XLIV International Symposium on Multiparticle Dynamics

Anisotropic flow of identified particles in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV measured with ALICE at the LHC

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for the ALICE Collaboration

A more complete review already given by P. CHRISTAKOGLOU

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Motivation

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

Anisotropic flow of identified particles is sensitive to the partonic degrees of freedom at the early times of a heavy-ion collision;

$v_n(p_T)$ allows to quantify:

1. rate of hydrodynamic radial expansion (mass dependence of v_n vs. p_T)
2. properties of the deconfined phase (e.g. viscosity)
3. details of hadronization mechanism (e.g. coalescence, fragmentation at high p_T)

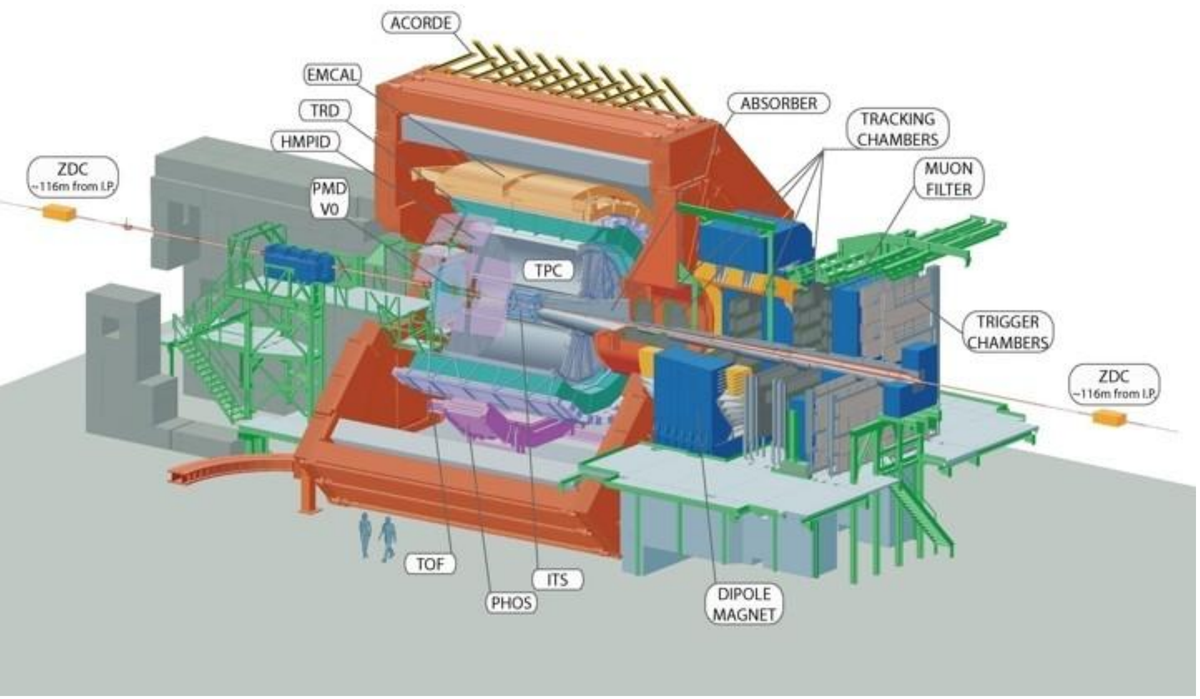
Outline

In this talk we present anisotropic flow of π, K, p, Λ, Ξ, Ω, ϕ and investigate the properties of v_2 and v_3 vs. transverse momentum:

1. particle mass dependence
2. comparison with hydrodynamic model calculations
3. comparison with measurements at RHIC
4. v_2/v_3 scaling properties with number of quarks.
5. p_T dependent fluctuations of flow angle and magnitude

A comparison of v_2 for p-Pb and Pb-Pb system is also reported.

Analysis details



VZERO detector
Two forward scintillator arrays
($-3.7<\eta<-1.7$, $2.8<\eta<5.1$):
centrality + triggering + event plane

Inner Tracking System (ITS)
($-0.8<\eta<0.8$)
Tracking + triggering

Time Projection Chambers (TPC):
($-0.8<\eta<0.8$)
Tracking + particle identification(PID)

DATA sample:
- Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV (2010 data, 10M events)
- p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV (2013 data, 100M events)

Time Of Flight (TOF):
($-0.8<\eta<0.8$)
PID

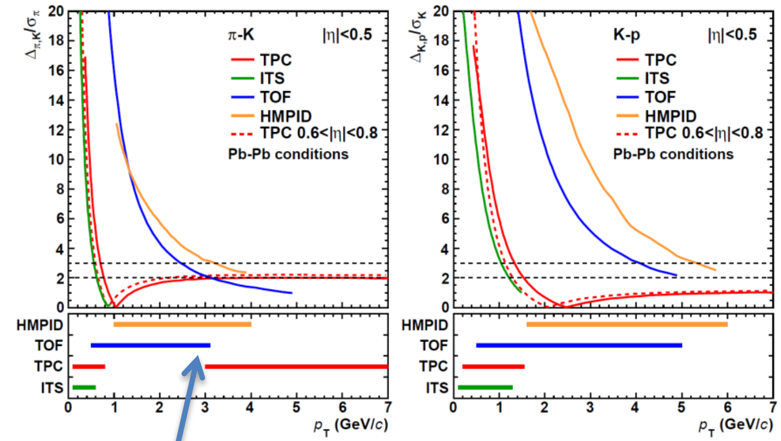
π, K and p/$\bar{p}$ identification

Particle Identification (PID) with TOF & TPC:

- Combination of TPC and TOF allows to reach a particle separation ⩾ 2σ in the full p_T range investigated.
- p_T range:
  - π → $0.2 < p_T < 6.0$ GeV/c
  - K → $0.3 < p_T < 4.0$ GeV/c
  - p → $0.3 < p_T < 6.0$ GeV/c
- PID cuts tuned in order to guarantee a purity: > 90%

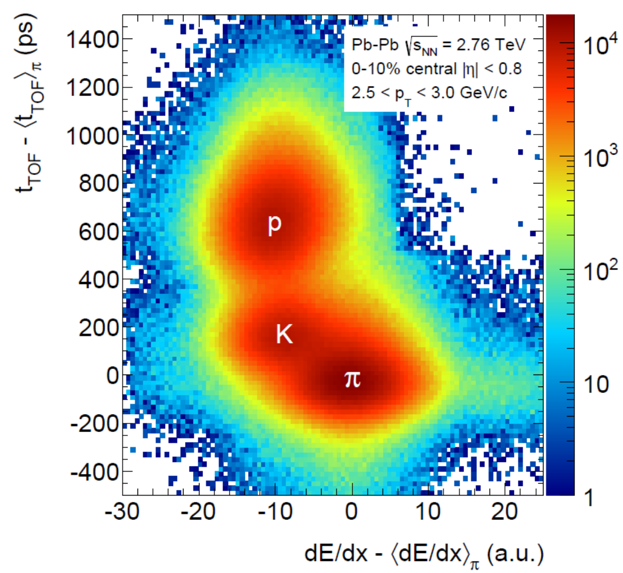
Identification at high p_T with TPC only:

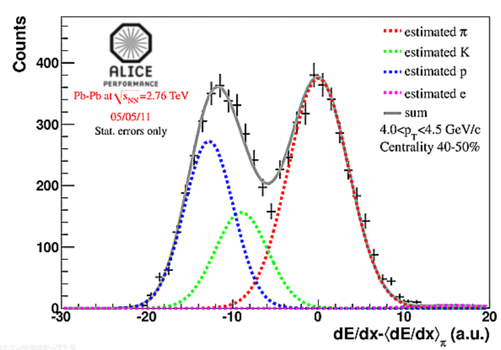
- purity cut on the TPC dE/dx signal:
- p_T range (in GeV/c):
- π and p → $3 < p_T < 16$
- purity: > 90% for pions, > 80% for protons



TPC and TOF PID is complementary

ALICE performance, arXiv:1402.4476





K^0_S, Λ, Ξ, Ω and φ reconstruction

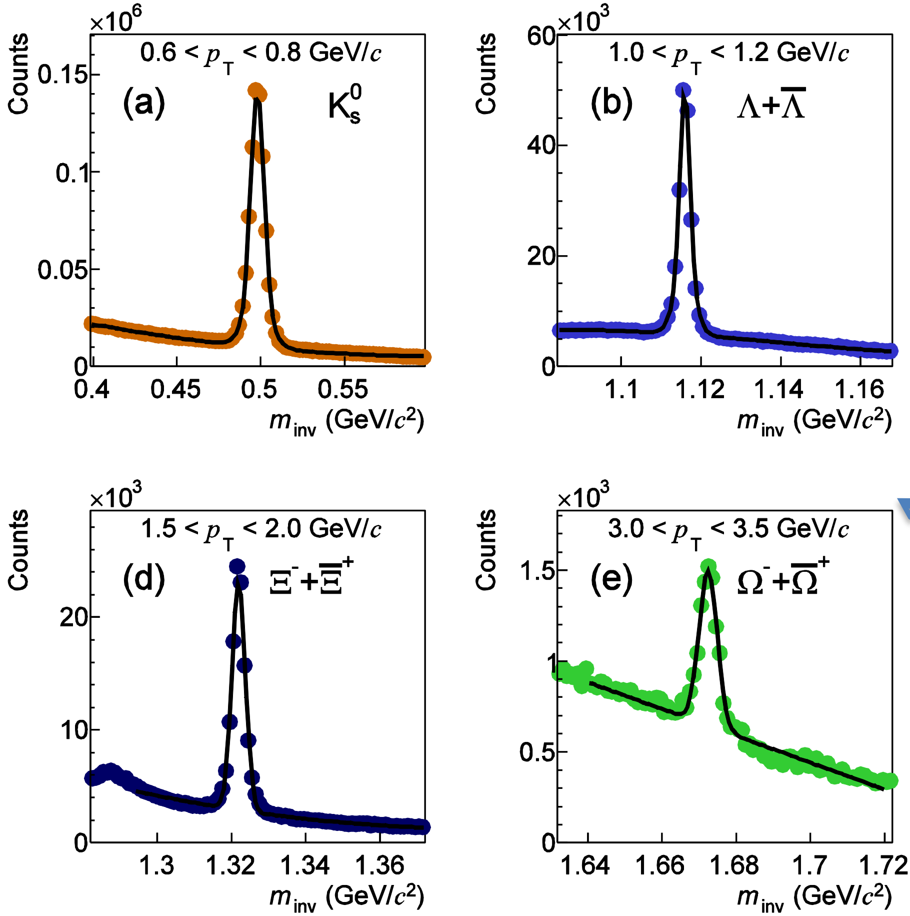
ALICE

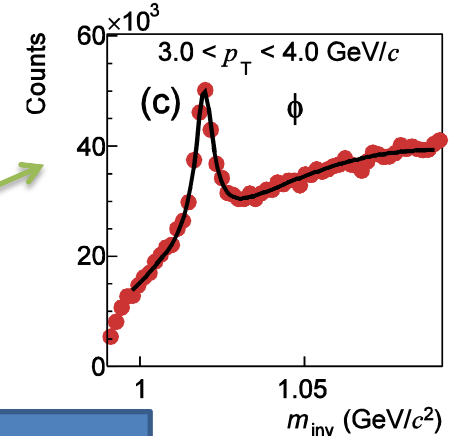
$K^0_S \rightarrow \pi\pi$

$\Lambda(\bar{\Lambda}) \rightarrow p(\bar{p})\pi$

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

$\phi \rightarrow KK$





$\Xi^{\pm} \rightarrow \Lambda\pi^{\pm}$

$\Omega^{\pm} \rightarrow \Lambda K^{\pm}$

Kaon PID applied

Topolgical cuts were applied:

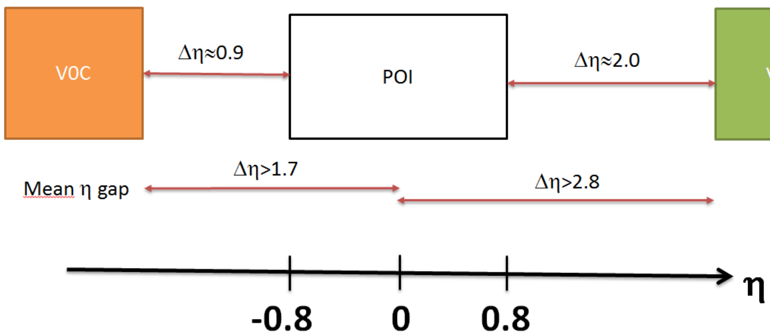
- Secondary vertex
- Decay kinematics

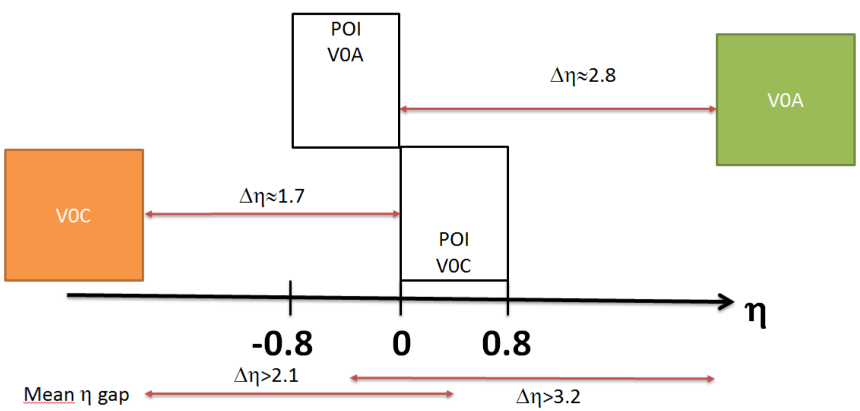
v_2 extracted fitting its dependence on the reconstructed invariant mass of the pairs.

$$v_2^{Tot}(m_{inv}) = v_2^{Sgn}\frac{N^{Sgn}}{N^{Tot}}(m_{inv}) + v_2^{Bg}\frac{N^{Bg}}{N^{Tot}}(m_{inv})$$

η gap to reduce non-flow

We investigated a couple of analysis setup to probe the sensitivity to non-flow contributions to the η gap between reaction plane particles (A and C) and Particles On Investigation (POI, B). Both the scenarios give consistent results according with a negligible residual effect by non-flow.





$$v_2 = \sqrt{\frac{\left\langle\left\langle \vec{u}_2^{\,B} \cdot \frac{\vec{Q}_2^{A*}}{M_A} \right\rangle\right\rangle \left\langle\left\langle \vec{u}_2^{\,B} \cdot \frac{\vec{Q}_2^{C*}}{M_C} \right\rangle\right\rangle}{\left\langle \frac{\vec{Q}_2^{A}}{M_A} \cdot \frac{\vec{Q}_2^{C*}}{M_C} \right\rangle}}$$

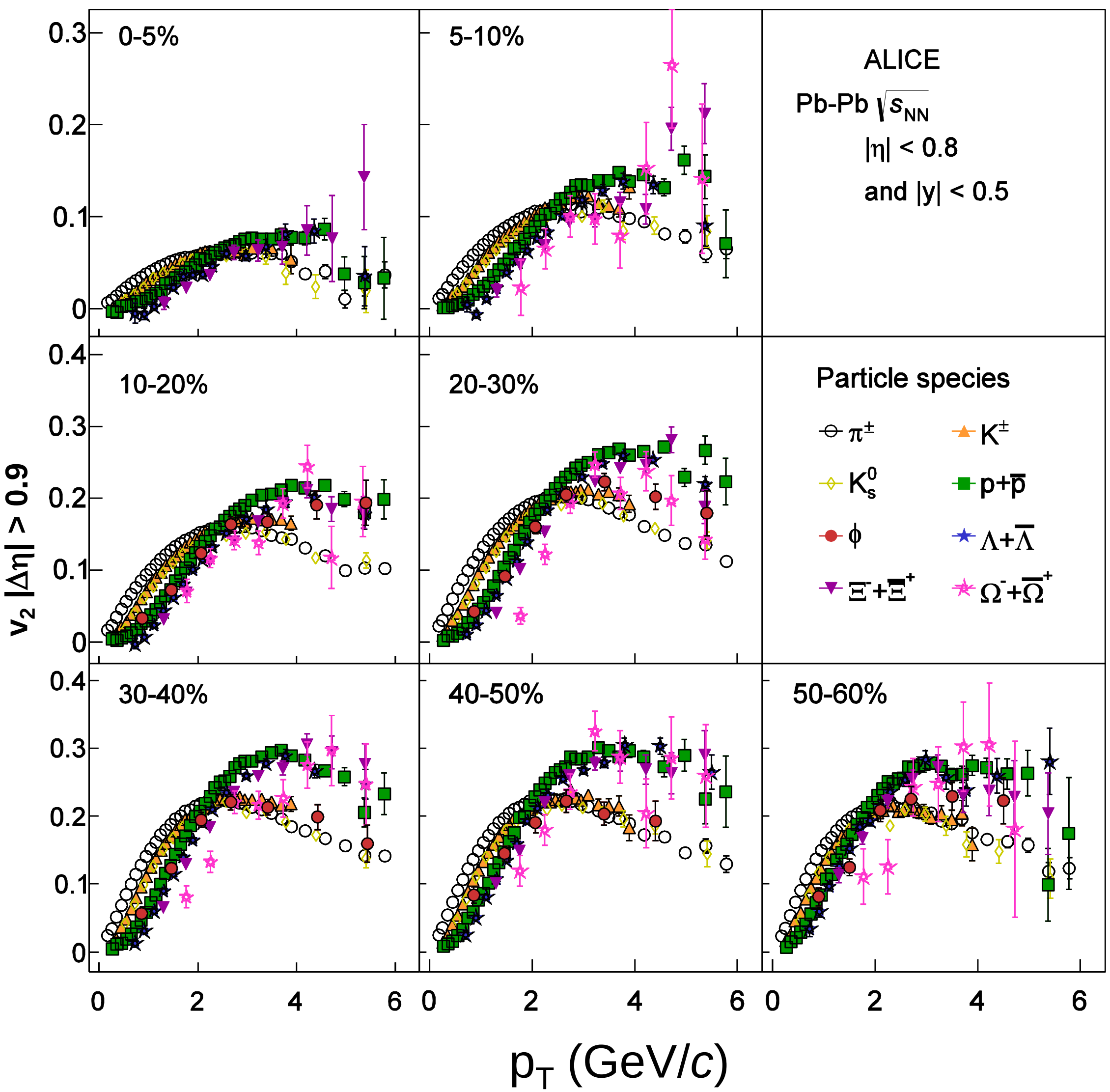
$$\text{with} \begin{cases} \vec{Q}_2^{A,C} = \sum_{\text{VZERO-A,C}} e^{i2\varphi_{RP}} \\ M_{A,C} = \sum_{\text{VZERO-A,C}} 1 \\ \left\langle \vec{u}_2^{\,B} \cdot \vec{X} \right\rangle = \left\langle e^{i2\varphi_{POI}} \cdot \vec{X} \right\rangle_{\text{selected tracks in the barrel}} \end{cases}$$

v_2 was extracted using Scalar Product method from this formula which takes into account multiplicity asymmetry in the two VZERO elements.

Elliptic flow of identified particles

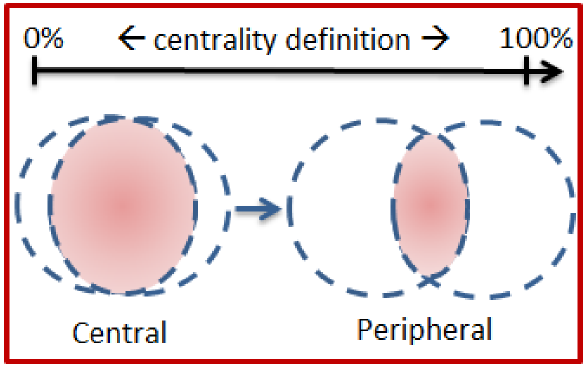
Many of next results (unless specified otherwise) were recently submitted to JHEP and are available in **arXiv:1405.4632**.

ALICE compilation for v_2

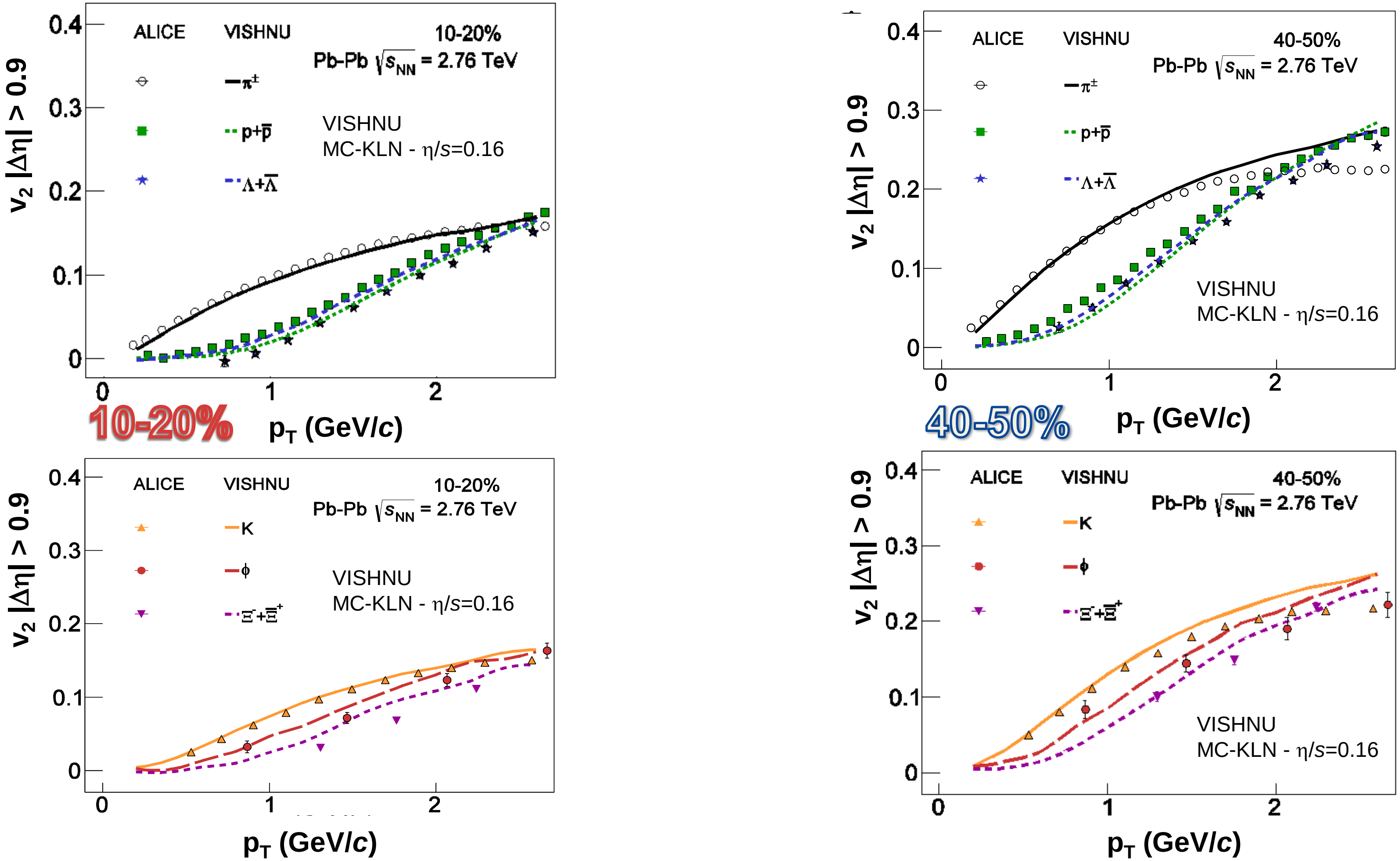


v_2 for π, $K^{\pm}$, p, $K^0{}_s$, Λ, Ξ and Ω:

1. Mass ordering observed for different species
   - Stronger in most central collisions → stronger radial flow
2. Crossing between proton and pion v_2 around p_T~2 GeV/c
3. Particle type dependence persists out to high p_T



Identified particle flow vs. hydro



Hydrodynamic models predict mass splitting

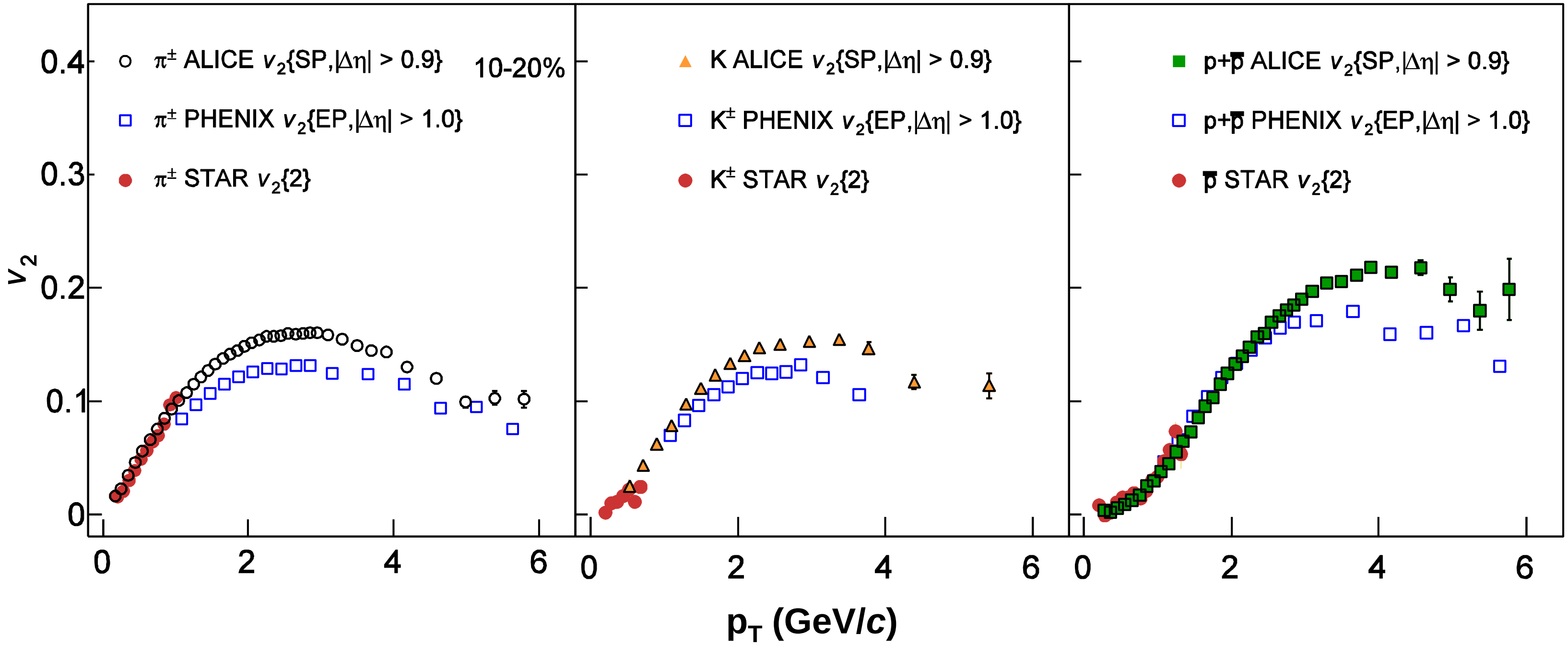
Hydrodynamic curves reproduce the main features of v_2 at low p_T:

- hadron re-scattering was included in VISHNU to reconcile proton data v_2.
- mass ordering in VISHNU is lost when comparing p and Λ

H. Song, S. A. Bass, U. Heinz, T. Hirano and C. Shen, **PRL 106,** 192301 (2012); **PRC 83** 054910 (2012) and H. Song, S. Bass and U. W. Heinz, arXiv:1311.0157

v_2 of π, K, p at LHC vs. RHIC

10-20%



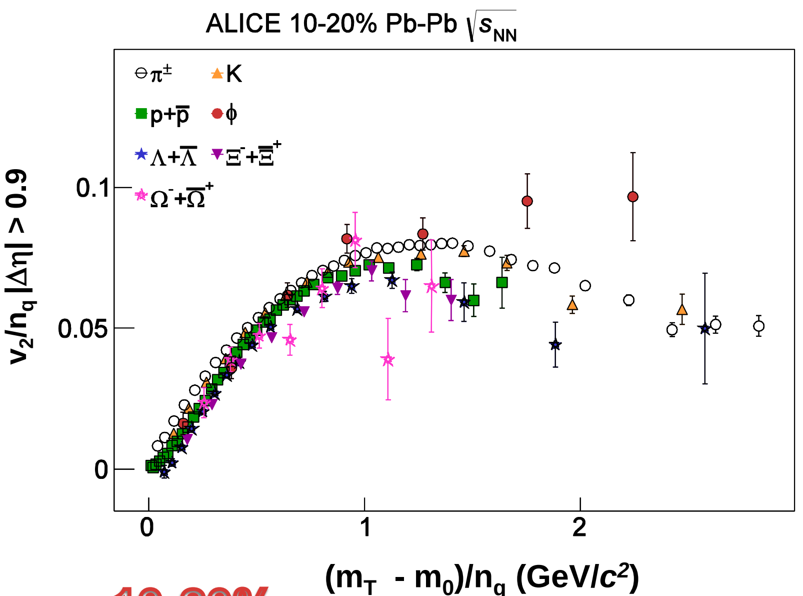
PHENIX data: **PRC 85,** 064914 (2012)
STAR data: **PRC 72** 014904 (2005)

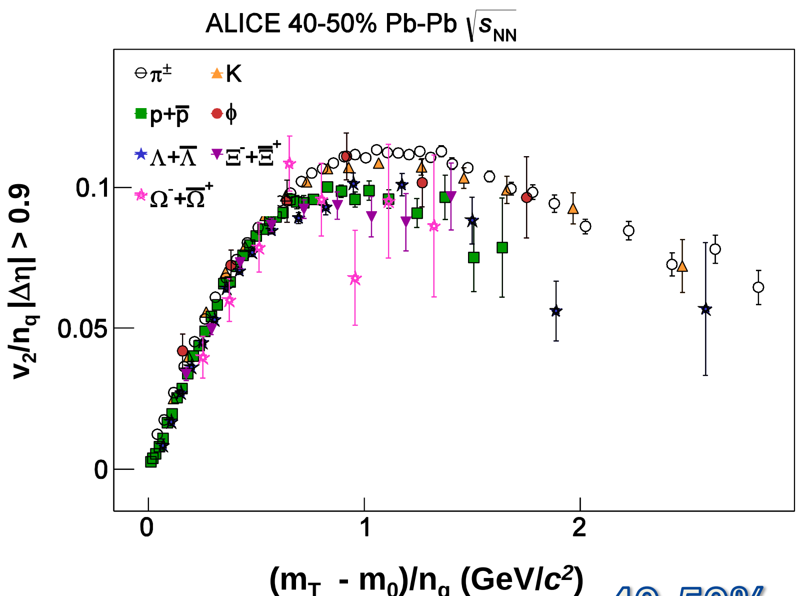
v_2 at LHC qualitatively similar to RHIC:

- v_2 measured at the LHC is slightly above the RHIC v_2 for pions and kaons
- v_2 of (anti-)protons reflects effect of larger radial flow at LHC

Elliptic flow scaling properties

v_2 scaled for the Number of Constituent Quarks (NCQ) vs KE_T/n_q





10-20%

40-50%

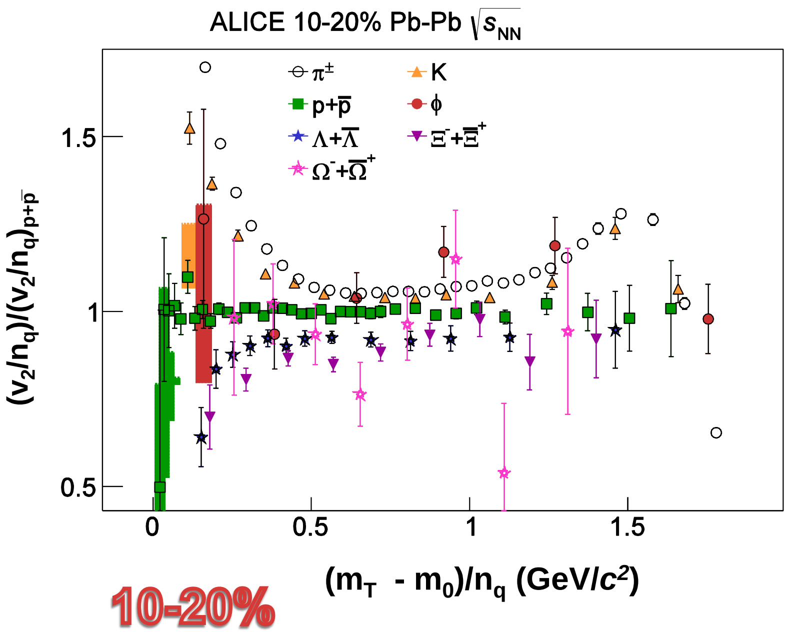
$$m_T = \sqrt{m^2 + p_T^2}$$

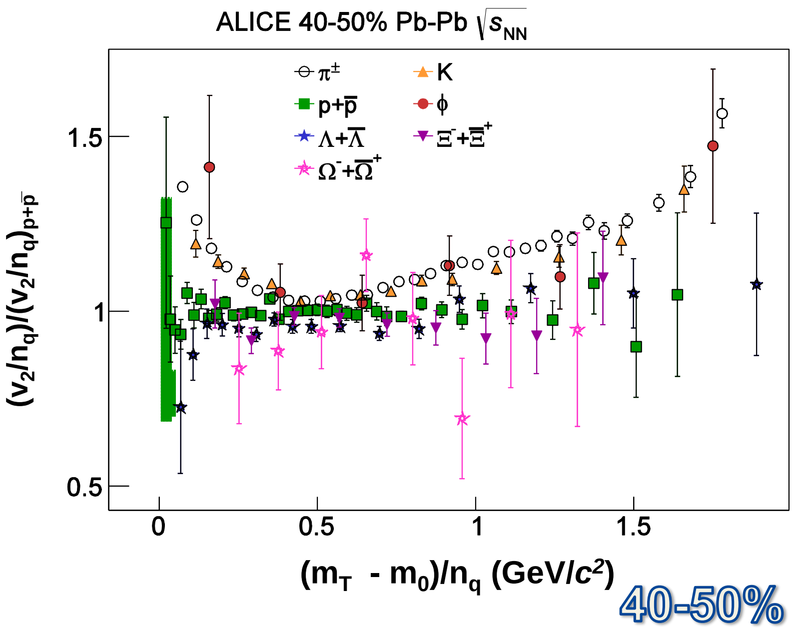
KE_T = Transverse Kinetic Energy = $m_T - m_0$

KE_T/n_q scaling:

- For low KE_T/n_q: the NCQ scaling is broken at the LHC
- For KE_T/n_q > 1 GeV/*c*: scaling holds at the level of 20%

v_2 scaled for the Number of Constituent Quarks (NCQ) vs KE_T/n_q
(ratio vs. proton)





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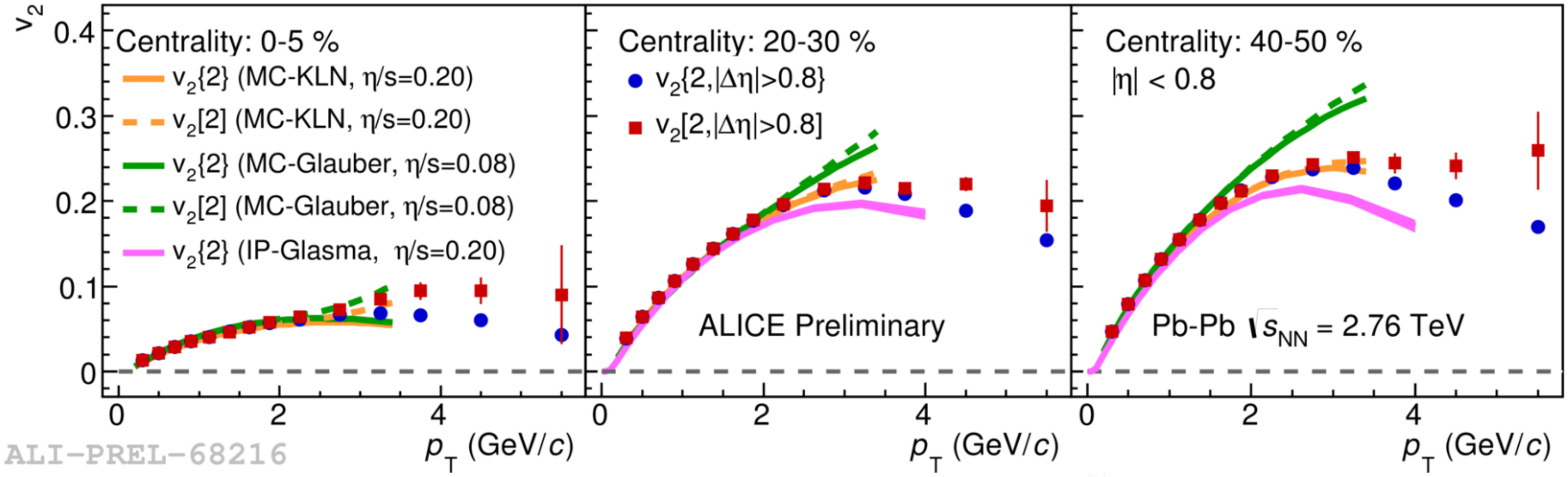
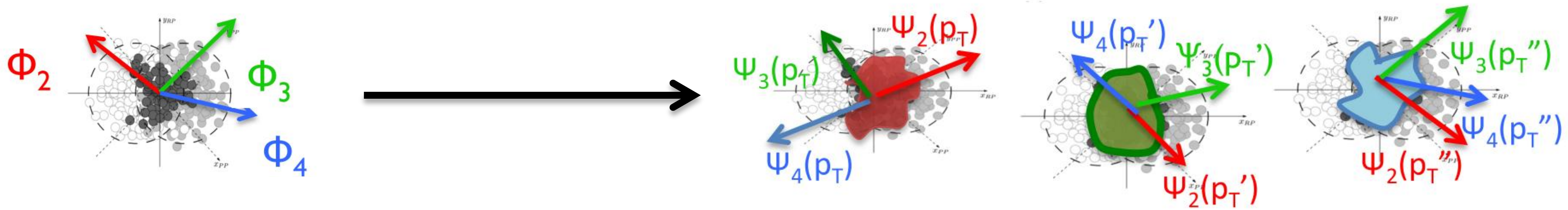
p_T dependent fluctuations of flow angle and magnitude



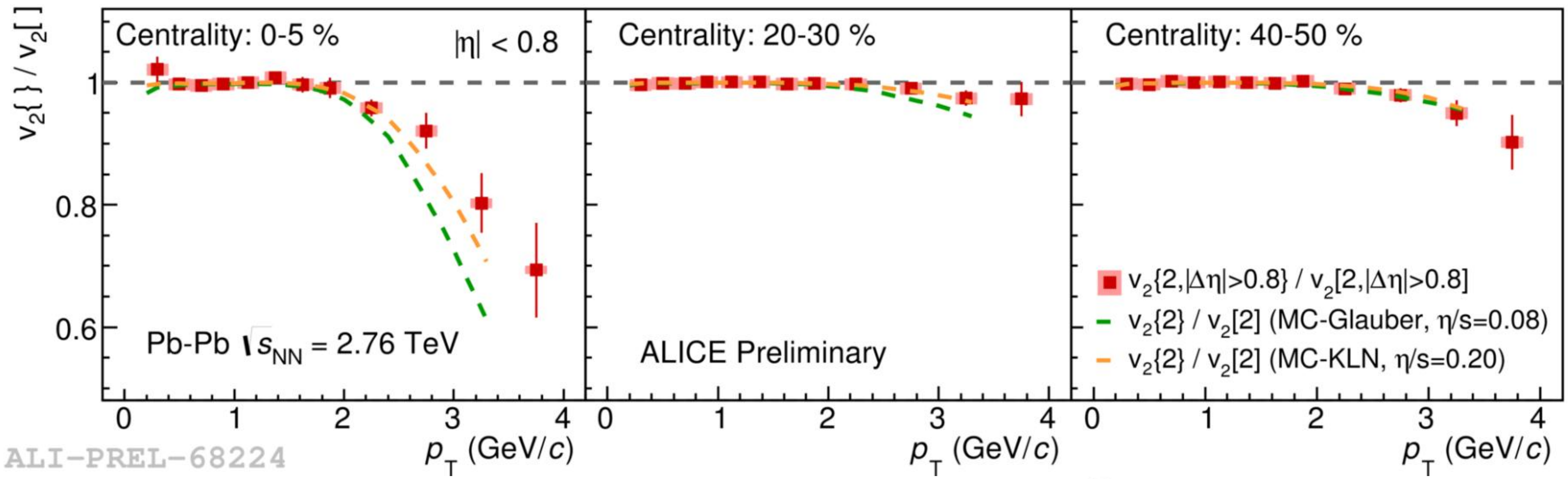


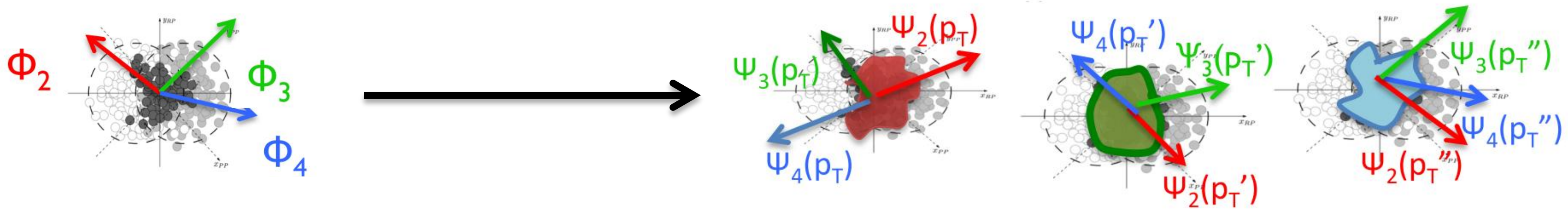
Recent hydrodynamic simulations predicted a p_T dependent flow angle and fluctuations →further constraints on the initial state and η/s

$v_2\{2\}$ and $v_2[2]$:
{} means Reference Flow particles taken in the full p_T range (common symmetry plane)
[] means Reference Flow particles take in in the same p_T range of the investigated particles ($\Psi(p_T)$)

MC-Glauber & MC-KLN: PRC 87, 034913
IP-Glasma: PRL 110, 012302

p_T dependent fluctuations of flow angle and magnitude





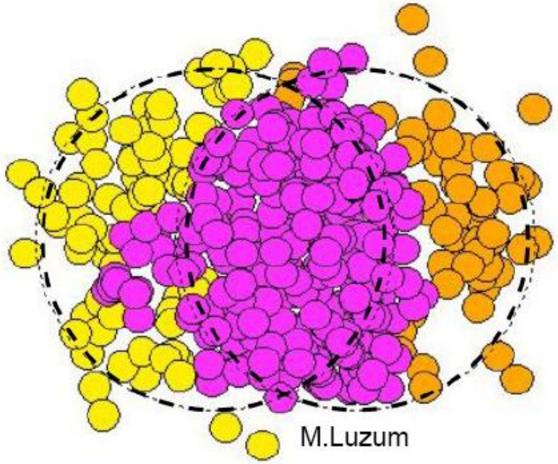
$v_2[2]$ vs $v_2\{2\}$:

- Hydrodynamic calculations, without non-flow, already overestimate the deviations
- Significant deviation for $p_T > 2$ GeV/*c* in most central collisions
- MC-KLN works better both for $v_2[2]$ and $v_2\{2\}$ up to high p_T
- An estimate of non-flow effects is currently under investigation

MC-Glauber & **MC-KLN**: PRC 87, 034913

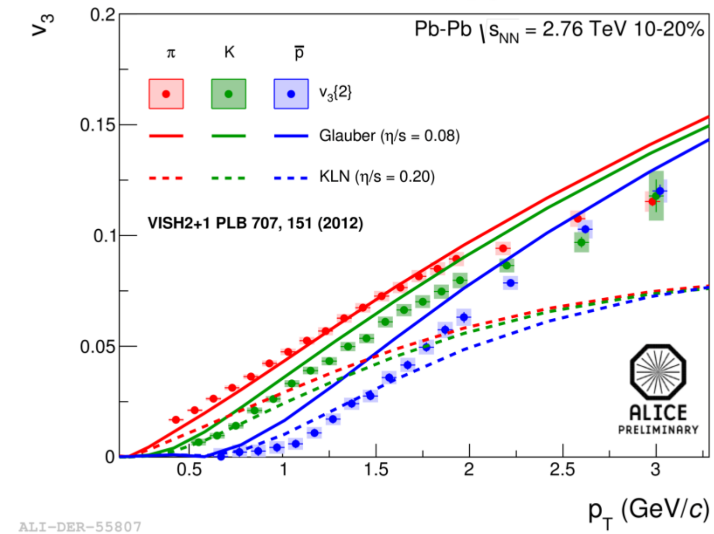
Identified particle triangular flow

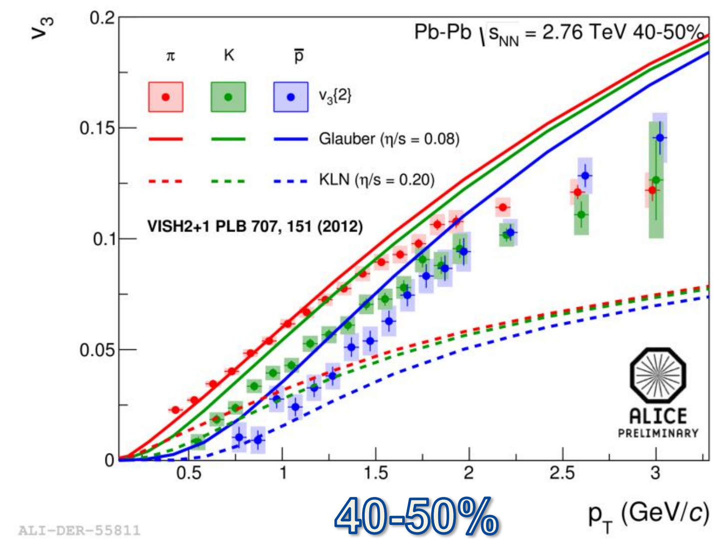
Triangular flow



J. Phys. G: Nucl. Part. Phys. 38 (2011) 124026

10-20%



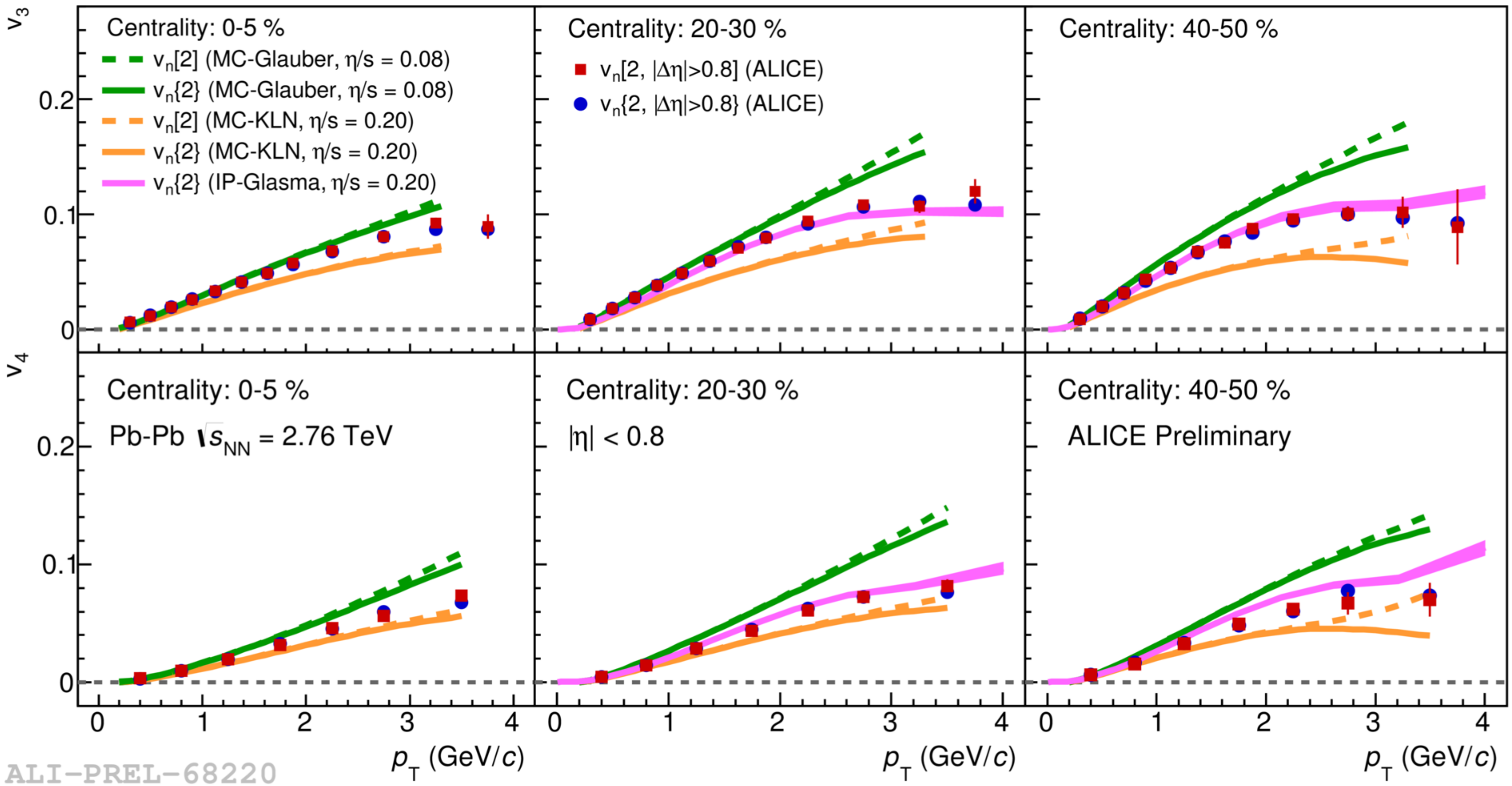


40-50%

- v_3 exhibits similar particle mass dependence as that of v_2
- The value of p_T at which v_3 of all species cross looks similar to that for v_2
- v_3 is quite sensitive to the input in the hydro models

Note:
$v_3\{2\}$ is without rapidity gap

…more harmonics

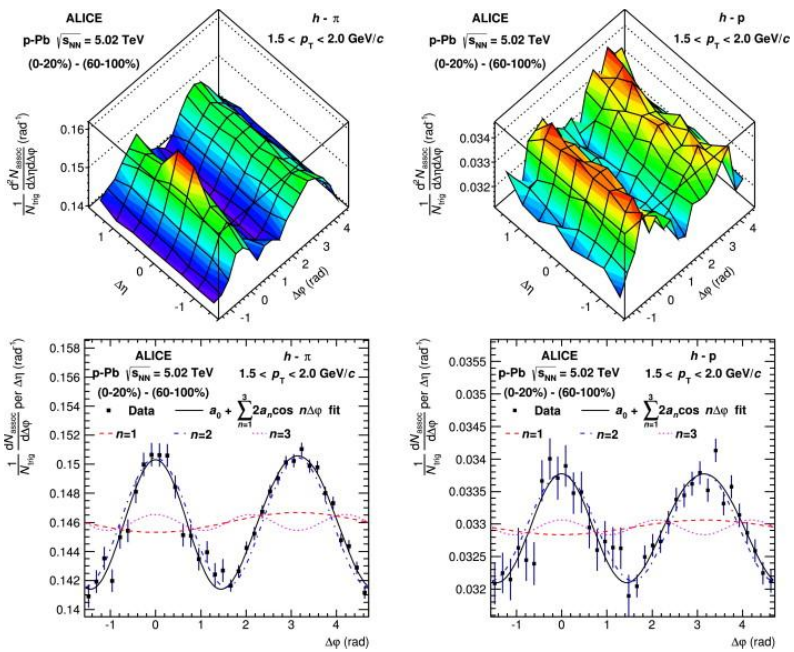


Nice agreement with IP-Glasma for $v_n\{2\}$ while MC-KLN and MC-Glauber do not describe the p_T dependence of v_3 and v_4

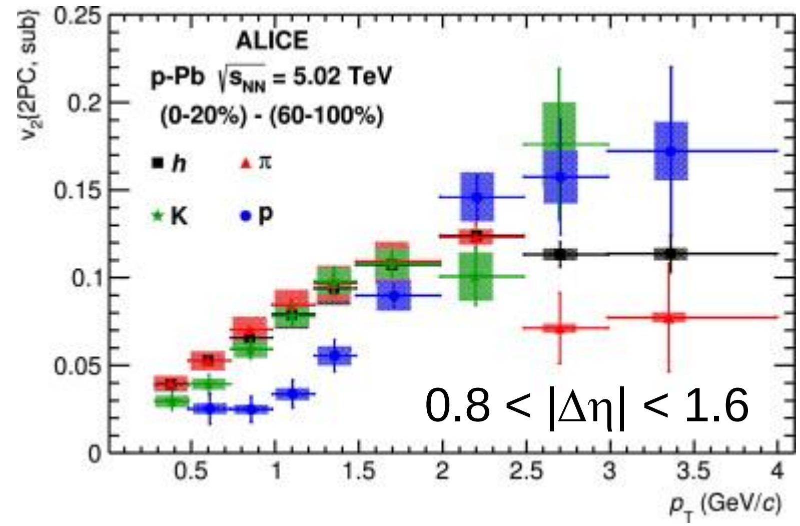
$v_n[2]$ vs $v_n\{2\}$:

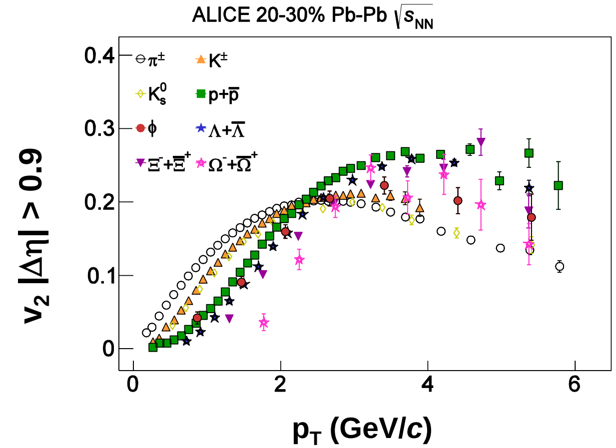
- No clear difference between $v_n[2]$ and $v_n\{2\}$

v_2 in p-Pb



Physics Letters B 726 (2013) 164–177





Qualitatively similar picture in p-Pb as in Pb-Pb:

- Crossing between proton and pion v_2 at p_T ~2 GeV/*c*
- Observe mass ordering at low p_T

Does it flow?

Summary

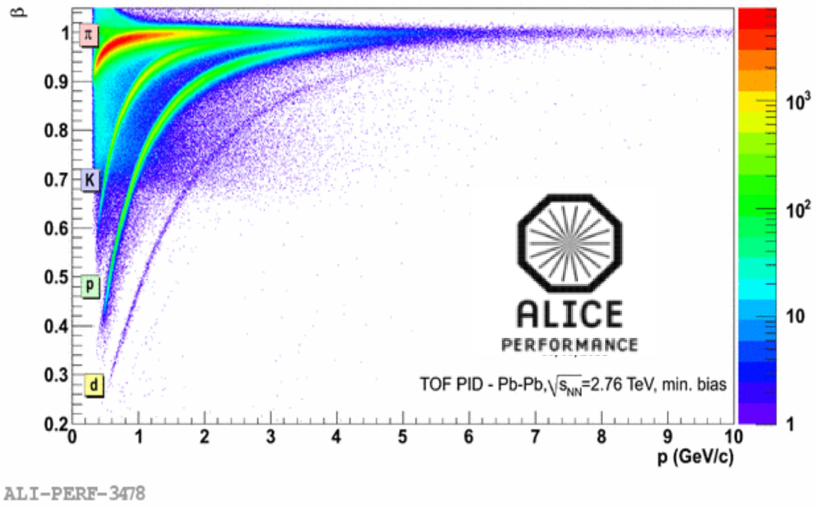
Elliptic flow of π, K, p, Λ, Ξ, Ω and ϕ is measured vs. transverse momentum for different collision centrality classes for Pb-Pb collision at 2.76 TeV:

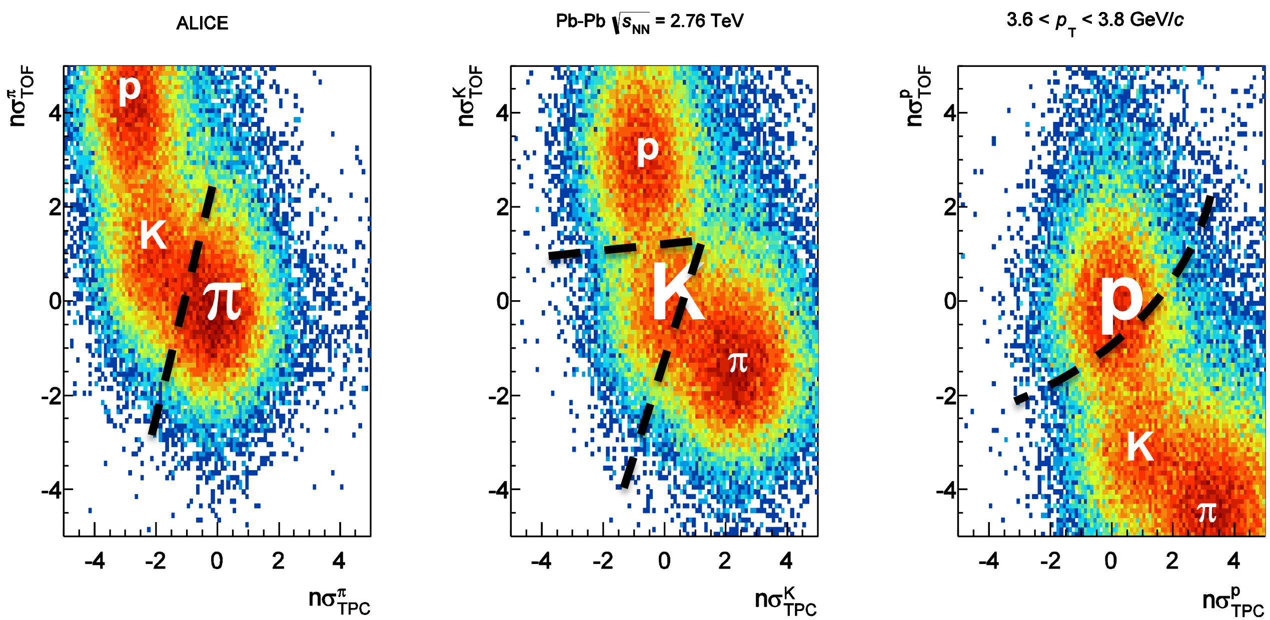
1. Main features of v_2 at low p_T are reproduced by hydro model calculations
2. Mass splitting is consistent with stronger radial flow at the LHC
3. NCQ scaling is only approximate (within 20%) at intermediate p_T
4. v_3 of π, K, and p/p has a similar mass dependence and crossing point as that of v_2
5. Flow angle and magnitude fluctuations may help to constrain initial conditions and viscosity in the models.

Moreover intriguing results were observed in p-Pb high multiplicity collisions revealing similar feature for v_2 as in Pb-Pb (is it flow?)

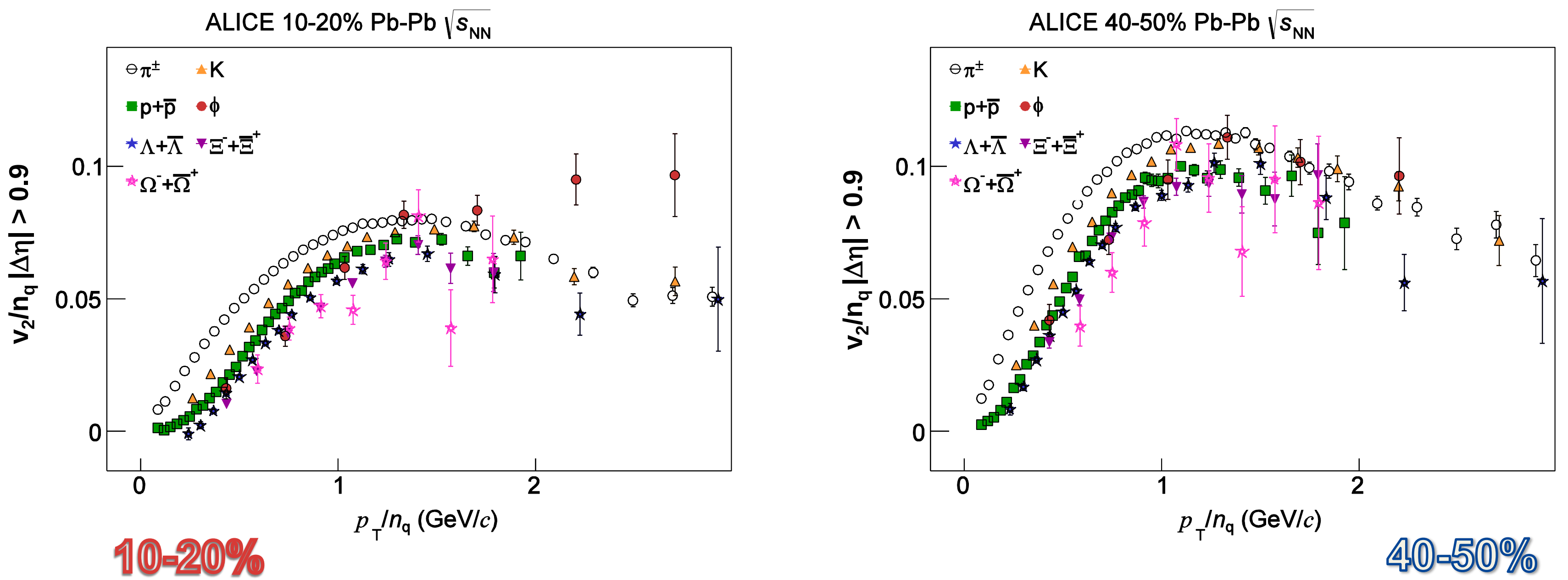
backup

π, K and p/$\bar{p}$ identification





v_2 scaled for the Number of Constituent Quarks (NCQ) vs p_T/n_q

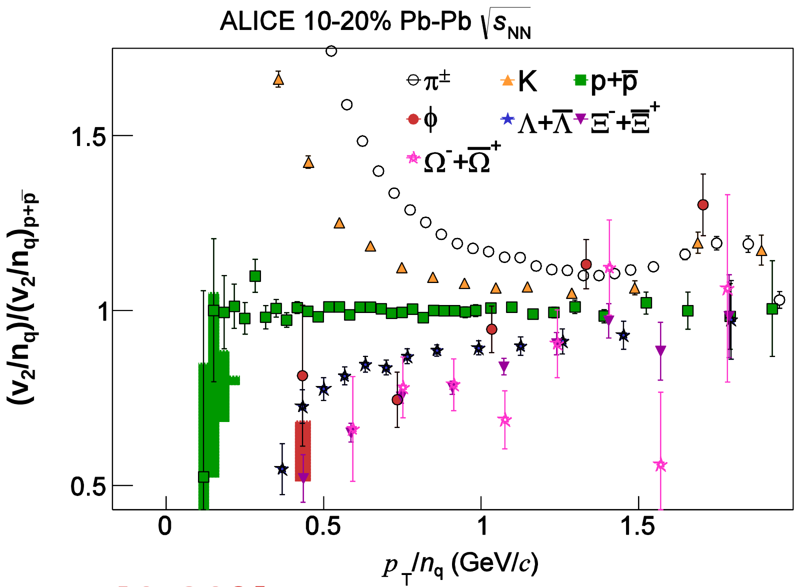


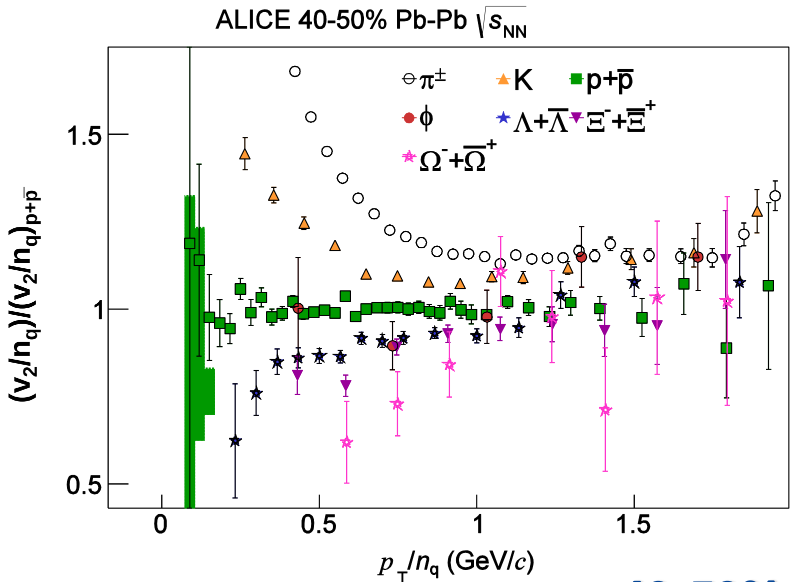
p_T/n_q (n_q=2 for mesons, n_q=3 for baryons) scaling:

- $v_2(p_T)$ for $3 < p_T < 6$ GeV/c can be used to test quark coalescence

v_2 scaled for the Number of Constituent Quarks (NCQ) vs p_T/n_q

(ratio vs. p)





10-20%

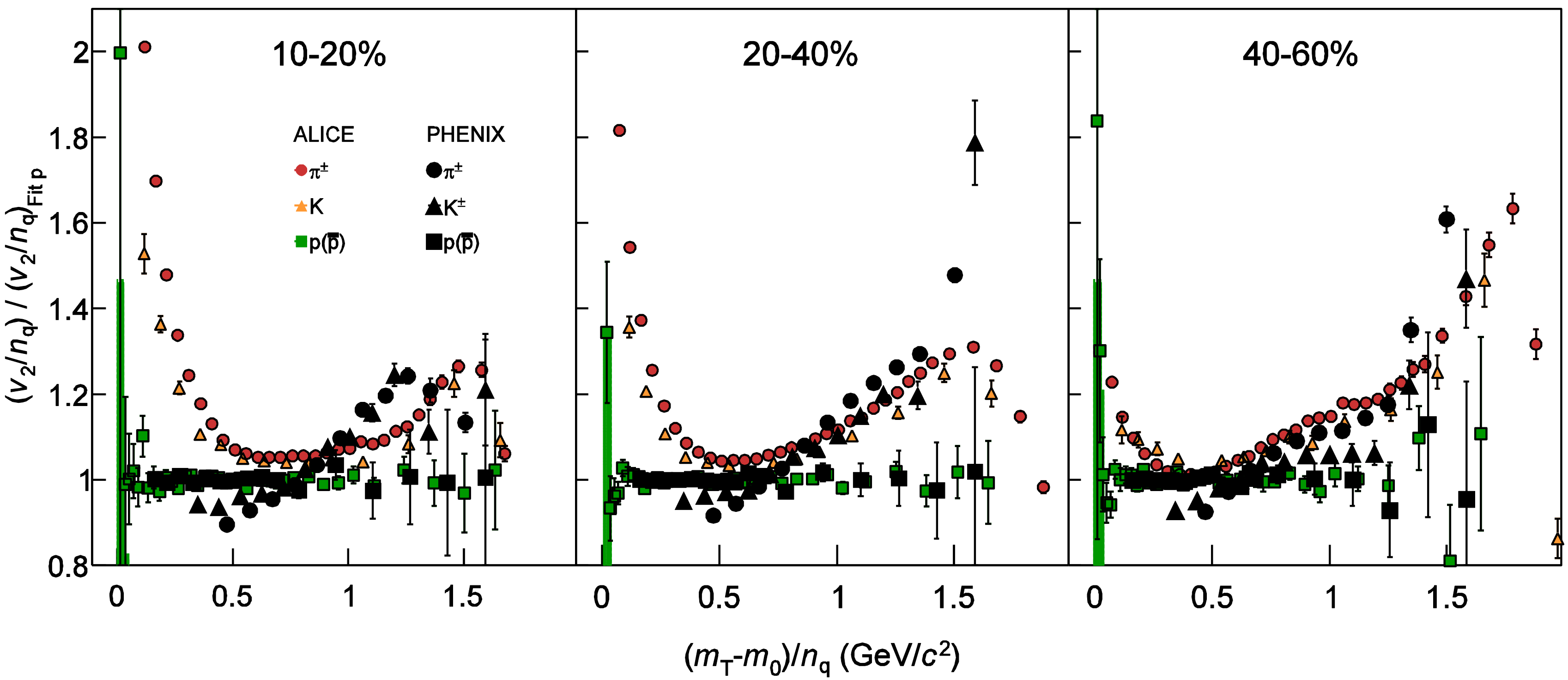
40-50%

p_T/n_q (n_q=2 for mesons, n_q=3 for baryons) scaling:

- $v_2(p_T)$ for $3 < p_T < 6$ GeV/c can be used to test quark coalescence
- v_2/n_q vs. p_T/n_q holds within 20% for intermediate p_T/n_q and is violated at low p_T/n_q

v_2 scaled for the Number of Constituent Quarks (NCQ) vs KE_T/n_q

(ratio vs. proton)



LHC vs RHIC

Triangular flow (NCQ)

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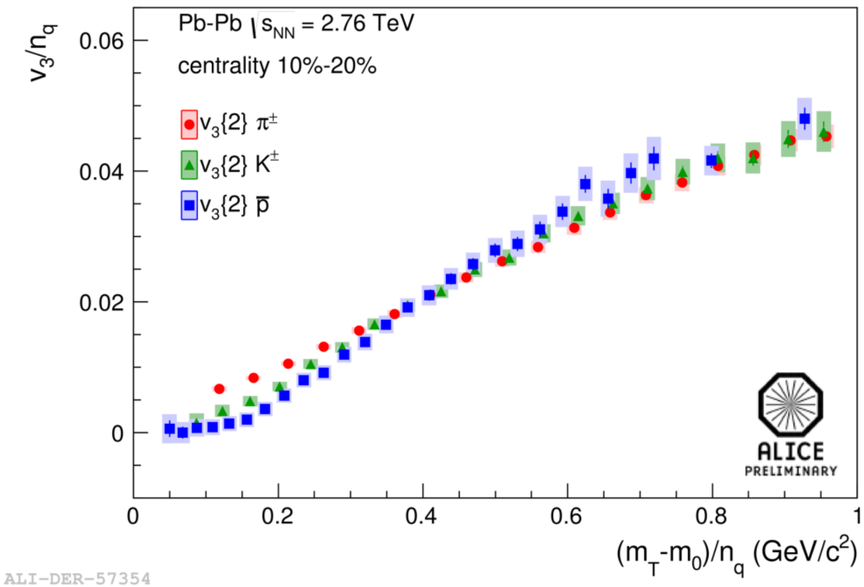

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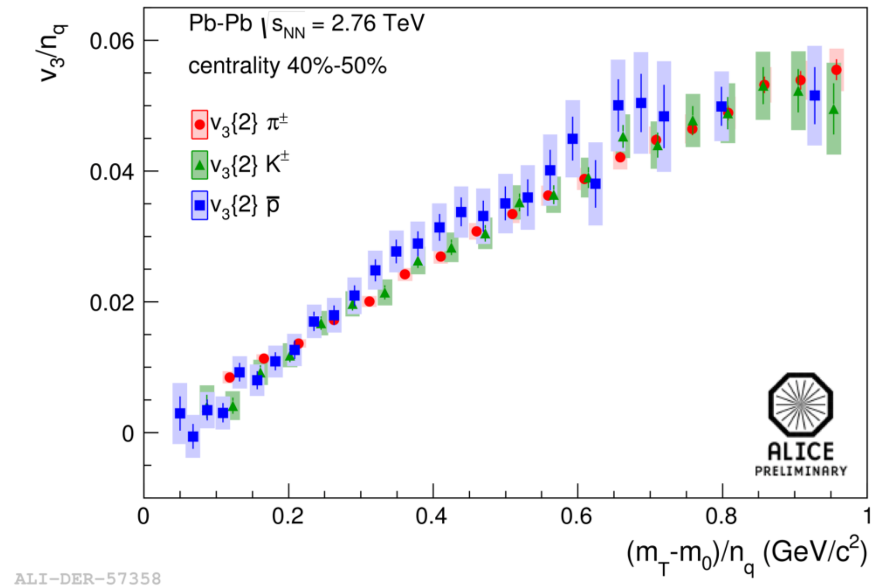
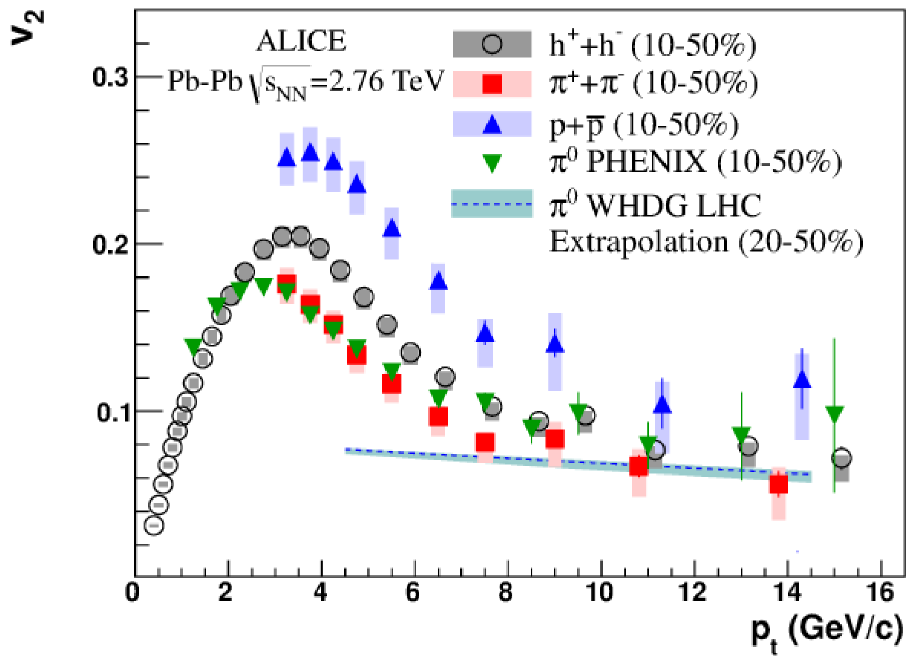


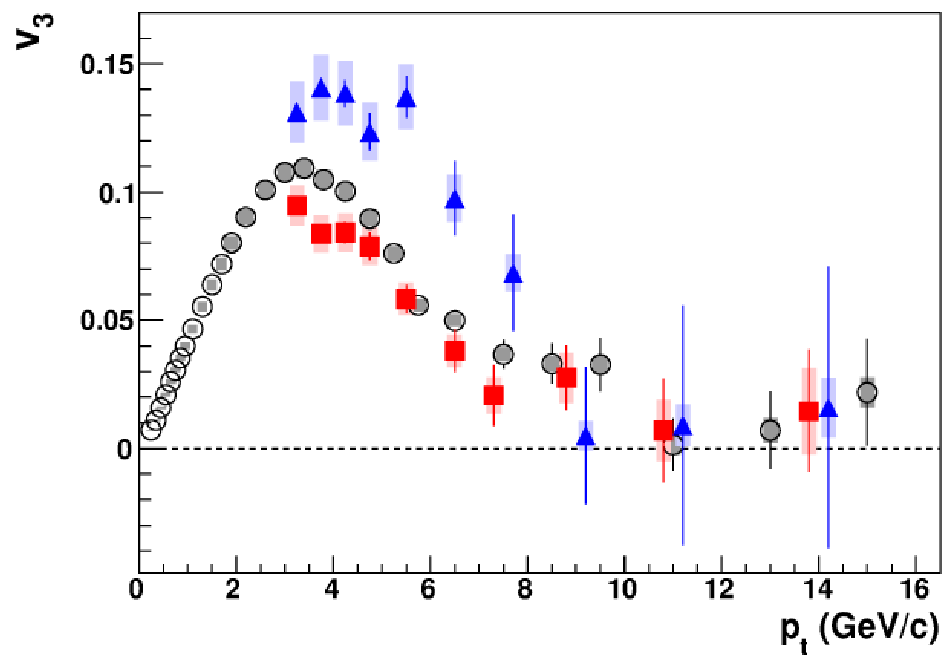
v_3 scales better with the number of constituent quarks w.r.t. v_2 (is it still broken in the most central collisions?).

Triangular flow

ALICE: Phys. Lett. B 719 (2013) 18
WHDG: Horowitz, Gyulassy, J. Phys. G **38, 124114 (2011)**

10-50%





1. up to $p_T \sim 8$ GeV/*c*, proton v_2 and v_3 is larger than that of pion
2. pion/proton v_2 at high transverse momenta ($p_T > 10$ GeV/*c*) is significant and non zero, while within experimental uncertainties v_3 is consistent with zero
3. Charged pion v_2 reproduced by WHDG π^0 predictions for $p_T > 7$ GeV/*c*
4. Charged pion v_2 similar in magnitude to PHENIX π^0 v_2