Mysteries of QCD

Collective Phenomena and Small Systems

Jan Fiete Grosse-Oetringhaus (CERN)
for the ALICE collaboration

LHC Days in Split
01.10.2024

Collective Phenomena and Small Systems

Strokkur Geyser, Iceland

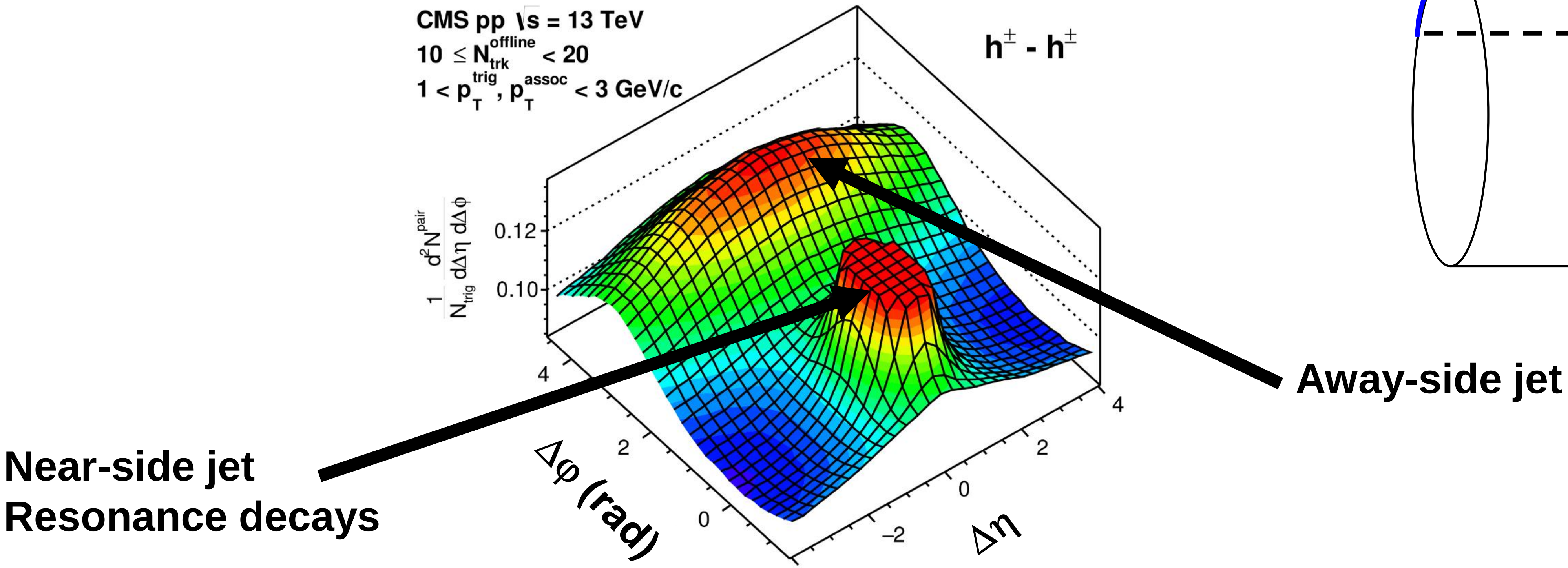
The emergence of collective phenomena in small systems has shaken the basic paradigms of the high-energy and heavy-ion physics fields

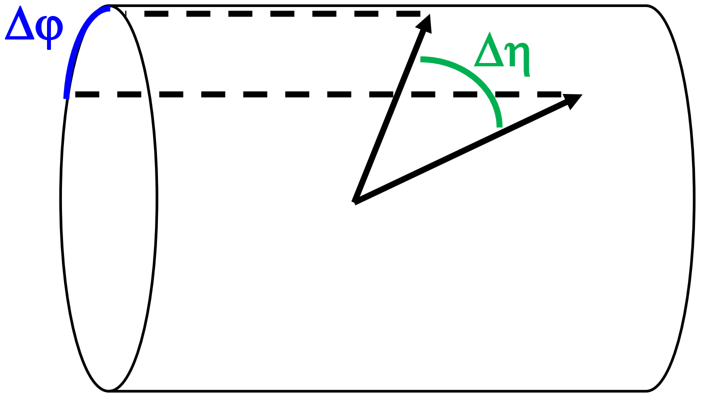
This talk discusses where we stand and what we can learn from it about fundamental QCD

None of the content of this talk was known
when LHC was proposed, and
when LHC started

Basics: Collective Phenomena

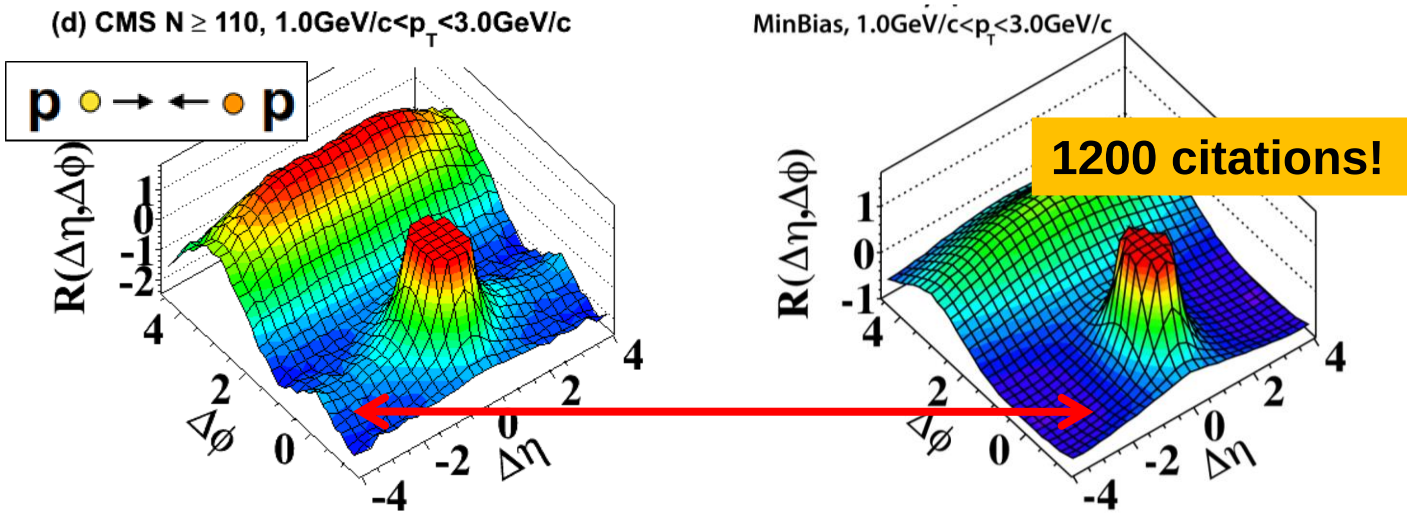
- Two-particle correlations
  - “Probably density” to find second particle



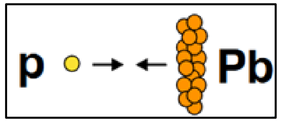


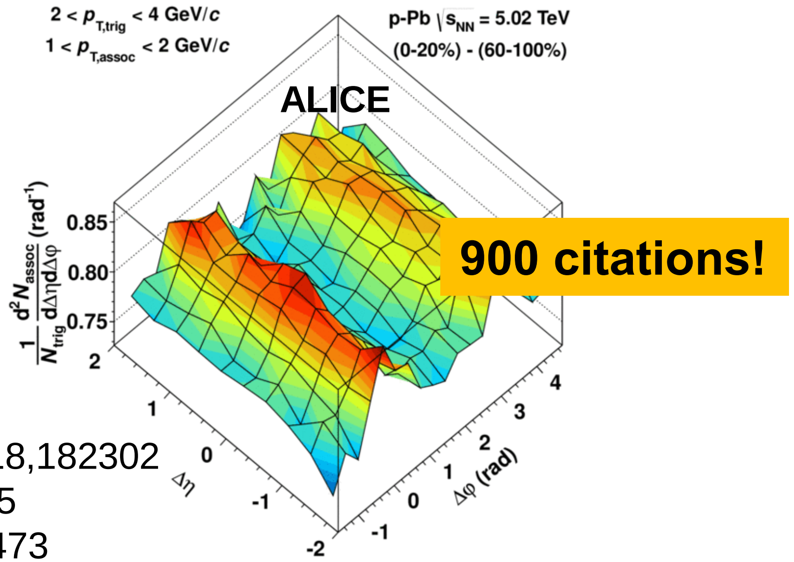
PLB 765 (2017) 193

First Discovery: Ridge and Ridges



CMS, JHEP1009(2010)091

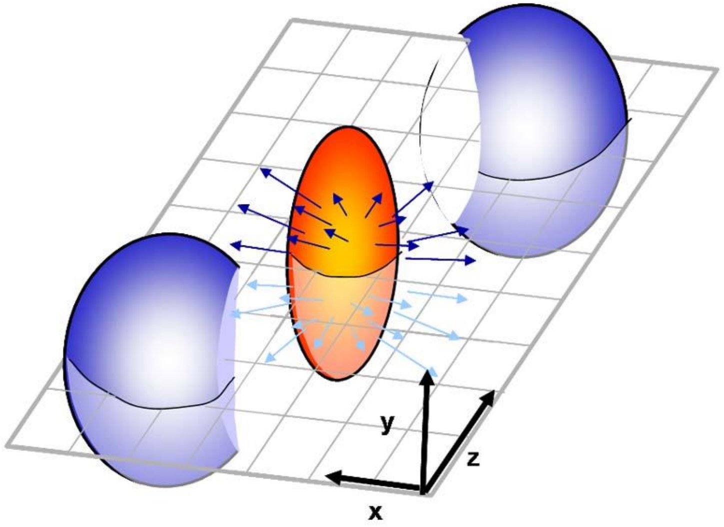




ALICE, PLB719 (2013) 29
and ATLAS, PRL110(2013)18,182302
and CMS, PLB718(2013)795
and LHCb, PLB762 (2016) 473

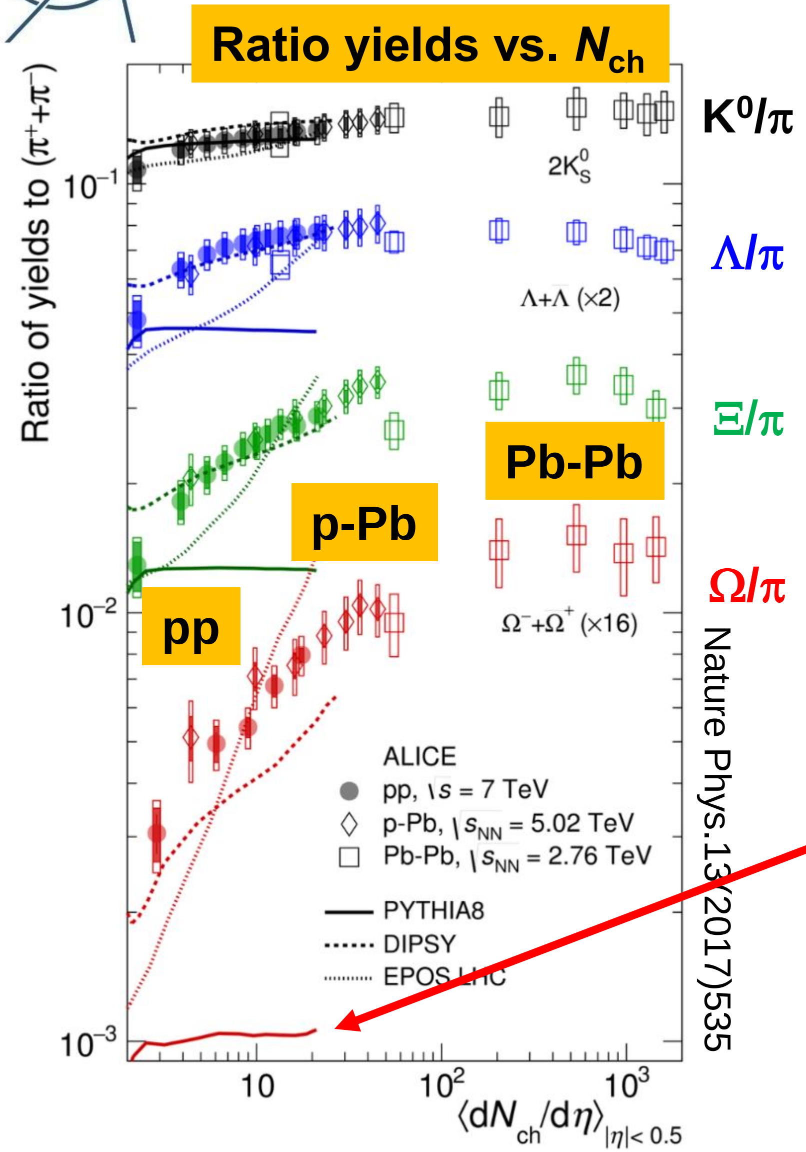
Unexpected in pp and p-Pb collisions

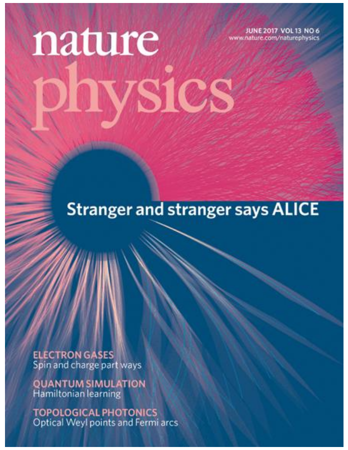
Well known from A-A collisions



Ridges are a direct consequence in hydrodynamic expansion description (called flow in heavy-ion collisions)

Second Discovery: Strangeness





Strange baryon production (K, Λ, Ξ, Ω) increases faster than multiplicity

Smooth across collision system from pp to Pb-Pb

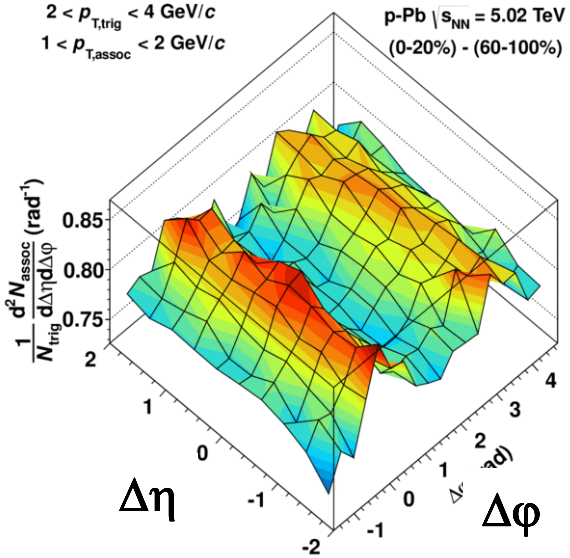
Historically, consequence of energetically cheaper production of $s\bar{s}$ in Quark-Gluon Plasma (compared to $K\bar{K}$ in vacuum)

s $\bar{s}$ vs. K $\bar{K}$

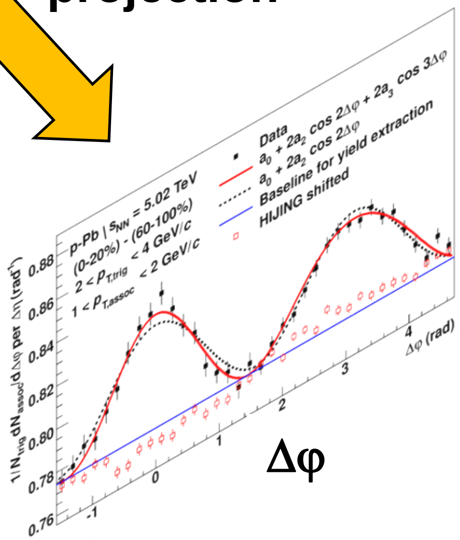
Traditional MC codes completely fail to reproduce trend

Torbjorn Sjostrand [1808.03117]: "we lack some fundamental insight on baryon production"

Basics: What is v_2?



projection



"the second Fourier harmonic of the ridge"

Fourier decomposition

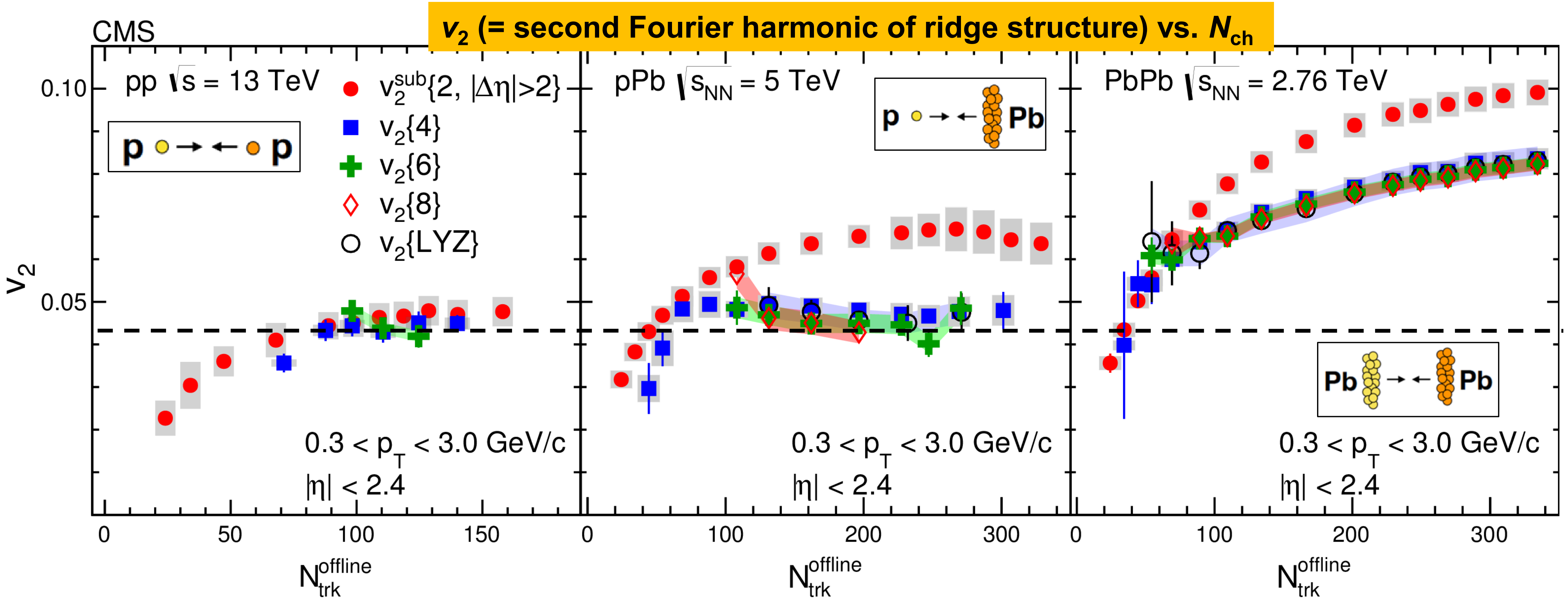
$$\frac{dN}{d\varphi} = A\left(1 + 2\sum_n v_n \cos n(\varphi - \Psi_n)\right)$$

Simplified view

Higher-Orders Collectivity

How many particles contribute to the phenomena?

v_2 (= second Fourier harmonic of ridge structure) vs. N_{ch}



Ridge component characterized with multi-particle correlations: pp ~ p-Pb < Pb-Pb
→ At least 6 particles involved above N_{ch} ≈ 90

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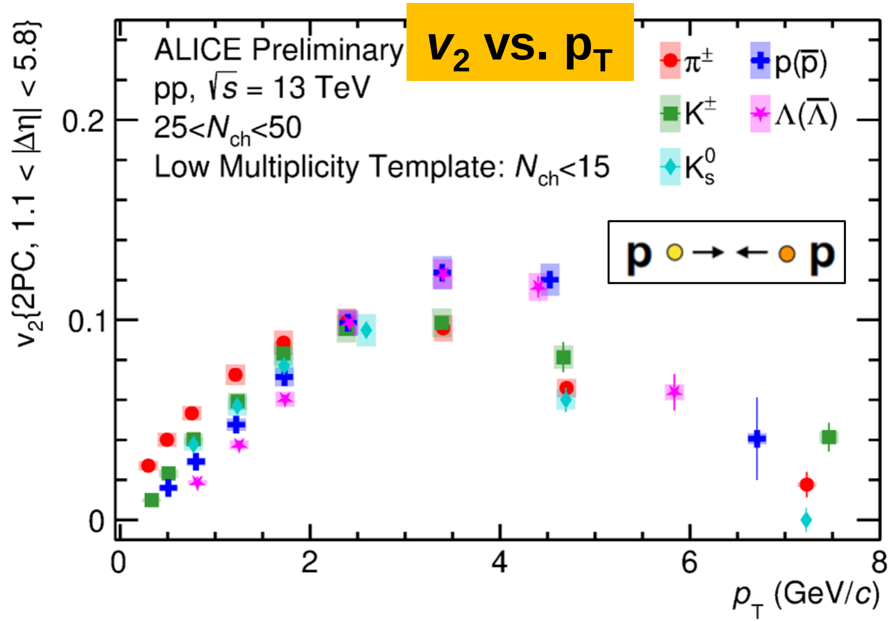
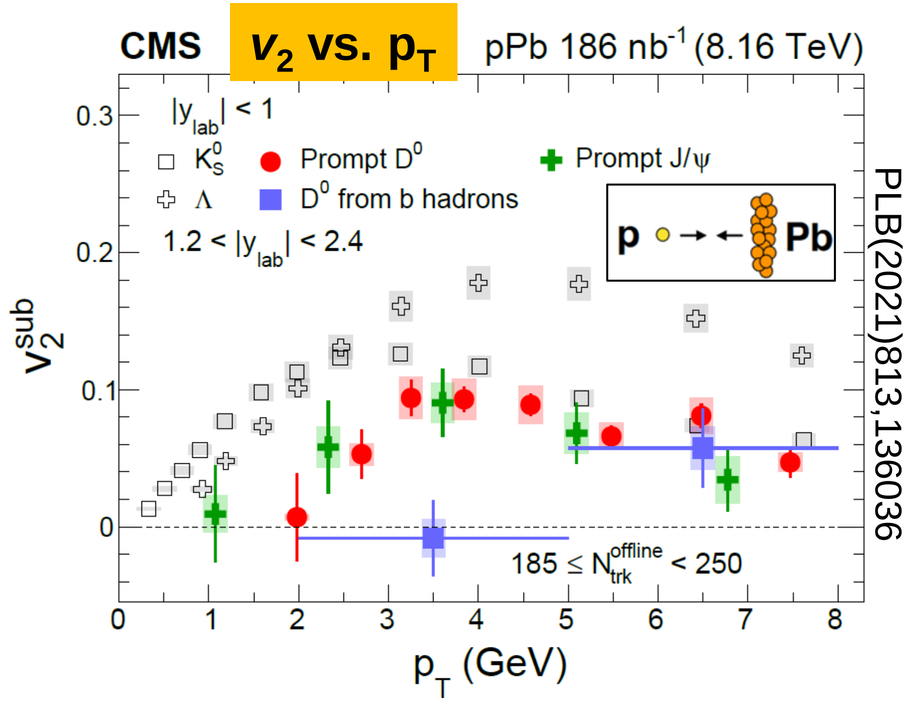
Identified-Particle Collectivity

- Light particles (π, K, p, ϕ, Λ) group by quark content (baryon vs. meson)
  - Large systems: shows partonic degrees of freedom
  - Also observed in high-multiplicity p-Pb and pp collisions



- Charm quarks show collective behaviour
  - Large systems: they thermalize in the medium
  - Also observed for D and J/ψ in high-multiplicity p-Pb coll.

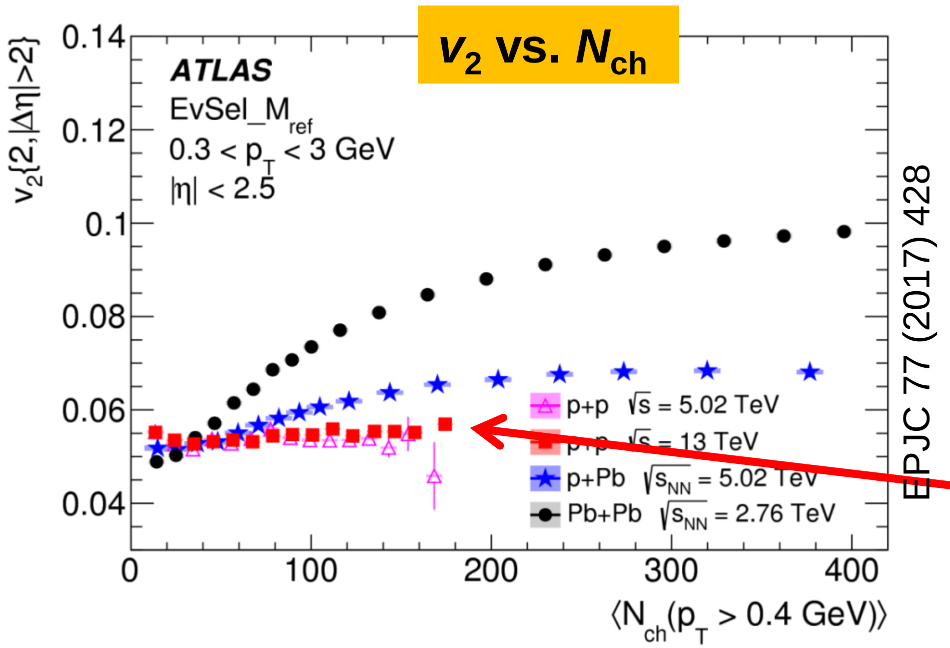


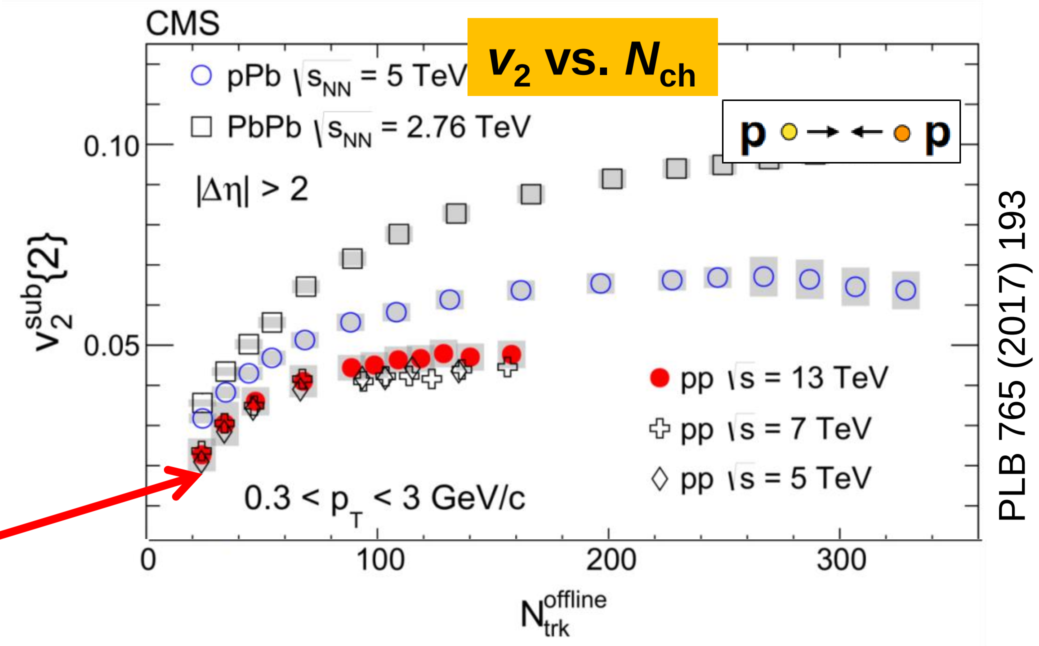
- Bottom quark flow in large systems
  - Large systems: they are affected by the medium
  - Hint in high-multiplicity p-Pb collisions

Low Multiplicity

Does the phenomena switch off?

- Low multiplicity dominated by jets, resonances
  → Ridge “too small to stick out” (~negligible in high-multiplicity pp or p-Pb)
- Extracting v_2 coefficient requires subtraction procedure (see backup)
  (see e.g. discussion in section 2.1 of arXiv:2407.07484)



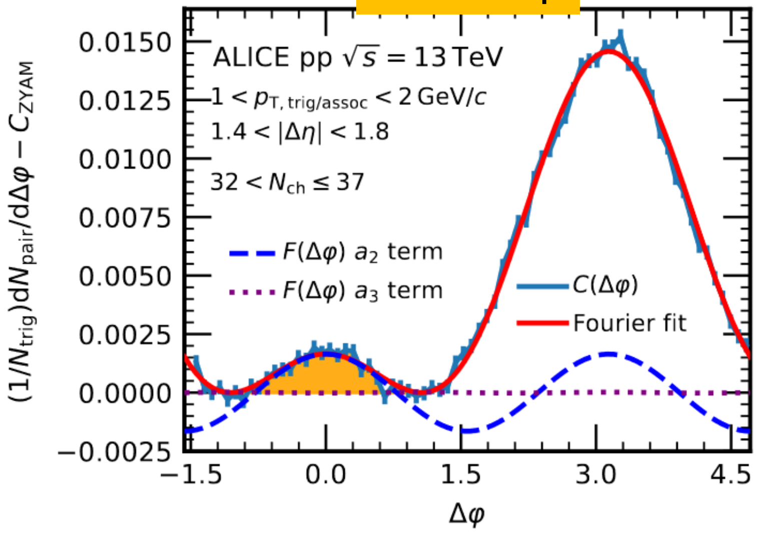


Experimental result procedure dependent – in particular at low multiplicity

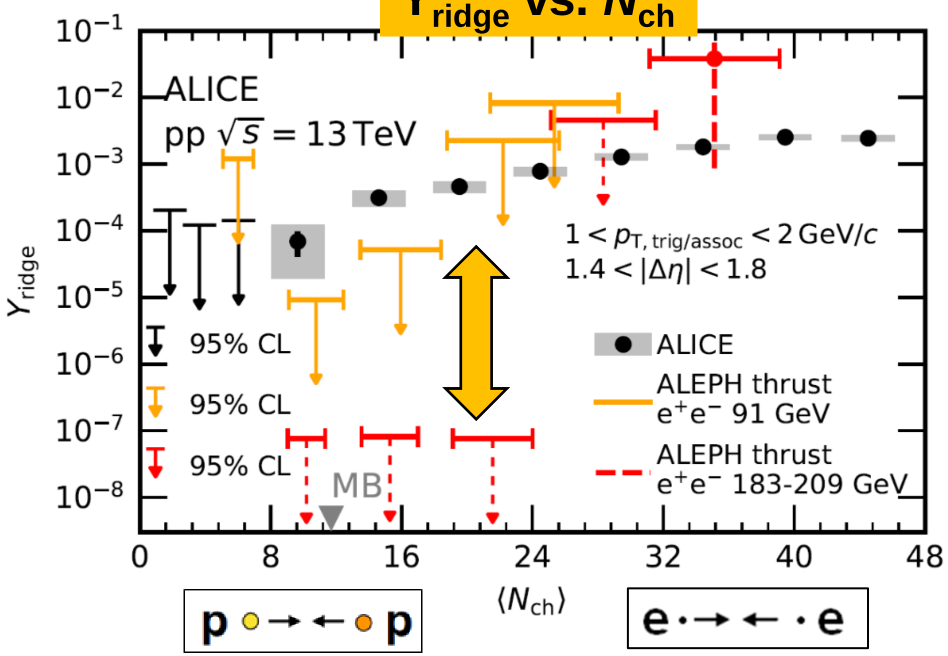
Low Multiplicity
and e^+e^- and ep

- Low-multiplicity pp collisions studied on near side
  - Ridge found for multiplicities as low as minimum bias
- Archived e^+e^- (ALEPH) and ep (HERA) data re-analyzed
  - Thrust axis analysis
  - No ridge observed
    (minor hint at high multiplicity, see backup)
- 5σ difference between pp and e^+e^- at the same multiplicity
  - Comparison as a function of multiplicity challenging

Y vs. Δφ



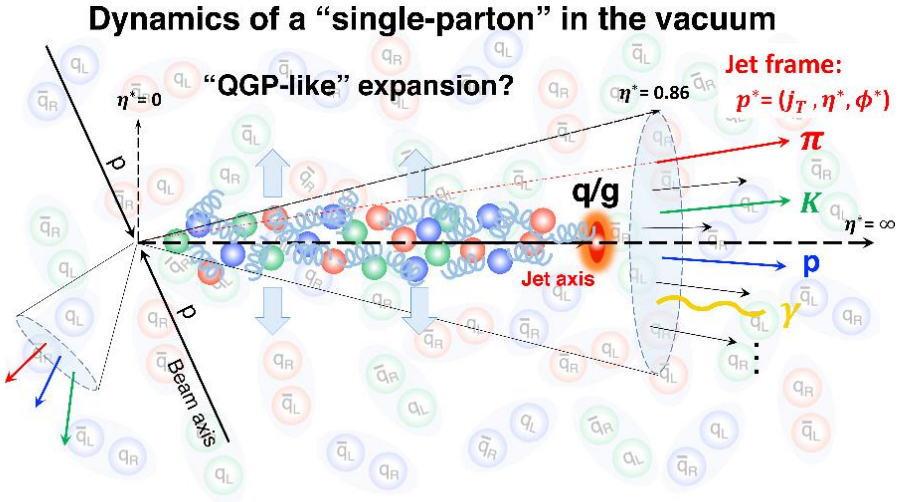
Y_{ridge} vs. N_{ch}

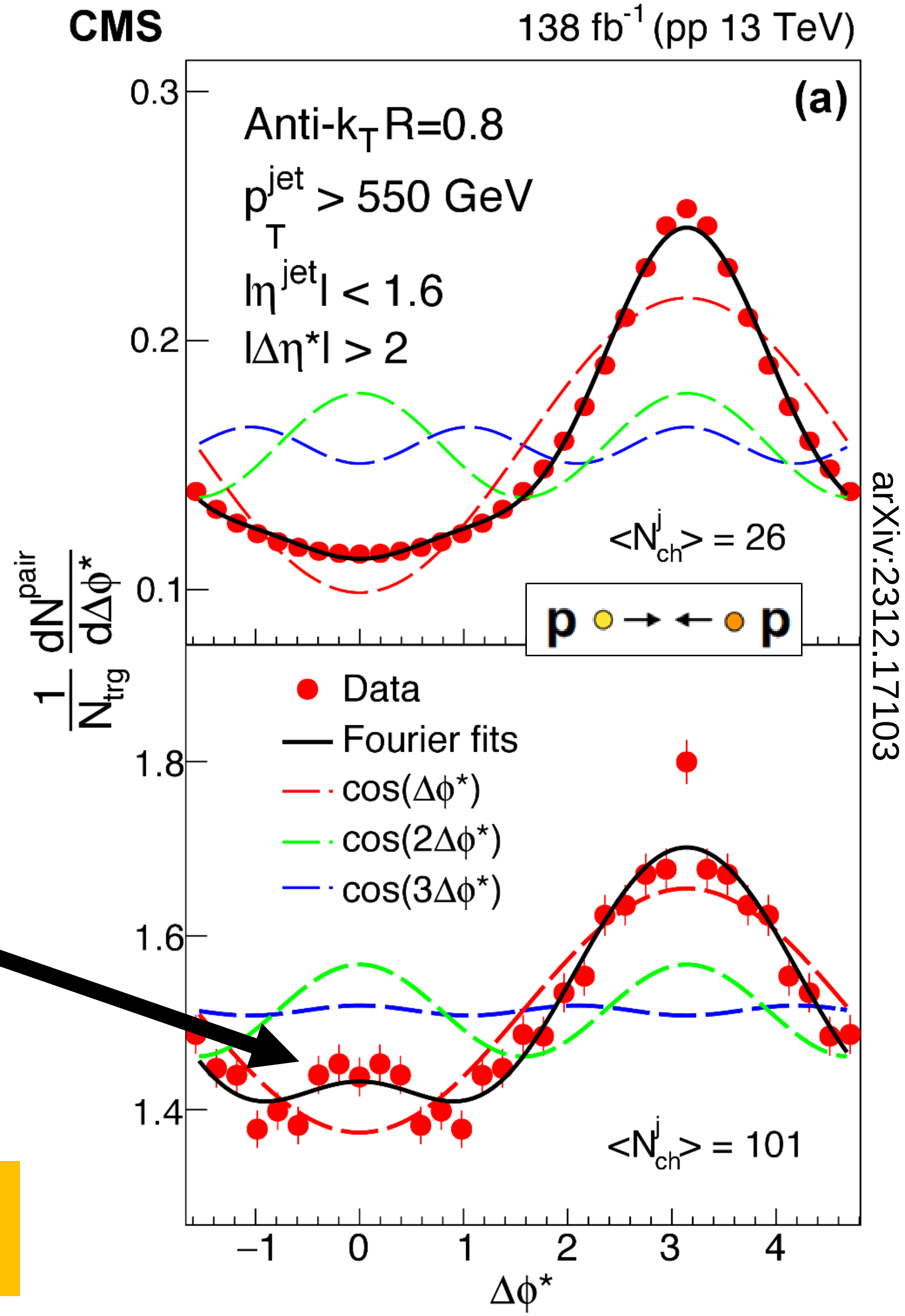


PRL132 (2024) 17, 172302

Very High Multiplicity Jets

- Particles in very dense jets
  - p_T > 550 GeV/c $<N_{ch}>$ = 101
- Rotation of jet "into" beam axis
- Ridge-like contribution



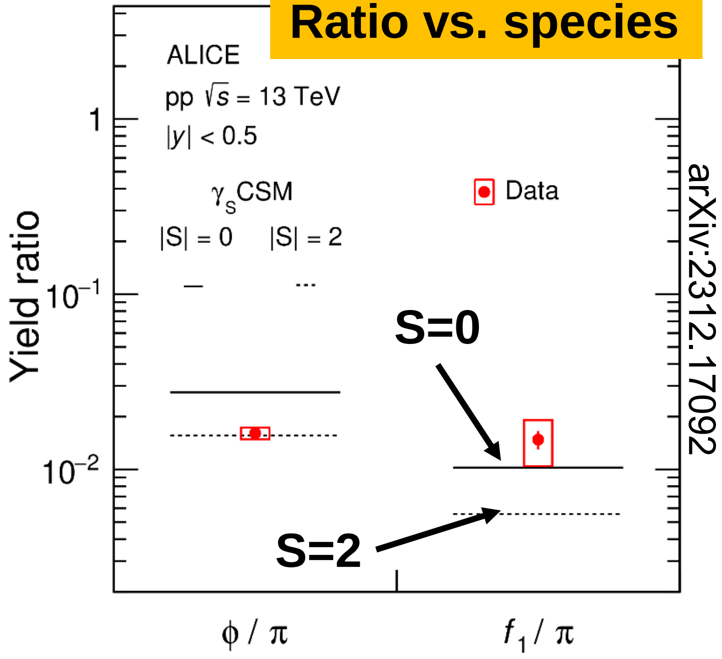


Can a single parton hadronization develop its own dense environment or is it a fundamental QCD ("not QGP") property?

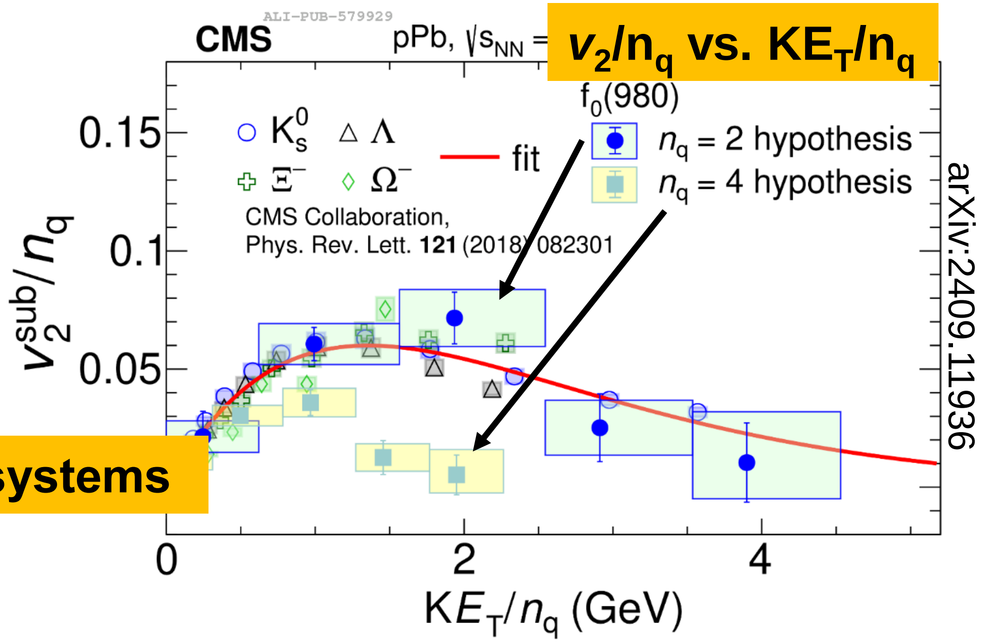
Nature of $f_0(980)$ and $f_1(1285)$

- Quark content of f states not known (number, content)
- Yield measurement of $f_1(1285) \rightarrow K^0_S K^{\pm}\pi^{\pm}$
  - Comparison to statistical hadronization model (see backup) assuming different strangeness content
  - → No strangeness content consistent with data
- v_2 measurement of $f_0(980) \rightarrow \pi\pi$
  - Constituent quark scaling ("NCQ scaling")
    - Amount of collectivity proportional to number of quarks
    - Leads to universal curve v_2/n_q vs. KE_T/n_q
  - → 2 quark hypothesis compatible with this model

Ratio vs. species



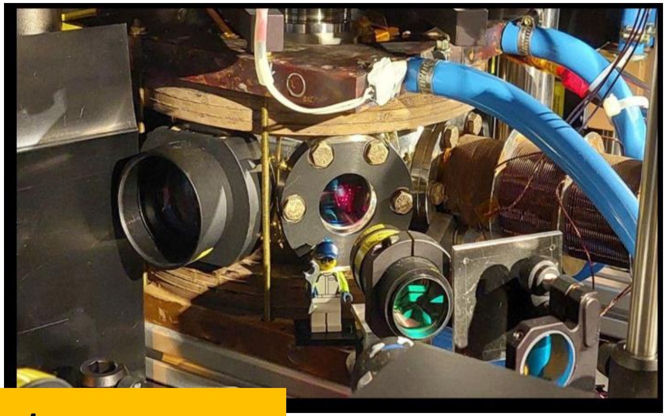
v_2/n_q vs. KE_T/n_q



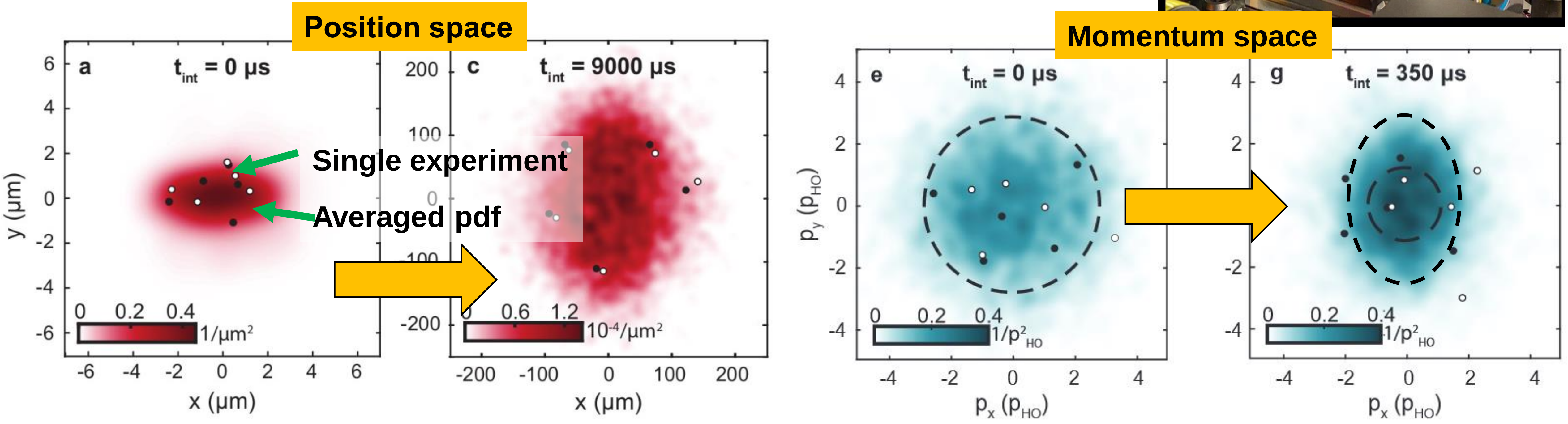
Large system concepts used* to shed light on objects in smaller systems

*assuming the concepts are valid in small systems

Collectivity with "large" objects



- About 10 ultracold Lithium atoms in elliptic trap

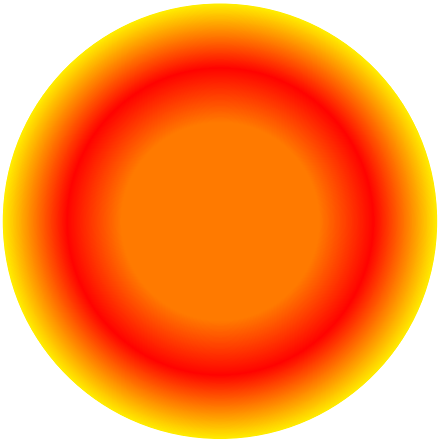


- Shape inversion + buildup of momentum anisotropy
- Above 6 atoms, hydrodynamic behavior observed

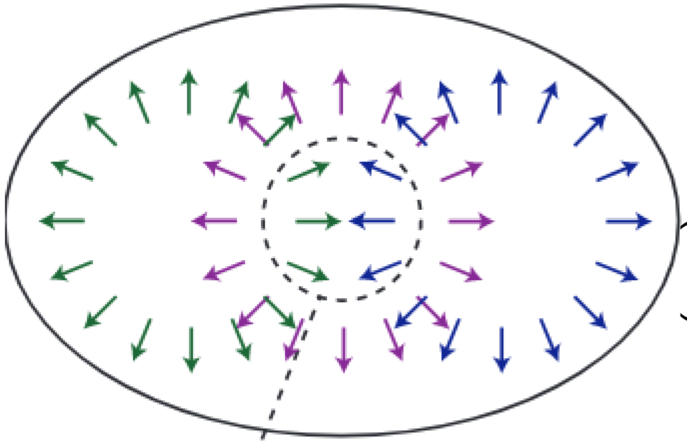
arXiv:2308.09699

Explanations

Hydrodynamic evolution

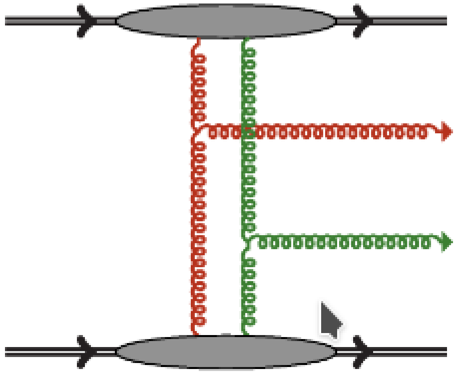


Kinetic theory / transport models



PLB783(2018) 274
PLB753(2016)506

Initial-momentum correlations



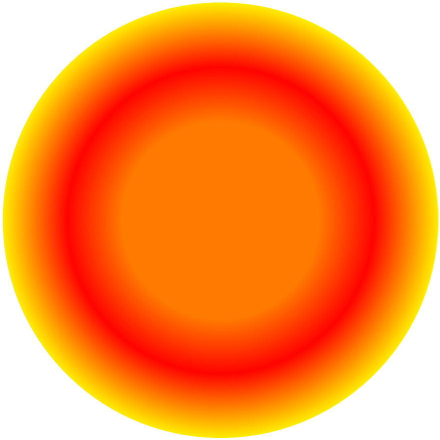
PRD87(2013) 9,094034

Many scatterings ⟷ Few scatterings ⟷ Initial conditions

(Perfect) fluid dynamics ↔ free streaming limit

Explanations: Hydrodynamics

Hydrodynamic evolution

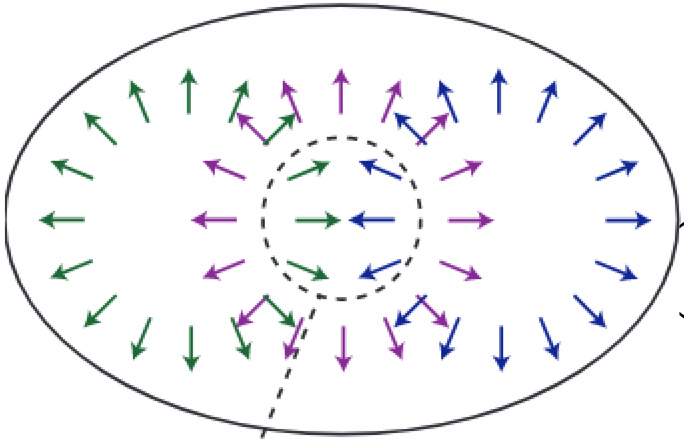


Many scatterings

- Is it “simply” as in large A-A systems?
- Description of large system needs
  - Rapid equilibration
    … rapid enough for pp?
  - Fluid dynamics
    … what is the smallest droplet?
  - Minimal dissipative properties
    … sufficient collectivity generated in small systems?
- Today’s models describe most of the data but need more ingredients than just fluid dynamics

Explanations: Kinetic Theory

Kinetic theory / transport models

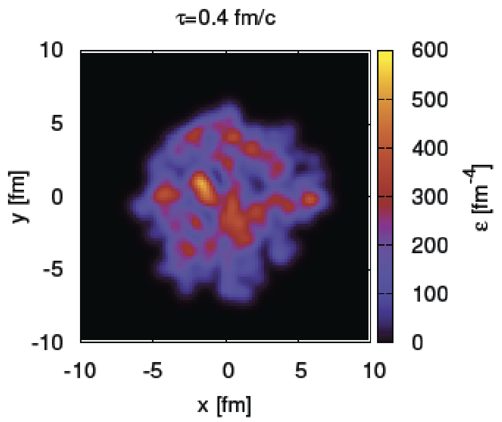


PLB783(2018) 274
PLB753(2016)506

Few scatterings

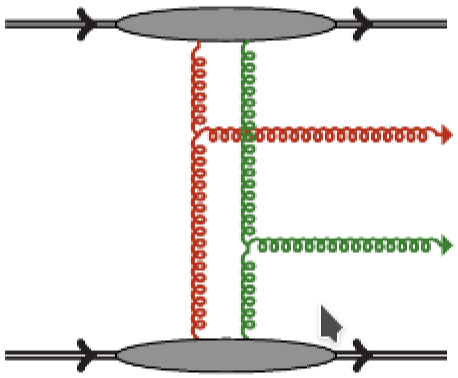
- Kinetic theory can be applied to arbitrary small systems
- Can interpolate smoothly between free-streaming limit and fluid dynamics in dense systems
- Formulation requires scale separation between wave packet size and mean free path
  - Not the case for $\alpha_S \sim 0.3$
  - In principle one is beyond valid regime

Explanations: Initial State



Initial-momentum correlations

- (Sub)nucleonic fluctuations in the incoming projectiles
- Saturation at low x
- Quantum interference between emissions from different sources



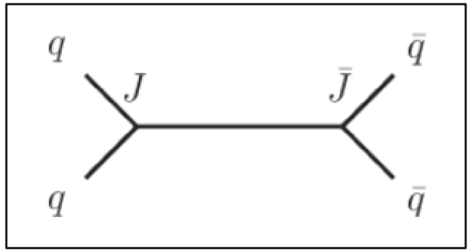
PRD87(2013) 9,094034

- Today, it is mostly excluded that a large fraction of the observed effects are due to initial-state momentum correlations
  (see e.g. PRL121 (2018) 5, 052301)

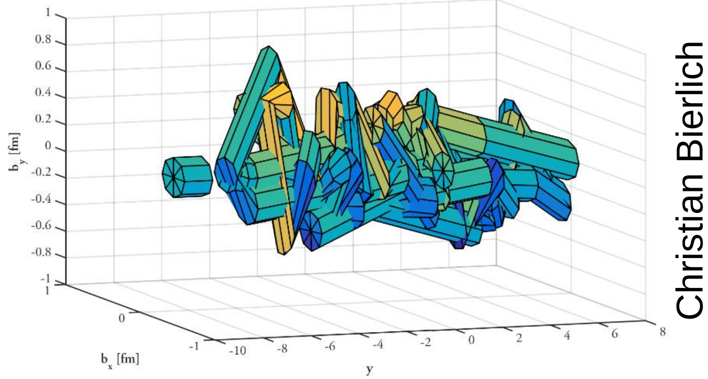
Initial conditions

Phenomenology

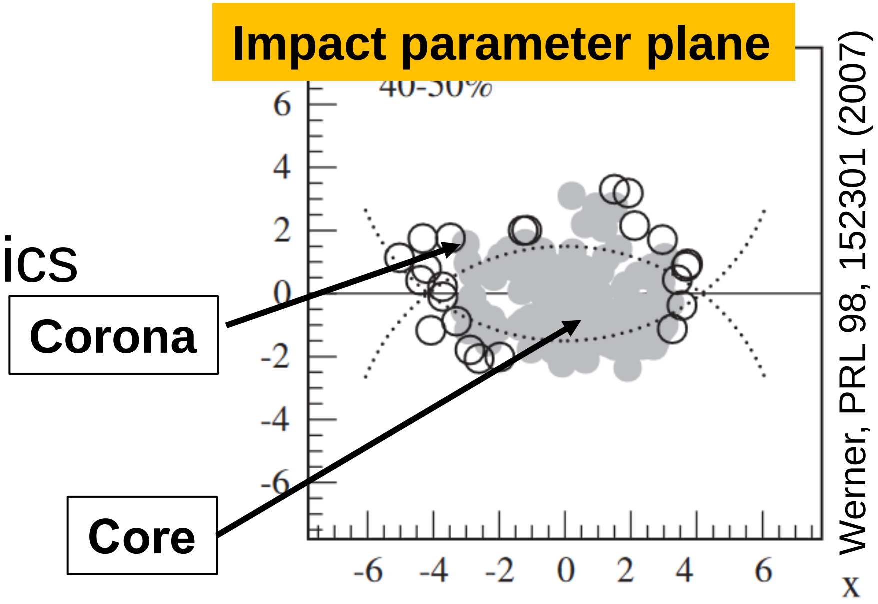
- Hadronization beyond incoherent superposition and leading color
  - Color reconnections for <p_T>
  - Junctions for baryon production like in PYTHIA
- Collective-like phenomena
  - Colour ropes like in PYTHIA/DIPSY
- Combining vacuum hadronization and hydrodynamics
  - Core-corona models like in EPOS
  - Corona: vacuum-like
  - Core: hydrodynamic evolution



JHEP 08(2015)003

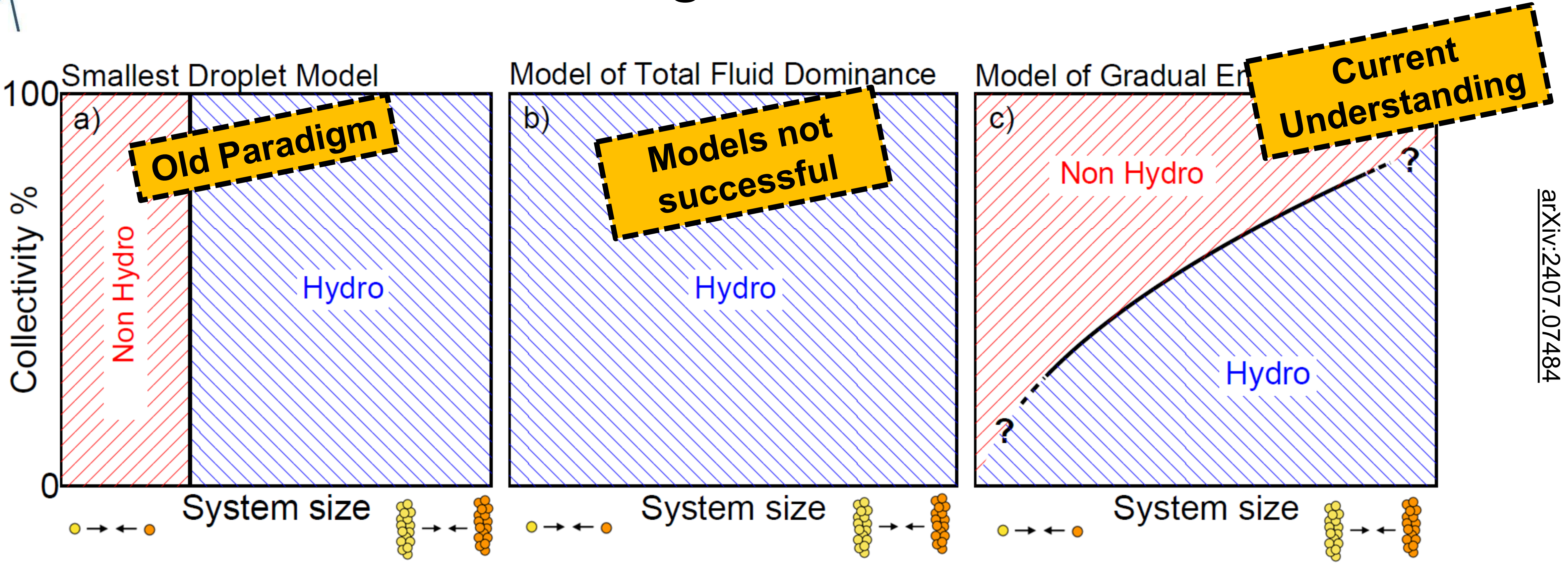


Christian Bierlich



Werner, PRL 98, 152301 (2007)

Big Picture



- Both hydrodynamic and non-fluid dynamic d.o.f. relevant at most (all?) sizes
- Influence on observables is size dependent
  - Experimental handle (species) to dial the relative contribution → tool to study QGP d.o.f.

Summary

- Small system observations challenge two paradigms at once
  - Smallest system in which heavy-ion "standard model" remains valid?
  - Can the standard tools for pp physics remain standard?
- Traditional HEP and traditional HI studies grow together
  - Tremendous experimental and theoretical progress in last 10+ years
  - The underlying QCD *is* the same theory
- New insights expected from future O-O and p-Pb runs

Read more in our recent review: Urs Wiedemann, JFGO: arXiv:2407.07484

Thank you for your attention!

Backup

More about small systems…

- Field shifted paradigm due to small system discoveries
  - Enormous experimental and theoretical work in the last 10+ years

Table 1. Summary of observables or effects in Pb–Pb, Xe–Xe and Au–Au collisions, as well as in high multiplicity p–Pb, a–A and pp collisions. References to key measurements are given. See text for details. Table adapted from Ref. [90] and extended by publications of the last 5 years.

Observable or effect	Pb–Pb, Xe–Xe, Au–Au	p–Pb, a–A (high N)	pp (high N)	Refs.
Near-side ridge yields	yes	yes	yes	83–86, 74, 76, 77, 79, 79, 100
Azimuthal anisotropy	v_1–v_9	v_1–v_5	v_2–v_4	84–86, 46, 73–89, 101, 102
Weak η dependence	yes	yes	yes	82, 90–98
Characteristic mass dependence	v_2–v_5	v_2, v_3	v_2	78, 81, 83, 87, 103–110
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	"$4 \approx 6$"	83, 84, 88, 96, 100, 111–123
Symmetric cumulants (SC)	up to $(5,3)$	only $(4,2)$, $(3,2)$	only $(4,2)$, $(3,2)$	86, 88, 124–130
Non-linear flow modes	up to v_7	not measured	not measured	89, 131, 132
Factorization breaking	$n = 2$–4, $\{2\}$, $\{4\}$	$n = 2, 3$, $\{2\}$	not measured	77, 85, 133–137
Event-by-event v_n distributions	v_2–v_4	not measured	not measured	138–140
Flow–p_T correlation	up to v_4	v_2	not measured	141, 142
Directed flow (from spectators)	yes	no	no	143
Charge-dependent correlations	yes	yes	yes	144–150
Low p_T spectra ("radial flow")	yes	yes	yes	52, 151–161
Intermediate p_T ("recombination")	yes	yes	yes	153, 156, 160, 162–166
Particle ratios	GC level	GC level	GC level	153, 154, 157, 158, 167, 168
Statistical model	$\gamma_s^{GC} = 1$	$\gamma_s^{GC} \approx 1$	$\gamma_s^{C} < 1$	52, 161, 169–171
HBT radii ($R(k_T)$, $R(\sqrt[3]{N})$)	$R_{out}/R_{side} \approx 1$	$R_{out}/R_{side} \lesssim 1$	$R_{out}/R_{side} \lesssim 1$	172–180
Direct photons at low p_T	yes	not measured	not observed	181–183
v_n in events with Z, jets	not measured	up to v_3	v_2	184–186
Jet constituent v_n	v_2	v_2	v_2 in jet frame	187, 188
Jet quenching through R_{AA}	yes	not observed	not observed	65, 67, 189–204
... through dijet asymmetry	yes	not observed	not observed	205–212
... through correlations	yes (Z–jet, γ–jet, h–jet)	not obs. (h–jet, jet–h)	not measured	204, 213–222
... through high p_T v_n and jet-v_n	yes	yes	not measured	184, 223–225
Heavy flavour anisotropy	up to v_3 (c), up to v_2 (b)	up to v_2	up to v_2	108, 226–248
Quarkonia production	suppressed	suppressed	not measured	232, 249–284

arXiv > hep-ex > arXiv:2407.07484

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Help

High Energy Physics - Experiment

[Submitted on 10 Jul 2024]

A Decade of Collectivity in Small Systems

Jan Fiete Grosse-Oetringhaus, Urs Achim Wiedemann

Signatures of collectivity, including azimuthally anisotropic and radial flow as well as characteristic hadrochemical dependencies, have been observed since long in (ultra)relativistic nucleus-nucleus collisions. They underpin the interpretation of these collision systems in terms of QGP formation and close-to-perfect fluidity. Remarkably, however, essentially all these signatures of collectivity have been identified within the last decade in collision systems as small as pp and p-Pb, where collective phenomena had been assumed to be absent traditionally. Precursor phenomena may have been found even in ep and e^+e^- collisions. This article provides a complete review of all data on small system collectivity. It reviews model simulations of these data where available. However, in the absence of a phenomenologically fully satisfactory description of collectivity across all system sizes, we focus in particular on the theoretical basis of all dynamical frameworks of collectivity invoked in heavy ion collisions, and their expected scaling with system size. Our discussion clarifies to what extent all dynamical explanations are challenged by the available data.

Comments: Invited article submitted for consideration in World Scientific Annual Review of Particle Physics

Read more in: arXiv:2407.07484

Subtraction Procedures

- Extracting v_2 coefficient requires subtraction procedure
- Low-multiplicity subtraction

$$\Delta Y(\Delta\varphi) = G' + N \sum_n 2v_n^2 \cos(n\Delta\varphi)$$

  – Exact for $v_2 \rightarrow 0$ for $M \rightarrow 0$ ($\alpha_N = 0$)

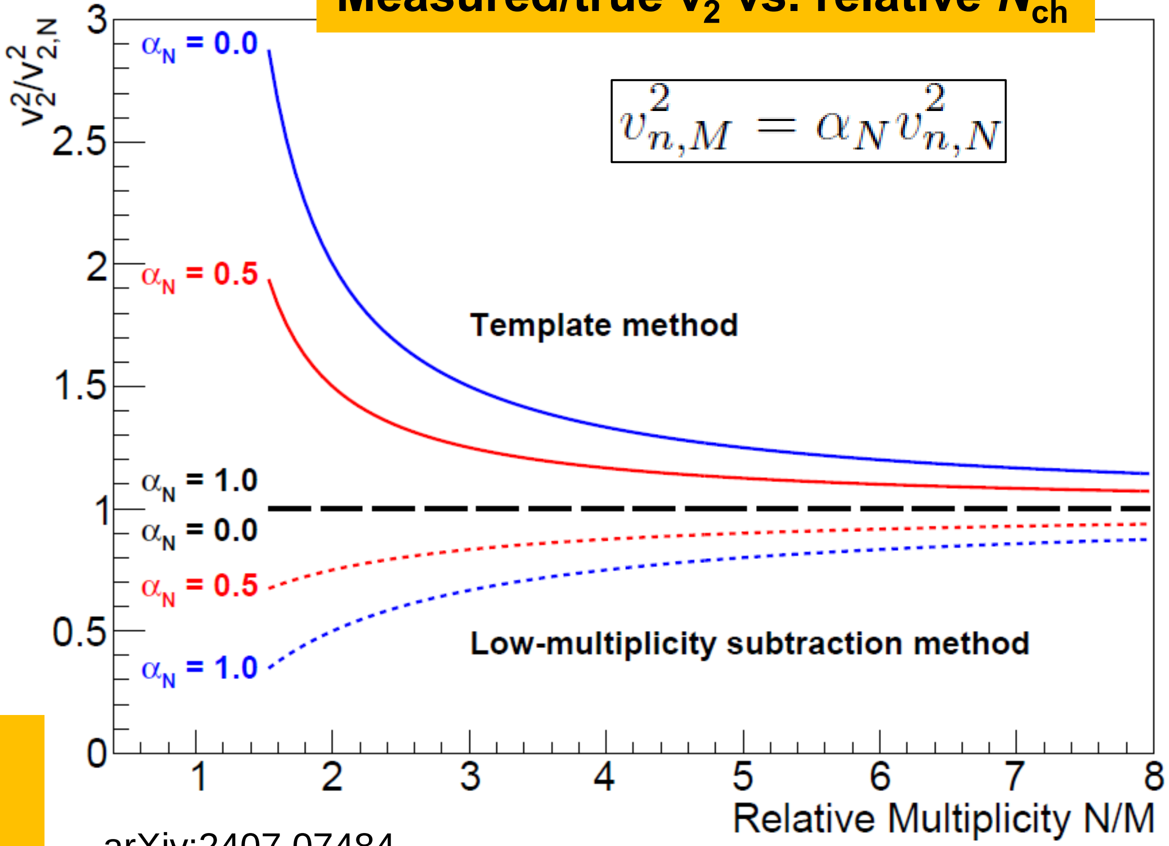
- Template fit method

$$\Delta Y(\Delta\varphi) = G\left(1 + \sum_n 2v_n^2 \cos(n\Delta\varphi)\right)$$

  – Exact for v_2 independent of M for small M ($\alpha_N = 1$)

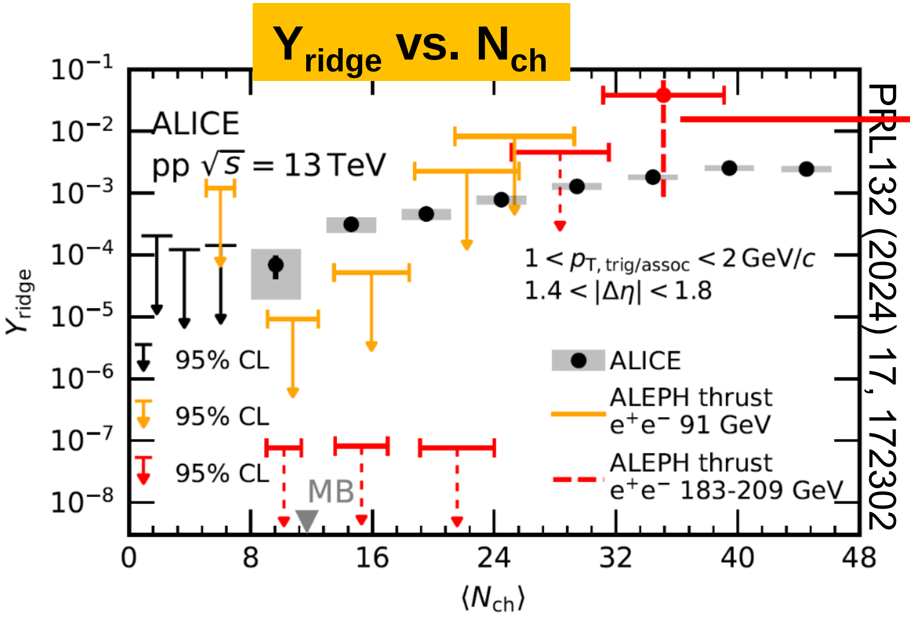
Experimental result procedure dependent – in particular at low multiplicity

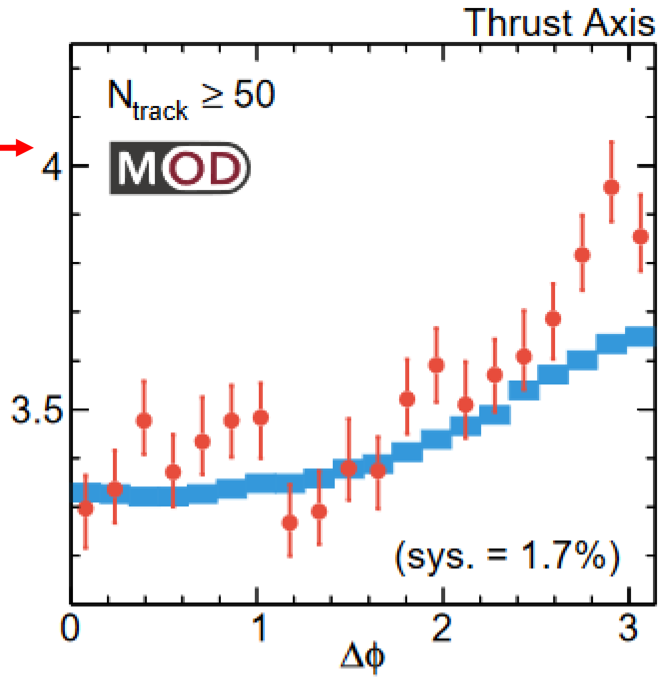
Measured/true v_2 vs. relative N_{ch}



arXiv:2407.07484

e^+e^- Highest Bin



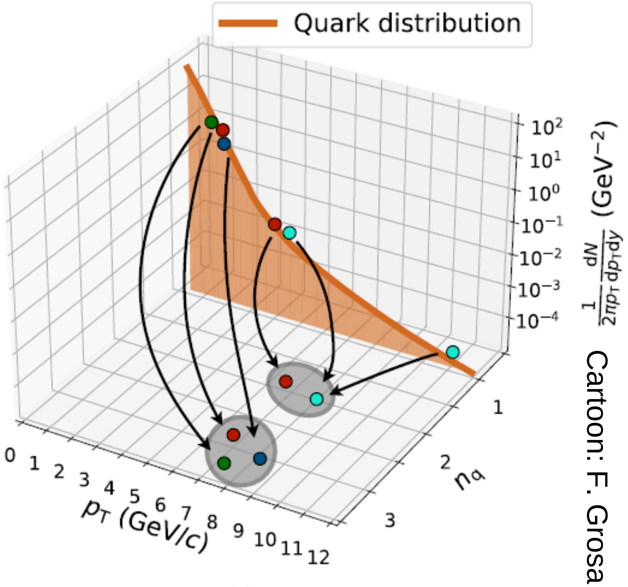


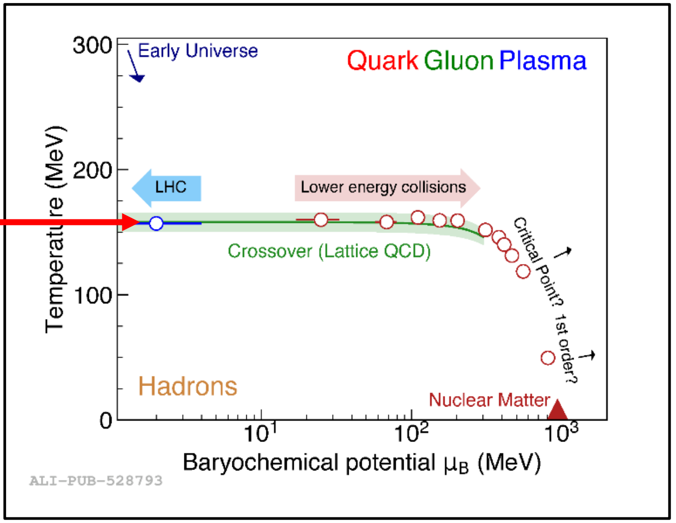
arXiv:2312.05084

1.02σ

Coalescence and Statistical Hadronization

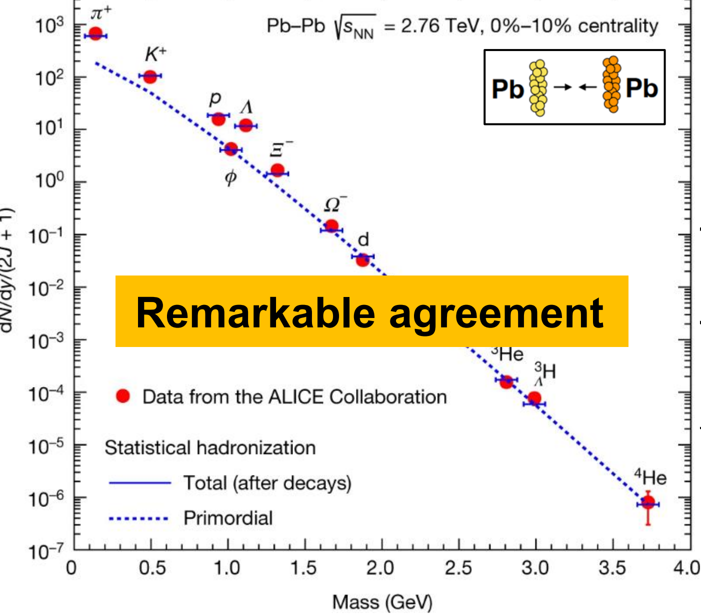
- Coalescence in filled phase space of quarks and gluons
  - Partons close in momentum and position space coalesce to hadrons
  - Probability is p_T dependent
  - Can be successfully applied to large objects
    - Nuclei have small binding energy and are formed late
- Statistical hadronization: Relativistic ideal quantum gas of hadrons in thermal and chemical equilibrium
  - 3 free parameters: V, T, μ_B
  - Central Pb-Pb at LHC
    - T = 156 ± 2 MeV
    - μ_B = 0.7 ± 3.8 MeV
    - V ~ 5000 ± 500 fm^3





11 different species

9 orders of magnitude



Nature 561 (2018) 7723, 321