Highlights from ALICE Pb-Pb results

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for the

ALICE Collaboration

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Argonne National Lab
Chicago, IL
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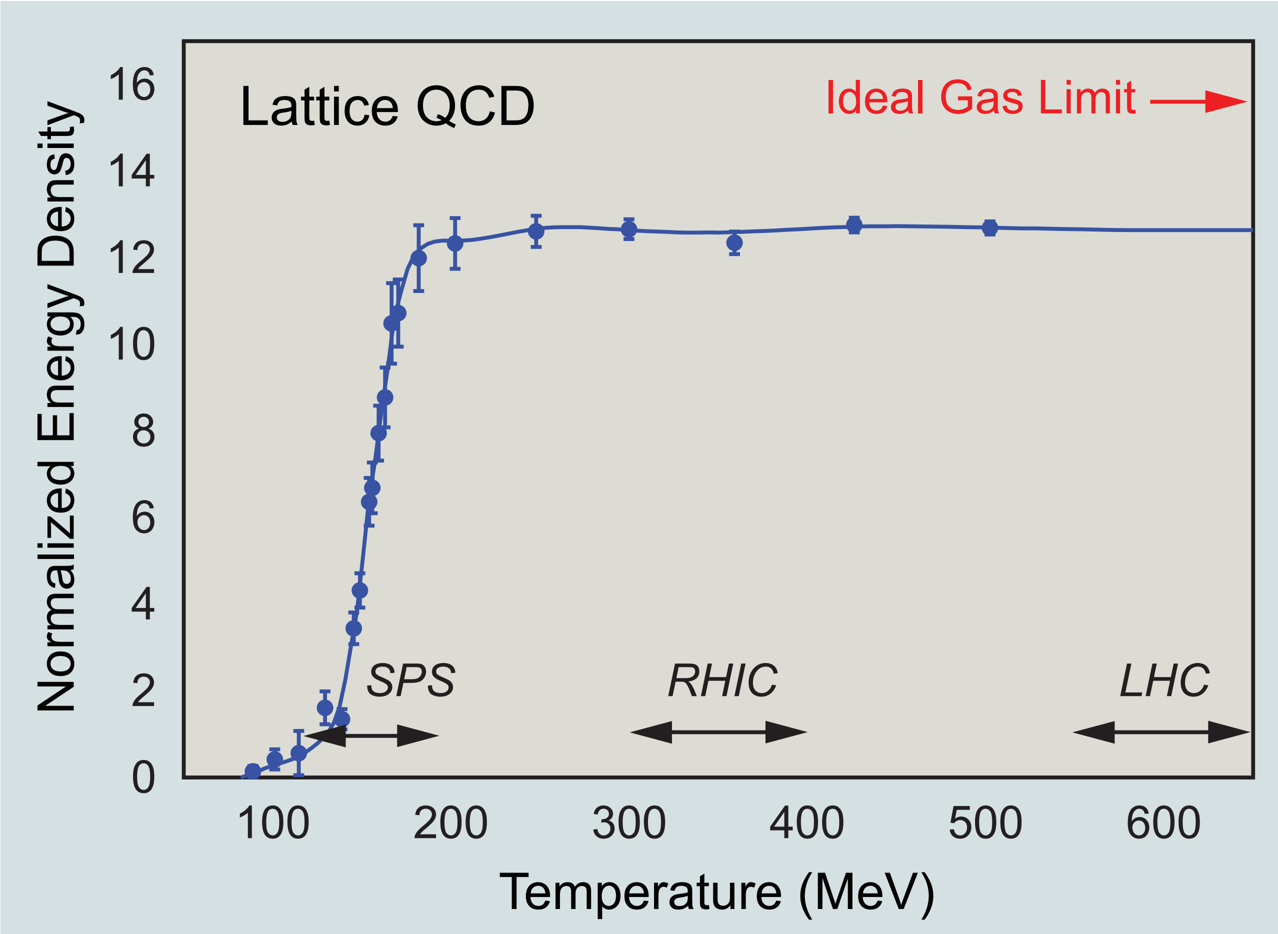
The science of ALICE

Defining questions:

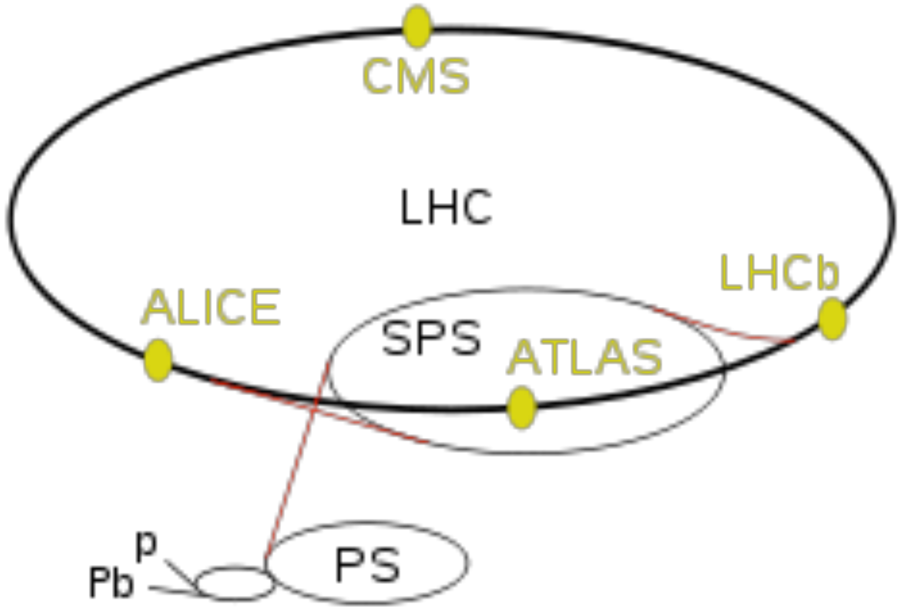
What are the phases of strongly interacting matter, and what roles do they play in the cosmos?

What does QCD predict for the properties of strongly interacting matter?



“The Frontiers of Science: A Long Range Plan”

http://science.energy.gov/np/nsac/



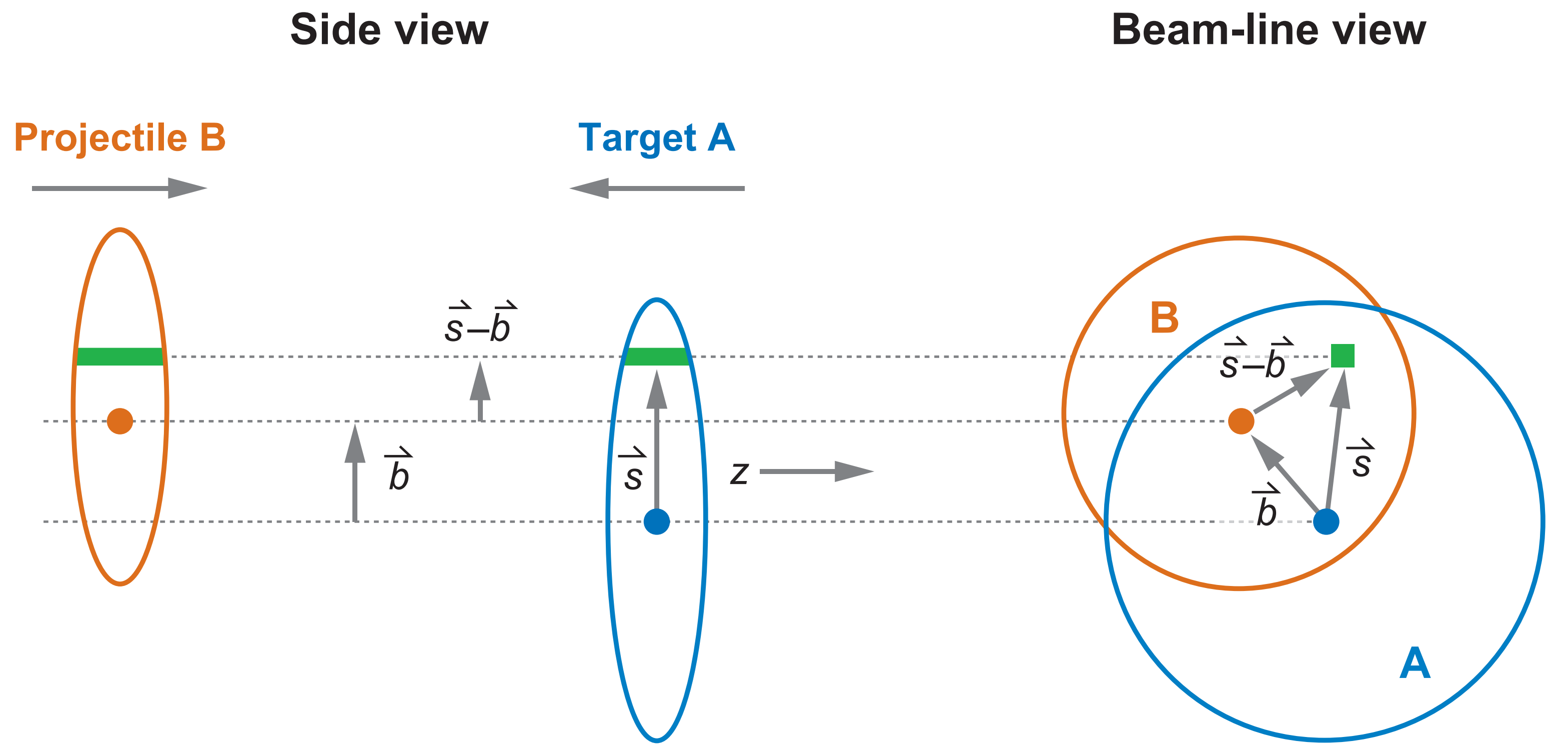
Heavy-ion collisions for HEP folks

Collision anatomy

Impact parameter

$0 < b < \sim 2R_{Pb}$ $(R_{Pb} \approx 6.6$ fm$)$

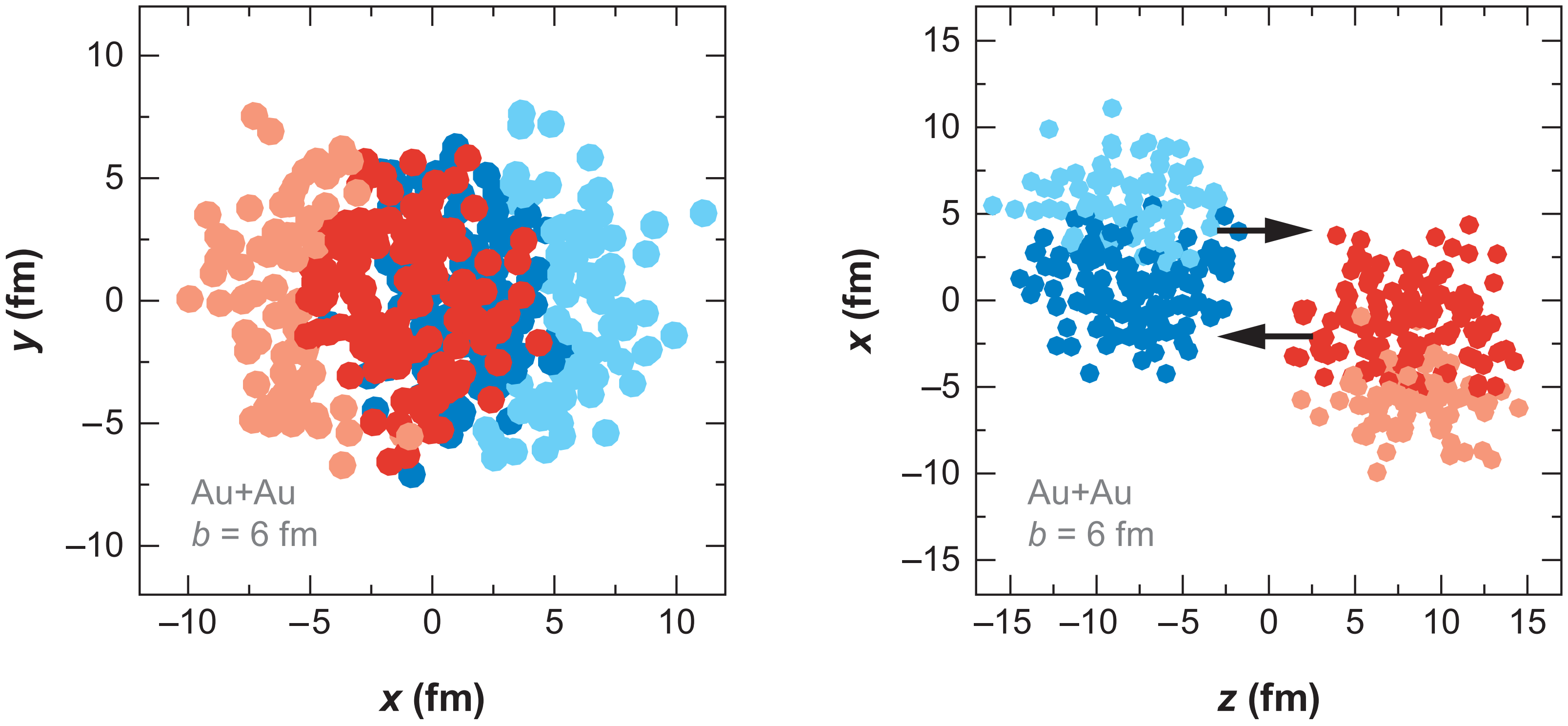
Nucleon position s
Nuclear density ρ(s, z)



Key quantities

N_{part}:
 # nucleons participating in collision

N_{coll}:
 # binary (nucleon-nucleon) collisions



"Glauber Modeling in High-Energy Nuclear Collisions"
Annu. Rev. Nucl. Part. Sci. 2007.57:205-243

Heavy-ion collisions for HEP folks

Collision Centrality

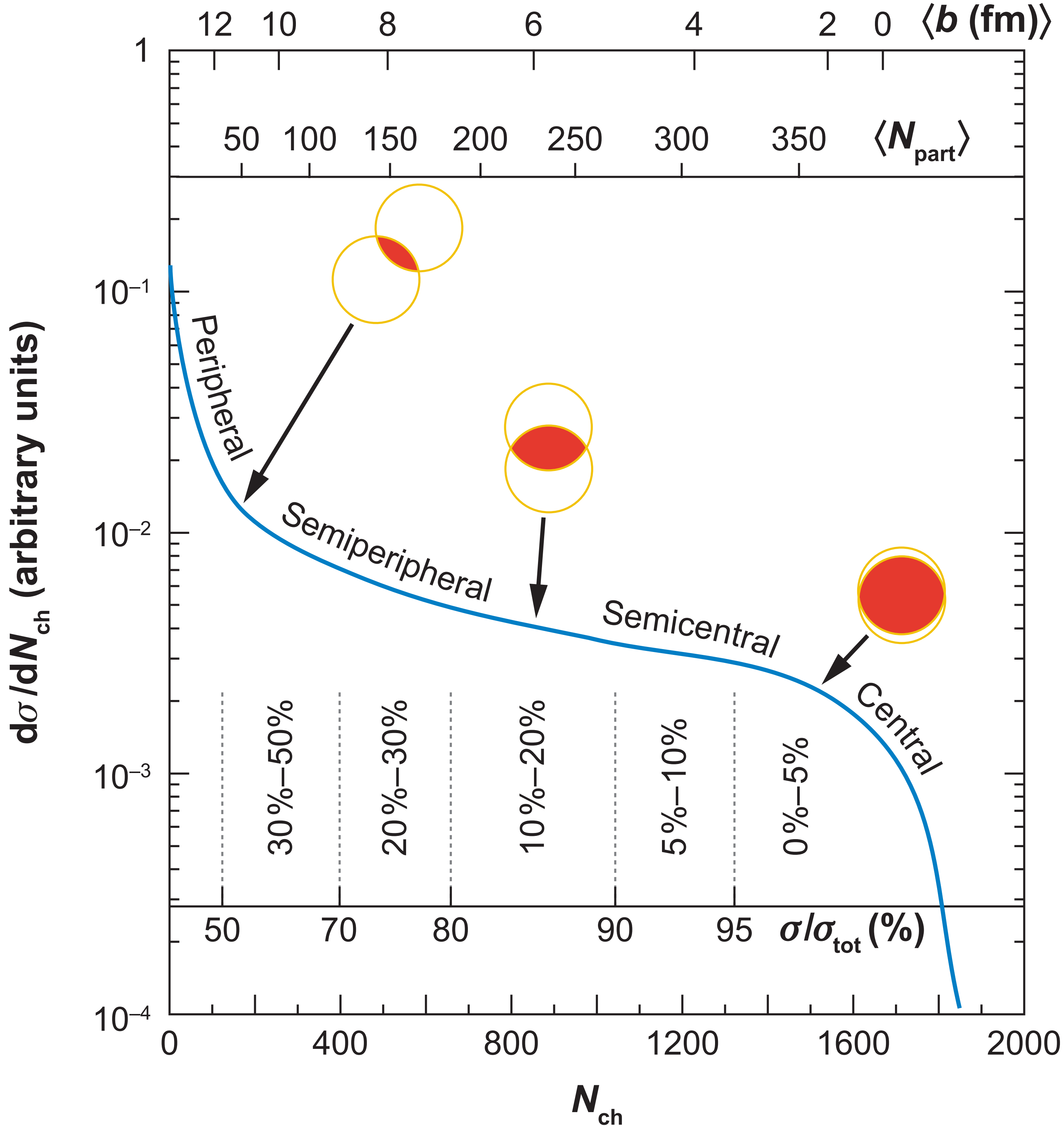
b, N_{part}, N_{coll} aren't directly measurable...
but multiplicity is (e.g. E_{zdc}, N_{ch}).

Assume measured N_{ch} relates monotonically (& inversely) to b

Bin real events in N_{ch} quantiles,
Glauber events in b quantiles,
& match them

The procedure has an uncertainty.

ALICE centrality resolution < 1%.



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Pb-Pb @ LHC: the November revolution

November 2009

First p-p collisions, 900 GeV

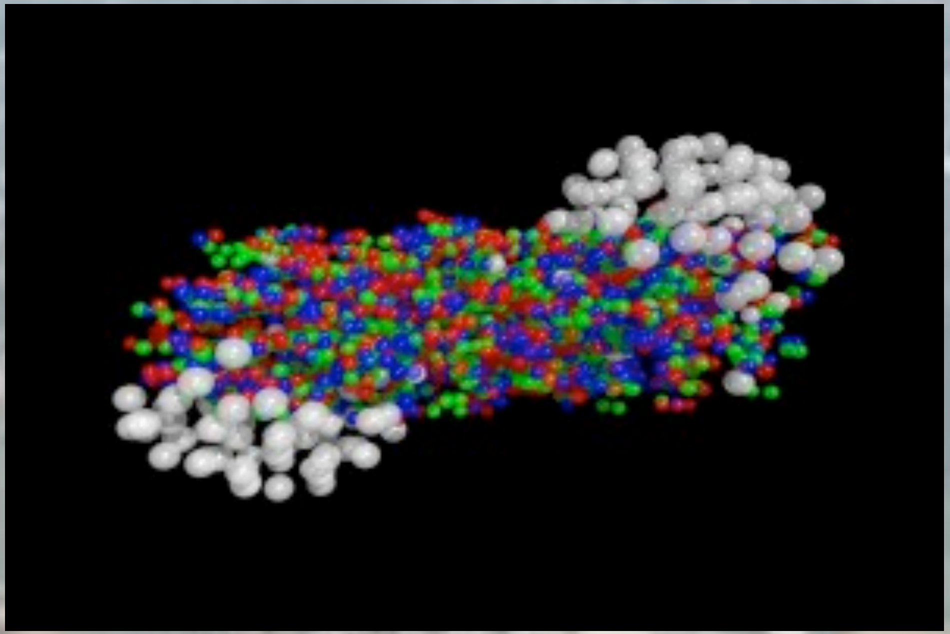
November 2010

First Pb-Pb collisions, 2.76 TeV

L_{PbPb} reached 2 x 10^{25} cm^{-2} s^{-1} (Pb-Pb Design luminosity = 10^{27})

November 2011

Expect 5x increase over 2010 ∫Ldt



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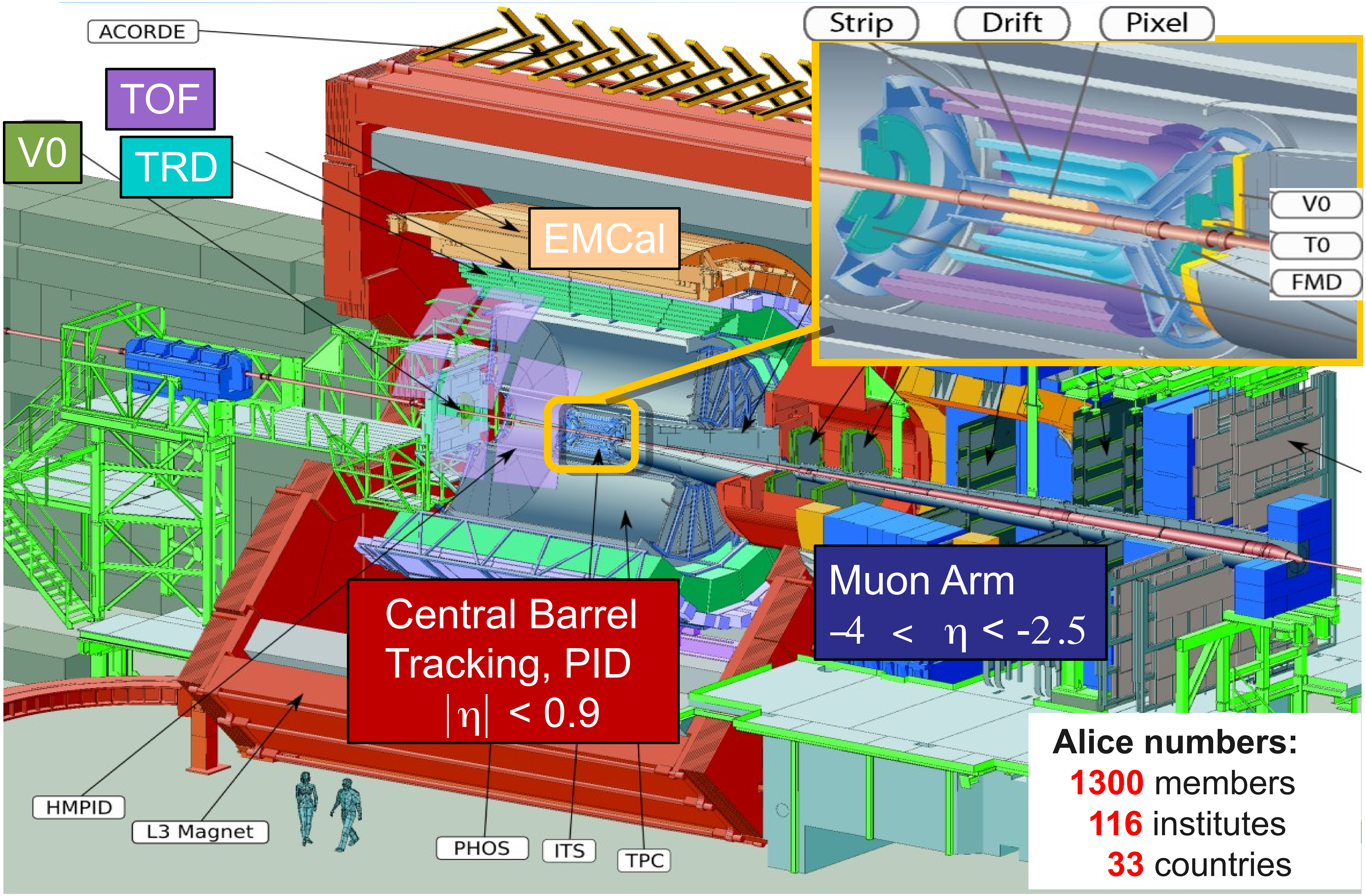
A Large Ion Collider Experiment

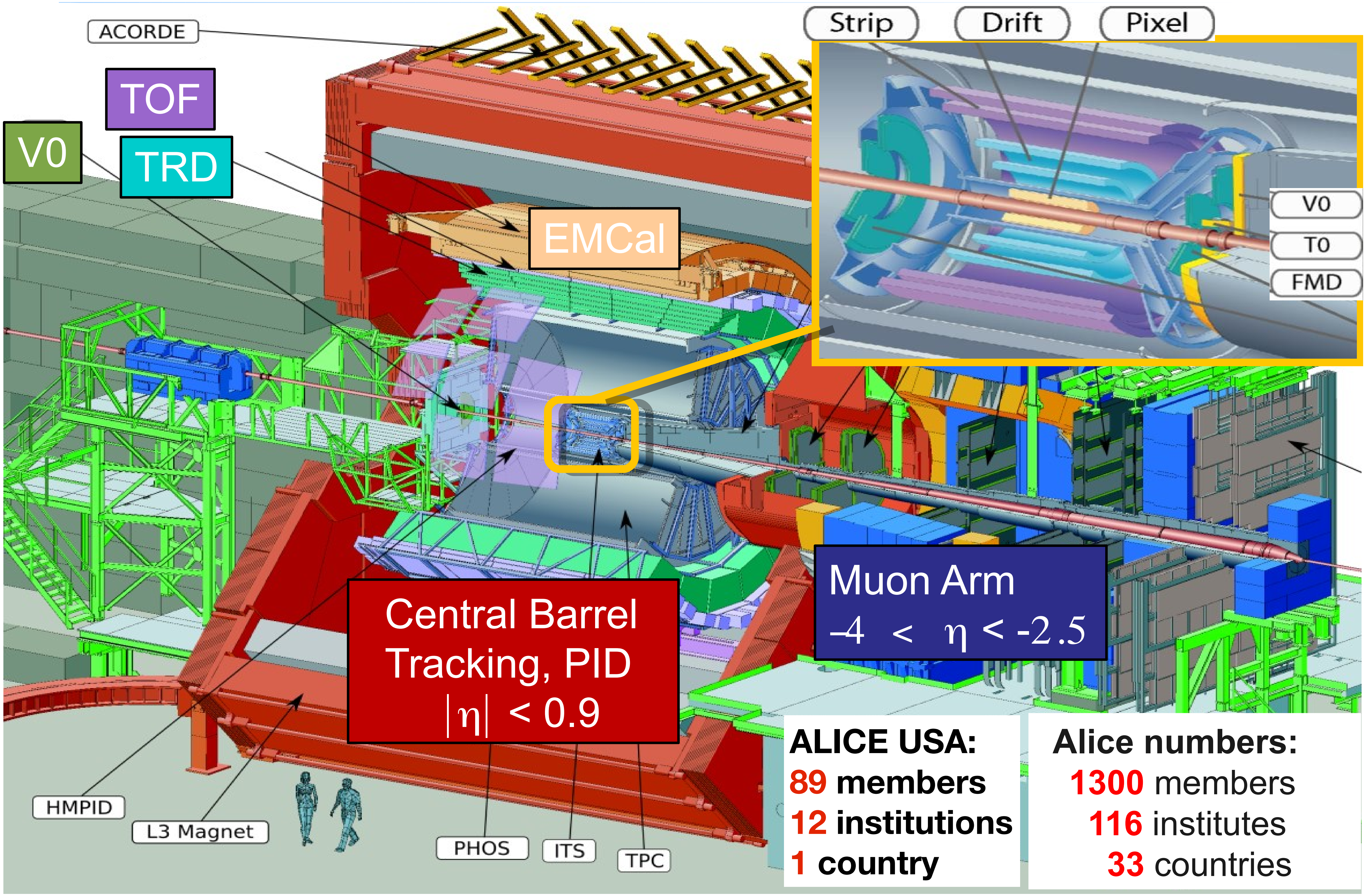


Central Barrel
Tracking, PID
$|\eta| < 0.9$

Muon Arm
$-4 < \eta < -2.5$

Alice numbers:
1300 members
116 institutes
33 countries

A Large Ion Collider Experiment



Central Barrel Tracking, PID $|\eta| < 0.9$

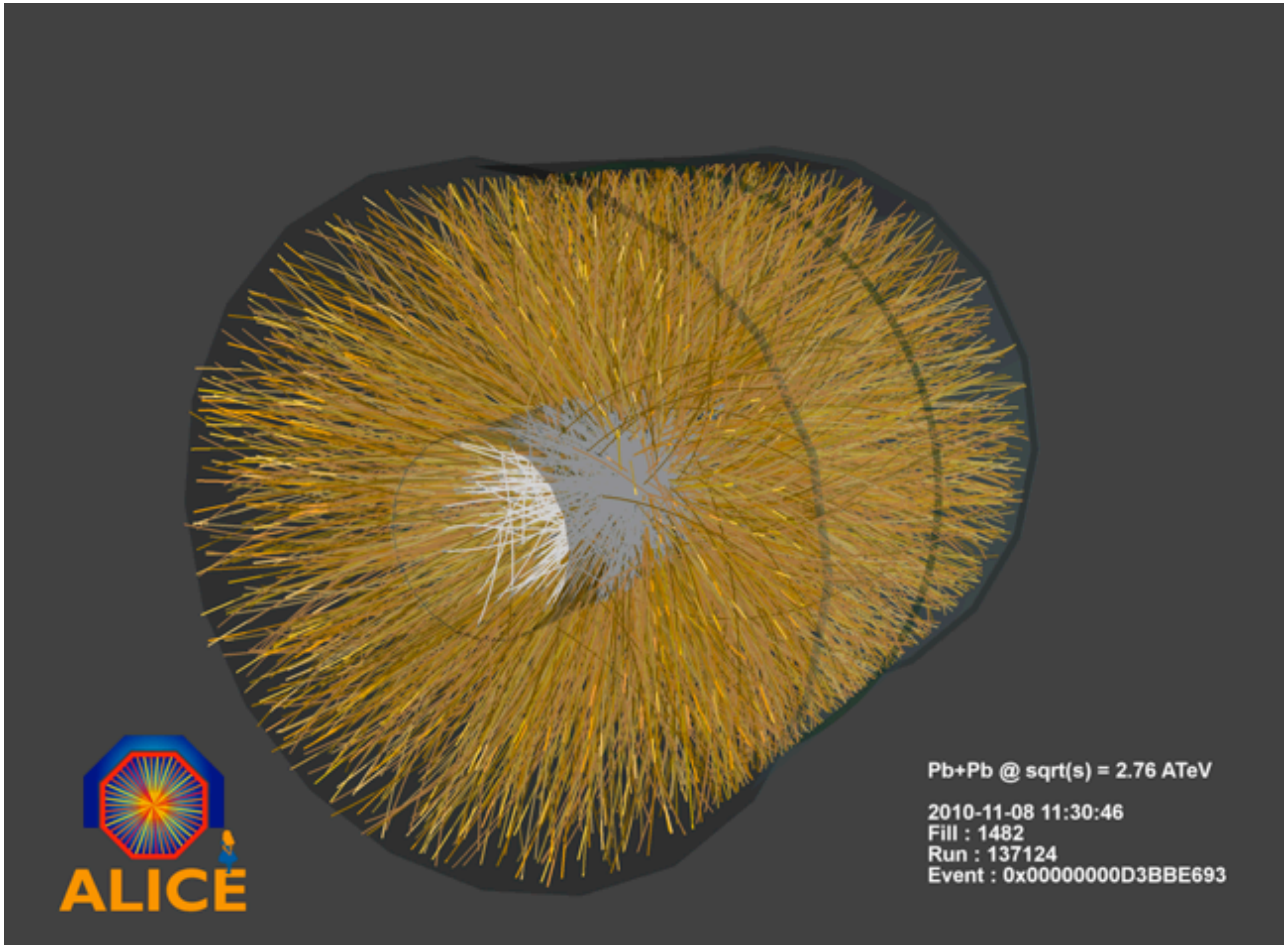
Muon Arm $-4 < \eta < -2.5$

ALICE USA:
89 members
12 institutions
1 country

Alice numbers:
1300 members
116 institutes
33 countries

Bulk/Global Observables

Multiplicity
Transverse Energy
Source Imaging

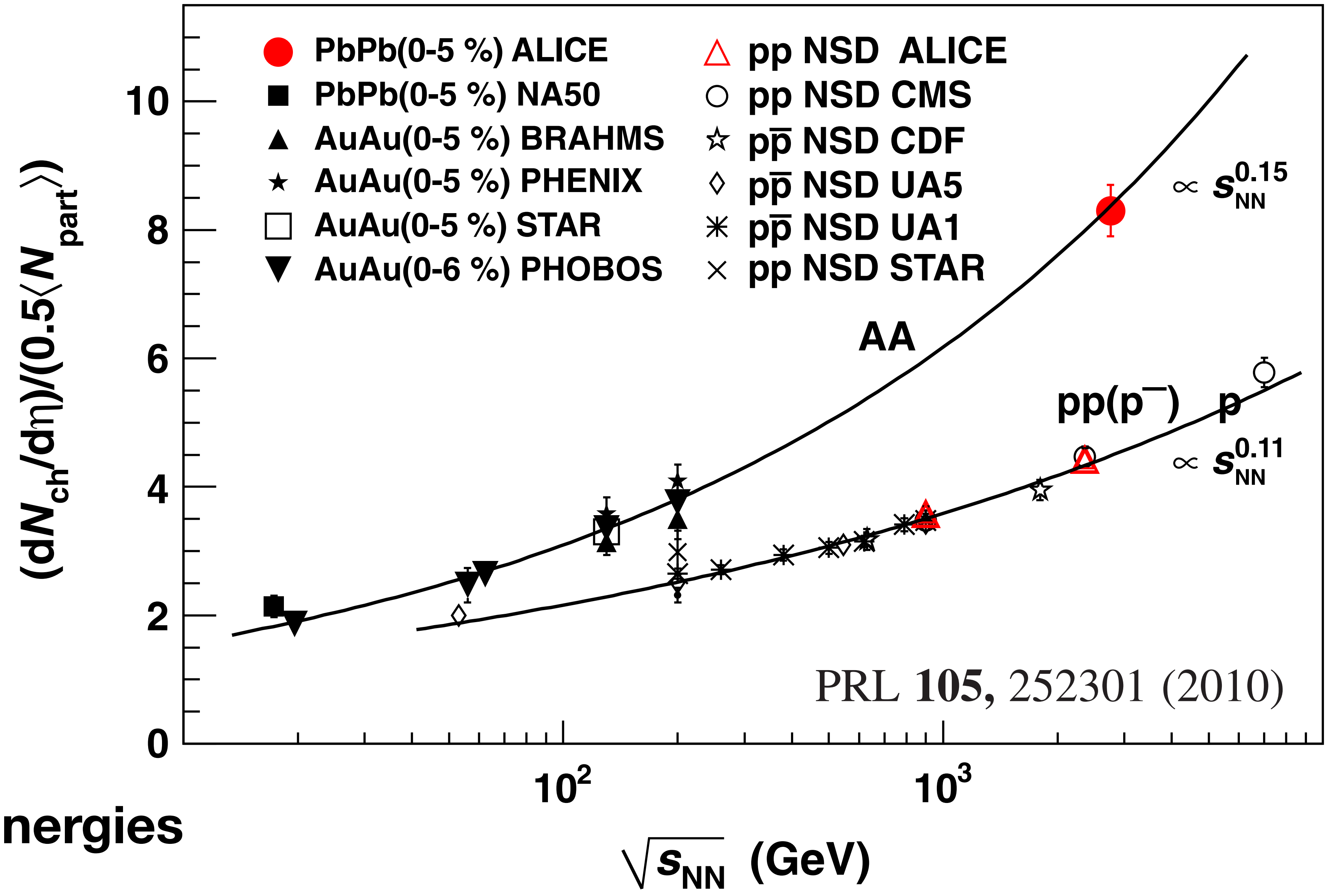


Charged Particle Multiplicity

For 0-5% most central collisions at 2.76 TeV:

$dN_{ch}/d\eta = 1584 \pm 76$ (sys.)

8.3 ± 0.4 per participating nucleon pair - higher than many expectations



Nuclear enhancement

~2x higher than at RHIC energies

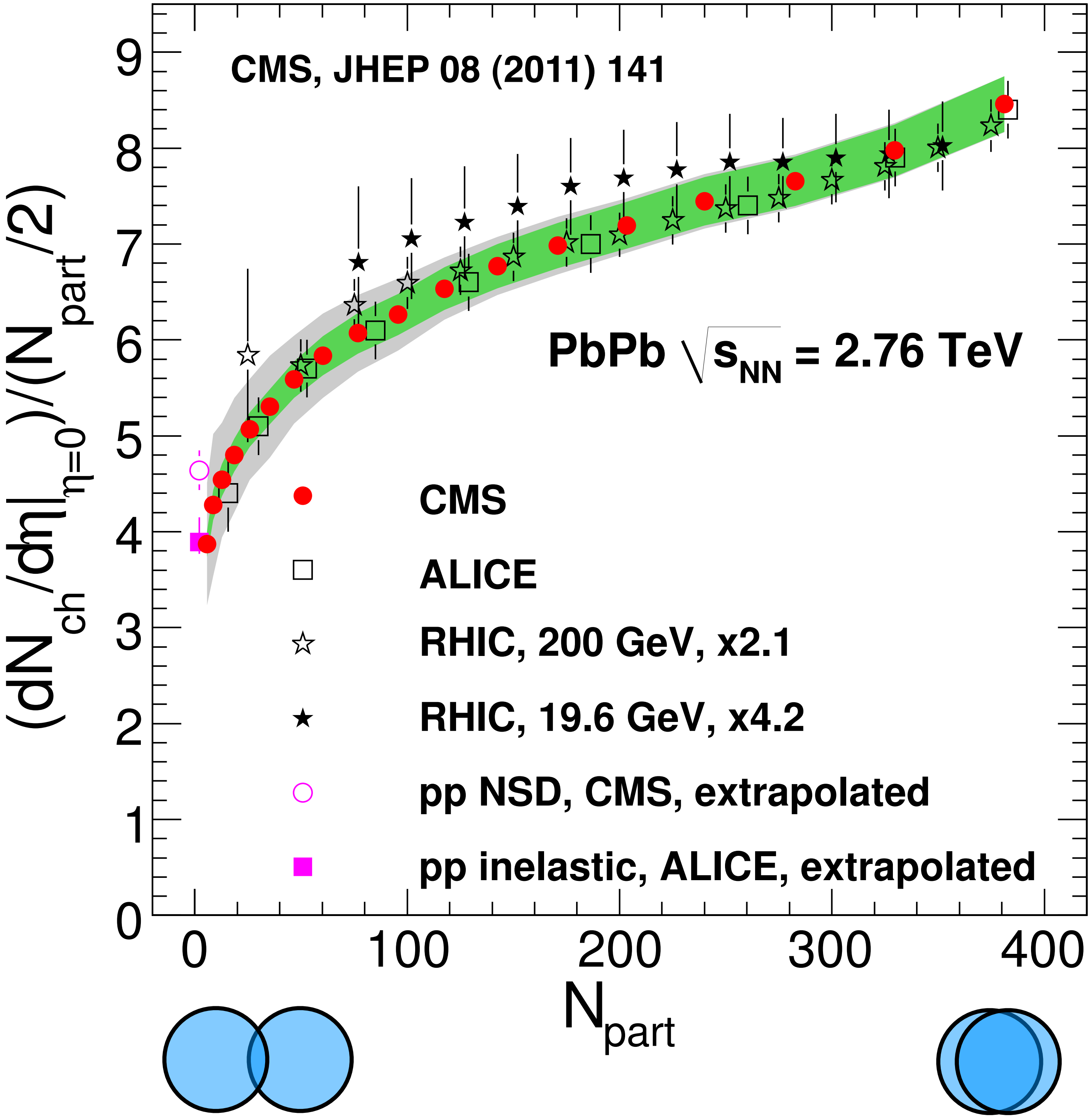
~2x higher than pp

Faster growth than for pp

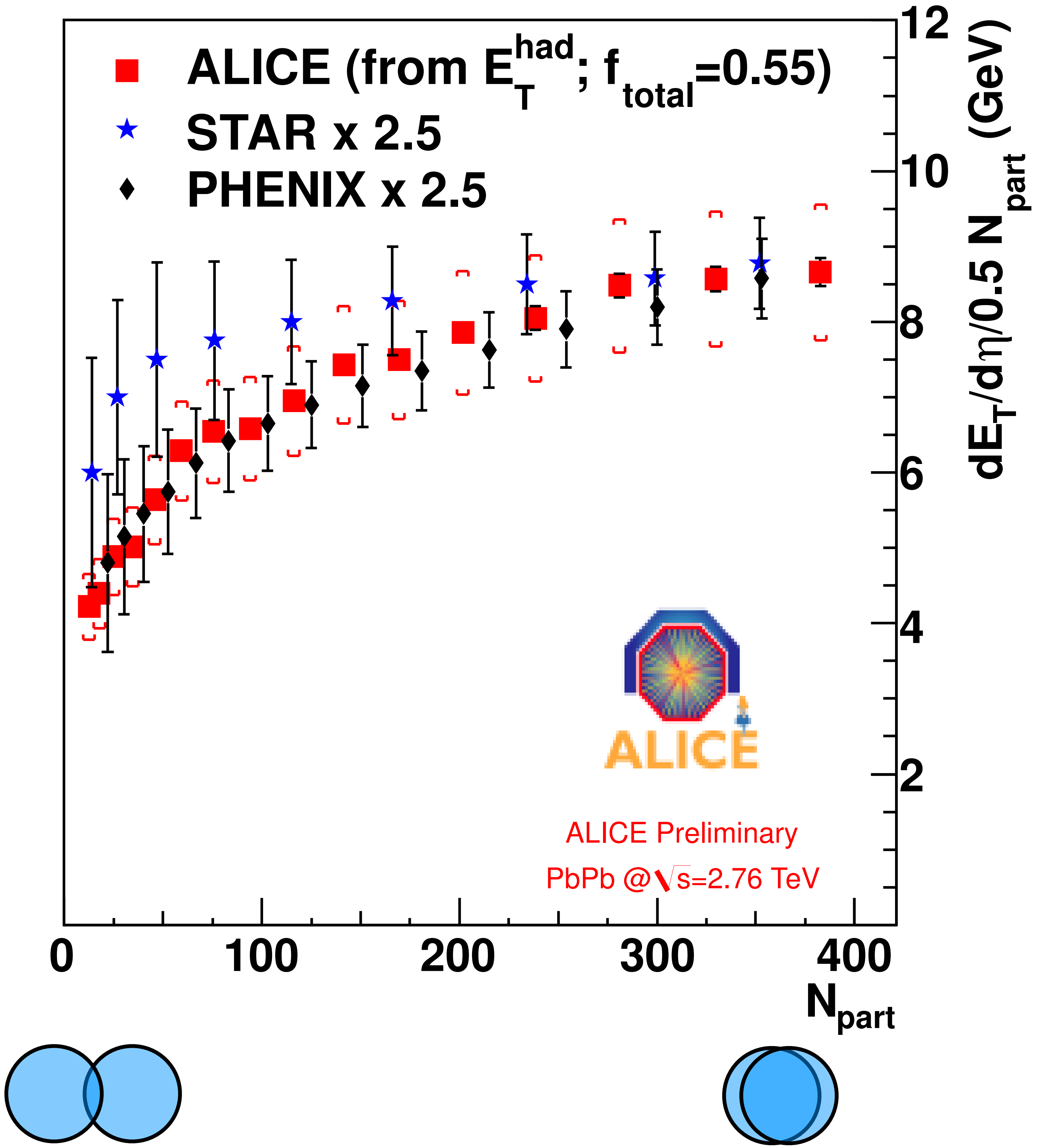
Centrality dependence of N_{ch}

Multiplicity vs. N_{part}

Same trends over 3 orders in √s (RHIC points are scaled)



Transverse Energy



$dE_T/d\eta$ vs. N_{part}

Measured using ALICE tracking detectors

Corrected by f_{total} from MC to get charged → total E_T

Trends

Again, LHC and RHIC have similar centrality dependence

~2.5x higher than at RHIC
Consistent with larger $\langle p_T \rangle$

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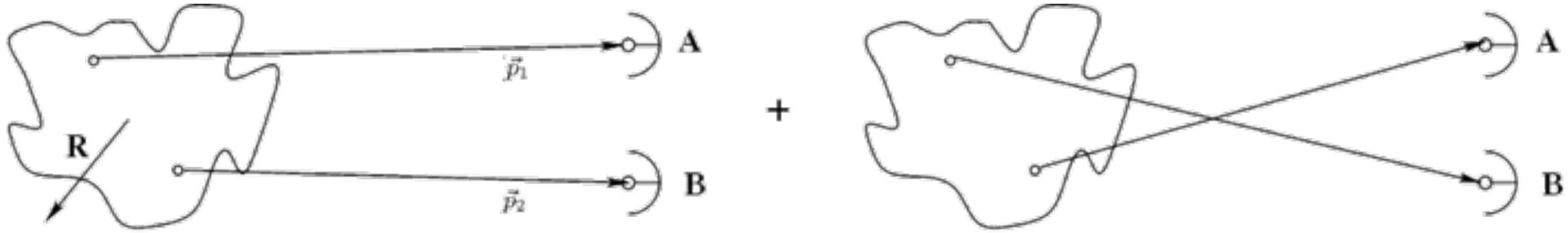
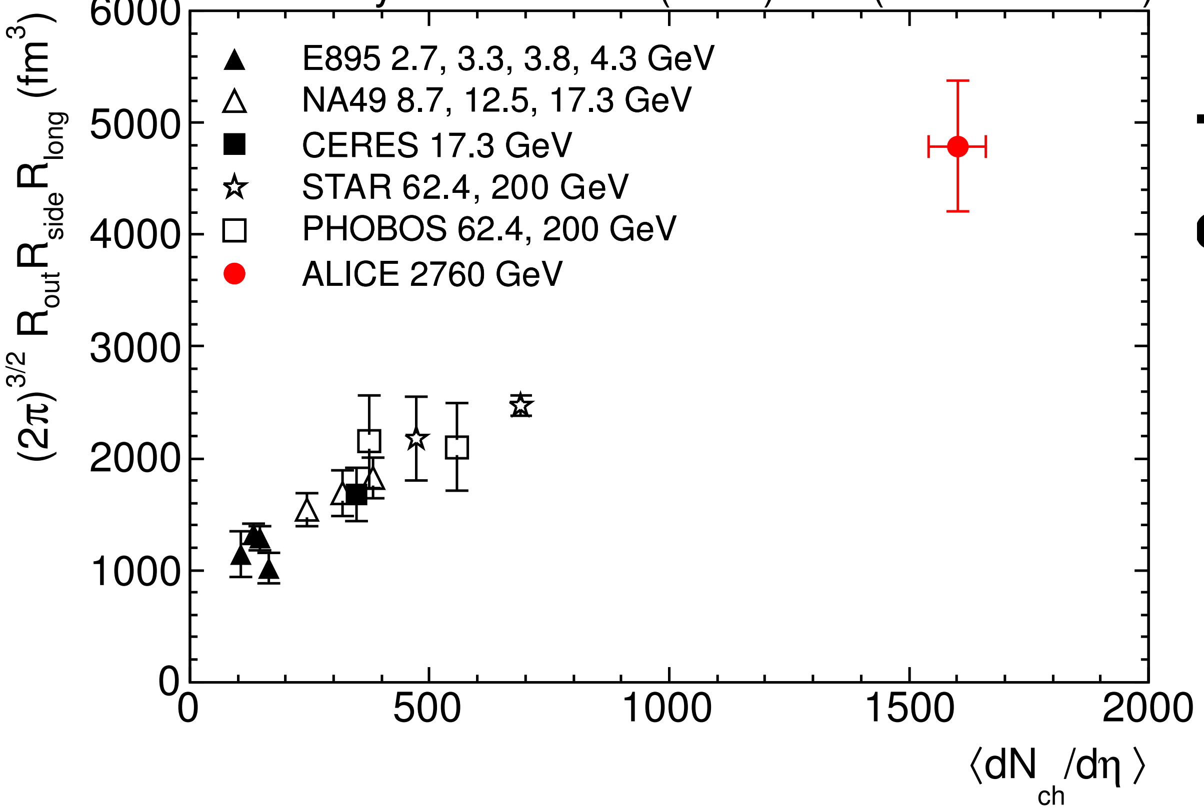
Source size from interferometry

Two-pion Bose-Einstein correlations

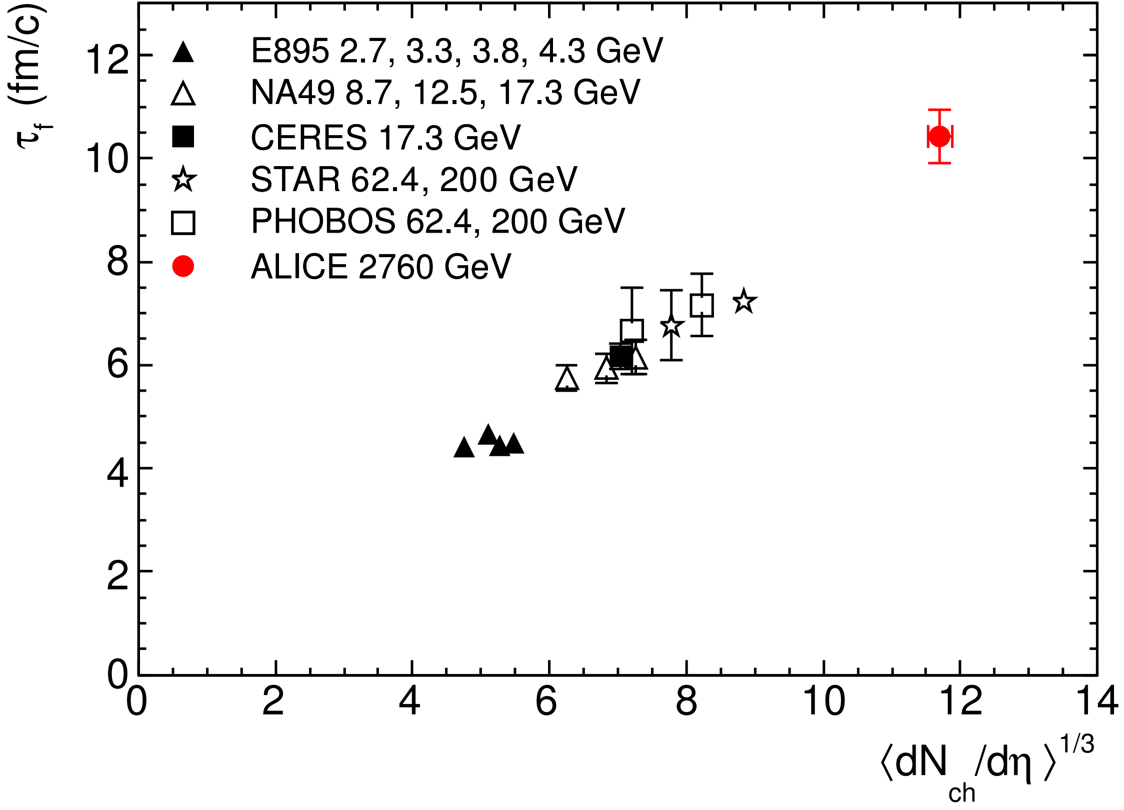




Phys. Lett. B 696 (2011) 328 (values scaled)

Freeze-out volume

Twice as large as Au+Au at RHIC in central collisions



Phys. Lett. B 696 (2011) 328

Decoupling time

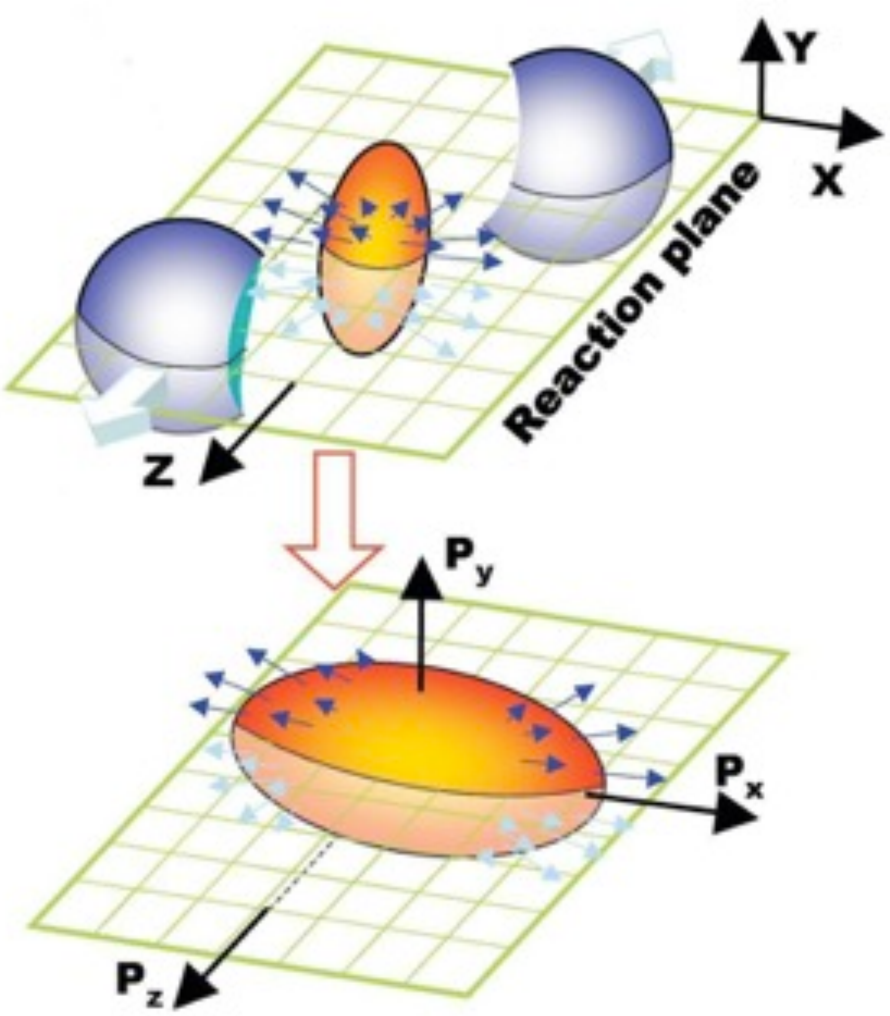
10-11 fm/c, 40% longer than at RHIC

Anisotropy and Correlations

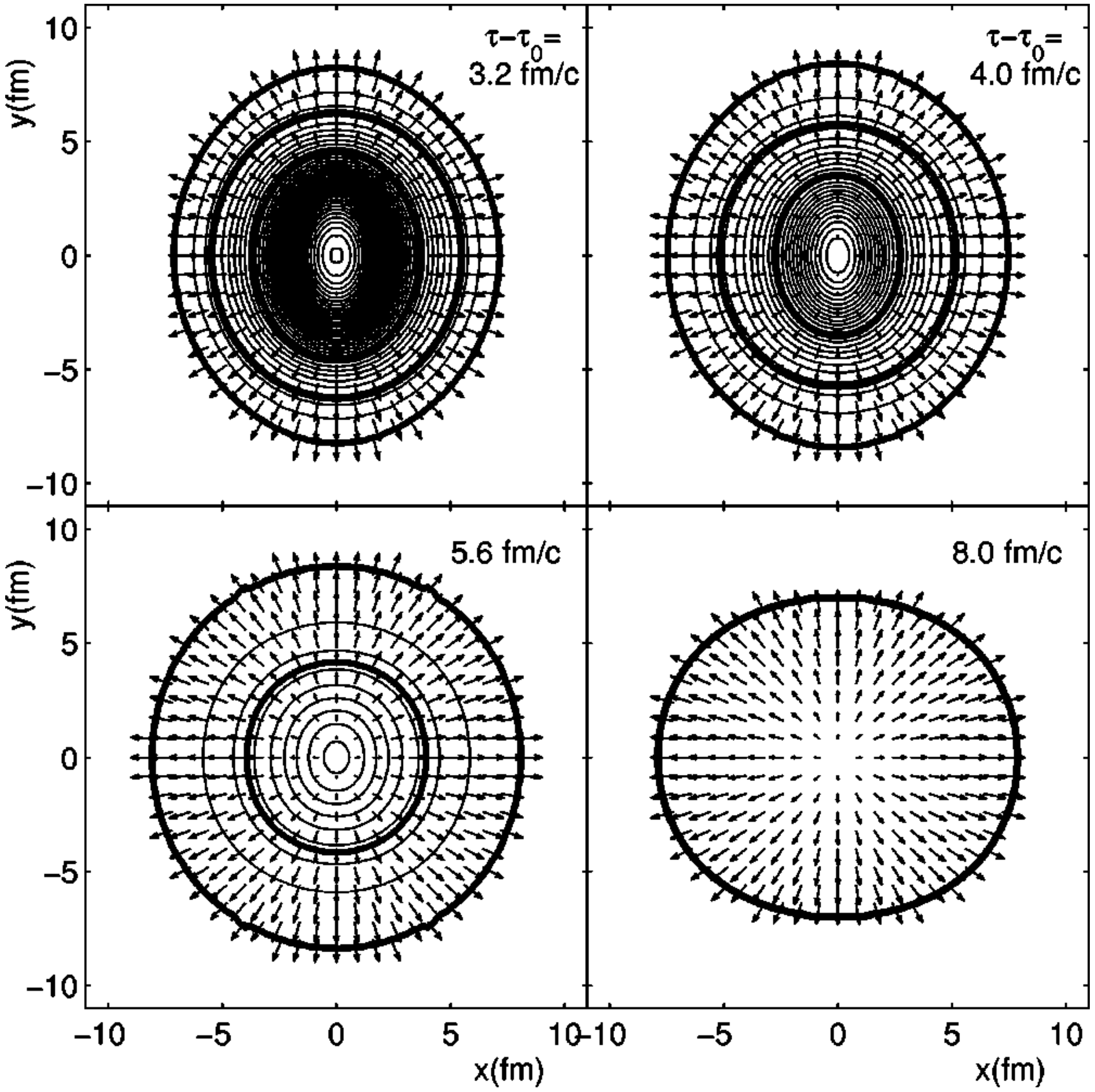
Elliptic flow
Higher-order anisotropy harmonics
Correlations and Fourier decomposition

Hydrodynamics and nuclear collisions

Elliptic flow of exploding fireball



PHYSICAL REVIEW C, VOLUME 62, 054909



Initial spatial eccentricity ⇒ final momentum eccentricity

Measure 2nd Fourier coefficient v₂

$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos n(\phi - \Psi_n)$$

$$v_n = \langle \cos n(\phi - \Psi_n) \rangle$$

Integrated v_2

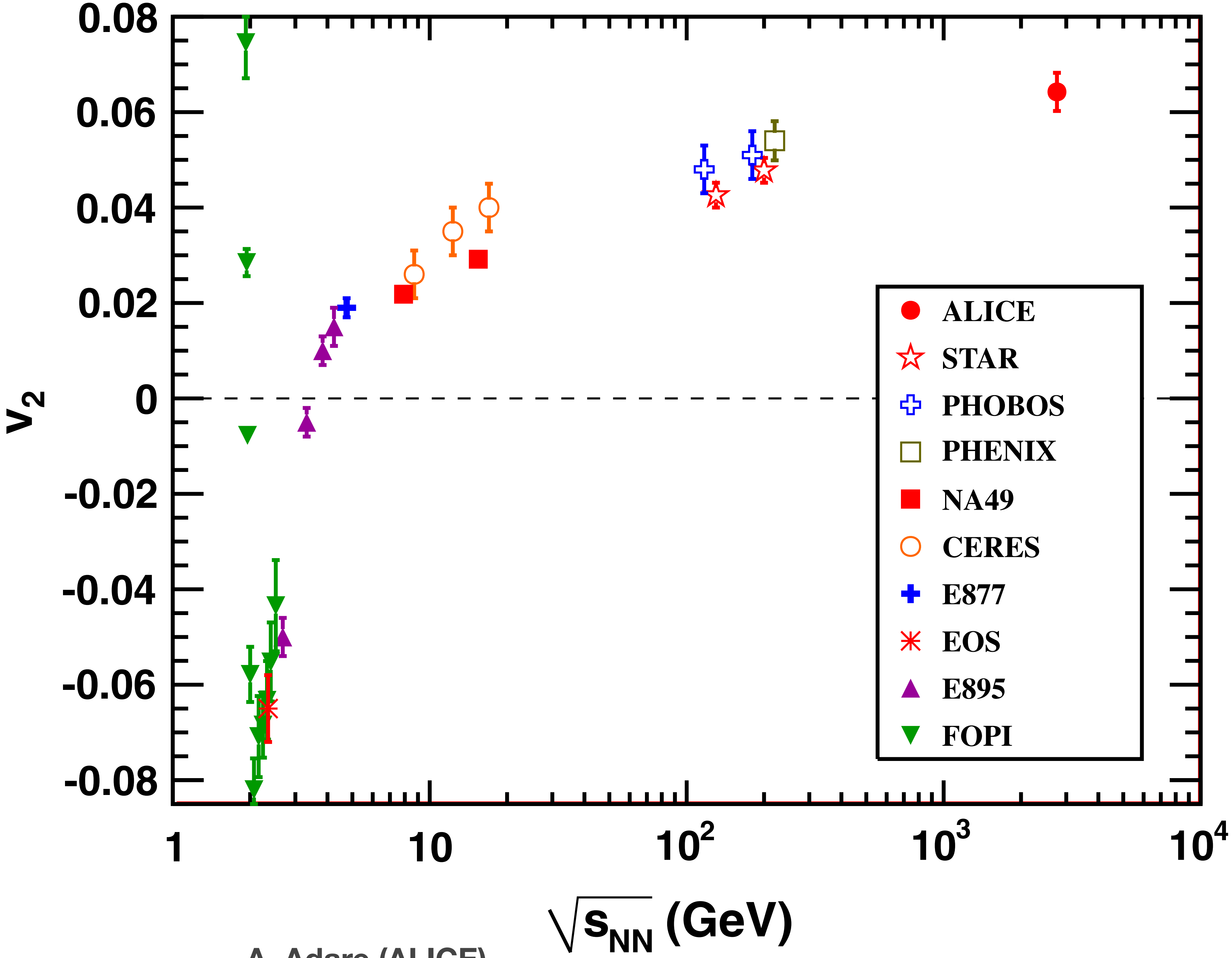
v_2 vs. collision energy for 20-30% most central collisions

Hydro behavior follows extrapolated RHIC trend

Flow at LHC
30% above RHIC

Not unexpected
(larger particle 〈pT〉)

PRL **105,** 252302 (2010)



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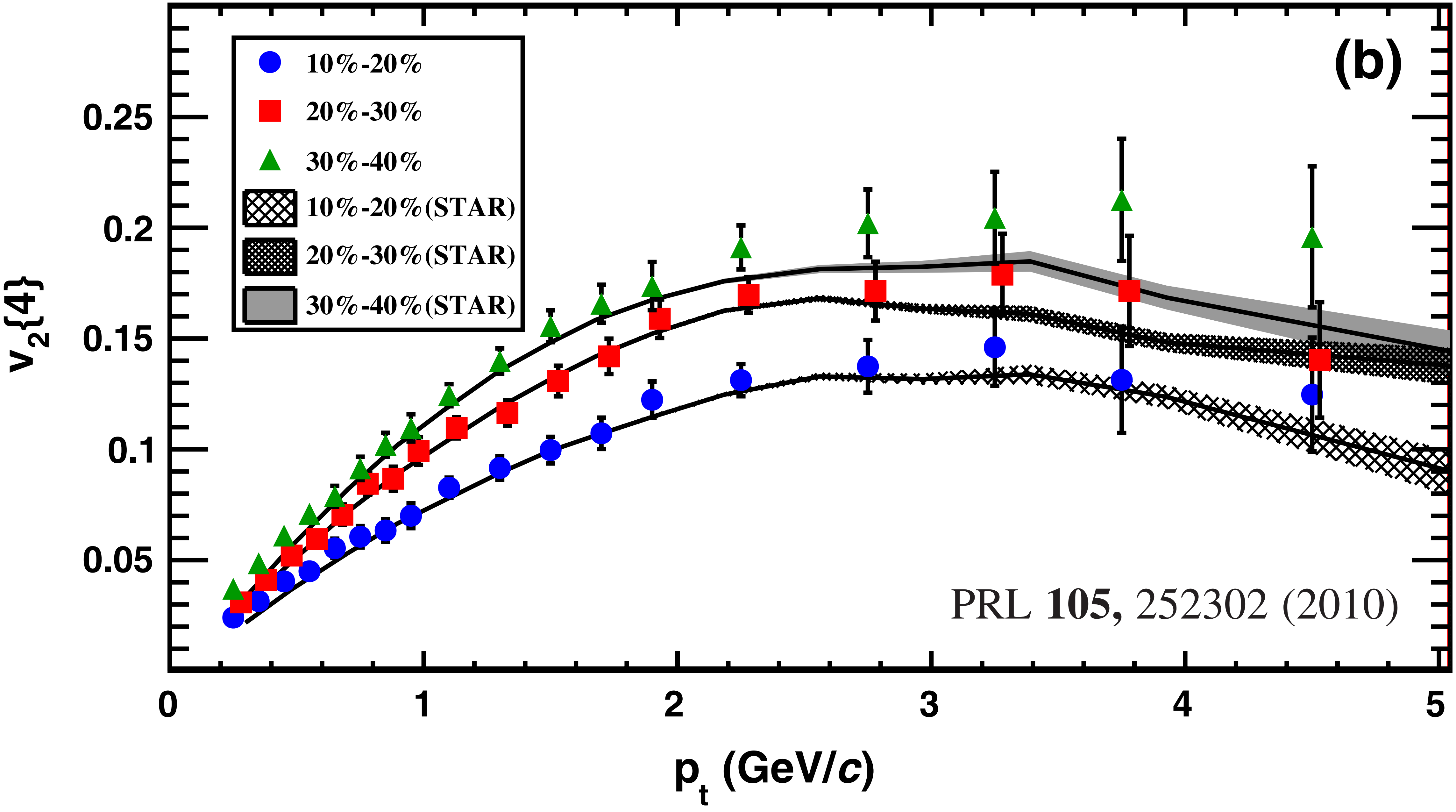
v_2 vs. p_T for unidentified particles

Matches RHIC within 5%

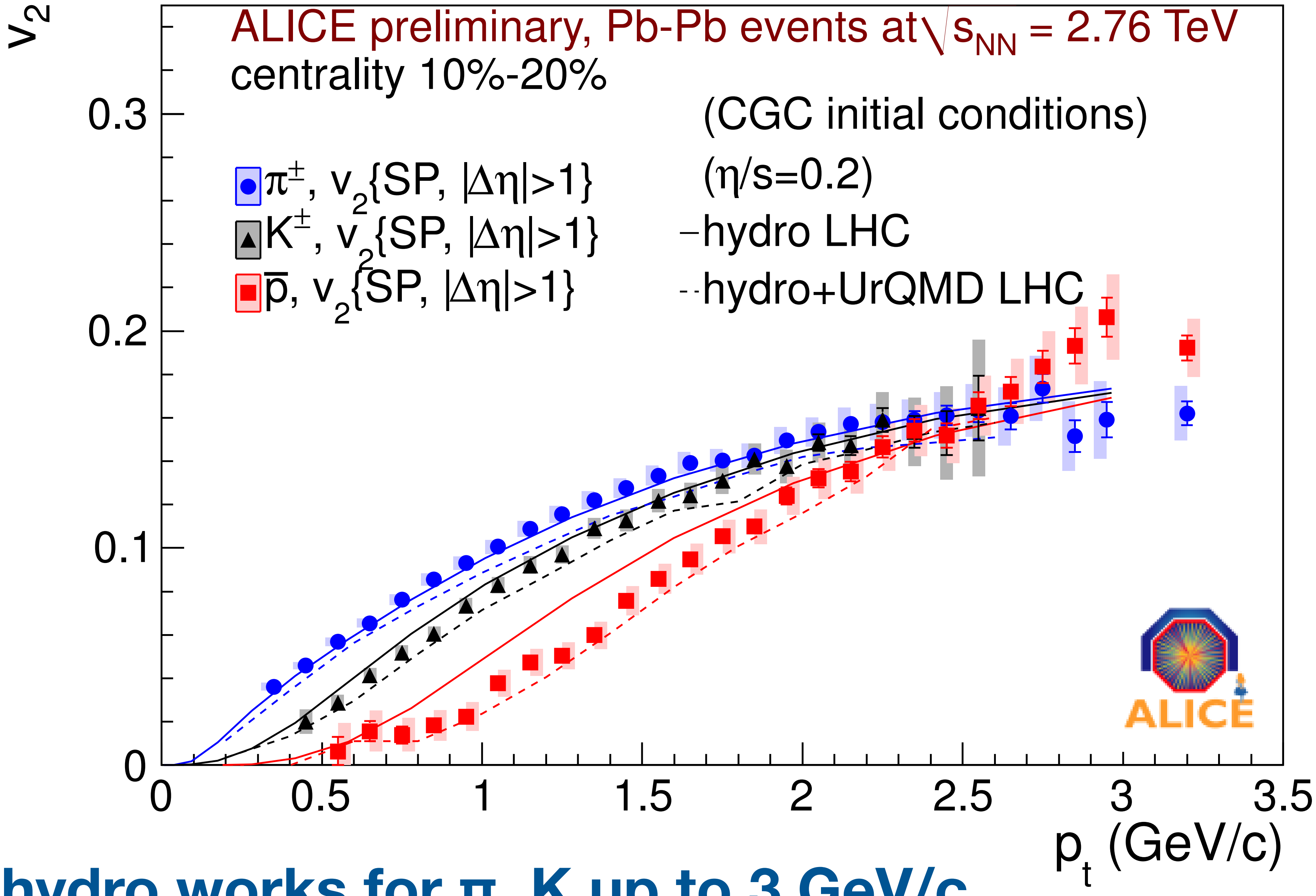


Agreement also consistent with hydro predictions (e.g. PRC 84 (2011) 044903)

Differential v_2: pions, kaons, protons

Significant mass dependence

Expected: radial flow gives all species similar β, thus different p_T



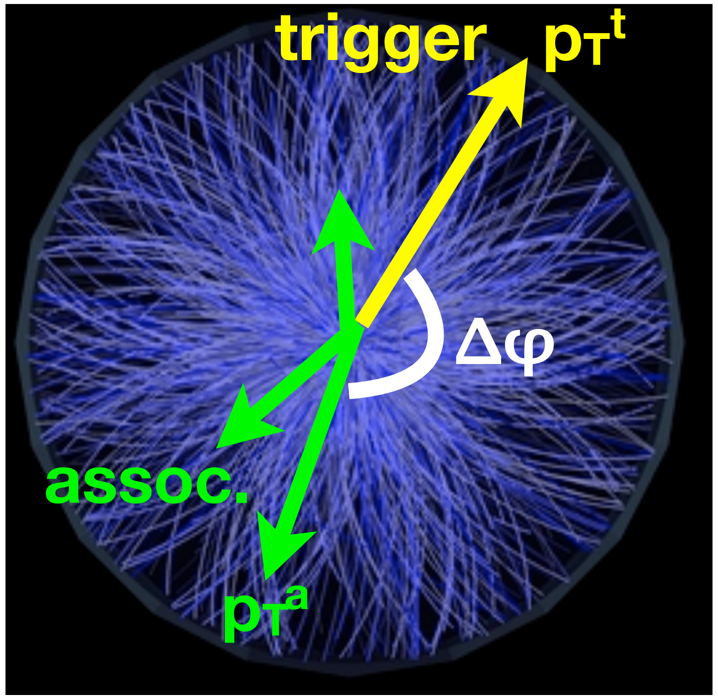
Viscous hydro works for π, K up to 3 GeV/c

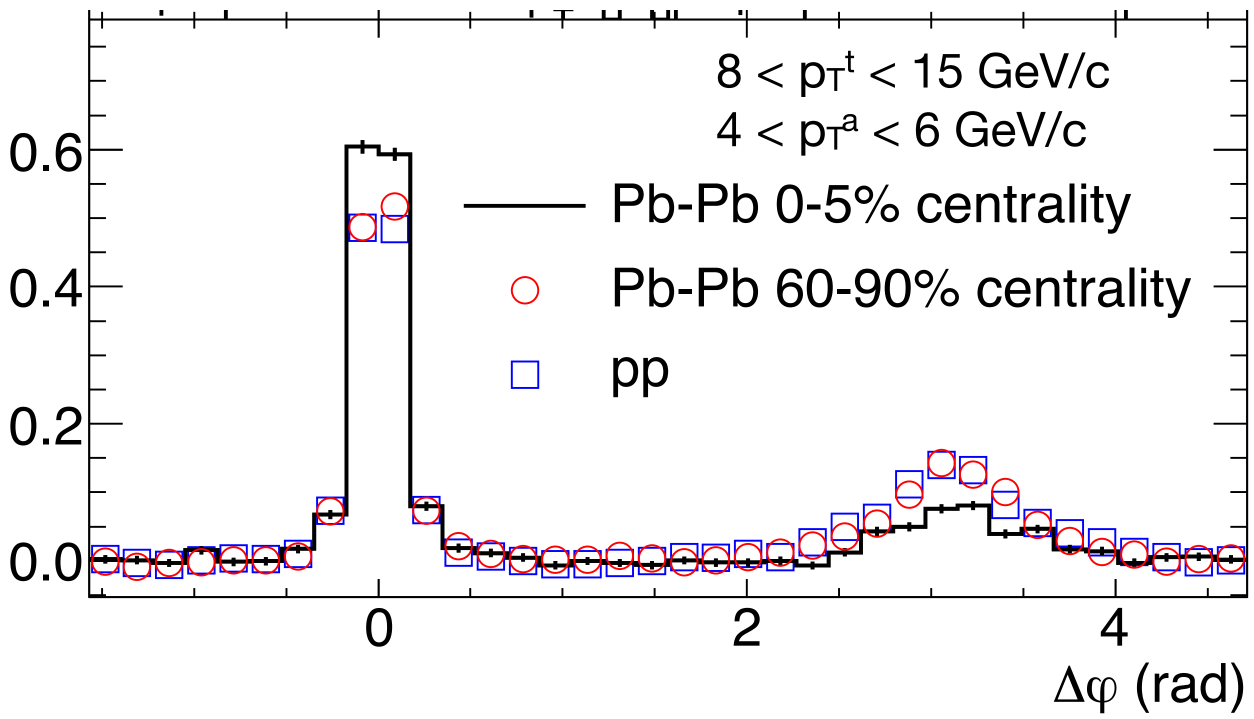
Need hadronic rescattering to match antiprotons in central data

(UrQMD/VISHNU, arXiv:1108.5323v1)

Two-particle correlations

arxiv:1109.2501
arxiv:1110.0121

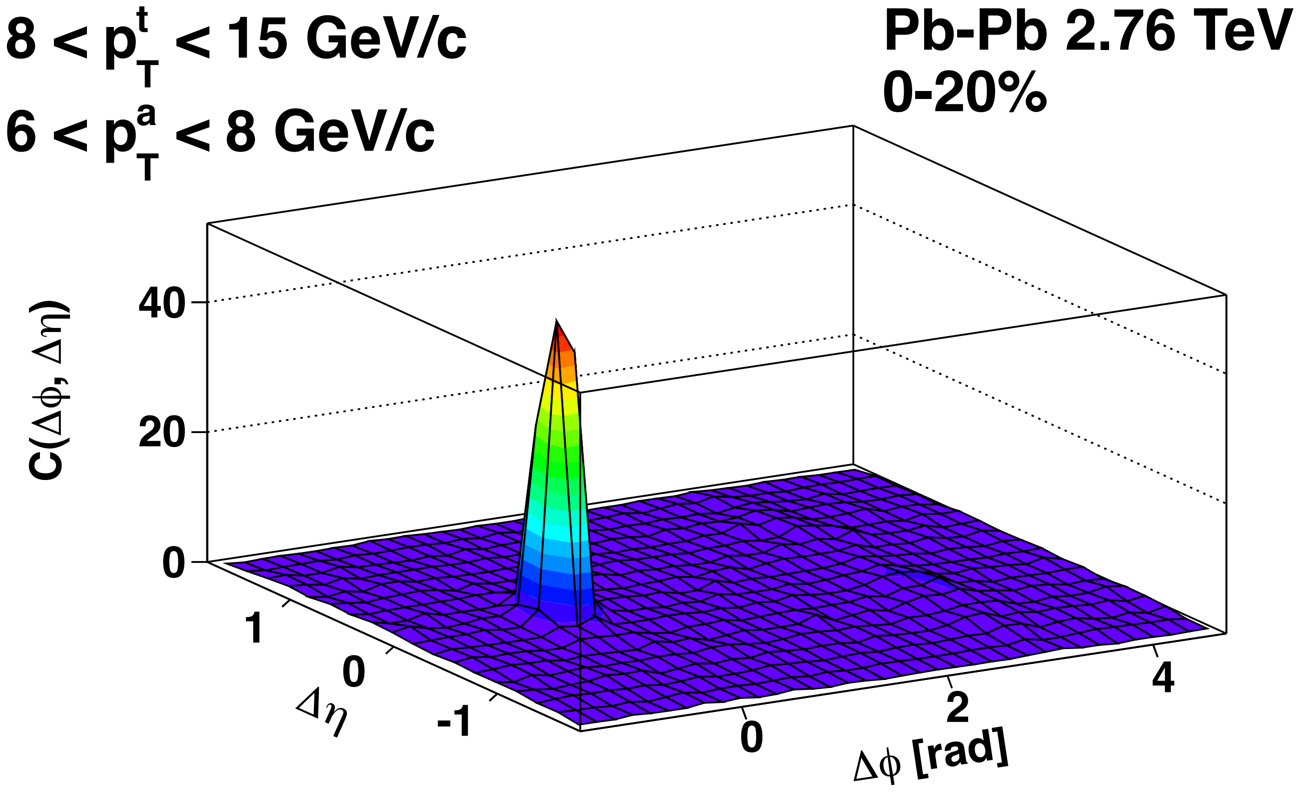




High-p_T correlations

From jet fragmentation, high pair density at $\Delta\varphi = 0$ ("near side") and $\Delta\varphi = \pi$ ("away side")

Shape similar to pp at high p_T



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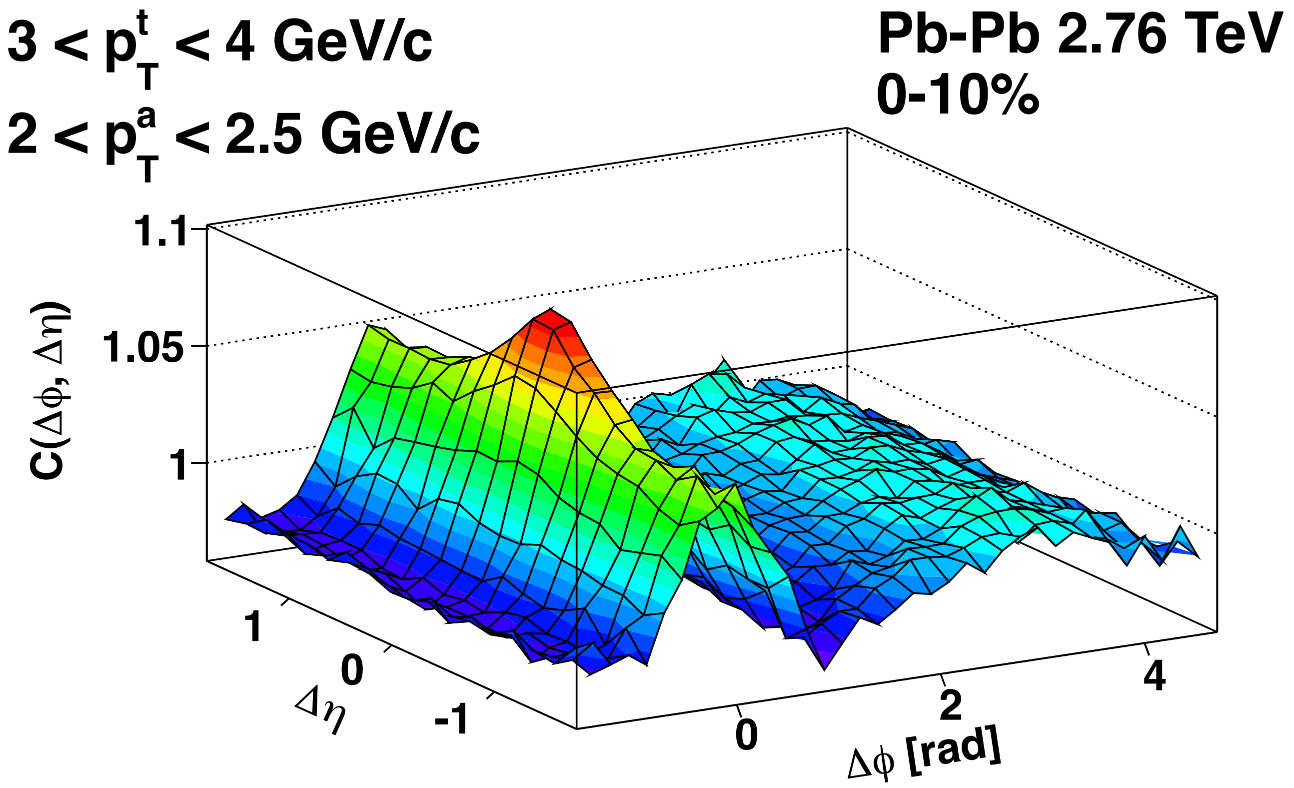
Two-particle correlations

arxiv:1109.2501

Low-p_T correlations

Broad away side

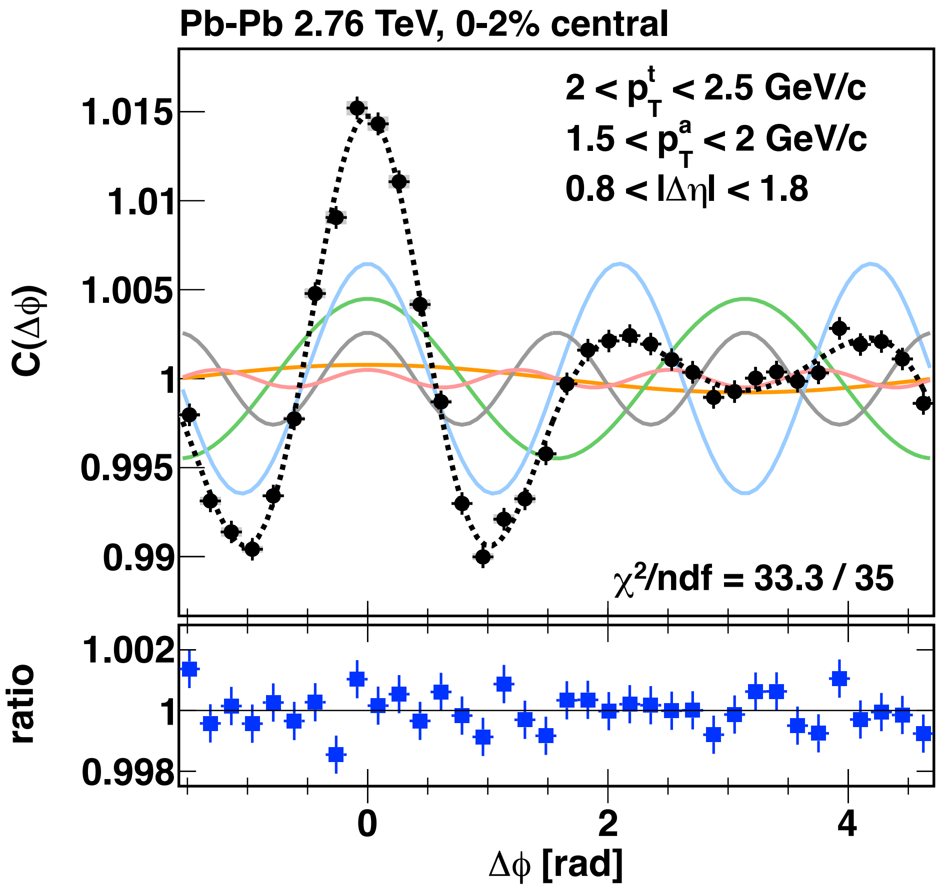
Near side “ridge” at large Δη



Ultra-central (0-2%), Δη > 0.8

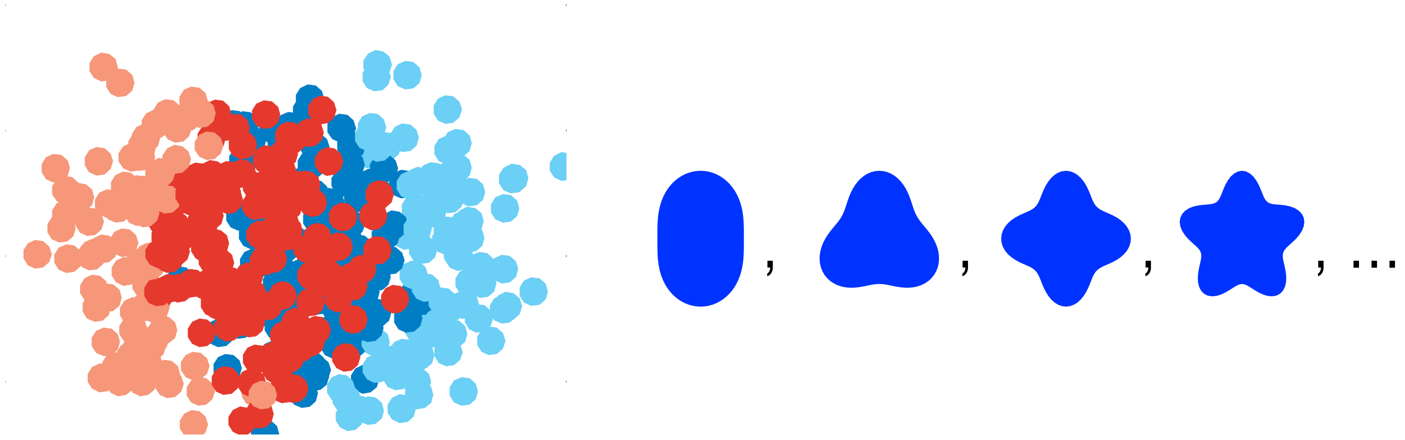
Doubly-peaked away side

n=3 is strongest harmonic



Initial state nonuniformities + hydro

Lead to higher-order flow harmonics



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Higher-order harmonics

v_n from 2-particle cumulant

Higher n terms help constrain viscous hydro models

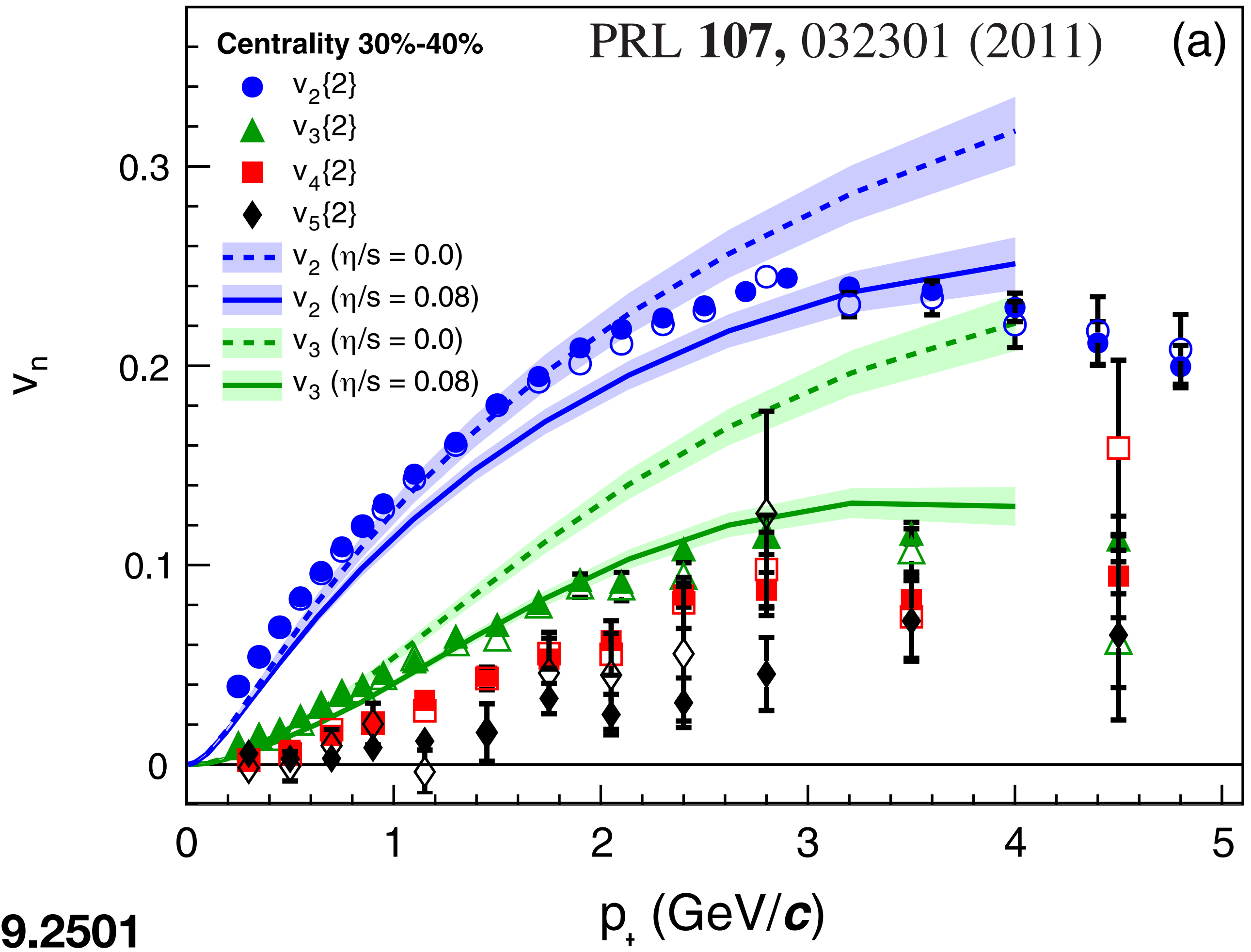
Stronger damping expected for higher n

v_n from 2-particle correlations

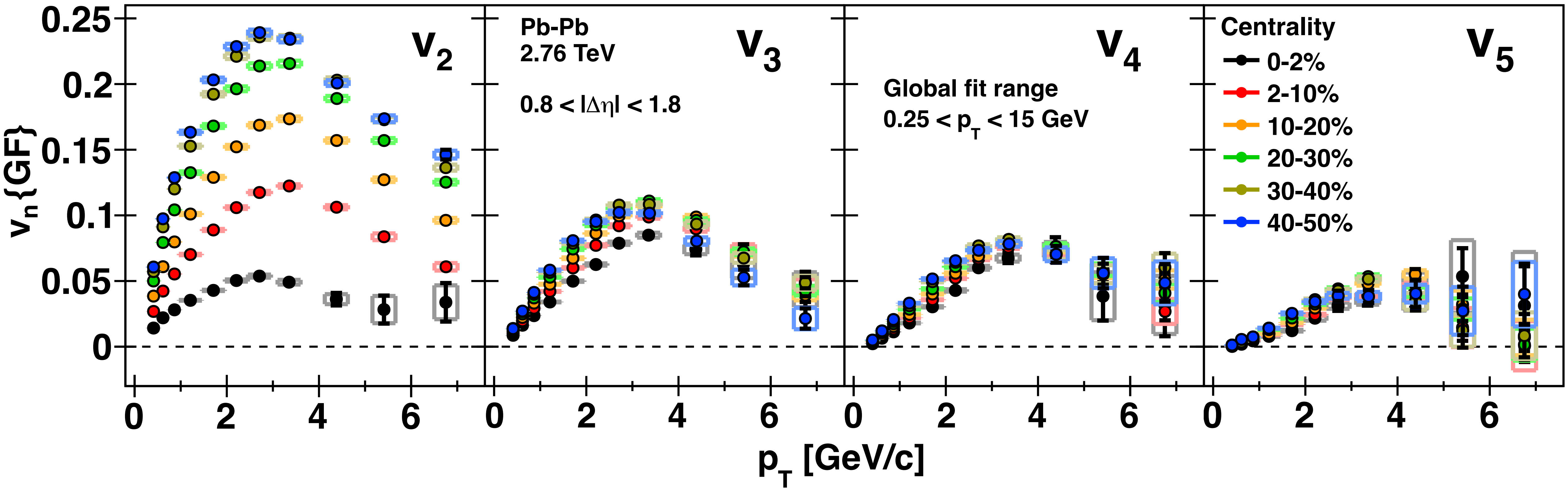
Centrality dependence

Strong for v_2: collision geometry

Weak for v_3+: fluctuations



arxiv:1109.2501



Identified Particles

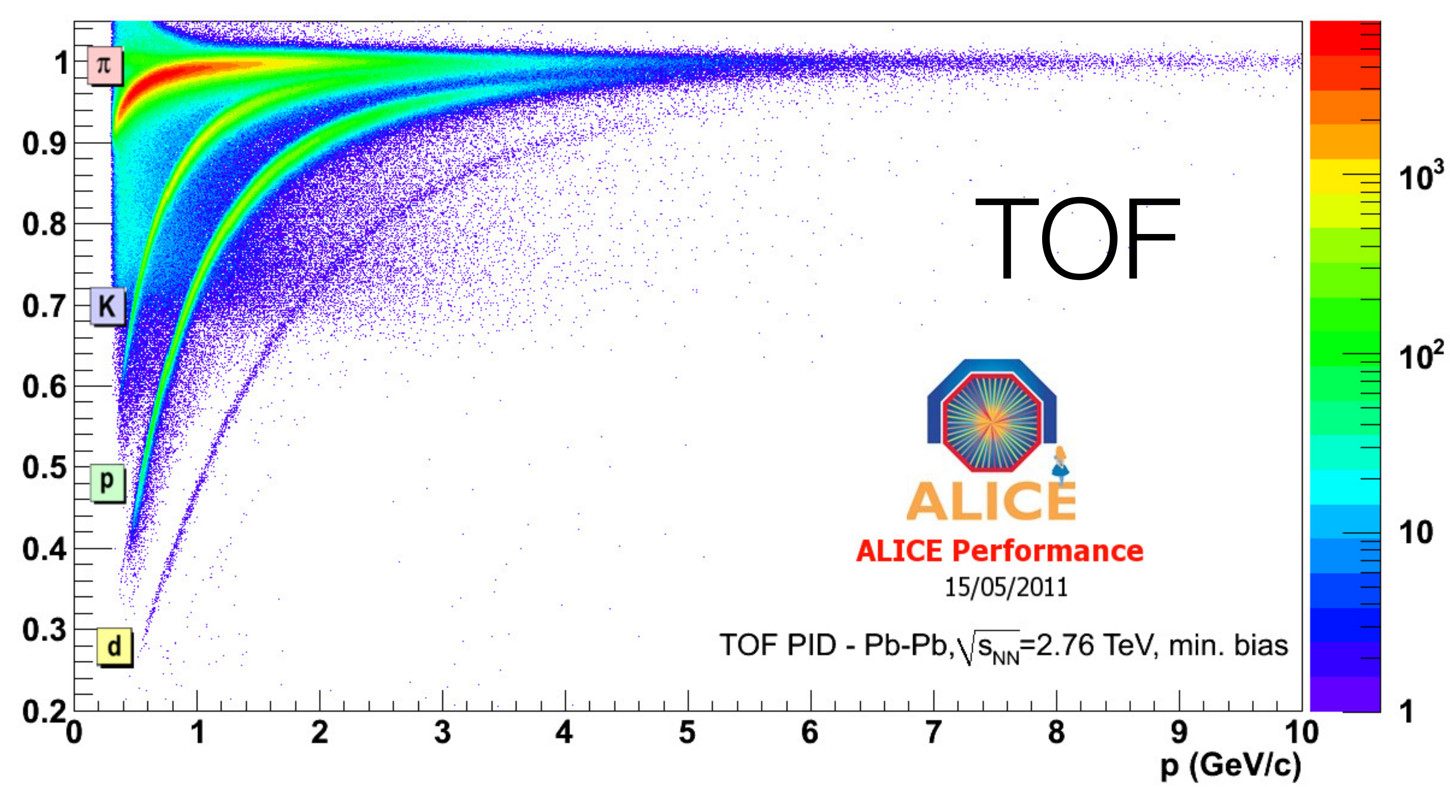
Spectra

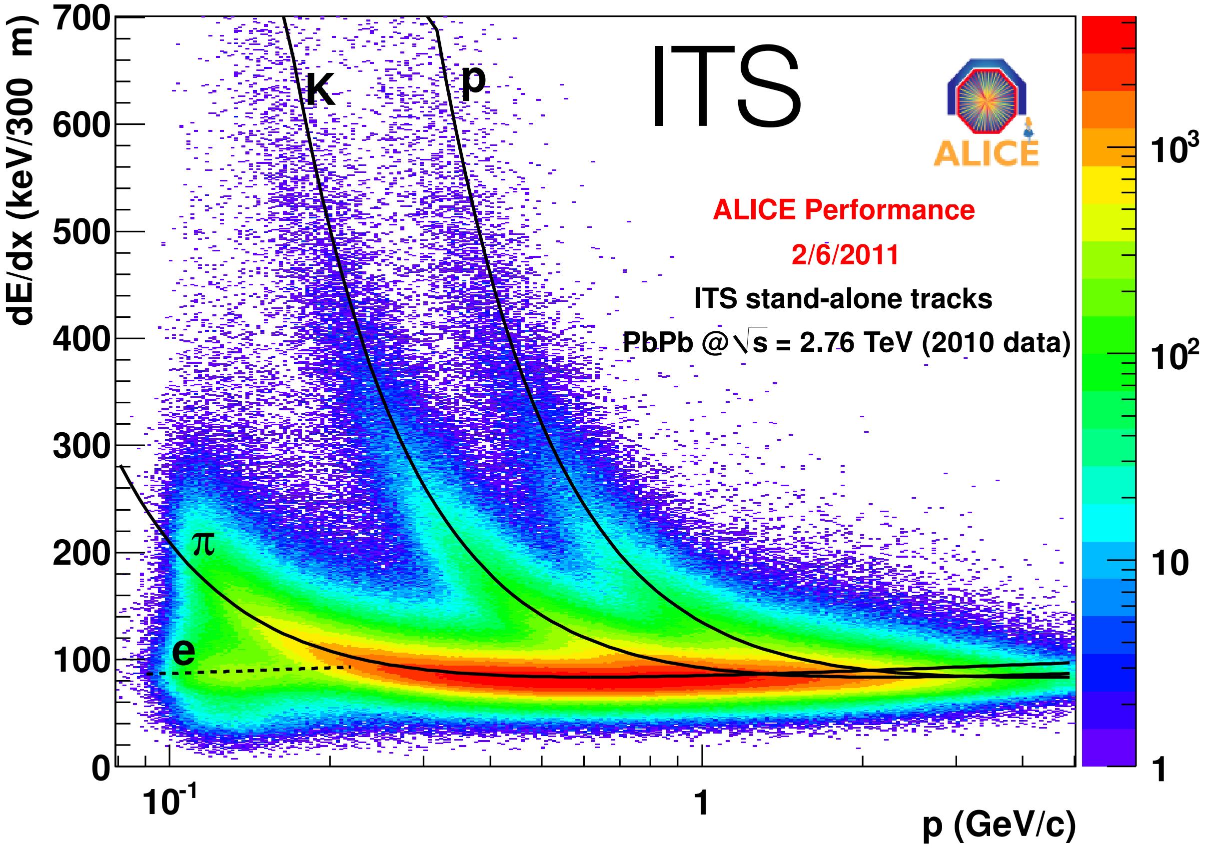
Particle ratios

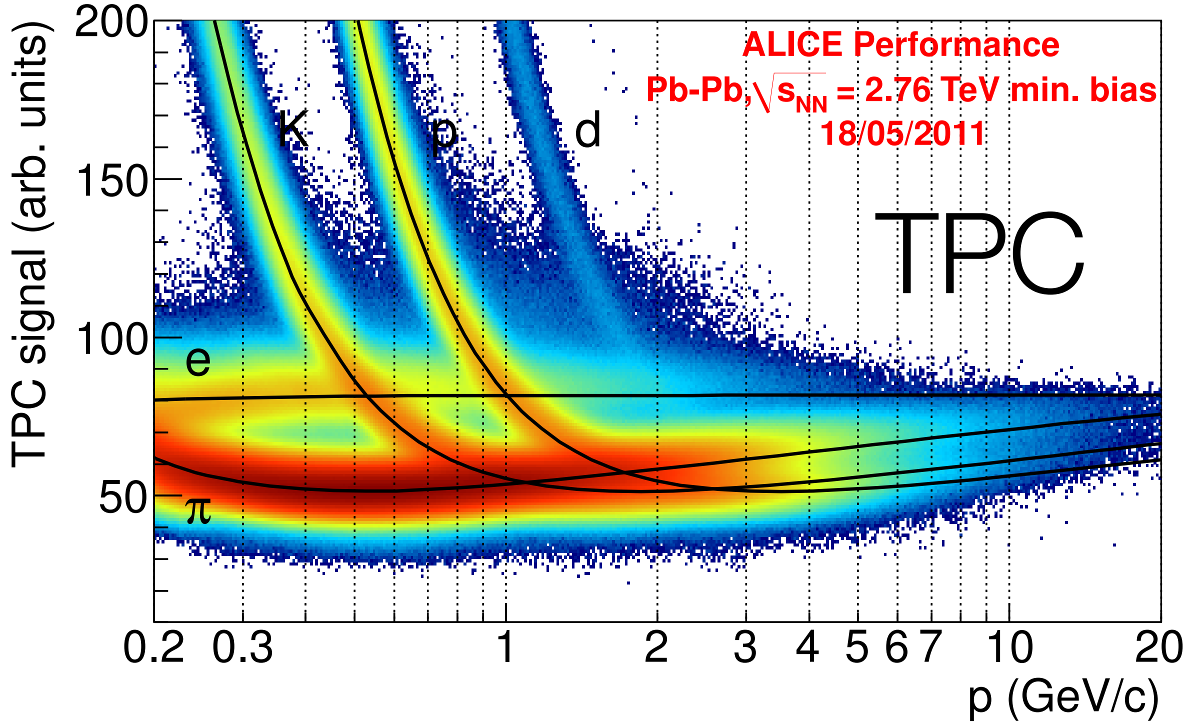
Identified Particles

Spectra

Particle ratios





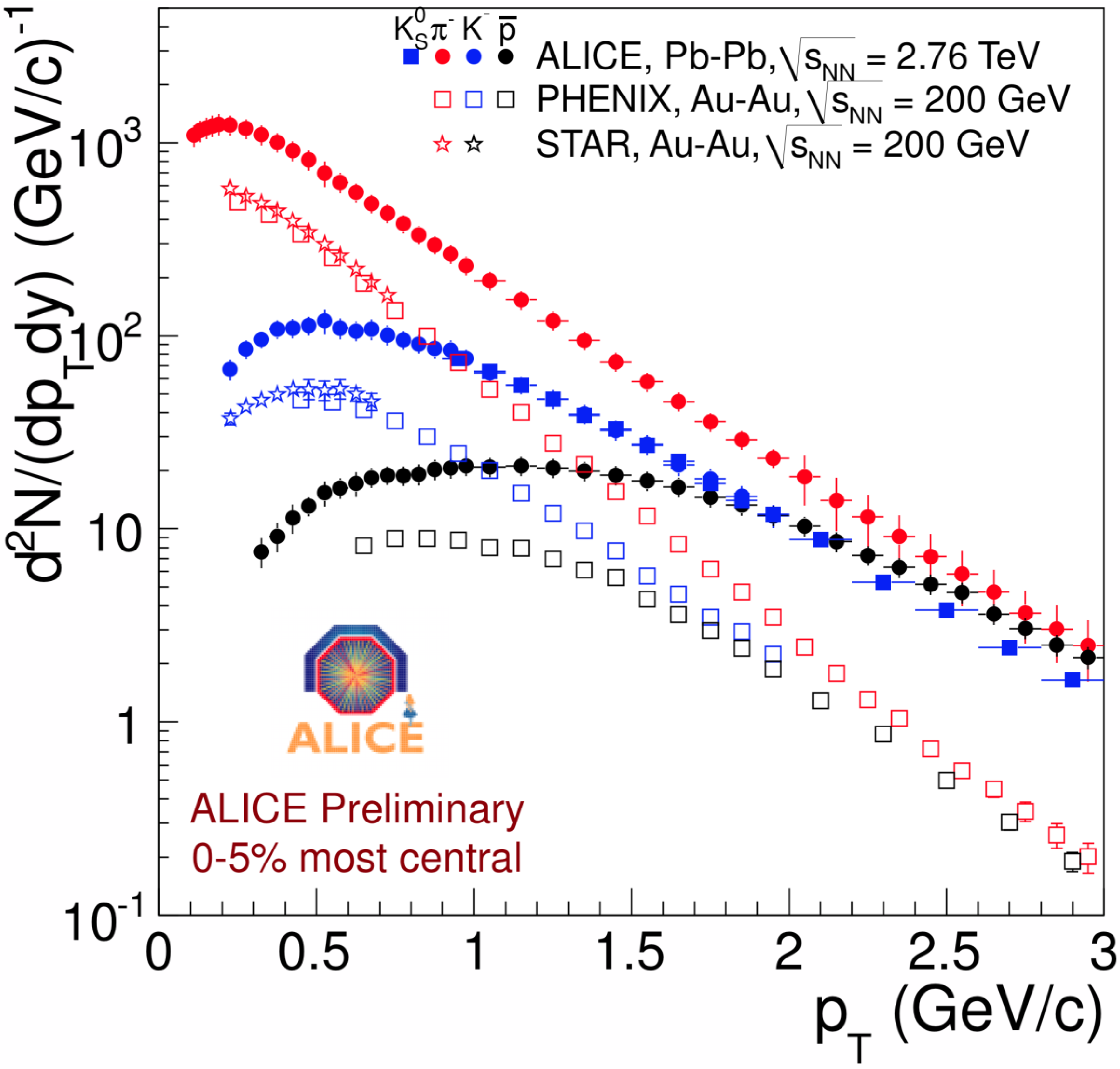


π, K, p spectra

Harder spectra and larger yield than at RHIC

Fits using "blast wave" model suggest large radial flow

Transverse flow velocity:
β = 2/3



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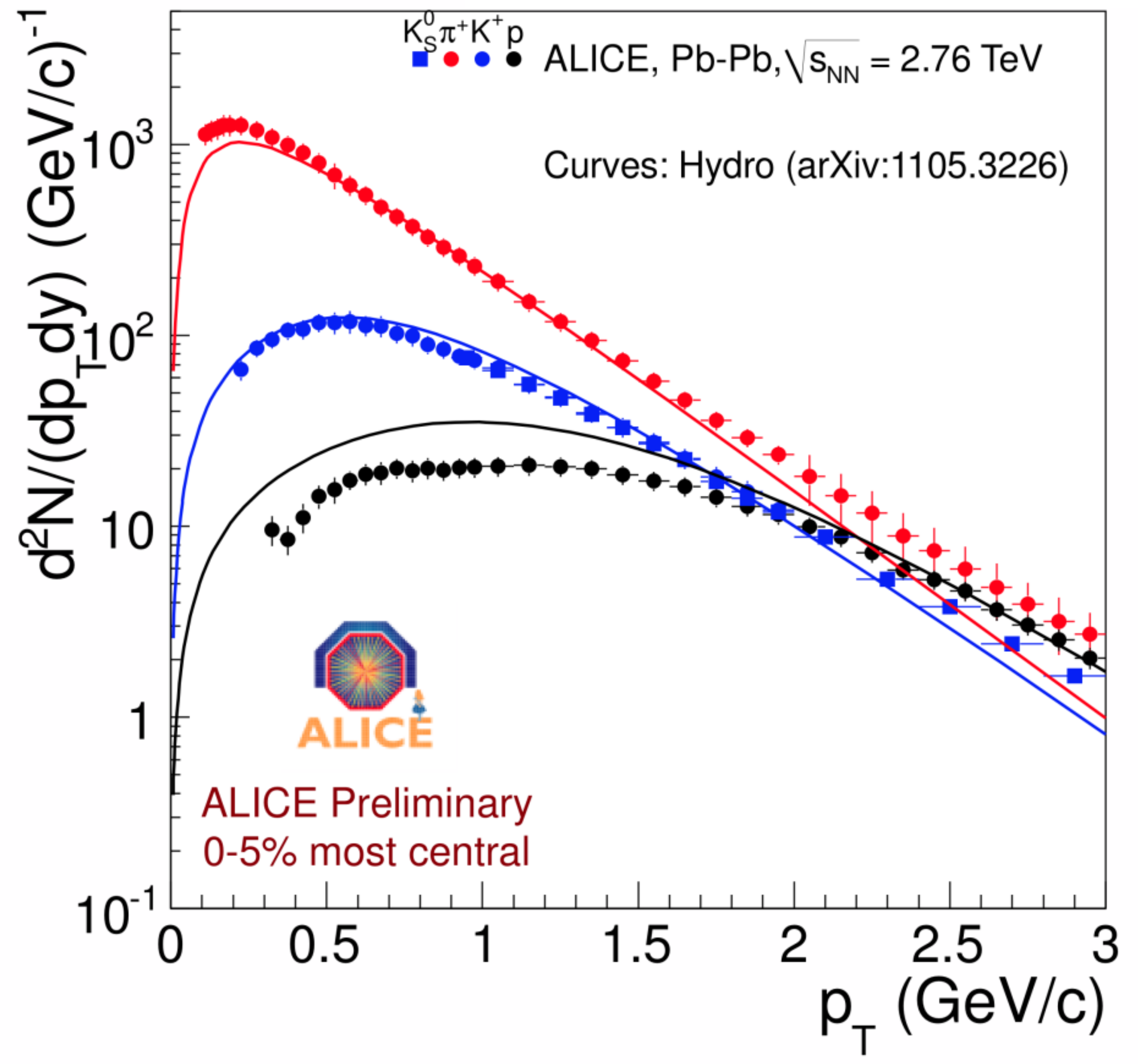
Comparison with hydro models

Harder spectra and lower proton yield than predictions

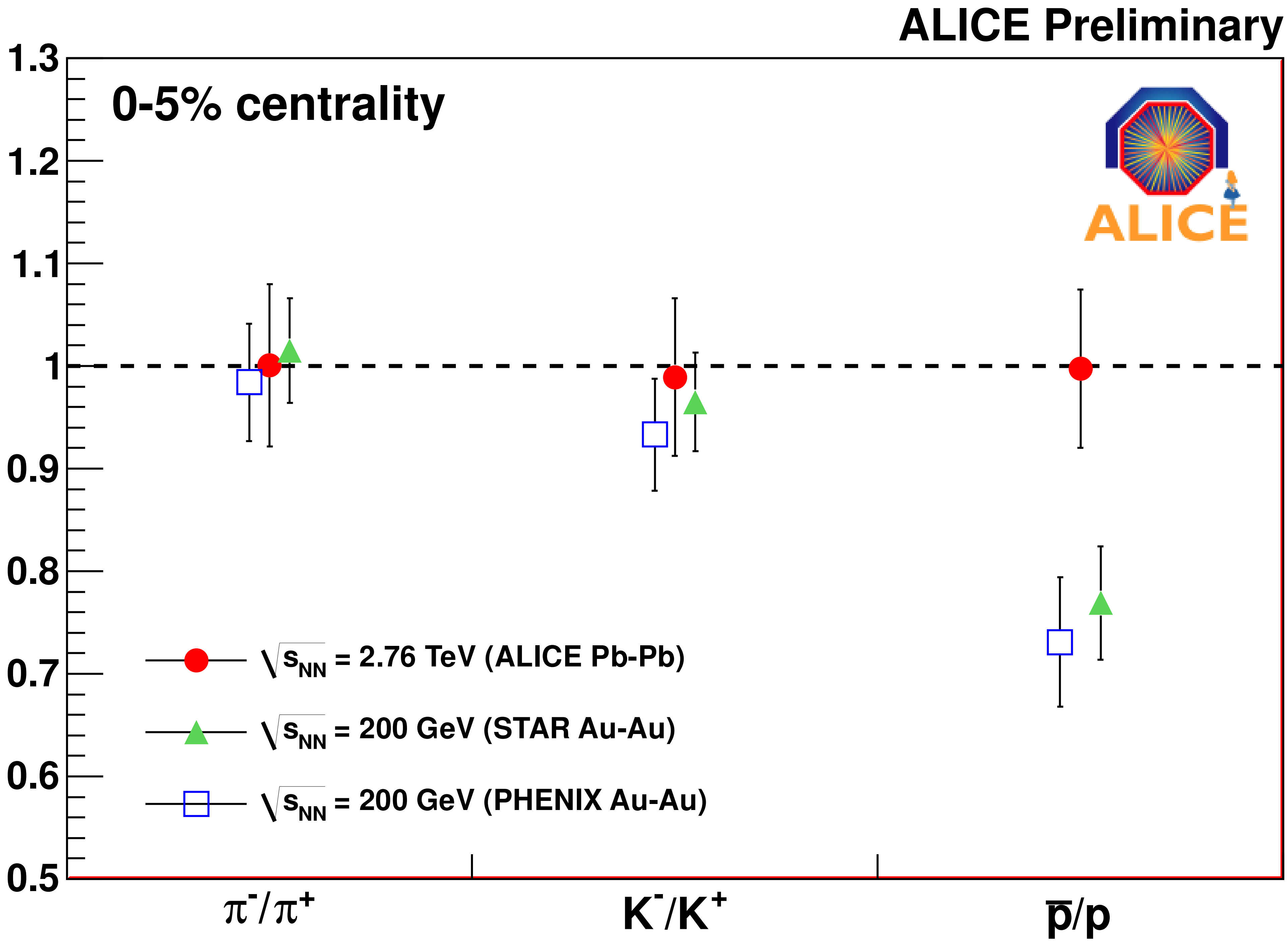


Chemical freezeout temperature T_{ch} lower than hydro expectation

Particle ratios

Symmetric particle - antiparticle production at LHC

$\mu_B \approx 0$



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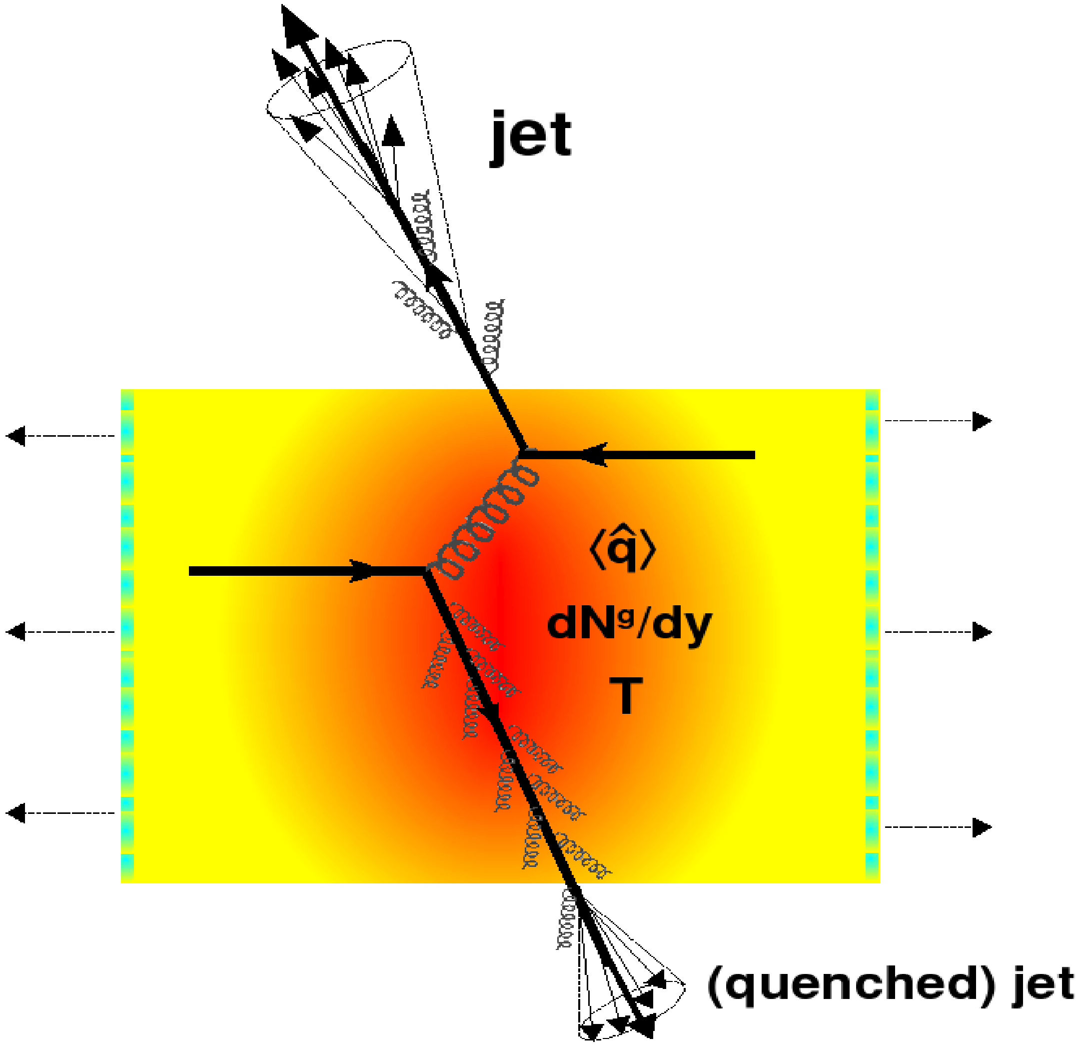
Energy Loss Observables

R_{AA}
- **unidentified particles**
- **heavy-flavor**
- **event-plane dependence**

High-p_T correlations

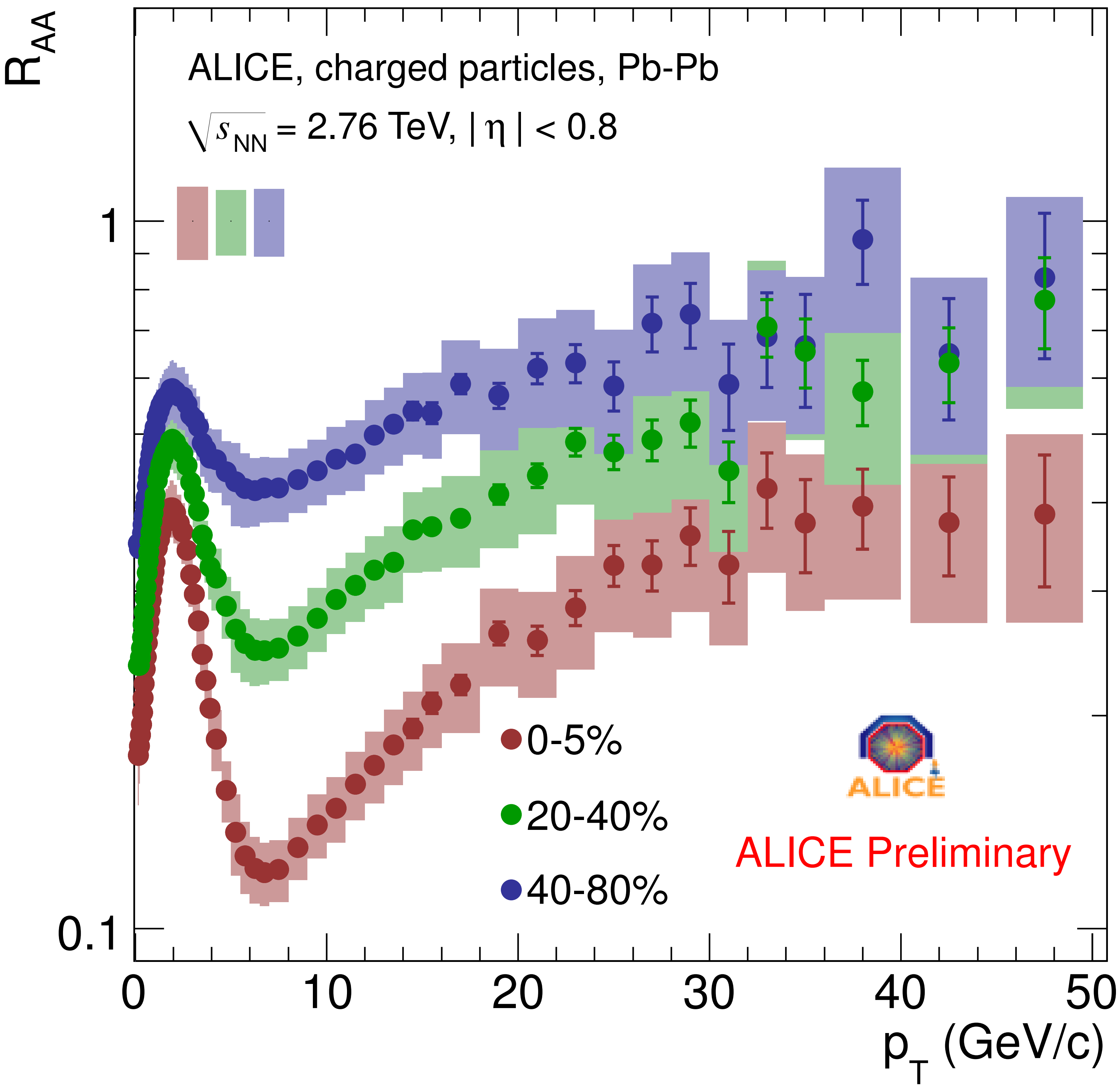
Not included:

high-p_T v2 (see talk by A. Dobrin)



“Jet Quenching”, D. d’Enterria
arxiv:0902.2011

Charged particle R_{AA}



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$$R_{AA} = \frac{\mathrm{d}N_{AA}/\mathrm{d}p_T^2\,\mathrm{d}y}{\langle N_{\mathrm{coll}}\rangle \mathrm{d}N_{pp}/\mathrm{d}p_T^2\,\mathrm{d}y}$$

P_T dependence

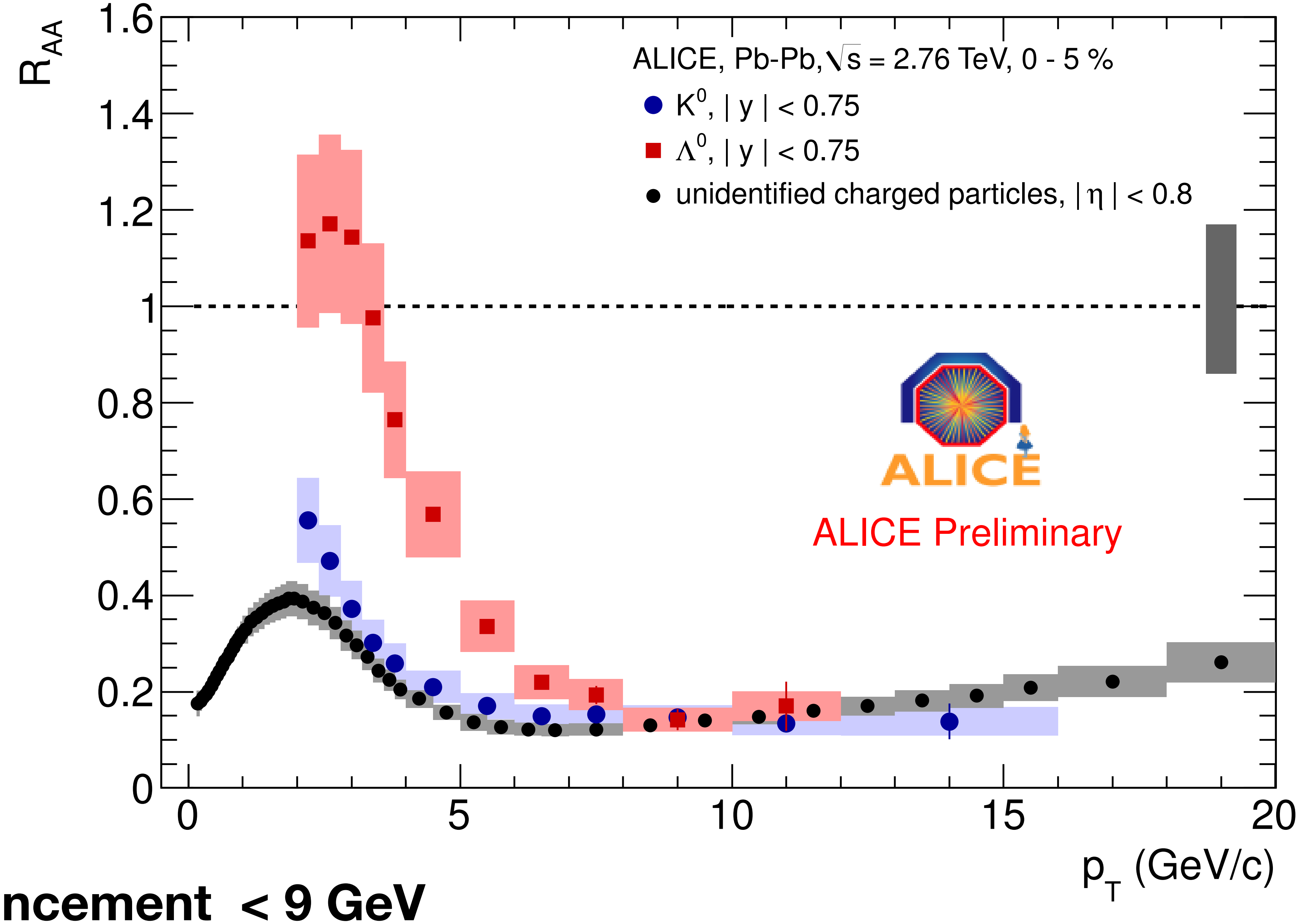
Min. at 6-7 GeV, rising with p_T
Consistent with pQCD expectations

Centrality dependence

Greater suppression for more central collisions

Identified particle R_{AA}

Strange quark nuclear modification



Strange baryon enhancement < 9 GeV
Strange meson modification similar to charged particles
All yields similarly suppressed at high p_T

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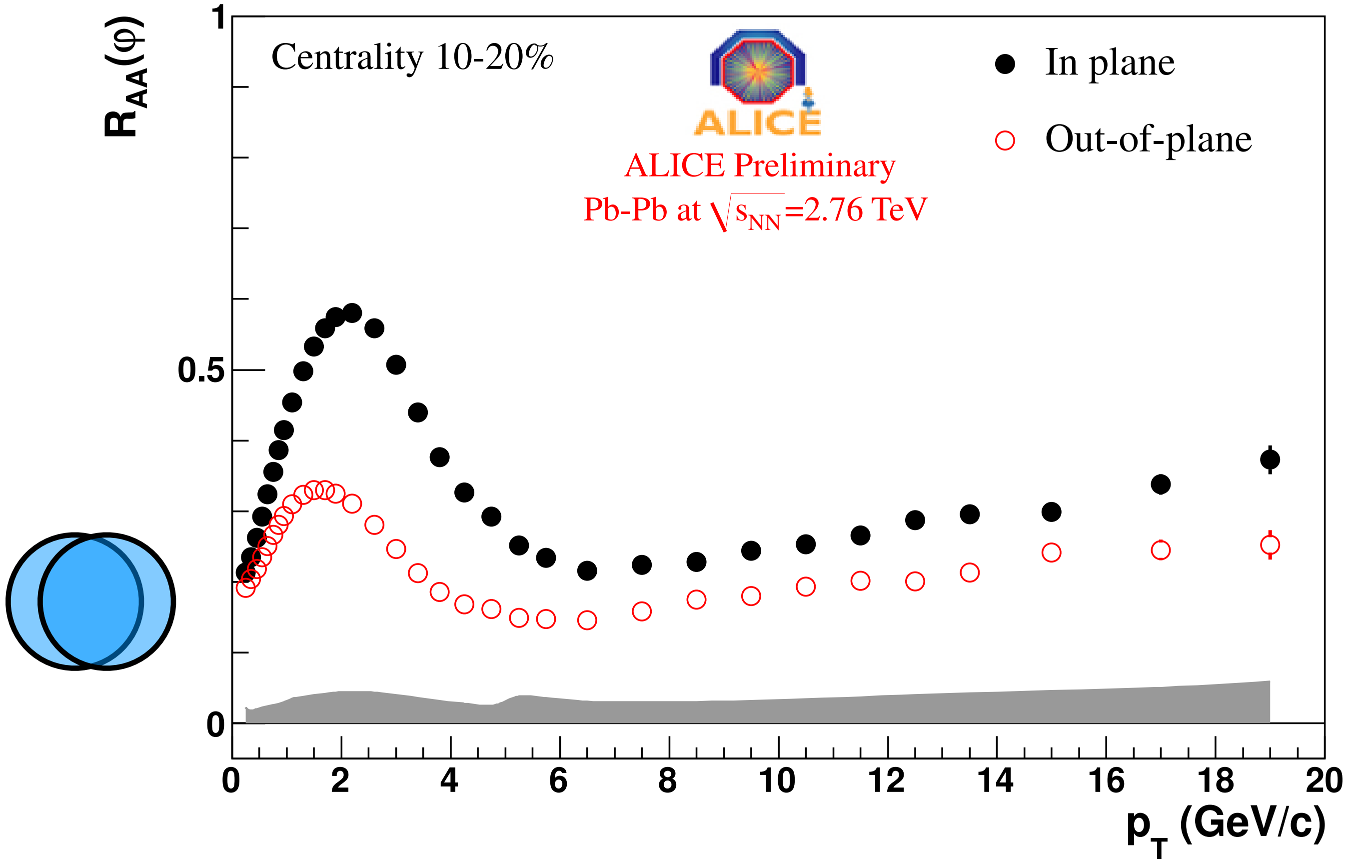
Reaction plane dependence

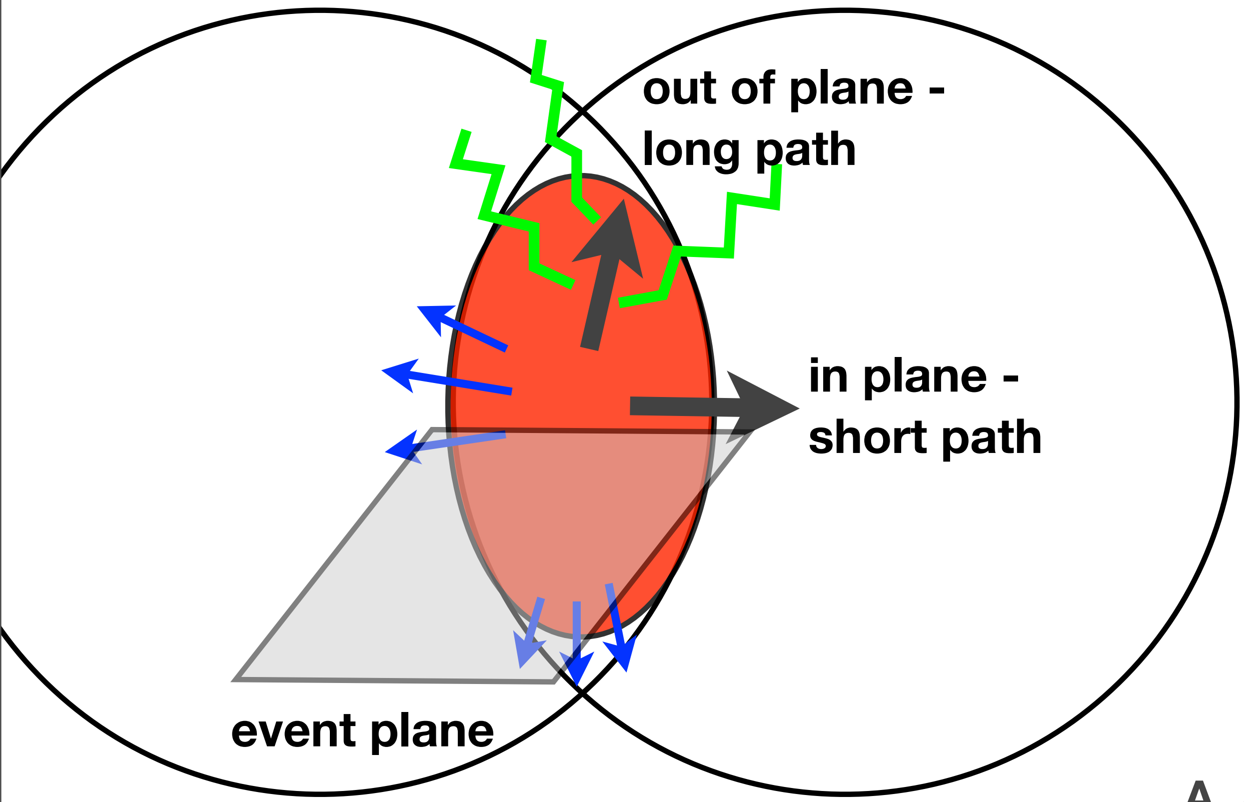
More suppression out-of-plane than in-plane

Path-length dependent quenching

Difference grows with aspect ratio

See talk by A. Dobrin





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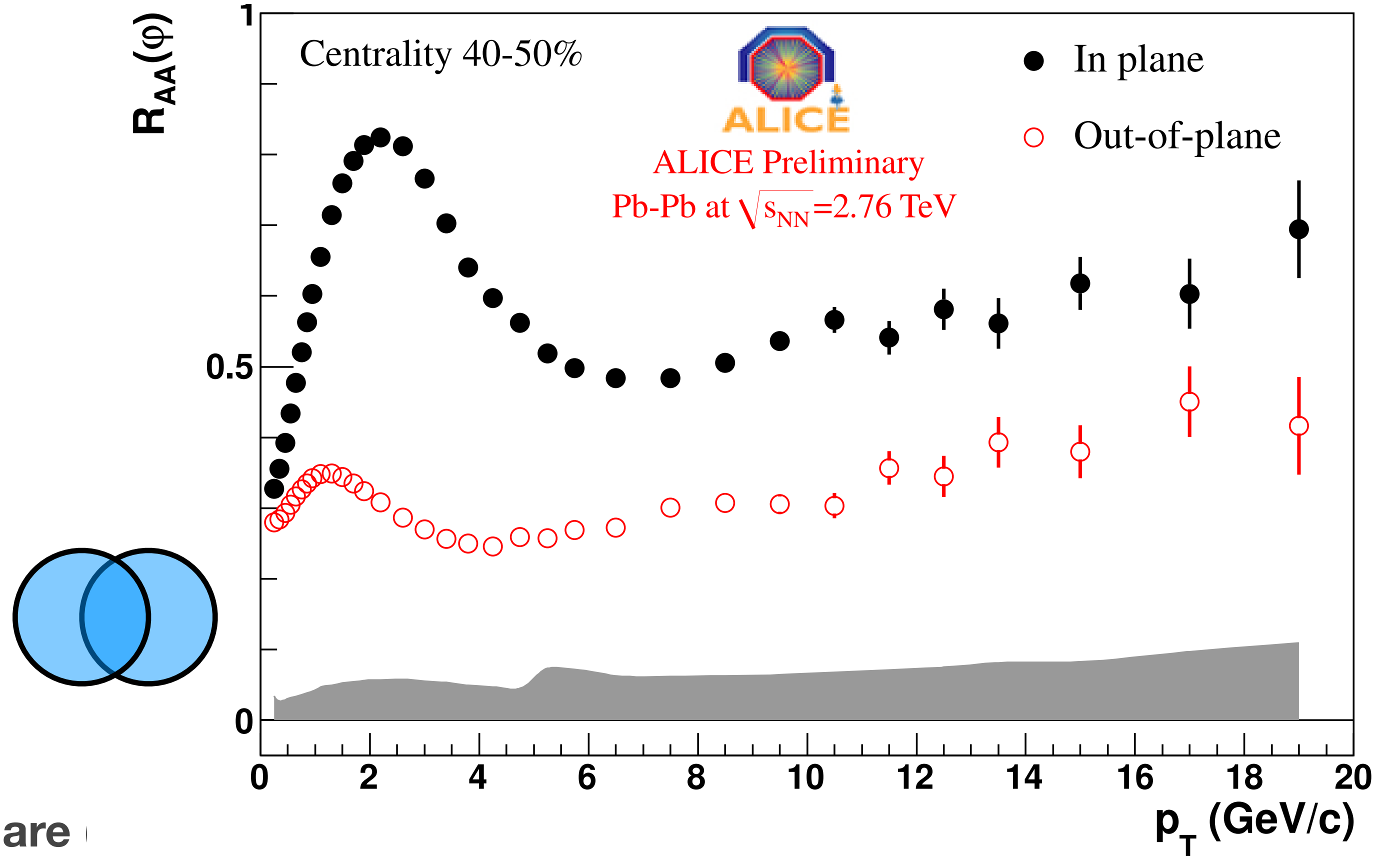


Jet pair yield modification

High-pT correlations

How do Pb-Pb yields compare to pp?

Calculate integrated yield per trigger particle in both systems

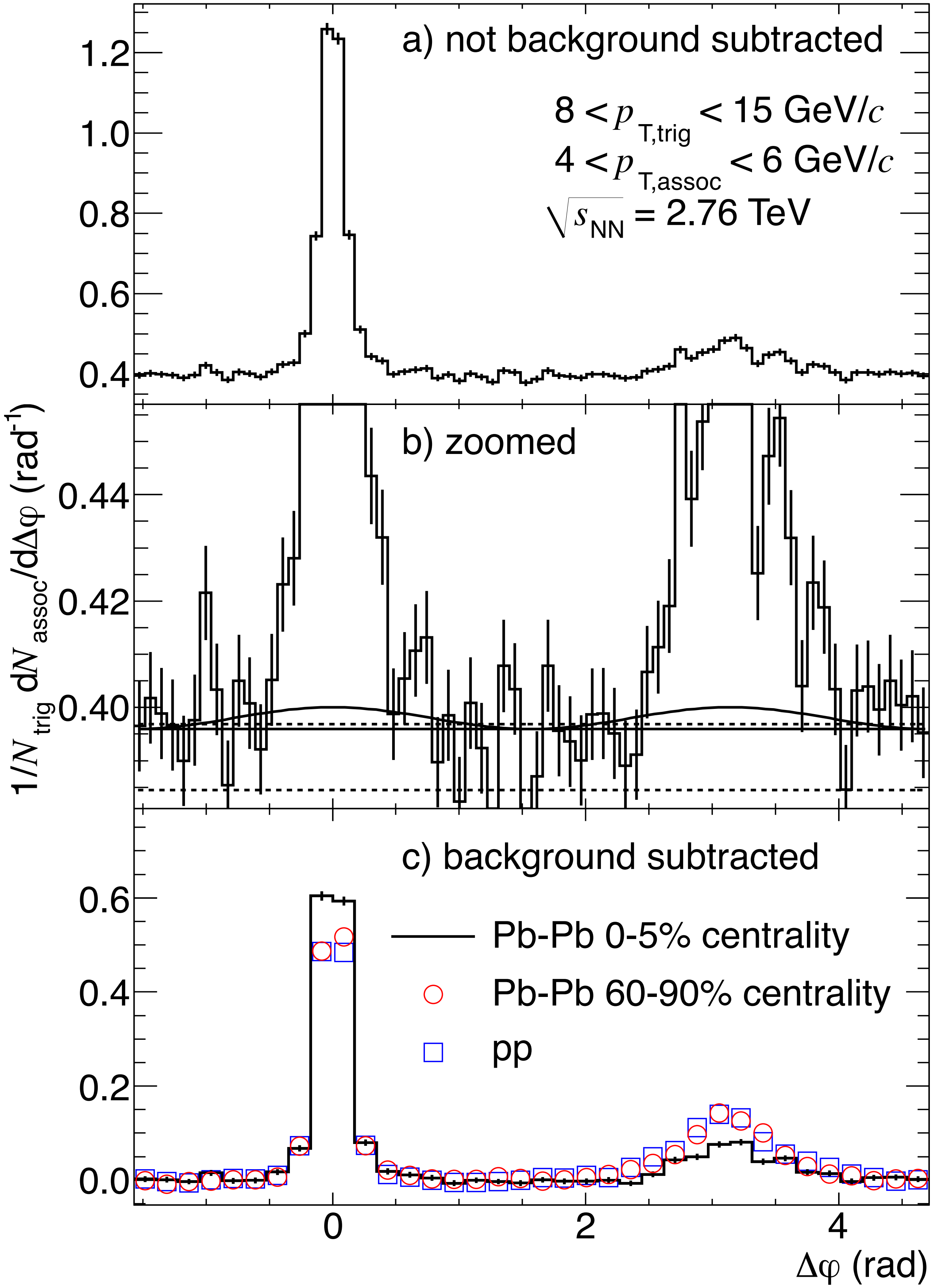
Requires removal of combinatoric non-jet background

Keep to high p_T

Flow ≪ jet-induced correlation

I_{AA}: Two-particle version of R_{AA}

$$I_{AA} = \frac{\left[\frac{1}{N_{\mathrm{trig}}}\frac{dN_{\mathrm{pairs}}}{d\Delta\phi}\right]_{PbPb}}{\left[\frac{1}{N_{\mathrm{trig}}}\frac{dN_{\mathrm{pairs}}}{d\Delta\phi}\right]_{pp}}$$



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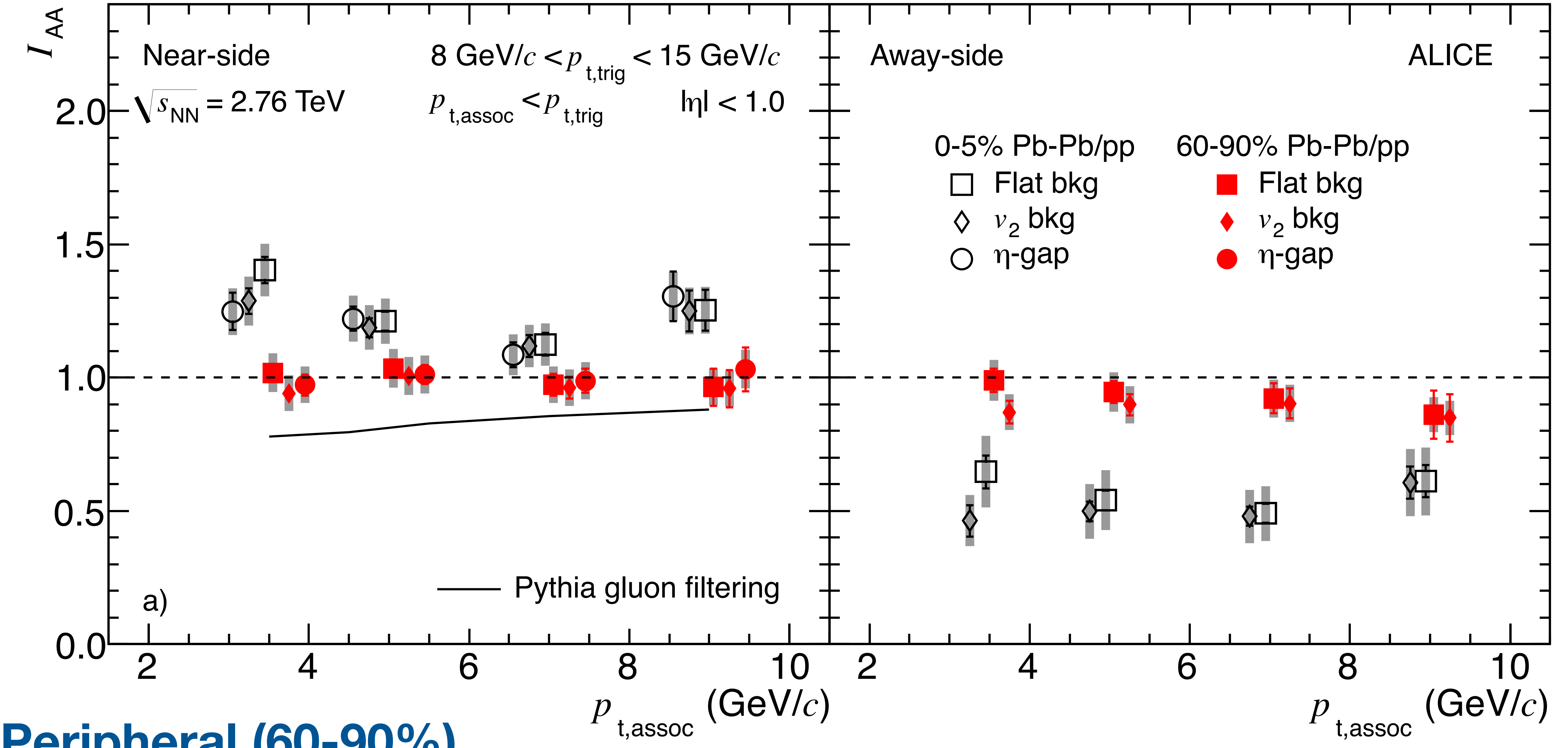
I_{AA} vs. associated p_T

arxiv:1110.0121



Peripheral (60-90%)

No strong modification

Central (0-5%)

Near-side enhancement ($I_{AA} \approx 1.2$); away-side suppression ($I_{AA} \approx 0.6$)

Both consistent with in-medium energy loss

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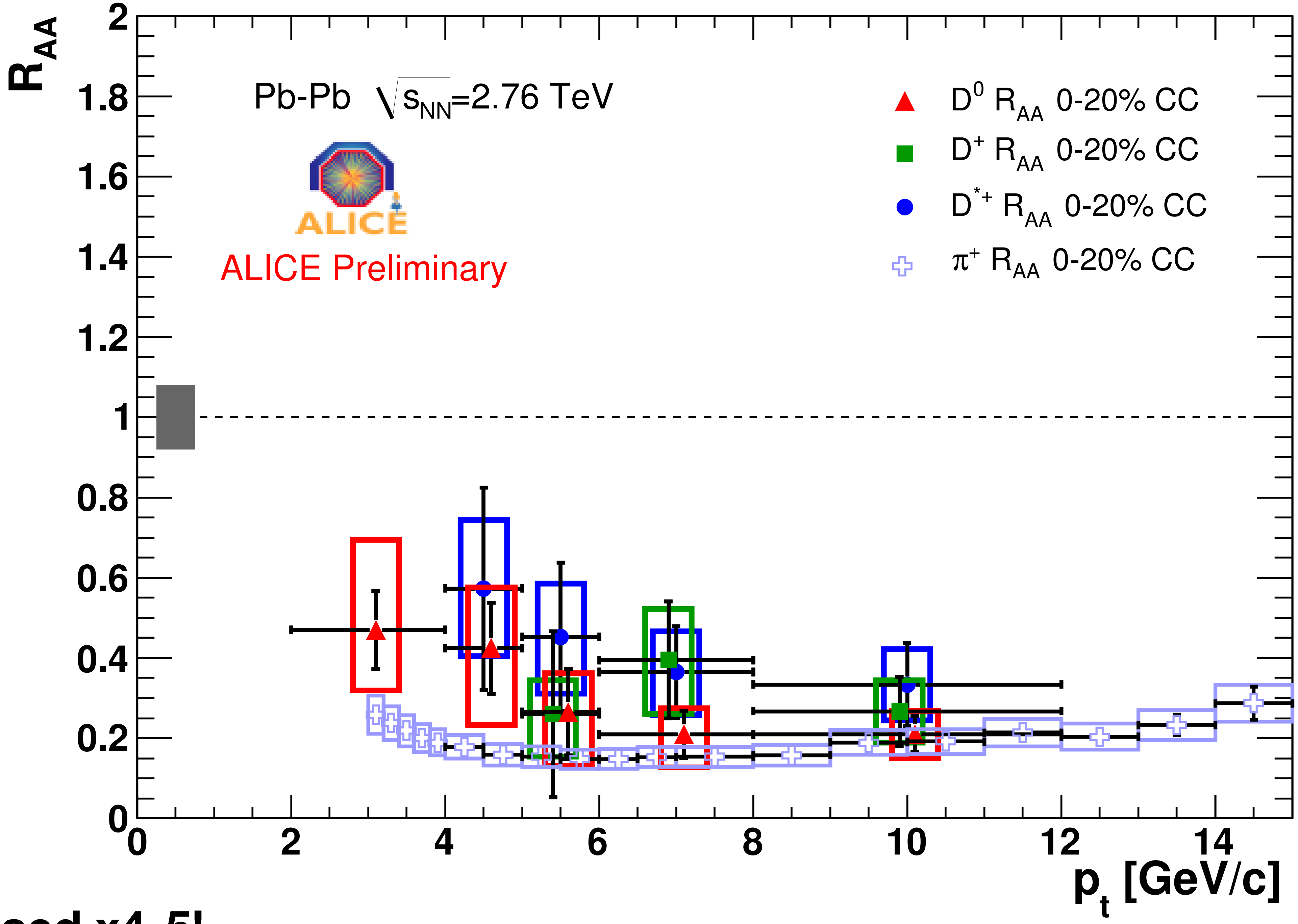
Heavy Flavor and Quarkonia

D meson suppression

pp reference from 7 TeV data, scaled to 2.76 with FONLL



At $p_T > 5$ GeV/c

Charm is suppressed x4-5!

Compatible with pion R_{AA}, perhaps $R_{AA}^D > R_{AA}^\pi$? Stay tuned for 2011 run

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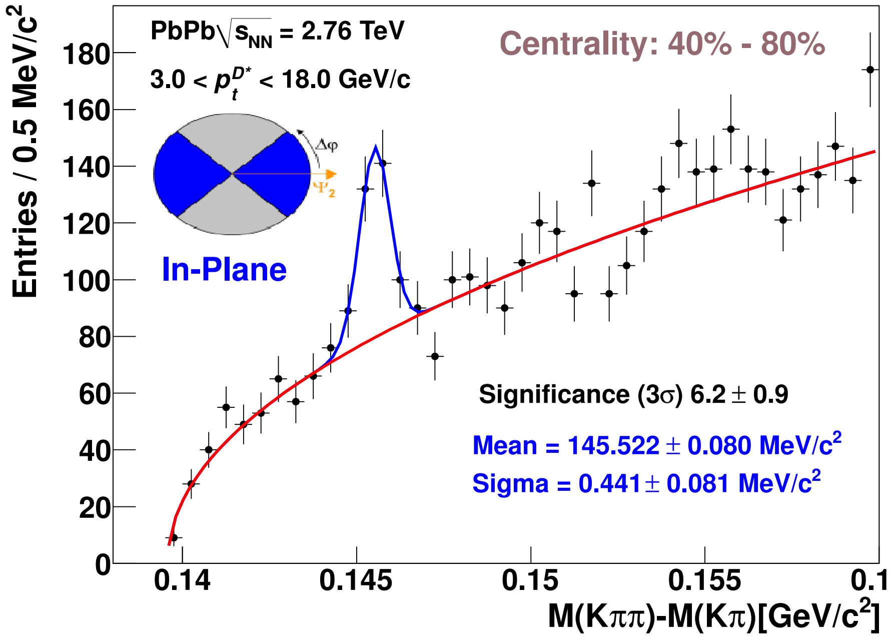
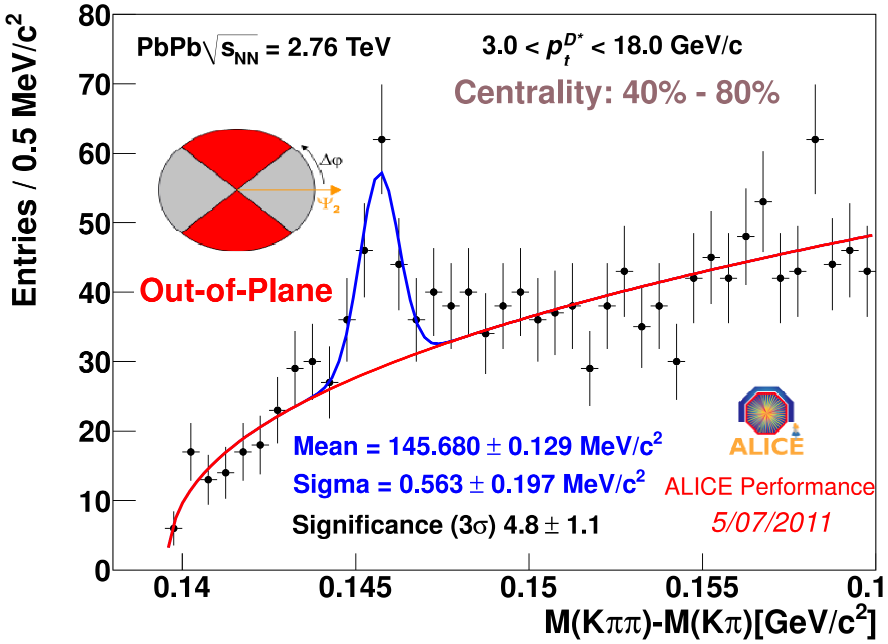
Open charm v_2

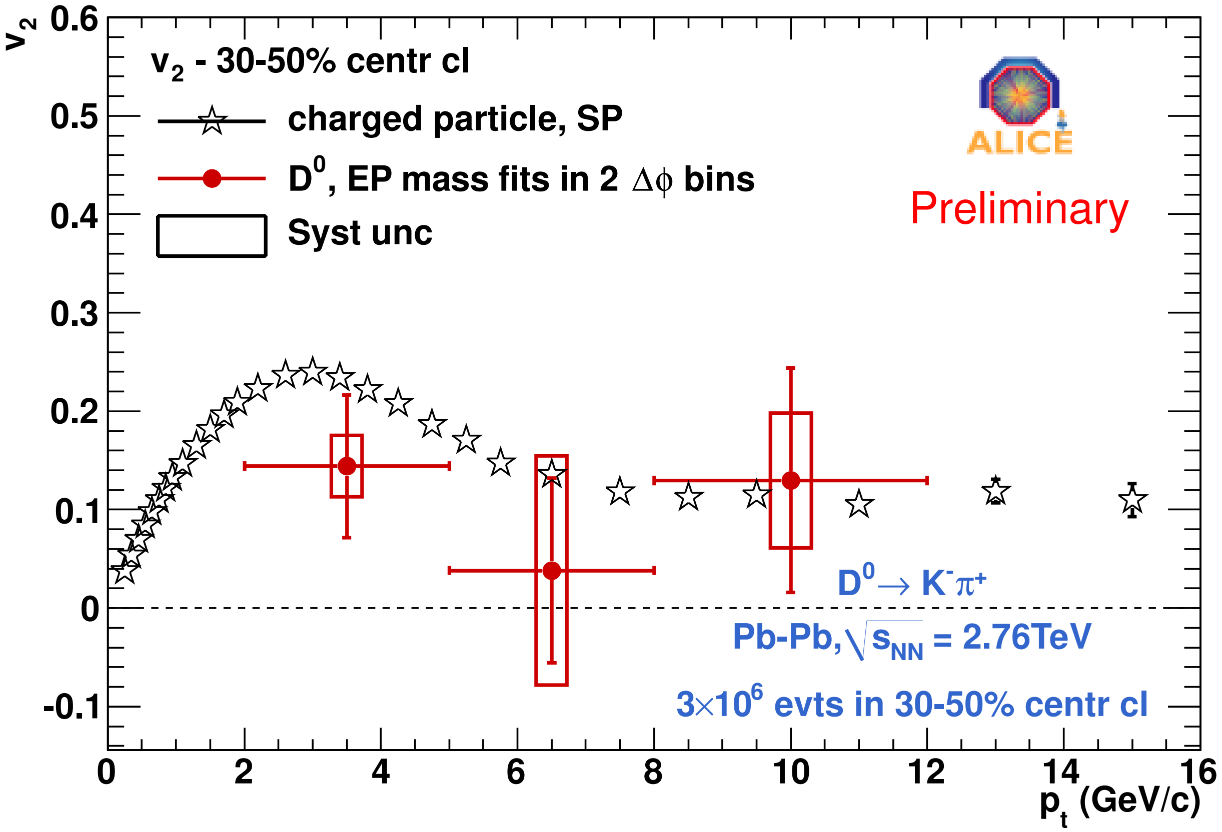
D^0 v_2: first heavy-ion measurement

Measure yield in 2 R.P. bins

$$v_2 = \frac{\pi}{4} \frac{N_{\text{in}} - N_{\text{out}}}{N_{\text{in}} + N_{\text{out}}}$$







Early hint that charm flows!

Eagerly awaiting higher statistics

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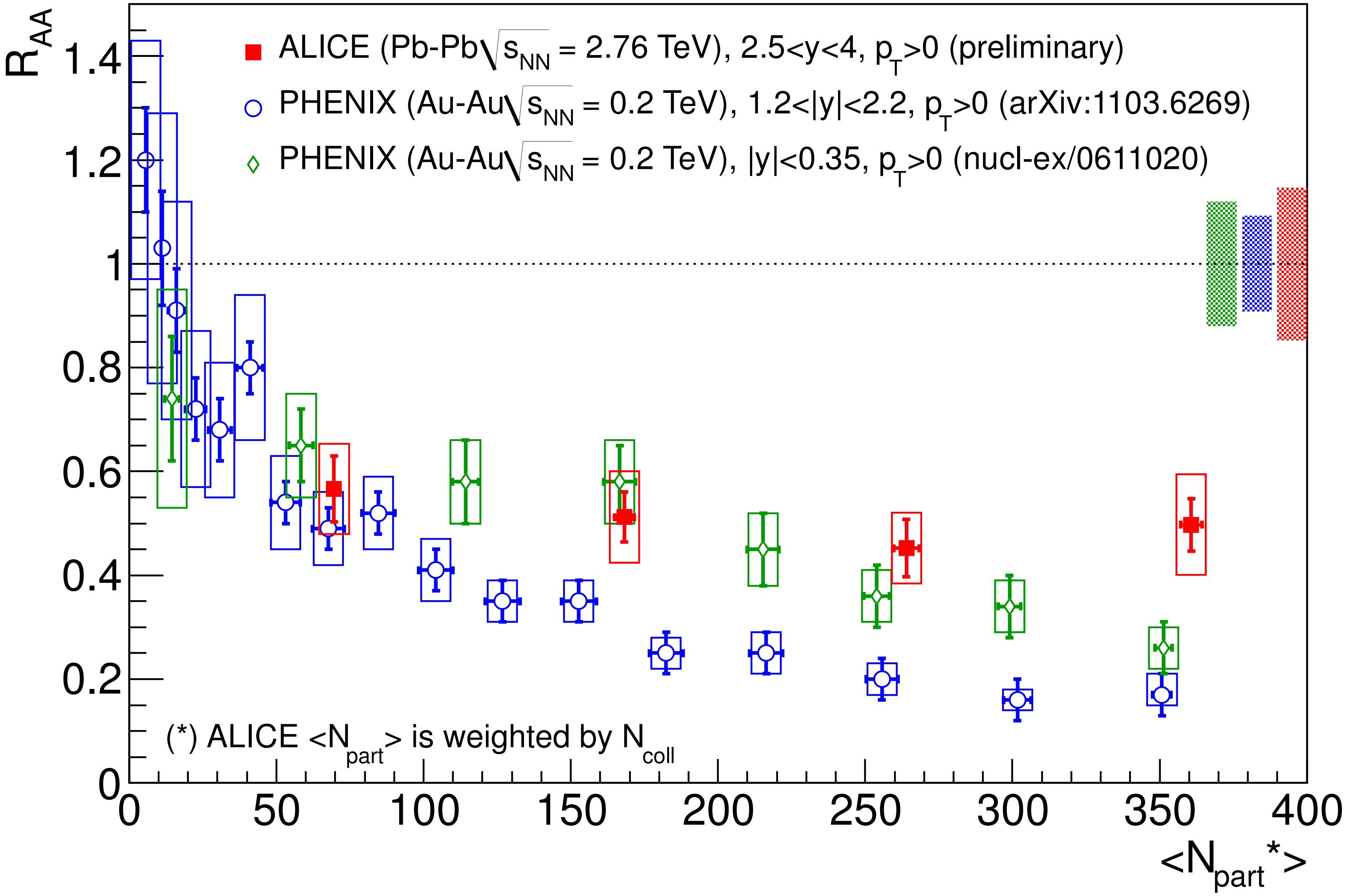
J/ψ suppression

From $J/\psi \rightarrow \mu^+\mu^-$ at forward rapidity

R_{AA} larger than at RHIC



Many effects to consider: initial-state / cold nuclear matter, recombination, color screening, ….

Summary & Outlook

Medium properties from Pb-Pb collisions

Source:

energy density > 15 GeV/fm^3 - 3x higher than at RHIC

particle multiplicity and source size 2x RHIC

lives 30% longer

Opacity:

strong quenching, even for heavy quarks

size & geometry-dependent; similar to RHIC

Fluidity:

viscous hydro (+ hadronic rescattering) describes anisotropy well at low-intermediate p_T

hydro + fluctuations naturally explain higher harmonics & correlation features

strong radial flow - $\beta \approx 2/3$

higher flow harmonics are helping to pin down QGP viscosity

Outlook

5x increase in dataset this November

p + Pb collisions!

EMCal trigger - jets to 200 GeV

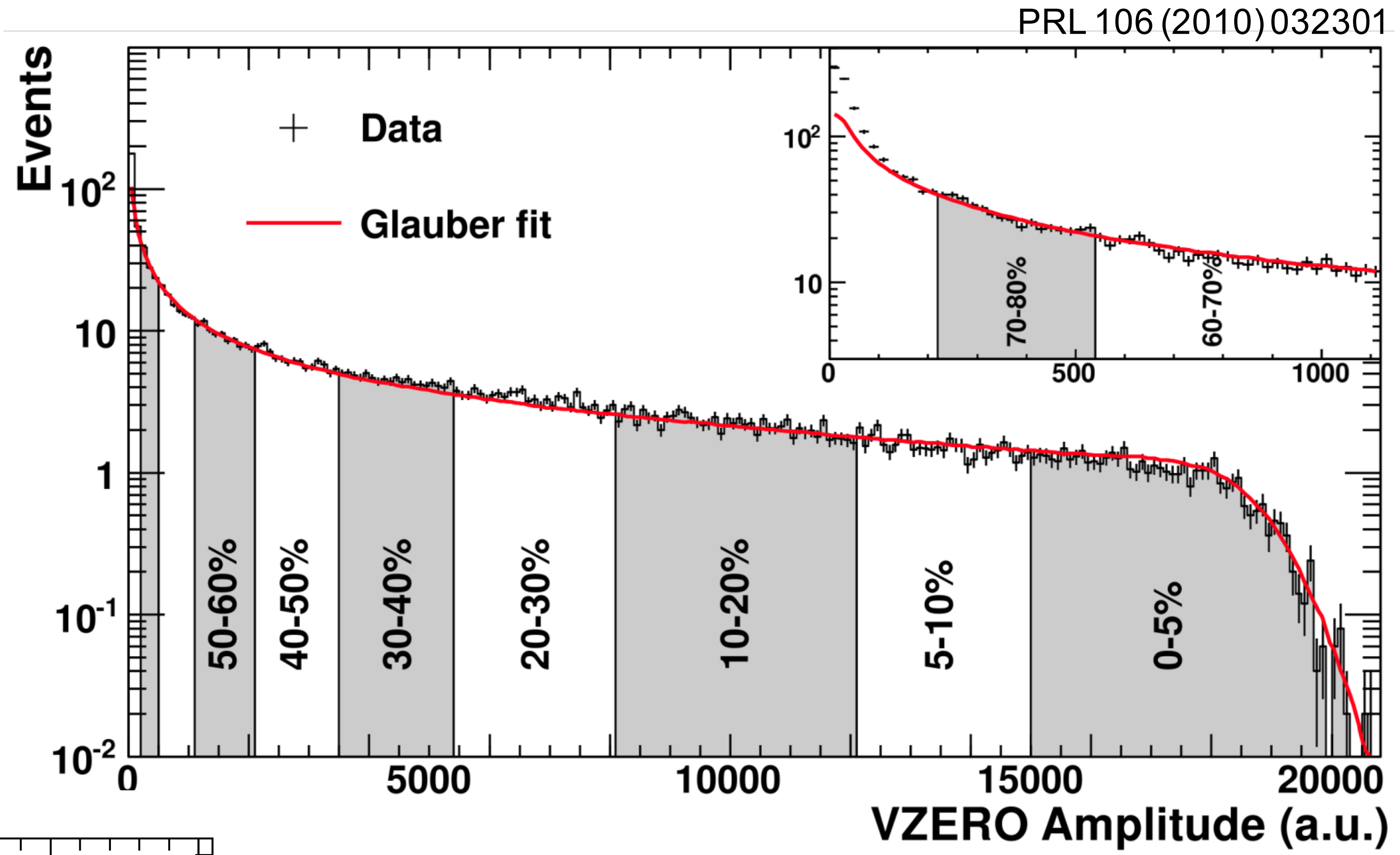
ALICE Publications

	arxiv date	system	energy (TeV)	observable	published in
1	28/11/09	pp	0.9	charged particle $dN/d\eta$	EPJC 65(2010)111
2	18/04/10	pp	0.9, 2.36	charged particle $dN/d\eta$, mult. distr.	EPJC 68(2010)89
3	20/04/10	pp	7	charged particle $dN/d\eta$, mult. distr.	EPJC 68(2010)345
4	28/06/10	pp	0.9, 7	antiproton/proton ratio	PRL 105(2010)072002
5	03/07/10	pp	0.9	pion HBT	PRD 82(2010)052001
6	05/07/10	pp	0.9	charged particle pT spectra	PLB 693(2010)53
7	17/11/10	PbPb	2.76	charged particle $dN/d\eta$	PRL 105(2010)252301
8	17/11/10	PbPb	2.76	charged particle v2	PRL 105(2010)252302
9	05/12/10	PbPb	2.76	charged particle RAA	PLB 696(2011)30
10	08/12/10	PbPb	2.76	centrality dependence of Nch	PRL 106(2011)032301
11	15/12/10	pp	0.9	K0, ϕ, Λ, cascade	EPJC 71(2011)1594
12	17/12/10	PbPb	2.76	pion HBT	PLB 696(2011)328
13	19/01/11	pp	0.9, 7	pion HBT	arXiv:1101.3665v1
14	21/01/11	pp	0.9	pion, kaon, proton	EPJC 71(2011)1655
15	02/05/11	pp	7	J/Ψ	arXiv:1105.0380v1
16	19/05/11	PbPb	2.76	charged particle v3, v4, v5	arXiv:1105.3865v1
17	12/09/11	PbPb	2.76	harmonic decomposition	arXiv:1109.2501v1
18	01/10/11	PbPb	2.76	charged particle IAA	arXiv:1110.0121v1

Extras

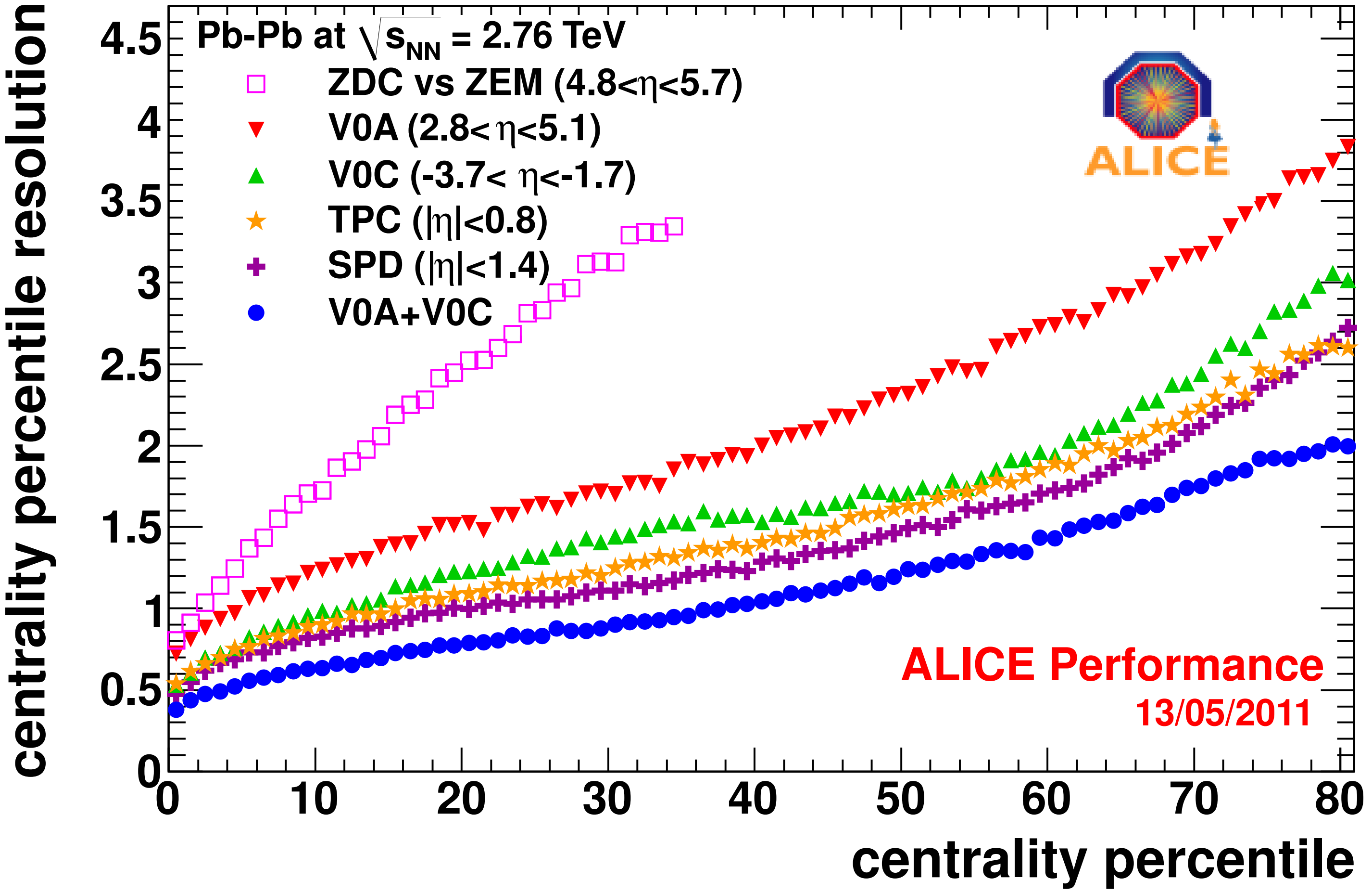
Centrality determination

PRL 106 (2010) 032301



VZERO signal ∝ multiplicity

Fit to a·Ncoll + b·Npart, where each source follows NBD



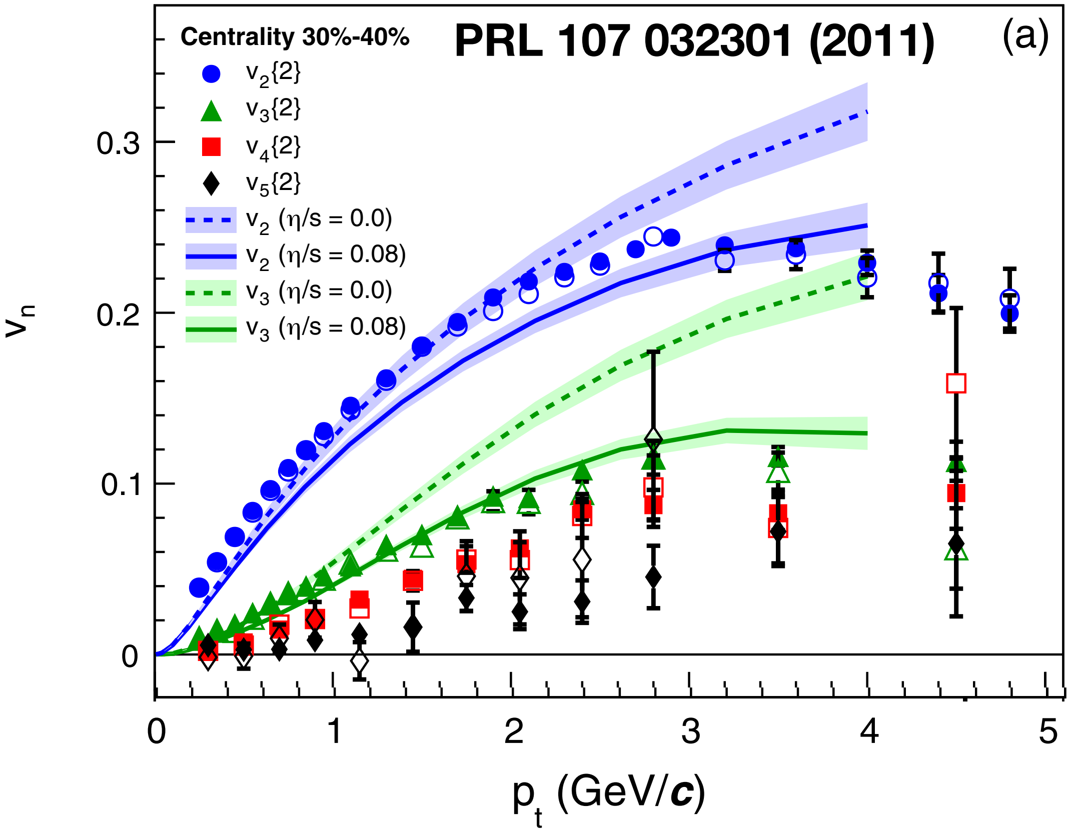
Resolution <1% for central events!

Single vs. pair Fourier decomposition

Single-particle anisotropy

(the familiar v_n coefficients)

$$\frac{\mathrm{dN}}{\mathrm{d}\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n(p_T)\cos\left(n(\phi - \Psi_n)\right)$$



Pair anisotropy

Similar form, but indep. of Ψ_n

$$\frac{\mathrm{dN}^{\mathrm{pairs}}}{\mathrm{d}\Delta\phi} \propto 1 + \sum_{n=1}^{\infty} 2V_{n\Delta}(p_T^t, p_T^a)\cos\left(n\Delta\phi\right)$$

Extract directly from 2-particle azimuthal correlations!

$$V_{n\Delta} \equiv \langle\cos\left(n\Delta\phi\right)\rangle = \sum_i C_i \cos(n\Delta\phi_i) \Big/ \sum_i C_i \,.$$

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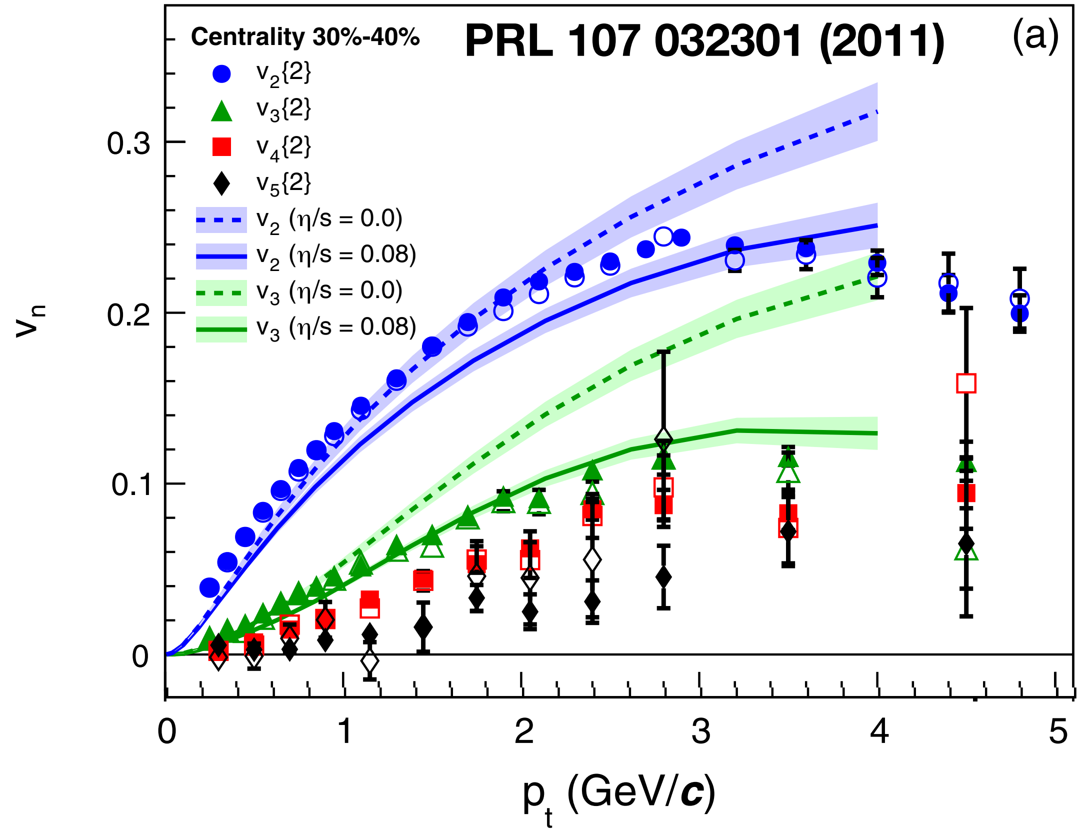
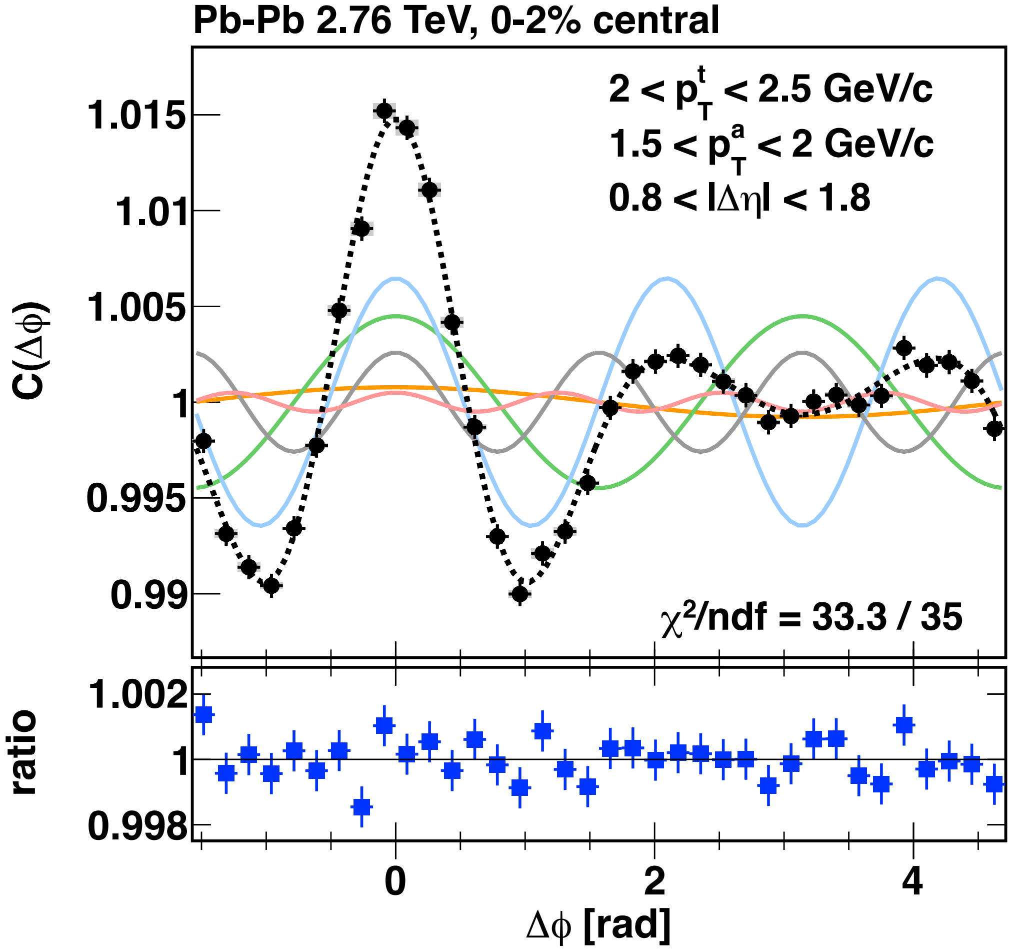




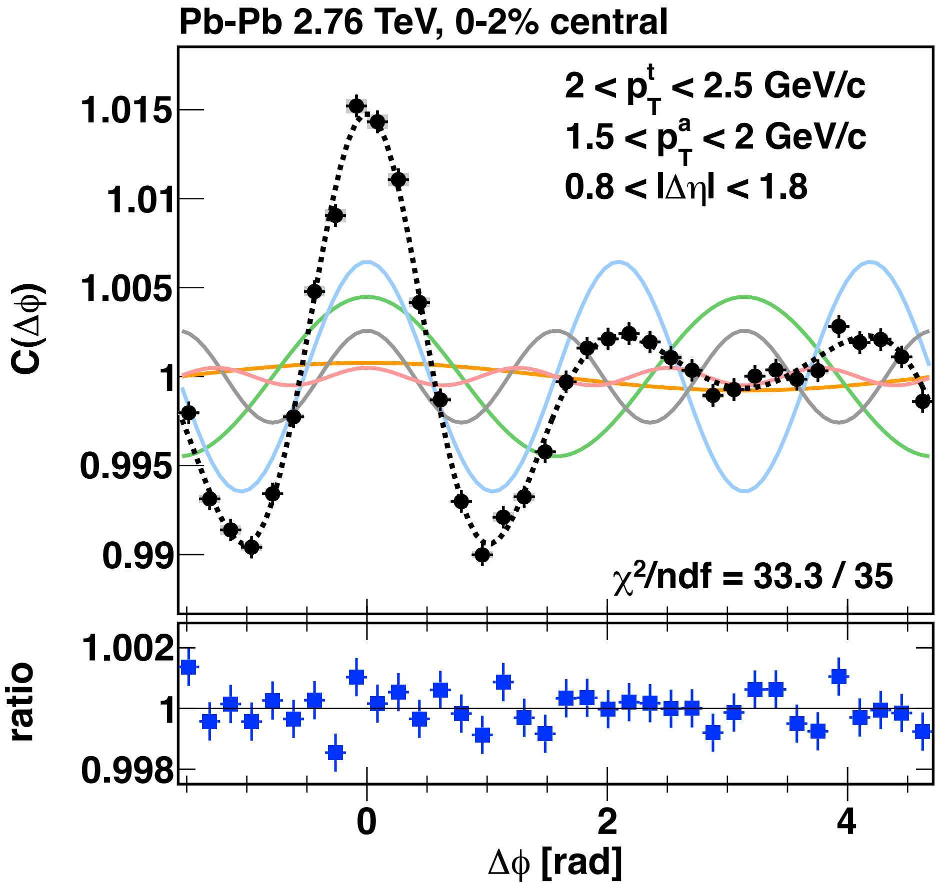
A. Adare (ALICE)

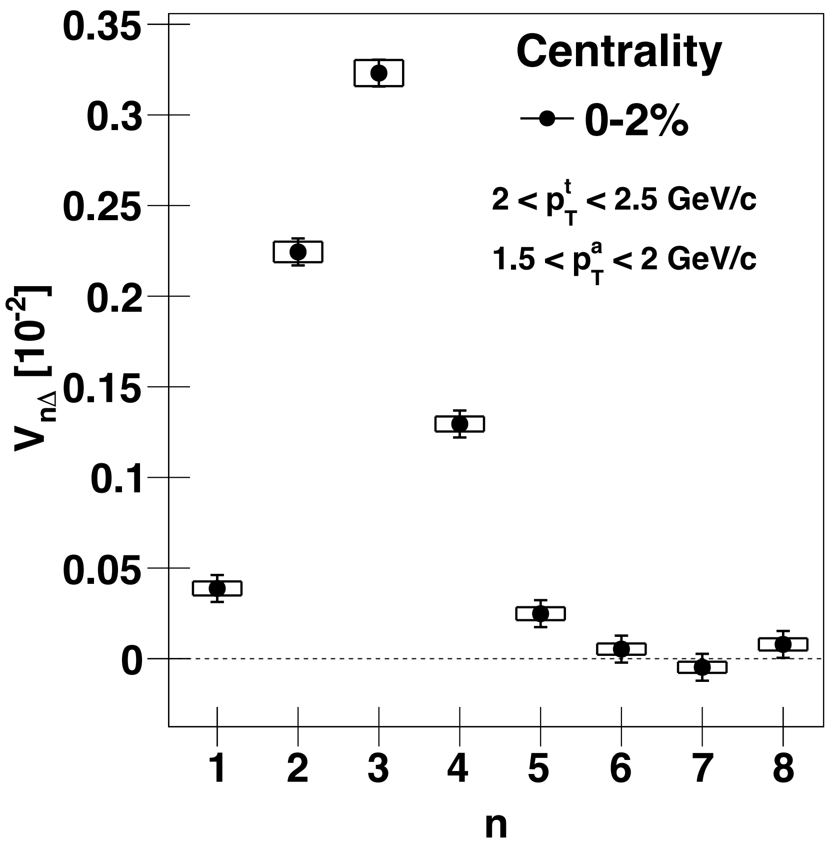
Fourier Decomposition

“Power spectrum” of pair Fourier components $V_{n\Delta}$

For ultra-central collisions, n = 3 dominates.

In bulk-dominated correlations, the n > 5 harmonics are weak.





$V_{2\Delta}$ dominates as collisions become less central.

Collision geometry, rather than fluctuations, becomes primary effect

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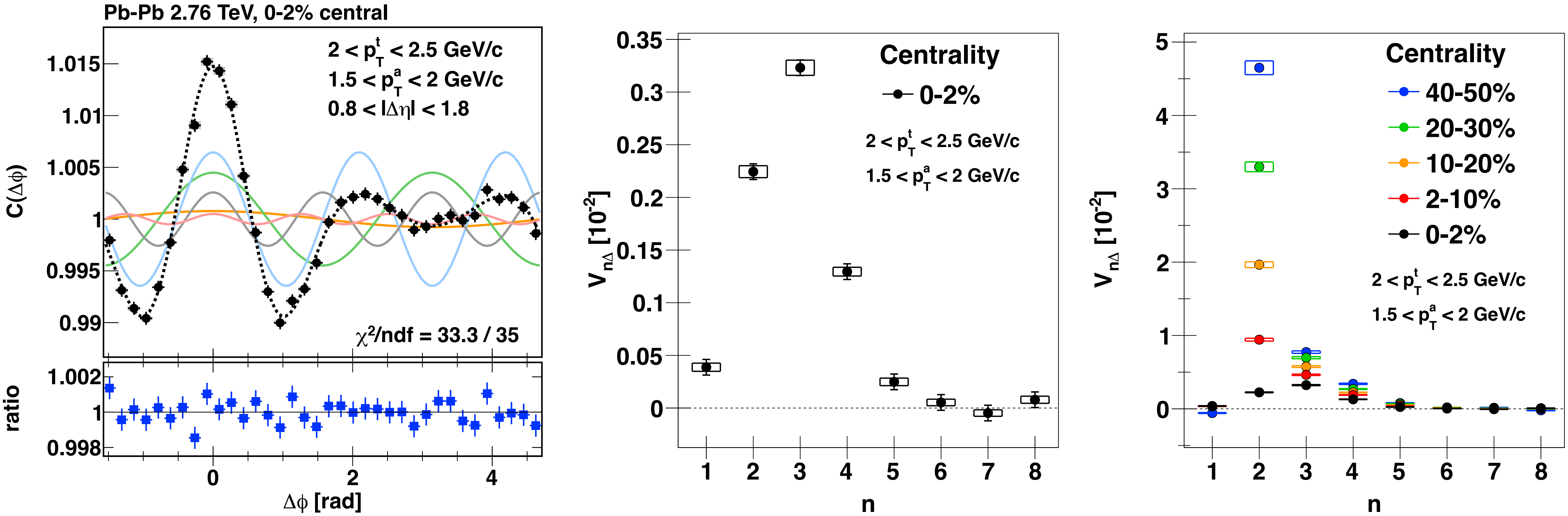

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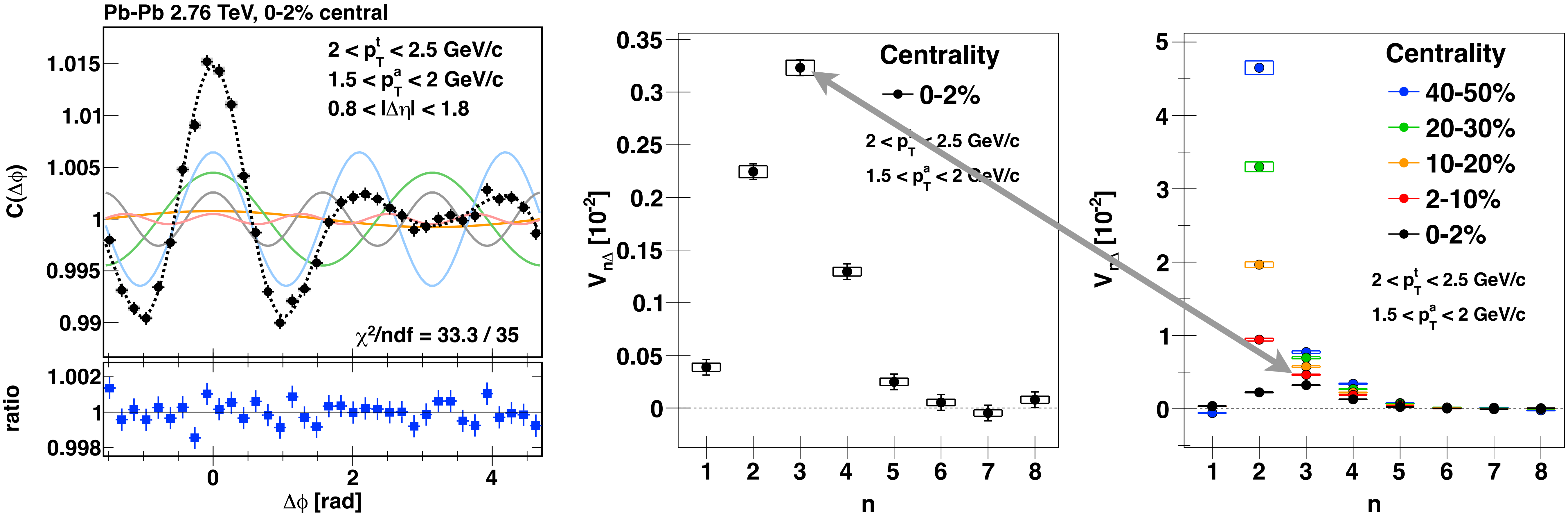

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The factorization hypothesis

Factorization of two-particle anisotropy

For pairs correlated to one another through a common symmetry plane Ψ_n, their correlation is dictated by bulk anisotropy:

$$\begin{aligned} V_{n\Delta}(p_T^t, p_T^a) &= \langle\langle e^{in(\phi_a - \phi_t)}\rangle\rangle \\ &= \langle\langle e^{in(\phi_a - \Psi_n)}\rangle\rangle\langle\langle e^{-in(\phi_t - \Psi_n)}\rangle\rangle \\ &= \langle v_n\{2\}(p_T^t)\, v_n\{2\}(p_T^a)\rangle. \end{aligned}$$

$V_{n\Delta}$ would be generated from one $v_n(p_T)$ curve, evaluated at p_T^t and p_T^a.

Factorization expected:

✓ **For correlations from collective flow.**

Flow is global and affects all particles in the event.

✗ **Not for pairs from fragmenting di-jets.**

Di-jet shapes are “local”, not strongly connected to Ψ_n.

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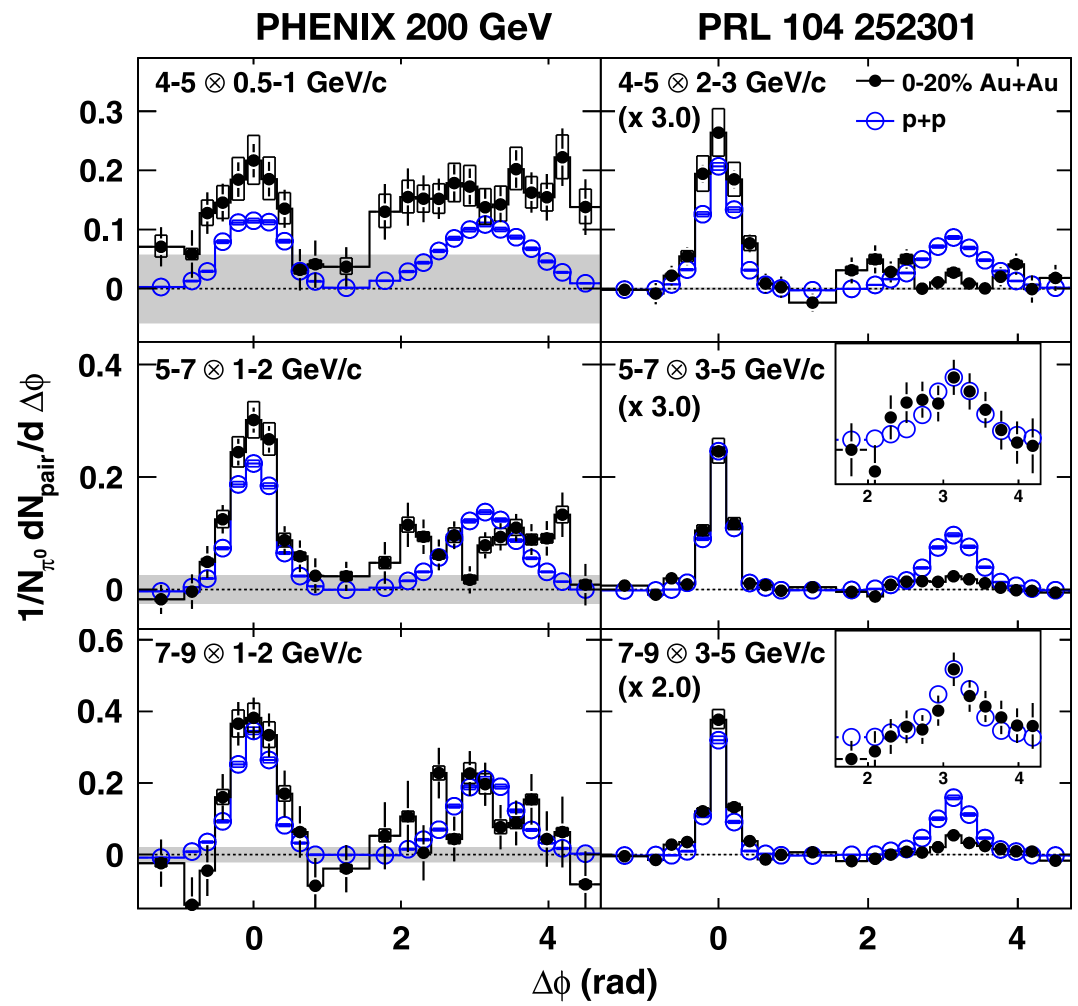

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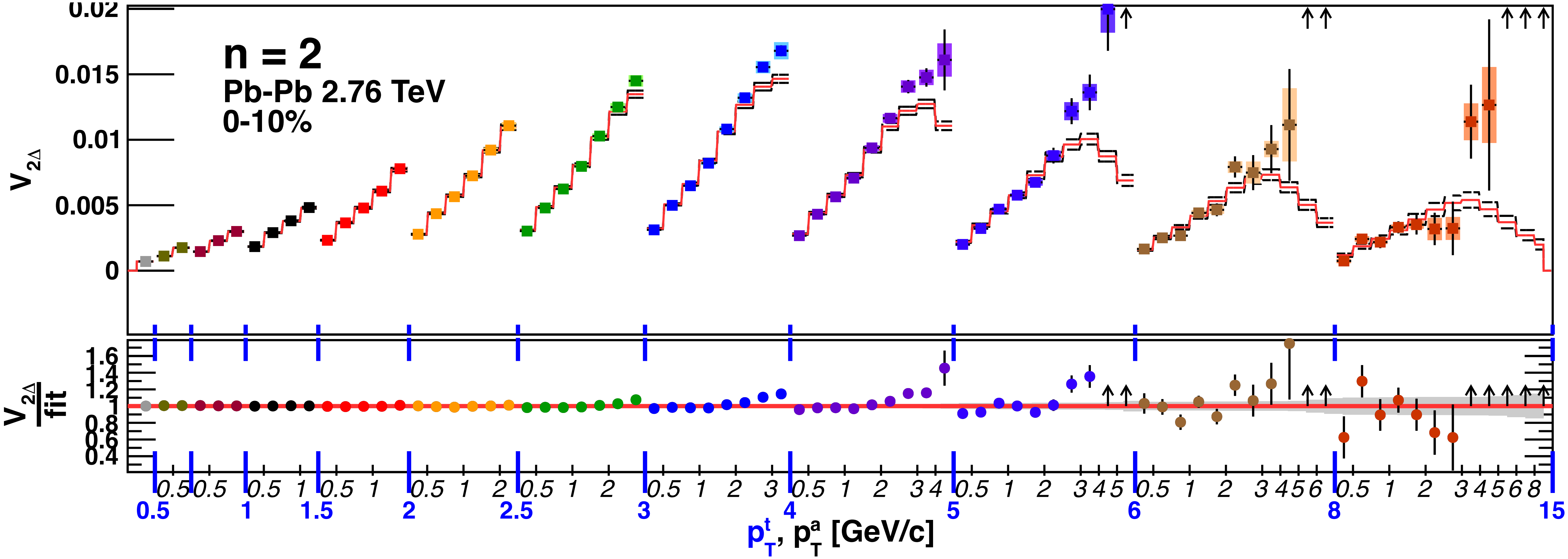
A. Adare (ALICE)

Testing factorization with a global fit

Improving on $V_{n\Delta} = v_n(p_T)^2$ with triggered correlations...

12 p_T^t bins, 12 p_T^a bins; $p_T^t \geq p_T^a$ ⇒ 78 $V_{n\Delta}$ points.

Fit all simultaneously to find $v_n(p_T)$ curve with best-fit $v_n(p_T^t) \times v_n(p_T^a)$ product.



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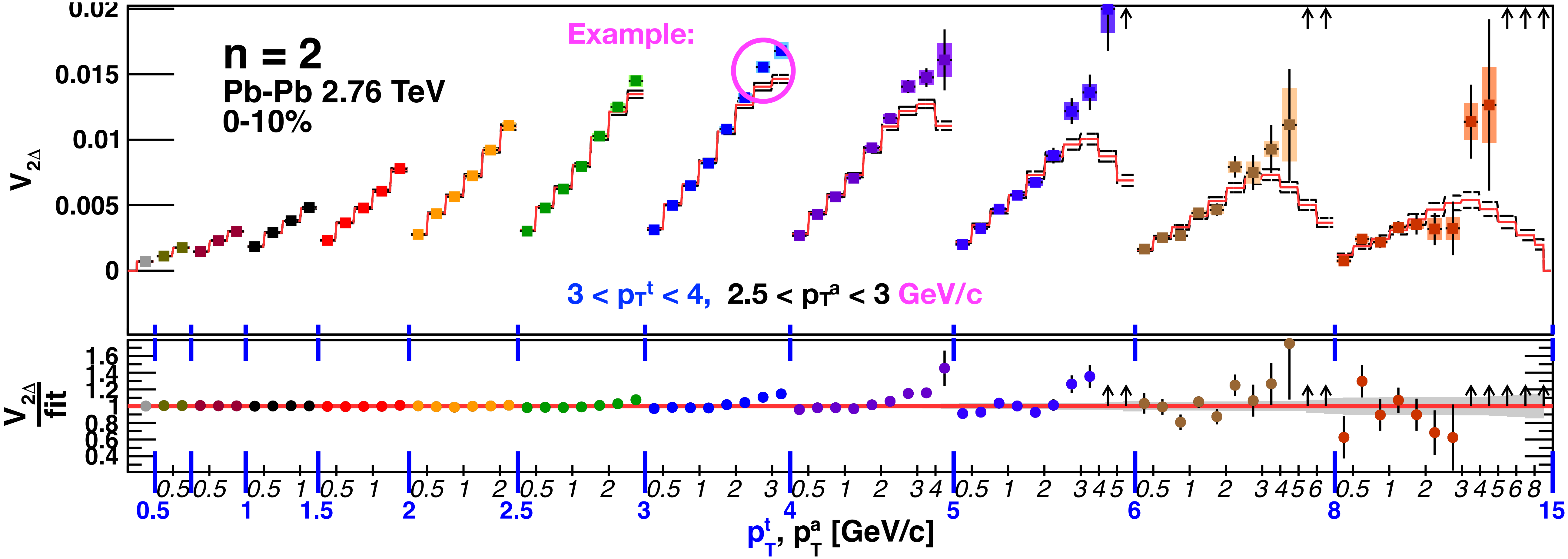

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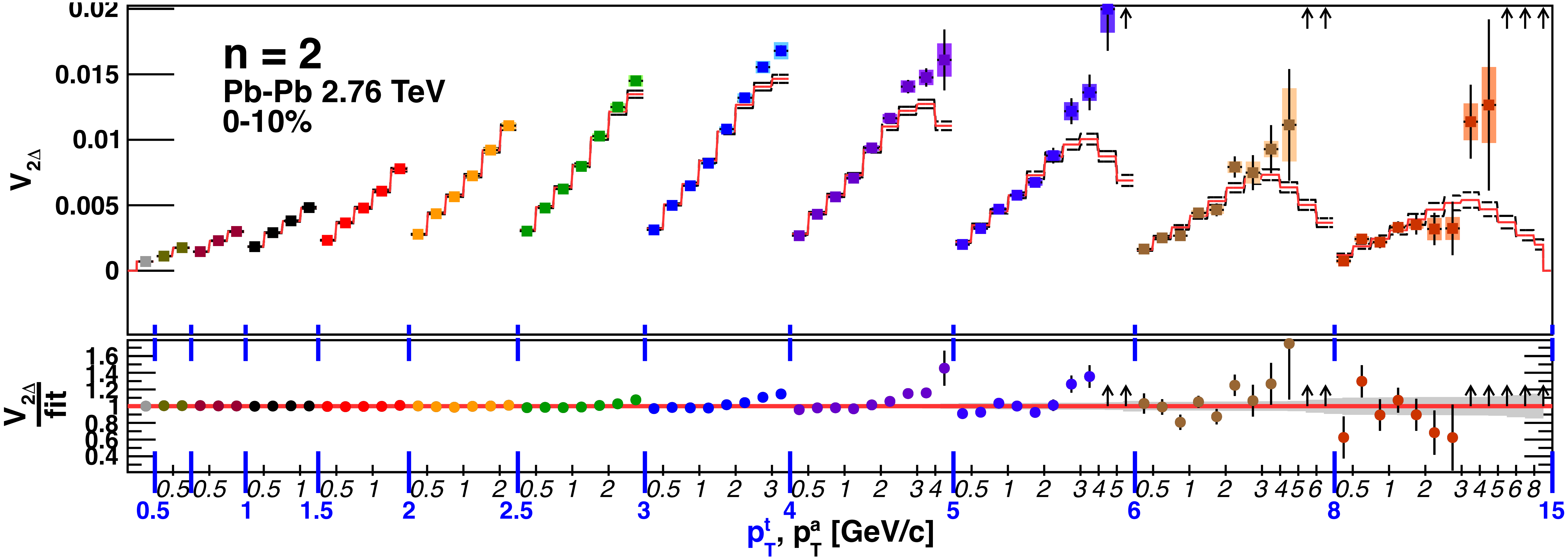

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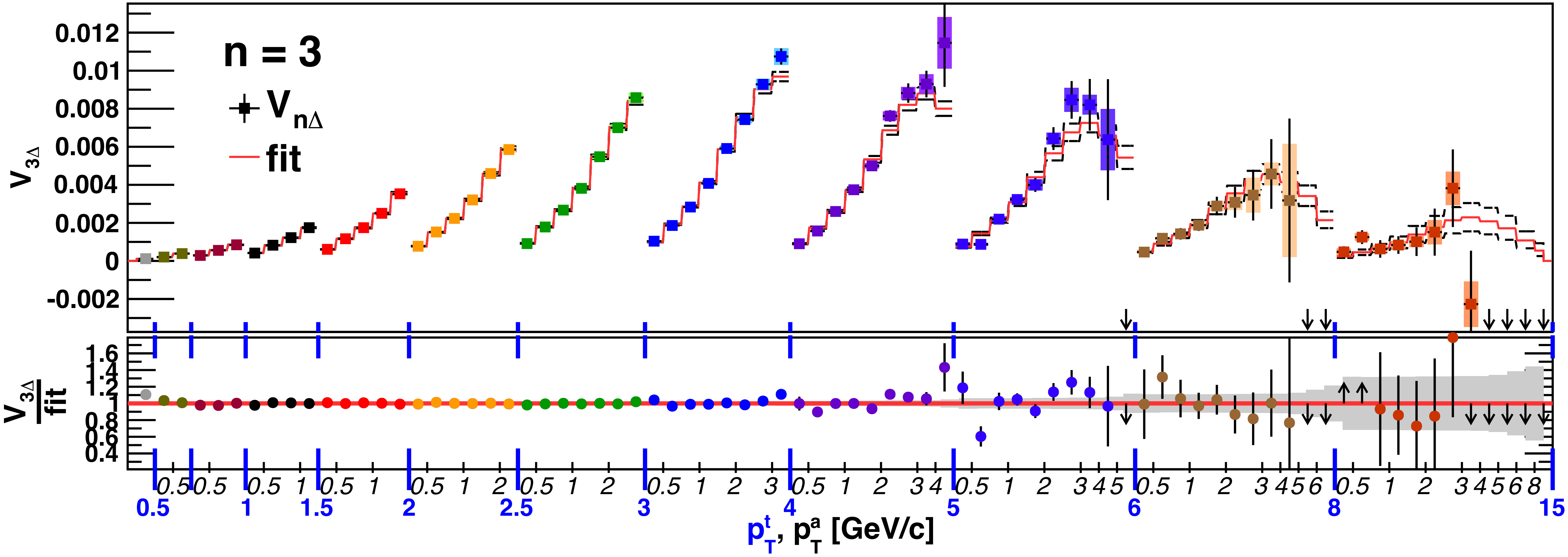

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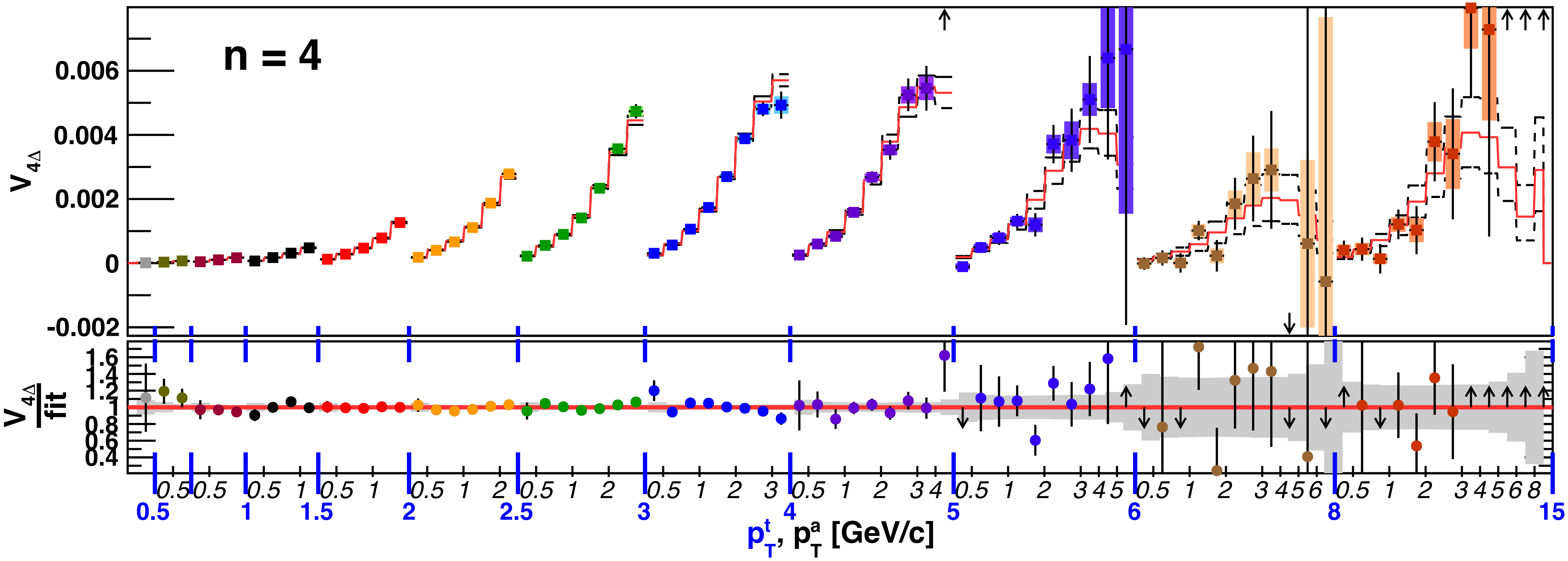

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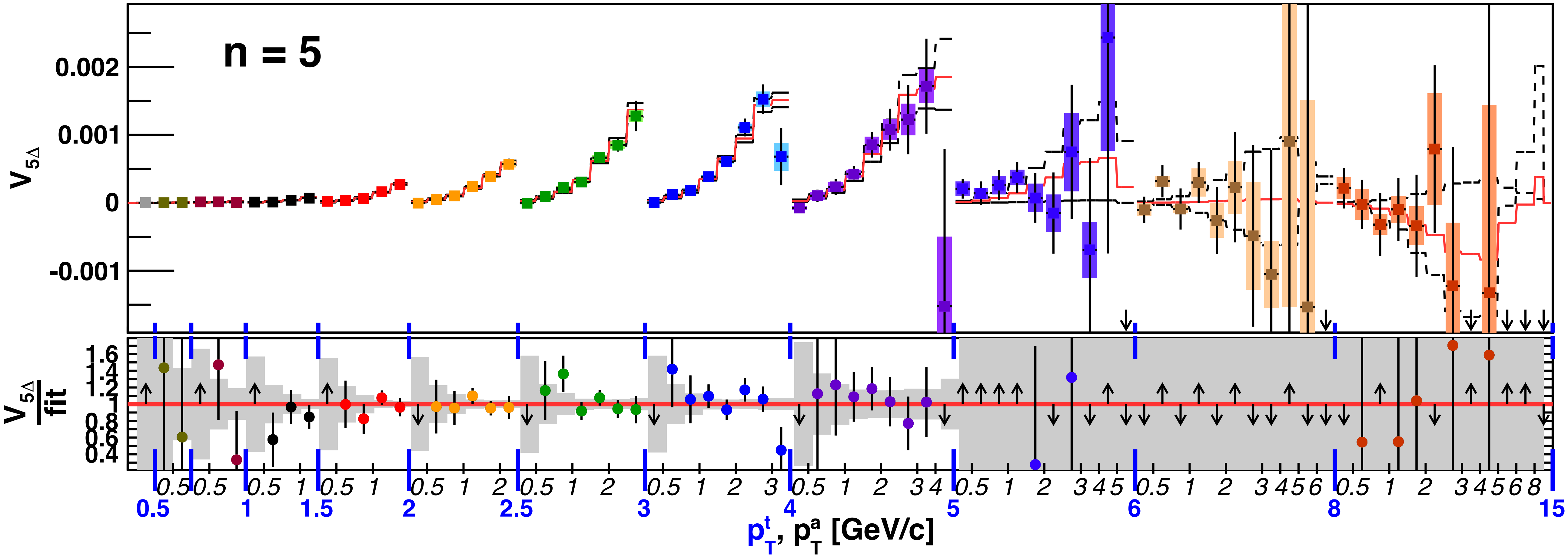

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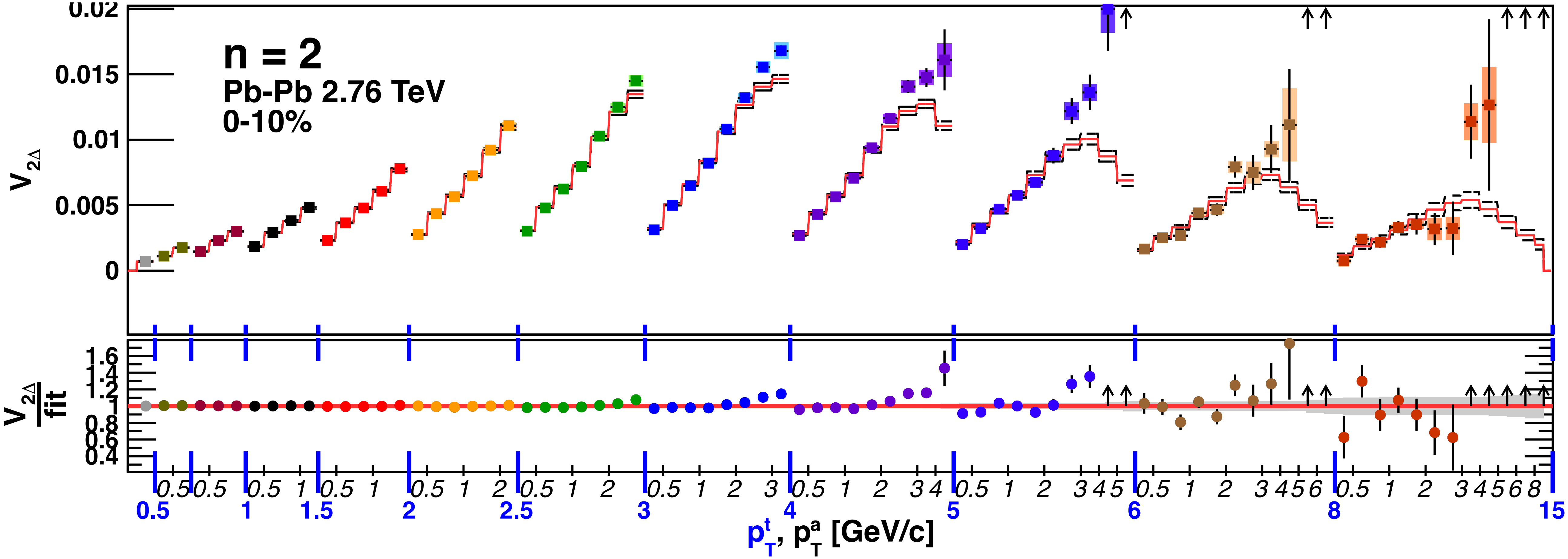

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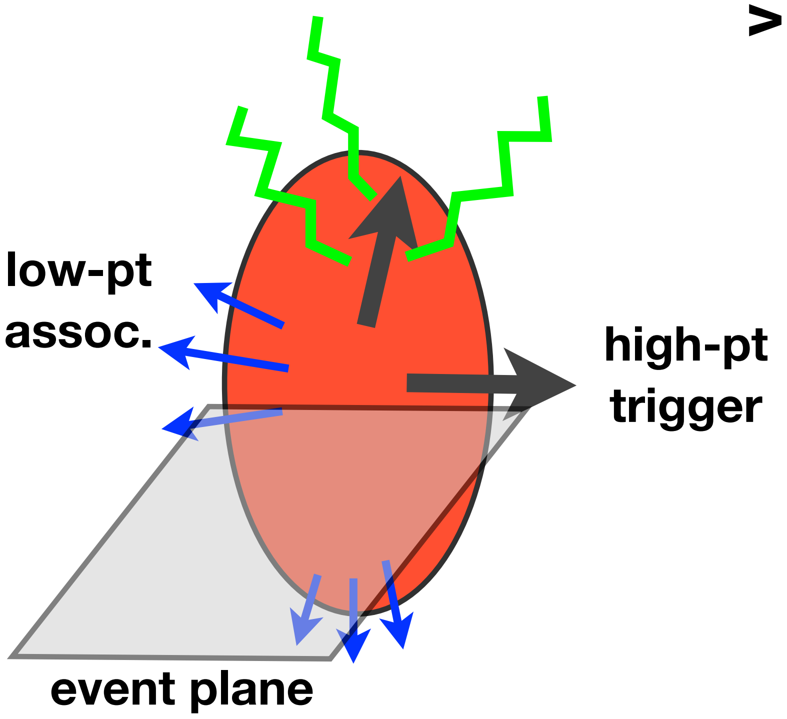
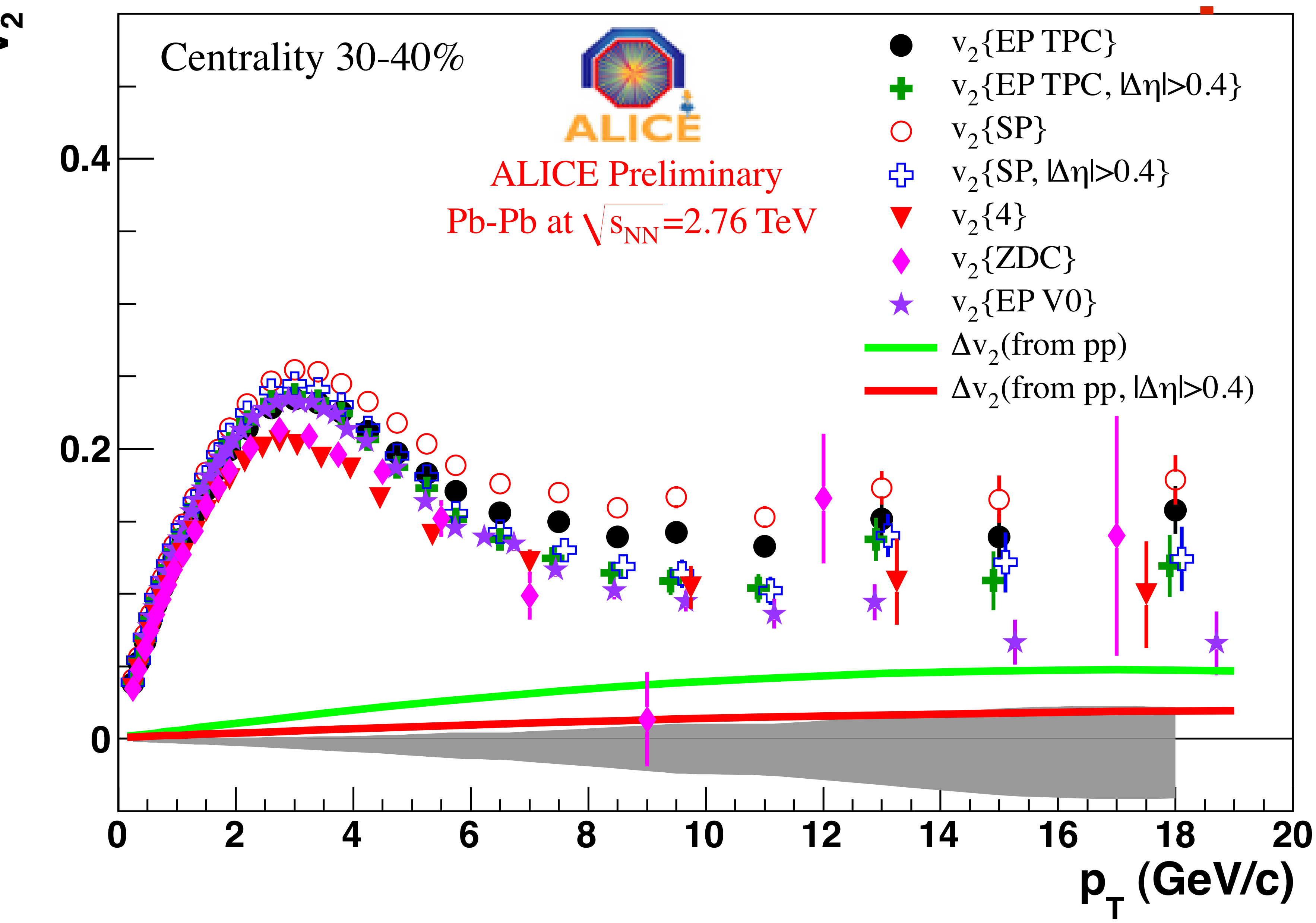
High-p_T^t anisotropy

High-pt v_n is finite, in fact fairly large

If from pathlength-dependent quenching, correlations should reflect it.

High-p_T^t, low p_T^a pair correlation due to quenching and flow, respectively.





Caveat:
in this plot, rapidity gap is only 0.4. ATLAS measures smaller v2 when using larger eta gap.

A. Adare (ALICE)

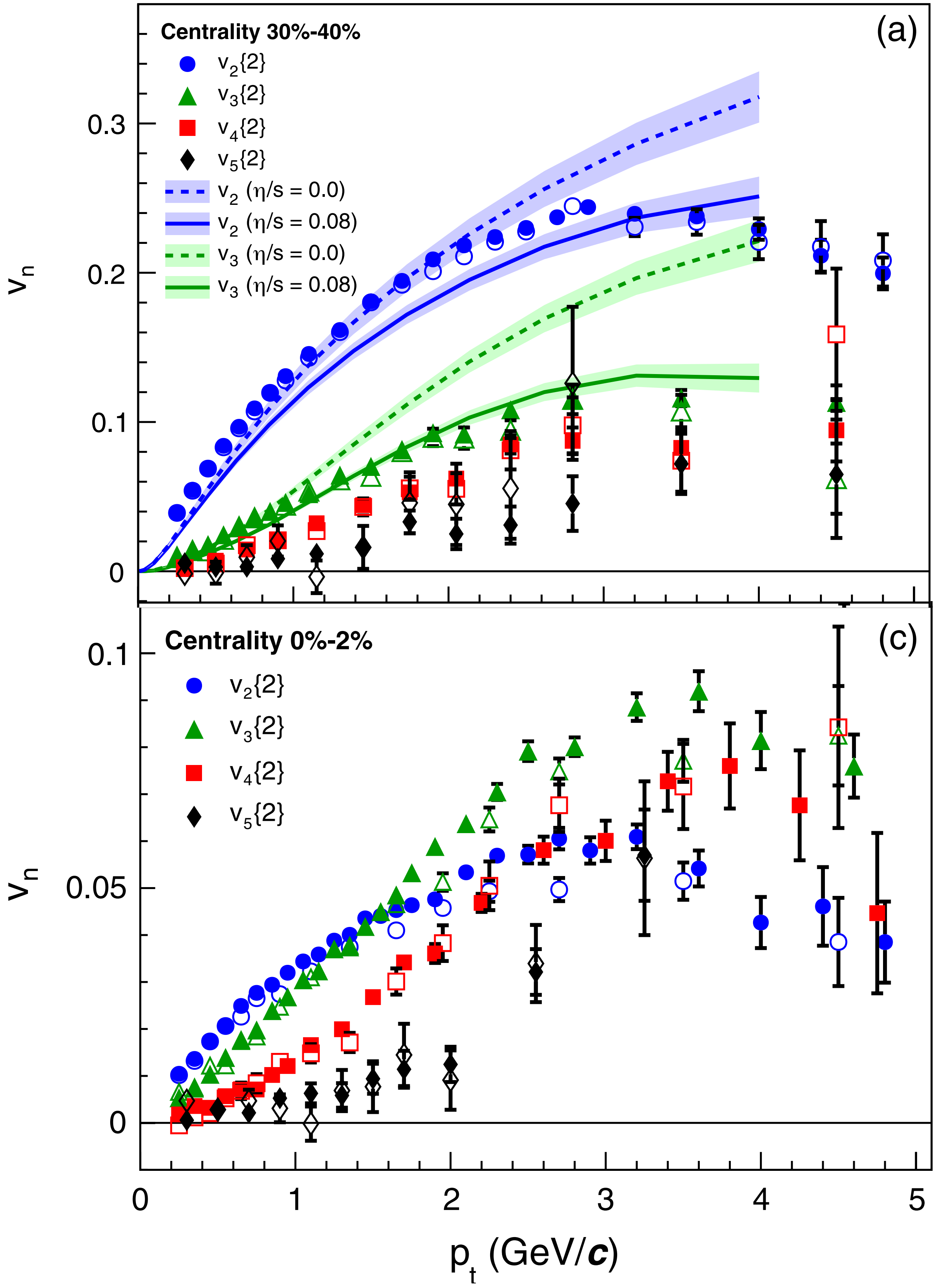
Comparison with ALICE $v_n\{2\}$

Published ALICE $v_n\{2\}$

PRL 107 032301 (2011)

Scalar-product (SP) method

$|\Delta\eta| > 1.0$



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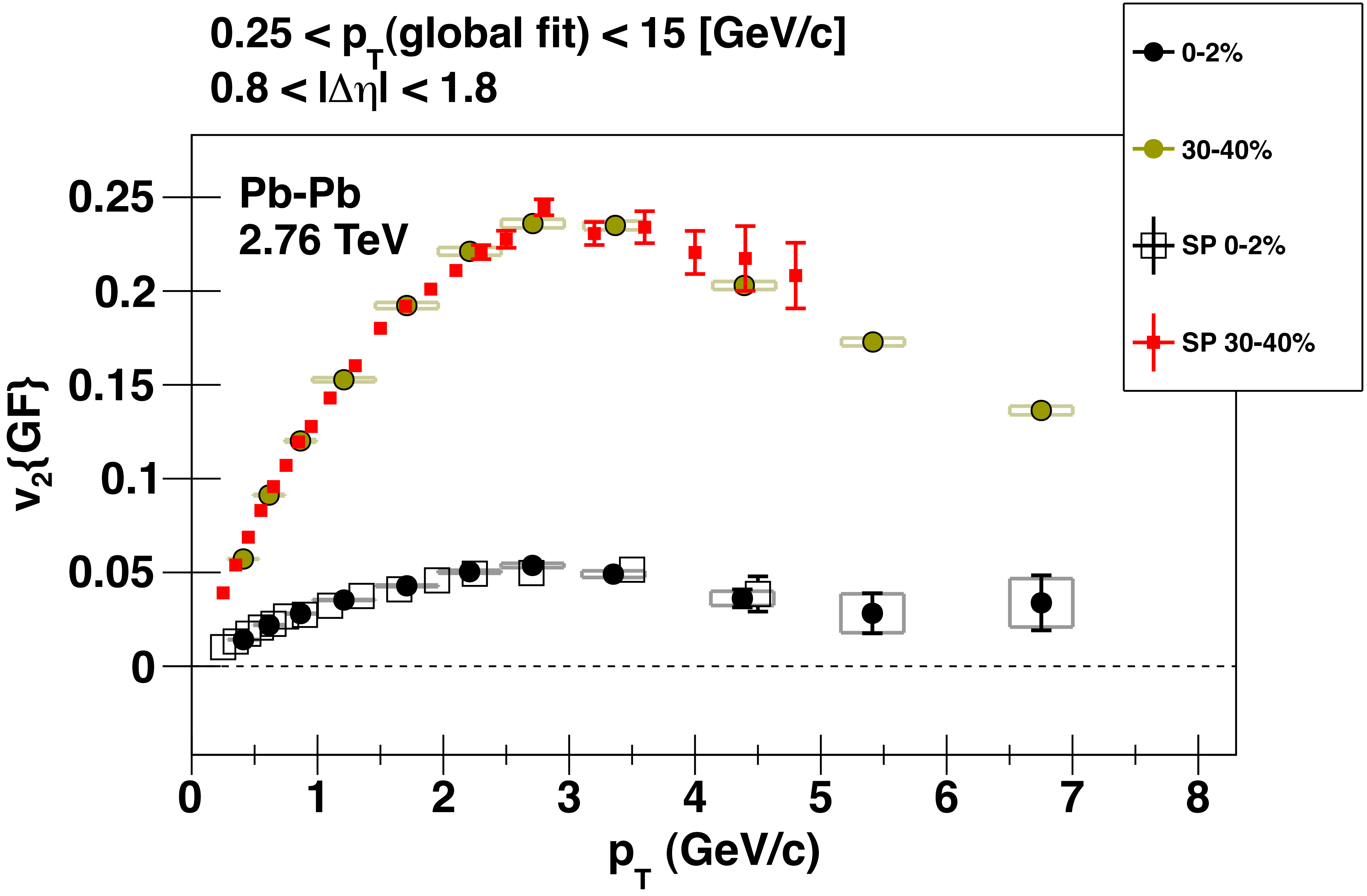

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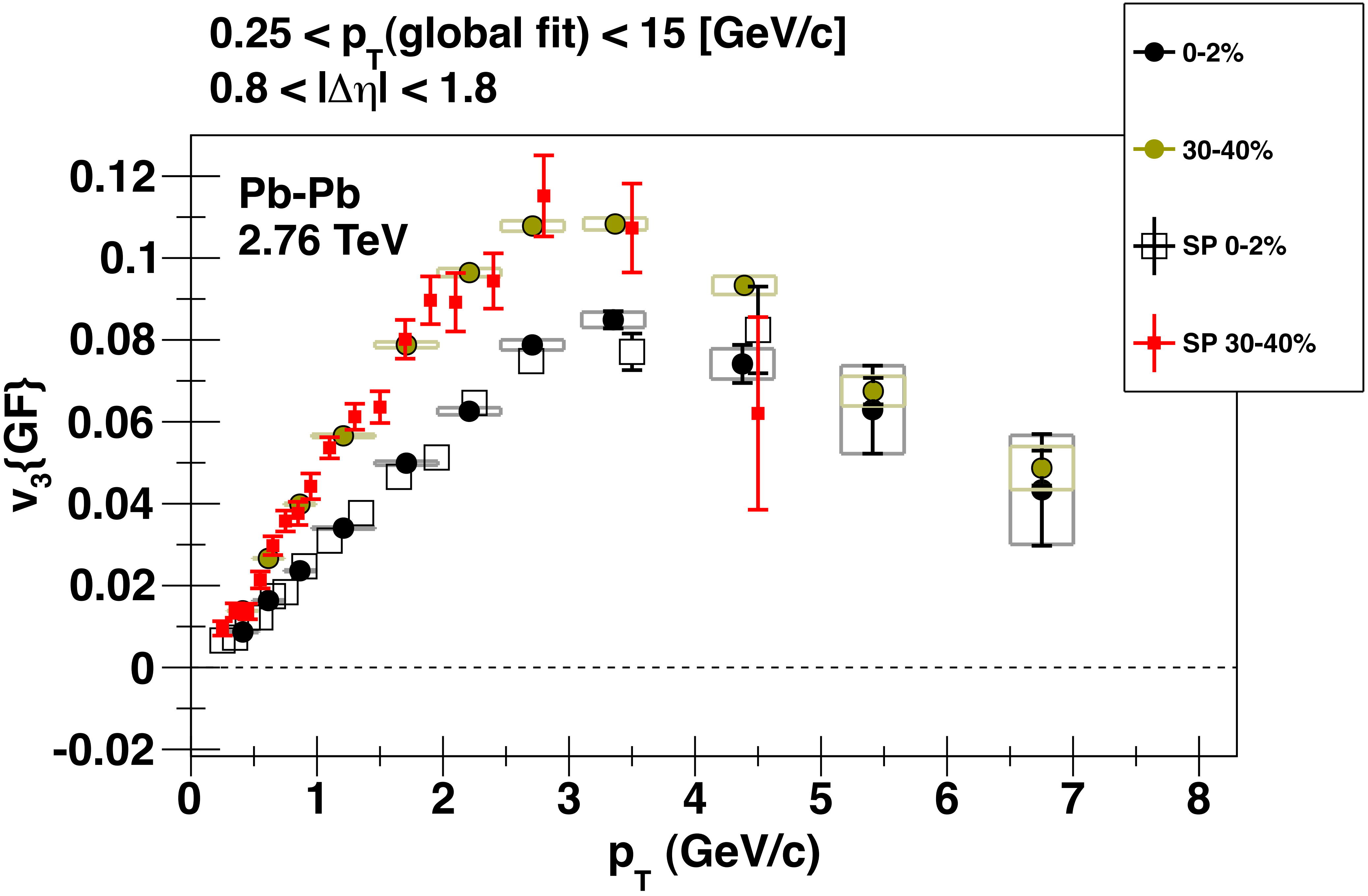

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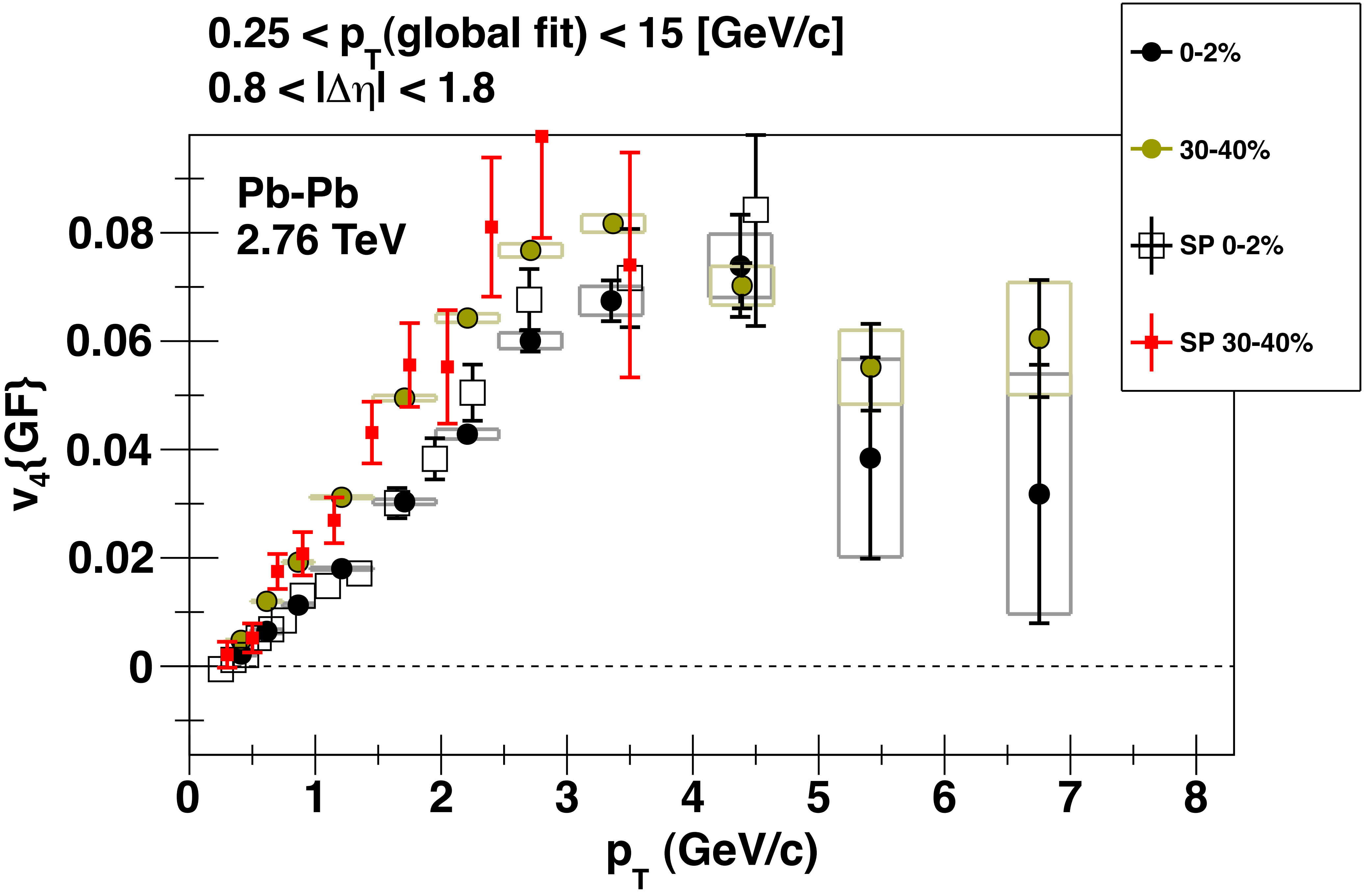

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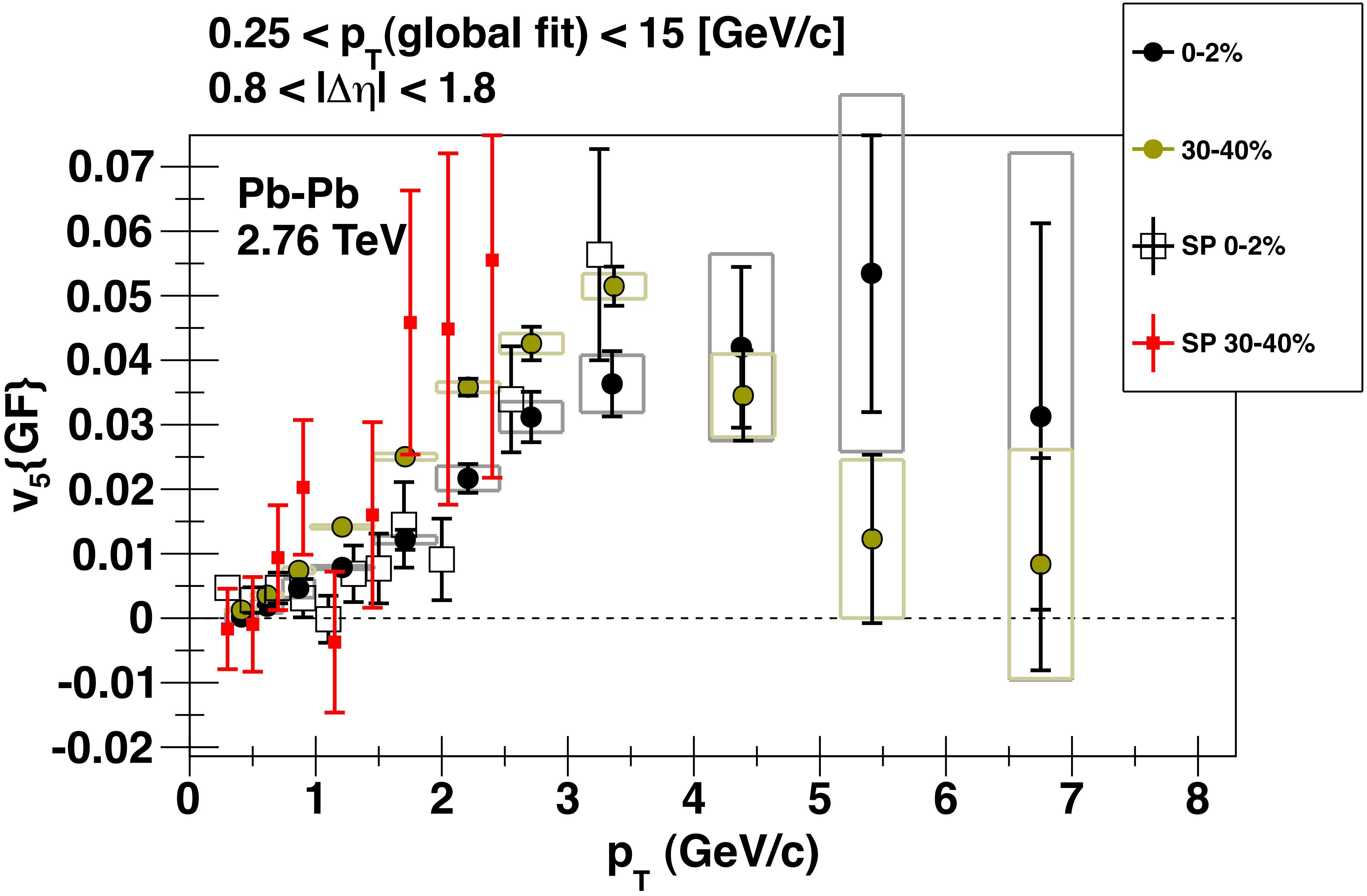

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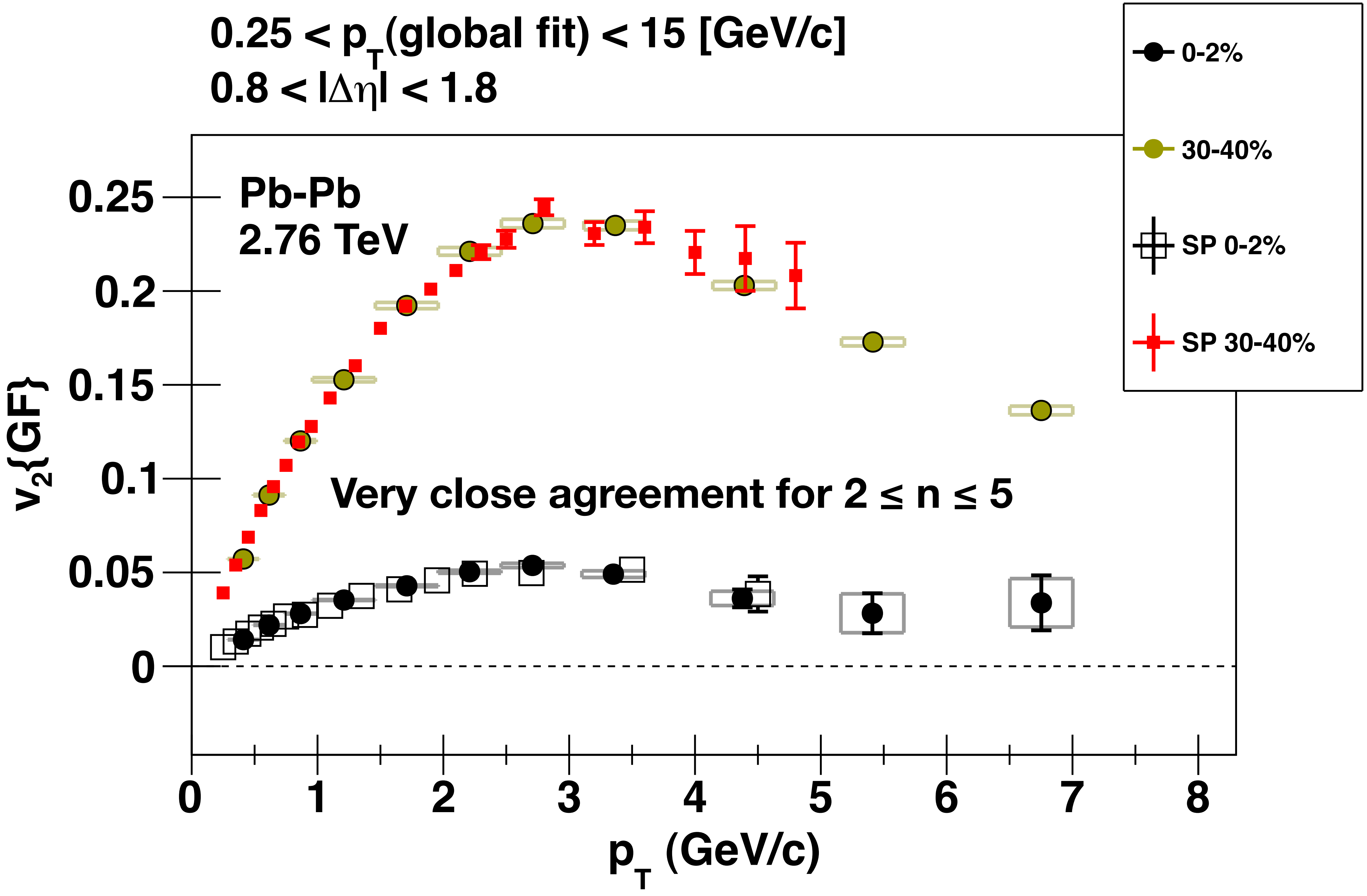
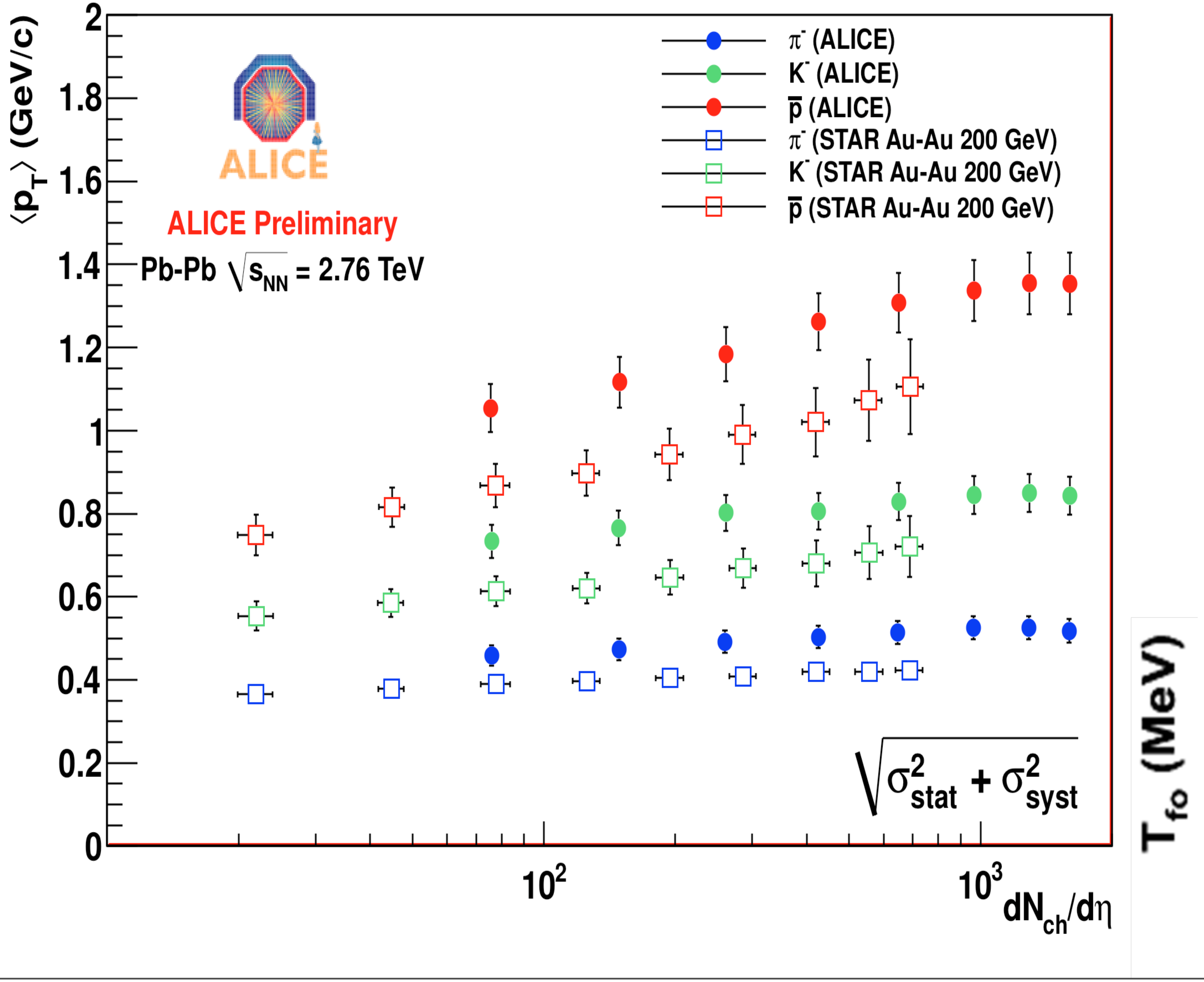


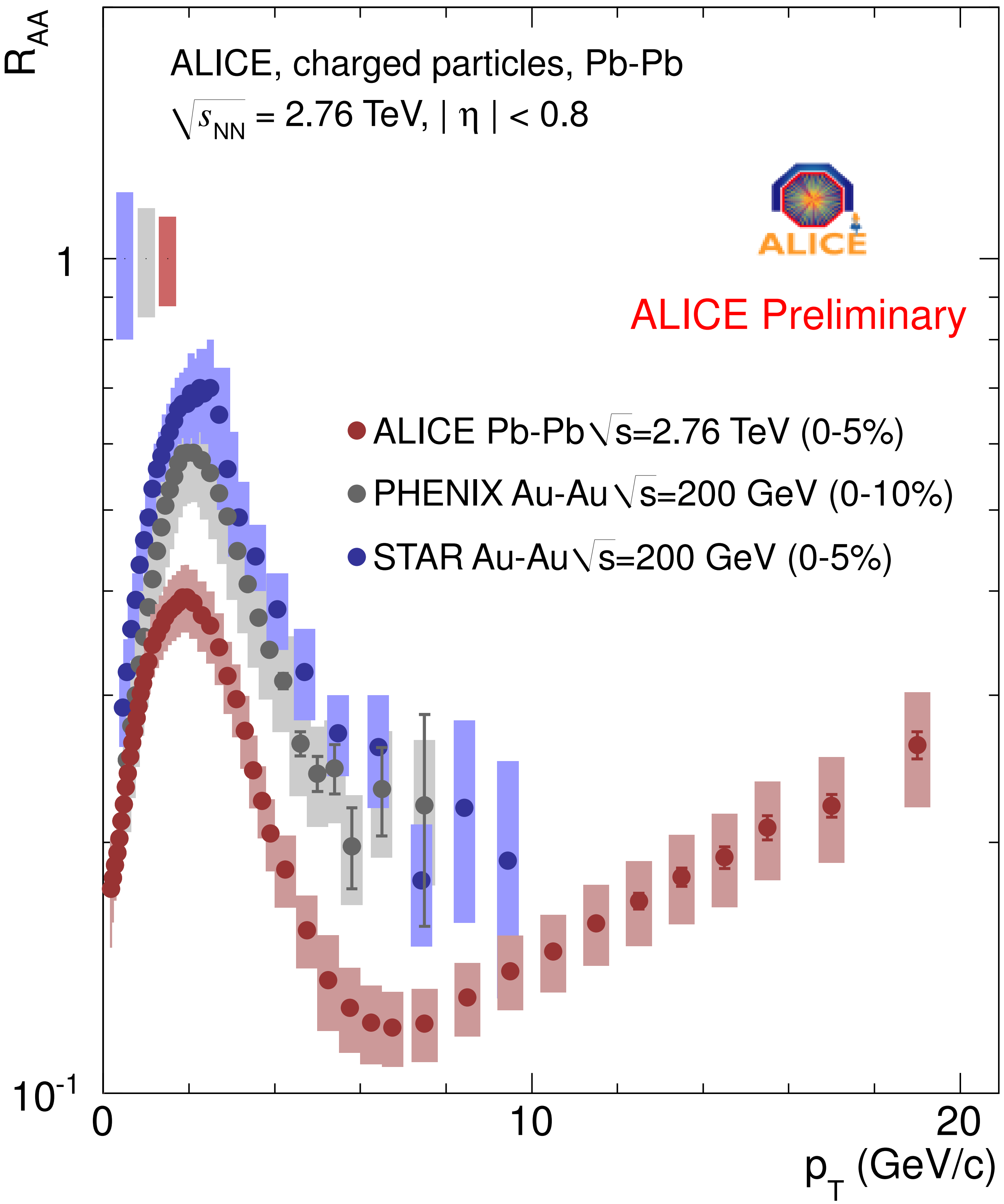
A. Adare (ALICE)

Identified hadron ⟨p_T⟩

About 20% higher than at RHIC for pions, kaons, and protons



Compared to RHIC



ALICE R_{AA} lower than at RHIC

Reflects larger PbPb system

A. Adare (ALICE)

The end