LHCP Boston 2024

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http://lhcp2024.cos.northeastern.edu

INSTITUTE OF SPACE SCIENCE
A subsidiary of INFLPR

Particle production and collectivity from small to large collision systems

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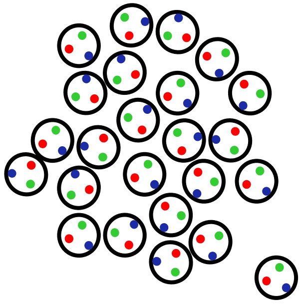
for the LHC Collaborations

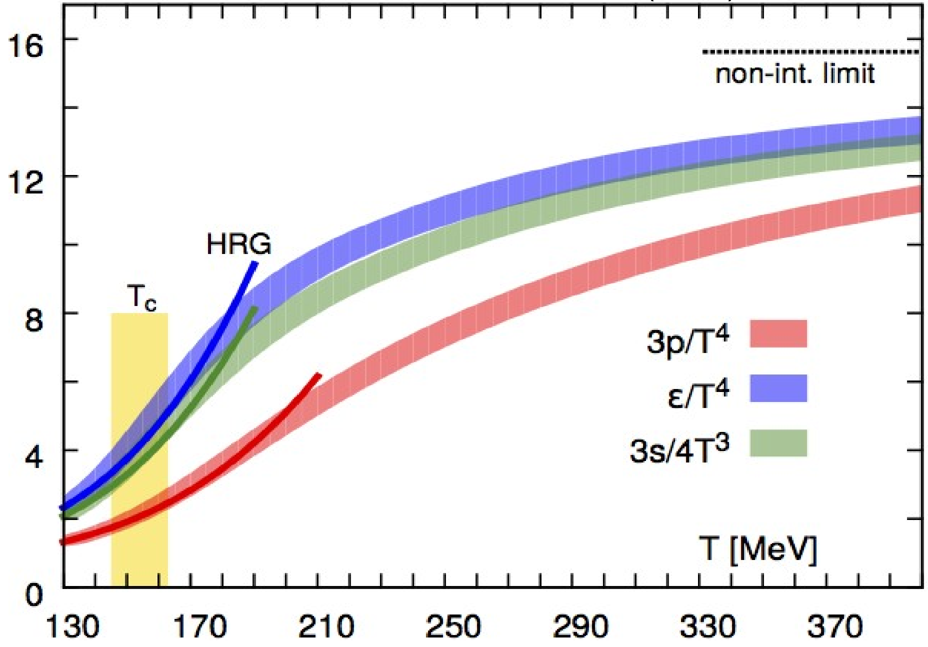
ALICE ATLAS EXPERIMENT CMS LHCb

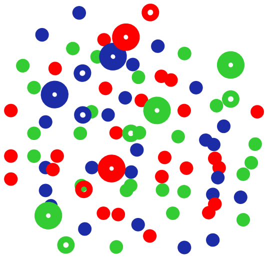
Lattice QCD: quark–gluon plasma (QGP)



nuclear matter
(confined)

hotQCD Collaboration, PRD 90 (2014) 094503





QGP
(deconfined)

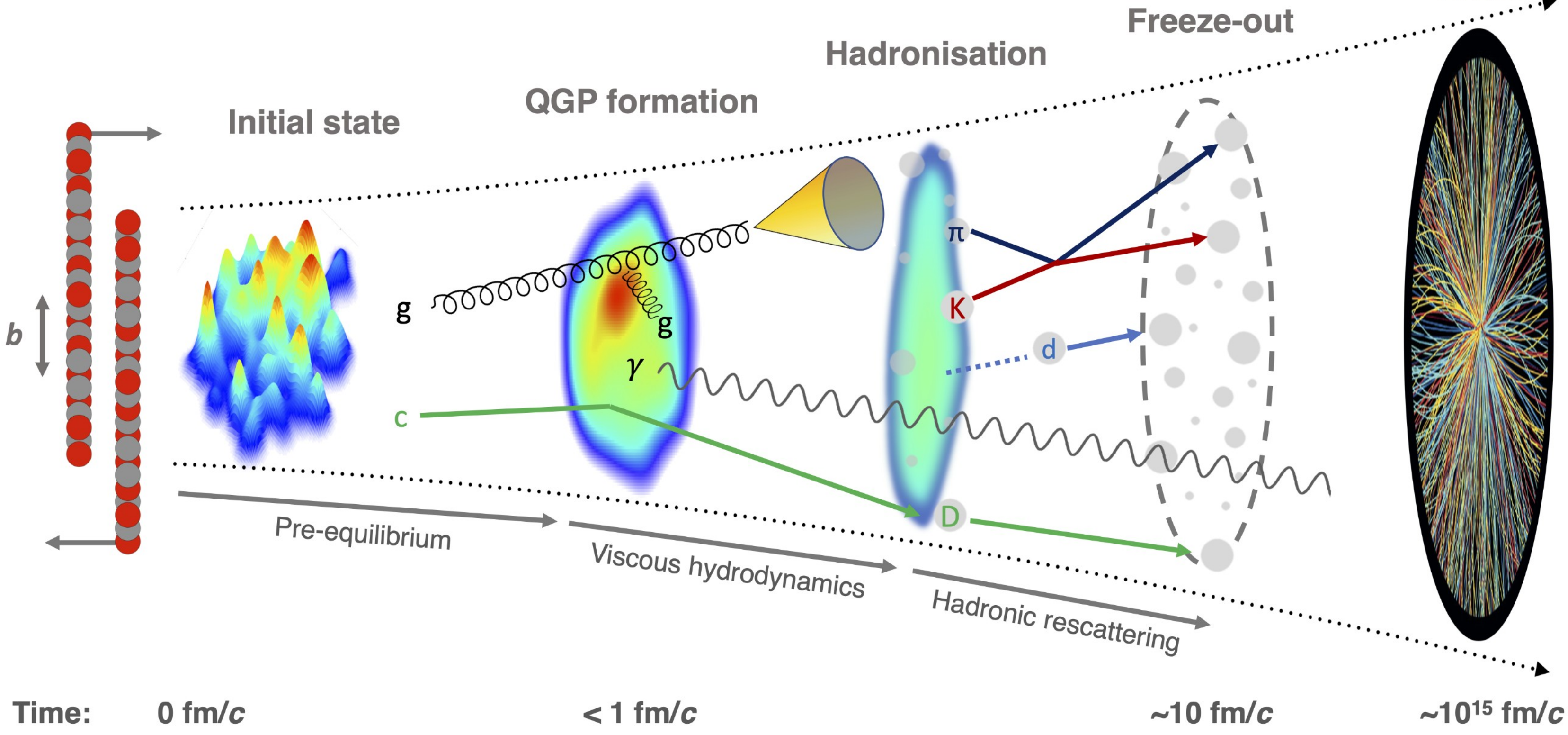
$$p = \frac{1}{3}\varepsilon = g\frac{\pi^2}{90}T^4$$

$$\frac{\varepsilon}{T^4} = g\frac{\pi^2}{30}$$

- Heating + compression → quark–gluon plasma (QGP): deconfined system of quarks and gluons
- Lattice QCD: transition expected to occur at energy density ε~0.5 GeV/fm^3 and temperature T~156 MeV
  - Conditions achieved in laboratory by colliding heavy ions

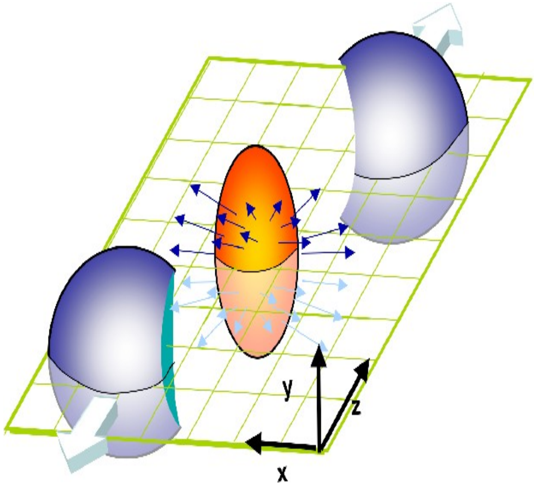
Heavy-ion collisions: quark–gluon plasma (QGP)

System cools down by (isentropic) expansion



ALICE, arXiv:2211.04384

Anisotropic flow



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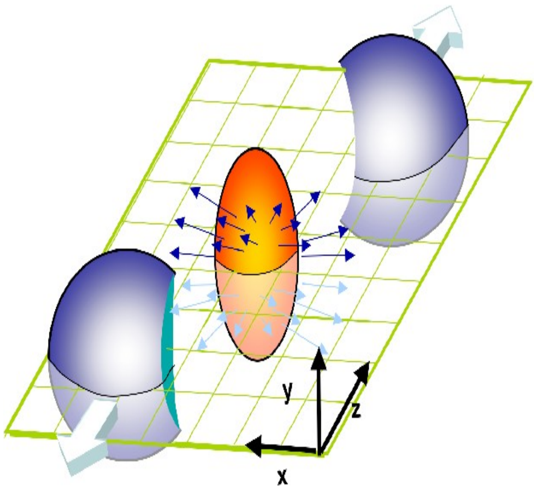
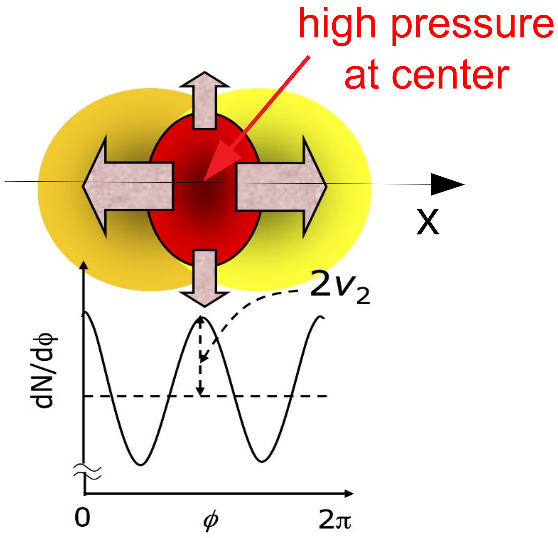
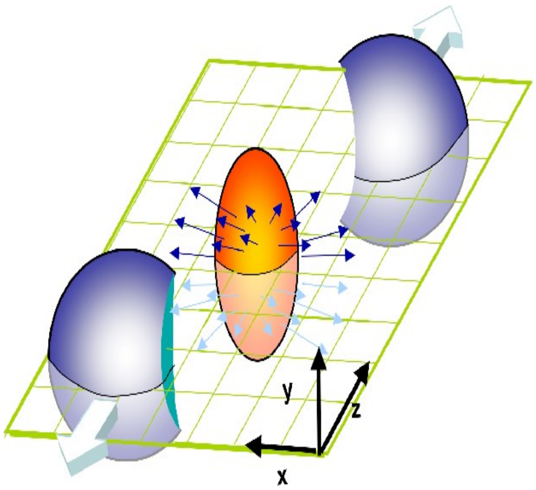


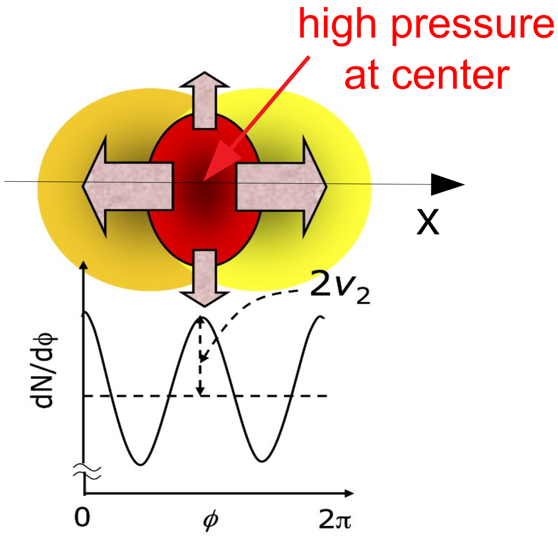


Pressure gradients (larger in the x direction) push bulk “out” → “flow”

More particles seen in the x-direction

Anisotropic flow





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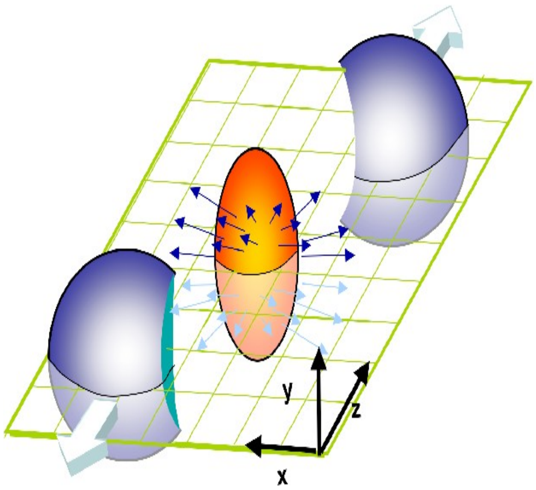
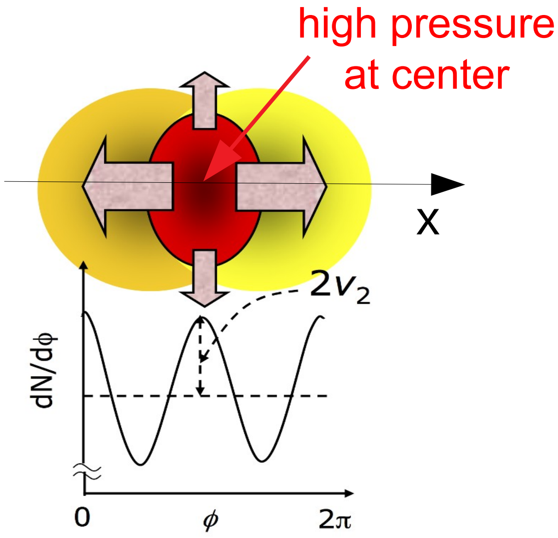
$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_T\,dp_T\,dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos\left(n\left(\varphi-\Psi_n\right)\right)\right)$$

- Anisotropic flow: initial spatial anisotropy → final momentum anisotropy via collective interactions

Anisotropic flow





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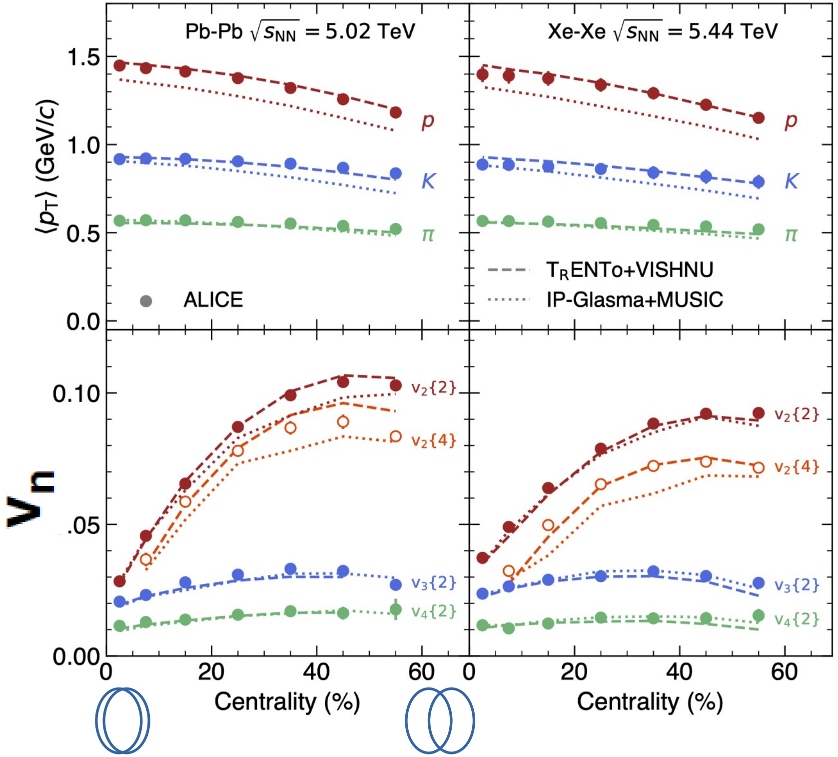
  - v_n quantify the event anisotropy

ALICE, arXiv:2211.04384



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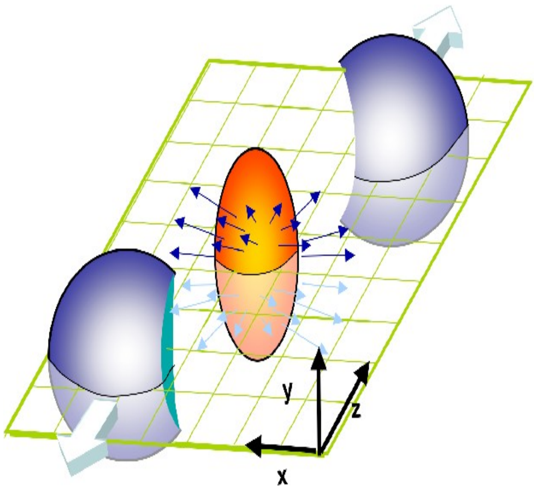

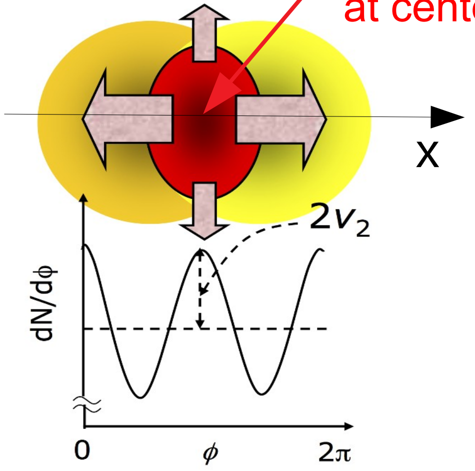

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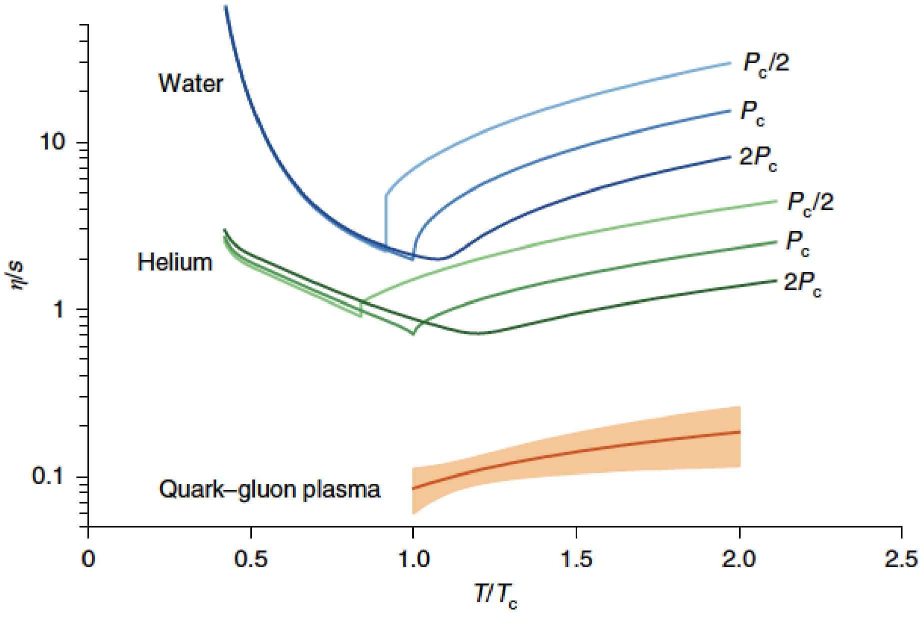
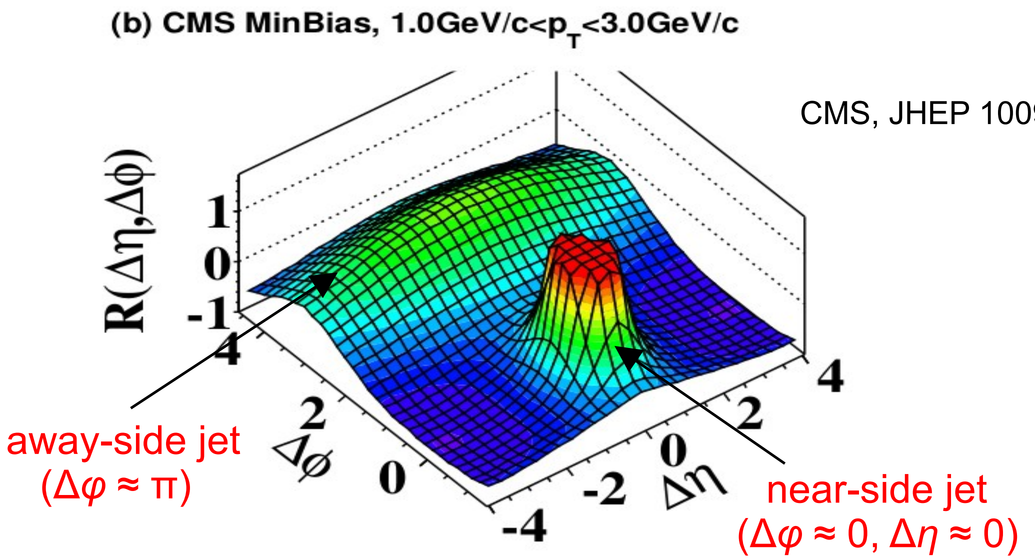
- Anisotropic flow: initial spatial anisotropy → final momentum anisotropy via collective interactions
  - v_n quantify the event anisotropy
- Characterize key QGP properties like viscosity
  - Nearly perfect fluid: $1/4\pi < \eta/s < 3/4\pi$

J. Bernhard et al., NP 19 (2019) 1113



Small collision systems: collectivity

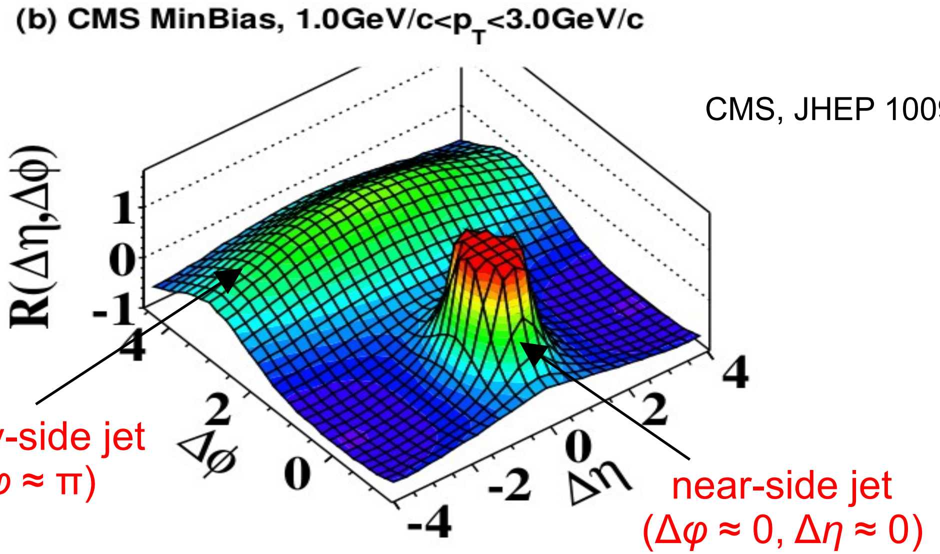


CMS, JHEP 1009 (2010) 091

- Minimum bias pp
  - Nonflow contributions
    - Near-side jet peak (+resonances, HBT effects)
    - Recoil jet in away side

ALICE, PLB 719 (2012) 29
ATLAS, PRL 116 (2016) 172301

Small collision systems: collectivity



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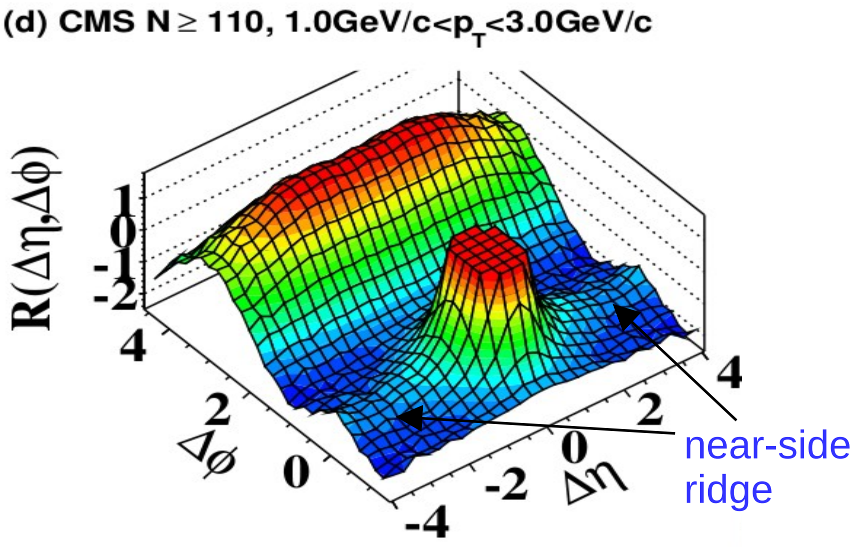

- Minimum bias pp
  - Nonflow contributions
    - Near-side jet peak (+resonances, HBT effects)
    - Recoil jet in away side

- High multiplicity pp
  - Near-side ridge, typical of collective systems
    - Decomposed into Fourier harmonics

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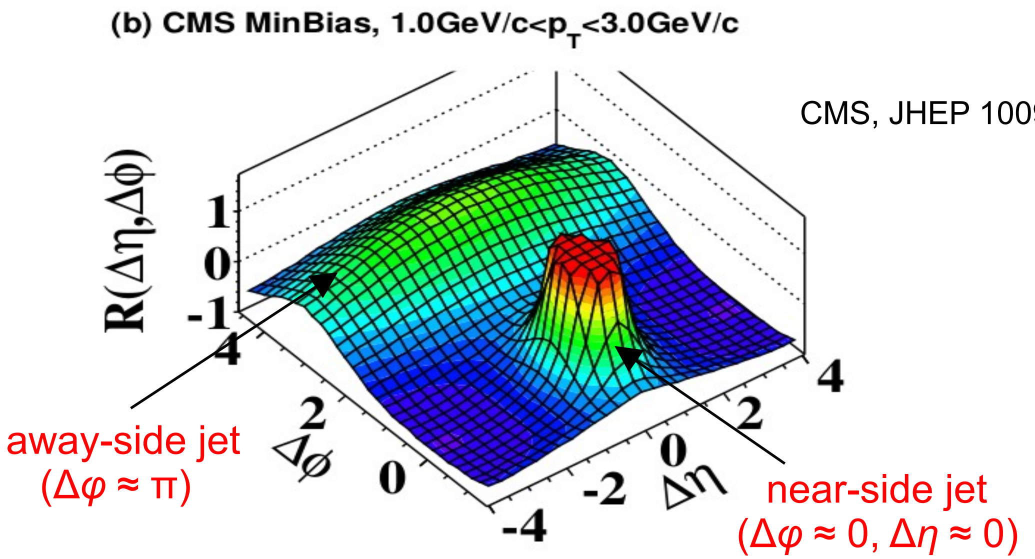
Small collision systems: collectivity



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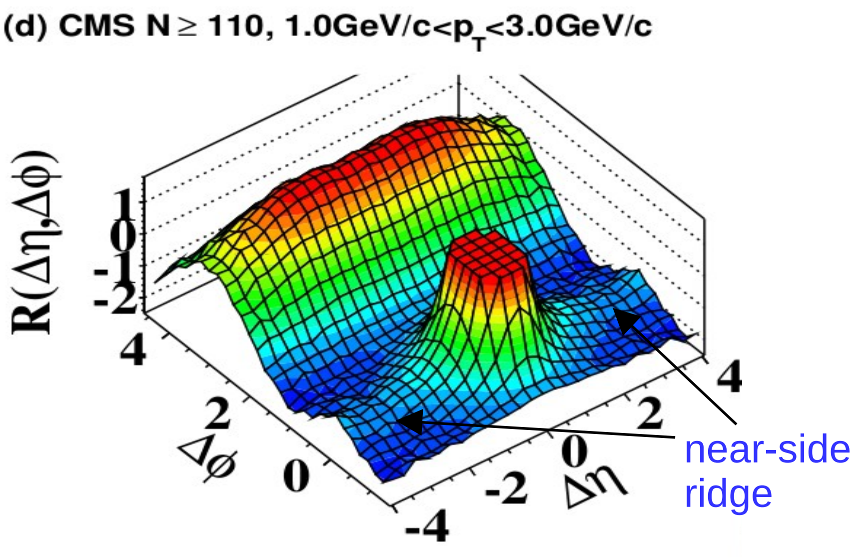

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ALICE, PLB 719 (2012) 29
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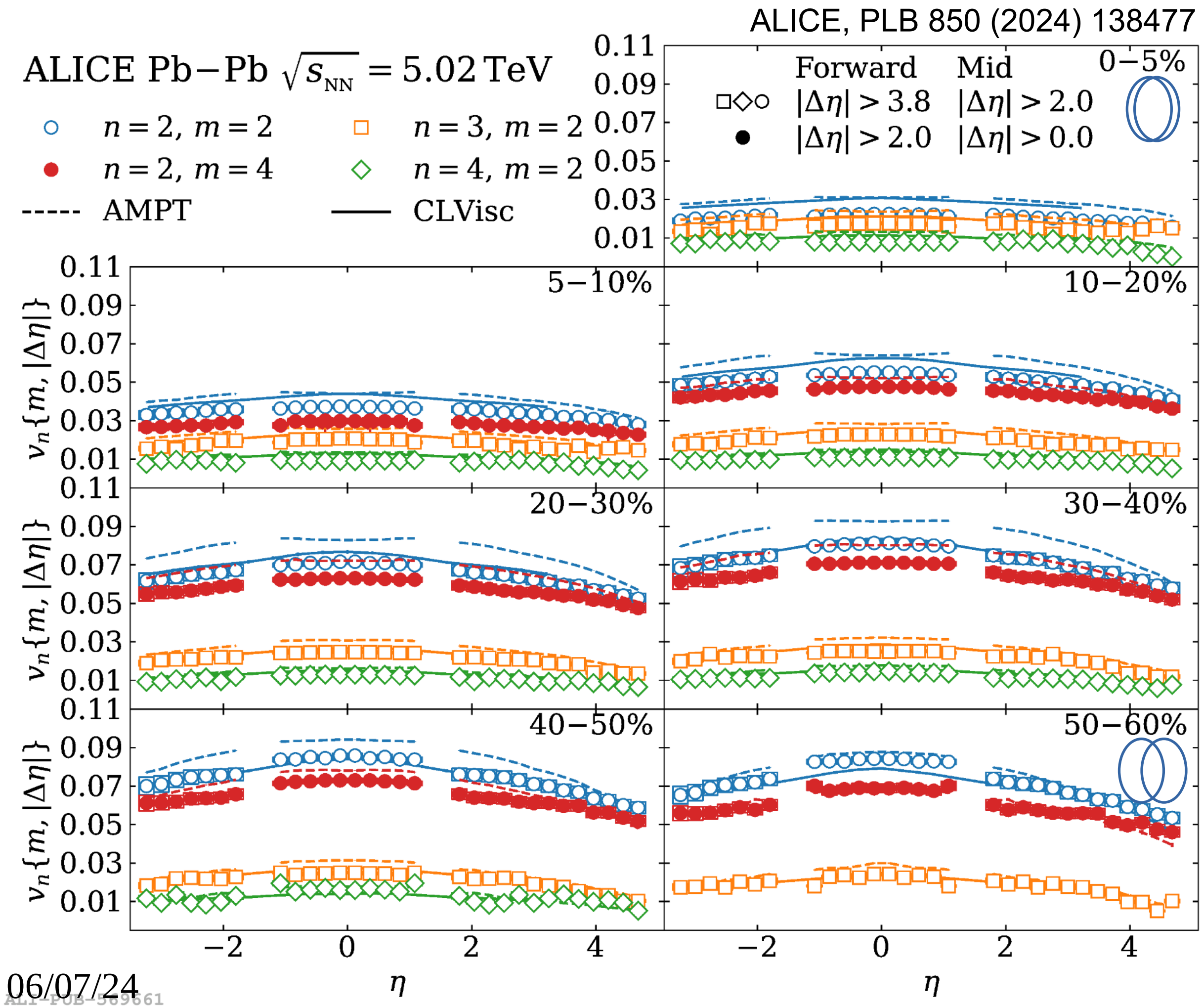
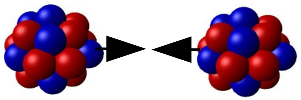
What is the origin of these collective effects?

Collectivity

Anisotropic flow at forward rapidity



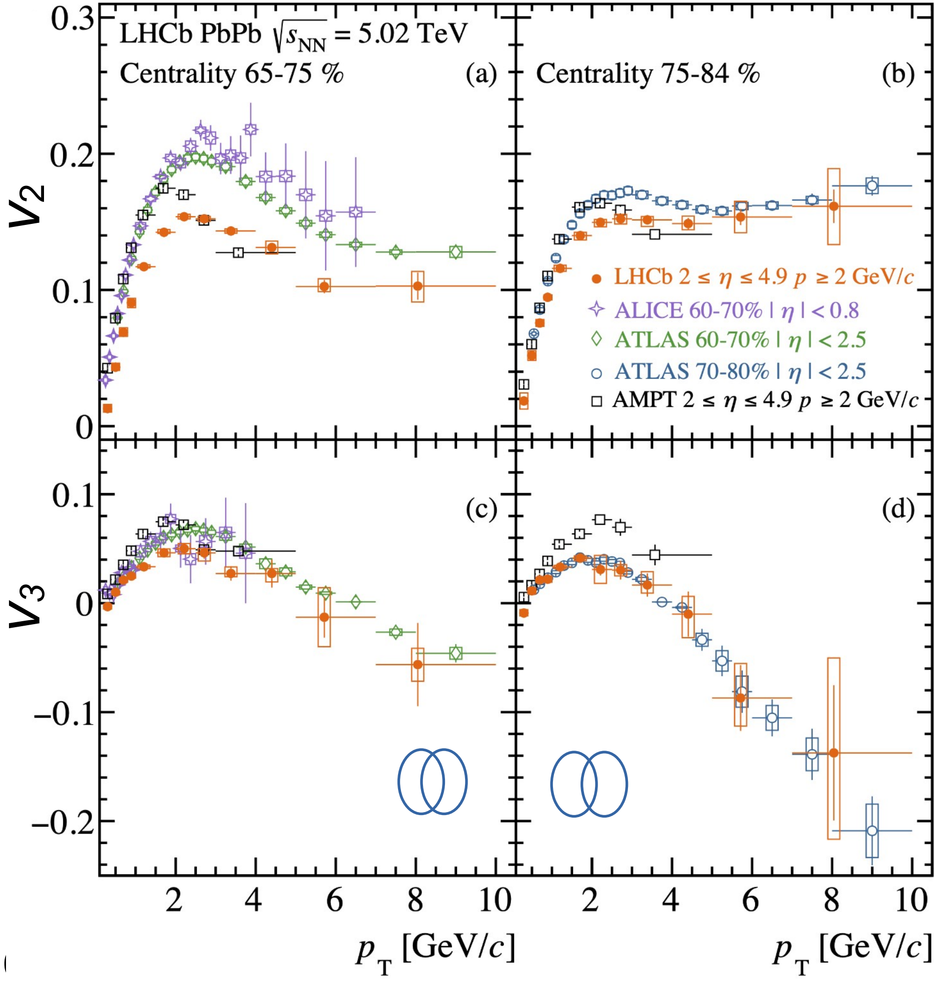


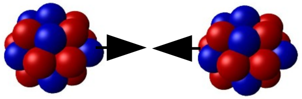
- Measurements of v_2, v_3, and v_4 coefficients are extended at large η
  - Hit-based analysis
- v_2 shows strong centrality dependence
- v_3 and v_4 reveal a modest centrality dependence
- Models overestimate the measured v_n coefficients
  - Constrain initial conditions

$$\frac{dN}{d\varphi} \sim 1 + \sum_{n=1}^{\infty} 2 v_n \cos(n(\varphi - \Psi_n))$$

Anisotropic flow at forward rapidity

LHCb, PRC 109 (2024) 054908

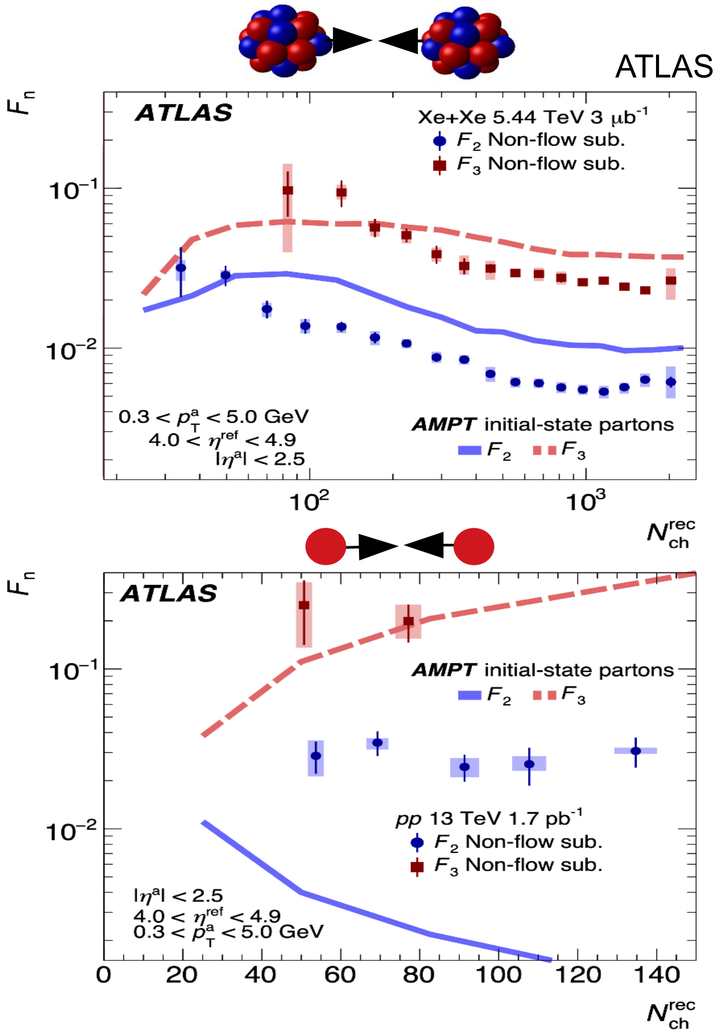




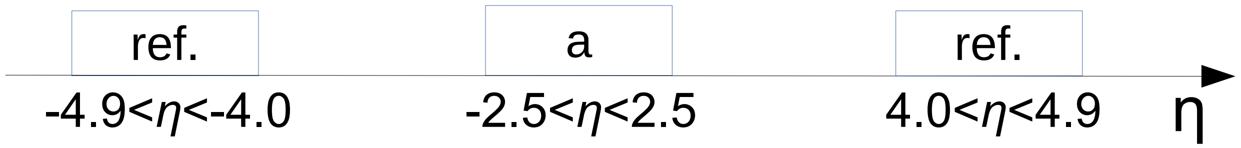
- Measurements of $v_2(p_T)$ and $v_3(p_T)$ coefficients at forward rapidity
  - Similar trends but different magnitudes than reported at central rapidity
    - Pseudorapidity range, nonflow contributions
  - Constrain models

Longitudinal flow decorrelations

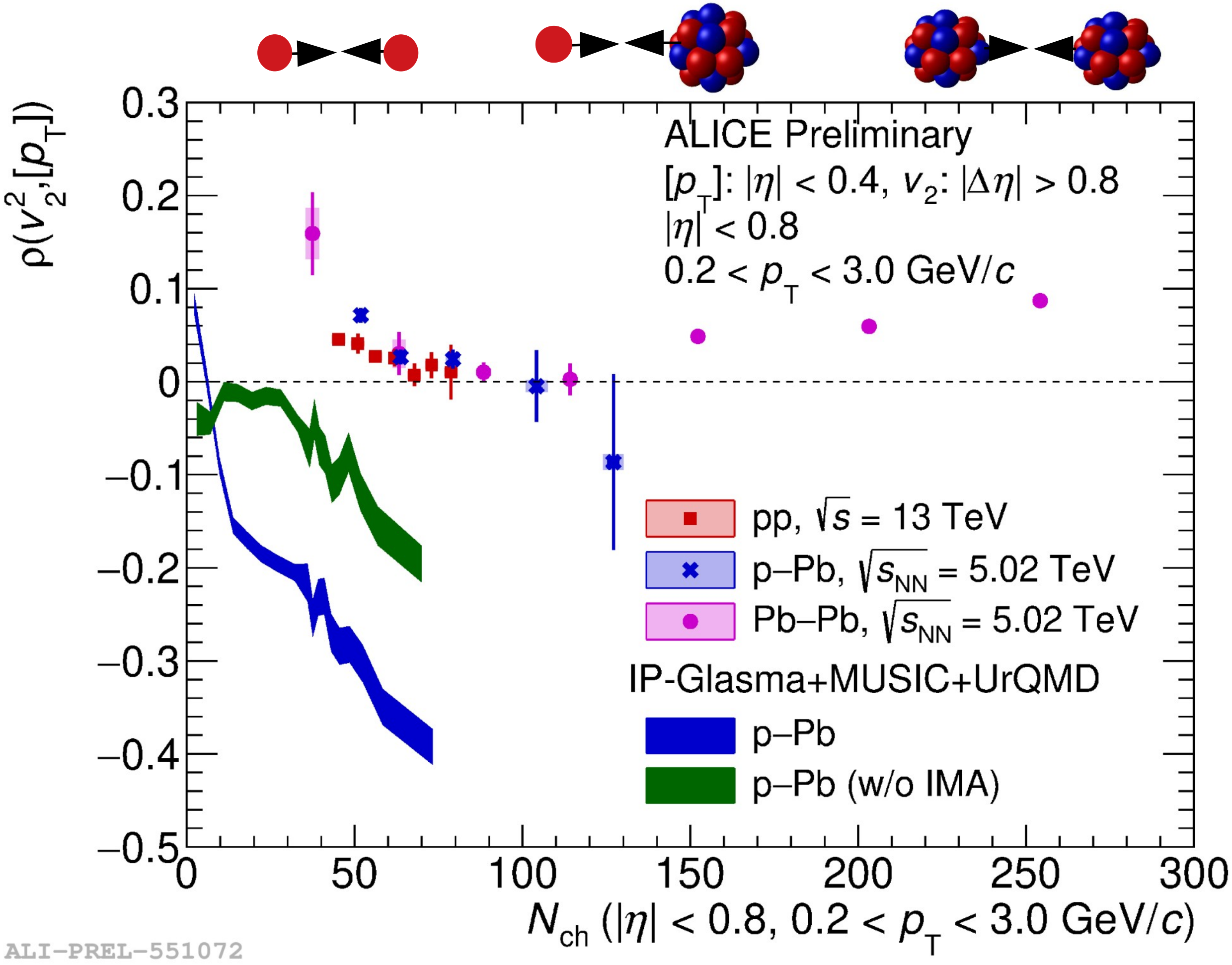
ATLAS, arXiv:2308.16745



- Constrain geometry in longitudinal direction
  - Measure 2-particle correlations between two η regions
  - Parametrize with $c_n = A_n(1 + F_n\eta + S_n\eta^2)$
    - F_n characterize the linear decorrelation strength
- Comparison with model with no geometric decorrelation
  - Qualitatively agreement in Xe–Xe but not in pp collsions
    - Evidence for longitudinal fluctuations in pp collisions possibly from subnucleonic structures



$v_2{}^2$-[p_T] correlations

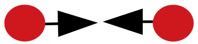


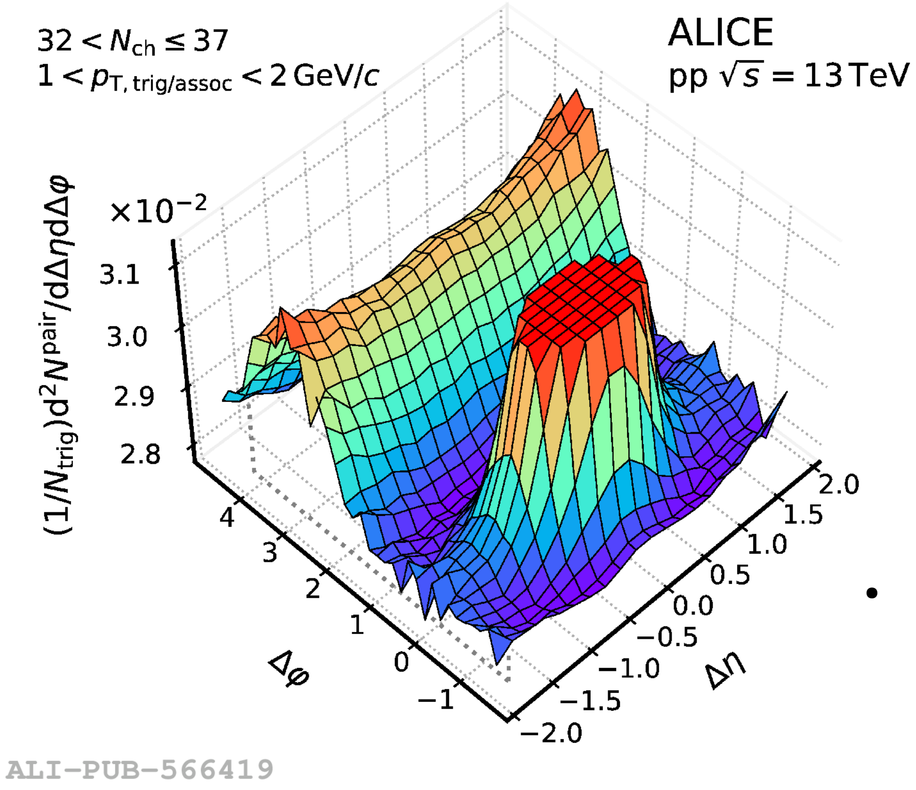
- Probe the initial stage
  - $\rho < 0$: geometric response
  - $\rho > 0$: Color Glass Condensate (CGC)
- Decreasing trend with increasing multiplicity in pp and p–Pb collisions
  - Not explained by simple geometry picture
  - Not described by a CGC-based hybrid model (w/wo initial momentum anisotropy)

$$\rho(v_n^2,[p_T]) = \frac{\mathrm{Cov}(v_n^2,[p_T])}{\sqrt{\mathrm{Var}(v_n^2)}\sqrt{c_k}}$$

Ridge yields

ALICE, PRL 132 (2024) 172302

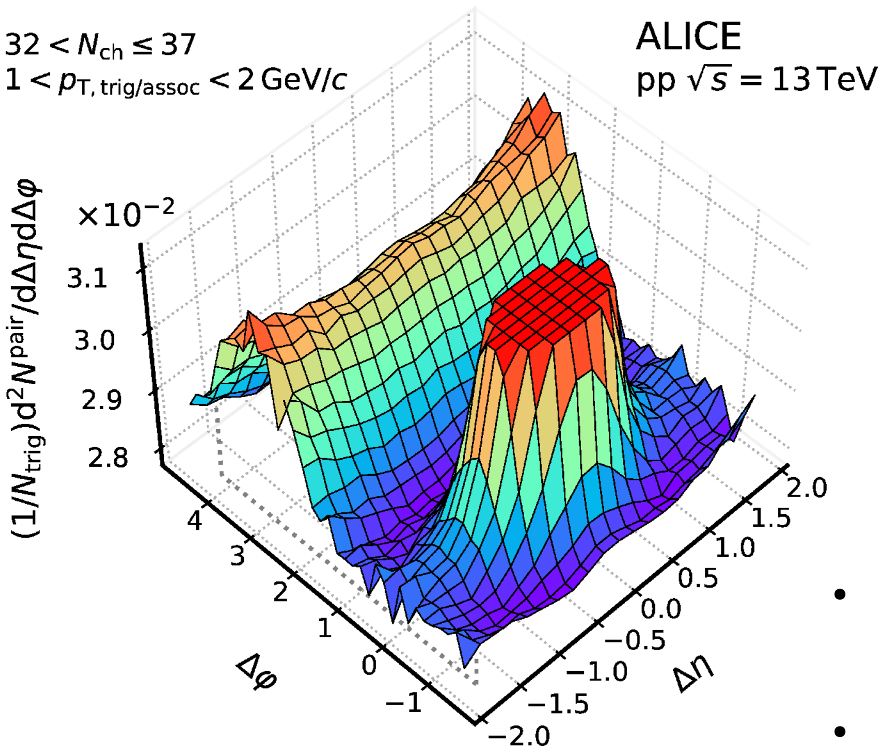


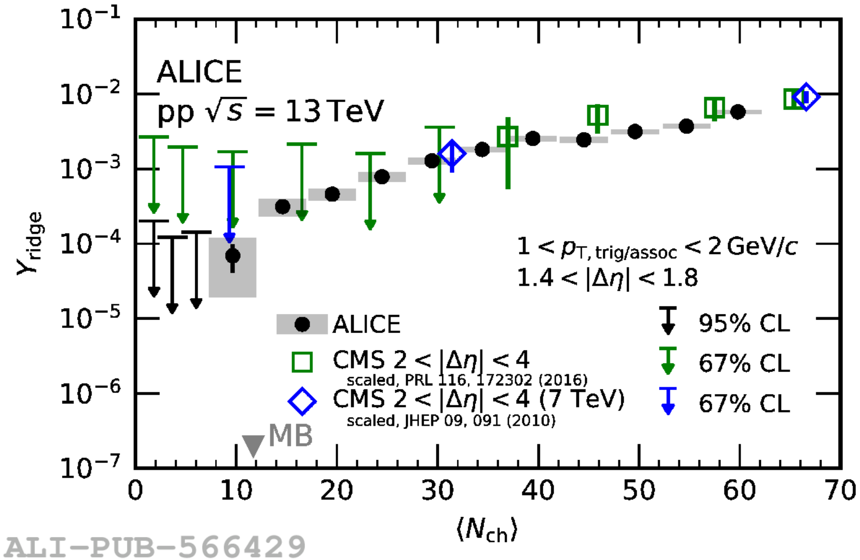


- Ridge yields to study collective effects down to low multiplicities
  - Overlap with e^+e^- results from ALEPH at $\sqrt{s}$ = 91 GeV

Ridge yields

ALICE, PRL 132 (2024) 172302

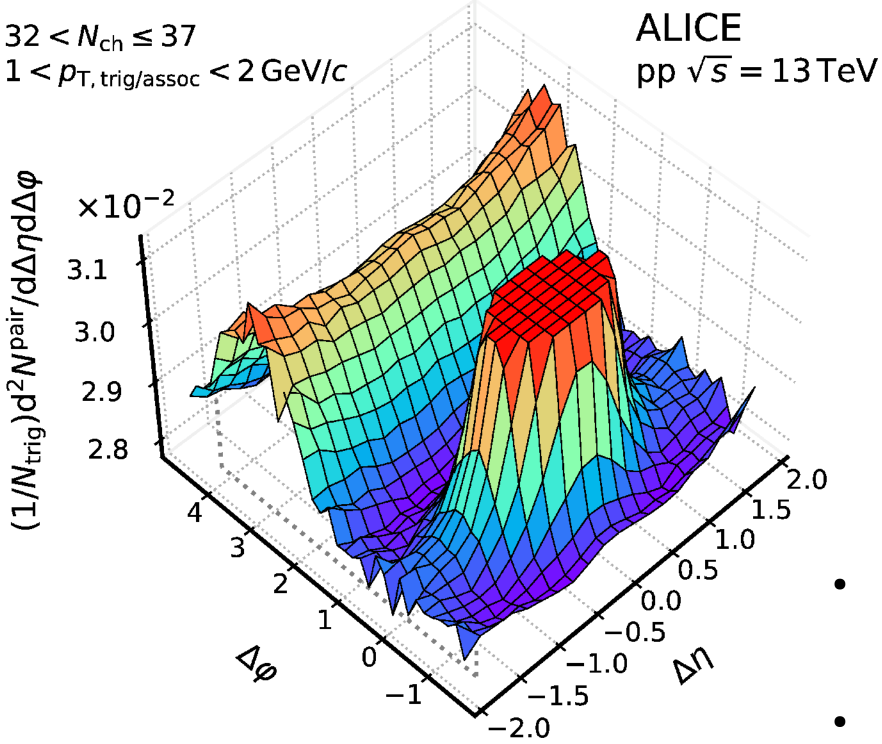




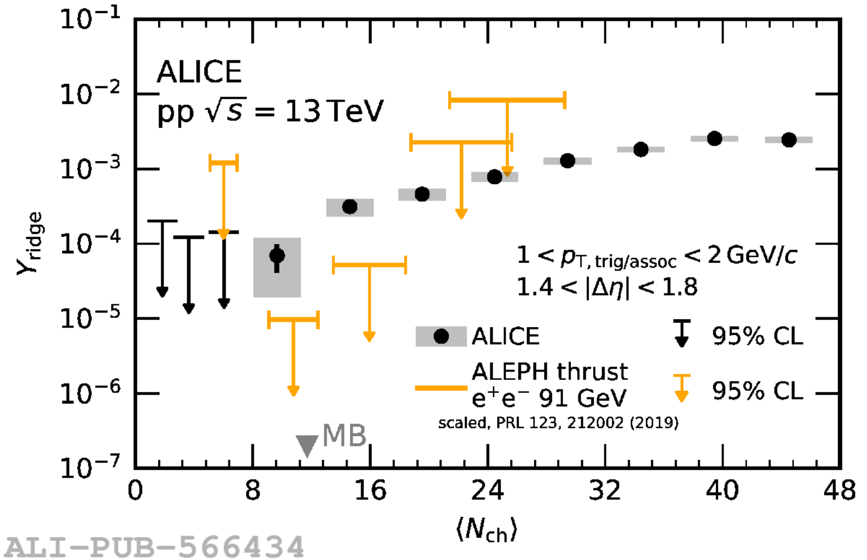
- Ridge yields to study collective effects down to low multiplicities
  - Overlap with e^+e^- results from ALEPH at $\sqrt{s}$ = 91 GeV
- Strong multiplicity dependence
  - Good agreement with CMS results

Ridge yields

ALICE, PRL 132 (2024) 172302



ALI-PUB-566419

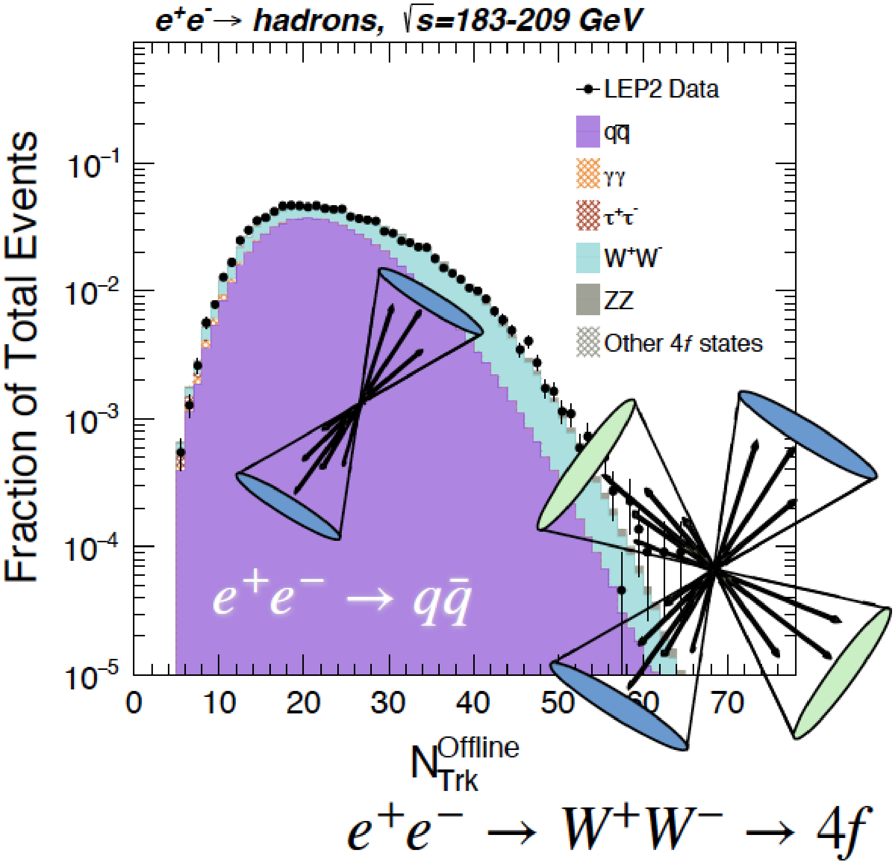


ALI-PUB-566434

- Ridge yields to study collective effects down to low multiplicities
  - Overlap with e^+e^- results from ALEPH at $\sqrt{s}$ = 91 GeV
- Strong multiplicity dependence
  - Good agreement with CMS results
  - Large differences between pp and e^+e^- results for $N_{ch} < 18$

Ridge yields

Y-C. Chen *et al.*, arXiv: 2312.05084



- 2-particle correlations on LEP-II e^+e^- data

Ridge yields

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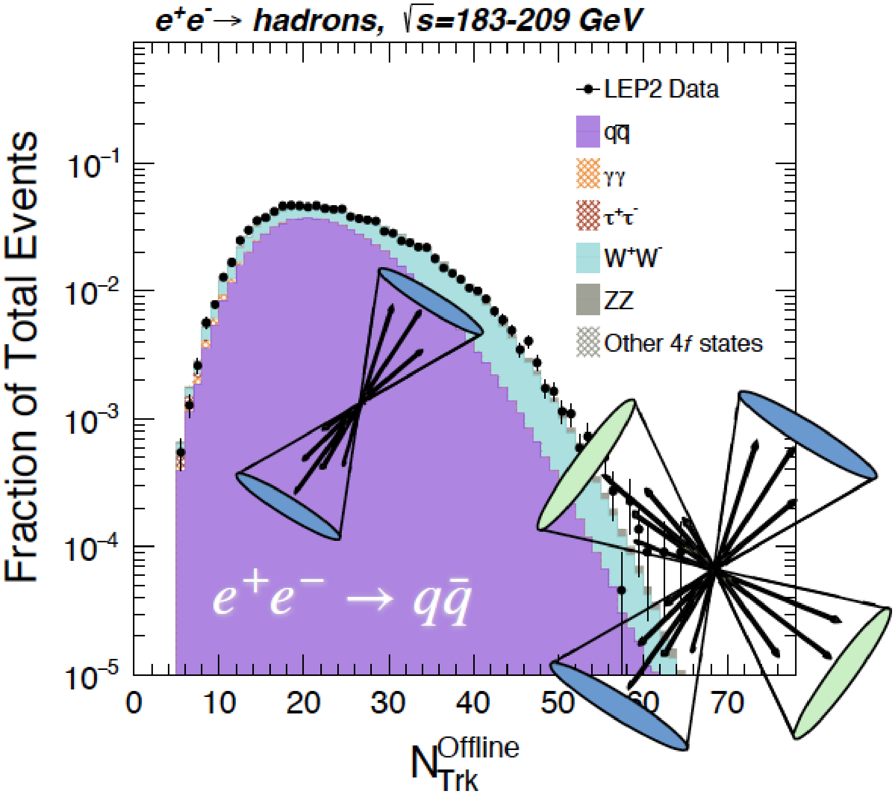
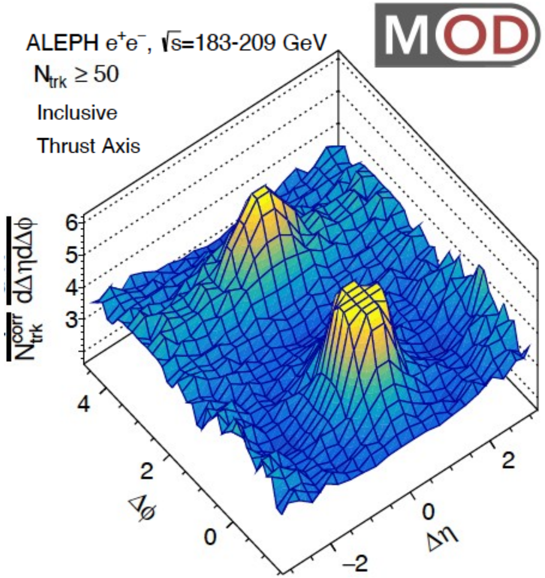
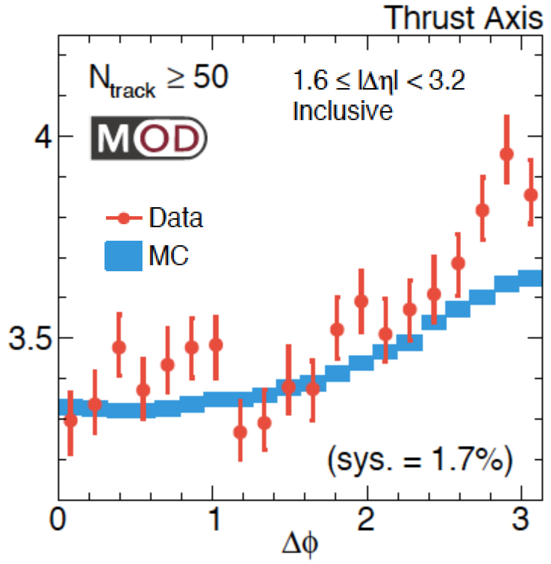


$$e^+e^- \rightarrow W^+W^- \rightarrow 4f$$





- 2-particle correlations on LEP-II e^+e^- data
- High multiplicity: excess of azimuthal anisotropy signals
  - Long-range near-side structure
  - Narrow away-side structure

Ridge yields

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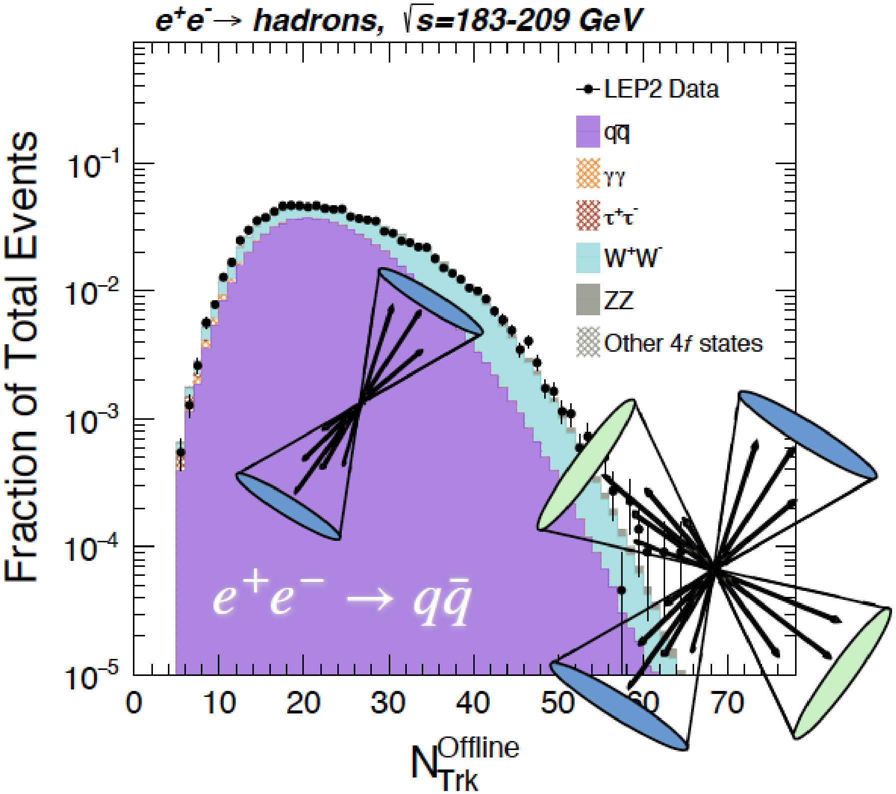

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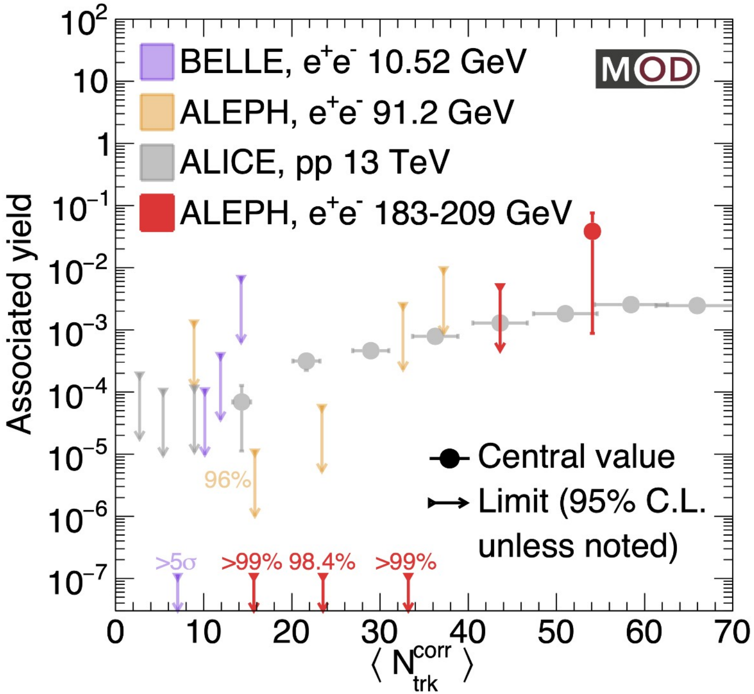
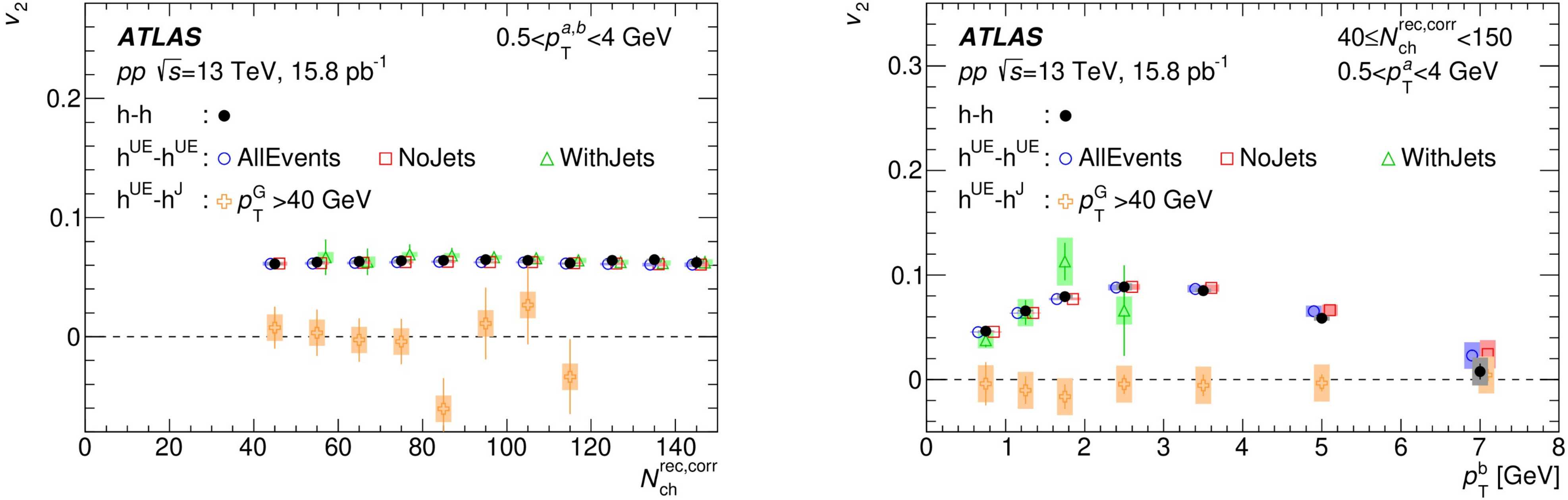


- 2-particle correlations on LEP-II e^+e^- data
- High multiplicity: excess of azimuthal anisotropy signals
  - Long-range near-side structure
  - Narrow away-side structure
- No ridge signals in e^+e^- for $N_{ch} < 40$

v_2 w/wo jets

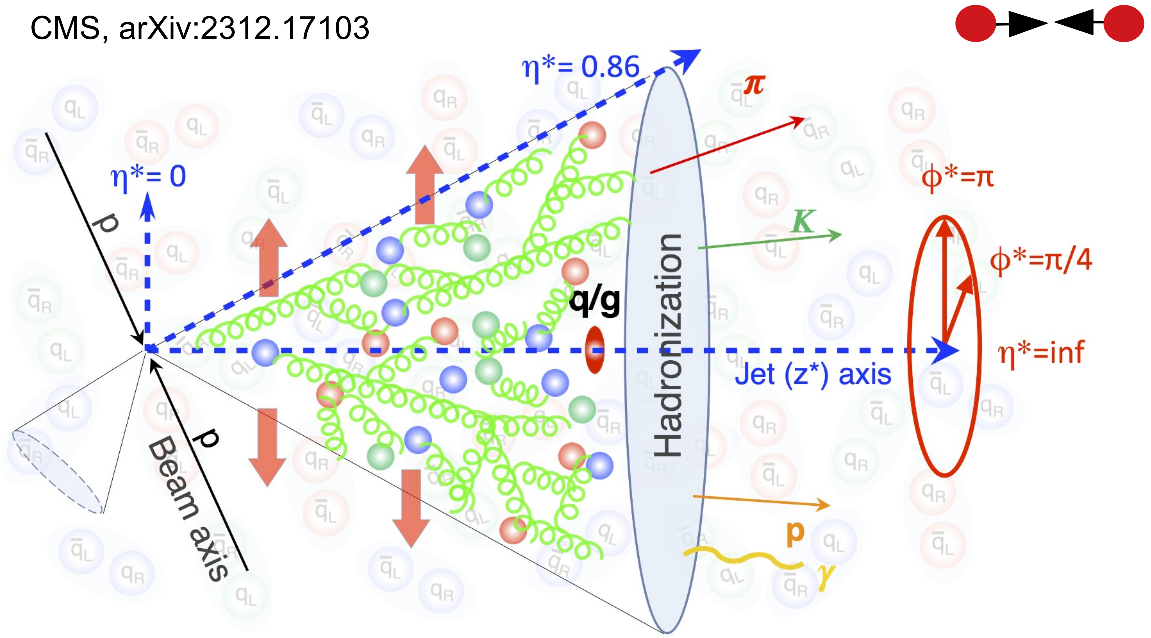
ATLAS, PRL 131 (2023) 162301



- Check if ridge is associated with jet production
  - 2-particle correlations for particles from UE or associated with jets
- No dependence on jets presence for v_2
- v_2~0 for UE–jet particles correlations

In-jet v_2

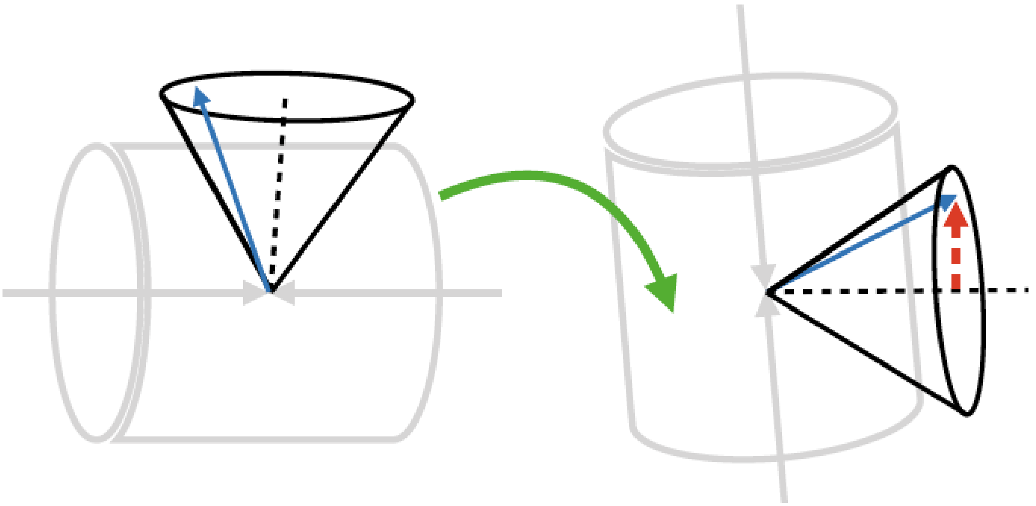
CMS, arXiv:2312.17103

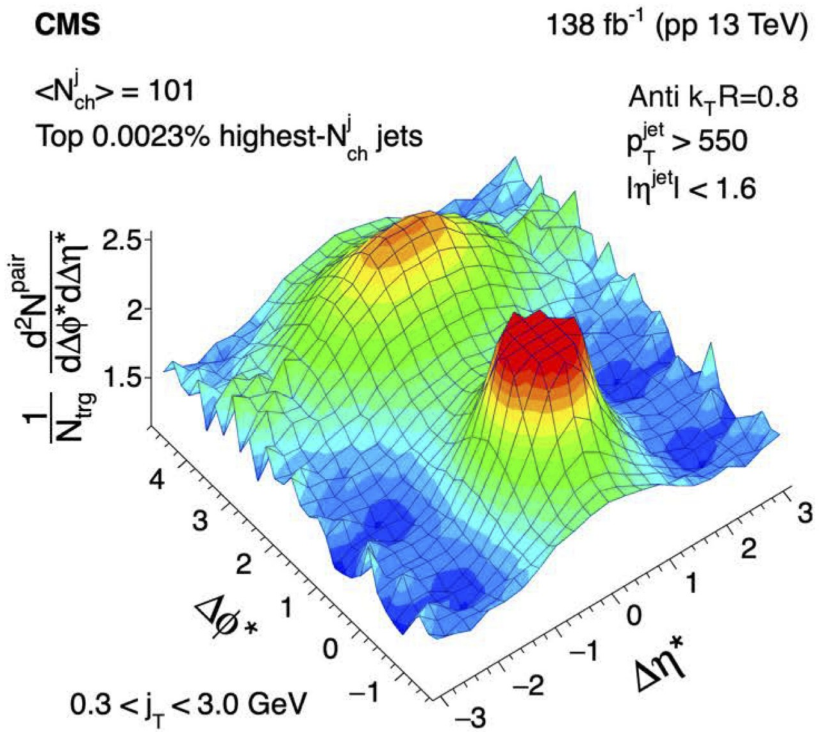


- Search for v_2 in individual jets

In-jet v_2

CMS, arXiv:2312.17103

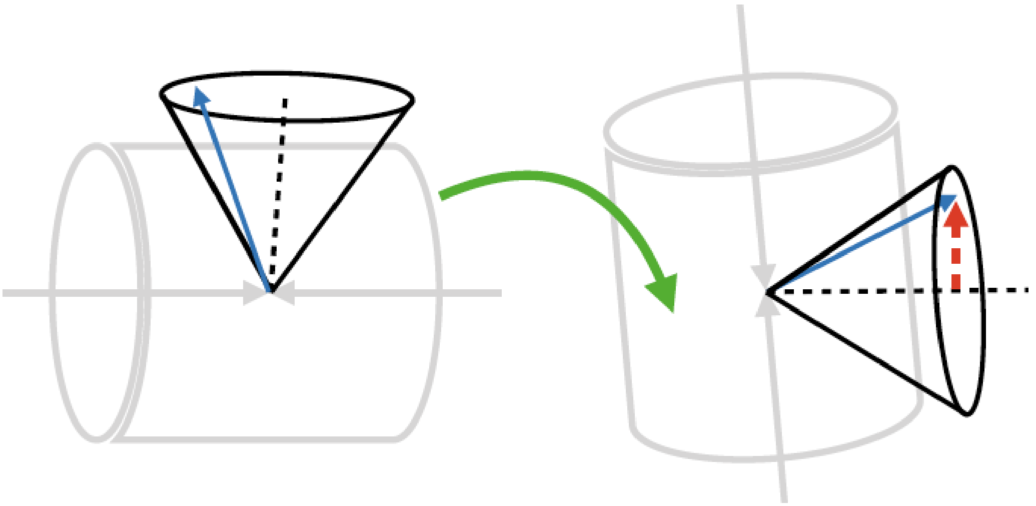


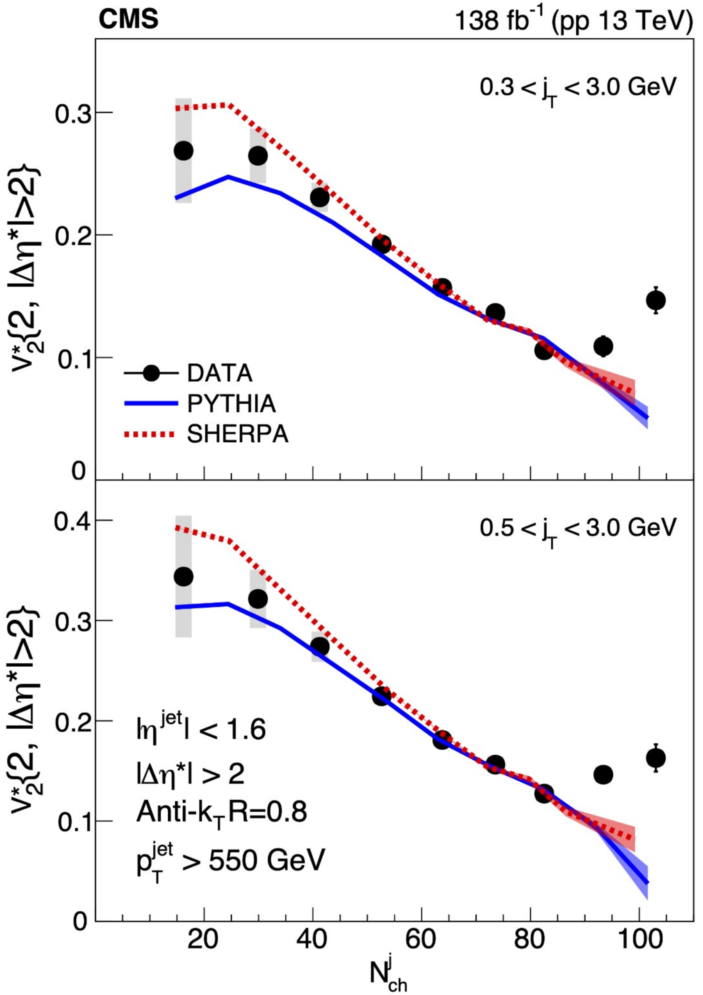


- Search for v_2 in individual jets
- 2-particle correlations in rotated frame

In-jet v_2

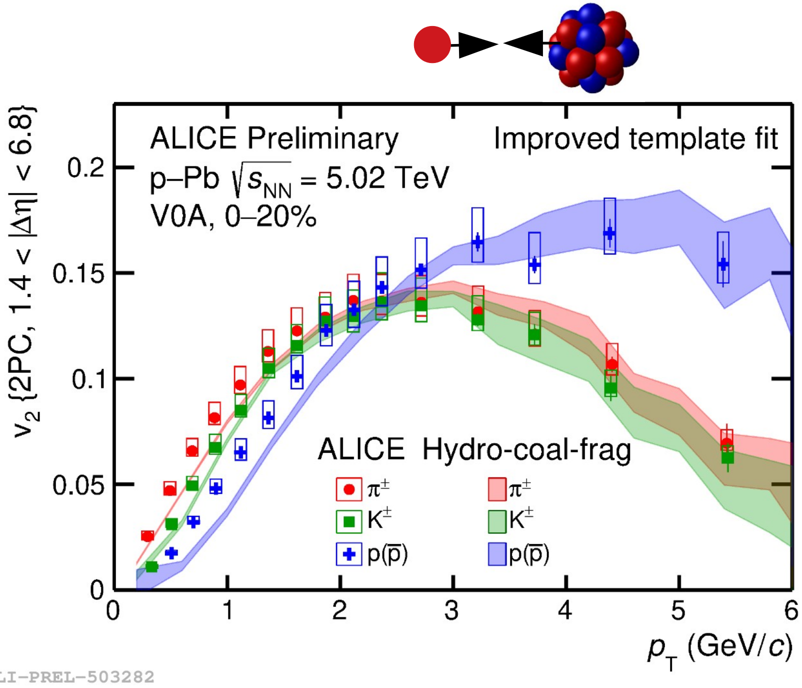
CMS, arXiv:2312.17103

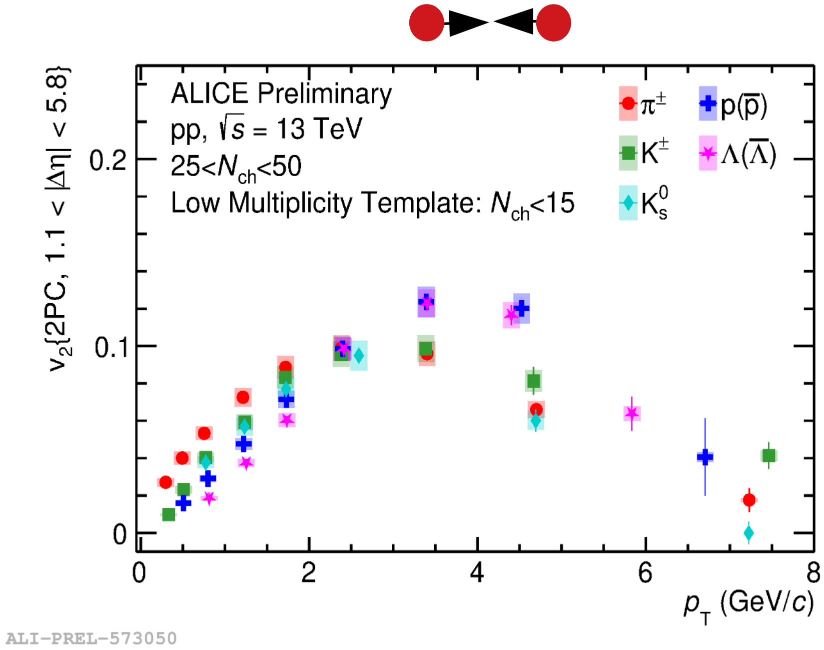




- Search for v_2 in individual jets
- 2-particle correlations in rotated frame
- $N_{ch}^{jet} < 80$: good agreement with MC
- $N_{ch}^{jet} > 80$: upward trend → collectivity in jets?

v_2 of identified particles

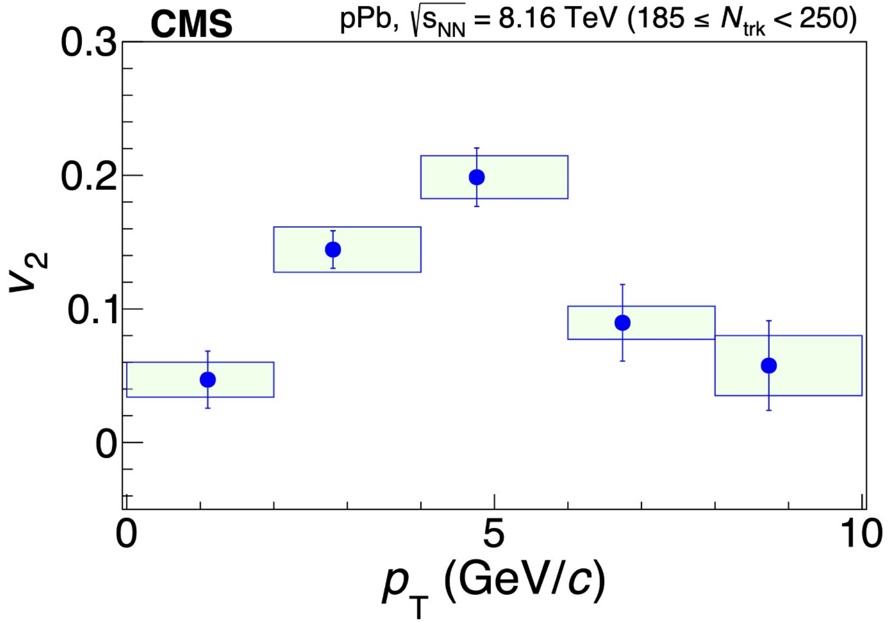


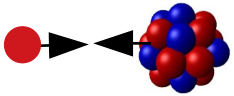


- Low p_T: consistent with mass ordering
- Intermediate p_T: particle type grouping
- Described by hydrodynamics with coalescence and jet fragmentation
  - No jet quenching yet!

v_2 of $f_0(980)$

CMS, arXiv:2312.17092





- Structure unknown: diquark, tetraquark, KK molecule
  - Use v_2/n_q scaling to extract number of quarks

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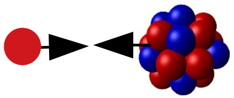
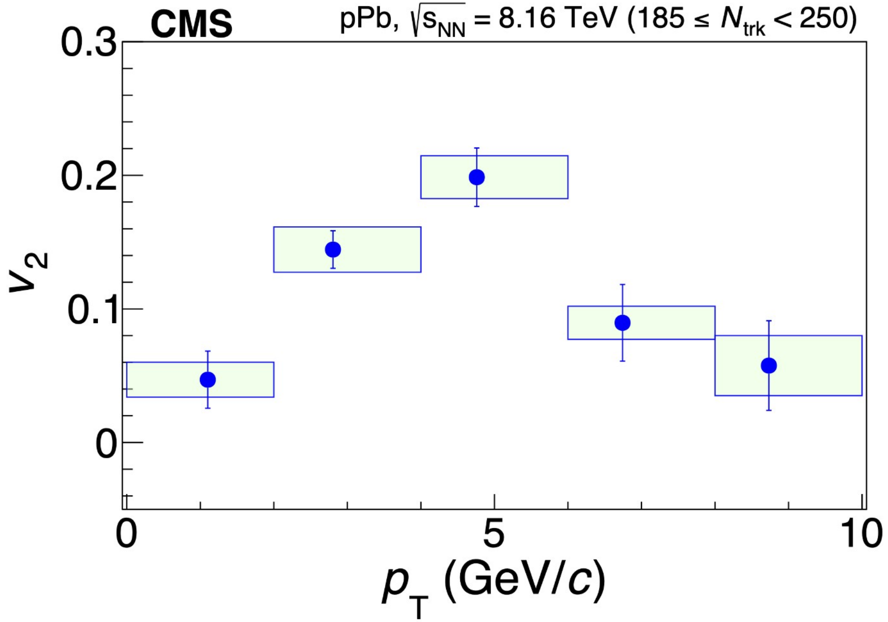
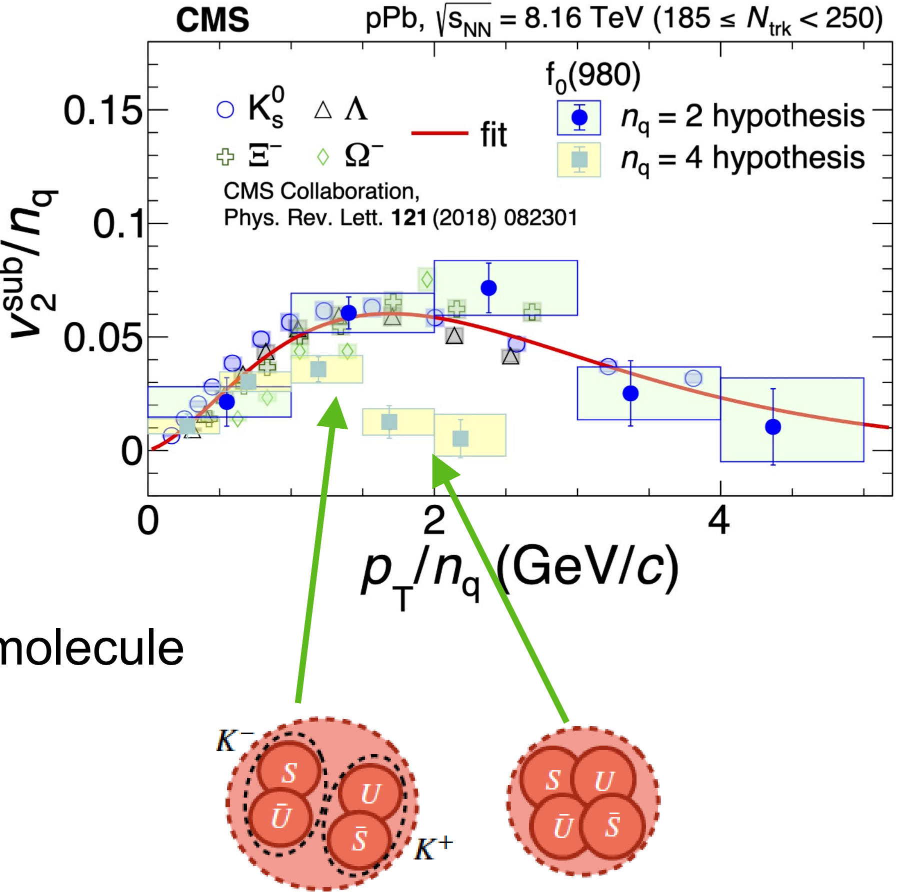


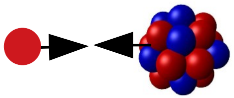


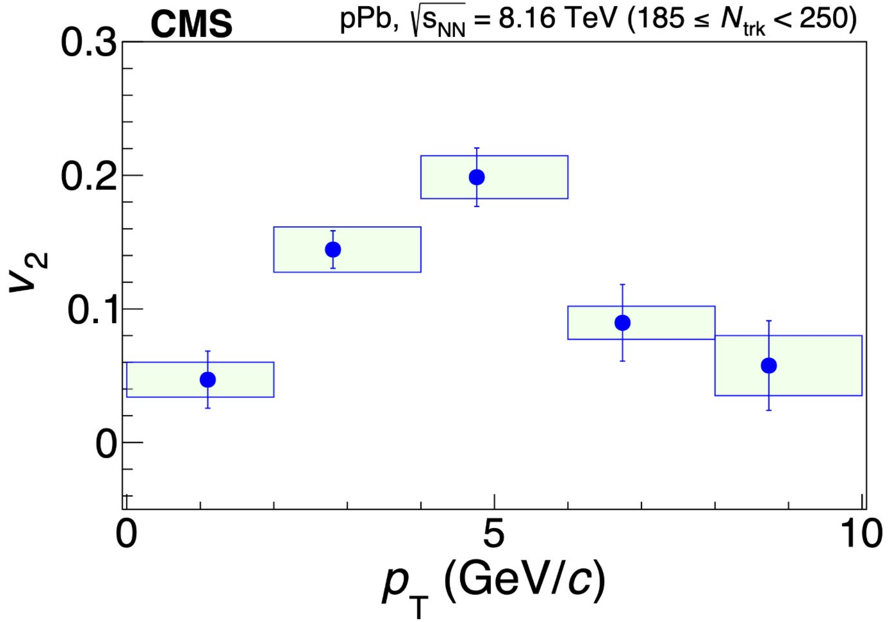


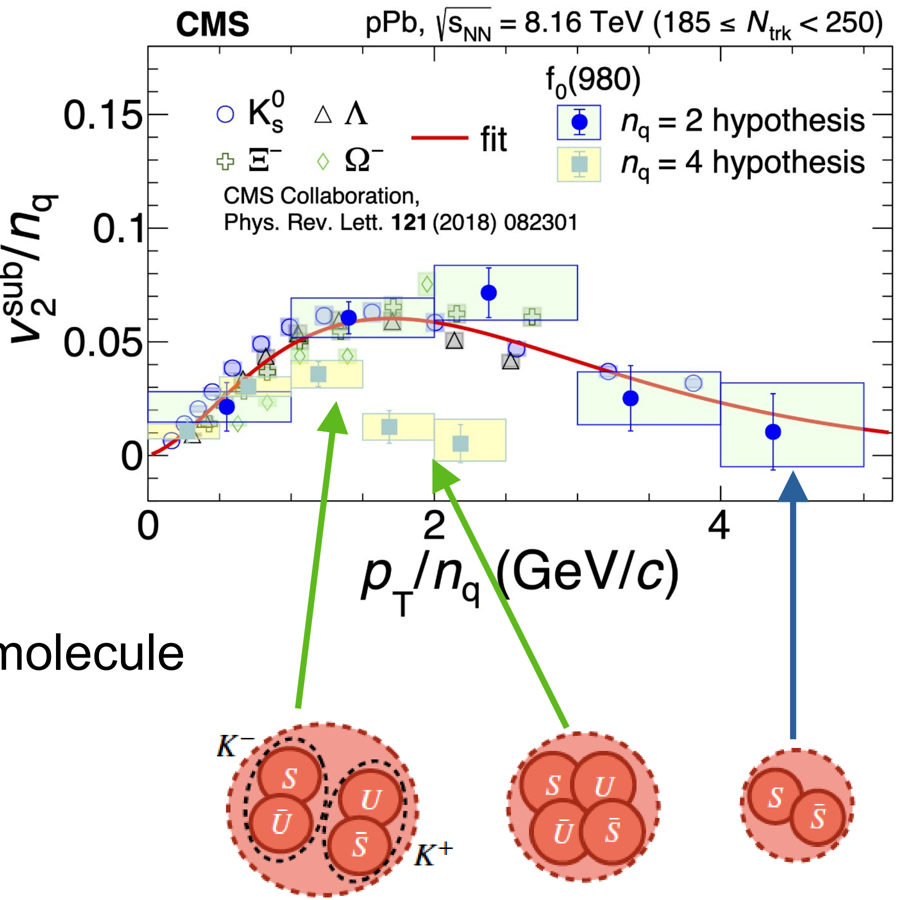
- Structure unknown: diquark, tetraquark, KK molecule
  - Use v_2/n_q scaling to extract number of quarks
- $n_q = 4$ excluded at ≥3.1σ

v_2 of $f_0(980)$

CMS, arXiv:2312.17092



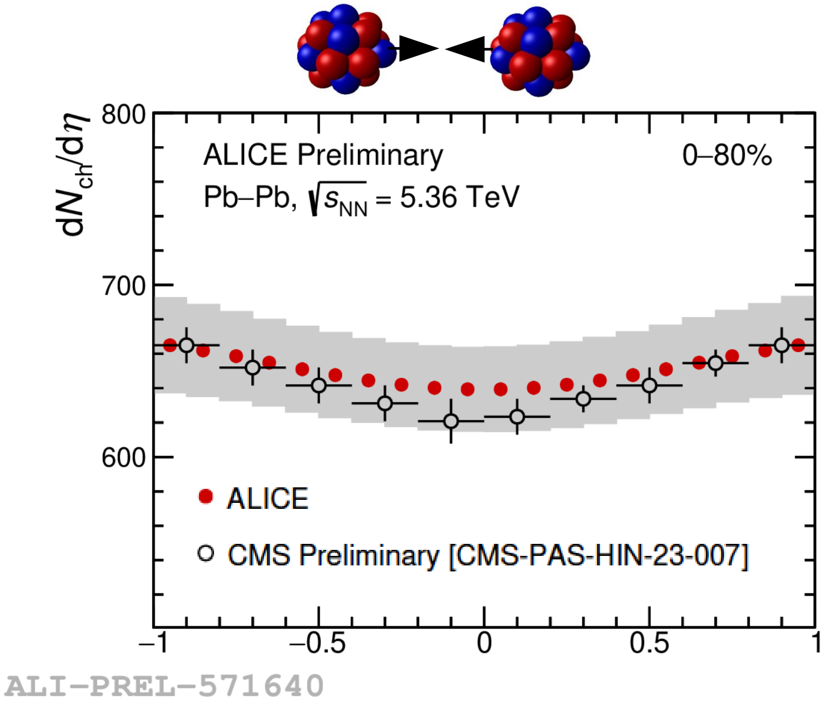




- Structure unknown: diquark, tetraquark, KK molecule
  - Use v_2/n_q scaling to extract number of quarks
- $n_q = 4$ excluded at ≥3.1σ
- $n_q = 2$ favored

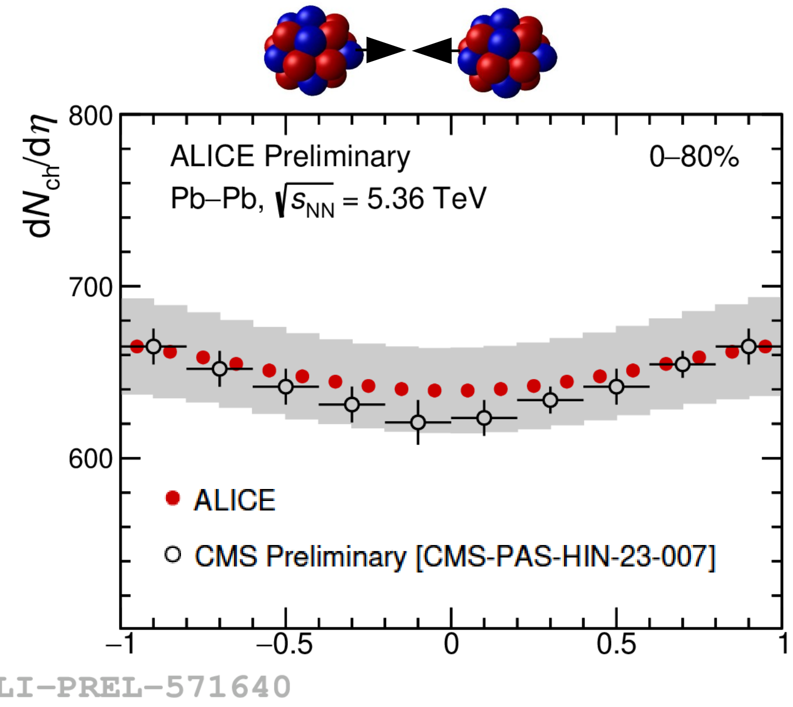
Particle production

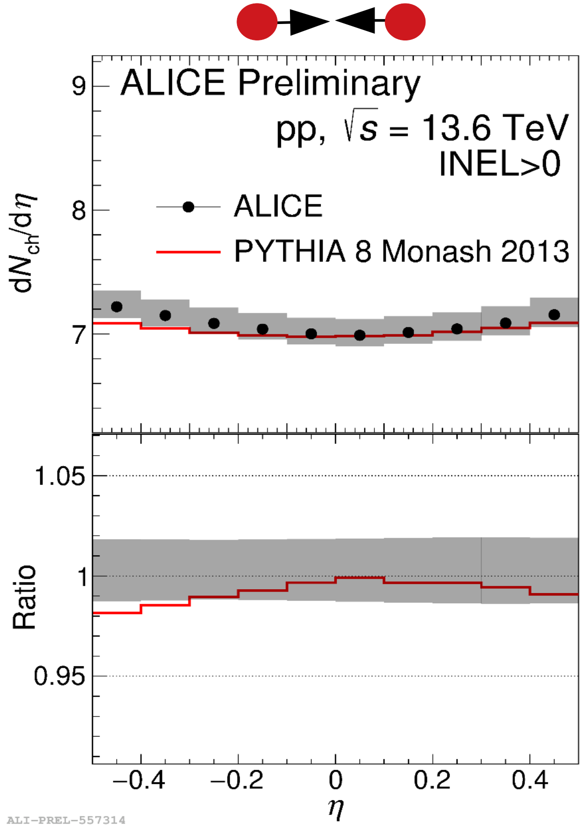
dN_{ch}/dη in Run 3



- dN_{ch}/dη measured at highest energy in Pb–Pb

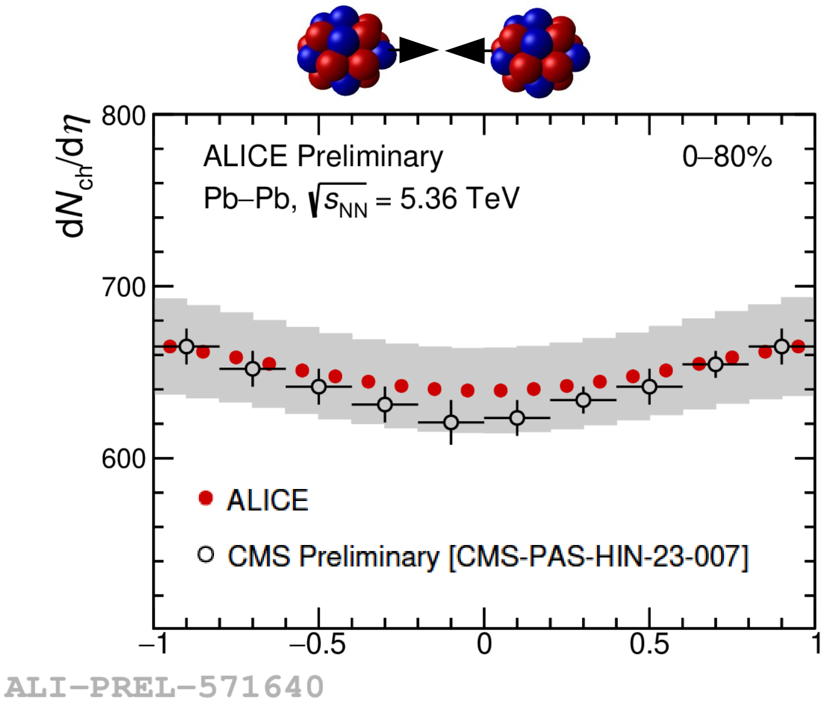
$dN_{ch}/d\eta$ in Run 3

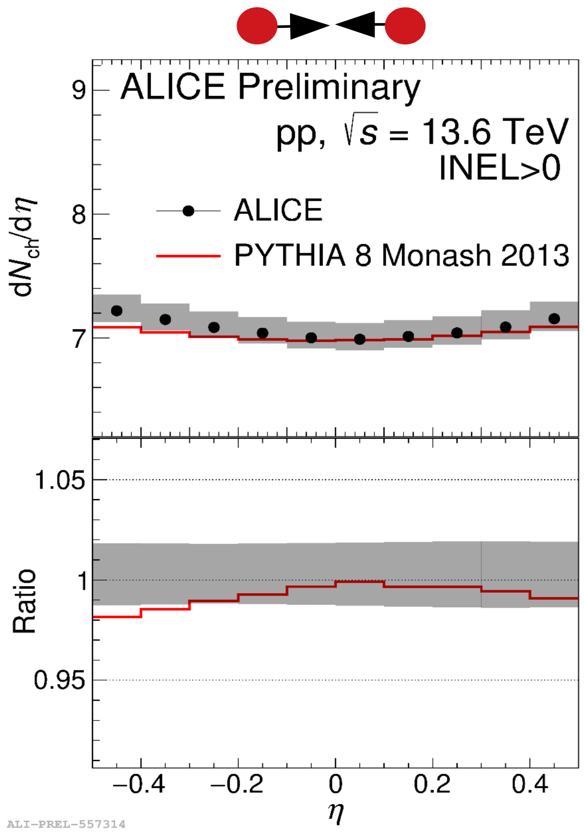




- $dN_{ch}/d\eta$ measured at highest energy in Pb–Pb and pp collisions

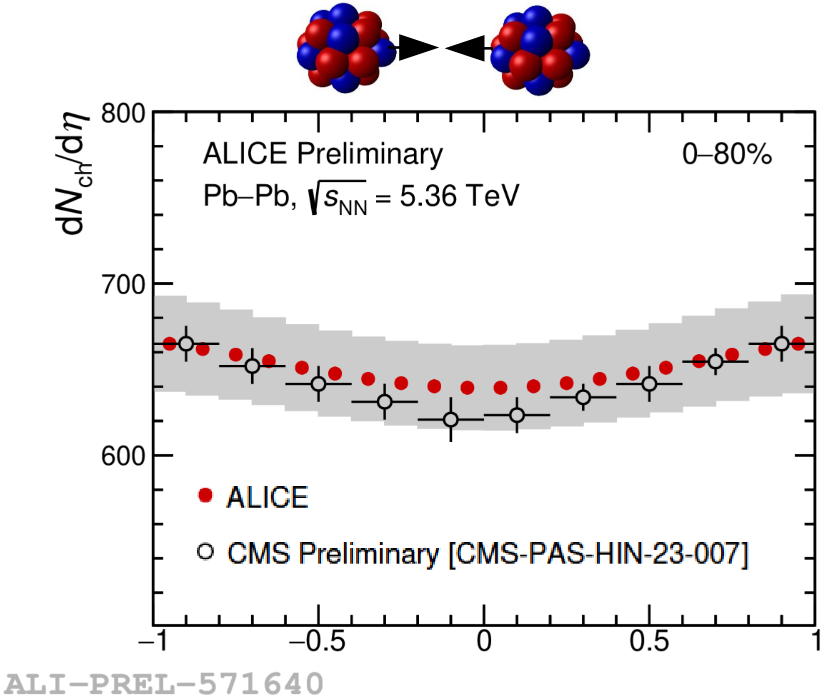
dN_{ch}/dη in Run 3

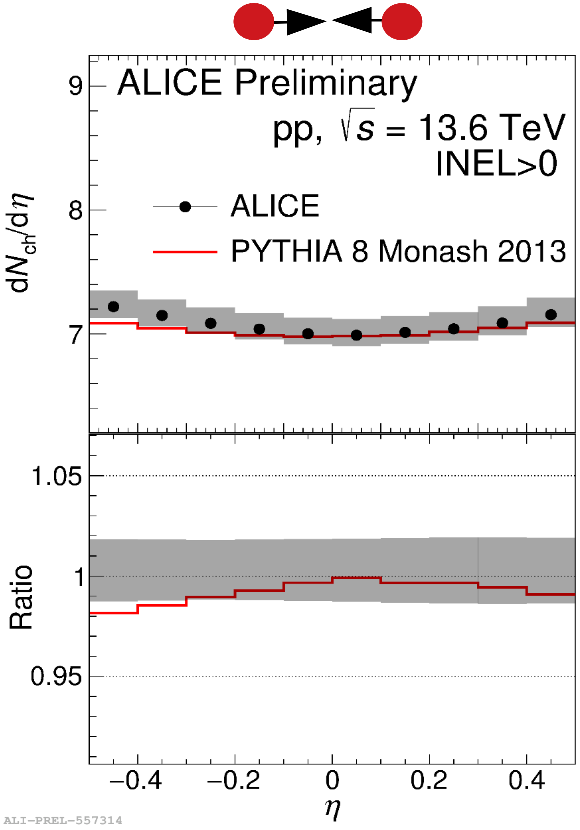




- dN_{ch}/dη measured at highest energy in Pb–Pb and pp collisions
- Magnitude and shape not fully described by MC calculations

dN_{ch}/dη in Run 3

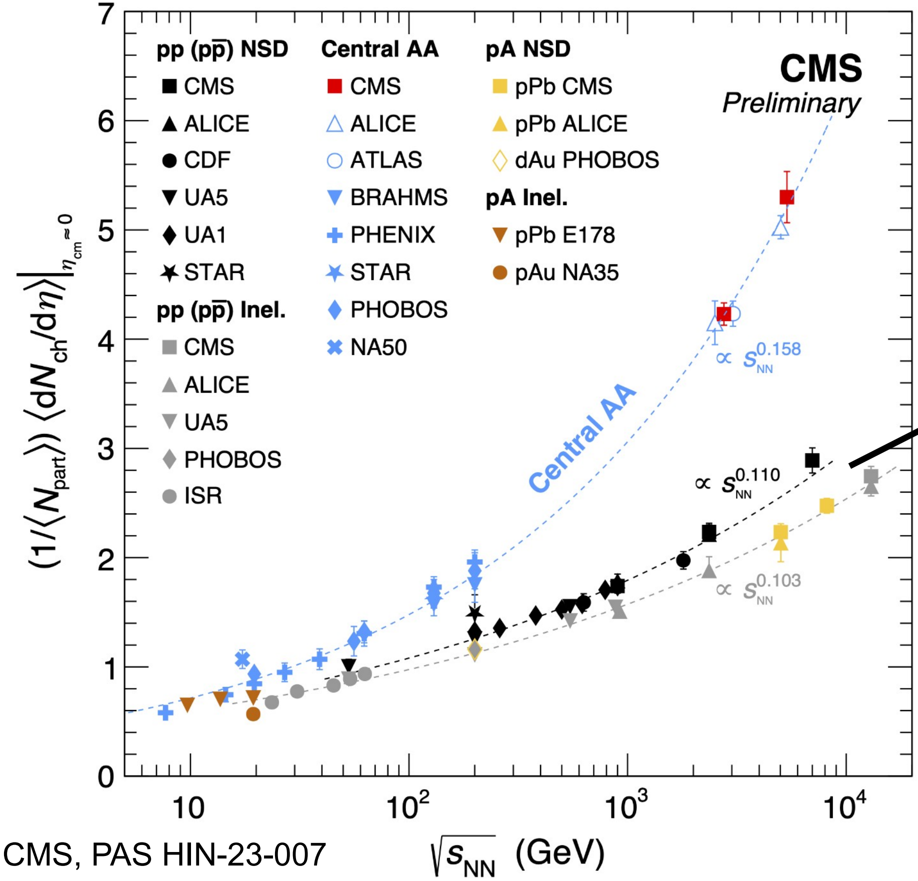




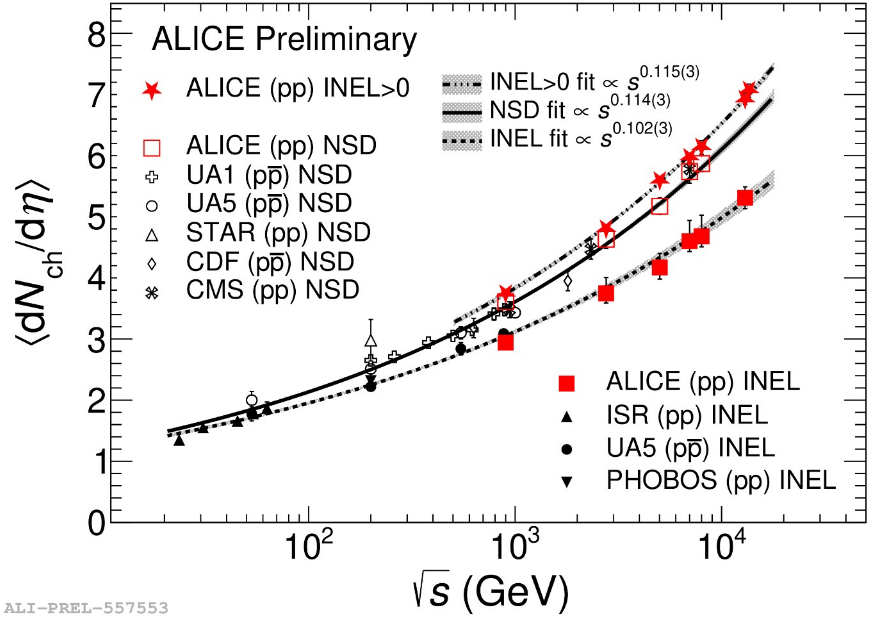
- Constrain initial conditions and evolution of AA collisions
- Constrain gluon saturation effects and nuclear shadowing

- dN_{ch}/dη measured at highest energy in Pb–Pb and pp collisions
- Magnitude and shape not fully described by MC calculations

$dN_{ch}/d\eta$ in Run 3

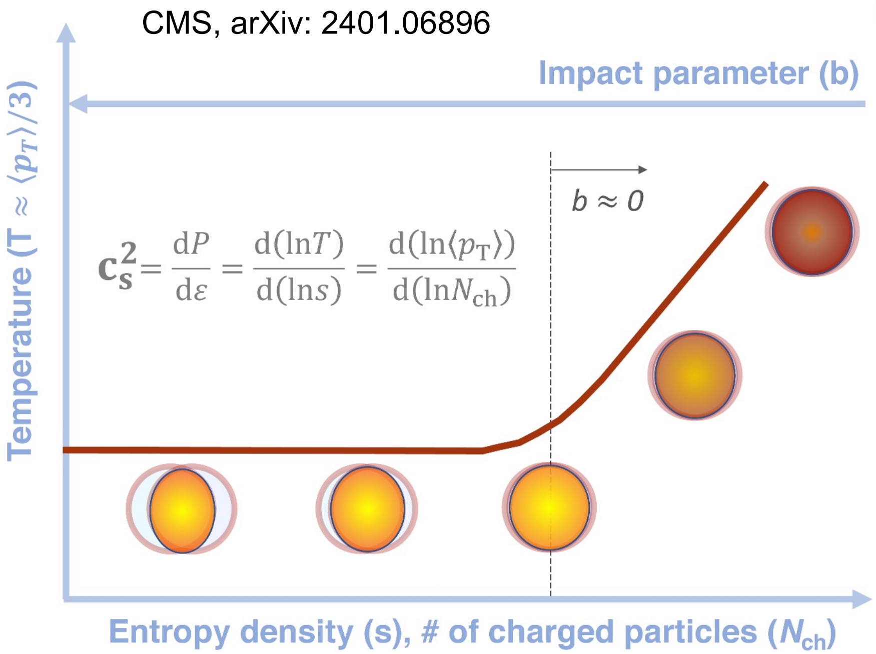


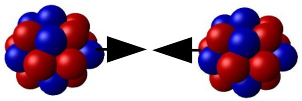
CMS, PAS HIN-23-007



- $\sqrt{s_{NN}}$ dependence consistent with power law from lower energies
  - Grows faster in AA than in pp collisions

Speed of sound in QGP

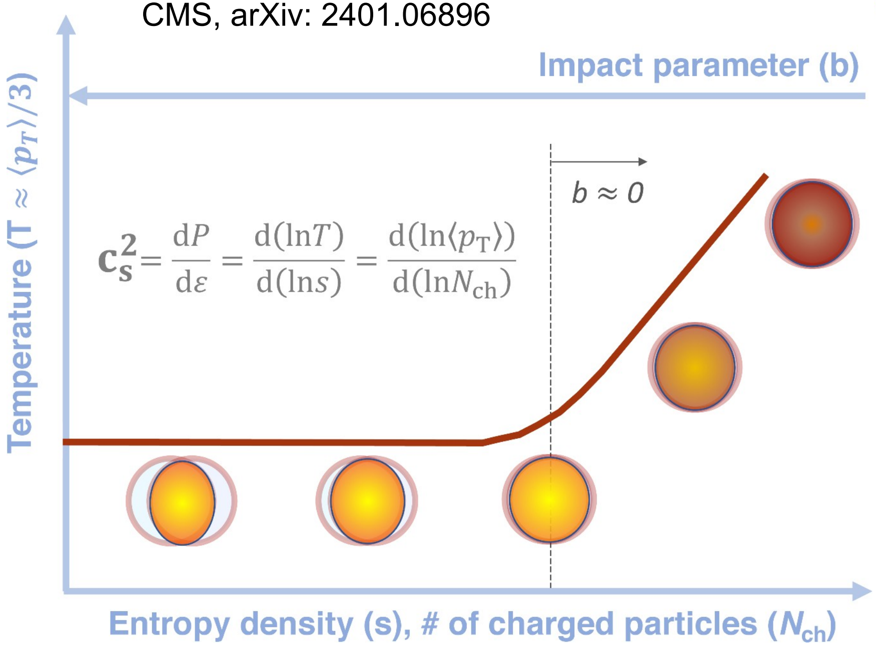


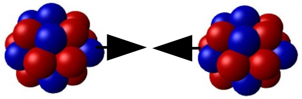


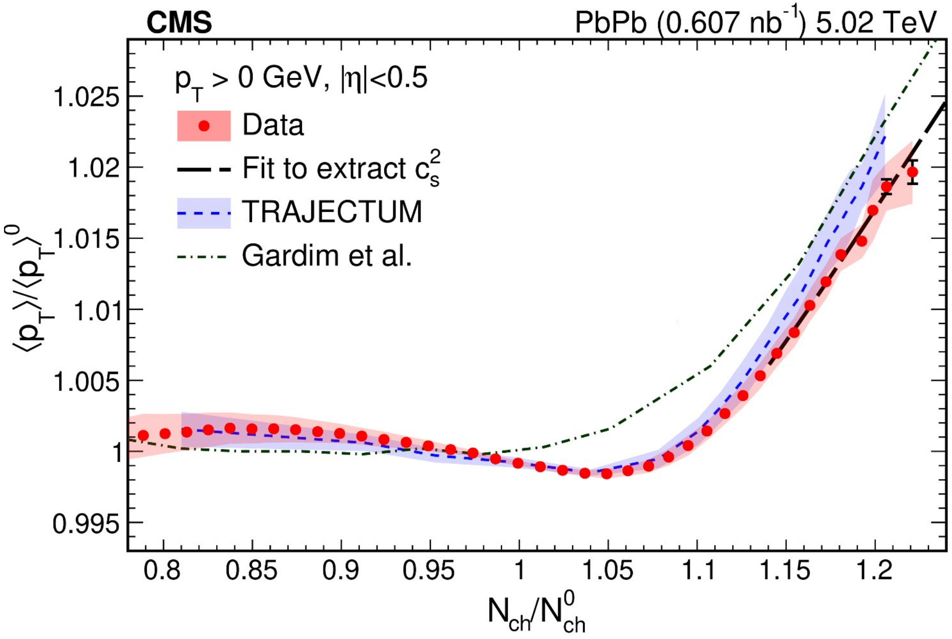
- c_s^2 can be extracted from $\langle p_T\rangle$ and N_{ch}

Speed of sound in QGP

CMS, arXiv: 2401.06896



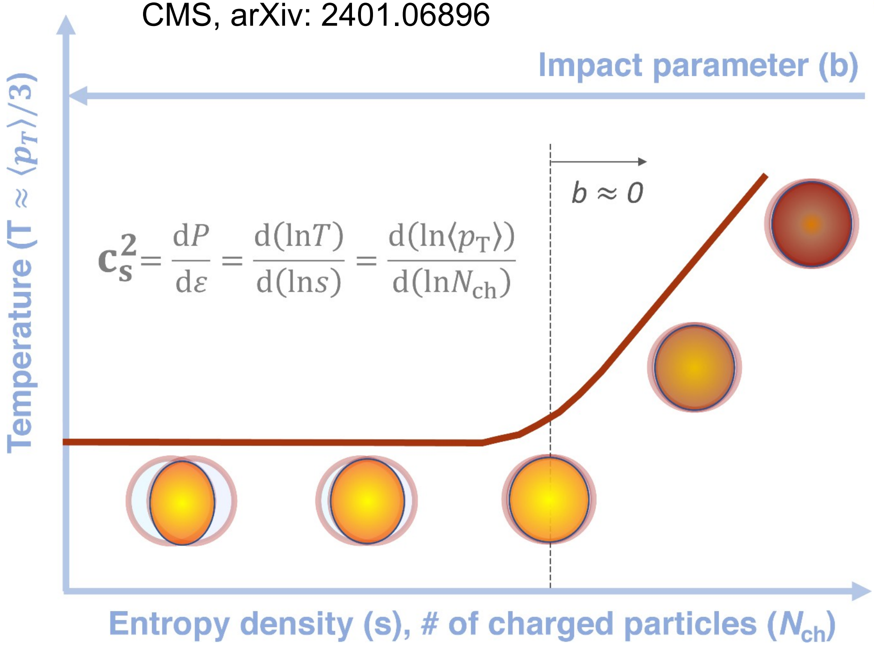


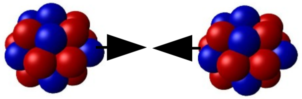


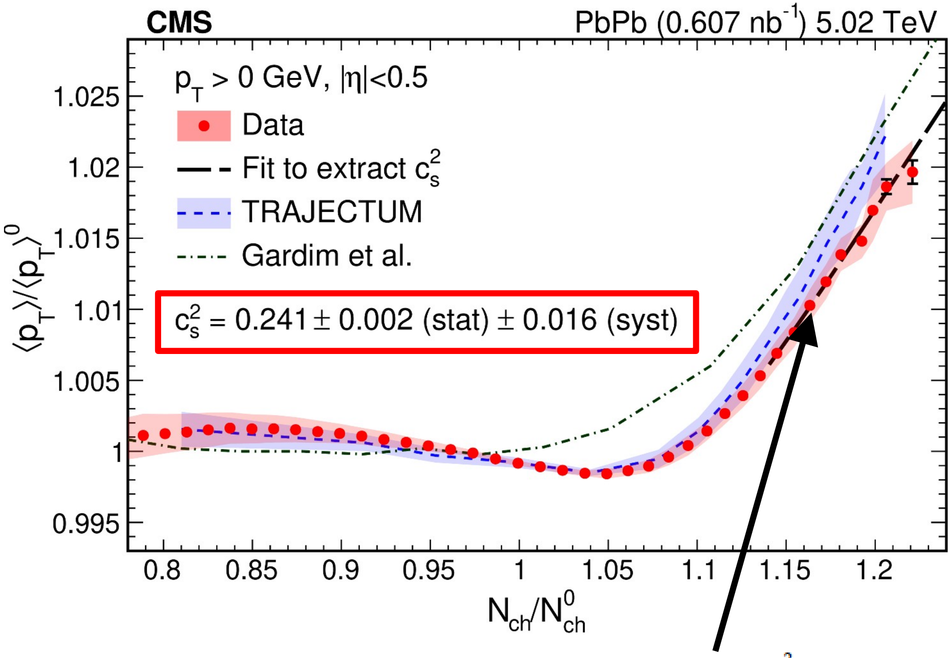
- c_s^2 can be extracted from $<p_T>$ and N_{ch}
- Models predict a rising slope at large N_{ch}

Speed of sound in QGP

CMS, arXiv: 2401.06896







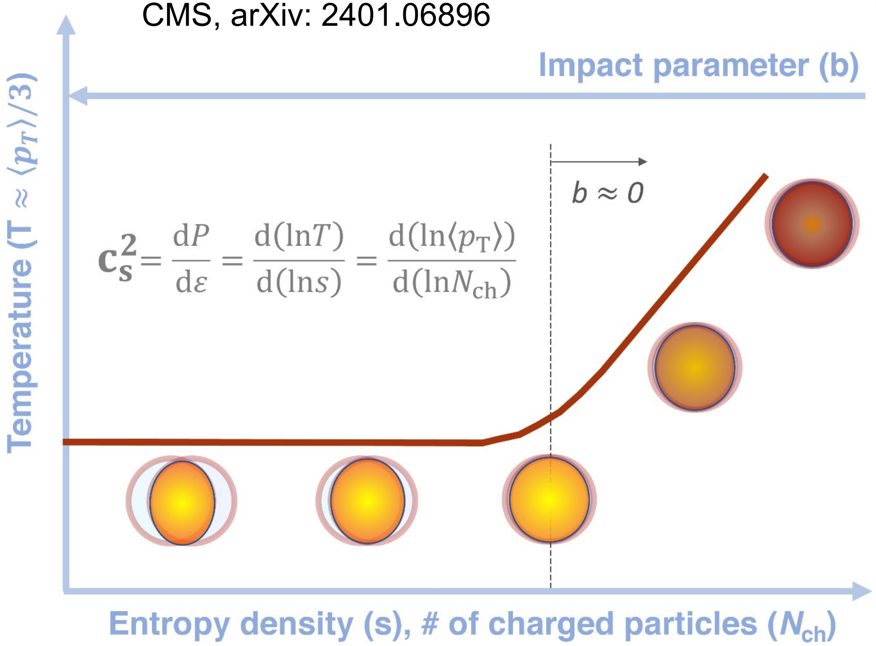
- c_s^2 can be extracted from $\langle p_T \rangle$ and N_{ch}
- Models predict a rising slope at large N_{ch}
  - Fit slope follows model calculations

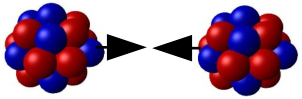
$$\langle p_T \rangle^{norm} = \left(\frac{N_{ch}^{norm}}{\langle \overline{N_{ch}^{knee}} | N_{ch}^{norm} \rangle} \right)^{c_s^2}$$

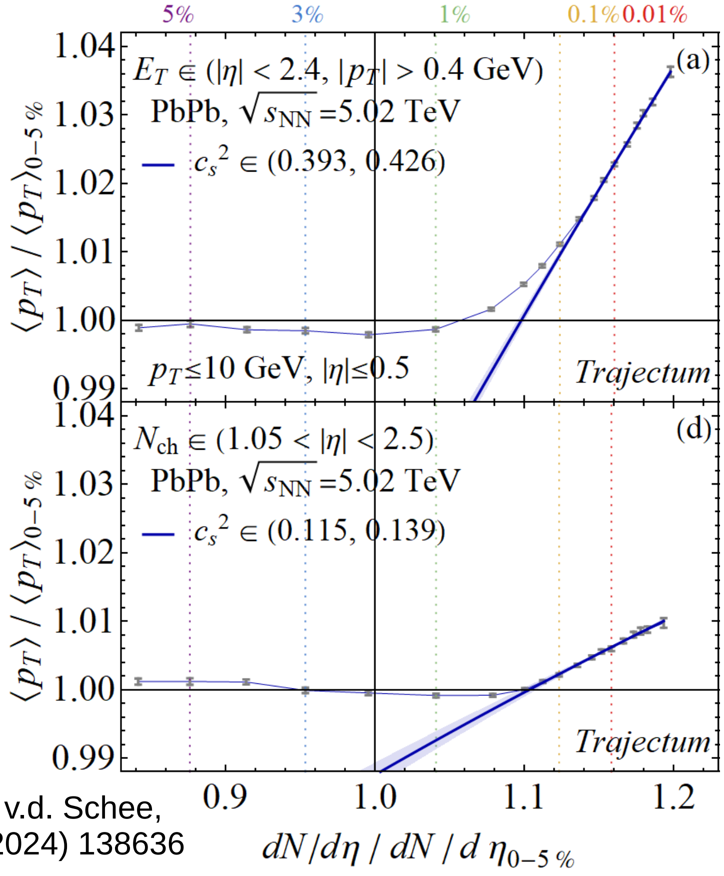
$$\langle \overline{N_{ch}^{knee}} | N_{ch}^{norm} \rangle = N_{ch}^{norm} - \sigma \sqrt{\frac{2}{\pi}} \frac{\exp\left(-\frac{(N_{ch}^{norm} - \overline{N_{ch}^{knee}})^2}{2\sigma^2} \right)}{\operatorname{erfc}\left(\frac{N_{ch}^{norm} - \overline{N_{ch}^{knee}}}{\sqrt{2}\sigma} \right)}$$

Speed of sound in QGP

CMS, arXiv: 2401.06896





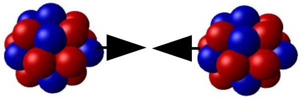


G. Nijs, W. v.d. Schee,
PLB 853 (2024) 138636

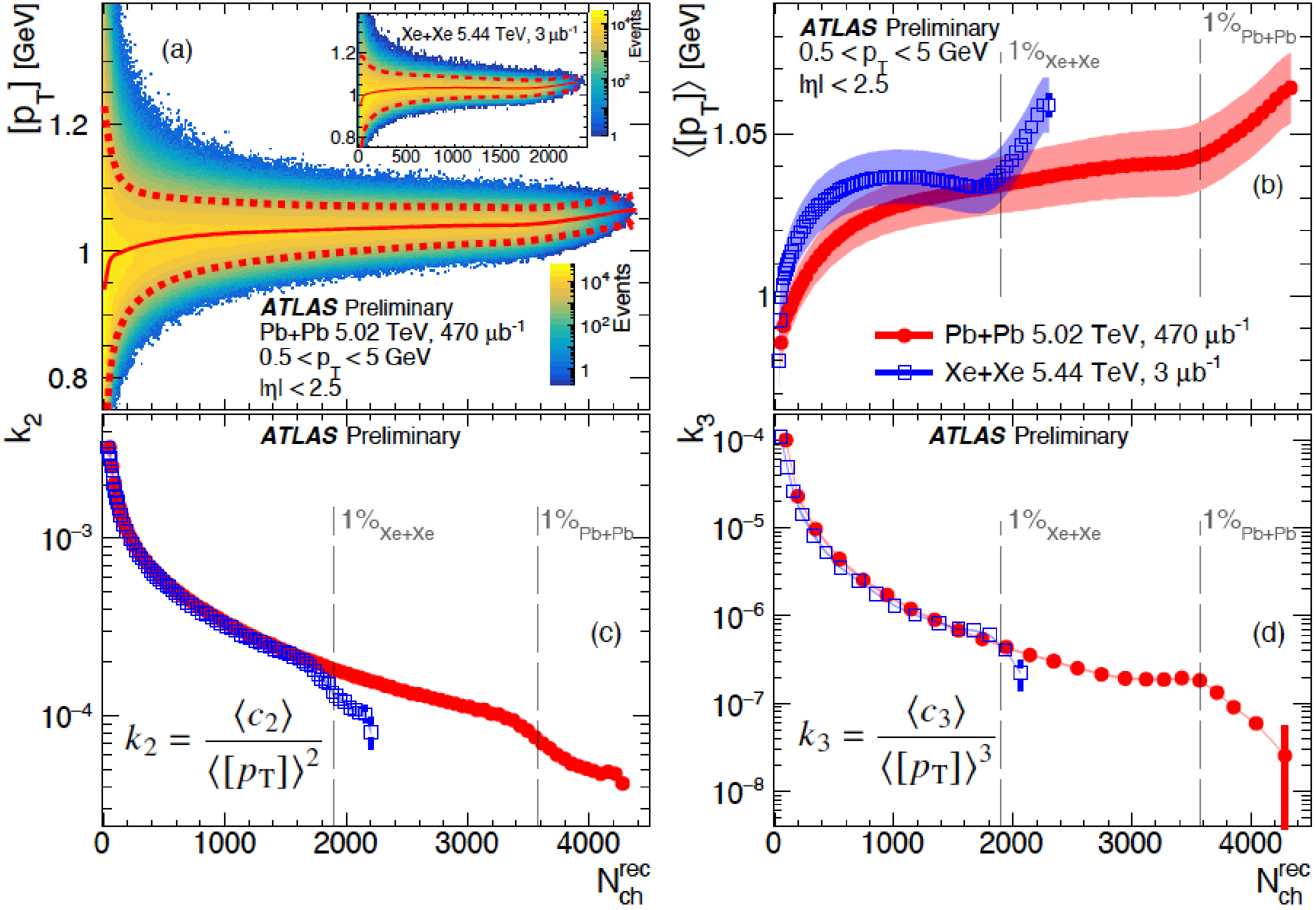
- c_s^2 can be extracted from $<p_T>$ and N_{ch}
- Models predict a rising slope at large N_{ch}
  - Fit slope follows model calculations
- Ongoing discussions about any potential bias from centrality selection

$<p_T>$ fluctuations

$$[p_T] = \frac{\sum_{i_1} w_{i_1} p_{T,i_1}}{\sum_{i_1} w_{i_1}}$$



ATLAS, CONF-2023-061

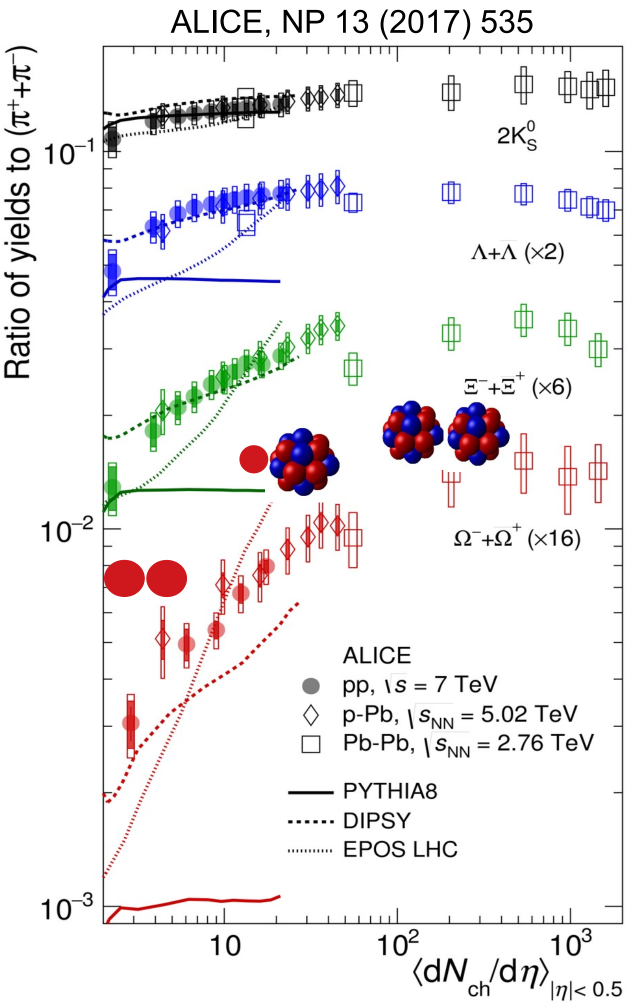


- Similar ATLAS measurement
  - Understand fluctuations in initial conditions
    - Geometric vs "intrinsic" fluctuations
  - Clear rise in $<[p_T]>$ and drop in variance κ_2
    - Expected from independent source models

R. Samanta et al., PRC 108 (2023) 024908
R. Samanta et al., PRC 109 (2024) L051902

$$c_n = \frac{\sum_{i_1 \neq \ldots \neq i_n} w_{i_1} .. w_{i_n} (p_{T,i_1} - \langle [p_T] \rangle) \ldots (p_{T,i_n} - \langle [p_T] \rangle)}{\sum_{i_1 \neq \ldots \neq i_n} w_{i_1} \ldots w_{i_n}}$$

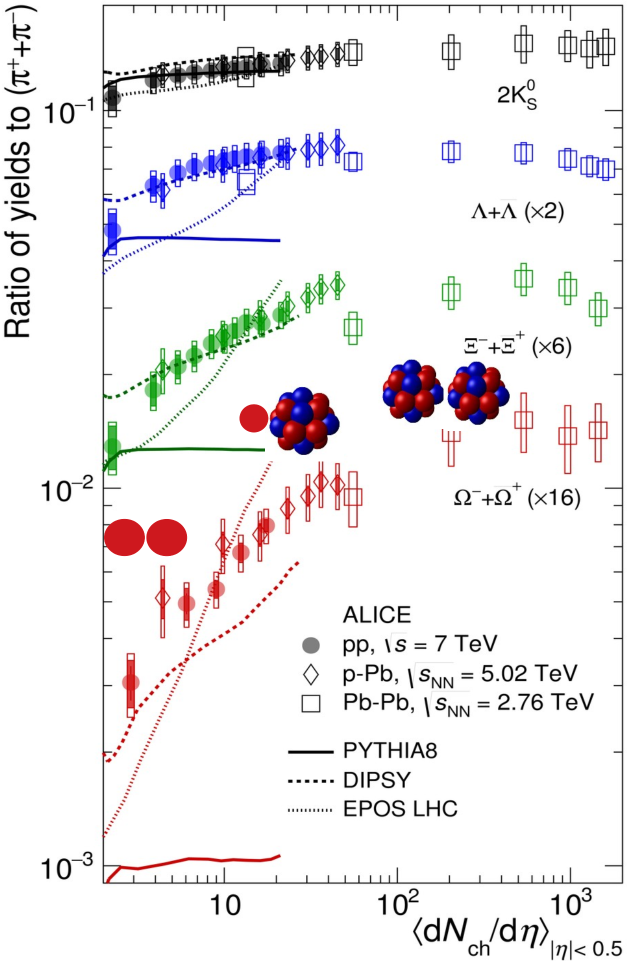
Strangeness enhancement

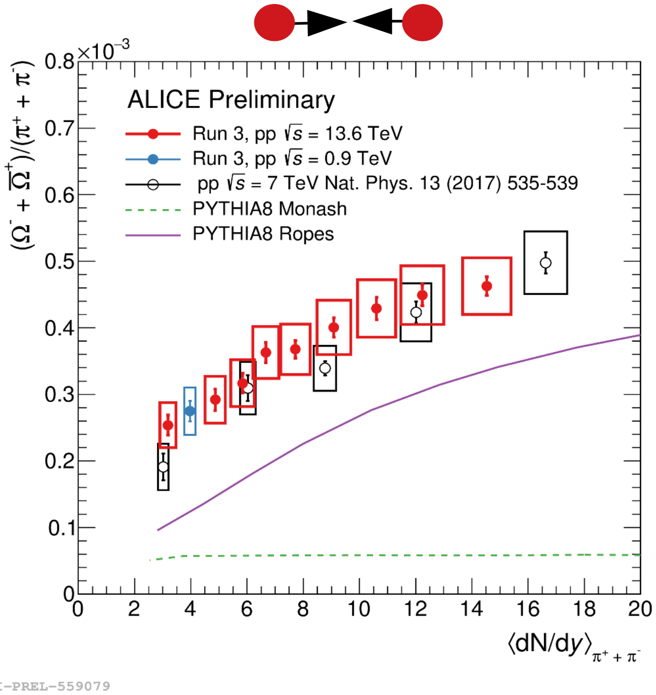


- Strangeness increases with multiplicity
  - Hierarchy with strangeness content

Strangeness enhancement

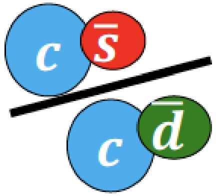
ALICE, NP 13 (2017) 535

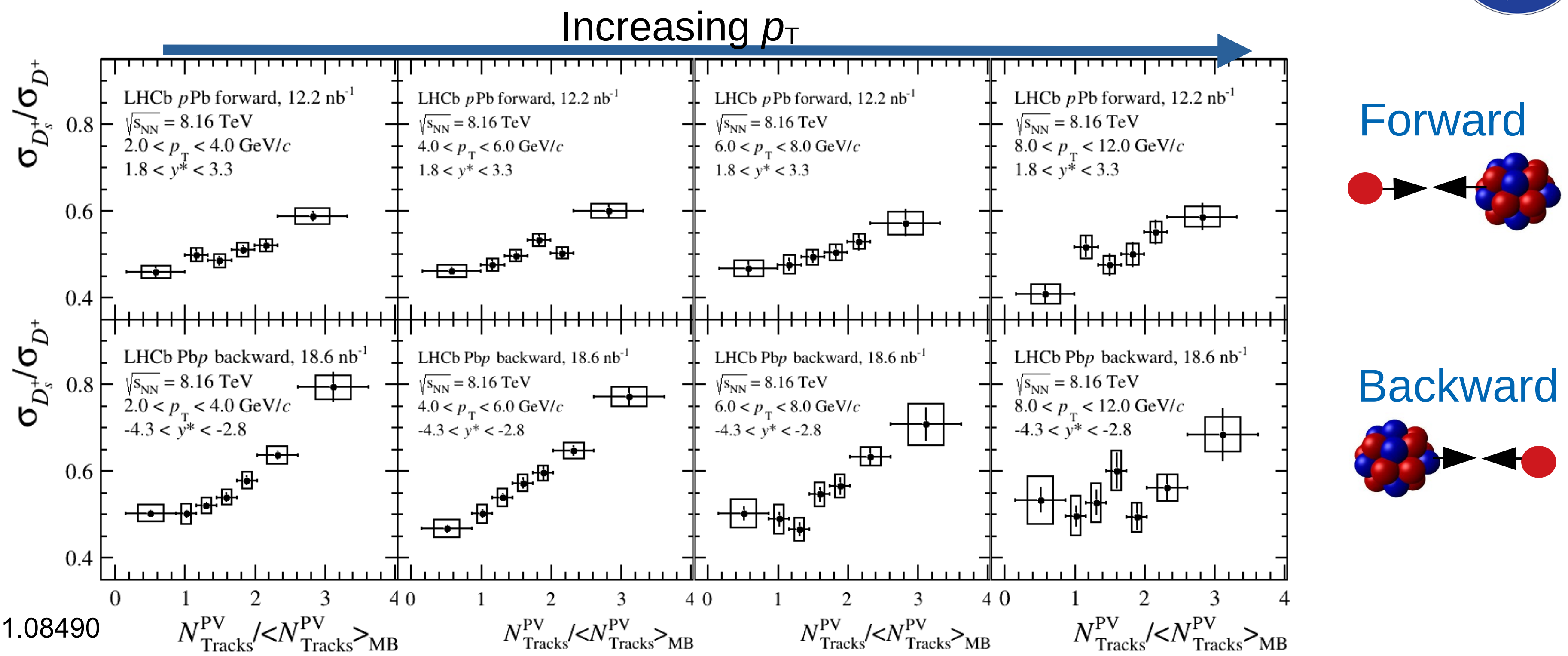




- Strangeness increases with multiplicity
  - Hierarchy with strangeness content
- More differential measurements in Run 3 → better constraints
  - pQCD-inspired models need extra mechanisms

Strangeness enhancement: charm

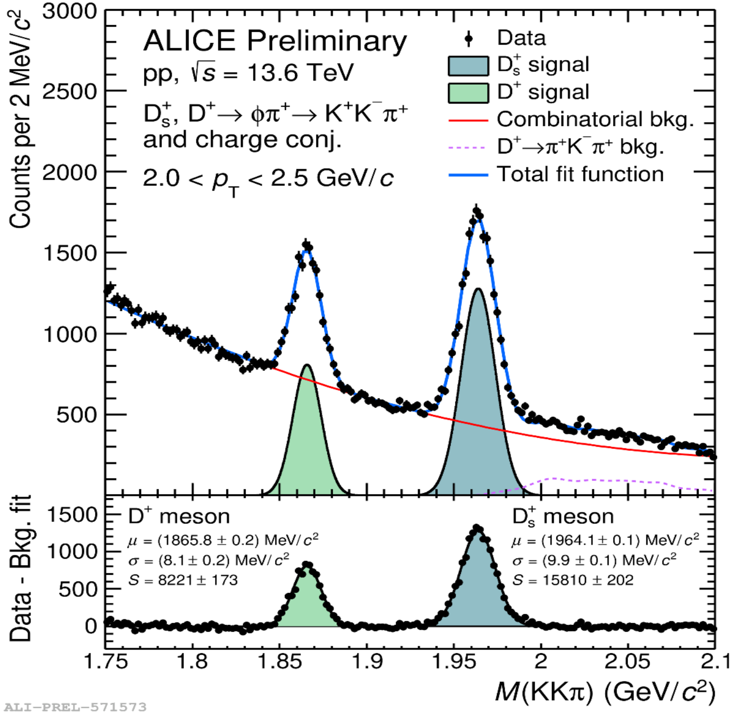


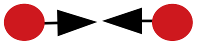


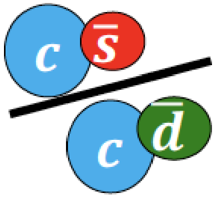
LHCb, arXiv: 2311.08490

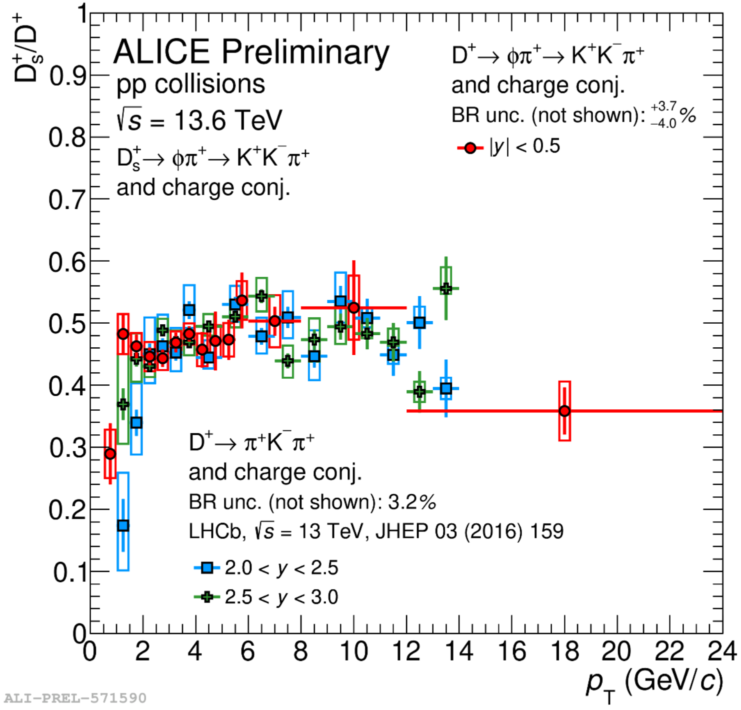
- Compare D mesons with and without s quark
- Ratio increases with multiplicity at low p_T and backward rapidity → coalescence for charm hadronization
  - Strangeness enhancement observed in the charm sector

Strangeness enhancement: charm









- Compare D mesons with and without s quark
- Good agreement with LHCb results
- Investigate the multiplicity dependence

Summary

- QGP properties and phase diagram understood much better
  - Initial conditions
  - Equation of state
  - Transport coefficients
  - Particle production mechanisms

- Collectivity and strangeness enhancement in small systems
  - Develop new techniques and more differential measurements
    - Pushing the limits to understand the responsible mechanism(s)