Collective Flow in pp collisions

You Zhou

Niels Bohr Institute, University of Copenhagen

Thanks to Panos C., Katarina G., Emil G., Shengli H., Jurgen S, Bjoern S., Wenbin Z., Debojit S. and Nu X. for discussions

Collective Flow in pp^{+} high Nch p-Pb -M.B. pp collisions

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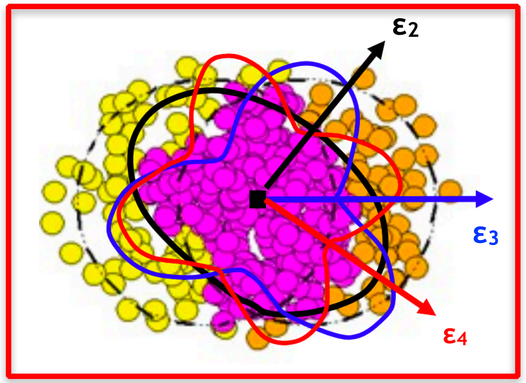

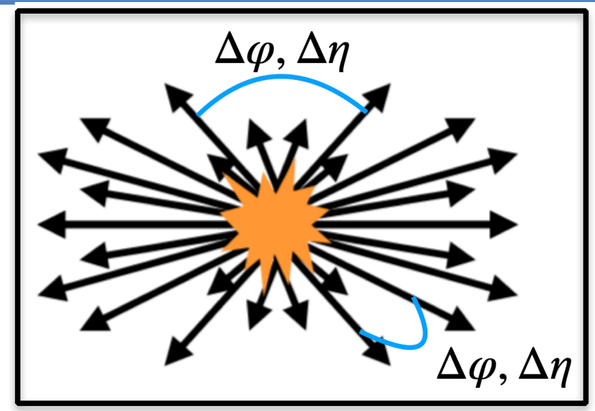

Jean-Yves Ollitrault, PRD 46, 229 (1992)

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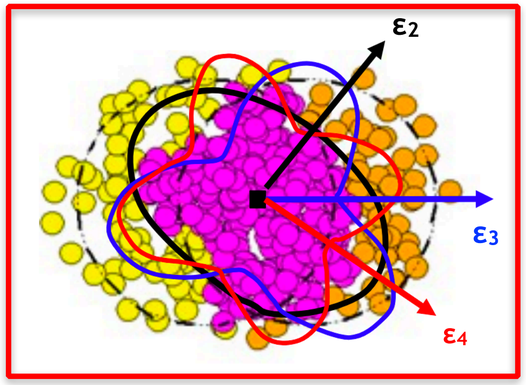

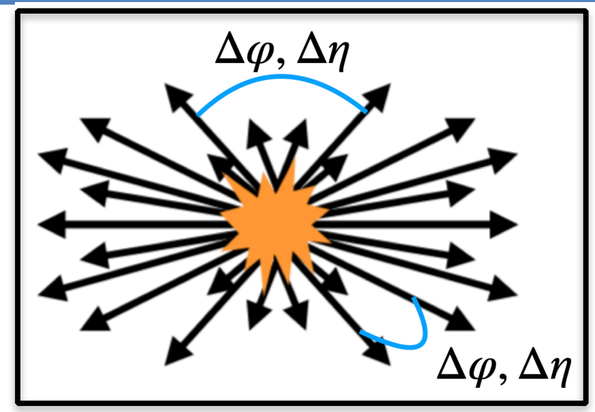

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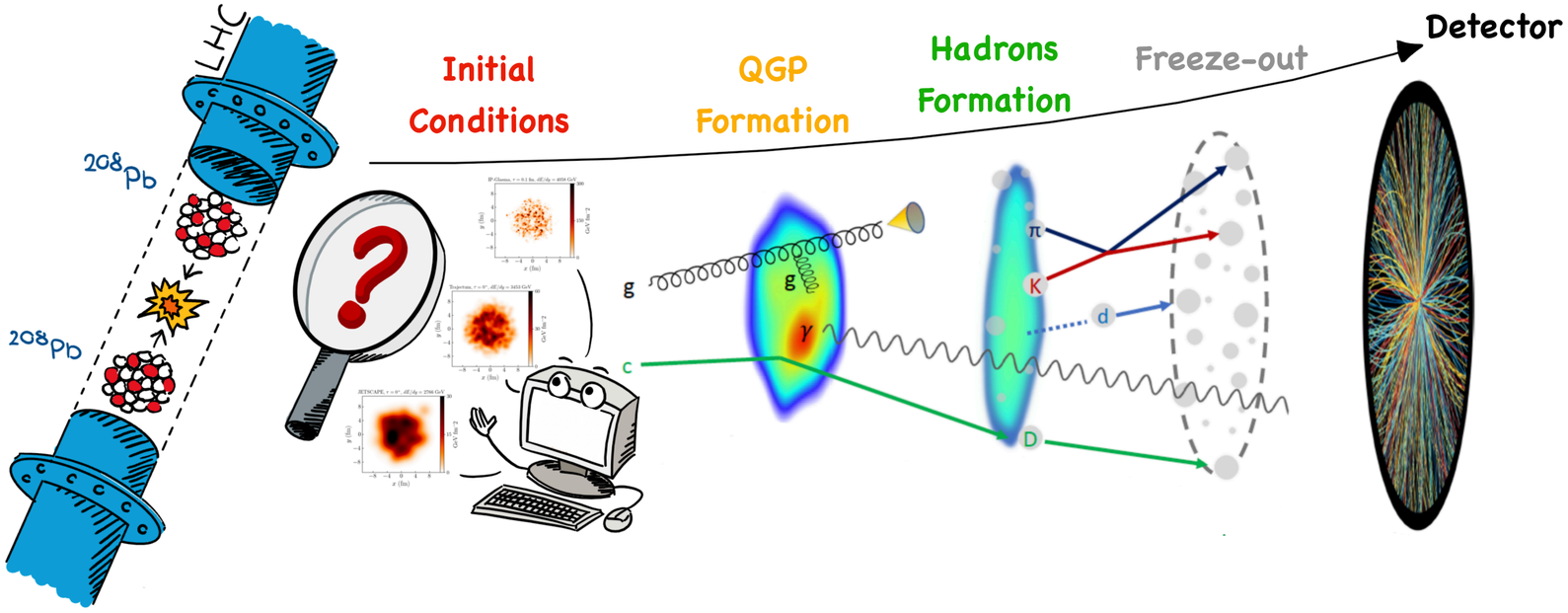

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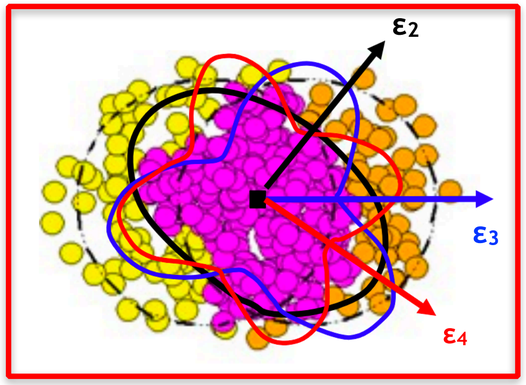

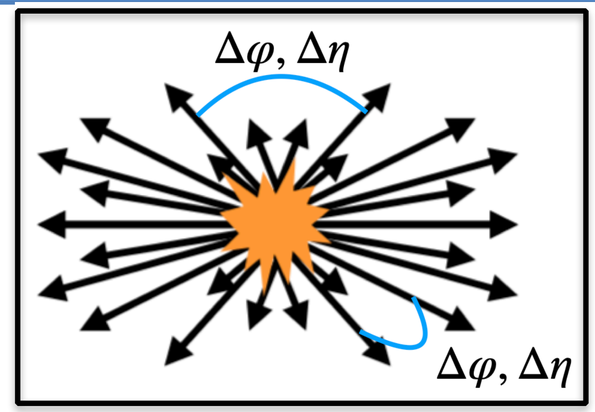

$$P(\varepsilon_m, \varepsilon_n, \varepsilon_k, ..., \Phi_m, \Phi_n, \Phi_k, ...) \Rightarrow P(v_m, v_n, v_k, ..., \Psi_m, \Psi_n, \Psi_k, ...)$$

How does v_n fluctuate	How does ψ_n fluctuate	How do v_n and v_m correlate	How do ψ_n and ψ_m correlate
$P(v_n)$	$P(\Psi_n)$	$P(v_m, v_n, v_k, ...)$	$P(\Psi_m, \Psi_n, \Psi_k, ...)$

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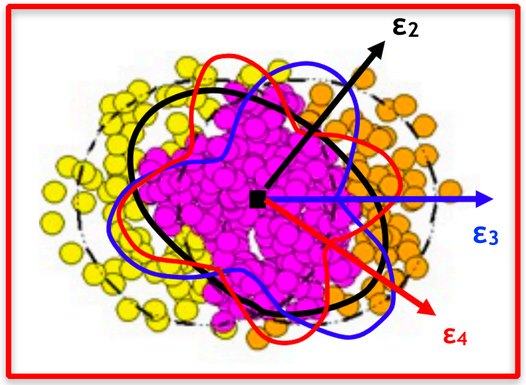

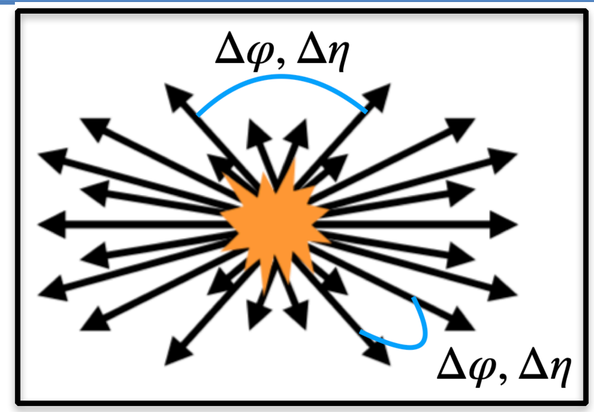

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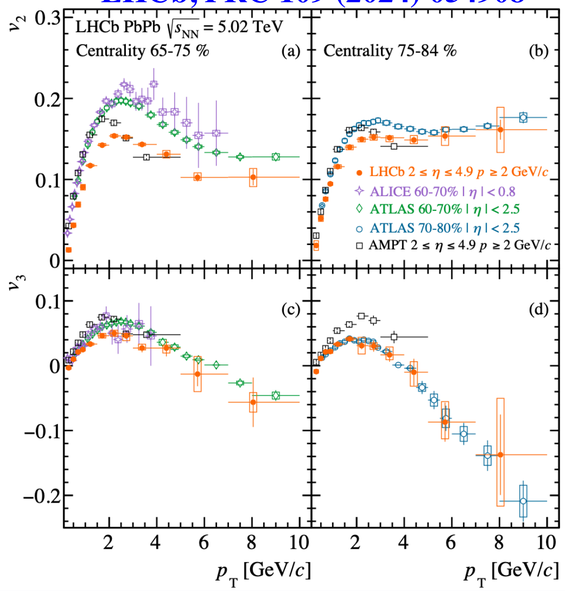
LHCb, PRC 109 (2024) 054908



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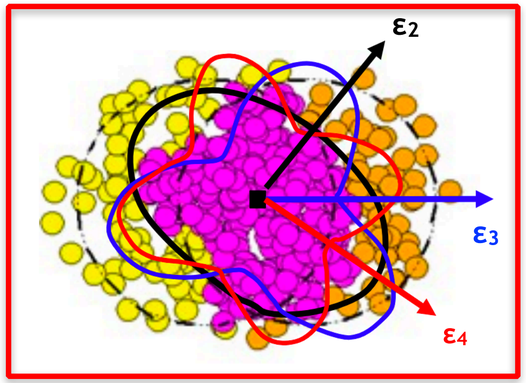

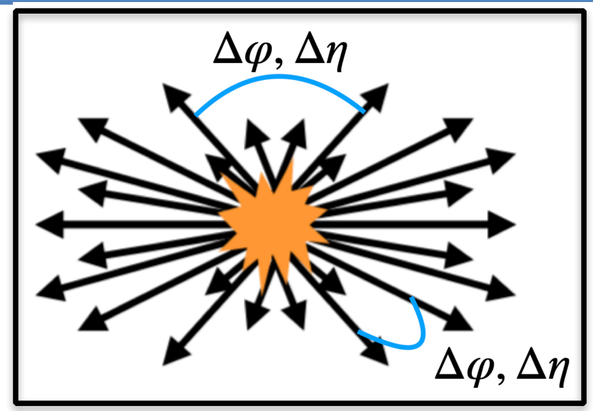

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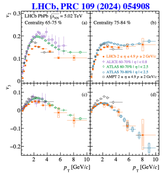

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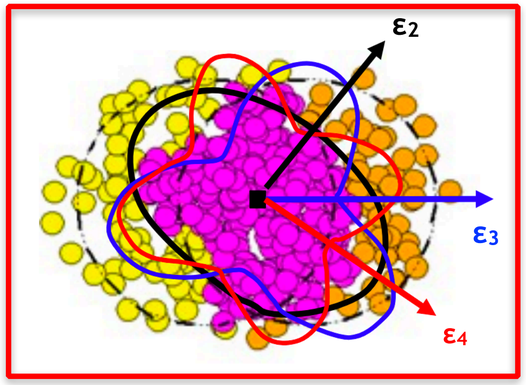

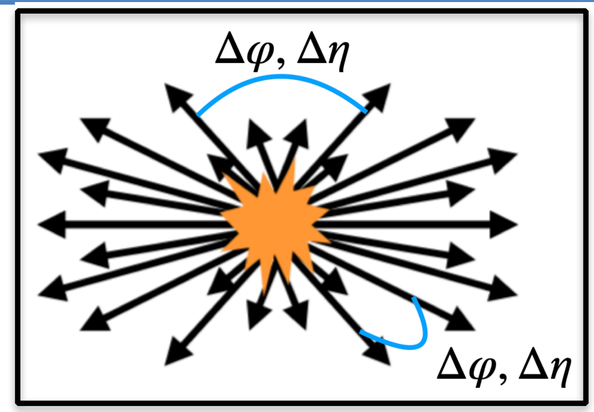

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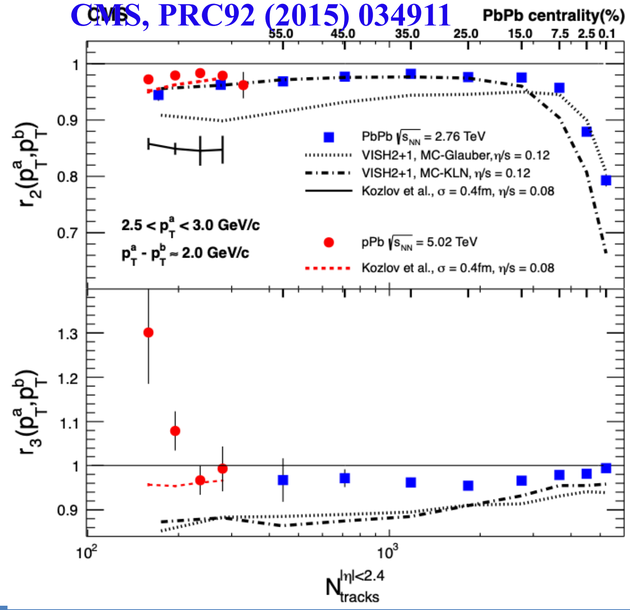

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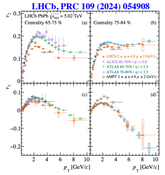

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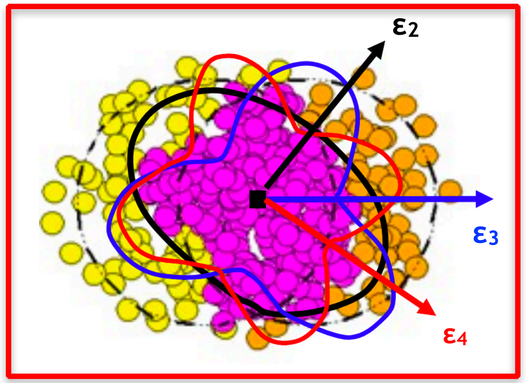

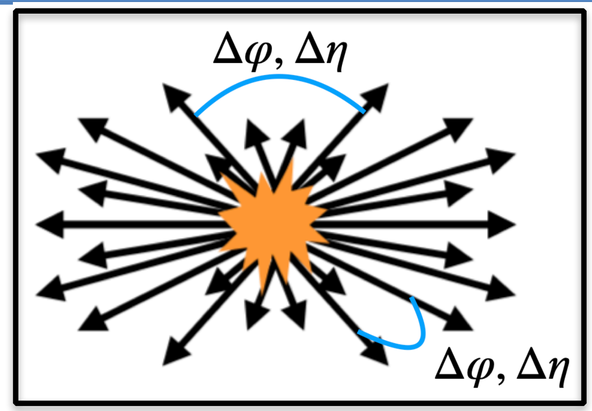

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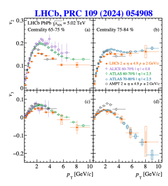

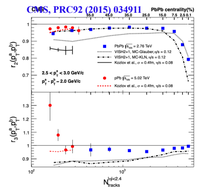

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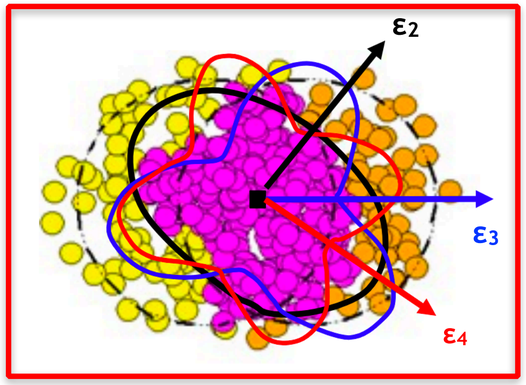

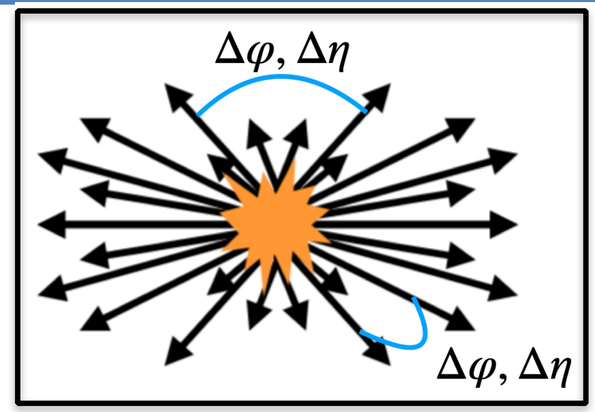

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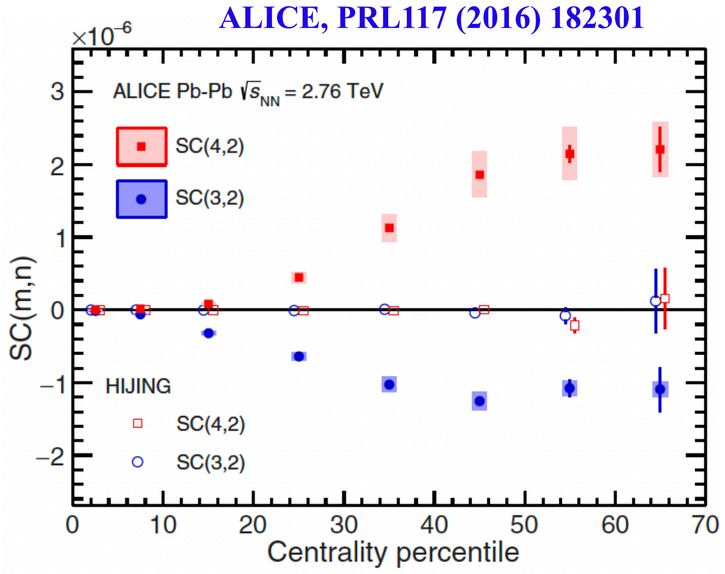

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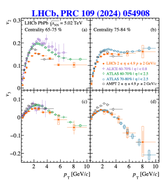

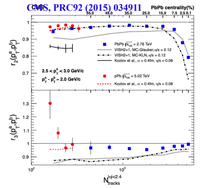

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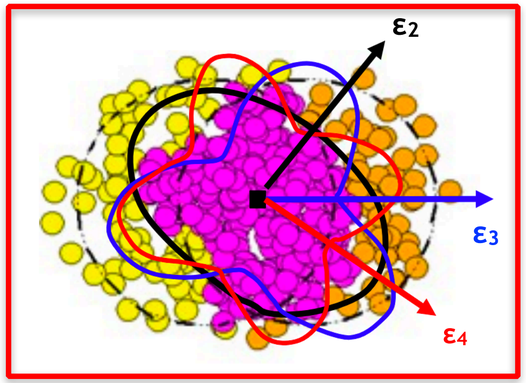

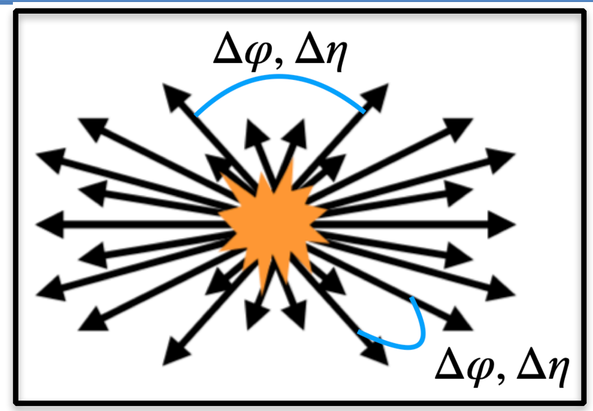

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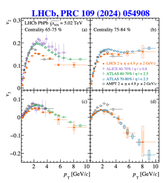

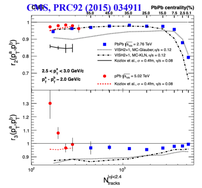

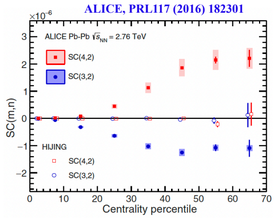

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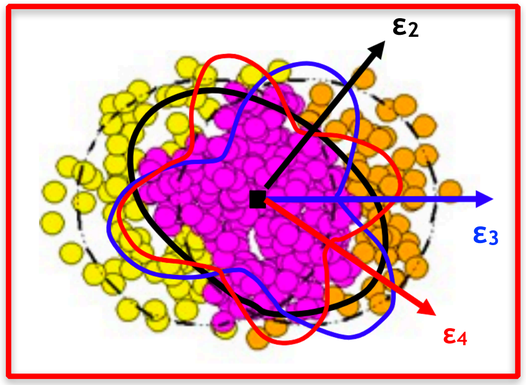

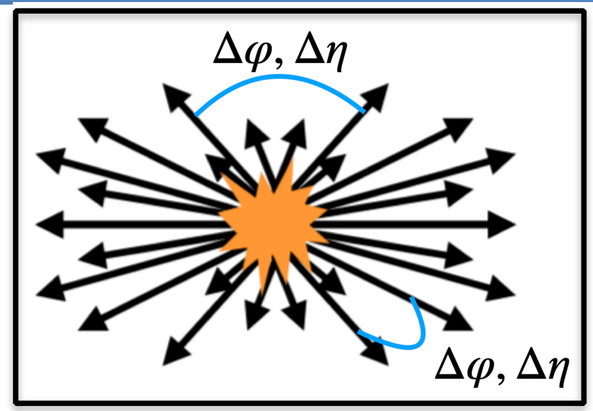

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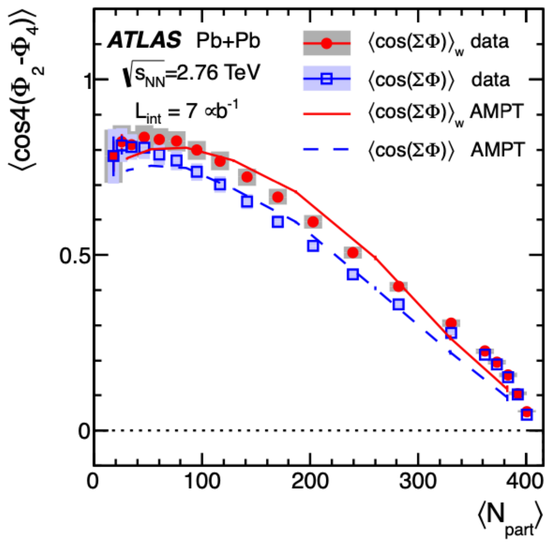
ATLAS, 90 (2014) 024905



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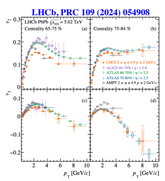

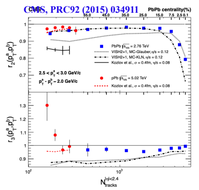

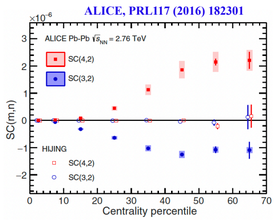

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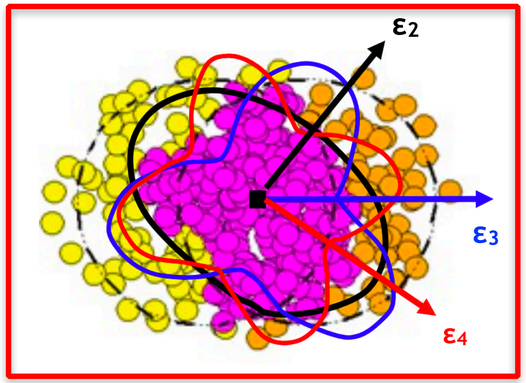

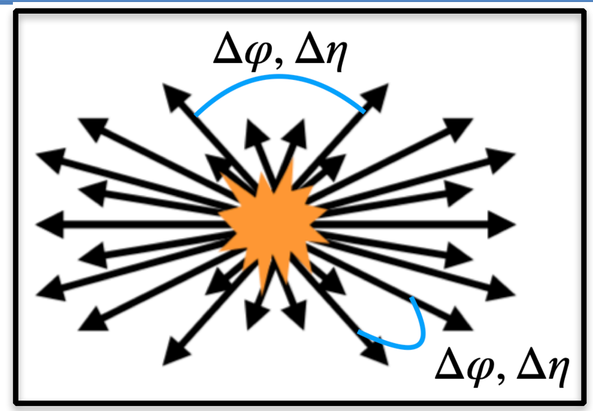

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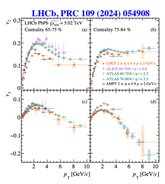
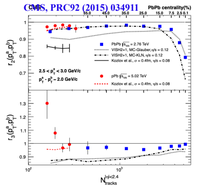
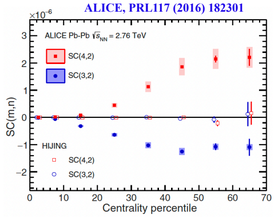
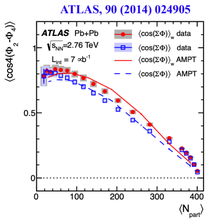


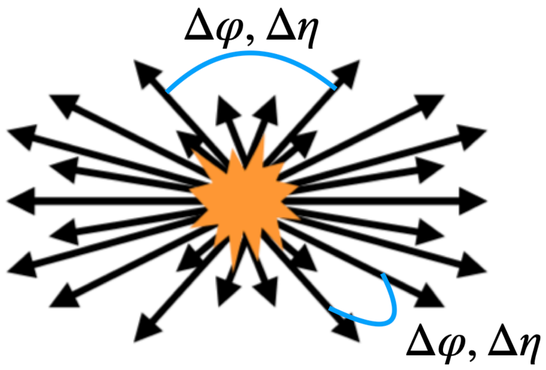






flow vs nonflow

Flow



❖ **Conceptually** flow is the global anisotropic particle expansion that described by a unified p.d.f.

Small system workshops:
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flow vs nonflow

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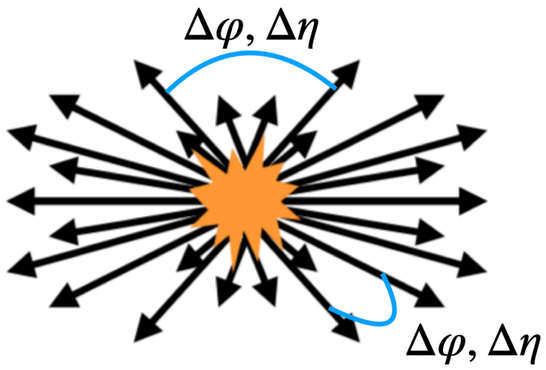
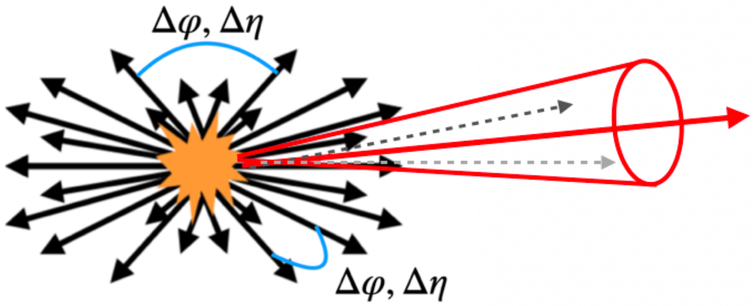
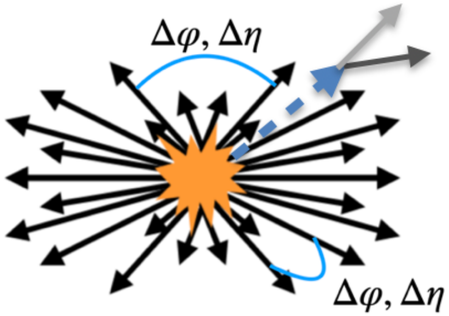


Nonflow

Jets



Resonances decay



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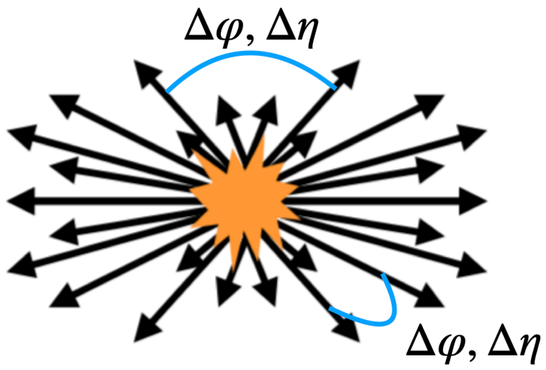
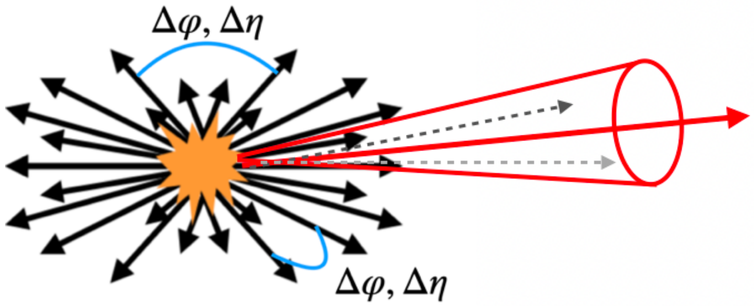
flow vs nonflow

Flow

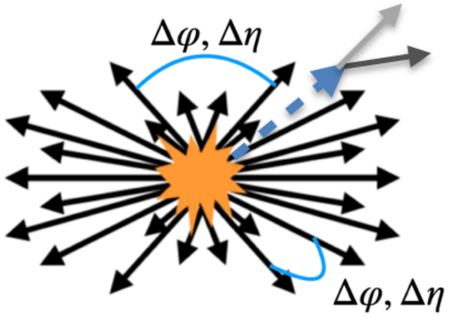


Nonflow

Jets



Resonances decay

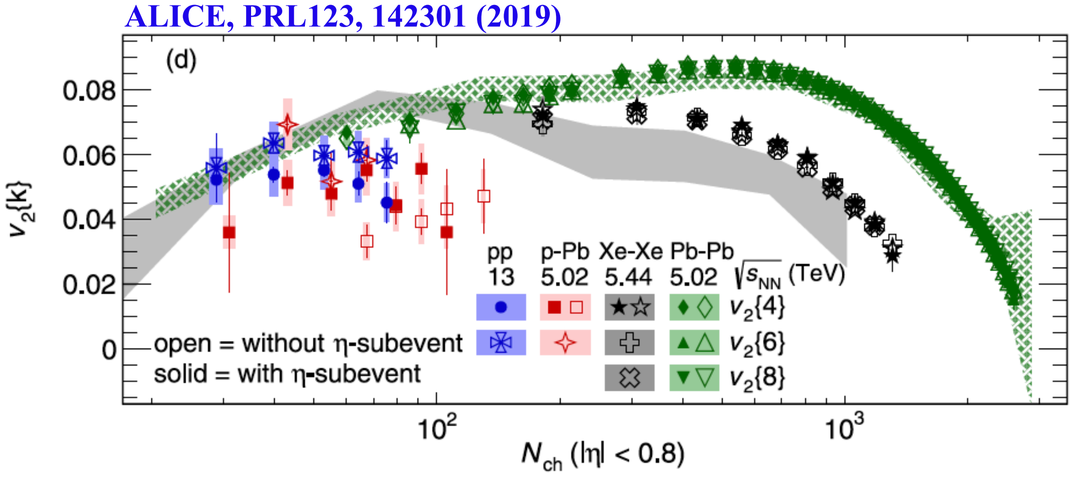


- **Conceptually** flow is the global anisotropic particle expansion that described by a unified p.d.f.
- **Working definition:** Long-Range Multi-particle correlations
  - Short-range correlation -> nonflow
  - Few particle correlations-> nonflow

Small system workshops:
NBI/Copenhagen (2017),
CCNU/Wuhan (2018),
Rice/Houston (2019),
SDU/Qingdao (2024)

Working definition for small systems

- **Working definition:** Long-Range Multi-particle correlations

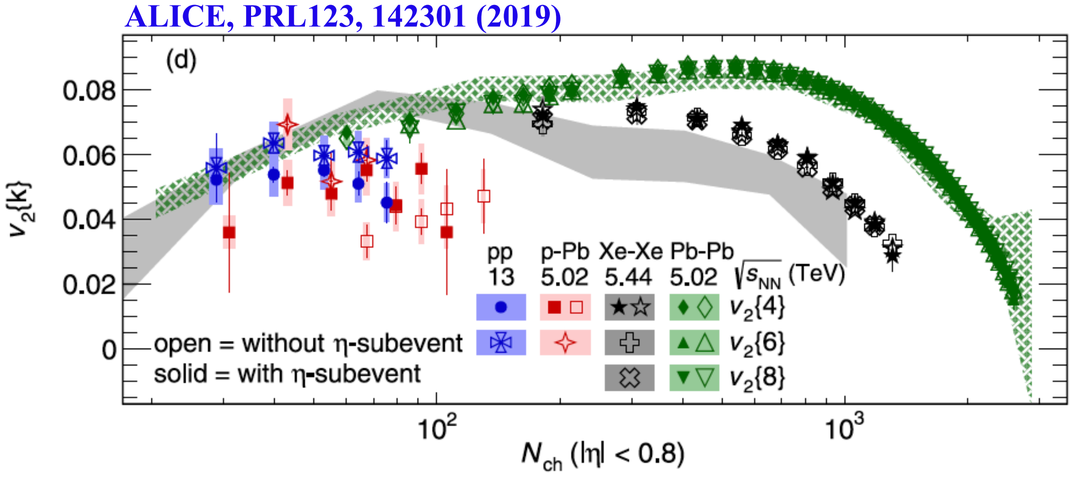


- $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
- $v_2\{k\}$ (2-sub) ≈ $v_2\{k\}$ (3-sub)
- Observation of flow in small systems

Working definition for small systems

- **Working definition:** Long-Range Multi-particle correlations

ALICE, PRL123, 142301 (2019)



- How about 2-particle (di-hadron) correlations?

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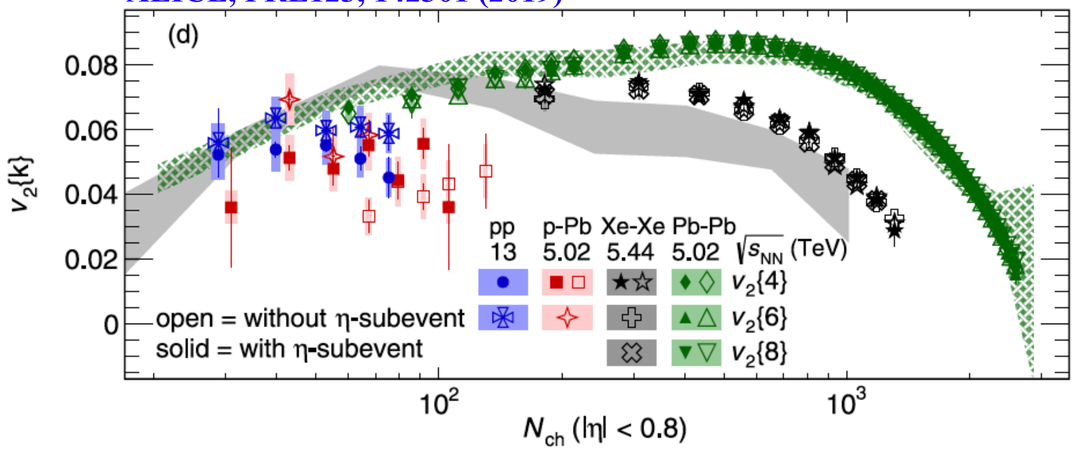

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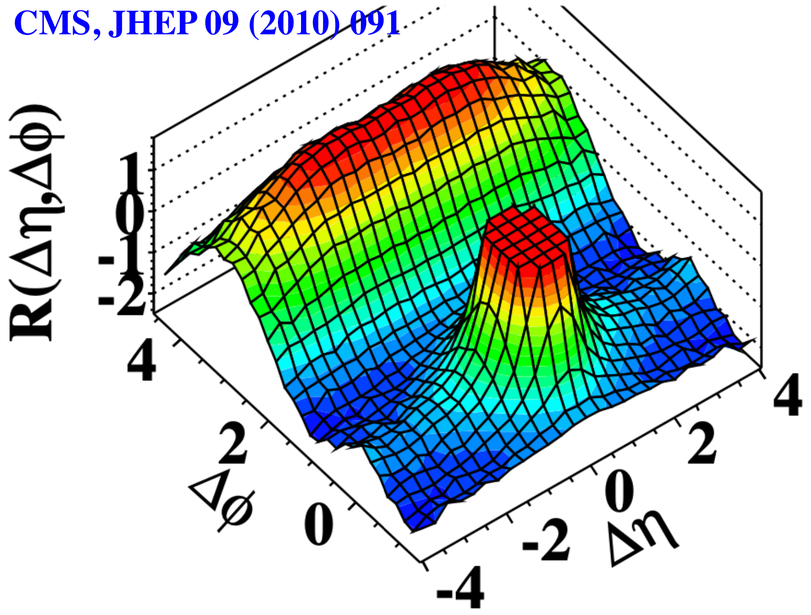
(d) CMS N ≥ 110, 1.0GeV/c<p_T<3.0GeV/c

CMS, JHEP 09 (2010) 091



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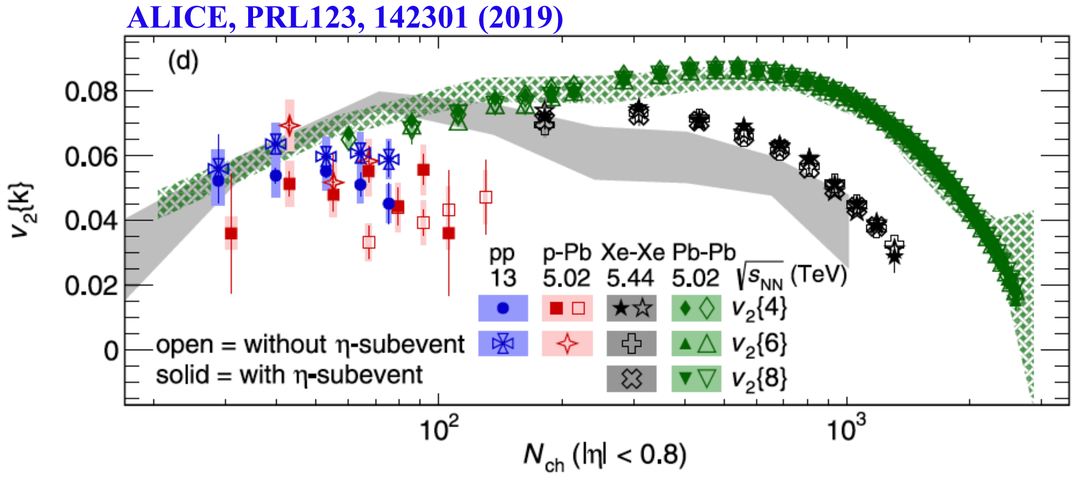

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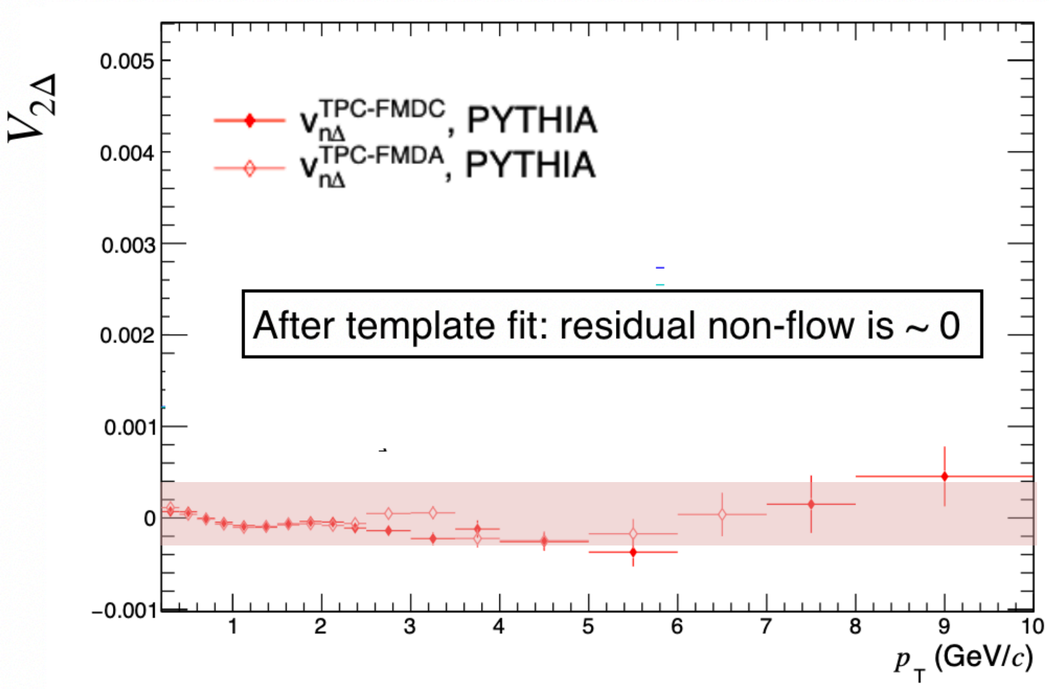
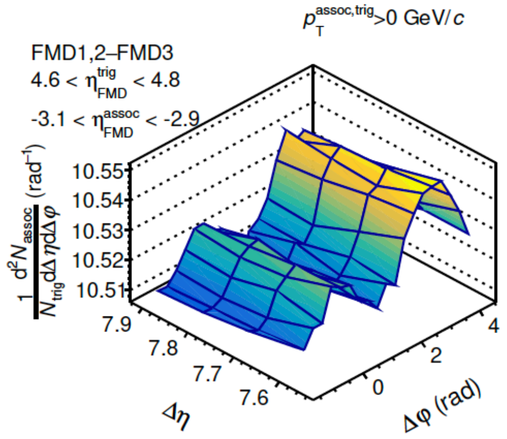


- The 2-particle correlations in the ***nonflow*** model, after subtraction, are compatible with zero (necessary conditions)

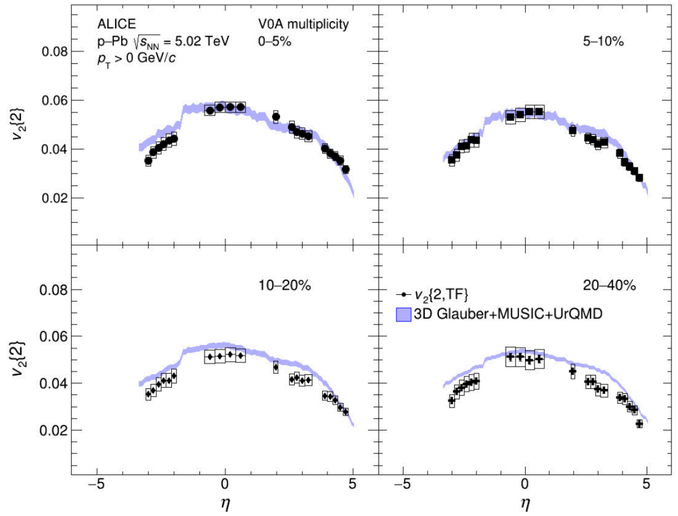
New papers on flow in small systems for SQM

New papers on flow in small systems for SQM

ALICE, PLB850 (2024) 138477



ALICE, PLB850 (2024) 138477



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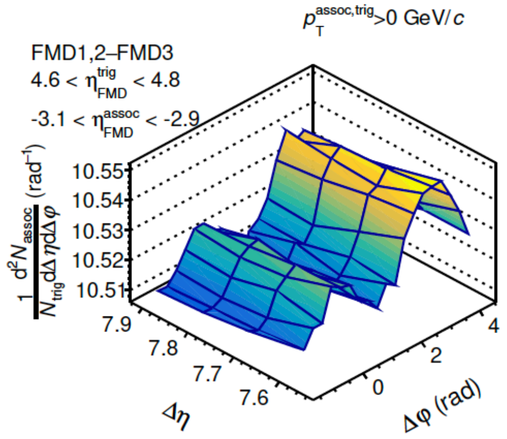

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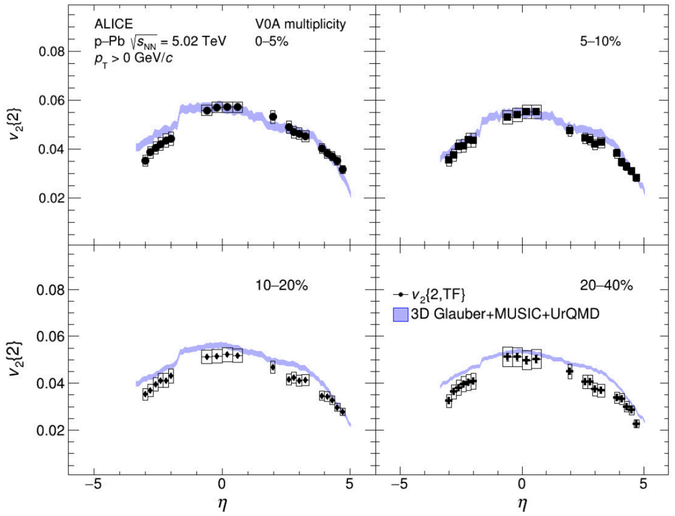
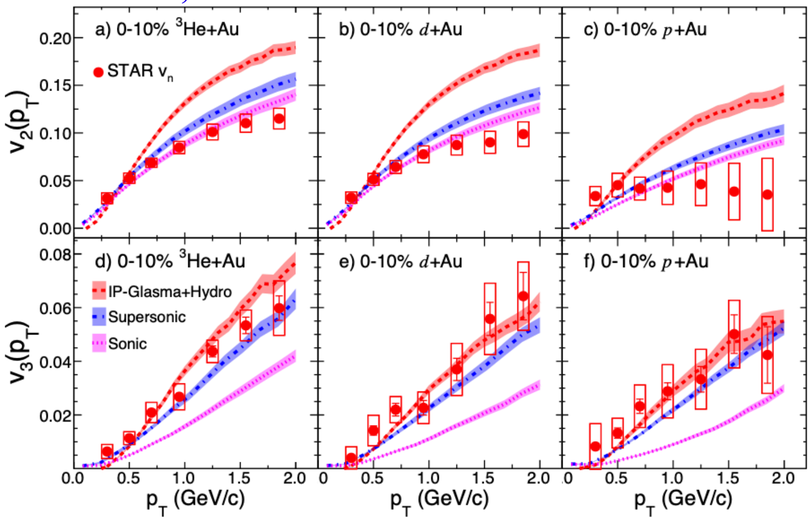


STAR, arXiv: 2312.07464



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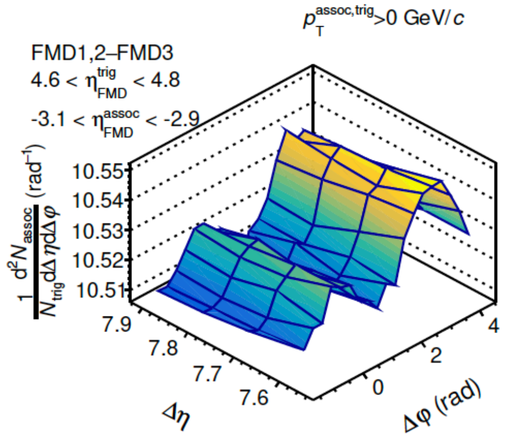

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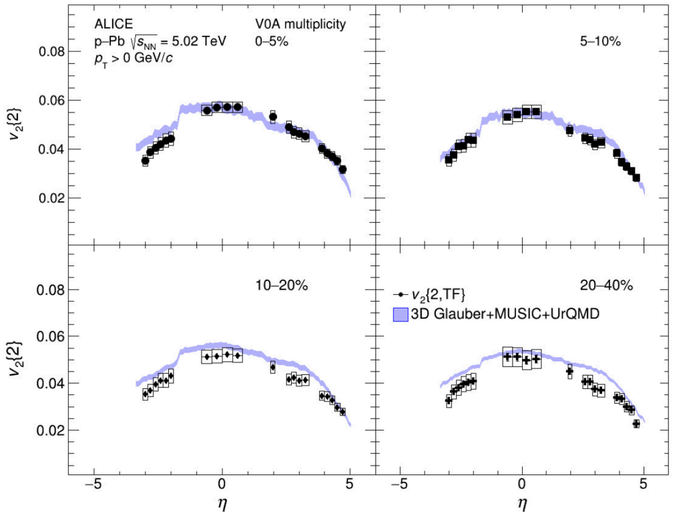

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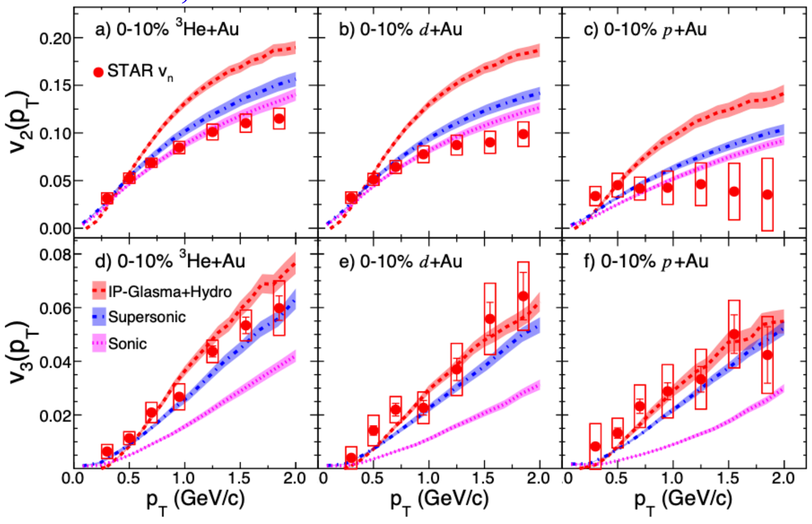
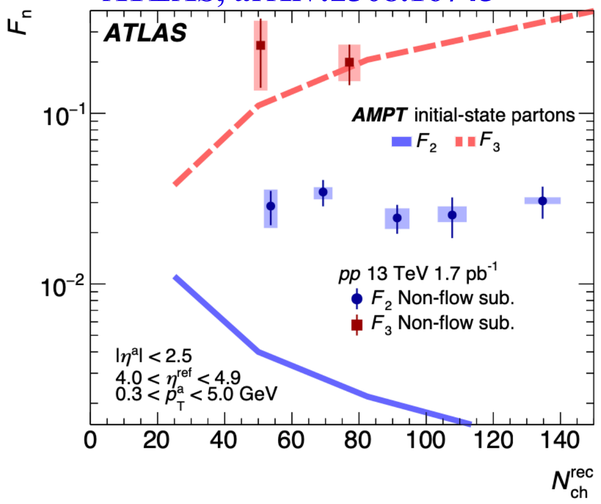


ATLAS, arXiv:2308.16745



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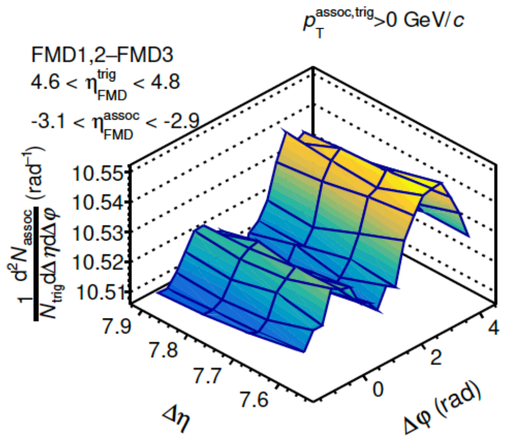
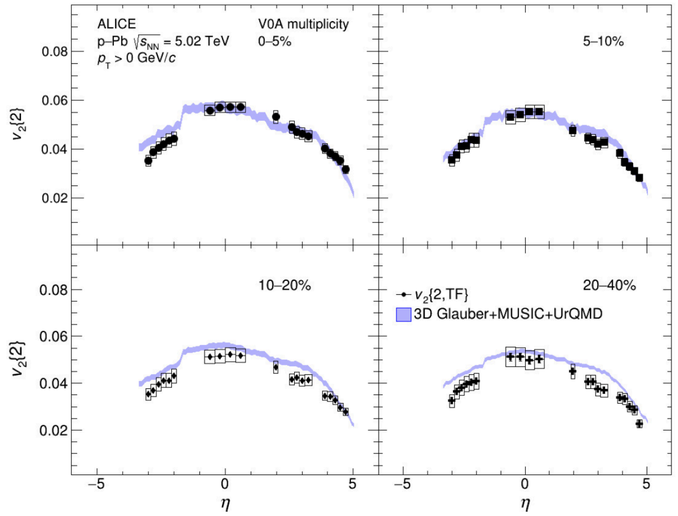
ALICE, PLB850 (2024) 138477



ALICE, PLB850 (2024) 138477



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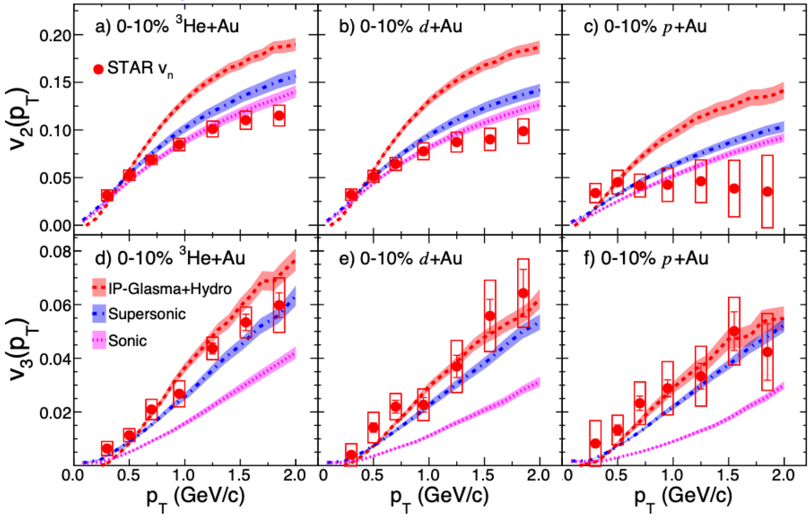
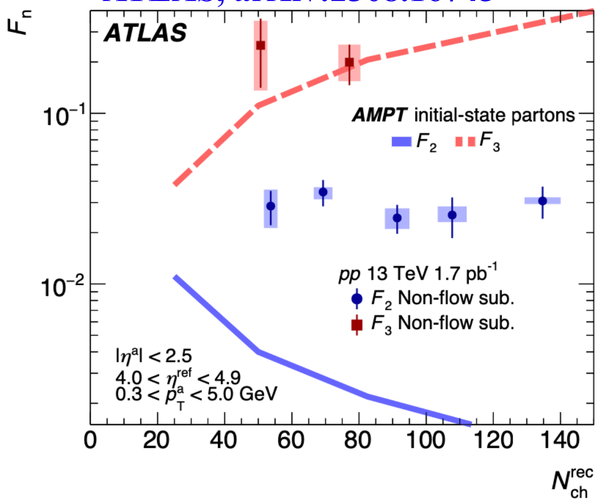
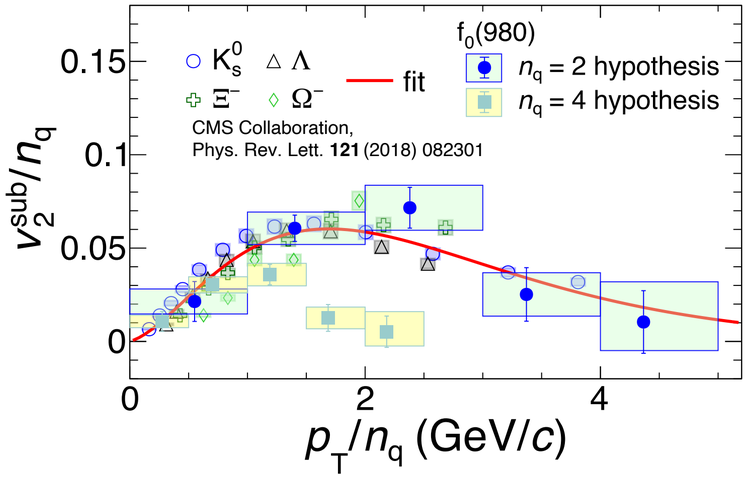


ATLAS, arXiv:2308.16745

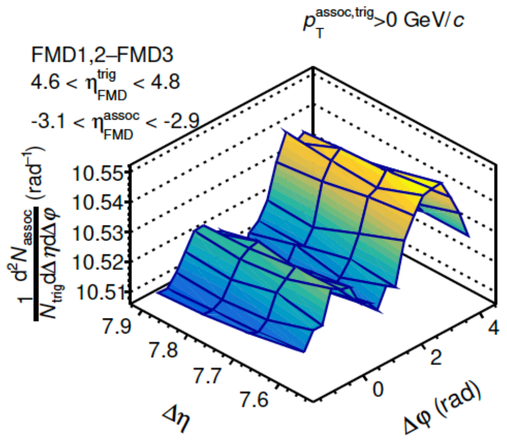


CMS, arXiv:2312.17092



New papers on flow in small systems for SQM

ALICE, PLB850 (2024) 138477



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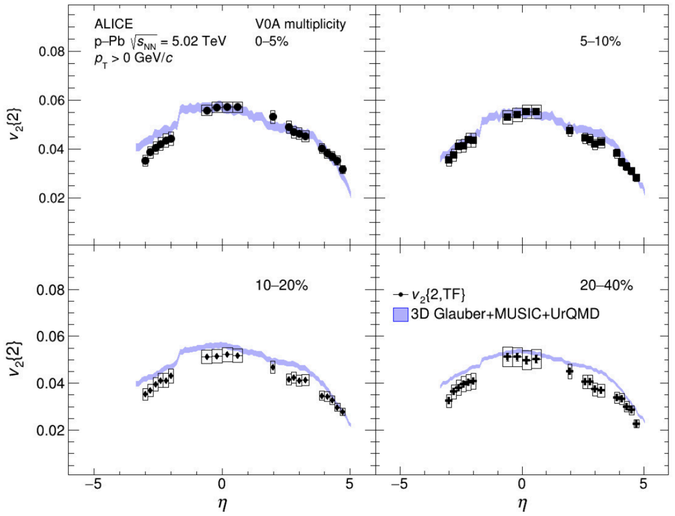

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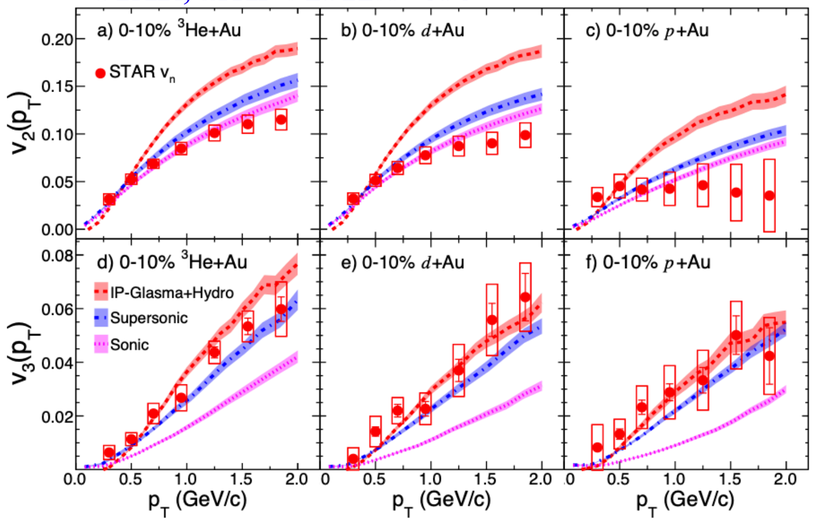

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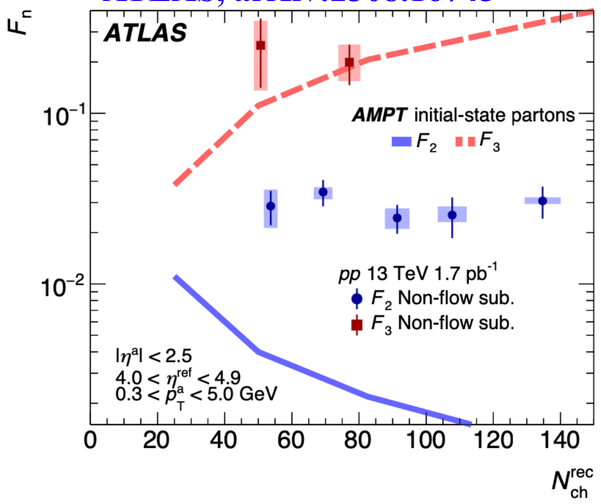

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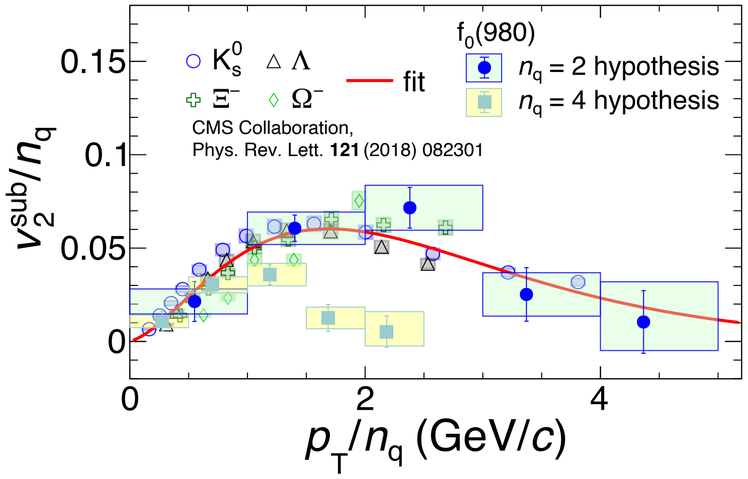
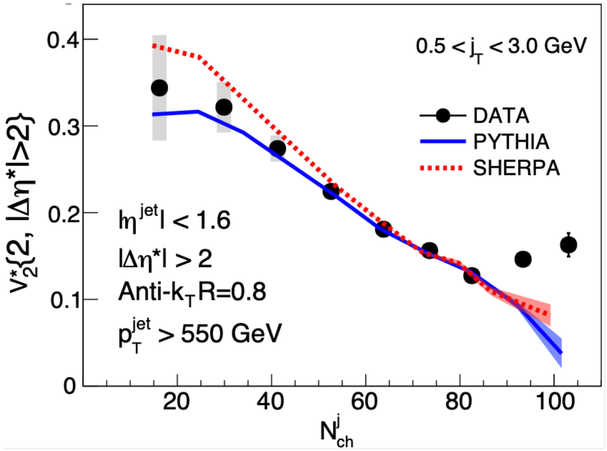


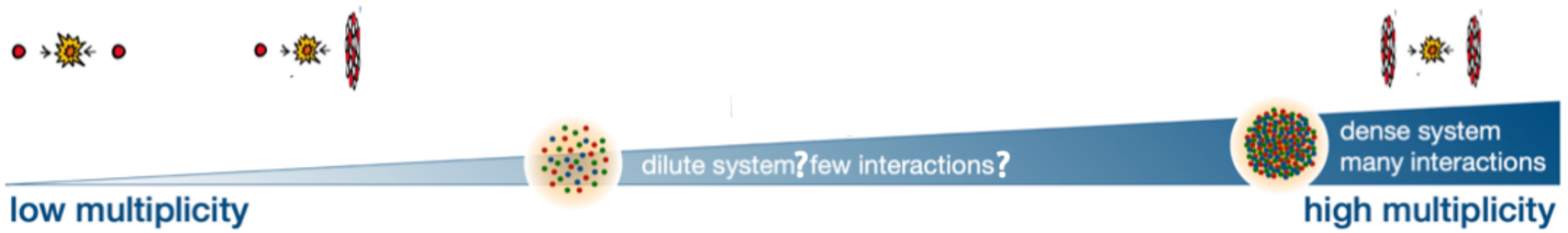
CMS, arXiv:2312.17103



Origin(s) of flow in small systems

Credit: Christian B.

- Collectivity in small systems challenges two paradigms at once!



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  1. How far down in systems size does the "SM of heavy ions" remain?

Origin(s) of flow in small systems

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- Collectivity in small systems challenges two paradigms at once!
  1. How far down in systems size does the "SM of heavy ions" remain?
  2. Can the standard tools for min bias pp remain standard?

Origin(s): geometry driven

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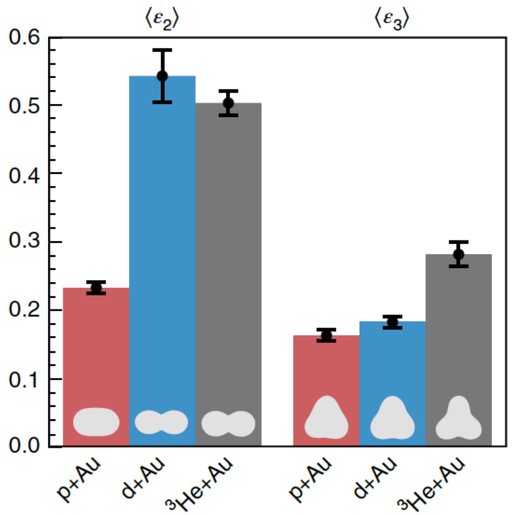

$$\varepsilon_2^{\mathrm{p+Au}} < \varepsilon_2^{\mathrm{d+Au}} \approx \varepsilon_2^{^3\mathrm{He+Au}}$$
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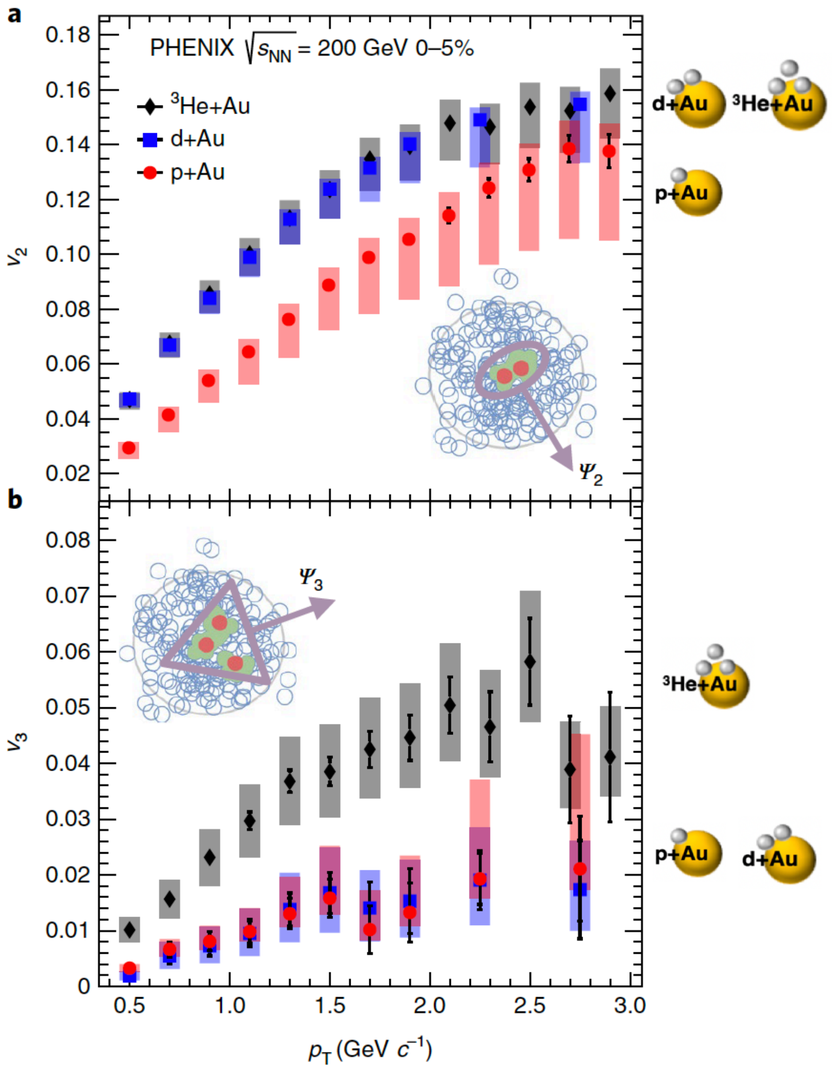
PHENIX, Nature Physics 15, 214 (2019)



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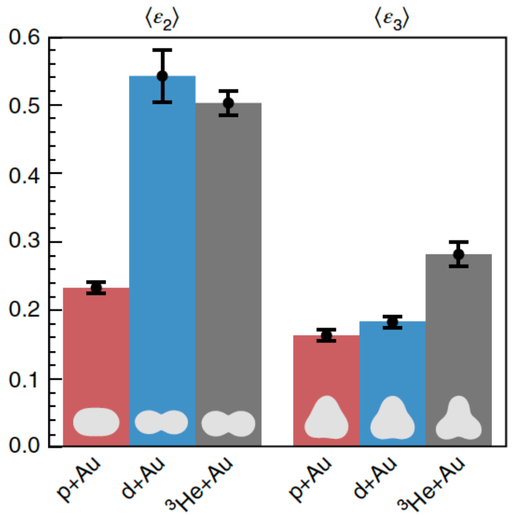

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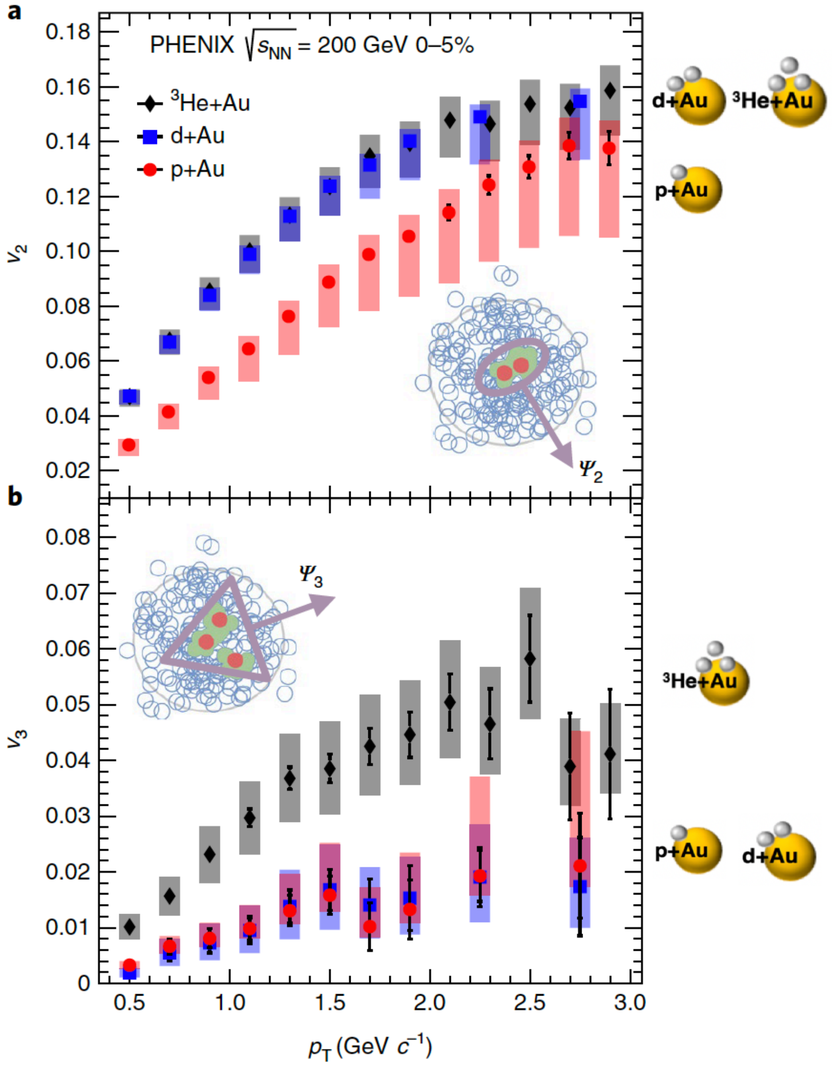
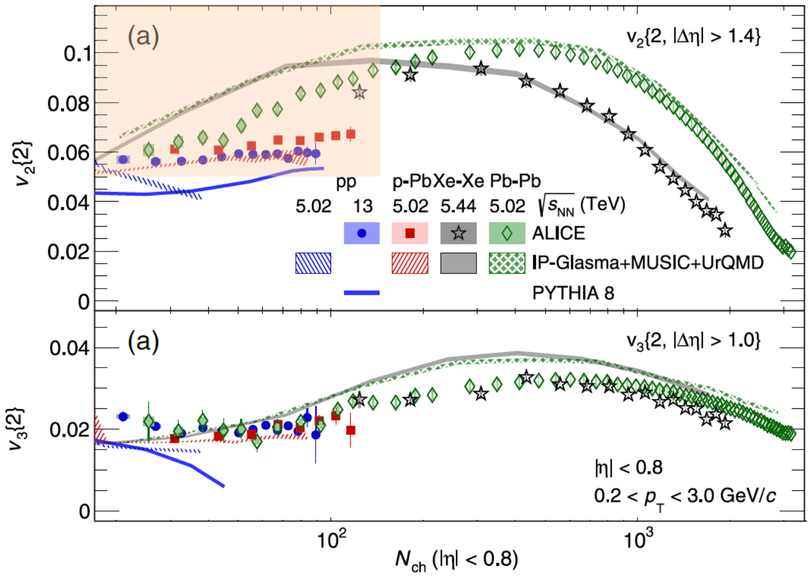


ALICE, PRL123, 142301 (2019)



v_2 pp < v_2 pPb < v_2 PbPb

v_3 pp ≈ v_3 pPb ≈ v_3 PbPb

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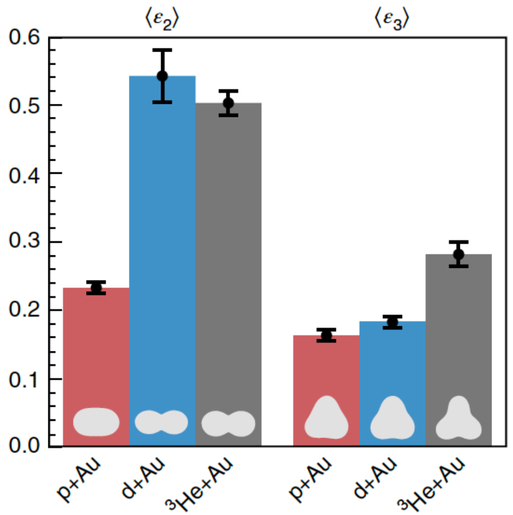

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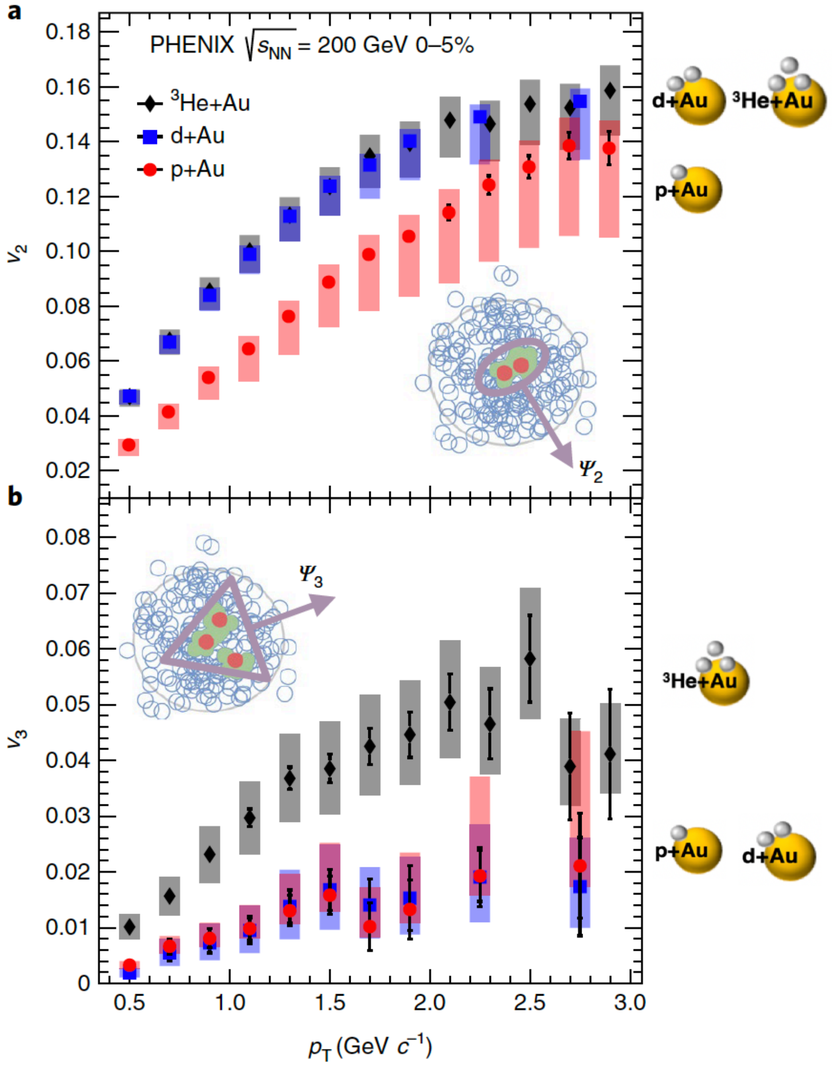

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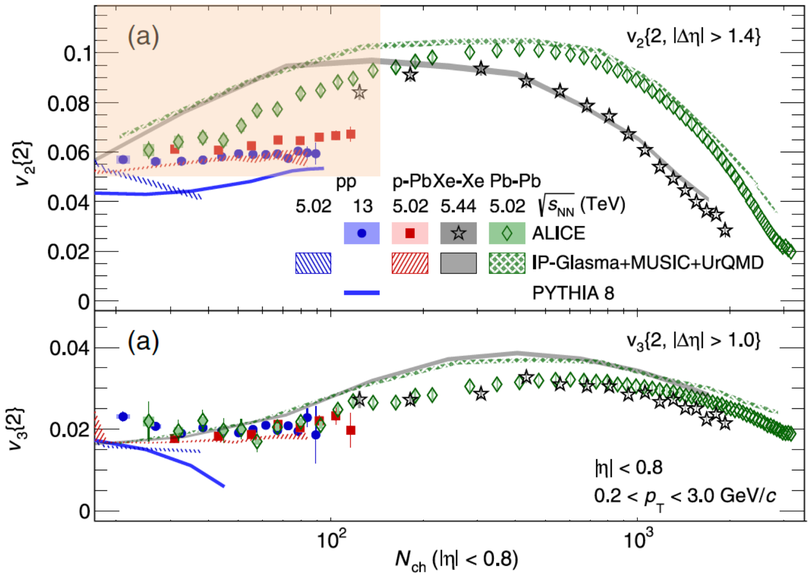

$$v_2\ ^{\mathrm{pp}} < v_2\ ^{\mathrm{pPb}} < v_2\ ^{\mathrm{PbPb}}$$
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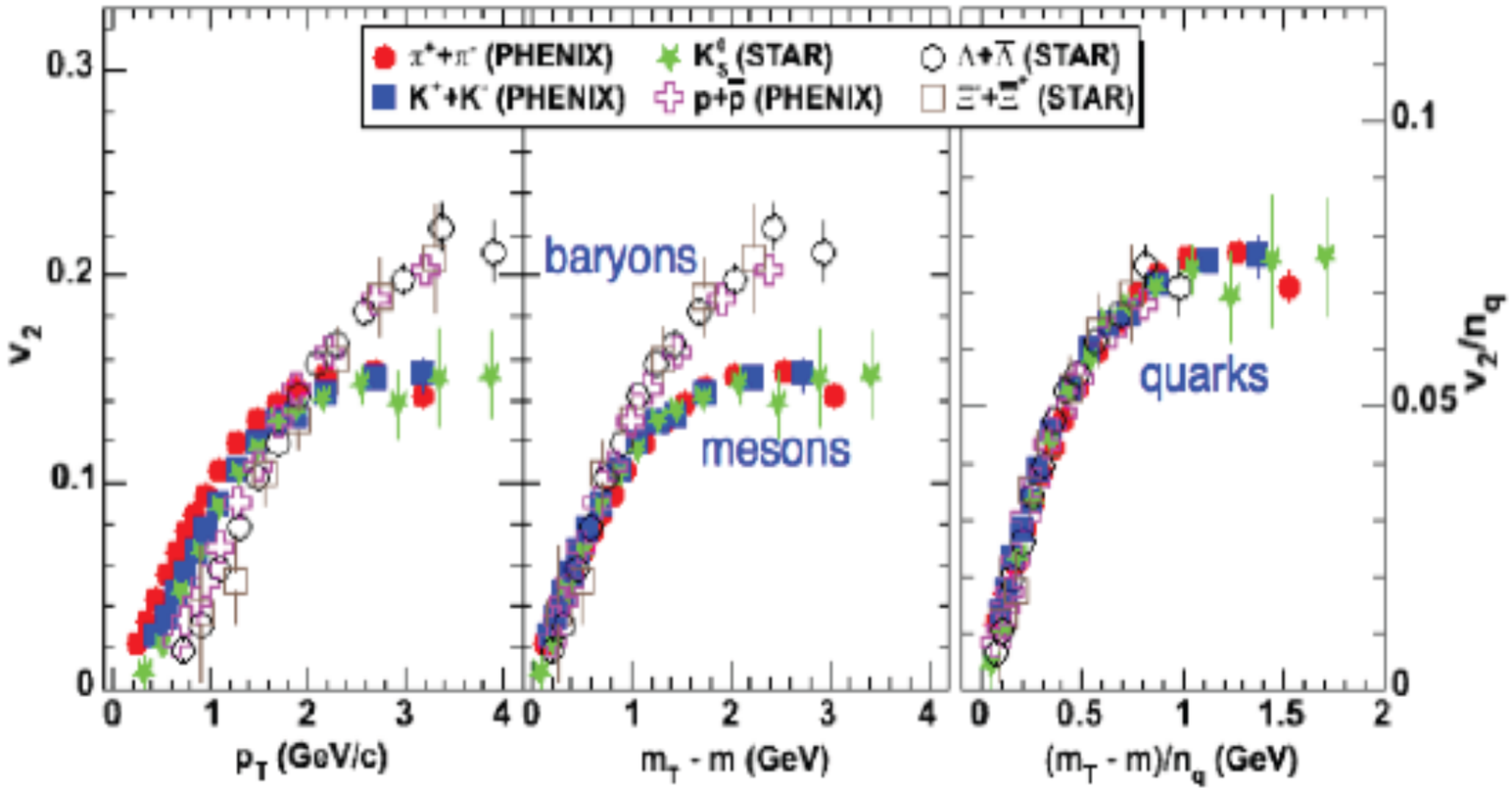
❖Flow in small systems is **initial geometry driven** through the *final state effects (FSE)*

- Which FSE? Hydro? Parton escape? String shoving? Others?

v_2 of identified hadron: smoking gun evidence of QGP

PHENIX, PRL98, 162301 (2007)



PID v_2 at top RHIC energy

v_2 of identified hadron: smoking gun evidence of QGP

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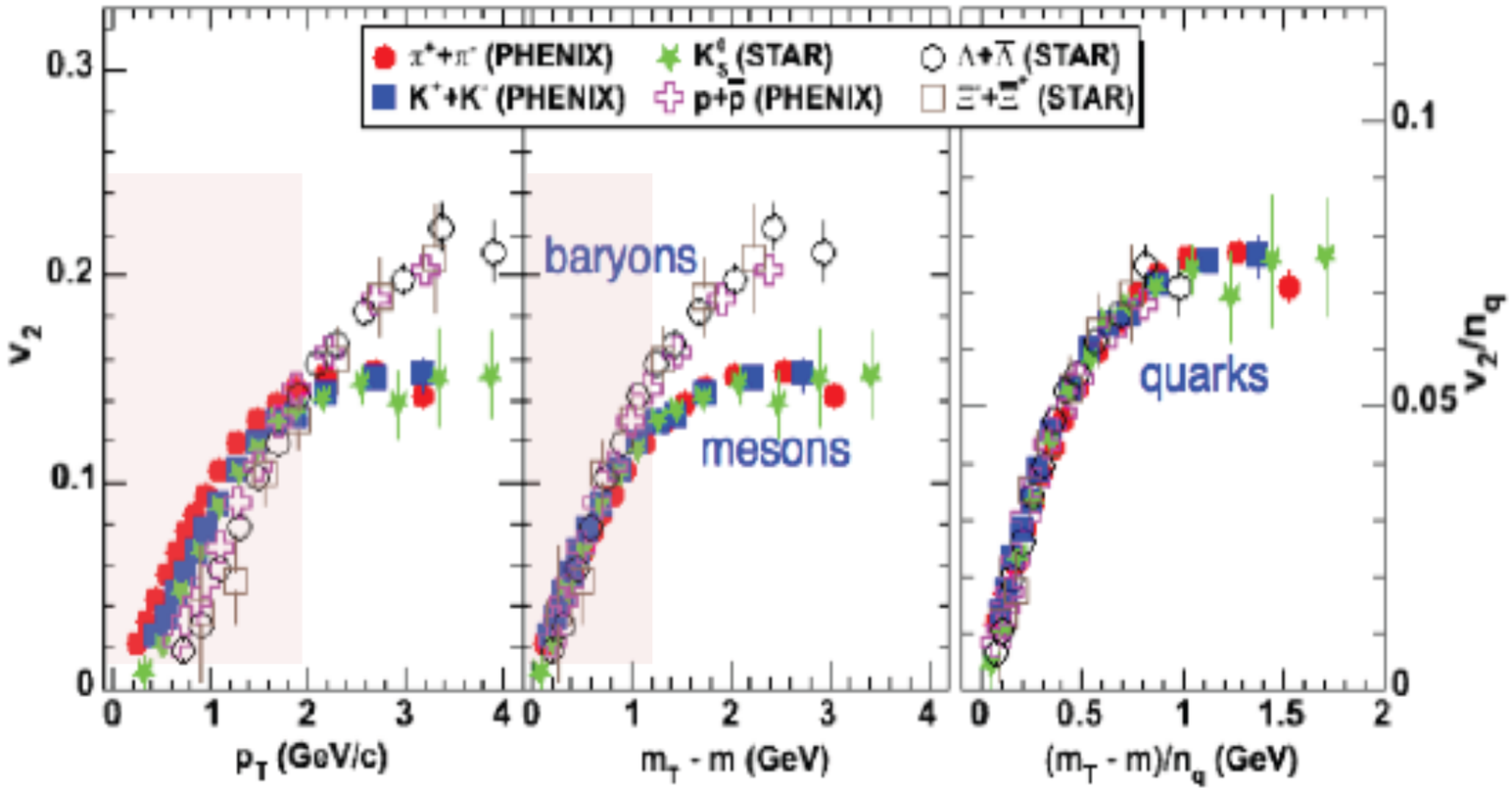

PID v_2 at top RHIC energy

- low p_T:
  - ➢mass ordering (described by hydrodynamics)

v_2 of identified hadron: smoking gun evidence of QGP

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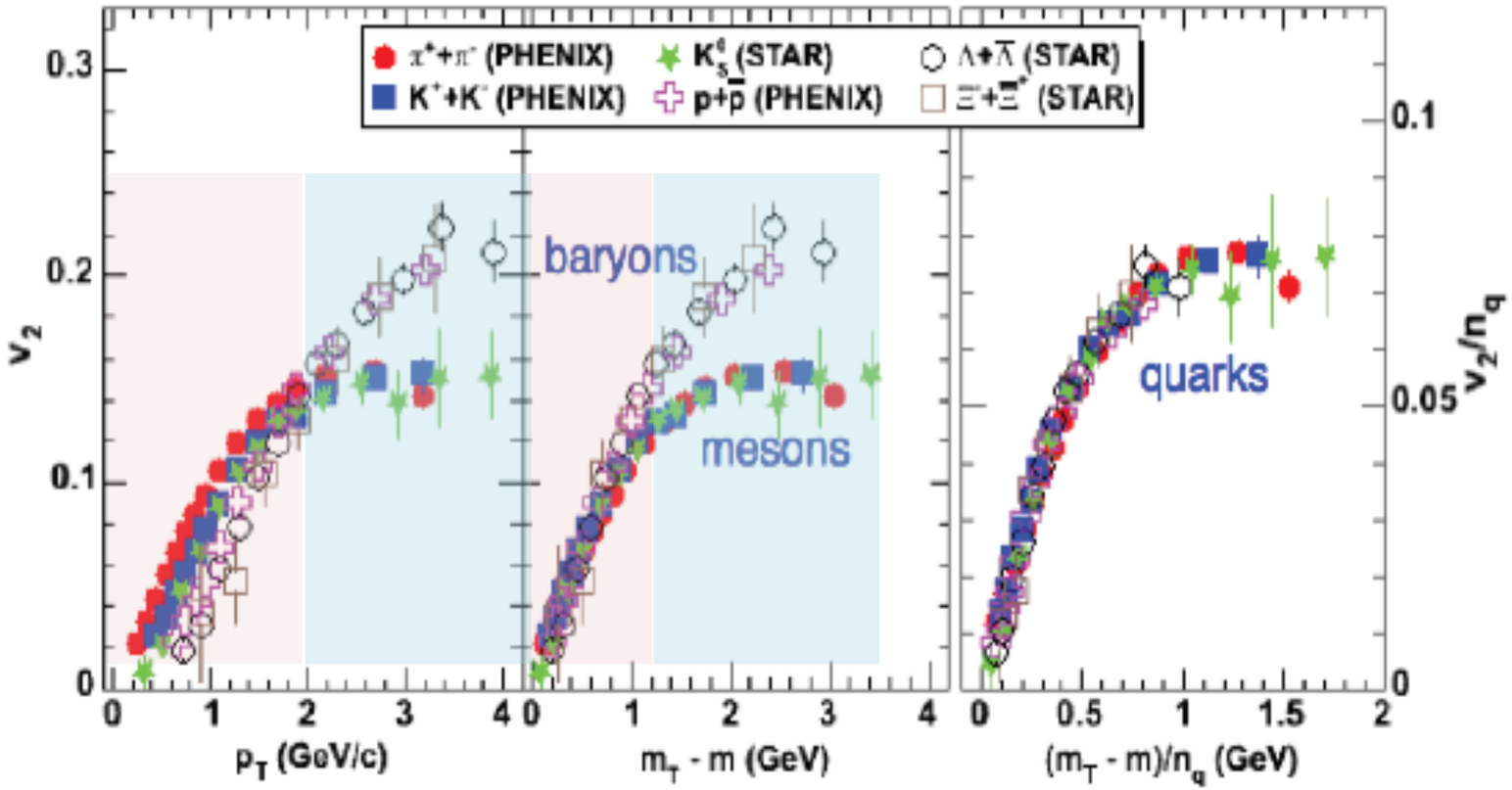
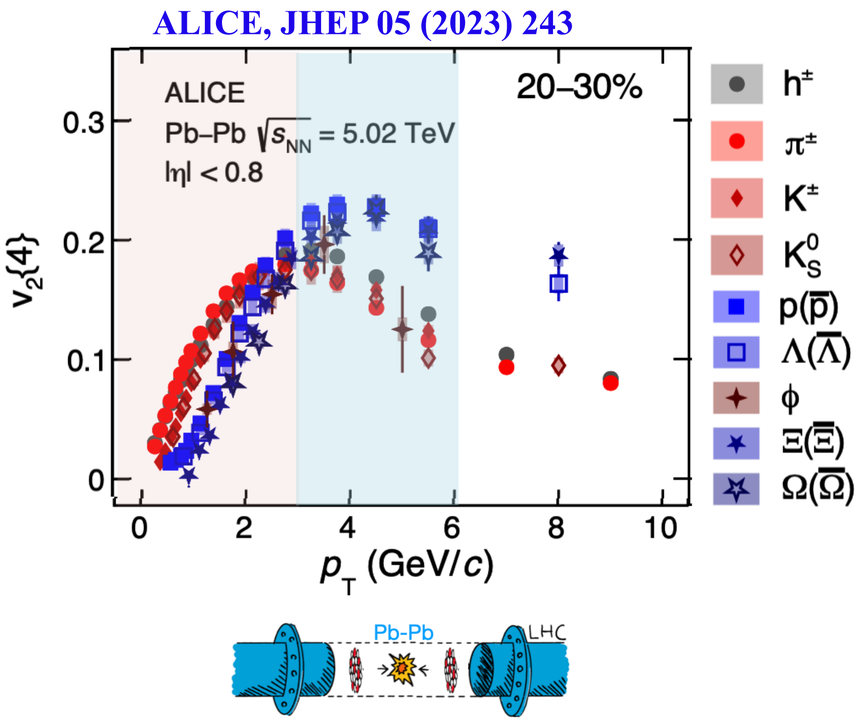


PID v_2 at top RHIC energy

- low p_T:
  - ➢mass ordering (described by hydrodynamics)

- intermediate p_T:
  - ➢Baryon and meson grouping and splitting (expected from quark-coalescence)

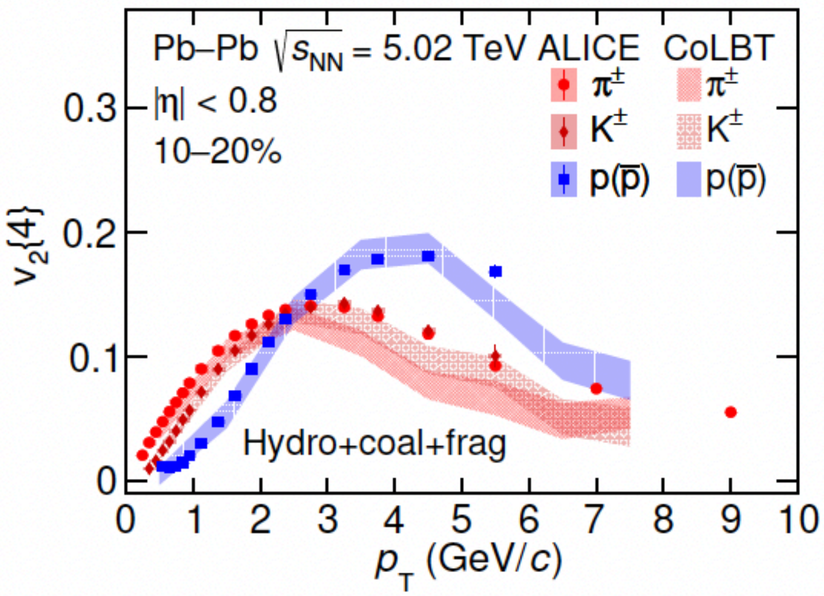
Partonic flow in Pb-Pb collisions



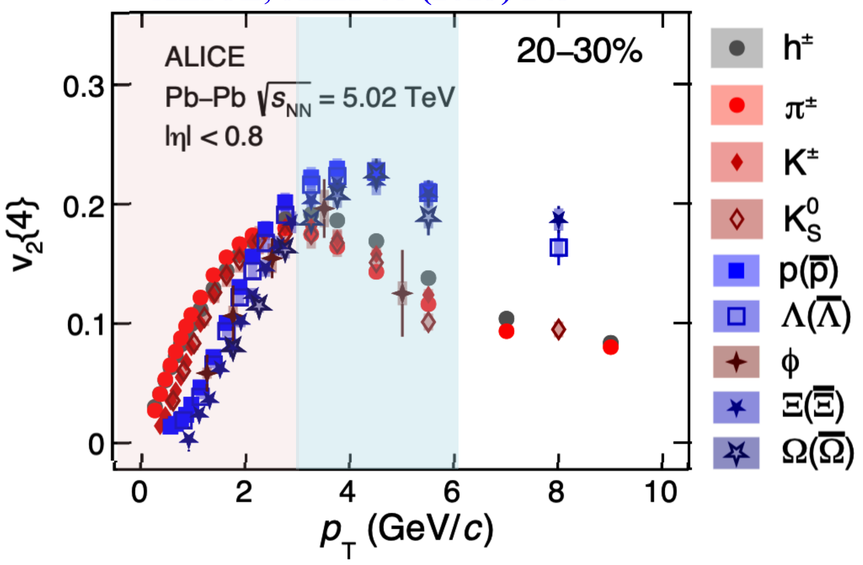
- **Partonic flow** in Pb-Pb.
  - low p_T (p_T < 3 GeV/c) - Mass ordering.
  - Intermediate p_T (3< p_T < 6 GeV/c)
    - Baryon-meson grouping (~1σ confidence)
    - Splitting between baryons and mesons v_2 (> 5σ confidence)

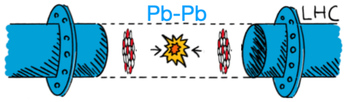
Partonic flow in Pb-Pb collisions

CoLBT: PRL128, 022302



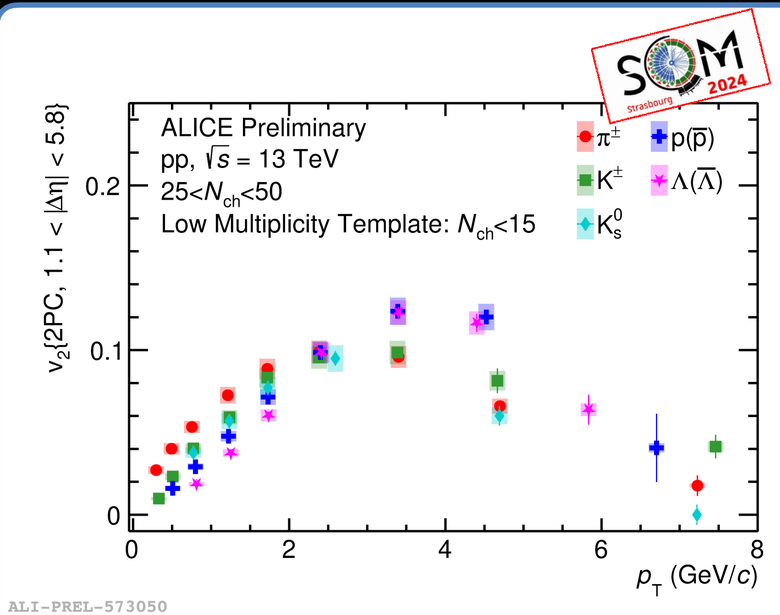
ALICE, JHEP 05 (2023) 243

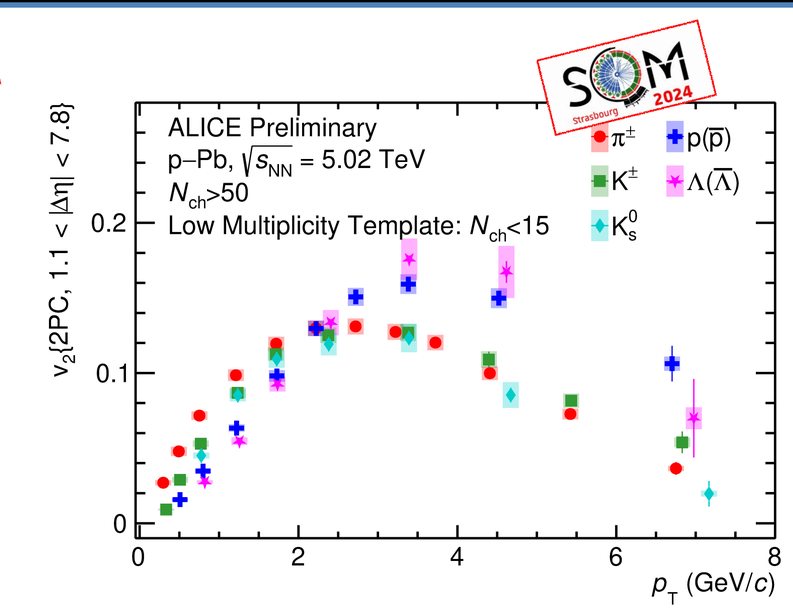


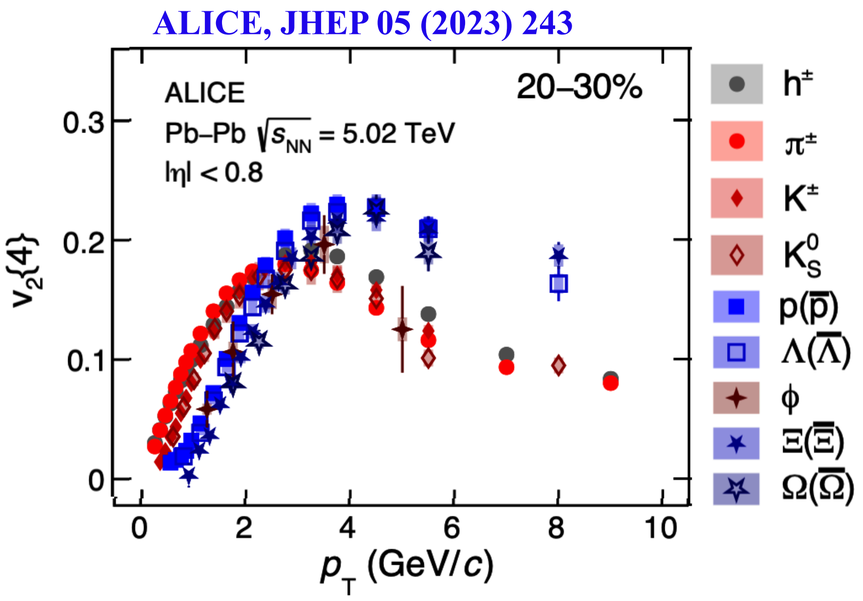


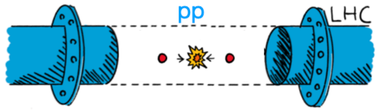
- **Partonic flow** in Pb-Pb. Well described by the model with hydro and quark-coalescence
  - low p_T (p_T < 3 GeV/c) - Mass ordering.
  - Intermediate p_T (3< p_T < 6 GeV/c)
    - Baryon-meson grouping (~1σ confidence)
    - Splitting between baryons and mesons v_2 (> 5σ confidence)

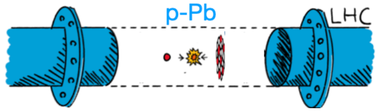
Partonic flow in **high multiplicity** p-Pb and pp

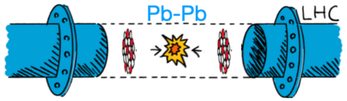






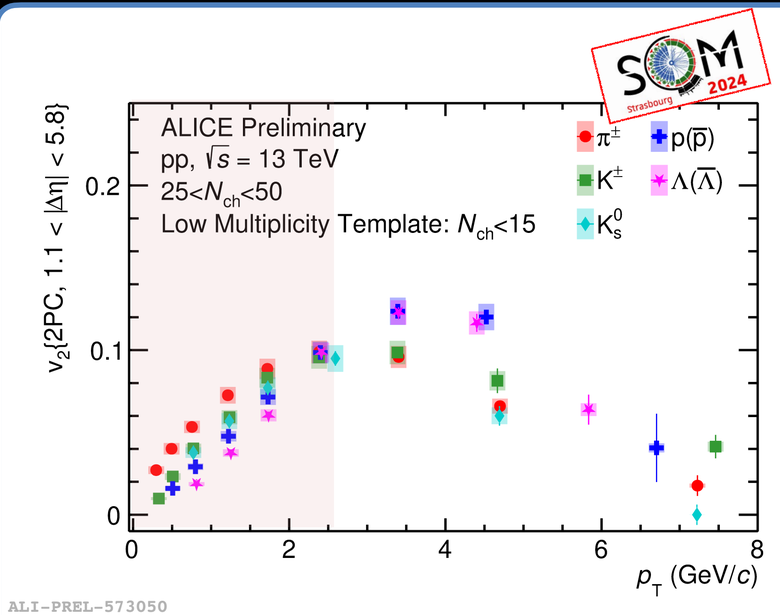


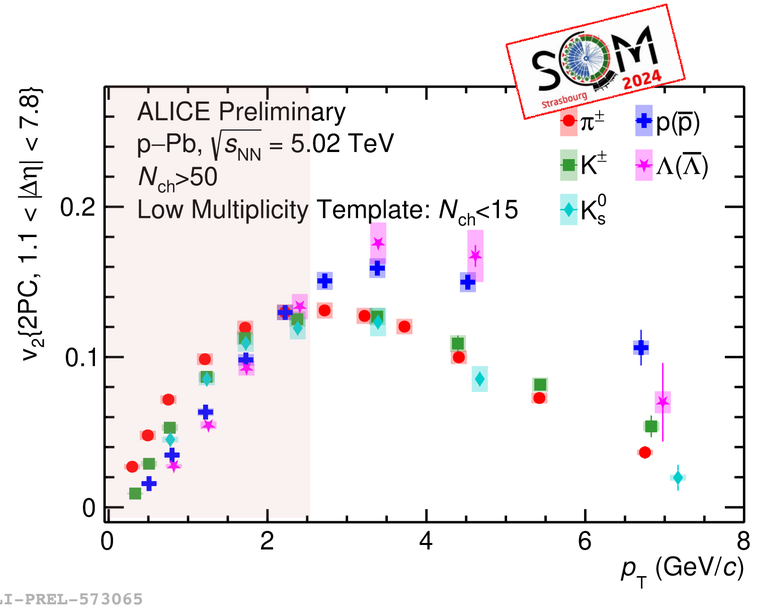


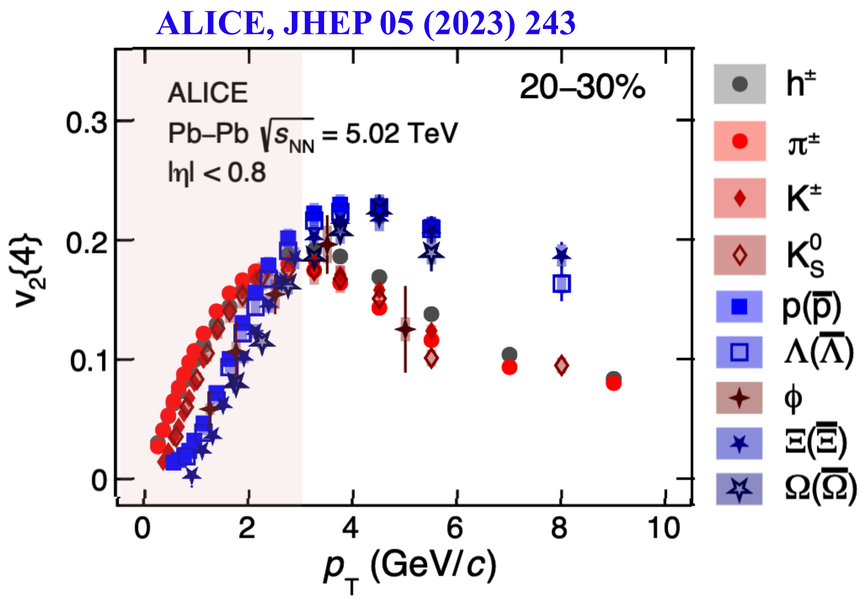


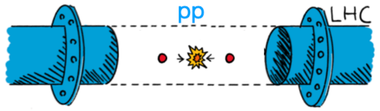
❖ **Similar observations** in Pb-Pb, high multiplicity p-Pb and pp collisions!

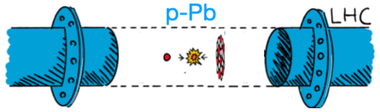
Partonic flow in **high multiplicity** p-Pb and pp

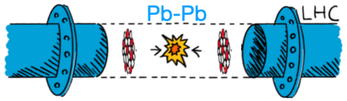












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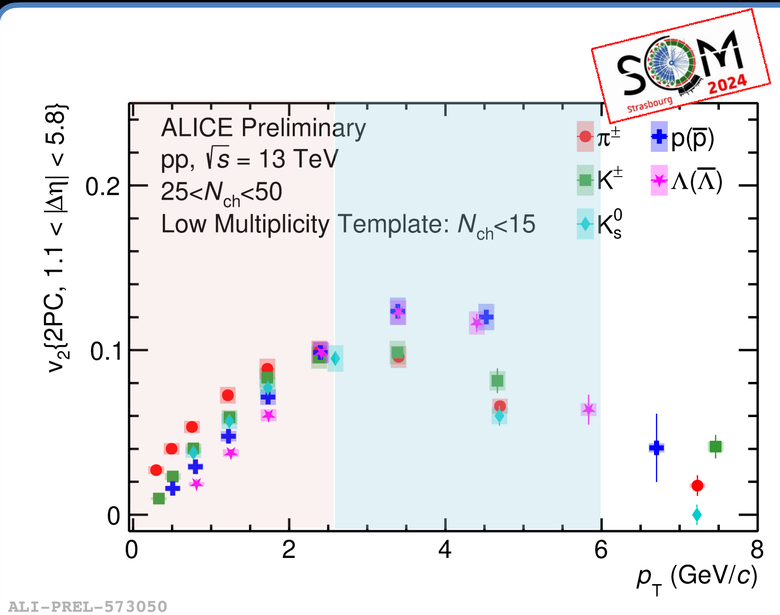
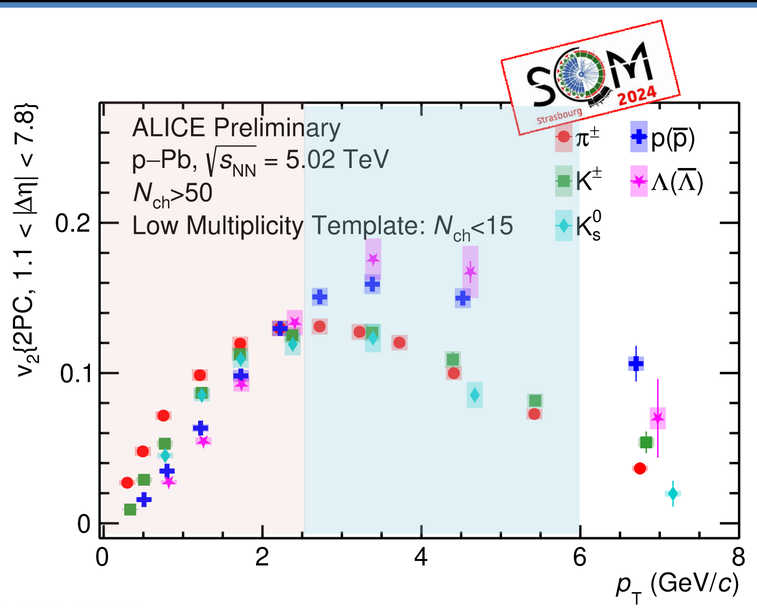
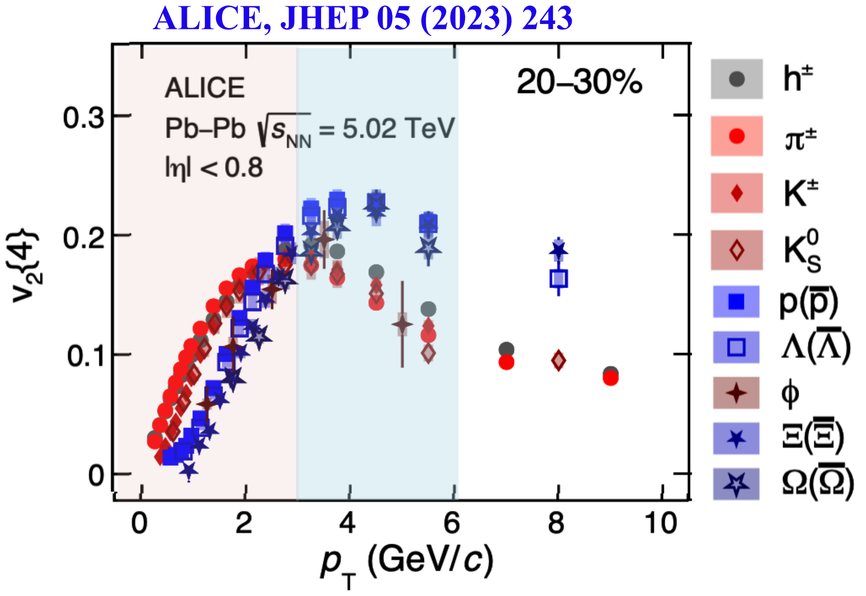
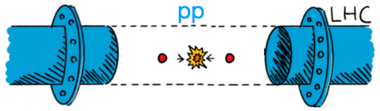
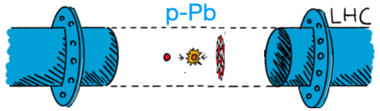
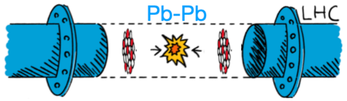








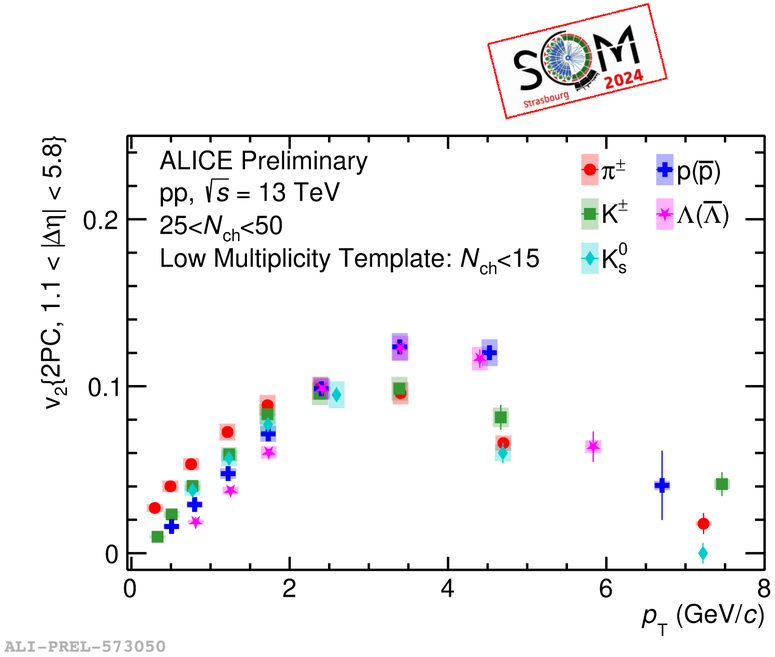


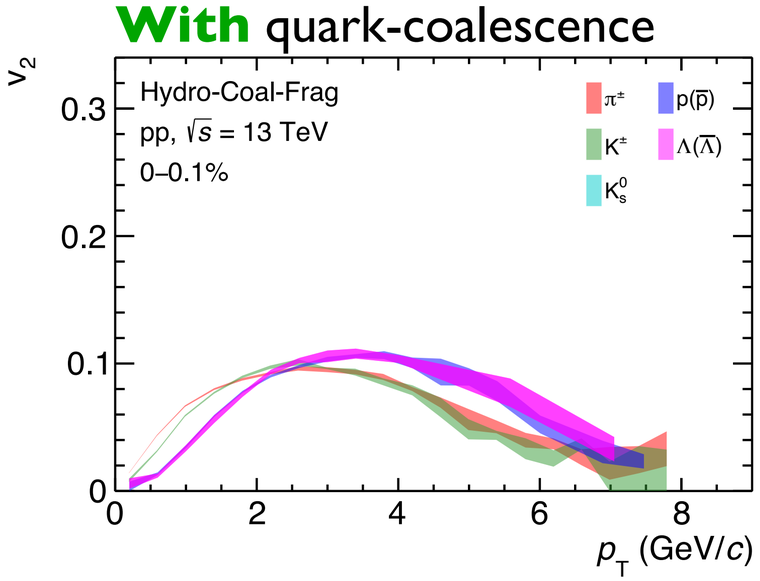


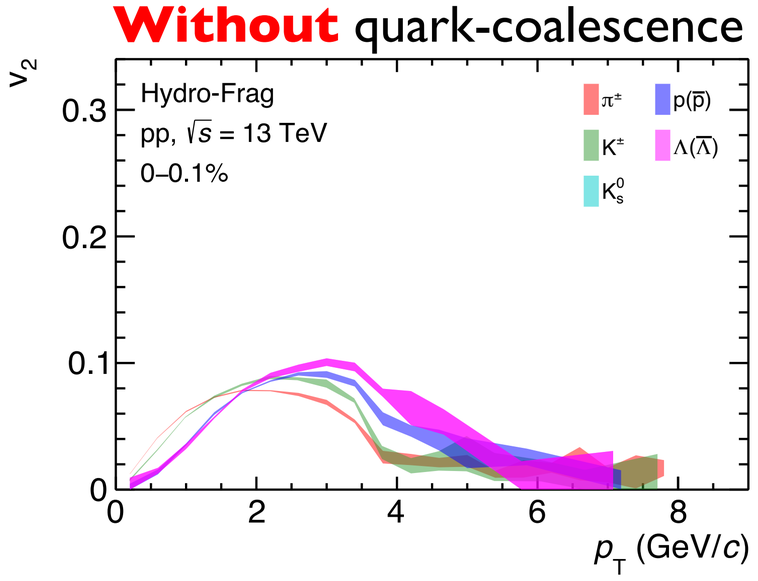
❖ **Similar observations** in Pb-Pb, high multiplicity p-Pb and pp collisions!

- low p_T (p_T < 3 GeV/c) - Mass ordering.
- Intermediate p_T (3< p_T < 6 GeV/c)
  - Baryon-meson grouping (~1σ confidence)
  - Splitting between baryons and mesons v_2 (> 5σ confidence)

Importance of quark-coalescence in small systems



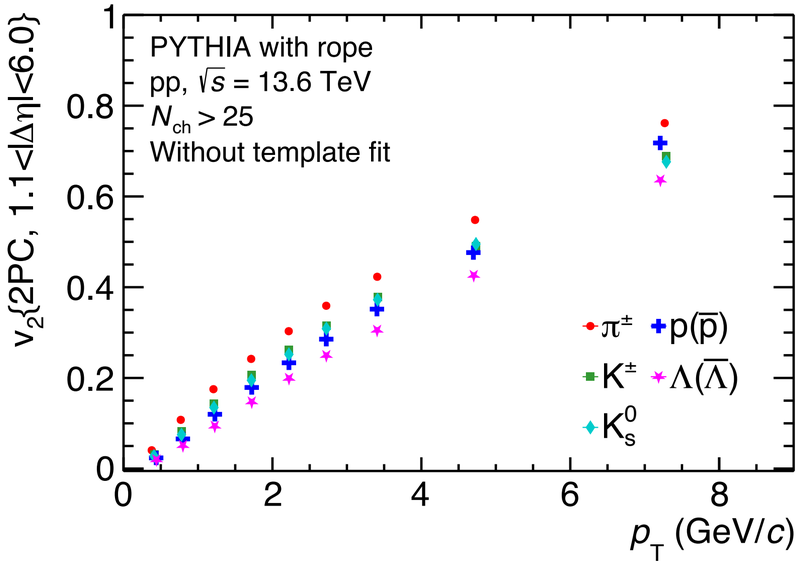




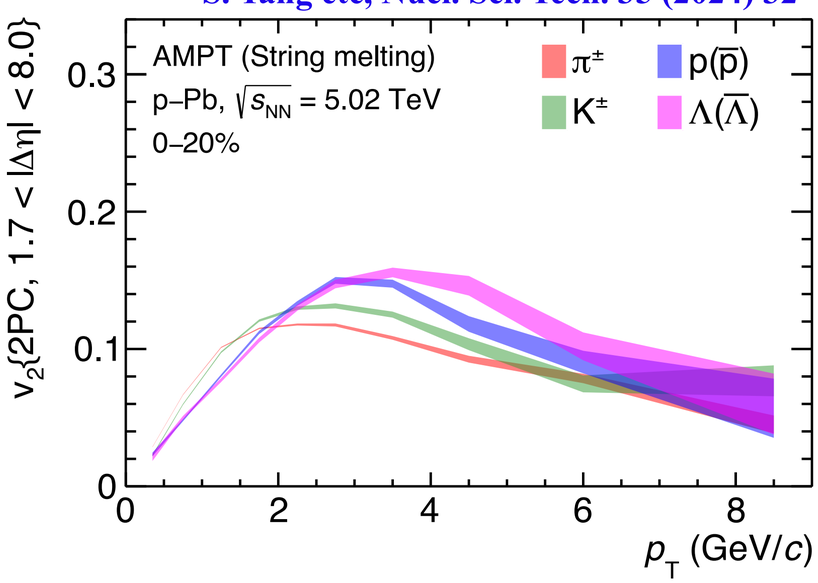
- Low p_T (p_T < 3 GeV/c)
  - Mass ordering, reproduced by both models (hydro dominant)
- Intermediate pT (3< p_T < 6 GeV/c)
  - **With** quark-coalescence: successfully reproduces baryon/meson grouping and splitting
  - **Without** quark-coalescence: mass dependence, fails to reproduce grouping and splitting effects

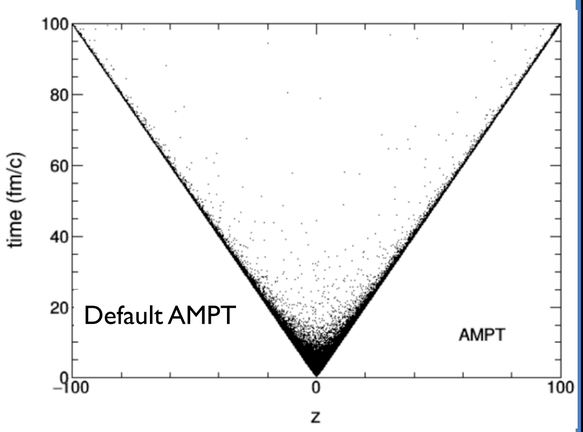
Model: W. Zhao etc., PRL125 (2020), 072301
Y. Wang etc, arXiv:2401.00913

Dense partonic matter (?)



S. Tang etc, Nucl. Sci. Tech. 35 (2024) 32





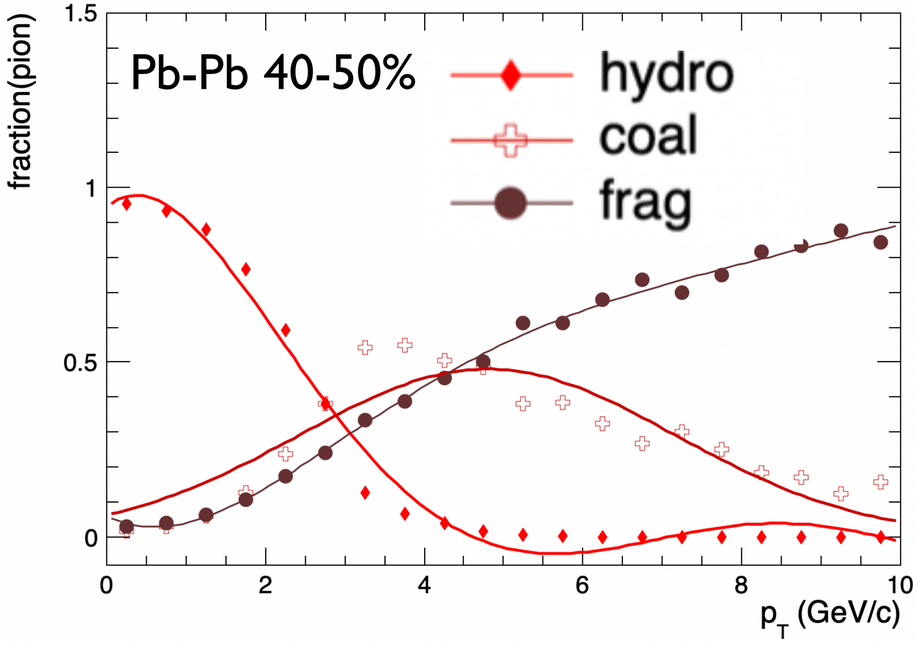
❖PYTHIA with rope, which well explains the strangeness enhancement without QGP formation, fails to predict the baryon/meson splitting and grouping, similar for UrQMD -> ***Importance of partonic matter***

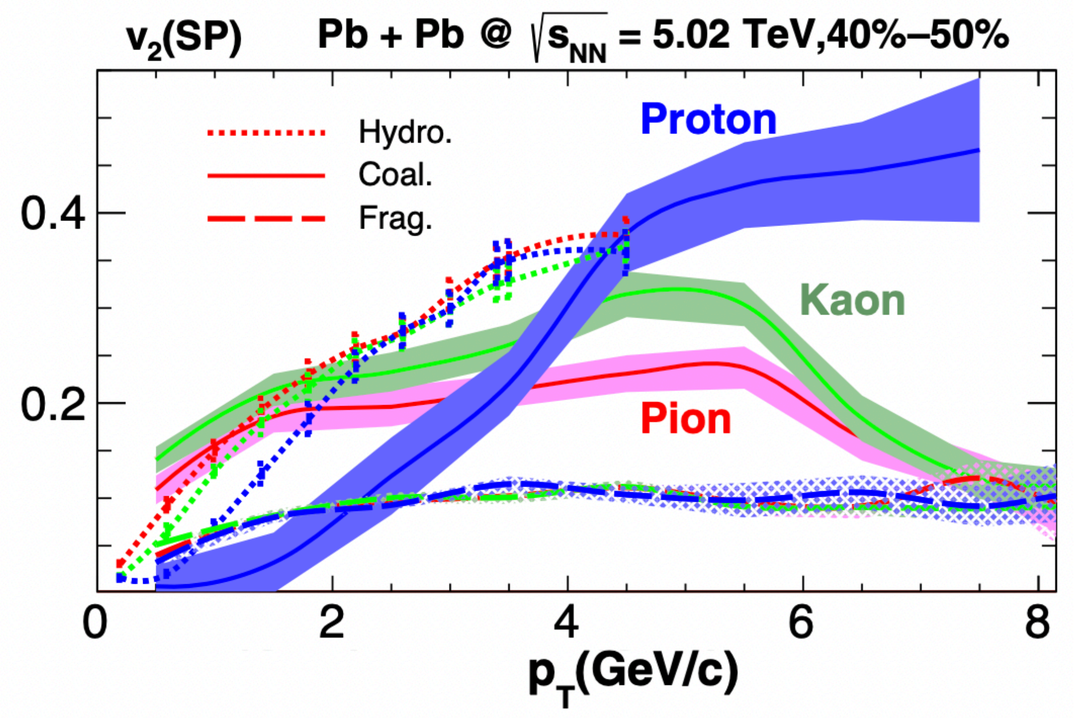
❖ Transport model with coalescence (AMPT) predicts only mass dependence.

- Even using same quark-coalescence code, AMPT fails to reproduce the baryon/meson grouping and splitting.
  -> System is too diluted to have a sufficient quark-coalescence.

❖Further suggests that one needs dense partonic matter with quark-coalescence to reproduce the data.

NCQ scaling is NOT an ideal tool





❖What do we learn:

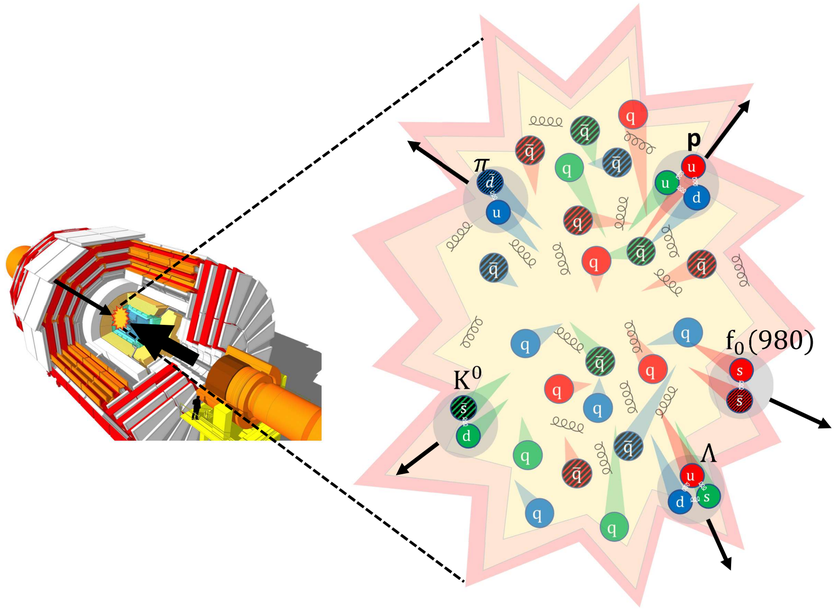
- hydro: $v_2(\pi) > v_2(K) > v_2(p)$ → No scaling
- quark-coal: $v_2(p) > v_2(K) \sim v_2(\pi)$ → scaling
- Jet-frag: $v_2(p) \sim v_2(K) \sim v_2(\pi)$. → No scaling
- ***Contributions from hydro & frag will break the NCQ scaling, as observed in Pb-Pb collisions and small systems***

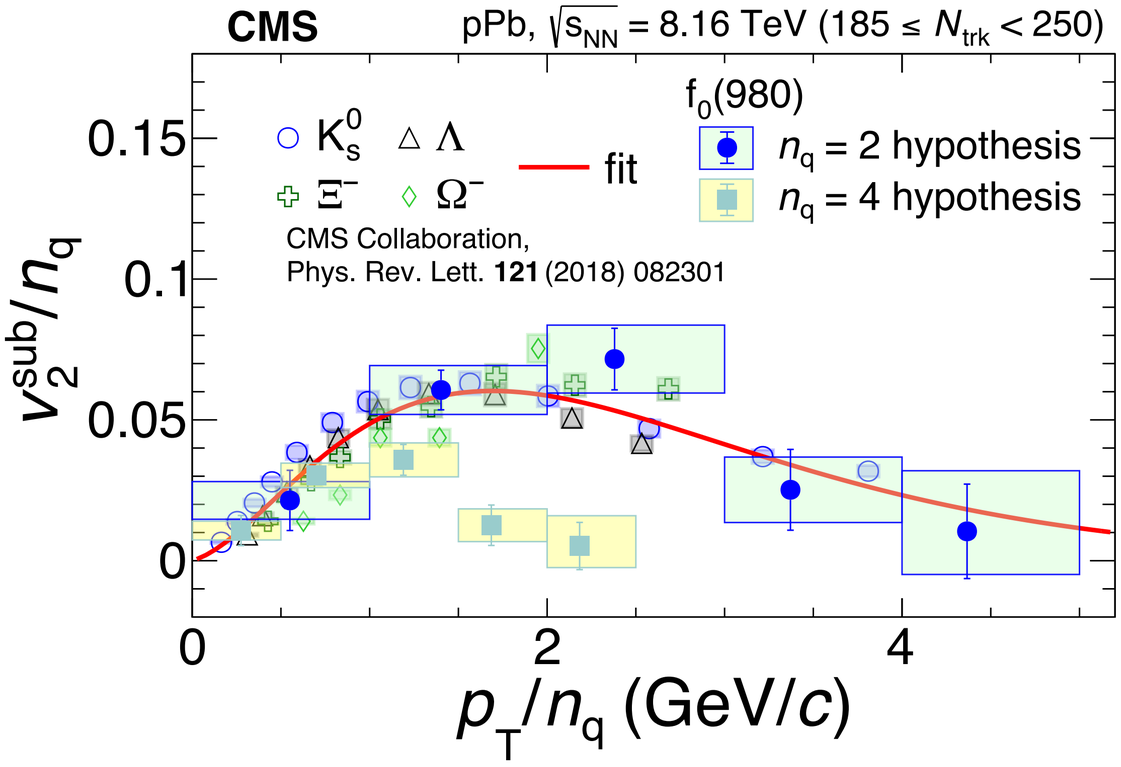
Model: W. Zhao etc., PRL128 (2022), 022302
W. Zhao etc., PRL125 (2020), 072301

Very detailed discussions:
ALICE, JHEP 05 (2023) 243

Can we use NCQ scaling to probe quark composition?

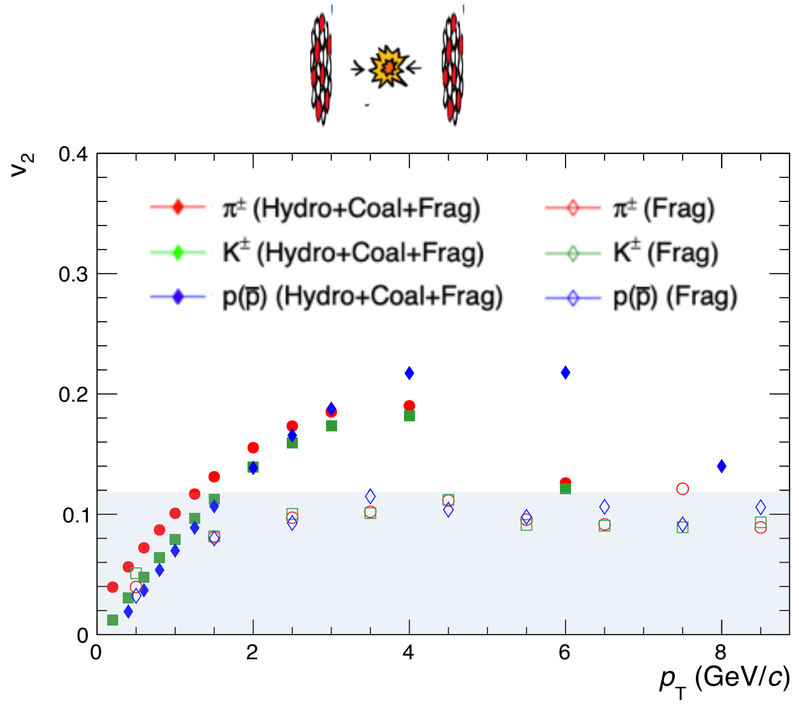
CMS, arXiv:2312.17092





- NCQ scaling broken in p-Pb collisions, and v_2(Baryons) / v_2(Mesons) ≠ 3/2
  - Should we use meson grouping to probe n_q=2 or n_q=4 hypothesis of $f_0(980)$?

Large v_2 but no parton energy loss: Puzzle (?)



❖ v_2 from jet-fragmentation with LBT (*one possible explanation*)

- v_2(jet-frag) in Pb-Pb is significant/dominant at high pt -> large parton energy loss

Calculations: Yuanyuan W etc
Figures from Wenya W.

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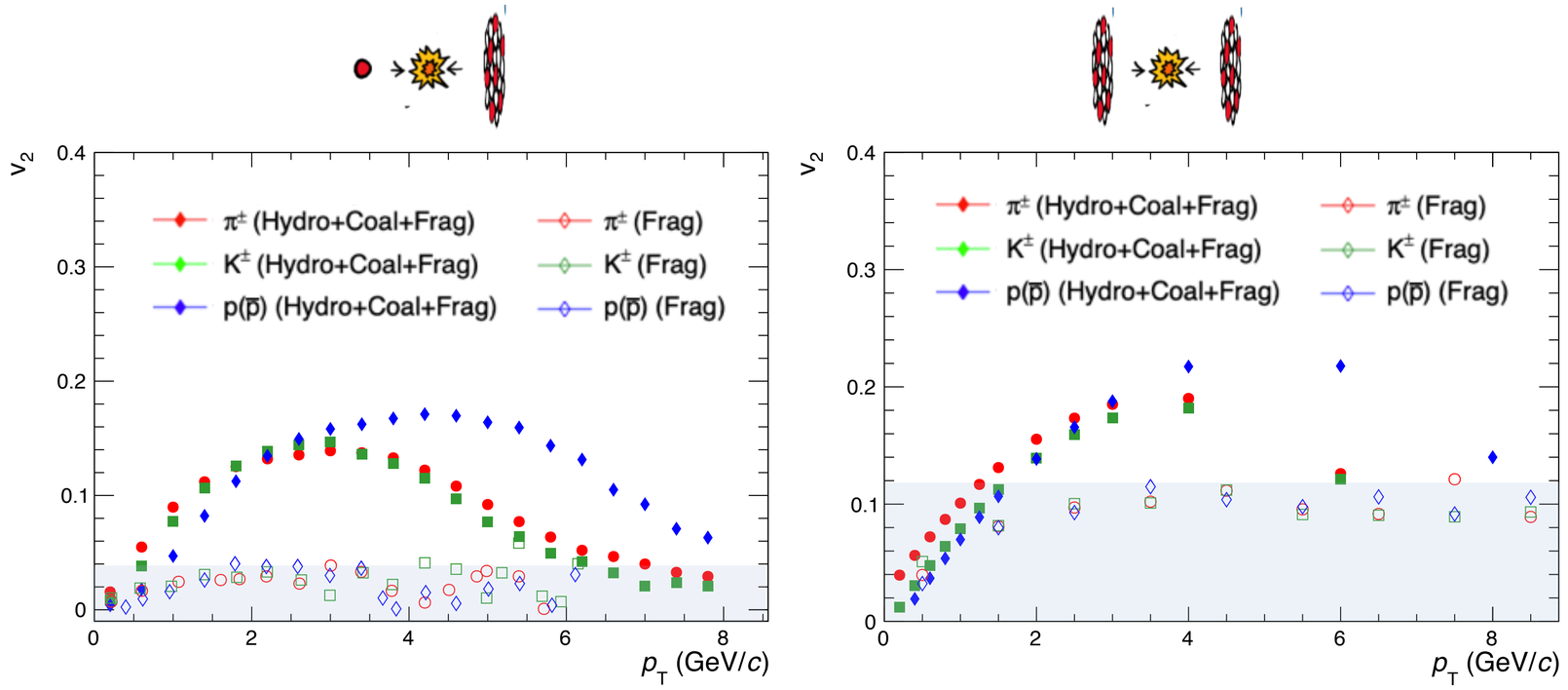

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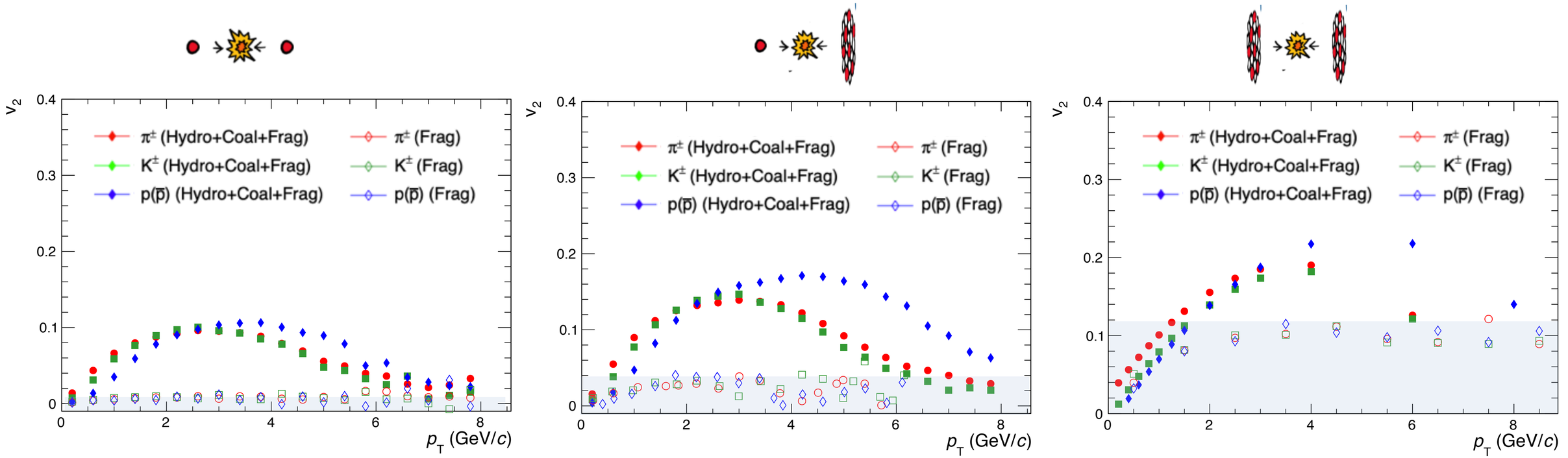

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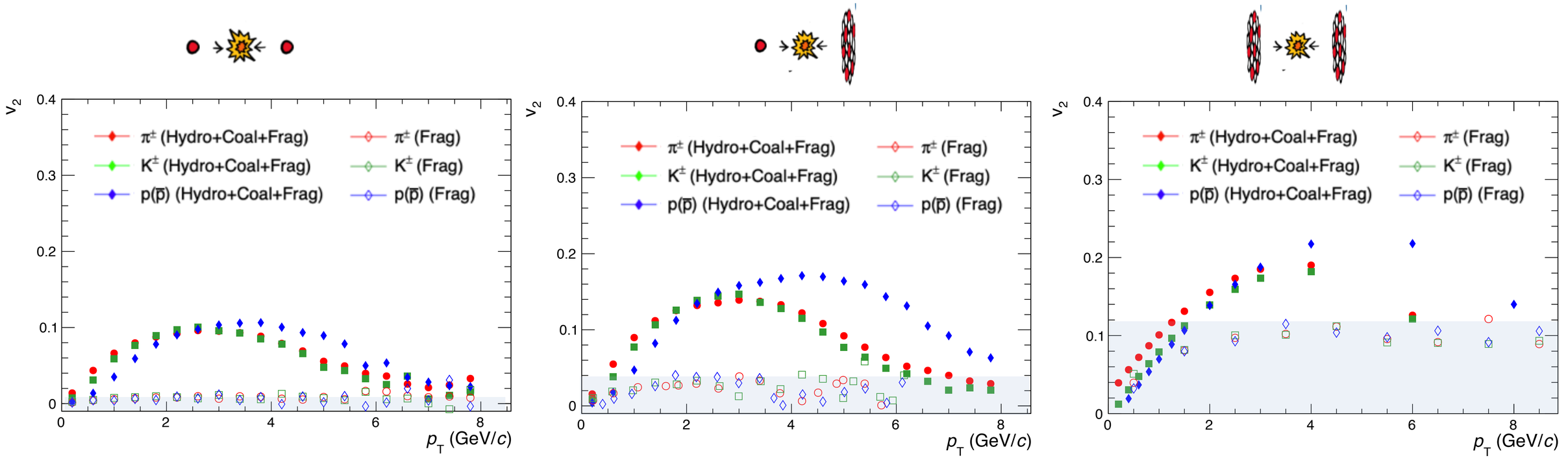

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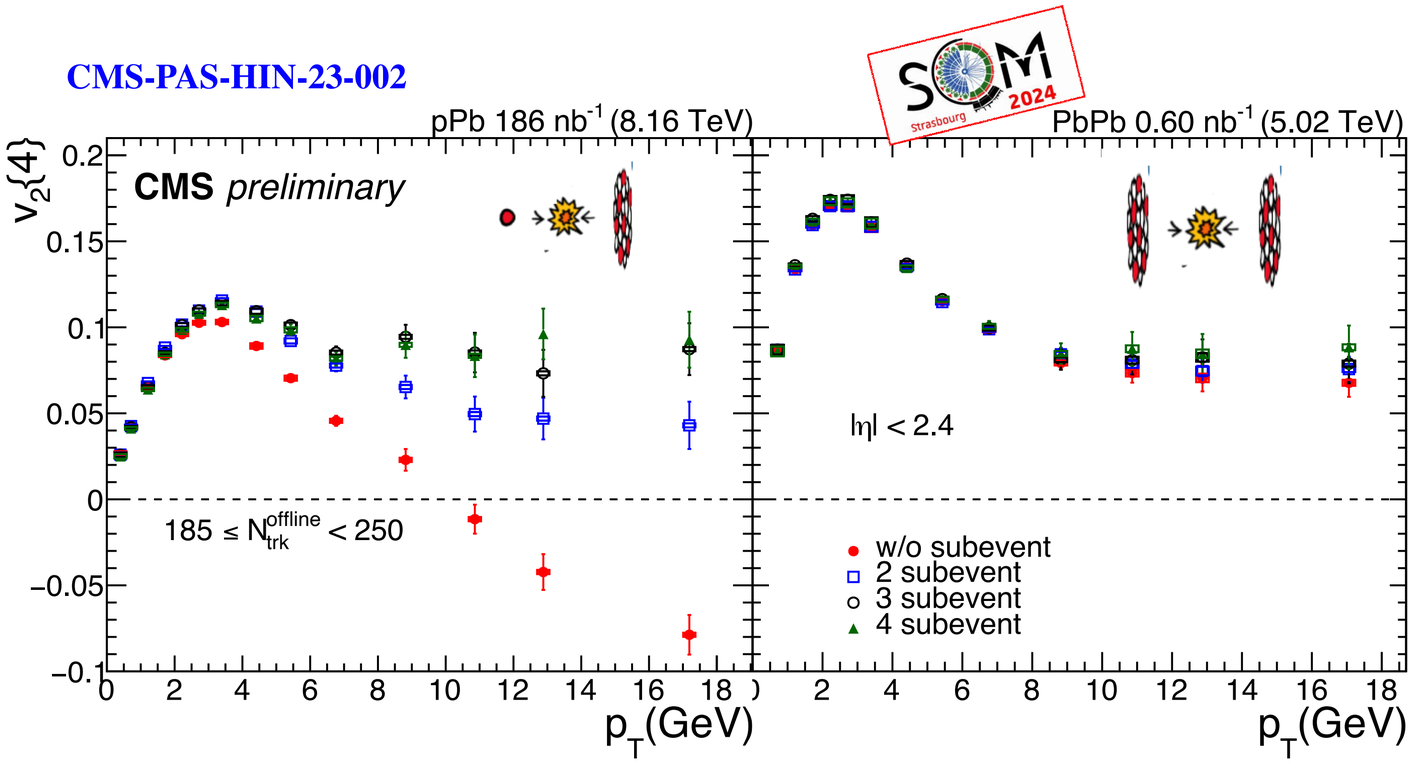
  - v_2(jet-frag) in p-Pb is very small and close to zero -> little to no parton energy loss
  - v_2(jet-frag) in pp is compatible with zero -> no parton energy loss
- Observed finite v_2 for the presented p_T in small systems
  -> contributions mainly from left-over hydro and/or quark-coalescence, not parton energy loss.

Calculations: Yuanyuan W etc
Figures from Wenya W.

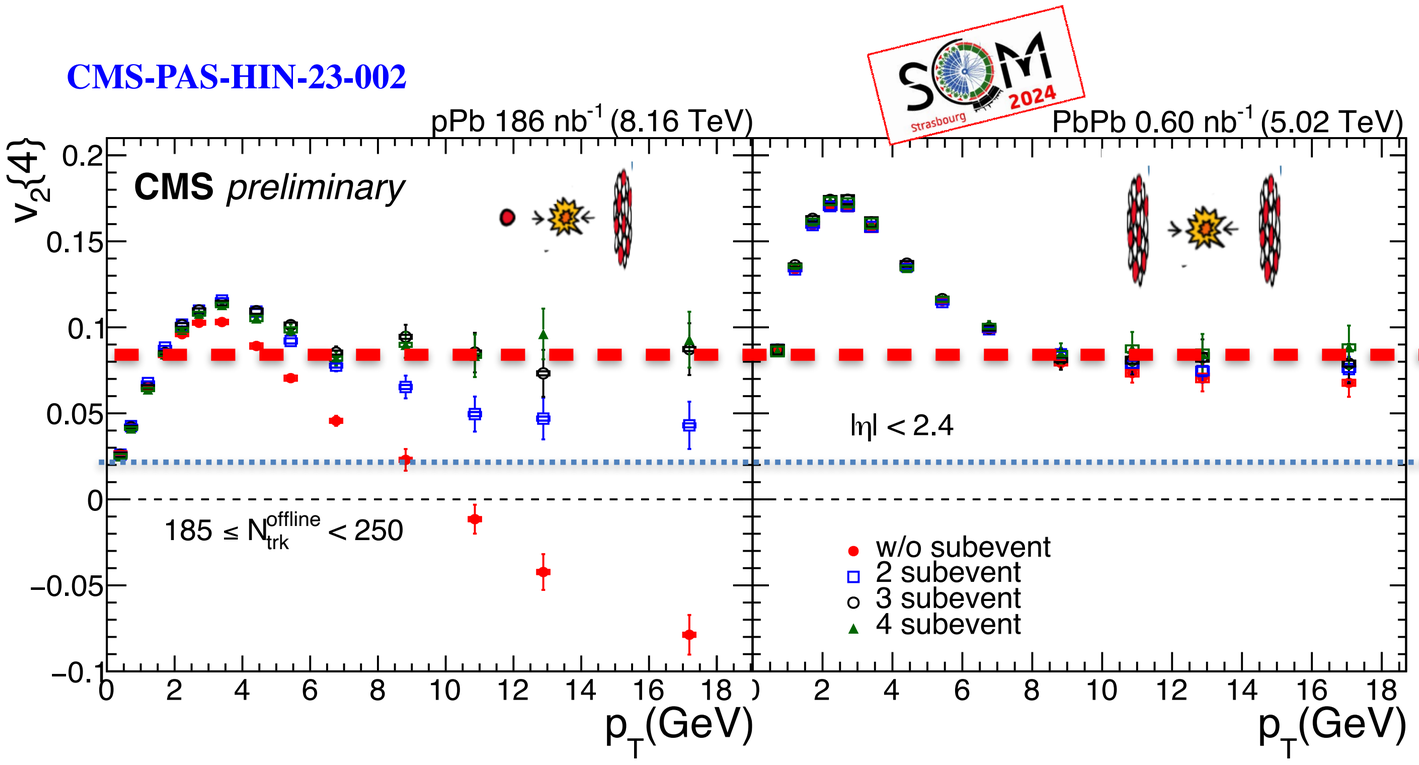
New issue?

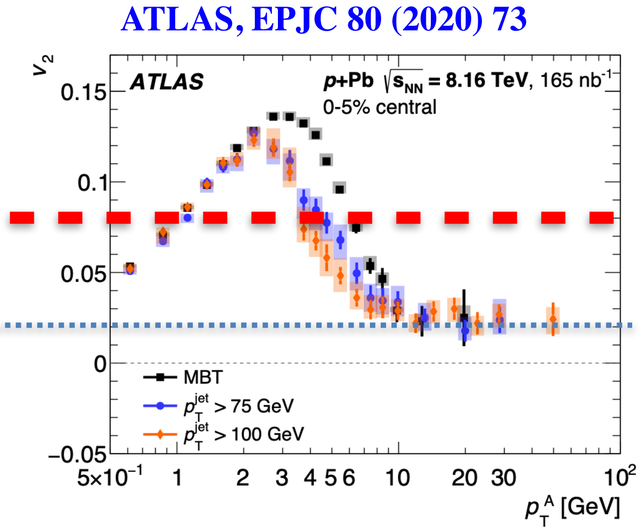


❖ For **p-Pb collisions**:

- $v_2\{4\}_{sub}$ (p-Pb)≈$v_2\{4\}_{sub}$ (Pb-Pb) at very high p_T, $v_2\{4\}$(CMS) > $v_2\{2\}$(ATLAS)

New issue?





CMS
$v_2\{4\}$ ~ 8%

ATLAS
$v_2\{2\}^{TF}$ ~2%

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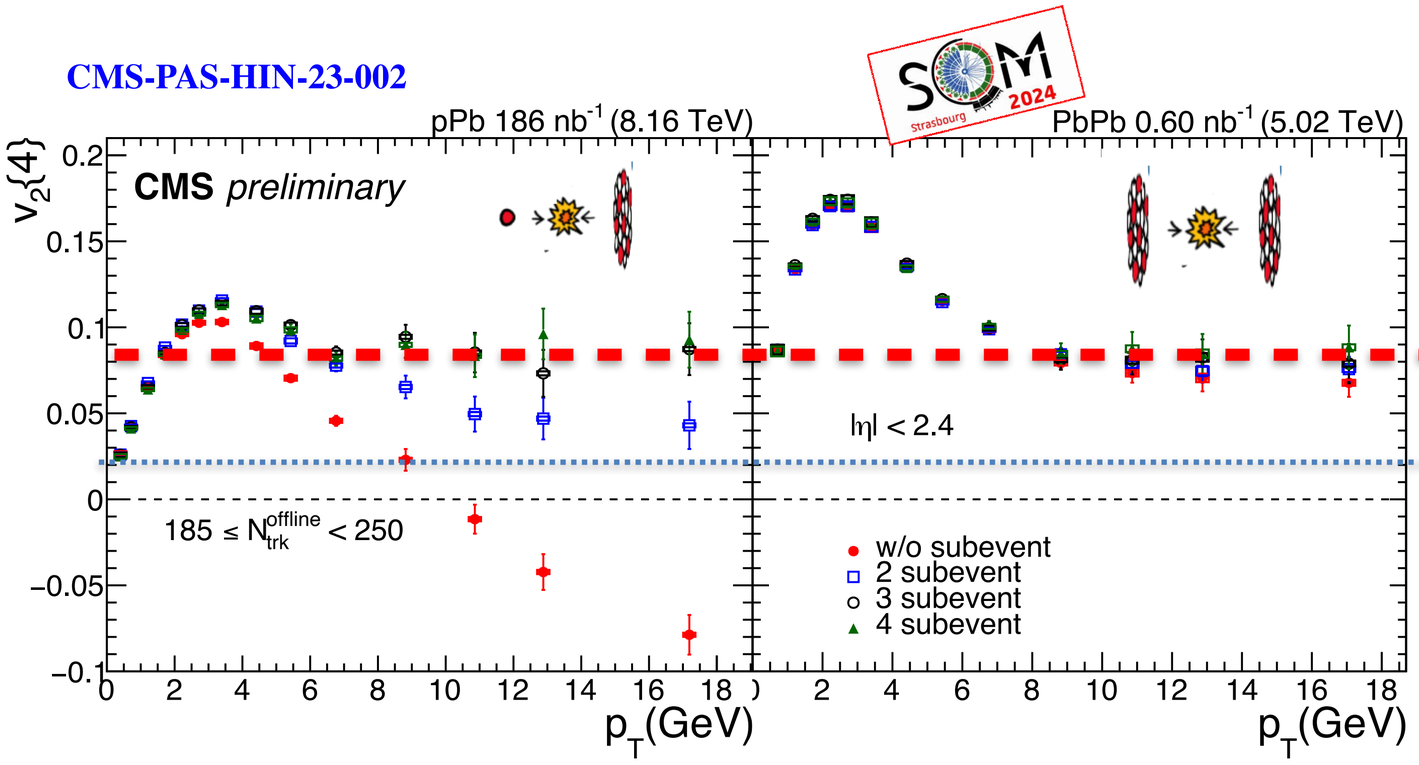

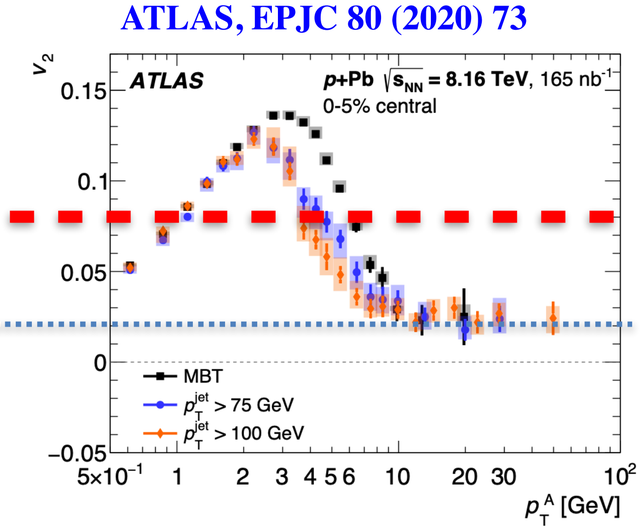

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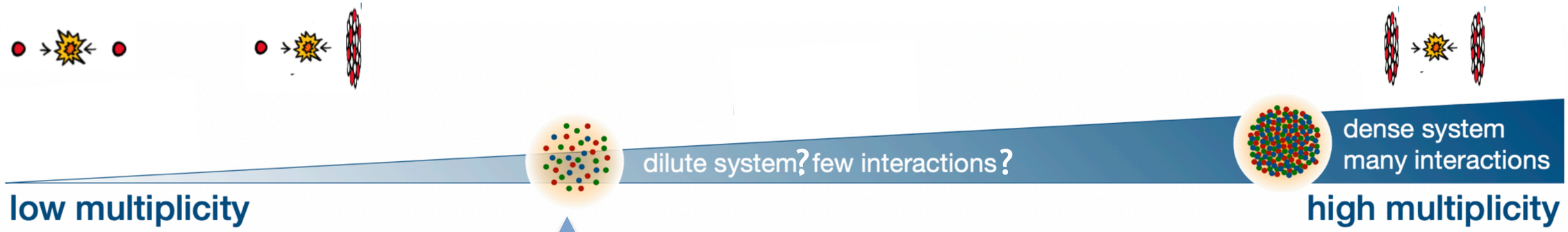
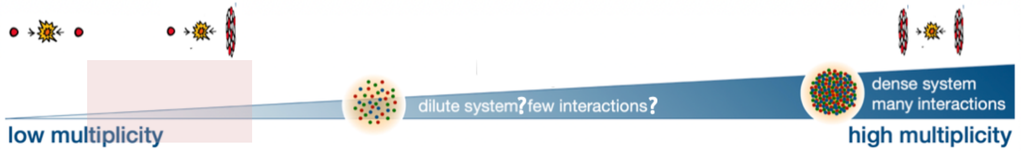
- $v_2\{4\}_{sub}$ (p-Pb)≈$v_2\{4\}_{sub}$ (Pb-Pb) at very high p_T, $v_2\{4\}$(CMS) > $v_2\{2\}$(ATLAS)
- Possibly experimental bias from fake flow (too many sub-events with too few particles) in CMS?
- Proposal: further understand the measurement before we think about theoretical explanation

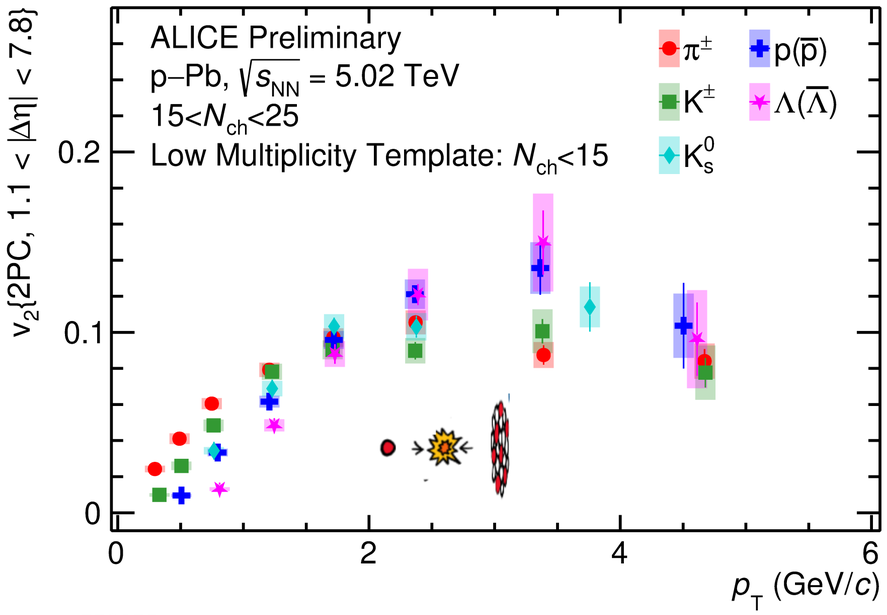
How small is small

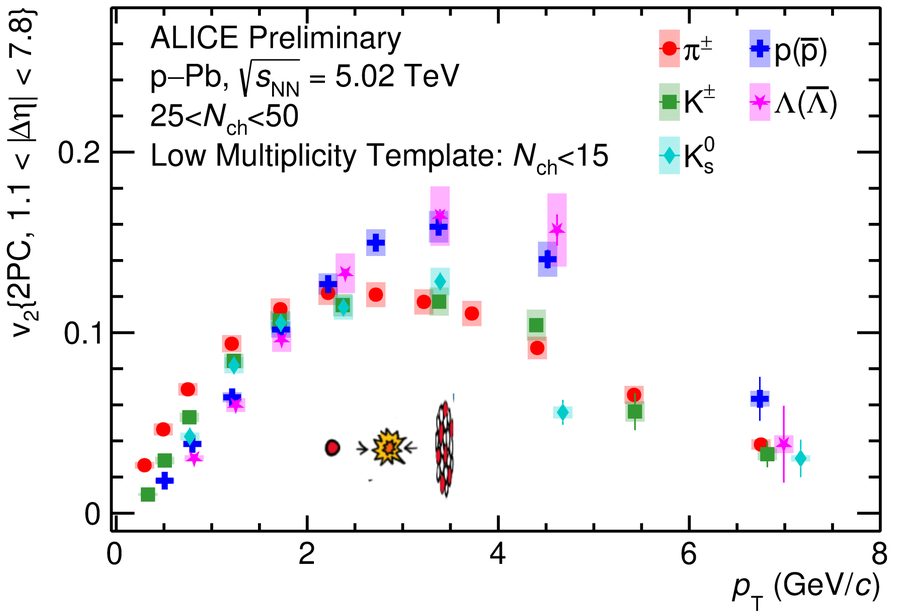


Dense partonic matter
with quark-coalescence

PID v_2 for low N_{ch} **p-Pb** collisions

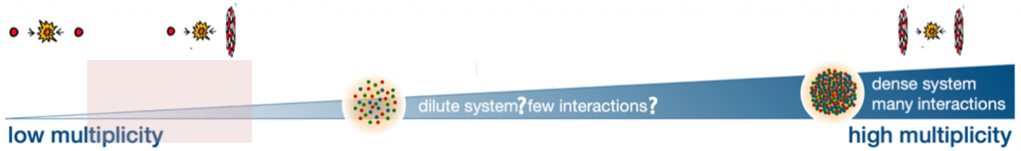


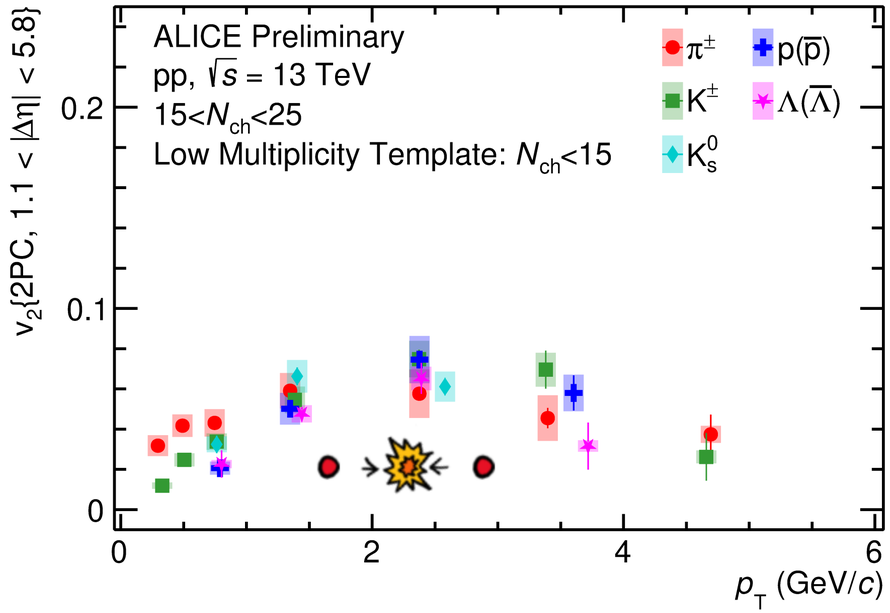


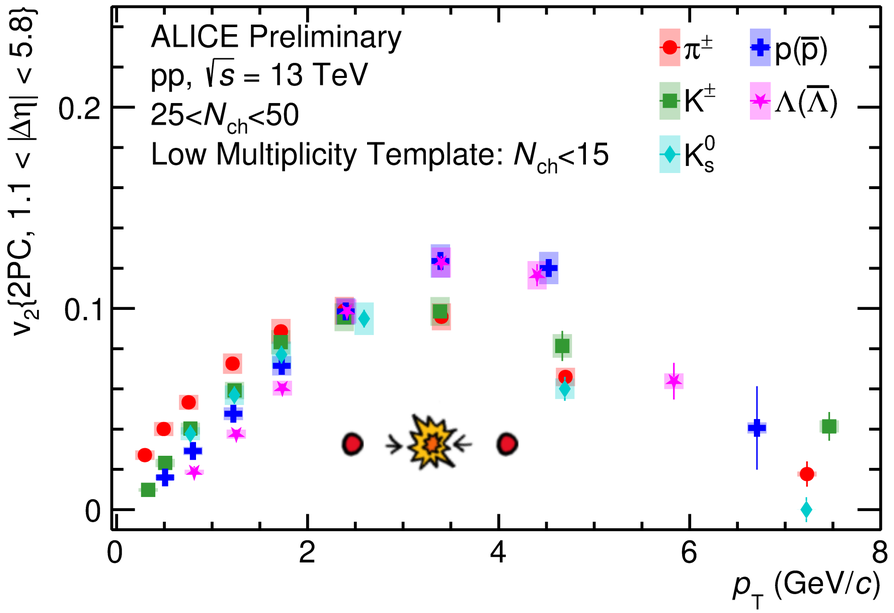


- For **p-Pb collisions**:
  - N_{ch} > 25: Baryon-meson grouping (~ 1σ confidence) and splitting (> 5σ confidence) of v_2 at intermediate p_T
  - 15 < N_{ch} < 25: grouping and splitting (within 2σ confidence), partonic flow picture is not very clear
  - Full investigations through careful data & model comparisons are ongoing

PID v_2 for low N_{ch} **pp** collisions



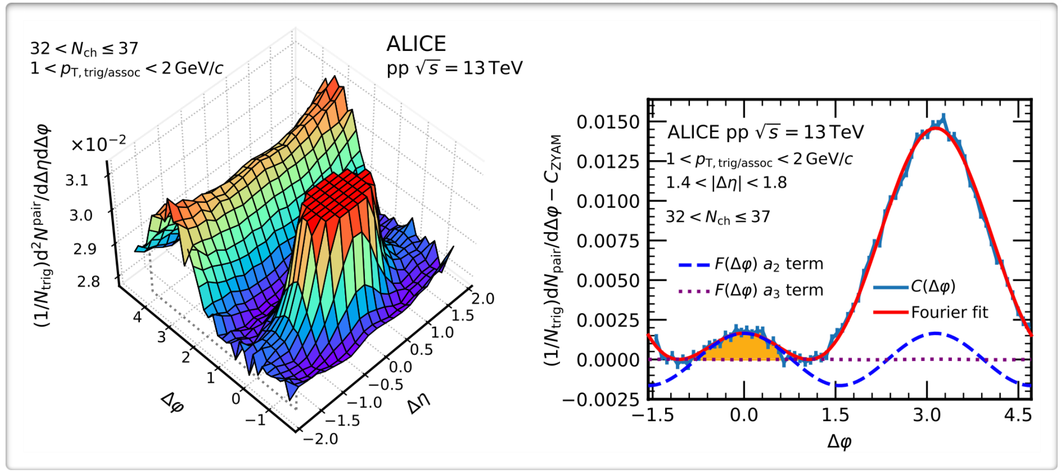




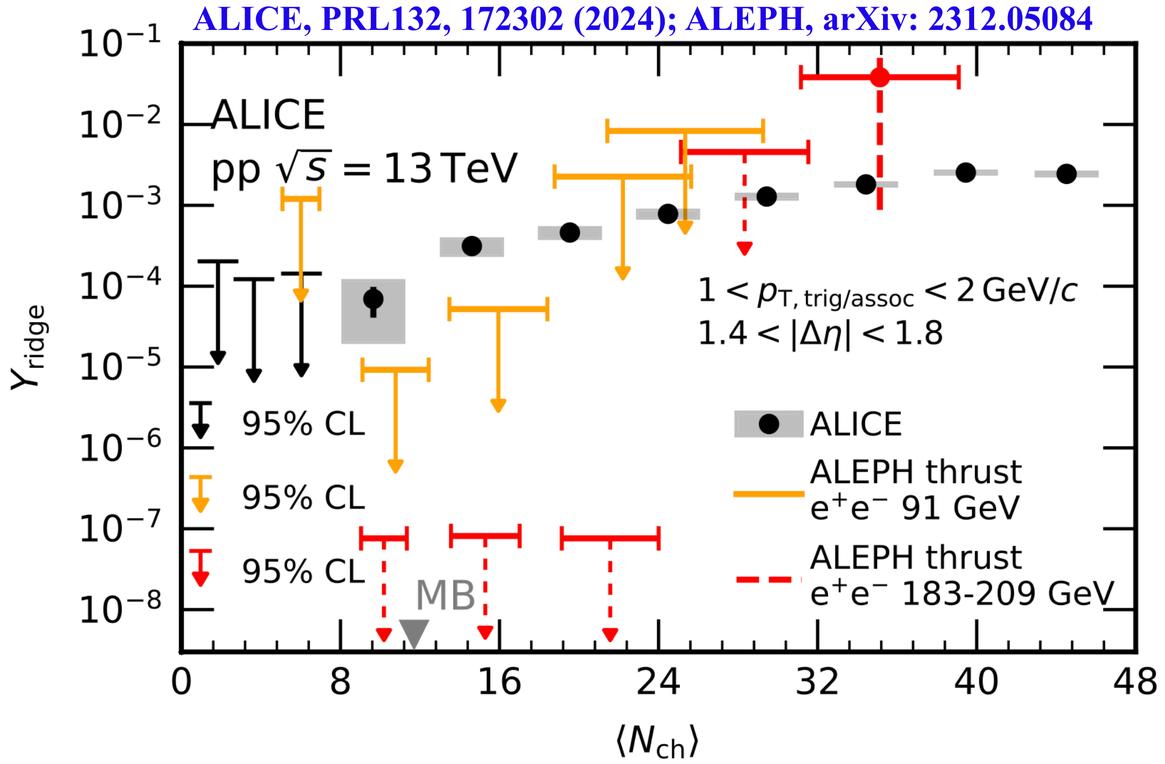
❖ For **pp collisions**:

- N_{ch} > 25 : Baryon-meson grouping (~ 1σ confidence) and splitting (5σ confidence) of v_2 at intermediate p_T
- 15 < N_{ch} < 25: grouping and splitting (within 1σ confidence) diminished!
- Full investigations through careful data & model comparisons are ongoing.

Ridge yields for low multiplicity pp and e^+e^-

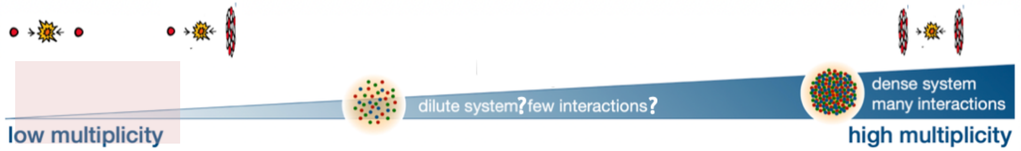


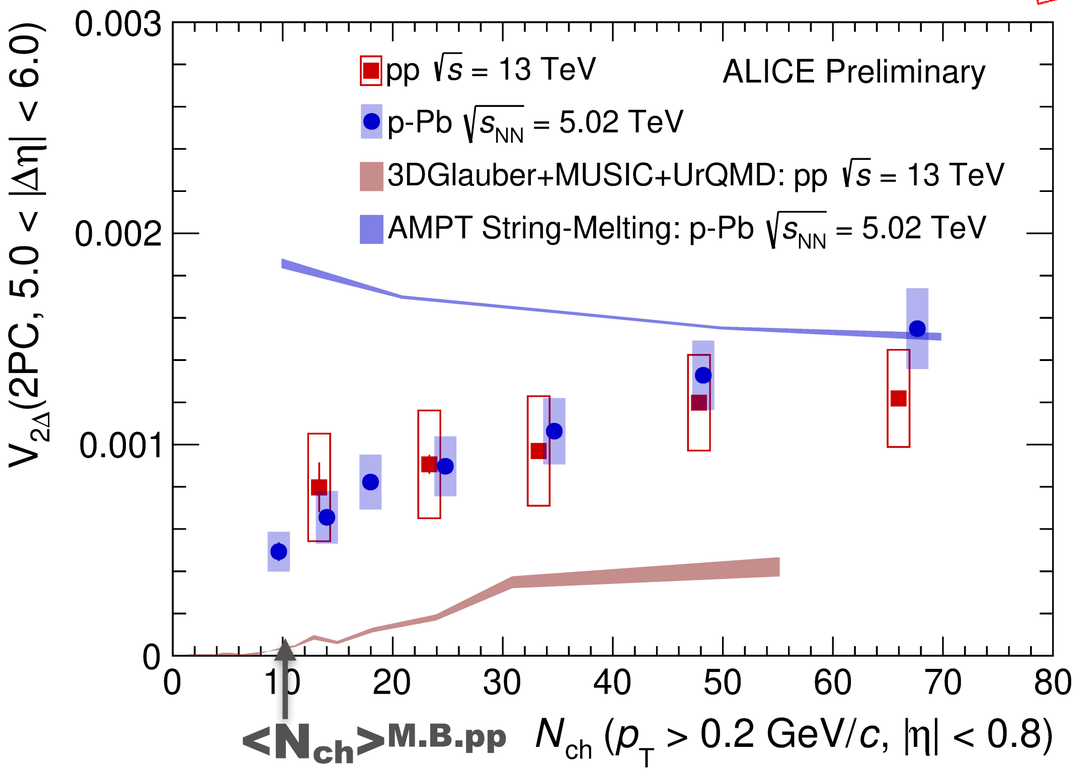
Caution: This is NOT collective flow measurements (no nonflow subtraction)



- pp collisions at low multiplicity (~ M.B.) exhibit larger ridge yield: $Y^{pp}_{ridge} > Y^{e^+e^-}_{ridge}$
  - 5σ (best) at 91 GeV, 6.3σ (best) at 183–209 GeV
  - the processes involved in e^+e^- do not contribute significantly to the emergence of long-range correlations in pp collisions

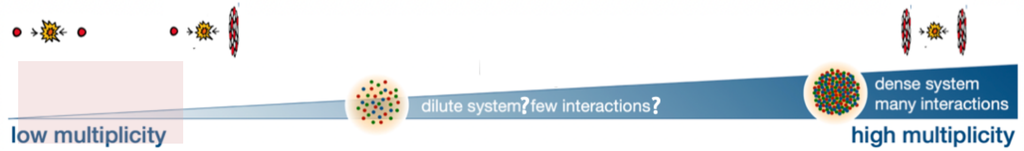
Observation of ultra-long-range correlation

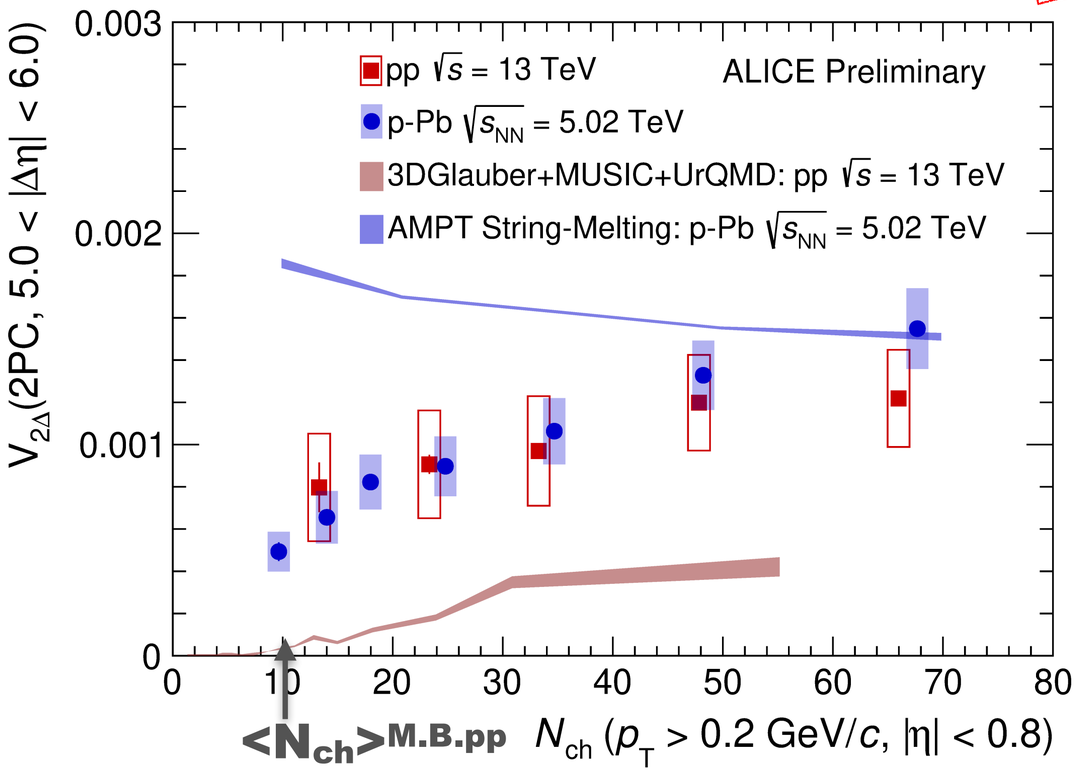




ALI-PREL-573662

Observation of ultra-long-range correlation





ALI-PREL-573662

- Observation of ***ultra-long-range correlation*** in ***low multiplicity*** region
- Currently huge discrepancies have been observed between data and model calculations
  - AMPT overestimates the p-Pb data
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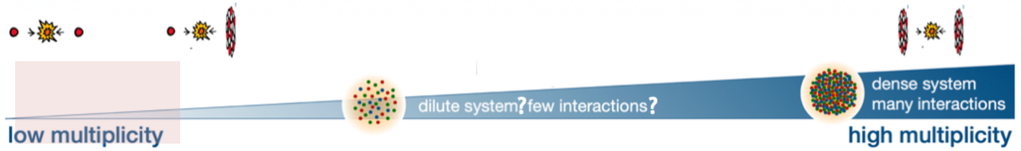

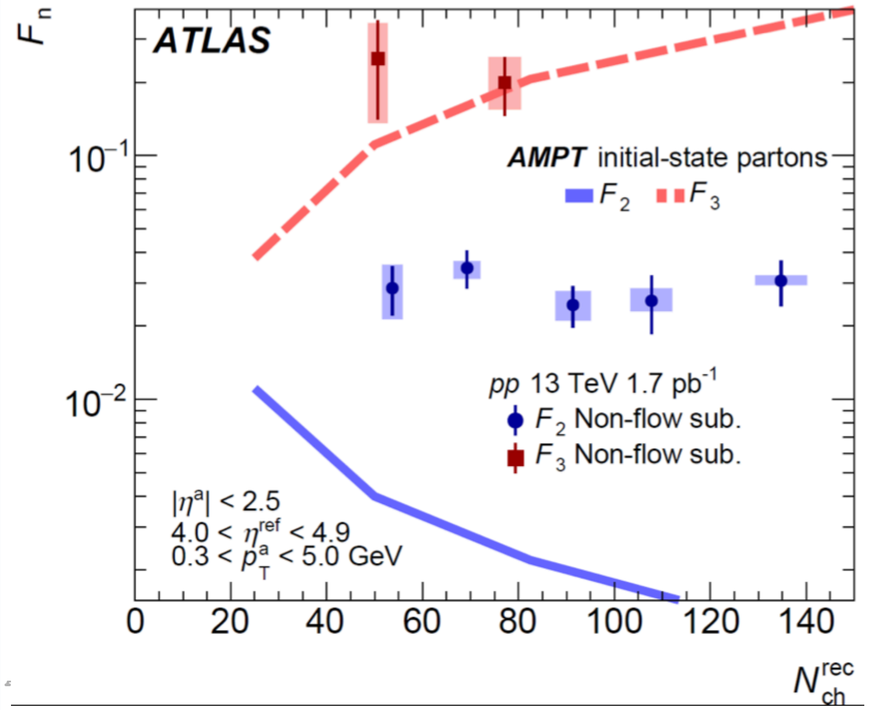

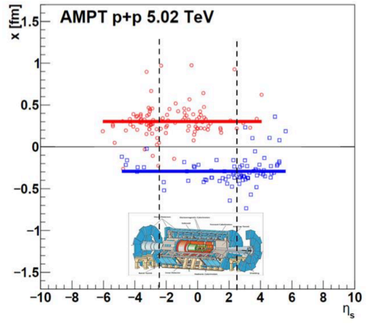

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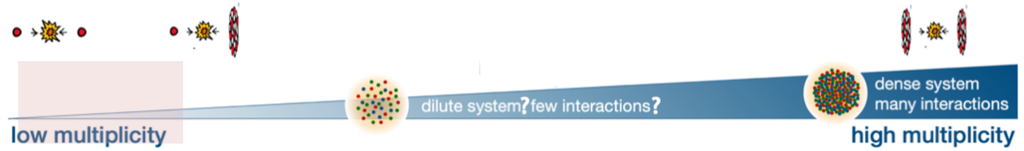

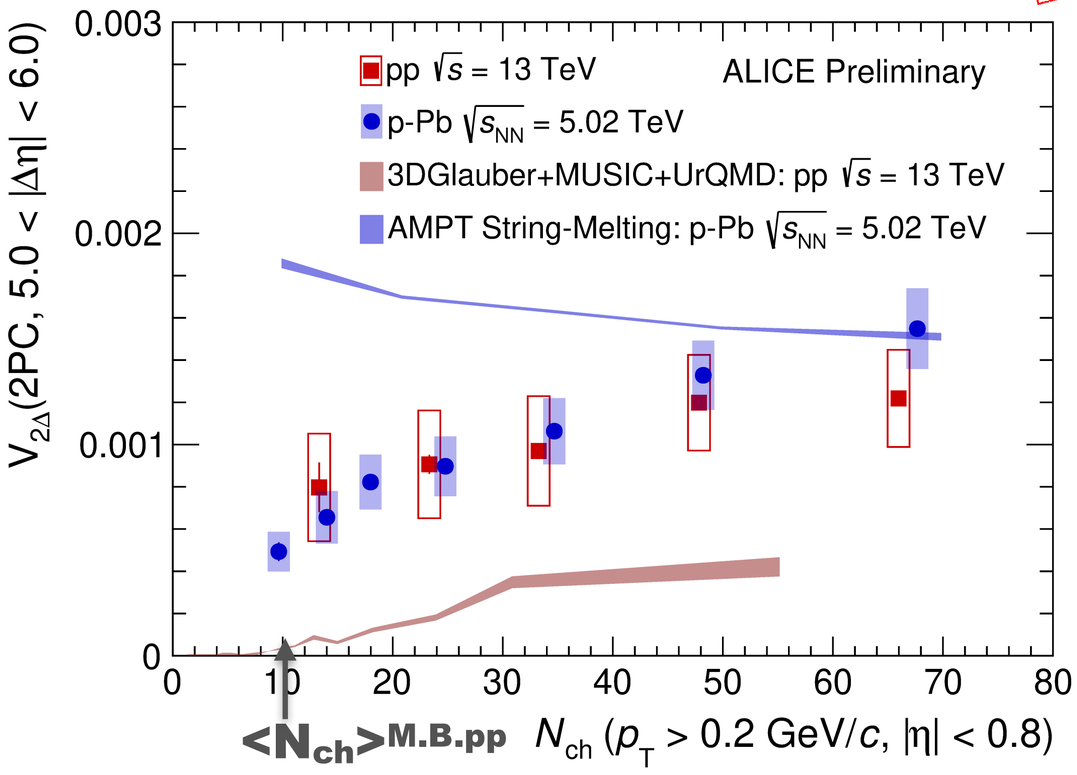

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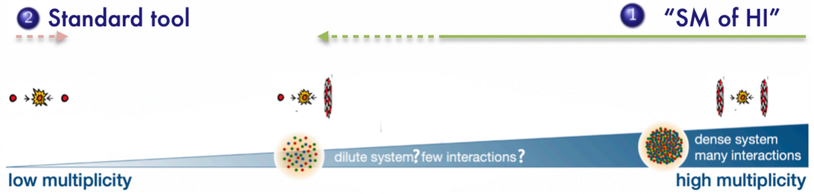
Take home message

- Another successful ***sQM*** with exciting results in small systems!

- Baryon/meson v_2 grouping and splitting, which were taken as the smoking gun evidence of QGP in HI collisions, observed in high-multiplicity small systems.
  - the ***"SM of HI"*** with the dense partonic matter with the quark-coalescence seems to work fine.



- Collective flow observed in small systems for both high multiplicity and low multiplicity (down to M.B. pp)
  - can the ***"Standard tool"*** in M.B. pp remain "standard" in M.B. pp?

Niels Bohr Institute

European Research Council
Established by the European Commission

Flow @ LHC-Run3

⋆PhD (ERC)

- Deadline on June 15th, 2024
- starting autumn 2024

⋆Postdoc 1 (ERC)

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⋆ **Contact You Zhou: *You.Zhou AT cern.ch***

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Backup

What is the meaning of multi-particle correlation

- What is the physics meaning of multi-particle correlation measurements in the events with a few produced particles
  - How can we understand 4-particle cumulant in the event with 6 produced particles

- What could be the physics bias (i.e., nonflow)
- What is the bias in Mathematics (do we have the "resolution" to measure "collective flow" for Nch < 5?

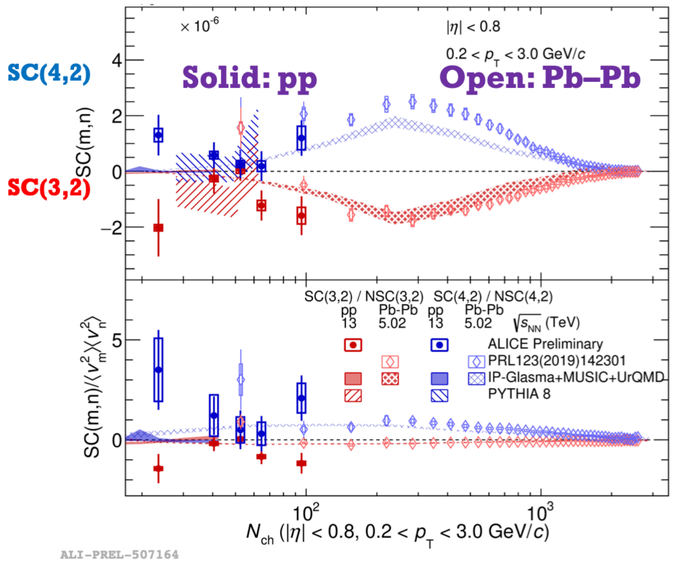
CERN-LPCC-2018-07
February 26, 2019

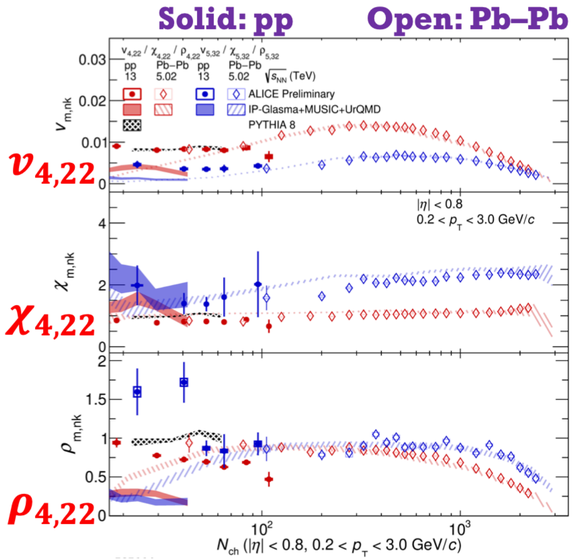
Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams

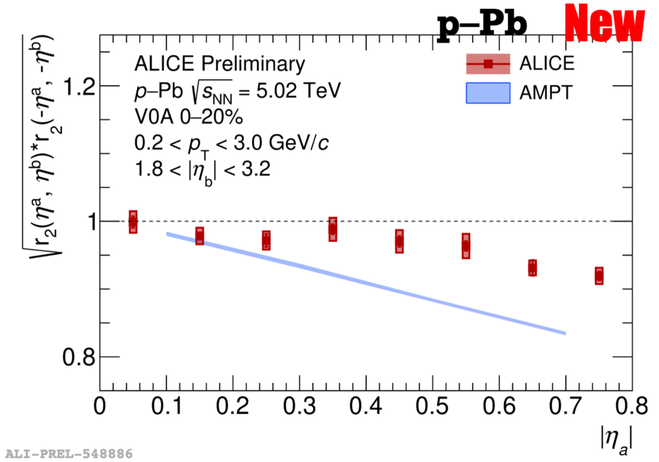
Report from Working Group 5 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

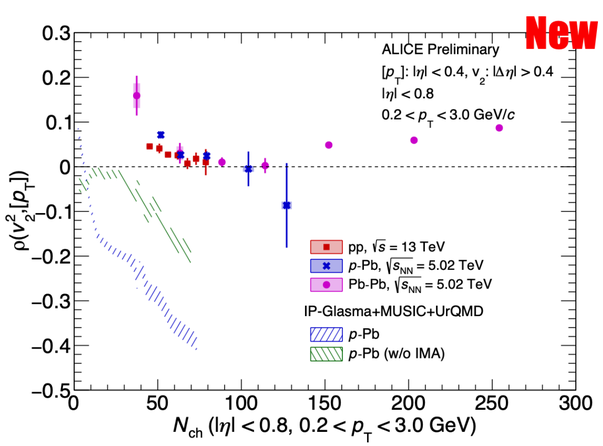
9 Emergence of hot and dense QCD matter in small systems

Observable or effect	Pb–Pb	p–Pb (high mult.)	pp (high mult.)
Low p_{T} spectra ("radial flow")	yes	yes	yes
Intermediate p_{T} ("recombination")	yes	yes	yes
Particle ratios Statistical model	GC level $\gamma_s^{\mathrm{GC}} = 1$, 10–30%	GC level except Ω $\gamma_s^{\mathrm{GC}} \approx 1$, 20–40%	GC level except Ω MB: $\gamma_s^{\mathrm{C}} < 1$, 20–40%
HBT radii ($R(k_{\mathrm{T}})$, $R(\sqrt[3]{N_{\mathrm{ch}}})$)	$R_{\mathrm{out}}/R_{\mathrm{side}} \approx 1$	$R_{\mathrm{out}}/R_{\mathrm{side}} \lesssim 1$	$R_{\mathrm{out}}/R_{\mathrm{side}} \lesssim 1$
Azimuthal anisotropy (v_{n}) (from two particle correlations)	v_1–v_7	v_1–v_5	v_2–v_4
Characteristic mass dependence	v_2–v_5	v_2, v_3	v_2
Directed flow (from spectators)	yes	no	no
Charge-dependent correlations	yes	yes	yes
Higher-order cumulants (mainly $v_2\{n\}$, $n \geq 4$)	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6$"
Symmetric cumulants	up to SC$(5,3)$	only SC$(4,2)$, SC$(3,2)$	only SC$(4,2)$, SC$(3,2)$
Non-linear flow modes	up to v_6	not measured	not measured
Weak η dependence	yes	yes	not measured
Factorization breaking	yes ($n = 2, 3$)	yes ($n = 2, 3$)	not measured
Event-by-event v_{n} distributions	$n = 2$–4	not measured	not measured
Direct photons at low p_{T}	yes	not measured	not observed
Jet quenching through dijet asymmetry	yes	not observed	not observed
Jet quenching through R_{AA}	yes	not observed	not observed
Jet quenching through correlations	yes (Z–jet, γ–jet, h–jet)	not observed (h–jet)	not measured
Heavy flavor anisotropy	yes	yes	not measured
Quarkonia production	suppressed[†]	suppressed	not measured

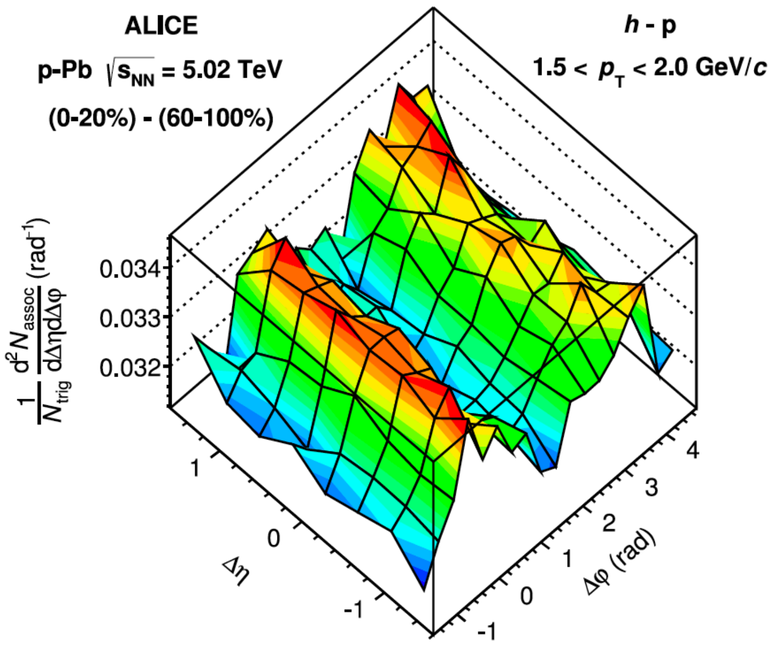




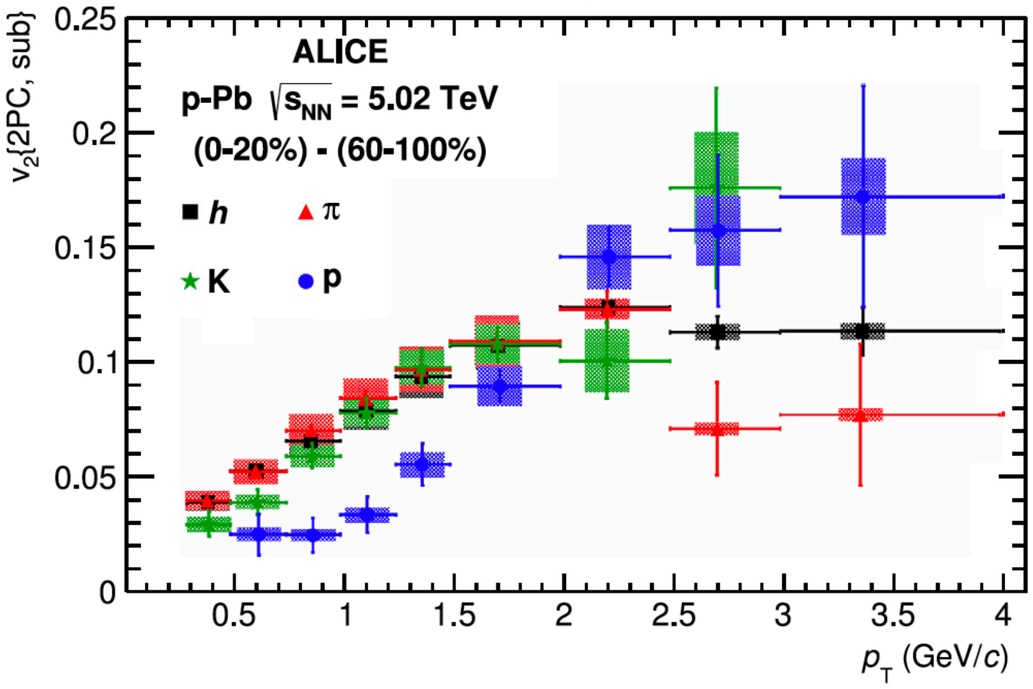




Here comes the story in small systems



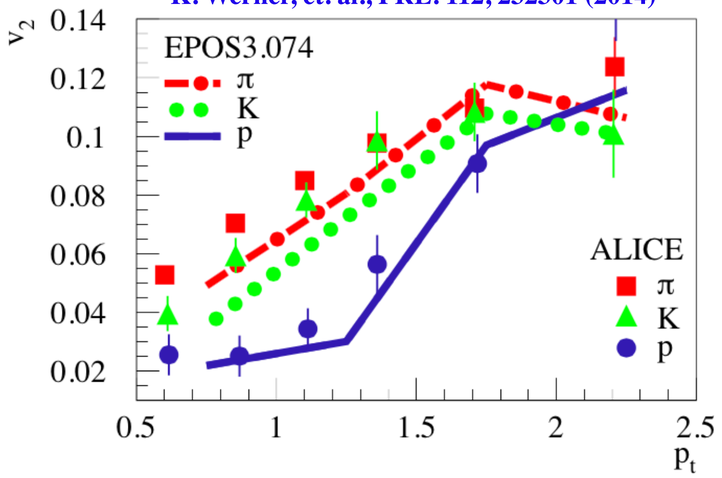
ALICE Collaboration, Physics Letters B 726 (2013) 164



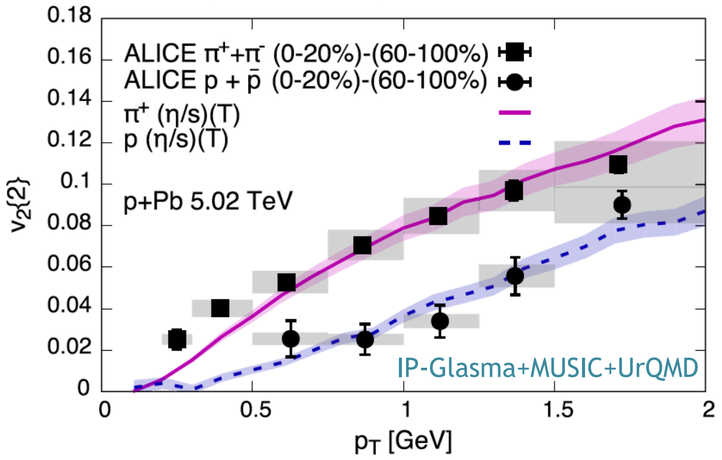
- Observation of long-range correlation between h-PID (qualitatively similar to AA collisions)
  - v_2(p) is significantly smaller than v_2(π) and v_2(K) at low p_T,
  - opposite is observed at 2.5-4.0 GeV/*c*
  - Crossing takes place at about 2 GeV/*c*

Theoretical explanations

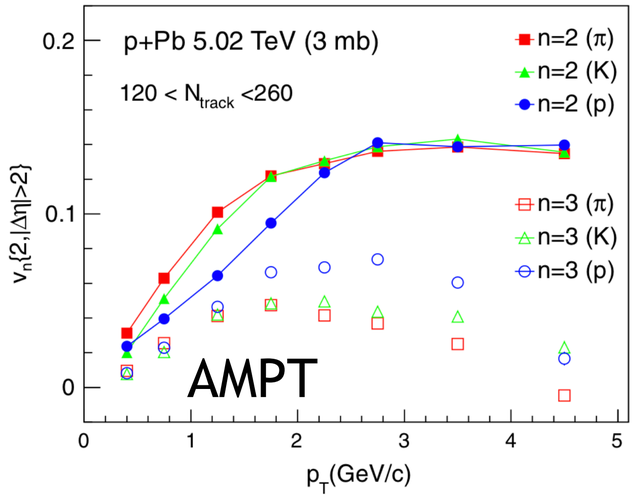
K. Werner, et. al., PRL. 112, 232301 (2014)



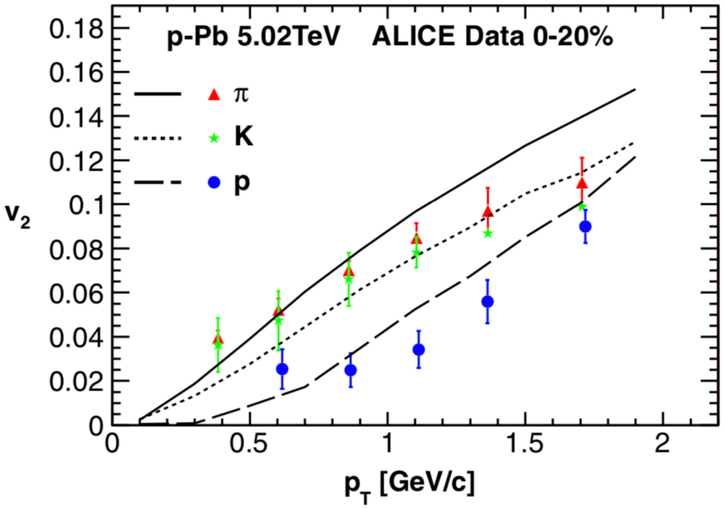
H. Mäntysaari et al. , Physics Letters B 772 (2017) 681



A. Bzdak, PRL 113, 252301 (2014)



P. Bozek etc, PRL 111, 172303 (2013)

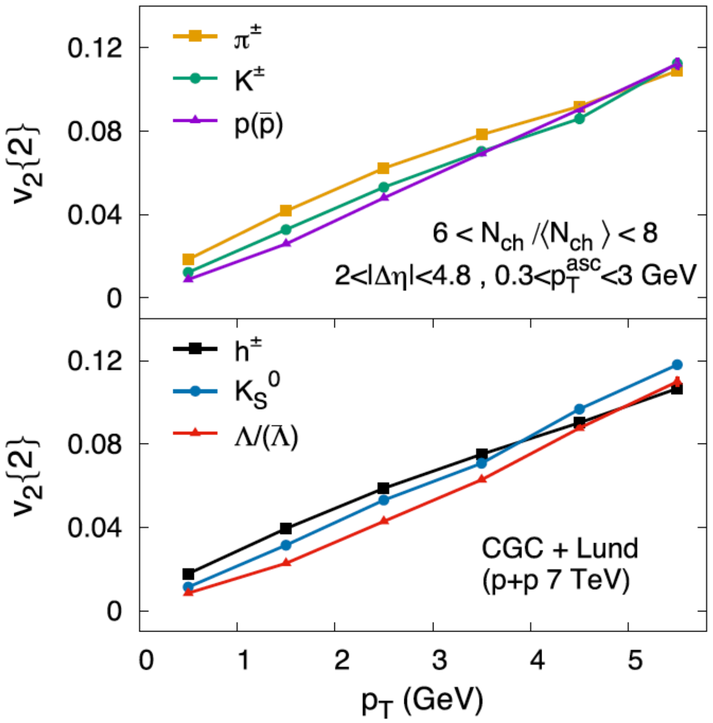


- Hydro and Transport model reproduce (qualitatively or semi-quantitatively) the mass ordering
  - Indication of QGP
  - the crossing is less clear (not pure hydro)

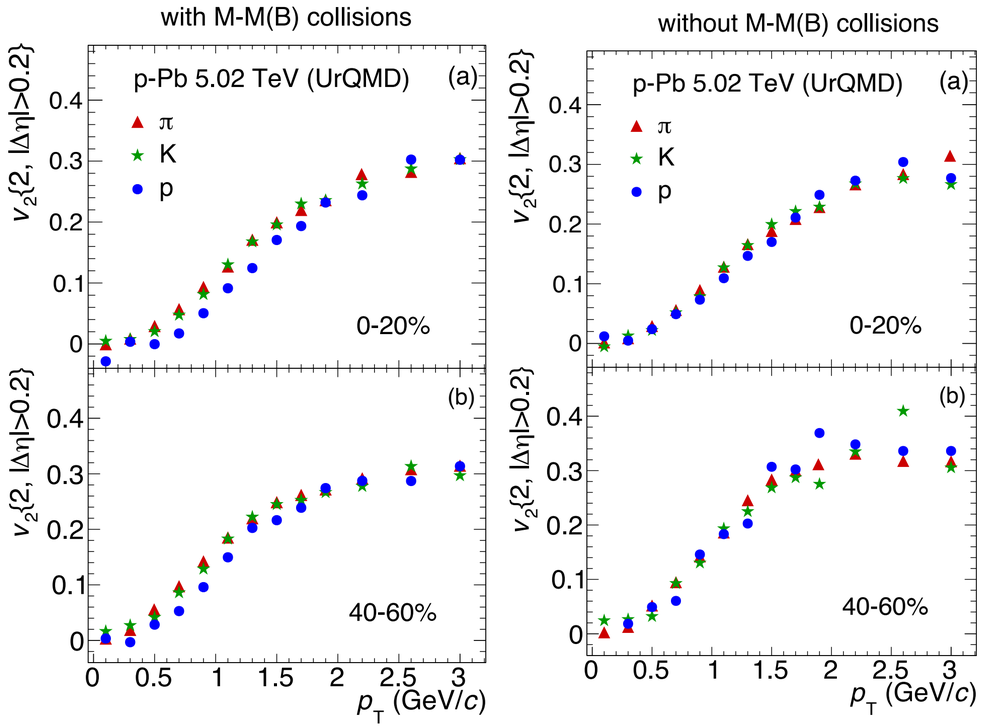
Note, AMPT does not predict NCQ scaling even there is partonic flow.

Mass ordering alone is not enough

B. Schenke etc, PRL117, 162301 (2016)

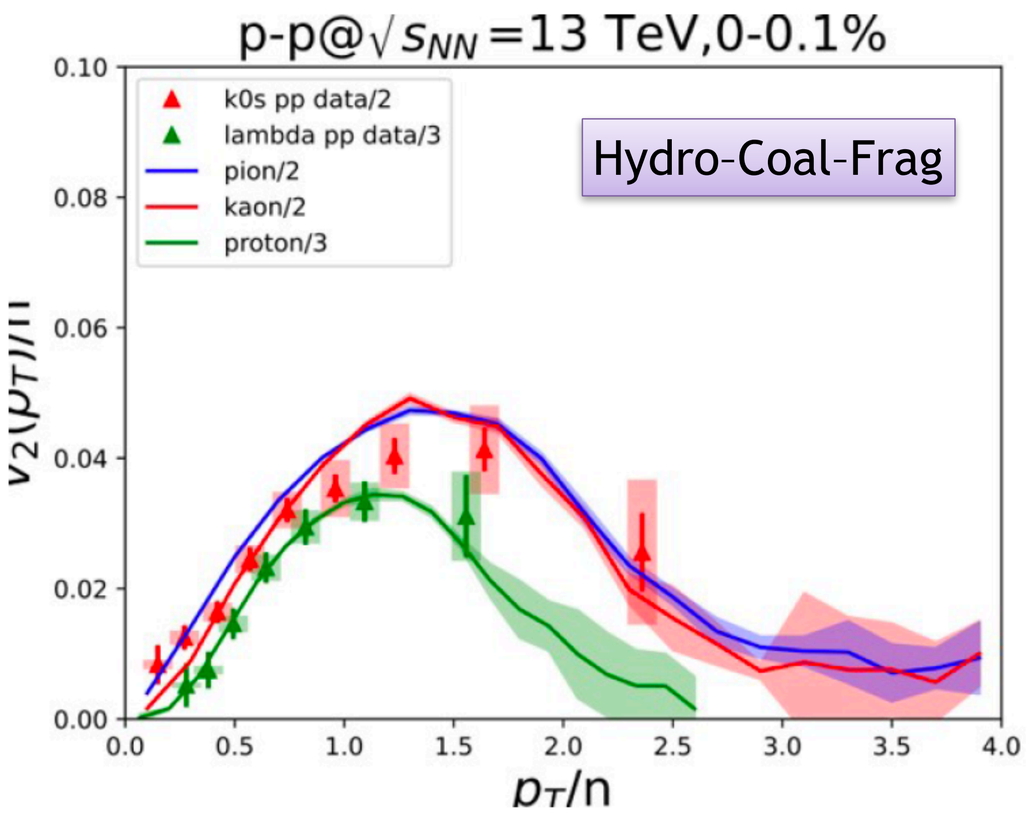


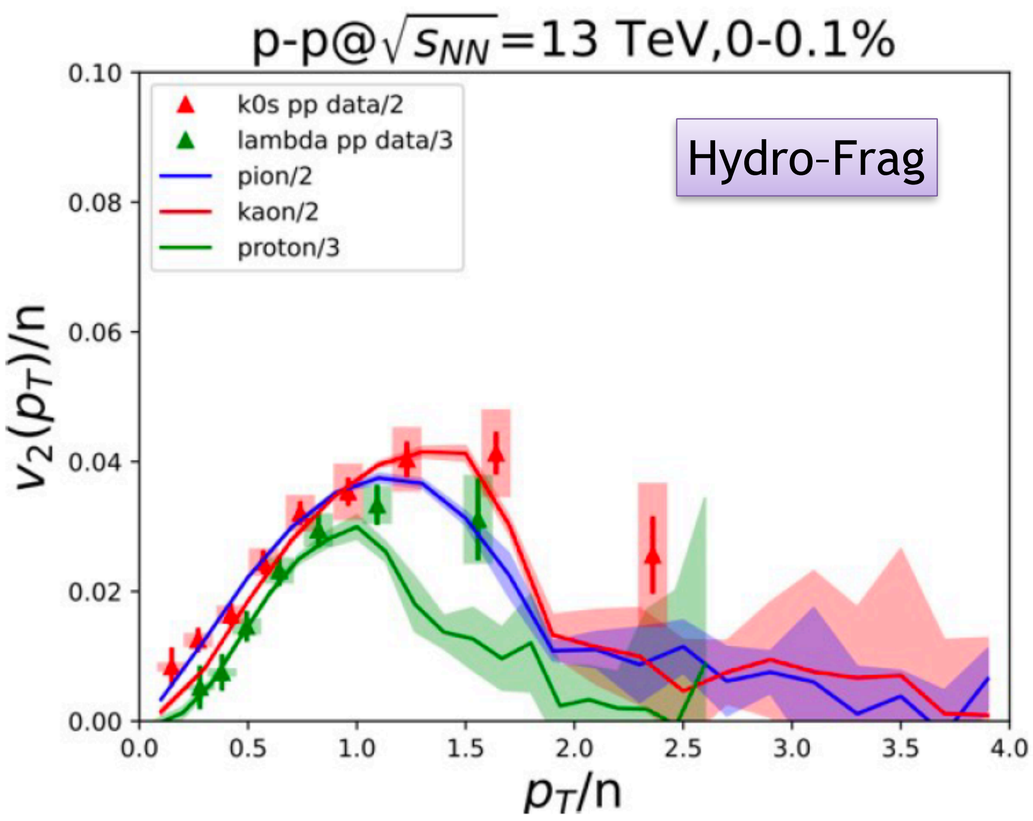
Y. Zhou et al., PRC 91, 064908 (2015)



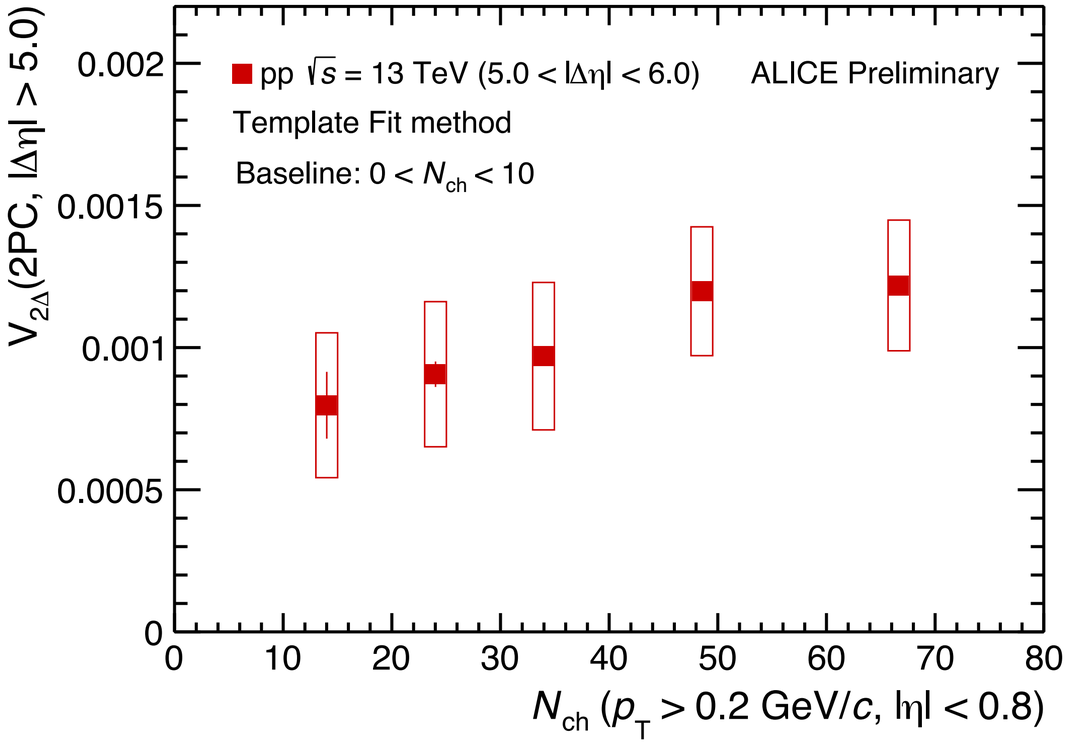
- The characteristic $v_2(p_T)$ mass-ordering is observed in CGC+Lund due to the initial stage effect
- It is also seen in UrQMD
  - the consequence of hadronic interactions
  - not necessarily associated with strong fluid-like expansions.
- No baryon-meson grouping

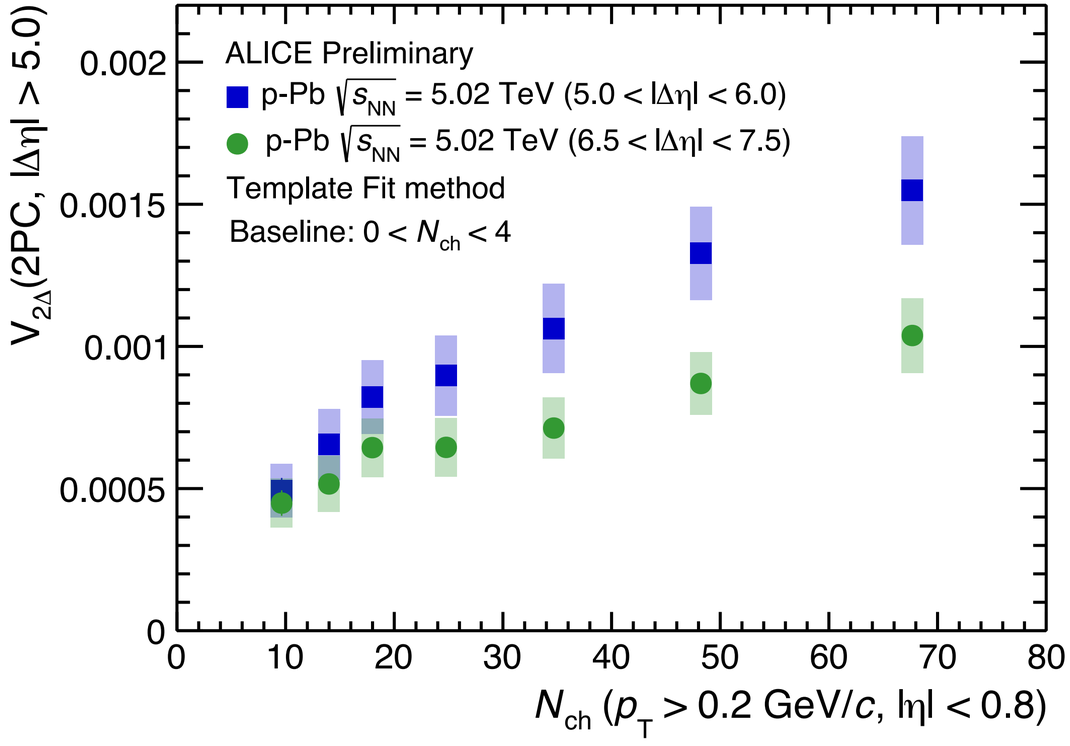
Behavior of NCQ scaling is predictable





Without quark-coal, the values of v_2 are smaller, in particular for baryons.


pp $\sqrt{s}$ = 13 TeV (5.0 < |Δη| < 6.0)
ALICE Preliminary
Template Fit method
Baseline: 0 < N_{ch} < 10
$V_{2\Delta}$(2PC, |Δη| > 5.0)
N_{ch} (p_T > 0.2 GeV/c, |η| < 0.8)


ALICE Preliminary
p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV (5.0 < |Δη| < 6.0)
p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV (6.5 < |Δη| < 7.5)
Template Fit method
Baseline: 0 < N_{ch} < 4
$V_{2\Delta}$(2PC, |Δη| > 5.0)
N_{ch} (p_T > 0.2 GeV/c, |η| < 0.8)