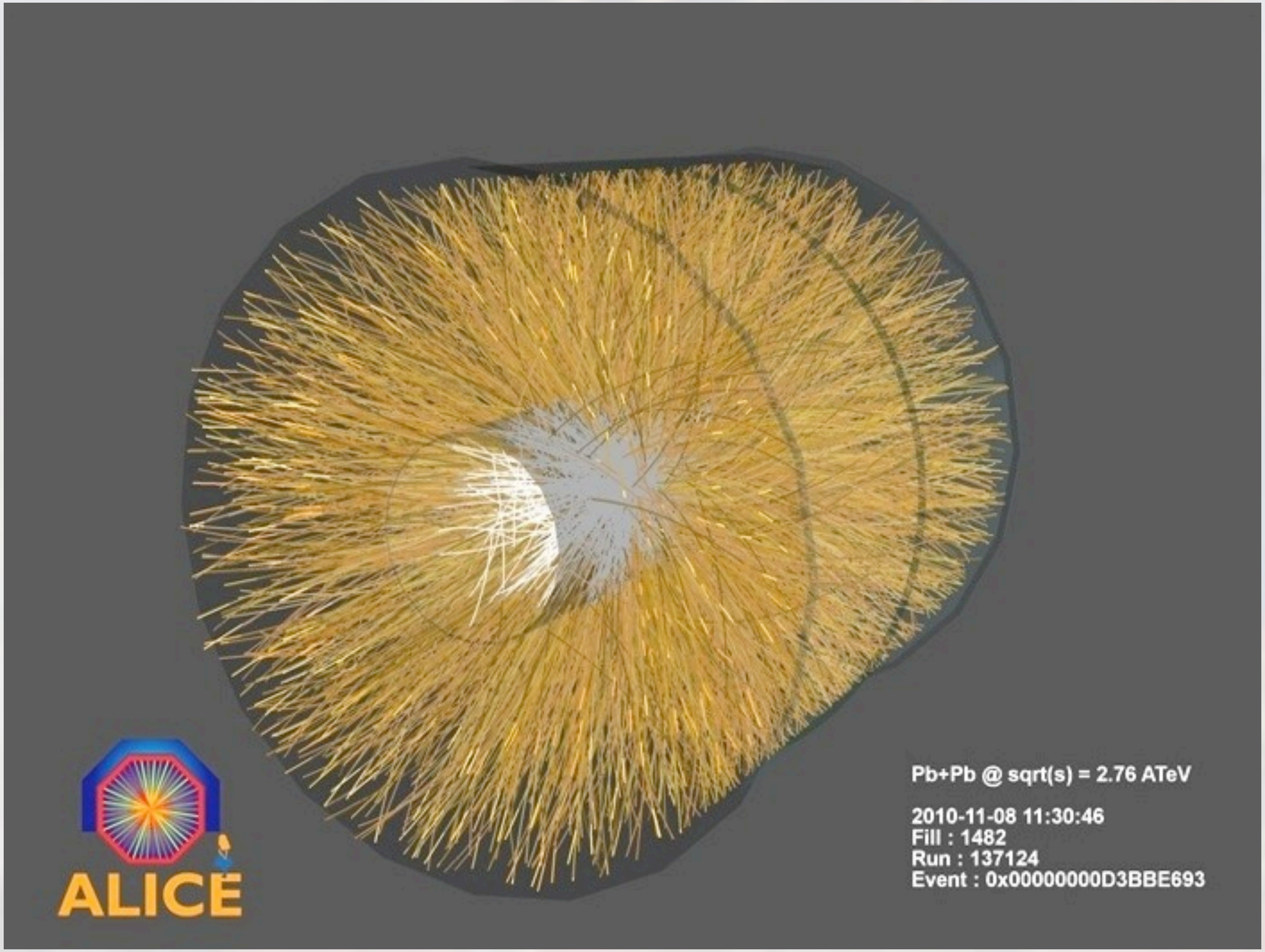
ALICE highlights

Sergei A. Voloshin Wayne State University
for the ALICE Collaboration



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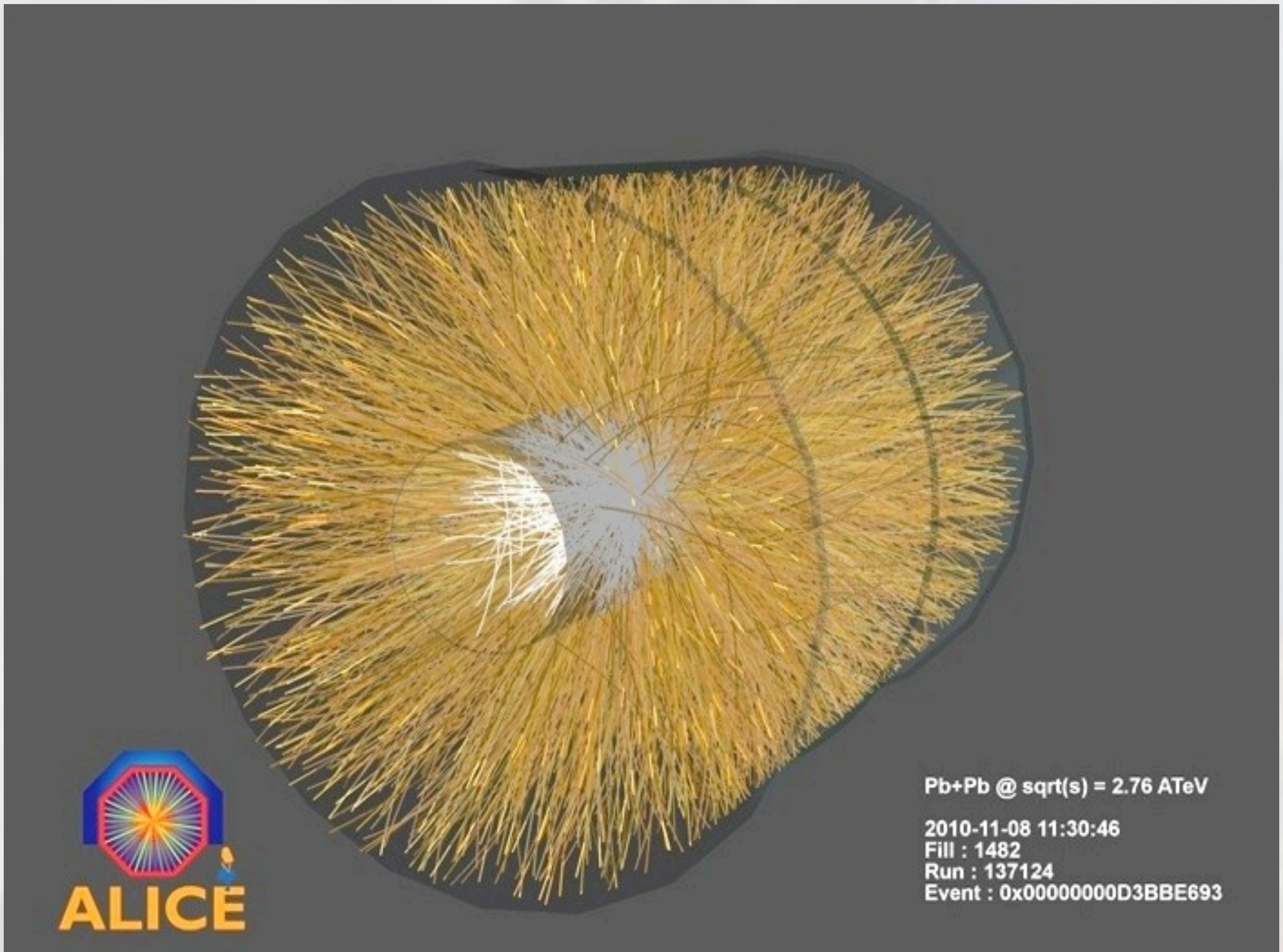


- Intro: QCD and ultrarelativistic nuclear collisions
- ALICE results
  - Global observables and spectra
  - Anisotropic flow
  - High-p_T particles and Jets
  - Heavy flavor and quarkonia
- Conclusions and perspectives

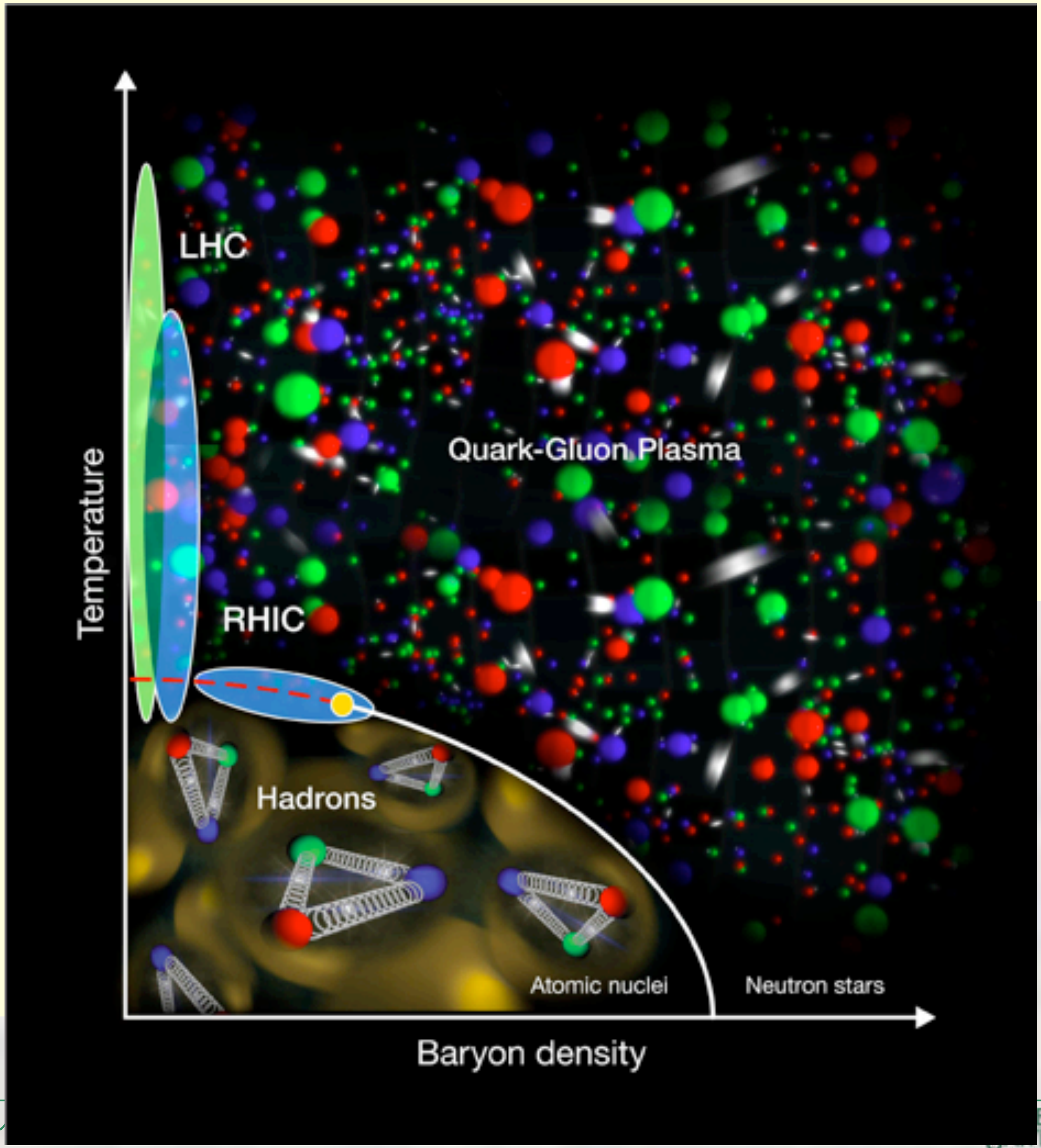
Physics of Heavy Ion Collisions

Short answer: QCD - strong interaction sector of the Standard Model

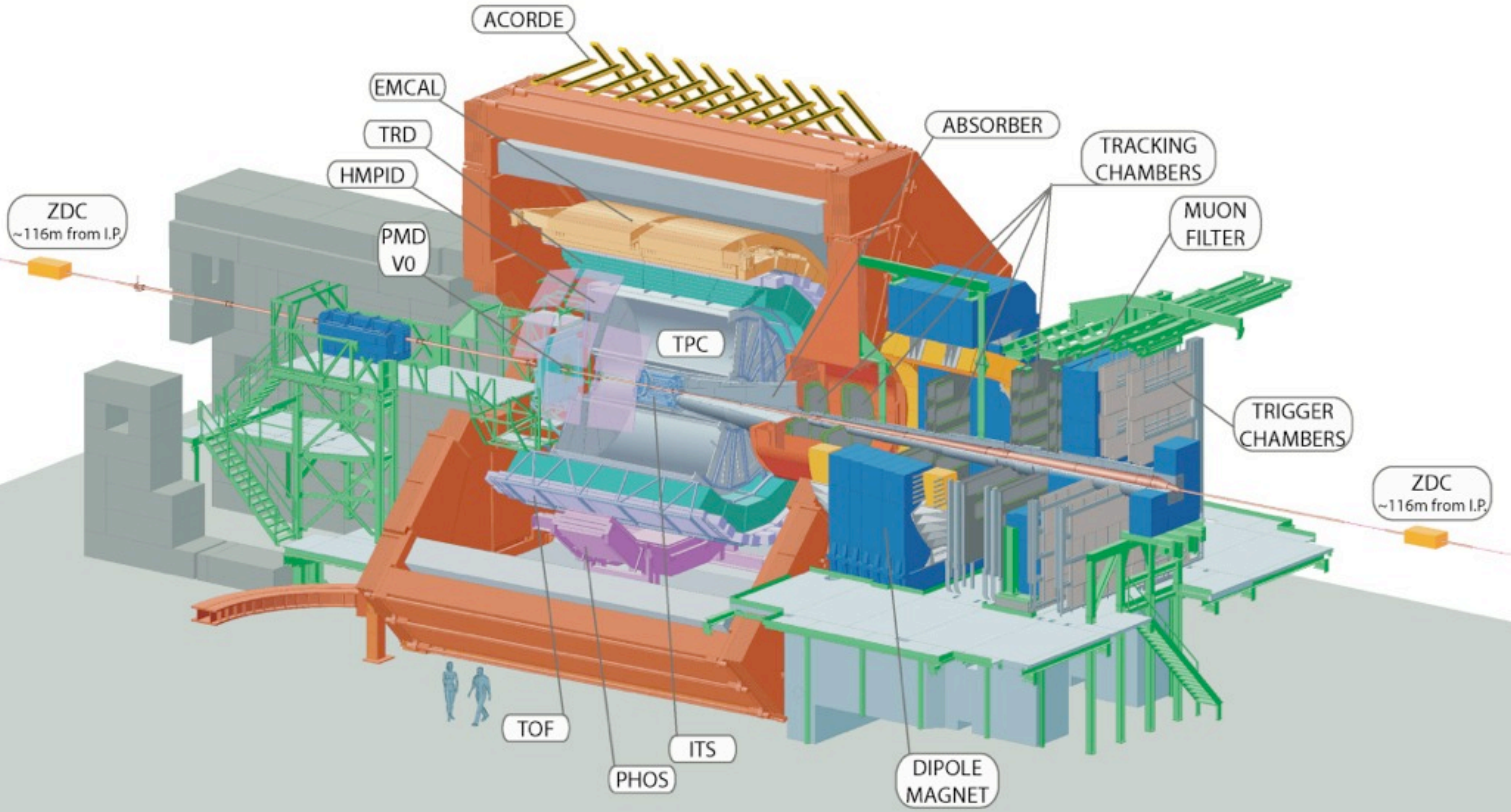
- ‘state of matter’ at high temperature & energy density: ‘The QGP’
  - hadrons are no longer the relevant d.o.f
  - partons are deconfined (not bound into composite particles)
  - chiral symmetry is restored (?)

- mission of URHI
  - study properties of the QGP phase
  - discover new aspects of QCD in the strongly coupled regime

- physics of multiparticle production
  - multiparton interactions, “clusters”,…
  - hadronization mechanism...



ALICE Detector

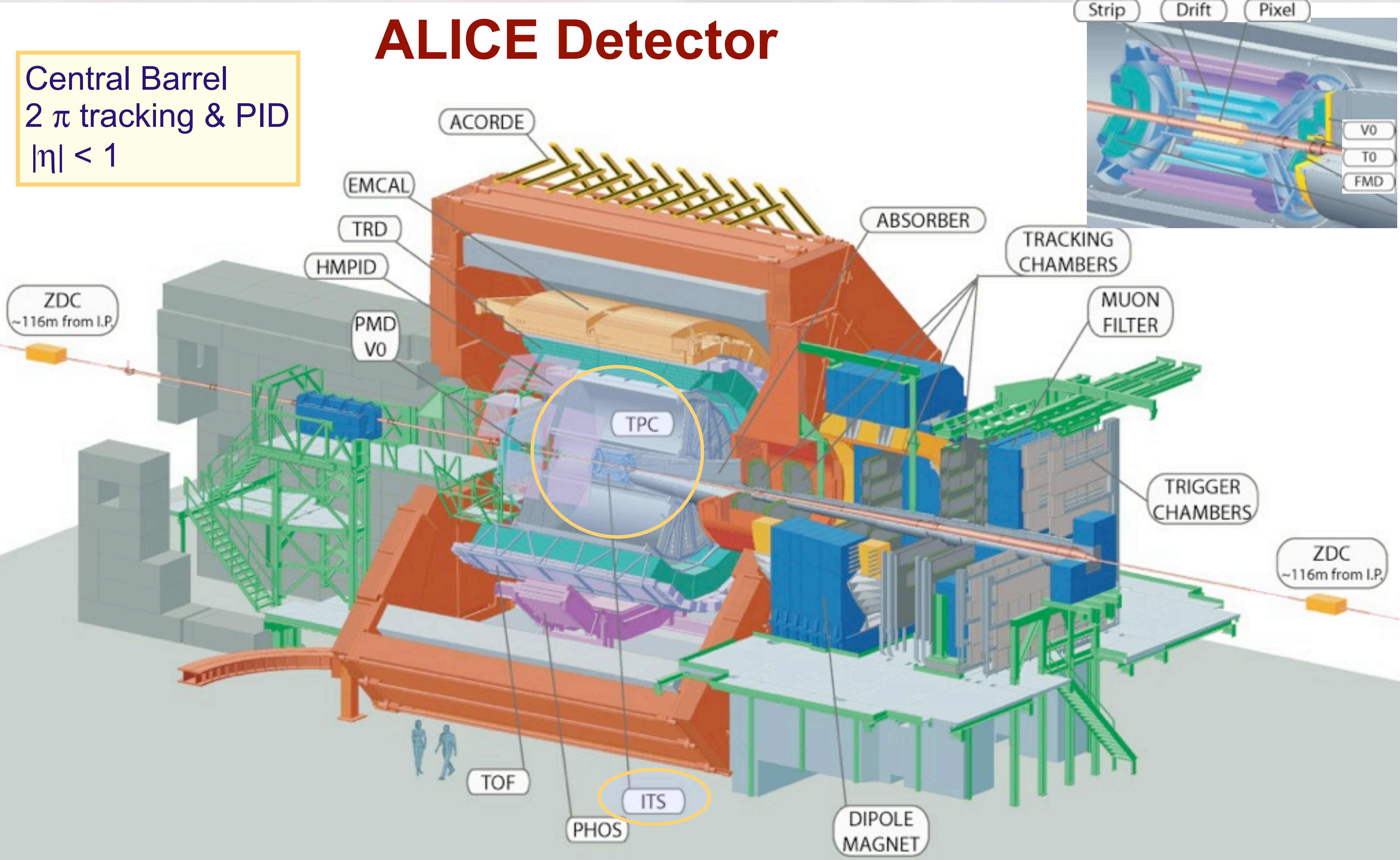


Detector:
Length: **26** meters
Height: **16** meters
Weight: **10,000** tons

Collaboration:
> 1000 Members
> 100 Institutes
> 30 countries

ALICE Detector

Central Barrel
2 π tracking & PID
$|\eta| < 1$



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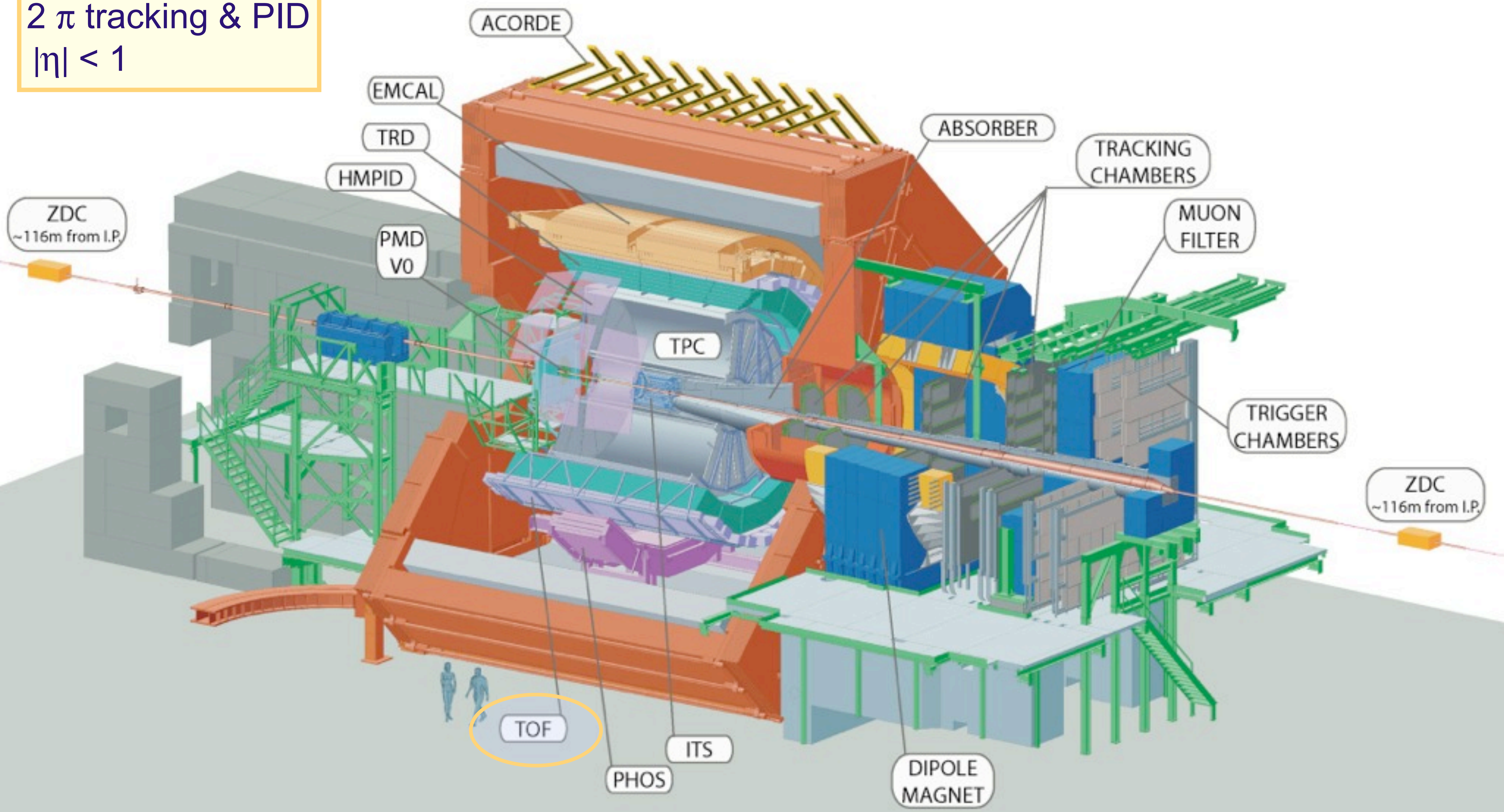

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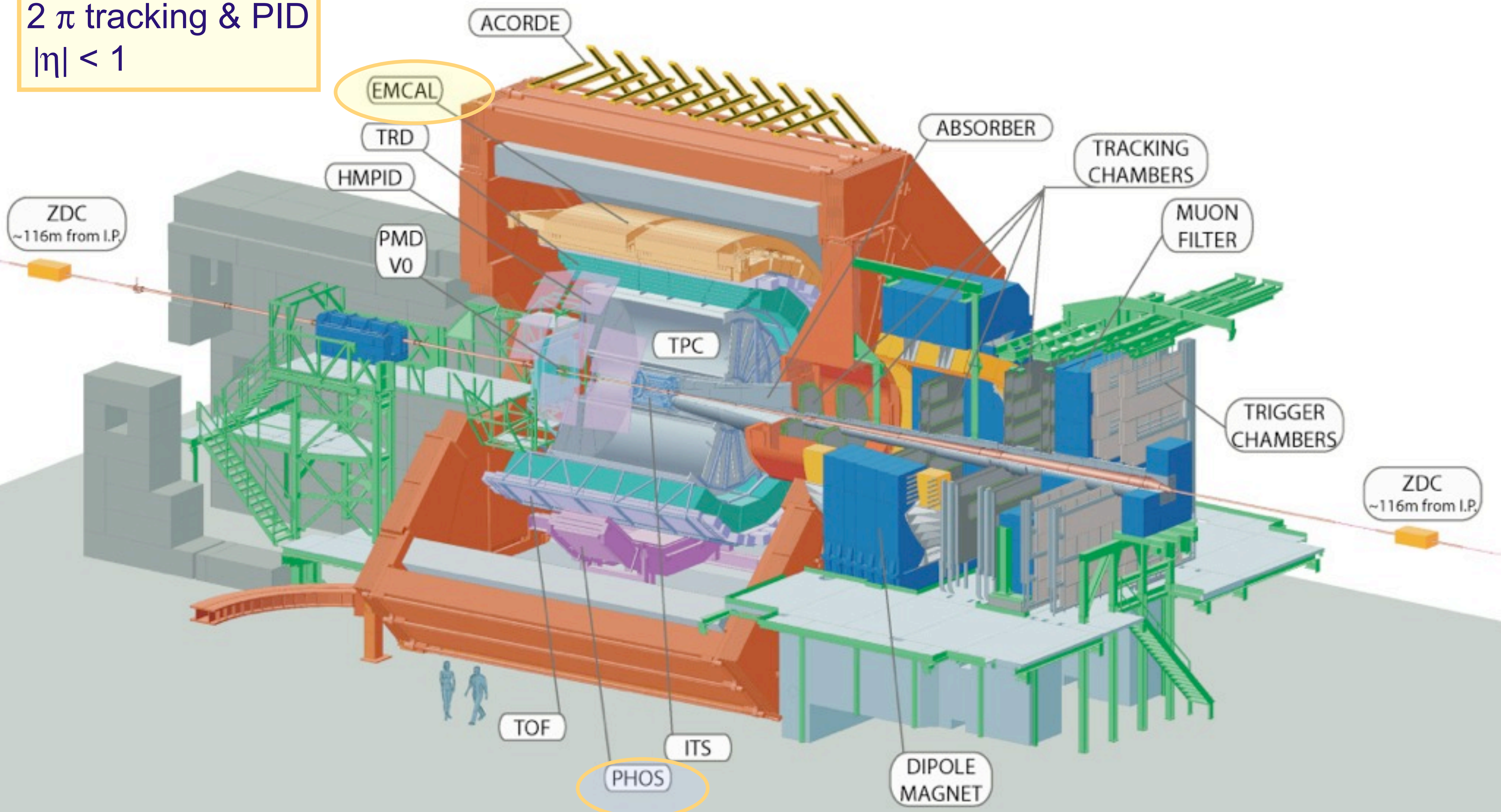

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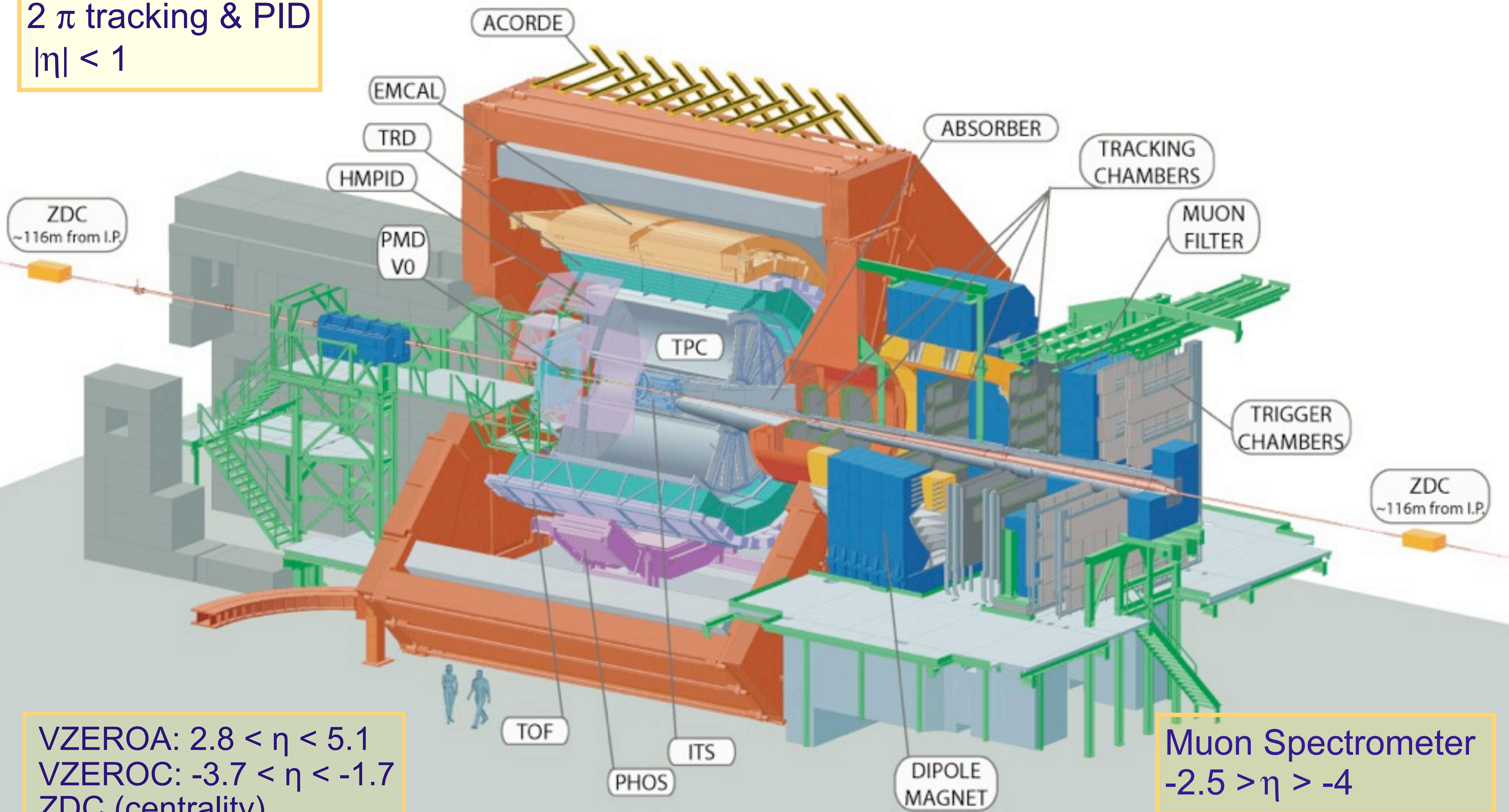

VZEROA: $2.8 < \eta < 5.1$
VZEROC: $-3.7 < \eta < -1.7$
ZDC (centrality)
FMD (N_{ch} $-3.4<\eta<5$)
PMD ($N\gamma$, N_{ch})

Muon Spectrometer
$-2.5 > \eta > -4$

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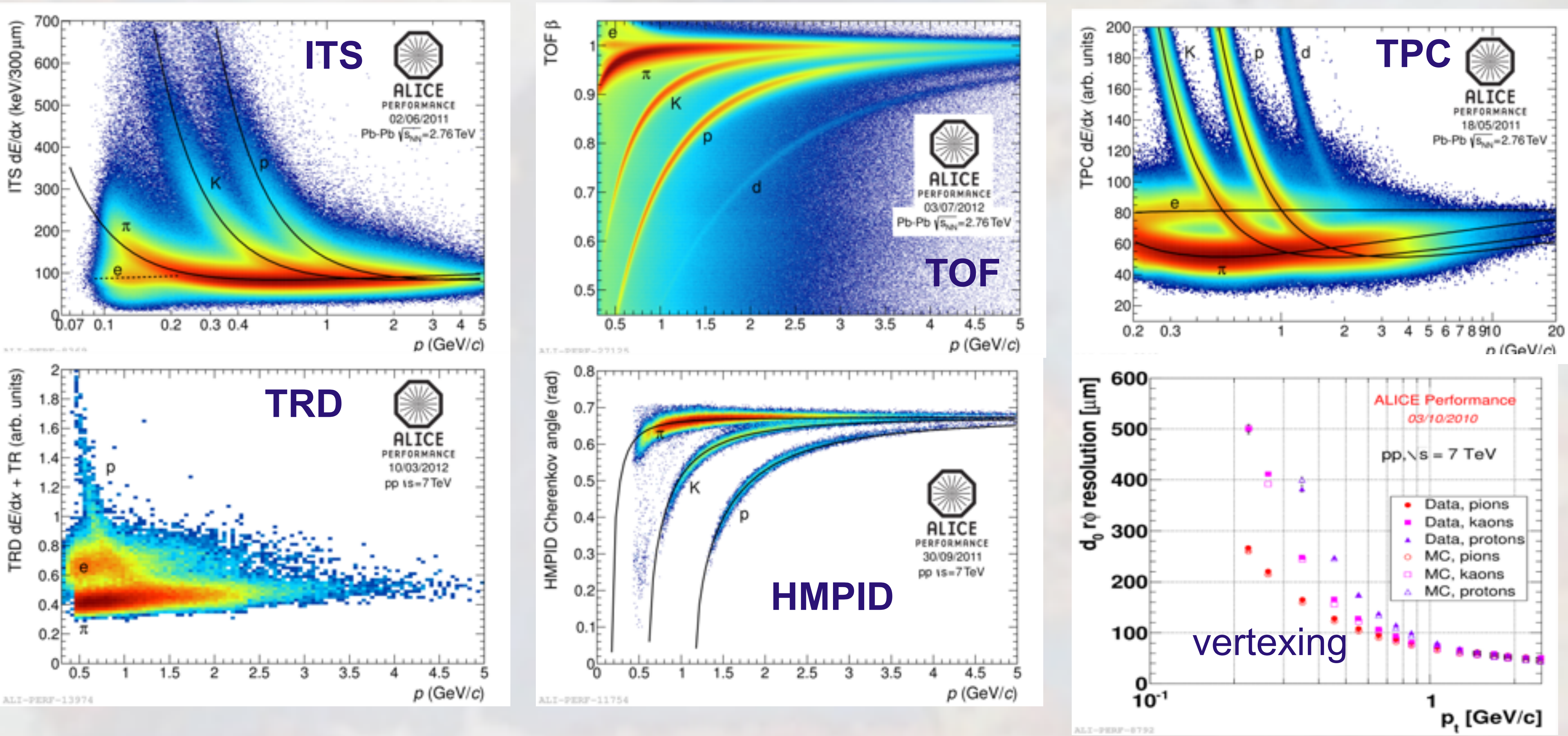
ALICE – main features

ALICE



Central Barrel →
- particle identification (practically all known techniques)
- excellent vertexing capability
- efficient tracking – down to ~ 100 MeV/*c*

Forward det. →
- particle detection over a large rapidity range

Muon Arm & C.B. →
- quarkonia detection down to p_T=0

ALICE data

ALICE

- Two heavy-ion runs at the LHC so far:
  - in 2010 – commissioning and the first data taking
  - in 2011 – (energy scaled) above nominal luminosity!
- pp data taken at different c.m. energies in 2009-2012:
  - 0.9, 2.36, 2.76, 7 and 8 TeV

  →reference for HI data *and* genuine pp physics
- p-Pb run foreseen in Jan-Feb 2013 (pilot run Sept. 2012)

year	system	energy $\sqrt{s_{NN}}$ TeV	integrated luminosity
2010	Pb – Pb	2.76	~ 10 μb^{-1}
2011	Pb – Pb	2.76	~ 0.1 nb^{-1}
2013	p – Pb	5.02	~ 30 nb^{-1}

Global observables and properties of the bulk

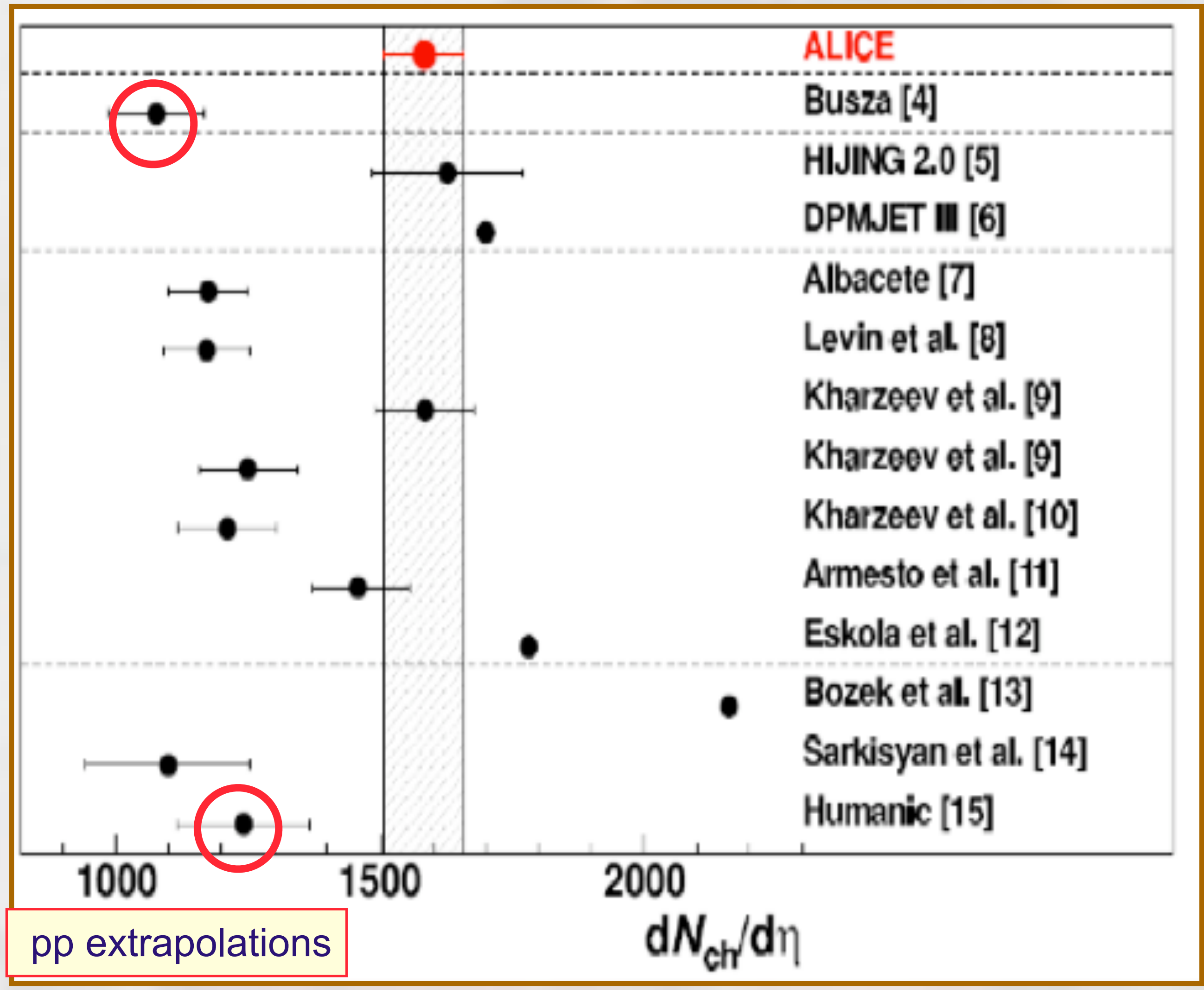
Multiplicity and energy density

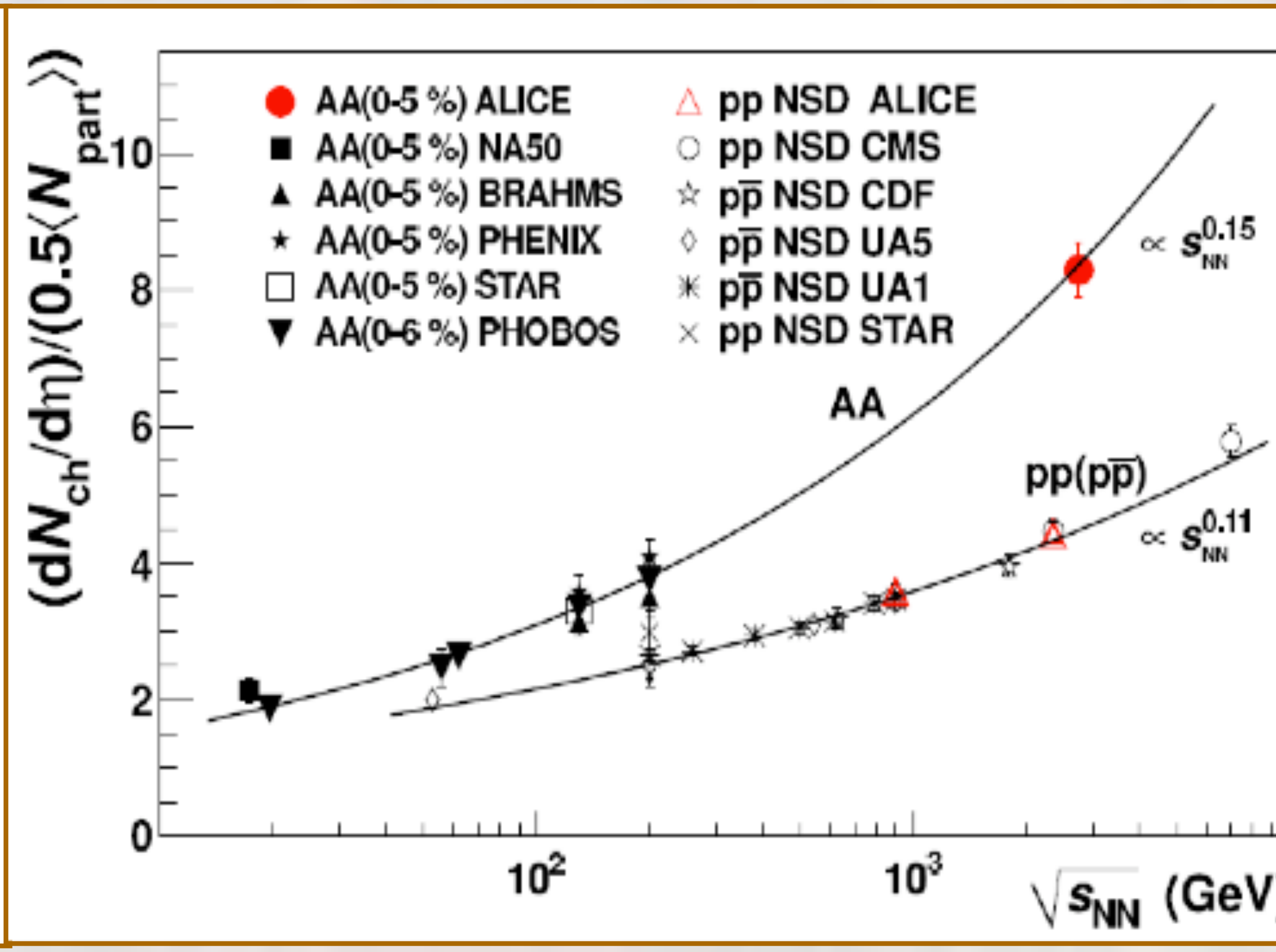
$dN_{ch}/d\eta \sim 1600 \pm 76$ (syst)

Energy density ≈ 3 x RHIC (fixed τ_0)
lower limit, likely τ_0(LHC) < τ_0(RHIC)

$$\varepsilon(\tau) = \frac{1}{\tau_0 A} \frac{dN}{dy} \langle m_t \rangle$$

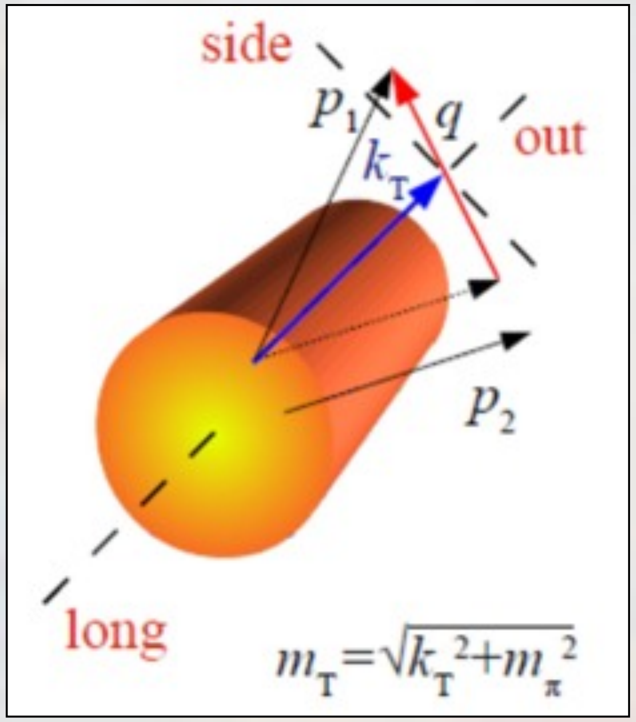
PRL105 (2010) 252301

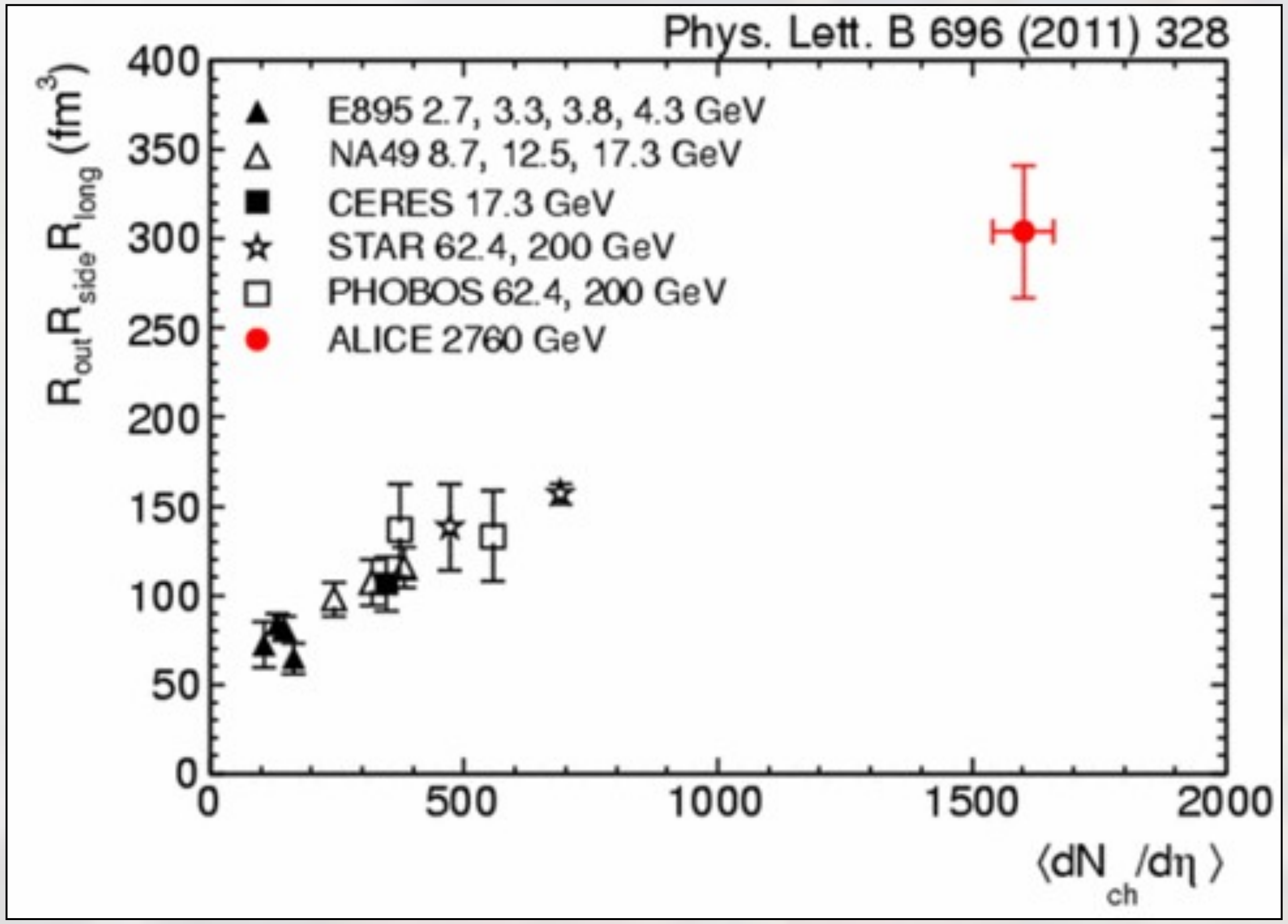


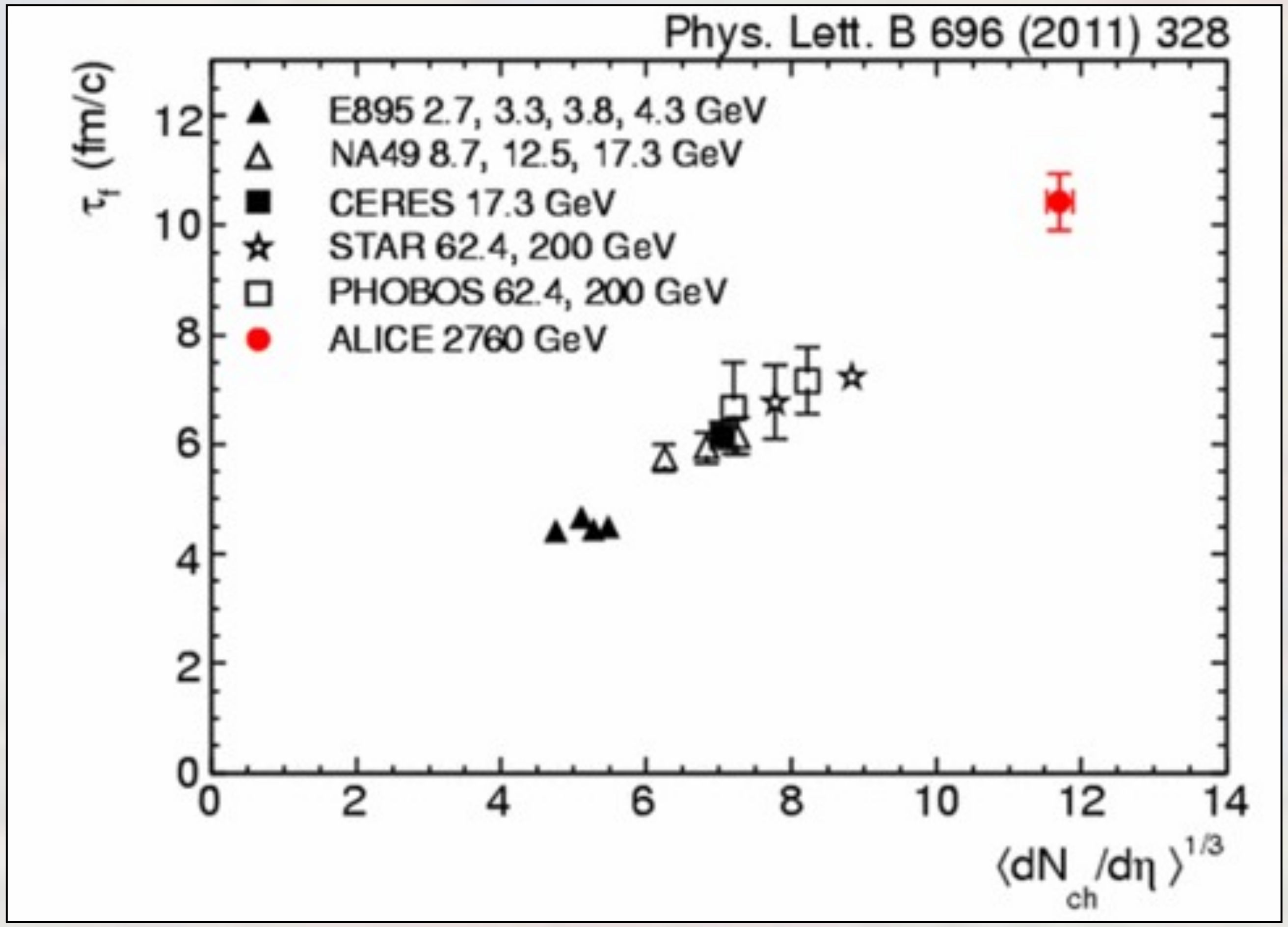


System size

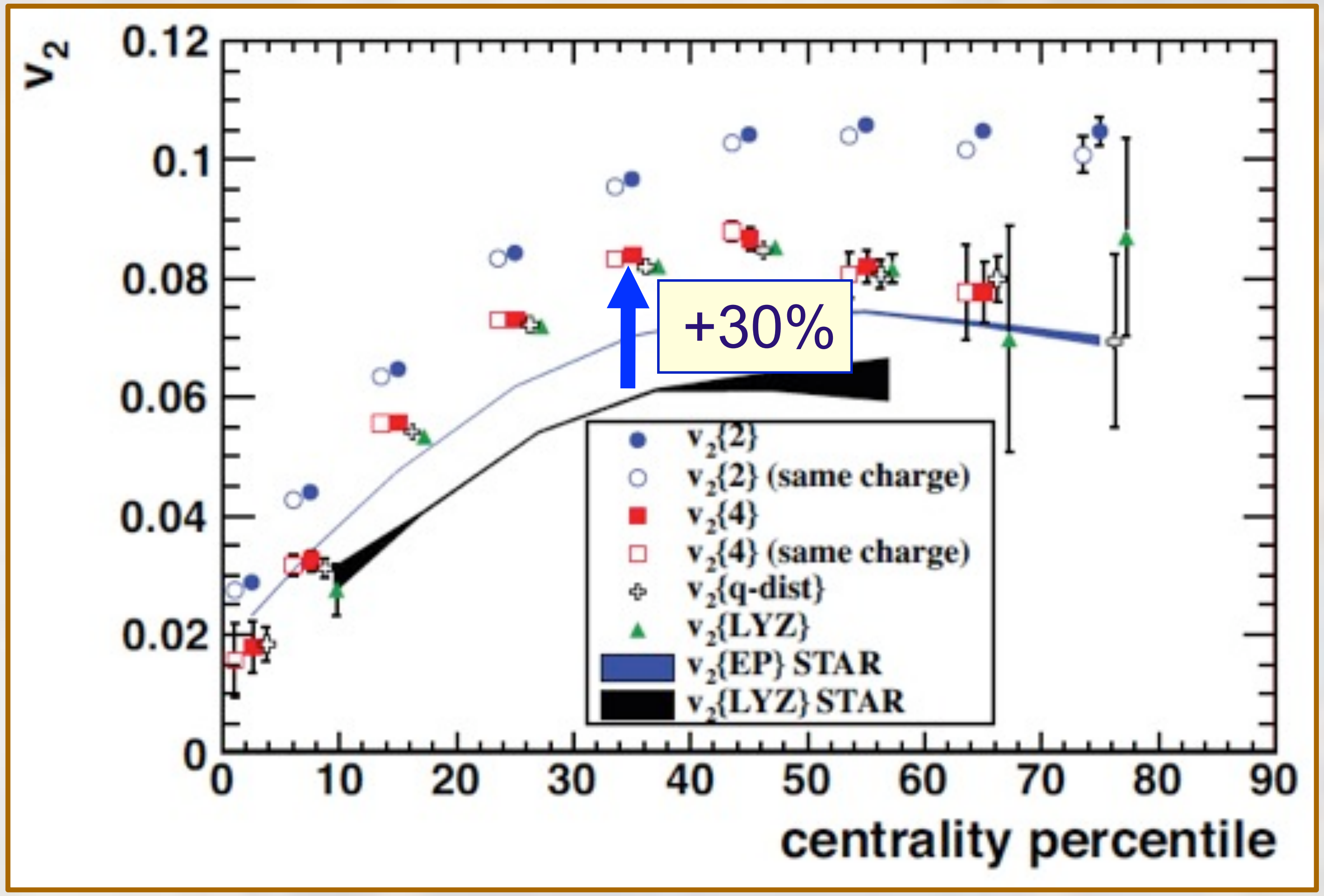
- ❑ Femtoscopy => Spatial and temporal extent of the particle emitting source
- ❑ Two-pion intensity intreferometry
  => HBT radii (R_{long}, R_{side}, R_{out})
  → Volume: twice w.r.t. RHIC
  → Lifetime: 40% higher w.r.t. RHIC

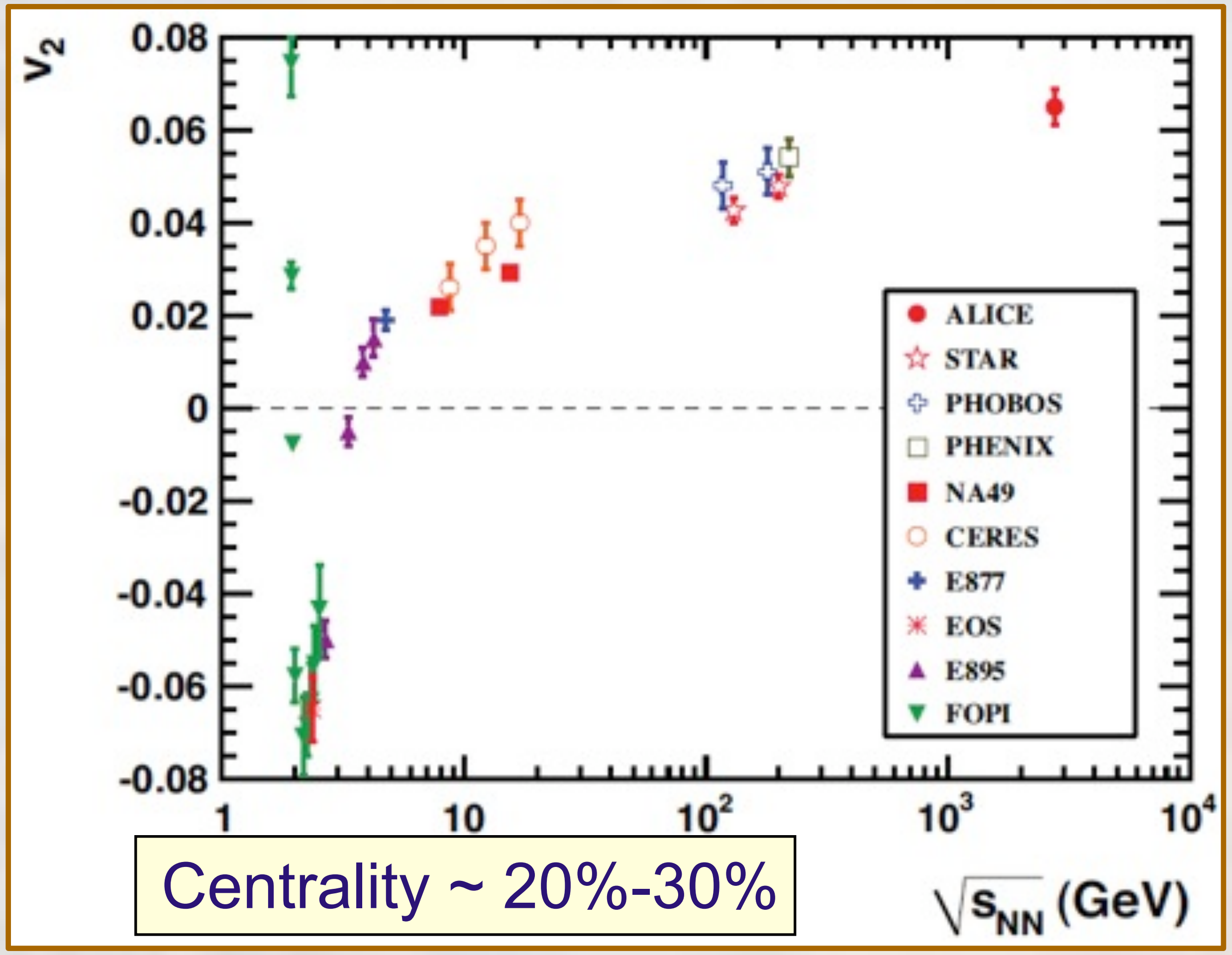






Elliptic flow vs collision energy

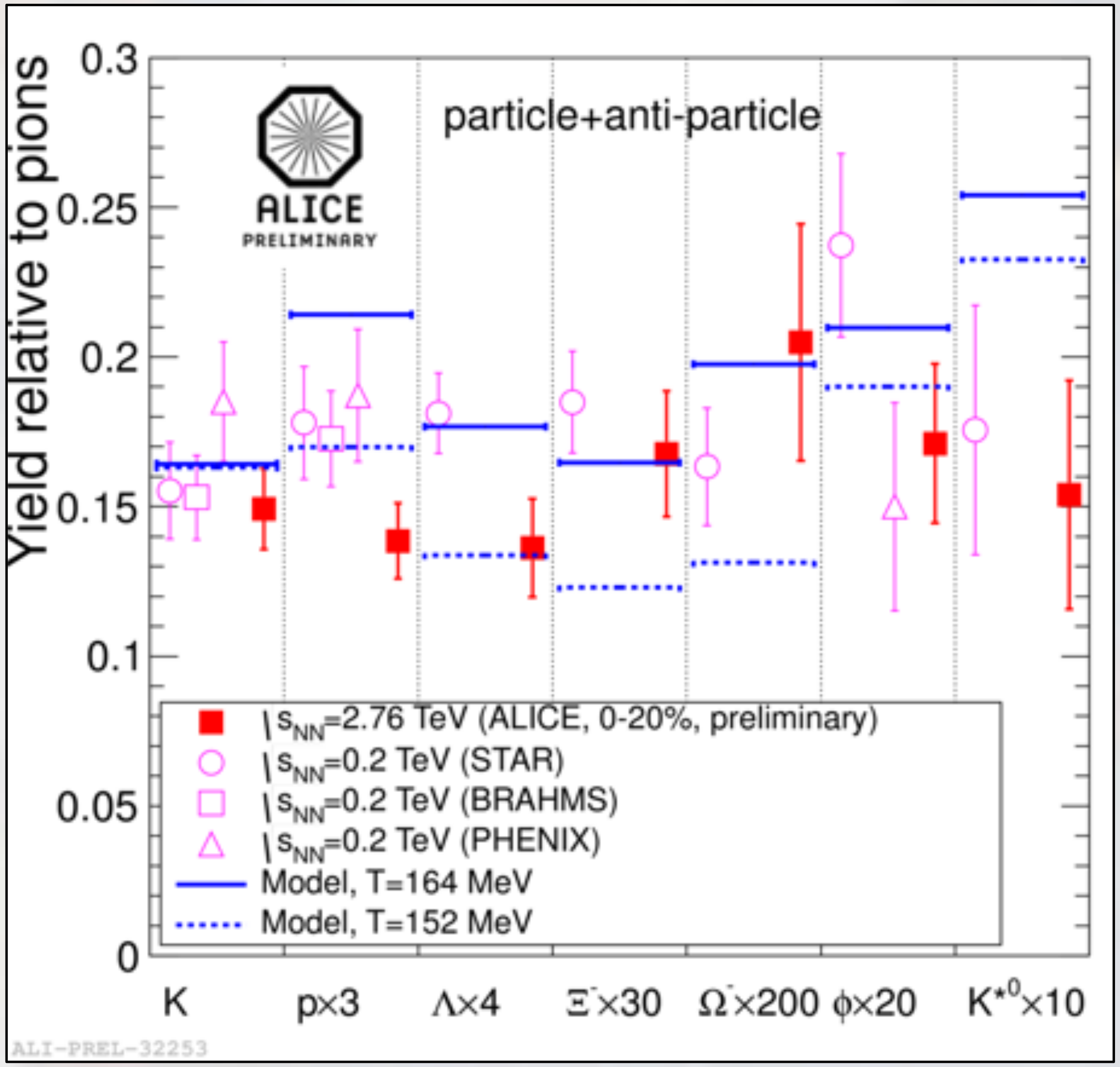


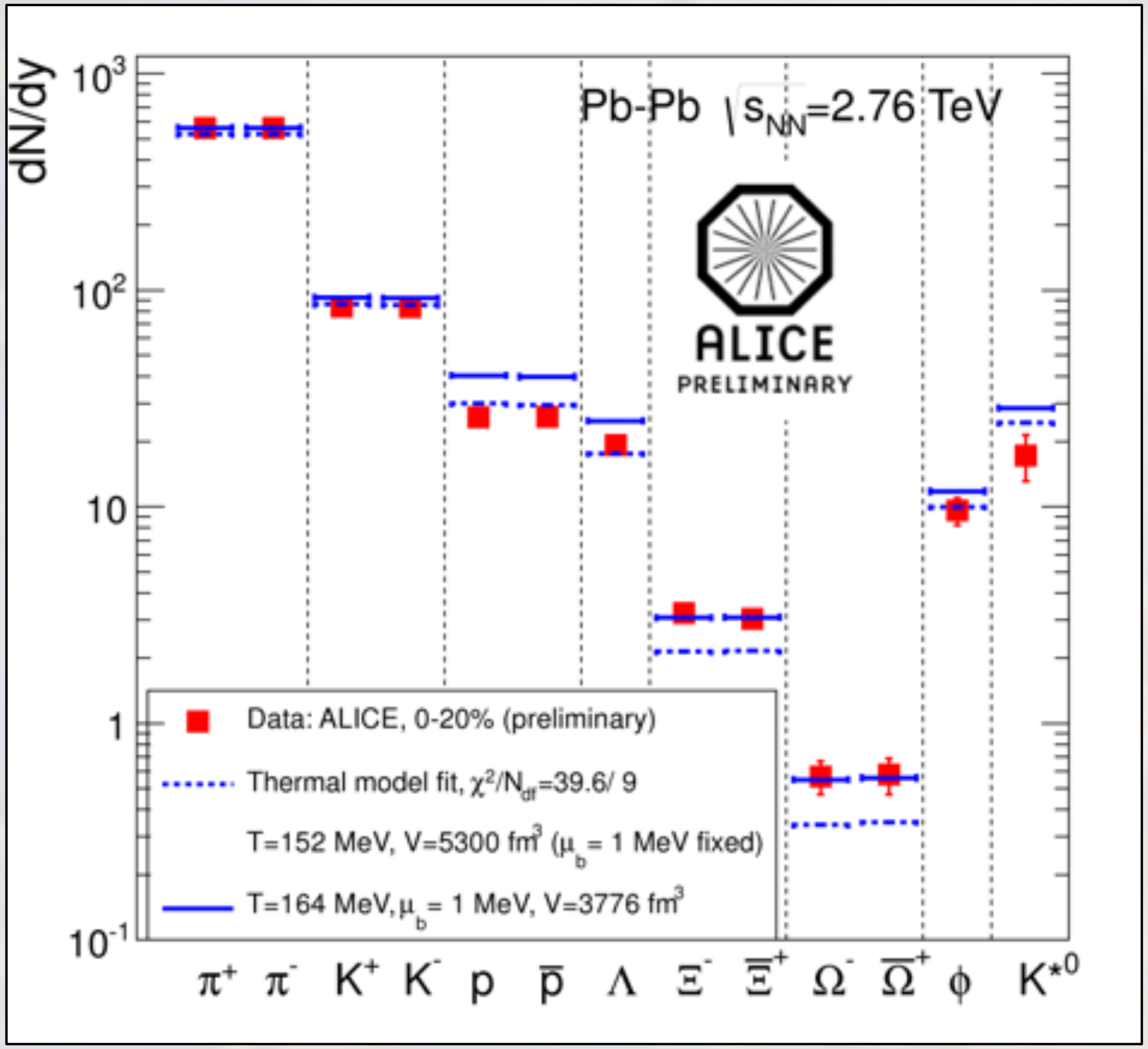


Increase in elliptic flow ~30%,
in agreement with hydrodynamics

CERN Press release, November 26, 2010:
'confirms that the much hotter plasma produced at the LHC behaves as a very low viscosity liquid (a perfect fluid)..'

Particle yields and ratios





Predicted temperature T=164 MeV

A.Andronic, P.Braun-Munzinger, J.Stachel NP A772 167

Thermal fit (w/o res.): T=152 MeV (χ^2/ndf = 40/9)

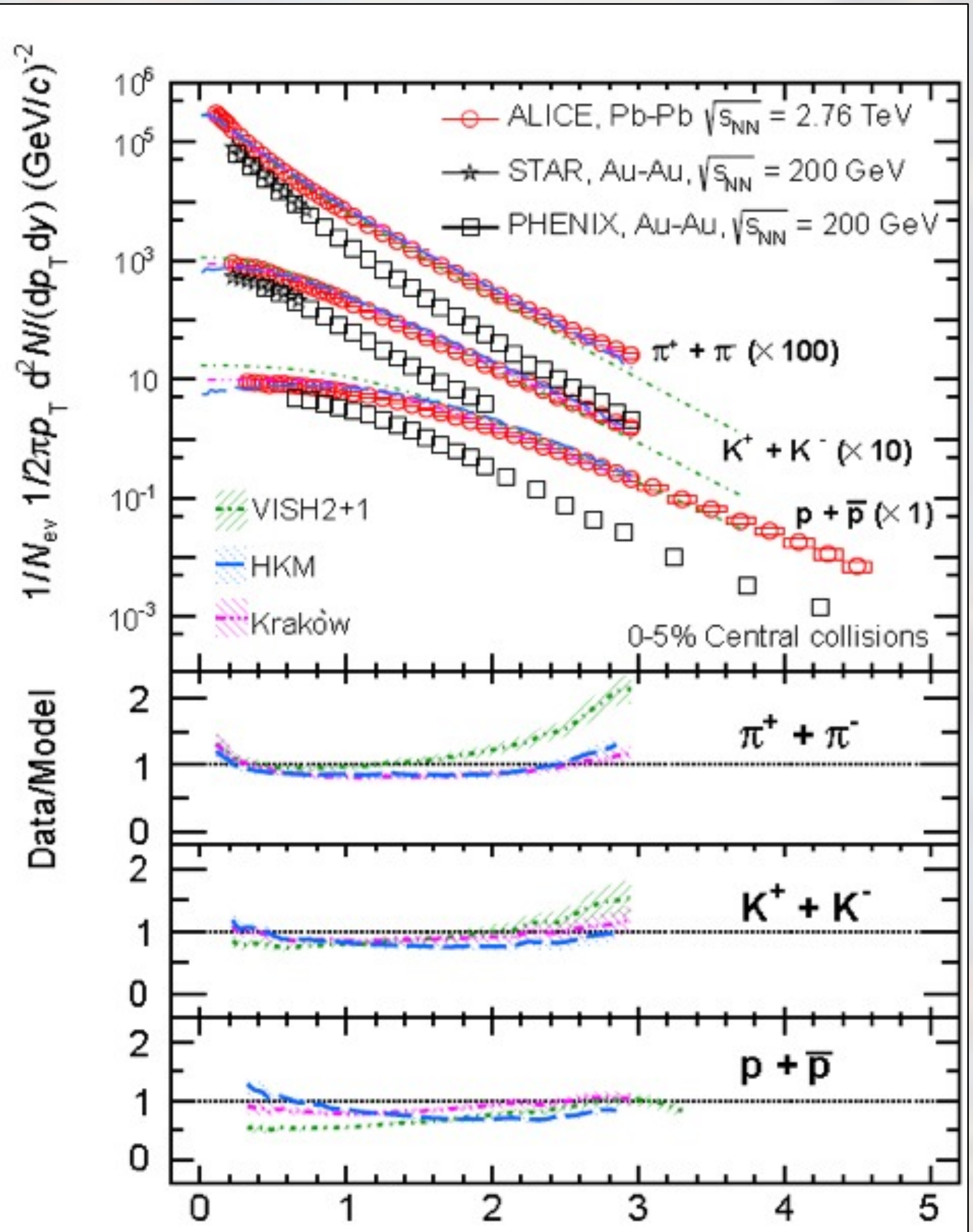
Ξ and Ω significantly higher than statistical model

p/π and Λ/π ratios at LHC lower than RHIC

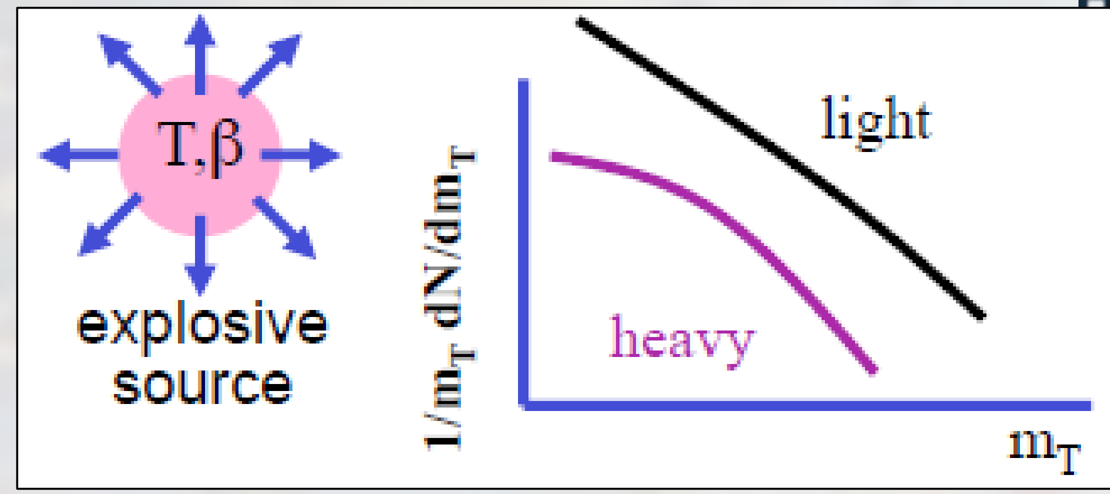
Hadronic re-interactions ?

F.Becattini et al. 1201.6349; J.Steinheimer et al. 1203.5302

Low-p_T particle production



arXiv:1208.1974 [hep-ex]



(low) p_T spectra : superposition of collective radial flow and thermal motion

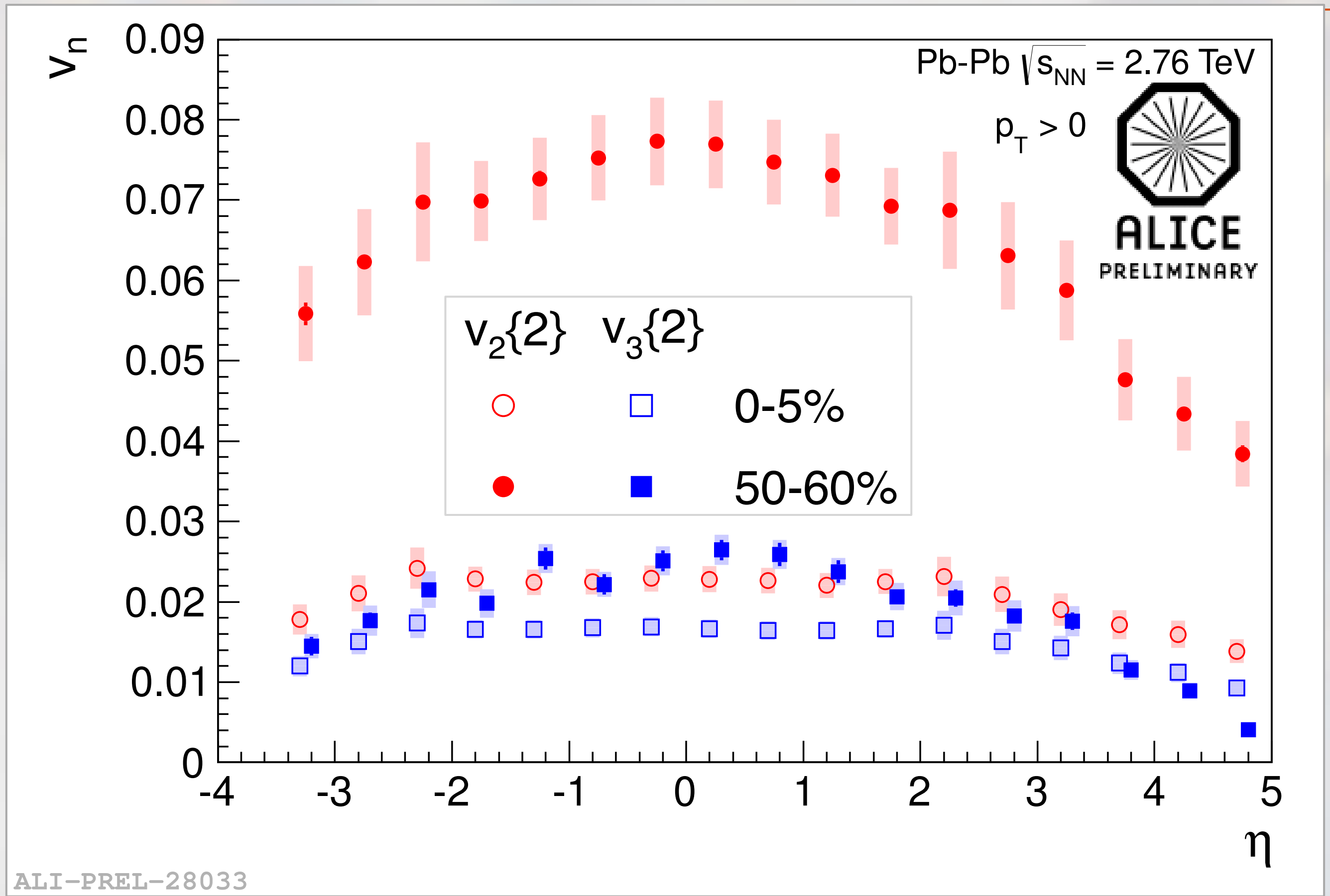
"Blast-Wave" fit to p_T spectra:

→ Radial flow velocity <β> ≈ 0.65 (10 % larger than at RHIC)

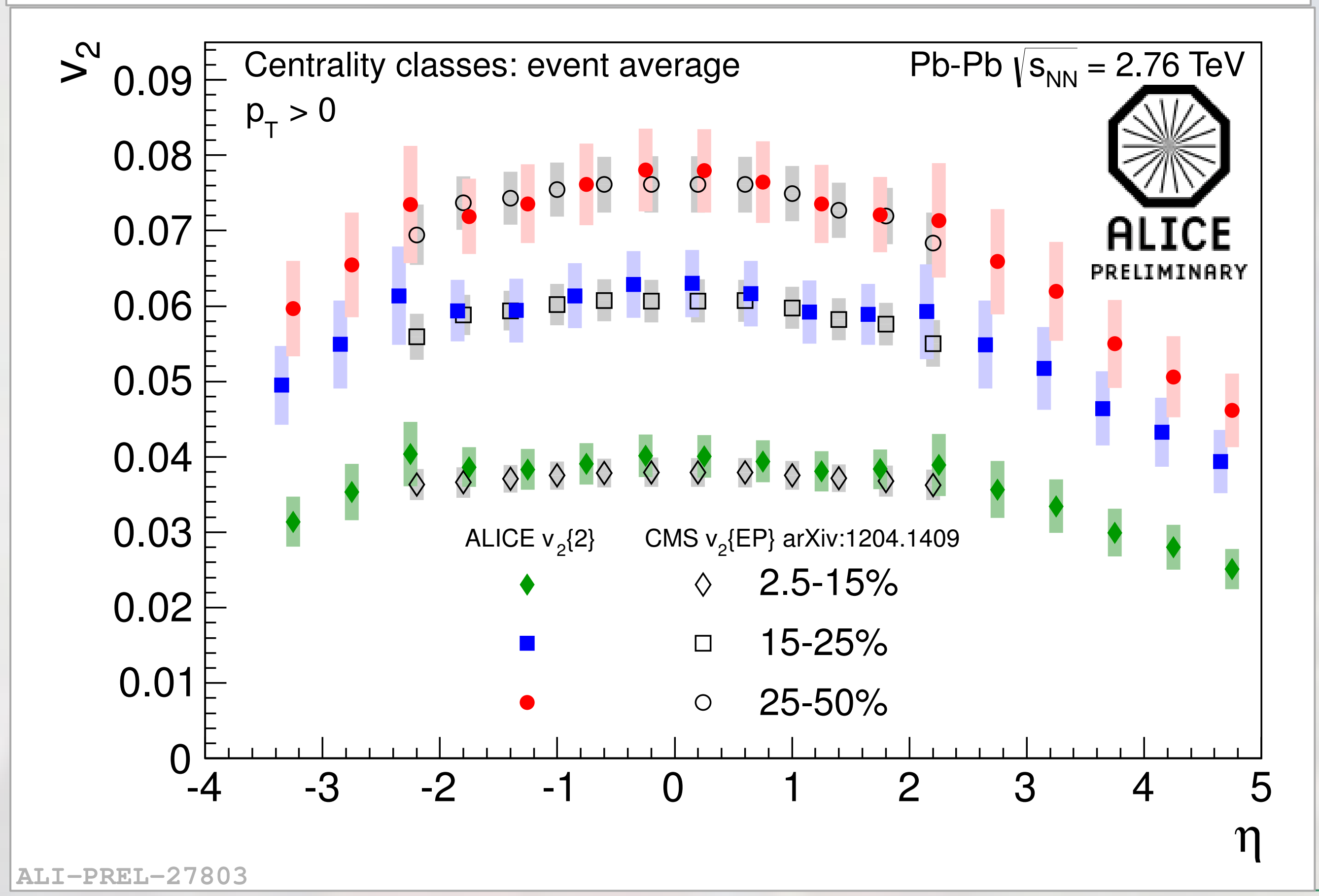
→ Kinetic freeze-out temp. T_K ≈ 95 MeV (same as RHIC within errors)

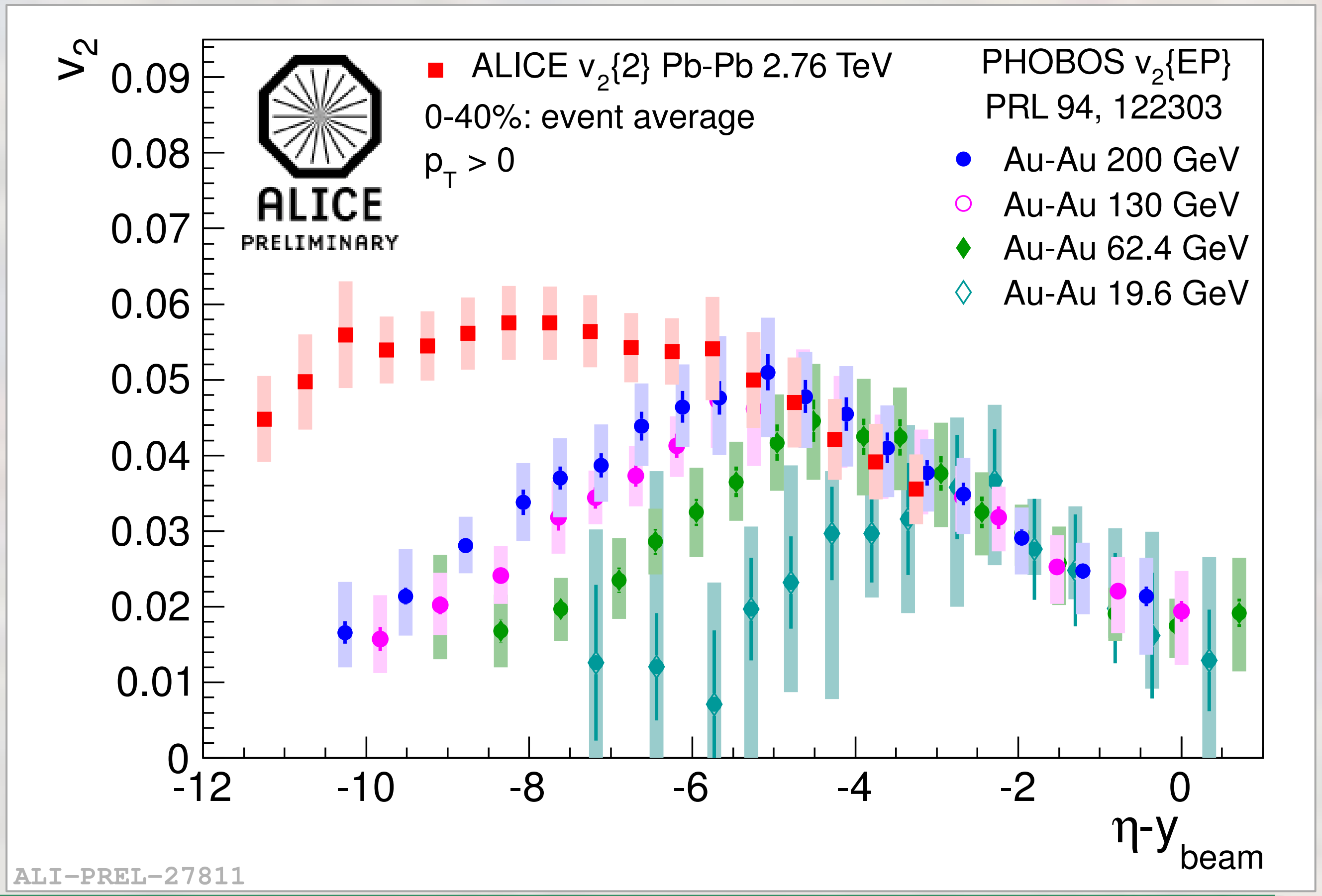
Extending the flow measurements

v_2 and v_3 , $-3.5 < \eta < 5.0$



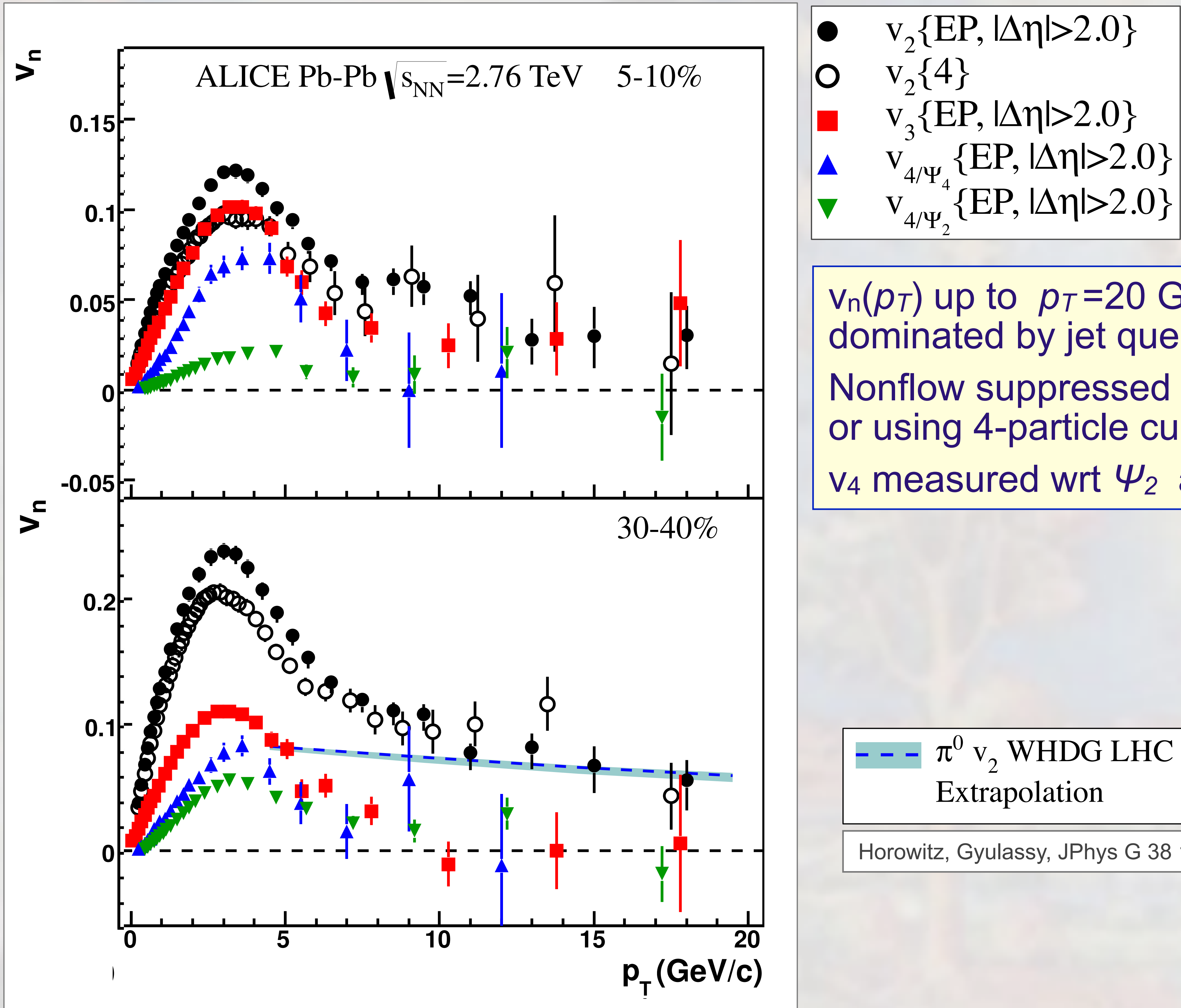
- using 2- and 4-particle correlations in FMD and SPD detectors, v_2 and v_3 measurements extended up to *η*=5
- good agreement with CMS in the overlapping region, |*η*|<2.4
- consistent with longitudinal scaling





v_2, v_3 and v_4 for p_T up to 20 GeV/c

ALICE: arXiv:1205.5761



$v_n(p_T)$ up to p_T=20 GeV/c, where flow is dominated by jet quenching mechanism

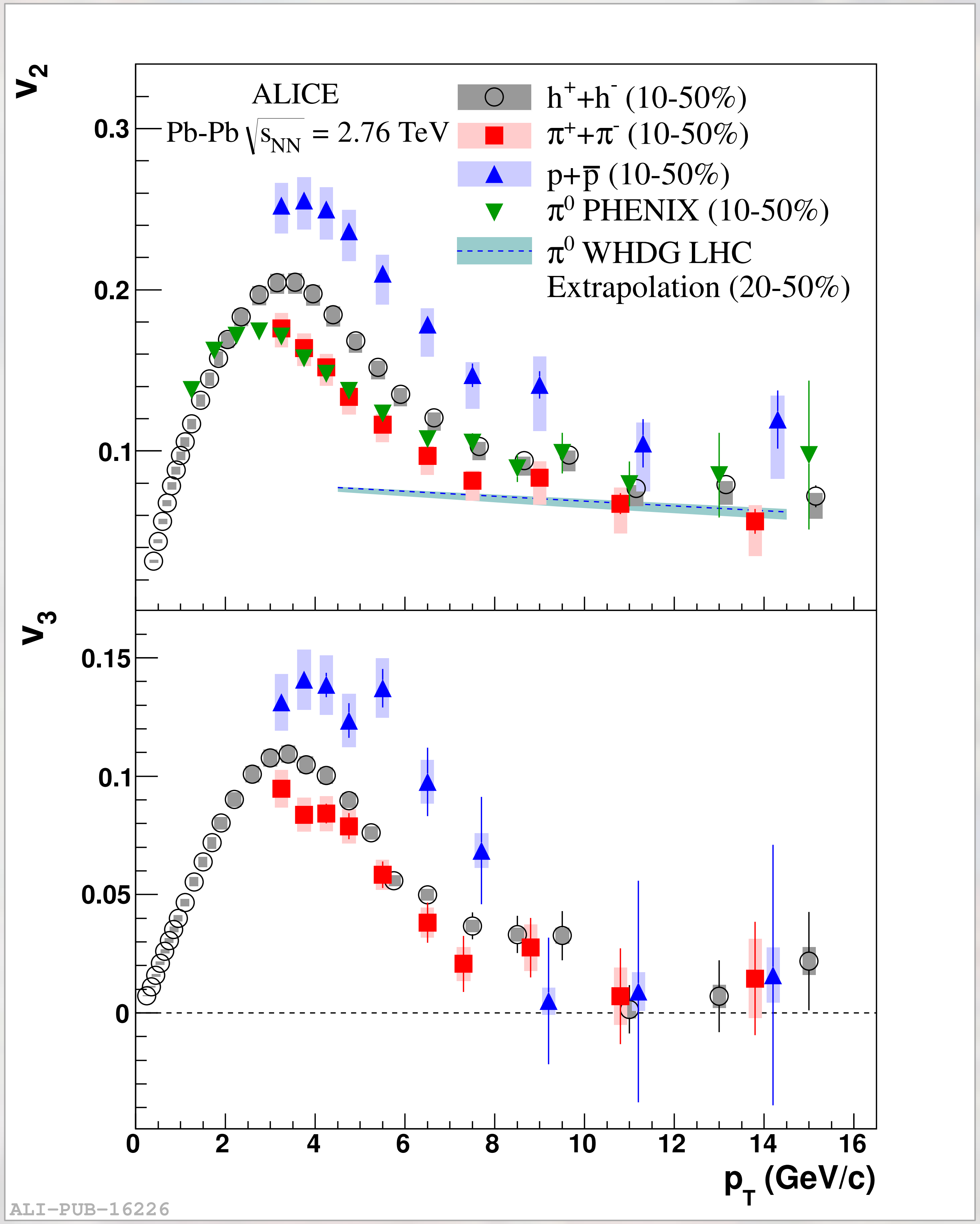
Nonflow suppressed either by rapidity gap or using 4-particle cumulans

v_4 measured wrt Ψ_2 and Ψ_4

Horowitz, Gyulassy, JPhys G 38 124114 (2011)

Proton and pion v_2 and v_3 at high p_T

ALICE: arXiv:1205.5761

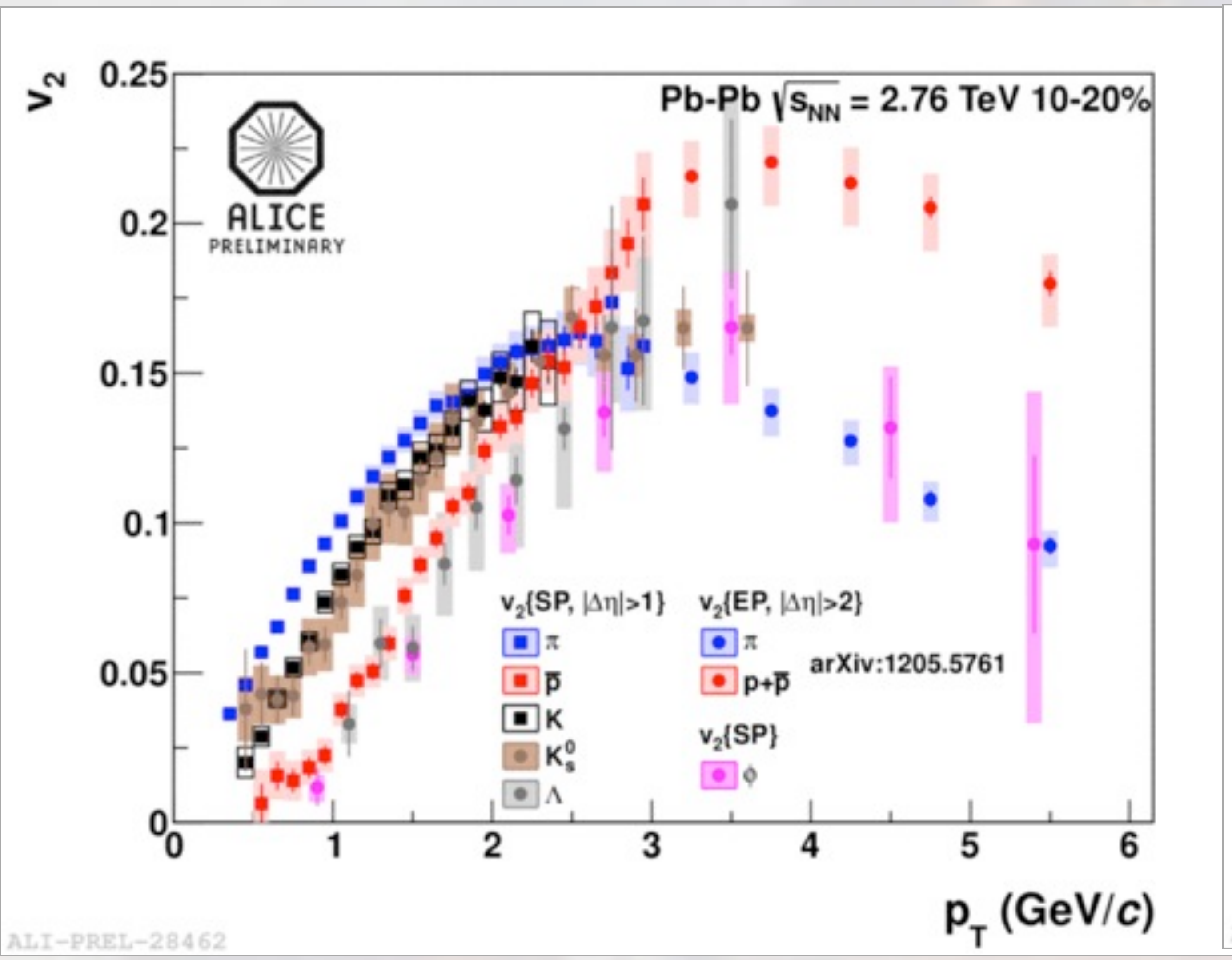


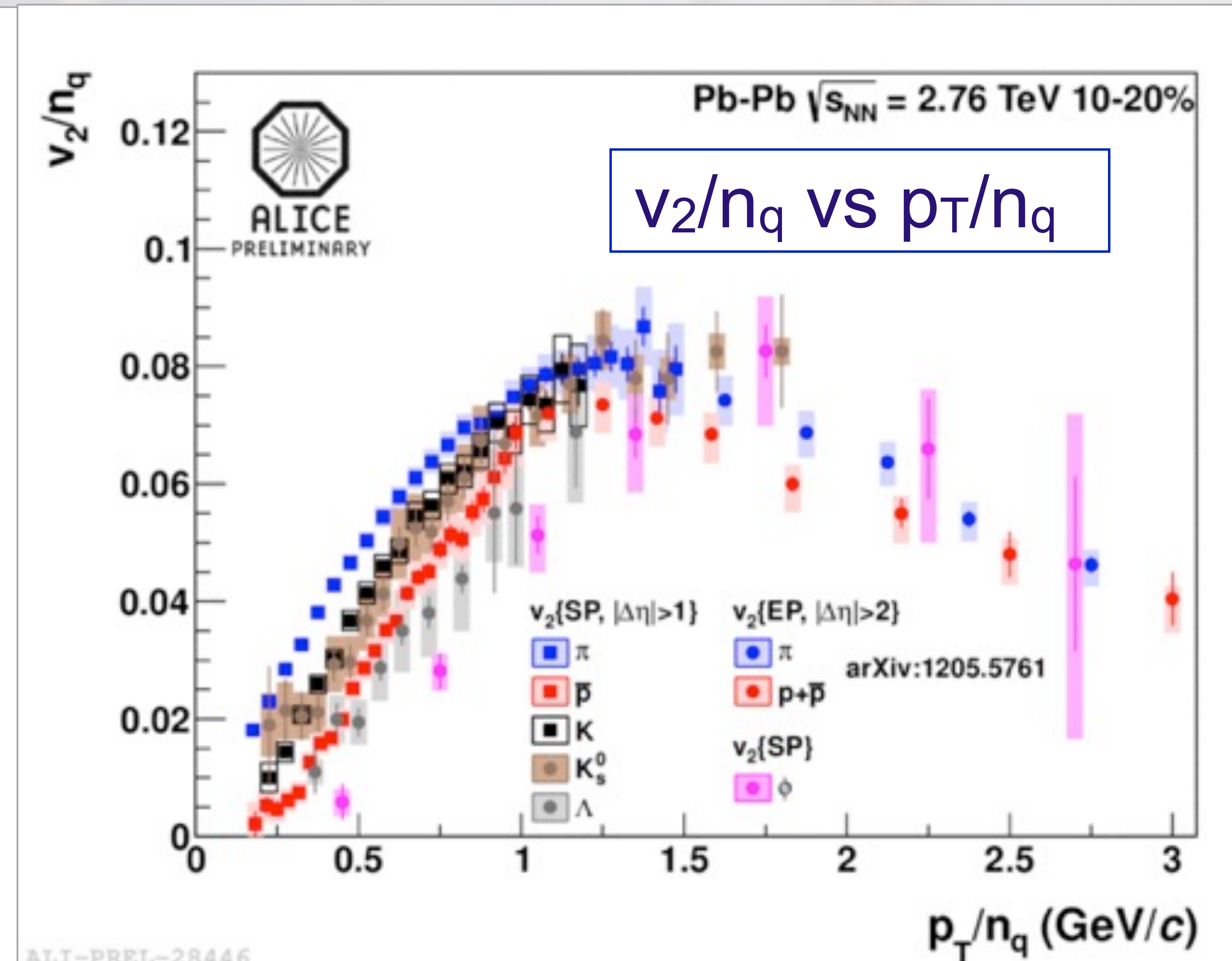
proton/pion splitting extends up to $p_T \simeq$ 10 GeV/c

v_3 approaches zero for all particle species

Identified particle v_2. NCQ scaling

ALICE



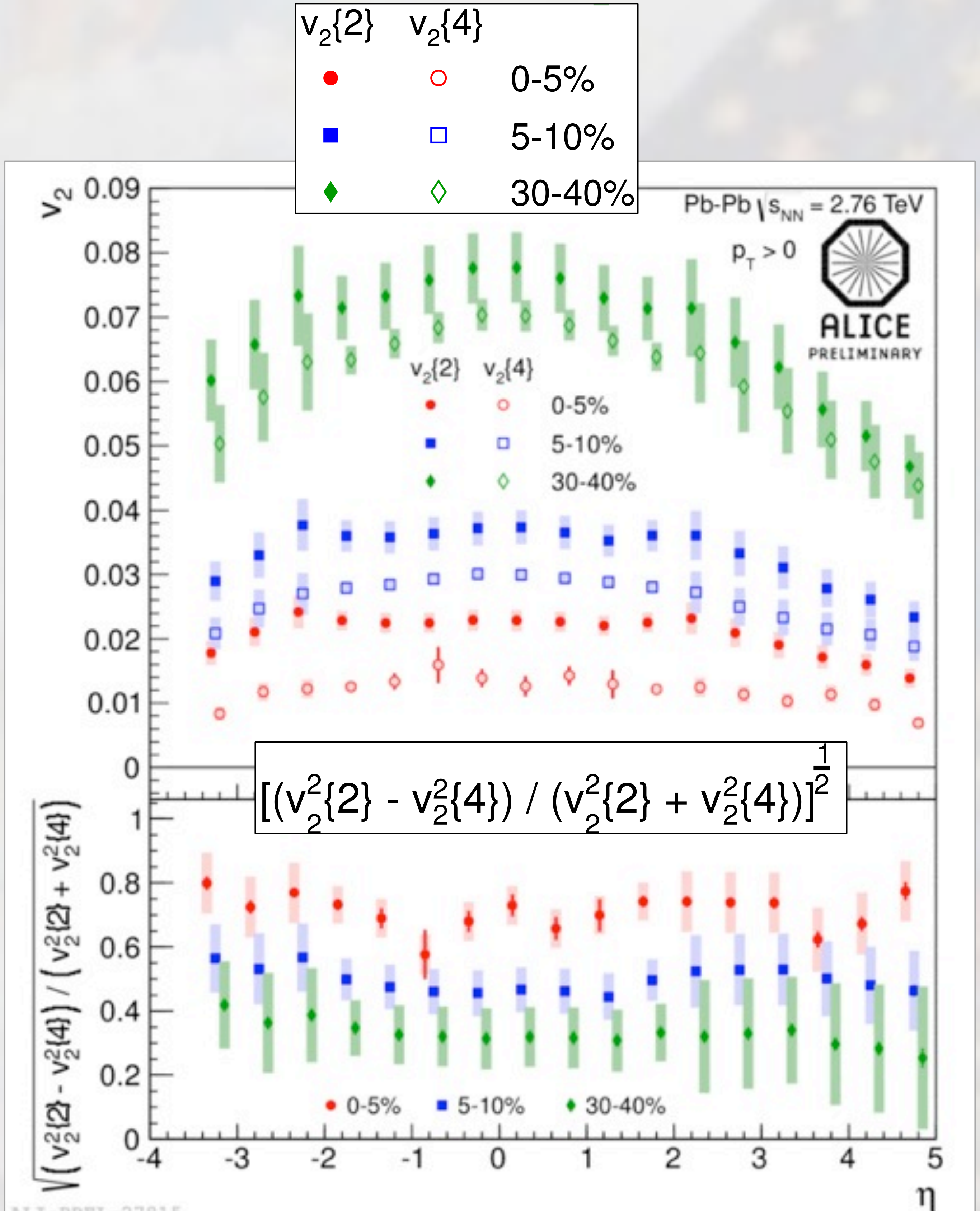


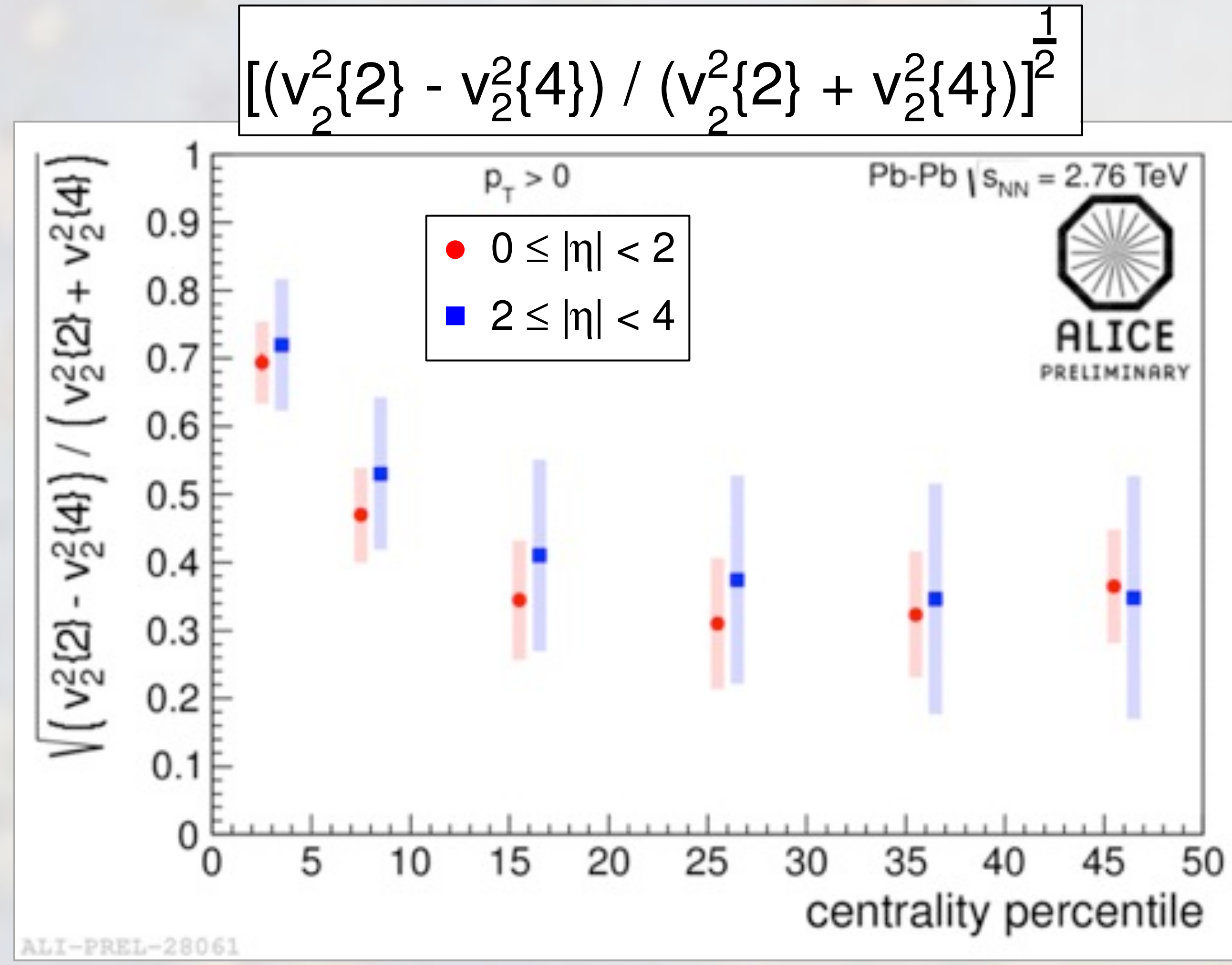
New: K^0, Λ, ϕ, and (not shown) Ξ, Ω

NCQ scaling: violation ~ 10-15% at p_T~1.2 GeV/c

ϕ-meson flow follows mass dependence at p_T < 3 GeV/c and "meson band" at higher p_T

Flow fluctuations vs η and centrality

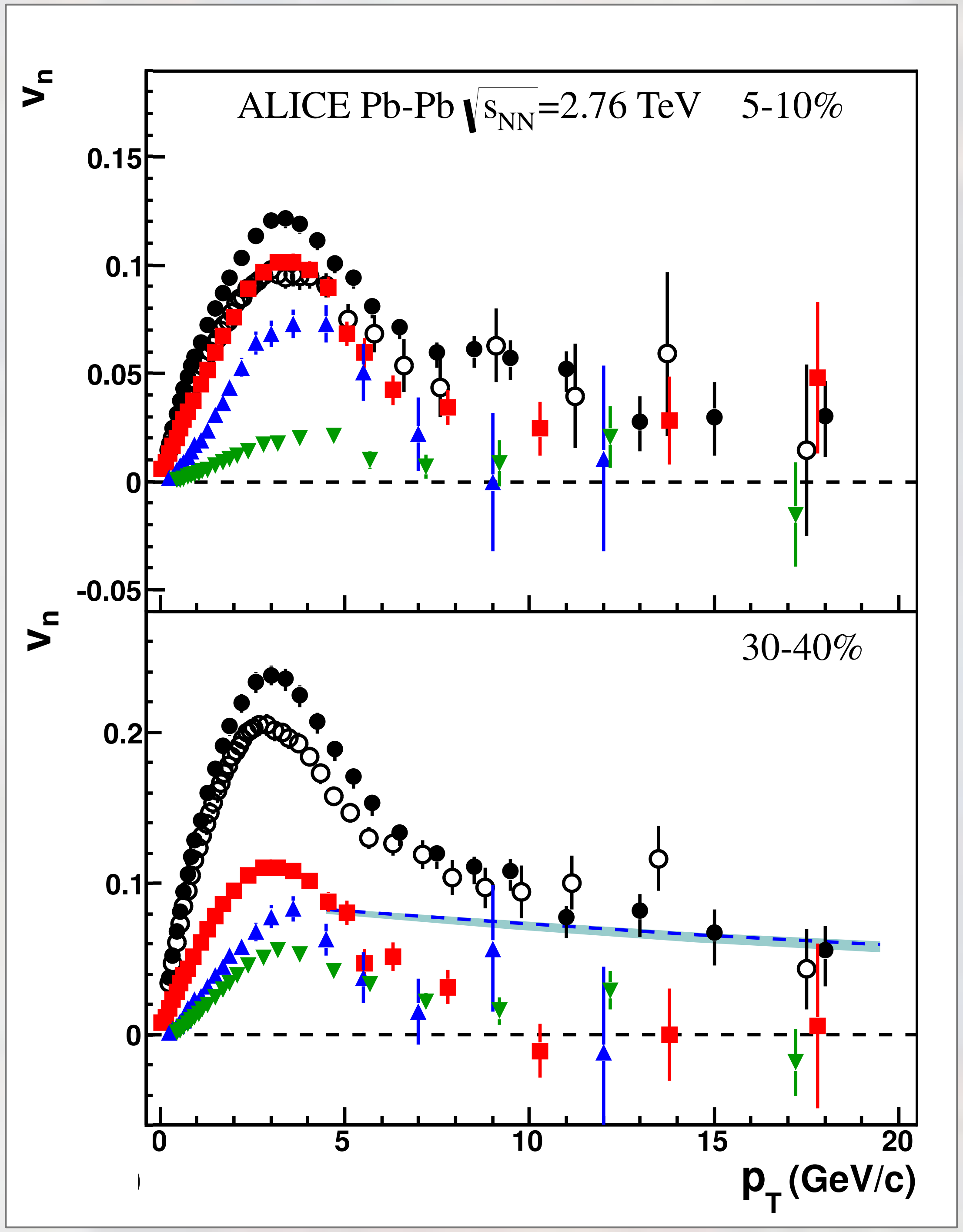




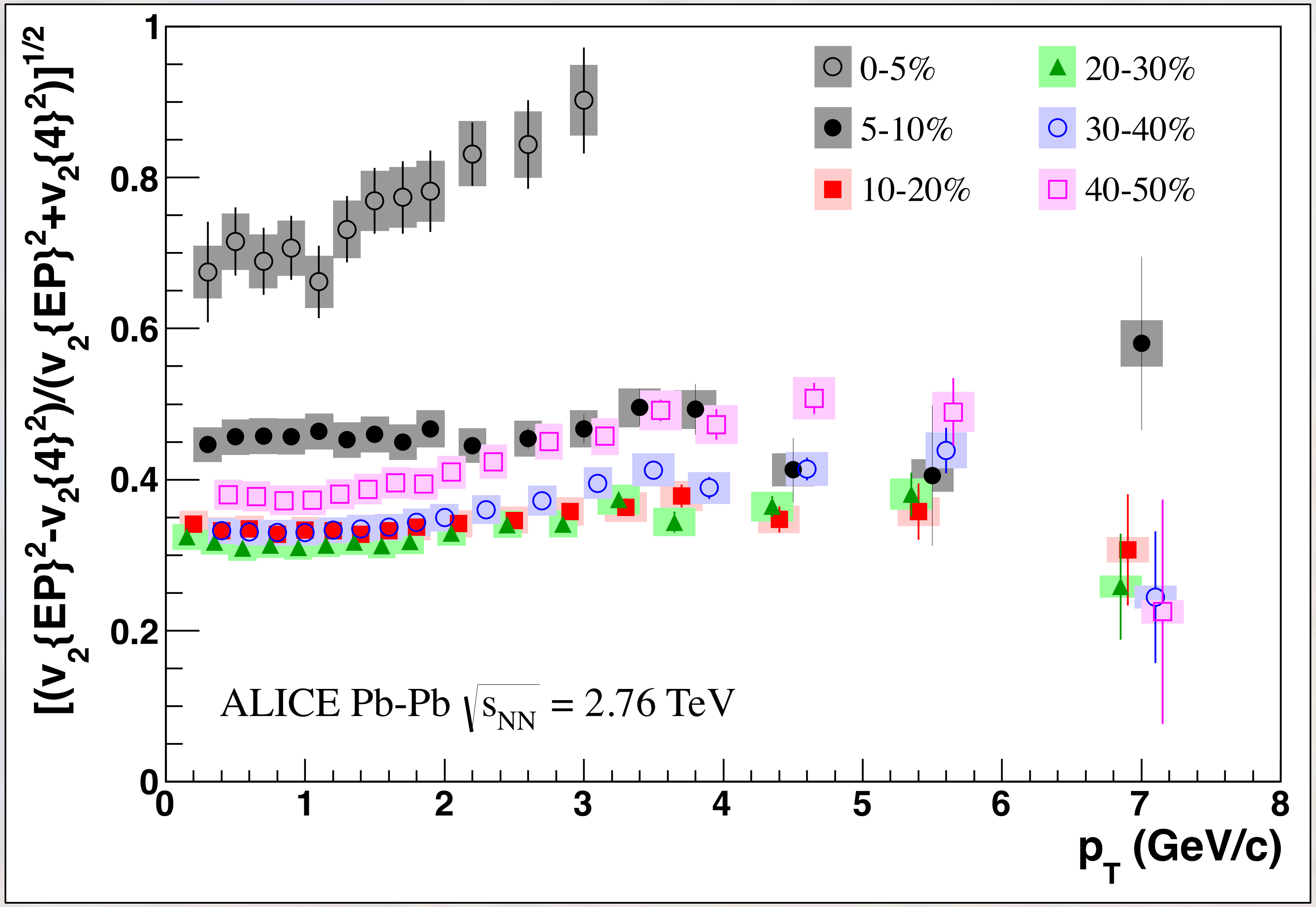
Fluctuations in the forward region are very similar to those at midrapidity at all centralities

Fluctuations vs p_T

ALICE: arXiv:1205.5761



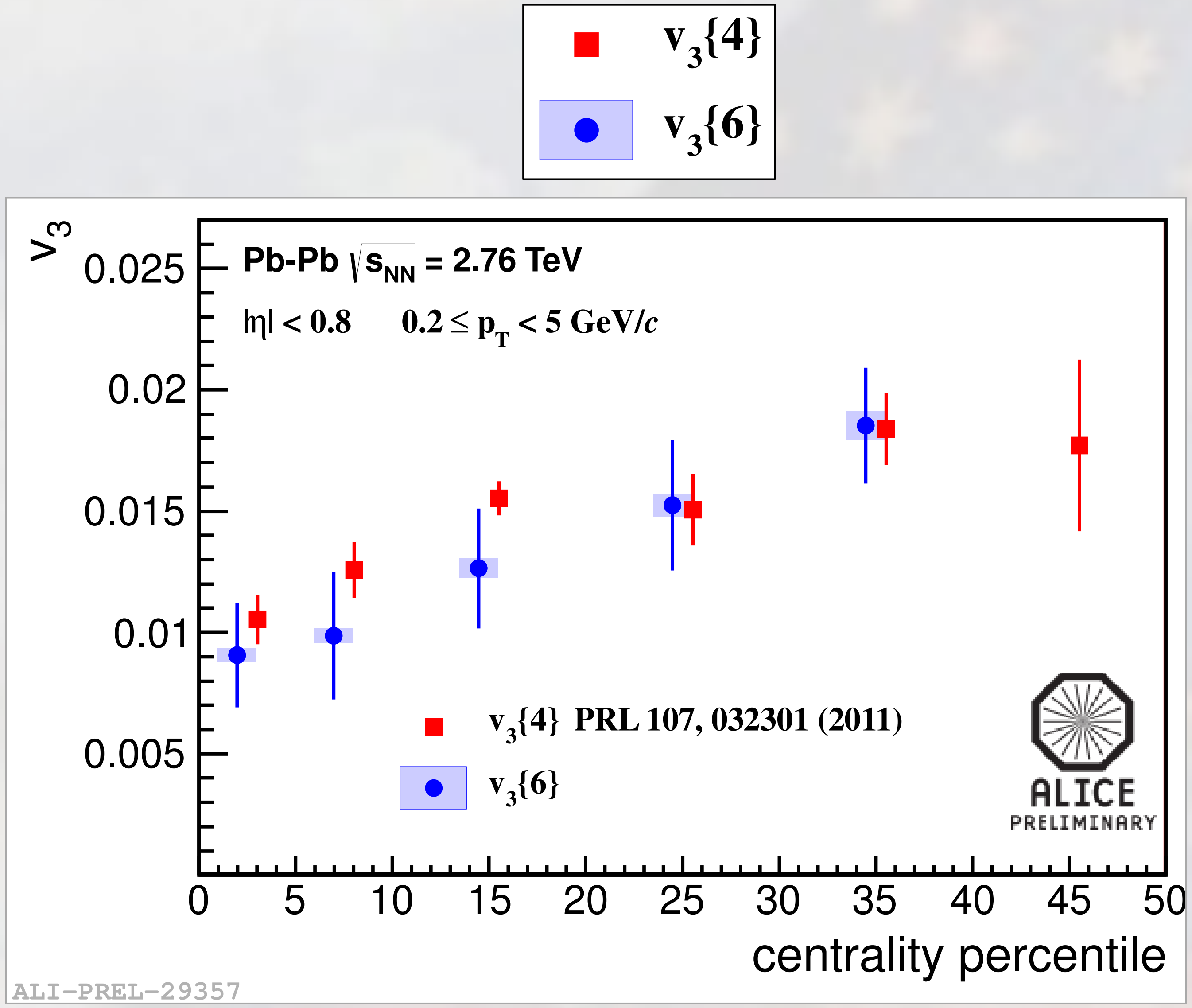
$((v_2\{EP\}^2-v_2\{4\}^2)/(v_2\{EP\}^2+v_2\{4\}^2))^{1/2}$

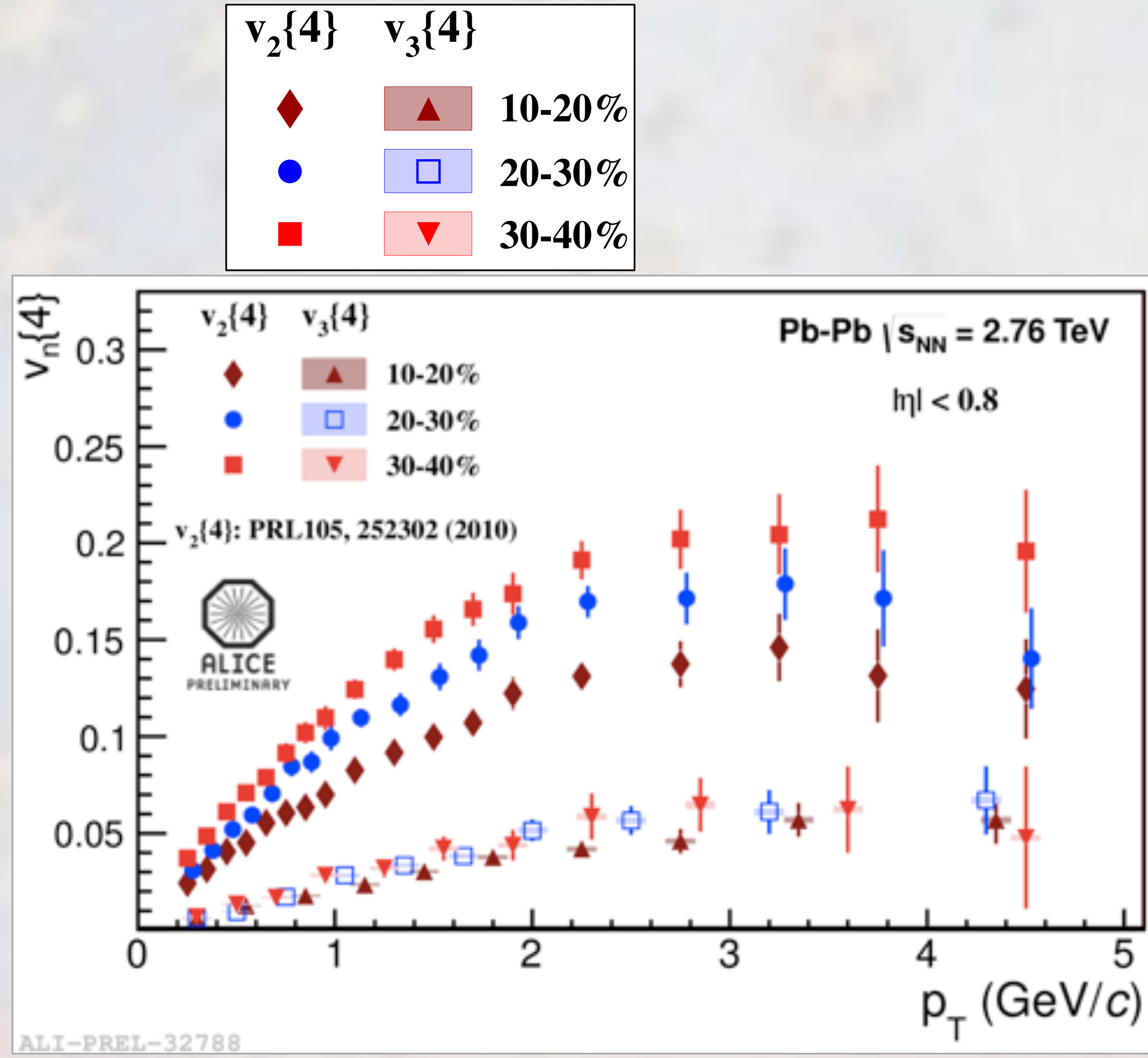


Fluctuations extend up to $p_T \sim$ 8 GeV/c with very similar magnitude

Note that v_4 measured wrt Ψ_2 and Ψ_4 becomes very similar at the same p_T

Higher harmonics with higher cumulants

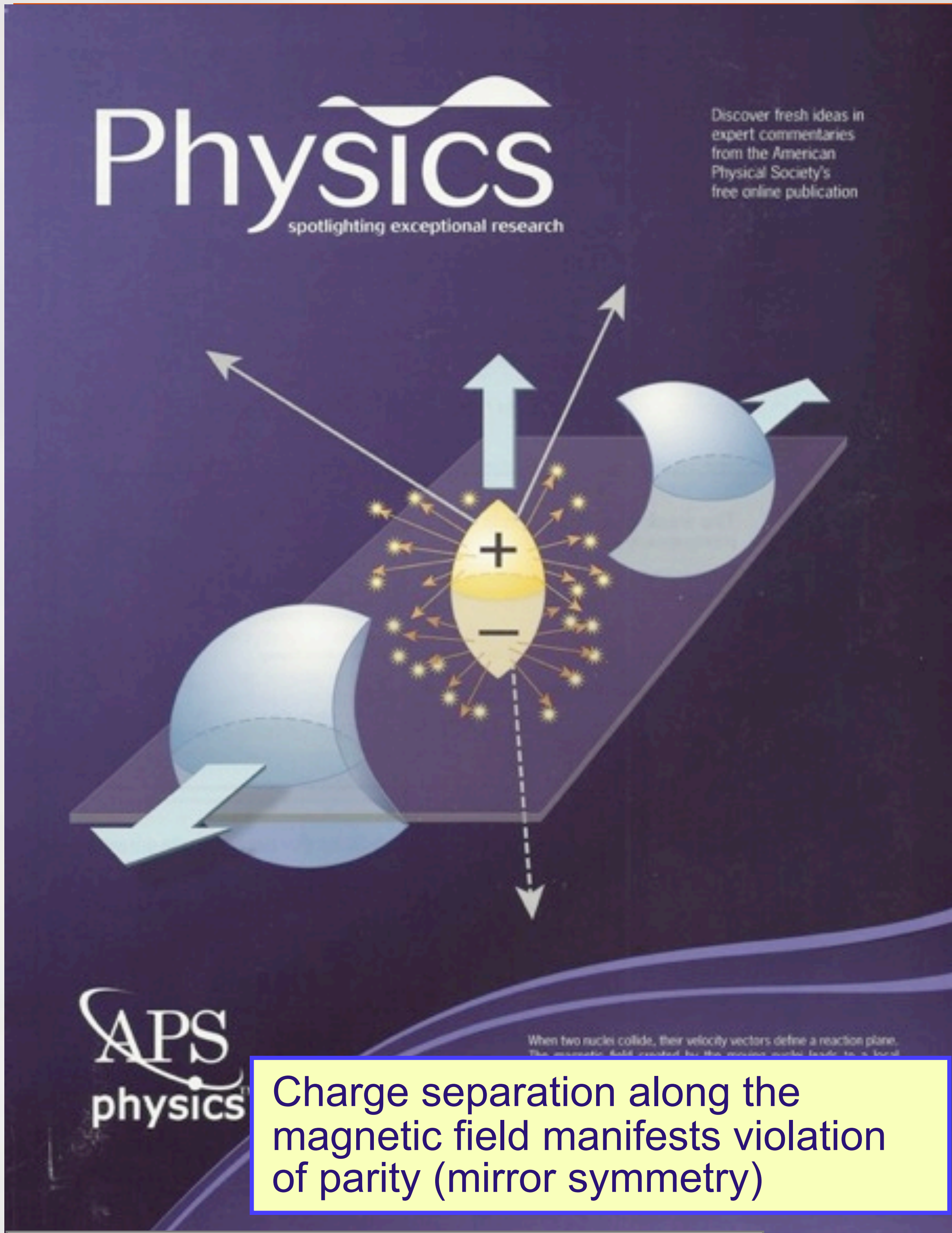




$v_3\{6\}$ is very similar to $v_3\{4\}$

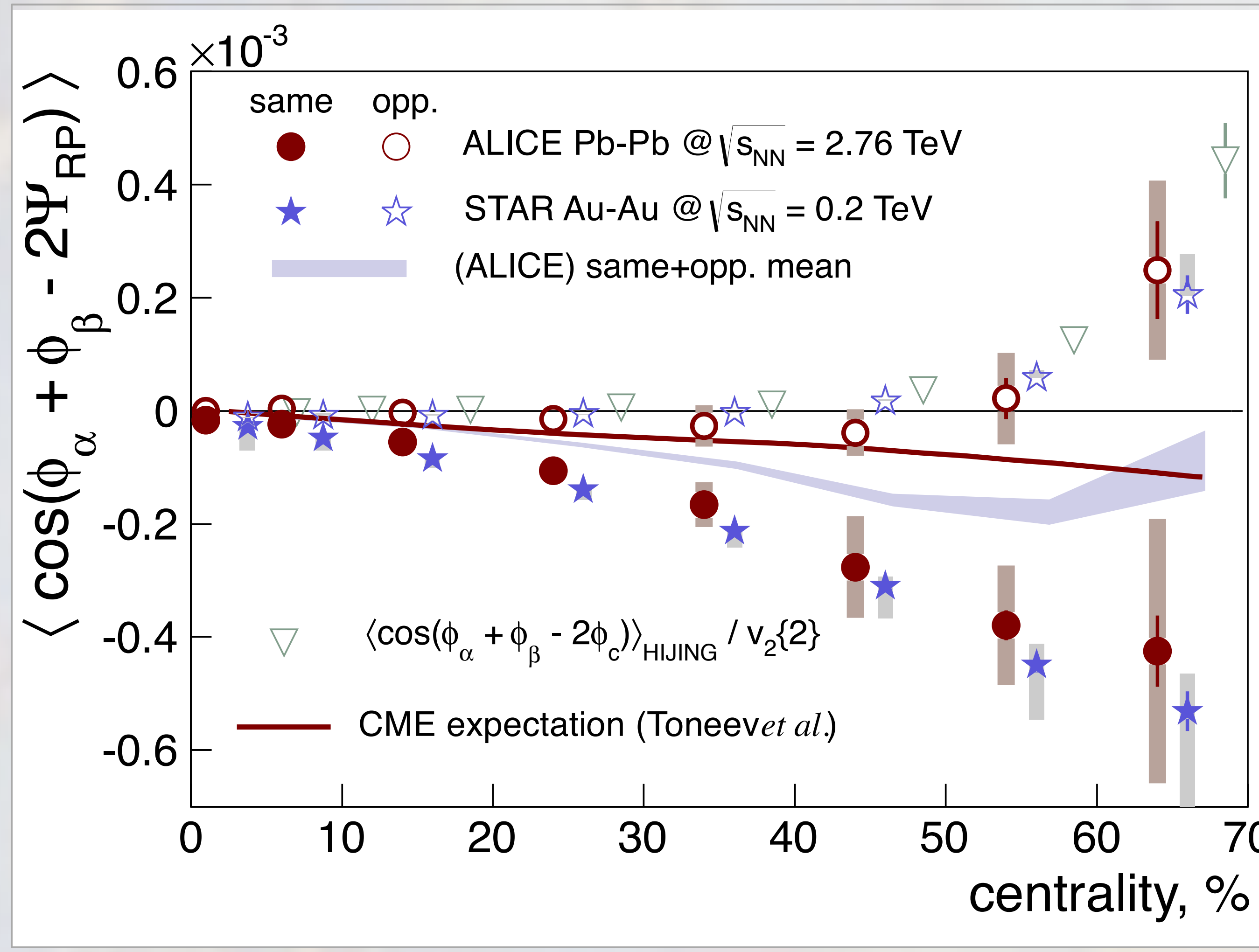
First $v_3\{4\}(p_T)$ measurements
Very weak centrality dependence

Searching for the Chiral Magnetic Effect



Charge separation along the magnetic field manifests violation of parity (mirror symmetry)

ALICE: arXiv:1207:0900



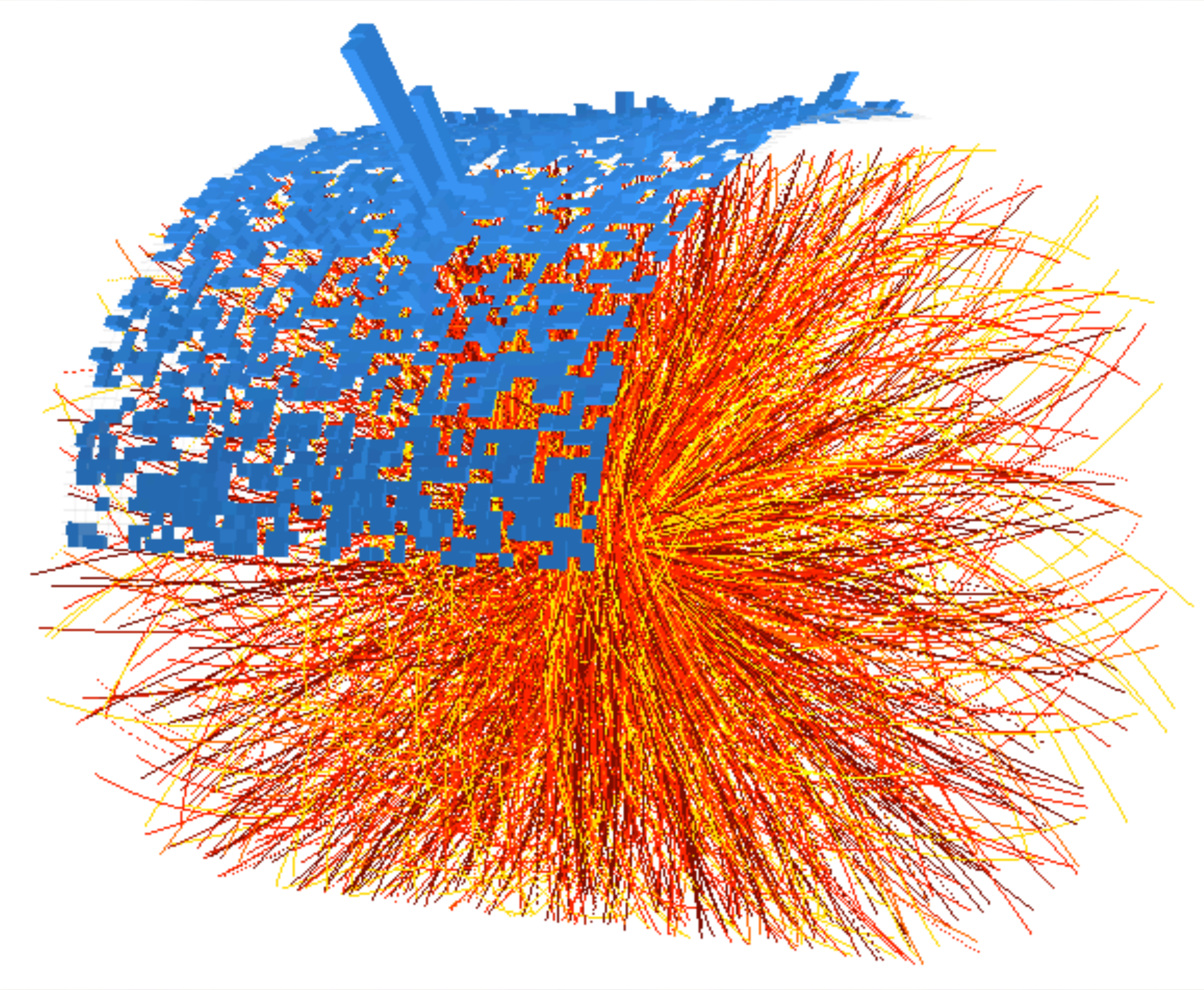
ALICE: charge dependent correlations qualitatively consistent with CME, and similar in strength to those observed by STAR.

No present event generator can reproduce the signal.

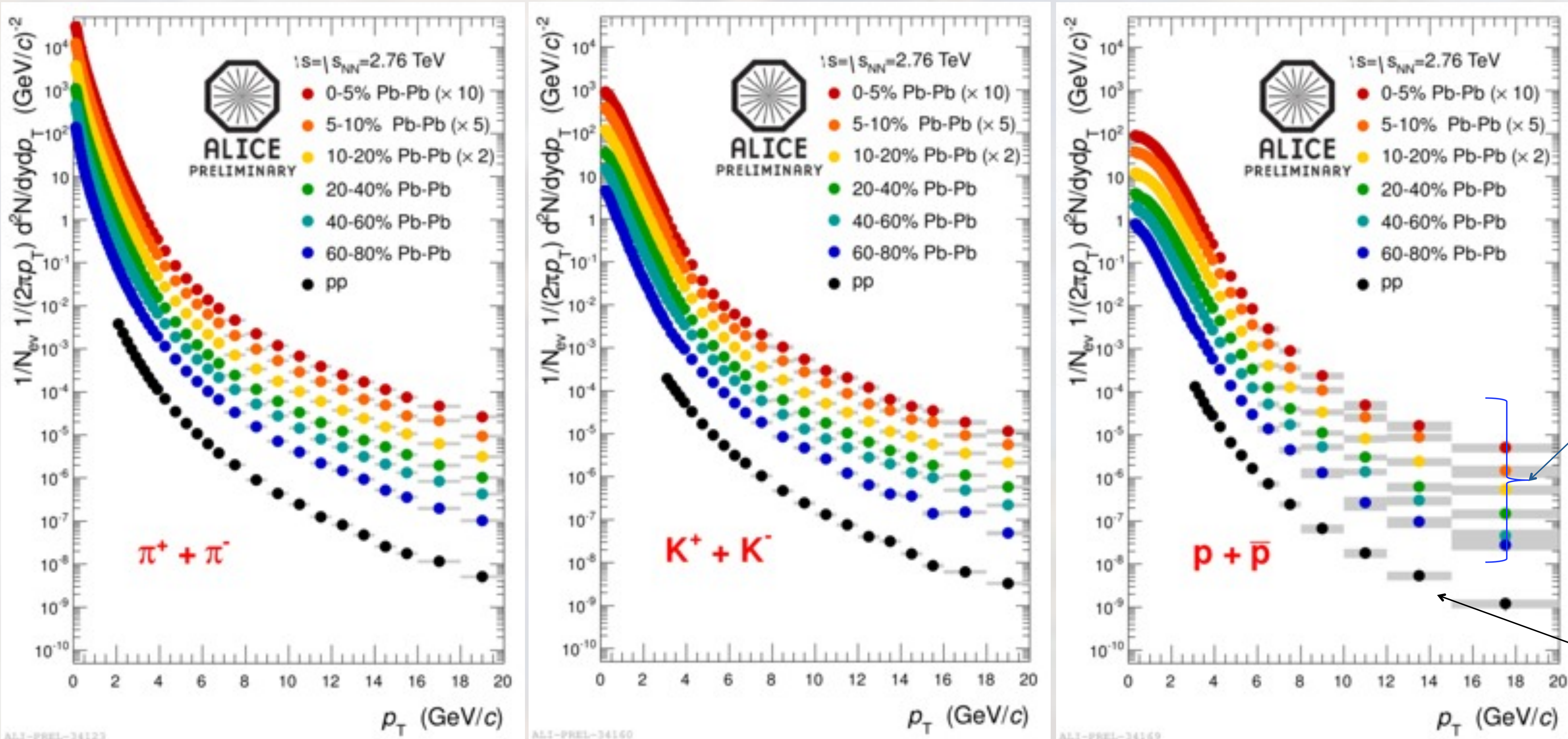
Kharzeev, PLB633 260 (2006)
Kharzeev, Zhitnitski, NPA797 67 (2007)
Khrazeev, McLerran, Waringa, NPA803 227 (2008)
Fukushima, Kharzeev, Waringa, PRD 78 074033 (2008)

Voloshin, PRC70 057901 (2004)

Hight p_T particle production and jets

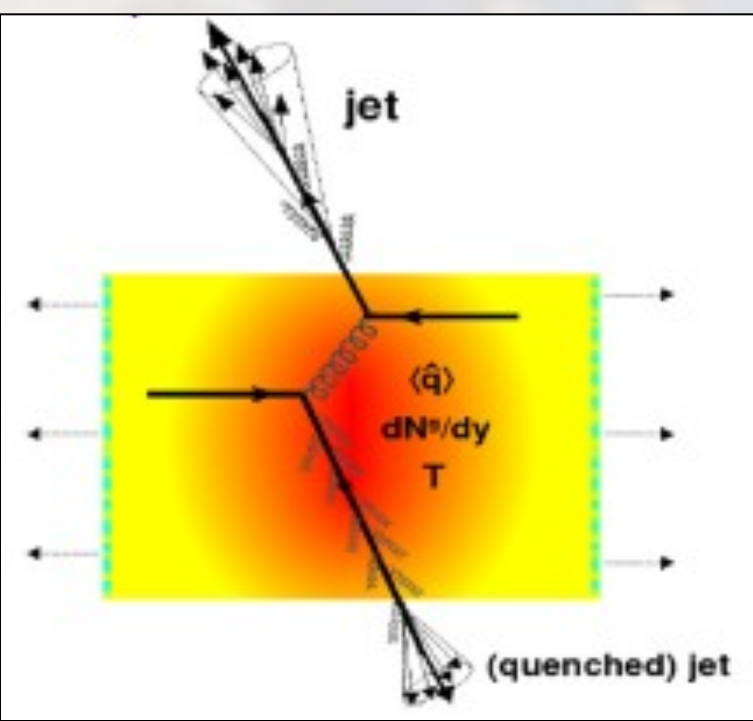


Particle spectra at high p_T



Pb-Pb at different centralities

Reference: pp collisions



Parton energy loss:

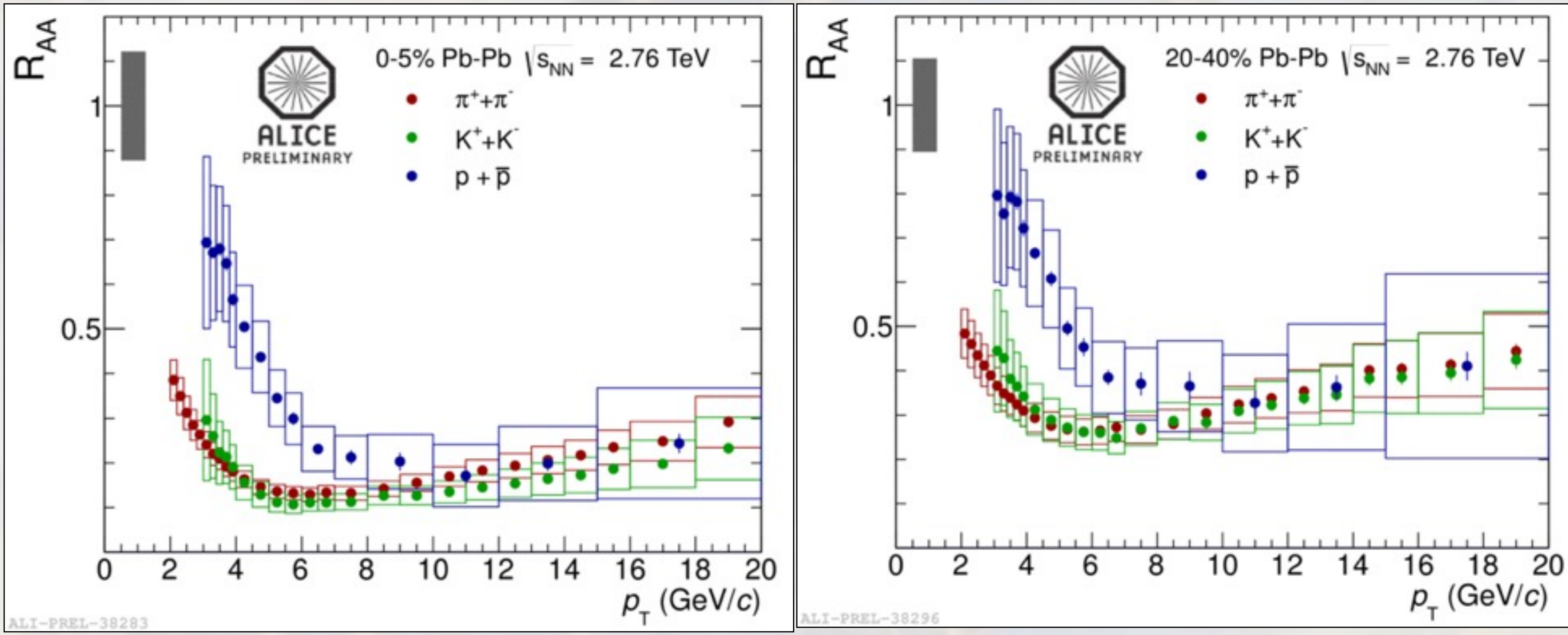
A parton passing through the QCD medium undergoes energy loss which results in the suppression of high-p_T hadron yields

Related observable:

nuclear modification factor R_{AA}

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{d^2N^{AA} / d\eta dp_T}{d^2N^{pp} / d\eta dp_T}$$

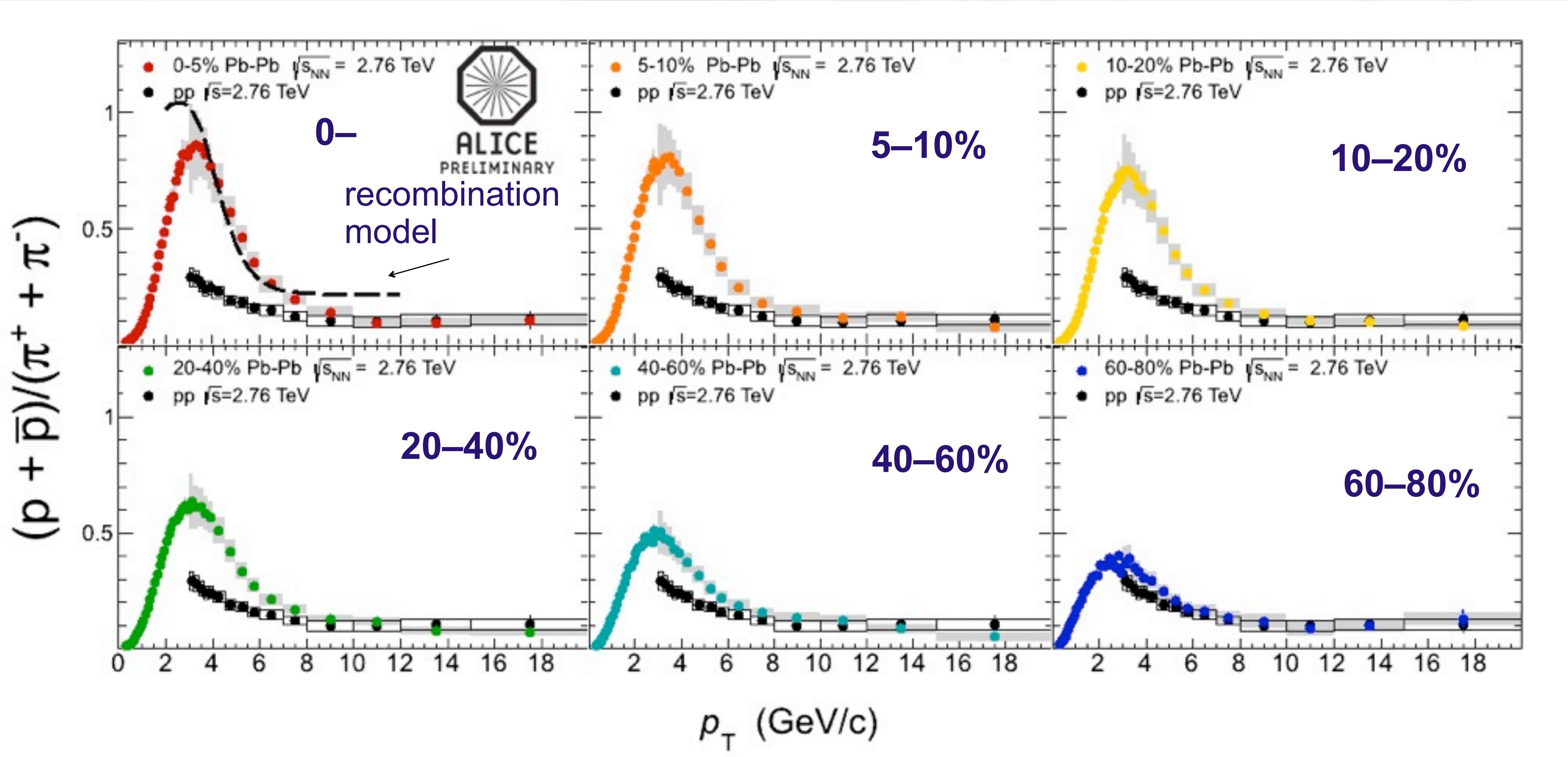
R_{AA} for identified particles



First measurement of (anti-)proton, K and π at high p_T (>7 GeV/c) :
- suggests that the medium does not affect the fragmentation.

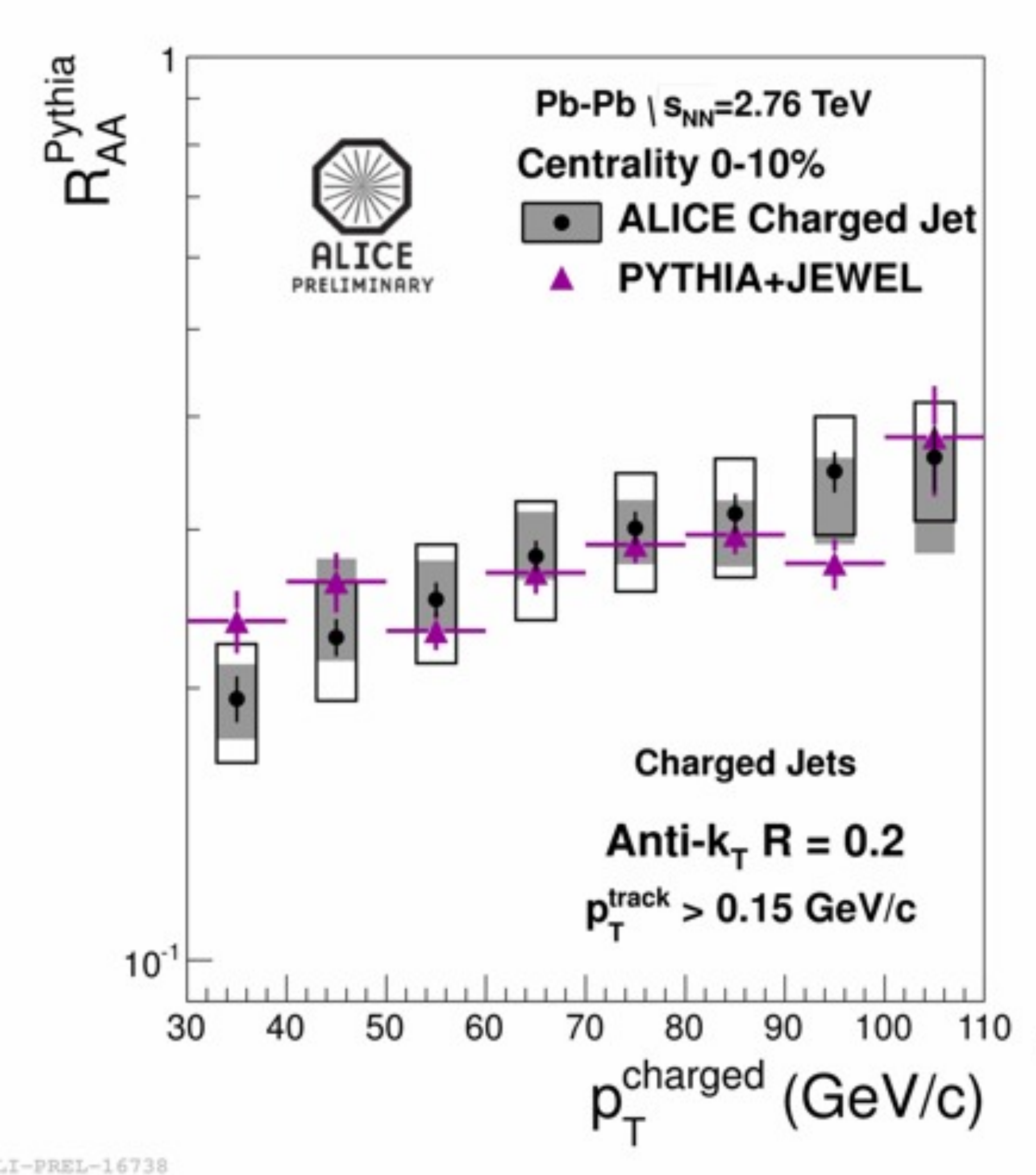
Baryon-to-meson ratio: p/π

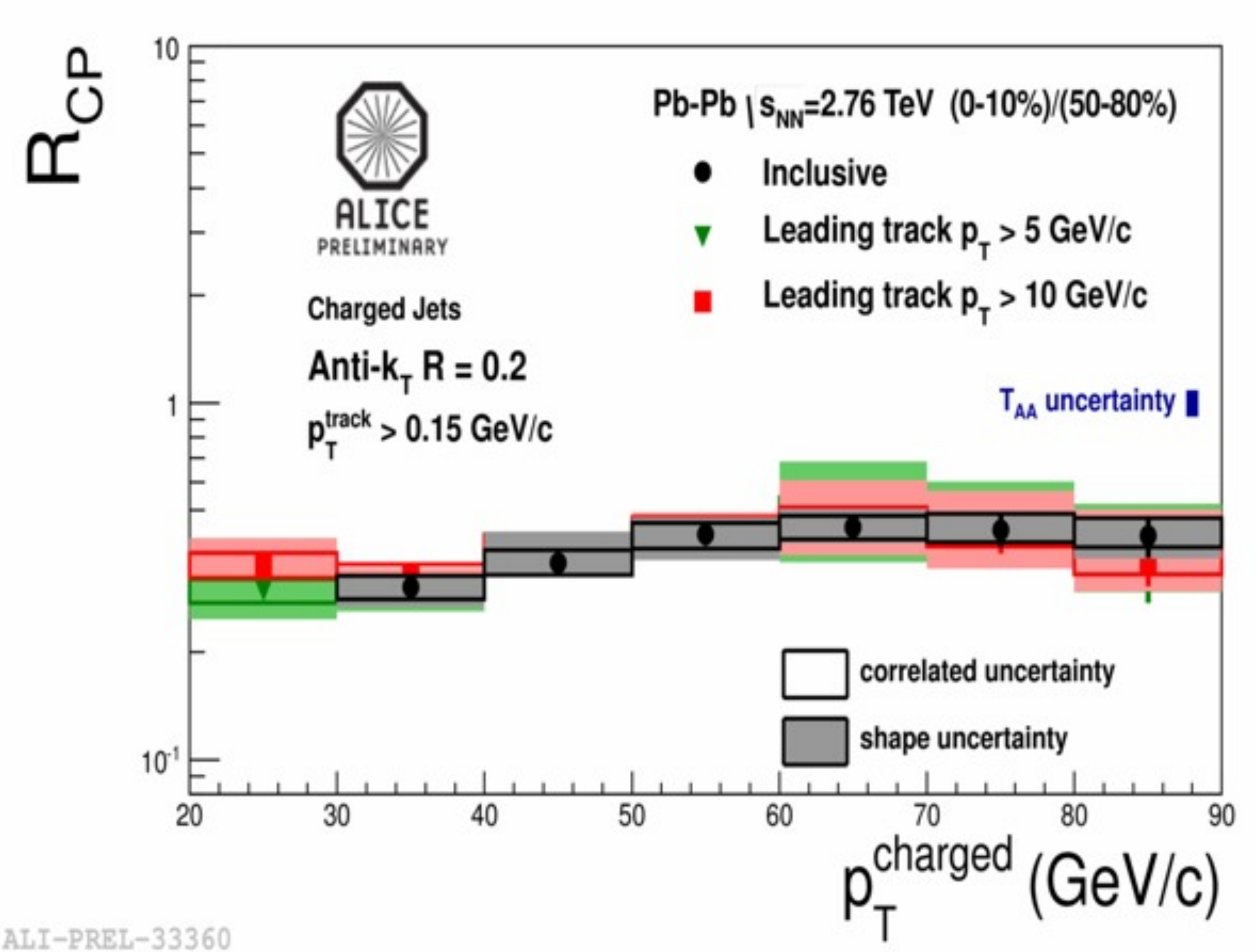
● proton–proton ●●●●●● Pb–Pb different centralities



p/π ratio at $p_T \approx 3$ GeV/*c* in 0–5% central Pb–Pb collisions factor ~ 3 higher than in pp
at p_T above ~ 10 GeV/*c* back to the "normal" pp value

Charged jet: R_{AA} and R_{CP}

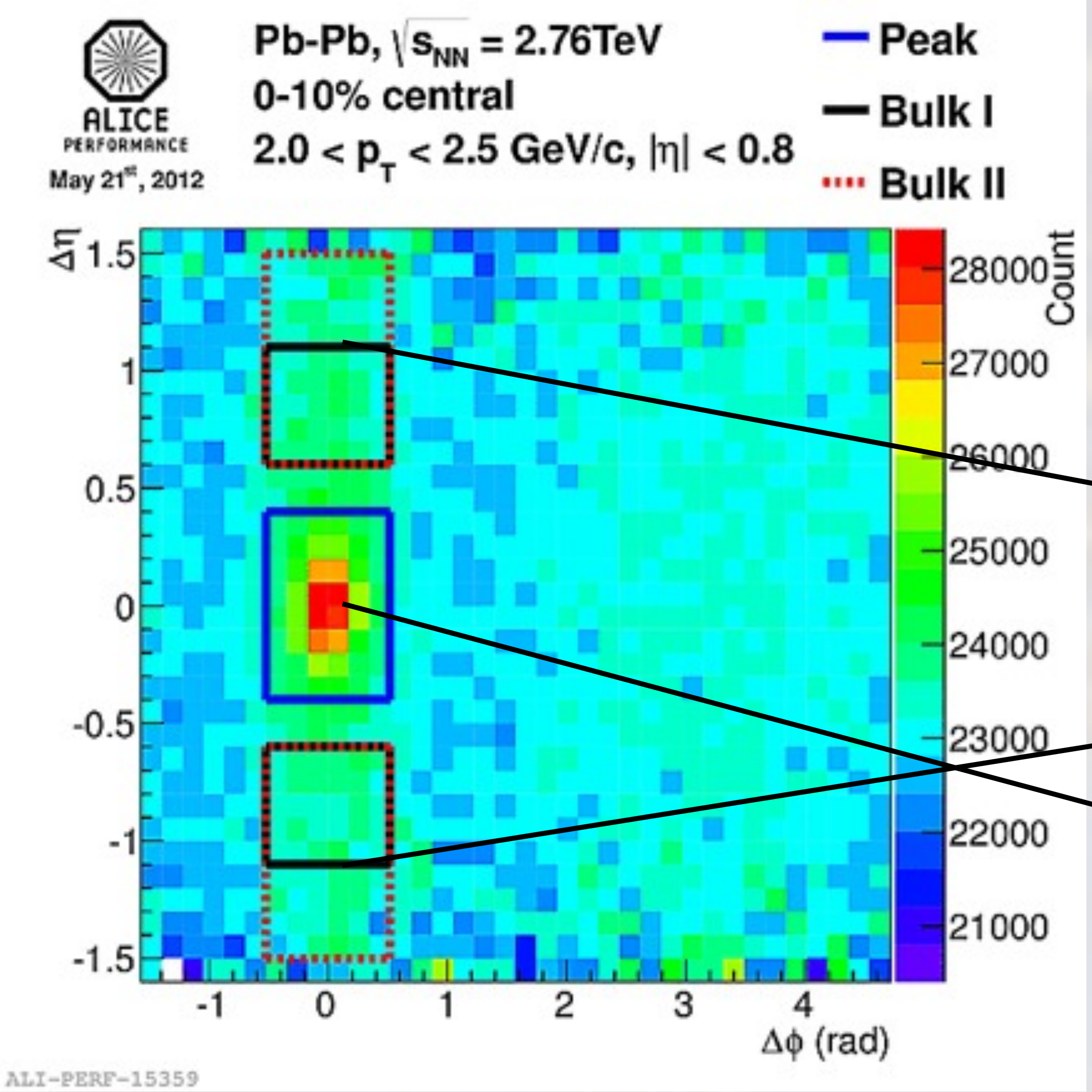


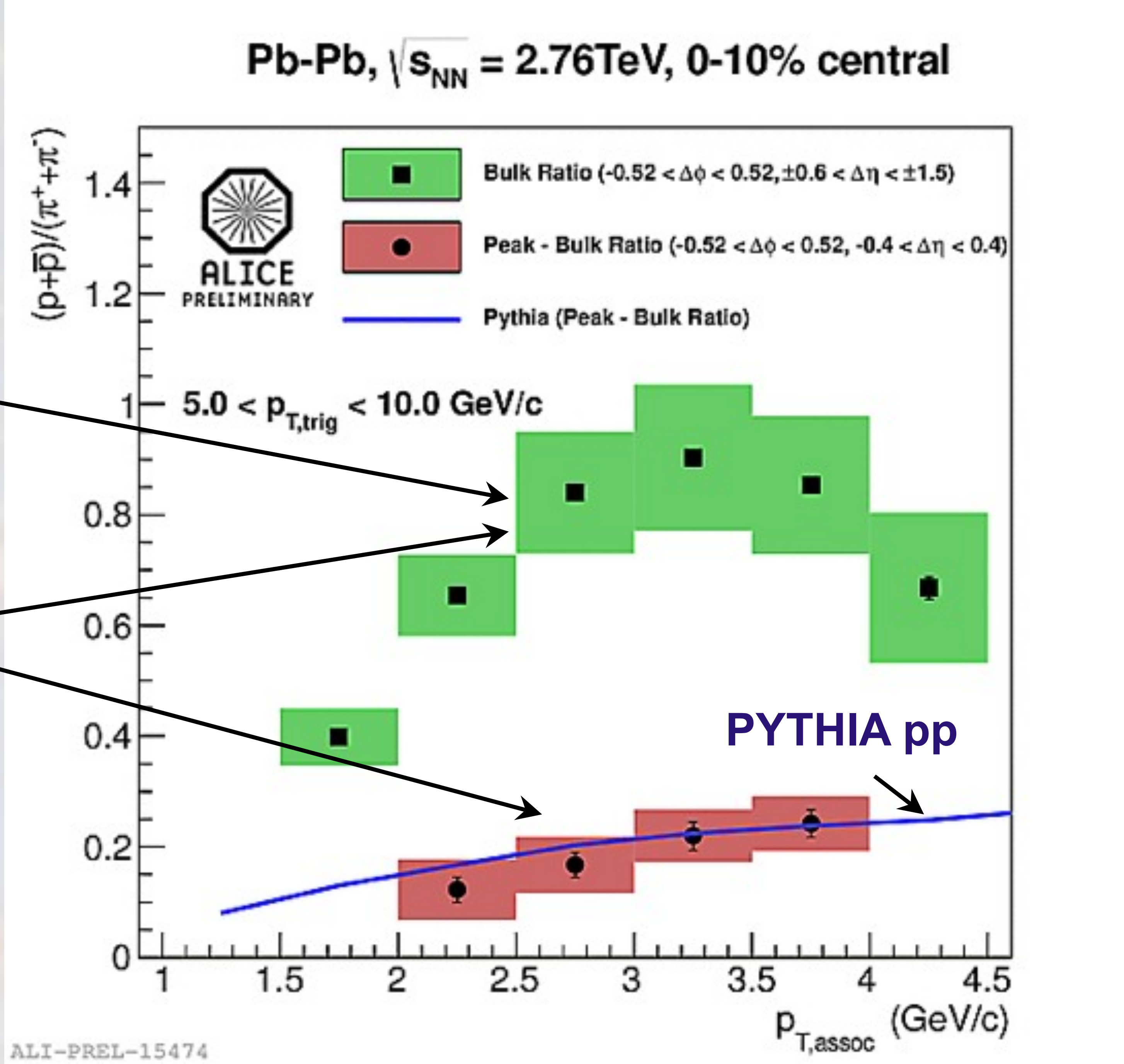


Strong jet suppression observed for jets reconstructed with charged particles
– R_{AA} (jet) is smaller than inclusive hadron $R_{AA}(h^{\pm})$ at similar parton p_T
– data are reasonably well described by JEWEL model

K.Zapp, I.Krauss, U.Wiedemann, arXiv:1111.6838

PID in jet structures





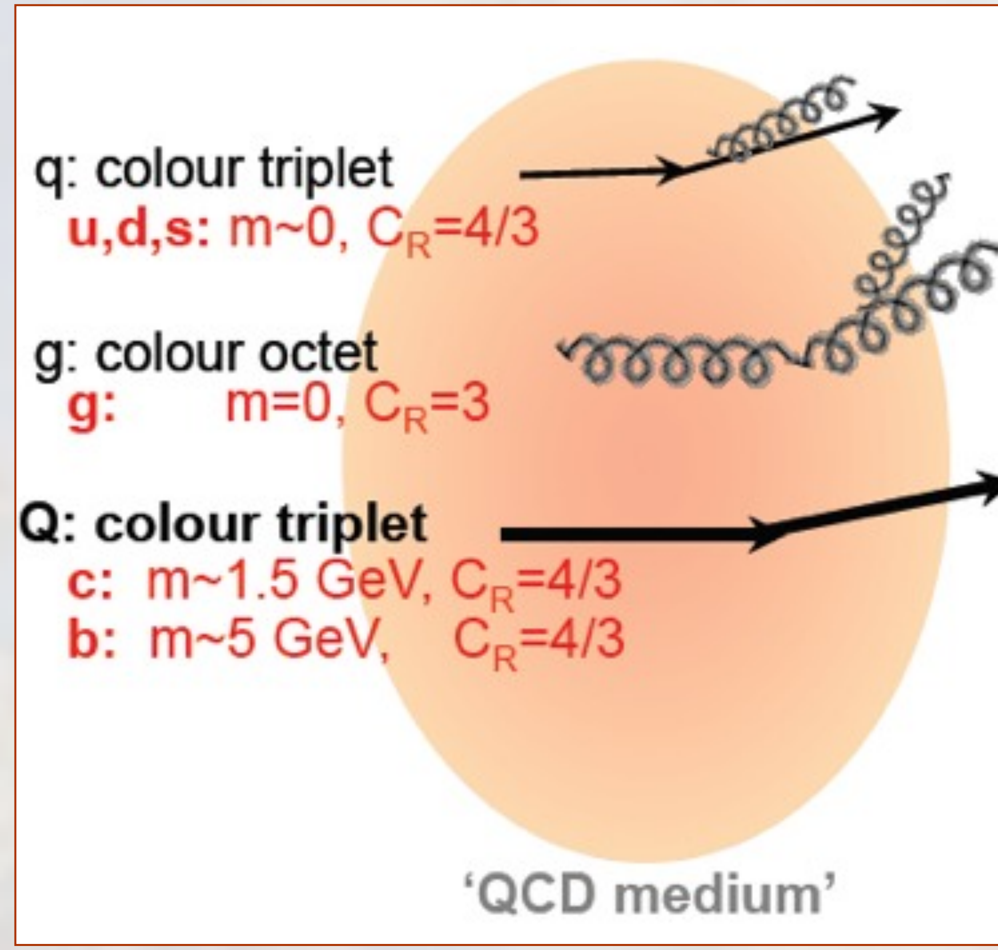
Near-side peak (after bulk subtraction): p/π ratio compatible with that of pp (PYTHIA)
Bulk region: p/π ratio strongly enhanced – compatible with overall baryon enhancement
Jet particle ratios not modified in medium? Could this still be surface bias?

Heavy flavor and quarkonia

Heavy Flavor

Heavy quarks produced in the early stages of the collisions → effective probe of the high-density medium created in heavy-ion collisions

In-medium energy loss expected to be smaller for heavy quarks than for light quarks and gluons due to color charge and dead cone effect [1]



Parton Energy Loss by

- medium-induced gluon radiation
- collisions with medium gluons

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

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

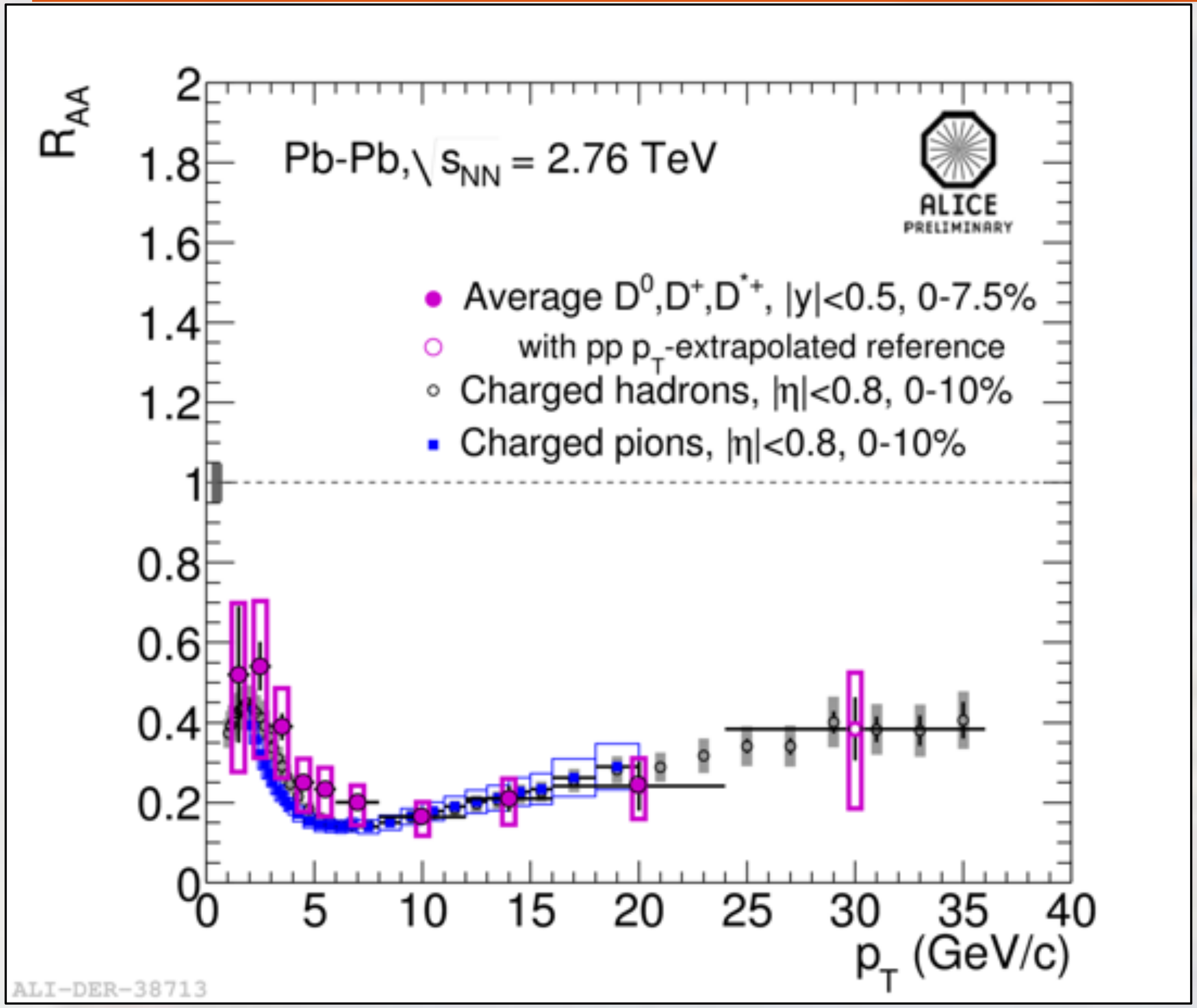
→ $R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B}$

Heavy Flavor detection in ALICE:

- Midrapidity:
  - D-mesons hadronic decay
  - electrons from semileptonic decays
- Forward rapidity
  - muons from semileptonic decays

[1] Dokshitzer and Kharzeev, PLB 519 (2001) 199. Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003. Djordjevic, Gyulassy, Horowitz, Wicks, NPA 783 (2007) 493.

D meson R_{AA}



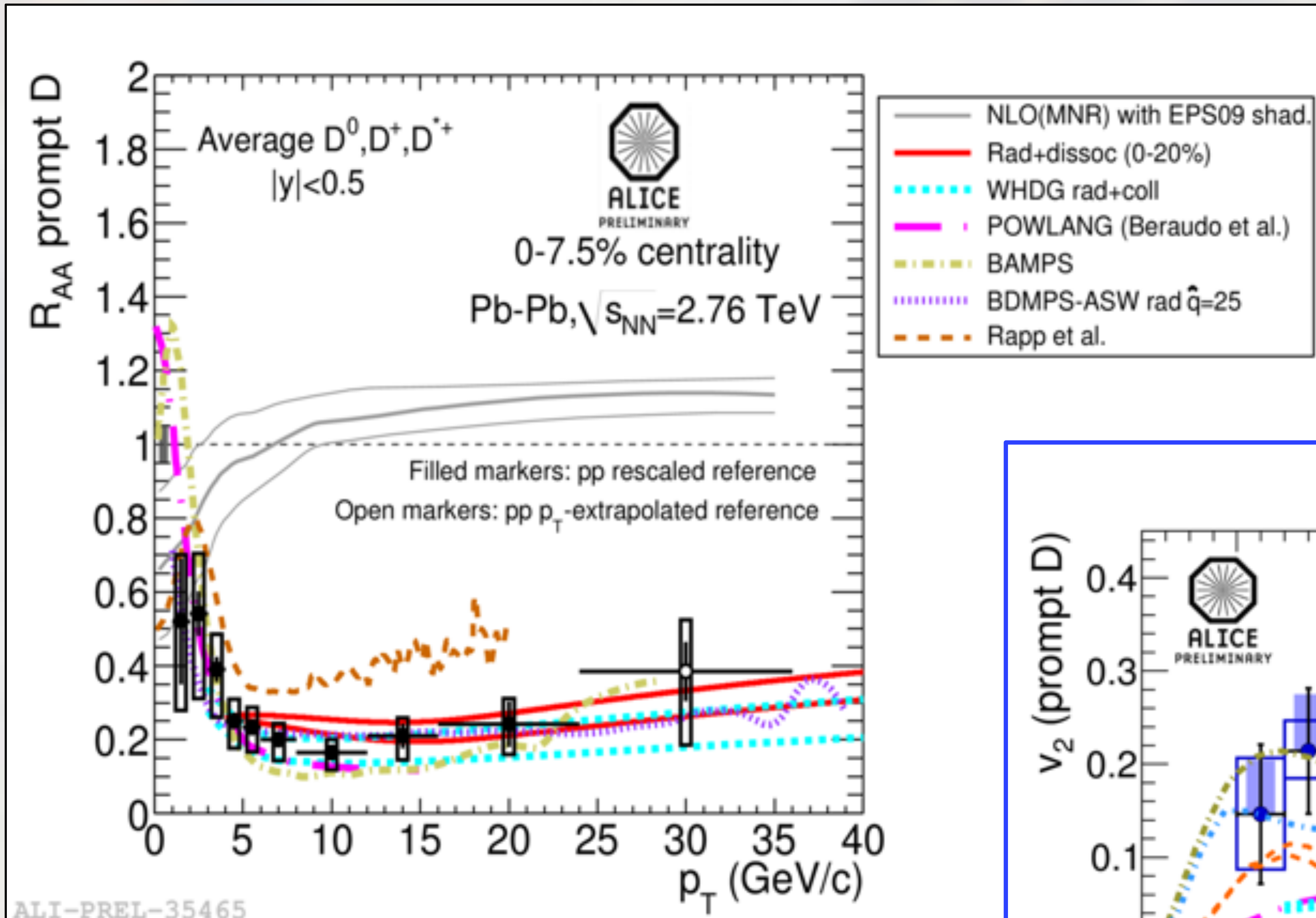
Average D-meson R_{AA}:

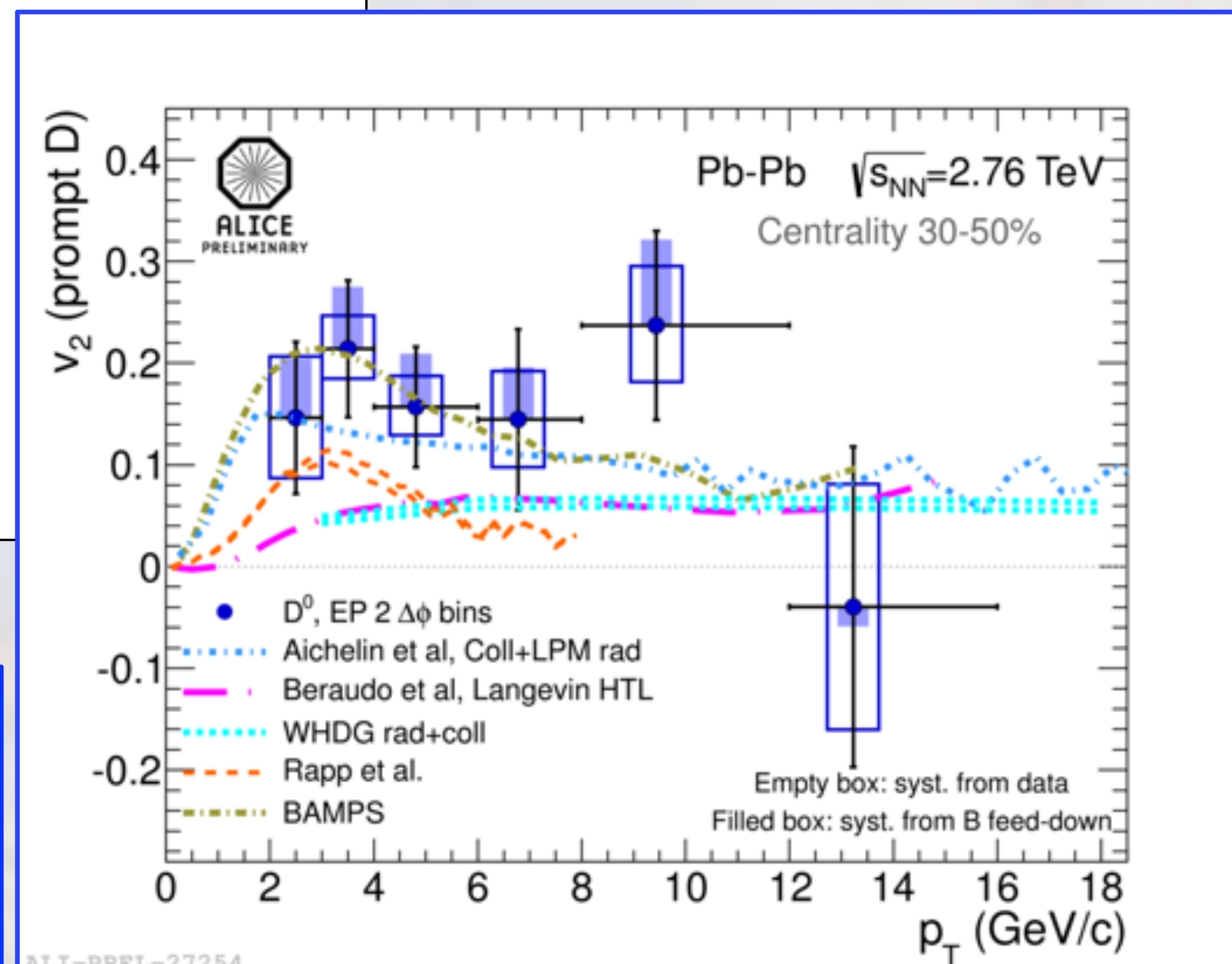
– p_T < 8 GeV/c hint of slightly less suppression than for light hadrons

– p_T > 8 GeV/c all are very similar, no indication of color charge depend.

D^0, D^+ and D^{*+} R_{AA} compatible within uncertainties in the measured range 1 -- 36 GeV/c.

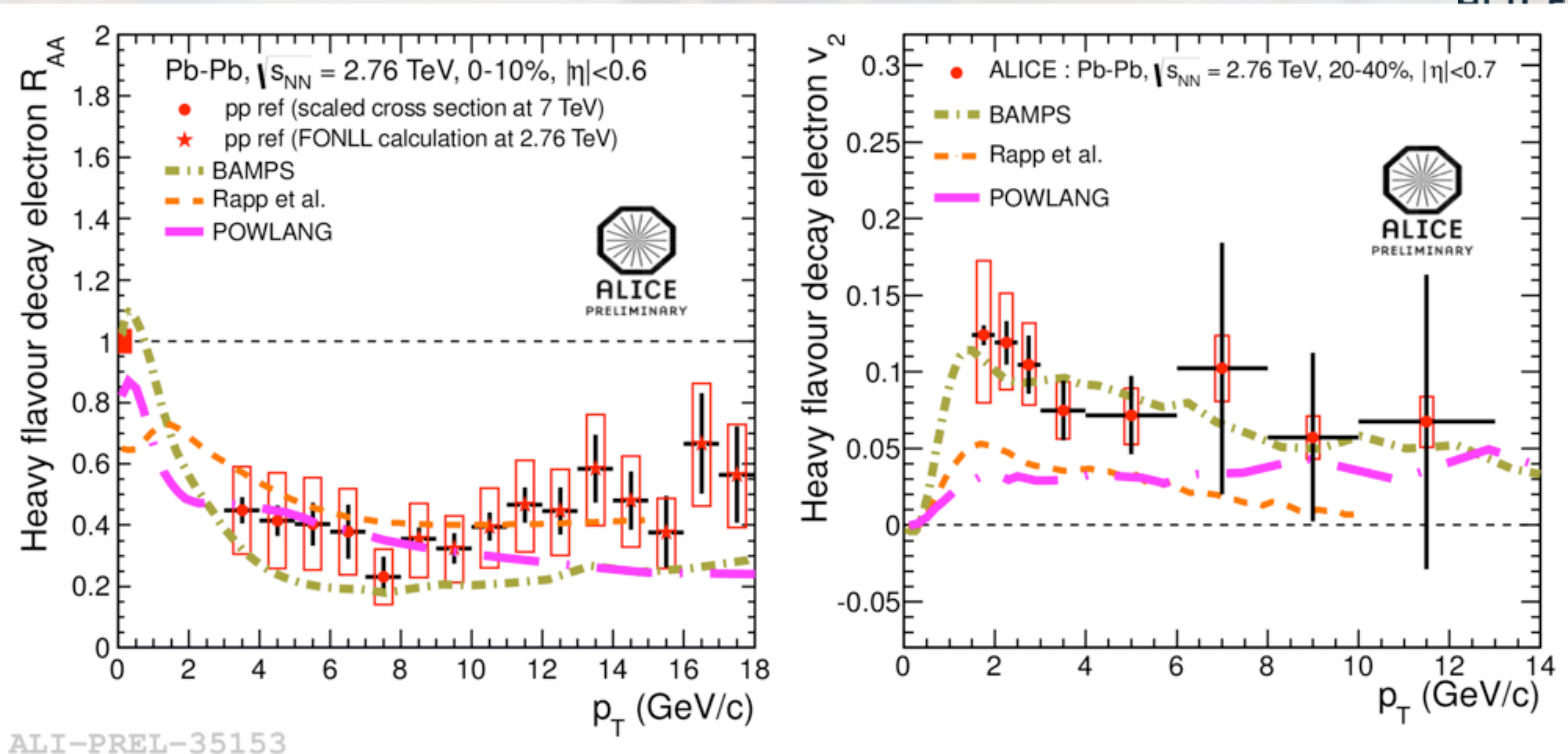
D meson elliptic flow





- D meson v_2 observed comparable to that of light hadrons
- Simultaneous description of R_{AA} and v_2: c-quark transport coefficient in medium

Heavy-flavor e(μ) R_{AA} & v_2

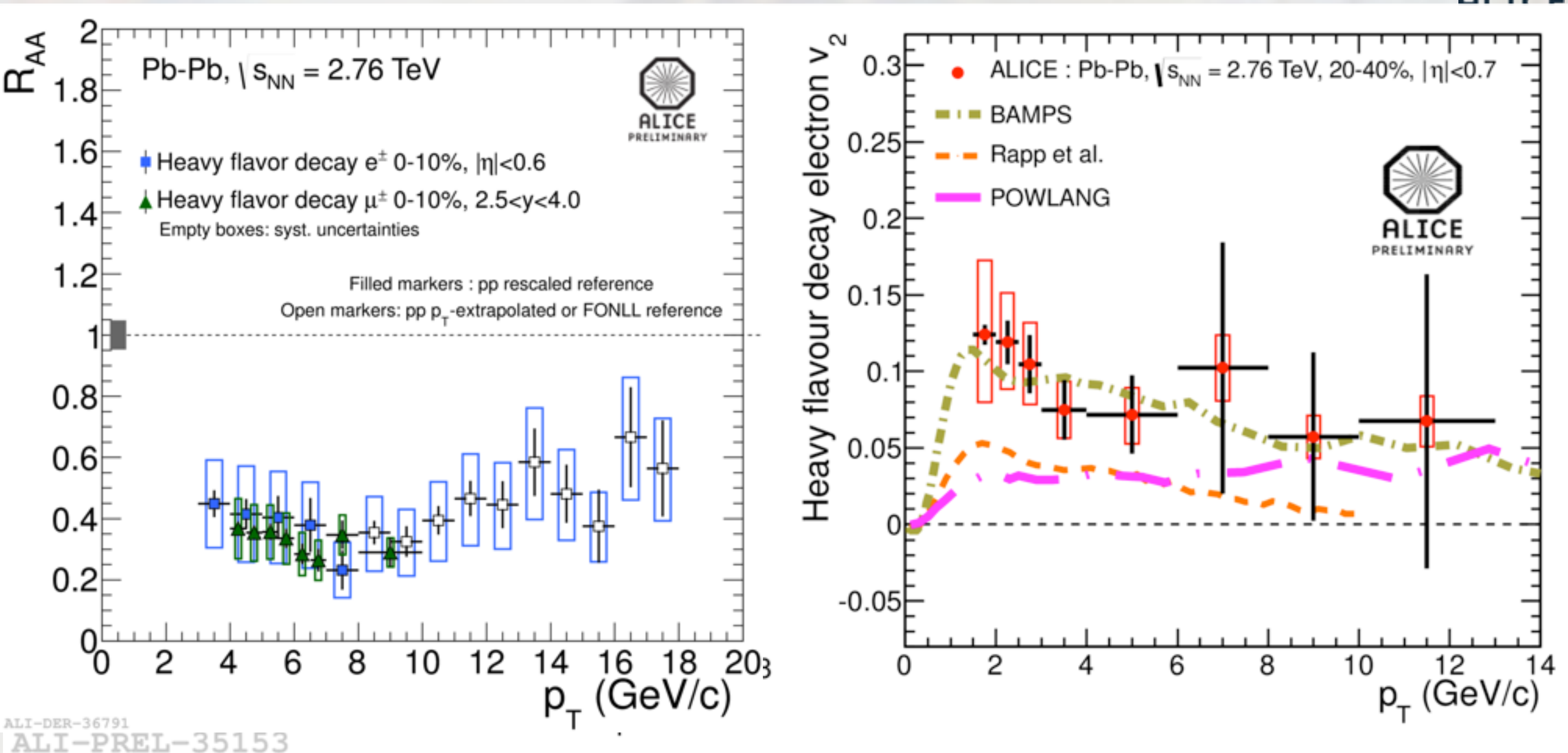


- HF electrons:
  - Strong suppression up to p_T 18 GeV/*c* in 0–10% centrality
  - Non-zero v_2 in 20–40% centrality class

→Ongoing effort to separate beauty contribution…

- HF muons : Suppression in forward region very similar to that of electrons

Heavy-flavor e(μ) R_{AA} & v_2



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→Ongoing effort to separate beauty contribution…

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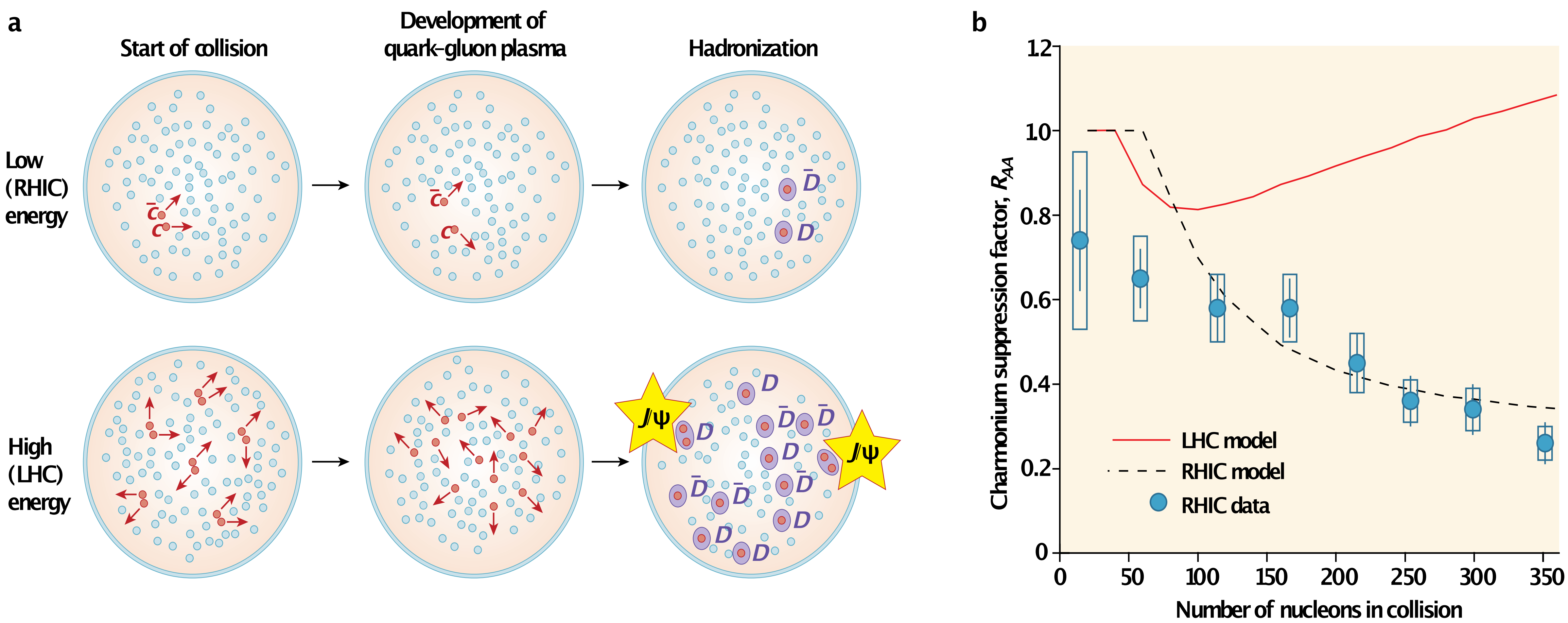
J/ψ suppression

- SPS & RHIC energies: Quarkonia suppression via colour screening
  → probe of deconfinement (Matsui and Satz, PLB 178 (1986) 416)
- LHC energies : Enhancement via (re)generation of quarkonia, due to the large heavy-quark multiplicity (A. Andronic et al.; PLB 571(2003) 36)



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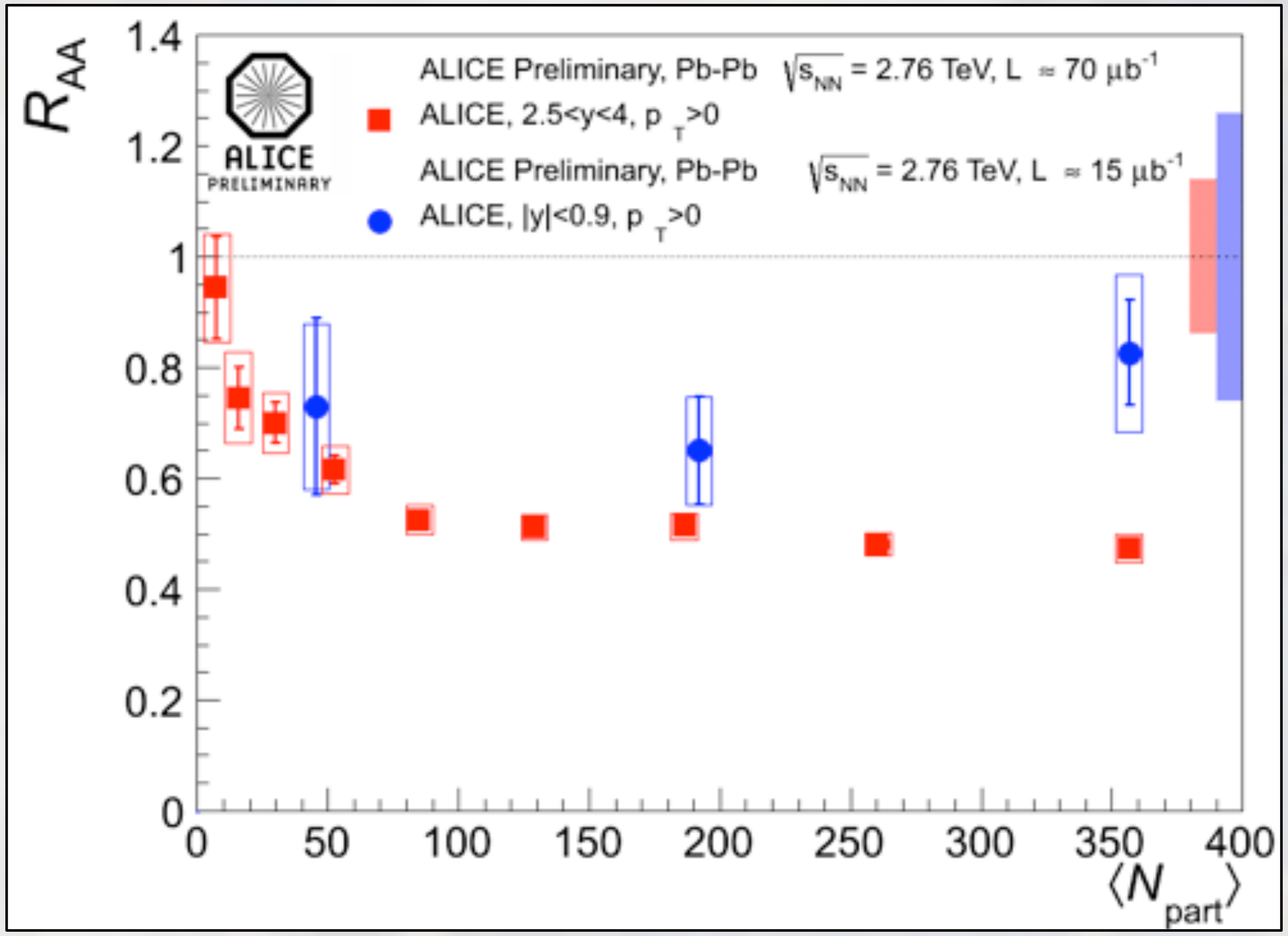
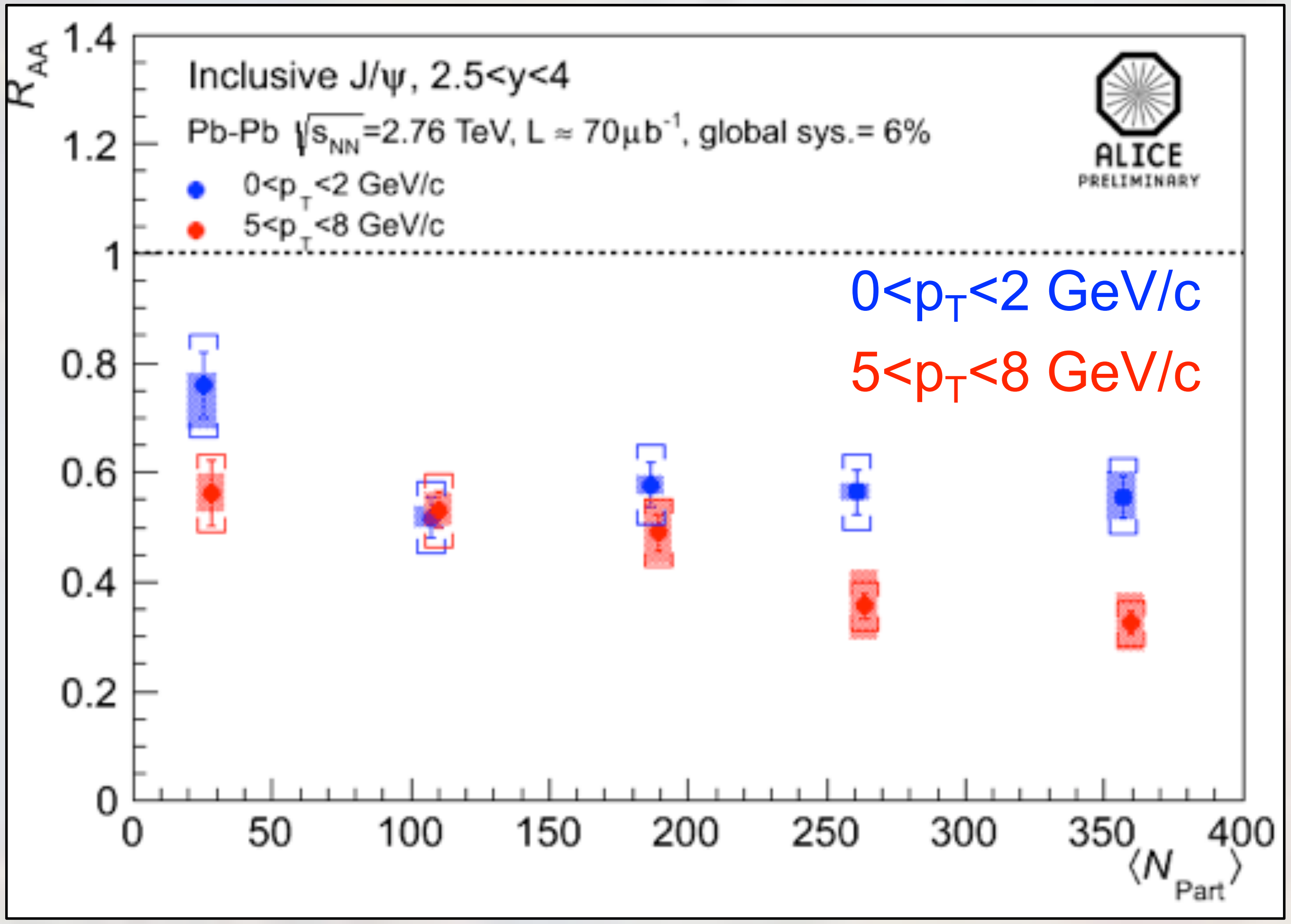
Braun-Munzinger & Stachel, Nature Vol. 448 (2007)

J/ψ R_{AA} centrality dependence

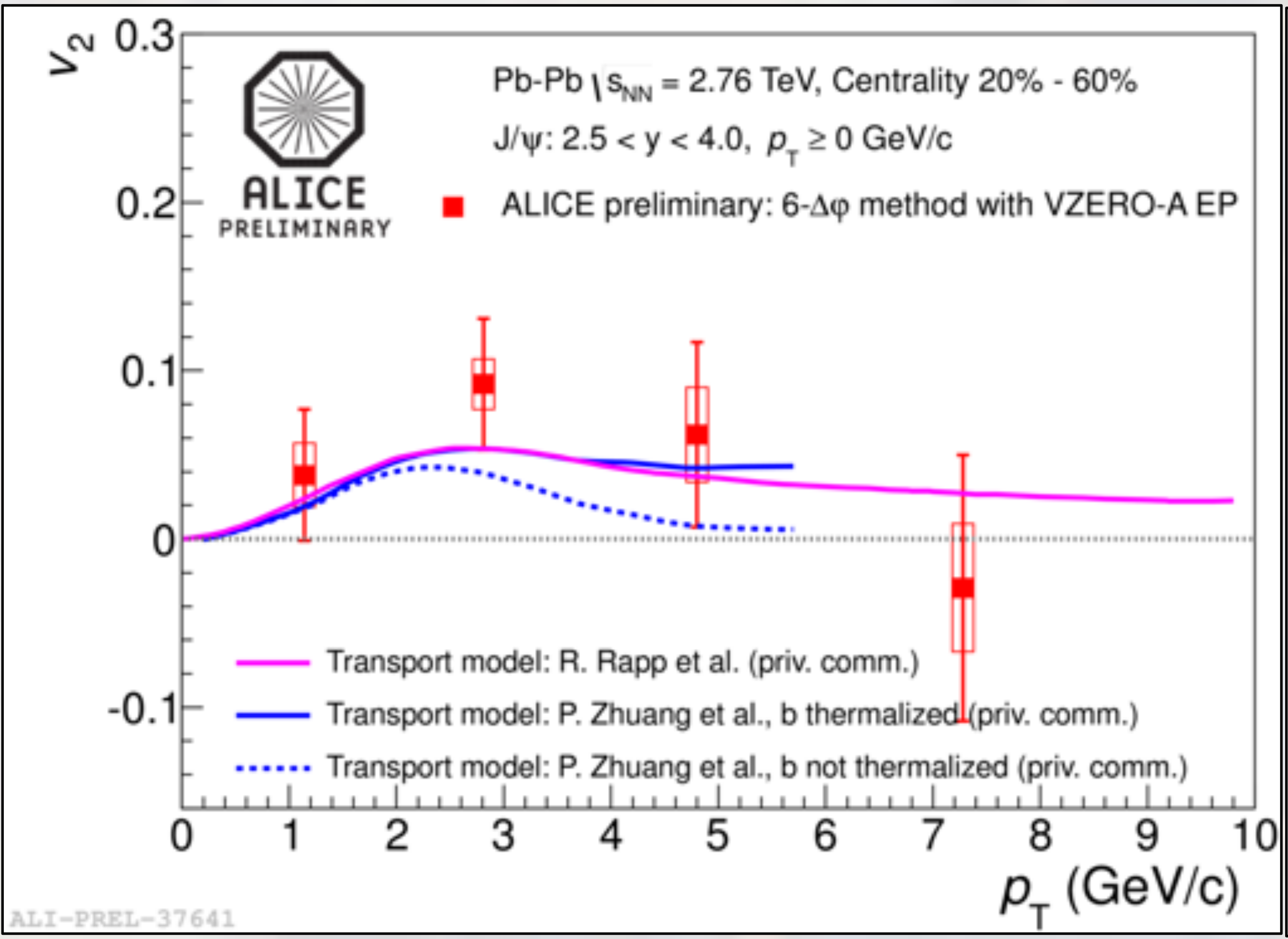


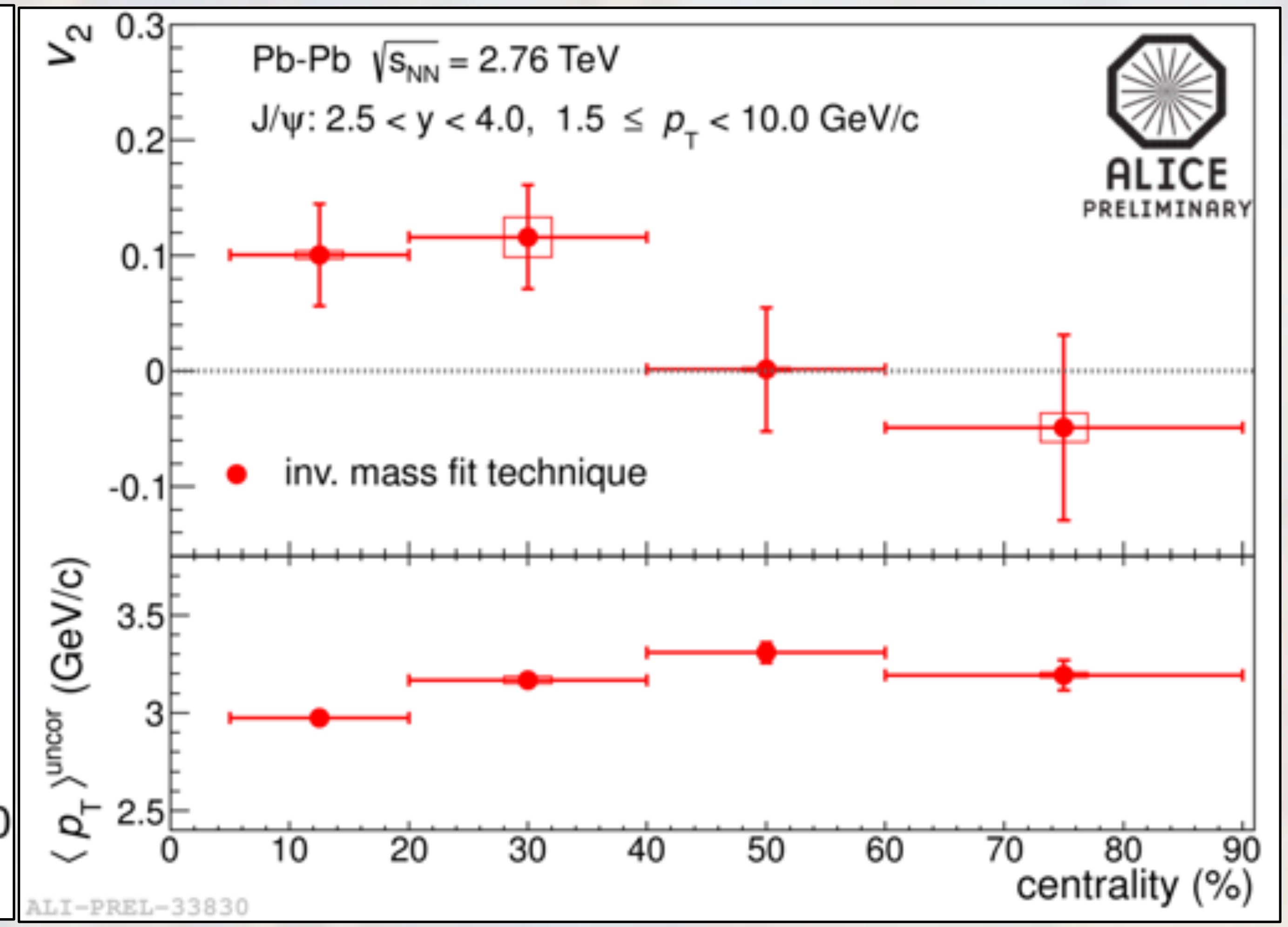


J/ψ suppression measurements both in central and forward regions
– from N_{part} > 100 suppression independent of centrality
– in central collisions, less suppression than at RHIC
– at low p_T (< 2 GeV/c) less suppression than at high p_T, especially in more central collisions

Indication of J/ψ regeneration at low p_T ?

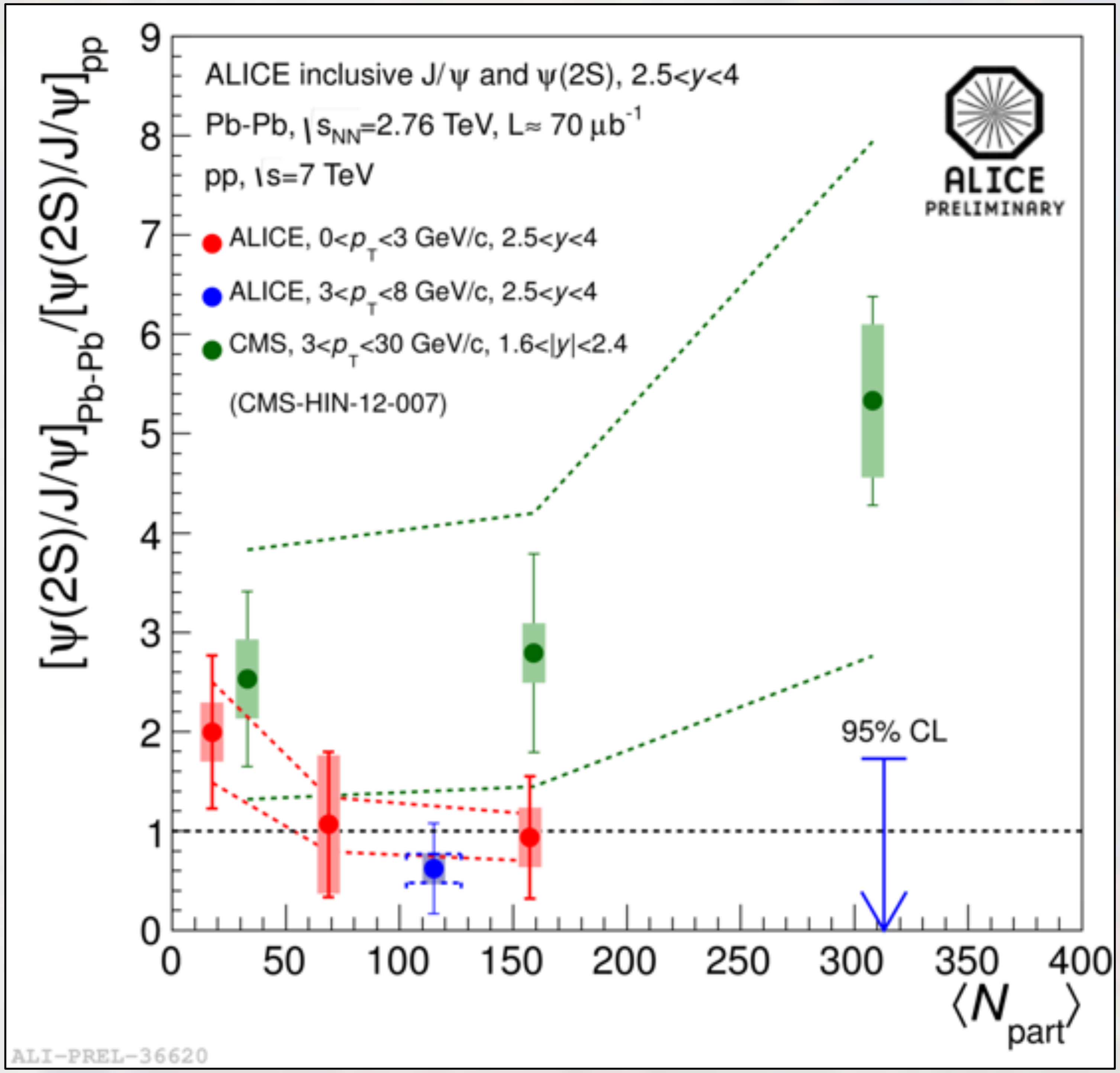
J/ψ elliptic flow





J/ψ produced by recombination of thermalized c-quarks should have non-zero elliptic flow
– measurements give a hint for non-zero v_2
– qualitative agreement with transport models, including regeneration
– complementary to indications obtained from J/ψ R_{AA} studies

ψ' to J/ψ double ratio

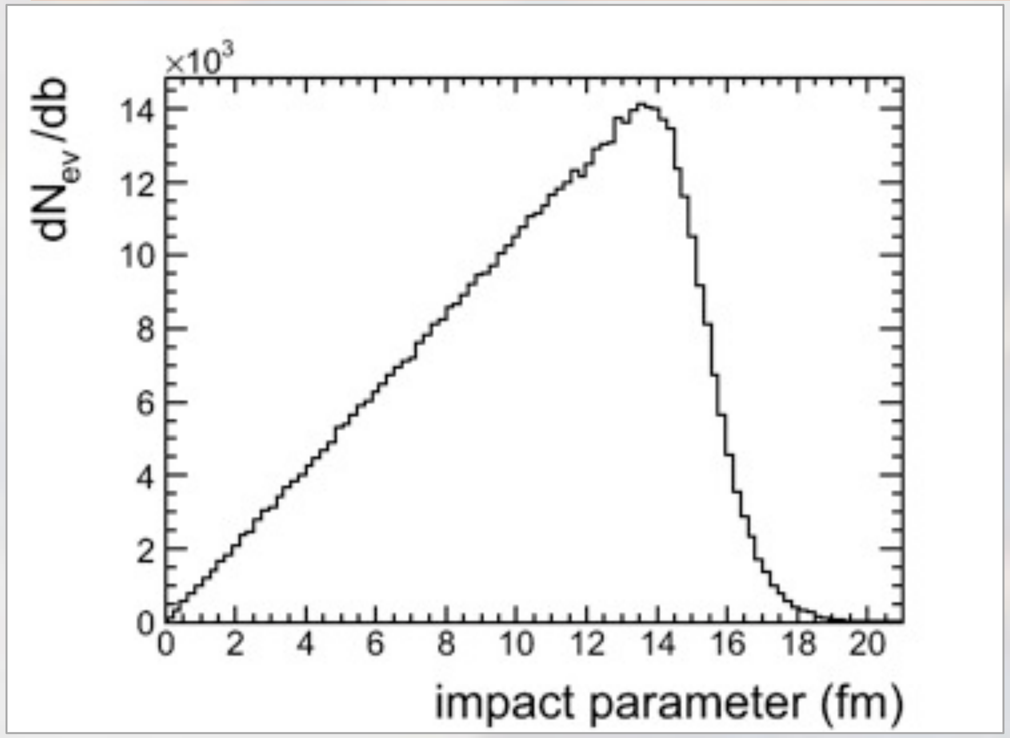


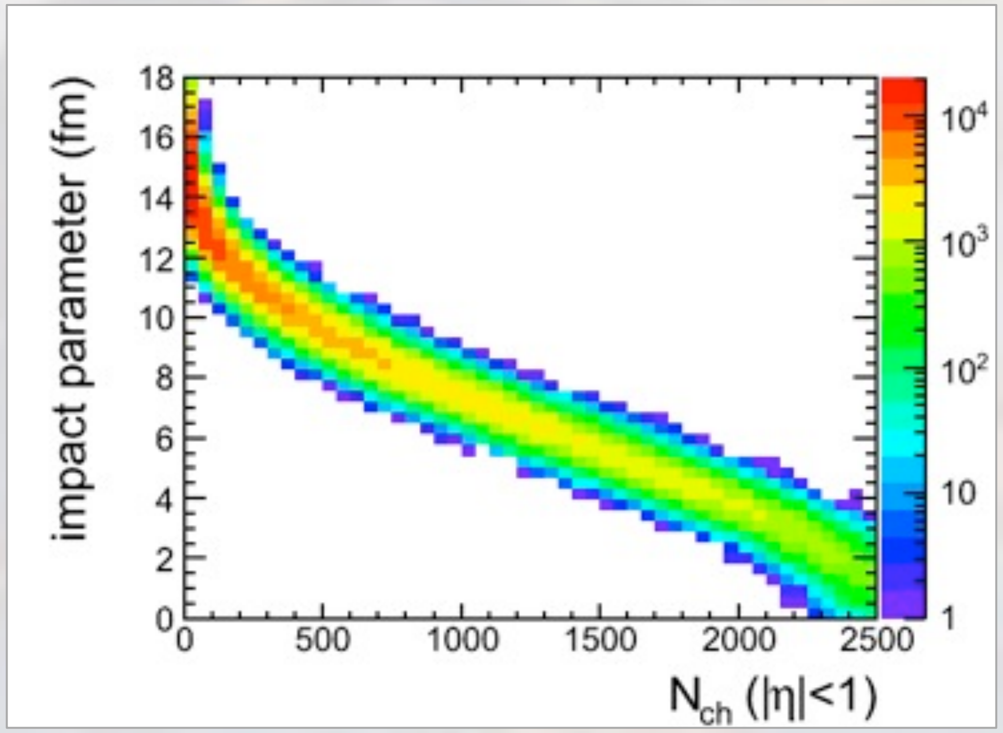
No firm conclusion on ψ' enhancement or suppression with centrality within current *stat.* and *syst.* uncertainties

Large ψ' enhancement with respect to J/ψ reported by CMS at p_T above 3 GeV/*c* not confirmed

New methods and ideas: Event Shape Engineering

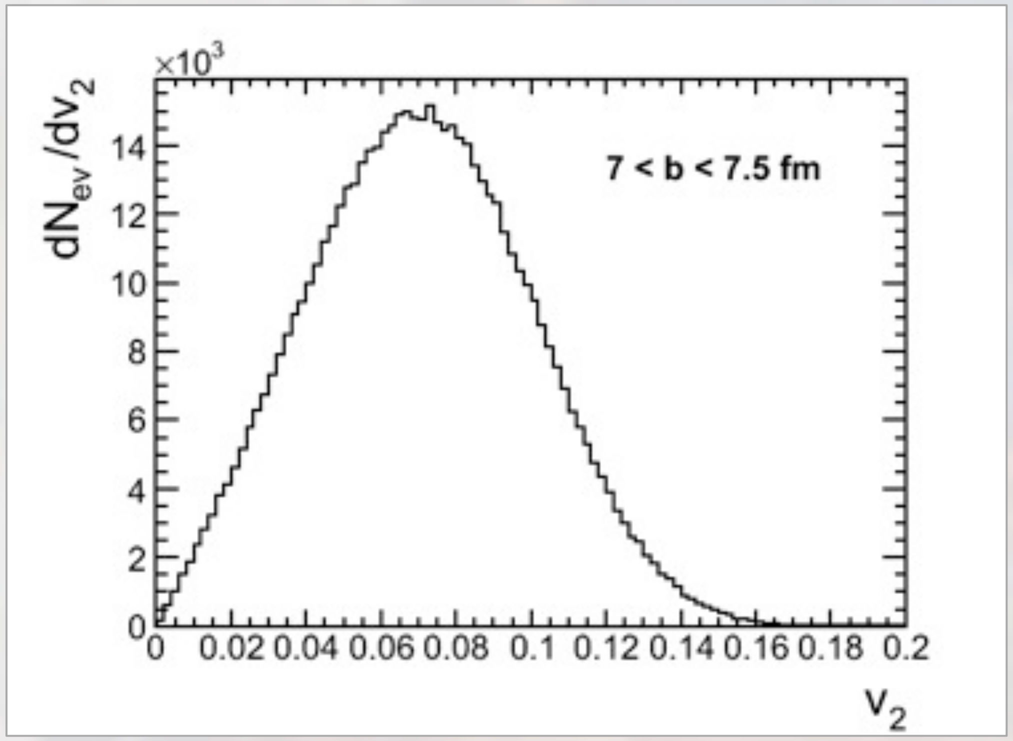
ESE: → Events(centrality,shape)





MC Glauber,with parameters tuned to LHC multiplicity and flow

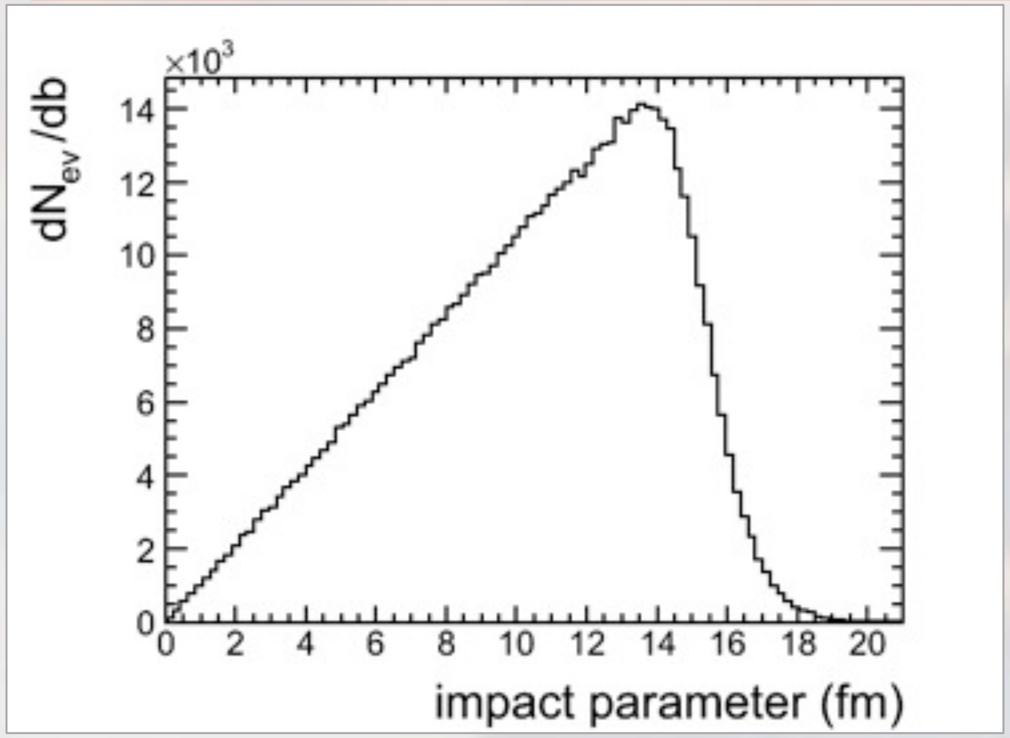
We can select centrality based on multiplicity

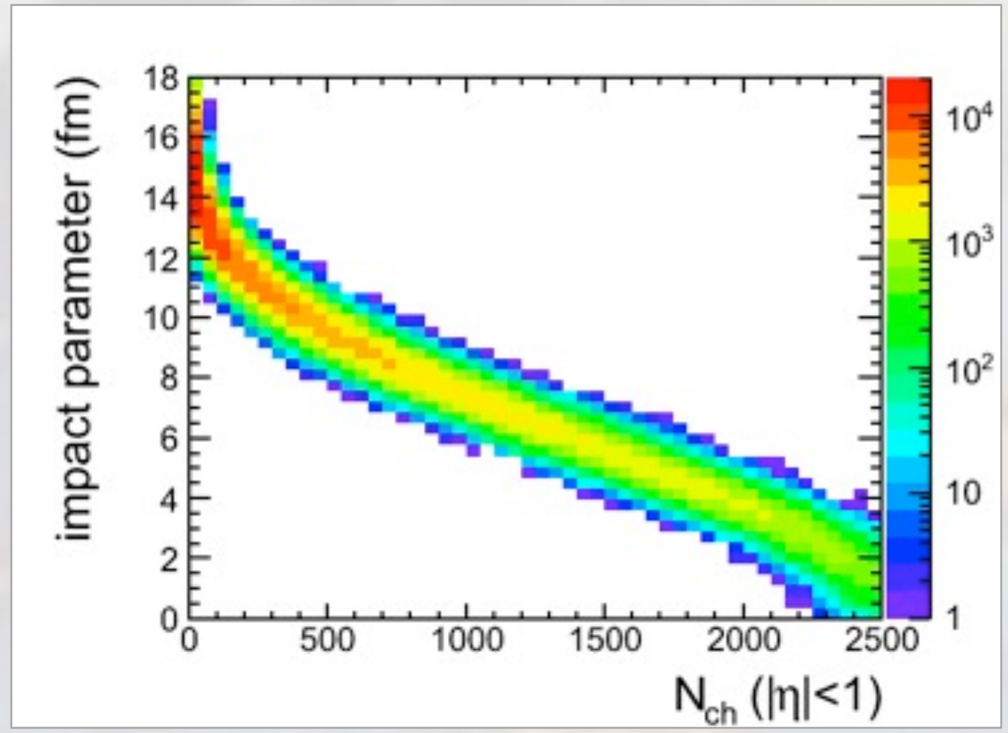


For e-by-e flow fluctuations, see poster by A. Timmins

For a fixed centrality, flow fluctuates. Can we select events with given v_n?

ESE: → Events(centrality,shape)





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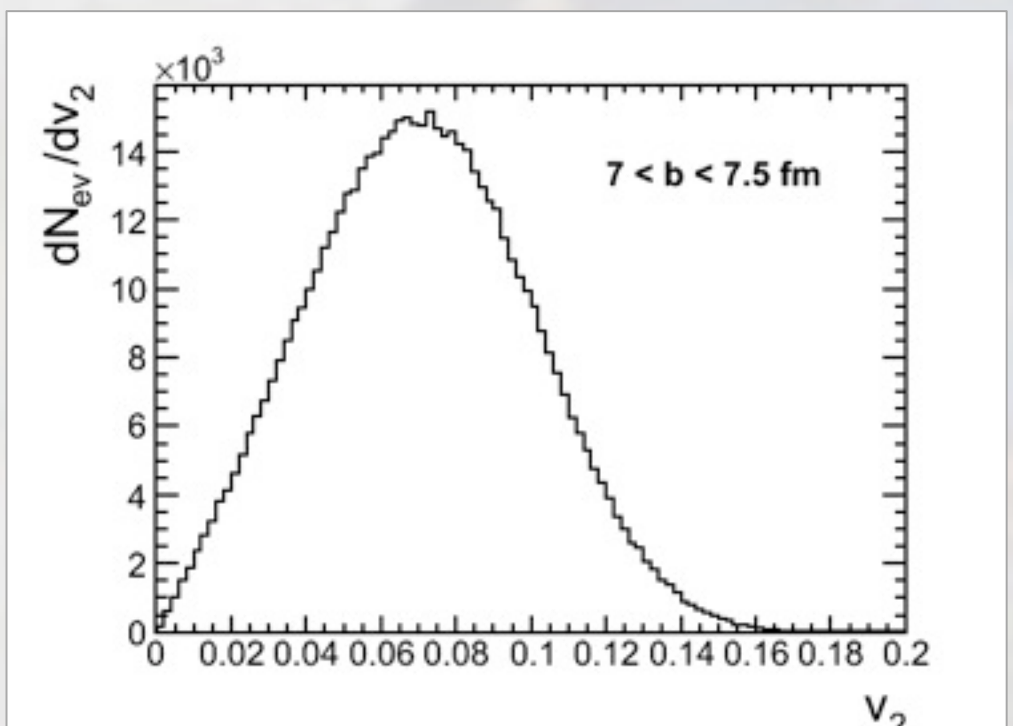
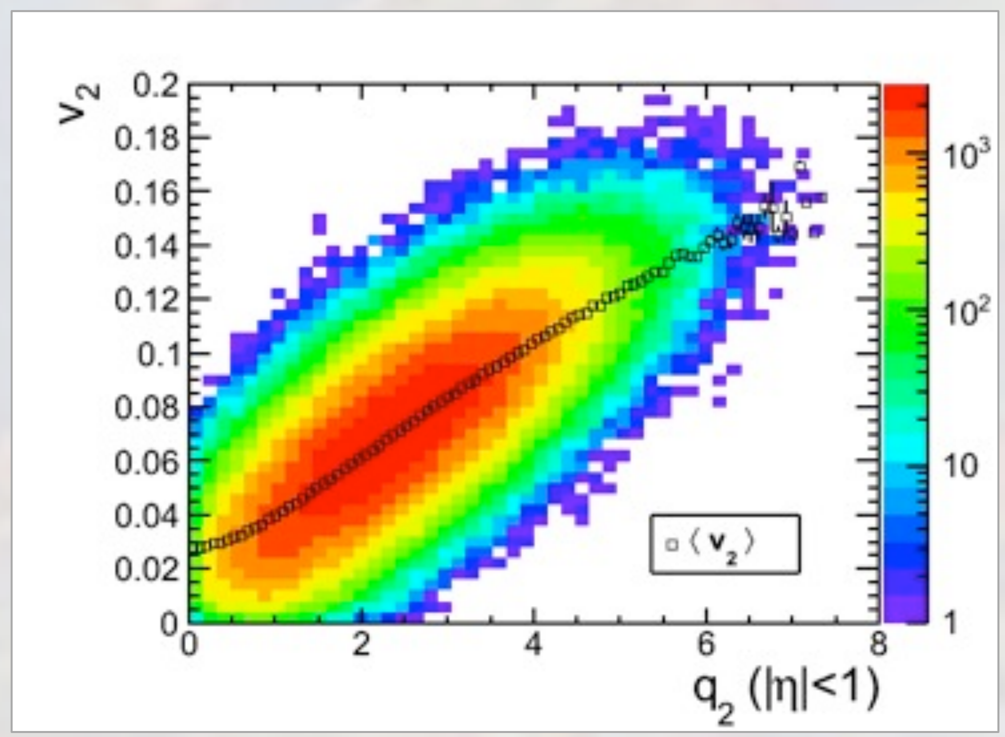




$$Q_{n,X} = \sum_{i=1}^{M} \cos(n\phi_i)$$

$$Q_{n,Y} = \sum_{i=1}^{M} \sin(n\phi_i)$$

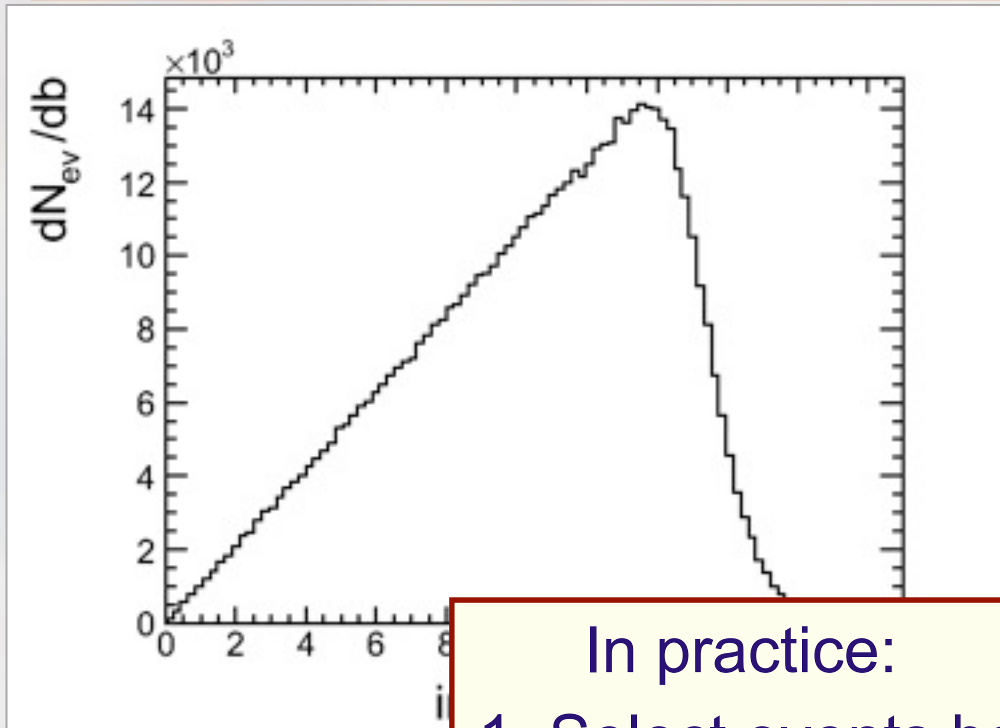
$$q_n = Q_n/\sqrt{M}$$

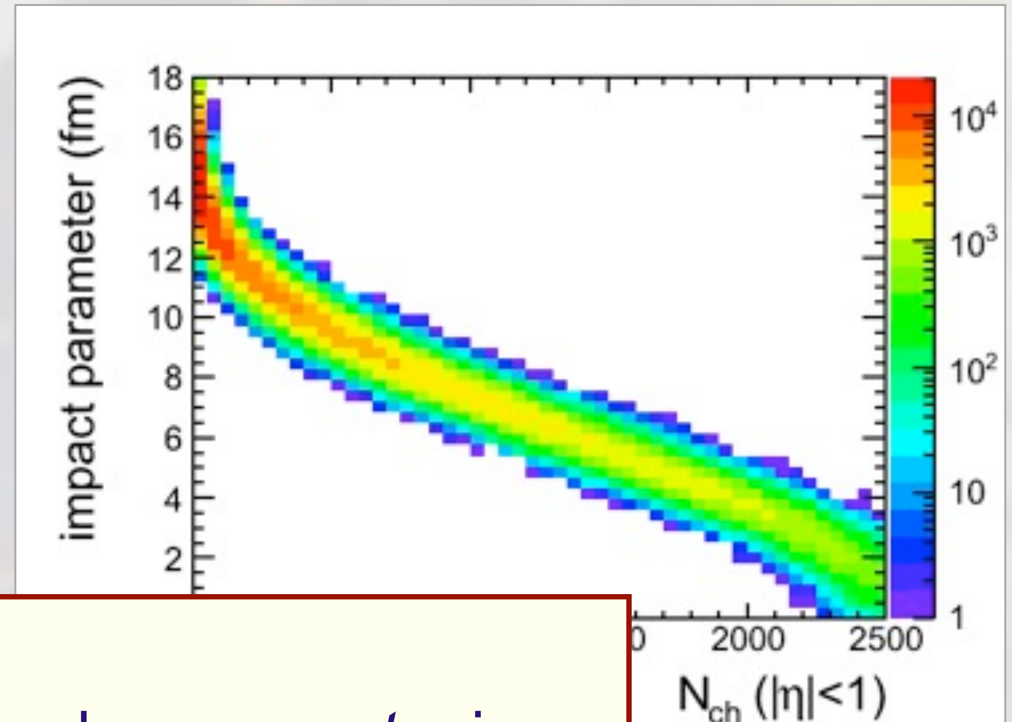
For a fixed centrality, flow fluctuates.
Can we select events with given v_n?

Yes, e.g. based on the length of flow vector.

Voloshin, PRL **105** 172301 (2010)

ESE: → Events(centrality,shape)



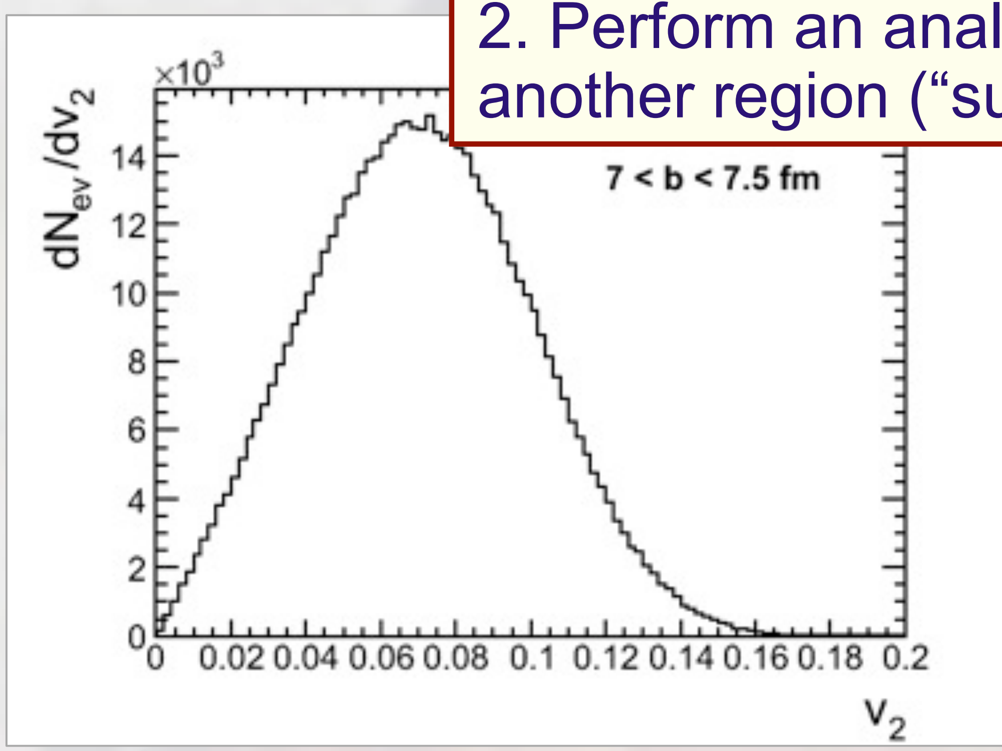


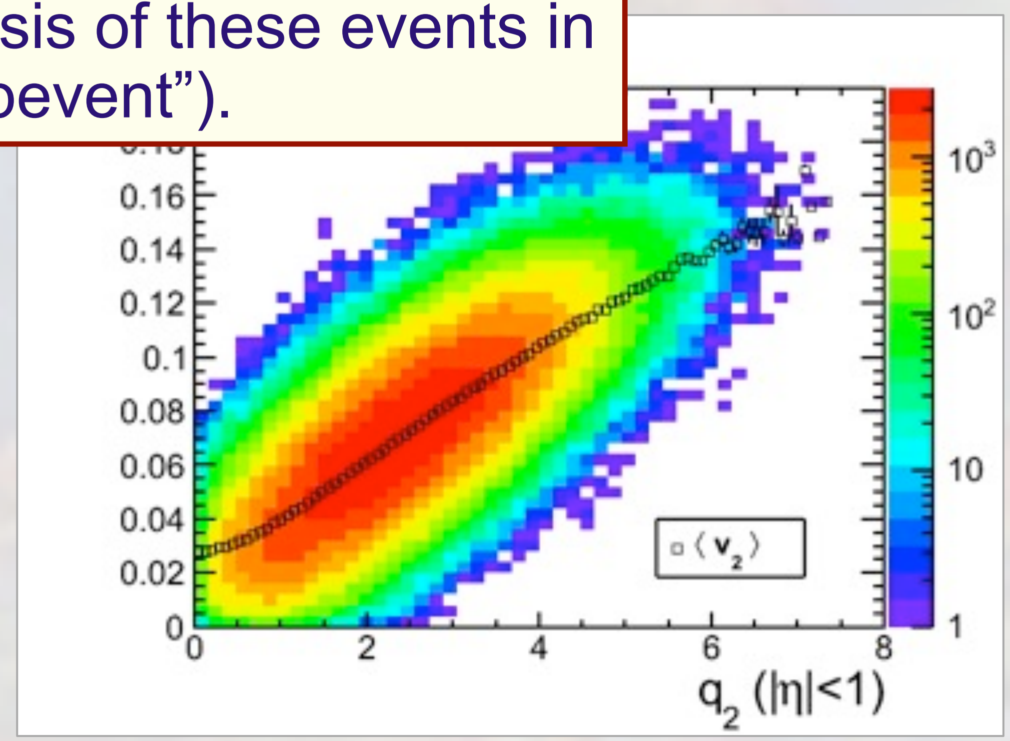
MC Glauber,with parameters tuned to LHC multiplicity and flow

licity

In practice:

1. Select events based on q_n*-vector* in one momentum region ("subevent")
2. Perform an analysis of these events in another region ("subevent").





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For a fixed centrality, flow fluctuates. Can we select events with given v_n?

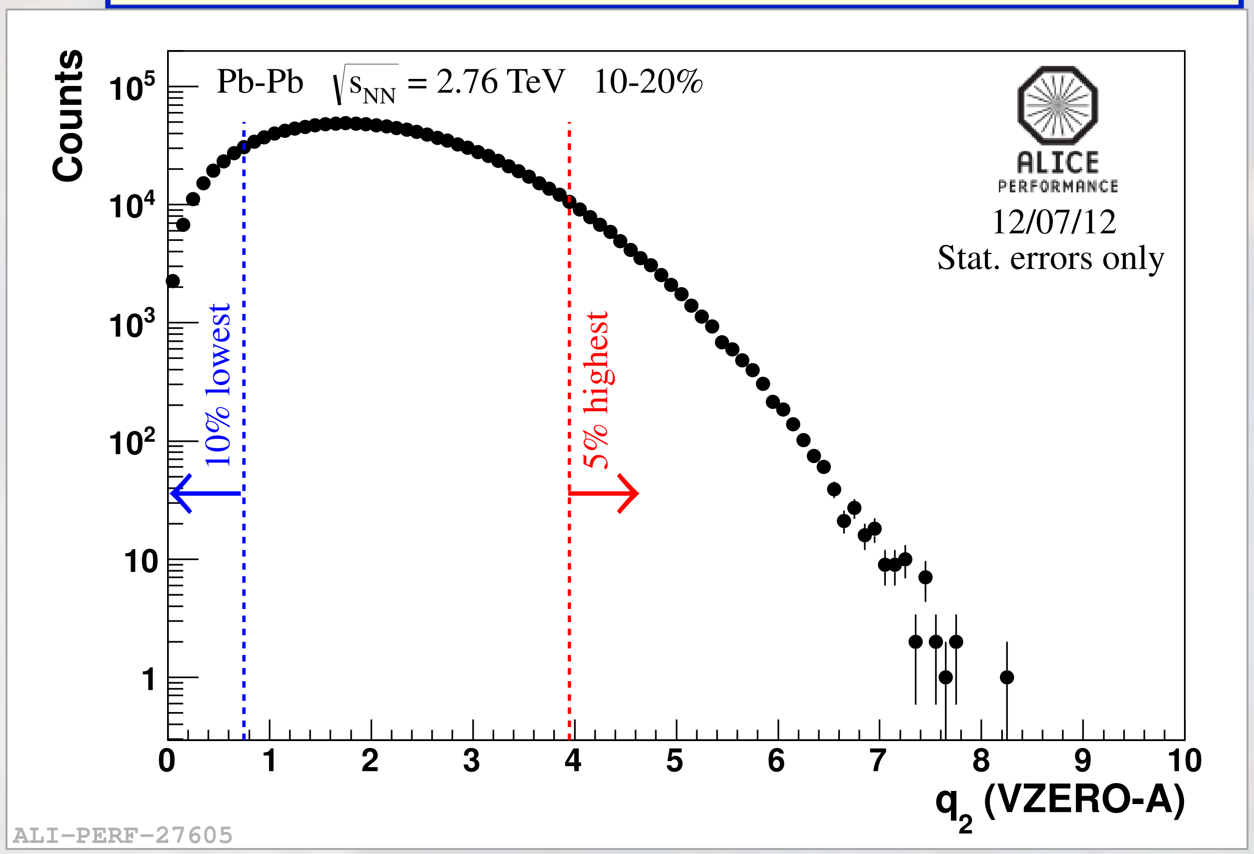
Yes, e.g. based on the length of flow vector.

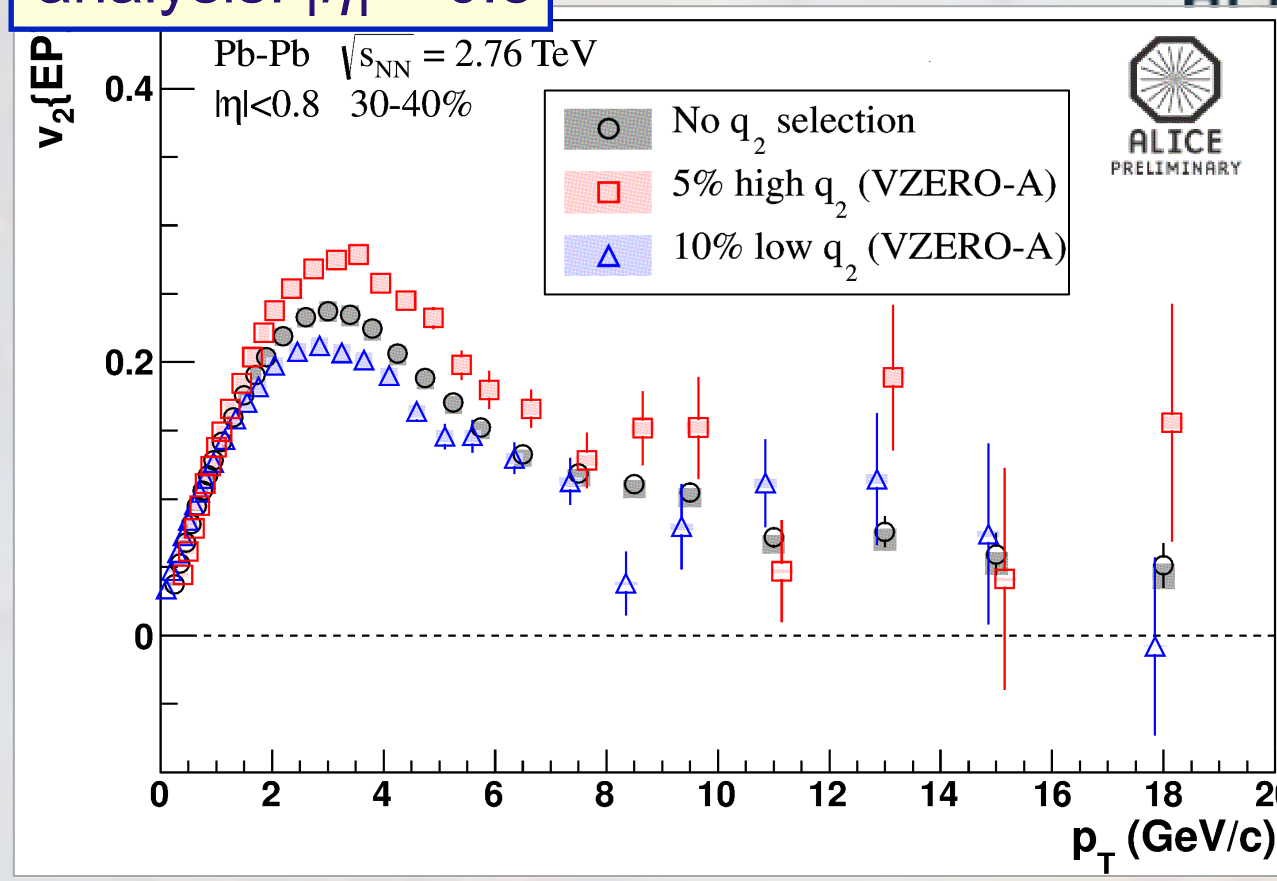
Voloshin, PRL **105** 172301 (2010)

Flow in SE events: p_T dependence

event selection q_2 vector: $2.8 < \eta < 5.1$

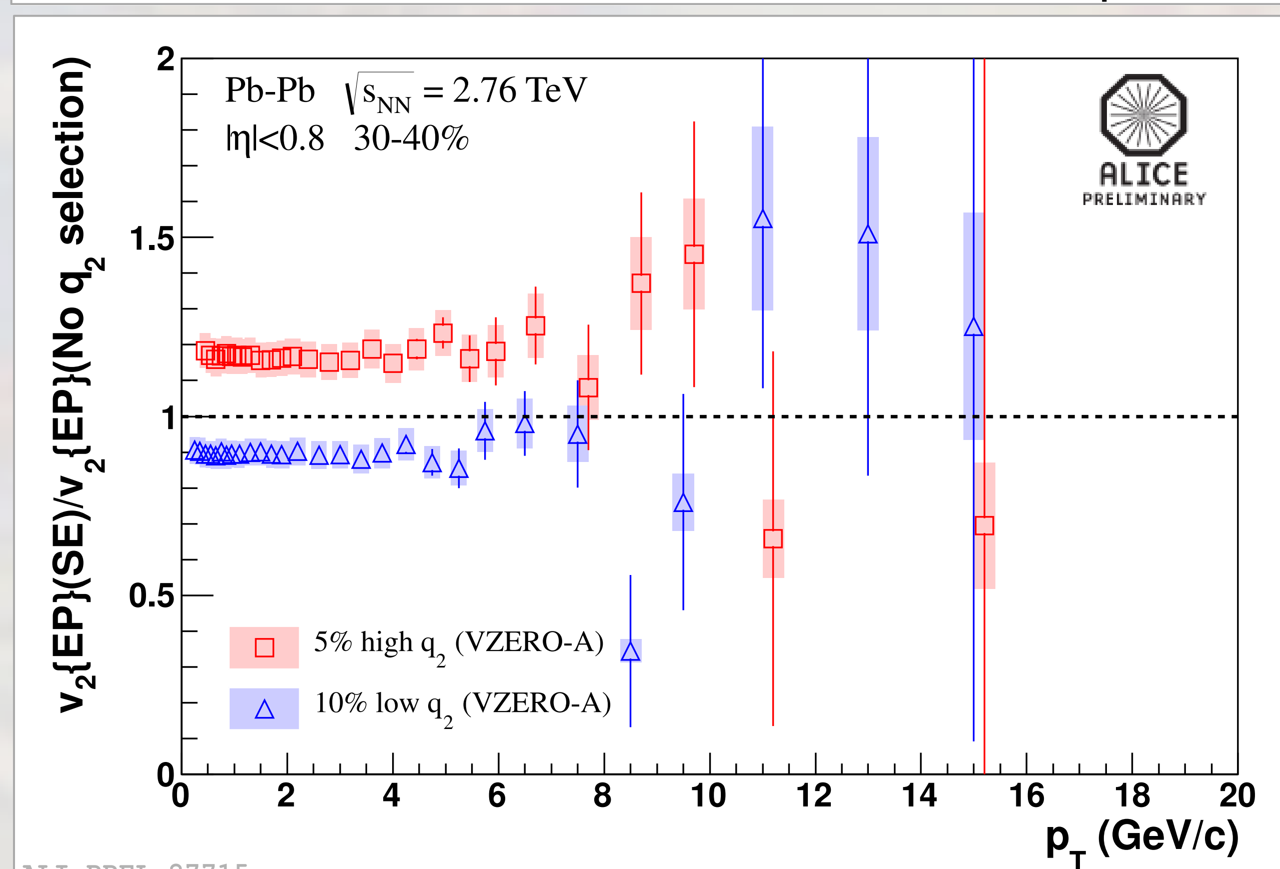
analysis: $|\eta| < 0.8$





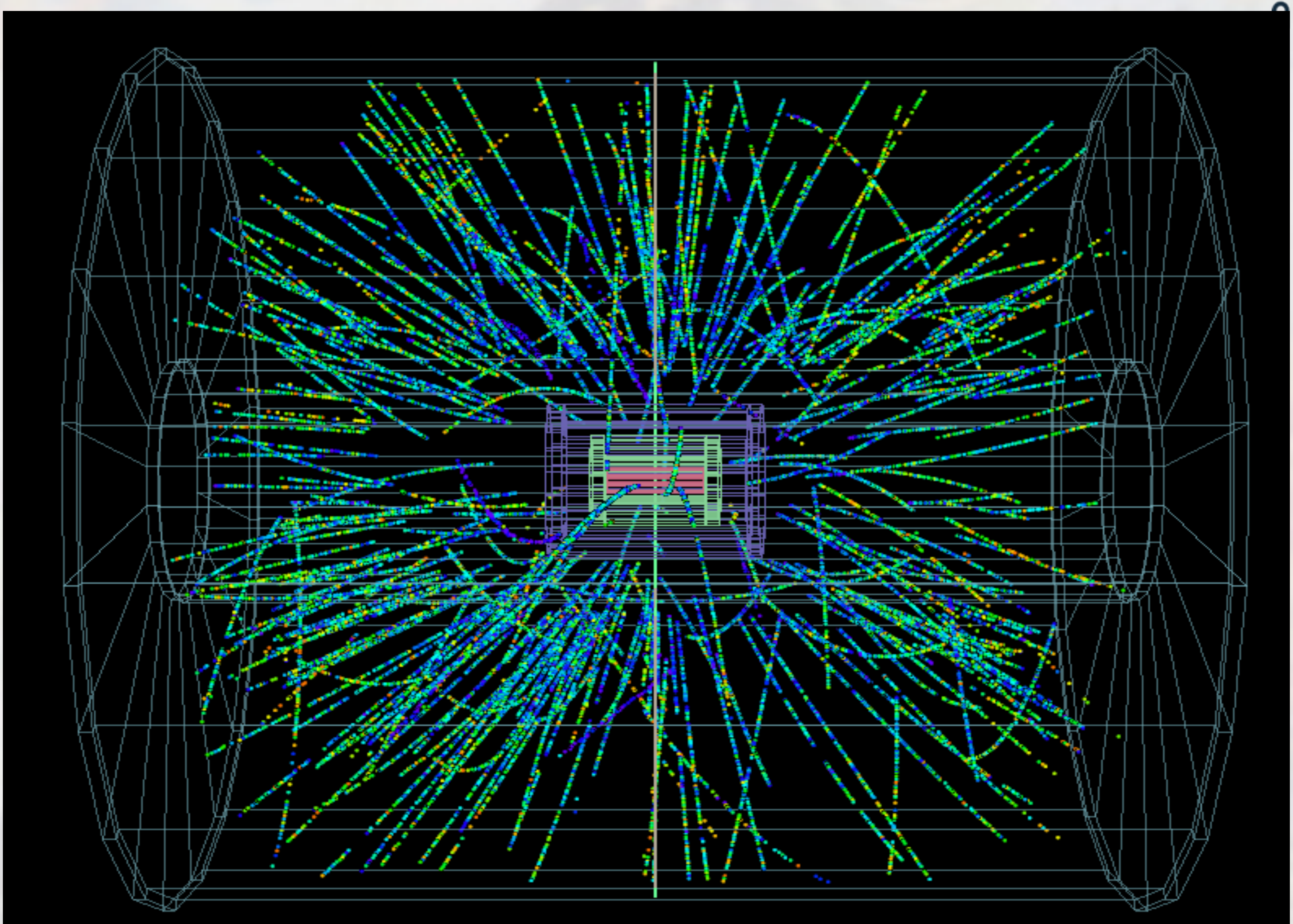
Initial shape fluctuation effect is very similar up to $p_T \sim 6$ GeV/c

Possibility to study events with similar centralities, but different shape (or similar shape, different multiplicities)

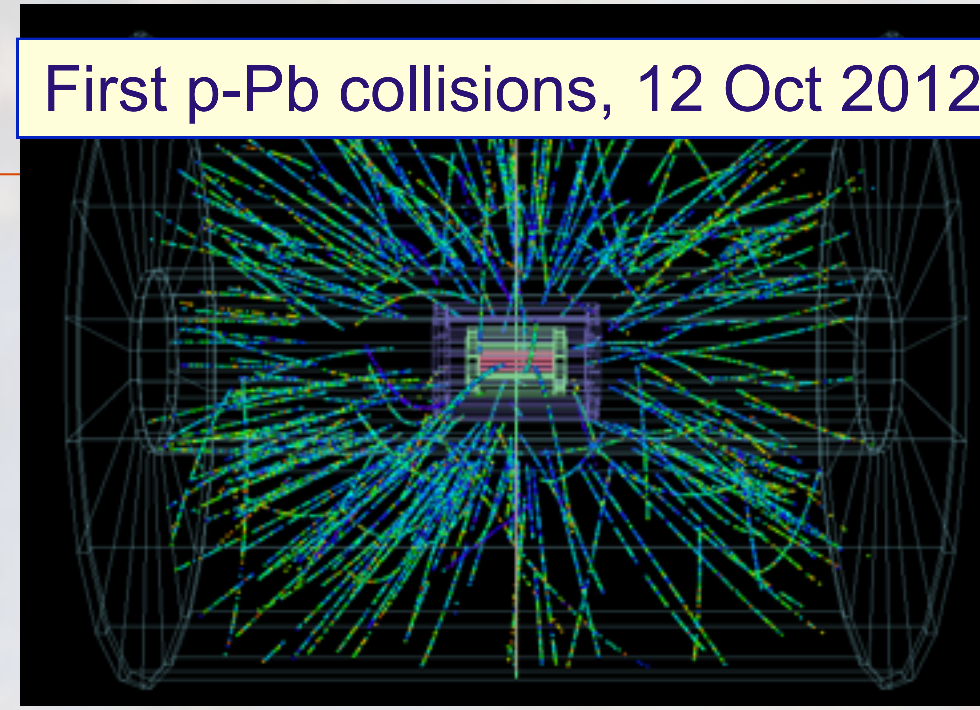


p-Pb collisions

First p-Pb collisions, 12 Oct 2012

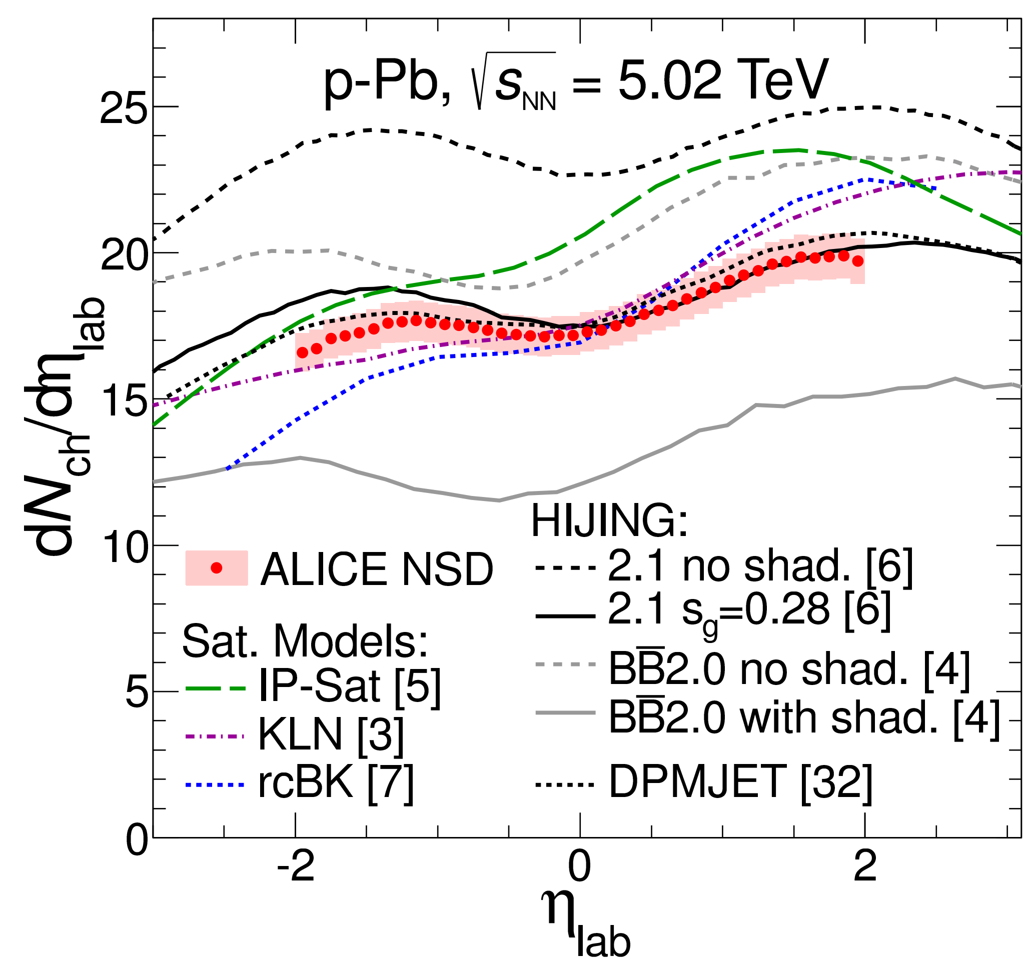


p-Pb collisions



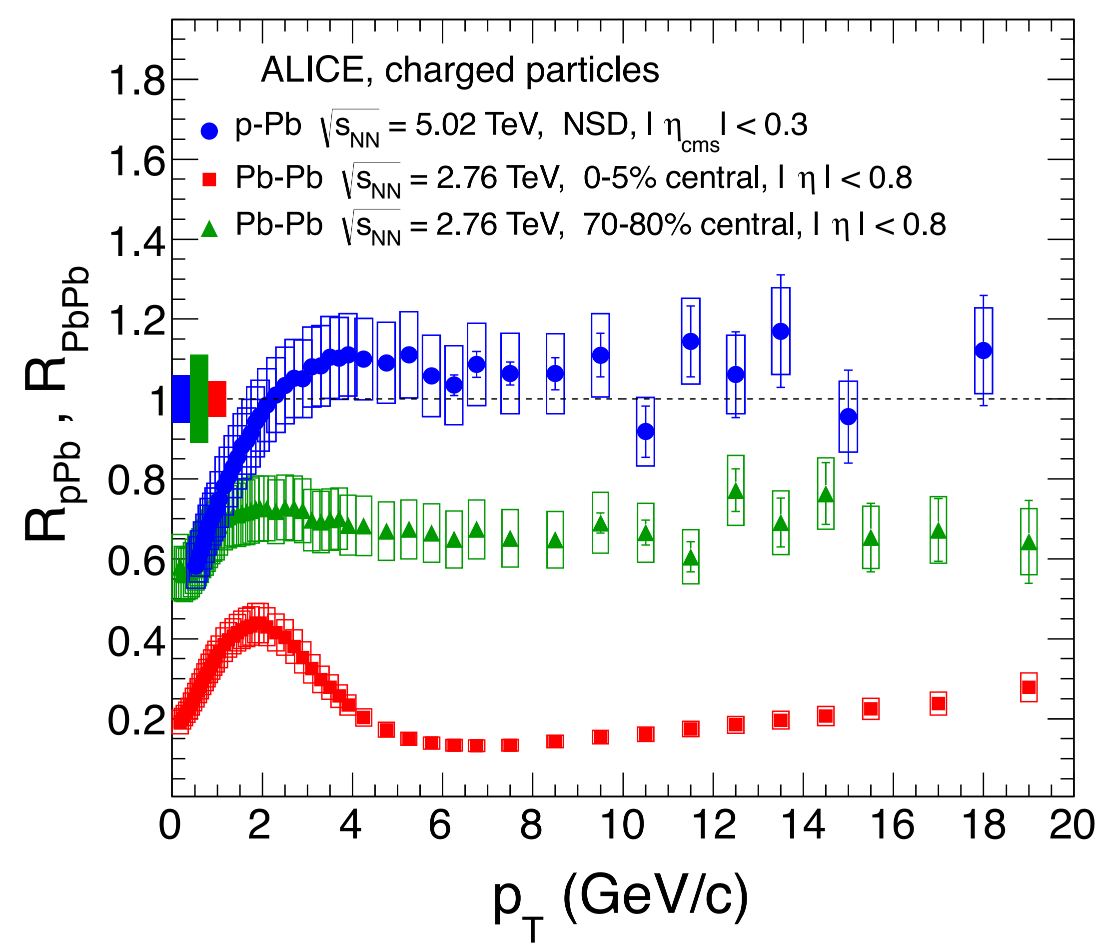
Pseudorapidity density of charged particles in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

arXiv:1210.3615v1 [nucl-ex] 12 Oct 2012



Transverse Momentum Distribution and Nuclear Modification Factor of Charged Particles in p–Pb Collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

arXiv:1210.4520v1 [nucl-ex] 16 Oct 2012



Summary

- ALICE is obtaining a wealth of physics results from the first two LHC heavy-ion runs:
  - bulk, soft probes:
    - spectra and flow of identified particles, flow fluctuations, thermal photons
  - high-p_T probes:
    - jet quenching and fragmentation, particle-type dependent correlations
  - heavy-flavour physics:
    - suppression and flow of D mesons, leptons, J/ψ
- Entering the precision measurement era:
  - before LS2 (2018): p–Pb and Pb–Pb, higher energy and complete approved ALICE detector
- Long-term upgrade for high-luminosity LHC based on:
  - ambitious physics program
  - clear detector upgrade plan for improved vertexing and tracking
  - high-rate capability of all subdetectors

ALICE future

ALICE

- ALICE heavy-ion program approved for ~ 1 nb^{-1}:
  - 2013–14 Long Shutdown 1 (LS1)
    - completion of TRD and CALs
  - 2015 Pb–Pb at $\sqrt{s_{NN}}$ = 5.1 TeV
  - 2016–17 (maybe combined in one year) Pb–Pb at $\sqrt{s_{NN}}$ = 5.5 TeV

  - 2018 Long Shutdown 2 (LS2)
  - 2019 probably Ar–Ar high-luminosity run
  - 2020 p–Pb comparison run at full energy
  - 2021 Pb–Pb run to complete initial ALICE programme
  - 2022 Long Shutdown 3 (LS3)

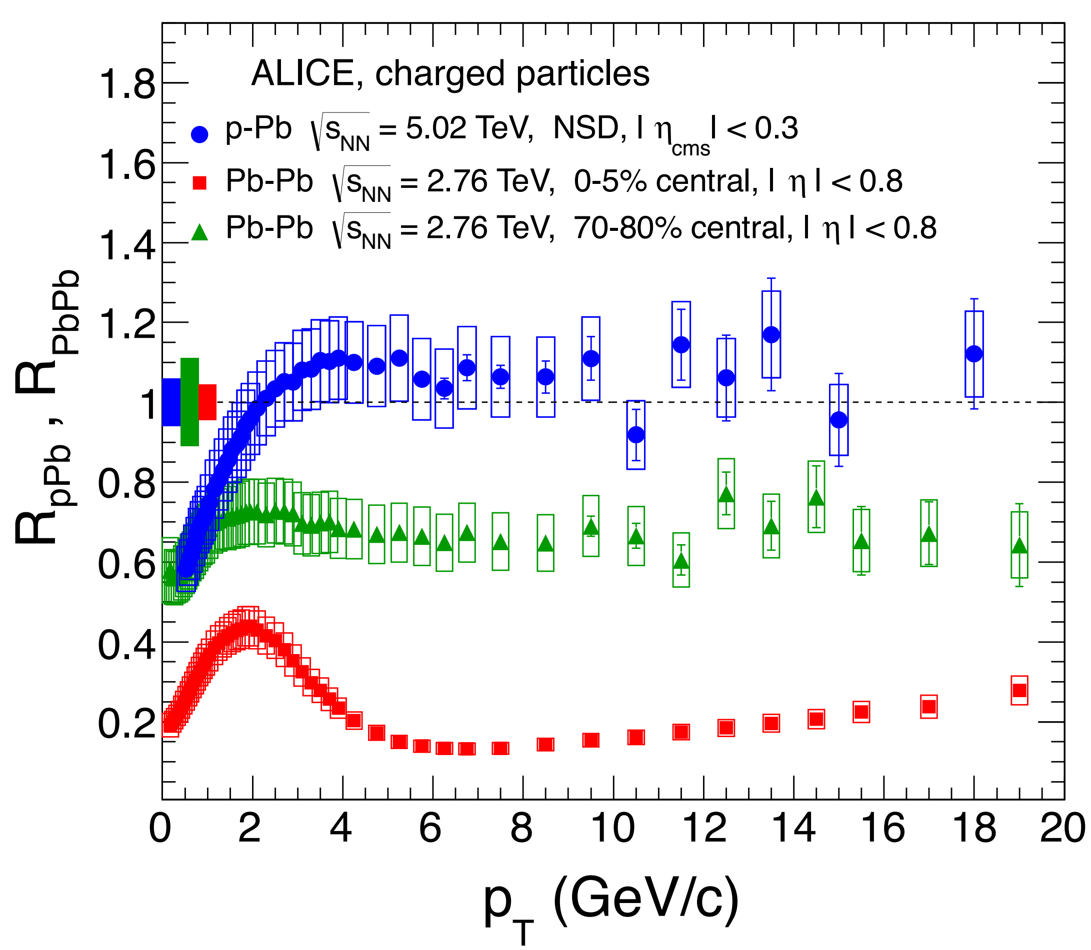
Order/choice of nuclei may change

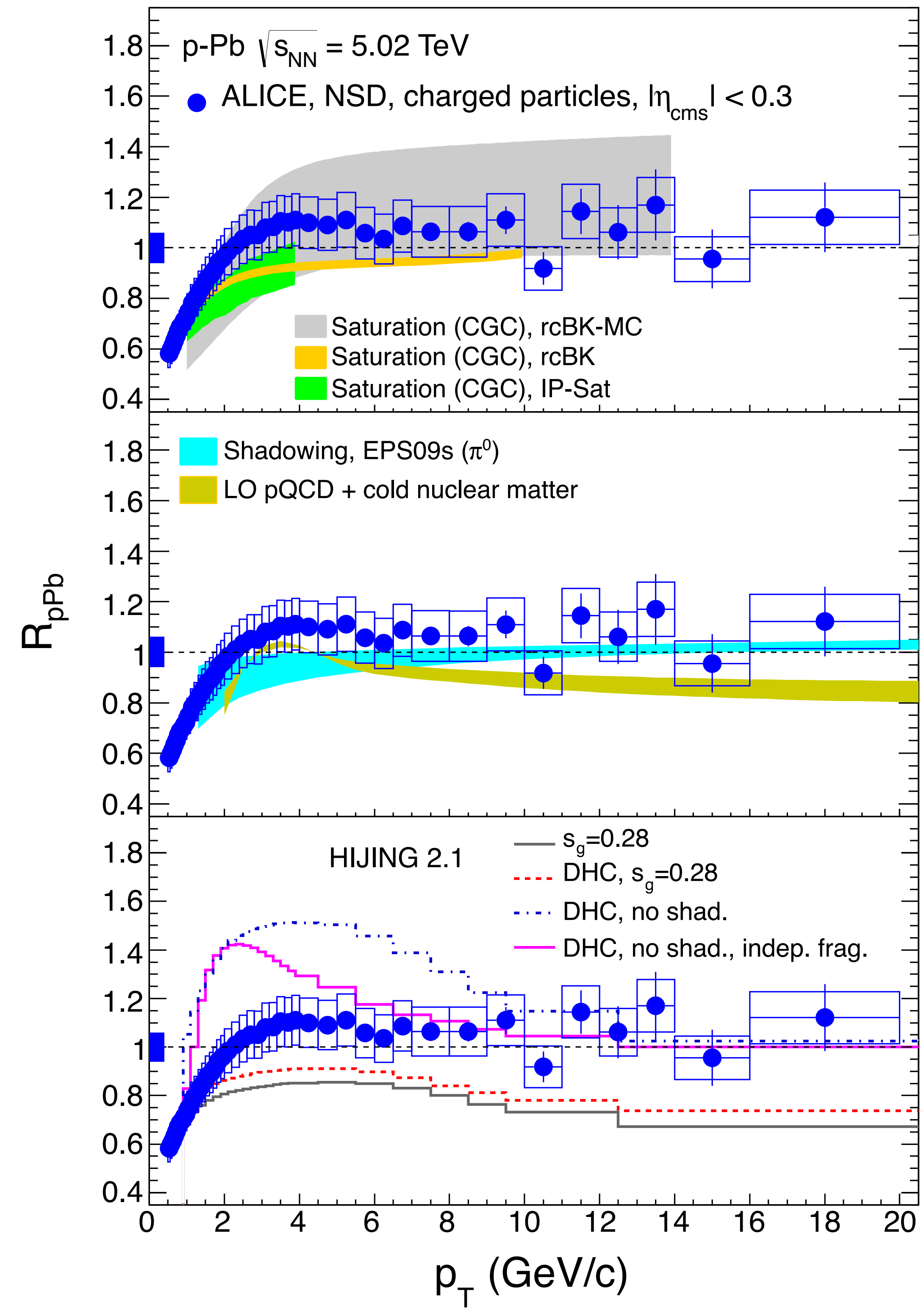
- This will improve statistical significance of our main results by a factor about 3
  - physics reach extended by the new energy and completion of TRD and CALs

EXTRA SLIDES

Transverse Momentum Distribution and Nuclear Modification Factor of Charged Particles in p–Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

arXiv:1210.4520v1 [nucl-ex] 16 Oct 2012





ALICE upgrade

- luminosity upgrade – 50 kHz target minimum-bias rate for Pb–Pb
- run ALICE at this high rate, inspecting all events

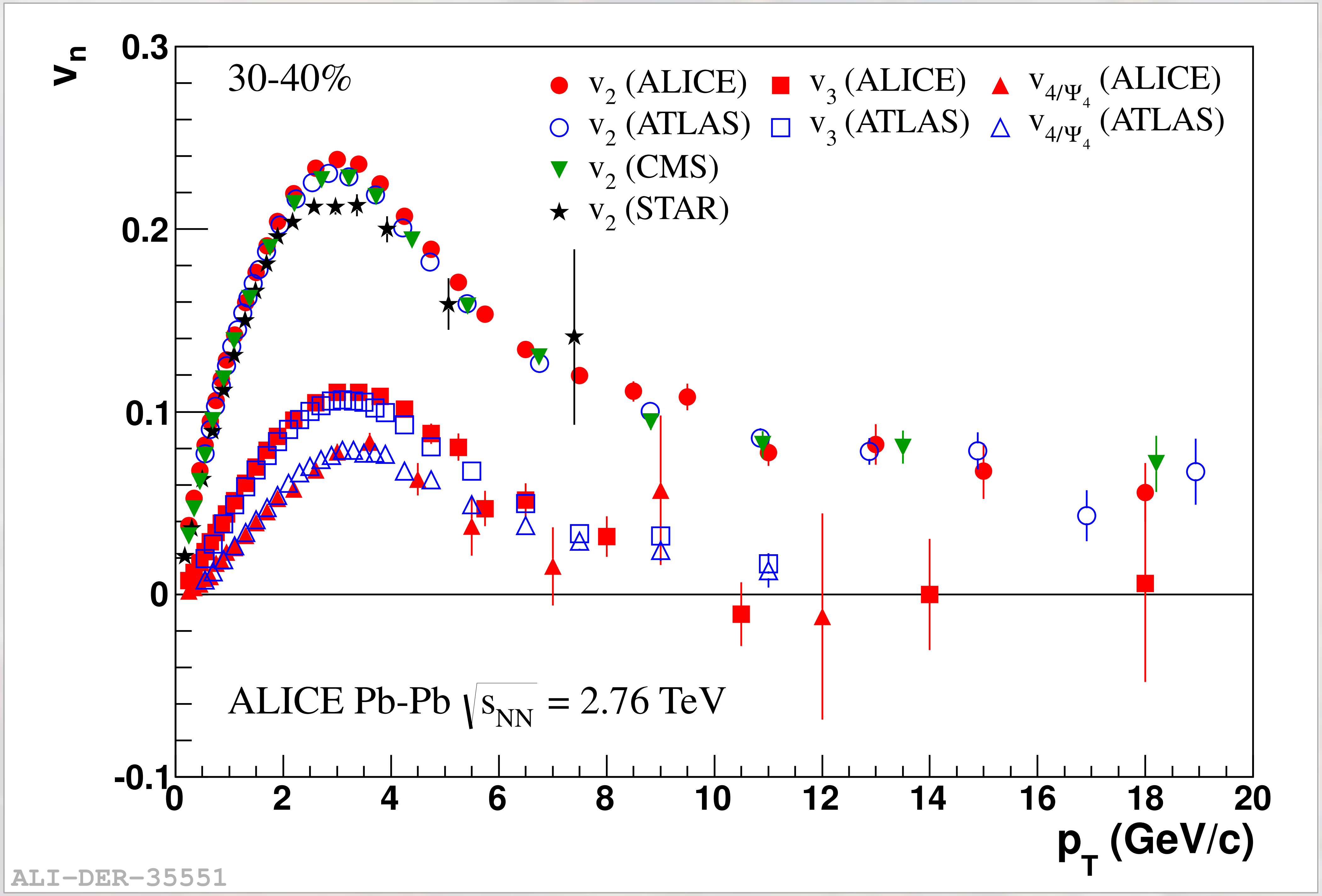
- improved vertexing and tracking at low p_T
- preserve particle-identification capability
- high-luminosity operation without dead-time

- new, smaller radius beam pipe
- new inner tracker (ITS) (performance and rate upgrade)
- high-rate upgrade for the readout of the TPC, TRD, TOF, CALs, DAQ-HLT, Muon-Arm and Trigger detectors

- target for installation and commissioning LS2 (2018)
- collect more than 10 nb^{-1} of integrated luminosity
  - implies running with heavy ions for a few years after LS3
- for core physics programme – factor > 100 increase in statistics
  - (maximum readout with present ALICE ~ 500 Hz)
- for triggered probes increase in statistics by factor > 10

$v_n(p_T)$, comparison with other experiments

ALICE: arXiv:1205.5761

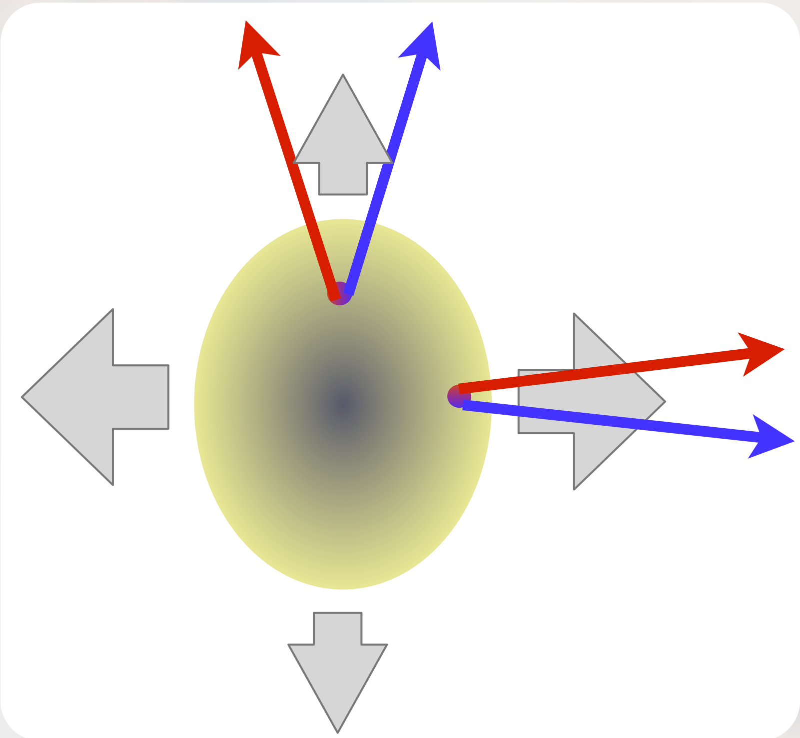


Good agreement with other experiments

CME background: “flowing clusters”

The only possible background ~ v_2

Voloshin, PRC70 057901 (2004)



One of the candidates: Local Charge Conservation at freeze-out + Radial + Elliptic Flow

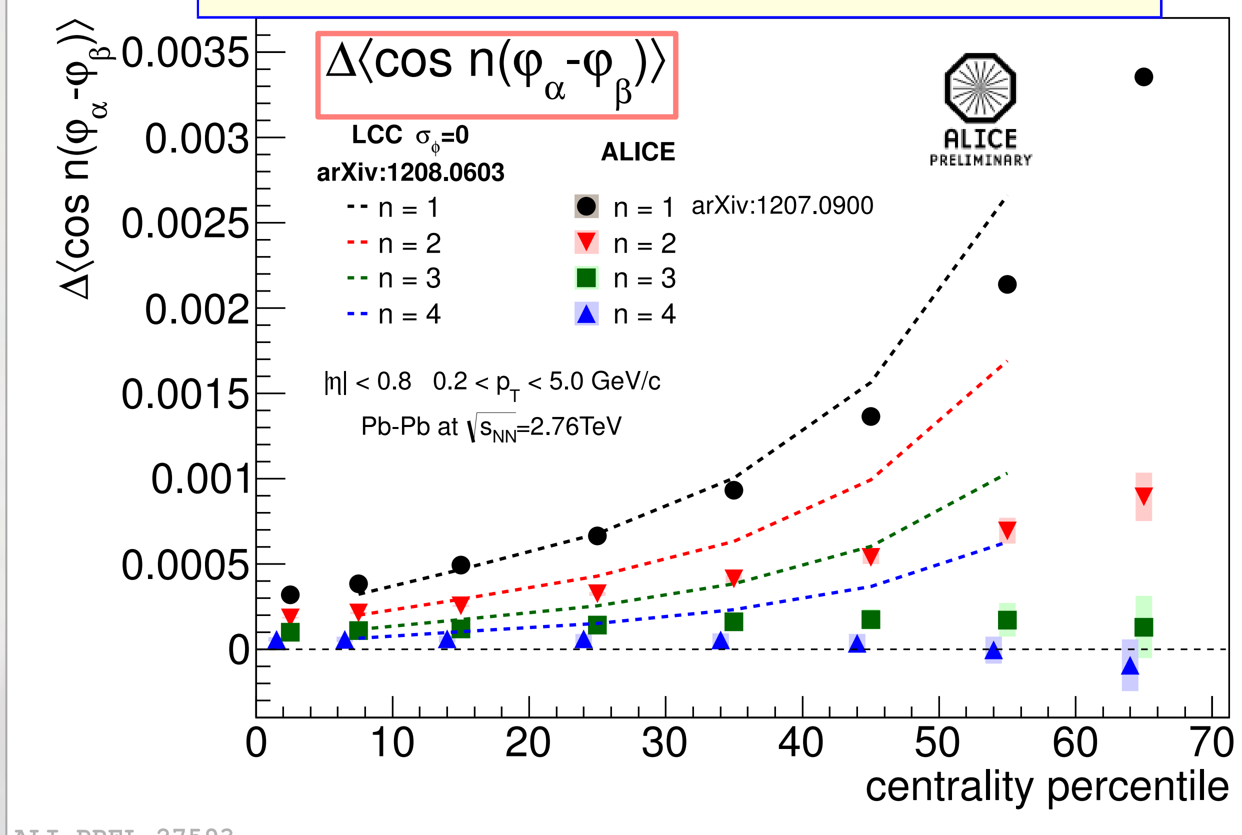
Blast wave model:

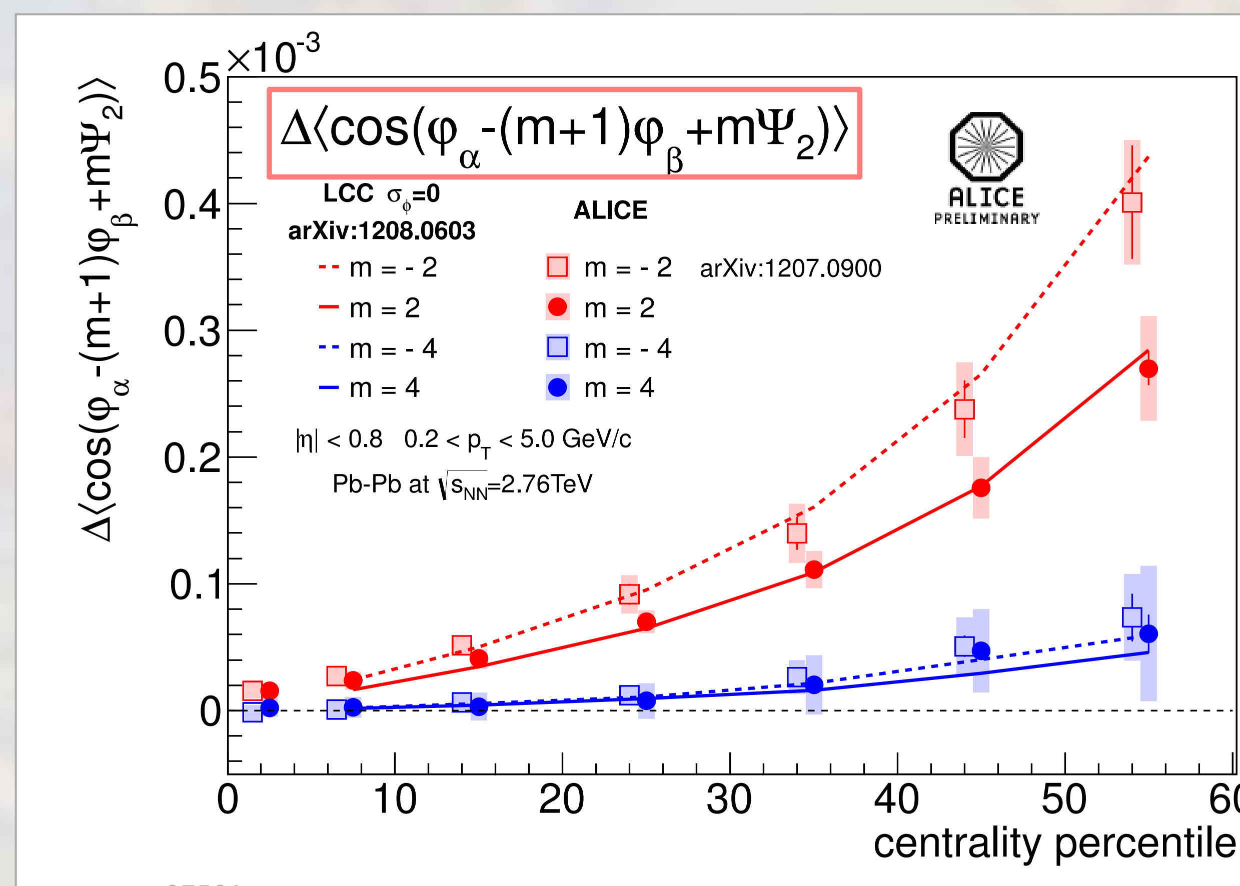
Schlichting and Pratt, PRC83 014913 (2011)

Hori, Gunji, Hamagaki, Schlichting, arXiv:1208.0603

- Correlations only between opposite charges
- To be consistent with data must be combined with (negative) charge independent correlations (e.g. momentum conservation).
- No event generator exhibits such strong correlations as predicted by Blast wave model

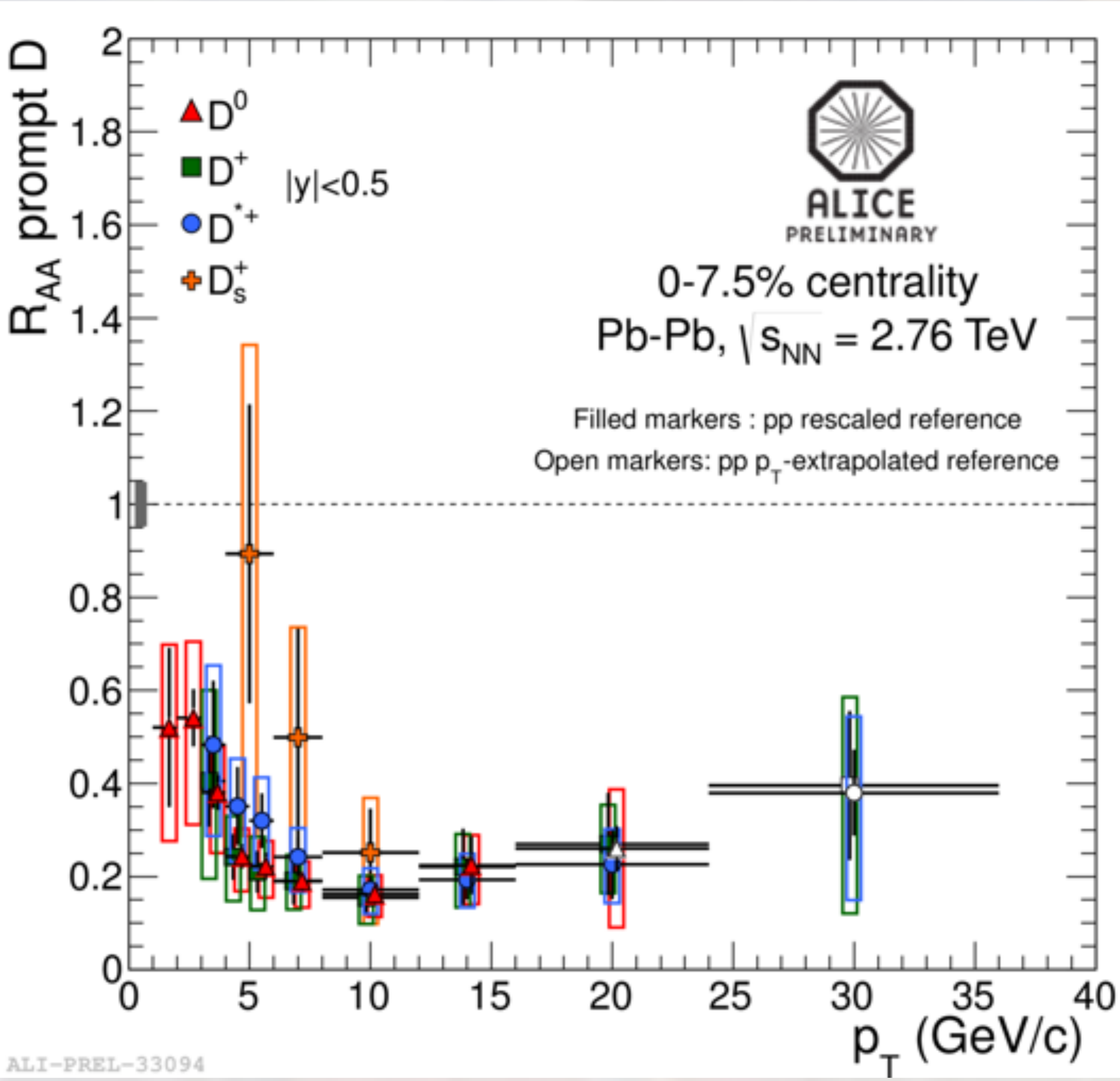
$$\Delta\langle\ldots\rangle = \langle\ldots\rangle_{\text{opposite}} - \langle\ldots\rangle_{\text{same}}$$

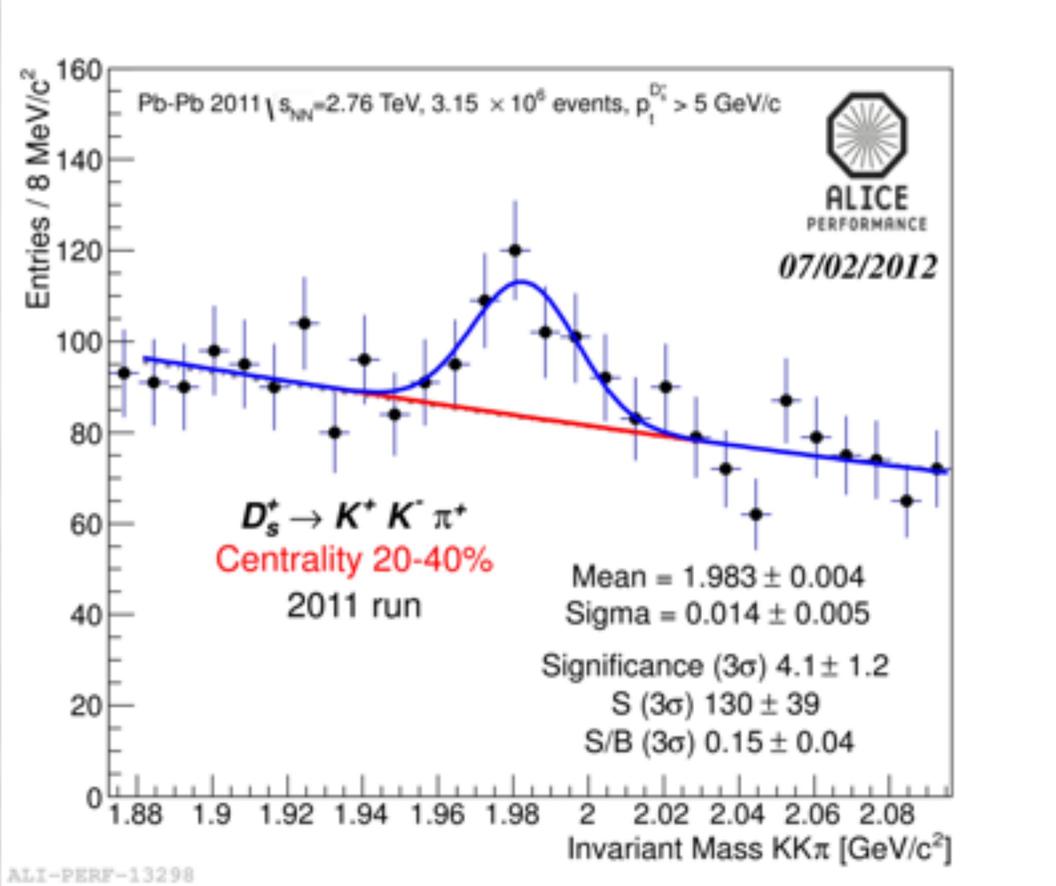




… adding D_s to charm R_{AA}

The relative yield of D^+_s with respect to non-strange D meson expected to be enhanced in Pb-Pb collisions in the intermediate momentumrange if charm quarks hadronize via recombination in the medium [1]

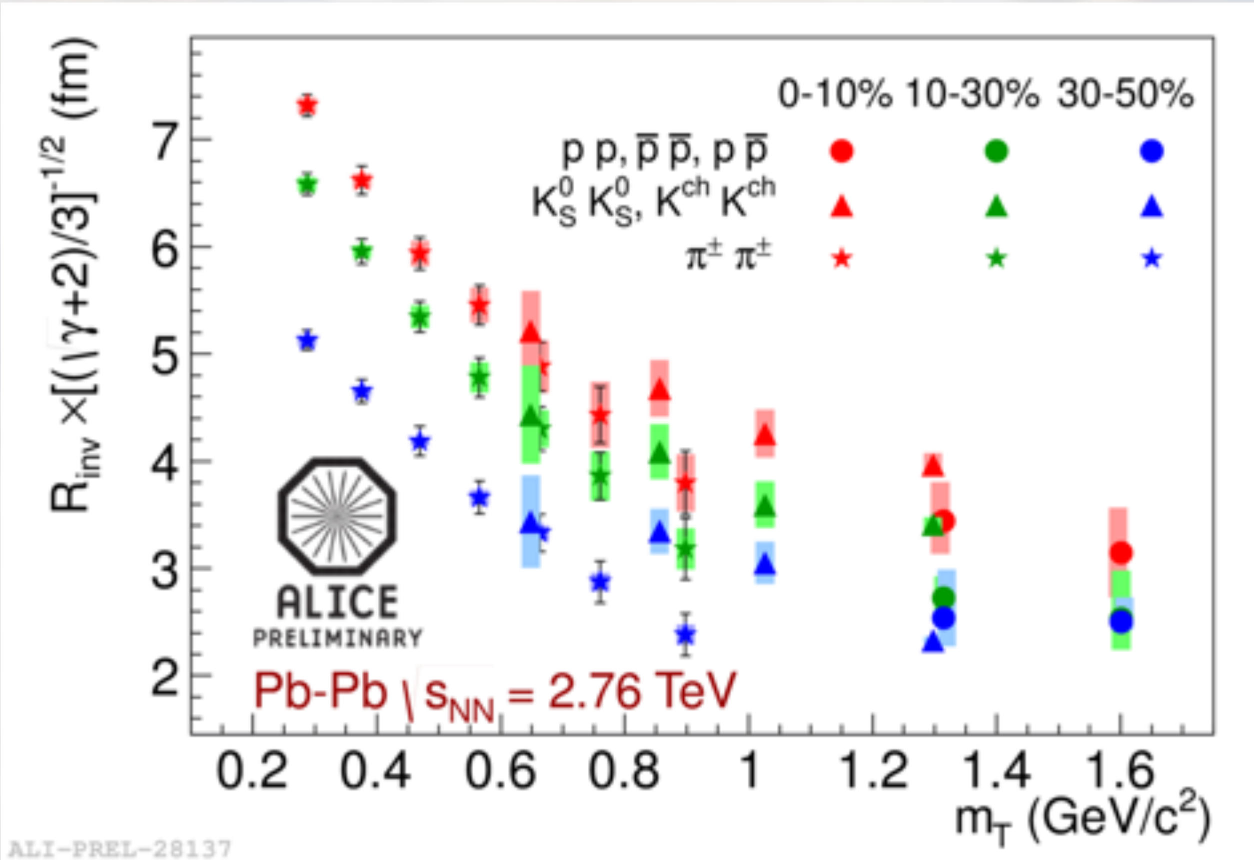


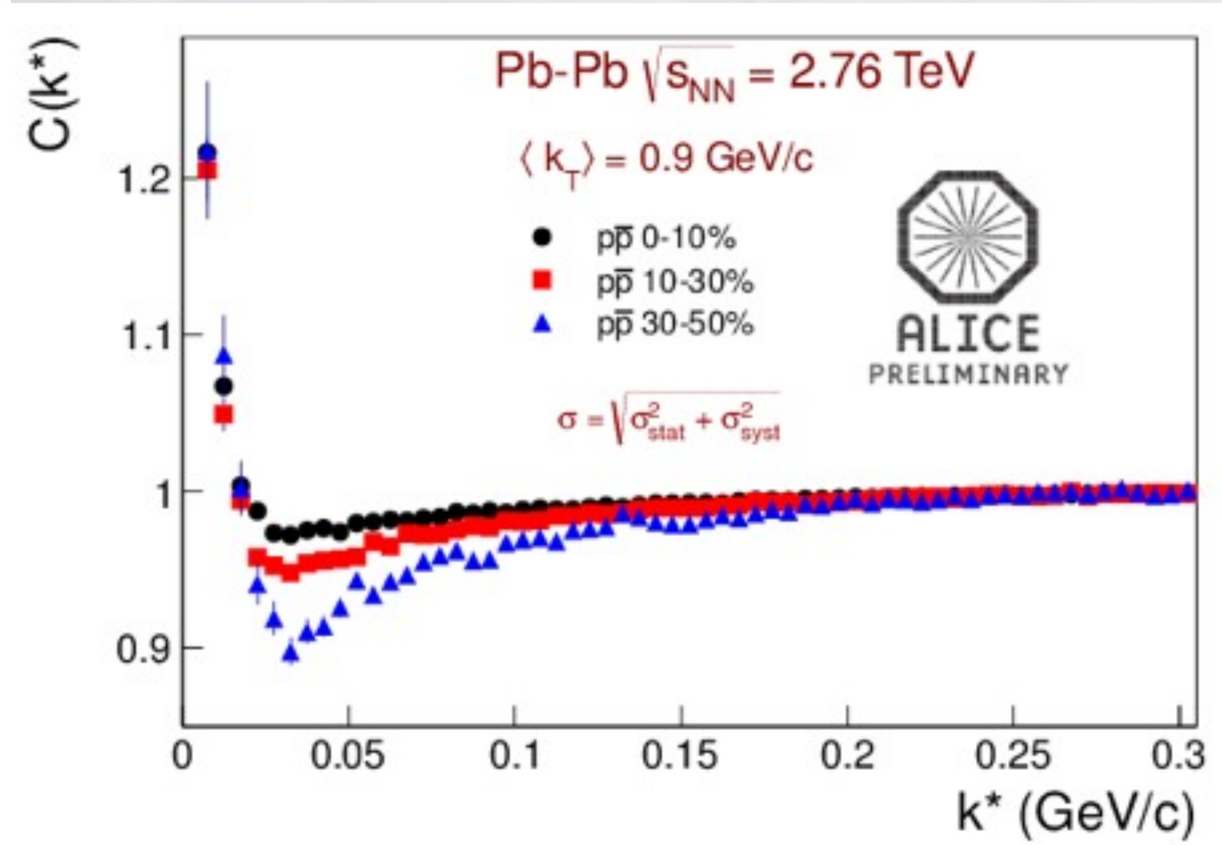


Strong suppression (~ 4–5) at p_T above 8 GeV/c ; uncertainty will improve with future pp and Pb–Pb data taking

[1] I. Kuznetsova, J. Rafelski, Eur.Phys.J.C51:113-133,2007; M. He, R. J. Fries and R. Rapp, arXiv:1204.4442 [nucl-th].

Baryon femtoscopy

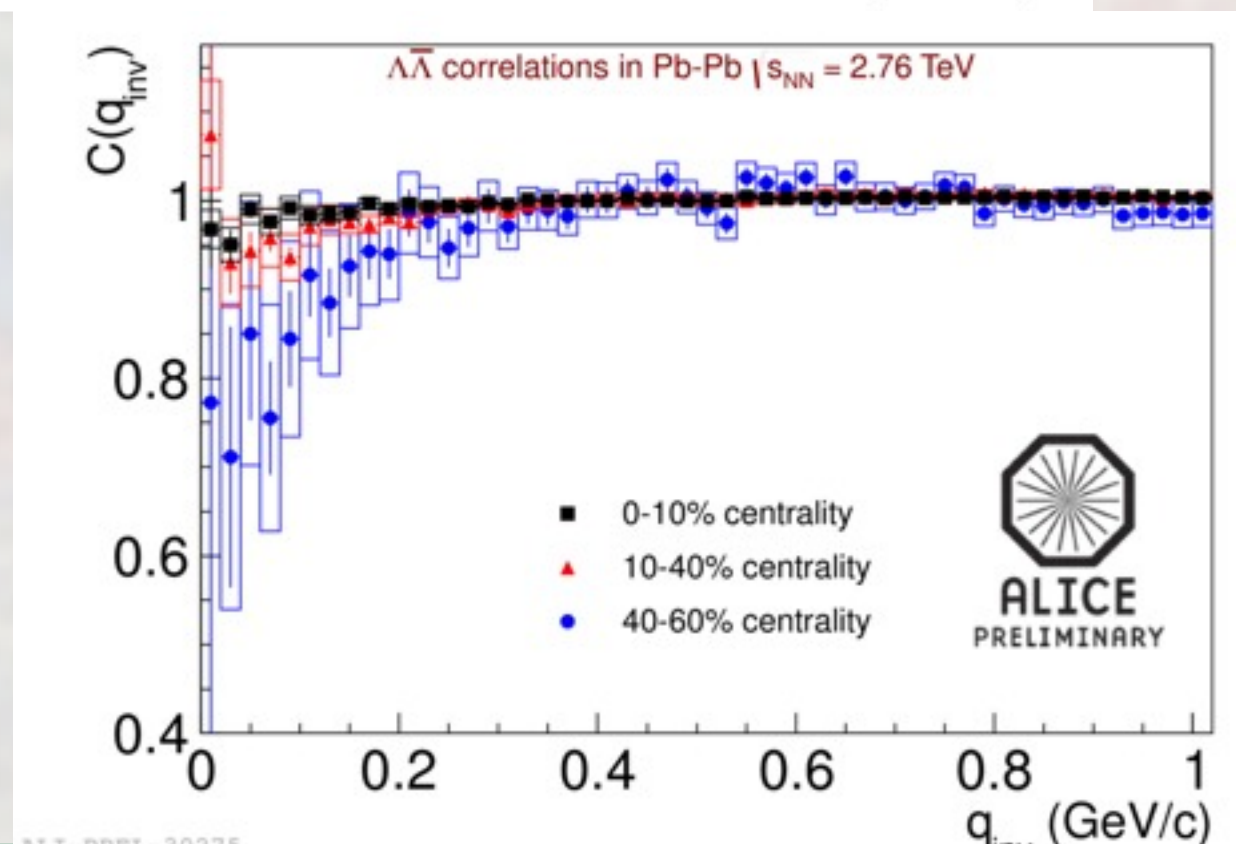




For the first time m_T-scaling of homogeneity length for all particle species
– consistent with hydro

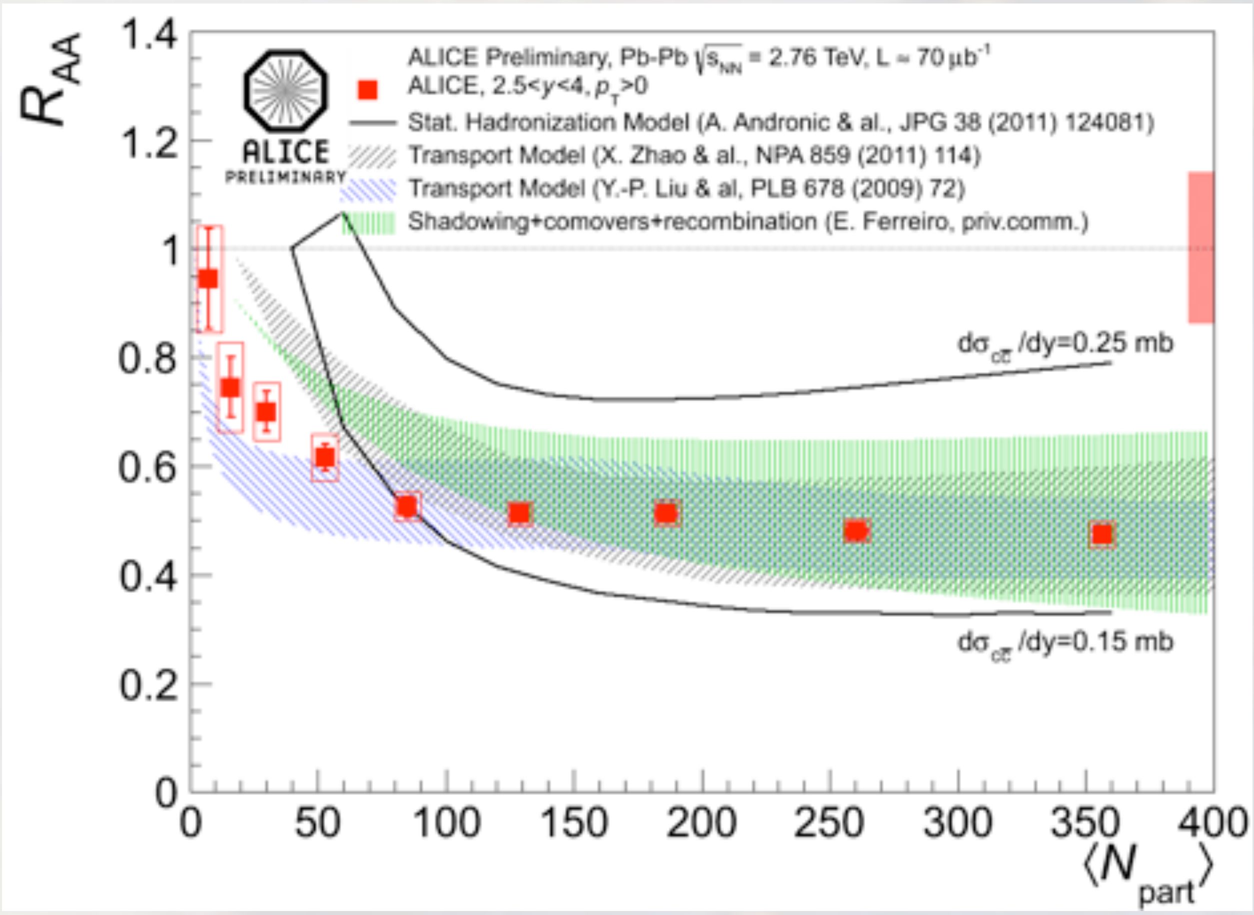
Baryon–antibaryon correlation function has large contribution from final state interaction
– measurement of annihilation cross section

Because of large density, p and Λ may be suppressed due to annihilation ?

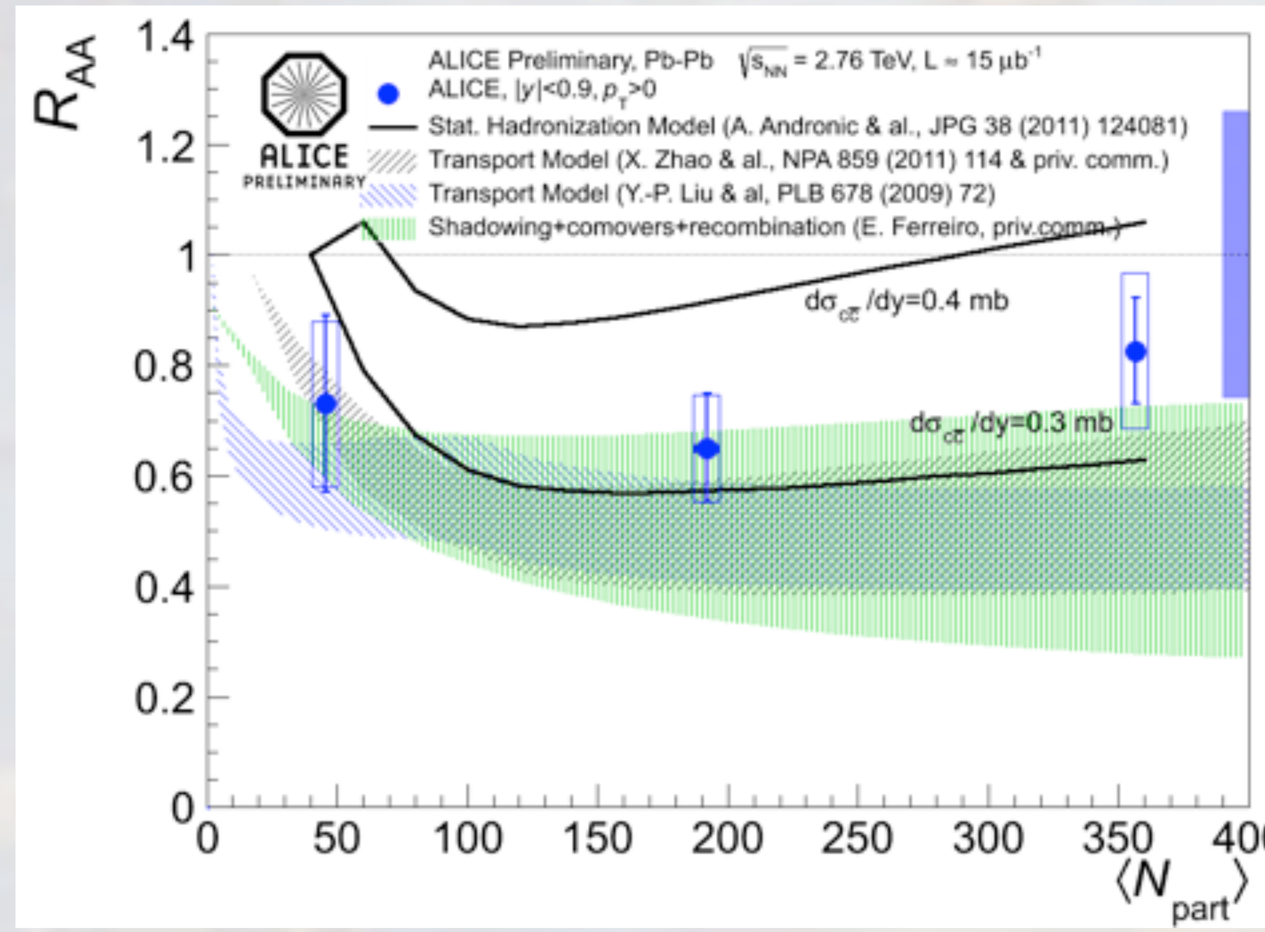


J/ψ : R_{AA} vs $\langle N_{part} \rangle$

Forward rapidity: J/ψ → $\mu^+\mu^-$



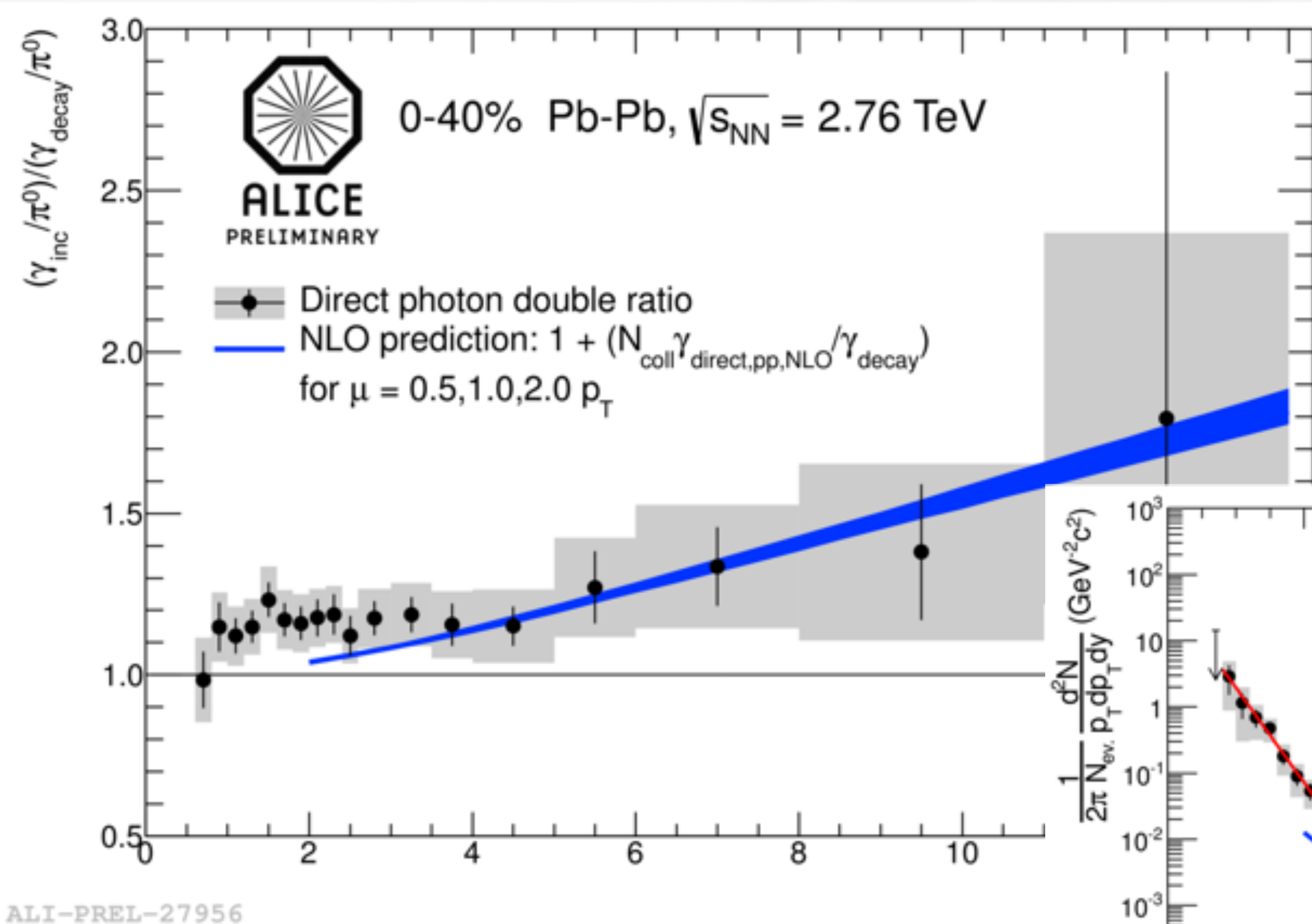
Mid rapidity: J/ψ → e^+e^-



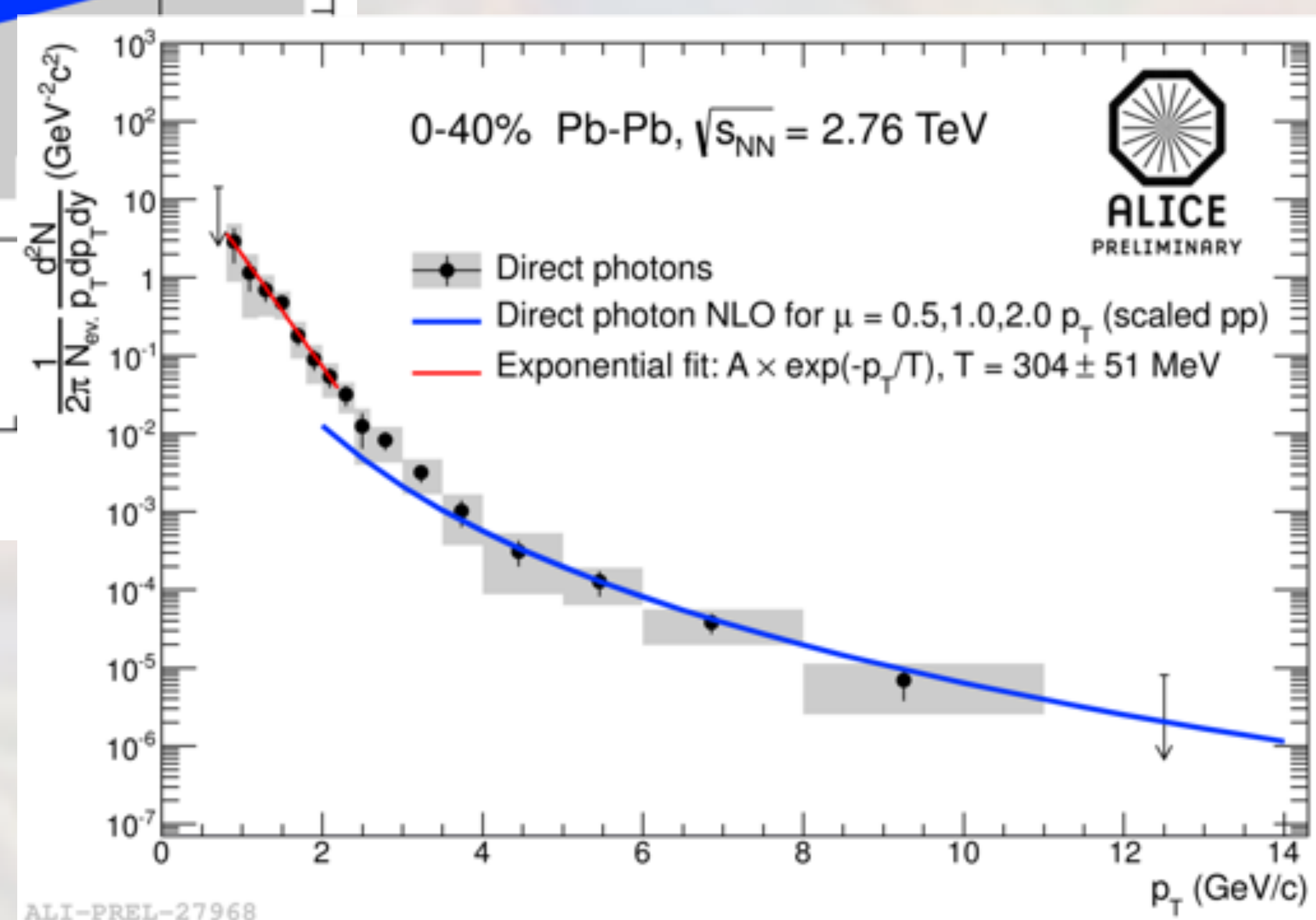
- Comparison with models
  - X.Zhao and R.Rapp, Nucl. Phys. A859(2011) 114
  - Y.Liu, Z. Qiu, N. Xu and P. Zhuang, Phys. Lett. B678(2009) 72
  - A. Capella et al., Eur. Phys. J. C58(2008) 437 and E. Ferreiro, priv. com.

- Models including a large fraction (>50% in central collisions) of J/ψ produced from (re)combination or models with all J/ψ produced at hadronization can describe ALICE results for central collisions in both rapidity ranges

Direct photon production



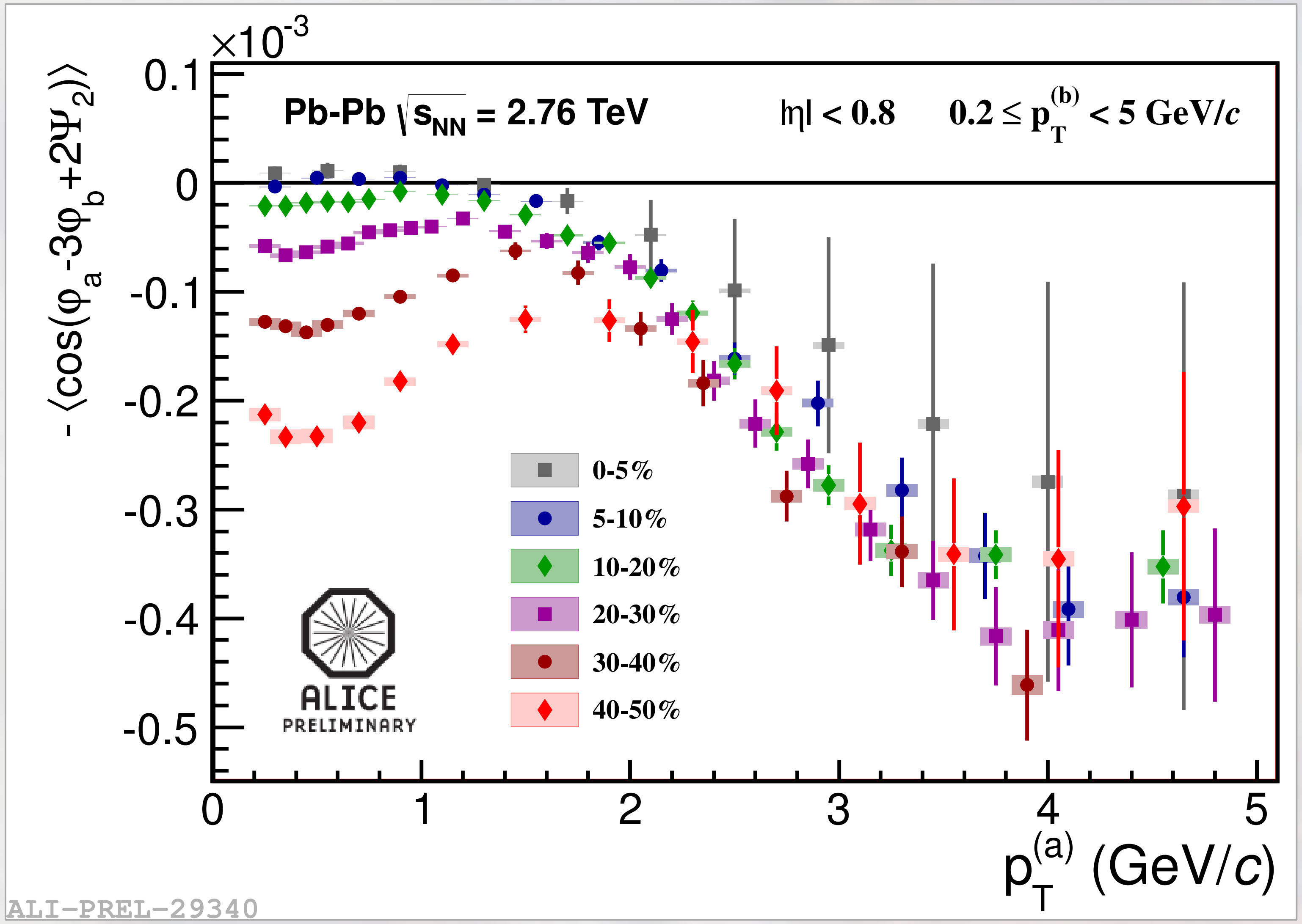
Exponential fit for p_T < 2.2 GeV/c
inv. slope T = 304±51 MeV
for 0–40% Pb–Pb at $\sqrt{s}$ 2.76 TeV
PHENIX: T = 221±19±19 MeV
for 0–20% Au–Au at $\sqrt{s}$ 200 GeV

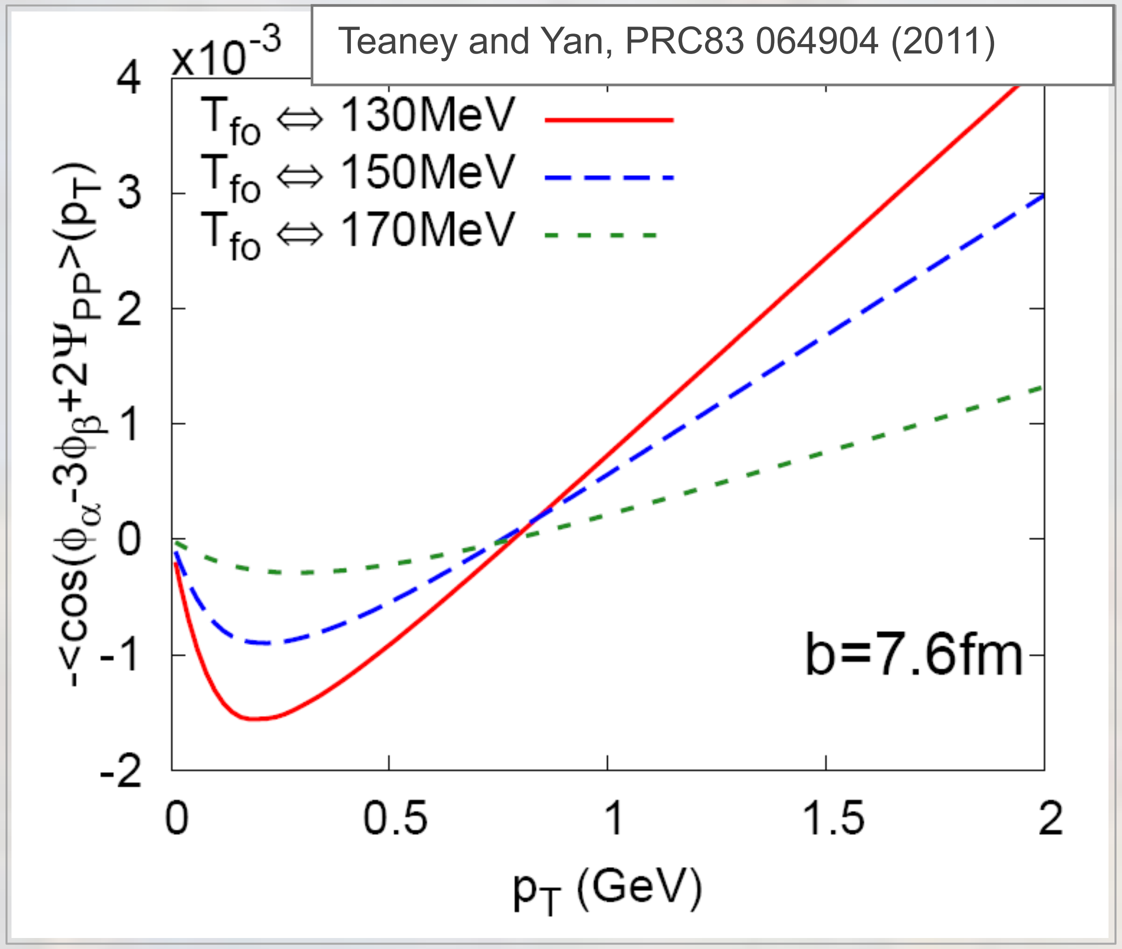


p_T < 2 GeV/c
~20% excess of direct photons
p_T > 4 GeV/c
agreement with N_{coll}-scaled NLO

Differential dipole flow

$- \langle \cos(\varphi_a - 3\varphi_b + 2\Psi_2) \rangle$

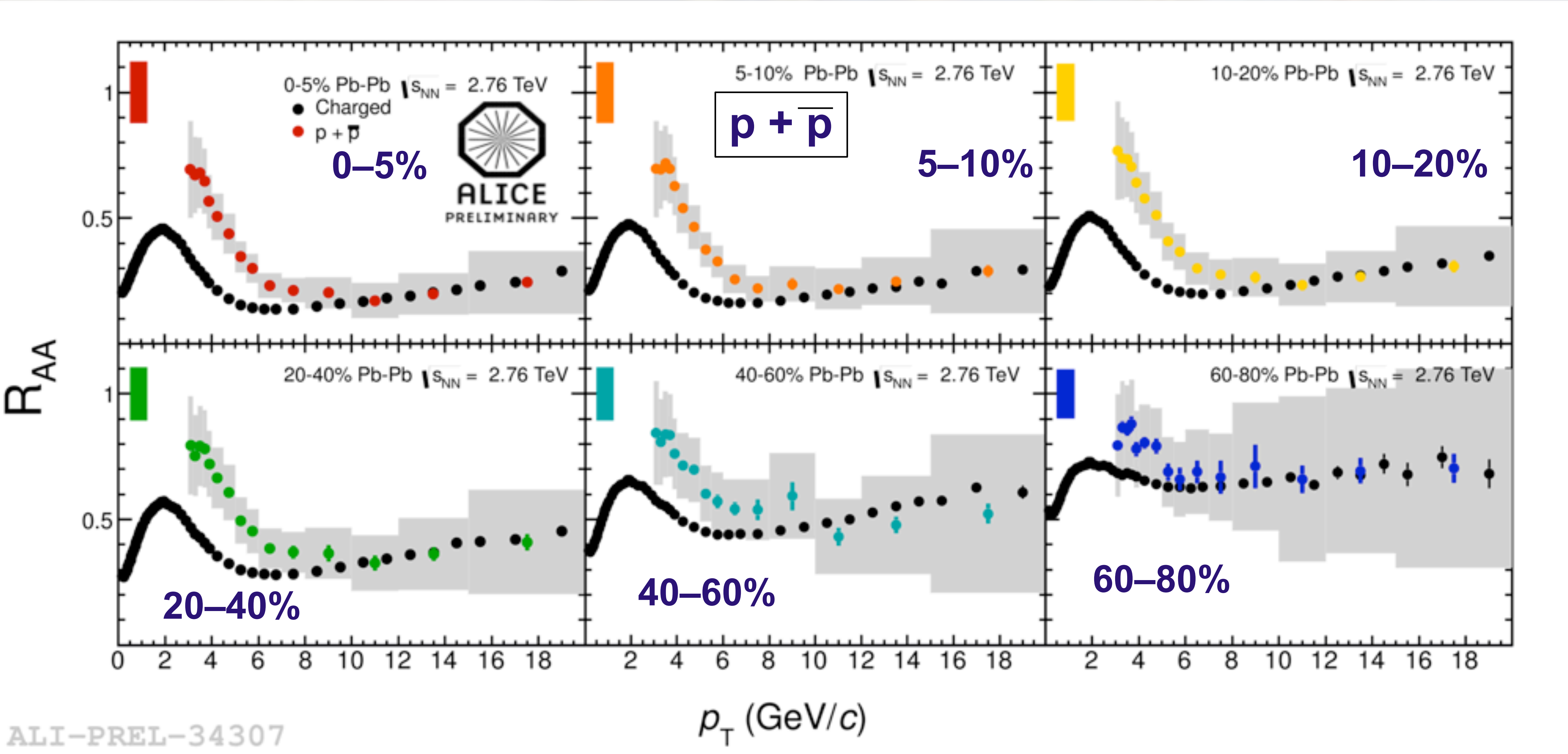




Differential dipole flow from 3-particle (all different harmonics) correlations.

p+pbar R_{AA}

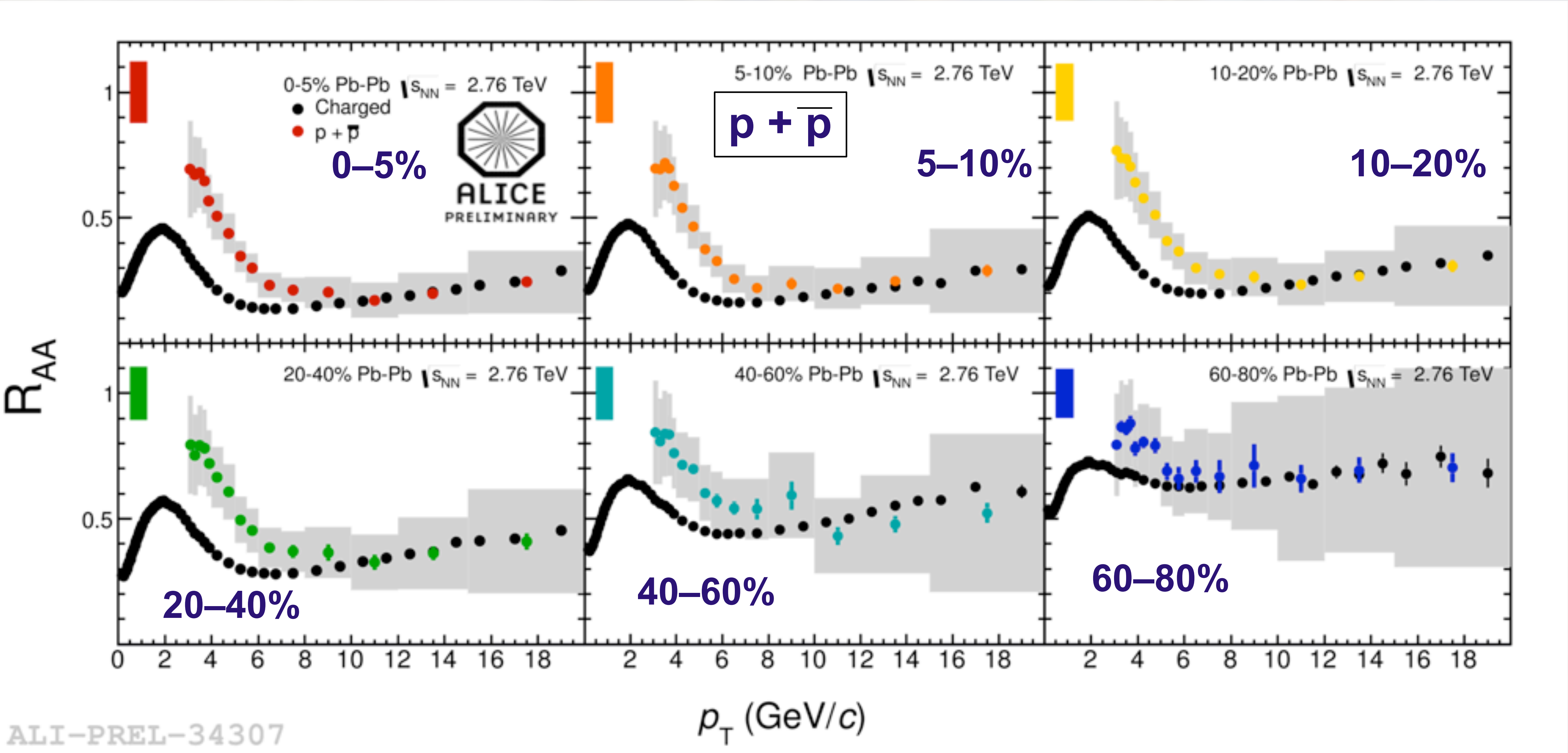
● charged particles ●●●●●● different centralities for identified particles



At higher p_T: R_{AA} are compatible

p+pbar R_{AA}

● charged particles ●●●●●● different centralities for identified particles



For p_T below ~ 7 GeV/c: $R_{AA}(\pi) < R_{AA}(h^{\pm})$, $R_{AA}(K) \approx R_{AA}(h^{\pm})$, $R_{AA}(p) > R_{AA}(h^{\pm})$

At higher p_T: R_{AA} are compatible