



Highlights from ALICE

DPG-Frühjahrstagung Dresden, March 4 - 8, 2013

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Ultra-Relativistic Heavy-Ion Physics: Study of Emergent Properties of QCD

- It is a hard problem to determine the properties of water and its phases (ice, water, steam) from the known properties of a water molecule



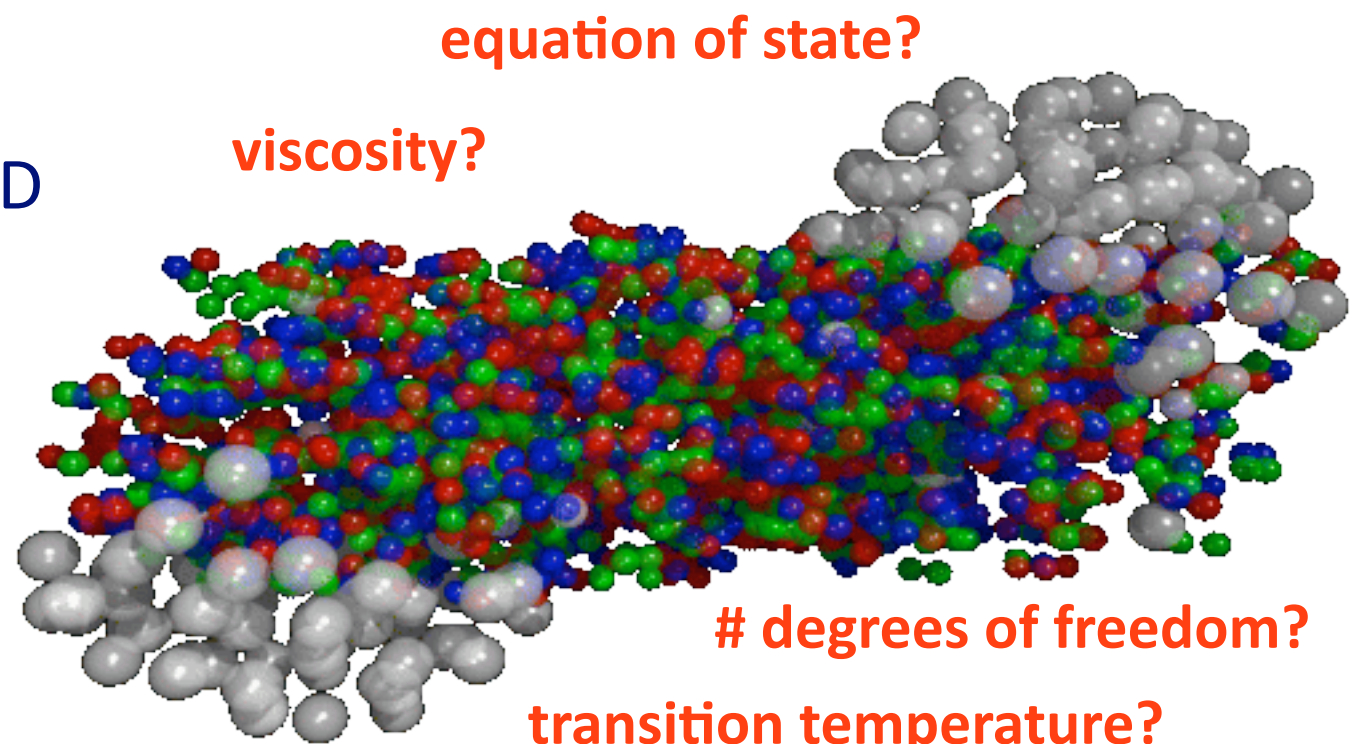
source: de.wikipedia.org



- Ultra-relativistic heavy-ion physics:
Study of **emergent properties** of QCD
(condensed-matter aspects of QCD)

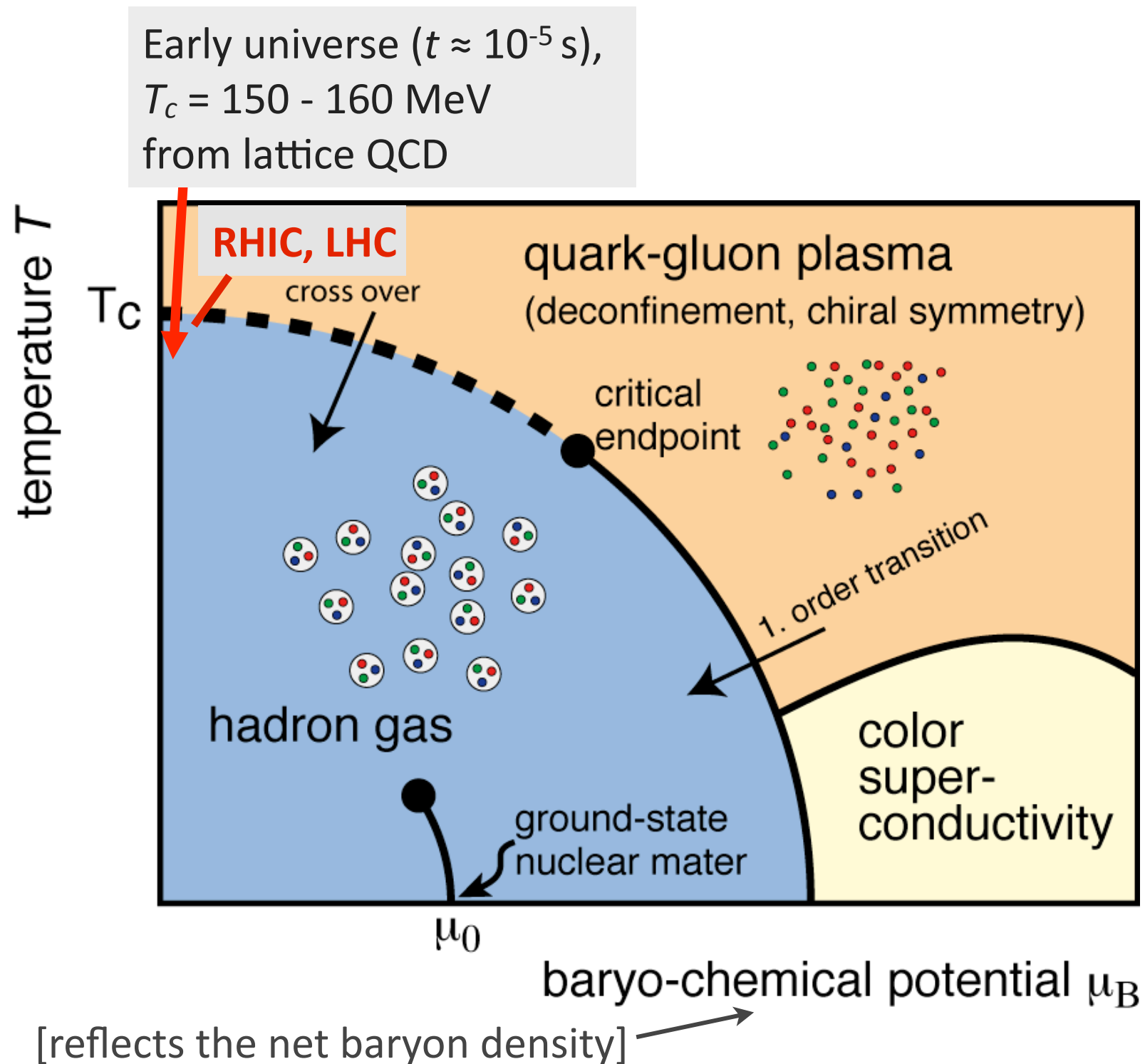
„More is different“

Philip W. Anderson, Science, 177, 1972, S. 393



source: urqmd.org

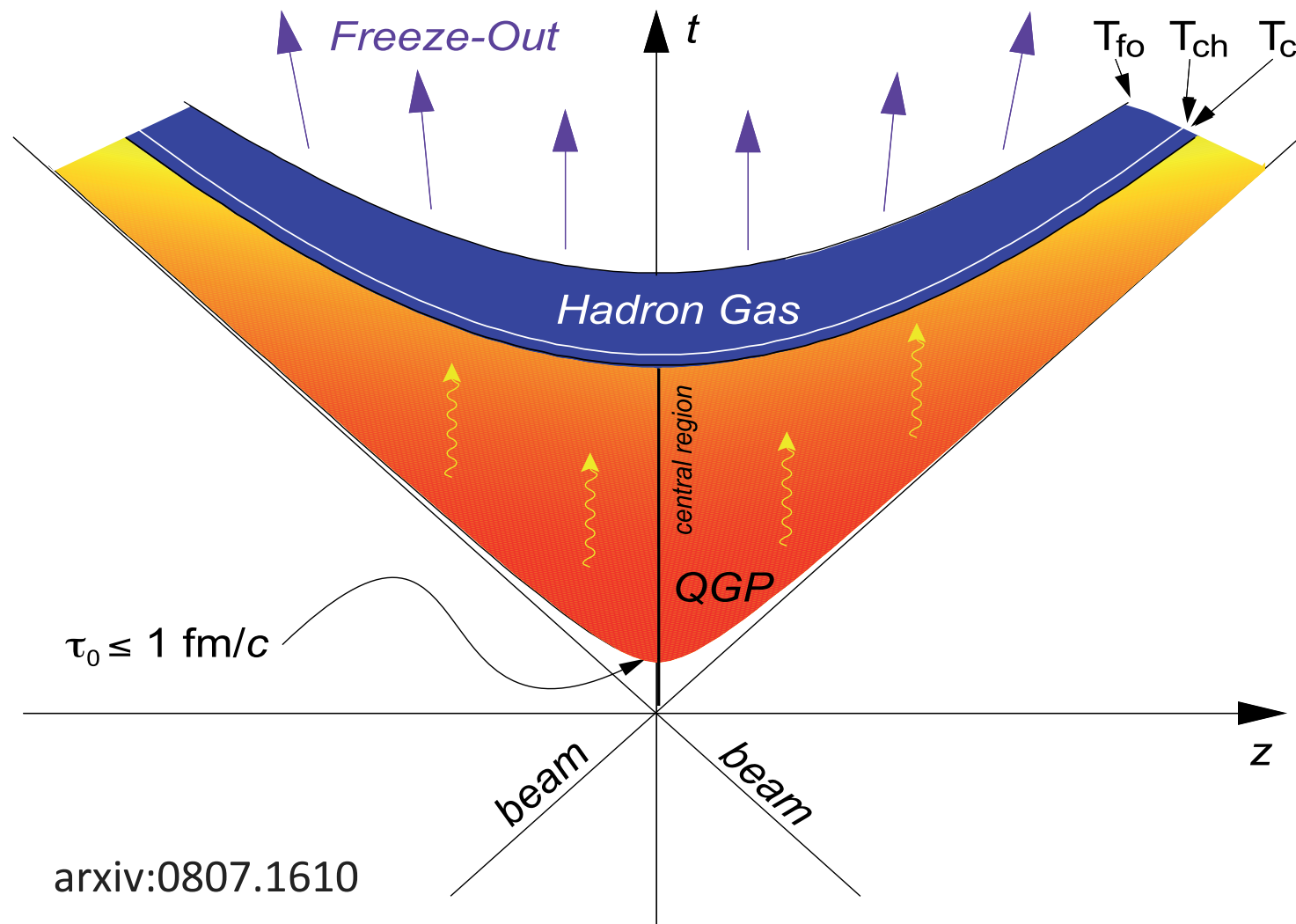
QCD in the High Temperature & High Density Sector



- Weakly coupled sector of QCD well tested (e.g. with jets)
- Heavy-ion physics: Strong coupling at large temperature
- Prediction from first QCD principles (lattice QCD): transition to QGP
 - ▶ $T_c = 150 - 160 \text{ MeV}$
 - ▶ $\epsilon_c \approx 0.5 \text{ GeV/fm}^3$

Heavy-ion physics = QCD thermodynamics

Towards a Standard Reaction Model: The Hydro Paradigm



arxiv:0807.1610

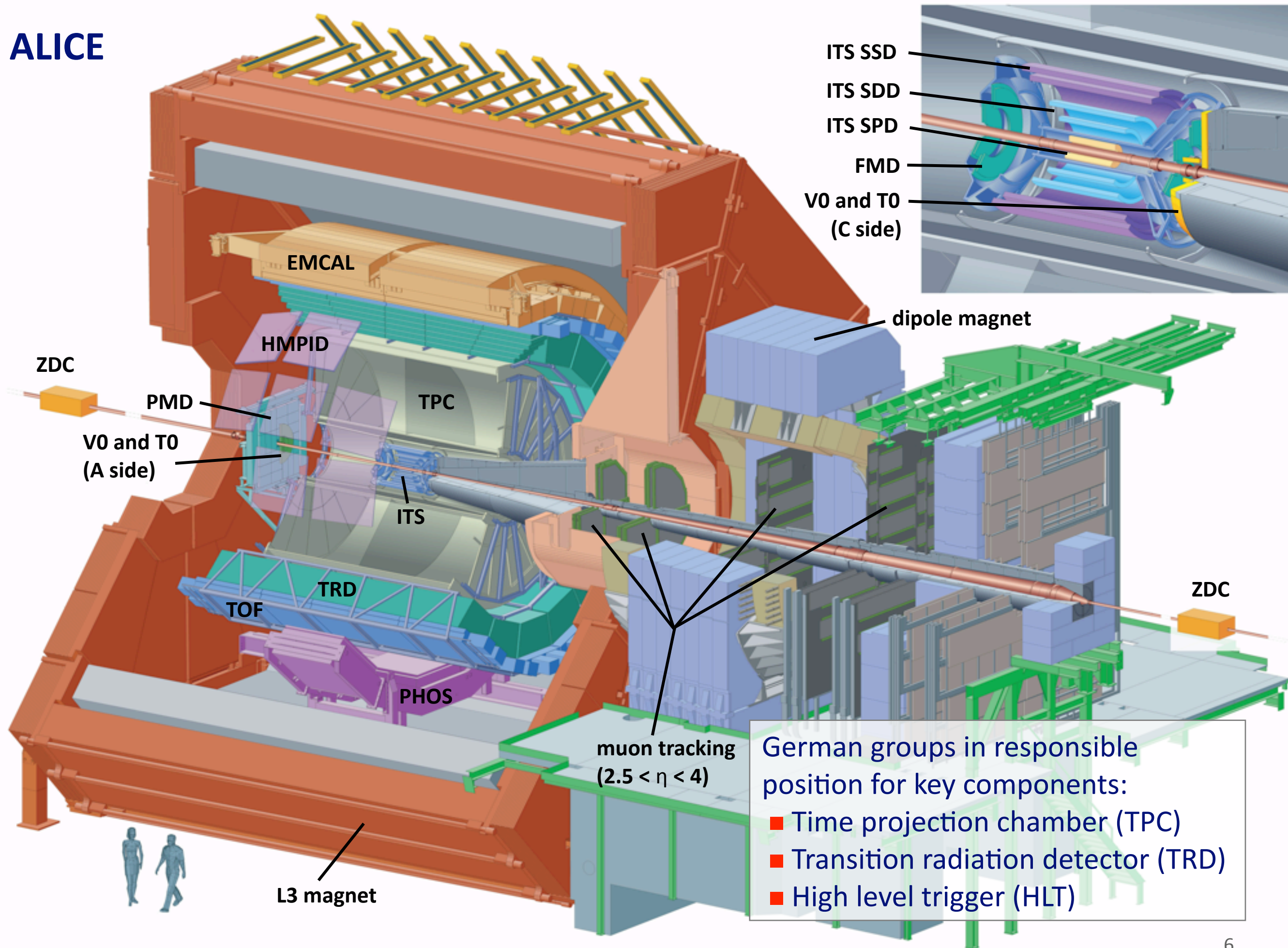
- Gluons liberated from the nuclear wave function during collision
- Rapid thermalization: QGP created at $\sim 1 \text{ fm}/c$
- Longitudinal and transverse expansion describable by almost ideal relativistic hydrodynamics ($\eta/s \approx 0$)*
- Transition QGP $\rightarrow$ hadrons
- Chemical freeze-out at $T_{\text{ch}} \approx T_c$ ($T_c = 150 - 160 \text{ MeV}$)
- Kinetic freeze-out at $T_{\text{fo}} \sim 100 \text{ MeV}$

* conjectured lower bound from string theory: $\eta/s|_{\text{min}} = 1/4\pi$
 Phys.Rev.Lett. 94 (2005) 111601

Hydrodynamic modeling essential for determination of medium properties, e.g. η/s

We need to turn all experimental knobs to test and, if necessary, amend the hydro picture

ALICE

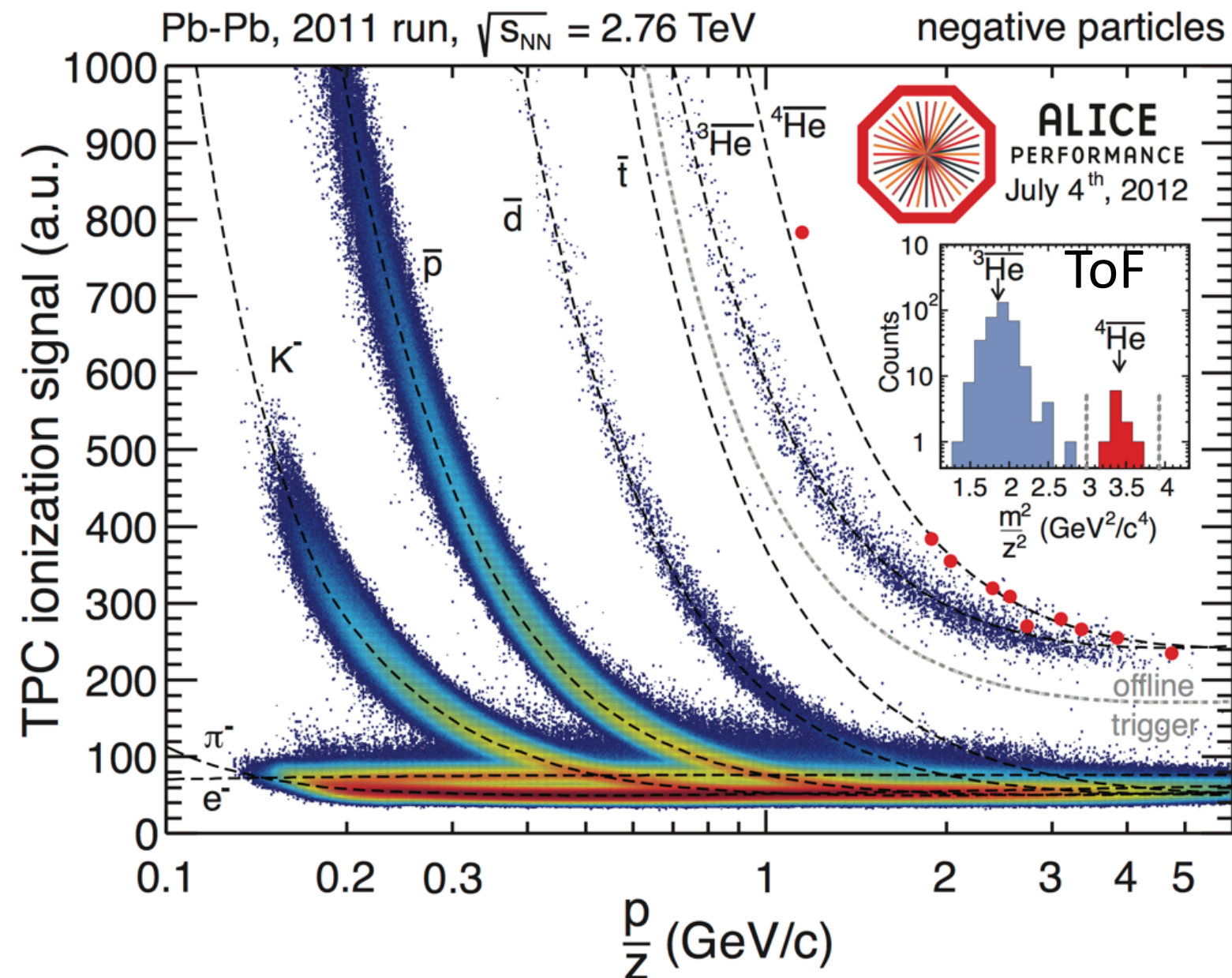


German groups in responsible position for key components:

- Time projection chamber (TPC)
- Transition radiation detector (TRD)
- High level trigger (HLT)

ALICE: Excellent Tracking and Particle Identification

Example of ALICE's PID capabilities:
Identification of anti nuclei up to anti- ^4He



- Robust tracking over large p_T range ($\sim 0.1 \text{ GeV}/c < p_T < 100 \text{ GeV}/c$)
- Very good secondary vertex resolution (e.g. for D and B mesons)
- Excellent momentum reconstruction + particle ID
 - ▶ dE/dx , time-of-flight, Cherenkov radiation, transition radiation, E/p from calorimeters

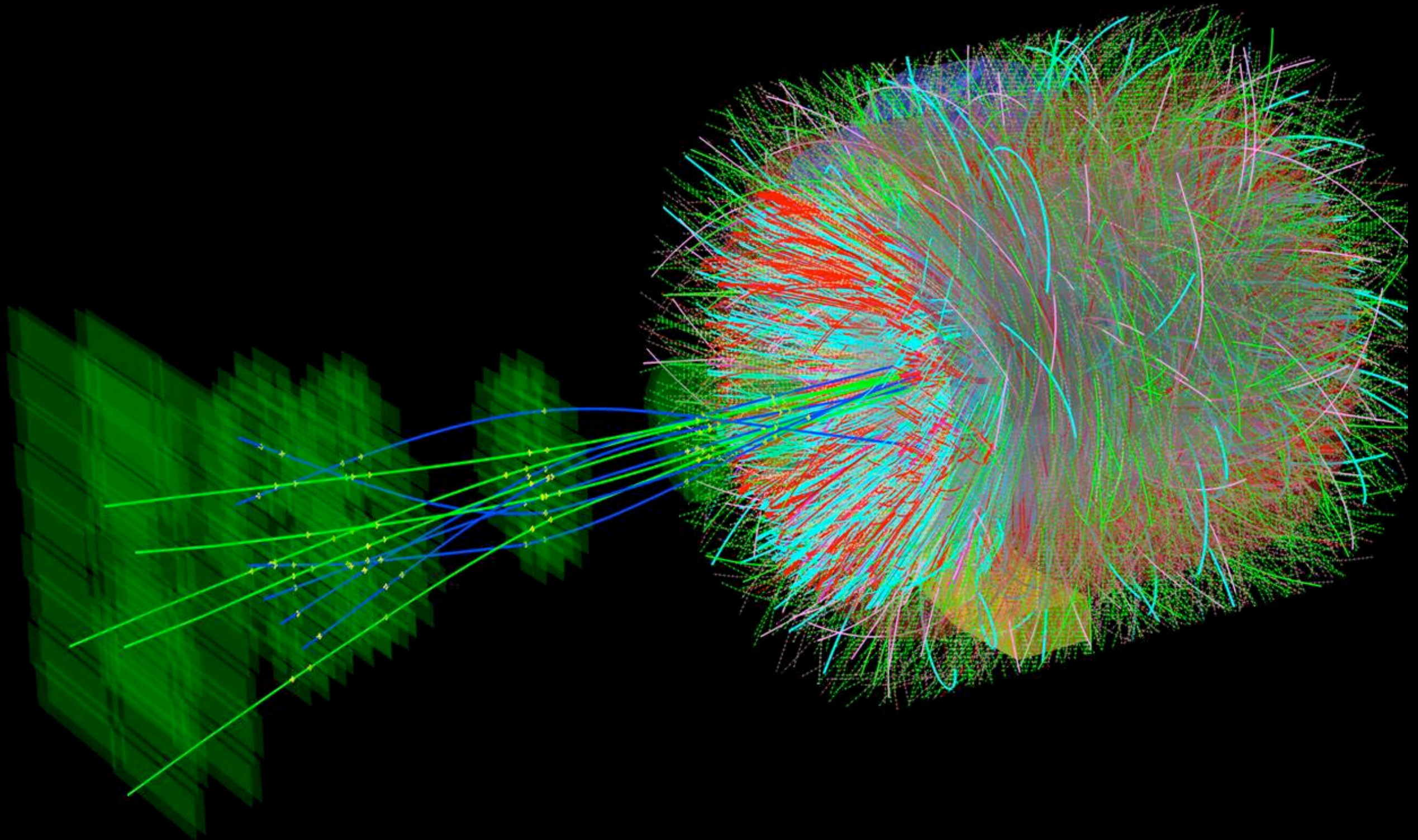
LHC Heavy-Ion Running

year	system	energy ($\sqrt{s_{NN}}$)	delivered int. luminosity
2010	Pb-Pb	2.76 TeV	$\sim 10 \mu\text{b}^{-1}$
2011	Pb-Pb	2.76 TeV	$\sim 150 \mu\text{b}^{-1}$
2013	p-Pb	5.02 TeV	$\sim 30 \text{nb}^{-1}$

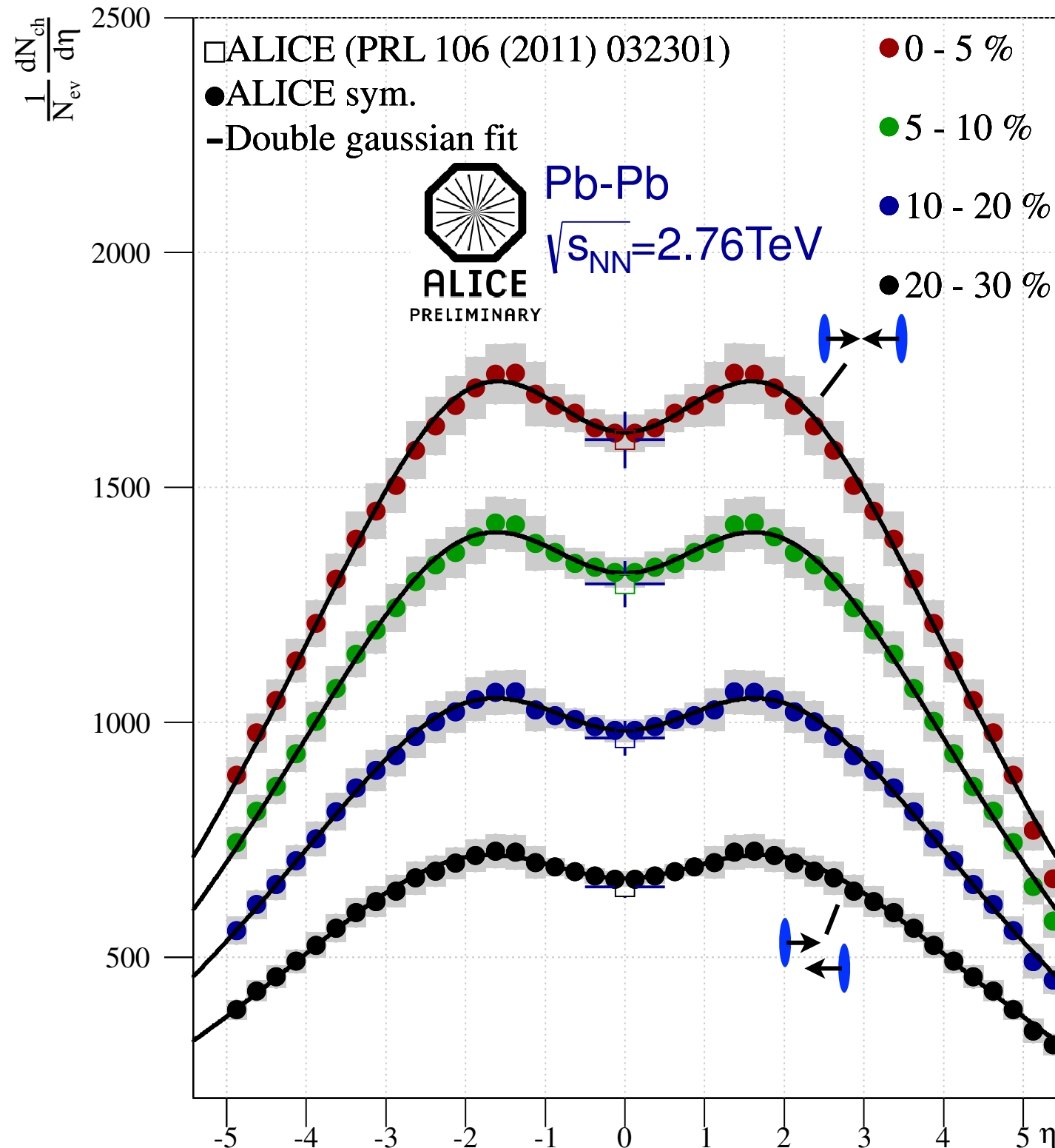
Luminosity reached in 2011: $2 \times 10^{26} \text{ cm}^{-2}\text{s}^{-1}$

Global Event Properties

Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV



Charged Particle Multiplicity in Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV



- $\sim 25\,000$ produces particles in total in central Pb-Pb (full phase space, charged + neutrals)

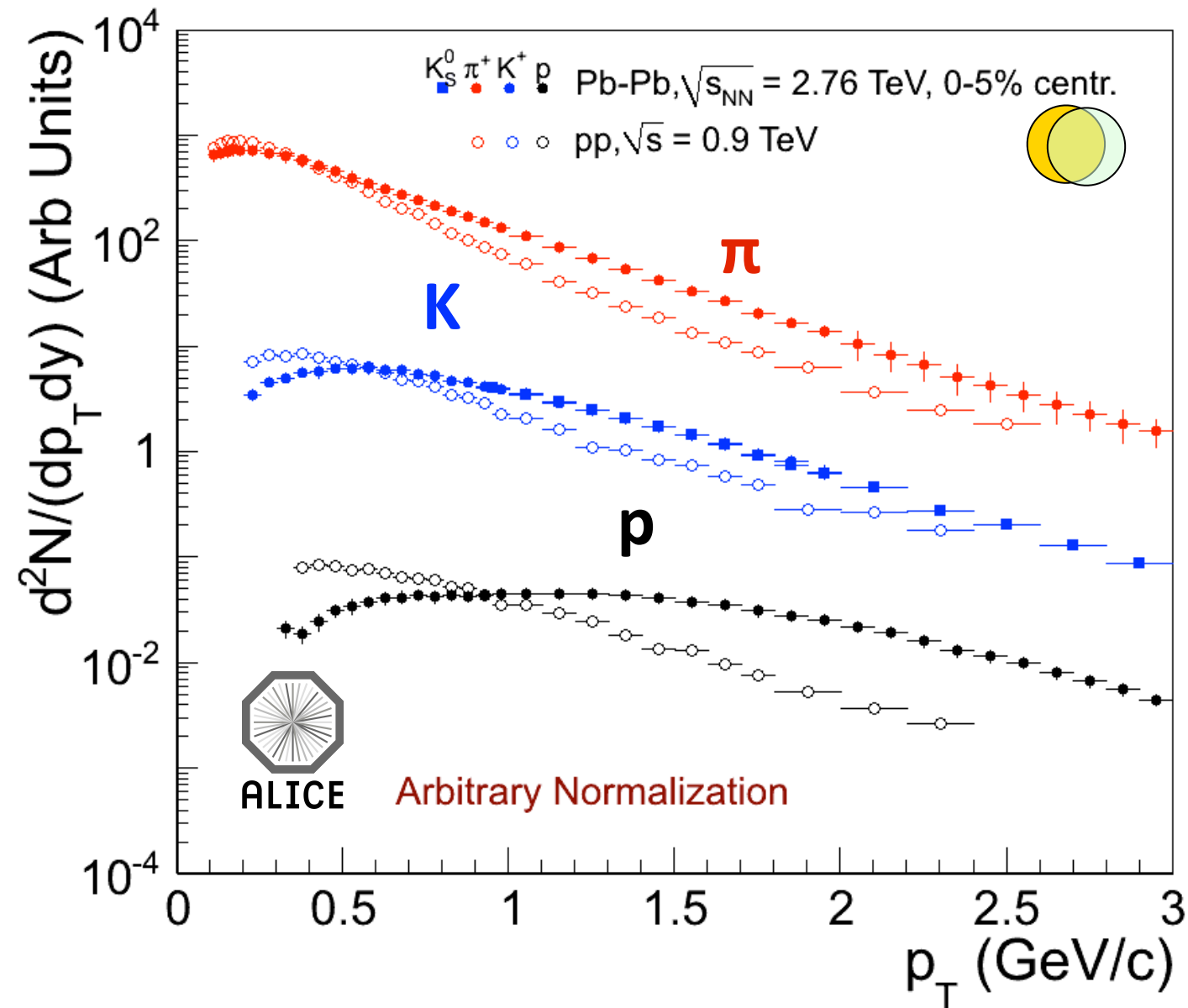
- Initial energy density (for $\tau_0 = 1 \text{ fm}/c$):

$$\varepsilon_{\text{LHC}} \approx 15 \text{ GeV}/\text{fm}^3 \approx 3 \times \varepsilon_{\text{RHIC}}$$

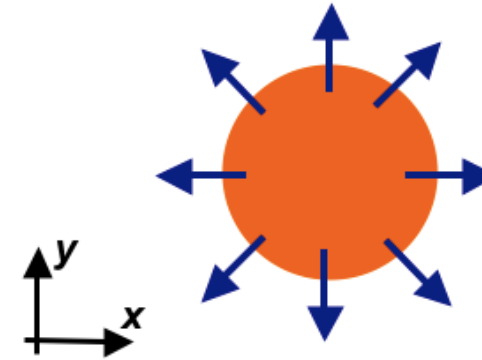
$$\varepsilon = \frac{dE_T/dy}{\tau_0 \pi R^2} \approx \frac{3}{2} \langle m_T \rangle \frac{dN_{\text{ch}}/d\eta}{\tau_0 \pi R^2}$$

Initial energy density at the LHC well above $\varepsilon_c \approx 0.5 \text{ GeV}/\text{fm}^3$

π , K, p Spectra in Pb-Pb at 2.76 TeV: Characteristic Features of Isotropic Radial Flow



Radial flow

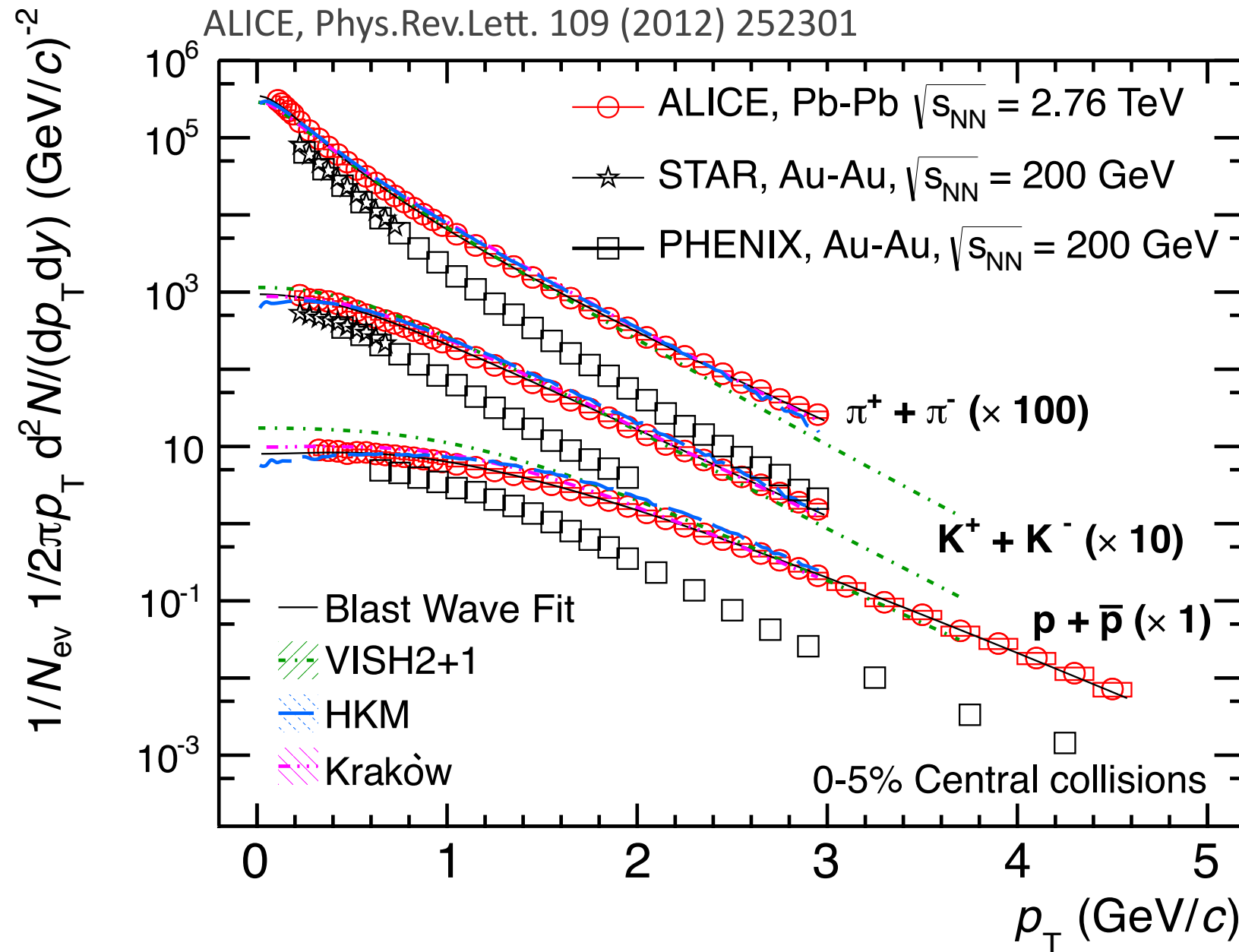


- Fireball pressure creates velocity profile
- Stronger modification of p_T spectra for heavier particles

$$p_T^{w/flow} = p_T^{w/o flow} + \beta_{T,flow} \gamma_{T,flow} m$$

Change of shape of p_T spectra from pp to Pb-Pb as expected from isotropic radial flow

π , K, p Spectra: Comparison to Hydro Models and RHIC Data



■ Hydro + hadronic cascade describes data (HKM)

■ Average flow velocities (from blast-wave fits)

▶ $\langle \beta_{T,flow} \rangle \approx 0.65 c$

▶ $\langle \beta_{T,flow} \rangle_{LHC} \approx 1.1 \times \langle \beta_{T,flow} \rangle_{RHIC}$

(full hydro modeling gives similar results)

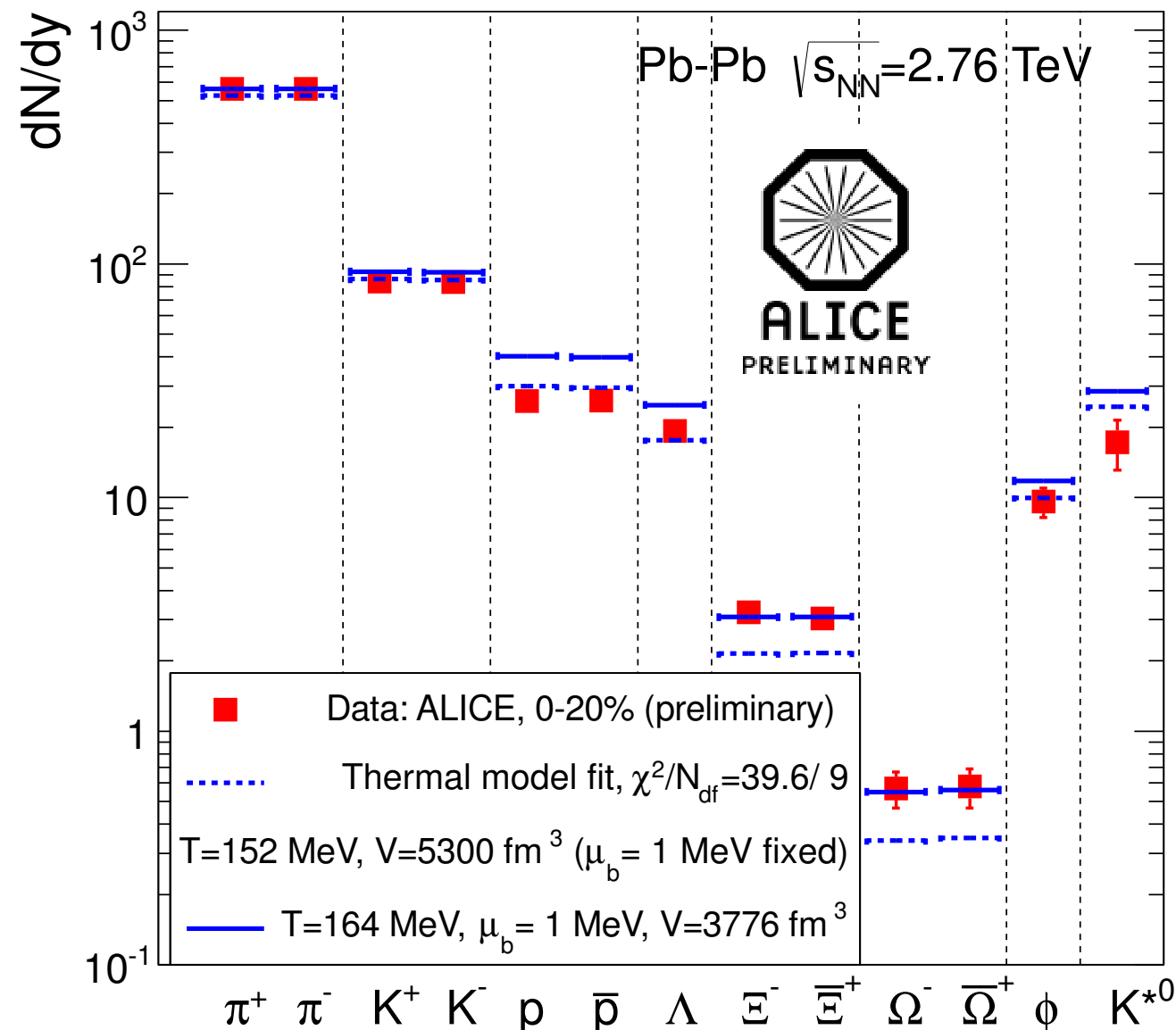
Data support hydro picture for QGP phase

Particle Yields: The Puzzle of the Small Proton Yields

statistical model:

$$n_i = \frac{g_i}{(2\pi)^3} \int \frac{1}{\exp\left(\frac{E_i - \mu_i}{T_{\text{ch}}}\right) \pm 1} d^3p$$

$$\mu_i = B_i \mu_B + S_i \mu_S + I_{3,i} \mu_{I_3}$$



- Strangeness enhancement in Pb-Pb relative to pp
 - ▶ 30% for K/π
 - ▶ > factor 3 for Ω/π
- Statistical model describes strangeness enhancement with $T_{\text{ch}} = 164$ MeV
- p/π off by factor > 1.5: puzzling, proton-antiproton annihilation in hadronic phase?
 Phys.Rev.Lett. 110 (2013) 042501

Small overall p/π ratio puzzling,
physical origin to be clarified

Anisotropic Collective Flow

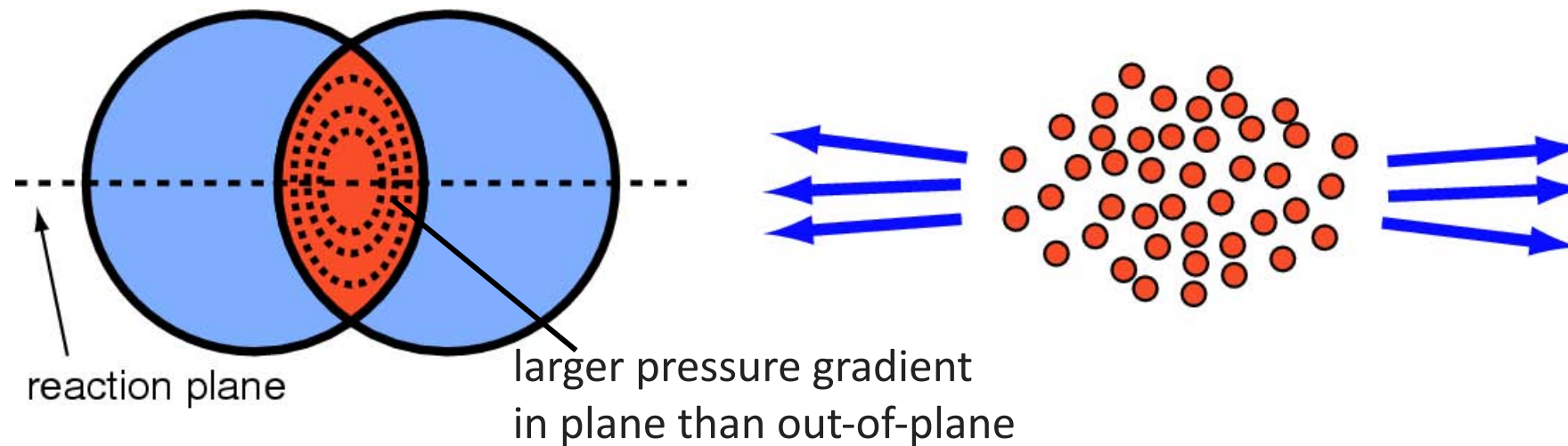
Anisotropic Flow

Classical view:

Initial spatial anisotropy



anisotropy in momentum space



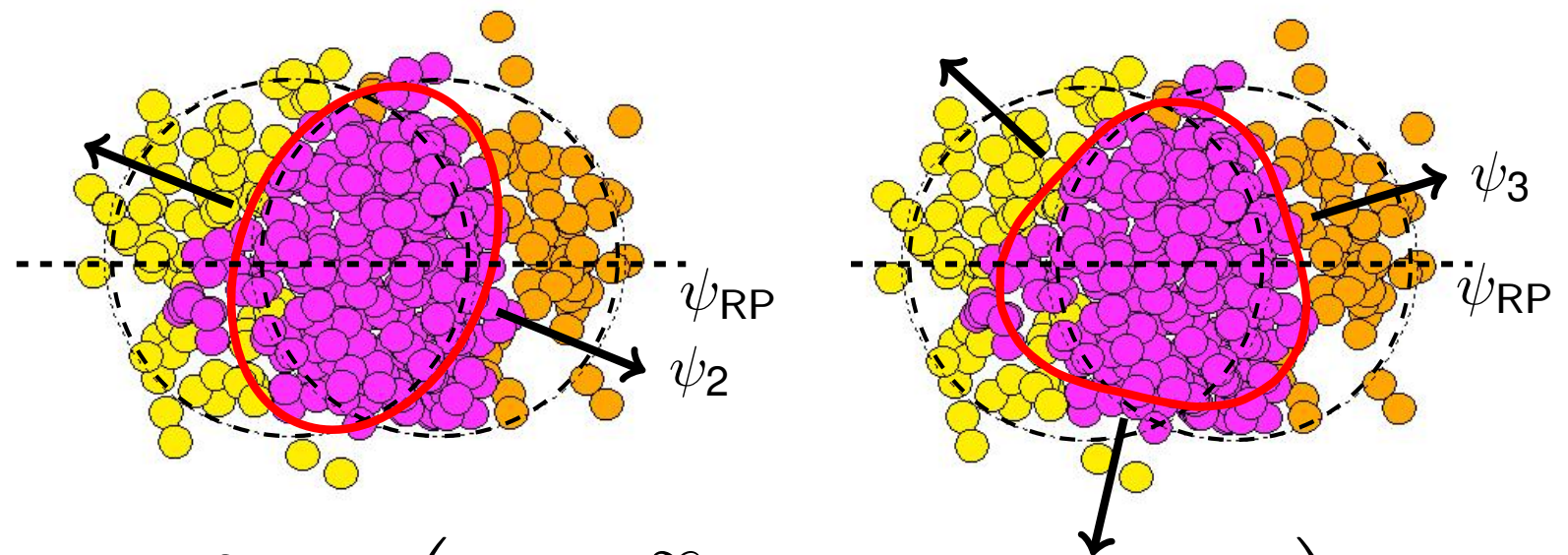
Revised picture (ca. 2010):

Importance of initial energy density fluctuations

$$\psi_2 \approx \psi_{RP}$$

ψ_2 not correlated with ψ_3

figure from arXiv:1107.0592



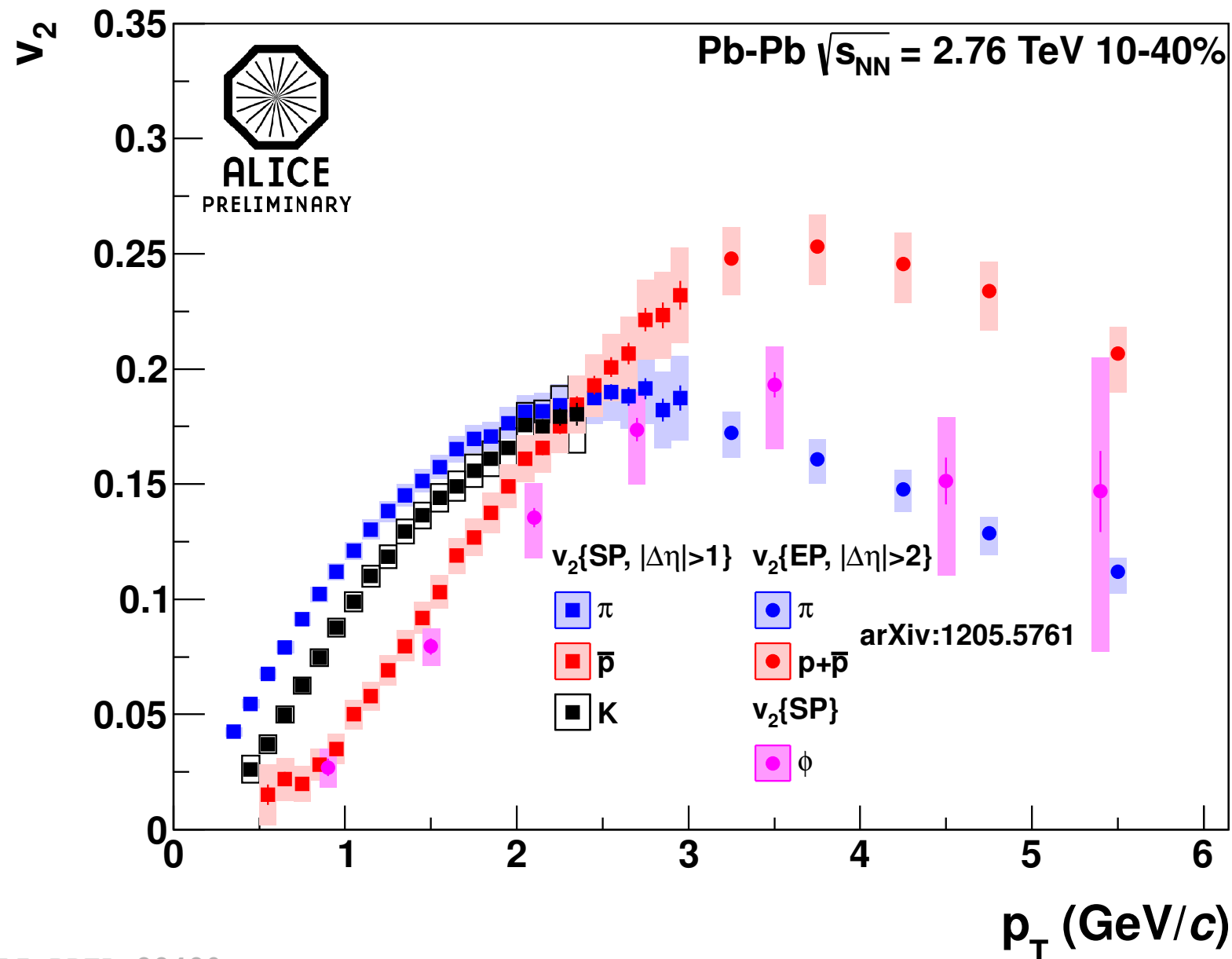
Fourier decomposition:

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

v_2 : elliptic flow,

v_3 : triangular flow

Identified Particle v_2 : Mass Ordering Supports Hydro Picture



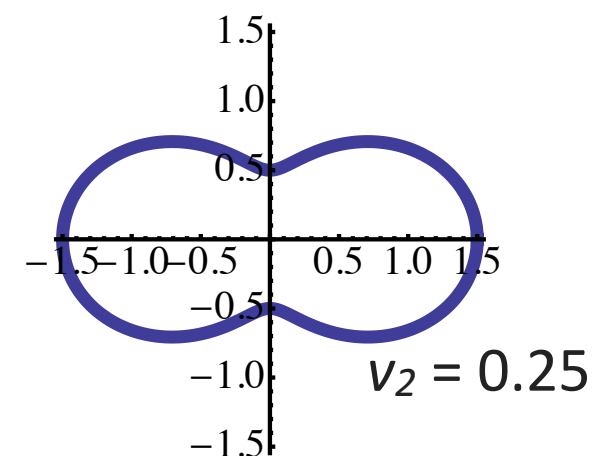
- Hydro predicts mass ordering

$$v_2 \sim \frac{1}{T} (p_T - \langle \beta_{T,\text{flow}} \rangle \cdot m_T)$$

$$m_T = \sqrt{m^2 + p_T^2}$$

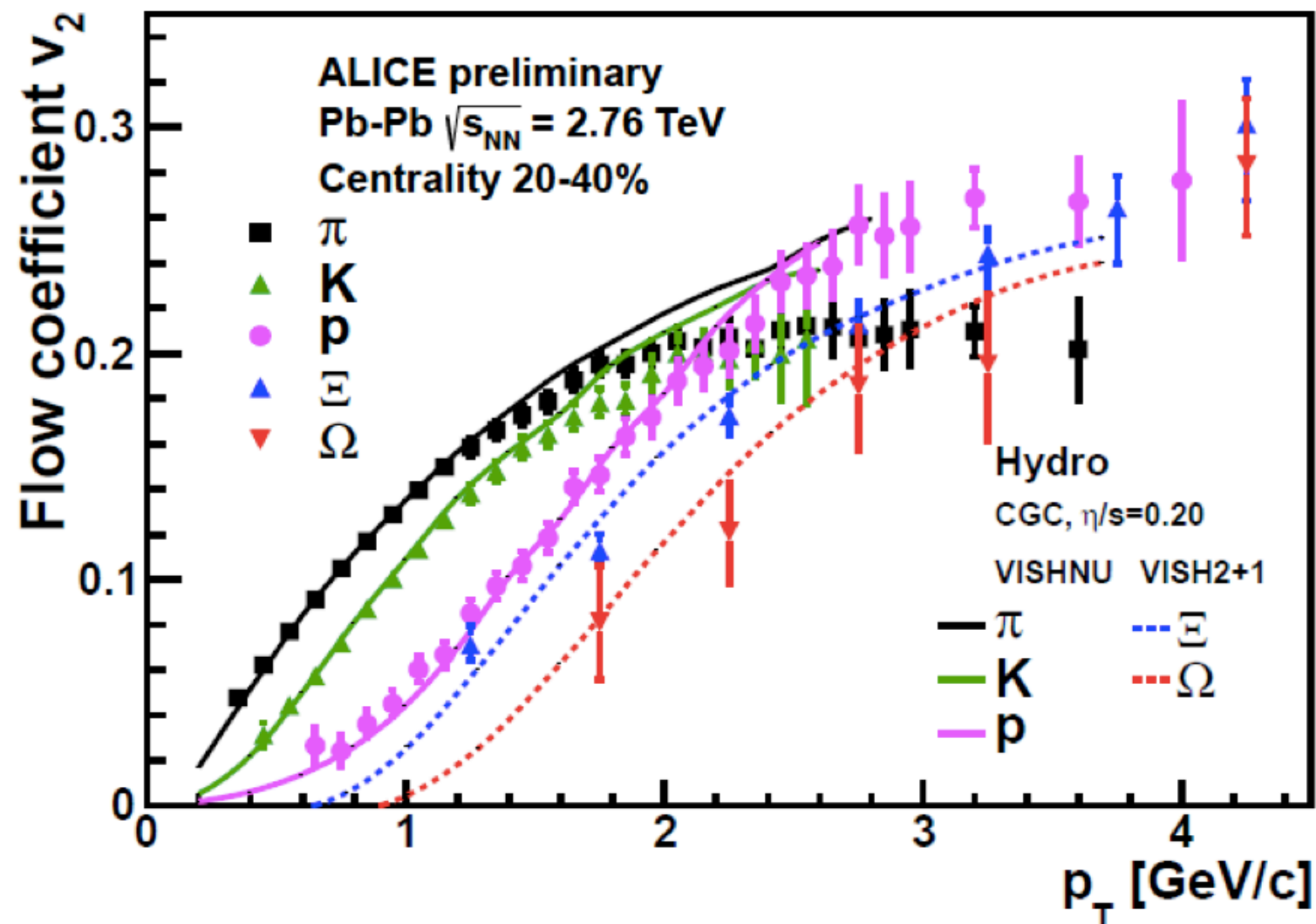
N. Borghini, J.-Y. Ollitrault,
Phys.Lett. B642 (2006) 227

- Indeed observed!



ALI-PREL-28480

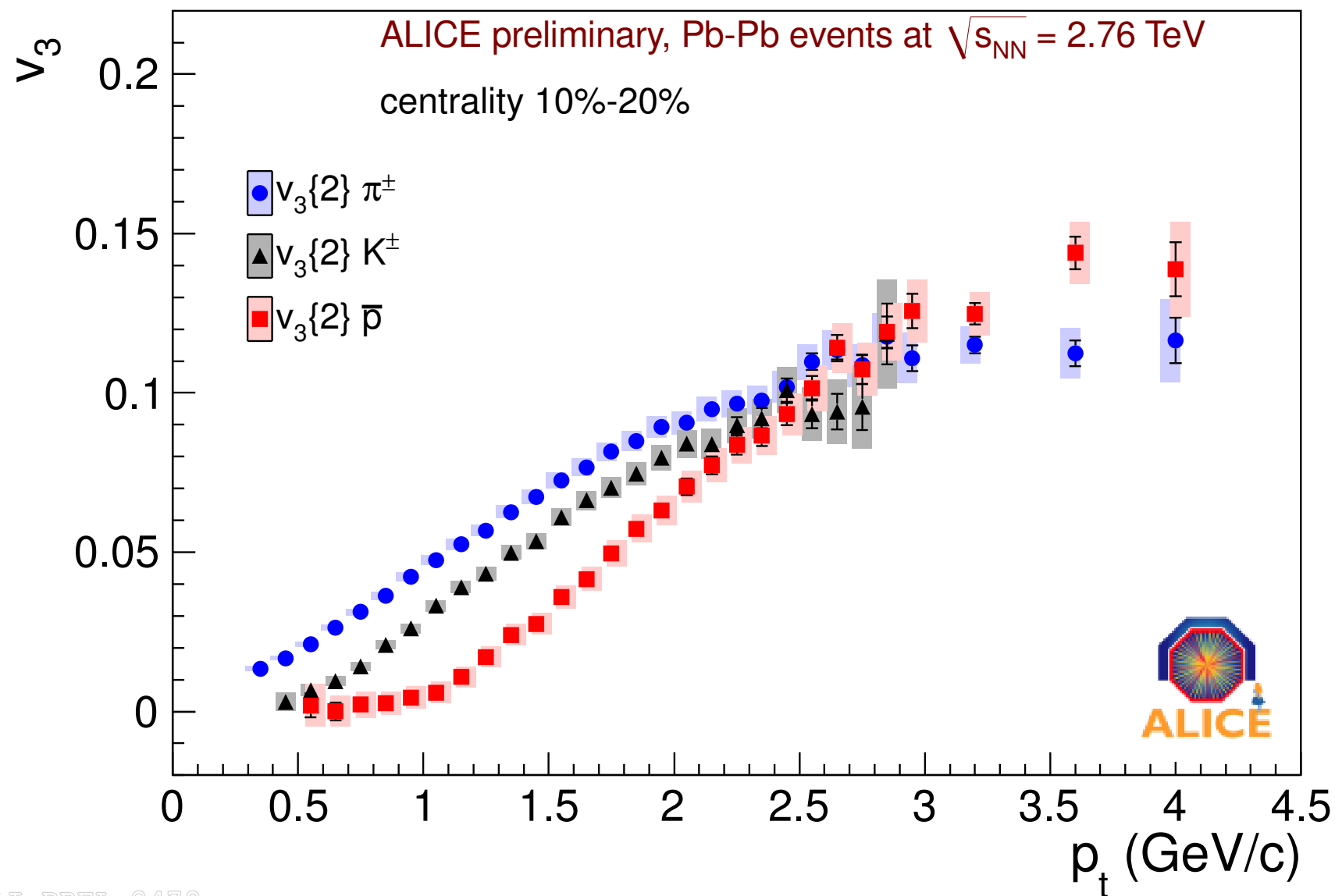
Hydro Models Describe Identified Particle v_2



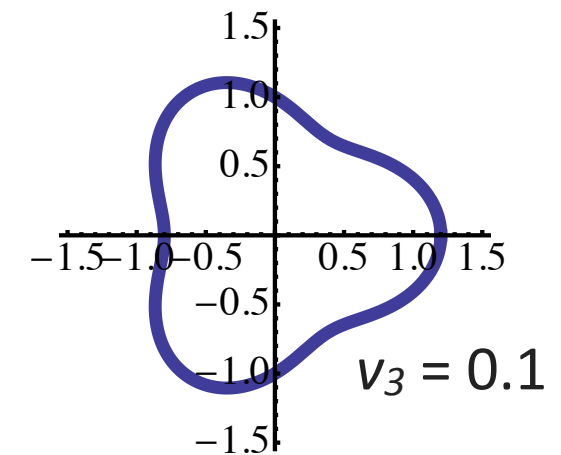
VISHNU
Heinz, Shen, Song,
arXiv:1108.5323

- Shear viscosity reduces differences between expansion velocities and leads to smaller v_2
- Hydro + hadronic cascade (VISHNU) describes data with $\eta/s \approx 0.2 = 2.5 \times 1/4\pi$ (color glass condensate initial condition)
- Current systematic uncertainty on η/s : 50% (e.g. modeling of initial state)

π, K, p v_3 : Mass Splitting As Expected From Hydro Flow



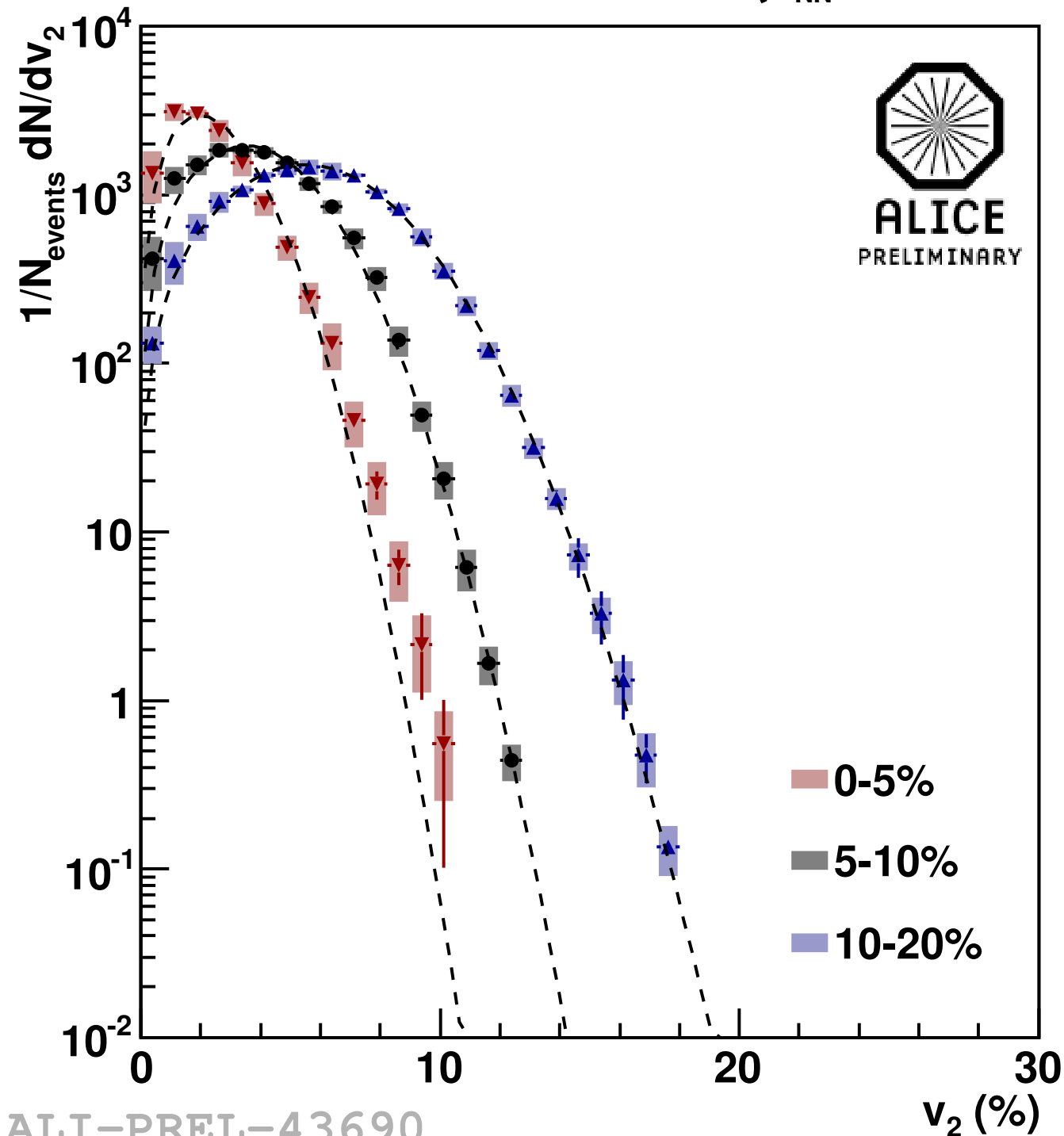
- Sizable v_3 observed
- Sensitivity of v_n to η/s increases with n



ALI-PREL-2479

Event-by-Event v_2 Distributions

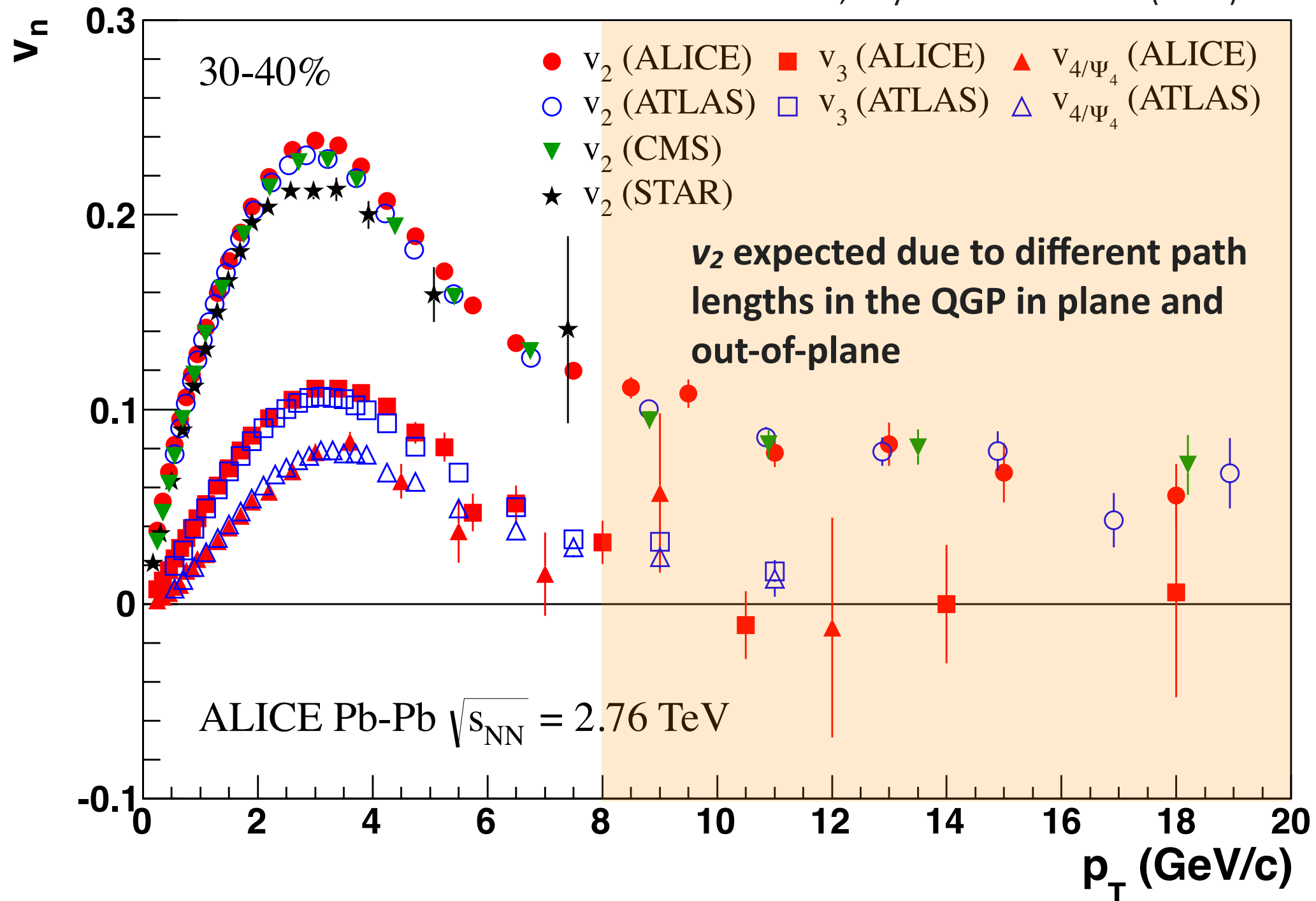
Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV



Direct measure of hydro response to initial energy density fluctuations.
Helps constrain η/s .

$v_2 > 0$ at Large p_T : Parton Energy Loss

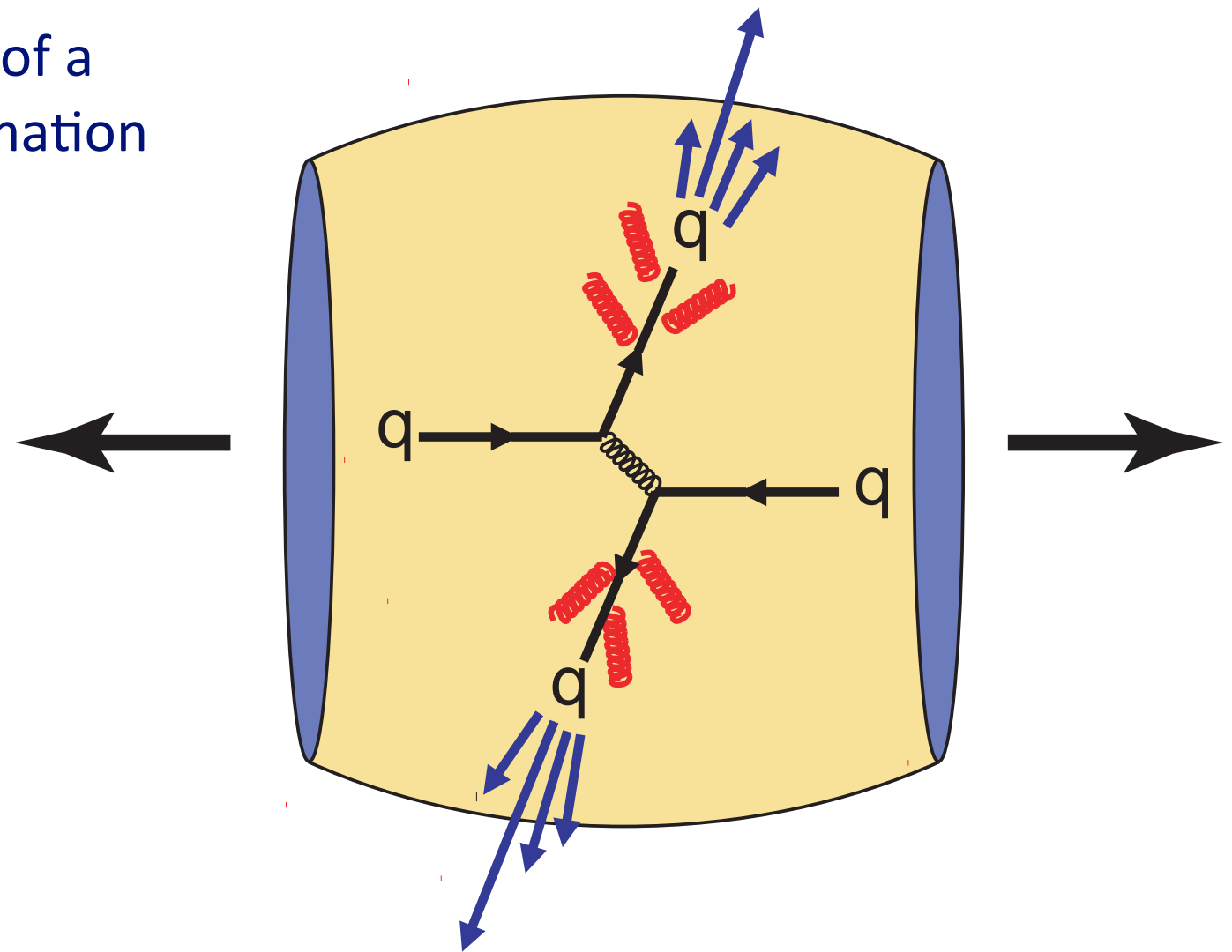
ALICE, Physics Letters B 719 (2013) 18



Jet Quenching

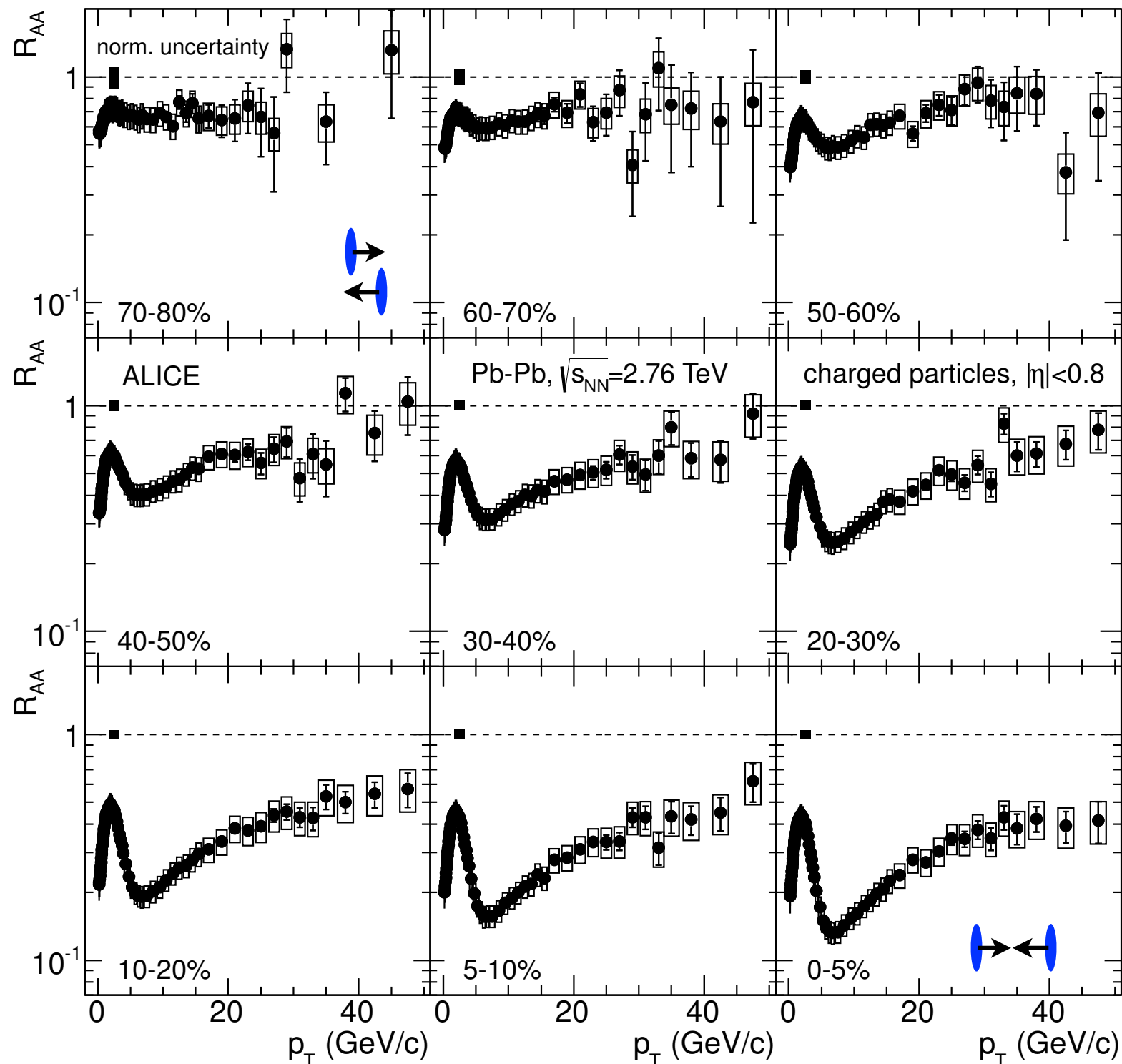
Hard Probes in Heavy-Ion Collisions

- Hard probes are a useful tool because
 - ▶ they are produced in the early stage of a heavy-ion collisions, prior to the formation of the quark-gluon plasma
 - ▶ their initial production rate can be calculated with perturbative QCD („calibrated probe“)
- Interplay between
 - ▶ Understanding of the mechanism of parton energy loss and
 - ▶ Characterization of the QGP



Charged Hadron R_{AA} in Pb-Pb at $\sqrt{s} = 2.76$ TeV

ALICE, Phys. Lett. B720, 42 (2013)



$$R_{AA} = \frac{dN/dp_T(A+A)}{\langle T_{AA} \rangle \times d\sigma/dp_T(p+p)}$$

$$\langle T_{AA} \rangle = \langle N_{\text{coll}} \rangle / \sigma_{\text{inel}}^{pp}$$

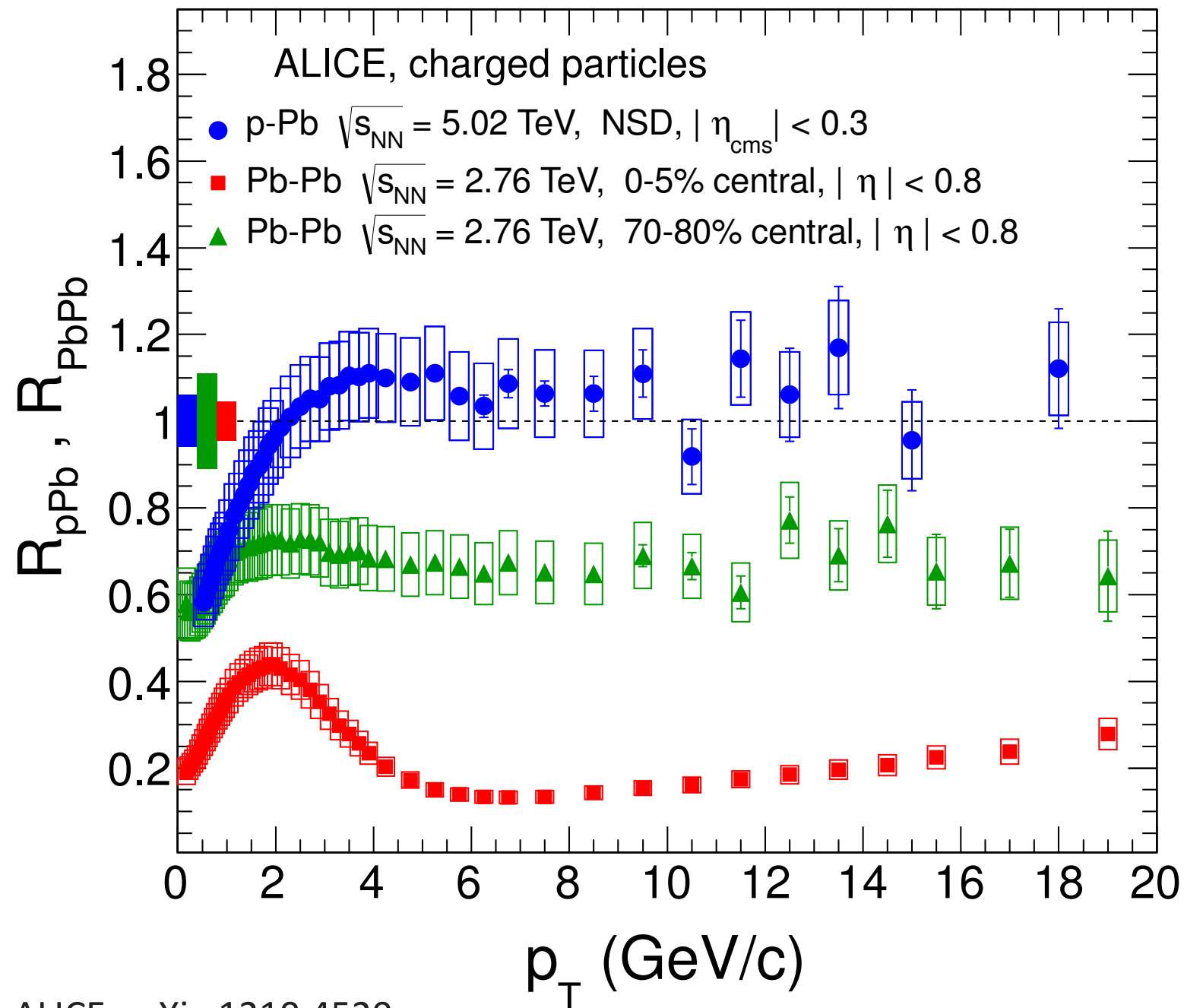
from Glauber calculation

- Expect $R_{AA} = 1$ in the hard scattering regime without nuclear effects ($p_T > 2$ GeV/c)
- Suppression by a factor 7 at $p_T \approx 6-7$ GeV/c
- Rise of R_{AA} for $p_T > 7$ GeV/c indicates decrease of relative parton energy loss $\Delta E/E$ with increasing E

p+Pb at $\sqrt{s} = 5.02$ TeV: No Suppression



p-Pb data from "pilot" run on Sep 13, 2012



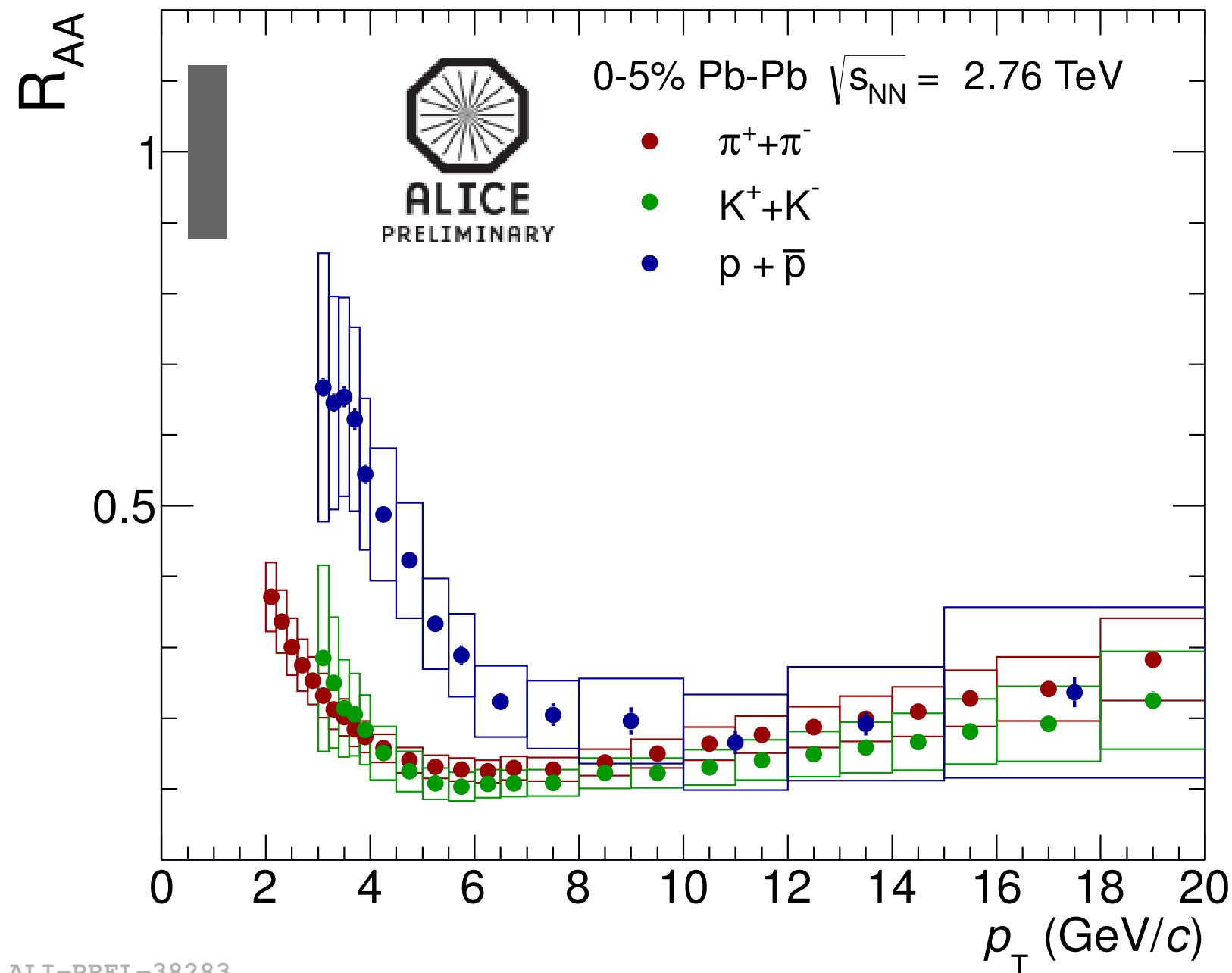
$$R_{pPb} = \frac{dN/dp_T(p + Pb)}{\langle T_{pPb} \rangle \times d\sigma/dp_T(p + p)}$$

$$\langle T_{pPb} \rangle = \langle N_{coll} \rangle / \sigma_{inel}^{pp}$$

pp reference interpolated
from measurements at
 $\sqrt{s} = 2.76$ and 7 TeV

Absence of suppression in p-Pb
confirms that suppression in
Pb-Pb is a final-state effect

R_{AA} for Identified Particles in Central Pb+Pb

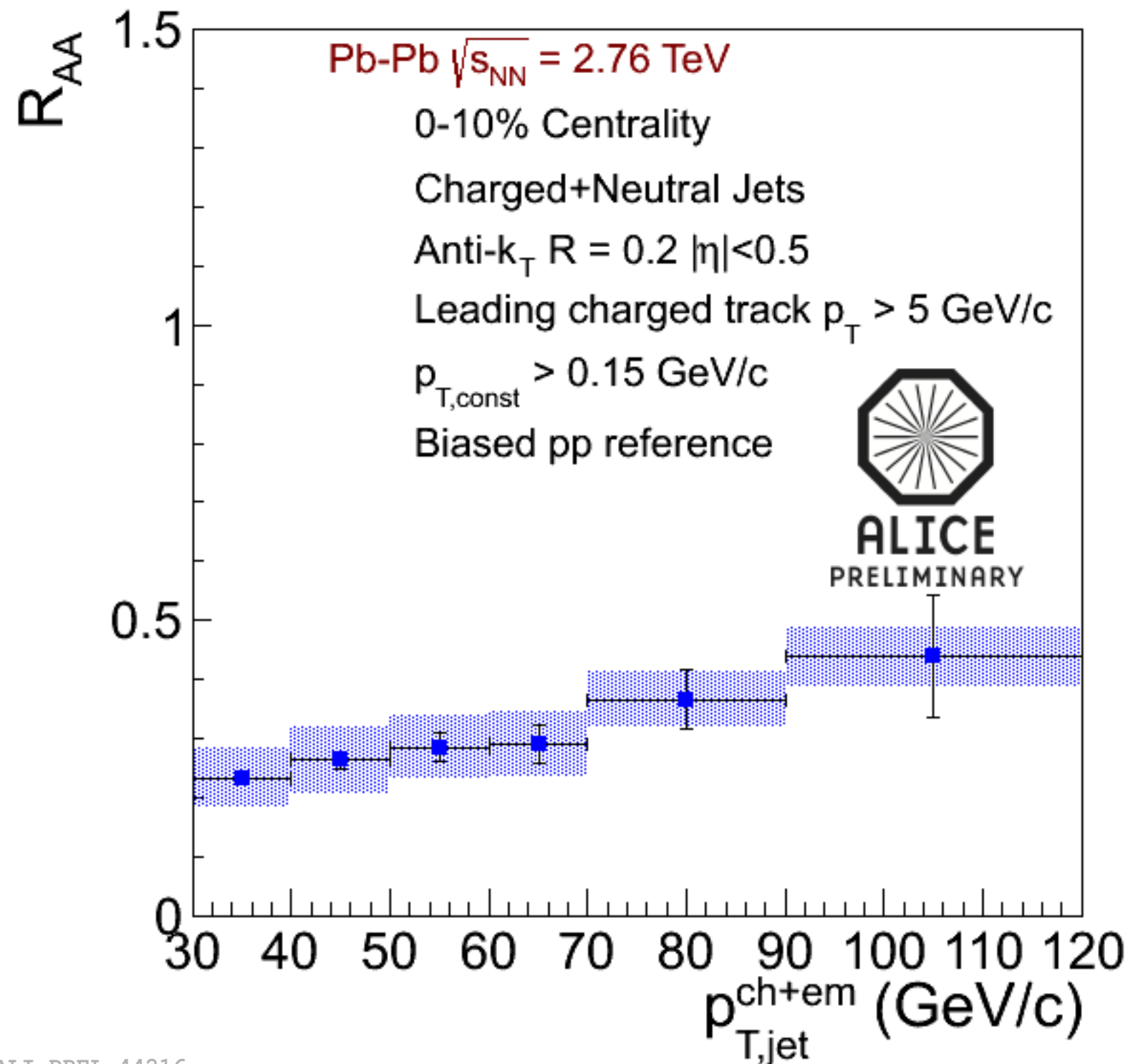


ALI-PREL-38283

- $R_{AA}(p) > R_{AA}(K) \approx R_{AA}(\pi)$ for $3 < p_T < 8$ GeV/c
- Similar p, K and π R_{AA} for $p_T > 8$ GeV/c

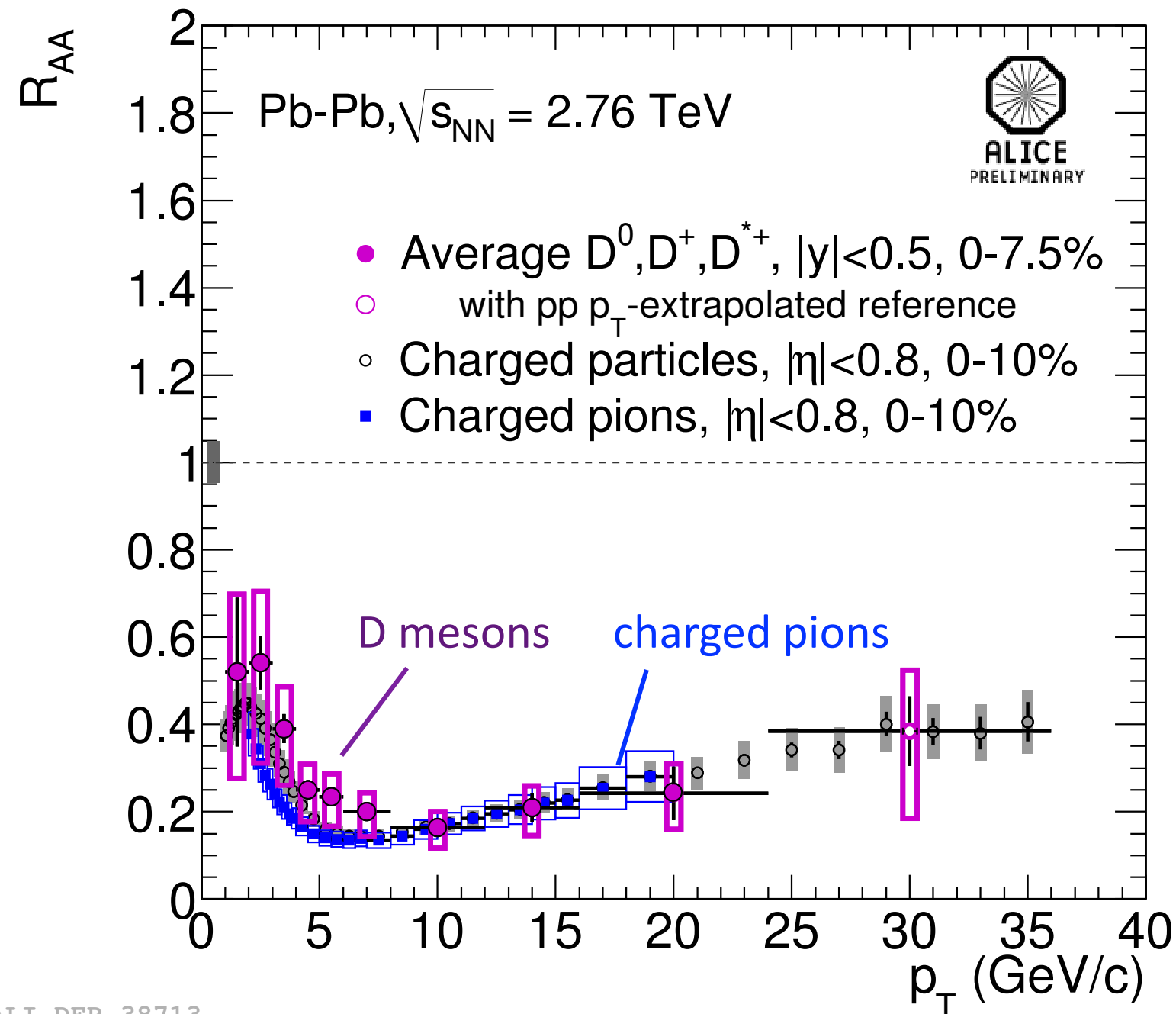
Leading-parton energy loss followed by fragmentation in QCD vacuum (as in pp) for $p_{T,\text{hadron}} > 8$ GeV/c?

Further Important Constraints for Jet Quenching Models from R_{AA} of Fully Reconstructed Jets



- Significant suppression also for jets (Anti- k_T , $R = 0.2$)
- Rise of jet R_{AA} with p_T as for single hadrons

D Meson R_{AA} : Charm Quark Energy Loss Surprisingly Similar to Quark and Gluon Energy Loss



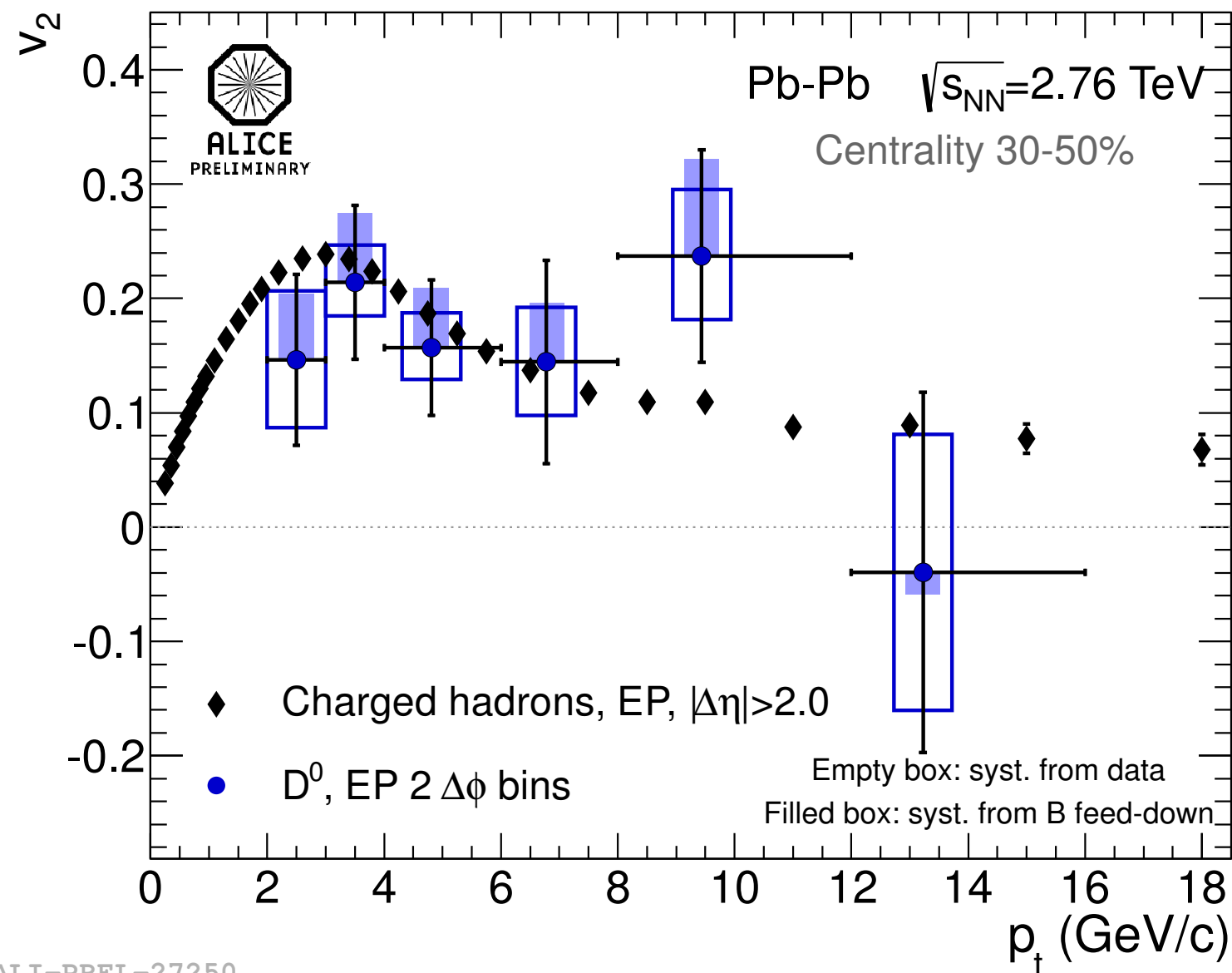
Radiative parton energy loss:

$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

color factor dead cone effect

- Strong suppression also for D mesons (which cannot be explained by shadowing)
- Suppression of D mesons and pions surprisingly similar
 - ▶ pions mainly from gluons
 - ▶ dead cone effect for c and b
- Little indication for expected hierarchy
(however, need to carefully consider also the steepness of the initial parton spectra)

Surprisingly Large Elliptic Flow for D Mesons



- $m_{c\text{-quark}} > 250 \times m_{u,d}$
- Not at all obvious that charm quarks take part in collective flow
- Observation
 - ▶ Significant v_2 for D mesons
 - ▶ Within current errors consistent with charged hadron v_2

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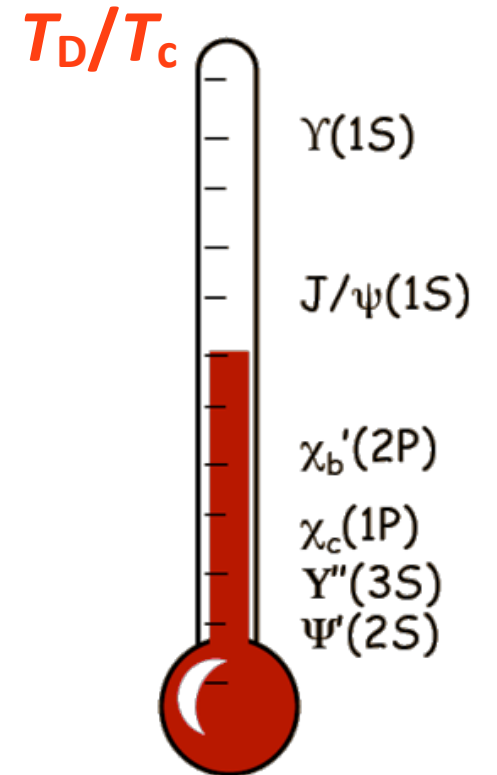
Charmonium

Quarkonia as QGP Signature: Suppression at Low $\sqrt{s_{NN}}$ and J/ψ Enhancement at High $\sqrt{s_{NN}}$?

■ Quarkonium suppression due to color screening

- ▶ Deconfined matter prevents binding of c anti-c (and b anti-b) quarks
- ▶ Dissociation temperature depends on binding energy
→ "QGP thermometer"

	r (fm)	T_D/T_c
J/ψ (1s)	0.42	1.2
ψ' (2s)	0.86	1.0
χ_c (1p)	0.67	1.0
Υ (1s)	0.21	2.0
Υ' (2s)	0.50	1.2
Υ'' (3s)	0.76	1.0



Exact values model dependent, trend stable

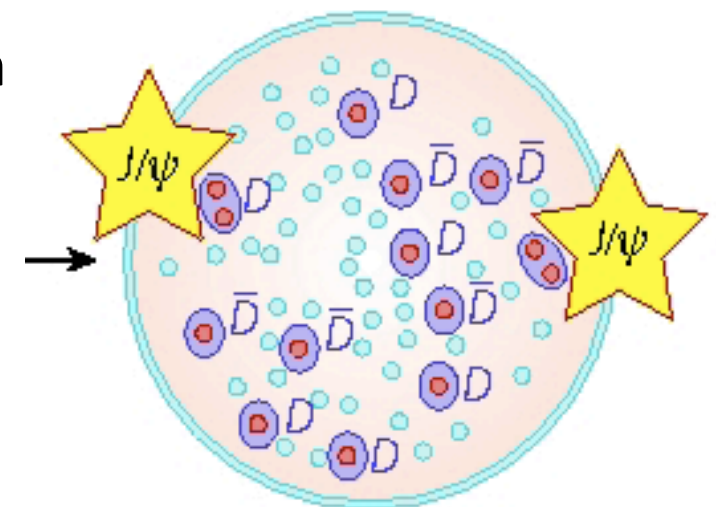
■ Coalescence picture for J/ψ 's

- ▶ J/ψ 's from quark coalescences at phase transition
- ▶ Expect J/ψ suppression at low beam energies (SPS, RHIC) and J/ψ enhancement at high energies (LHC)

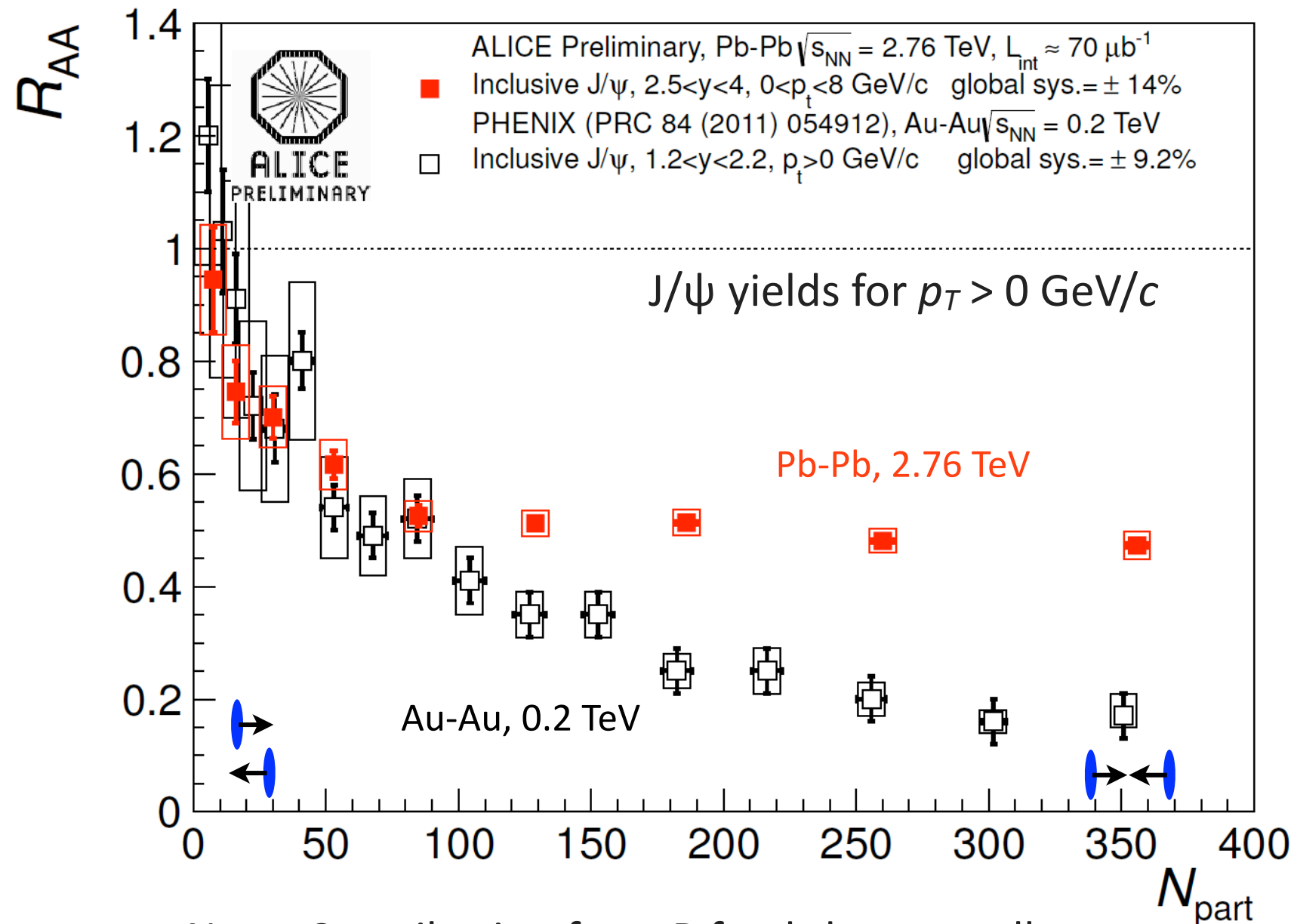
Braun-Munzinger, Stachel, Nature 448 (2007) 302-309

~ 100 $c\bar{c}$ pairs in central Pb+Pb at the LHC

→ J/ψ through coalescence?



J/ψ R_{AA} : Less Suppression at the LHC than at RHIC

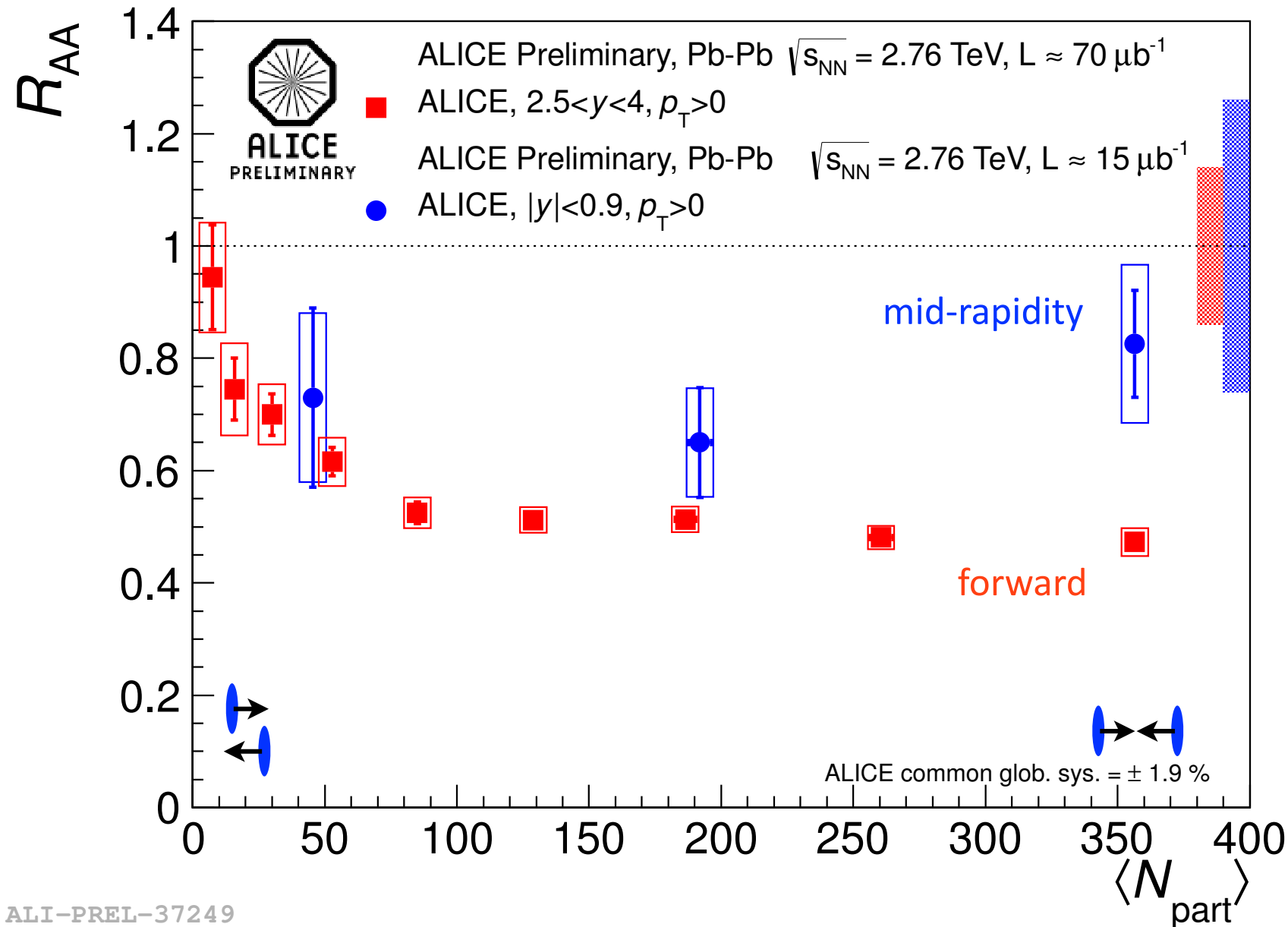


Note: Contribution from B feed-down small:
 $\sim 10\%$ (from pp-measurement)

Qualitatively consistent with J/ψ coalescence picture

- Expect larger suppression at the LHC if J/ψ suppression due to color screening is the dominant effect
- Observation:
 - ▶ Weaker suppression at the LHC
 - ▶ J/ψ constant at the LHC for $N_{part} > 75$ ($R_{AA} \approx 0.5$ [$p_T > 0$ GeV/c])

J/ψ R_{AA} : Stronger Suppression at Forward Rapidities

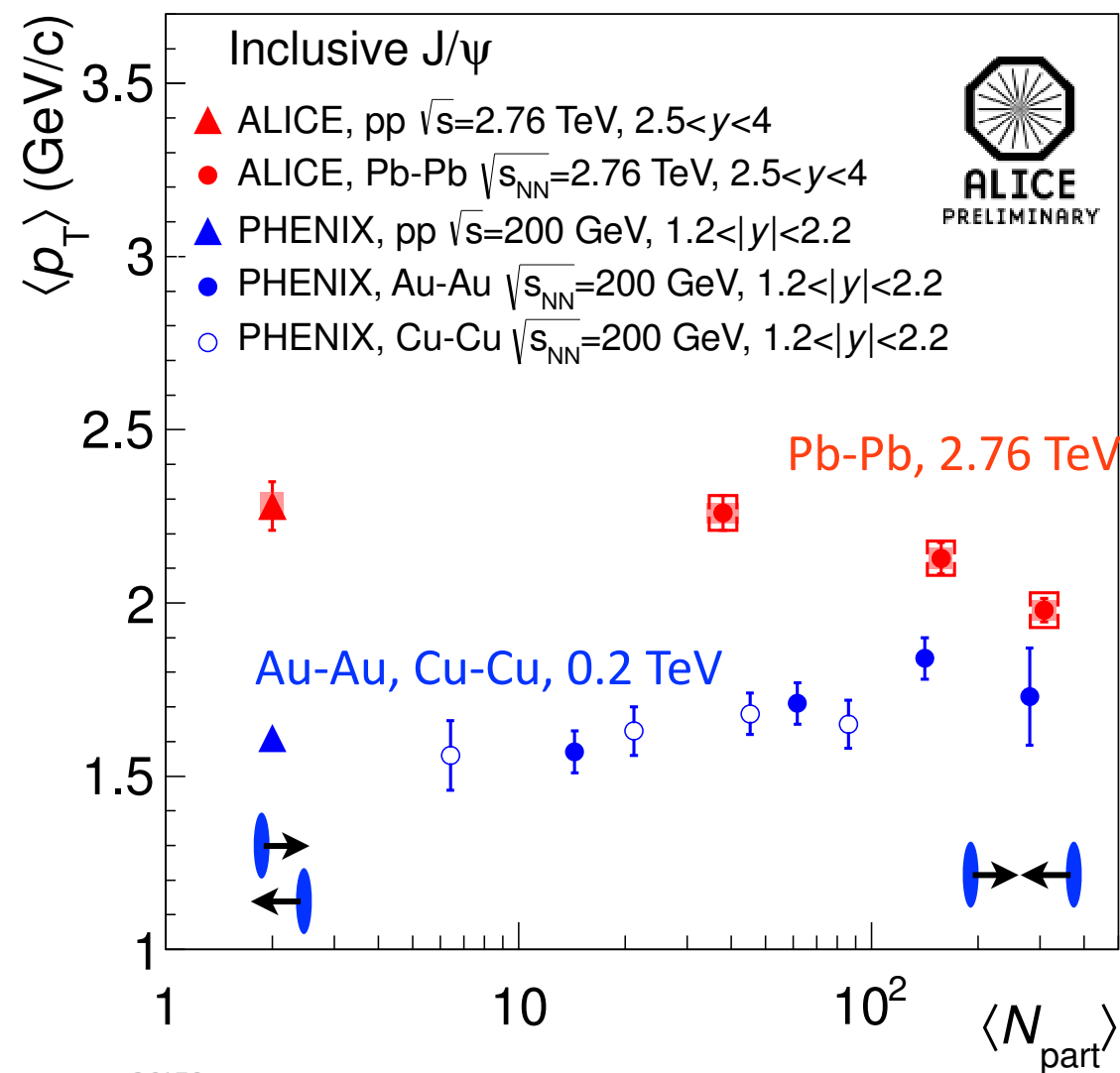


Expect opposite trend if J/ψ suppression is driven by energy density

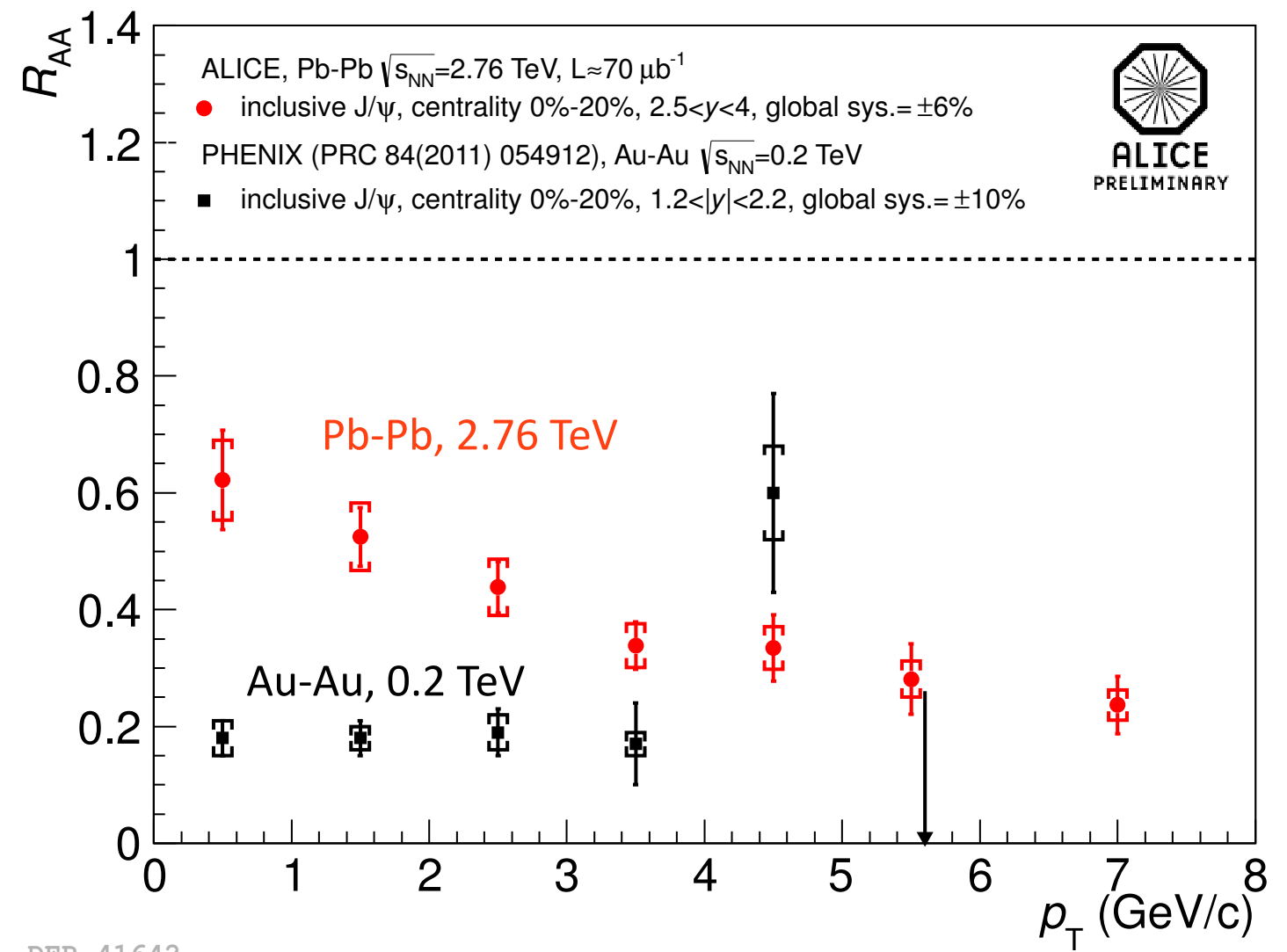
Qualitatively consistent with J/ψ coalescence picture

ALI-PREL-37249

Centrality Dependence of J/ψ $\langle p_T \rangle$ and p_T Dependence of the J/ψ R_{AA} Qualitatively Consistent with the Coalescence Picture



ALI-PREL-36179

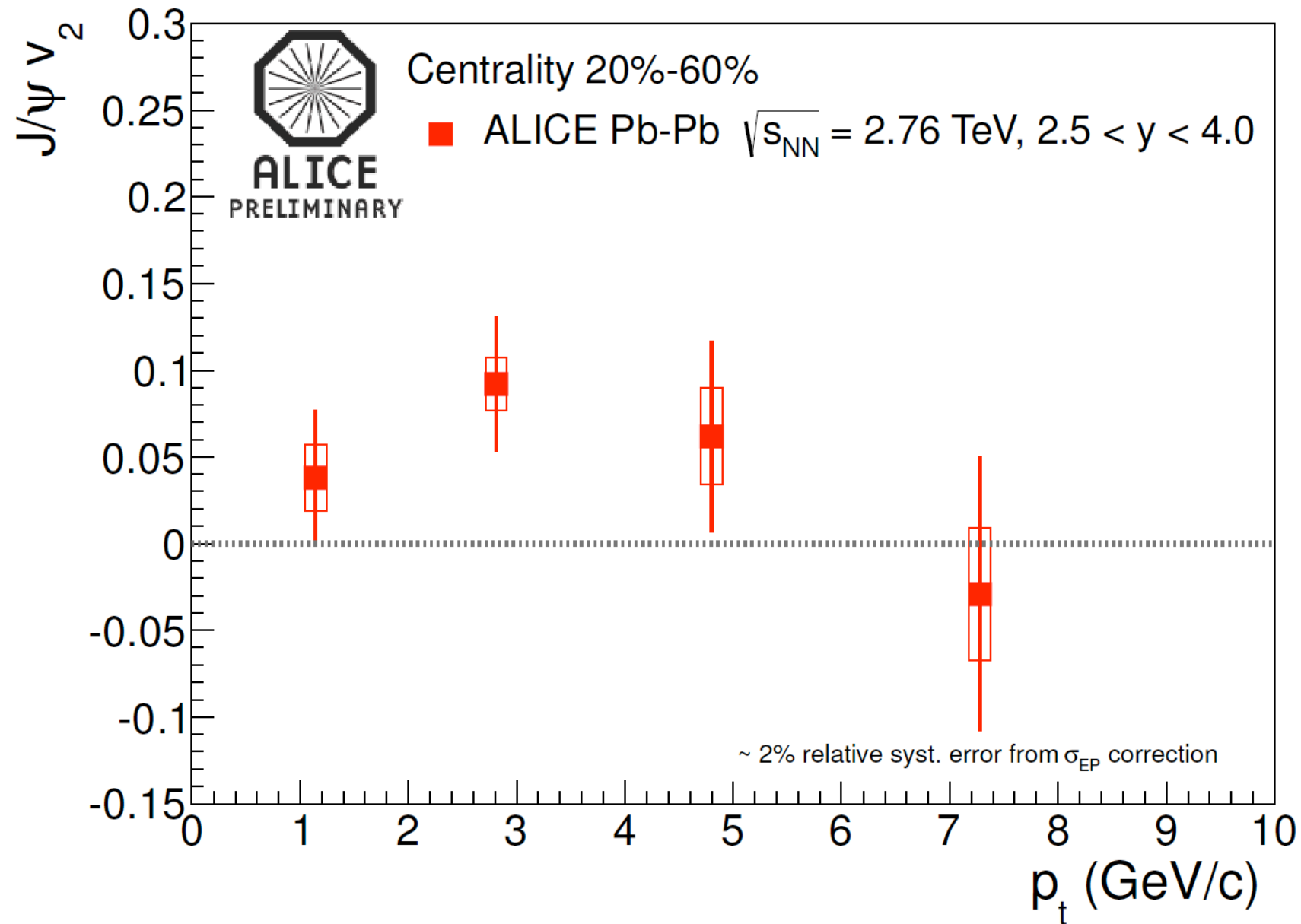


-DER-41642

Decrease of J/ψ R_{AA} in central Pb-Pb.
Not observed at lower energies or
for other particles species at the LHC.

Less suppression of J/ψ R_{AA} at low p_T at LHC,
in contrast to constant $R_{AA}(p_T)$ at RHIC

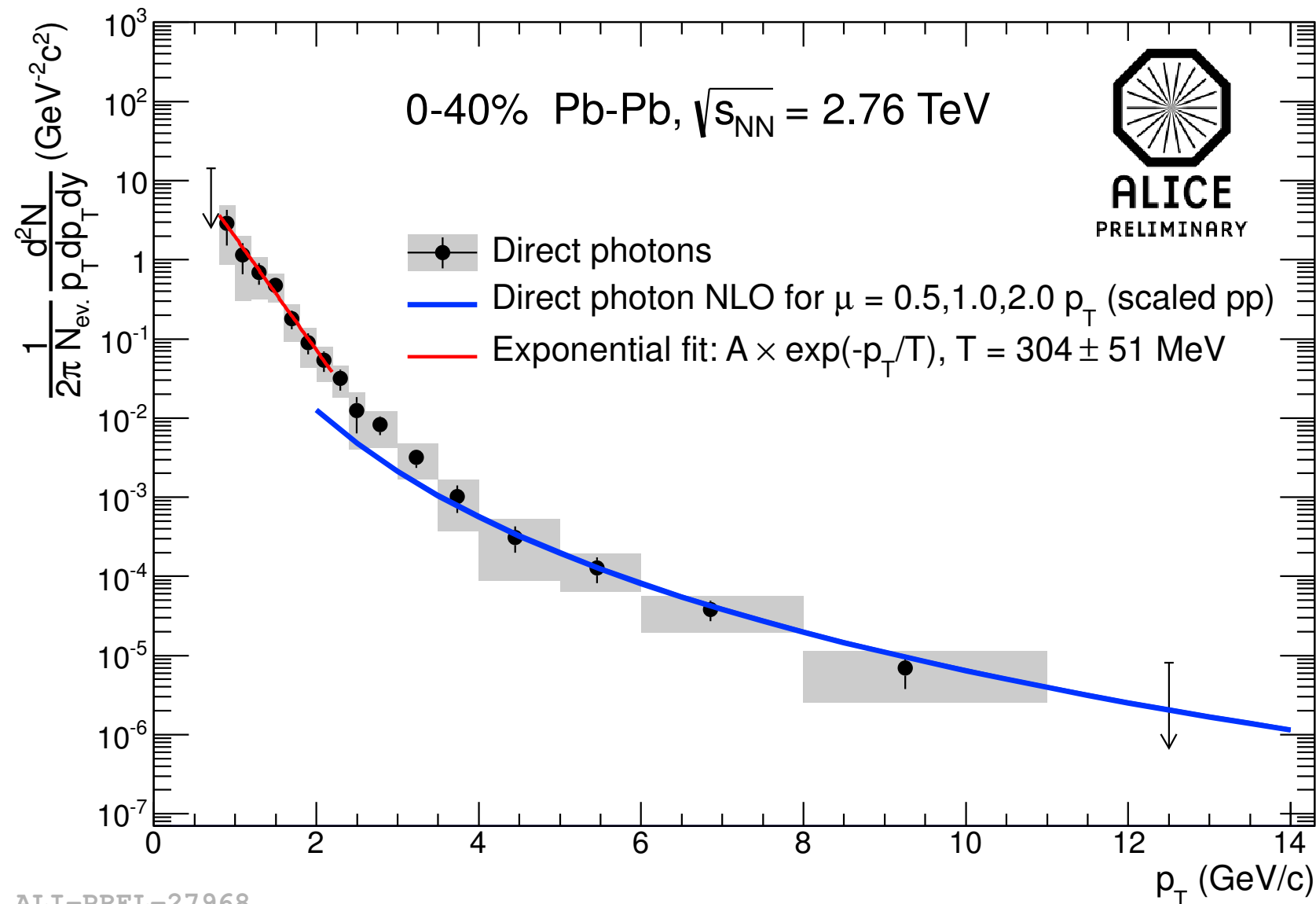
Significant J/ψ Elliptic Flow (as Expected in Coalescence Models)



- Indication for $J/\psi v_2 > 0$ for $2 < p_T < 4$ GeV/c
- Significance: 2.2σ

Thermal Photons

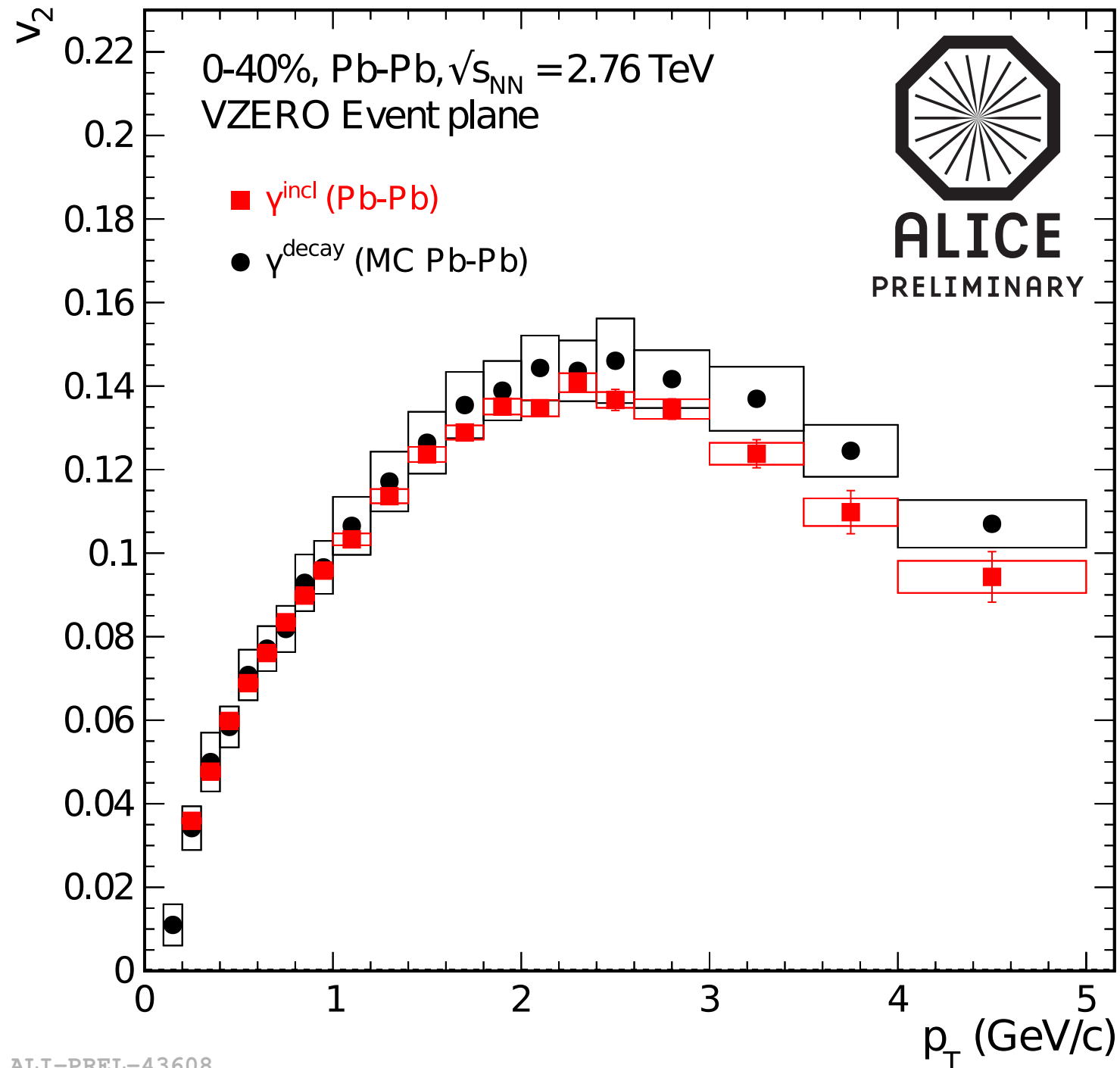
Direct Photon Spectrum in Central Pb-Pb



Conventional wisdom:
 Direct photons predominantly from early hot QGP phase when flow has not fully built up (then inv. slope T is related to QGP temperature).
 Expect small direct-photon v_2 in this case.

- Photons reconstructed via e^+e^- tracks from conversion in detector material ($p_{conv} \approx 8.5\%$)
- π^0 spectrum from same photon sample
- $\gamma_{direct} := \gamma_{inclusive} - \gamma_{decay}$
- Excess above decay photons: $\sim 15\%$
 (for $1 < p_T < 5$ GeV/c, 0-40% Pb+Pb)
- Low p_T direct photon spectrum exponential with inv. slope parameter $T = 304 \pm 51$ MeV

Measurement of the Direct-Photon v_2



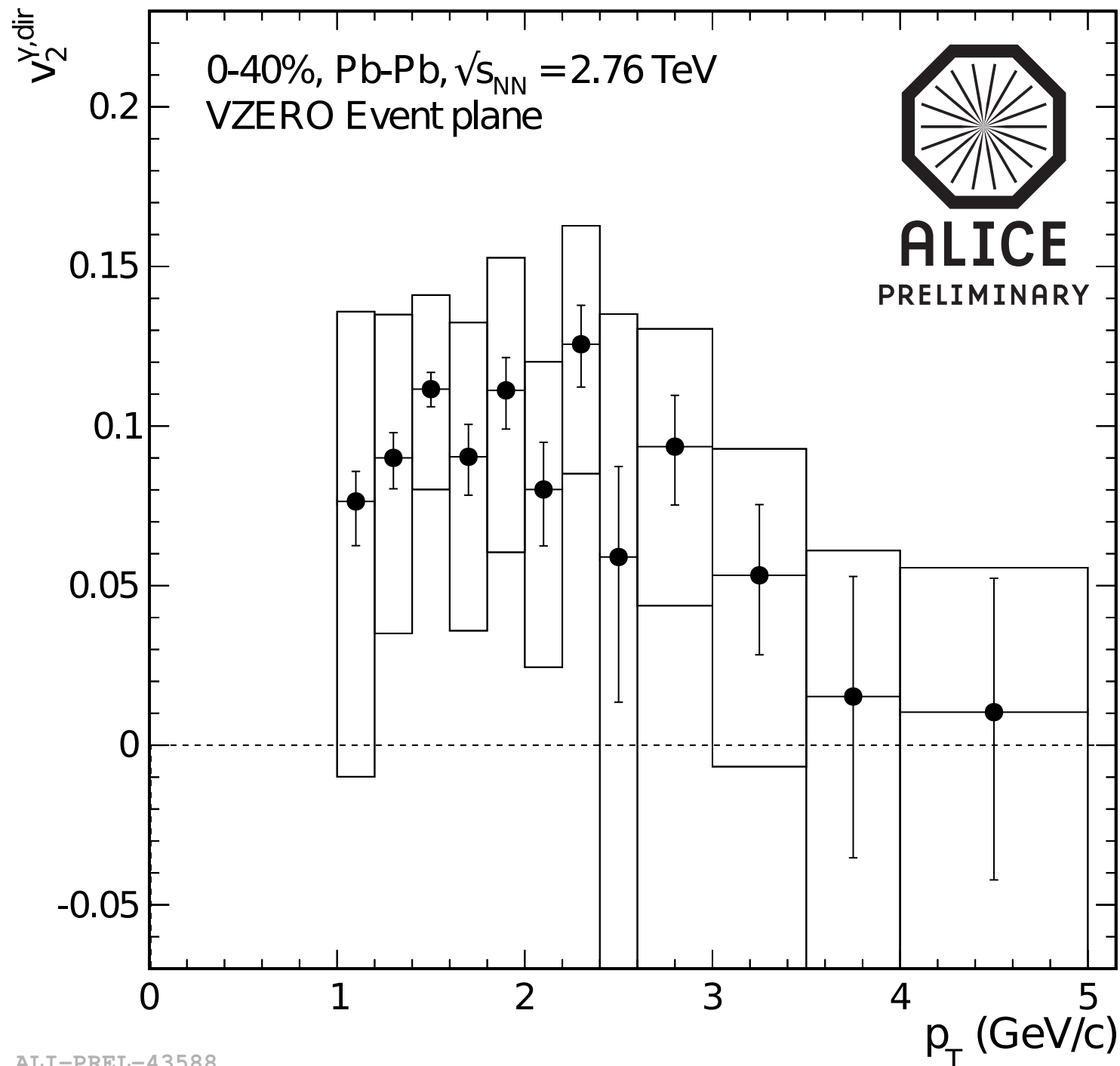
ALI-PREL-43608

- Measure inclusive photon v_2
- Subtract decay photon v_2

$$v_2^{\gamma, \text{dir}} = \frac{R v_2^{\gamma, \text{incl}} - v_2^{\gamma, \text{decay}}}{R - 1}$$

$$R = \gamma^{\text{incl}} / \gamma^{\text{decay}}$$

Large Direct-Photon Elliptic Flow: A Big Puzzle!



ALI-PREL-43588

- Direct-photon v_2 much larger than expected in most hydro models
- Possible solution (van Hees, Rapp)
 - ▶ Flow builds up faster than expected
 - ▶ Thermal photon rates in hadron gas so far underestimated
 - ▶ Large inv. slope of would then result from blueshift:

$$T_{\text{slope}} = \sqrt{\frac{1 + \beta_{\text{flow}}}{1 - \beta_{\text{flow}}}} T$$

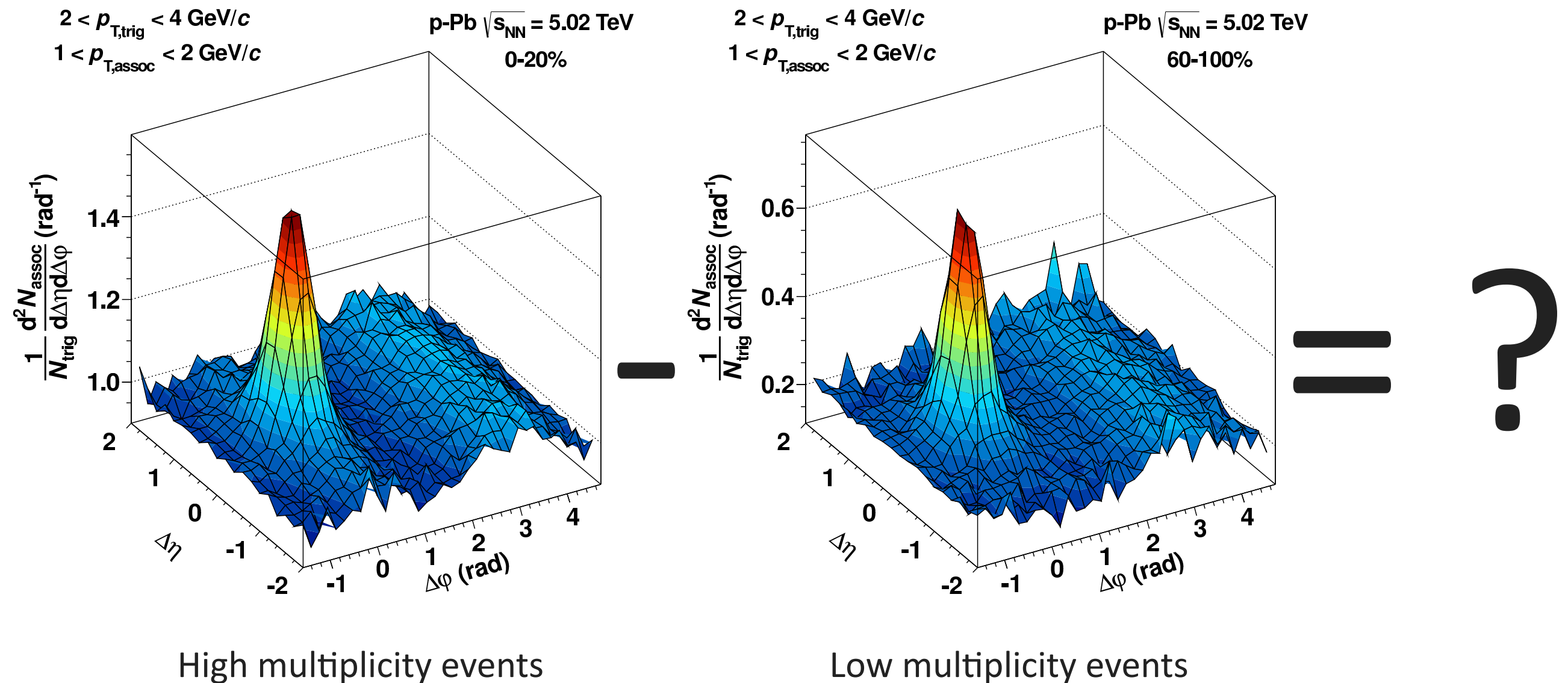
Large direct-photon v_2 challenges the standard hydro picture

Heavy-Ion-Like Effects in p-Pb?

Per-Trigger Charged Hadron Yields in Low and High-Multiplicity p-Pb Collisions at $\sqrt{s} = 5.02$ GeV

Two-Particle correlations: jet-like correlations + X

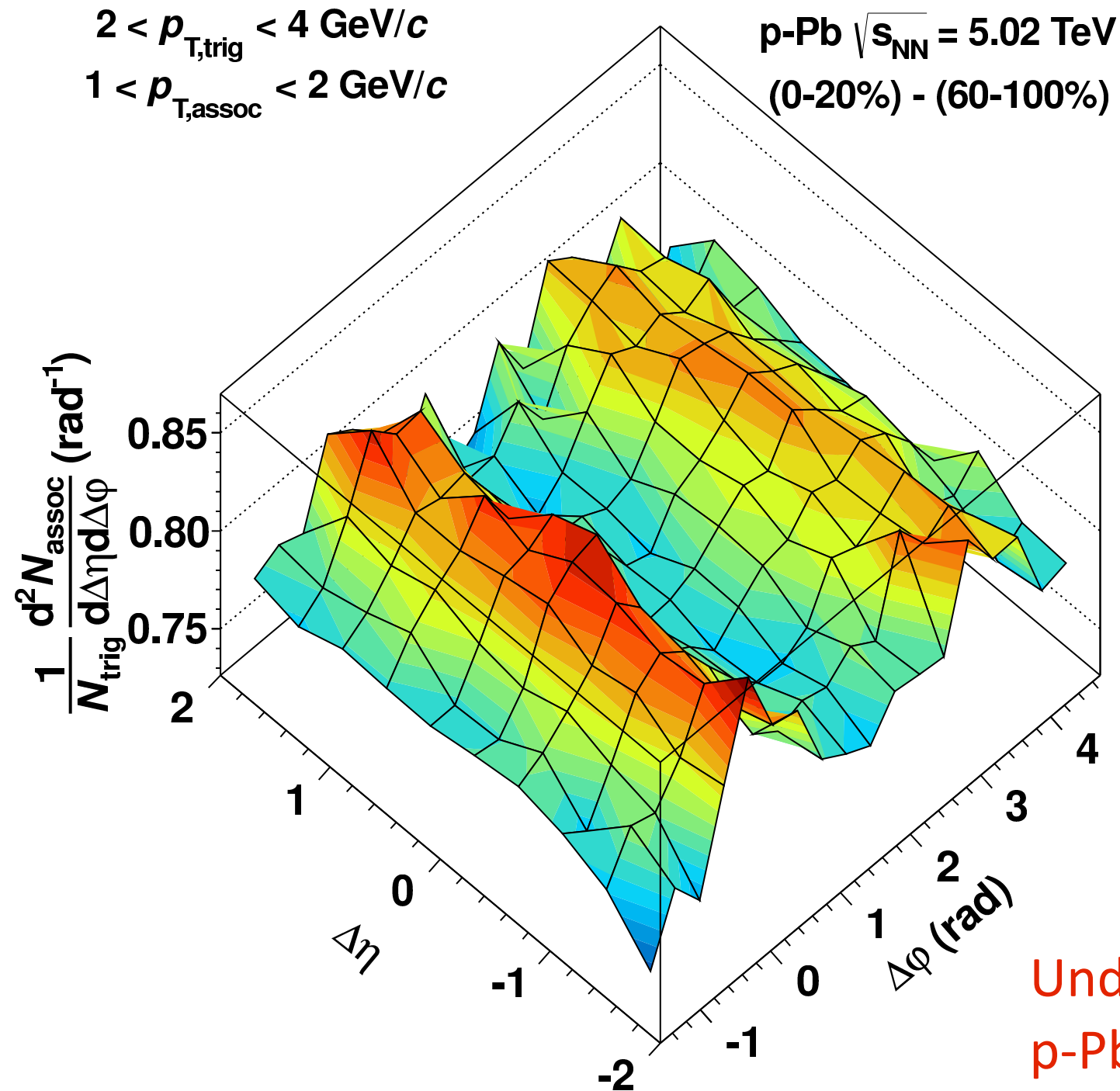
ALICE, Phys.Lett. B719 (2013) 29-41



Check what remains if one subtracts the jet-like correlation.

Implicit assumption: Shape of jet correlation same for both multiplicity classes

Remaining Correlation: Double-Hump Structure



- Two ridges along $\Delta\eta$ at $\Delta\phi = 0$ and π
- Looks qualitatively like flow signal in Pb-Pb
- Nicely described by $v_2 + v_3$ component
- Intense debate, possible explanations:
 - ▶ Hydro flow in p-Pb?
 - ▶ Effect of gluon saturation (color glass condensate)?

Understanding the flow-like correlation in p-Pb will provide deeper understanding of flow signals in Pb-Pb

Conclusions

■ Radial and anisotropic flow

- ▶ Hydro describes general features at low p_T (spectra, v_n)
- ▶ v_2 and higher harmonics seem to reflect hydro response to initial energy density fluctuations
- ▶ $\eta/s \approx 0.2 = 2.5 \times 1/4\pi$
- ▶ Large direct-photon v_2 a big surprise and a challenge for the hydro picture

■ Jet quenching

- ▶ Surprisingly similar suppression for pions and D mesons
- ▶ More advanced theory needed to extract medium properties from wealth of data

■ Charmonium

- ▶ Qualitatively consistent with coalescence of deconfined charm quarks

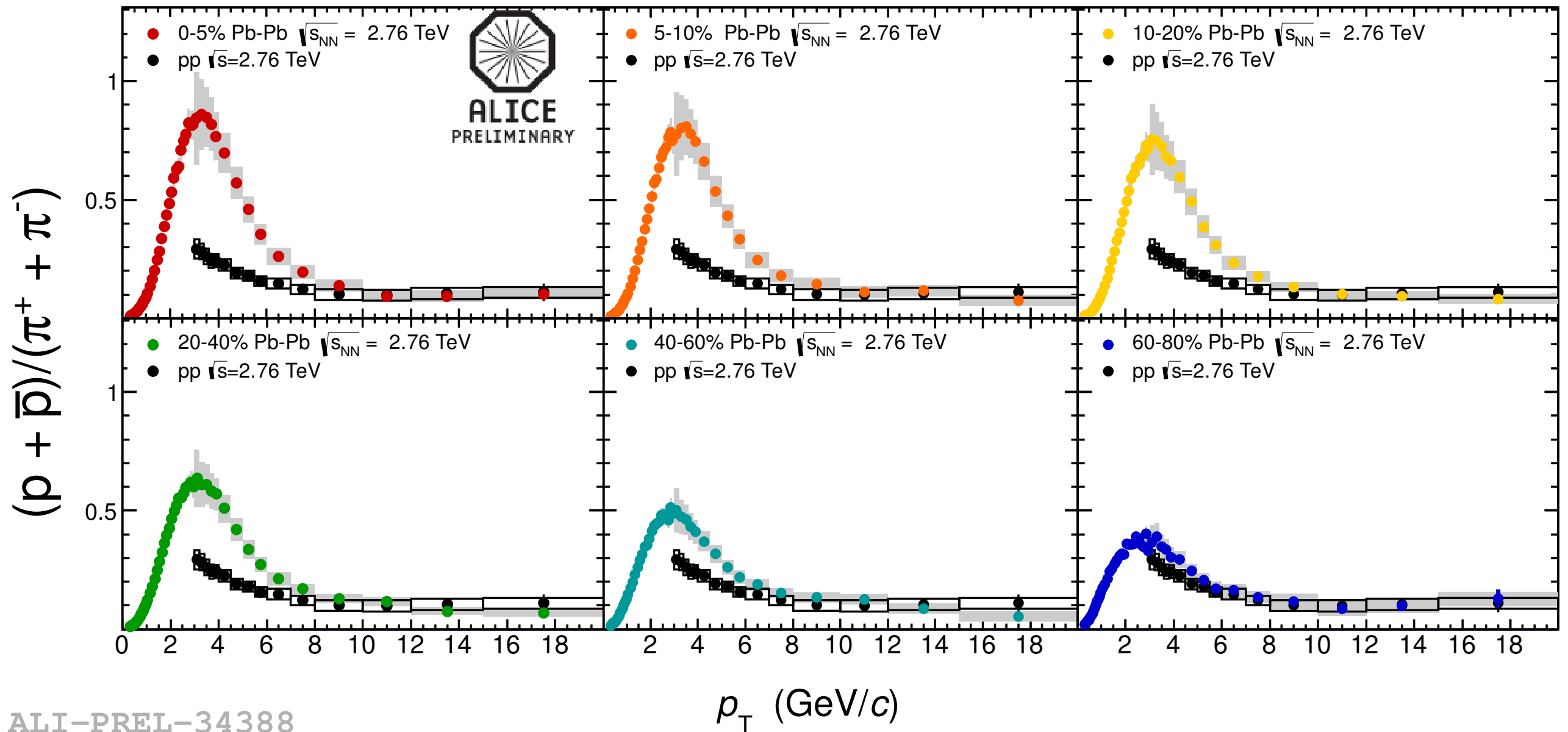
Comprehensive set of data from first two heavy-ion runs.
Future measurements with higher statistics will allow to pin down emergent properties of QCD with high precision.

ALICE Talks at the DPG Spring Meeting 2013

- Mo, 11:00 HK 3.1: Heavy-flavour measurements in the semi-elect. decay channel in pp and Pb–Pb with ALICE at the LHC — •Markus Fasel
- Mo, 11:30 HK 3.2: Measurement of B meson production in pp at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 7$ TeV via displaced electrons in ALICE — •Markus Heide
- Mo, 11:45 HK 3.3: Background subtraction techniques for heavy-flavour electrons with ALICE at the LHC — •Christian Alberto Schmidt
- Mo, 12:00 HK 3.4: Trennung der Charm- und Beautyproduktion in pp- und Pb-Pb-Kollisionen mit ALICE — •Martin Völkl
- Mo, 12:30 HK 3.6: b-Jet tagging in ALICE — •Linus Feldkamp
- Mo, 16:45 HK 16.1: Jet Reconstruction in Pb-Pb and pp collisions with the ALICE experiment — •Oliver Busch
- Mo, 17:15 HK 16.2: Jet fragmentation into strange hadrons in Pb-Pb collisions with ALICE at the LHC — •Alice Zimmermann
- Mo, 17:30 HK 17.4: J/ψ measurements in pp collisions with the ALICE apparatus at the LHC — •Jan Wagner
- Mo, 18:15 HK 16.6 :Correction of detector effects with the HBOM method in event background fluctuations
- Mo, 18:30 HK 16.7: Triggering on Jets with the ALICE TRD — •Jochen Klein
- Mo, 18:15 HK 17.7: Low-mass dielectron measurement for pp collisions with ALICE — •Markus K. Köhler
- Mo, 18:15 HK 22.6: ALICE TRD GTU Online Tracking Performance in $\sqrt{s} = 7 - 8$ TeV pp collisions — •Rettig F., Kirsch St., and Lindenstruth V.
- Di, 14:00 HK 29.1: J/ψ production in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV measured with ALICE at the LHC — •Jens Wiechula
- Di, 14:30 HK 29.2: J/ψ -Hadron Correlations in Proton-Proton Collisions and J/ψ in Proton-Lead Collisions with the Central Barrel of ALICE at the LHC
- Di, 14:30 HK 35.2: Upgrade des ALICE Inner Tracking Systems und die Auswirkung auf Messungen schwerer Quarks — •Johannes Stiller
- Di, 14:45 HK 29.3: Perspectives of ψ' and χ_c measurements in ALICE — •Steffen Weber
- Di, 15:00 HK 29.4: Electron Trigger with the ALICE TRD — •Uwe Westerhoff
- Di, 15:30 HK 29.6: Elliptic Flow of J/ψ at Mid-Rapidity in Pb–Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ALICE experiment — •Julian Book
- Di, 14:30 HK 34.2: Exploiting Unused Cluster Resources with Virtualization — •Stefan Boettger and Udo Kebschull
- Di, 14:45 HK 34.3: Experience Report: System Management at the ALICE HLT Cluster — •Camilo Lara et al.
- Di, 15:45 HK 34.7: Read-Out Receiver Card Upgrade for ALICE DAQ and HLT — •Heiko Engel and Udo Kebschull
- Di, 16:45 HK 39.1: pT Spectra of Charged Particles measured in pp, p-Pb and Pb-Pb Collisions with ALICE at the LHC — •Michael Linus Knichel
- Di, 17:15 HK 39.2: Pseudorapidity density of charged particles in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV measured with ALICE at the LHC — •Jonas Anielski
- Di, 17:15 HK 40.2: Production of Low Mass Dielectrons in Pb-Pb collisions with ALICE — •Christoph Baumann
- Di, 17:30 HK 40.3: ω and ϕ Meson Analysis via the Dielectron Channel in pp at $\sqrt{s} = 7$ TeV with ALICE — •Mahmut Özdemir
- Di, 17:45 HK 40.4: Prospects of Low-Mass Dielectron Measurements in ALICE with an upgraded Central Barrel Detector — •Patrick Reichelt
- Di, 18:00 HK 39.5: Average pT in pp, Pb–Pb and p–Pb collisions with ALICE — •Marco Marquard and Philipp Luettig
- Di, 18:00 HK 40.5: Measurement of direct photons in pp and Pb-Pb collisions with ALICE — •Martin Wilde
- Di, 18:15 HK 39.6: Event-by-event mean pT fluctuations measured by the ALICE experiment at the LHC — •Stefan Heckel
- Do, 14:00 HK 62.1: (Anti-)matter and hyper-matter production at the LHC with ALICE — •Nicole Martin
- Do, 14:00 HK 68.1: Offline Signal Tail-Correction for the ALICE TPC — •Mesut Arslanok
- Do, 14:45 HK 62.3: Strange particle production in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with ALICE at the LHC — •Maria Nicassio
- Do, 15:00 HK 62.4: Elliptic Flow Measurement of Heavy Flavour Decay Electrons in Pb-Pb Collisions at $\sqrt{s} = 2.76$ TeV with ALICE — •Theodor Rascanu
- Do, 15:45 HK 65.7: Central Diffraction in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV with the ALICE Experiment — •Felix Reidt
- Do, 16:45 HK 80.1: Status and future of the ALICE TPC, a high-resolution detector for the highest particle multiplicities — •Christian Lippmann
- Do, 17:15 HK 80.2: First results from the ALICE GEM TPC prototype test — •Piotr Gasik
- Do, 18:45 HK 80.8: Simulationen zur Gasverstärkung im ALICE-TRD und einem Driftmonitor GOOFIE — •Stephan Dyba

Extra Slides

Large p/π Ratio in Central Pb+Pb around $p_T \approx 3.5$ GeV/c

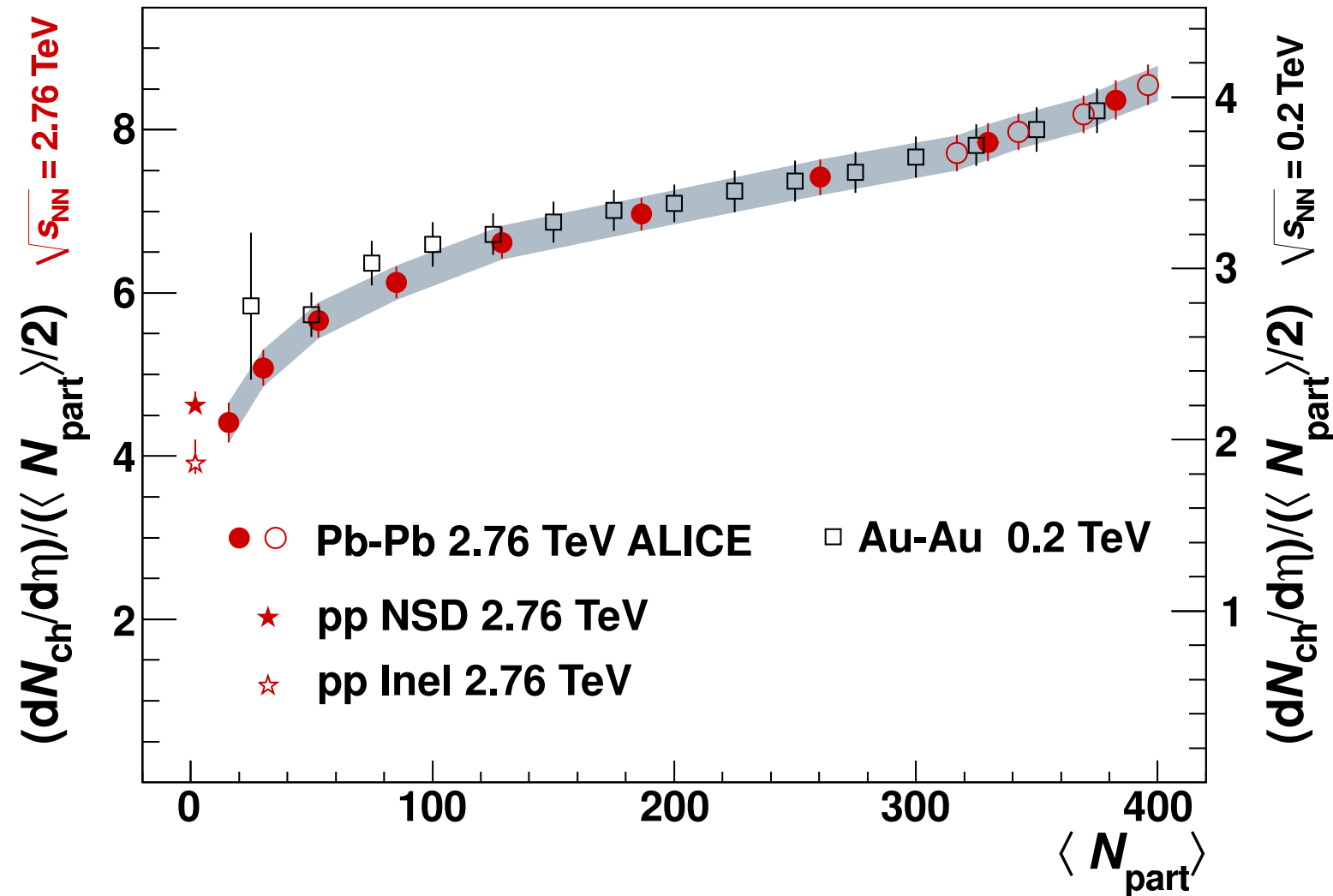


ALI-PREL-34388

Radial flow+ quark coalescence? Interplay between jets and expanding bulk (EPOS)?
 → A challenge to theory

Charged Particle Multiplicity in Pb+Pb at $\sqrt{s_{NN}} = 2.76$ TeV

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



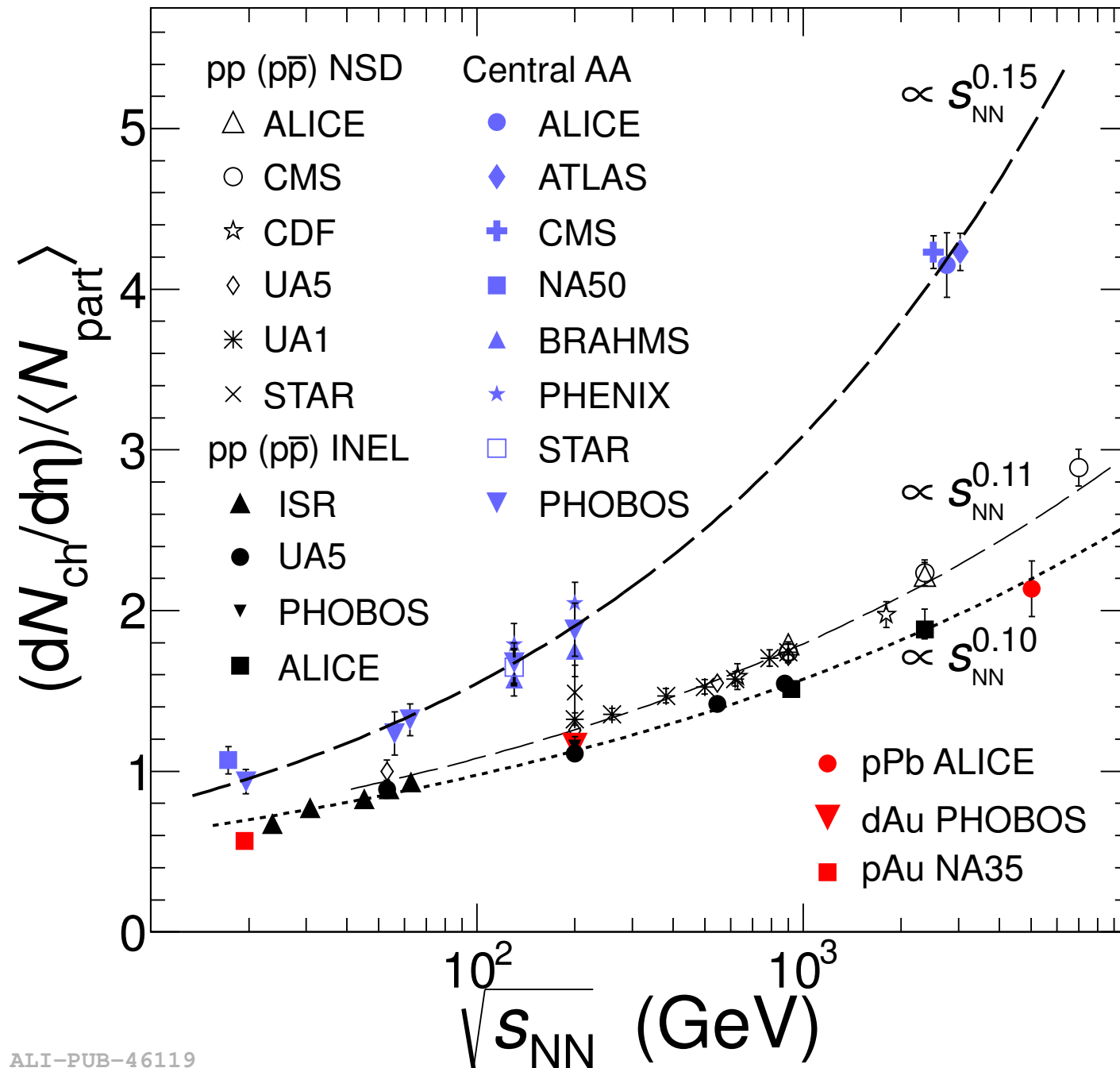
- $\sim 30\,000$ particles in total in central Pb+Pb
- Relative increase from p+p to A+A identical at RHIC and LHC (holds for $20 < \sqrt{s_{NN}} < 2760$ GeV)
- Initial energy density (for $\tau_0 = 1$ fm/c):
 $\epsilon_{\text{LHC}} \approx 15 \text{ GeV/fm}^3 \approx 3 \times \epsilon_{\text{RHIC}}$

$$\epsilon = \frac{dE_T/dy}{\tau_0 \pi R^2} \approx \frac{3}{2} \langle m_T \rangle \frac{dN_{\text{ch}}/d\eta}{\tau_0 \pi R^2}$$

Initial energy density at LHC and RHIC well above $\epsilon_c \approx 0.5 \text{ GeV/fm}^3$

Charged Particle Multiplicity in Pb+Pb at $\sqrt{s_{NN}} = 2.76$ TeV

ALICE, Phys.Rev.Lett. 105 (2010) 252301



ALI-PUB-46119

■ ~ 30 000 particles in total in central Pb+Pb

■ Power law increase of $dN_{ch}/d\eta / (N_{part}/2)$

▶ p+p: $\sim s^{0.11}$

▶ central A+A: $\sim s^{0.15}$

■ Initial energy density (for $\tau_0 = 1$ fm/c):

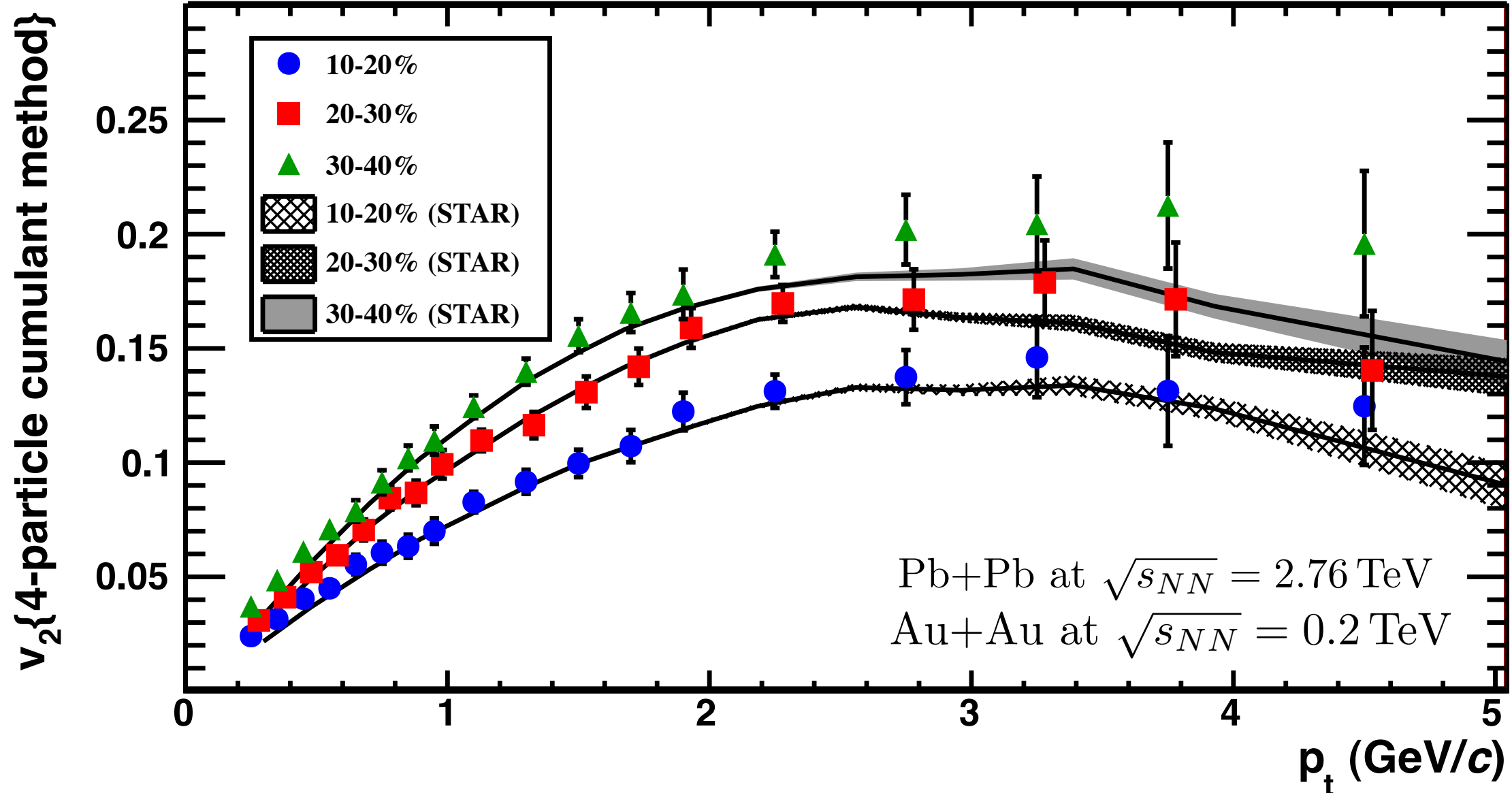
$$\epsilon_{LHC} \approx 15 \text{ GeV/fm}^3 \approx 3 \times \epsilon_{RHIC}$$

$$\epsilon = \frac{dE_T/dy}{\tau_0 \pi R^2} \approx \frac{3}{2} \langle m_T \rangle \frac{dN_{ch}/d\eta}{\tau_0 \pi R^2}$$

Initial energy density at LHC and RHIC well above $\epsilon_c \approx 0.5 \text{ GeV/fm}^3$

Similar Charged Hadron $v_2(p_T)$ at RHIC and LHC

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

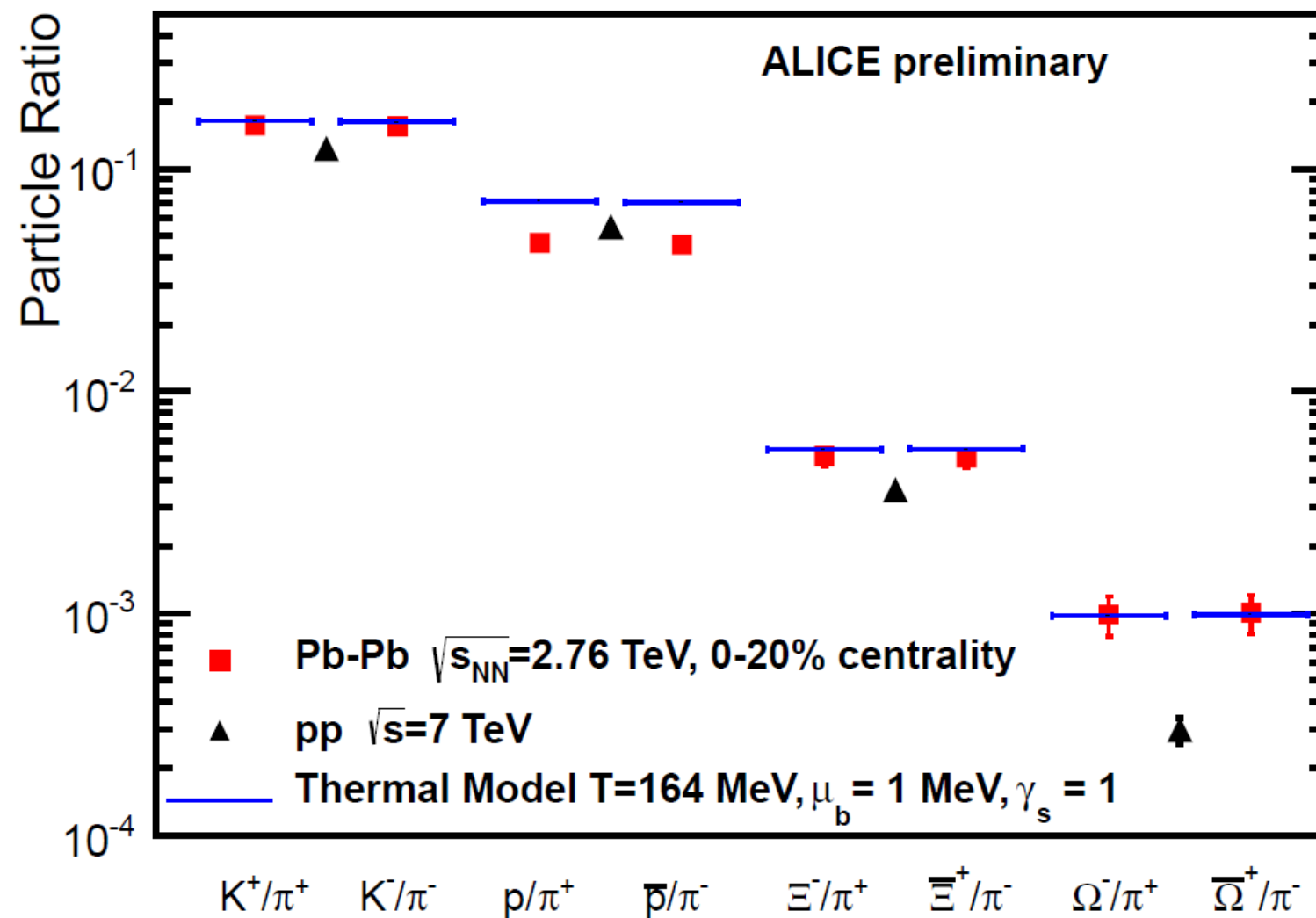


- $v_2(p_T)[\text{LHC}] = v_2(p_T)[\text{RHIC}]$, despite factor 14 increase in $\sqrt{s_{NN}}$
- p_T -integrated v_2 at LHC 30% larger due to larger $\langle p_T \rangle$

Particle Ratios: The Puzzle of the Small Proton Yields

statistical model:

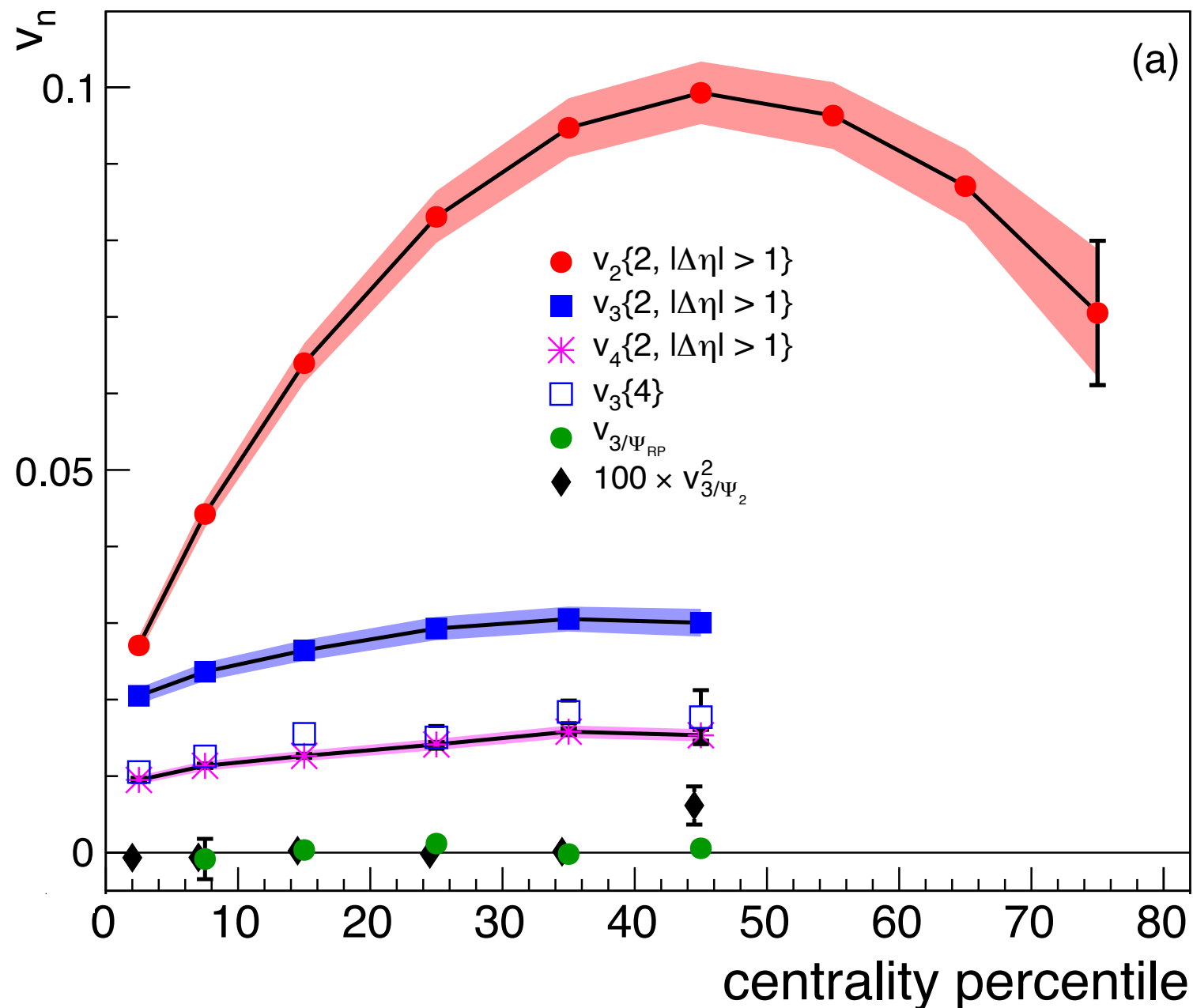
$$n_i = \frac{g_i}{(2\pi)^3} \int \frac{1}{\exp\left(\frac{E_i - \mu(B_i, S_i)}{T_{\text{ch}}} \pm 1\right)} d^3p$$



- Statistical/thermal model
 - ▶ two free parameters:
 T_{ch} and μ_B
- Strangeness enhancement in Pb+Pb nicely describes with $T_{\text{ch}} = 164$ MeV $\approx T_c$
 - ▶ 30% for kaons
 - ▶ > factor 3 for Ω
- p/π off by factor > 1.5: very puzzling, proton-antiproton annihilation in hadronic phase?

Small overall p/π ratio puzzling, physical origin to be clarified

Higher harmonics: Centrality Dependence (Charged Hadrons)

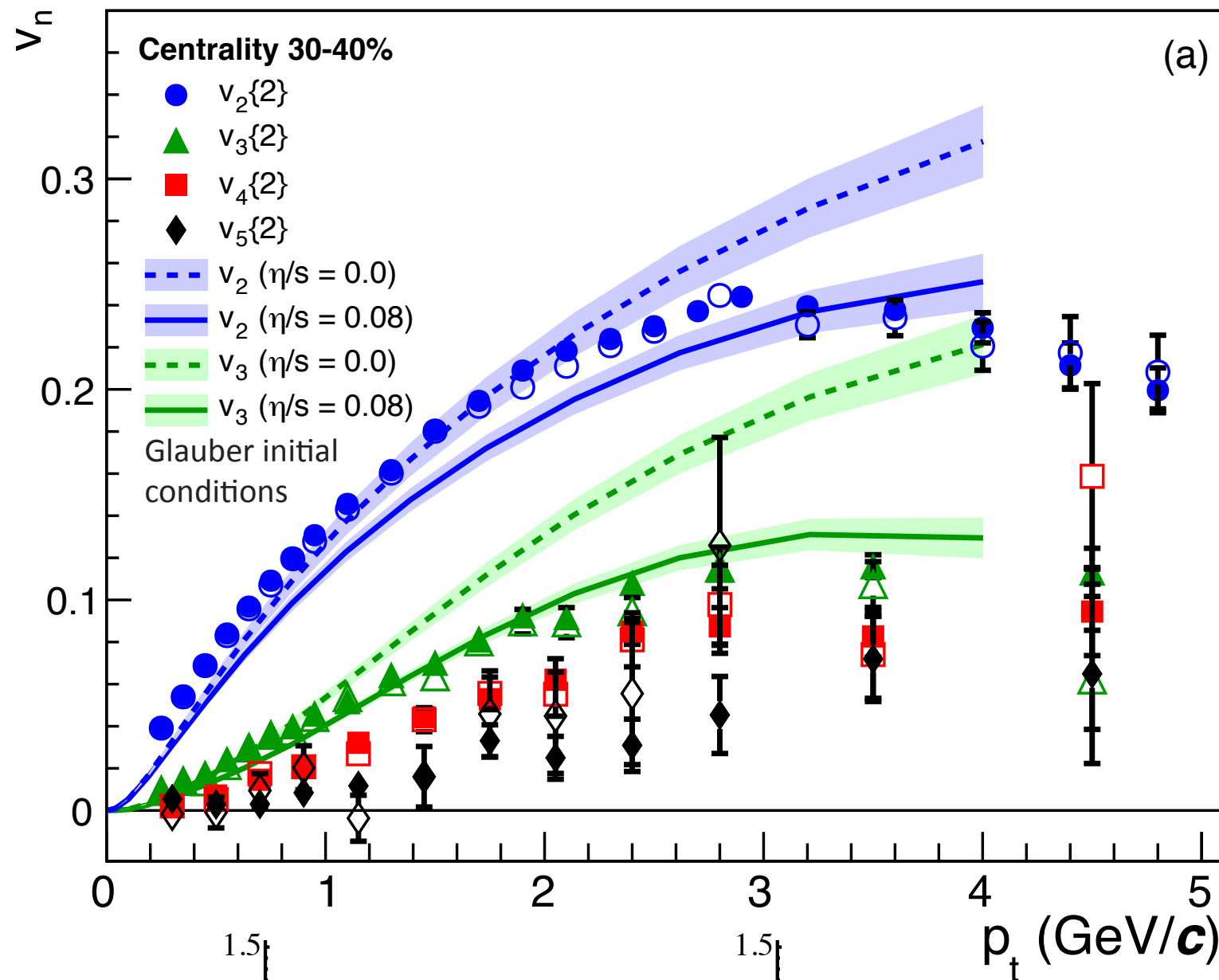


- Weak centrality dependence of v_3 and v_4
- Mid-central: $v_2 > v_3$
- Central: $v_2 \approx v_3$

Consistent with v_3 from hydro response to initial energy density fluctuations

Charged Hadrons: Higher Harmonics (v_2, v_3, v_4, v_5)

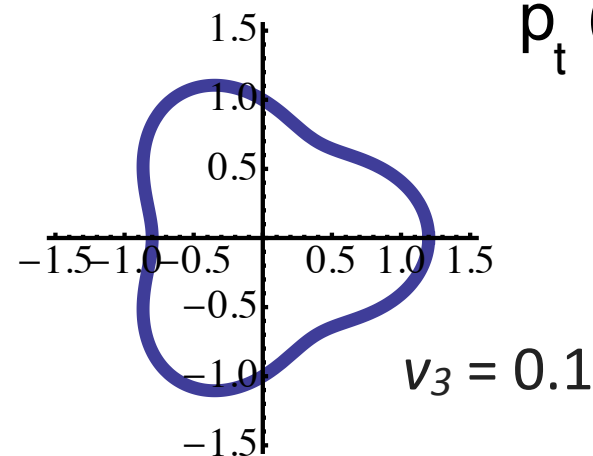
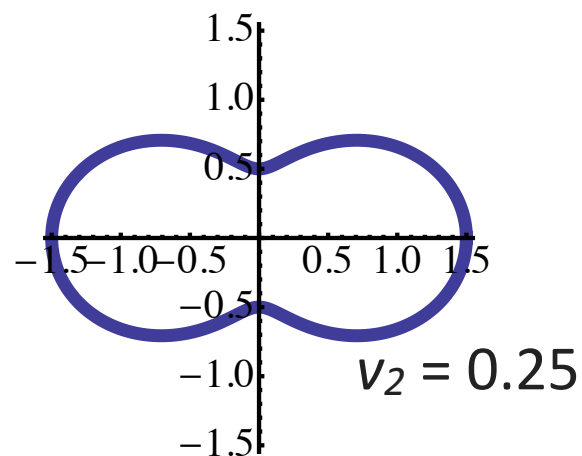
ALICE, Phys.Rev.Lett. 107 (2011) 032301



■ Sizeable v_3 observed

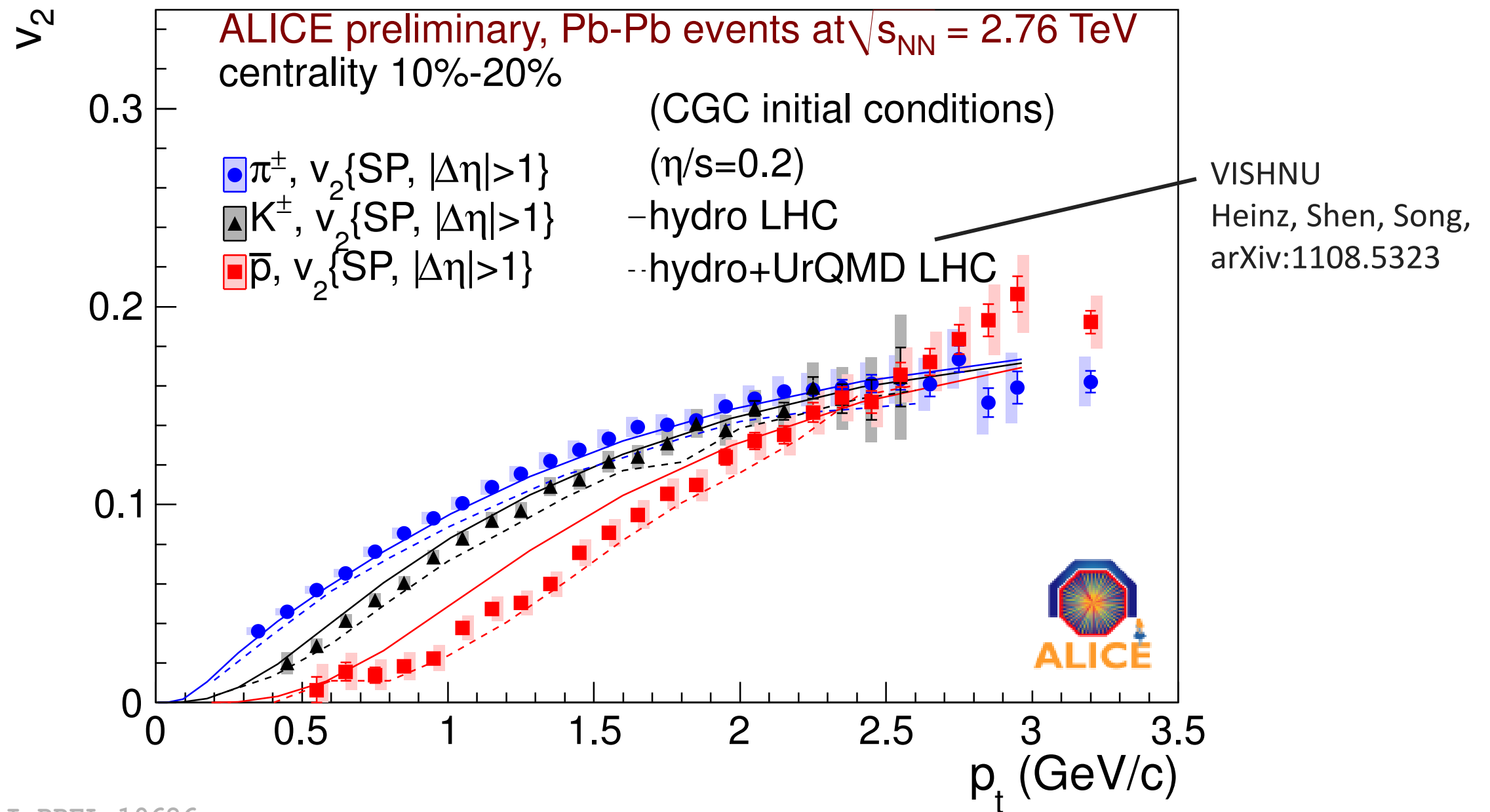
■ Hydro:

- ▶ Shear viscosity reduces differences between expansion velocities and leads to smaller v_n
- ▶ v_n depend both on initial energy density distribution and its fluctuations (Glauber MC, CGC) and η/s



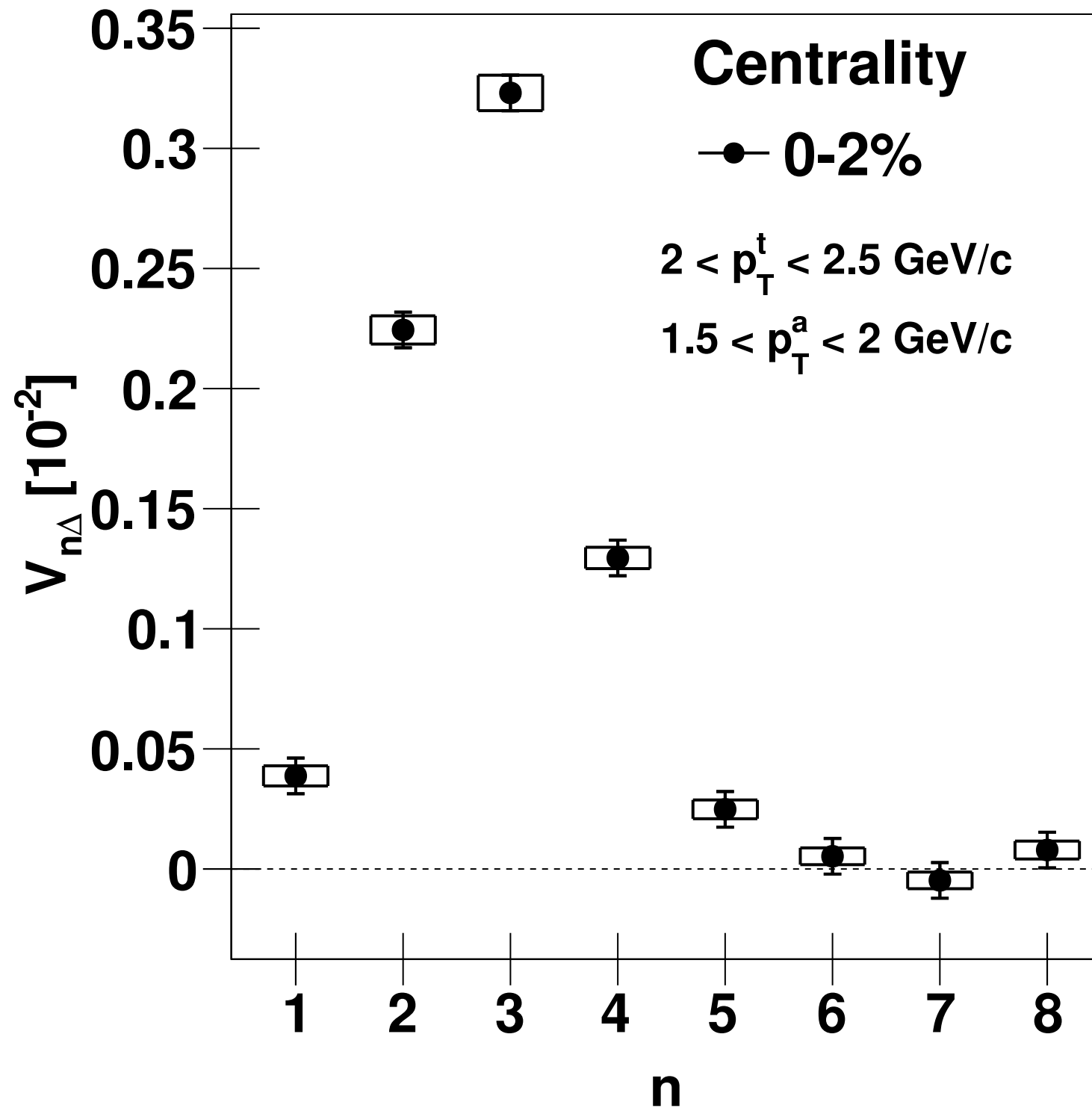
Higher harmonics
increase sensitivity to η/s

Example for the Description of the Identified Particle v_2 with a Hydrodynamic Model

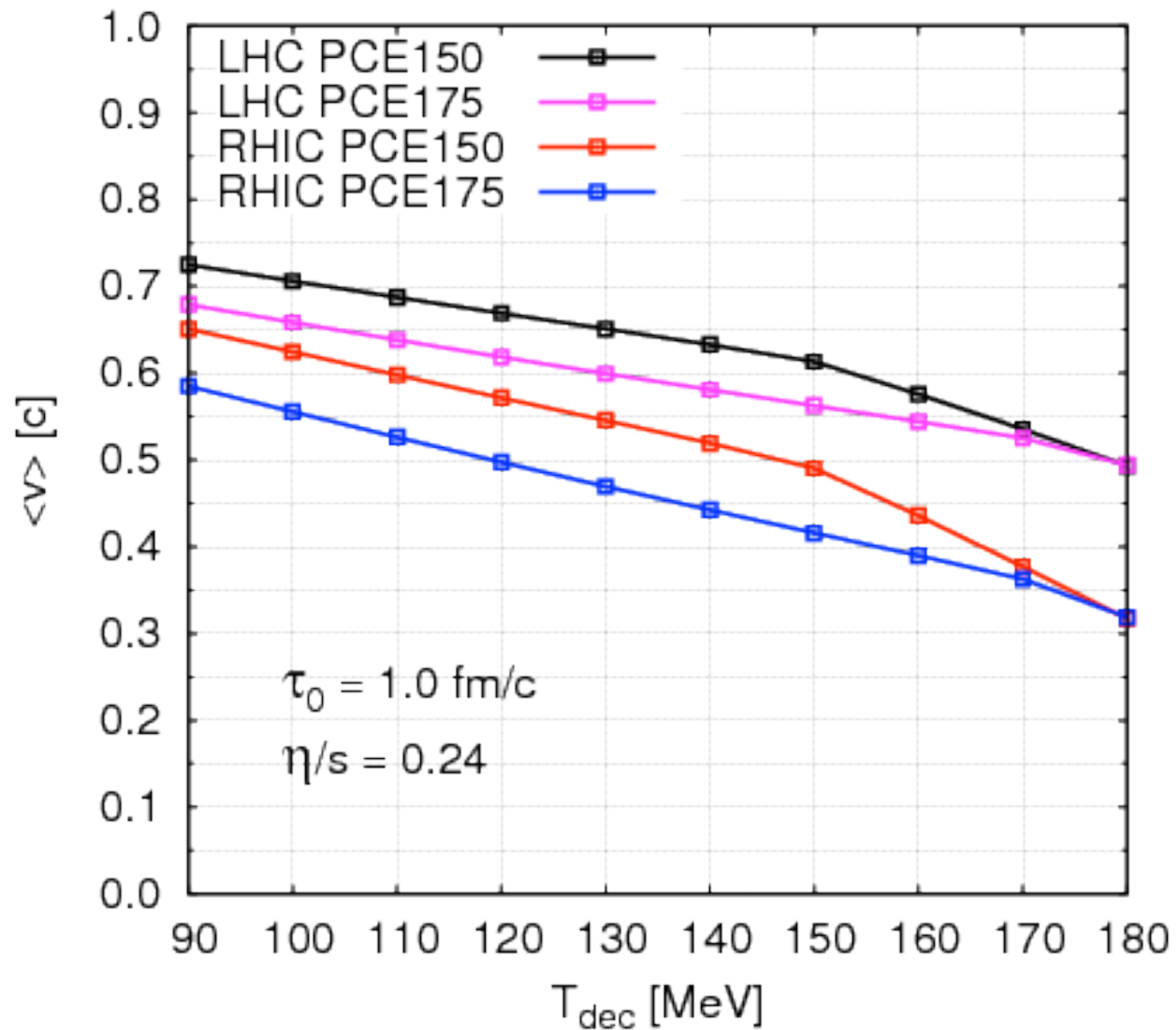


Hydro model for QGP phase + hadronic cascade describes v_2 data with
 $\eta/s \approx 0.2 = 2.5 \times 1/4\pi$ (with color glass condensate initial conditions)

Higher Flow Harmonics

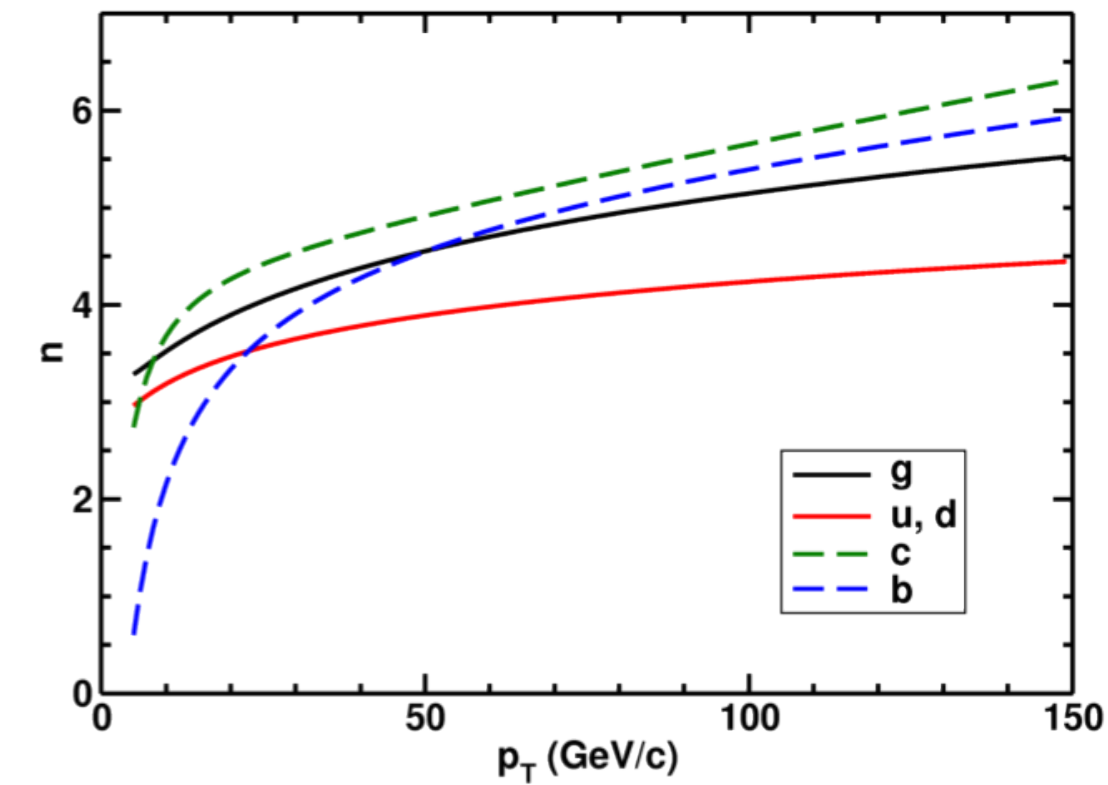


Average Radial Flow From Full Hydro Calculation

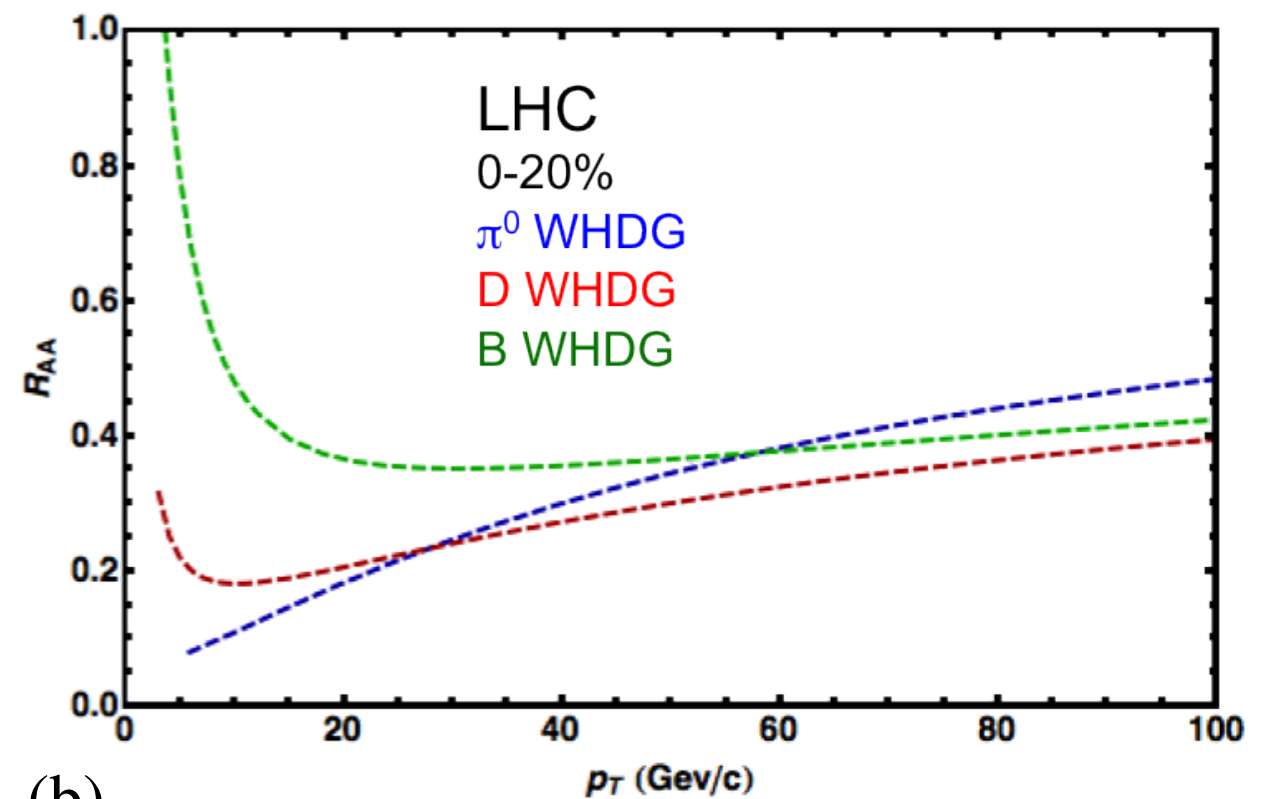


Parton Flavor Dependence of R_{AA}

arXiv:1210.8330



(a)



(b)