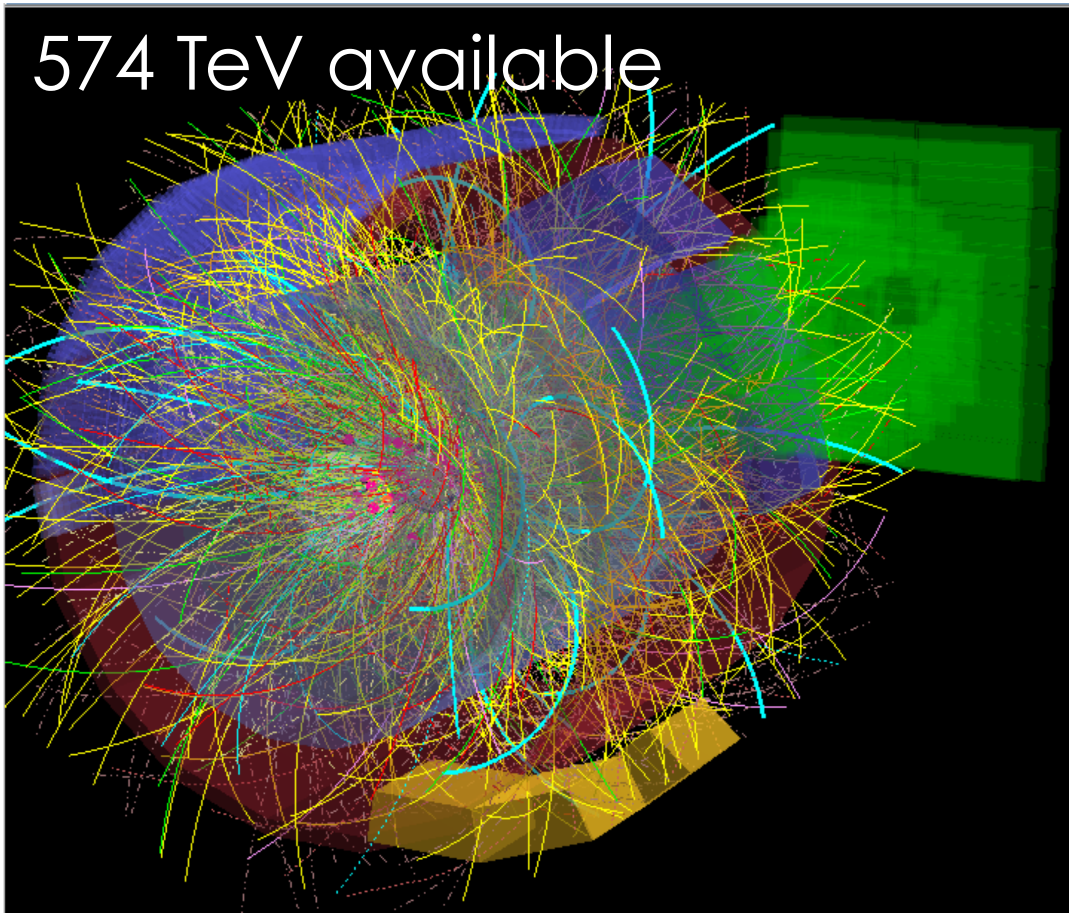
OVERVIEW OF HEAVY IONS RESULTS FROM ALICE

Pasquale Di Nezza

INFN Frascati

LHC and Ultrarelativistic HI Collisions, LNF 18/01/12

Highest energy man-made collisions ever!



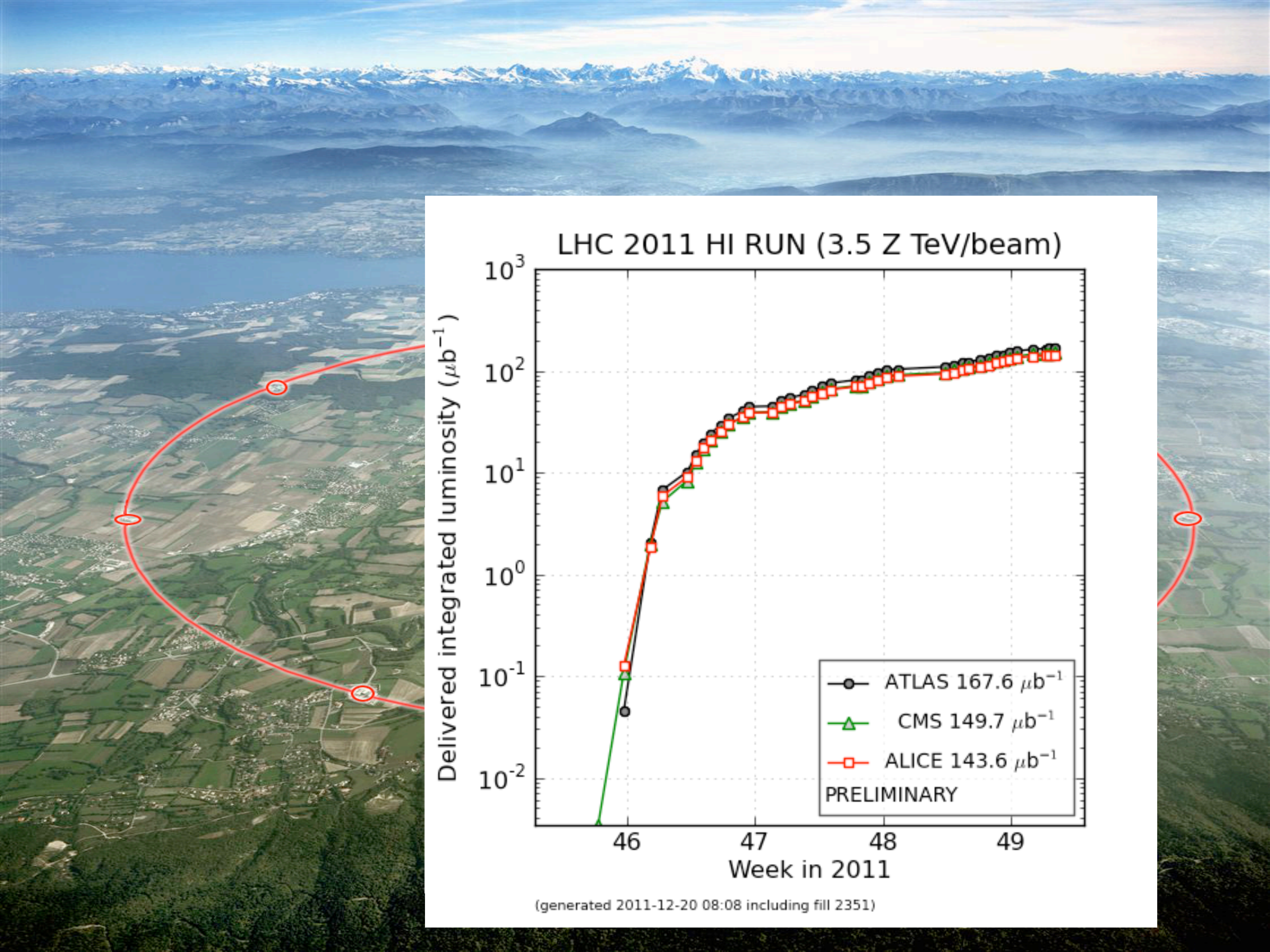
>3000 charged particles in the TPC in a central event

2010:
$>8\mu b^{-1}$ in 4 weeks
$\mathscr{L}_{PbPb} > 2x10^{25}$
(~1/20 $\mathscr{L}_{maxPbPb}$)

Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV wealth of results from only 1 month of running

2011 Pb+Pb run
- > 1kHz hadronic
- Integrated lumi >10 x 2010
- New triggers and optimization

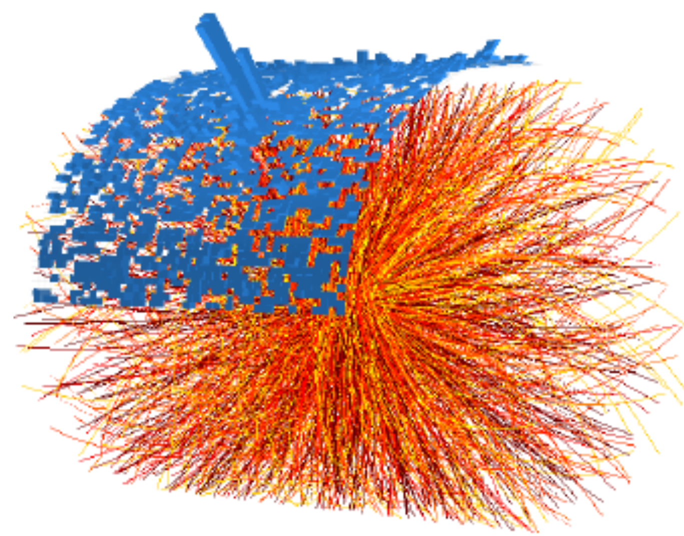
2012 p+Pb running
- First tests promising

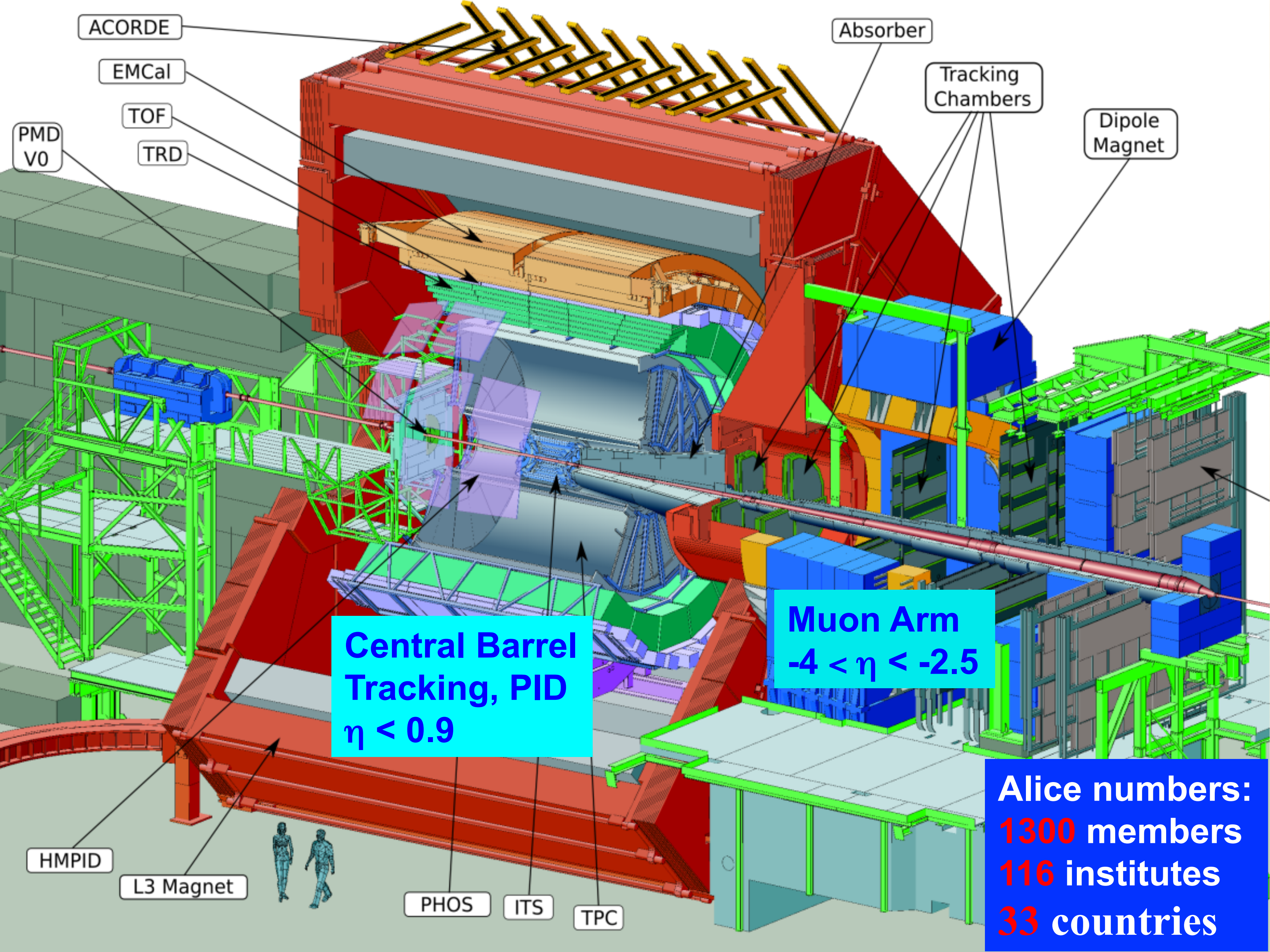

LHC 2011 HI RUN (3.5 Z TeV/beam)
Delivered integrated luminosity (μb^{-1})
Week in 2011
ATLAS 167.6 μb^{-1}
CMS 149.7 μb^{-1}
ALICE 143.6 μb^{-1}
PRELIMINARY
(generated 2011-12-20 08:08 including fill 2351)

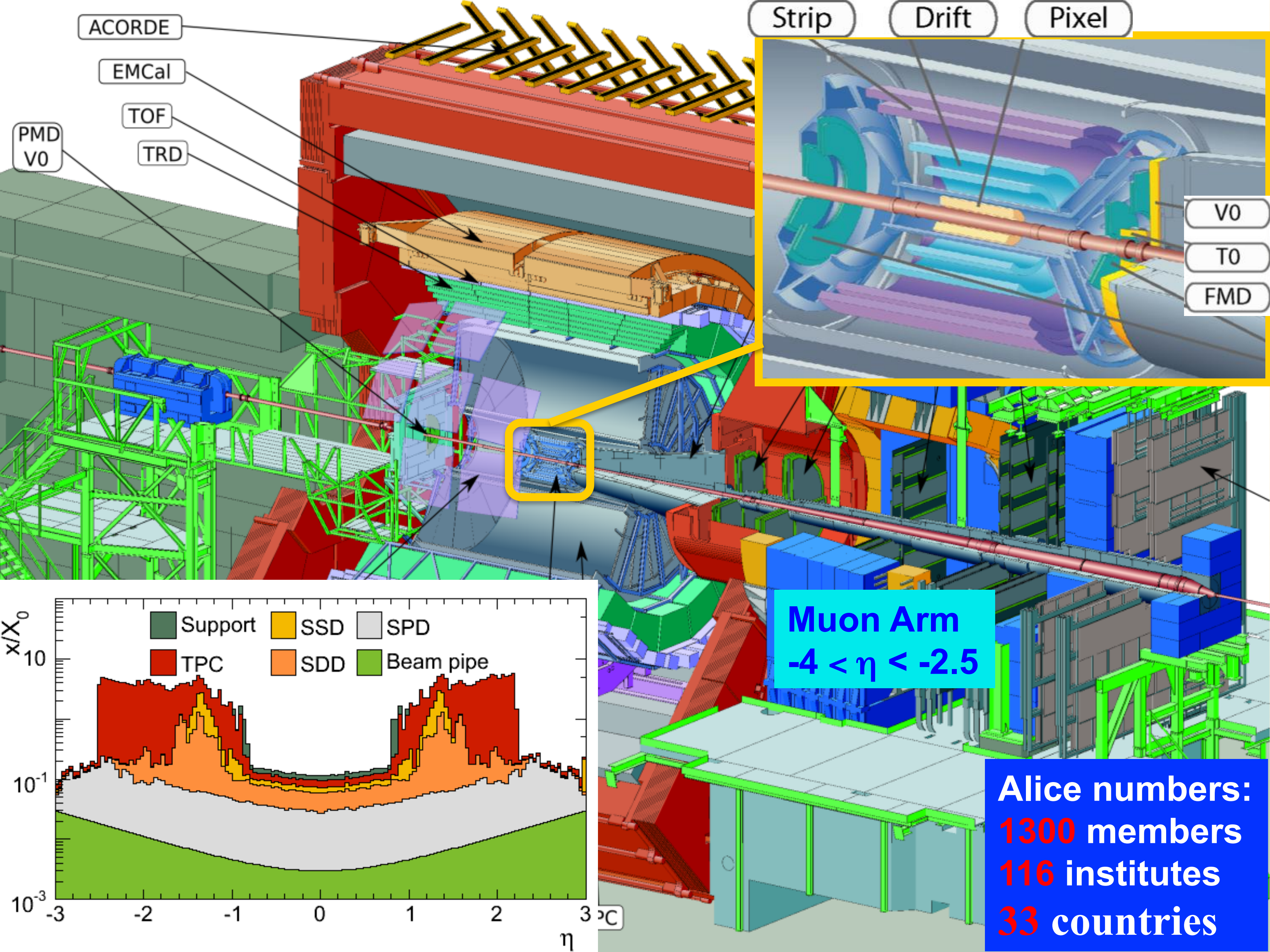
Event statistics per trigger class (status 6 Dec. 2011)

Trigger	Events
MinBias	8.3 M
Central	27.5 M
Semi-Central	32.1 M
EMCAL Jet	9.4 M
EMCAL Gamma	7.2 M
Barrel UPC	7.9 M
PHOS π^0	1.9 M
MUON Single	27.9 M
MUON UPC	3.0 M
MUON dimuon	20.0 M

- Trigger mix optimized to enhanced statistics of rare probes
- ~10x more statistics (centrality and rare triggers) collected as compared to 2010

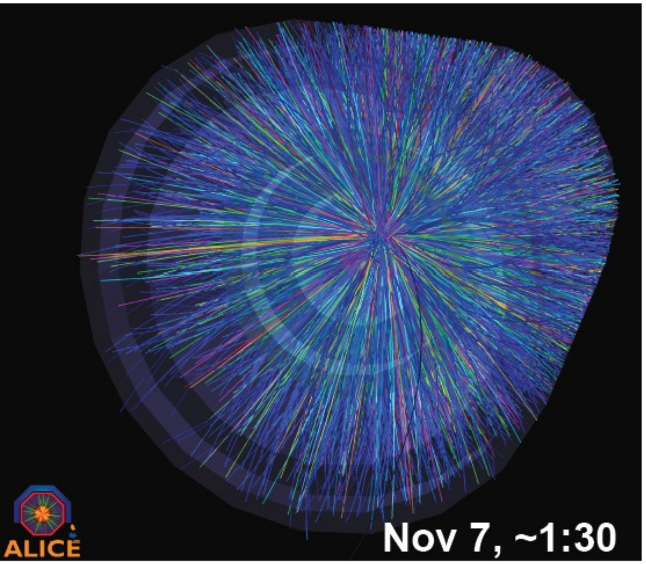


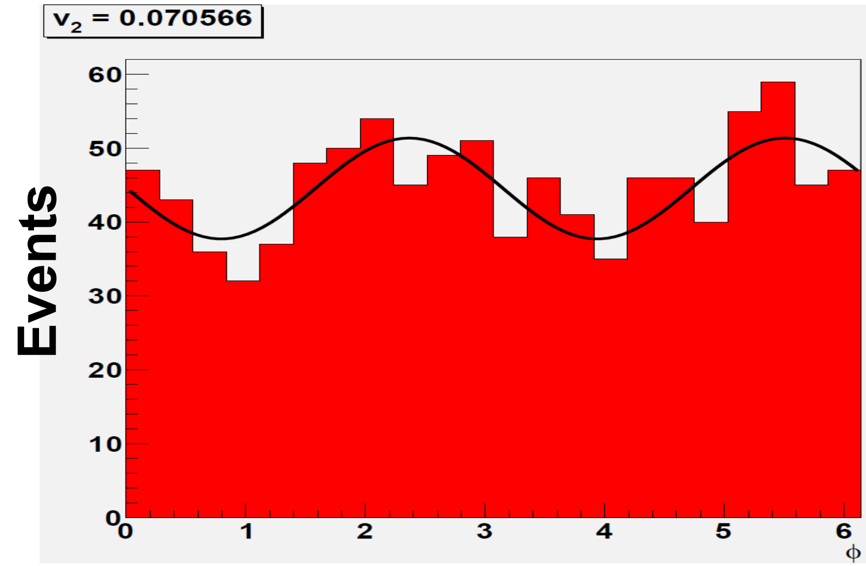

ACORDE
EMCal
TOF
TRD
PMD
V0
Absorber
Tracking Chambers
Dipole Magnet
Central Barrel
Tracking, PID
η < 0.9
Muon Arm
-4 < η < -2.5
Alice numbers:
1300 members
116 institutes
33 countries
HMPID
L3 Magnet
PHOS
ITS
TPC

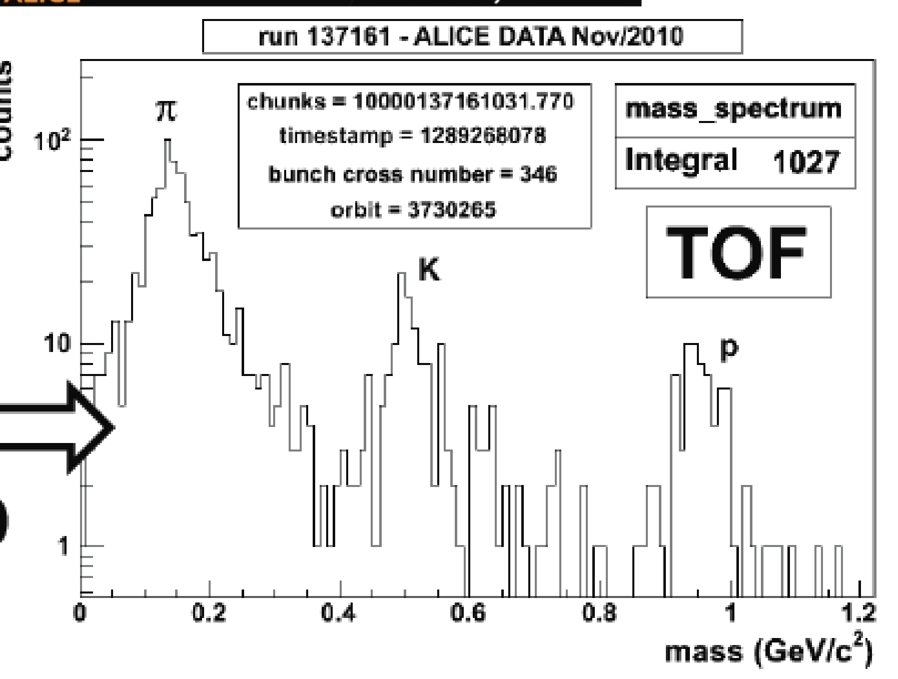

ACORDE
EMCal
TOF
PMD
V0
TRD
Strip
Drift
Pixel
V0
T0
FMD
x/X0
Support
SSD
SPD
TPC
SDD
Beam pipe
10
10^-1
10^-3
-3
-2
-1
0
1
2
3
η
Muon Arm
-4 < η < -2.5
Alice numbers:
1300 members
116 institutes
33 countries

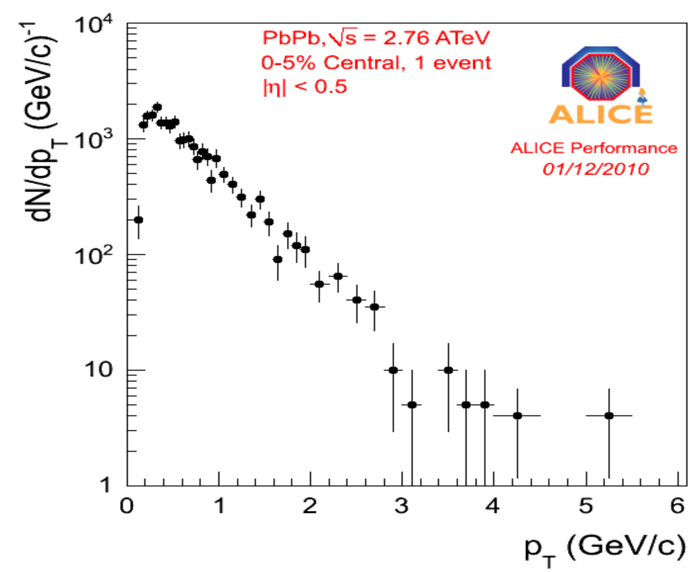
A Single Event

- Properties of average events instead of average event properties



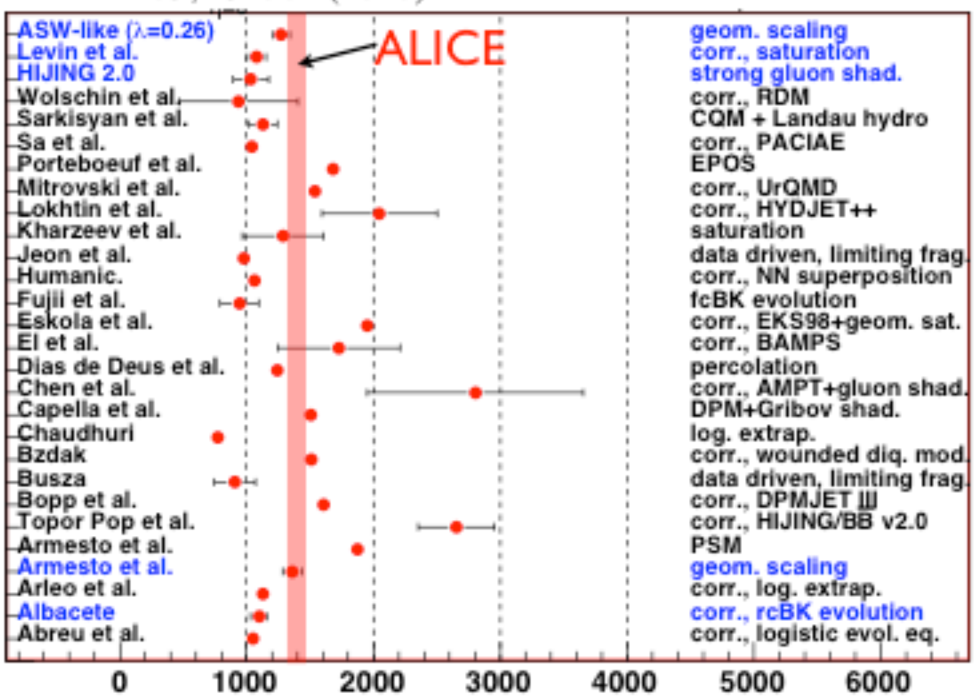






First result: Charged particle multiplicity

PRL 105, 252301 (2010)

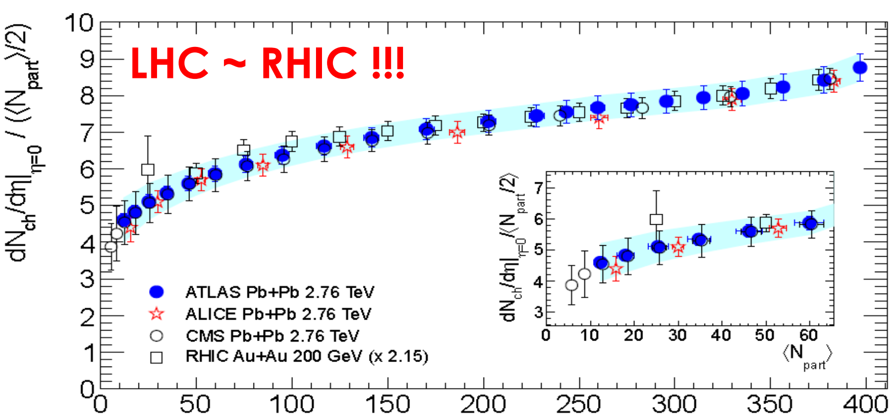


5% most central events:

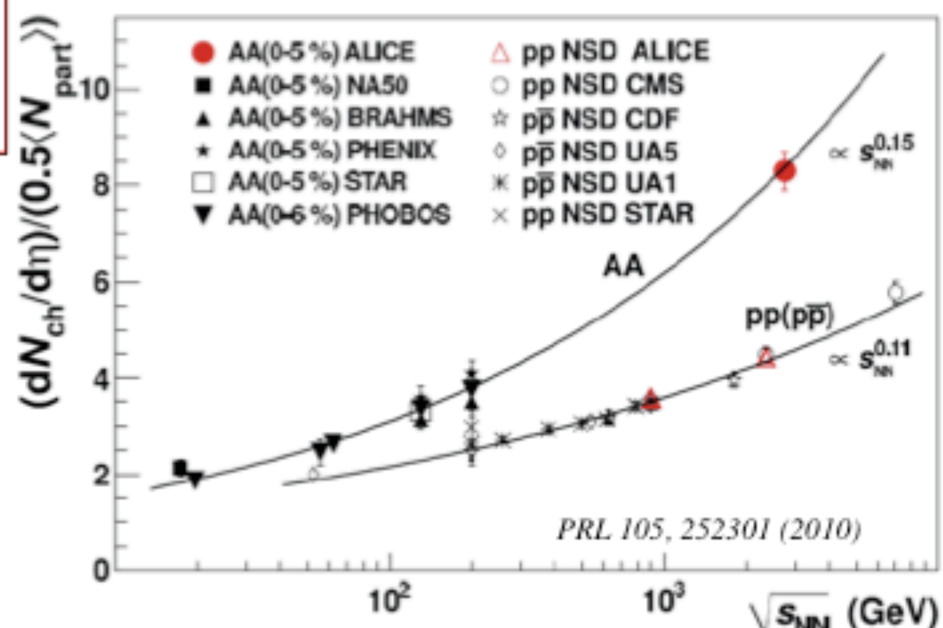
$dN_{ch}/d\eta = 1584 \pm 4(stat) \pm 76\ (sys)$

First few events "killed" many models

Particle production somewhat higher than expected: Shadowing/Saturation models favored



ArXiv:1108.6027v1



Growth with energy faster in AA than in pp $s^{0.15}$ vs $s^{0.11}$ → nuclear amplification

$dN_{ch}/d\eta$ – Centrality Dependence vs Theory

Two-component models:

Soft processes $dN_{ch}/d\eta \sim N_{\text{scattered nucleons (participants)}} \sim N_{part}$

∴ "nuclear amplification" → independent of √s

Hard processes $dN_{ch}/d\eta \sim N_{\text{nucleon-nucleon collisions}}$

∴ increased importance with √s & centrality

- DPMJET MC
  - Rises too strongly with N_{part}
- HIJING MC (2.0), no quenching
  - Centrality dependent – Gluon shadowing
  - Tuned to 0-5% central

Saturation-type models:

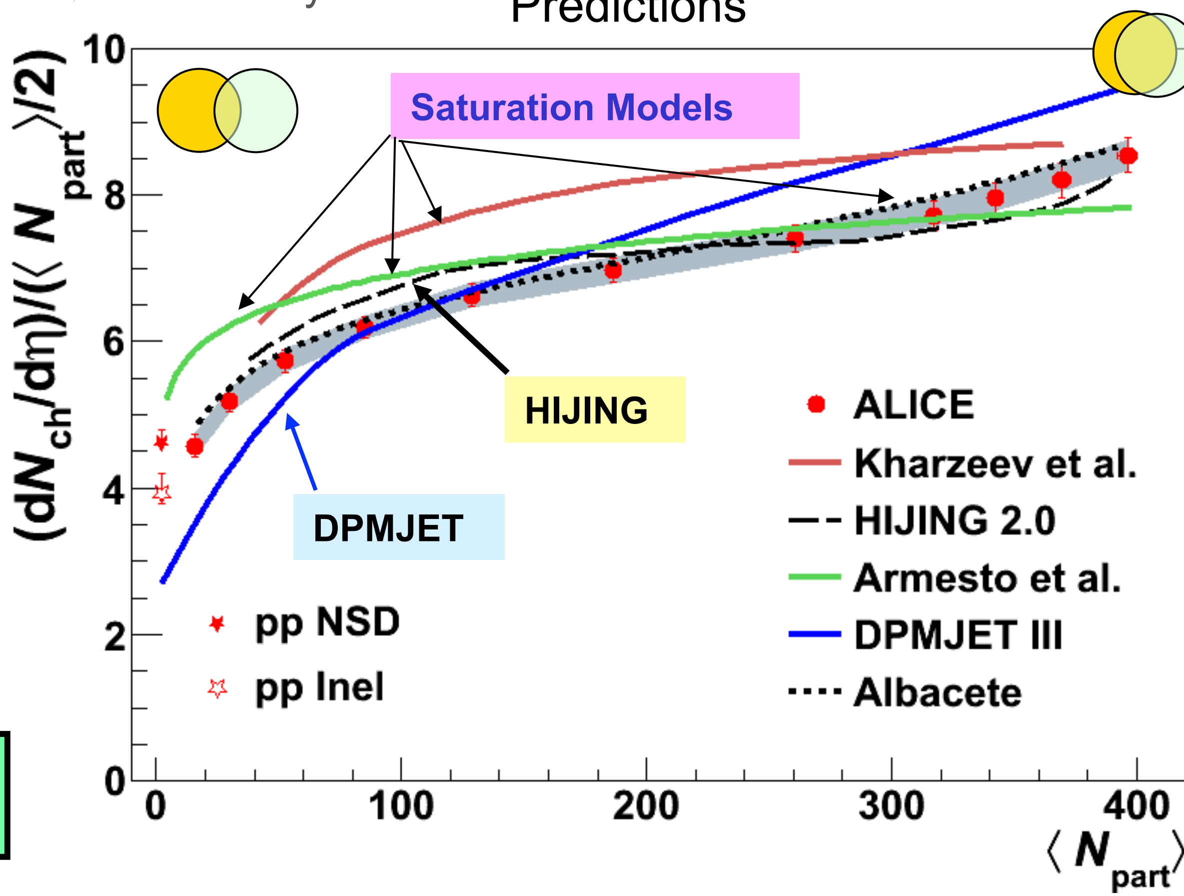
Parametrization of saturation scale vs √s & centrality (A)

geometric scaling

Data favor models with moderation of particle production vs centrality

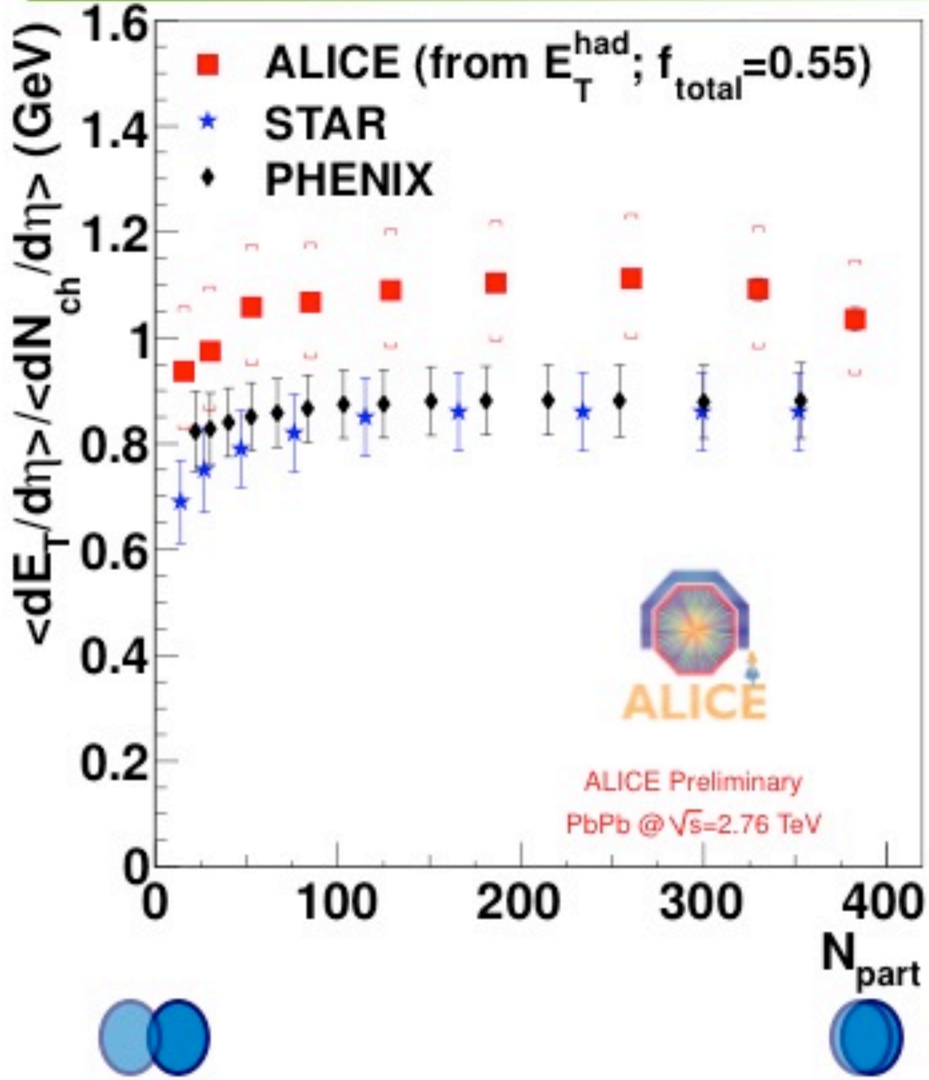
Important constraint for models & sensitive to details of initial state, saturation, evolution….!

Predictions



ALICE, Phys. Rev. Lett. 106, 032301 (2011)

Energy density

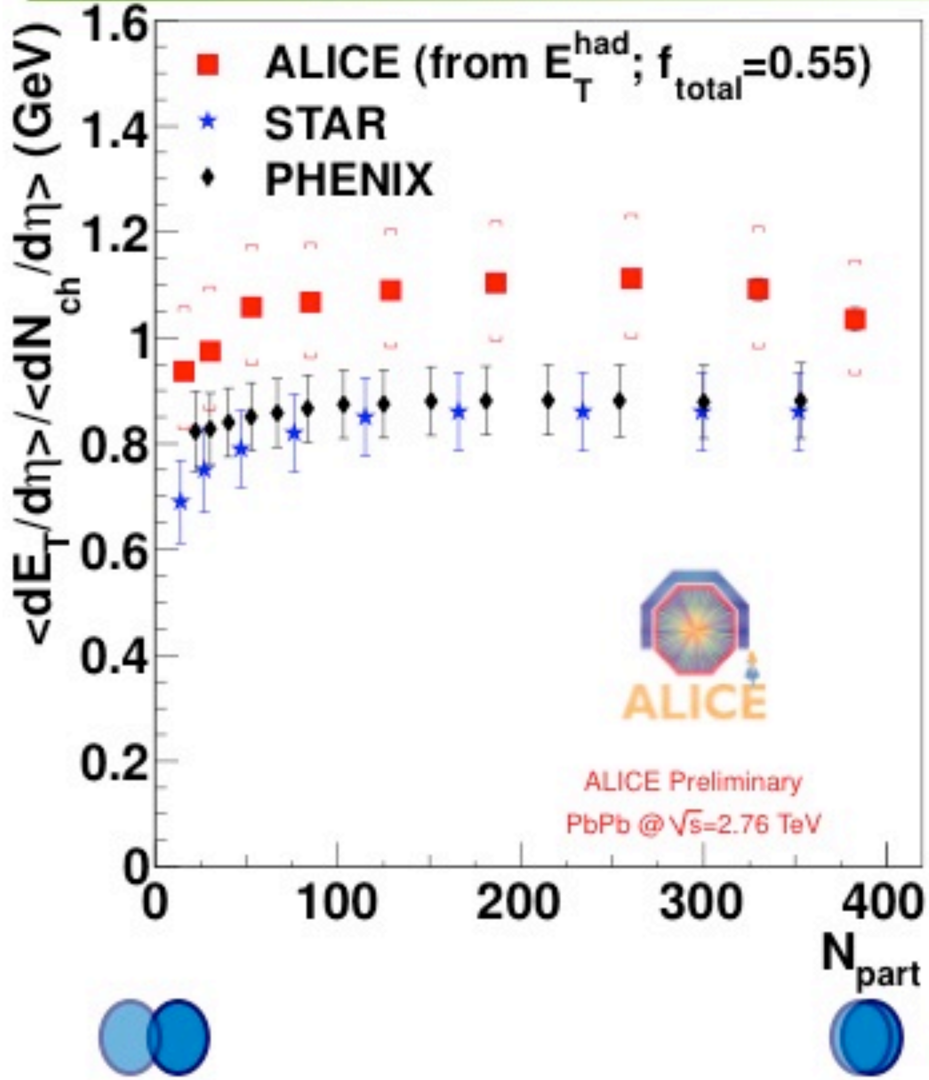


$dE_T/d\eta$ per participant pair

- LHC ~ 2.5 RHIC
- Similar centrality dependence

$$\epsilon\tau_{LHC} \geq 2.5\epsilon\tau_{RHIC}$$

Energy density



$$\epsilon\tau_{LHC} \geq 2.5\epsilon\tau_{RHIC}$$

$dE_T/d\eta$ per participant pair

- LHC ~ 2.5 RHIC
- Similar centrality dependence

Energy density of the medium:

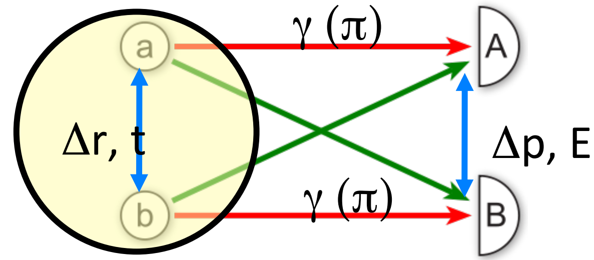
$$\epsilon_{Bj}(\tau) = \frac{1}{\tau\pi R^2}\frac{dE_T}{d\eta}$$

$R=1.2A^{1/3}$ fm

- $\tau\varepsilon_{LHC} \sim 15$ GeV/(fm^{2}c)
- $\tau\varepsilon_{RHIC} = 5.4 \pm 0.6$ GeV/(fm^{2}c)

(remember $\varepsilon_C \approx 0.70$ GeV/fm^3)

Space-time evolution of the system

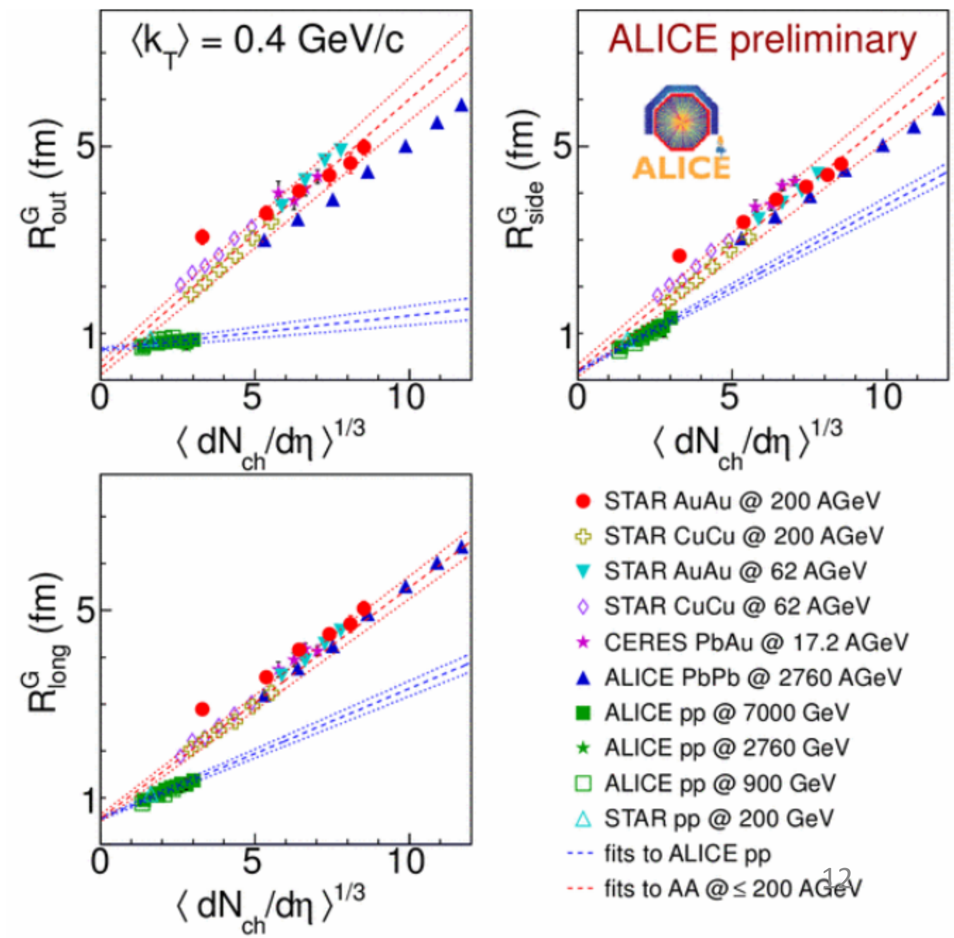


Observe volume using QM interferometry for bosons (ideas from 1950's)

•Used by astronomers to measure star sizes with photons (Hanburry, Brown-Twiss)

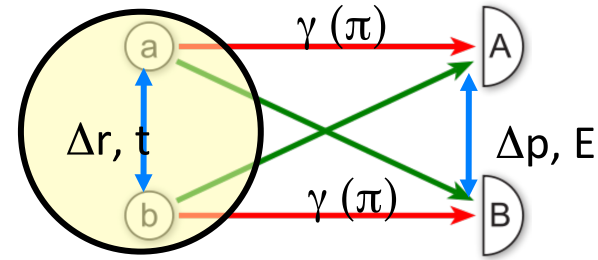
•Used in particle physics to measure source size with pions (Goldhaber)

- HBT radii scale roughly linearly with multiplicity$^{1/3}$ in pp and PbPb
- HBT radii in PbPb vs. trend from lower energy AA:
  - R_{long}: perfectly agree
  - R_{side}: reasonably agree
  - R_{out}: clearly below the trend
- Behaviour of all 3 radii in qualitative agreement with hydro expectations
  - R_{out}/R_{side} decreases with √s due to higher initial temperature

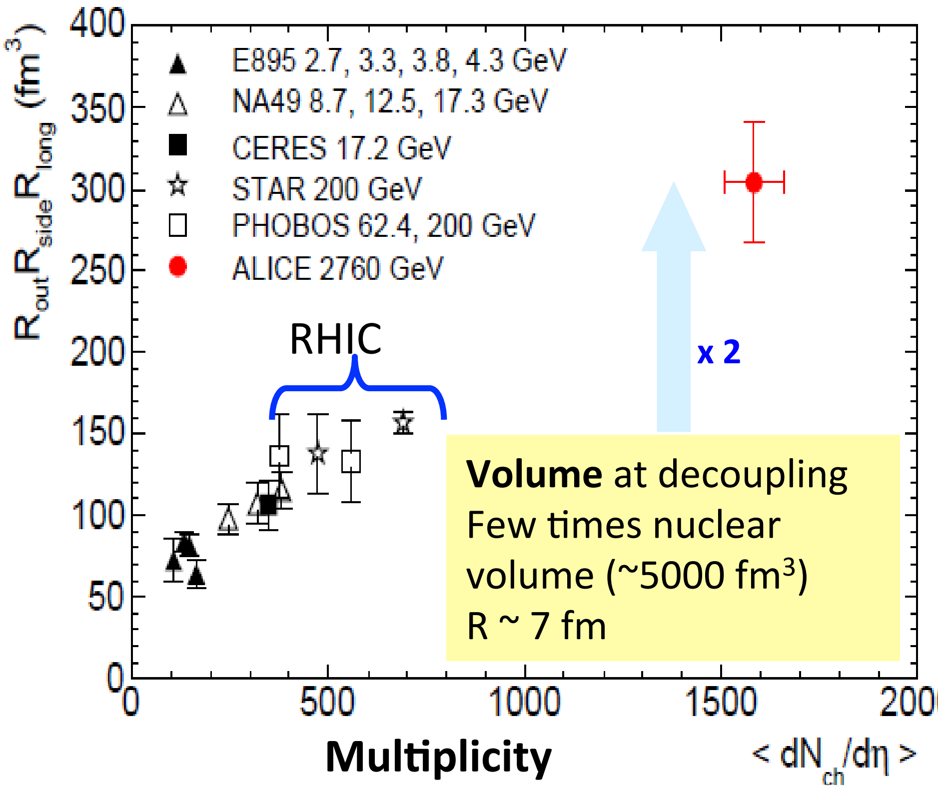


Space-time evolution of the system

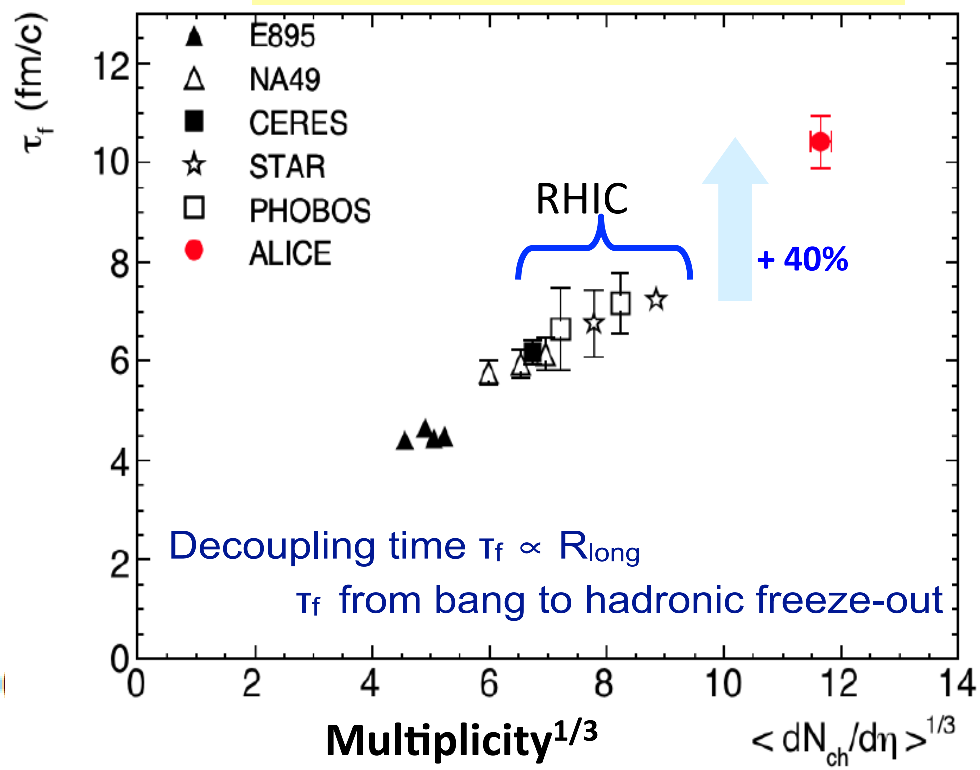
PLB 696, 328 (2011)



V scales ~ linearly with multiplicity



Lifetime: from collision to
'freeze-out' (hadron decoupling)

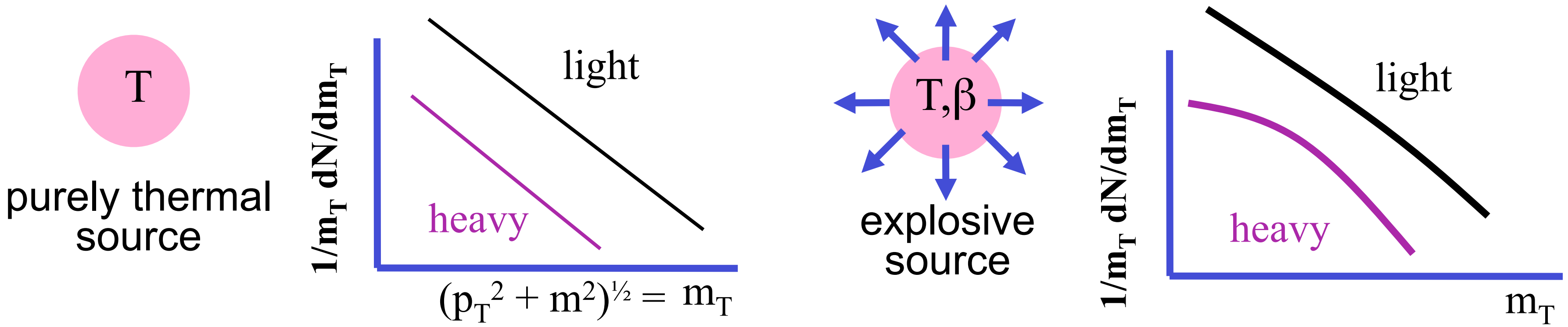


Source at LHC is larger and
lives longer than at RHIC

Determining the temperature

Thermal source emits "Blackbody" radiation

→ p_T spectra reveal temperature of QGP



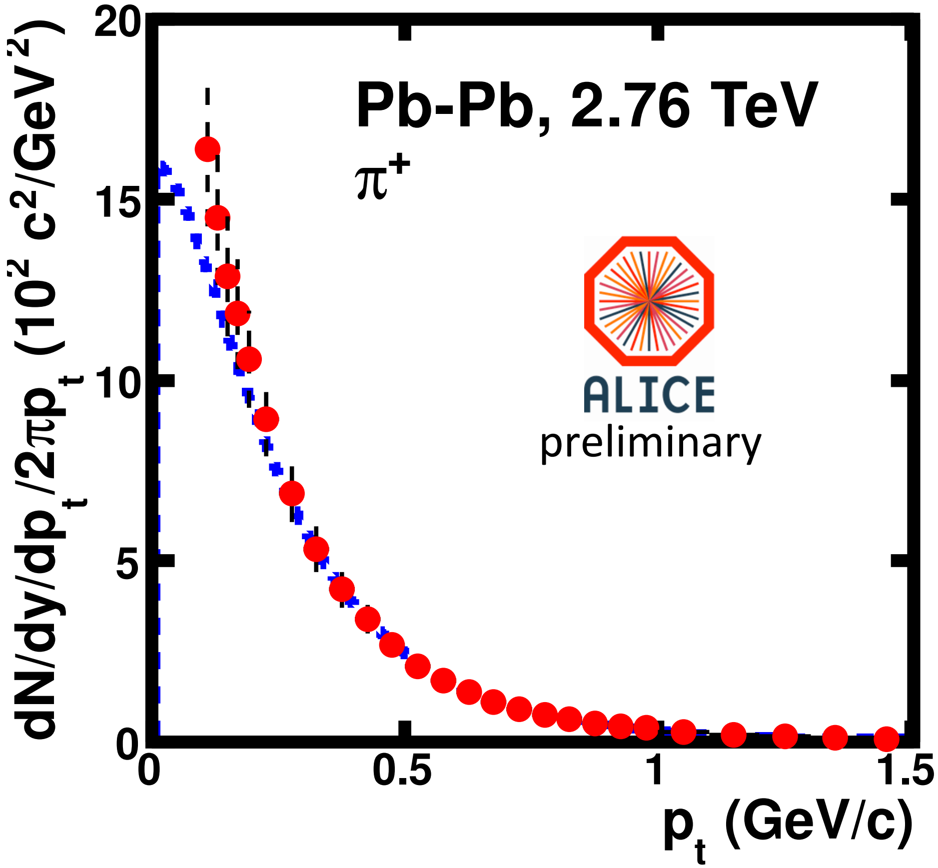
Different spectral shapes for particles of differing mass
→ strong collective radial flow

π light so not/hardly affected by flow

Determining the temperature

Thermal source emits "Blackbody" radiation

→ p_T spectra reveal temperature of QGP



$T_{fo,LHC} \sim T_{fo,RHIC}$

Fit to central data T ~80 MeV

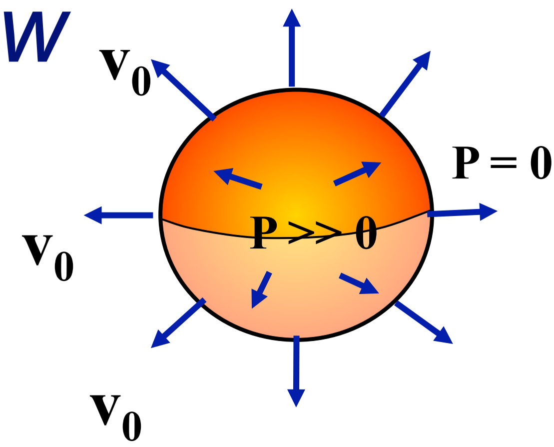
$$E = \frac{3}{2}kT$$

$$T = \frac{2E}{3k}$$

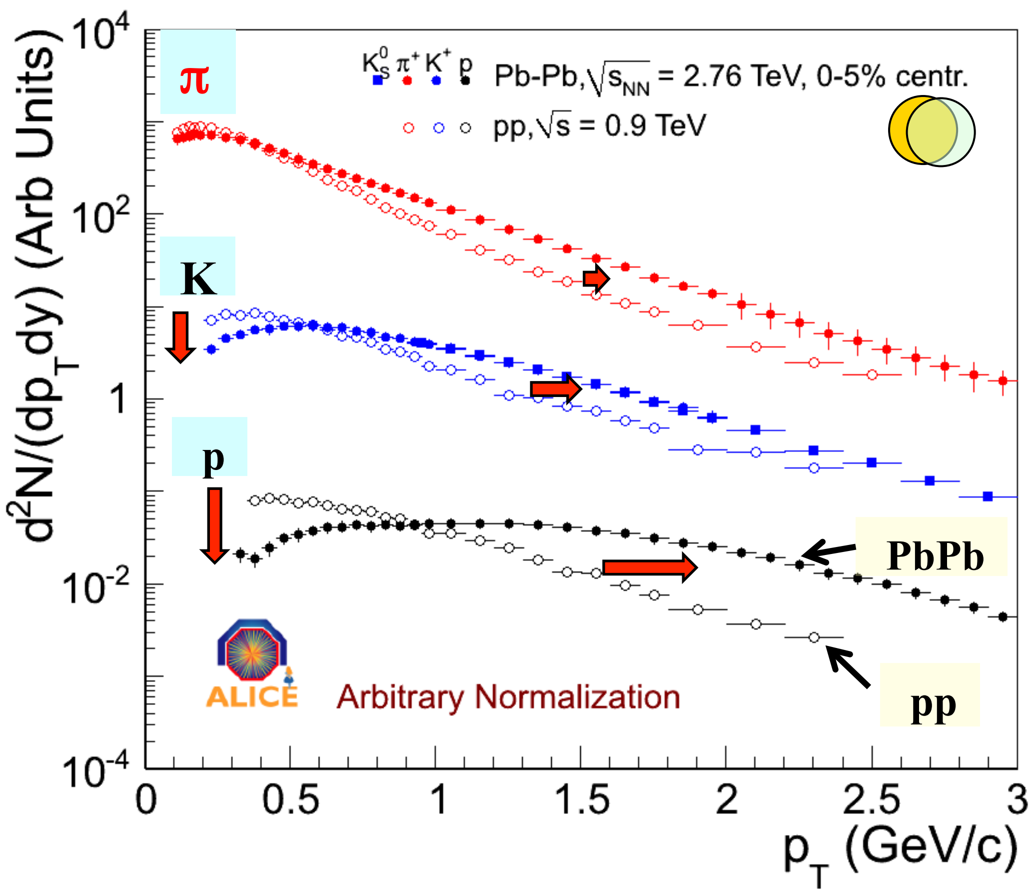
$$= \frac{2 \times 80 \times 10^6}{3 \times 1.4 \times 10^{-23}} \times 1.6 \times 10^{-19}$$

$$\sim 9 \times 10^{11} K$$

Initial temperature and radial flow

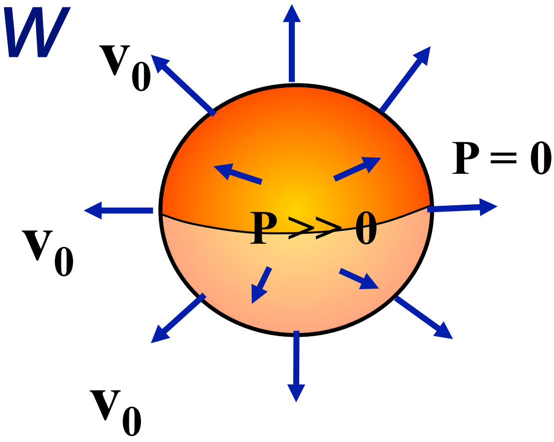


Flow velocity depends on equation of state
Momentum distributions for different mass particles show characteristic differences wrt pp

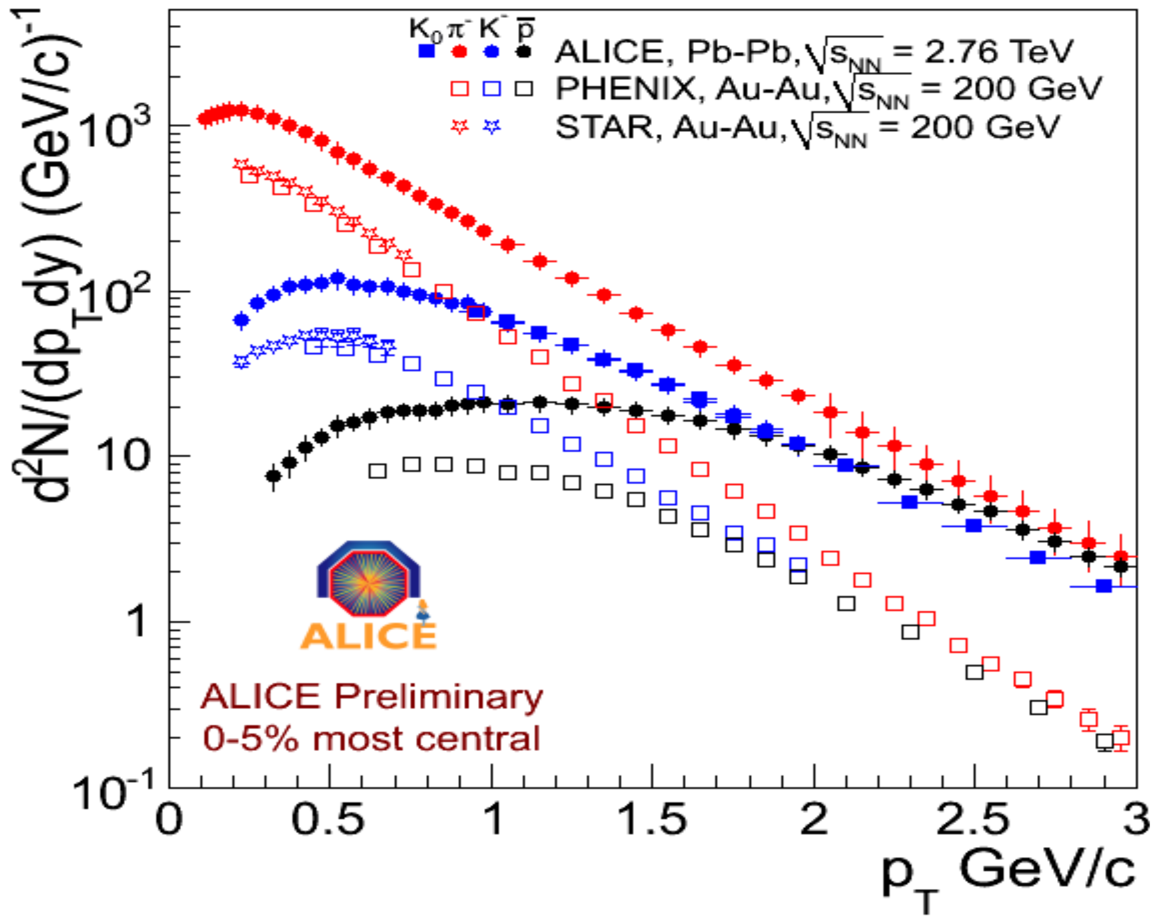


Good agreement between different kaon analyses

Initial temperature and radial flow



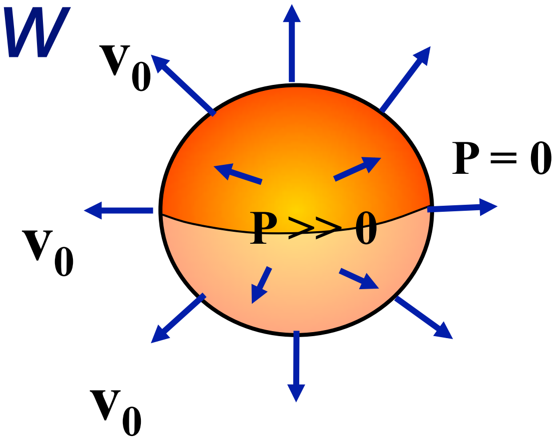
Flow velocity depends on equation of state
Momentum distributions for different mass particles show characteristic differences wrt pp

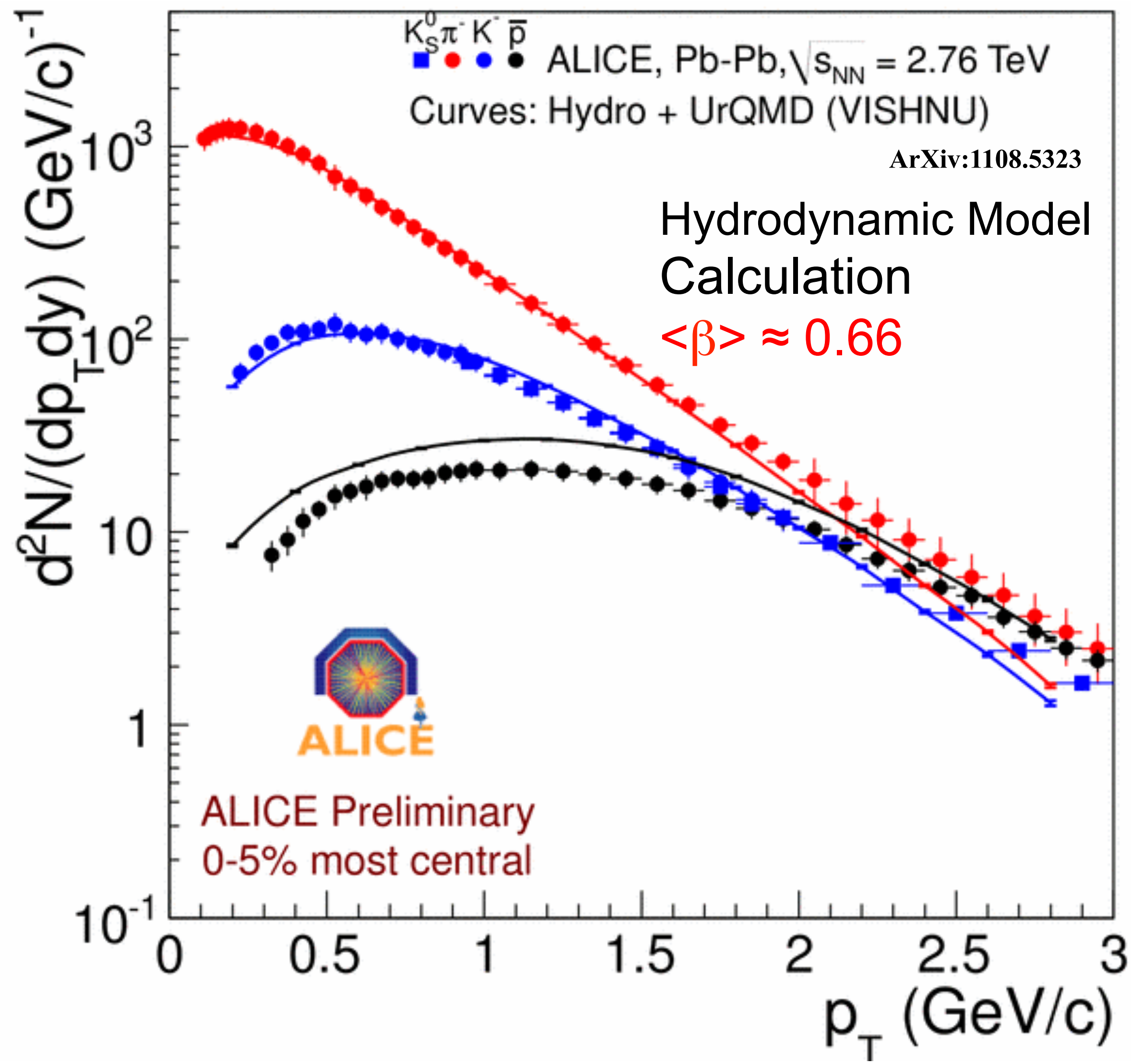


Significant changes in slope compared to RHIC, especially for protons

Spectra much harder and higher yield

Initial temperature and radial flow





Spectra harder and proton yield lower than hydro predictions

Very strong radial flow

$\beta_{LHC} \approx 0.66c \sim 1.1\ \beta_{RHIC}$

$T_{kin,LHC} = T_{kin,LHC} \sim 80$ MeV

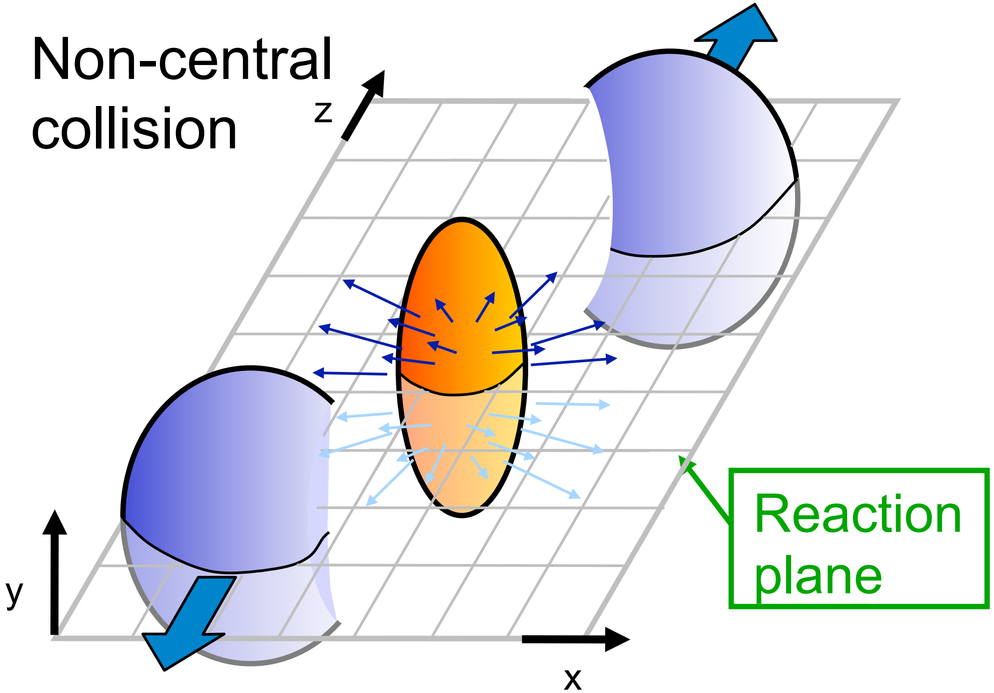
From Hydro:

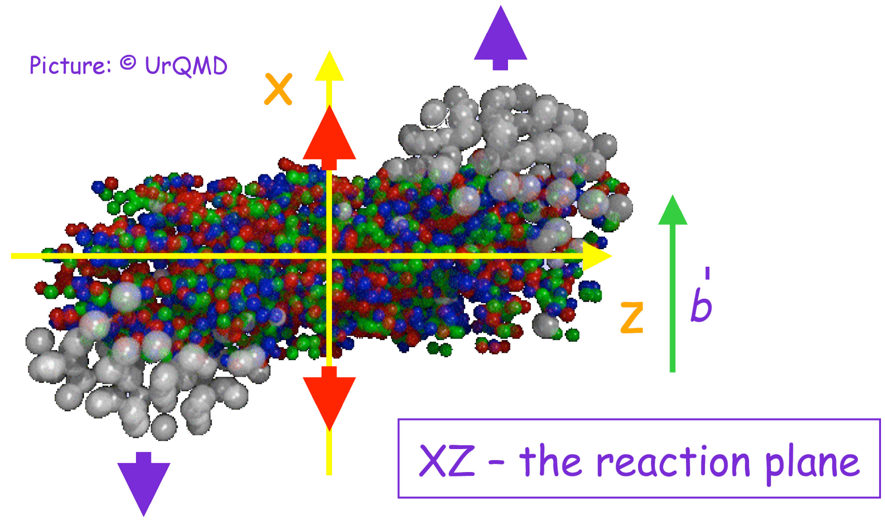
$T_{LHC} \sim 420$ MeV

$T_{LHC} \sim 1.2\text{-}1.3 T_{RHIC}$

(M.Luzum P.and Romatschke 2009 *PRL*. **103** 262302)

Geometry of a heavy-ion collision





"<u>peripheral</u>" collision ($b \sim b_{max}$)

"<u>central</u>" collision ($b \sim 0$)

Number of participants (N_{part}):

number of incoming nucleons (participants) in the overlap region

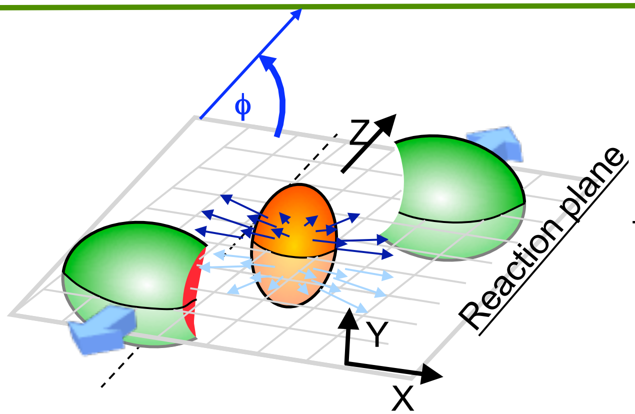
Number of binary collisions (N_{bin}):

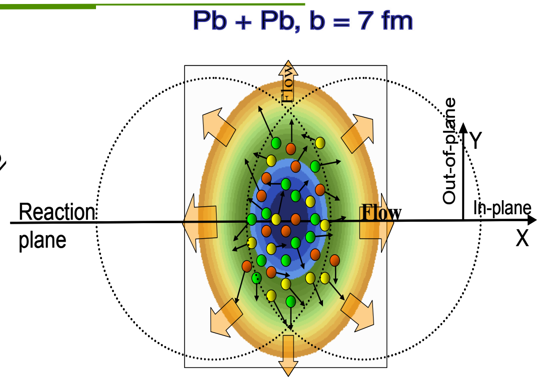
number of equivalent inelastic nucleon-nucleon collisions

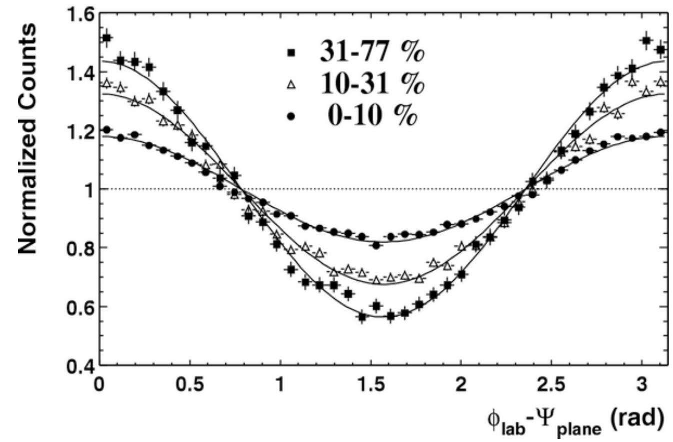
$N_{bin} \geq N_{part}$

More central collisions produce more particles

Anisotropic/Elliptic flow



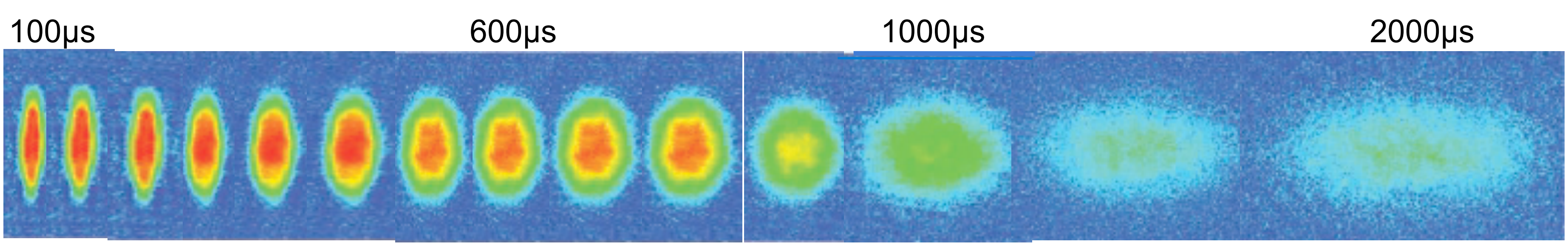




Almond shape overlap region in coordinate space → Interactions/ Rescattering → Anisotropy in momentum space

$dN/d\phi \sim 1+2\, v_2(p_T)\cos(2\phi) + \ldots.$ $\phi = \mathrm{atan}(p_y/p_x)$ $v_2 = \langle \cos 2\phi \rangle$

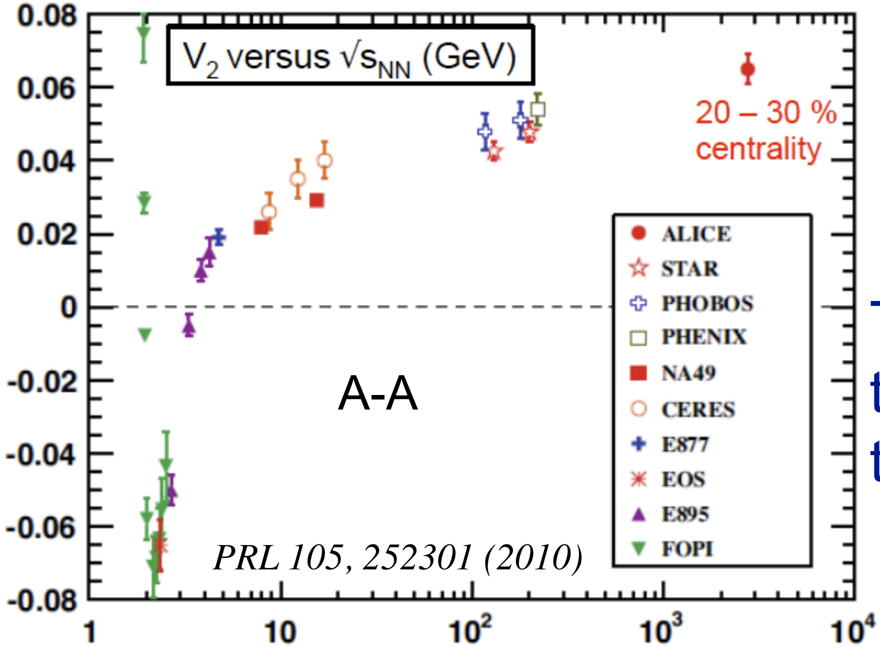
v_2: 2^{nd} harmonic Fourier coefficient in $dN/d\phi$ with respect to the reaction plane



Time

–M. Gehm, S. Granade, S. Hemmer, K, O'Hara, J. Thomas - **Science** 298 **2179 (2002)**

Elliptic flow

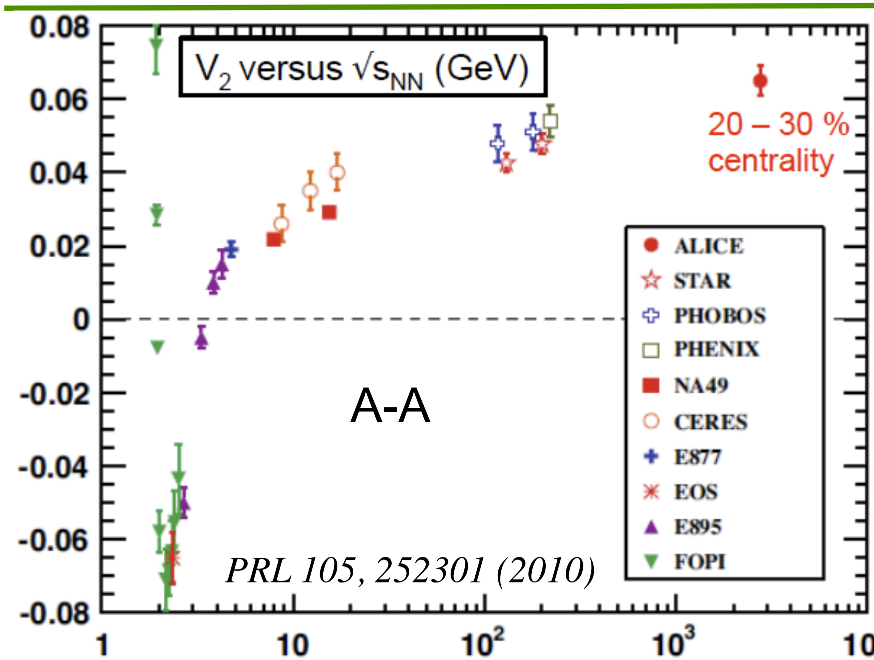


Hydro behavior continues at LHC

v_2 (p_T int.) LHC ~1.3x (p_T int.) RHIC

The overall increase is consistent with the increased radial expansion leading to a higher mean p_T

Elliptic flow

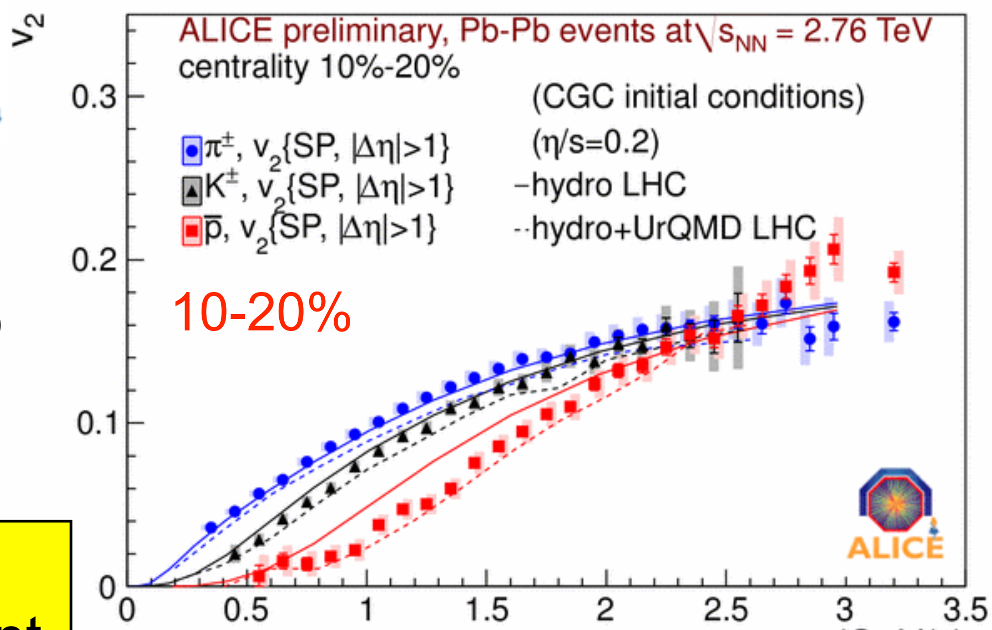


Hydro behavior continues at LHC

v_2 (p_T int.) LHC ~1.3x (p_T int.) RHIC

The overall increase is consistent with the increased radial expansion leading to a higher mean p_T

Mass dependence strong due to large radial flow - predicted by viscous hydro. (Heinz et. al, arXiv:1105.3226)



(Heinz et al, arXiv:1108.5323)

Radial flow too small from hydro. for protons

Hadronic re-scatterings play an important role in flow development

LHC bulk summary

- Energy density > 15 GeV/fm^3
- Freeze-out volume ~ 5000 fm^3
- Lifetime of source 10-11 fm/c
- Radial flow 0.66c
- Thermalization temperature 420 MeV
- Thermal freeze-out temperature 80 MeV
- Elliptic flow as expected from hydro-dynamical calculations with viscous corrections and hadronic re-scattering

Hydrodynamic Evolution of System

C. Shen, QM 2011

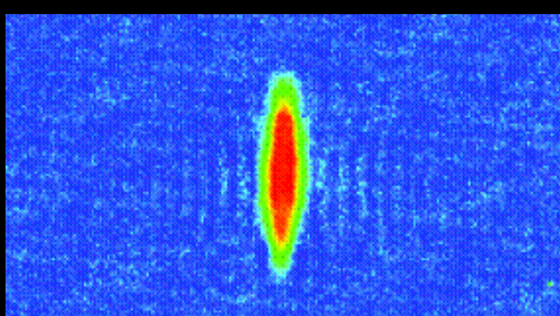
Ref: C. Shen, U. Heinz, P. Huovinen, H. Song, arXiv:1105.3226.

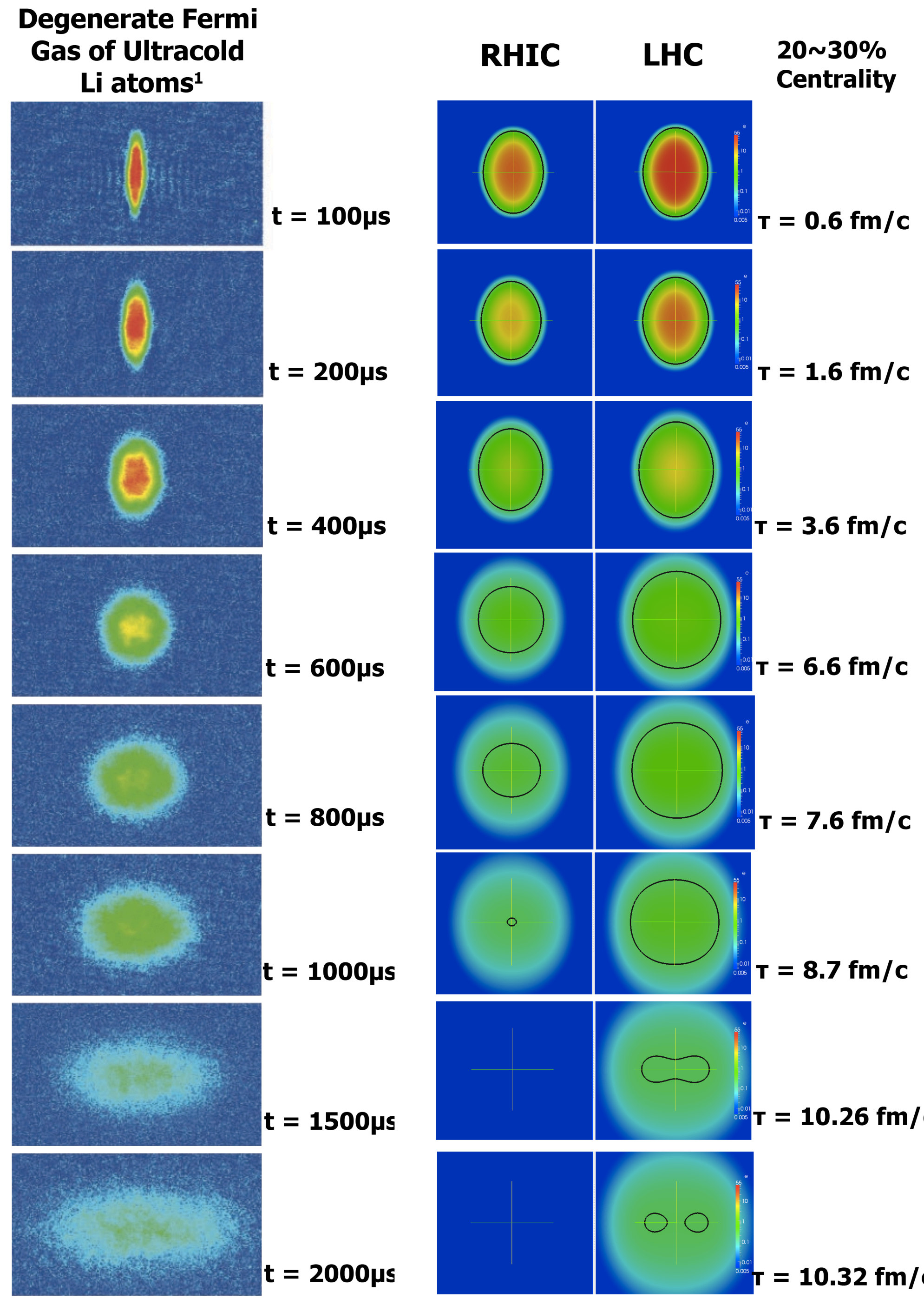
Hydro evolution at RHIC and LHC: 20-30% peripheral AuAu or PbPb

Black curves: freeze out surface at $T_{kin\ FO}$= 120MeV

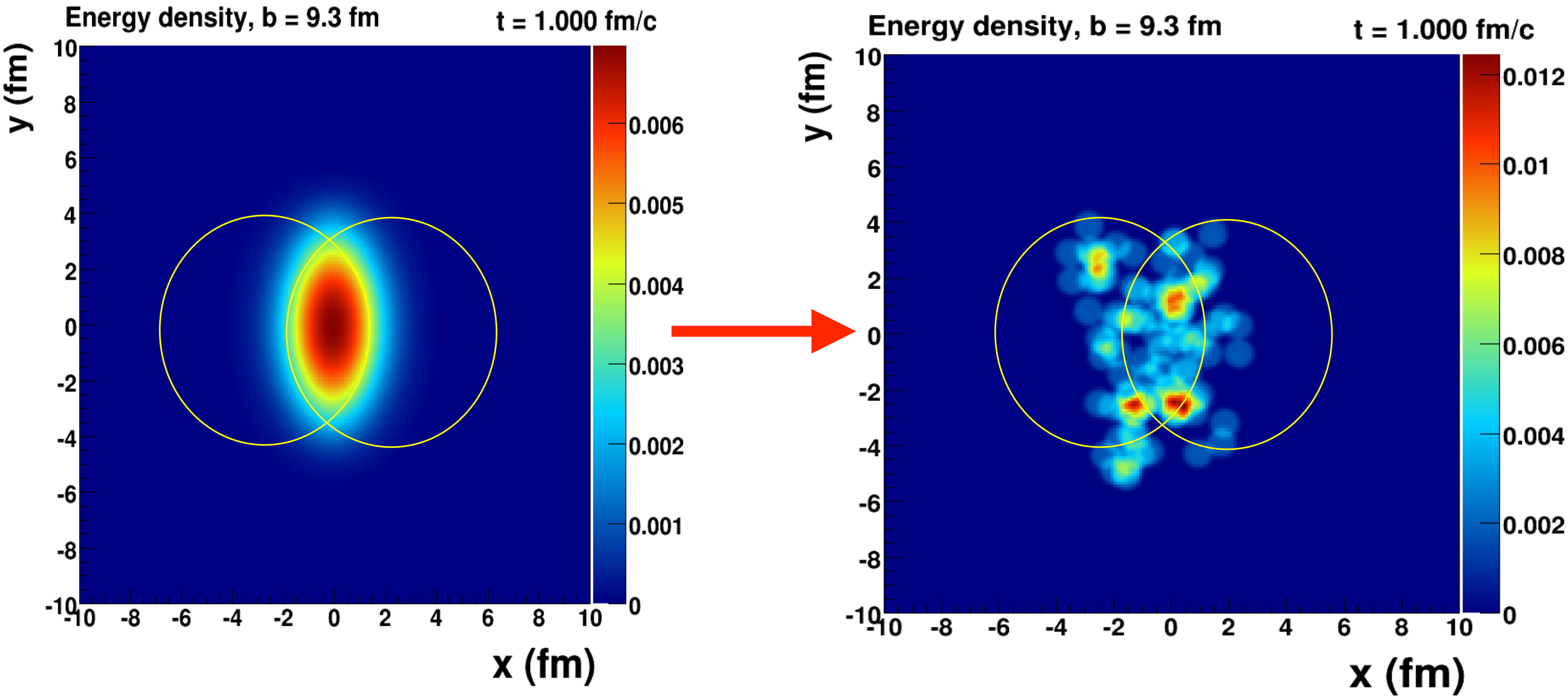
LHC **expansion rate >>** RHIC rate

- Stronger hydro force -> **more v_2**
- Rips apart fireball (in two) along the reaction plane near FO!



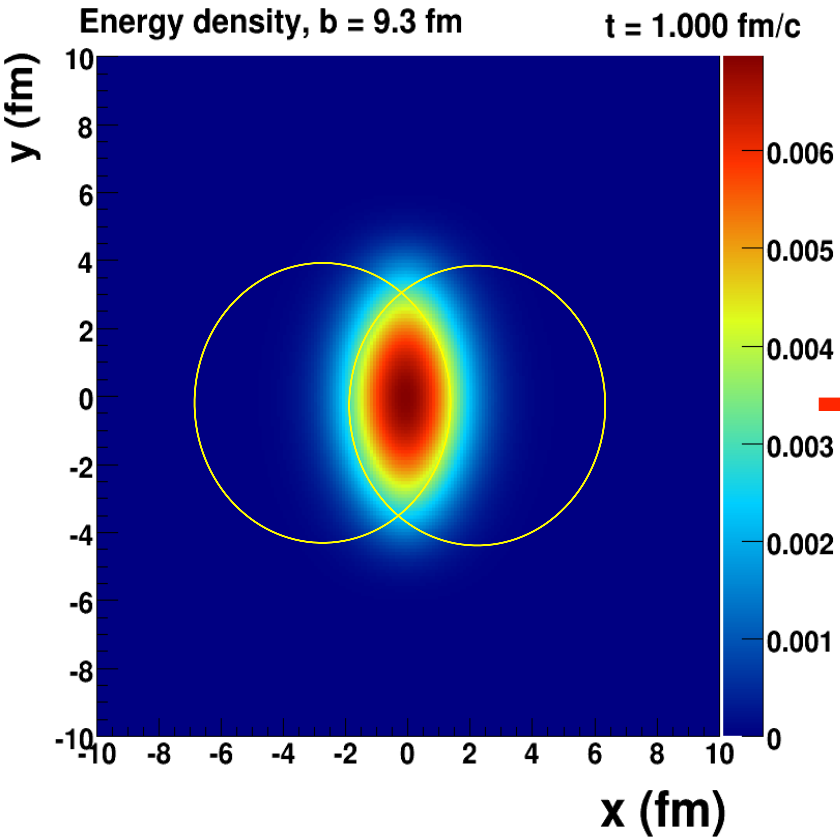


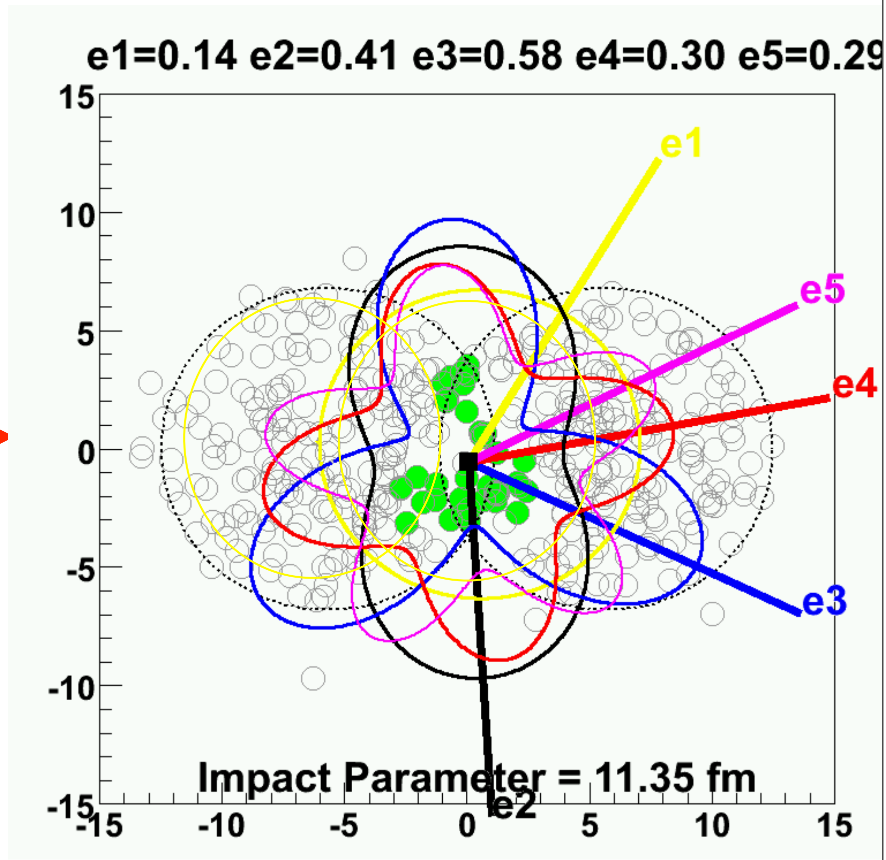
Initial conditions are complex



Event-by-event hydrodynamical needed to account for fluctuations

Initial conditions are complex





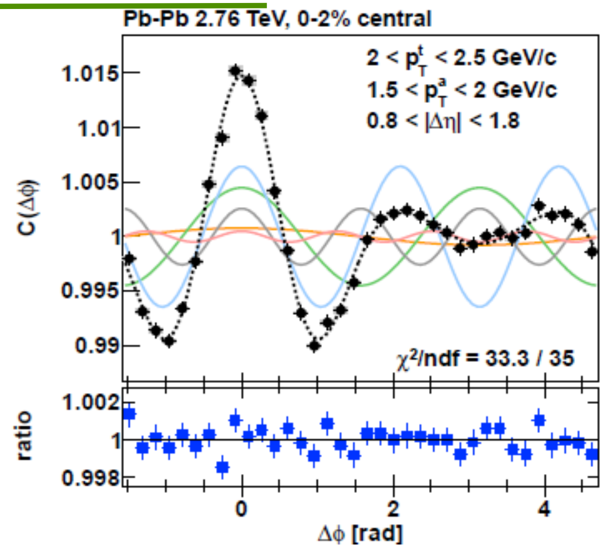
Event-by-event hydrodynamical needed to account for fluctuations

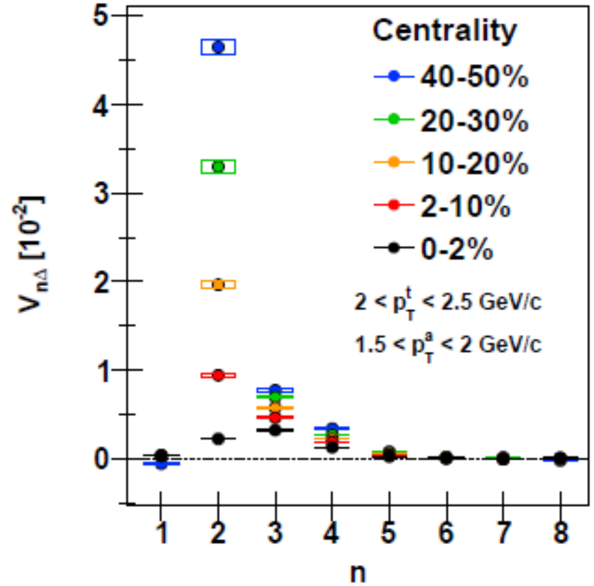
Higher harmonics (v_n) than elliptic flow (v_2) present

Higher harmonics

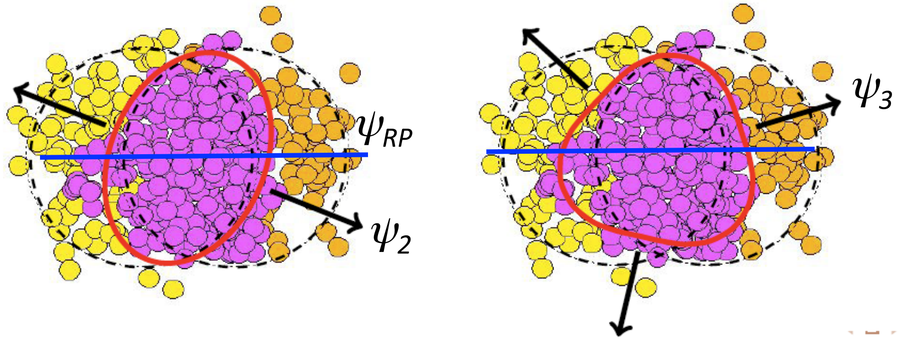
First 5 v_n components seem to be all that's needed to describe correlations

arXiv:1109.2501



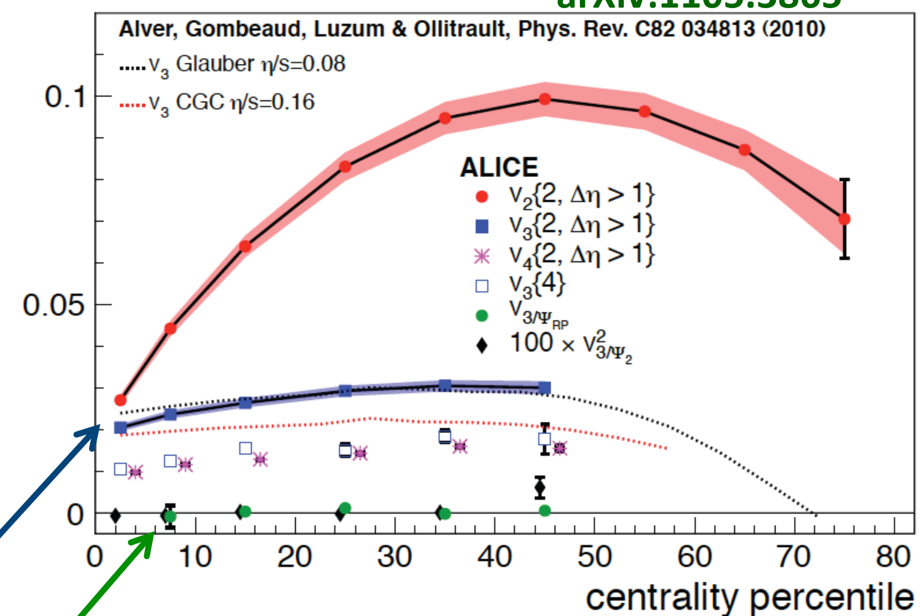


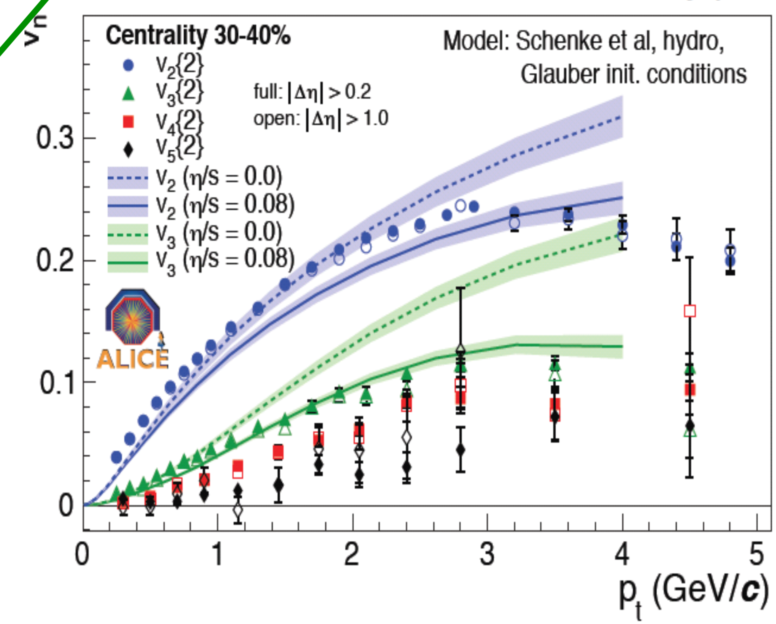
Higher harmonics



- Fluctuations in the initial nucleon distribution
  - Event-by-event fluctuation of the symmetry plane Ψ_n w.r.t. Ψ_{RP}
  - Odd harmonics are not null
- v_3 (“triangular”) harmonic:
  - v_3 has weaker centrality dependence than v_2
  - When calculated w.r.t. participant plane, v_3 vanishes (as expected, if due to fluctuations)
- Similar p_T dependence for all harmonics
  - v_3 sensitive to shear viscosity h/s and to assumption on initial parton density

arXiv:1105.3865

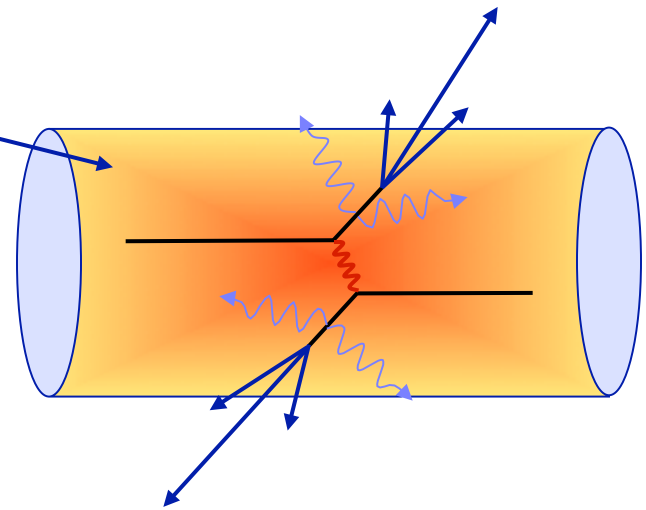




Hard probes of QCD matter

Heavy-ion collisions produce
'quasi-thermal' QCD matter

Dominated by soft partons
p ~ T ~ 100-300 MeV



Hard-scatterings produce 'quasi-free' partons
⇒ Initial-state production known from pQCD
⇒ Probe medium through energy loss

Use the strength of pQCD to explore QCD matter

Sensitive to medium density, transport properties

The LHC is a hard probes machine

LHC

Jet spectrum powerlaw

An LHC Pb-Pb year:

1 month ~ 10^6 seconds

Need 10^4 “events” in a year to make a measurement:

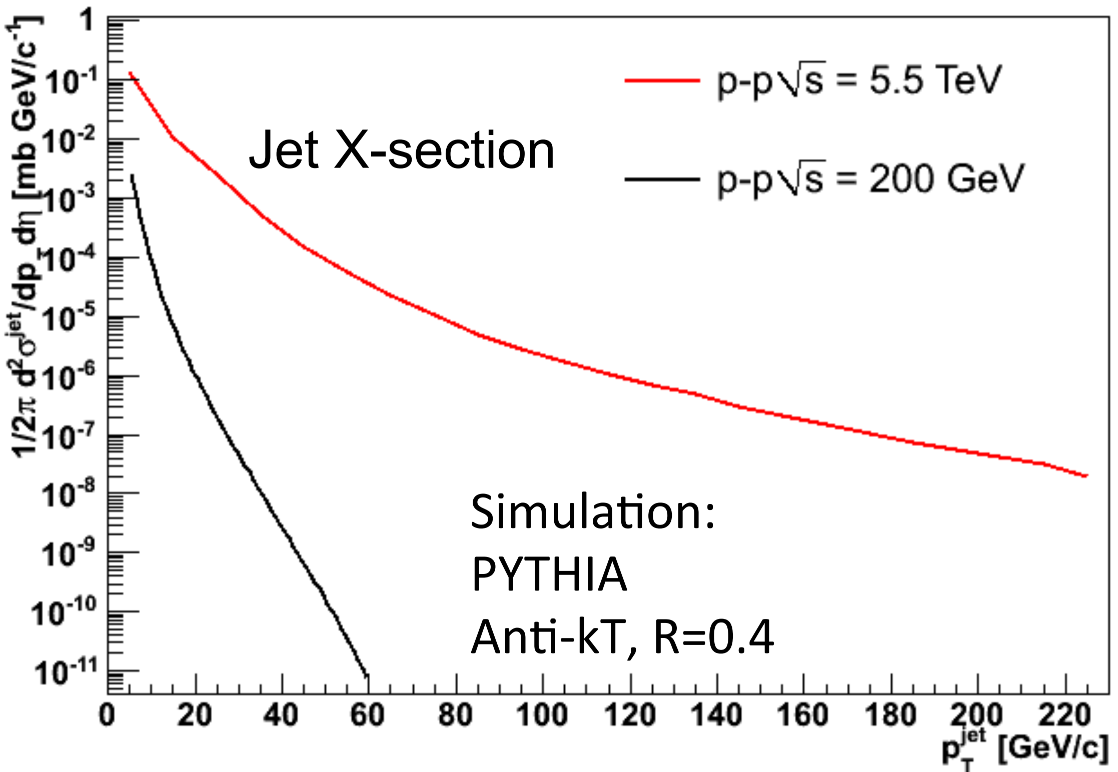
inclusive jets E_T < 200 GeV

di-jets E_T < 170 GeV

π^0 p_T <75 GeV

inclusive γ p_T<45 GeV

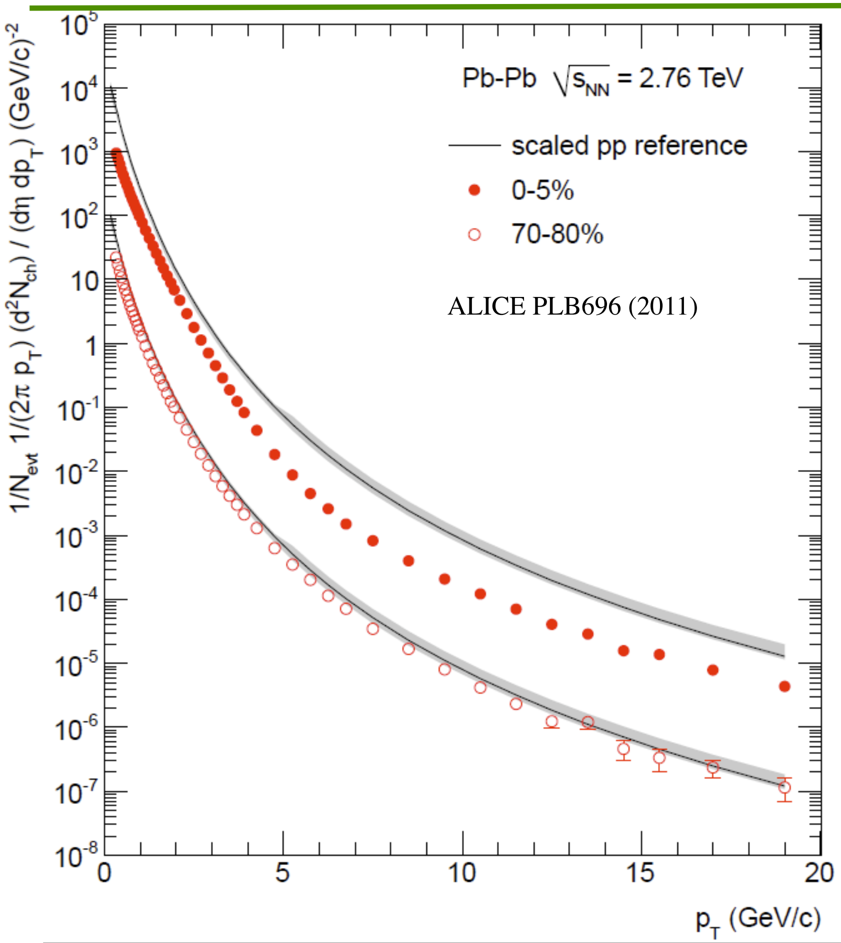
inclusive e p_T<30 GeV



- σ_{cc} (LHC) ~ 10 σ_{cc} (RHIC)
- σ_{bb} (LHC) ~ 100 σ_{bb} (RHIC)

Hard probes are no longer rare probes

Hard process - high p_T



Clear shape change at high p_T for central collisions

p-p reference:

Interpolation of 0.9 and 7 TeV data

7 TeV data scaled by NLO QCD calc.

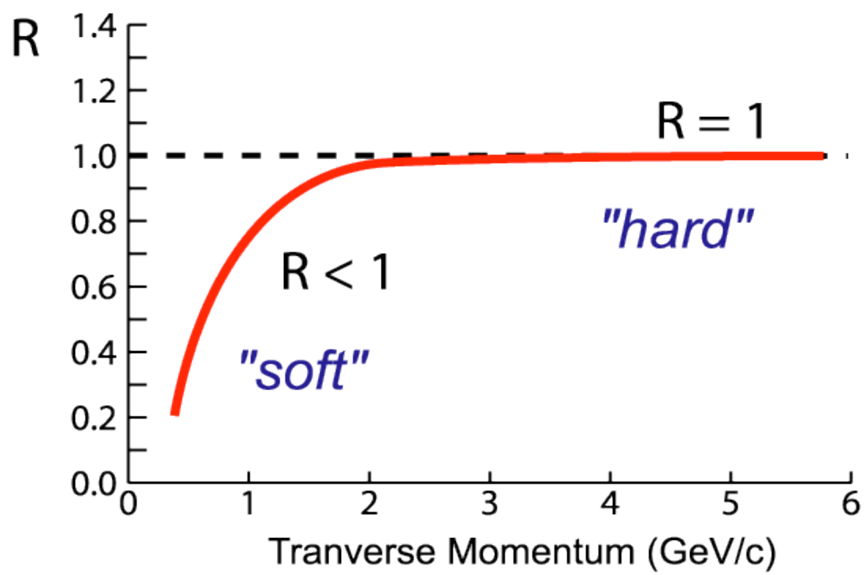
Clearer picture via Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{Yield(A-A)(p_T)}{Yield(p-p)(p_T) \times N_{bin}}$$

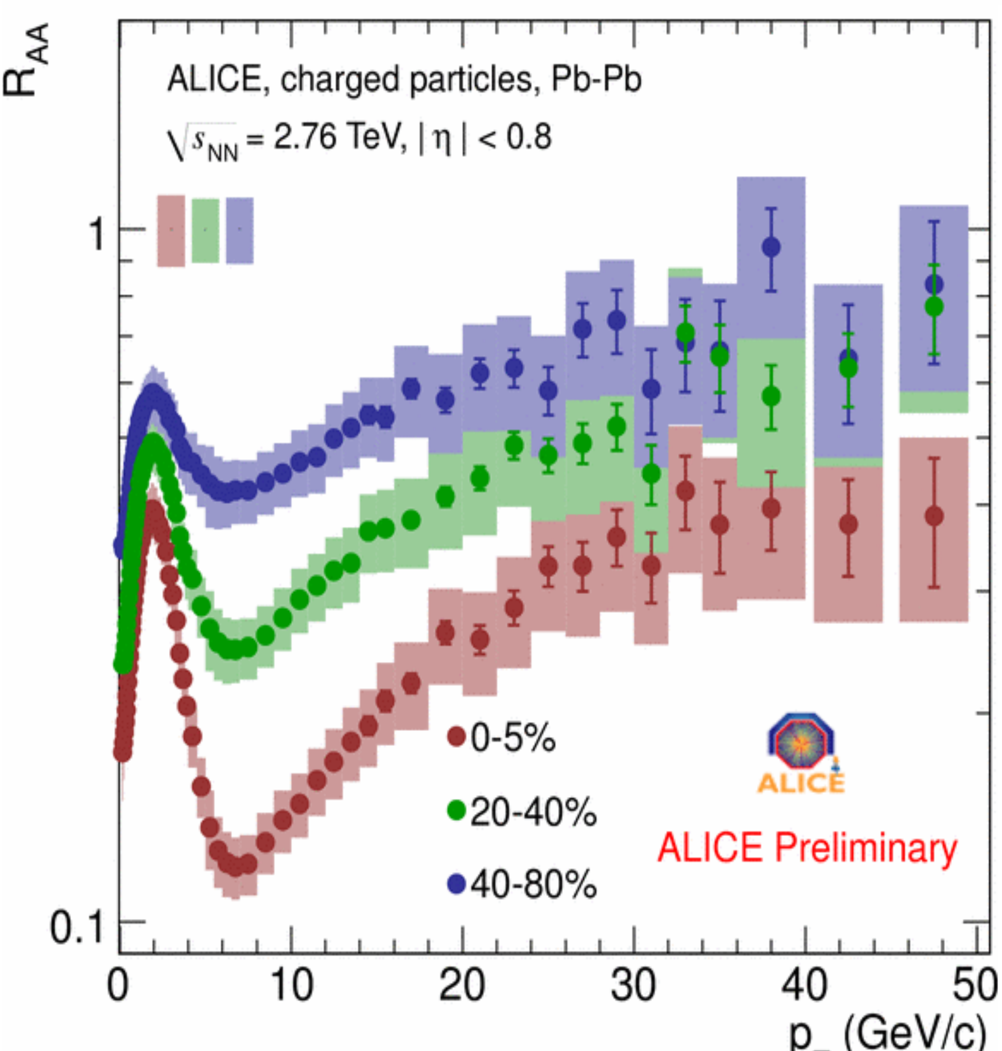
No "Effect":

R = 1 at higher momenta where hard processes dominate

R<1 at high p_T if QGP affecting parton's propagation

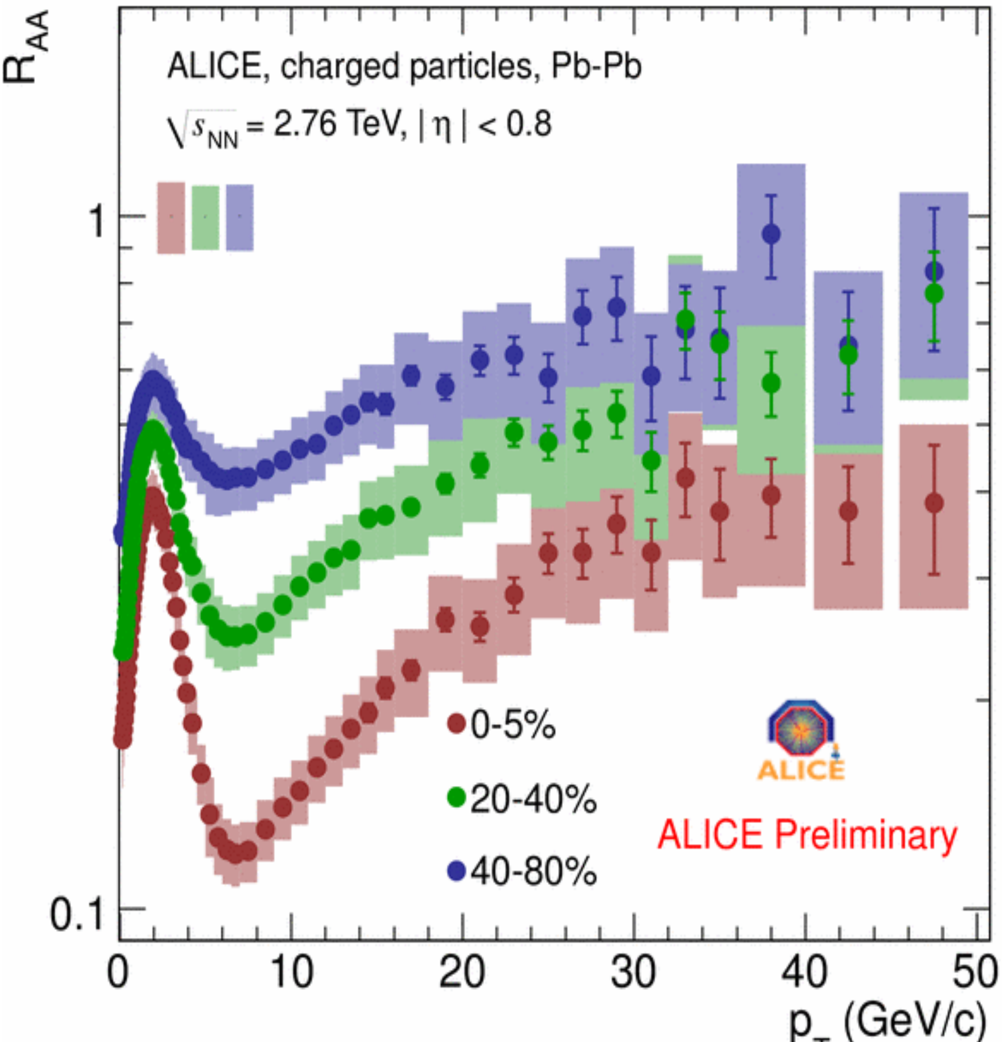


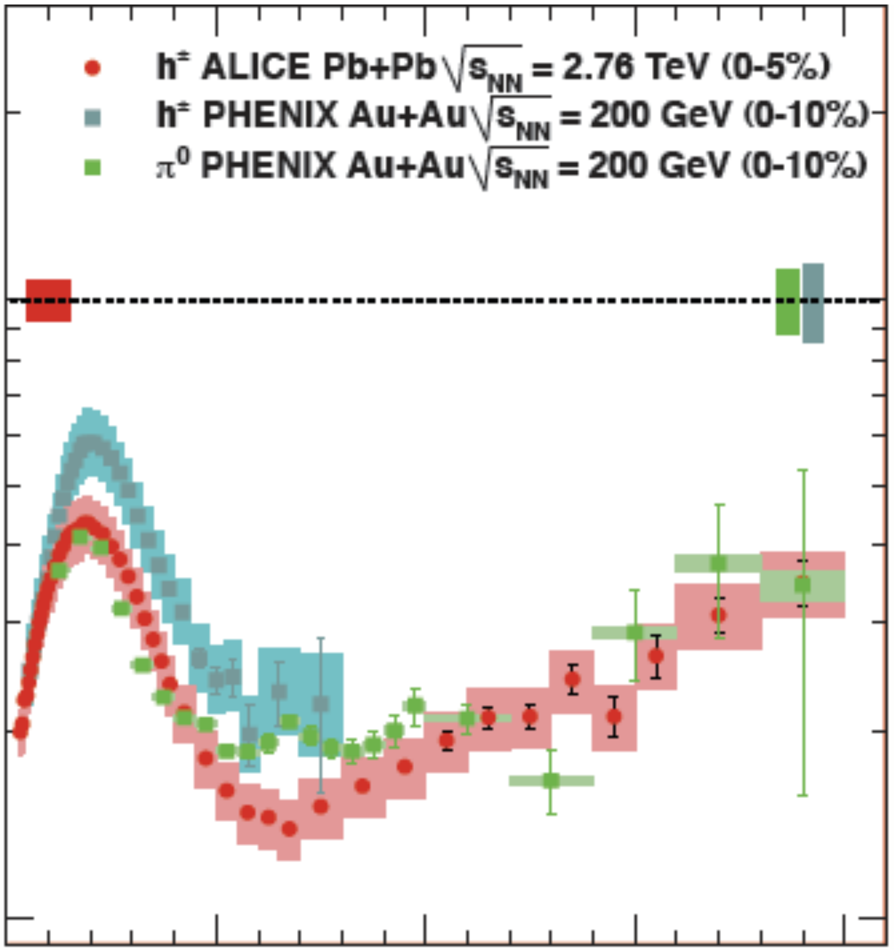
Strong high p_T suppression



Suppression strongest in central events → more medium

Strong high p_T suppression



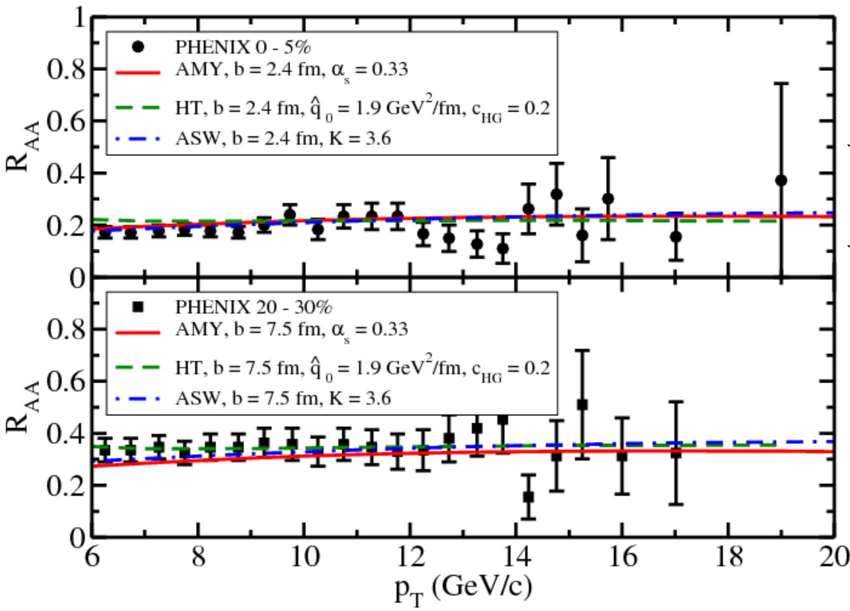


Min.R_{AA}(LHC) = 0.5xMin.R_{AA}(RHIC)

Suppression strongest in central events → more medium

flatter spectrum → **more opaque medium**

Comparing to theory



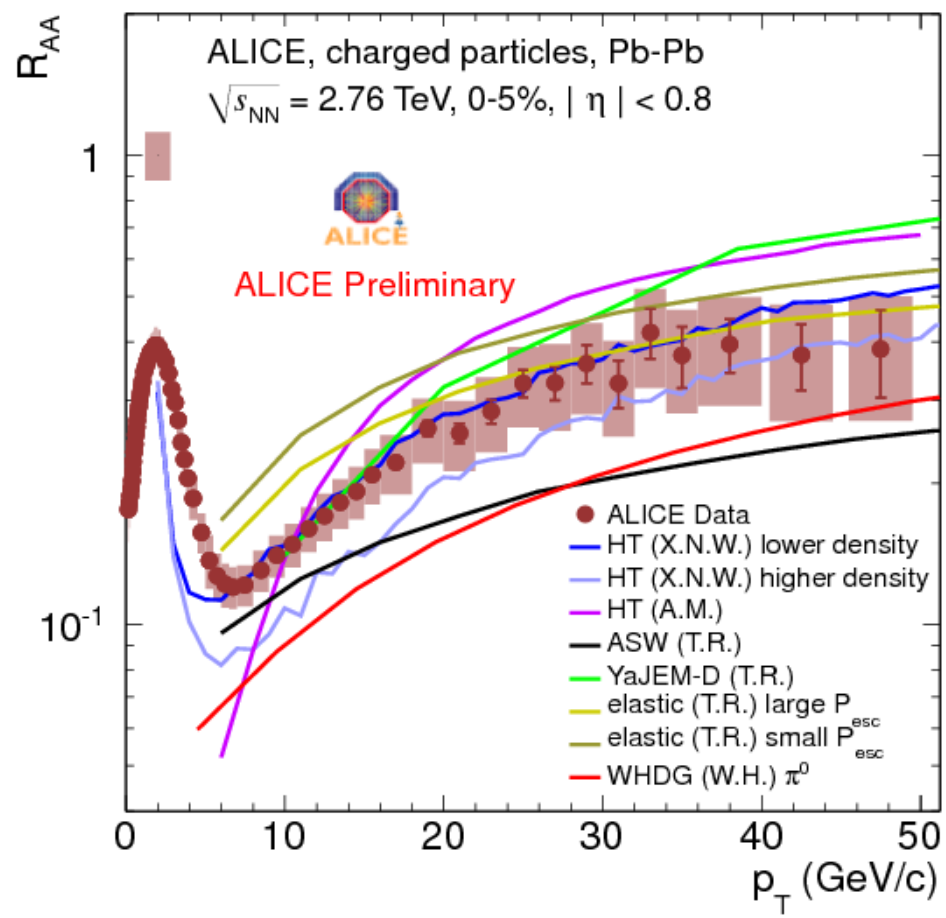
Bass et al, PRC79, 024901

Medium density tuned to RHIC data, scaled with multiplicity

All calculations show increase with p_T

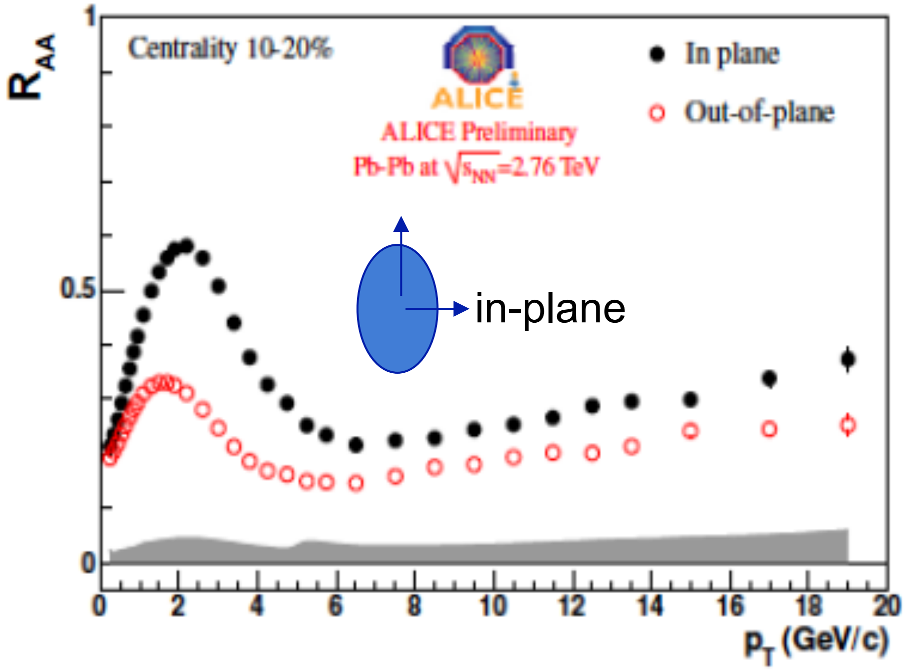
Well-known radiative formalisms ASW, WHDG predict too much suppression (HT better?)

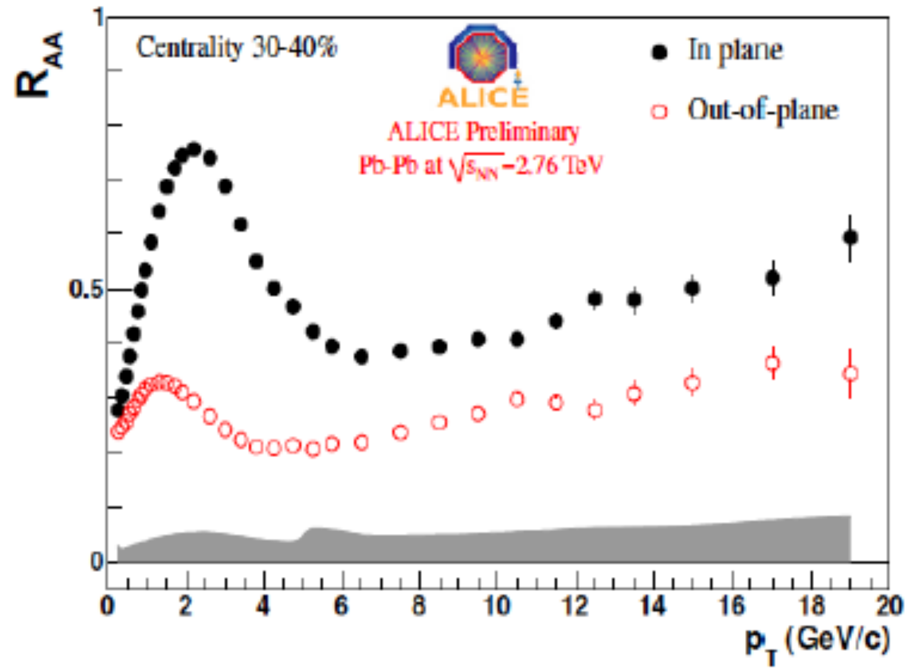
HT: X-N Wang et al, arXiv:1102.5614 (PRC)
HT: Majumder, Shen, arXiv:1103.0809
TR: T. Renk et al, arXiv:1103.5308 (PRC)
WHDG: Horowitz and Gyulassy, arXiv:1104.4958

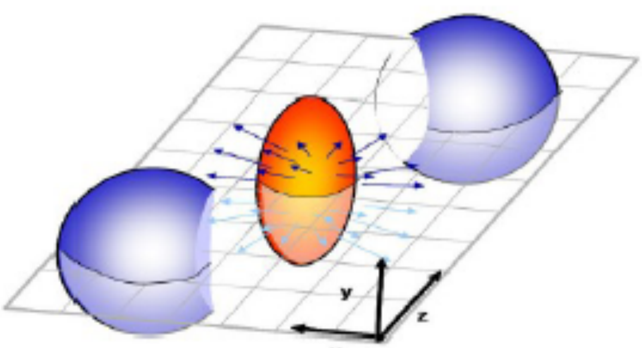


- Still not possible to trace-back fundamental physics information
- Need time to sort out theory uncertainties

Reaction plane dependence of R_{AA}





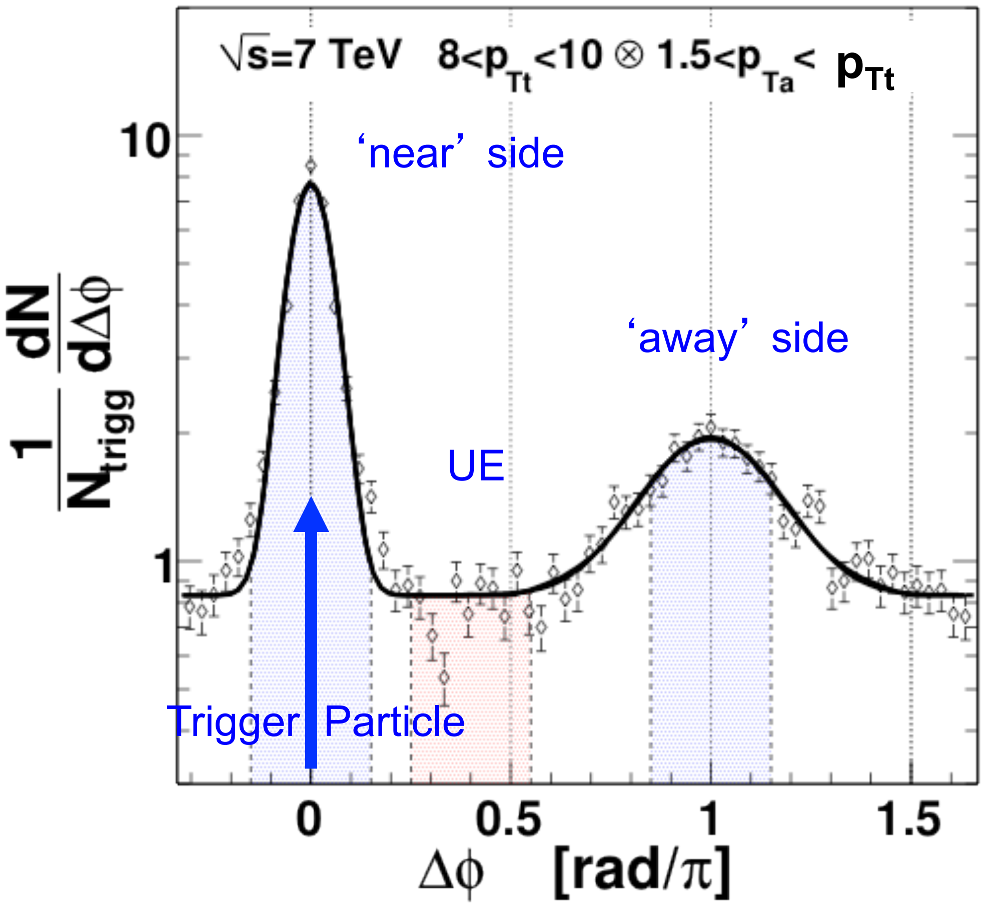


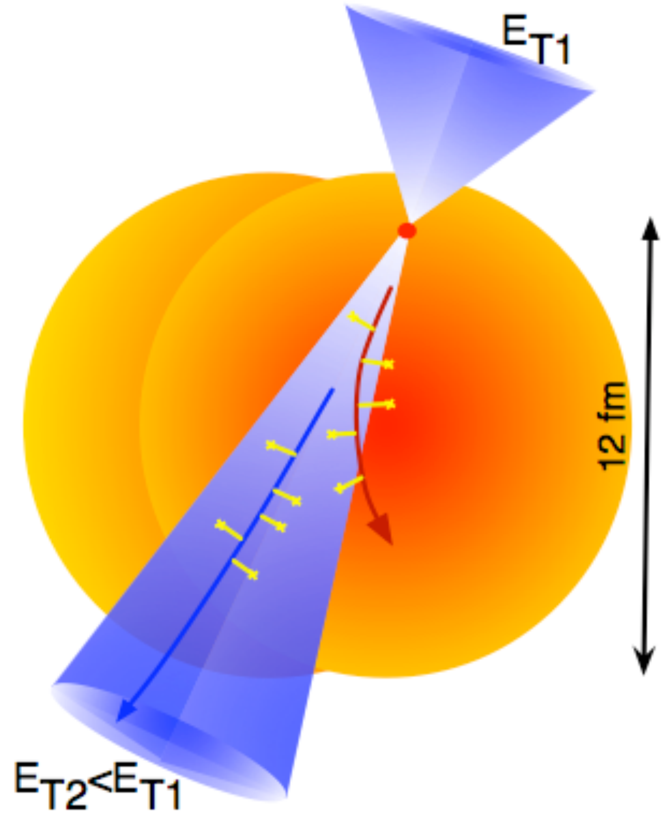
Non-central Collisions

$$R_{AA}(\phi) = R_{AA}\left(1 + 2v_2\cos(2\phi)\right)$$

- Φ measured w.r.t reaction plane
- **Strong path length dependence of parton energy loss (studies just started)**

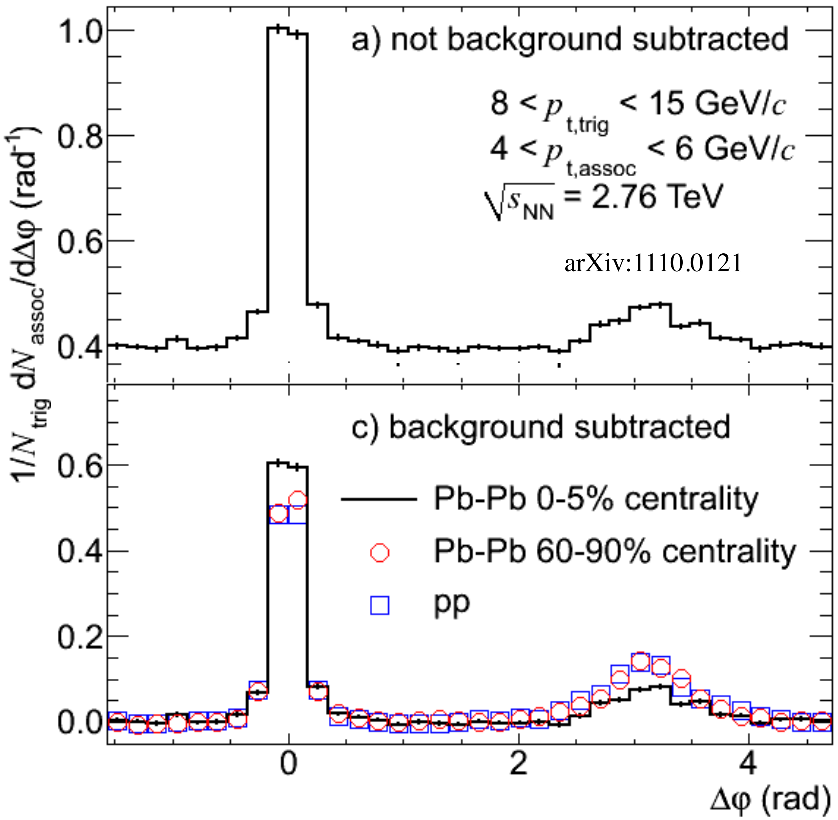
High p_T Particle Correlations





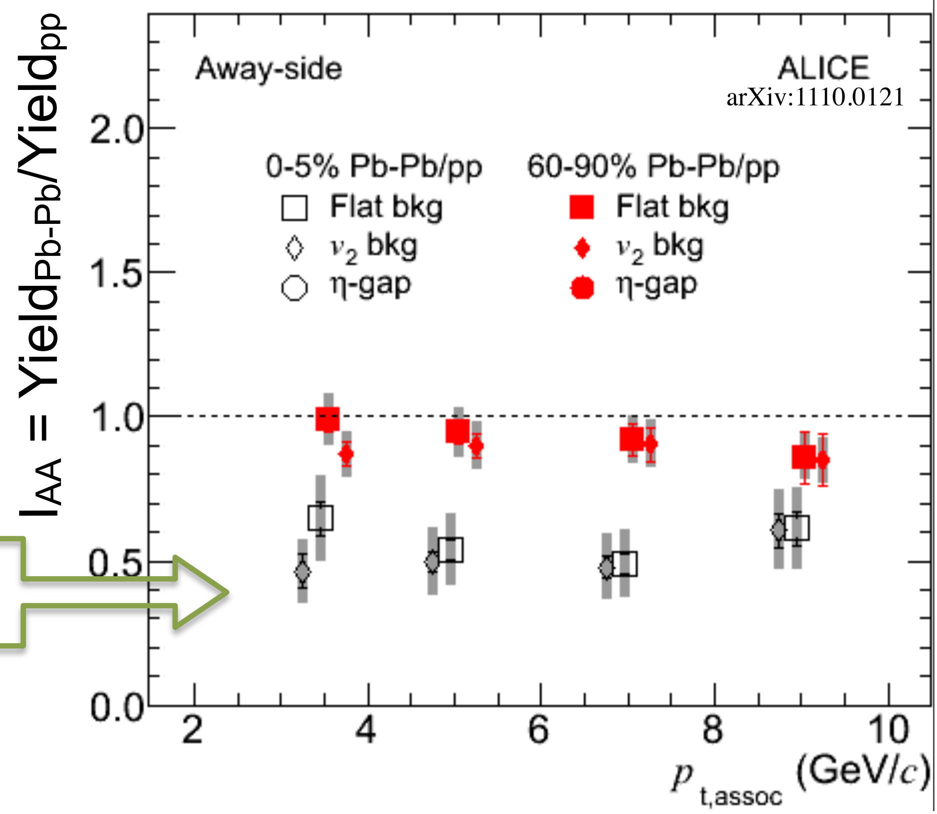
Trigger Particle: highest p_T particle in event (p_{Tt})
Associate Particle: all the others (p_{Ta})

Away-side jet suppression



Very little background when high p_T triggers applied

Central Pb-Pb away-side jet clearly suppressed

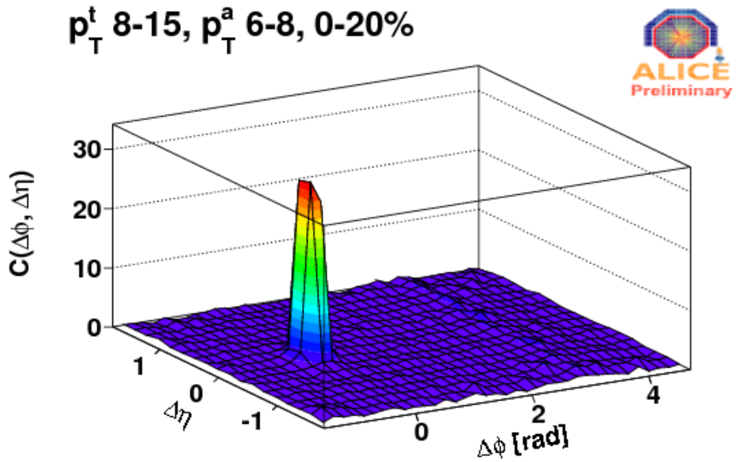


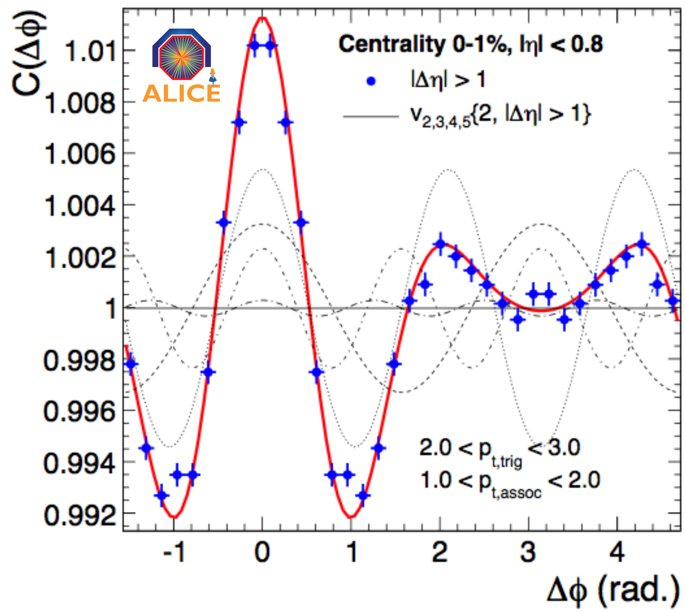
Central data suppressed by ~factor 2

Peripheral data consistent with pp

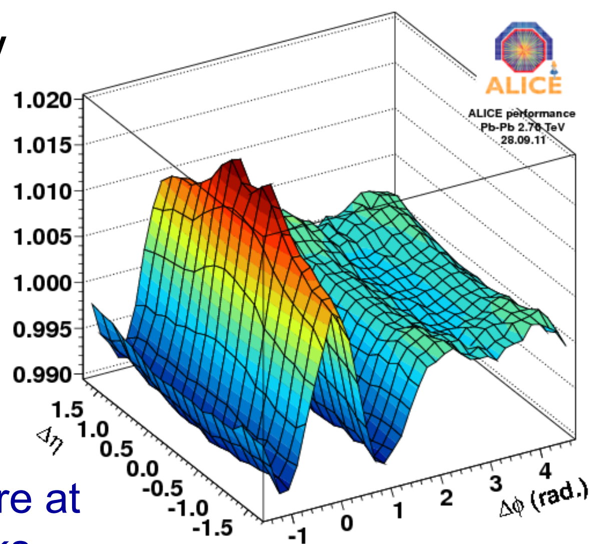
Effect of medium clearly visible

Di-hadrons at lower p_T



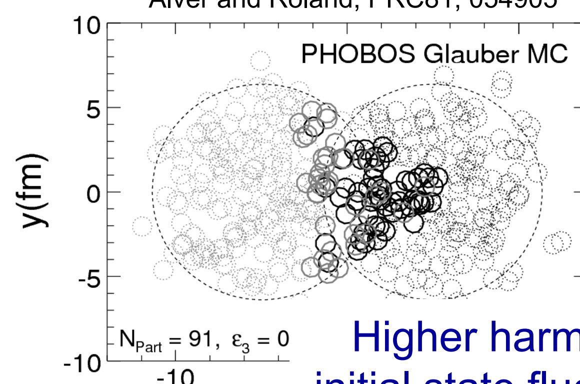


$2 < p_{T,trig} < 4$ GeV
$1 < p_{T,assoc} < 2$ GeV
0-2% central



Di-hadron structure at low p_T: three peaks

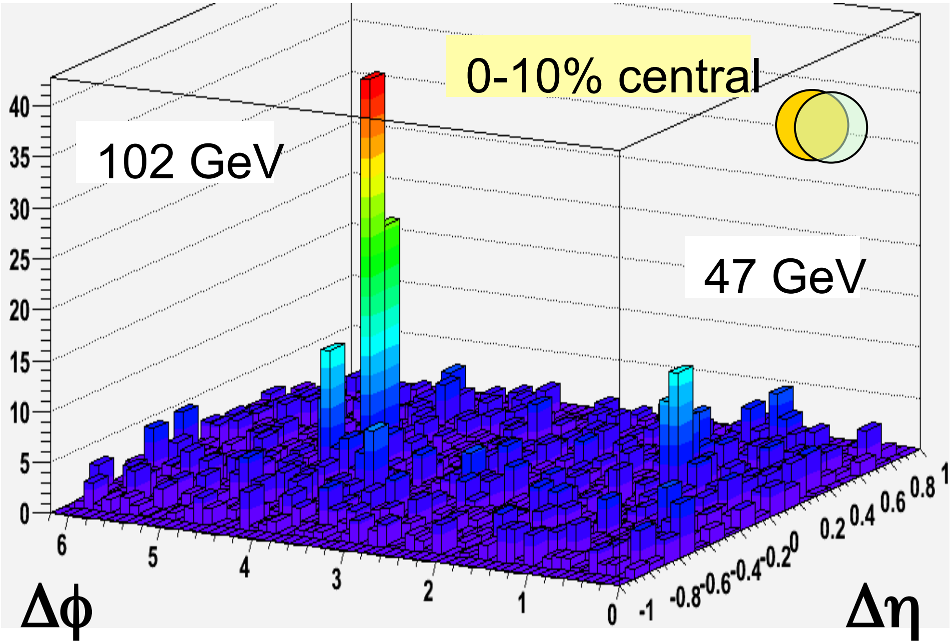
Alver and Roland, PRC81, 054905

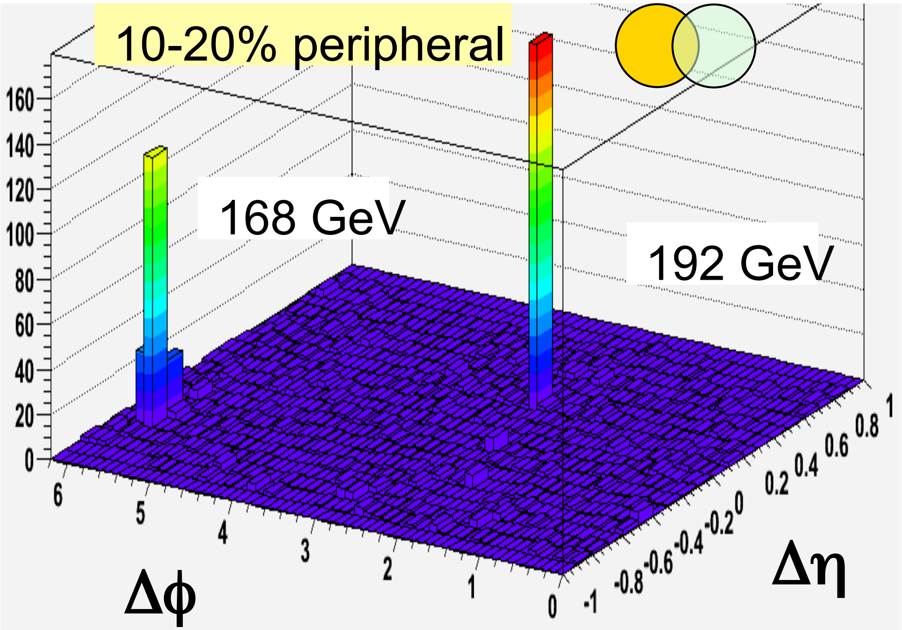


Higher harmonics from initial state fluctuations (v_3) visible in final state

Di-hadrons at low p_T measure bulk correlations

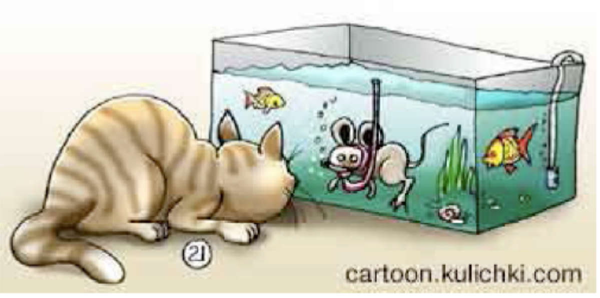
Jets



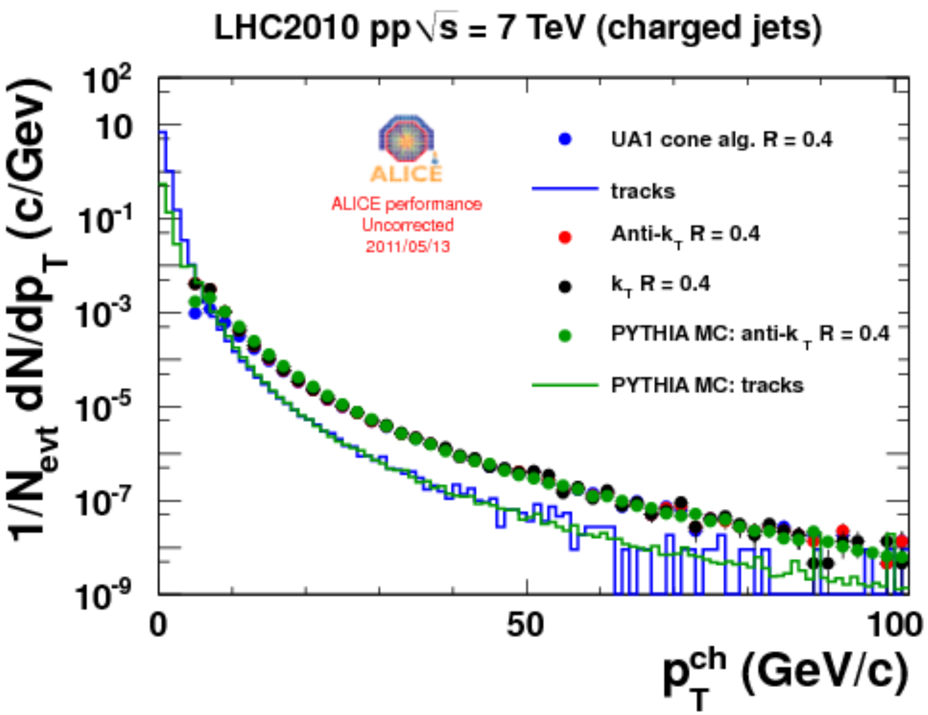


$$\left\langle \delta p_T \right\rangle = \left\langle \delta p_T^{hadronization} \right\rangle + \left\langle \delta p_T^{perturbative\_radiation} \right\rangle + \left\langle \delta p_T^{underlying\_events} \right\rangle$$

Wealth of new intriguing phenomena in the medium!

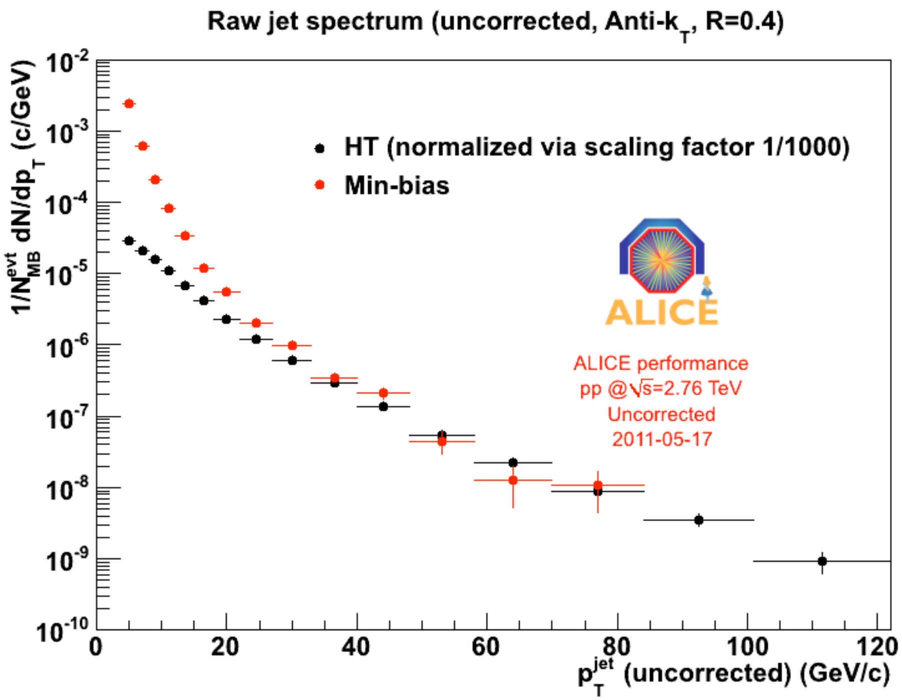


Jets in pp



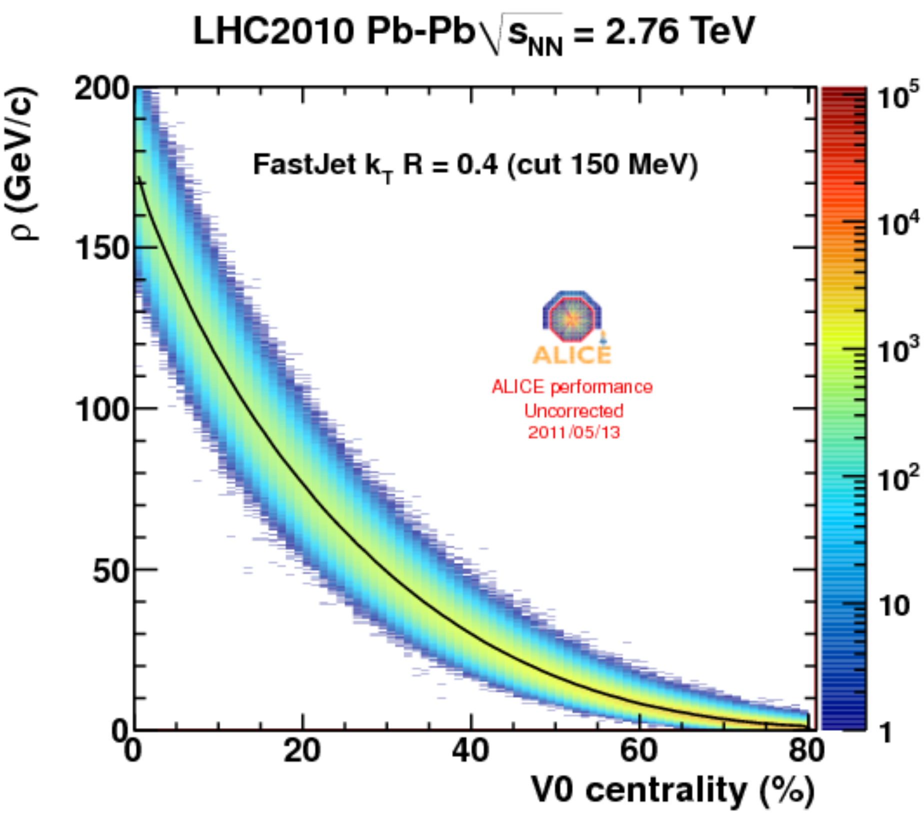
p+p charged jets
well described by PYTHIA

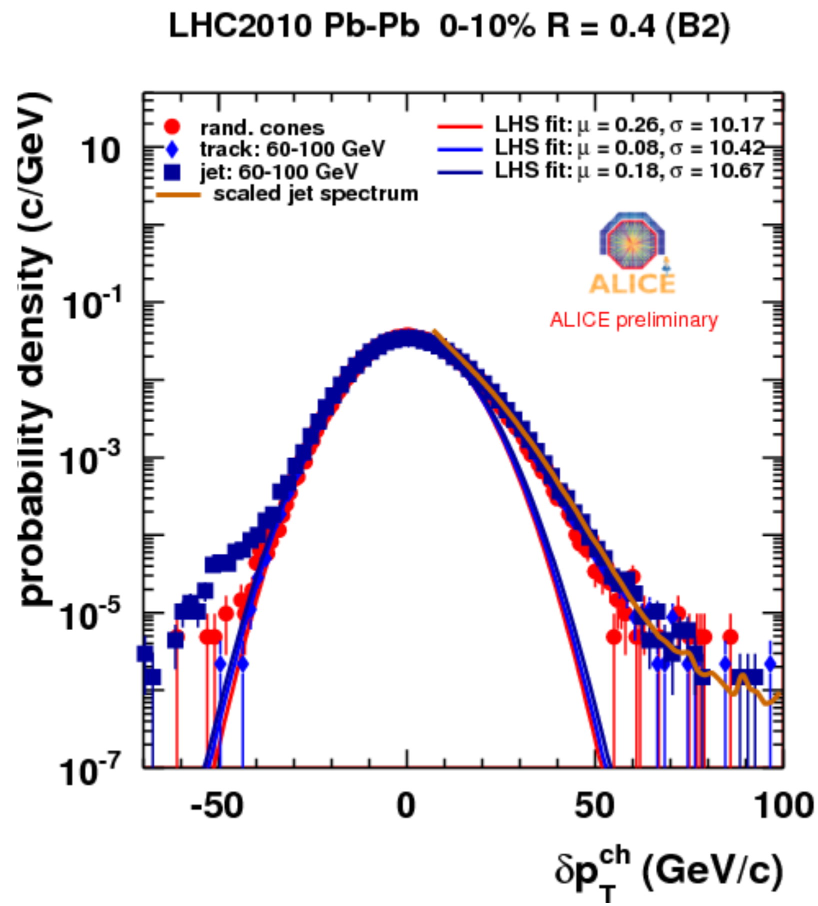
EMCal
Installed in winter 2010/2011



EMCal jet trigger commissioned
in p+p

Jets in HI





Large uncorrelated background density in heavy ion collisions
ρ ~ 170 GeV/c in central events

Measure background fluctuations ‘in situ’:
Random cones, embedding give similar results

not gaussian: tail from jets

σ_{gauss} = 10 GeV/*c* for central events

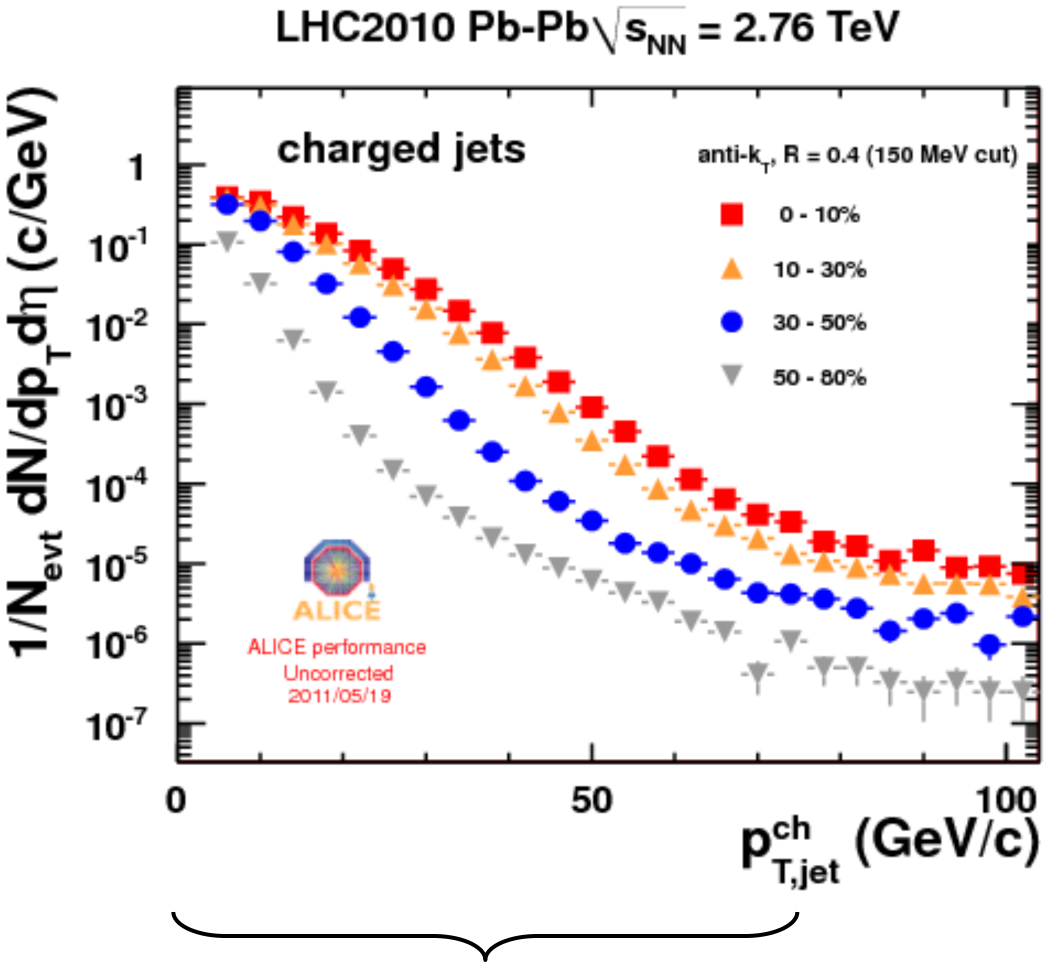
Jets in HI

Subtract uncorrelated background:

$$p_{T,jet} = p_{T,meas} - \rho_{bkg} A_{jet}$$

Fluctuations remain after subtraction

Unfolding of fluctuations needed: in progress…



Reconstructed jet spectrum
Dominated by background fluctuations
for p_T < 60-80 GeV/c (central events)

Outlook

- Future already happened!
  - LHC is running fast

- Alice:
  - 2010+11 have been memorable years!
    - Excellent performance of the detector, data analysis has smoothly and quickly delivered the first physics results

  - Large quantitative step with respect to RHIC
    - Waiting for becoming qualitative

  - Second PbPb run (2011) ended few weeks ago
    - Luminosity already above design specification
    - Increase in statistics more than factor 10
    - Rare probes are not rare anymore

  - *Test of pA running*

Conclusions and Perspectives