Review of Heavy-Ion Results from the CERN LHC

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ICTDHEP
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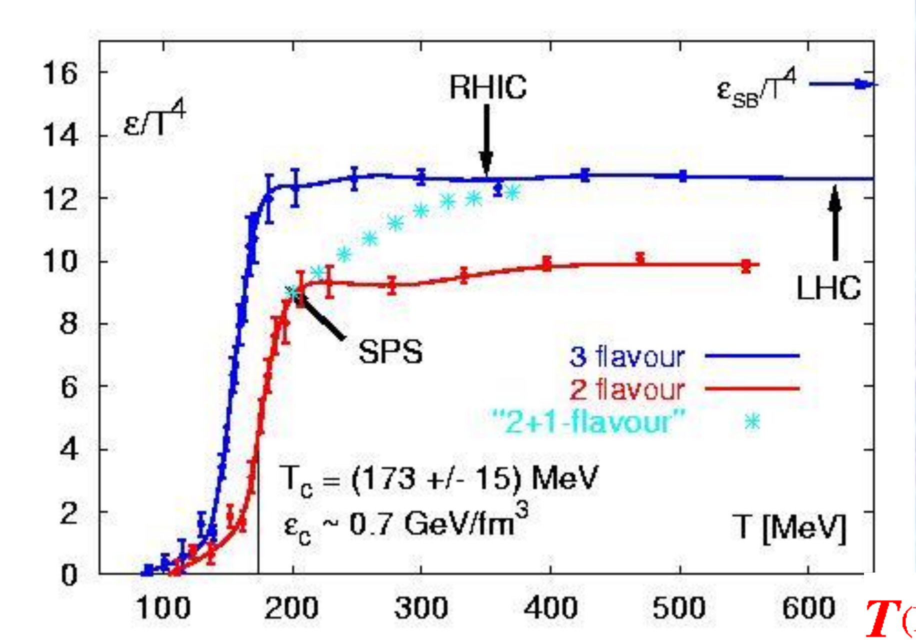
Aims of Heavy-Ion Programme

- Study strongly interacting matter at extreme energy densities over large volumes and long time-scales (study of QCD at its natural scale, Λ_{QCD} ~ 200 MeV).
- Study the QCD phase transition from nuclear matter to a deconfined state of quarks and gluons - The Quark-Gluon Plasma.
- Study the physics of the Quark-Gluon Plasma (QCD under extreme conditions).

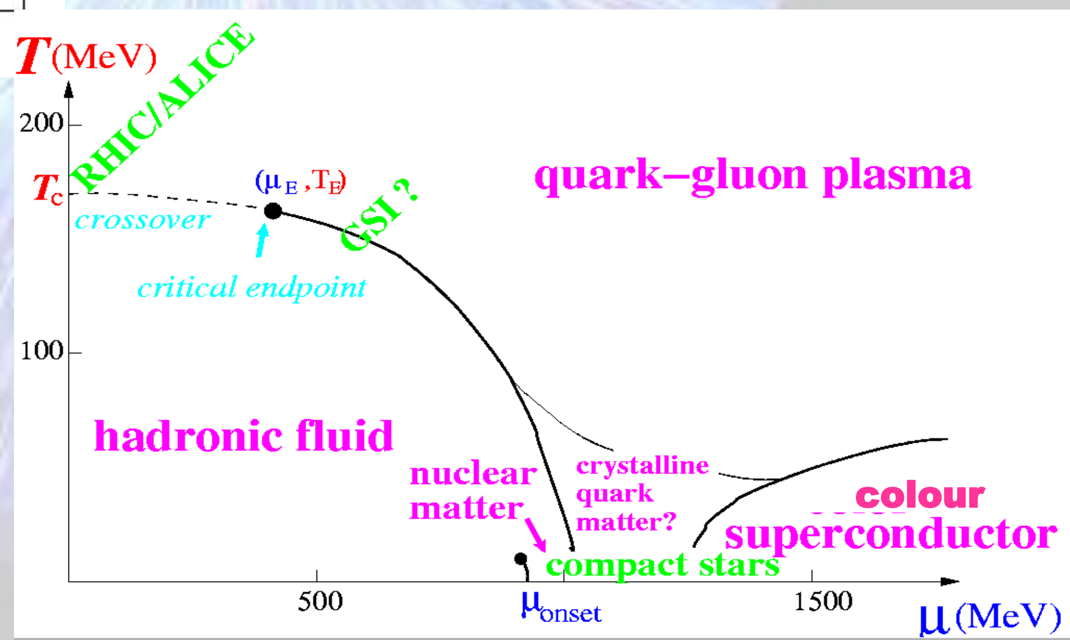
Phases of Strongly Interacting Matter



Lattice QCD, $\mu_B = 0$

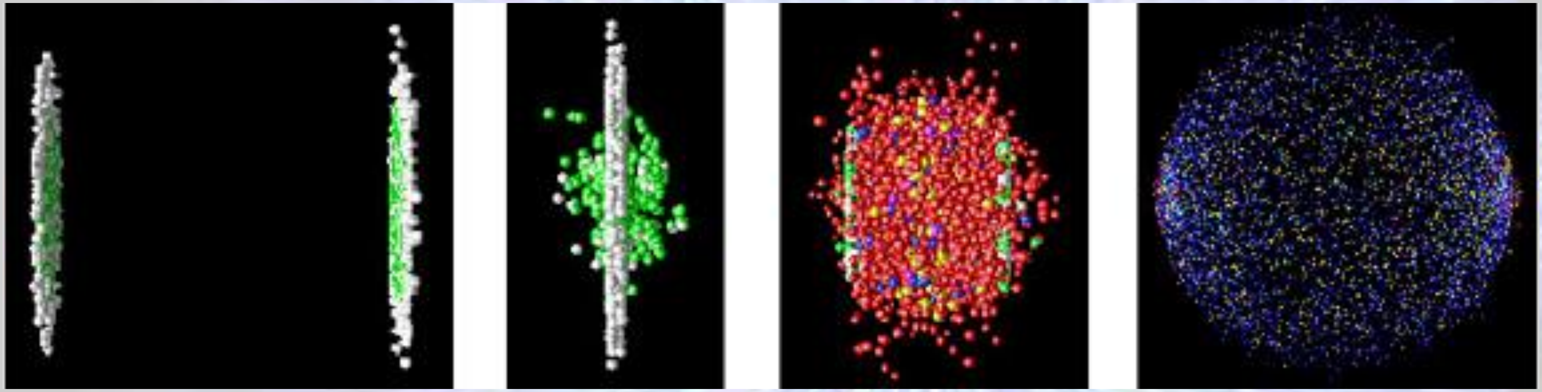
Both statistical and lattice QCD predict that nuclear matter will undergo a phase transition, in to a deconfined state of quarks and gluons – a quark-gluon plasma, at a temperature of,
T ~ 170 MeV and energy density,
$\varepsilon \sim 1\ \mathrm{GeV/fm^3}$.

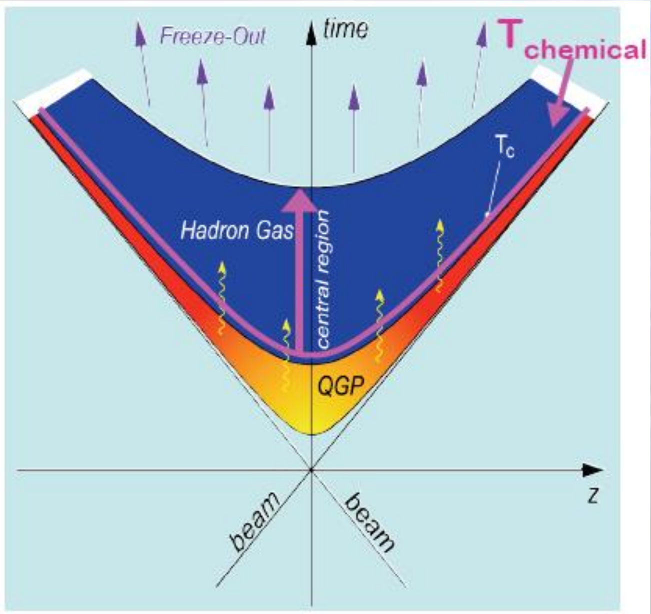
Heavy-Ion collisions far exceed these temperatures & densities at the LHC.



Heavy Ion Collisions

Create QGP by colliding ultra-relativistic heavy ions



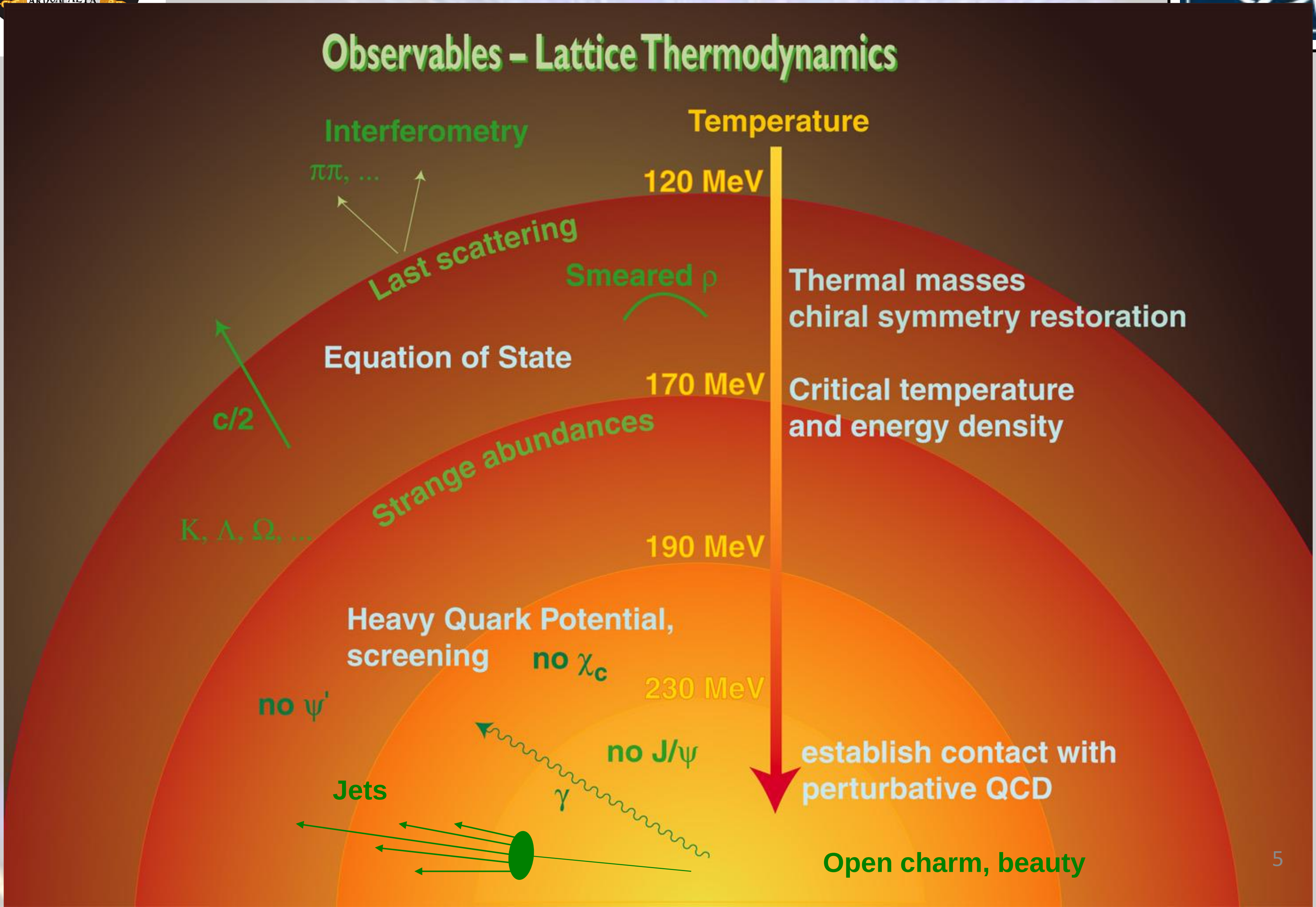


pre-equilibration ⇒ QGP ⇒
hadronisation ⇒ freeze out

Colliders: AGS, SPS, RHIC, LHC

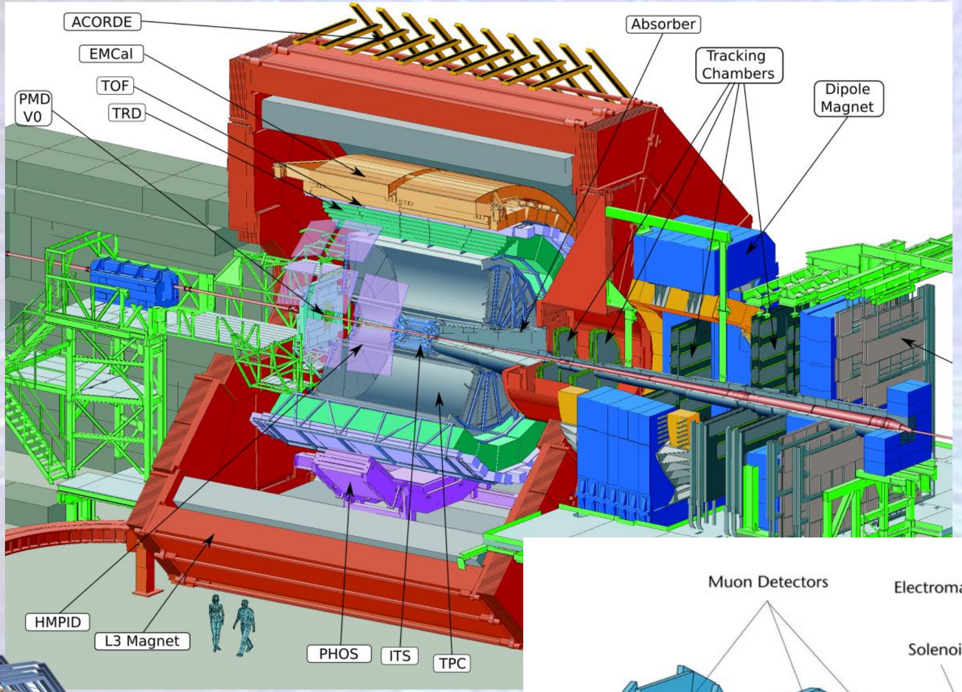
$\sqrt{S_{NN}}$ (GeV) = 5.4 19 200 2760 (5500)

Observables

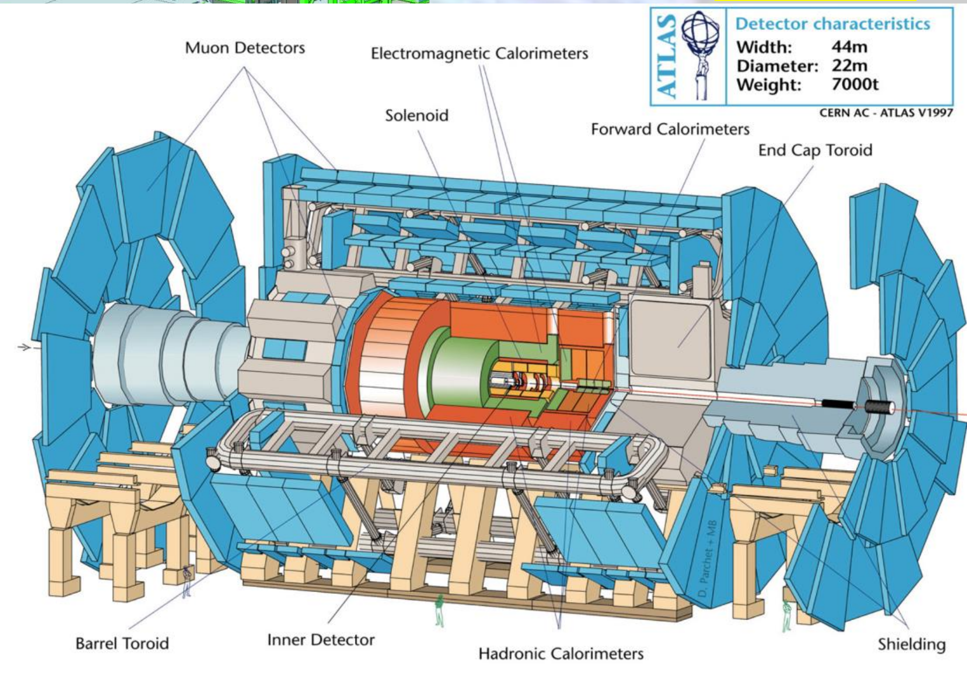


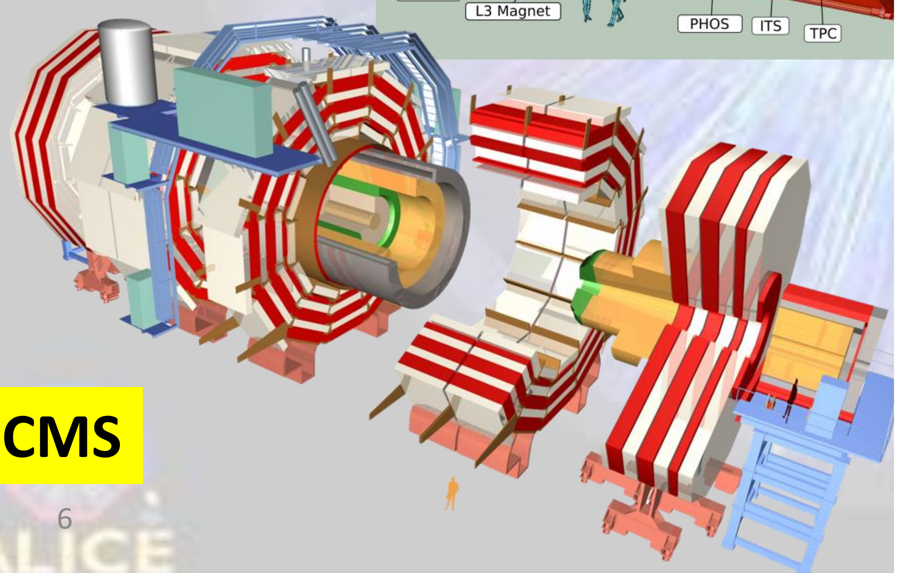
LHC Detectors

ALICE



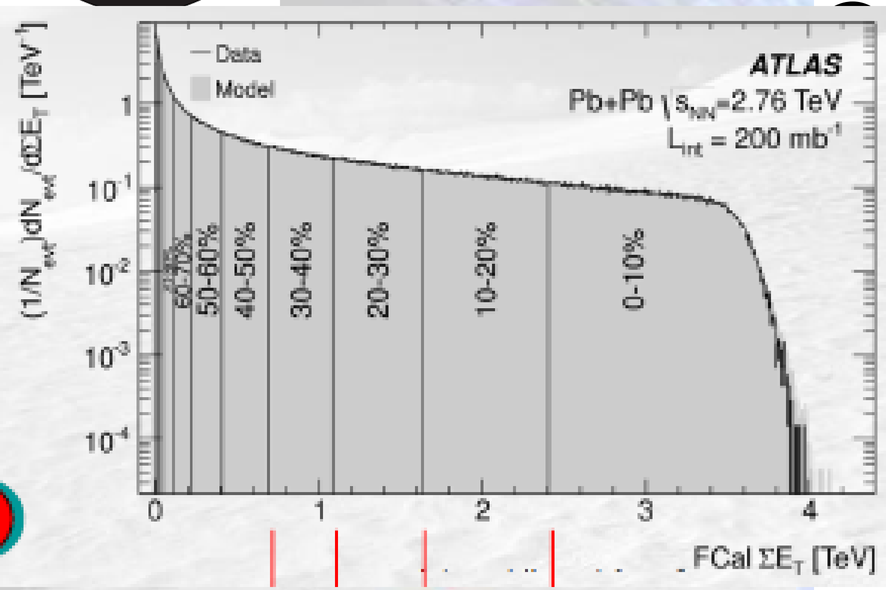
ATLAS

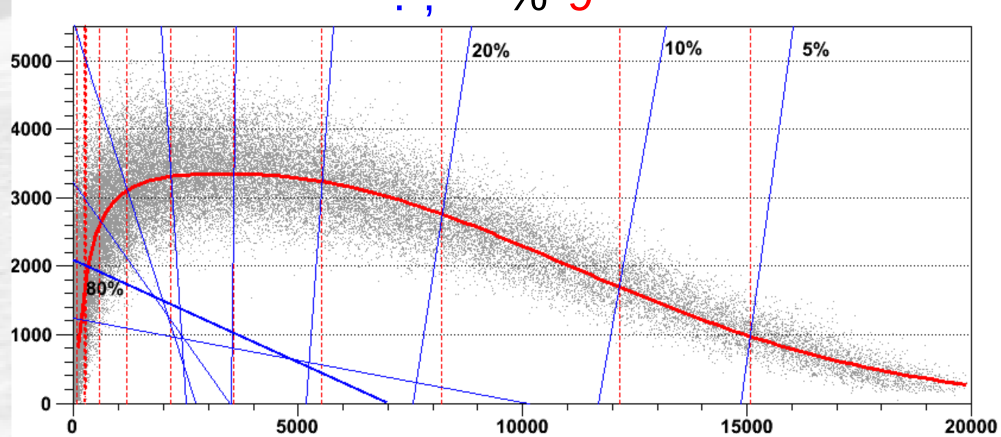


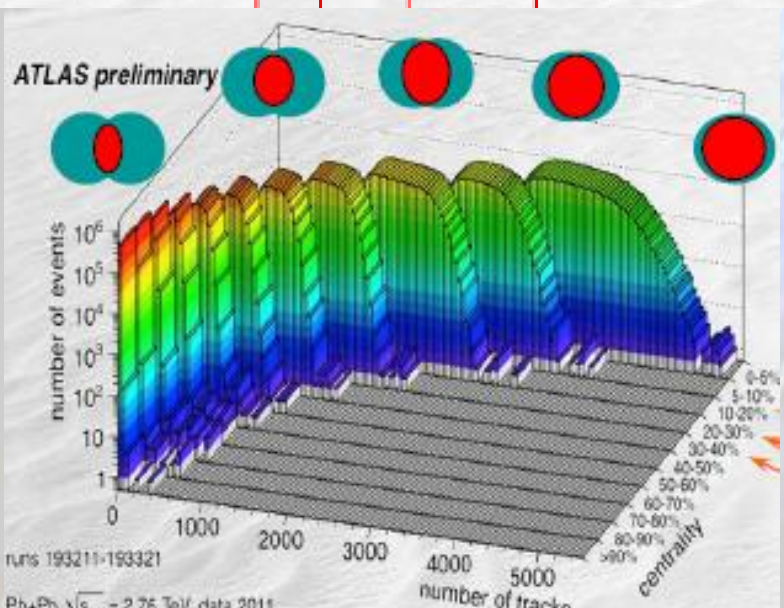


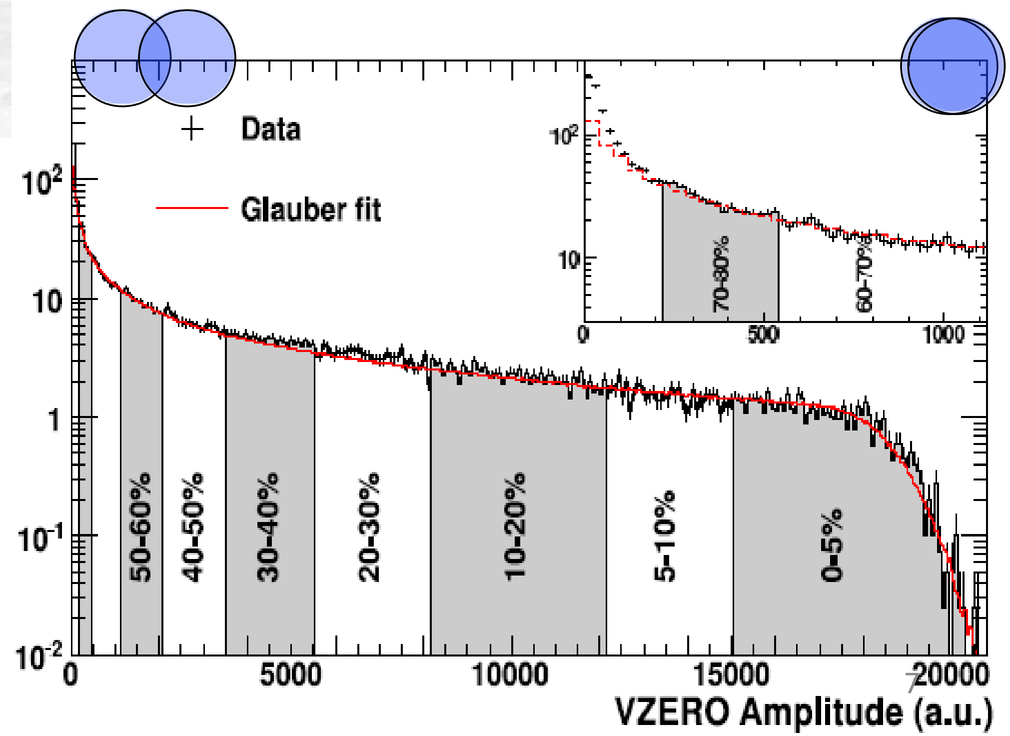
CMS

Centrality Selection – Glauber Model





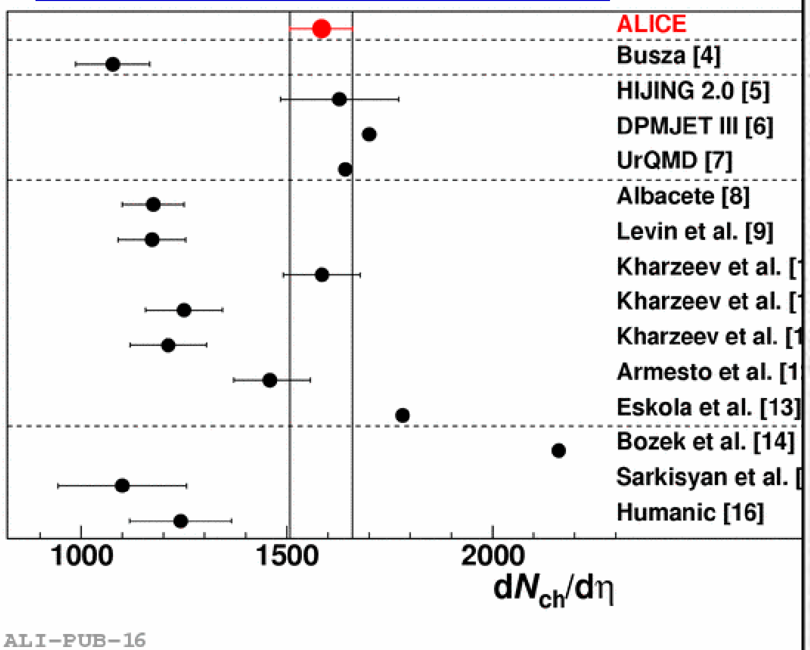




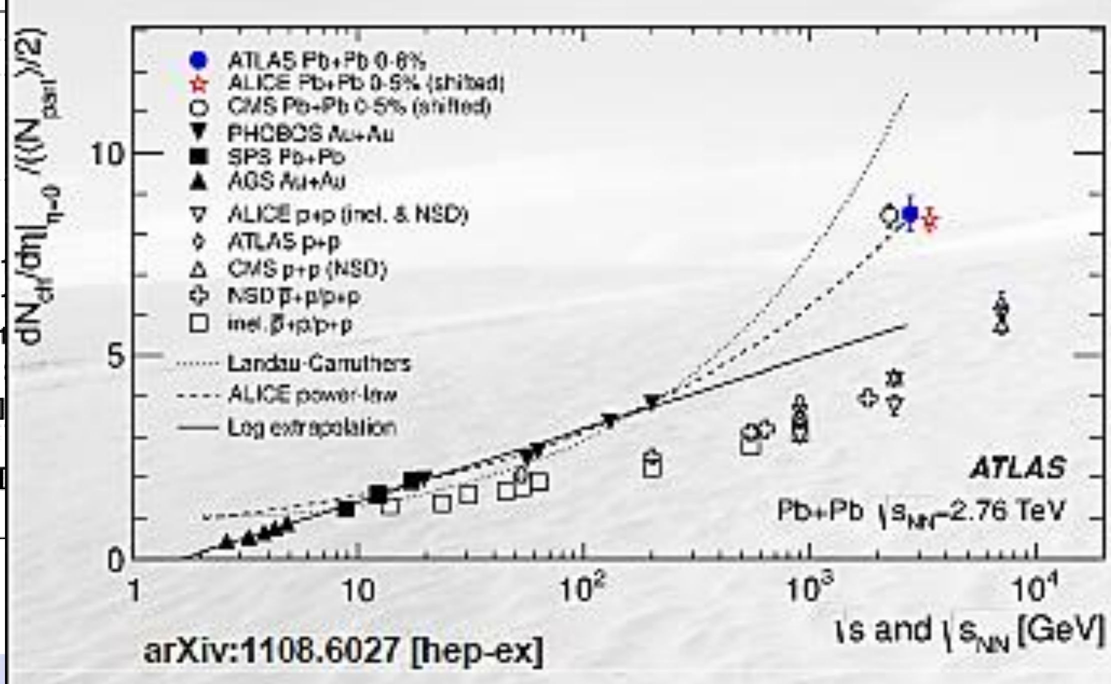
Charged Particle Multiplicity

Phys. Rev. Lett. 105, 252301 (2010)
Phys. Rev. Lett. 106, 032301 (2011)

$dN_{ch}/d\eta$ (Pb-Pb) Theory



$dN_{ch}/d\eta$ versus $\sqrt{s}$



$dN_{ch}/d\eta = 1584 \pm 4$ (stat.) ± 76 (syst.)

Rises with $\sqrt{s}$ faster than pp
Fits power law: Pb-Pb ~ $s^{0.15}$

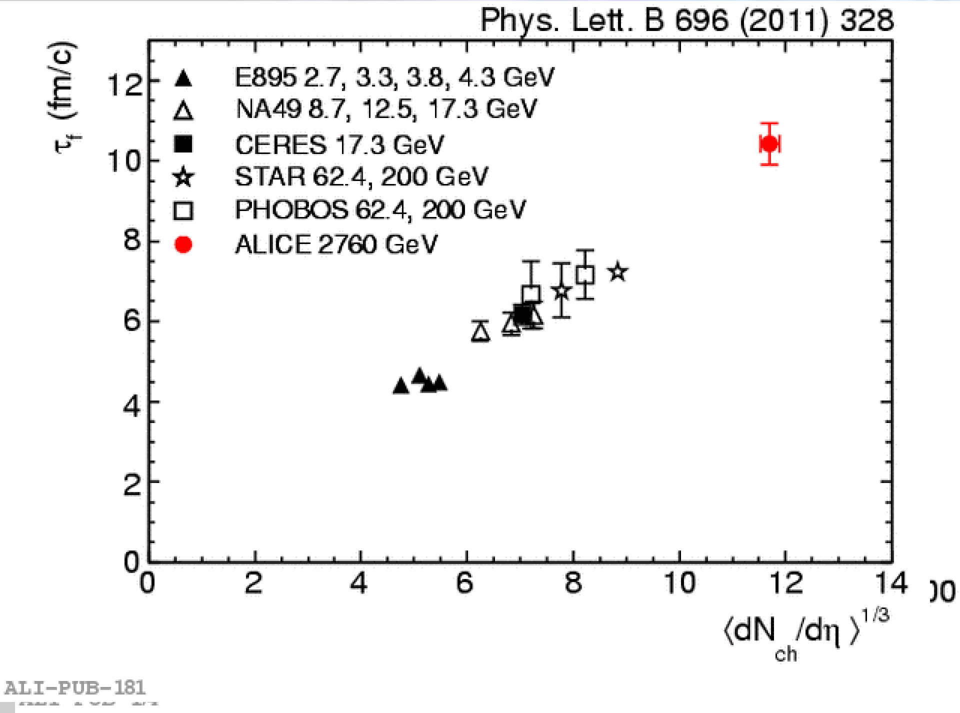
Larger than most model predictions – good agreement between LHC experiments

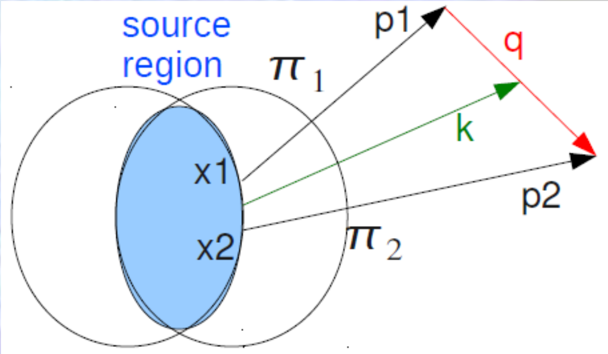
Bjorken formula estimates energy density, **ε > 15 GeV/fm^3** (3 x RHIC)

Bose–Einstein correlations (HBT)

QM enhancement of identical Bosons at small momentum difference

enhancement of e.g. like-sign pions at low momentum difference qinv=|p1-p2|,



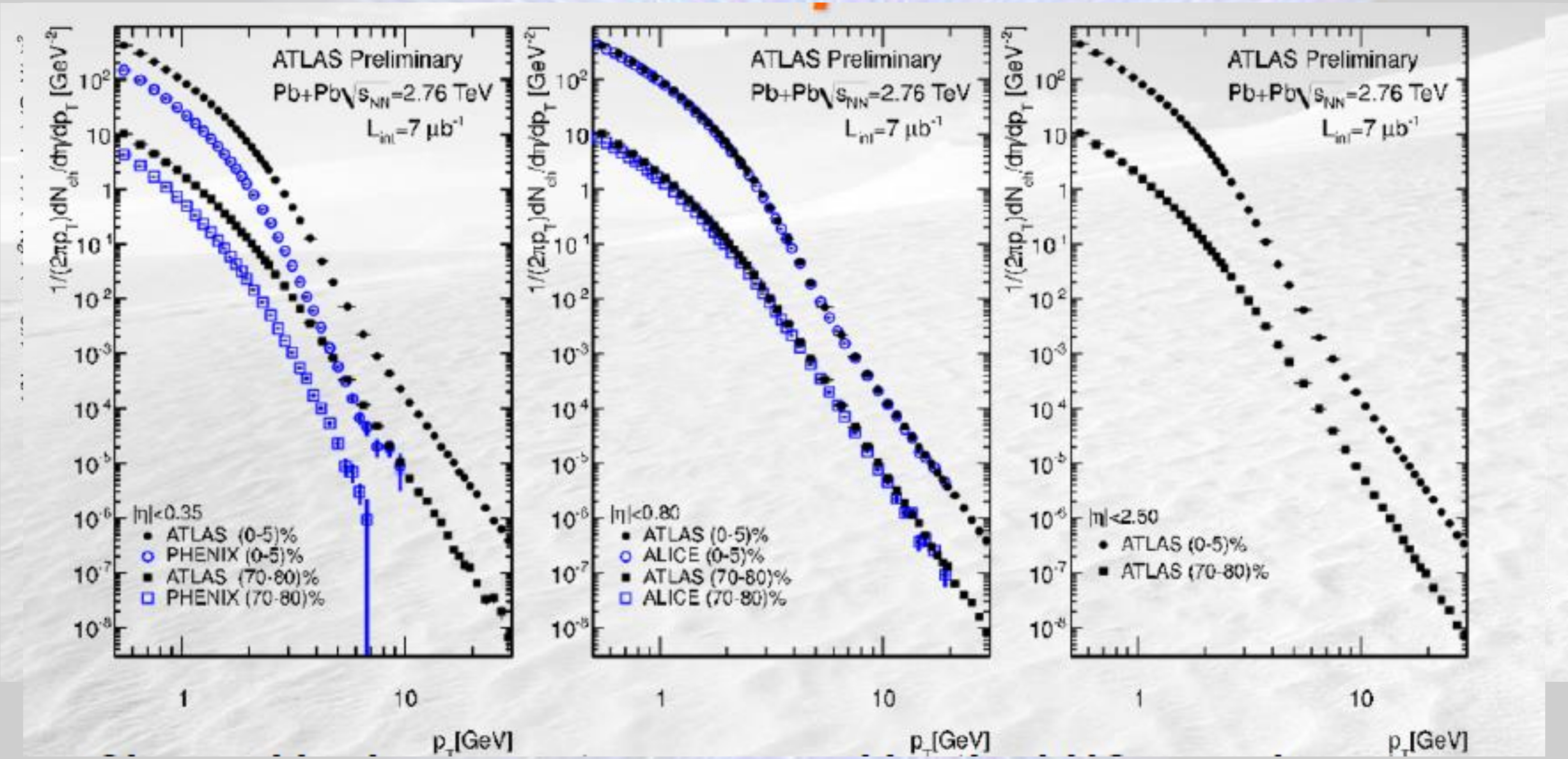


- medium size: 2x larger than at RHIC
  - $R_{out}R_{side}R_{long}$ ~ 300 fm^3
  - Volume ~ 5000 fm^3
- medium life time: 40% longer than at RHIC
  - τ ~ 10-11 fm/c

ALICE, Phys. Lett. B 696 (2011) 328.

Particle spectra

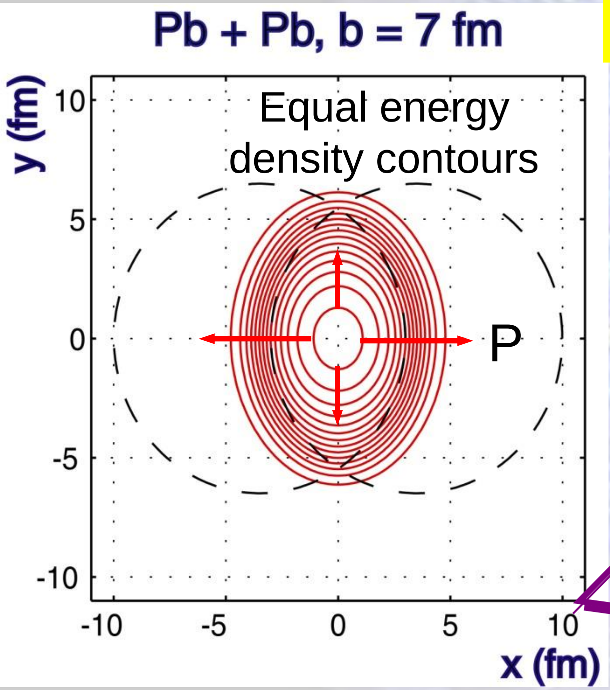
LHC results agree well between experiments

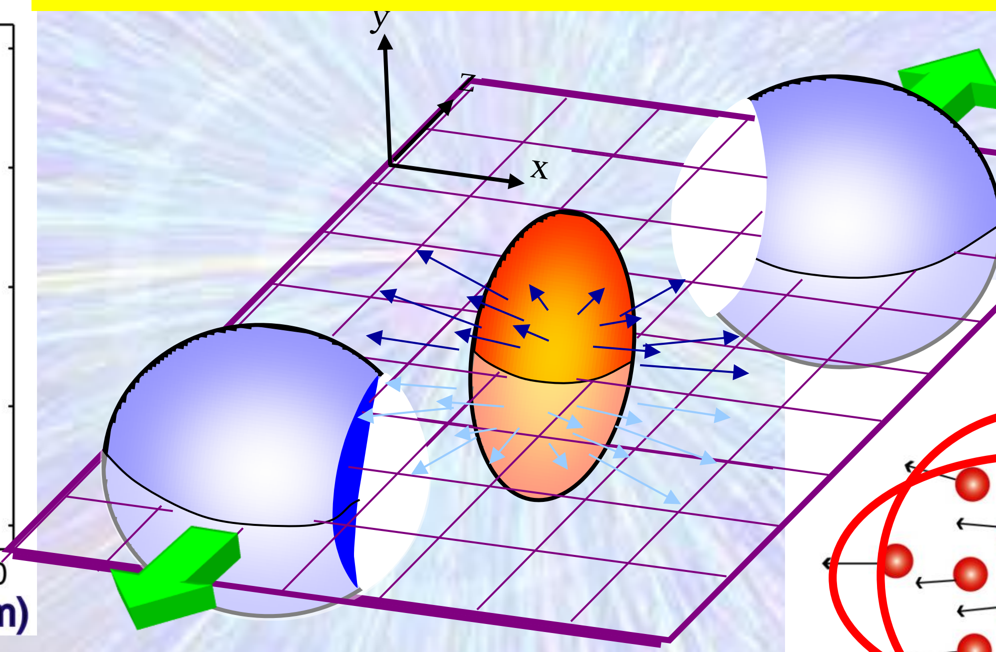


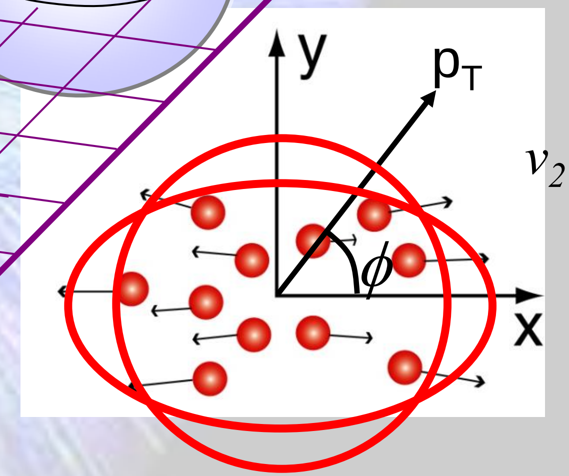
Very significant changes in slope compared to RHIC
Good agree between experiments e.g. ALICE/ATLAS in this case

Does QGP have elliptic Flow?

Study angular dependence of emitted particles







$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos[n(\phi-\Psi_r)]\right)$$

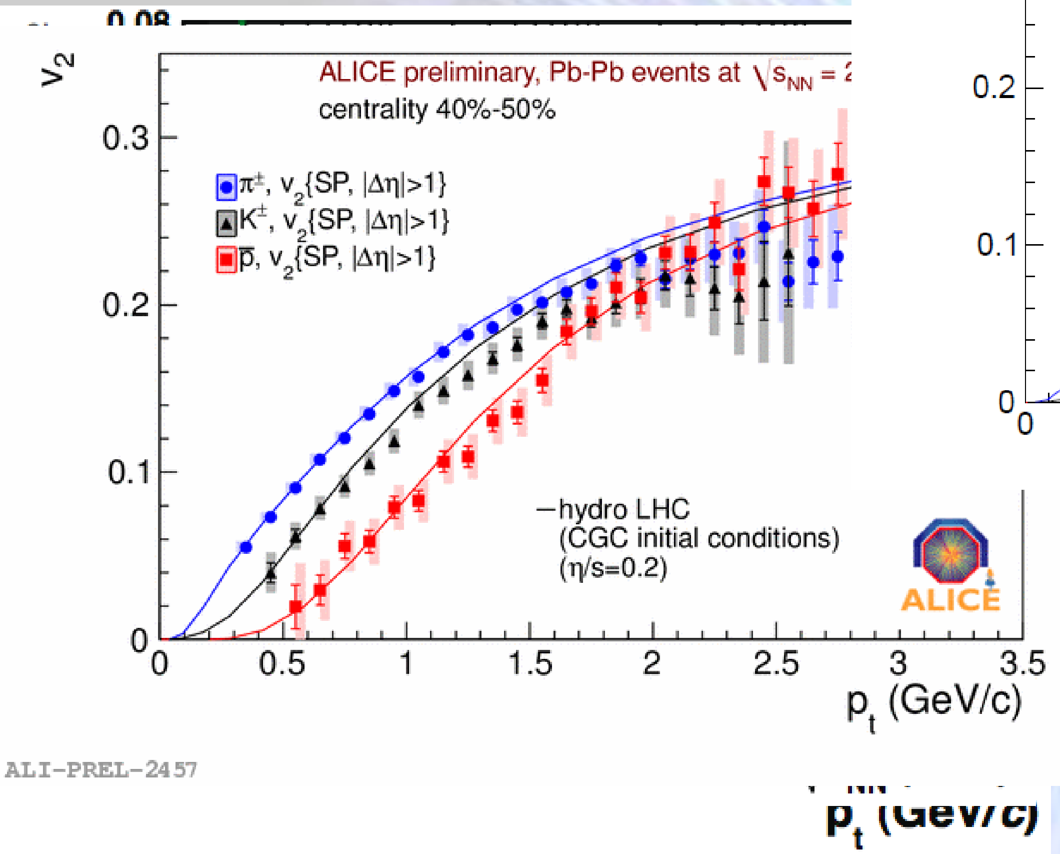
Fourier coefficient

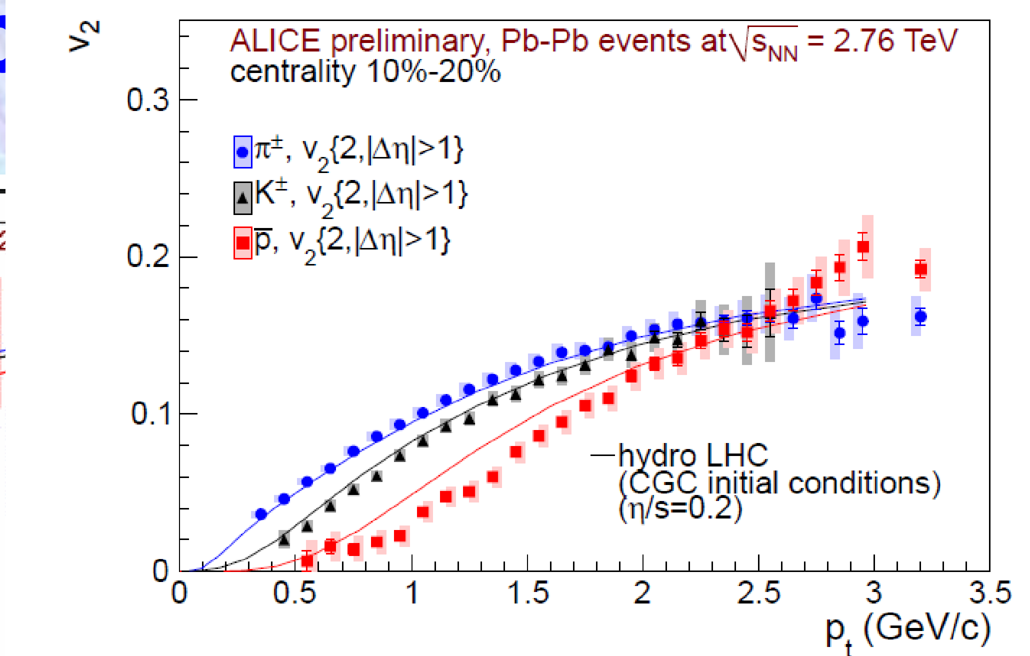
Angle of reaction plane

$$v_2=\langle\cos 2\phi\rangle$$

V_1 = directed flow. V_2 = elliptic flow.

Ellip



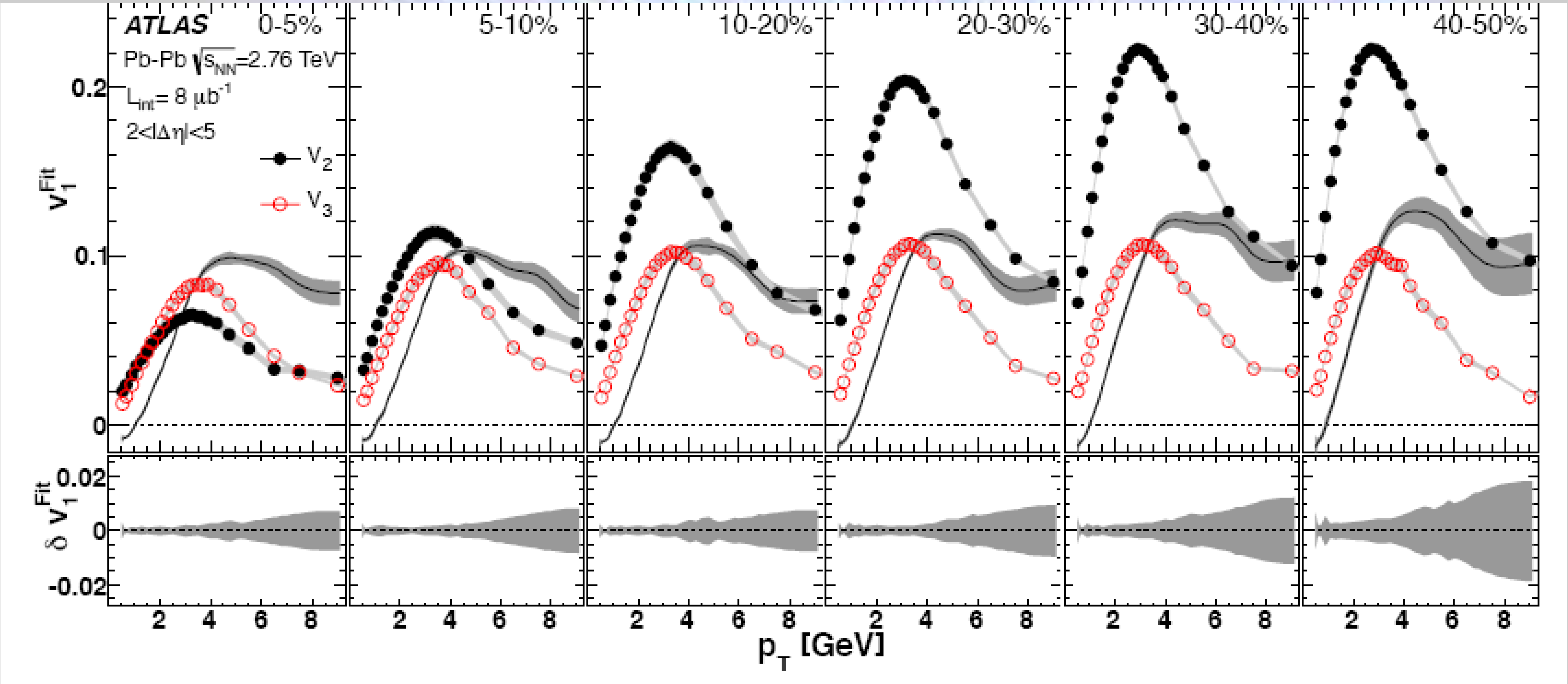


- π,K reproduced by hydro calculation
- p ok for semi-peripheral but is a remaining challenge for central collisions

ALICE, Phys. Rev. Lett. 105 (2010) 252302.

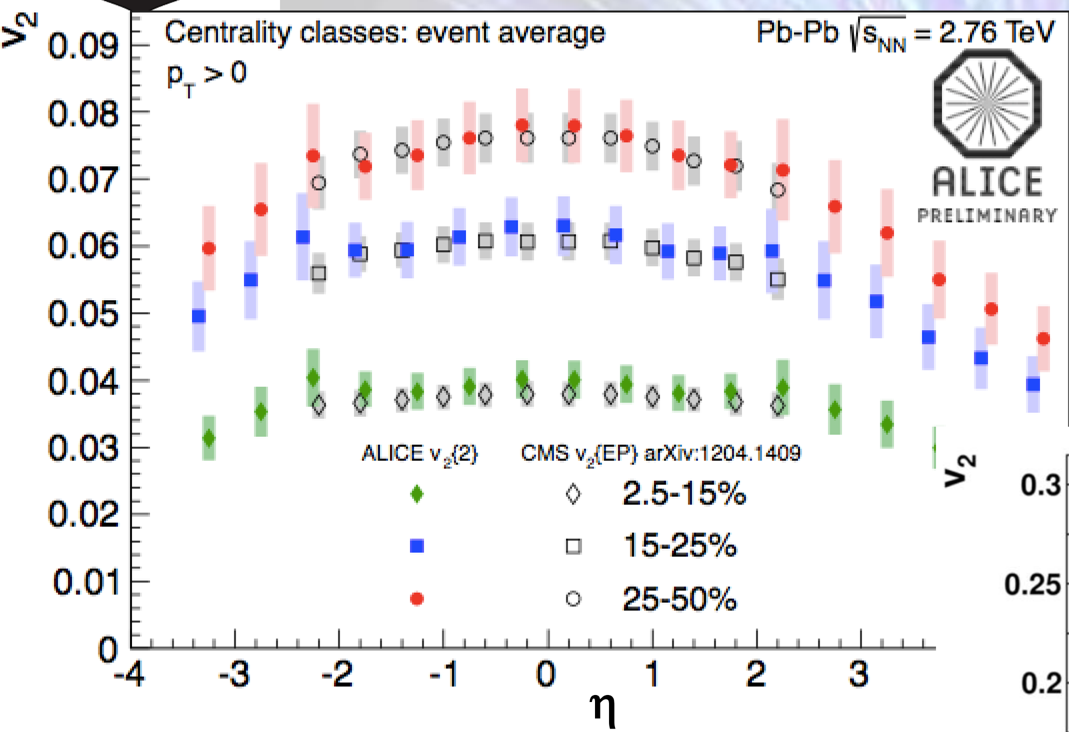
Hydro-calcs.: Shen, Heinz, Huovinen and Song, arXiv:1105.3226.

Flow vs Centrality

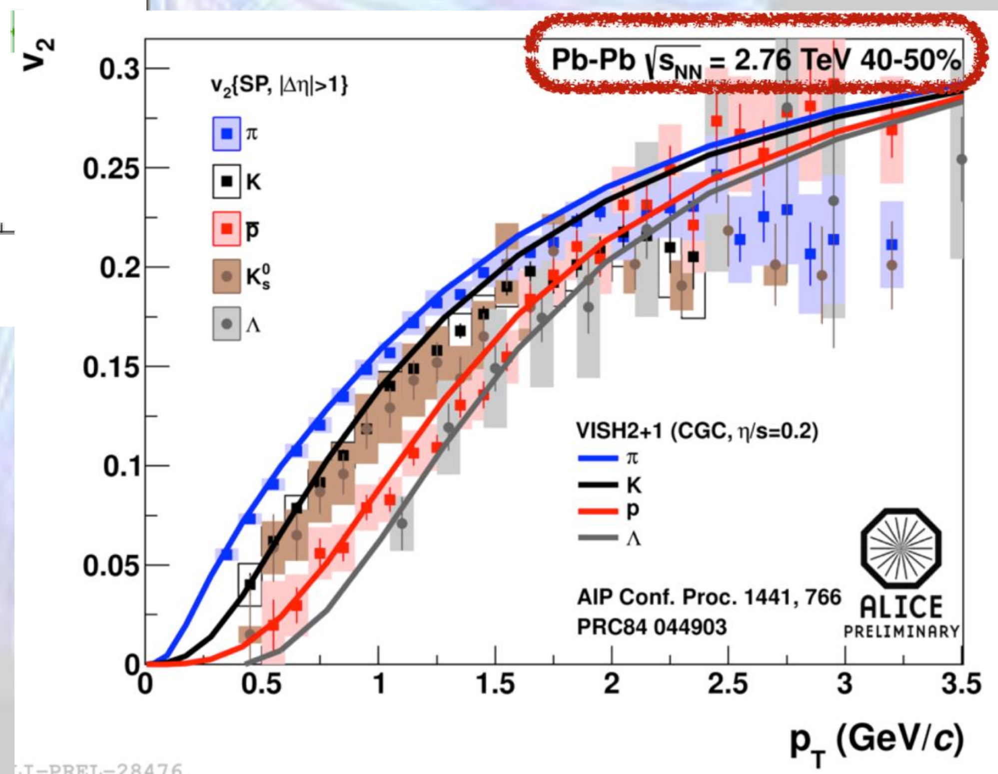


Flow strongest for semi-peripheral collisions (central collisions too symmetric).

Elliptic Flow



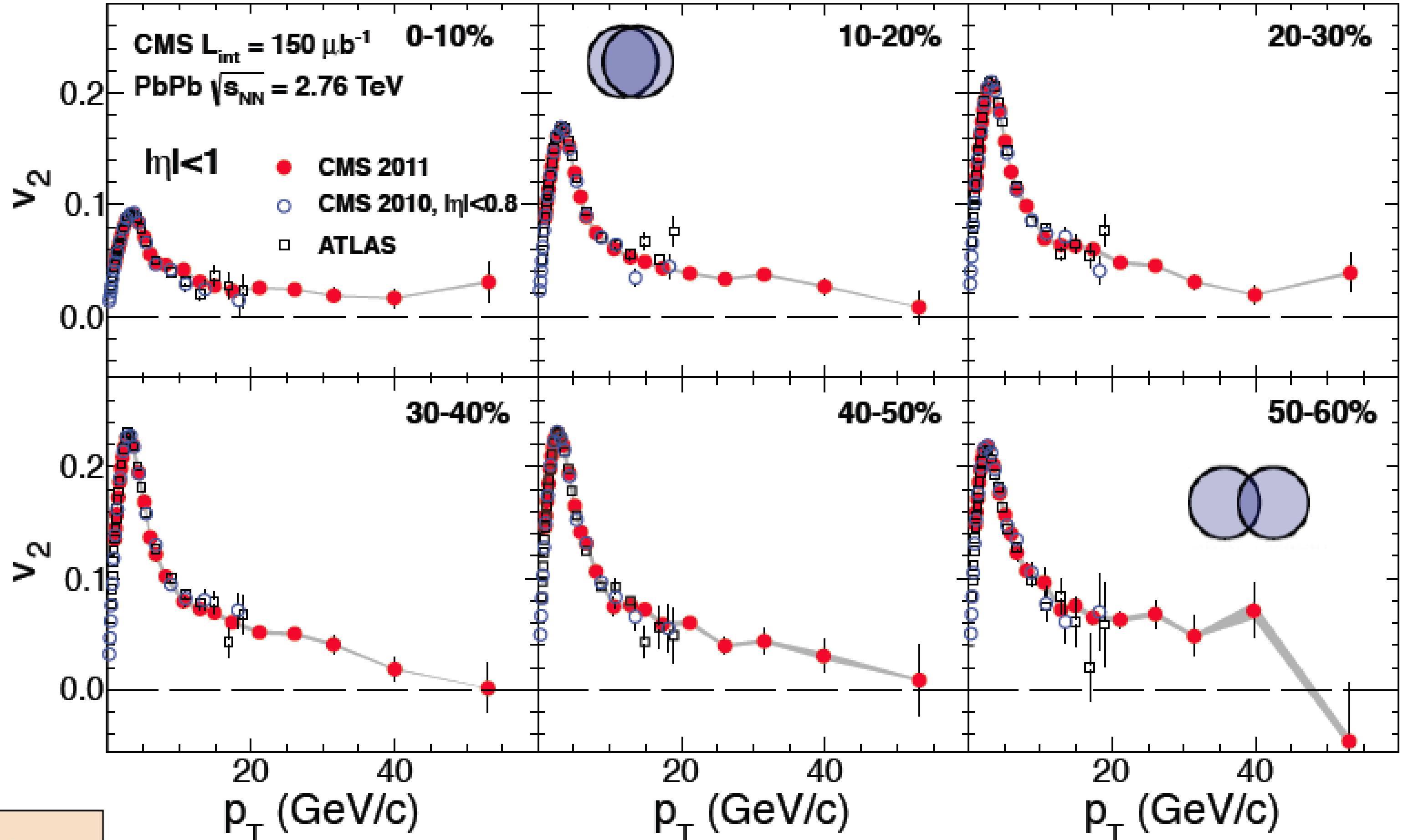
- V_2 decreases with centrality (as expected)
- ALICE and CMS data agree



v_2 and spectra show clear mass ordering, in AA, expected in collective expansion scenario: elliptic and radial flow

V_2 at High P_T

arXiv:1204.1850

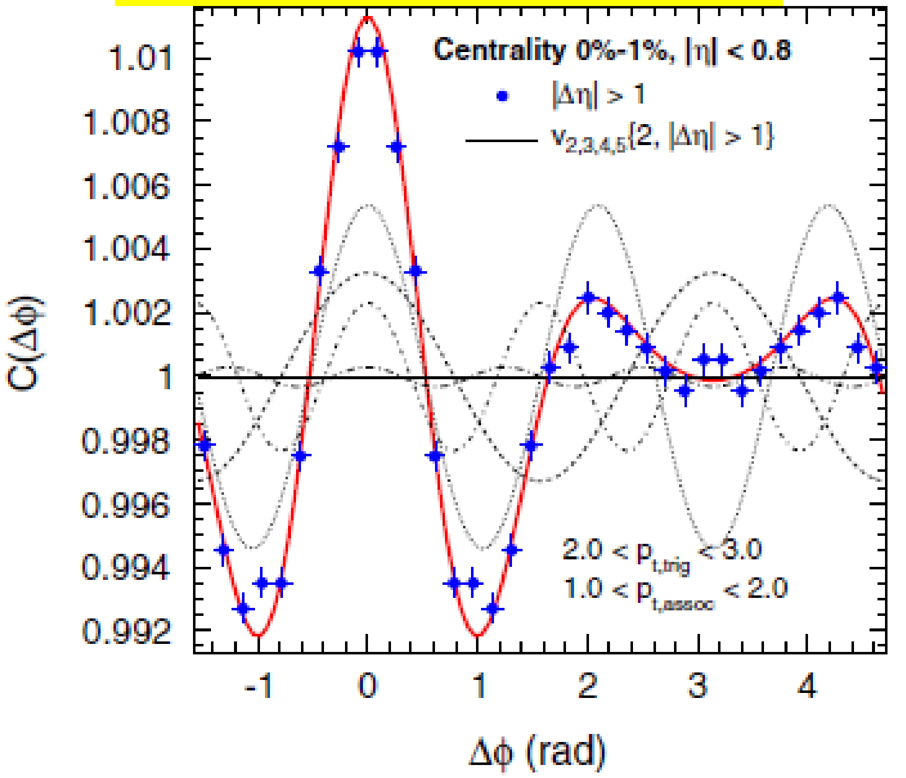


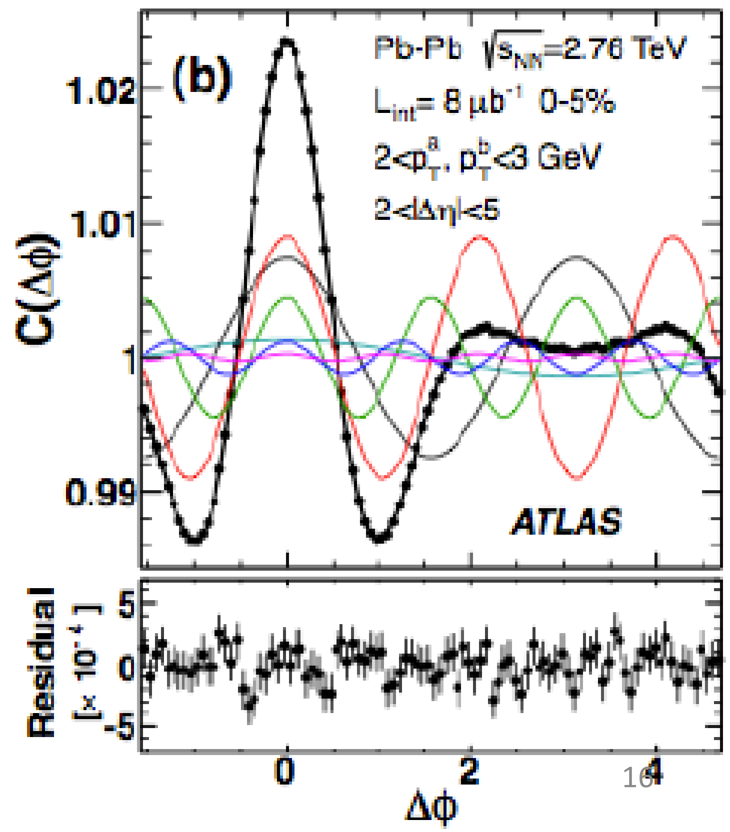
V_2 drops to zero at high P_T

Elliptic Flow – Higher Orders

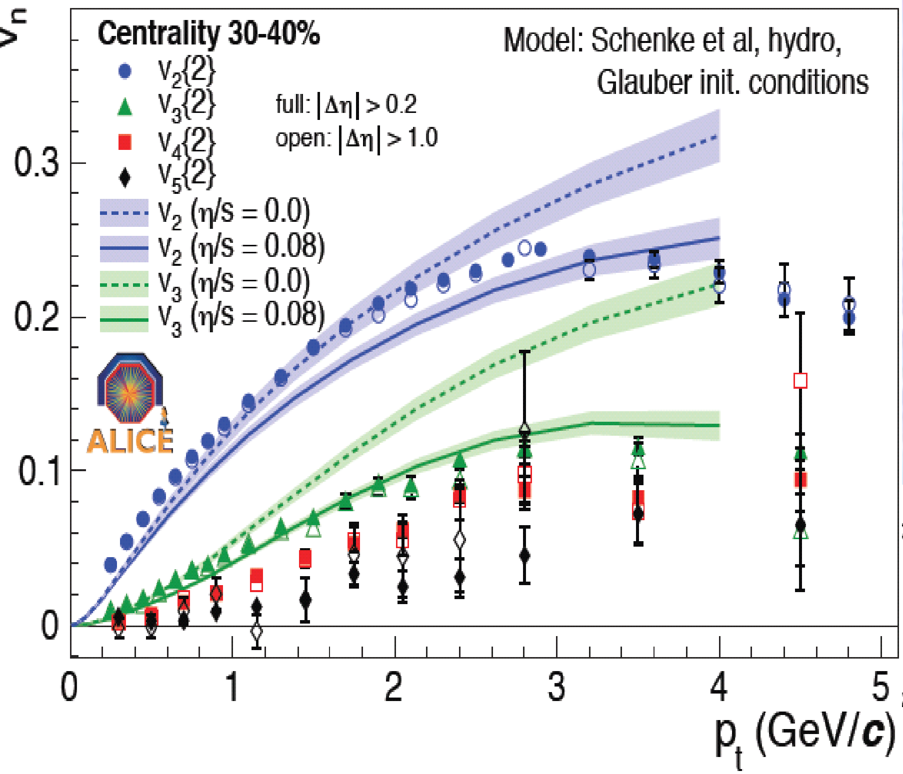
Superposition of flow harmonics, including higher orders, is sufficient to describe Ridge and Cone effects without implying medium response.

Phys. Rev. Lett. 107, 032301 (2011)

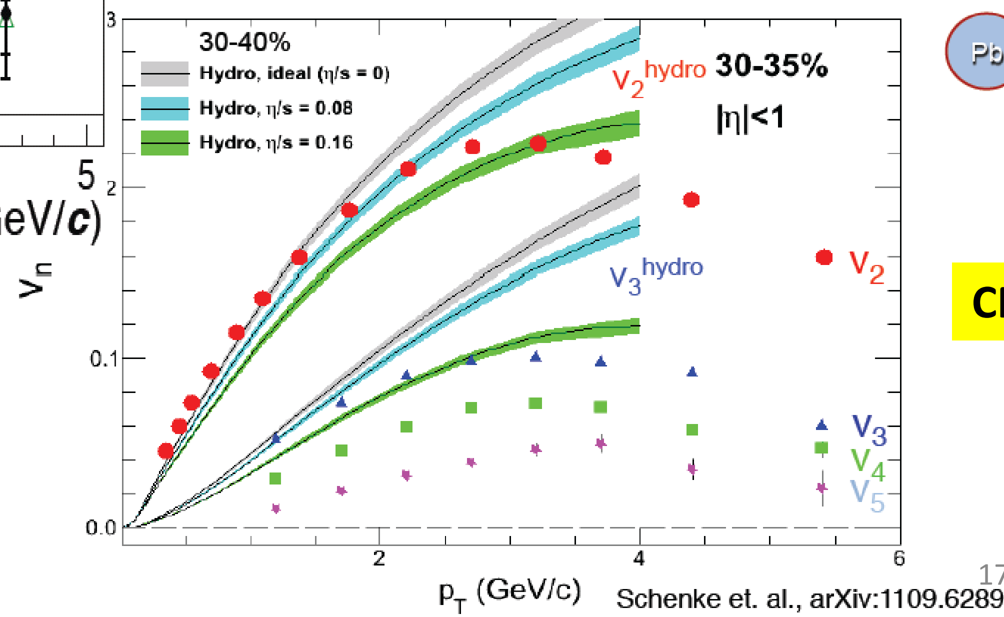




Full Harmonic Spectrum



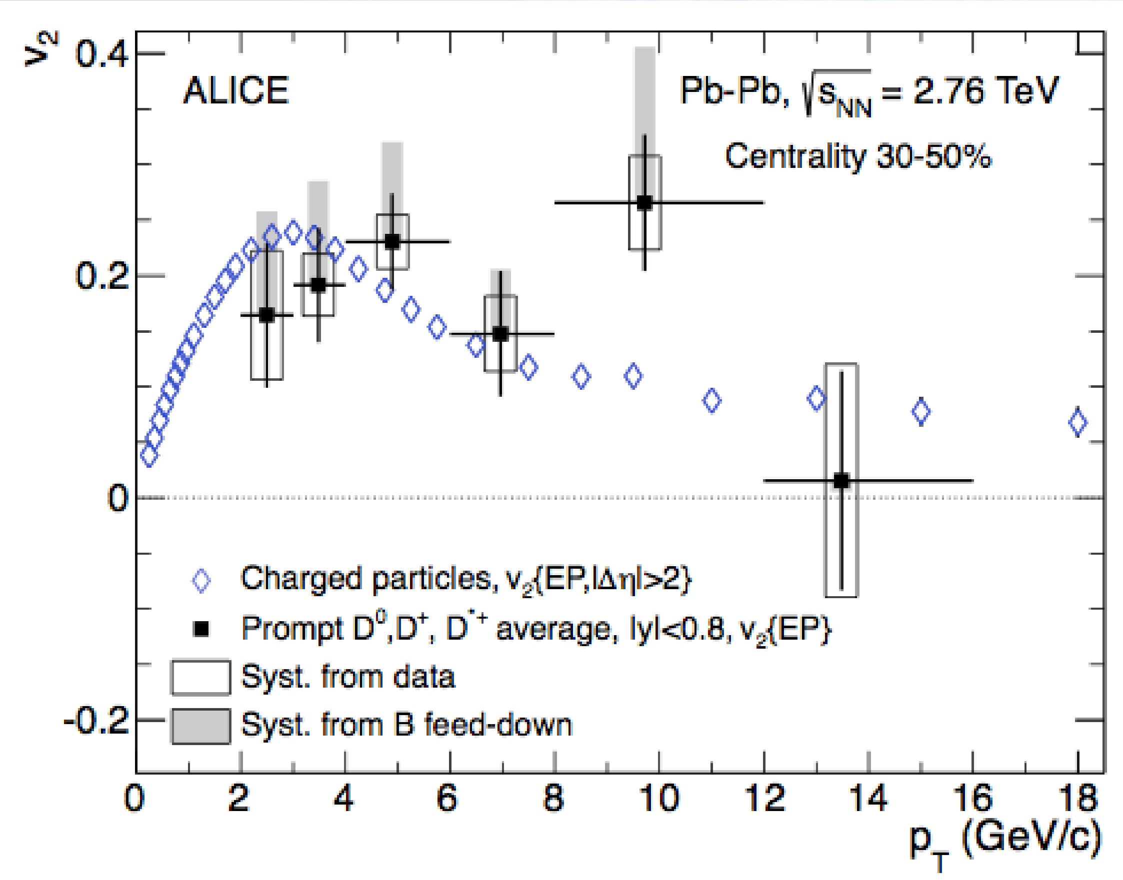
Measure multi Vn - Over-constrain Hydro Models to get η/s, initial conditions etc.



Pb Pb

CMS

Elliptic Flow Charm



- ➢Non zero D meson v_2 (3σ in $2 < p_T < 6$ GeV/c)
- ➢Comparable with charged hadrons elliptic flow

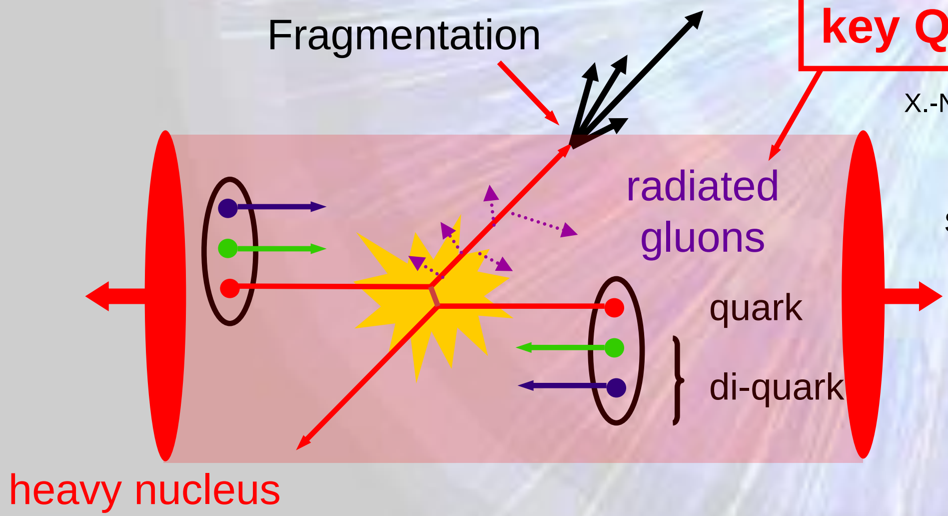
Jets in heavy ion collisions

- Studying deconfinement with jets

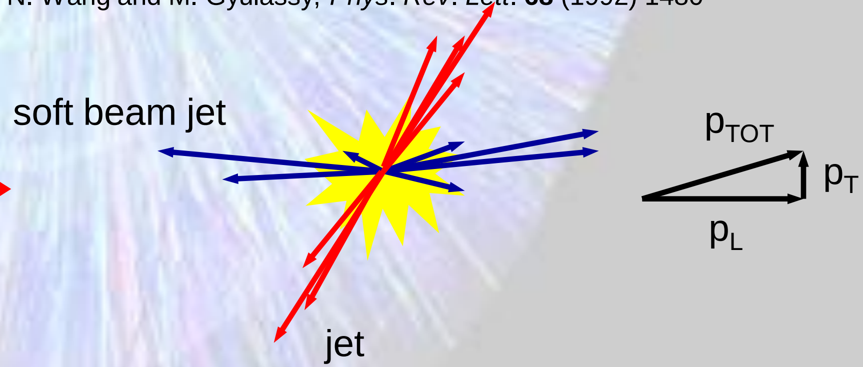
Free quarks not allowed
when quark, anti-quark pairs are produced they fly apart producing back-to-back 'jets' of particles

key QCD prediction: jets are quenched

X.-N. Wang and M. Gyulassy, *Phys*. *Rev*. *Lett*. **68** (1992) 1480



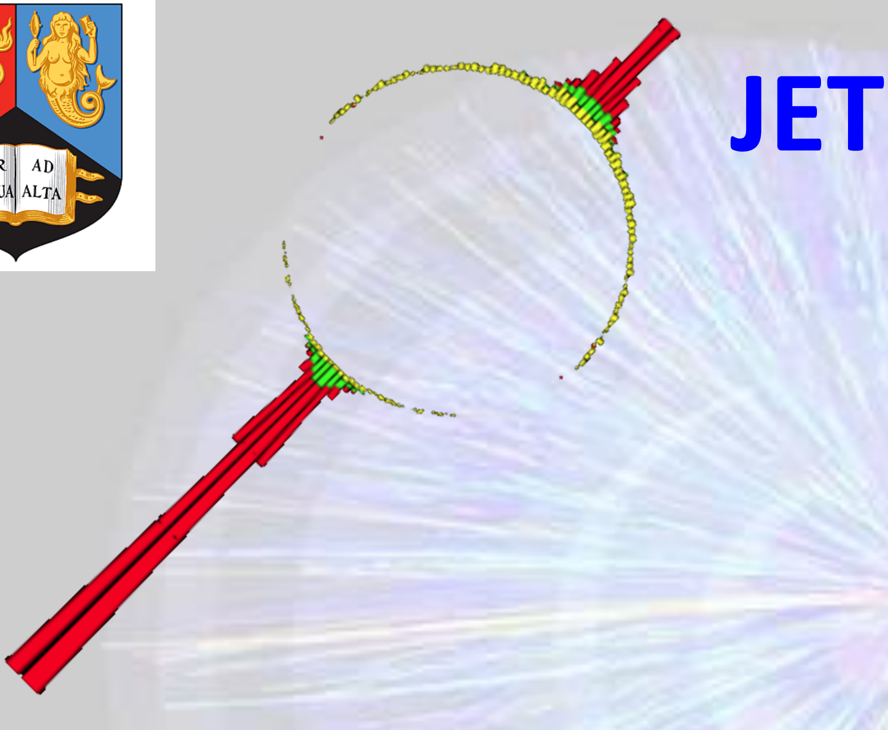
Interaction at the quark (parton) level

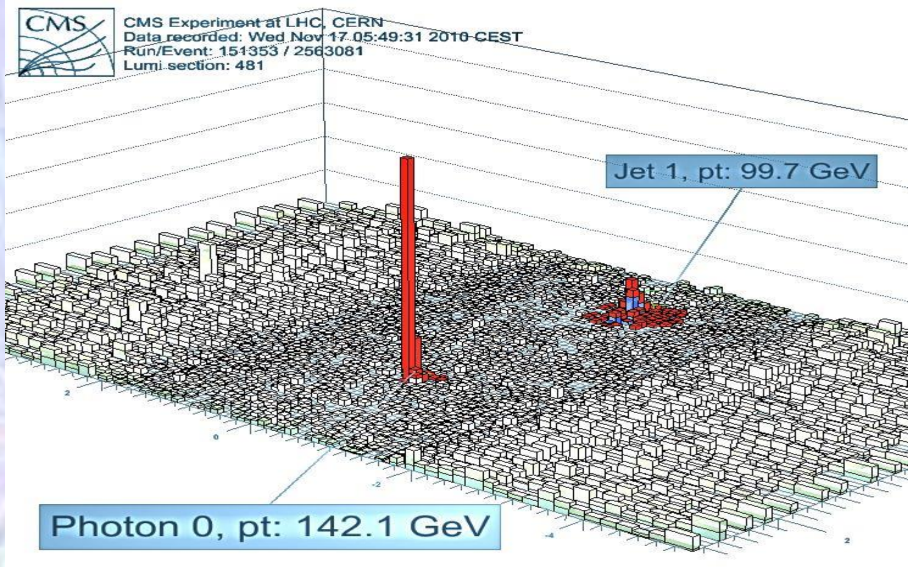


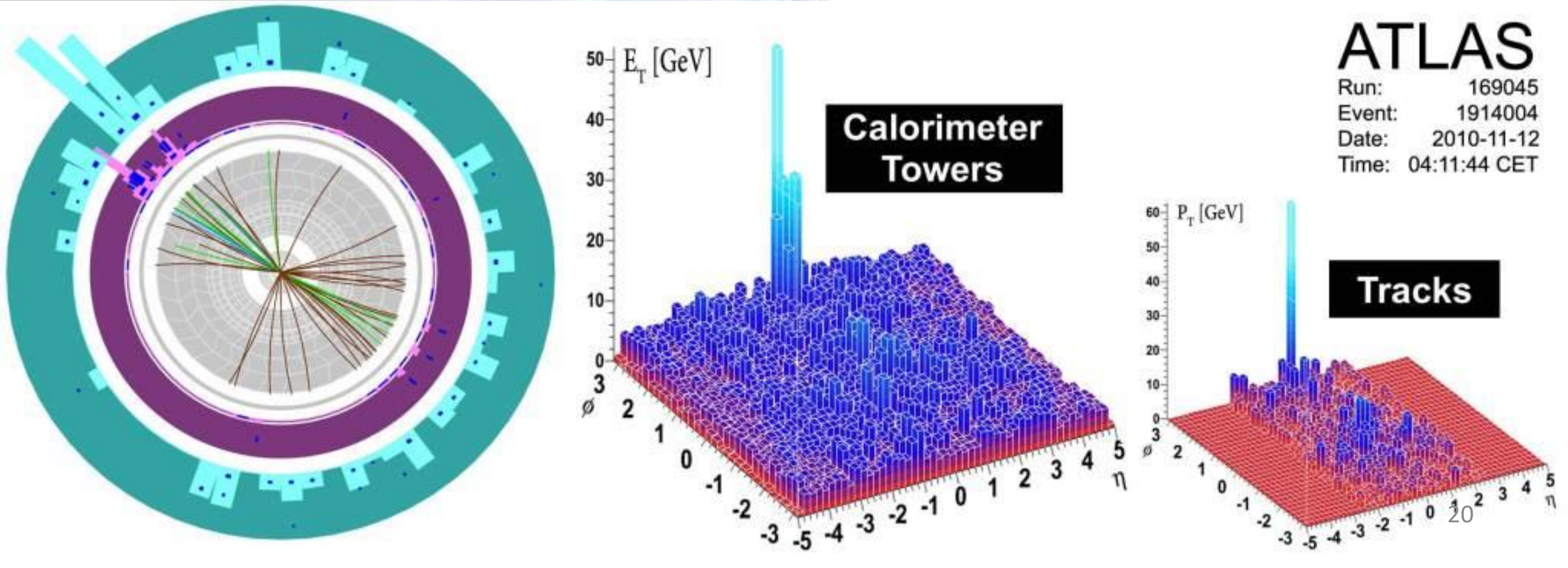
The same interaction at the hadron level

Quarks remain free in QGP and lose energy while travelling through

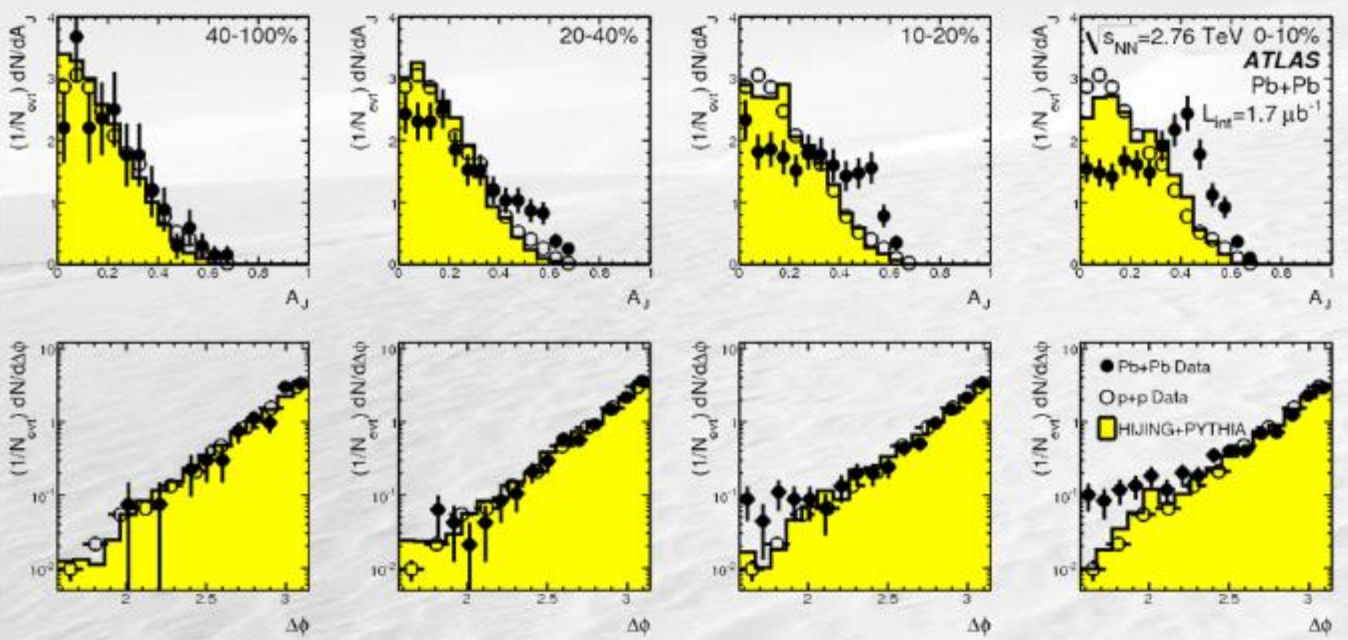
JETS




CMS
CMS Experiment at LHC, CERN
Data recorded: Wed Nov 17 05:49:31 2010 CEST
Run/Event: 151353 / 2563081
Lumi section: 481
Jet 1, pt: 99.7 GeV
Photon 0, pt: 142.1 GeV

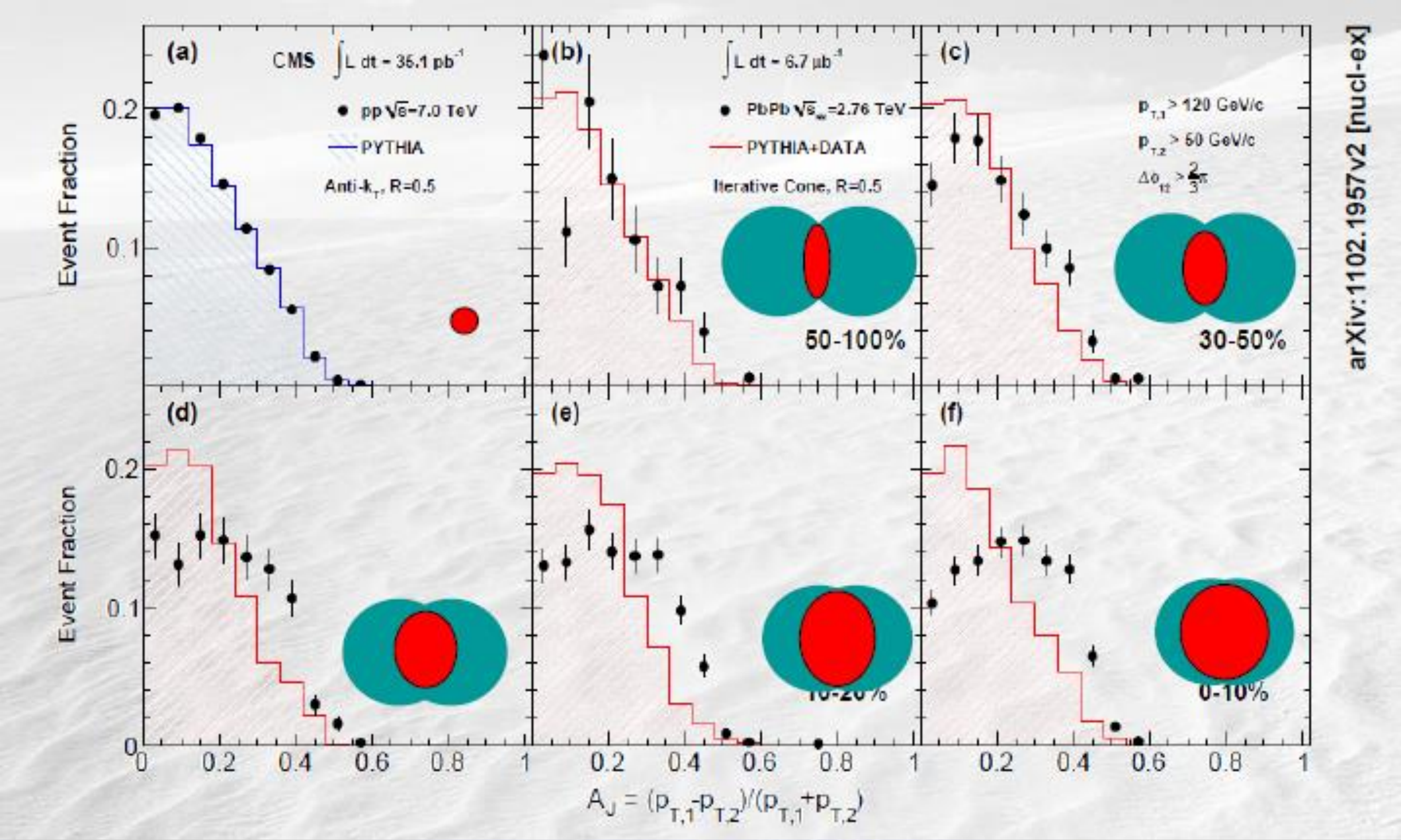

ATLAS
Run: 169045
Event: 1914004
Date: 2010-11-12
Time: 04:11:44 CET
Calorimeter Towers
E_T [GeV]
Tracks
P_T [GeV]
ø
η

Jet Suppression



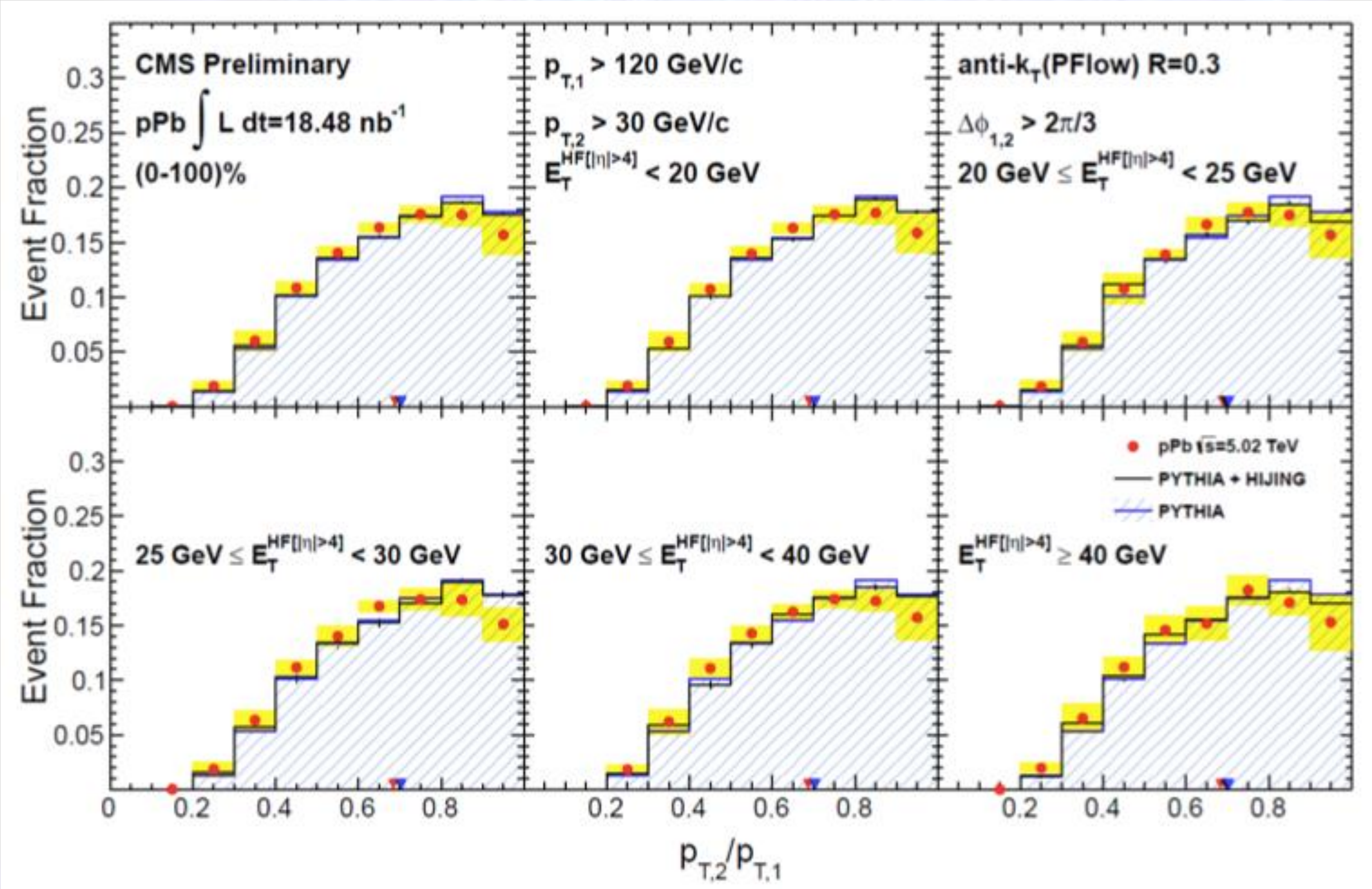
Significant imbalance between leading and sub-leading jets for central collisions

Jet Suppression



Also seen by CMS

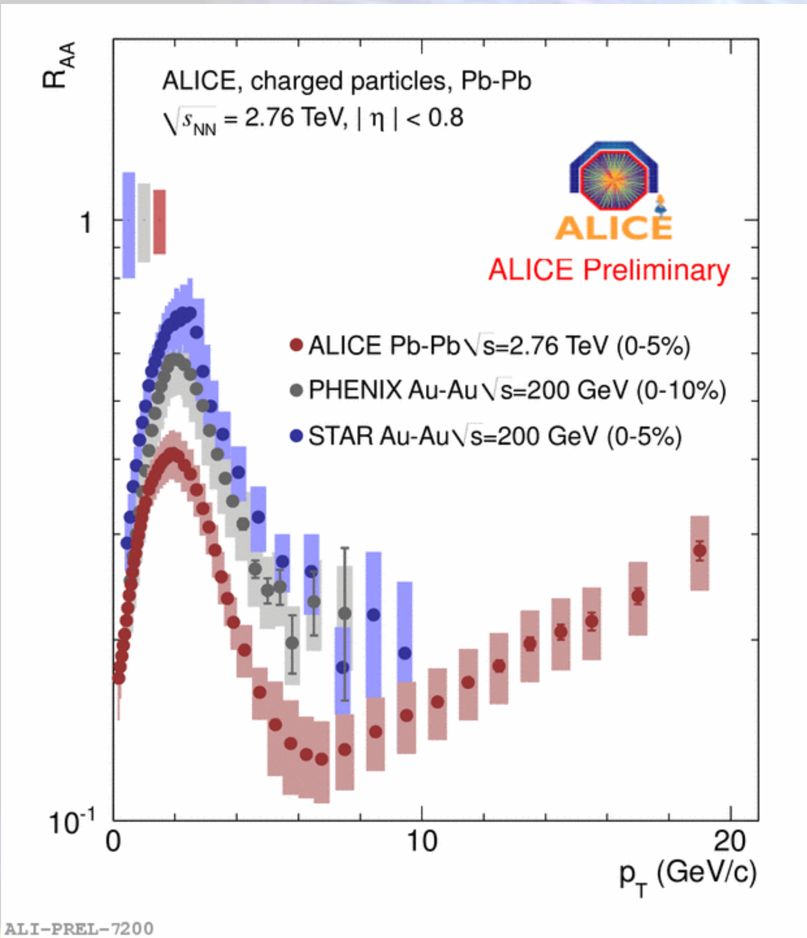
No Jet Suppression in p-Pb



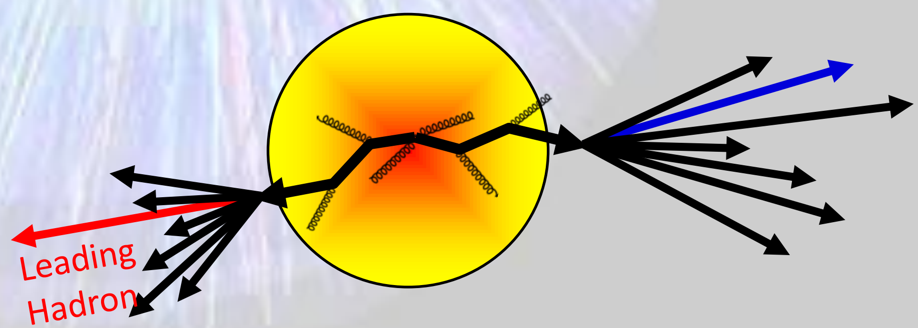
Nuclear Modification Factor

Divide p_T spectra in Pb-Pb by p-p (with suitable normalisation factor)

$$R_{AA}^{D}(p_T) = \frac{d\sigma_{AA}^{D}/dp_T}{<N_{coll}> \times d\sigma_{pp}^{D}/dp_T}$$

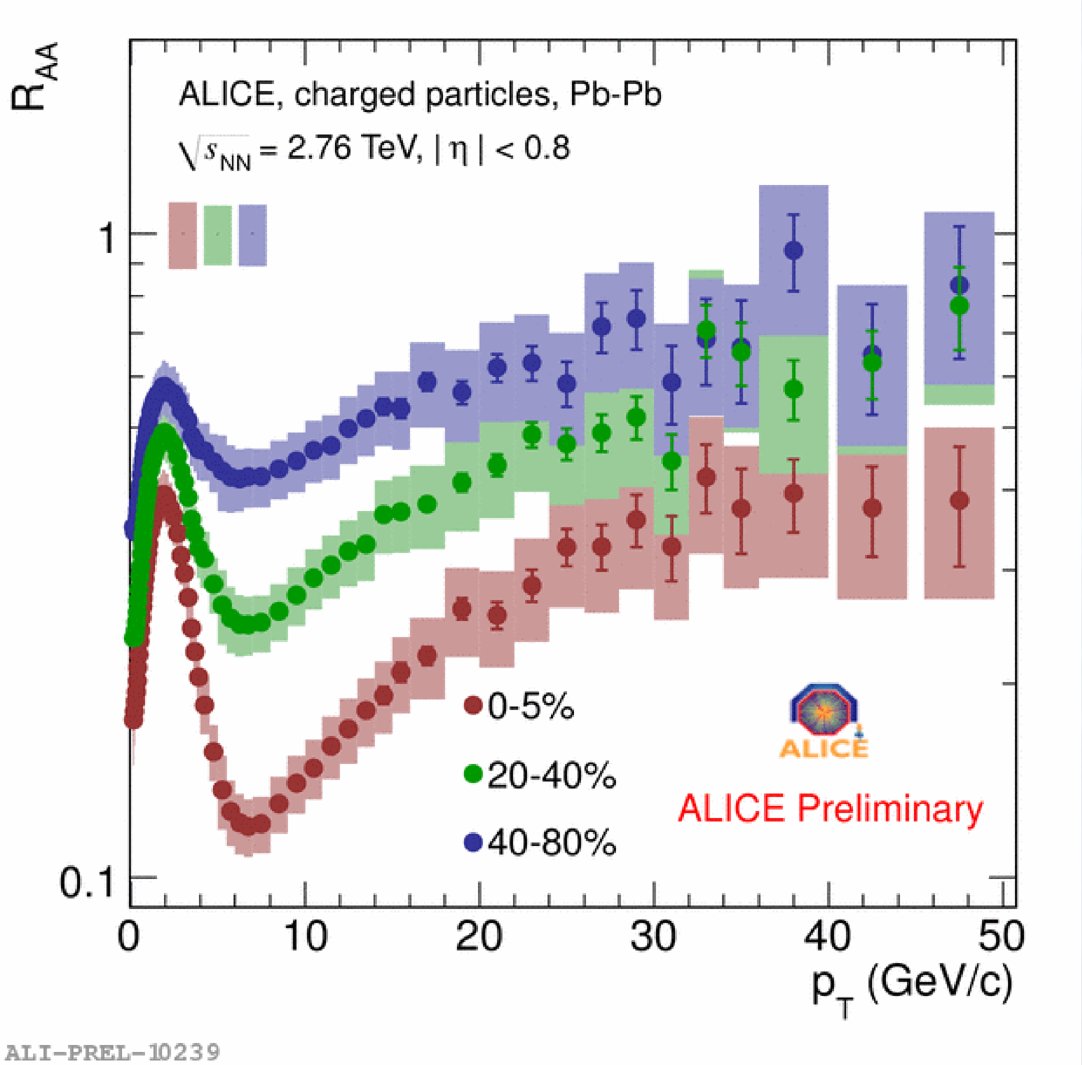


- particle interaction with medium
- stronger suppression at LHC
- ~factor 7 at 7 GeV/c



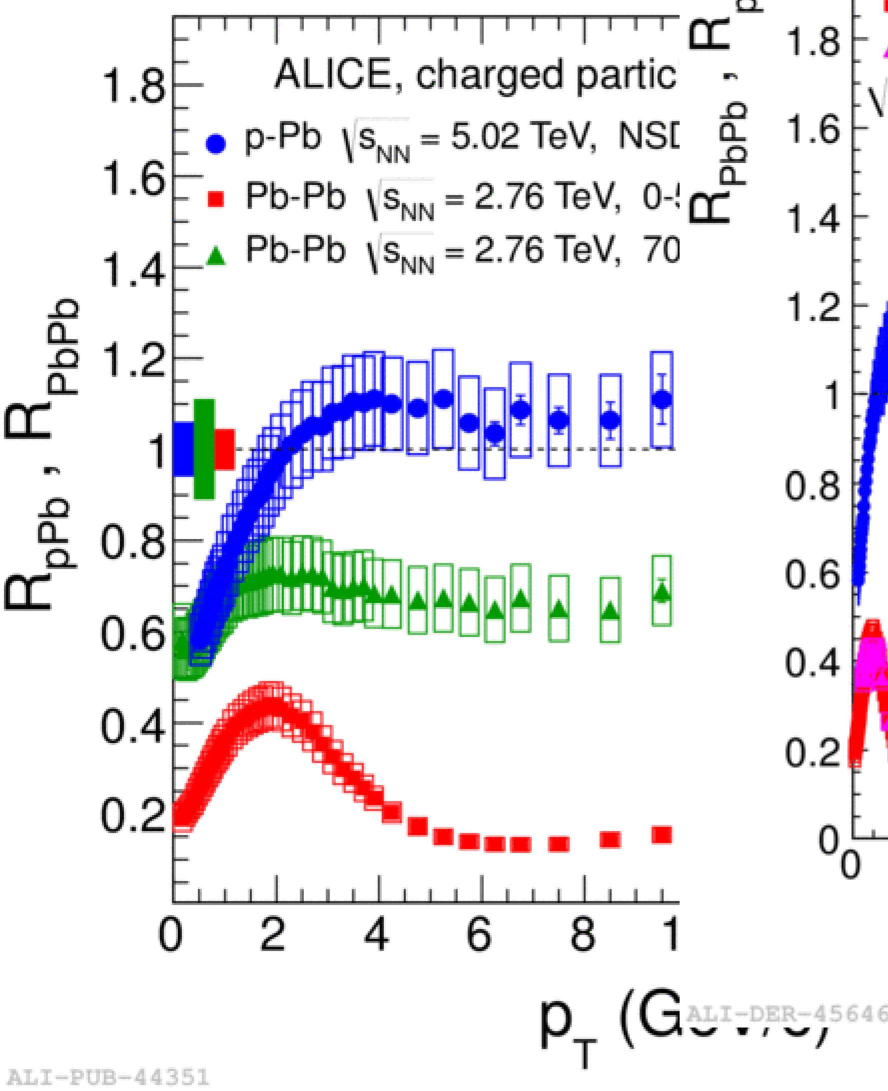
quark-gluon plasma

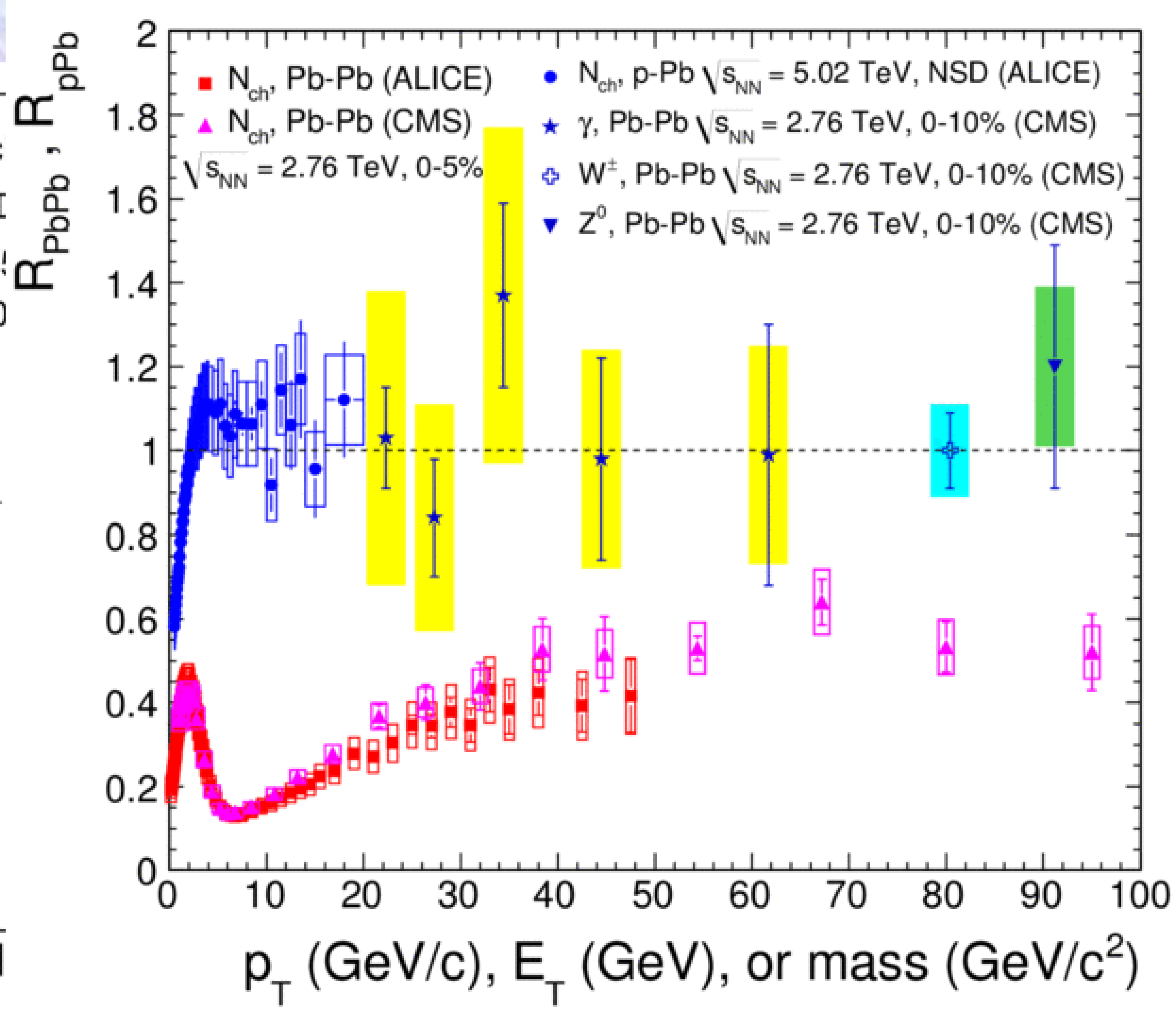
R_{AA} vs centrality



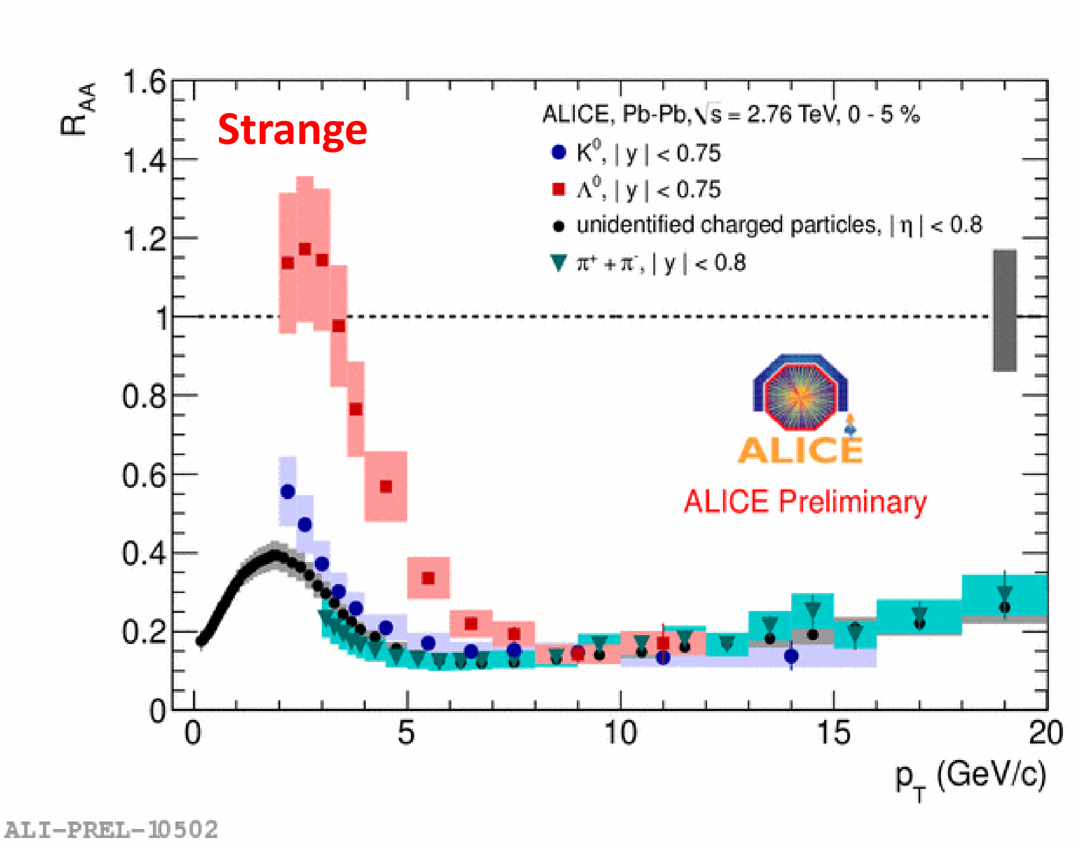
- Suppression increases with centrality.
- Minimum remains around 6-7 GeV/c

R_{pA} & R_{AA} for γs, Ws & Zs



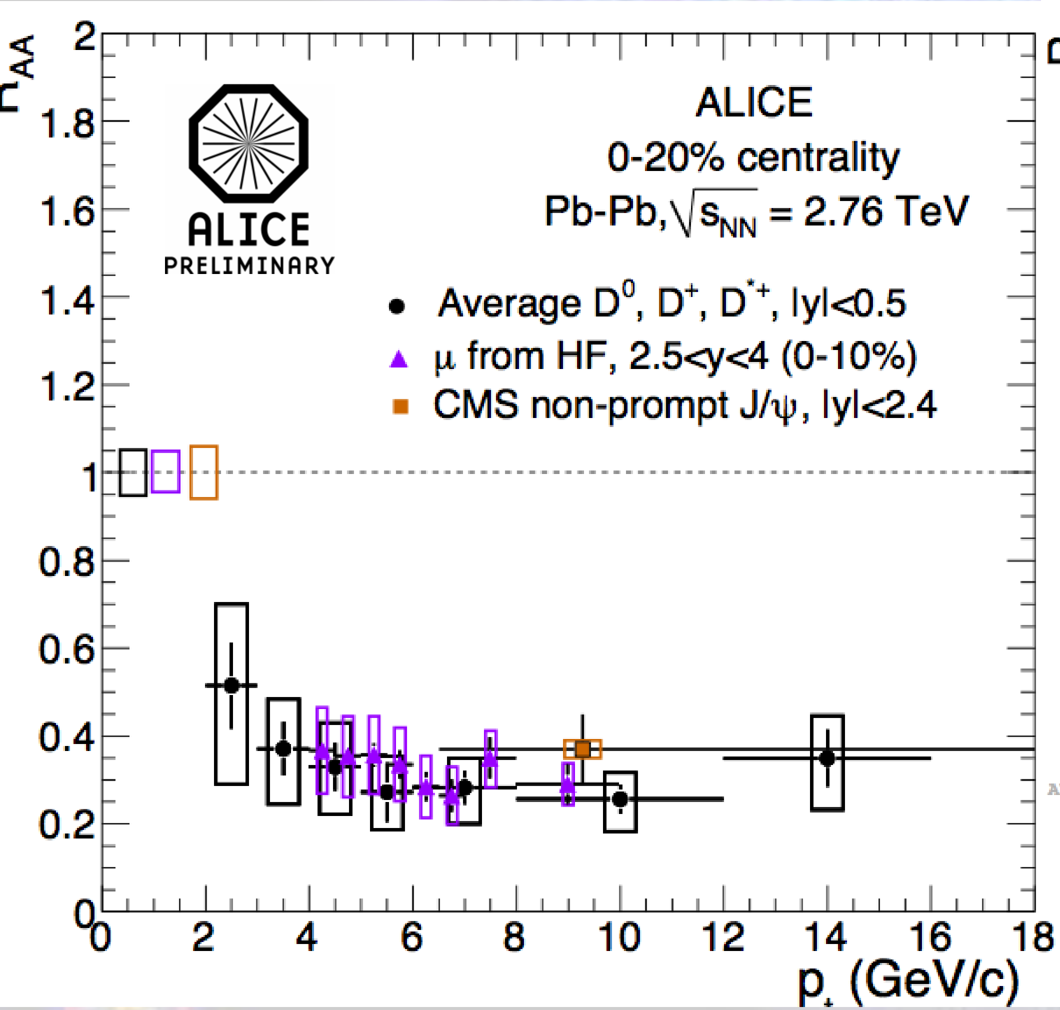


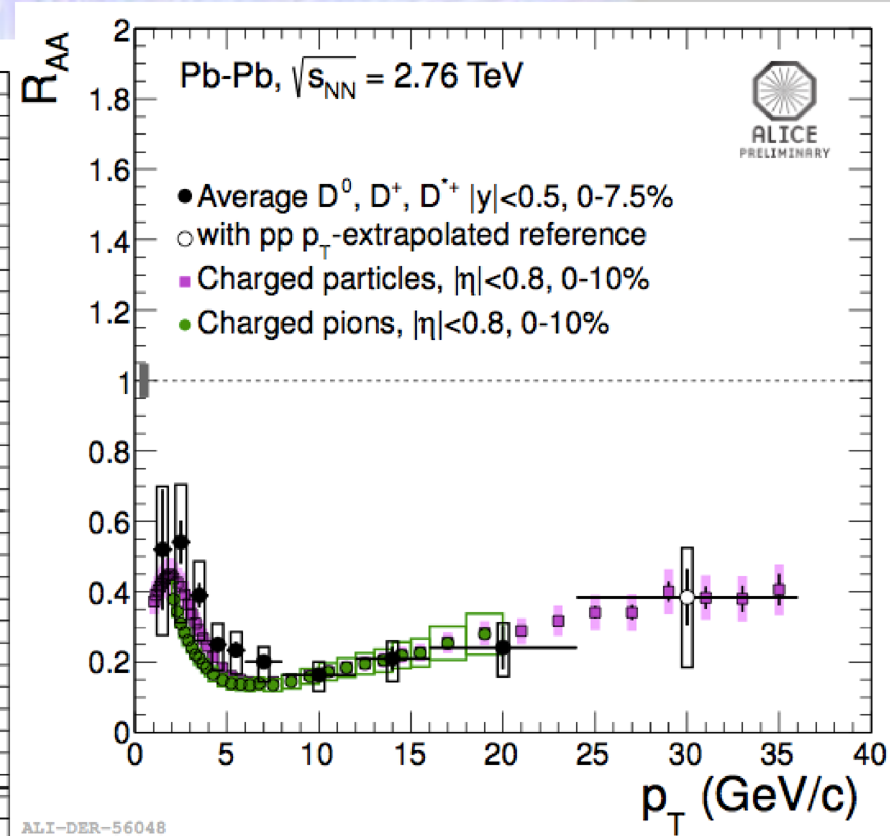
R_{AA} for different particles



- **For hadrons containing heavy quarks, smaller suppression expected**
- Enhancement of Λ/K clearly seen
- At high p_T (>8-10 GeV/c) R_{AA} universality for light hadrons

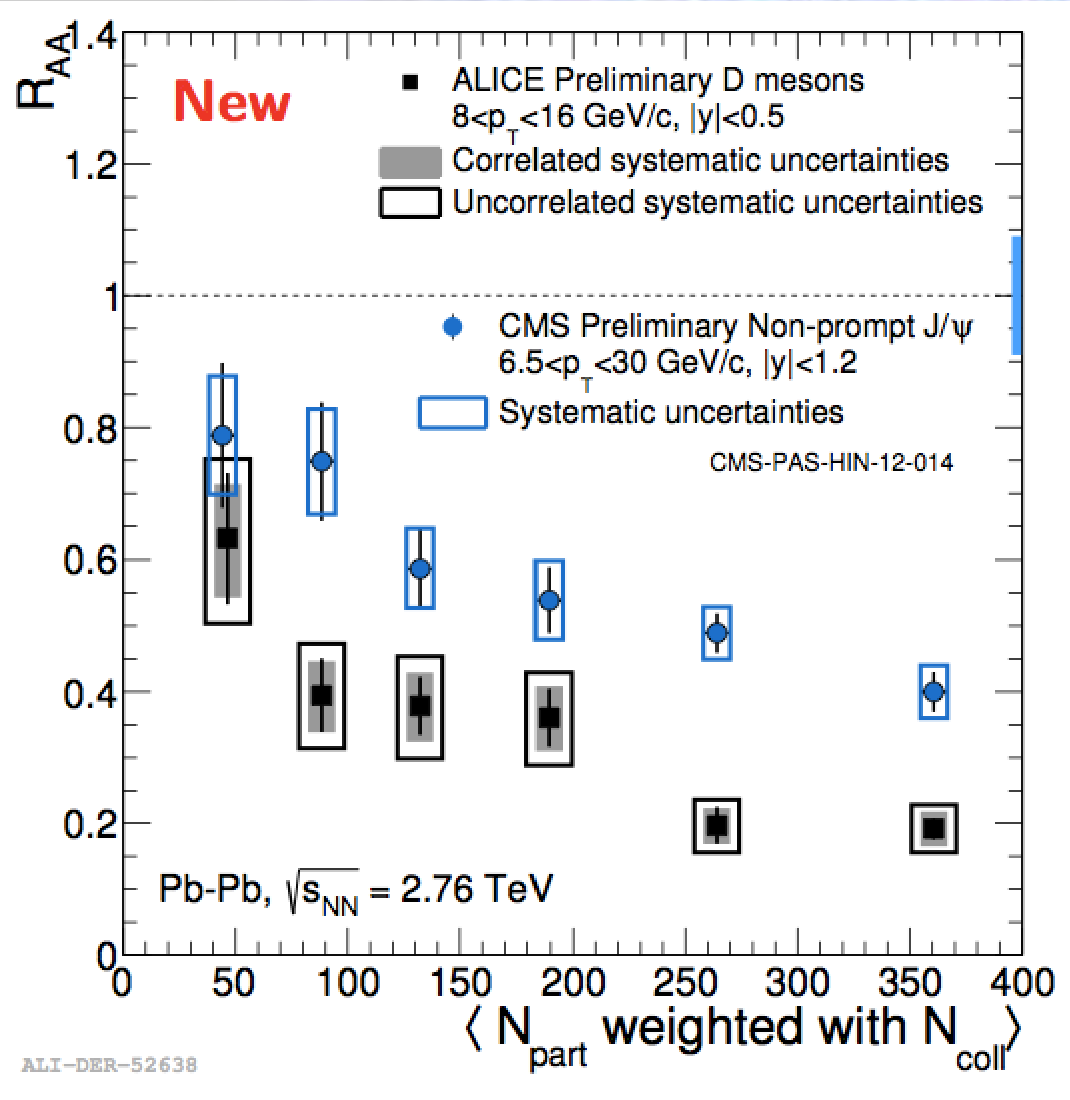
R_{AA} for Heavy Flavour





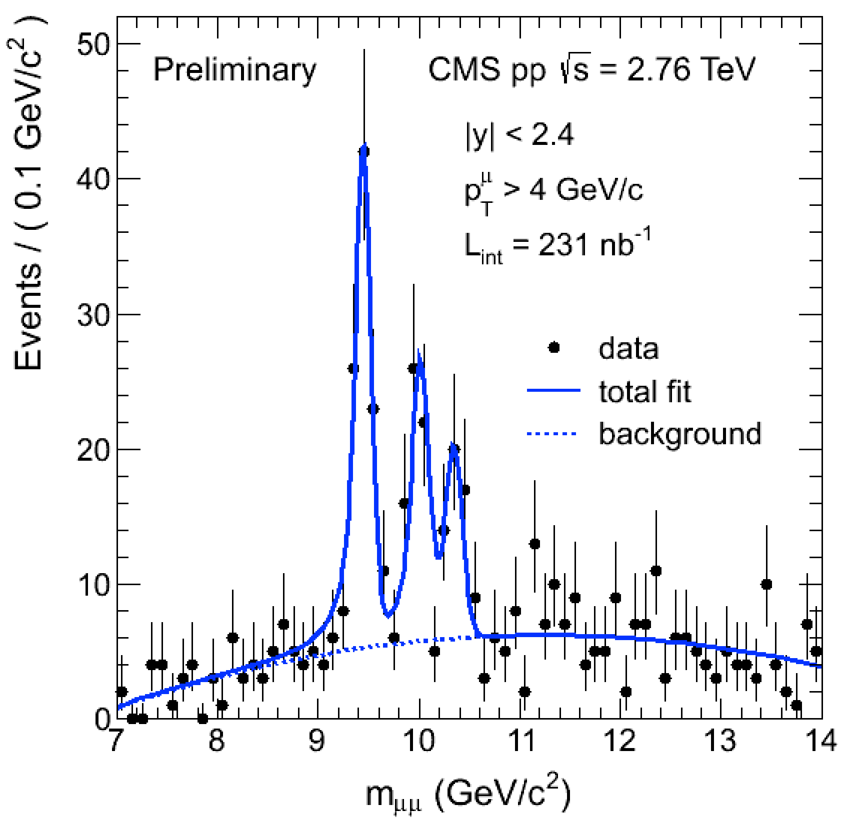
- **Maybe a hint of hierarchy w.r.t pions!**

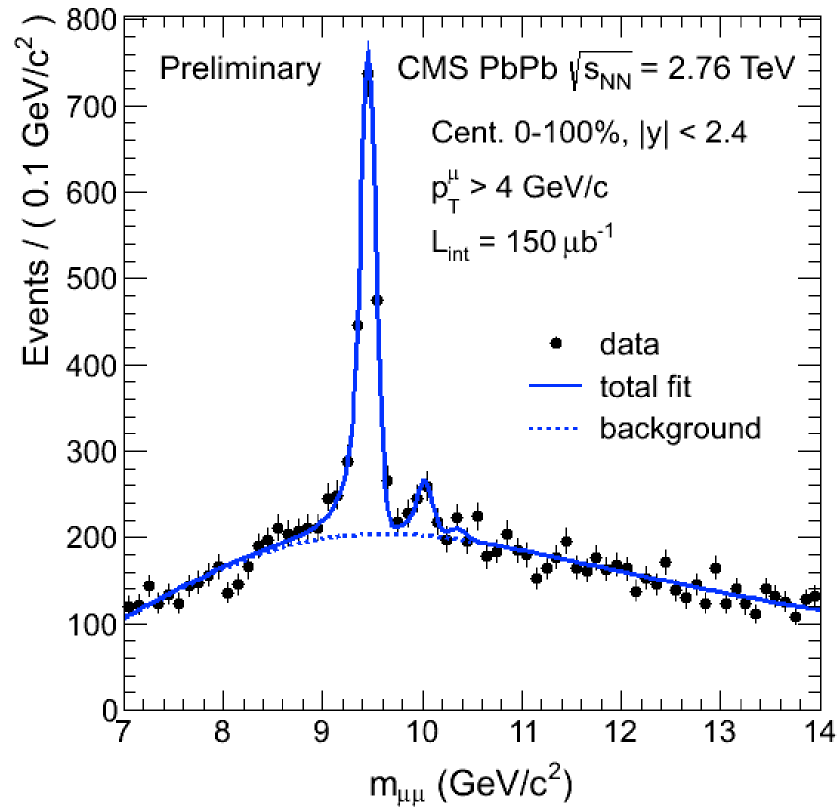
R_{AA} Charm vs Bottom



- Comparing charm from ALICE and bottom (beauty) from CMS.
- First hint of flavour hierarchy

Υ Suppression





$N_{Y(2S)}/N_{Y(1S)}|_{pp} = 0.56 \pm 0.13 \pm 0.01$ $N_{Y(2S)}/N_{Y(1S)}|_{PbPb} = 0.12 \pm 0.03 \pm 0.01$

$N_{Y(3S)}/N_{Y(1S)}|_{pp} = 0.21 \pm 0.11 \pm 0.02$ $N_{Y(3S)}/N_{Y(1S)}|_{PbPb} < 0.07$

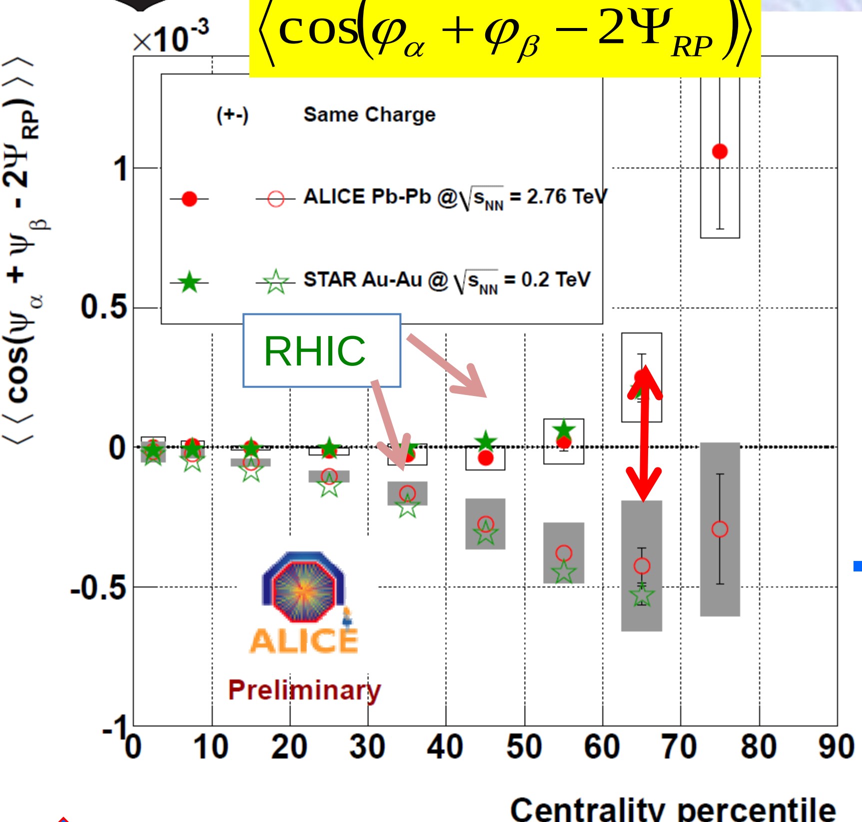
Ratios not corrected for acceptance and efficiency

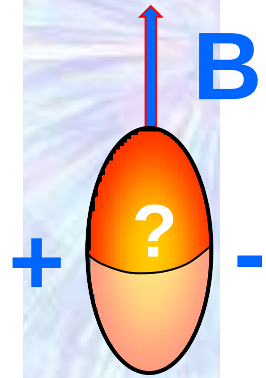
Summary

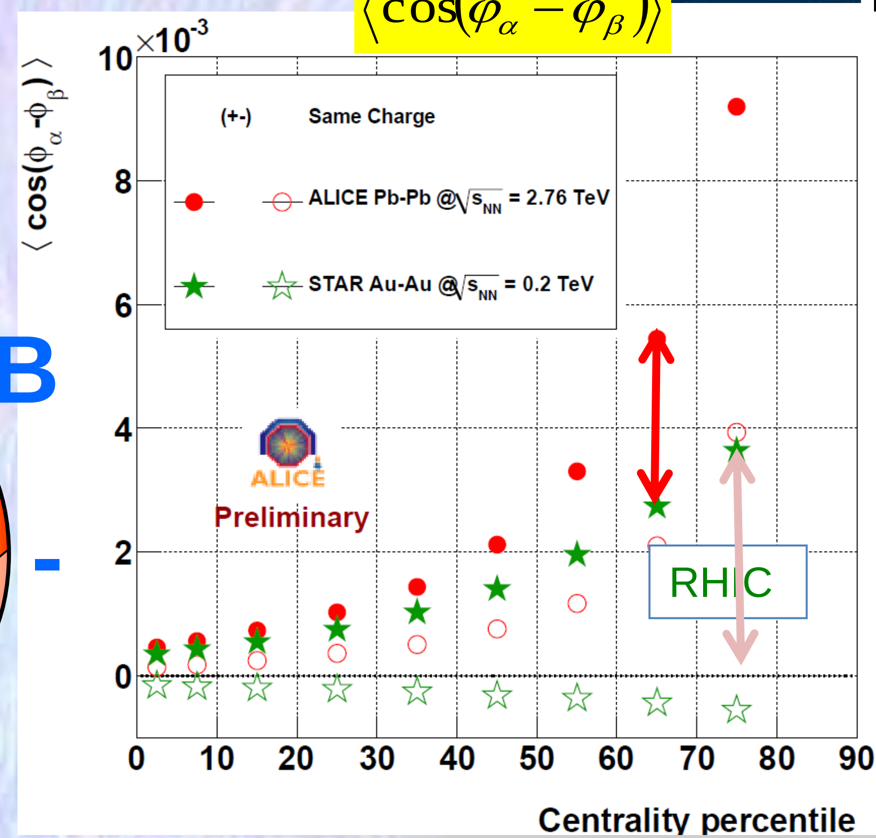
- **We have started to piece together the standard model of heavy-ion collisions**
- We have measured many of the global features
  - **Phase transition temperature** - Agrees with theory **T_c ~ 164 MeV**
  - **Energy density** - Over 10x critical energy density, **ε > 15 GeV/fm^3**
  - **size & lifetime** of system ~ **5000 fm^3, τ ~ 10-11 fm/c**
- Started to measure dynamical features
  - **Strong elliptical flow – ideal liquid**
  - **Strong suppression of jets and high p_T particles**
  - **Little evidence of quark mass dependence on energy loss for lighter quarks (unlike predictions – although dependence seen between charm and bottom)**
  - ϒ’ and ϒ’’ suppressed.
- We are at the early stages of a 10+ year programme and have just scratched the surface.
- **lots of work and exciting physics to look forward to.**
- Thank you for listening

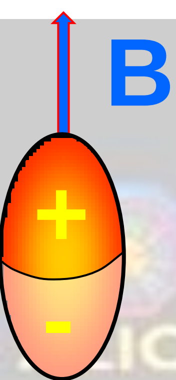
Backup Slides

Chiral Magnetic Effect
(~~'strong parity violation'~~)







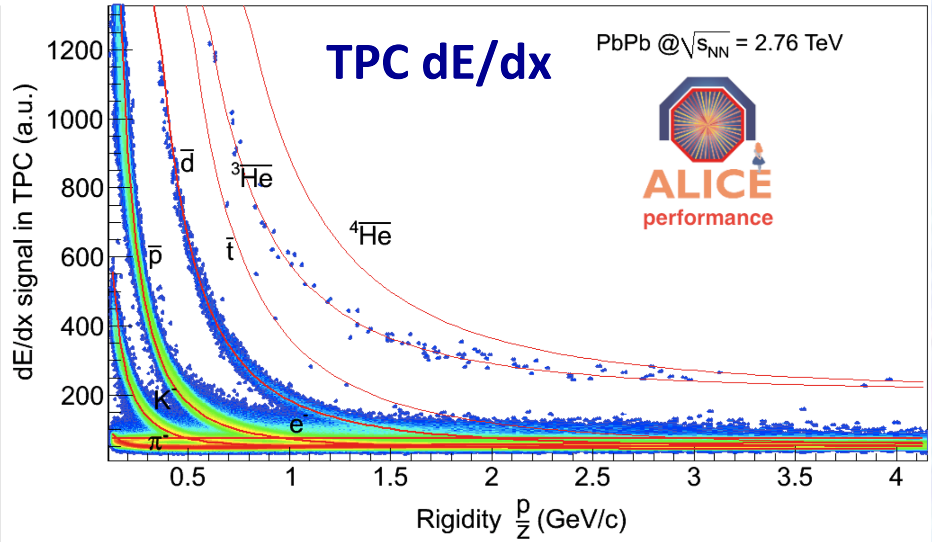


Same charge correlations **positive**
Opposite charge correlations **negative**
RHIC ≈ LHC
so

Local Parity Violation in strong magnetic Field ?

RHIC : (++), (+-) **different sign** and magnitude
LHC: (++),(+-) **same sign**, similar magnitude

Particle Identification



ITS Silicon Drift/Strip dE/dx