Pb-Pb and p-Pb results with the ALICE Experiment at the CERN LHC

MinJung Kweon
Heavy Ion Meeting 2013-06, June 28 2013

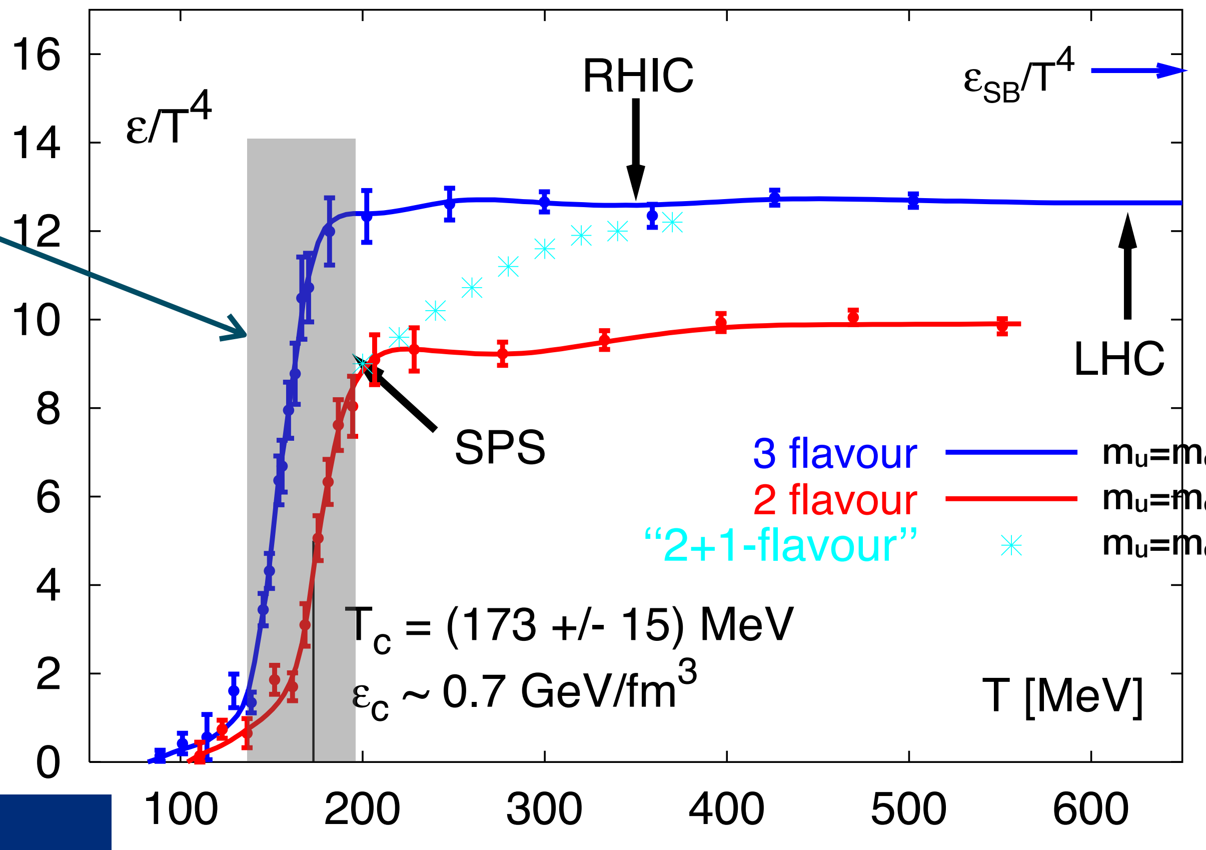
Introduction

- In heavy nuclei collisions at high energies,
  - quarks and gluons become free,
  - form a high density colour deconfined state of strongly interacting matter.
- Lattice QCD predicts a phase transition to QGP
  - high temperatures
  - energy density reached

Sharp increase of energy density

Phase transition from Hadron gas to QGP at $T=T_c$ ~ 170 MeV

Lattice QCD calculation



Outline

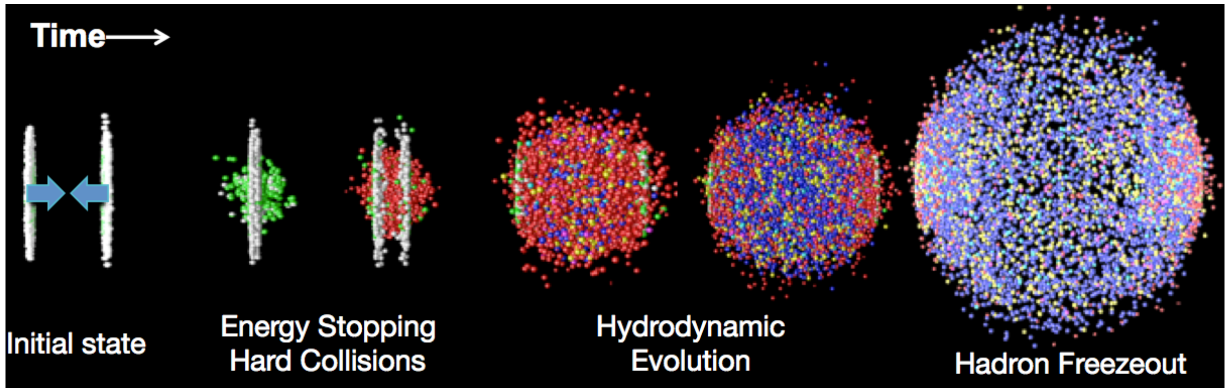
Bulk Particle Production

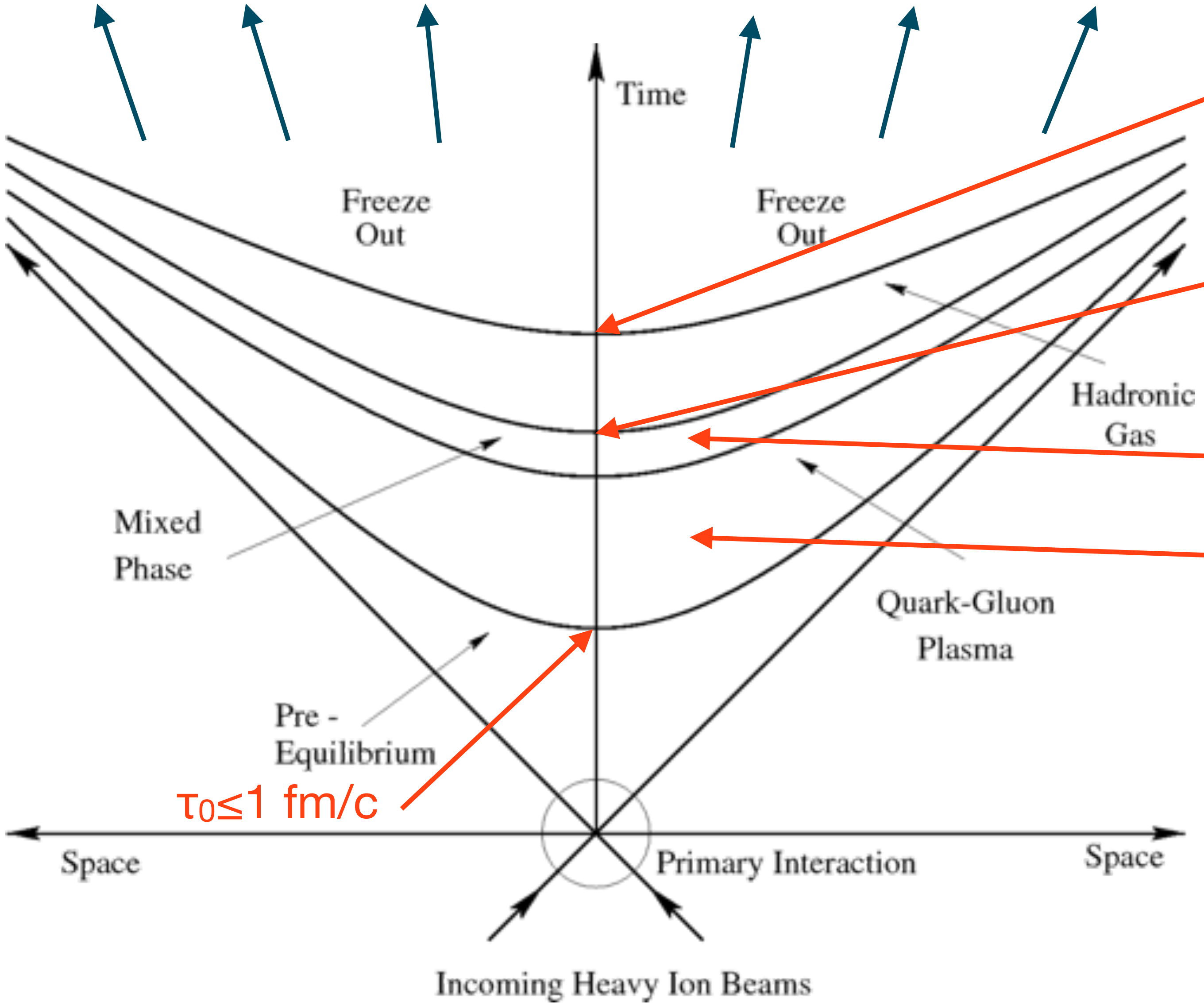
Flow

Nuclear modification factor

Two particle correlation (Jet Bulk Interaction)

Heavy Ion Collisions: Space Time Evolution



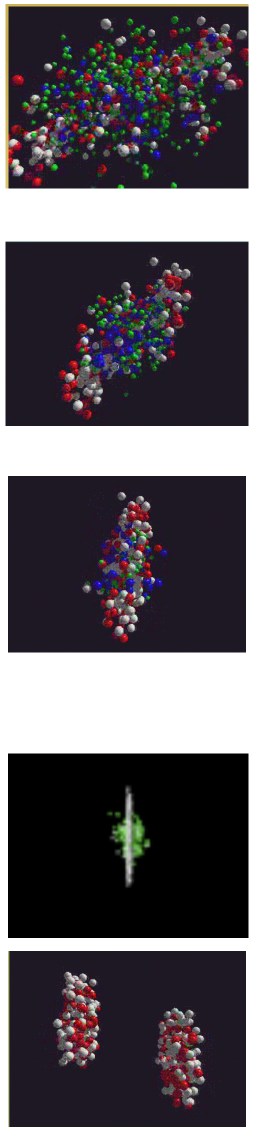


Thermal freeze-out:
kinematics distributions are fixed

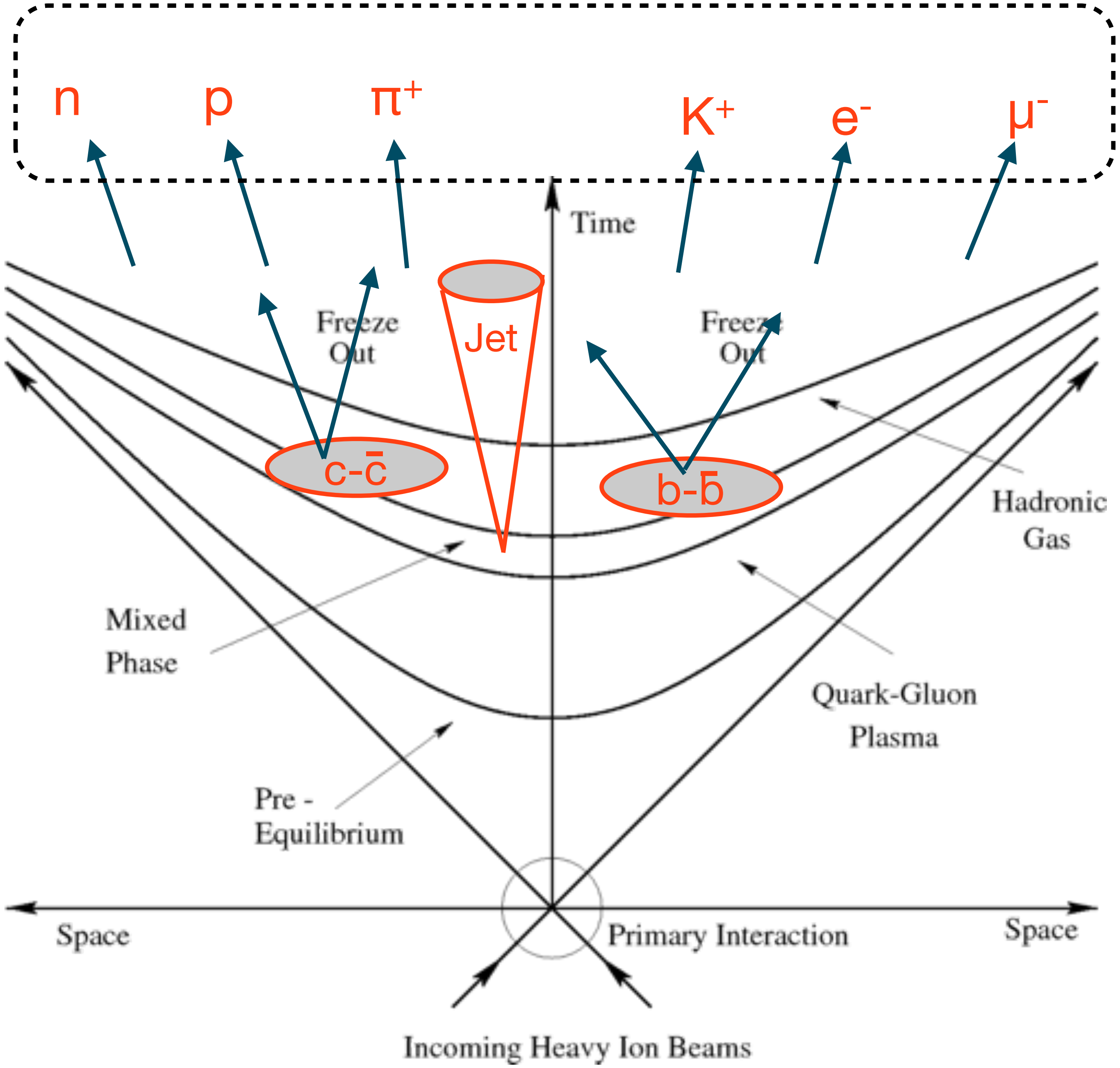
Chemical freeze-out:
constituents of particles are fixed

Hadronization:
q-g combines to create hadrons

QGP:
thermalization of q-g (if $T>T_c$)



Heavy Ion Collisions: Space Time Evolution



Detected particles

Experimental Observables: Charged hadrons, Jets, Heavy mesons, photons, J/ψ...

Deduce the nuclear properties and test the QCD predictions

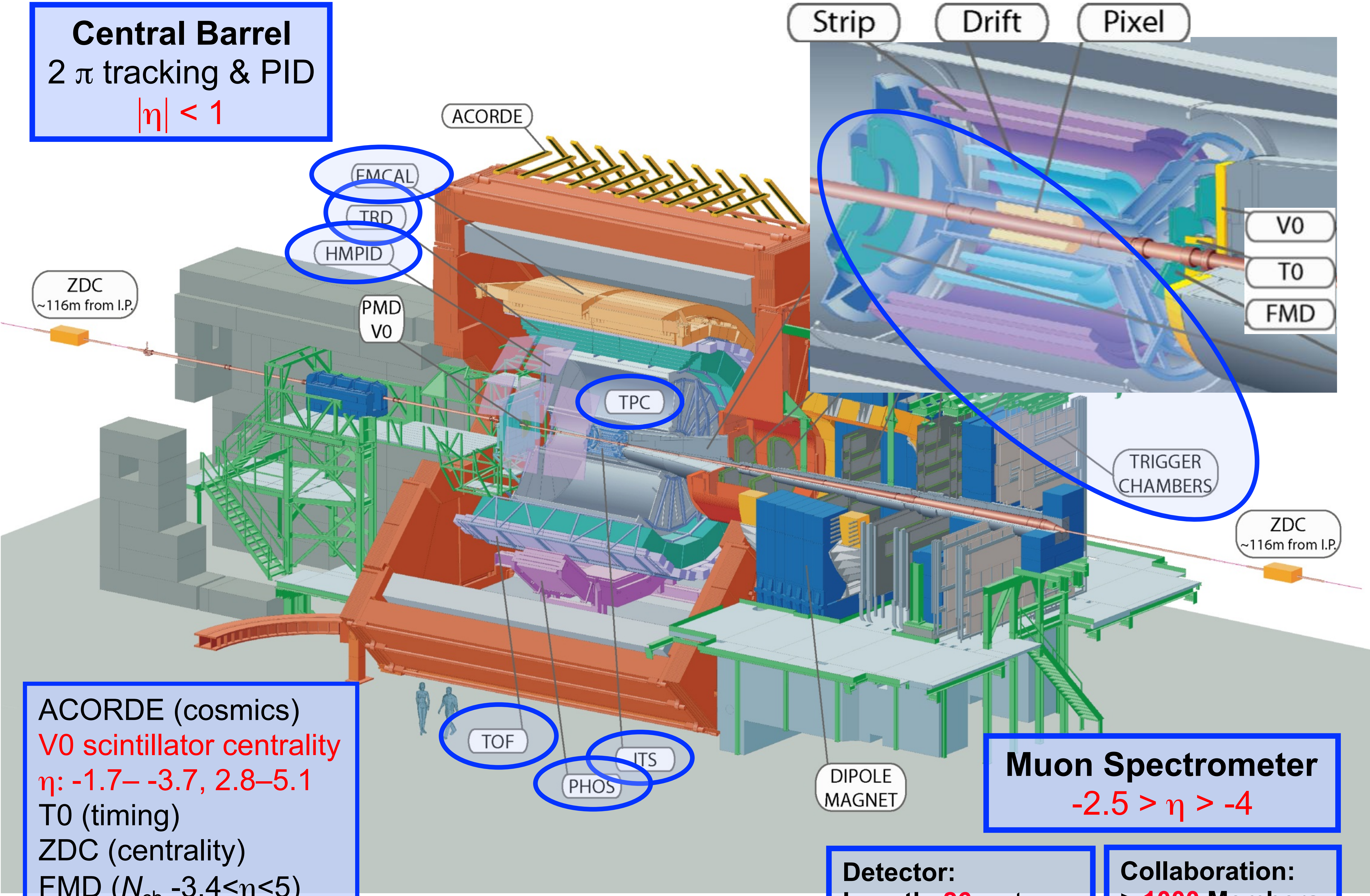
- **Model predictions**
  - With QGP
  - Without QGP
- **Experimental observables**
  - p-p
  - pA or peripheral A-A
  - Central A-A
- **Test QCD**
  - Vacuum
  - Hadronic matter
  - QGP

comparison

Central Barrel

2 π tracking & PID

|η| < 1



ACORDE (cosmics)
V0 scintillator centrality
η: -1.7– -3.7, 2.8–5.1
T0 (timing)
ZDC (centrality)
FMD (N_{ch} -3.4<η<5)
PMD (N_{γ}, N_{ch})

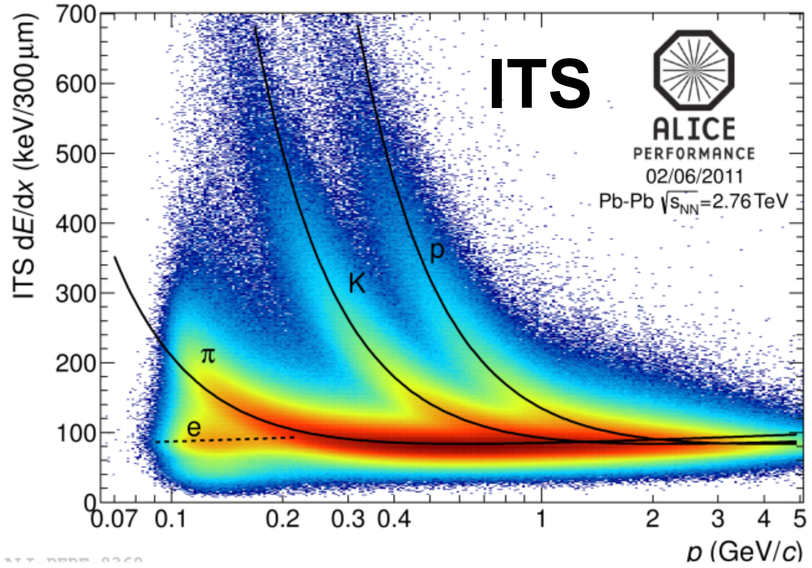
Muon Spectrometer

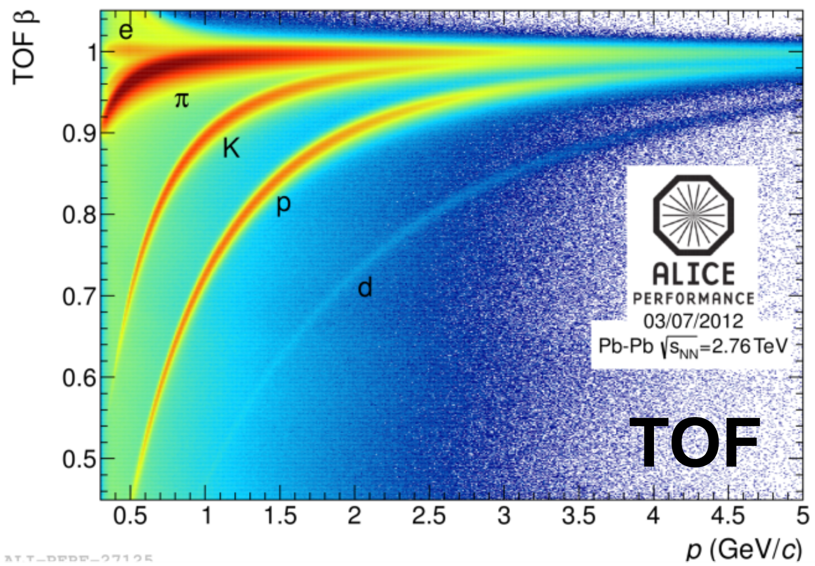
-2.5 > η > -4

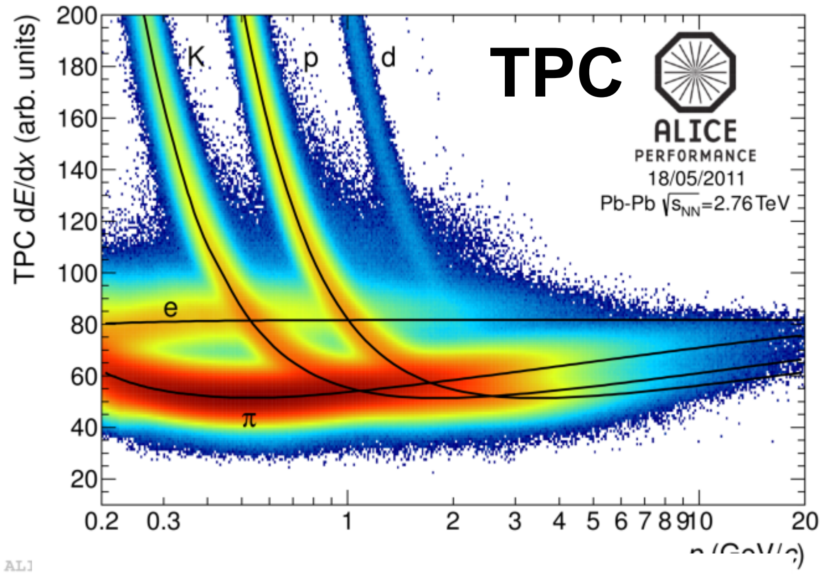
Detector:
Length: **26** meters
Height: **16** meters
Weight: **10,000** tons

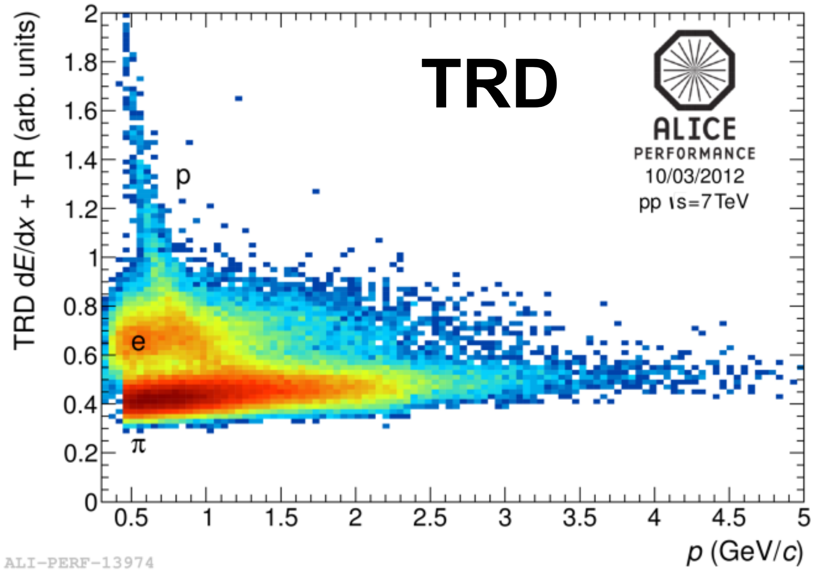
Collaboration:
> 1000 Members
> 100 Institutes
> 30 countries

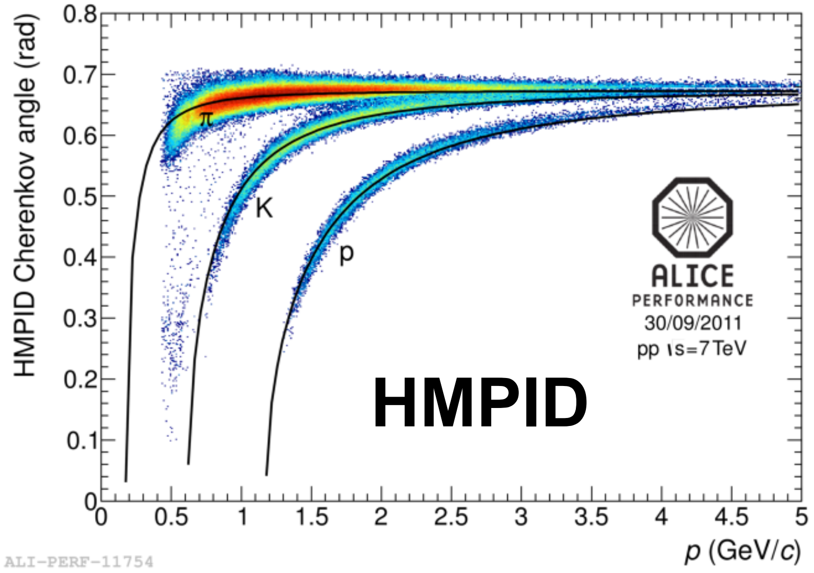
ALICE - dedicated heavy-ion experiment at the LHC

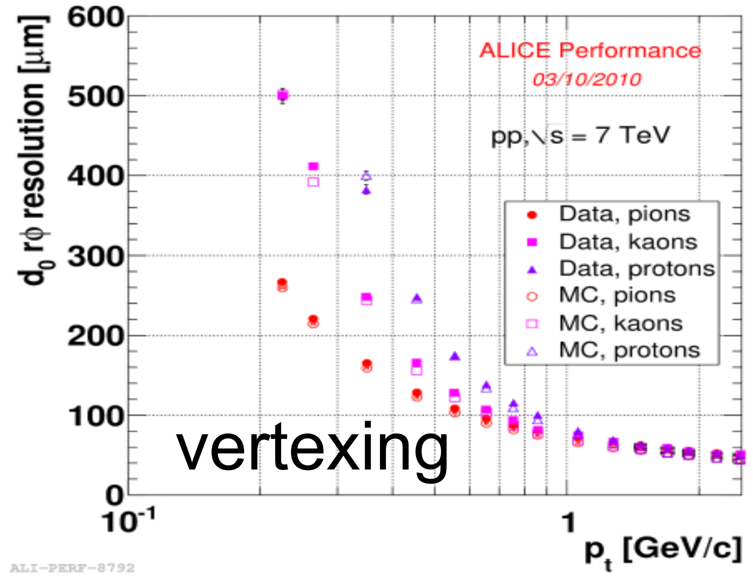












vertexing

- Particle identification (practically all known techniques)
- Extremely low-mass tracker ~ 10% of X_0
- Excellent vertexing capability
- Efficient low-momentum tracking – down to ~ 100 MeV/*c*

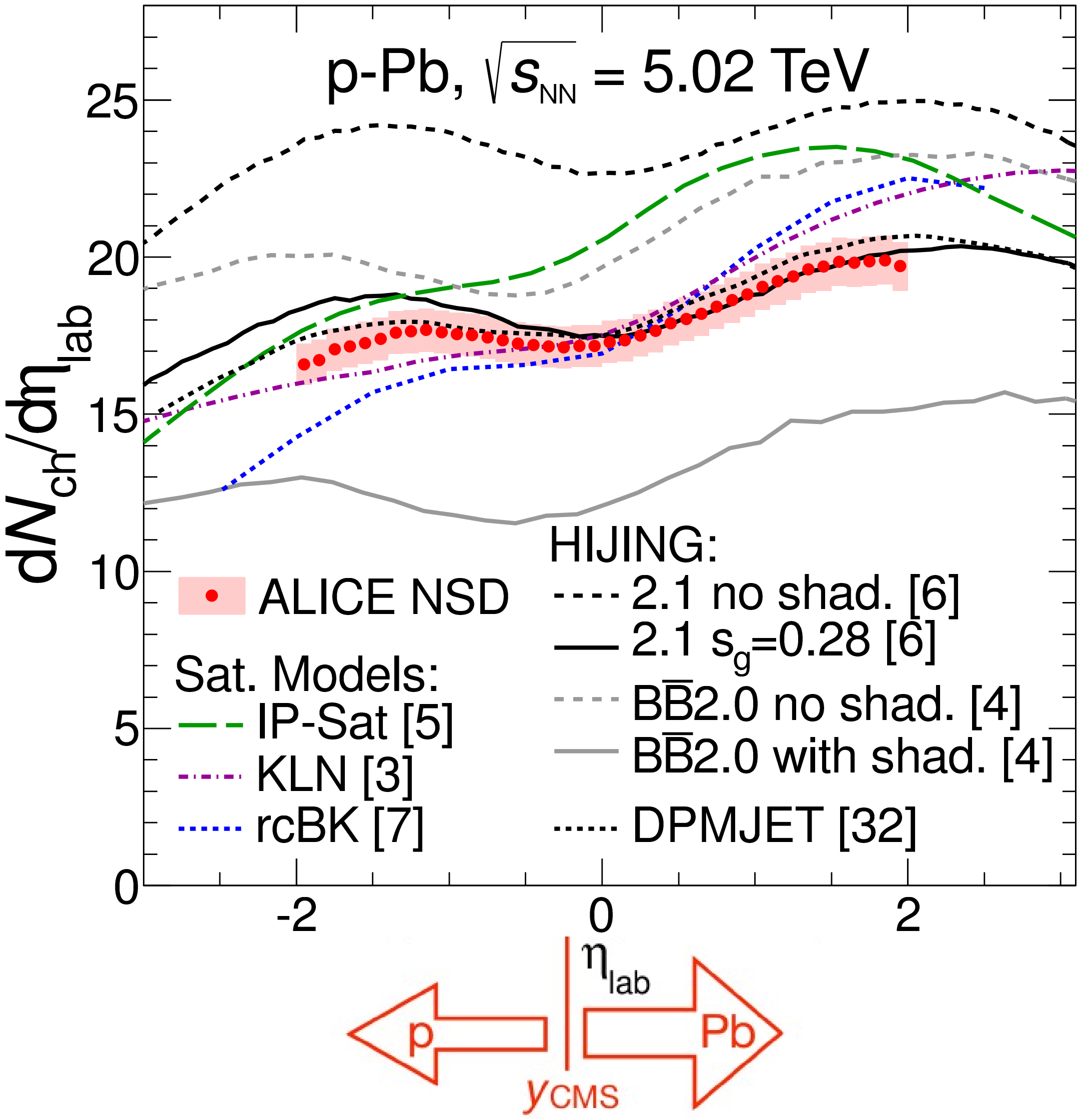
Bulk Particle Production

Energy, Centrality, and Rapidity dependence

Charged-particle production: pseudorapidity distributions

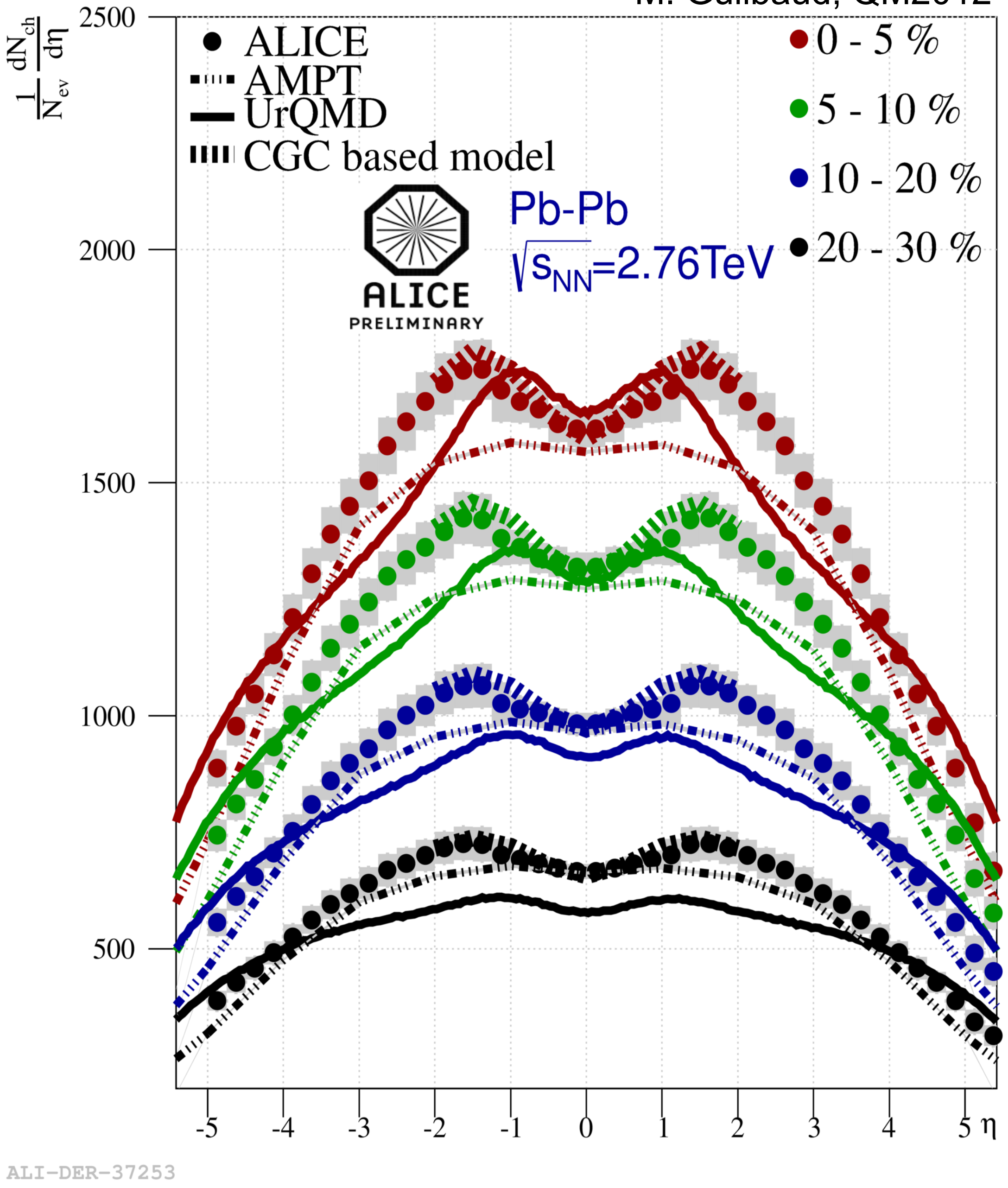
p-Pb

arXiv:1210.3615



Pb-Pb

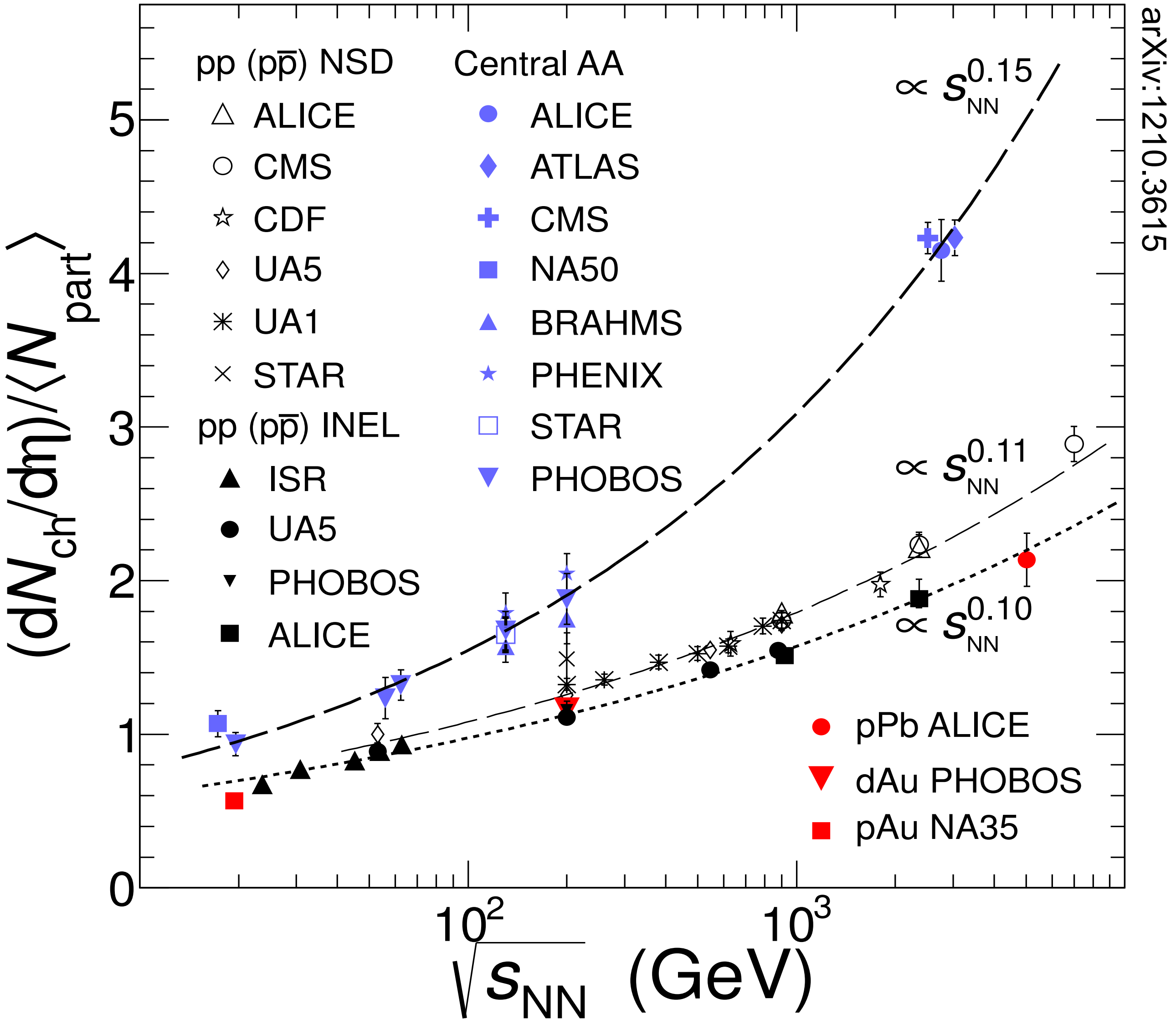
M. Guilbaud, QM2012



- constrains initial conditions of heavy-ion collision
- models with shadowing or saturation describe the measurement within 20%
- saturation models too steep

- constrains description of dynamics of heavy-ion collision

Charged-particle production: collision energy dependence

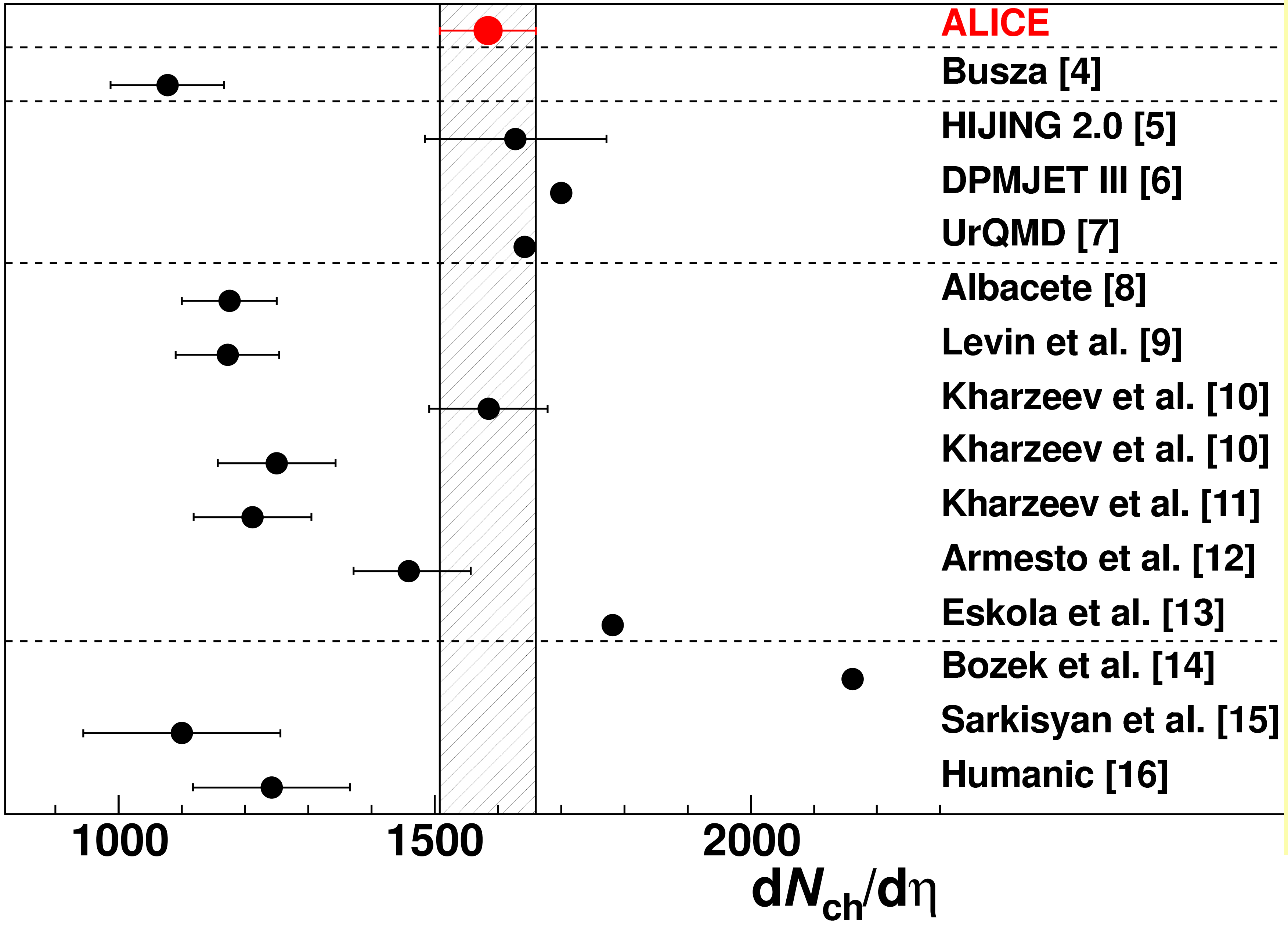


- LHC 2 times higher than RHIC
- Pb-Pb 2 times higher than pp
- p-Pb like INEL pp
- steeper growth in AA than in pp and p-A

Charged-particle production in Pb-Pb: comparison with models

The most central 5%

PRL 105 (2010) 252301



extrapolation in sqrt(s)

adj. to pp, no jet quench.

pQCD

initial state gluon saturation

hydro + final parton sat.

extrapolation from pp

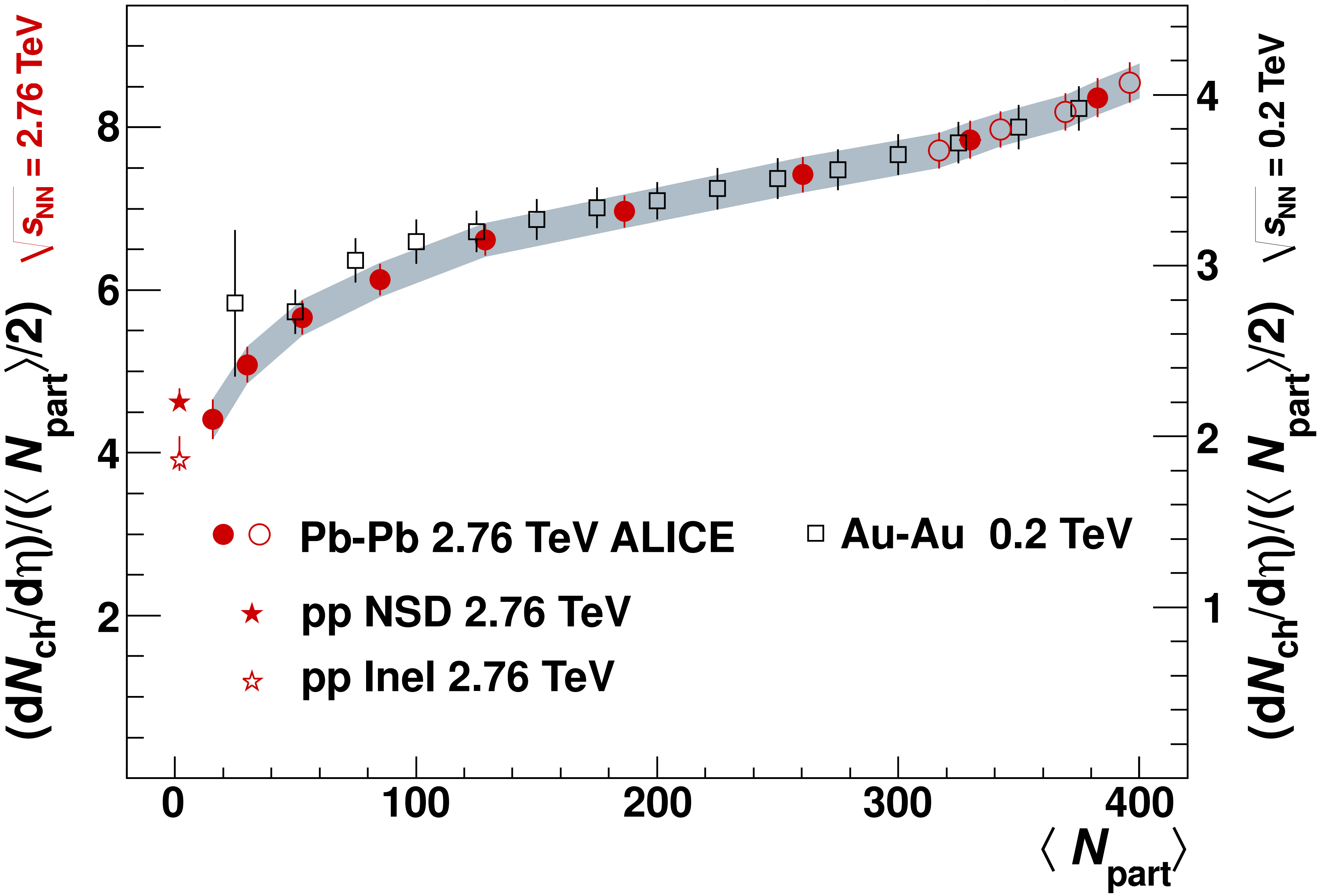
Landau hydro

Pythia+ rescattering

higher yield than expected (by most)

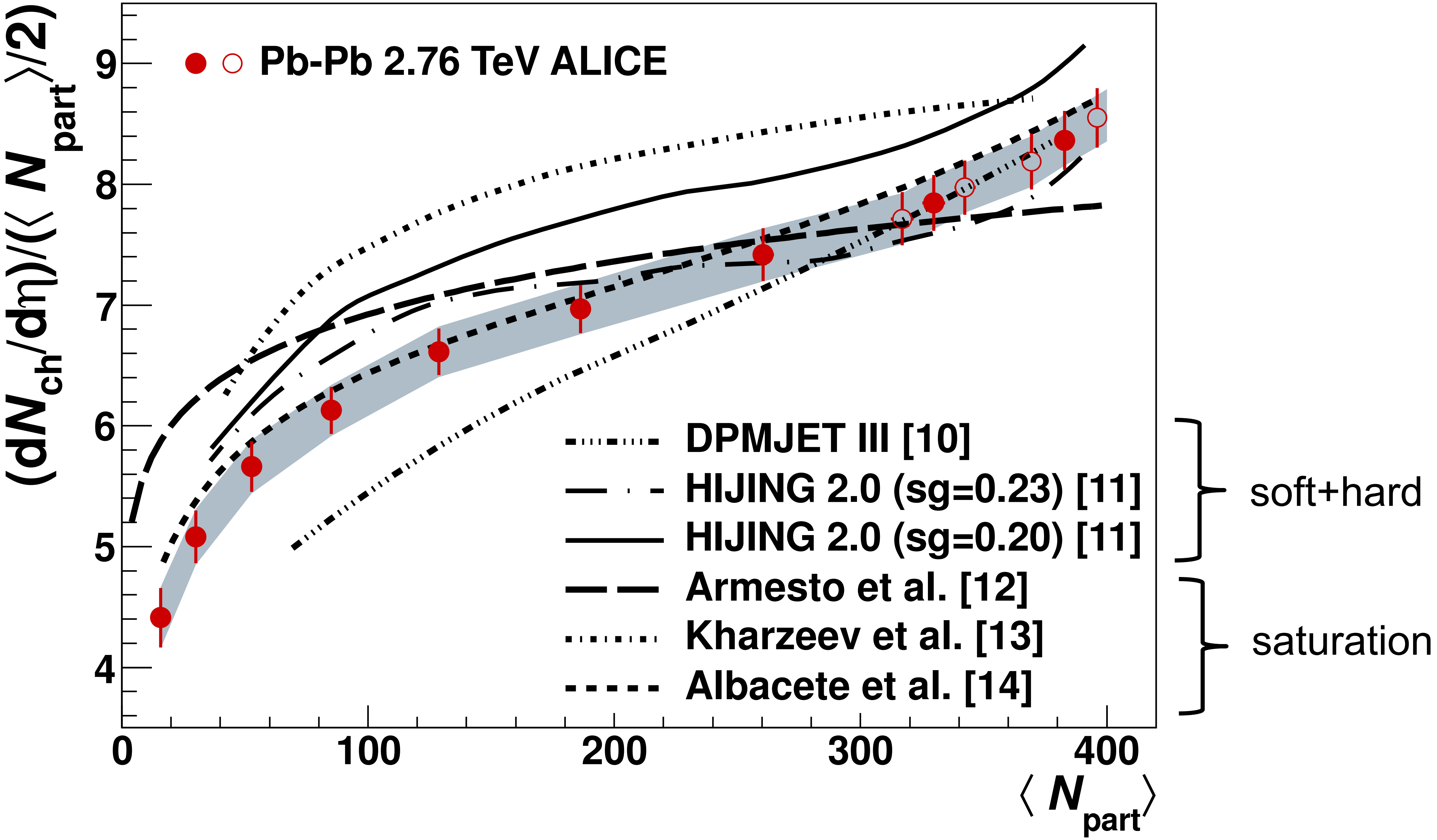
Charged-particle production: centrality dependence

PRL 106 (2010) 032301



~2 times more particles than at RHIC, same centrality dependence

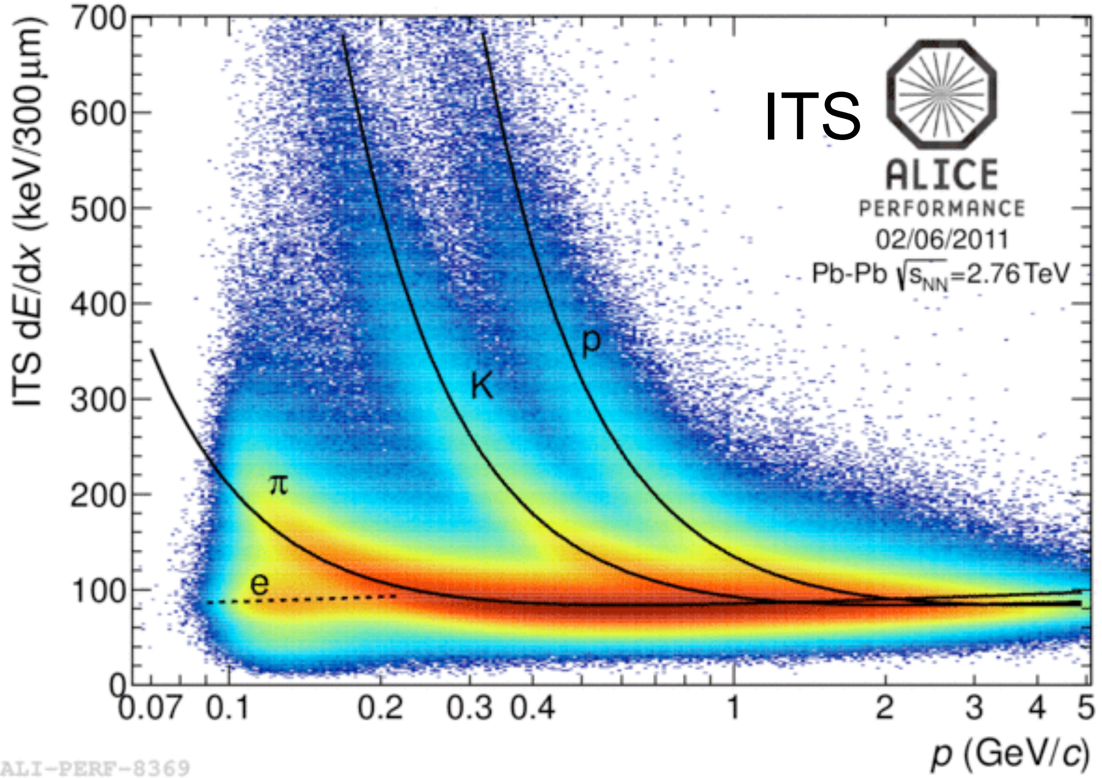
Charged-particle production: centrality dependence



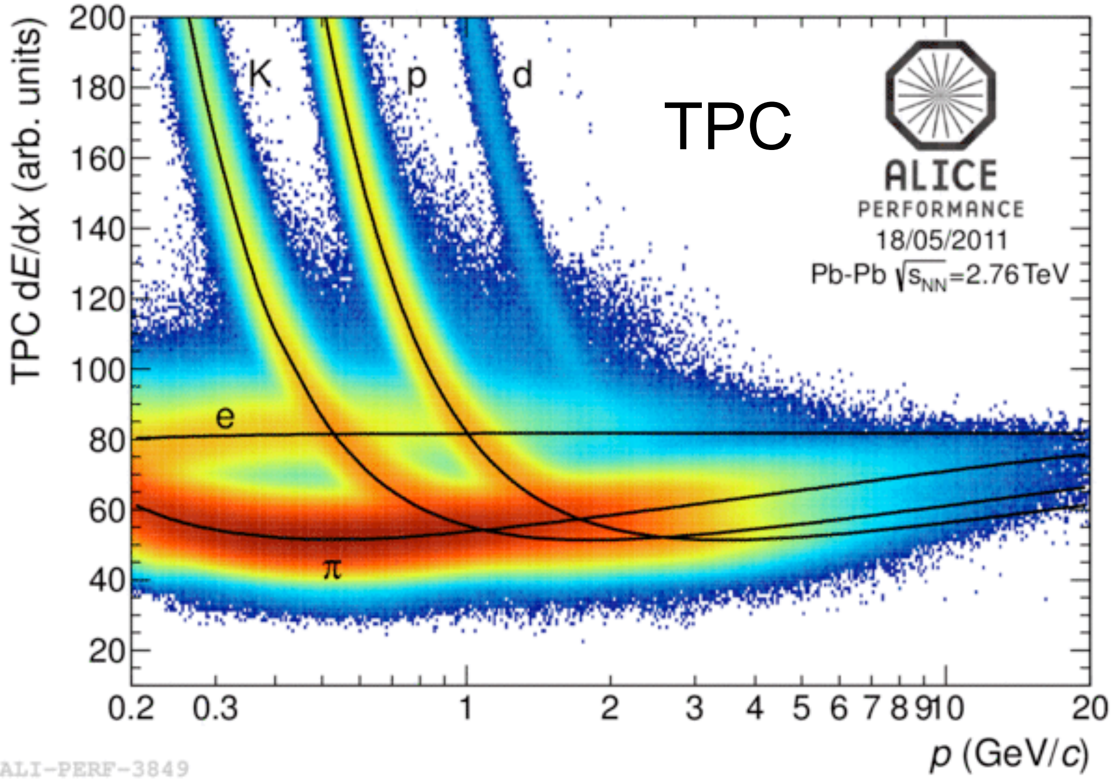
PRL 106 (2010) 032301

- general trend reasonably reproduced by majority of the models
- individual differences larger than the difference between the two groups

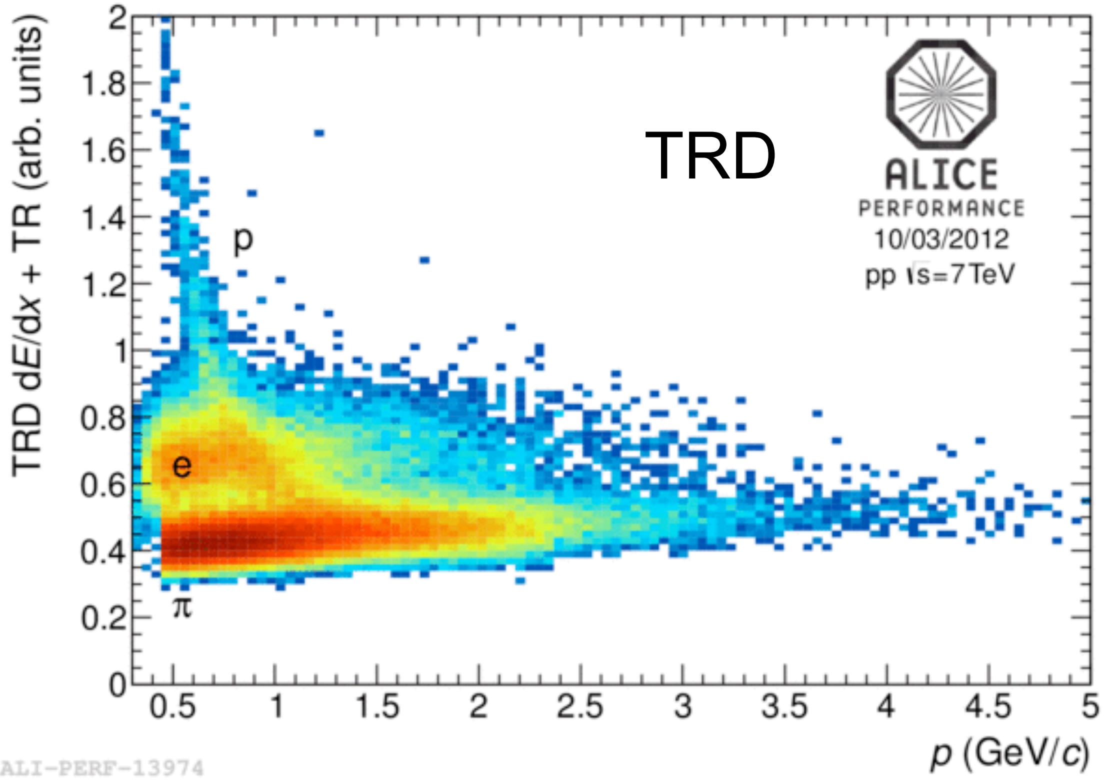
Hadron Identification



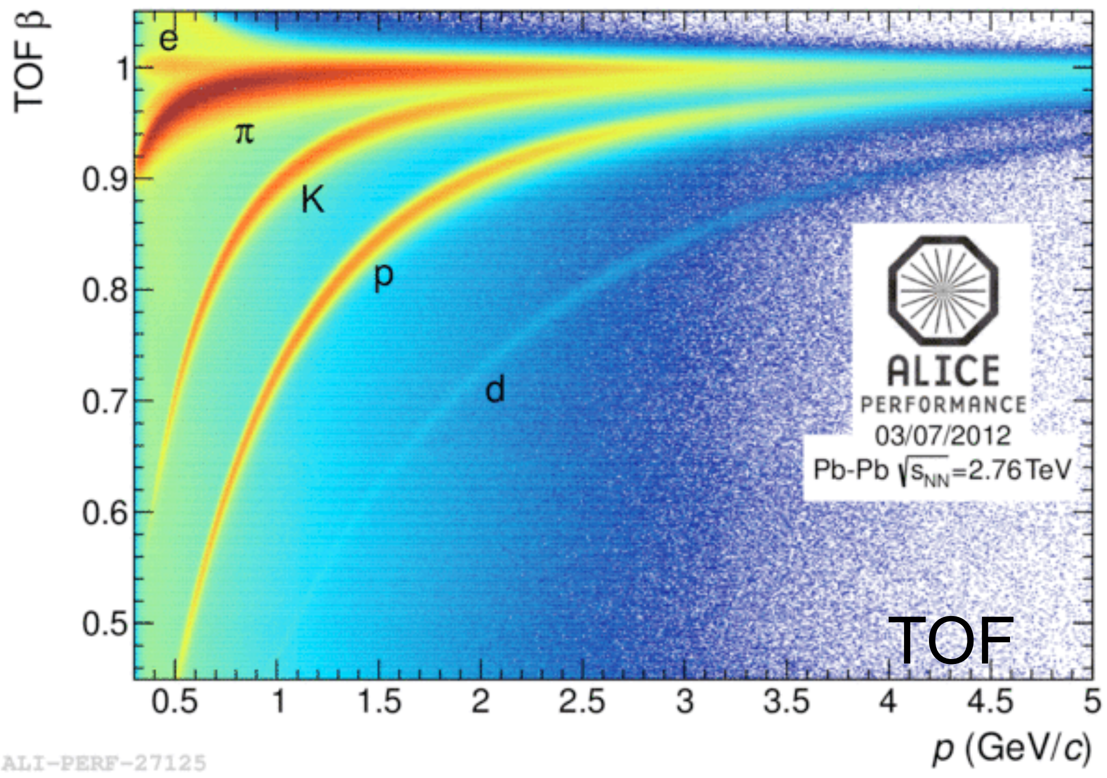
ALI-PERF-8369



ALI-PERF-3849

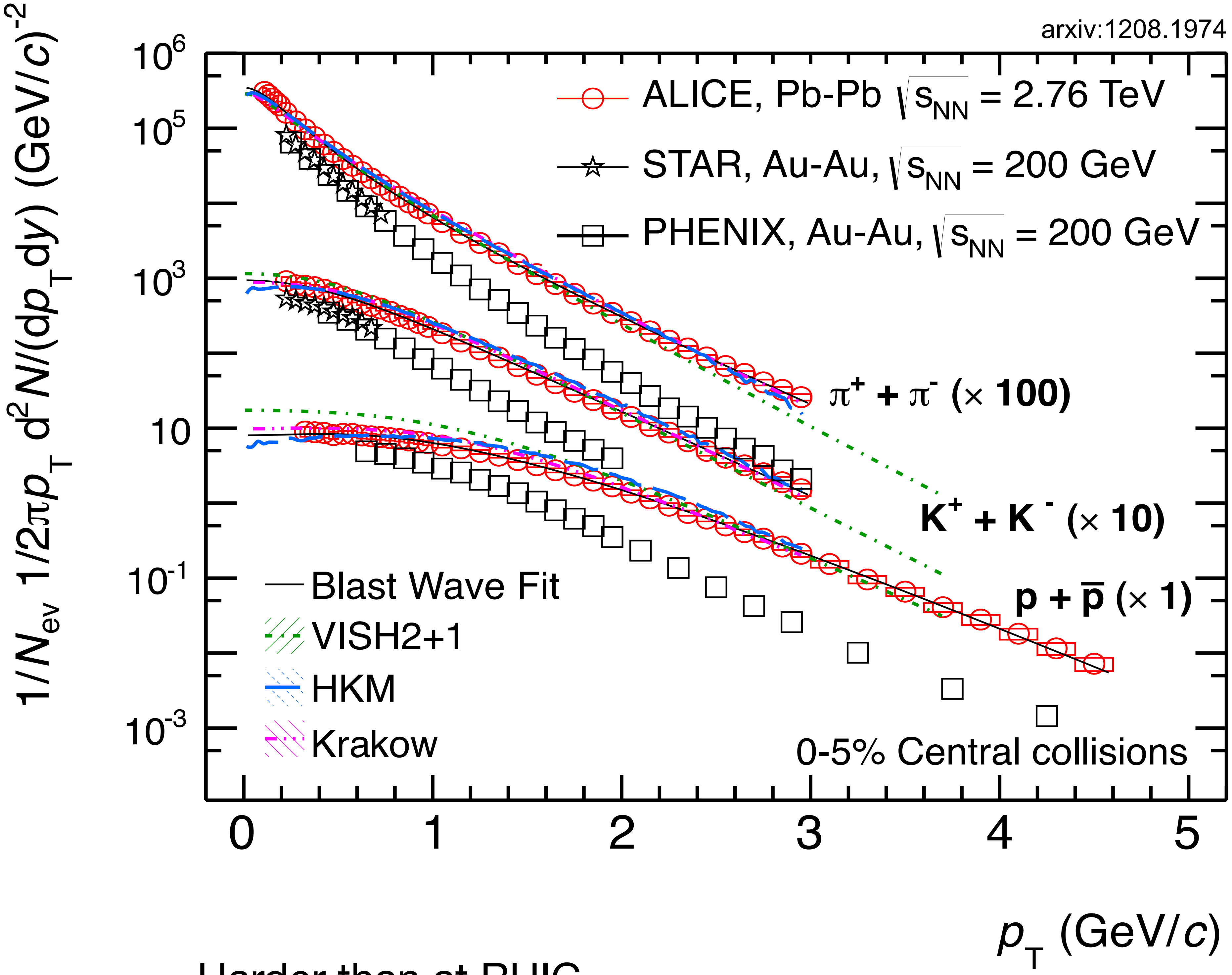


ALI-PERF-13974



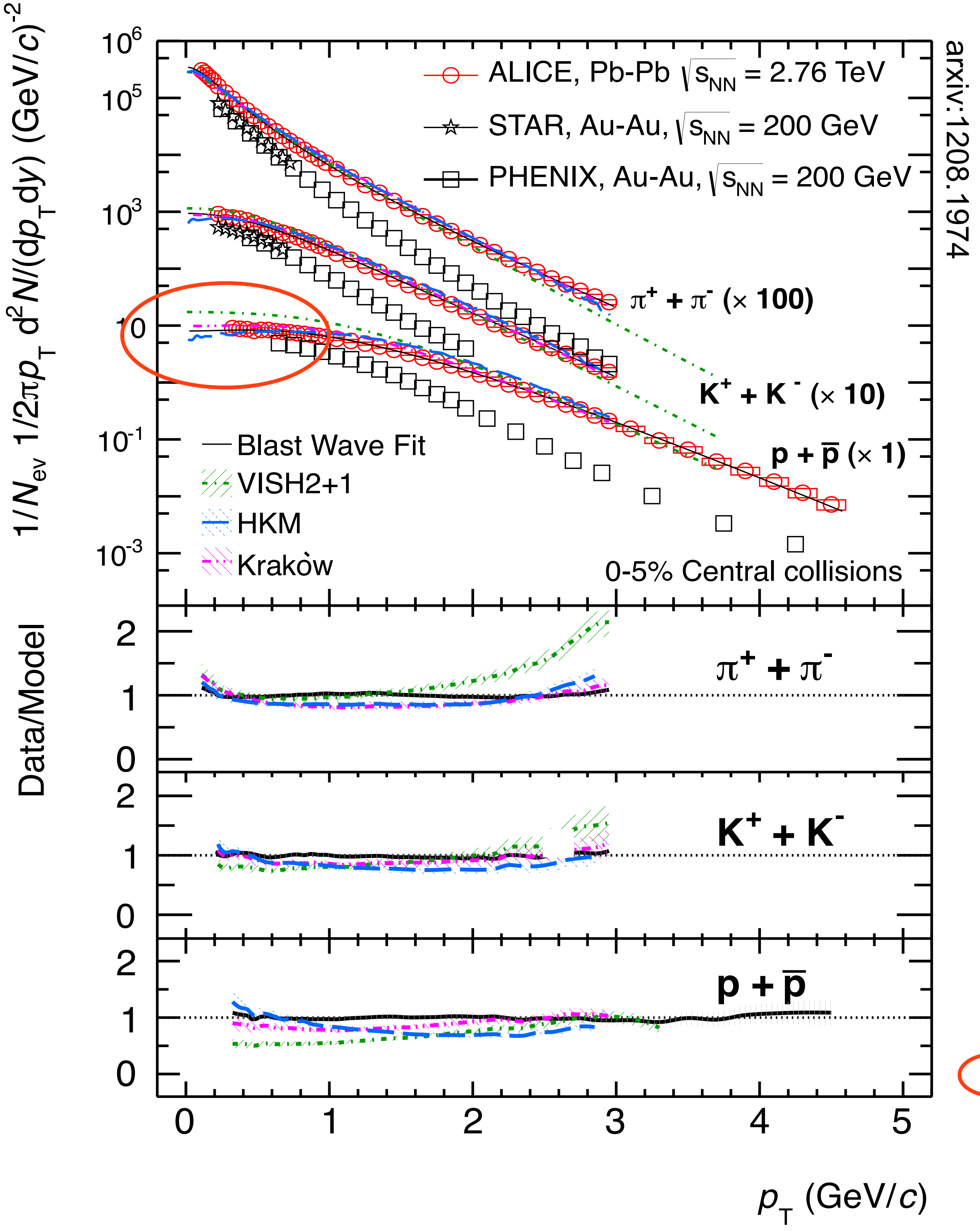
ALI-PERF-27125

Identified hadron spectra - comparison to RHIC



Harder than at RHIC

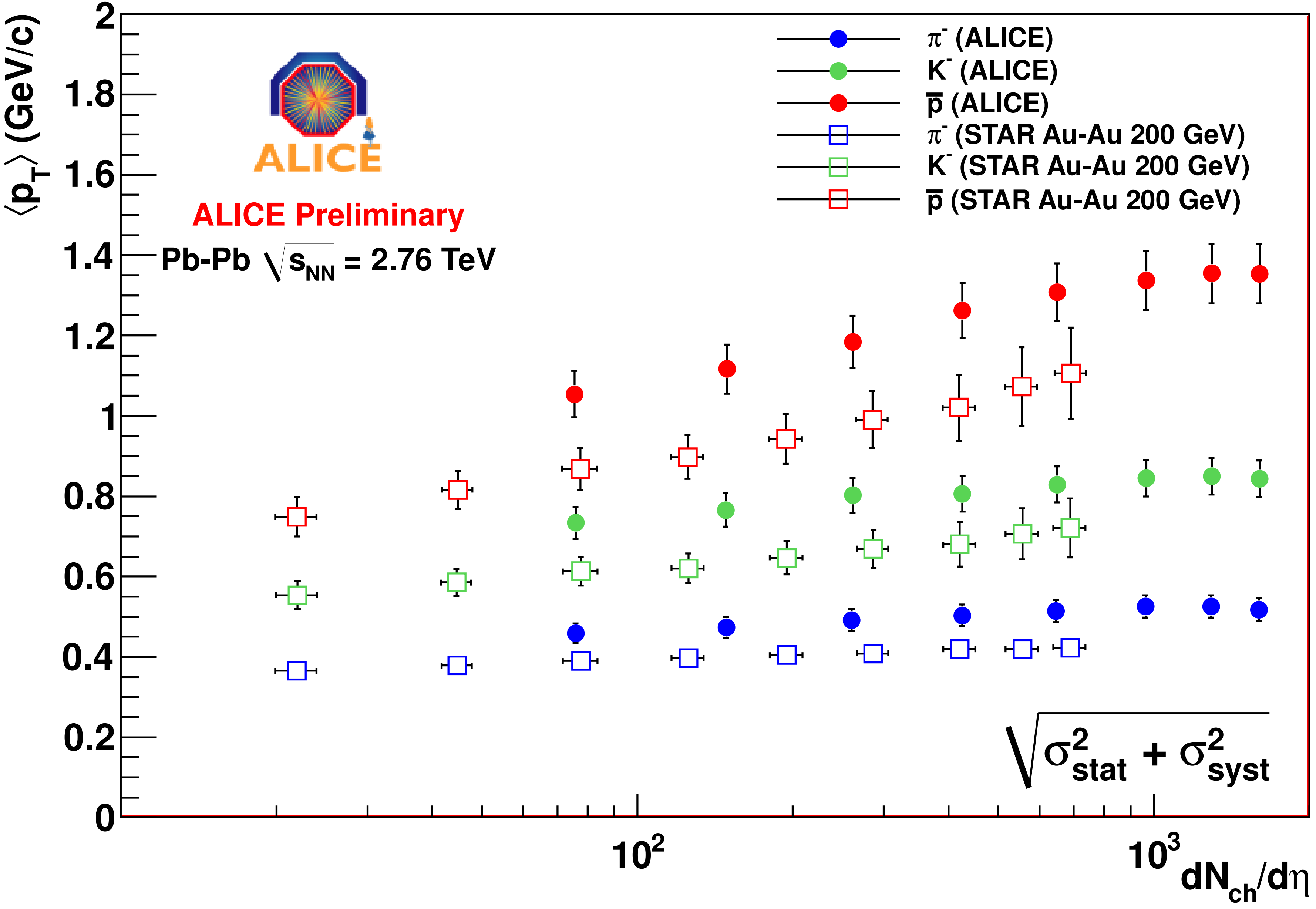
Identified hadron spectra - comparison to models



- harder than VISH2+1
- described by Krakow and HKM (early flow, cross-over, realistic EOS, resonances)
- less protons than predicted by hydro

Mean p_T of identified hadrons

M. Floris, QM2011

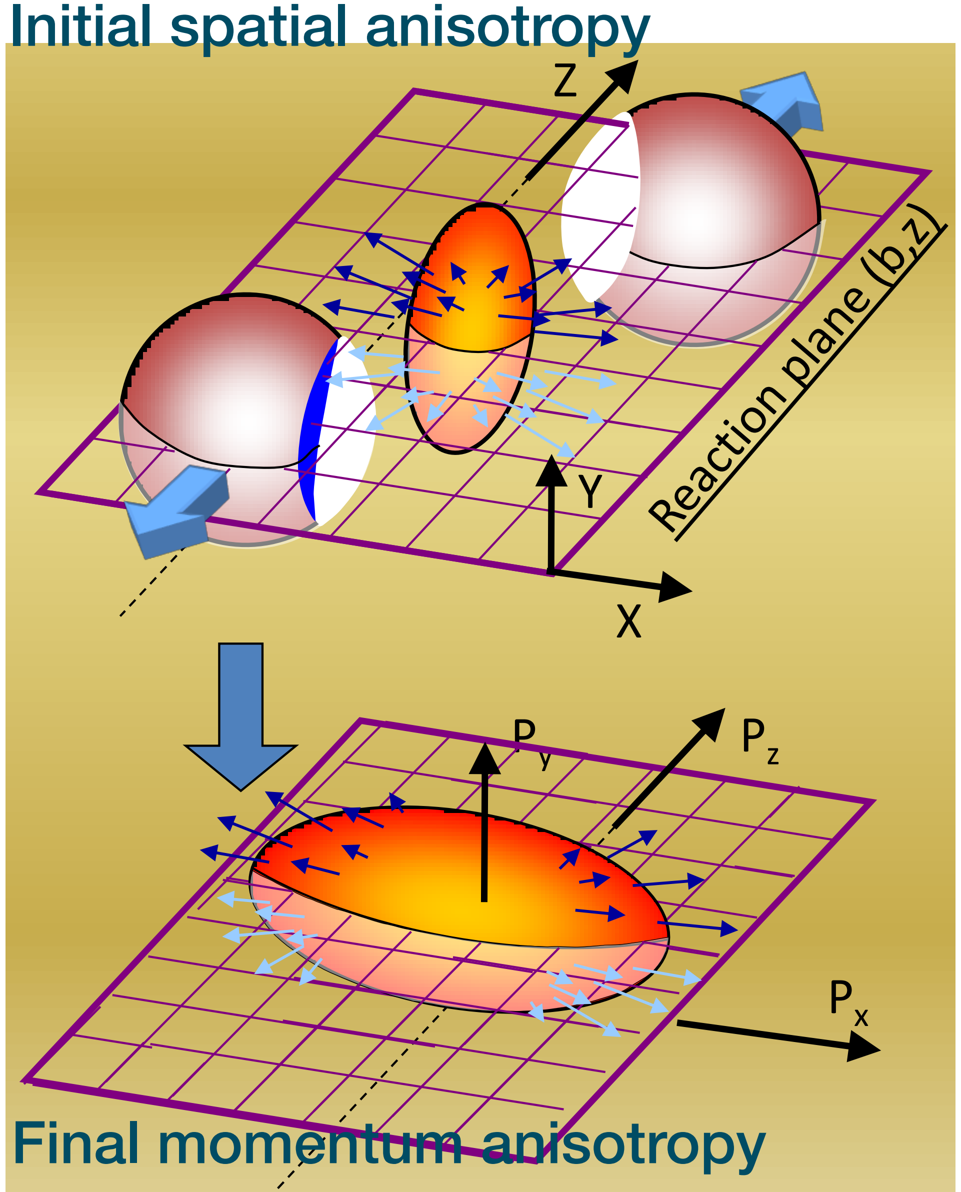


$\langle p_T \rangle$ ~20% higher than at RHIC at the same multiplicity

Flow

Particle flow: Collective Motion of Particles

Initial spatial anisotropy



Final momentum anisotropy reflected in azimuthal distributions

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

At the beginning of the collision: the nuclear overlap region is an ellipsoid.

The gradient of pressure is largest in the shortest direction of the ellipsoid

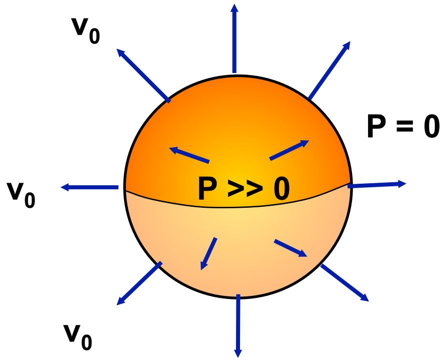
The initial spatial anisotropy evolves
→Momentum-space anisotropy

Fourier expansion of azimuthal distributions

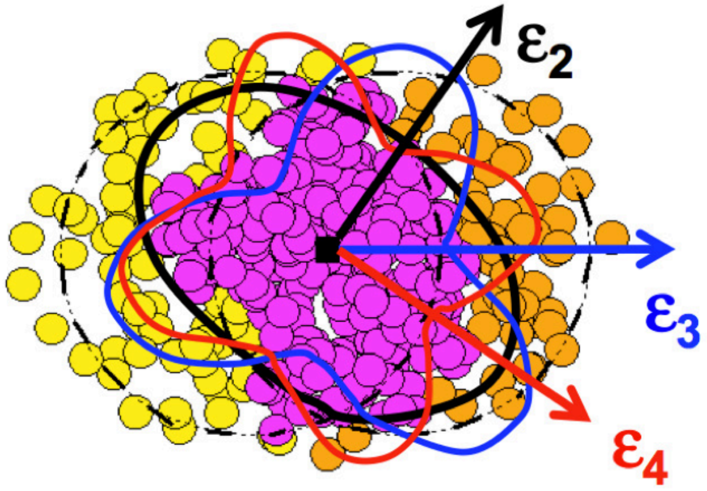
$$\frac{dN}{d\varphi} \propto 1 + 2v_1\cos[\varphi - \Psi_1] + 2v_2\cos[2(\varphi - \Psi_2)] + 2v_3\cos[3(\varphi - \Psi_3)] + ..$$

$$v_1 = \langle\cos(\varphi)\rangle \quad \text{"}\mathit{directed\ \ flow}\text{"} \qquad v_2 = \langle\cos(2\varphi)\rangle \quad \text{"}\mathit{elliptic\ \ flow}\text{"}$$

Isotropic (radial) flow

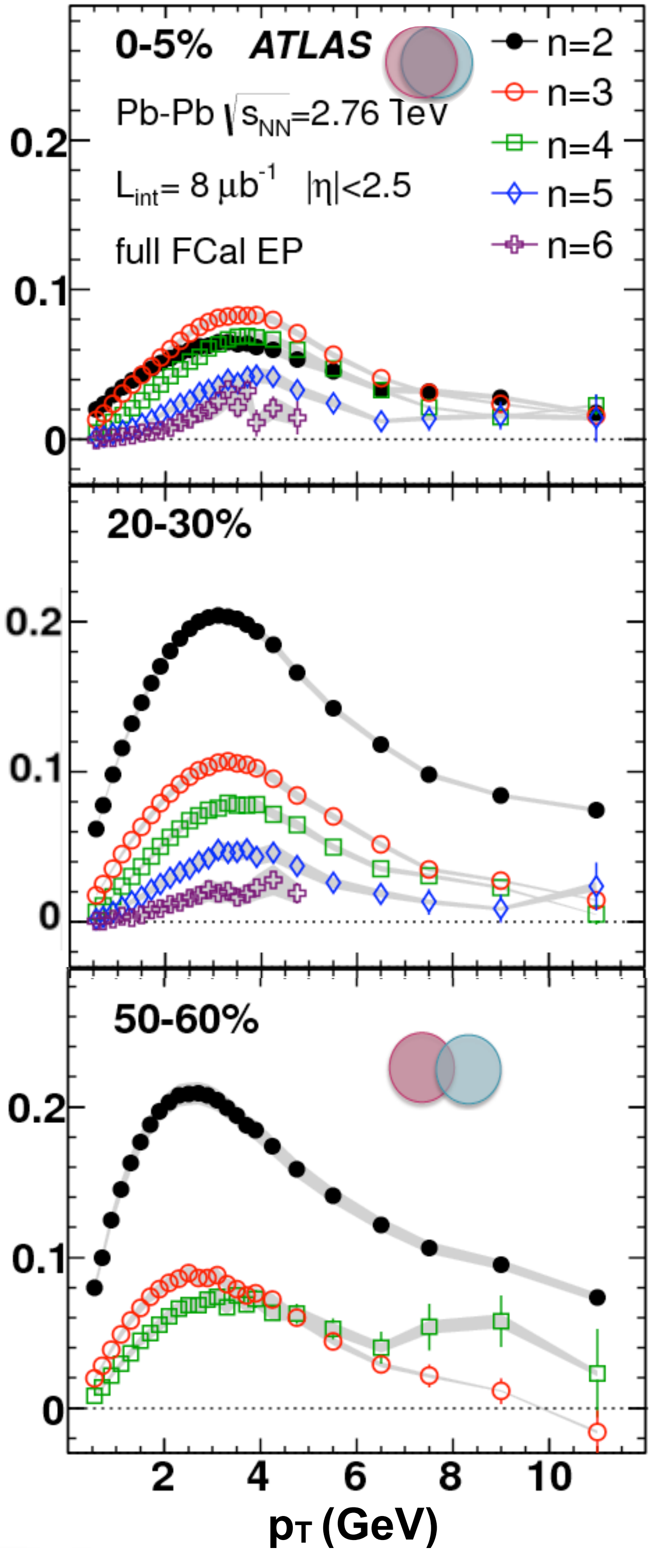


Not a smooth almond



Anatomy of flow harmonics (v_n)

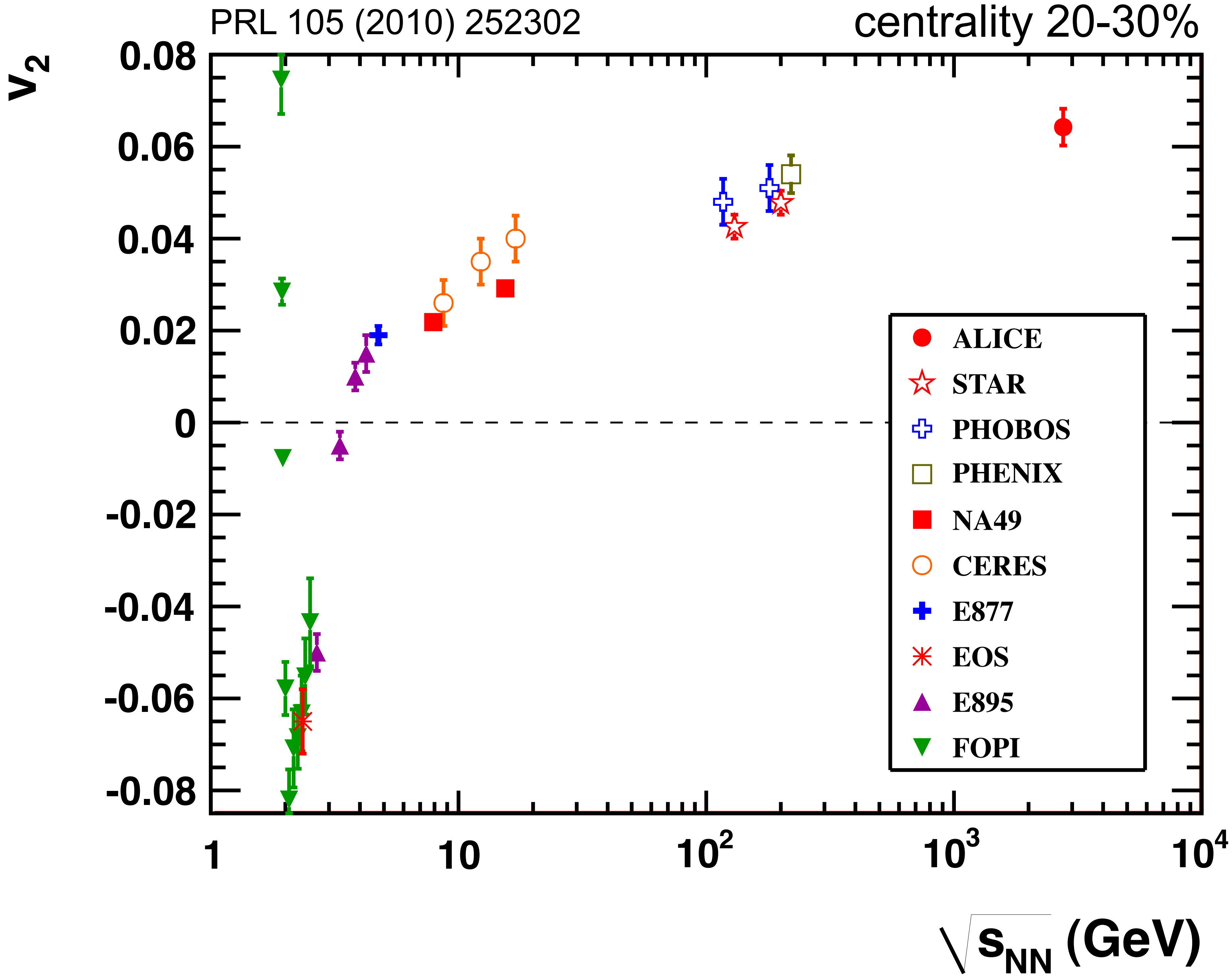
$$\frac{dN}{d\varphi} \propto 1 + 2v_1\cos[\varphi - \Psi_1] + 2v_2\cos[2(\varphi - \Psi_2)] + 2v_3\cos[3(\varphi - \Psi_3)] + ..$$

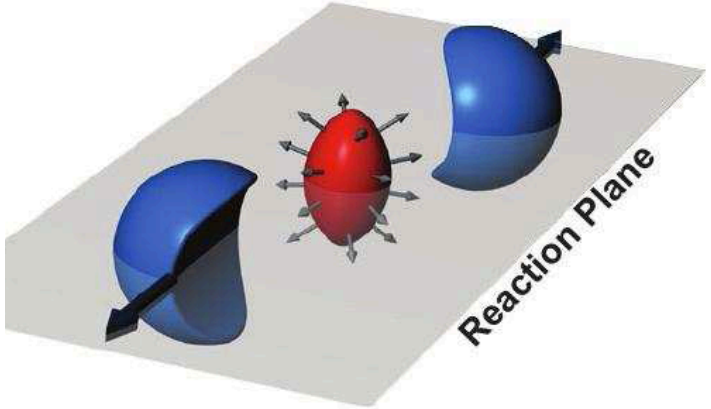


- v_2 dominates for non-central collisions
  - “Elliptic Flow”
- Higher harmonics: v_n studies
  - Fluctuations, transport
- $v_3 \sim v_2$ for central collisions
  - Fluctuations
- Transverse Momentum Regions
  - Low p_T ($\lesssim$ 3 GeV/*c*): collective hydrodynamic expansion
  - Intermediate p_T ($\lesssim$ 8 GeV/*c*): soft-hard interplay, recombination
  - High p_T: jet suppression vs path length

ATLAS, PRC86 014907 (2012)
ALICE, PRL107 032301 (2011), CMS, PRC 87 014902 (2013)

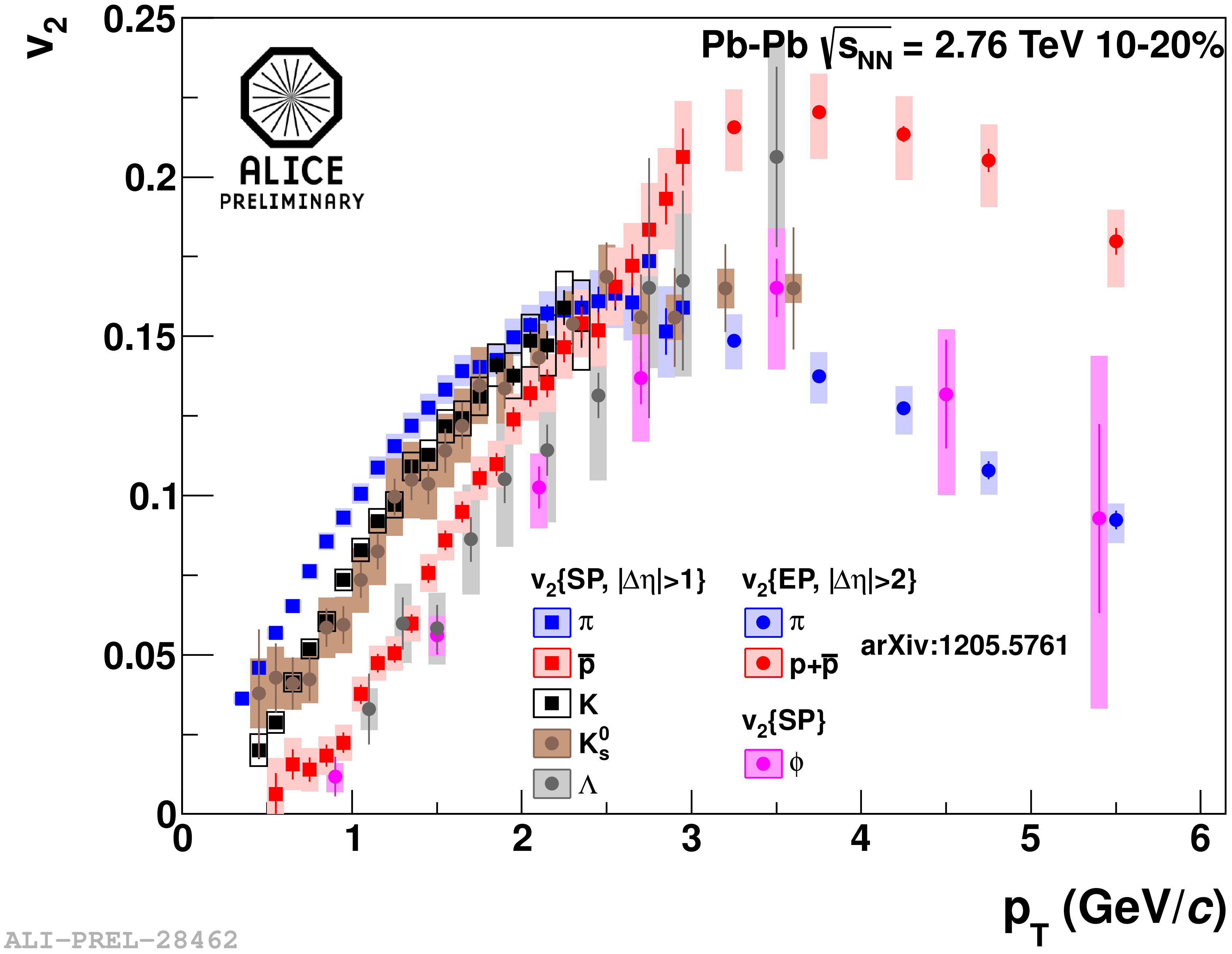
Elliptic flow in Au and Pb collisions





hydrodynamic behavior continues at LHC energies

Elliptic flow of identified hadrons

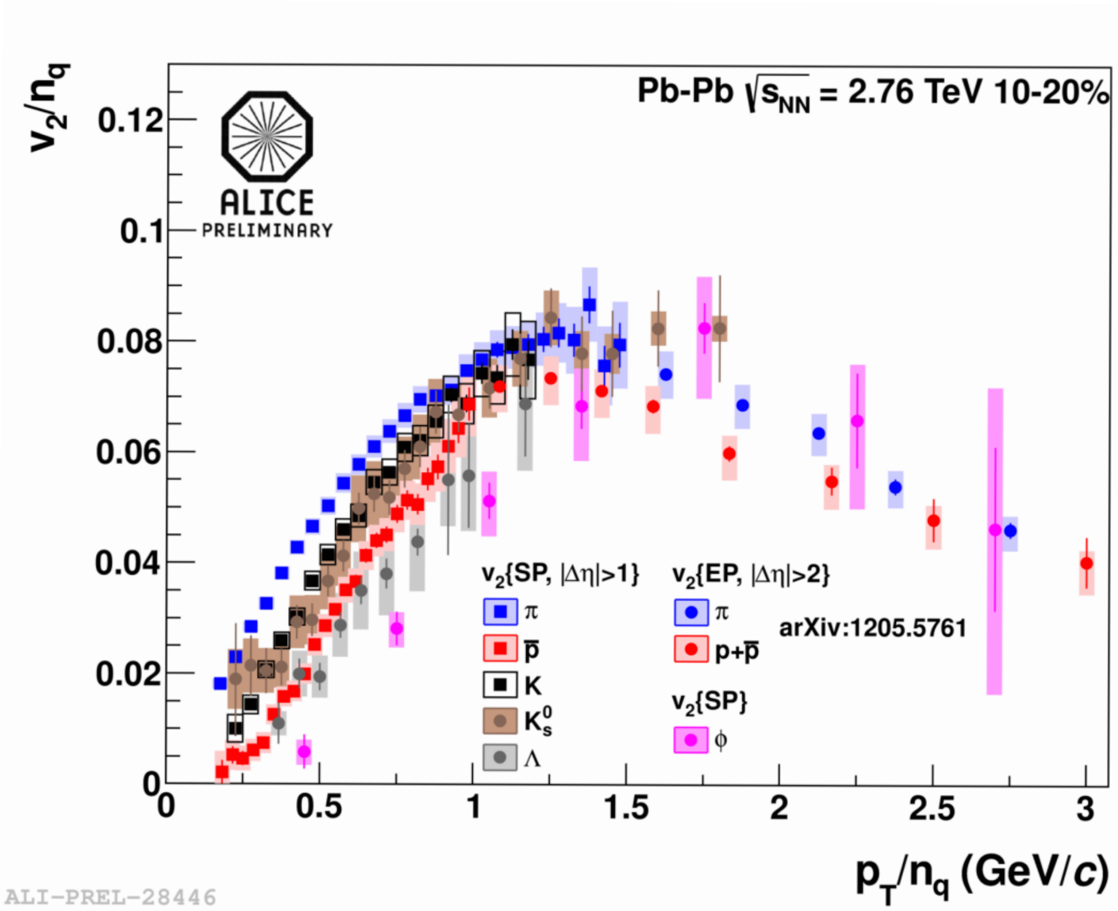


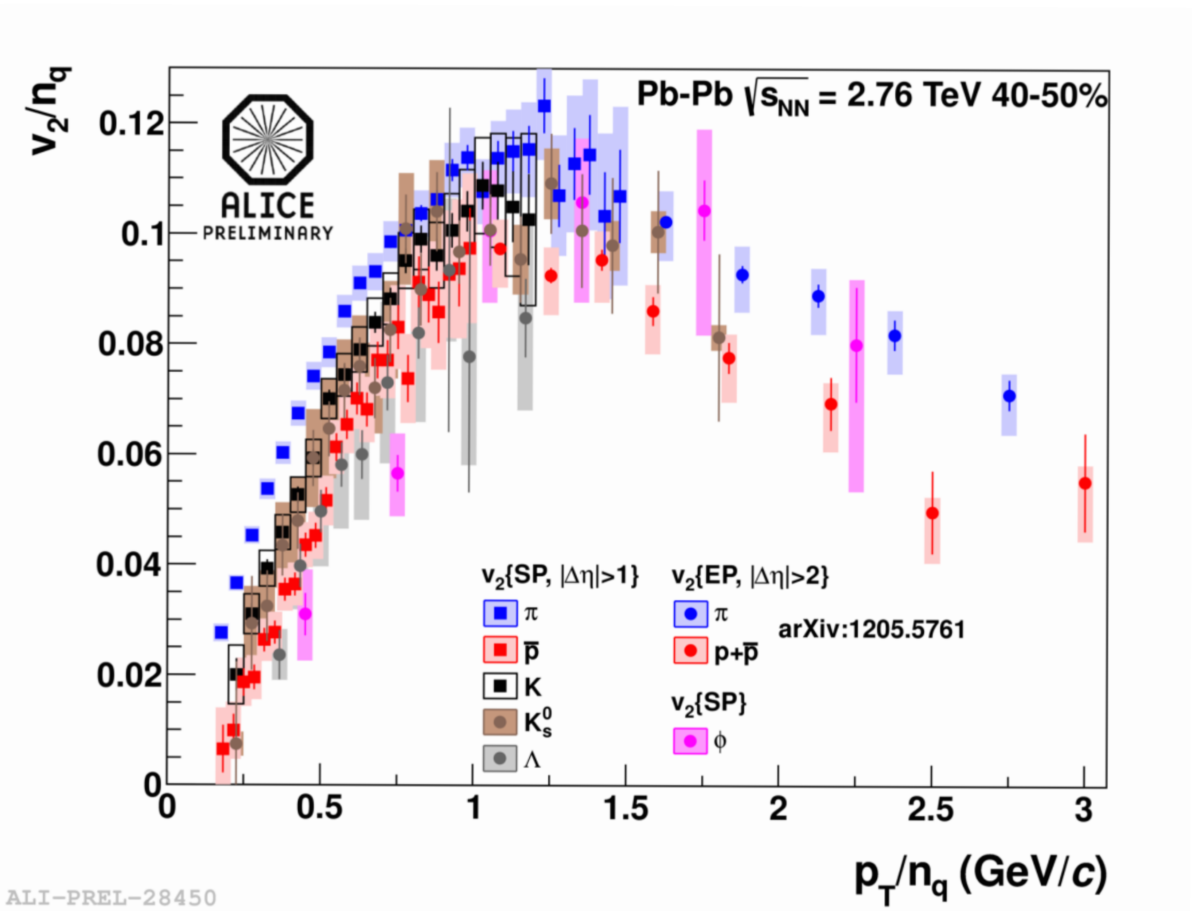
Additional constraints on collective evolution

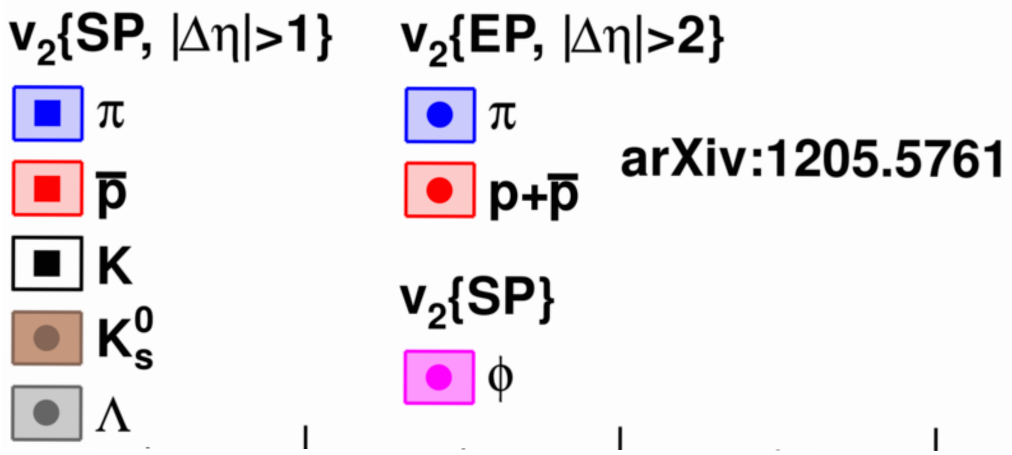
v_2 for π, p, $K^{\pm}$, K^0_s, Λ, ϕ (not shown for Ξ, Ω)

ϕ at low p_T (<3 GeV/c) follows mass hierarchy – at higher p_T joins mesons

Elliptic flow of identified hadrons



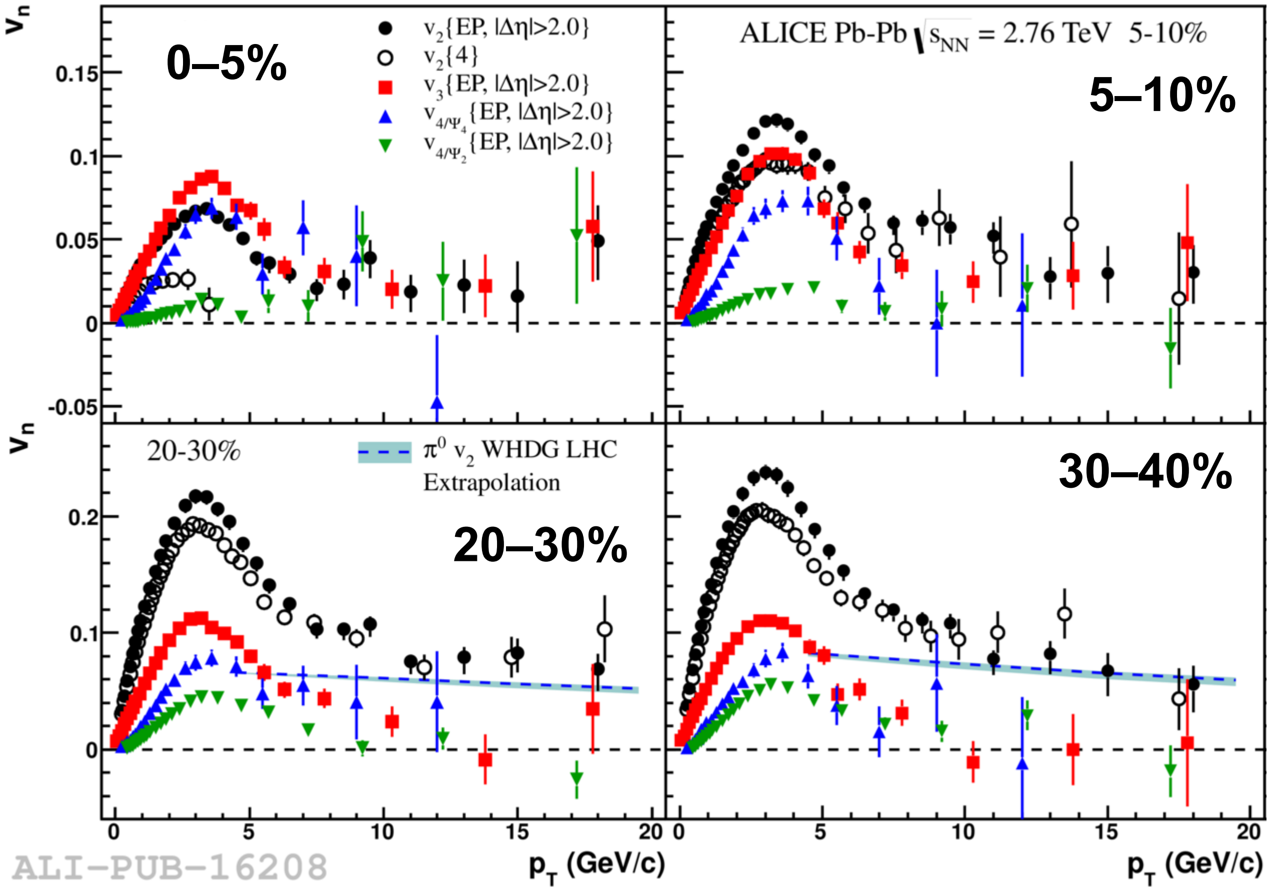


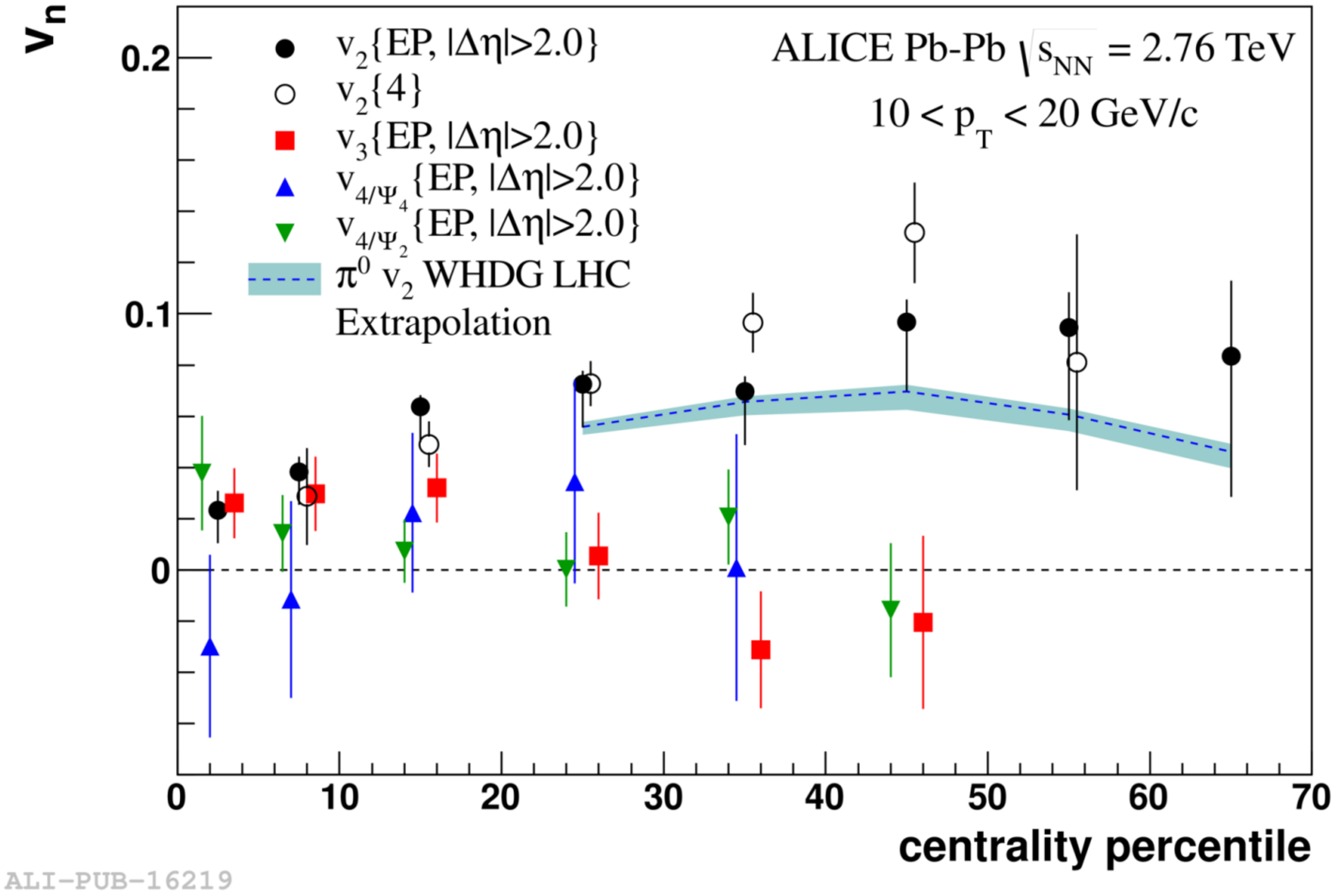


v_2 for π, p, $K^{\pm}$, K^0_s, Λ, ϕ (not shown for Ξ, Ω)
ϕ at low p_T (<3 GeV/c) follows mass hierarchy
– at higher p_T joins mesons

NCQ scaling: violation ~ 10% at low p_T

v_2, v_3, v_4 versus p_T





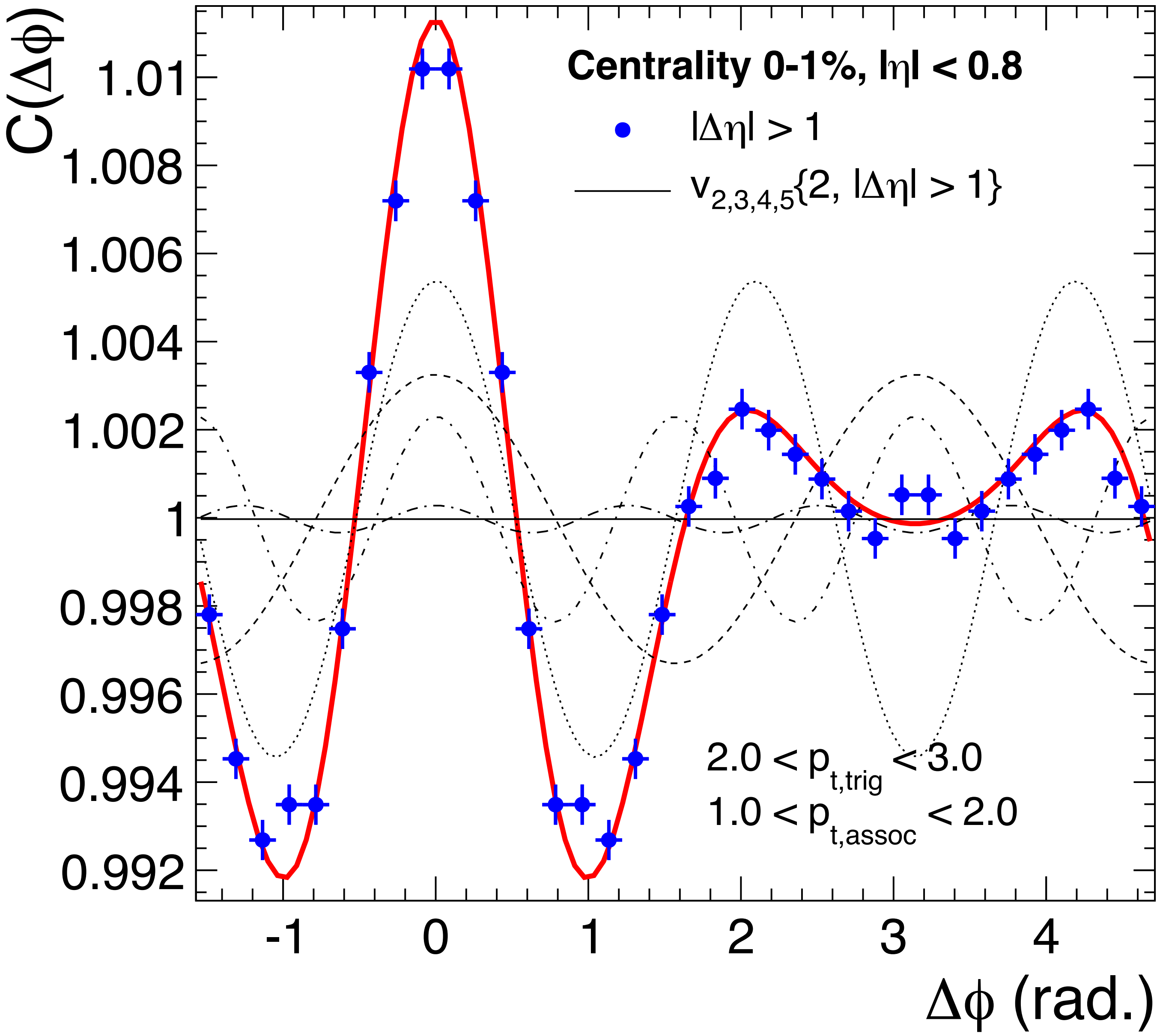
v_n measurements up to 20 GeV/*c* – where dominated by jet quenching
Non-flow effects suppressed by rapidity gap or using higher cumulants
Non-zero value of v_2 at high p_T both for $\Delta\eta > 2$ and 4-particle cumulant

v_3 and v_4 diminish above 10 GeV/*c* – indication of disappearance of fluctuations at high p_T

- v_3 is not related to reaction plane
- v_3 only weakly depends on centrality

Higher harmonics of flow

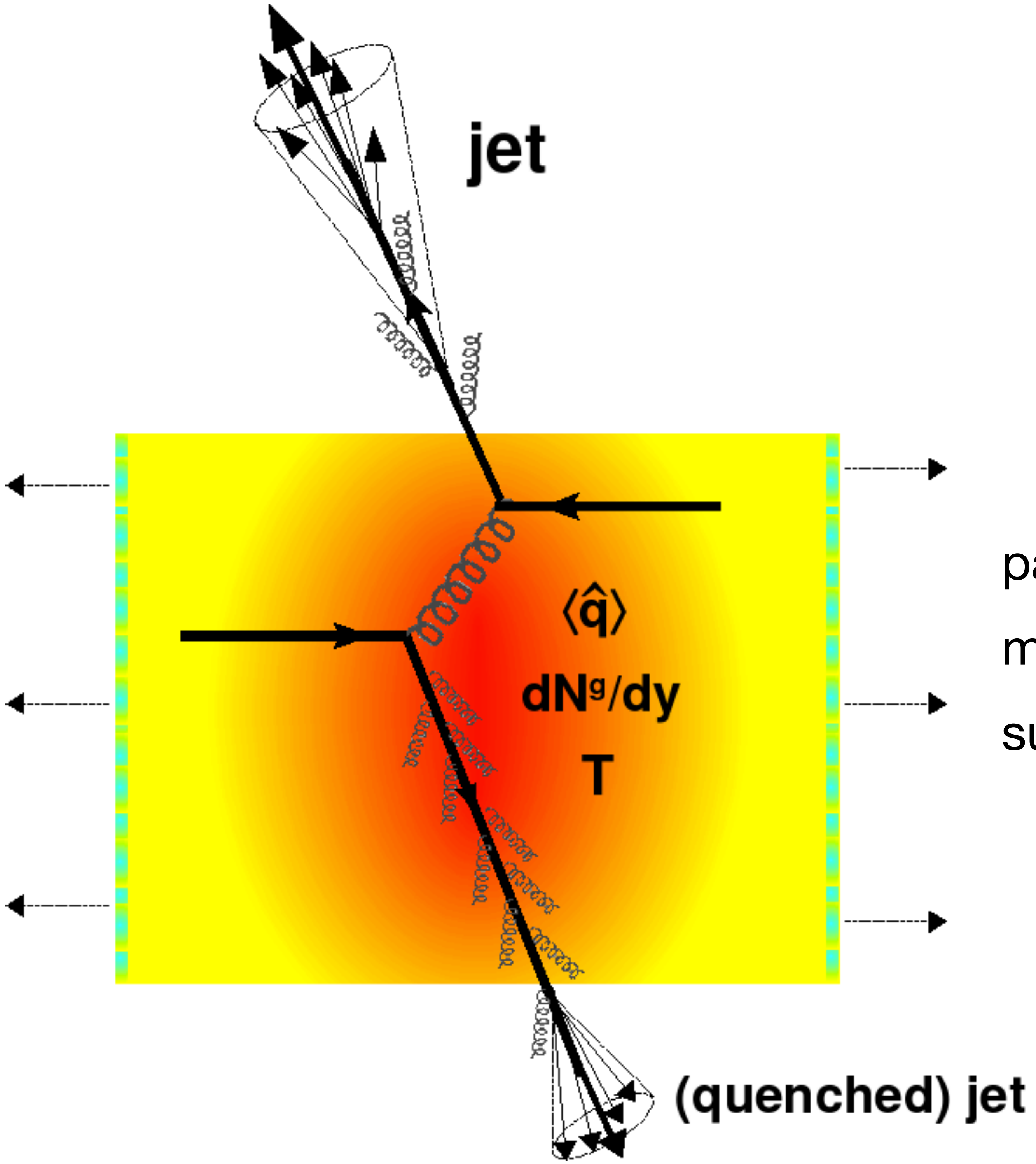
PRL 107 (2011) 032301



- the azimuthal correlations at high p_T fully described by the flow coefficients

Probing QCD Matter

Nuclear modification factor

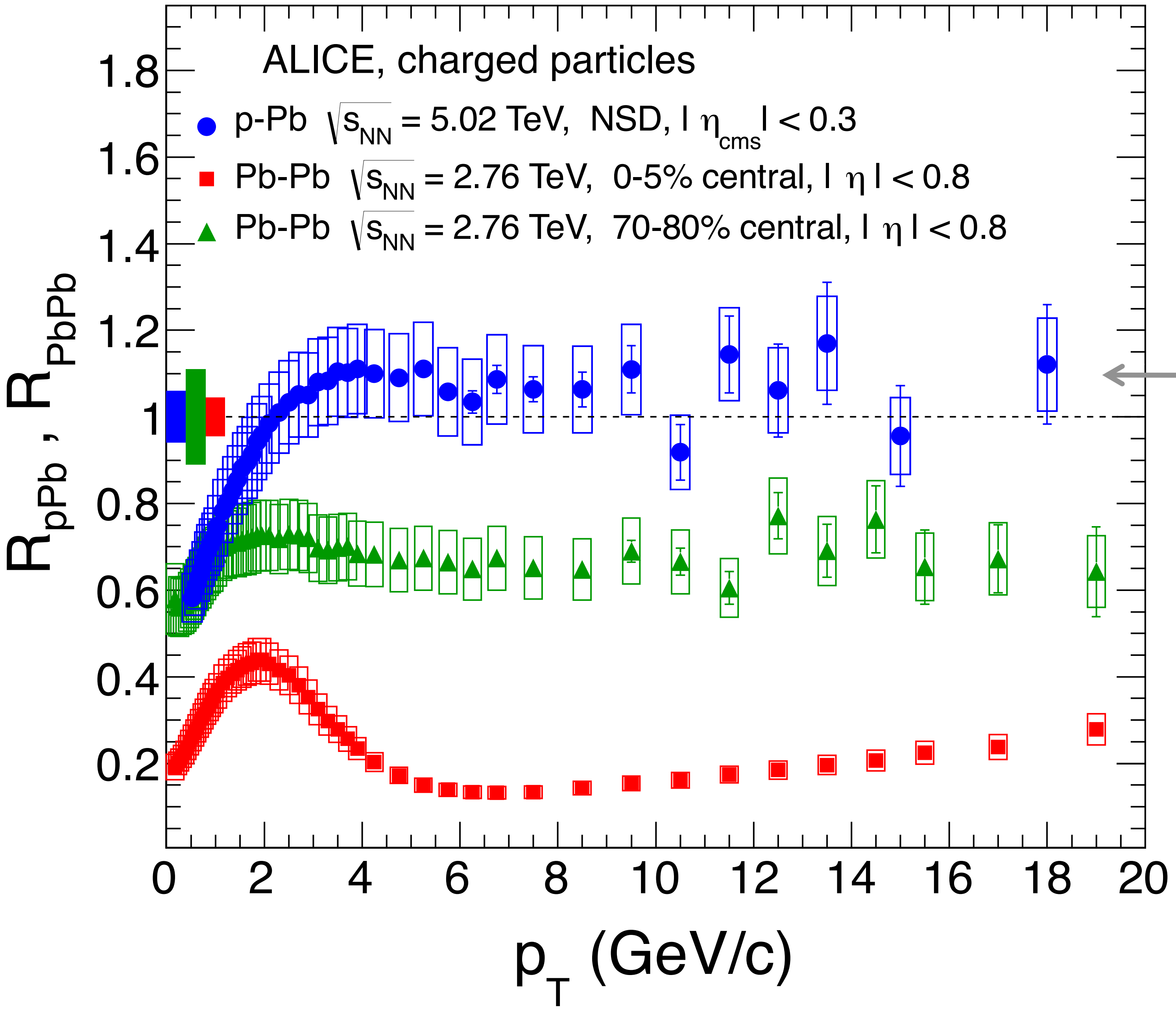


parton energy loss in color medium

manifesting as

suppression of high-p_T particles in Pb-Pb

Nuclear modification factor



PRL 110 (2013) 082302

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

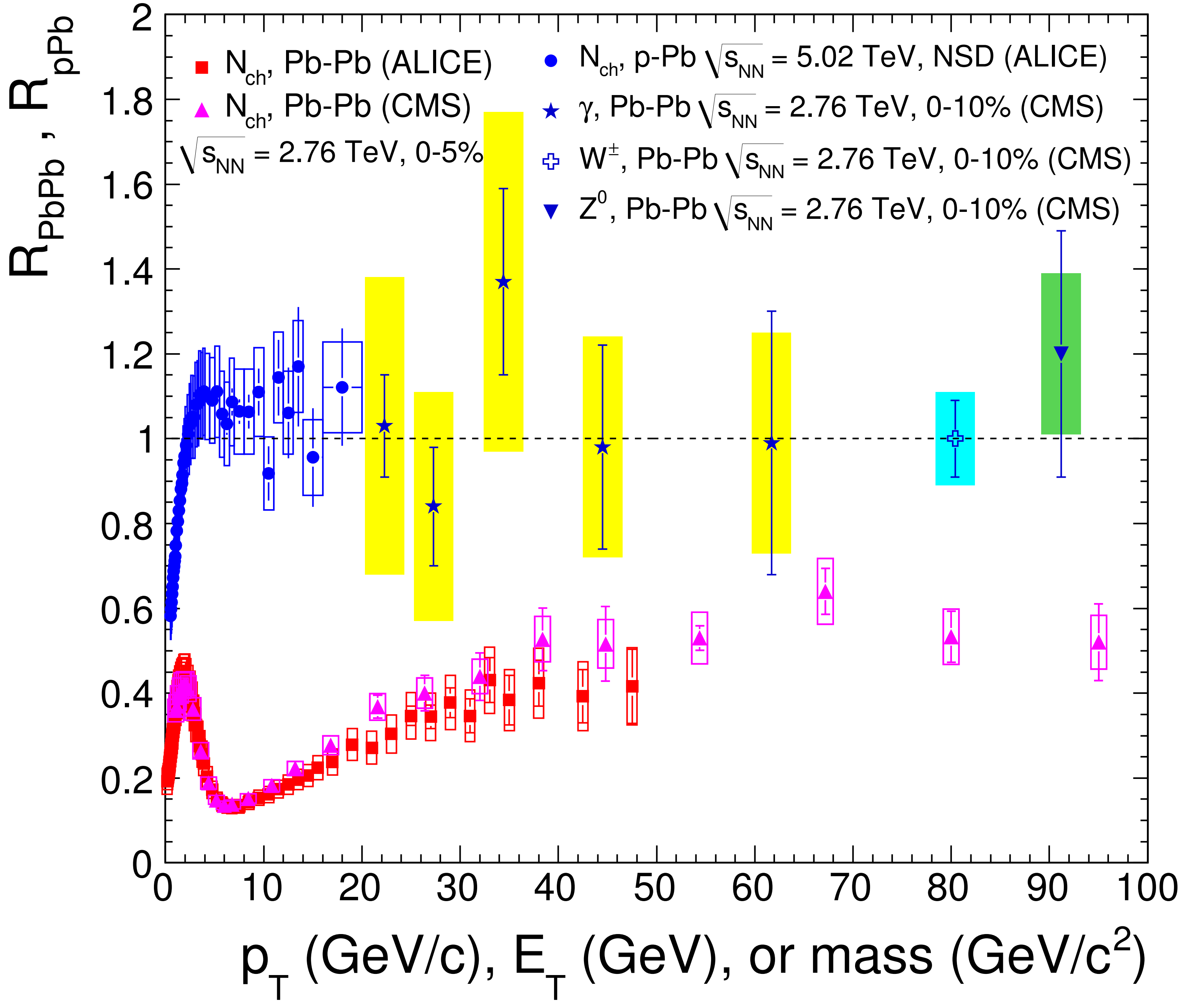
- R_{pPb} (Pb (at mid-rapidity) consistent with unity for p_T > 2 GeV/c
- High-p_T charged particles exhibit binary scaling
- Unlike in PbPb, no suppression at high p_T is observed
- Suppression at high p_T in PbPb is not an initial state effect

suppression in Pb-Pb

parton energy loss in QCD medium

Rise at high p_T: relative energy loss decreasing with p_T

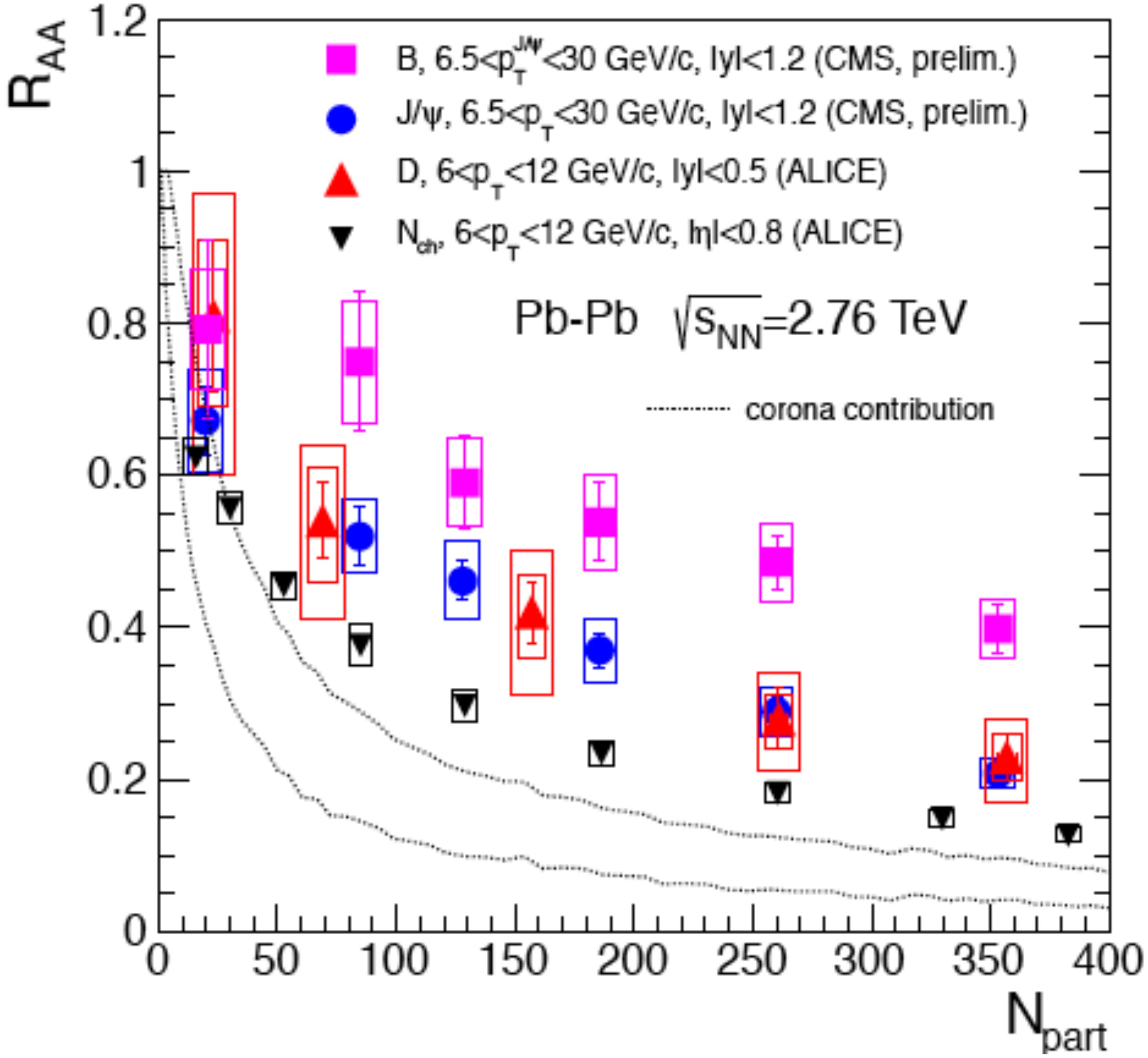
Nuclear modification factor



ALI-DER-45646

no suppression of photons, W, Z^0 in Pb-Pb

Mass dependent energy loss



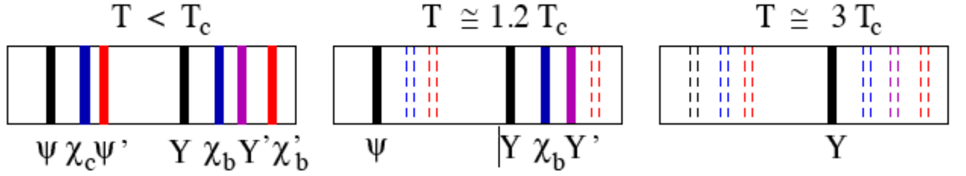
less suppression for heavy quarks

B < D, J/Ψ < charged particles

But kinematic ranges (w.r.t. to parent quarks) are not exactly the same

J/Psi suppression - or enhancement

sequential suppression



PLB 178 (1986) 416

statistical hadronization c+cbar→J/Psi PLB 490 (2000) 196

both effects expected to be stronger at LHC than at RHIC

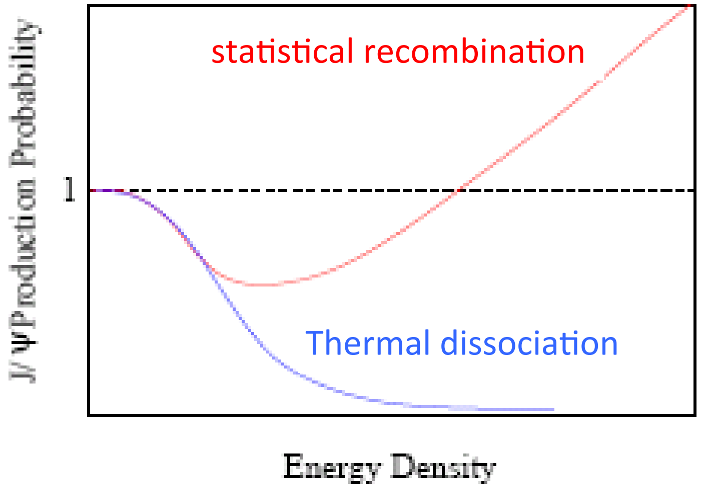
LHC vs. RHIC

Larger energy density

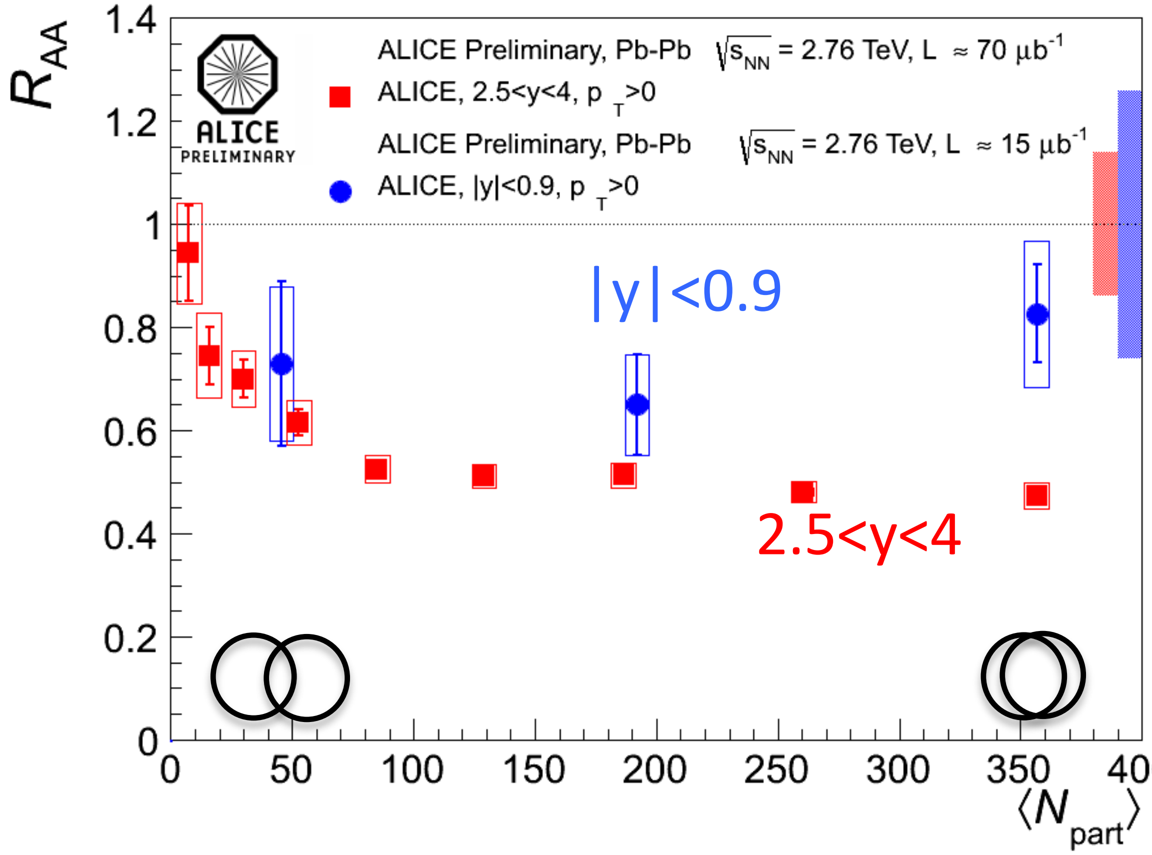
→stronger suppression

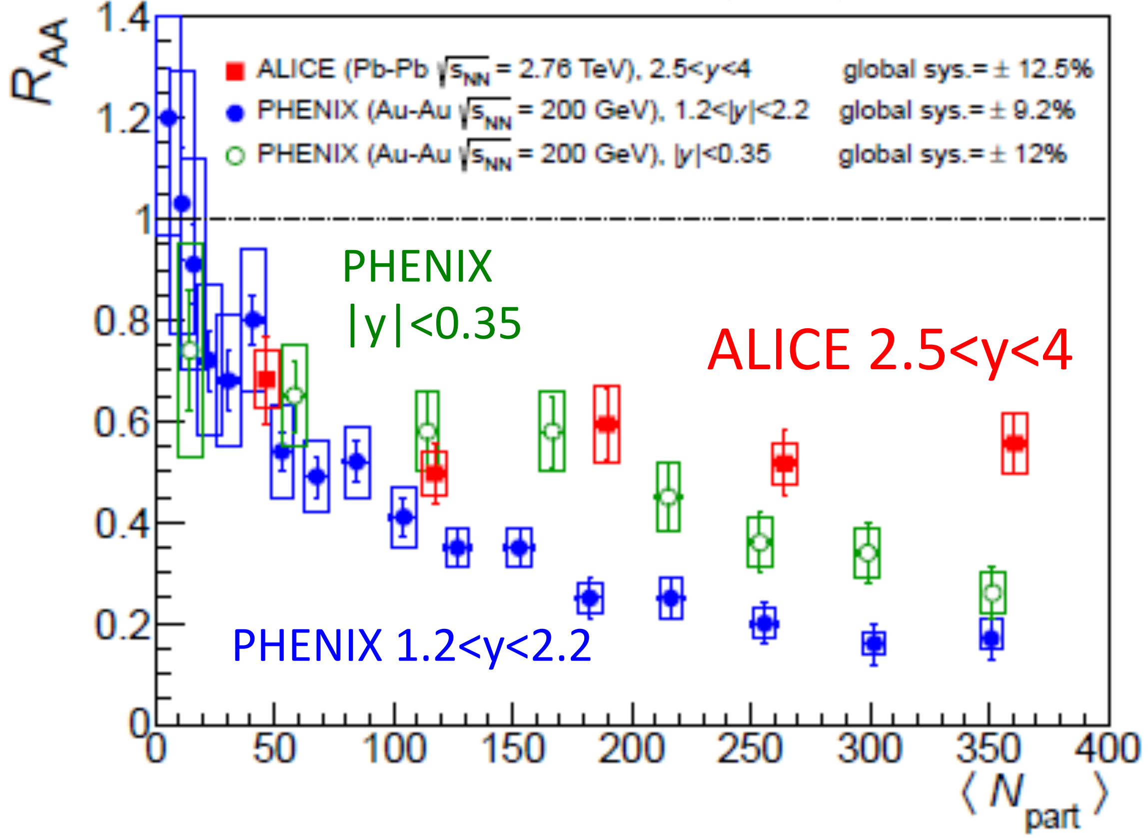
Higher $c\bar{c}$ multiplicity

→larger recombination



PRL 109 (2012) 072301



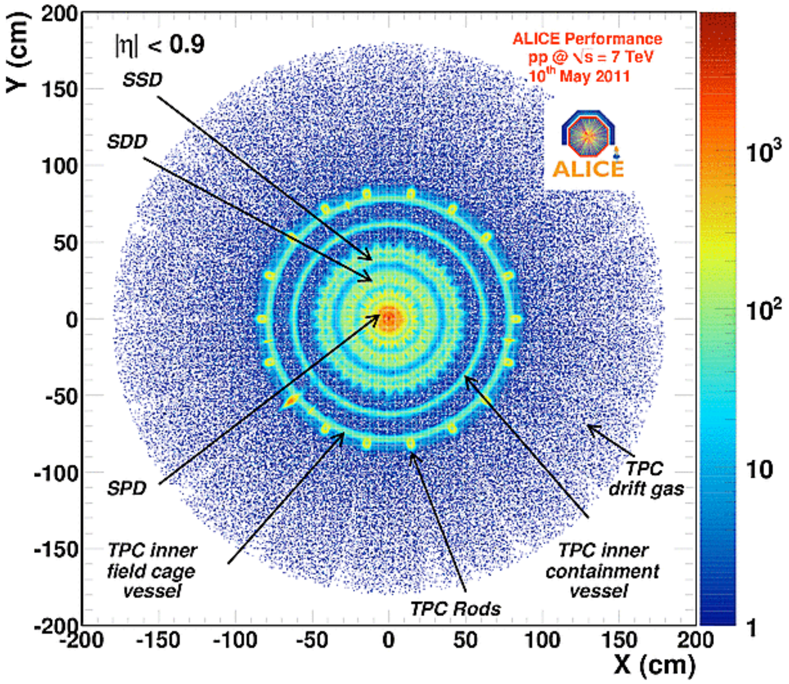


Inclusive J/ψ suppression measurements both in central and forward regions for p_T>0:

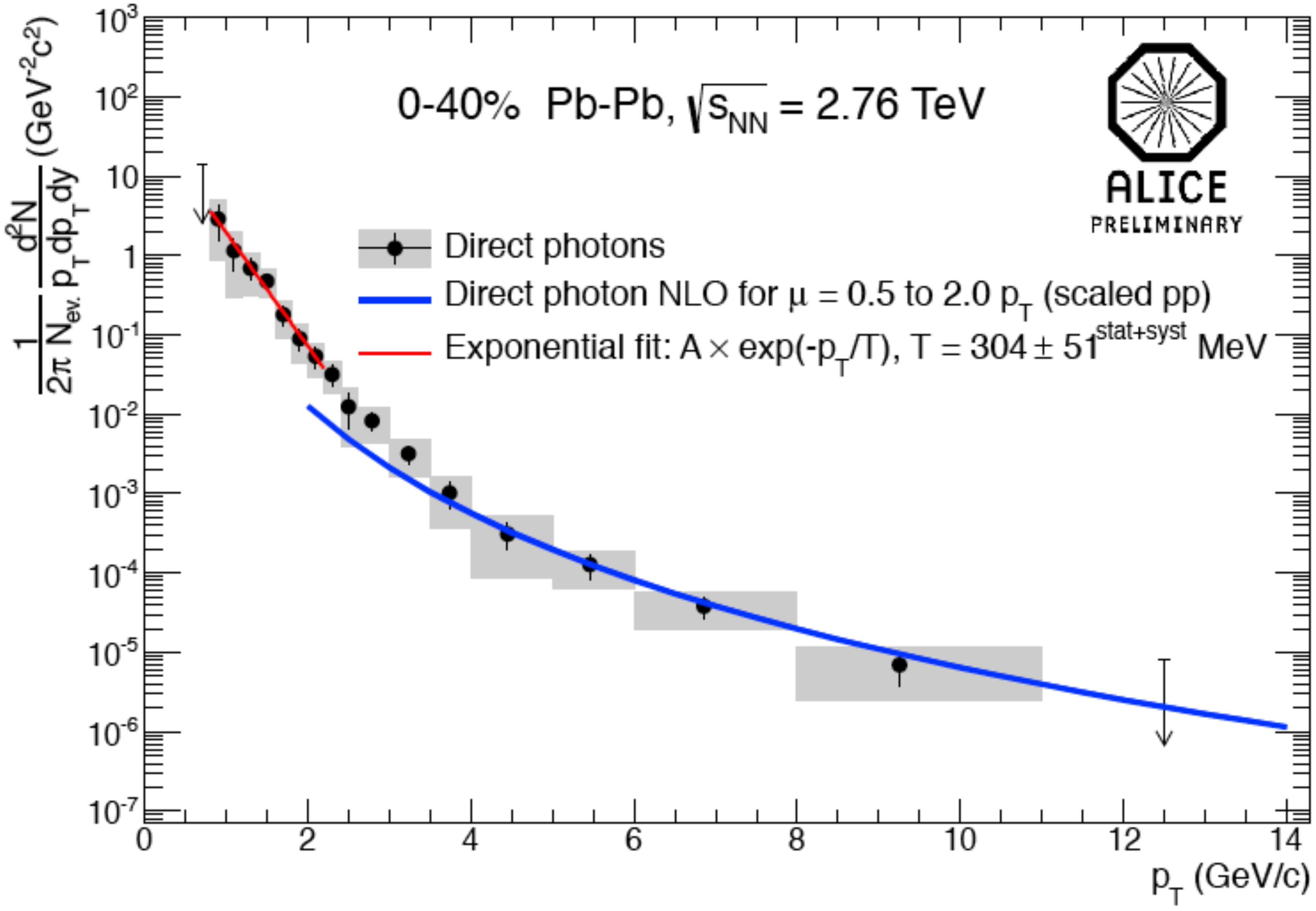
- from N_{part} > 100 suppression independent of centrality
- in central collisions, less suppression than at RHIC

Hot photons

photons measured via conversions into e+e-



arXiv:1210.5958



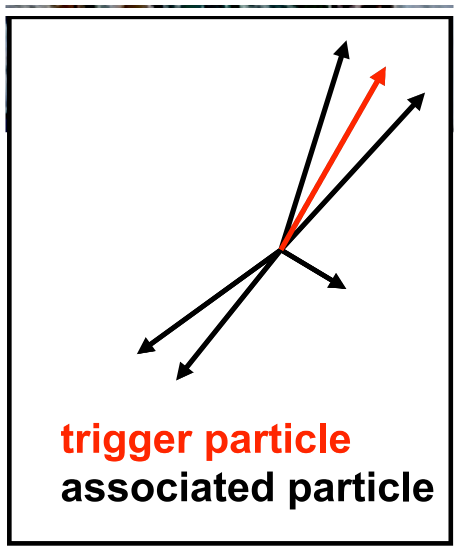
Exponential fit for $p_T < 2.2$ GeV/c inverse slope T = 304±51 MeV
for 0–40% Pb–Pb at $\sqrt{s}$ = 2.76 TeV

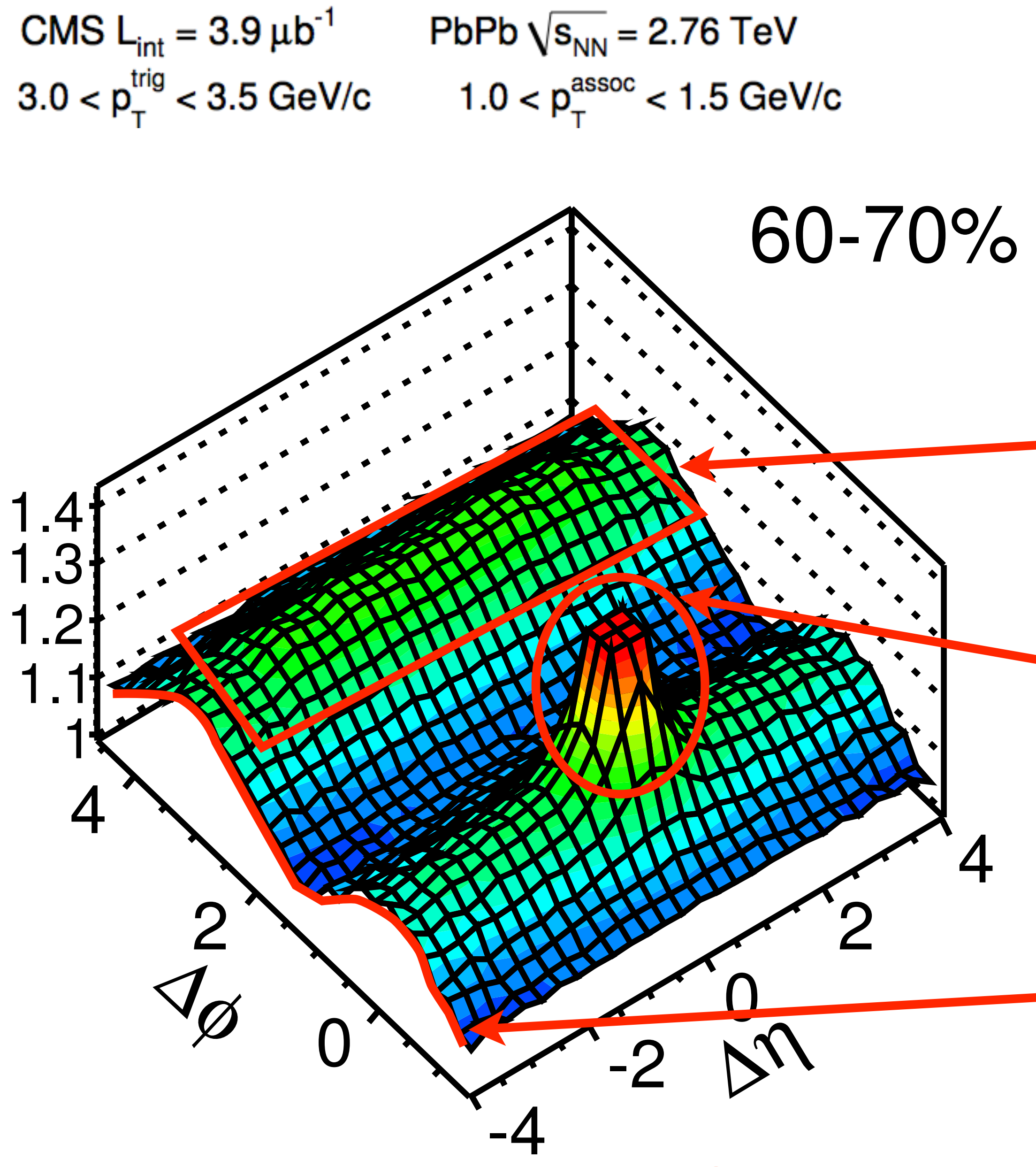
PHENIX: T = 221±19±19 MeV for 0–20% Au–Au at $\sqrt{s}$ = 200 GeV

photon temperature higher than T_C

Jet Bulk Interaction

Two particle correlations





Recoil (away-side) jet
($\Delta\phi$ ~ π, elongated in $\Delta\eta$)

Near-side jet
($\Delta\phi$ ~ 0, $\Delta\eta$ ~ 0)

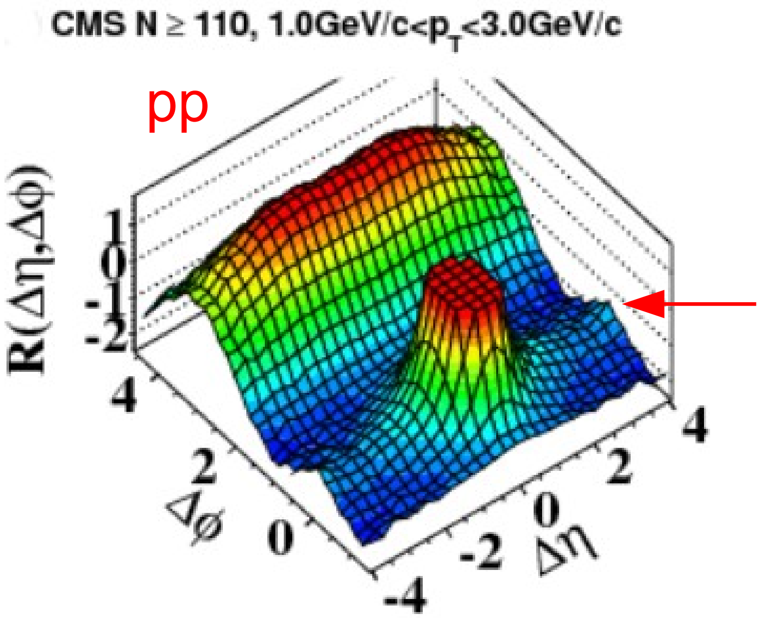
Azimuthal modulation (v_n)

CMS. EP JC 72 (2012) 2012

Correlations originating from jets and other sources

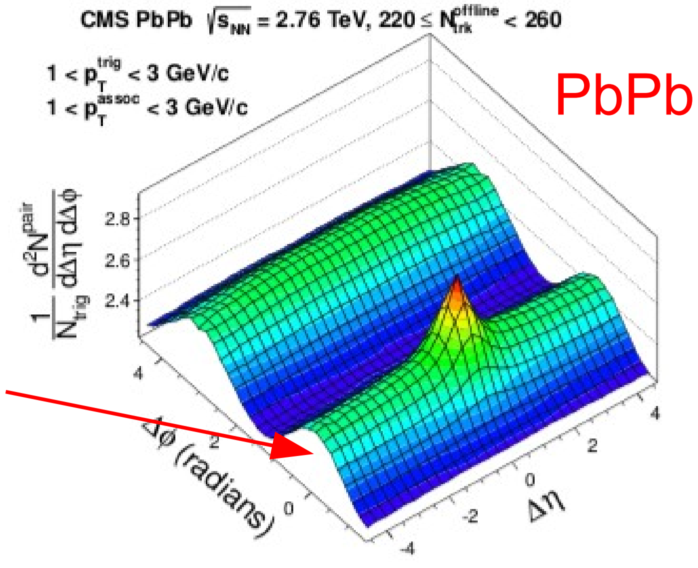
Two-particle correlations are a powerful tool to explore the mechanism of particle production in collisions of hadrons and nuclei at high energy. Such studies involve measuring the distributions of relative angles ϕ and η between pairs of particles.

Two particle correlations in η

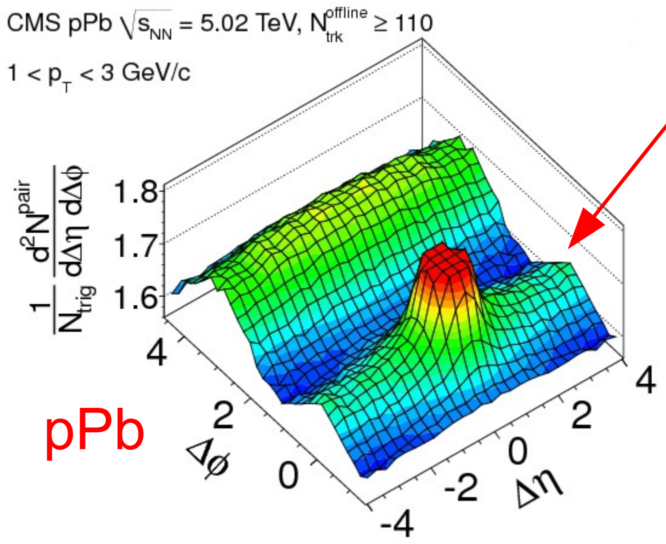


CMS, JHEP 1009 (2010) 91

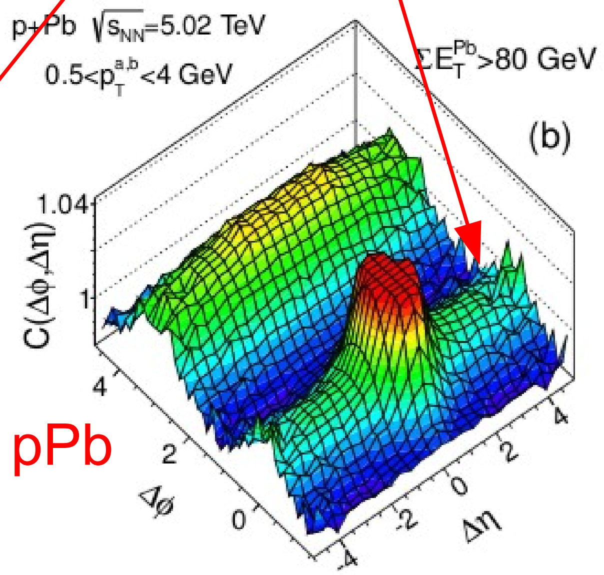
Near-side ridges apparent in high multiplicity events at LHC energies



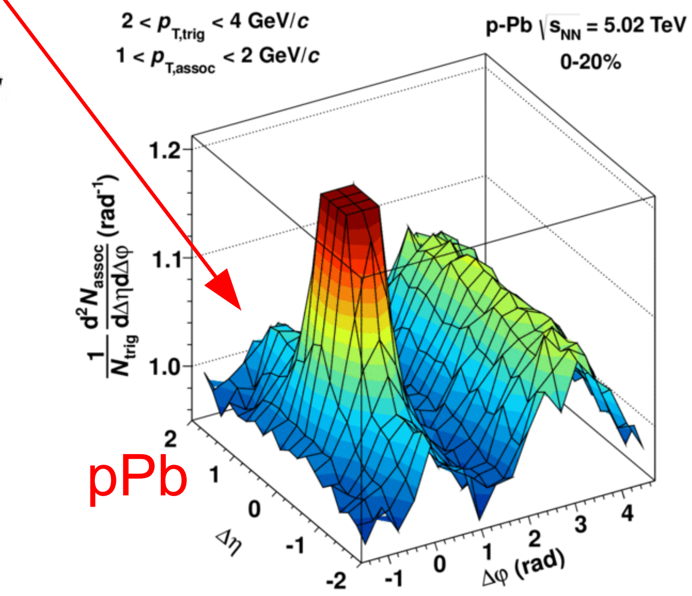
CMS, arXiv:1305.0609



CMS, PLB 718 (2012) 795



ATLAS, arXiv:1212.5198



ALICE, PLB 719 (2013) 29

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

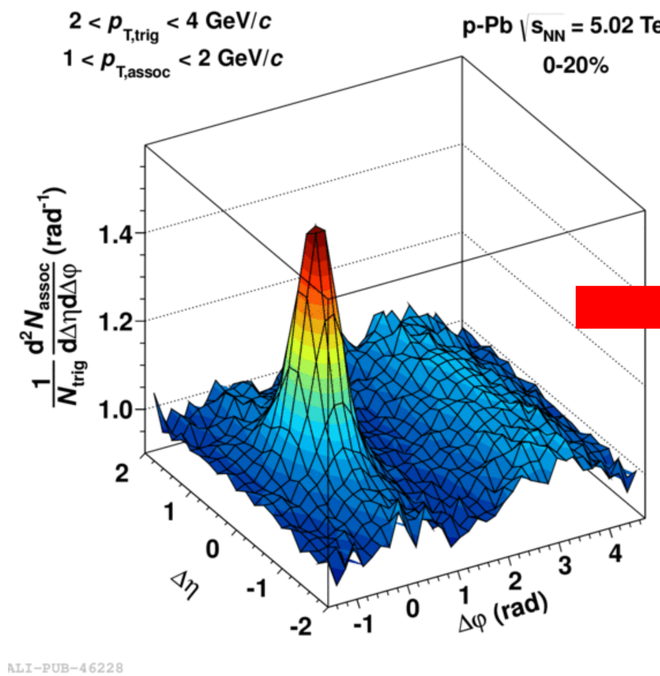
In PbPb, long-range correlations can be explained by flow harmonics (v_n)

In high-multiplicity p-Pb, a ridge develops

Extraction of double ridge structure in p-Pb

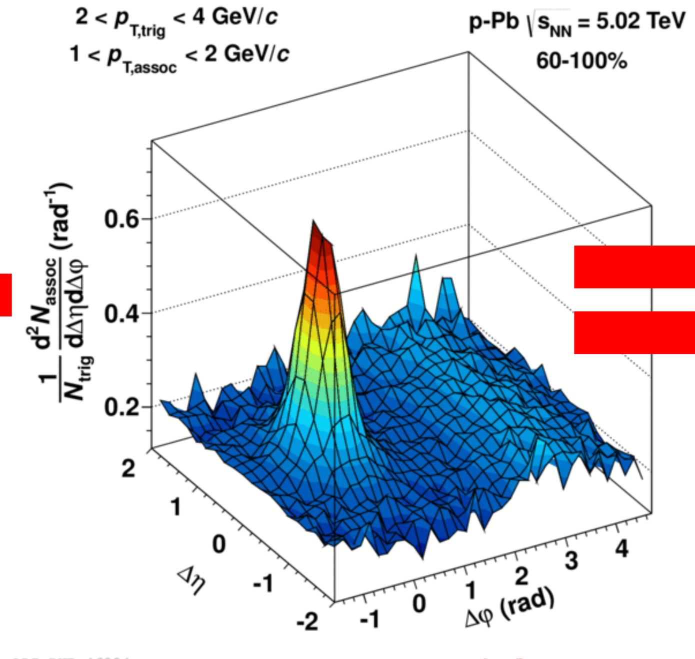
ALICE, PLB 719 (2013) 29

Difference between central and peripheral



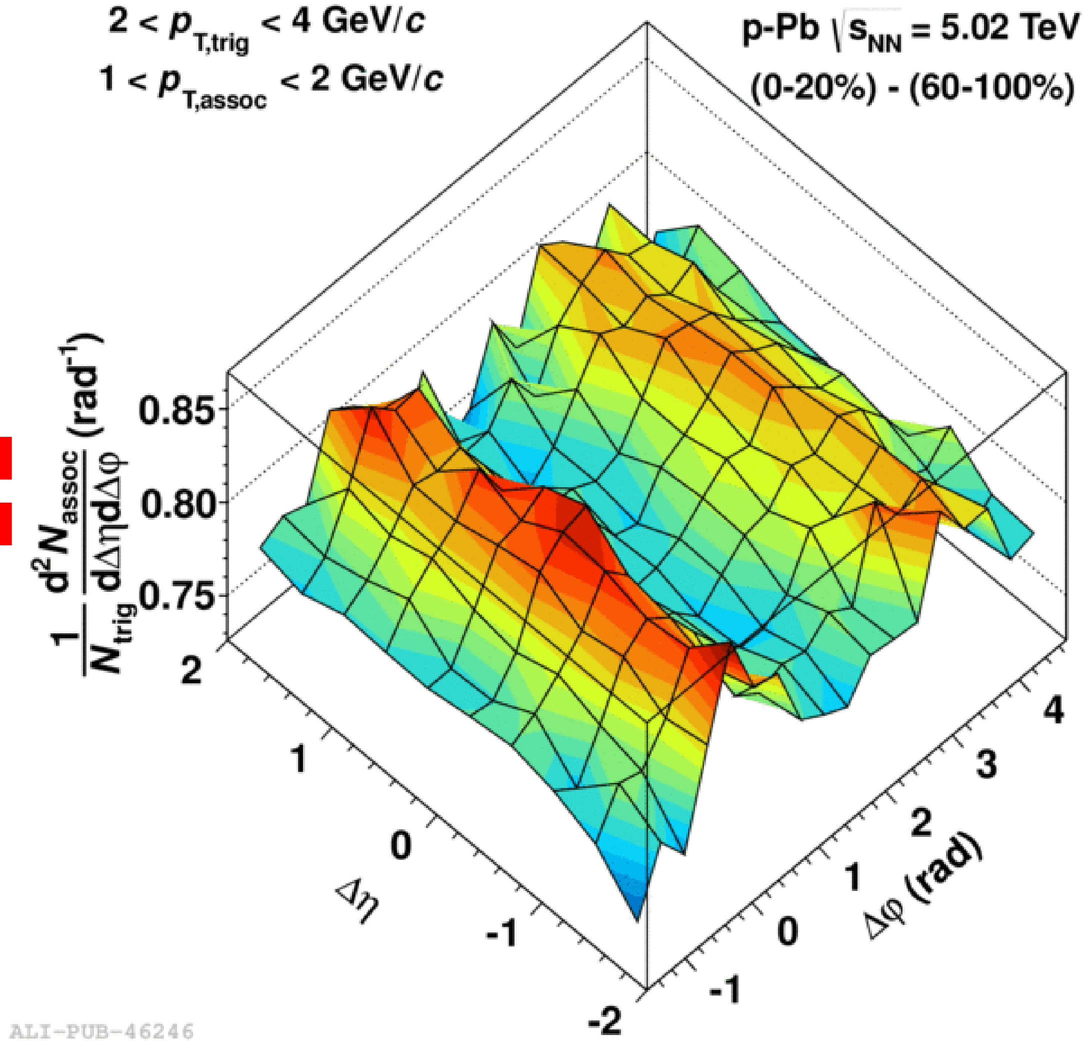
0-20%

−



60-100%

=



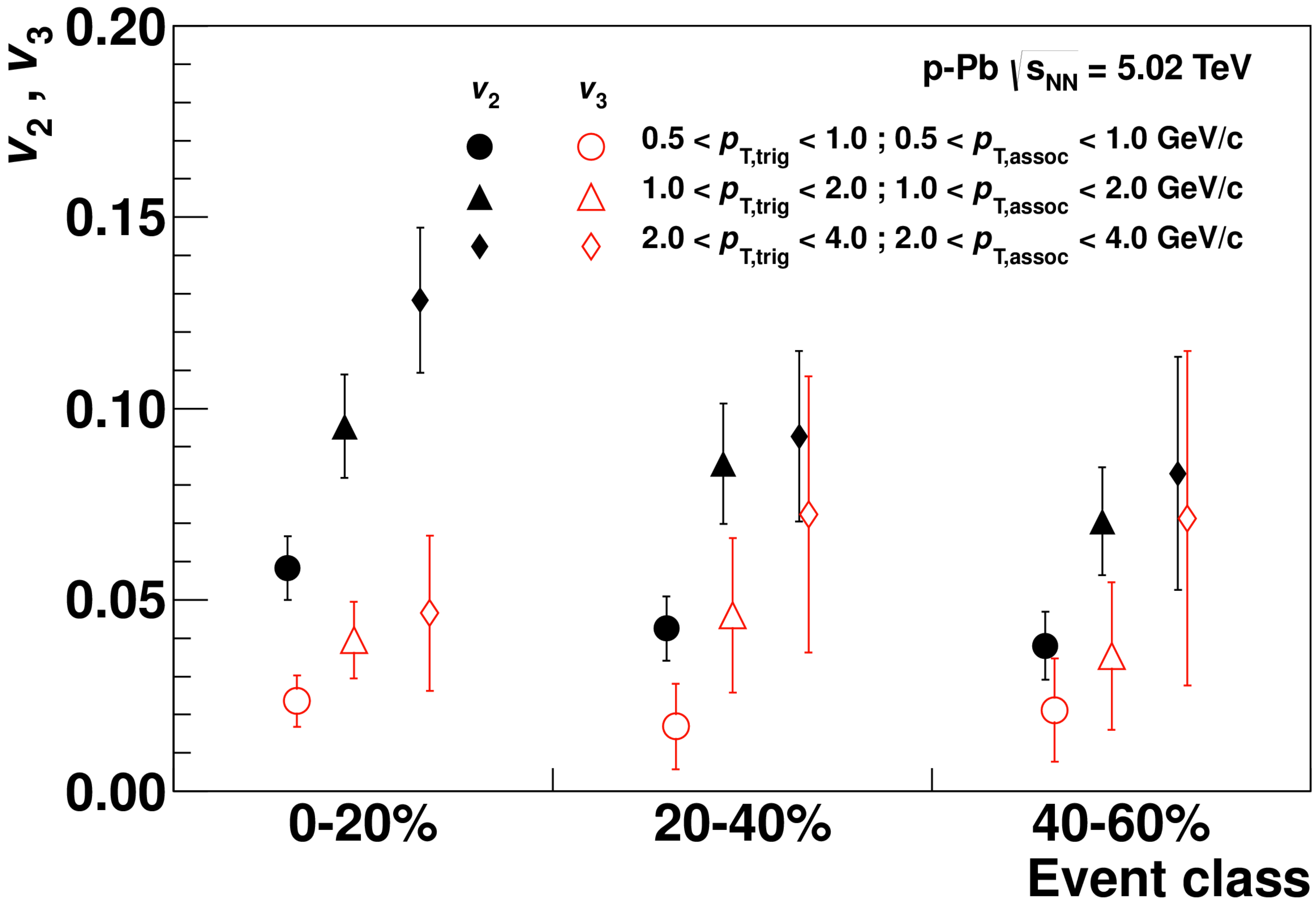
Extract double ridge structure by subtracting the jet-like correlations

It has been verified that the 60-100% class is similar to pp

The near-side ridge is accompanied by an almost identical ridge structure on the away-side

Properties of this double ridge

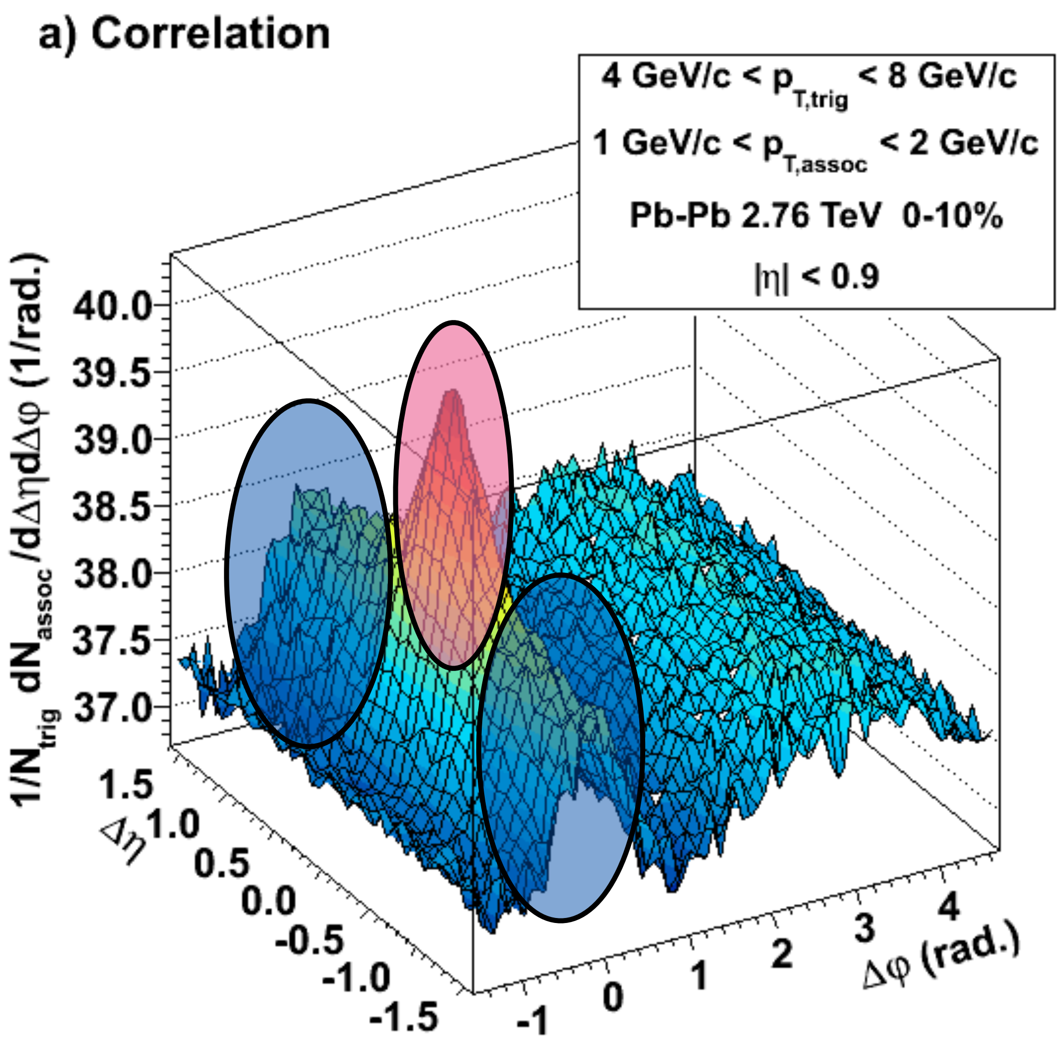
arXiv:1212.2001

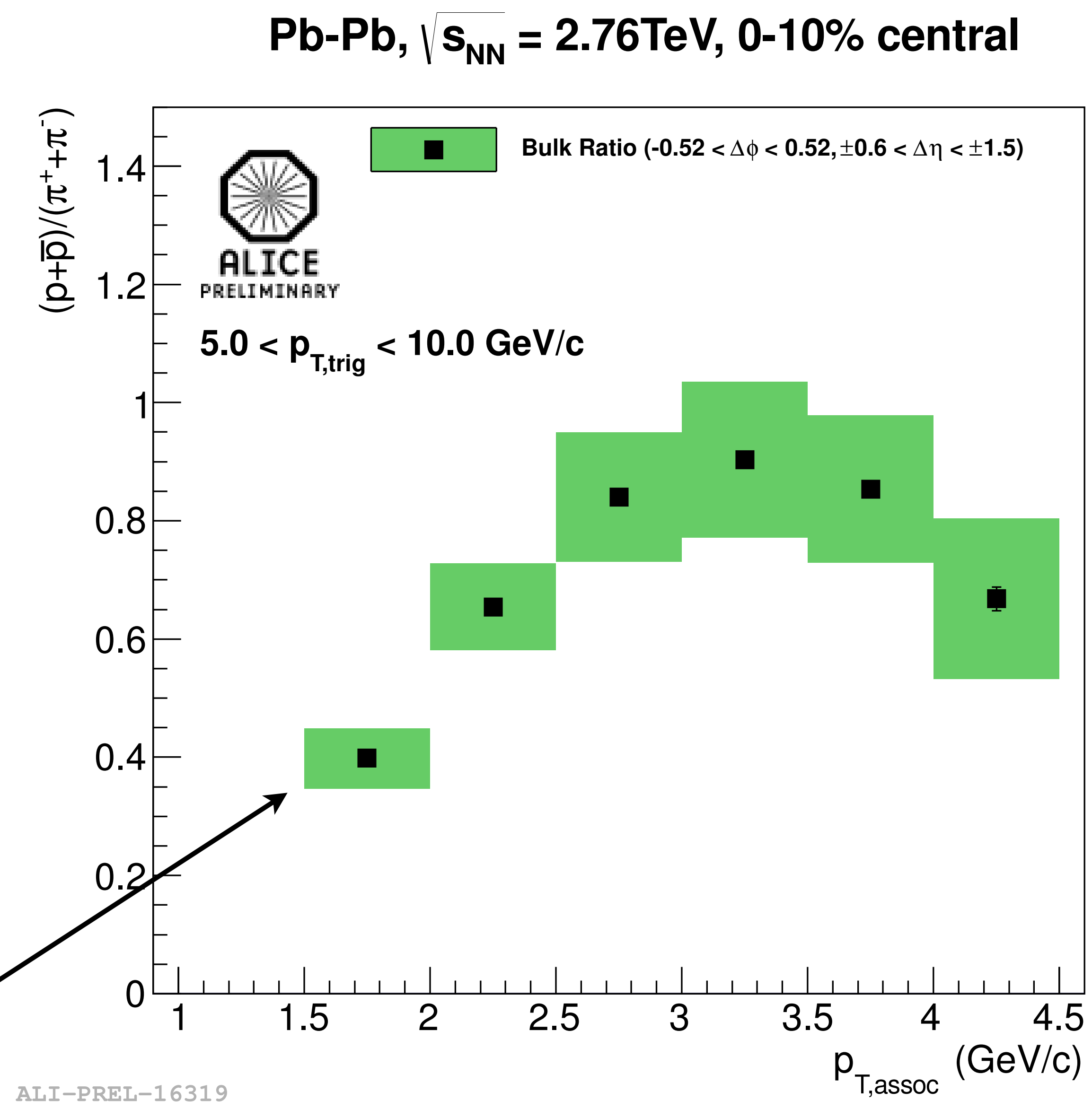


Fourier analysis of the ridge→v_2 and v_3 like flow: increase with p_T

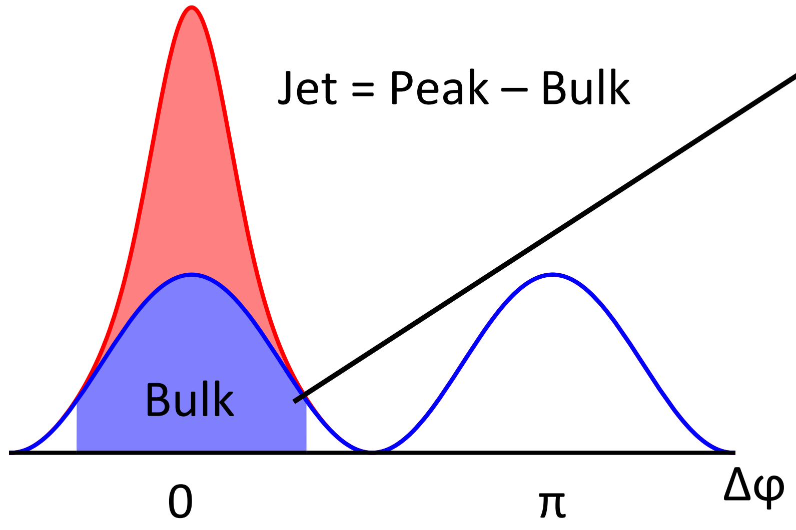
unlike flow: increase with centrality

Intermediate p_T in the bulk and in the jet

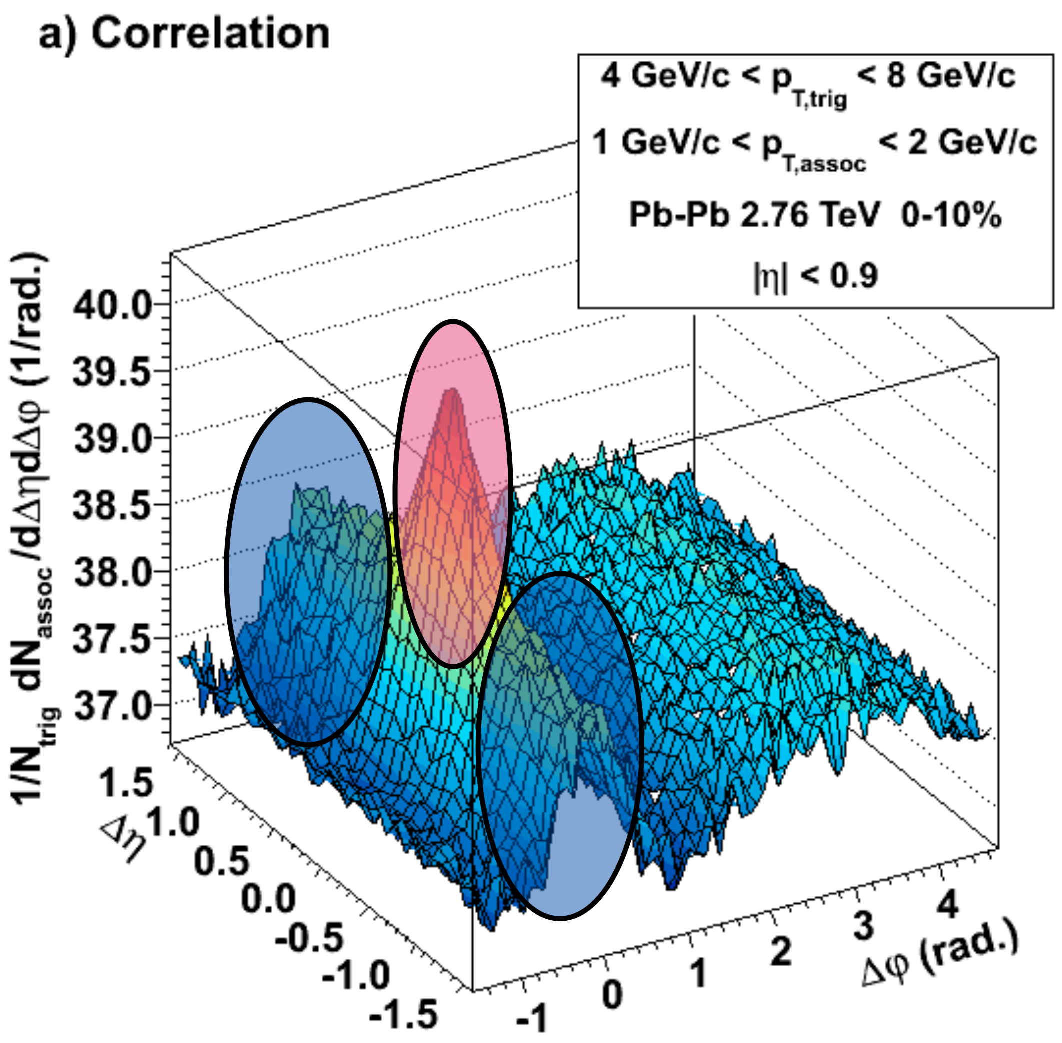

a) Correlation

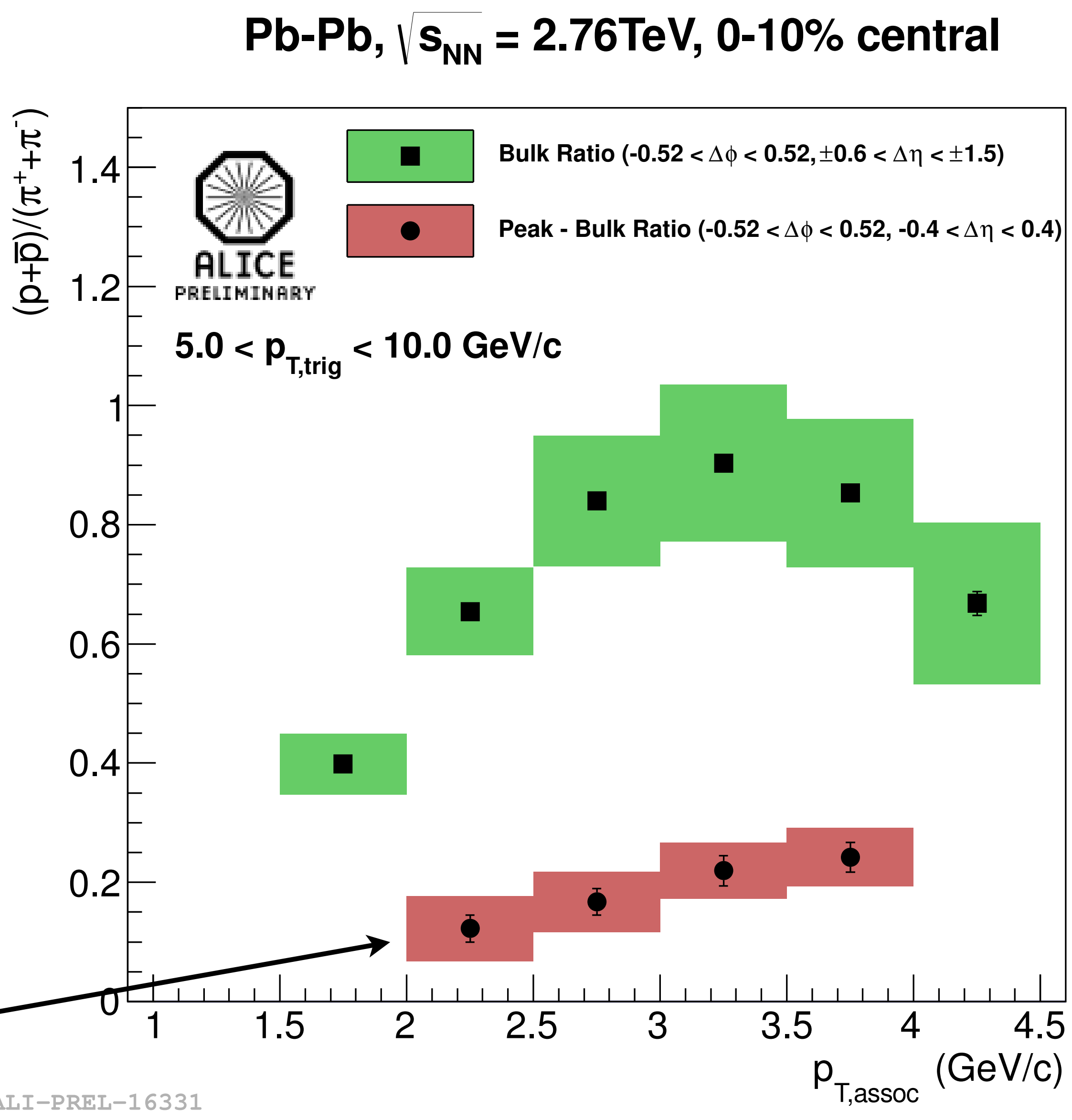

Pb-Pb, $\sqrt{s_{NN}}$ = 2.76TeV, 0-10% central

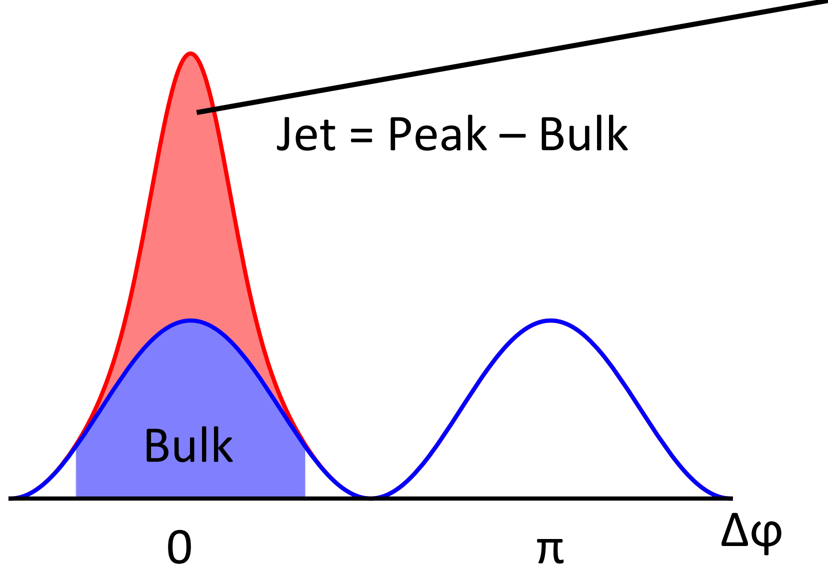
ALI-PREL-16319


Jet = Peak – Bulk

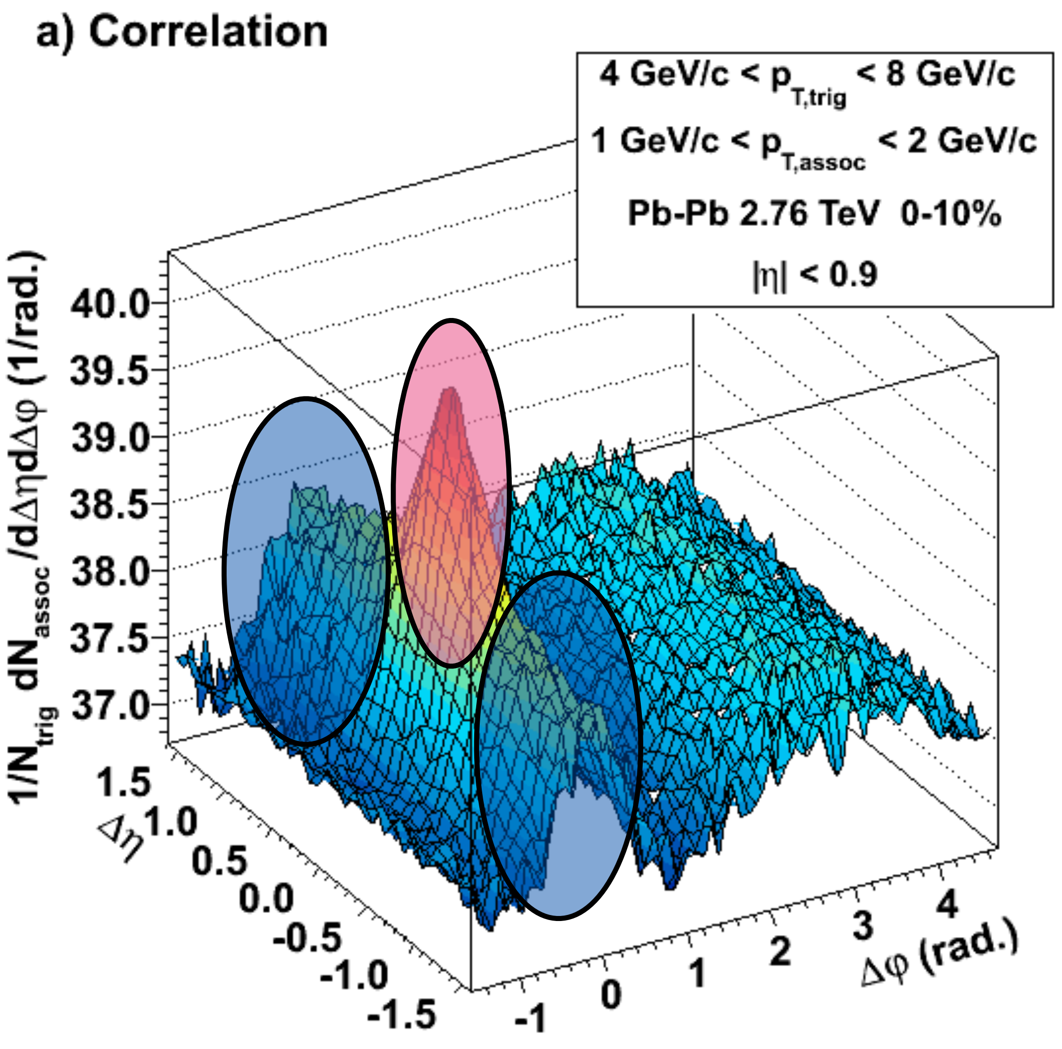
Intermediate p_T in the bulk and in the jet

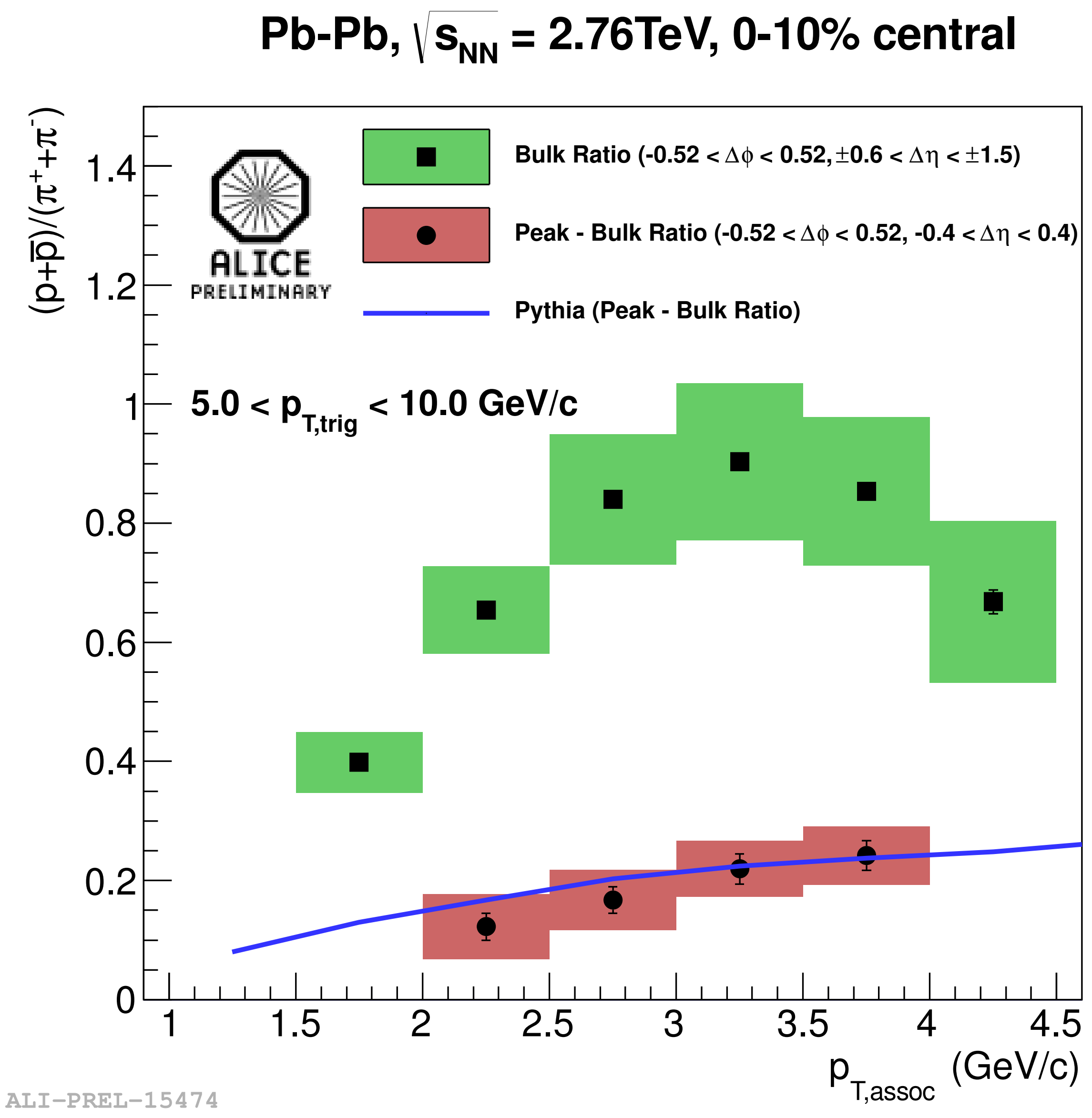


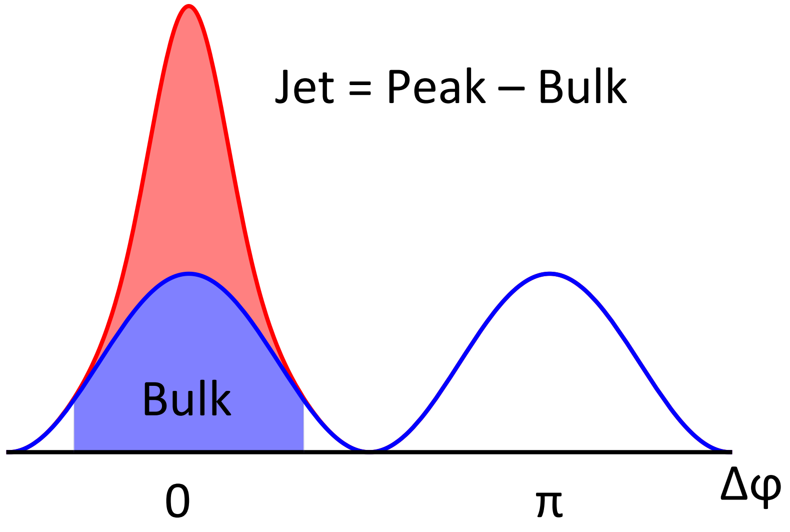




Intermediate p_T in the bulk and in the jet







Near-side peak (after bulk subtraction): p/π ratio compatible with that of pp (PYTHIA)

Bulk region: p/π ratio strongly enhanced – compatible with overall baryon enhancement

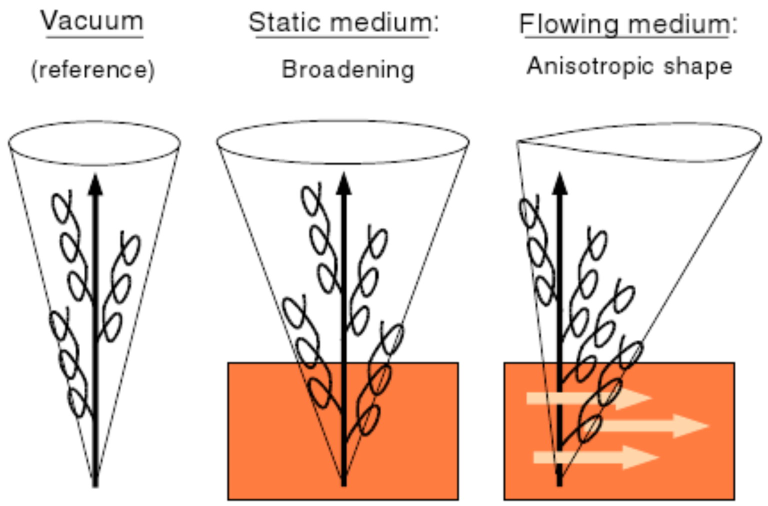
The “baryon anomaly” is a bulk effect!

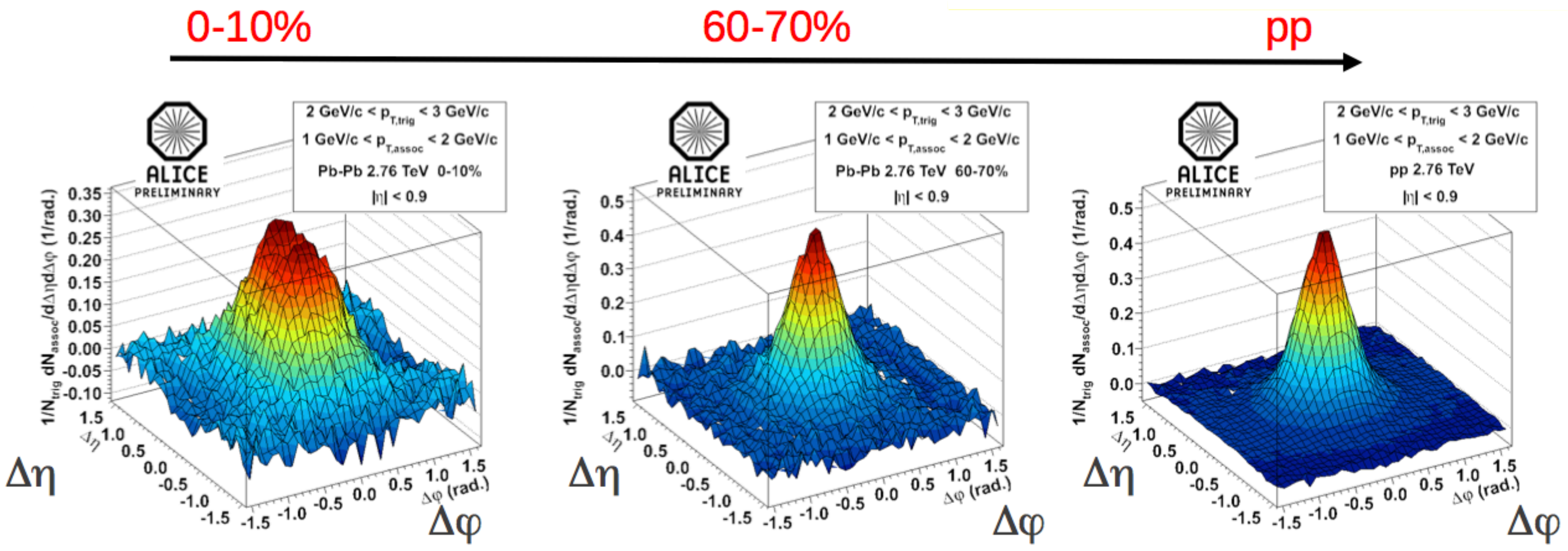
Jet particle ratios not modified in medium?

Could this still be surface bias?

Jet peak shape deformation

Can longitudinal flow deform the conical jet shape?
(Armesto et al, PRL 93, 242301 (2004))





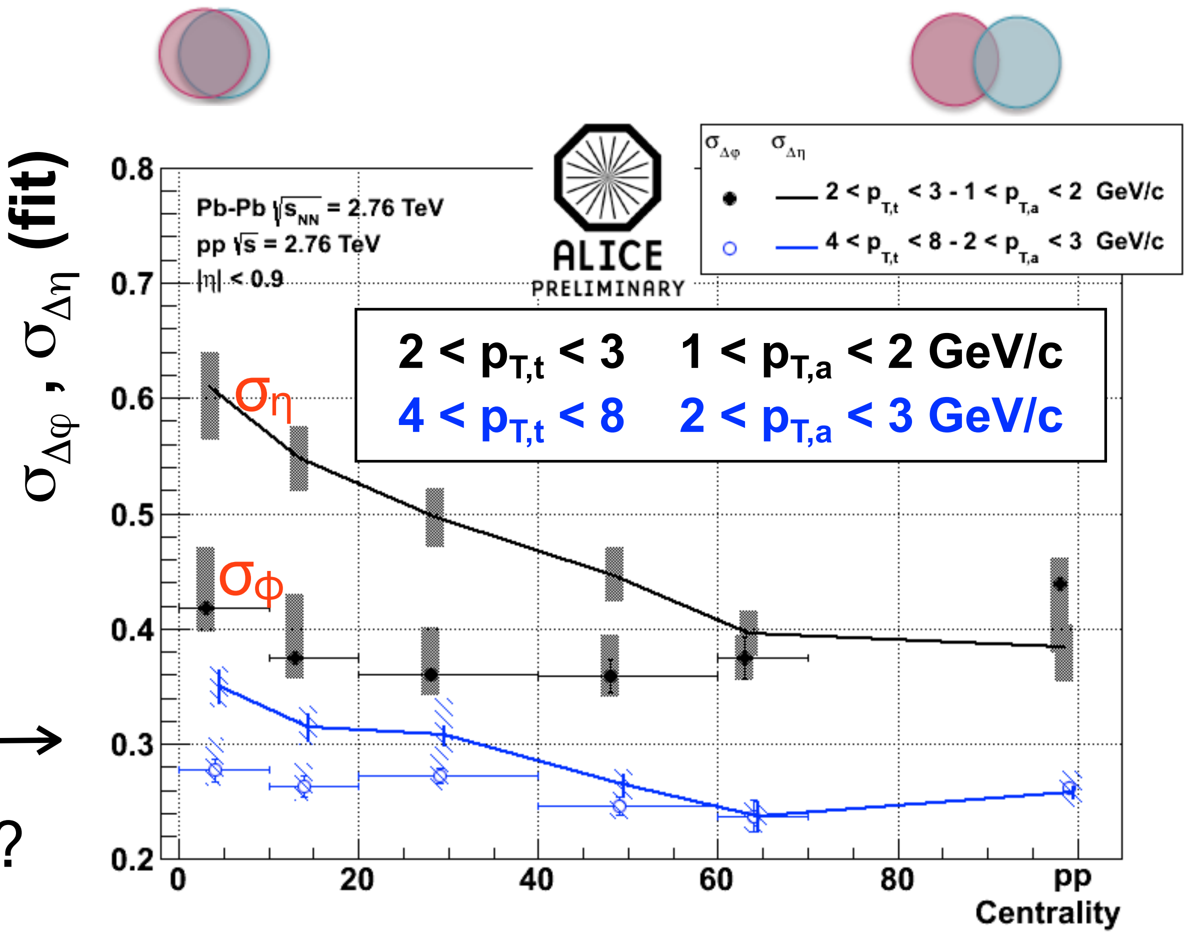
Jet peak shape deformation

Can longitudinal flow deform the conical jet shape?
(Armesto et al, PRL 93, 242301 (2004))

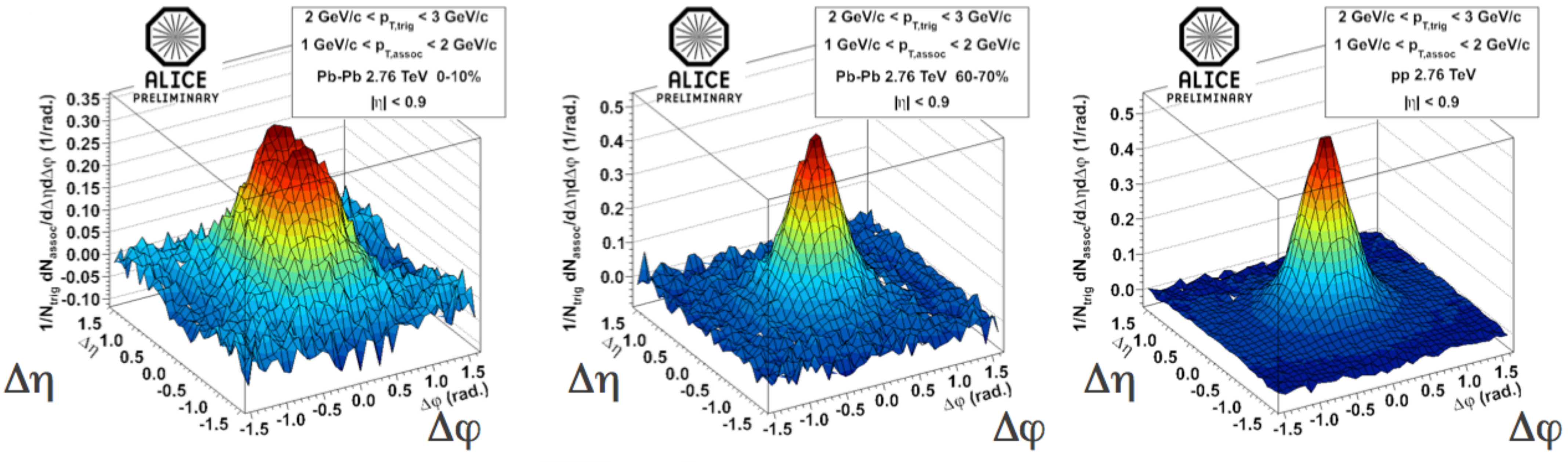
Significant increase of $\sigma_{\Delta\eta}$ towards central events

Evolution of near-side-peak σ_η and σ_ϕ with centrality →

Influence of flowing medium?



0-10% → 60-70% → pp



Summary

New insight into the reaction dynamics from LHC

- Mach cone and ridge challenged
- proton puzzle: lower yield, lower v_2 than expected
- nuclear suppression decreasing at very high pt (R_{AA} increasing)
- J/Psi production via statistical regeneration
- ridges in high-multiplicity pp and p-Pb collisions

~2 x higher than at RHIC

- particle production
- homogeneity volume

~10-30% higher than at RHIC

- transverse flow
- mean transverse momentum
- integrated elliptic flow
- mass-splitting of v_2

Like at RHIC

- centrality dependence of particle production
- centrality dependence of v_2
- transverse momentum dependence of v_2

Thank you for your attention!

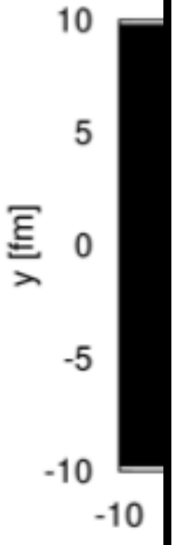
Backup

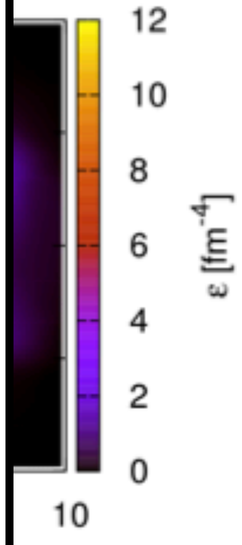
- The goal of ultra-relativistic nucleus–nucleus collisions is to study nuclear matter under extreme conditions. For non-central collisions, in the plane perpendicular to the beam direction, the geometrical overlap region, where the highly Lorentz contracted nuclei intersect and where the initial interactions occur, is azimuthally anisotropic. This initial spatial asymmetry is converted via interactions into an anisotropy in momentum space, a phenomenon referred to as transverse anisotropic flow (for a review see [1]). Anisotropic flow has become a key observable for the characterization of the properties and the evolution of the system created in a nucleus–nucleus collision.

- The models shown in Figs. 13, 14, and 15 give for central collisions a fair description of the data. In the region p_T ≲ 3 GeV/c (Kraków [46]), p_T ≲ 1.5 GeV/c (HKM[47]) and p_T ≲ 3 GeV/c (EPOS [48], with the exception of protons which are underestimated by about 30% at low p_T), the models describe the experimental data within ~20%, supporting a hydrodynamic interpreta- tion of the p_T spectra in central collisions at the LHC. VISH2+1[49] is a viscous hydrodynamic model that reproduces fairly well the pion and kaon distributions up to $p_T \sim$ 2 GeV/c, but it misses the protons, both in shape and absolute abundance in all centrality bins. In this version of the model the yields are thermal, with a chemical temperature $T_{ch} = 165$ MeV, extrapolated from lower energies. The difference between VISH2+1 and the data are possibly due to the lack of an explicit description of the hadronic phase in the model. This idea is supported by the comparison with HKM [47, 50]. HKM is a model similar to VISH2+1, in which after the hy- drodynamic phase particles are injected into a hadronic cascade model (UrQMD), which further transports them until final decoupling. The hadronic phase builds up additional radial flow and affects particle ratios due to the hadronic interactions. As can be seen, this model yields a better description of the data. The protons at low p_T, and hence their total number, are rather well reproduced, even if the slope is significantly smaller than in the data. Antibaryon-baryon anni- hilation is an important ingredient for the description of particle yields in this model [47, 50]. The Kraków [51, 52] model, on the other hand, uses an ansatz to describe deviation from equi- librium due to viscous corrections at freeze-out, which seems successful in reproducing the data. A general feature of these models is that, going to more peripheral events, the theoretical curves deviate from the data at high p_T (Figs. 14 and 15). This is similar to what is observed in the comparison to the blast-wave fits, and shows the limits of the hydrodynamical models. As speculated in [46], this could indicate the onset of a non-thermal (hard) component, which in more peripheral collisions is not dominated by the flow-boosted thermal component. This picture is further substantiated by the change in the local slopes as seen in Fig. 6.

The EPOS (2.17v3) model [48] aims at describing all p_T domains with the same dynamical picture. In this model, the initial hard scattering creates "flux tubes" which either escape the medium and hadronize as jets, or contribute to the bulk matter, described in terms of hydrodynamics. After hadronization, particles are transported with a hadronic cascade model (UrQMD). EPOS shows a good agreement with the data for central and semi-central collisions. A calcu- lation done with the same model, but disabling the late hadronic phase, yields a significantly worse description [48], indicating the important role of the late hadronic interactions in this model. An EPOS calculation for peripheral collisions was not available at the time of writing, but it will be important to see how well the peripheral data can be described in this model, since it should include all relevant physics processes. Several other models implementing similar ideas (hydrodynamics model coupled to a hadronic cascade code, possibly with a description of fluctuations in the initial condition) are available in the literature [53, 54] but not discussed in this paper. The simultaneous description of additional variables, such as the v_n azimuthal flow coefficients within the same model, will help in differentiating different hydrodynamical model scenarios.

Figure 16 shows the $p/\pi = (p + \bar{p})/(\pi^+ + \pi^-)$ and $K/\pi = (K^+ + K^-)/(\pi^+ + \pi^-)$ ratios as a function of p_T. Both ratios are seen to increase as a function of centrality at intermediate p_T with a corresponding depletion at low p_T (the p_T integrated ratios show little dependence on centrality, Fig. 9). The p/π ratio, in particular, shows a more pronounced increase, reaching a value of about 0.9 at $p_T = 3$ GeV/c. This is reminiscent of the increase in the baryon-to- meson ratio observed at RHIC in the intermediate p_T region [19, 55], which is suggestive of the recombination picture after 6 fm/c

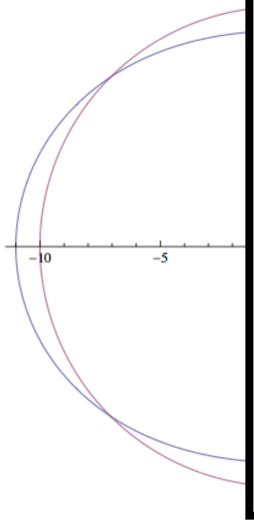


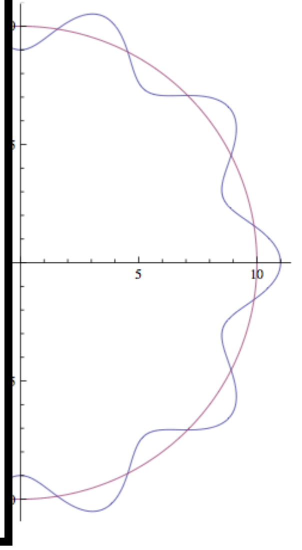


Understand initial conditions and fluctuations; measure the transport properties (e.g. η/s) of the medium

Observables:

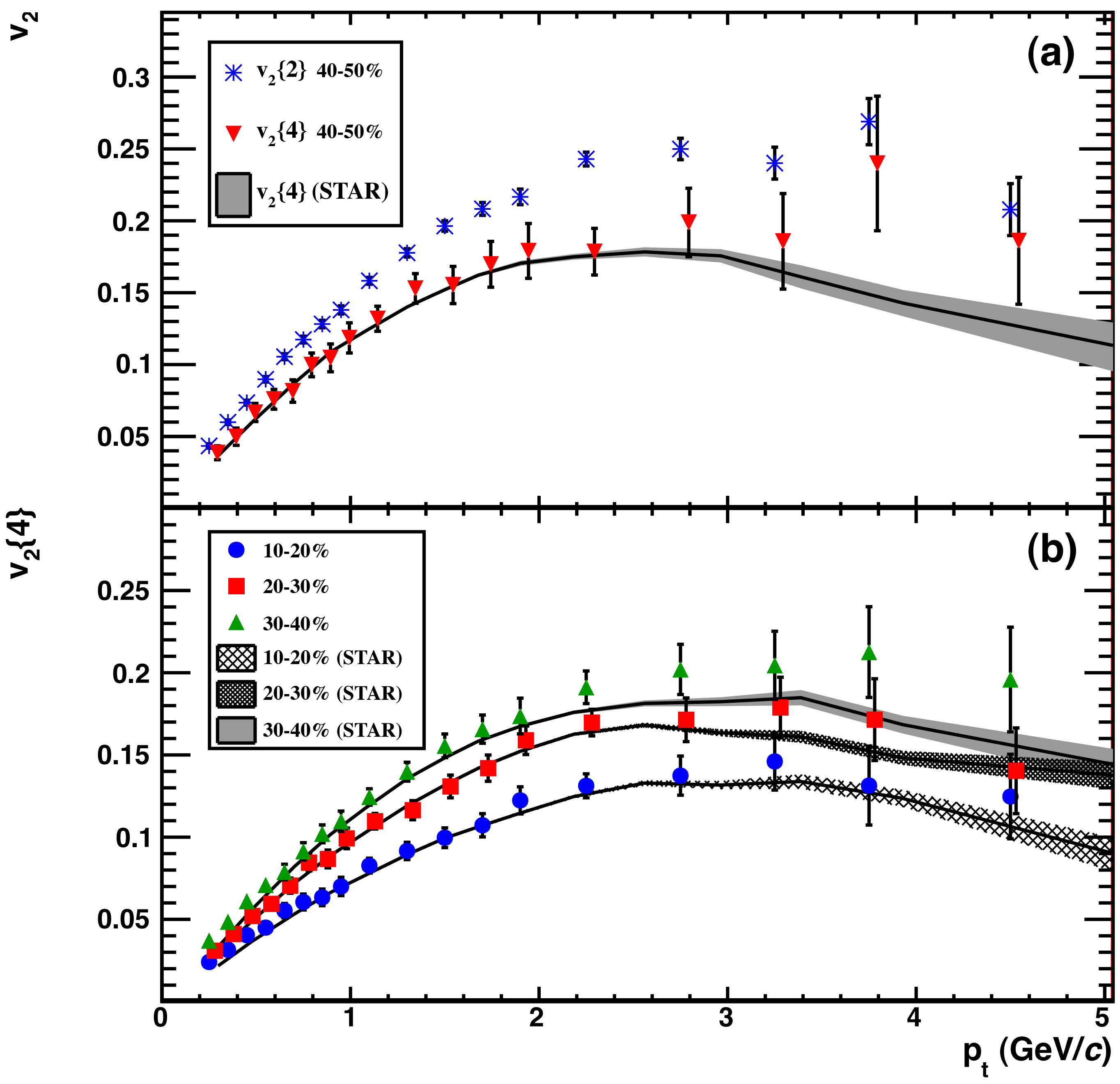
Higher harmonics
Event by Event fluctuation
Studies as a function of EbyE flow
Event plane correlations
Ultra central events





S Jeon et al, QM 2012, B. Schenke, et al. PRL106, 042301 (2011)

Elliptic flow



PRL 105 (2010) 252302

- same p_T dependence as at RHIC (and below, down to 40 GeV!)
- inclusive v_2 at LHC higher only because $\langle p_T \rangle$ higher

- Two-particle correlations are a powerful tool to explore the mechanism of particle production in collisions of hadrons and nuclei at high energy. Such studies involve measuring the distributions of relative angles $\Delta\varphi$ and $\Delta\eta$ between pairs of particles: a "trigger" particle in a certain transverse momentum $p_{\mathrm{T,trig}}$ interval and an "associated" particle in a $p_{\mathrm{T,assoc}}$ interval, where $\Delta\varphi$ and $\Delta\eta$ are the differences in azimuthal angle φ and pseudorapidity η between the two particles.

In proton–proton (pp) collisions, the correlation at ($\Delta\varphi \approx 0$, $\Delta\eta \approx 0$) for $p_{\mathrm{T,trig}} > 2$ GeV/c is dominated by the "near-side" jet peak, where trigger and associated particles originate from a fragmenting parton, and at $\Delta\varphi \approx \pi$ by the recoil or "away-side" jet [1]. The away-side structure is elongated along $\Delta\eta$ due to the longitudinal momentum distribution of partons in the colliding protons. In nucleus–nucleus collisions, the jet-related correlations are modified and additional structures emerge, which persist over a long range in $\Delta\eta$ on the near side and on the away side [2–14]. The shape of these distributions when decomposed into a Fourier series defined by v_n coefficients [15] is found to be dominated by contributions from terms with $n = 2$ and $n = 3$ [6,7,9–14]. The v_n coefficients are sensitive to the geometry of the initial state of the colliding nuclei [16,17] and can be related to the transport

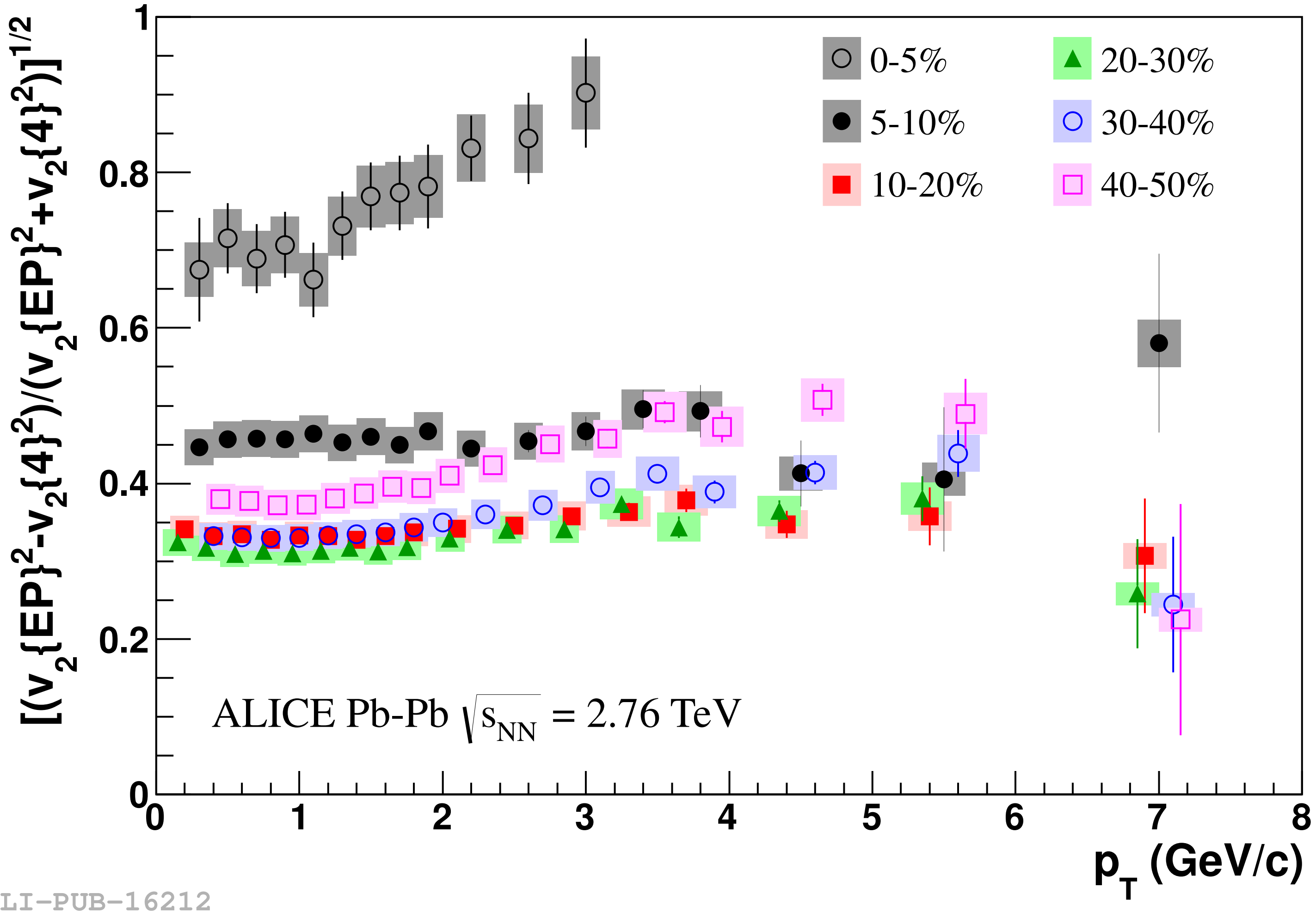
- properties of the strongly-interacting de-confined matter via hydrodynamic models [18–20].

Recently, measurements in pp collisions at a centre-of-mass energy $\sqrt{s} = 7$ TeV [21] and in proton–lead (p–Pb) collisions at a nucleon–nucleon centre-of-mass energy $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [22] have revealed long-range ($2 < |\Delta\eta| < 4$) near-side ($\Delta\varphi \approx 0$) correlations in events with significantly higher-than-average particle multiplicity. Various mechanisms have been proposed to explain the origin of these ridge-like correlations in high-multiplicity pp and p–Pb events. These mechanisms include colour connections forming along the longitudinal direction [23–26], jet-medium [27] and multi-parton induced [28,29] interactions, and collective effects arising in the high-density system possibly formed in these collisions [30–35]. $\sqrt{}$

-

v_2 Fluctuations

$\propto \sigma_{v_2}/\langle v_2\rangle$ for small flow



5–30% centrality, relative flow fluctuations independent of momentum up to $p_T \sim 8$ GeV/c

Common origin for flow fluctuations (fluctuations of the initial collision geometry)?

ALICE, PLB 719 18 (2013)

See also: ATLAS-CONF-2012-118

Summary

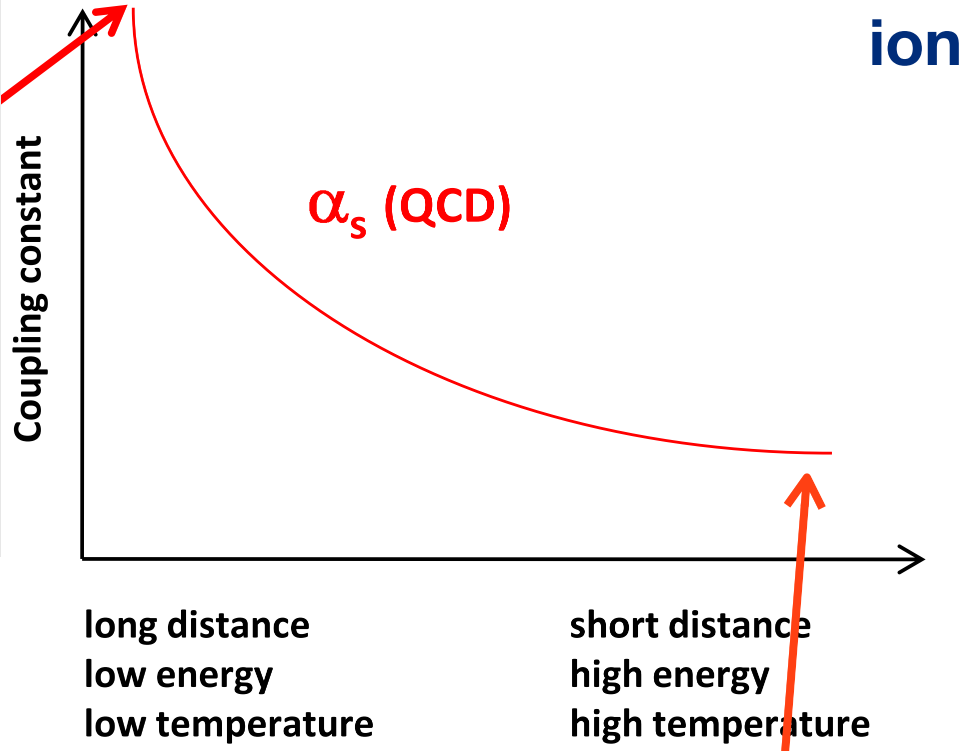
- Soft Particle Production, Flow and Correlations Observables: essential information on system
- Hydrodynamics describes the evolution of the system
- Initial conditions and Fluctuations play crucial role: progress in understanding of initial conditions
- Late hadronic phase (potentially) affects the observables
- Many new results from the LHC experiments: accessing precision measurement of properties of deconfined matter

QCD: Running coupling constant (α_s)

Confinement

At long distance : strength between quarks become stronger. quarks cannot be separate and they are bound into hadrons

⇒ **Not possible to observe free quarks**



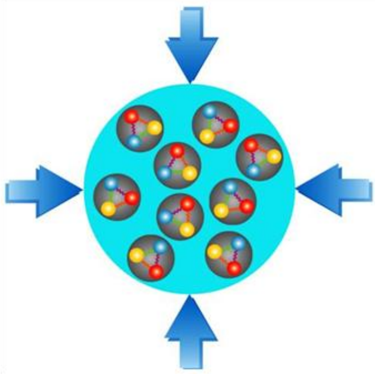
Nobel prize 2004
Gross, Politzer, Wilczek

Asymptotic freedom

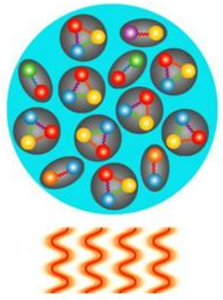
At short distance : interactions become weak quarks can be considered as free in hadrons

⇒ **QCD predict the creation of a deconfined state of the matter called : Quark Gluon Plasma (QGP)**

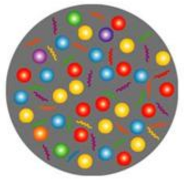
If we can compress and/or increase the temperature of heavy ions, quarks can be deconfined



Compression:
Nucleons will overlap themselves and lose their identity



Heating:
QCD vacuum is thermally excited, and above a critical temperature quarks are deconfined



Quark Gluon Plasma

QCD Prediction: Estimation of the T of the Phase Transition

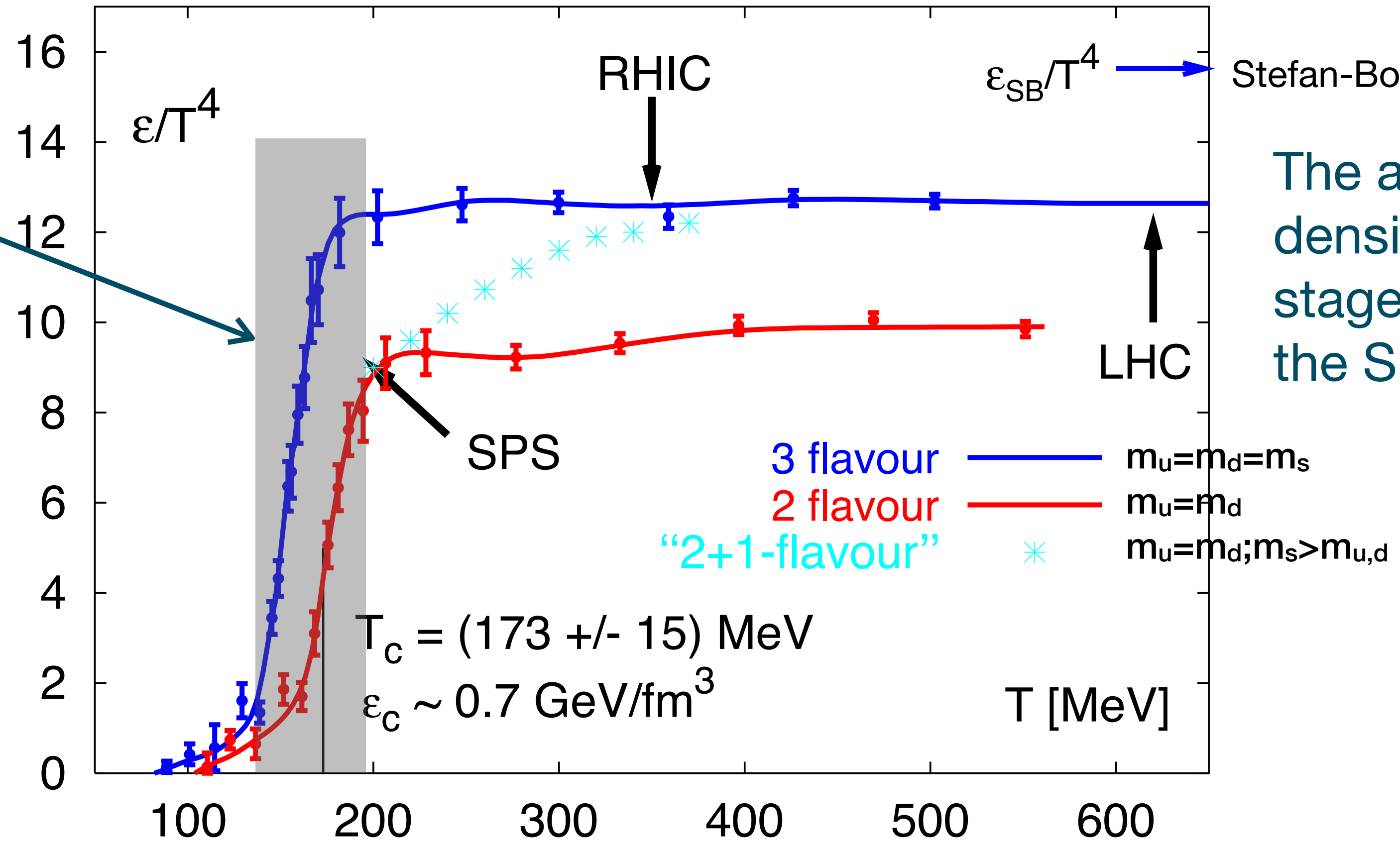
: Energy density related to the degree of freedom of the system

Hadron gas : degree of freedom of pions
QGP : degree of freedom of quarks (3 colors for each flavour) + gluons (8 colors)

Lattice QCD calculation

Sharp increase of energy density

Phase transition from Hadron gas to QGP at $T=T_c \sim 170$ MeV



Stefan-Boltzmann limit for a gas of free particles

The arrows indicating the energy densities reached in the initial stage of heavy ion collisions at the SPS, RHIC and LHC

F. Karsch and E. Laermann
hep-lat:0305025

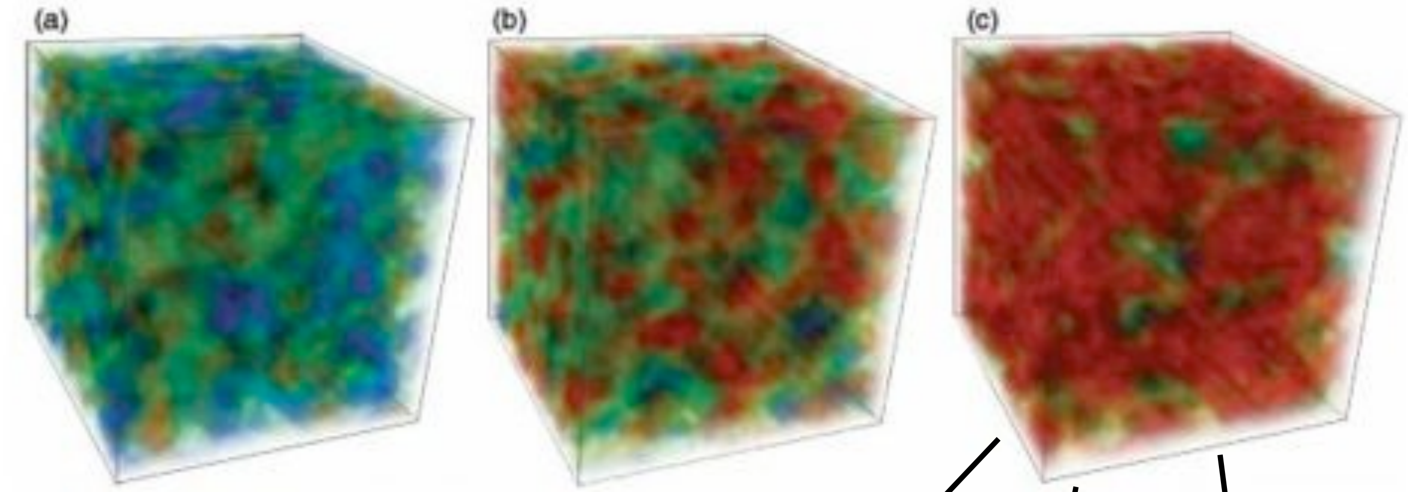
Temperature ~ 170 MeV (~ 10^{12} K)

Lattice QCD: rigorous way of doing calculations in non-perturbative regime of QCD discretization on a space-time lattice

QGP is a New State of Matter

Atomic property: we see in everyday world

Lattice QCD simulation



A lattice quantum chromodynamics (QCD) simulation shows when matter is heated to about 170 megaelectronvolts, or about 2 trillion degrees, it melts into a quark–gluon plasma. (a) Protons, neutrons, and other nuclear particles exist below the transition temperature. (b) When the transition occurs, (c) a hot plasma emerges full of quarks and gluons. Blue indicates confined quarks, and red indicates deconfined quarks.

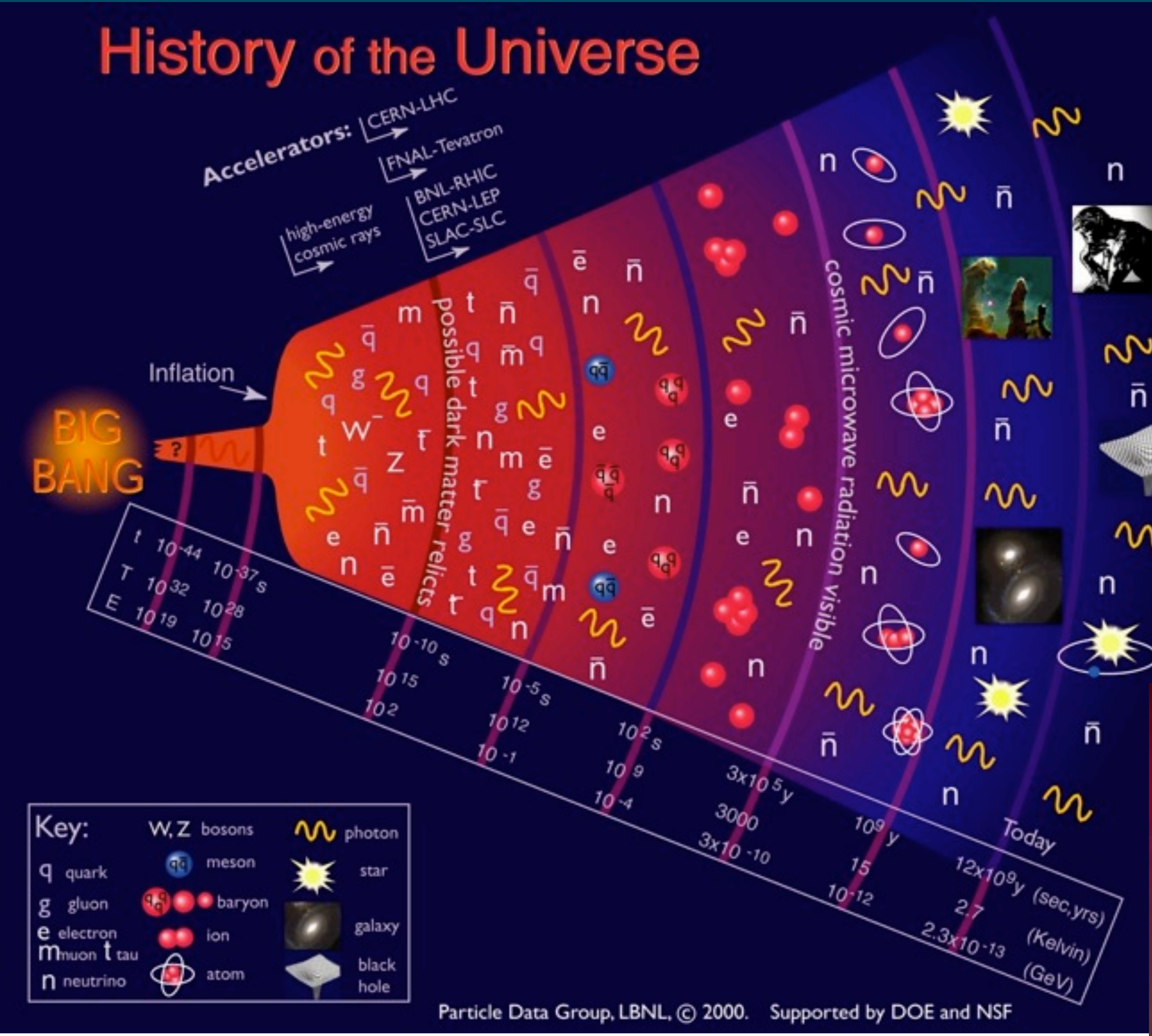
Gas?

Plasma?

Liquid?

Subatomic property

Theory for History of the Universe: Big Bang Theory



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

10^{-32} to 10^{-10}s, temperature decrease from 10^{27} to 10^{15}°C > T_C

Universe could be composed of a <<soup>> of quark and anti-quark = QGP

What are the property of the universe very early on?
How are they evolved into the matters in the current universe?
Answering to the origin of the matter composing the current universe...

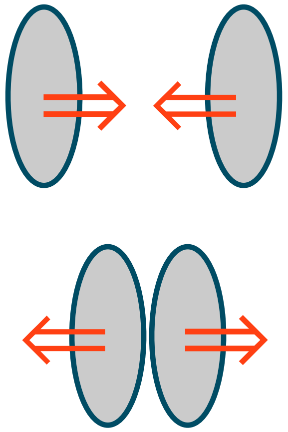
The QCD Phase Diagram

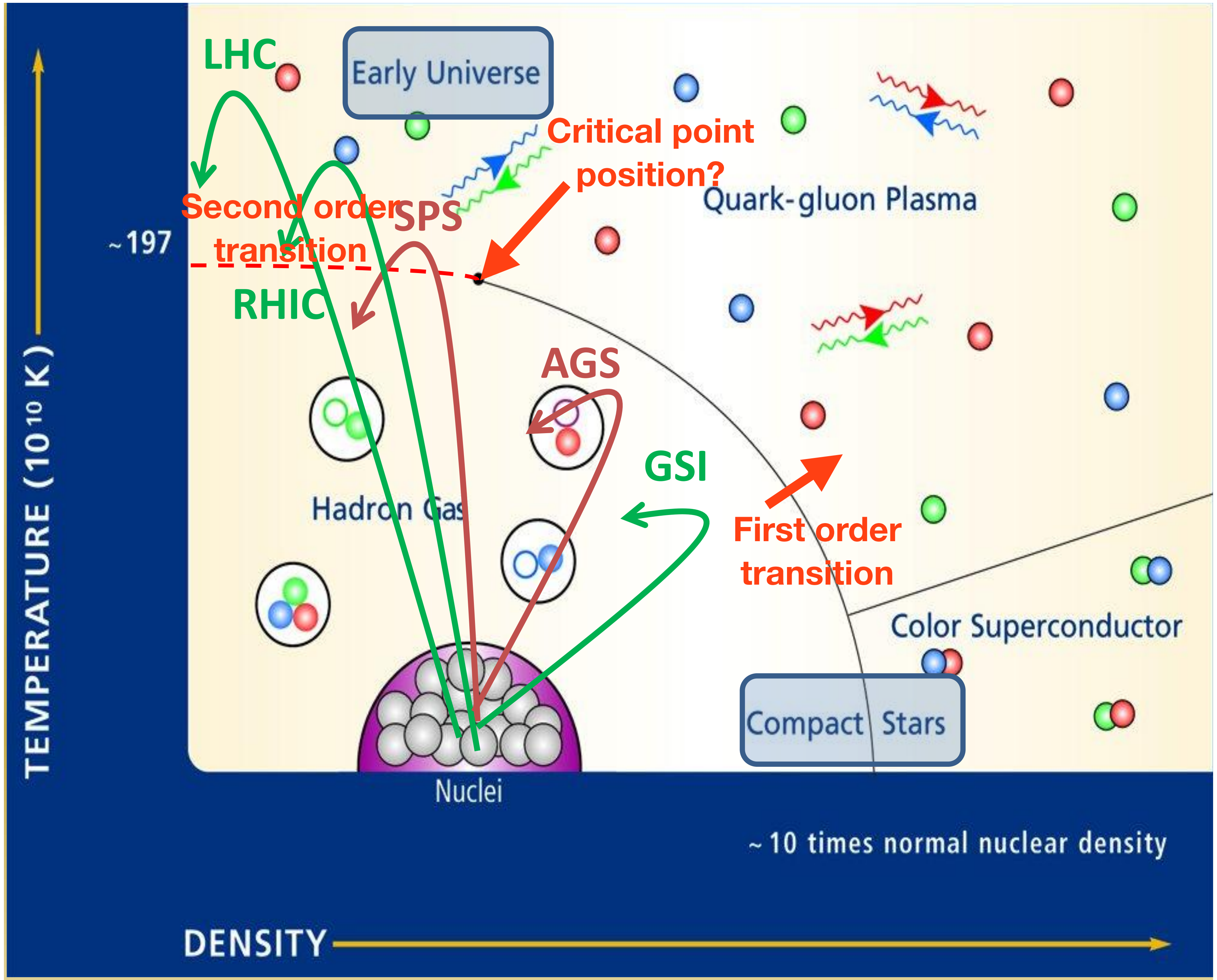
: Study how collective phenomena and macroscopic properties of strongly interacting matter emerge from fundamental interactions

Transparency important

⇓

Increase of the temperature at low density

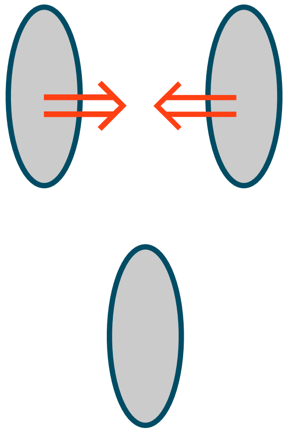




Stopping power important

⇓

Increase of the density

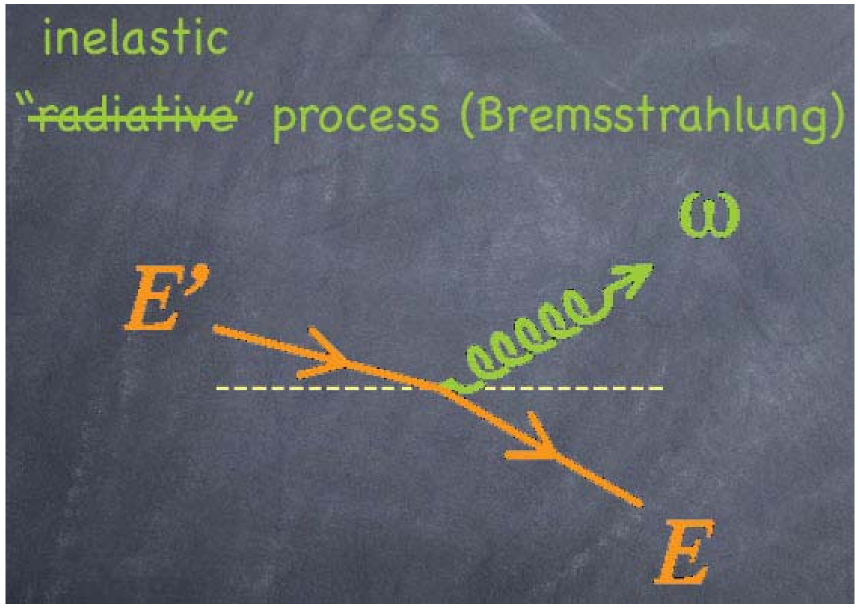


LHC: $\sqrt{s_{NN}}$ = 5.5 TeV, RHIC: $\sqrt{s_{NN}}$ = 200 GeV, SPS: $\sqrt{s_{NN}}$ = 17 GeV, AGS: $\sqrt{s_{NN}}$ = 4.5 GeV, GSI: $\sqrt{s_{NN}}$ = 2 GeV

What we observe: varies depending on the created matter property and interactions between the matter and parton

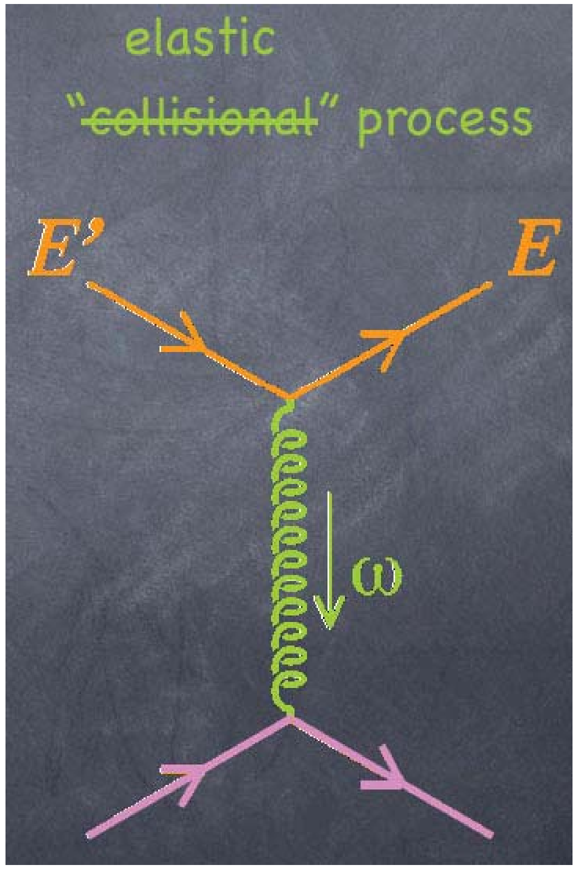
Models of high-p_T parton energy loss

Two different “categories” of models of parton energy loss, depending on the basic underlying process:



Theories and models of radiative energy loss

- **LPM-effect based approaches: BDMPS-Z & AMY**
- **Opacity expansion: GLV; (AS)W**
- **Medium-enhanced higher-twist effects**
- **Medium-modified MLLA**



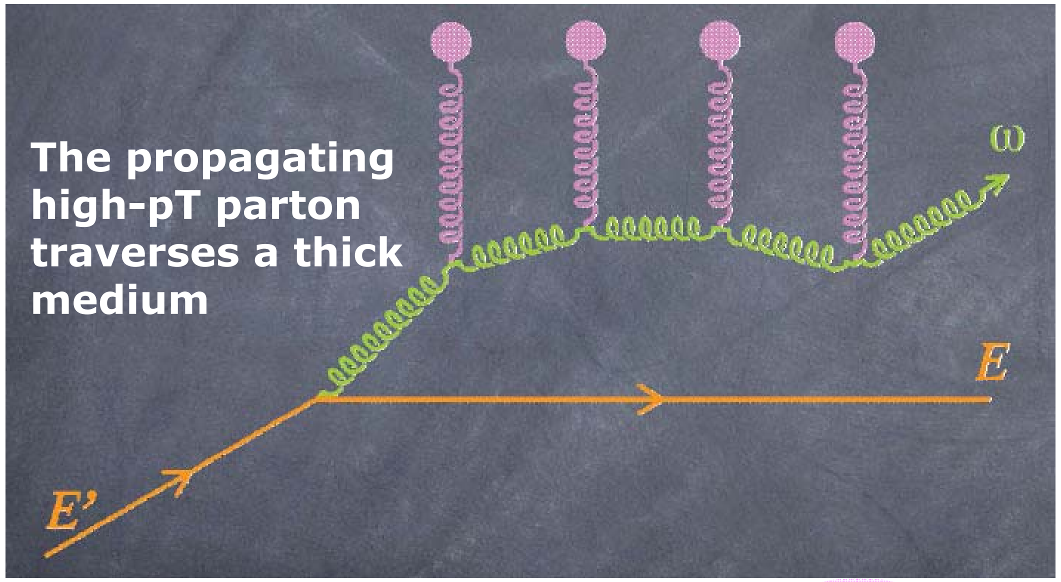
Theories and models of collisional energy loss

- **Regards as negligible!**
- **BUT => it is sizable?**

Example of Energy Loss Model

Energy loss by multiple soft scattering

: Models based on the Landau-Pomeranchuk-Migdal effect



It radiates soft gluons, which scatter coherently on independent color charges in the medium, resulting in a medium-modified gluon energy spectrum

Medium properties can be characterized by a single constant : BDMPS, AMY

e.g. transport coefficient $\hat{q} \equiv \frac{\mu^2}{\lambda}$ ‘average k_T-kick per mean-free-path’

$$\omega \frac{dI_{LPM}}{d\omega dz} = \left(\frac{\lambda}{l_{coherent}} \right) \omega \frac{dI_{\text{Bethe Heitler}}}{d\omega dz} = \sqrt{\frac{\hat{q}}{\omega}} \frac{\alpha_S N_C}{\pi}$$

: Gluon radiation spectrum

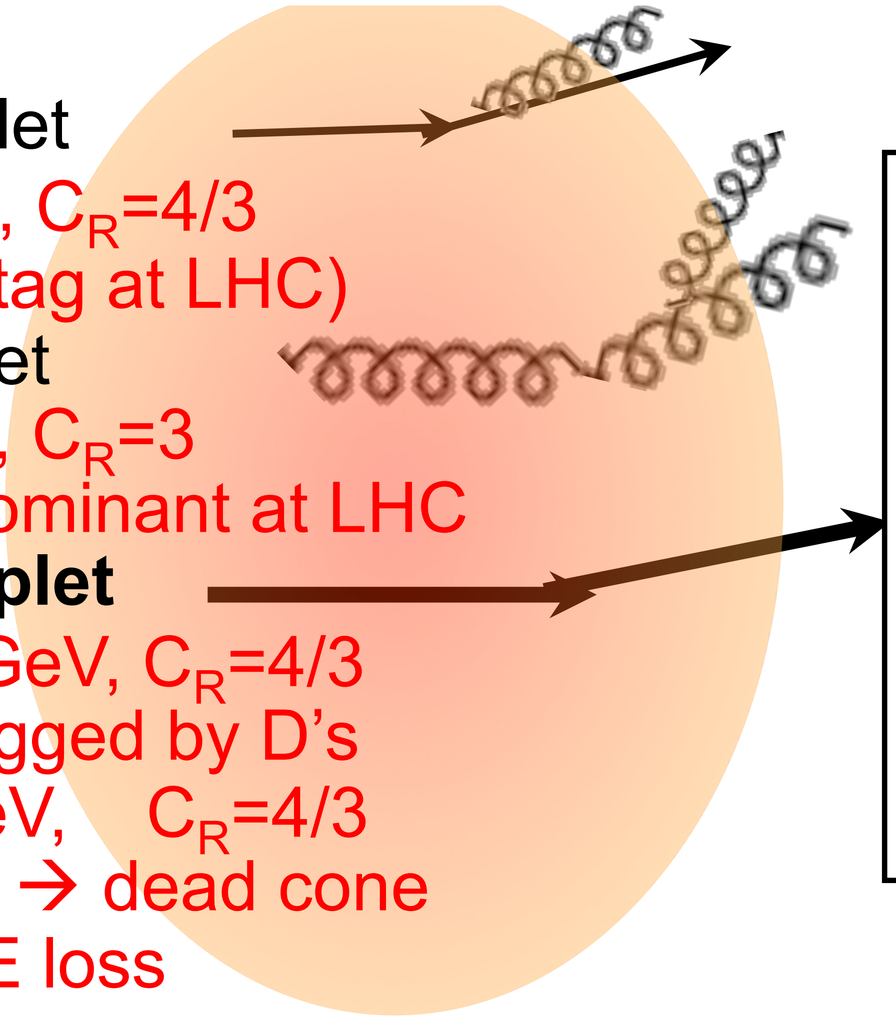
$$\Delta E_{med} = \int^{\boxed{L}} dz \int^{\boxed{\omega_C}} d\omega\, \omega \frac{dI_{LPM}}{d\omega dz} \sim \alpha_S \sqrt{\hat{q}\omega_C}\, L \sim \alpha_S \hat{q} \boxed{L^2}$$

$\Delta E \propto L^2$ for a static medium

Longitudinal expansion reduces $\Delta E \sim L^2$ to $\Delta E \sim L$

What I have been more interested in

Heavy quark energy loss mechanism in the created matter



q: colour triplet

u,d,s: m~0, C_R=4/3
(difficult to tag at LHC)

g: colour octet

g: m=0, C_R=3
> E loss, dominant at LHC

Q: colour triplet

c: m~1.5 GeV, C_R=4/3
small m, tagged by D's

b: m~5 GeV, C_R=4/3
large mass → dead cone
→ < E loss

'Quark Matter'

Color charge dependence of energy loss

$$\omega \frac{dI}{d\omega} \propto \alpha_s C_R f(\omega),$$

$$C_R = 3(4/3)\ \ for\ g(q)$$

$$\Delta E(\varepsilon_{medium}; C_R, m, L)$$

Prediction: $\Delta E_g > \Delta E_{c\approx q} > \Delta E_b$

Need to measure heavy quark energy loss compare to that of light partons in medium

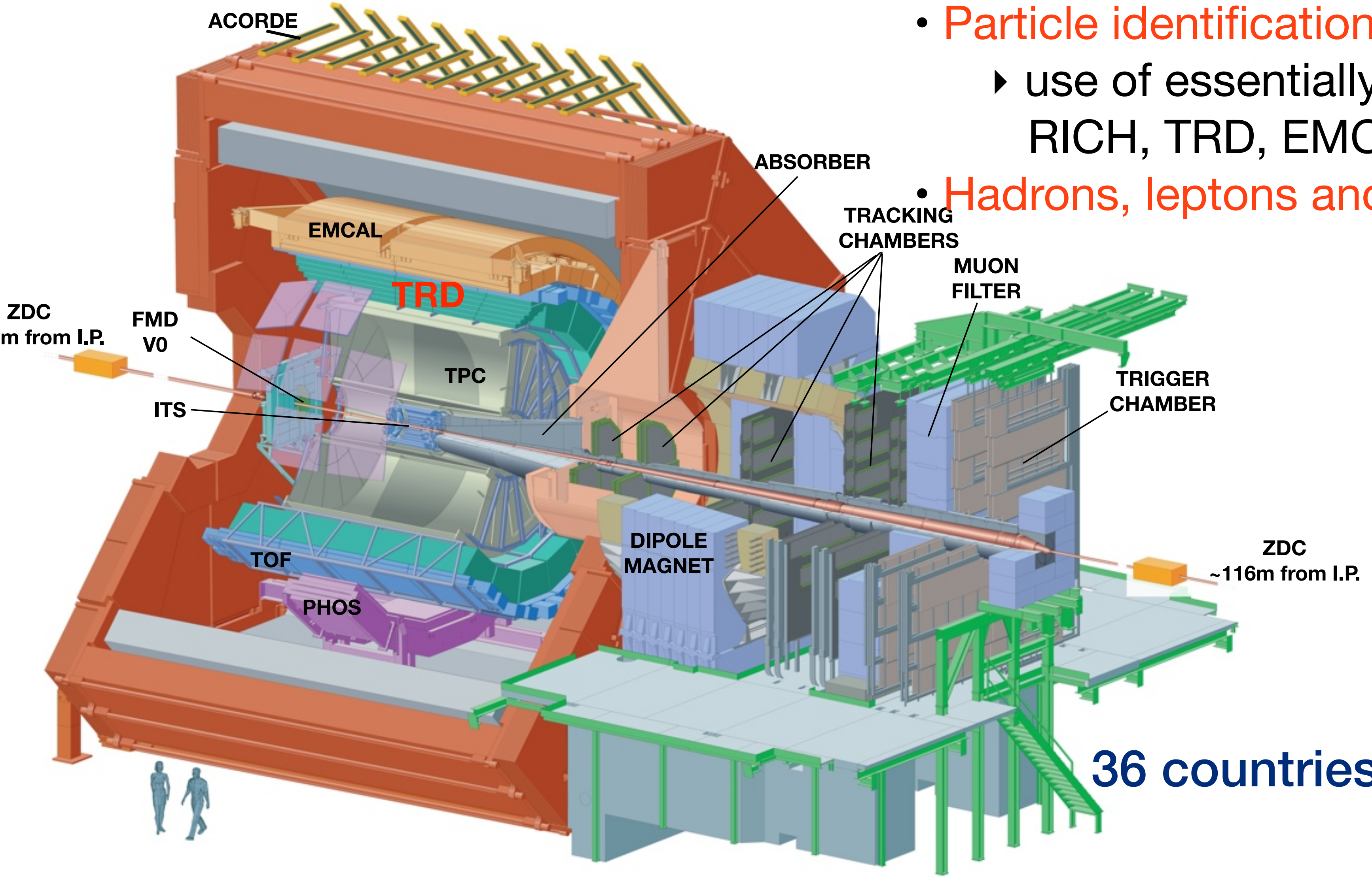
Need to measure the energy loss of charm and beauty quarks separately

A Large Ion Collider Experiment (ALICE)

Designed to discover and understand the New Created Matter (Quark-Gluon Plasma)

⇒ Only dedicated experiment at LHC, must be comprehensive and able to cover all relevant observables

- VERY robust tracking for p_T from 0.1 GeV/c to 100 GeV/c
  - high-granularity 3D detectors with many space points per track (560 million pixels in the TPC alone, giving 180 space points/track)
  - very low material budget ($< 10\% X_0$ in $r < 2.5$ m)
- Particle identification over a very large p_T range
  - use of essentially all known technologies: TOF, dE/dx, RICH, TRD, EMCal, topology
- Hadrons, leptons and photons + Excellent vertexing



36 countries, 132 institutes, 1200 members

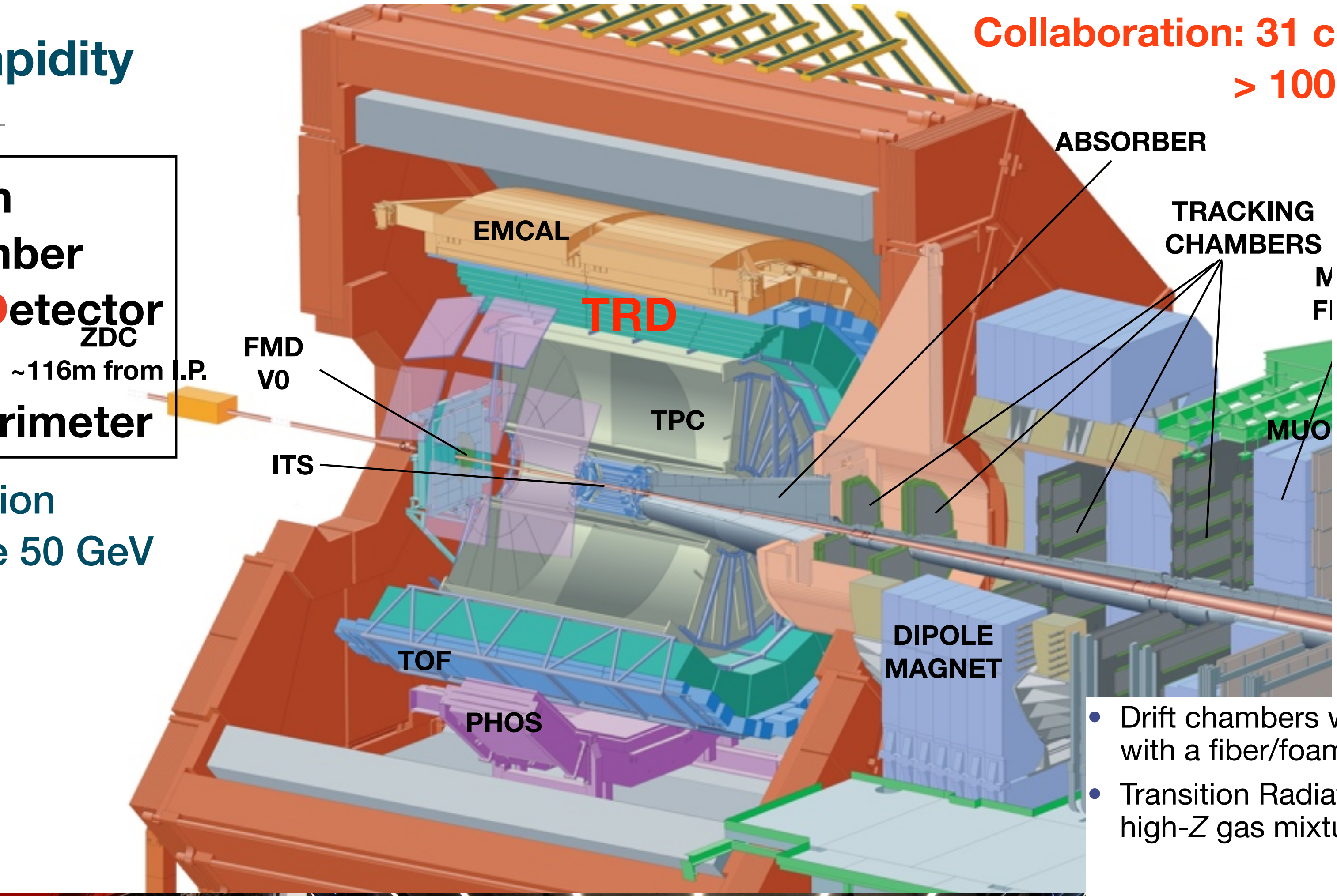
Lepton Analysis in A Large Ion Collider Experiment

Electron at Mid Rapidity (|η| < 0.8)

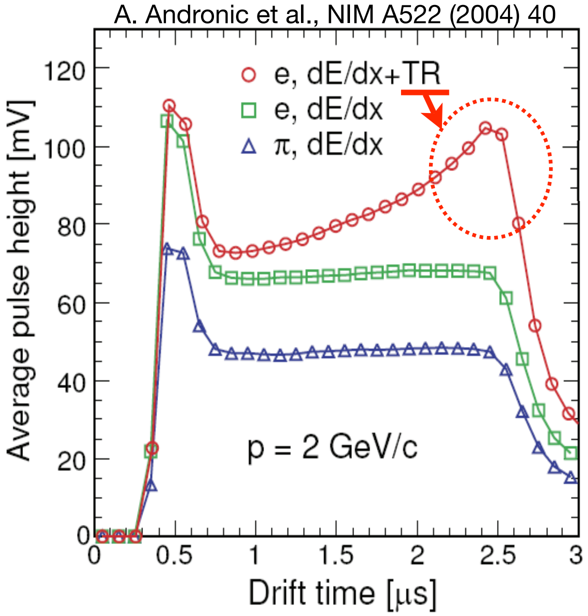
Inner Tracking System
Time Projection Chamber
Transition Radiation Detector
Time Of Flight
ElectroMagnetic Calorimeter

Electron identification
from ~100 MeV to above 50 GeV

Collaboration: 31 contries, 109 institutes, > 1000 people

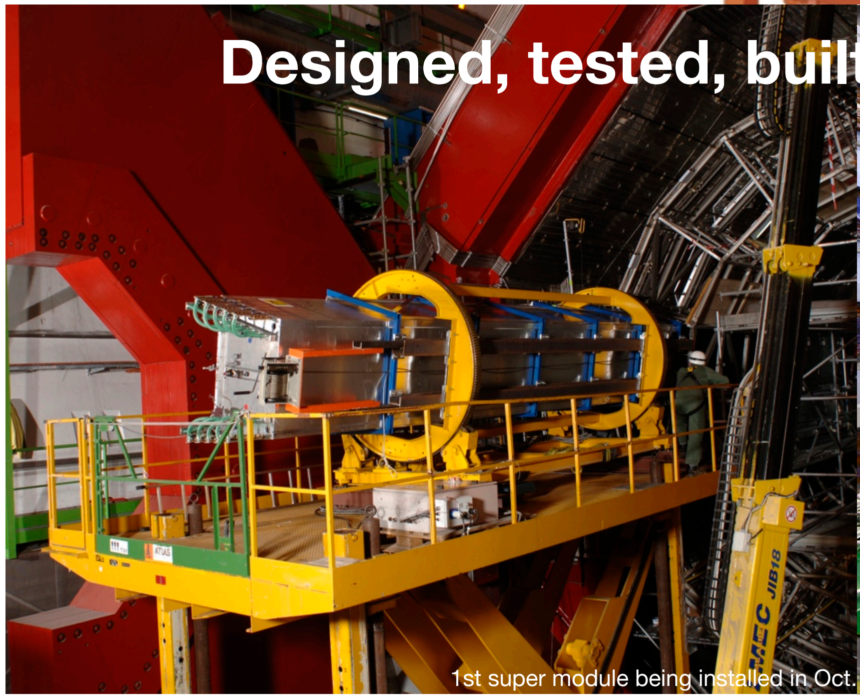


A. Andronic et al., NIM A522 (2004) 40



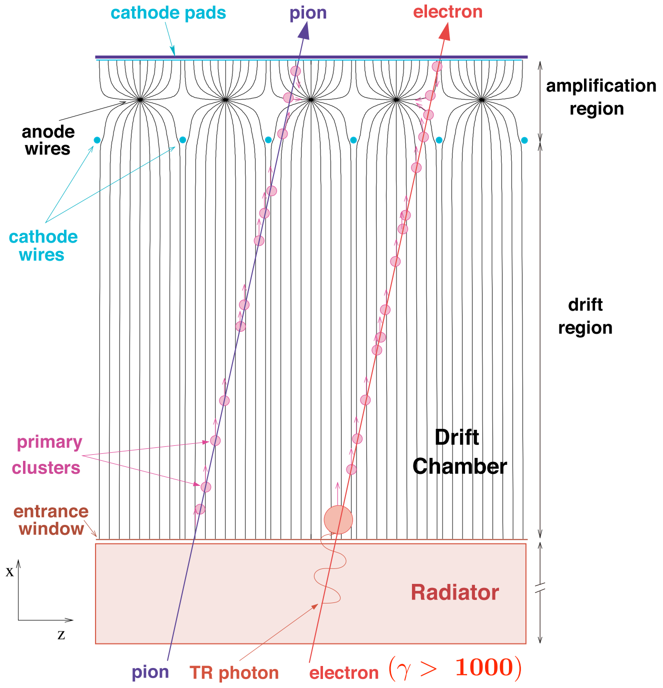
- Drift chambers with cathode pad readout combined with a fiber/foam sandwich radiator in front
- Transition Radiation (TR) photons are absorbed by high-Z gas mixture (Xe + CO_2)

Designed, tested, built in Heidelberg University



1st super module being installed in Oct.

2nd layer being tested in the super mod



Characteristics of Heavy Ion Collisions

Particle Production and Energy density ε:

Produced Particles: $dN_{ch}/d\eta \sim 1600 \pm 76$ (syst)

~ 30,000 particles in total, ~ 400 times pp

$$\varepsilon(\tau) = \frac{E}{V} = \frac{1}{\tau_0 A}\frac{dN}{dy} < m_t >$$

$$\varepsilon \sim 10 GeV / fm^3$$

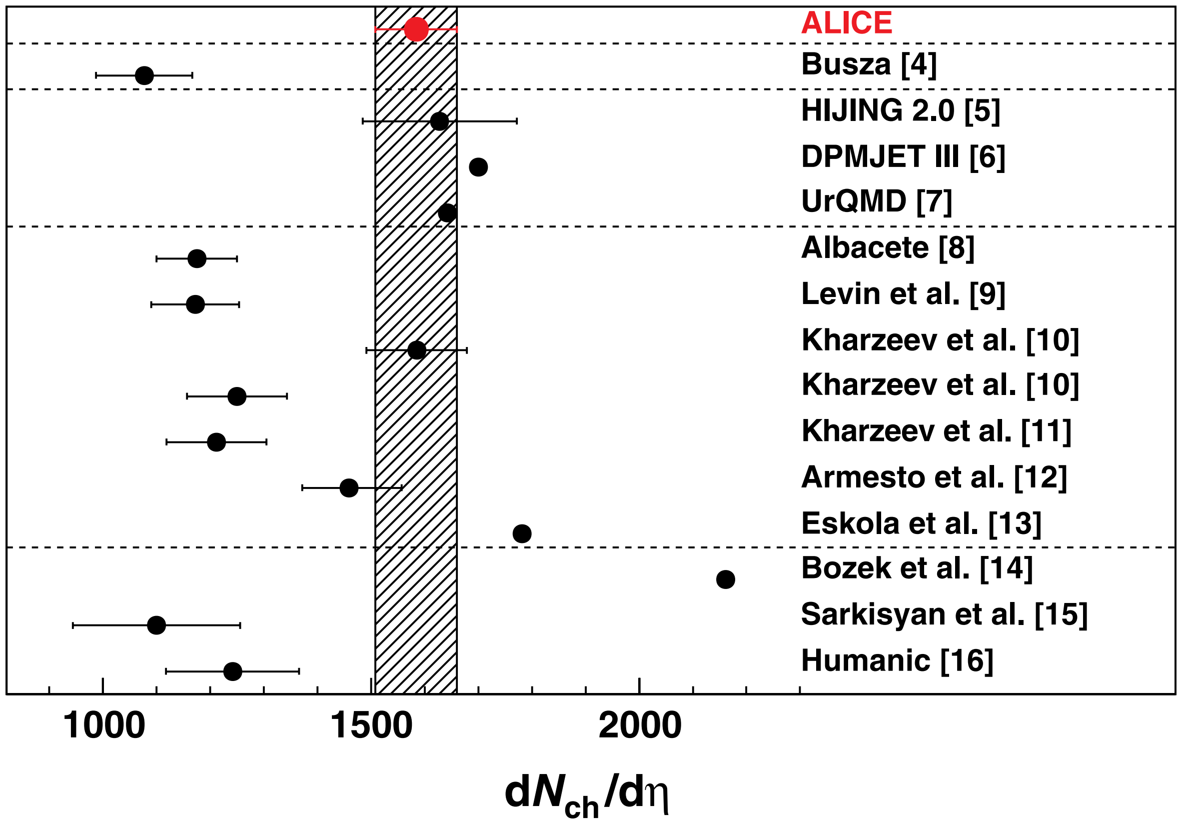
Energy density ε > 3 x RHIC

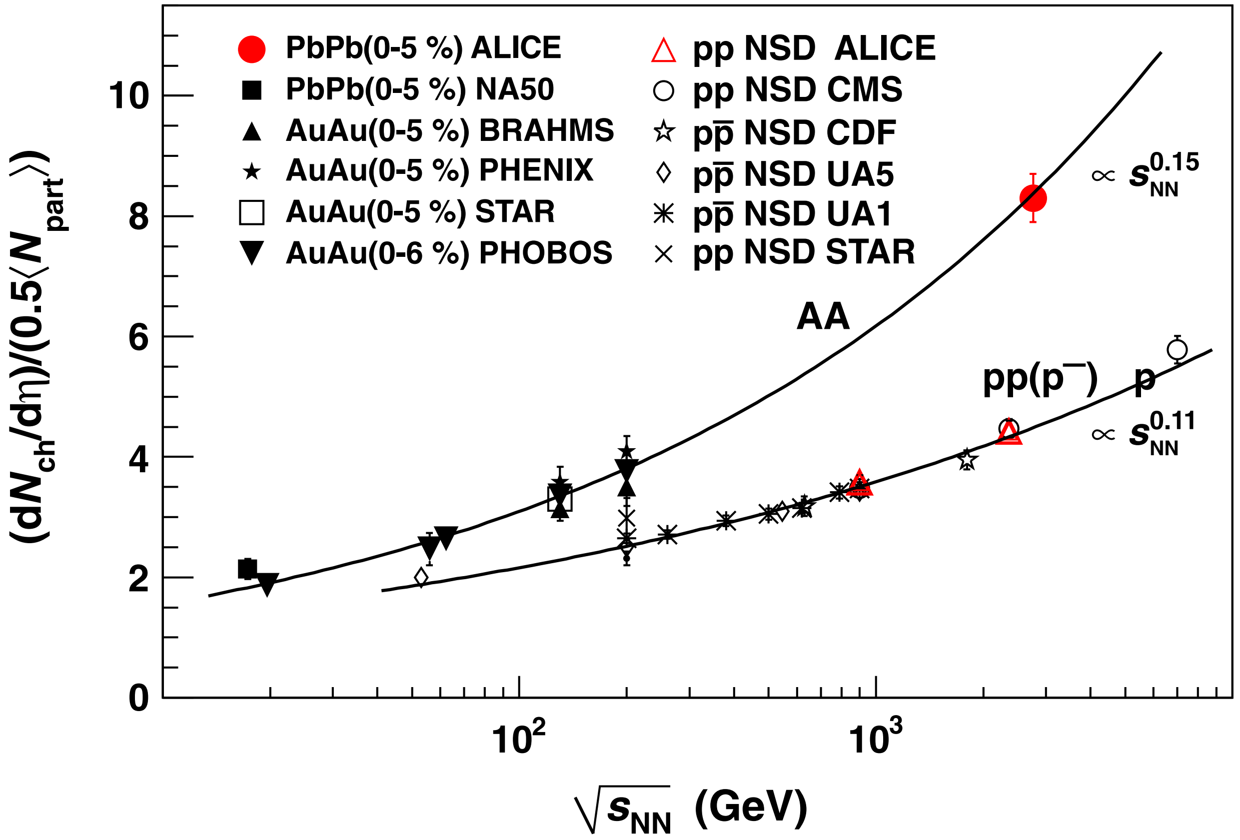
Matter under extreme conditions: ~50 times the density of neutron star core (40 billion tons/cm^3)

≡

50 protons packed into the volume of one proton, more than enough for deconfinement!

PRL **105,** 252301 (2010)





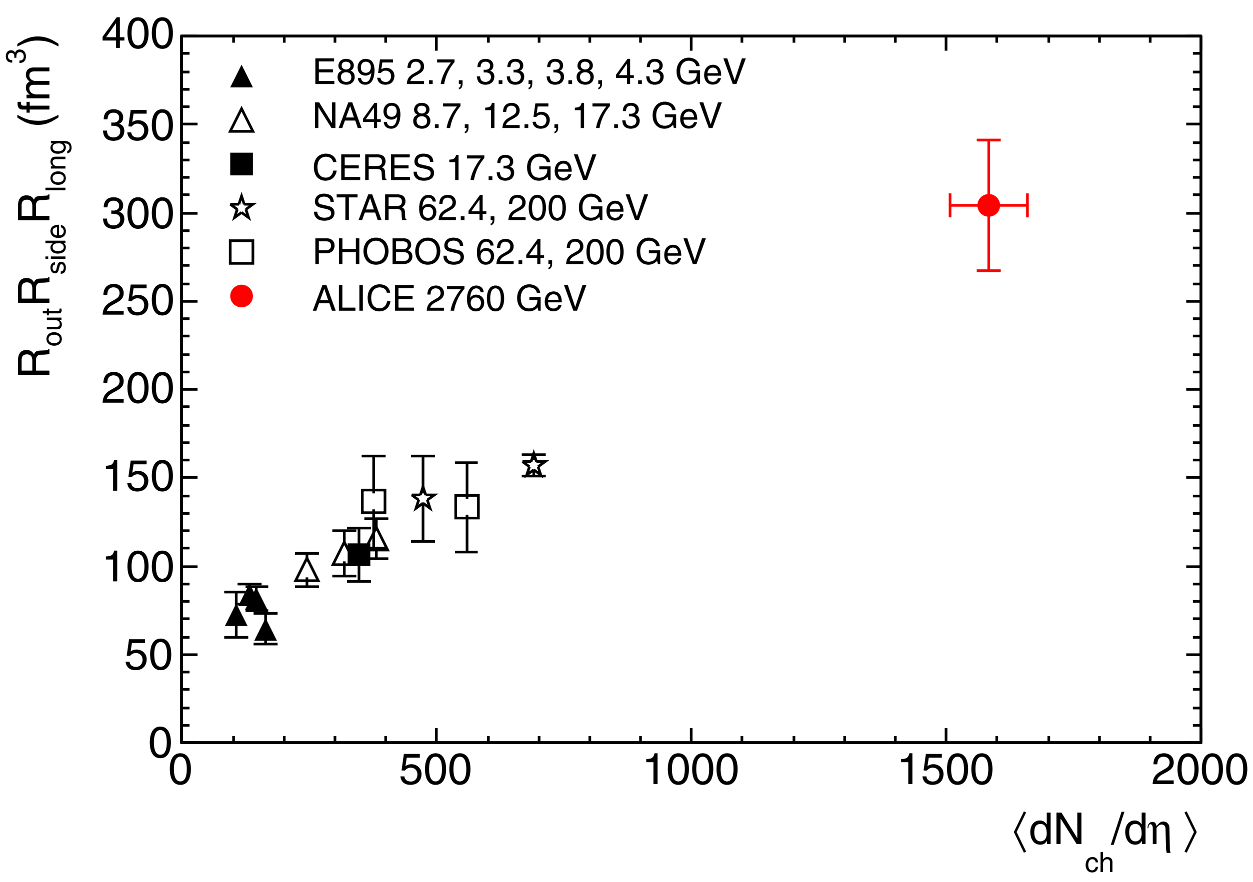
Volume and Lifetime of the created matter

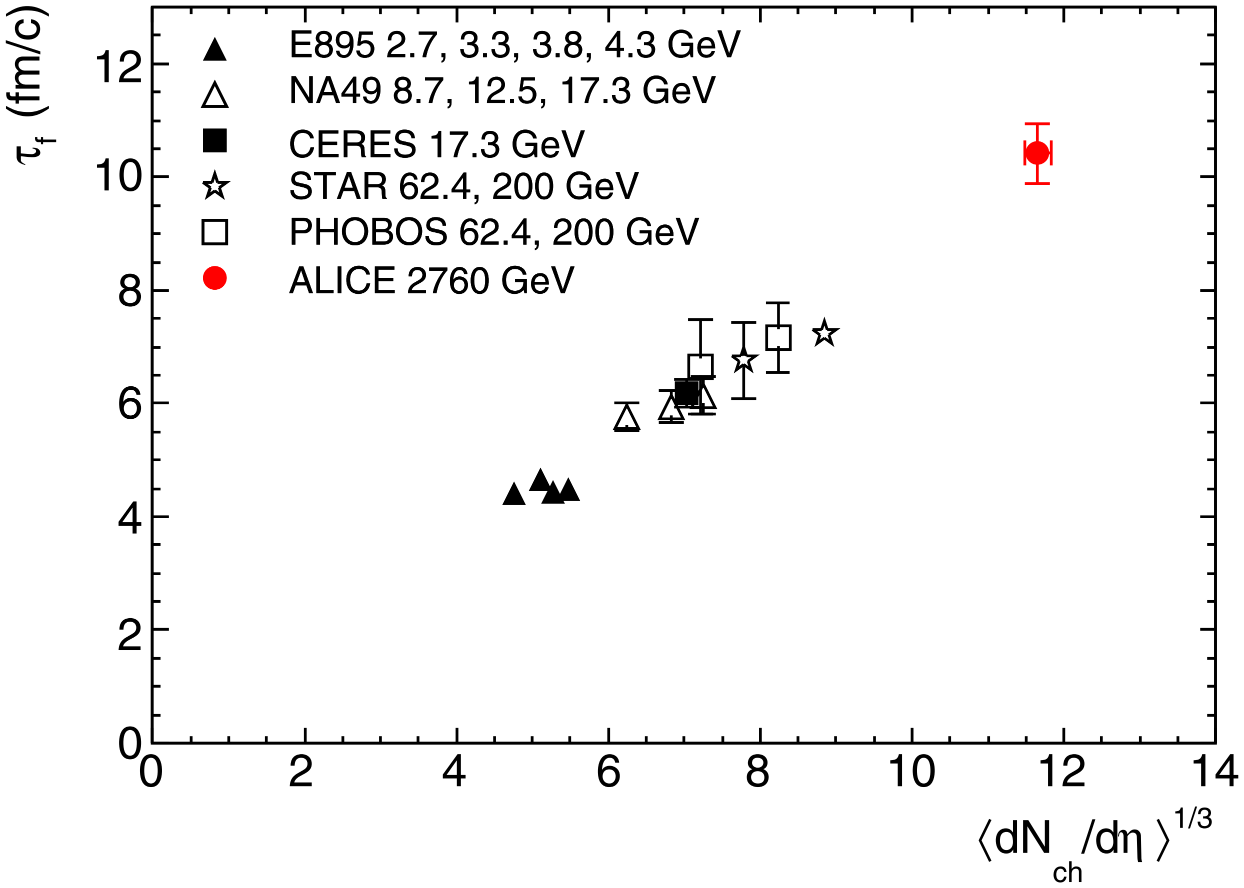
Identical particle interferometry to measure extend of dynamical evolving source (HBT, Bose-Einstein correlations)

- Volume ≈ 300 fm^3 (≈ 2 x RHIC)
- Lifetime ≈ 10 fm/c (≈ +20%)

Volume at ‘freeze-out’(hadron decoupling)
Lifetime from collision to ‘freeze-out’

note: 1fm/c ~ 0.33×10^{-23}s



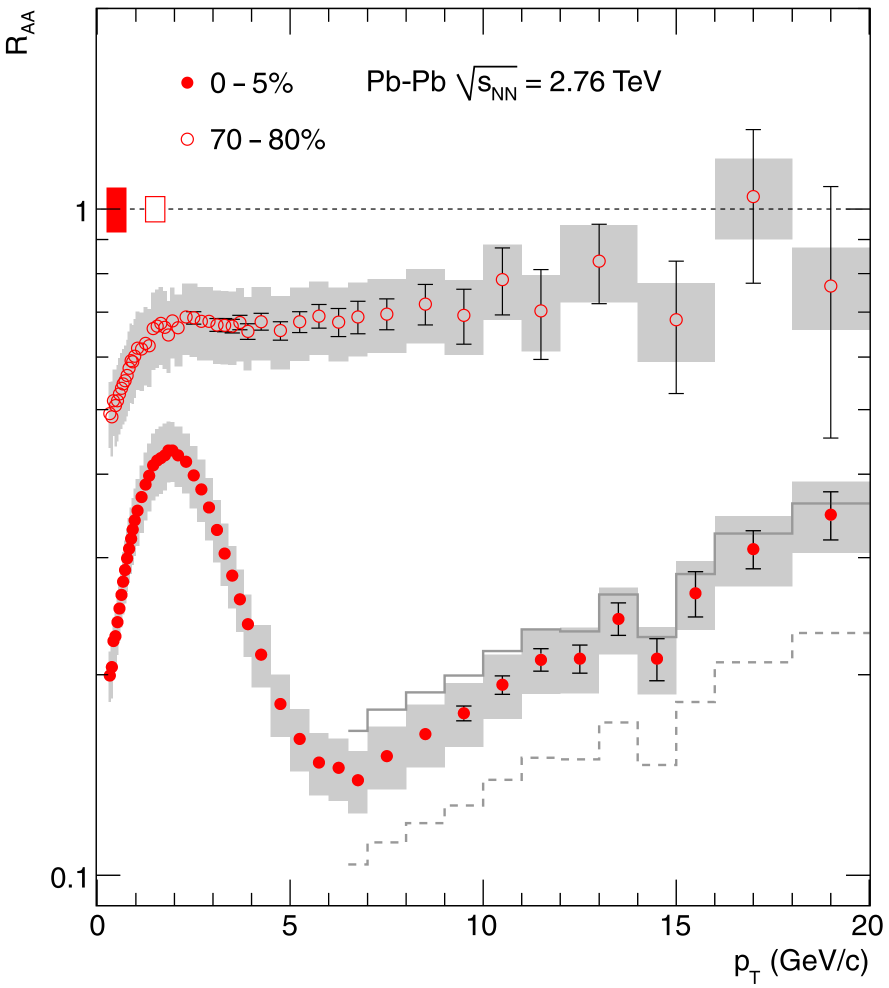


Lives 10^{40} less than current age of universe

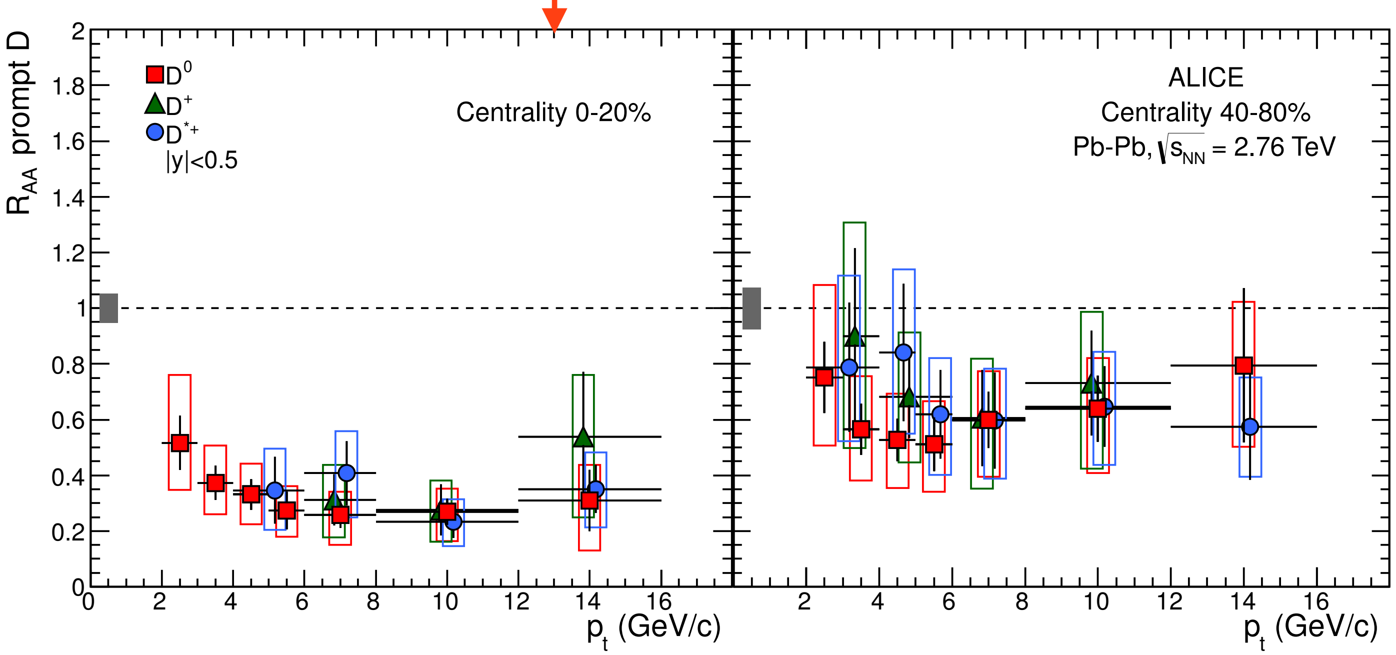
Parton Energy Loss: via Nuclear Modification Factor

$$R_{AA}(p_T) = \frac{(1/N_{\rm evt}^{AA})\, d^2N_{\rm ch}^{AA}/d\eta\, dp_T}{\langle N_{\rm coll}\rangle (1/N_{\rm evt}^{pp})\, d^2N_{\rm ch}^{pp}/d\eta\, dp_T}$$

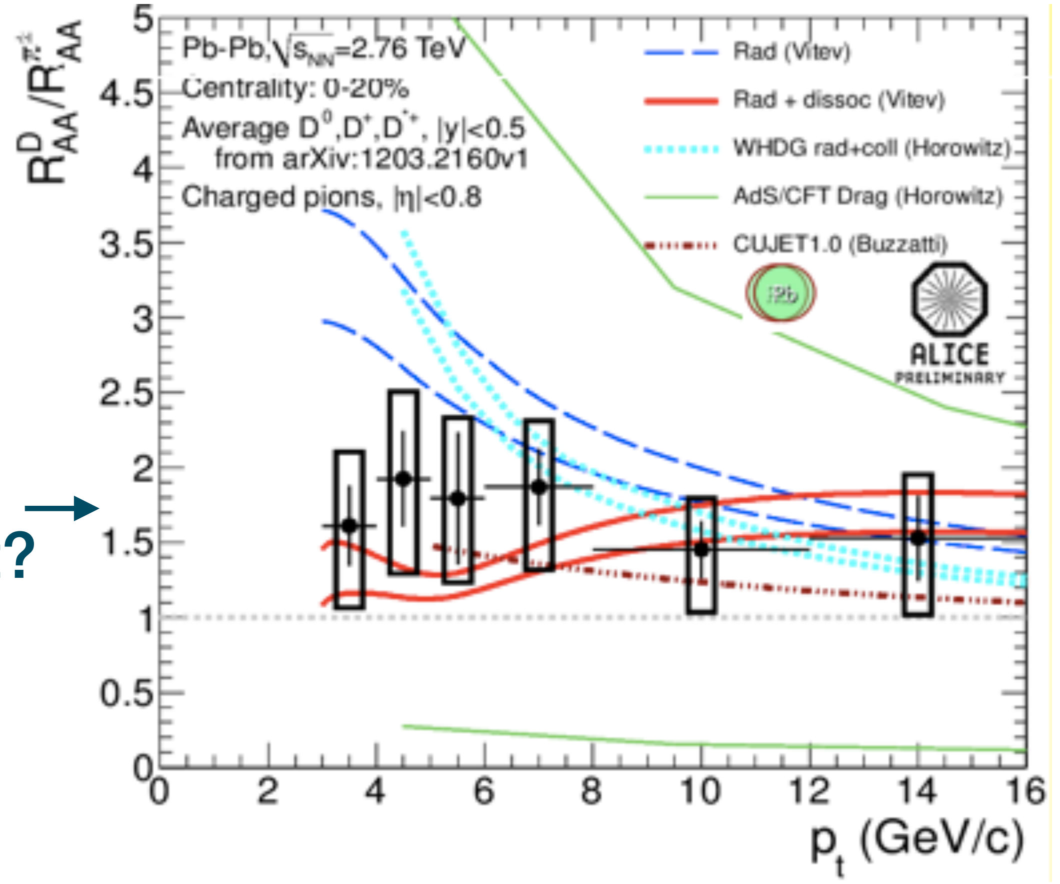
- Nuclear modification factor $R_{AA}(p_T)$ for charged particles produced in 0-5% centrality range ⇒ Strong suppression even larger than at RHIC



- Nuclear modification factor $R_{AA}(p_T)$ for prompt D mesons ⇒ Strong suppression



First indication of colour charge effect? →

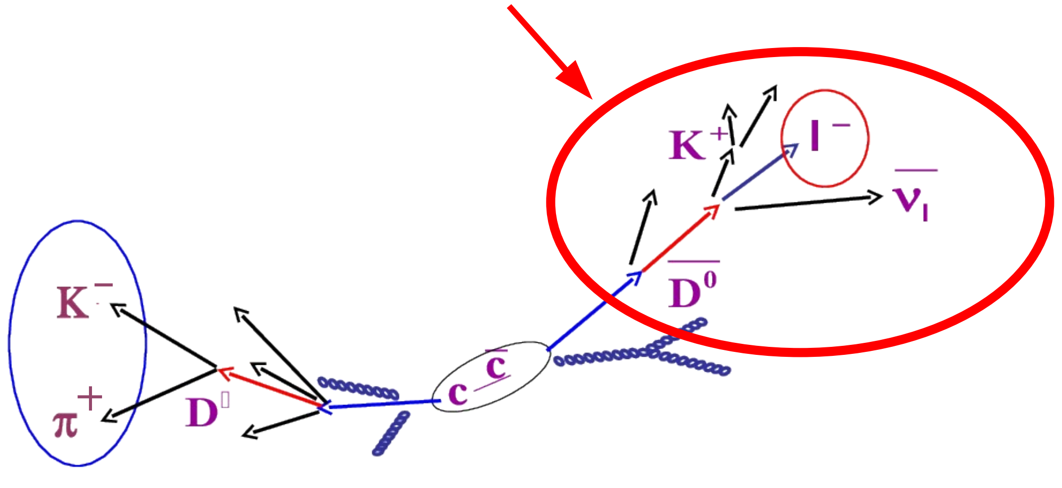


Essential quantitative constraint for parton energy loss models!

via New Method

First B Measurement

Measure the $c\bar{c}$ and $b\bar{b}$ production cross sections through **semileptonic decays** of open charm and open beauty hadrons:



Branching Ratios:

$c \to e + X$ $\mathcal{O}(9.6\%)$

$b \to e + X$ $\mathcal{O}(11\%)$

$b \to c \to e + X$ $\mathcal{O}(10\%)$

D,B → e + X

⇒ Measured inclusive electrons

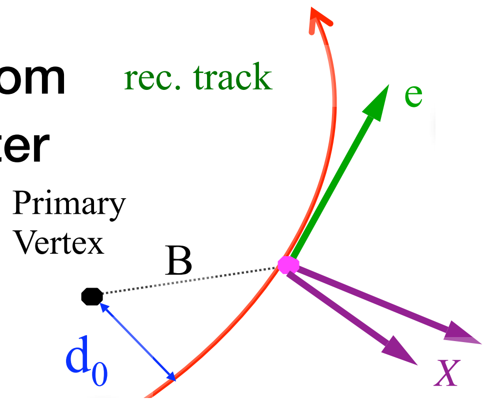
-

cocktail of background electrons based on data ⇨

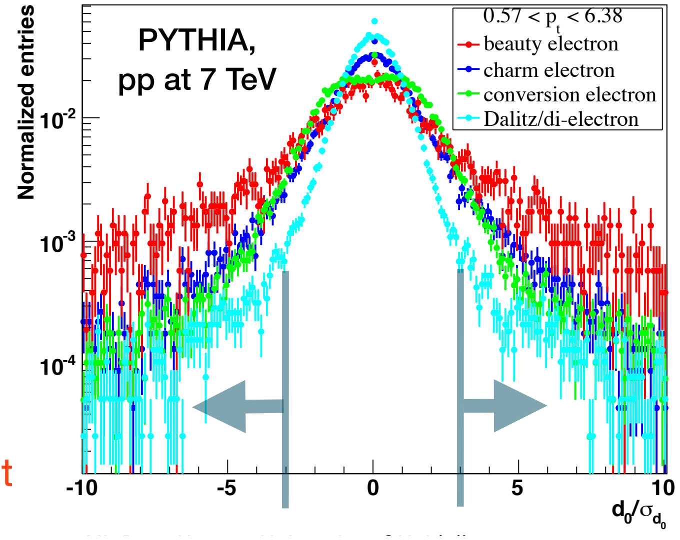
- photonic, Dalitz/dielectron decays of mesons based on measured π^0,η spectrum and m_T scaled spectrum for heavier mesons $(\eta',\rho,\omega,\varphi)$
- direct radiation based on NLO calculation
- J/Ψ and Υ based on measurement

B → e + X

⇒ Preferential selection of electrons from B decay via their large impact parameter d_0 ($(c\tau)_B$ ~ 500 μm, B meson mass ~ 5 GeV/c^2)

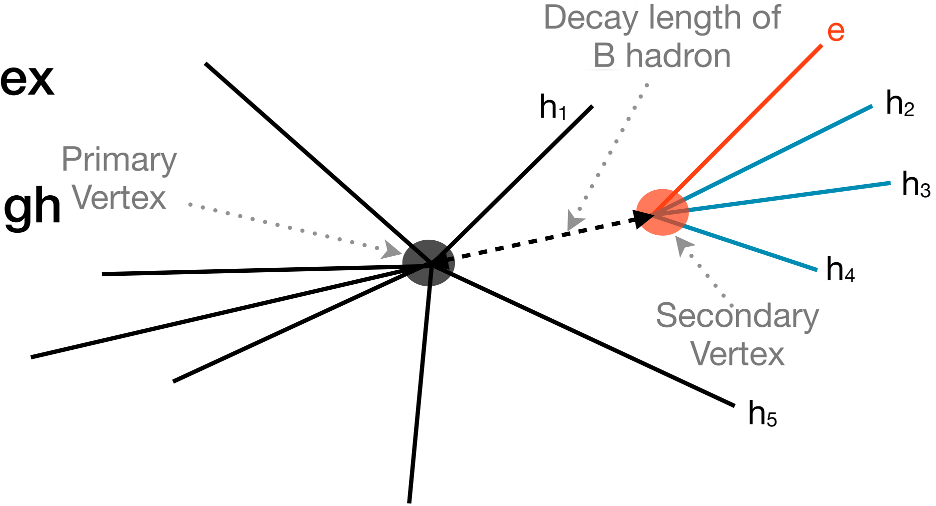


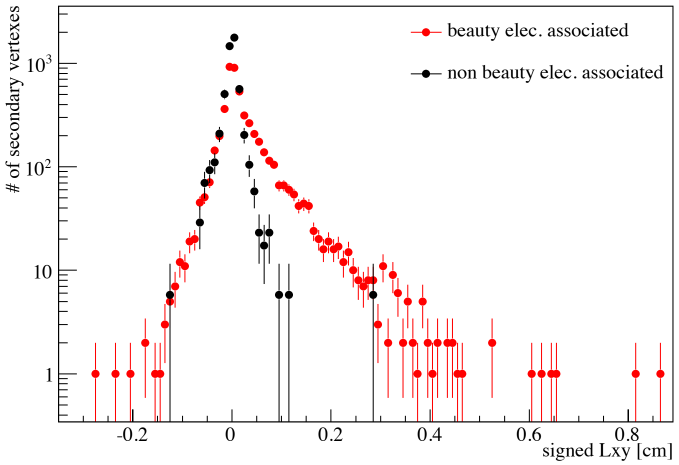
d_0: Transverse impact



B tagging

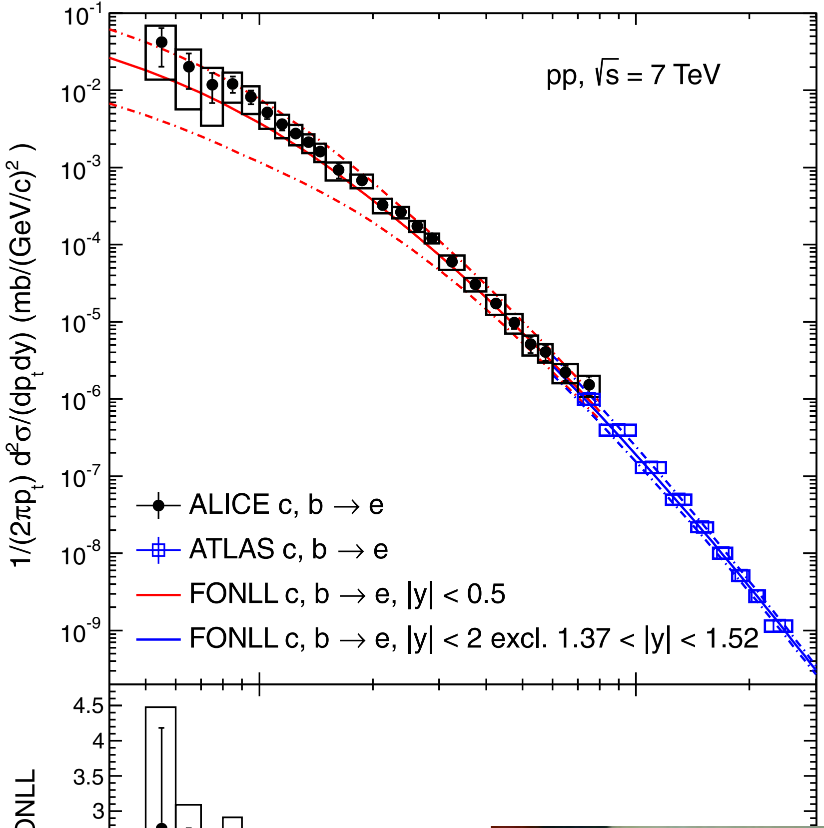
⇒ Secondary vertex reconstruction of beauty decay through electron + hadrons



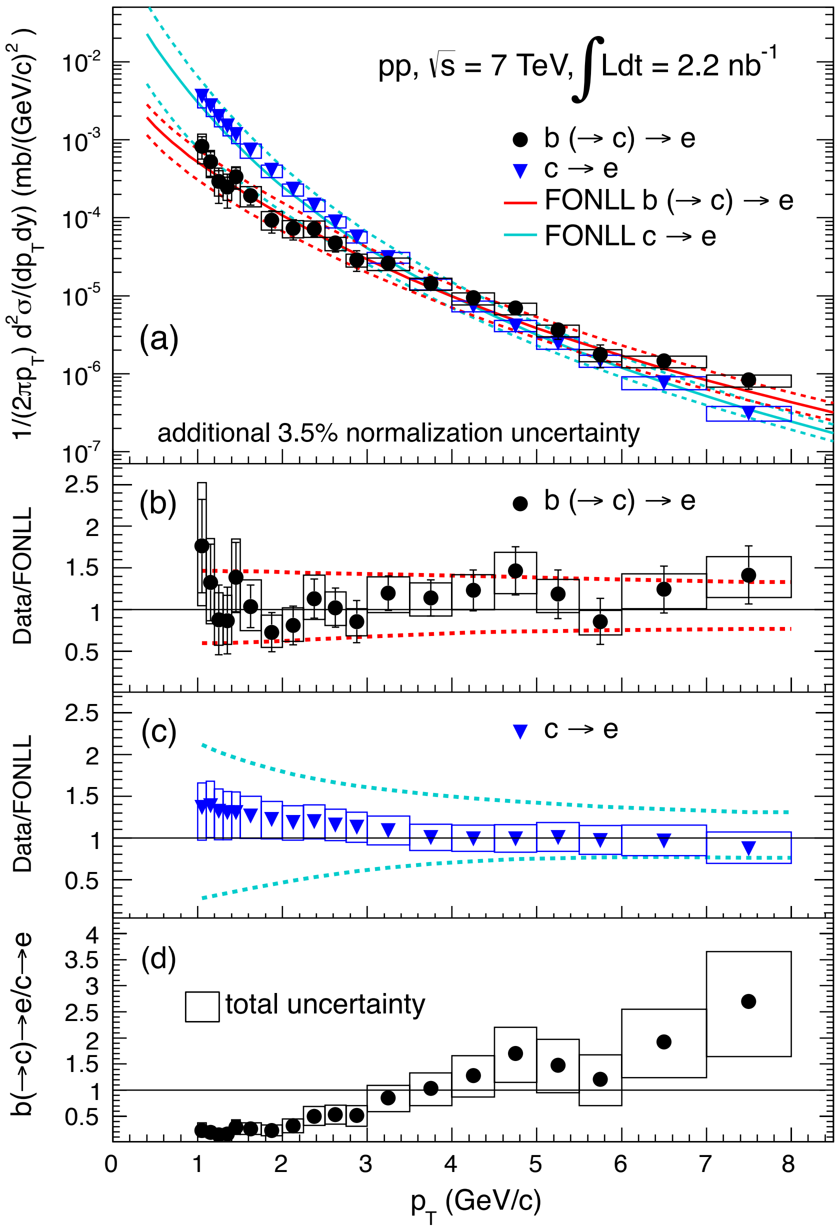


Heavy Quark Measurement via Semi-electronic Decays

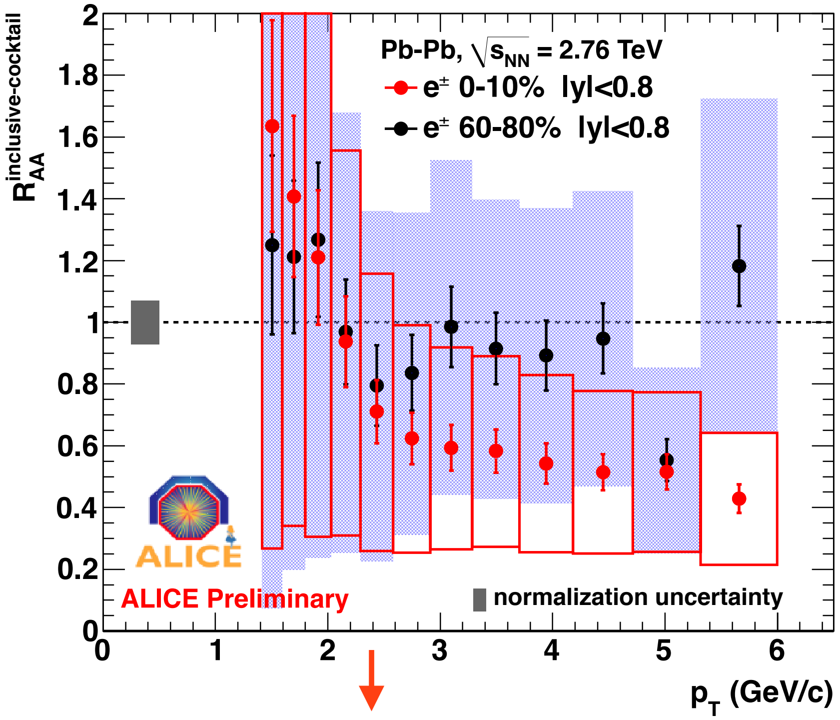
PHYSICAL REVIEW D **86,** 112007 (2012)



PLB DOI: 10.1016/j.physletb.2013.01.069



Within the experimental and theoretical uncertainties FONLL in agreement with both measurements.



Heavy flavour electrons are suppressed for central PbPb collisions

Suppression pattern is similar to those of other hadrons

Heavy flavour electron flow,
Heavy quark jets...: not mentioned

Observables, observables, observables...

- Jet Quenching
- Quarkonium suppression (Thermometer of the plasma): Less suppressed than RHIC
- Thermal photon
- Ratio between yield of particles
- Low mass resonances
- ....

Group Genius

The capacity of a group of individuals to tap into the power of collaboration in a way that produces outcomes that surprise even themselves.

- A team that successfully leverages its combined wisdom can generate genuinely new solutions that aren't traceable back to any one individual to produce fresh ideas that the group is passionate about, resulting in a dramatic performance improvement
- example: Wikipedia, GisikIn

그룹 지니어스: 평범한 사람들이 모여 비범한 성과를 만들어 내는 집단적 천재성

철학은? 모든 사람에게는 고유의 강점이 있고 '협업 방식'은 고유의 잠재적 능력을 드러나게 한다

The Creative Power of Collaboration

(but obviously, there are also many 'sole' genius! :))

Epilogue: We are miners

A friend of mine told me one episode from one of our colleagues.

On one occasion, he invited his parents to the experimental area in ALICE and showed them with proud how big the experimental setups are. Then, his mother said, “You look like a miner!”. He expected a kind of words expressing admiration he has in mind to the setups rather than a comment about his appearance.

The scene in the above picture is the typical scenery in the experimental area located at 60 m down from the earth surface. So I think his mother made a proper observation and indeed we are all like miners who work on finding out values in the dark.

Heavy Quark Energy Loss in Medium

Dead Cone Effect

- In vacuum, gluon radiation is suppressed at angles smaller than the ratio of the quark mass M_Q to its energy E_Q

Gluonsstrahlung probability $\propto \dfrac{1}{\left[\theta^2 + (M_Q/E_Q)^2\right]^2}$

- In medium, dead cone implies lower energy loss

(Dokshitzer and Kharzeev, PLB 519 (2001) 199.)

⇒ suppression of high-energy tail of medium induced gluon radiation for heavy quarks (more pronounced for beauty)

Color charge dependence of energy loss

gluon radiation spectrum by the parton propagation in the medium:

$$\omega \frac{dI}{d\omega} \propto \alpha_s C_R f(\omega)$$

$$, where \quad C_R = 3 \ \ for\ g, \ \frac{4}{3} \ \ for\ q$$

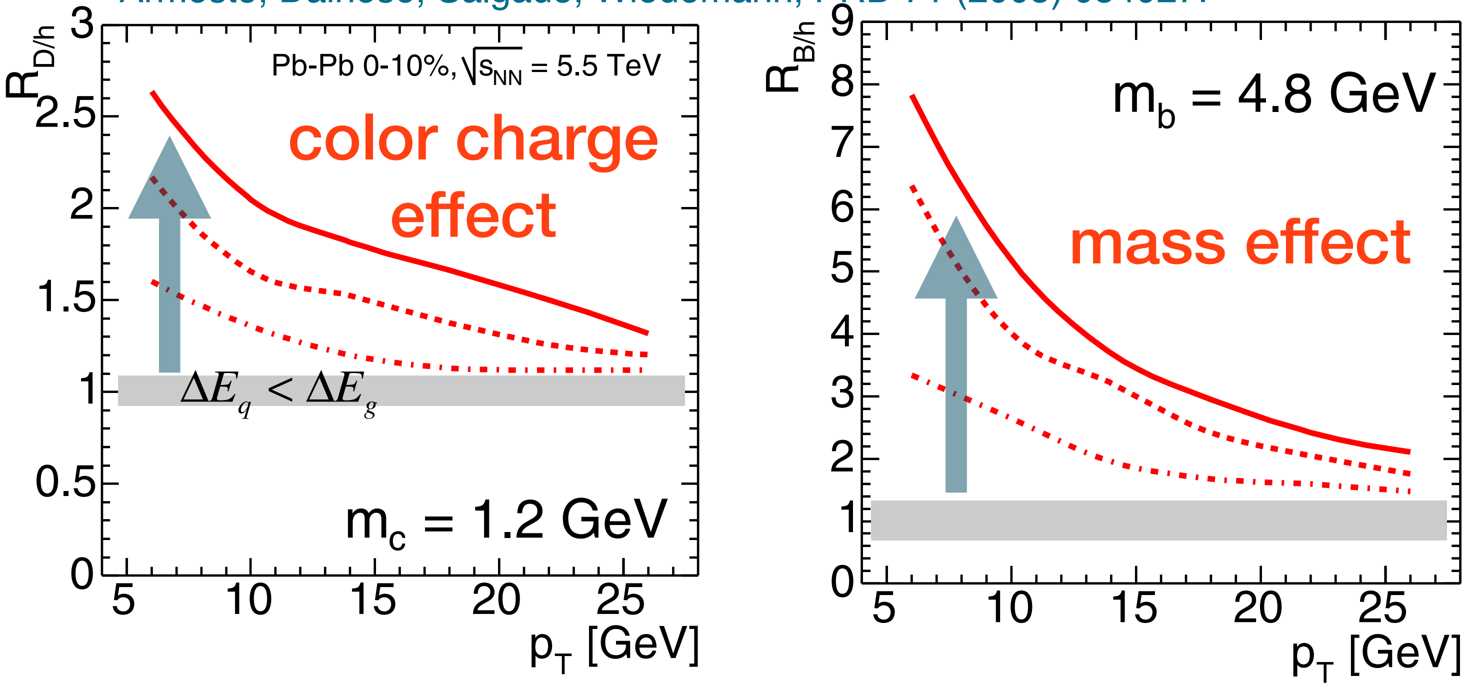
$$\boxed{R^{\pi}_{AA} < R^{D}_{AA} < R^{B}_{AA}}$$

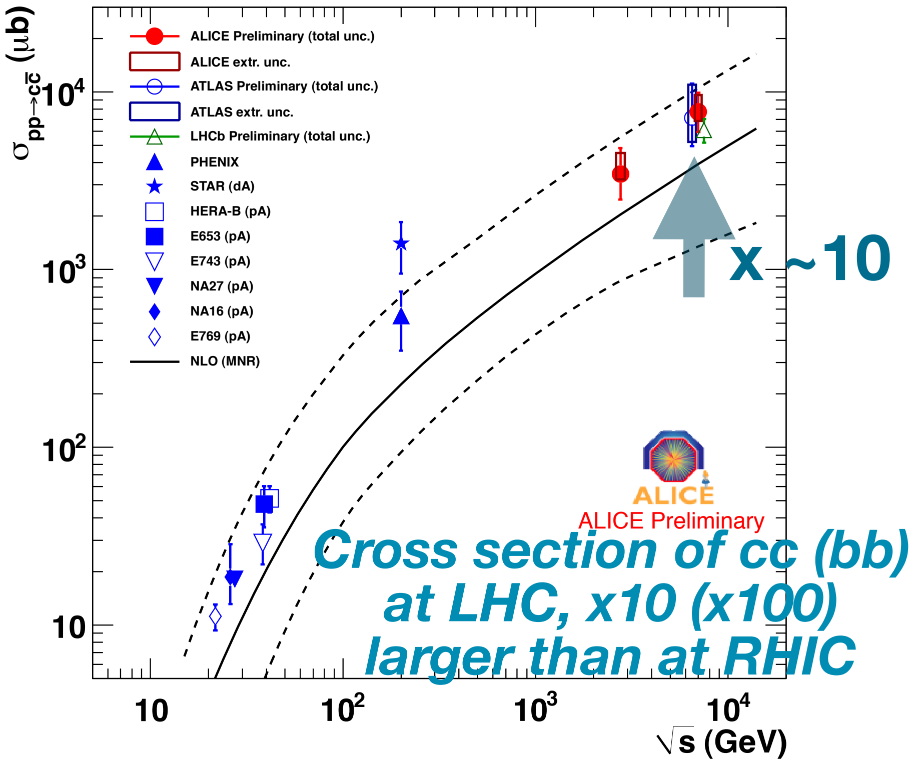
$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

At LHC...

$R_{D/h}$: Heavy-to-light ratios

Armesto, Dainese, Salgado, Wiedemann, PRD 71 (2005) 054027.





Cross section of cc (bb) at LHC, x10 (x100) larger than at RHIC

Proton-proton collisions: provide important test of pQCD in a new energy domain and heavy ion reference