High Density QCD
with Heavy-Ion and Proton Beams

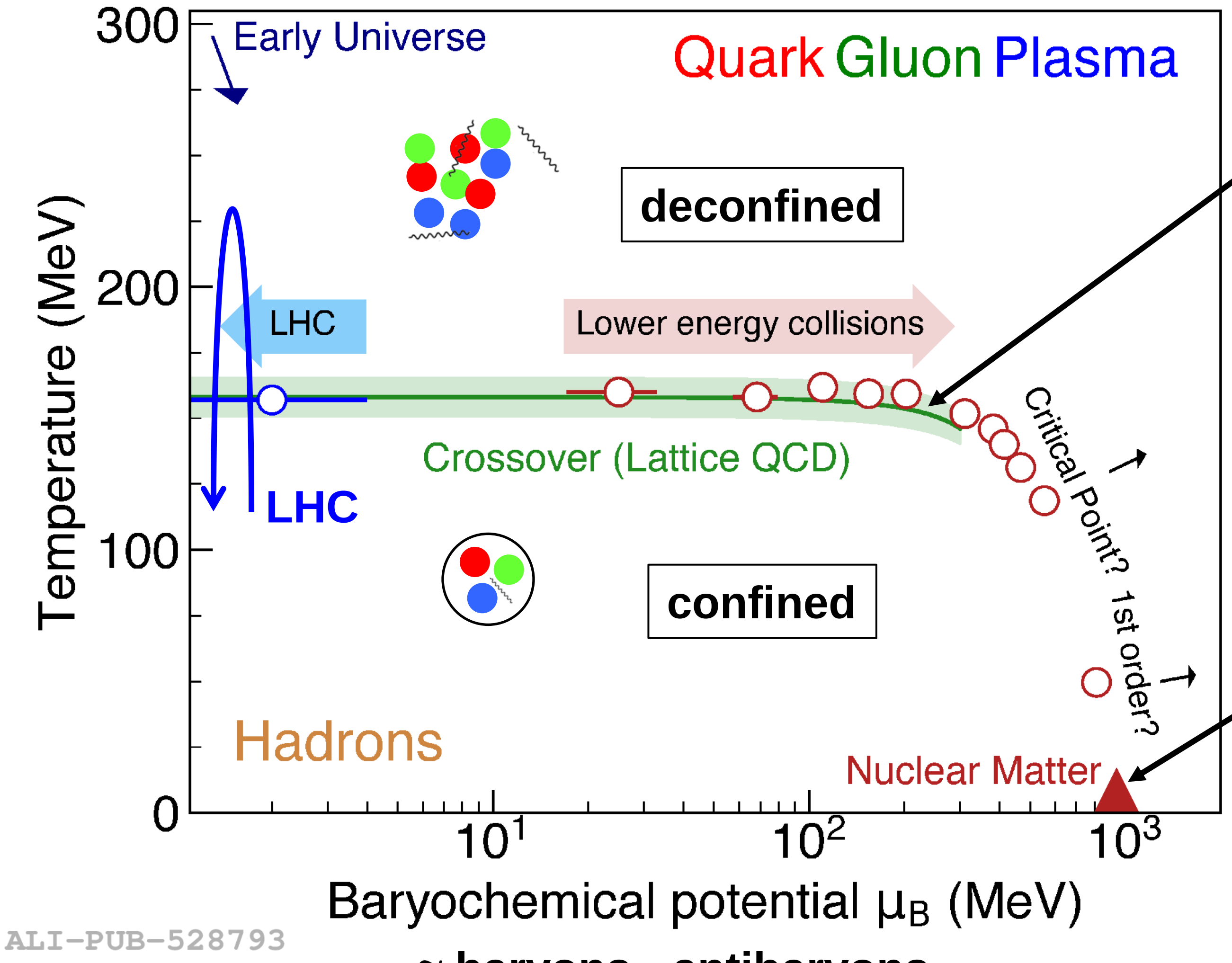
Jan Fiete Grosse-Oetringhaus (CERN)

Niels Bohr Institute, Copenhagen

08.08.2024

Concepts

QCD Phase Diagram



Phase transition

“We” are here

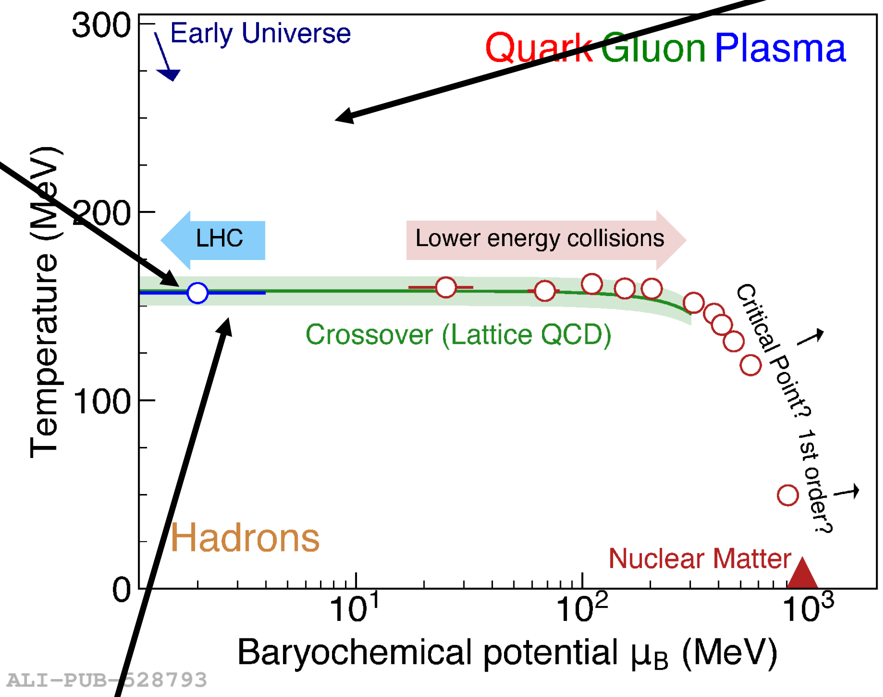
≅ **baryons - antibaryons**

adapted from
arXiv:2211.04384

Questions (for today)

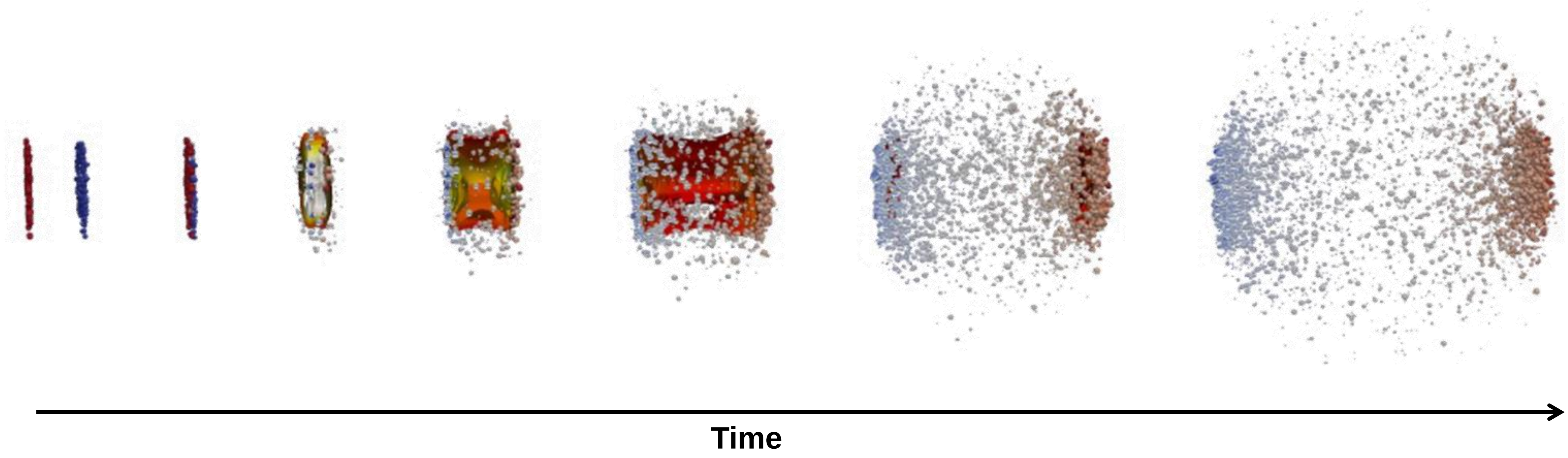
How is the transition between deconfined and confined phase?

What is the nature of the QGP?



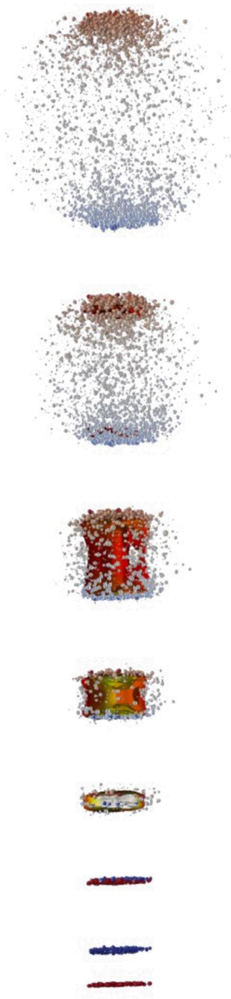
How is the onset of QGP production?
Emergence of QGP phenomena?

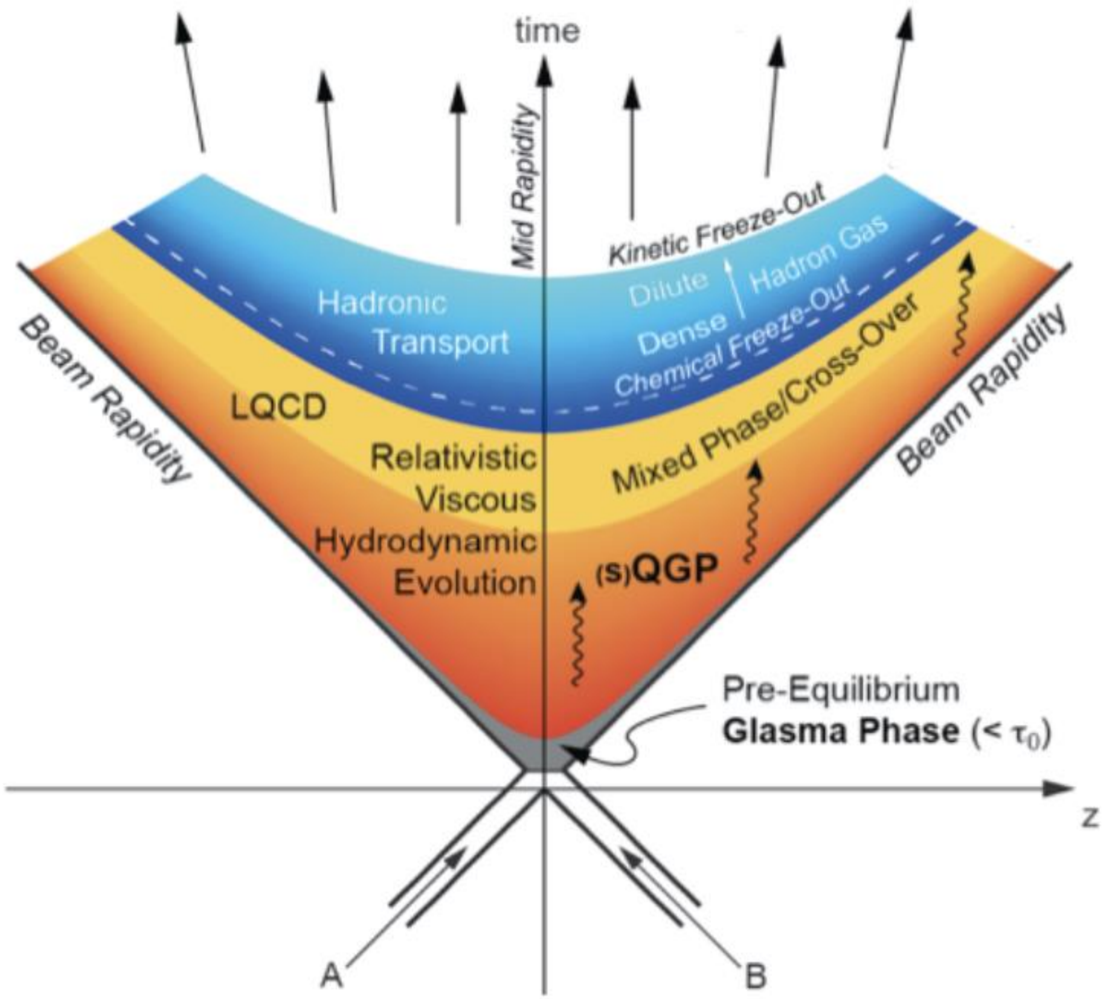
Heavy-Ion Collision, conceptually…



MADAI collaboration

Heavy-Ion Collision, conceptually…



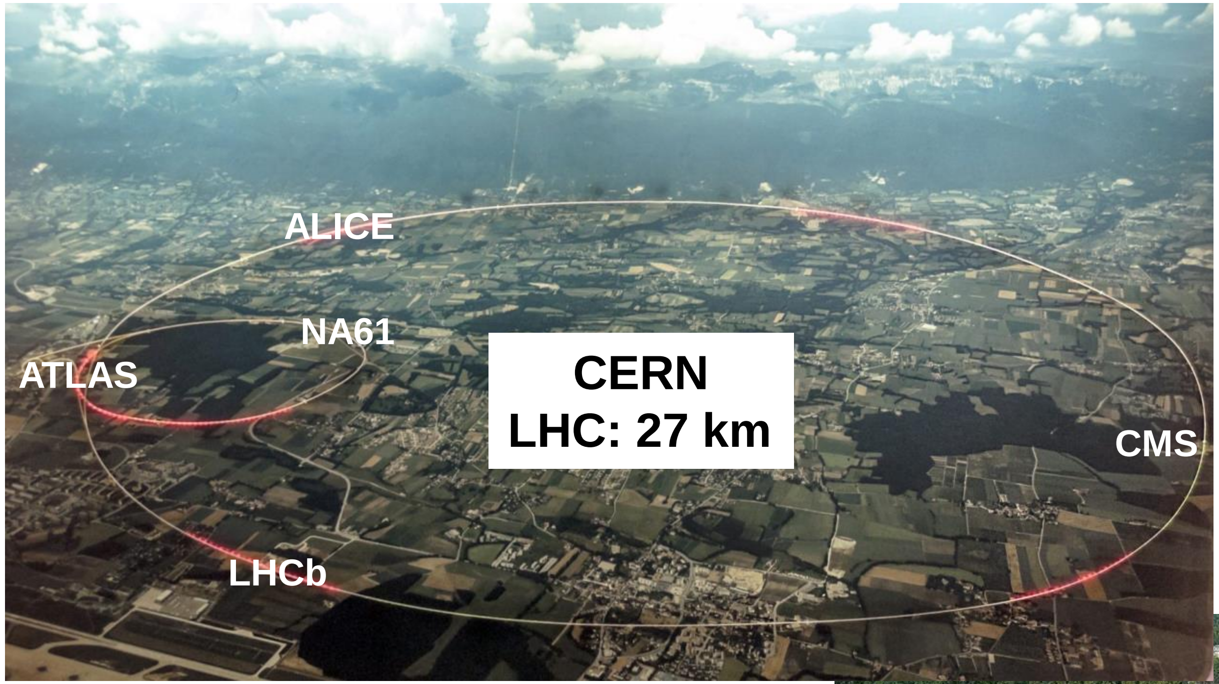


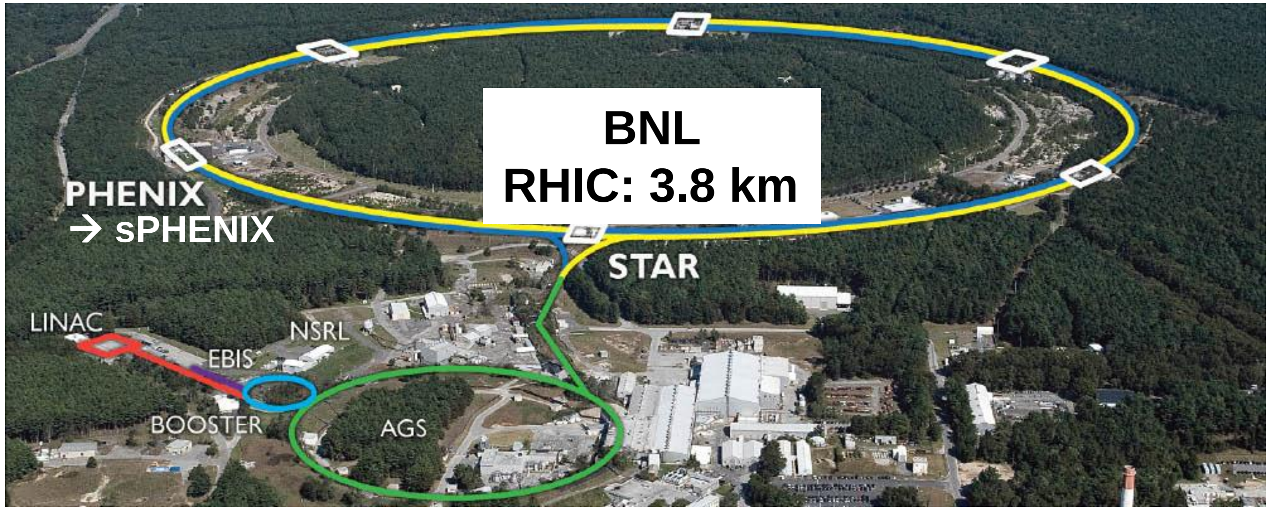
Time

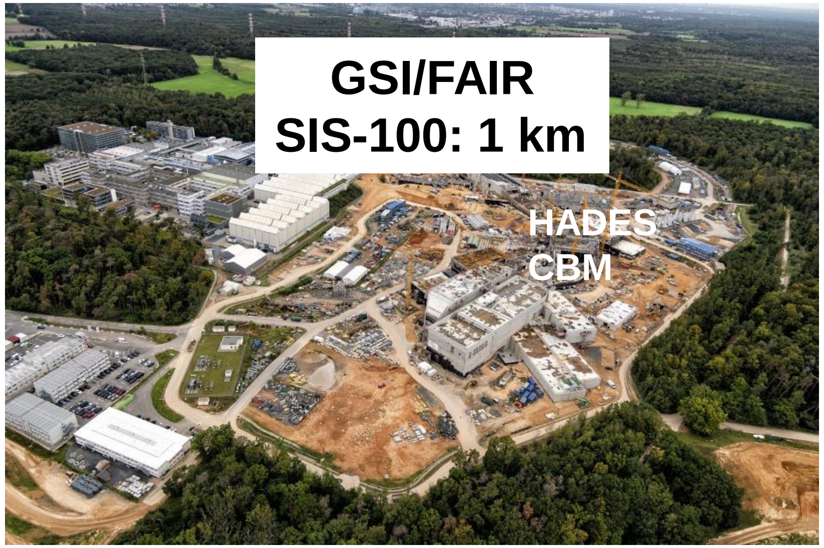
particle detection	t = 3 cm/c
kinetic freeze-out	t = 10 fm/c
chemical freeze-out hadronization	
hydrodynamic evolution	
pre-equilibrium	t = ~1 fm/c
collision	t = 0 fm/c

1 fm/c = $3 \cdot 10^{-24}$ s

Heavy-Ion Collision, experimentally…

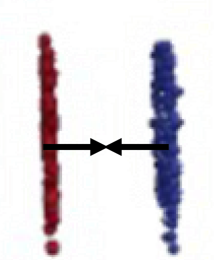






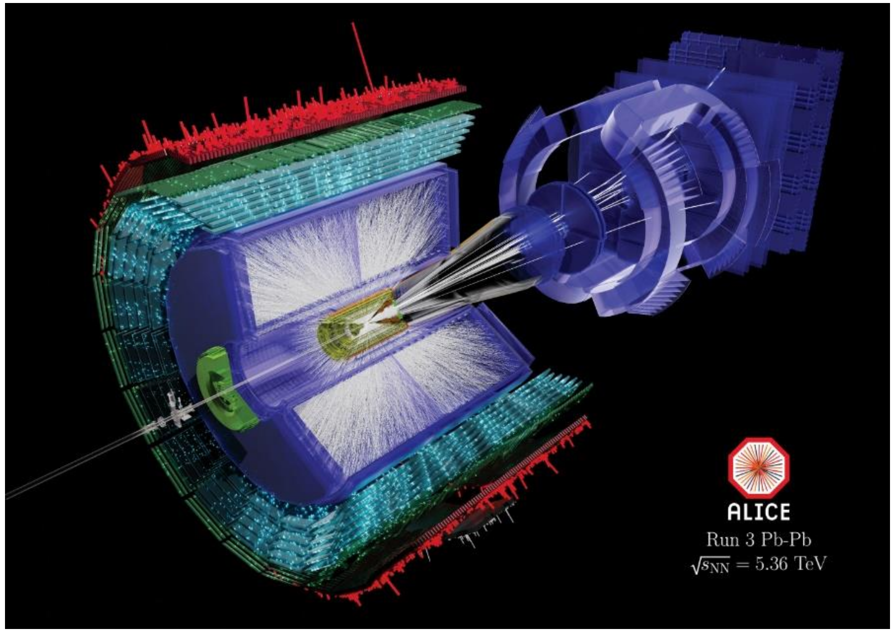
Significant impact of Russian aggression against Ukraine

Heavy-Ion Collision, experimentally…



- LHC (Run 3): $^{208}_{82}Pb$ on $^{208}_{82}Pb$ at $\sqrt{s_{NN}}$ = 5.36 TeV
  - Center-of-mass energy for hard processes
- Total available collision energy: $\sqrt{s_{Pb\text{-}Pb}}$ = 1.1 PeV
- Immense collisions with thousands of tracks
  - Imagine a pp collisions with pile up of about 400

pp: $\sqrt{s}$ = 13.6 TeV
Pb-Pb per nucleon pair:
$\sqrt{s_{NN}}$ = 82/208 * $\sqrt{s}$ = 5.36 TeV
Total energy:
$\sqrt{s_{Pb\text{-}Pb}}$ = 208 * $\sqrt{s_{NN}}$ = 1115 TeV



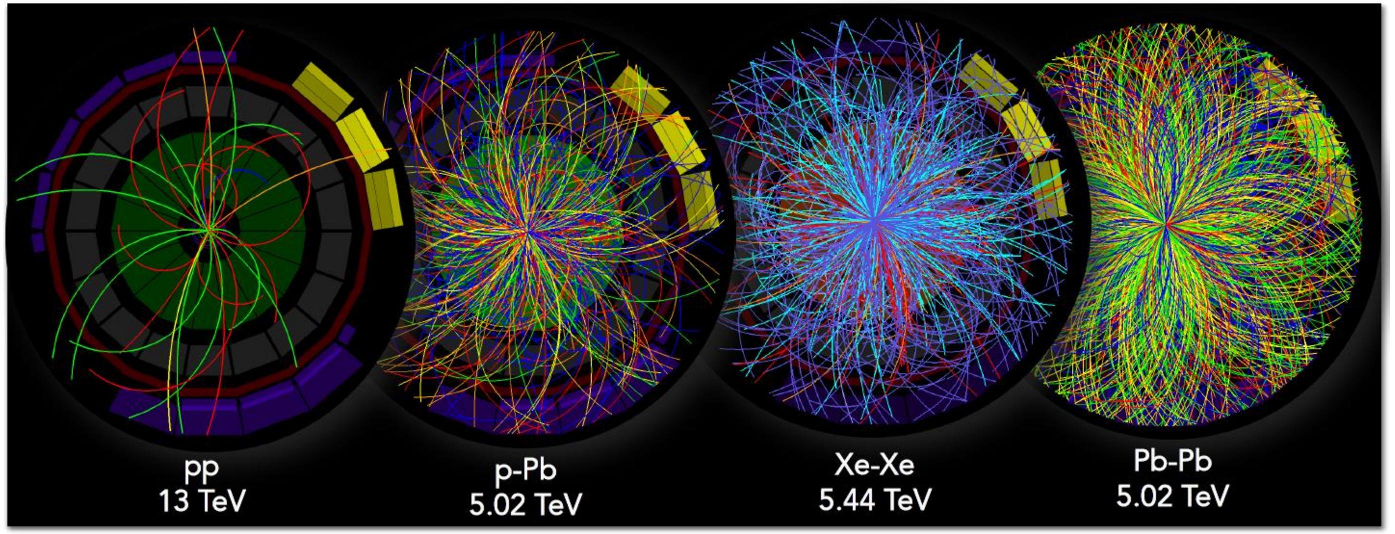
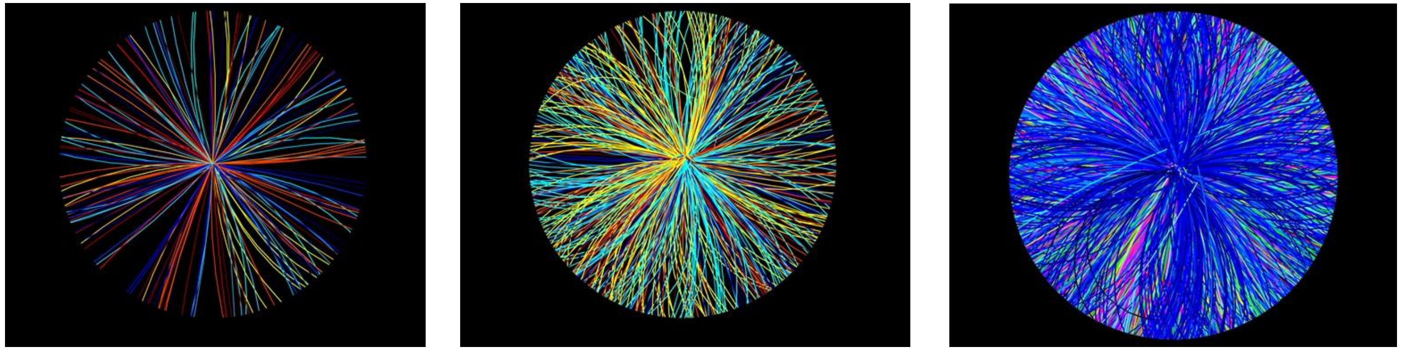


Image: Alexander Kalweit

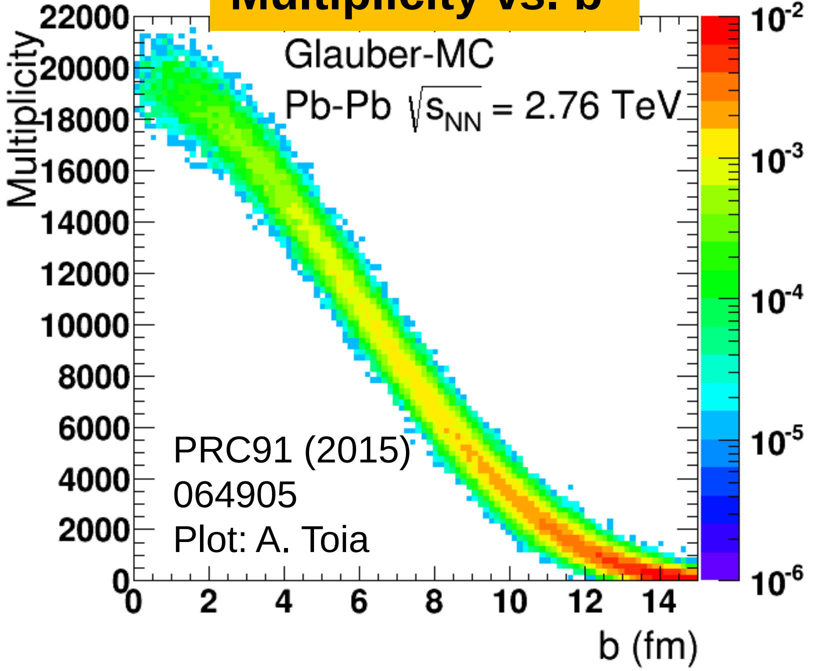
Centrality

- Impact parameter available experimentally
  - Not the case for pp: "hidden" parameter
  - Multiplicity is global event property (forward N_{ch} ~ mid N_{ch})

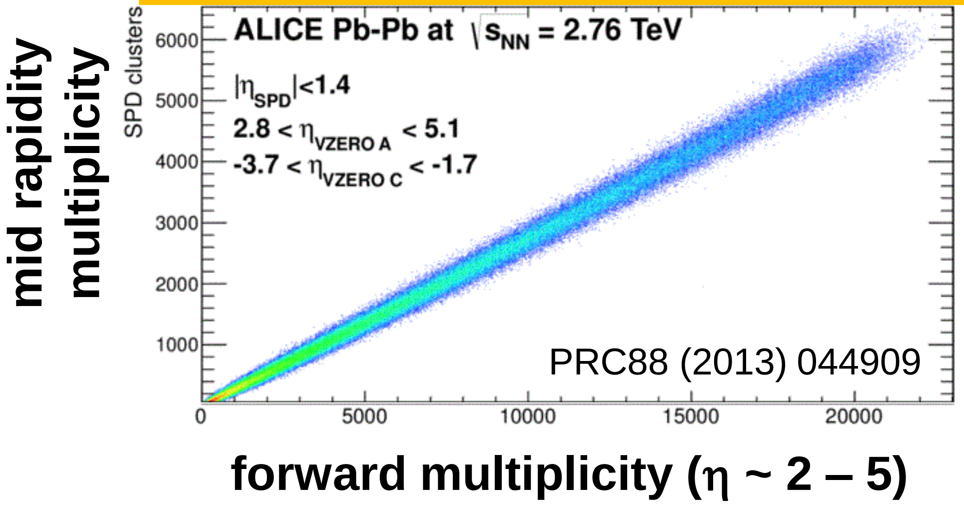


Low multiplicity ⟶ **High multiplicity**

Multiplicity vs. b



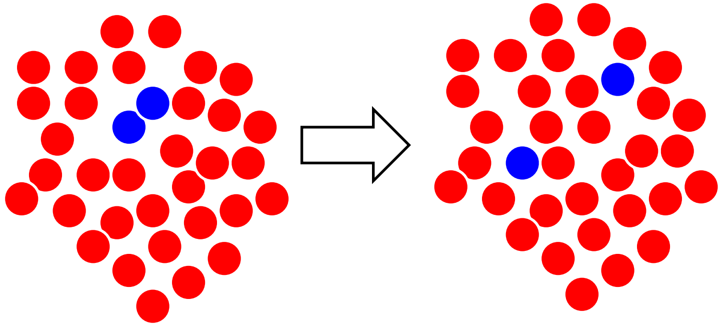
Mid rapidity vs. forward multiplicity



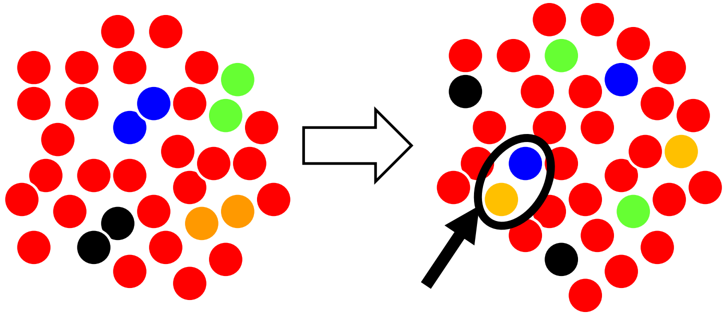
QGP Key Properties

J/ψ

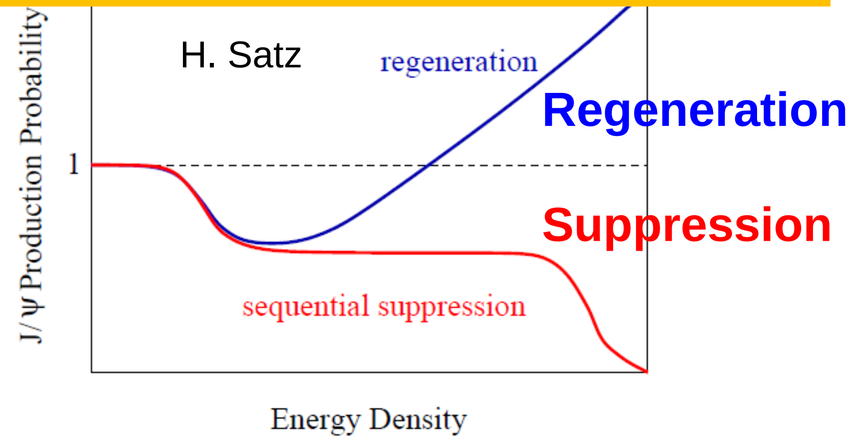
- The QGP affects bound-state formation
- Binding potential of quarkonia is modified
- ccbar produced in hard scattering does not hadronize to J/ψ in presence of medium



- Large ccbar density → regeneration

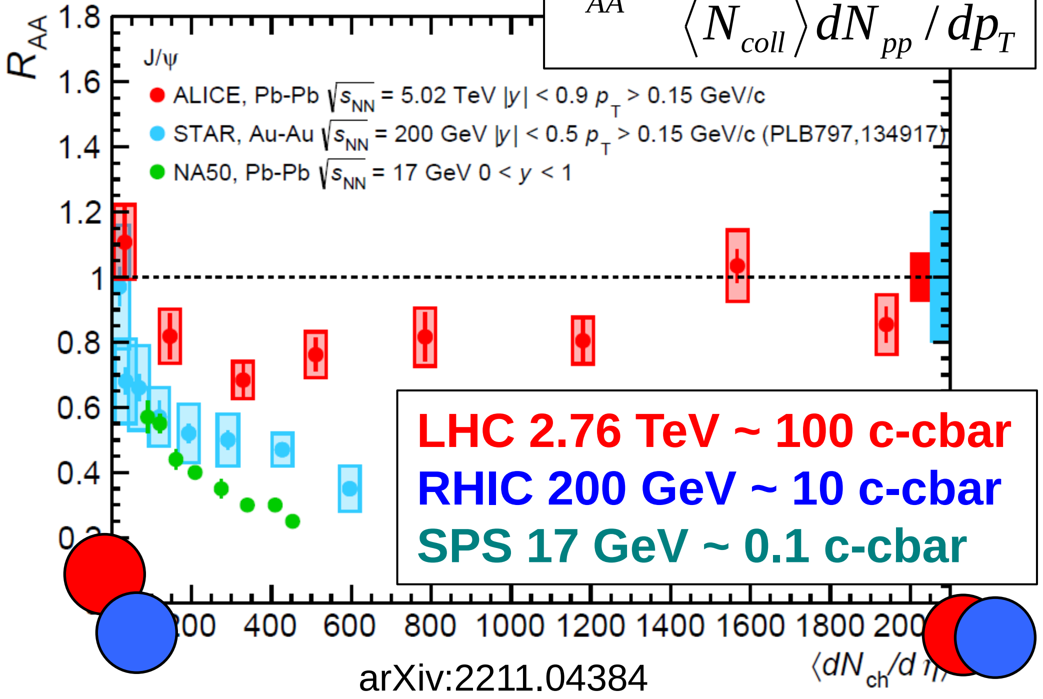


J/ψ modification vs. energy density



R_{AA} vs. multiplicity

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



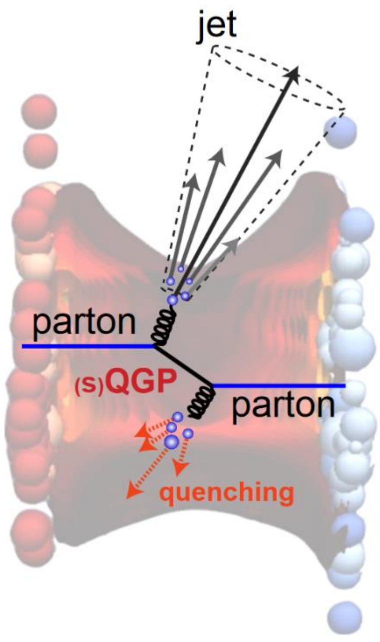
LHC 2.76 TeV ~ 100 c-cbar
RHIC 200 GeV ~ 10 c-cbar
SPS 17 GeV ~ 0.1 c-cbar

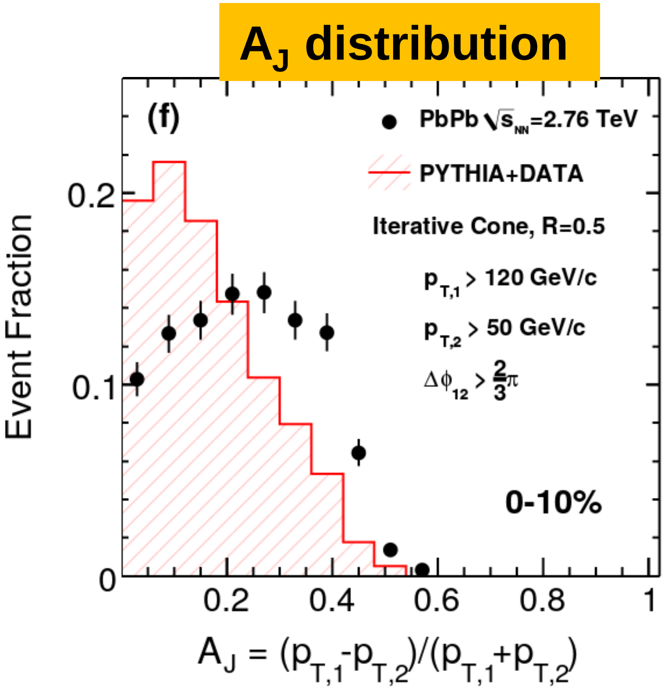
arXiv:2211.04384

Jet Quenching

PRL105:252303,2010

- The QGP alters jet energies
  - Radiative and collisional energy loss due to interactions of traversing parton with quarks and gluons in the medium
- Back-to-back jets significantly altered

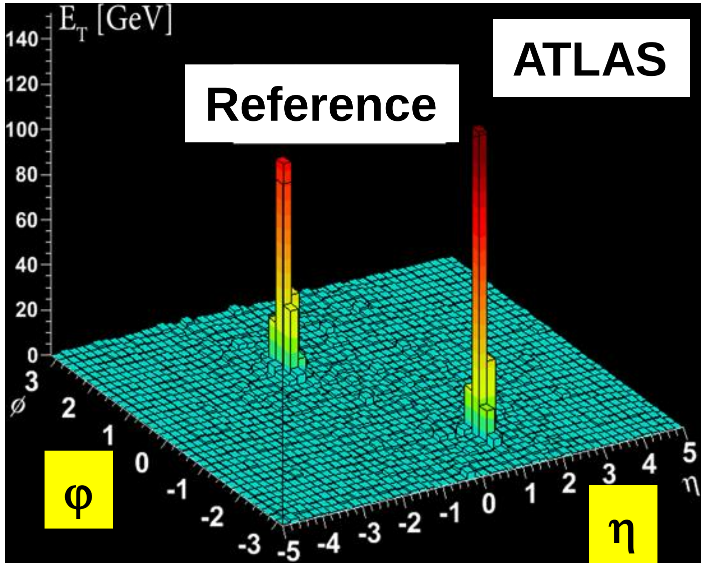


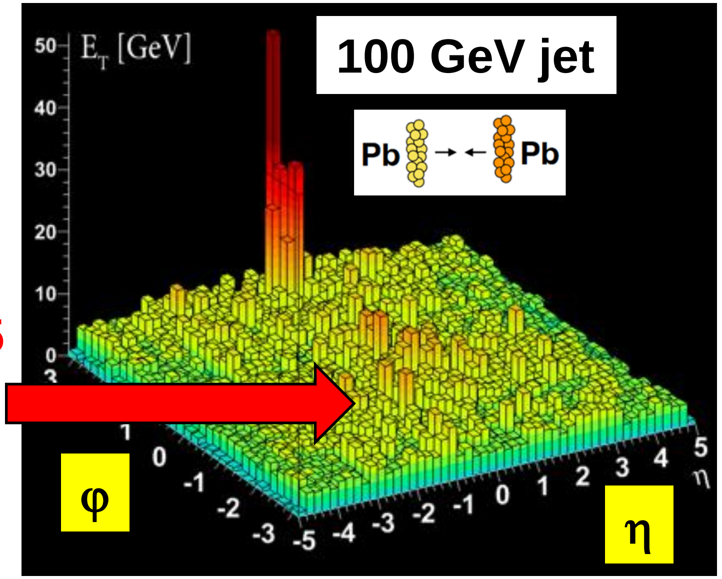


$$A_J = \frac{|p_{T1} - p_{T2}|}{p_{T1} + p_{T2}}$$

$p_{T1} = p_{T2} \rightarrow A_J = 0$

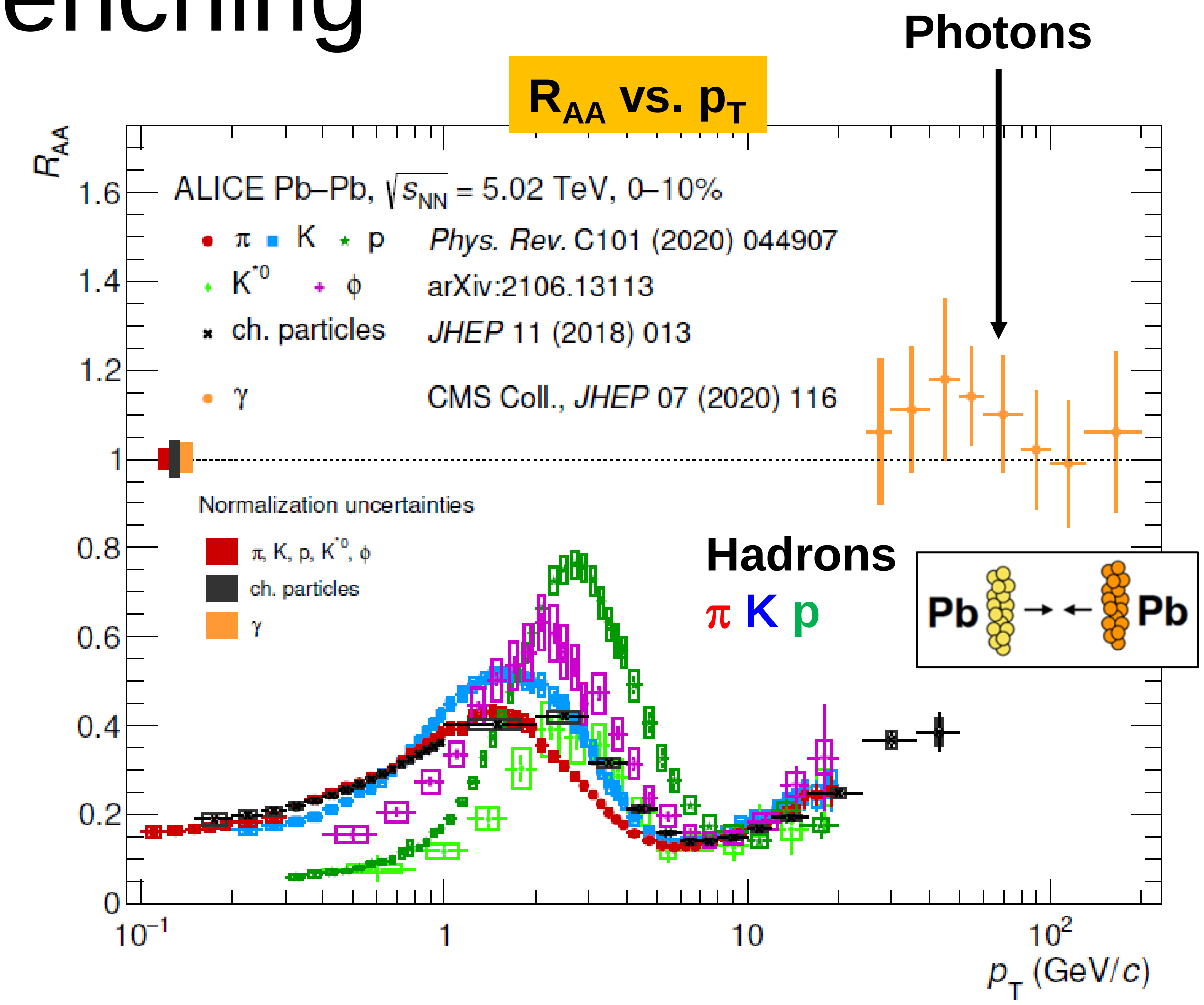
$1/3\ p_{T1} = p_{T2} \rightarrow A_J = 0.5$





Jet Quenching

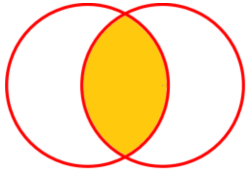
- For all strongly interacting probes
  - Significant suppression (R_{AA} ~ 0.14)
    - Ratio of steeply falling spectra
  - Different dynamics depending on particle
    - Dependence on mass and quark content
- EW probes (γ, Z, W) not suppressed
  - Do not interact with QGP
  - Confirm correct scaling of R_{AA}
- Used to constrain QGP properties
  - Needs modelling (see later…)



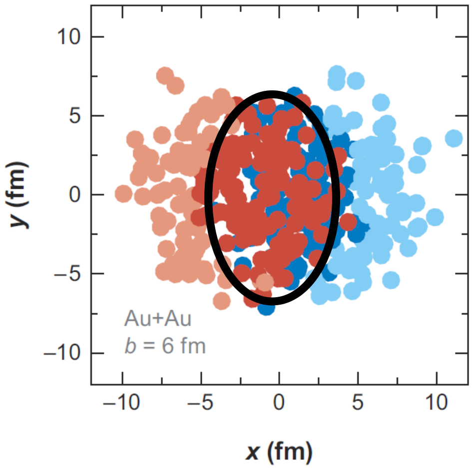
$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle dN_{pp}/dp_T}$$

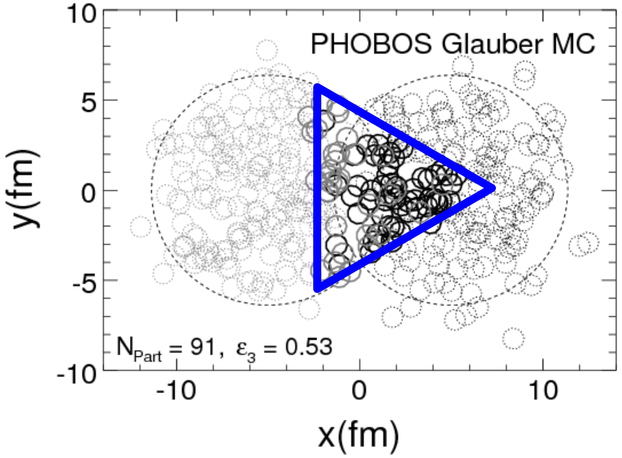
arXiv:2211.04384

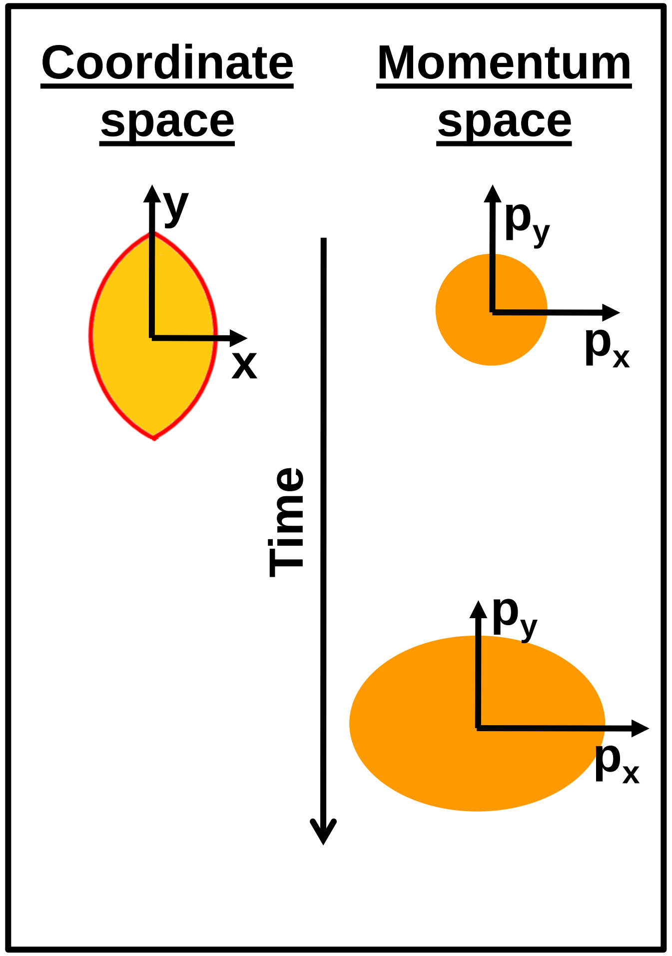
A Flowing System



- Collision zone not isotropic (coordinate space)
- Pressure gradient → momentum-space anisotropy
  - Requires reinteractions, strongly-coupled system
- Access to event-by-event fluctuations of nucleon density







- Measurable through azimuthal distribution of particles

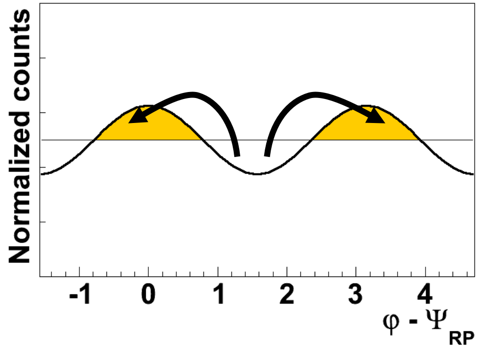
$$\frac{dN}{d\varphi} = A\left(1 + 2\sum_n v_n \cos n(\varphi - \Psi_n)\right)$$

nucl-ex/0701025, PRC81 (2010) 054905

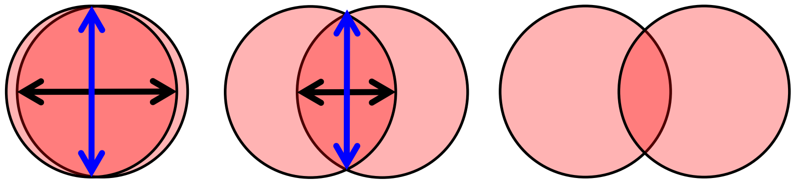
Flow coefficients v_n

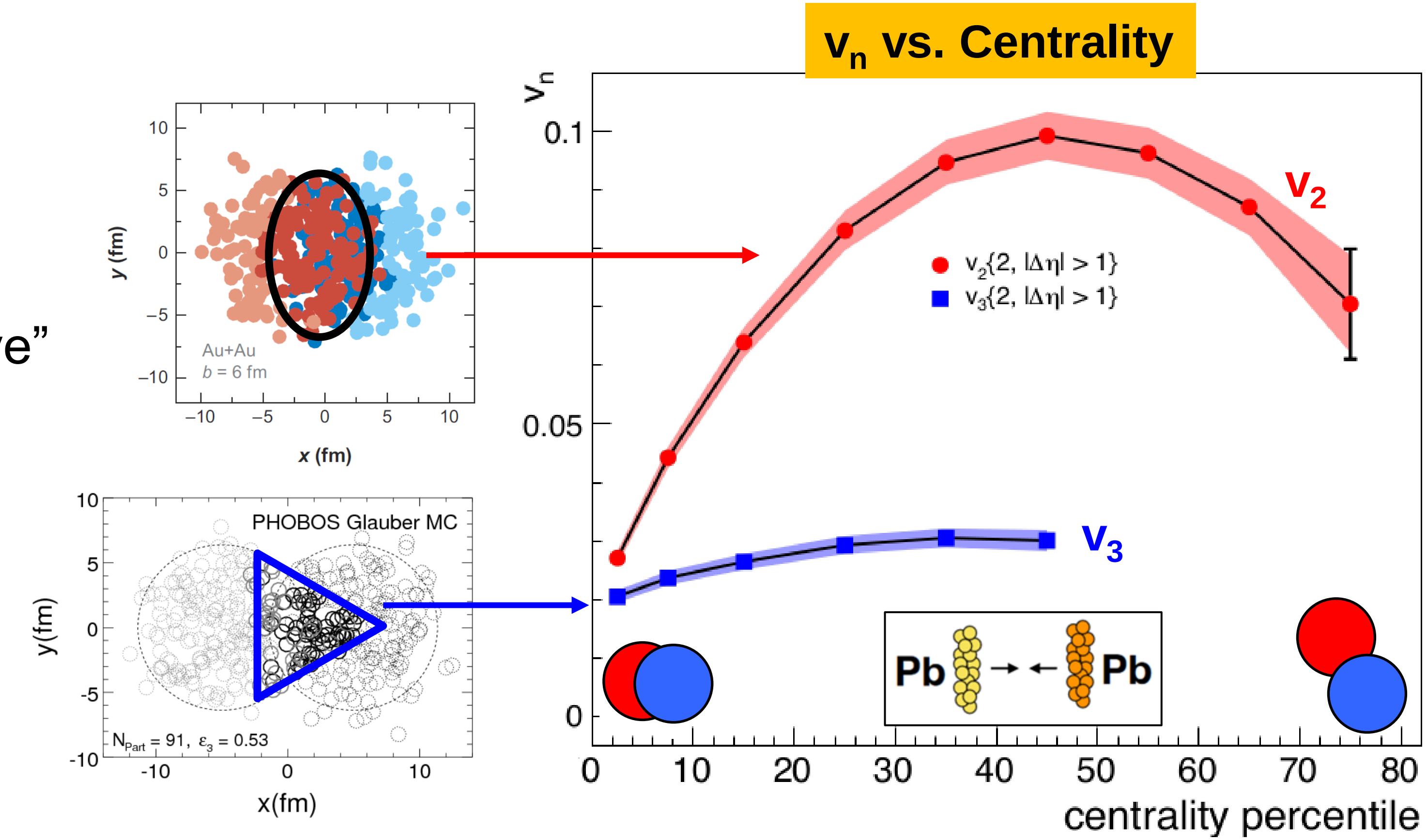
$$\frac{dN}{d\varphi} = A\left(1+2\sum_n v_n \cos n(\varphi-\Psi_n)\right)$$

- Magnitude depends on n
  - E.g. $2v_2$ = 20% of particles “move” from out-of-plane to in-plane



- Clear centrality dependence



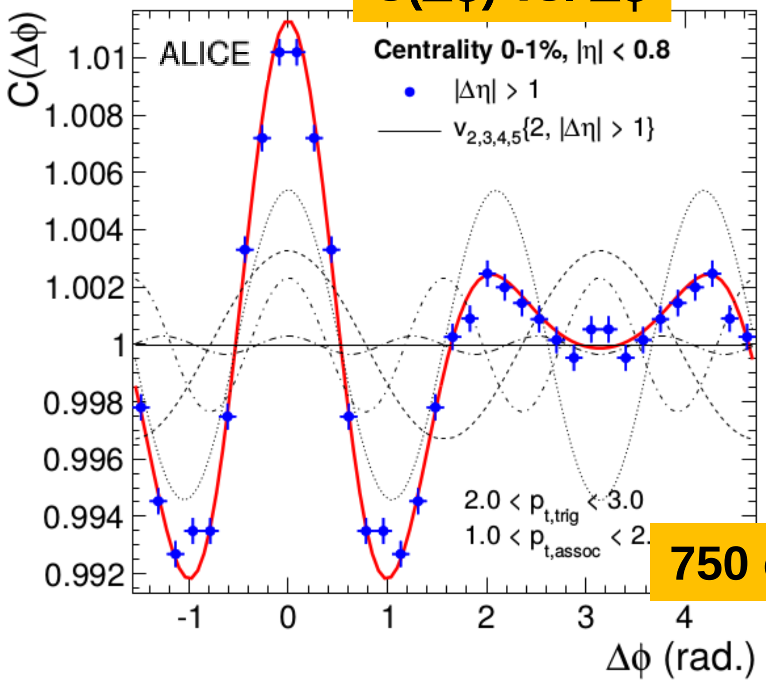


PRL107, 032301 (2011)

Higher Orders

- Azimuthal distribution entirely described up to 5th order
- Finer structures can be extracted with high statistics (n = 9, at present)

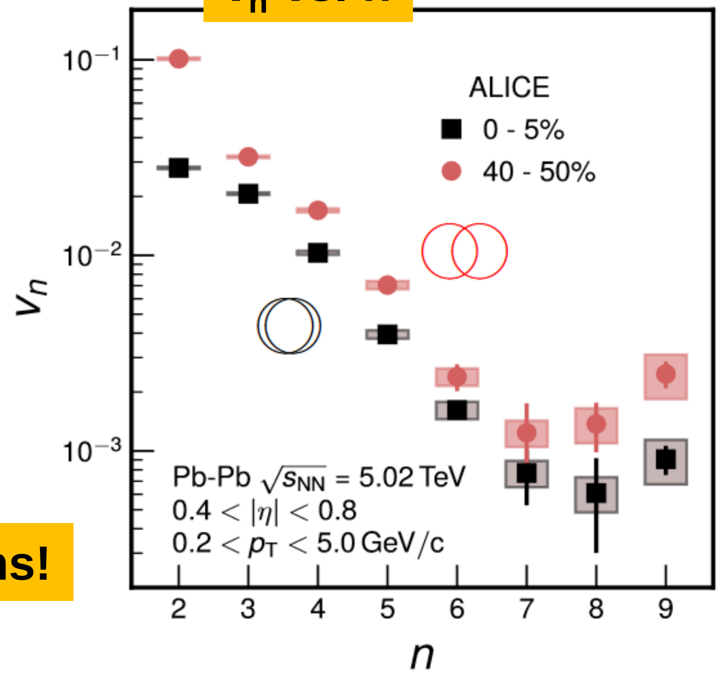
C(Δφ) vs. Δφ



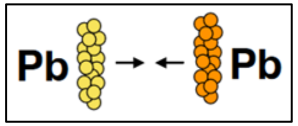
PRL107, 032301 (2011)

750 citations!

v_n vs. n



JHEP05(2020)085

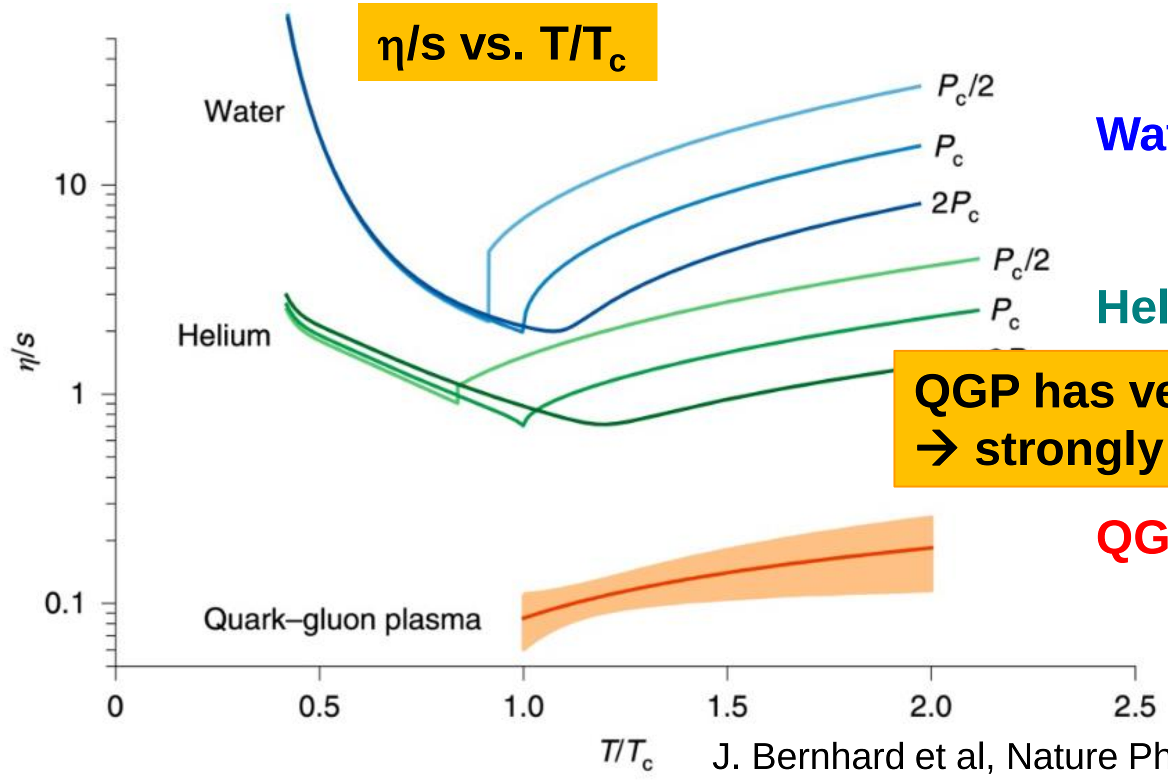


Compact description of the data
Direct link to medium transport coefficients

Transport Coefficient: Shear Viscosity

- Shear viscosity η/s washes out initial-state anisotropies
  - Large influence on higher-order flow
- Bayesian estimates for QGP medium properties

η/s vs. T/T_c



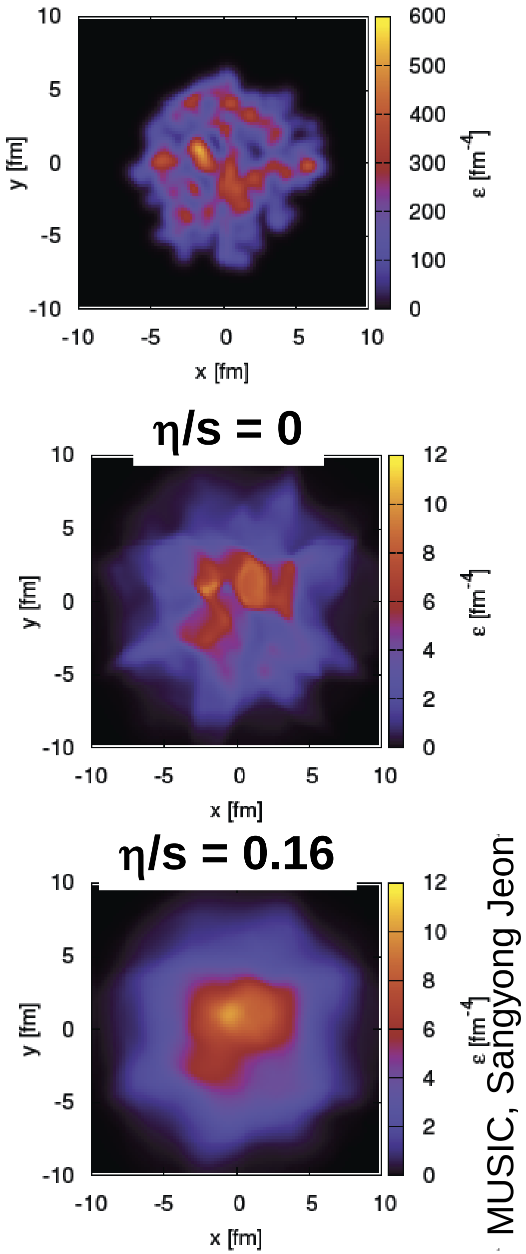
Water

Helium

QGP has very small shear viscosity → strongly coupled

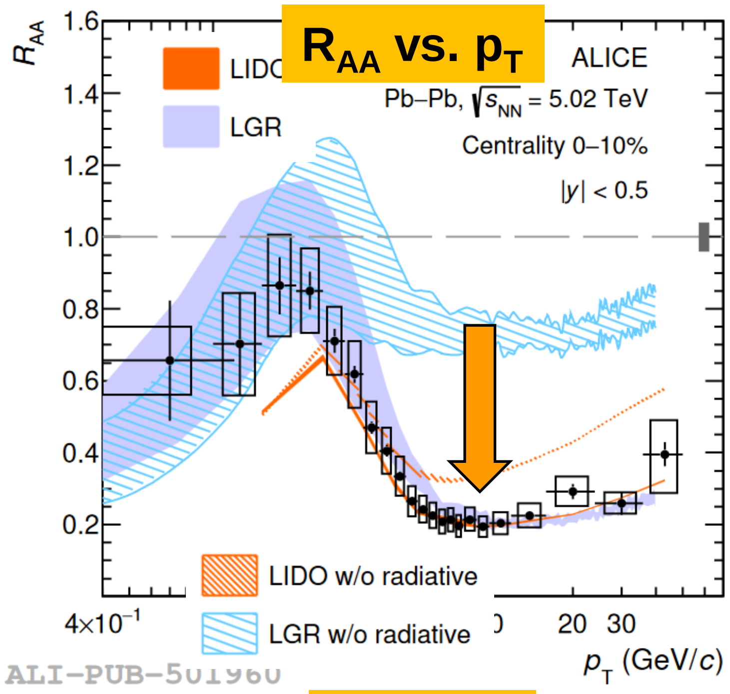
QGP

J. Bernhard et al, Nature Physics 15, 1113 (2019)

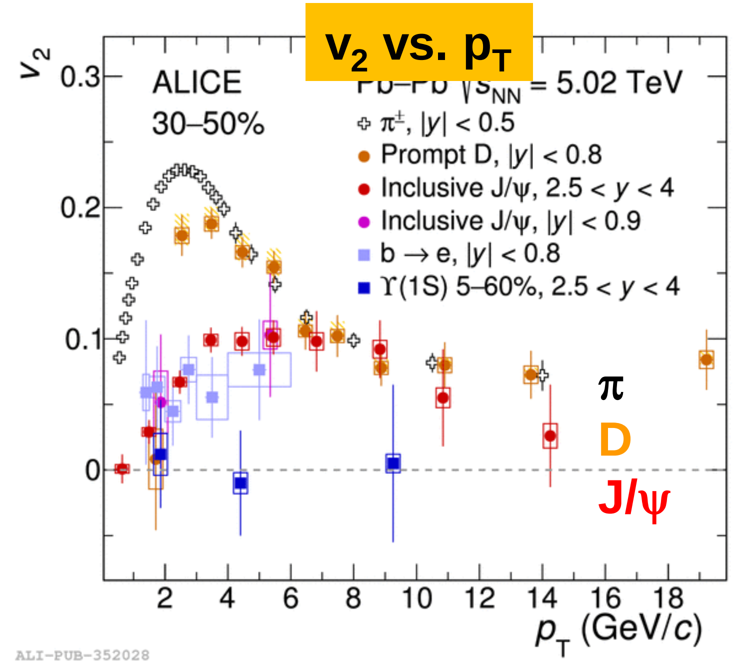


Heavy Quarks

- Charm and beauty produced in initial scattering ($\tau_{HF} < \tau_{QGP}$ formation)
  - Initial production calculable perturbatively
  - Undergoes entire medium evolution ("Brownian motion markers")
- Experimentally challenging probe
  - Secondary vertex reconstruction, small branching ratios, large combinatorics
- D mesons strongly suppressed
  - Collisional and radiative energy loss visible
- Sizable v_2 and v_3 for D and J/ψ, and v_2 for b → e
  - Charmed hadrons and beauty (electrons) flow with medium
  - Thermalization (= sufficient re-interactions)



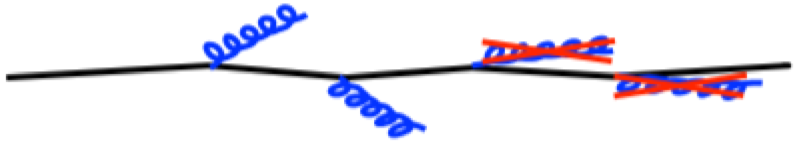
JHEP 01 (2022) 174



compiled from
JHEP09(2018)006, PRL126,162001(2021), PLB 813
(2021)136054, PRL123,192301(2019), JHEP10(2020)141

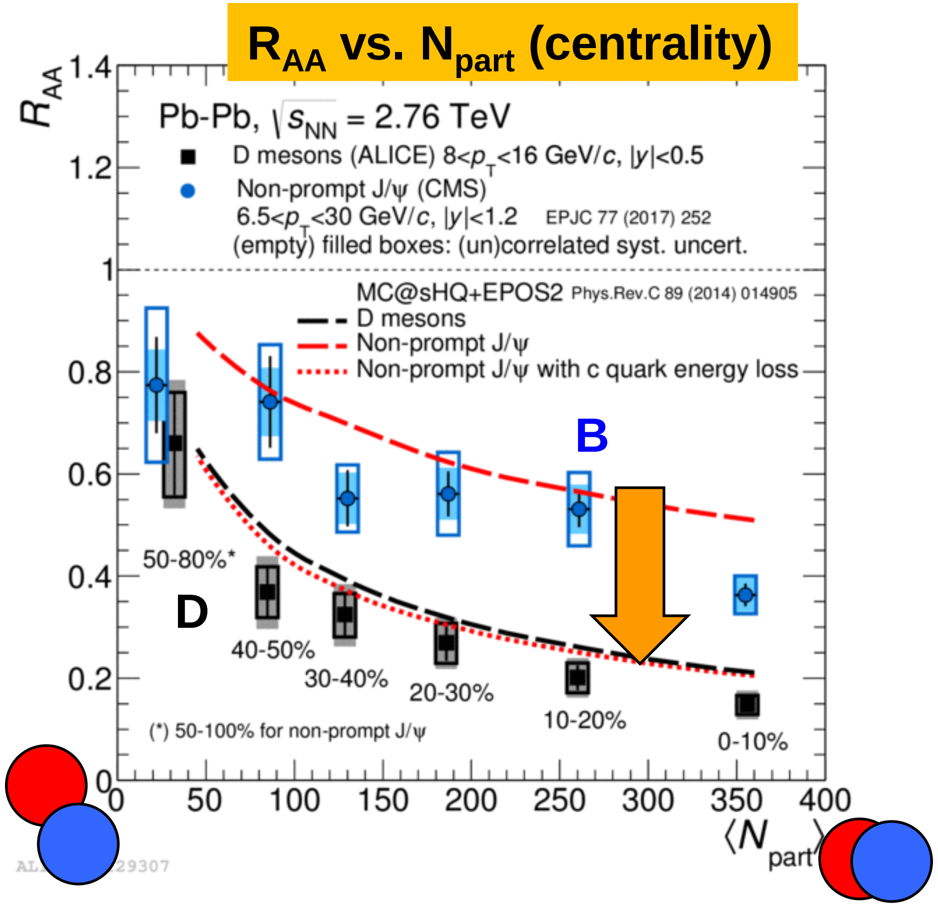
Quark-Mass Dependence

- Energy loss depends on quark mass
  - Dead cone effect: gluon radiation in vacuum suppressed for angles θ < m/E = 1/γ by $\left(1+\frac{m/E}{\theta}\right)^2$



- Observed with B → non-prompt J/ψ at high p_T

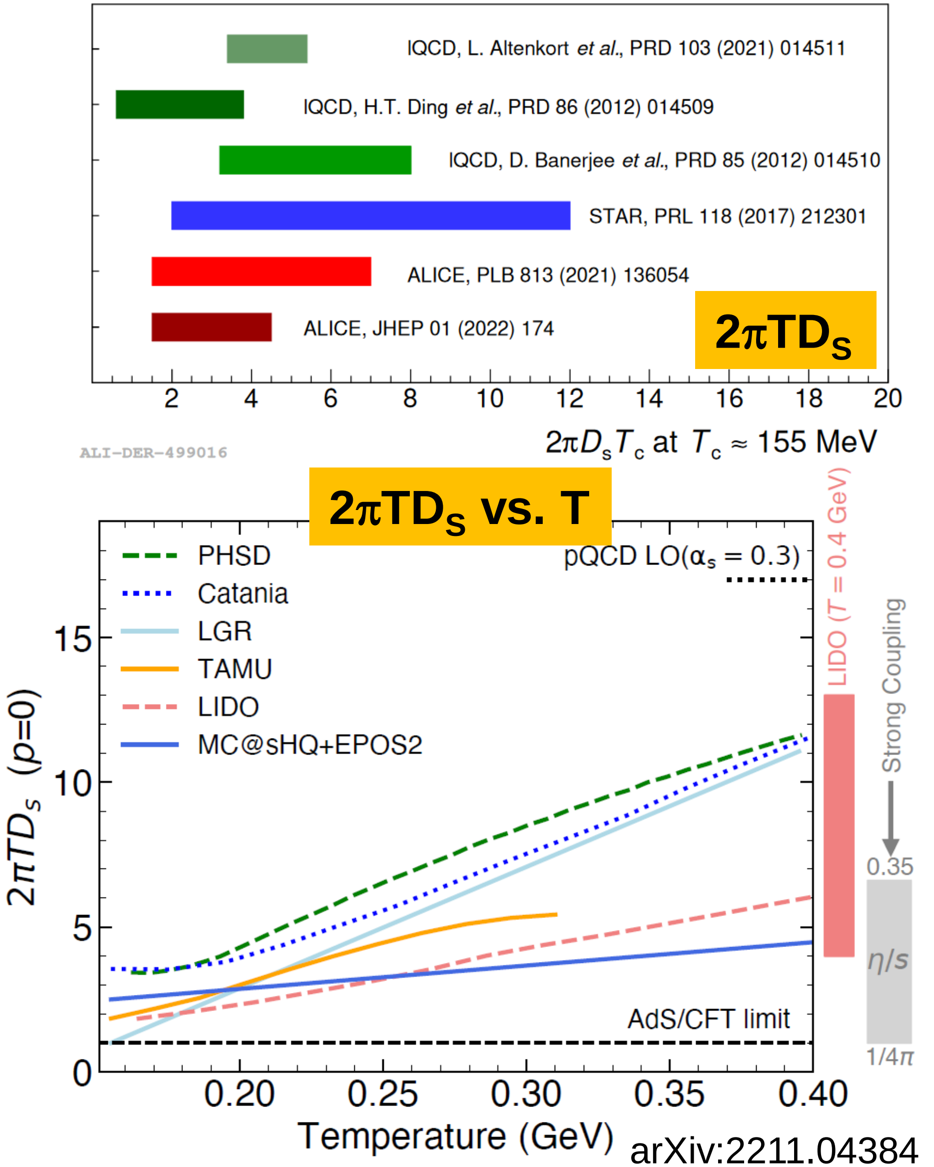
- Models need to simultaneously describe both



Transport coefficient: Spatial Diffusion

- Combined model fits of charm (R_{AA} + v_n)
- Constraints on spatial diffusion coefficient
  - Governing Brownian motion of charm in medium
  - Strongly coupled (D_S small) → moves “with” the QGP
  - Weakly coupled (D_S large) → few independent scatters
  - Strong temperature dependence
    - Strongly coupled at low T
    - Coupling model-dependent at large T
  - At phase transition: $1.5 < 2\pi D_S T < 4.5$
- Relaxation time (approach to equilibrium)
  - 3-9 fm/c at phase transition

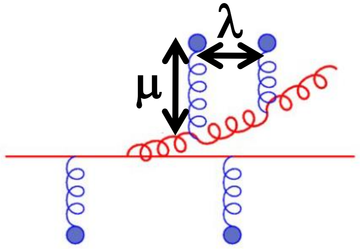
→ Charm thermalizes in QGP (t ~ 10 fm/c)



arXiv:2211.04384

Transport Coefficient: Quenching Power

- Quenching power characterized by “qhat”



$$\hat{q} = \frac{\mu^2}{\lambda}$$

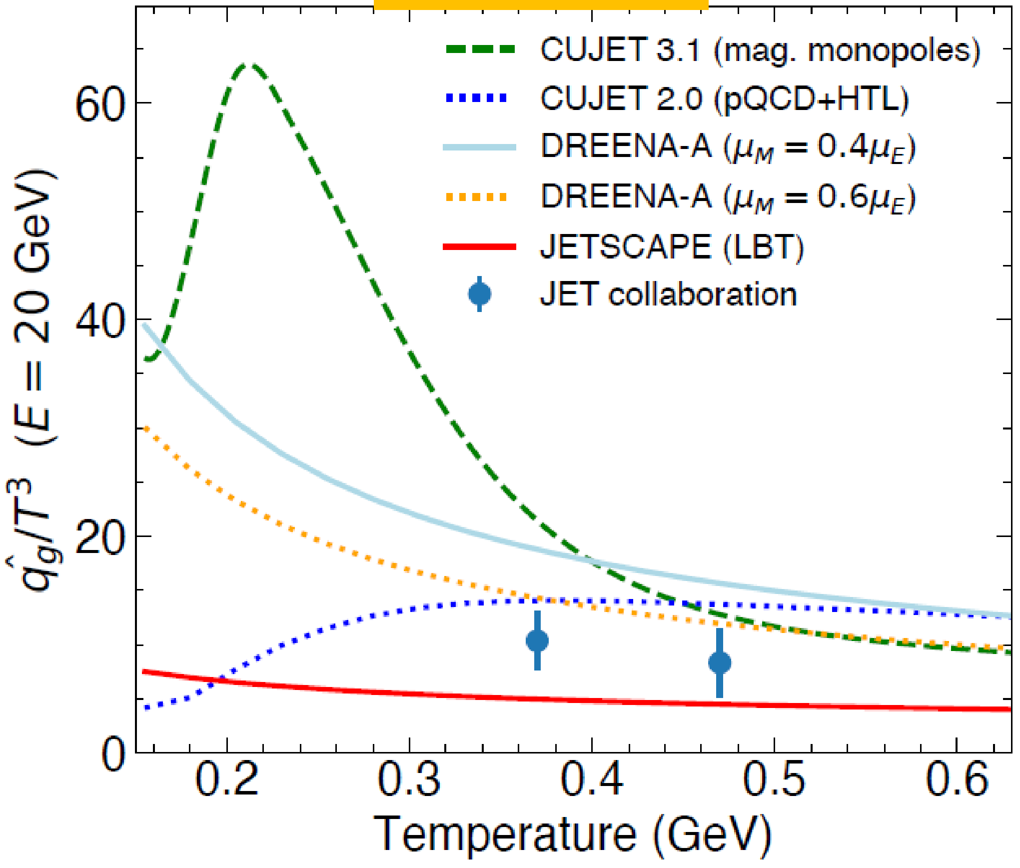
average transverse momentum transfer (μ^2)

mean free path (λ)

- Strong temperature dependence
  – Cubic dependence on temperature
  – Various approaches: weak-coupling approaches, monopoles, Bayesian estimates
  – Large spread at lower T where quenching is overall smaller
  – Similar values at large T
- Most stringent from Bayesian estimates (JETSCAPE)

$$\hat{q} \approx 1.5 \frac{\text{GeV}^2}{\text{fm}}$$

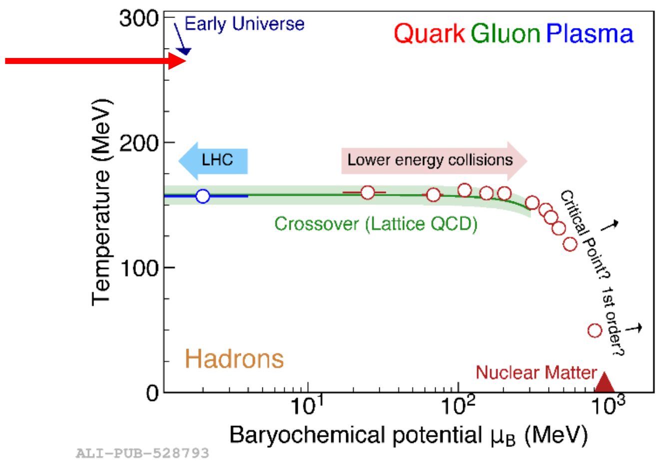
qhat/T³ vs. T



arXiv:2211.04384

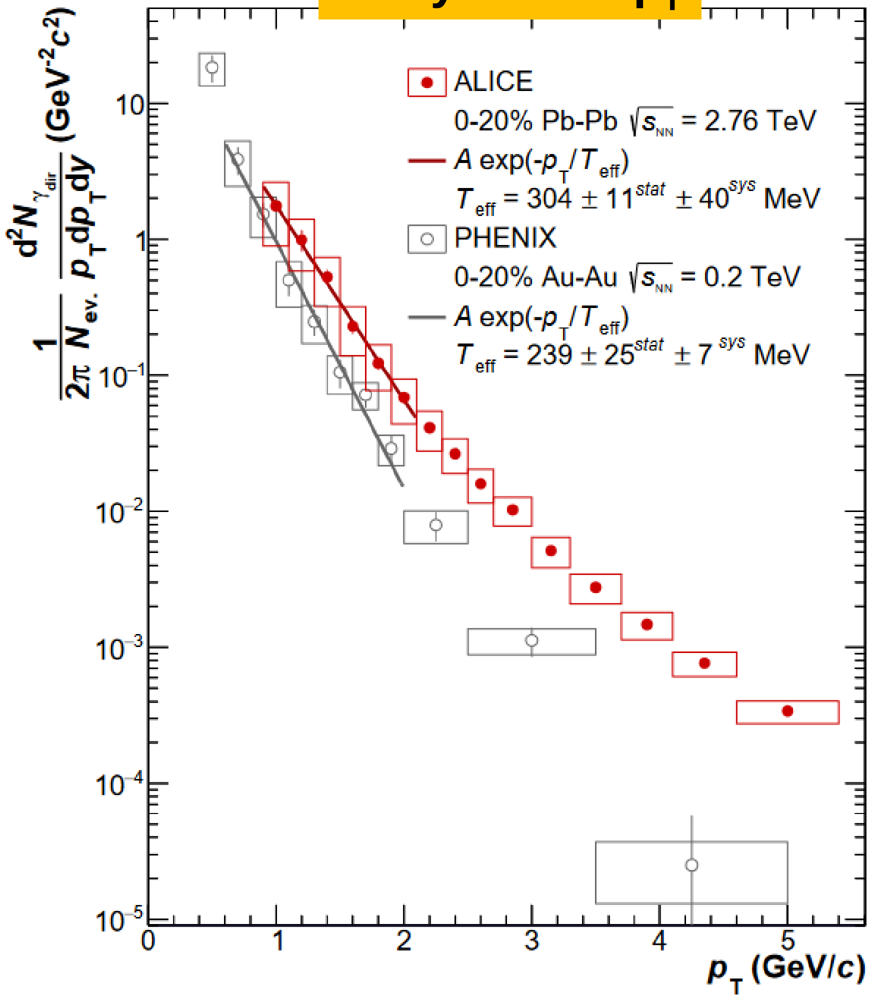
QGP Temperature

- Photons emitted by the medium
  - Signals from all phases of medium evolution
  - Mix of temperatures → effective temperature
- Temperature from slope of photon yield
- Large initial temperature
  - T ~ 300 MeV at LHC ($\sqrt{s_{NN}}$ = 2.76 TeV)
  - T ~ 240 MeV at RHIC ($\sqrt{s_{NN}}$ = 0.2 TeV)



Large initial temperatures in heavy-ion collisions

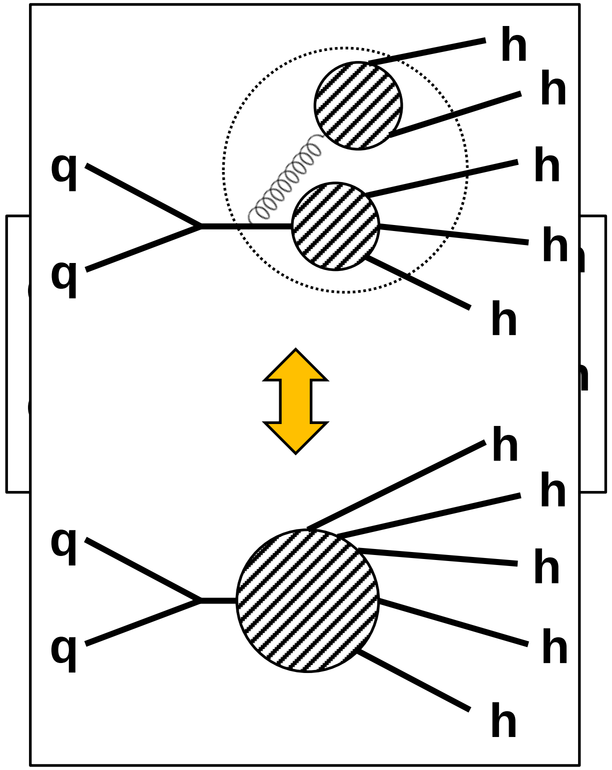
Inv. yield vs. p_T



Phys. Lett. B 754 (2016) 235-248
ALICE-PUBLIC-2015-007

Transition from QGP to Hadrons

Hadronization

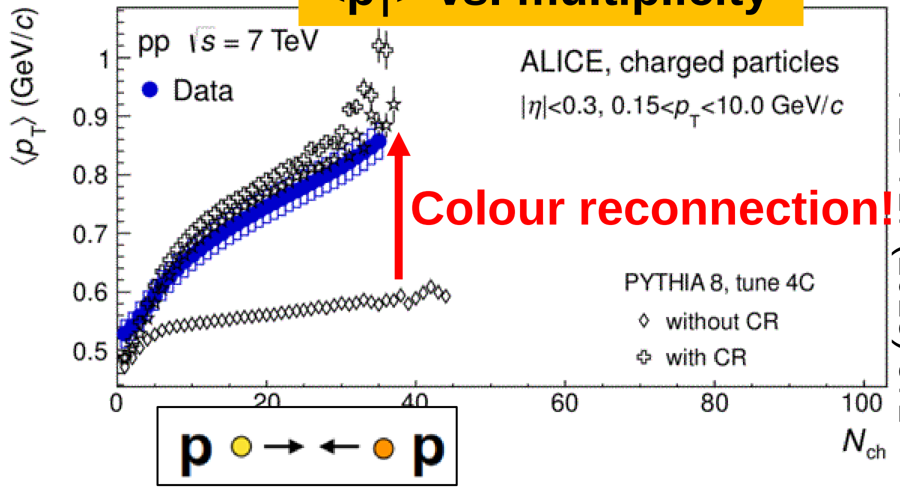


- Hadronization is a non-perturbative process
  - No first-principle description
  - Λ_{QCD}… but when does it begin exactly?
  - Understanding is very important, as a fundamental element of QCD
    - Affects all observables which measure hadrons
    - Needed for background estimates, including in searches
  - Experiment guides the way hand-in-hand with theory-inspired phenomenological models
- Initially: Factorized description of hadron production

$$\sigma_{pp\to hx} = PDF(x_a,Q^2)PDF(x_b,Q^2)\otimes\sigma_{ab\to q\bar{q}}\otimes D_{q\to h}(z,Q^2)$$

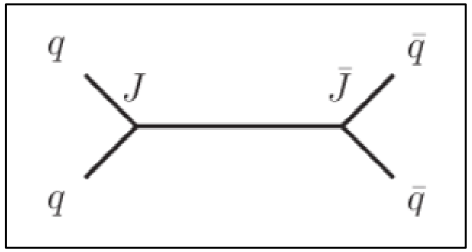
  - Multiple interactions within collision combined incoherently
- But: Picture fails when multiplicity increases
  - Addition of e.g. colour reconnection needed

$<p_T>$ vs. multiplicity

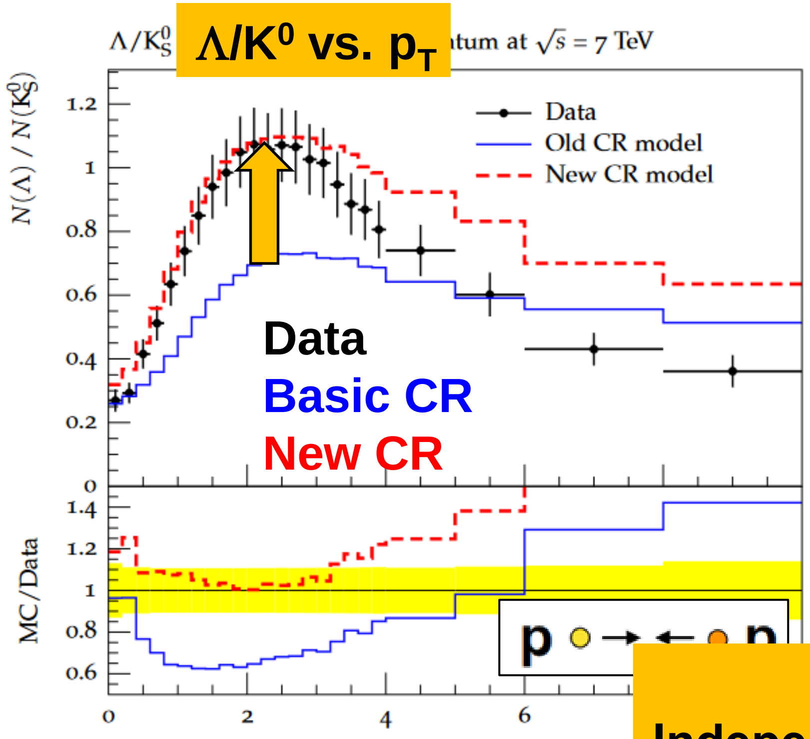


PLB 727 (2013) 371

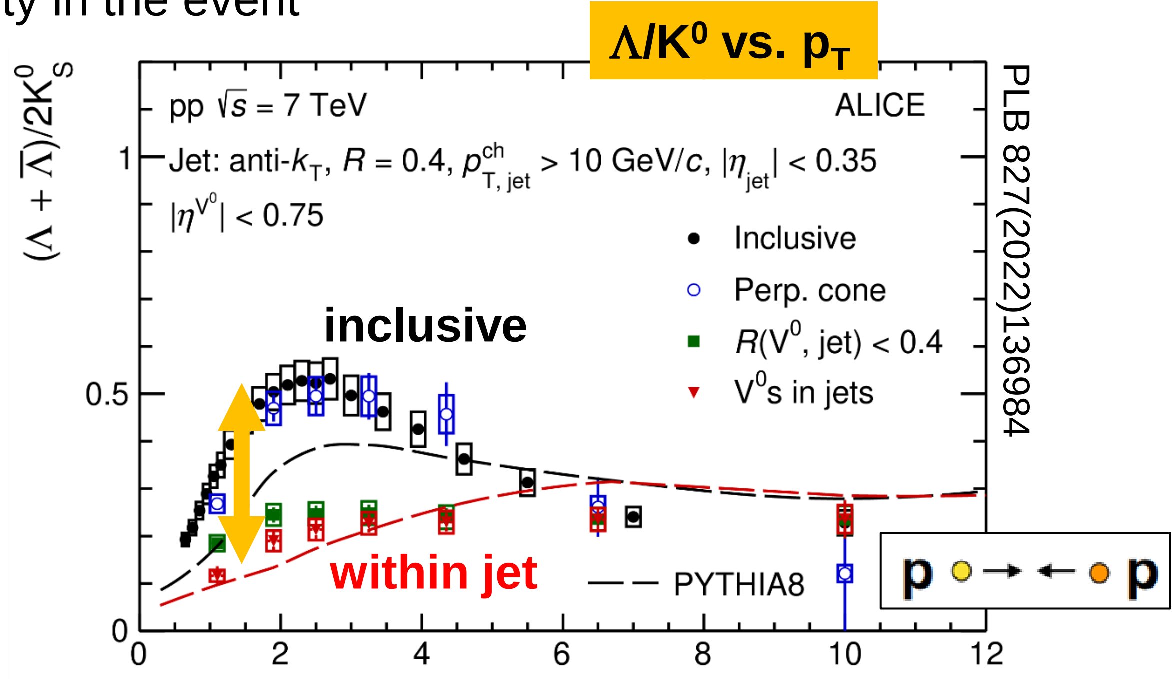
Baryon Production



- Baryon production (e.g. Λ) not described by e^+e^- inspired models
  - E.g. in Pythia, need for more than basic color reconnections (e.g. junctions, JHEP 08(2015)003)
- Baryon enhancement not visible for jet constituents
  - Fragmentation remains independent of other activity in the event



Christiansen, Skands, JHEP 08 (2015



PLB 827(2022)136984

Fragmentation within jets unaltered (e^+e^- like).
Independent and "higher-order" fragmentation present in same collision

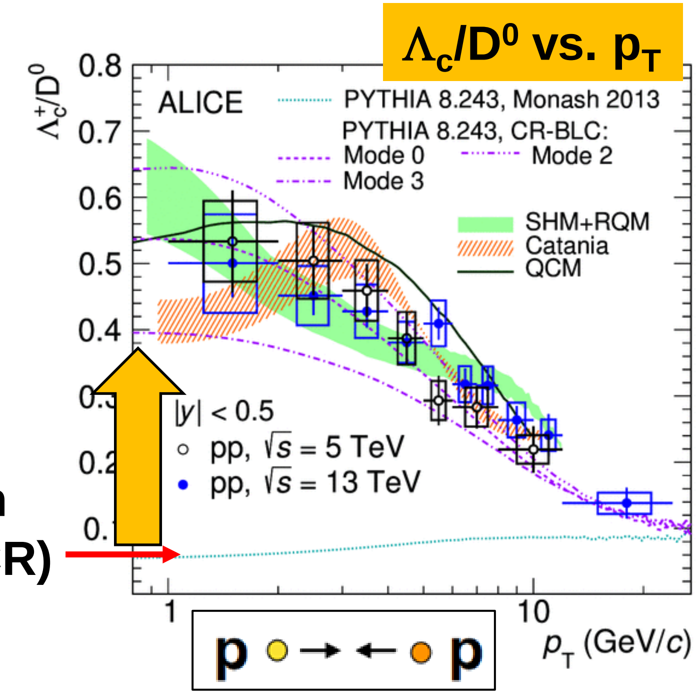
Charm Sector

- Charm and beauty produced in hard scattering, rarely in string fragmentation

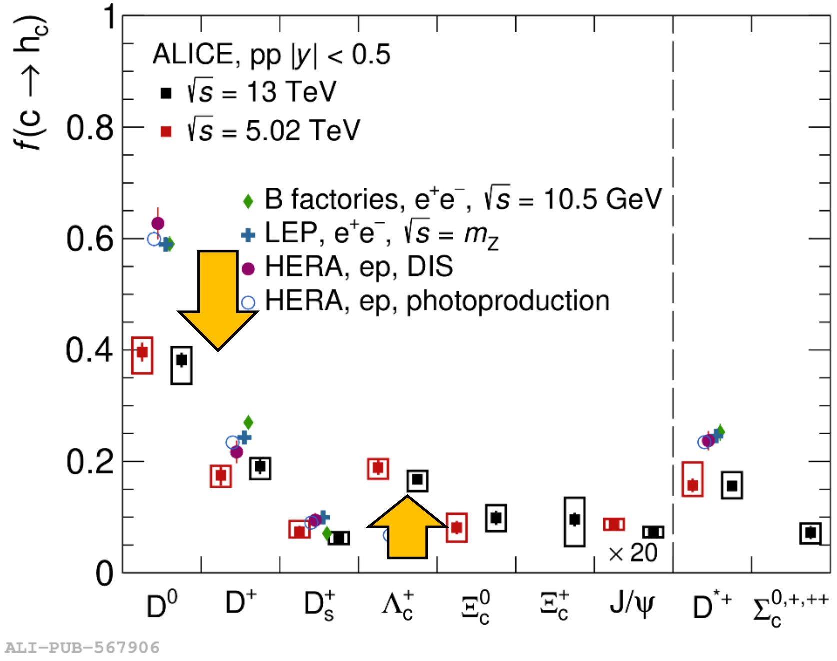
- Baryon enhancement also in charm sector
  – Surprise: Λ_c/D significantly larger than e^+e^- expectation
  – Pythia with reconnections beyond leading colour works

- Significant effect on fragmentation fractions
  – Less D^0 in pp than in e^+e^- and ep
  – More Λ_c in pp than e^+e^- and ep

e^+e^- expectation (including LO CR)



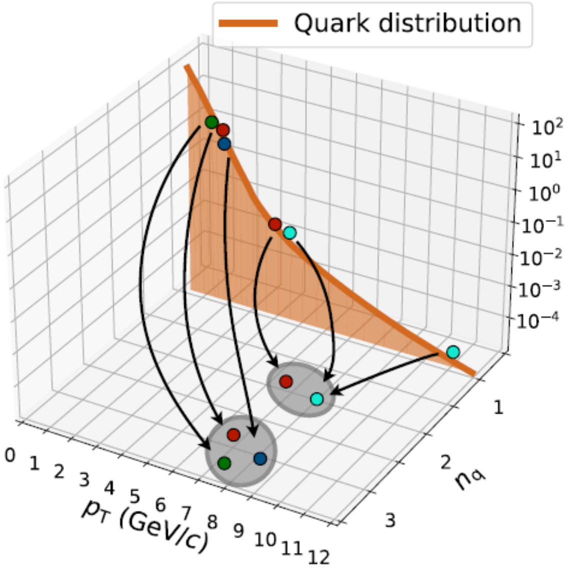
PRL128 (2022) 012001



JHEP 12 (2023) 086

Coalescence and Statistical Hadronization

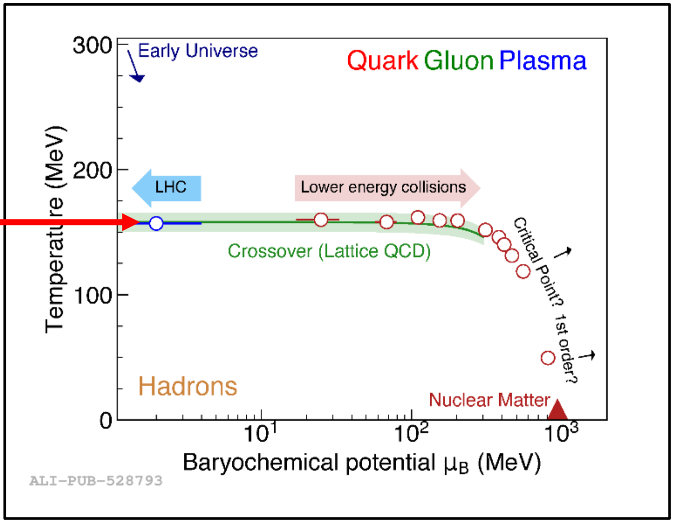
- Coalescence in filled phase space of quarks and gluons
  - Partons close in momentum and position space coalesce to hadrons
  - Probability is p_T dependent
  - Can be successfully applied to large objects
    - Nuclei have small binding energy and are formed late
- Statistical hadronization: Relativistic 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

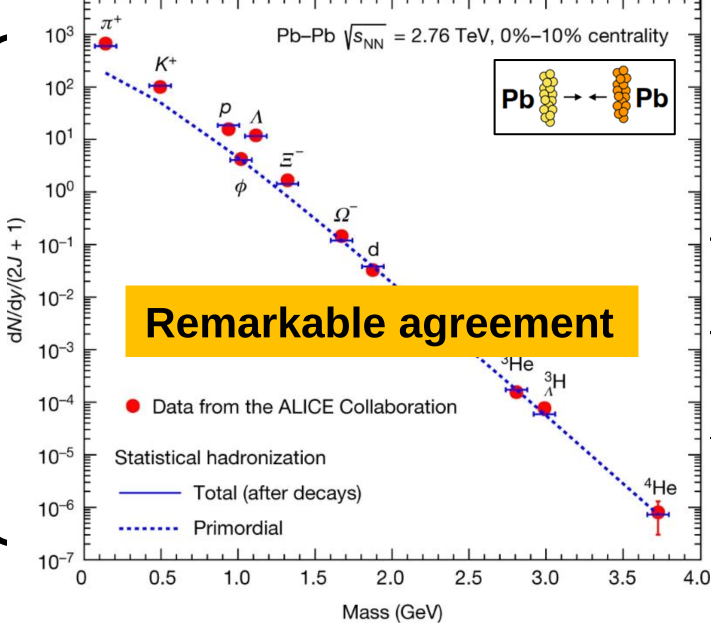


Cartoon: F. Grosa

11 different species

9 orders of magnitude



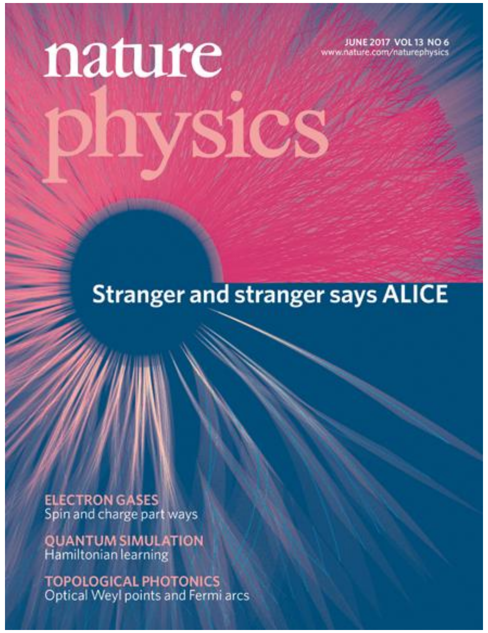


Nature 561 (2018) 7723, 321

Onset of QGP Production

Strangeness Enhancement

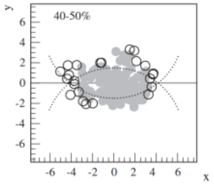
- Hadronization for strange particles density-dependent
- Strange particle production increases with multiplicity
  - K/π, Λ/π, Ξ/π, Ω/π
  - from pp, over p-Pb, to Pb-Pb



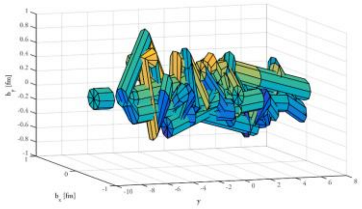
❌ Independent fragmentation

$D_{q \to h}(z, Q^2)$

✅ EPOS (core-corona)

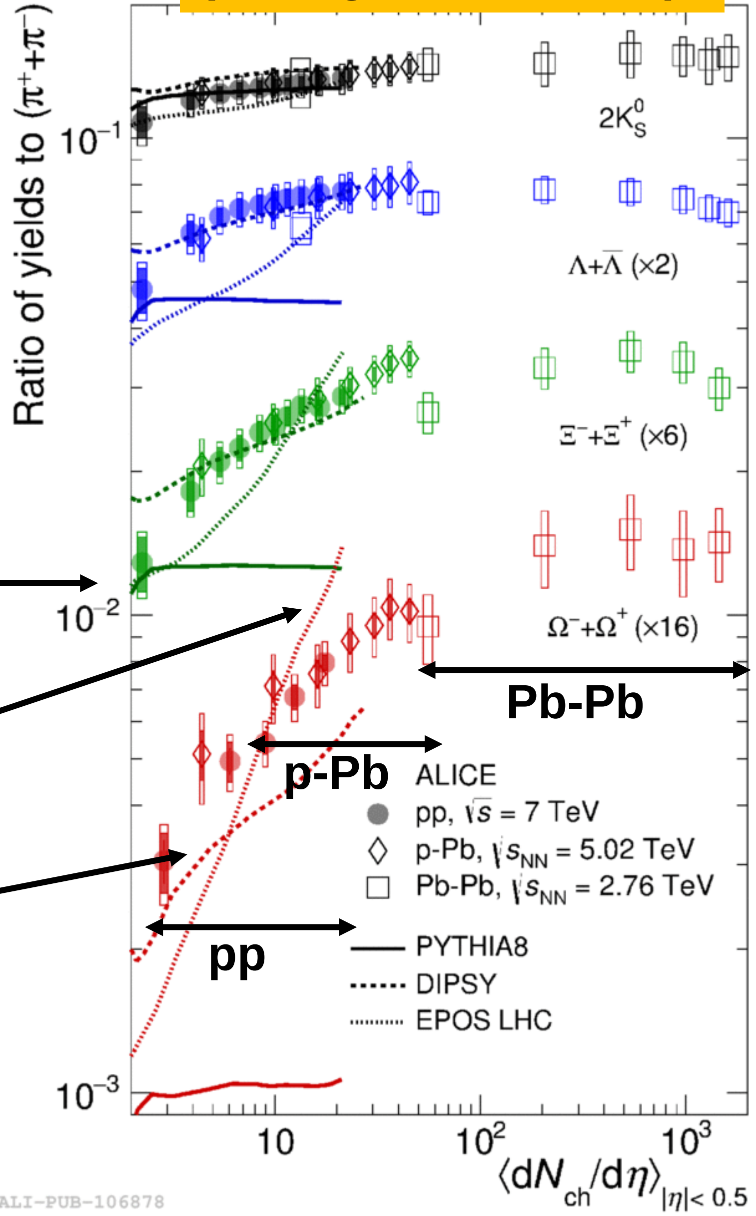


✅ Colour rope mechanism (DIPSY)



Christian Bierlich

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

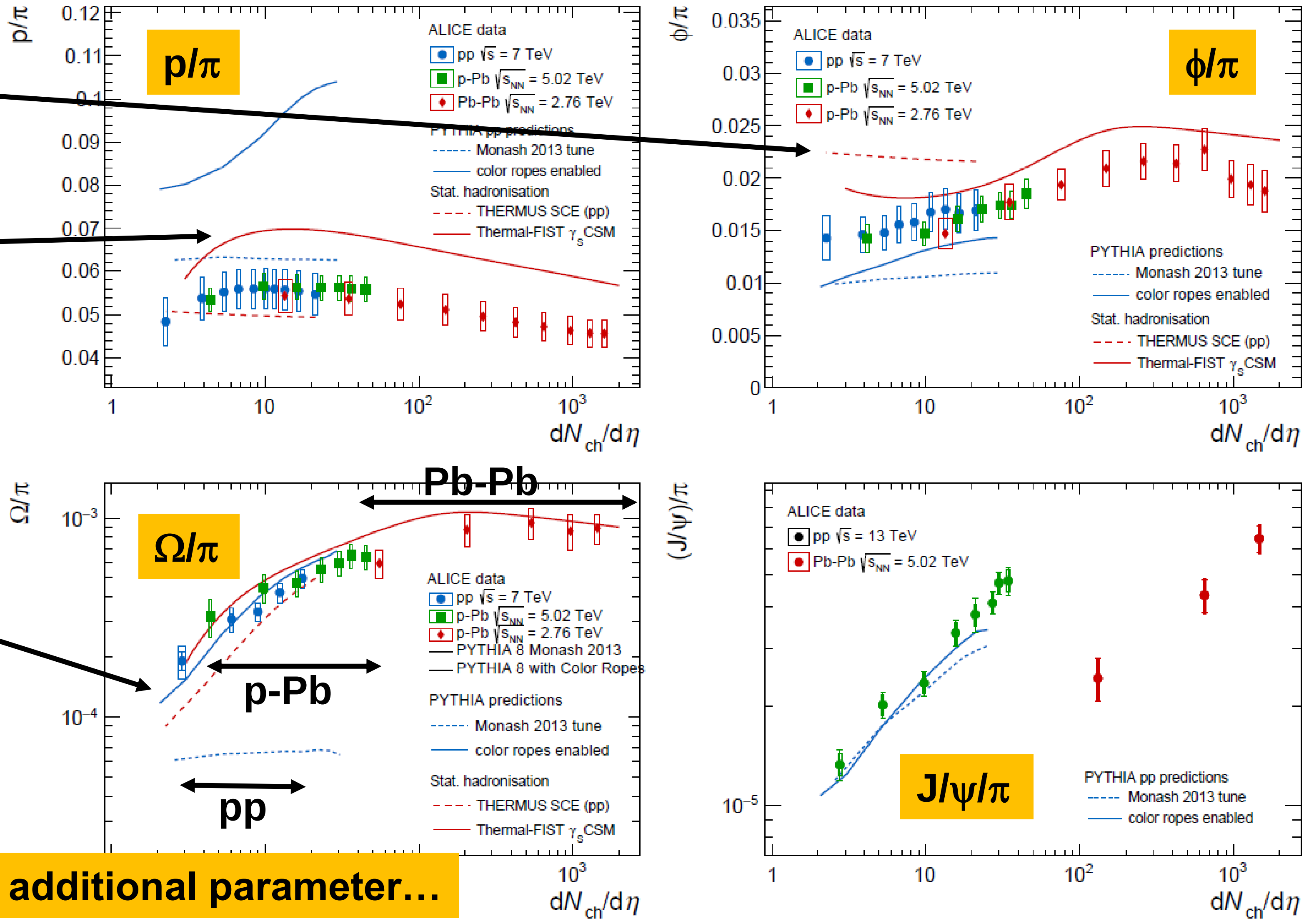


Nature Phys. 13 (2017) 535

Statistical Hadronization Model in pp and p-Pb

arXiv:2211.04384

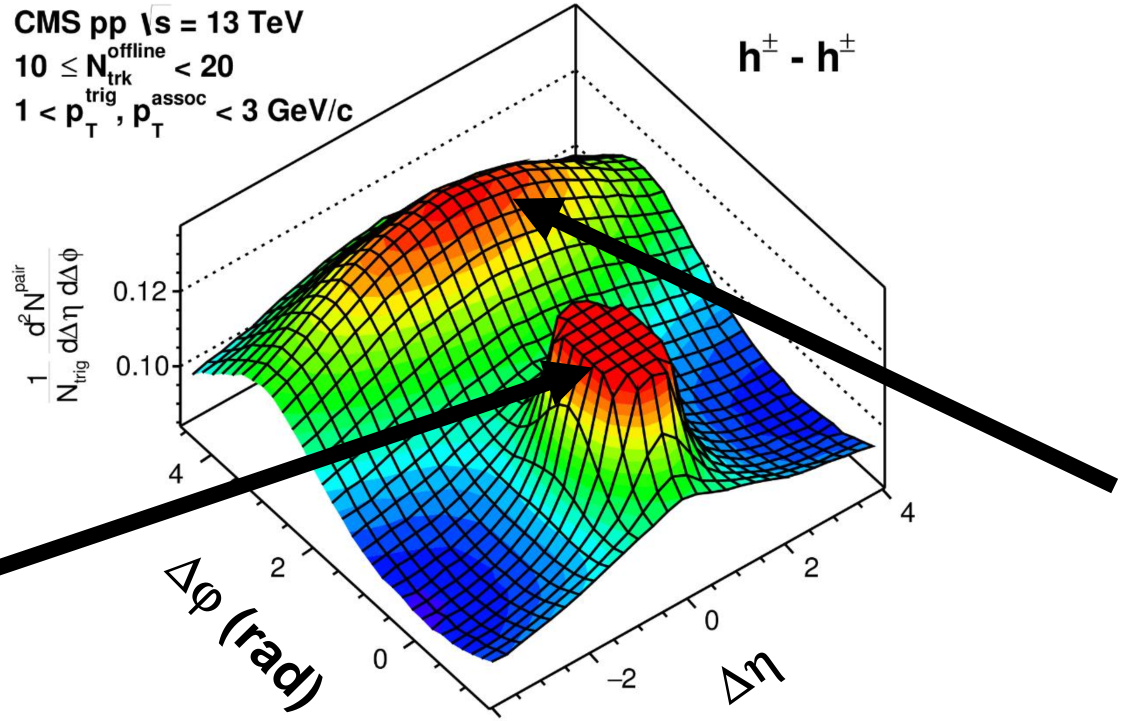
- THERMUS SCE
  - With fixed T
  - No good description
- Thermal-FIST
  - Multiplicity dependent T
  - Strangeness suppression parameter γ_S
  - Good description: ϕ/π and Ω/π
  - p/π only qualitative
- Colour ropes in Pythia
  - Successful for ϕ/π and Ω/π
  - Far off for p/π



SHM works in small systems but needs additional parameter…

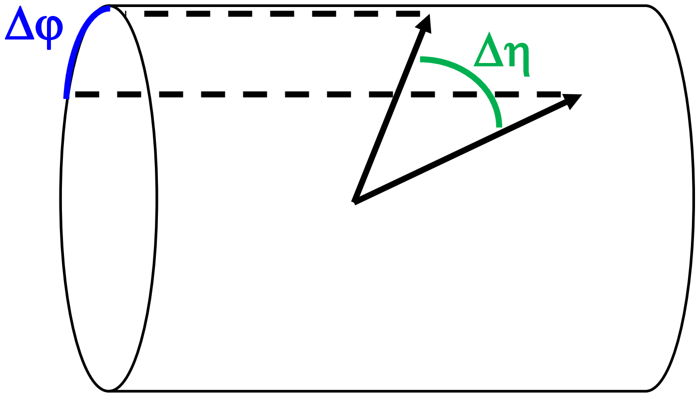
Collective Phenomena

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



Near-side jet
Resonance decays

Away-side jet

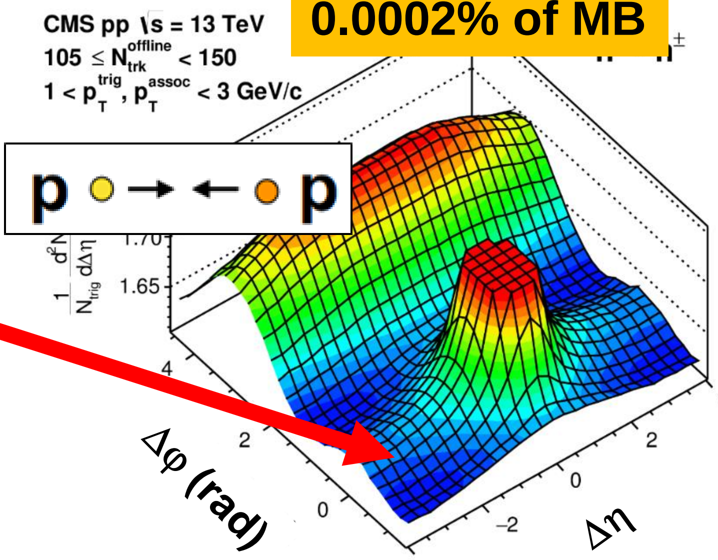


PLB 765 (2017) 193

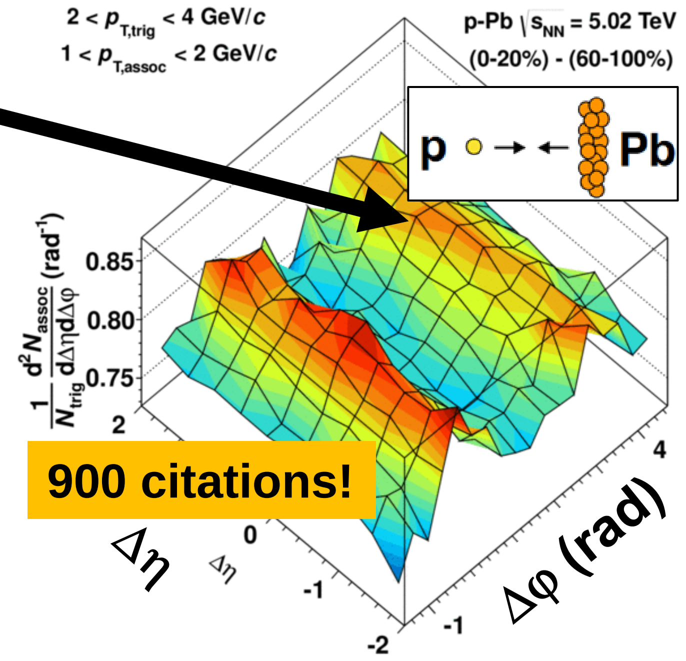
Collective Phenomena

- Striking observation of long-range ridge structures
  - First publication: JHEP 09 (2010) 091 **1200 citations!**
- Initially seen in high-multiplicity in pp and p-Pb
  - Jet subtraction procedure revealed almost symmetric away-side component
- Entire field emerged; paradigm shift
  - What is smallest system for which heavy ion “standard model” remains valid?
  - Can the standard tools for pp physics remain standard?

0.0002% of MB



CMS, PLB 765 (2017) 193



900 citations!

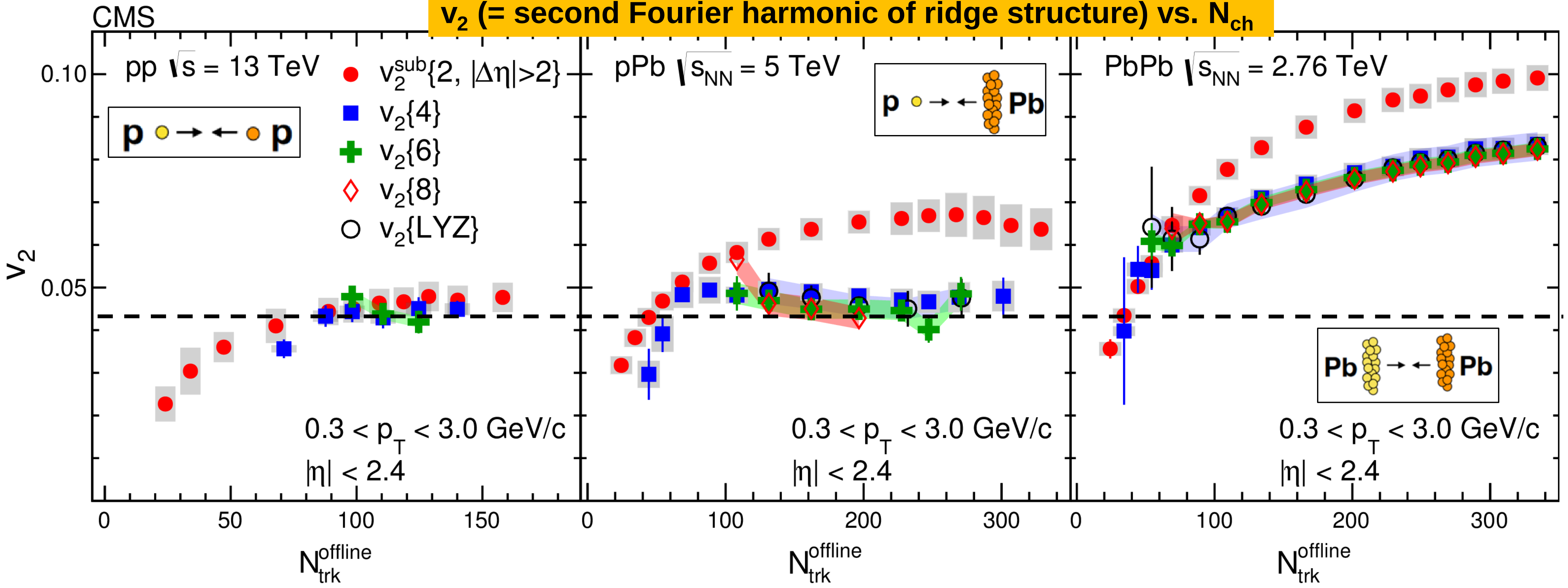
ALICE, PLB719 (2013) 29

Intriguing interpretations involving QGP in small systems

Higher-Orders Collectivity

How many particles contribute to the phenomena?

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

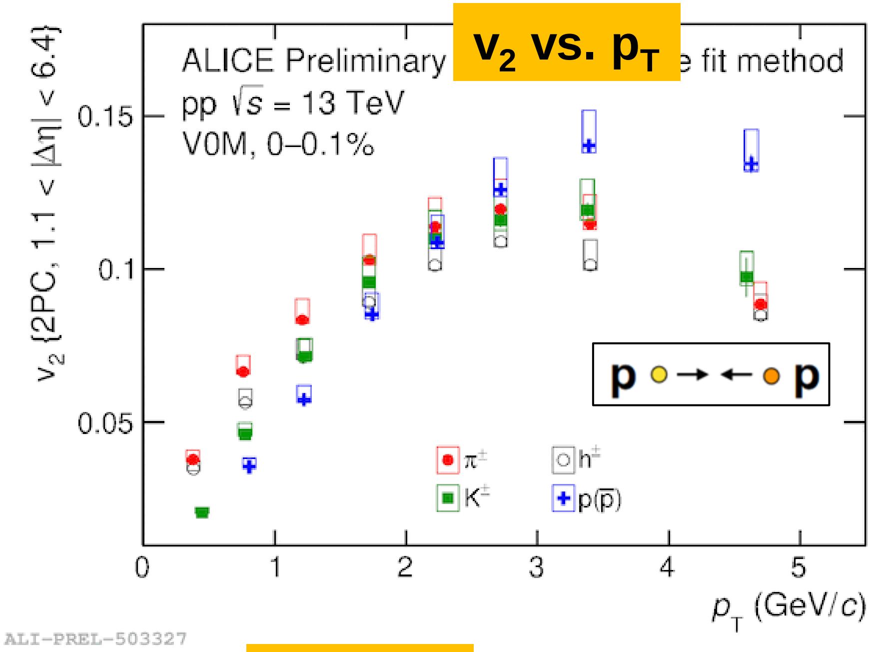


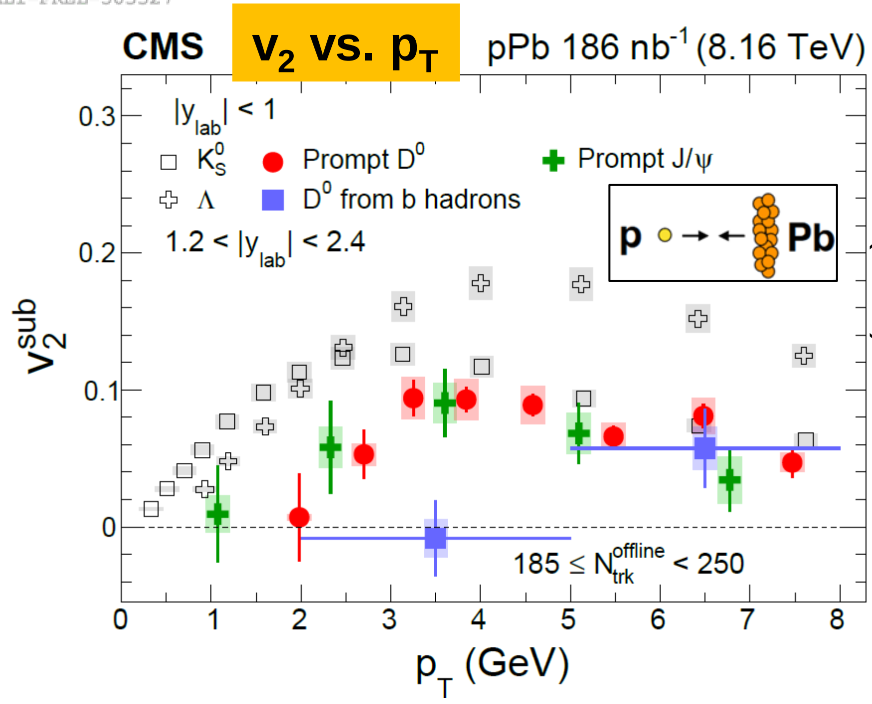
Ridge component characterized with multi-particle correlations: pp ~ p-Pb < Pb-Pb
→ At least 6 particles involved above $N_{ch} \approx 90$

PLB 765 (2017) 193

Identified-Particle Collectivity

- Light particles (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
- Charm quarks show collective behaviour
  - Large systems: they thermalize in the medium
  - Also observed for D and J/ψ in high-multiplicity p-Pb
- Bottom quark flow in large systems
  - Large systems: they are affected by the medium
  - Hint in high-multiplicity p-Pb





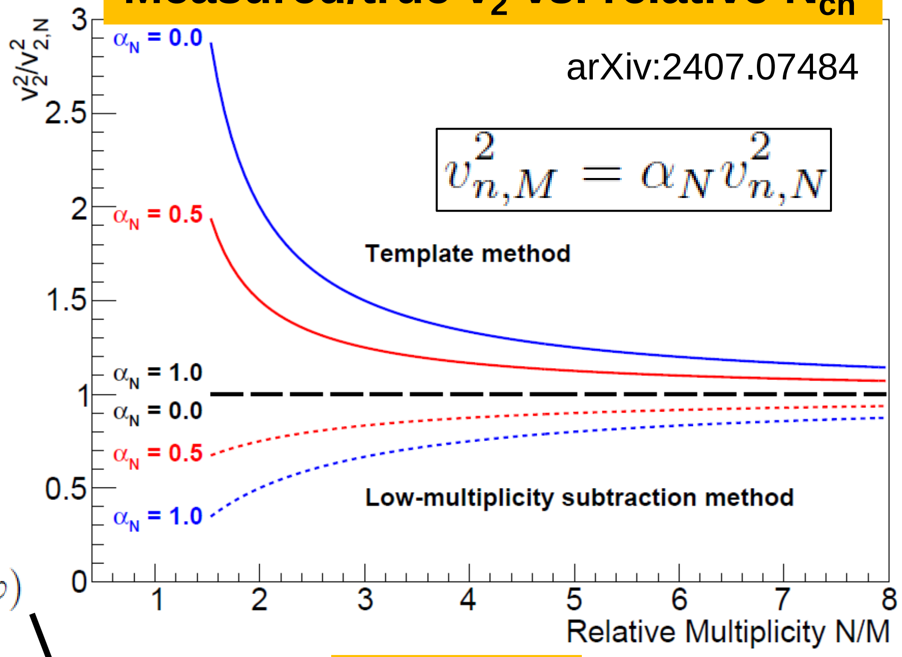
Low Multiplicity

Does the phenomena switch off?

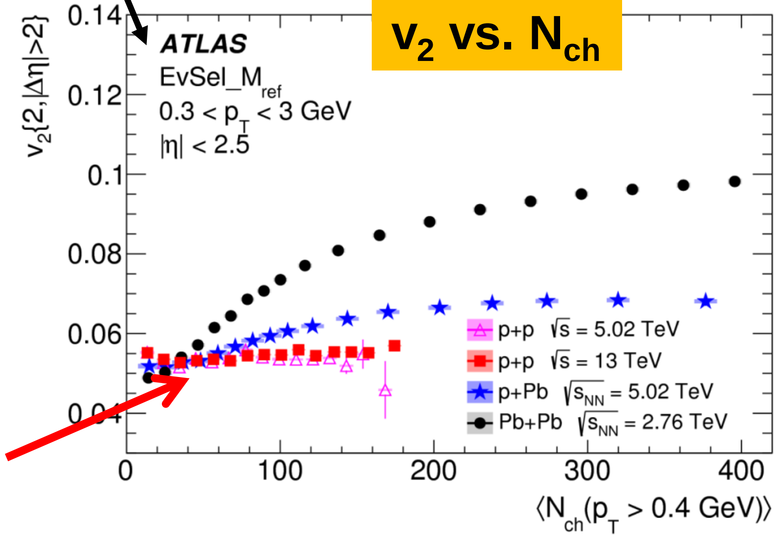
- Low multiplicity dominated by jets, resonances (~negligible in high-multiplicity pp or p-Pb)
- Key problem: Ridge "too small to stick out"
  - Extracting v_2 coefficient requires subtraction procedure
    - Low-multiplicity subtraction $\Delta Y(\Delta\varphi) = G' + N\sum 2v_n^2\cos(n\Delta\varphi)$
    - Template fit method $\Delta Y(\Delta\varphi) = G\left(1 + \sum_n 2v_n^2\cos(n\Delta\varphi)\right)$

Measured/true v_2 vs. relative N_{ch}

arXiv:2407.07484

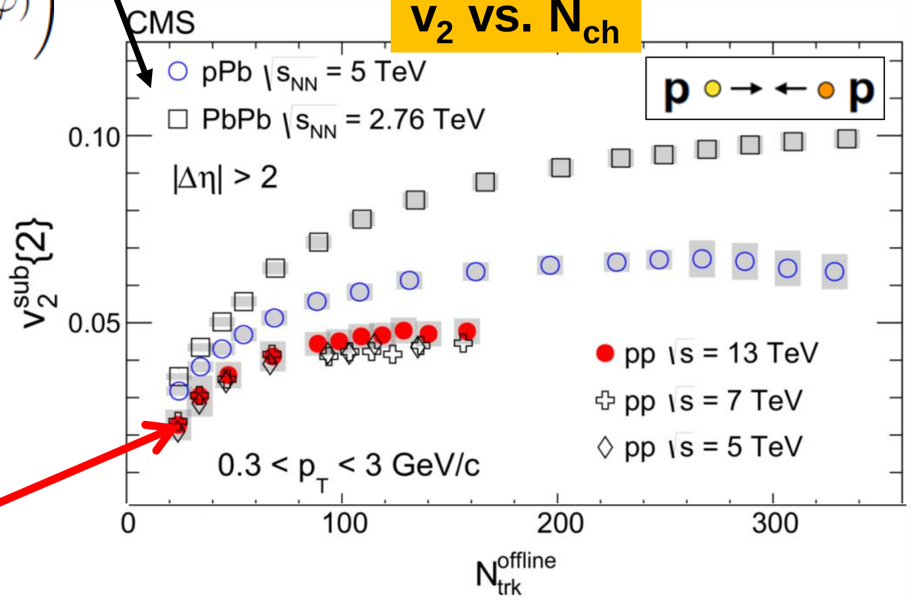


v_2 vs. N_{ch}



EPJC 77 (2017) 428

v_2 vs. N_{ch}



PLB 765 (2017) 193

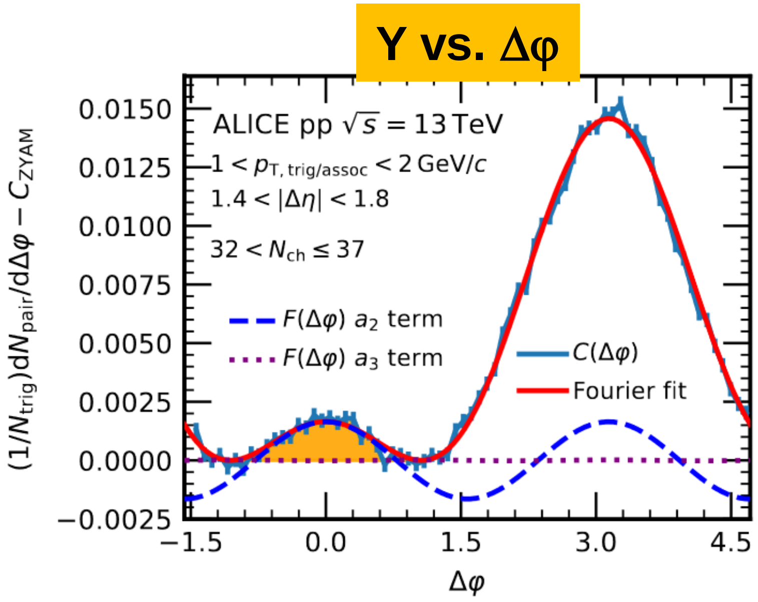
p → ← p

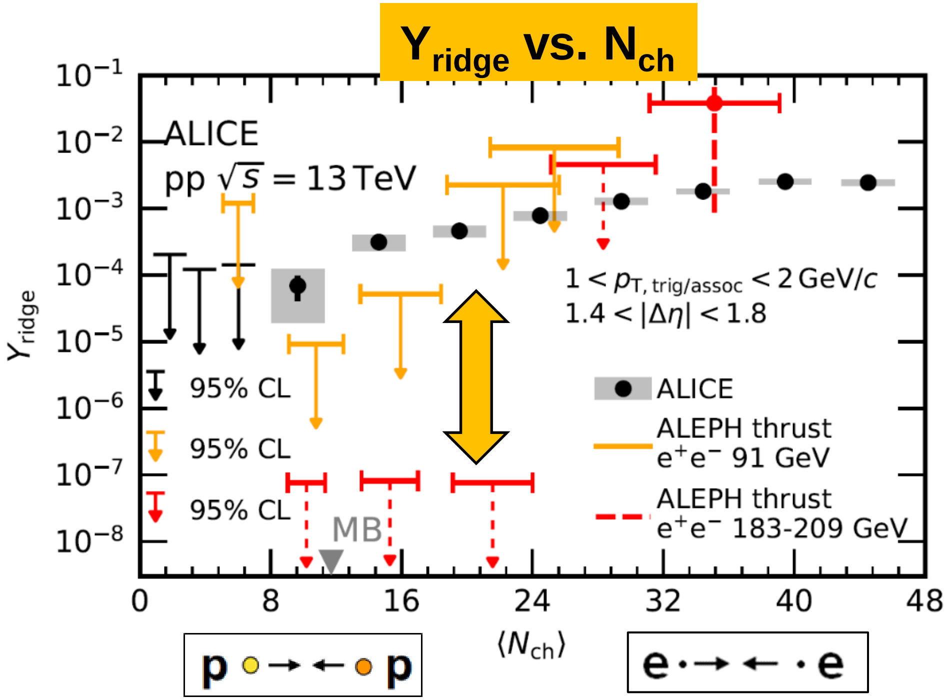
p → ← p

Experimental result procedure dependent – in particular at low multiplicity

Even smaller systems
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

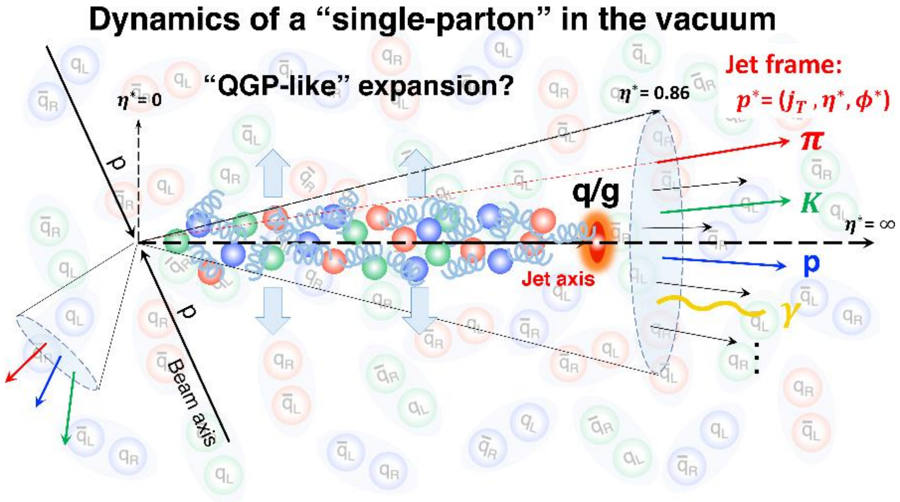


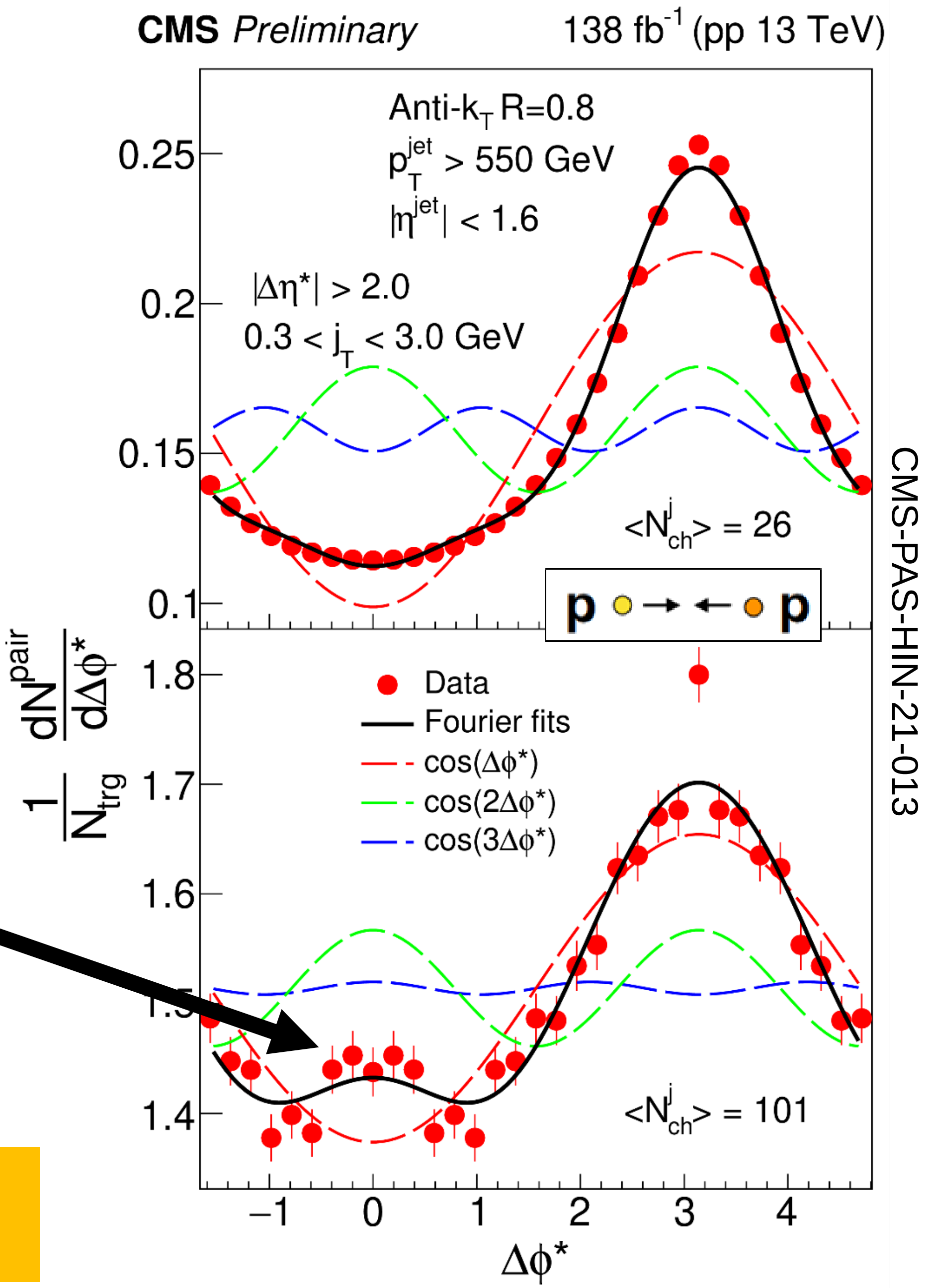


PRL132 (2024) 17, 172302

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?

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 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

Search...

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

Nature of the QGP

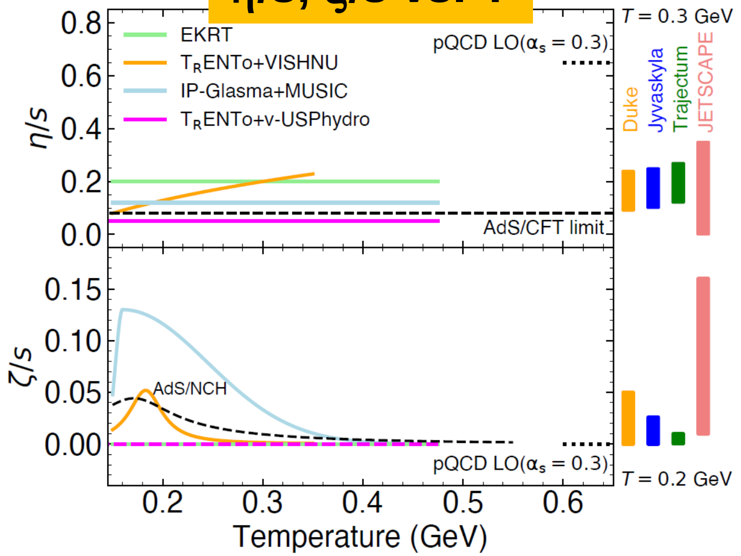
Summary

- Particle production significantly altered
- Distinct phenomena connected to quark and gluons as degrees of freedom

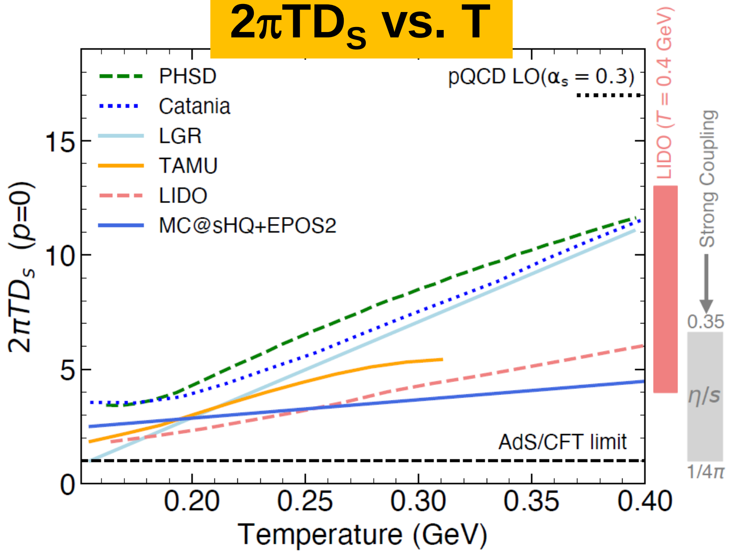
Summary: Transport Coefficients

- QGP studies allow to constrain several transport coefficients
- Shear viscosity η/s washes out initial-state anisotropies
- Bulk viscosity ζ/s which reduces rate of radial expansion
- Spatial diffusion coefficient D_S governing motion of charm
- Quenching power $\hat{q}$ governing the energy loss of traversing partons

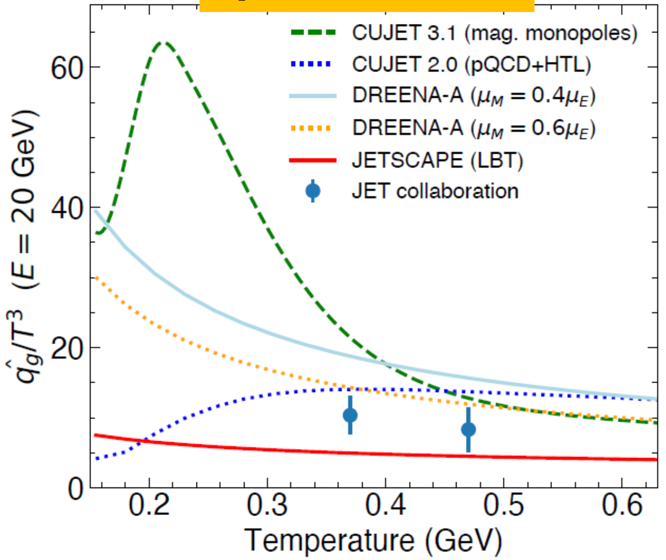
η/s, ζ/s vs. T



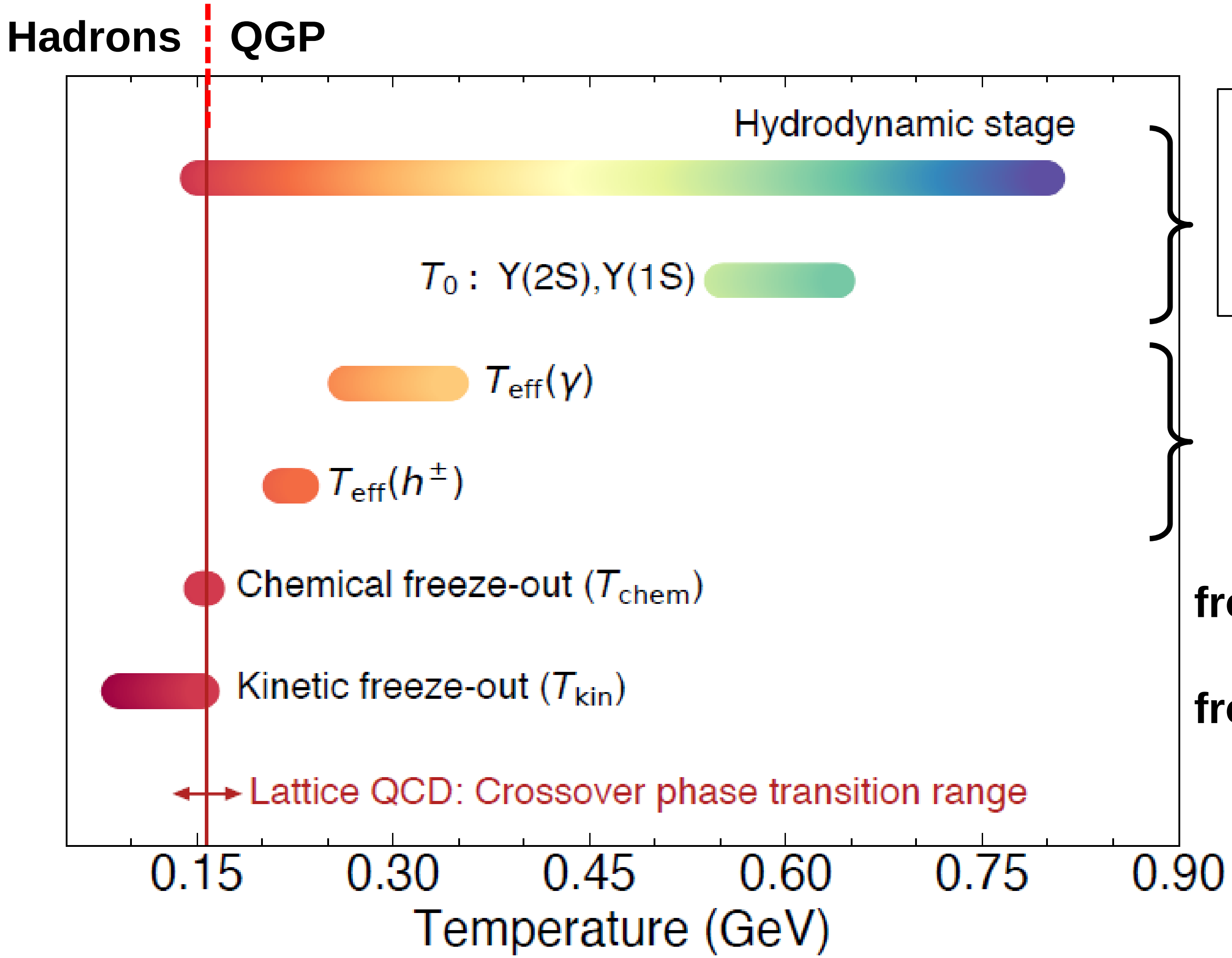
2πTD$_S$ vs. T



qhat/T^3 vs. T



Summary: Temperatures



Depends on model and τ_0:
- **IP-Glasma+MUSIC: up to 0.8 GeV**
- **TRENTO+VISHNU: up to 0.35 GeV**
- **From ϒ: up to 0.64 GeV**

effective temperatures averaged over medium lifetime

from Statistical Hadronization Model

from Blast-Wave fits

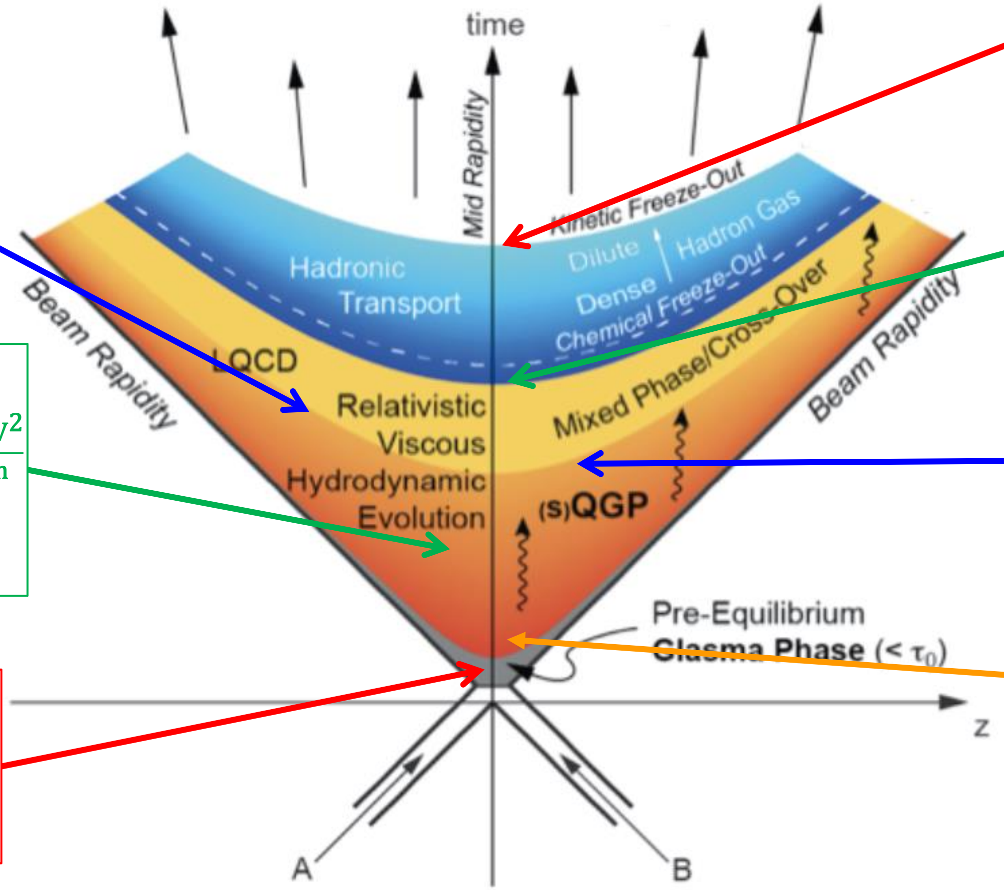
Summary: Medium Evolution

Large pressure
↓
collective flow

Dense medium
↓
Energy loss,
Quarkonia melting

$\hat{q} \approx 1.5\ \frac{\text{GeV}^2}{\text{fm}}$

Density fluctuations
↓
spatial anisotropies



Kinetical freeze-out
T ~ 90 – 150 MeV

Chemical freeze-out
T ~ 156 MeV
V ~ 5000 fm^3

Viscous hydrodynamics
η/s ~ 0.08 – 0.24

Initial temperature
T > 300 – 800 MeV

Values for central $\sqrt{s_{NN}}$ = 2.76 TeV collisions (LHC)

Future

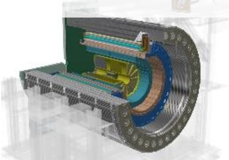
High-Energy Frontier

LHC + RHIC

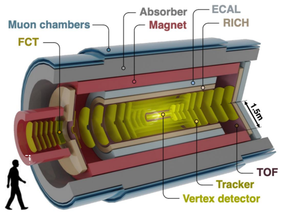
Major upgrades completed in 2021

Major upgrades in 2026-28

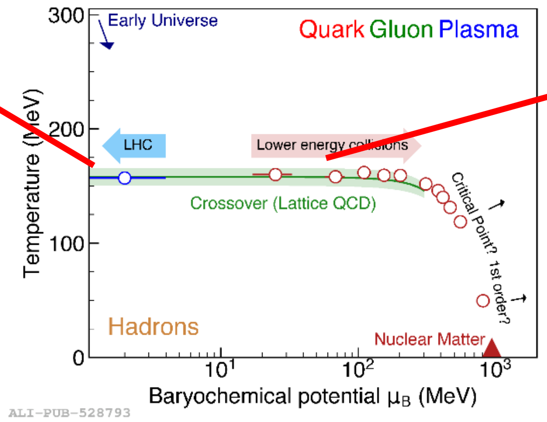
sPHENIX



Data-taking since 2023



ALICE 3 (2035?)

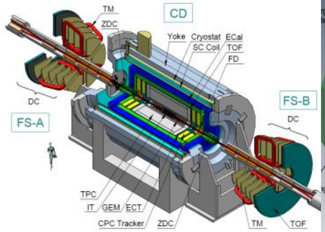


Large-μ_B Frontier

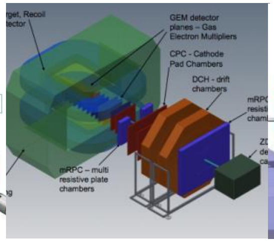
RHIC + FAIR

NICA + SPS

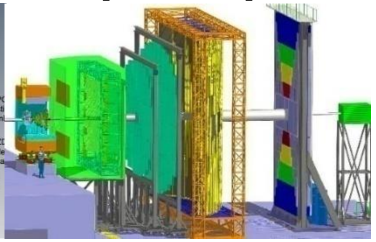
MPD (?)



BM@N

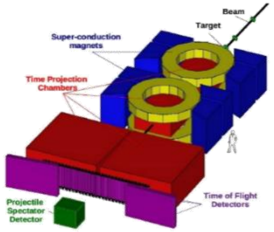


CBM (2028?)

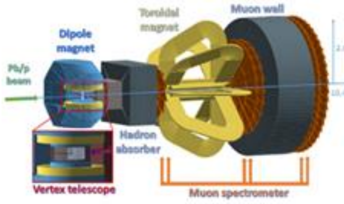


HADES

NA61/SHINE



NA60+ (?)



10 nb^{-1} Pb-Pb → **10^{11} MB events**

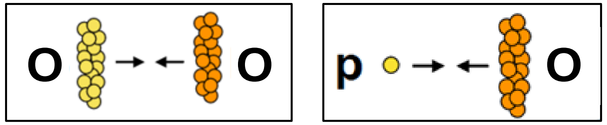
LHC 2022-32

35 nb^{-1} Au-Au → **10^{11} MB events**

RHIC 2023-26

200 pb^{-1} pp → **10^6 events N_{ch} > 12 <N_{ch}> (250 particles in $|\eta|$ < 1.5)**

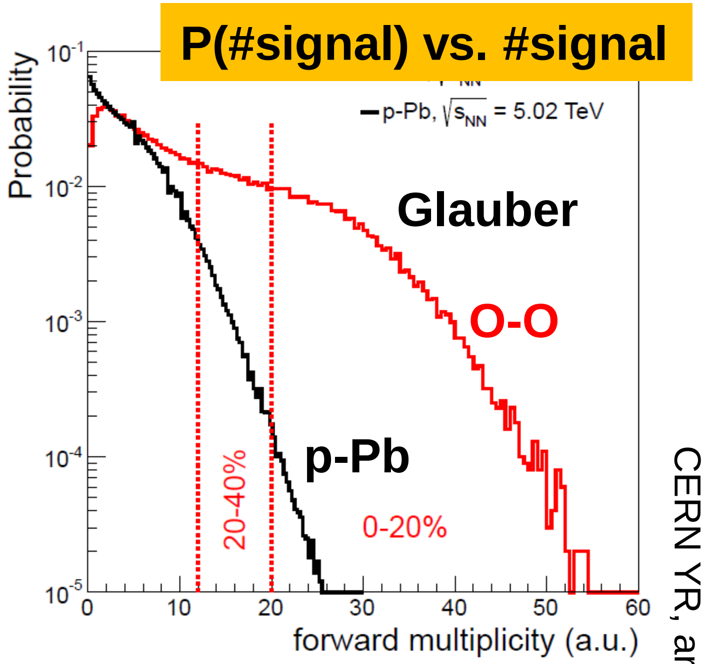
LHC 2022-25

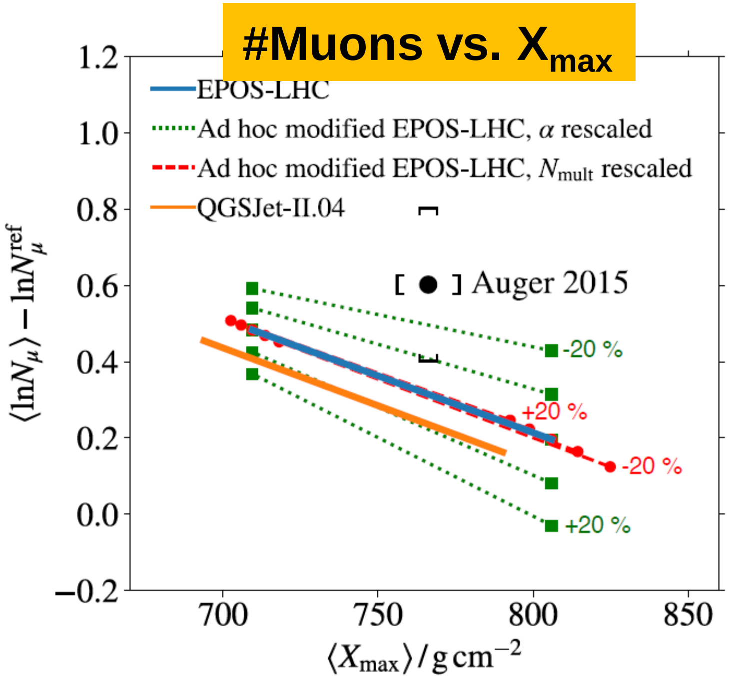


Run 3

Oxygen Run

- O-O, p-O collisions in LHC planned for July 2025
  - 3 days p-O: ALICE: p-O: 2 nb^{-1}, ~10^8 events
  - 1 day O-O: ALICE: O-O: 0.5 nb^{-1}, ~$7x10^7$ events
- AA geometry but N_{ch}, N_{part}, N_{coll} as p-Pb
  - Centrality shoulder allows geometry selection (N_{coll}, ε_2)
- System large enough to exhibit jet quenching
  - Critical test for energy loss for short path lengths
  - If no quenching in O-O
    → also p-Pb has insufficient energy density for quenching
- Cosmic-ray community expressed strong interest in p-O to constrain models for cosmic-ray showers
  - Muon deficit in cosmic-ray simulations mitigated by adding collective effects or strangeness
    (see e.g. arXiv:1902.08124)





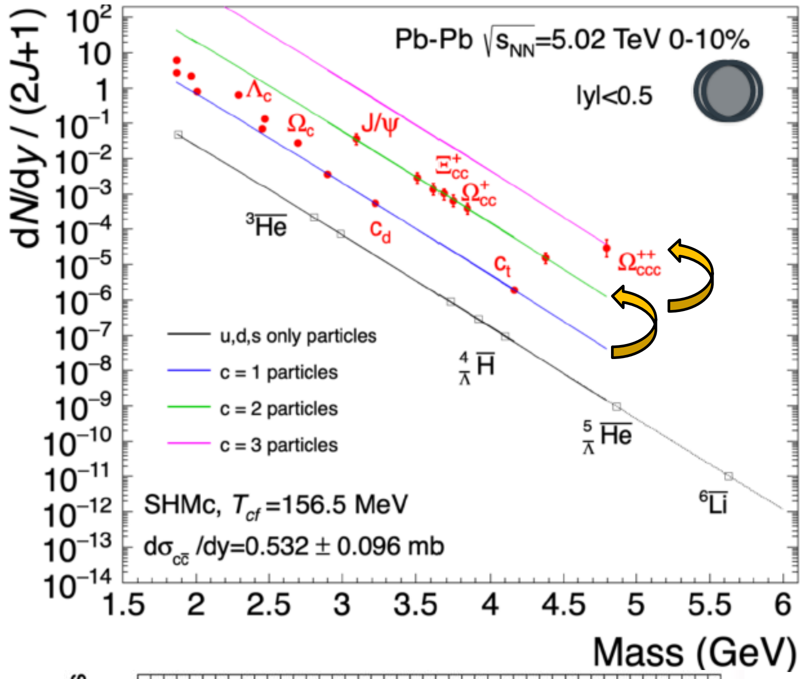
CERN YR, arXiv:1812.06772

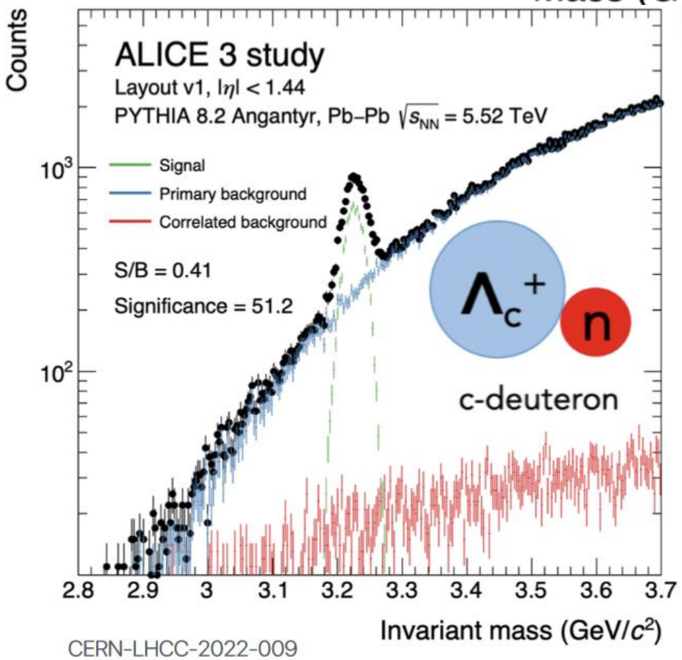
Run 5 and 6

ALICE 3 @ LHC

- Detector for LHC Run 5 and 6 (2035-41)
- $\sqrt{s_{NN}}$ = 5-6 TeV (PbPb, XeXe, InIn?, KrKr?)
  - Species driven by detector design and physics (no scan!)
- Thermal leptons
  - Precise medium temperature, chiral symmetry restoration
- Multiple charm (Ξ_{cc}, Ω_{cc}, …) production

  $\Xi_{CC}^{++} \rightarrow \Xi_C^{+}\pi^{+} \rightarrow \Xi^{-}\pi^{+}\pi^{+}\ \pi^{+}$ $\quad$ $\Omega_{CC}^{+} \rightarrow \Omega_C^{0}\pi^{+} \rightarrow \Omega^{-}\pi^{+}\ \pi^{+}$
  - Hadronization models; coalescence on quark level
- Heavy-quark correlations: D^0-D^0 for QGP scattering
- Quarkonia beyond S-wave: χ_c and χ_b
  - Dynamics of bound-state interactions within QGP
- Hadronic interactions and bound-state formation
  - For example: D-D* and c-deuteron
- Ultra-soft photons





CERN-LHCC-2022-009

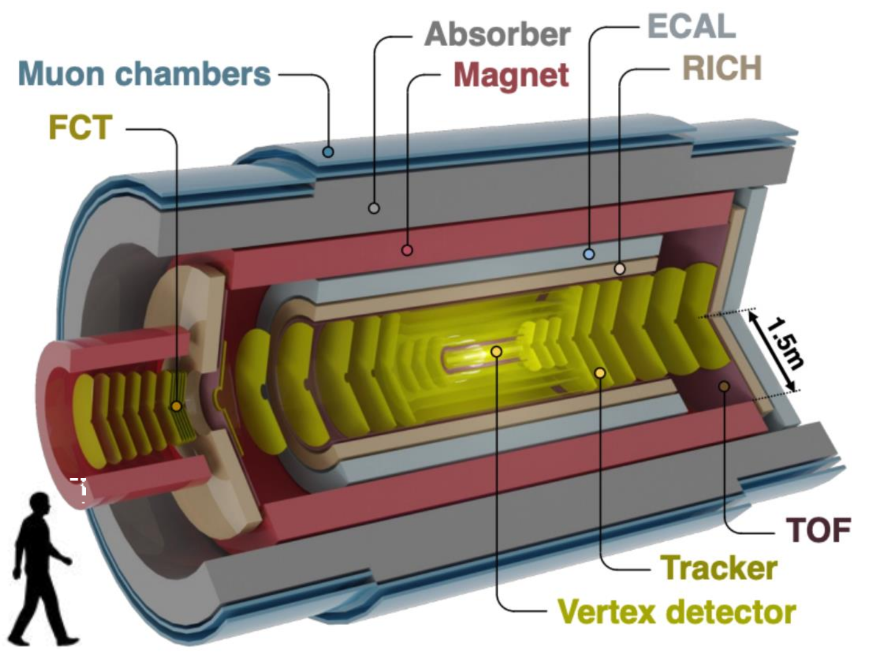
arXiv:2211.02491

Run 5 and 6

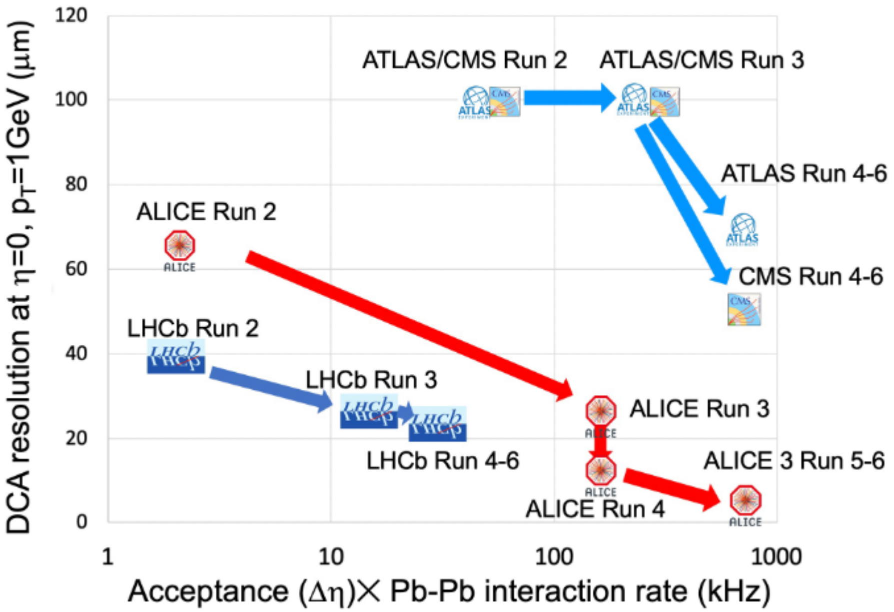
ALICE 3 @ LHC

- Retractable vertex detector 5 mm from beam
  - Pointing resolution 3-4 μm @ 1 GeV
  - X/X_0 ~ 0.1% per layer
- All-silicon tracker (p_T resolution 1% @ 1 GeV)
- ECAL, RICH and muon detectors
- Continuous readout and online processing
  Pb-Pb: 35 nb^{-1} | pp 18 fb^{-1}
- Strangeness tracking: a MHz bubble chamber

- Status & Plan
  - LoI submitted in 2022. Positive assessment by LHCC
  - Scoping document to be submitted this year
  - Installation in LHC LS4 (2033-2034)
  - Data taking in LHC Run 5 and 6 (2035-2041)

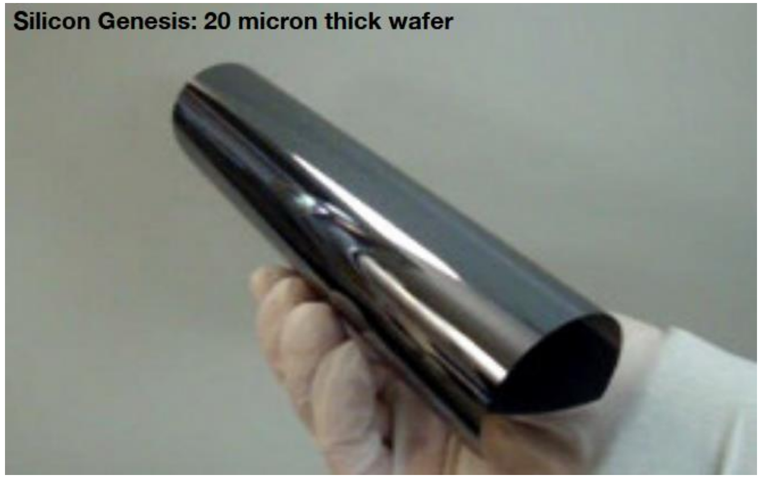


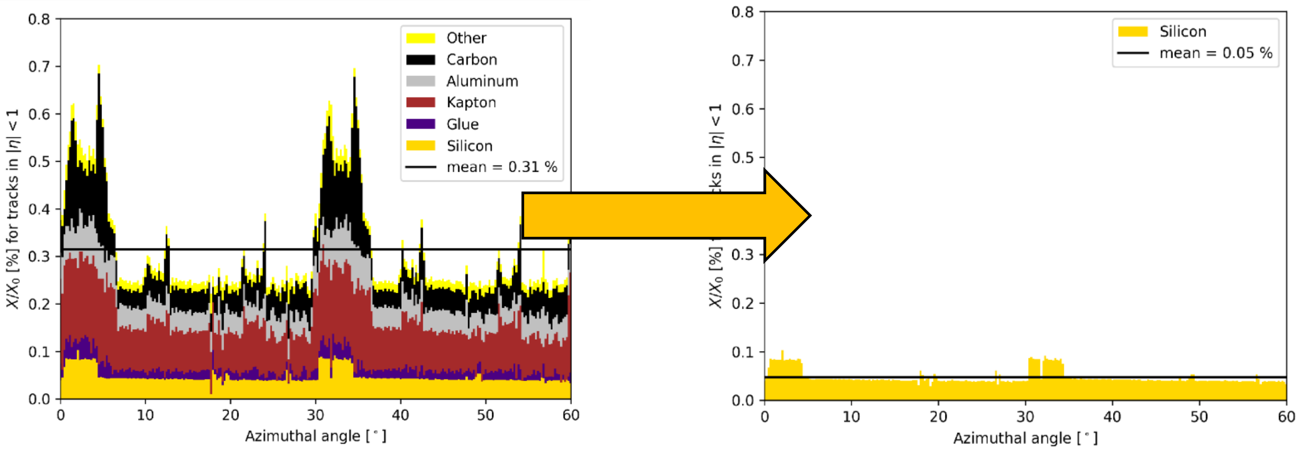
arXiv:2211.02491

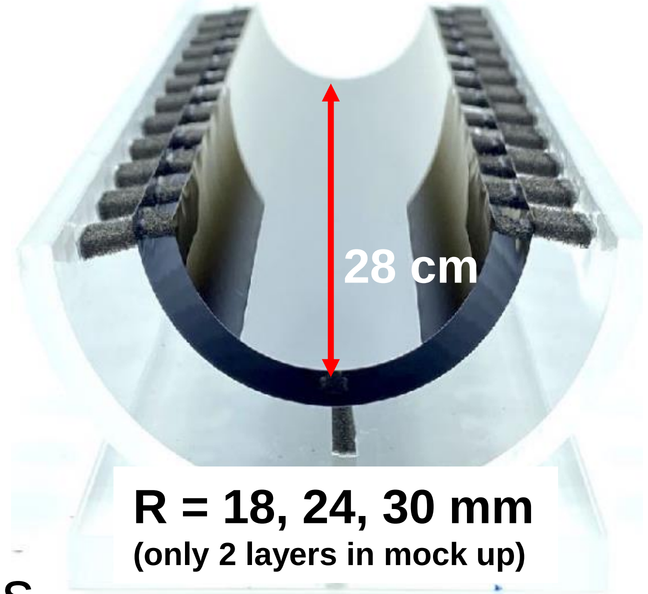


Silicon R&D

- ALICE ITS2 demonstrated: large scale (~10 m^2) use of monolithic active pixel sensors (MAPS), 50 μm thin
- Ongoing R&D for ITS3
  - Wafer-scale sensors using stitching + bending
  - "Zero-mass" detector: 0.02-0.04% X/X_0 per layer
  - Carbon foam + air cooling (power consumption < 20 mW/cm^2)



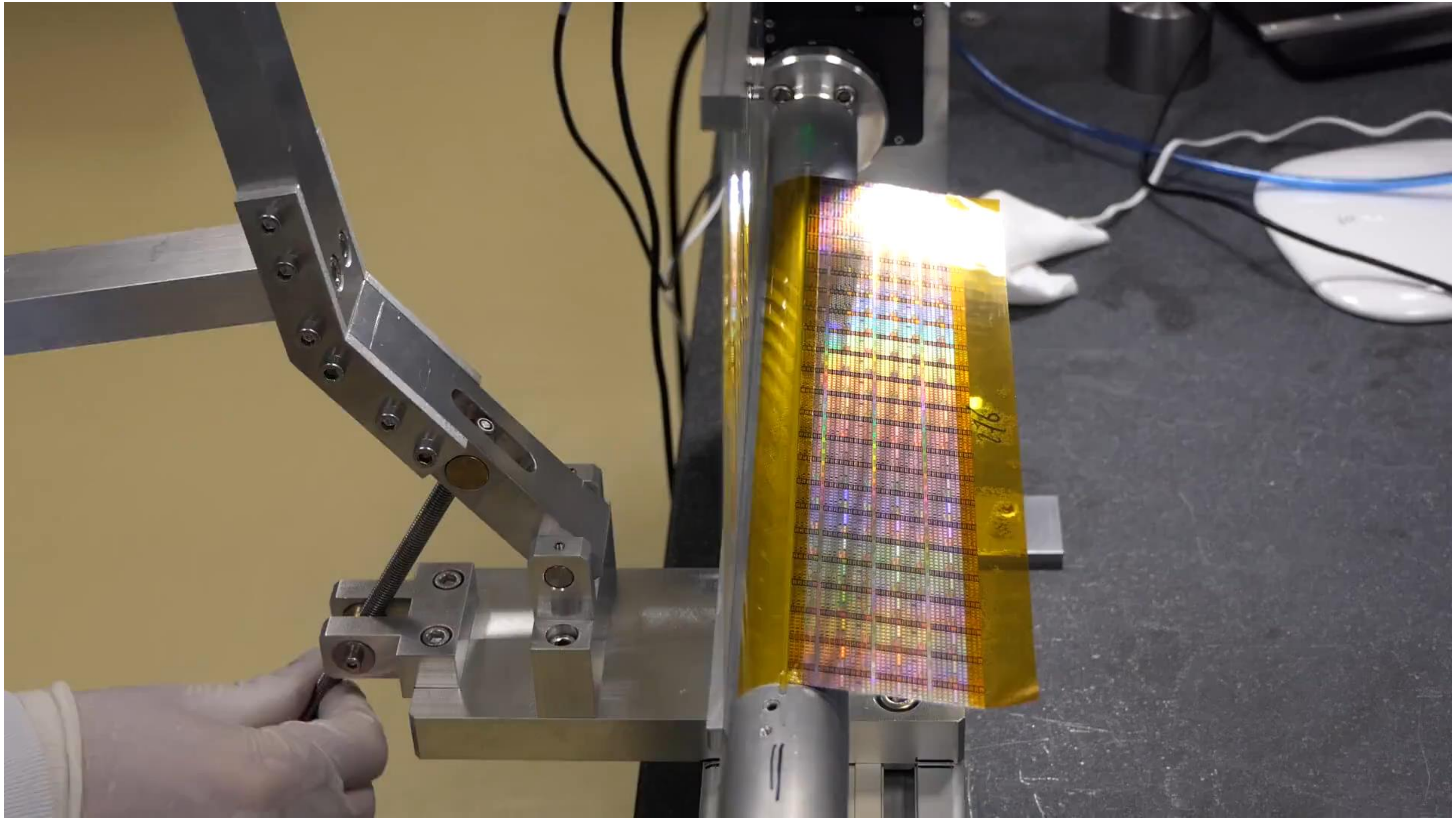




- ALICE 3 R&D for picosecond timing and radiation hardness

More details, see seminar by Magnus Mager

Bending an ITS3 Sensor



r = 18 mm !

LHC Schedule

Summary

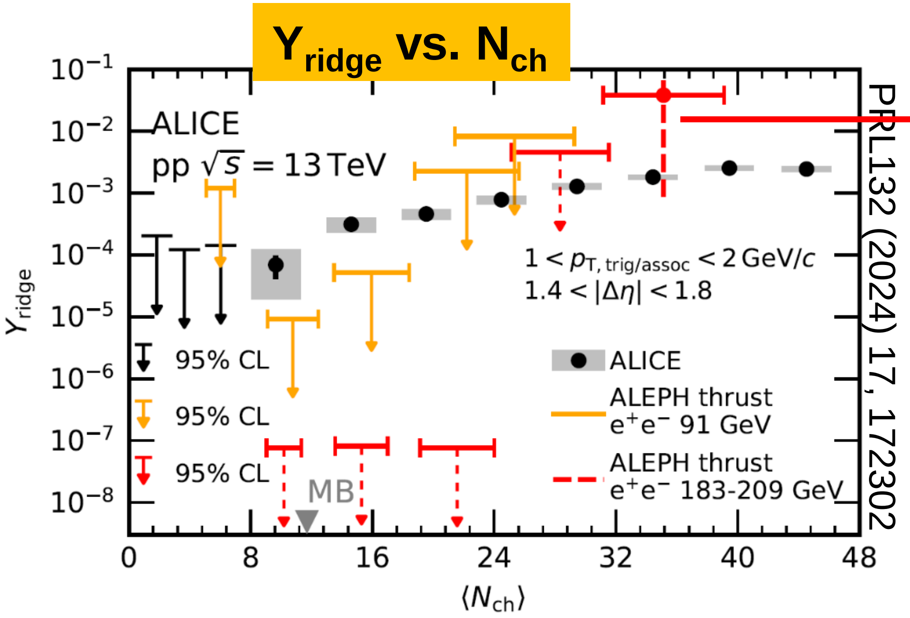
Unique environment created in high-energy heavy-ion collisions

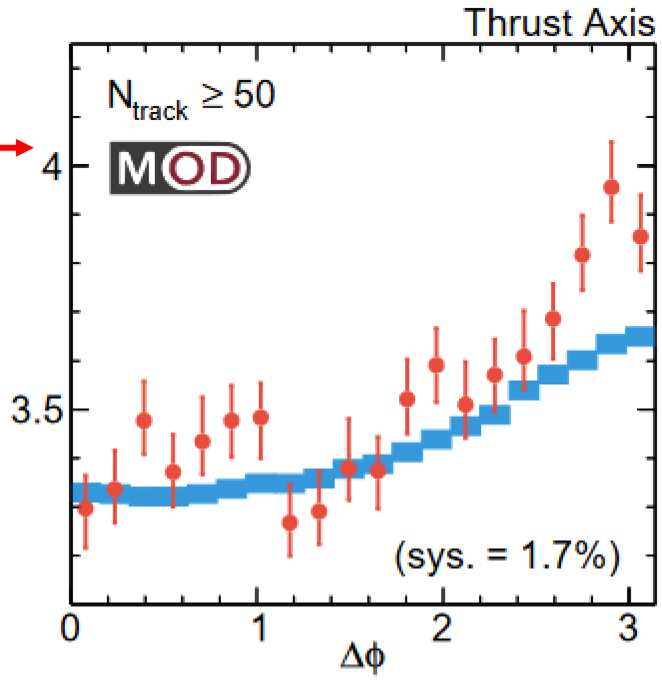
- Precise characterization of QGP matter
  - Strongly interacting with very small viscosity
  - Particle production significantly altered
- Small-system observations (“collectivity”) challenge two paradigms at once
  - What is smallest system for which heavy ion “standard model” remains valid?
  - Can the standard tools for pp physics remain standard?
  - Challenge to find *universal* hadronization model for these phenomena
- Future programme until end of LHC (in 2041)
  - Measure QGP dynamics with charm states
  - Study multi-charm production and temperature evolution of QGP

Thank you for your attention!

Backup

e^+e^- Highest Bin





arXiv:2312.05084

1.02σ