# A Decade of Collectivity in Small Systems

Jan Fiete Grosse-Oetringhaus (CERN)

Light Ions at the LHC

11.11.2024

"And early on, still with proton beams, we tripped over another surprise – the first, and arguably still the most unexpected, LHC discovery. A feeble, but distinct, very long-range correlation between particles, never before seen in any elementary collisions […]. *(Jurgen Schukraft, Recollections, 18.10.24)*

"We have immediately set-up an independent analysis (control group) and organized a full set of tests and cross-checks to kill the effect. […] If we are here today it is because we didn't succeed to kill it."
(Guido Tonelli, LHC seminar, 21.10.10)

"This is a subtle effect in a complex environment – careful work is needed to establish physical origin"
(Gunther Roland, LHC seminar, 21.10.10)

# 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

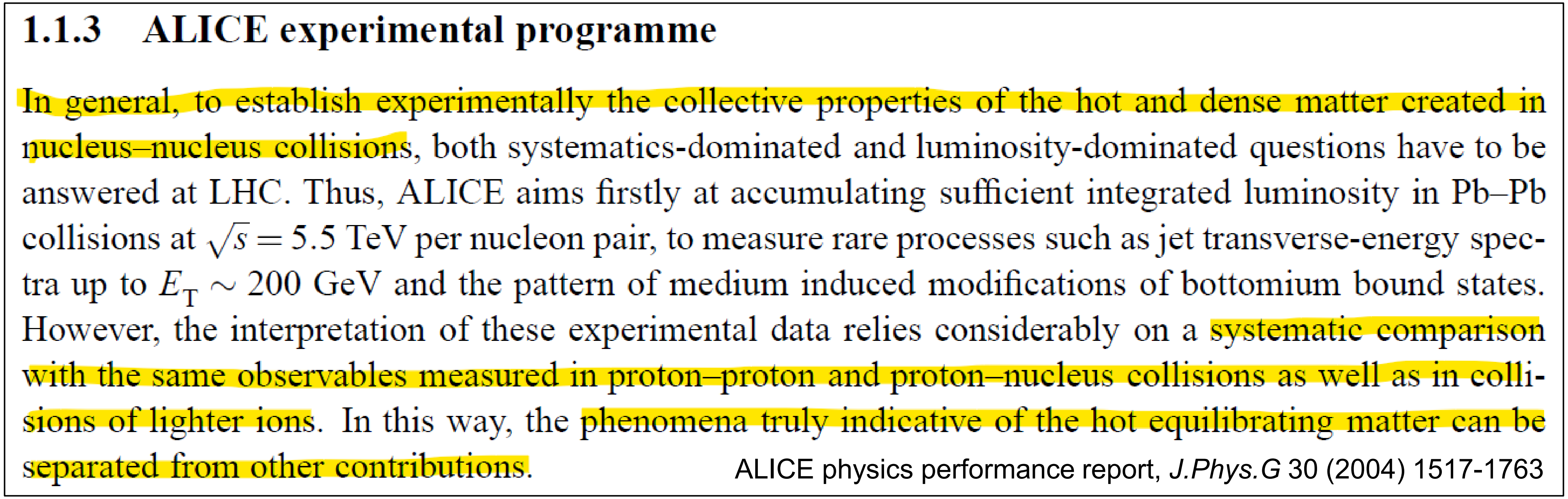
# Paradigm 15 Years Ago

## Small and large systems governed by totally different physics

**Single-process limit**
**Vacuum**

**Thermal limit**
**Dense system**

which is directly reflected in experimental programs at that time

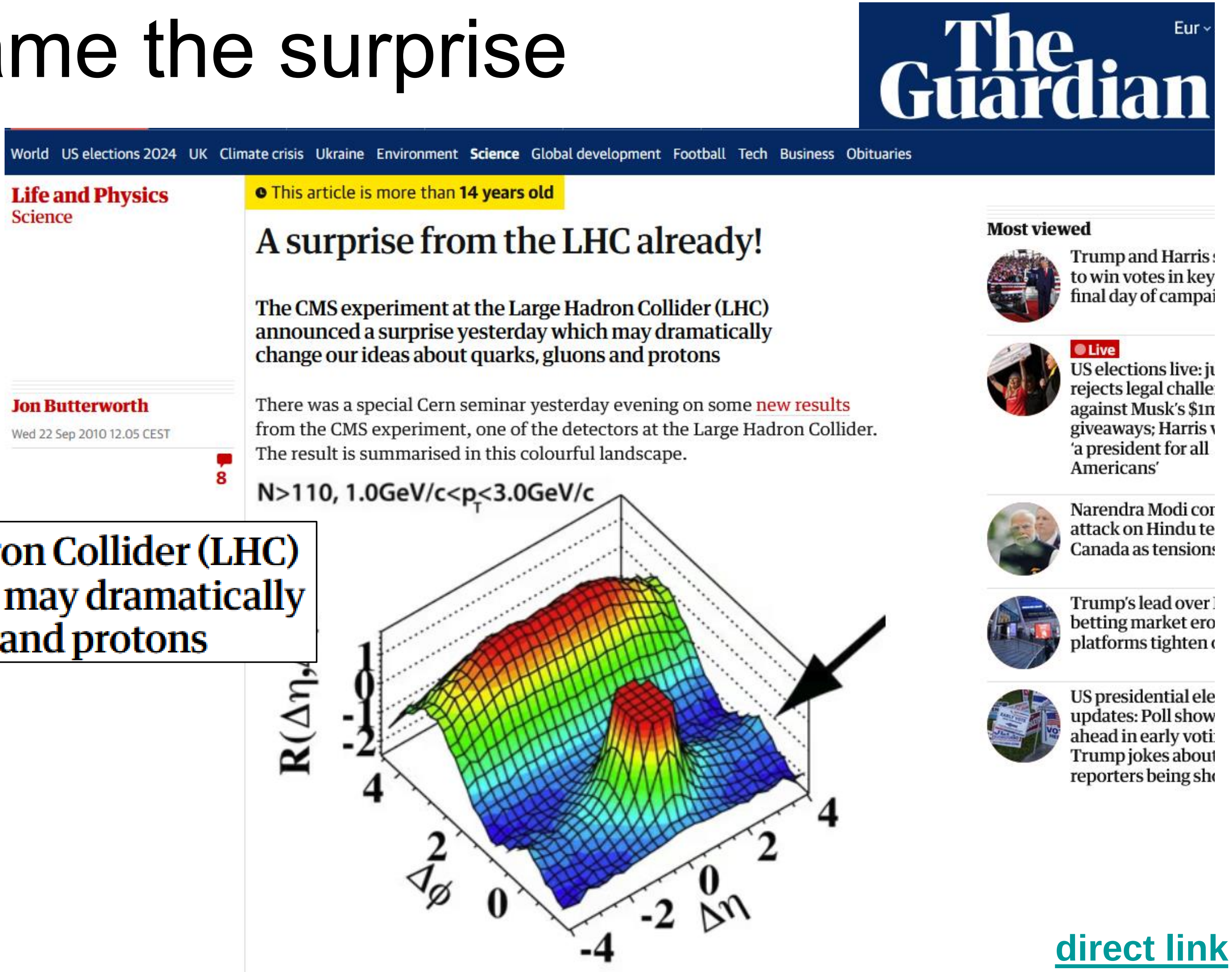


### 1.1.3 ALICE experimental programme

In general, to establish experimentally the collective properties of the hot and dense matter created in nucleus–nucleus collisions, both systematics-dominated and luminosity-dominated questions have to be answered at LHC. Thus, ALICE aims firstly at accumulating sufficient integrated luminosity in Pb–Pb collisions at $\sqrt{s} = 5.5$ TeV per nucleon pair, to measure rare processes such as jet transverse-energy spectra up to $E_T \sim 200$ GeV and the pattern of medium induced modifications of bottomium bound states. However, the interpretation of these experimental data relies considerably on a systematic comparison with the same observables measured in proton–proton and proton–nucleus collisions as well as in collisions of lighter ions. In this way, the phenomena truly indicative of the hot equilibrating matter can be separated from other contributions.

ALICE physics performance report, *J.Phys.G* 30 (2004) 1517-1763

# … and then came the surprise



The Guardian

Eur

World US elections 2024 UK Climate crisis Ukraine Environment **Science** Global development Football Tech Business Obituaries

**Life and Physics**
Science

This article is more than **14 years old**

## A surprise from the LHC already!

**The CMS experiment at the Large Hadron Collider (LHC) announced a surprise yesterday which may dramatically change our ideas about quarks, gluons and protons**

**Jon Butterworth**
Wed 22 Sep 2010 12.05 CEST

8

There was a special Cern seminar yesterday evening on some new results from the CMS experiment, one of the detectors at the Large Hadron Collider. The result is summarised in this colourful landscape.

**Most viewed**

Trump and Harris
to win votes in key
final day of campai

Live
US elections live: ju
rejects legal challe
against Musk's $1m
giveaways; Harris
'a president for all
Americans'

Narendra Modi co
attack on Hindu te
Canada as tension

Trump's lead over
betting market ero
platforms tighten

US presidential ele
updates: Poll show
ahead in early voti
Trump jokes about
reporters being sh

**22.09.2010** →

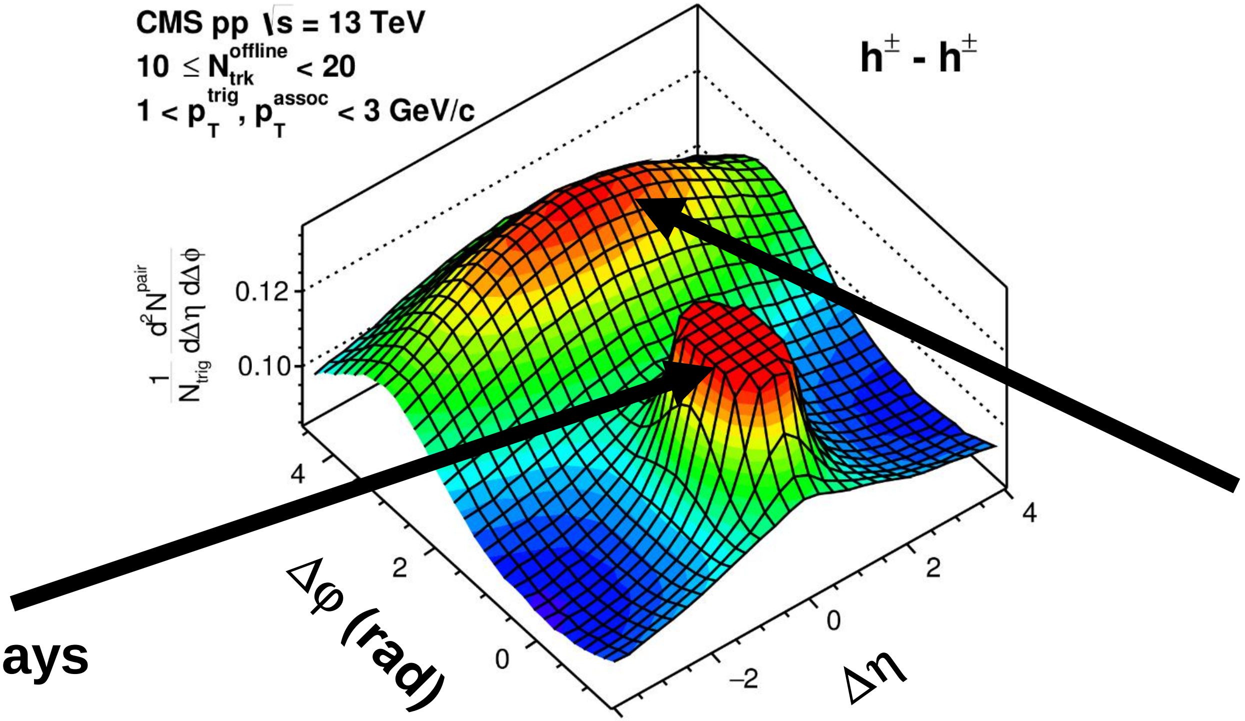
> The CMS experiment at the Large Hadron Collider (LHC) announced a surprise yesterday which may dramatically change our ideas about quarks, gluons and protons

direct link

# First Discovery:
# The Ridge

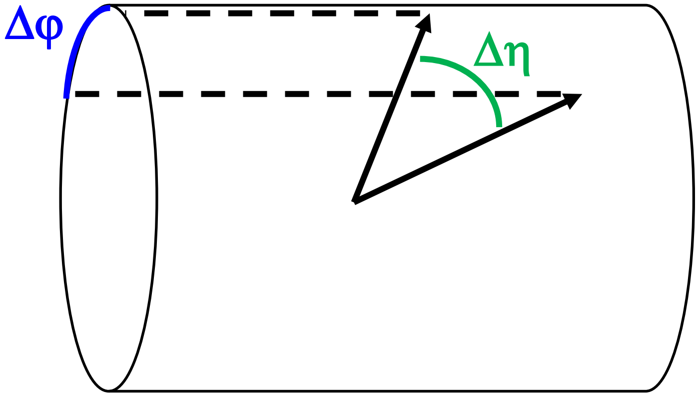
# Basics: Collective Phenomena

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



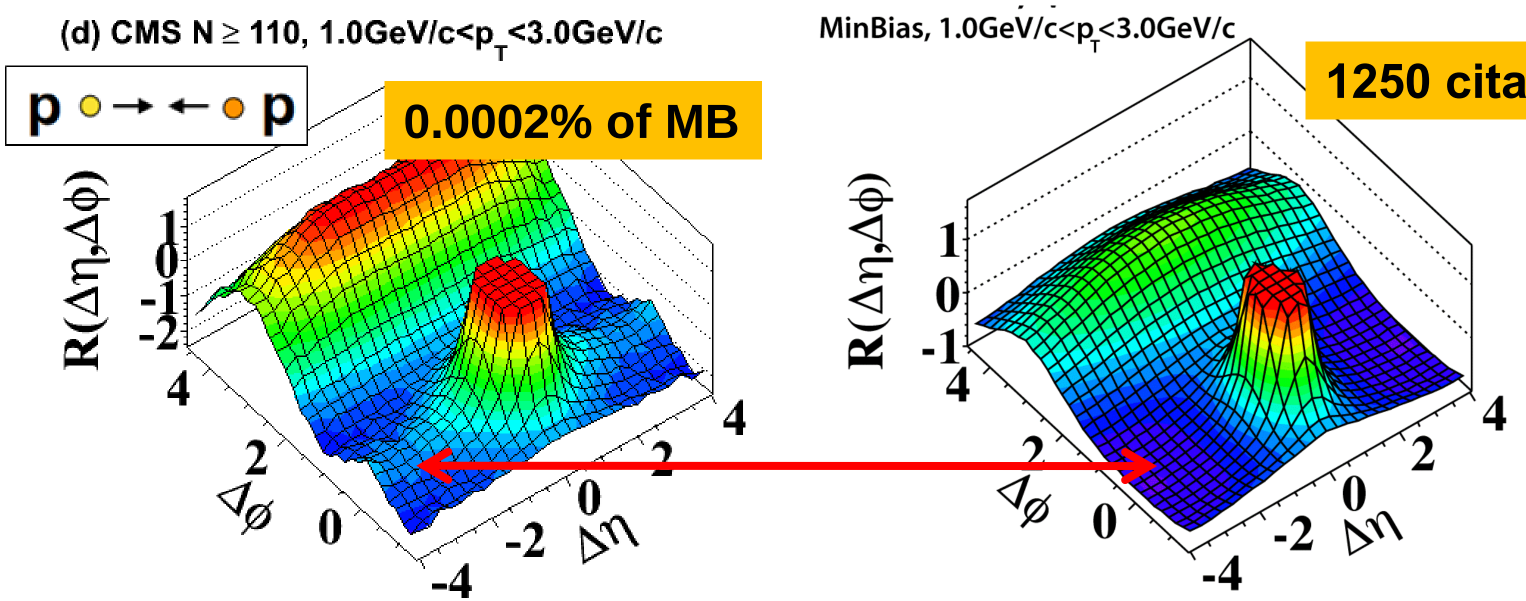
**Near-side jet**
**Resonance decays**

**Away-side jet**



PLB 765 (2017) 193

# First Discovery: Ridge

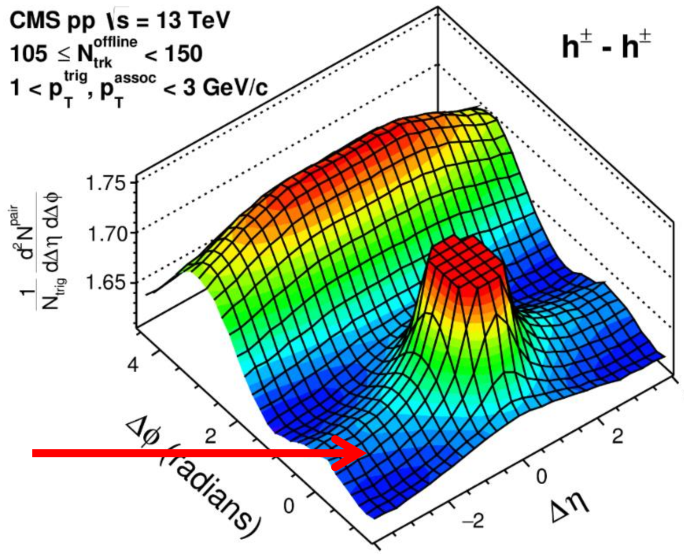


**0.0002% of MB**

**1250 citations!**

CMS, JHEP1009(2010)091

**Higher statistics version (from 2017):**

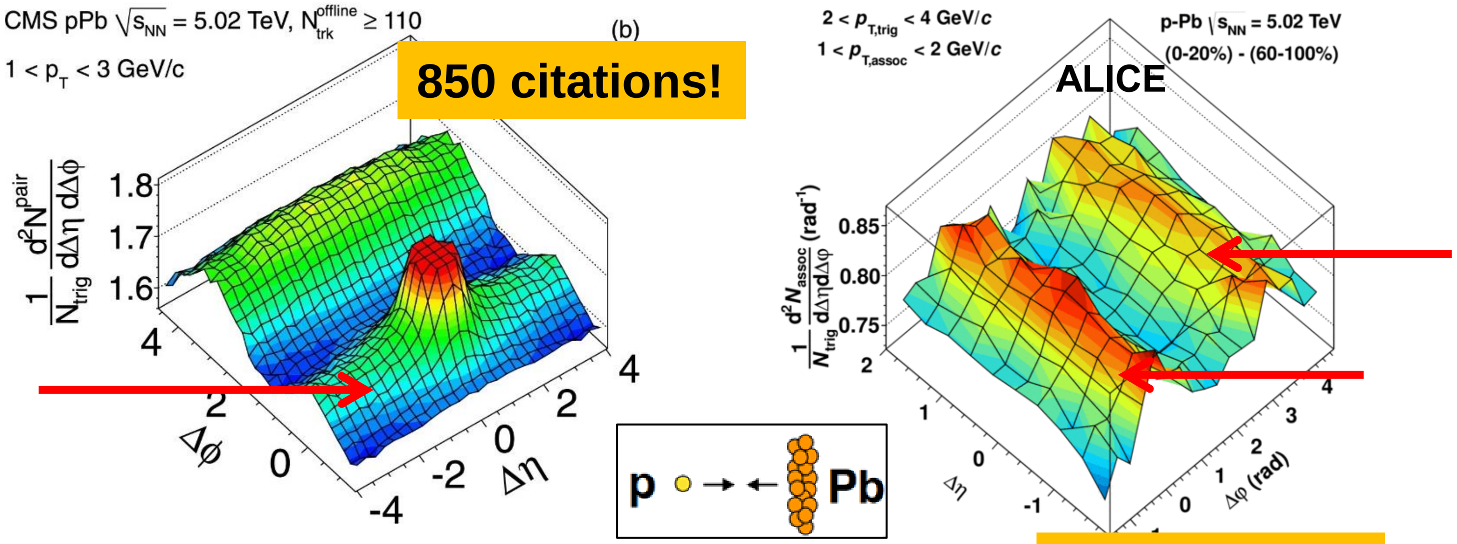


CMS, PLB 765 (2017) 193

**Remarkably, the community was not yet intrigued enough, and the topic went somehow dormant again**

# First Discovery: Ridge and Ridges

- Same feature observed in p-Pb collisions
- Second ridge discovered
  (with subtraction procedure, see later)



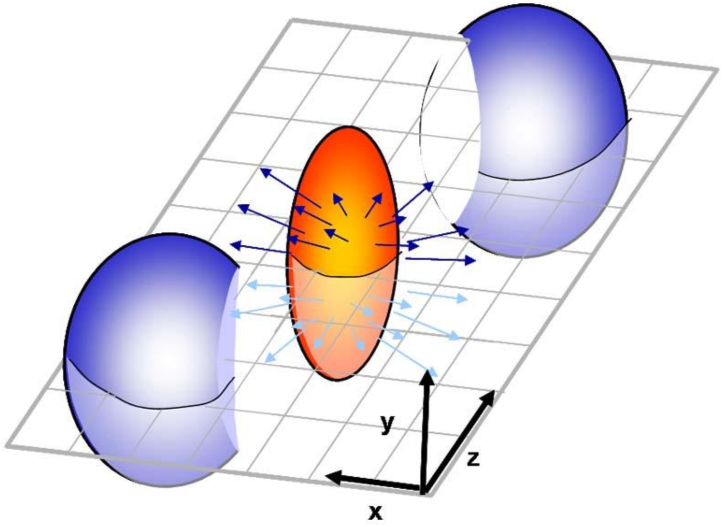
850 citations!

950 citations!

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

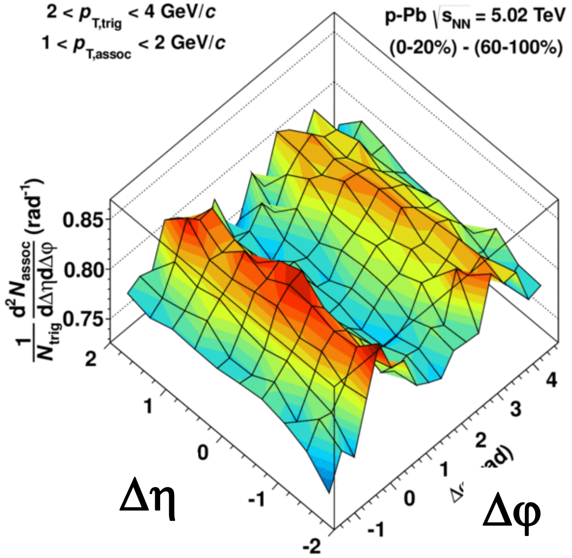
Unexpected in pp and p-Pb collisions

Well known from A-A collisions



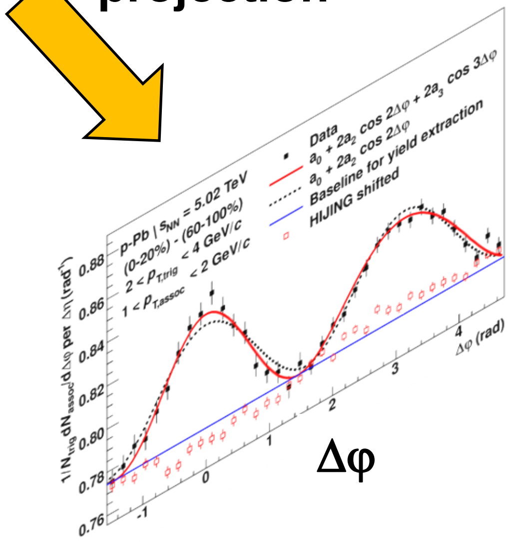
Ridges are a direct consequence in hydrodynamic expansion description (called flow in heavy-ion collisions)

# Basics: What is $v_2$?



**"the second Fourier harmonic of the ridge"**

**projection**



**Fourier decomposition**

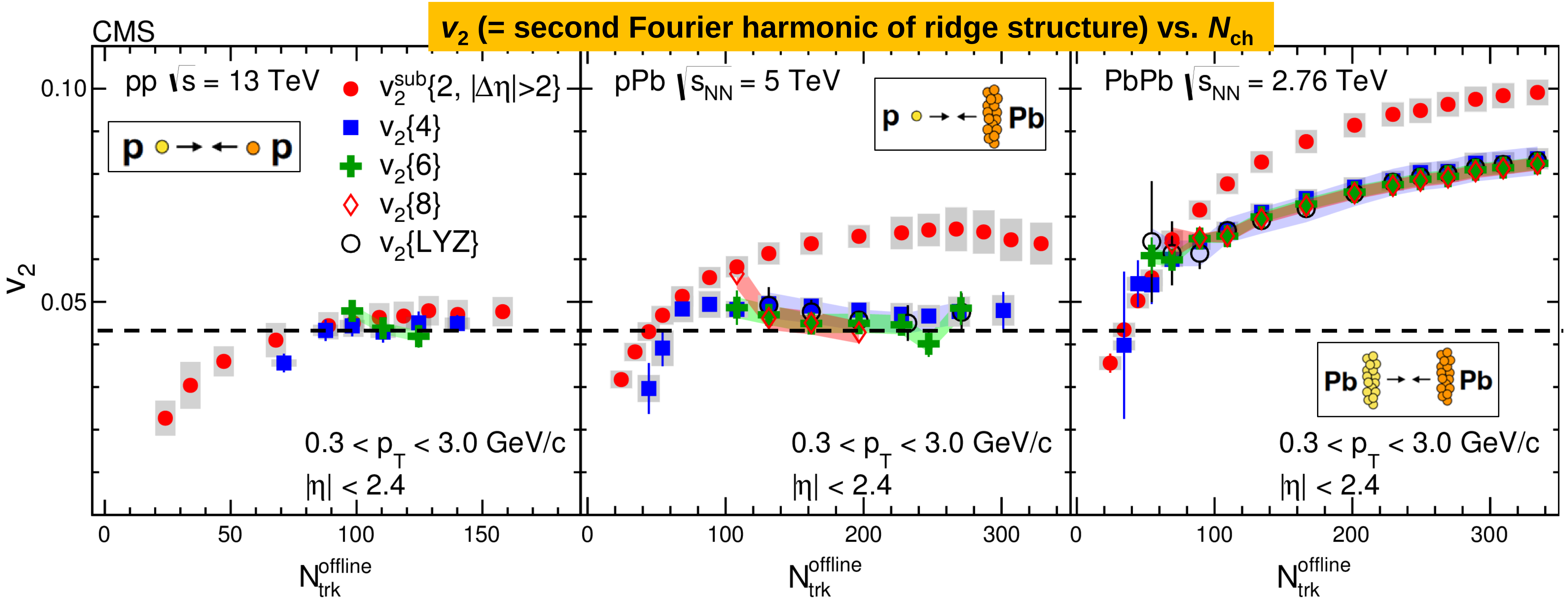
$$\boxed{\frac{dN}{d\varphi} = A\left(1+2\sum_n \underline{v_n} \cos n(\varphi-\Psi_n)\right)}$$

Simplified view

# Higher-Orders Collectivity

How many particles contribute to the phenomena?

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

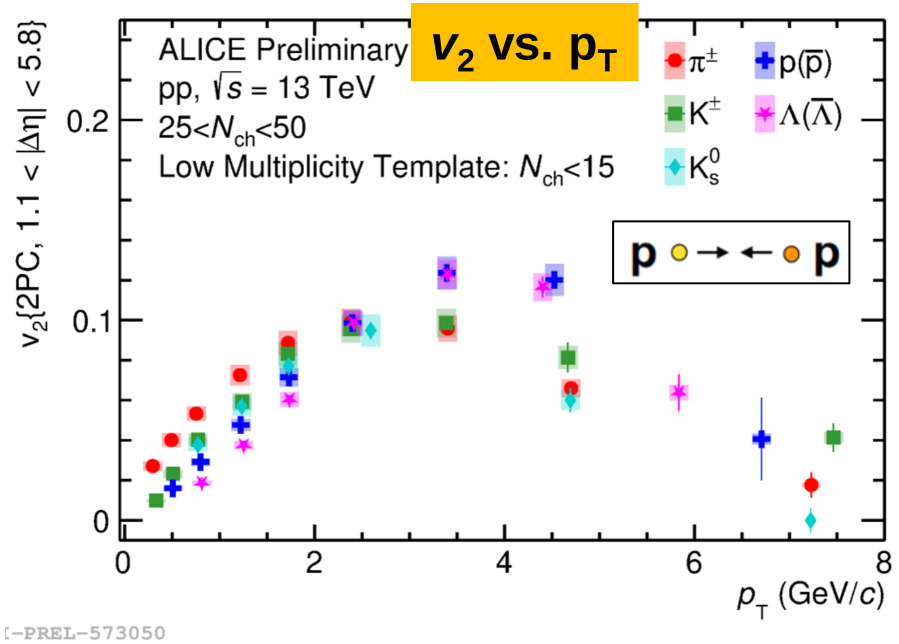


**Ridge component characterized with multi-particle correlations: pp ~ p-Pb < Pb-Pb**
**→ At least 6 particles involved above $N_{ch} \approx 90$**

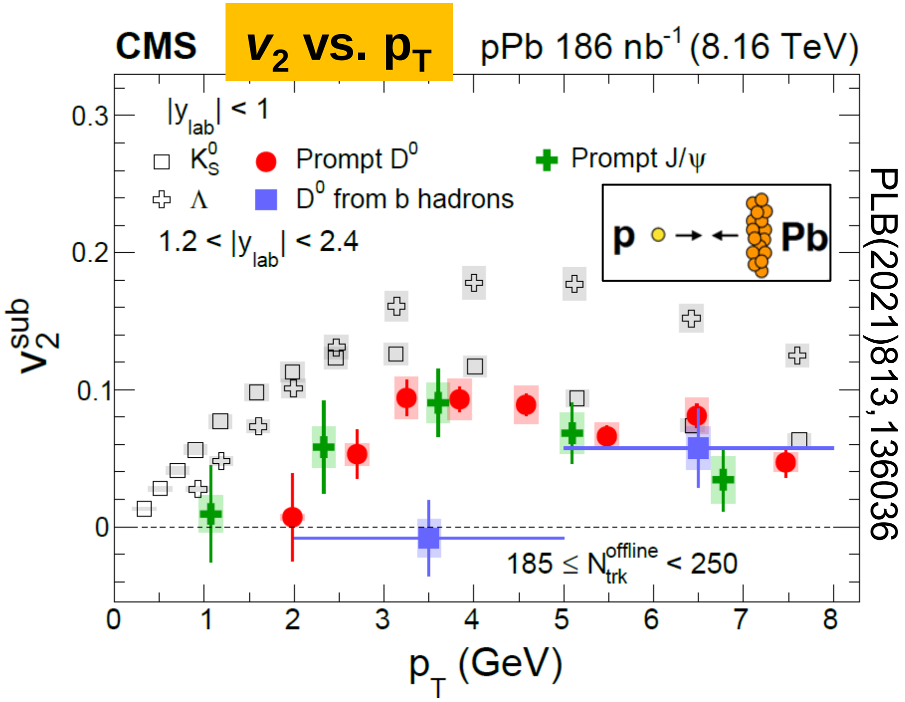
PLB 765 (2017) 193

# Identified-Particle Collectivity

- Light particles ($\pi$, K, p, $\phi$, $\Lambda$) 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/$\psi$ in high-multiplicity p-Pb coll.

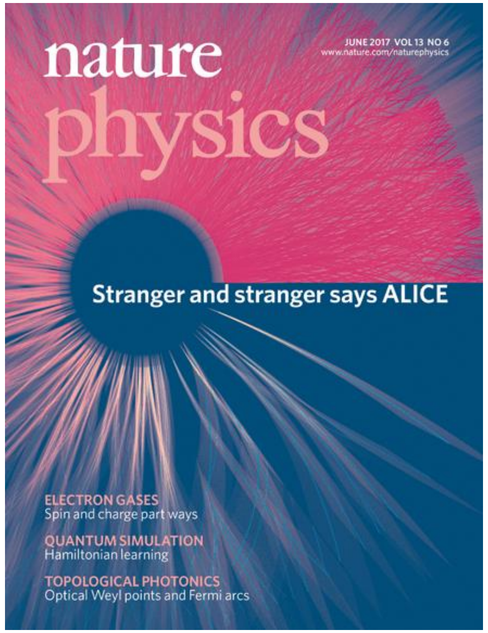


- Bottom quark flow in large systems
  - Large systems: affected by the medium (except $\Upsilon$)
  - Hint in high-multiplicity p-Pb collisions

# Second Discovery: Strangeness Enhancement

# Strangeness Enhancement

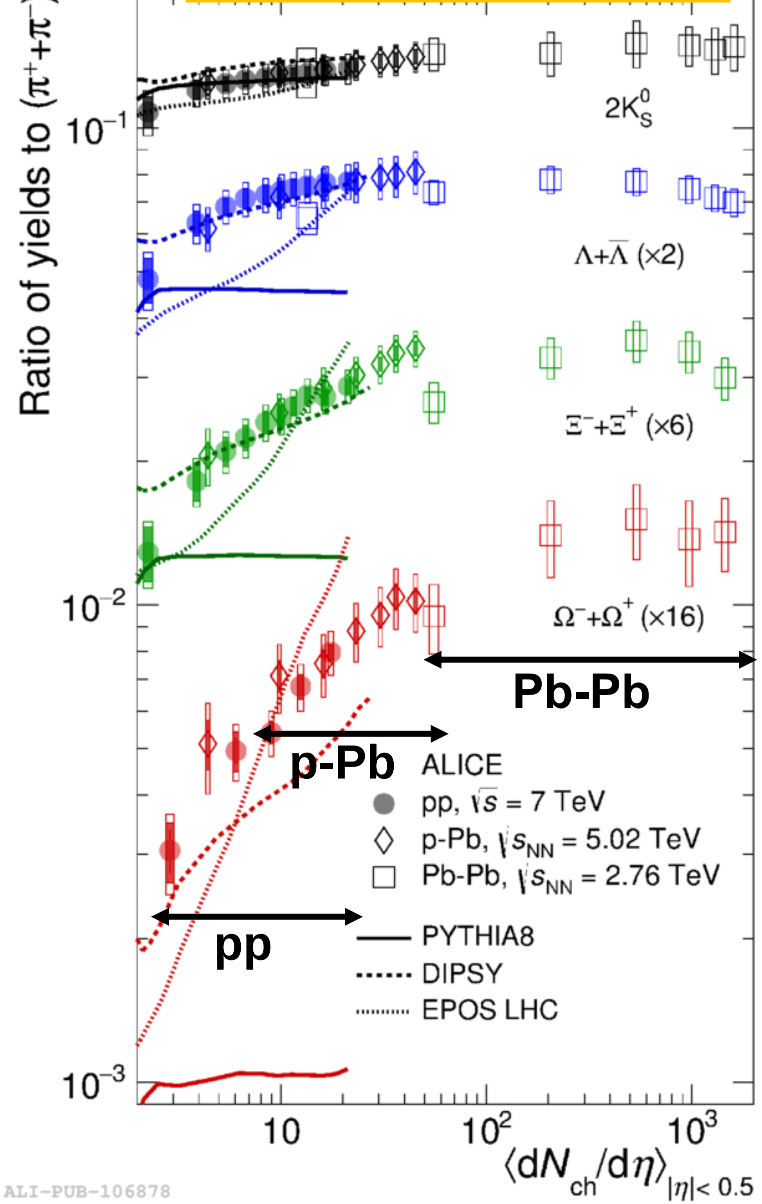
- Strange baryon production (K, $\Lambda$, $\Xi$, $\Omega$) increases faster than multiplicity
- Smooth across collision system from pp to Pb-Pb



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. $K$ $\bar{K}$

**Strange/$\pi$ vs. $dN_{ch}/d\eta$**
**(Strange = K, $\Lambda$, $\Xi$, $\Omega$)**



Nature Phys. 13 (2017) 535

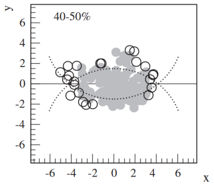
# Strangeness Enhancement

- Strange baryon production (K, Λ, Ξ, Ω) increases faster than multiplicity
- Smooth across collision system from pp to Pb-Pb

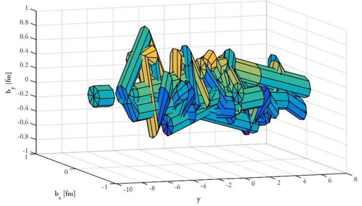
☒ Independent fragmentation

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

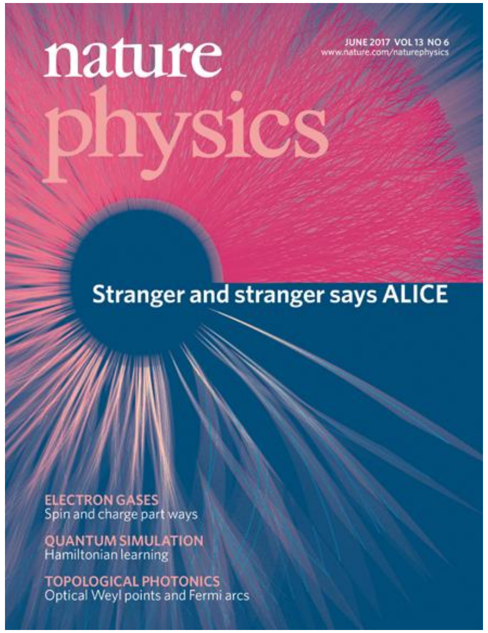
☑ EPOS (core-corona)



☑ Colour rope mechanism (DIPSY)



Christian Bierlich


nature physics

JUNE 2017 VOL 13 NO 6
www.nature.com/naturephysics

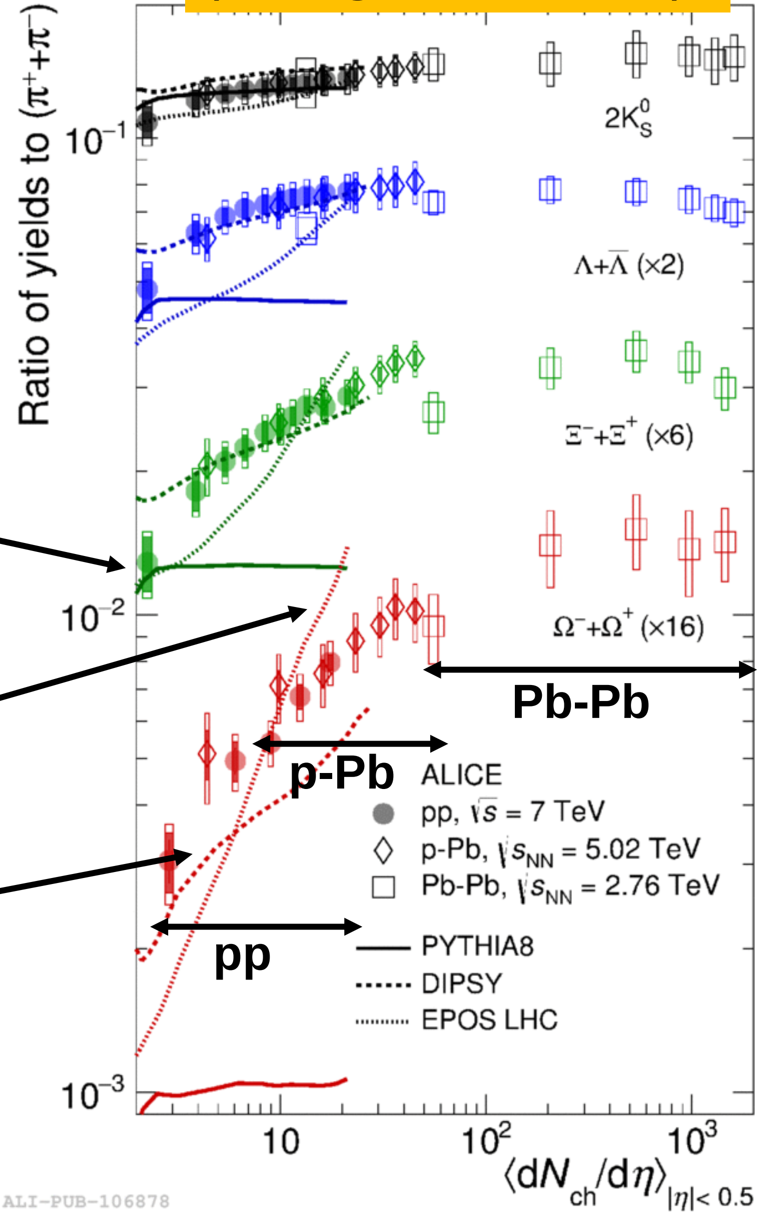
Stranger and stranger says ALICE

ELECTRON GASES
Spin and charge part ways

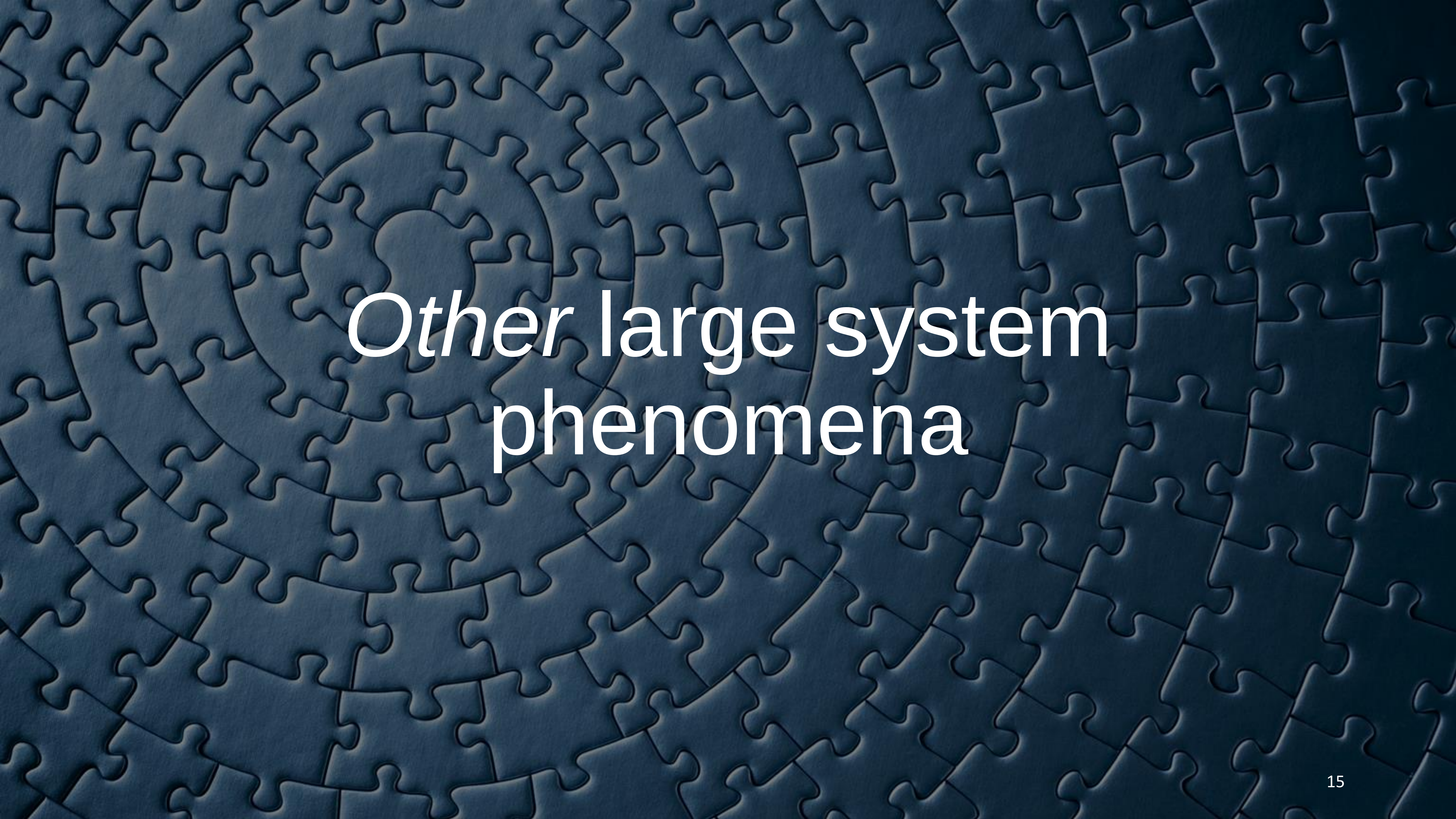
QUANTUM SIMULATION
Hamiltonian learning

TOPOLOGICAL PHOTONICS
Optical Weyl points and Fermi arcs

**Strange/π vs. $dN_{ch}/d\eta$**
**(Strange = K, Λ, Ξ, Ω)**



Nature Phys. 13 (2017) 535



# *Other* large system phenomena

# Energy Loss

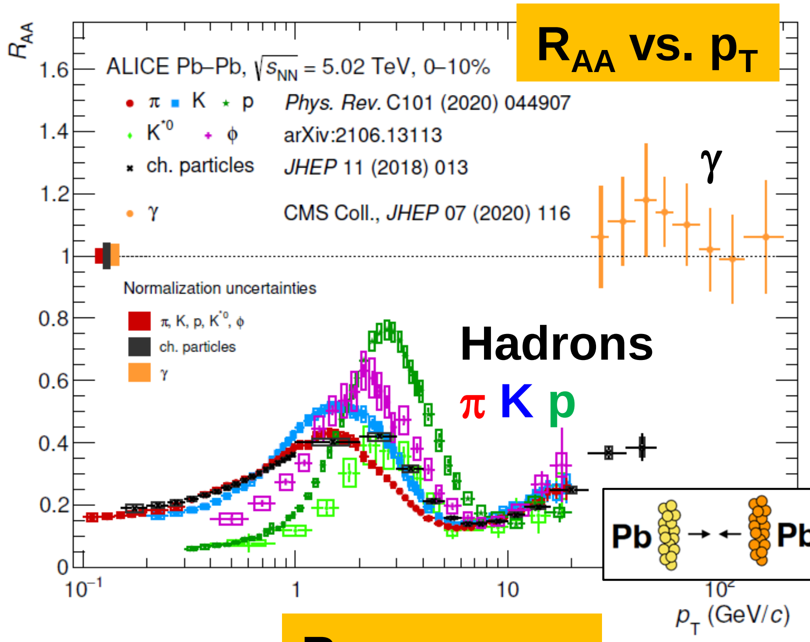
- Sizable multi-particle collective phenomena involving most species
  - If observed phenomena are due to final-state interactions, partons should lose energy
- Clear sign of energy loss in Pb-Pb collisions

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle dN_{pp}/dp_T}$$

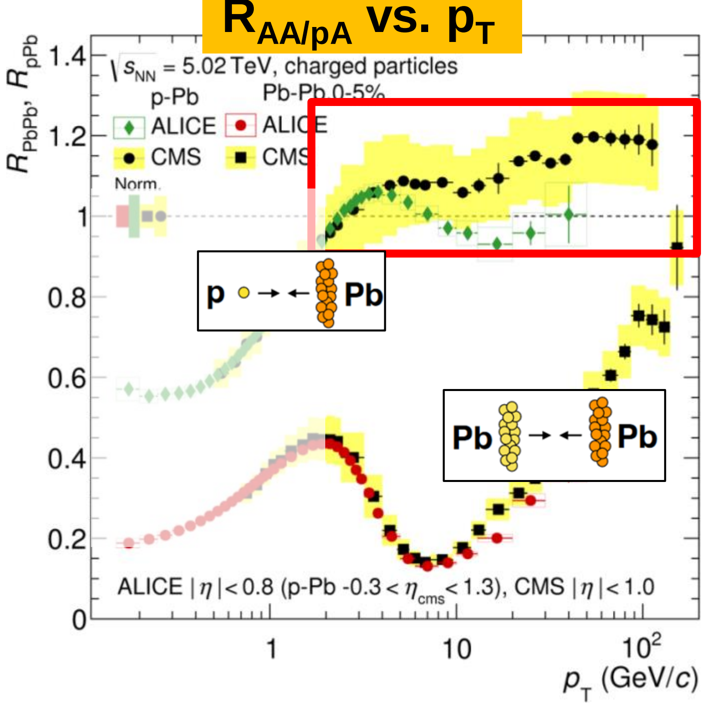
**$R_{AA}$ = 1 → no modification**

**$R_{AA}$ != 1 → medium effects**

- No sign of suppression in p-Pb collisions for hadrons, D and B mesons



arXiv:2211.04384



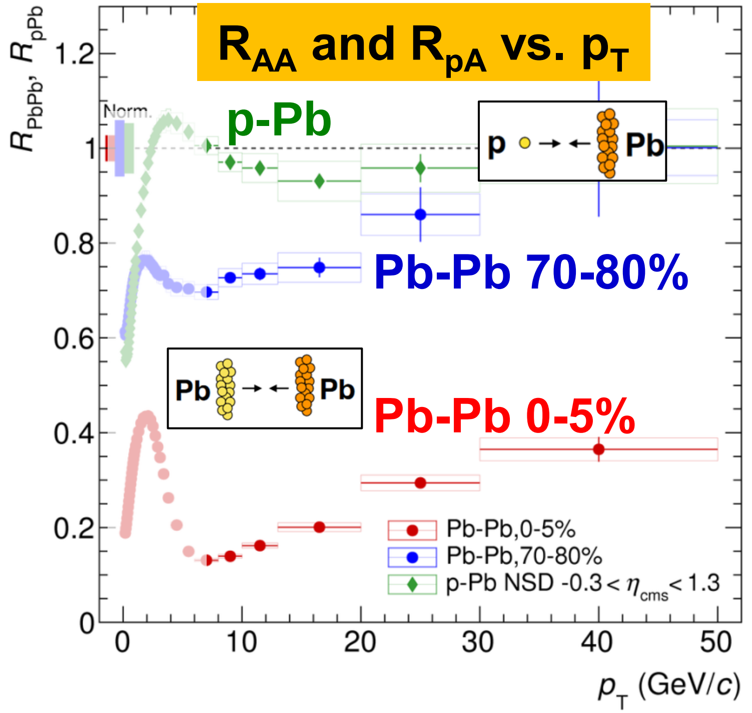
JHEP 1811 (2018) 013

# Absence of Energy Loss

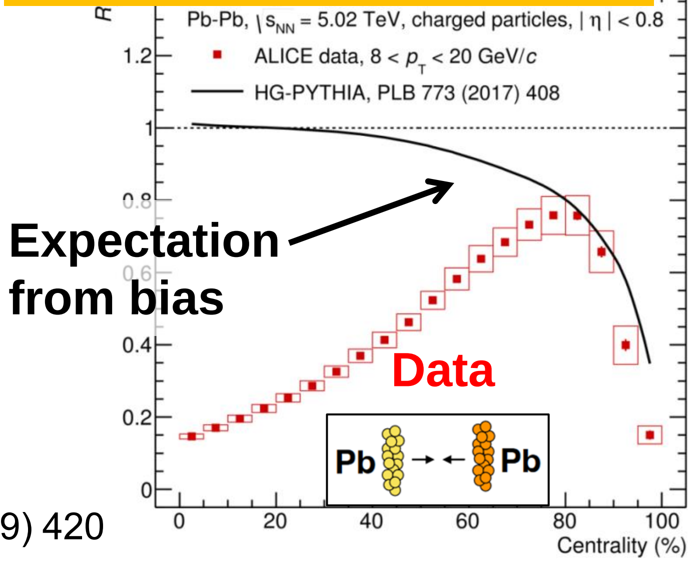
- No evidence of parton energy loss in p-Pb collisions
  - However, present in all Pb-Pb collisions
- When does energy loss turn on?
- Peripheral Pb-Pb has same size as average p-Pb
  - $R_{AA}$ ~ 0.8 (peripheral Pb-Pb) vs. $R_{pA}$ ~ 1 (p-Pb)
- Measurement in 80-100% clarified inconsistency
  - Reproduced by simple superposition model HG-PYTHIA (Loizides, Morsch, PLB773 (2017) 408)
  - Peripheral Pb-Pb: average NN impact parameter larger than in pp
- Negligible energy loss *already* in peripheral Pb-Pb coll.
  - Therefore, expectation in $R_{pA}$ also negligible

JHEP 04 (2017) 039, JHEP 1811 (2018) 013

**$R_{AA}$ and $R_{pA}$ vs. $p_T$**



**$R_{AA}$ (high $p_T$) vs. centrality**

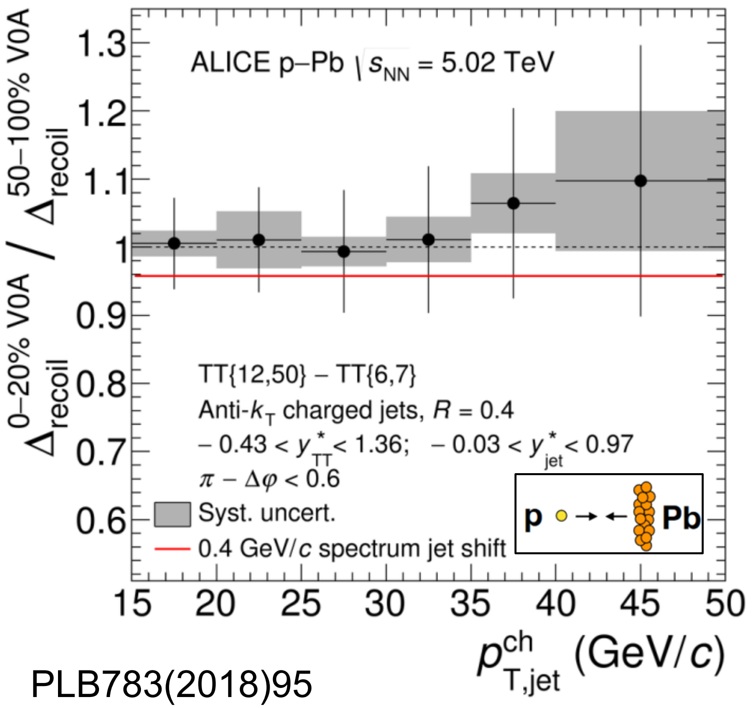


PLB793 (2019) 420

# Search for Energy Loss

- Single-particle observables (“$R_{pA}$”) not sensitive
- Coincidence measurements → h-jet, jet-$\gamma$, jet-Z correlations

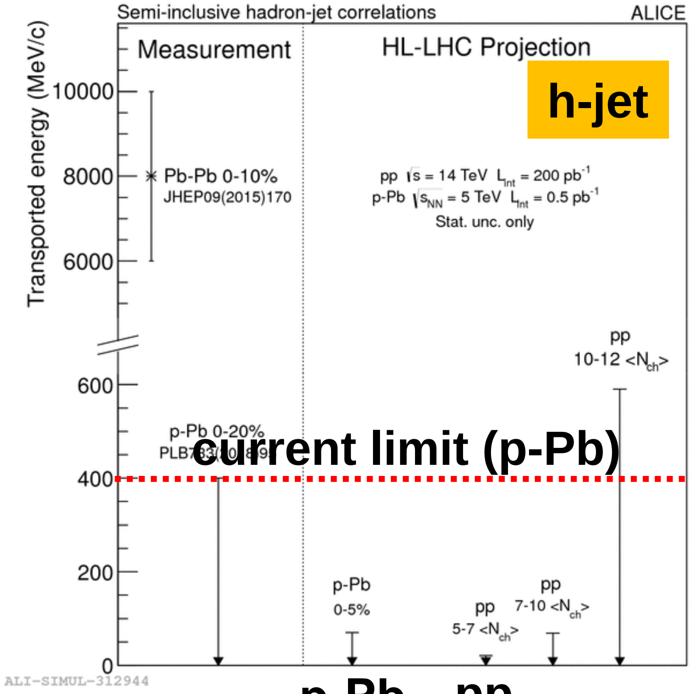
**h-jet coincidence**



PLB783(2018)95

**Transported energy:**
**in-cone → out-of-cone**

**Pb-Pb: ~8000 MeV/c**
**p-Pb: < 400 MeV/c (at 90% CL)**



**h-jet**

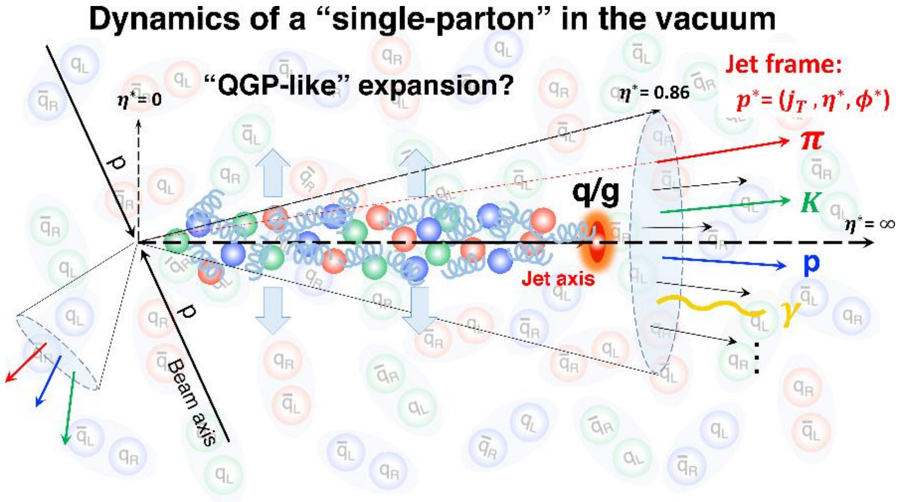
**current limit (p-Pb)**

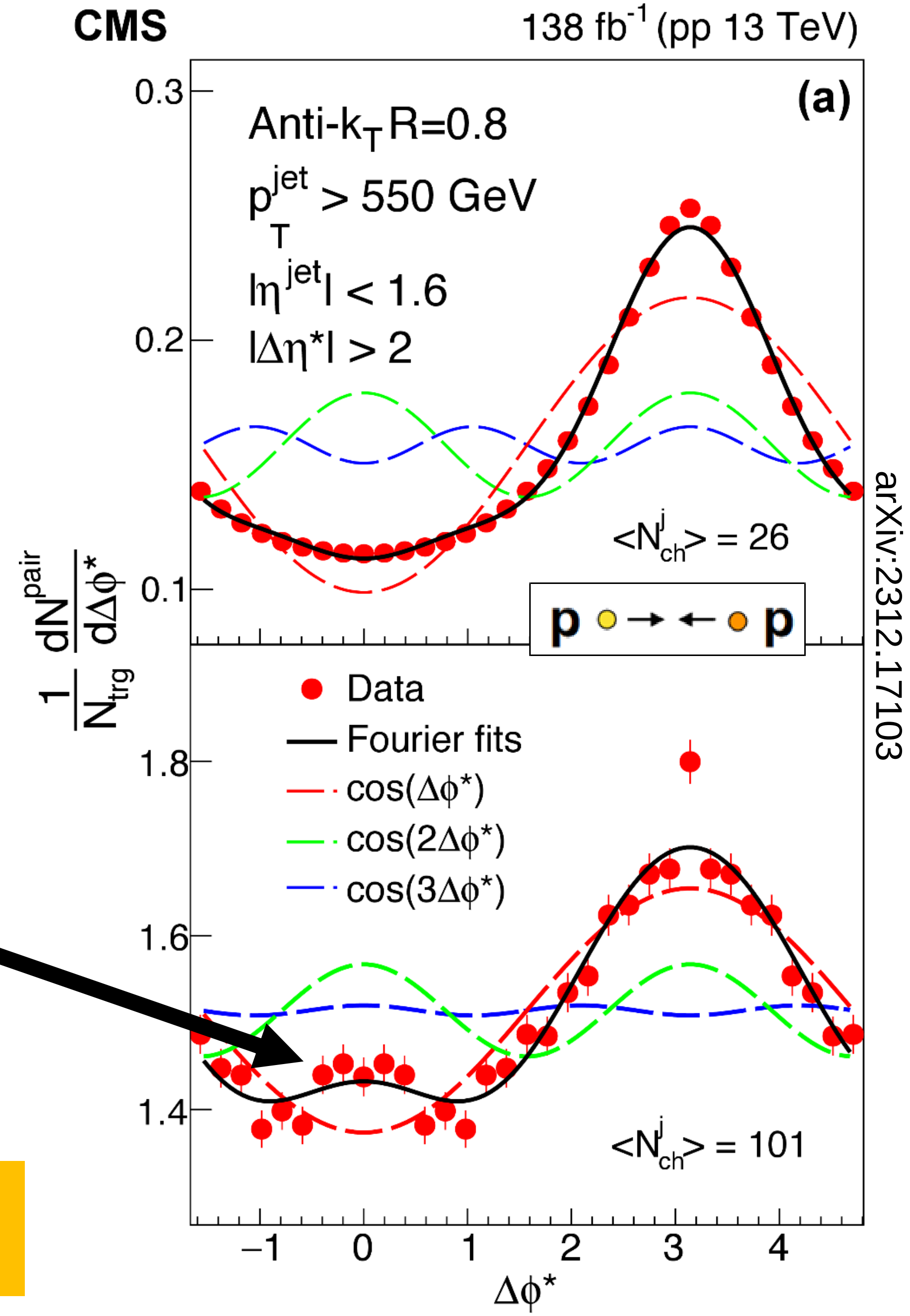
**p-Pb** **pp**

arXiv:1812.06772

# Very High Multiplicity Jets

- Particles in very dense jets
  - $p_T > 550$ GeV/c    $\langle N_{ch} \rangle = 101$
- 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?**

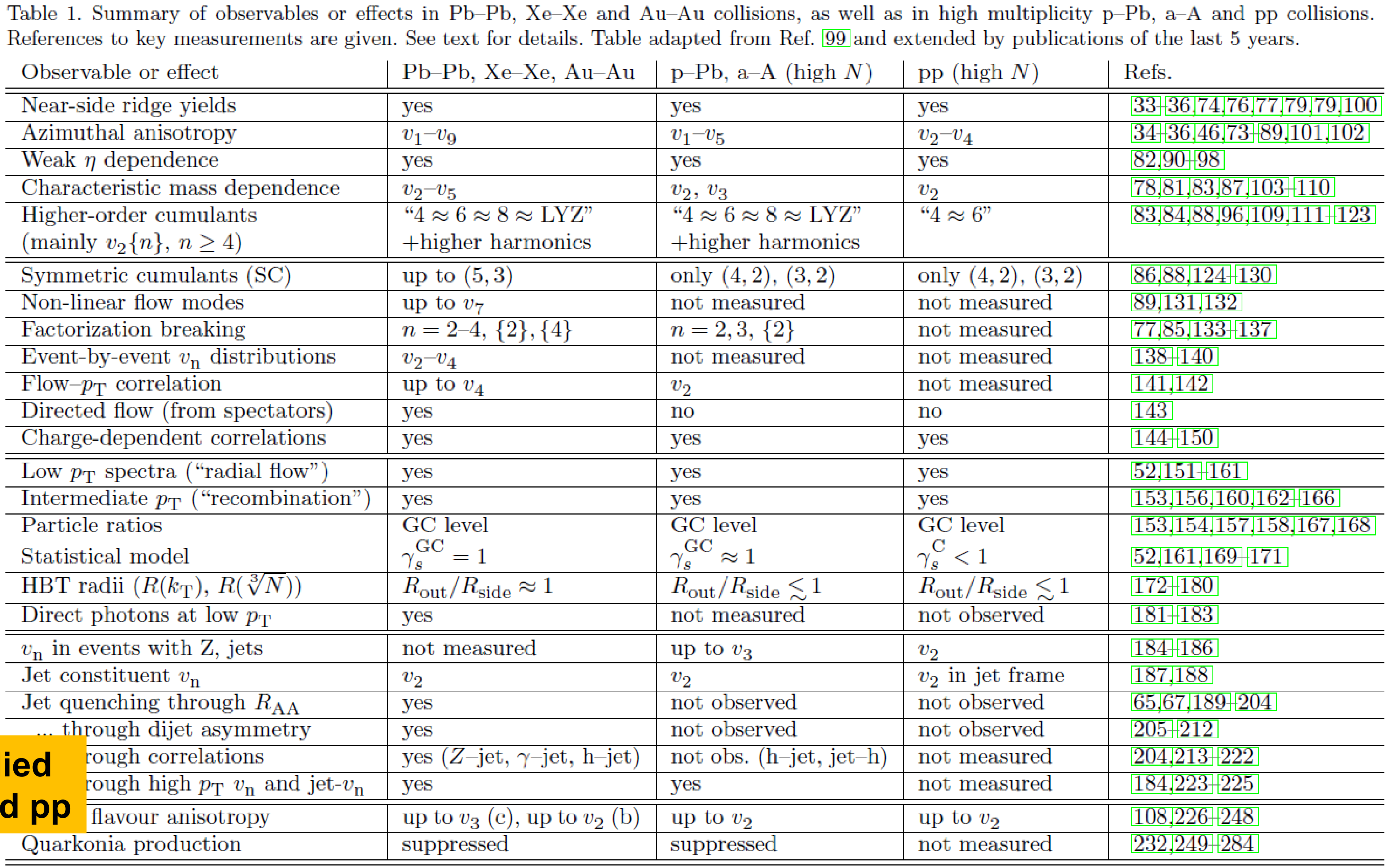


Table 1. Summary of observables or effects in Pb–Pb, Xe–Xe and Au–Au collisions, as well as in high multiplicity p–Pb, a–A and pp collisions. References to key measurements are given. See text for details. Table adapted from Ref. [99] and extended by publications of the last 5 years.

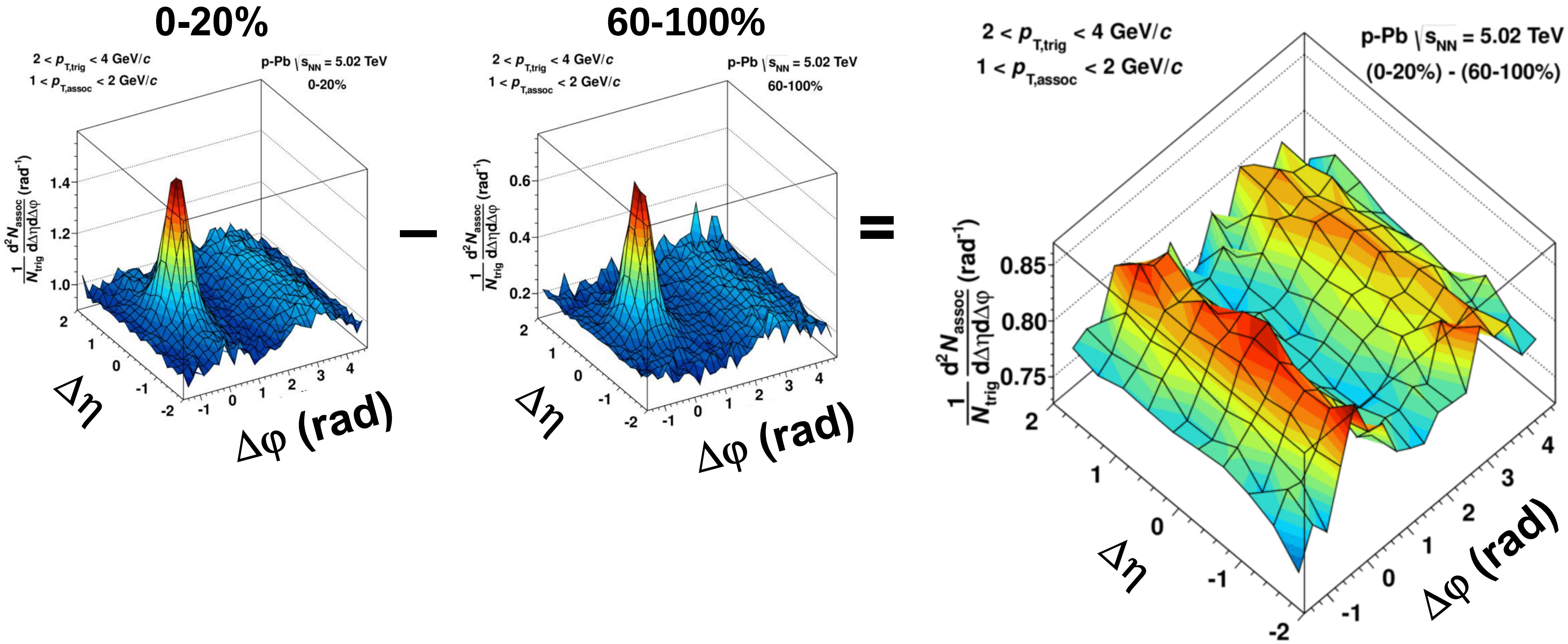
| Observable or effect | Pb–Pb, Xe–Xe, Au–Au | p–Pb, a–A (high $N$) | pp (high $N$) | Refs. |
|---|---|---|---|---|
| Near-side ridge yields | yes | yes | yes | 33–36,74,76,77,79,79,100 |
| Azimuthal anisotropy | $v_1$–$v_9$ | $v_1$–$v_5$ | $v_2$–$v_4$ | 34–36,46,73–89,101,102 |
| Weak $\eta$ dependence | 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<br>(mainly $v_2\{n\}$, $n \geq 4$) | "$4 \approx 6 \approx 8 \approx$ LYZ"<br>+higher harmonics | "$4 \approx 6 \approx 8 \approx$ LYZ"<br>+higher harmonics | "$4 \approx 6$" | 83,84,88,96,109,111–123 |
| 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 $v_{\mathrm{n}}$ distributions | $v_2$–$v_4$ | not measured | not measured | 138–140 |
| Flow–$p_{\mathrm{T}}$ 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 $p_{\mathrm{T}}$ spectra ("radial flow") | yes | yes | yes | 52,151–161 |
| Intermediate $p_{\mathrm{T}}$ ("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 | $\gamma_s^{\mathrm{GC}} = 1$ | $\gamma_s^{\mathrm{GC}} \approx 1$ | $\gamma_s^{\mathrm{C}} < 1$ | 52,161,169–171 |
| HBT radii ($R(k_{\mathrm{T}})$, $R(\sqrt[3]{N})$) | $R_{\mathrm{out}}/R_{\mathrm{side}} \approx 1$ | $R_{\mathrm{out}}/R_{\mathrm{side}} \lesssim 1$ | $R_{\mathrm{out}}/R_{\mathrm{side}} \lesssim 1$ | 172–180 |
| Direct photons at low $p_{\mathrm{T}}$ | yes | not measured | not observed | 181–183 |
| $v_{\mathrm{n}}$ in events with Z, jets | not measured | up to $v_3$ | $v_2$ | 184–186 |
| Jet constituent $v_{\mathrm{n}}$ | $v_2$ | $v_2$ | $v_2$ in jet frame | 187,188 |
| Jet quenching through $R_{\mathrm{AA}}$ | yes | not observed | not observed | 65,67,189–204 |
| ... through dijet asymmetry | yes | not observed | not observed | 205–212 |
| rough correlations | yes ($Z$–jet, $\gamma$–jet, h–jet) | not obs. (h–jet, jet–h) | not measured | 204,213–222 |
| rough high $p_{\mathrm{T}}$ $v_{\mathrm{n}}$ and jet-$v_{\mathrm{n}}$ | yes | yes | not measured | 184,223–225 |
| 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 |

**Most observables studied in AA, high mult. pA and pp**

arXiv:2407.07484

# Even Smaller Systems…

# Basics: Subtraction Procedures



**worked well as long as the statistical uncertainties were large…**

PLB719 (2013) 29

# Subtraction Procedures

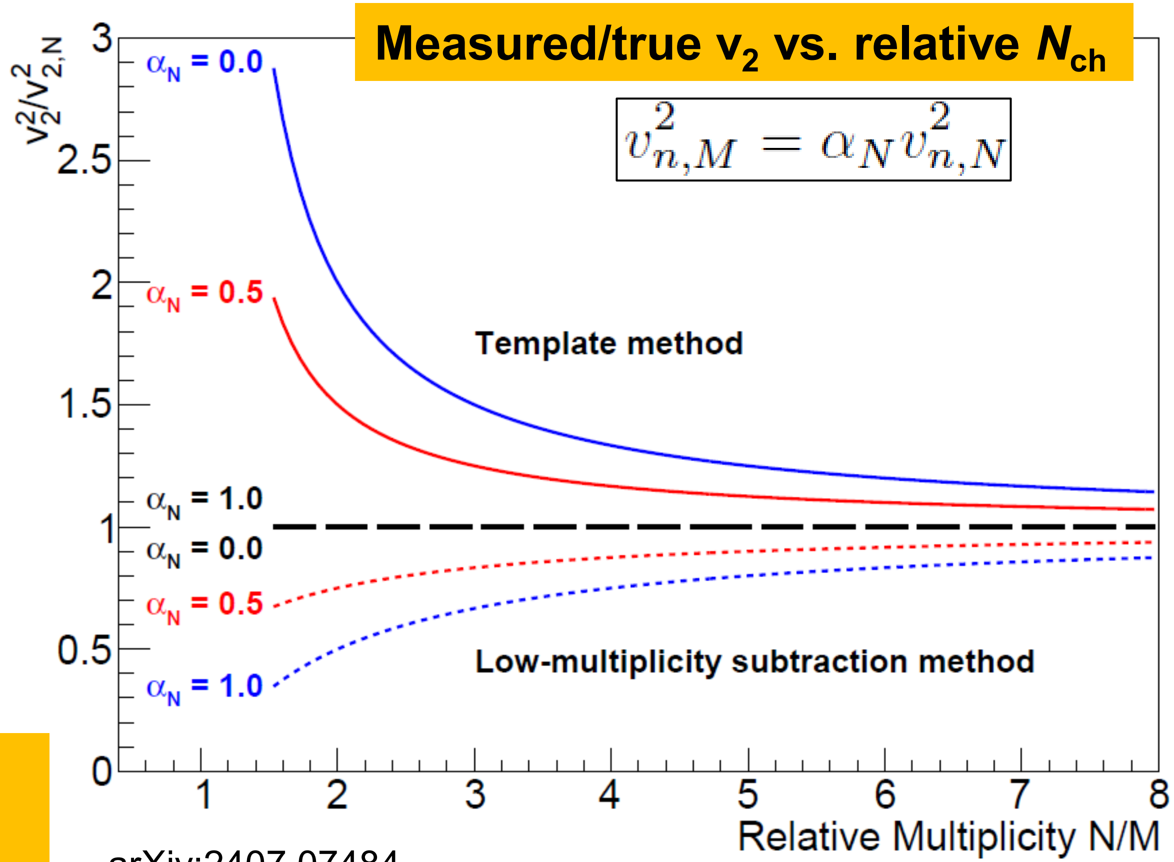
- Extracting $v_2$ coefficient requires subtraction procedure $\Delta Y(\Delta\varphi) = Y_N - a\,Y_M$
- Accuracy of procedures depends on $v_2(N_{ch})$. Let's assume: $v^2_{n,M} = \alpha_N v^2_{n,N}$
- Low-multiplicity subtraction

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

  - 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 ($\alpha_N = 1$)



arXiv:2407.07484

**Experimental result procedure dependent – in particular at low multiplicity**

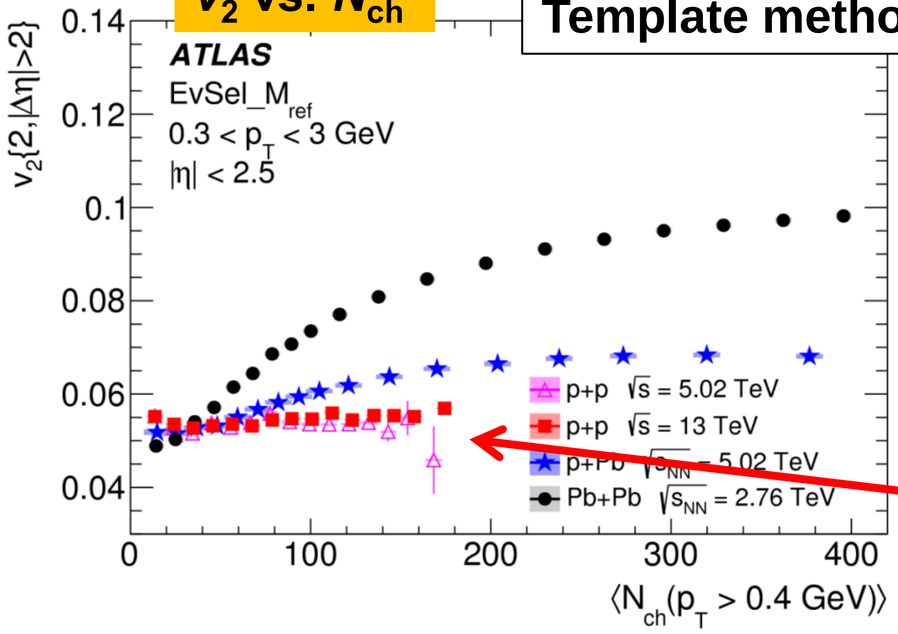
# Low Multiplicity

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)

**$v_2$ vs. $N_{ch}$**

**Template method**

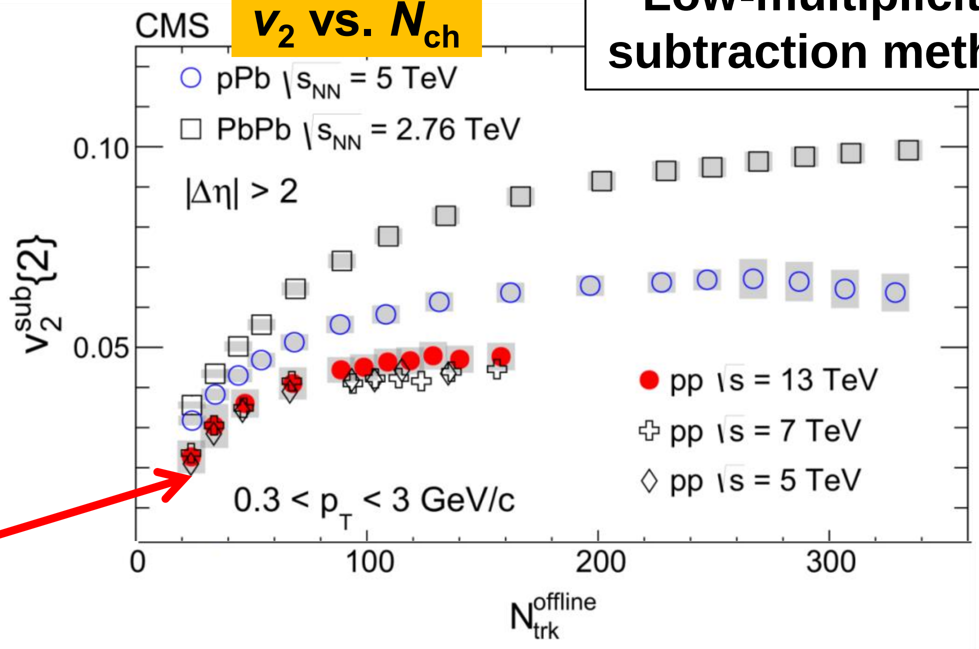


EPJC 77 (2017) 428

**p → ← p**

**$v_2$ vs. $N_{ch}$**

**Low-multiplicity subtraction method**



PLB 765 (2017) 193

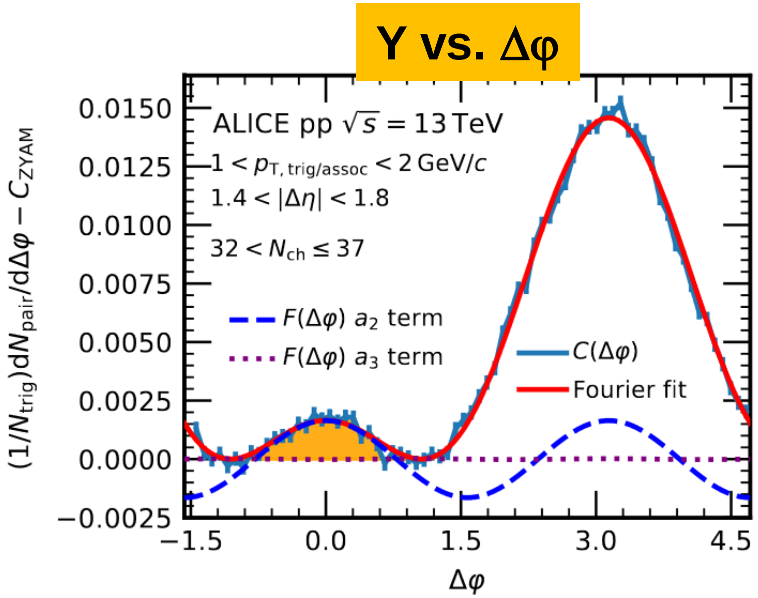
**Experimental result procedure dependent – in particular at low multiplicity**

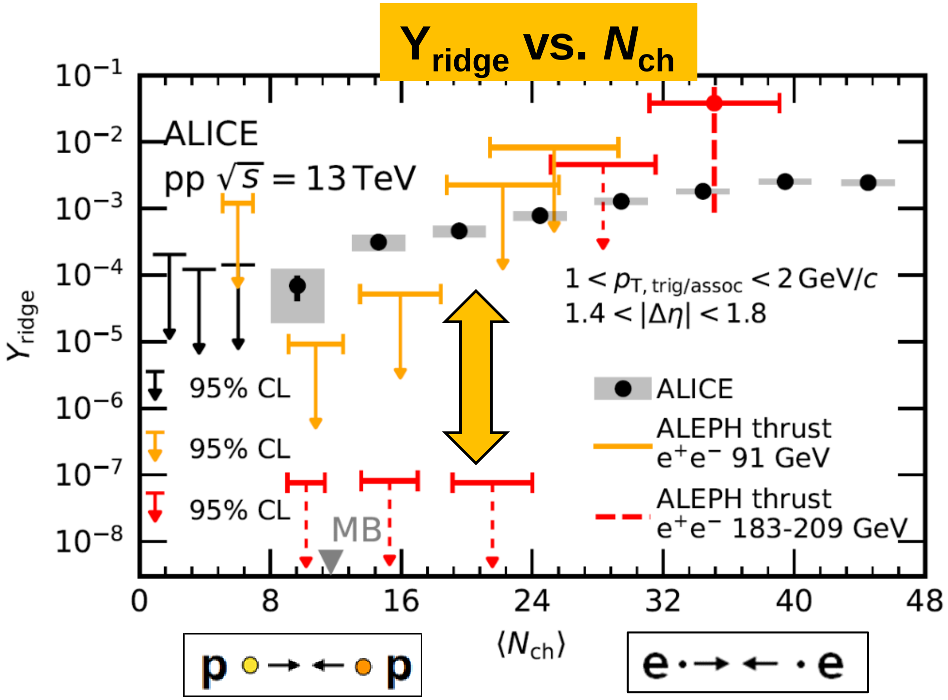
# Low Multiplicity
## and $e^+e^-$ and ep

- Low-multiplicity pp collisions studied on near side
  - Near-side ridge found for $N_{ch}$ as low as minimum bias

- $e^+e^-$ (ALEPH) and ep (HERA) data re-analyzed
  - Thrust axis analysis on archived data
  - 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
    (see backup)

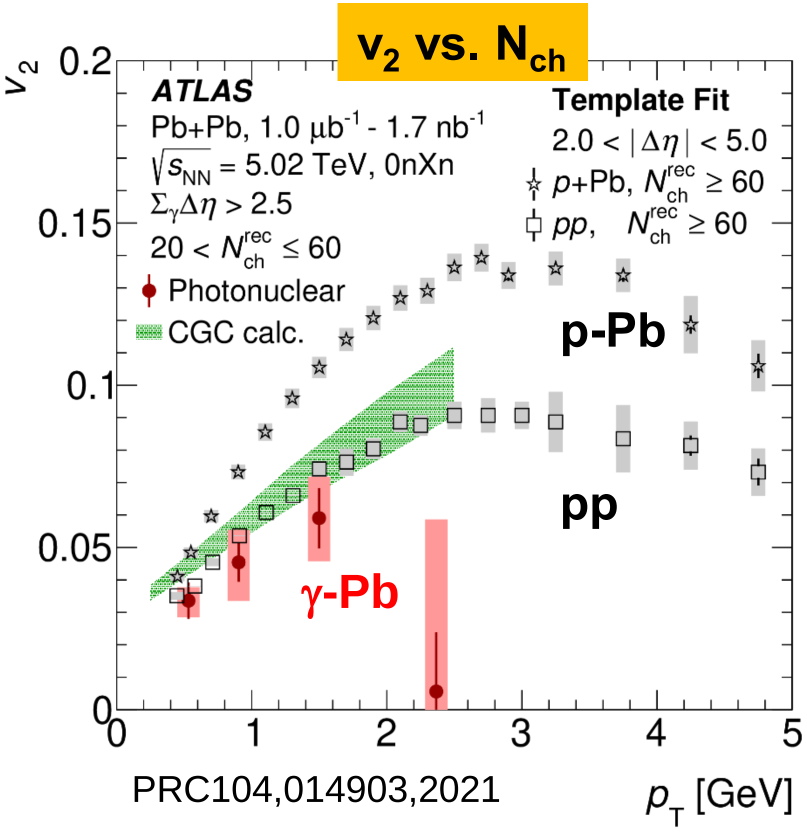




PRL 132 (2024) 17, 172302

# Ridge in γ-p and γ-Pb Collisions

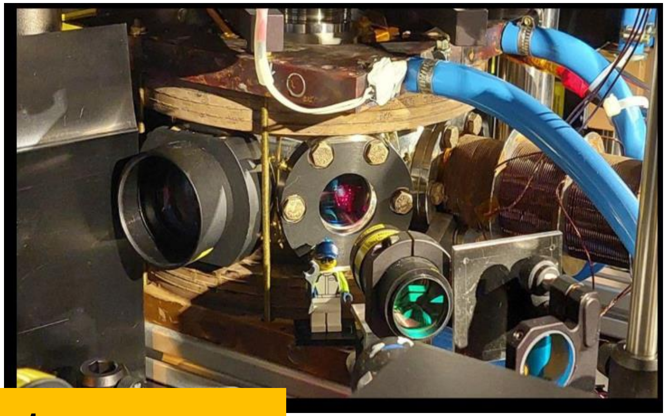
- Ultra-peripheral Pb-Pb collisions give access to γ-p and γ-Pb collisions (electromagnetic cloud)
  - Interpreted as probe of the initial state
- Extremely small signal
  - Subtraction methods needed
- γ-p
  - No ridge structures ($v_2$ explained by “standard” MCs), (PLB,844:137905,2023)
- γ-Pb
  - $v_2$ finite
  - Magnitude similar to pp, about 50% smaller than p-Pb



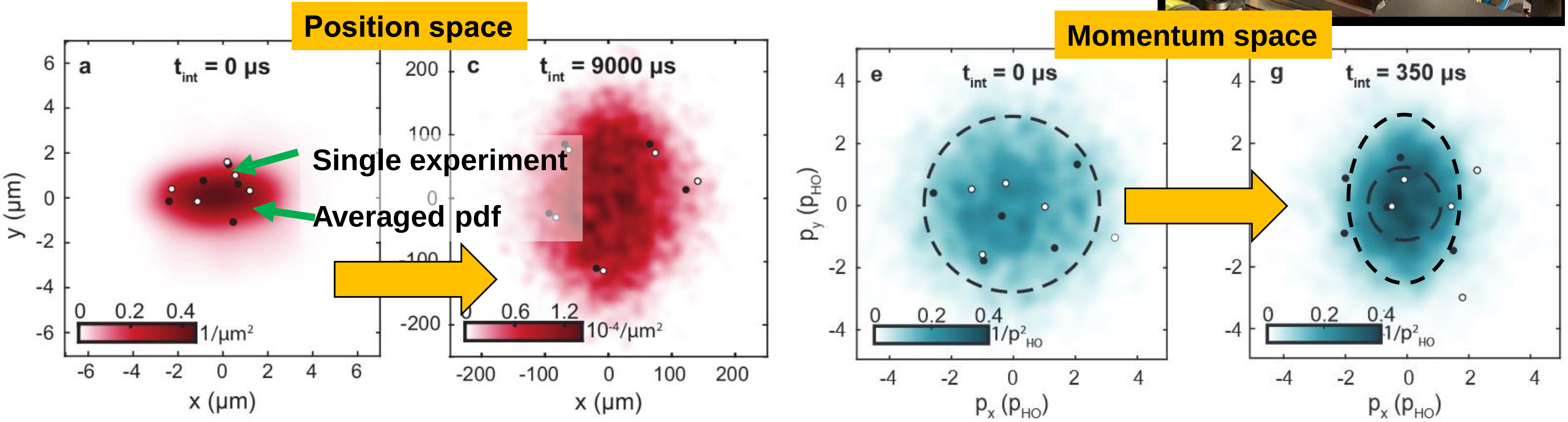
**$v_2$ vs. $N_{ch}$**

PRC104,014903,2021

# Collectivity with "large" objects



- About 10 ultracold Lithium atoms in elliptic trap



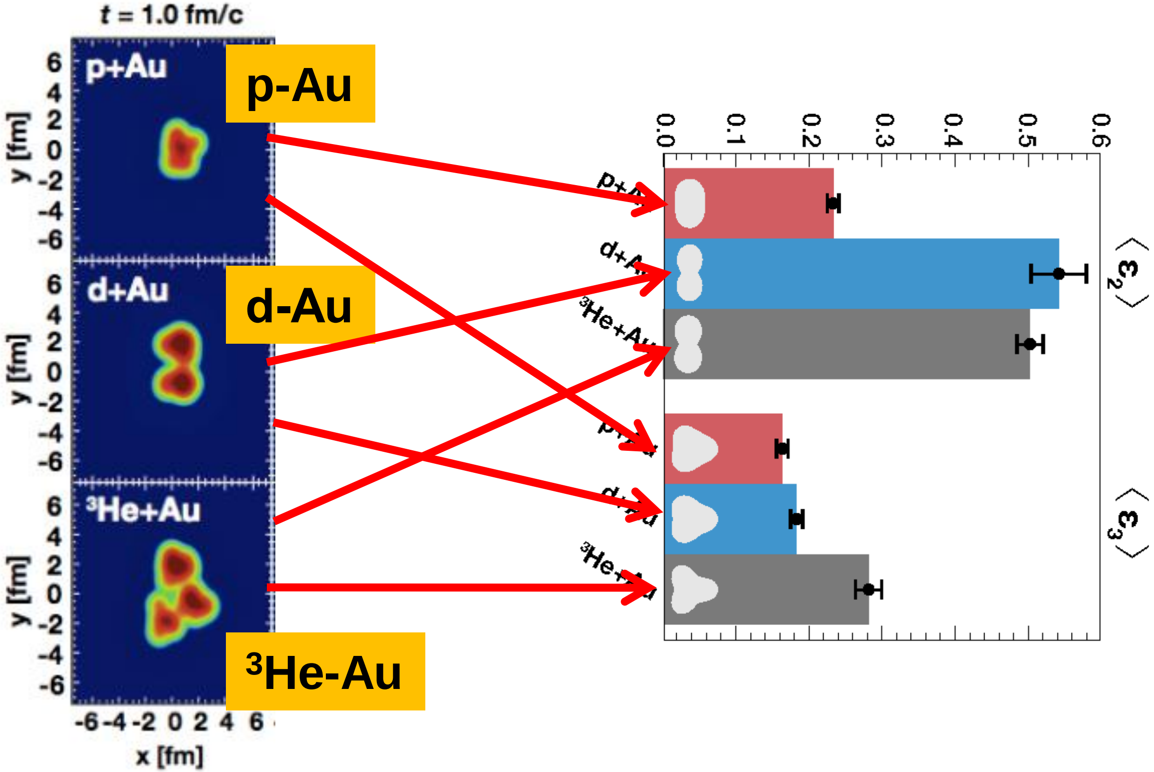
- Shape inversion + buildup of momentum anisotropy
- Above 6 atoms, hydrodynamic behavior observed

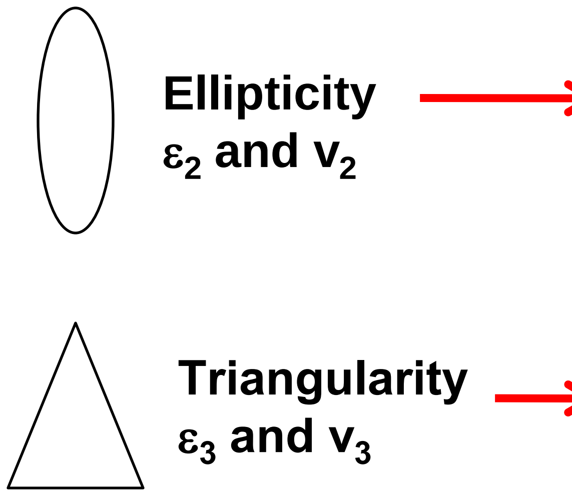
arXiv:2308.09699

# Other Ion Species

# Quark-Gluon droplets engineered

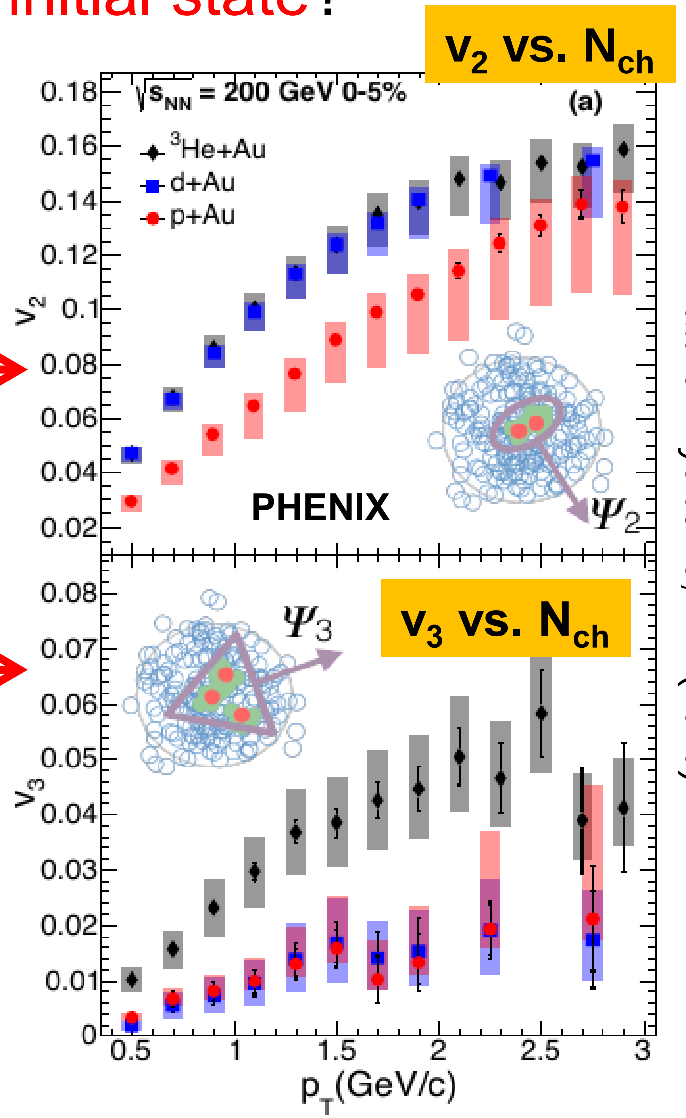
What is the relation to the overlap shape of the initial state?





**Ellipticity**
$\varepsilon_2$ and $v_2$

**Triangularity**
$\varepsilon_3$ and $v_3$



Nature Physics 15, 214 (2019)

**Initial-state anisotropy imprinted on final-state observable**
**Requires hydrodynamic expansion (spatial → momentum)**

⚠ **but…**

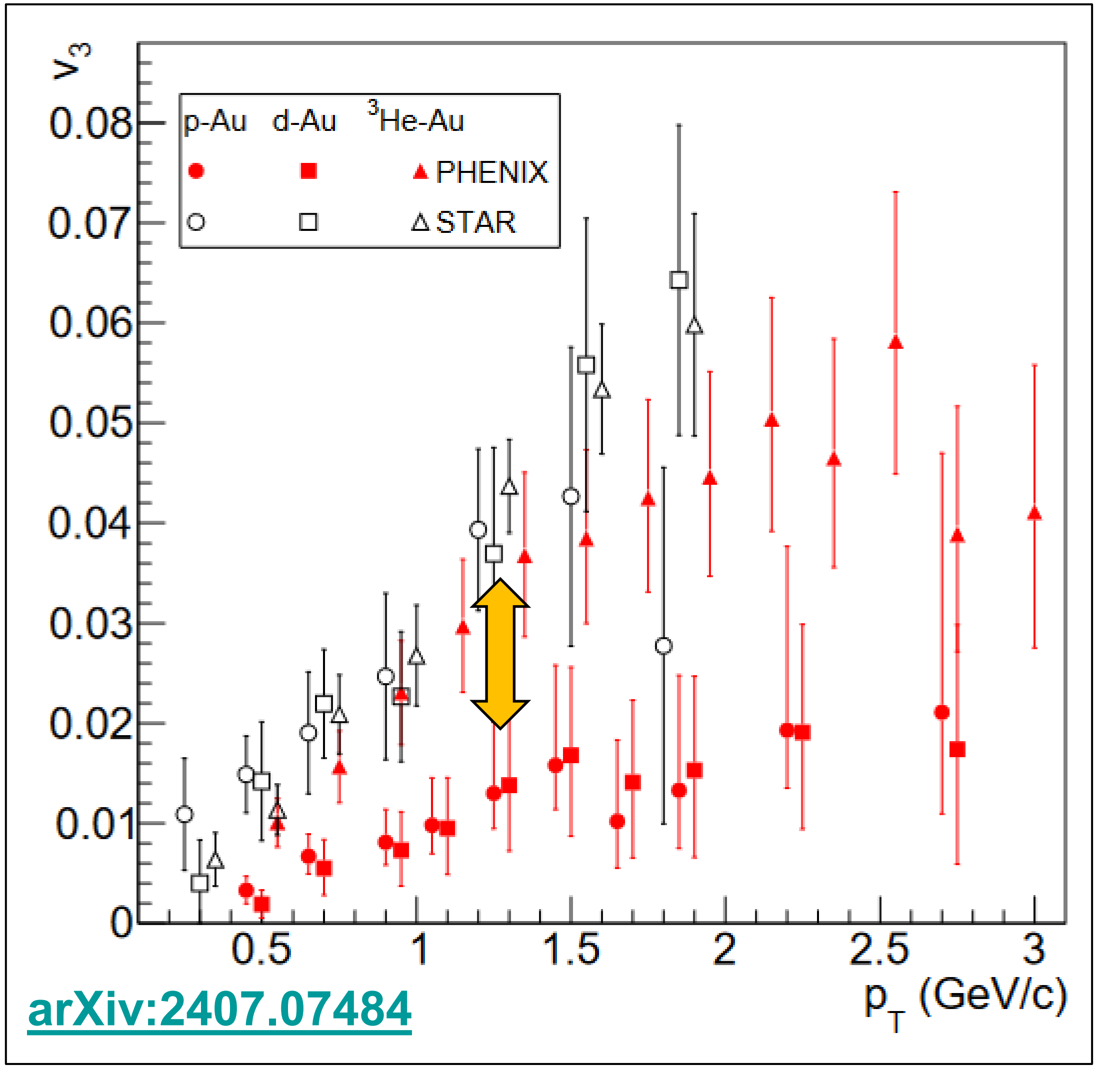
# Quark-Gluon droplets engineered

What is the relation to the overlap shape of the initial state?

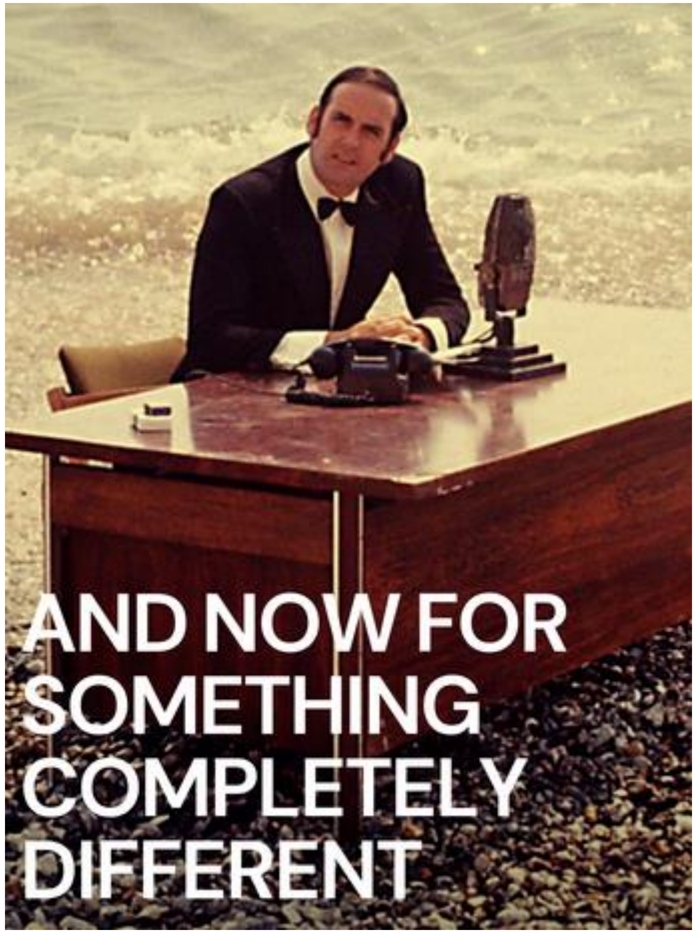
⚠ STAR and PHENIX inconsistent

- Different picture emerges
  - PHENIX: $v_3$ larger in $^3$He-Au wrt p-Au, d-Au (Nature Physics 15, 214 (2019))
  - STAR: $v_3$ in p-Au, d-Au, $^3$He-Au similar (PRL130(24):242301, 2023)
- Only part of differences can be attributed to method differences (e.g. PRC107(1):014904, 2023)
  - PHENIX: event-plane method with detectors at $-3.9 < \eta < -3.1$ and $|\eta| < 0.35$
  - STAR: template method with both particles within $|\eta| < 0.9$ and an $\eta$-gap of 1 unit

**Very important to resolve this experimental discrepancy!**



arXiv:2407.07484

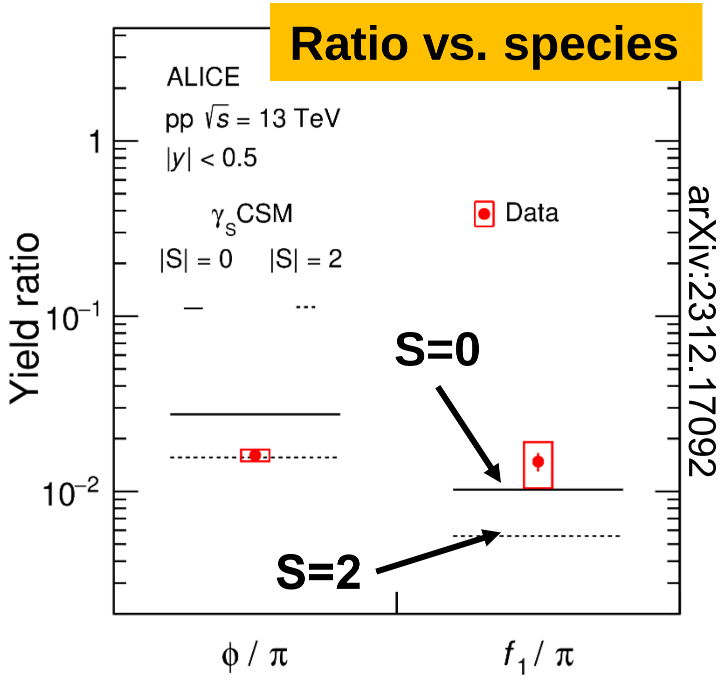

AND NOW FOR
SOMETHING
COMPLETELY
DIFFERENT

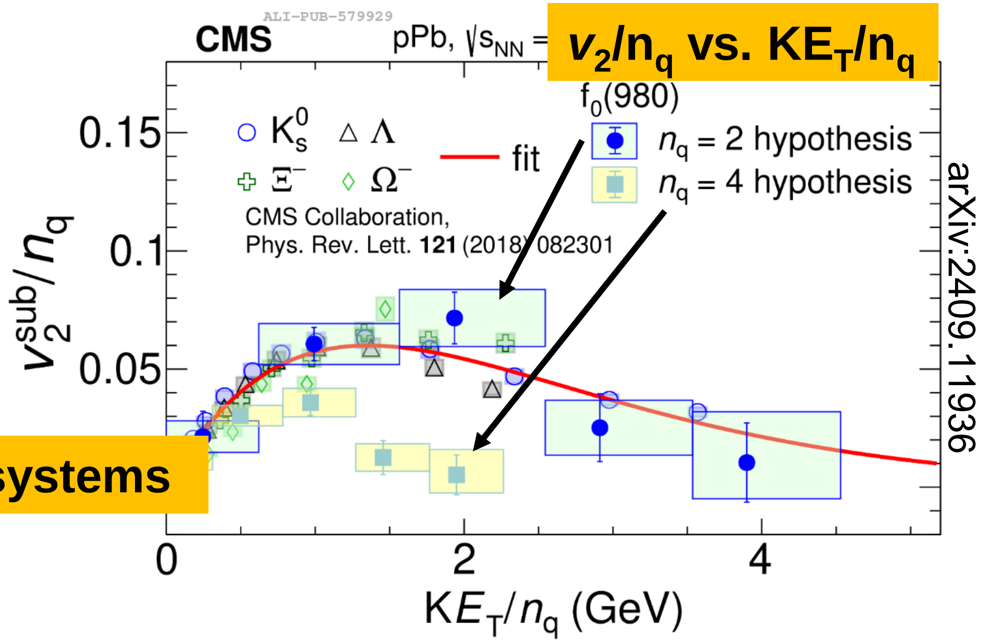
# Nature of $f_0(980)$ and $f_1(1285)$

- 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 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





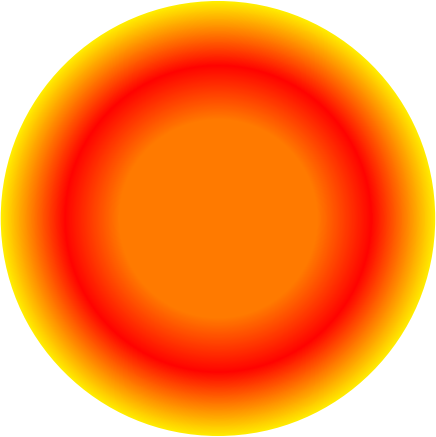
**Large system concepts used* to shed light on objects in smaller systems**

*assuming the concepts are valid in small systems

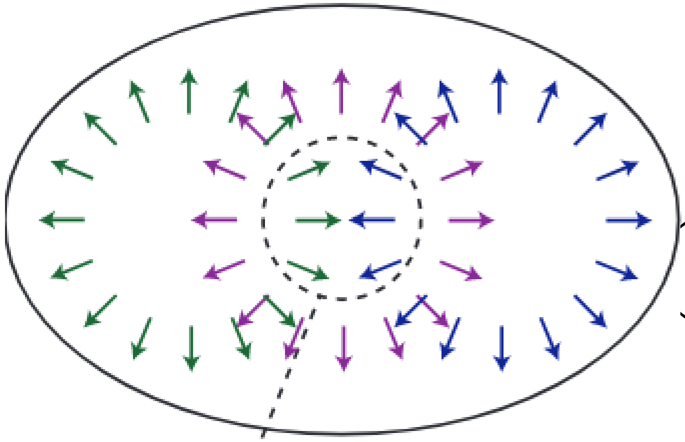
# Explanations

# Explanations

Hydrodynamic evolution

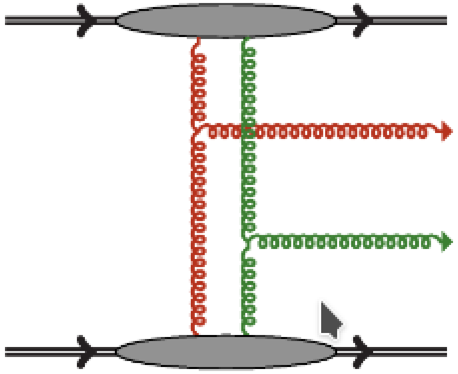


Kinetic theory / transport models



PLB783(2018) 274
PLB753(2016)506

Initial-momentum correlations



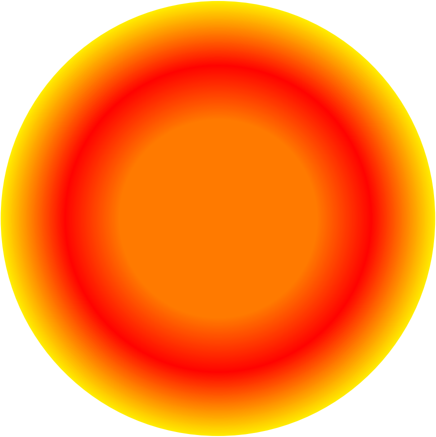
PRD87(2013) 9,094034

Many scatterings ↔ Few scatterings ↔ Initial conditions

(Perfect) fluid dynamics ↔ free streaming limit

# Explanations: Hydrodynamics

Hydrodynamic evolution

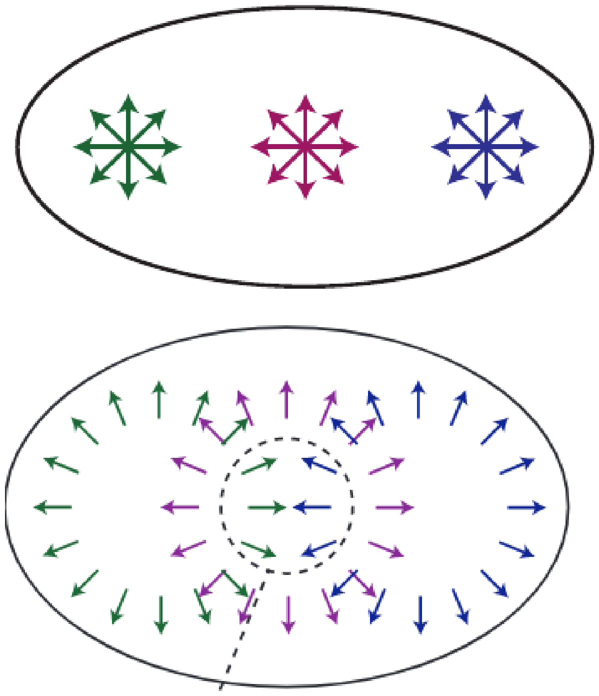


Many scatterings

- 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

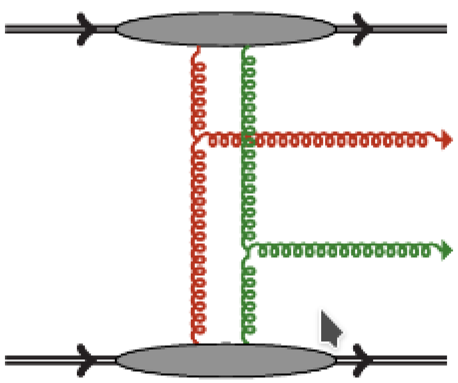
PLB753(2016)506

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
- Yet, MC implementation AMPT reproduces $v_n$ with small number of interactions

# Explanations: Initial State

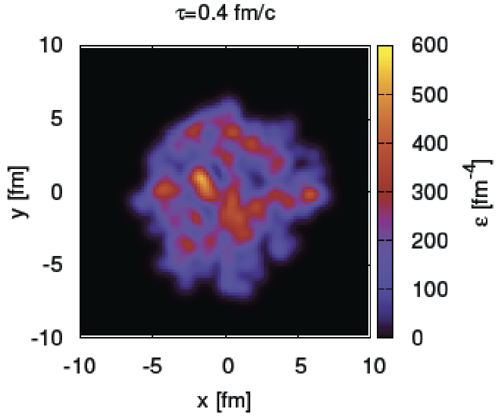
Initial-momentum correlations



PRD87(2013) 9,094034

Initial conditions

- (Sub)nucleonic fluctuations in the incoming projectiles



- Saturation at low x
- Quantum interference between emissions from different sources

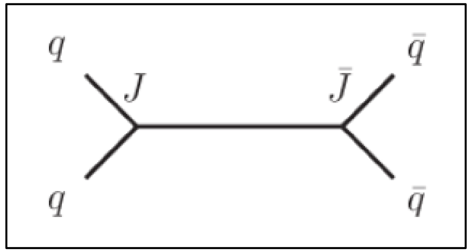
- Today, it is mostly excluded that a large fraction of the observed effects are due to initial-state momentum correlations
(see e.g. PRL121 (2018) 5, 052301)

# Phenomenology

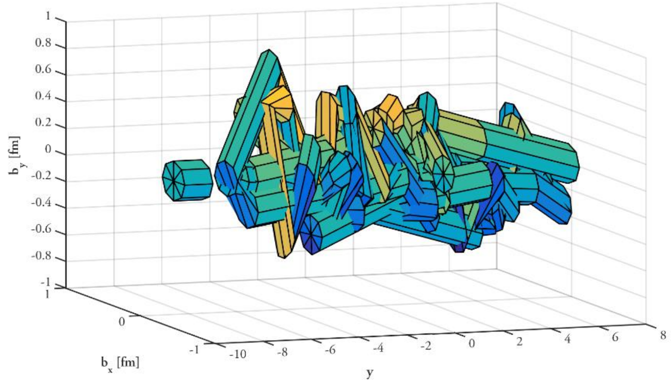
- Hadronization beyond incoherent superposition and leading color
  - Color reconnections for $\langle p_T \rangle$
  - Junctions for baryon production like in PYTHIA

- Collective-like phenomena
  - Colour ropes like in PYTHIA/DIPSY

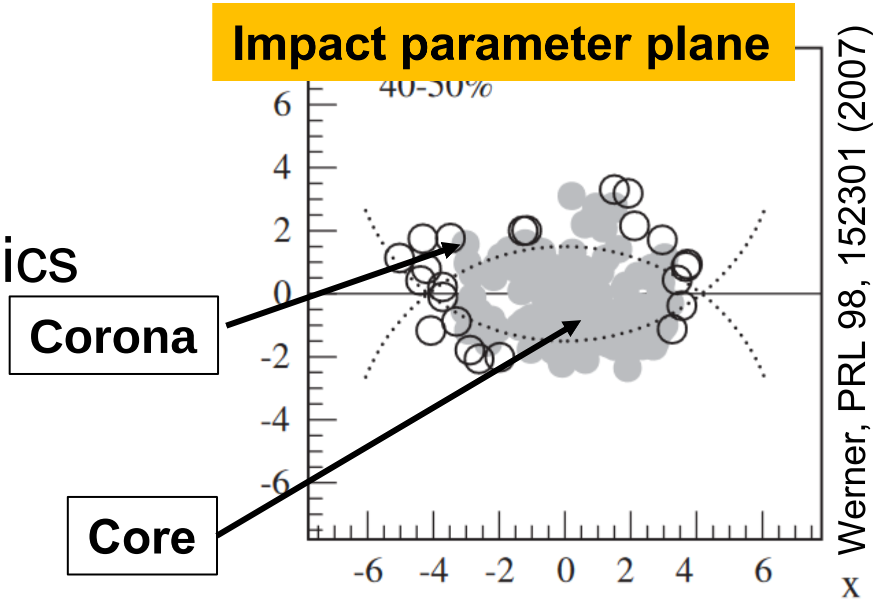
- Combining vacuum hadronization and hydrodynamics
  - Core-corona models like in EPOS
  - Corona: vacuum-like
  - Core: hydrodynamic evolution



JHEP 08(2015)003



Christian Bierlich


Impact parameter plane

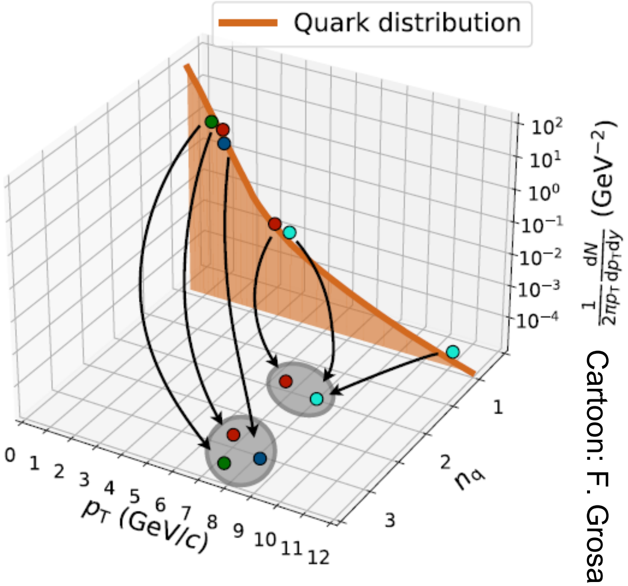
Corona

Core

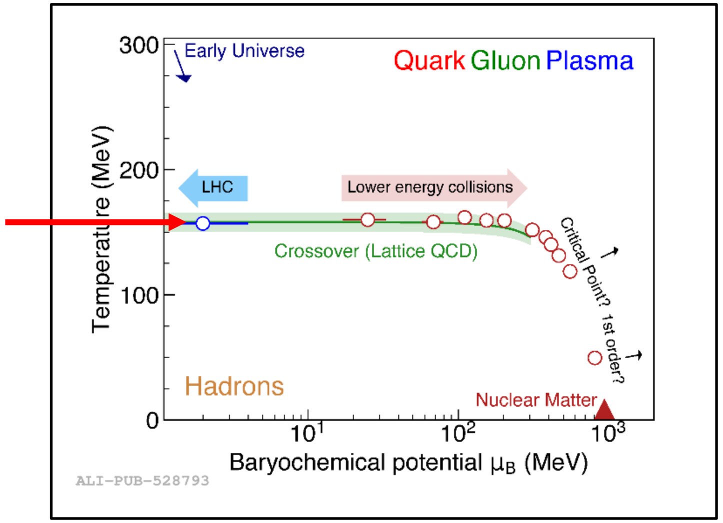
Werner, PRL 98, 152301 (2007)

# 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, $\mu_B$
  - Central Pb-Pb at LHC
    - T = 156 ± 2 MeV
    - $\mu_B$ = 0.7 ± 3.8 MeV
    - V ~ 5000 ± 500 $fm^3$

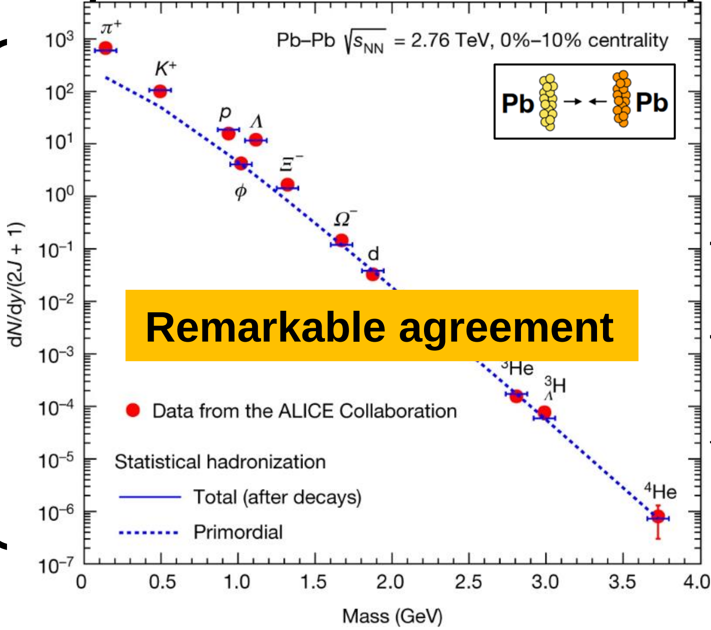


Cartoon: F. Grosa



**11 different species**

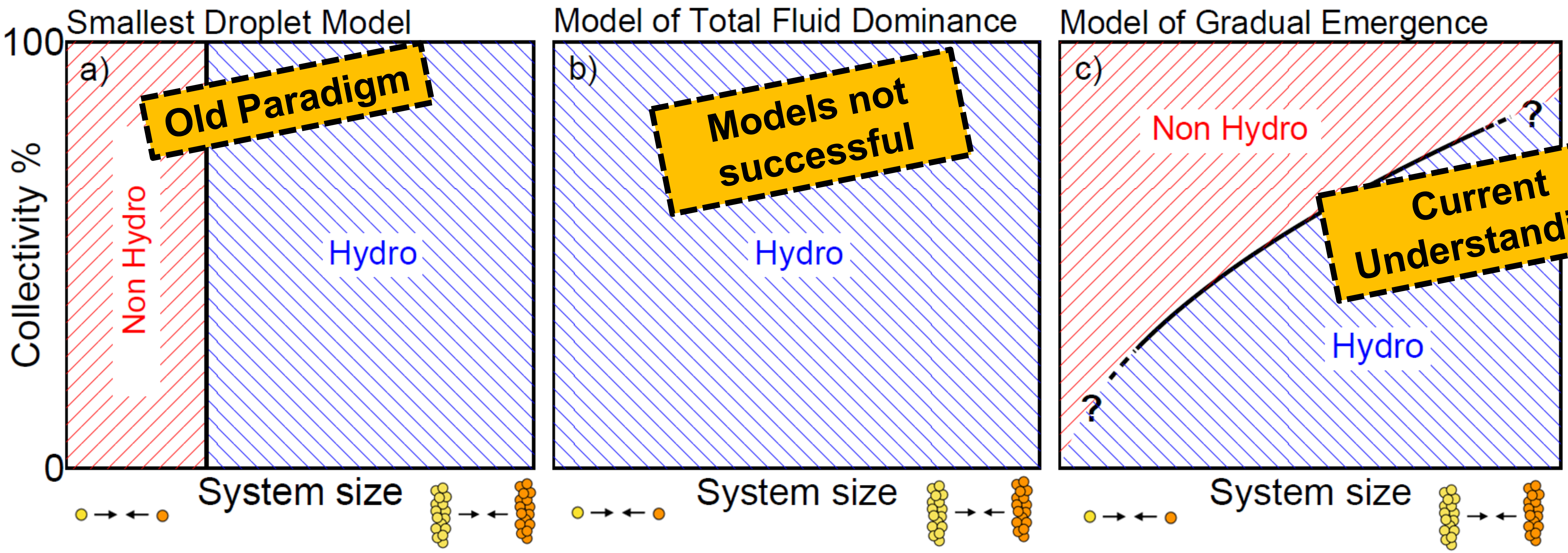
**9 orders of magnitude**



**Remarkable agreement**

Nature 561 (2018) 7723, 321

# Big Picture



**Old Paradigm**

**Models not successful**

**Current Understanding**

arXiv:2407.07484

- 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.

# More about small systems…

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

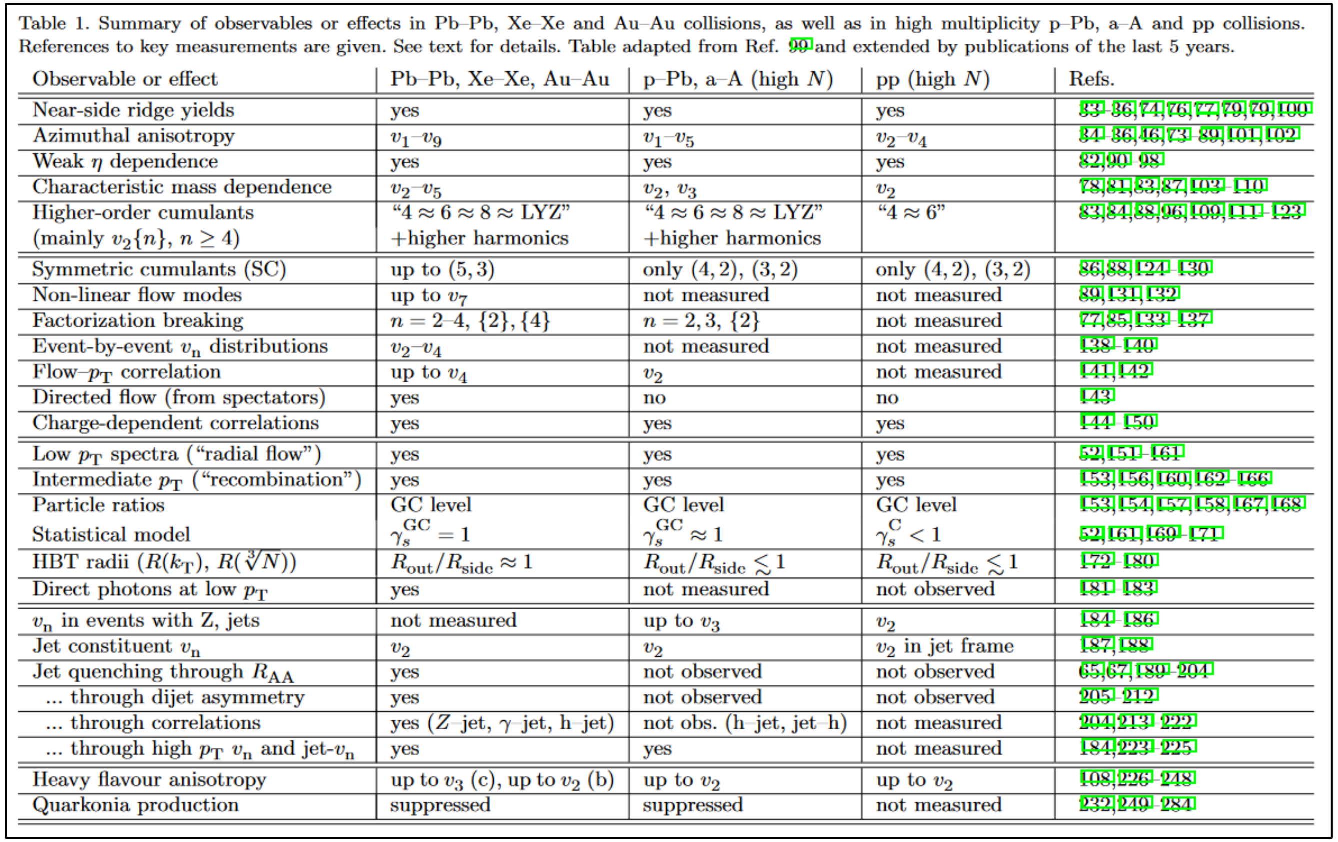
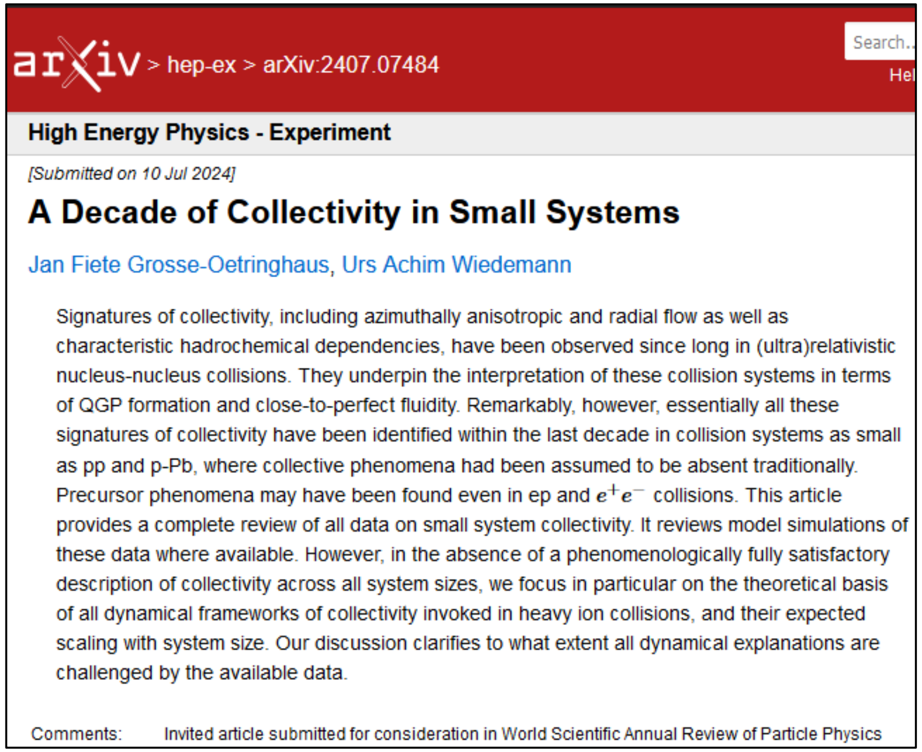


Table 1. Summary of observables or effects in Pb–Pb, Xe–Xe and Au–Au collisions, as well as in high multiplicity p–Pb, a–A and pp collisions. References to key measurements are given. See text for details. Table adapted from Ref. [99] and extended by publications of the last 5 years.

| 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 $\eta$ 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 | "$4 \approx 6$" | [83,84,88,96,109,111–123] |
| 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, $\gamma$–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] |



**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**

# 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 O-O, p-O, p-Pb and p-X (?) runs
- More about the last decade in our review: Wiedemann, JFGO: arXiv:2407.07484
- Let’s discuss the next decade at this workshop

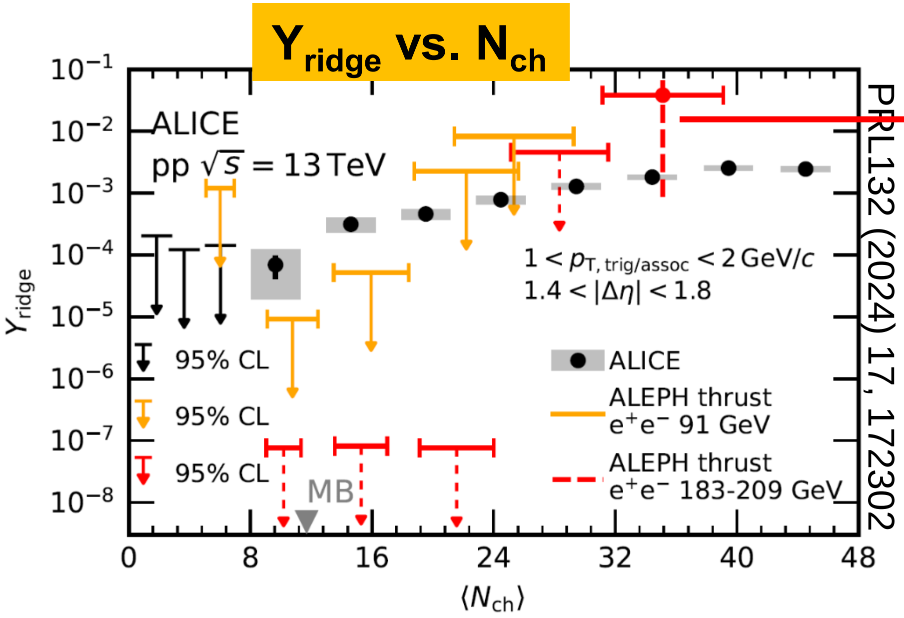
**Thank you for your attention!**

Strokkur Geyser, Iceland

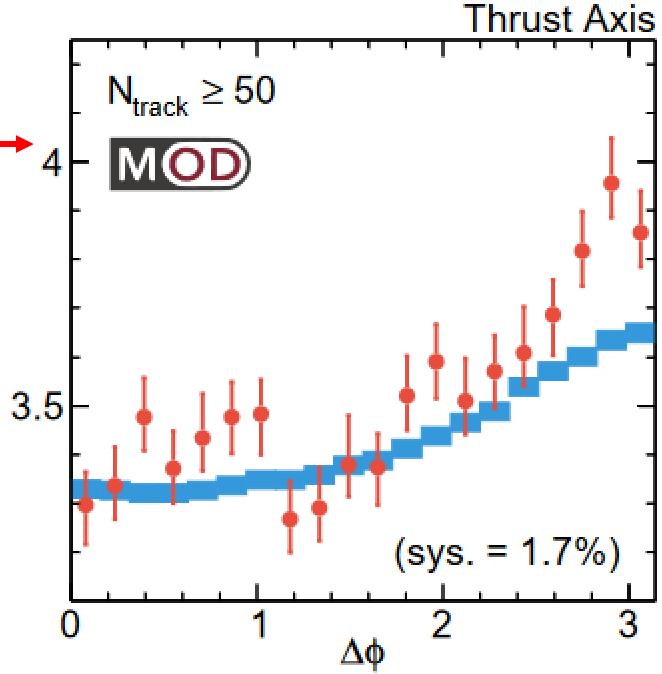
# Backup

# $e^+e^-$ Highest Bin

**$Y_{ridge}$ vs. $N_{ch}$**



PRL132 (2024) 17, 172302



arXiv:2312.05084

**$1.02\sigma$**

# Conversion of ALEPH multiplicity

- Estimate the limits of uncertainty on the conversion of the multiplicity
- Target: multiplicity defined by accepted particles within $|\eta| < 1.0$, $p_\mathrm{T} > 0.2\,\mathrm{GeV}/c$
- Multiplicity conversion between different systems and experiments is done using PYTHIA
  1. Simulate pp at $\sqrt{s} = 13\,\mathrm{TeV}$ in both experimental acceptances. Multiplicity ratio to obtain $\alpha_\mathrm{A}$
  2. Simulate $\mathrm{e^+e^-}$ at $\sqrt{s} = 91\,\mathrm{GeV}$ in both experimental acceptances. Multiplicity ratio to obtain $\alpha_\mathrm{B}$

| Method | Experiment | Corr. factor $\alpha_{\mathrm{A/B}}$ |
|---|---|---|
| PYTHIA | ALEPH pp 13 TeV | 0.57 (A) |
| | ALEPH $\mathrm{e^+e^-}$ 91 GeV | 0.78 (B) |
| Flat $\mathrm{d}N/\mathrm{d}\eta$ | ALEPH | 0.63 |

| Experiment | $\lvert\eta_\mathrm{max}\rvert$ | $p_{\mathrm{T,min}}$ | $\sqrt{s}$ |
|---|---|---|---|
| ALICE pp | 1.0 | 0.2 | 13 TeV |
| ALEPH $\mathrm{e^+e^-}$ | 1.738 | 0.2 | 91 GeV |