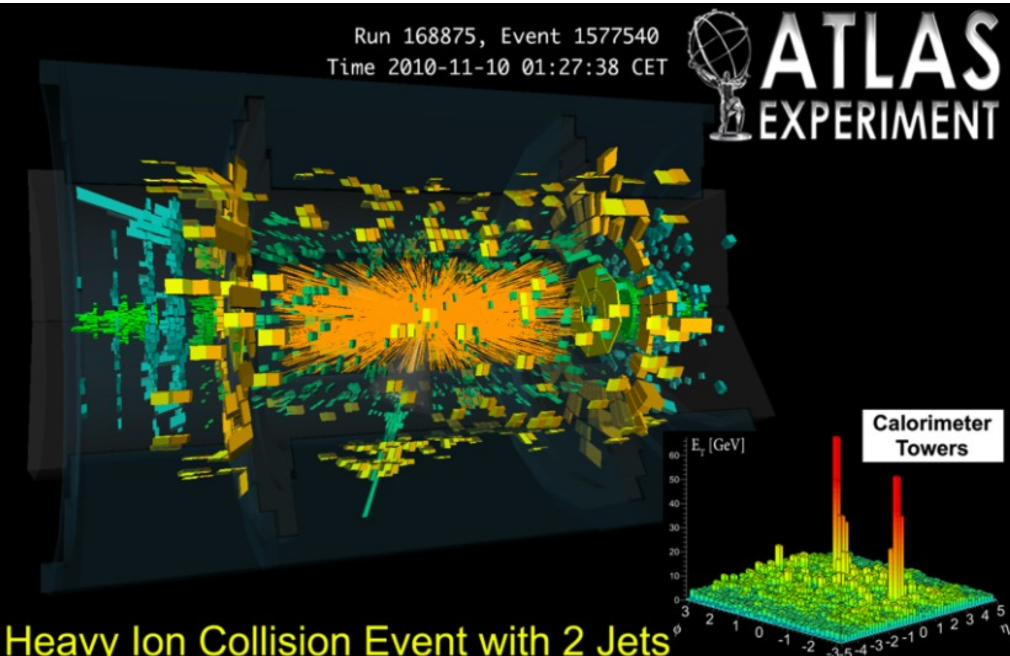
Bass et al, PRC79, 024901

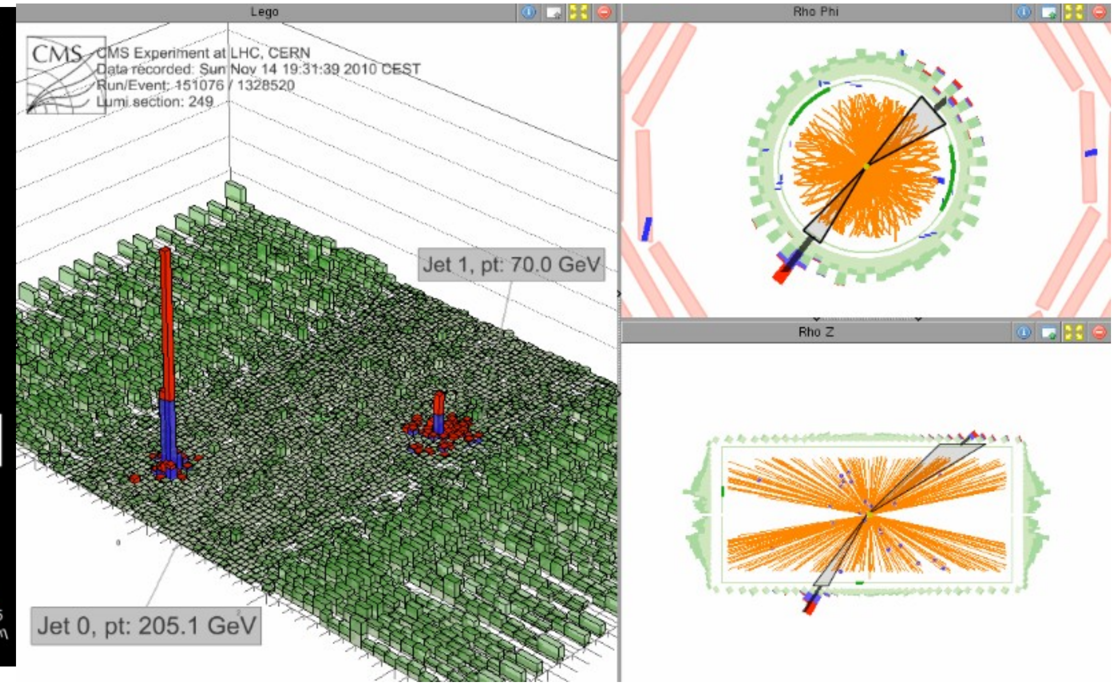
All formalisms can match R_{AA}, but large differences in medium density

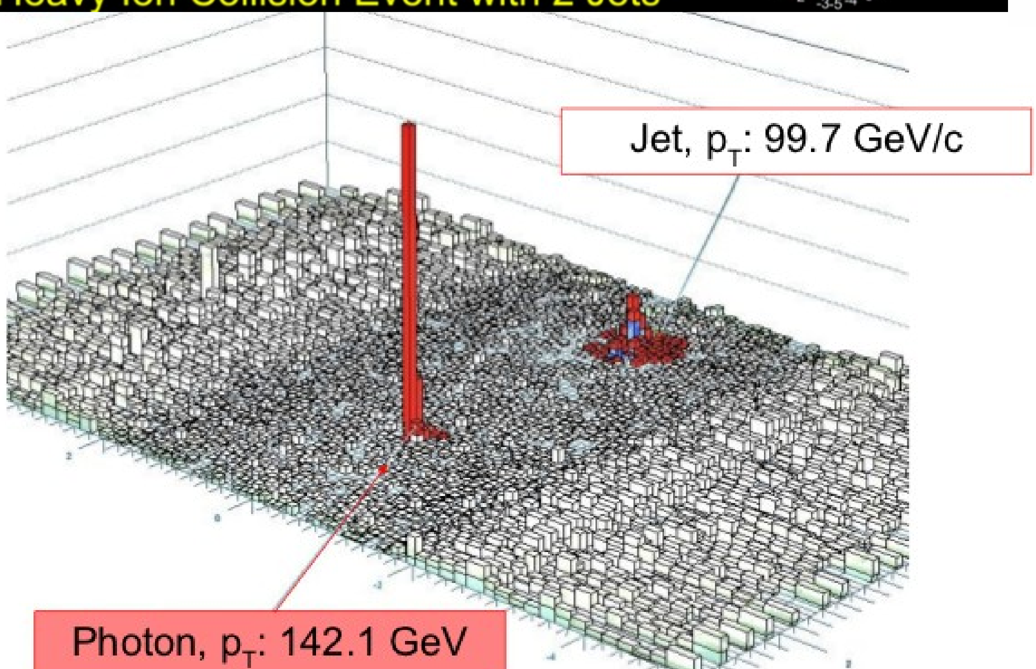
After long discussions, it turns out that these differences are mostly due to uncontrolled approximations in the calculations
→ Best guess: the truth is somewhere in-between

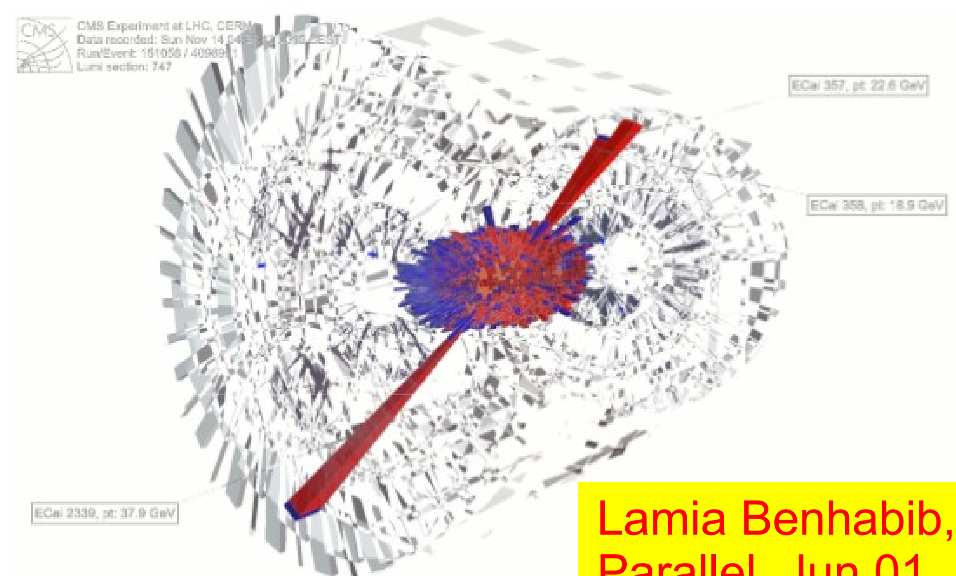
At RHIC: ΔE large compared to E, differential measurements difficult

Eye of the LHC!







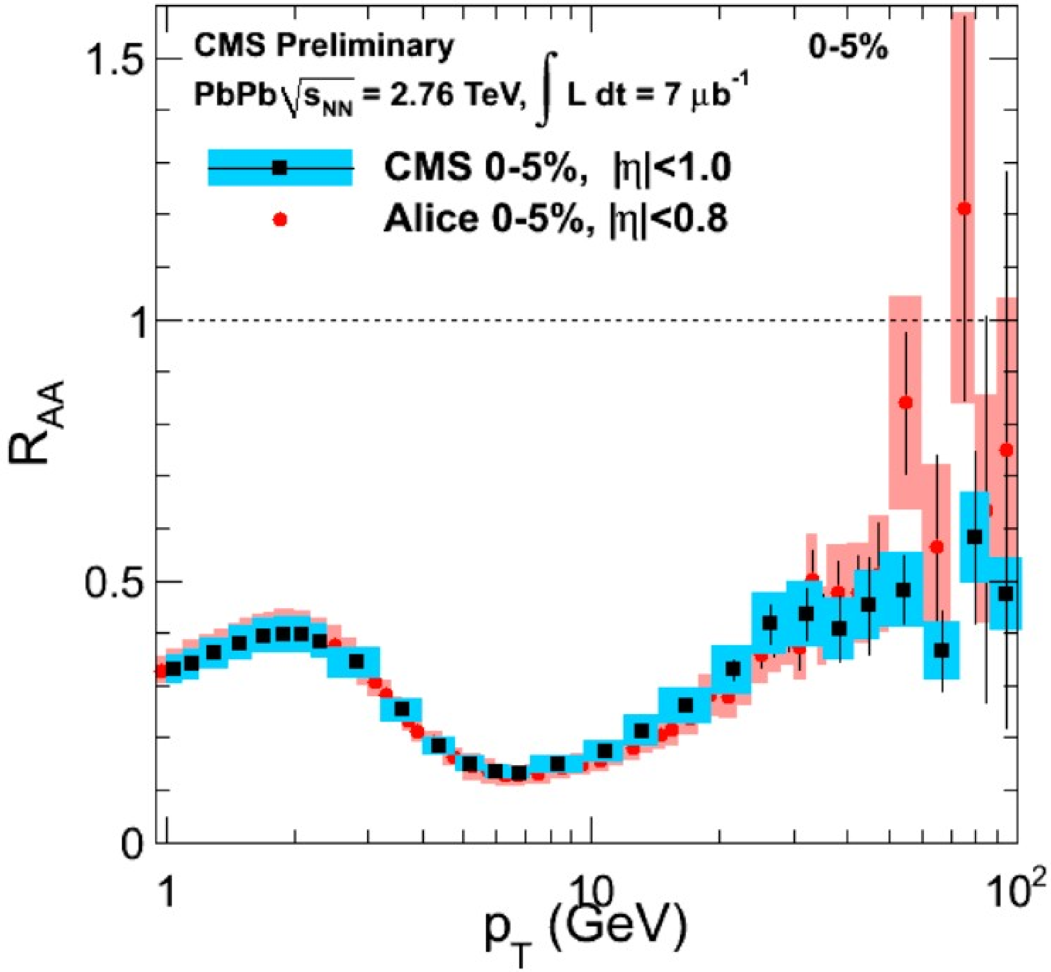


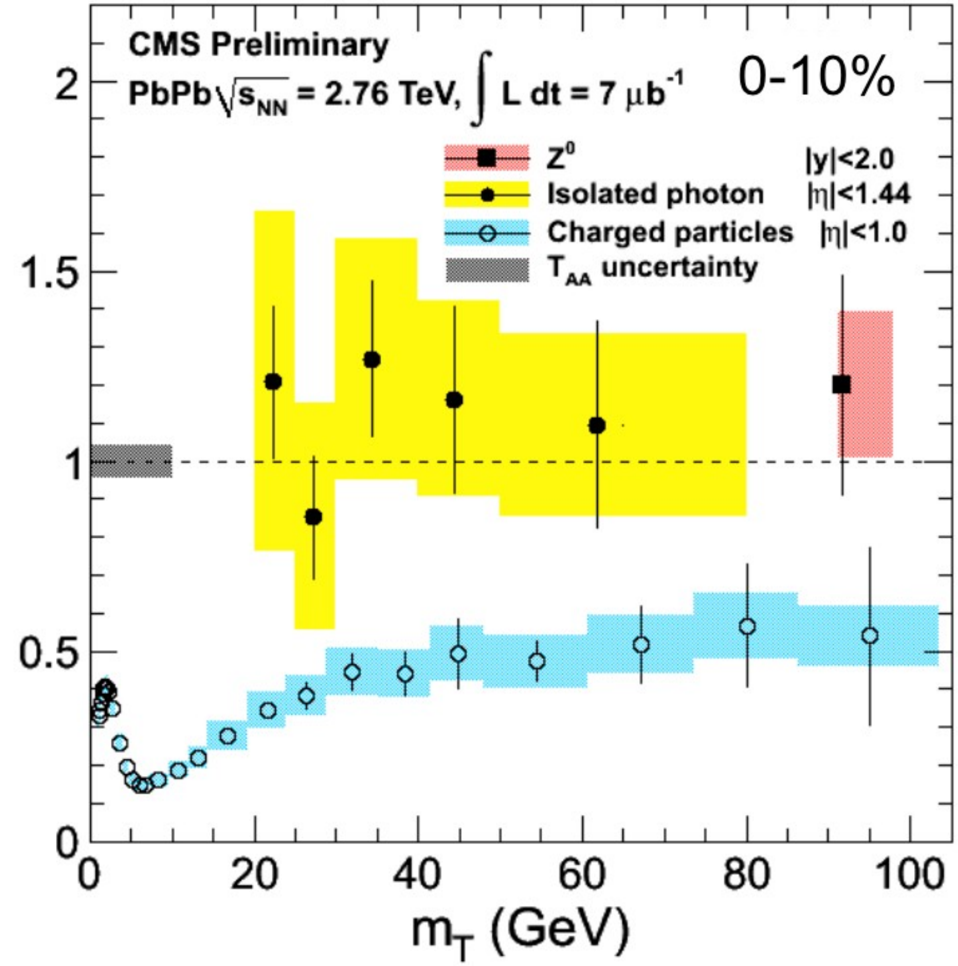
Lamia Benhabib,
Parallel, Jun 01

Nuclear modification factor at LHC

H.Appelshaeuser (ALICE)

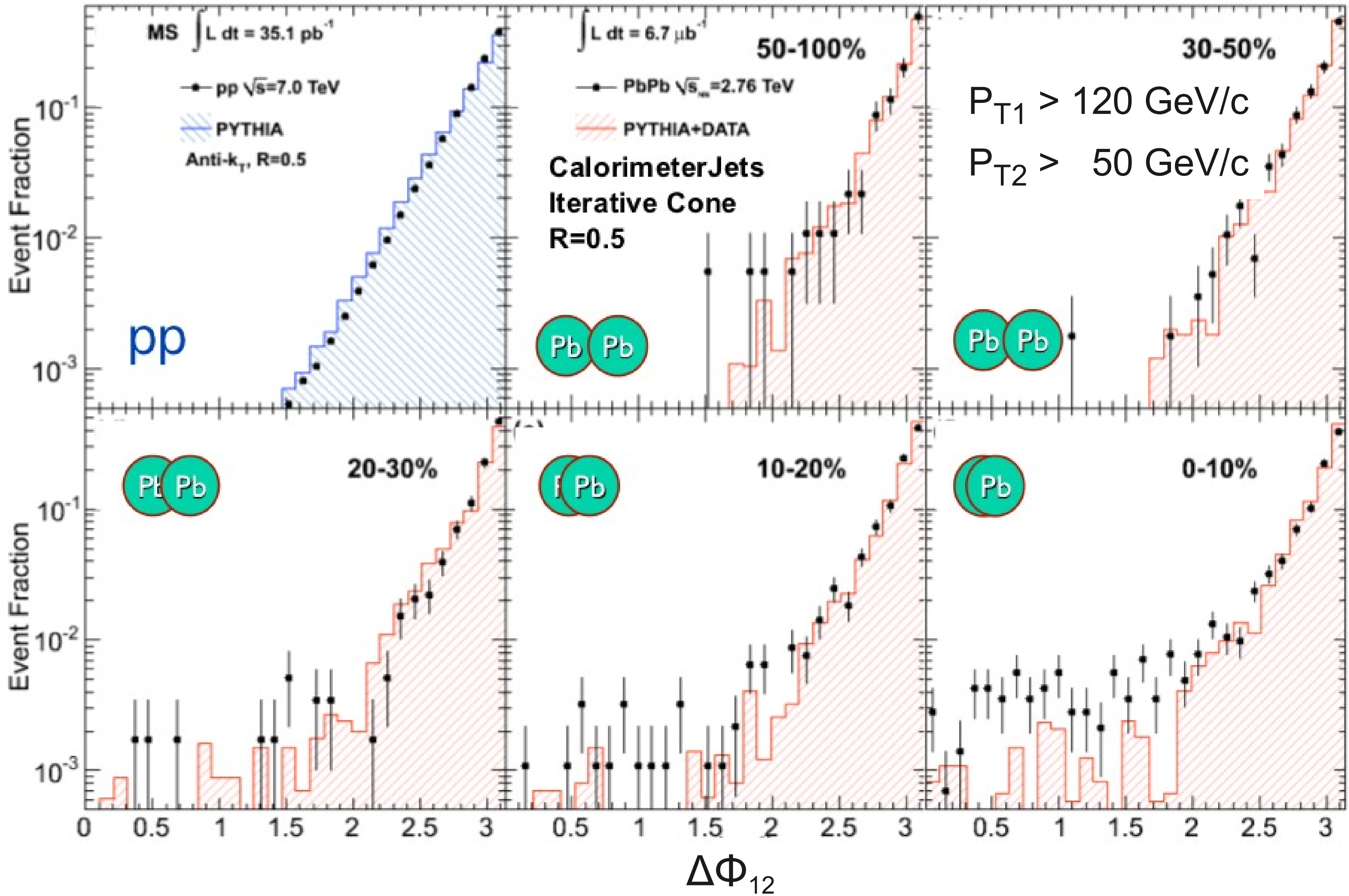
Y.Lee (CMS) QM11





Strong quenching of charged hadrons observed with pronounced p_T dependence. Within uncertainties no modification by initial state for colorless probes.

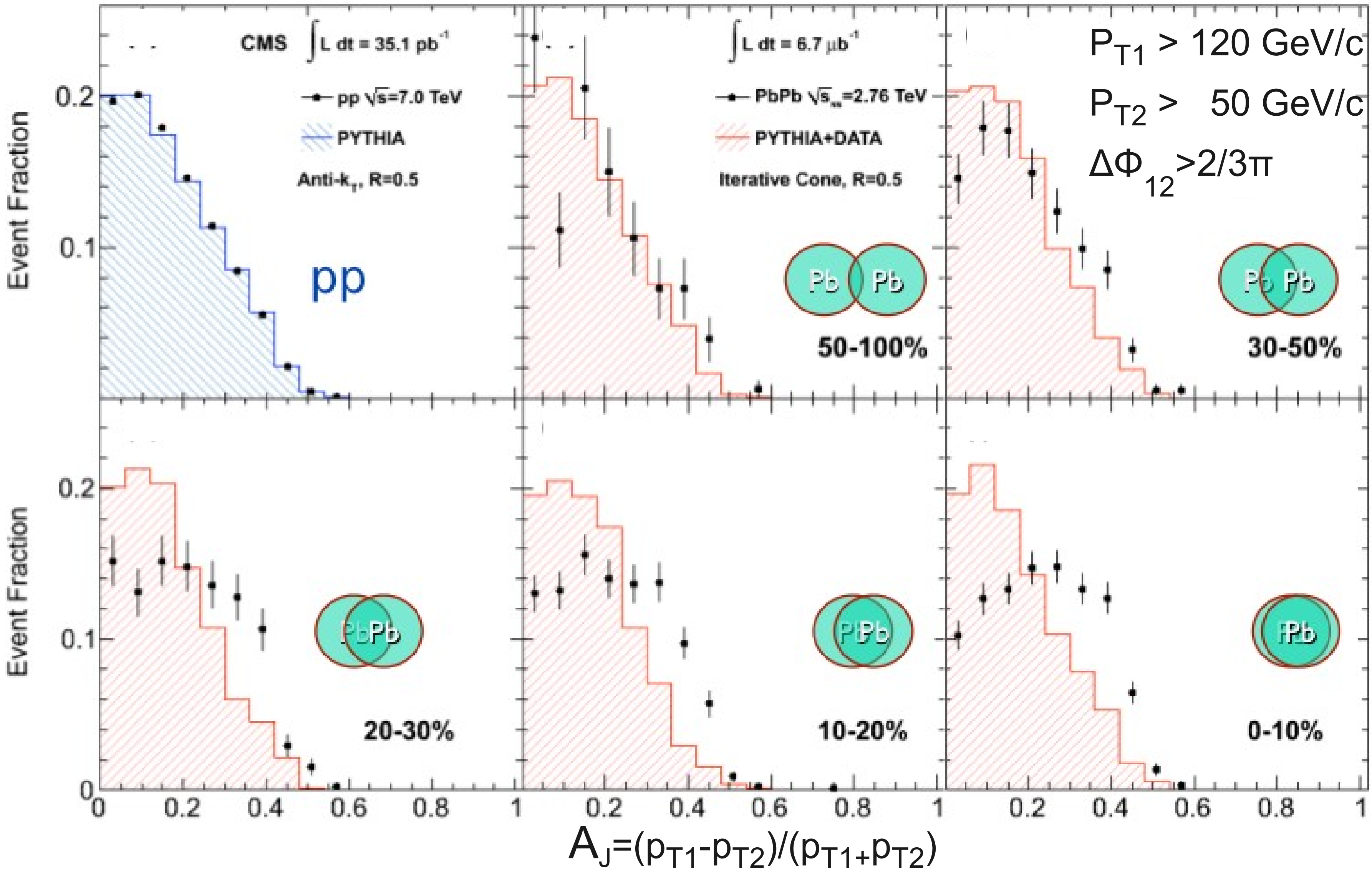
Dijet angular correlation



Propagation of high p_T partons in a dense nuclear medium does not lead to visible angular decorrelation

C.Roland (CMS) QM11

Dijet energy imbalance



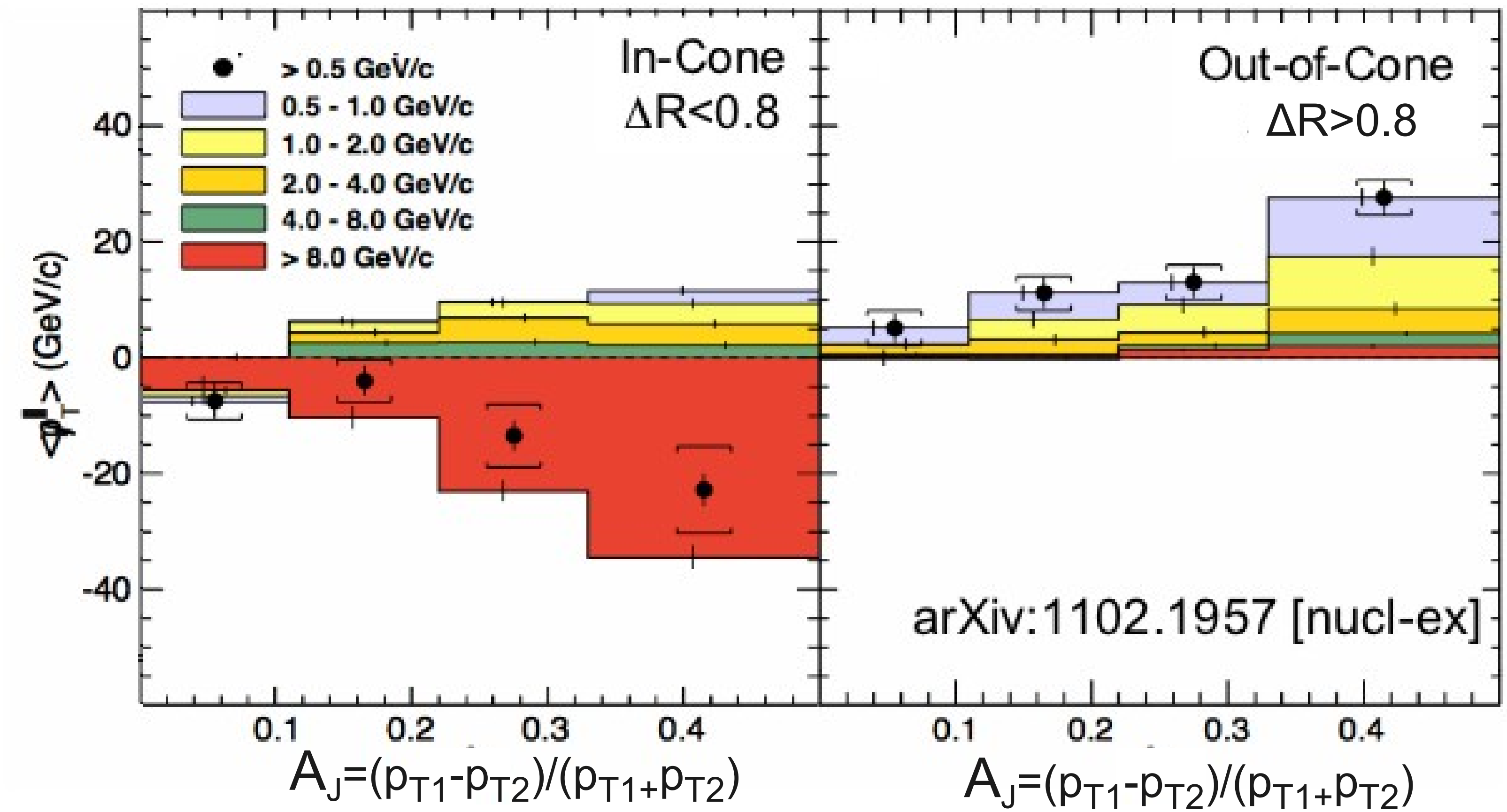
C.Roland (CMS) QM11

Parton energy loss is observed as a strong energy imbalance in central PbPb

Track momentum sum

Track momentum sum relative to leading jet axis

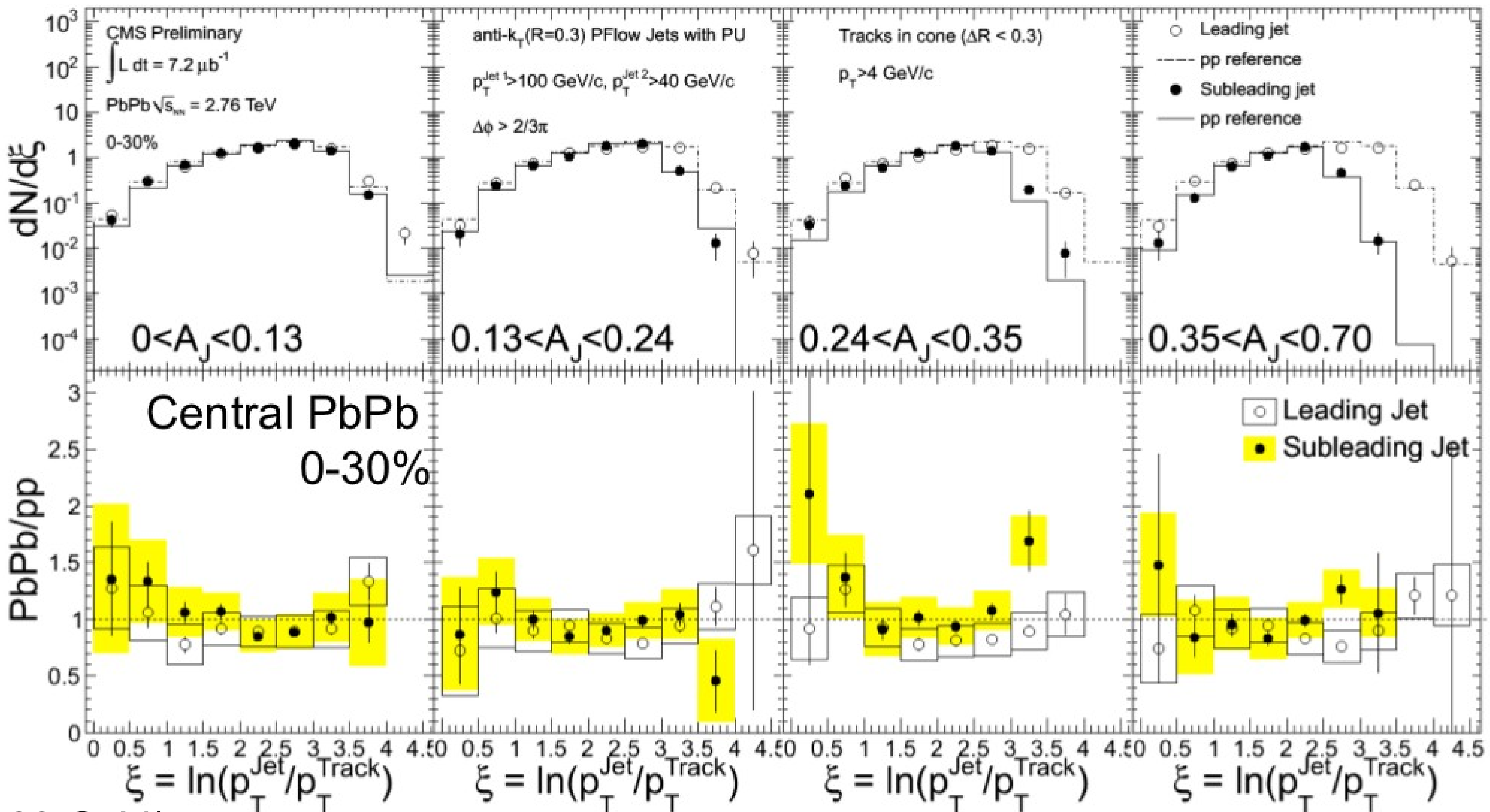
$$\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$



C.Roland (CMS) QM11

The momentum difference in the dijet is balanced by low p_T particles at large angles outside the cone (0.8)

Fragmentation vs dijet imbalance



R=0.3

P_{T1} > 100 GeV/c

P_{T2} >   40 GeV/c

$\Delta\Phi_{12}$>2/3π

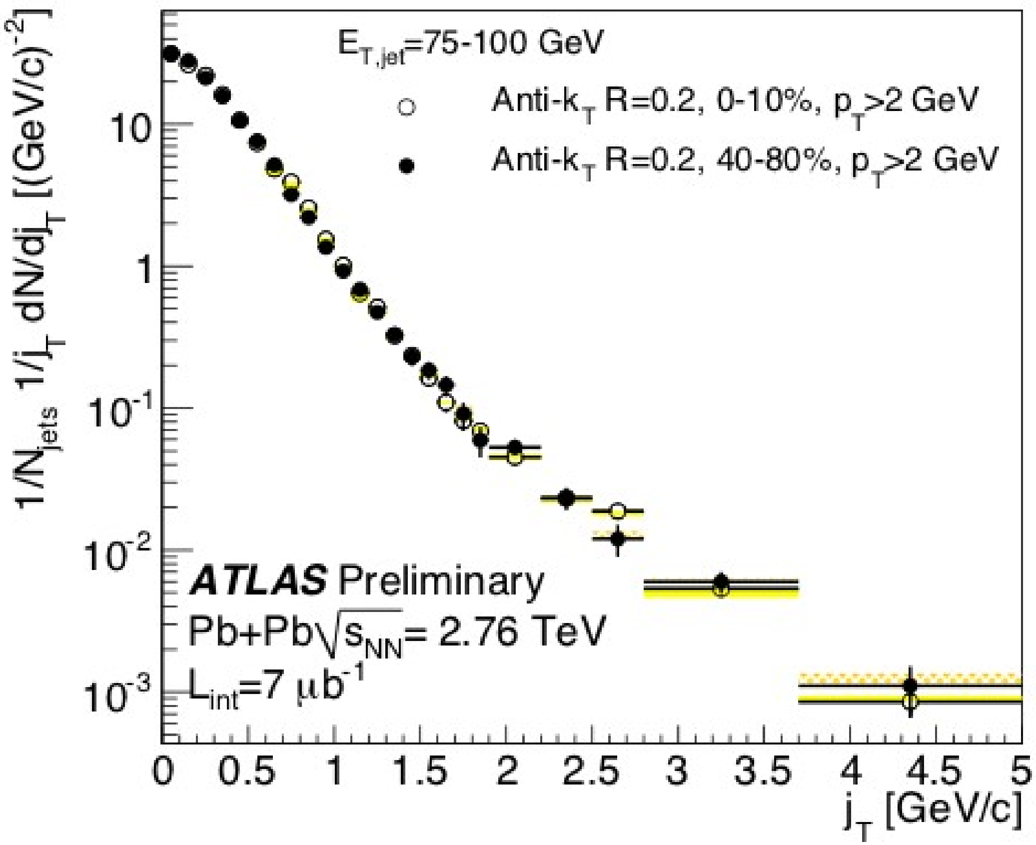
Track P_T>4 GeV/c

C.Roland (CMS) QM11

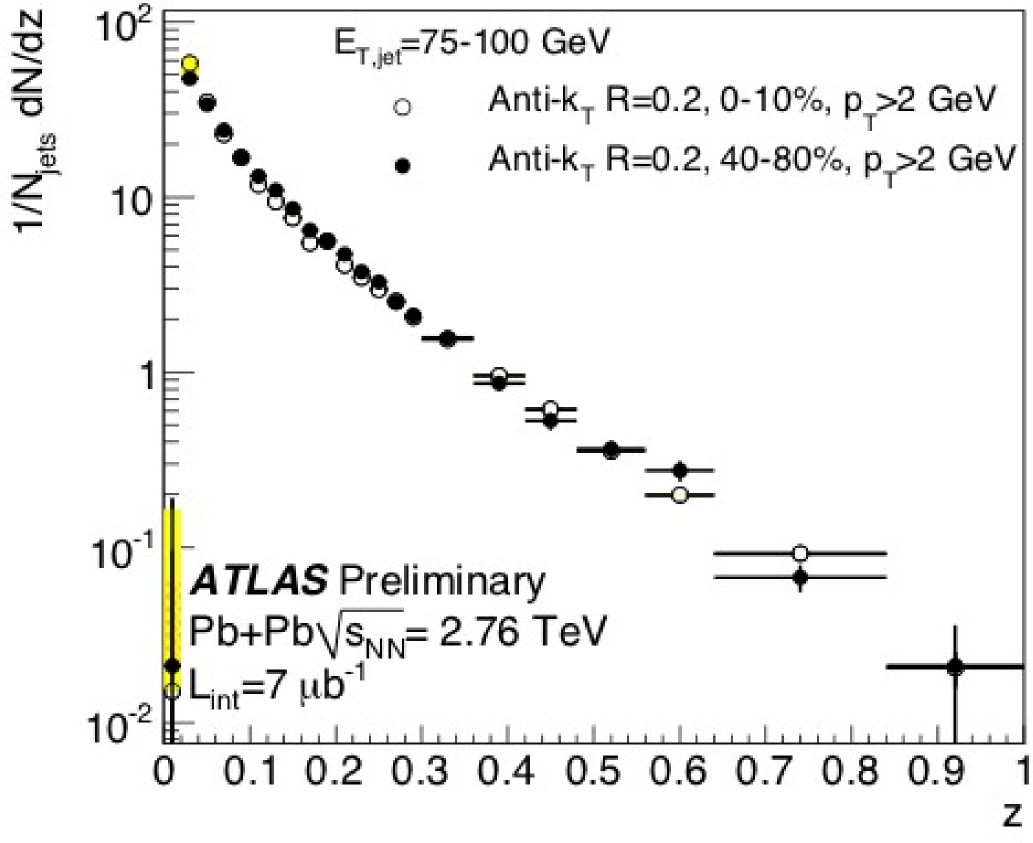
Fragmentation pattern independent of energy lost (A_J).
Consistent with partons fragmenting in vacuum.

Fragmentation functions in PbPb

Transverse fragmentation function



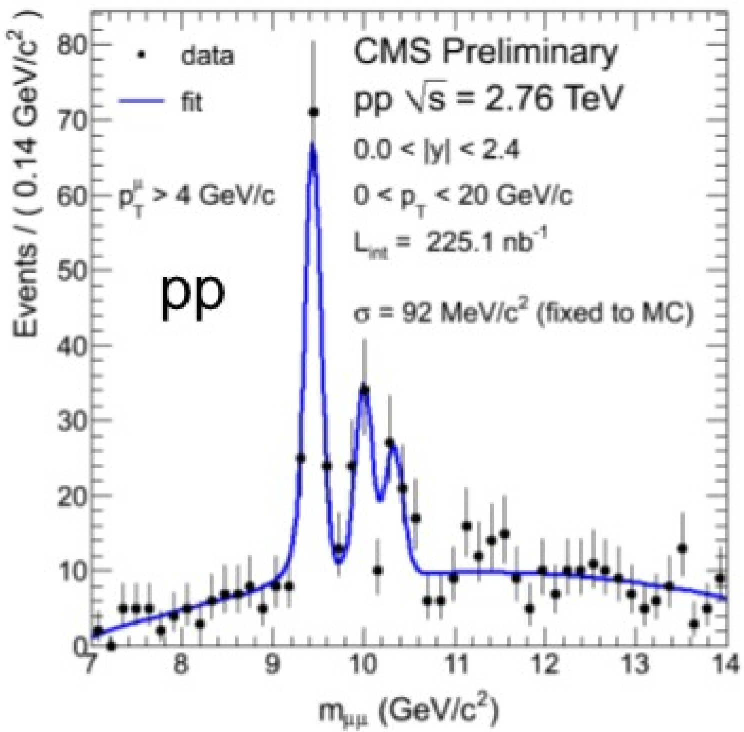
Longitudinal fragmentation function

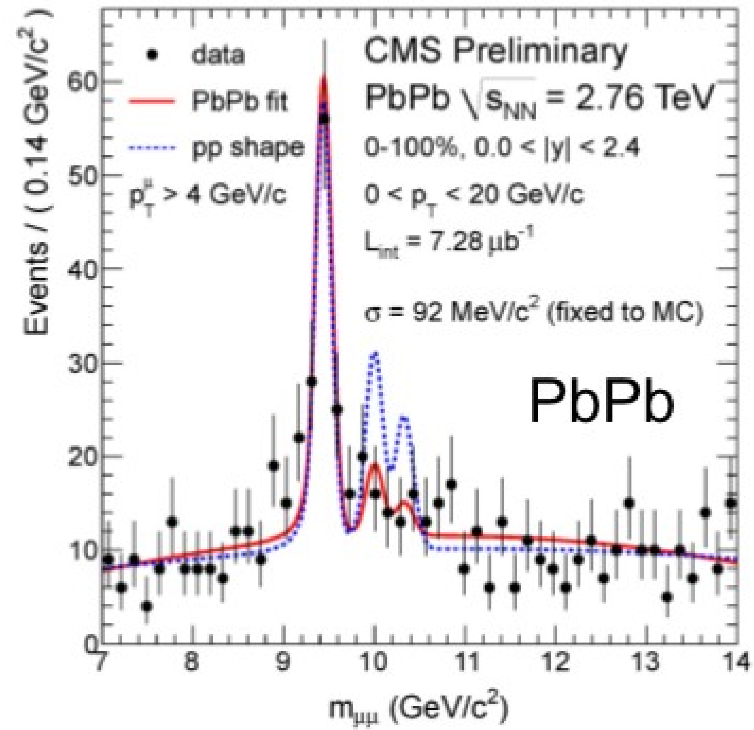


No strong modification of fragmentation function between peripheral and central. Unexpected in a radiative energy loss scenario.

B.Cole (ATLAS) QM11

Suppression of Upsilon (2S,3S)





$$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02 \qquad \Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

- Excited states Υ(2S,3S) relative to Υ(1S) are suppressed
- Probability to obtain measured value, or lower, if the real double ratio is unity, has been calculated to be less than 1%

C.Silvestre (CMS) QM11

Summary

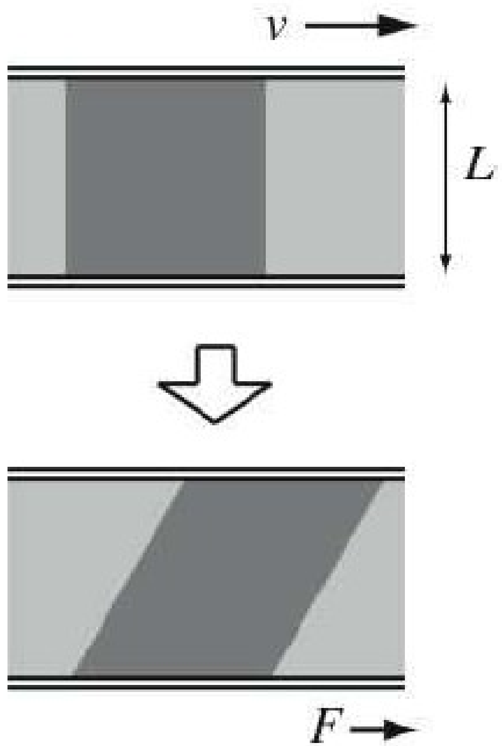
- LHC is there, also for heavy ions! (Thanks to machine for a great start)
  - Characterization of its bulk properties well underway
    - 3 times higher initial density than at top RHIC energy
    - Similar centrality dependence for flow and multiplicity
    - Very low viscosity fluid
  - Triangular flow (and higher harmonics) measured
    - Provide further constraints on η/s
- LHC is a hard probes machine
  - Much higher p_T reach than at RHIC already with first data set
  - Also qualitatively new probes
    - Dijet energy balance point to significant energy loss of dijets
    - However, jet fragmentation functions seem not to be modified
    - May point to a different energy loss picture than previously thought of?
    - Excited Upsilon states are suppressed
- More data from LHC available that I did not cover (see QM11 conf. link)

Special thanks to CMS, ATLAS, ALICE, STAR+PHENIX collaborations for exiting results at QM11

Extra

Shear viscosity in fluids

Shear viscosity characterizes the efficiency of momentum transport

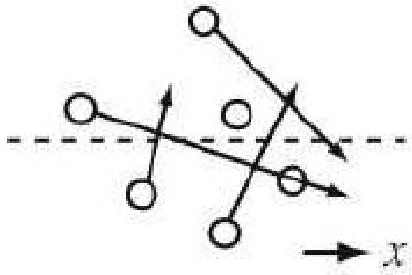


$$\frac{F}{A} = \eta \frac{v}{L}$$

$$\eta = \rho \langle v \rangle \lambda_{mfp} \sim \frac{1}{\sigma}$$

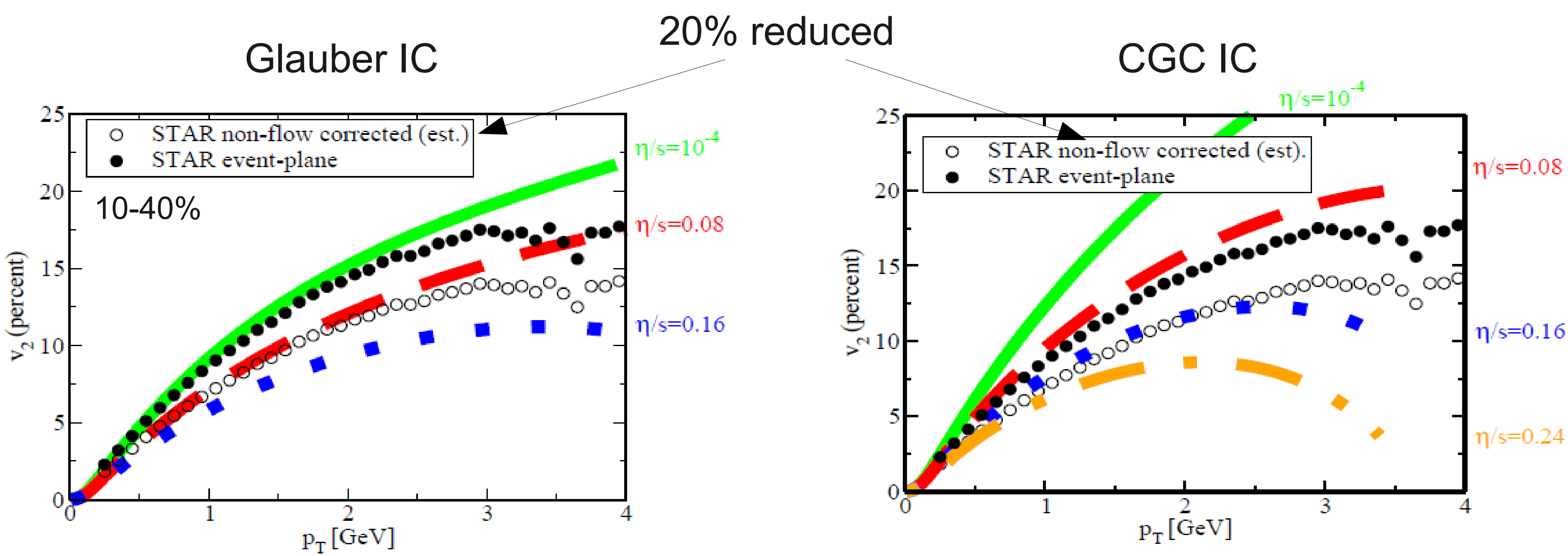
Large quasi-particle interaction cross section σ

- ➔Strongly-coupled matter
- ➔Small shear viscosity
- ➔”perfect liquid”



AdS/CFT and kinetic theory: $\frac{\eta}{s} = \frac{1}{4\pi} \sim 0.08$

How viscous is the fluid at RHIC?



State-of-art results from second-order conformal hydro-dynamics (2+1D) yield a low shear viscosity to entropy ratio.

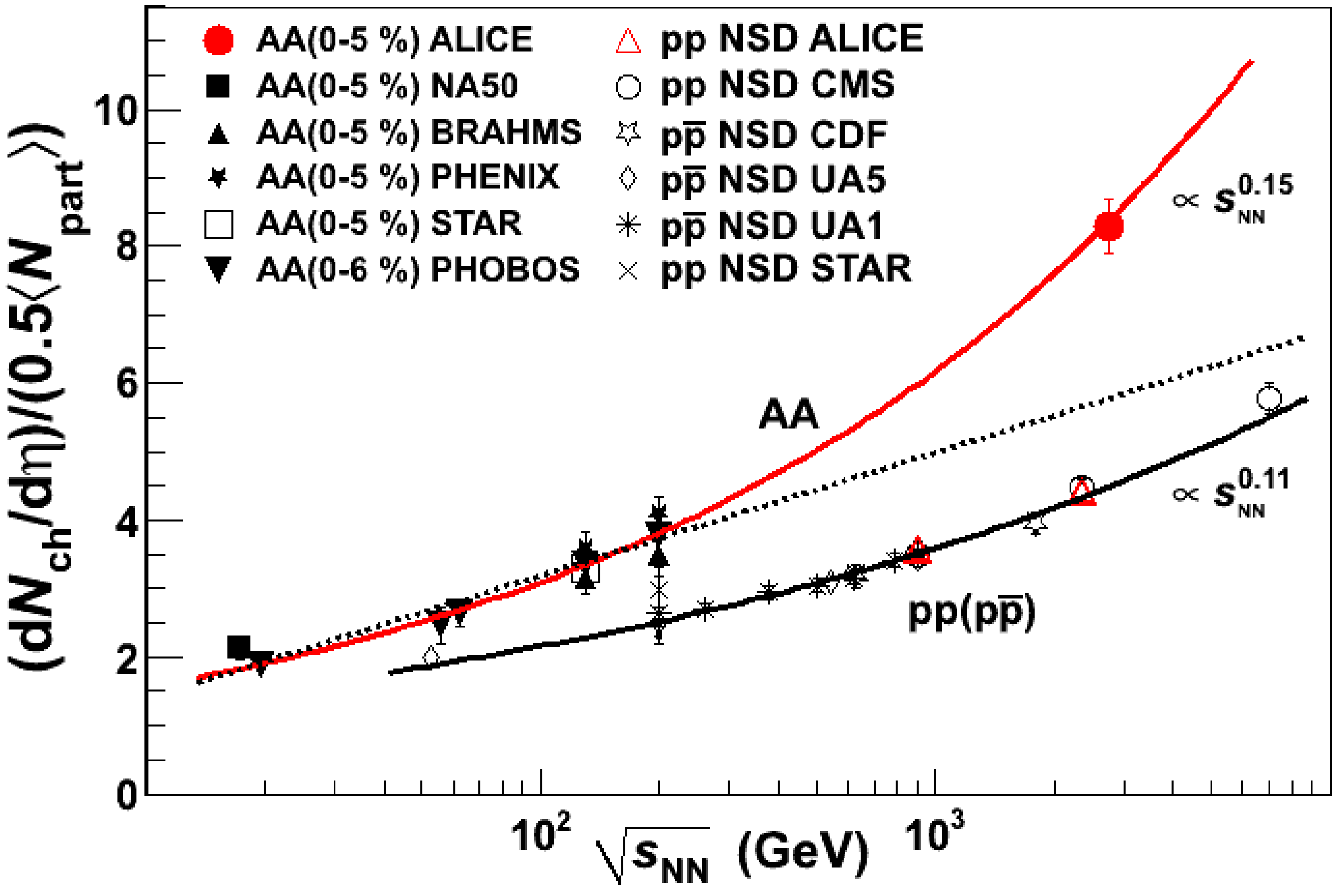
General consensus (from QM09) that: $\frac{\eta}{s} < 6 \times \frac{1}{4\pi}$

Reduced errors on v_2 data allows to study 20% effects.

Luzum, Romatschke, PRC 78 034915 (2008); PRC 79 039903 (2009)

LHC dNch/dη: Energy dependence

Measured dNch/dη = 1584 ± 76 (sys.)   PRL, 105, 252301 (2010)



Pre-LHC fit
(~ln s_{NN})

Pb+Pb ($\sqrt{s_{NN}}$=2.76 TeV)

→ 1.9 x pp (NSD)
($\sqrt{s_{NN}}$=2.36 TeV)

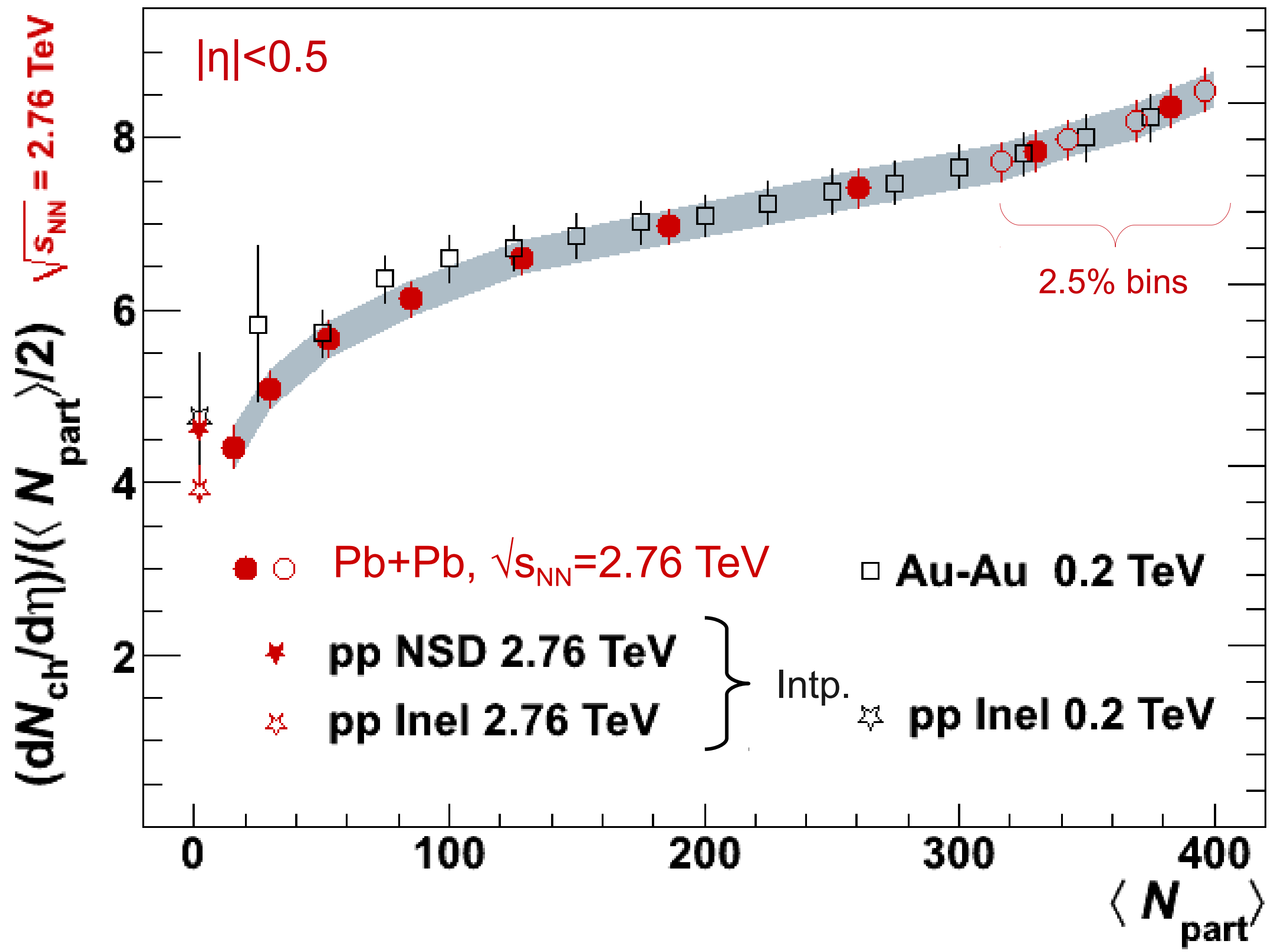
→ 2.2 x central Au+Au
($\sqrt{s_{NN}}$=0.2 TeV)

$\sqrt{s_{NN}}$=2.76 TeV Pb+Pb, 0-5% central, |η|<0.5

2 dNch/dη / <Npart> = 8.3 ± 0.4 (sys.)

LHC dNch/dη: Centrality dependence

PRL, 106, 032301 (2011)



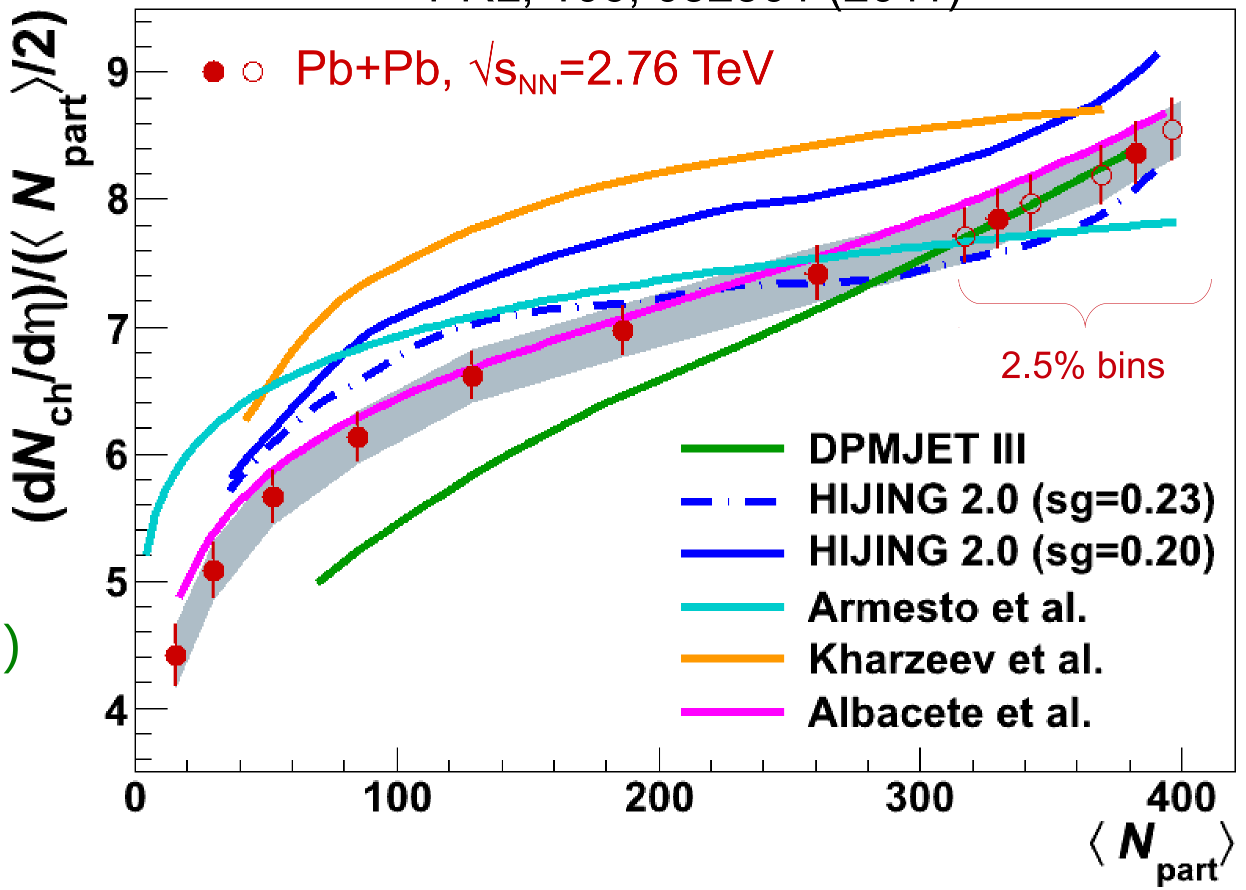
RHIC data scaled by 2.1

LHC centrality evolution very similar to RHIC

LHC dNch/dη: Centrality vs models

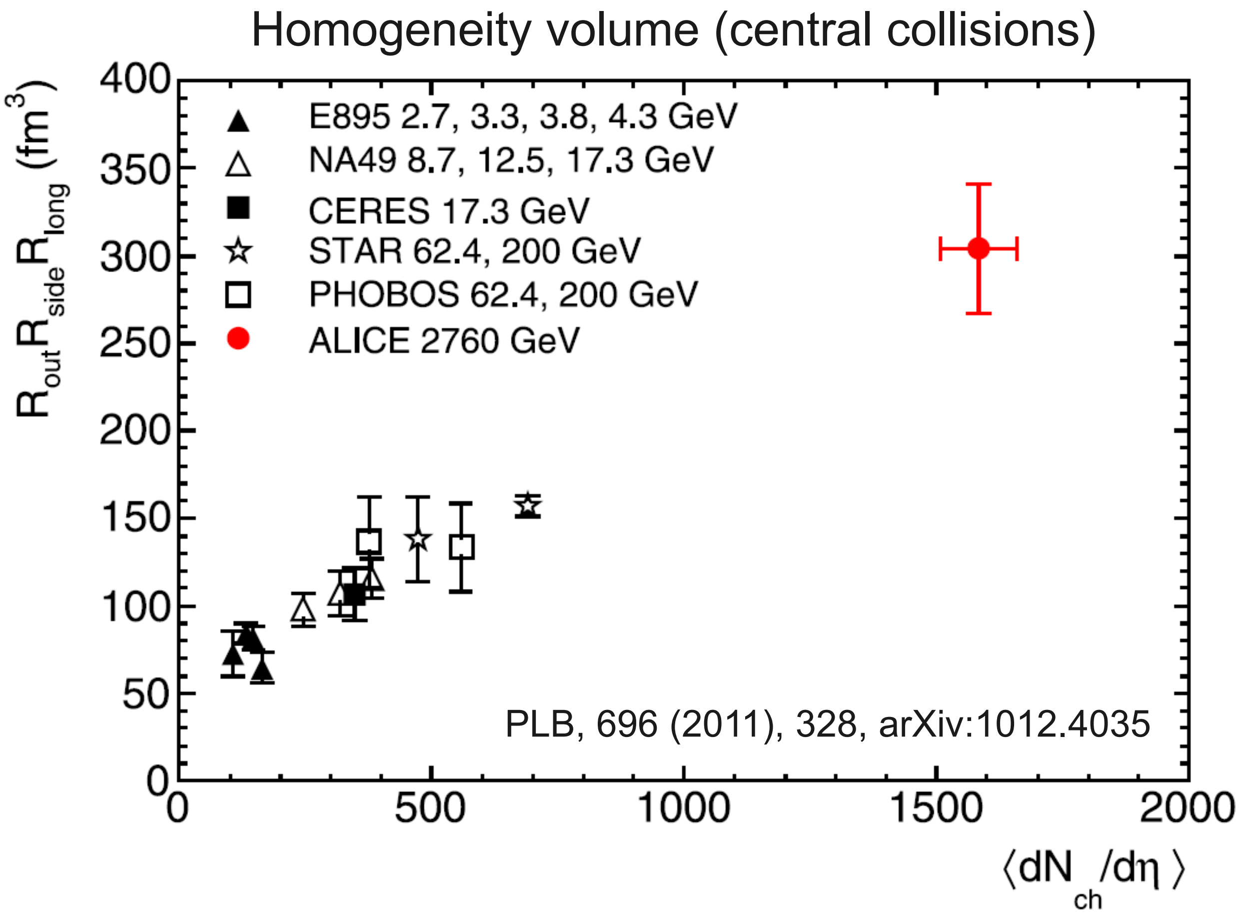
- Two-component models
  - Soft (~Npart) and hard (~Ncoll) processes
- Saturation-type models
  - Parametrization of the saturation scale with energy (s) + centrality (A)
- Comparison to data
  - DPMJET (with string fusion) stronger rise than data
  - HIJING 2.0 (no quenching)
    - Strong centrality dependent gluon shadowing
    - Fine-tuned to 0-5% dN/dη
  - Saturation models
    - Some saturate too much

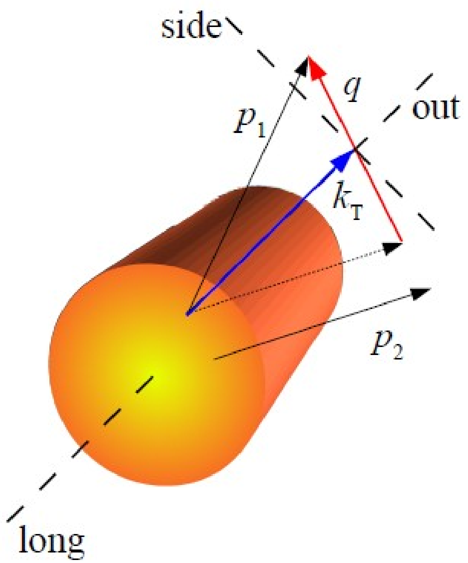
PRL, 106, 032301 (2011)



Models incorporating a moderation of the multiplicity with centrality are favored by the data (as at RHIC)

LHC: Freeze-out volume

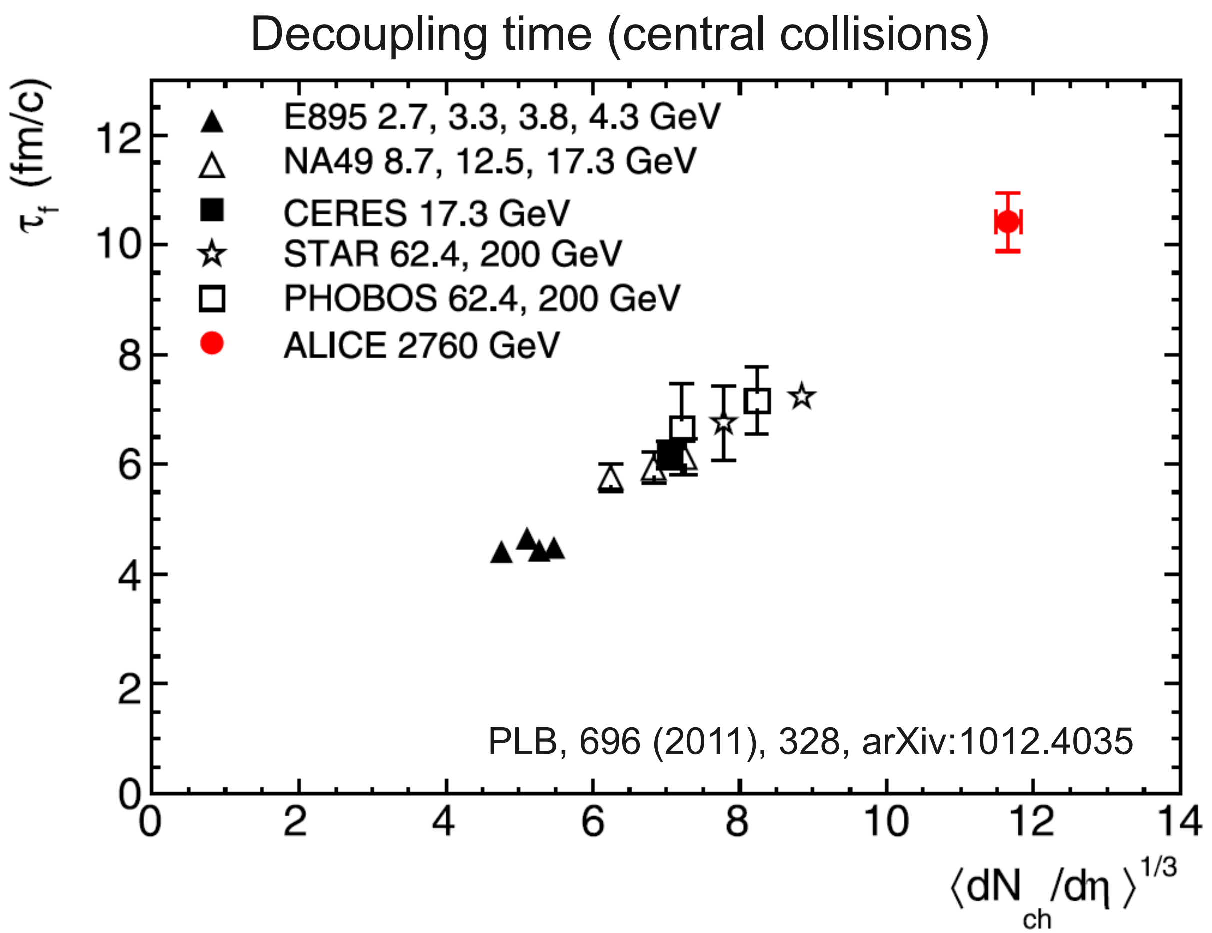




$R_{out}R_{side}R_{long}$ → V(Freeze-out) linear dependence on dNch/dη

V_{LHC} = 300 fm^3 ~ 2 x V_{RHIC}

LHC: Decoupling time



R_{long} ► Decoupling time τ_f linear dependence on $dNch/d\eta^{1/3}$

τ_f(LHC) = 10-11 fm/c ~ 1.4 x τ_f(RHIC)

Flow methods

Two-particle cumulant

$$v\{2\}=\sqrt{\langle\cos(\phi_1-\phi_2)\rangle}$$

Measures:

$$v\{2\}^2=\langle v\rangle^2+\sigma_{v_2}^2+\delta$$
$$v\gg 1/\sqrt{M}$$

Four-particle cumulant

$$v\{4\}=\left(2\langle\cos(\phi_1-\phi_2)\rangle^2-\langle\cos(\phi_1+\phi_2-\phi_3-\phi_4)\rangle\right)^{1/4}$$

Measures:

$$v\{4\}^2=\langle v\rangle^2-\sigma_{v_2}^2$$
$$v\gg 1/M^{3/4}$$

$$v\{subEP\}=\frac{\langle\cos(\phi-\psi_A)\rangle}{R}$$
$$R=\sqrt{\langle\cos(\psi_A-\psi_B)\rangle}$$

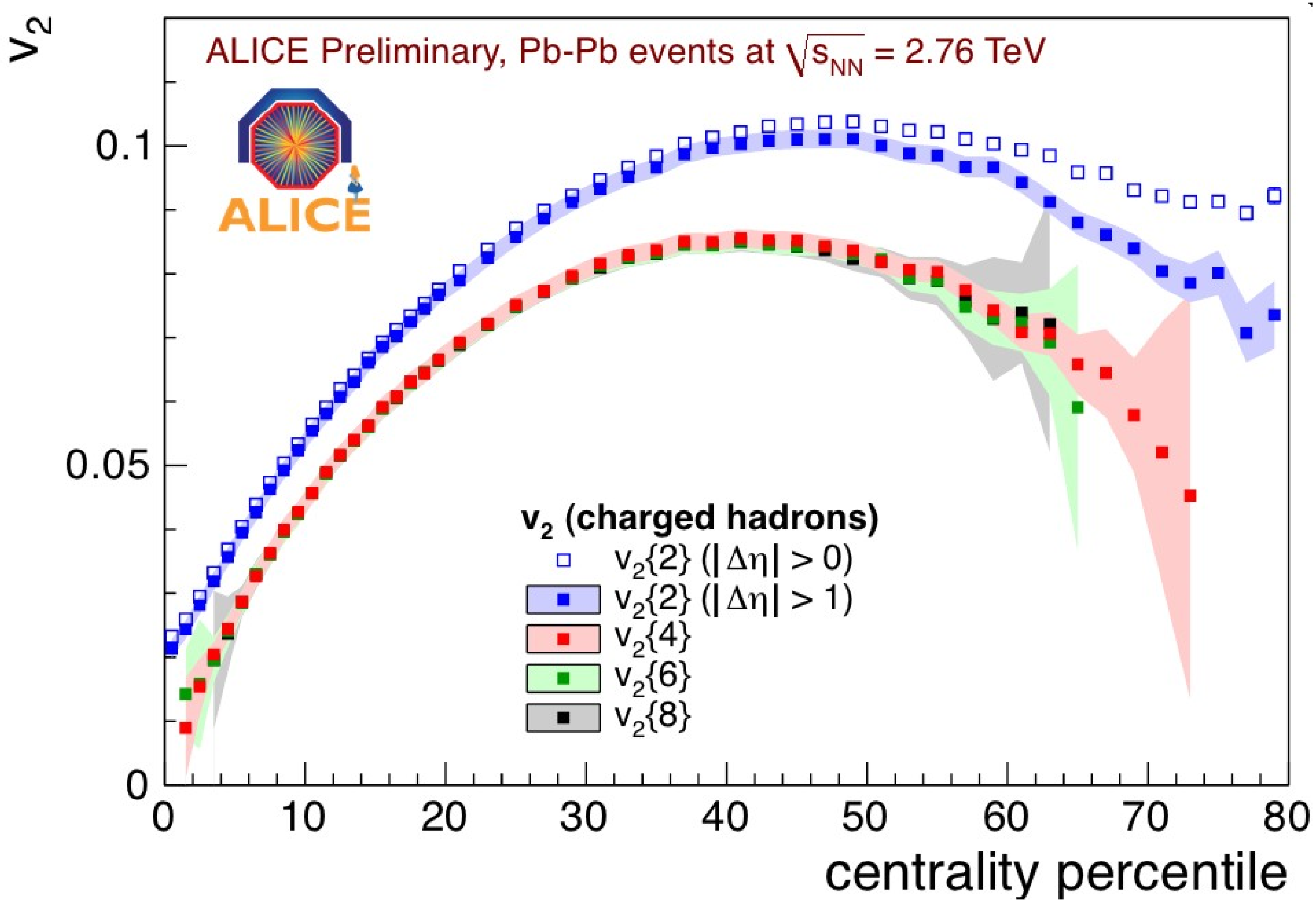
Measures:

$$v\{subEP\}^2=\langle v\rangle^2+\left(1-f(R)\right)\sigma_{v_2}^2+\left(1-2f(R)\right)\delta$$

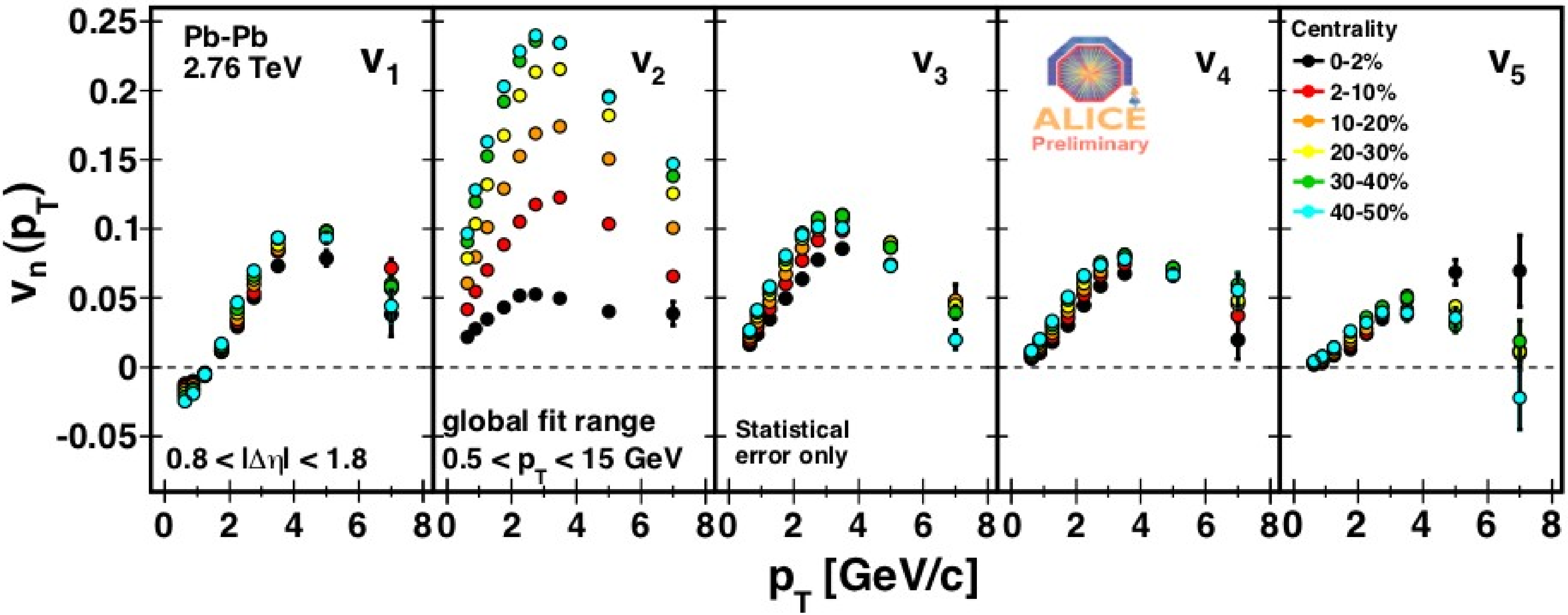
NB: For simplicity, n (as index and in cos terms) dropped

Ollitrault, Poskanzer, Voloshin
PRC 80 80 014904 (2009)

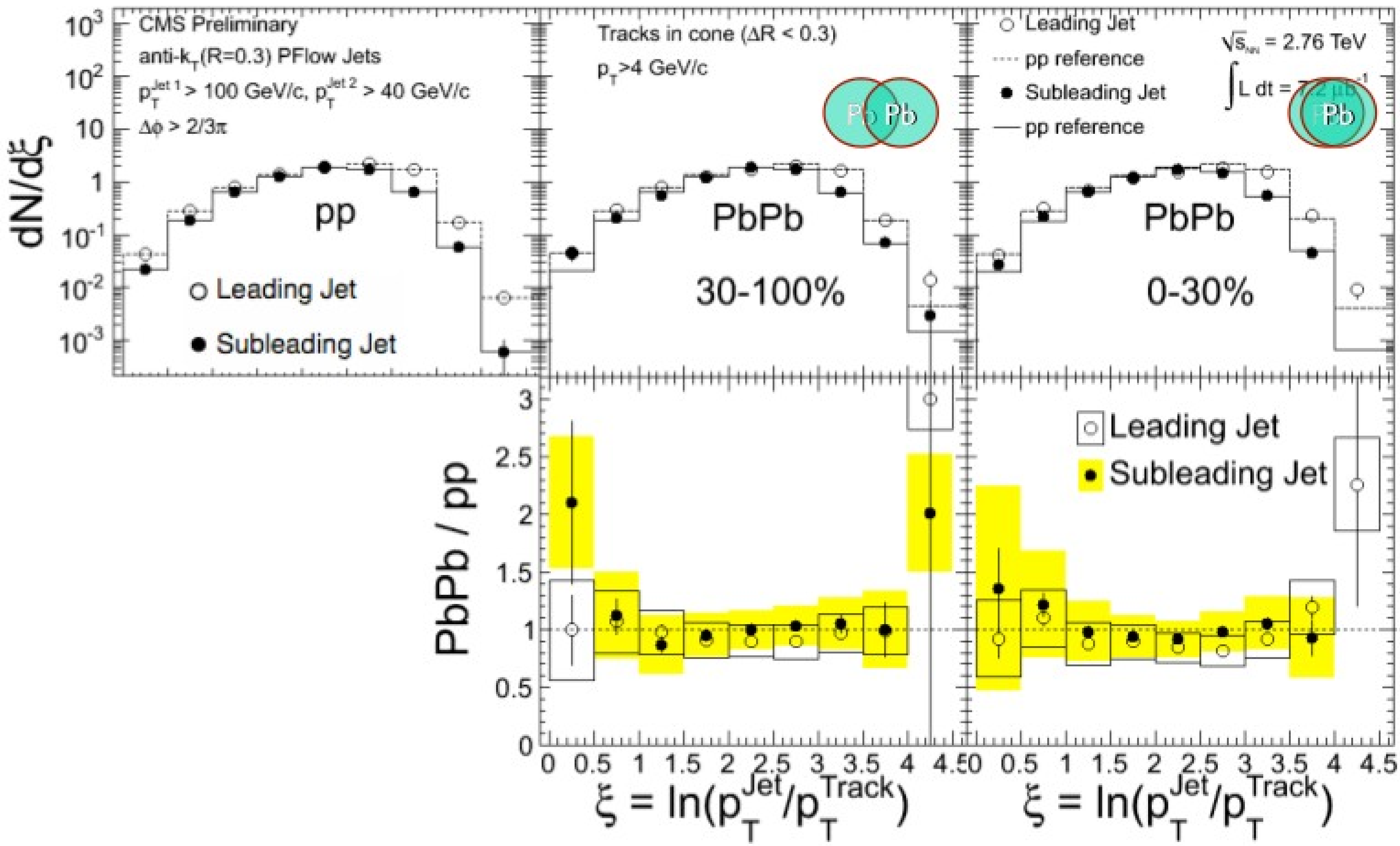
Higher cumulant results at the LHC



Measured higher harmonics



Fragmentation functions in pp/PbPb



Leading and subleading jets fragment like jets of corresponding energy in pp.

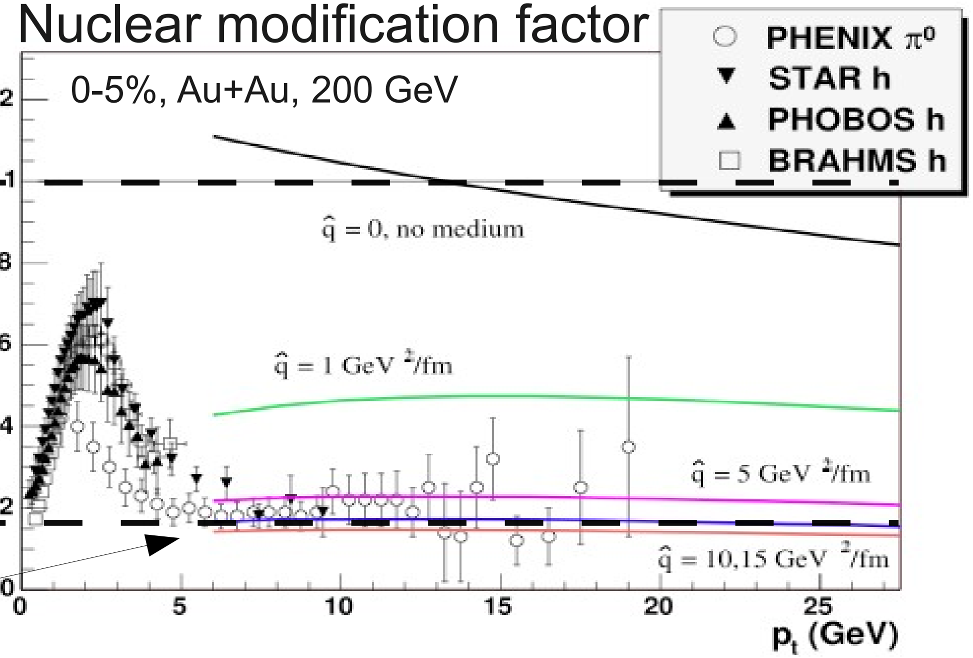
C.Roland (CMS) QM11

How dense is the medium?

Nuclear modification factor

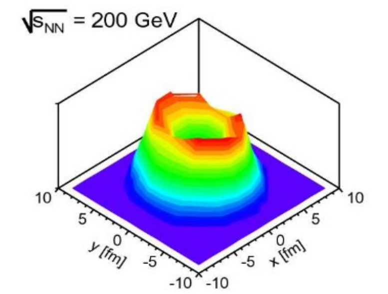
Expected yield wrt pp (N_{coll} scaling)

N_{part} scaling



Maximal suppression?

$$N_{coll} \times \frac{S}{V} \approx N_{part}/2$$

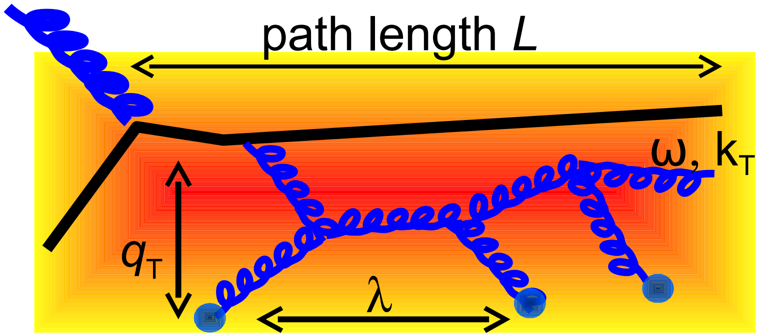


Origin of partons that yield >5GeV hadron in central Au+Au

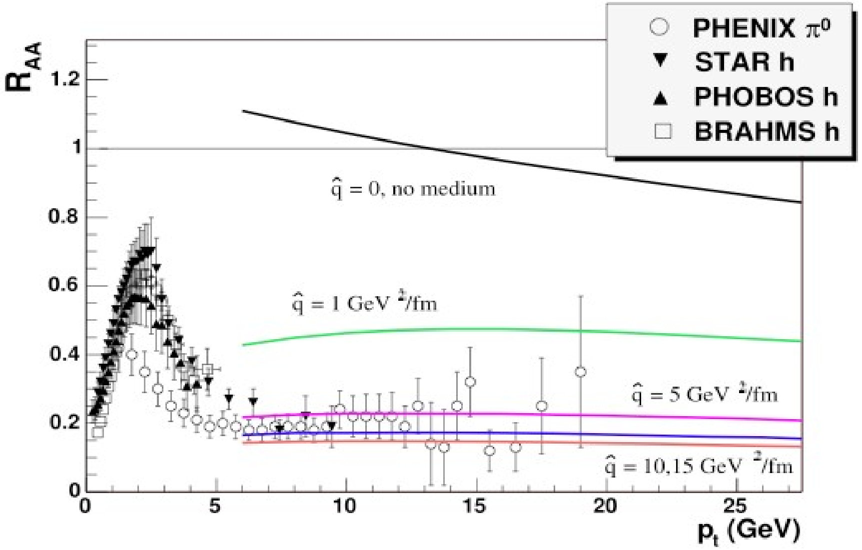
The medium is “black”: Leading spectra are suppressed by up to a factor of 5-6 wrt collision weighted pp reference

Escola et al., NPA 747 511 (2005)
Dainese et al., EPJC 38 461 (2005)

Parton energy loss in BDMPS-Z-ASW



$\hat{q} = \frac{\langle q_T^2 \rangle}{\lambda}$ encodes medium properties



$$\left.\frac{d^2\sigma^h_{\mathrm{quenched}}}{dp_T\,dy}\right|_{y\approx 0} = \sum_{a,b,j} \int dF_{ab}\, d\Delta E_j\, dz_j\, dp^{\mathrm{init}}_{T,j} \left.\frac{d^2\sigma^{ab\to jX}}{dp^{\mathrm{init}}_{T,j}\,dy}\right|_{y\approx 0} \times$$

$$\delta\left(p^{\mathrm{init}}_{T,j} - p_{T,j} - \Delta E_j\right) P\left(\Delta E_j; C_j, \hat{q}_j, L_j, p_{T,j}\right) \frac{D_{h/j}(z_j)}{z_j^2}$$

Calculations lead to larger values of $\hat{q}$ than expected from pQCD arguments

Baier et al., NPB 483 291 (1997)
Zakharov, JTEPL 63 952 (1996)
Salgado, Wiedemann, PRD 68 014008 (2003)

Relating R_{AA} to models at LHC