A Large Ion Collider Experiment

Highlights from ALICE

DPG-Frühjahrstagung Dresden, March 4 - 8, 2013

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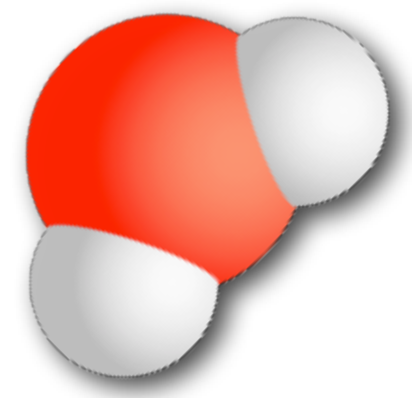
BMBF Forschungsschwerpunkt ALICE Experiment 201

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

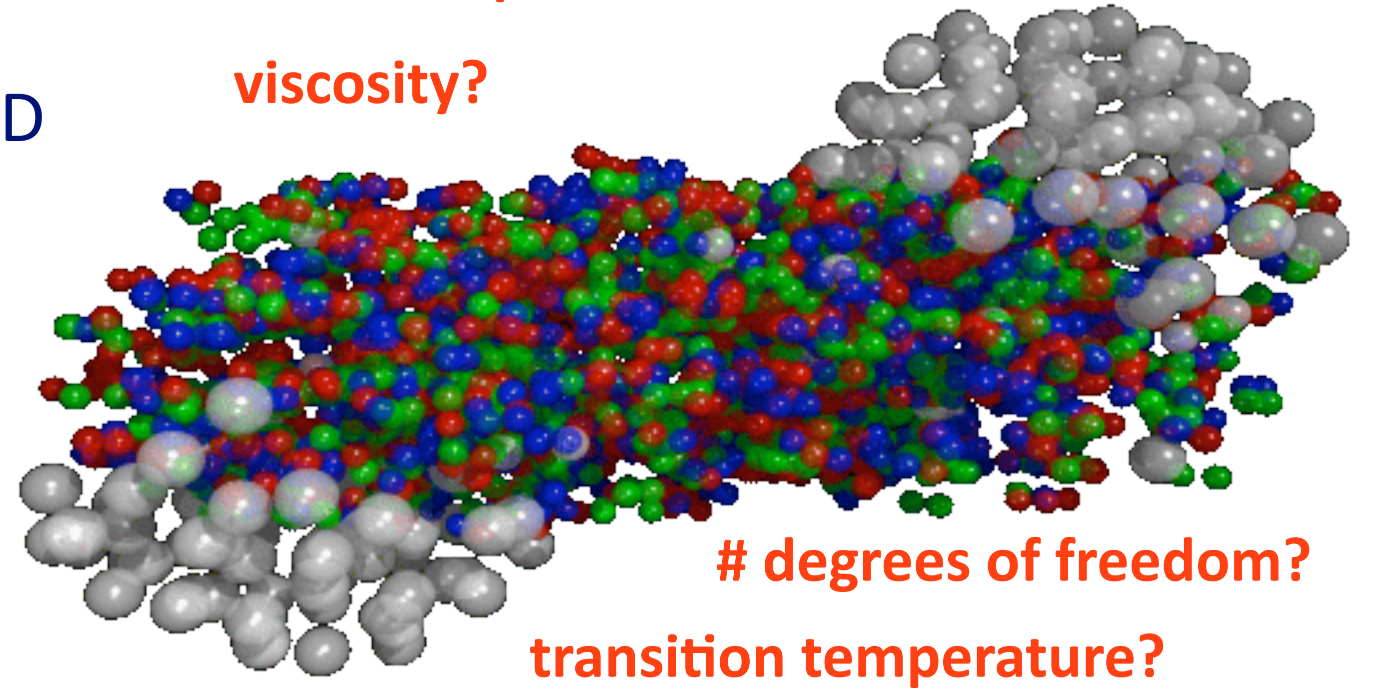


source: de.wikipedia.org

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

equation of state?

viscosity?



degrees of freedom?

transition temperature?

source: urqmd.org

„More is different"

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

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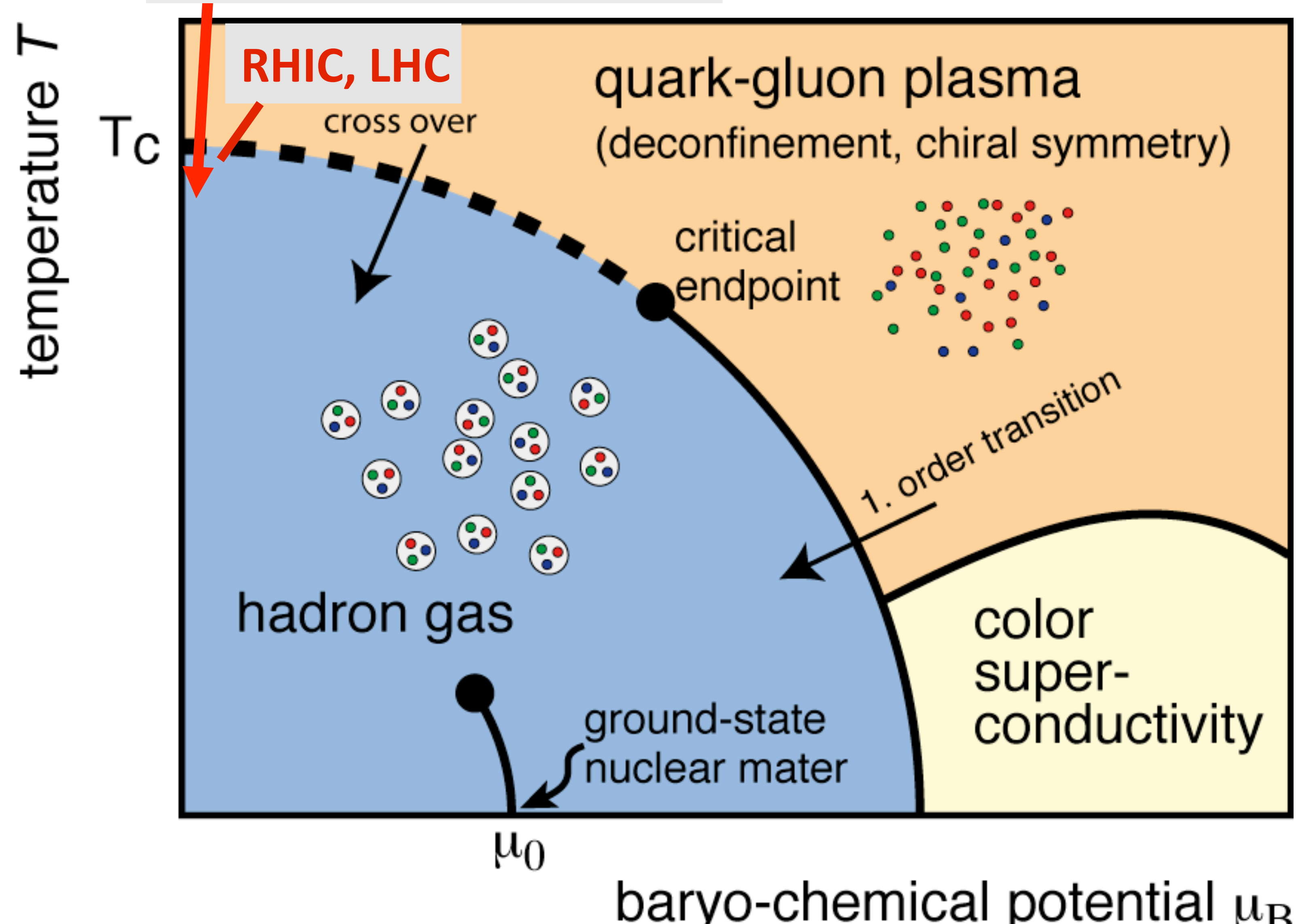
QCD in the High Temperature & High Density Sector

Early universe ($t \approx 10^{-5}$ s),
T_c = 150 - 160 MeV
from lattice QCD

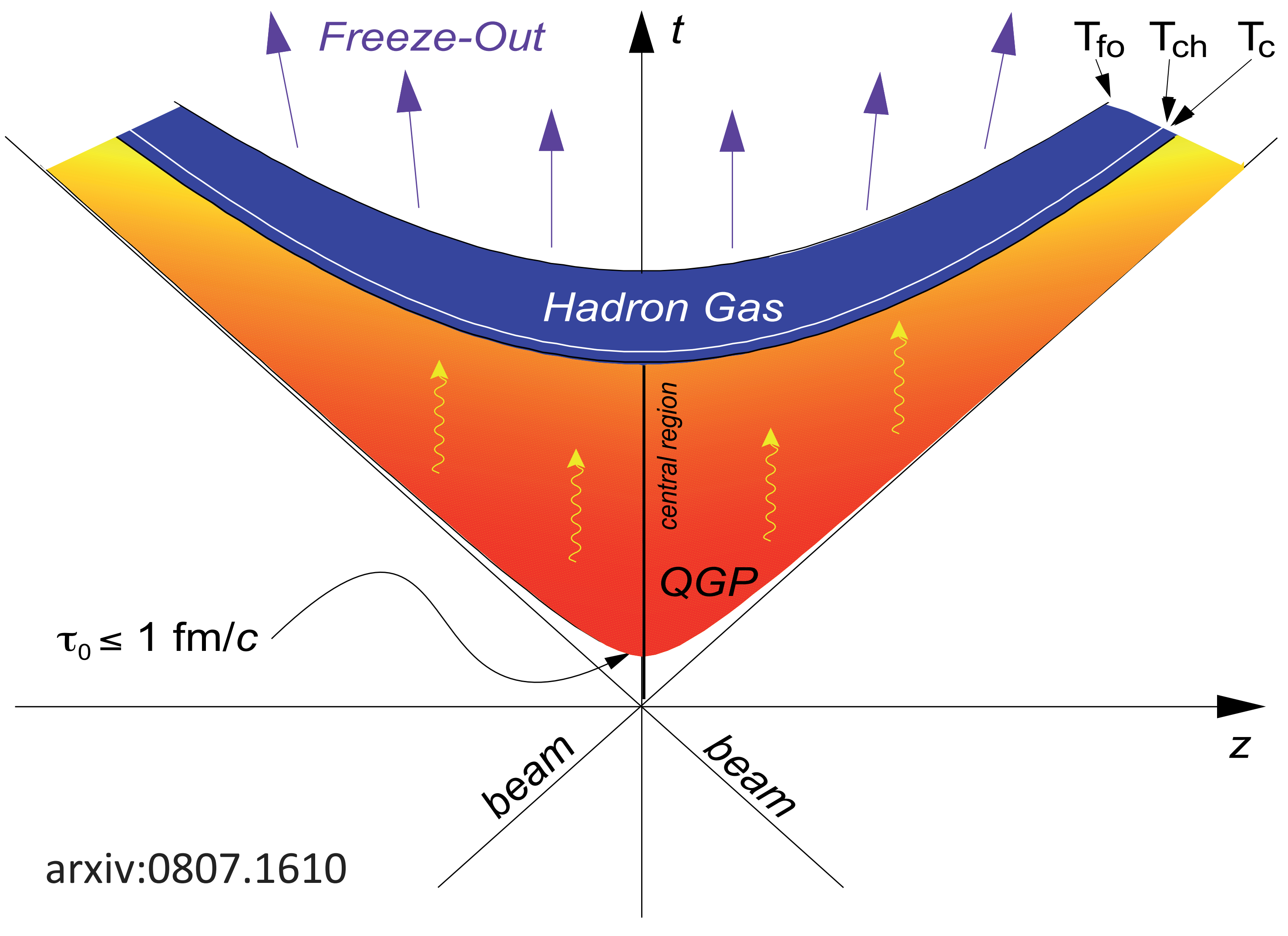


[reflects the net baryon density]

- 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 MeV
  - $\varepsilon_c \approx 0.5$ 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 ~ 1 fm/c
- Longitudinal and transverse expansion describable by almost ideal relativistic hydrodynamics ($\eta/s \approx 0$)*
- Transition QGP → hadrons
- Chemical freeze-out at $T_{ch} \approx T_c$ (T_c = 150 - 160 MeV)
- Kinetic freeze-out at T_{fo} ~ 100 MeV

* conjectured lower bound from string theory: $\eta/s|_{min} = 1/4\pi$
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

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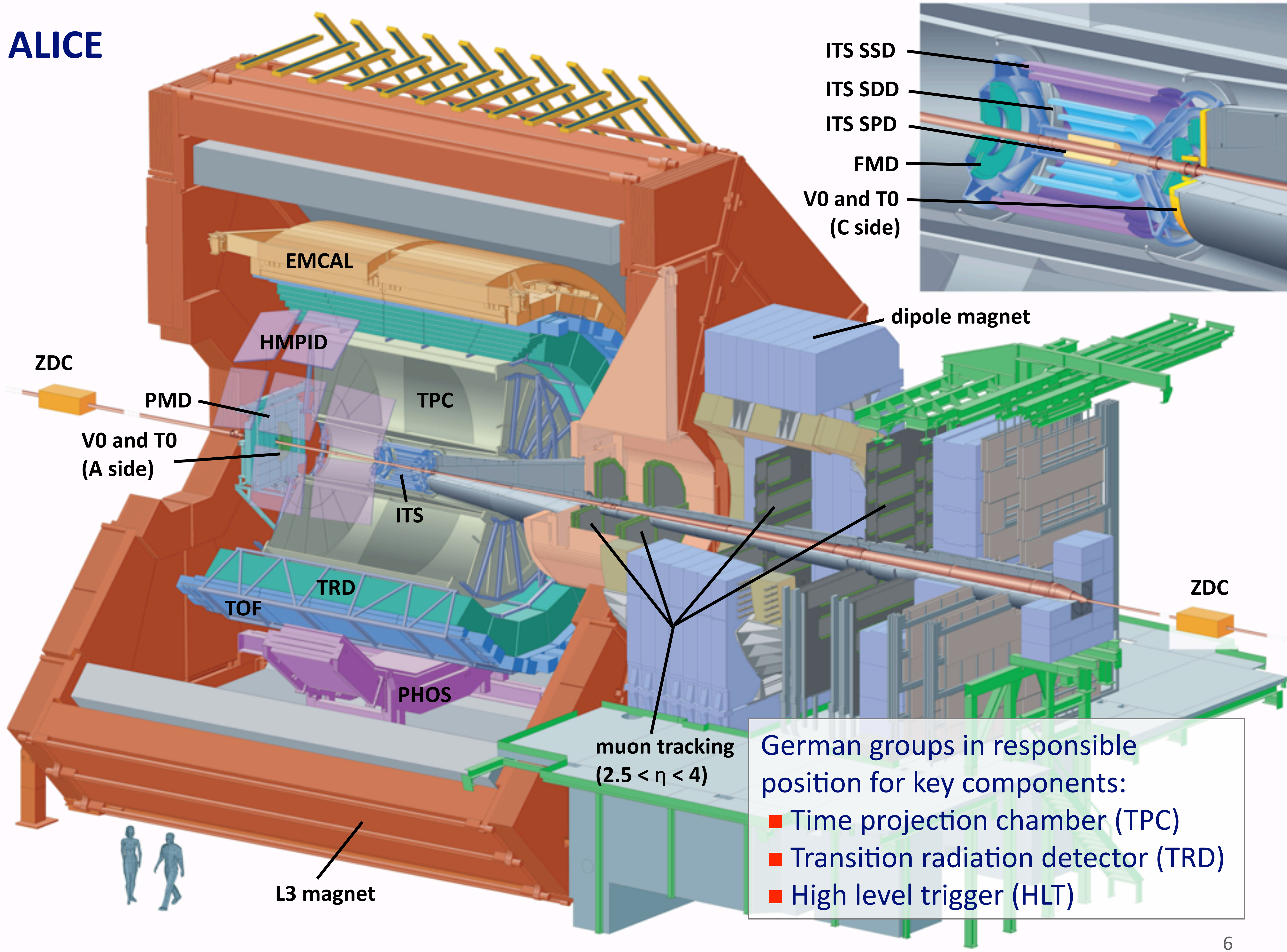
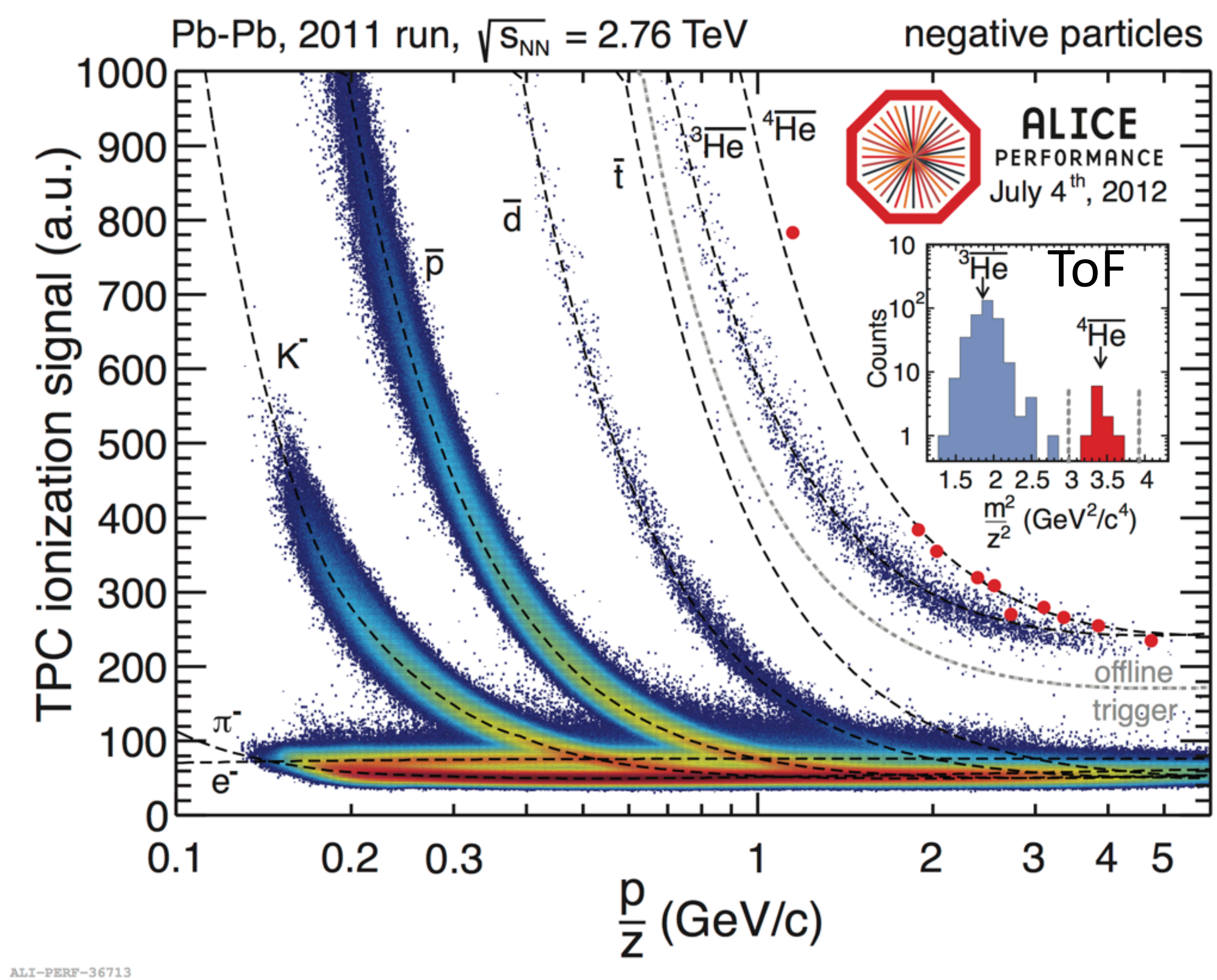


German groups in responsible position for key components:

- 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-^{4}He



- Robust tracking over large p_T range ($\sim$ 0.1 GeV/c < p_T < 100 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

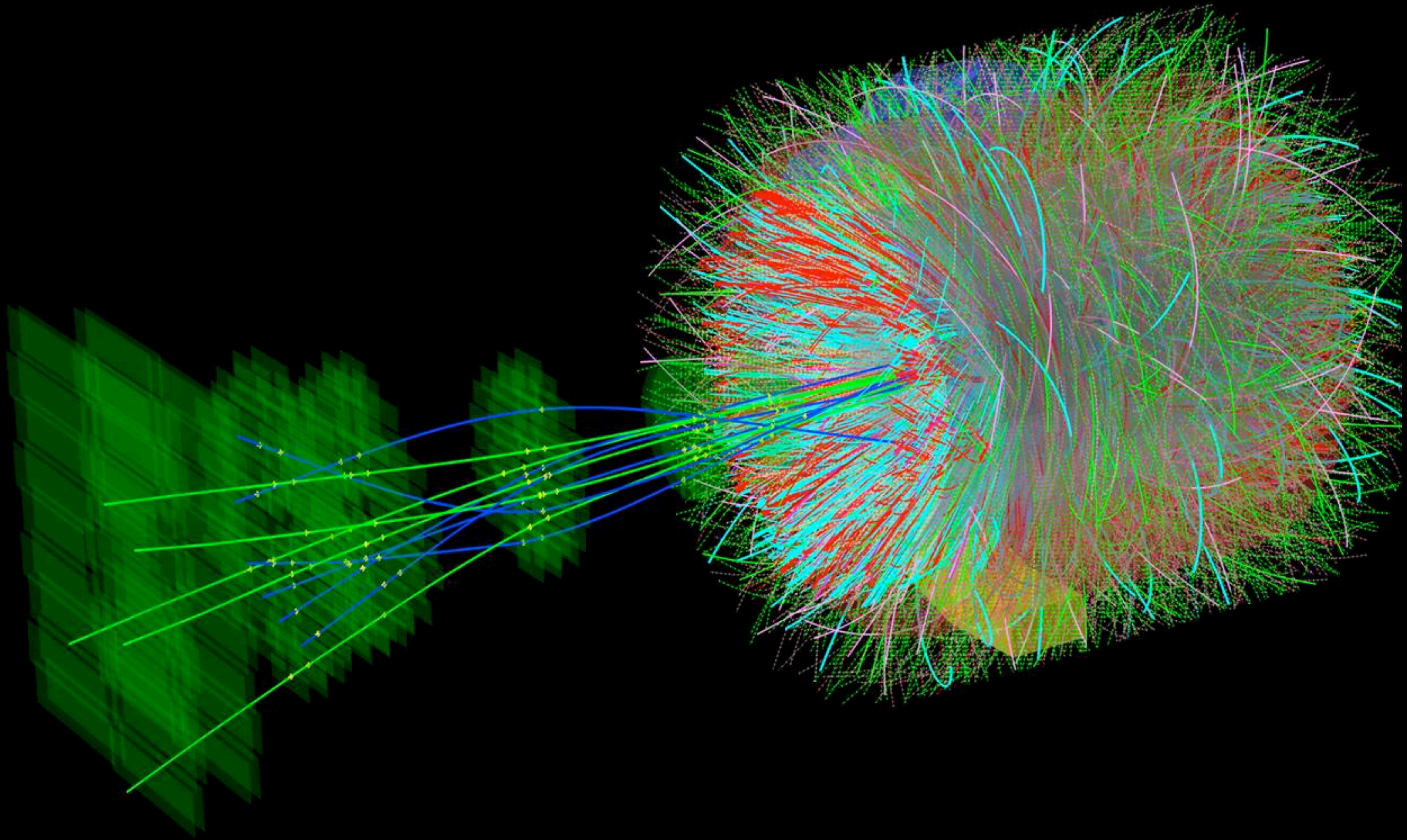
LHC Heavy-Ion Running

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

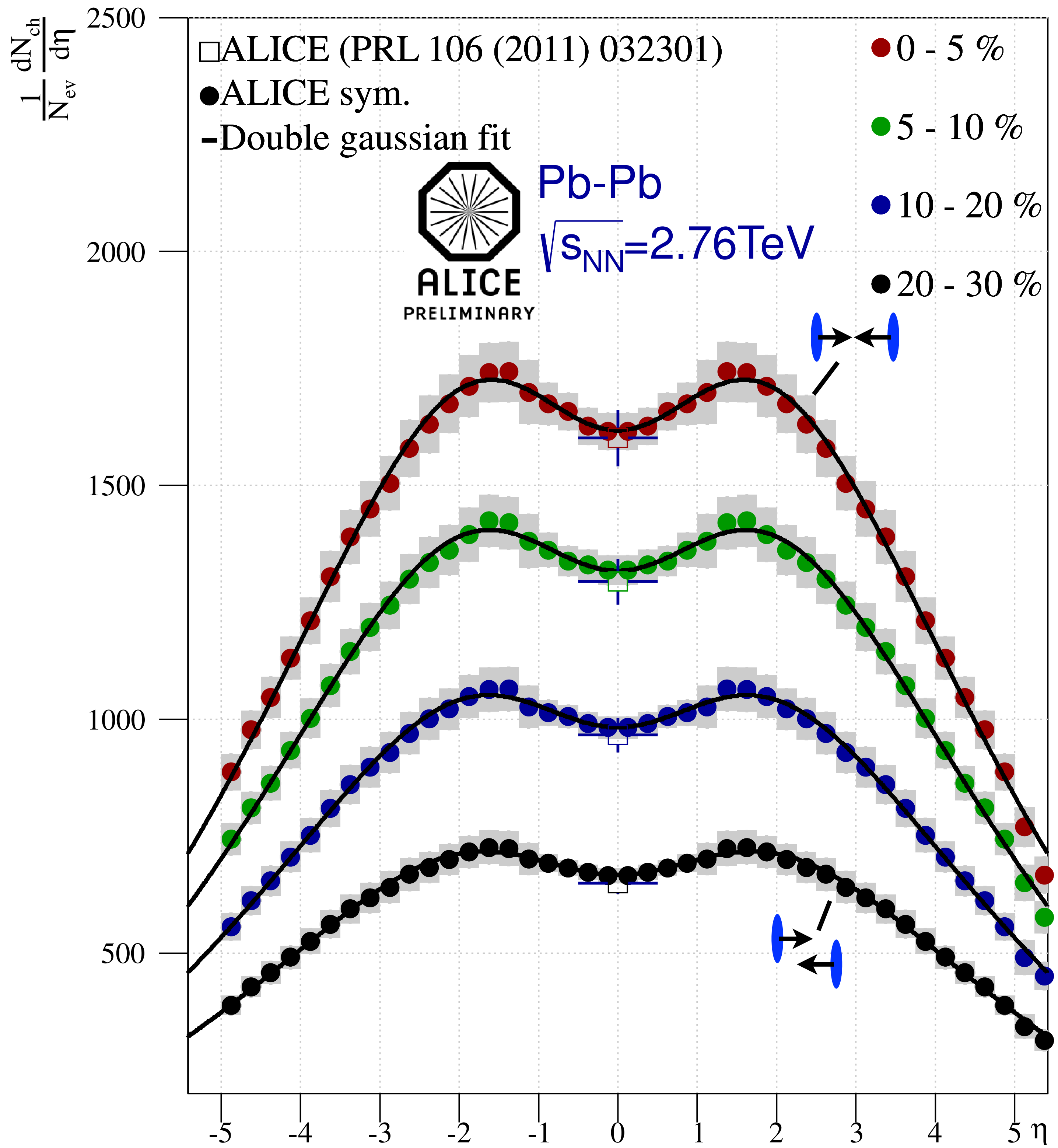
Luminosity reached in 2011: 2×10^{26} $cm^{-2}s^{-1}$

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



ALI-PREL-37241

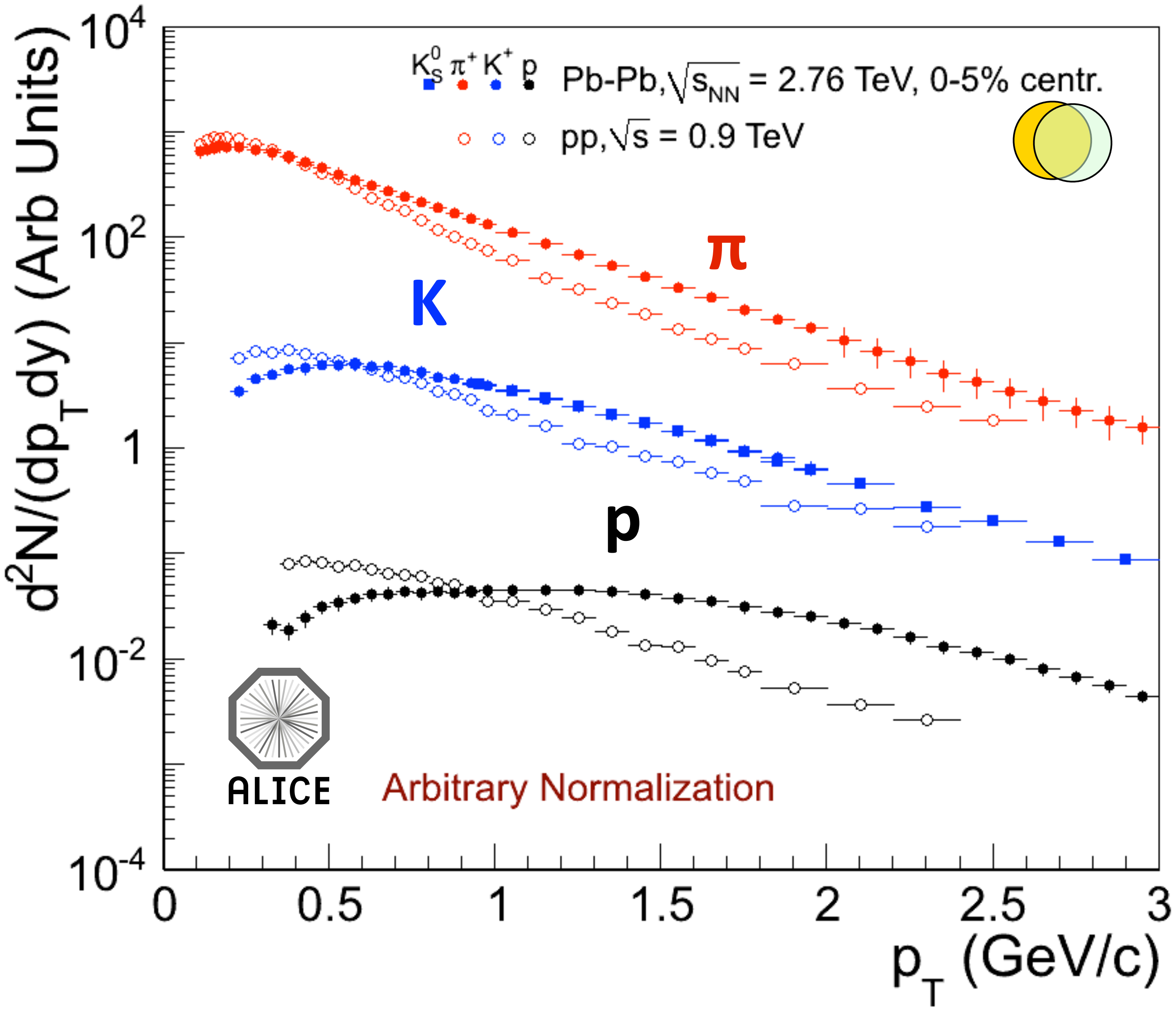
- ~ 25 000 produces particles in total in central Pb-Pb
  (full phase space, charged + neutrals)

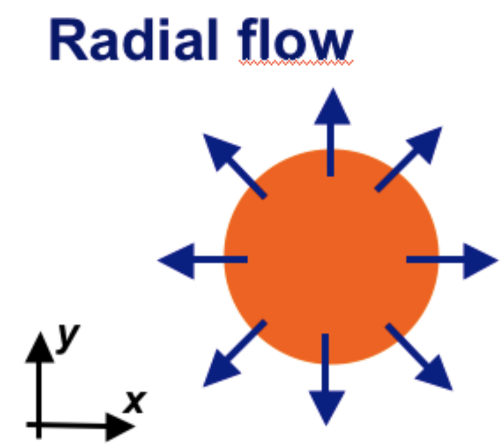
- Initial energy density
  (for τ_0 = 1 fm/*c*):
  $\varepsilon_{LHC} \approx 15\ \mathrm{GeV/fm^3} \approx 3 \times \varepsilon_{RHIC}$

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

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

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





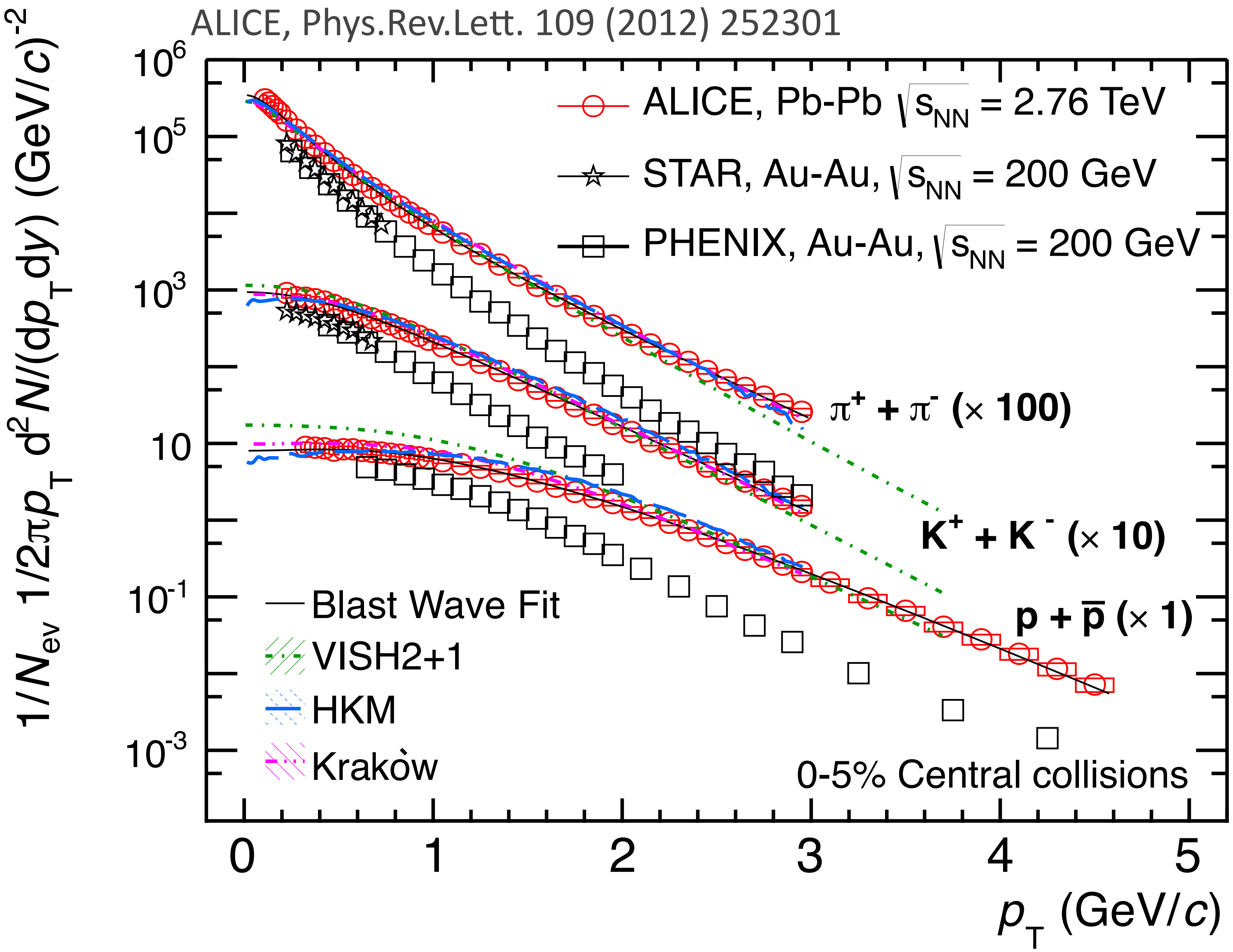
- Fireball pressure creates velocity profile
- Stronger modification of p_T spectra for heavier particles

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

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

ALICE, Phys.Rev.Lett. 109 (2012) 252301



- 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

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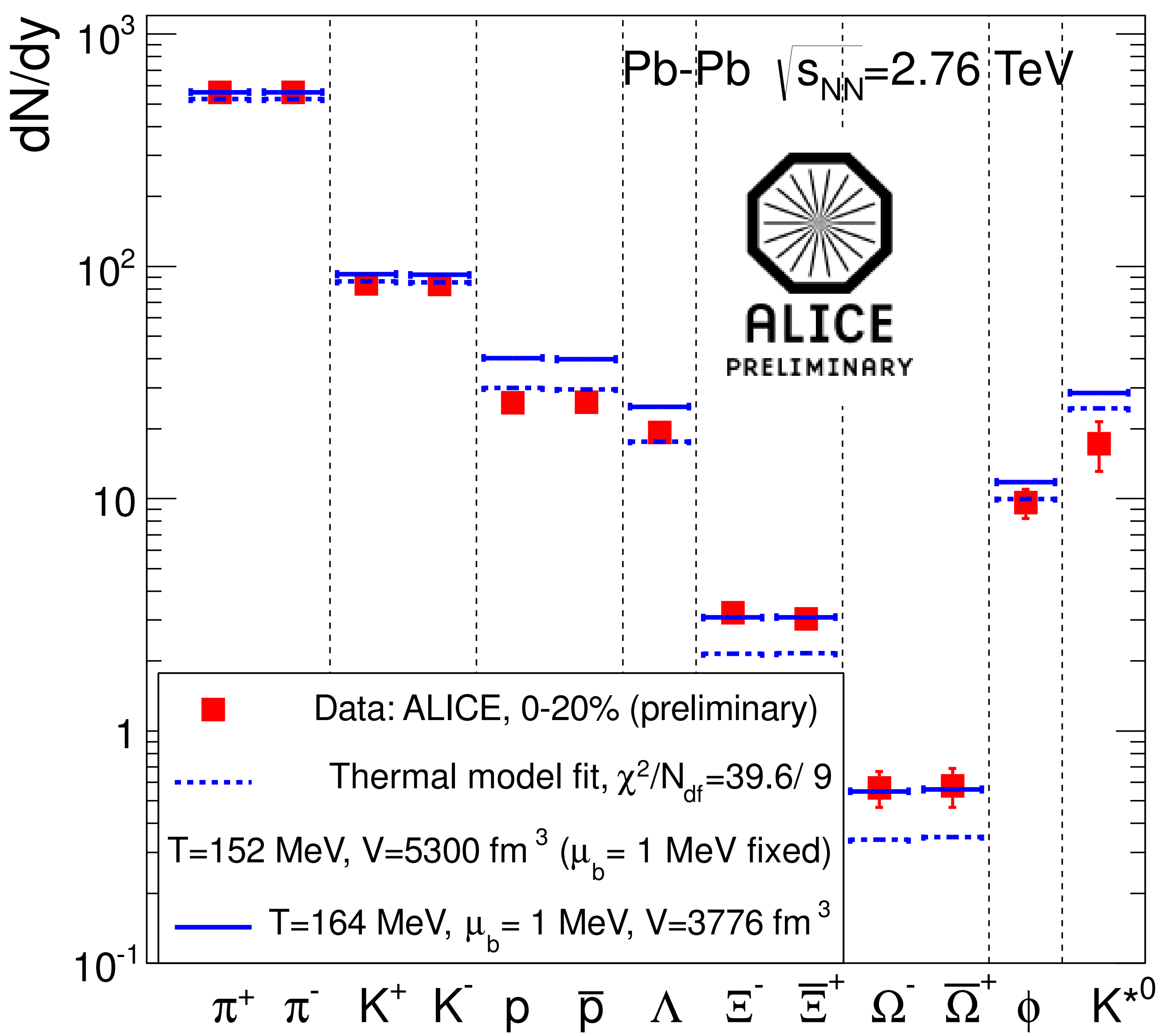
Particle Yields: The Puzzle of the Small Proton Yields

statistical model:

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

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



ALI-DER-37755

- Strangeness enhancement in Pb-Pb relative to pp
  - 30% for K/π
  - > factor 3 for Ω/π
- Statistical model describes strangeness enhancement with $T_{\rm ch}$ = 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

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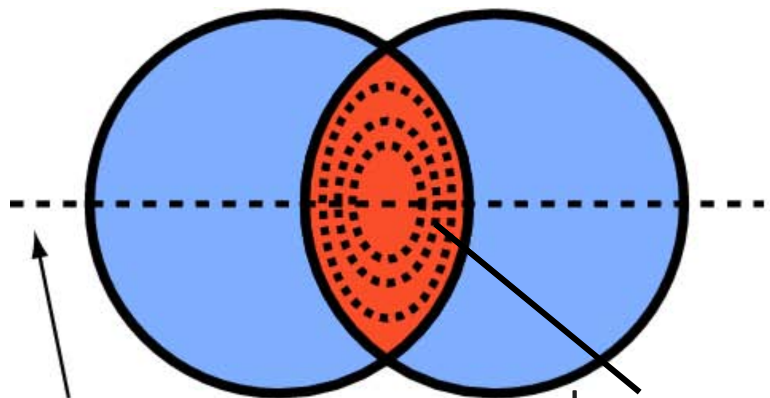
Anisotropic Flow

Classical view:

Initial spatial anisotropy ➜ anisotropy in momentum space



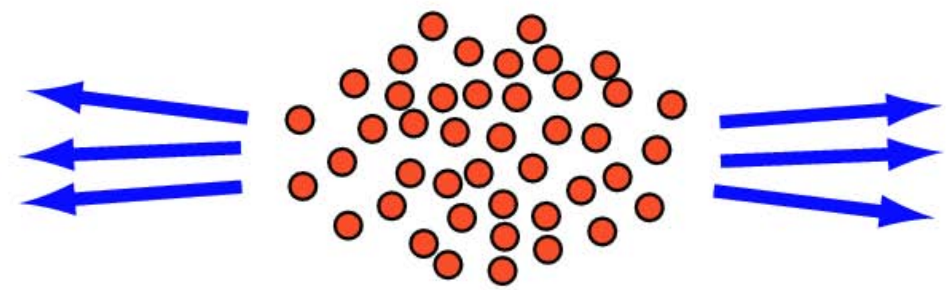


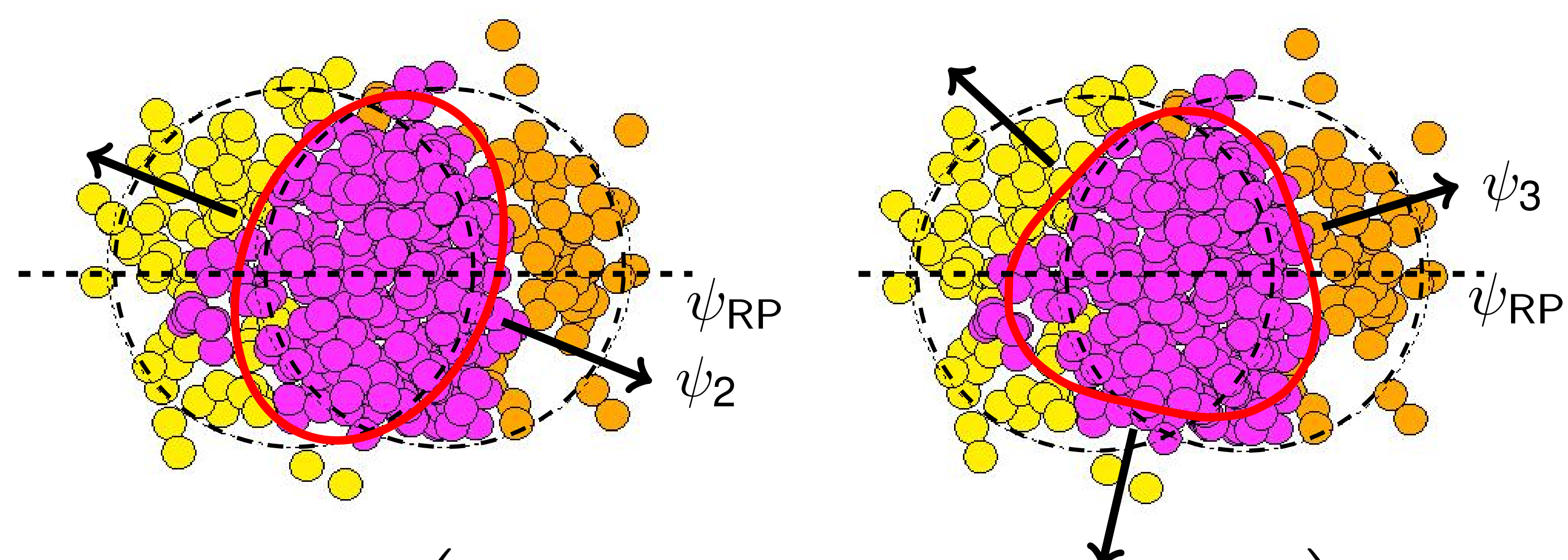
figure from arXiv:1107.0592

Revised picture (ca. 2010):

Importance of initial energy density fluctuations

$\psi_2 \approx \psi_{RP}$

ψ_2 not correlated with ψ_3

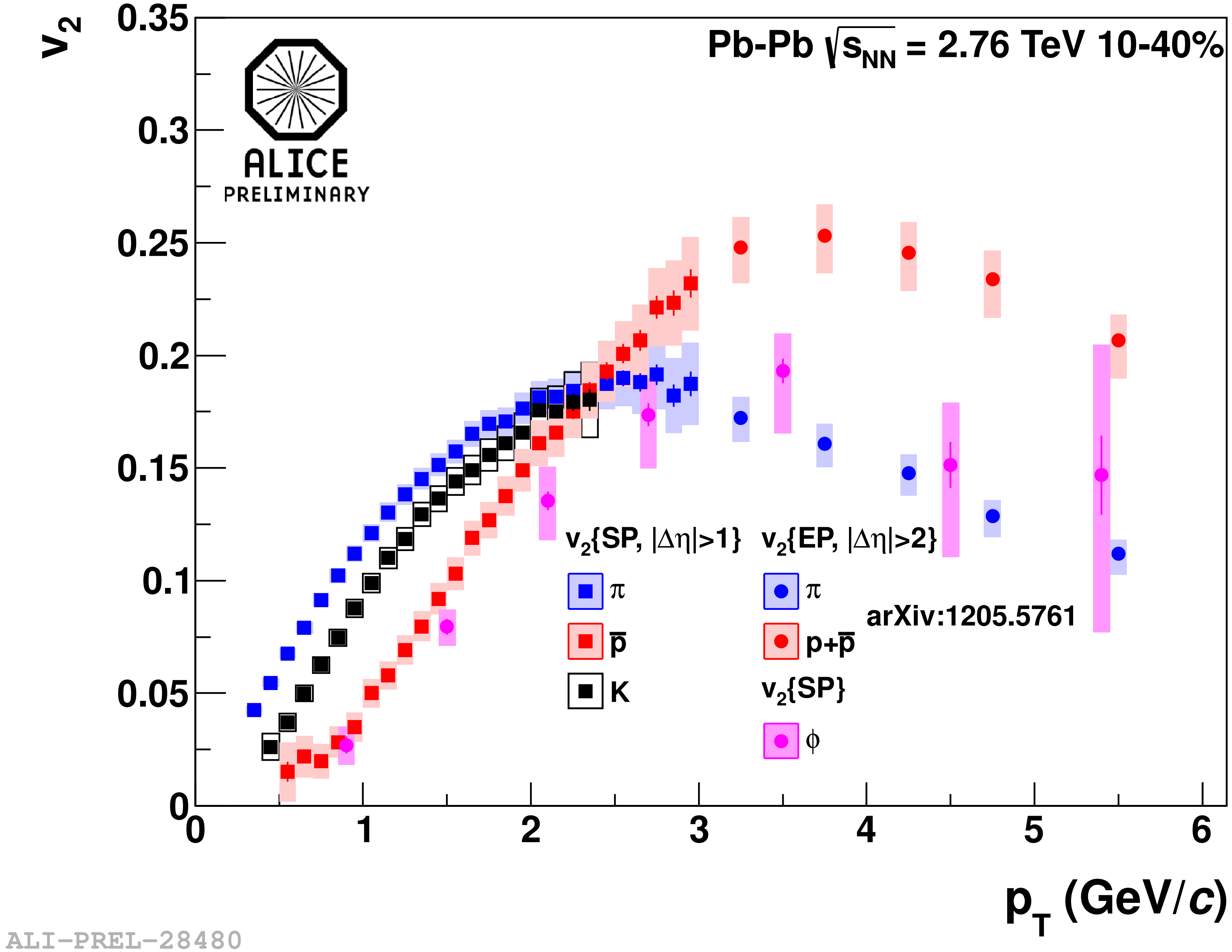


Fourier decomposition:

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

v_2 : elliptic flow, v_3 : triangular flow

Identified Particle v_2: Mass Ordering Supports Hydro Picture



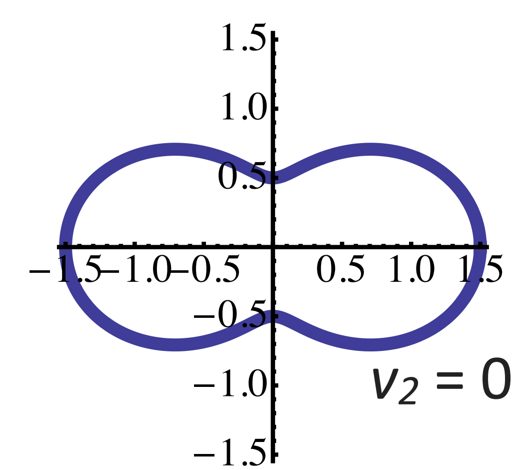
- Hydro predicts mass ordering

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

$$\left[m_T = \sqrt{m^2 + p_T^2} \right]$$

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

- Indeed observed!



$v_2 = 0.25$

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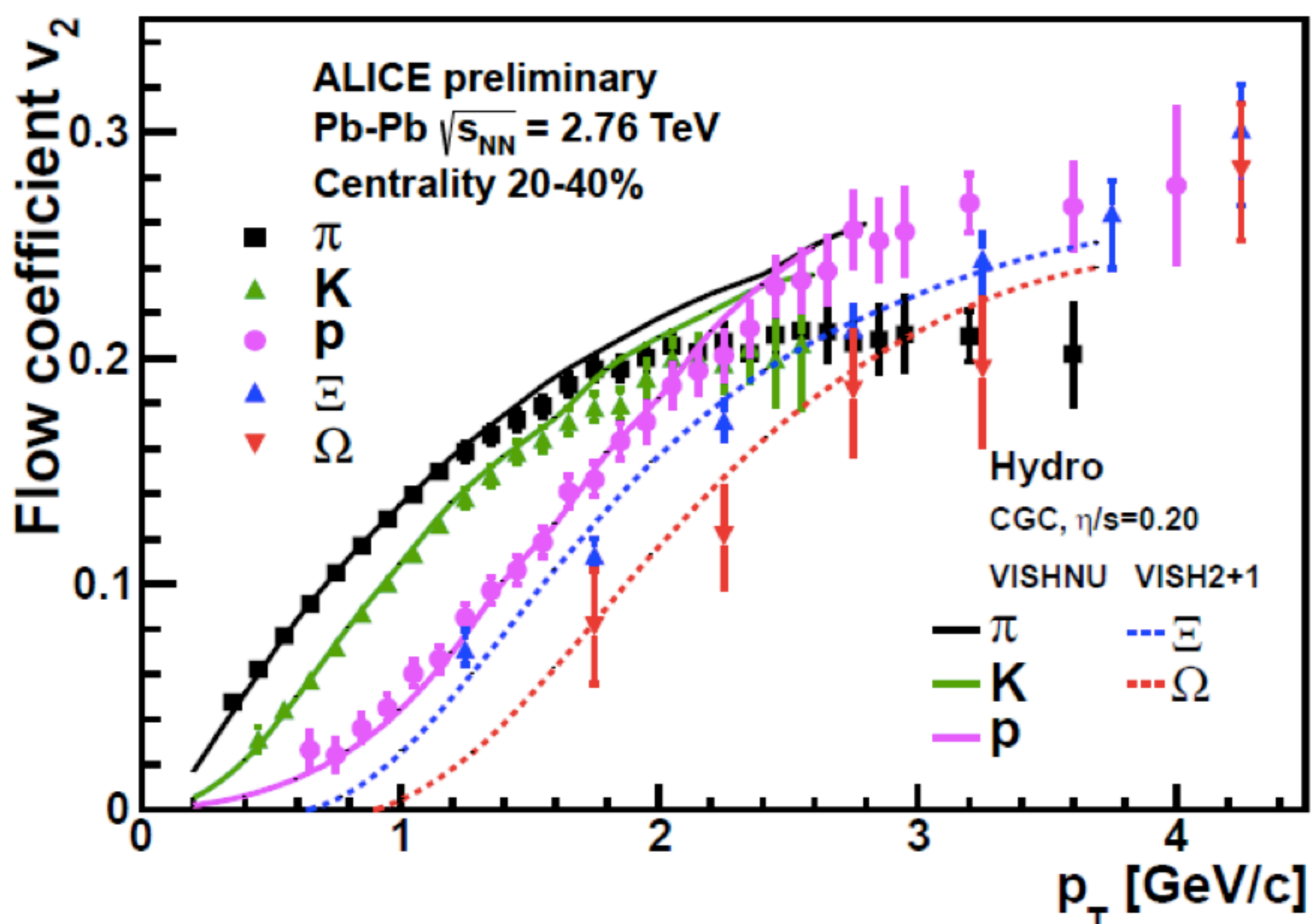
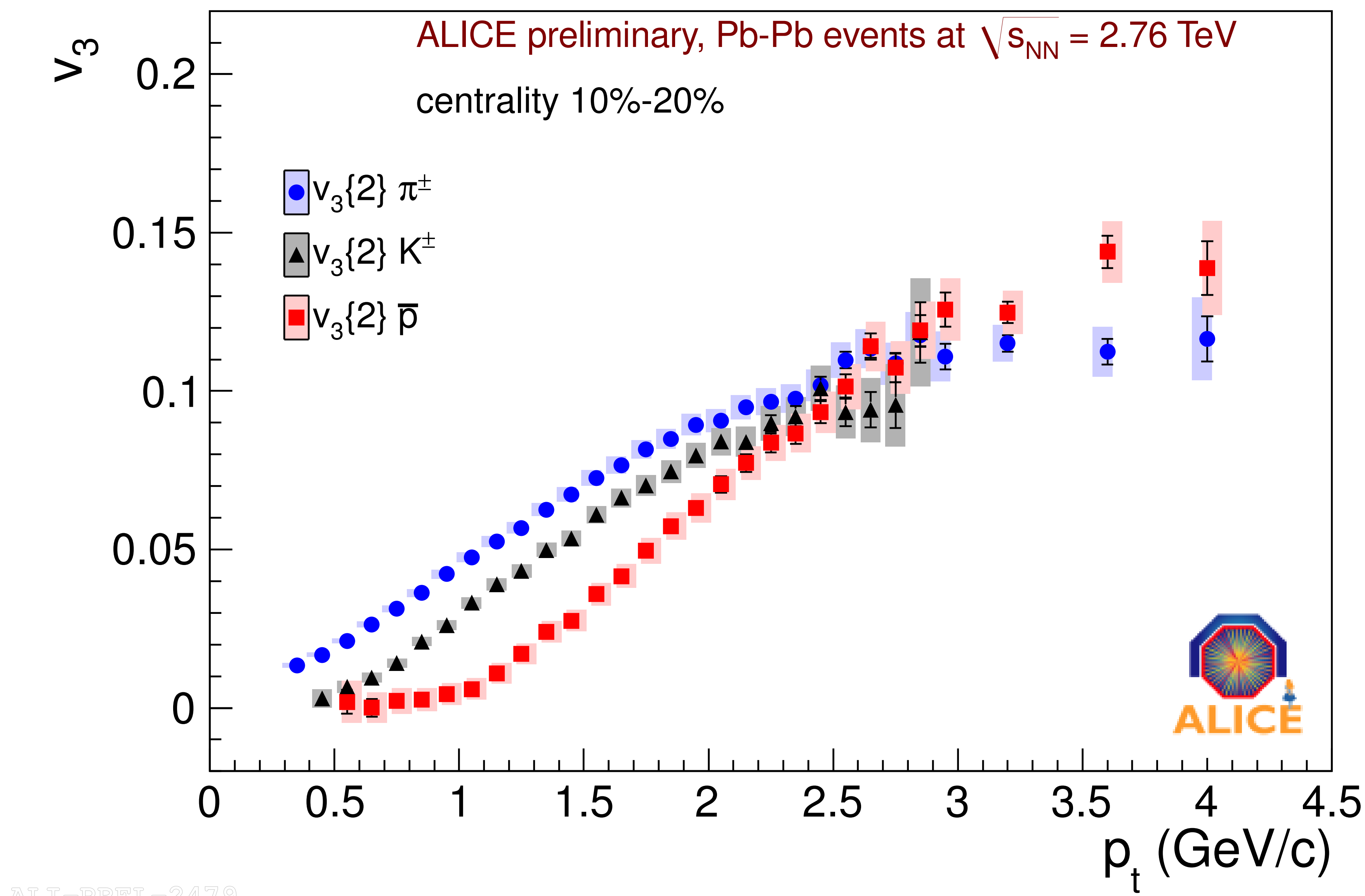
Hydro Models Describe Identified Particle v_2



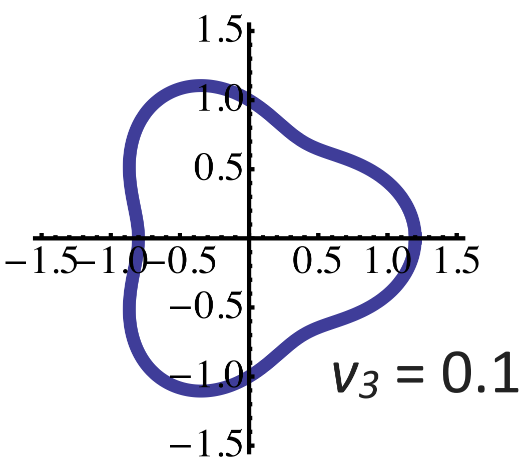
VISHNU
Heinz, Shen, Song,
arXiv:1108.5323

- 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)

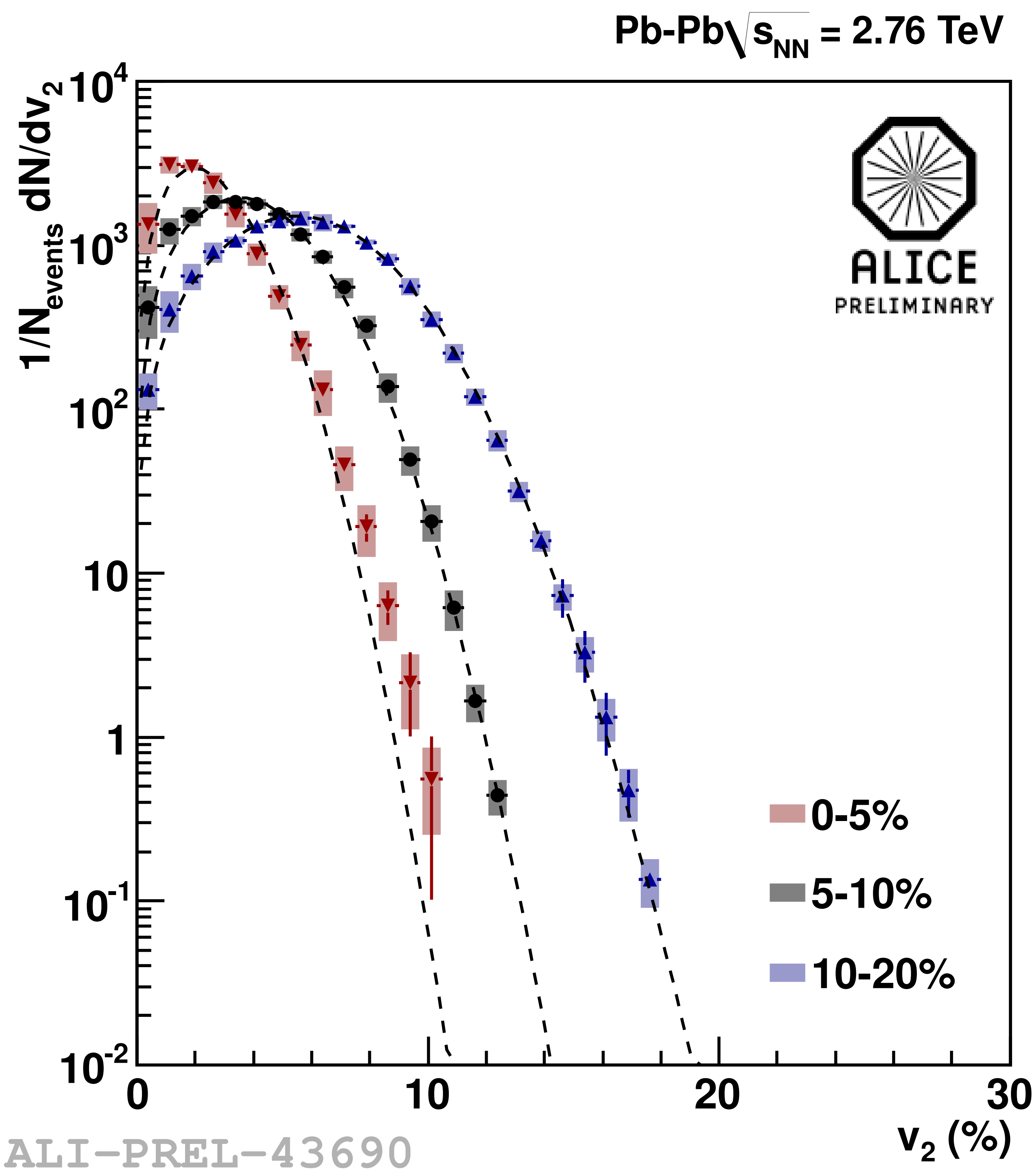
π, K, p v_3: Mass Splitting As Expected From Hydro Flow



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



Event-by-Event v_2 Distributions



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

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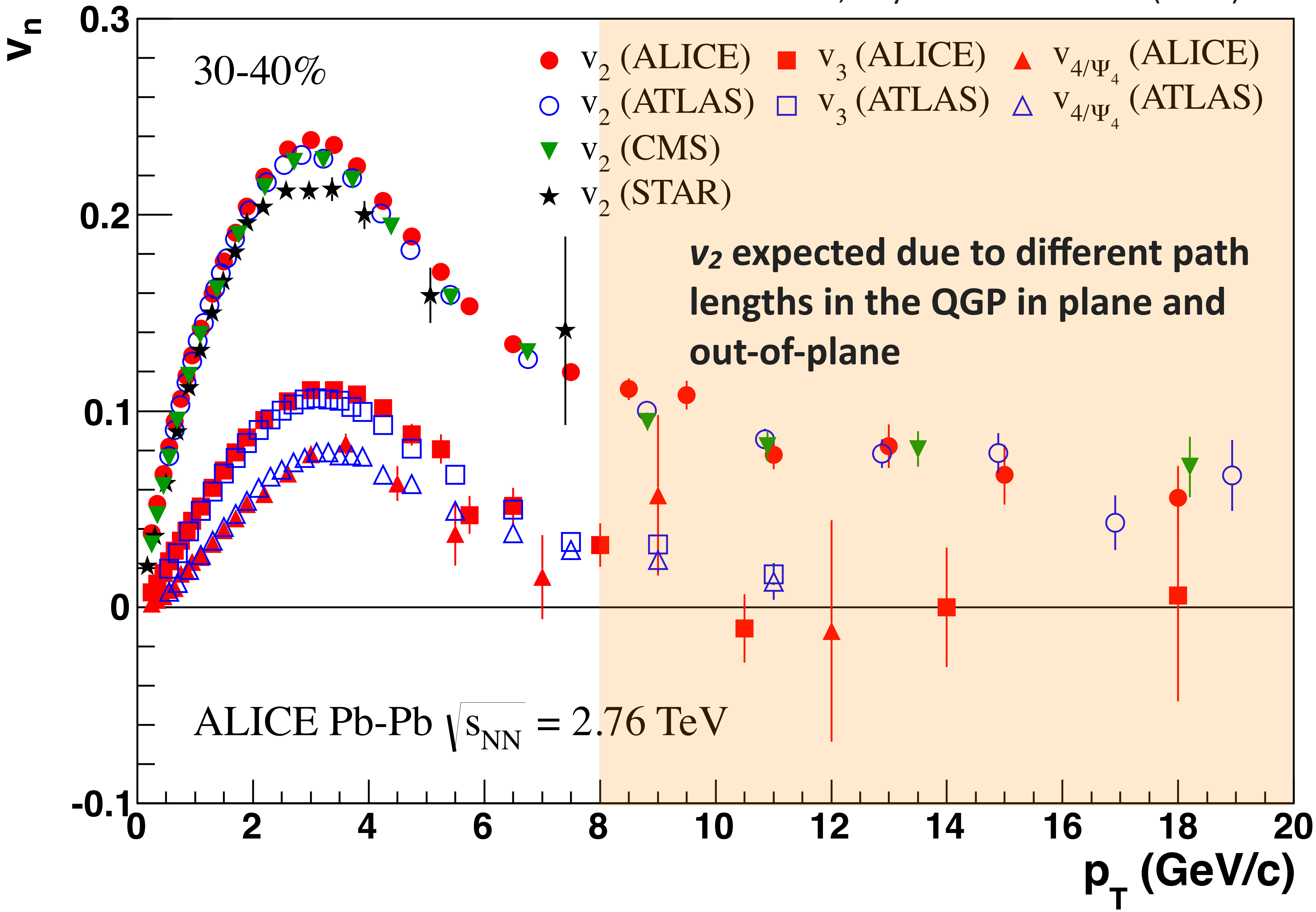
$v_2 > 0$ at Large p_T: Parton Energy Loss

ALICE, Physics Letters B 719 (2013) 18

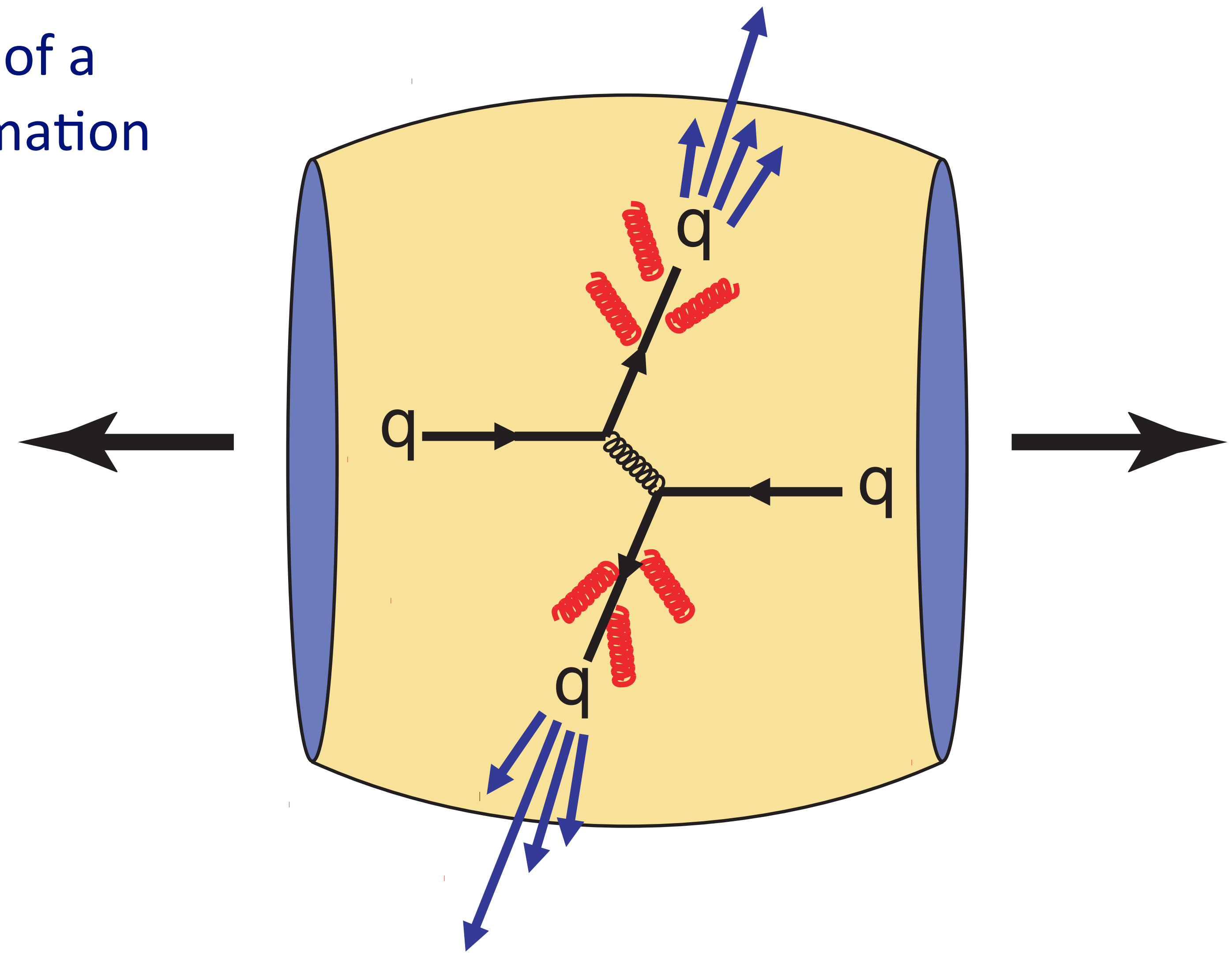


v_2 expected due to different path lengths in the QGP in plane and out-of-plane

Jet Quenching

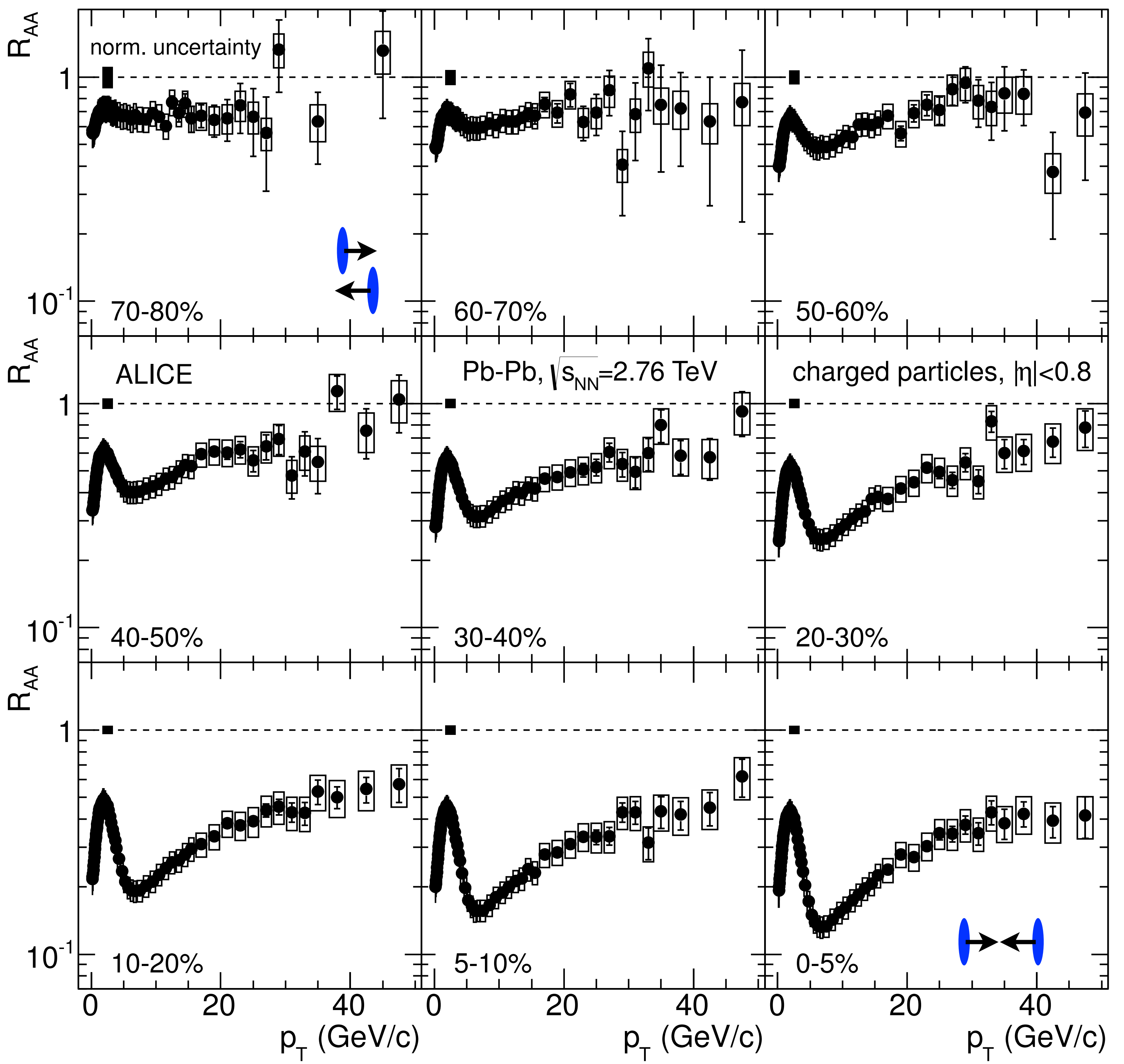
Hard Probes in Heavy-Ion Collisions

- 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)



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

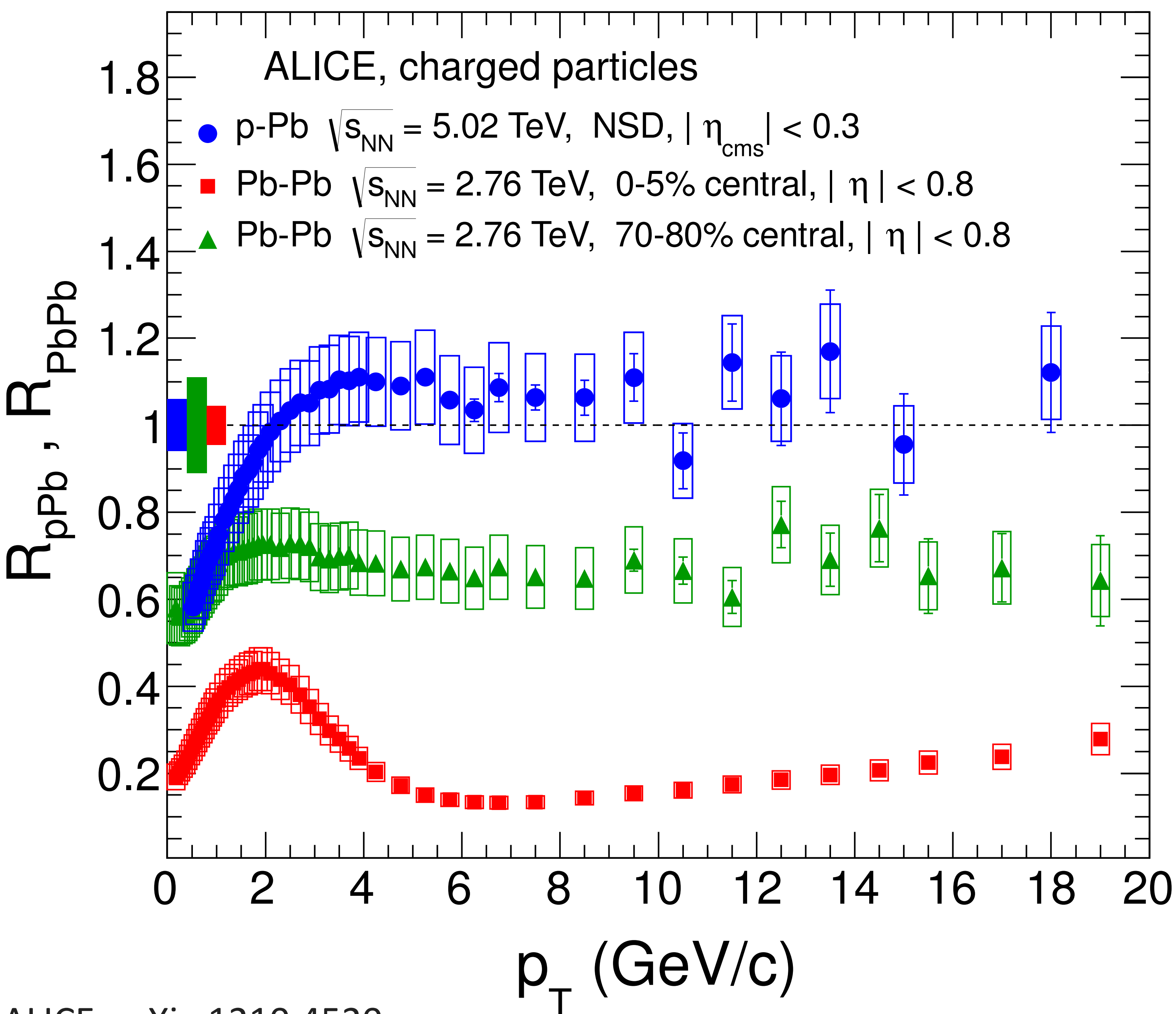
$$\langle T_{AA} \rangle = \langle N_{coll} \rangle / \sigma_{inel}^{pp}$$

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 √s = 5.02 TeV: No Suppression

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



ALICE, arXiv:1210.4520

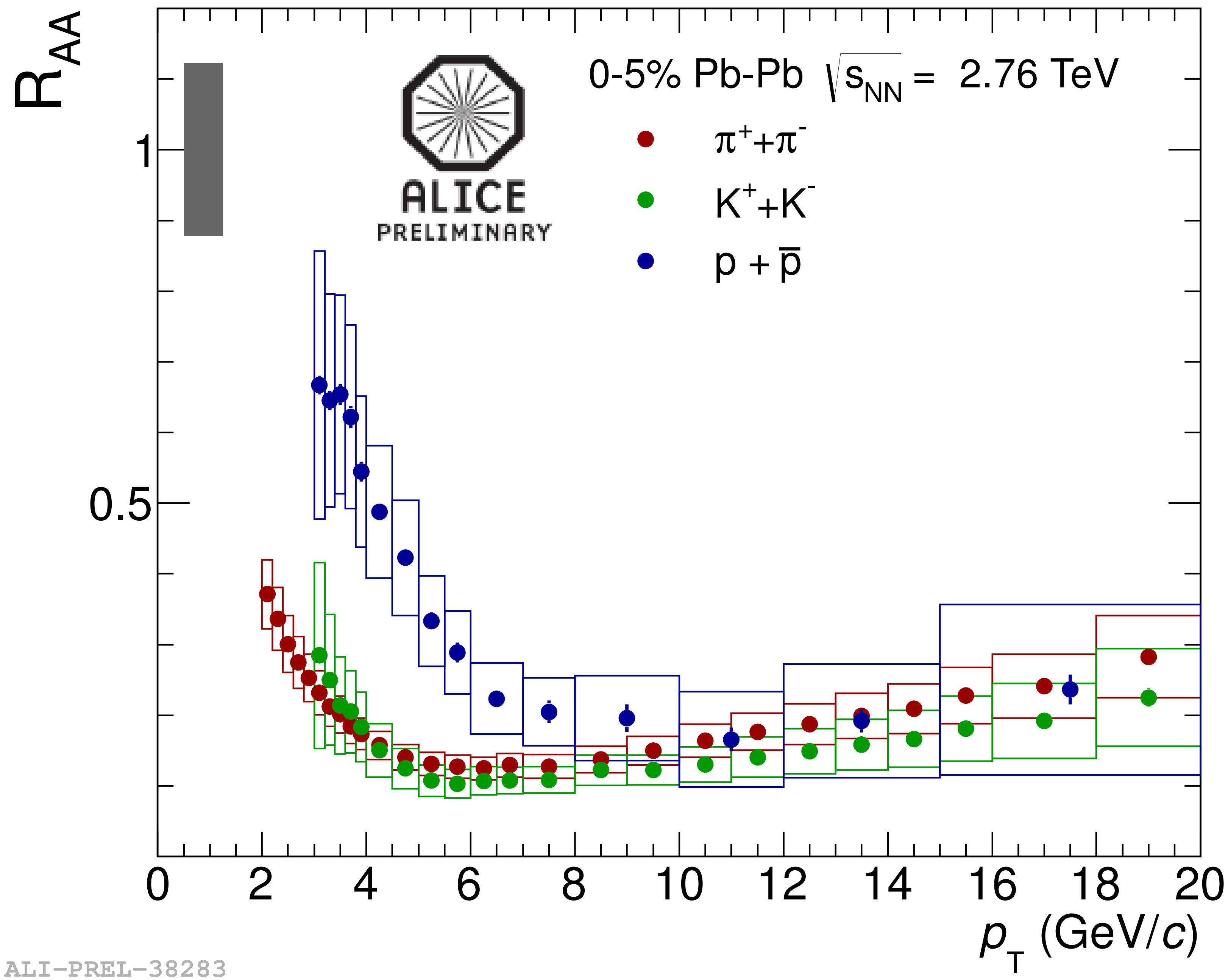
$$R_{pPb} = \frac{dN/dp_T(p+Pb)}{\langle T_{pPb}\rangle \times d\sigma/dp_T(p+p)}$$

$$\langle T_{pPb}\rangle = \langle N_{\rm coll}\rangle / \sigma^{pp}_{\rm inel}$$

pp reference interpolated from measurements at √s = 2.76 and 7 TeV

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

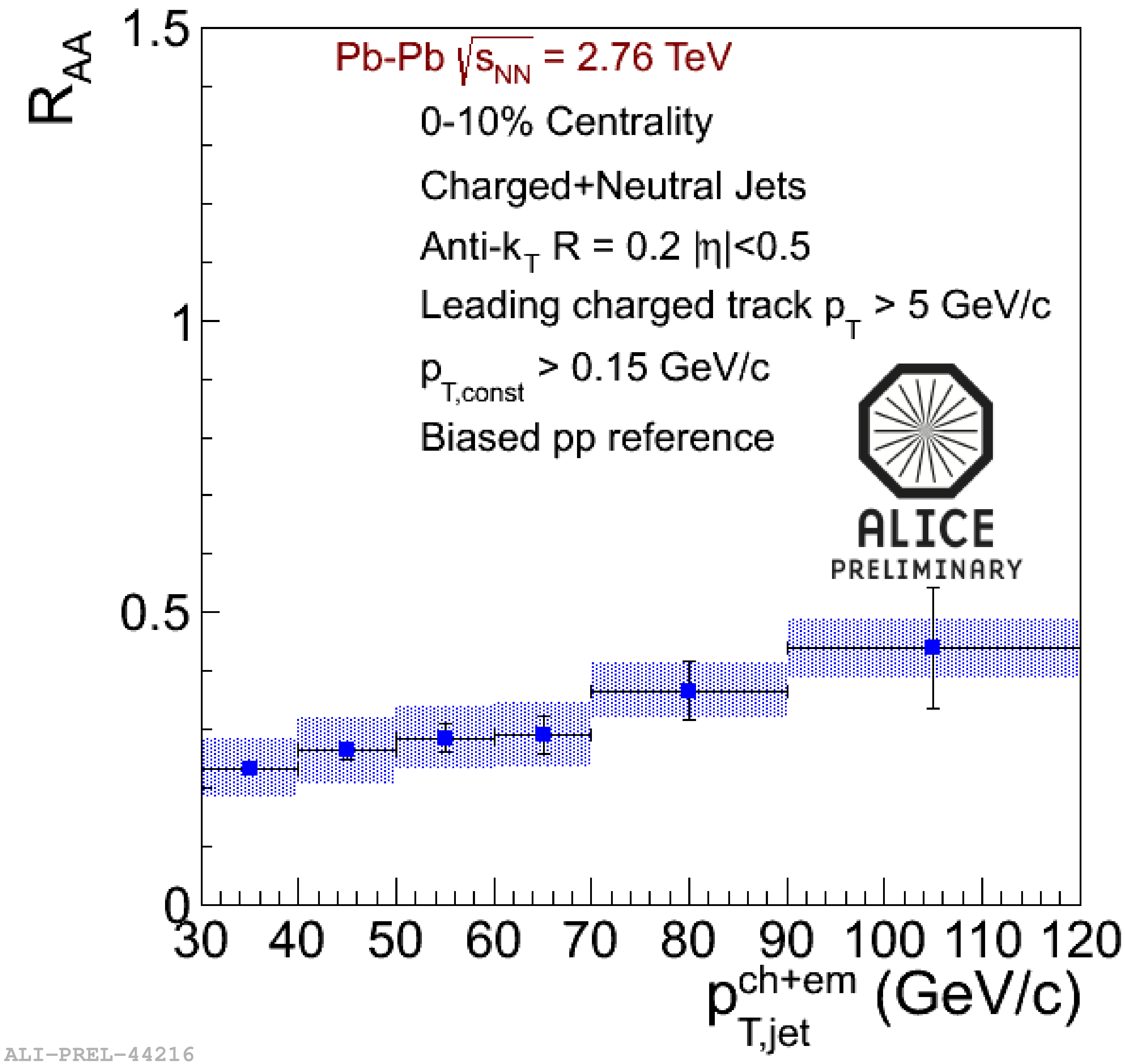
R_{AA} for Identified Particles in Central Pb+Pb



- $R_{AA}(p) > R_{AA}(K) \approx R_{AA}(\pi)$ 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 $p_{T,\mathrm{hadron}} > 8$ 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

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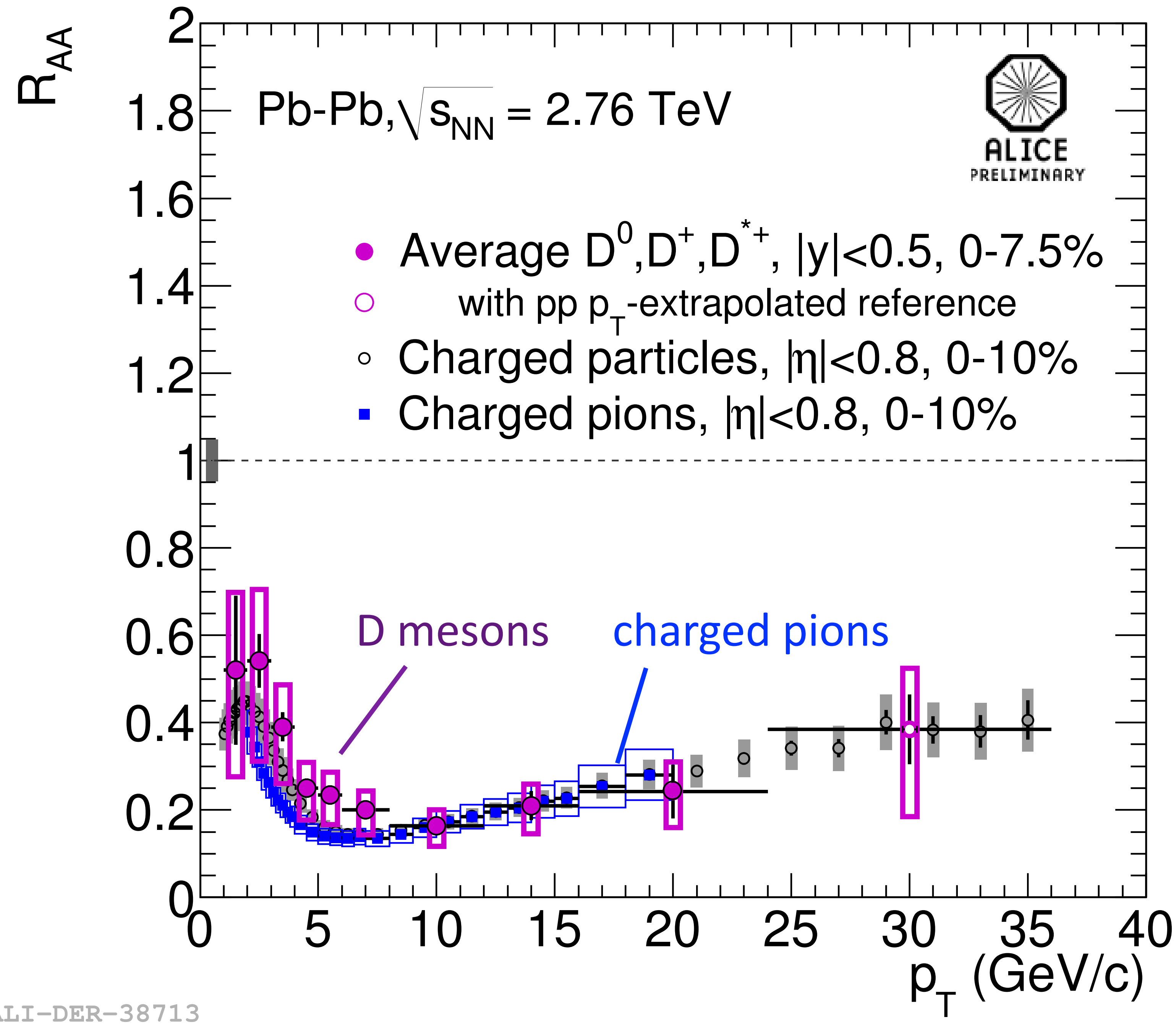
D Meson R_{AA}: Charm Quark Energy Loss Surprisingly Similar to Quark and Gluon Energy Loss



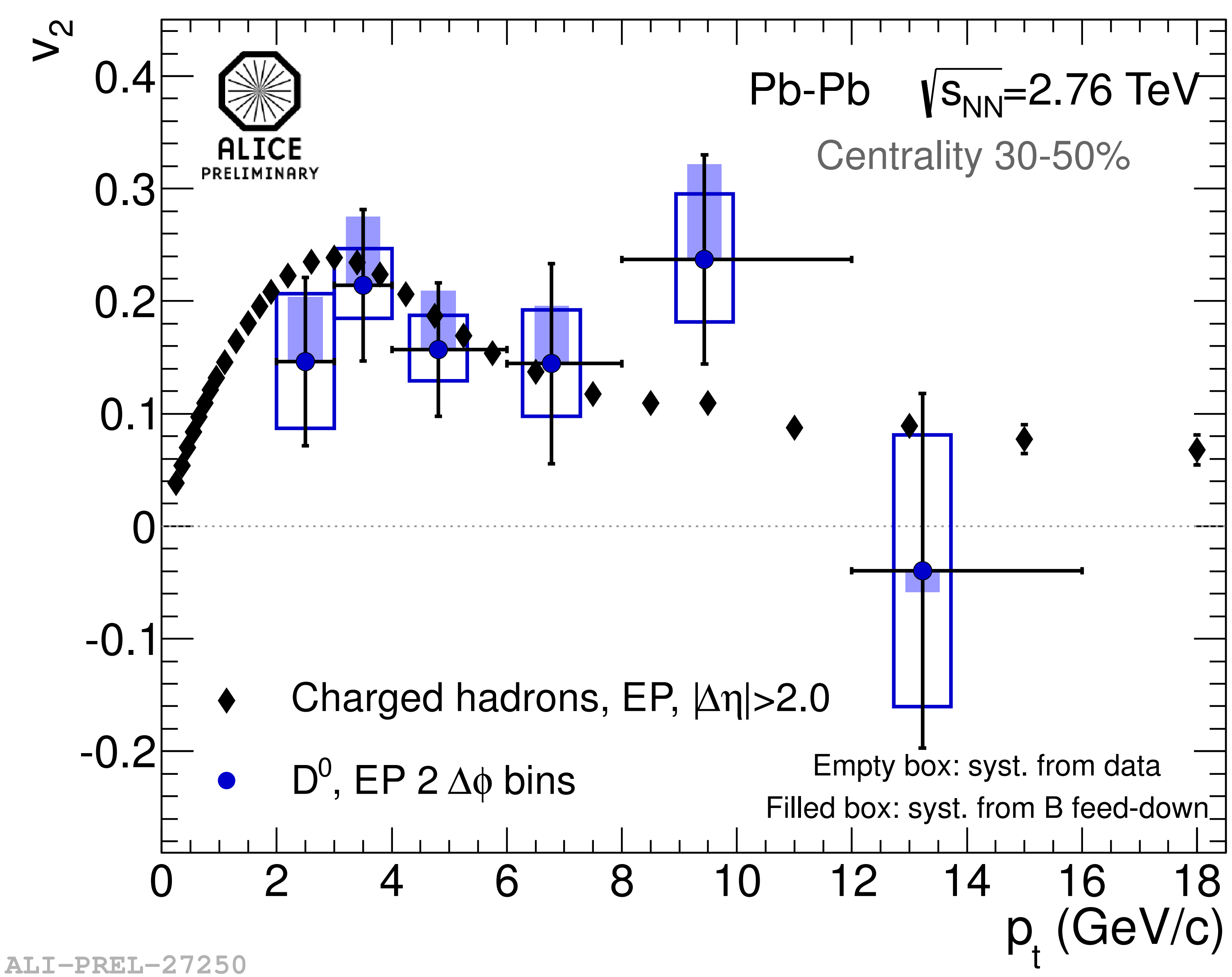
Radiative parton energy loss:

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

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 careful consider also the steepness of the initial parton spectra)

Surprisingly Large Elliptic Flow for D Mesons



- $m_{\text{c-quark}} > 250 \times m_{\text{u,d}}$
- 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

Charmonium

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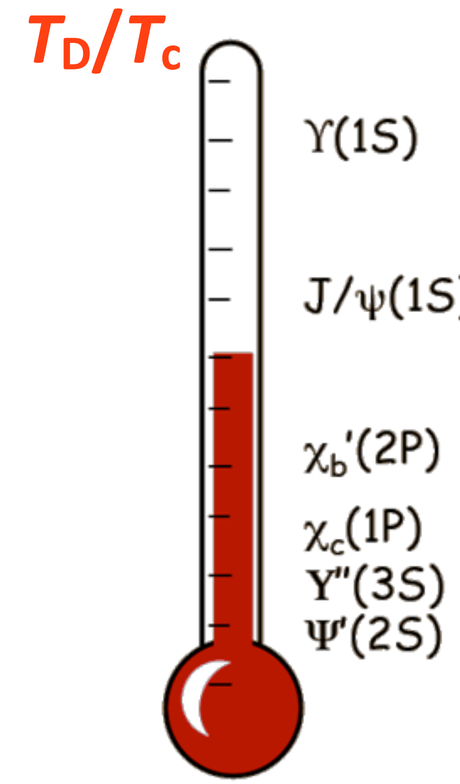
Quarkonia as QGP Signature: Suppression at Low $\sqrt{s_{NN}}$ and J/ψ Enhancement at High $\sqrt{s_{NN}}$?

- 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
χc (1p)	0.67	1.0
ϒ (1s)	0.21	2.0
ϒ' (2s)	0.50	1.2
ϒ'' (3s)	0.76	1.0



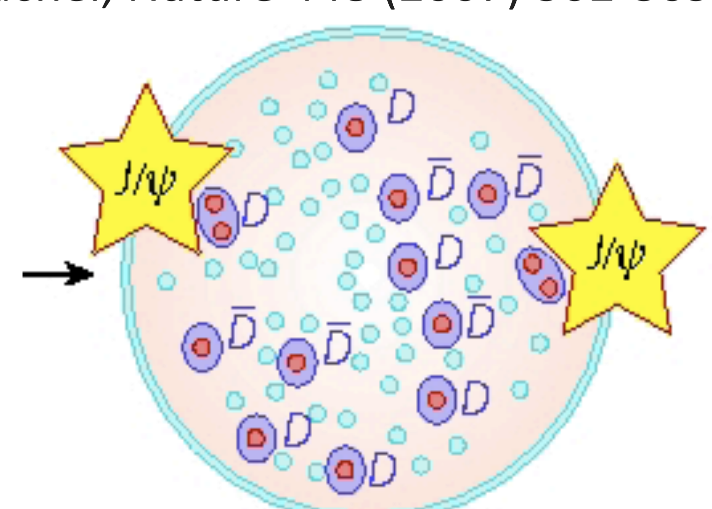
Exact values model dependent, trend stable

- 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)

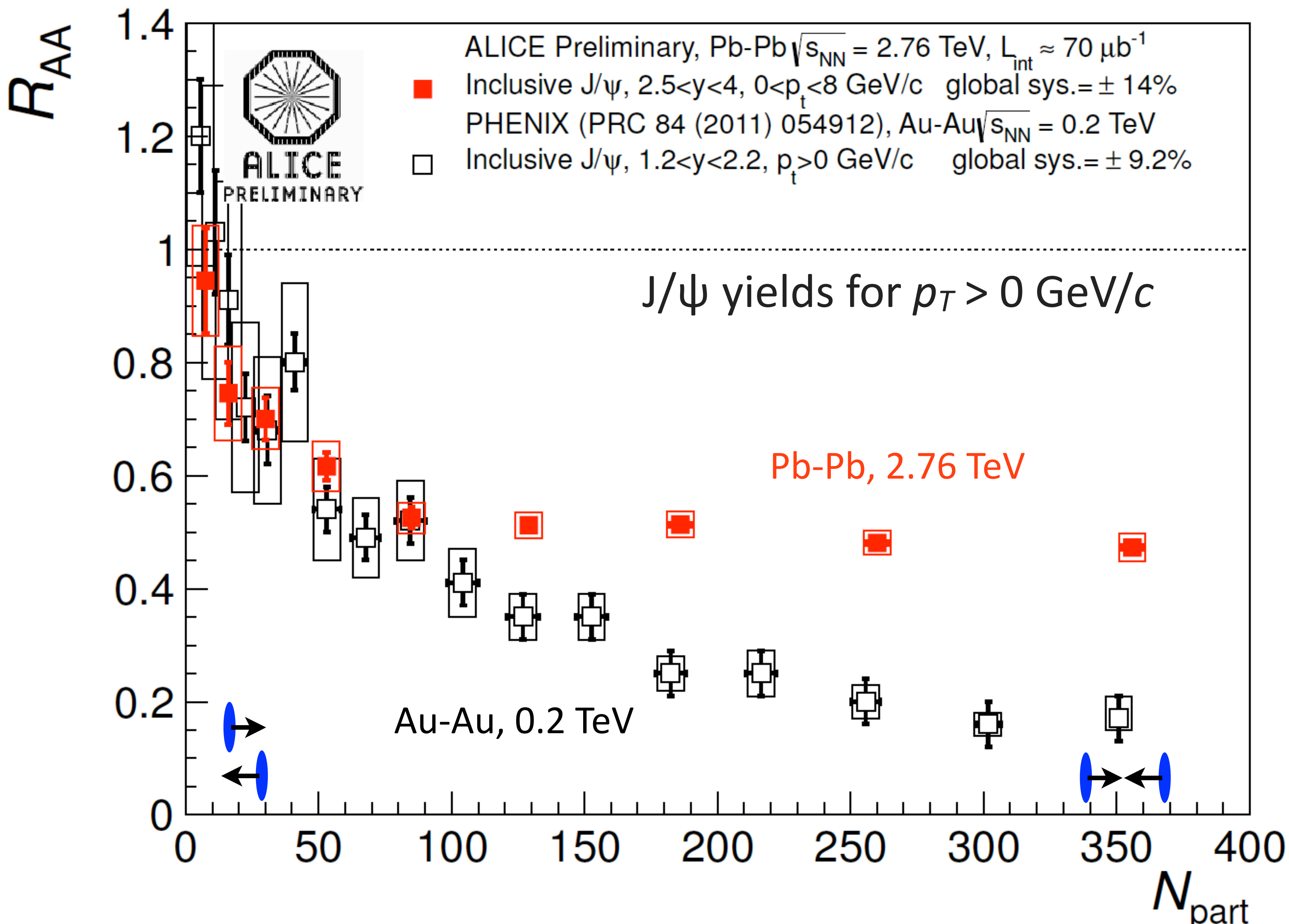
Braun-Munzinger, Stachel, Nature 448 (2007) 302-309

~ 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

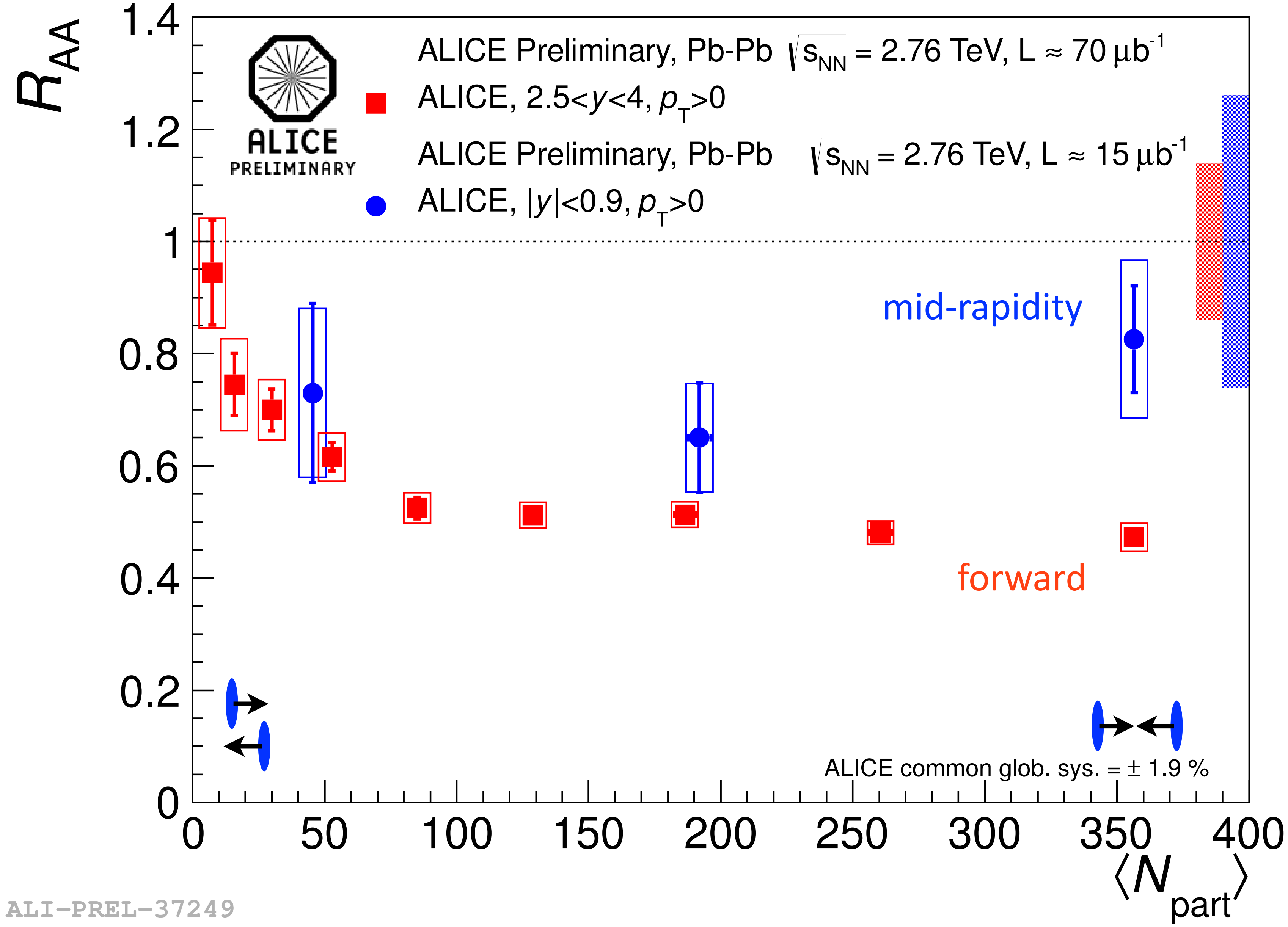


Note: Contribution from B feed-down small:
~ 10% (from pp-measurement)

- 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])

Qualitatively consistent with J/ψ coalescence picture

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

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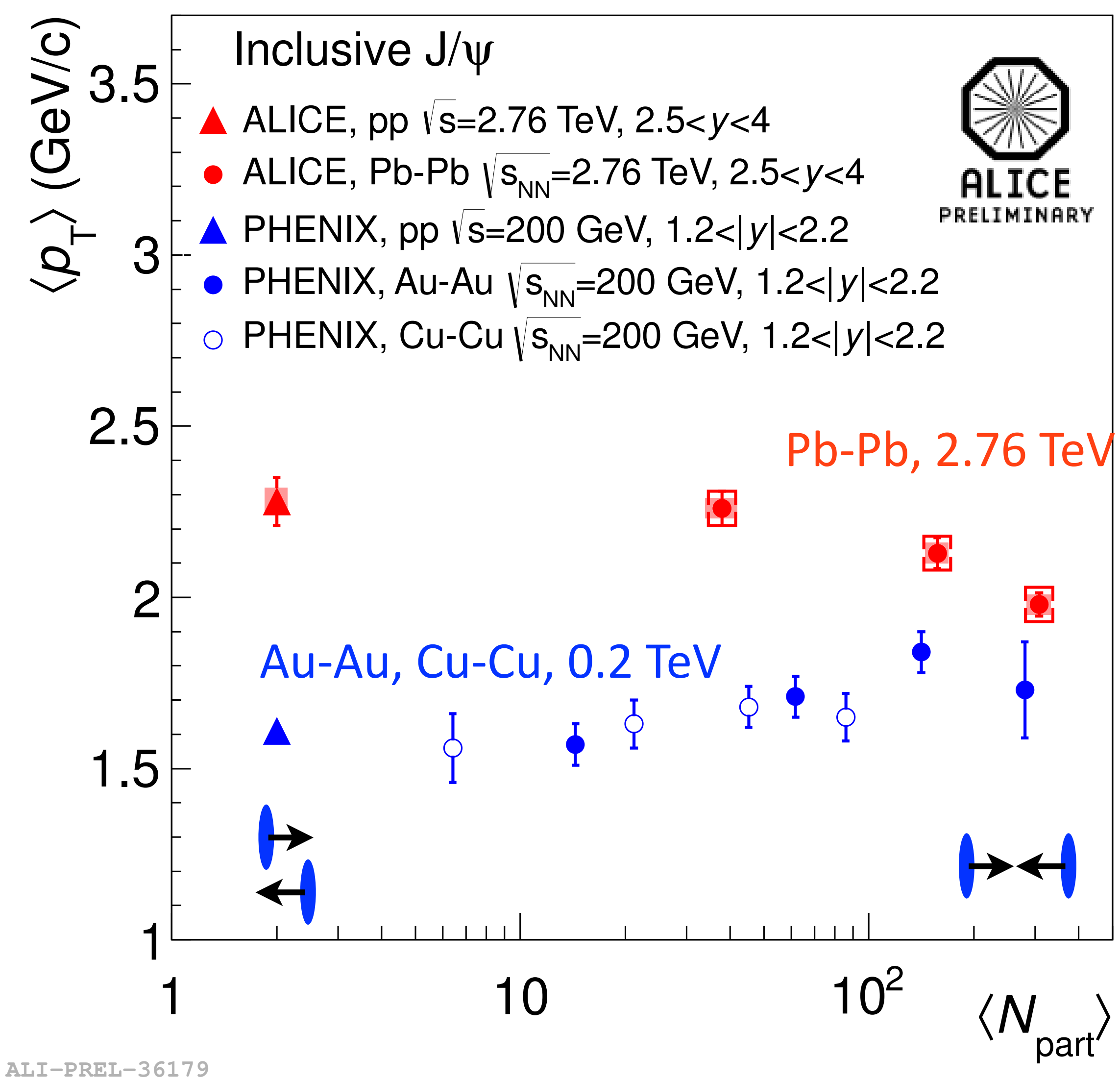
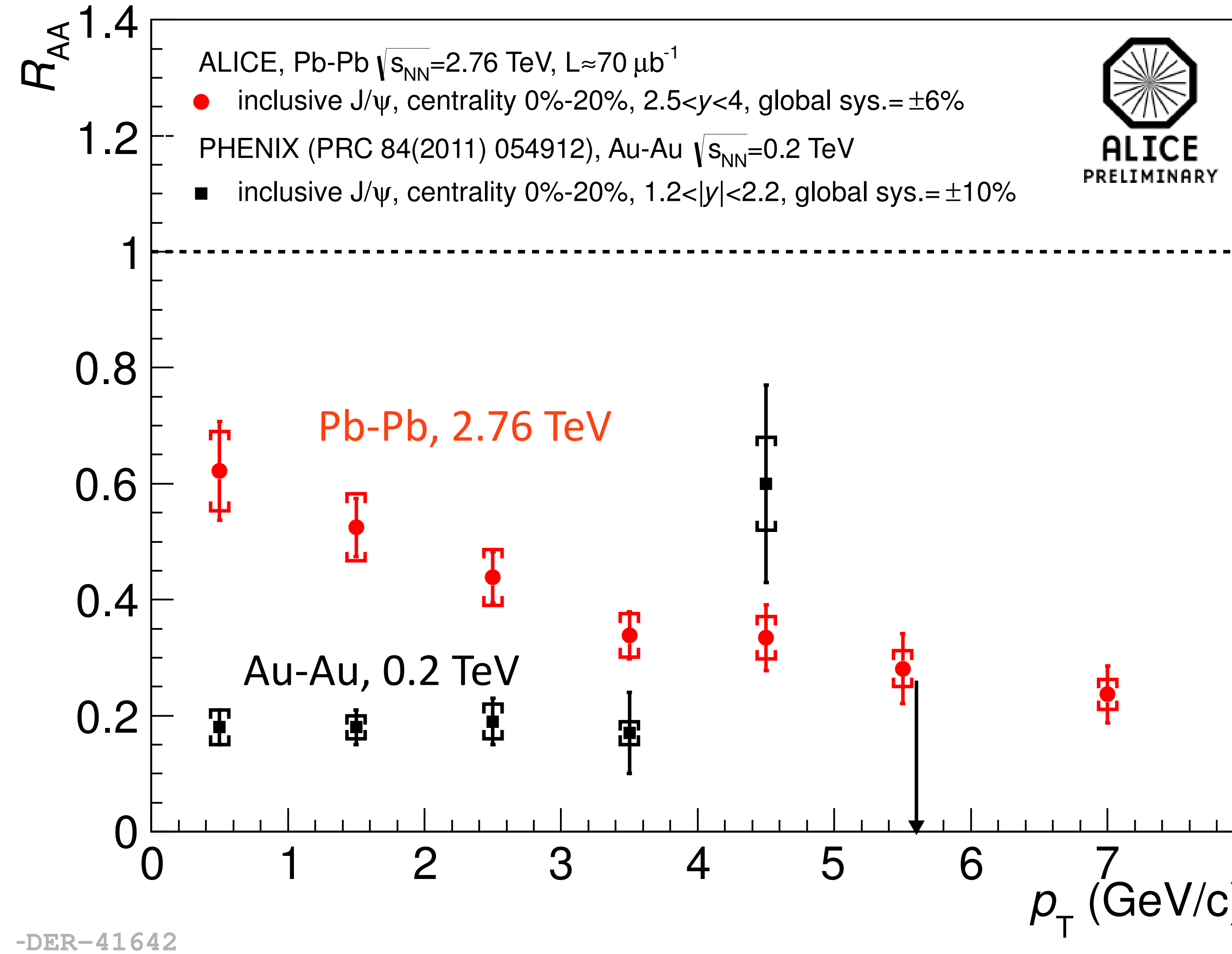
Centrality Dependence of J/ψ $\langle p_T \rangle$ and p_T Dependence of the J/ψ R_{AA} Qualitatively Consistent with the Coalescence Picture

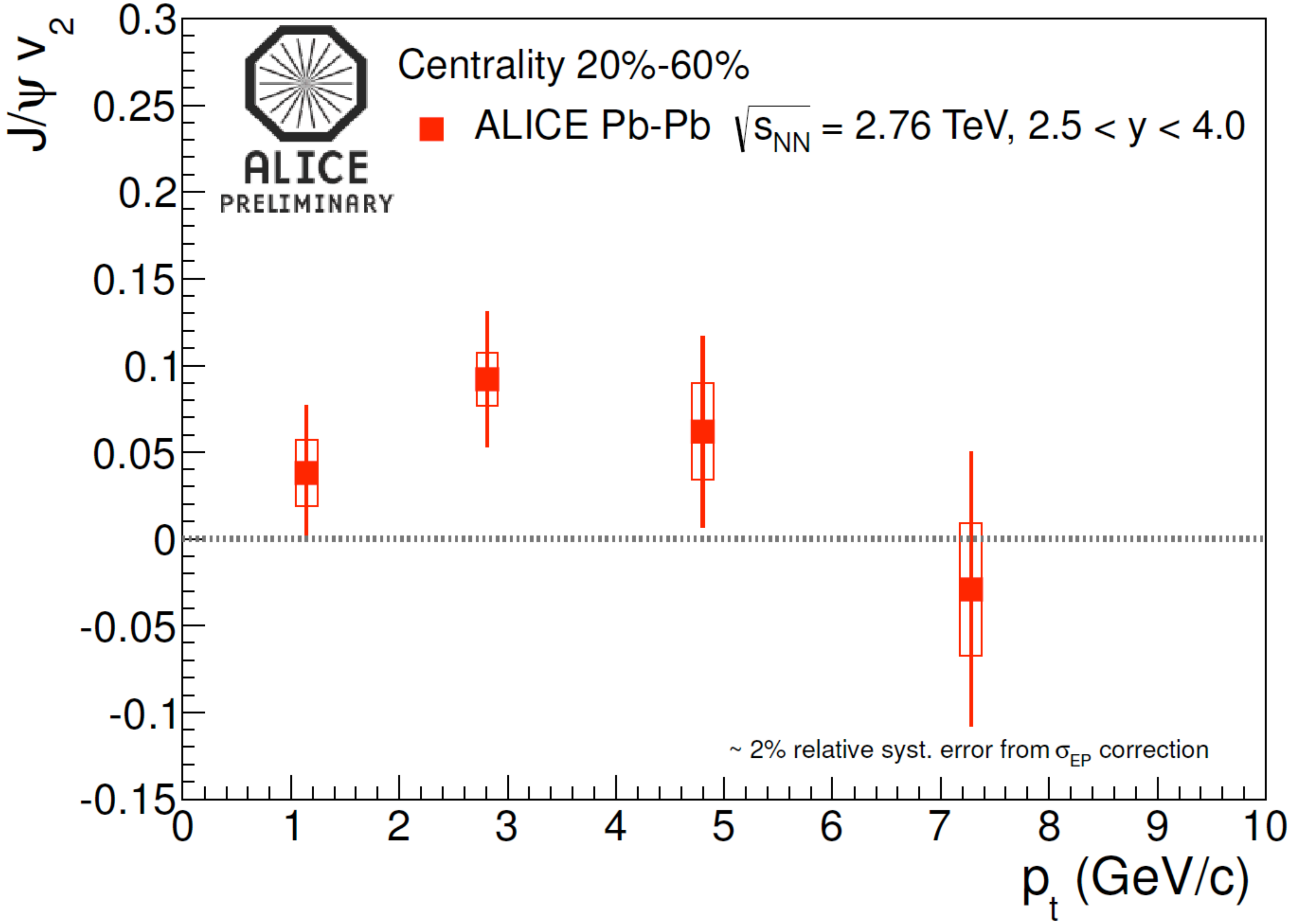




Decrease of J/ψ R_{AA} in central Pb-Pb. Not observed at lower energies or for other particles species at the LHC.

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

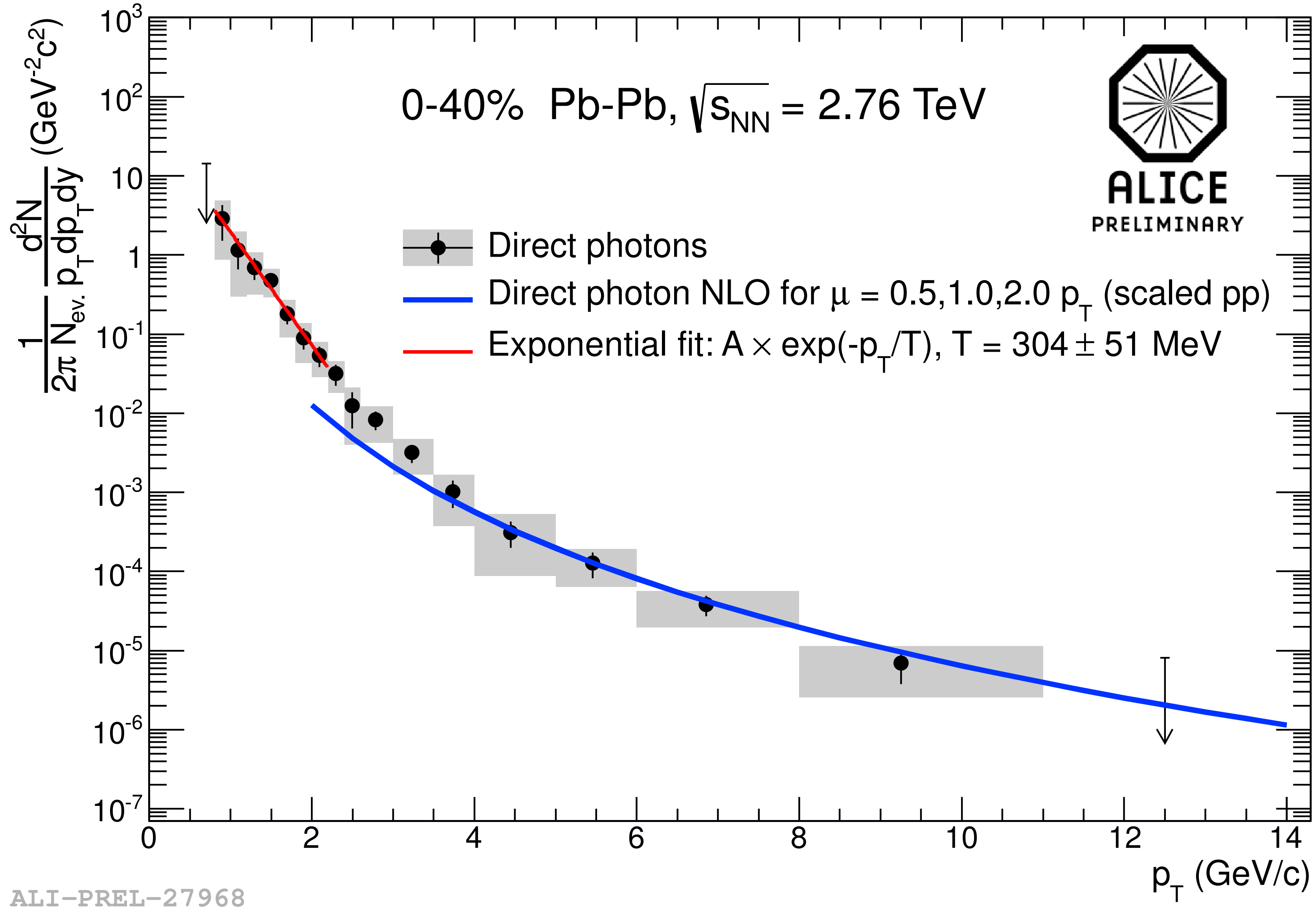
Significant J/ψ Elliptic Flow (as Expected in Coalescence Models)



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

Thermal Photons

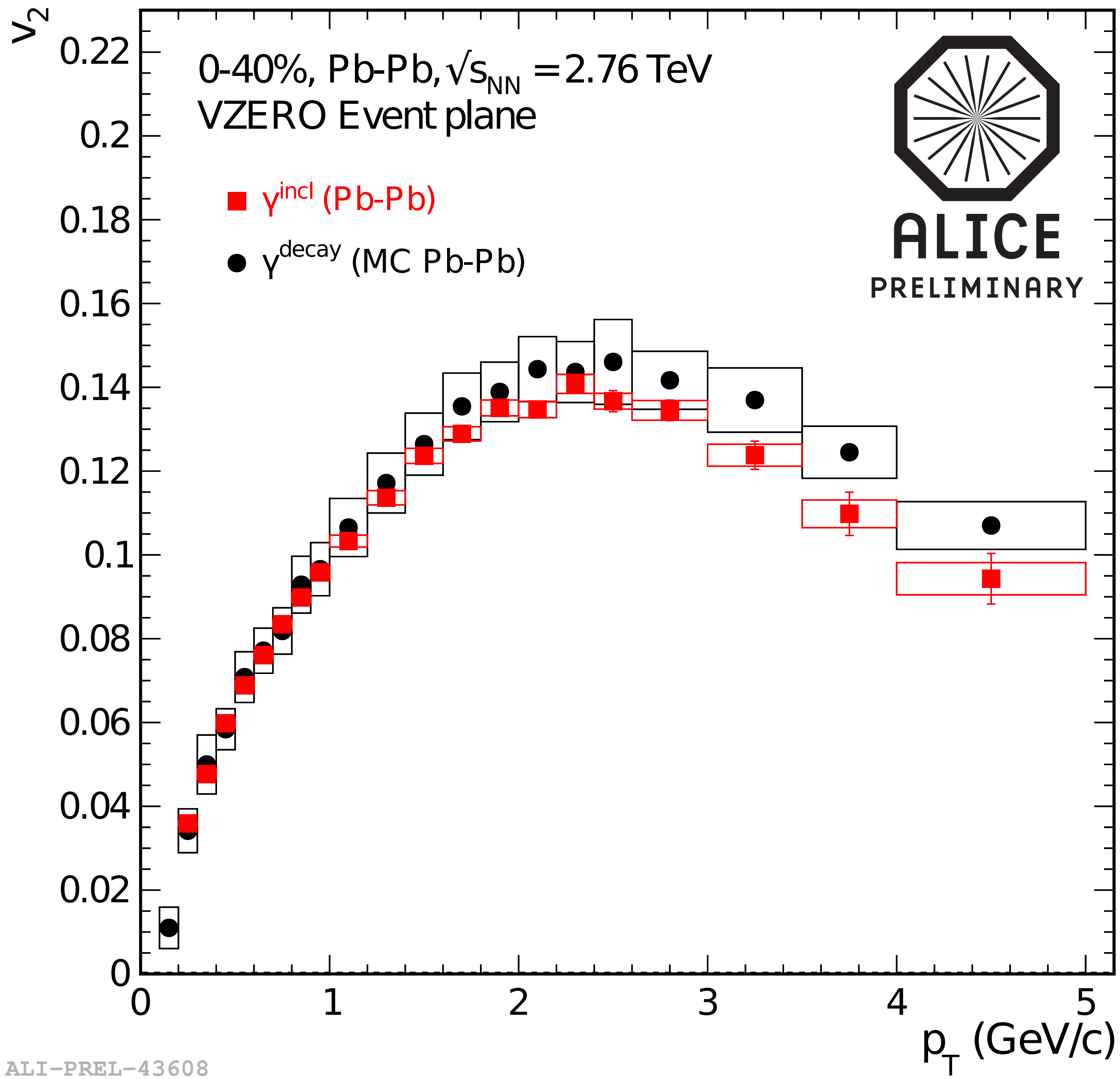
Direct Photon Spectrum in Central Pb-Pb



- 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: ~ 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

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.

Measurement of the Direct-Photon v_2



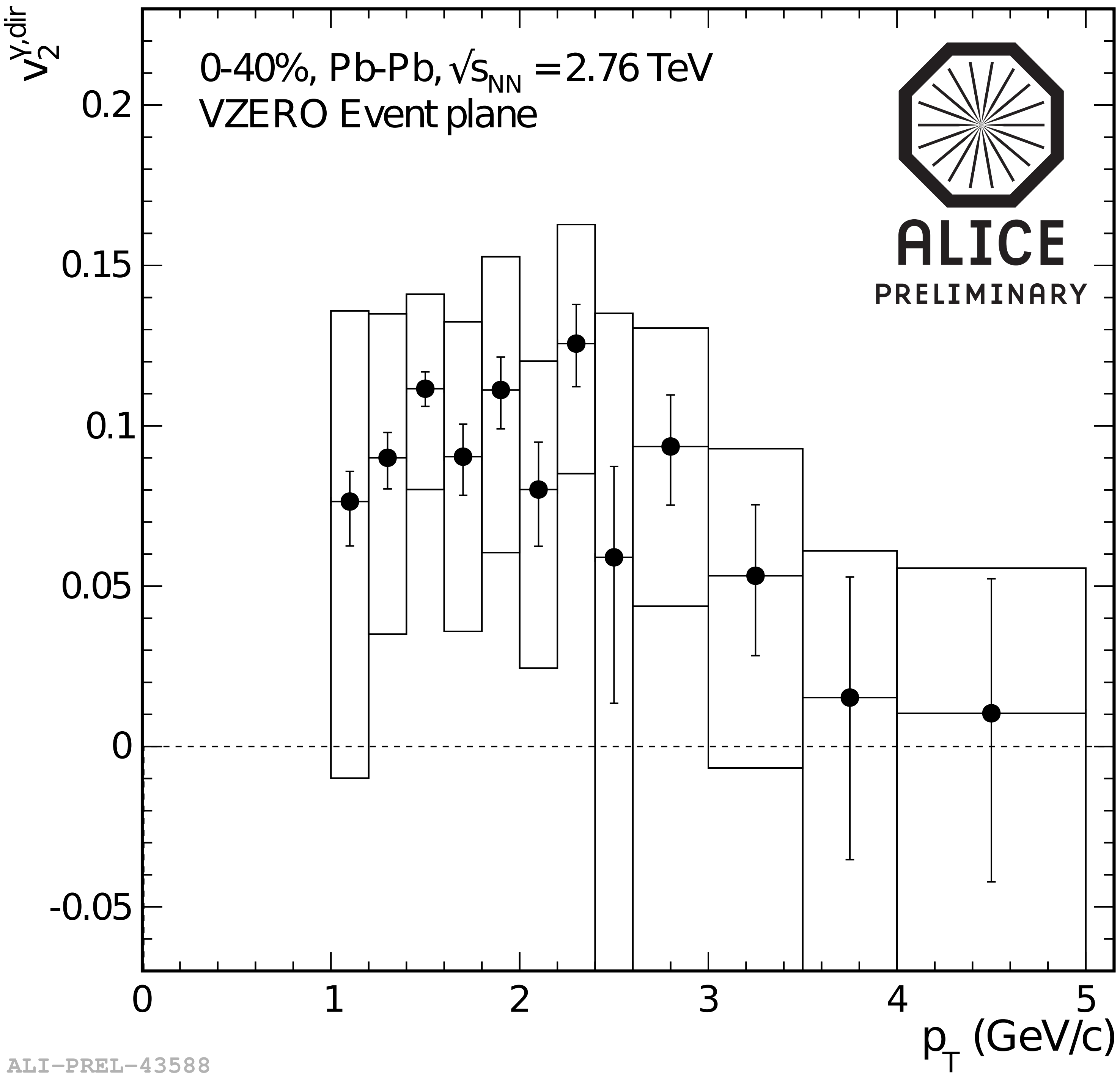
ALI-PREL-43608

- Measure inclusive photon v_2
- Subtract decay photon v_2

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

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

Large Direct-Photon Elliptic Flow: A Big Puzzle!



- 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:

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

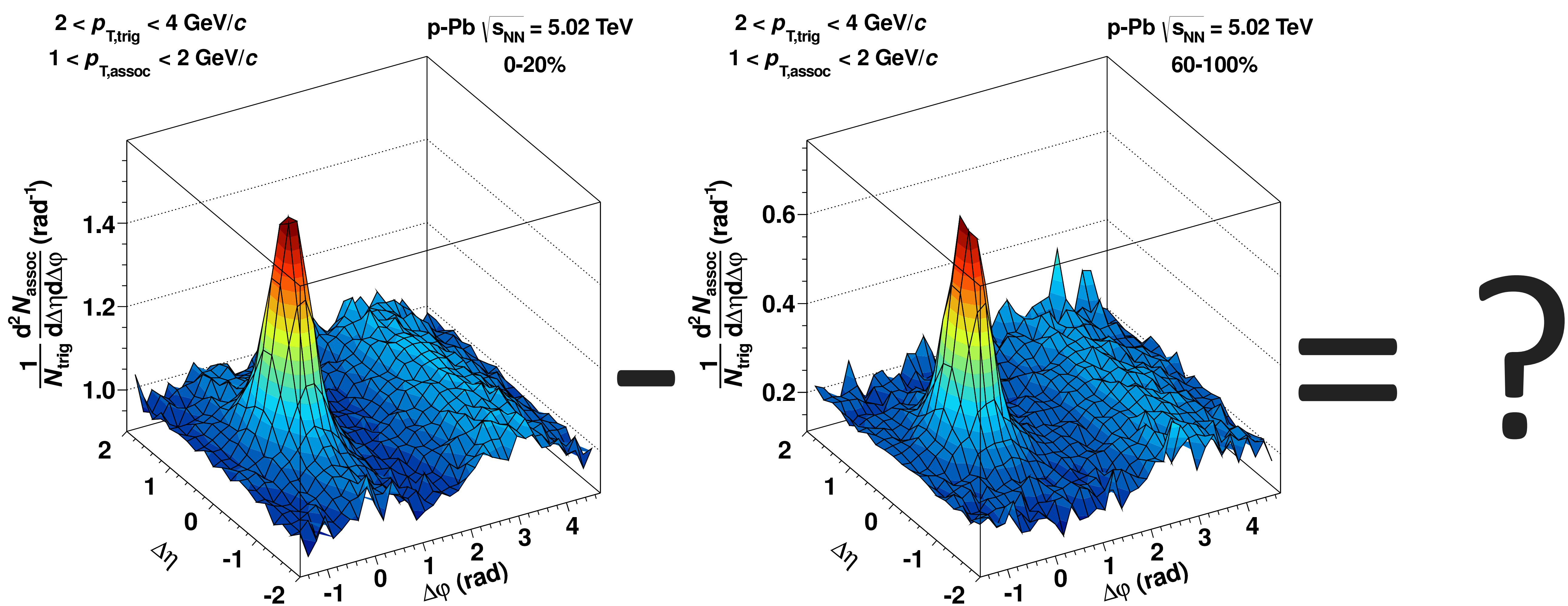
Large direct-photon v_2 challenges the standard hydro picture

Heavy-Ion-Like Effects in p-Pb?

Per-Trigger Charged Hadron Yields in Low and High-Multiplicity p-Pb Collisions at √s = 5.02 GeV

Two-Particle correlations: jet-like correlations + *X*

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

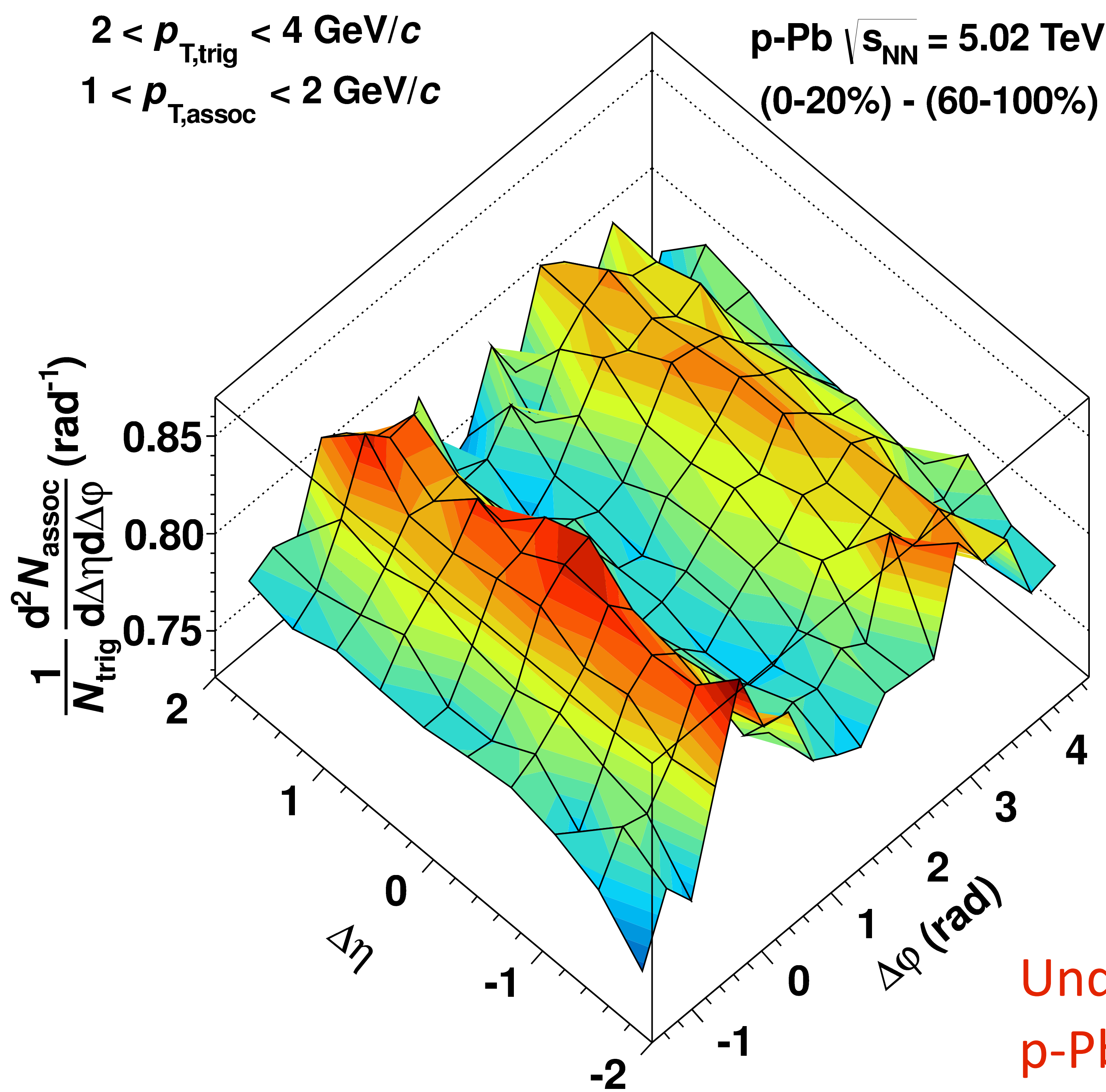


High multiplicity events — Low multiplicity events

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



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

- 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.

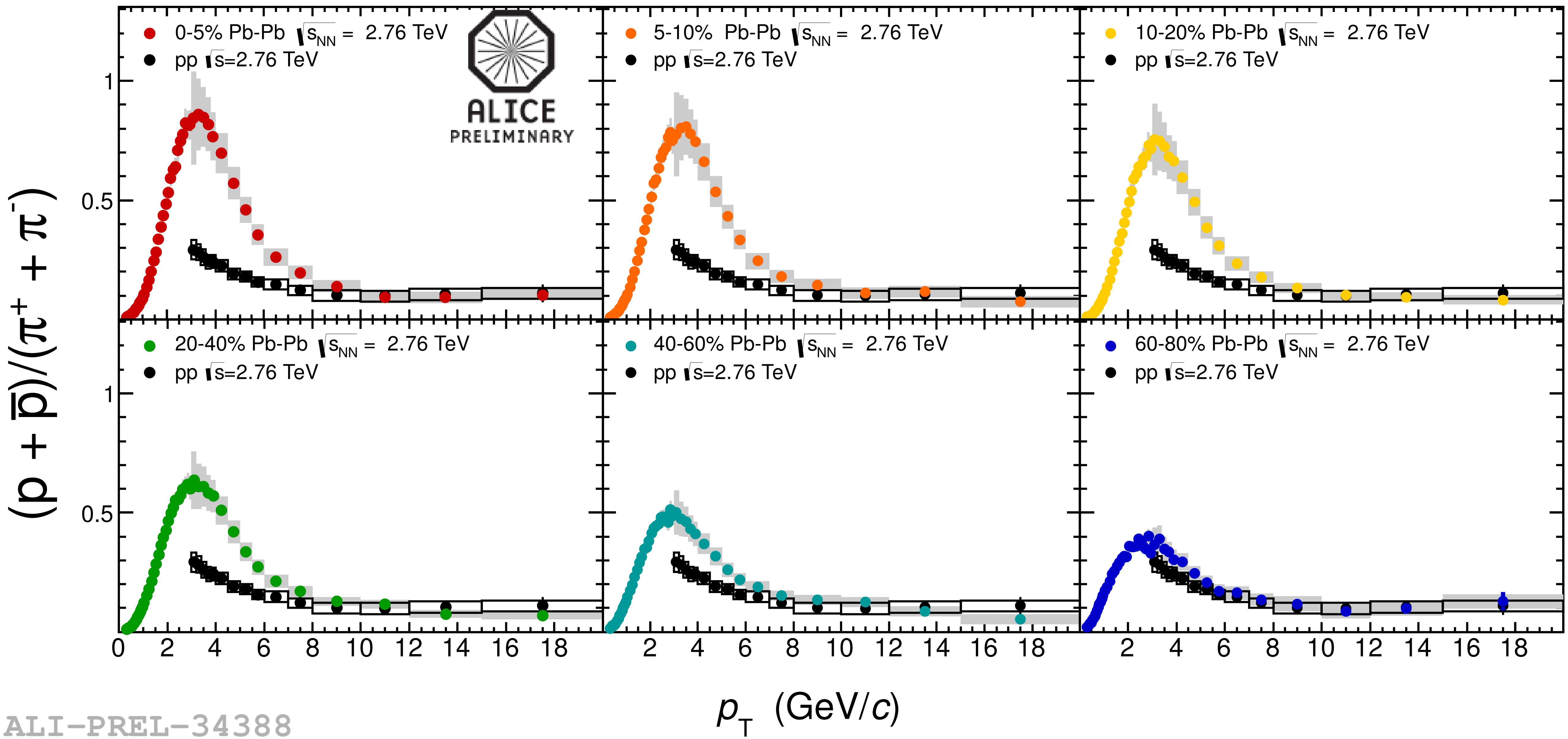
ALICE Talks at the DPG Spring Meeting 2013

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 χc 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: p_T 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 p_T 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 p_T 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 Arslandok
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 $\sqrt{s}$ 2.76TeV 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

ALICE

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



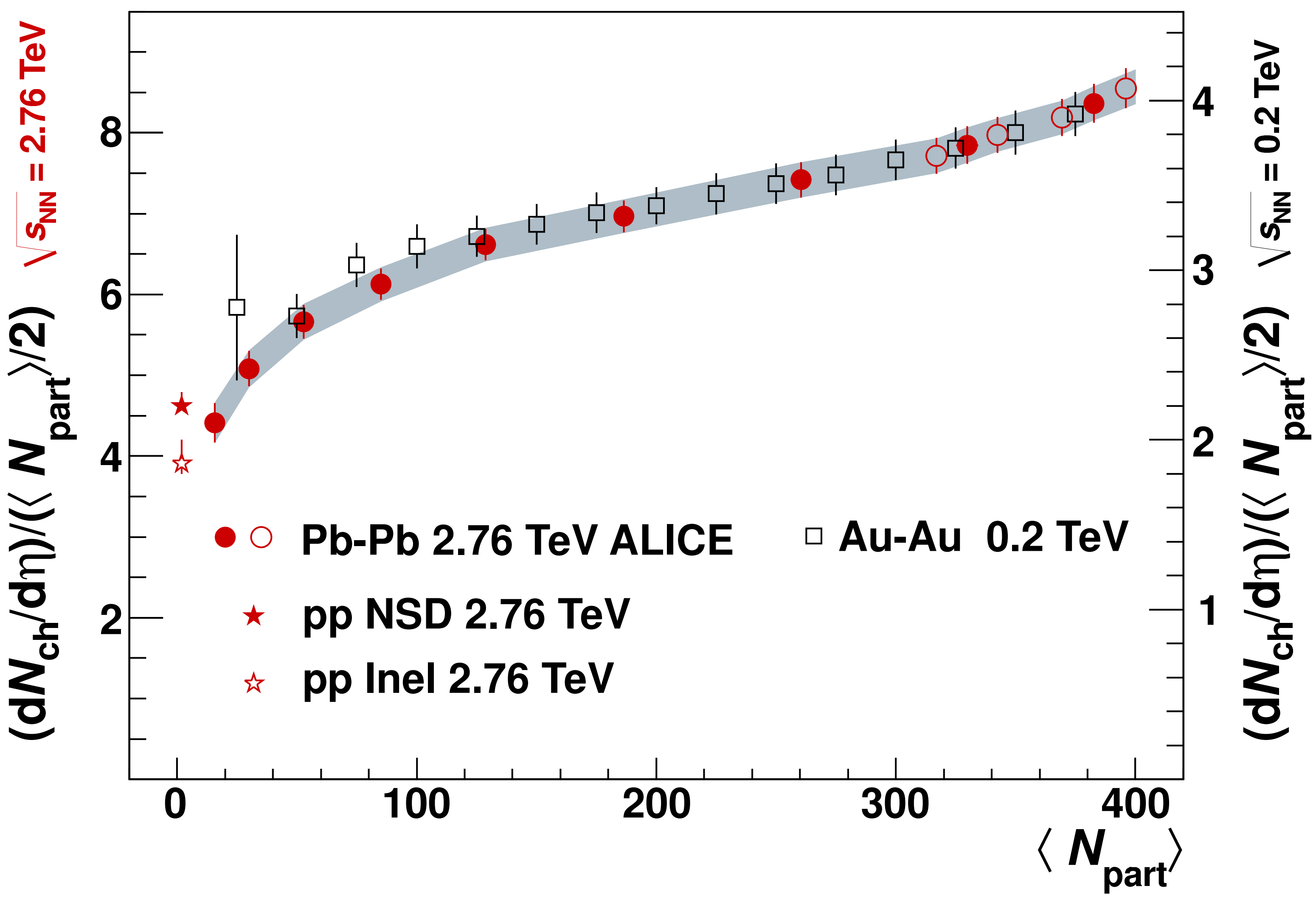
Radial flow+ quark coalescence? Interplay between jets and expanding bulk (EPOS)?

→ A challenge to theory

EPOS, K. Werner et al., Phys.Rev. C85 (2012) 064907

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

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



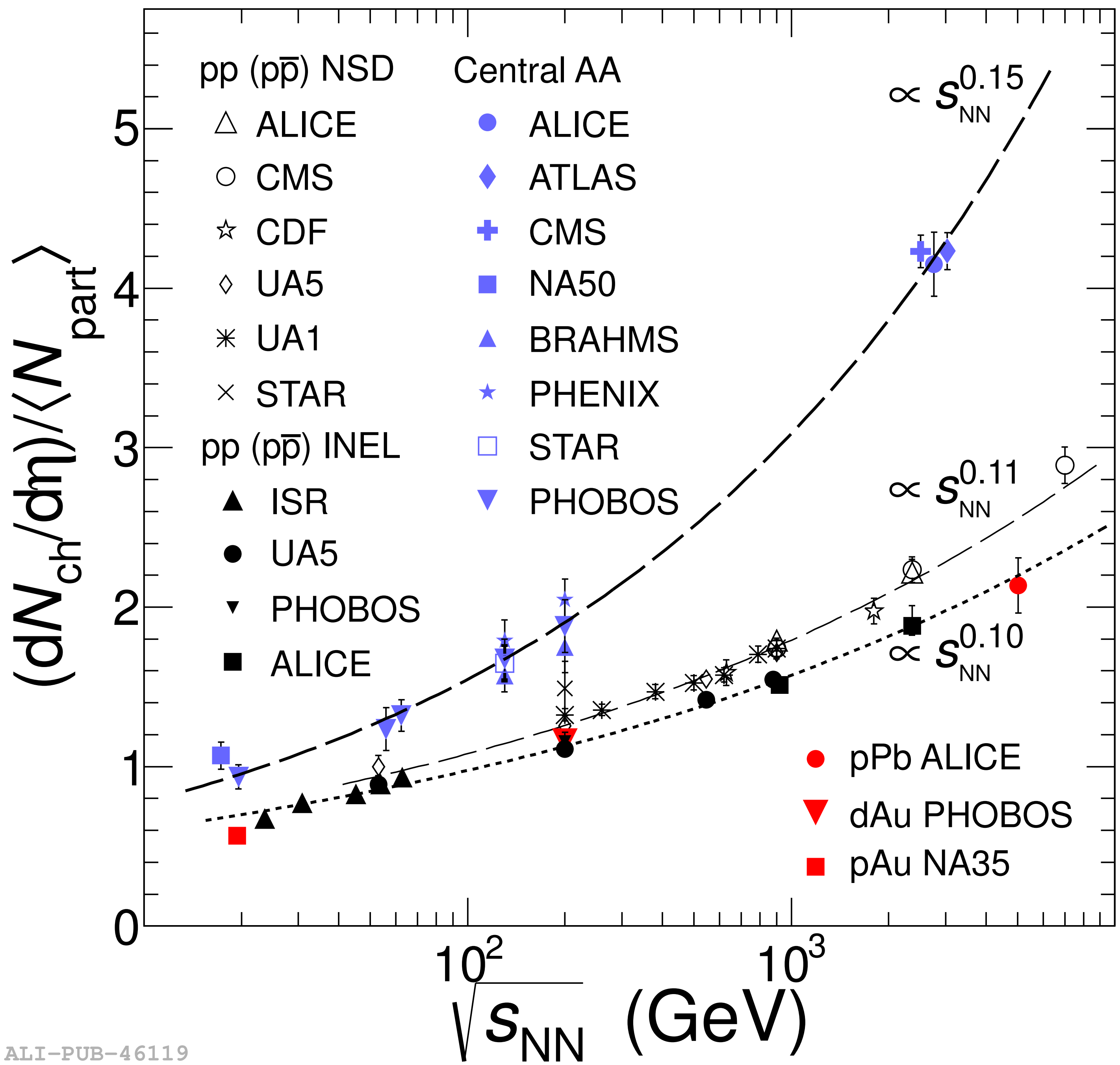
- ~ 30 000 particles in total in central Pb+Pb
- Relative increase from p+p to A+A identical at RHIC and LHC (holds for 20 < $\sqrt{s_{NN}}$ < 2760 GeV)
- Initial energy density (for τ_0 = 1 fm/c): $\varepsilon_{LHC} \approx 15\ \mathrm{GeV/fm^3} \approx 3 \times \varepsilon_{RHIC}$

$$\varepsilon = \frac{\mathrm{d}E_T/\mathrm{d}y}{\tau_0 \pi R^2} \approx \frac{3}{2}\langle m_T \rangle \frac{\mathrm{d}N_{ch}/\mathrm{d}\eta}{\tau_0 \pi R^2}$$

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

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

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



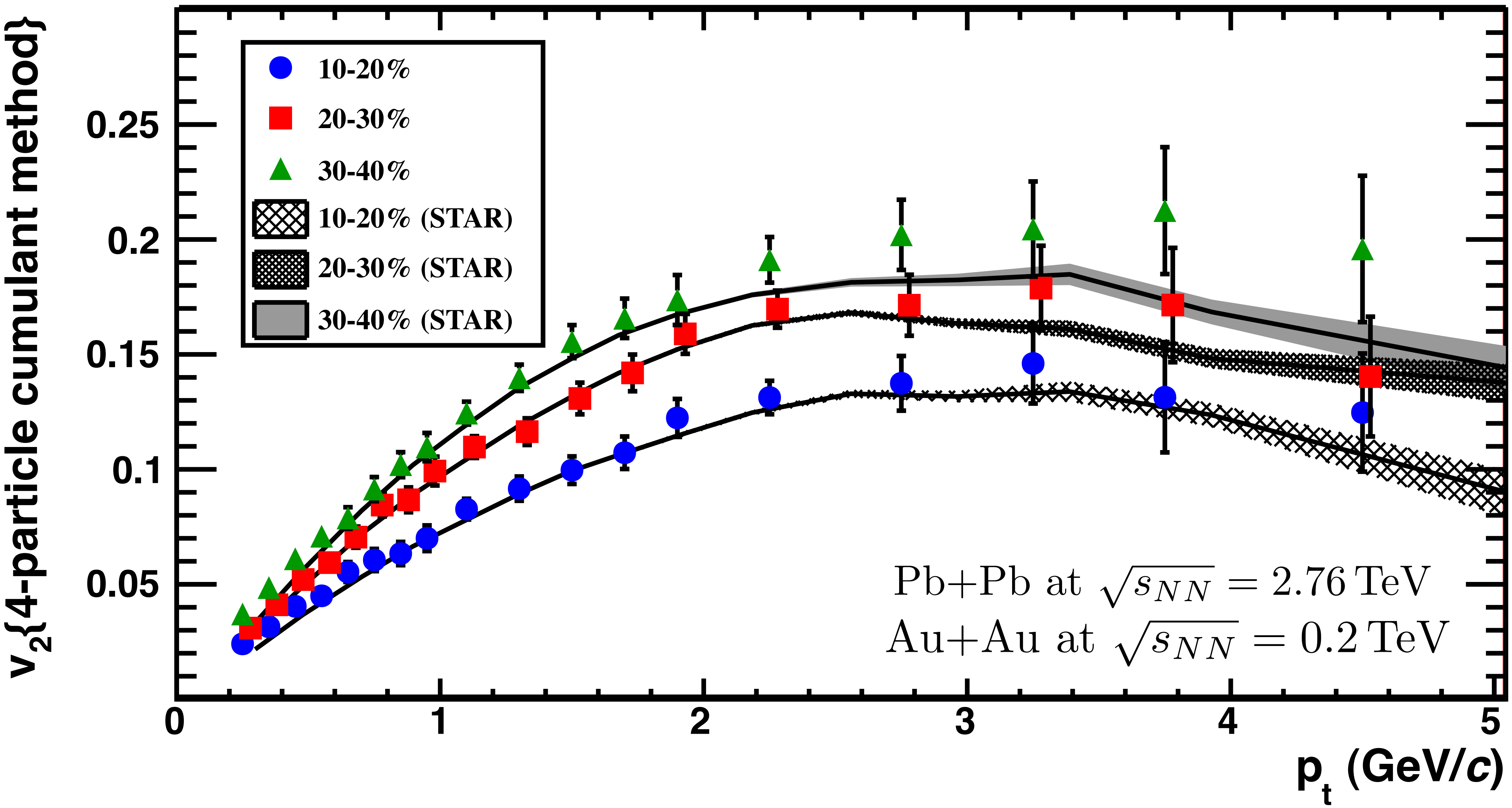
- ~ 30 000 particles in total in central Pb+Pb
- Power law increase of $dN_{ch}/d\eta$ / $(N_{part}/2)$
  - p+p: ~ $s^{0.11}$
  - central A+A: ~ $s^{0.15}$
- Initial energy density (for τ_0 = 1 fm/c): $\varepsilon_{LHC} \approx 15$ GeV/fm^3 ≈ 3 × ε_{RHIC}

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

Initial energy density at LHC and RHIC well above $\varepsilon_c \approx 0.5$ GeV/fm^3

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

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



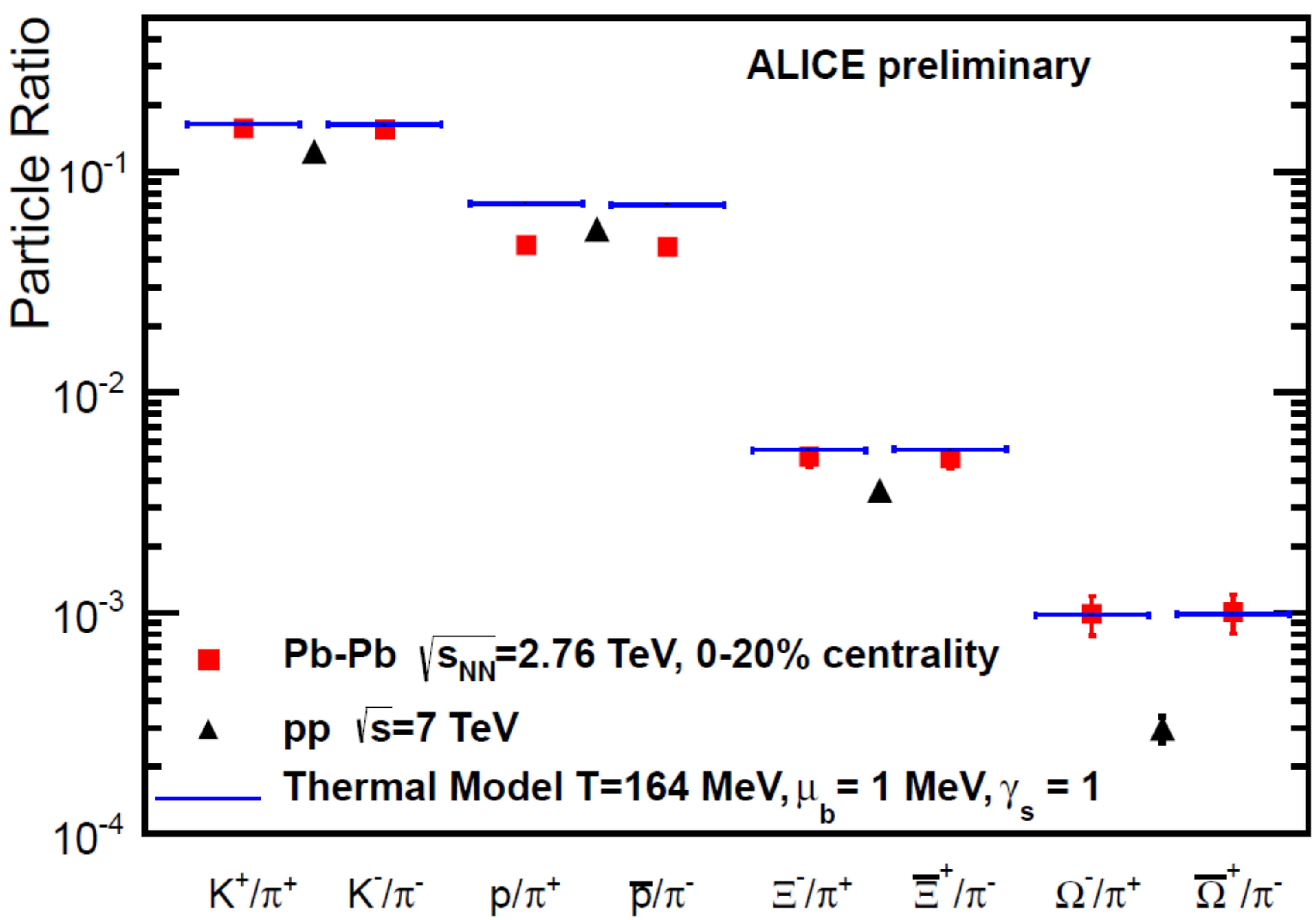
- $v_2(p_T)$[LHC] = $v_2(p_T)$[RHIC], despite factor 14 increase in $\sqrt{s_{NN}}$
- p_T-integrated v_2 at LHC 30% larger due to larger $\langle p_T \rangle$

ALICE

Particle Ratios: The Puzzle of the Small Proton Yields

statistical model:

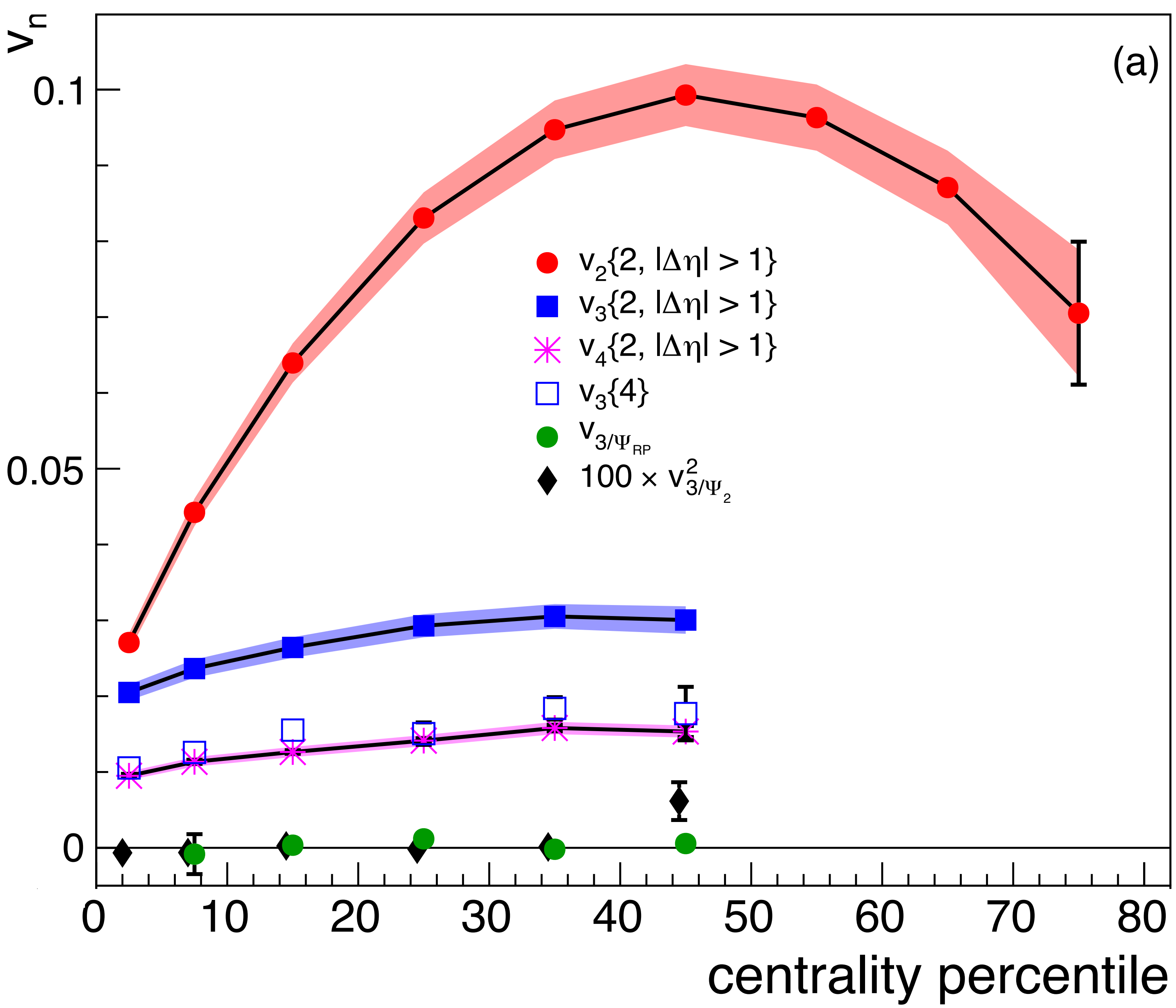
$$n_i = \frac{g_i}{(2\pi)^3} \int \frac{1}{\exp\left(\frac{E_i - \mu(B_i, S_i)}{T_{\mathrm{ch}}} \pm 1\right)} \mathrm{d}^3 p$$



- Statistical/thermal model
  - two free parameters: T_{ch} and μ_B
- Strangeness enhancement in Pb+Pb nicely describes with T_{ch} = 164 MeV ≈ 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)

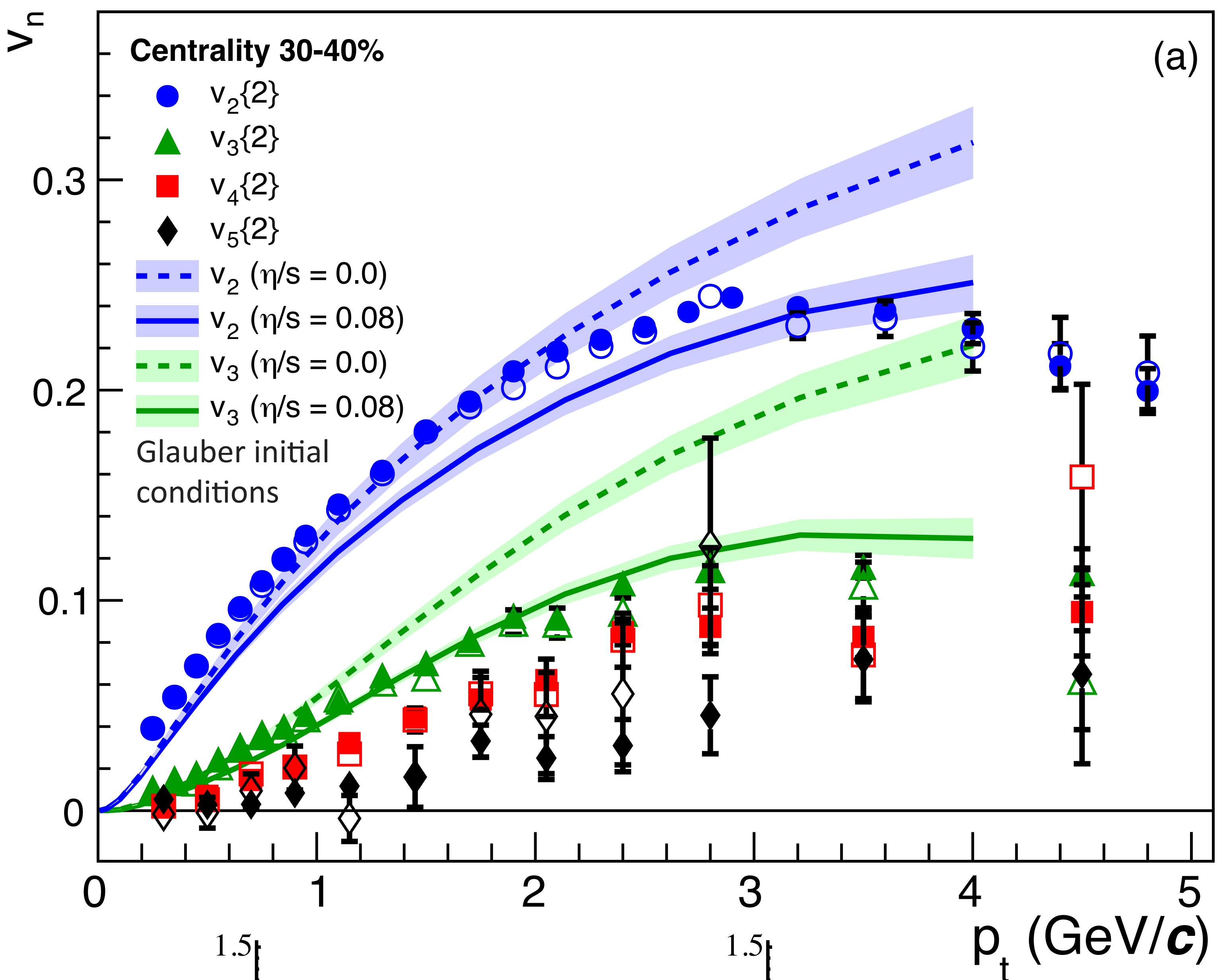


- Weak centrality dependence of v_3 and v_4
- Mid-central: $v_2 > v_3$
- Central: $v_2 \approx v_3$

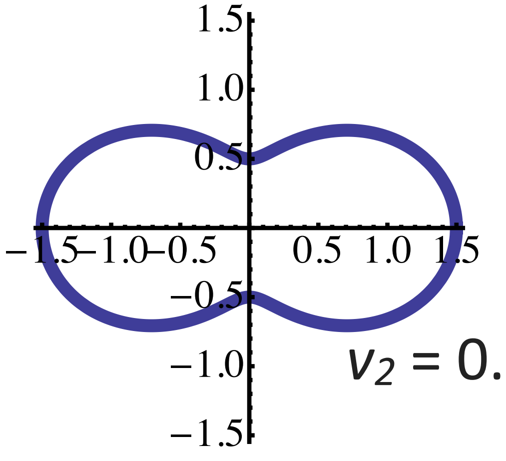
Consistent with v_3 from hydro response to initial energy density fluctuations

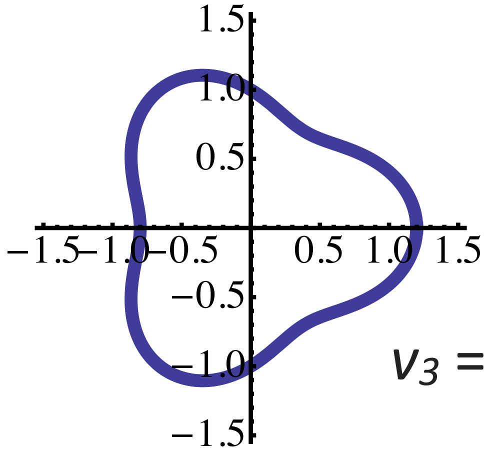
Charged Hadrons: Higher Harmonics (v_2, v_3, v_4, v_5)

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



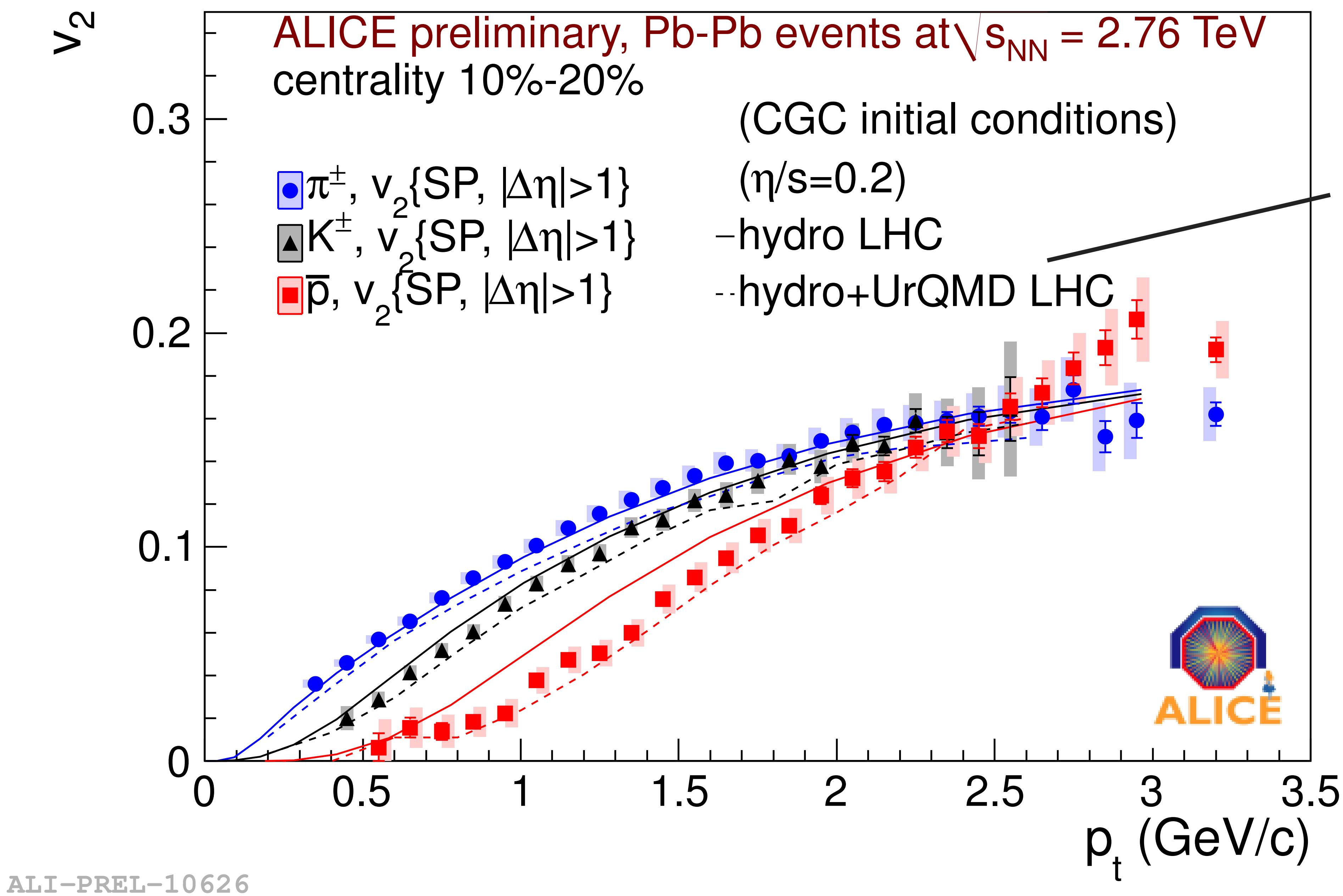
- Sizeable v_3 observed
- Hydro:
  - Shear viscosity reduces differences between expansion velocities and leads to smaller v_n
  - v_n depend both on initial energy density distribution and its fluctuations (Glauber MC, CGC) and η/s





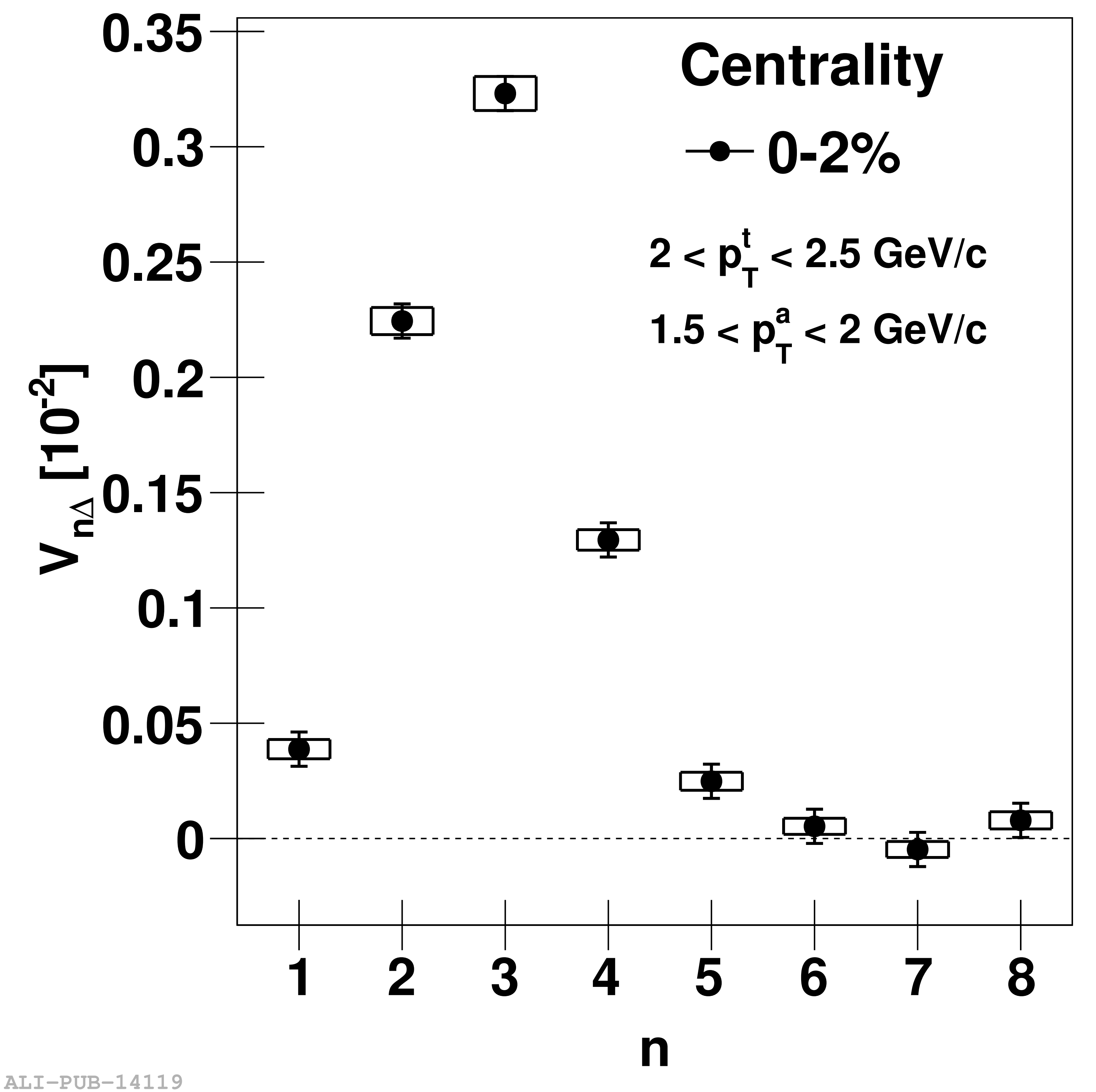
Higher harmonics increase sensitivity to η/s

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

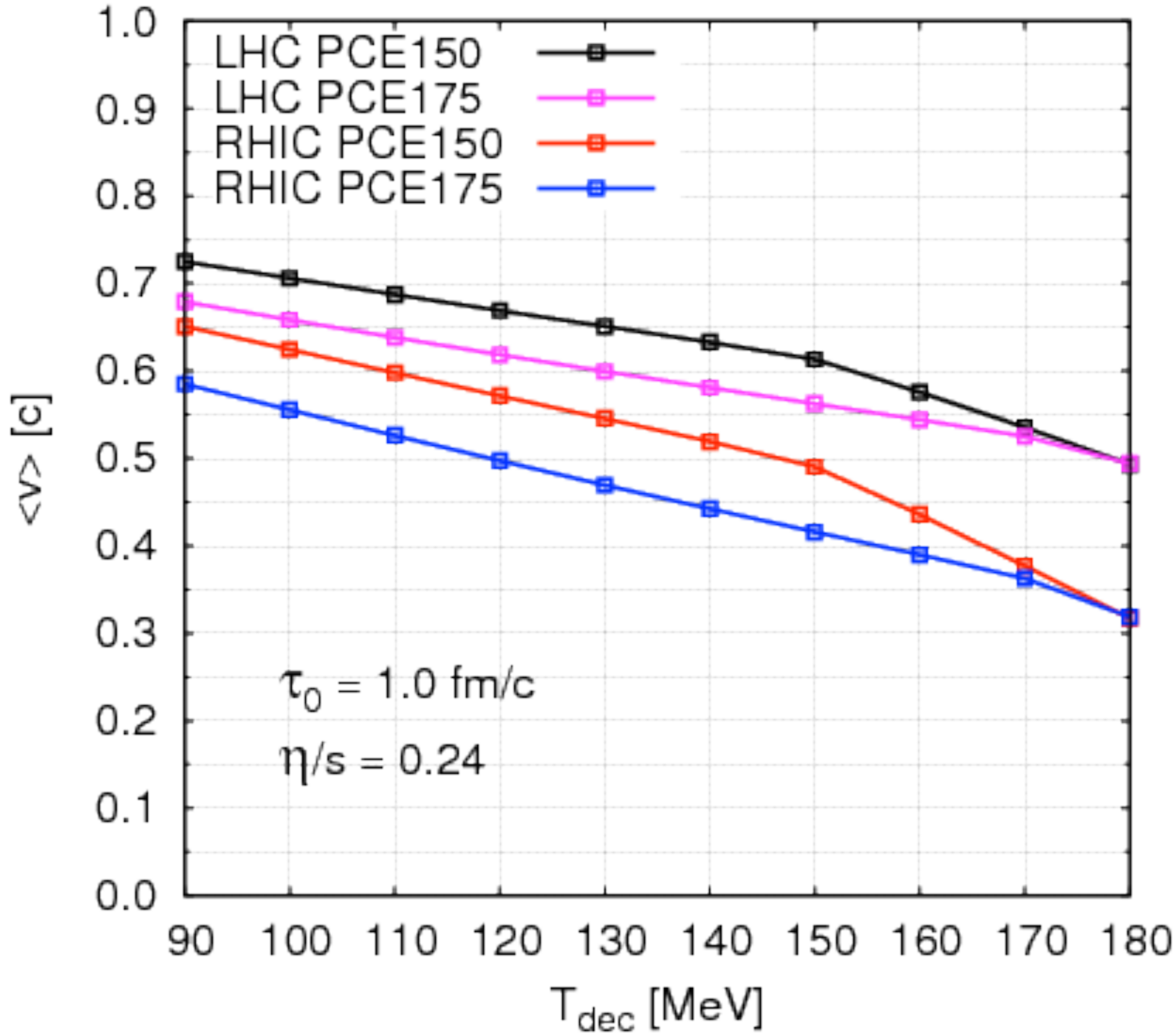


Hydro model for QGP phase + hadronic cascade describes v_2 data with
η/s ≈ 0.2 = 2.5 × 1/4π (with color glass condensate initial conditions)

Higher Flow Harmonics

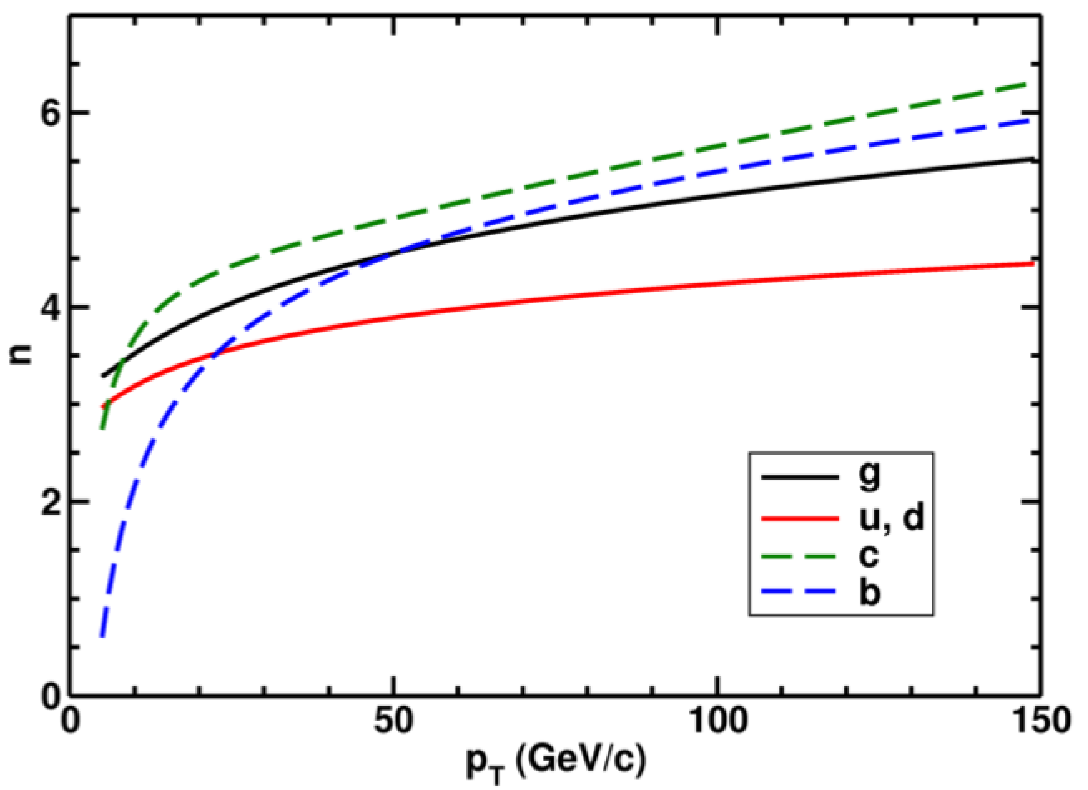


Average Radial Flow From Full Hydro Calculation

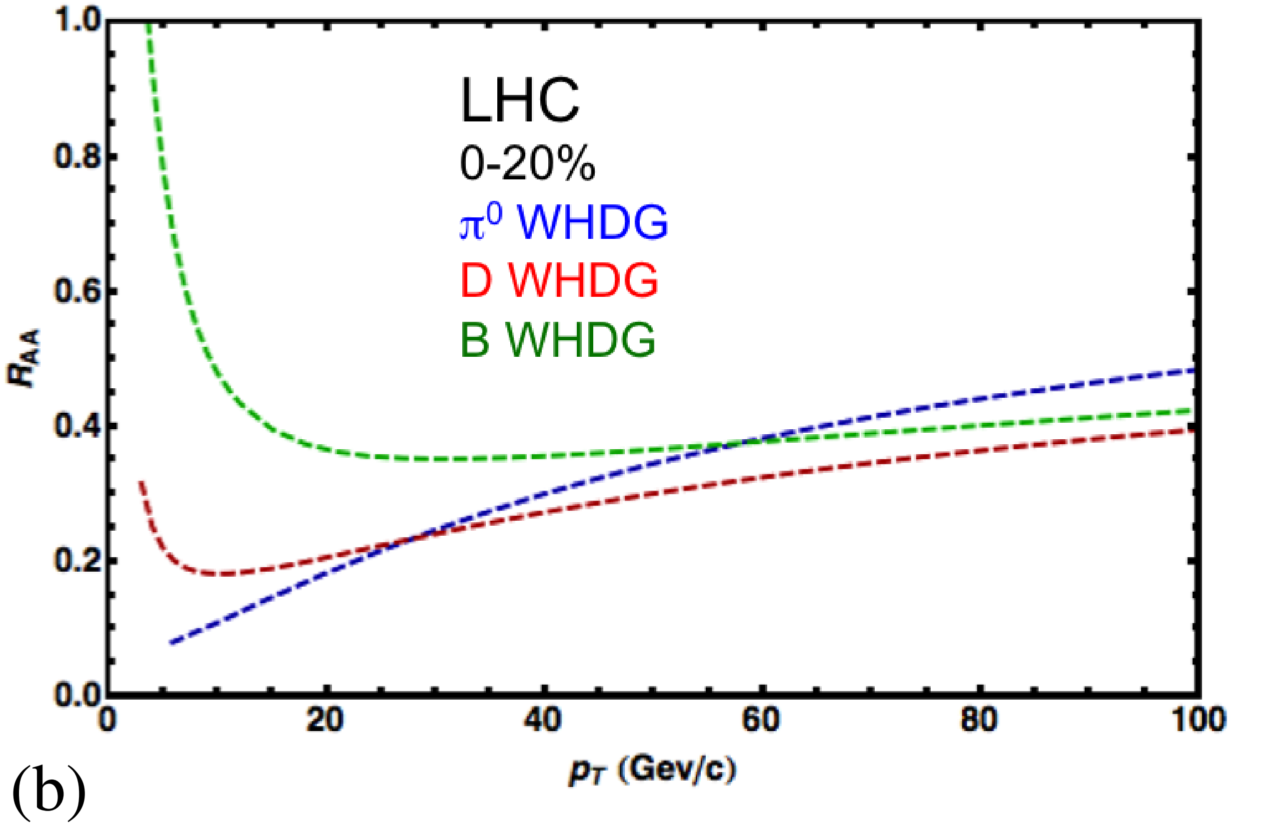


Parton Flavor Dependence of R_{AA}

arXiv:1210.8330



(a)



(b)