



# Flow of identified particles

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LHCb 2015, Saint-Petersburg  
(on behalf of the ALICE Collaboration)

LHCb 2015

## In this talk:

- Anisotropic flow of identified particles *vs.* transverse momentum
- Scaling properties of  $v_2$  and  $v_3$  with number of quarks
- Flow in p-Pb?

## Focus on LHC results (ALICE and CMS)

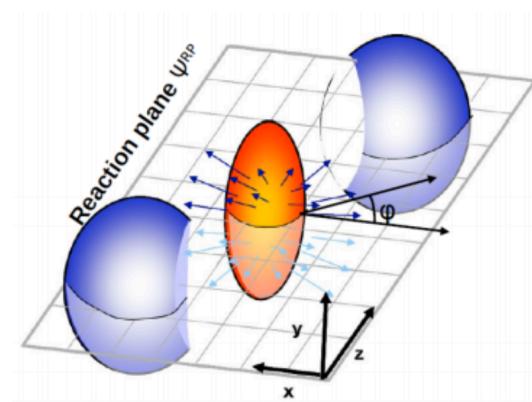
# Motivation

Anisotropic flow is a response of the system created in a heavy-ion collision to the anisotropies in the **initial geometry** and **multiple interactions** in the created medium.

Angular distribution of reconstructed charged particles can be expanded into a Fourier series w.r.t. reaction plane  $\Psi_R$ :

$$\frac{dN}{d\varphi} \sim 1 + 2 \sum_{n=1}^{\infty} v_n \cos n(\varphi - \Psi_R) = 1 + 2v_1 \cos(\varphi - \Psi_1) + 2v_2 \cos 2(\varphi - \Psi_2) + 2v_3 \cos 3(\varphi - \Psi_3) + \dots$$

$v_2$  – elliptic flow,  $v_3$  – triangular flow,  $v_4, v_5, \dots$



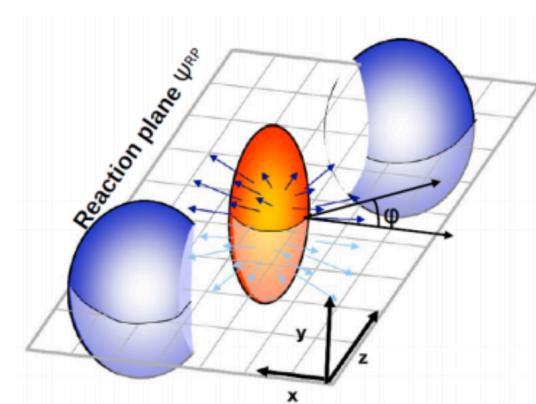
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Anisotropic flow of **identified particles** is sensitive to the partonic degrees of freedom at the early times of a heavy-ion collision.

$v_n(p_T)$  allows quantification of:

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  $p_T$ )

# Elliptic flow of identified hadrons at ALICE\*

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

$\pi$ , K, p,  $K^0_s$ ,  $\Lambda$ ,  $\Xi$ ,  $\Omega$ ,  $\phi$

*\*based on ALICE paper  
JHEP 06 (2015) 190  
(arXiv:1405.4632)*



# ALICE experimental setup

## Inner Tracking System (ITS)

( $-0.9 < \eta < 0.9$ )

Tracking + triggering

## Time Projection Chamber (TPC)

( $-0.8 < \eta < 0.8$ )

Tracking + particle identification (PID)

## Time Of Flight (TOF)

( $-0.8 < \eta < 0.8$ )

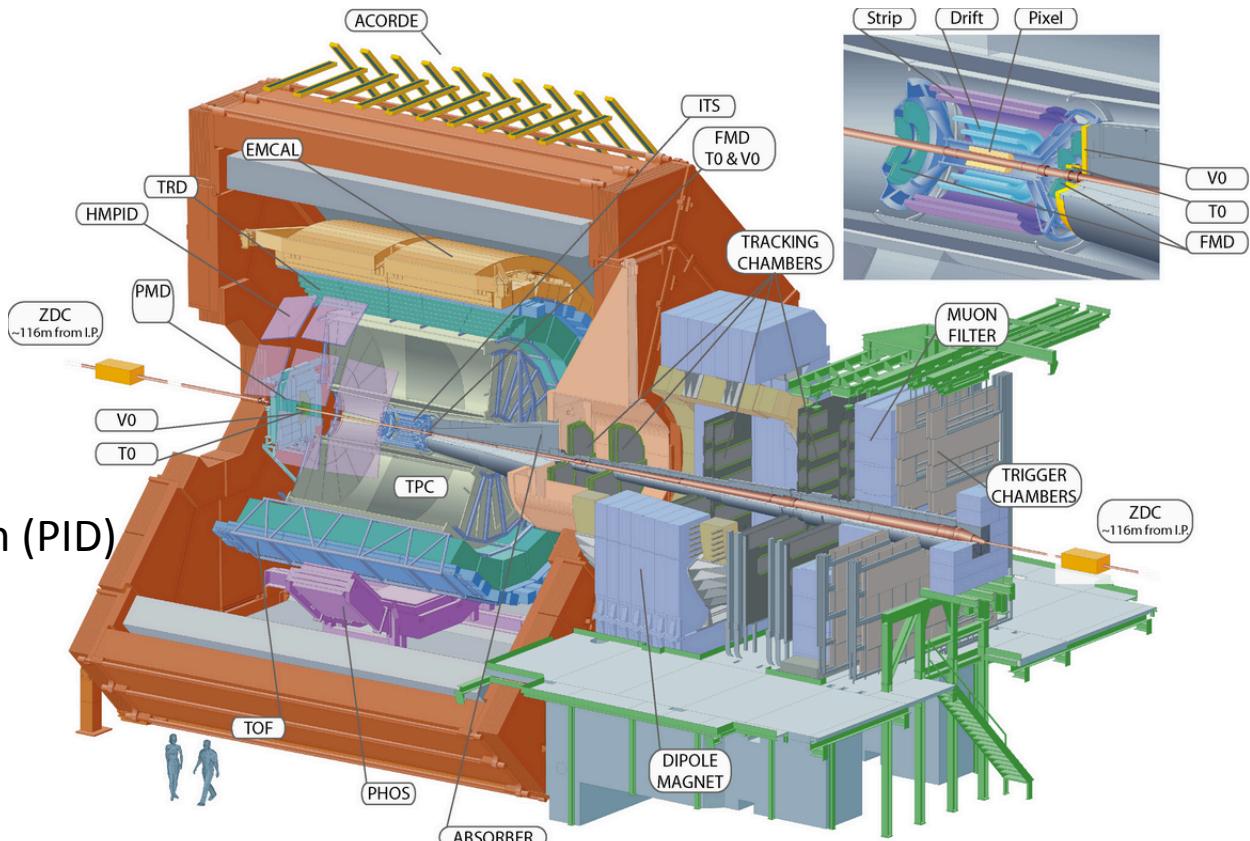
PID

## VZERO detector

Two forward scintillator arrays

( $-3.7 < \eta < -1.7, 2.8 < \eta < 5.1$ )

centrality + triggering



Analyzed data samples:

- 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)

# Particle Identification of $\pi$ , K, p

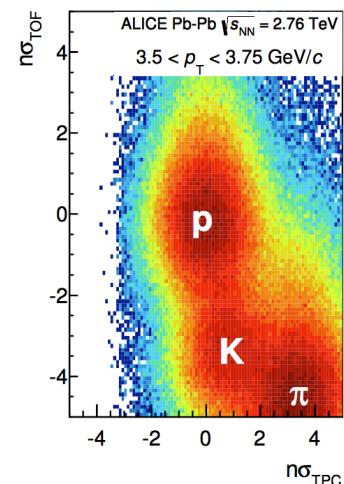
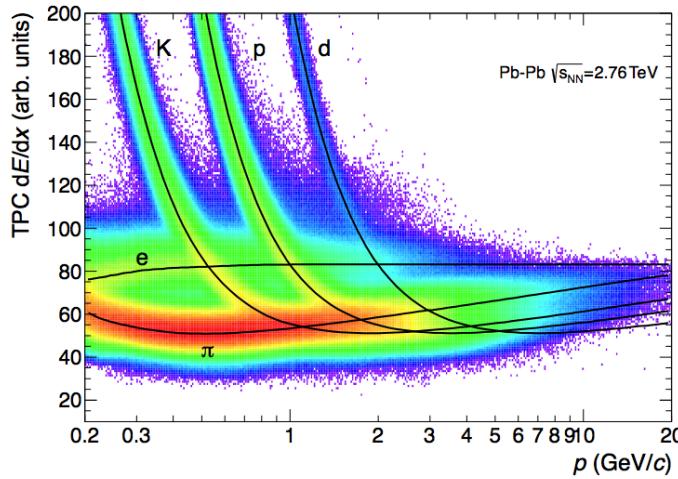
Use of **TPC & TOF** information

$p_T$  ranges:

$\pi$ :  $0.2 < p_T < 6.0 \text{ GeV}/c$

K:  $0.3 < p_T < 4.0 \text{ GeV}/c$

p:  $0.3 < p_T < 6.0 \text{ GeV}/c$



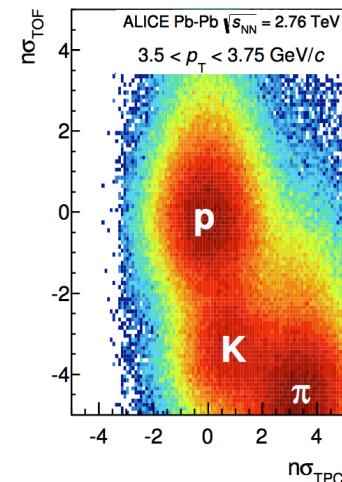
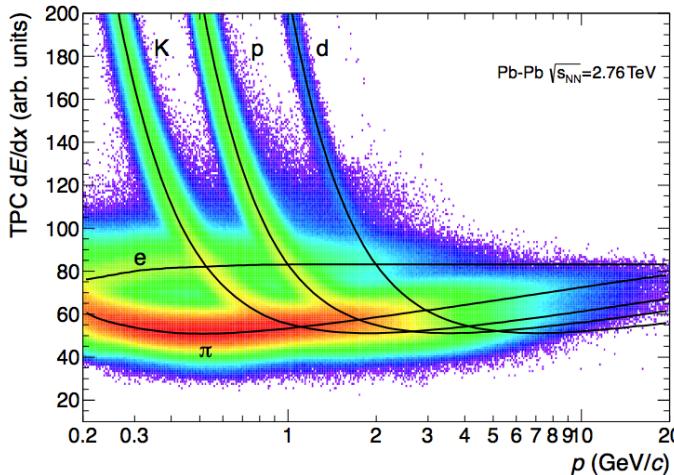
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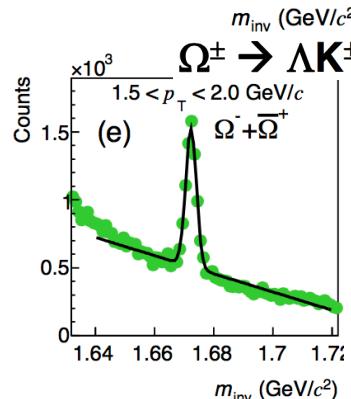
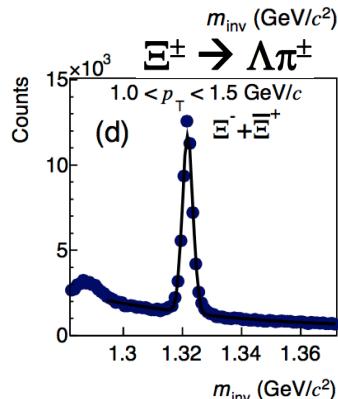
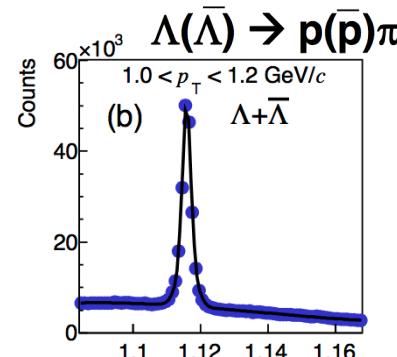
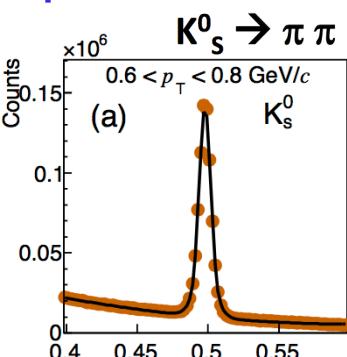


## $K^0_S$ , $\Lambda$ , $\Xi$ , $\Omega$ and $\phi$ reconstruction

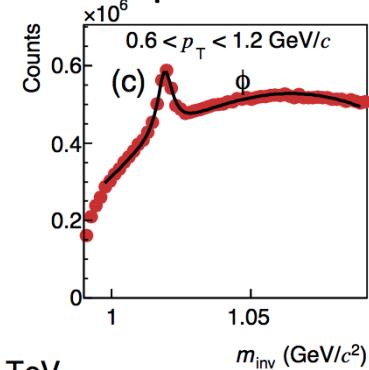
**Topological cuts:**

- Secondary vertex
- Decay kinematics

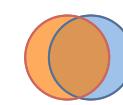
rapidity range:  
 $|y| < 0.5$



$\phi$ : by Kaon PID



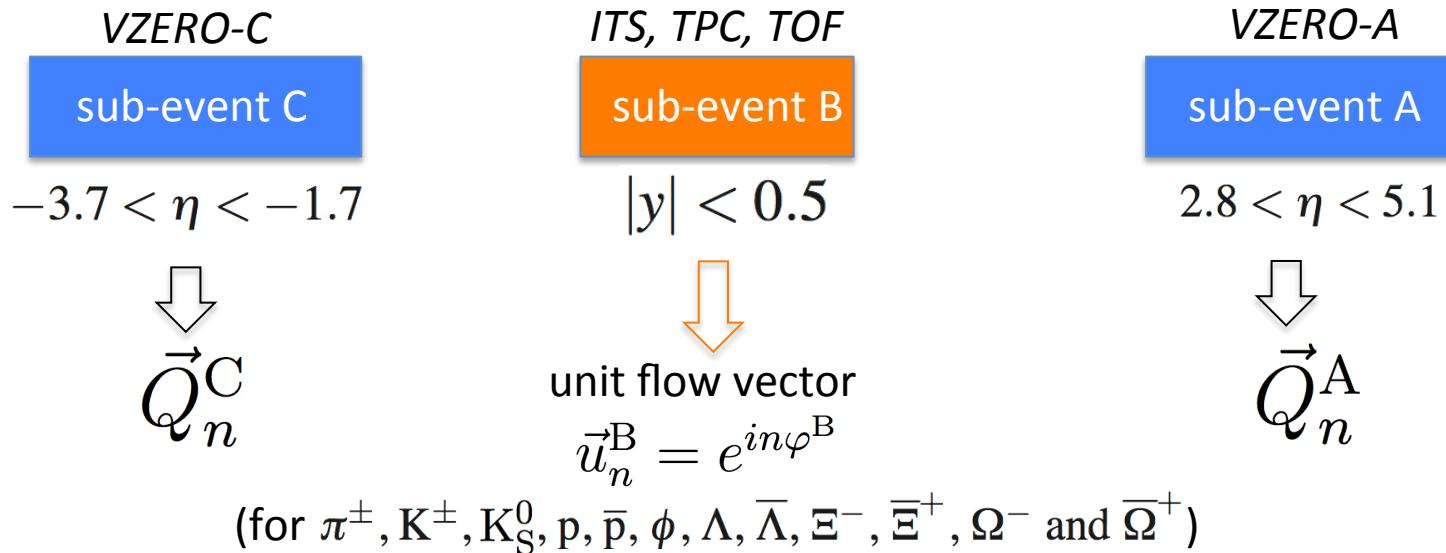
Pb-Pb  $\sqrt{s_{NN}} = 2.76 \text{ TeV}$   
Centrality 10-20%



# Extraction of $v_2$ by Scalar Product method\*

Q-vector is computed from “reference flow particles”  $\vec{Q}_n = \sum_{i \in \text{RFP}} w_i e^{in\varphi_i}$

Three sub-events A, B and C:

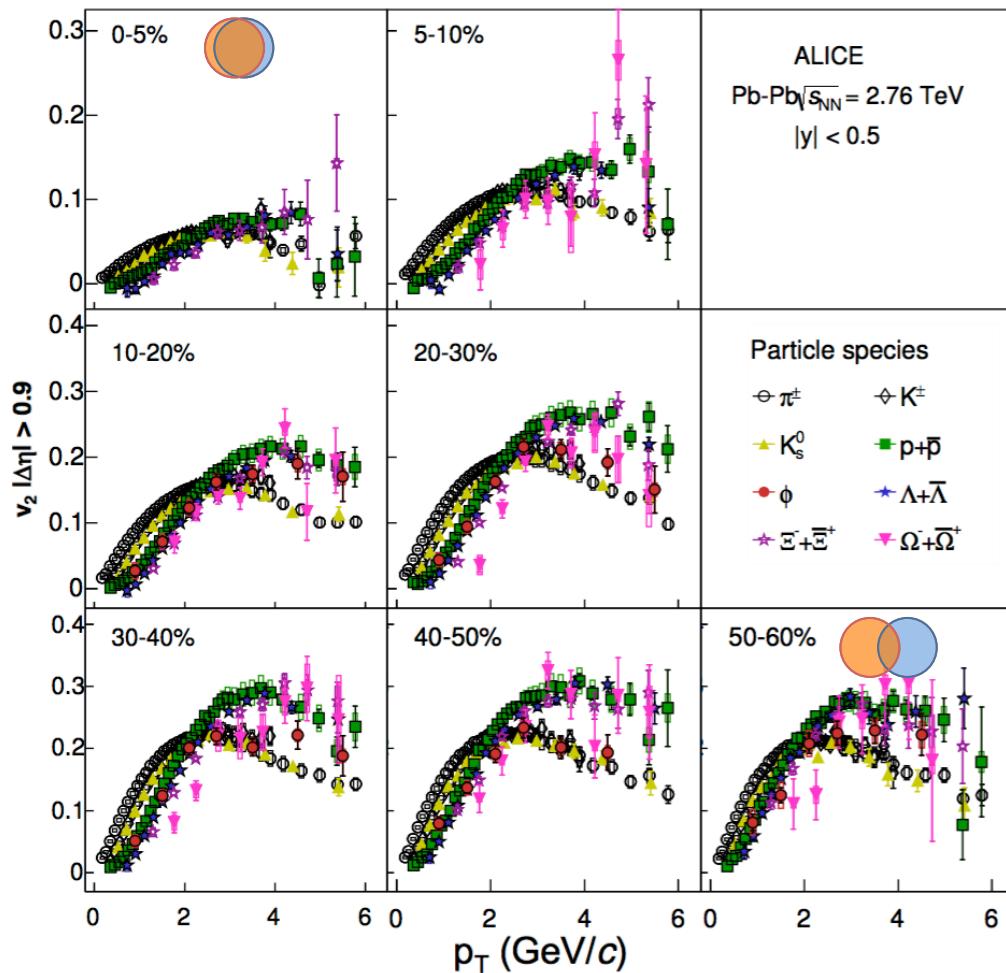


$$\nu_2 = \sqrt{\frac{\left\langle \left\langle \vec{u}_2^B \cdot \frac{\vec{Q}_2^{A*}}{M_A} \right\rangle \right\rangle \left\langle \left\langle \vec{u}_2^B \cdot \frac{\vec{Q}_2^{C*}}{M_C} \right\rangle \right\rangle}{\left\langle \frac{\vec{Q}_2^A}{M_A} \cdot \frac{\vec{Q}_2^{C*}}{M_C} \right\rangle}}$$

$$|\Delta\eta| > 0.9$$

\*S.A. Voloshin, A.M. Poskanzer and R. Snellings,  
 Collective Phenomena in Non-Central Nuclear  
 Collisions, in Relativistic Heavy Ion Physics,  
 Landolt-Bornstein series, Springer-Verlag, Berlin  
 Germany (2010), pg. 293

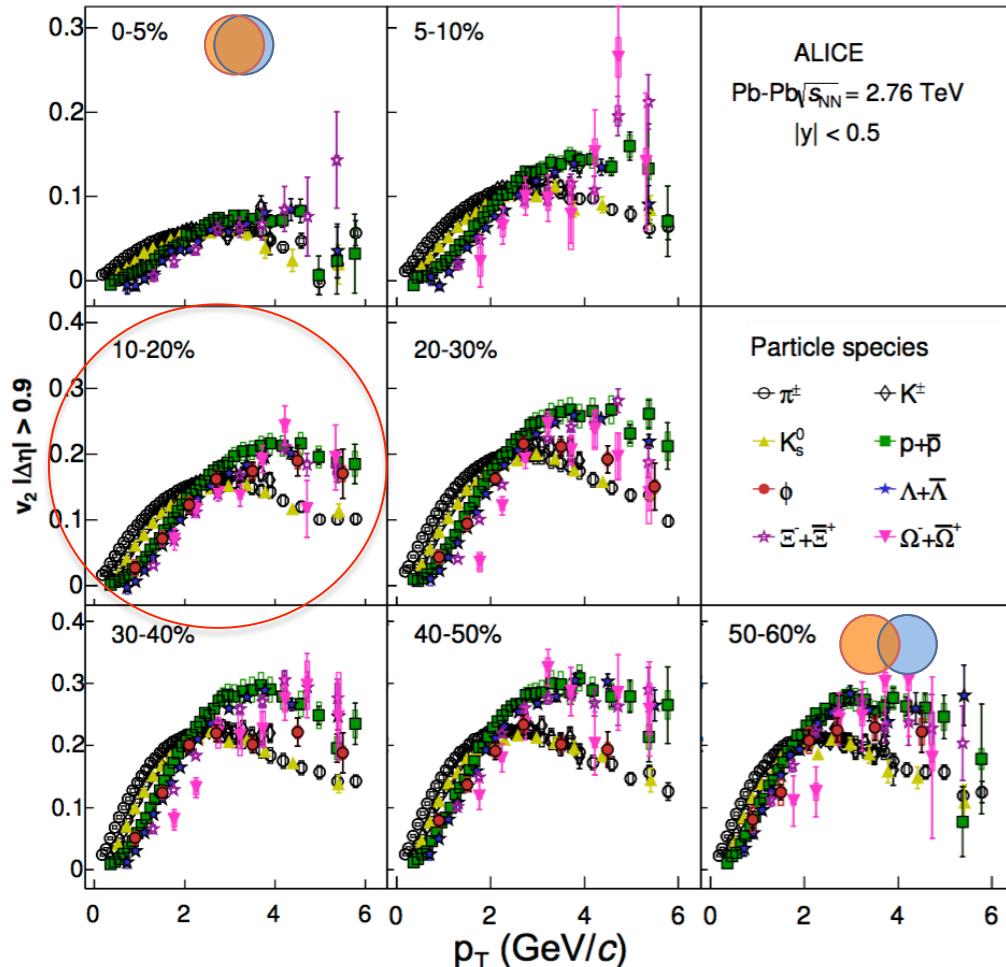
## $v_2$ in Pb-Pb for different centralities



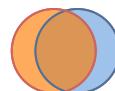
### $v_2$ for $\pi$ , $K^\pm$ , $p$ , $K_s^0$ , $\Lambda$ , $\Xi$ and $\Omega$ :

- Mass ordering observed for many species
- Stronger in most central collisions  $\rightarrow$  stronger radial flow
- Crossing between proton and pion  $v_2$  around  $p_T \sim 3$  GeV/c in the most central events
- Particle type dependence persists out to high  $p_T$

## $v_2$ in Pb-Pb for different centralities



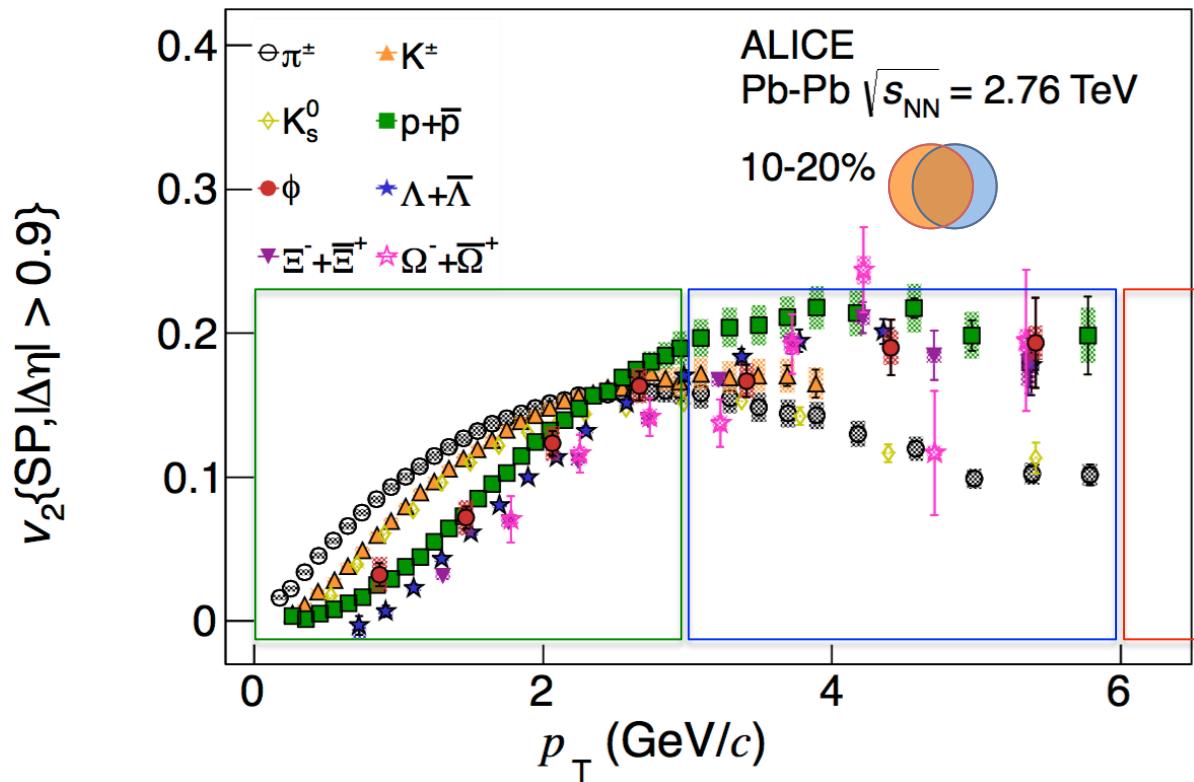
Look closer at 10-20% centrality class...



### $v_2$ for $\pi$ , $K^\pm$ , $p$ , $K_s^0$ , $\Lambda$ , $\Xi$ and $\Omega$ :

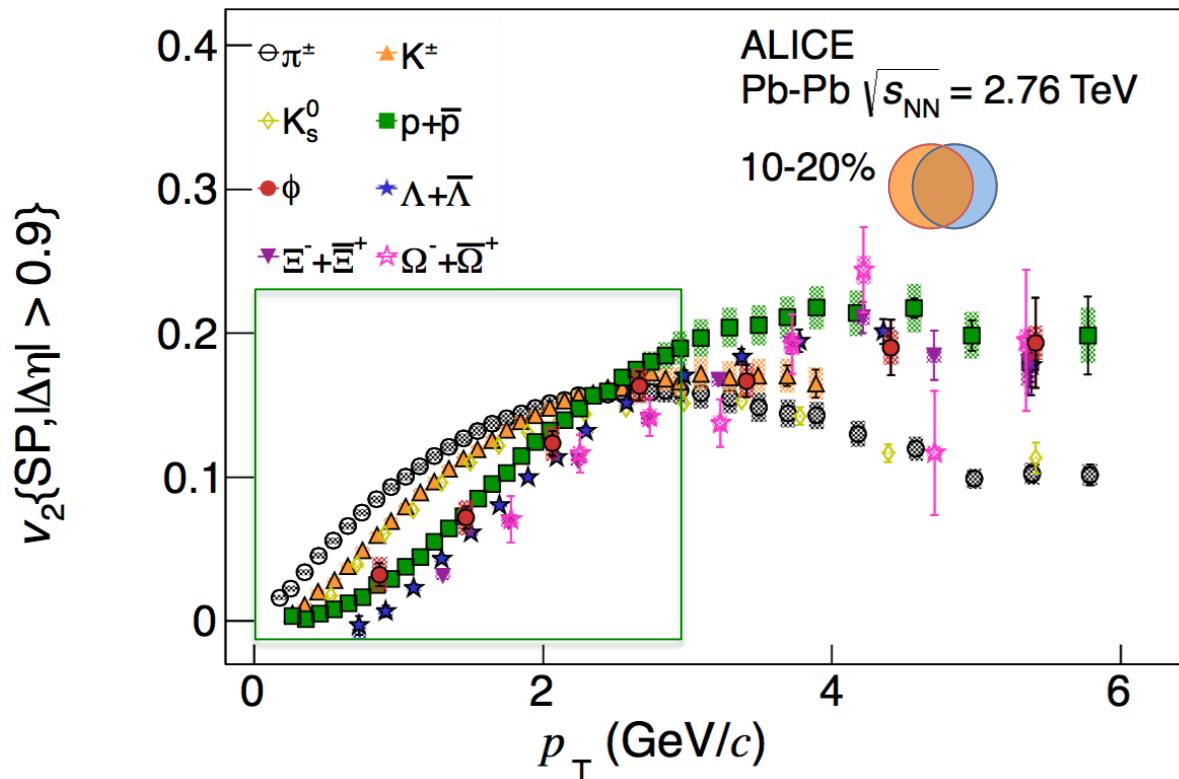
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# $v_2$ in different $p_T$ ranges

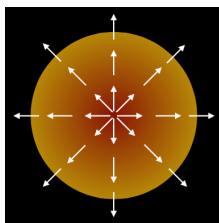


The three momentum ranges:  
 low ( $p_T < 3$  GeV/c)  
 intermediate ( $3 < p_T < 6$  GeV/c)  
 high ( $p_T > 6$  GeV/c)

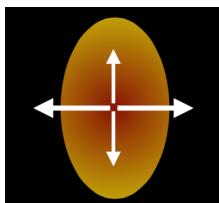
## $v_2$ at low $p_T$



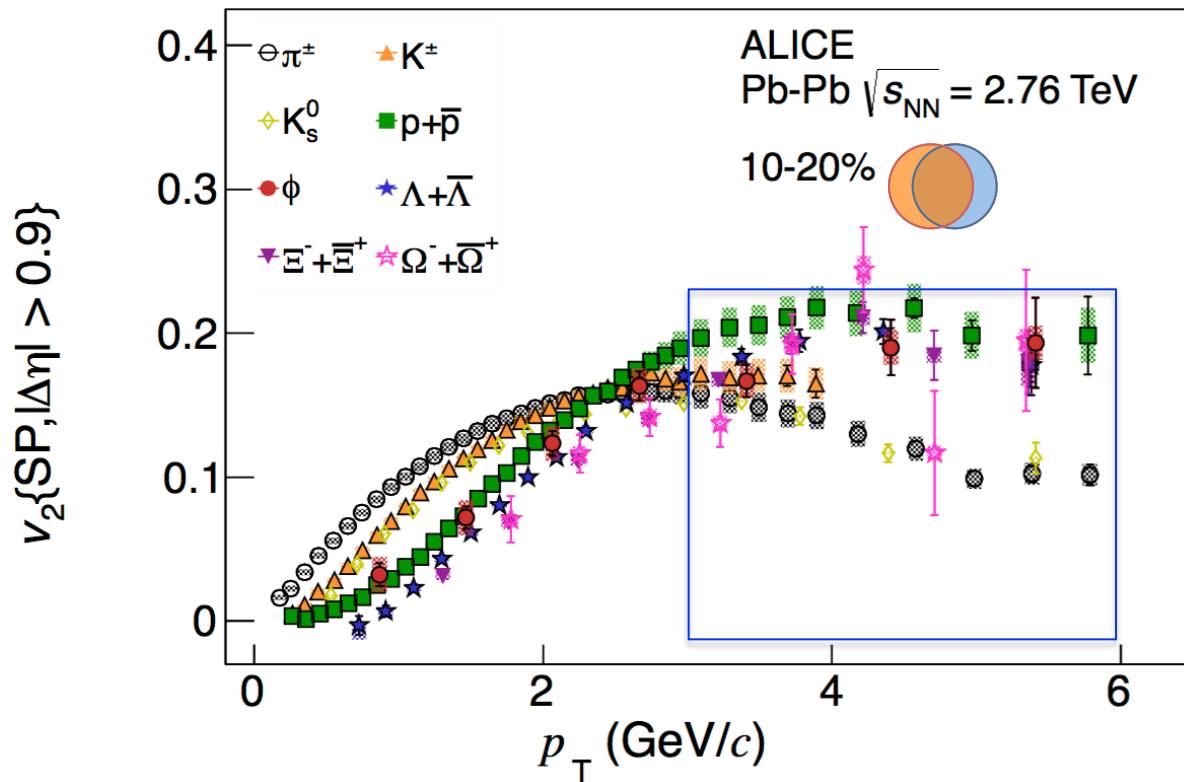
Mass ordering at low  $p_T$  ( $p_T < 3$  GeV/c): interplay between **elliptic** and **radial** flow



Radial flow pushes particles to higher  $p_T$ , heavier particles “feel” the boost more  
 $\rightarrow$  the higher the mass the larger the low  $p_T$  depletion

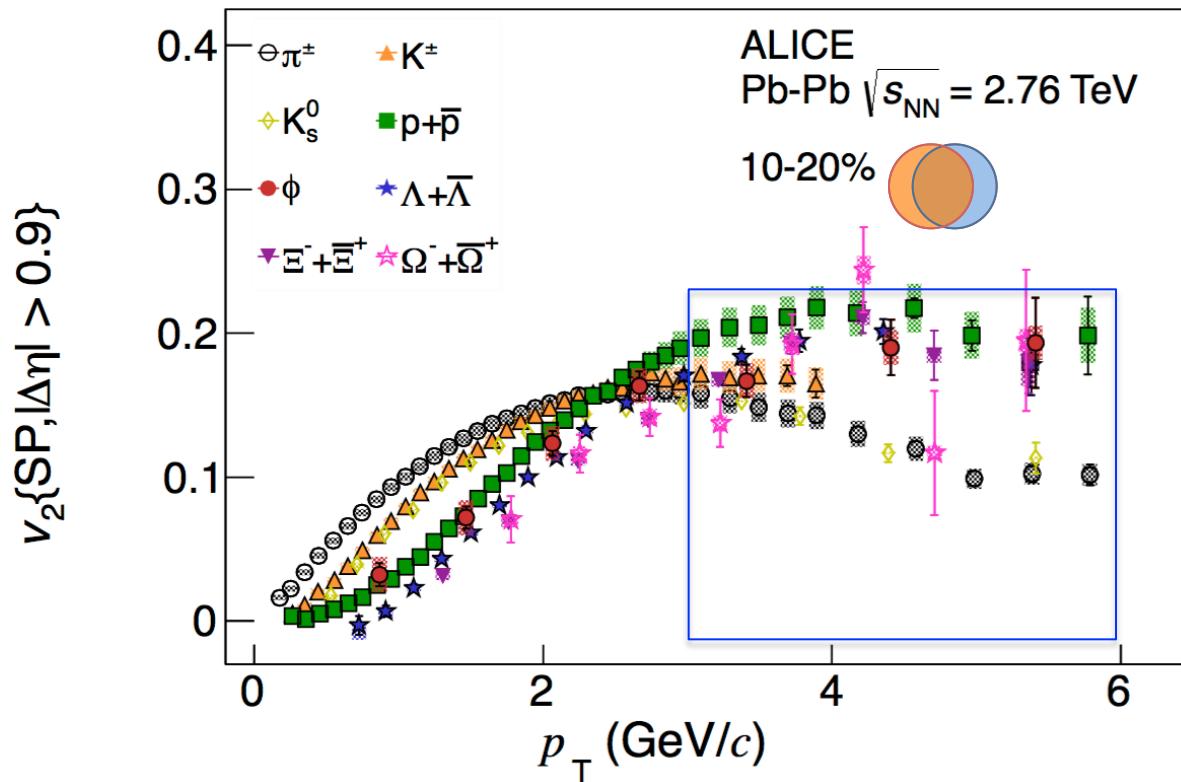


Larger “push” in-plane than out-of-plane as a function of mass  
**Larger low- $p_T$  depletion in-plane than out-of-plane**  
 $\rightarrow$  lower  $v_2$  in a mass dependent way

$v_2$  at intermediate  $p_T$ 

intermediate  $p_T$  ( $3 < p_T < 6$  GeV/ $c$ ):  
~grouping based on type  
(mesons/baryons)

# Behavior of $v_2$ for $\phi$ -meson



intermediate  $p_T$  ( $3 < p_T < 6 \text{ GeV}/c$ ):  
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(mesons/baryons)

## $\phi$ -meson:

At low  $p_T$  ( $p_T < 3 \text{ GeV}/c$ ):

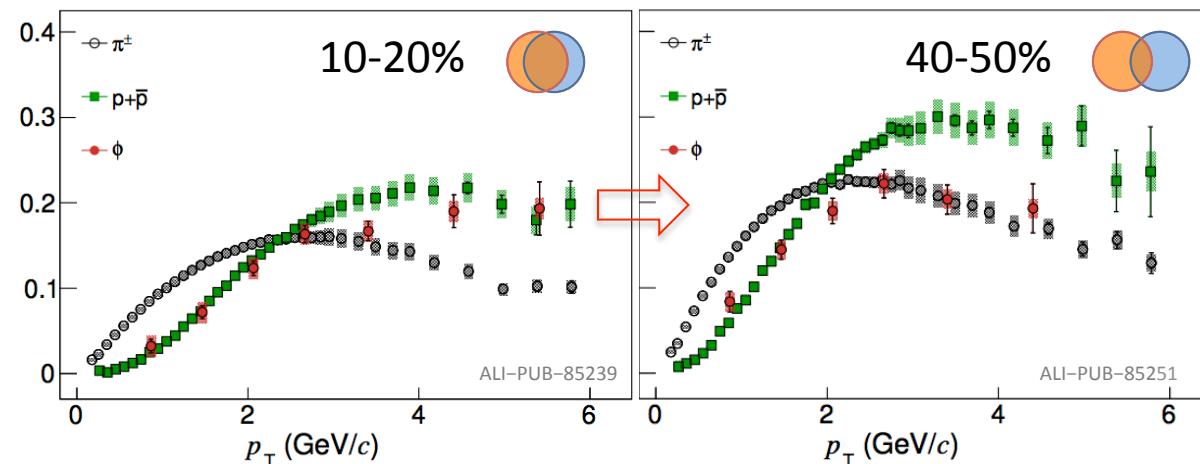
- mass ordering

At intermediate  $p_T$ :

the  $\phi$ -meson follows

- baryon band for *central* events
- meson band for *peripheral* events

Behavior of  $\phi$ -meson challenges  
the coalescence picture

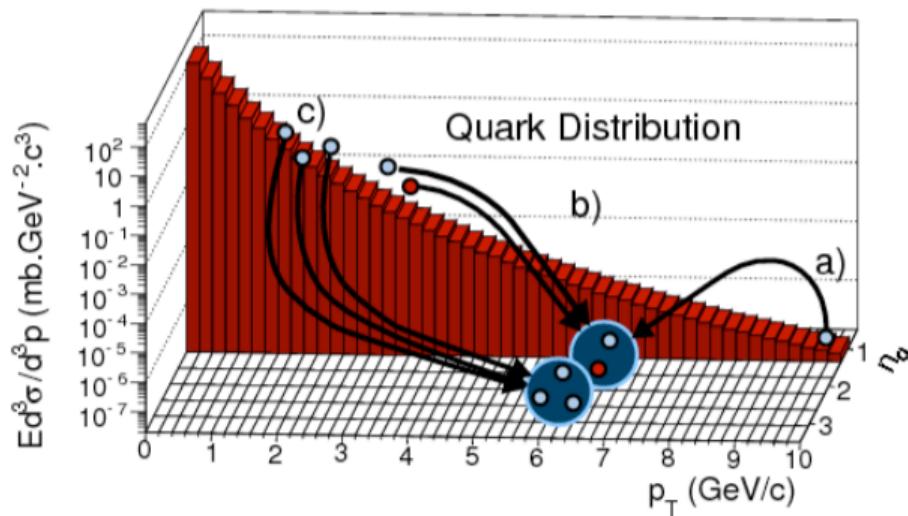


# Test of scaling properties

Number of constituent quark (NCQ) scaling approximately holds at RHIC

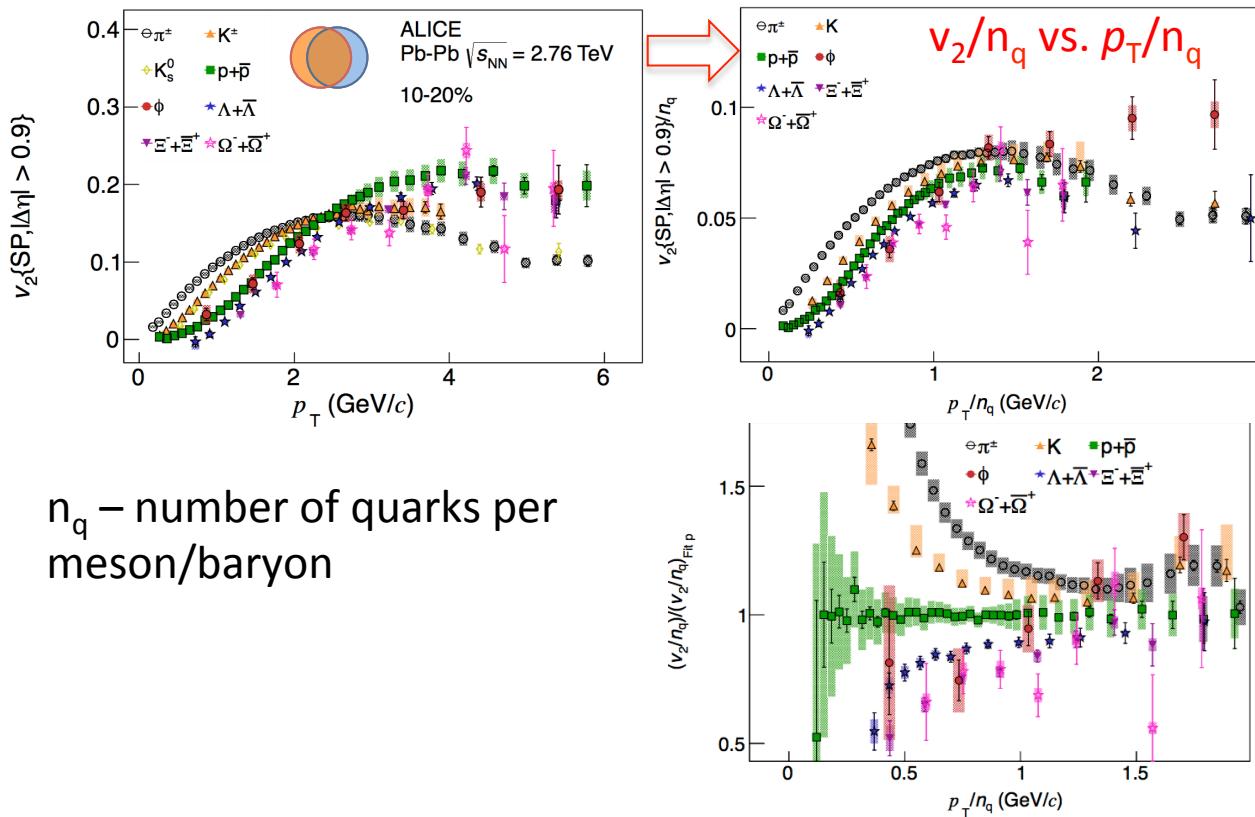
- quarks coalescence as the dominant mechanism of hadron formation?
- NCQ scaling was considered as “evidence” of quark degrees of freedom which dominate in the early stages of AA collisions, when collective flow develops

Eur.Phys.J.C62:237-242,2009



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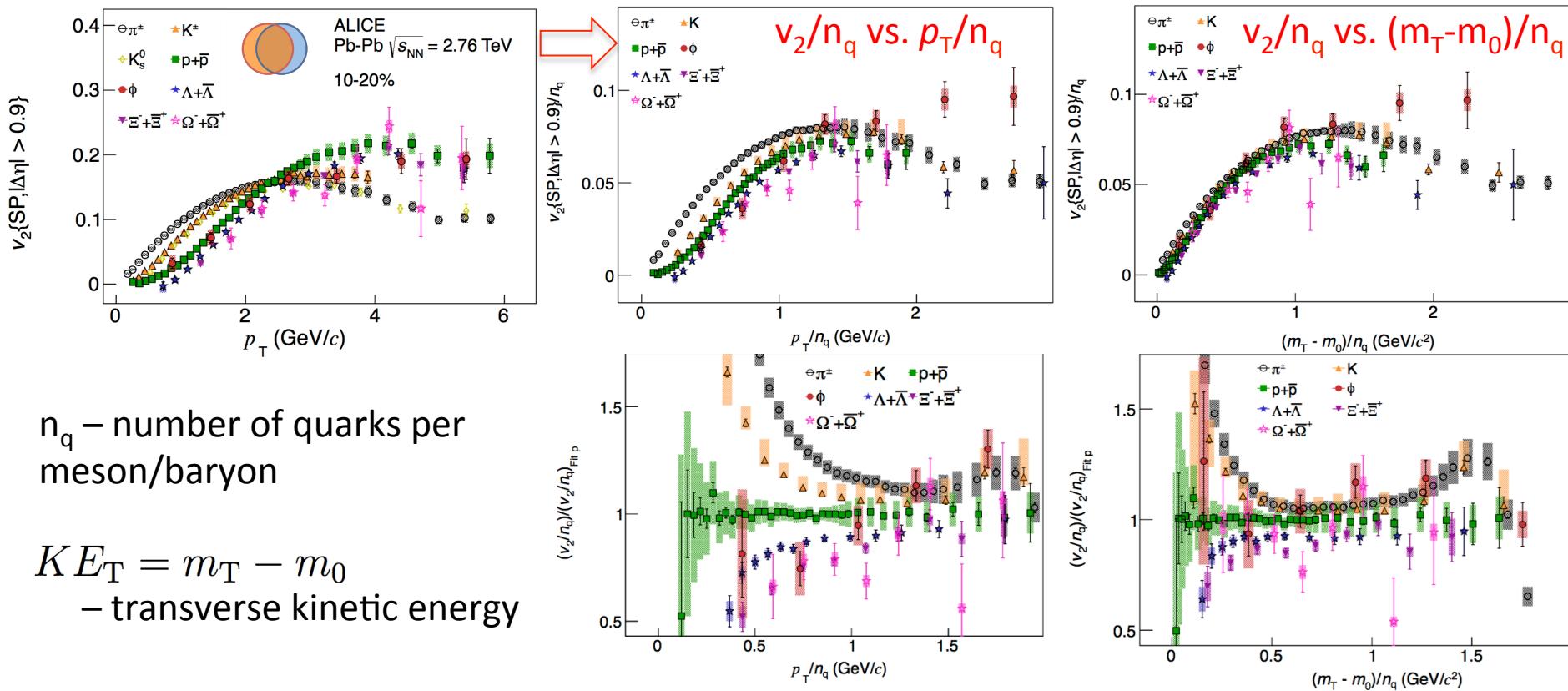
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n<sub>q</sub> – number of quarks per meson/baryon

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$n_q$  – number of quarks per meson/baryon

$KE_T = m_T - m_0$   
– transverse kinetic energy

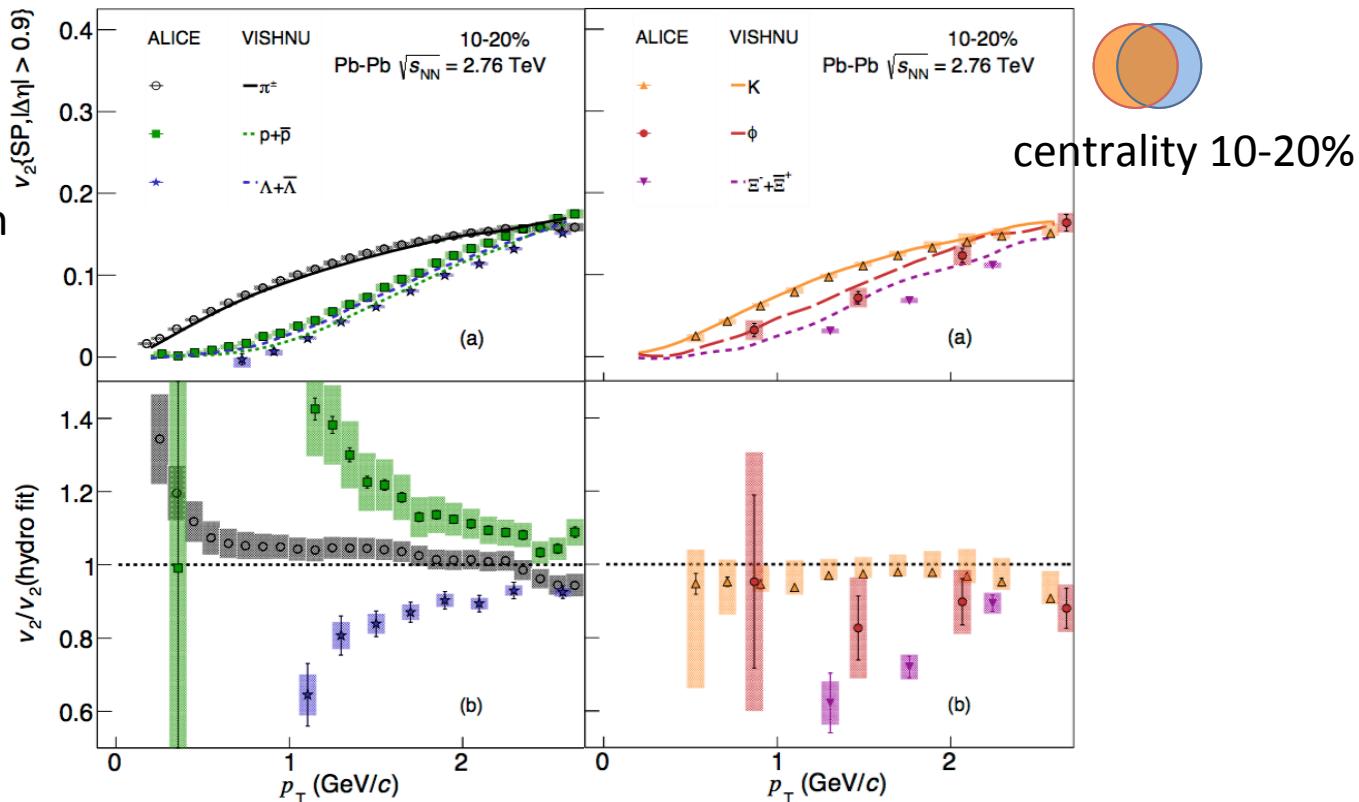
deviations from an exact scaling at the level of  $\pm 20\%$

$\rightarrow v_2 / n_q$  vs.  $p_T / n_q$  and  $KE_T / n_q$  shows that the scaling is only approximate

# Comparison with hydrodynamic calculations (VISHNU)

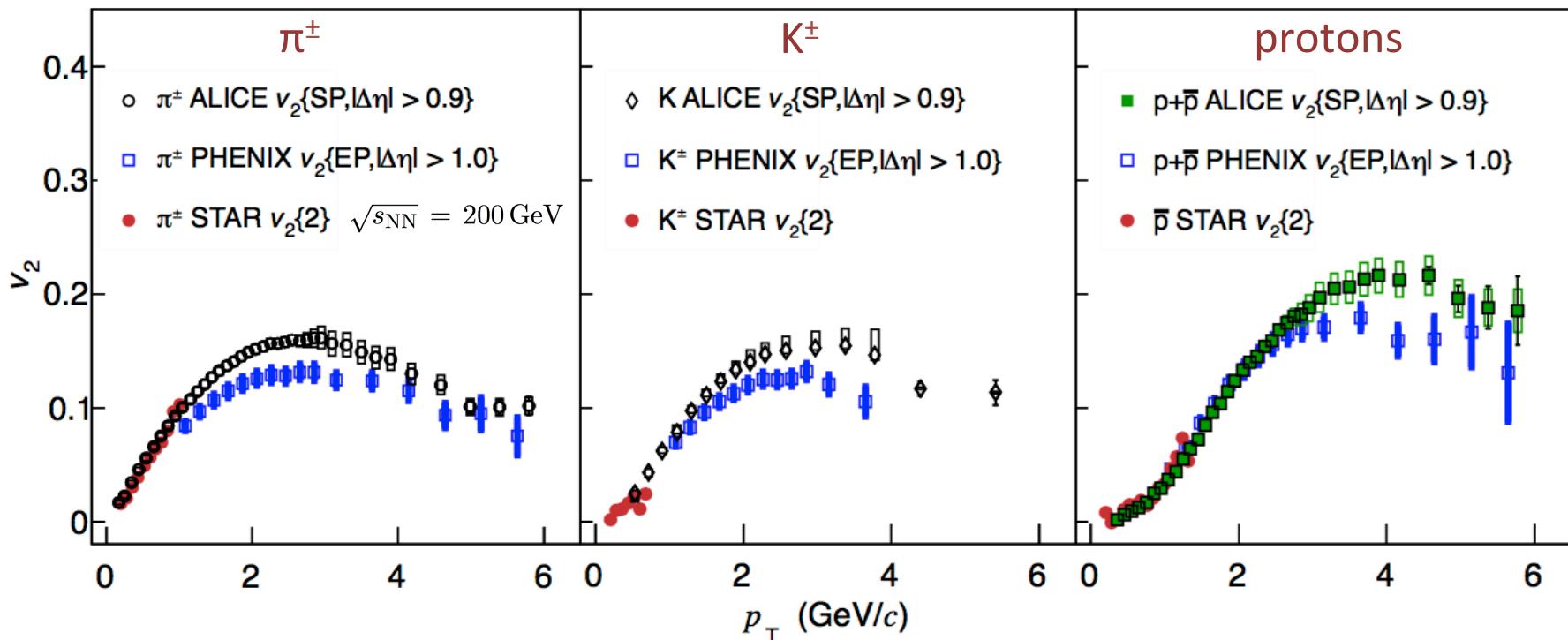
VISHNU model:  
hydrodynamical evolution  
+ hadronic cascade

arXiv:1201.5026 [nucl-th]



- VISHNU gives a **qualitatively similar** picture as in experiment
- the model does not preserve observed mass ordering for protons,  $\Lambda$ ,  $\Xi$

This could indicate that the implementation of the hadronic cascade phase and the hadronic cross-sections within the model need further improvements.

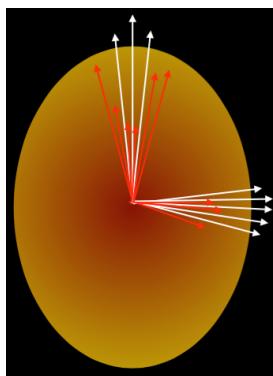
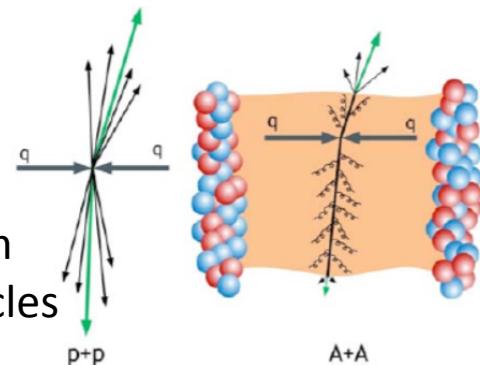


- At low  $p_T$  ( $p_T < 1.5$  GeV/c) the  $v_2(p_T)$  from STAR and ALICE exhibits qualitatively similar behavior.
- For  $p_T > 1.5$  GeV/c for  $\pi^\pm$ ,  $K^\pm$  and for  $p_T > 2.5$  GeV/c for p, the  $v_2$  at the LHC are significantly higher than at the lower energies.
- **Warning:** measurements are done with different methods
  - different sensitivity to non-flow effects → difficult to make quantitative comparison

## $v_2$ at high $p_T$ ( $p_T > 6 \text{ GeV}/c$ )

Probing the path length dependence:

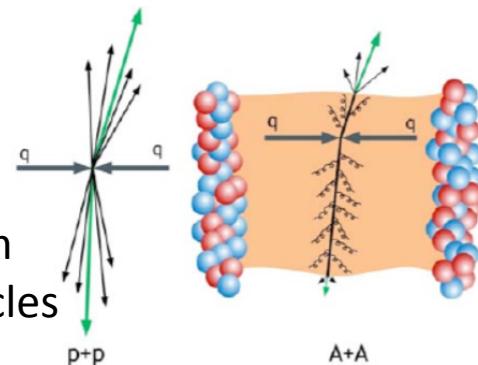
- particles flying **in-plane** have to travel through **less** amount of medium
- one expects to see an azimuthal dependence of jets and high  $p_T$  particles



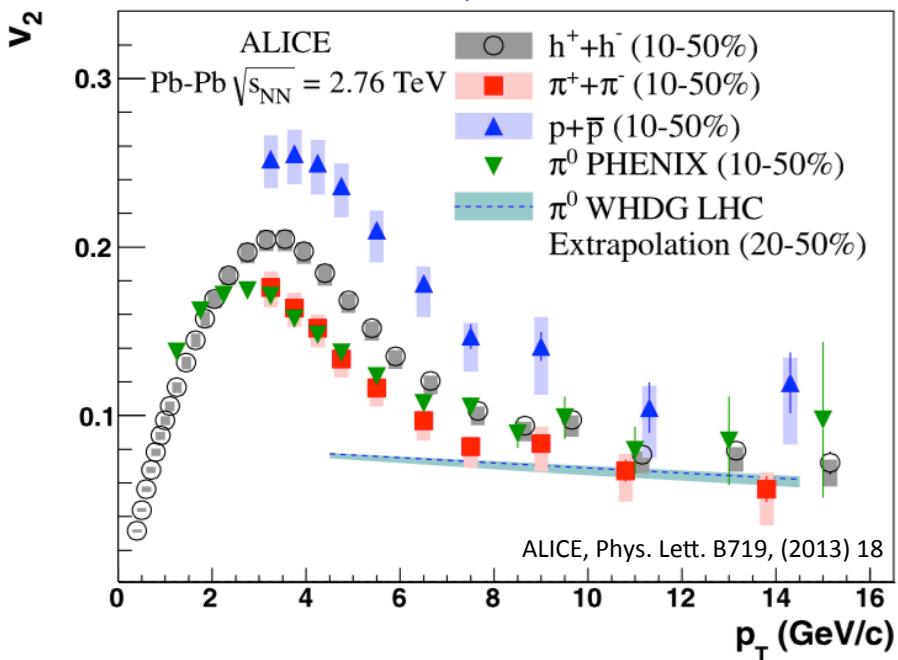
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$\pi^\pm$  and  $p$  at high  $p_T$ :

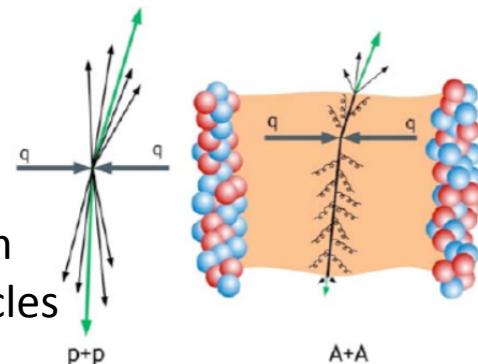


- Significant  $v_2$  for all particle species at high  $p_T$
- No significant particle species dependence for  $p_T > 10 \text{ GeV}/c$

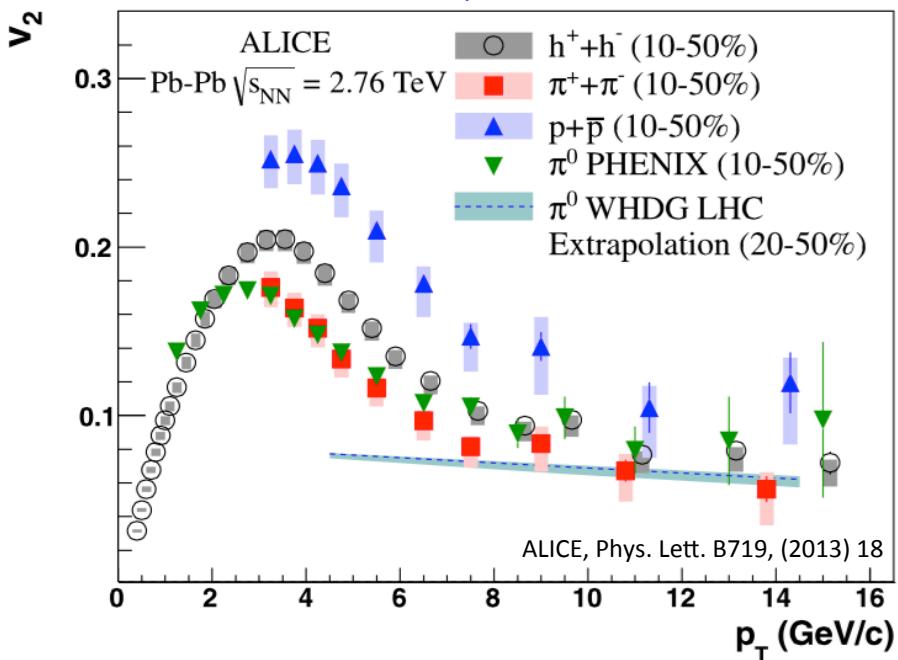
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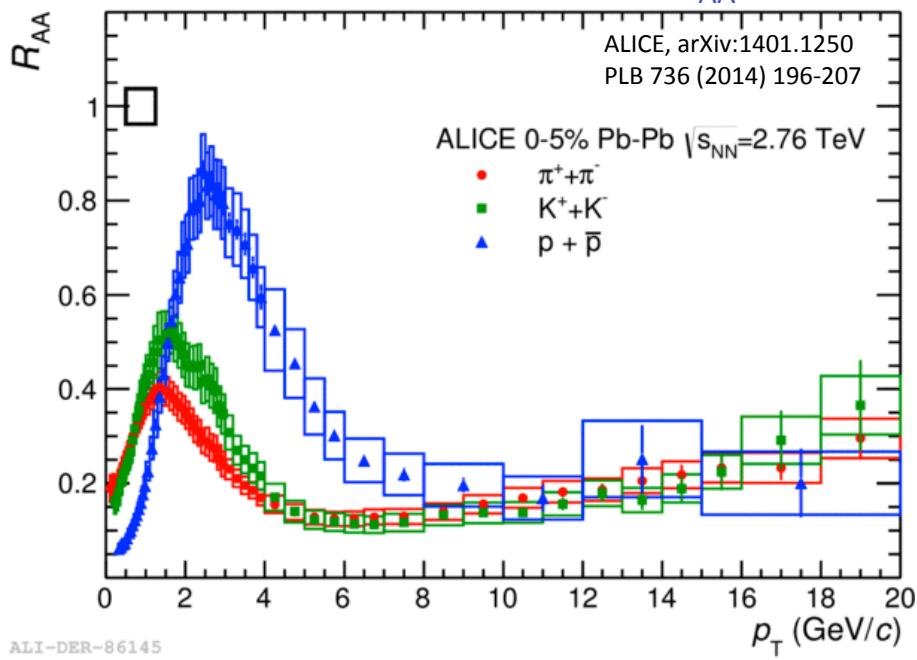
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$\pi^\pm$  and  $p$  at high  $p_T$ :



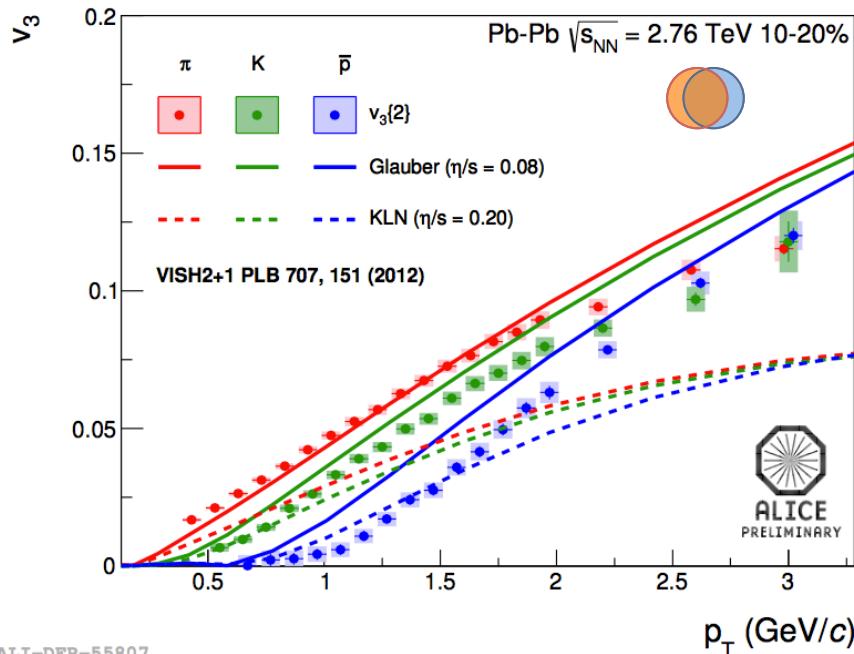
Nuclear modification factor  $R_{AA}$ :



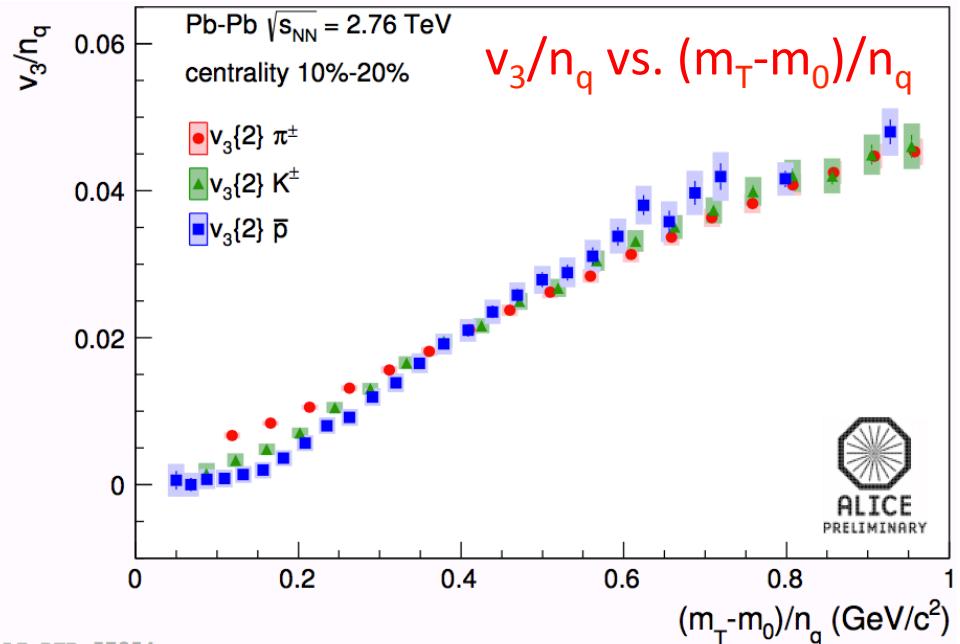
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- No significant particle species dependence for  $p_T > 10 \text{ GeV}/c$

- Large suppression of high  $p_T$  particles
- Suppression does not depend on particle species for  $p_T > 10 \text{ GeV}/c$

# Adding $v_3$ into consideration



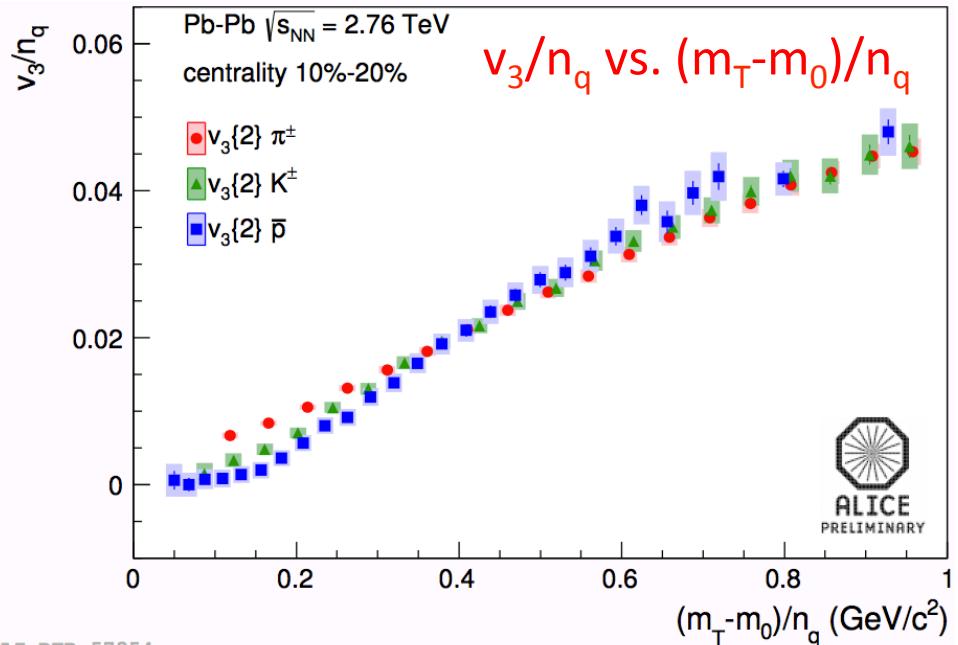
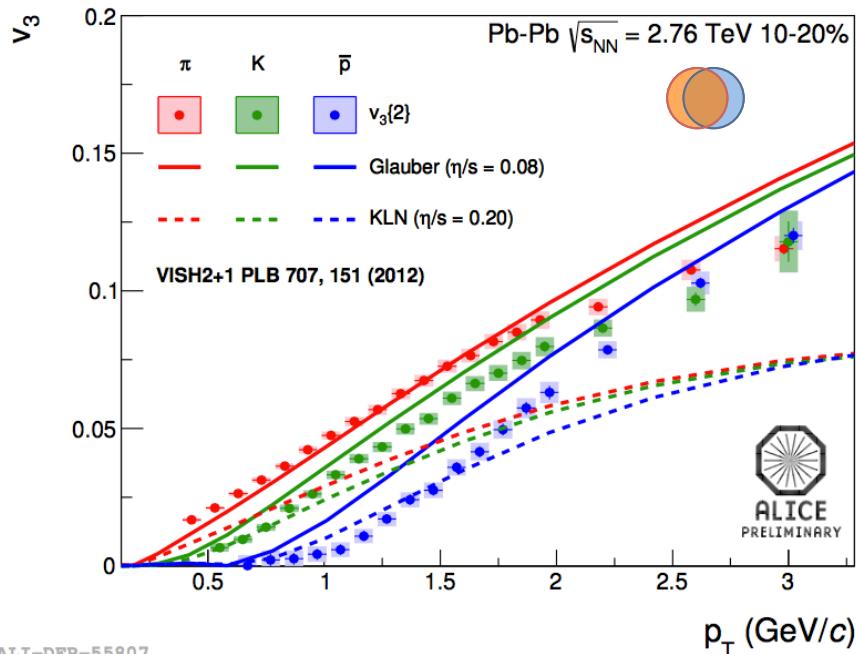
ALI-DER-55807



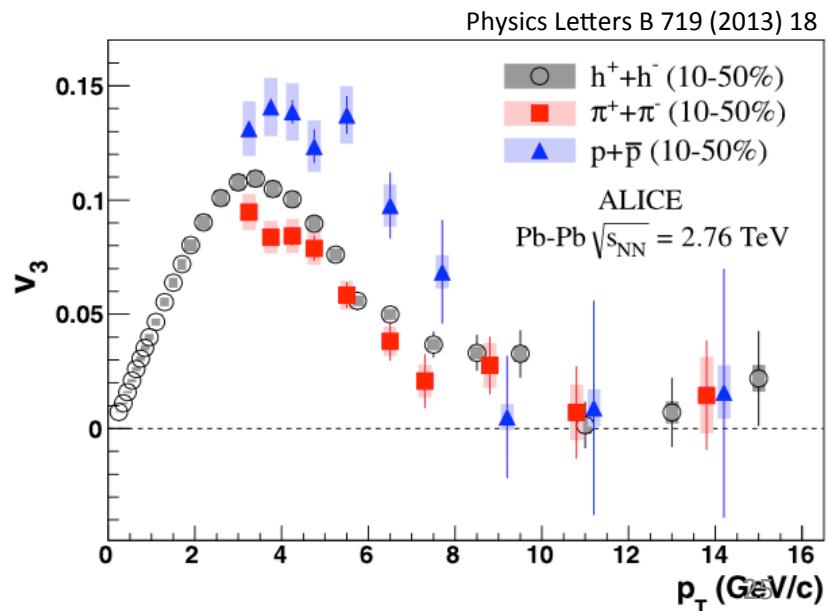
Physics Letters B 719 (2013) 18

- **Low  $p_T$ :** mass ordering as expected from the hydro picture
- $v_3$  of  $\pi$  and  $p$  cross at intermediate  $p_T$  as expected from coalescence
- NCQ scaling of  $v_3$  works better than for  $v_2$  but it is still only approximate

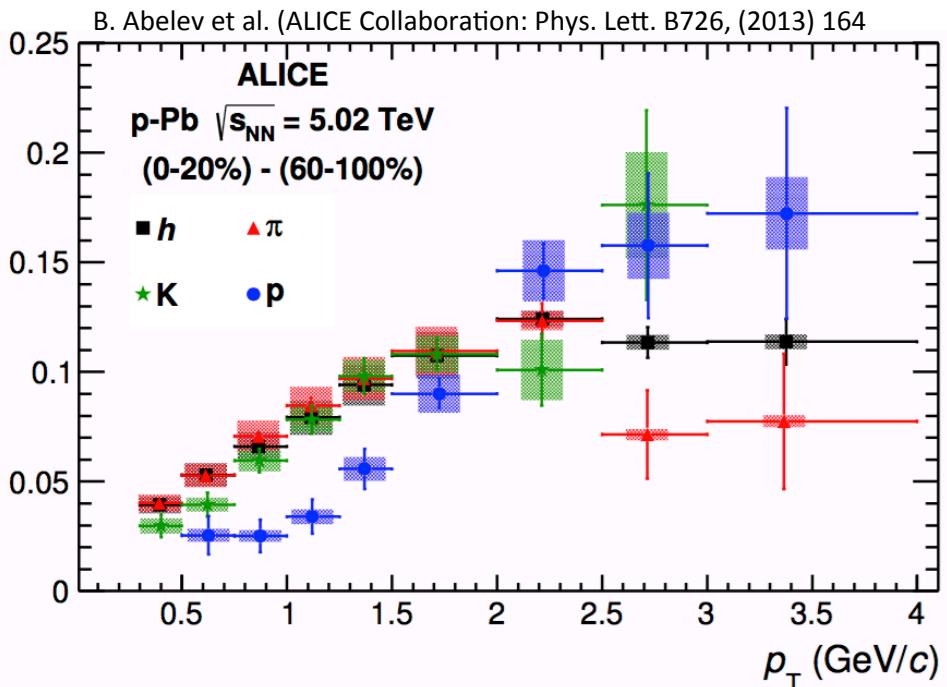
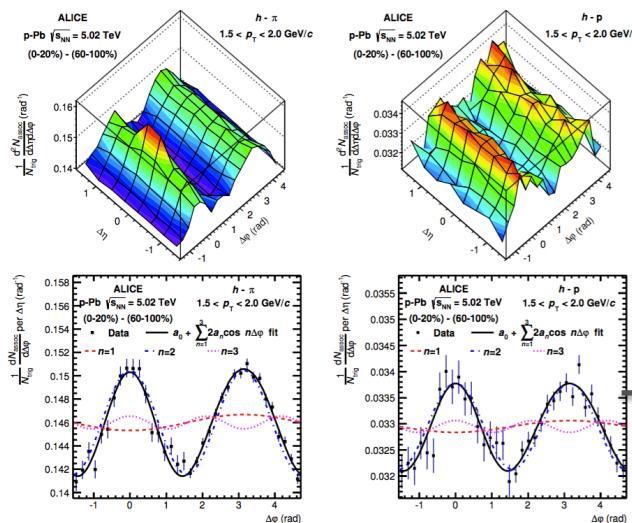
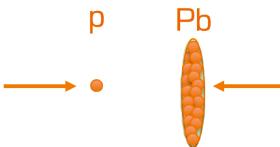
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- NCQ scaling of  $v_3$  works better than for  $v_2$  but it is still only approximate
  - High  $p_T$ :  $v_3$  of  $p$  are larger than that of  $\pi$  out to  $p_T=8$  GeV/c

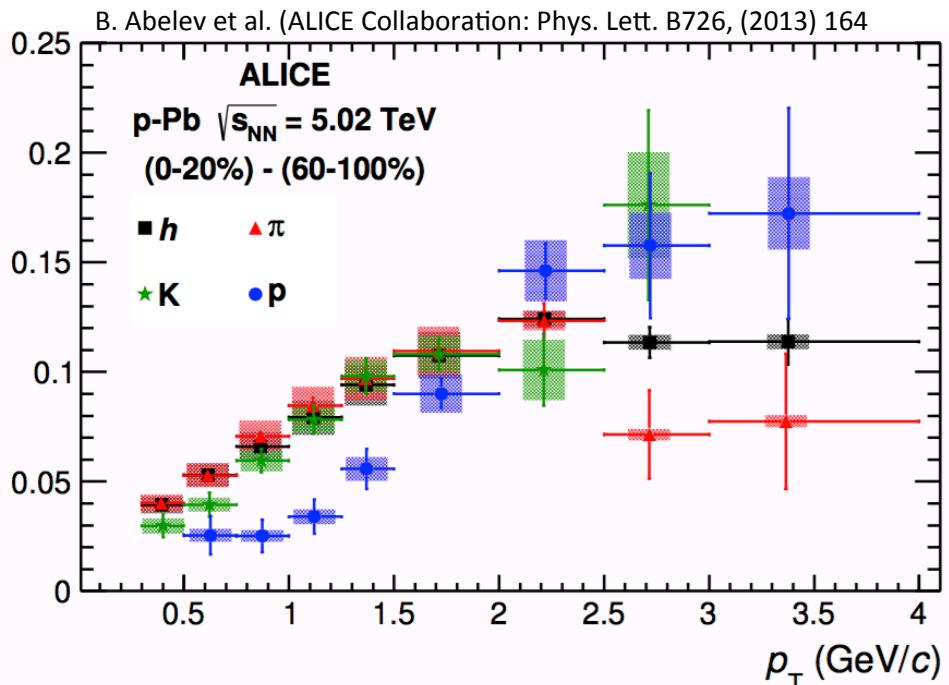
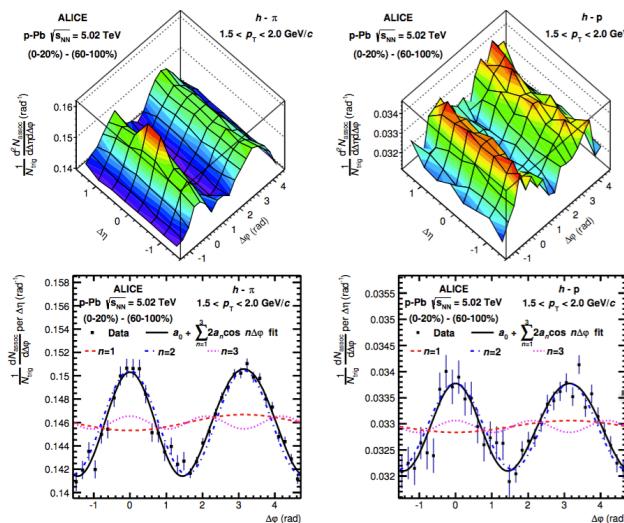
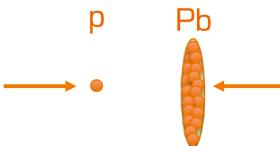


# p-Pb also flows?..



- Fourier coefficient  $v_2$  was extracted from two-particle correlations with subtraction using low multiplicity events
- In high-multiplicity p-Pb collisions:
  - $p_T < 2 \text{ GeV}/c$ :  $v_2$  is larger for  $\pi$  than for protons
  - at  $p_T 3\text{--}4 \text{ GeV}/c$ ,  $v_2$  for protons is higher than for  $\pi$

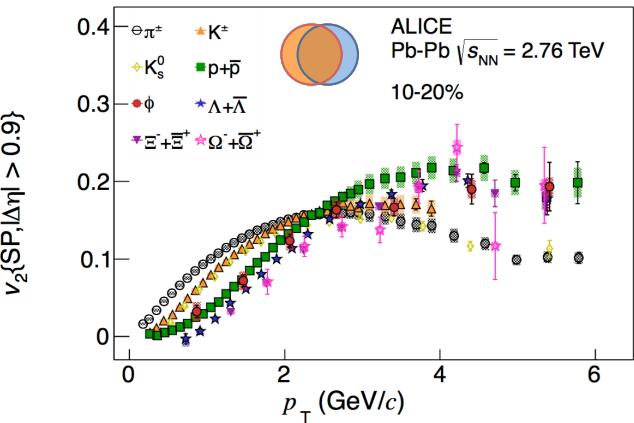
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  - at  $p_T 3-4 \text{ GeV}/c$ ,  $v_2$  for protons is higher than for  $\pi$

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

→ Flow not only in A-A but also in smaller systems?

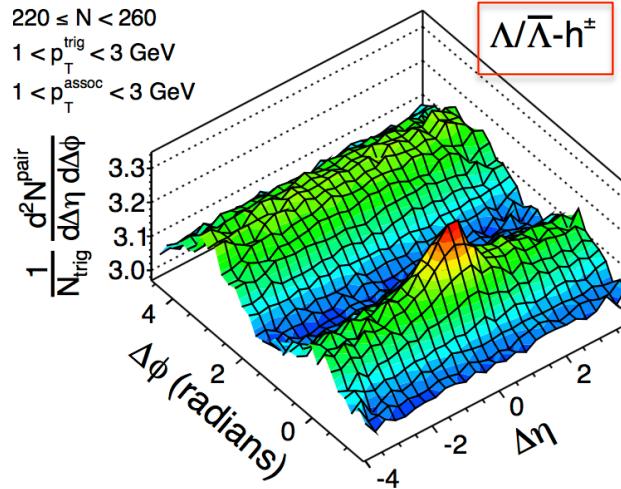
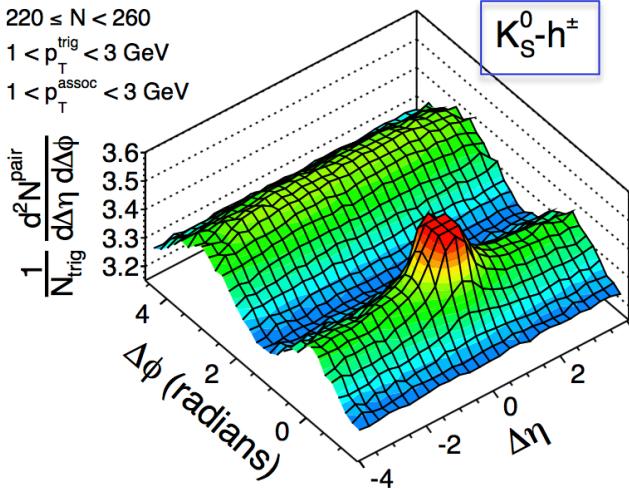


Explore pPb further:

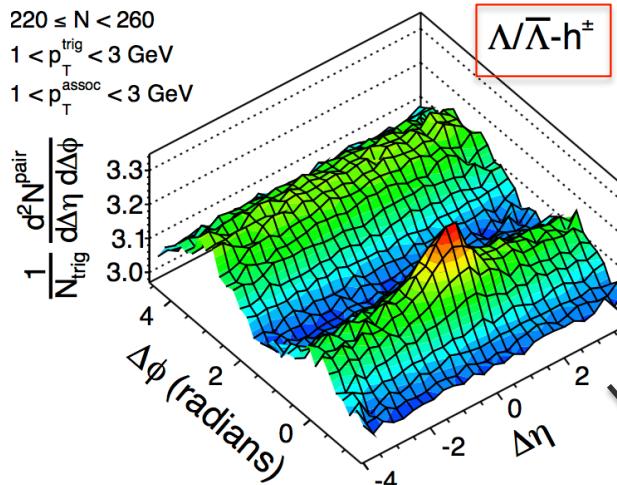
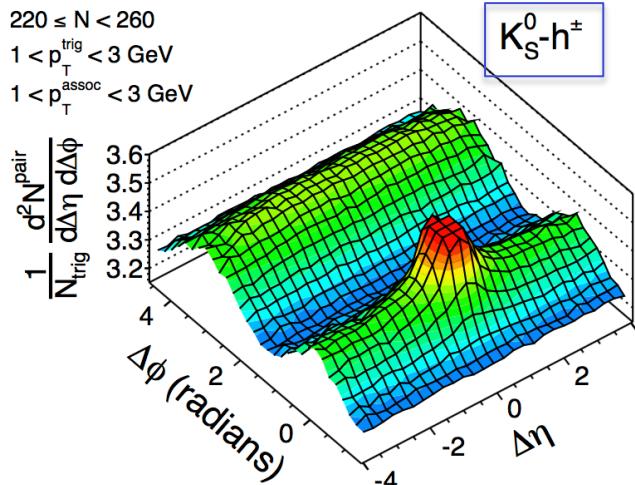
CMS pPb  $\sqrt{s_{NN}} = 5.02$  TeV

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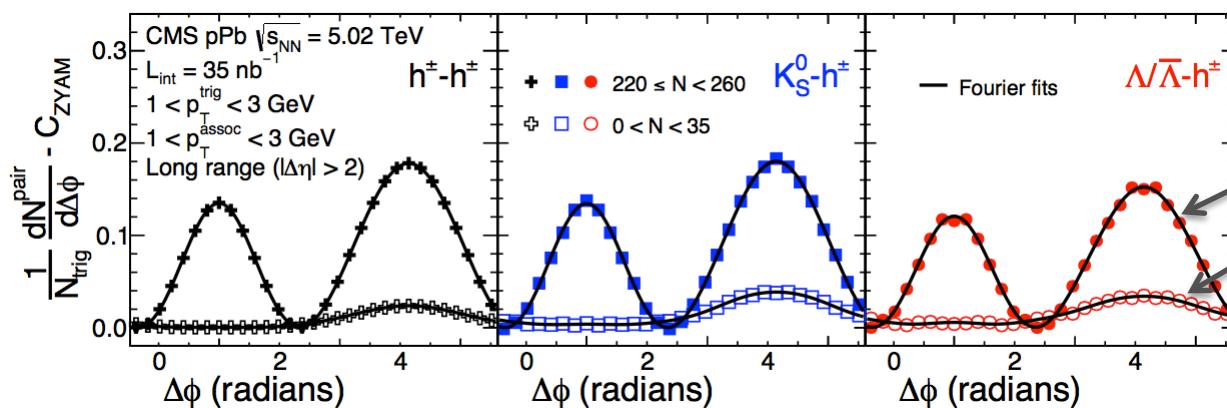
## $v_2$ and $v_3$ of strange hadrons from long-range two-particle correlations



2D two-particle correlations  
for high-multiplicity events

$v_2$  and  $v_3$  of strange hadrons from long-range two-particle correlations

2D two-particle correlations  
for high-multiplicity events



$|\Delta\eta| > 2$   
to remove short-range correlations

high multiplicity  
low multiplicity

Extraction of  $v_n$  harmonics:

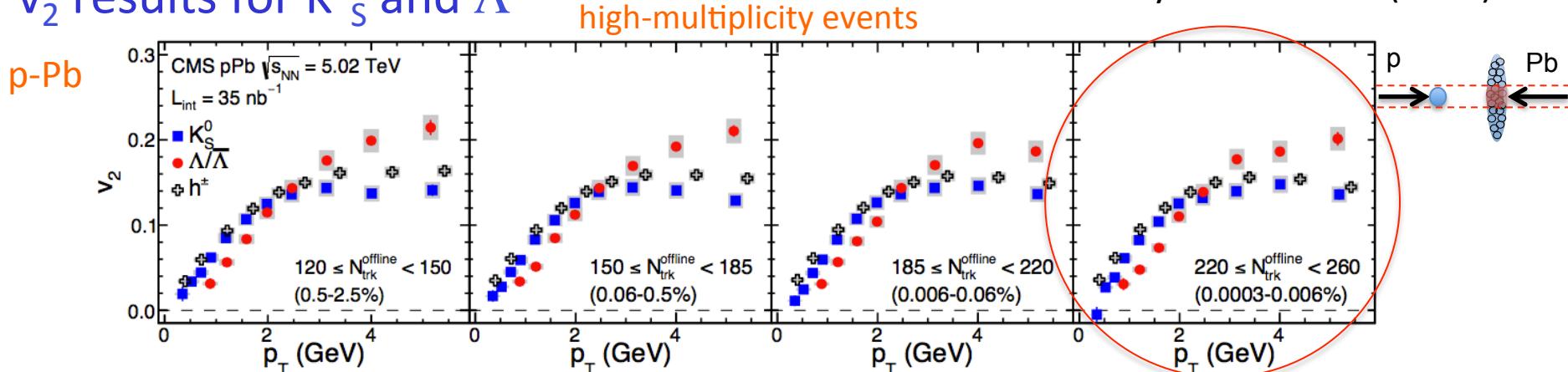
$$\frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta\phi} = \frac{N_{\text{assoc}}}{2\pi} \left[ 1 + \sum_n 2V_{n\Delta} \cos(n\Delta\phi) \right]$$

$$V_{n\Delta}(p_T^{\text{trig}}, p_T^{\text{assoc}}) = v_n(p_T^{\text{trig}}) \times v_n(p_T^{\text{assoc}})$$

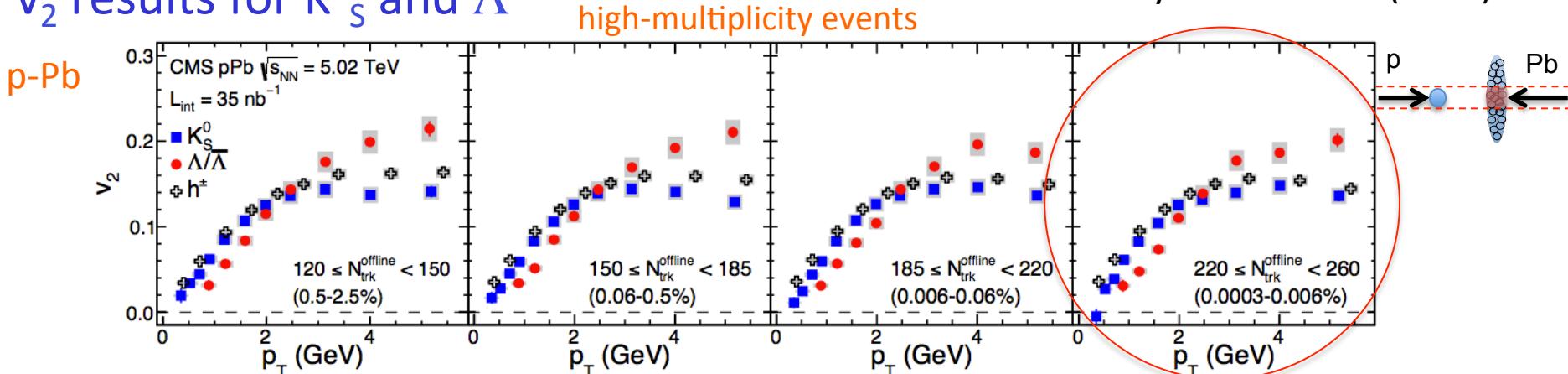


$$v_n(p_T^{V^0}) = \frac{V_{n\Delta}(p_T^{V^0}, p_T^{\text{ref}})}{\sqrt{V_{n\Delta}(p_T^{\text{ref}}, p_T^{\text{ref}})}}$$

$$n = 2, 3$$

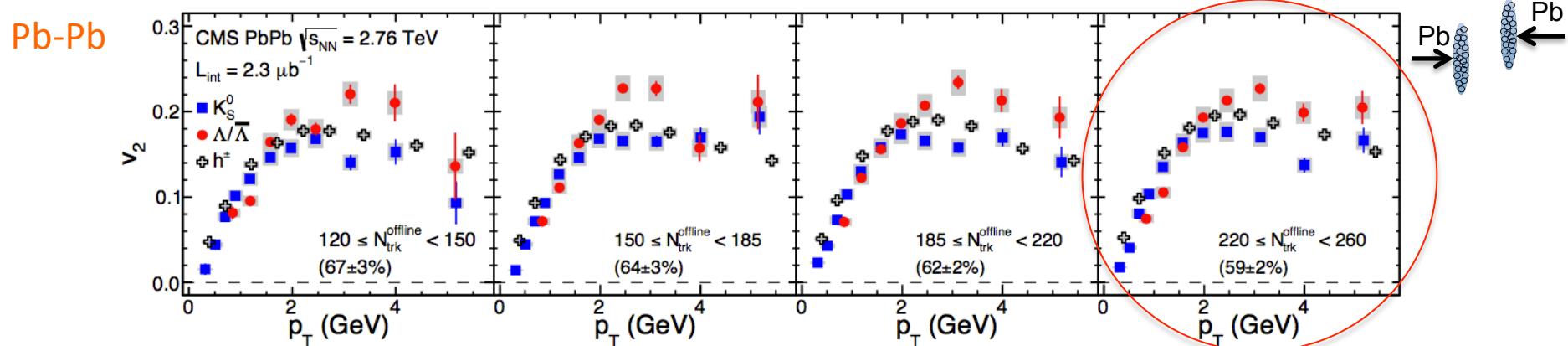


- In  $p_T < 2$  GeV for all high-multiplicity ranges, the  $v_2$  values of  $K_S^0$  particles are larger than those for  $\Lambda$  → mass ordering
- At higher  $p_T$ , the  $v_2$  values of  $\Lambda$  are larger than those of  $K_S^0$ .



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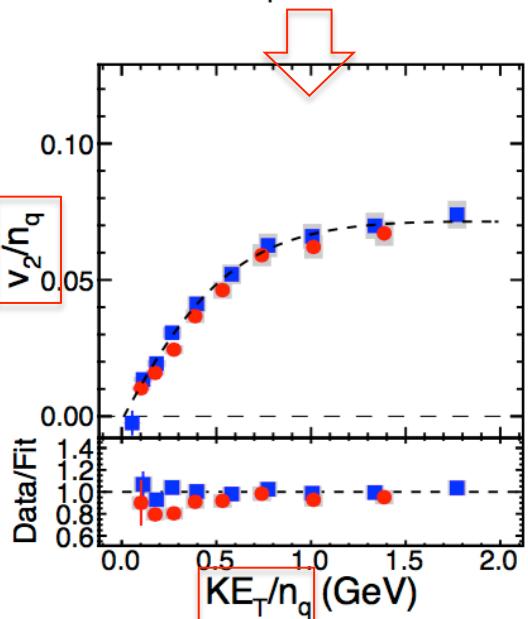
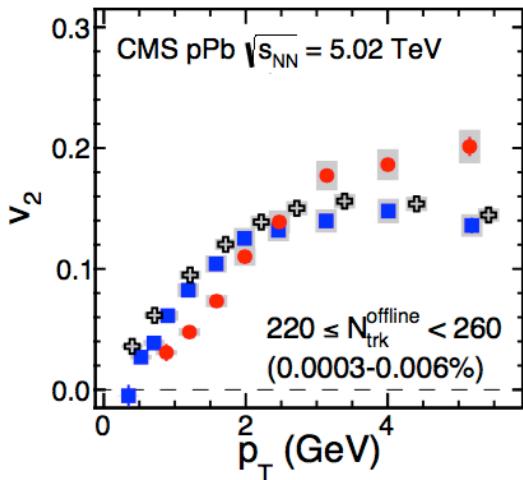
Compare to semi-peripheral PbPb data with *similar multiplicities*:



- Pb-Pb data: mass ordering is *less evident* than in pPb for all multiplicity ranges → stronger radial flow in pPb?  
 (due to higher energy density in system with smaller size)

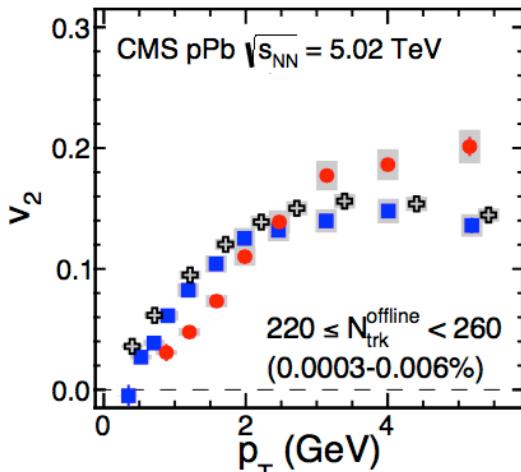
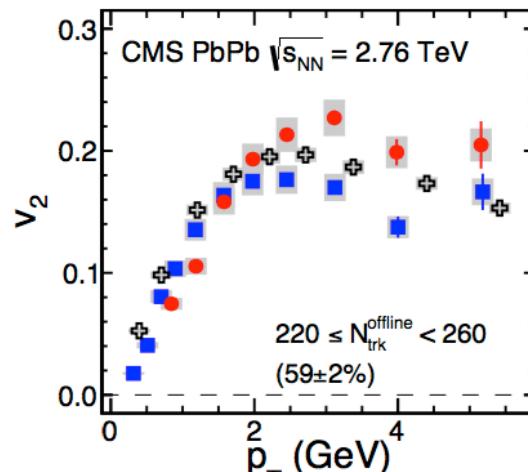
$v_2/n_q$  as a function of  $KE_T/n_q$  for  $K^0_S$  and  $\Lambda$

p-Pb high-multiplicity events

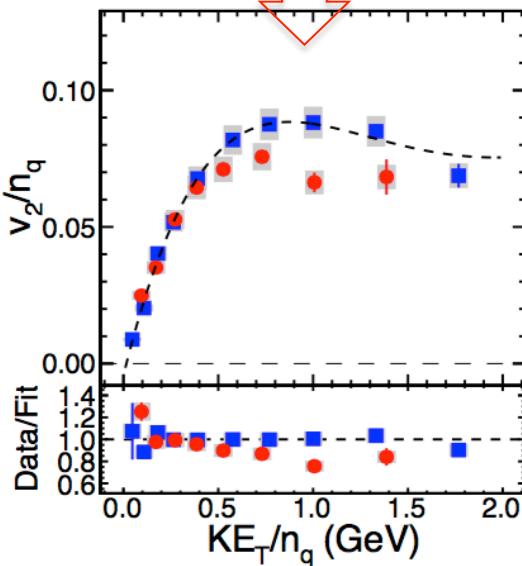
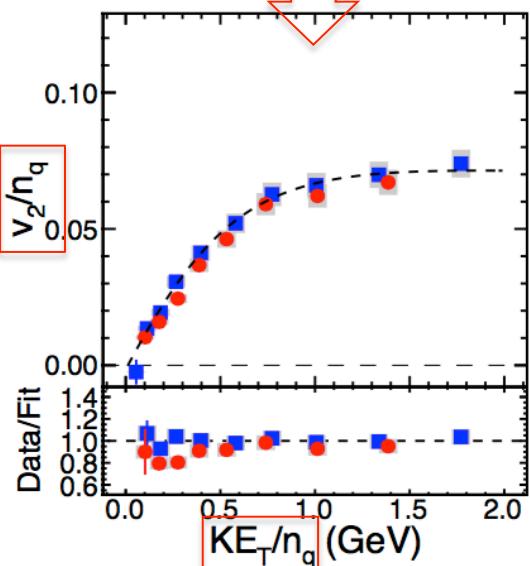


$$KE_T = \sqrt{m^2 + p_T^2} - m$$

- After scaling by  $n_q$ , the  $v_2$  distributions for  $K^0_S$  and  $\Lambda$  are  $\sim$  in agreement
- Scaling is valid to better than 10% over most of the  $KE_T/n_q$

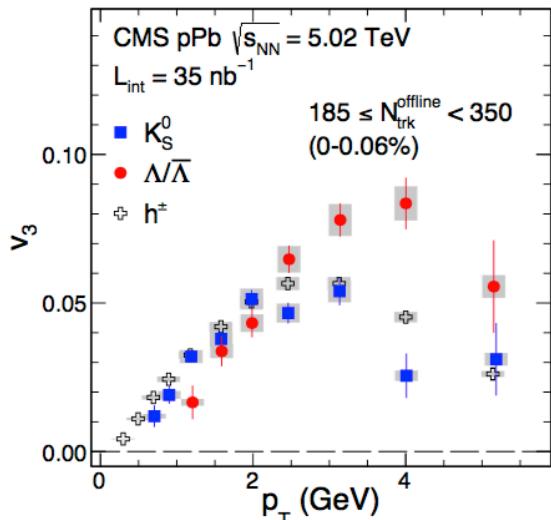
$v_2/n_q$  as a function of  $KE_T/n_q$  for  $K^0_S$  and  $\Lambda$ **p-Pb** high-multiplicity events**Pb-Pb** peripheral events

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- PbPb  $v_2$ : stronger violation of  $n_q$  scaling at similar multiplicities (up to 25%)

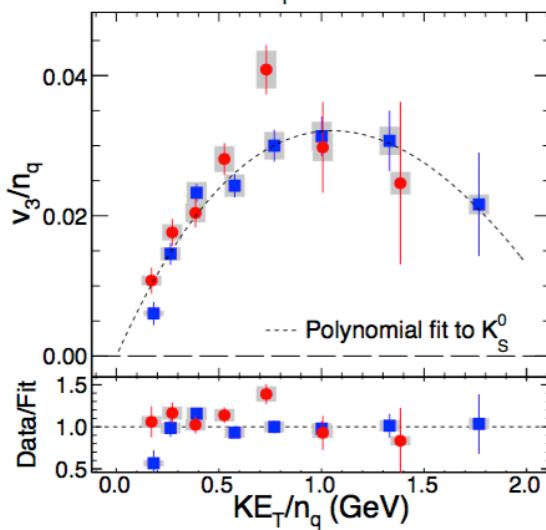
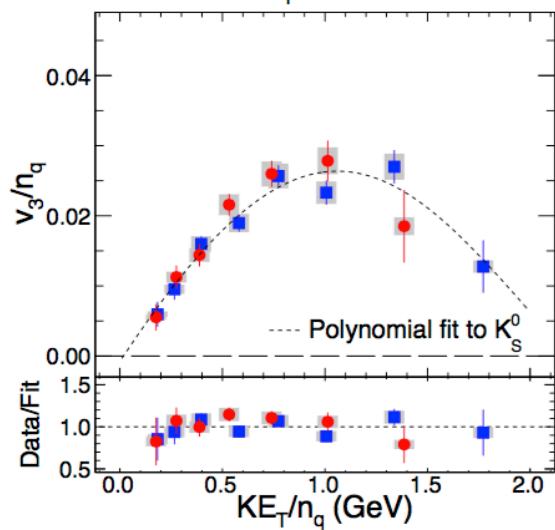
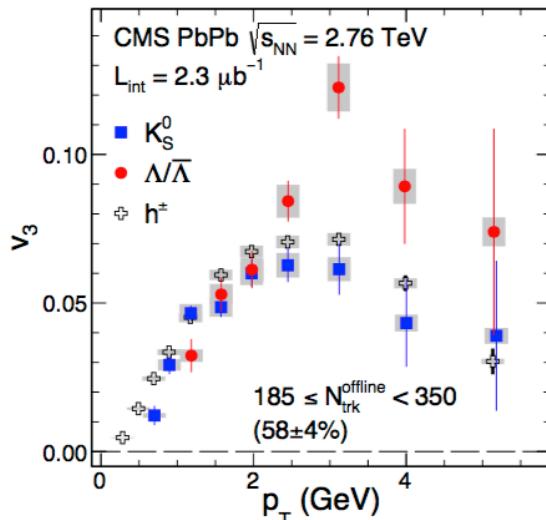


$$KE_T = \sqrt{m^2 + p_T^2} - m$$

p-Pb high-multiplicity events



Pb-Pb peripheral events



- A similar species dependence of  $v_3$  to that of  $v_2$  is observed for  $K_S^0$  and  $\Lambda$
- $v_3$  values scaled by  $n_q$  match at 20% level over the full  $KE_T/n_q$  range, within stat. uncertainties

# Summary

Anisotropic flow of identified particles is measured at LHC  
in Pb-Pb collisions at 2.76 TeV and p-Pb collisions at 5.02 TeV.

## Pb-Pb collisions:

- Mass splitting is consistent with stronger radial flow at the LHC and is reproduced by the hydrodynamic model calculations (VISHNU).
- For  $3 < p_T < 6$  GeV/c, particles tend to group according to their type, i.e. mesons and baryons.
- NCQ scaling is only approximate (within 20%) at intermediate  $p_T$ .
- High  $p_T$ :  $v_2$  of  $\pi$  and p are consistent within uncertainties for  $p_T > 10$  GeV/c.
- $v_3$  of  $\pi$ , K, and p has a similar mass dependence as that of  $v_2$ .

## p-Pb high-multiplicity collisions:

- similar features for  $v_2$  and  $v_3$  as in Pb-Pb → flow in small systems?..

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*Thank you for your attention!*

# Backup slide

# Evidence of the collective nature of correlations in pPb!

$$v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\text{LYZ}, \infty\}$$

Phys.Rev.Lett. 115, 012301 (2015)

