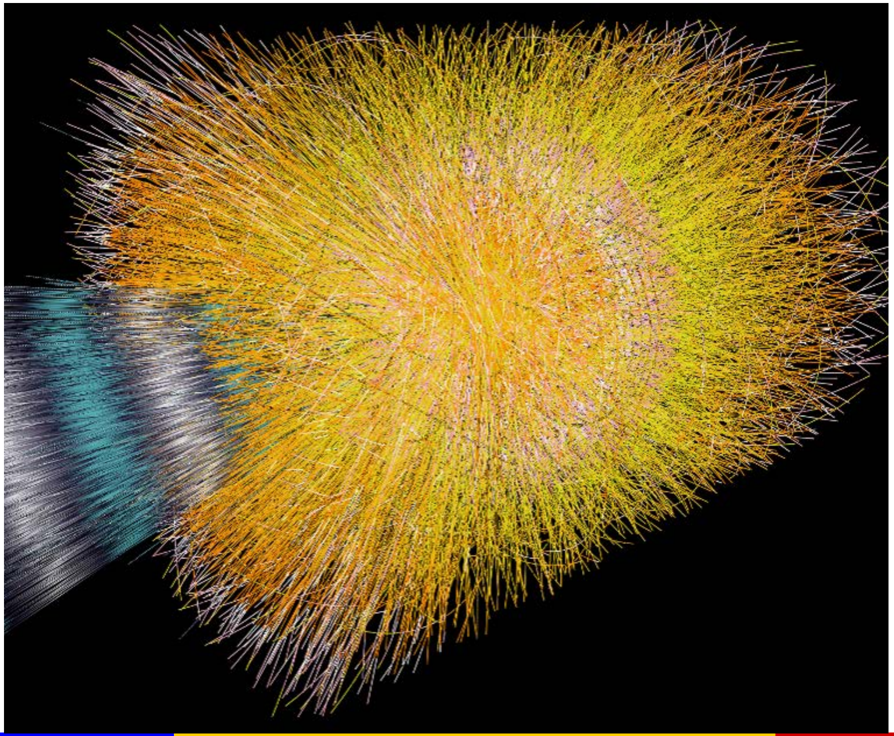


Heavy Ions at LHC

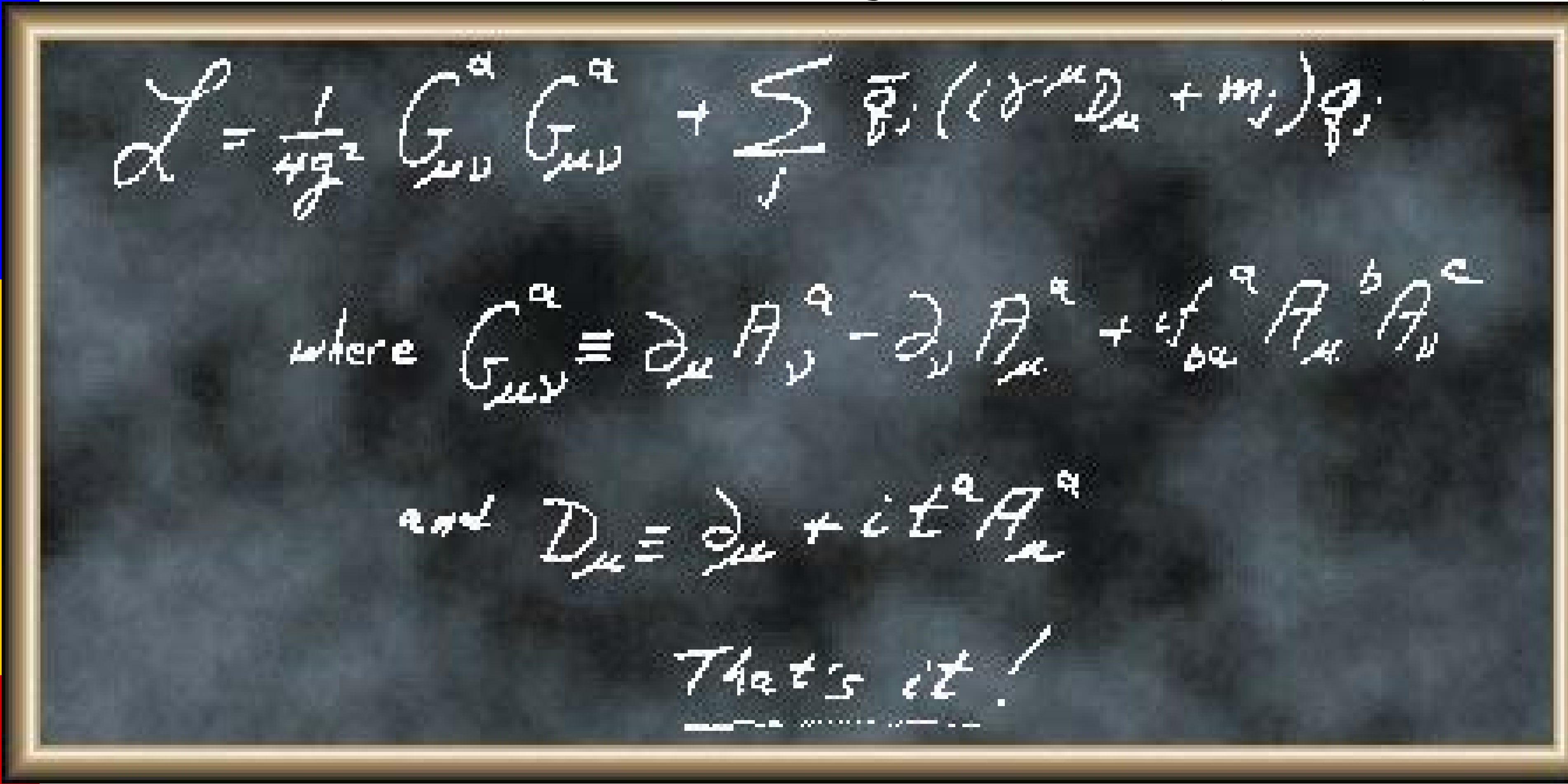
R. Lietava

The University of Birmingham

Outlook

- **QGP**
- **Event characterisation**
- **Soft probes**
  - **Interferometry**
  - **Multiplicity, Transverse energy, Energy density**
  - **Flow and correlations**
- **Hard Probes**
  - **Quarkonia**
  - **Jet quenching**
    - **High pt suppression (h^-,D0,J/ψ,γ,Z,...)**
    - **Reconstructed jets**
- **Summary**

Quantum ChromoDynamics (QCD)



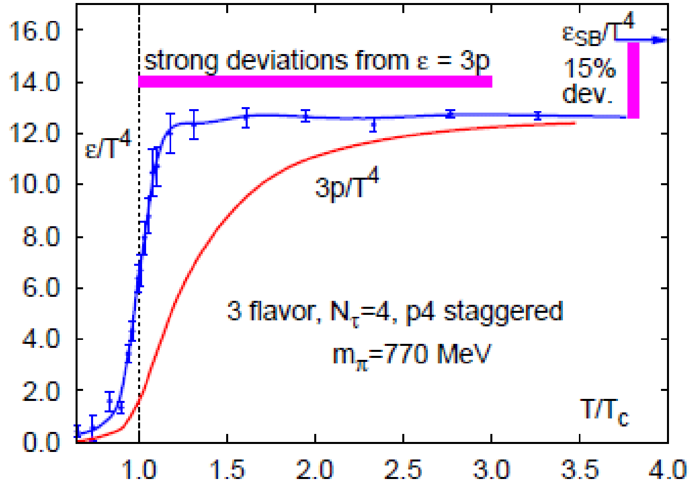
QCD confinement – free quarks never observed !

QCD vacuum not well understood.

Heavy ions – study QCD at high temperature and density

Quark Gluon Plasma

- Latice QCD: transition hadrons -> quarks and gluons



QCD EoS

QGP is not ideal gas !

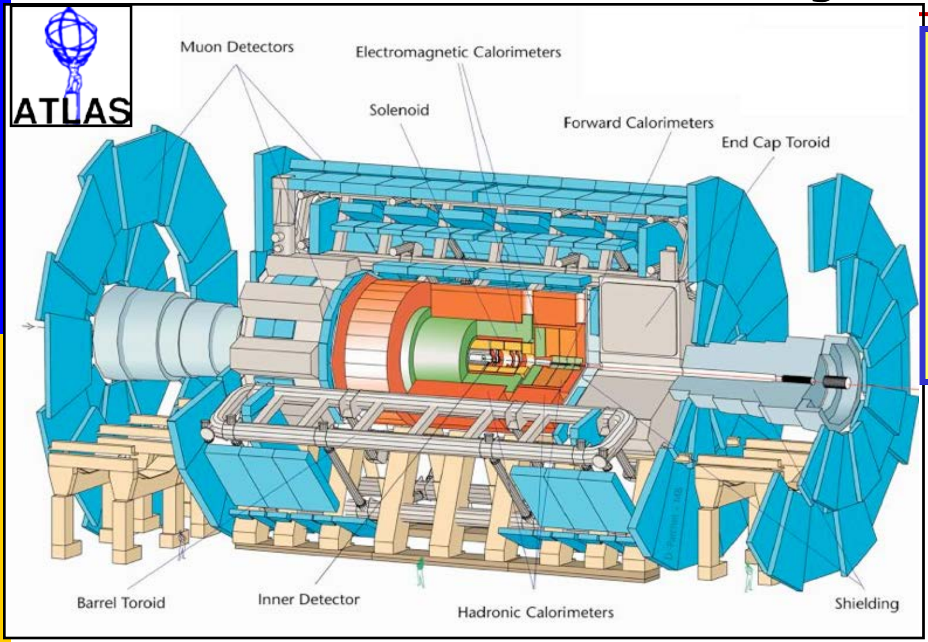
$$p = \frac{\varepsilon}{3} = \left(g_B + \frac{7}{8} g_F \right) \frac{\pi^2 T^4}{90}$$

$g_B = 8_c * 2_s = 16$

$g_F = 3_f * 3_c * 2_s * 2_a = 36$

- Relativistic Heavy Ion Collider (RHIC):
  - Macroscopic liquid:
    - System size > mean free path
    - System lifetime > relaxation time
  - Perfect: shear viscosity/entropy ~ 0
- LHC :
  - System is bigger, denser, hotter
  - Abundant production of hard probes

LHC Heavy Ion Program



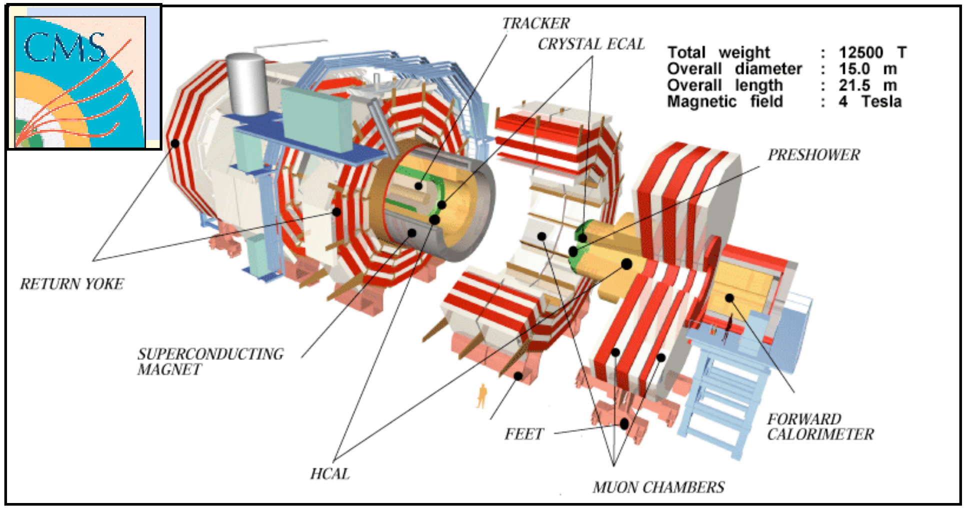
LHC Heavy Ion Data-taking

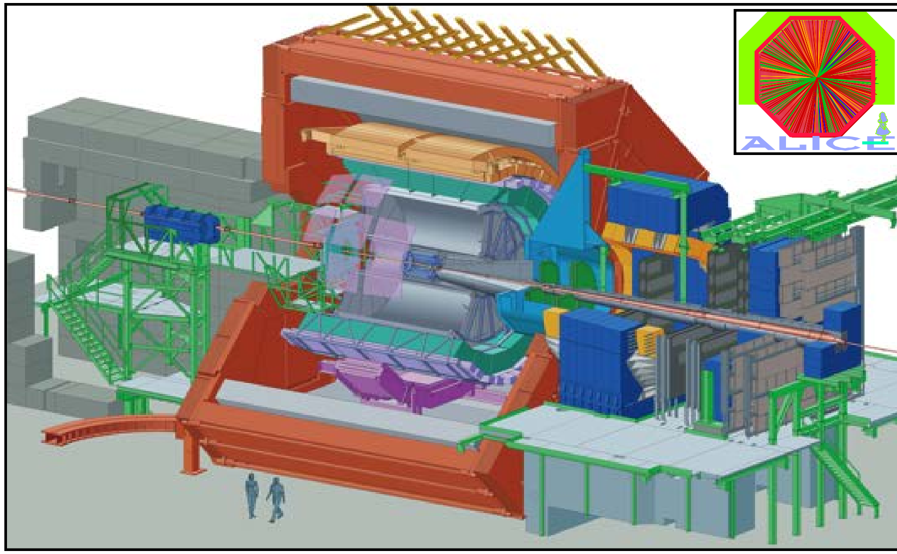
Design: Pb + Pb at $\sqrt{s_{NN}}$ = 5.5 TeV

(1 month per year)

Nov. 2010: Pb + Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

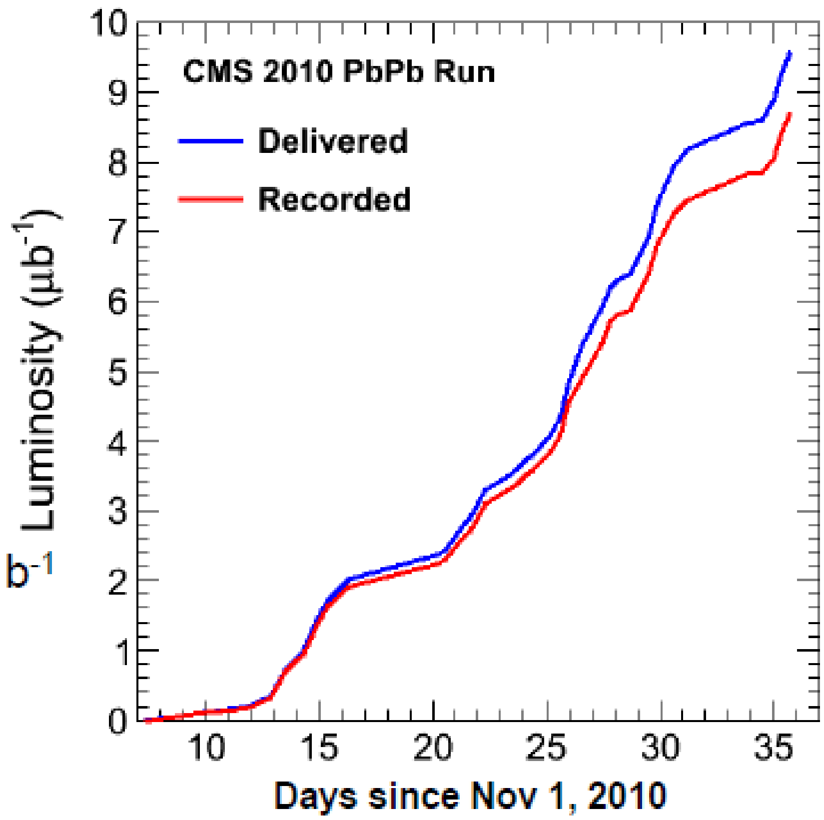
- LHC Collider Detectors
  - ATLAS
  - CMS
  - ALICE





Pb–Pb Luminosity

B.Wyslouch, CMS, EPIC2011



Delivered integrated luminosity ~ 9 μb^{-1}

Luminosity achieved $L = 2–3 \times 10^{25}\ cm^{-2}s^{-1}$

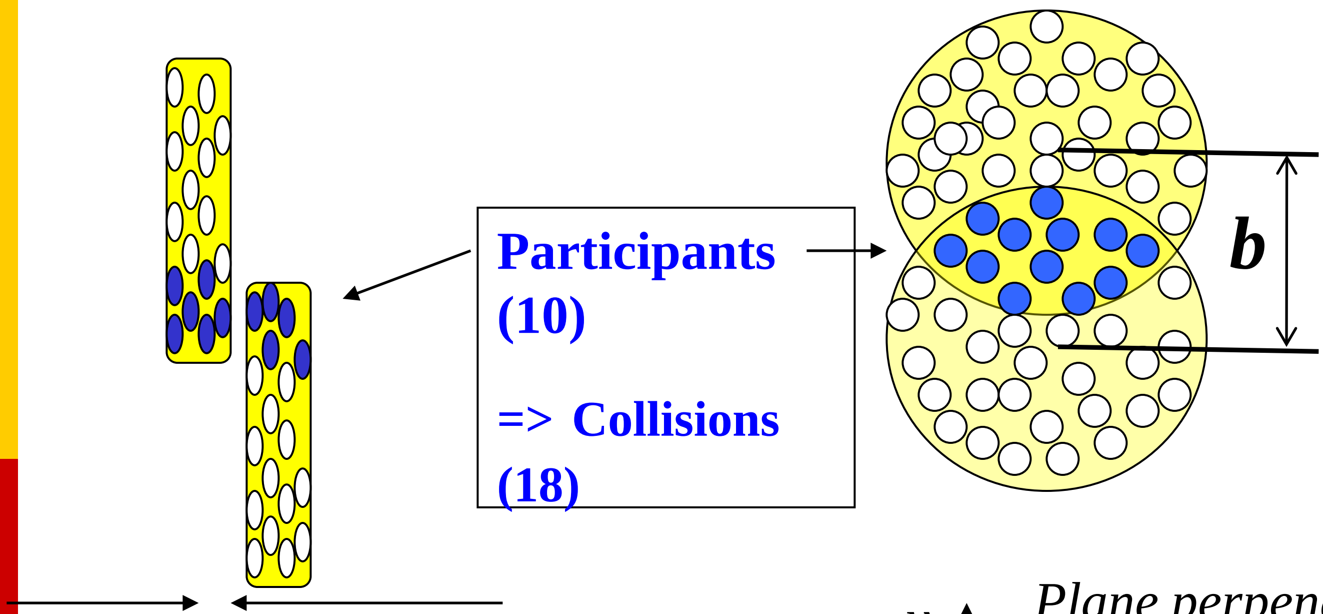
ATLAS very similar to CMS

ALICE recorded ~ 50% due to TPC dead time

Heavy Ion Collision Centrality

Controls the volume and shape of the system

Multiplicity and energy of produced particles are correlated with geometry of collisions.



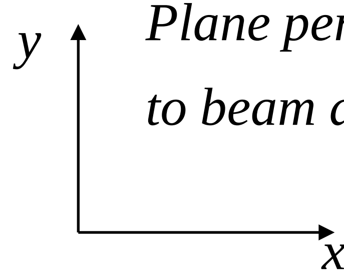
Beam direction

Measured distribution:

- **Track multiplicity**
- **Transverse energy**
- **Forward energy**

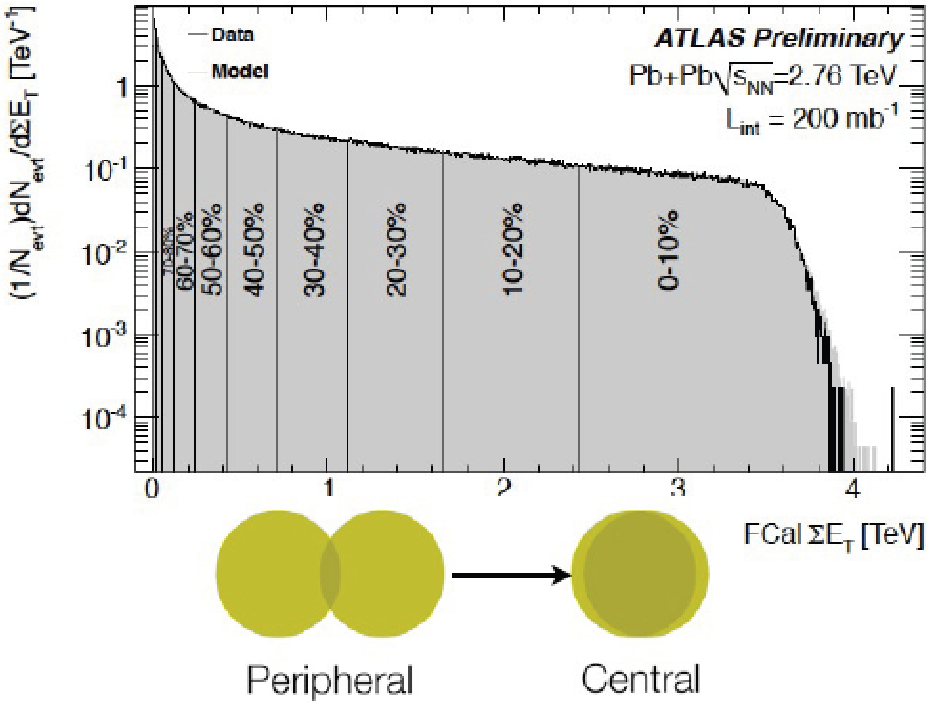
Variables:

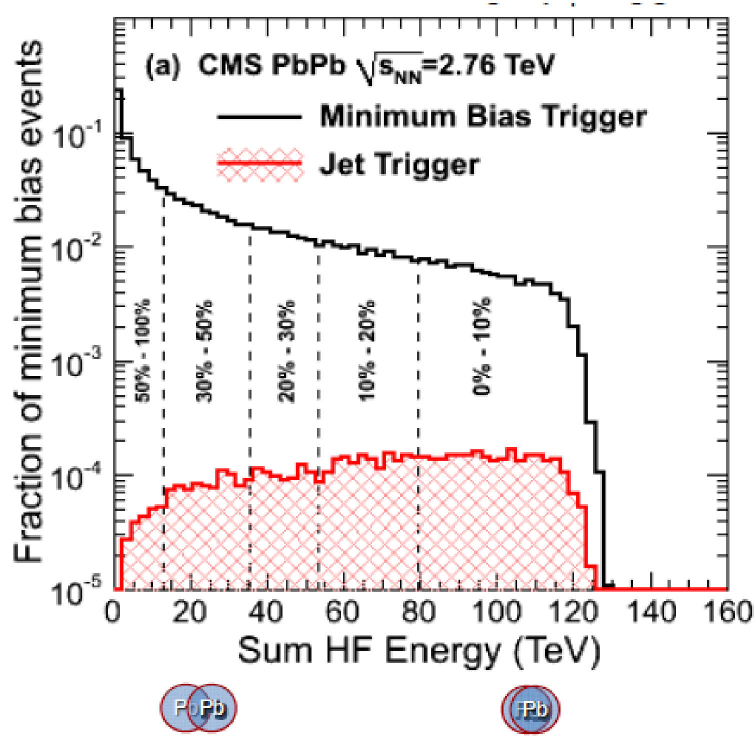
- **impact parameter**
- **participants**
- **collisions**
- **percentile of x section**

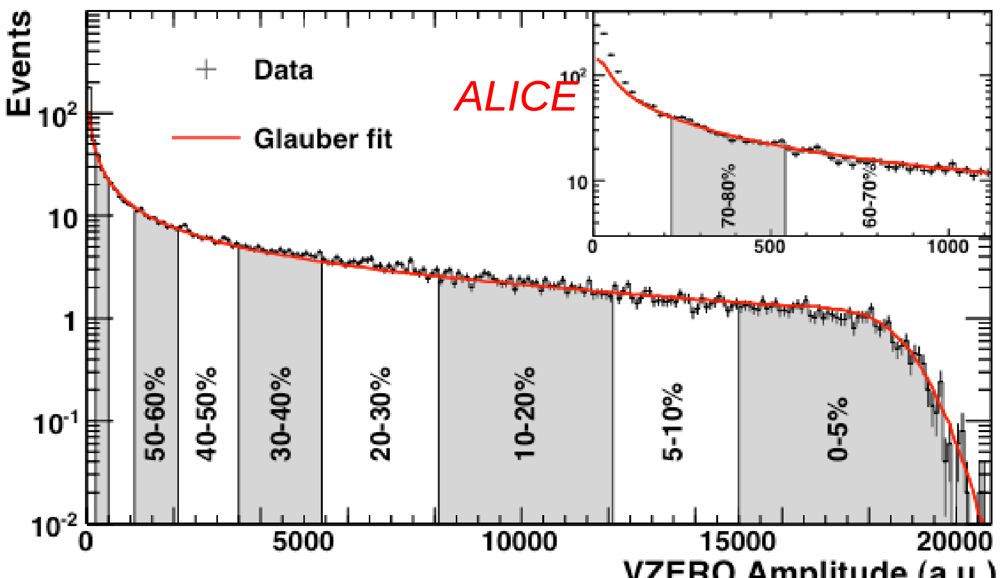


Plane perpendicular to beam direction

Centrality selection







S.White, ATLAS, EPIC2011

B.Wyslouch, CMS,EPIC2011

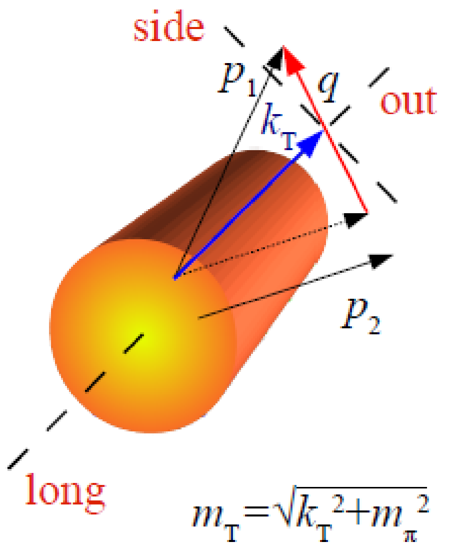
M.Nicassio, ALICE, EPIC2011

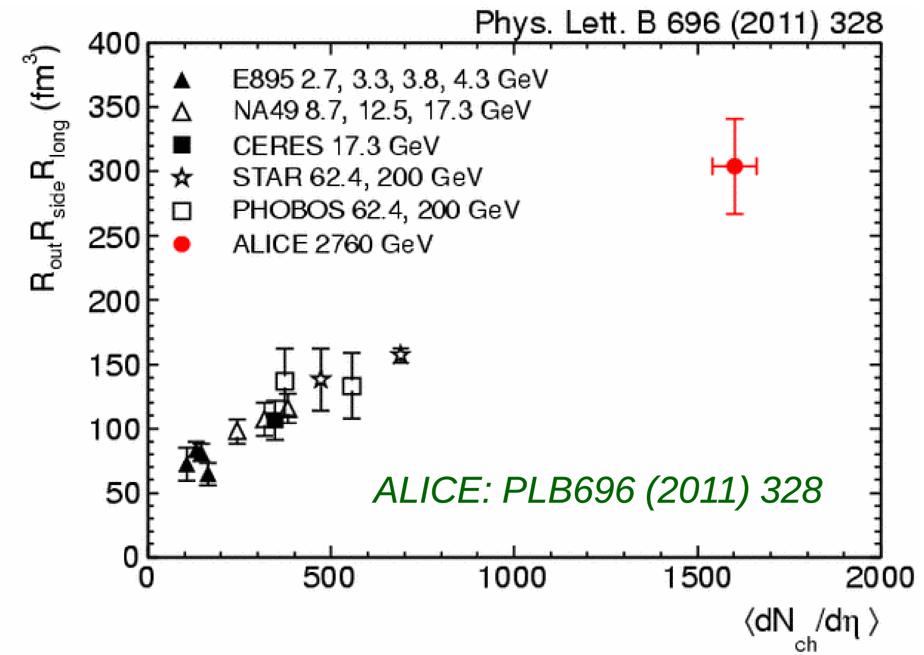
Soft Probes

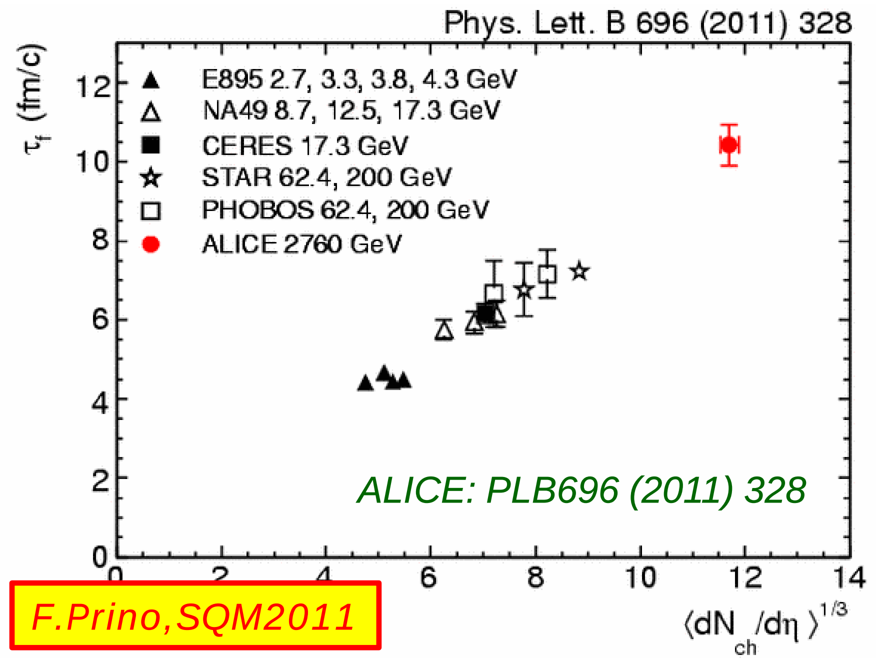
- Interferometry of identical particles
- Charged particle multiplicity , E_T, ε
- Transverse momentum spectra
- Radial flow
- Anisotropic flow

System size

- Spatial extent of the particle emitting source extracted from interferometry of identical bosons
  - Two-particle momentum correlations in 3 orthogonal directions -> HBT radii (R_{long}, R_{side}, R_{out})
  - Size: twice w.r.t. RHIC
  - Lifetime: 40% higher w.r.t. RHIC





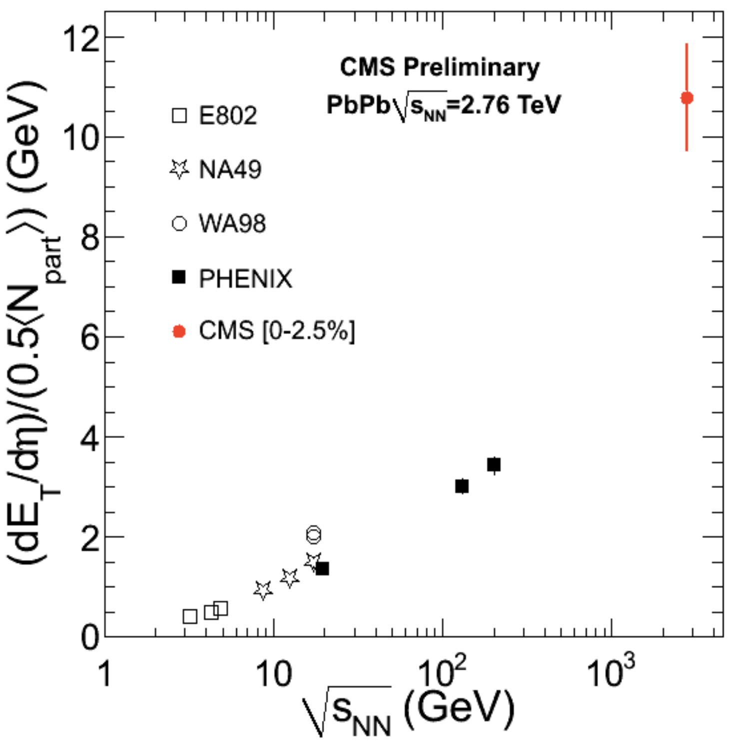


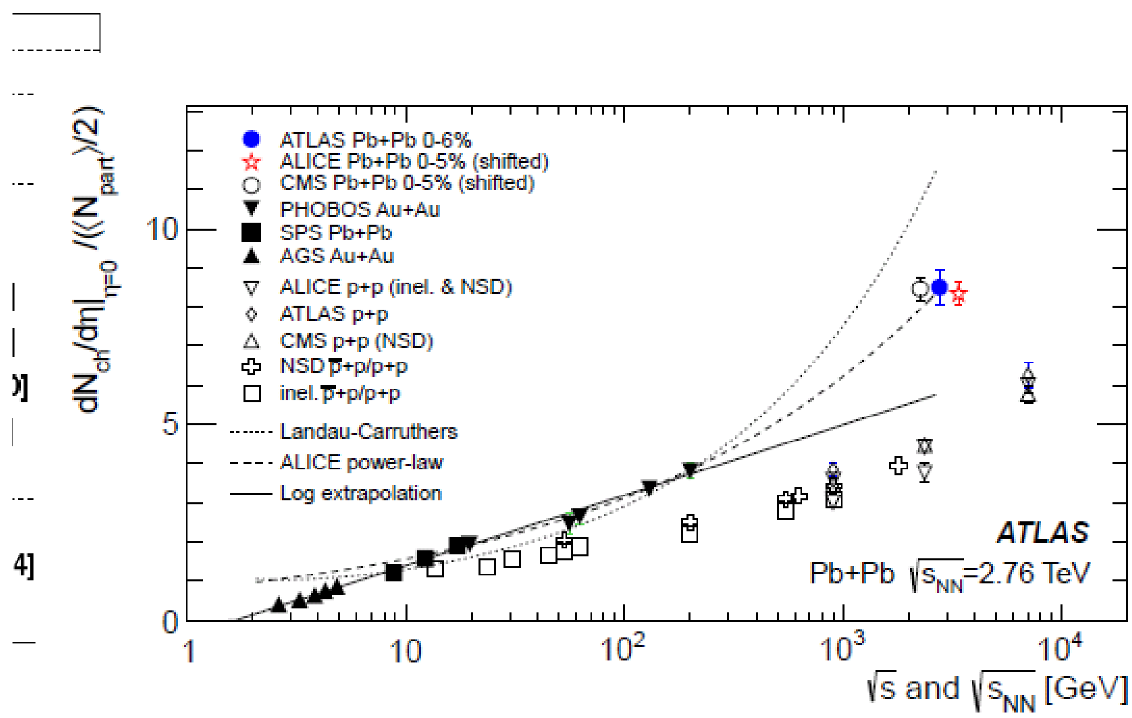
F.Prino,SQM2011

Multiplicity, E_T and ε

- Particle Production and Energy density ε:
  - Produced Particles: **$dN_{ch}/d\eta \approx 1600 \pm 76$ (syst)**
    - ≈ 30,000 particles in total, ≈ 400 times pp !
    - somewhat on high side of expectations (tuned to RHIC)
    - growth with energy faster in AA
  - **Energy density ε > 3 x RHIC** (fixed τ_0,)
  - **Temperature + 30 %**

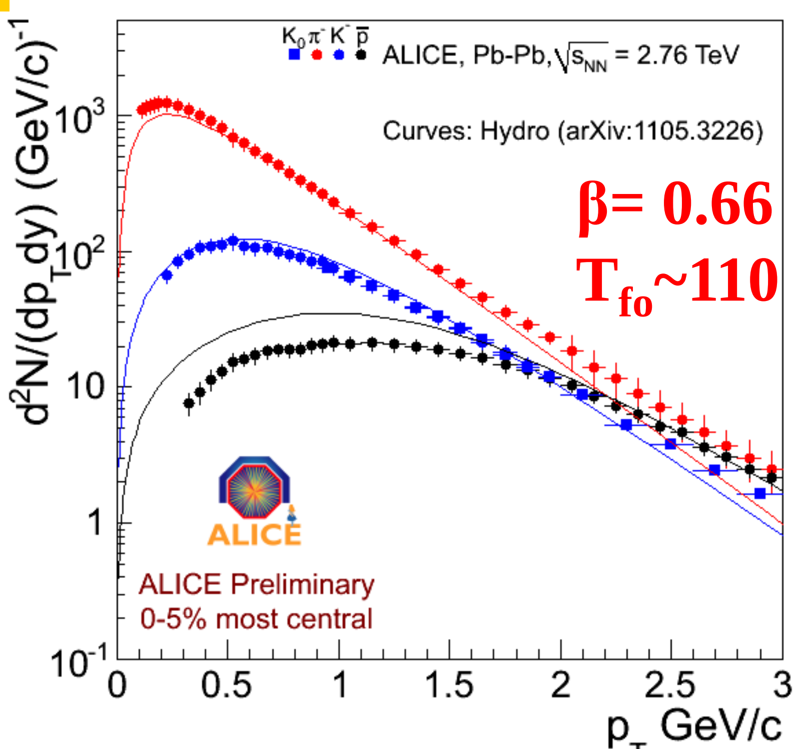
$$\varepsilon(\tau) = \frac{E}{V} = \frac{1}{\tau_0 A}\frac{dE_T}{dy}$$





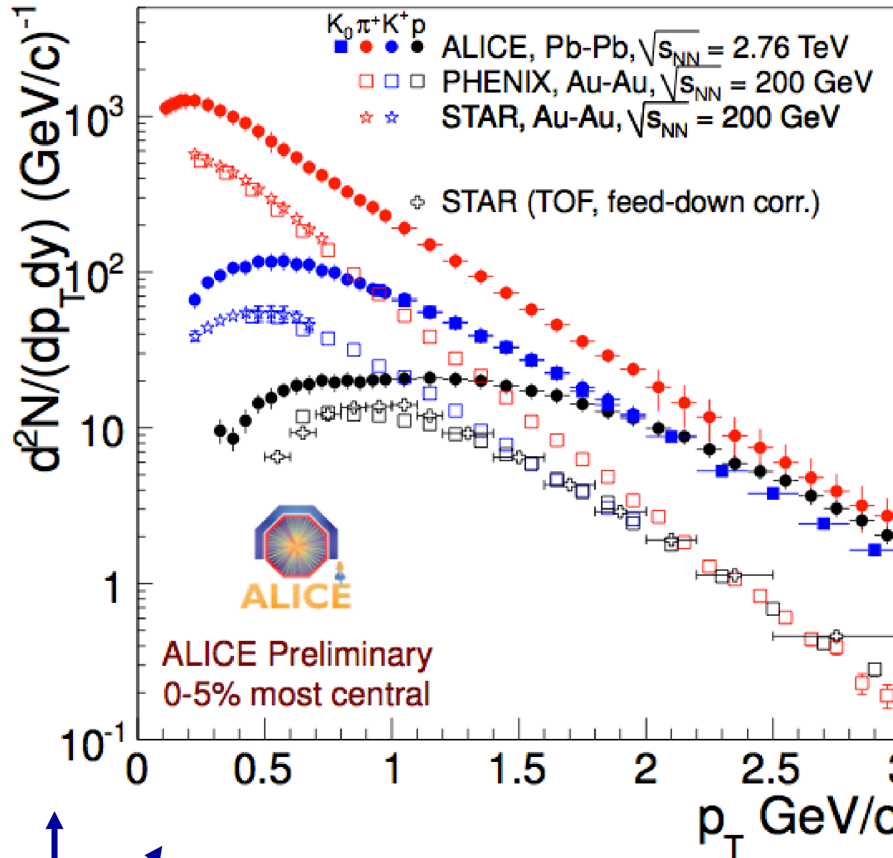
Charged particle spectra
Radial Flow

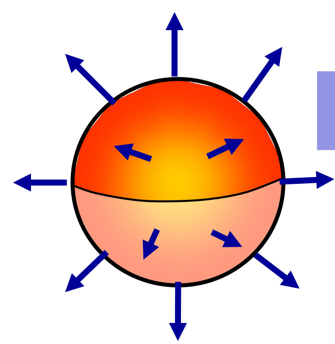
- K, π, p spectra **0-5% central collisions**
- Very clear flattening and higher tails at $\sqrt{s_{NN}}$=2.76 TeV
- Quantify with blastwave parameter studies: **radial flow β**=v_0/c and freezout temperature T_{fo}



β= 0.66

T_{fo}~110 MeV





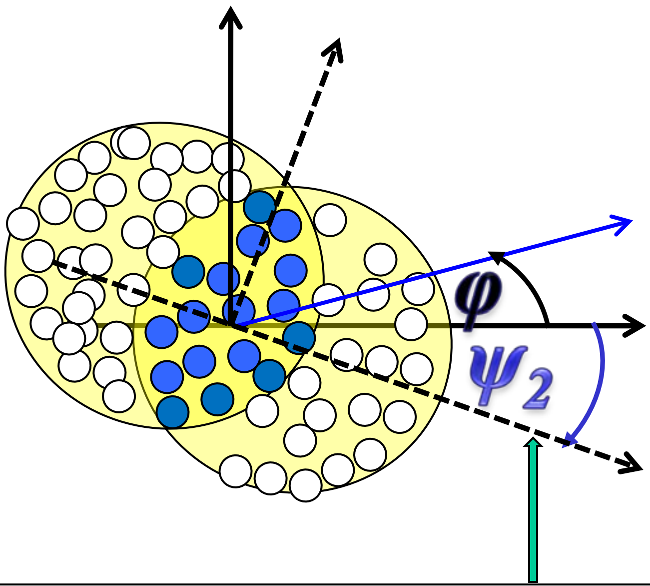
L.Barnby , ALICE, EPIC2011

Anisotropic Flow

- Fourier expansion in azimuthal distribution:

$$\frac{dN}{p_T dp_T dy d\varphi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T dy}\left(1 + 2v_1\cos(\varphi - \psi_1) + 2v_2\cos(2(\varphi - \psi_2)) + \ldots\right)$$

- φ – azimuthal angle



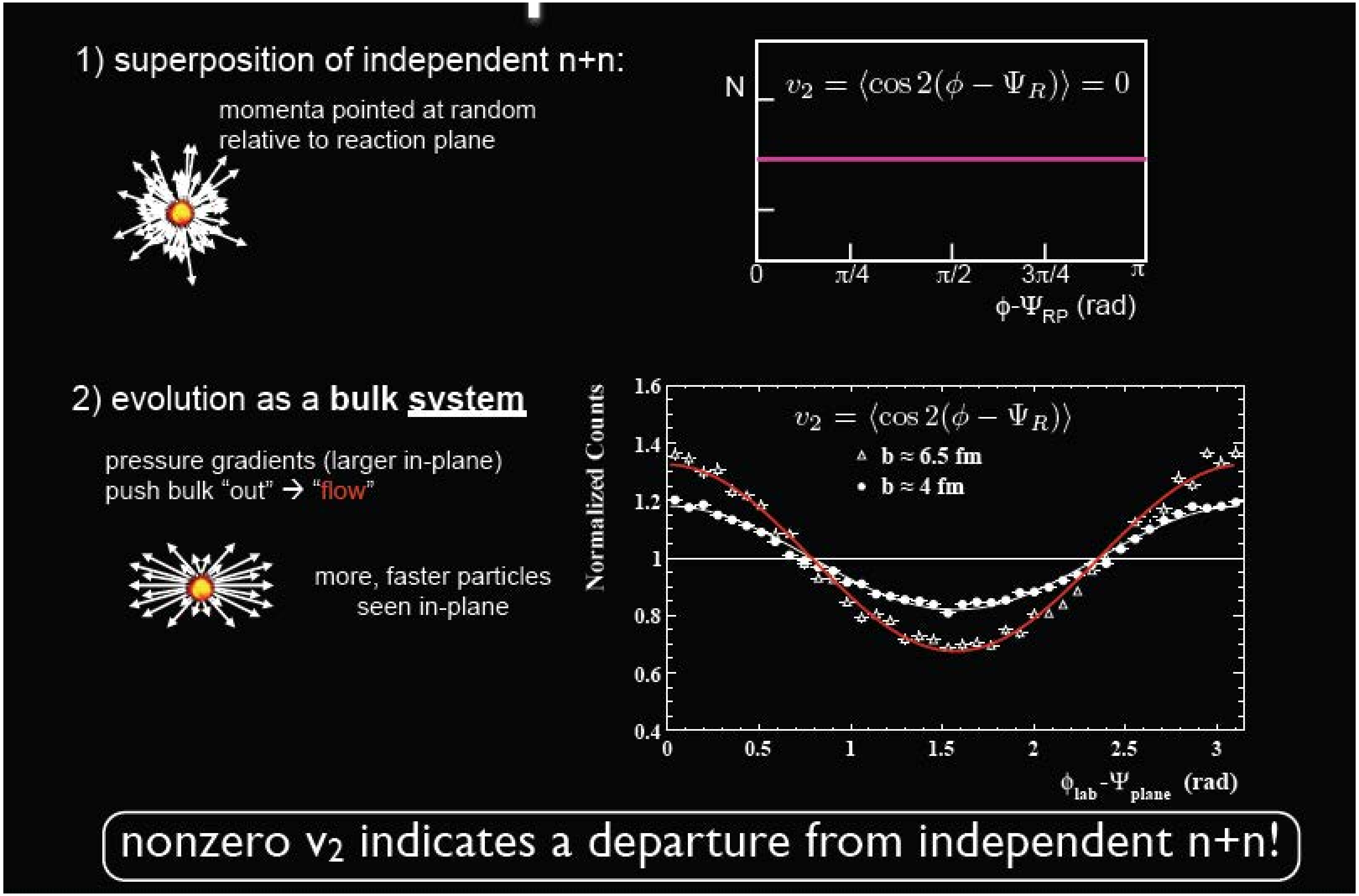
In non-central collisions participant area is not azimuthally symmetric: system evolution transfer this anisotropy from coordinate space to momentum space

Collision Plane :
- Defined by Beam and Impact Parameter

v_1 - direct flow

v_2 - elliptic flow, dominant for system symmetric wrt Collision Plane

Elliptic flow - v_2



Adopted from R.Snellings

Physics of elliptic flow

Elliptic flow depends on:

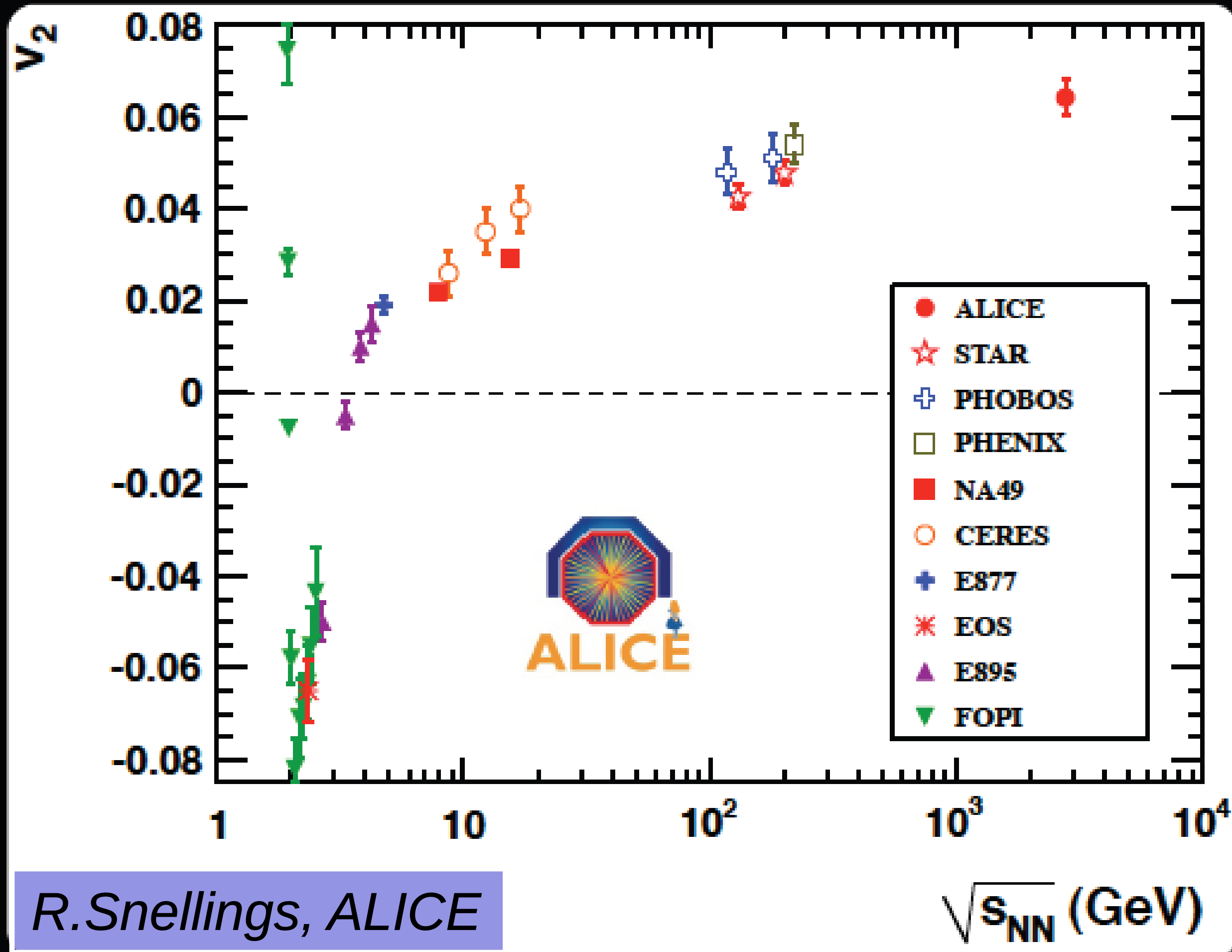
- Initial conditions
- Fluid properties
  - Equation of state
  - Shear viscosity

Shear viscosity: $\eta = n < p > \lambda = < p > / \sigma$

Small viscosity η => large cross section σ
=> strongly interacting fluid

The Perfect Liquid

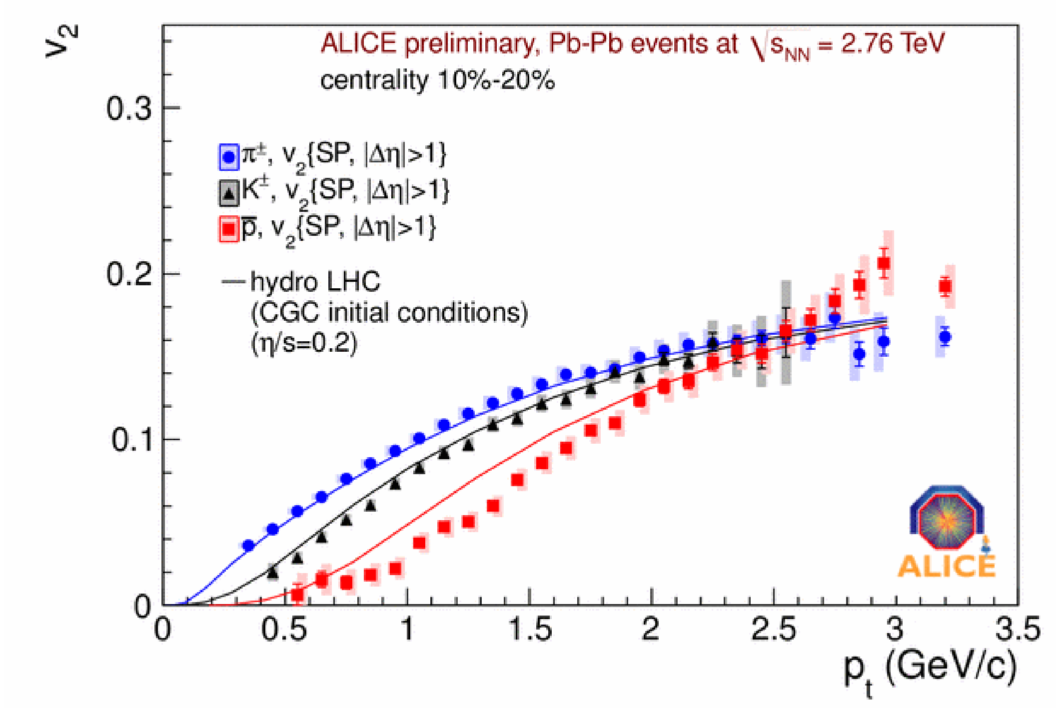
K. Aamodt et al. (ALICE Collaboration)
PRL 105, 252302 (2010)

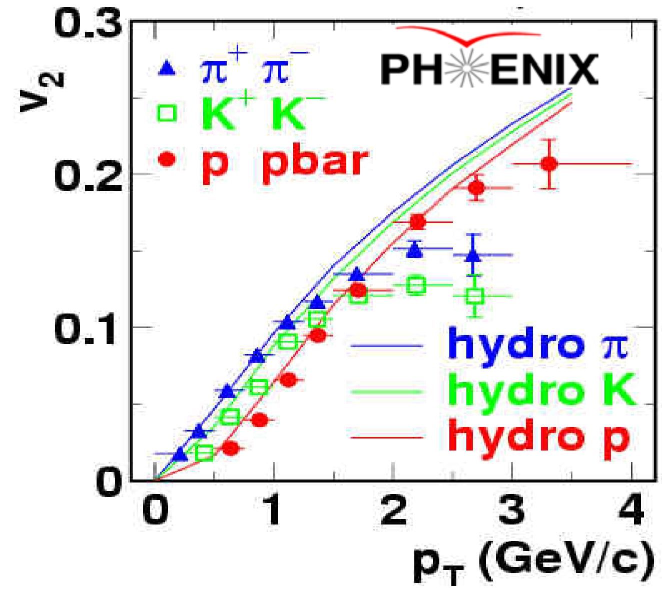


The system produced at the LHC behaves as a very low viscosity fluid (a perfect fluid)

Hydrodynamics and v_2

- comparison of identified particles $v_2(p_T)$ with hydro prediction – mass splitting described

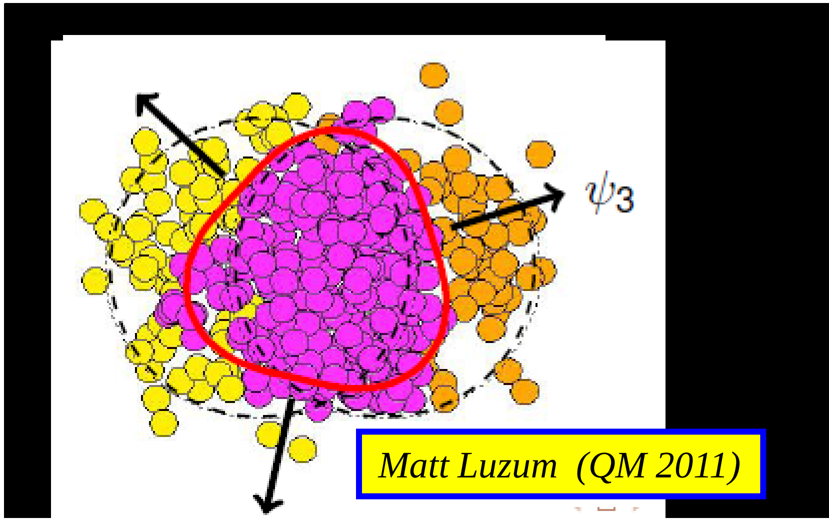


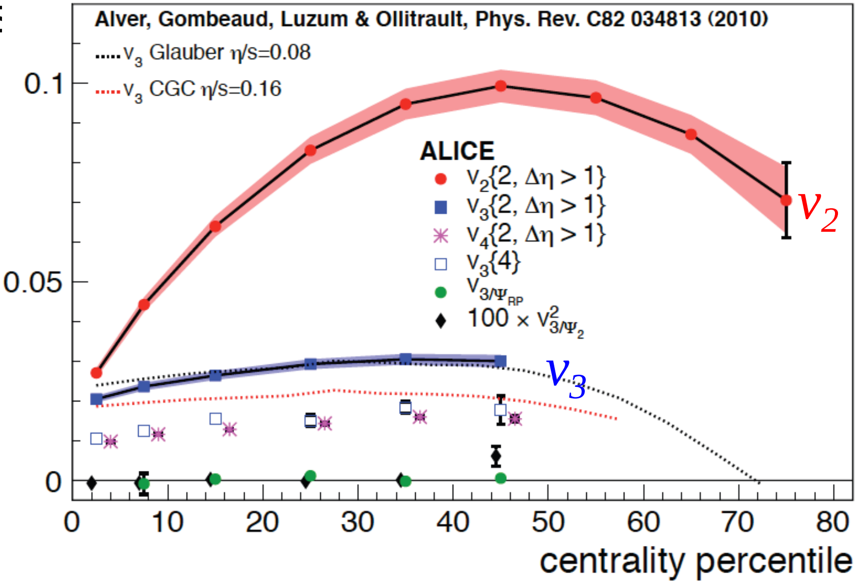


- (calculation by C Shen et al.: arXiv:1105.3226 [nucl-th])
- **Protons are to be understood**

Fluctuations → v_3

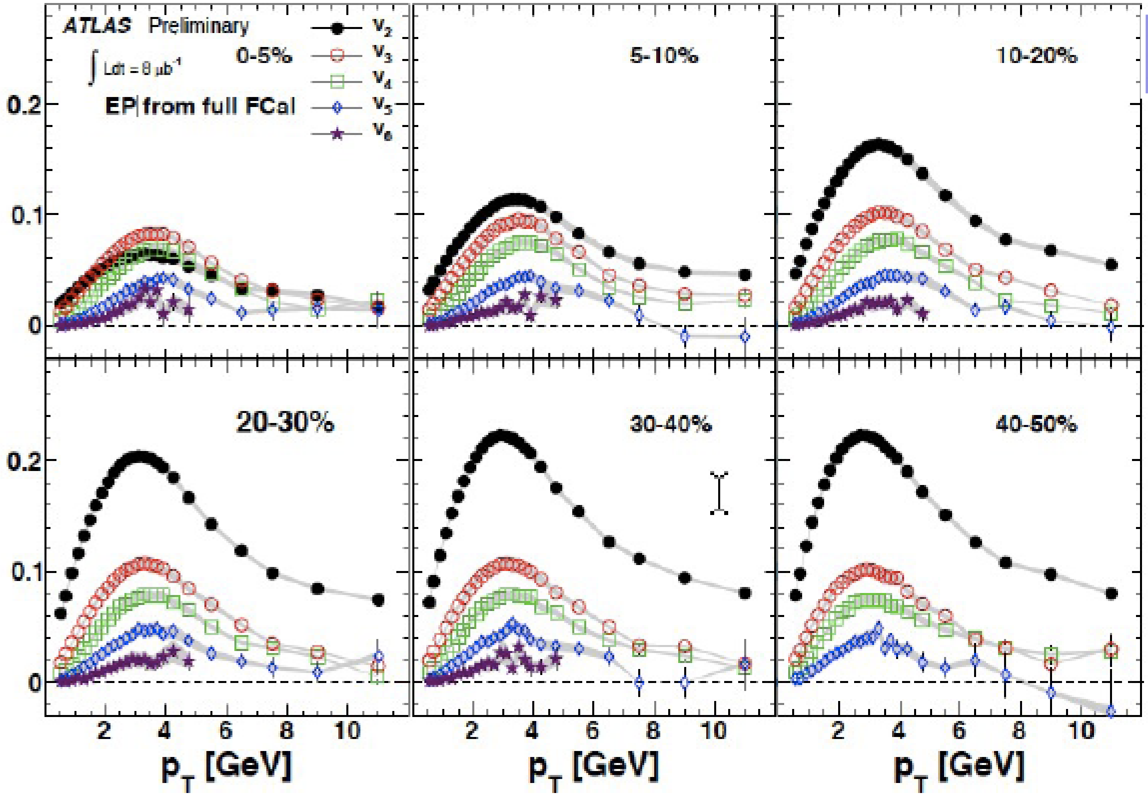
- "ideal" shape of participants' overlap is ~ elliptic
  - in particular: no odd harmonics expected
  - participants' plane coincides with event plane
- but fluctuations in initial conditions:
  - participants plane != event plane
  - → v_3 ("triangular") harmonic appears [B Alver & G Roland, PRC81 (2010) 054905]
- and indeed, v3 != 0 !
- v_3 has weaker centrality dependence than v_2





ALICE: PRL 107 (2011) 032301

Higher harmonics

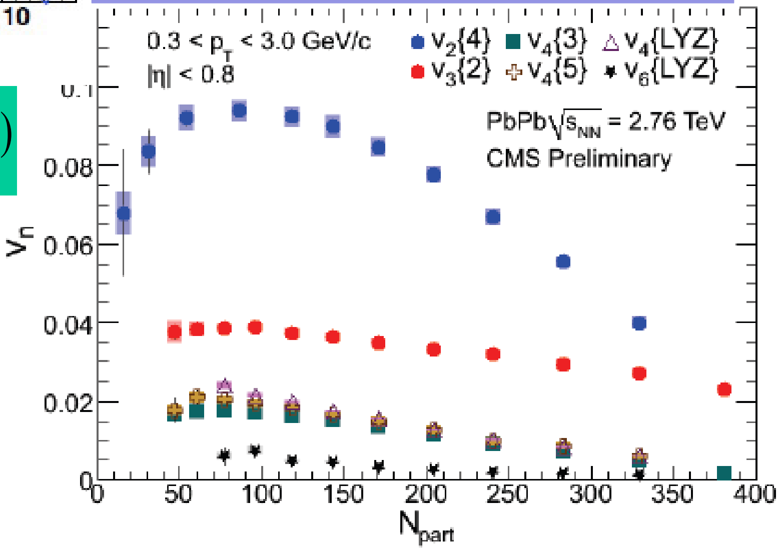


S.White, ATLAS, EPIC2011

- $v_{n+1} < v_n$
- v_{n+1} less centrality dependent than v_n

$$\frac{dN}{p_T dp_T dy d\varphi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T dy}\left(1 + 2v_2\cos(\varphi - \psi_2) + 2v_3\cos(2(\varphi - \psi_3)) + \ldots\right)$$

M.Issah, CMS, EPIC2011



v_n – information on viscosity, n > 2

2 Particle Correlations and Flow

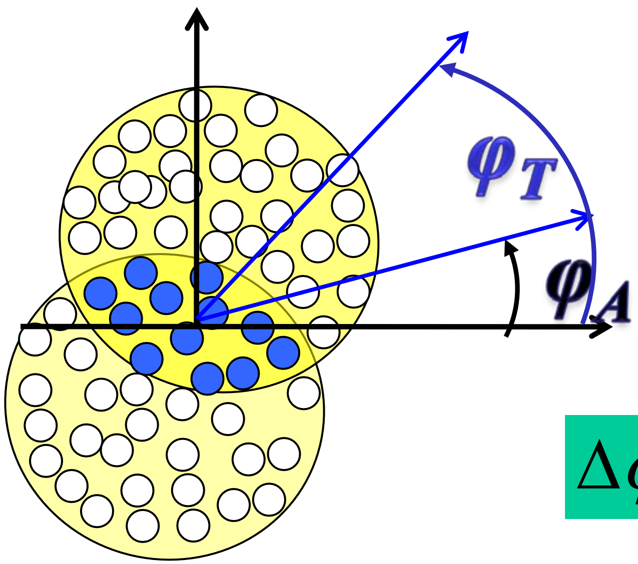
- Fourier expansion in azimuthal distribution:

$$\frac{dN}{d\Delta\varphi} = \left(1 + 2v_1 \cos(\Delta\varphi) + 2v_2 \cos(2\Delta\varphi) + \ldots\right)$$

- **If flow dominates than:**

$$v_i = v_i^A * v_i^T$$

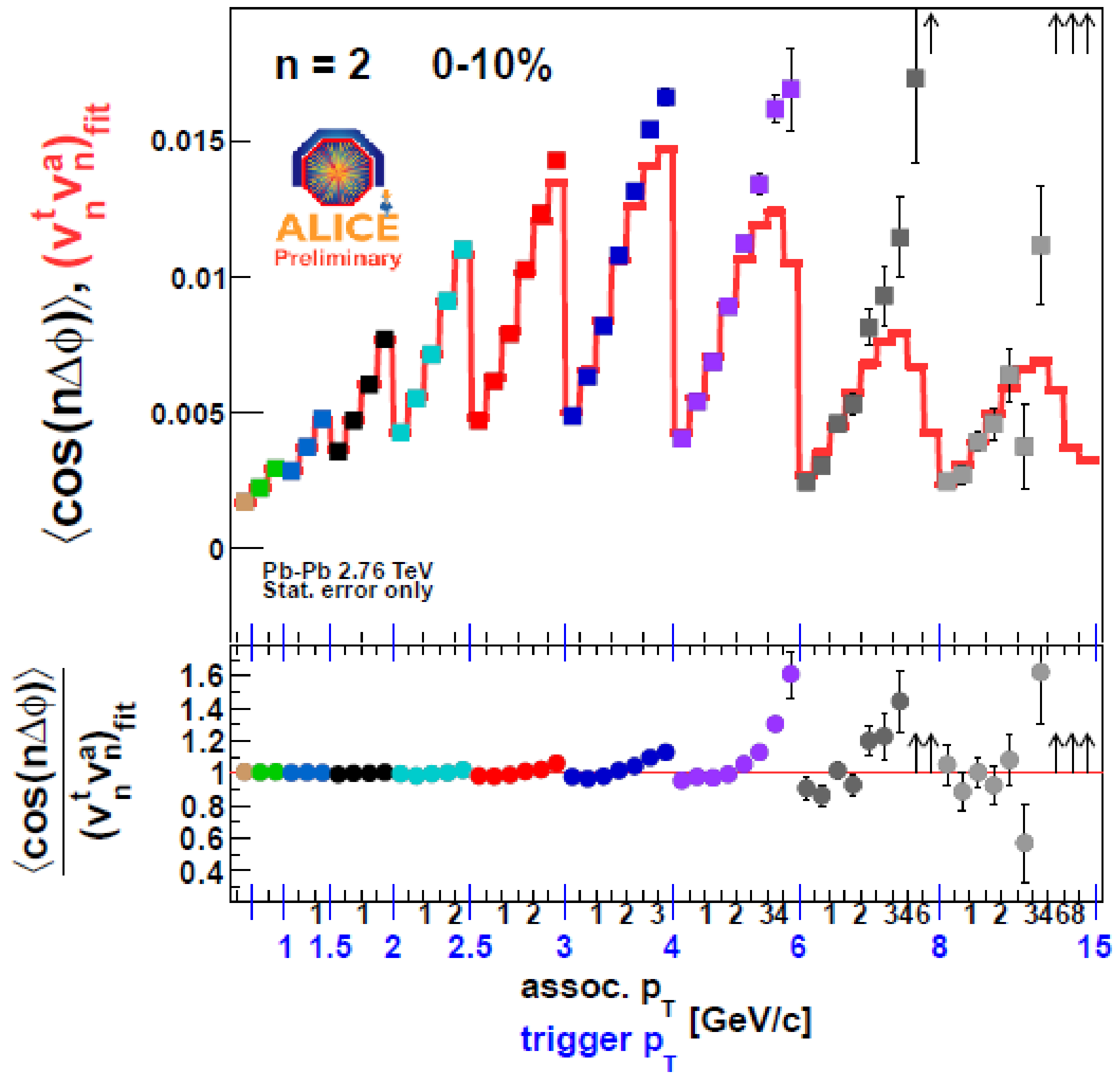
Flow Fourier coefficients



$$\Delta\varphi = \varphi_T - \varphi_A$$

Flow vs Non-Flow Correlations

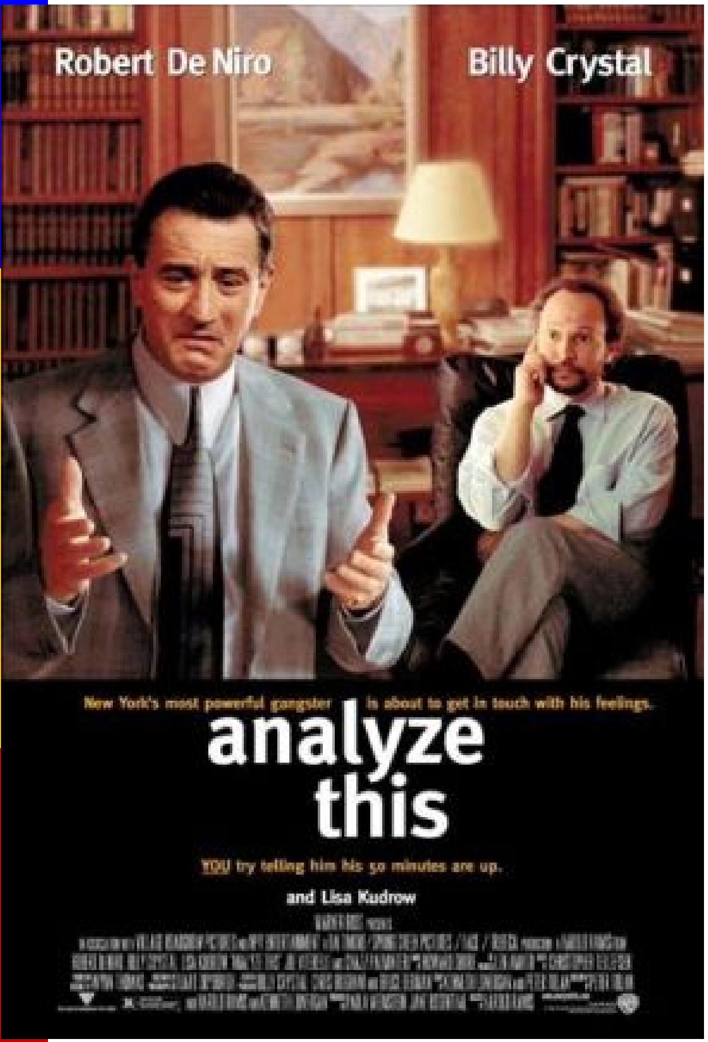
- Compare single calculated values with global fit
- To some extent, a good fit suggests flow-type correlations, while a poor fit implies non-flow effects
- v_2 to v_5 factorize until p_T ~ 3-4 GeV/c, then jet-like correlations dominate
- v_1 factorization problematic (influence of away-side jet)

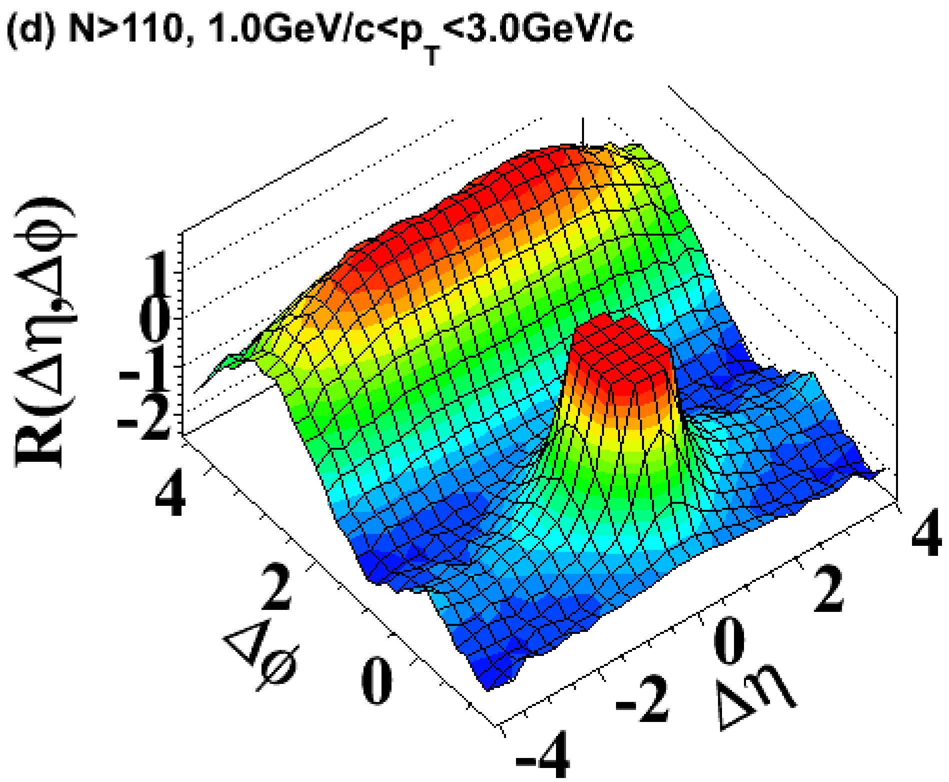


Anisotropic Flow Summary

- Centrality and p_t dependences of various v_n constraint
  - initial conditions (CGC vs Glauber)
  - viscosity – η/s
- There is no hydro calculation (yet) describing simultaneously data on v_2 and v_3 ,....
- 2 particle correlations consistent with flow for $p_T < 3\text{-}4$ GeV/c

Speaking of which…





Full Fourier decomposition of the CMS pp ridge?

The nuclear modification factor

- quantify departure from binary scaling in AA
  - ratio of yield in AA versus reference collisions
- e.g.: reference is pp → R_{AA}

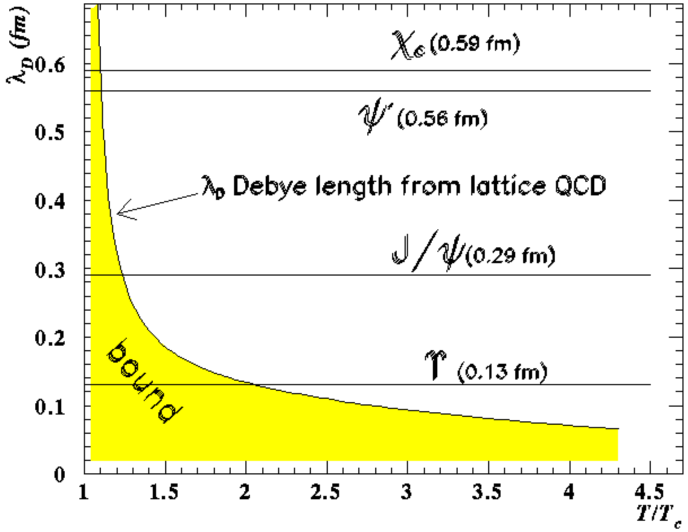
$$R_{\mathrm{AA}} = \frac{\mathrm{Yield}_{\mathrm{AA}}}{\mathrm{Yield}_{\mathrm{pp}}} \cdot \frac{1}{\left\langle Nbin \right\rangle_{\mathrm{AA}}}$$

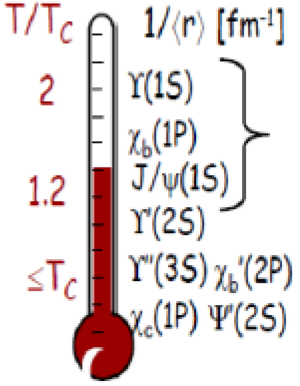
- ...or peripheral AA → R_{CP} (“central to peripheral”)

$$R_{\mathrm{cp}} = \frac{\mathrm{Yield}_{\mathrm{AA,\,central}}}{\mathrm{Yield}_{\mathrm{AA,\,periph}}} \cdot \frac{\left\langle Nbin \right\rangle_{\mathrm{AA,periph}}}{\left\langle Nbin \right\rangle_{\mathrm{AA,\,central}}}$$

Quarkonia suppression

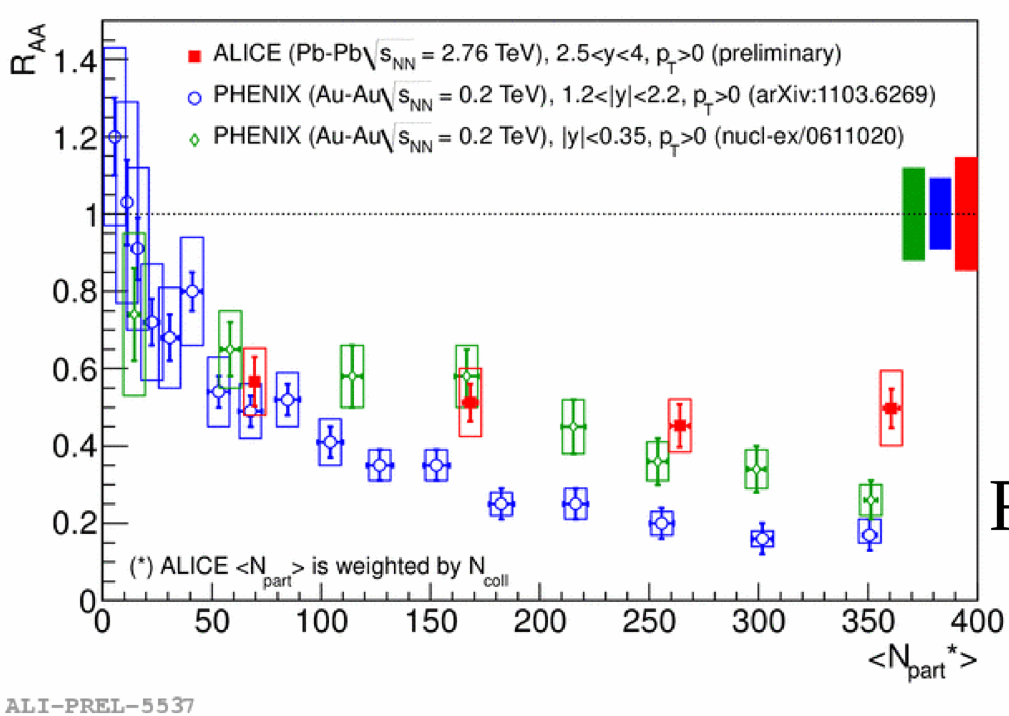
- In the plasma phase the interaction potential is expected to be screened beyond the Debye length λ_D (analogous to e.m. Debye screening):
- Charmonium (cc) and bottonium (bb) states with r > λ_D will not bind; their production will be **suppressed**
- Recombination of cc and bb **regenerates** quarkonia





J/ψ @ LHC: forward y, low p_T

- LHC: $2.5 < y < 4$, $p_T > 0$ (ALICE)
- **Less suppression than RHIC:**
  $1.2 < y < 2.2$, $p_T > 0$ (PHENIX)
- As suppressed as RHIC: $|y| < 0.35$. $pT > 0$ (PHENIX)



$$R_{AA} = \frac{\text{Yield}_{AA}}{\text{Yield}_{pp}} \cdot \frac{1}{\langle Nbin \rangle_{AA}}$$

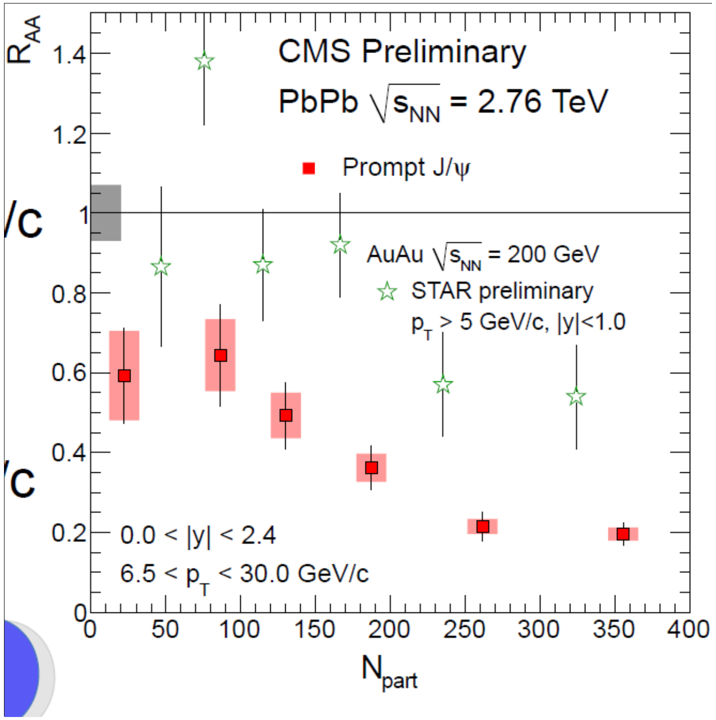
Recombination ?

Ginés Martínez – ALICE (QM2011)

J/ψ @ LHC: central y, high p_T

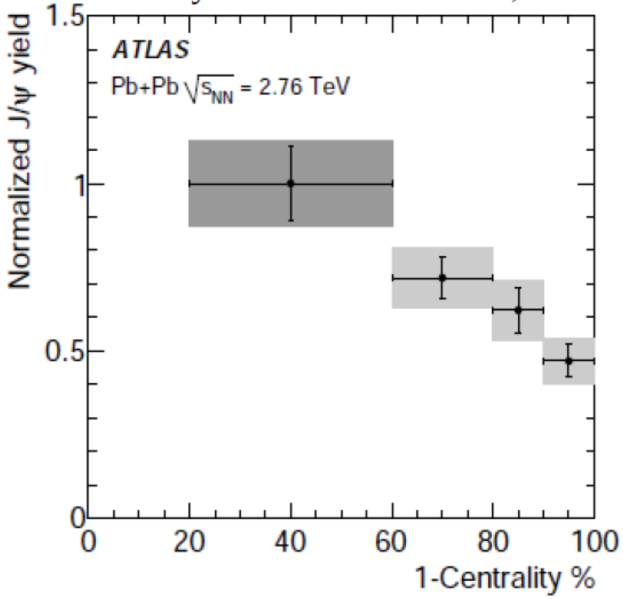
- LHC: $|y| < 2.4$, $p_T > 6.5$ GeV/c (CMS) prompt J/ψ

$$R_{AA} = \frac{\text{Yield}_{AA}}{\text{Yield}_{pp}} \cdot \frac{1}{\langle Nbin \rangle_{AA}}$$



CMS: PAS HIN-10-006

Phys.Lett.B697:294-312,2011



ATLAS: PLB 697 (2011) 294

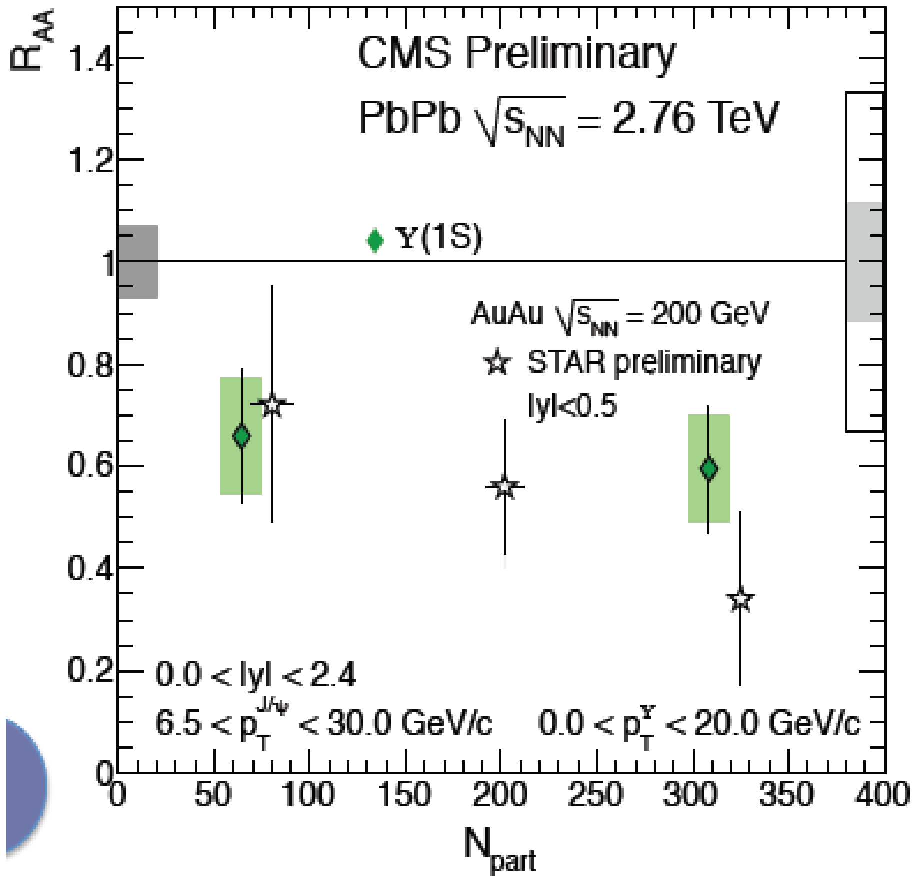
→ **more suppressed than RHIC:**

→ $|y| < 1$. $pT > 5$ GeV/c (STAR)

inclusive J/ ψ

Υ(1S) suppression

CMS: PAS HIN-10-006

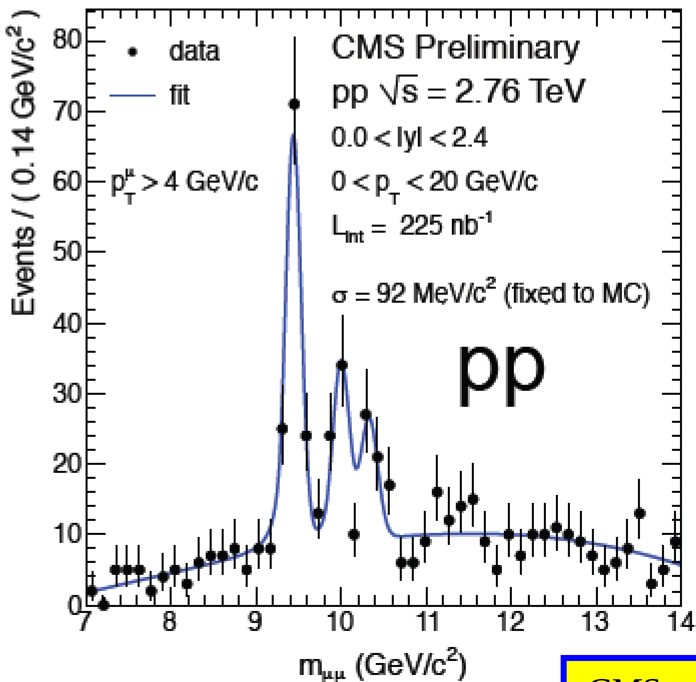


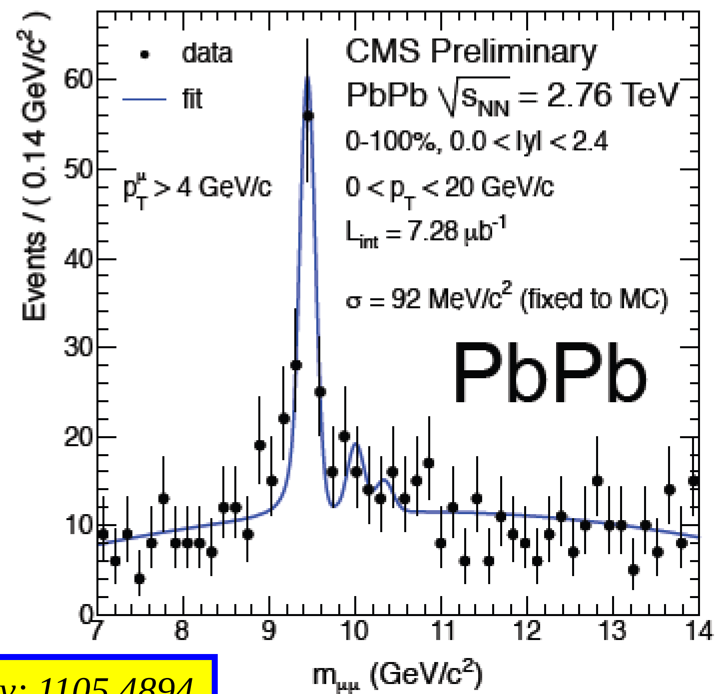
– CMS Υ(1S) R_{AA}(0-100) = 0.62 ± 0.11 ± 0.10

– STAR Υ(1+2+3S) R_{AA}(0-60) = 0.56 ± 0.11 $^{+0.02}_{-0.10}$

Υ(2S+3S) suppression

- additional suppression for Υ(2S+3S) w.r.t. Υ(1S) ?





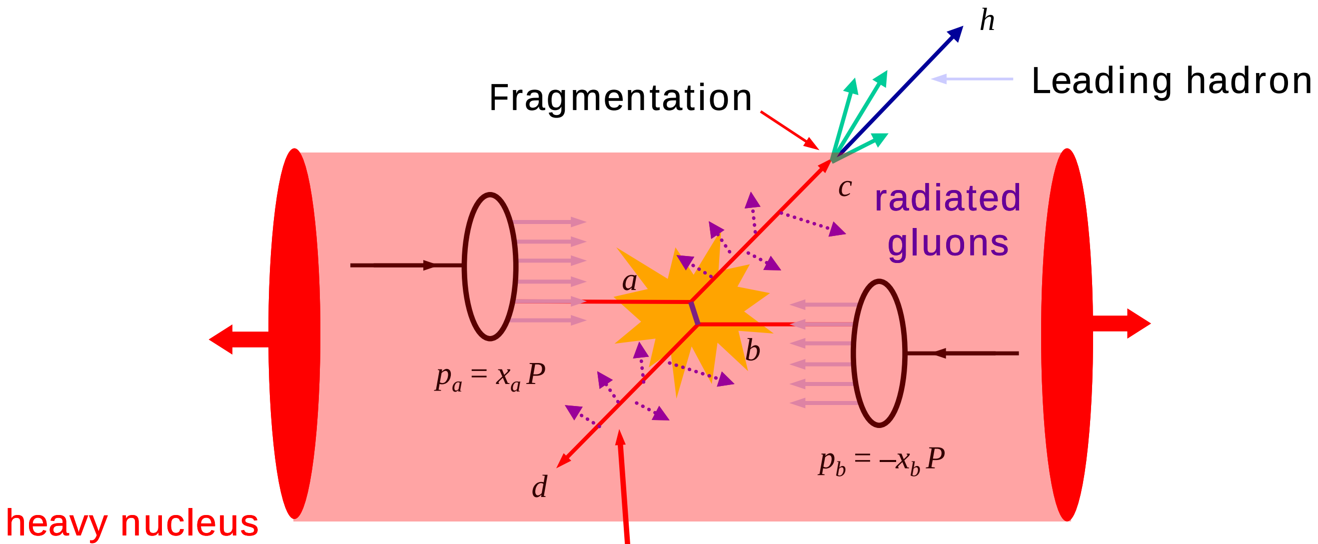
CMS: arXiv: 1105.4894

$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{\text{Pb-Pb}}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}} = 0.31^{+0.19}_{-0.15}(\text{stat}) \pm 0.03(\text{syst}),$$

Quarkonia Summary

- Υ and J/ψ suppressed by same amount ?
- Suppression depends on y and pt
- the future runs should allow us to establish quantitatively the complete quarkonium suppression(/recombination?) pattern
  - high statistic measurements
  - open flavour baseline / contamination
  - pA baseline

Jets in medium



Key prediction: jets are quenched

- collisional energy loss (Bjorken)
- radiative energy loss (Wang and Gyulassy)

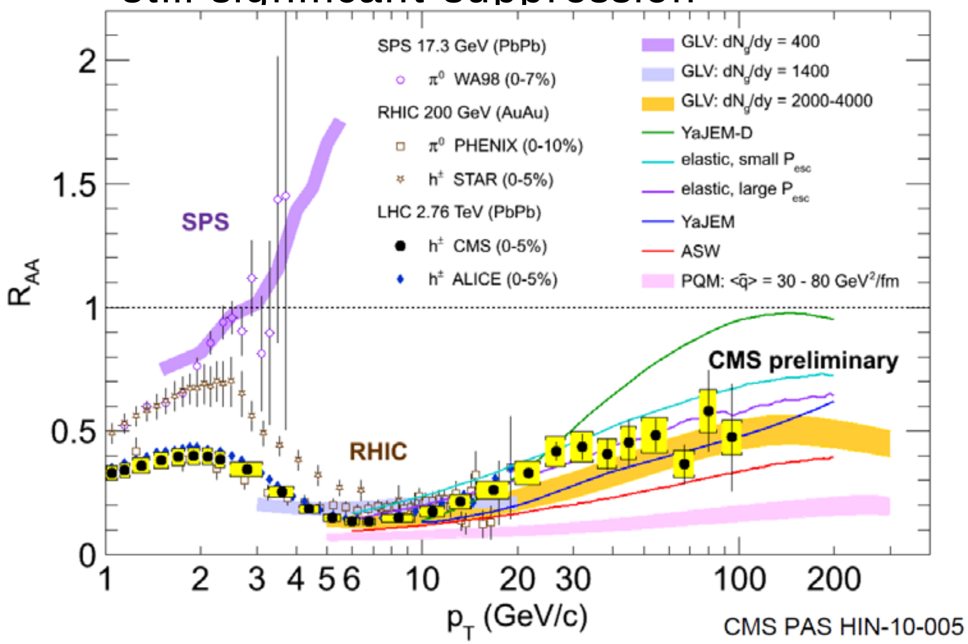
J.D. Bjorken Fermilab preprint PUB-82/59-THY (August 1982).
X.-N. Wang and M. Gyulassy, *Phys. Rev. Lett.* **68** (1992) 1480

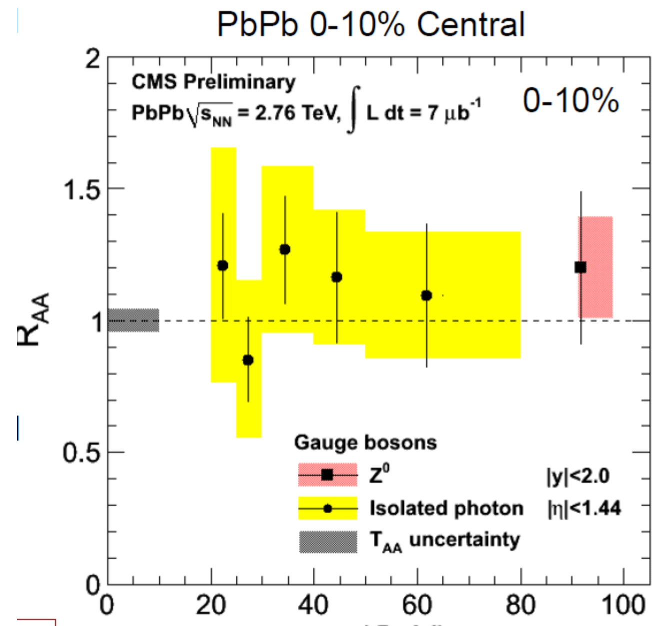
$$R_{AA} = \frac{\text{Yield}_{AA}}{\text{Yield}_{pp}} \cdot \frac{1}{\langle Nbin \rangle_{AA}}$$

R_{AA} at LHC

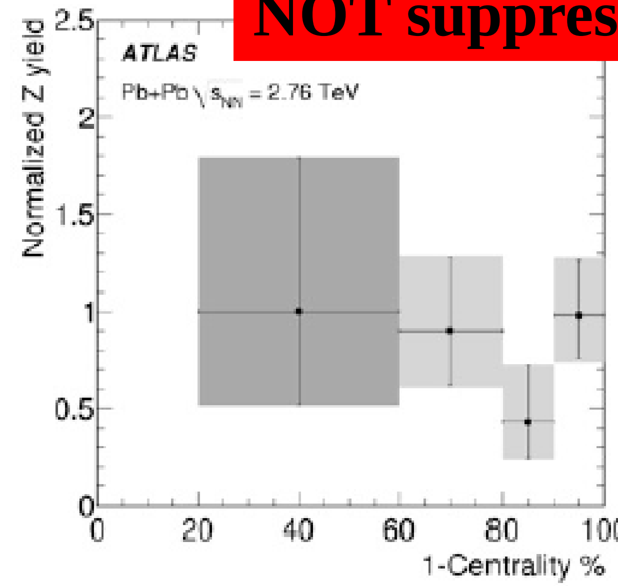
Non colour probes

- $R_{AA}(p_T)$ for charged particles produced in 0-5% centrality range
  - minimum (~ 0.14) for p_T ~ 6-7 GeV/c
  - then slow increase at high p_T
  - still significant suppression





NOT suppressed

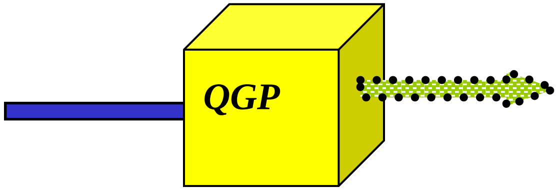


- essential quantitative constraint for parton energy loss models!

Jet quenching

- Jet quenching = Energy loss of fast parton in matter
  - **jet(parton) E -> jet E' (=E-ΔE) + soft gluons (ΔE)**
  - **modified jet fragmentation function f(z)** (= number & energy distribution of hadrons) via matter **induced gluon radiation**/scattering
- QCD energy loss $\Delta E = f(m) \times c_q \times q \times L^2 \times f(E)$ depends on:
  - **q** : 'transport coefficient ' = property of medium (QGP >> nuclear matter)
  - **L**: size of medium (~ L^2)
  - c_q: parton type (gluon > quark)
  - **f(*m*)** : quark mass (light q > heavy Q)
  - **f(*E*)** : jet energy (ΔE = constant or ~ ln(E))

beams of hard probes

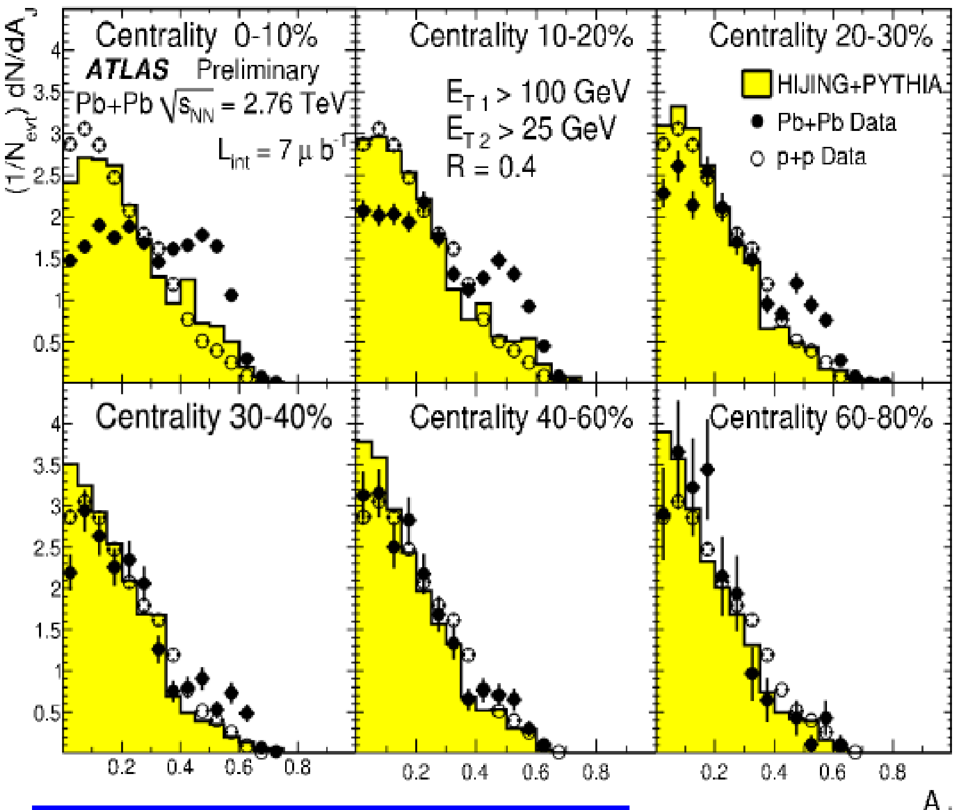


1) How much energy is lost ?
measure 'hard' fragments
2) Where (and how) is it lost ?
3) Shows expected scaling ?

How much is lost ?

- imbalance quantified by the di-jet asymmetry variable A_J :

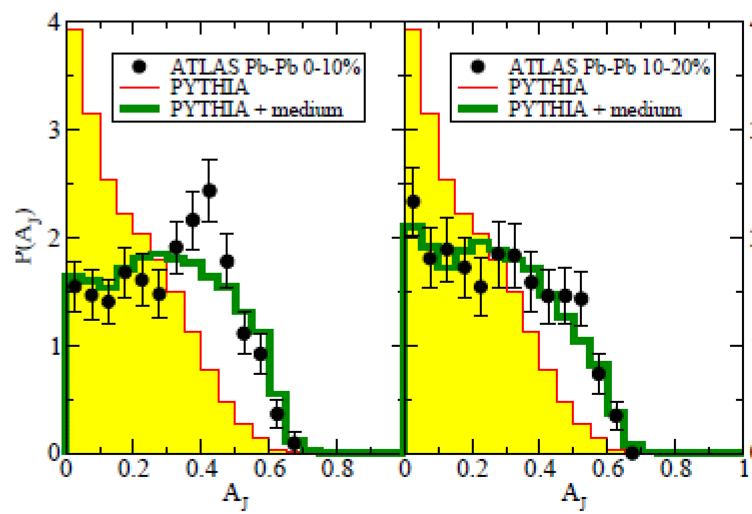
$$R = 0.4 \qquad |\eta| < 2.8$$



ATLAS: PRL105 (2010) 252303

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \qquad \begin{array}{l} E_{T1} > 100 GeV \\ E_{T2} > 25 GeV \end{array}$$

- with increasing centrality:
  - → enhancement of asymmetric di-jets with respect to pp
  - → & HIJING + PYTHIA simulation
- **ΔE~20 GeV**
- **Consistent with RHIC**

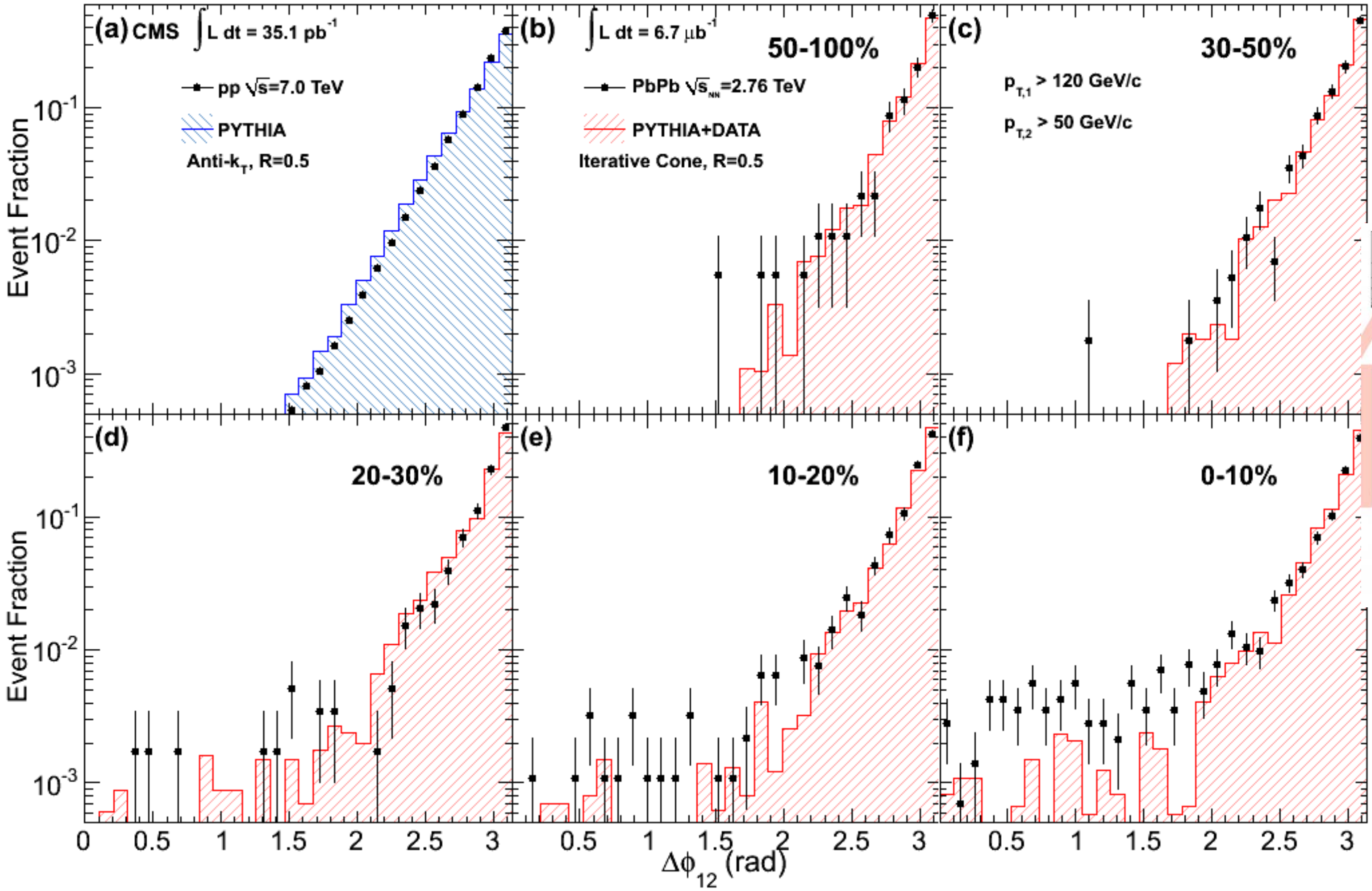


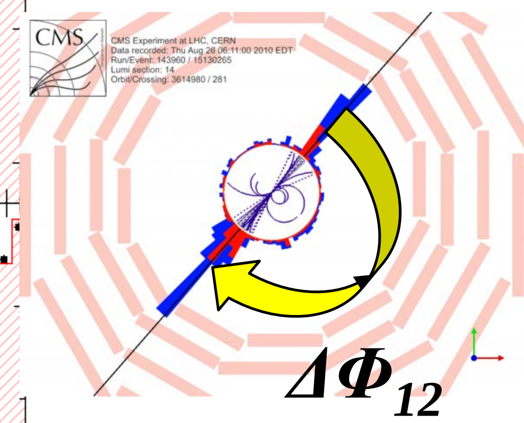
Qin,Muleer:Phys.Rev.Lett. 106 (2011) 162302

gham

Where is it lost ?

No visible angular decorrelation in Δφ wrt pp collisions!





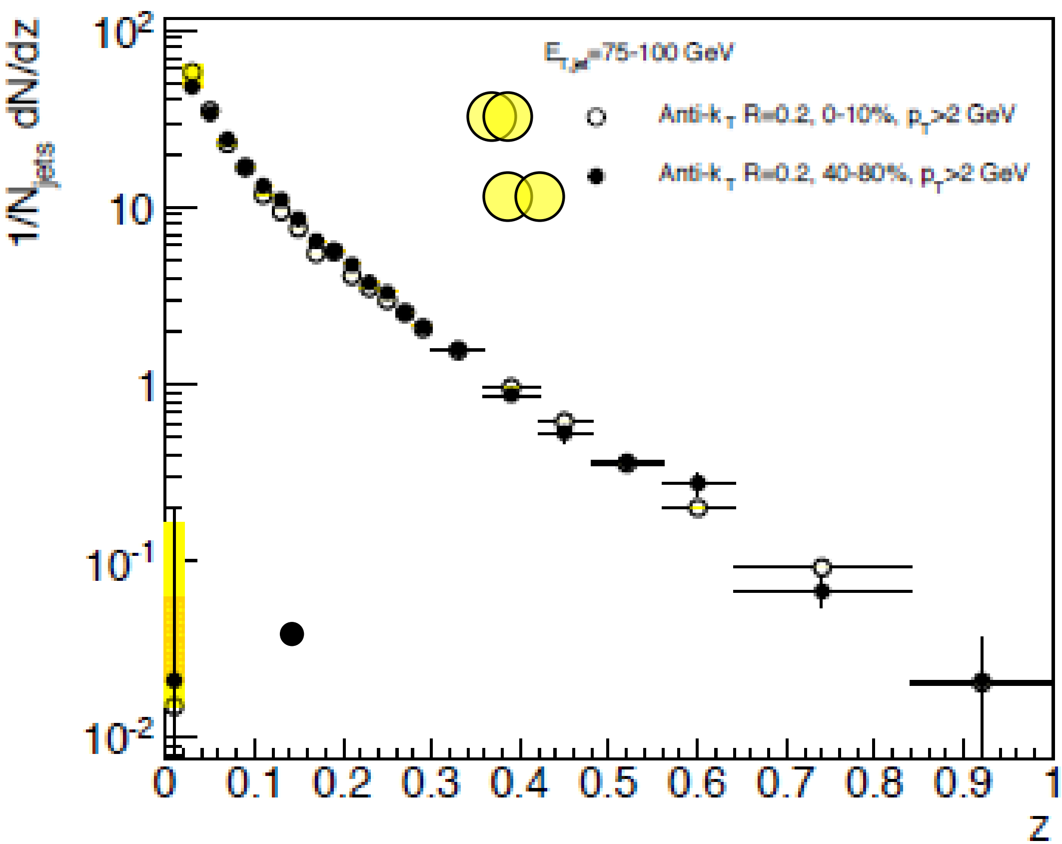
CMS: arXiv:1102.1957

→ large imbalance effect on jet energy, but very little effect on jet direction!

How is it lost ?

Jet fragmentation function

- distribution of the momenta of the fragments along the jet axis



Brian Cole – ATLAS (QM2011)

$$z = \frac{p_T^{hadron} \cdot \cos(\Delta R)}{E_T^{jet}}$$

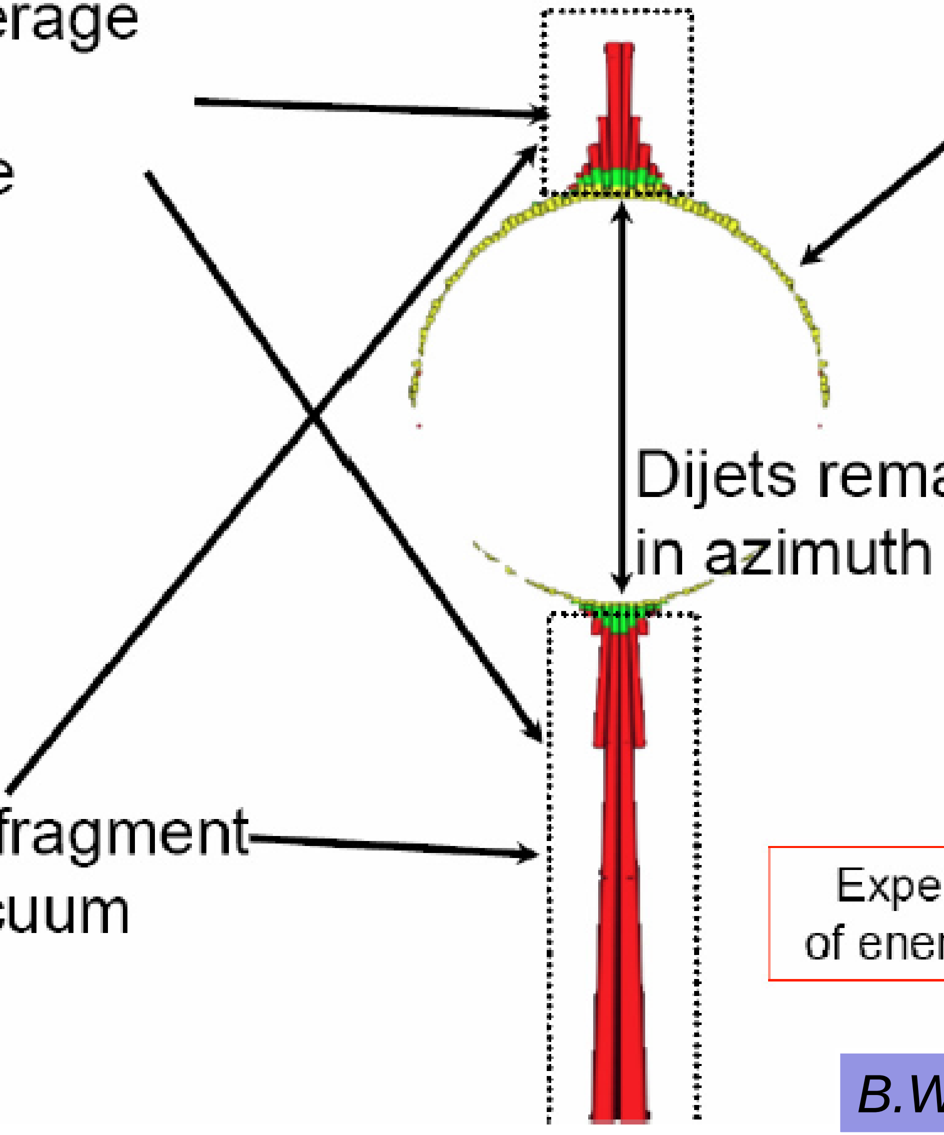
- **distribution is very similar in central and peripheral events**
  - although quenching is very different…

→ apparently no effect from quenching inside the jet cone…

Jet "quenching": what have we learned so far?

Large average dijet p_T imbalance

p_T difference is found at low p_T far away from jet



Dijets remain back-to-back in azimuth

Partons fragment as in vacuum

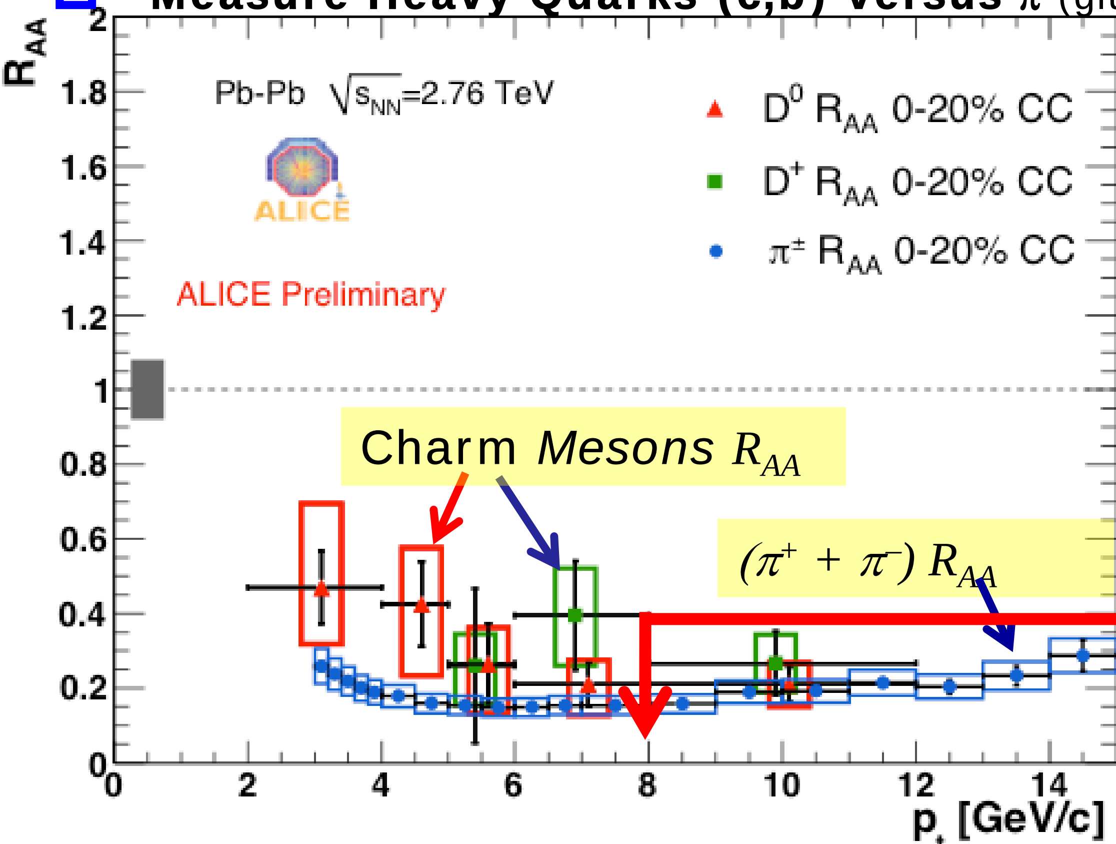
Experimental characterization of energy flow in dijet final states

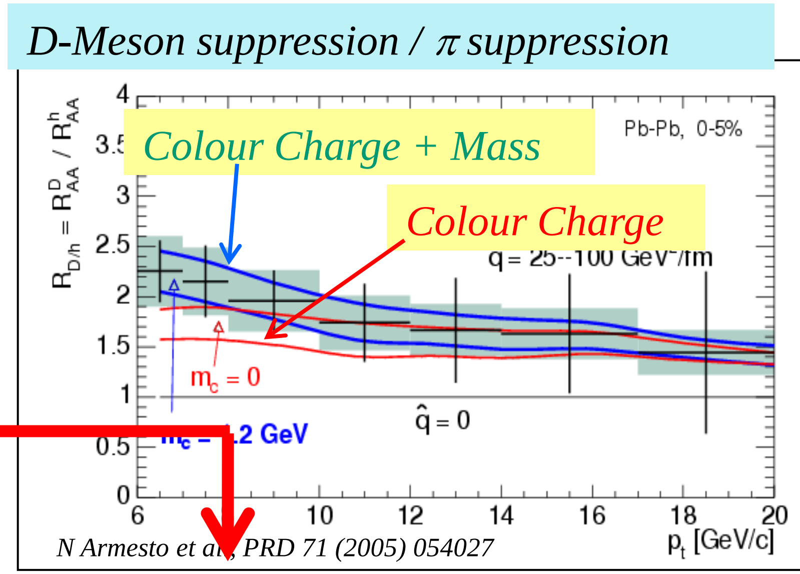
B.Wyslouch, CMS, EPIC2011

S. Mehdiabadi

Mass & Colour Charge Dependence

- **Measure Heavy Quarks (c,b) versus π** (gluon fragmentation dominates π at LHC)





- **R_{AA} <u>prompt</u> charm ≈ R_{AA} <u>pions</u> for p_T > 5-6 GeV**

  expected difference factor 2 @ 8 GeV

- R_{AA} charm > R_{AA} π for p_T < 5 GeV ?

jet quenching

$\Delta E \sim f(m) \times c_q \times \hat{q} \times L^2 \times f(E)$

Needs better statistics & quantitative comparison with other models

Summary

- Journey started ~35 years ago: QGP was presumed
- QGP observed at LHC !
  - **Collective flow**
    - **Strongly interacting liquid – hydro works**
    - Estimate of viscosity ?
  - **Jet quenching**
    - **Back to back jets strongly suppressed**
    - Dynamic of quenching ?
  - Quarkonia dissolution versus recombination ?
  - Heavy flavour: Are heavy quarks really suppressed as much as light quarks and gluons ?
- **HI SM Model describing simultaneously all observables !**

Superdense Matter: Neutrons or Asymptotically Free Quarks?

J. C. Collins and M. J. Perry
Mathematics and Theoretical Physics, University of Cambridge,
Cambridge CB3 9EW, England

(Received 6 January 1975)

Our basic picture then is that matter at densities higher than nuclear consists of a quark soup. The quarks become free at sufficiently high density. A specific realization is an asymptotically

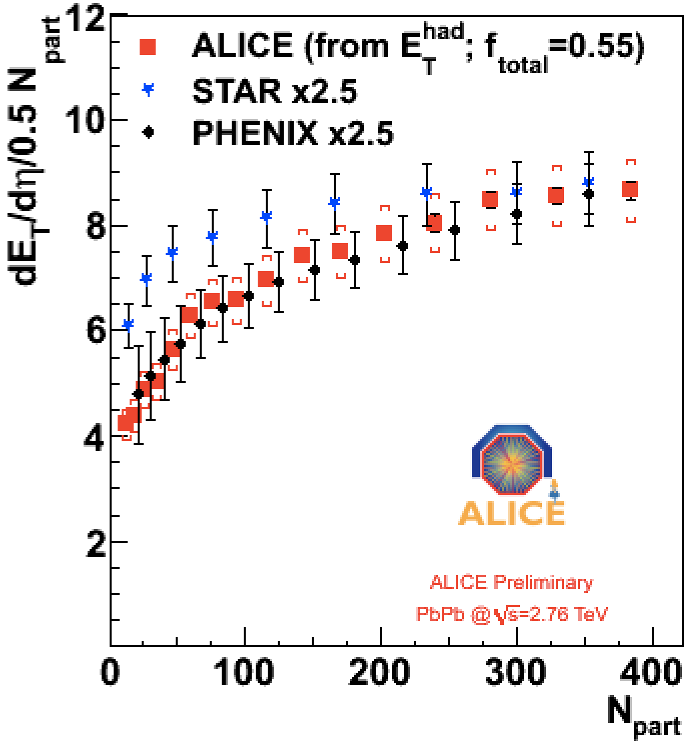
The journey to terra incognita of heavy ions continues!

Back up

Energy density

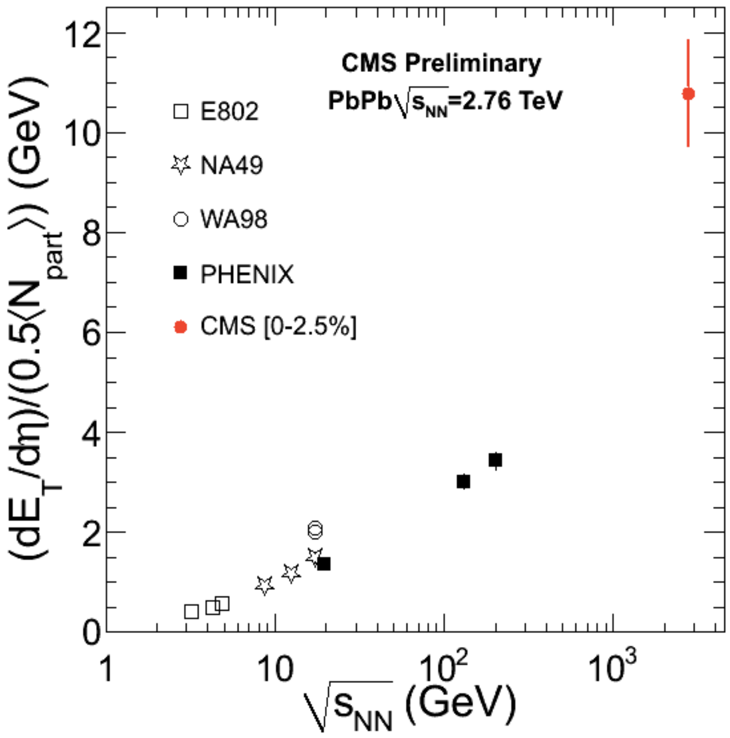
Transverse energy density per participant pair: 2.5 x RHIC

Consistent with 20% increase in <pt>



J.Harris, ALICE, EPIC2011

B.Wyslouch, CMS, EPIC2011

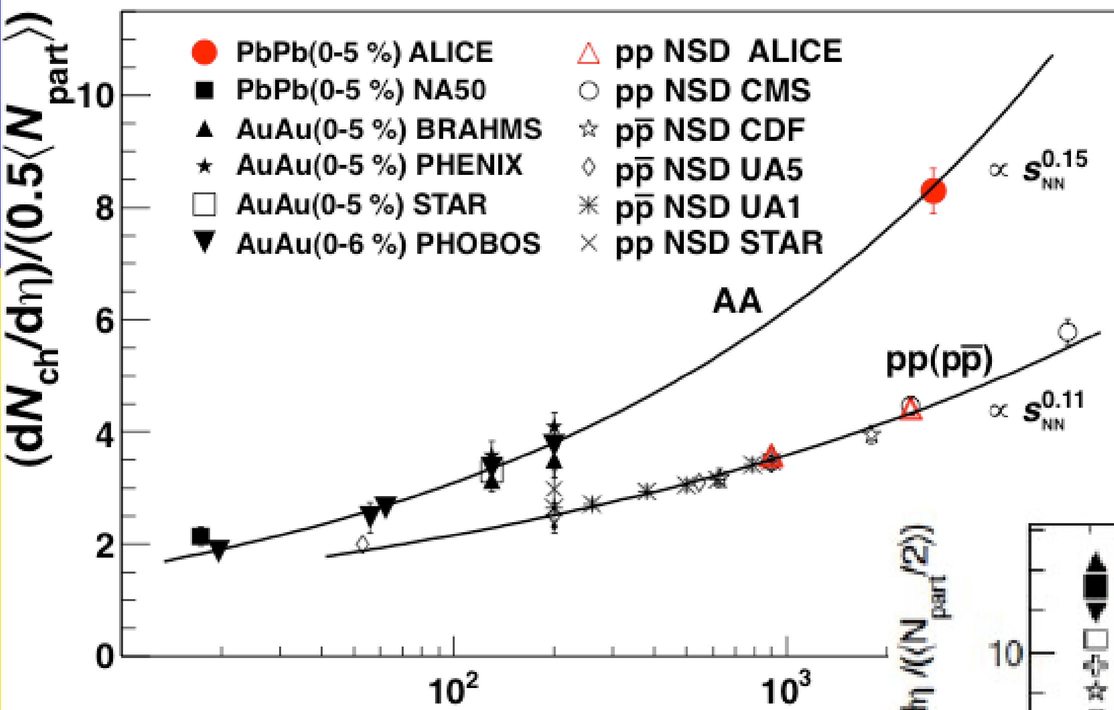


Bjorken energy density x time: 2.8

for 5% of most central collisions

$$\varepsilon = \frac{1}{\pi R^2 \tau}\frac{dE_t}{dy} \qquad R = 1.12\ A^{1/3} fm$$

Energy dependence



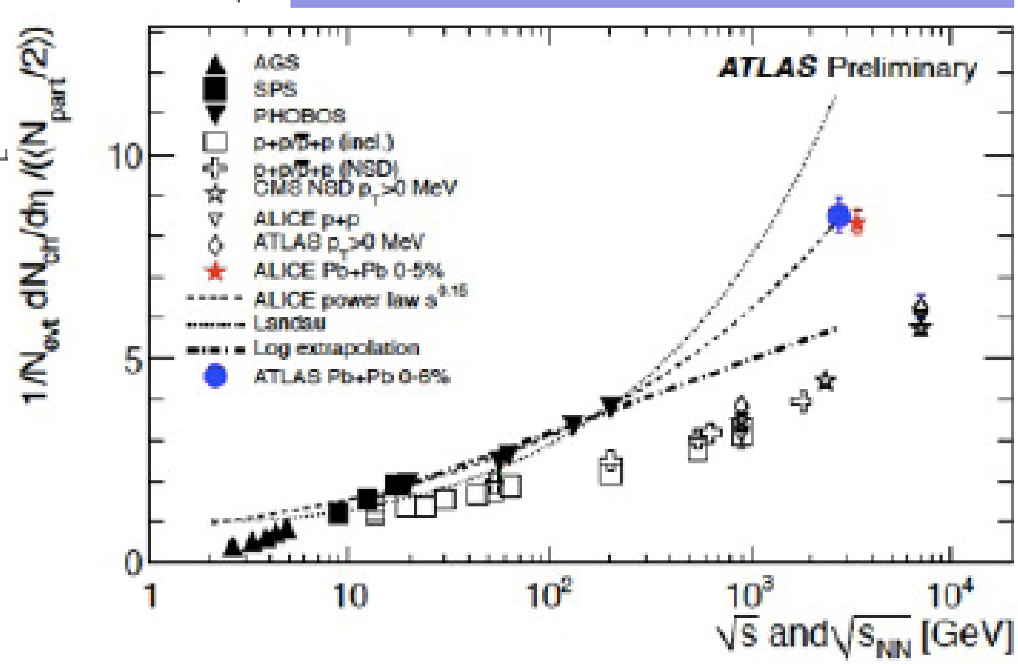
- *growing faster then pp*

-2.2 compared to RHIC

-1.9 compared to pp

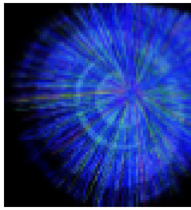
S.White, ATLAS,EPIC2011

M.Nicassio, ALICE, EPIC2011



Agreement among experiments

Charged Particle Multiplicity Density at mid-Rapidity

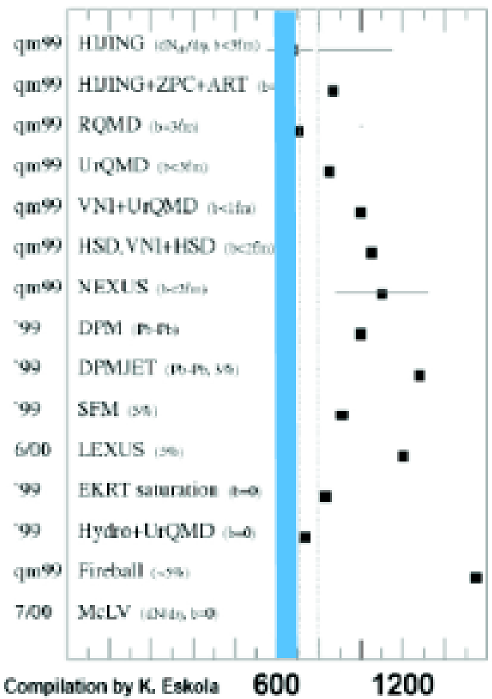


$$\left.\frac{dN^{AA}_{ch}}{d\eta}\right|_{\eta=0}$$

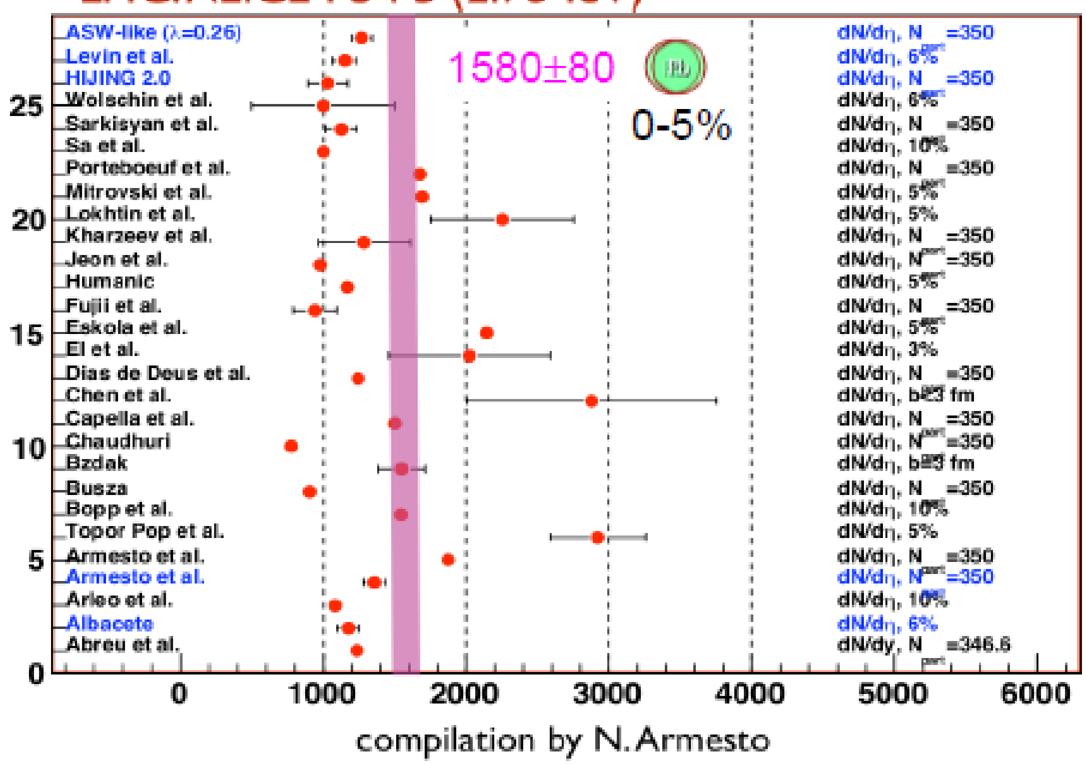
At RHIC the low charge particle multiplicity was a surprise and ruled out most of the models ...

No wonder, predictions for LHC were a little bit on the low side ...

RHIC: PHOBOS Au-Au (0.2 TeV)



LHC: ALICE Pb-Pb (2.76 TeV) Phys. Rev. Lett. 106, 032301 (2011)



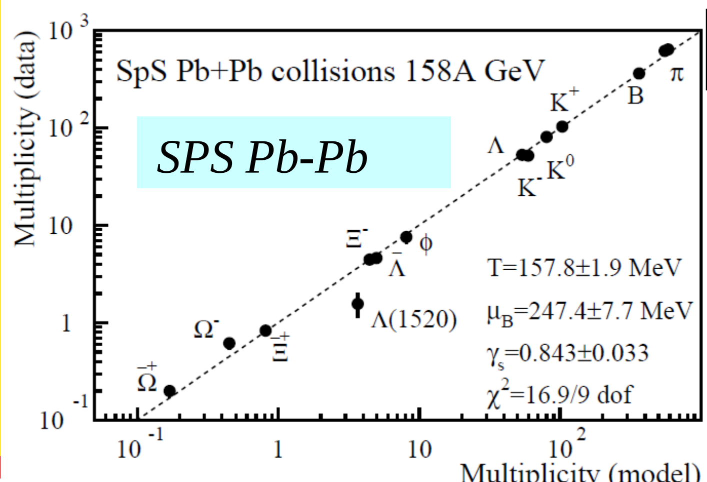
Particle ratios

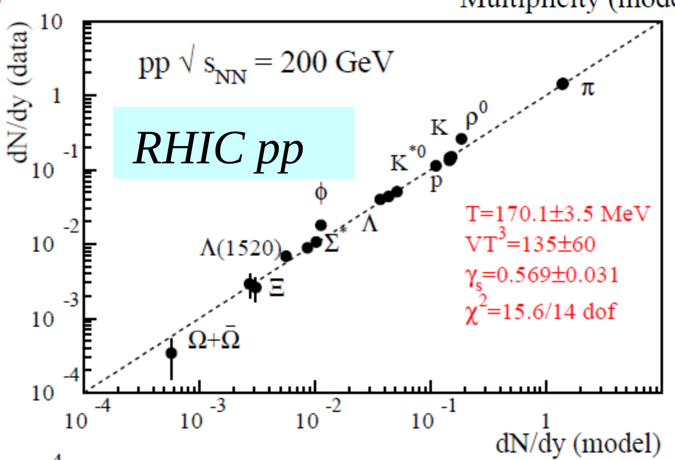
In general well described (~10%) by statistical (thermal) model

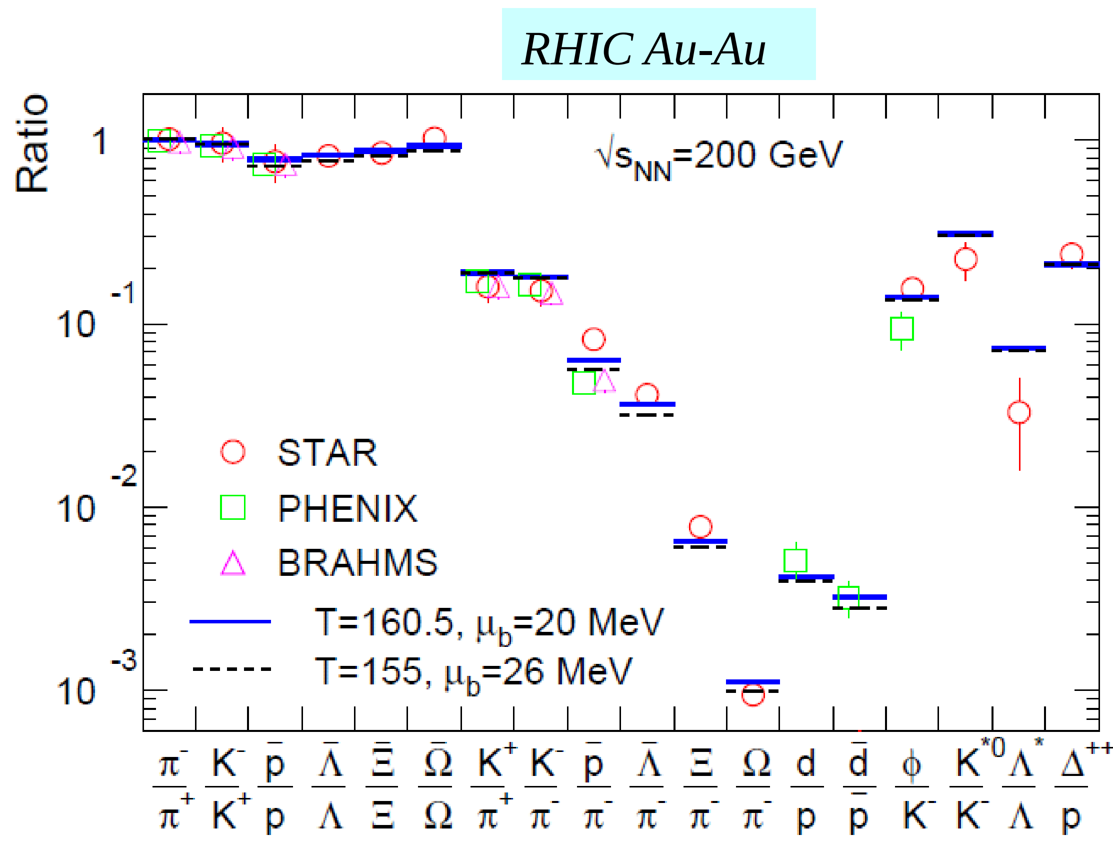
- $P(m) \sim e^{-(m/T)}$
  - **T** Temperature
  - μ_b Baryo-chemical potential
  - γ_s Strangeness suppression

$$N_i/V = \frac{g_i}{(2\pi)^3}\gamma_S^{S_i}\int \frac{1}{\exp\left(\frac{E_i-\mu_B B_i-\mu_S S_i}{T_{chem}}\right)\pm 1}d^3p,$$

T_{ch}: 160-170 MeV γ_s : 0.9-1 (AA), 0.5-0.6 (pp)

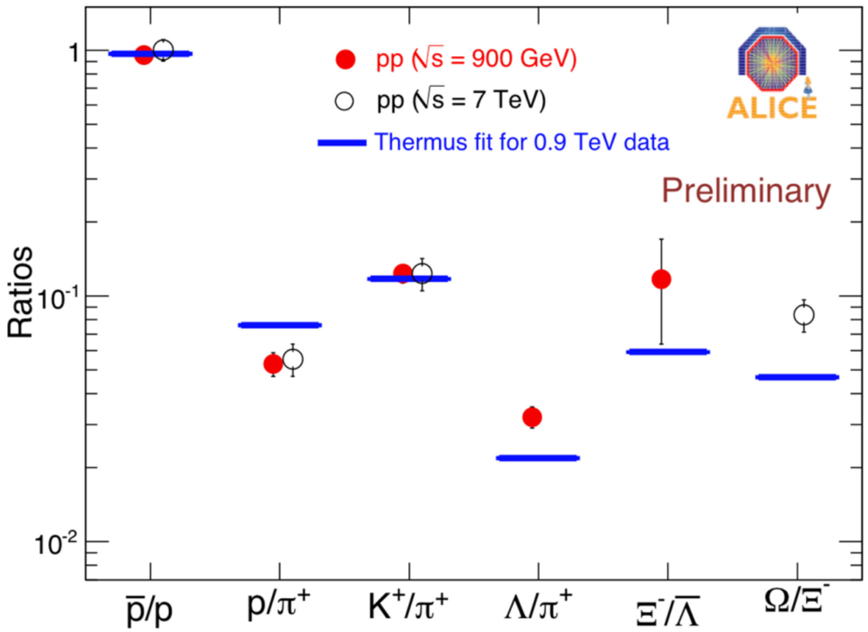






Thermal model at LHC

pp: 900 GeV & 7 TeV



pp:

-Thermal fit rather poor

Pb-Pb:

- **K/π** grows slightly from pp value

-**p/π** ≈ like pp

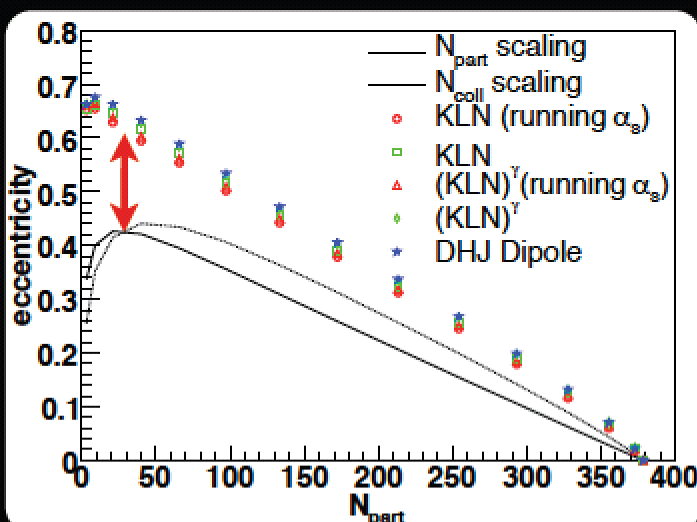
-p/π off by factor > 1.5 from thermal predictions !

but very compatible with RHIC !!

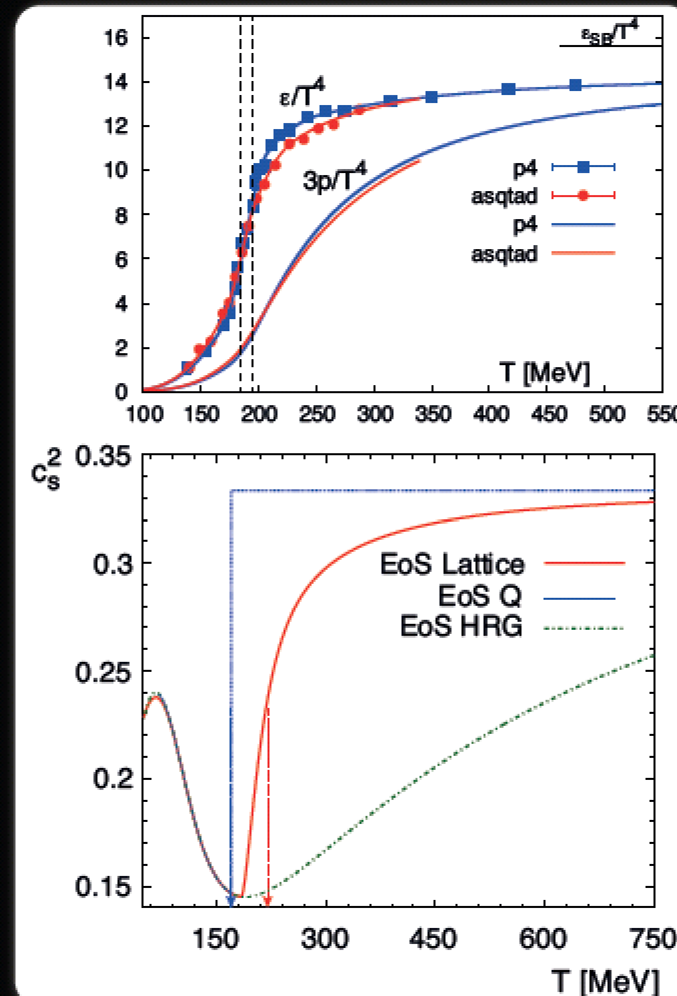
Before we can conclude anything
we need more particle species..

Physics of elliptic flow

Elliptic flow v_2 depends on fluid properties: the EoS via $c_s^2 = \frac{\partial p}{\partial \varepsilon}$, shear viscosity over entropy ratio η/s but also on: initial conditions: particular initial spatial eccentricity ε_2



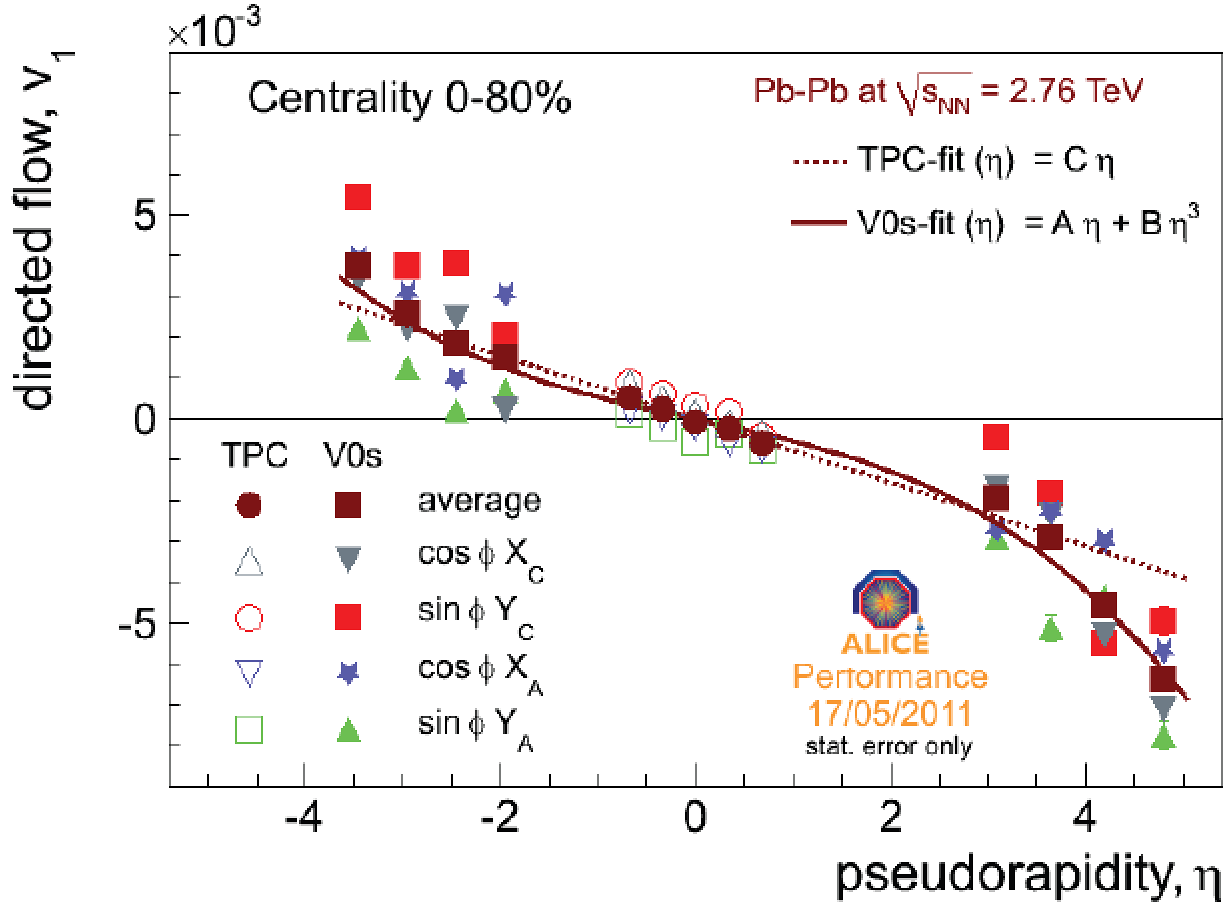
H-J. Drescher et al., Phys.Rev.C74:044905,2006



10

Adopted from R.Snellings

Direct flow

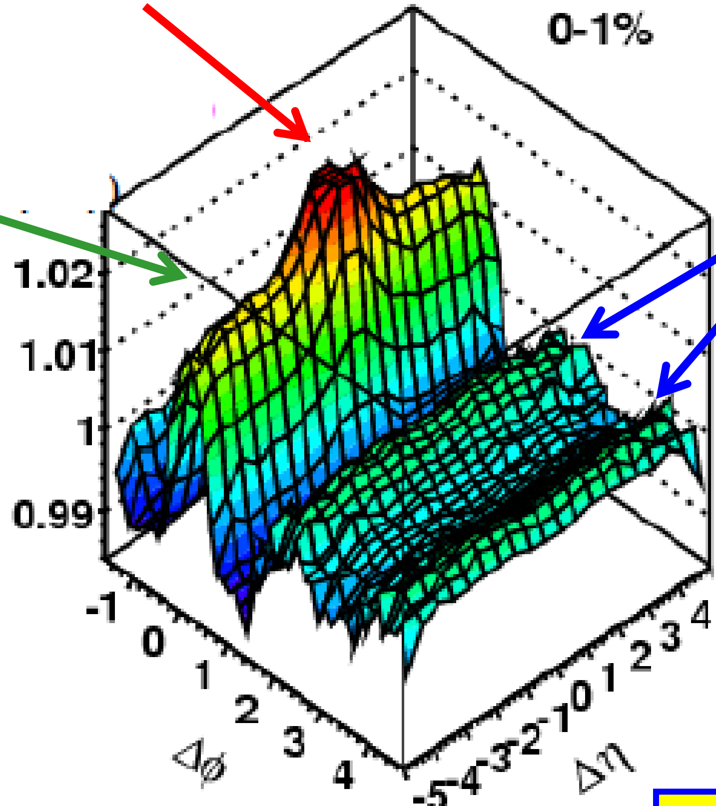


G. Eyyubova QM2011

Structures in (Δη,Δφ)

near side jet peak

long range structure
in η on near side
aka "the ridge"



two shoulders
on away side
(at 120° and 240 °)
aka "the Mach cone"

ATLAS-CONF-2011-074

Fourier analysis at large Δη, moderate p_T

Near side jet excluded by $|\Delta\eta| > 0.8$ gap

Ridge at Δφ=0 remains

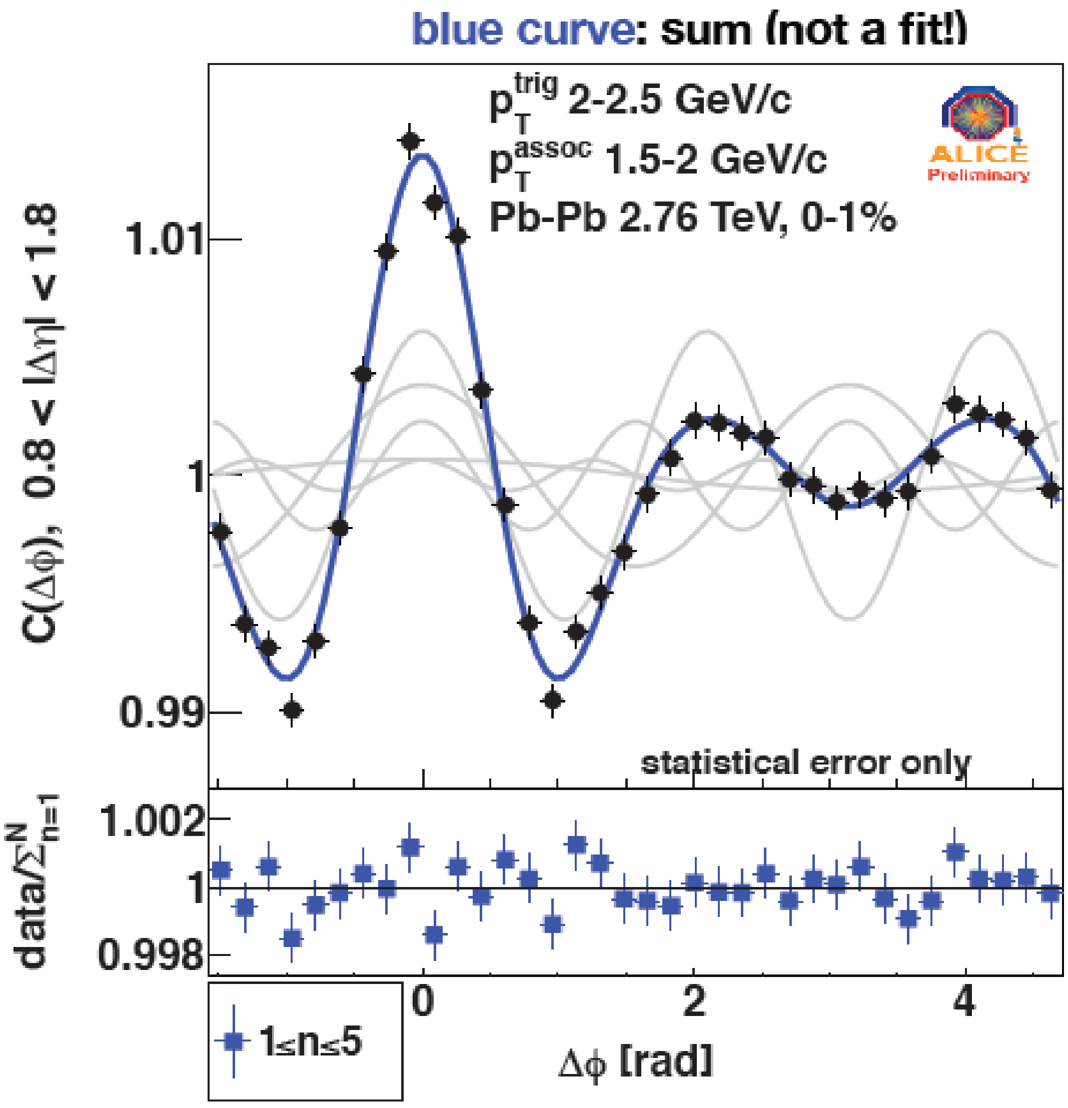
2-particle Fourier coeffs.

Extract directly from C(Δφ):

$$\langle \cos n\Delta\phi \rangle = \frac{\int d\Delta\phi \, C(\Delta\phi) \cos n\Delta\phi}{\int d\Delta\phi \, C(\Delta\phi)}$$

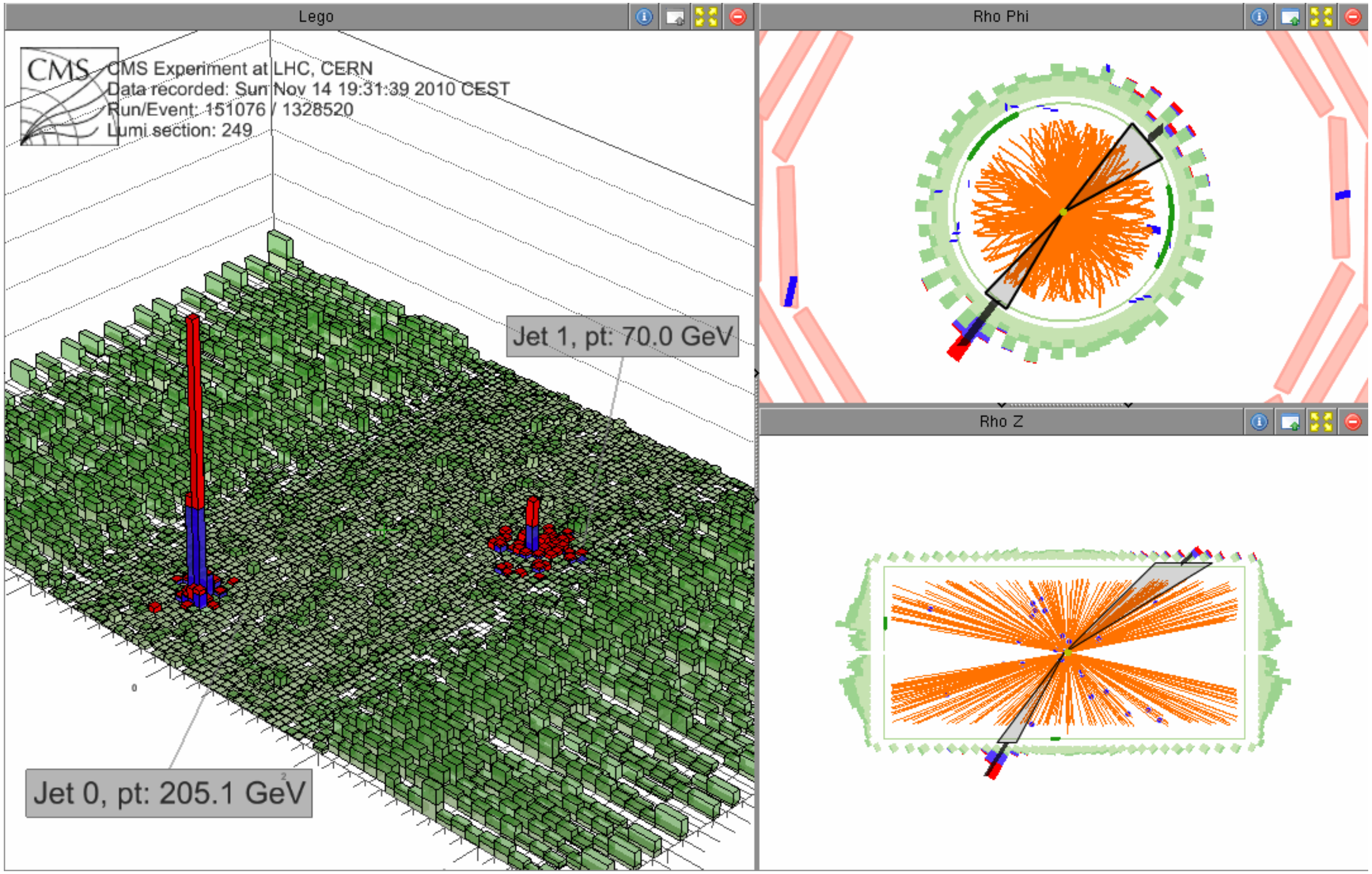
Here, the first 5 moments describe shape at per-mille level.

Andrew Adare – ALICE



Di-jet imbalance

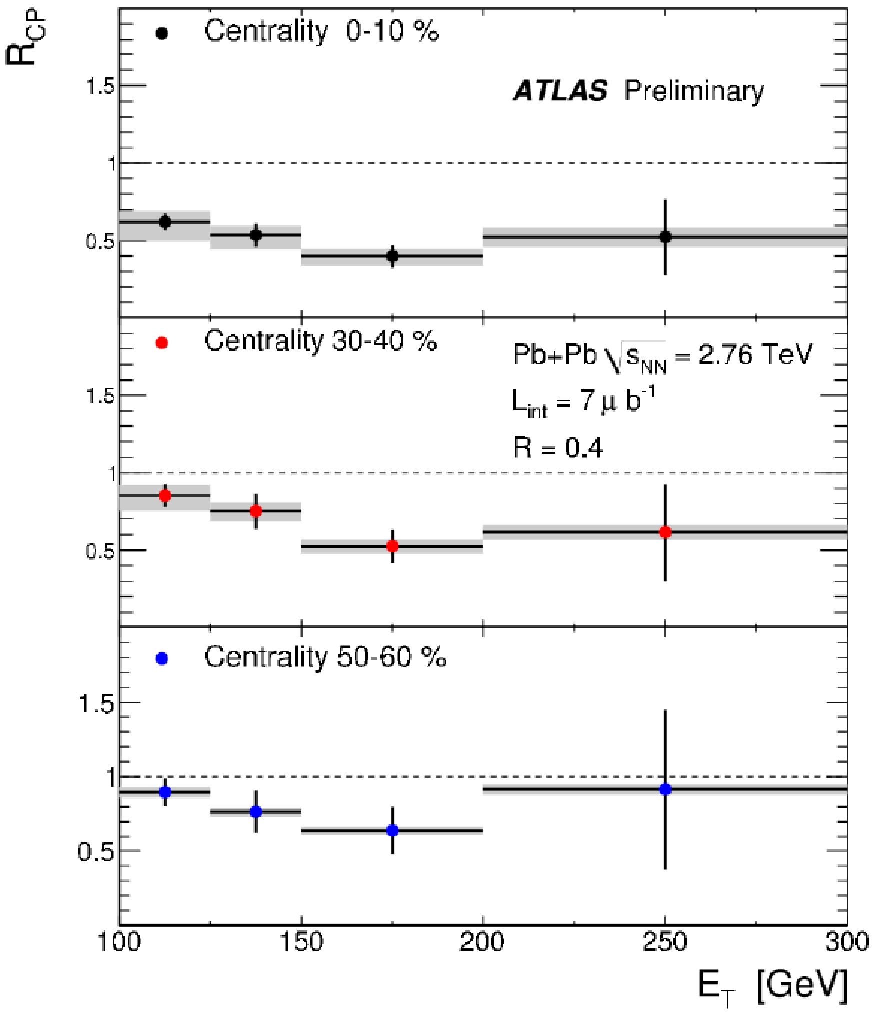
- Pb-Pb events with large di-jet imbalance observed at the LHC



→ recoiling jet strongly quenched!

CMS: arXiv:1102.1957

Jet nuclear modification factor



$$R_{CP} = \frac{<Nbin>_{Central}\ \mathrm{Yield}_{Central}}{<Nbin>_{Peripheral}\ \mathrm{Yield}_{Peripheral}}$$

→ substantial suppression of jet production

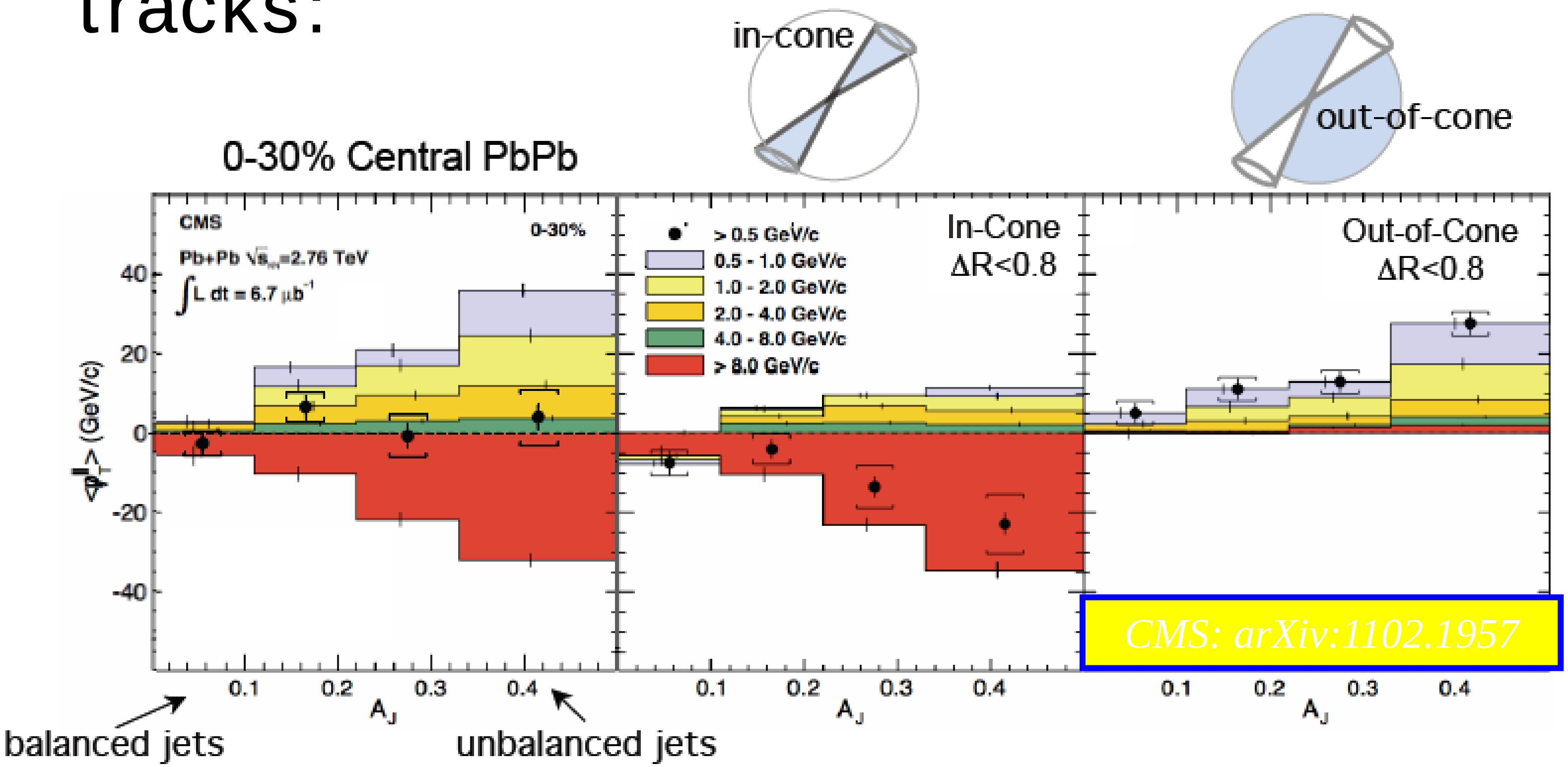
- in central Pb-Pb wrt binary-scaled peripheral

→ out to very large jet energies!

Brian Cole – ATLAS (QM2011)

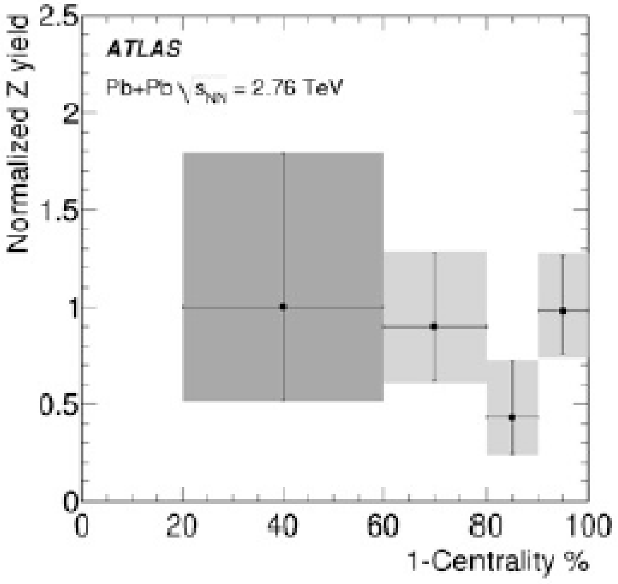
Where does the energy end up?

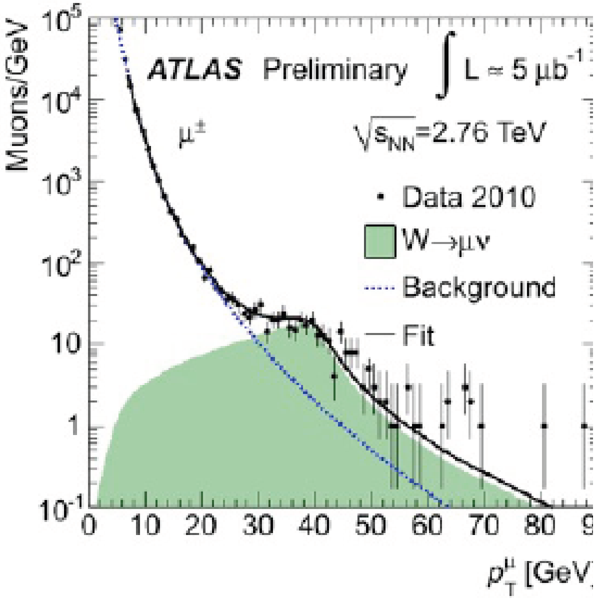
- nice analysis by CMS using reconstructed tracks:

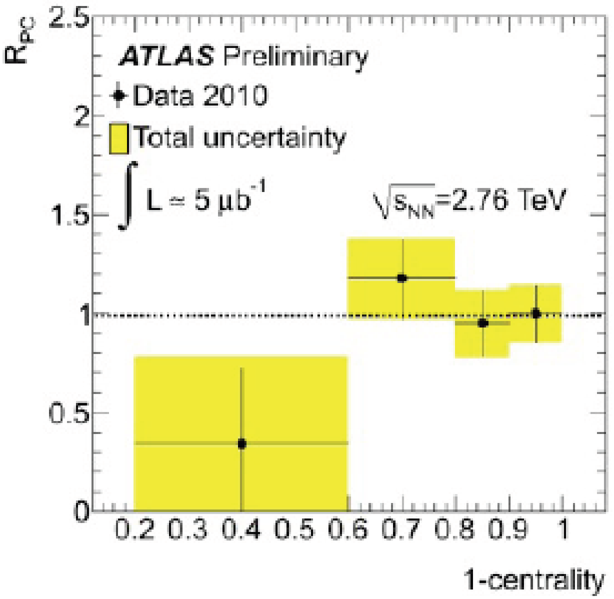


→ momentum difference is balanced by low momentum particles outside of the jet cone

Z and W from ATLAS

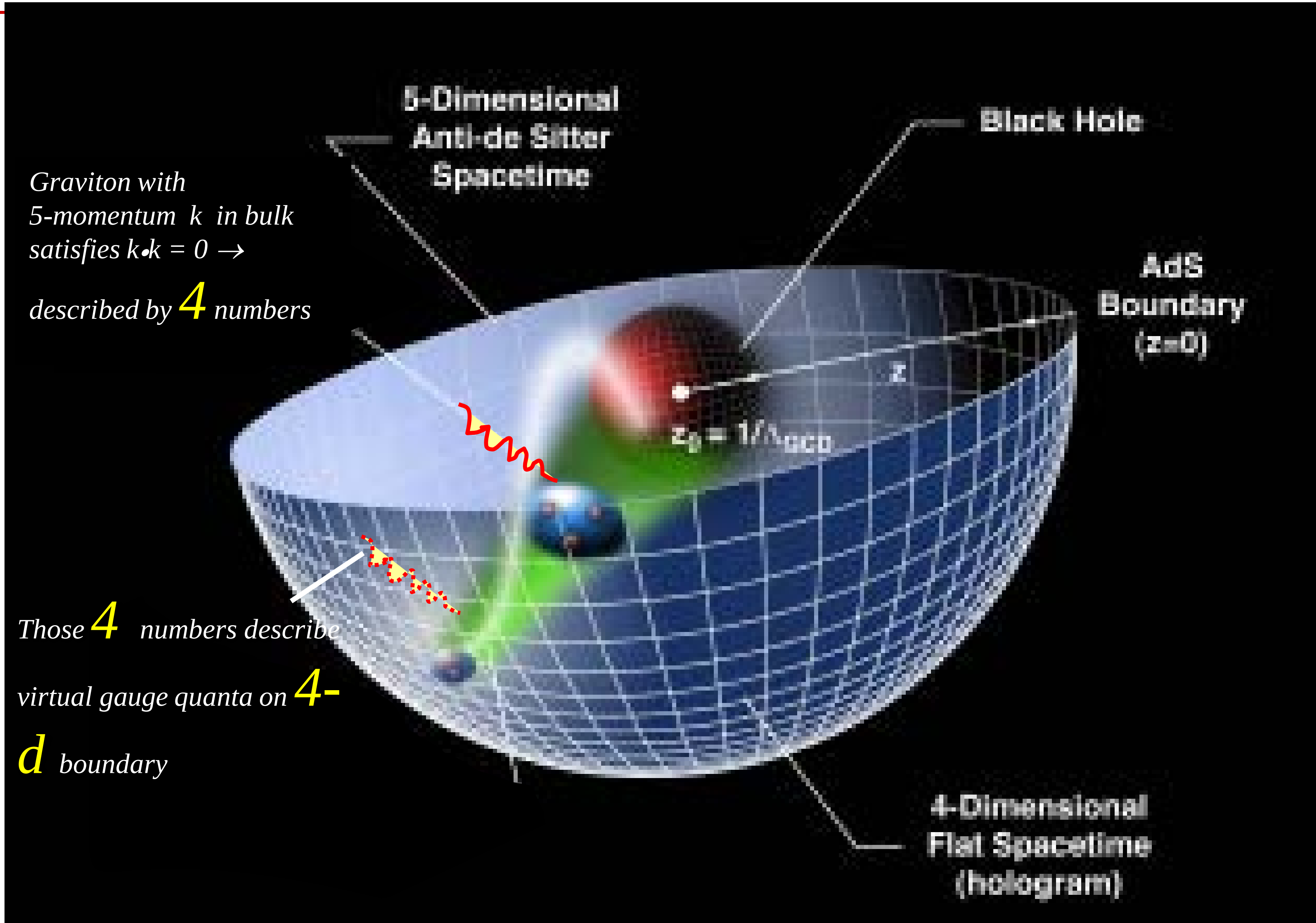






S.White, ATLAS, EPIC 2011

AdS / CFT in a Picture



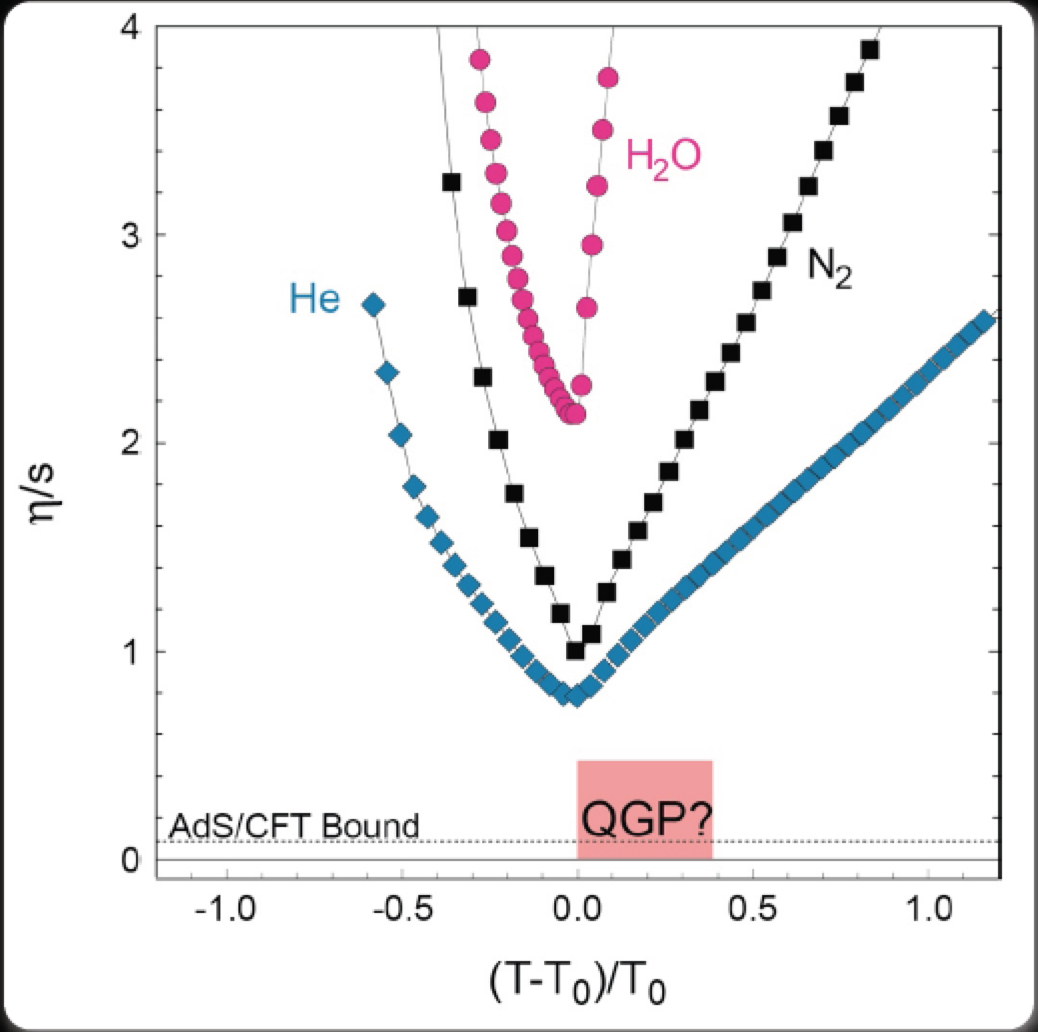
(Adopted from S. Brodsky figure)

The Perfect Liquid?

model calculations suggest that the RHIC v_2 results are close to the ideal hydrodynamical limit.

these calculations place an upper limit on η/s which is smaller than ~ 4 x AdS/CFT bound

main uncertainties on η/s due to uncertainties in the initial conditions and the unknown dependence of η/s versus temperature



Based on R. Lacey et al., Phys.Rev.Lett.98:092301,2007.

Heavy Ion Program