Flow coefficients of identified particles in large and small systems

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Flow of identified particles...

Is a rather **broad** topic ... especially for 30 minutes

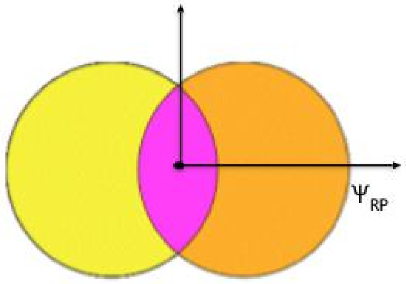
These slides: very **incomplete** overview of some **recent** results

Apologies in advance if I **miss** something .... or lean to much towards ALICE

That's what the **discussion** is for !

Starting with a QM2018 slide from You Zhou ... :

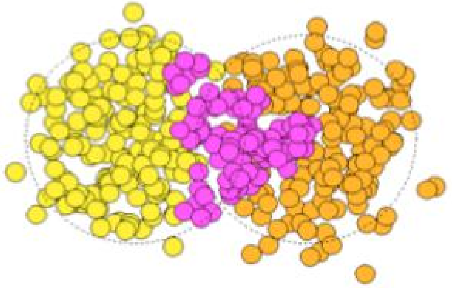
1992



$v_2\{\Psi_{RP}\} = \langle \cos 2(\phi - \Psi_{RP}) \rangle$

Ψ_{RP}: Reaction Plane

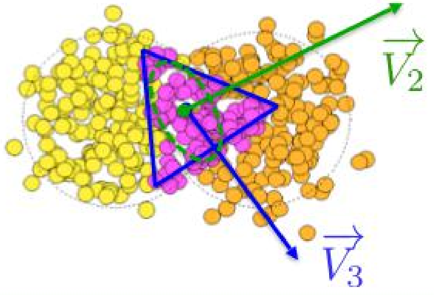
2010



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

- Flow coefficient v_n
- E-by-E v_n fluctuations

2014



$\vec{V_m} = v_m e^{-im\Psi_m}$

$\vec{V_n} = v_n \, e^{-in\Psi_n}$

- de-correlations of Vn vs p_T & η
- correlations between v_n and v_m ?
- correlations between ψ_n and ψ_m ?

Event-plane (1998)

PHYSICAL REVIEW C VOLUME 58, NUMBER 3 SEPTEMBER 1998

Methods for analyzing anisotropic flow in relativistic nuclear collisions

A. M. Poskanzer[1] and S. A. Voloshin[2,*]
[1]Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720
[2]Physikalisches Institut der Universität Heidelberg, Heidelberg, Germany
(Received 20 May 1998)

The strategy and techniques for analyzing anisotropic flow (directed, elliptic, etc.) in relativistic nuclear collisions are presented. The emphasis is on the use of the Fourier expansion of azimuthal distributions. We present formulas relevant for this approach, and in particular, show how the event multiplicity enters into the event plane resolution. We also discuss the role of nonflow correlations and a method for introducing flow into a simulation. [S0556-2813(98)04109-0]

Q-Cumulant (2010)

PHYSICAL REVIEW C 83, 044913 (2011)

Flow analysis with cumulants: Direct calculations

Ante Bilandzic,[1,2] Raimond Snellings,[2] and Sergei Voloshin[3]
[1]Nikhef, Science Park 105, NL-1098 XG Amsterdam, The Netherlands
[2]Utrecht University, P.O. Box 80000, NL-3508 TA Utrecht, The Netherlands
[3]Wayne State University, 666 West Hancock Street, Detroit, Michigan 48201, USA
(Received 6 October 2010; published 26 April 2011)

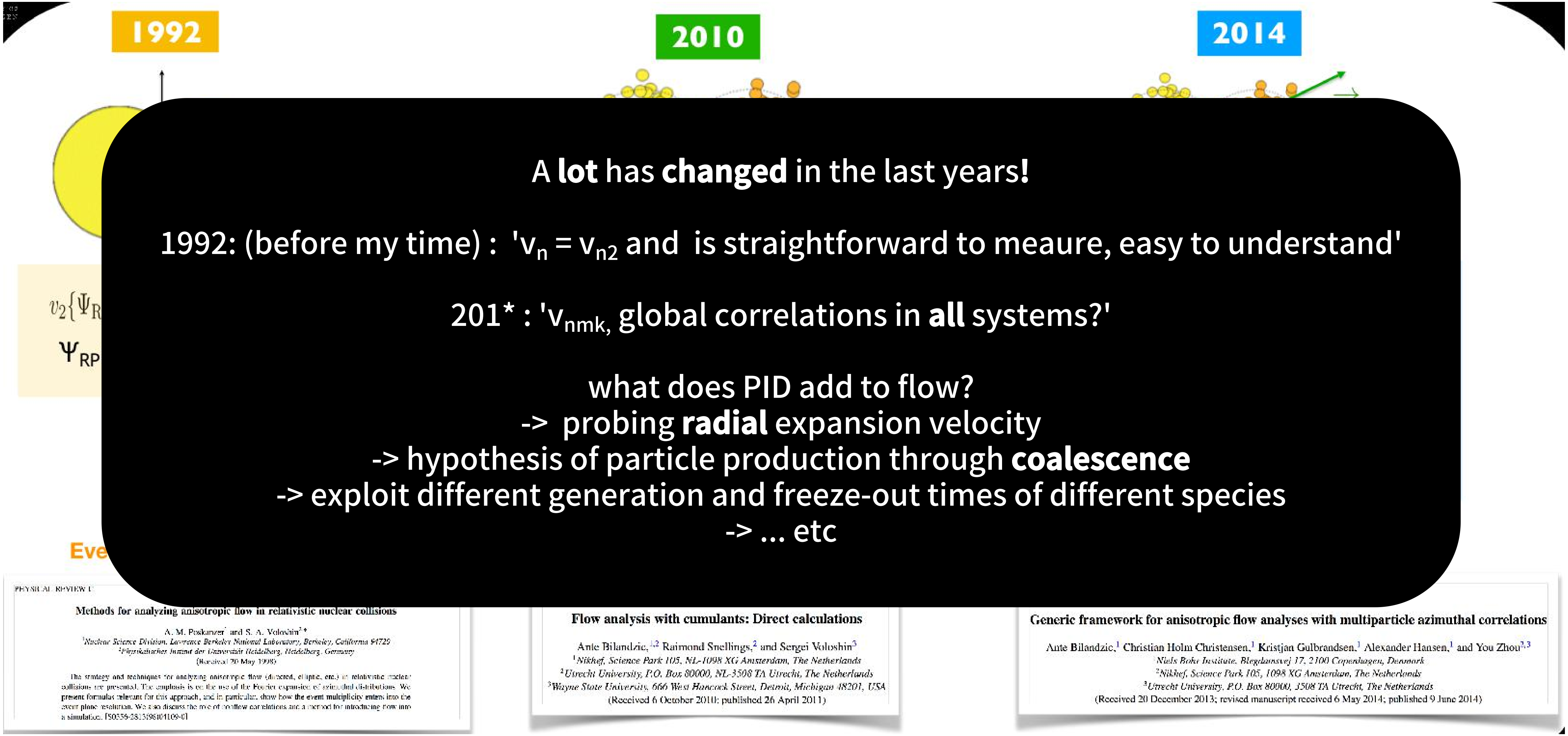
Generic framework (2014)

PHYSICAL REVIEW C 89, 064904 (2014)

Generic framework for anisotropic flow analyses with multiparticle azimuthal correlations

Ante Bilandzic,[1] Christian Holm Christensen,[1] Kristjan Gulbrandsen,[1] Alexander Hansen,[1] and You Zhou[2,3]
[1]Niels Bohr Institute, Blegdamsvej 17, 2100 Copenhagen, Denmark
[2]Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands
[3]Utrecht University, P.O. Box 80000, 3508 TA Utrecht, The Netherlands
(Received 20 December 2013; revised manuscript received 6 May 2014; published 9 June 2014)

stealing a QM slide from You ... :

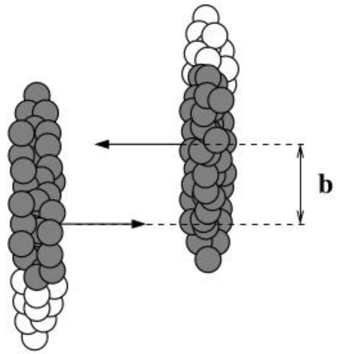


A **lot** has **changed** in the last years!

1992: (before my time) : '$v_n = v_{n2}$ and is straightforward to meaure, easy to understand'

201* : 'v_{nmk}, global correlations in **all** systems?'

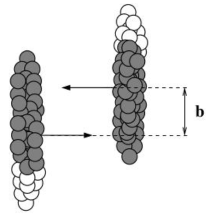
what does PID add to flow?
-> probing **radial** expansion velocity
-> hypothesis of particle production through **coalescence**
-> exploit different generation and freeze-out times of different species
-> ... etc

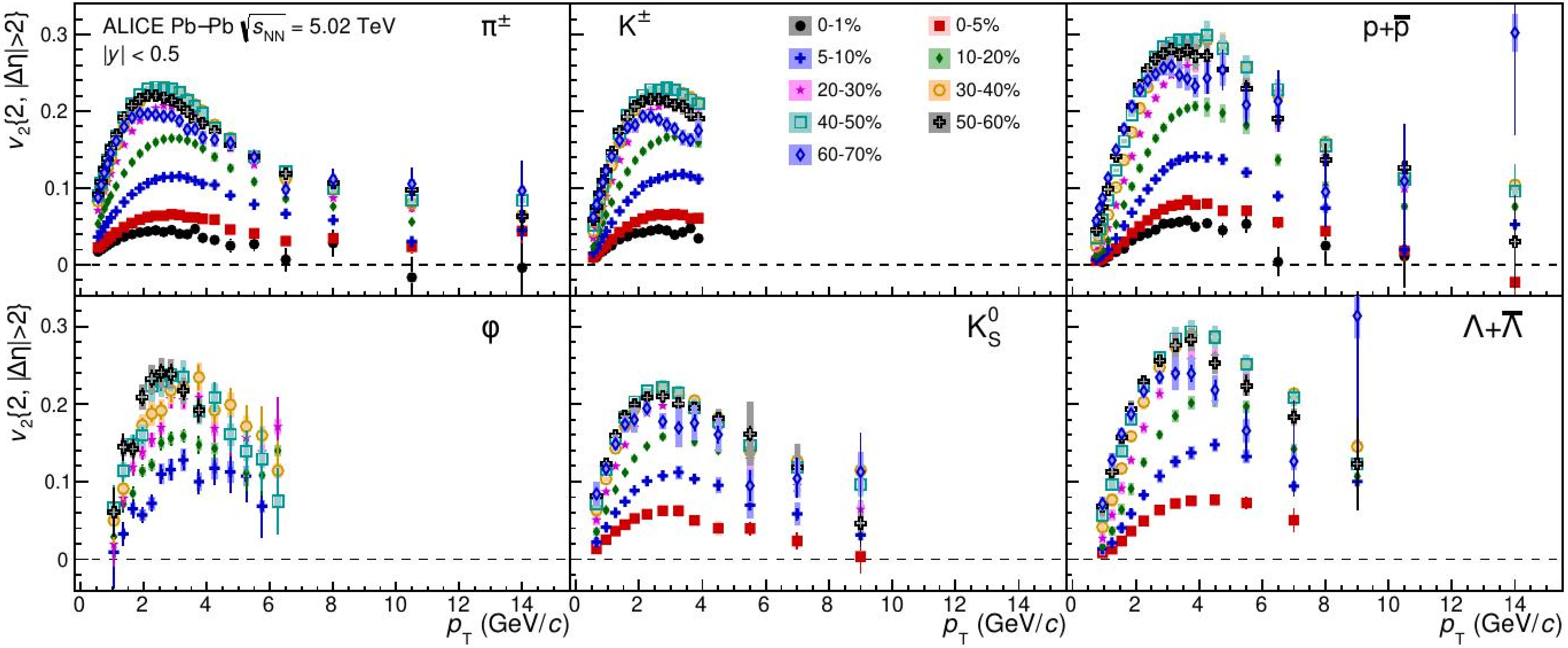


PID v_n: 'The basics' : Pb-Pb collisions @ 5.02 TeV

recent results from the ALICE collaboration - arXiv 1805.04390

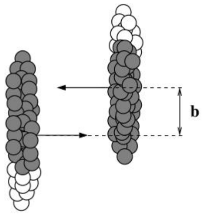
v_2 of identified particles @ 5.02 TeV

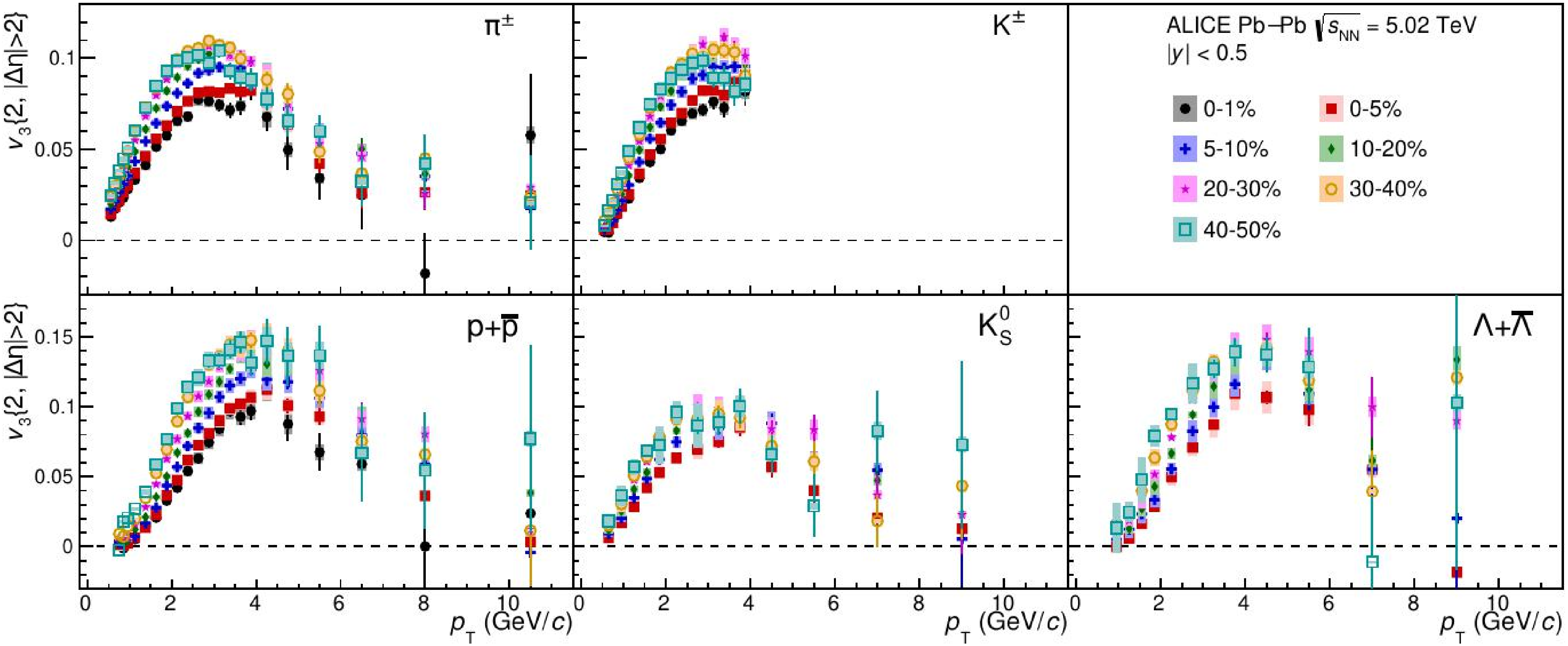




v₂ increases with centrality up to ~40-50% - linear scaling with eccentricity
more peripheral: shorter system lifetime
ultra-central (0-1%) positive v_2 reflection of initial state inhomogeneities

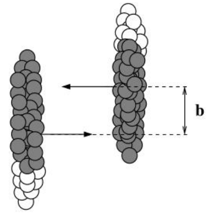
v_3 of identified particles @ 5.02 TeV

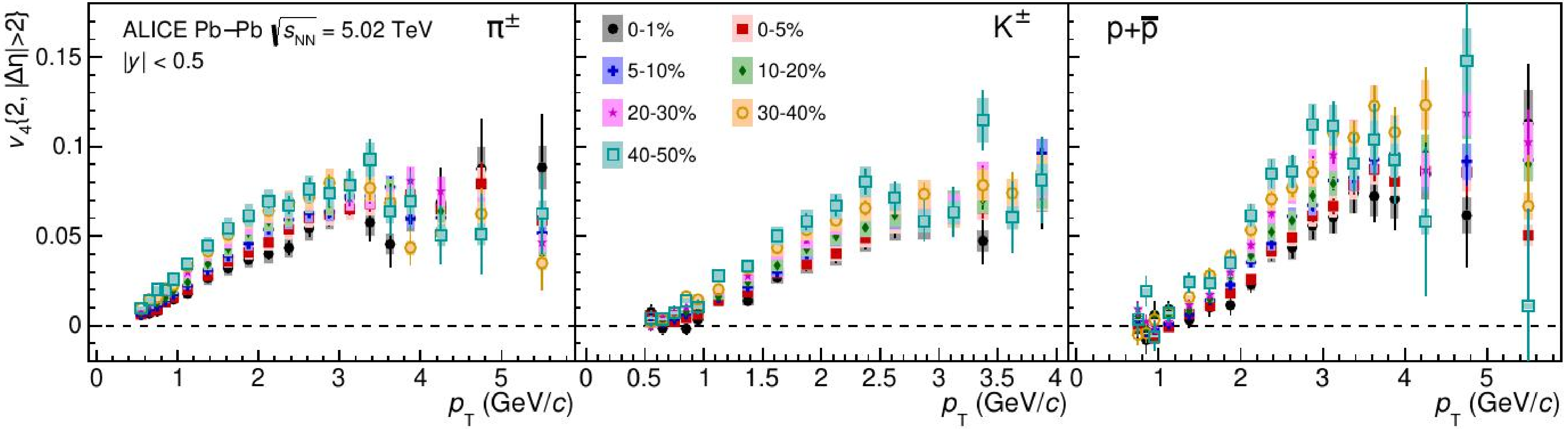




non-zero v_3 up to ~ 8GeV/c, no centrality dependence
non-zero v_3: imhomogeneities in initial quark and gluon density
dampening of η/s more strongly reflected in v_3 than v_2

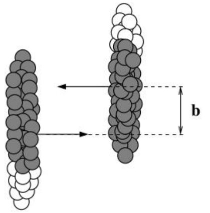
v_4 of identified particles @ 5.02 TeV



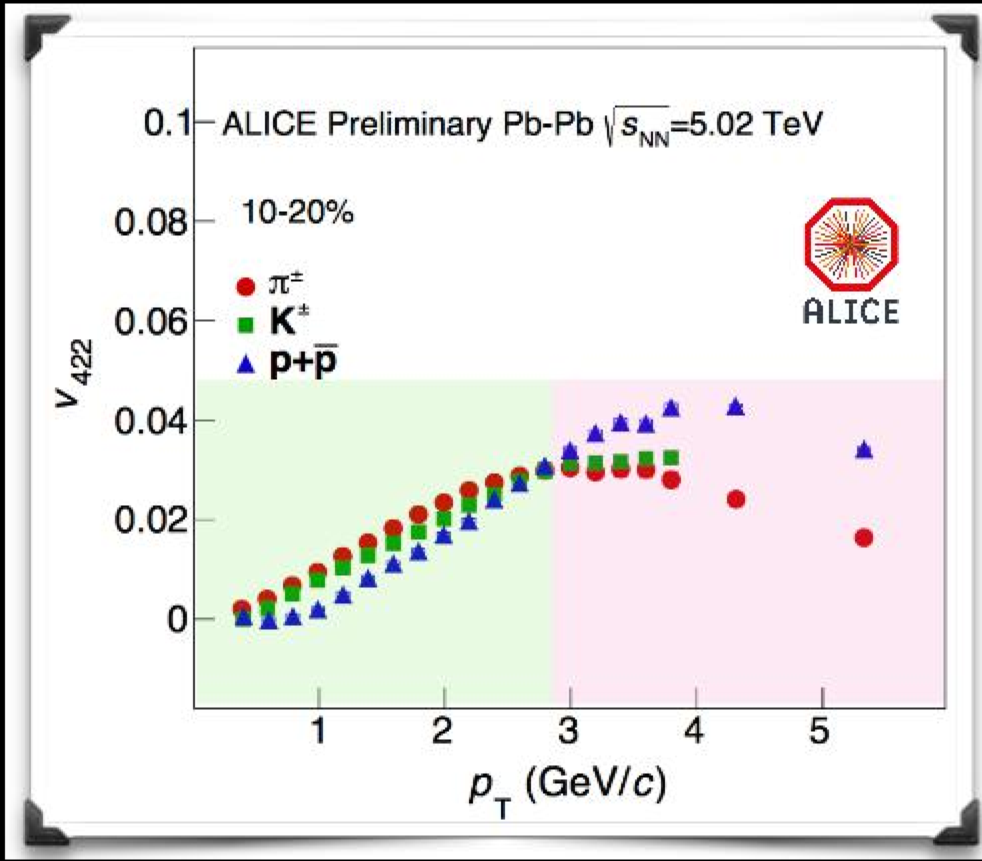


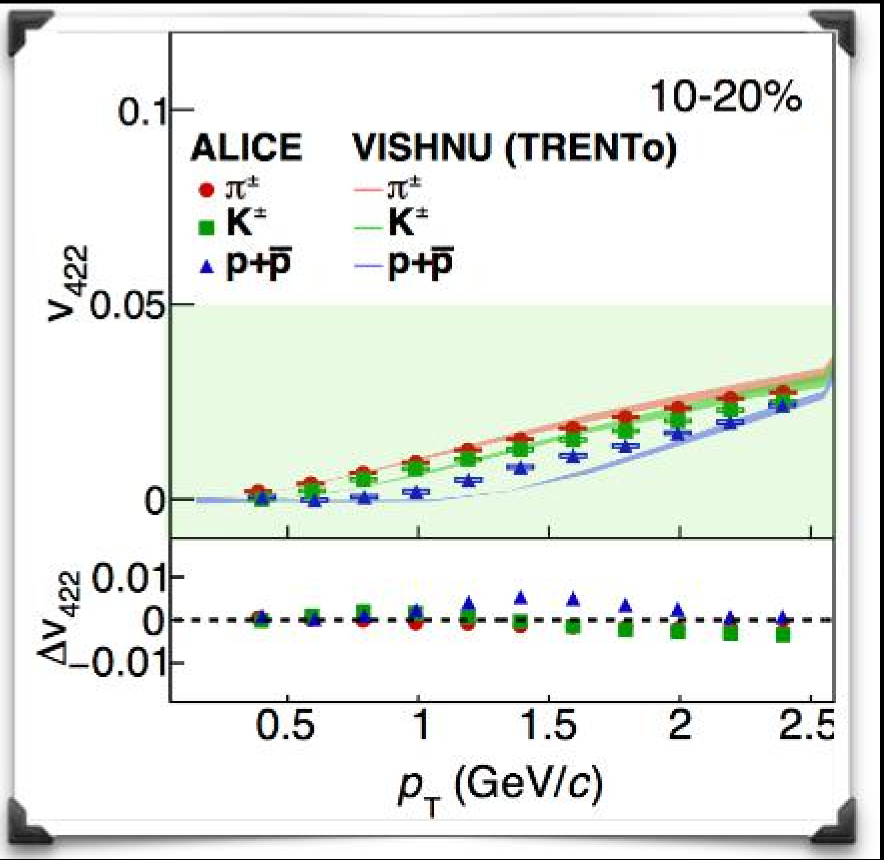
v_4: a special harmonic
generated by inital geometry but also fluctuations and non-linear response of the medium
non-zero over full (albeit limited) momentum range for all species

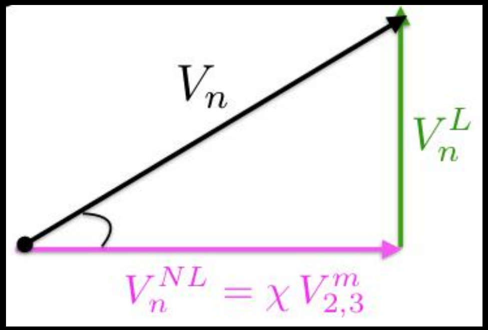
v_2 of identified particles @ 5.02 TeV



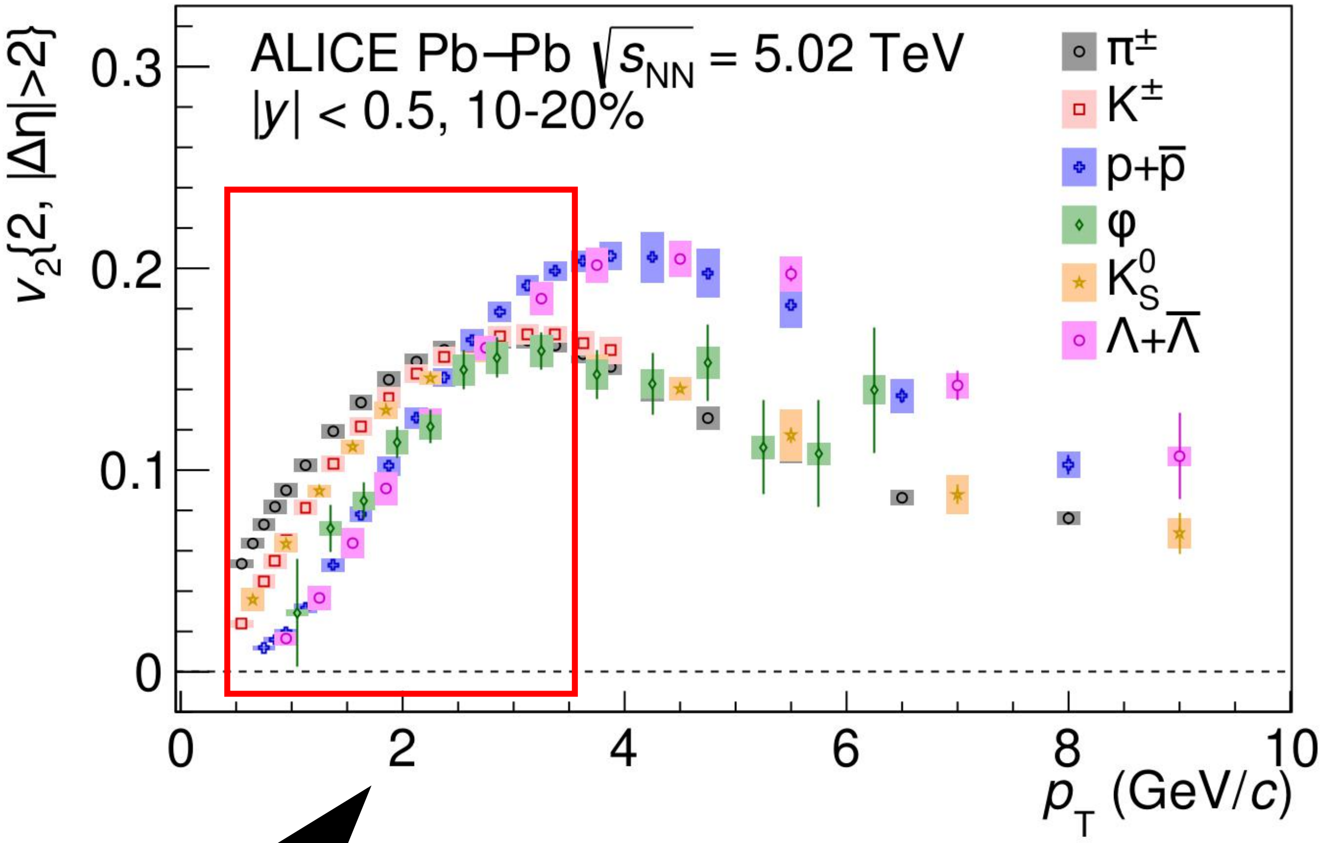
non-linear flow modes:
first measurements of $v_{n,mk}(p_T)$ for identified particles



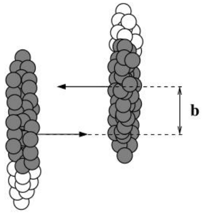




$$V_n = V_n^{NL} + V_n^L$$



mass ordering from radial flow

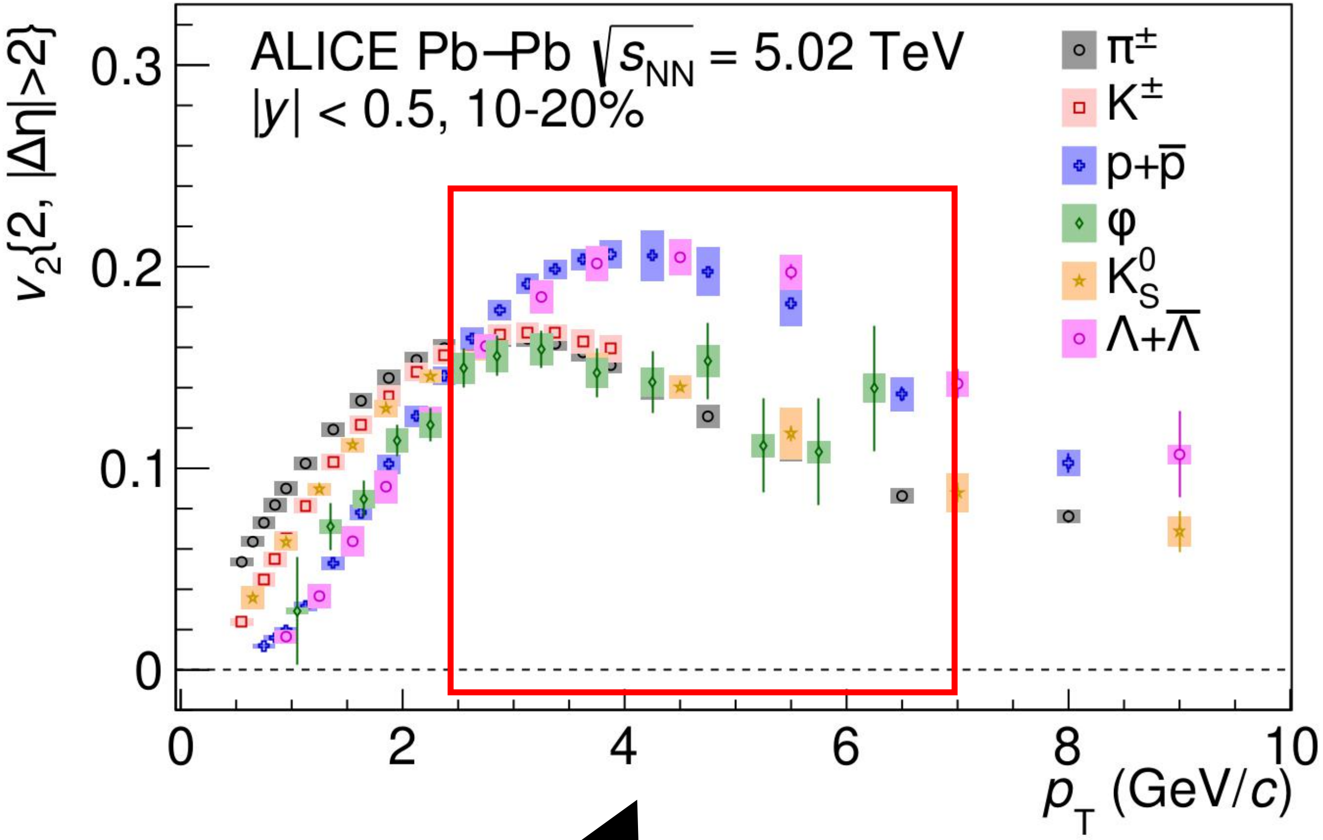


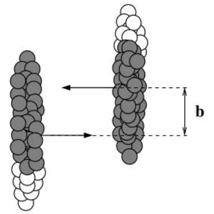
v_n are sensitive to the **full evolution** of the collision system

- Initial conditions → QGP phase → hadronization

Three kinematic regions of interest

- Low p_T ($\lesssim$ 2 GeV/c) - **hydrodynamic** expansion
- Intermediate p_T ($2 \lesssim p_T \lesssim 7$ GeV/c) - quark **scaling** ?
- High p_T ($\gtrsim$ 7 GeV/c) - parton **energy loss**





baryon / meson splitting
quark coalescence ?

v_n are sensitive to the **full evolution** of the collision system

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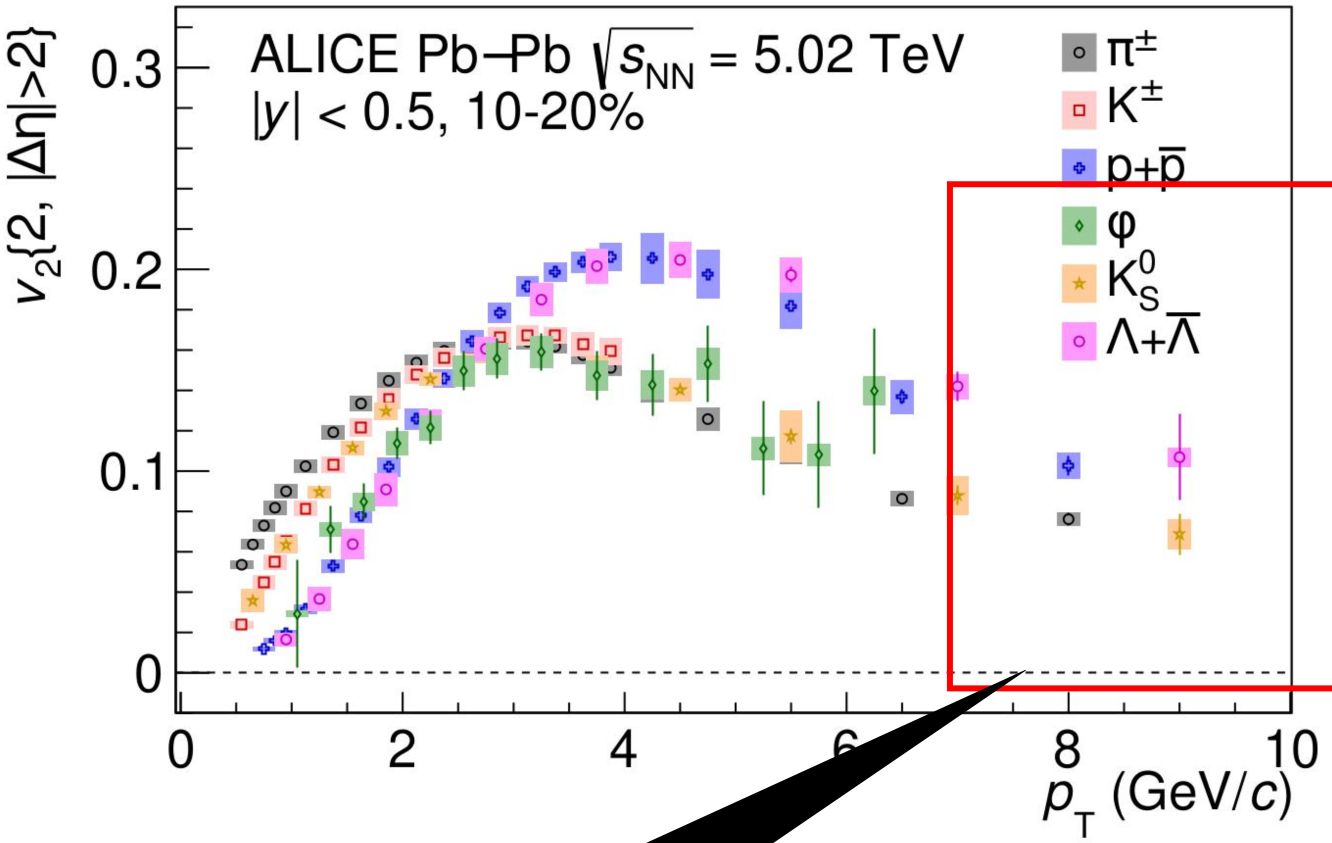

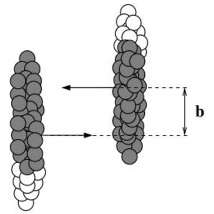

jet quenching

v_n are sensitive to the **full evolution** of the collision system

- Initial conditions → QGP phase → hadronization

Three kinematic regions of interest

- Low p_T ($\lesssim$ 2 GeV/c) - **hydrodynamic** expansion
- Intermediate p_T ($2 \lesssim p_T \lesssim 7$ GeV/c) - quark **scaling** ?
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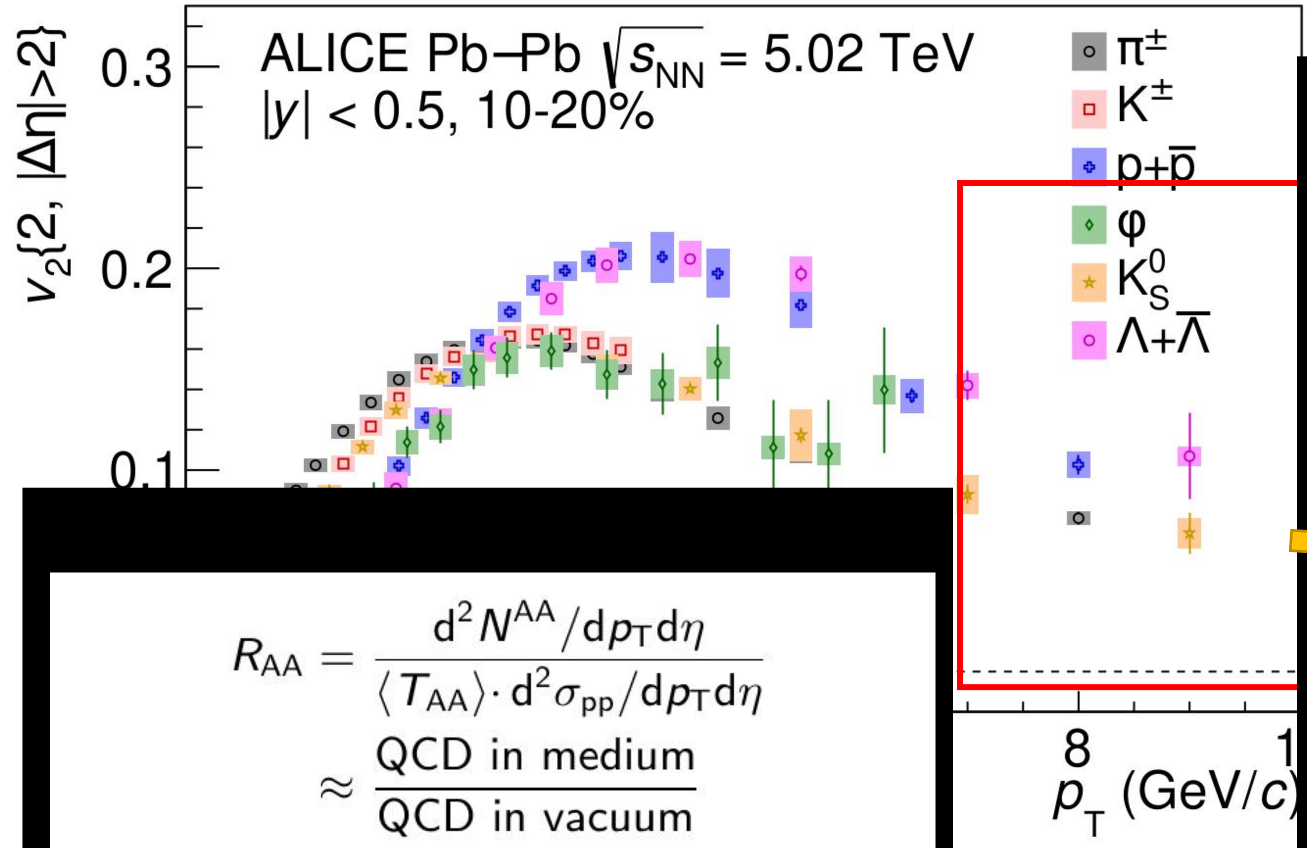


$$R_{AA} = \frac{d^2N^{AA}/dp_T d\eta}{\langle T_{AA}\rangle \cdot d^2\sigma_{pp}/dp_T d\eta} \approx \frac{\text{QCD in medium}}{\text{QCD in vacuum}}$$

R_{AA}'s and v_2 differ up to p_T ~ 10 GeV, then converge

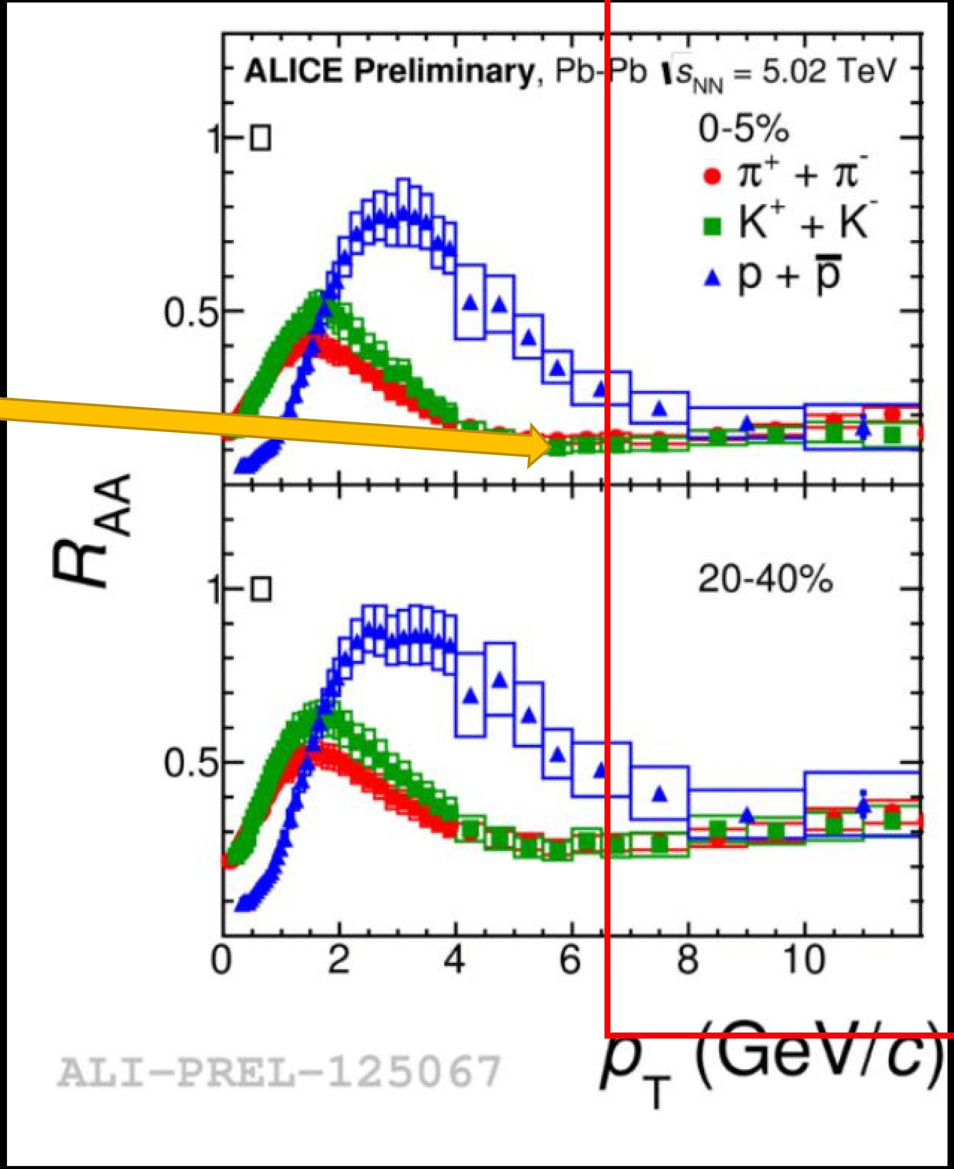
energy loss 'species blind': incurred prior to hadronization

v_n are sensitiv

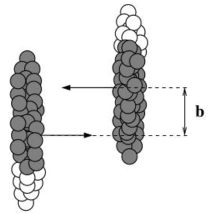
- Initial co

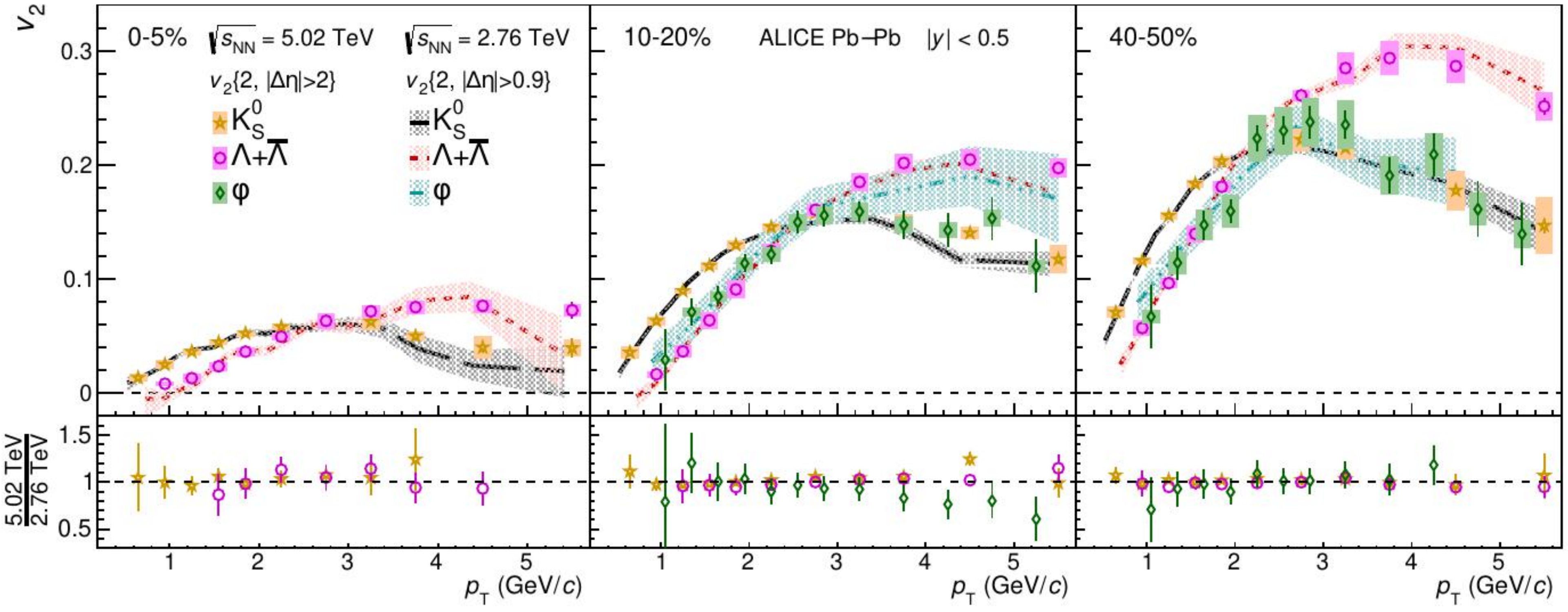
Three kinemat

- Low p_T
- Intermed
- High p_T



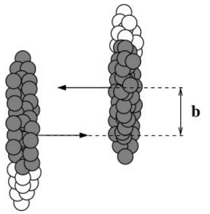
Collision energy dependence of v_n

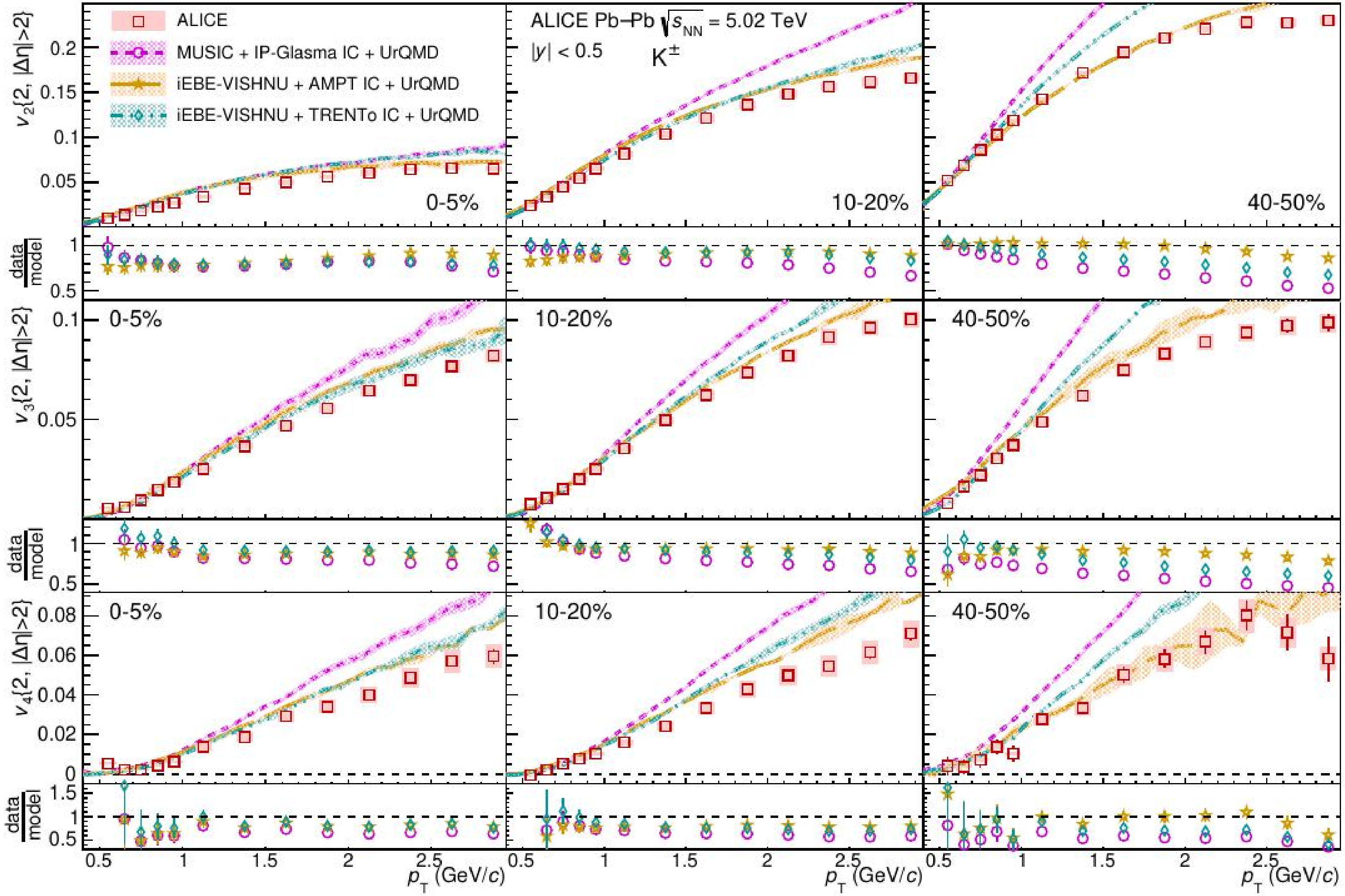




does a **higher center-of-mass energy** lead to a **larger radial flow?**
hypothesis: v_n of heavier particles suppressed at low p_T for higher collision energy
not possible to resolve: precision gain mostly at high p_T - solves 'φ puzzle' though

What do we learn from this ?





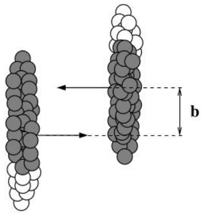
Novel constraints via model comparisons

1) MUSIC hydro, IP-Glasma initial state
2) iEBE-VISHNU using AMPT initial conditions
3) iEBE-VISHNU using TrENTO initial conditions

> Good agreement for **2)** for π, p, K vn (v_3 and v_4 in paper)
> Comparison to MUSIC suggests bulk viscosity plays limited role ?

Strong feeddown? Contaminations? Methods?

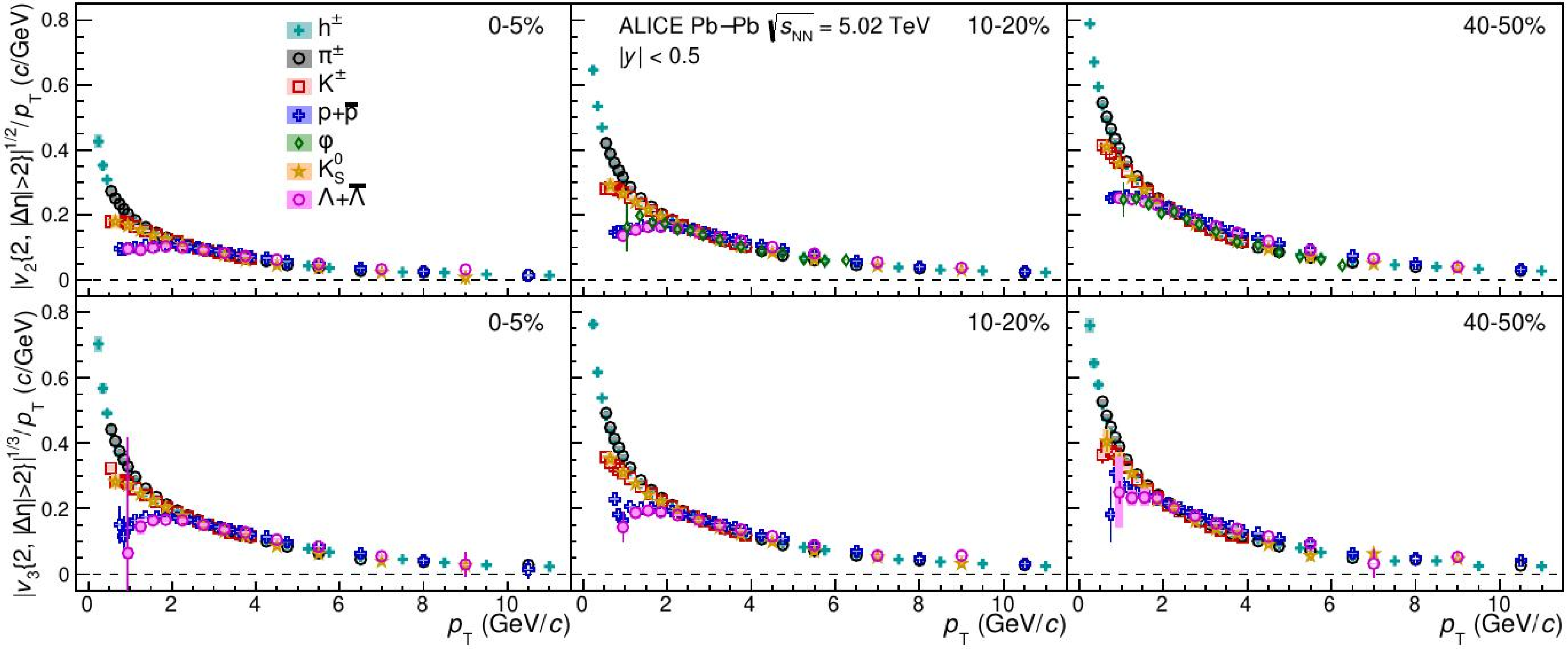
A purely hydrodynamical system ?



PLB477 51-58 'in ideal hydrodynamics, $v_n \sim p_T^n$ up to $p_T \sim M$ for paricles with mass M'

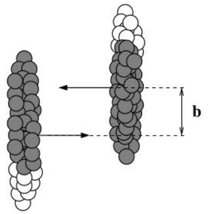
v_2

v_3

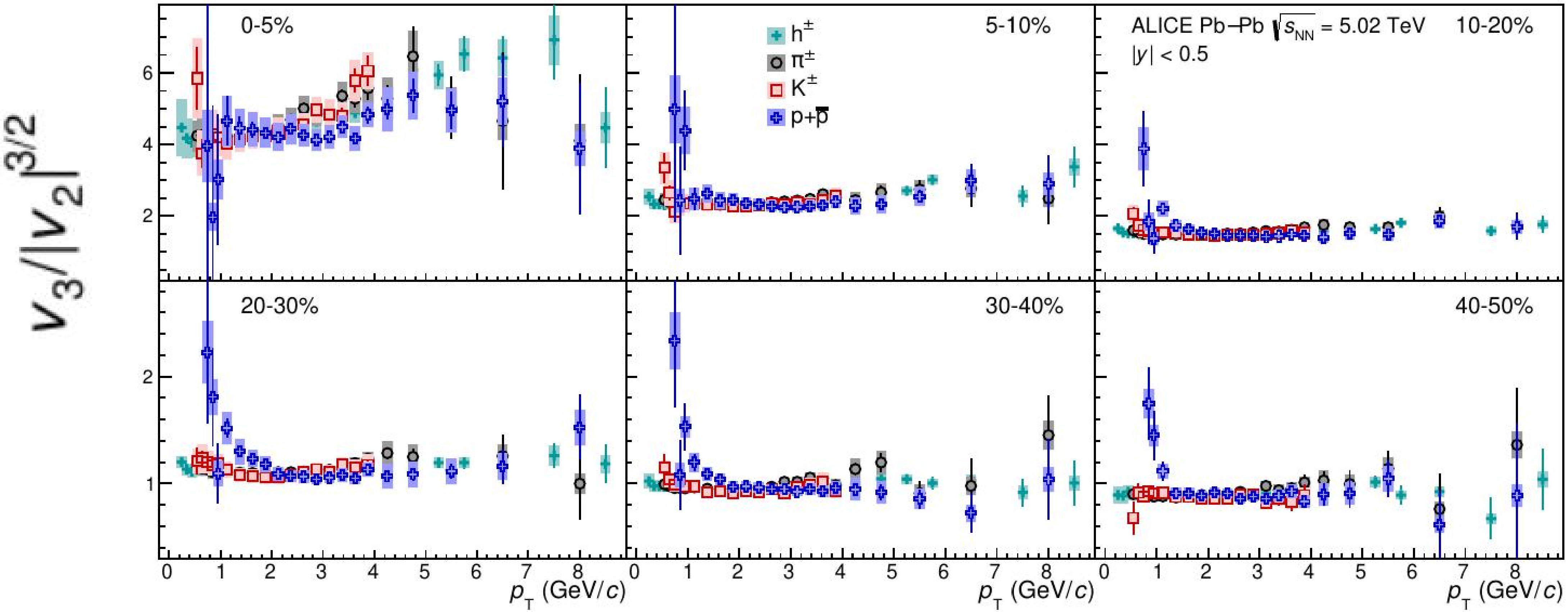


Idea: $v_n \sim p_T^n$ so, $|v_n|^{1/n} / p_T$ should be **constant**
Only holds at very low momenta - pure hydro limit ?

A purely hydrodynamical system ?

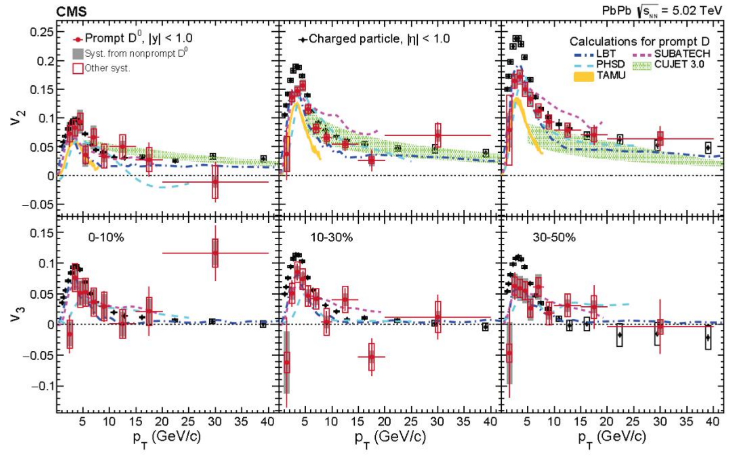


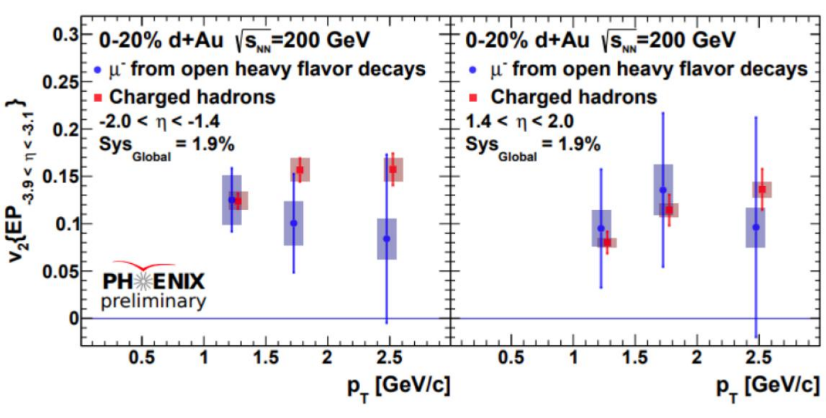
Taking it further: if '$v_n \sim p_T^n$, $v_n / |v_m|^{n/m}$ is constant'



no obvious p_T dependence for charged hadrons for > 5% centrality
cenral collisions: deviations because of fluctuating initial geometry?
proton band not constant at low p_T : signature of radial flow ?

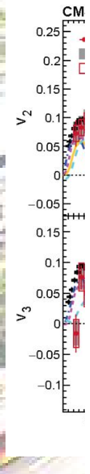
so far the 'conventional' part

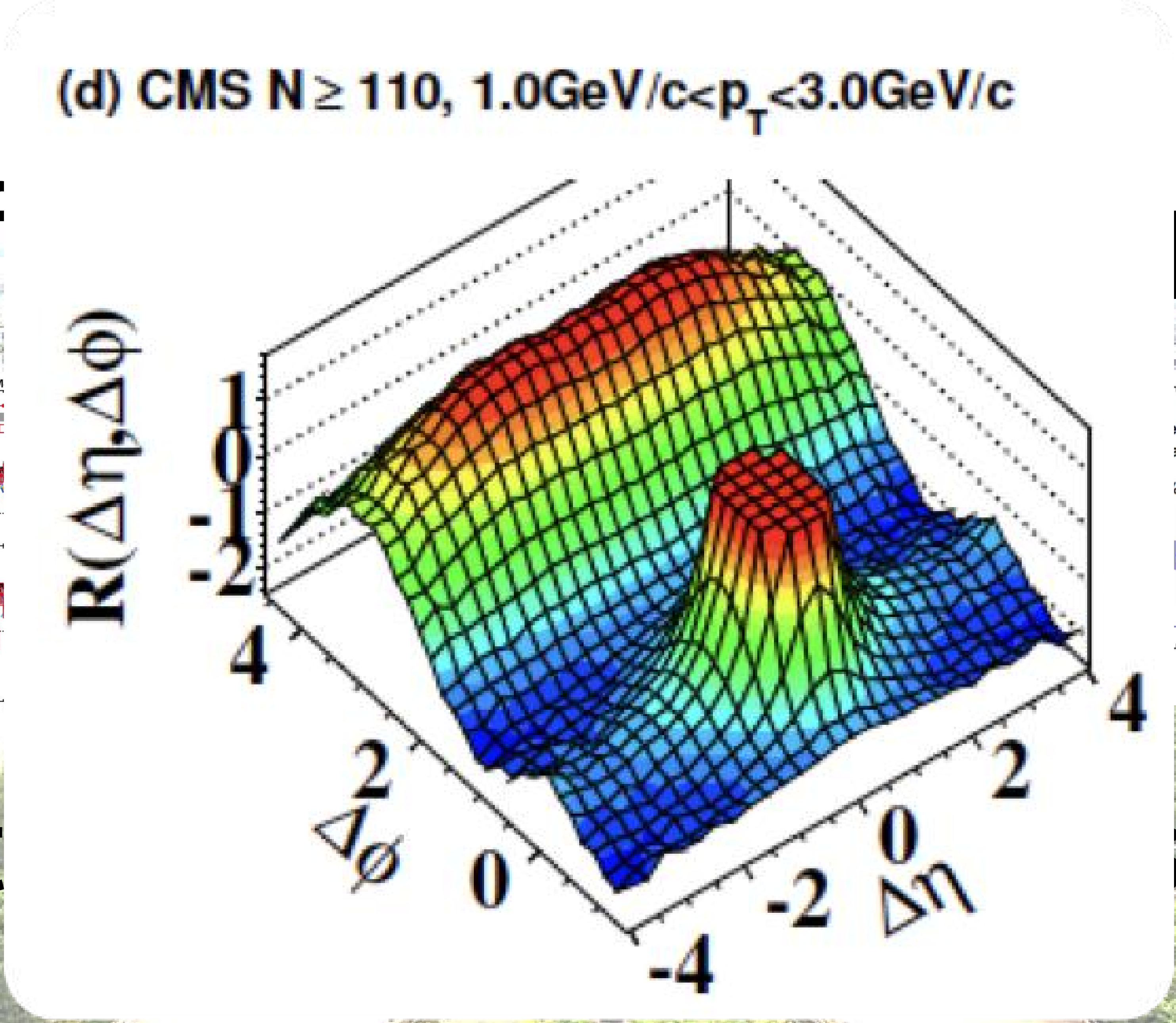


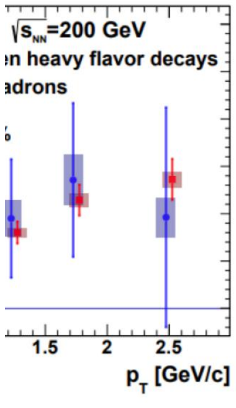


but what about **small** systems ?

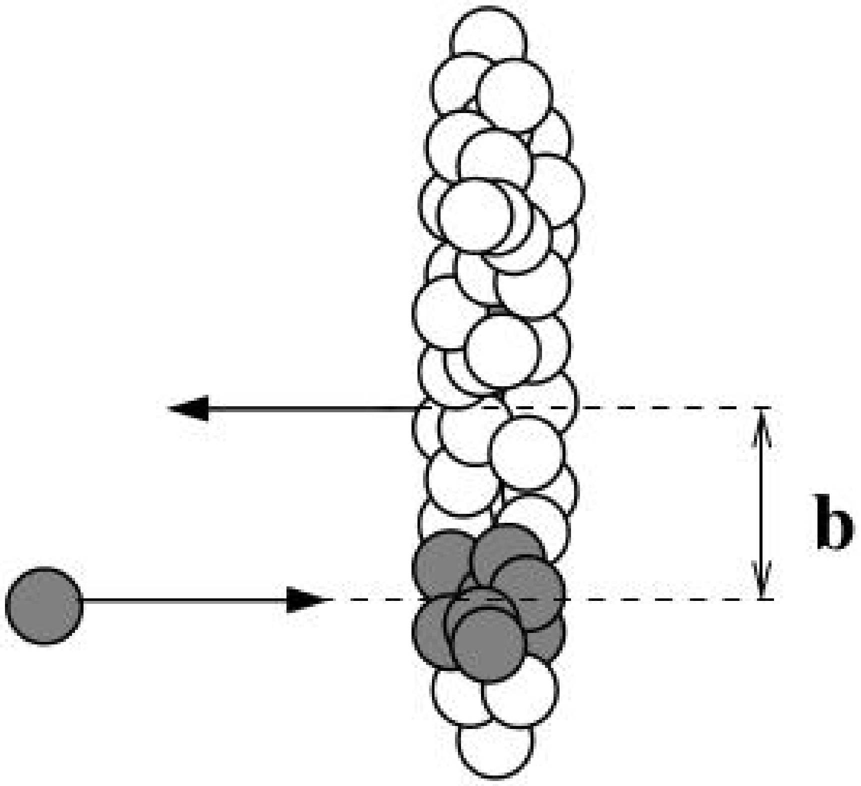
so f… part



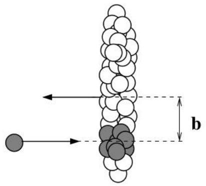




but … stems ?

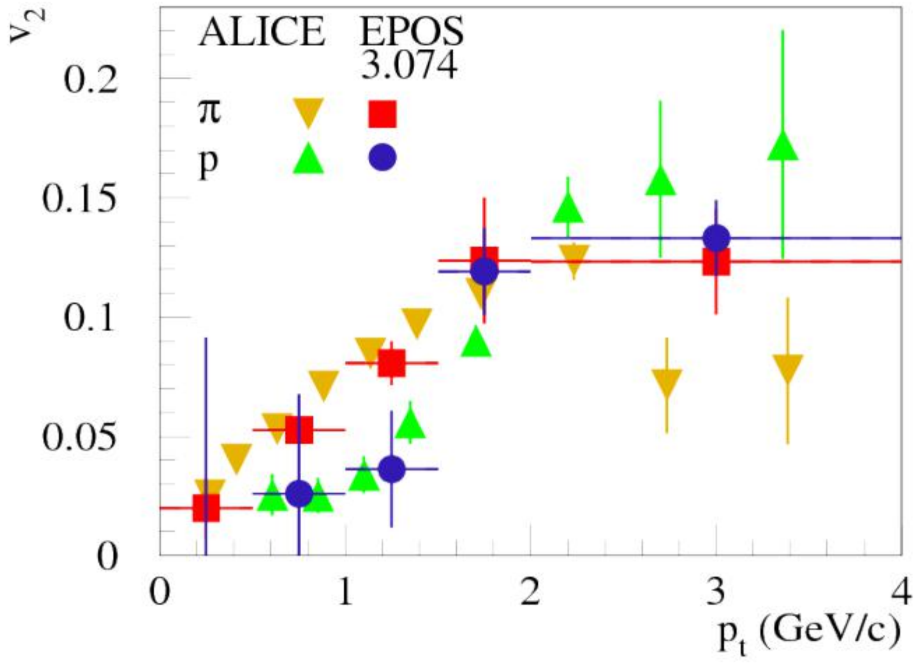


Run II @ the LHC, PID flow

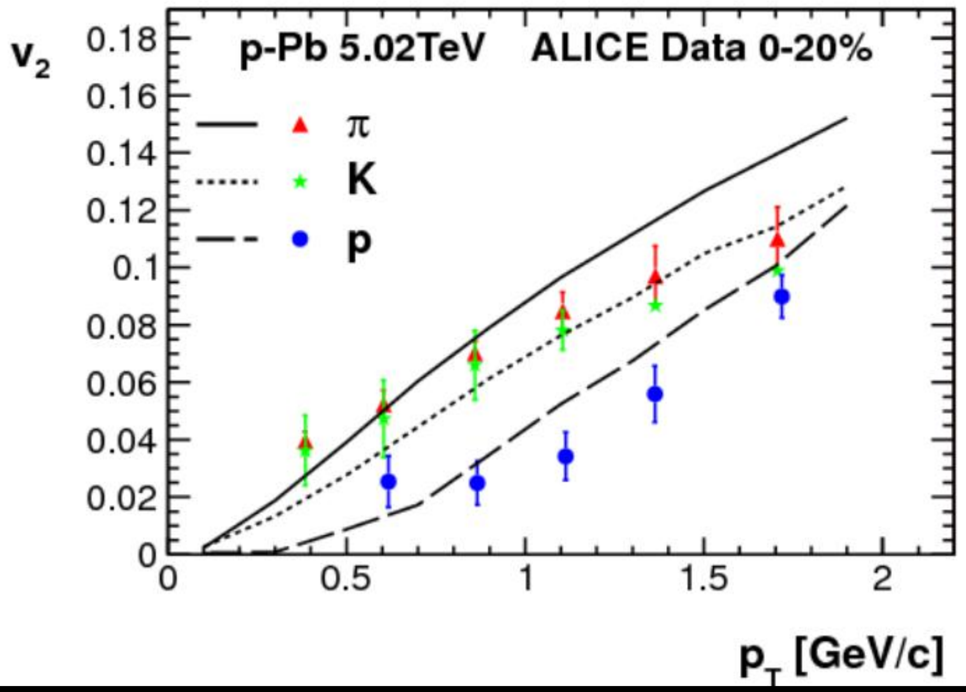


Starting off ... what to expect ?

[Werner et al., PRL 112 (2014) no. 23]

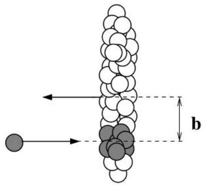


[Bozek et al., PRL 111 (2013) 172303]



mass splitting: evidence of long-range collectivity in p-Pb collisions?
small experimental uncertainties crucial for model validation

Starting off … what to expect ?



Initial state effects → “CGC picture”

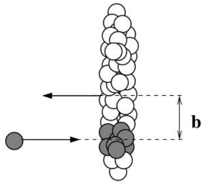
- Target and projectiles described as dense coloured objects
- Anisotropy induced by scattering off domains of e-by-e fluctuating color charged fields (classical YM equations)

Particles are produced from initial state non-homogeneous momentum-space distribution

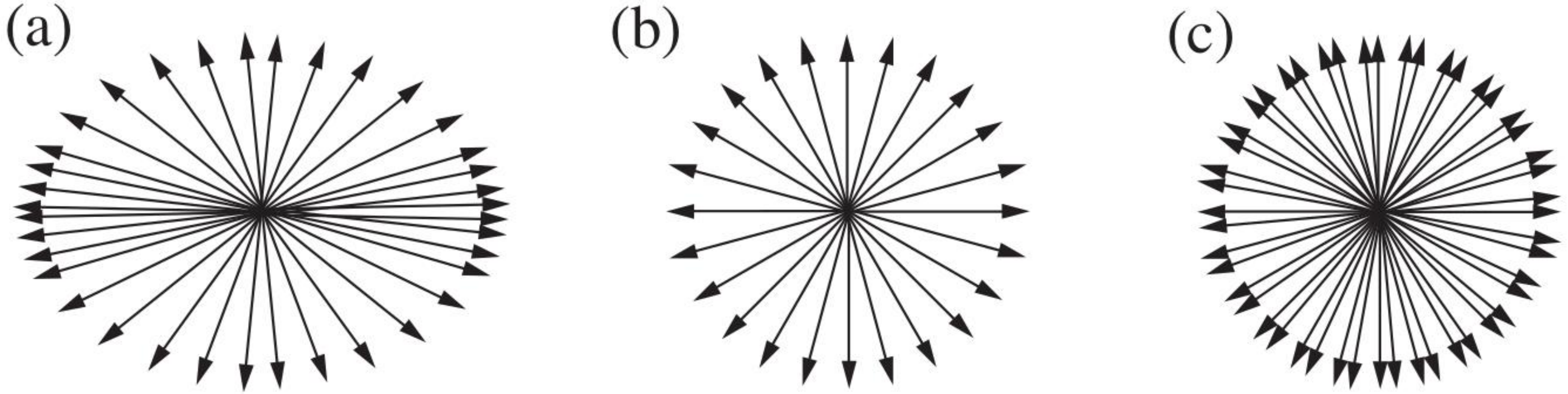
Final state effects → “hydrodynamical picture”

- $\lambda_{mfp} \ll$ system size, $K_n \ll 1$ (Knudsen number → ratio of micro to macroscopic scales e.g. relaxation time λ_{mfp} ~ vs inverse of expansion rate
- Conversion of structures/correlations in coordinate space into structures/correlations in momentum space

Applicability of hydro: particles get their momentum-space correlations from final state interactions during the evolution of the system

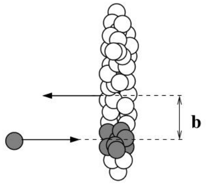


Non-flow: an ilusive intruder

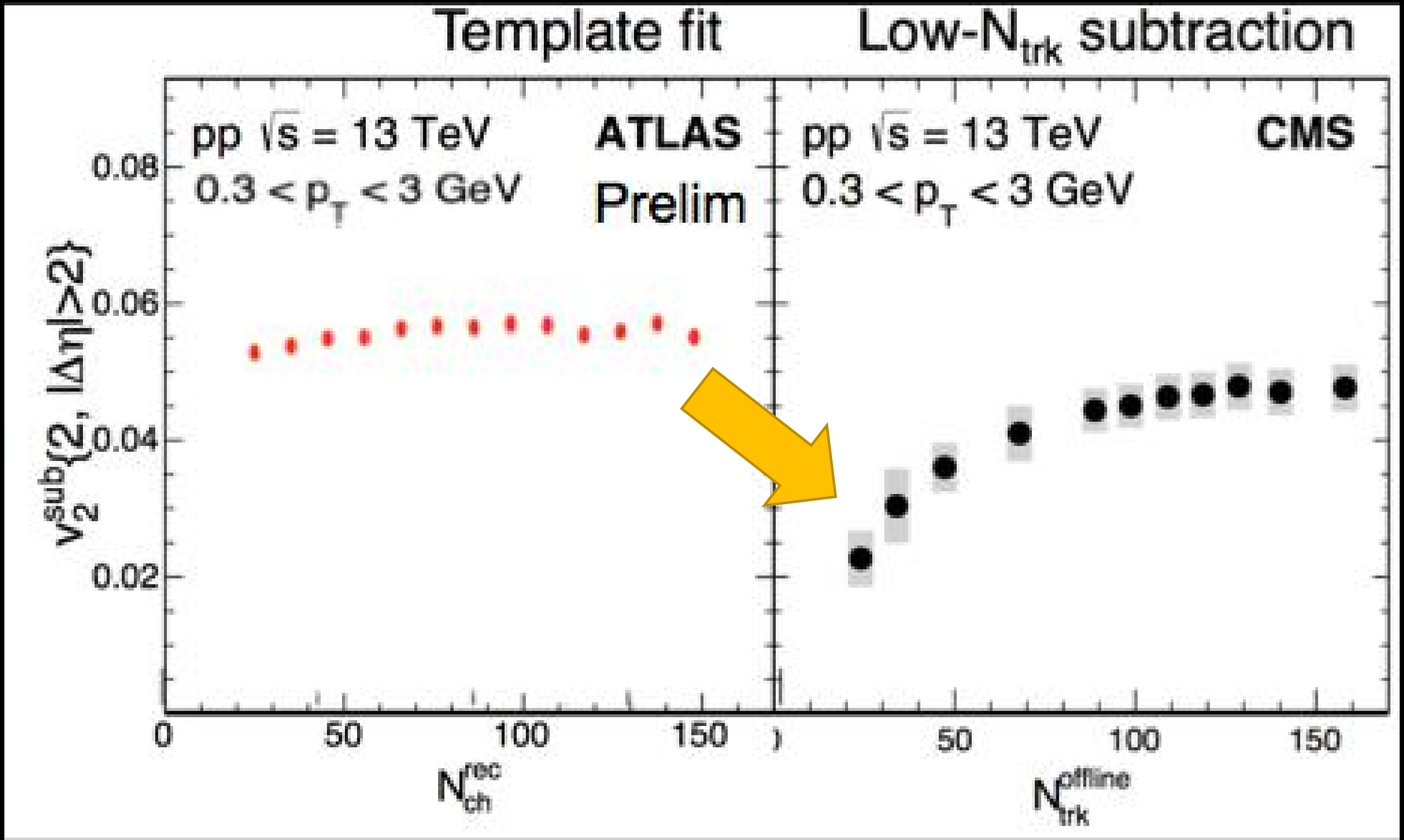


Template fitting → 'ATLAS method'
- -Subtract the low multiplicity class **including** low multiplicity “pedestal”
- -Assumes that the low multiplicity class has **residual “flow”**

"Peripheral" subtraction method → 'CMS (and ALICE p-Pb) method'
- -Subtract the low multiplicity class **not including** low multiplicity “pedestal”
- -Assumes that the low multiplicity class has **no residual “flow”**



Non-flow: an ilusive intruder



Template fit | d → CMS (and LICE
Subtract
includir | y class **not**
Assu | ‘pedestal”
class | ıultiplicity class
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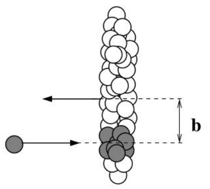
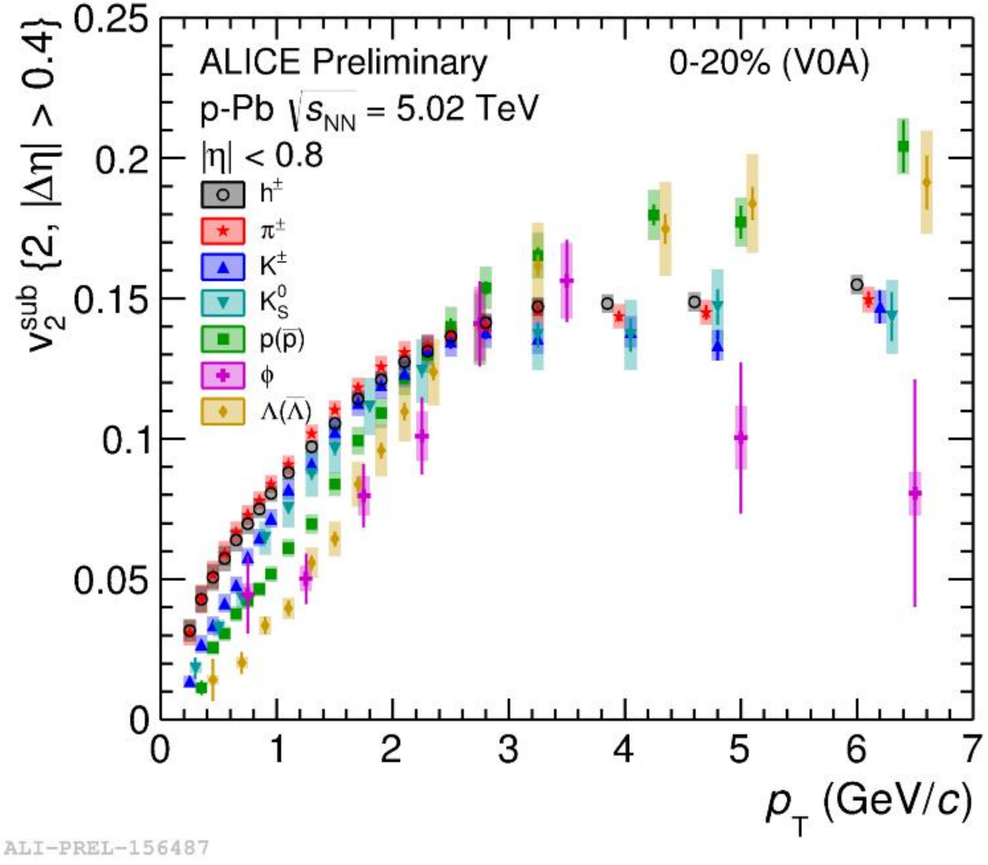
PID v_2 in pPb collisions @ 5.02 TeV



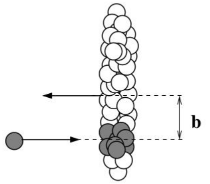


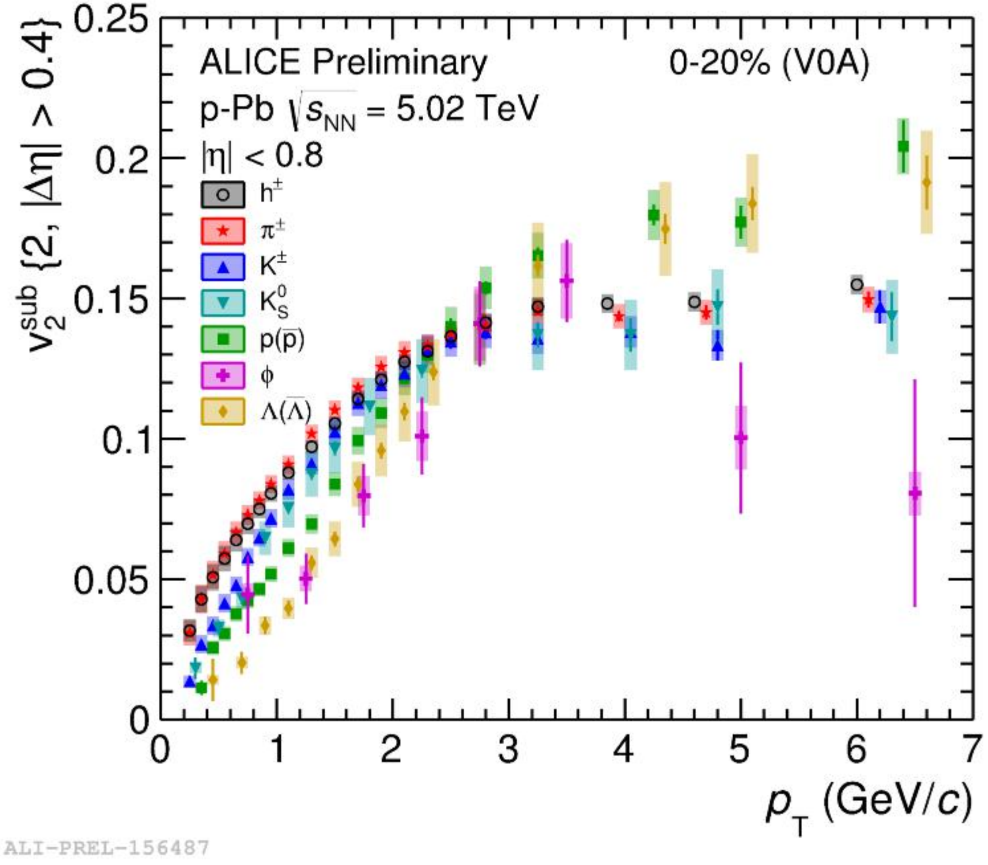
- $v_2(p_T)$ of identified hadrons in 5.02 TeV p-Pb using Run II data
  - Non-flow subtracted results using MB 13 TeV pp collisions
  - First ALICE measurement of K^0_S, $\Lambda(\bar{\Lambda})$ and ϕ v_2 in small systems

- Similar features as Pb-Pb measurements
  - Clear mass ordering (low p_T region)
    - Qualitatively predicted by hydrodynamic models
  - Indication of baryon/meson grouping (intermediate p_T)

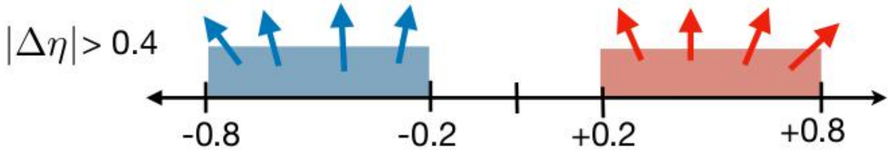
NB credit: V. Pacik, QM2018

PID v_2 in pPb collisions @ 5.02 TeV





Pseudorapidity separation partially suppresses short-range correlations



Additional non-flow subtraction performed on cumulants using MB pp collisions

$$v_2^{\mathrm{pPb,sub}}(p_T) = \frac{d_2^{\mathrm{pPb}}\{2\} - k \cdot d_2^{\mathrm{pp}}\{2\}}{\sqrt{c_2^{\mathrm{pPb}}\{2\} - k \cdot c_2^{\mathrm{pp}}\{2\}}}$$

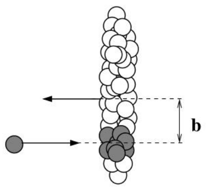
Contribution of non-flow scaled by mean event multiplicities

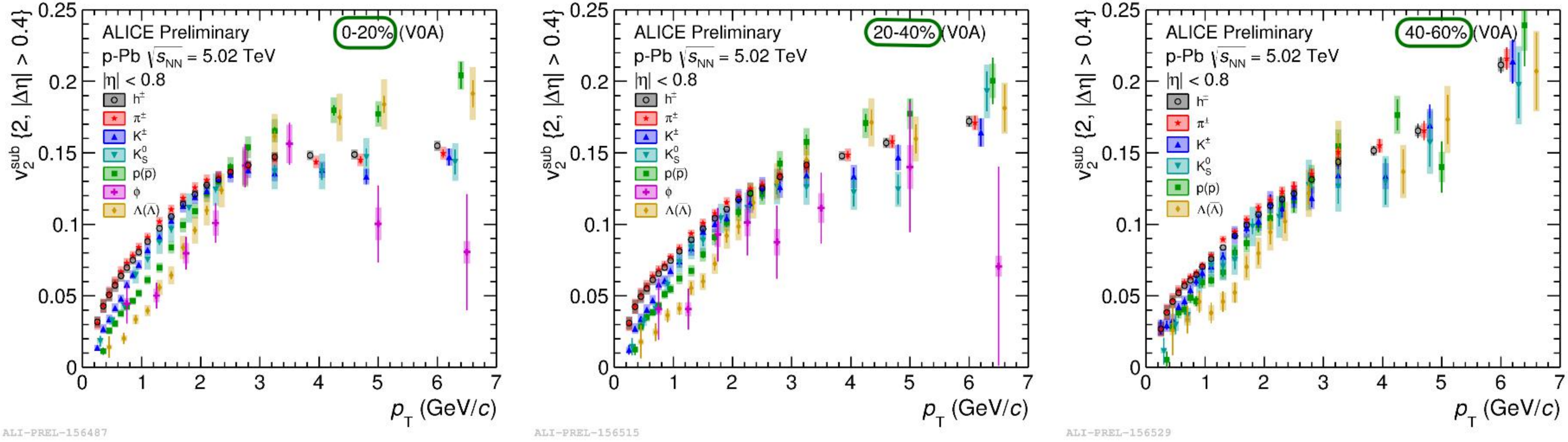
- Based on assumption for non-flow **[Voloshin et al., arXiv:0809.2949]**

$$\delta_n \propto \frac{1}{M} \quad \Rightarrow \quad k = \frac{\langle M \rangle^{\mathrm{pp}}}{\langle M \rangle^{\mathrm{pPb}}}$$

NB credit: V. Pacik, QM2018

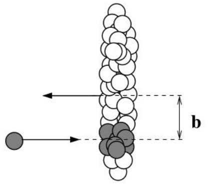
PID v_2 in pPb - multiplicity dependence

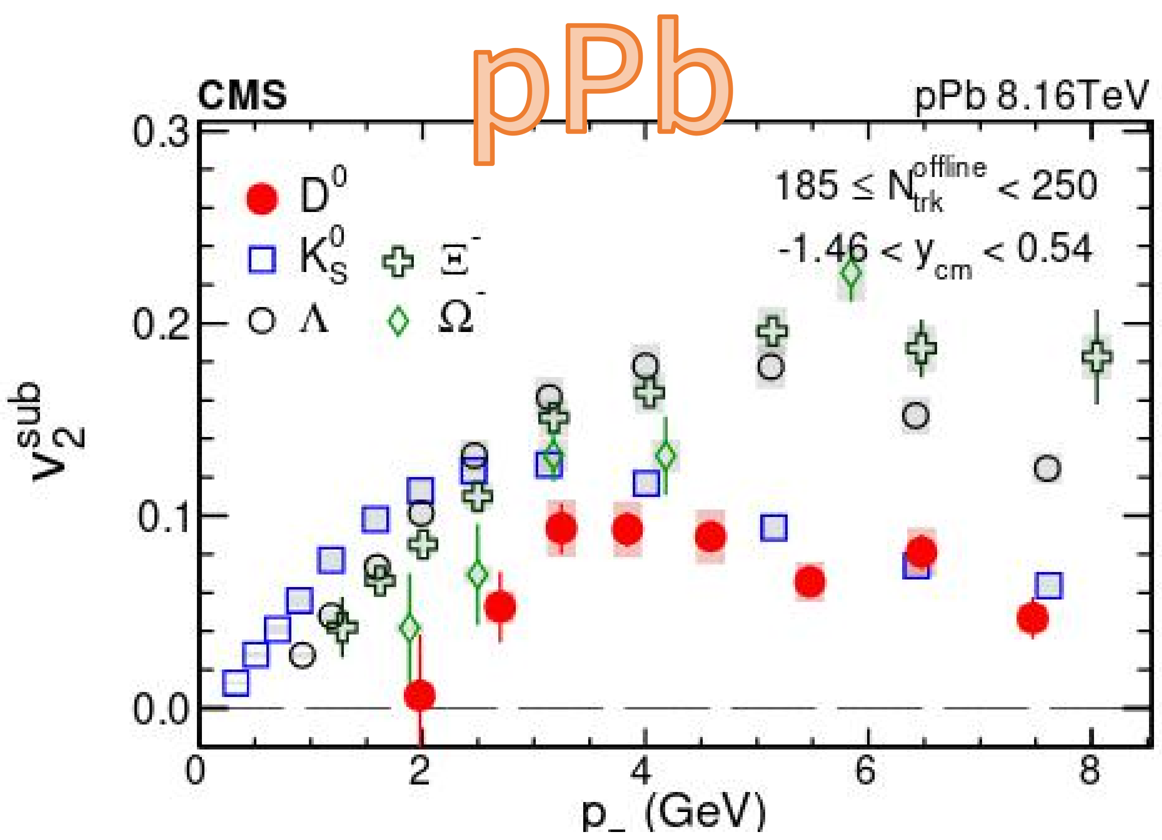


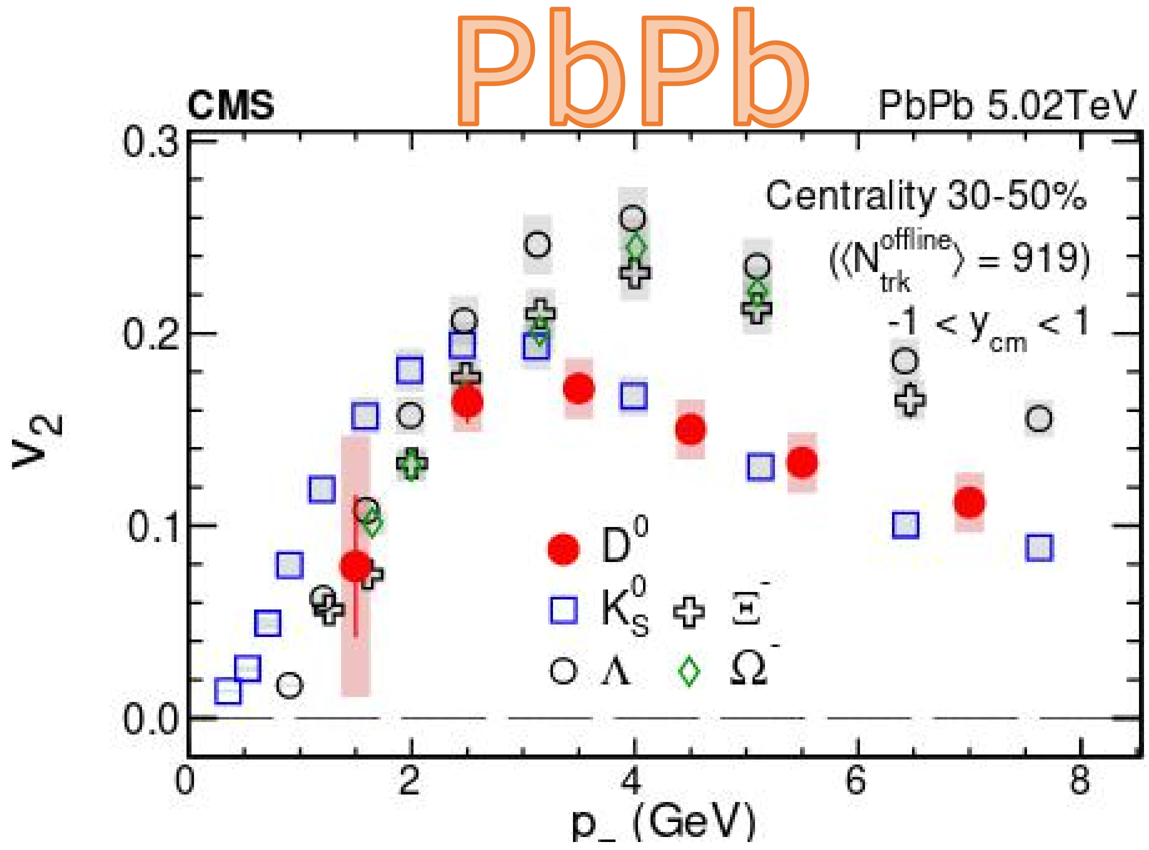


high multiplicity events - mass ordering (low p^T) and baryon / meson splitting (high p_T)
low multiplicity events - mass ordering persists, baryon / meson splitting vanishes

Strange hadrons in pPb @ CMS

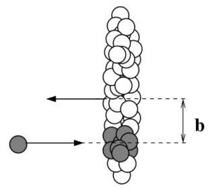


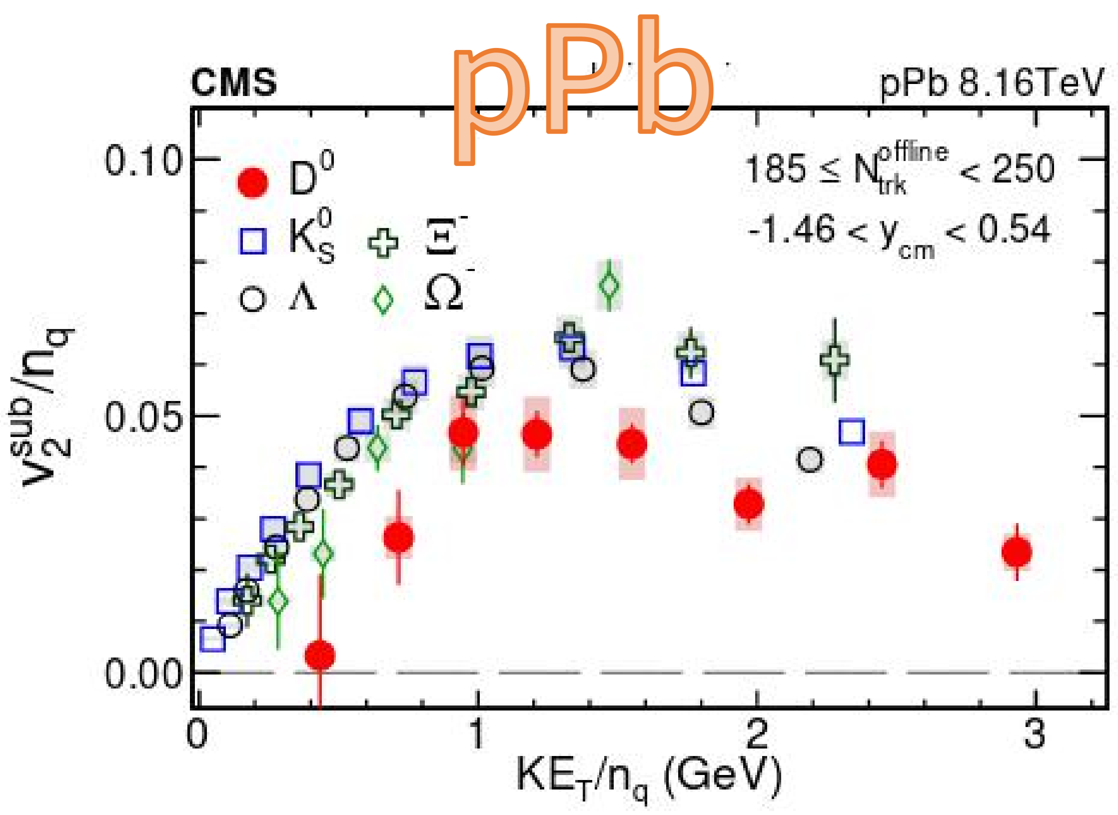


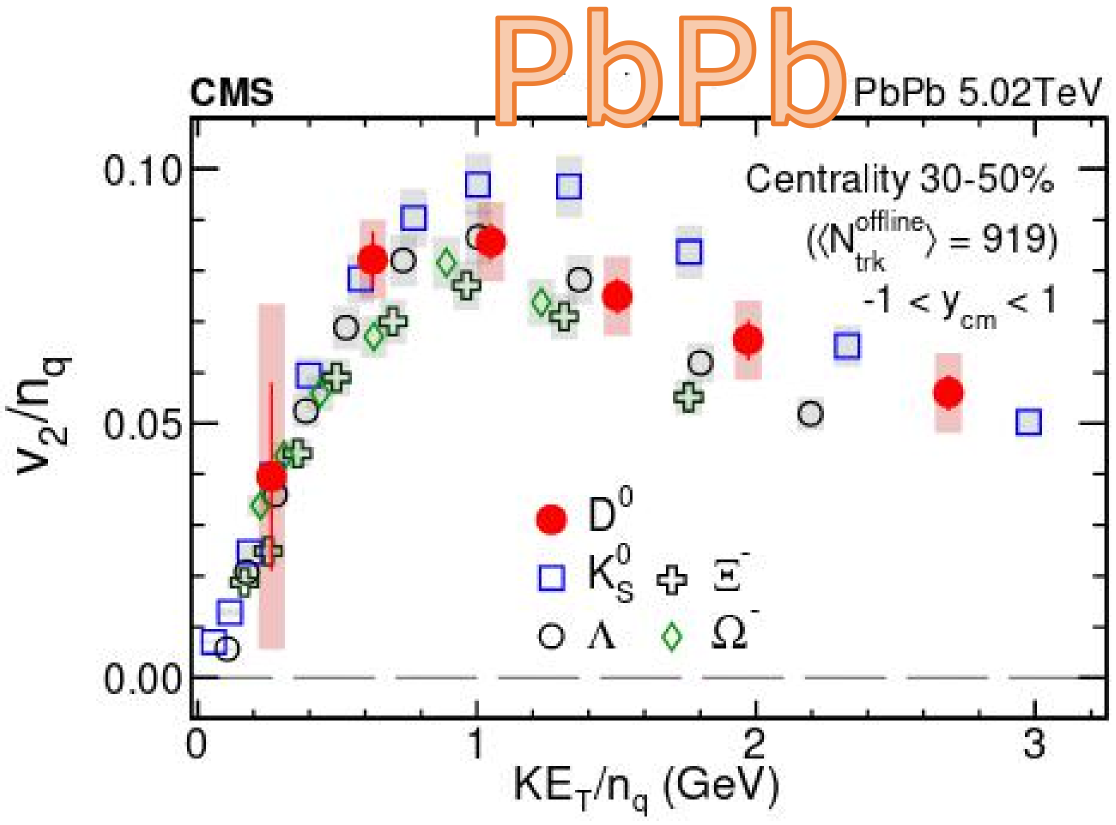


very high precision of K^0_s and Λ v_2
first observation of non-zero D^0 meson v_2 in pPb

NCQ scaling @ CMS

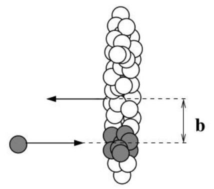




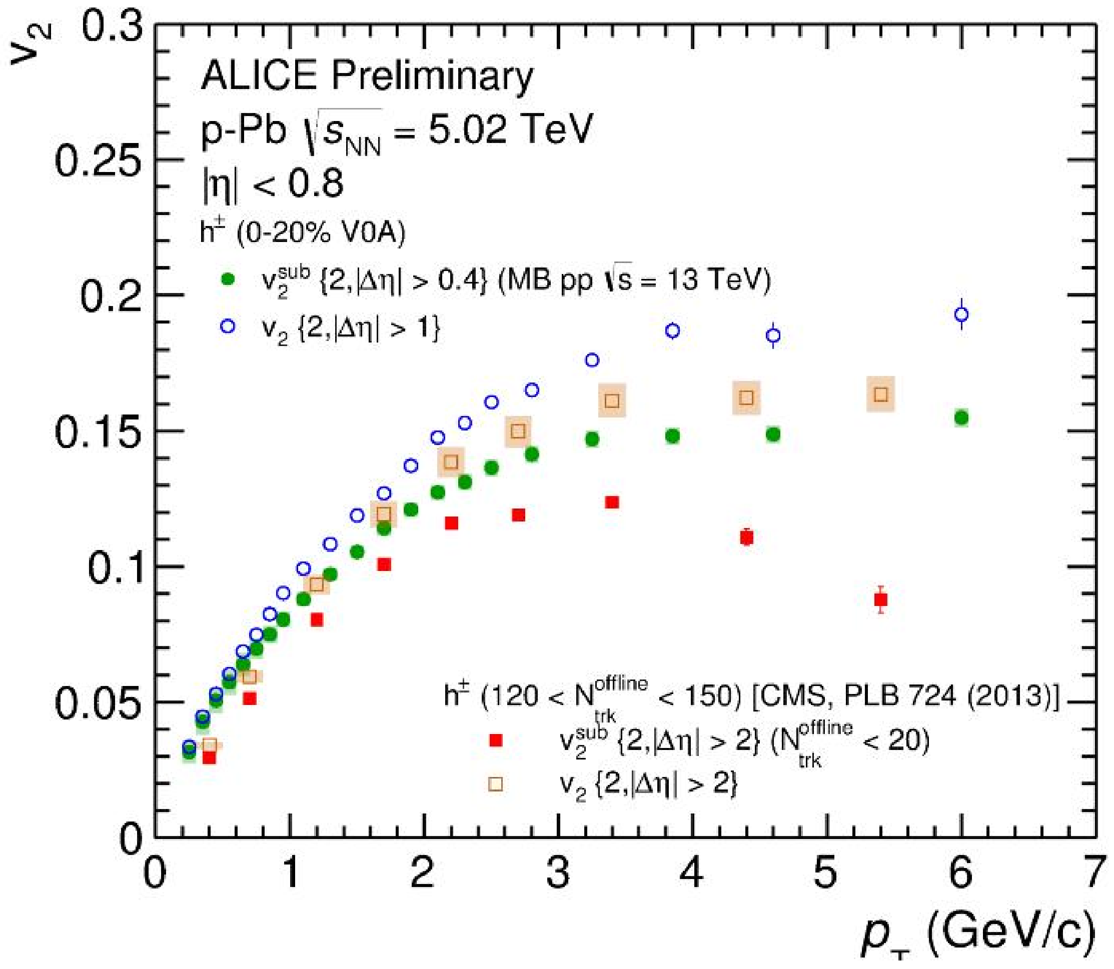


scaling test show that D^0 meson might be less coupled to the medium in small systems

Comparisons - devils & details



NB credit: V. Pacik, QM2018

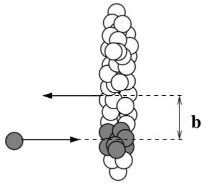


- Differences in methodology
  - v_2 extraction (2PC vs Q-Cumulants)
  - Event classification (selection)
  - Pseudo-rapidity regions
- Similar non-flow subtraction prescription …

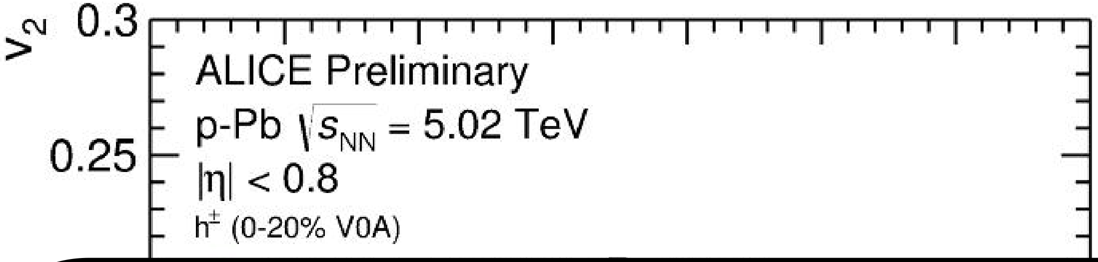
$$V_{n\Delta}^{\rm sub} = V_{n\Delta} - V_{n\Delta}(N_{\rm trk}^{\rm offline} < 20) \times \frac{N_{\rm assoc}(N_{\rm trk}^{\rm offline} < 20)}{N_{\rm assoc}} \times \frac{Y_{\rm jet}}{Y_{\rm jet}(N_{\rm trk}^{\rm offline} < 20)}, \quad (9)$$

  - … but additional scaling factor

Comparisons - devils & details



NB credit: V. Pacik, QM2018



- Differences in methodology
  - v_2 extraction (2PC vs Q-Cumulants)
  - Event classification (selection)

again repeating a fundamental problem of correlation measurements in small systems

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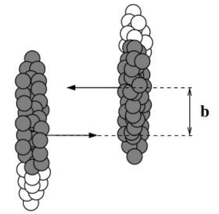
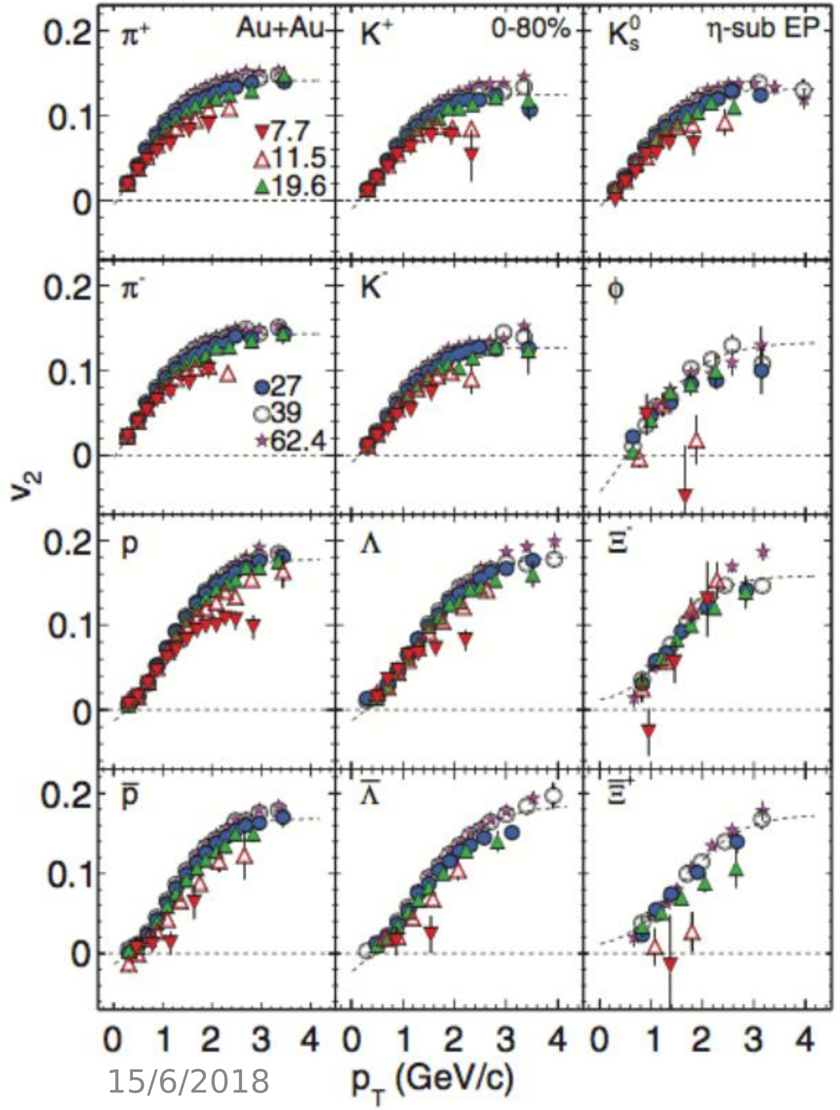
for a meaningful inter experimental / theoretical definition, we need to have a clear, experimental definition of our observables !

if time permits … the LHC doesn't tell the full story

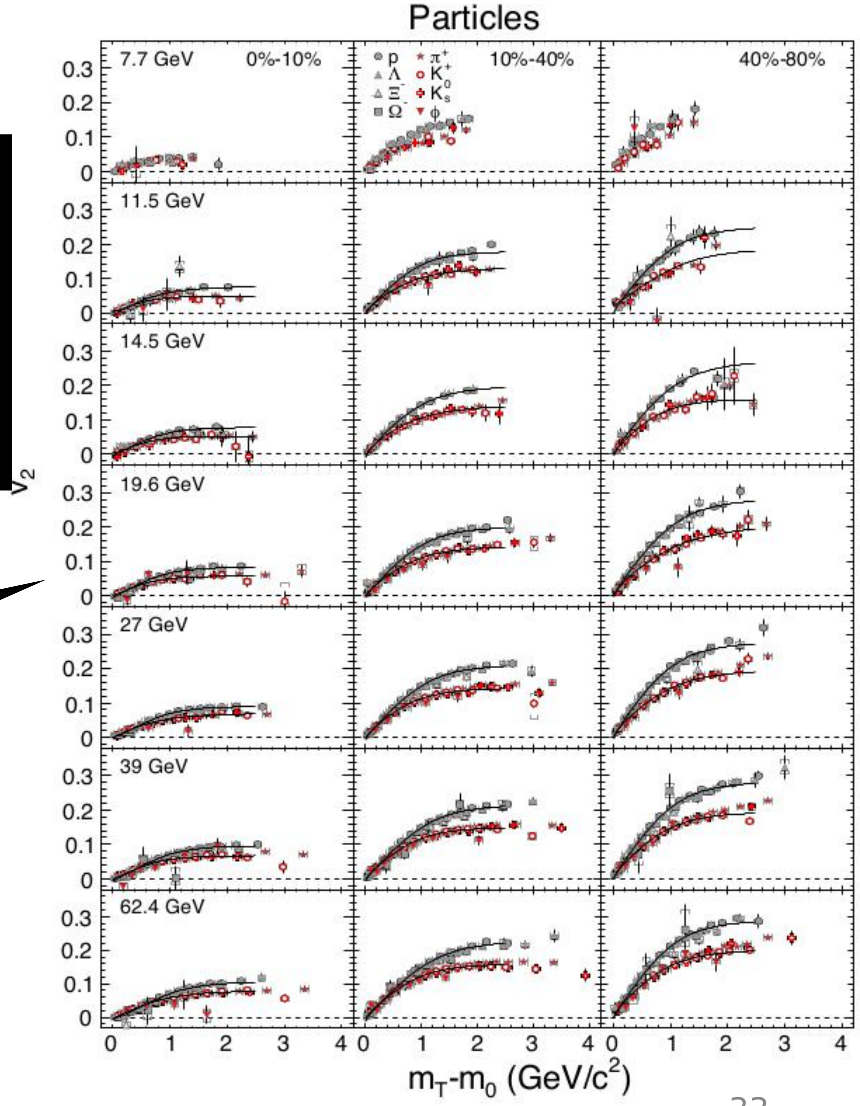
PID v_2 @ STAR beam energy scan





similar $v_2(p_T)$ shape for various species

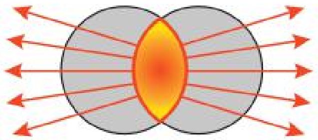
baryon / meson splitting only vanishes @ 7.7 GeV !



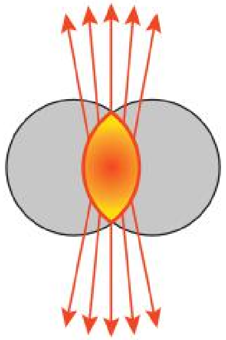
STAR: Phys. Rev. C 88, 014902 (2013)

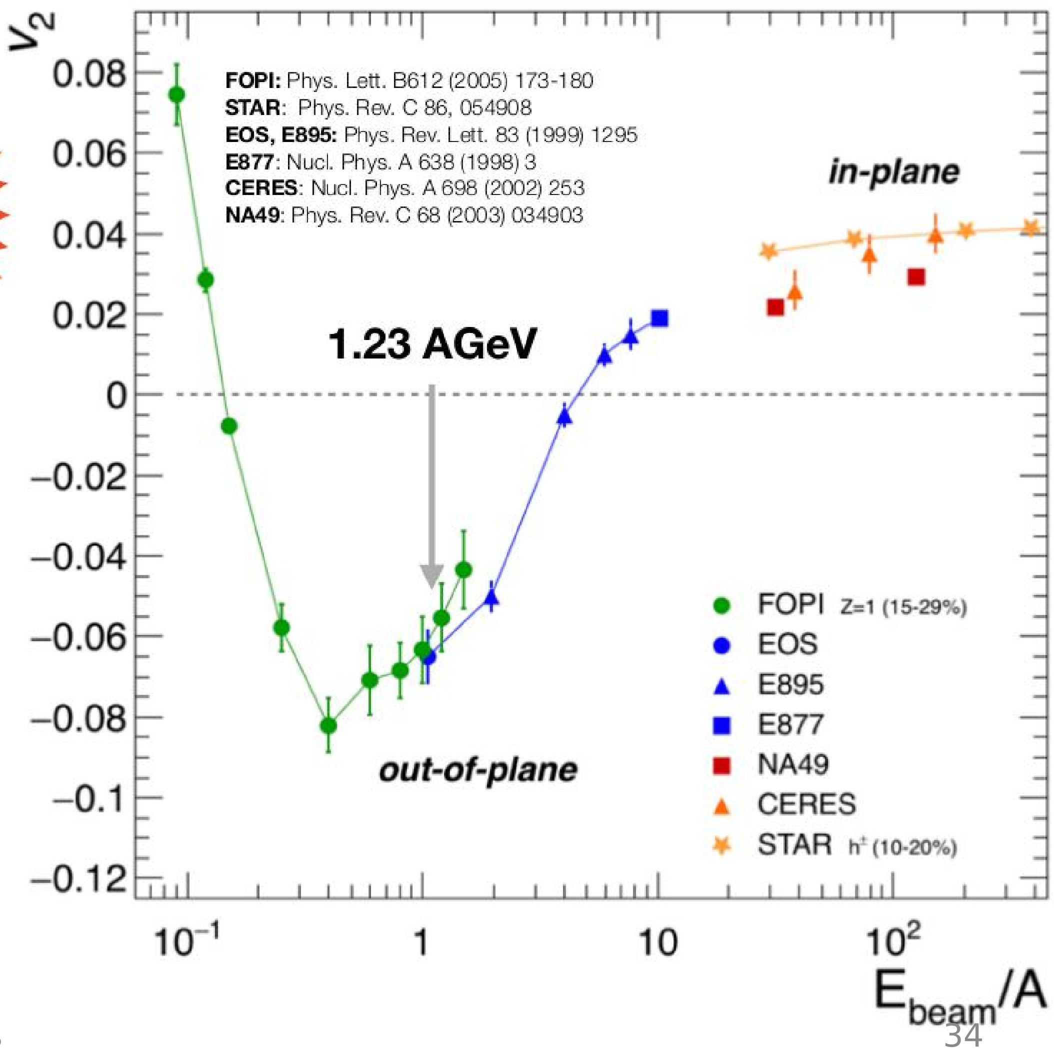
PID v_n at HADES: exploring (even) lower energies

- In-plane $v_2>0$
  - Short spectator passing time
    $\tau_{passing} \ll \tau_{expansion}$
  - Pressure gradient



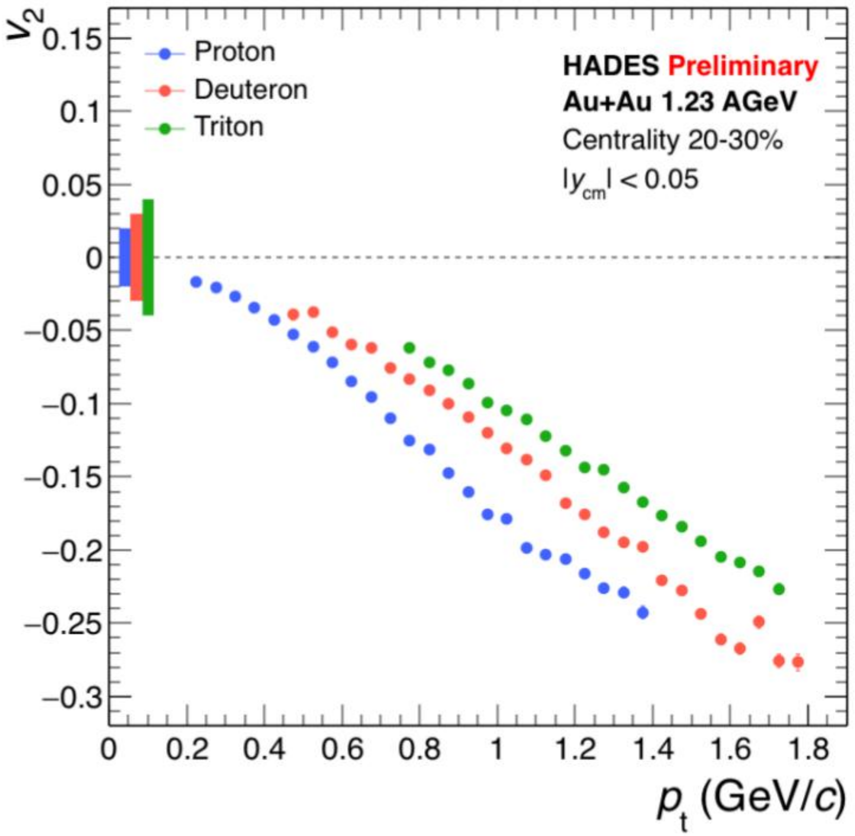
- Out-of-plane $v_2<0$
  - Long spectator passing time
    $\tau_{passing} \geq \tau_{expansion}$
  - Squeeze-out

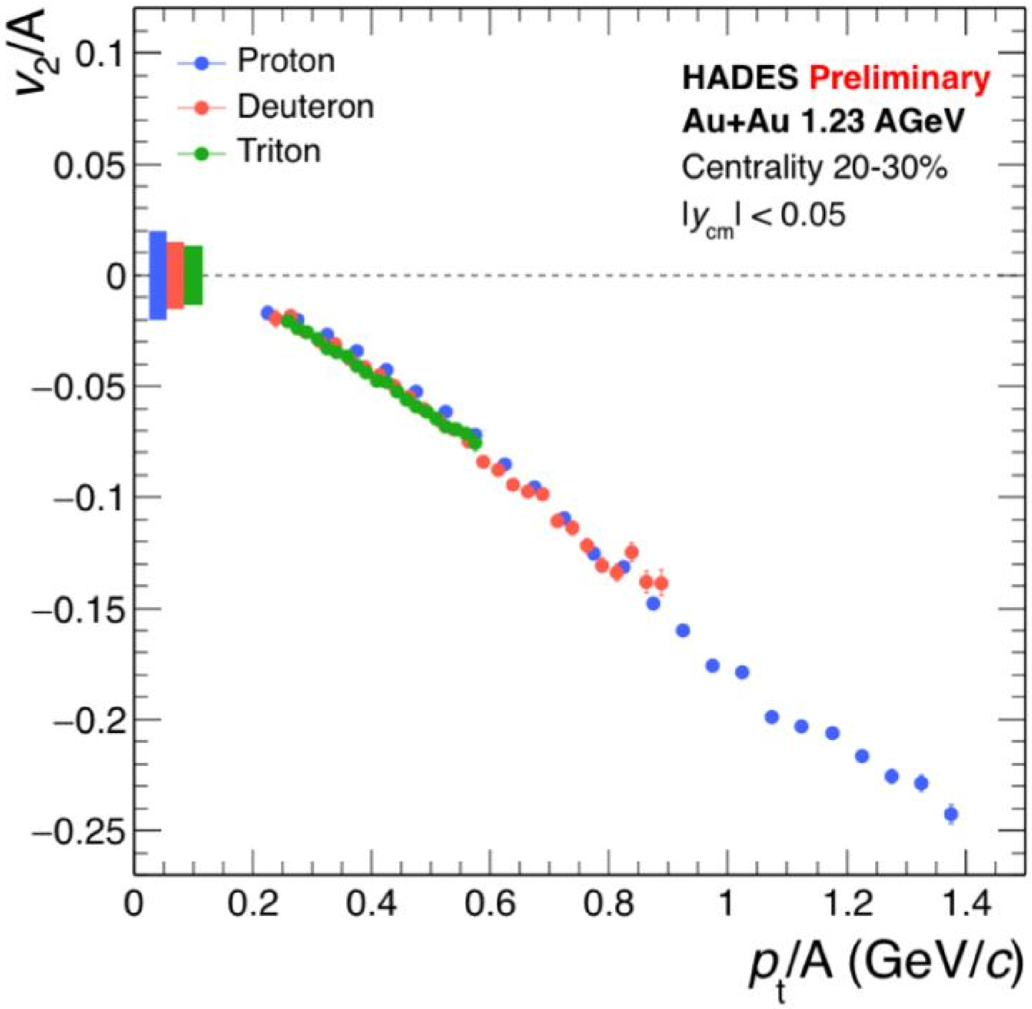




NB credit: B. Kardan, QM2018

PID v_2 @ 1.23 AGeV

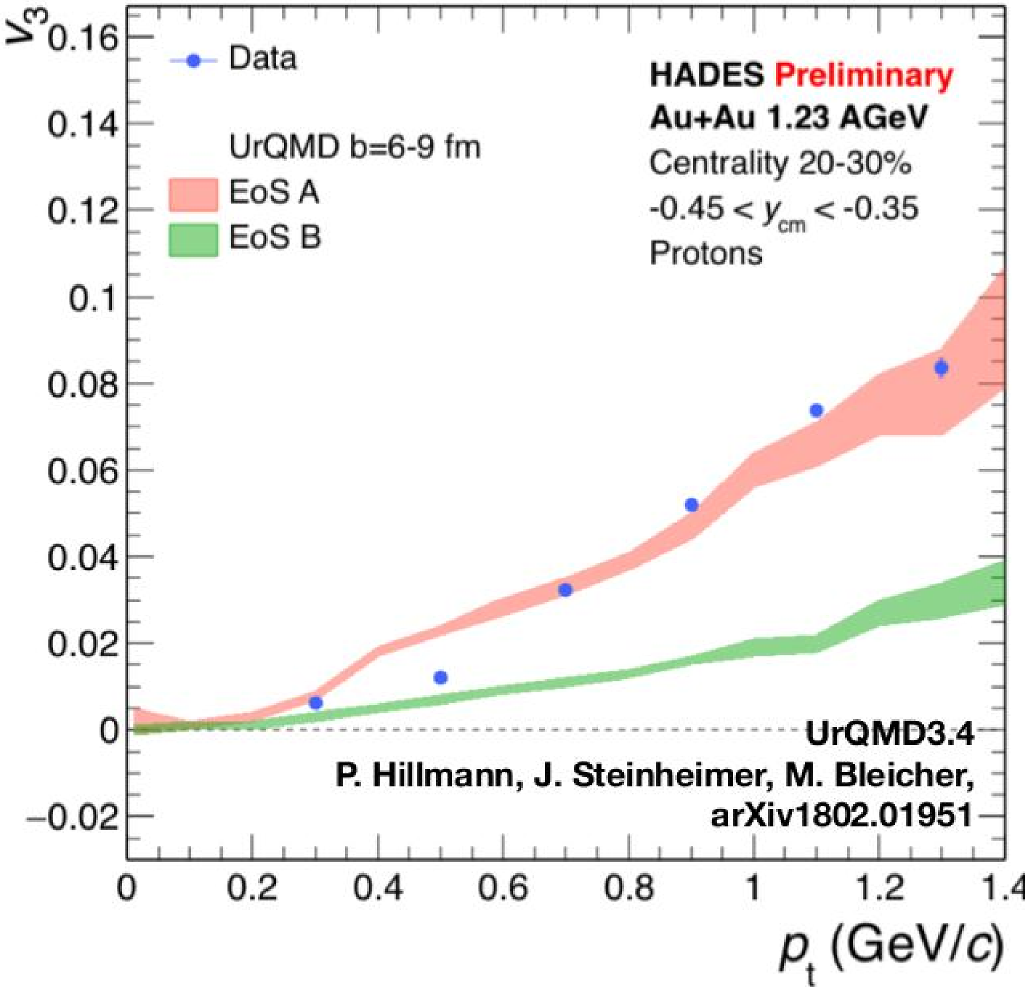


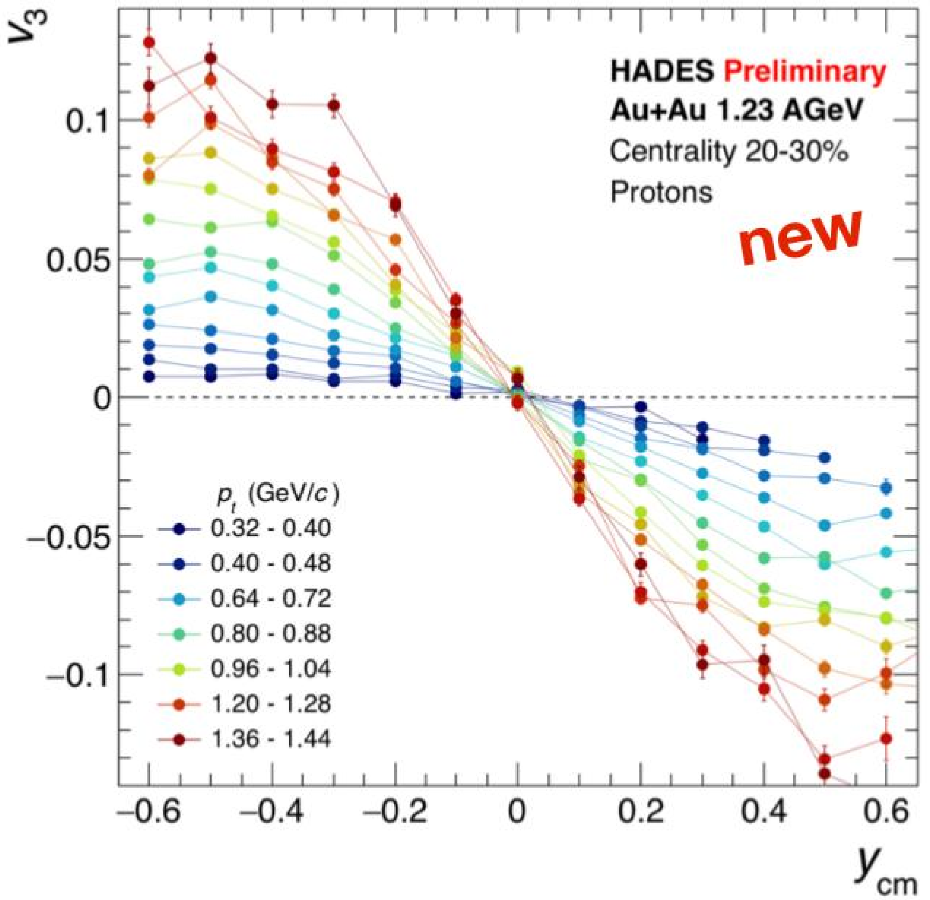


'squeeze-out' v_2 of protons, deuterons and triton
scaling of v_2 and p_T with nuclear mass number A
as expected from nucleon coalescnence

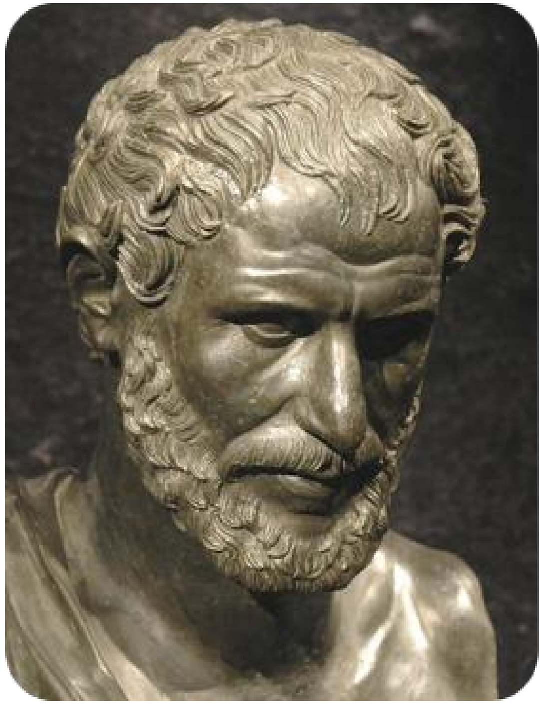
PID v_3 @ 1.23 AGeV

UrQMD predicts high sensitivity of v_3 to EoS





Τα πάντα ρει…



PID flow: wealth of measurements available

high precision in p_T centrality from LHC run 2
high precision as function of beam energy from STAR
pushing to lowest energies with HADES

fundamental questions
- discerning between initial state and final state effects
- treatment of non-flow