SEMINARIO DE FÍSICA DE ALTAS ENERGÍAS

Instituto de Ciencias Nucleares UNAM

UNAM Seminar
June 20, 2024

An introduction to Heavy Ion Physics and CLASH

P. Christiansen
(Lund University)

or “Why are heavy-ion physicists the Slytherins of particle physics!”

Outline

- A brief introduction to QCD and the Quark Gluon Plasma (QGP)
- The good: quarkonium
- The bad (?): the perfect liquid
- The ugly (?): QGP in small systems
- The CLASH
- The crazy (?): perfect QCD

Outline

- A brief introduction to QCD and the Quark Gluon Plasma (QGP)
- The good: quarkonium
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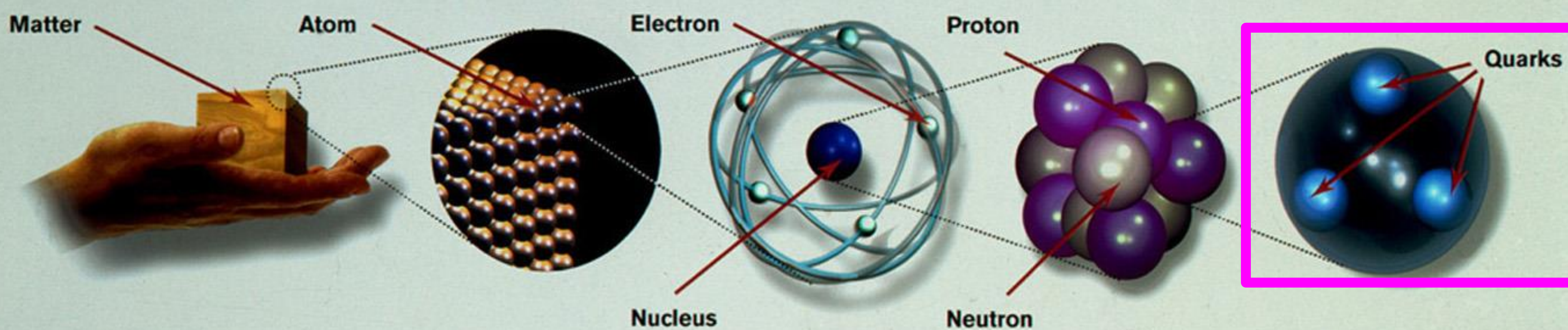
- The CLASH
- ~~The crazy (?): perfect QCD~~
  - No time! Read it on arXiv:2301.13467 ☺



Matter particles
All ordinary particles belong to this group

These particles existed just after the Big Bang. Now they are found only in cosmic rays and accelerators

	LEPTONS		QUARKS	
FIRST FAMILY	**Electron** Responsible for electricity and chemical reactions; it has a charge of -1	**Electron neutrino** Particle with no electric charge, and possibly no mass; billions fly through your body every second	**Up** Has an electric charge of plus two-thirds; protons contain two, neutrons contain one	**Down** Has an electric charge of minus one-third; protons contain one, neutrons contain two
SECOND FAMILY	**Muon** A heavier relative of the electron; it lives for two-millionths of a second	**Muon neutrino** Created along with muons when some particles decay	**Charm** A heavier relative of the up; found in 1974	**Strange** A heavier relative of the down; found in 1964
THIRD FAMILY	**Tau** Heavier still; it is extremely unstable. It was discovered in 1975	**Tau neutrino** not yet discovered but believed to exist	**Top** Heavier still	**Bottom** Heavier still; measuring bottom quarks is an important test of electroweak theory

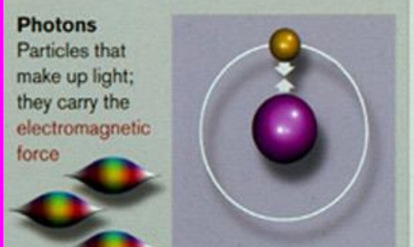
Force particles
These particles transmit the four fundamental forces of nature although gravitons have so far not been discovered

Gluons
Carriers of the strong force between quarks

Felt by:
quarks

The explosive release of nuclear energy is the result of the strong force

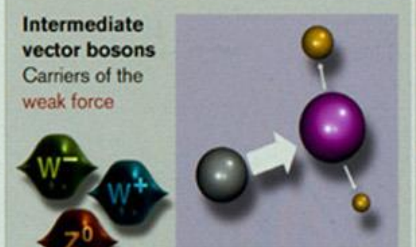
Photons
Particles that make up light; they carry the electromagnetic force



Felt by:
quarks and charged leptons

Electricity, magnetism and chemistry are all the results of electro-magnetic force

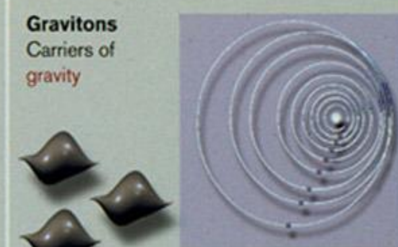
Intermediate vector bosons
Carriers of the weak force



Felt by:
quarks and leptons

Some forms of radio-activity are the result of the weak force

Gravitons
Carriers of gravity



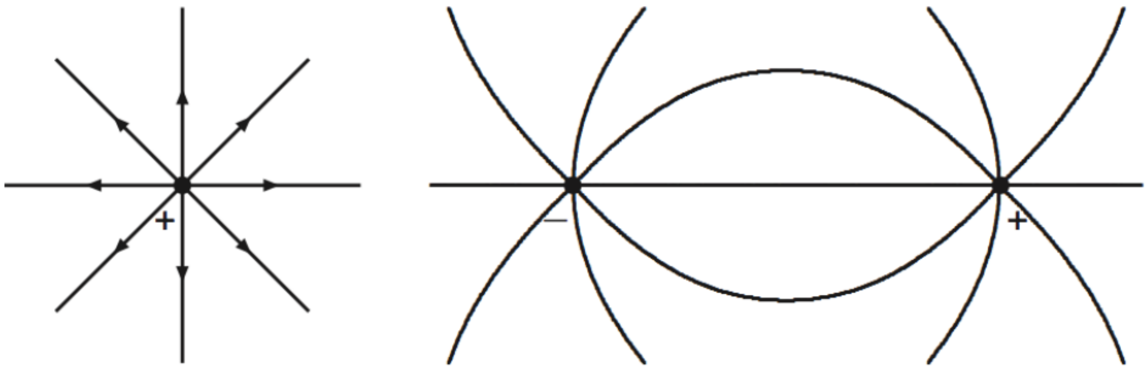
Felt by:
all particles with mass

All the weight we experience is the result of the gravitational force

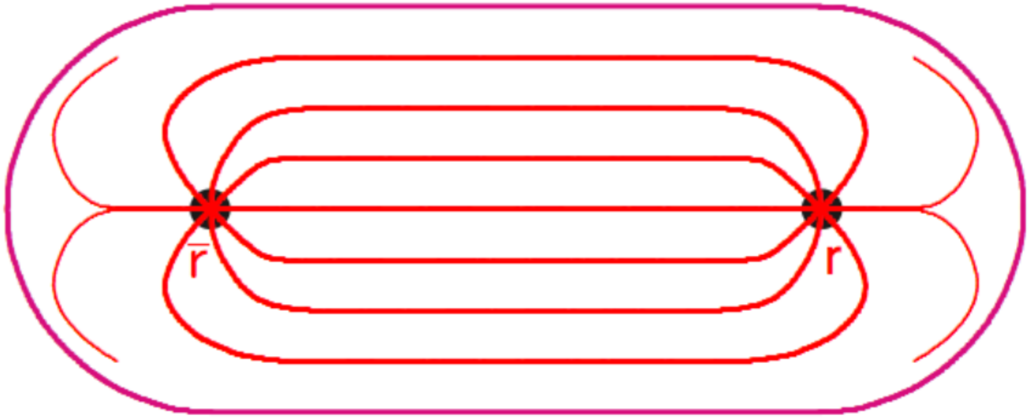
GRAPHICS: PETER CROWTHER

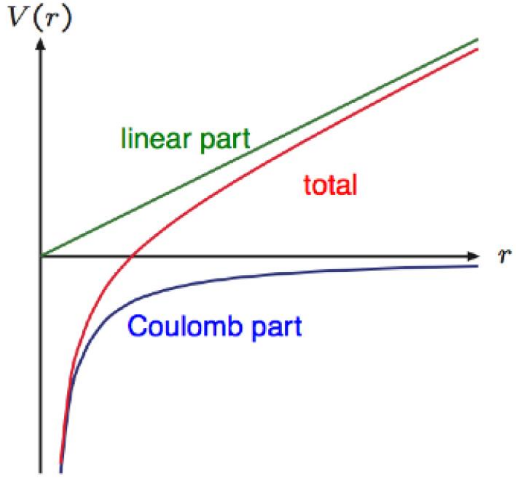
QED vs QCD

QED: superposition principle



QCD: color fields interact (form flux tube at long distance)

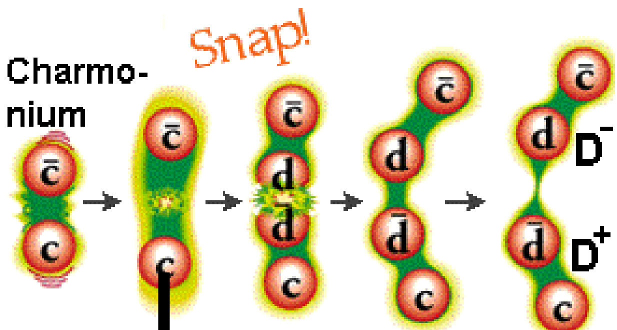




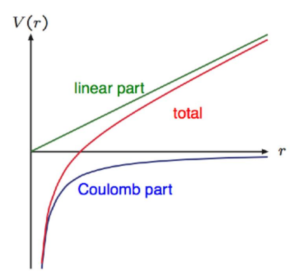
Basis of Lund string model

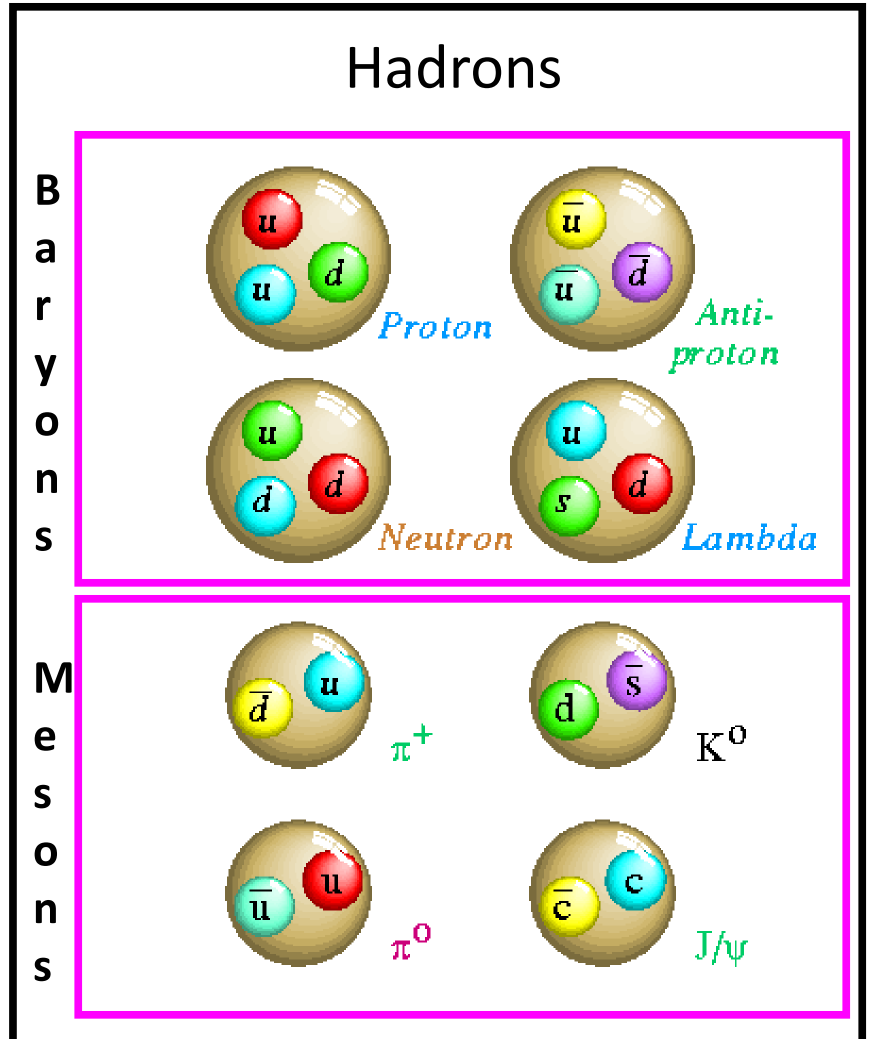
The strong interaction: Quantum Chromo Dynamics (QCD)

3 strong charges (red, green, blue)
Particles in nature are color neutral
Quarks are "confined"



(Force ~ 1 GeV/fm)

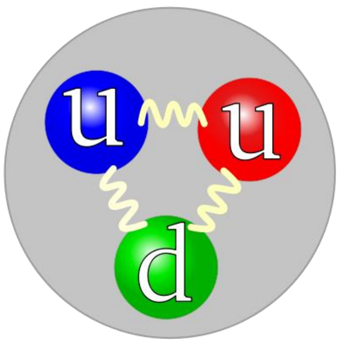


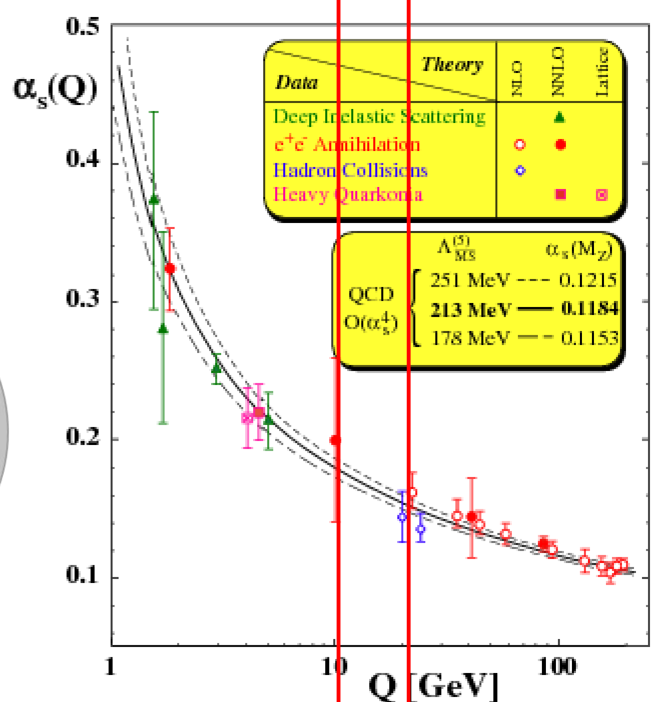


The first challenge: the two limits of QCD

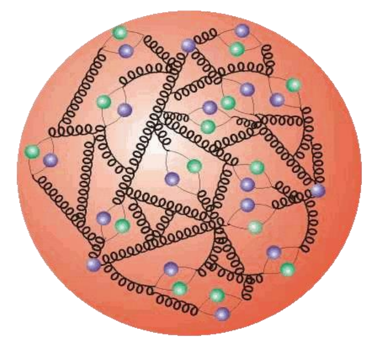
- 2 limits

SOFT





HARD



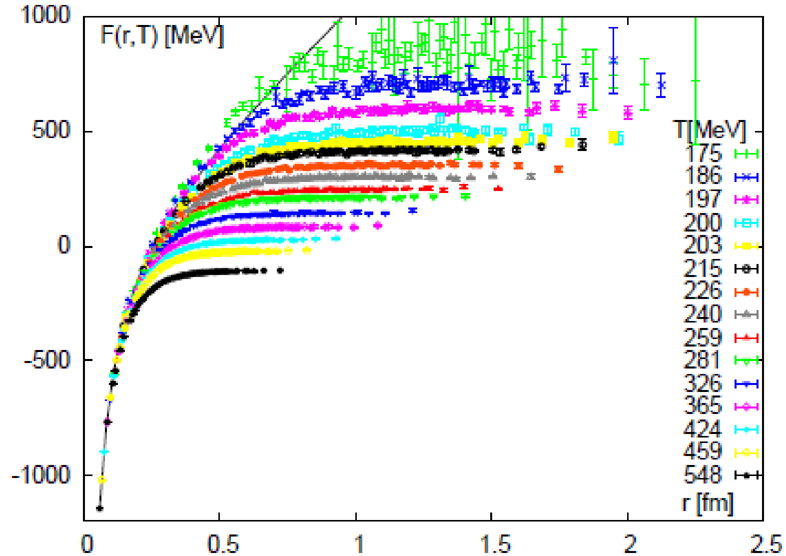
Non-perturbative physics
(knows the equations but not how to solve them)
Bulk properties (=QGP)

Perturbative physics
(theoretical predictions)
Rare jets (=probes)

Solution (?): use lattice QCD

First question we will ask:
What happens to the heavy-quark potential when we heat up the system

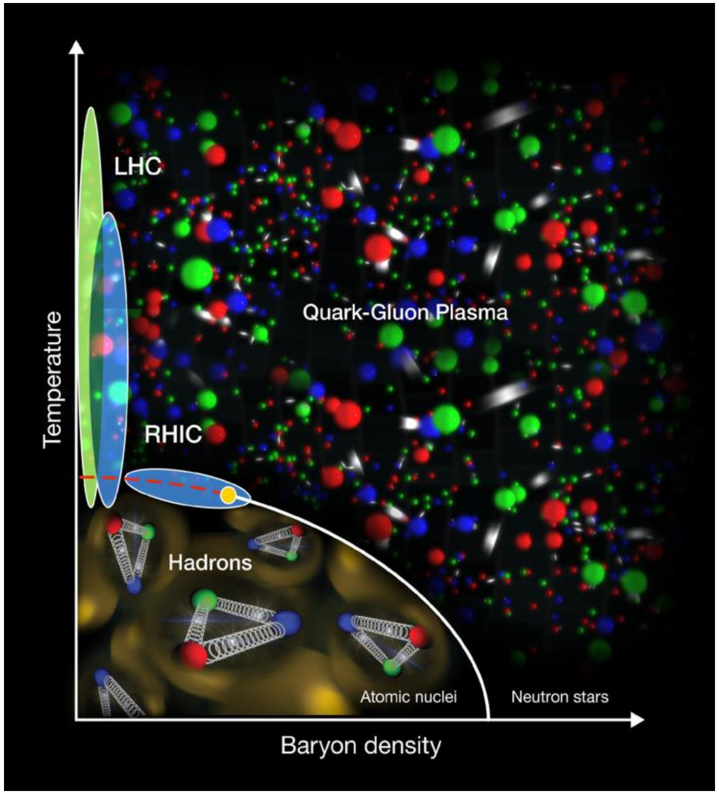
Lattice QCD results for the heavy quark potential (free energy): arXiv:0710.0498



The long-range force will be screened in the plasma.
This should lead to deconfinement!

Deconfinement at high energy densities

Tc ~ 160 MeV
(~2.000.000.000.000 K)

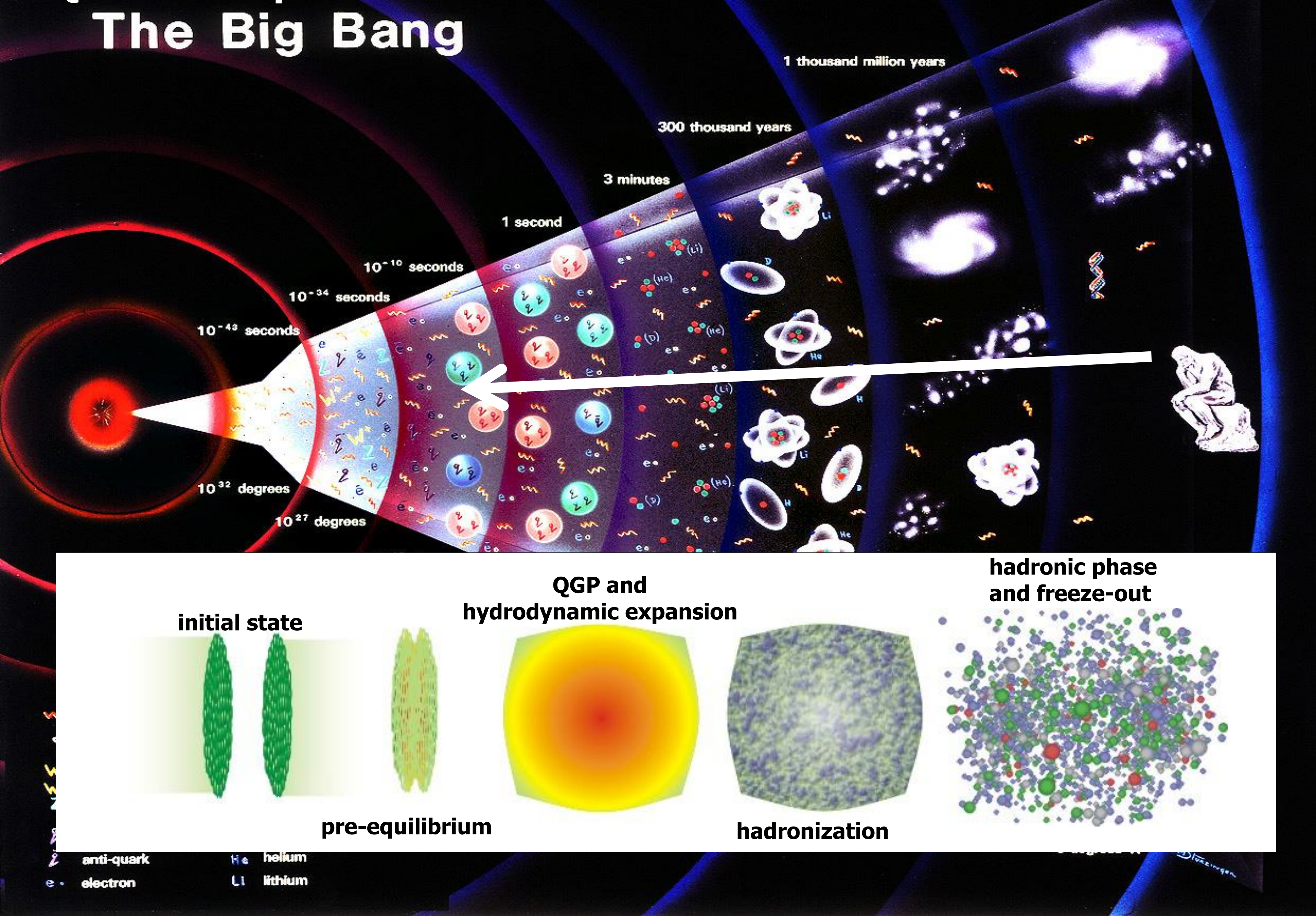


At high energy densities a new form of matter exists:

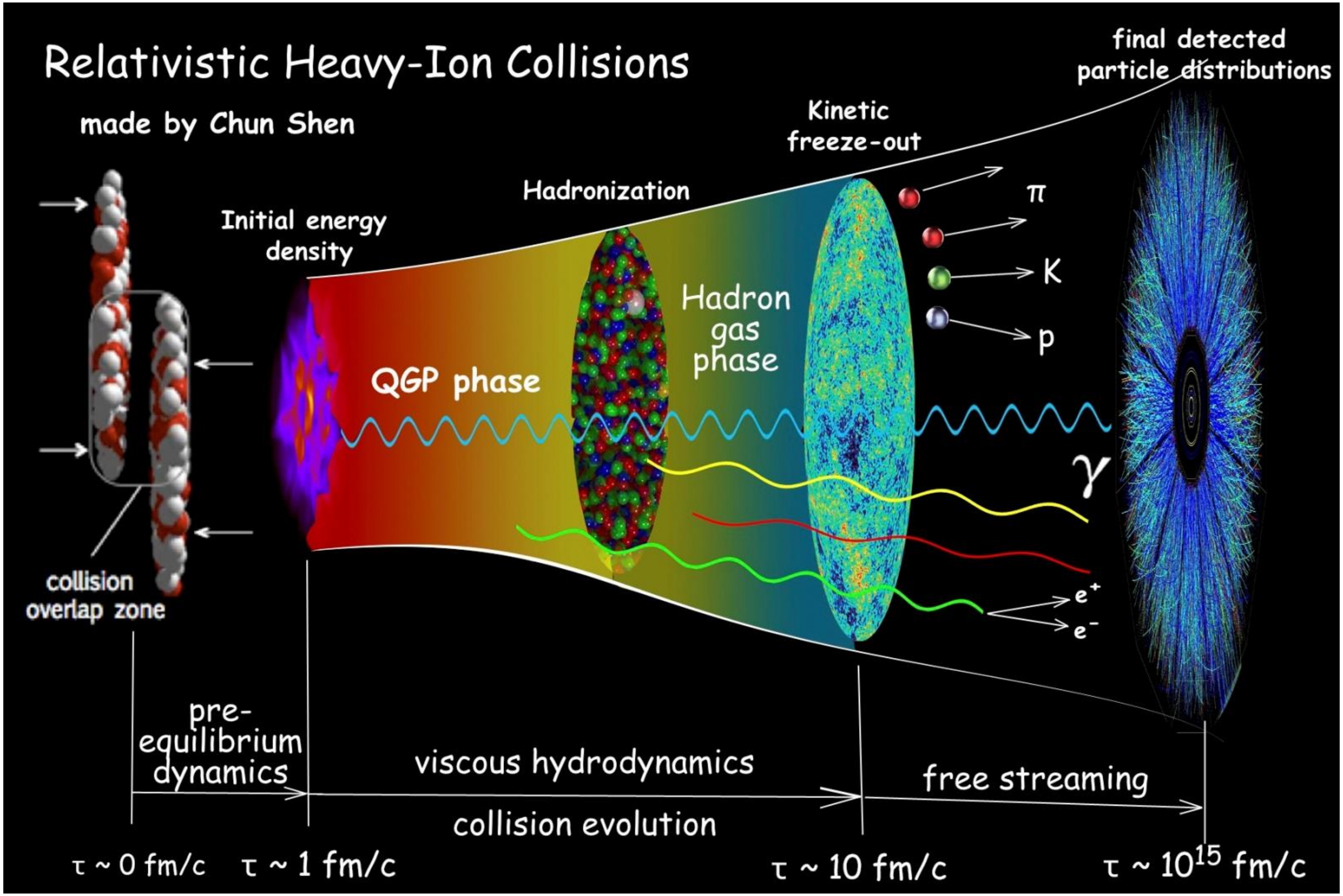
Quark-Gluon Plasma, where quarks&gluons are deconfined

I will only talk about the high temperature transition which is what we probe in heavy-ion collisions

QGP – the phase of the universe a few micro seconds after

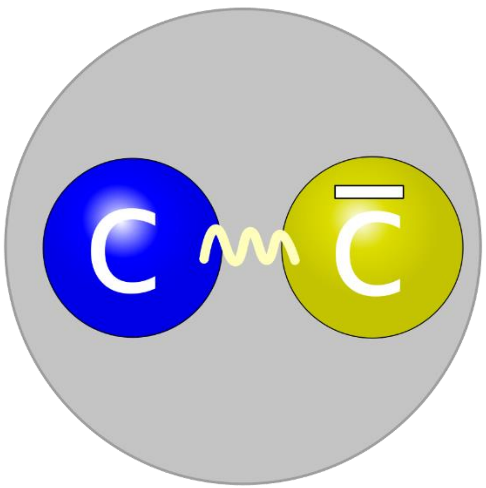


The second challenge: we cannot easily directly observe the QGP

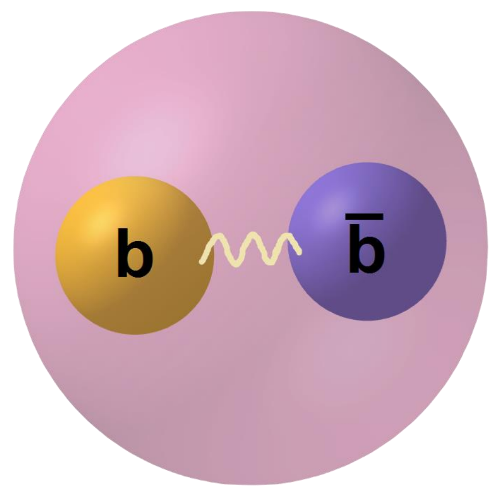


The good: quarkonium

J/ψ: 1S, (ψ': 2S)



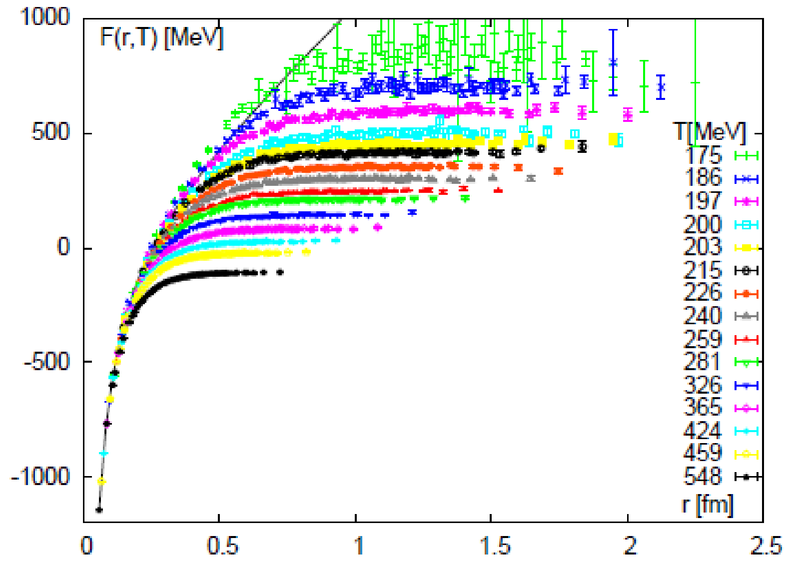
ϒ: 1S, 2S, 3S

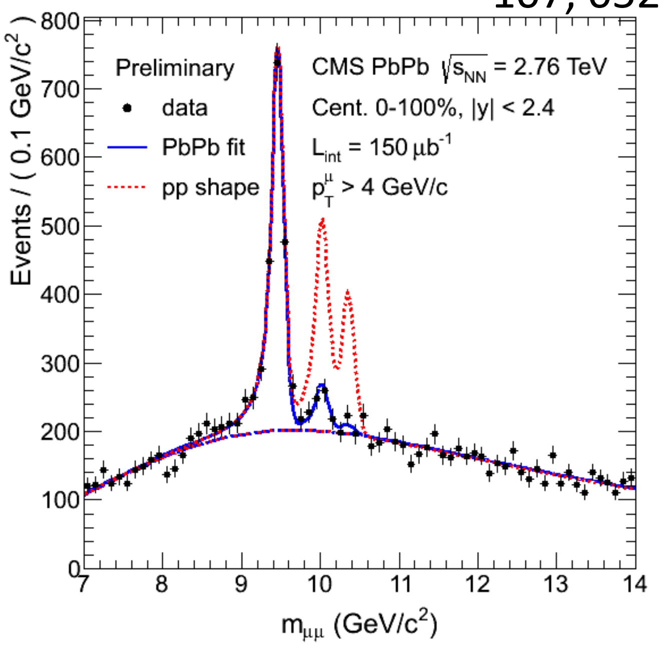


LHC has delivered

ϒ: 1S 2S 3S

Published in PRL 107, 052302



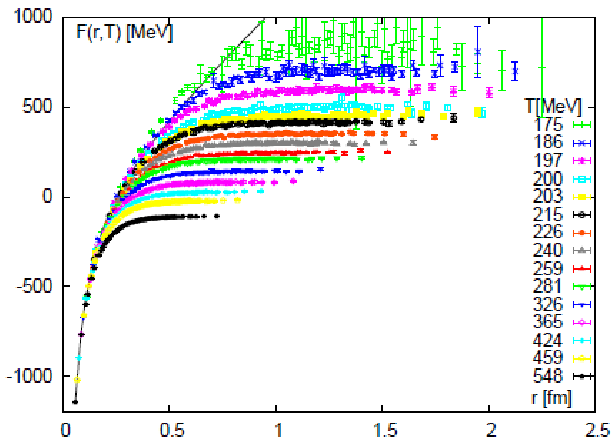


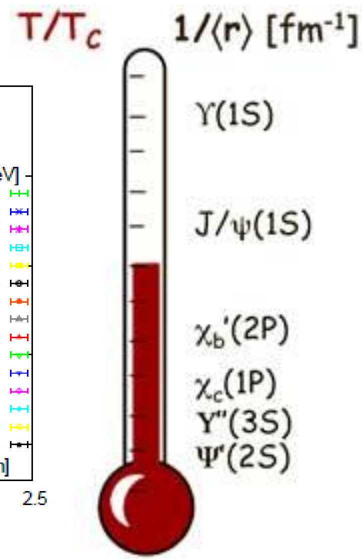
CMS has proven to be a marvelous detector for bottomonium

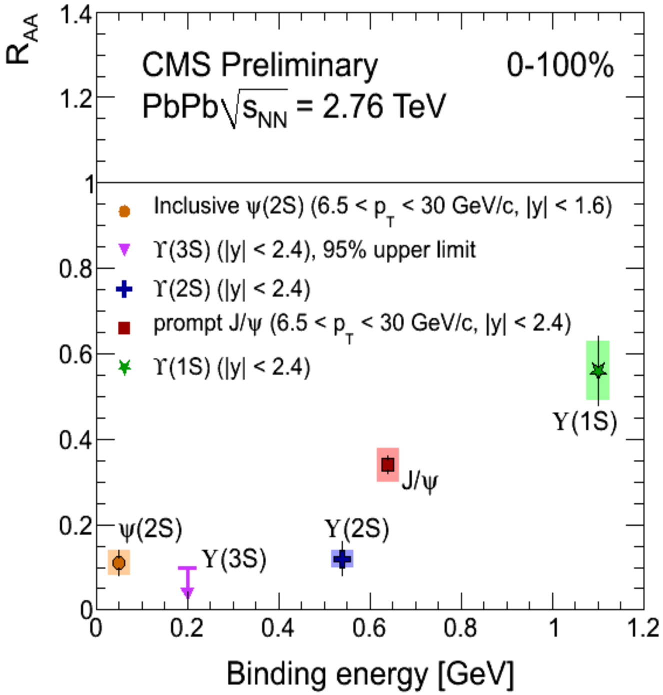
ALICE can complement by going to lower p_T for charmonium

Suppression of heavy quarkonia can work as a thermometer

Note: 6.5<p_T<30 GeV for J/ψ and ψ(2s)



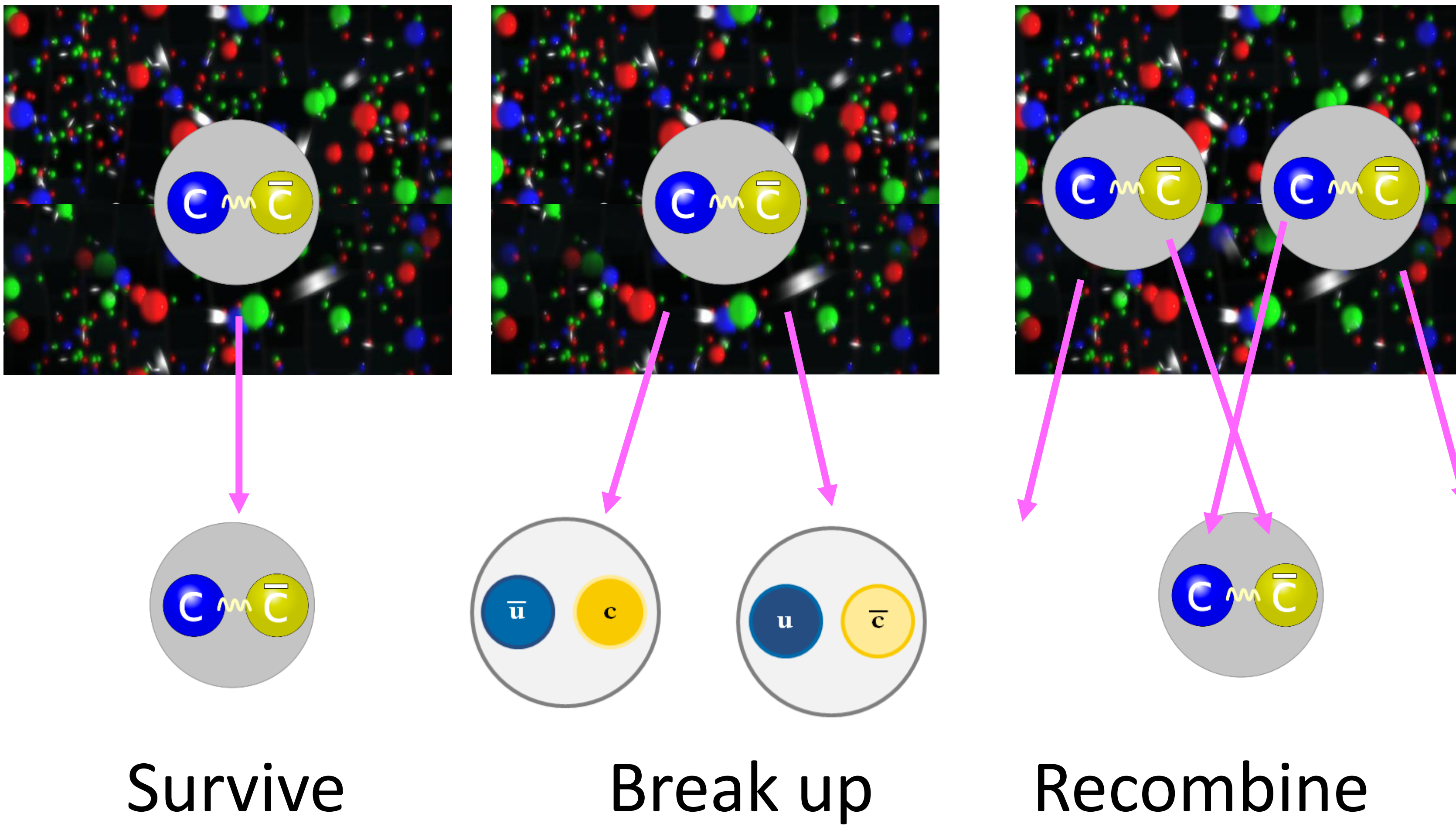




Suppression qualitatively depends on binding energy as predicted

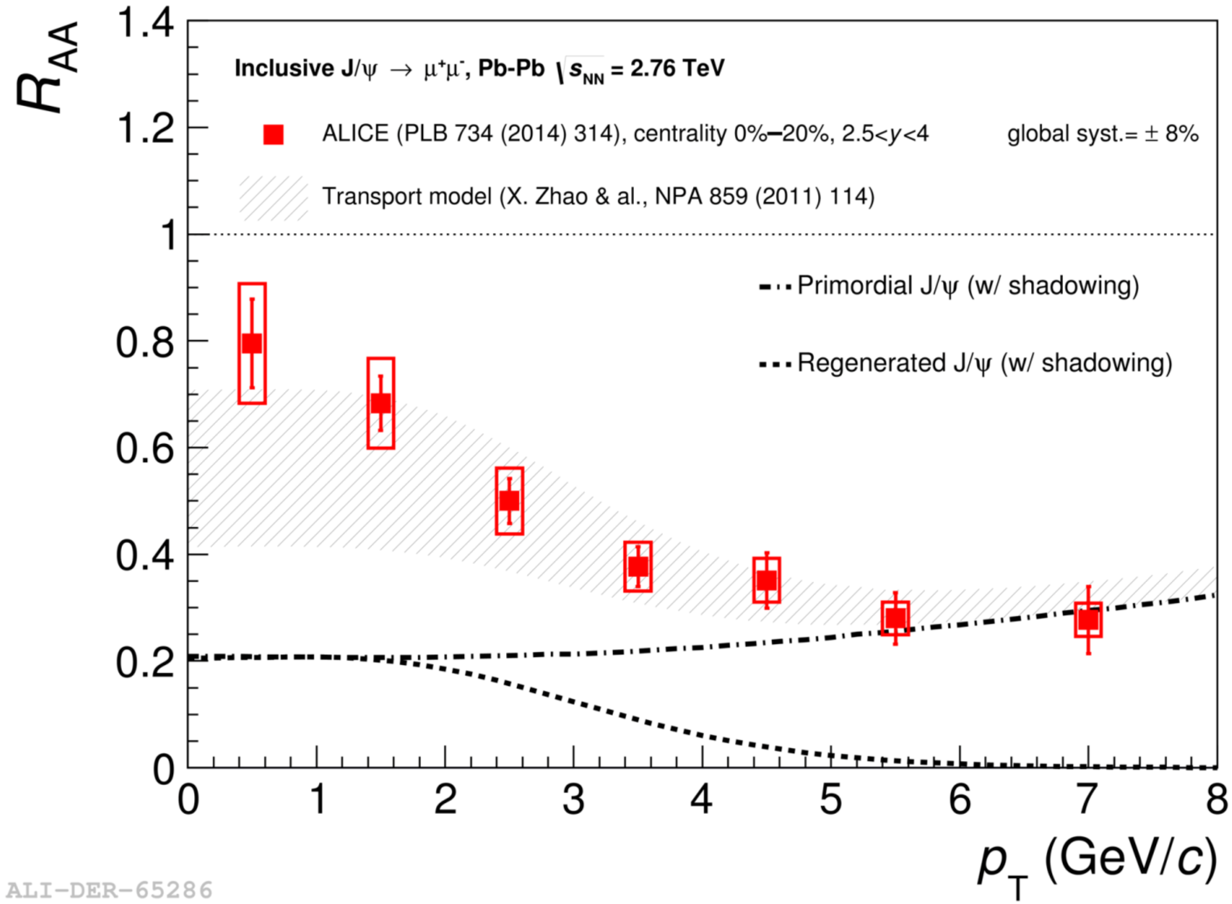
A lot of devils in the details that I skip.

J/ψ in the QGP at high energies



Requires high charm denisty

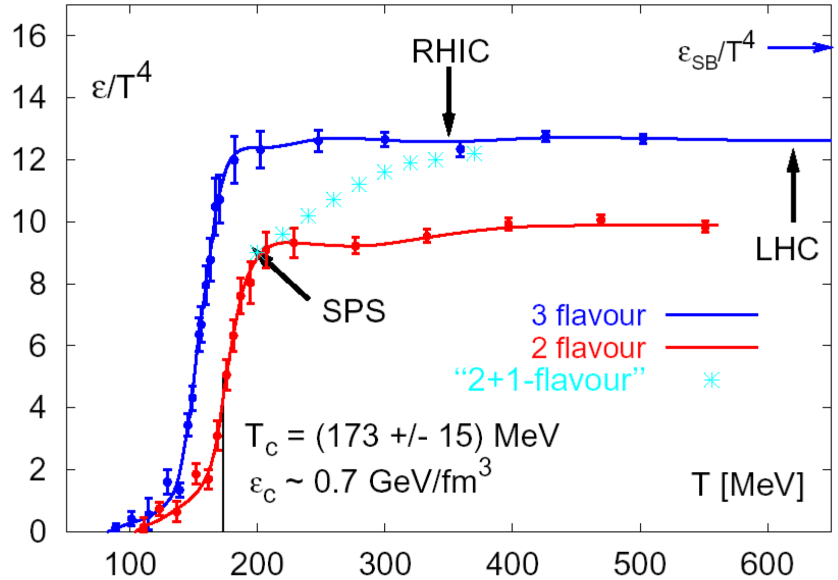
J/ψ recombination



One needs to include recombination/regeneration to explain the data.

The bad (?): the perfect liquid

Lattice QCD calculation of the energy density



$$\varepsilon_{Quark-Gluon\ gas} = \frac{\pi^2}{30}\left(2\times 8+\frac{7}{8}2\times 2\times 3\times 3\right)T^4$$

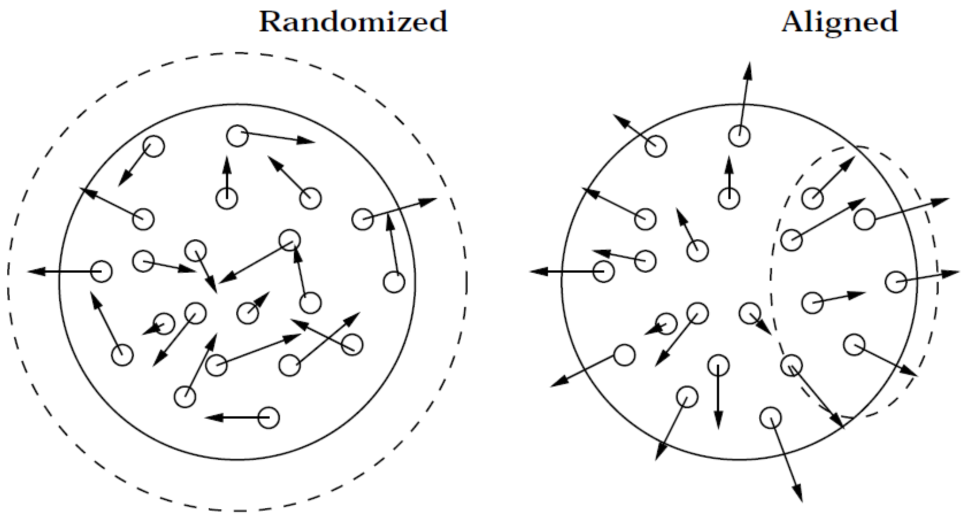
Gluon spin and color

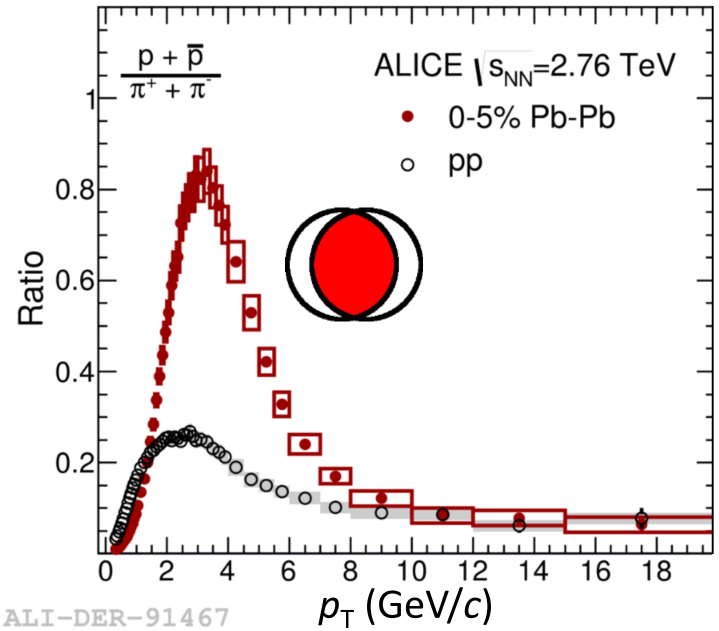
(Anti+)quark spin, color and flavor

Several things pointed to that the QGP should behave more like a gas:

- The energy density found in lattice QCD calculations
- The screening of the long-range force
- The running of the coupling constant
- Ideas inspired by bag models

Radial flow



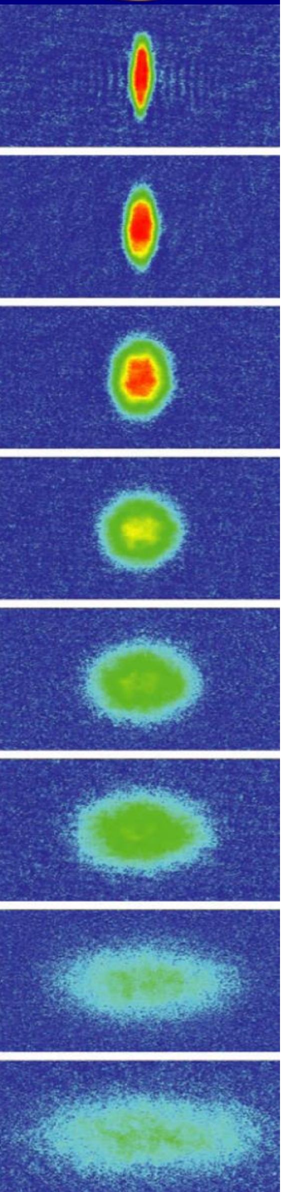


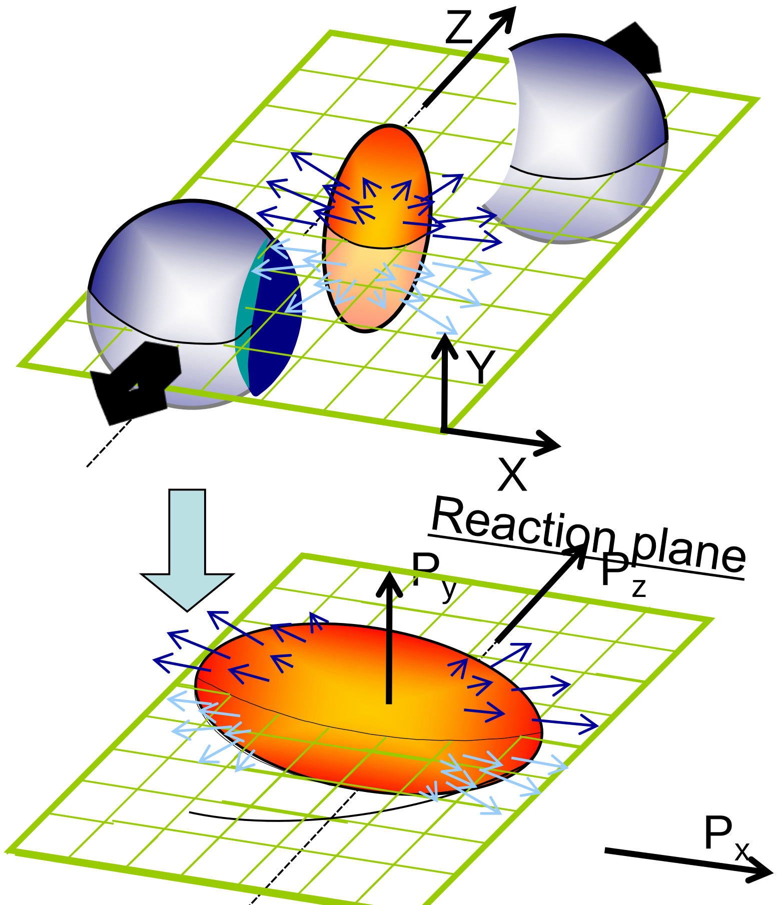
- Flow in general plays a very important role in heavy-ion collisions.
- We believe that flow in the partonic phase is imprinted on the final state hadrons at freeze out.

Flow velocity β_r → mass dependent boost:

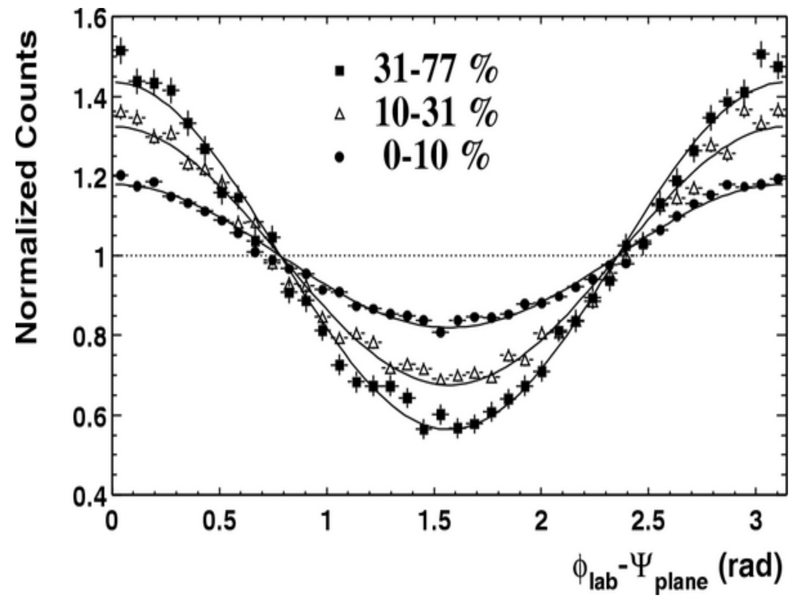
$p_T \sim \gamma\beta_r m$ (for particle initially at rest)

Elliptic flow (v_2)



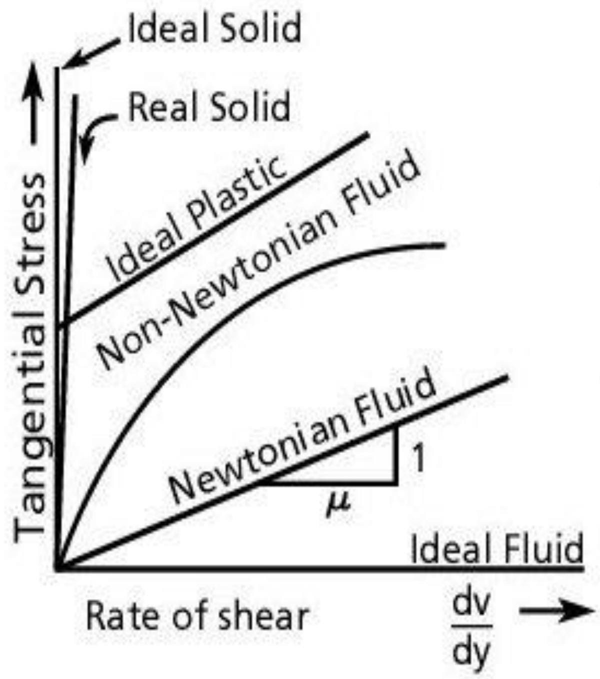


Fourier decomposition:
$dN/d\Delta\phi = 1 + 2\, v_2 \cos(2\, \Delta\phi)$



Initial spatial anisotropy → Strong pressure gradients → v_2 Azimuthal anisotropy → **Sensitivity to early expansion**

Shear viscosity



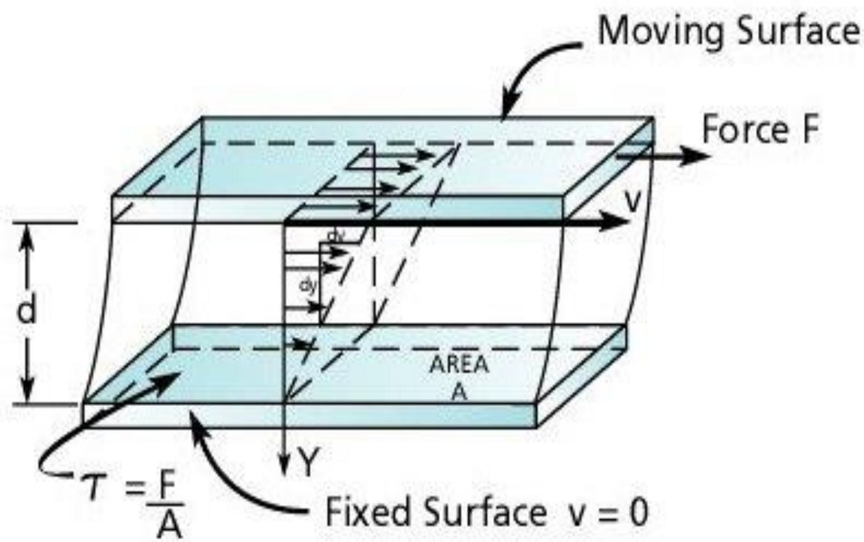
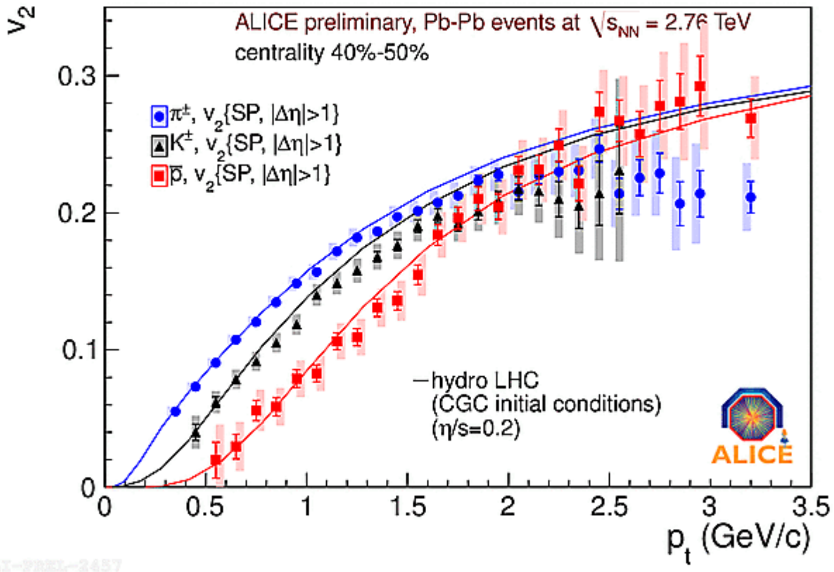
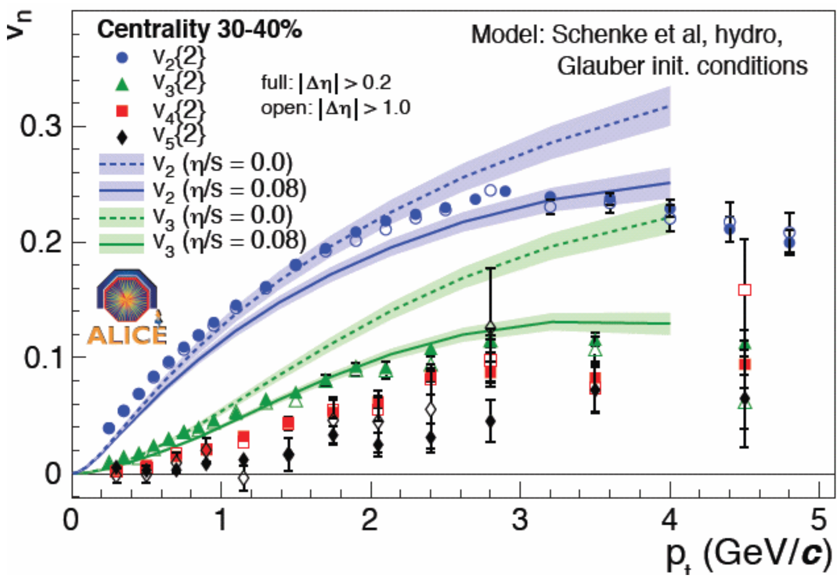


Figure taken from http://www.pumpfundamentals.com/about_fluids.htm

The shear force is given as F=ηAv/d
The shear vicosity-to-entropy density ratio, η/s, is a unitless quantity for characterizing fluids.

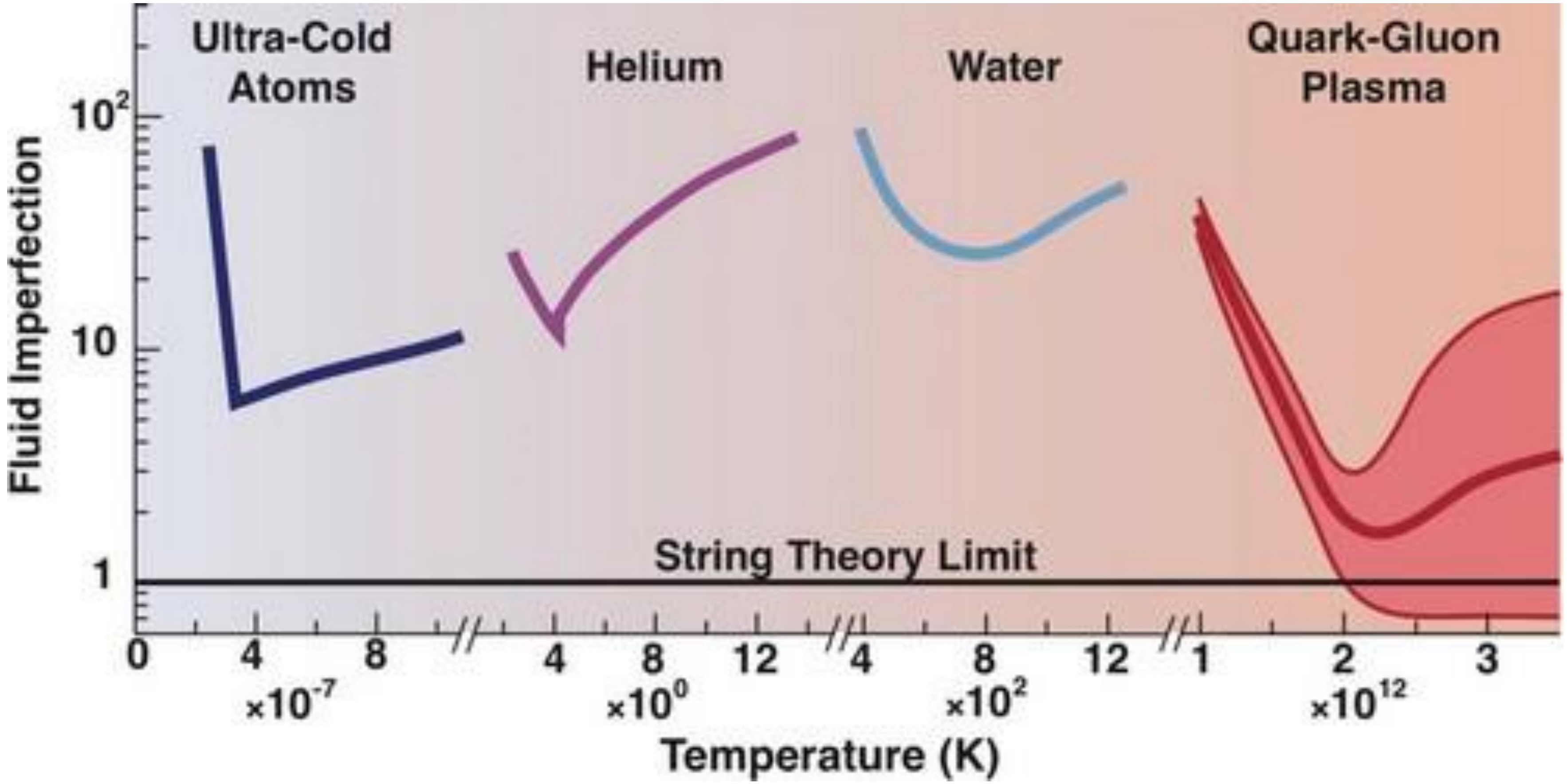
Elliptic flow and triangular flow is almost ideal!



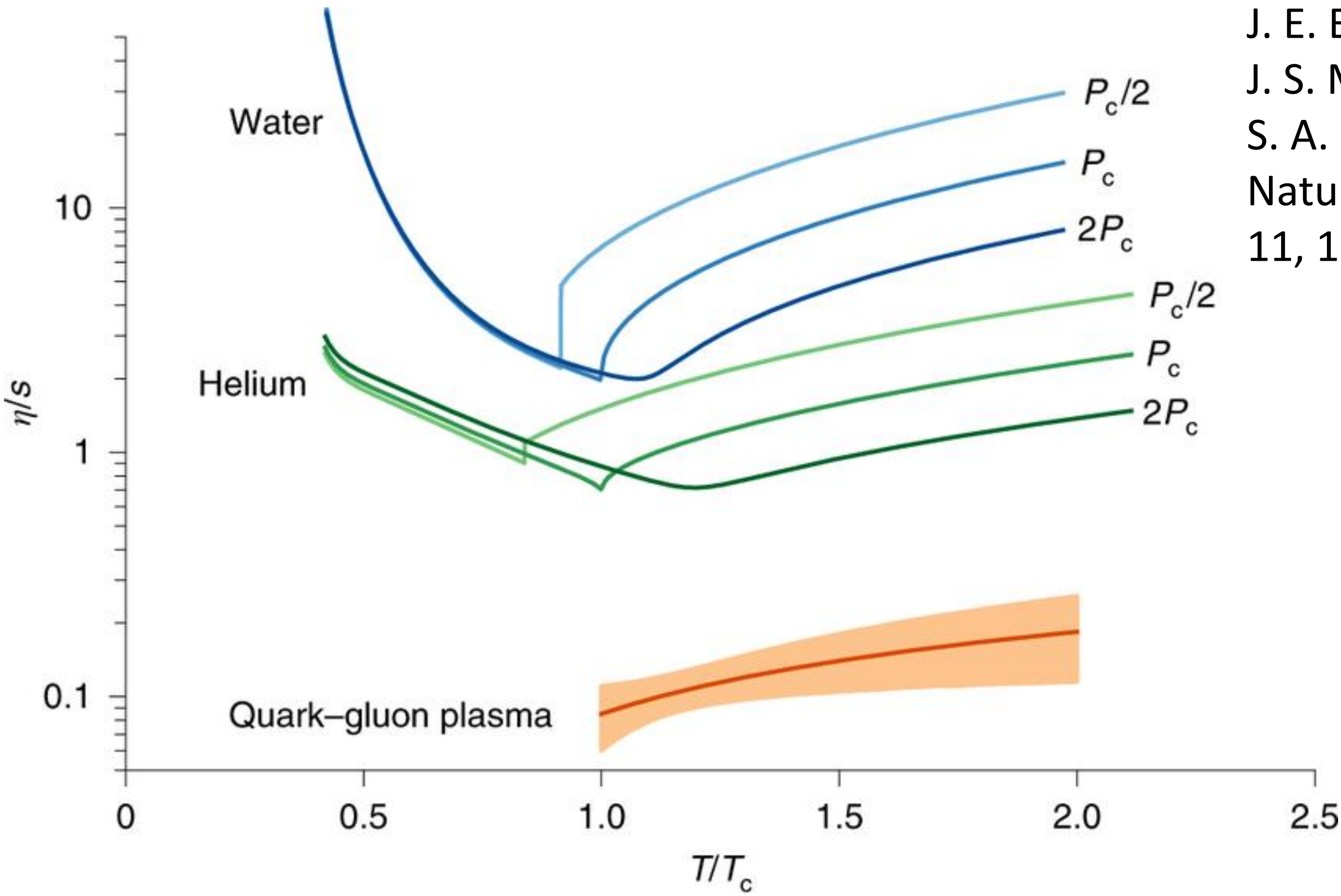


- Huge flow at intermediate p_T:
  - 2 times more particles in plane than out
  - Nearly ideal fluid
- Significant higher order flow caused by fluctuations – also described by nearly ideal hydro + initial state

The QGP fluid compared to other fluids



Recent comparison



J. E. Bernhard,
J. S. Moreland,
S. A. Bass
Nature Phys. 15 (2019) 11, 1113

Because of the very low η/s (shear viscosity-to-entropy density) we think the QGP is a perfect liquid!

The QGP is less like a crowd and more like a synchro team

- We went looking for a gas, but we found the strongest interacting liquid known to mankind

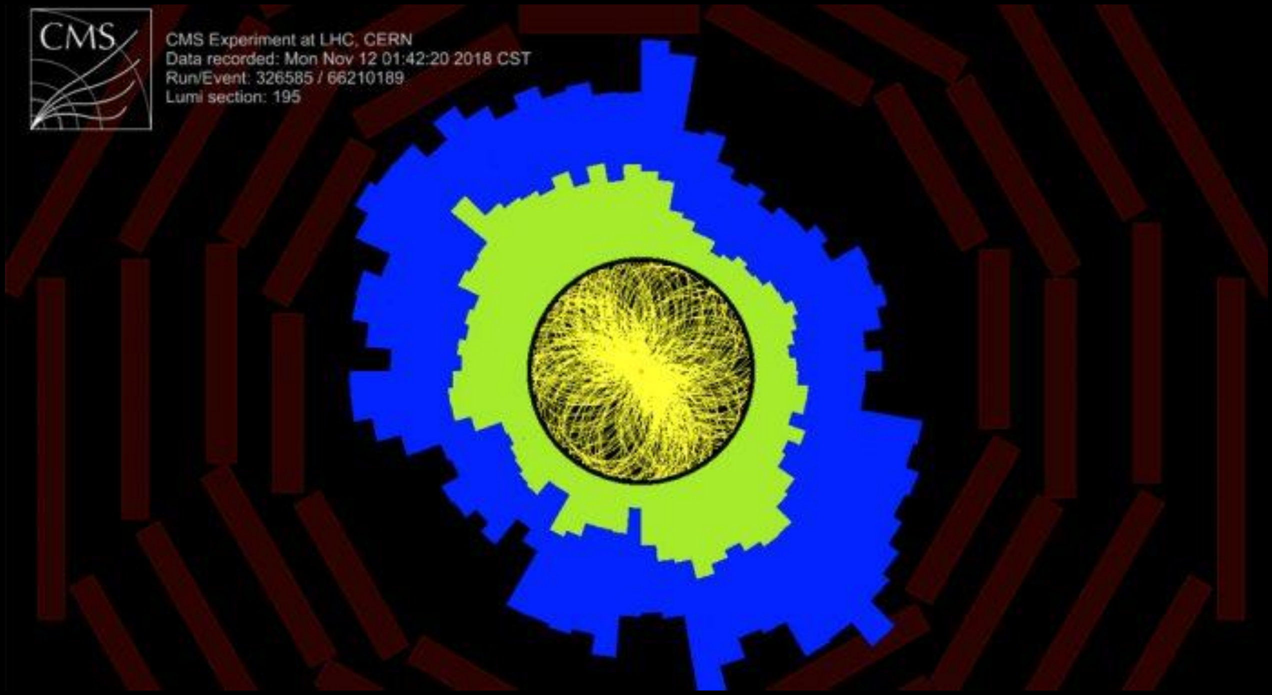
Third challenge

- We have no precise idea of what a Quark-Gluon Plasma should look like
- That is IMO why we are the Slytherins of the LHC experiments: we do not have a solid theoretical foundation
- New paradigm (?) for why we study the QGP
  - Circumvent traditional problem that while quarks and gluons are the fundamental degrees of freedom we observe hadrons to directly study the QCD dynamics of quarks and gluons

We are a mix of explorers…
...and gold diggers!

Perfect liquid – the purest gold!

Perfect liquid expansion is almost reversible
➔Almost no entropy production!?
➔We can "photograph" the initial overlap



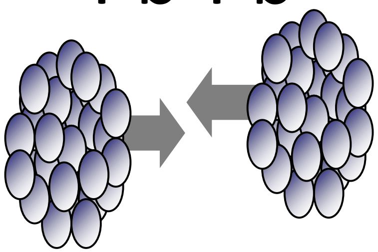
The ugly (?): QGP in small systems

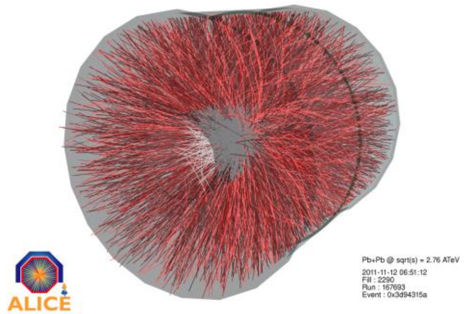
Now we keep exploring and digging!

The effect of system size:

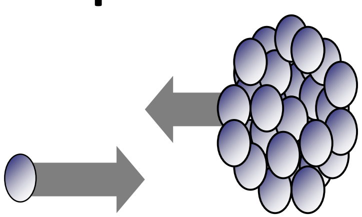
Macroscopic effects in small systems?

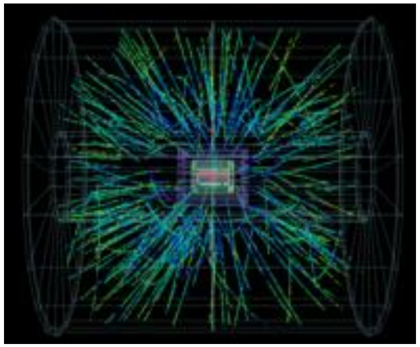
Pb-Pb



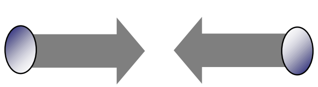


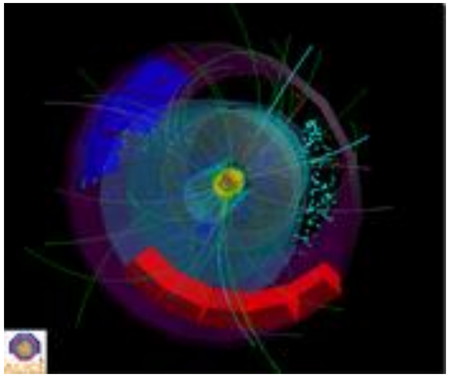
p-Pb





pp



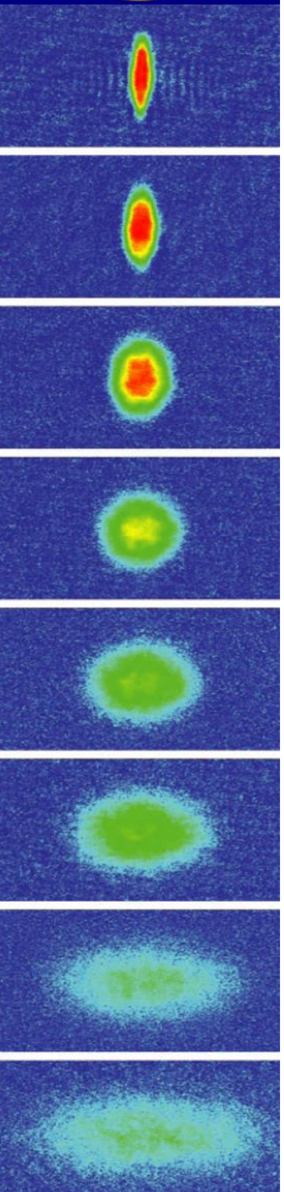


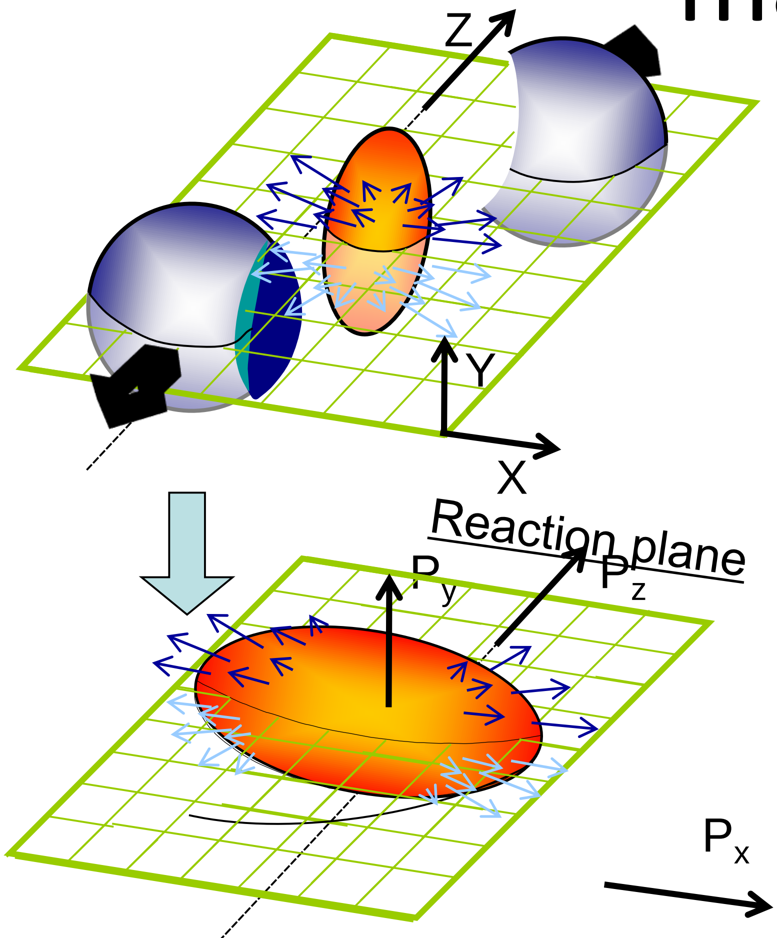
Hot nuclear matter

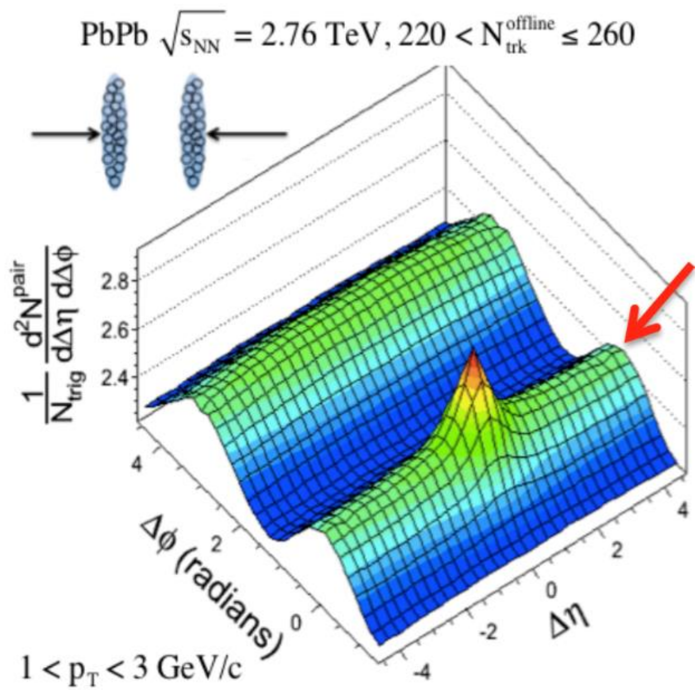
Cold nuclear matter

QCD baseline

The ridge: a fingerprint of the macroscopic QGP

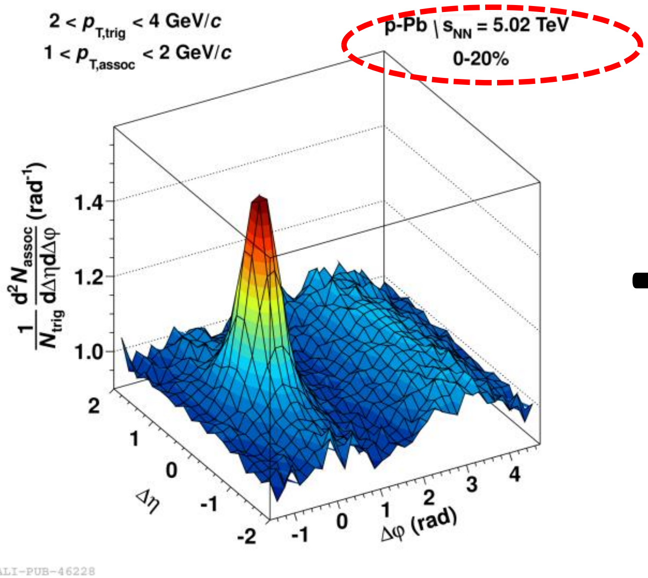






Initial spatial anisotropy → Strong pressure gradients → v_2 Azimuthal anisotropy → **Sensitivity to early expansion**

The rise of the double ridge



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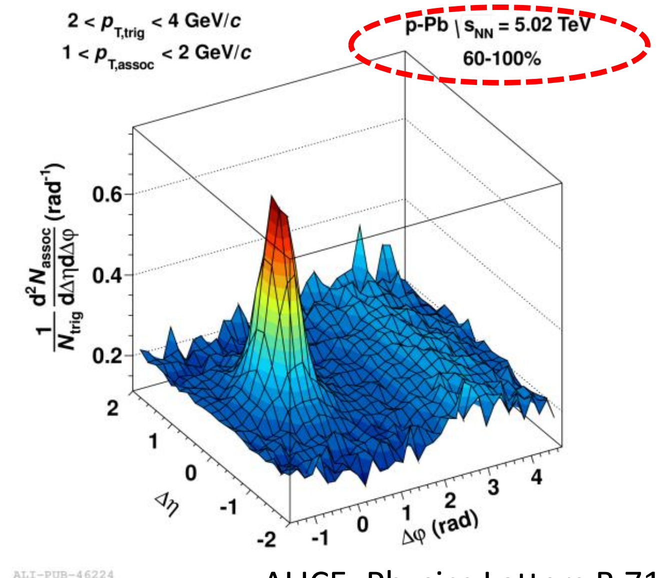

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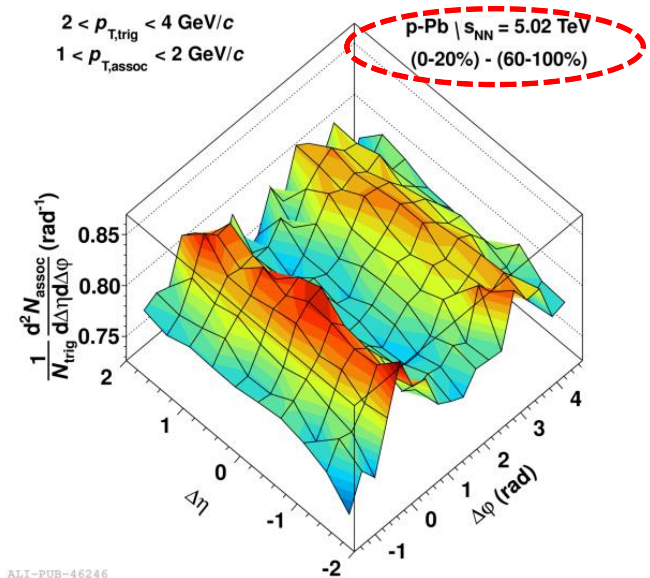
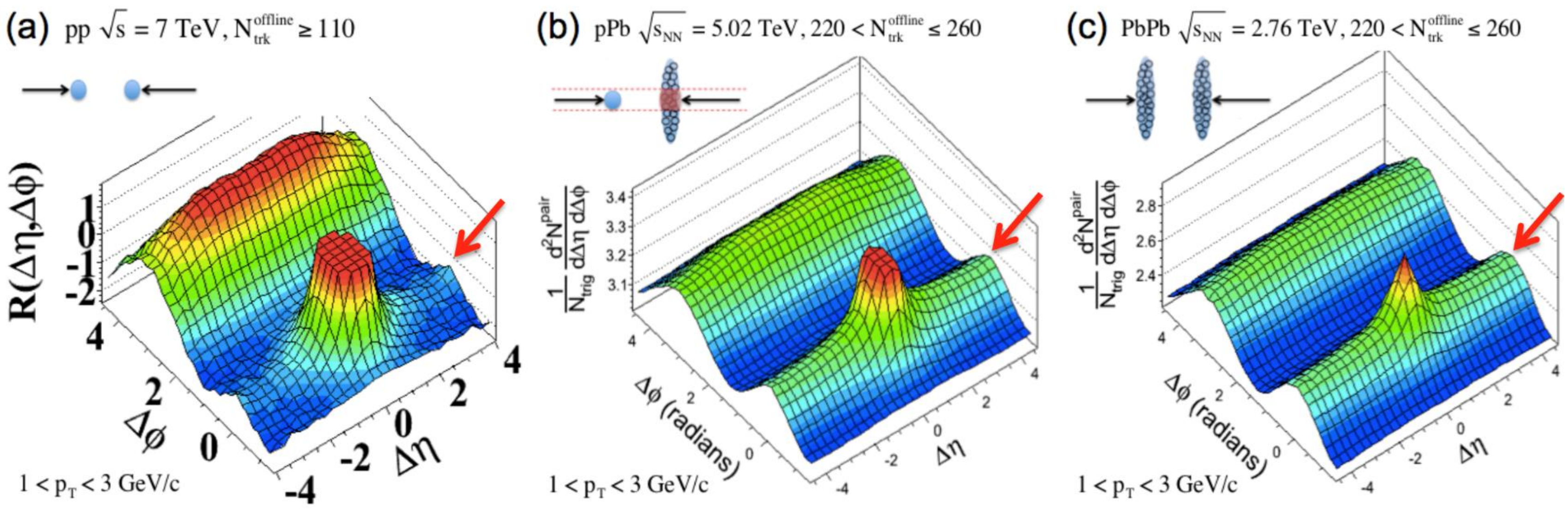
ALICE: Physics Letters B 719 (2013)



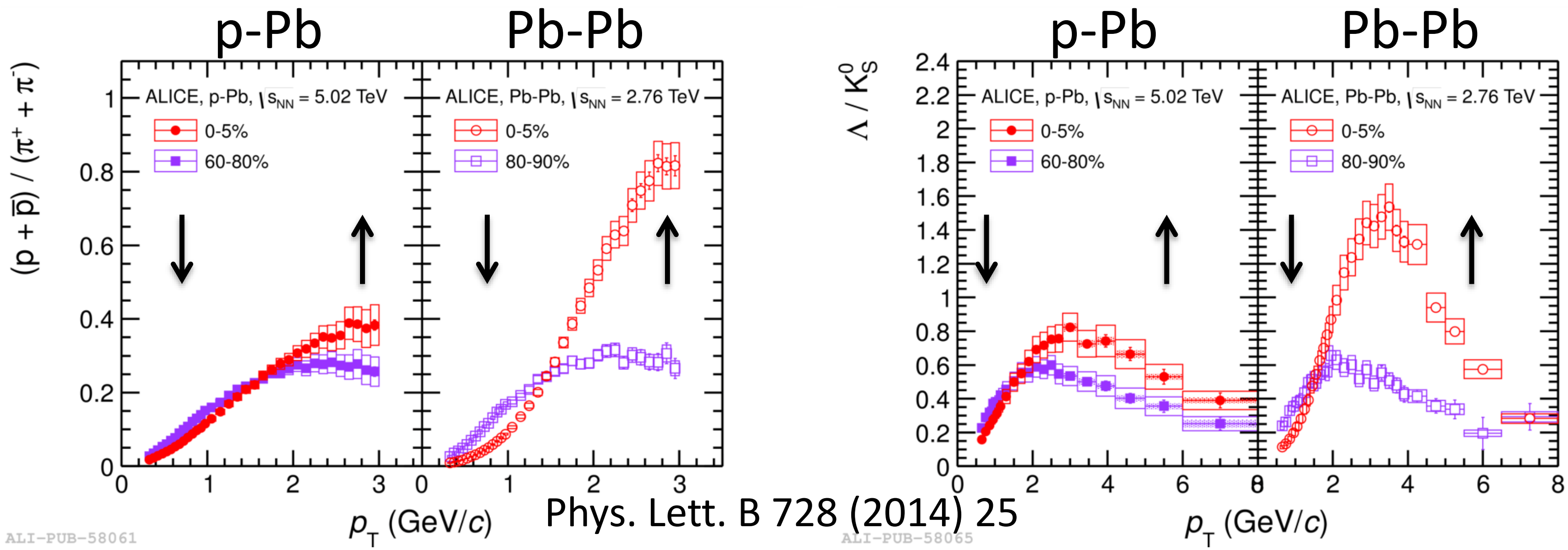
- Double ridge structure reminiscent of azimuthal flow in Pb-Pb collisions

Ridges in all systems



The perfect liquid is produced in all systems suggesting that small QCD systems produce “macroscopic” matter

Particle ratios in p-Pb and Pb-Pb show similar radial flow features



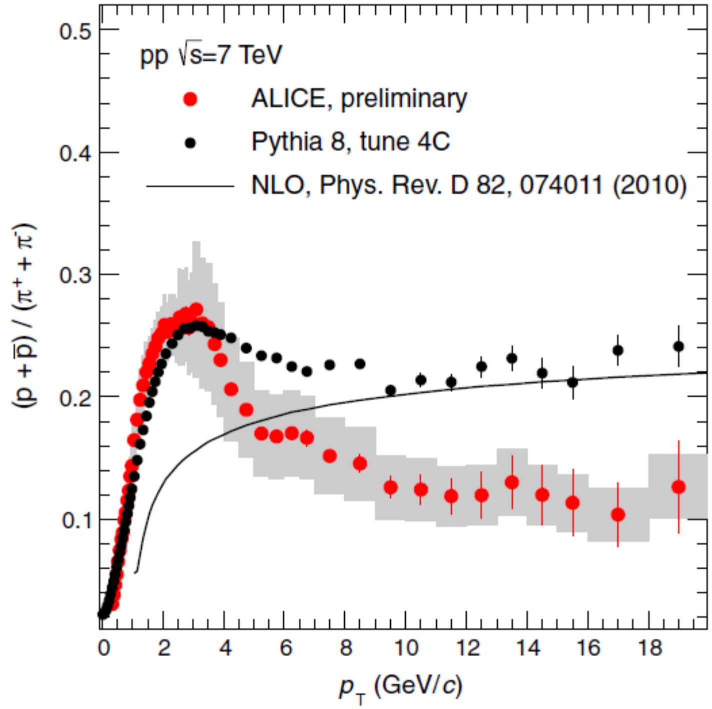
Phys. Lett. B 728 (2014) 25

- Characteristic evolution of p/π and Λ/ K^0_S with multiplicity is reminiscent of Pb-Pb where it is believed to be due to radial flow

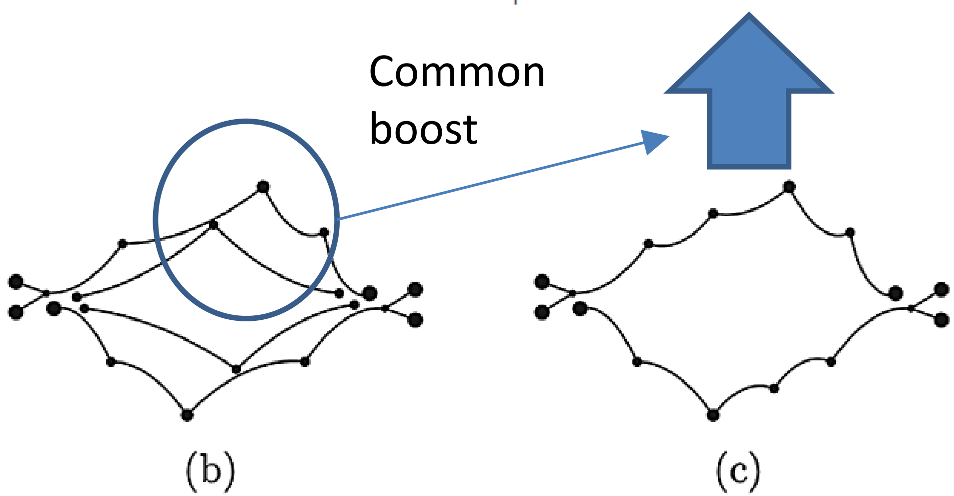
The Mexican angle

- Visited UNAM 1 month in 2011 (EPLANET)
  - Ongoing collaboration since then
  - Common workshops: QCD challenges from pp to AA collisions, Taxco (2016), Puebla (2017), Lund (2019), Padova (2023), Muenster (2024)

The “flow peak” in pp



Realized that Color Reconnection (CR) in PYTHIA gives rise to flow like boosts
Antonio Ortiz Velasquez, Peter Christiansen, Eleazar Cuautle Flores, Ivonne Maldonado Cervantes, Guy Paić, PRL 111, 042001 (2013).
For details, see T. Sjöstrand, arXiv:1310.8073.



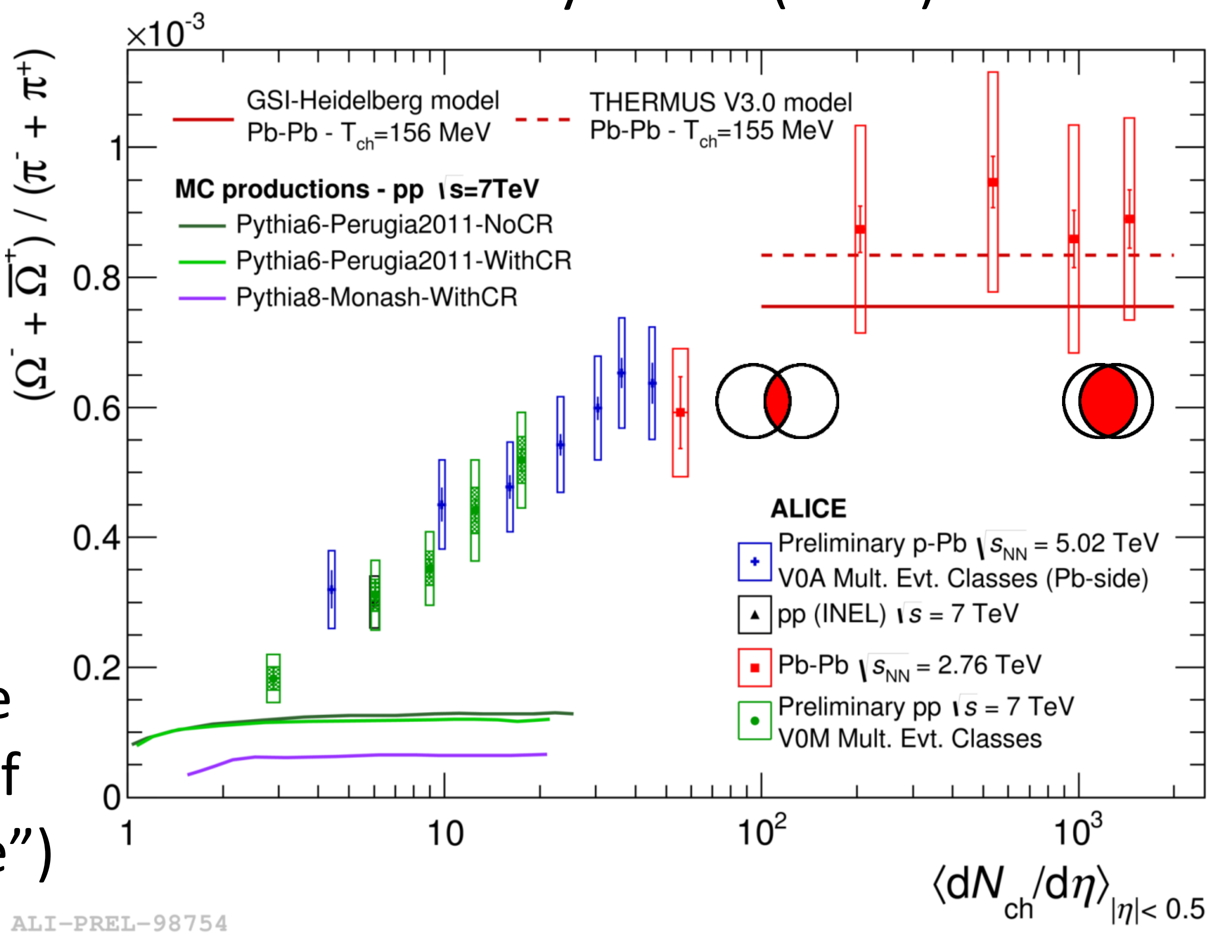
CR can be a microscopic model of flow
→ Renewed interest in CR

Alternative to hydrodynamics

pp phenomenologists' favorite figure from ICHEP 2016

Nature Physics 13 (2017) 535

(sss)

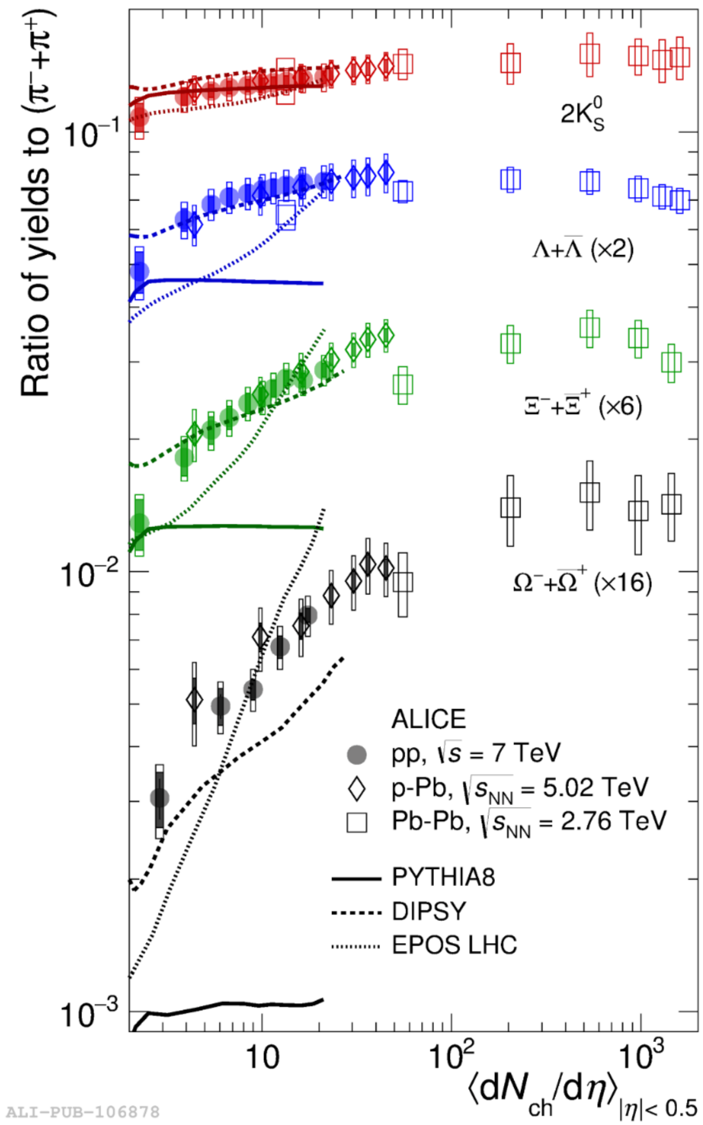


AA limit

$e^{+}+e^{-}$like ("more of the same")

Need new physics mechanisms to describe increase!

Integrated particle ratios



DIPSY Color rope model: C. Bierlich, G. Gustafson, L. Lönnblad, A. Tarasov (Jefferson Lab), JHEP 1503 (2015) 148

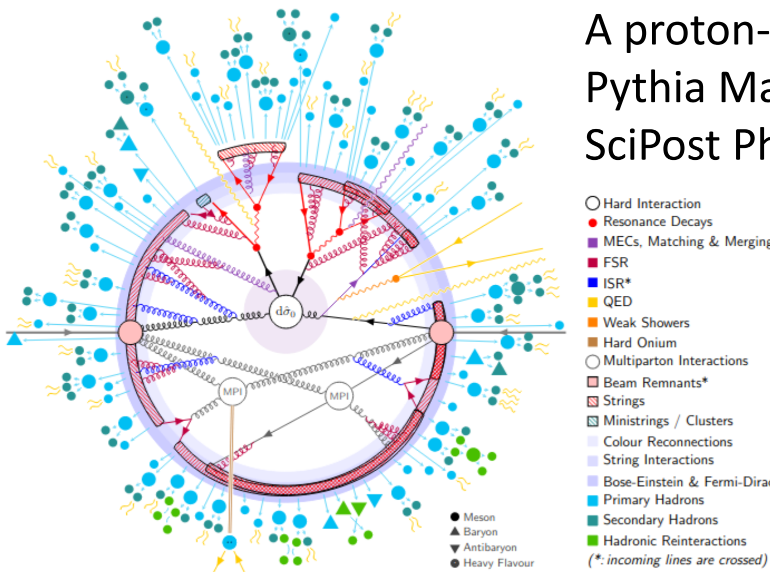
Nature Physics 13 (2017) 535

The CLASH: Macroscopic (top-down) vs microscopic (bottom up) models

- Stat. thermal model
  - Canonical
  - Grand-canonical
- Hydrodynamics
  - Radial flow
  - Azimuthal anisotropic

- Tunneling of $q\bar{q}$-pairs
  - Strings
  - Ropes
- String interactions
  - Color reconnection
  - Shoving

CLASH experimental angle: "Event Engineering"



A proton-proton collision in Pythia
Pythia Manual,
SciPost Phys.Codeb. 2022 (2022) 8

Figure 1: Schematic of the structure of a pp → $t\bar{t}$ event, as modelled by PYTHIA.

- Discovery → Control/Isolation
- Question: can we control strangeness enhancement? E.g., switch on and off strangeness enhancement for a fixed multiplicity

Two ideas tested in CLASH

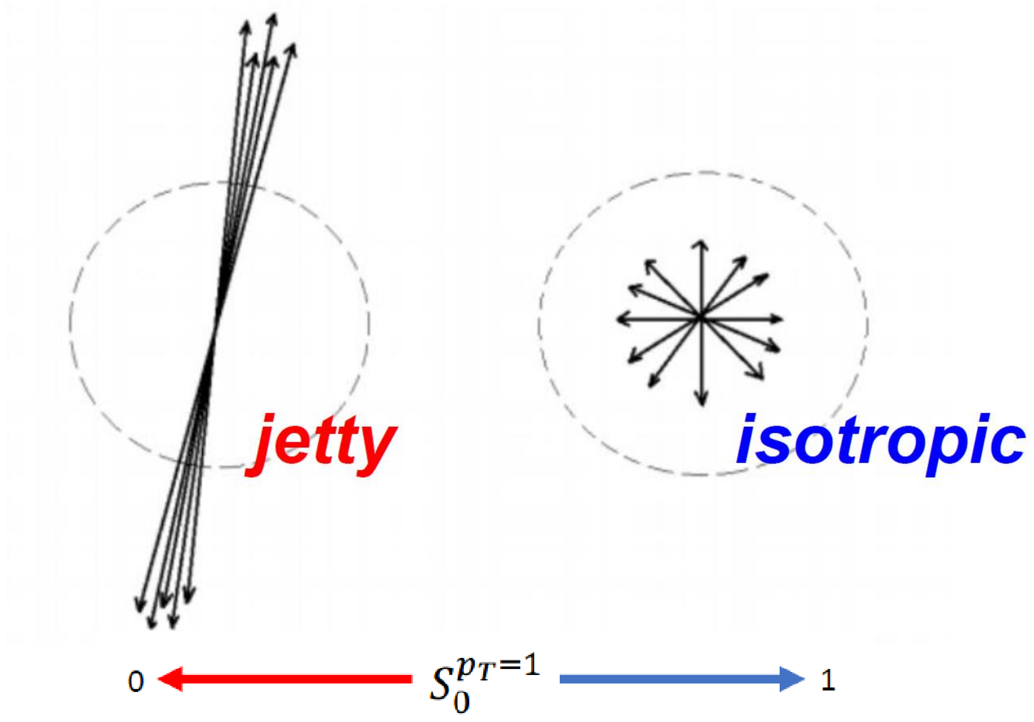
- No time to show: Relative Transverse Activity (R_T)
  - PhD thesis: Omar Vazquez Rueda (UNAM → Lund → University of Houston)
    - ALICE, JHEP 06 (2023) 027 (π, K, p)
  - PhD thesis: Oliver Matonoha
    - To be published (K_S^0, ϕ, Λ, Ξ)

- Transverse Spherocity (S_O)
  - Extension (N_{ch} → Particle identification) of ideas and work proposed by Antonio Ortiz (see later)
  - PhD thesis: Adrian Nassirpour
    - ALICE, JHEP 05 (2024) 184

Transverse Spherocity S_O

Define the unweighted transverse spherocity:

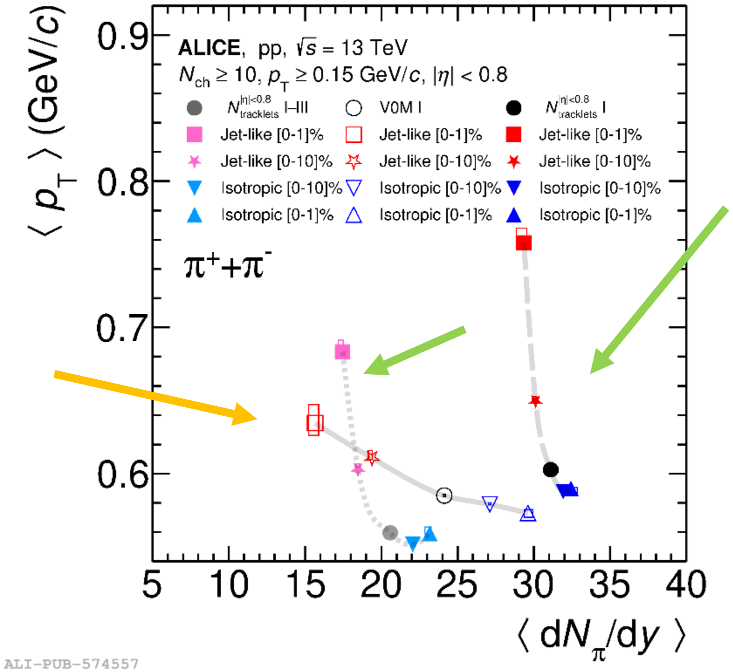
$$S_O^{p_T=1} = \frac{\pi^2}{4} \min_{\hat{n}} \left(\frac{\Sigma_{tracks} |\hat{p}_T \times \hat{n}|}{N_{tracks}} \right)^2$$



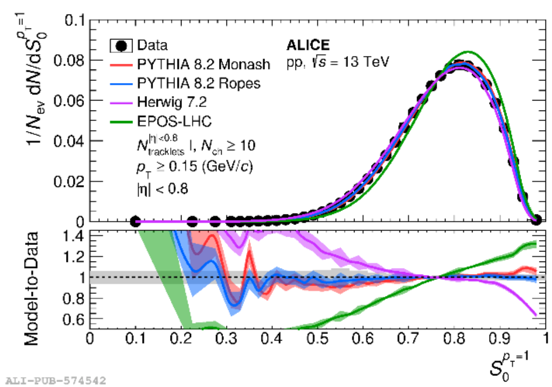
- Most other ALICE results were for the p_T-weighted S_O
  - We need this change because we study shortlived and neutral particles
  - Will call it S_O in the following

The effect of S_O selection for different multiplicity estimators

Forward estimator
Different region than where we measure S_O
Shown for top 10%.
(typically used in ALICE to avoid autocorrelations)



Mid-rapidity estimator
Same region where we measure S_O

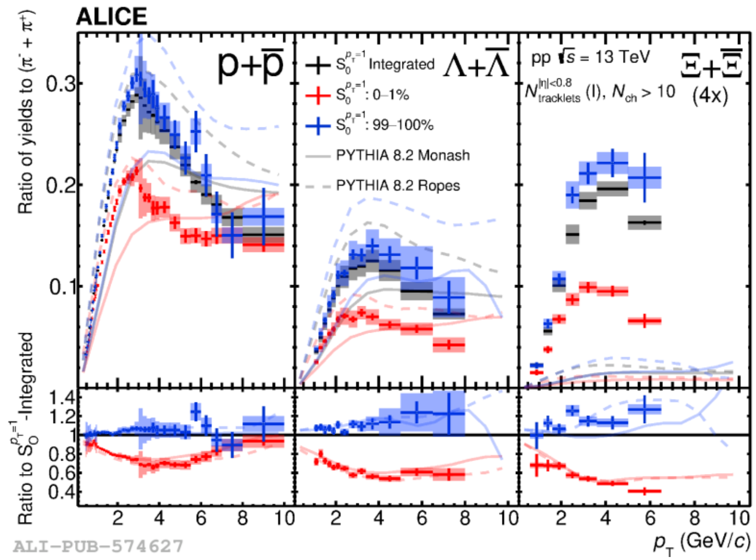


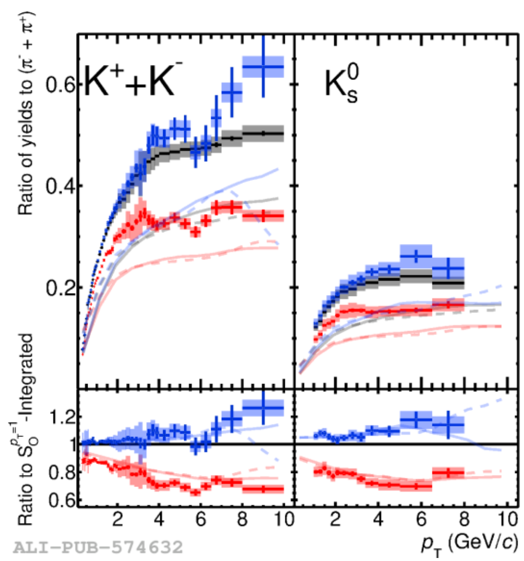
- Physics we can address with S_O depends on where we select the multiplicity
- The following results are all done with the mid-rapidity estimator
  - This ensures that multiplicity is almost constant so that we mainly select harder or softer events

Results top 1% multiplicity and top 1% S_O (0.01% of events)

- Large differences between jetty and isotropic ratios ✓
- Events without S_O selection are similar to isotropic
  - QGP-like effects dominates
    - Perfect liquid?
  - Hard physics is outlier

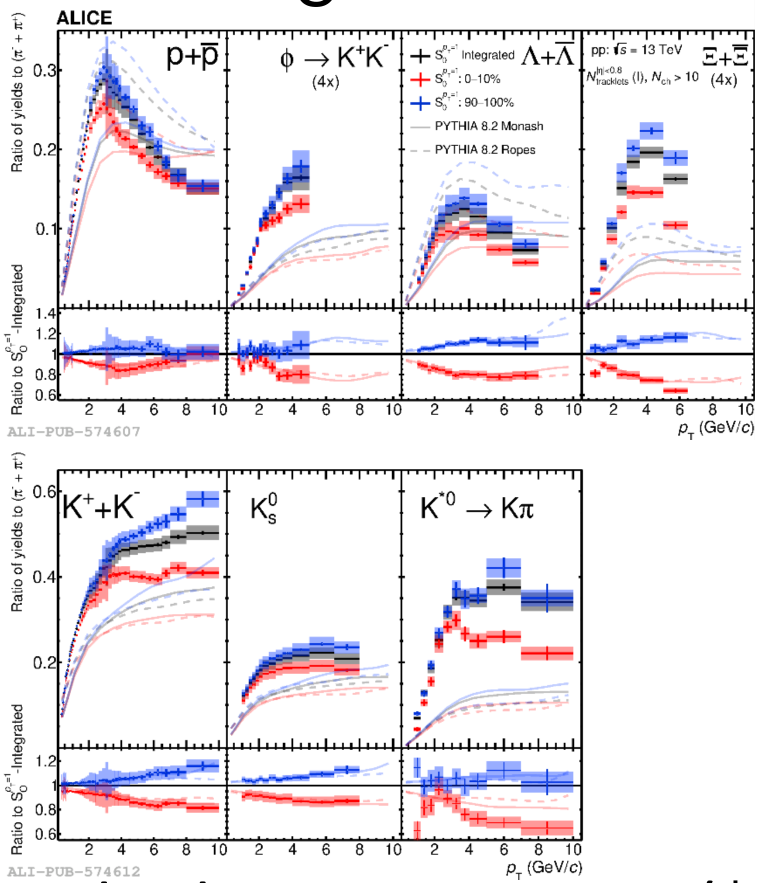
- Jet-like events
  - Radial-flow "peaks" are reduced
  - Strangeness is significantly reduced at high p_T





ALICE, JHEP 05 (2024) 184

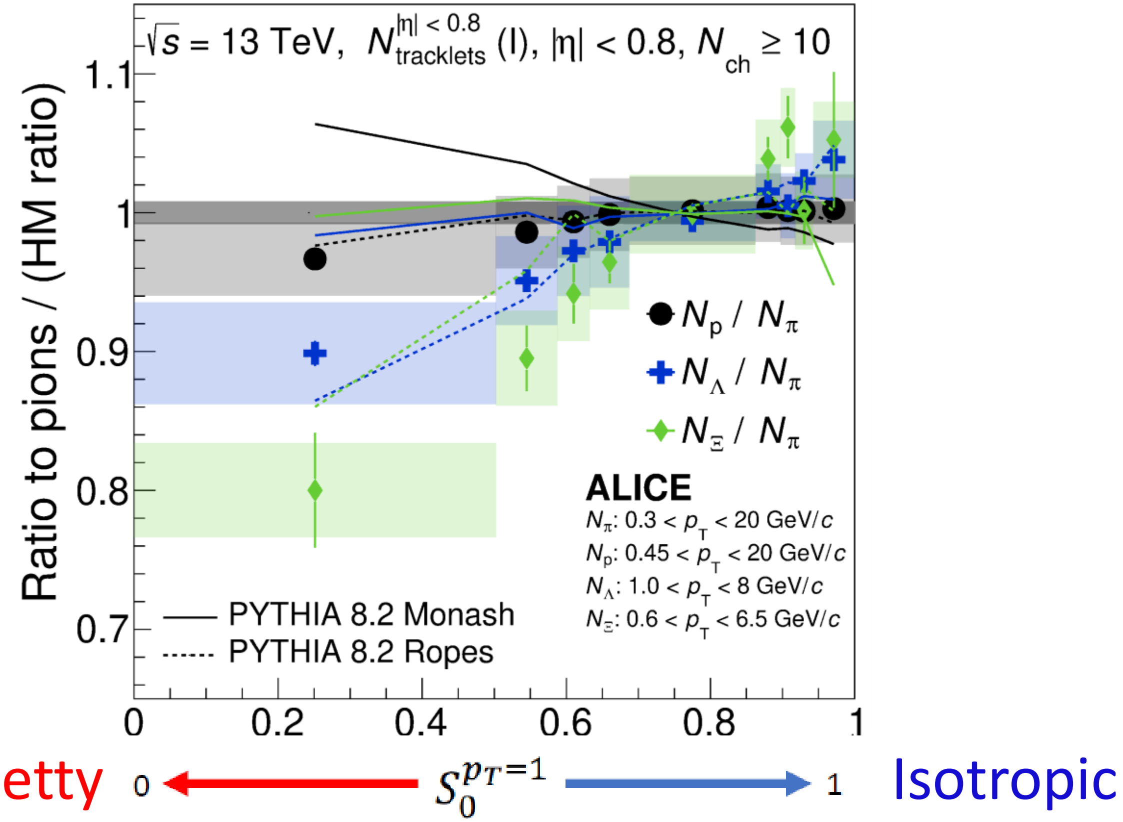
Results top 1% multiplicity and top 10% S_O (0.1% of events)



ALICE, JHEP 05 (2024) 184

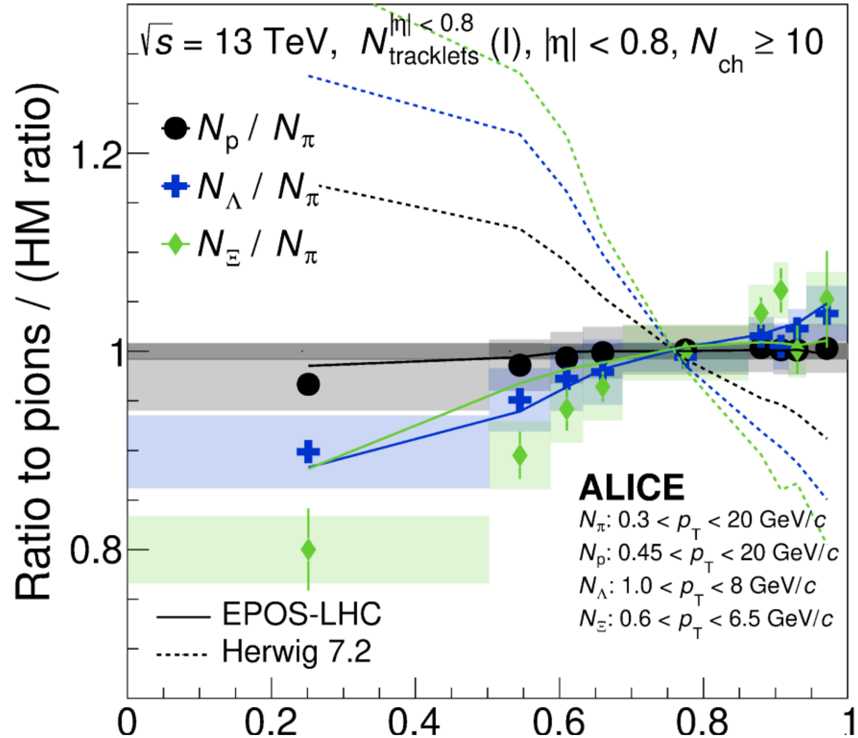
- For top 10% we also have resonances (φ and K^{*0})
  - Require more statistics due to event mixing background
- Vs top 1%: effects are reduced but trends are the same

Strangeness enhancement vs S_O (top 1% multiplicity)



- We can control the strangeness enhancement with S_O ✓
  - The effect is bigger for Ξ (S=2) than for Λ (S=1)
- Pythia ropes can describe the enhancement qualitatively

Strangeness enhancement vs S_O (top 1% multiplicity)

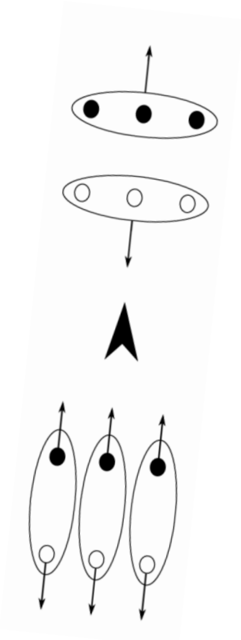


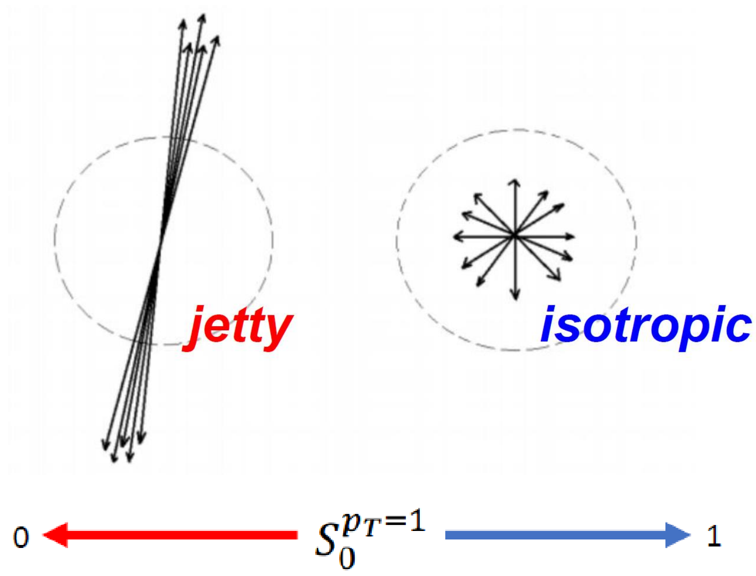
Jetty 0 ← $S_0^{p_T=1}$ → 1 Isotropic

- EPOS LHC captures the trend
  - The QGP core is reduced in jetty events
- HERWIG has opposite trend?! (next slide)

Why Herwig is wrong

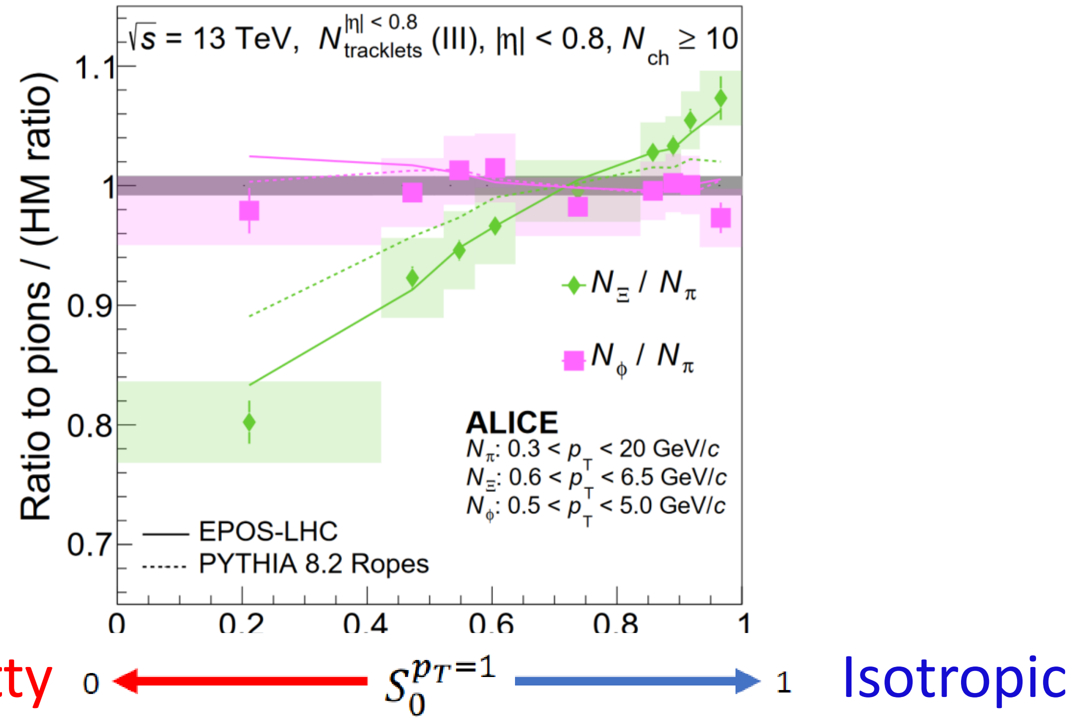
S. Gieseke,
P. Kirchgaeßer,
S. Plätzer
Eur.Phys.J.C 78 (2018) 2, 99





- Herwig produces a baryon enhancement by allowing 3 mesons close in phase space to form a baryon-antibaryon pair
  - But this will be more likely to happen in pencil-like events!
  - What about quark coalescence models?

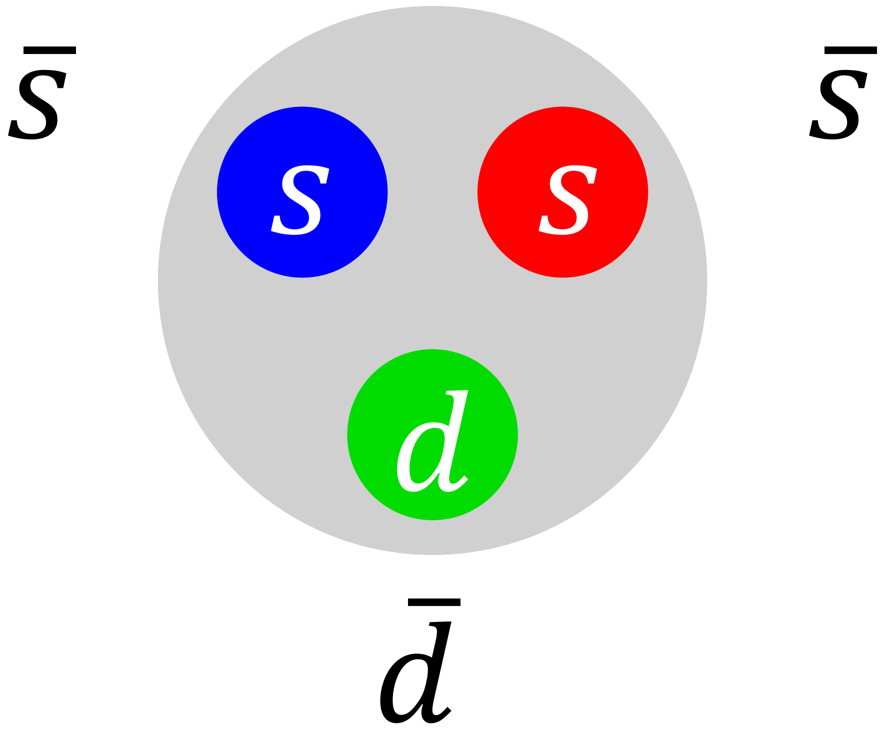
Strangeness enhancement vs S_O (top 10% multiplicity)



- ϕ ($\approx s\bar{s}$) and Ξ (ssd) follows different trends
- Data and models agree
  - Surprising for Pythia where ϕ is produced via 2 $s\bar{s}$ breakings
    - Suggests that the effect is mostly due to junctions
- How can we differentiate between EPOS and Pythia Ropes?

Answer: look at the how the strange quarks are balanced

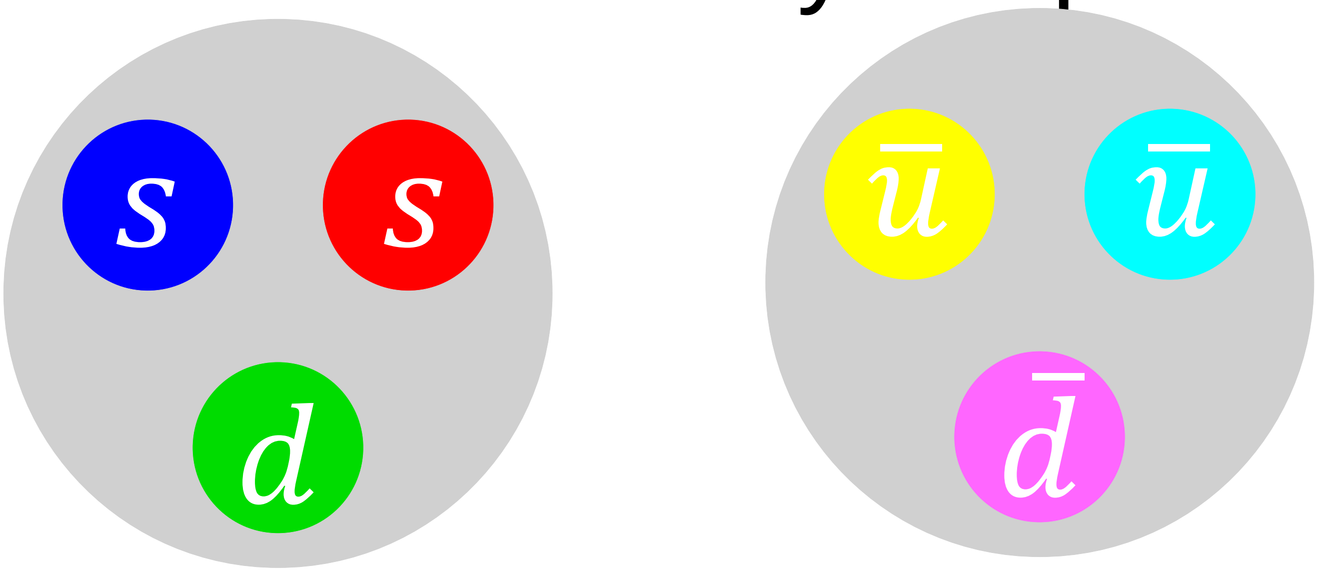
Ξ (Xi) baryon



QGP:
We naively expect that in a QGP the quarks will be deconfined and so eventually the quark pairs will drift apart in phase space.

Lund string:
Most quarks and antiquarks are produced together during hadronization.

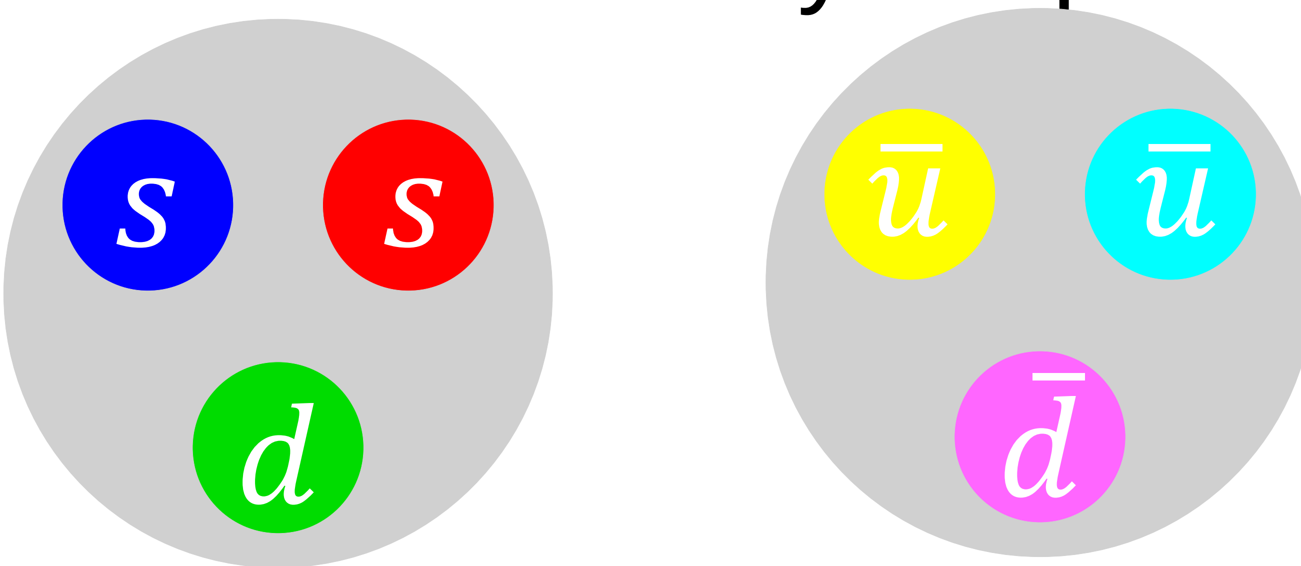
The easiest case: Ξ balanced by antiproton

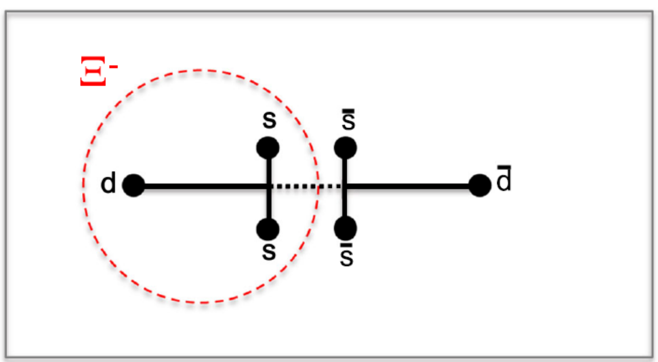


QGP:

We expect that the balancing occurs on a statistical basis so this can happen.

The easiest case:
Ξ balanced by antiproton

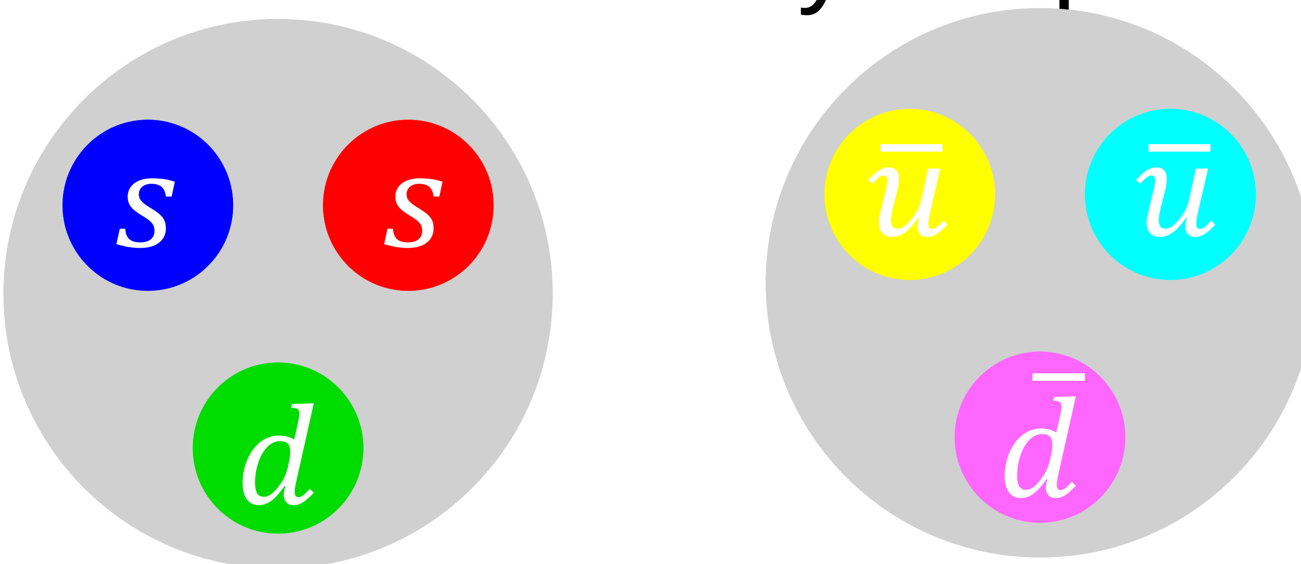


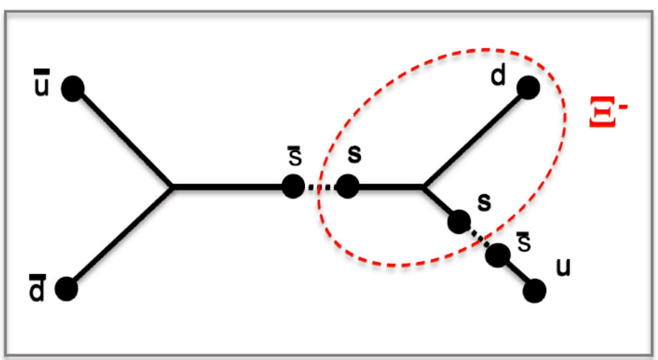


Normal Lund string and ropes: Ξ almost never balanced by antiproton but instead typically by antistrange baryons and even anti-Ξ!

Idea from CLASH workshop write up: J. Adolfsson et al, Eur. Phys. J. A 56 (2020) 11, 288, “QCD challenges from pp to A–A collisions”

The easiest case:
Ξ balanced by antiproton



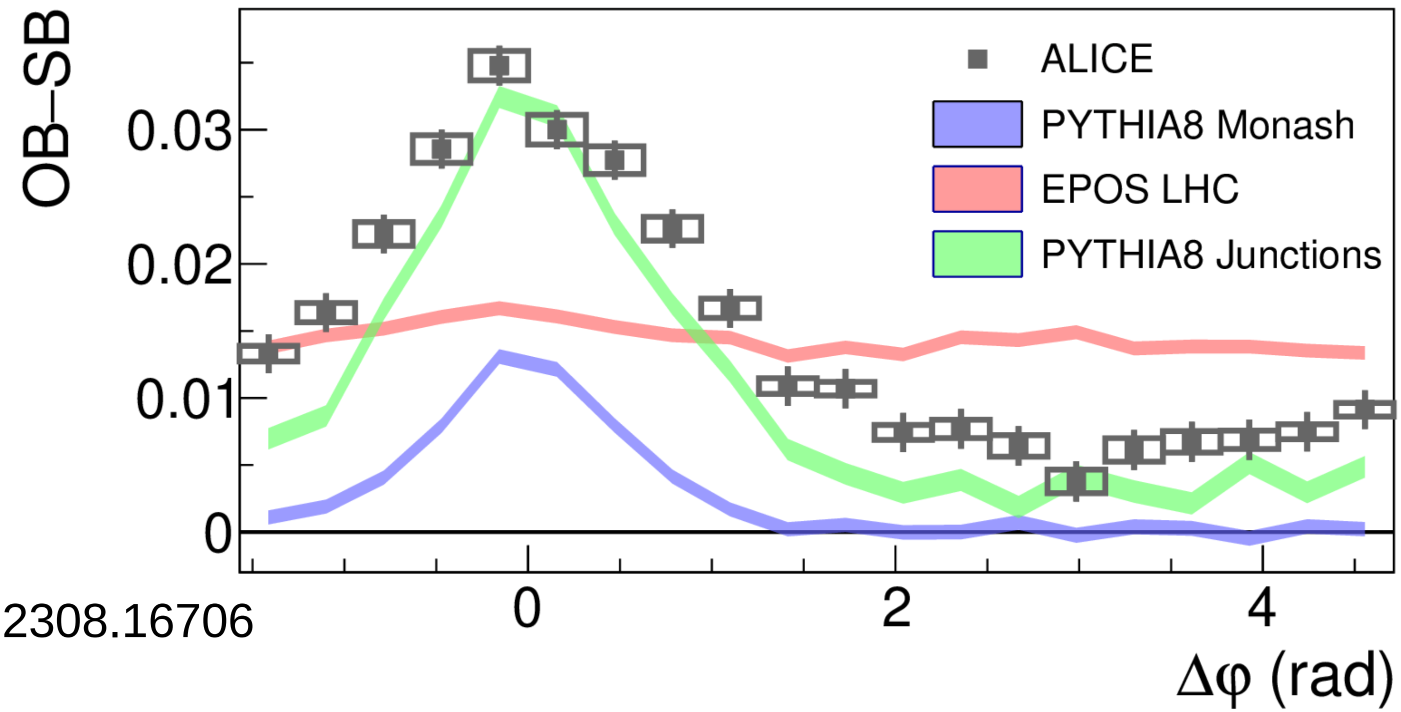


Junction:

Ξ balanced more by kaons and less by antistrange baryons. Broader correlations in rapidity.

Idea from CLASH workshop write up: J. Adolfsson et al, Eur. Phys. J. A 56 (2020) 11, 288, "QCD challenges from pp to A–A collisions"

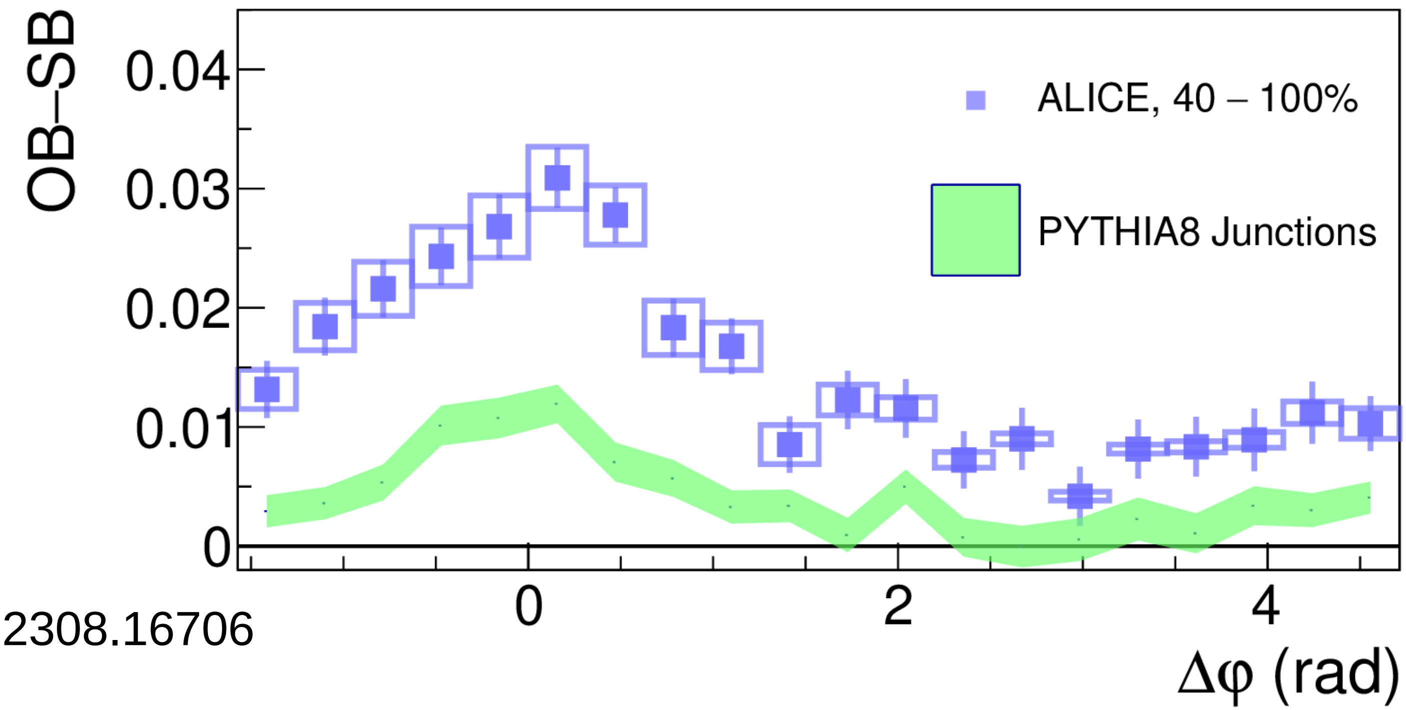
Microscopic balance of Ξ by antiprotons: MB results



arXiv:2308.16706

- EPOS (QGP) model: no structure due to extreme assumption of grand-canonical ensemble
- Pythia8 Monash: fails since this almost never happens
- Pythia8 Junctions: describes well the data

Microscopic balance of Ξ by antiprotons: low mult results

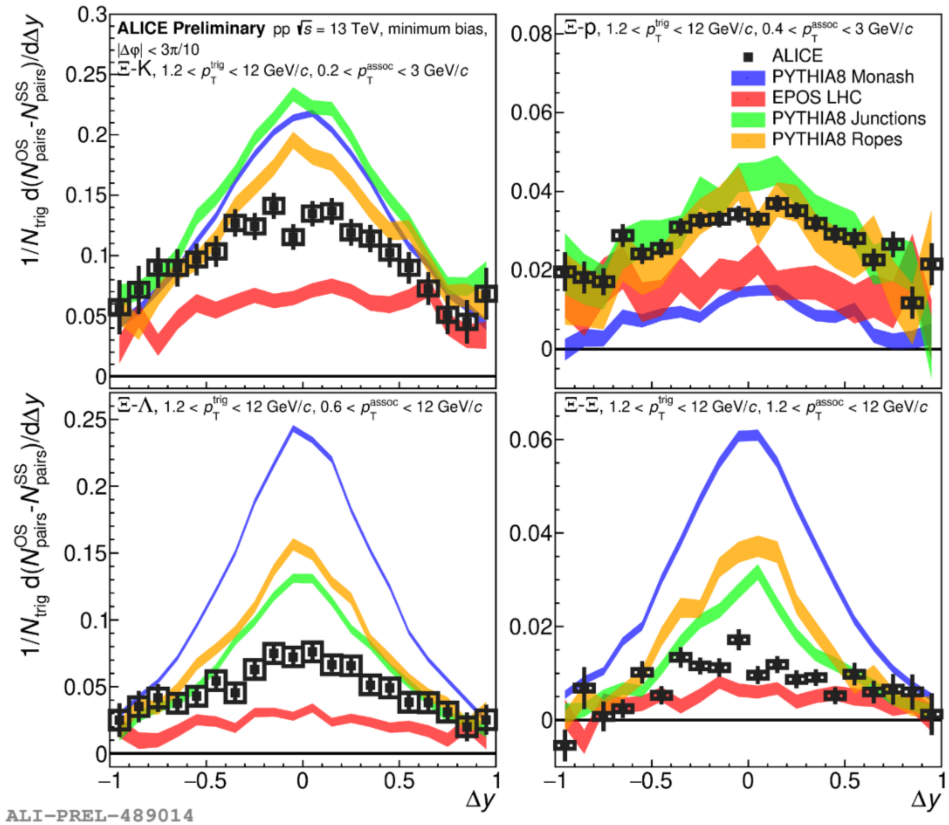


arXiv:2308.16706

- Pythia8 Junctions: fails to describe the data since in the low multiplicity limit it must agree with Monash (no CR)
- But why does nature prefer such a complicated process where strangeness is balanced by two mesons?

Part of the work of Jonatan Adolfsson's PhD Thesis

Ξ-K Ξ-p



Ξ-Λ Ξ-Ξ

ALICE congratulates its PhD thesis award winner

2 JULY, 2021

Jonatan Adolfsson (LU)

ALICE Spokesperson Luciano Musa (left) awards the prize to Jonatan Adolfsson (right) in the virtual presence of Collaboration Board Chair Silvia Masciocchi and the Chairs of the Thesis Award Committee, Giuseppe Bruno and Philippe Crochet (Image: CERN)

https://home.cern/news/news/cern/alice-congratulates-its-phd-thesis-award-winner

- He studied many more combinations, see arXiv:2308.16706

Future outlook

- The study of the microscopic balance is something we want to keep pursuing
  - Xi (ssd) $\rightarrow$ Omega (sss)
  - 2 particles $\rightarrow$ 3 particles
  - ssbar $\rightarrow$ ccbar

Thank You!