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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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 coefficients covered in this talk

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)

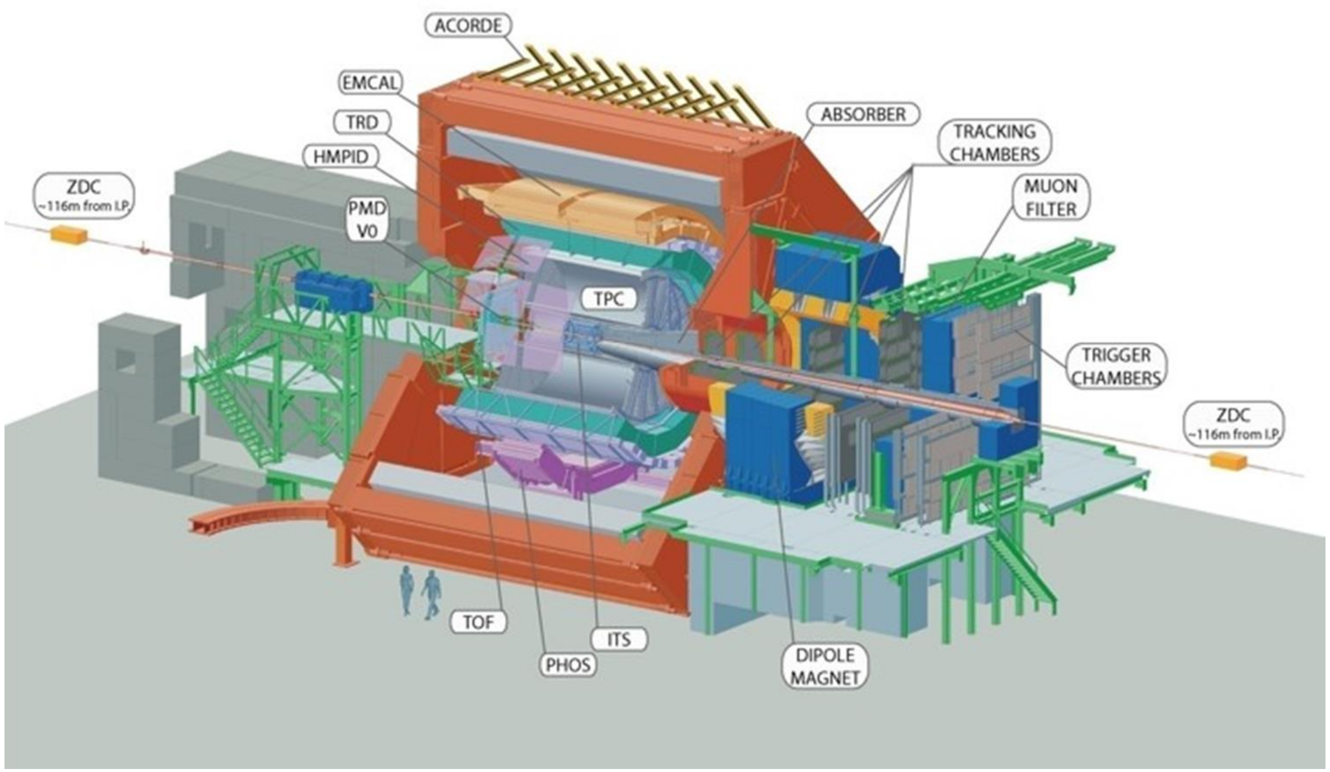
Outline

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

1. particle mass dependence
2. quark (light/strange) content
3. comparison with hydrodynamic model calculations
4. comparison with measurements at RHIC
5. v_2/v_3 scaling properties with number of quarks and transverse kinetic energy.

A comparison of v_2 for p-Pb and PbPb 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)

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

DATA sample:

Å Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV (2010 data, 10M events)

Å p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV (2013 data, 100M events)

π, K and p/$\bar{\text{p}}$ identification

Particle identification with TOF & TPC:

Åasymmetric β-cut to select a high purity sample of π, **K** and **p**.

Å 2σ cut in the TPC dE/dx.

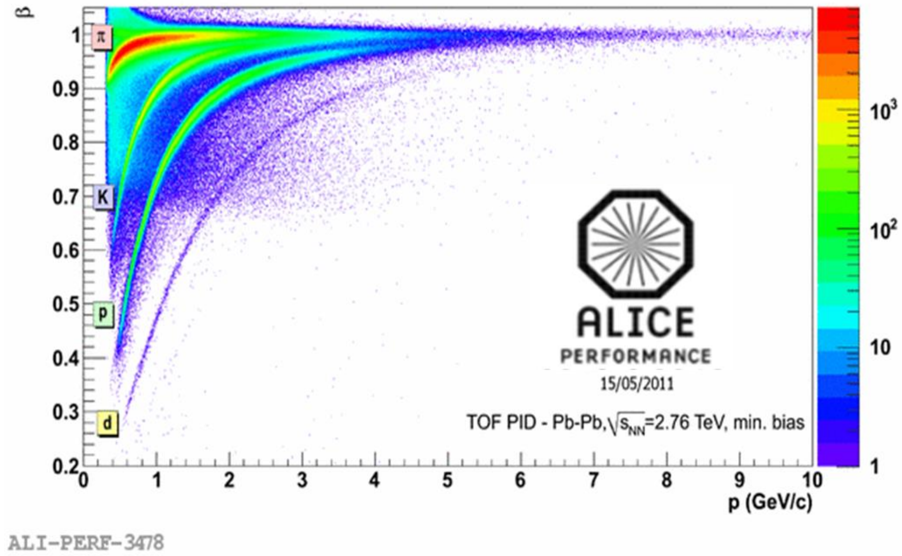
Å p_T range:

Å $\pi \rightarrow 0.3 < p_T < 3.5$ GeV/*c*

Å K $\rightarrow 0.4 < p_T < 2.5$ GeV/*c*

Å p $\rightarrow 0.5 < p_T < 4.0$ GeV/*c*

Å purity: > 90%



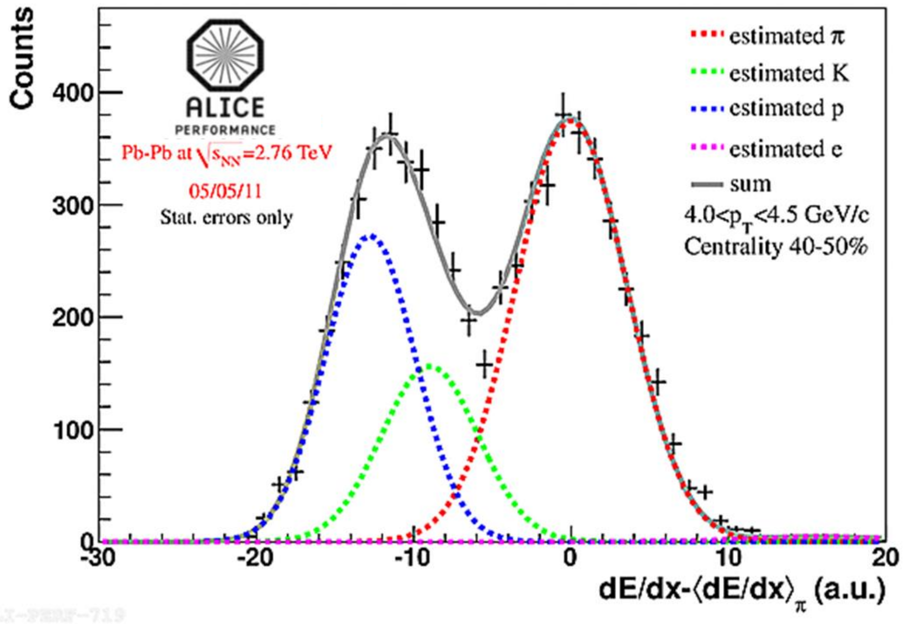
Identification at high pT with TPC:

Åpurity cut on the TPC dE/dx signal:

Åp_T range (in GeV/*c*):

Å π and p $\rightarrow 3 < p_T < 16$

Åpurity: > 90% for pions, > 80% for protons



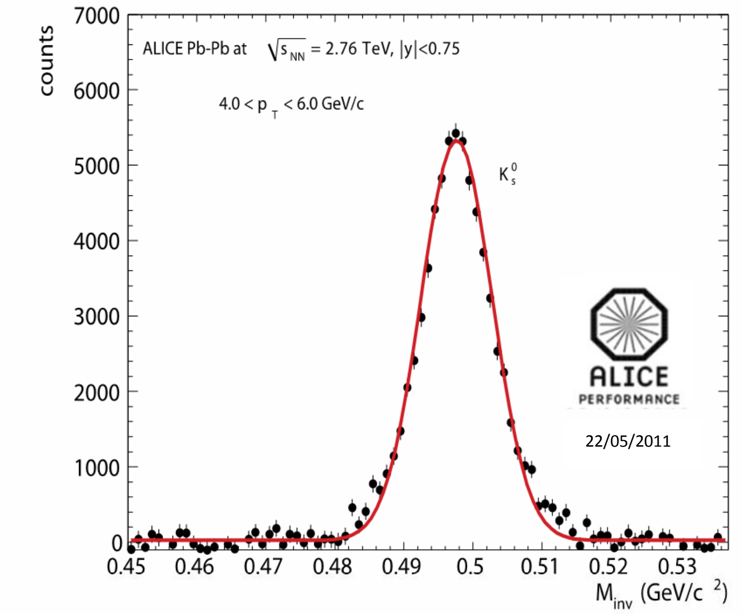
K^0_s, Λ, Ξ and Ω reconstuction

$K^0_s \rightarrow \pi\,\pi$

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

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

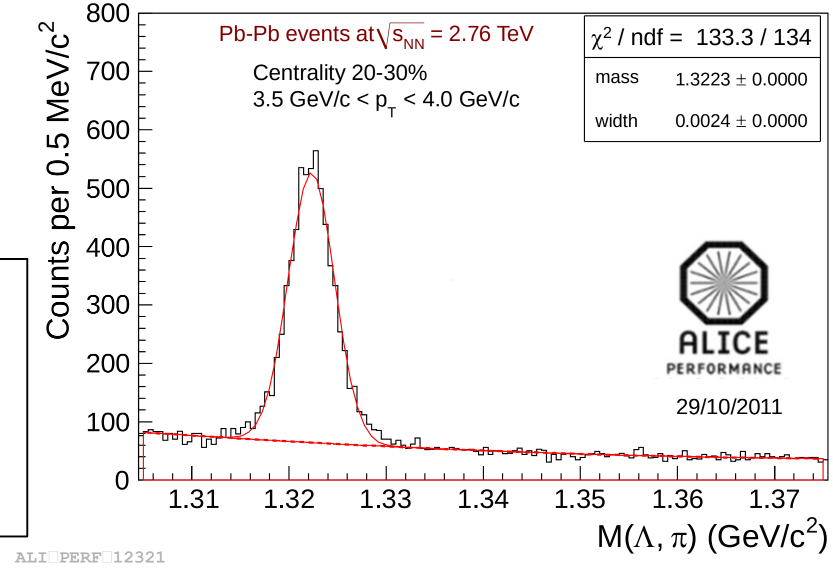
$\Omega^{\pm} \rightarrow \Lambda K^{\pm}$

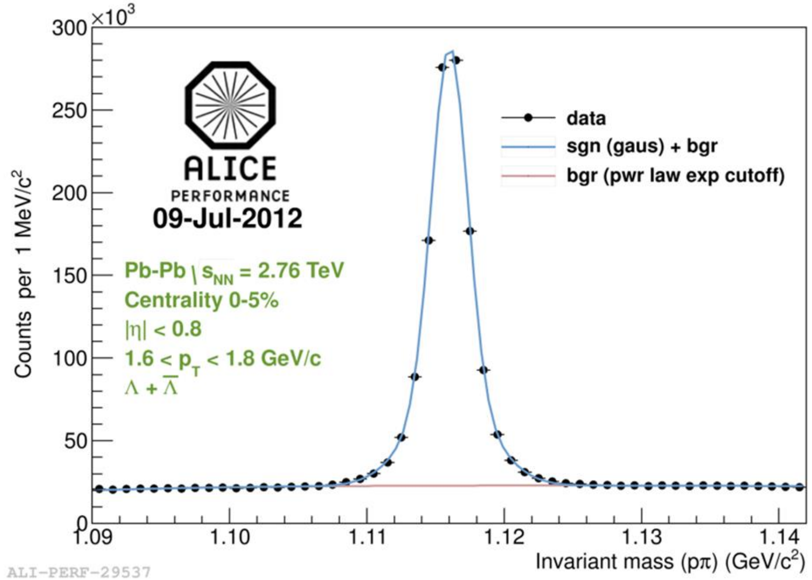


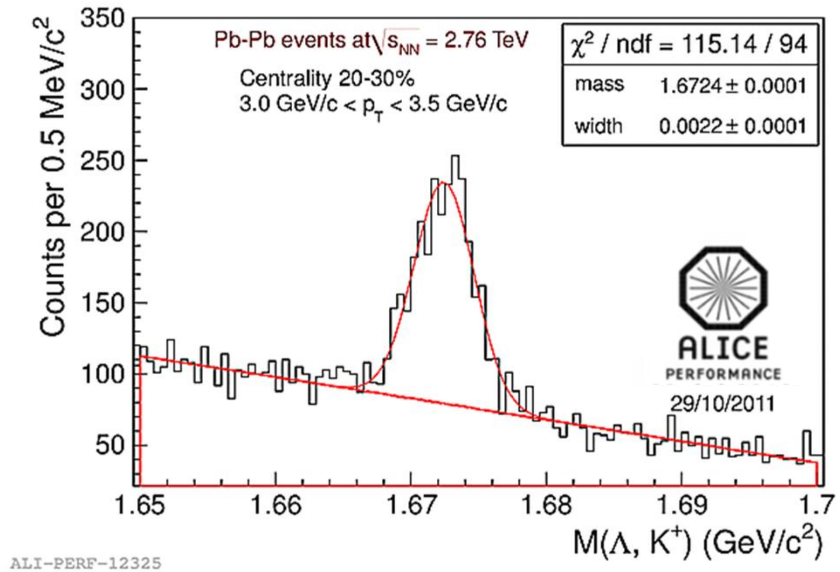
Topolgical cuts were applied:

Å Secondary vertex

Å Decay kinematics

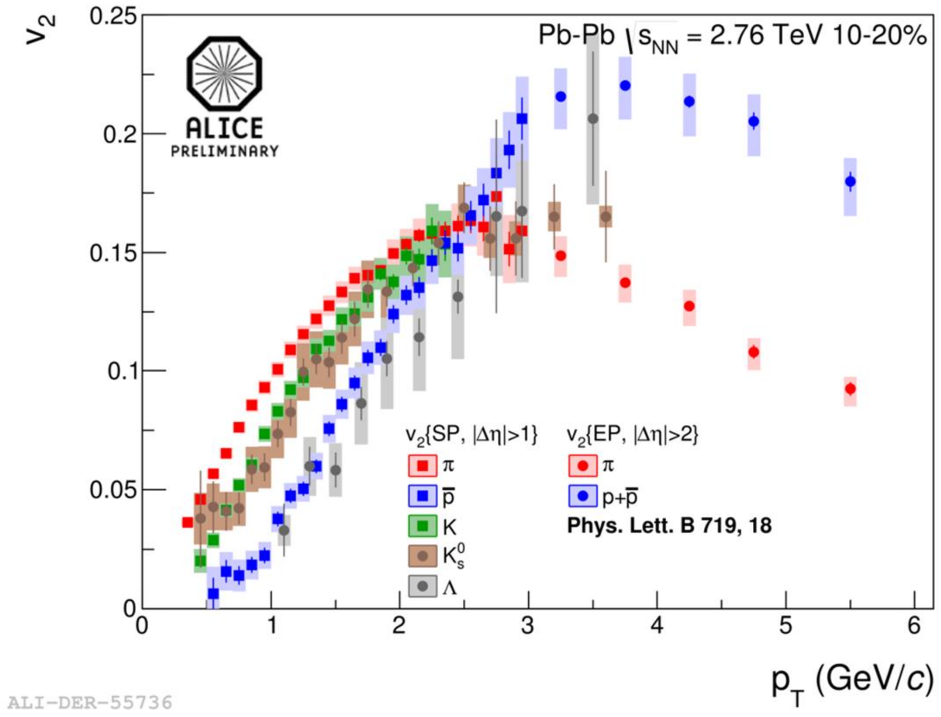


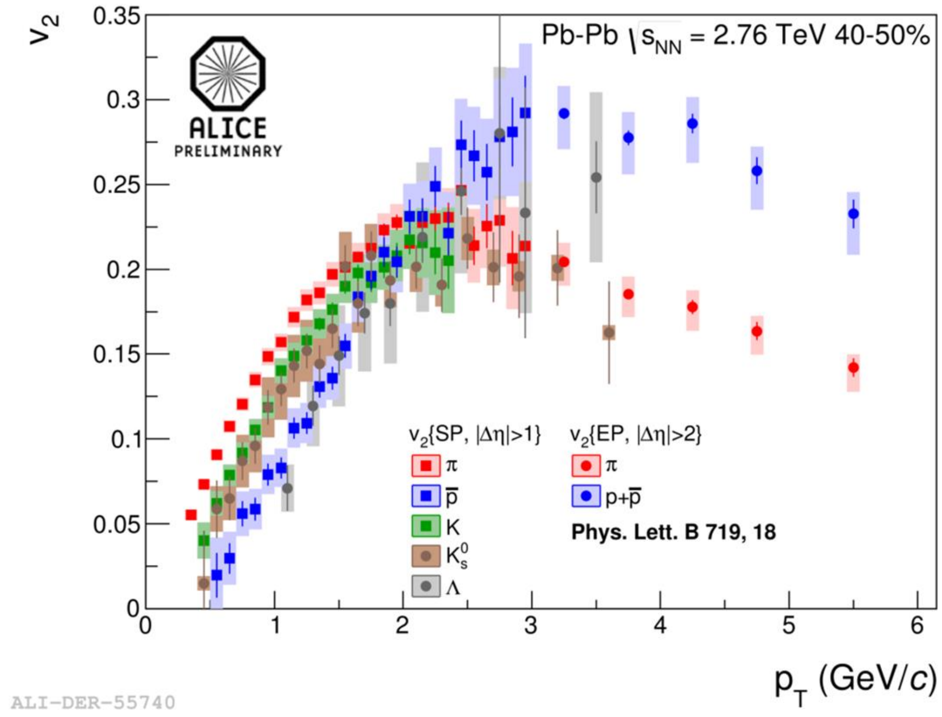




Elliptic flow of identified particles

ALICE compilation for v_2

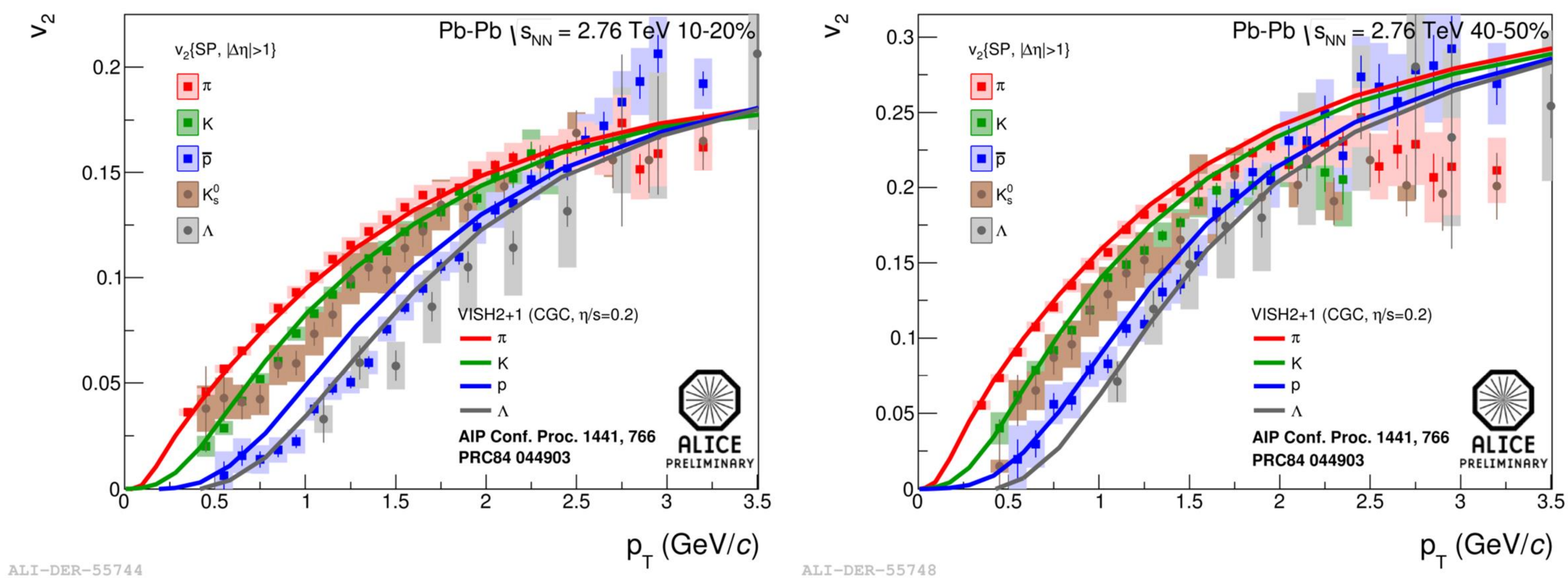




Collection of ALICE v_2 for π, $K^{\pm}$, p, K^0_s, Λ:

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



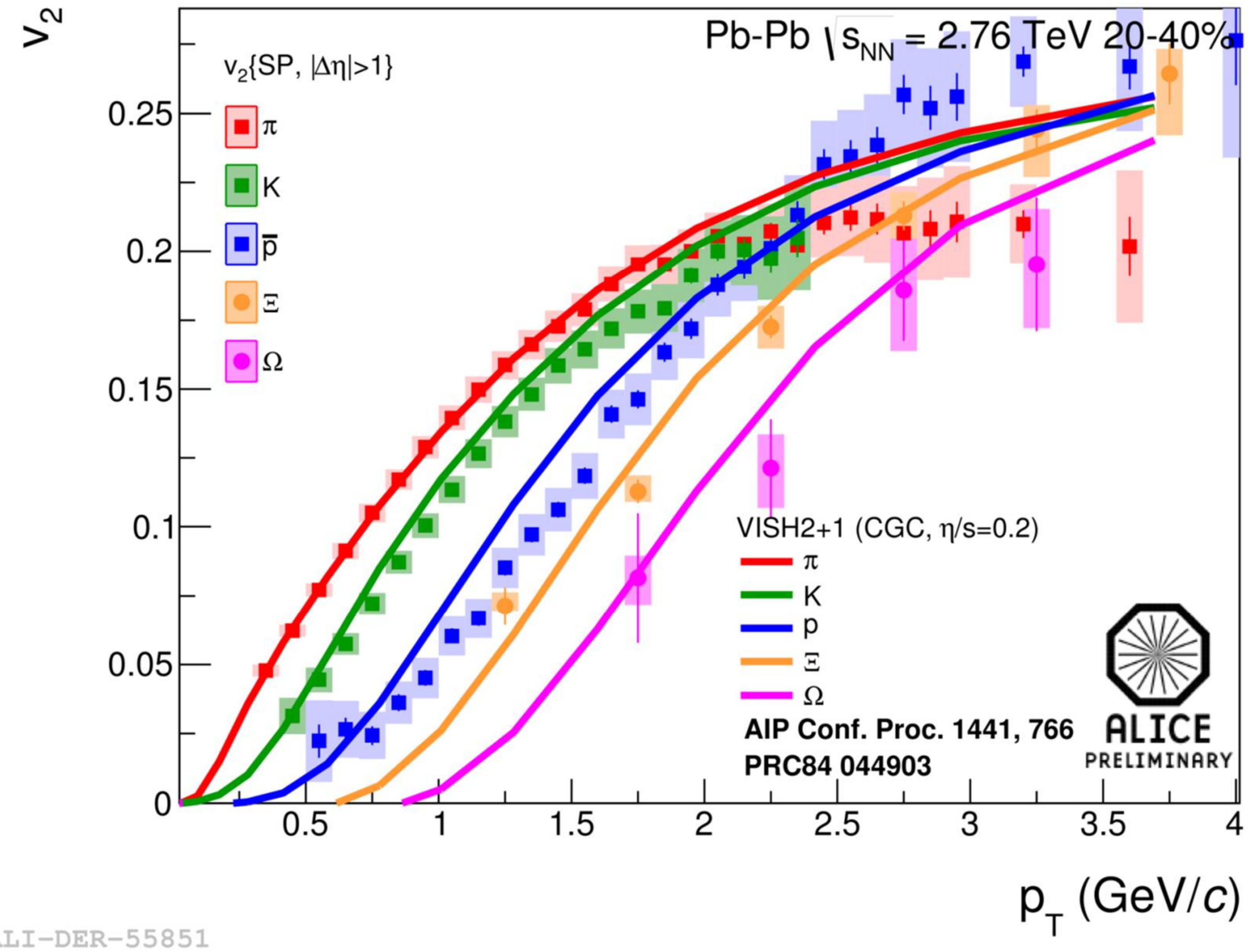
Hydro → U. W. Heinz, C. Shen, and H. Song, **AIP Conf. Proc. 1441**, 766-770 (2012)

Hydrodynamic models predict mass splitting

Hydrodynamic curves reproduce the main features of v_2 at low p_T

- better description of the mass splitting in peripheral than in central collisions
- hadron rescattering could help to reconcile data and hydro prediction

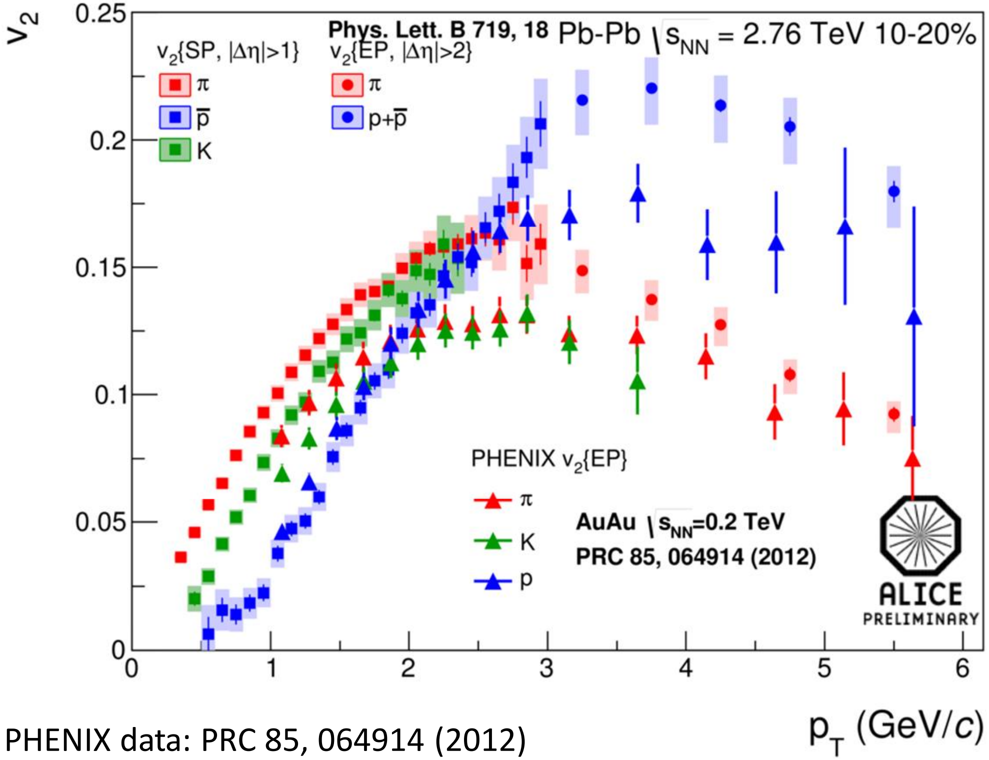
Ξ and Ω flow vs. hydro



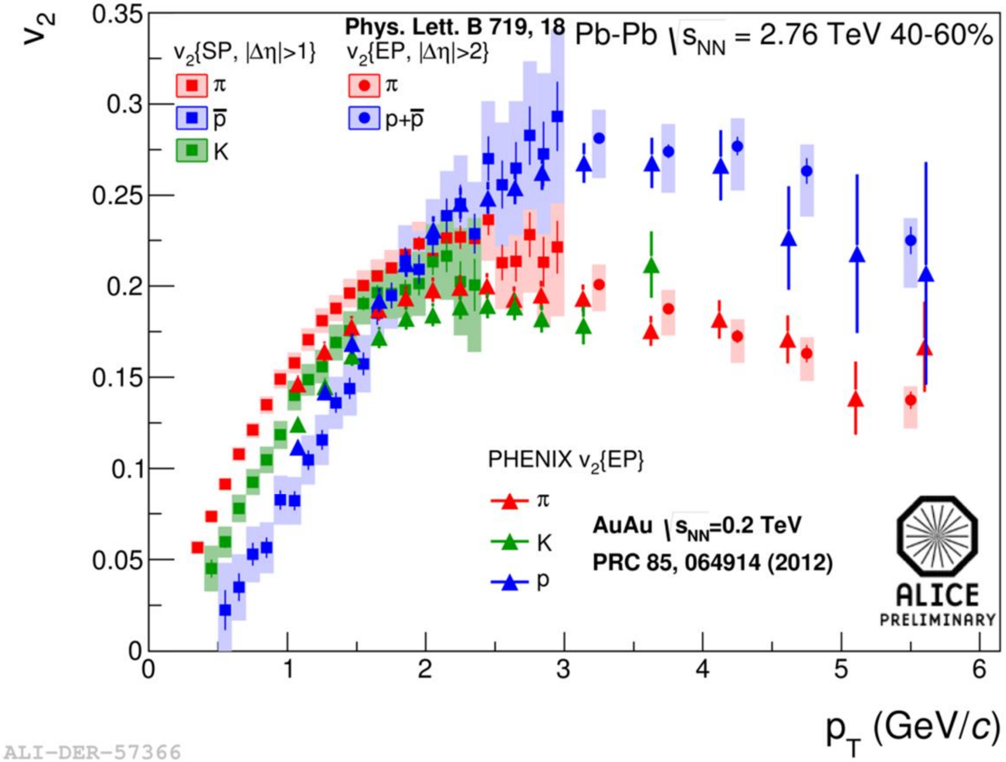
Hydrodynamic model calculations reproduce larger boost towards higher p_T for Ξ and Ω (Heinz, Shen, Song, AIP Conf. Proc. 1441, 766 (2012); PRC84 044903)

v_2 of ´ , K, p at LHC vs. RHIC

10-20%



40-60%



PHENIX data: PRC 85, 064914 (2012)

ALI-DER-57366

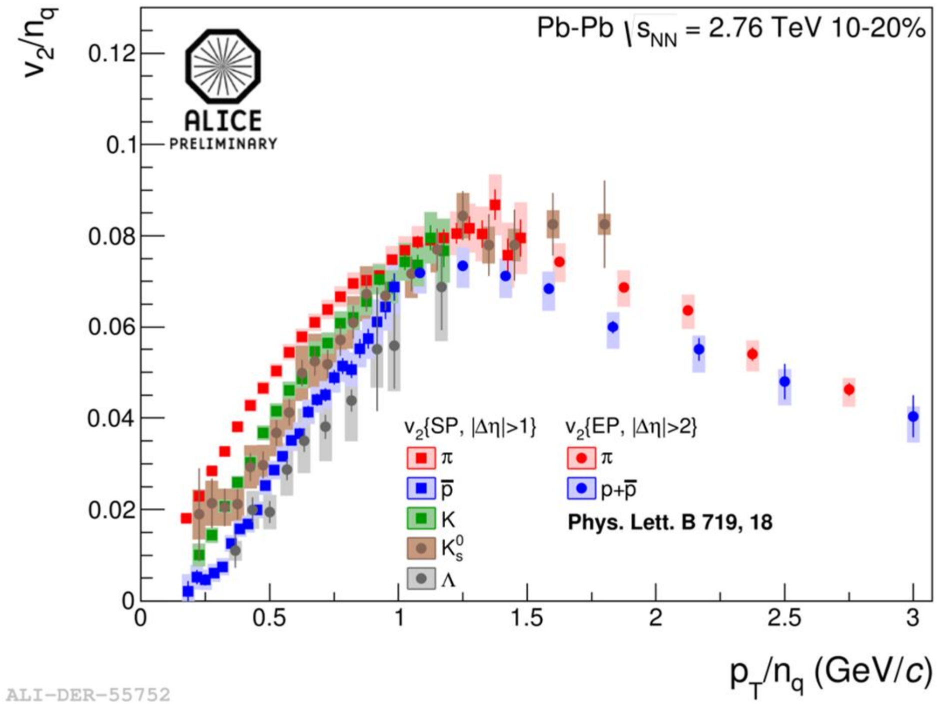
v_2 at LHC qualitatively similar to RHIC:

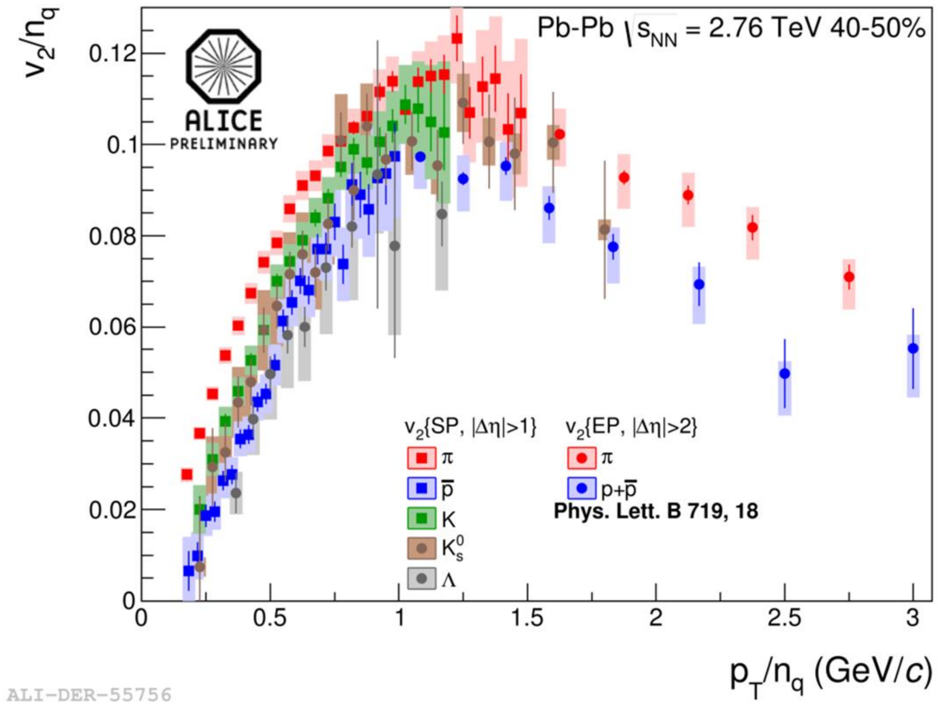
Åv_2 measured at the LHC is slightly above the RHIC v_2 for pions and kaons

Åv_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 p_T/n_q

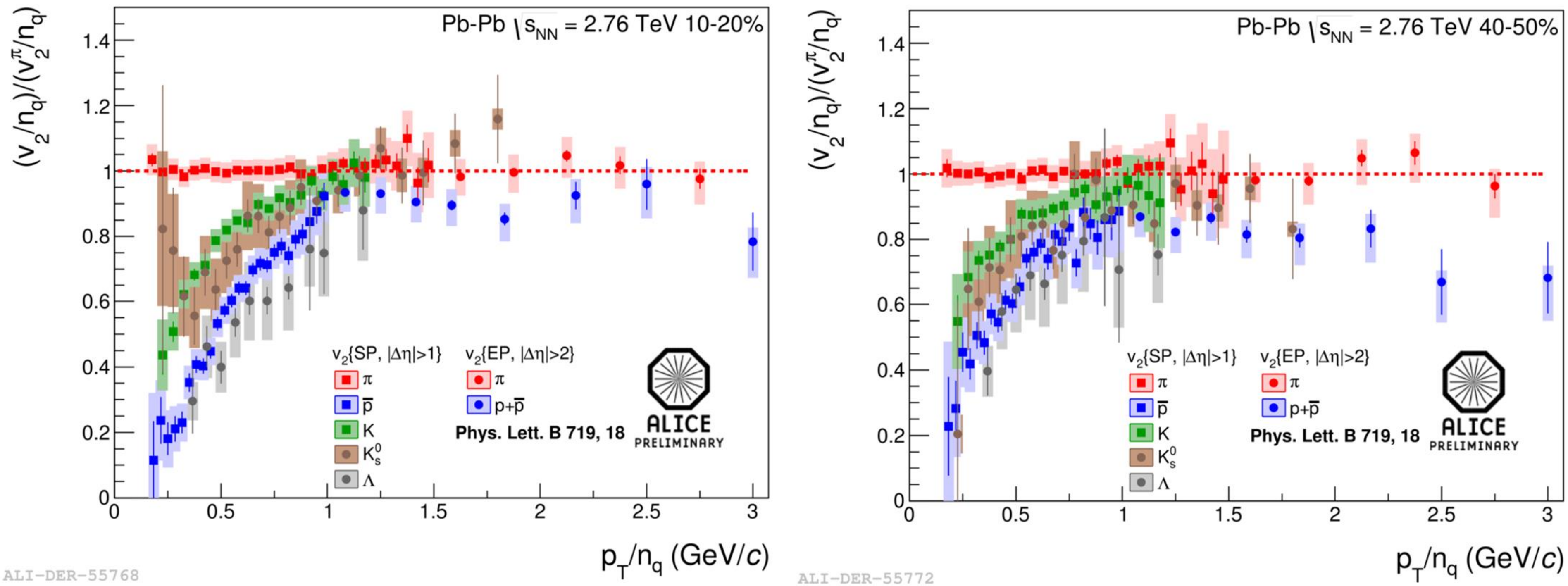




p_T/n_q (n_q=2 for mesons, n_q=3 for baryons) scaling:

Å$v_2(p_T)$ 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. π)

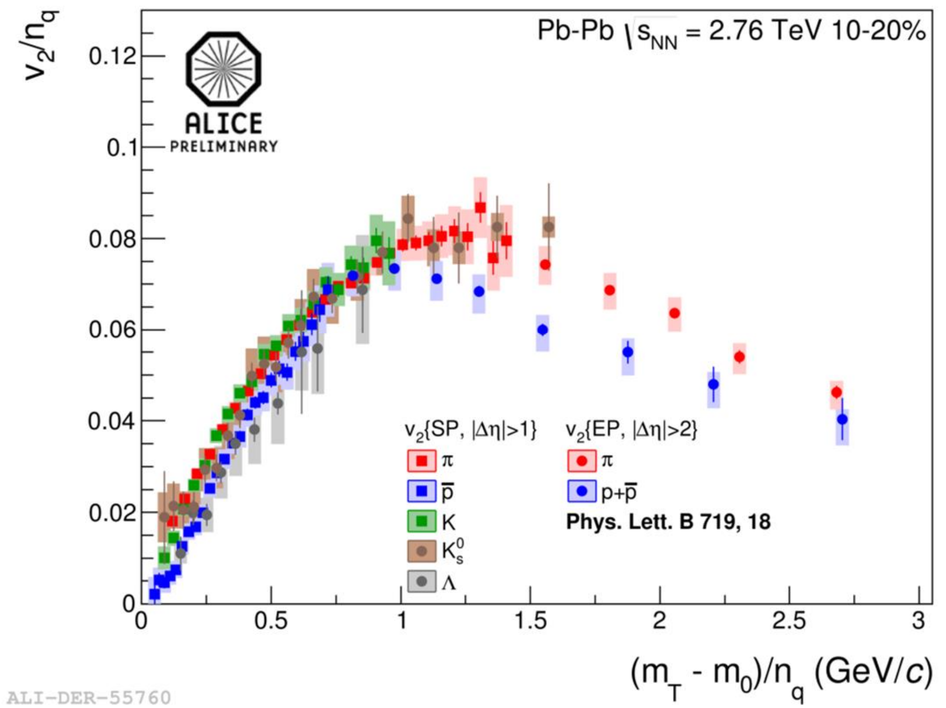


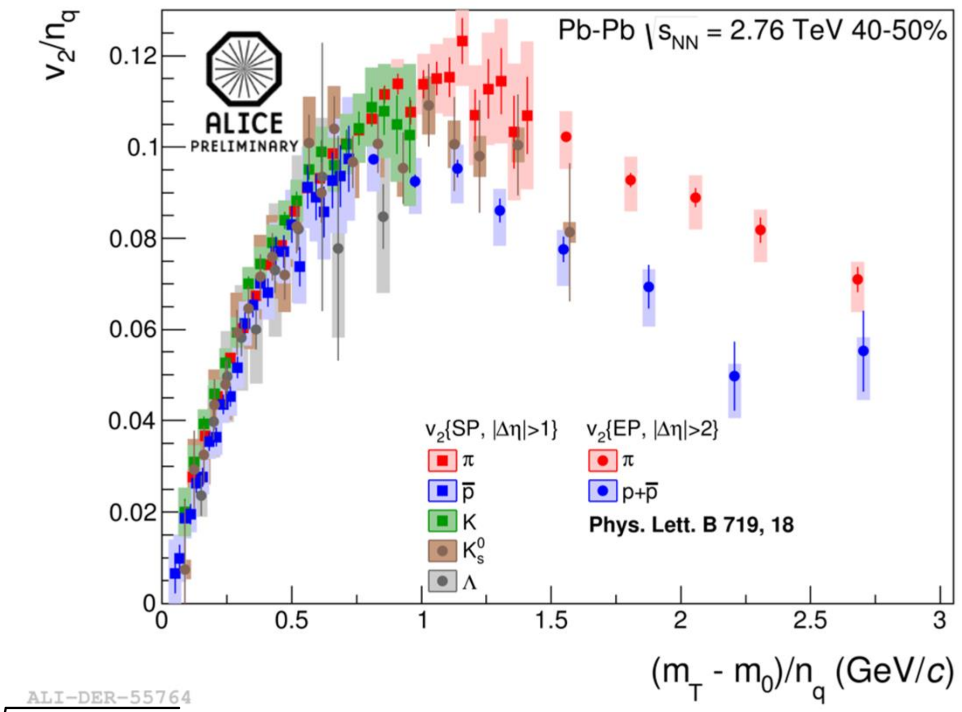
p_T/n_q (n_q=2 for mesons, n_q=3 for baryons) scaling:

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

Åv_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





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

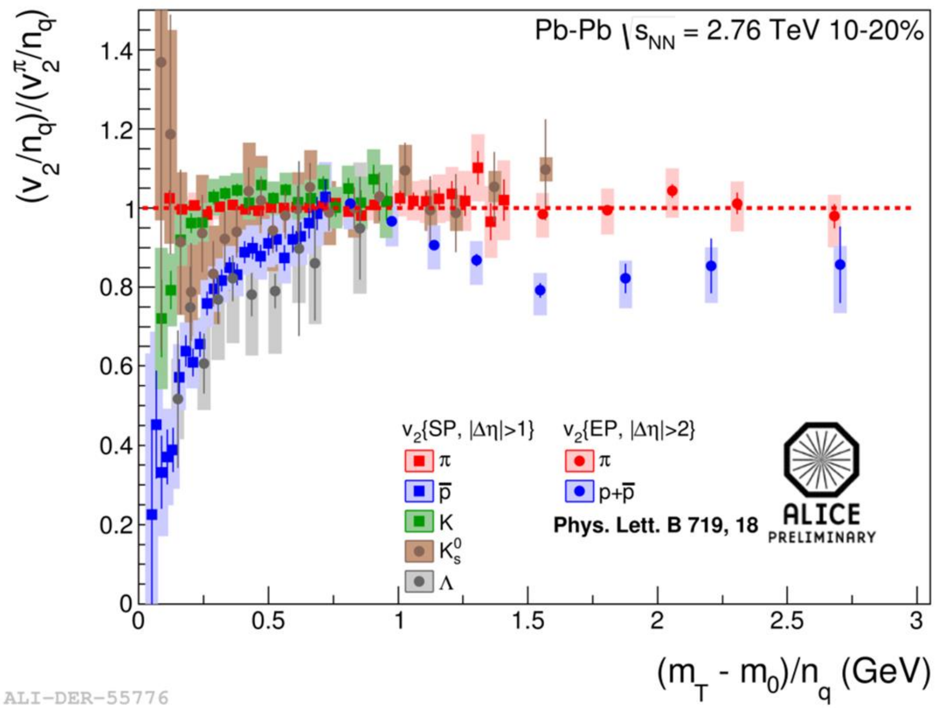
KE_T = Transverse Kinetic Energy = $m_T - m_0$

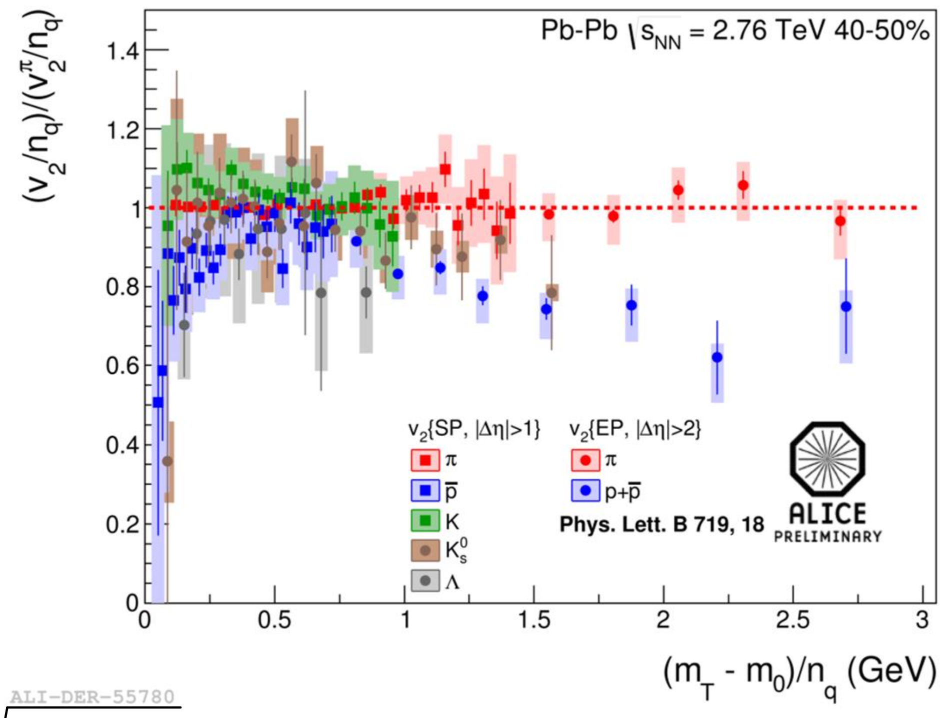
KE_T/n_q scaling:

- 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. π)





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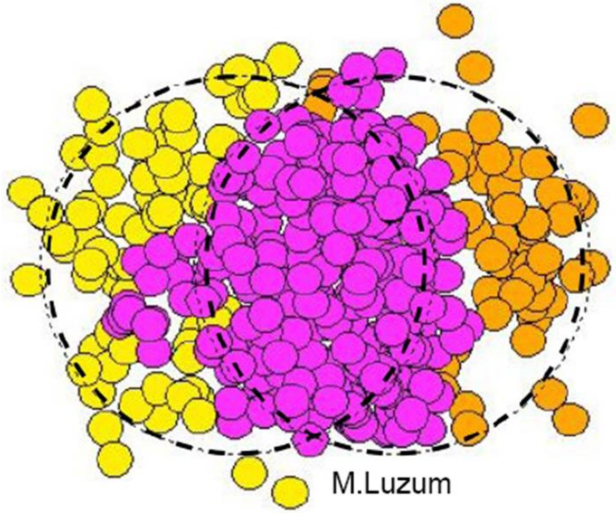
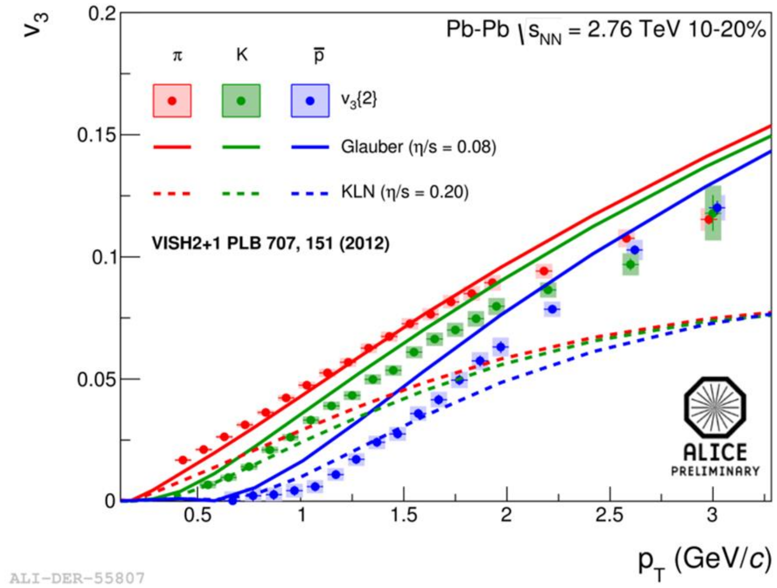
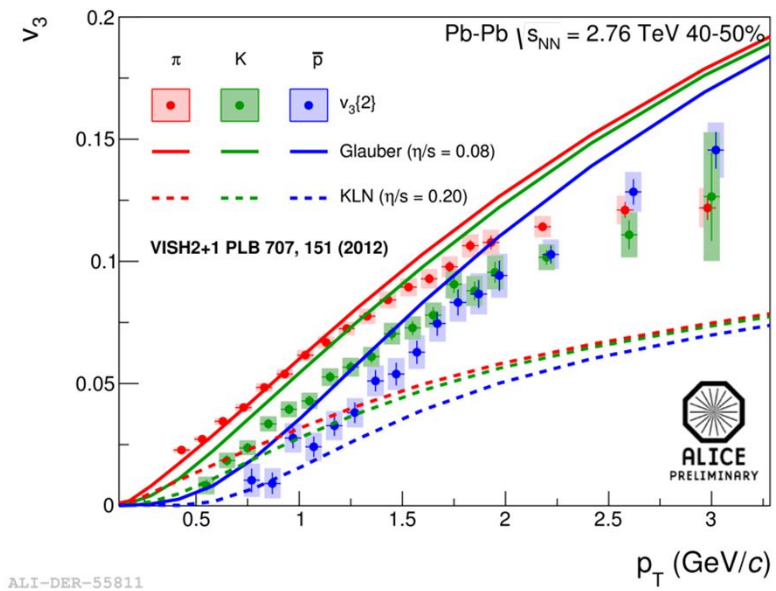
Identified particle triangular flow

Triangular flow







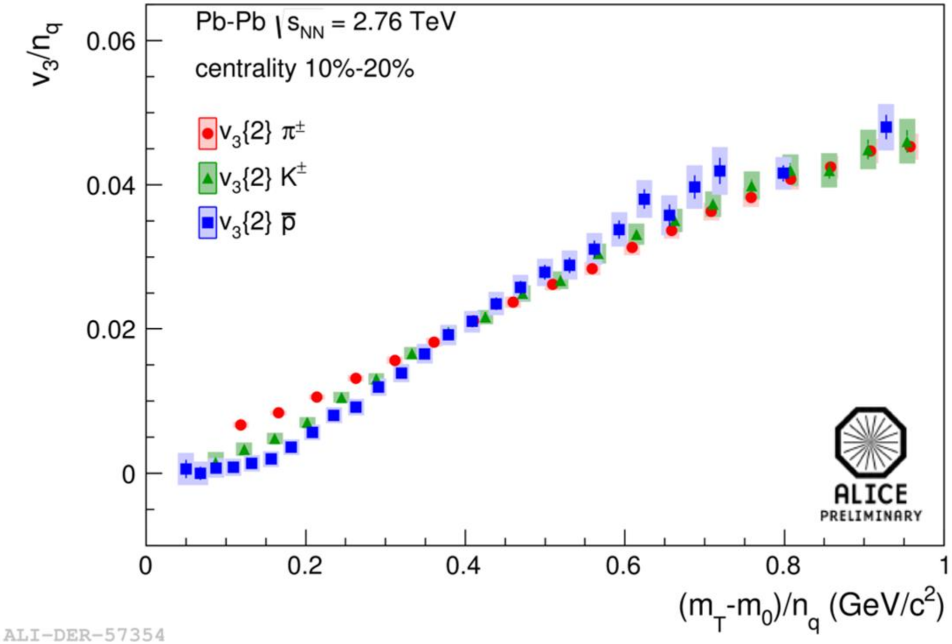
Åv_3 exhibits similar particle mass dependence as that of v_2

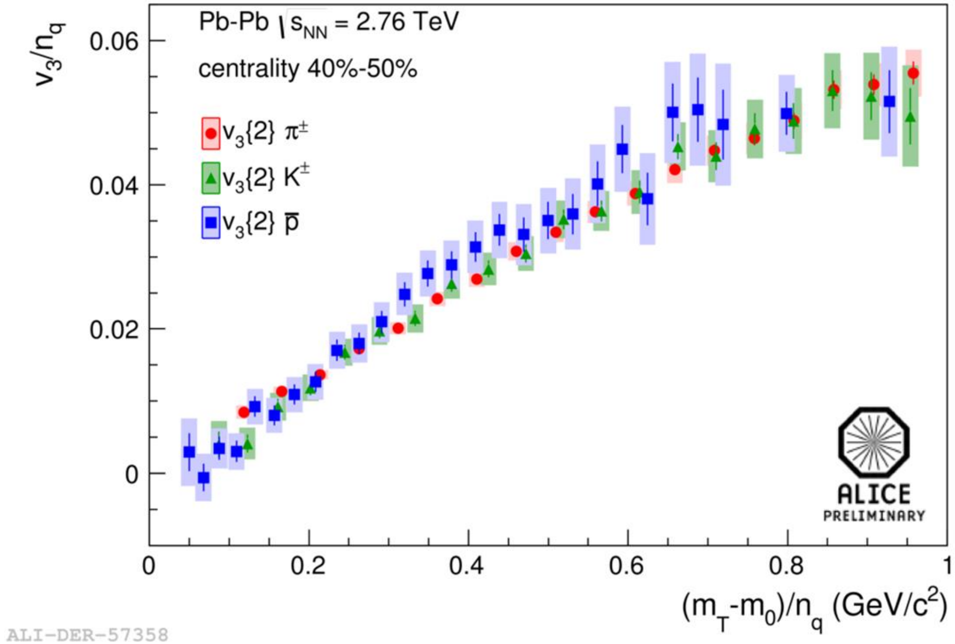
ÅThe value of p_T at which v_3 of all species cross looks similar to that for v_2

Åv_3 is quite sensitive to the input in the hydro models

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

Triangular flow (NCQ)



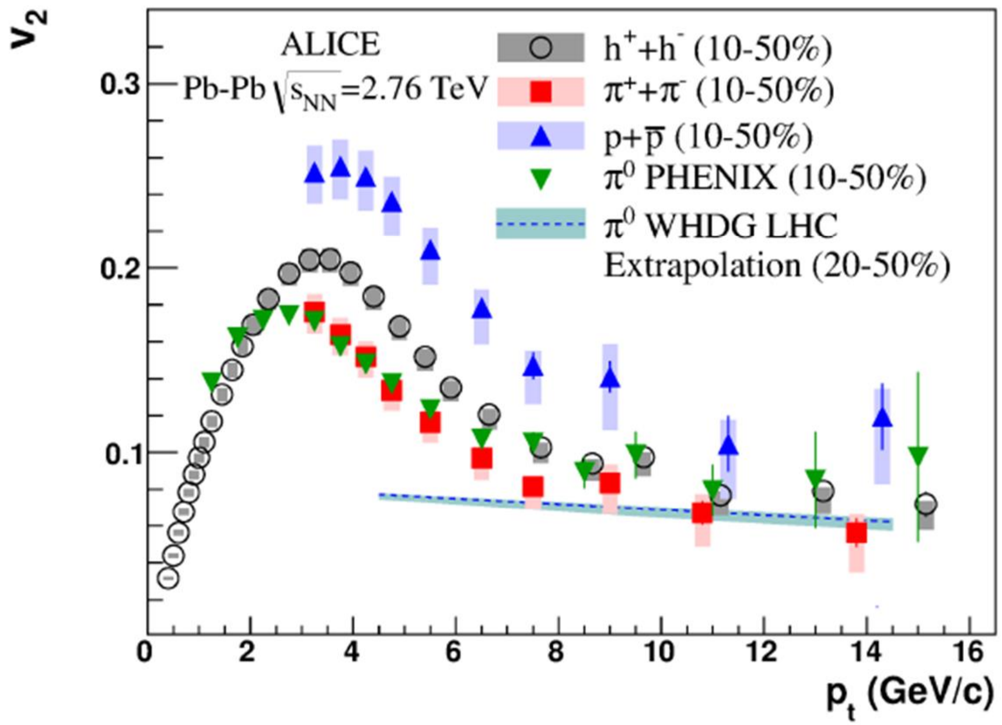


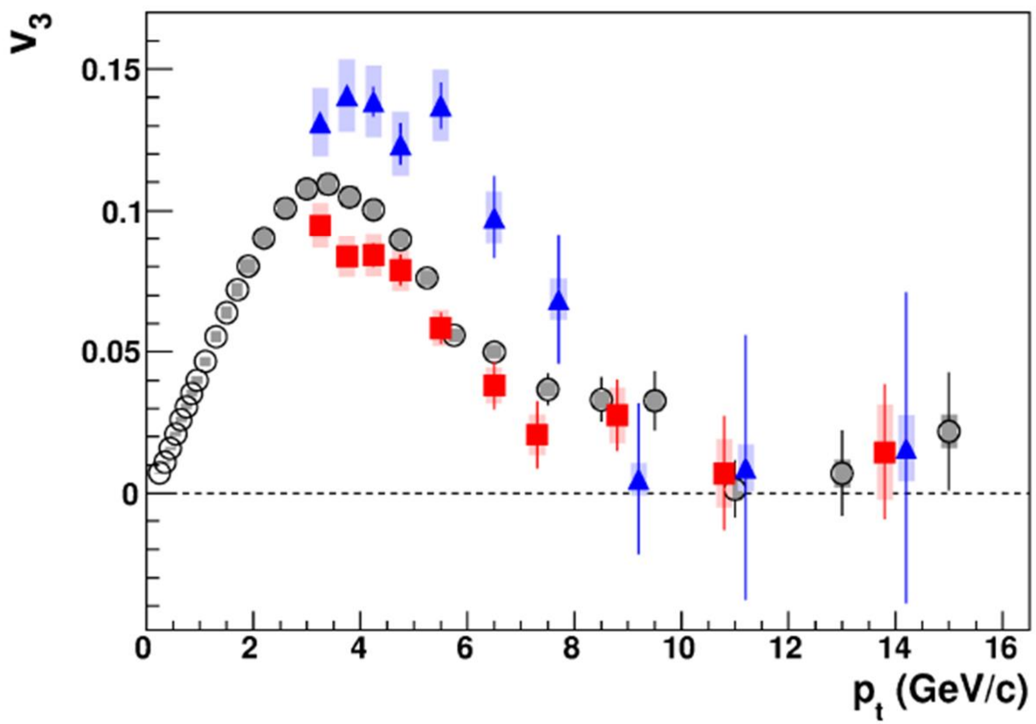
v_3 scales better with the number of constituent quarks w.r.t. v_2 (is it still broken in the most central collisions?).

Triangular flow

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

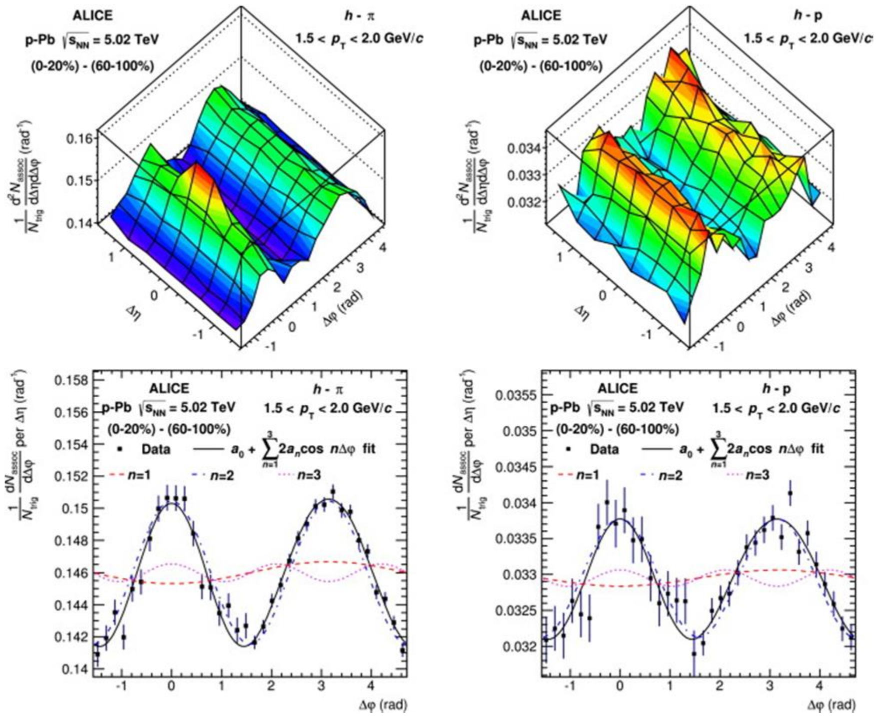
10-50%



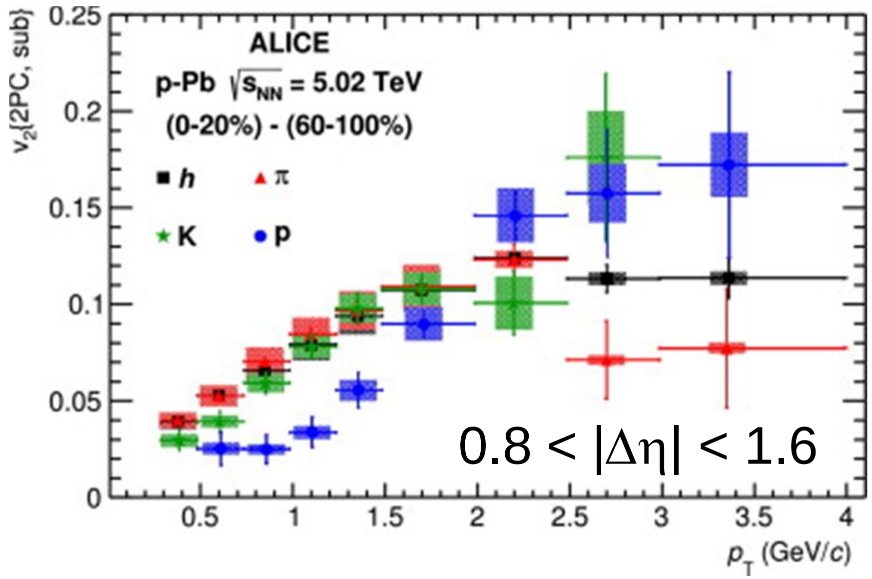


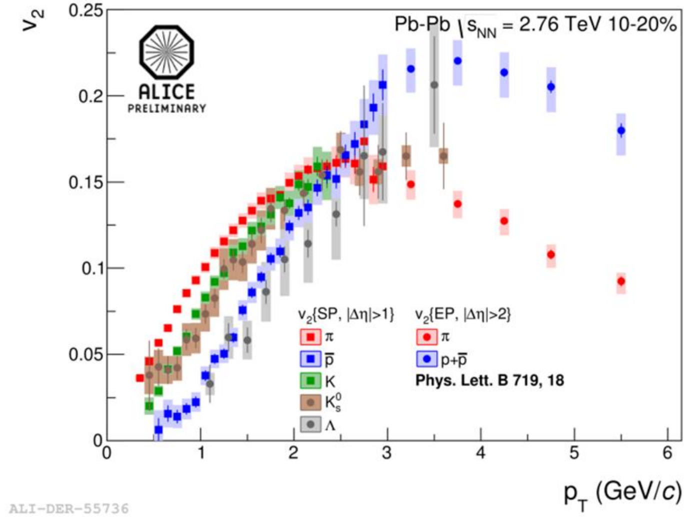
1. up to $p_T \sim 8$ GeV/*c*, proton v_2 and v_3 is larger than that of pion
2. pion/proton v_2 at high transverse momenta ($p_T > 10$ GeV/*c*) is significant and non zero, while within experimental uncertainties v_3 is consistent with zero
3. Charged pion v_2 reproduced by WHDG ´ ^{0} predictions for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

v_2 in p-Pb



Physics Letters B 726 (2013) 164ï 177





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

ÅCrossing between proton and pion v_2 at p_T ~2 GeV/*c*

ÅObserve mass ordering at low p_T

Does it flow?

Summary

Elliptic flow of ´ , K, p, Λ, Ξ, Ω 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 broken at low p_T, while it is only approximate (within 20%) at intermediate p_T
4. Proton v_2 and v_3 is higher than that of the pion out to at least p_T=8 GeV/*c*
   - Particle type dependence persists out to high p_T
5. v_3 of ´ , K, and p/$\bar{p}$ has a similar mass dependence and crossing point as that of v_2

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