Flow Harmonics and Jet Suppression at the ALICE

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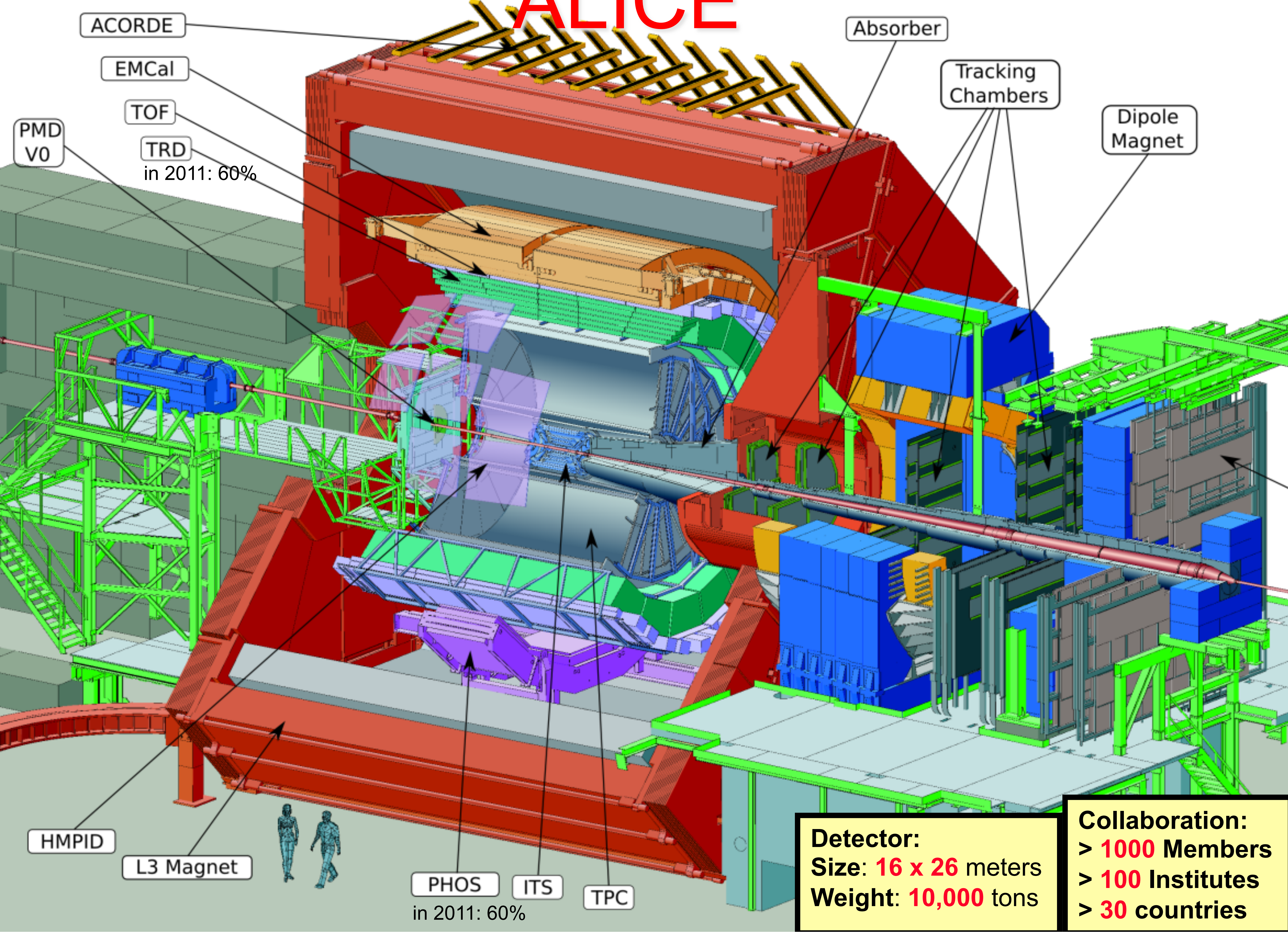
Inha University
Heavy Ion Meeting in Korea, Fall 2013

<u>Outline of the talk</u>

- ALICE apparatus
- Jet cross section and structure
- Flow harmonics
- Summary

Introduction

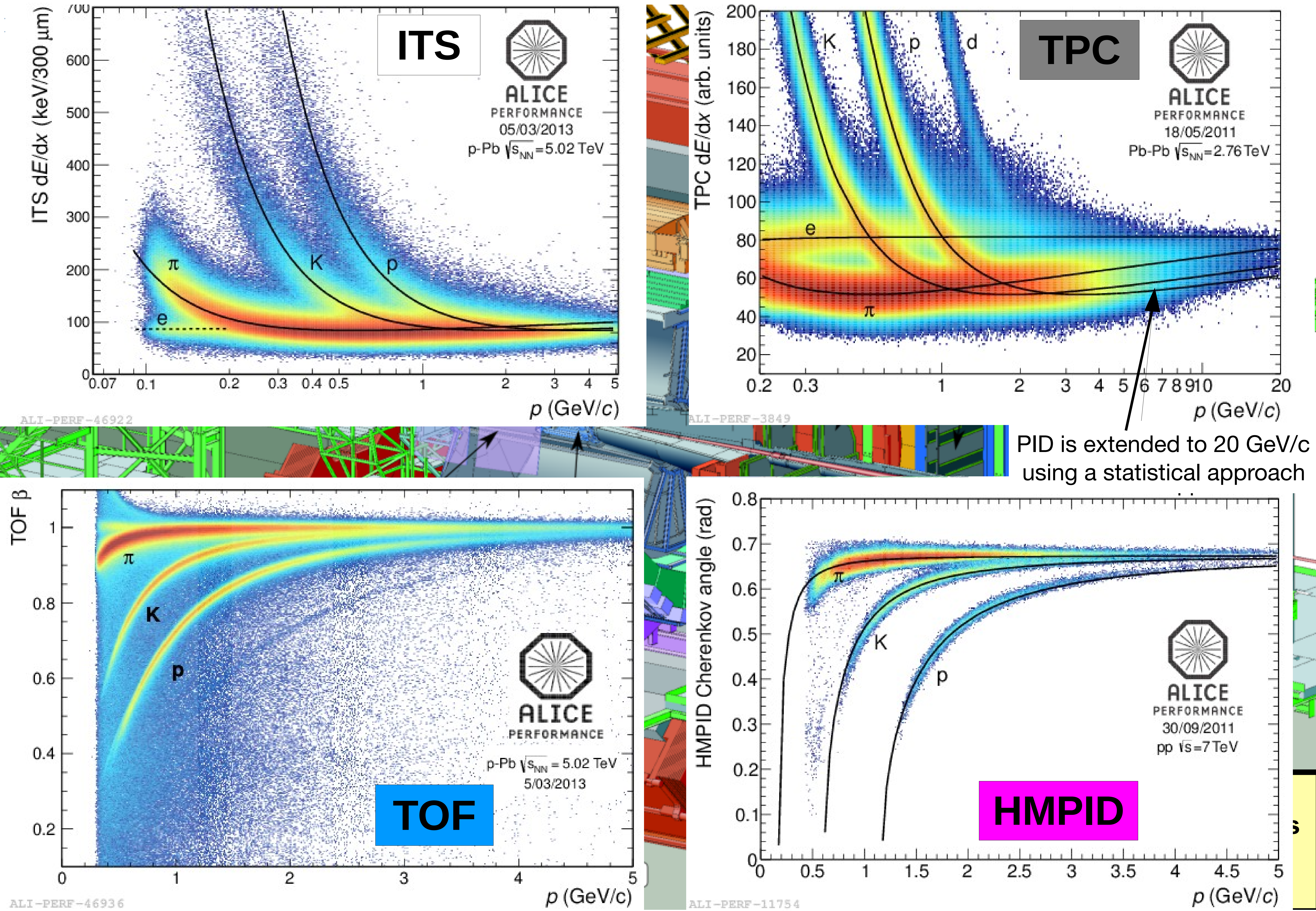
ALICE



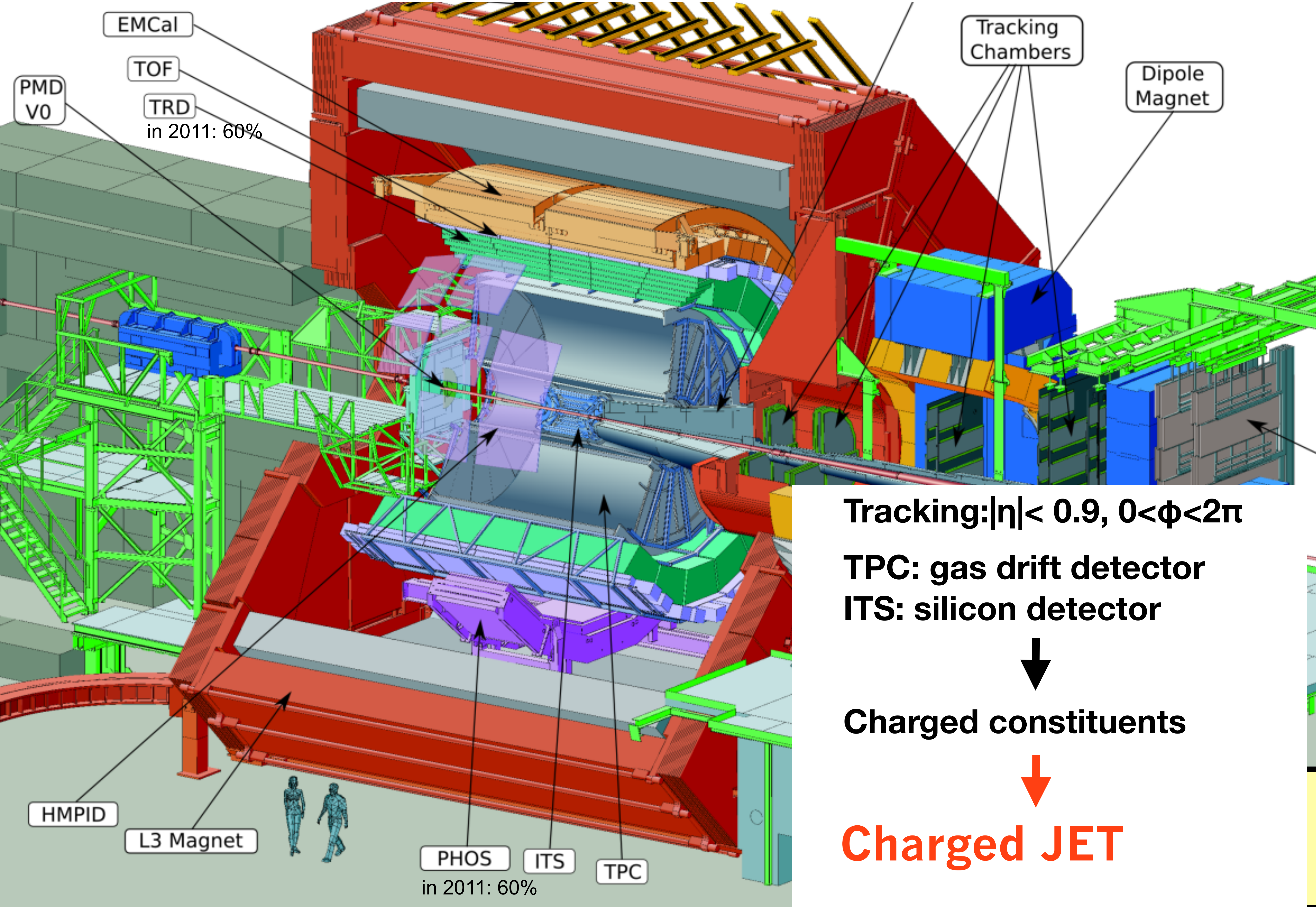
Detector:
Size: **16 x 26** meters
Weight: **10,000** tons

Collaboration:
> 1000 Members
> 100 Institutes
> 30 countries

Particle identification in ALICE



Charged jet at ALICE



Tracking: $|\eta| < 0.9$, $0 < \phi < 2\pi$

TPC: gas drift detector
ITS: silicon detector

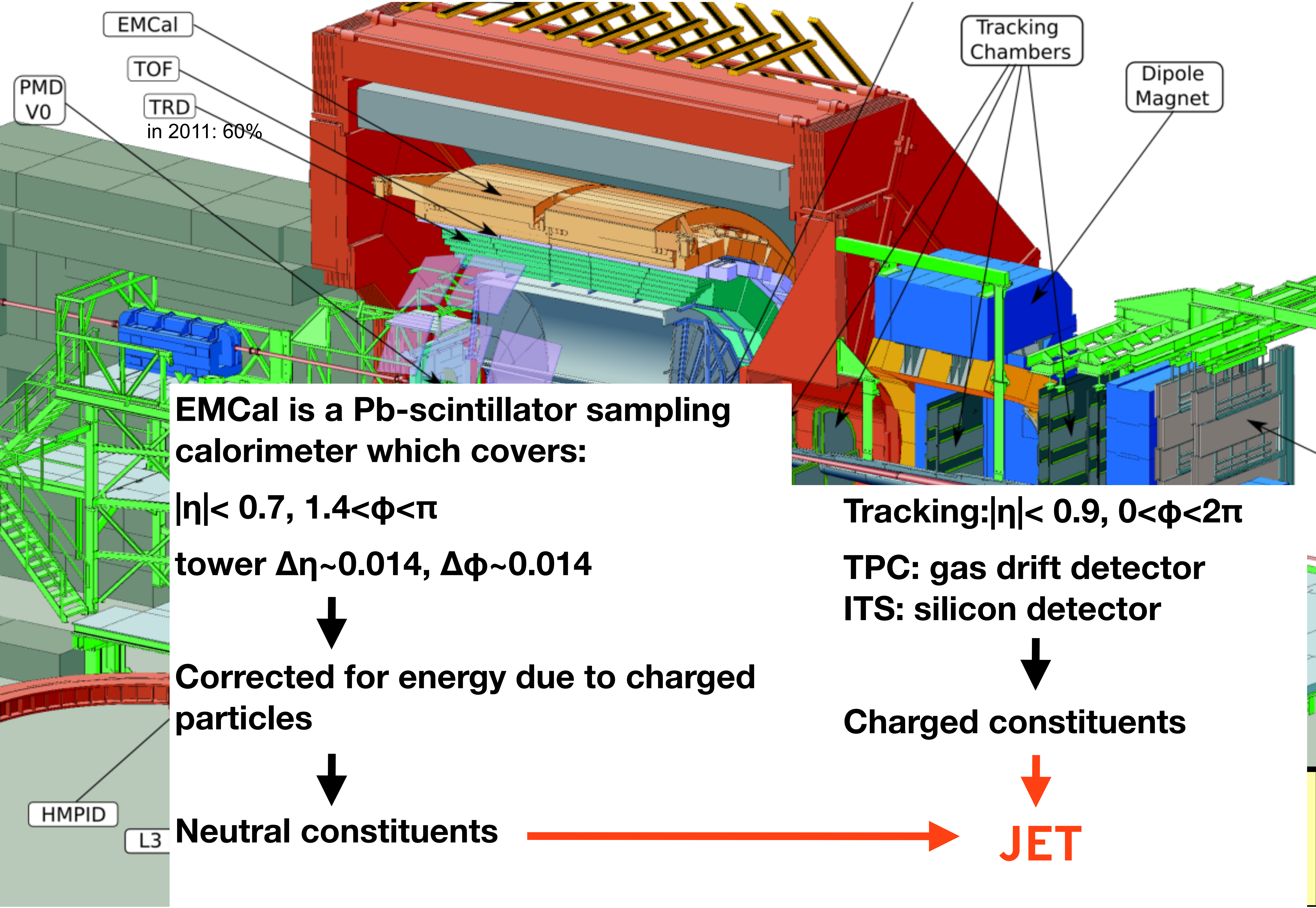
↓

Charged constituents

↓

Charged JET

Full jet at ALICE



EMCal is a Pb-scintillator sampling calorimeter which covers:

|η|< 0.7, 1.4<ϕ<π

tower Δη~0.014, Δϕ~0.014

↓

Corrected for energy due to charged particles

↓

Neutral constituents → **JET**

Tracking:|η|< 0.9, 0<ϕ<2π

TPC: gas drift detector
ITS: silicon detector

↓

Charged constituents

↓

JET

Jet reconstruction in ALICE

- **There is no unambiguous jet definition**
  - Algorithms must be IR and collinear safe

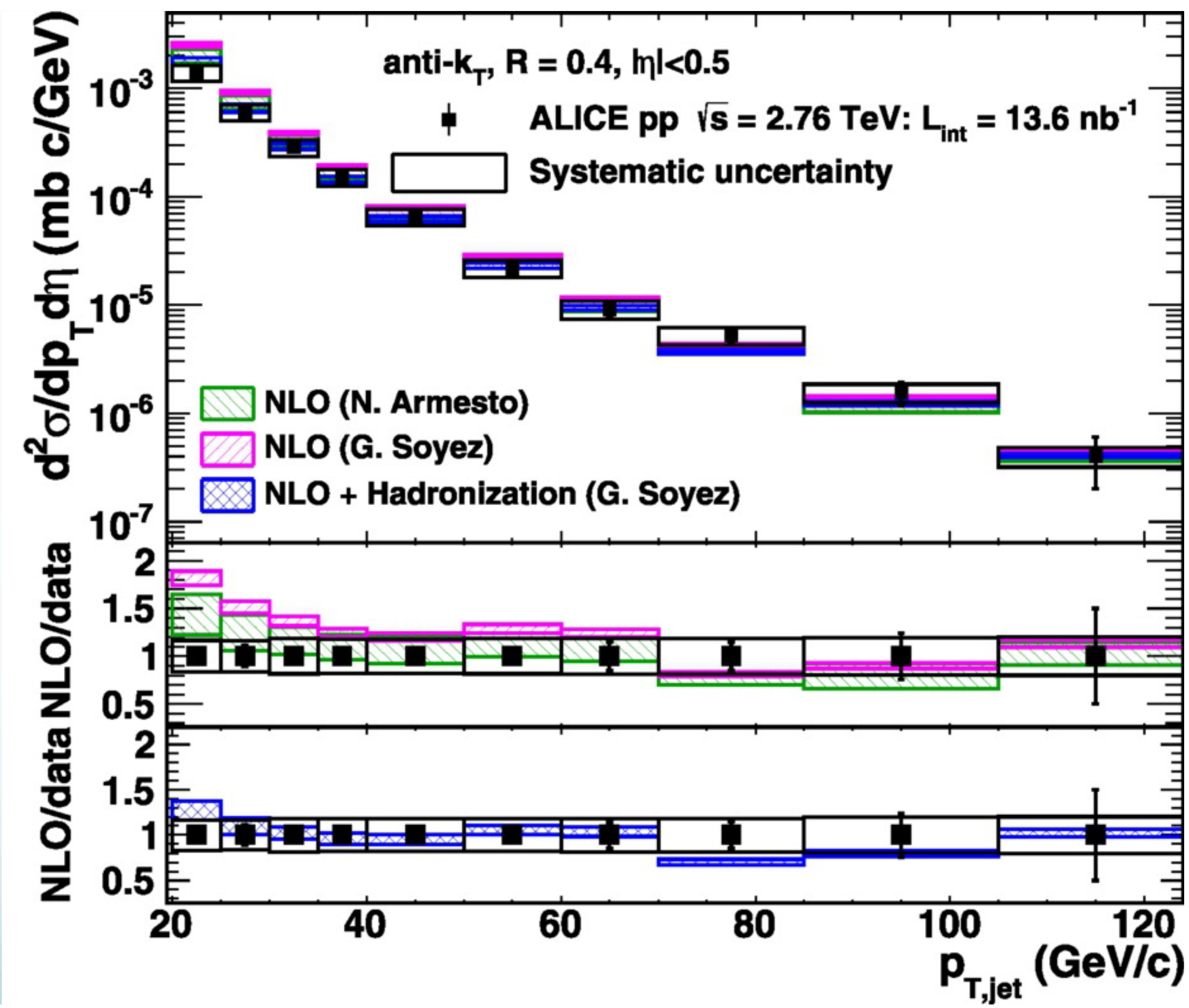
- **Fluctuating background and combinatorial jets require care in HI analyses**

- **Input to the jet finder**
  - Charged tracks (ITS+TPC) with $p_T > 150$ MeV/c
  - EMCal clusters corrected for charged particle contamination

- **FastJet package: Anti-k_T (k_T used for background)**
  - R = 0.2 – 0.6

Jets in pp

Jets Cross Section in pp

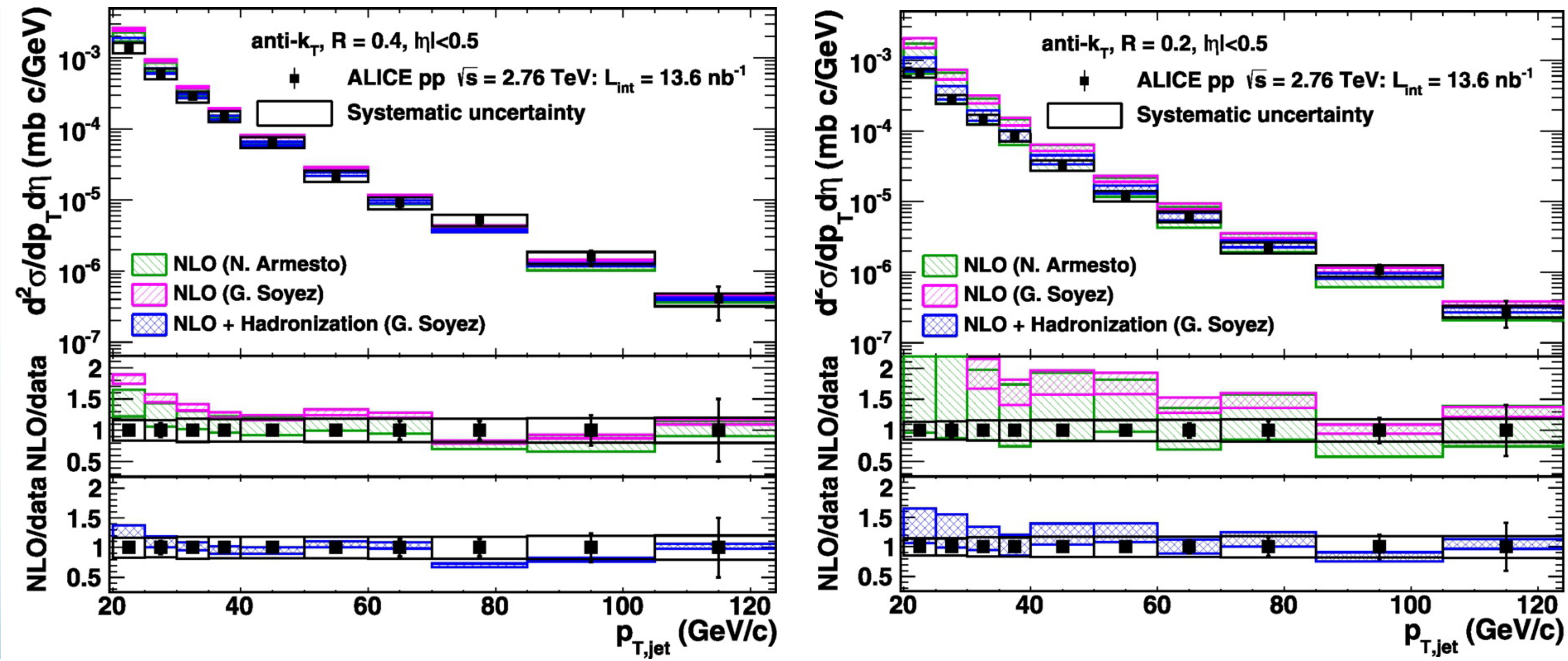


Hadronization needed for theory-data agreement

- Important reference for Pb-Pb collisions
- Good agreement between data and NLO calculations

⇒Jets are a well calibrated probe for the QGP

Jets Cross Section in pp

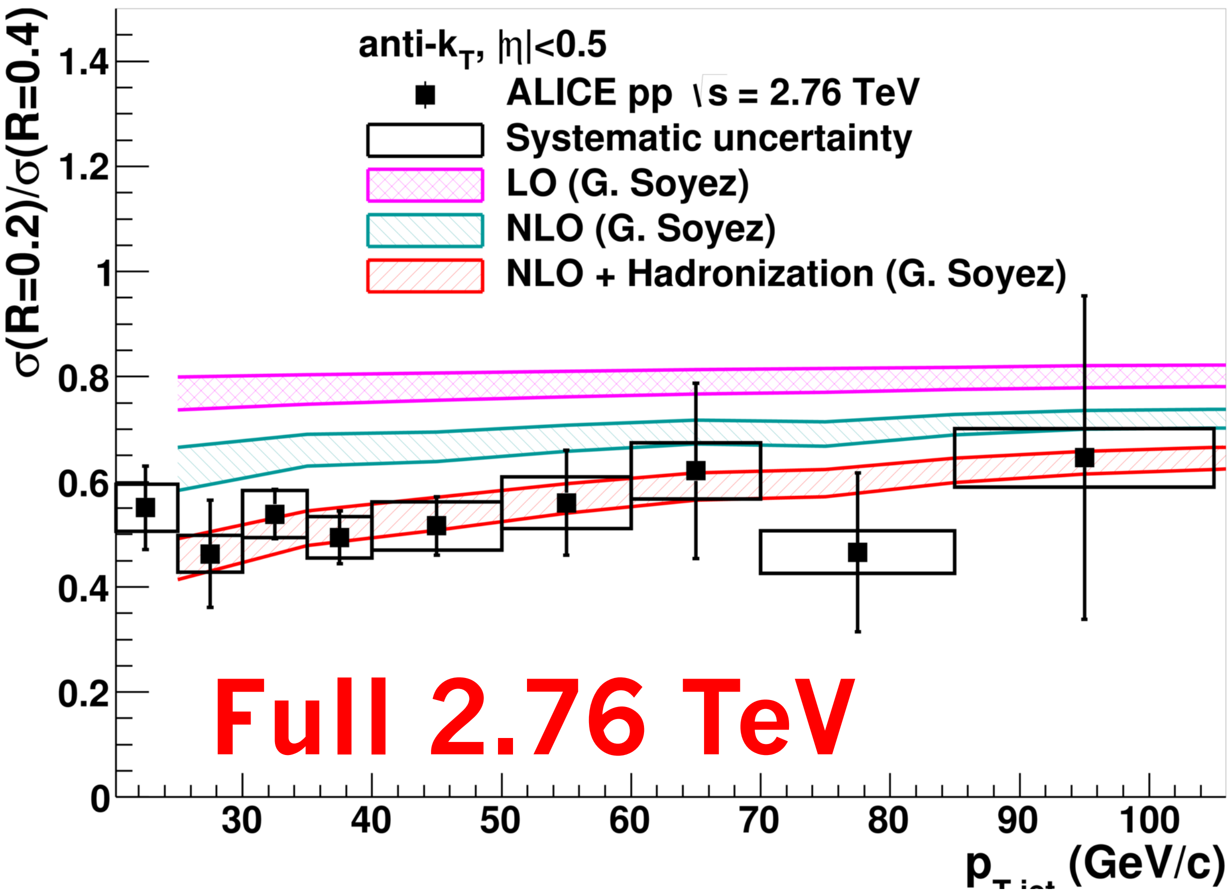


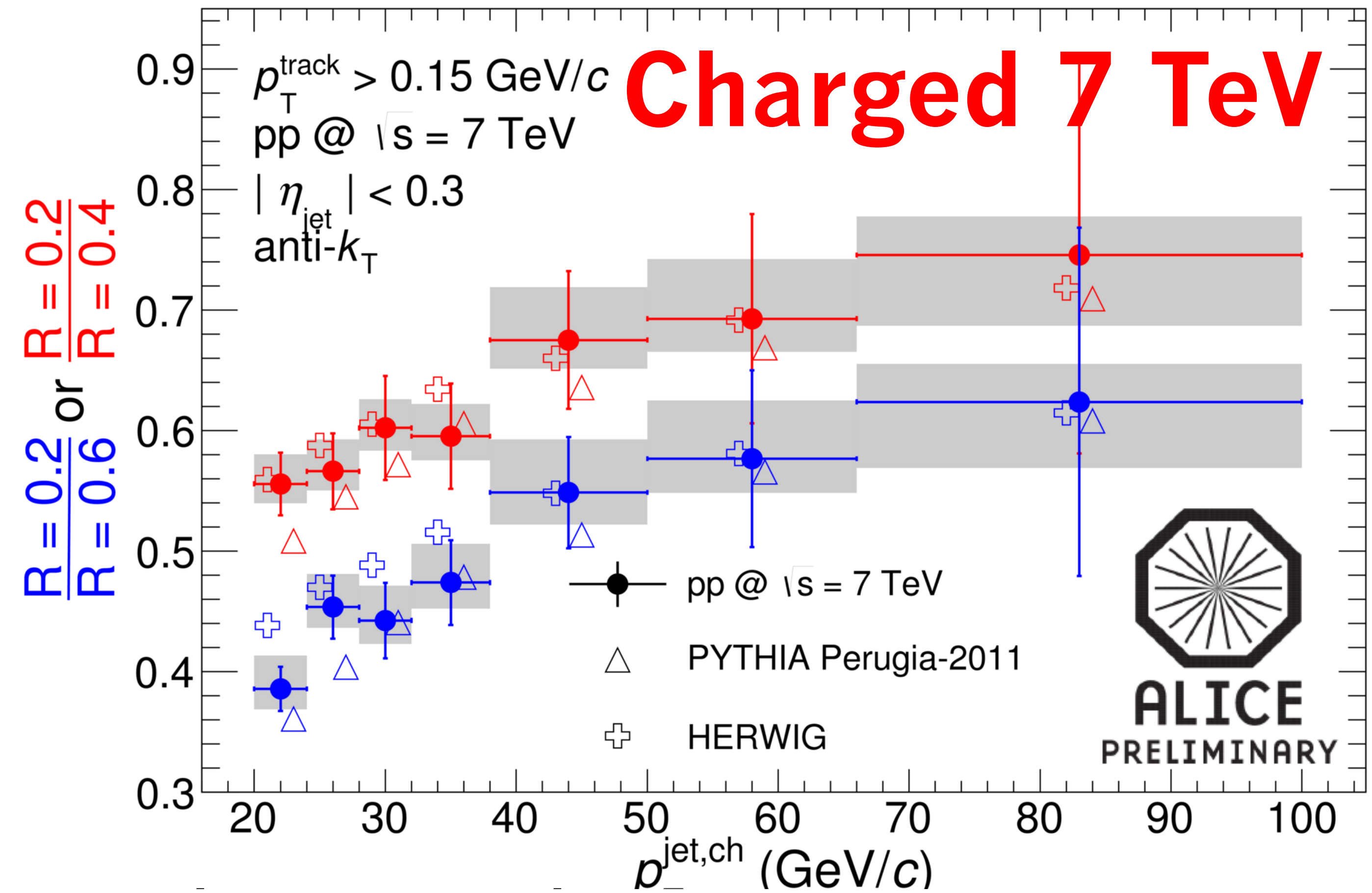
Agreement between data and NLO calculations

is good for both R = 0.2 and 0.4

Jet cross section ratio

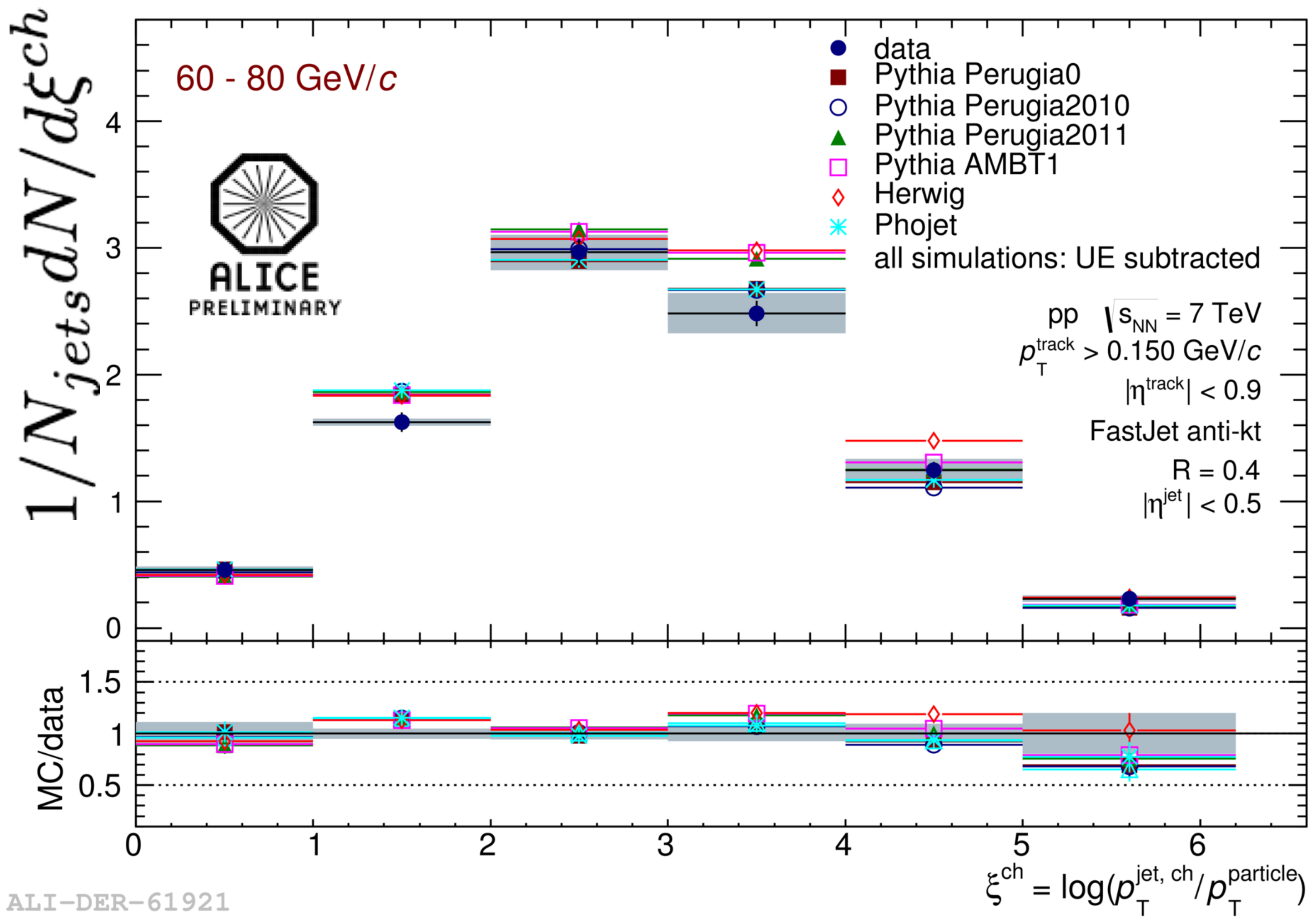
arXiv:1301.3475
PLB: 10.1016/j.physletb.2013.04.026





- Hadronization necessary for theory-data agreement
- Jet structure
- Jet broadening due to medium effects could change this ratio

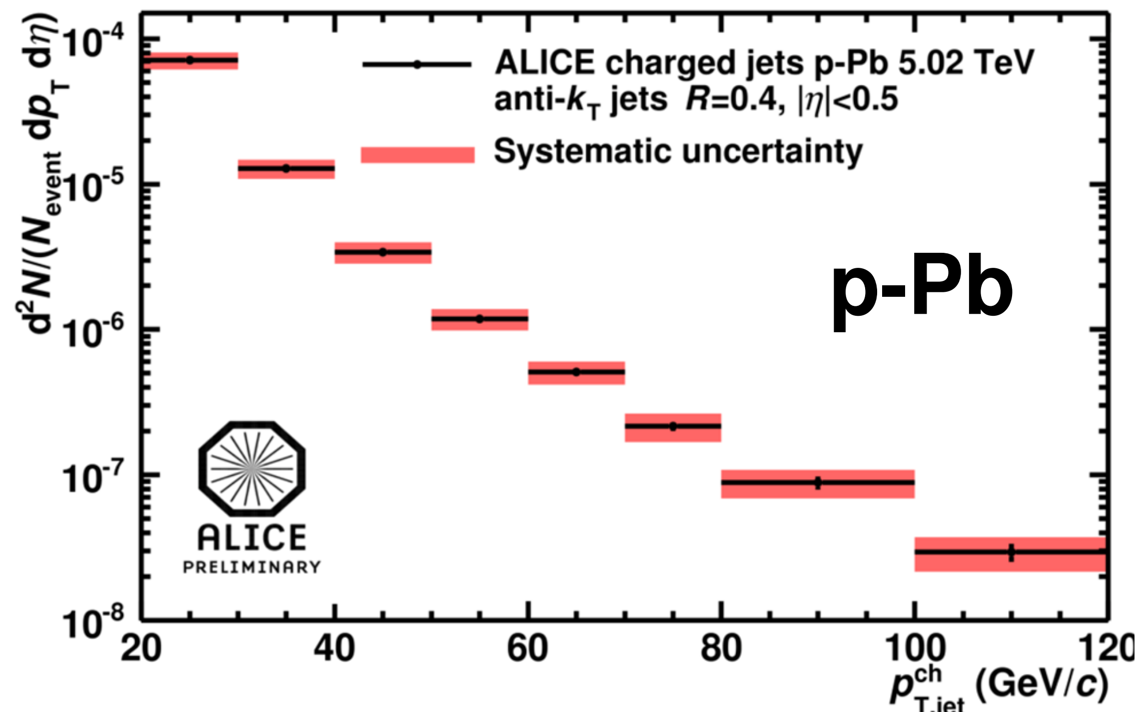
Fragmentation spectrum



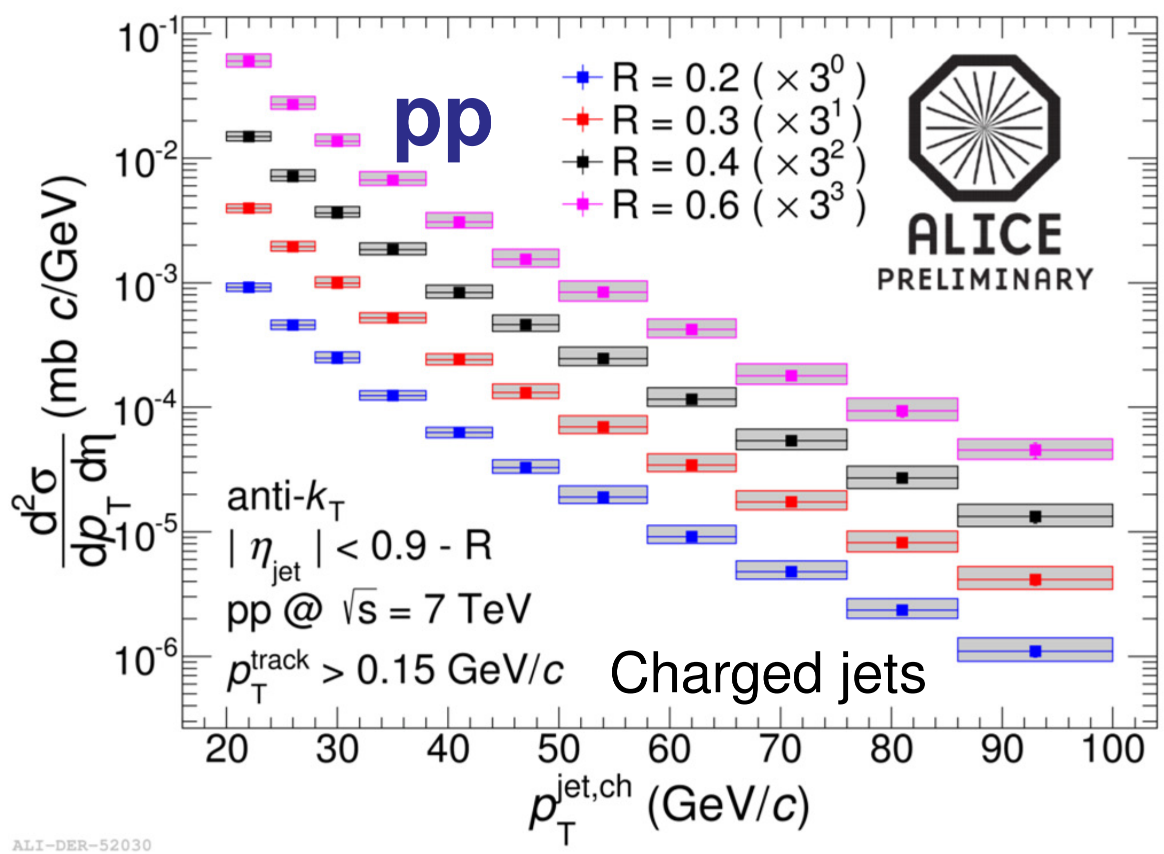
Jet constituent analyses are more differential structure measurements than cross-section ratio

Jets in p-Pb

Jet cross section in pp and p-Pb

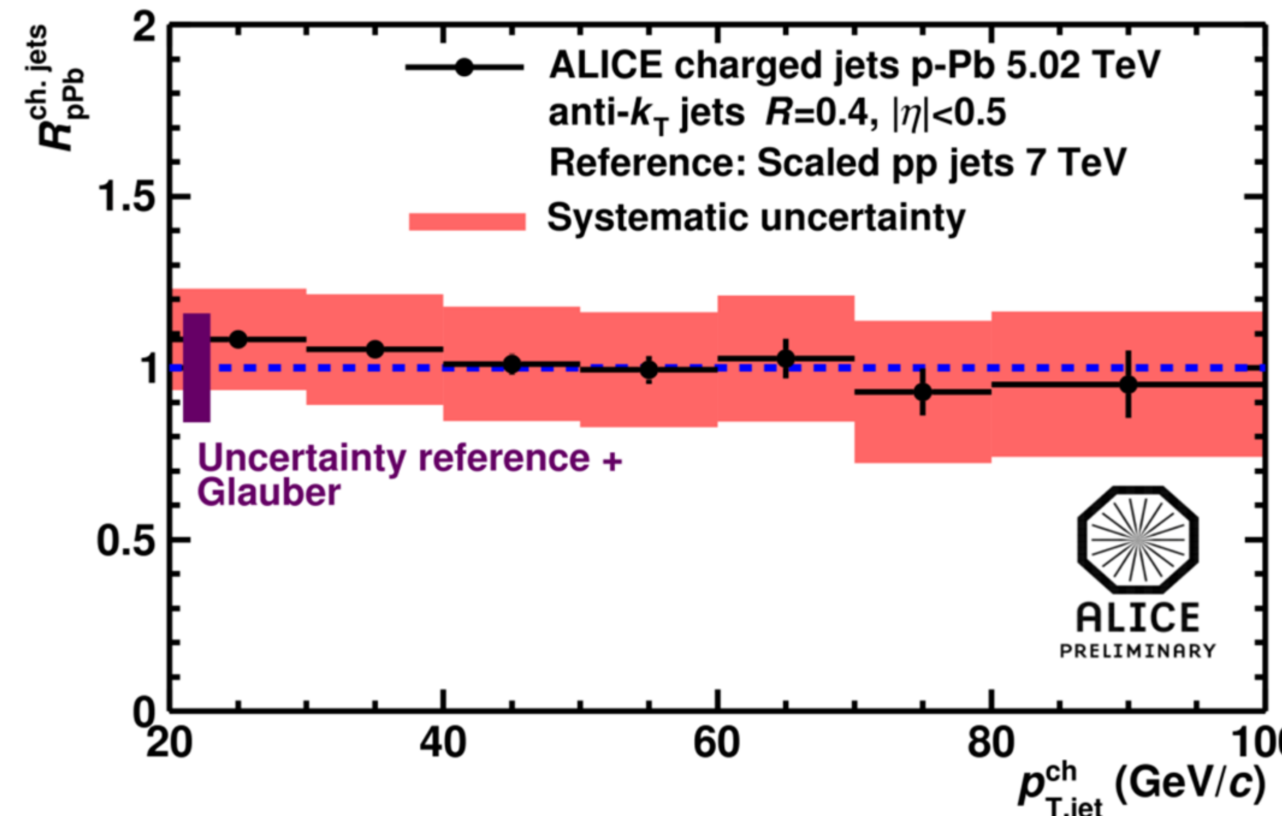


ALI-PREL-53825



ALI-DER-52030

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

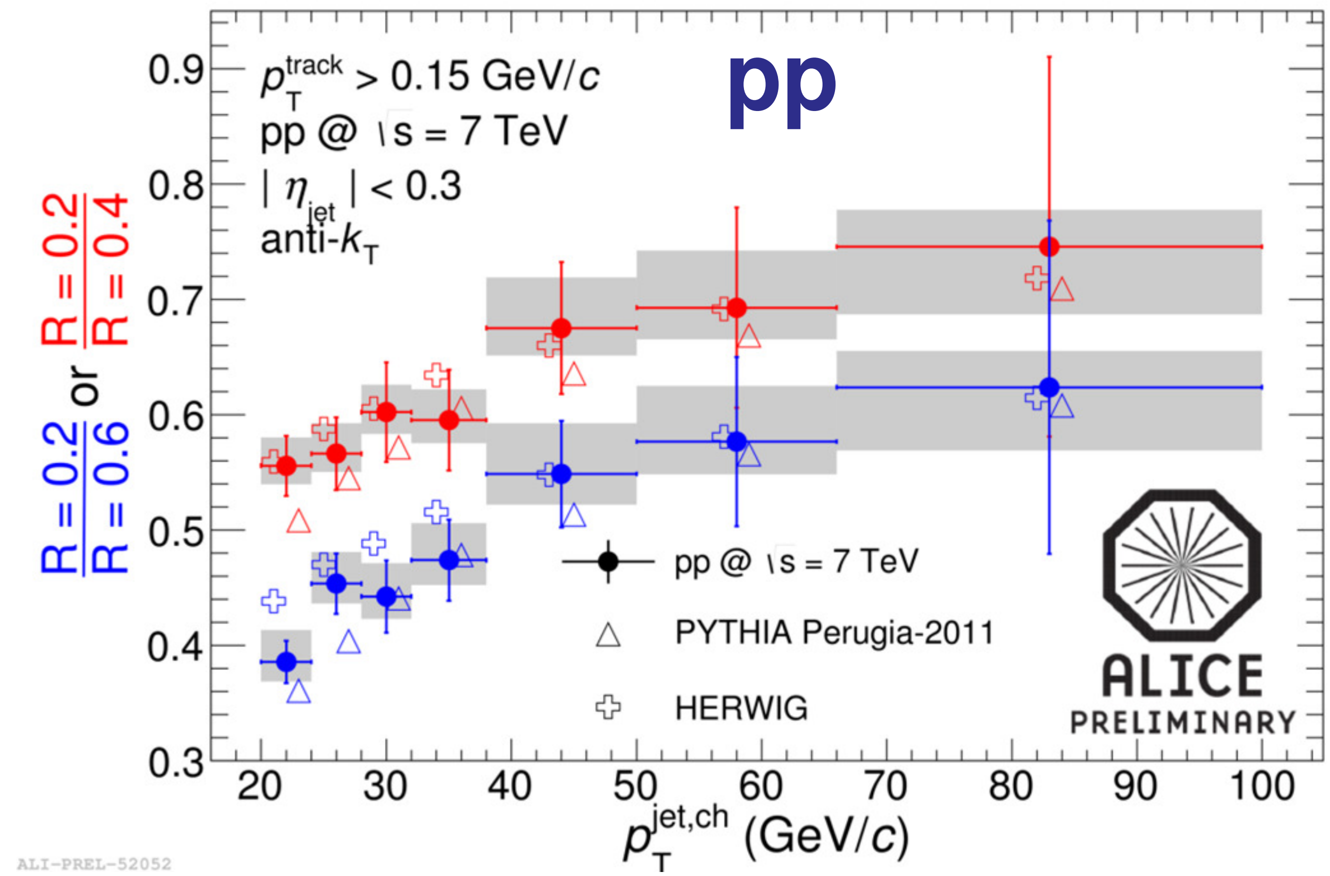


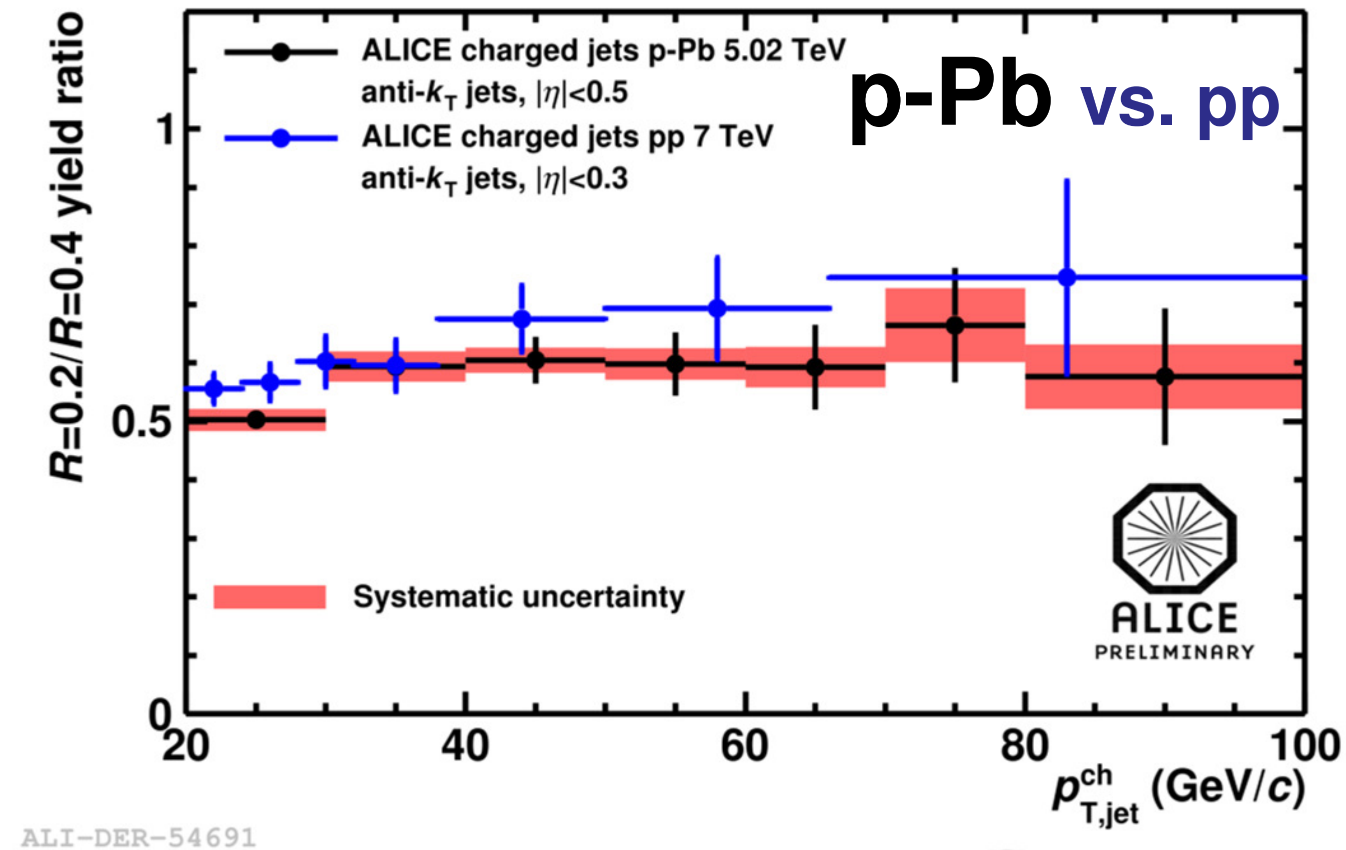
ALI-PREL-53801

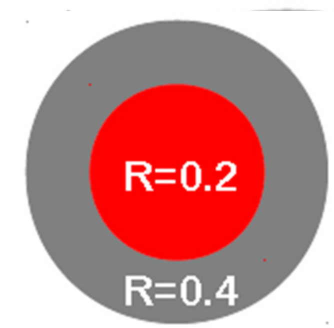
No modification of jet cross section in p-Pb relative to pp

⇒ **binary scaling holds**

Jet structure in pp and p-Pb







Ratio σ(R=0.2)/σ(R=0.4)

Sensitive to the profile of the jet energy density

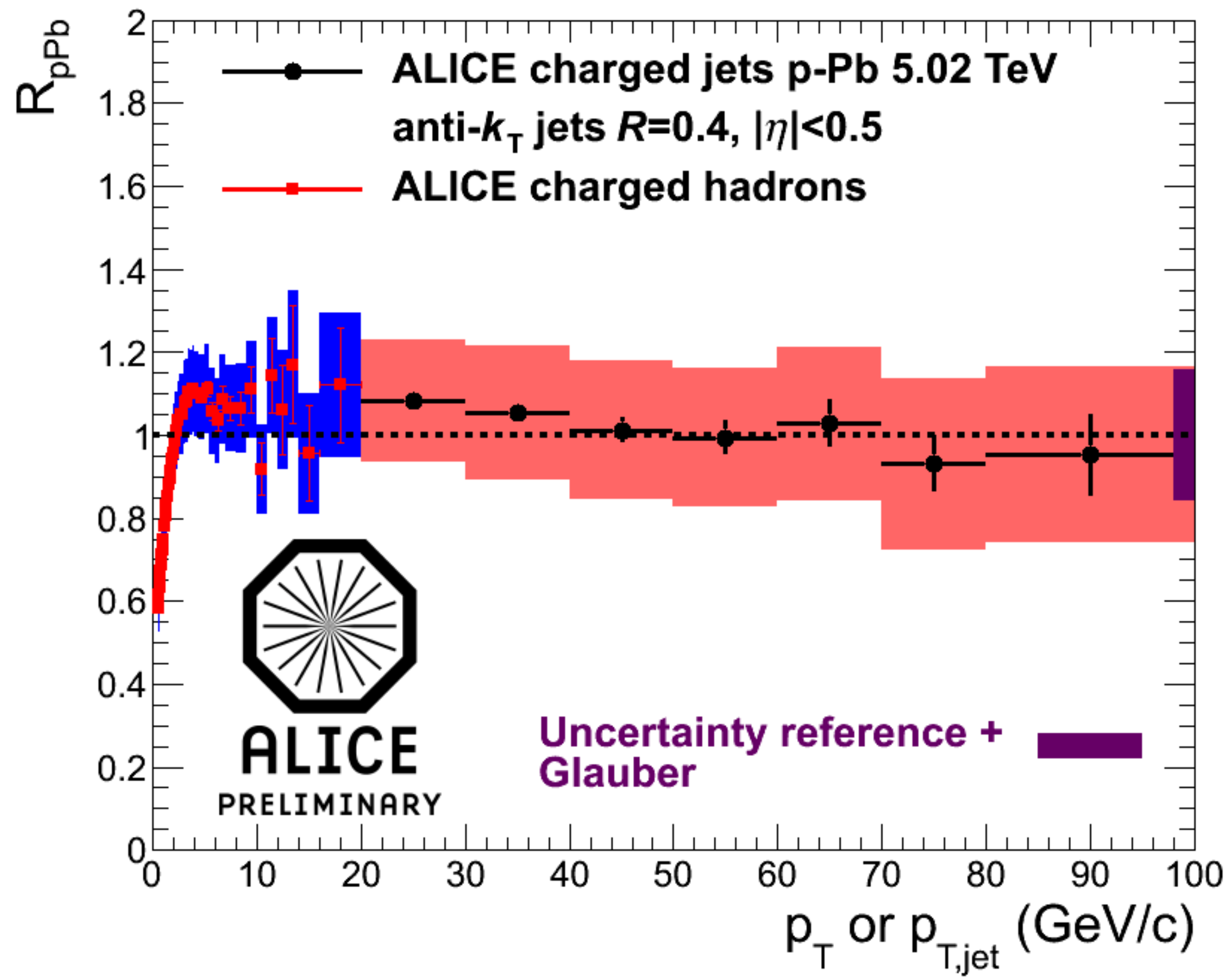
Compatible in p-Pb and pp (and PYTHIA)

No indication of jet structure modification due to CNM effects

Note: comparison between different CMS

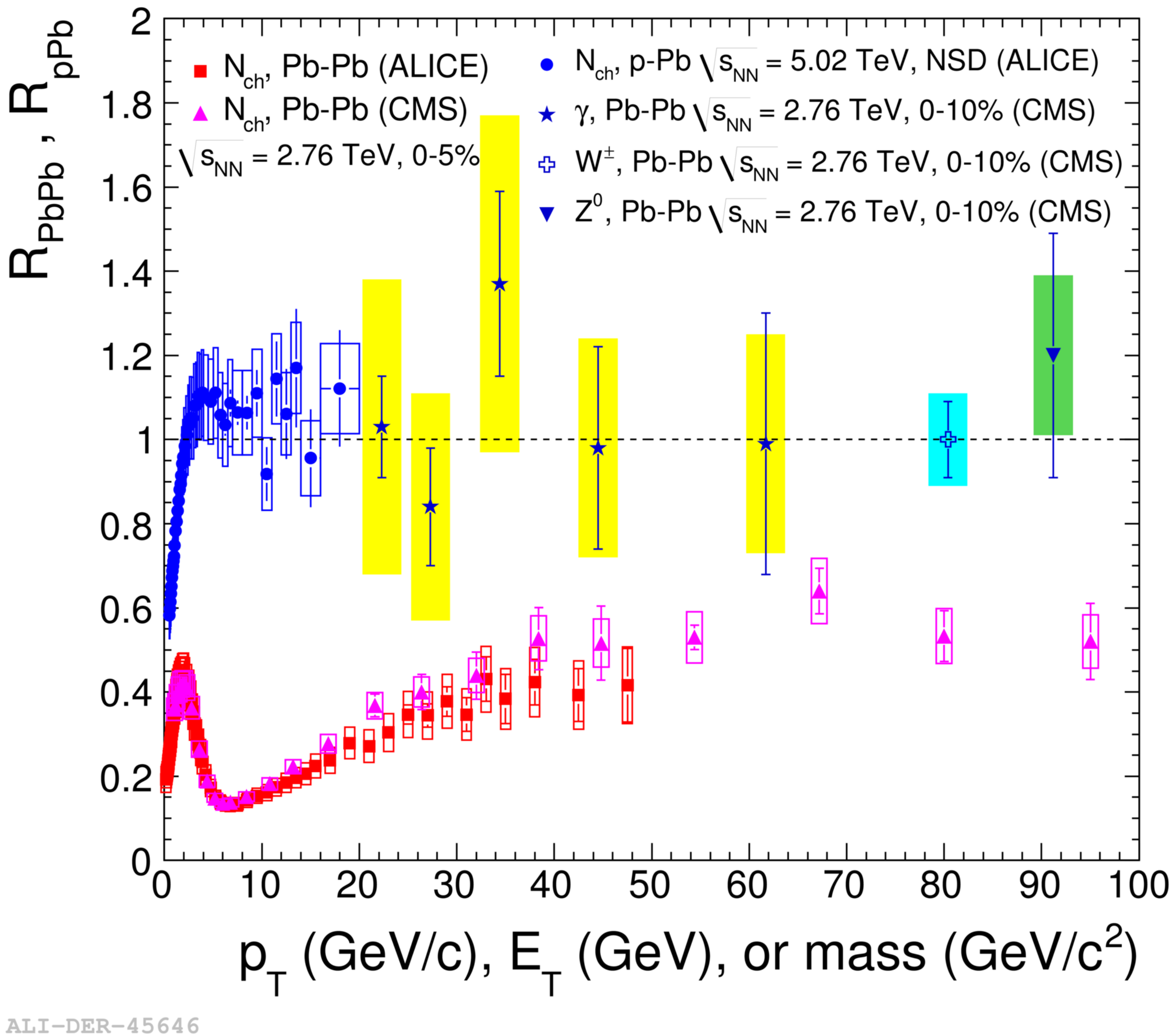
pp and p-Pb jets

- We have established a good baseline for heavy ion jet measurements by quantifying observables in both pp and p-Pb
  - pp jets observables agree well with models
- Jets do not appear to be greatly modified in p-Pb compared to pp
  - more differential analyses are on-going.



Jets in Pb-Pb

R_{Pb-Pb} for single particles



ALICE-arxiv:1210.4520, 1208.2711

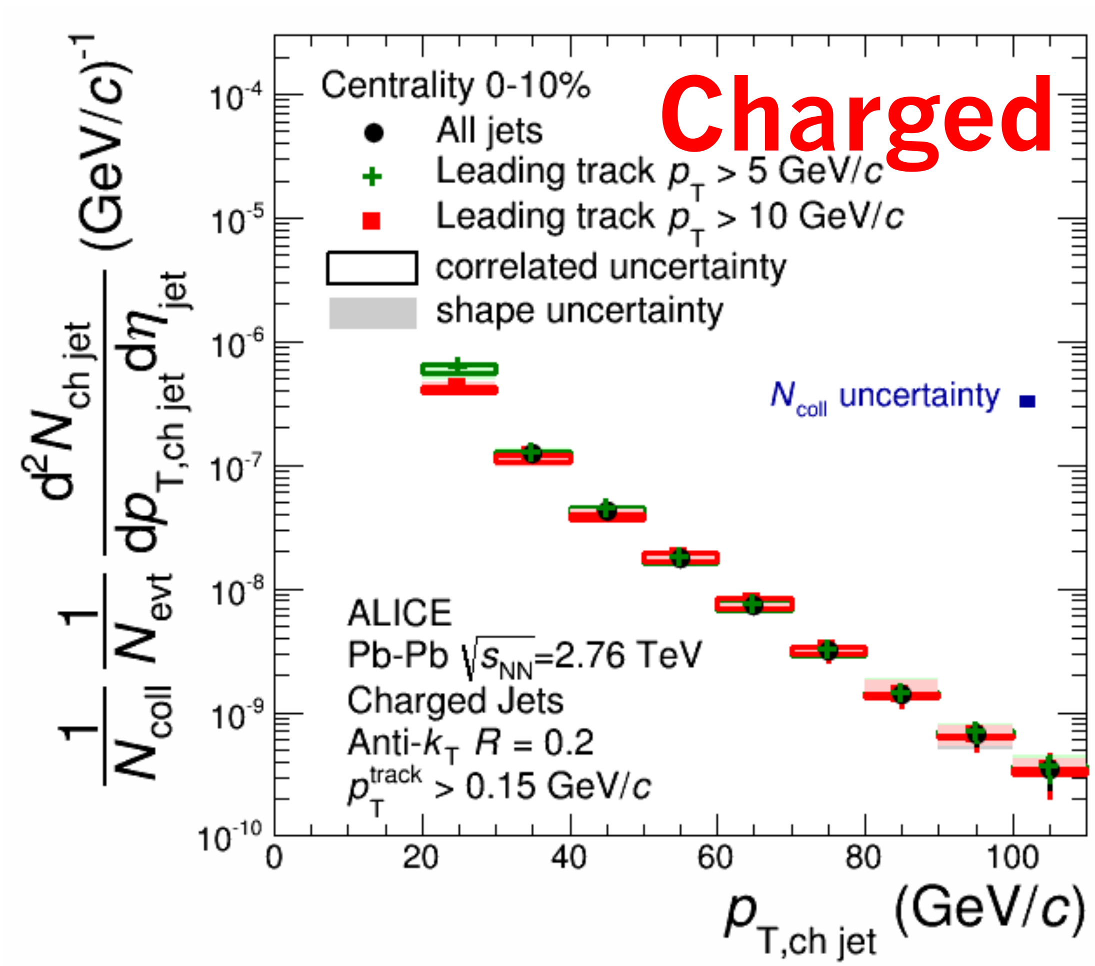
CMS-arxiv:1205.6334, 1102.5435, 1201.3093

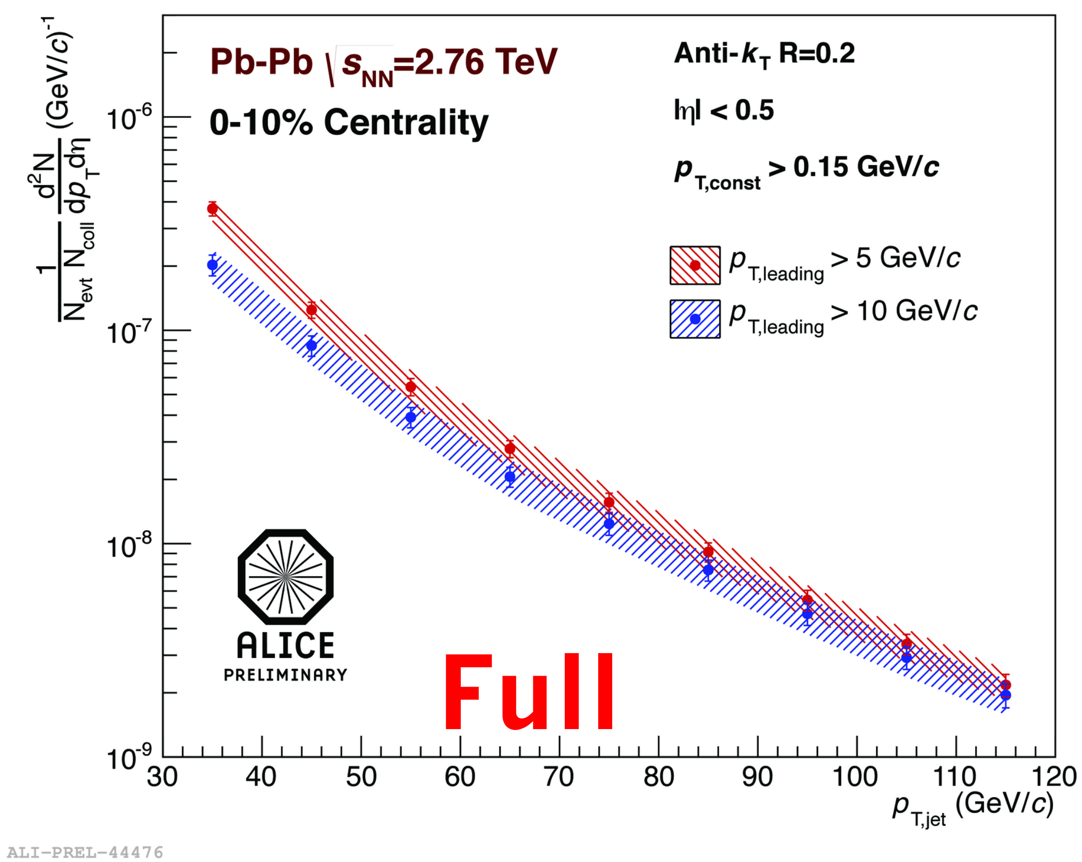
- Charged hadrons are suppressed in heavy ion collisions
- Need to quantify suppression mechanisms

⇒Jet spectra and structure

Heavy ion challenge

- **Jet finding algorithms will cluster "jets" from soft background**
  - Combinatorial jets (fake)
  - Depend on R and jet constituent p_T
- **2 methods to remove fake jets**
  - Leading track bias, h-jet correlations



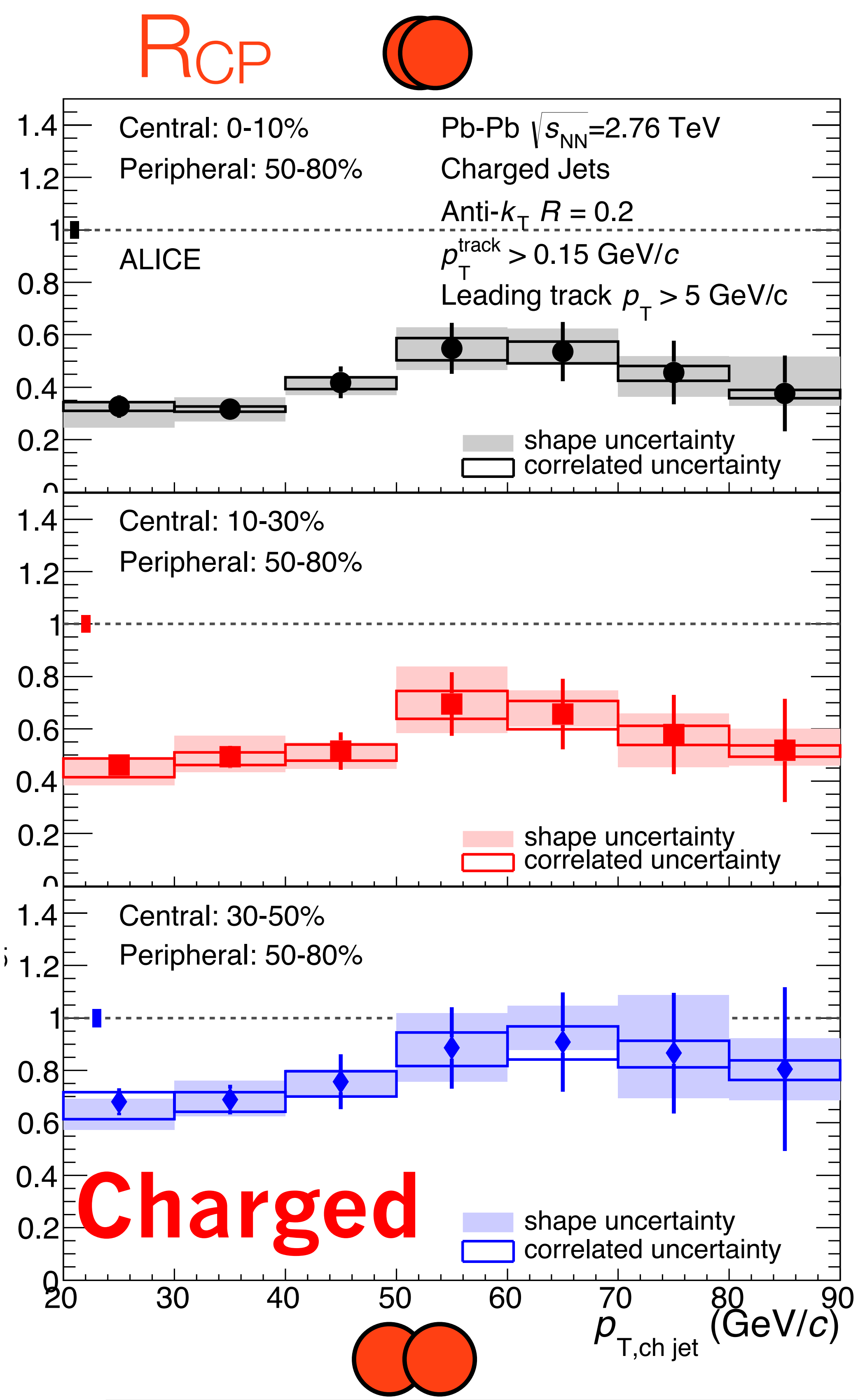


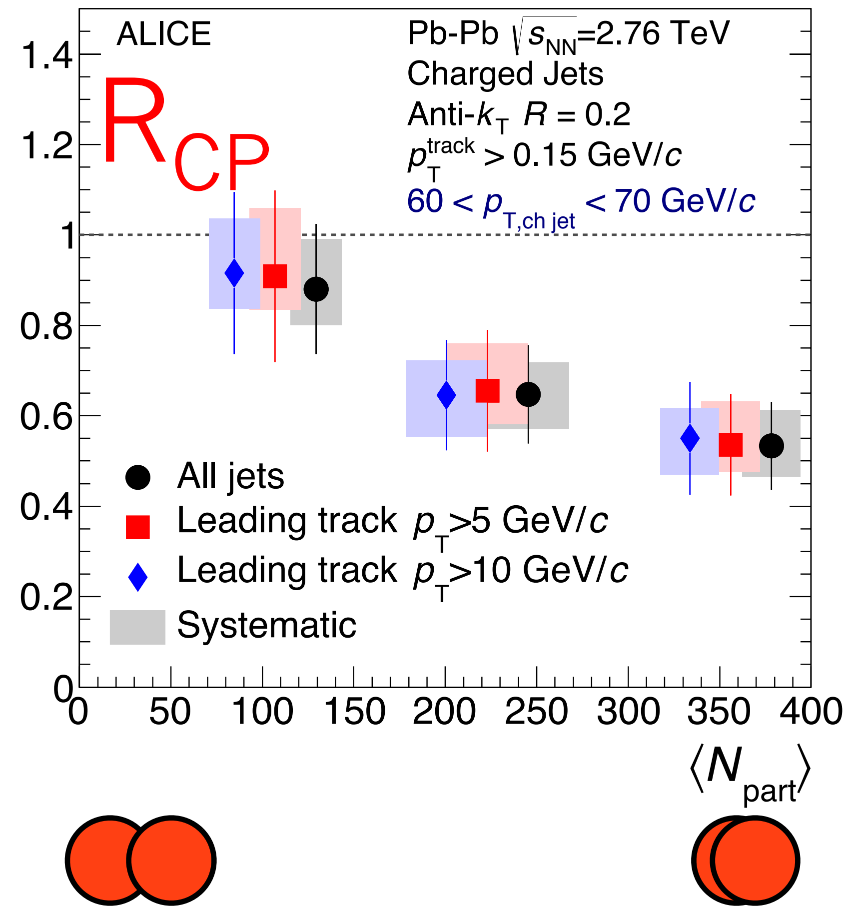
arXiv:1304.6668

Leading track bias removes combinatorial jets but biases the fragmentation
ALICE uses a leading track bias of $p_{T,track}$ > 5 GeV/c

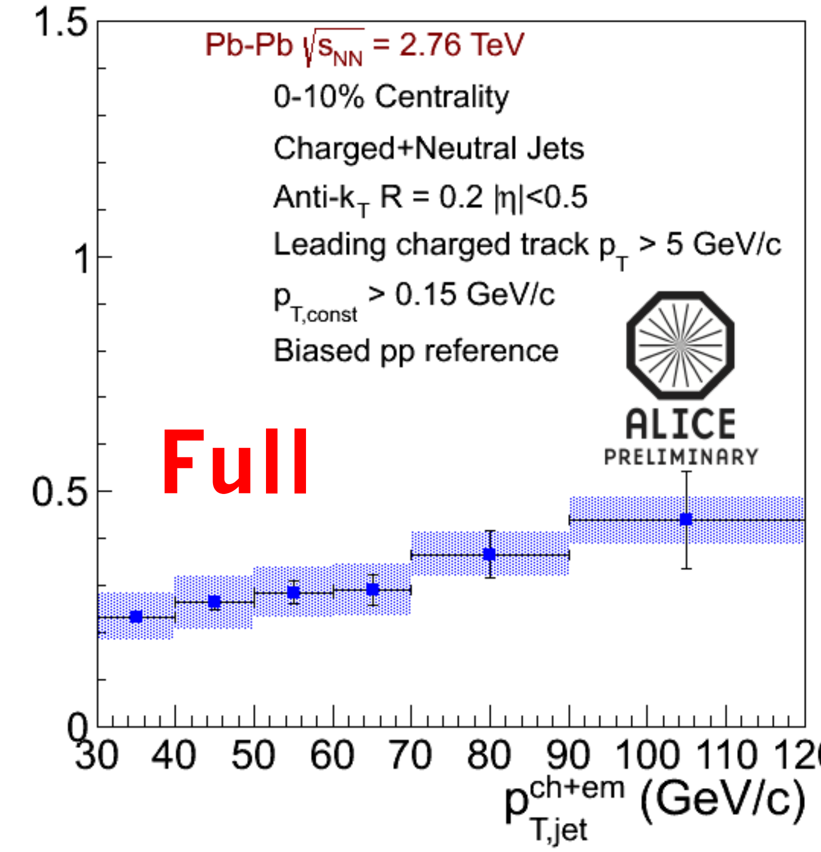
Jet R_{AA} and R_{CP}

R_{CP}



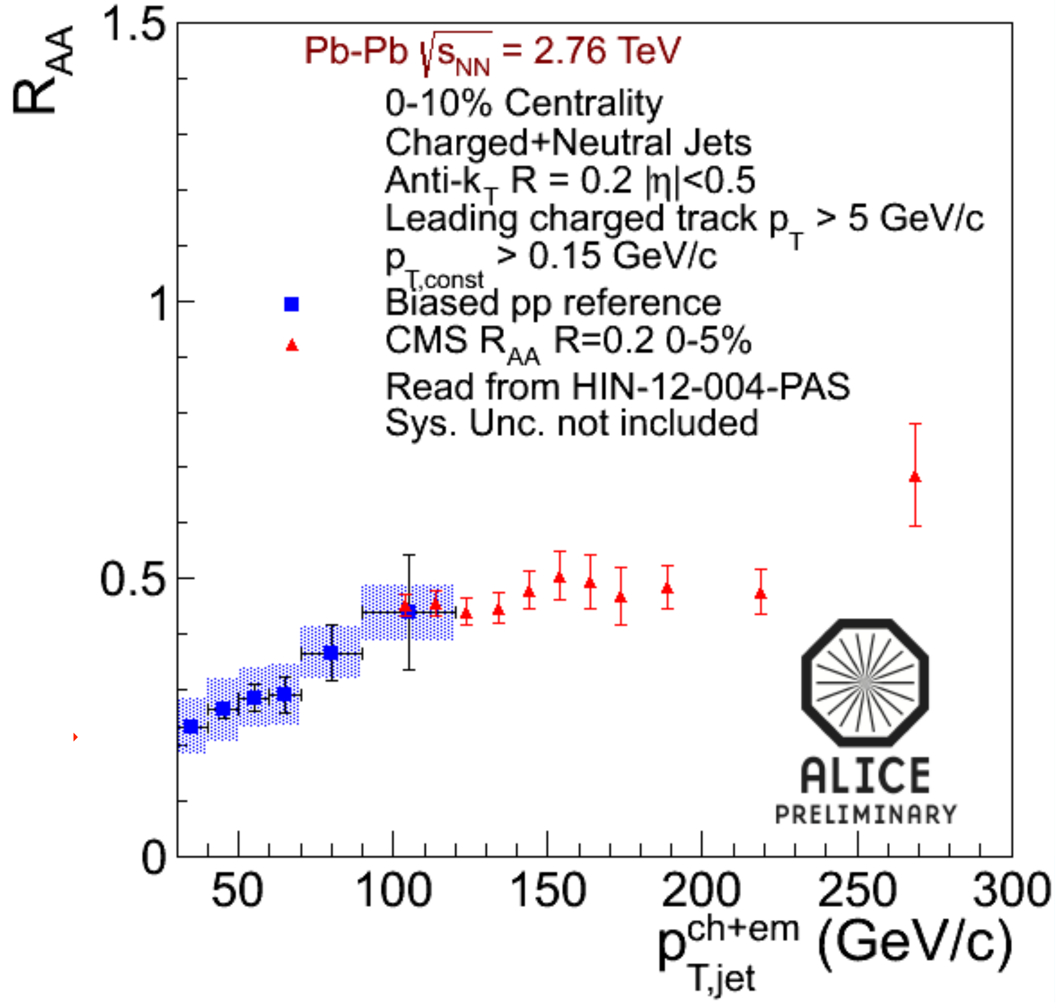


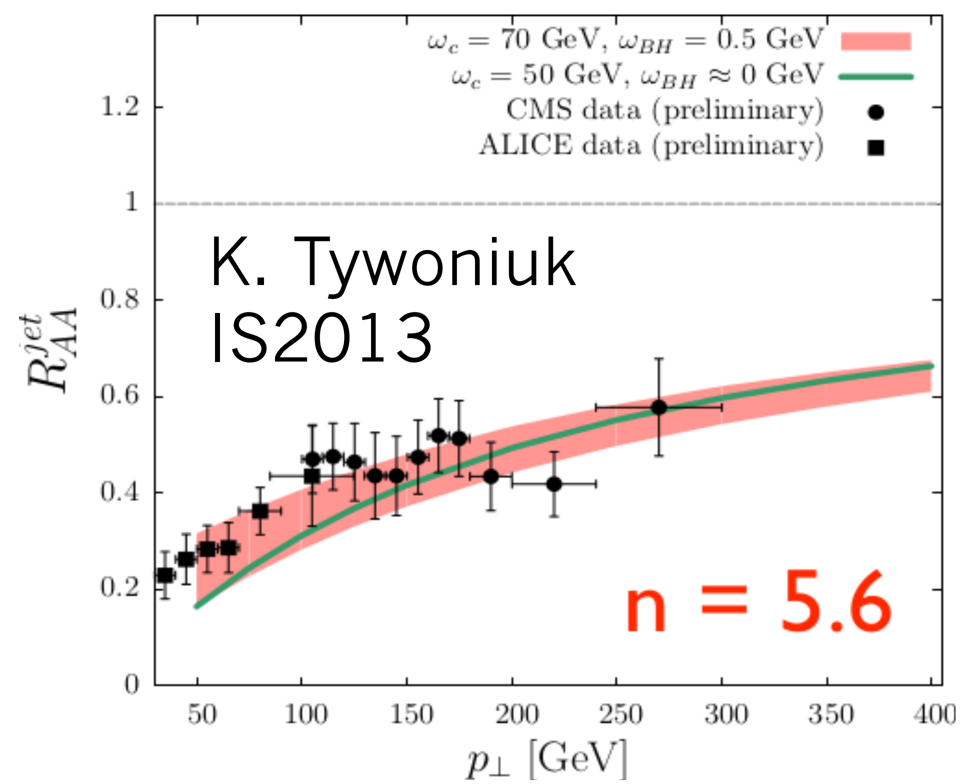
R_{AA}



Jets are suppressed in a centrality and p_T dependent manner

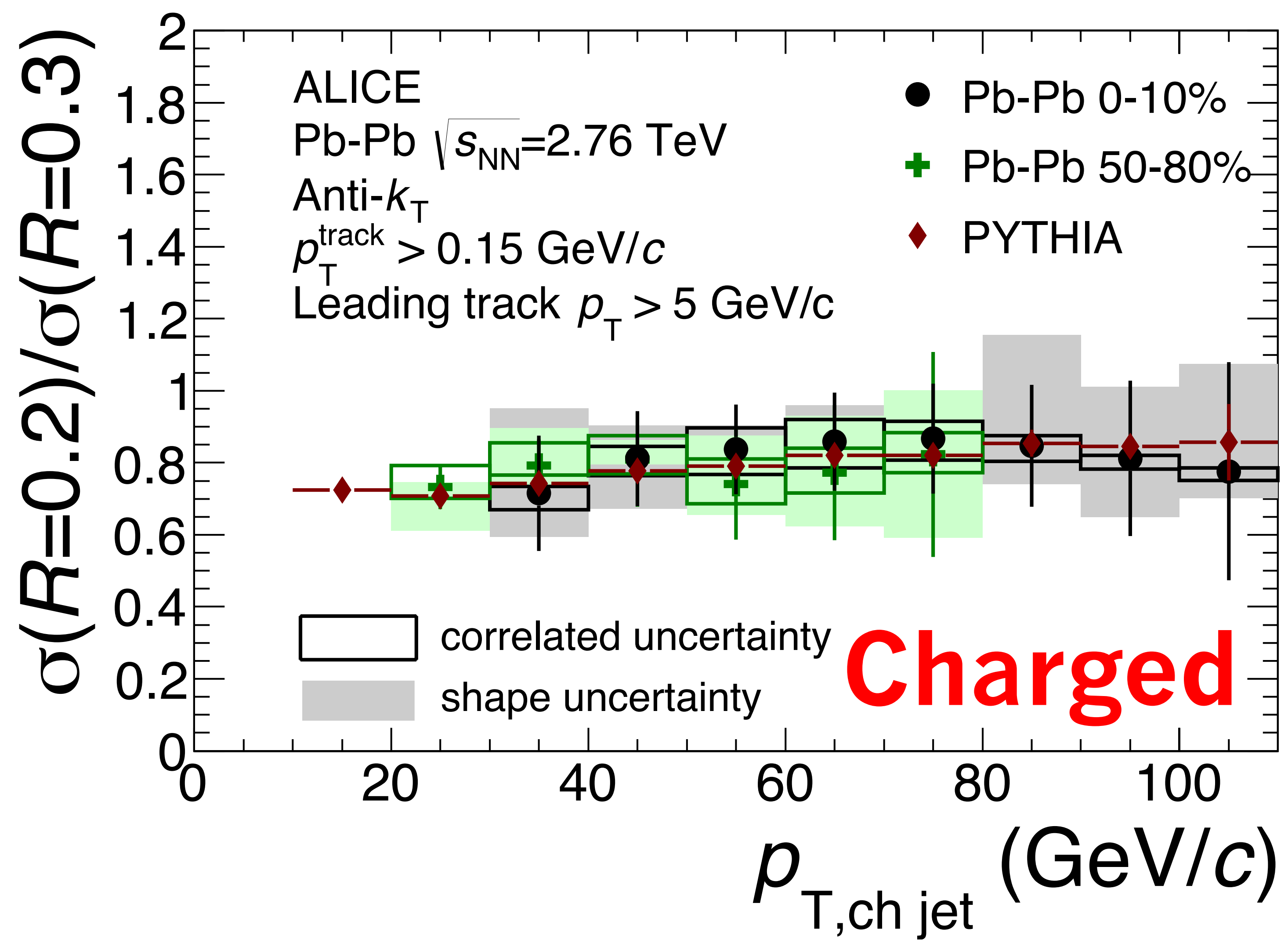
R_{AA} models and comparison





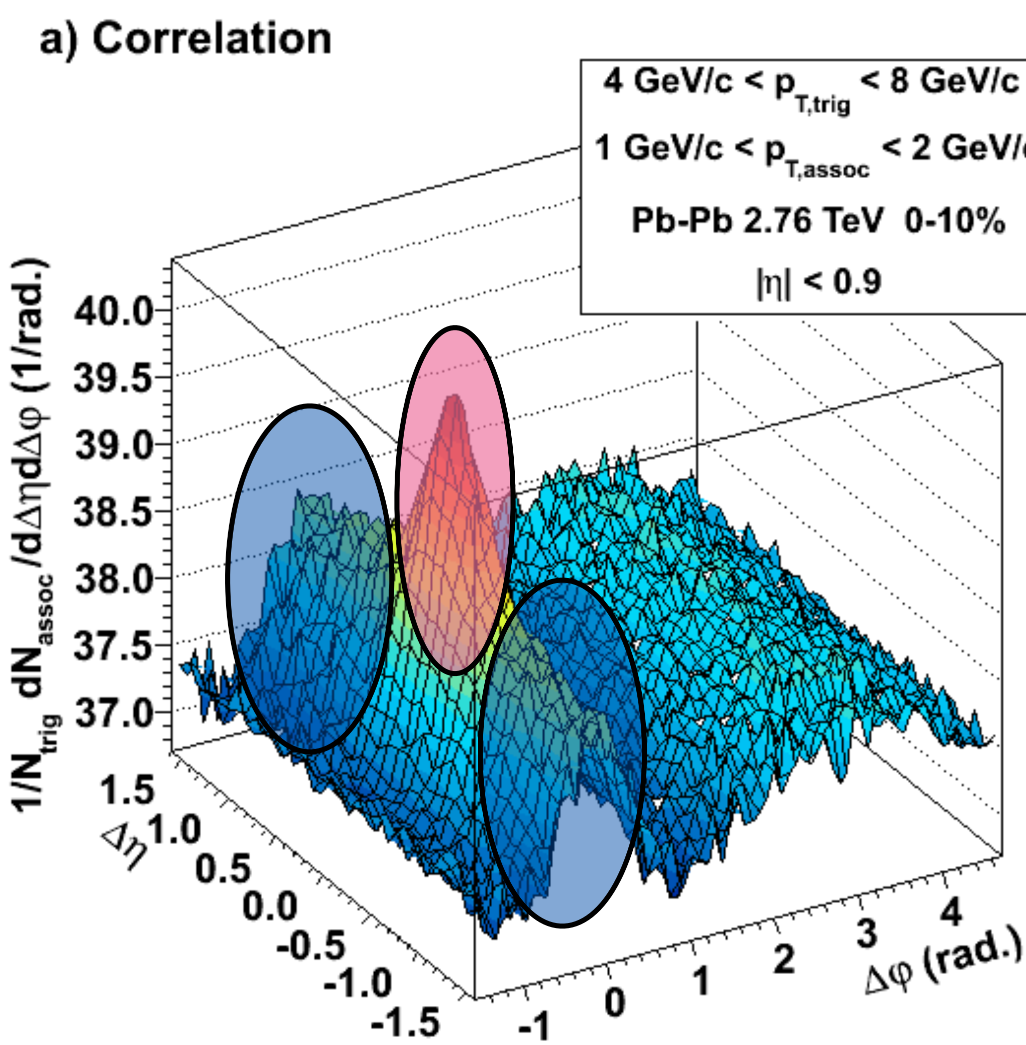
- Direct connection between charged hadron and jet R_{AA} requires theory interpretation
- Understanding jet quenching requires well developed models

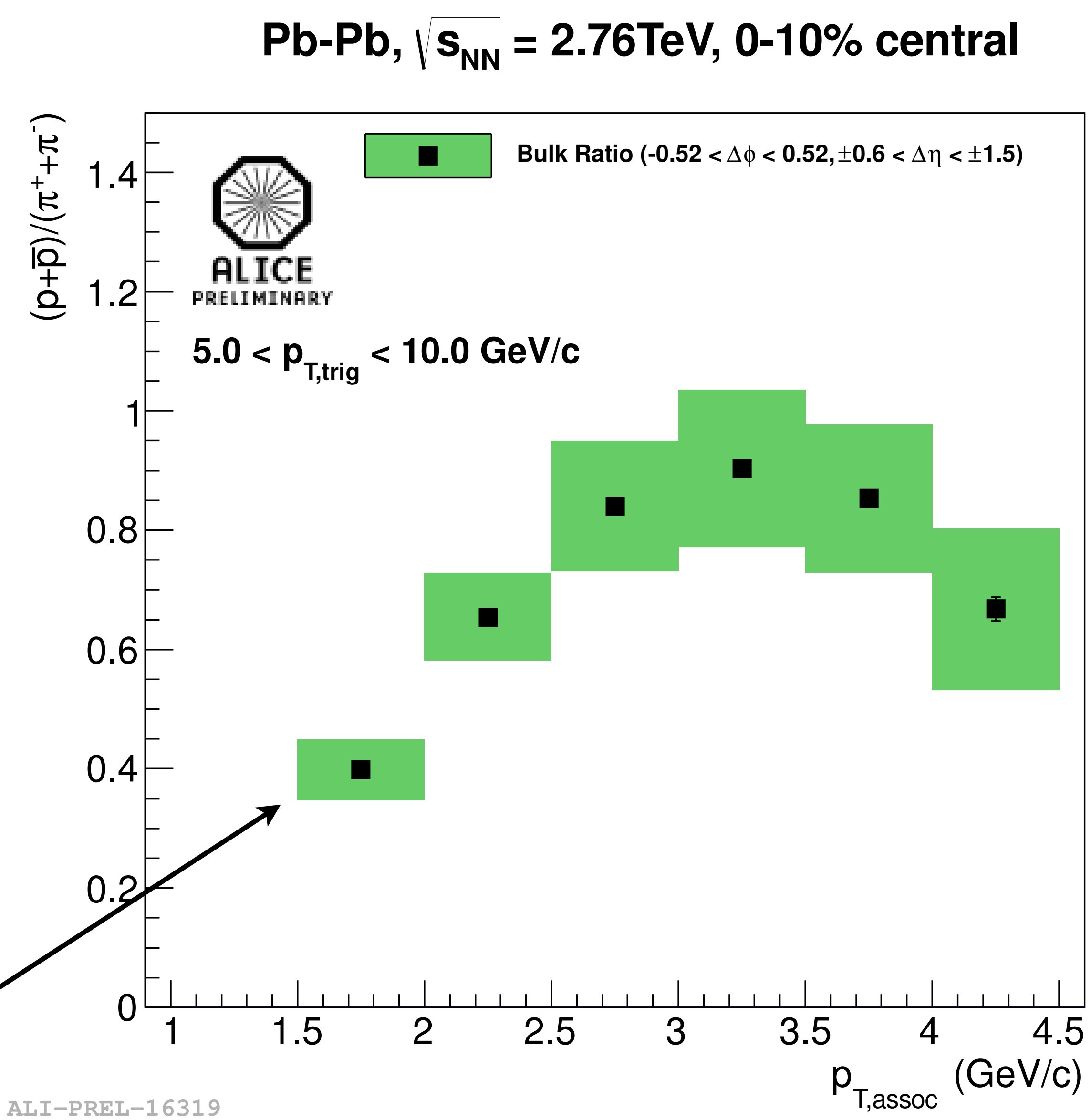
Ratio of jet spectra

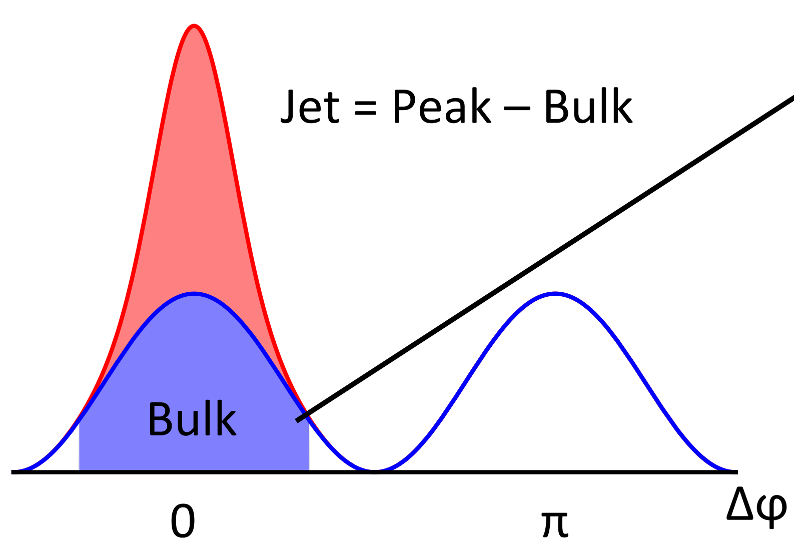


- No evidence of jet structure modification in jet core
- Charged jet ratio σ(R=0.2)/σ(R=0.3) consistent with vacuum jets (PYTHIA) no centrality dependence

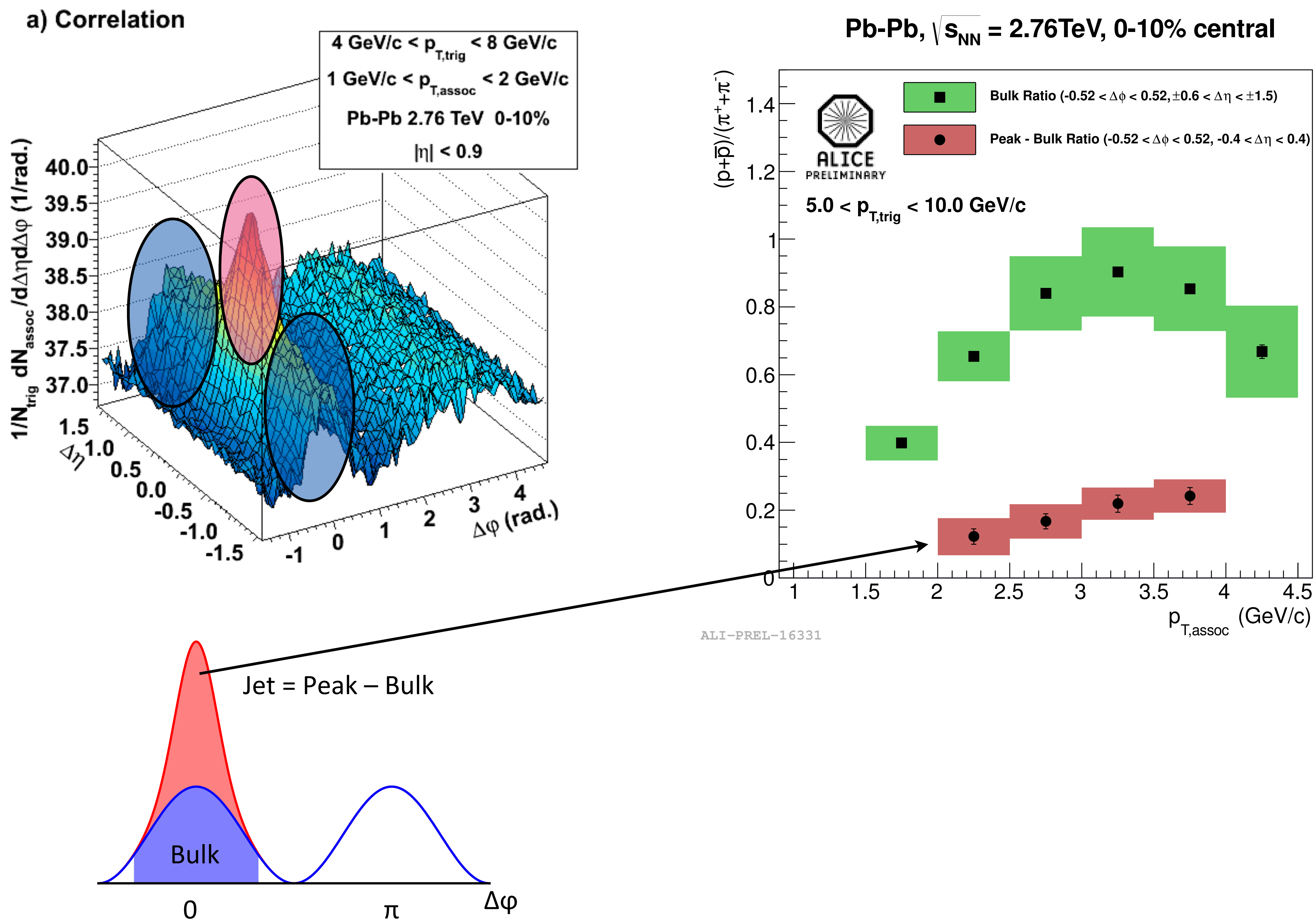
Intermediate p_T in the bulk in the jet



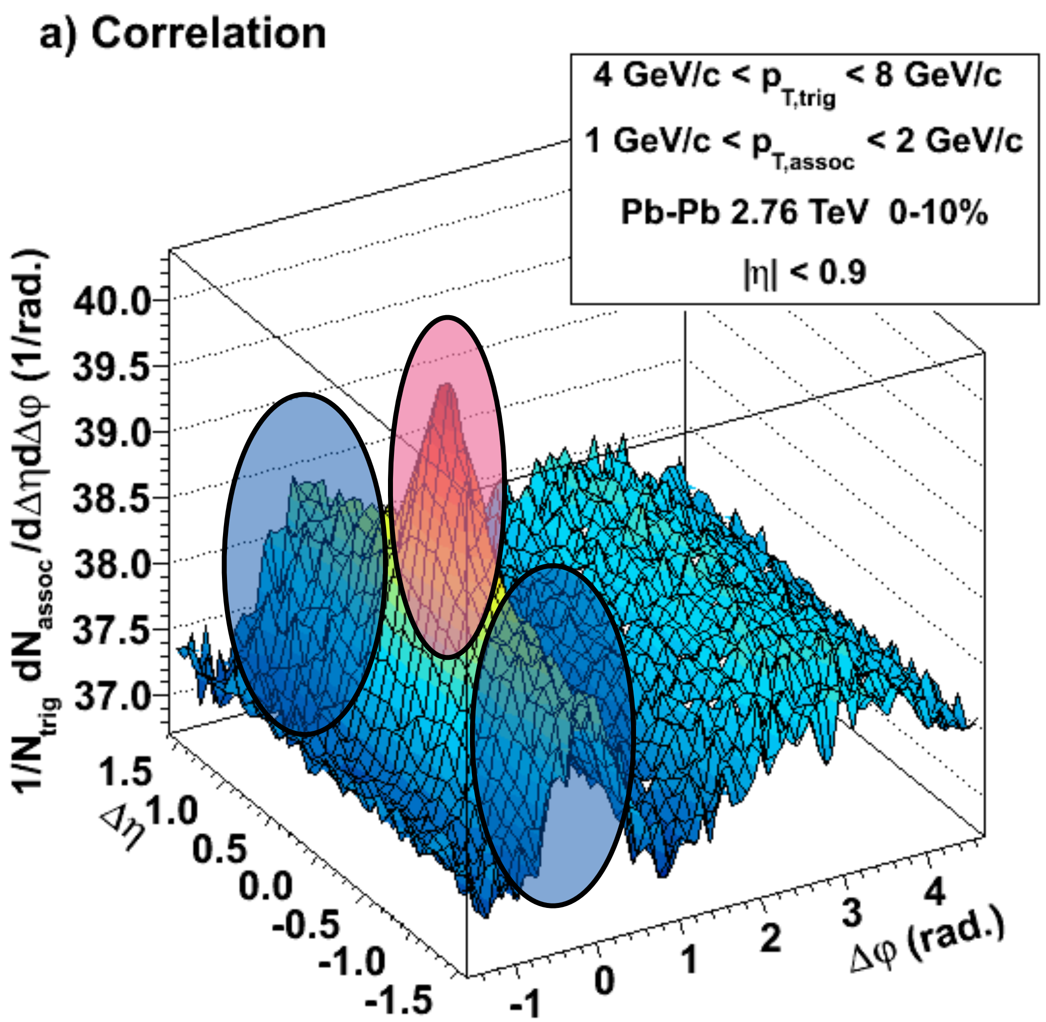


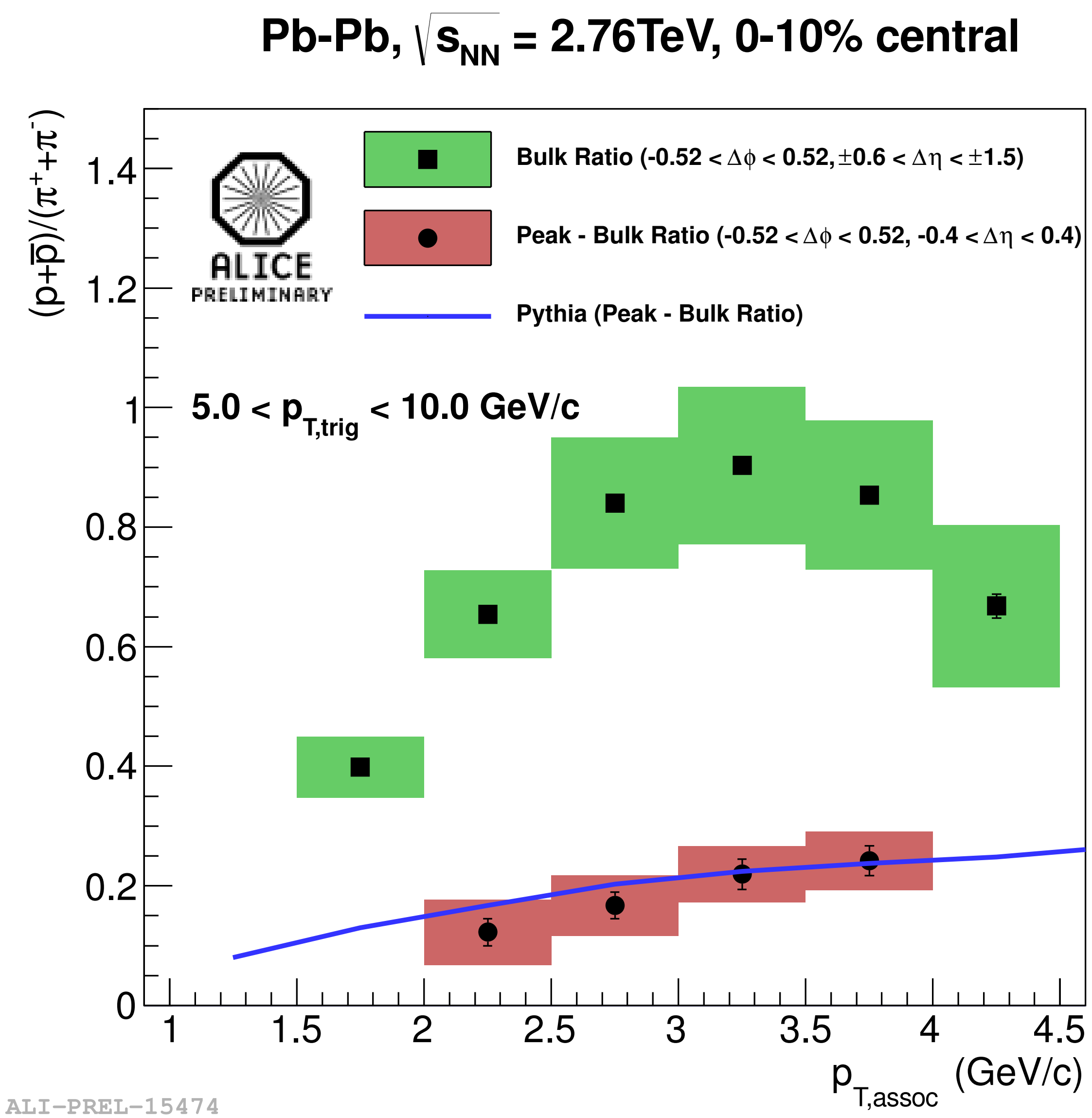


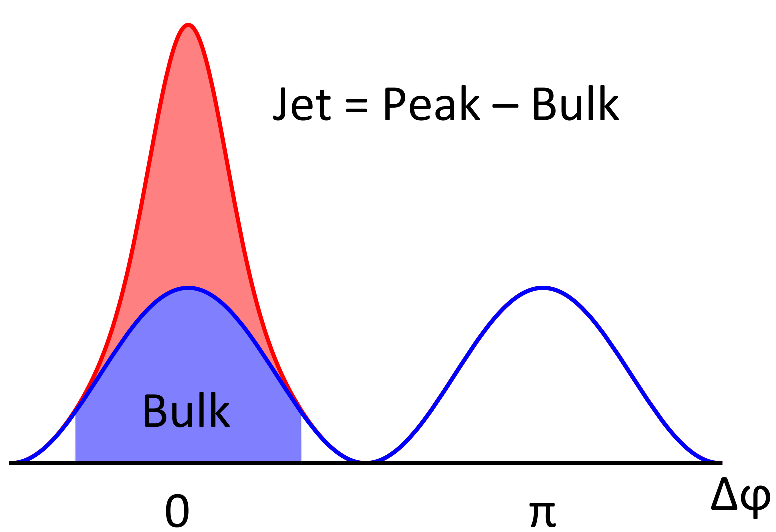
Intermediate p_T in the bulk in the jet



Intermediate p_T in the bulk in the jet







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

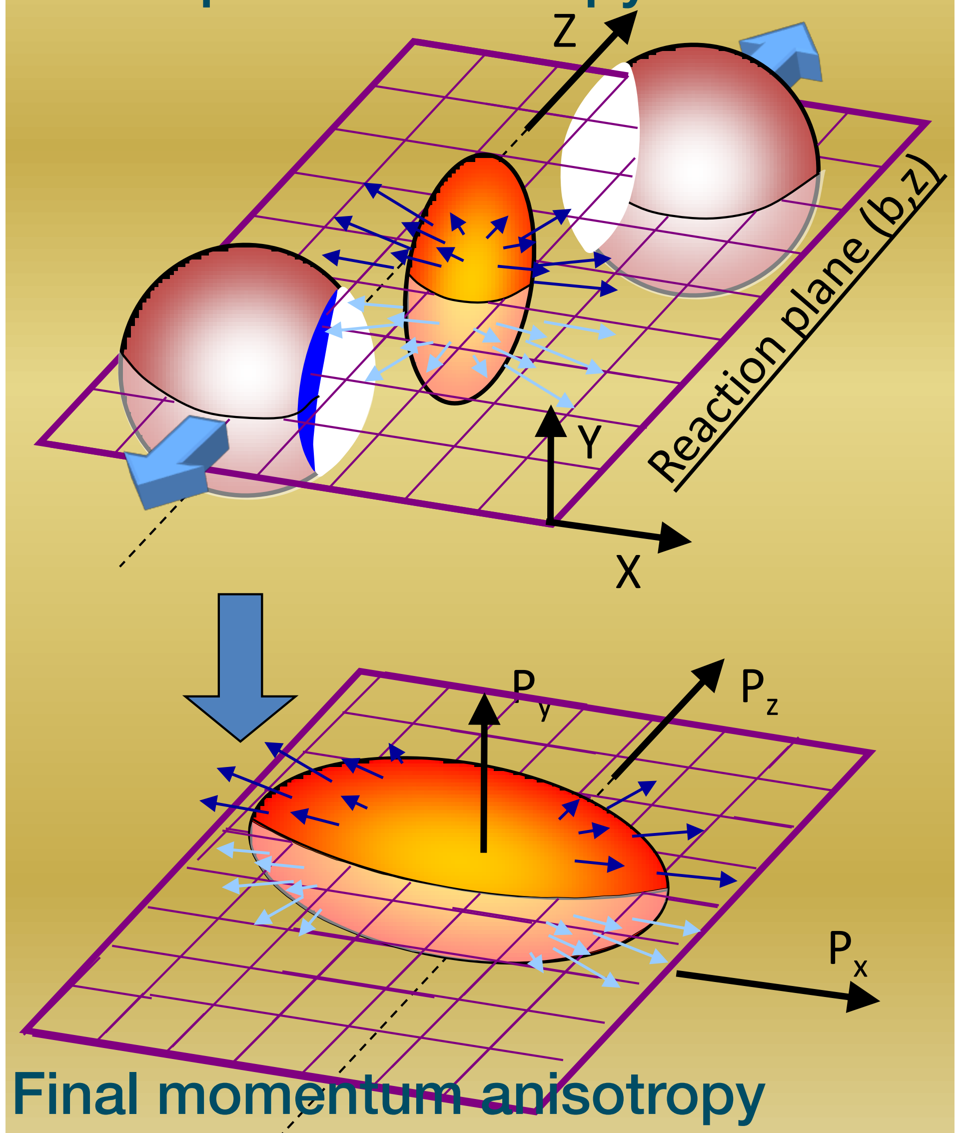
Bulk region: p/π ratio strongly enhanced – compatible with overall baryon enhancement

The "baryon anomaly" is a bulk effect!

Jet particle ratios not modified in medium?

Particle flow: Collective motion of particles

Initial spatial anisotropy



Final momentum anisotropy reflected in azimuthal distributions

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

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

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

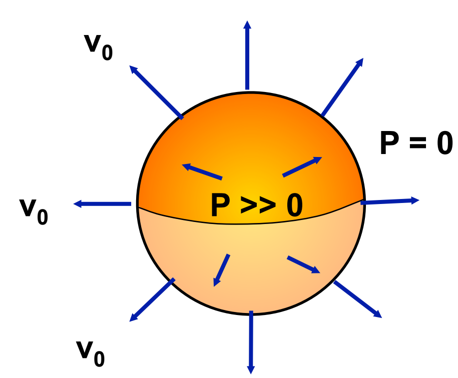
The initial spatial anisotropy evolves
→Momentum-space anisotropy

Fourier expansion of azimuthal distributions

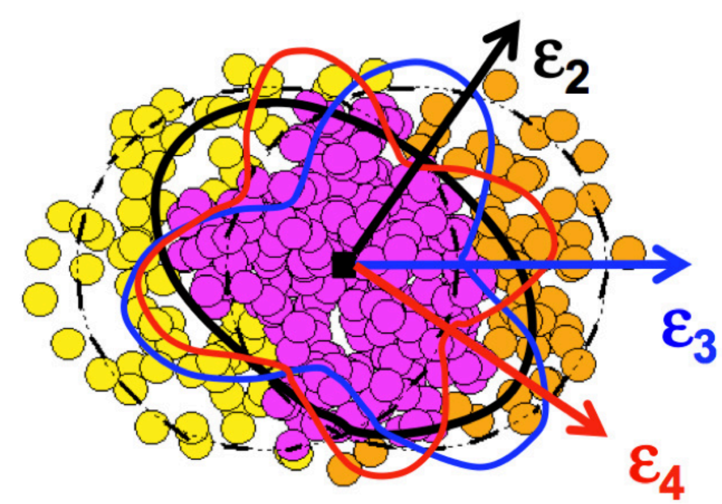
$$\frac{dN}{d\varphi} \propto 1 + 2v_1\cos[\varphi - \Psi_1] + 2v_2\cos[2(\varphi - \Psi_2)] + 2v_3\cos[3(\varphi - \Psi_3)] + ..$$

$v_1 = \langle \cos(\varphi) \rangle$ "*directed flow*" $v_2 = \langle \cos(2\varphi) \rangle$ "*elliptic flow*"

Isotropic (radial) flow

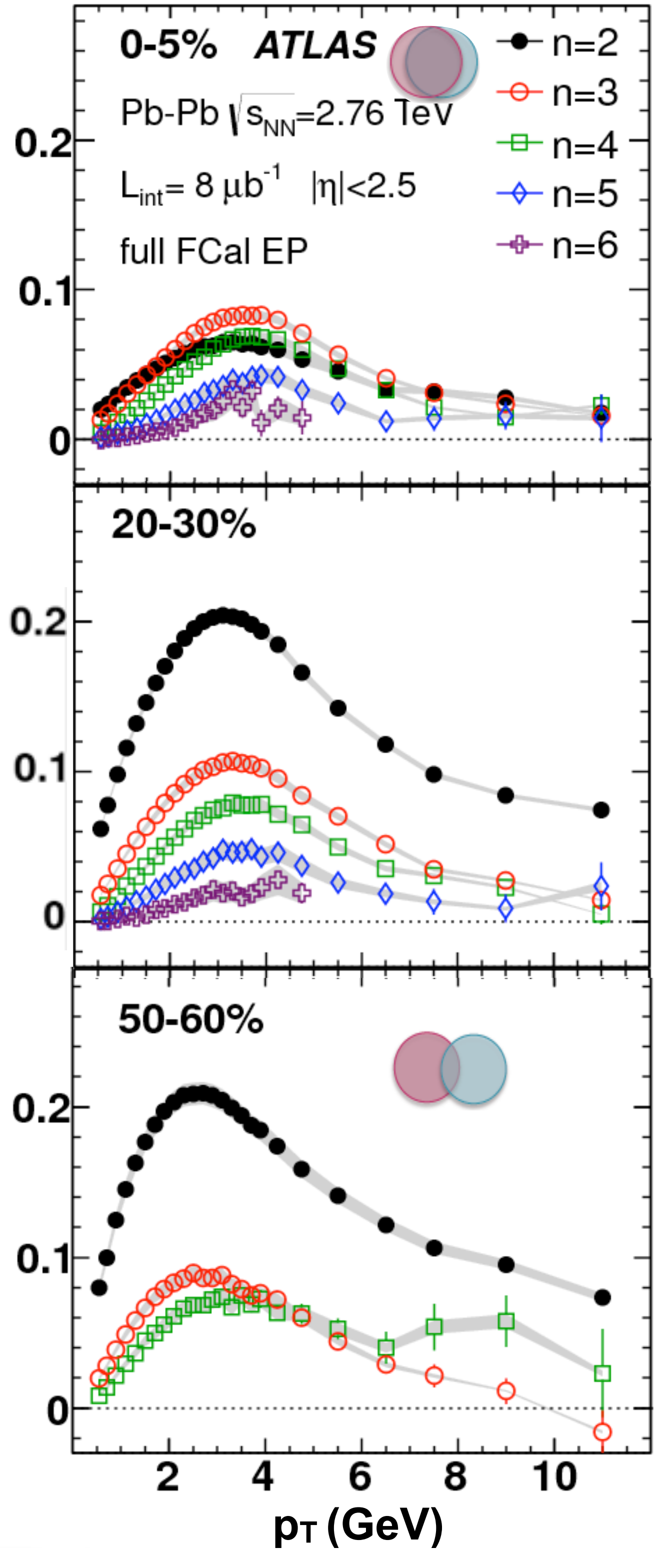


Not a smooth almond



Anatomy of flow harmonics (v_n)

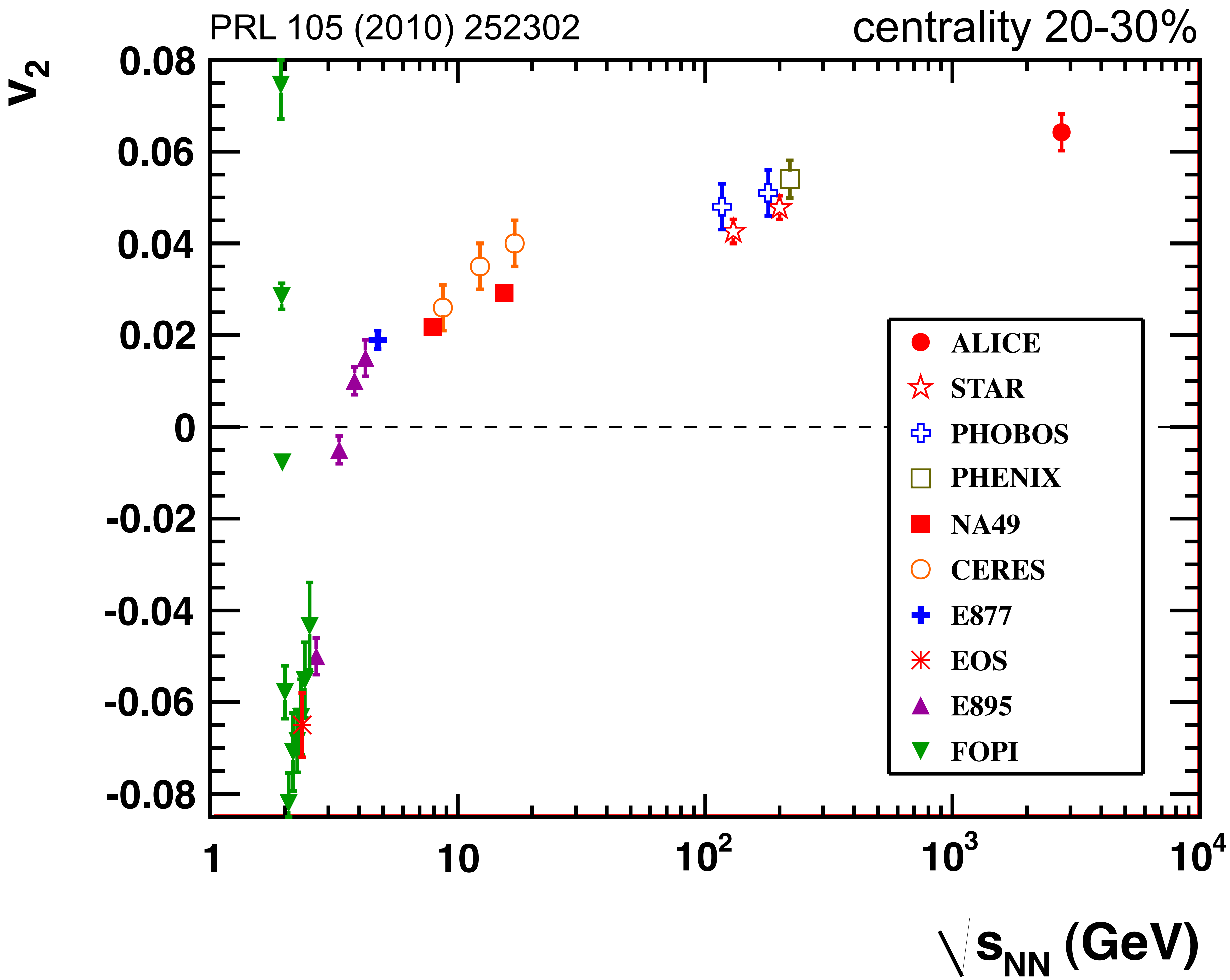
$$\frac{dN}{d\varphi} \propto 1 + 2v_1\cos[\varphi - \Psi_1] + 2v_2\cos[2(\varphi - \Psi_2)] + 2v_3\cos[3(\varphi - \Psi_3)] + ..$$

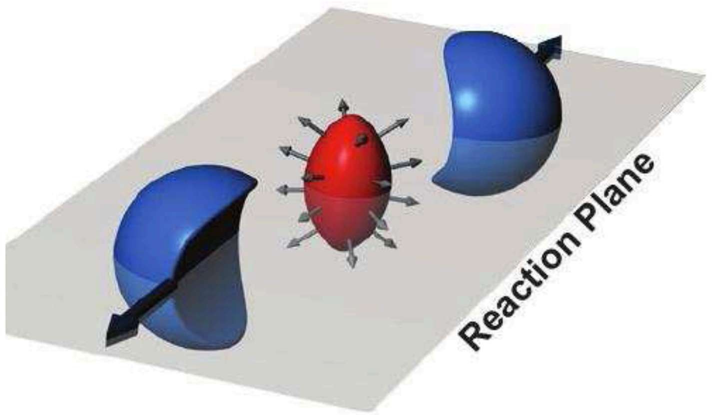


- v_2 dominates for non-central collisions
  - "Elliptic Flow"
- Higher harmonics: v_n studies
  - Fluctuations, transport
- $v_3 \sim v_2$ for central collisions
  - Fluctuations
- Transverse Momentum Regions
  - Low p_T ($\lesssim$ 3 GeV/c): collective hydrodynamic expansion
  - Intermediate p_T ($\lesssim$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

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

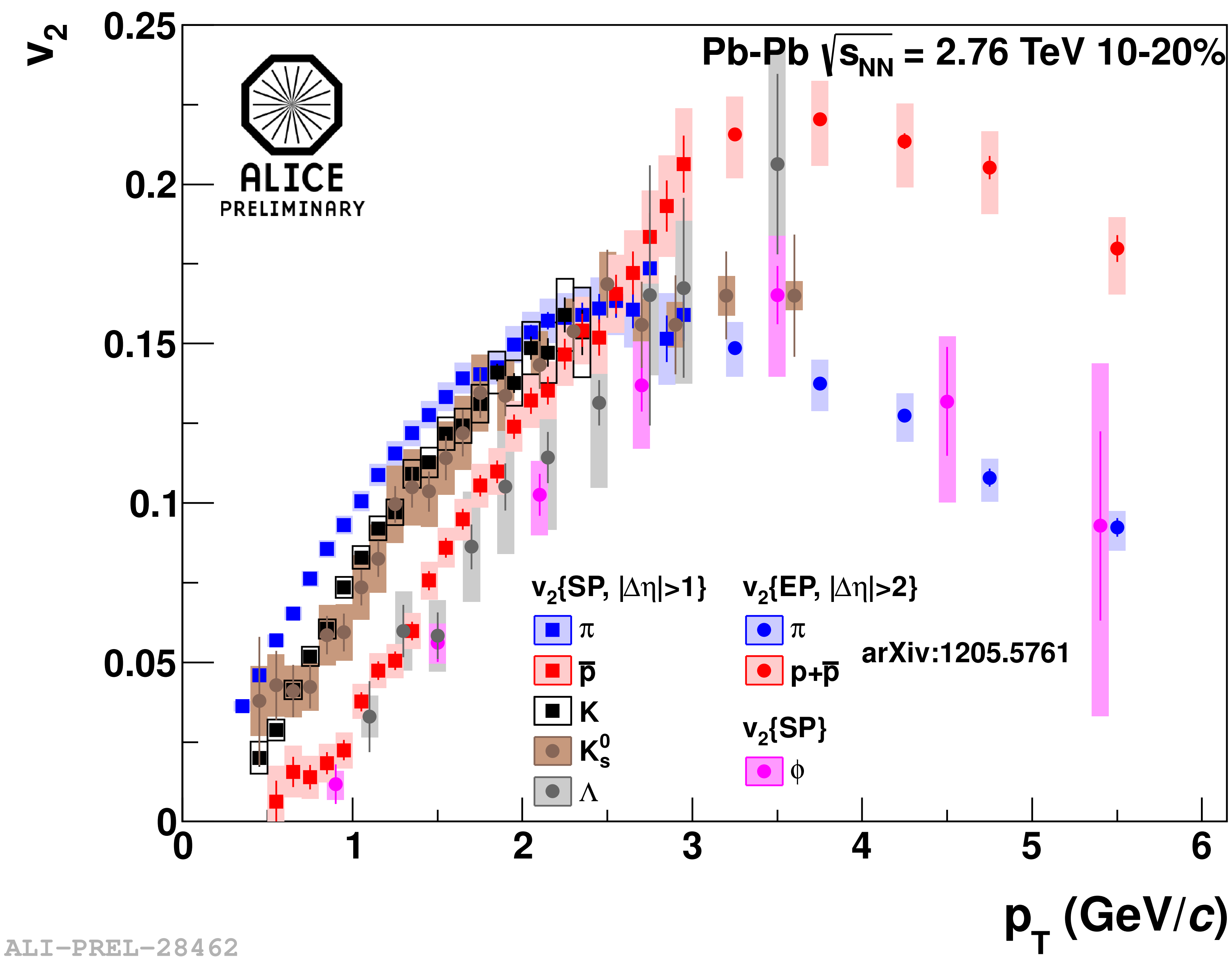
Elliptic flow in Au and Pb collisions





hydrodynamic behavior continues at LHC energies

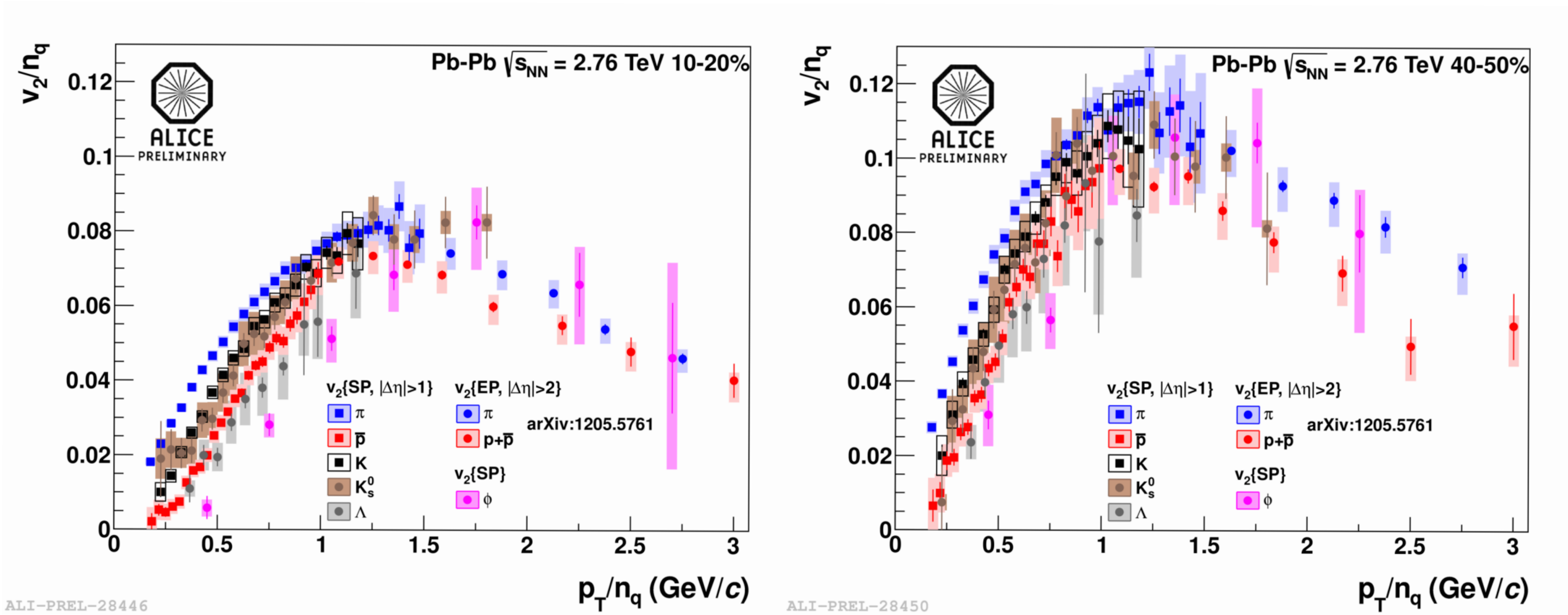
Elliptic flow of identified hadrons

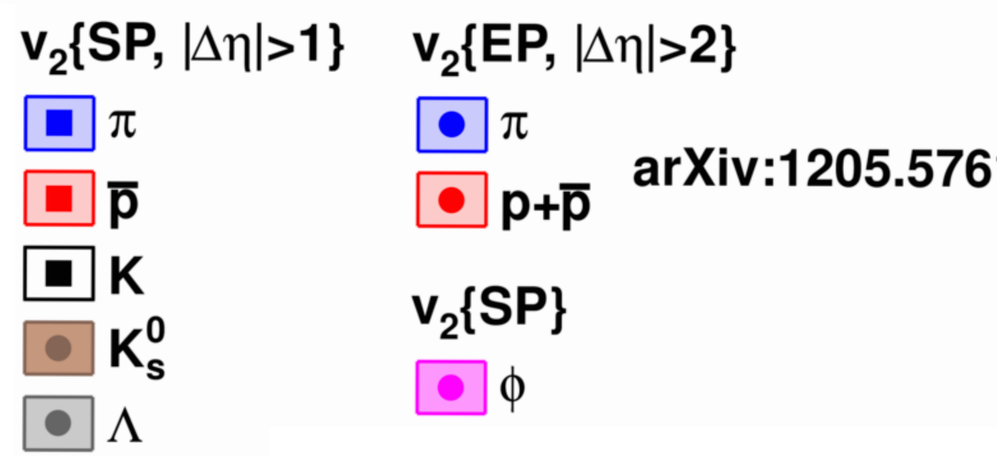


Additional constraints on collective evolution

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

Elliptic flow of identified hadrons

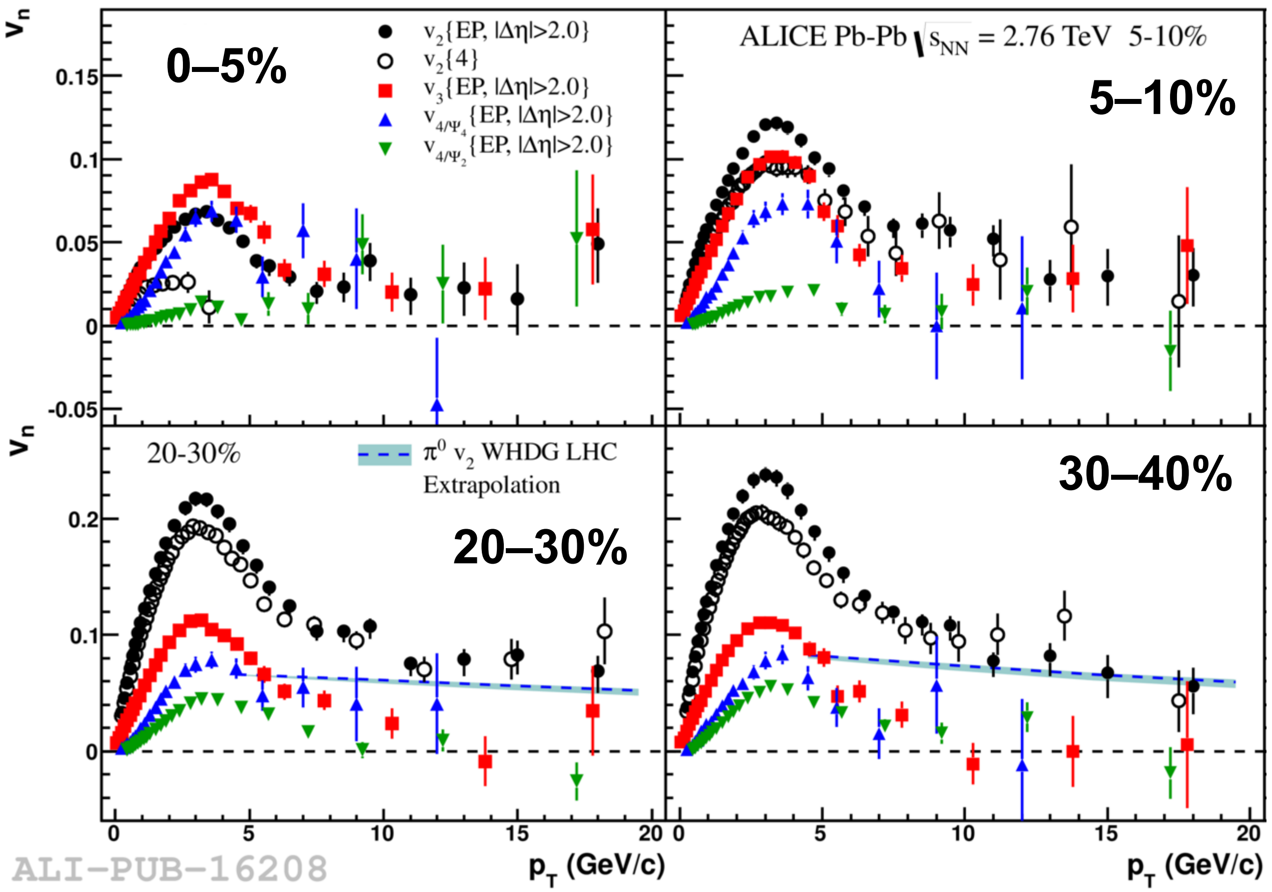


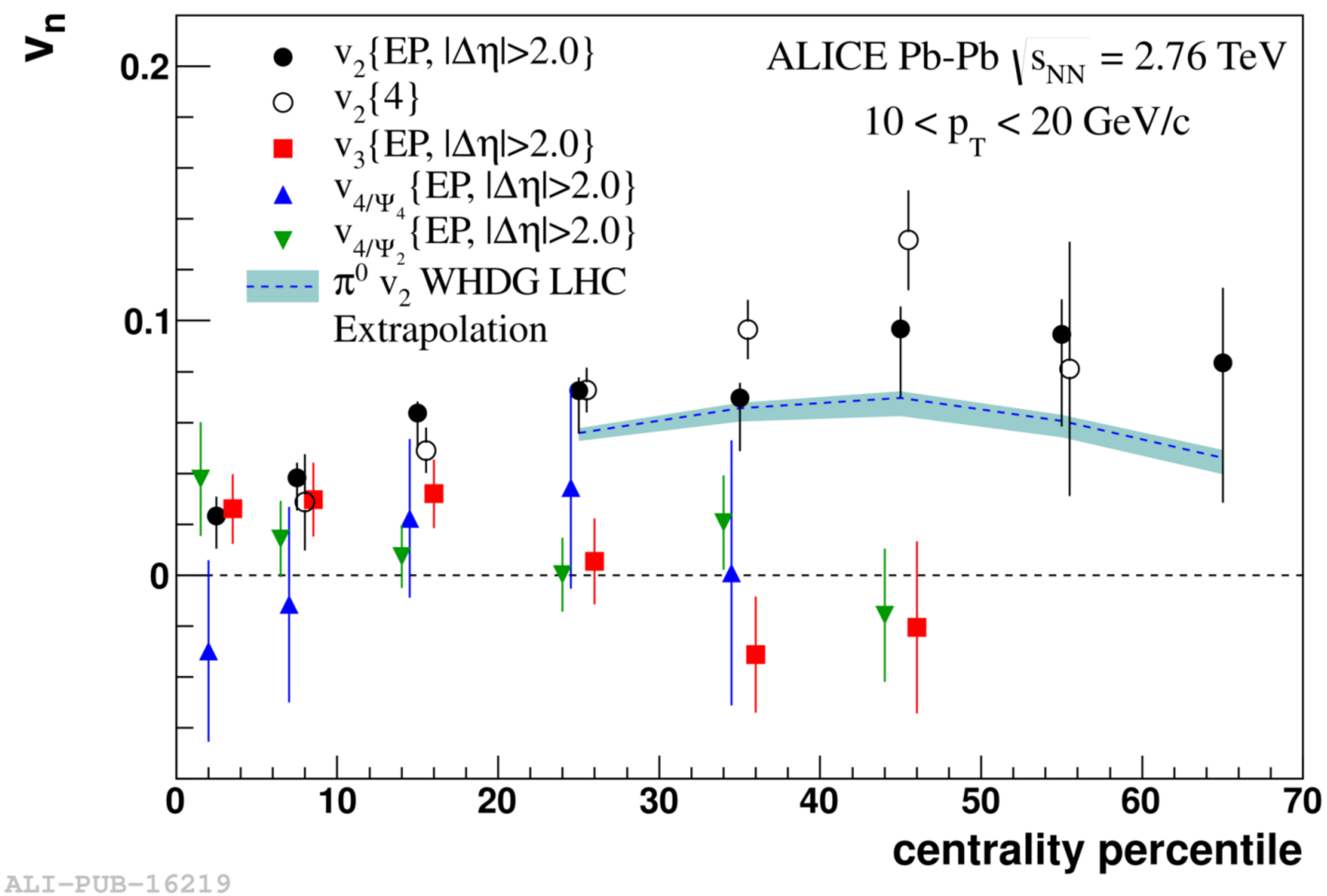


v_2 for π, p, $K^{\pm}$, K^0_s, Λ, φ (not shown for Ξ, Ω)
φ at low p_T (<3 GeV/c) follows mass hierarchy
– at higher p_T joins mesons

NCQ scaling: violation ~ 10% at low p_T

v_2, v_3, v_4 versus p_T



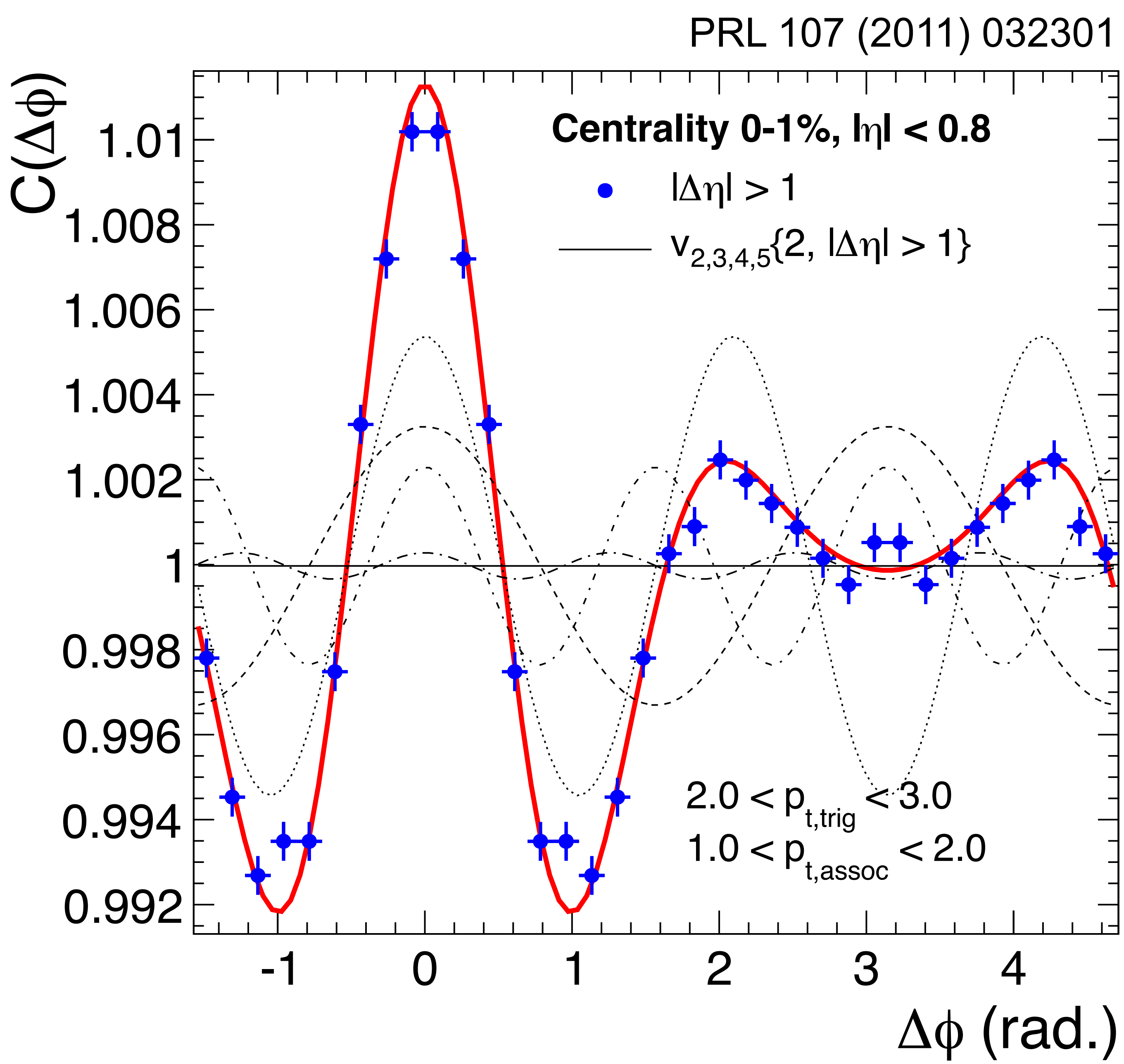


v_n measurements up to 20 GeV/c – where dominated by jet quenching
Non-flow effects suppressed by rapidity gap or using higher cumulants
Non-zero value of v_2 at high p_T both for $\Delta\eta > 2$ and 4-particle cumulant

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

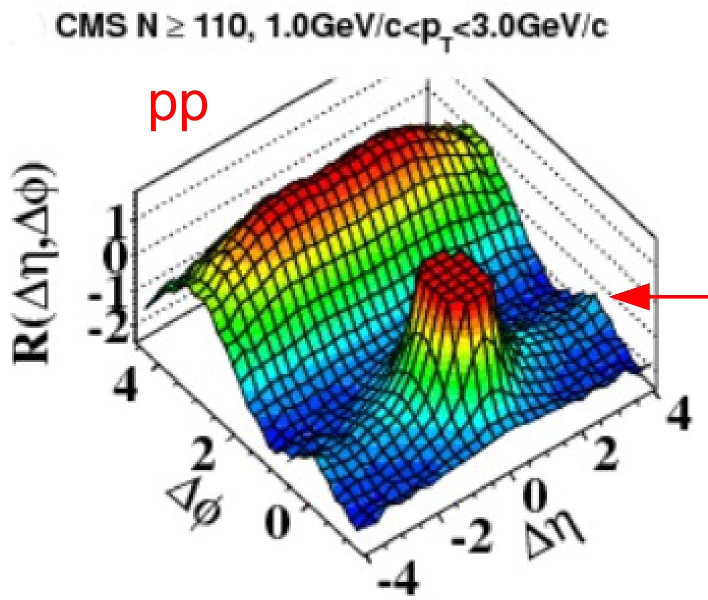
- v_3 is not related to reaction plane
- v_3 only weakly depends on centrality

Higher harmonics of flow



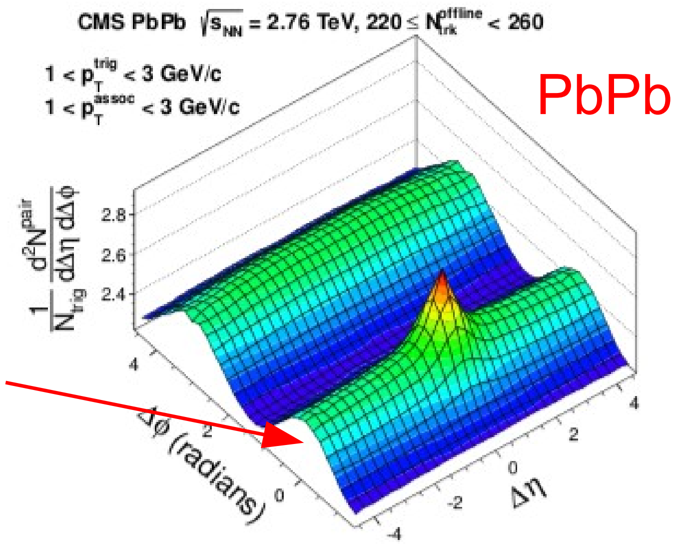
- the azimuthal correlations at high p_T fully described by the flow coefficients

Two particle correlation in η

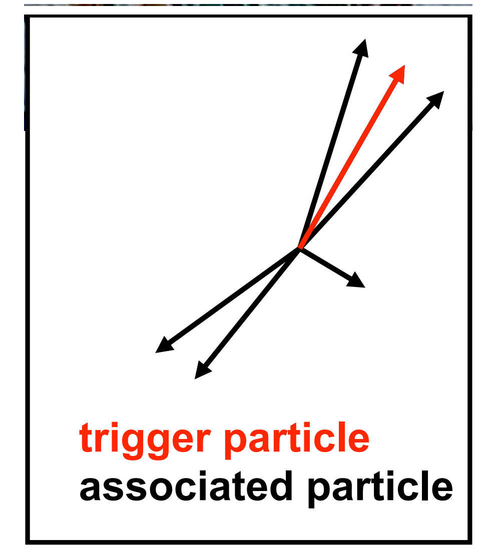


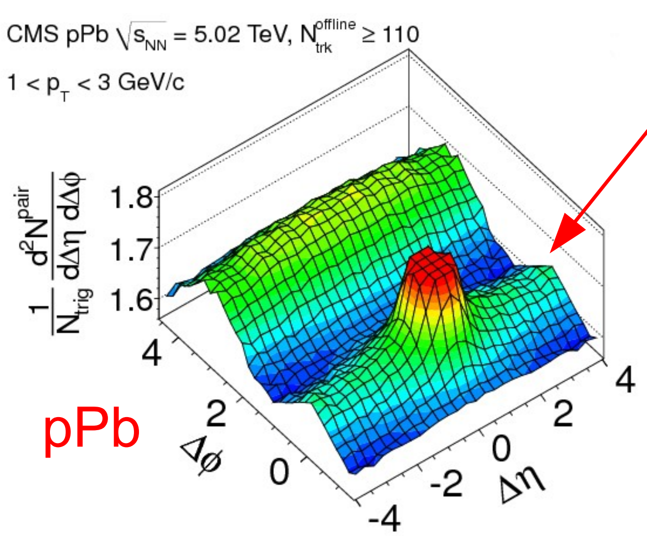
CMS, JHEP 1009 (2010) 91

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

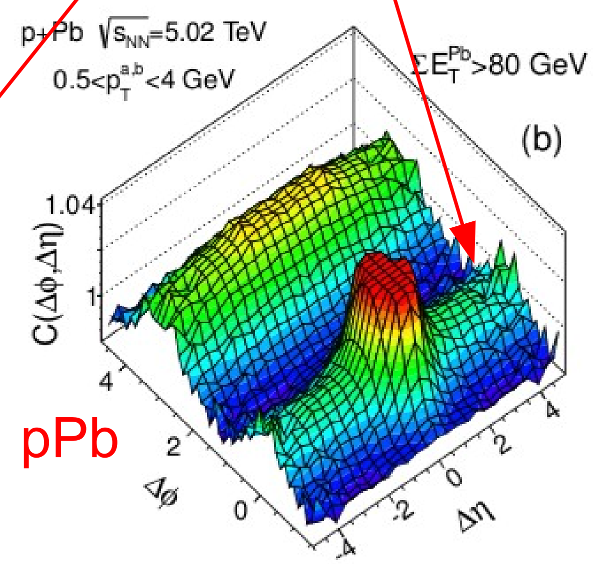


CMS, arXiv:1305.0609

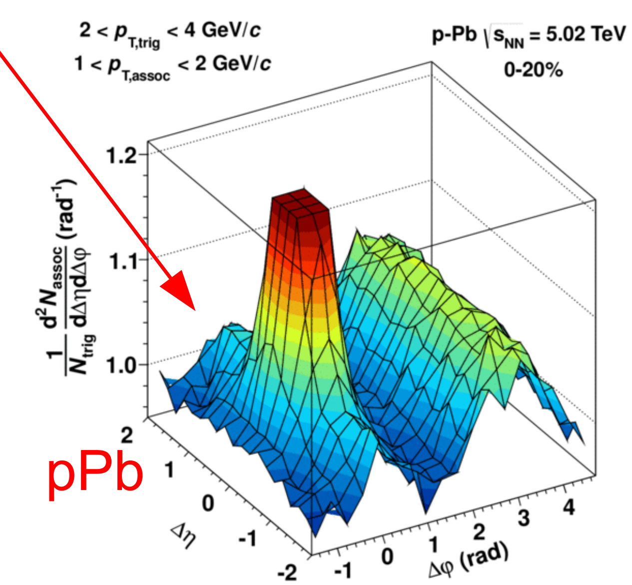




CMS, PLB 718 (2012) 795

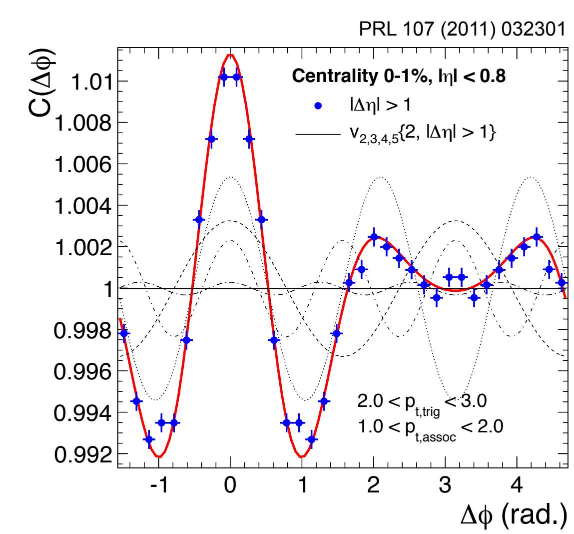


ATLAS, arXiv:1212.5198



ALICE, PLB 719 (2013) 29

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



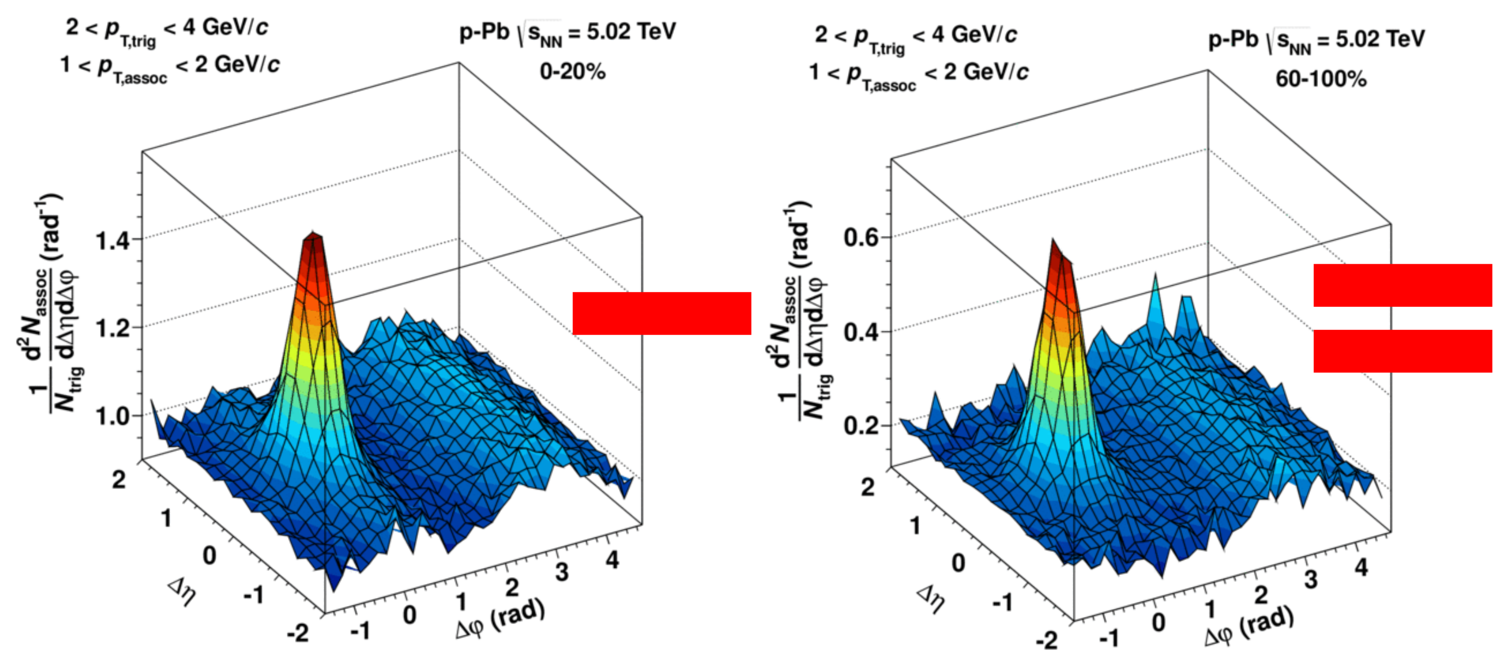
In PbPb, long-range correlations can be explained by flow harmonics (v_n)

In high-multiplicity p-Pb, a ridge develops

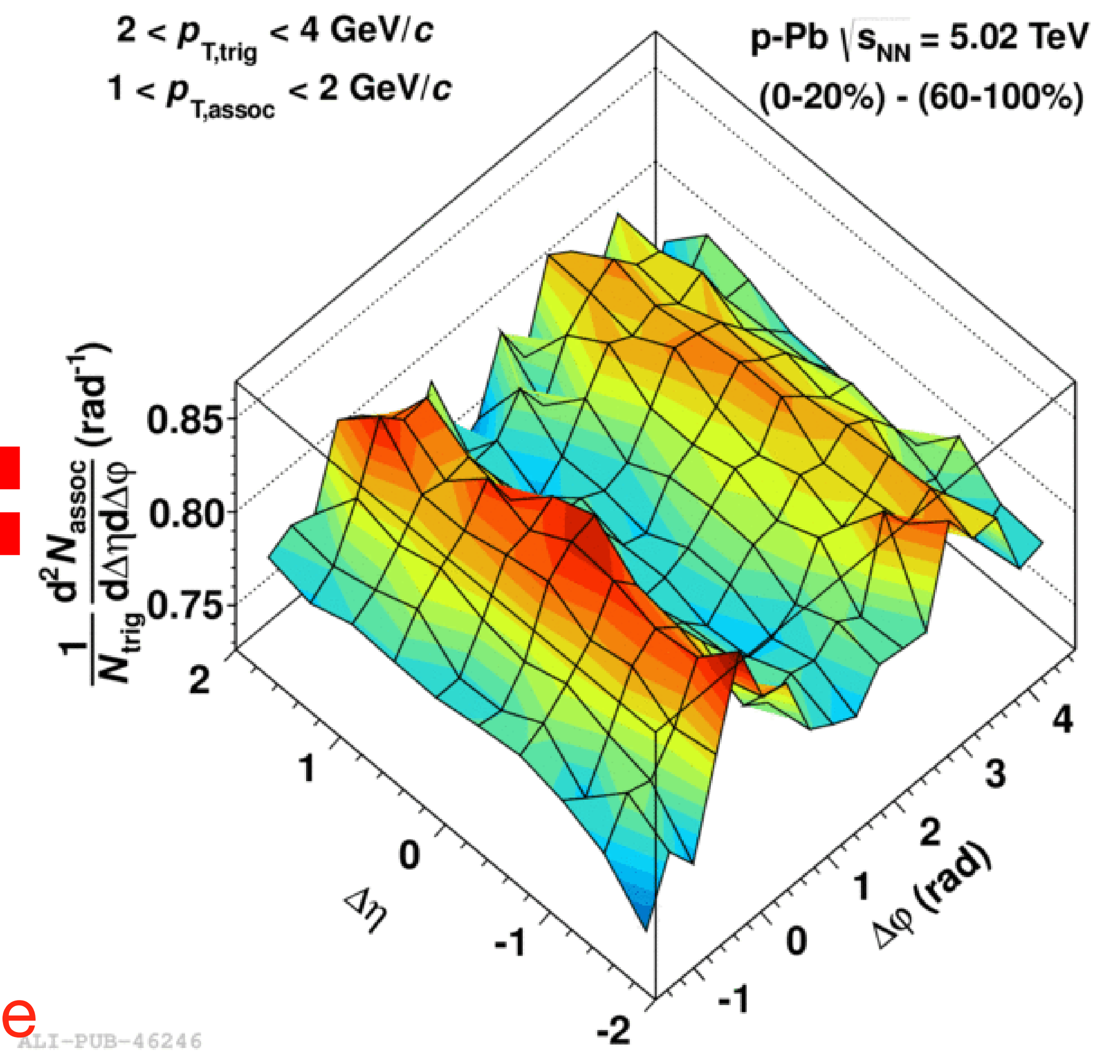
Double ridge (two twin long range) structure

ALICE, PLB 719 (2013) 29

Difference between central and peripheral



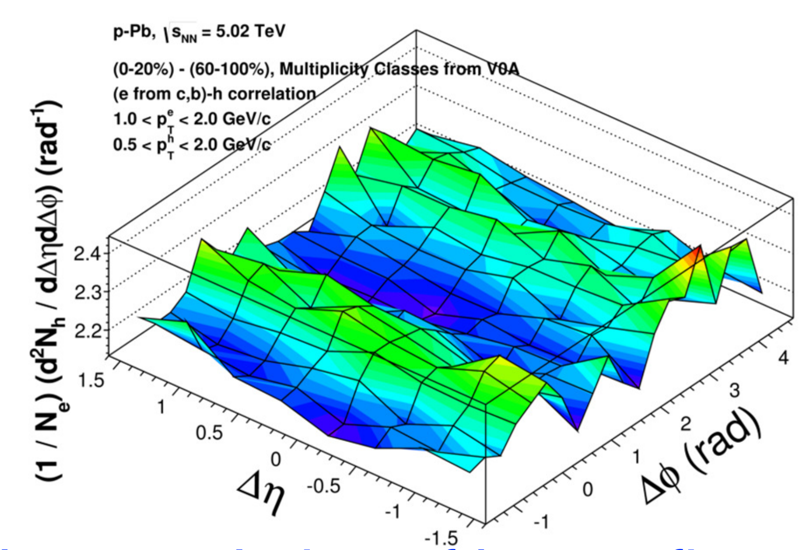
0-20% 60-100%



Extract double ridge structure by subtracting the jet-like correlations

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

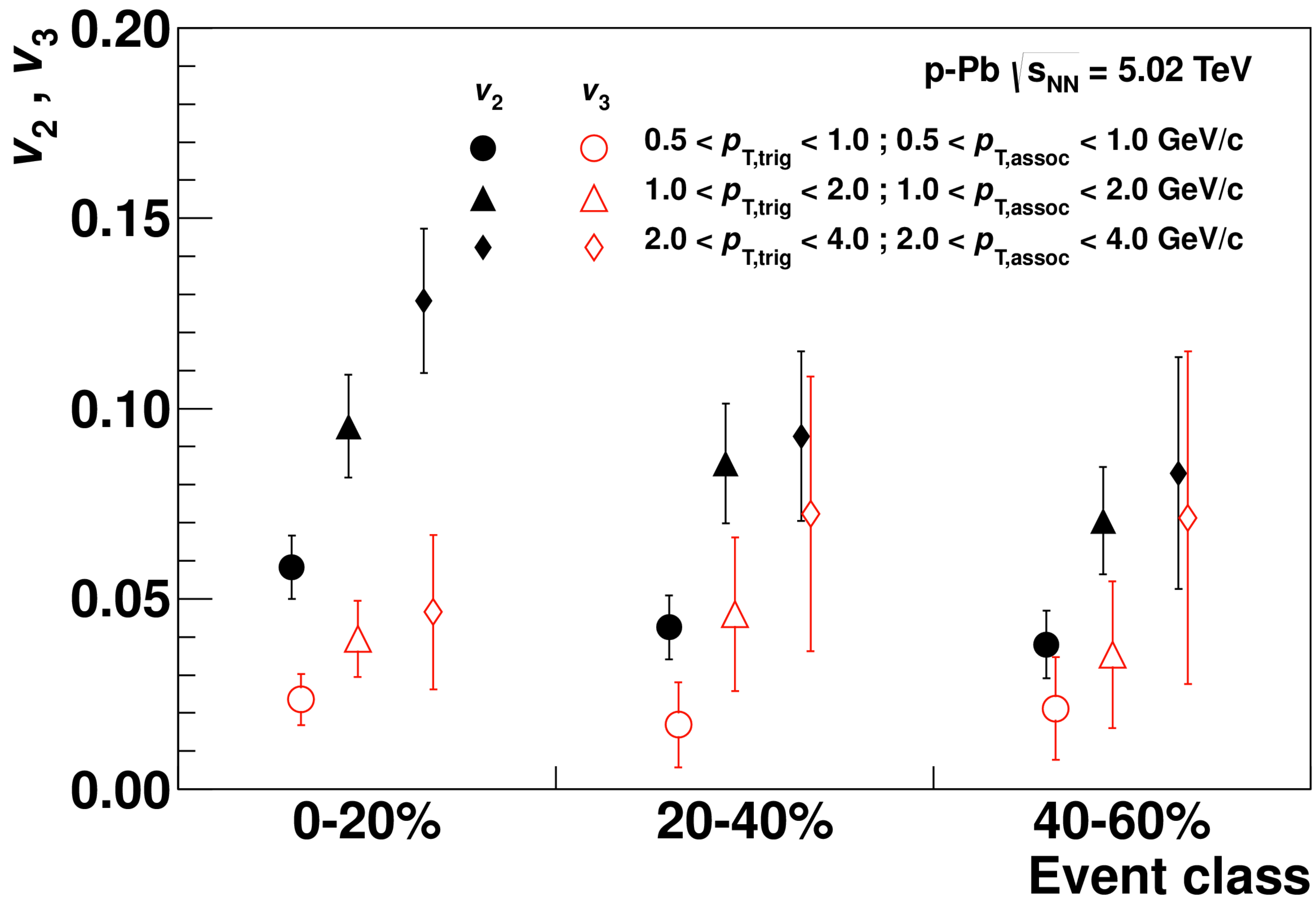
The near-side ridge is accompanied by an almost identical ridge structure on the away-side



Double ridge seen also in the correlation of heavy-flavour decay electrons with hadrons

Property of double ridge

arXiv:1212.2001



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

unlike flow: increase with centrality

Summary

- **In Pb-Pb collisions ALICE has shown that**
  - **Jets are suppressed $R_{AA,}$ $R_{CP} < 1$**
  - **Ratio of jet cross-sections in HI collisions consistent with vacuum case**
  - **Hadron-jet analysis allows for a larger R**
  - **Compatible with no energy redistribution within R=0.5**
- **CNM do not play a large role for jet observables $\Rightarrow$ $R_{pPb} = 1$**
  - **k_T is in agreement with the vacuum case**
  - **Good baseline for future 5.5 TeV Pb-Pb collisions!**
- **New insight into the reaction dynamics from LHC**
  - **ridges in high-multiplicity pp and p-Pb collisions**
  - **mass-splitting of v2**