# Flow of strange and charm particles in Pb-Pb at ALICE

## Characterising the QCD matter

Carlos E. Pérez Lara* for the ALICE collaboration

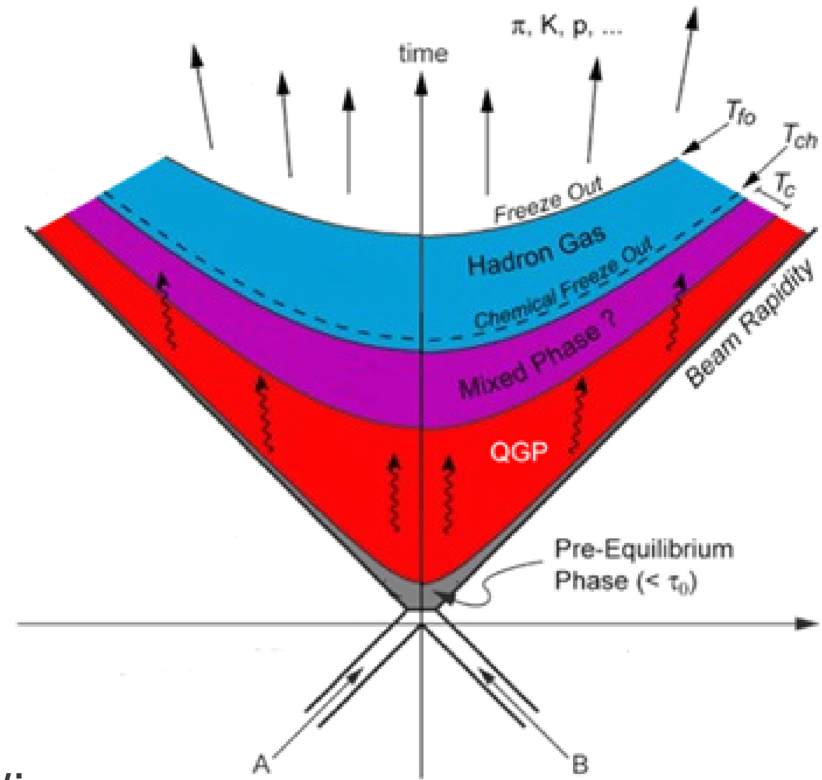
*Nikhef and Utrecht University

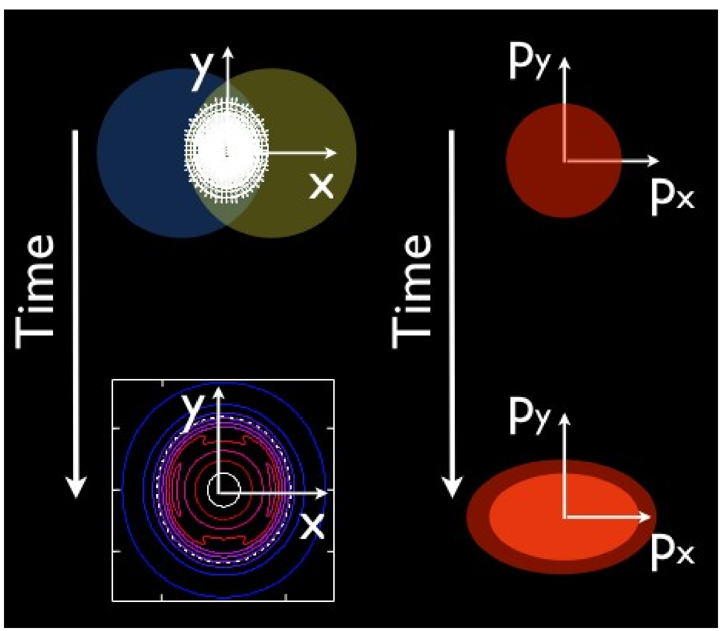
# Collective phenomena and flow

Hot QCD matter is created in HIC: strongly interacting phase

No direct experimental access to it

One of the main probes to this phase is **anisotropic flow**




Anisotropic flow:

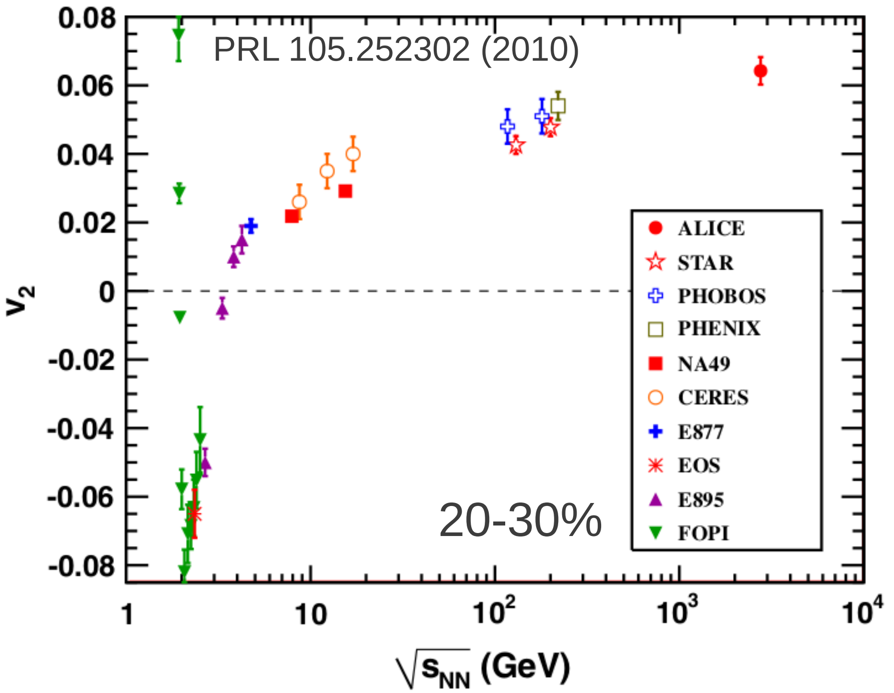
Initial space asymmetry is converted into momentum anisotropy of the produced particles

This anisotropy is quantified by Fourier decomposition of azimuthal distribution

$$v_n = \langle \cos[n(\phi - \psi_n)] \rangle$$

# What does $v_2$ tell us?

- Very low viscous fluid
- At LHC integrated $v_2$ increases by 30%
  - Constrains η/s



# What does $v_2$ tell us?

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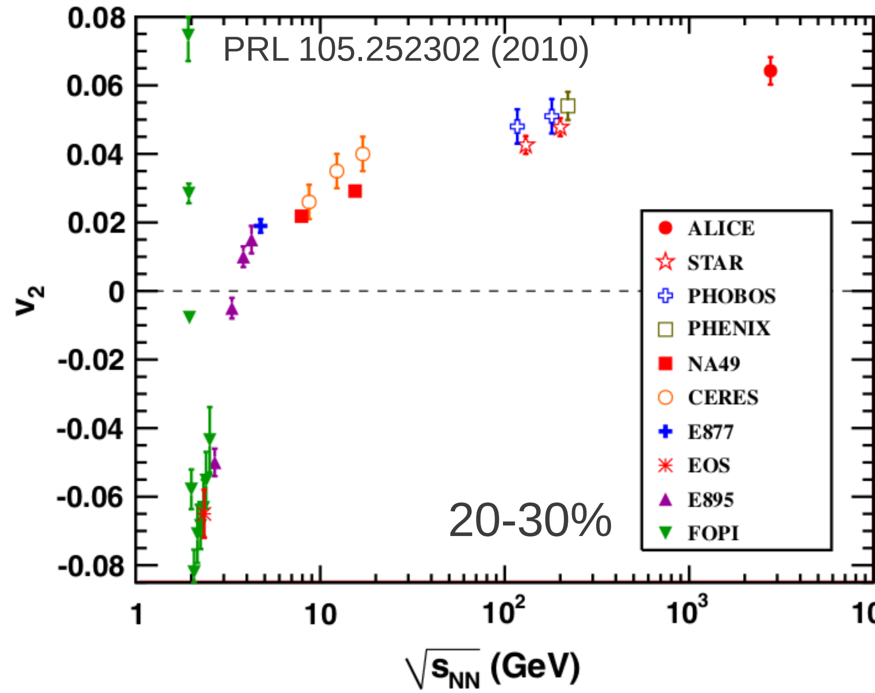
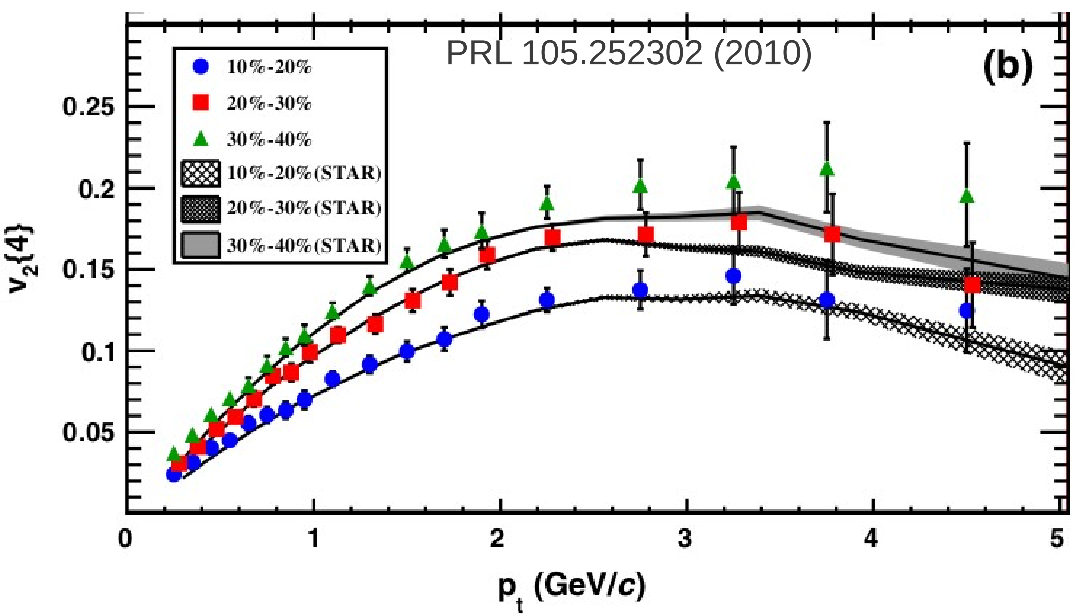
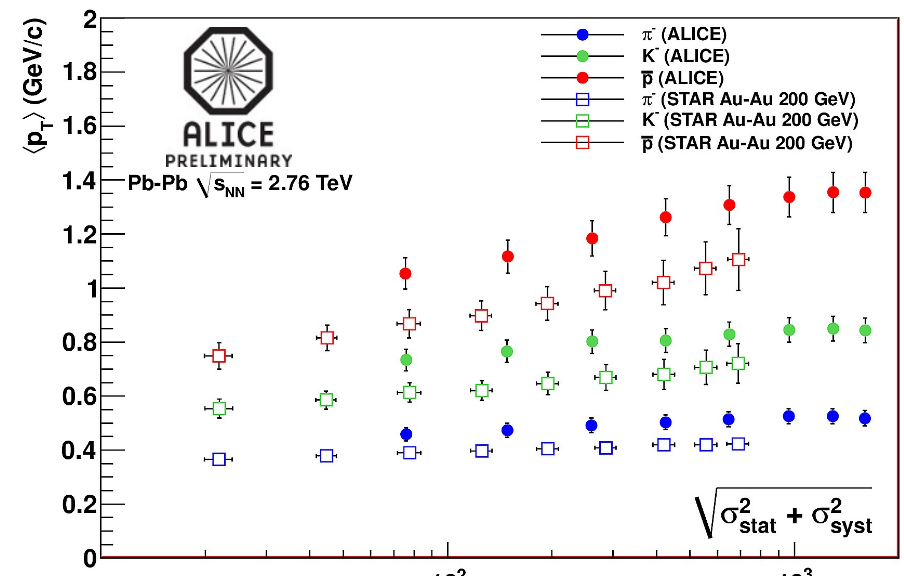
$$\langle v_2 \rangle = \frac{\int v_2\,(p_T)\,\frac{d}{dp_T}N\,dp_T}{\int \frac{d}{dp_T}N\,dp_T}$$

- Differential $v_2$ similar to RHIC
- <pt> increased compared to RHIC
  - Sensitivity to <β>

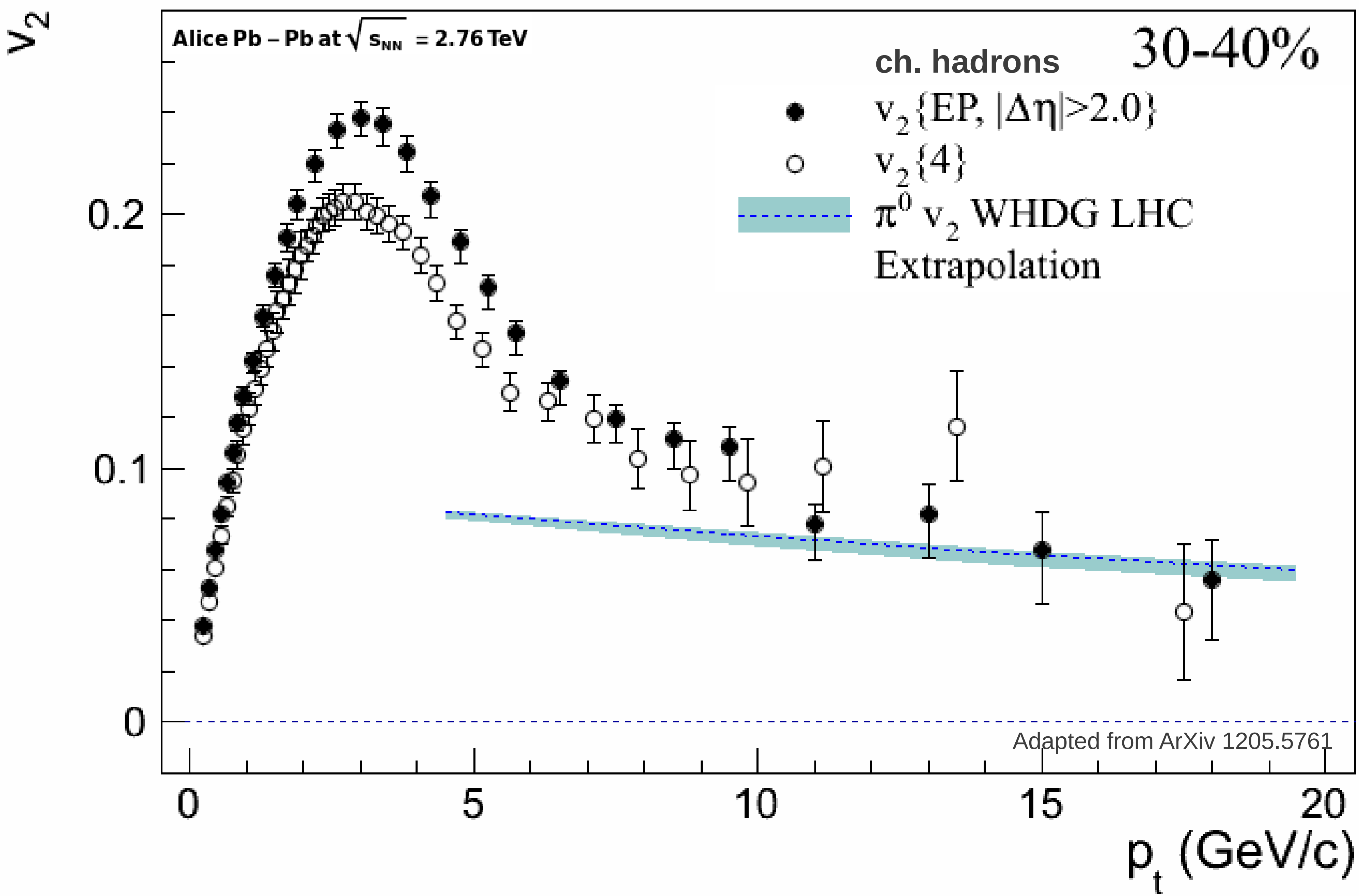


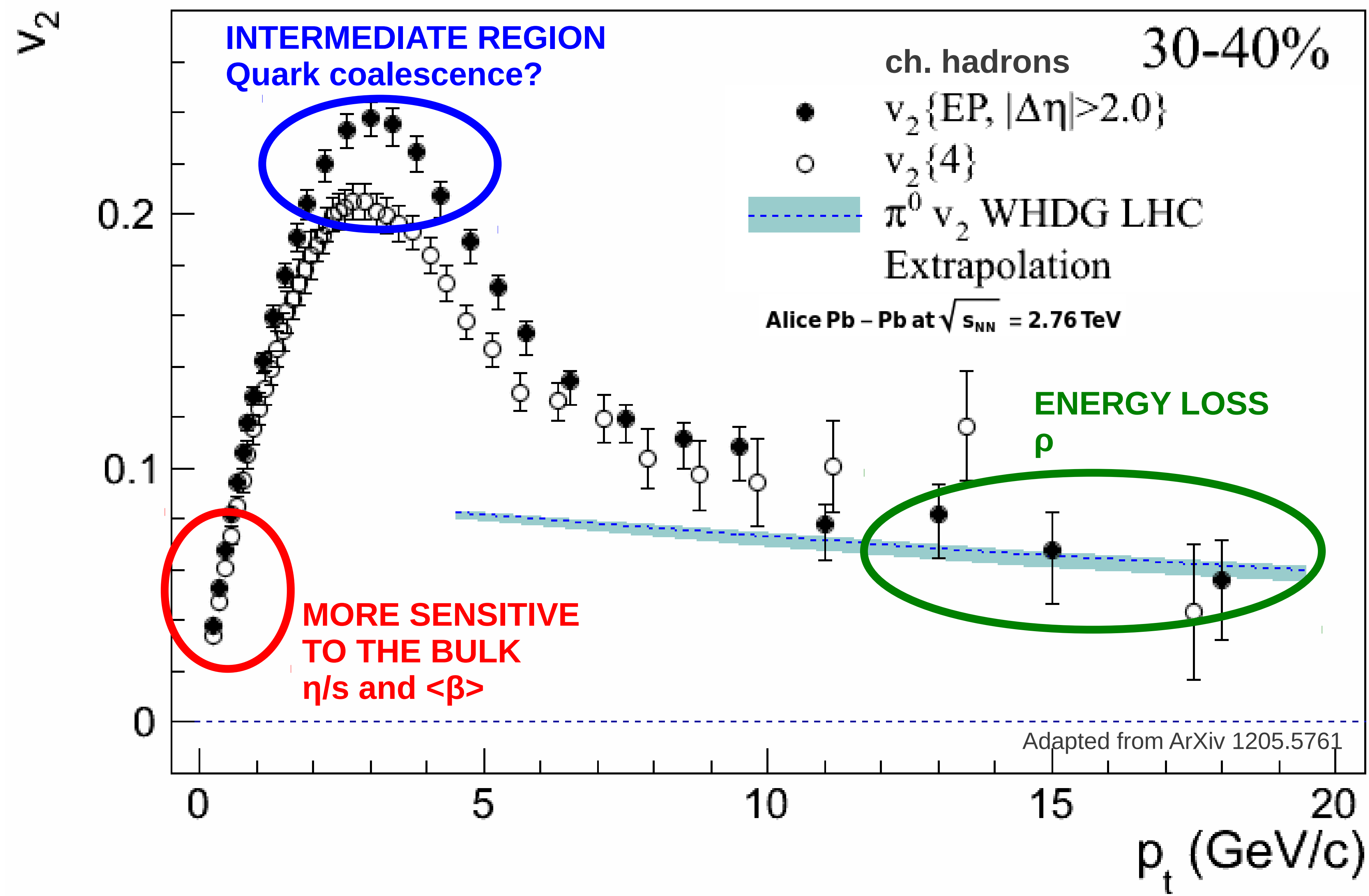




More on particle production: **F. Bellini**

# Elliptic flow at LHC



# Three distinct regions for analysis



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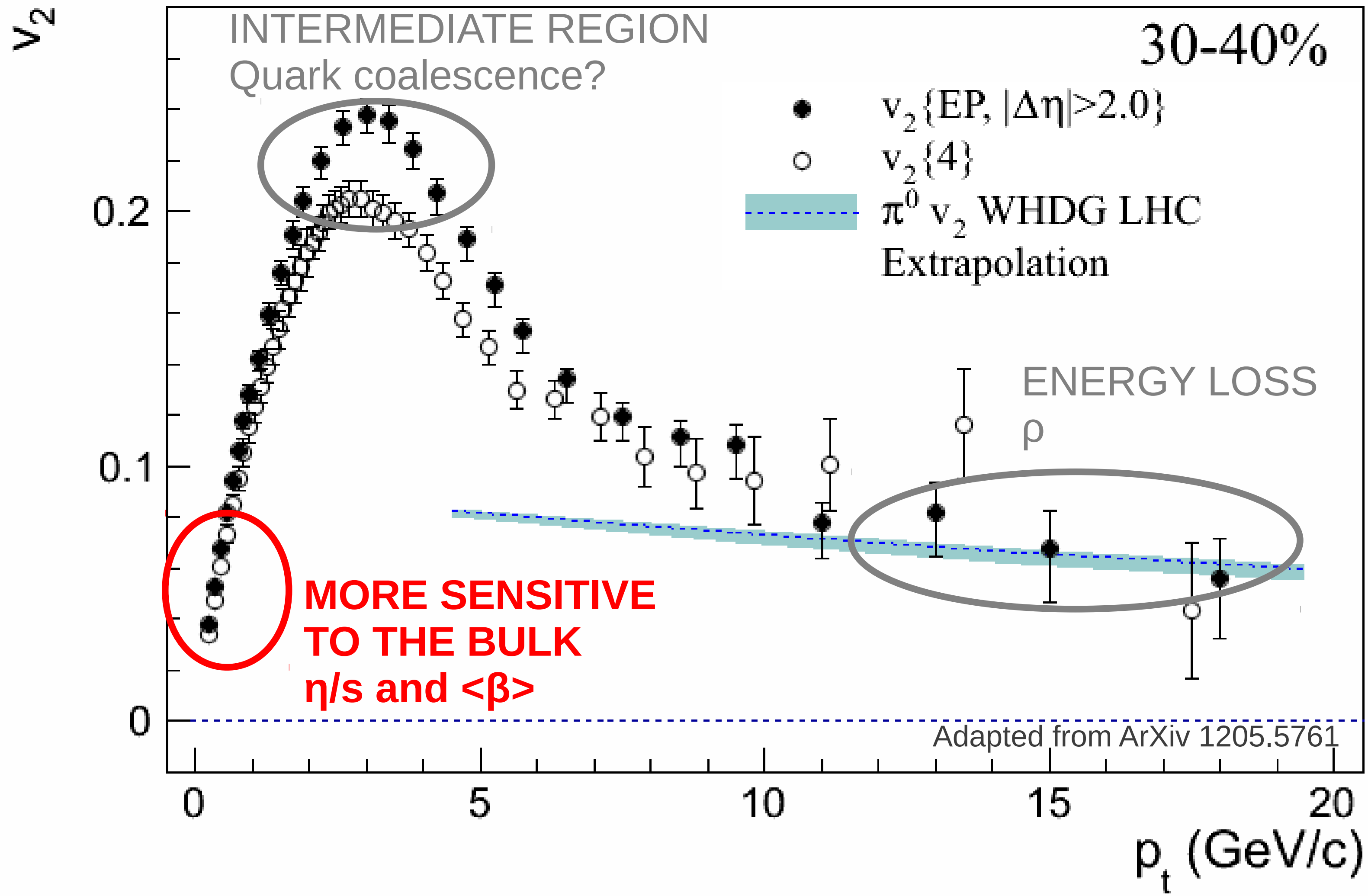
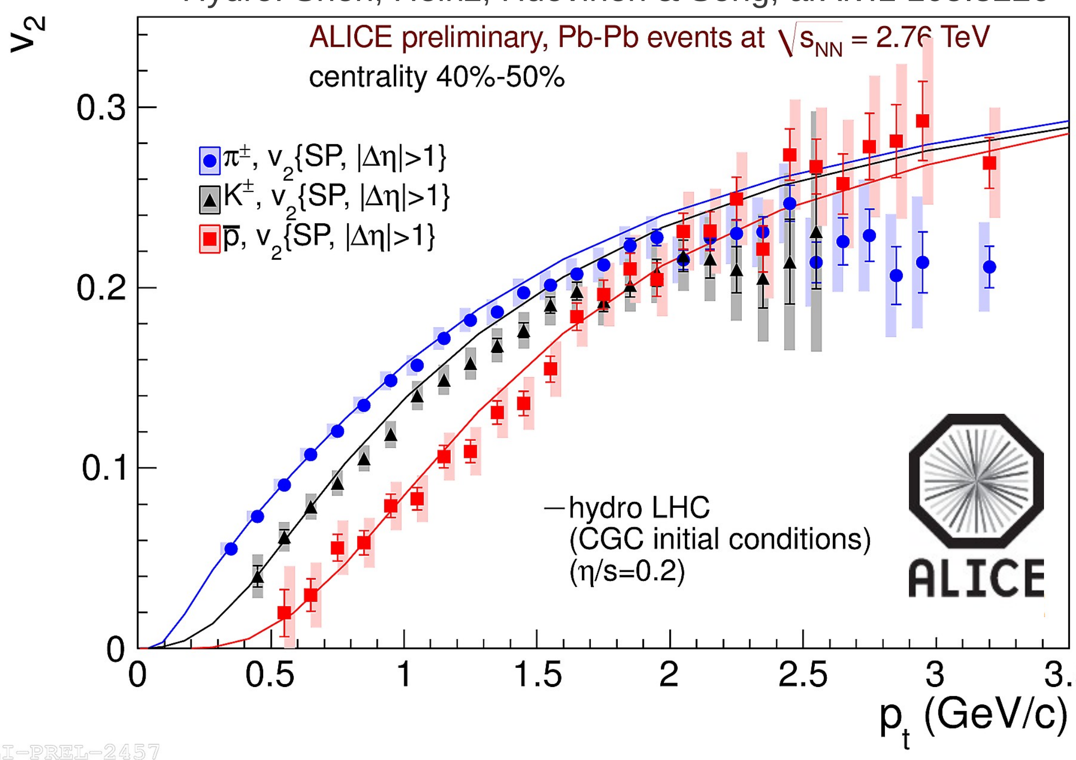



- **[low pt] measure the intensive properties of the medium (η/s and β)**
- [intermediate pt] give handle on the hadronization mechanism
- [high pt] measure the path length dependence in medium

# Probe for properties of the bulk

Hydro: Shen, Heinz, Huovinen & Song, arXiv:1 105.3226




- Mass dependence of $v_2$ observed at LHC energies
- Viscous-hydrodynamical calculations reproduce $v_2$ mass splitting

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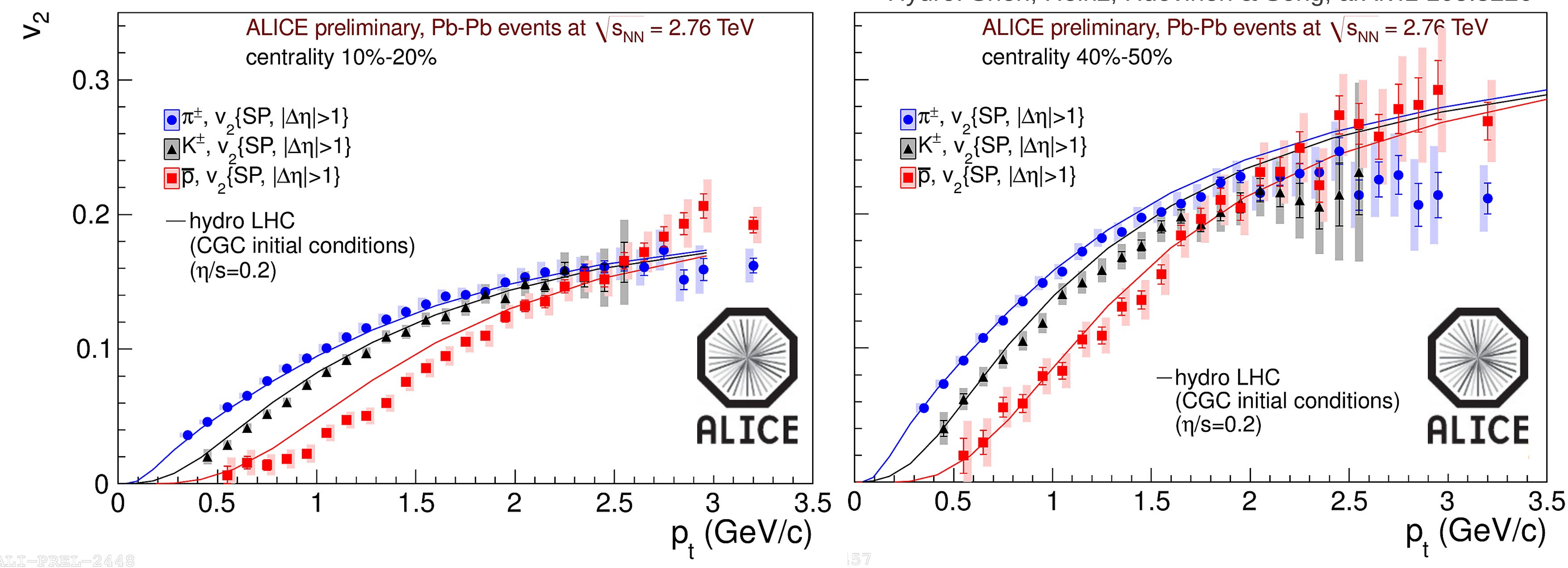
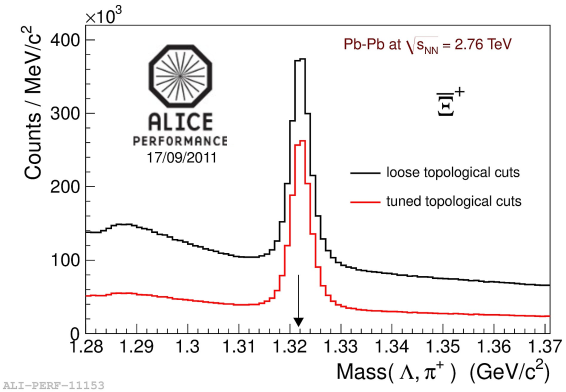
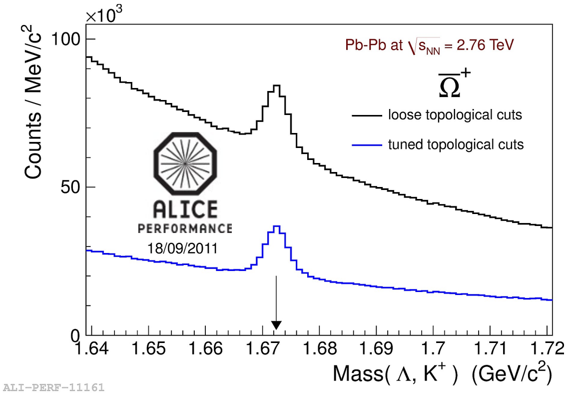



- Mass dependence of elliptic flow observed at LHC energies
- Viscous-hydrodynamical calculations reproduce $v_2$ mass splitting for pions, kaons
- Hydro alone does not reproduce protons for most central collisions
  - Additional collectivity might develop during hadronic phase

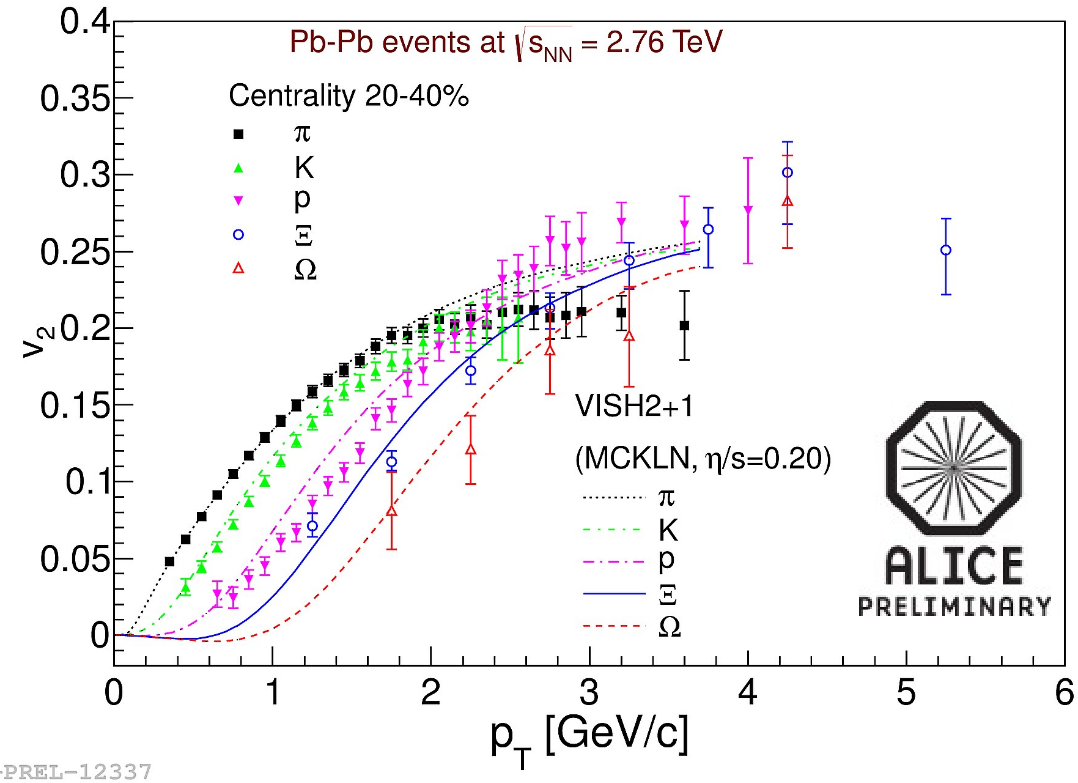
    (e.g. two-phased models: hydro+UrQMD )

# Probe for properties of the bulk



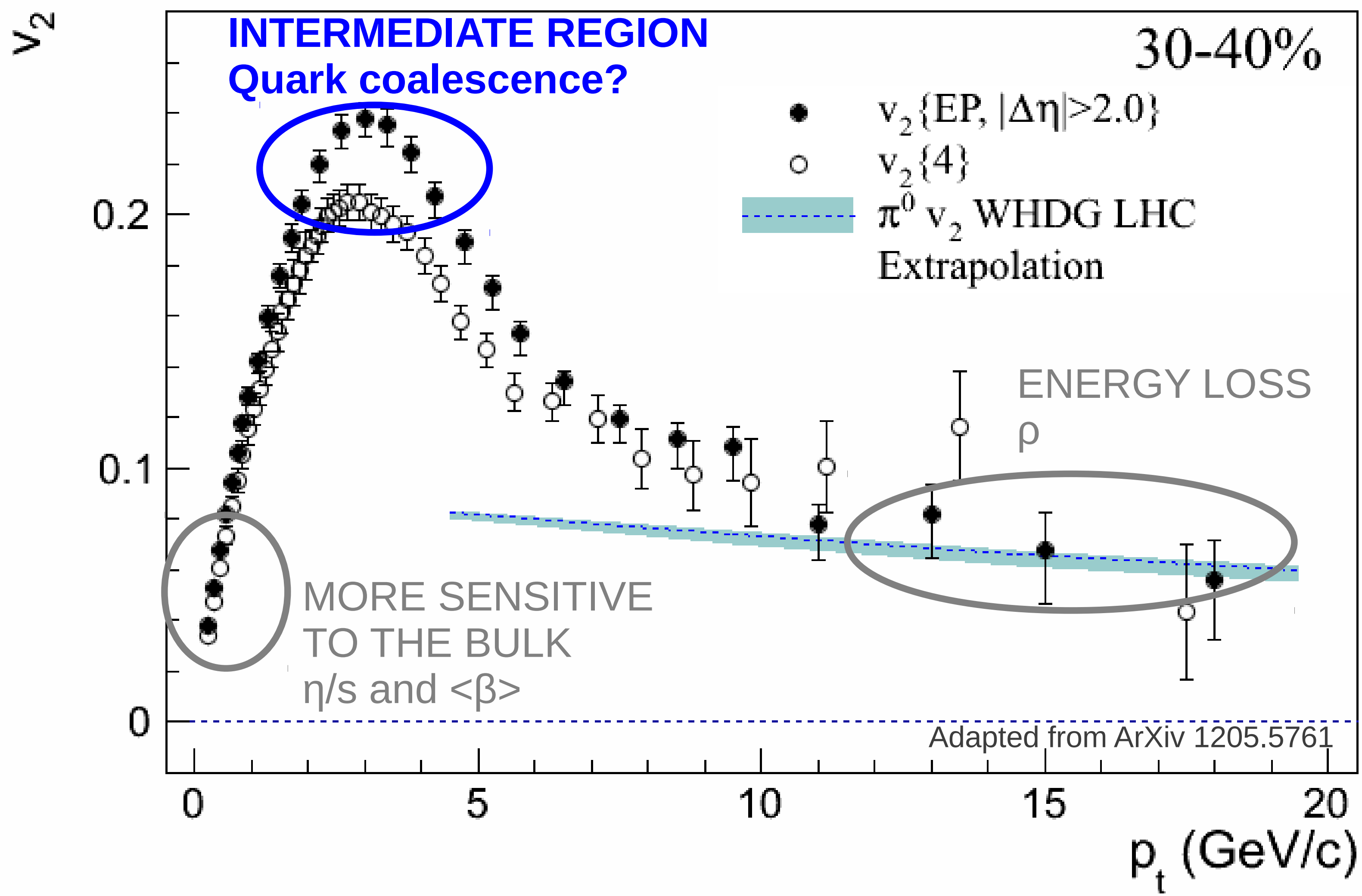




Hyperons improve understanding of the medium




- Mass dependence of elliptic flow observed at LHC energies
- Viscous-hydrodynamical calculations describe $v_2$ for pions, kaons and hyperons rather well
- Baryons develop higher elliptic flow than mesons
  - coalescence?

# Three distinct regions for analysis

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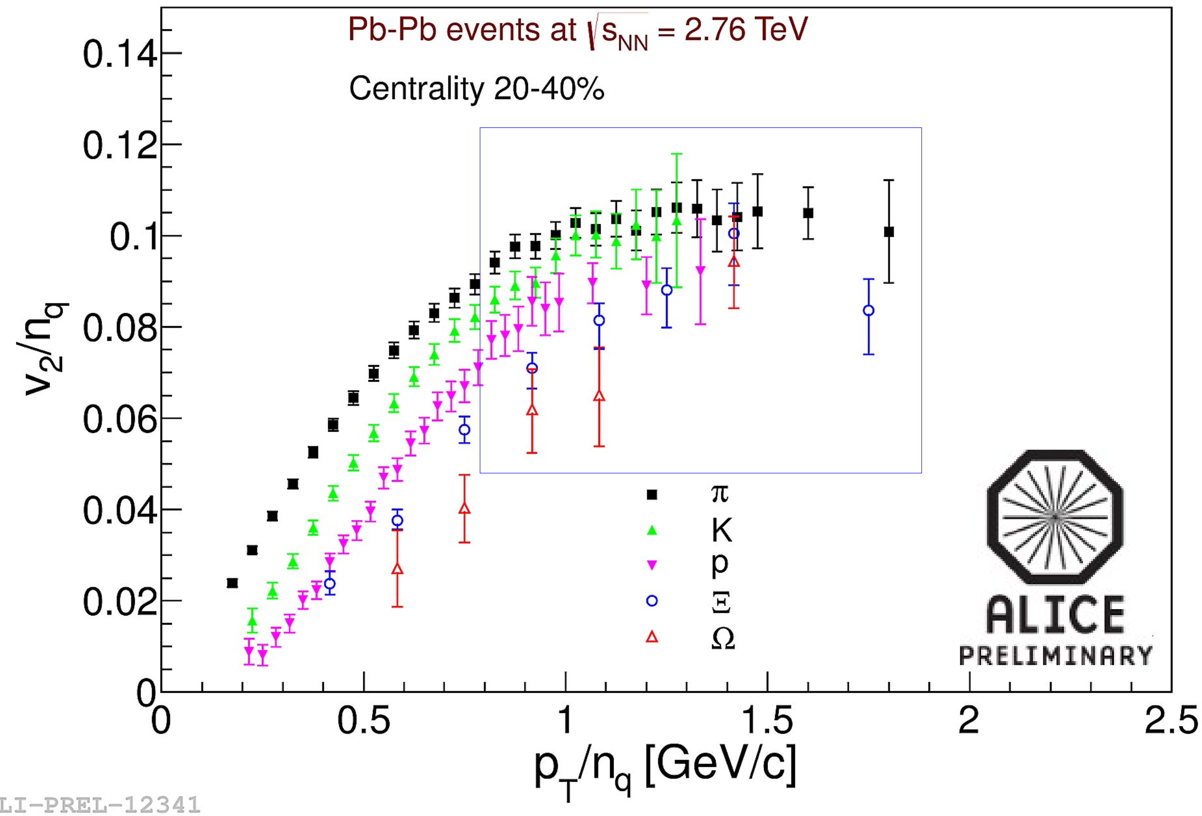
# Quark coalescence?




- Deviation from quark scaling observed
  - Original coalescence picture broken

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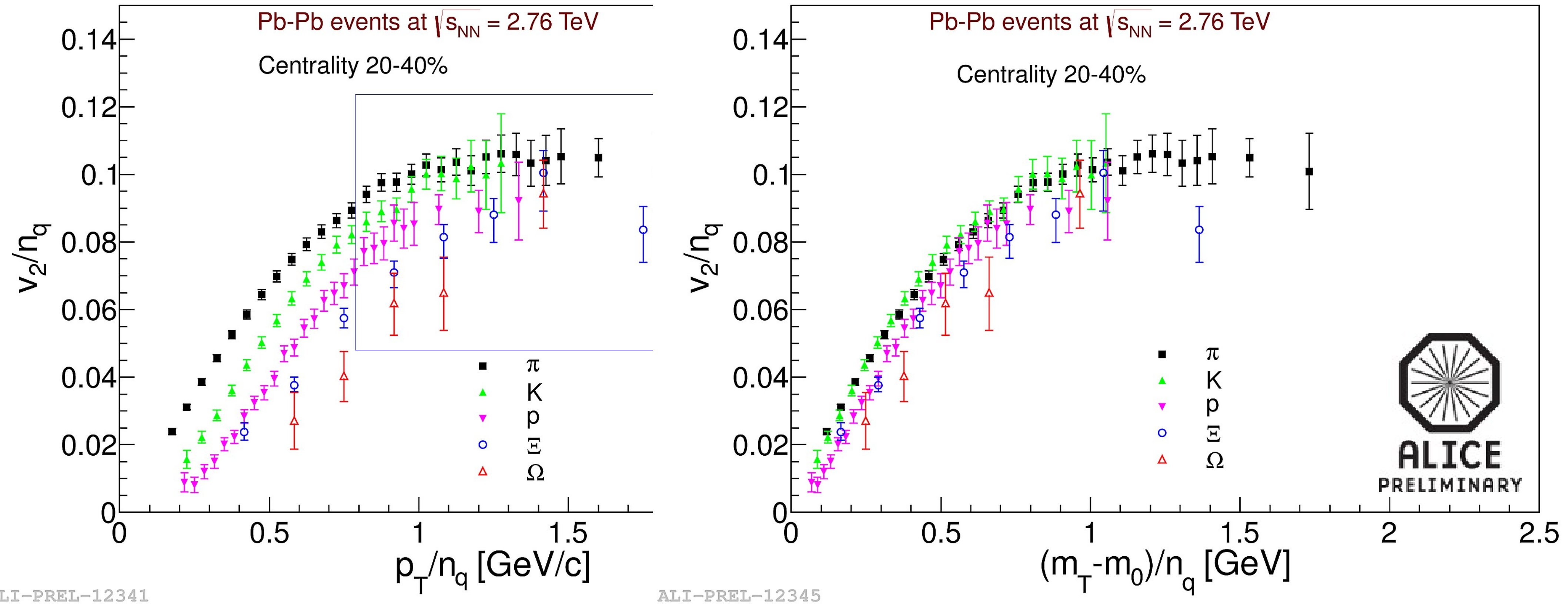
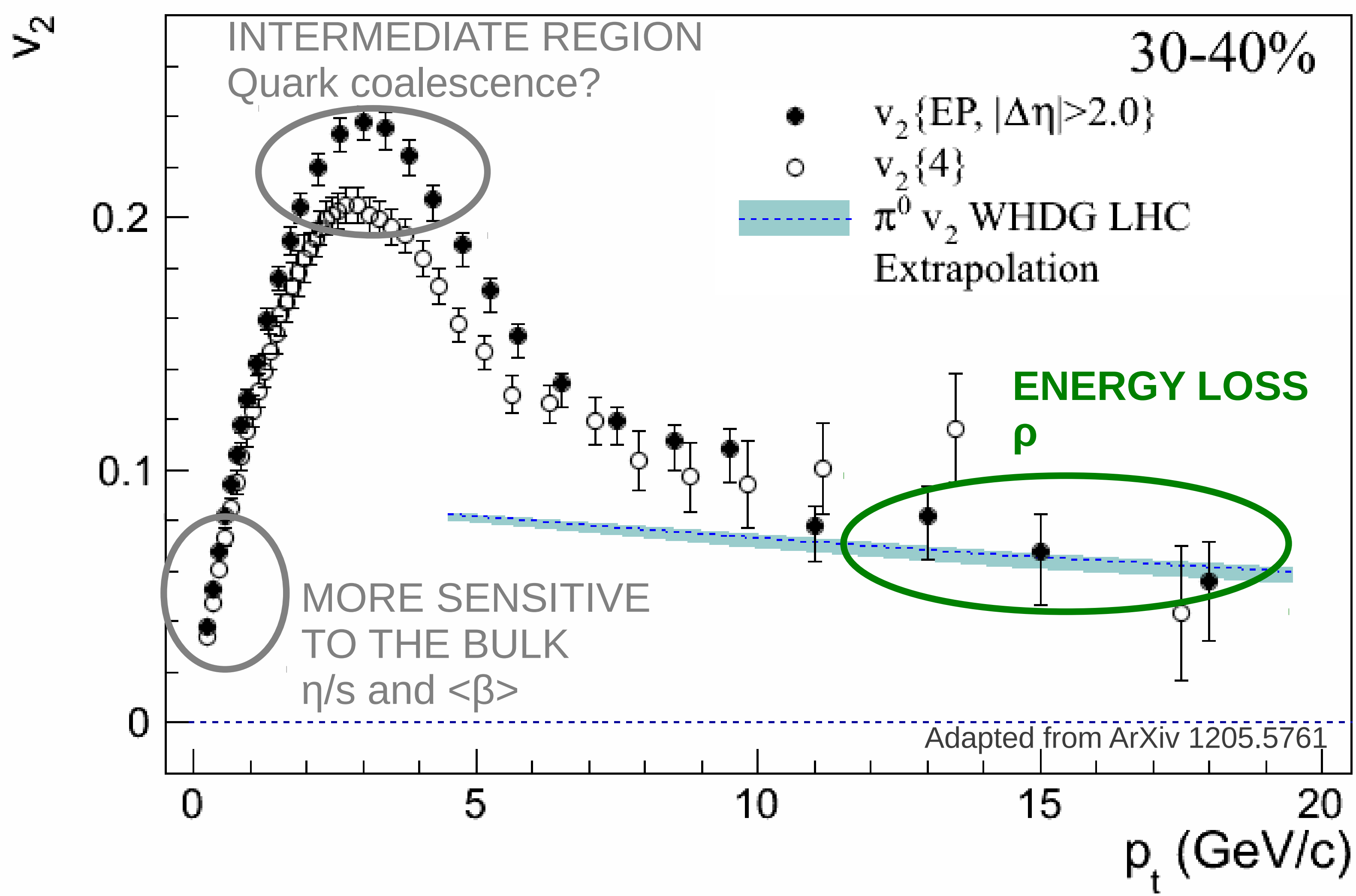



- Deviation from quark scaling observed
  - Original coalescence picture broken
- Scaled by (mt-m0)/nq baryons (and mesons separately) cluster together
- Results with higher statistics may clarify the picture

# Three distinct regions for analysis

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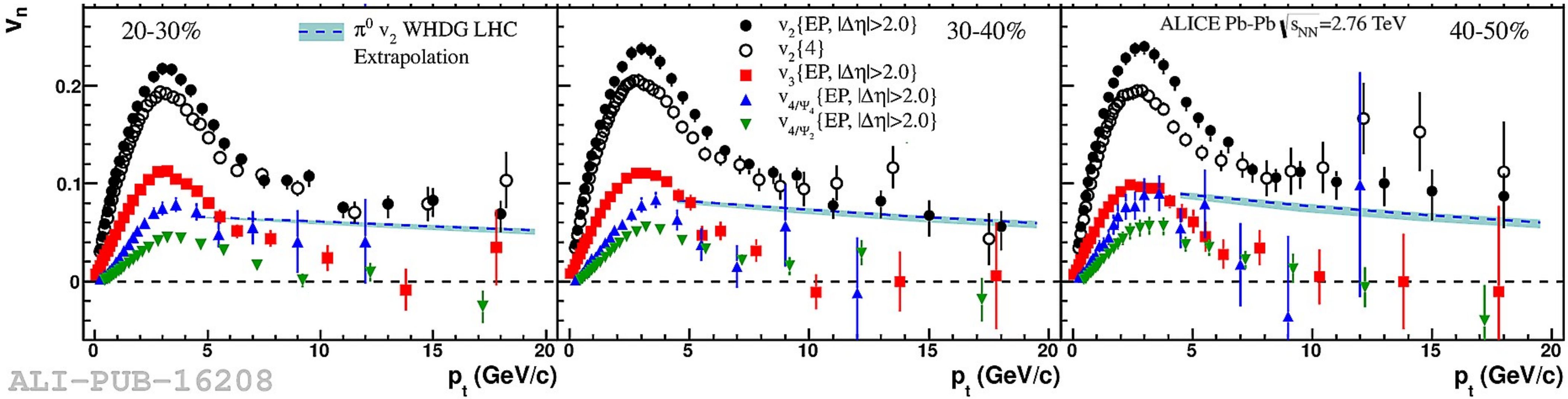
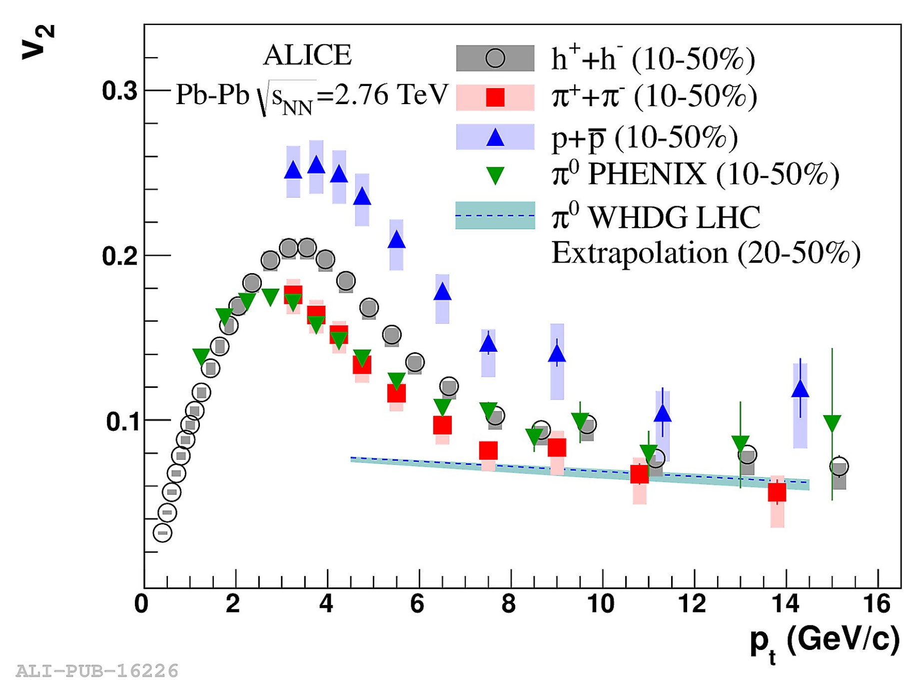
# Path dependence in medium

**More on high-pt $v_2$: A. Nyatha**

Extracted from ArXiv 1205.5761




- v2 is sizeable, positive and weakly pt dependent from 10 GeV/c for all centralities
  - WHGD (coll & rad energy loss of partons) explains fairly well the data
- Proton and pion v2 are different up to 8 GeV/c
- Measurements of other identified particles with strange quark content are coming

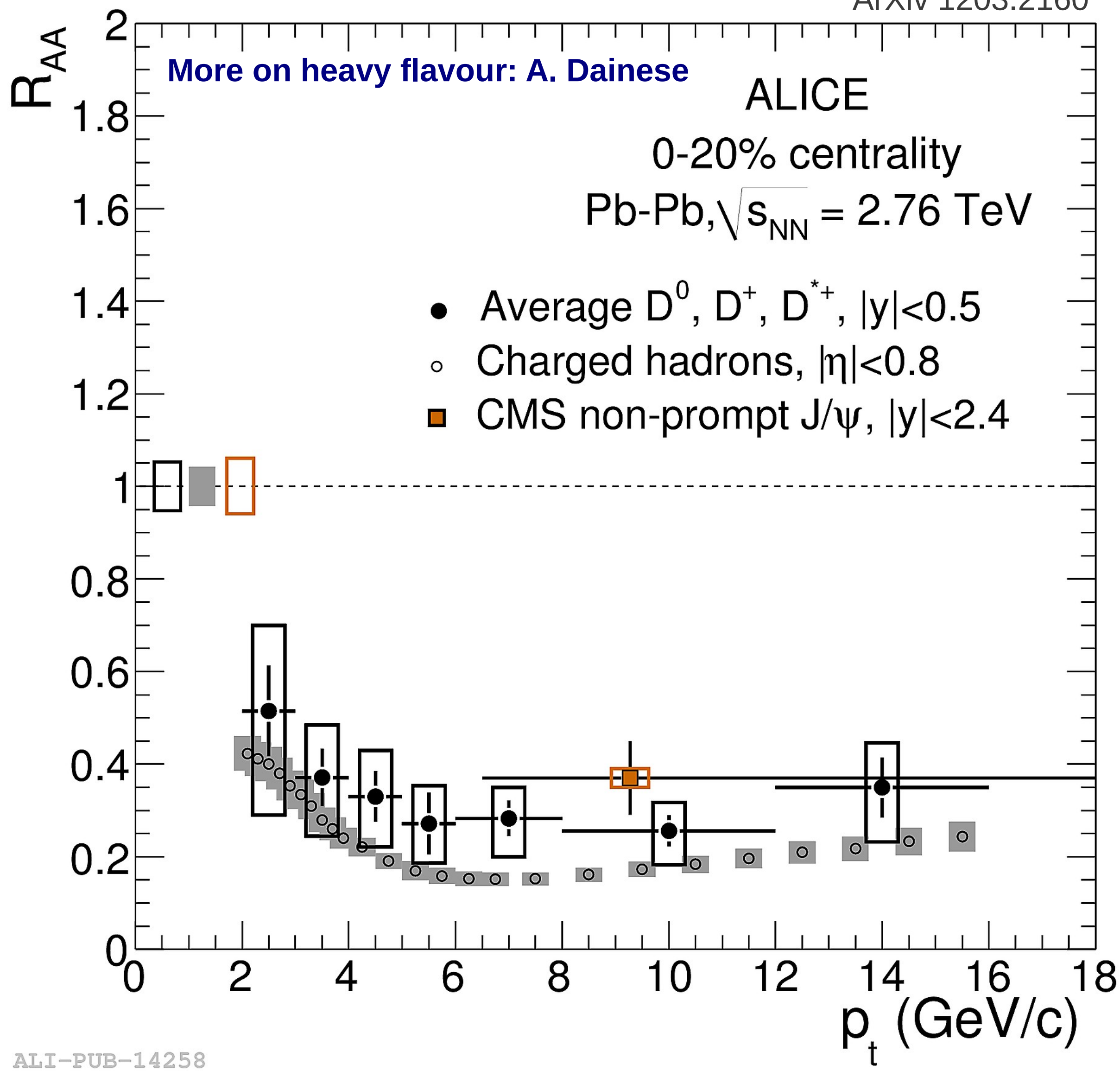


# Charm: an insightful probe

- Charm is produced in the initial collision, not in medium
  - High sensitivity to the early state of system

- Less radiative effect than lighter quarks while going through the medium?
- Path attenuation in medium might depend on azimuthal direction wrt symmetry plane
- Where (and how) does charm hadronize?

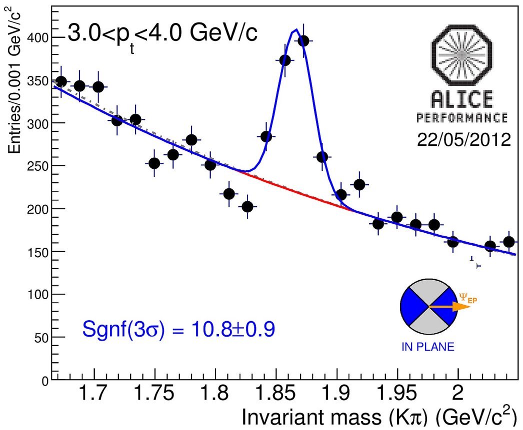
ArXiv 1203.2160

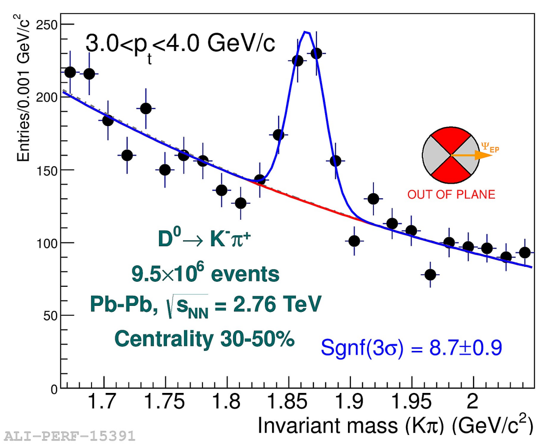


# How was the D0 $v_2$ measured?

## Two DeltaPhi Bins

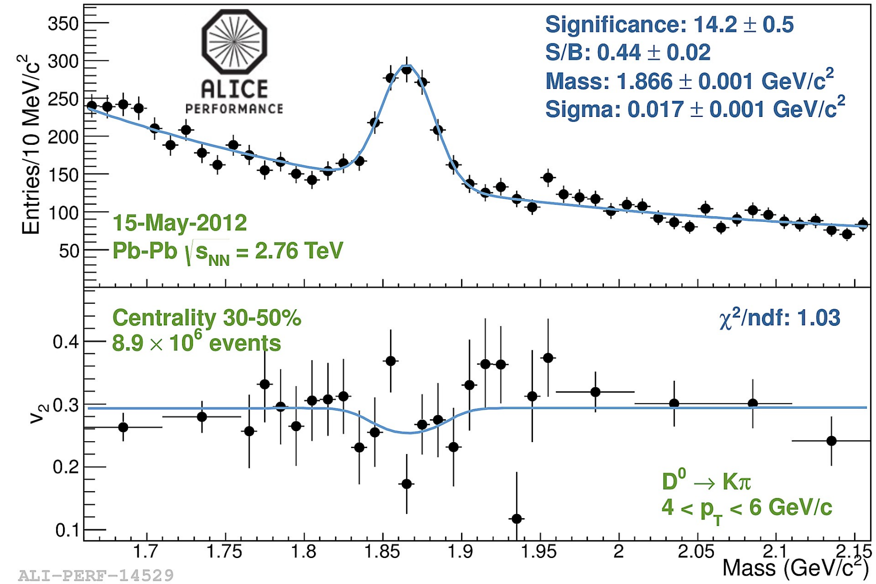
1. Divide phase space into two phi regions
2. Compute the asymmetry in yield




## Multi-band particle correlations

1. Correlate candidates per mass band with Q
2. Fit simultaneously the yield and $v_2$



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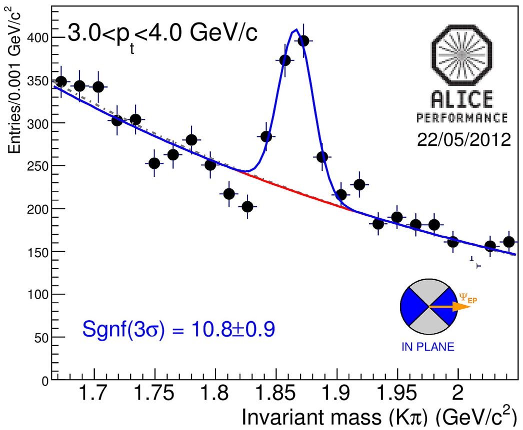


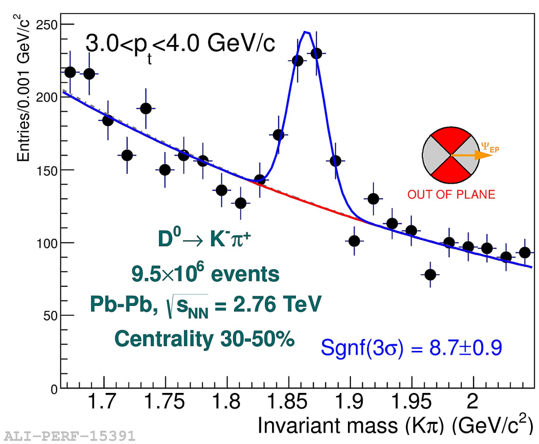


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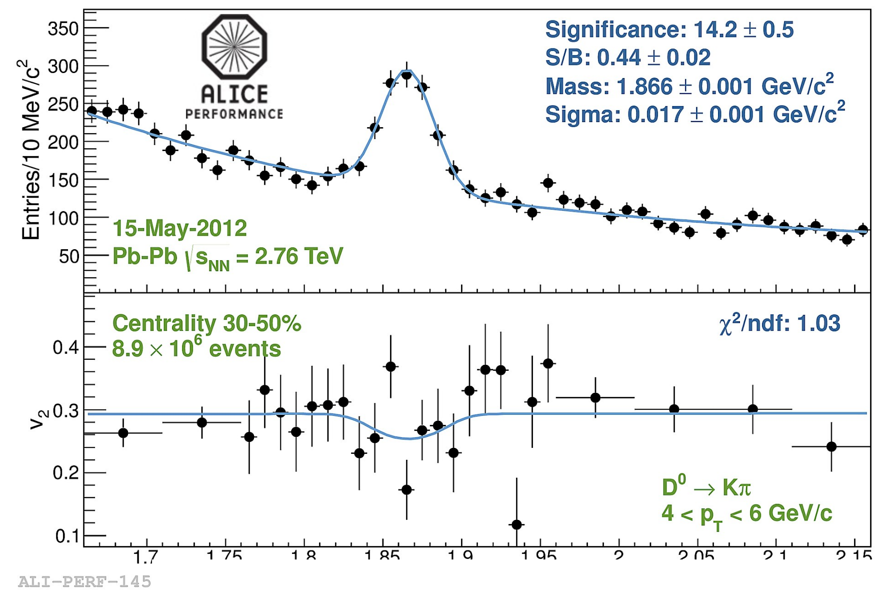
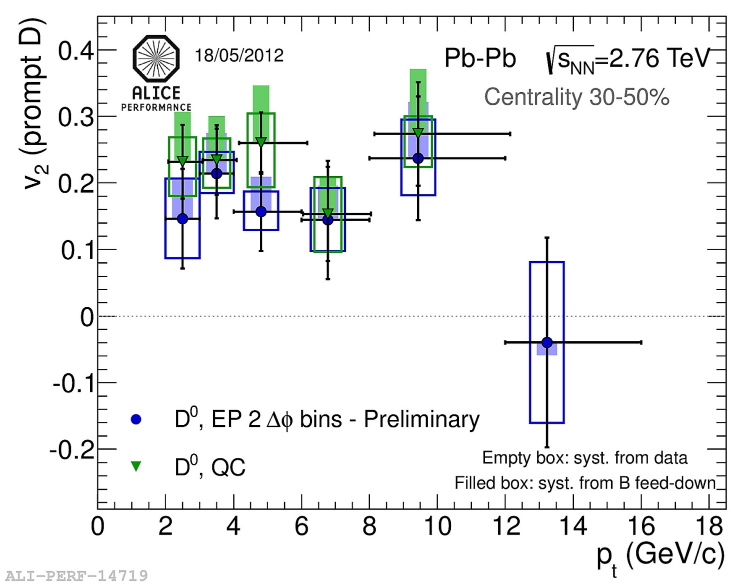
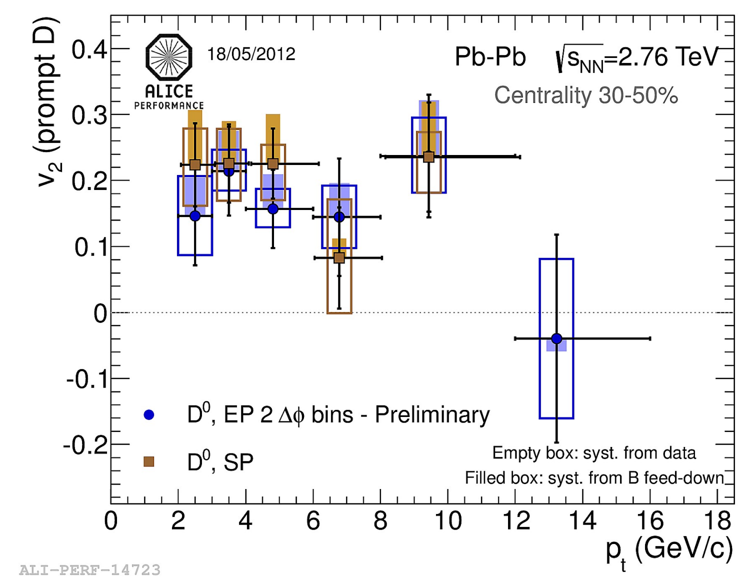



**Three different estimators arise to the same $v_2$**



# Does charm flow?

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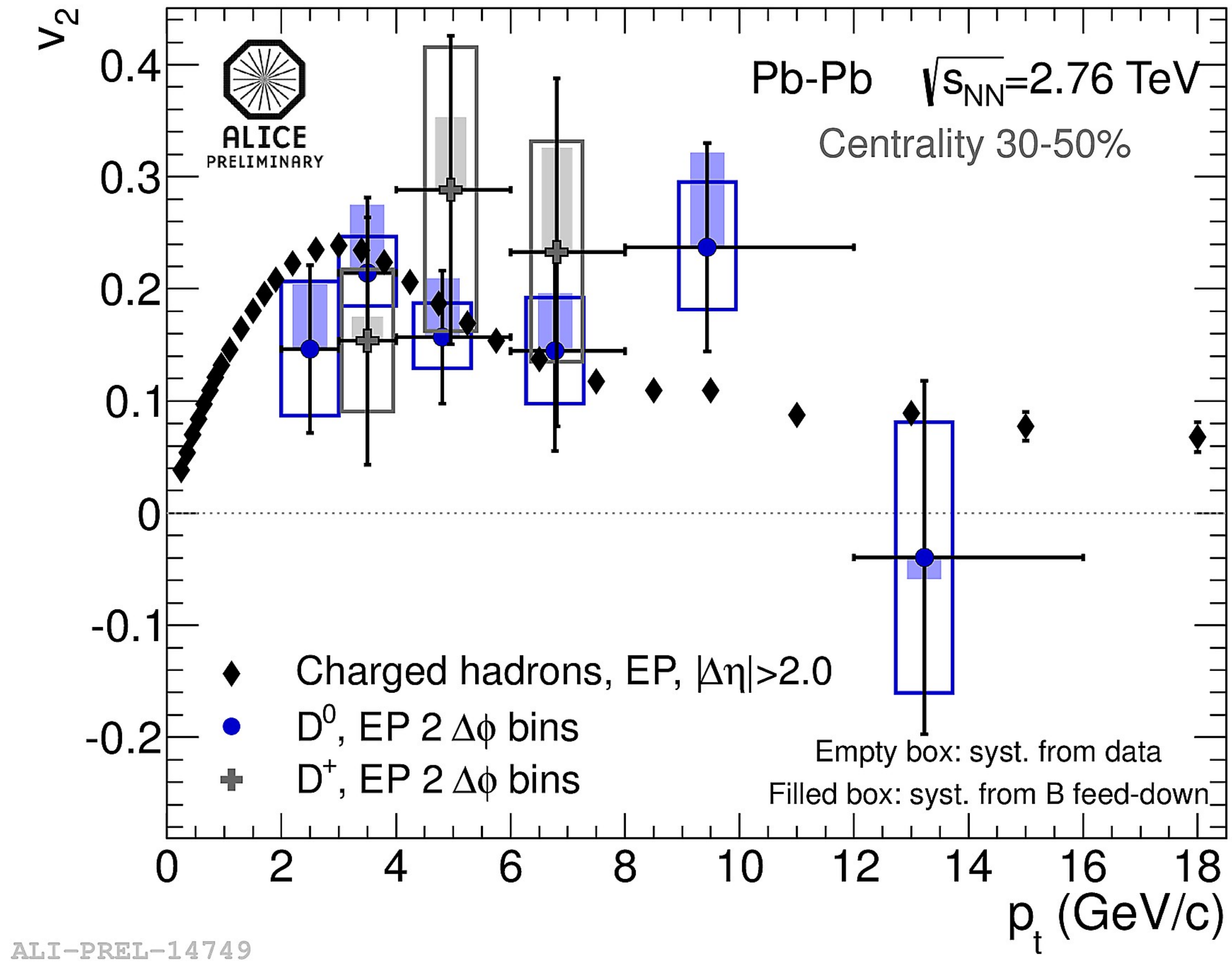
- 3σ effect for open charm in CC 30-50%
- Charm picking up light quarks from the bulk?



# Conclusions

- Anisotropic flow measurements provide strong constrains on η/s, β and ρ of the hot QCD matter

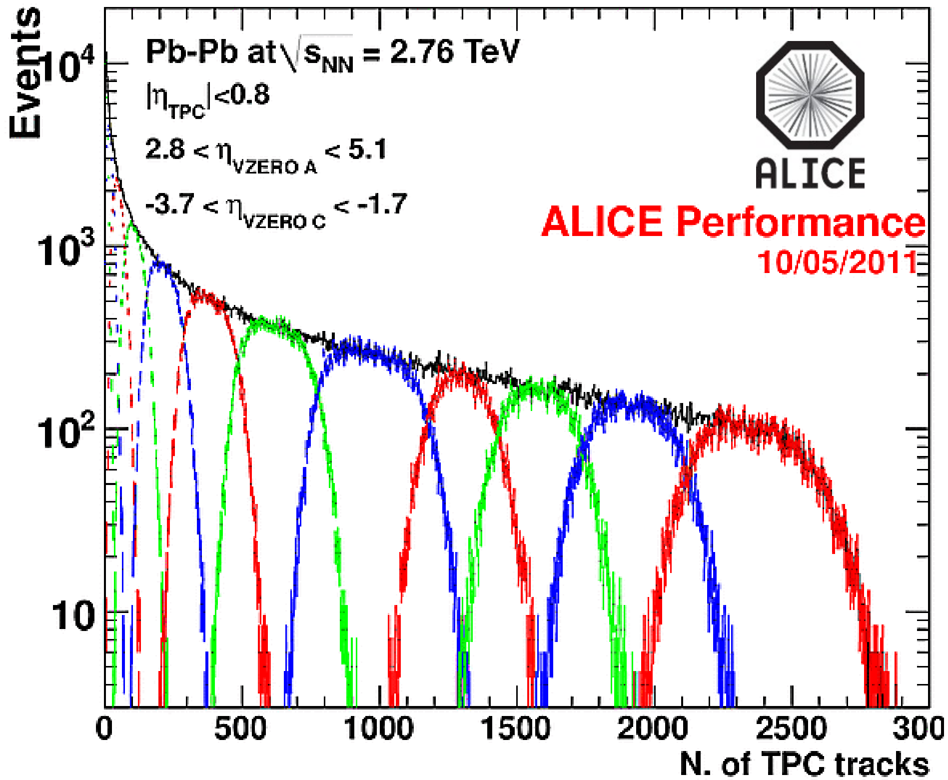
- The main features of $v_2$ below 2 GeV/c are consistent with hydrodynamic model calculations
  - $v_2$ mass splitting at LHC is larger than at RHIC top energy
  - $v_2$ of pion and kaon are described well by hydrodynamic models
  - Significant part of proton $v_2$ might be developed during hadronic phase

- We have a hint of open charm flow

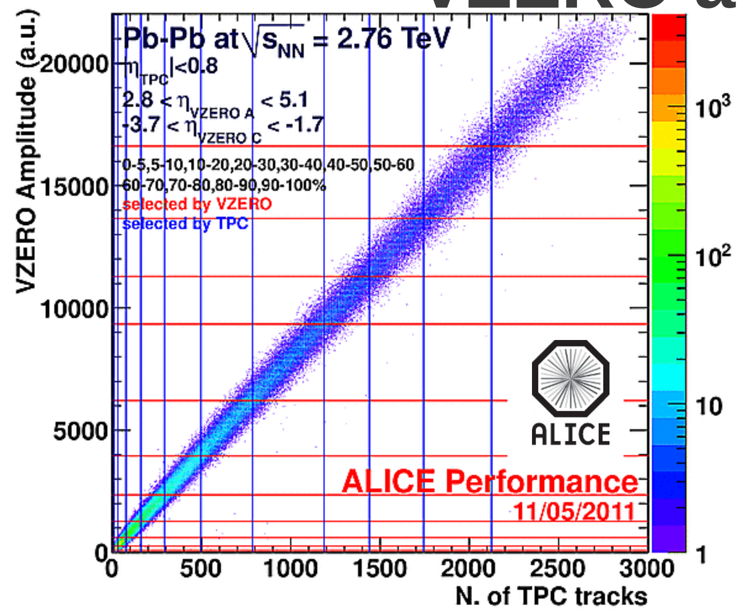
Thanks

# Frequently asked questions

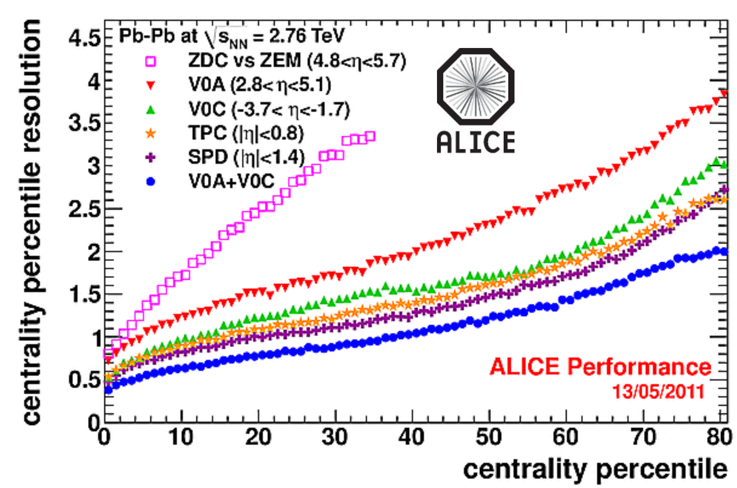
# How is the centrality determined?




**Corr. between TPC multiplicity and VZERO amplitude**



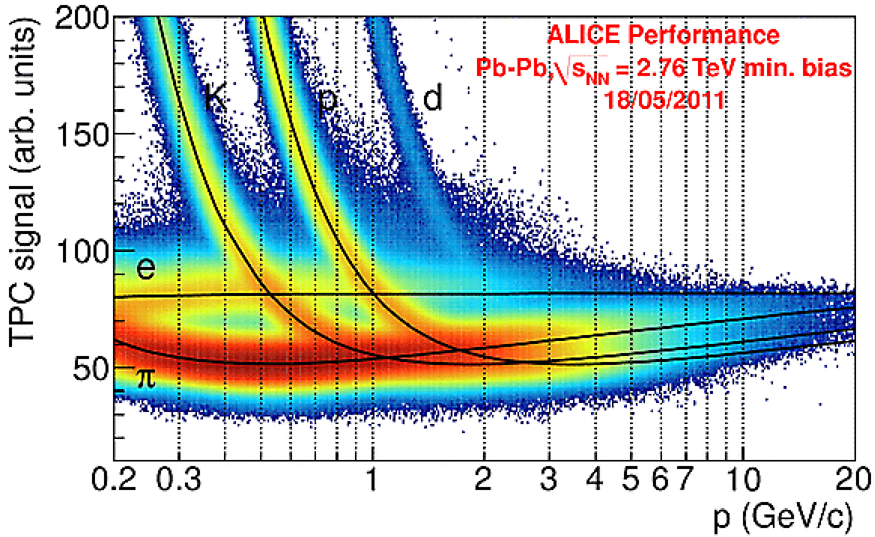

**Centrality estimated by scaling multiplicity using Glauber model**



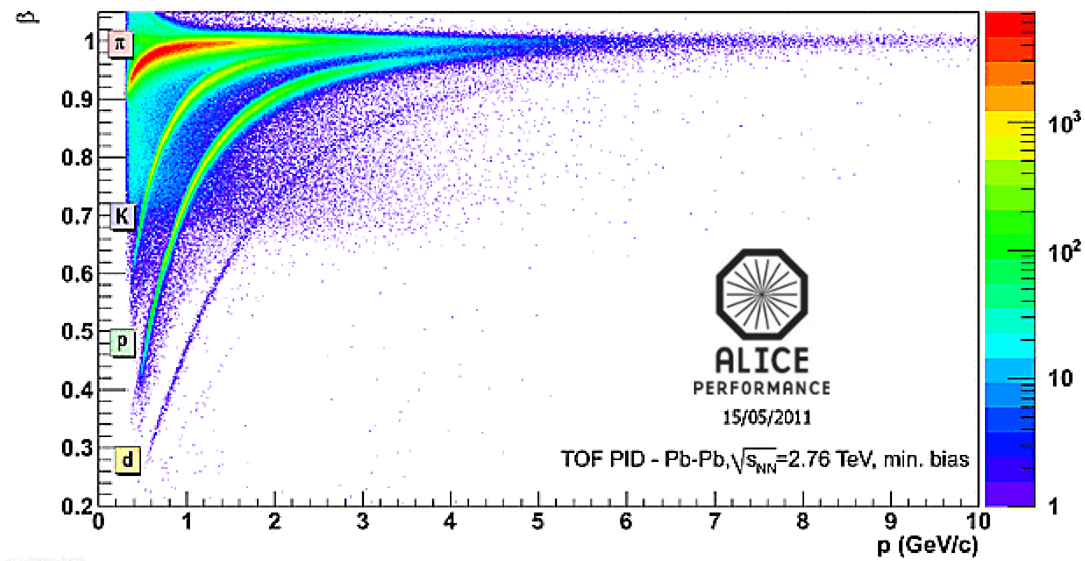

More details in PhysRevLett.106.032301

# How does ALICE identify particles?

## Time Projection Chamber (TPC)




## Time Of Flight (TOF)

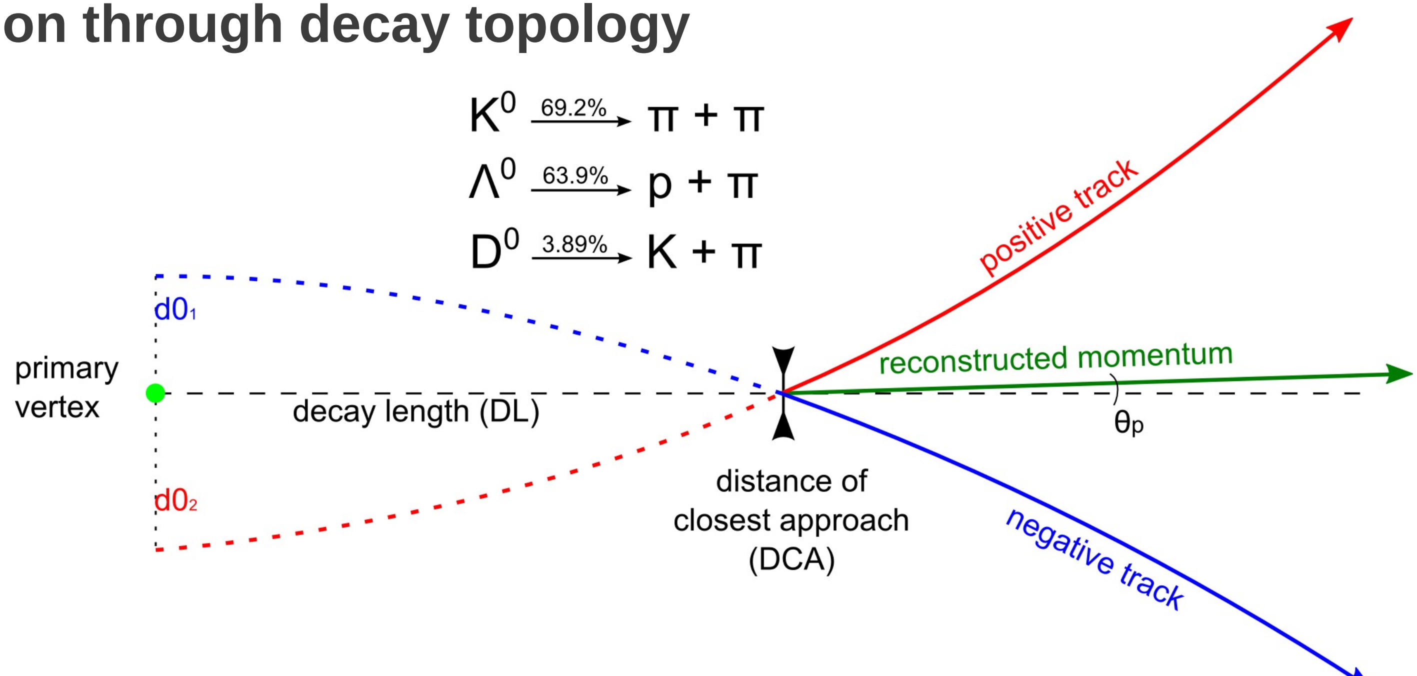



## Reconstruction through decay topology

$K^0 \xrightarrow{69.2\%} \pi + \pi$

$\Lambda^0 \xrightarrow{63.9\%} p + \pi$

$D^0 \xrightarrow{3.89\%} K + \pi$



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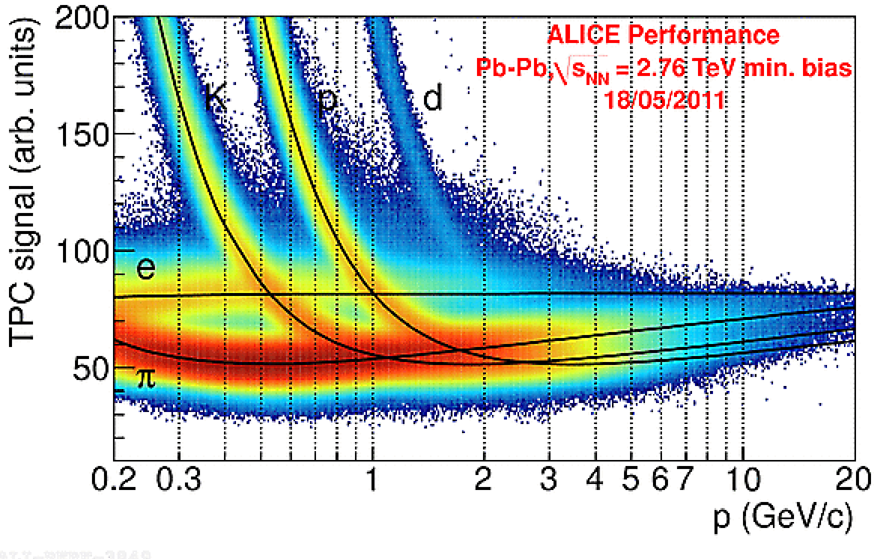


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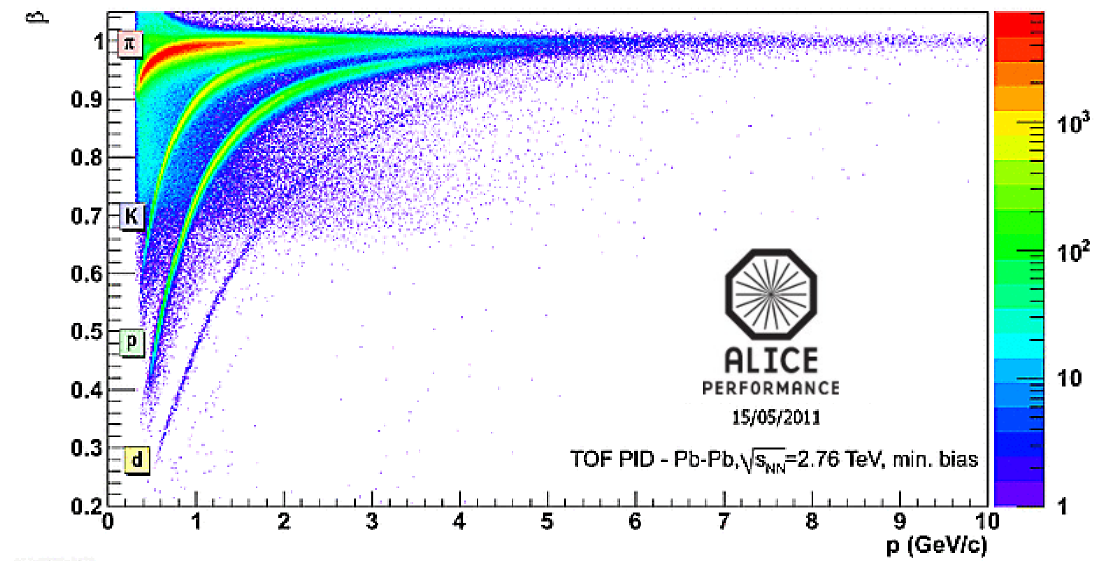
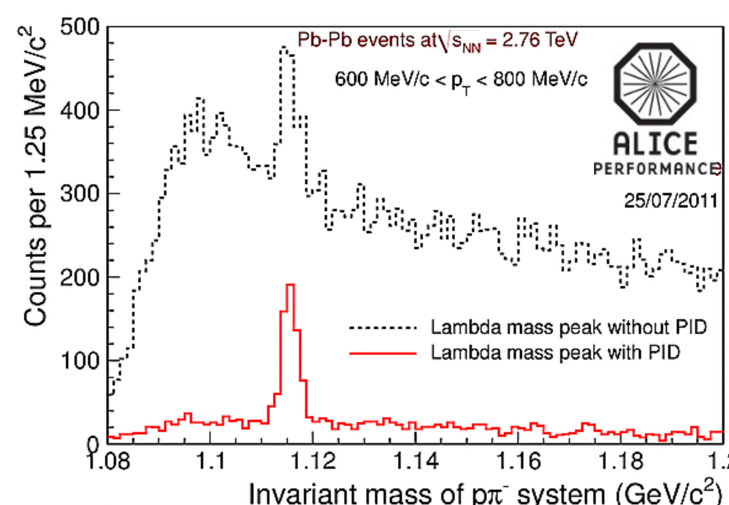
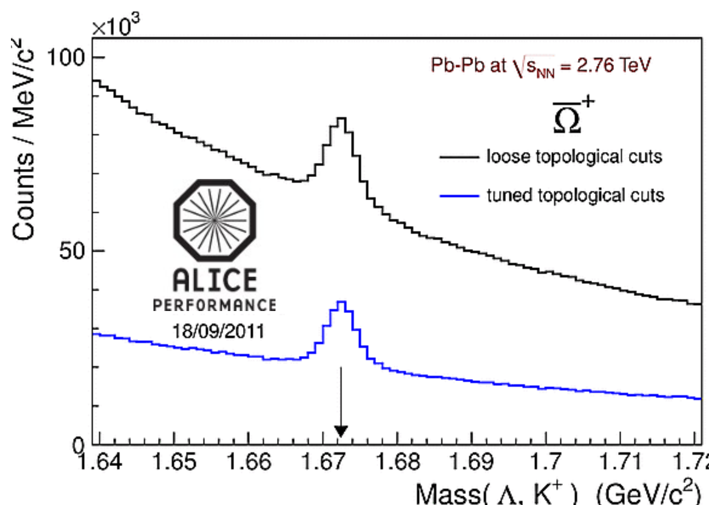
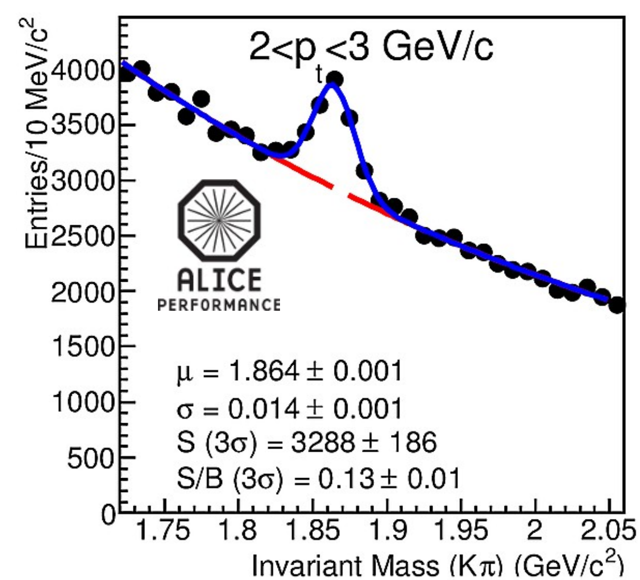


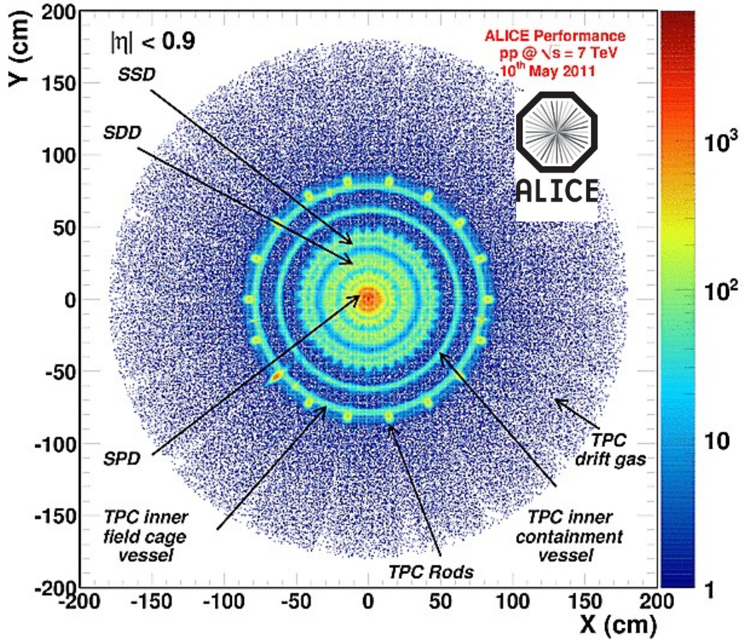

- Single track PID: we can go down to 0.15 GeV/c
- n-prongs and cascades also down to very low pt

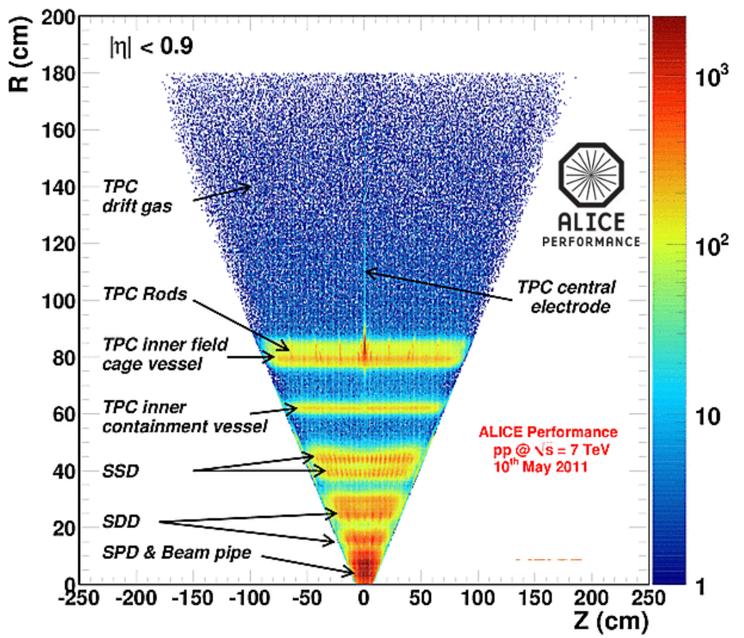


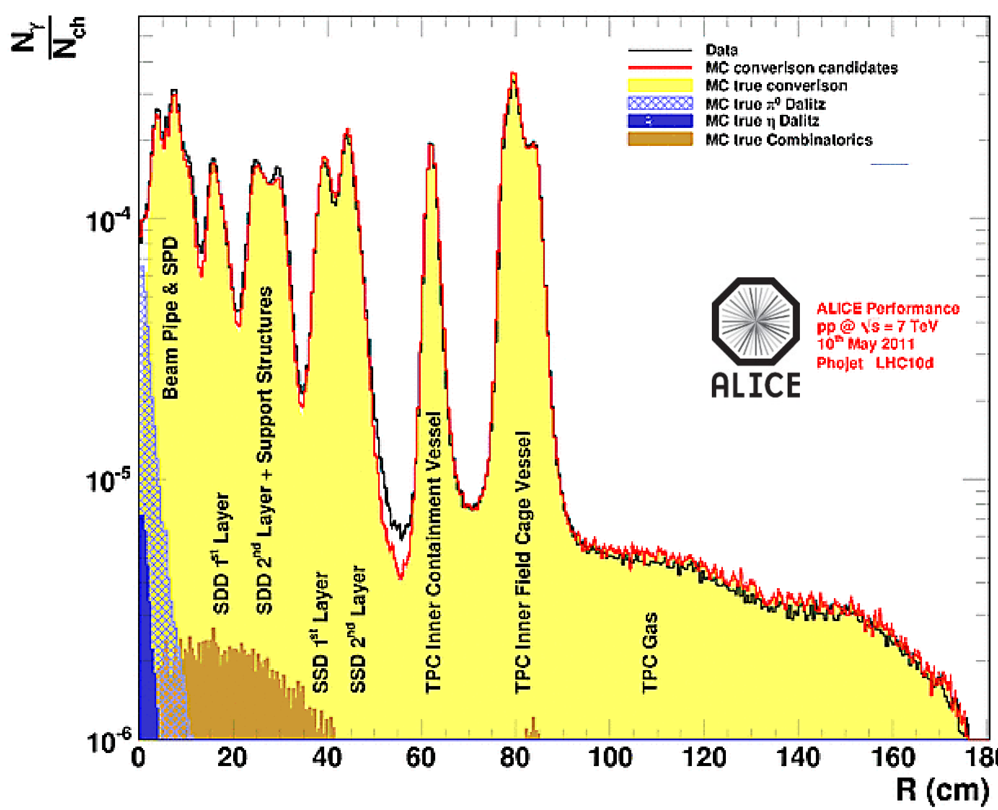



# What about conversions?



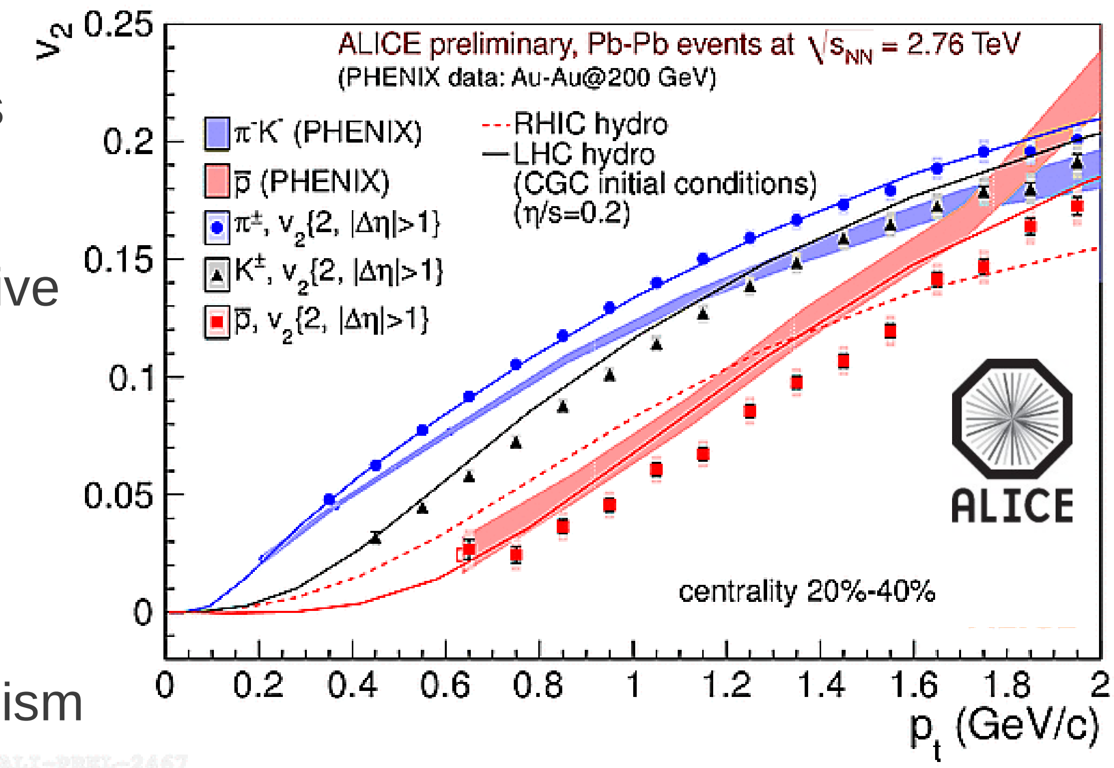

**Very light material budget allows for high precision low pt tracking and vertex determination**



# vn of identified particles says more

Level 1: Hadron analysis

- **Radial** flow boosts **spectra** of species
- **Elliptic** flow constrains η/s
  - Higher harmonics even more sensitive to shear viscosity




Level 2: Parton analysis

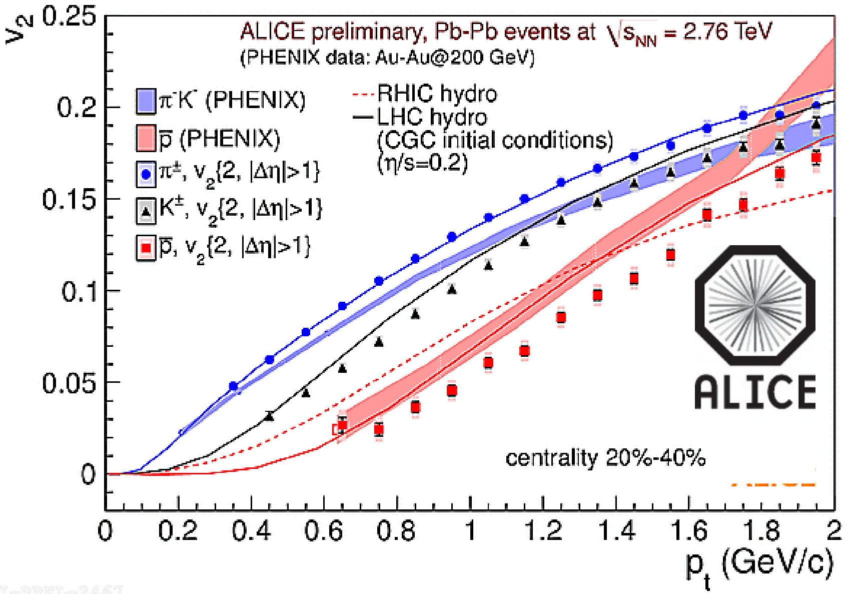
- Collectivity of **deconfined partons**
- Handle on particle production mechanism

Level 3: Hot QCD system analysis

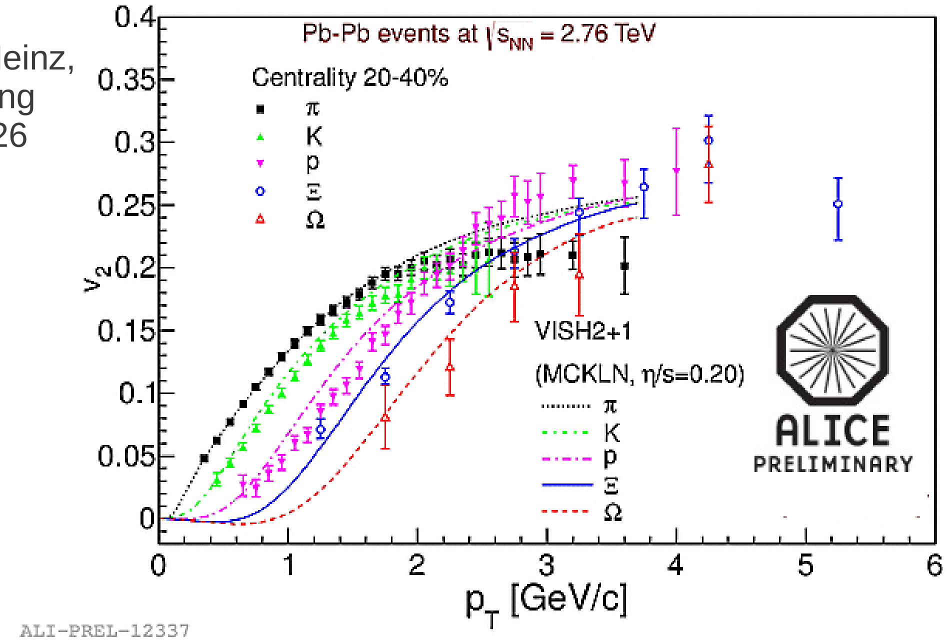
- All different components give strong constrains to the thermodynamic properties of the rapidly expanding QCD matter

**Complementary information for all-in-one characterization (together with spectra, abundances, HBT, particle correlations, quenching, … )**

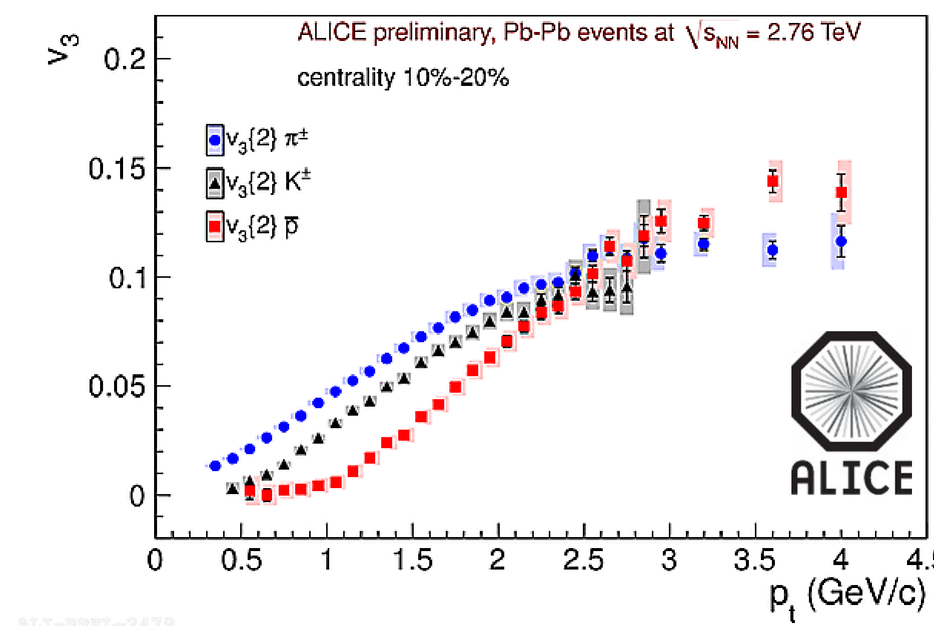
# “Flow”



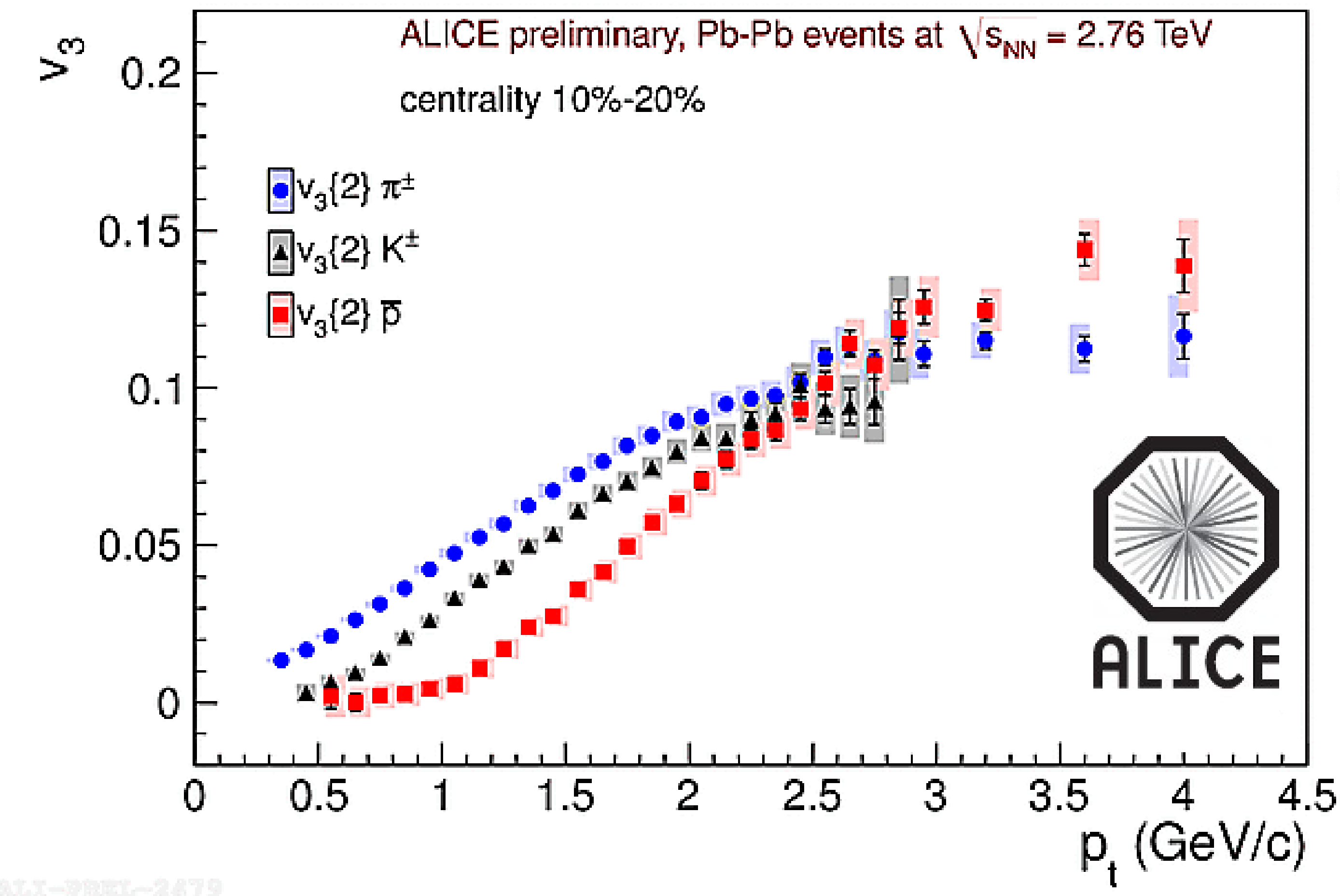

Hydro: Shen, Heinz, Huovinen & Song arXiv:1 105.3226

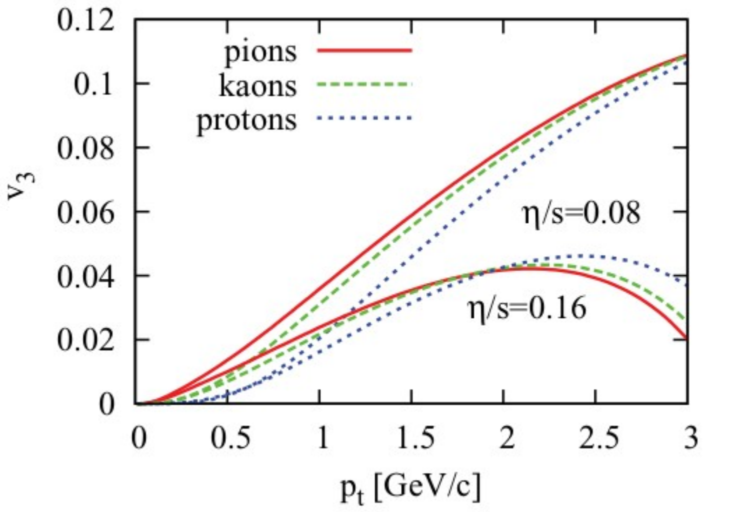



- Mass dependence of elliptic flow also observed at LHC energies
- Viscous hydro describes v2 for pions and kaons rather well
  - For protons, there is a clear discrepancy
- Low viscosity of the system allow for sizeable higher harmonics
  - Mass ordering from Hydro also observed



# v3 as a more sensitive η/s probe

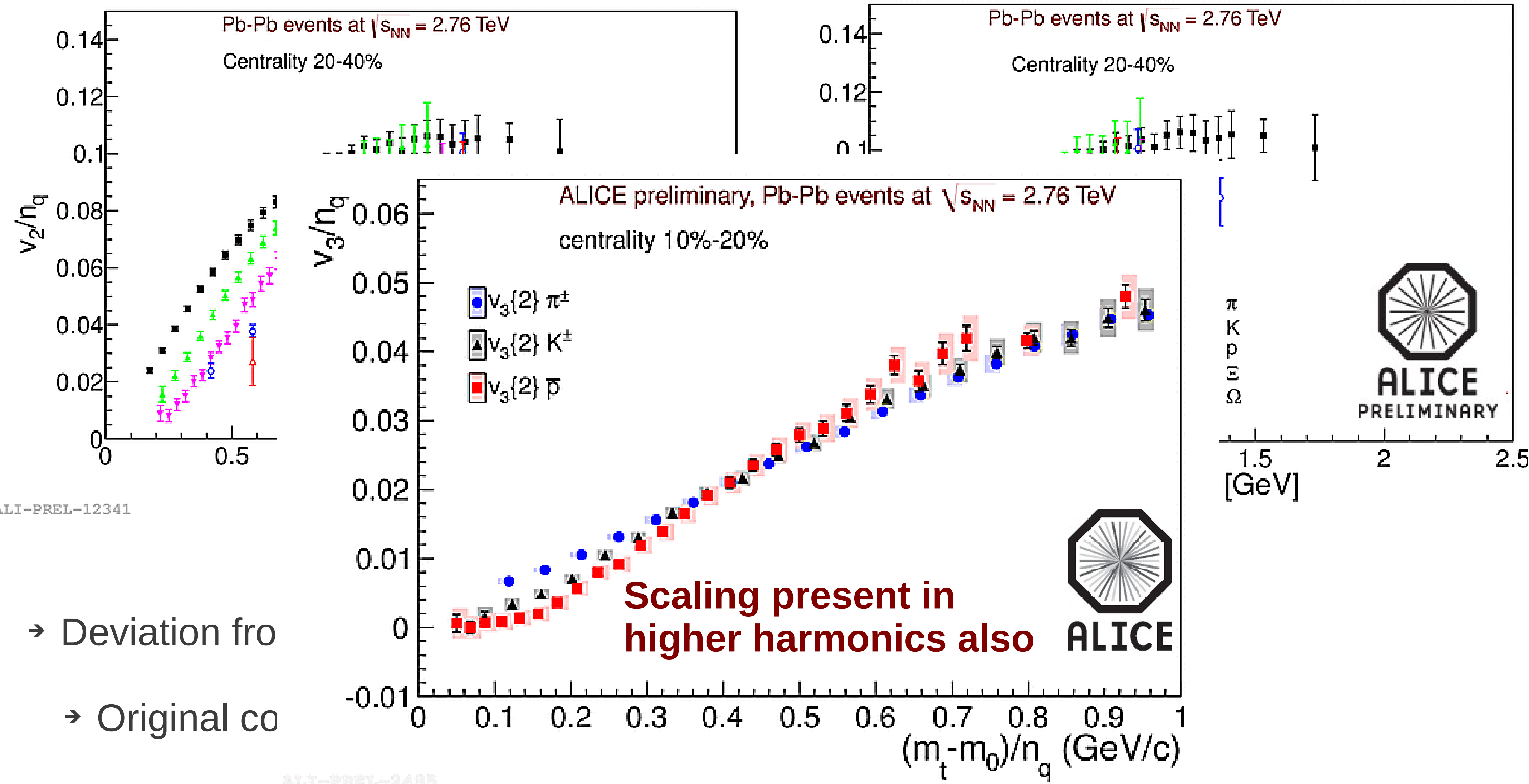



Hydro: Alve, Gombeaud, Luzum & Ollitrault
Phys. Rev. C 82 034913 (2010)

- Low viscosity of the system allow for sizeable higher harmonics
  - v3 expected to be even more sensitive to η/s
- v3 also present mass ordering as predicted by hydrodynamical models

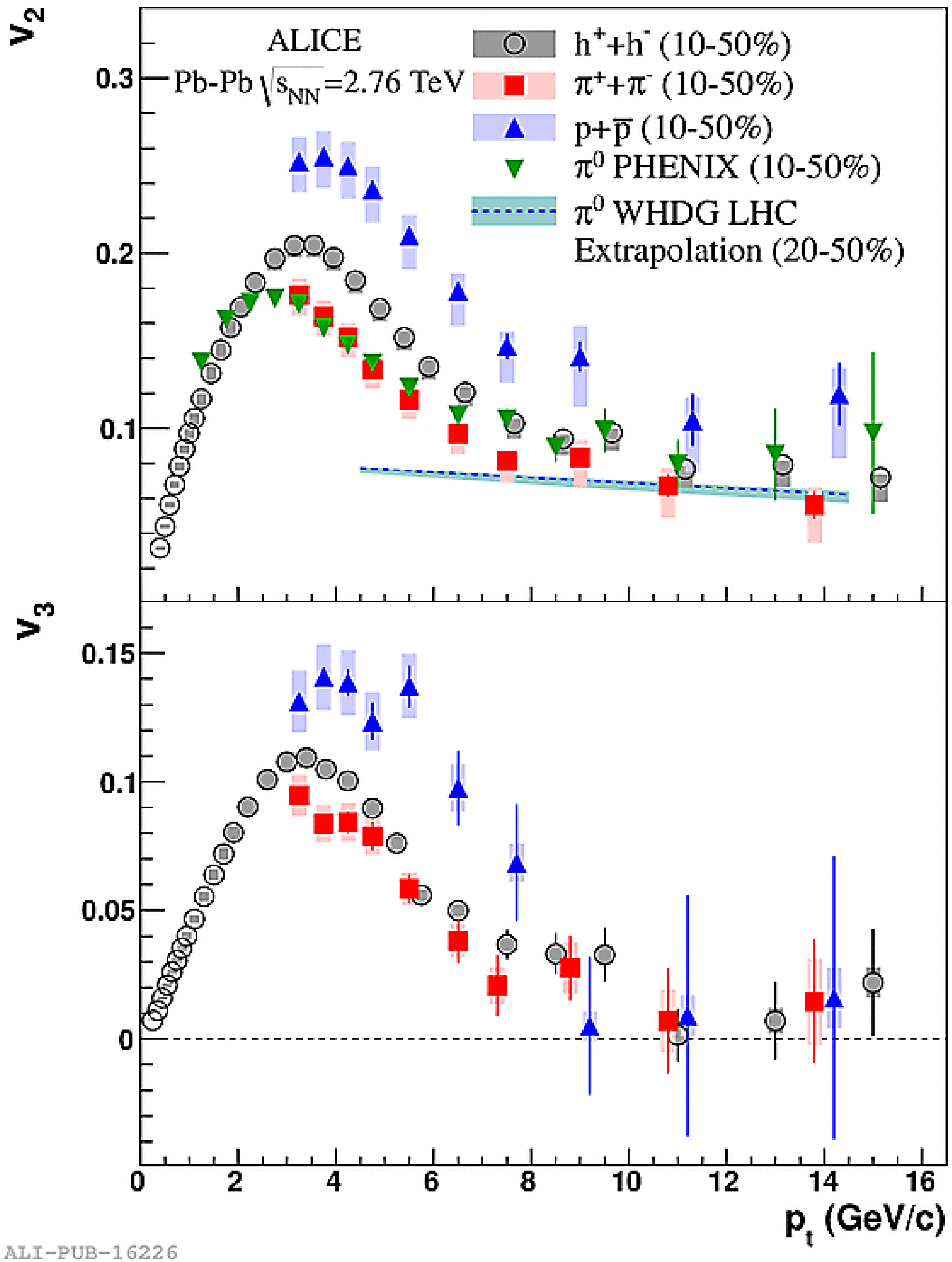
# Probe for hadronization mechanism




- Deviation fro
  - Original co
  - For (mt-m0)/nq scaling, Xi and omegas cluster together with protons.
    - Meson-baryon “mechanism”?

# Punch-through of jet though medium?

ArXiv 1205.5761




- Protons v2 is significantly higher than pion v2 up to 8 GeV/c
  - Qualitatively explained by models

# How is the event plane determined?

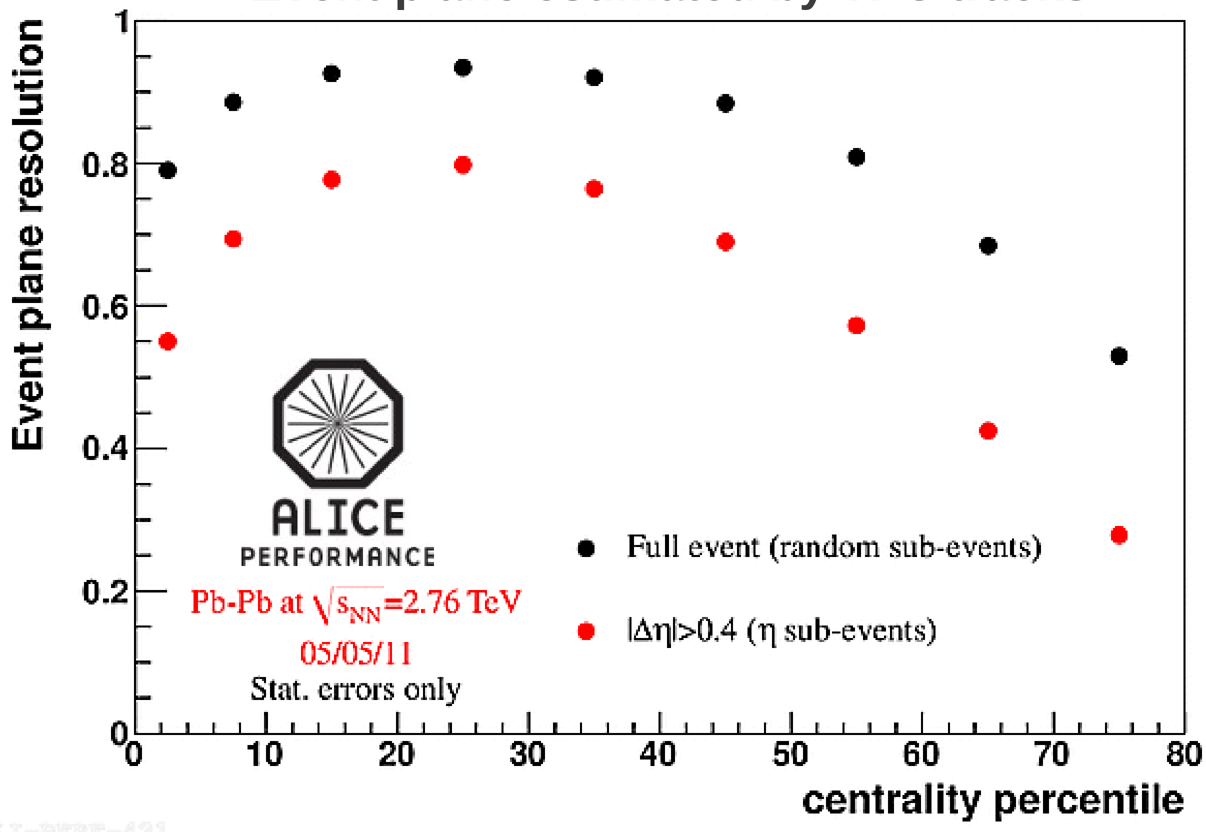
**The Q vector**

$$Q_n = \sum_{i=1}^{M} \mathrm{Exp}[i n \phi_i]$$

**The "Event Plane" angle**

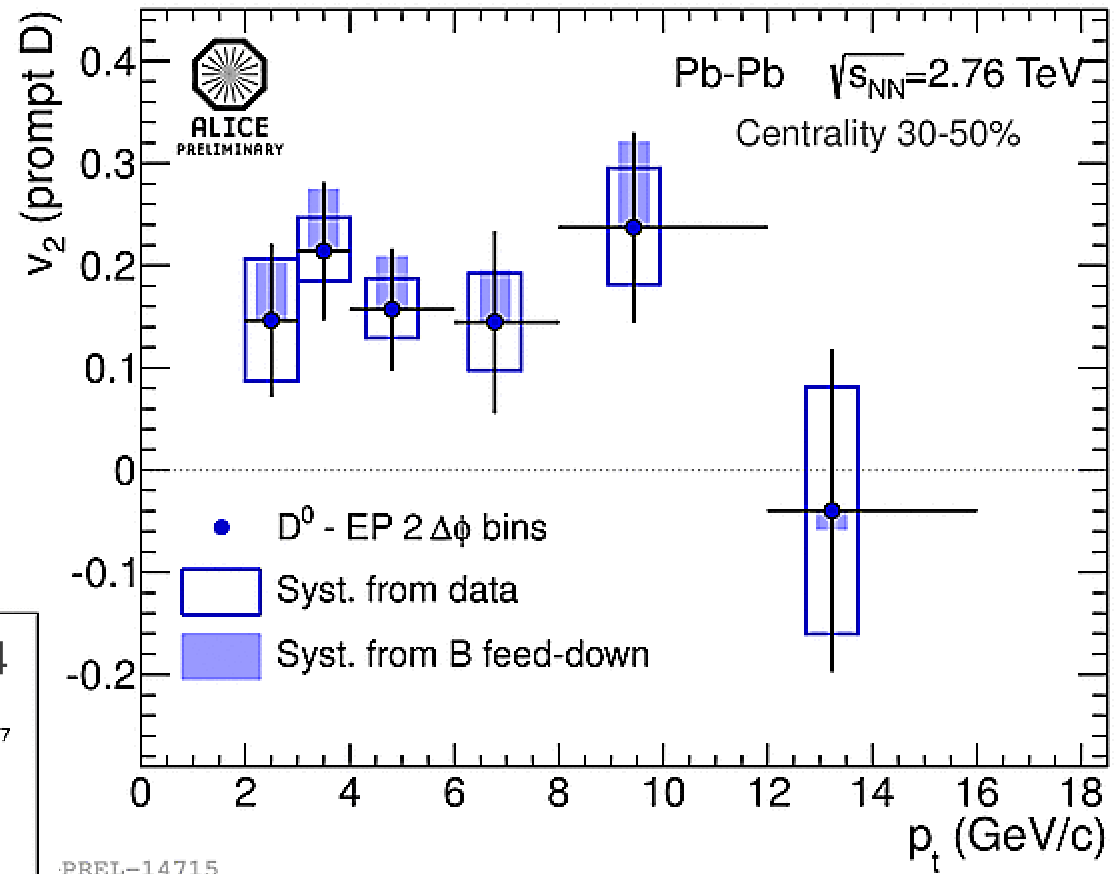
$$\psi_2 = \mathrm{Arg}[Q_2]$$

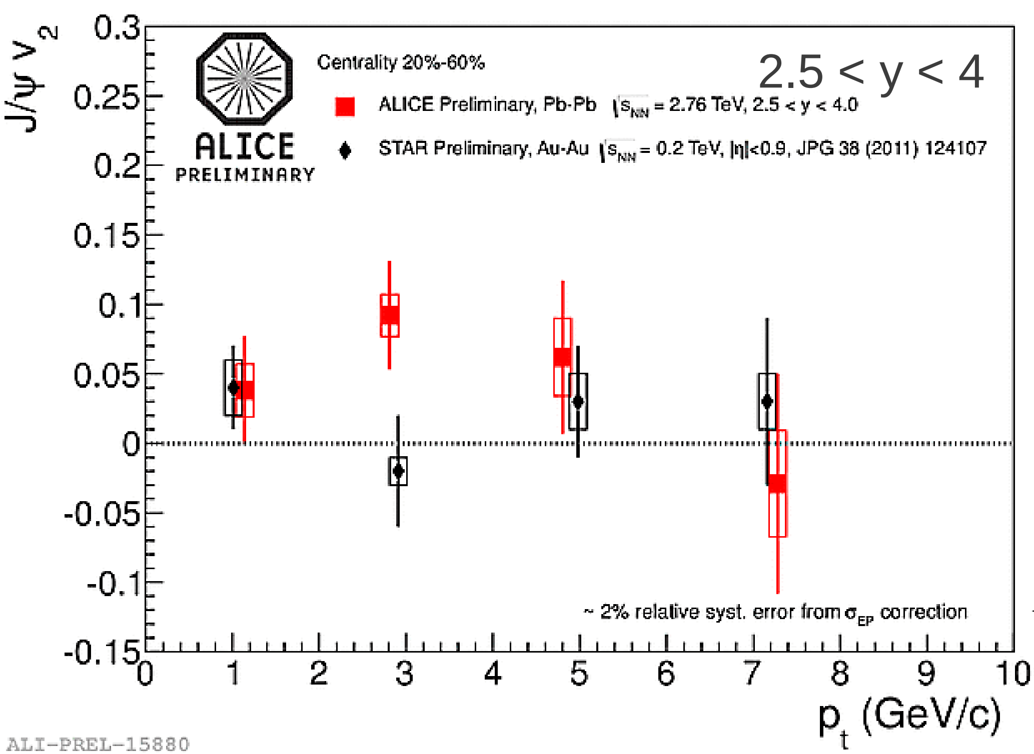
**Event plane estimated by TPC tracks**



# Does charm flow?

- Charm picking up quarks from the bulk?
- At low pt (2-5 GeV/c) there may be room for sensitivity to the bulk
  - 3 sigma effect for open charm in CC 30-50%




- 2.2 sigma effect for in-plane anisotropy in forward quarkonia in 2-4 GeV/c

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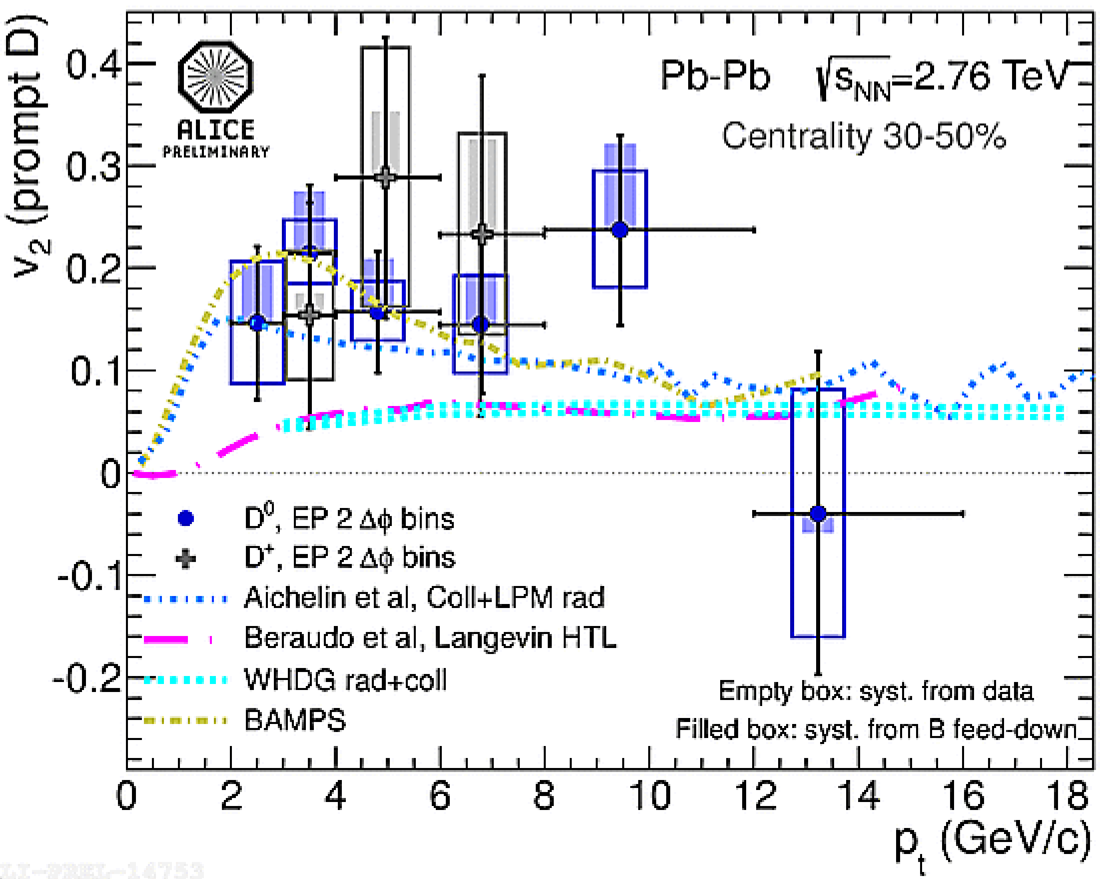
- At low pt (2-5 GeV/c) there may be room for sensitivity to the bulk
  - 3 sigma effect for open charm in CC 30-50%
- Some of the available models for charm reproduce the effect
  - But failed to ensemble it together with the nuclear modification factor




Exciting times ahead!