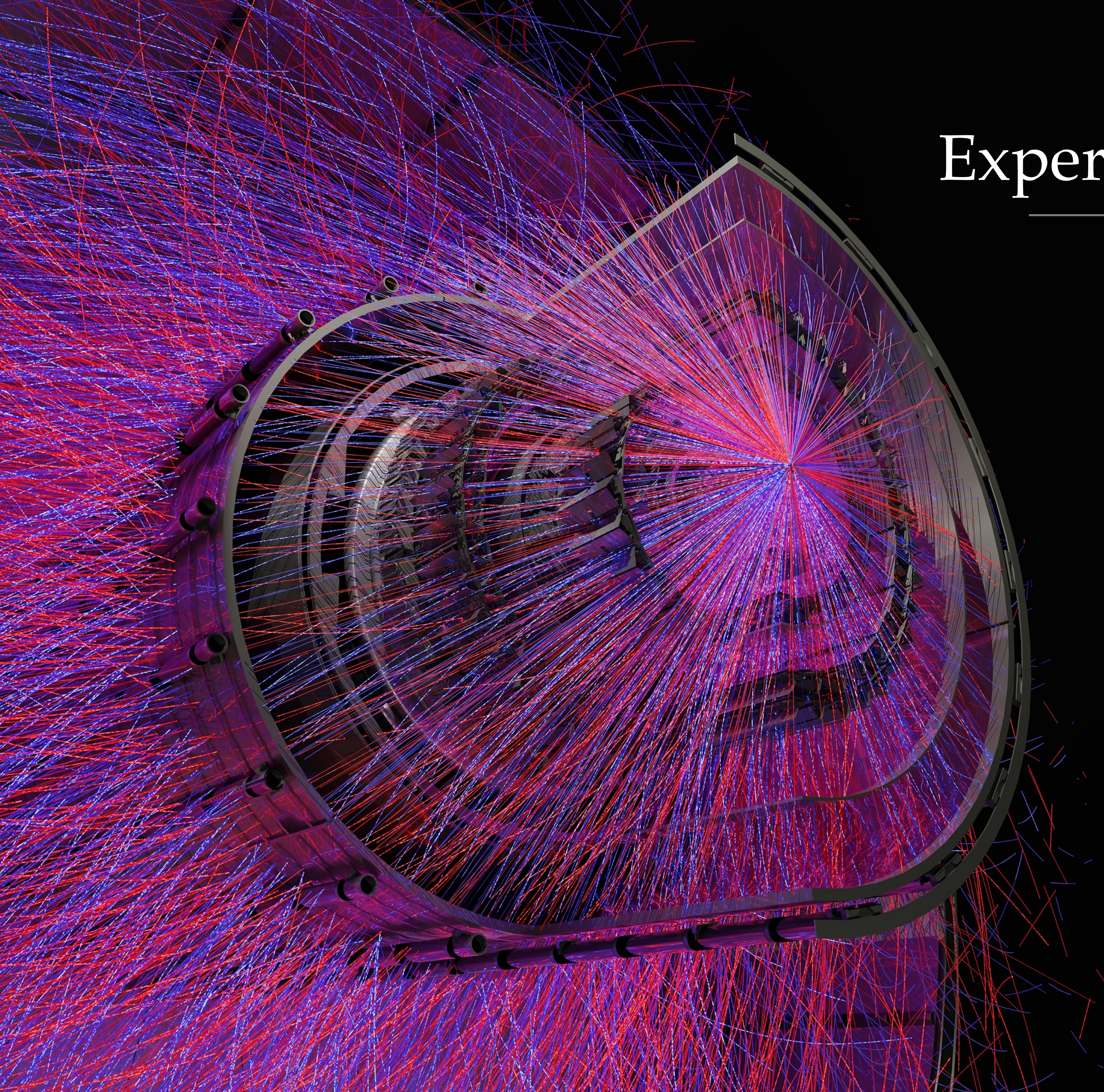


A brief introduction to

Experimental heavy-ion physics

Strangeness in Quark Matter 2024

David Dobrigkeit Chinellato

Thanks for discussions and materials:
Francesca Bellini, Auguste Besson,
Pol-Bernard Gossiaux, Antonin Maire,
Jean-Yves Ollitraut

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

SQM Strasbourg 2024
Strangeness in Quark Matter

The standard model of particle physics

Constituents of matter

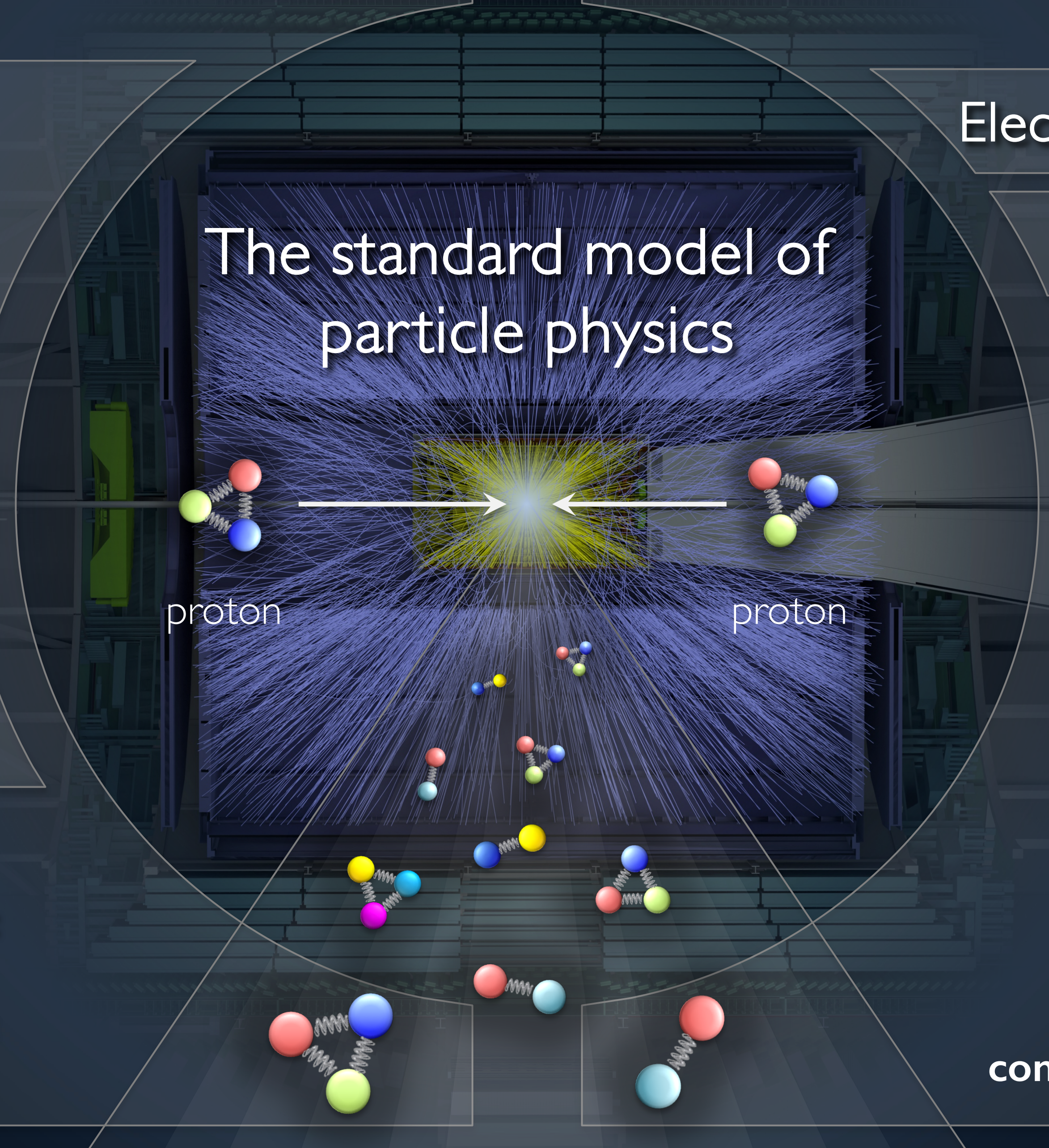
e	μ	τ
ν_e	ν_μ	ν_τ

6 leptons

u	s	b
d	c	t

6 quarks

→ Quarks carry color charge:
Red, green, blue
→ Antiquarks carry anticolor:
cyan, magenta, yellow



Fundamental interactions

Electromagnetic interaction

Weak interaction

Strong interaction

Gravity

→ Interactions occur via the exchange of force carriers: photons, Z/W, gluons and the Higgs

→ Quarks may ordinarily only be found confined into colorless hadrons

→ Can we understand **confinement and hadronization?**

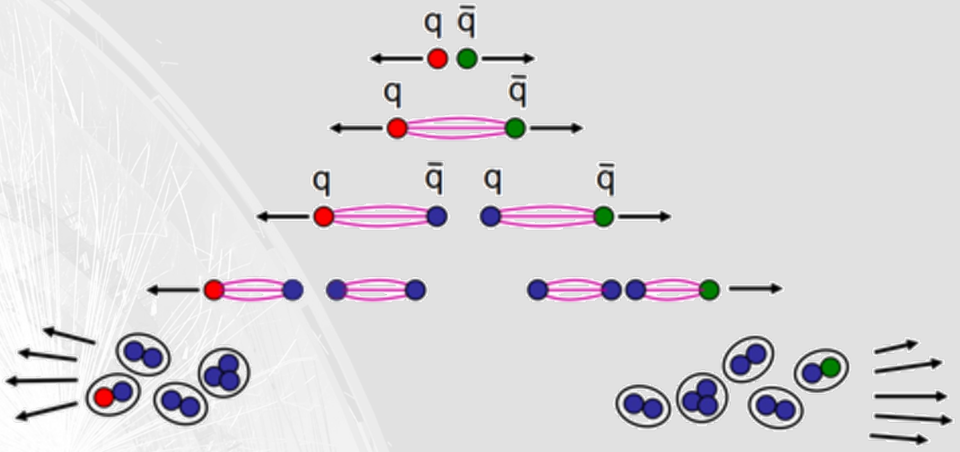
Understanding confinement

Properties of the QCD vacuum:

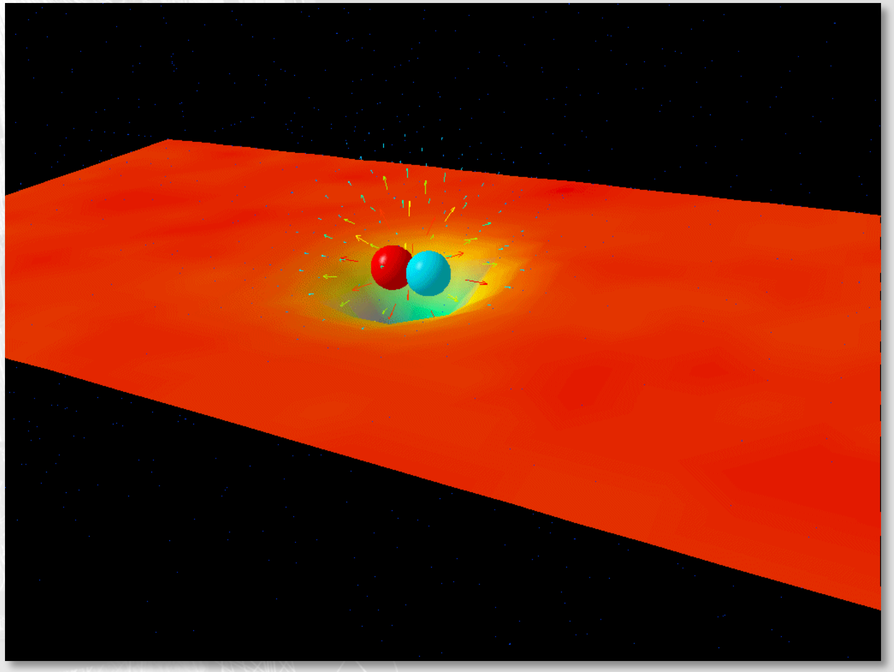
- Gluon-gluon self-interaction (non-abelian)
- QCD field lines compressed in flux tube (or "string")

The q-qbar potential is of the form (Cornell potential):

$$V(r) = -\frac{a}{r} + \sigma r$$

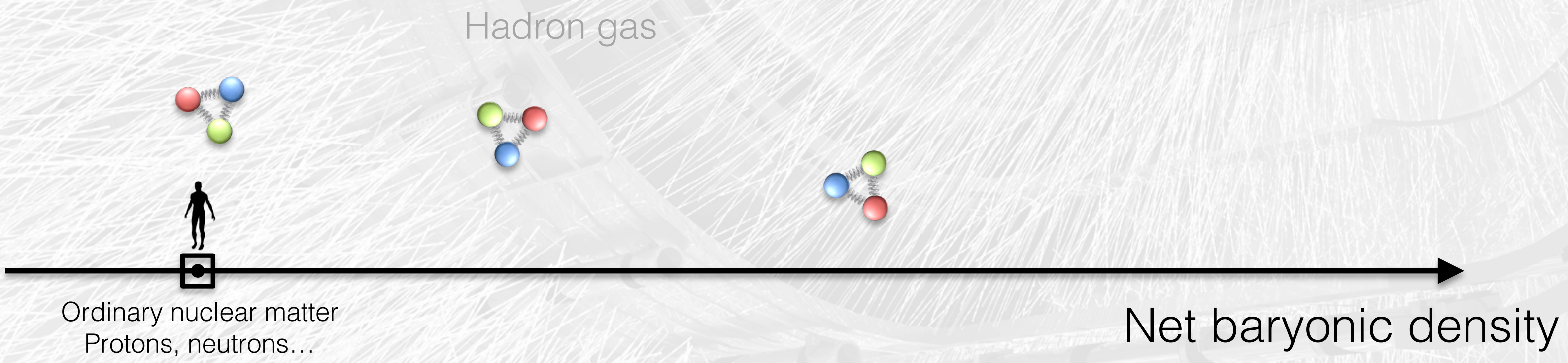


Source: http://www.physics.adelaide.edu.au/



- The potential grows with distance
- If pulled apart, the energy in the string increases
- A new q-qbar pair is created once the energy is above production threshold
- No free quark can be obtained by breaking a flux tube → confinement

The phase diagram of QCD matter



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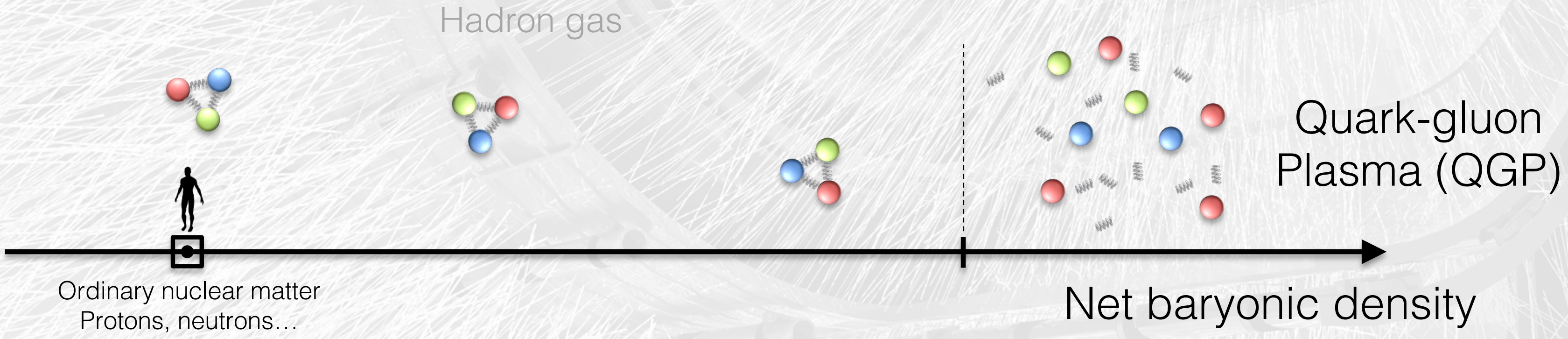
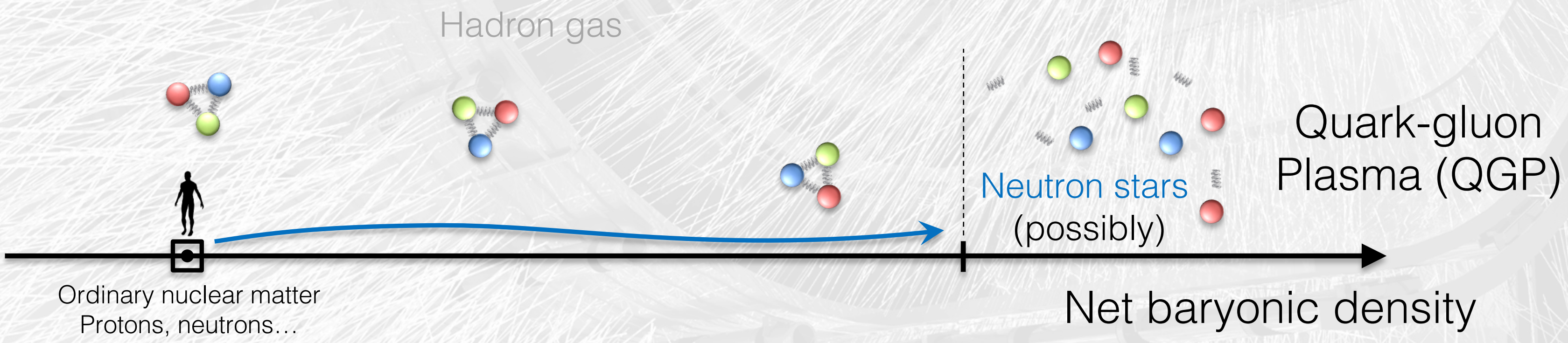


The phase diagram of QCD matter

How can this be studied?

- **High baryonic density**: cosmology, neutron stars
  - Actually not easy to study!



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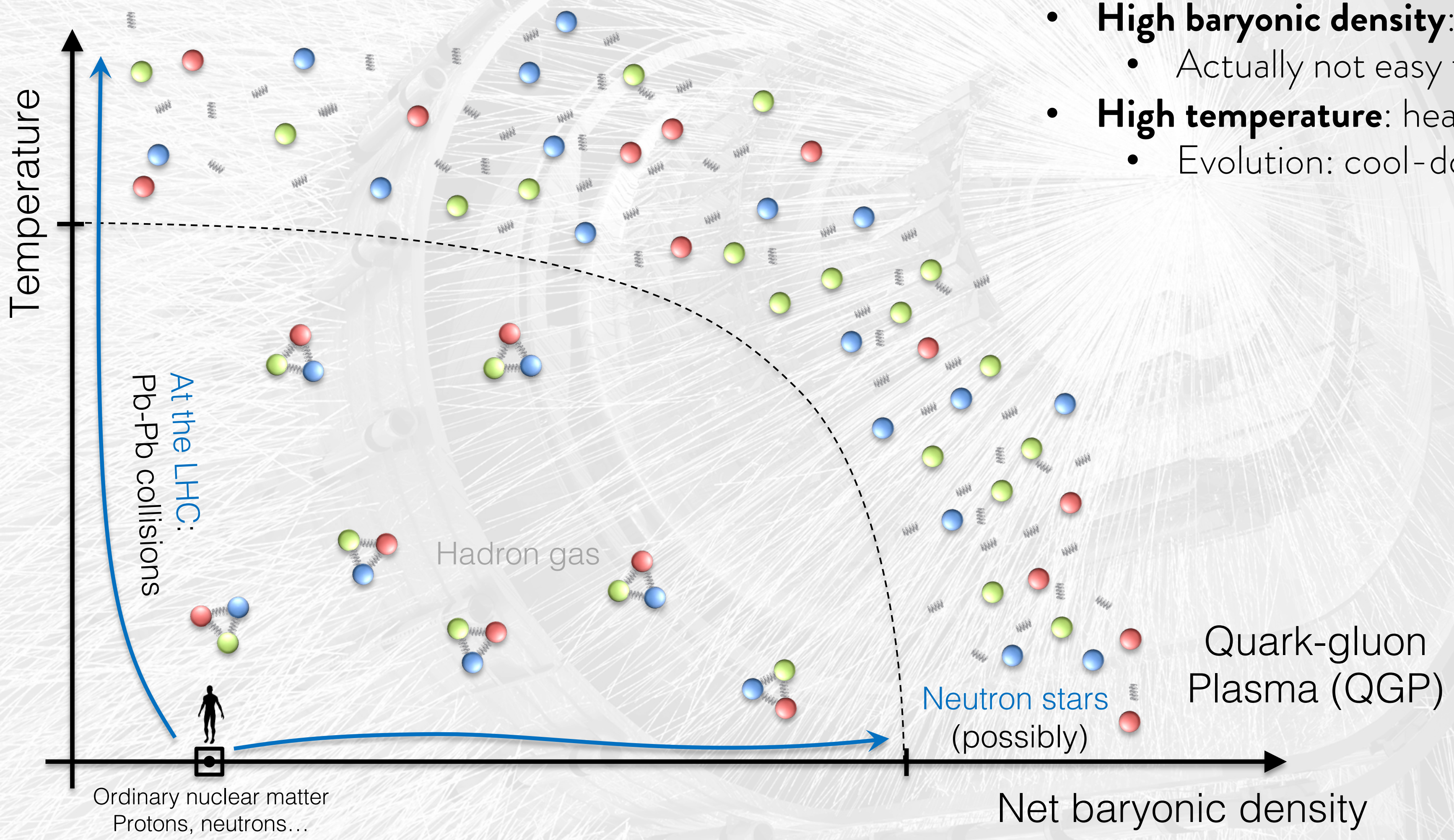

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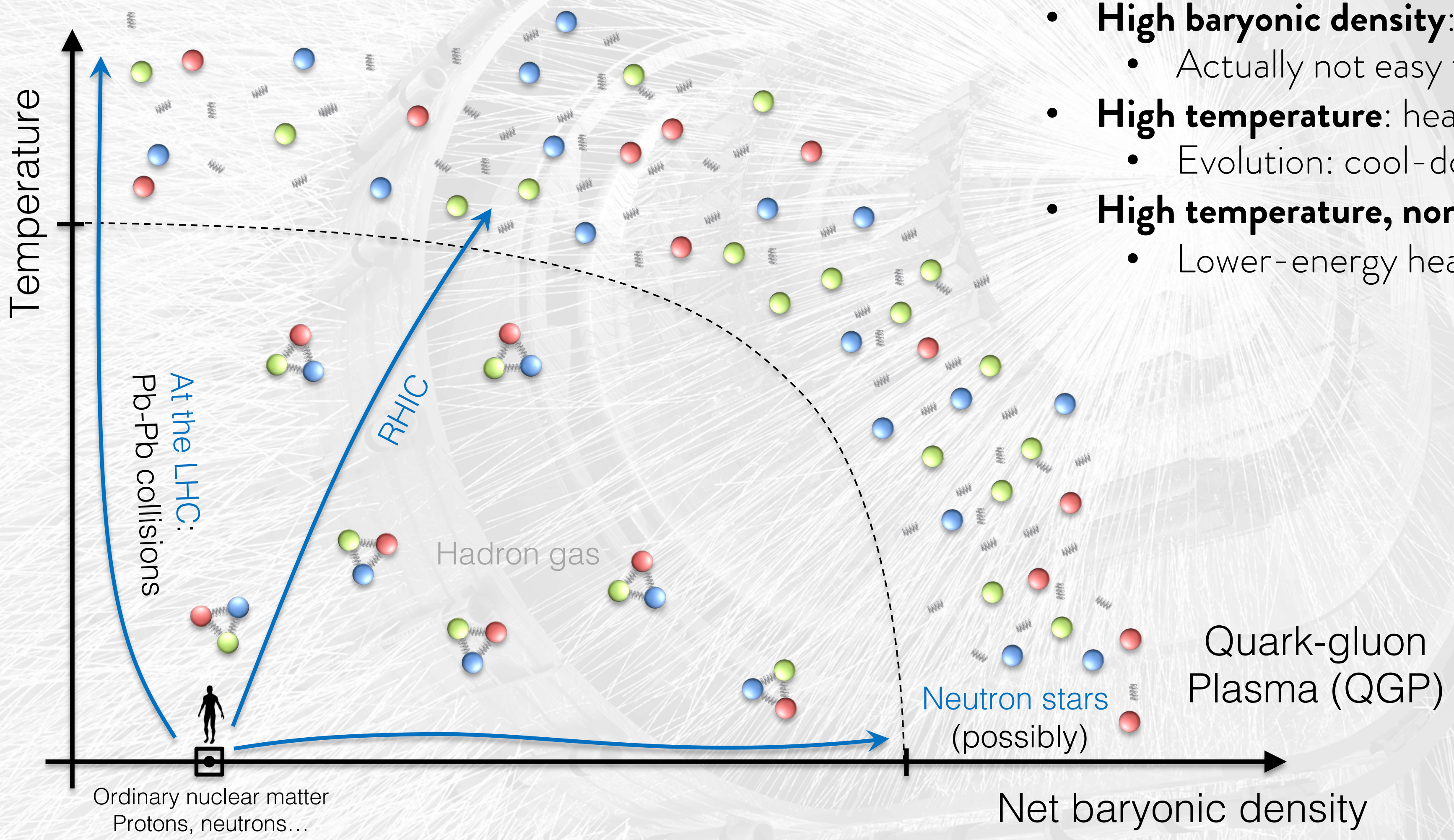

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  - Lower-energy heavy-ion collisions (RHIC, …)

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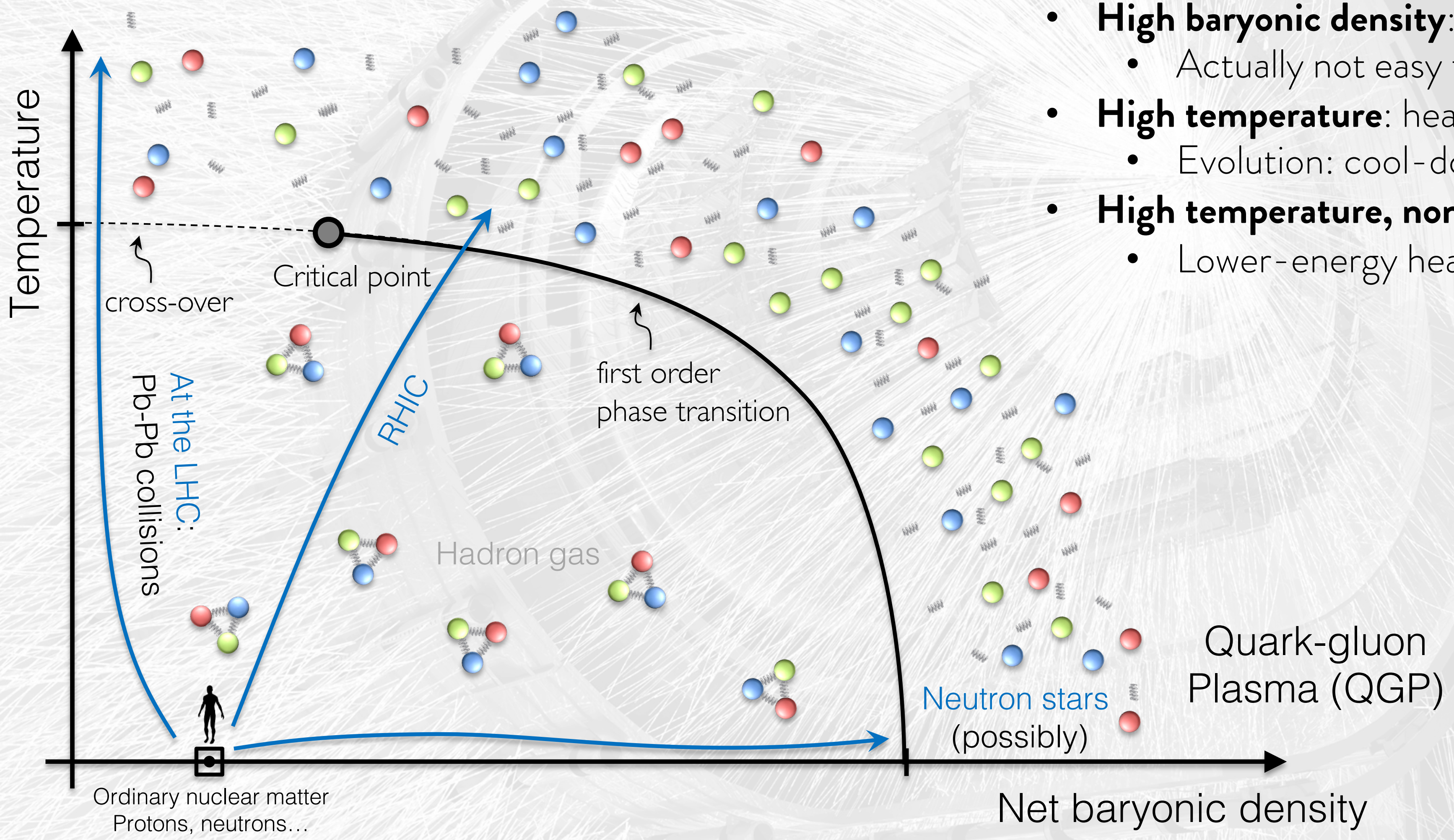

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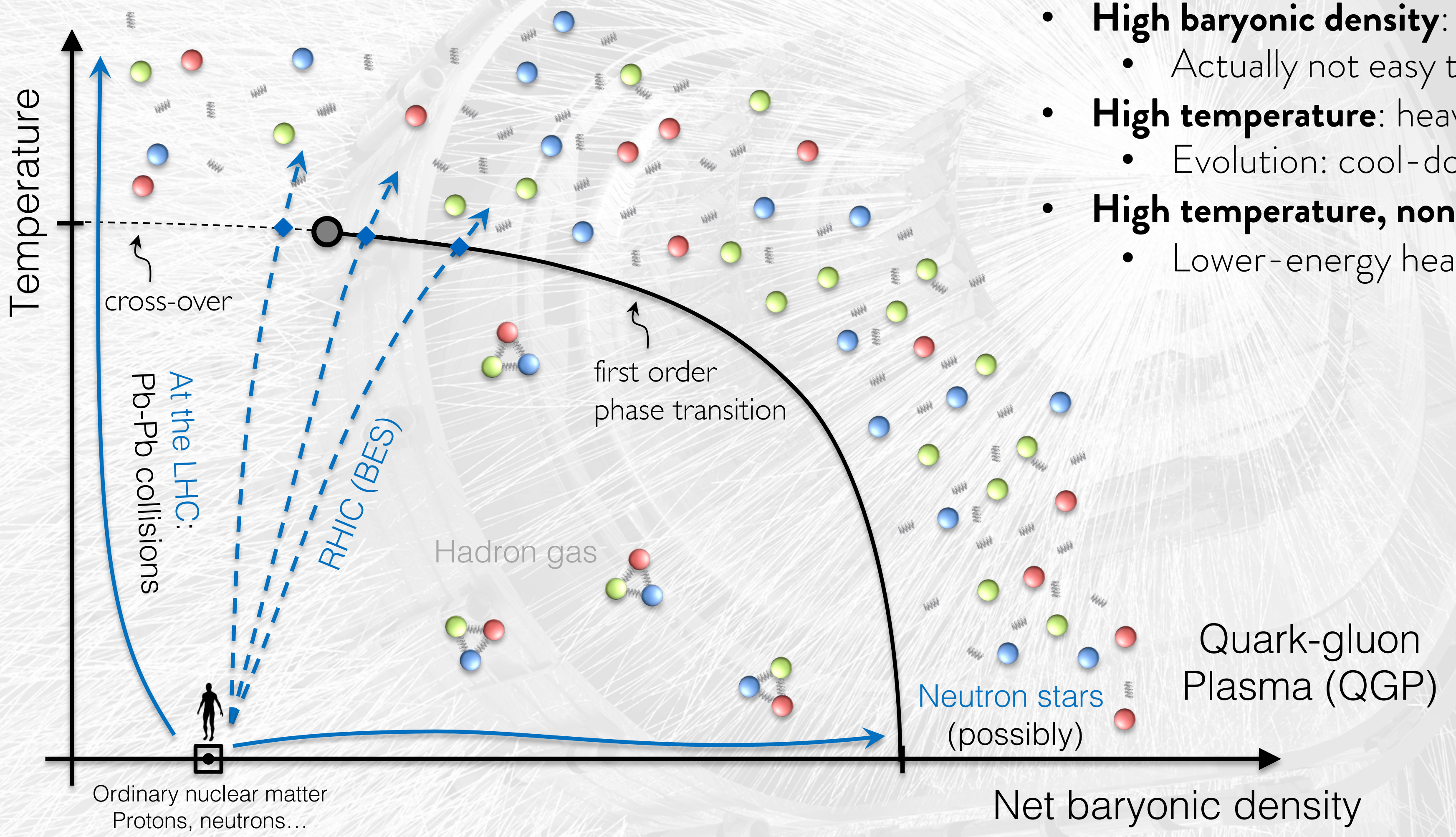

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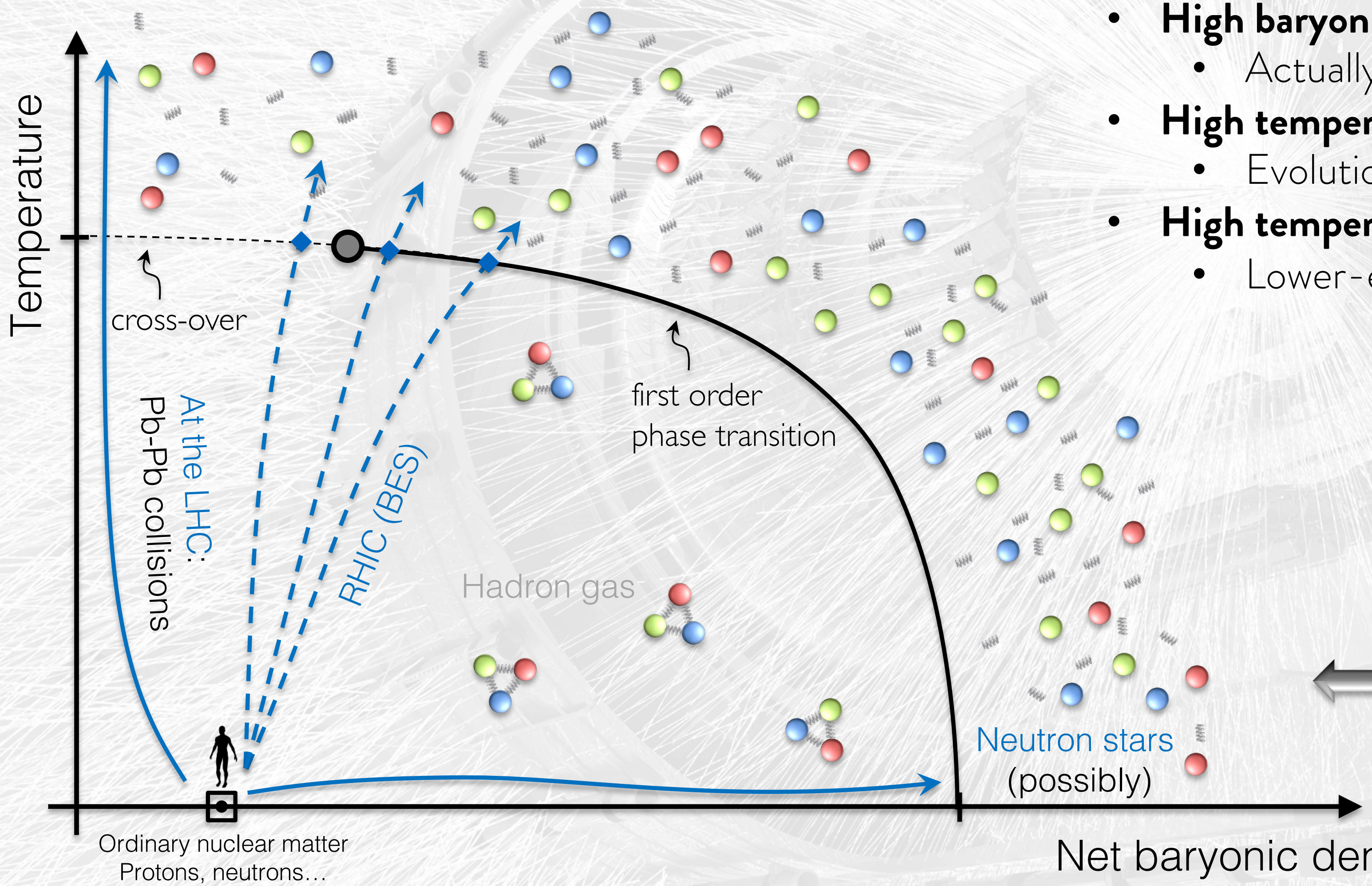

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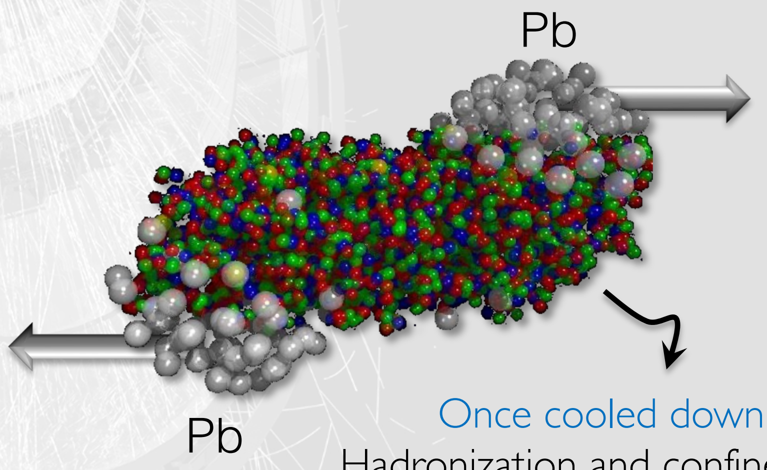


Once cooled down:
Hadronization and confinement into structures (hadrons, nuclei)

Which QCD energy regime are we dealing with?

Having in mind:

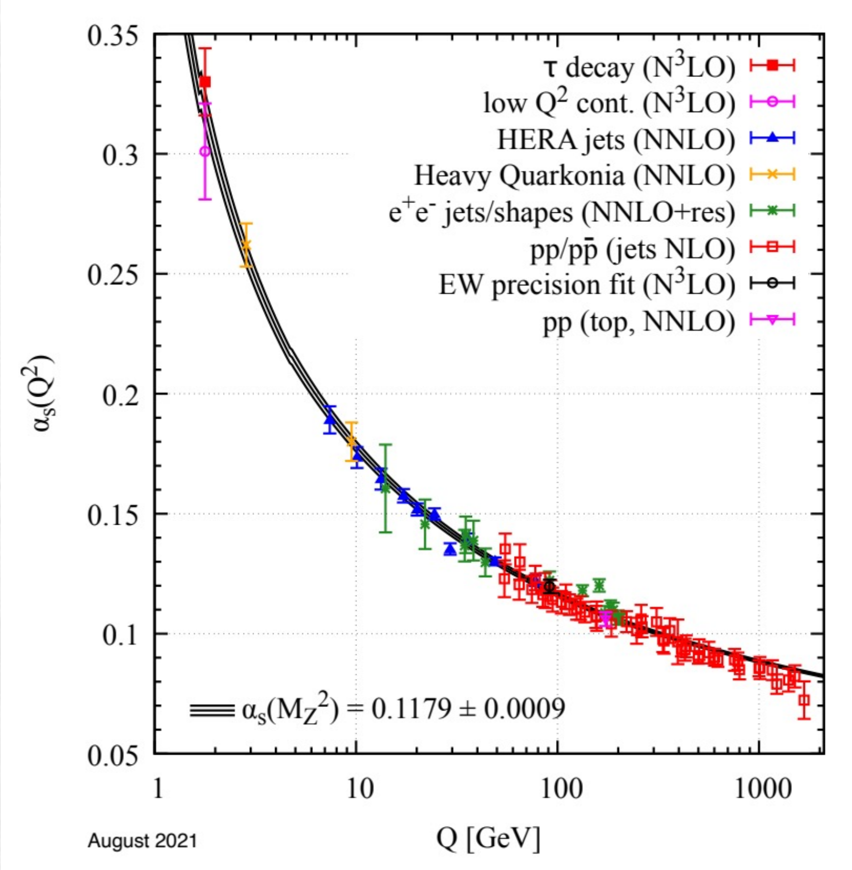
- $\Lambda_{QCD}(m_{Z,} N_f = 3) = 244$ MeV

In addition, At T = 200 MeV, the typical kinetic energy

- for a non-relativistic particle is $E = 3/2\ k_B T = 300$ MeV
- for a relativistic particle is $E = 3 k_B T = 600$ MeV

Low Q → α_s is not small!
→ The QCD transition is a non-perturbative QCD problem

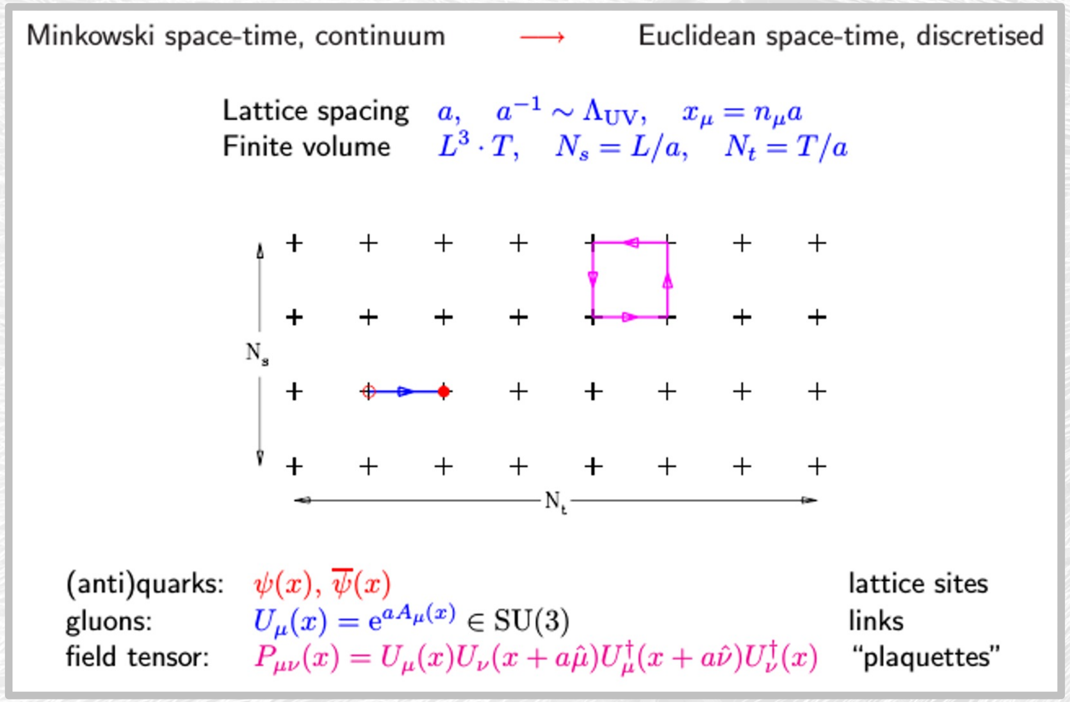
- Need models to deal with (phenomenology)
- Use Lattice QCD for calculations from first principles



Source: Particle Data Group (2021)

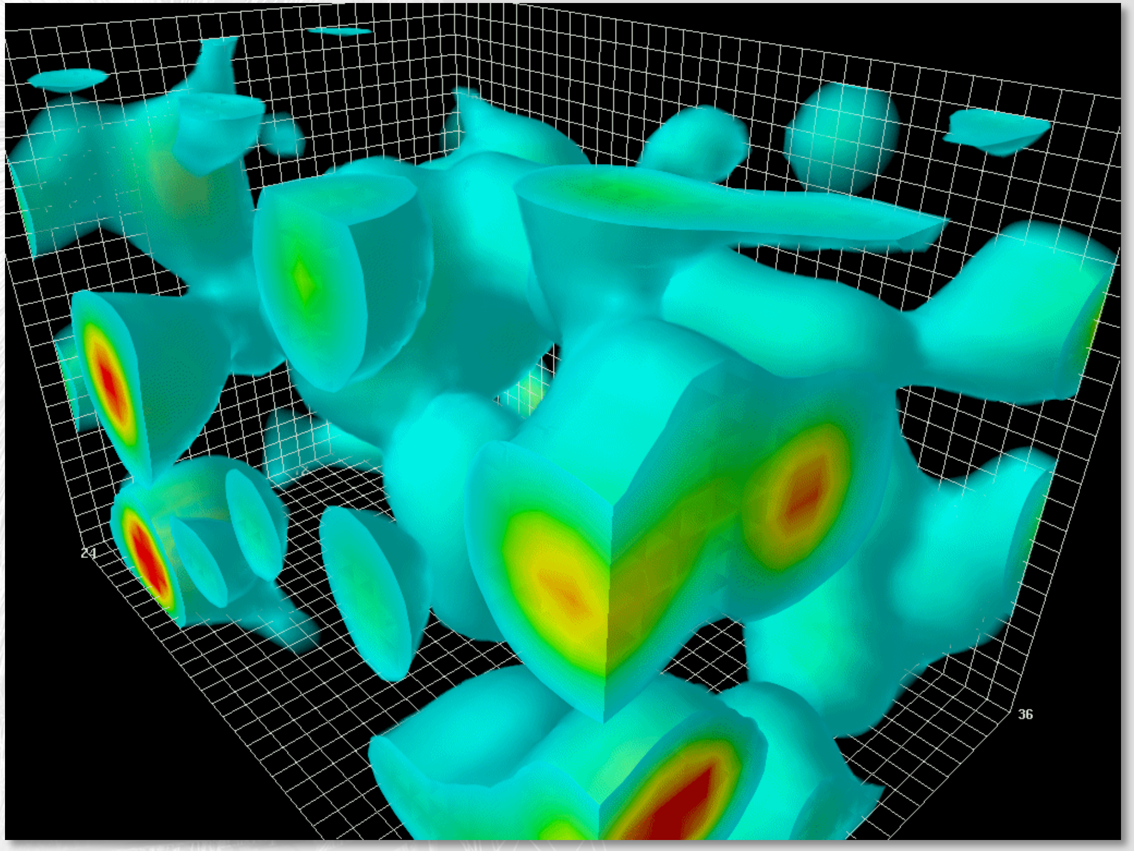
QCD on the lattice (LQCD): non-perturbative QCD calculations

Wittig, U. Mainz LQCD, sl.14



LQCD
→ Wikipedia - LQCD
→ Wittig, U. Mainz LQCD
(If theoretical interest for LQCD, R. Gupta, 150 pages, Introduction to LQCD)

Fluctuating quark / gluon fields
in discrete space-time lattice



Source: www.physics.adelaide.edu

So far, so good…

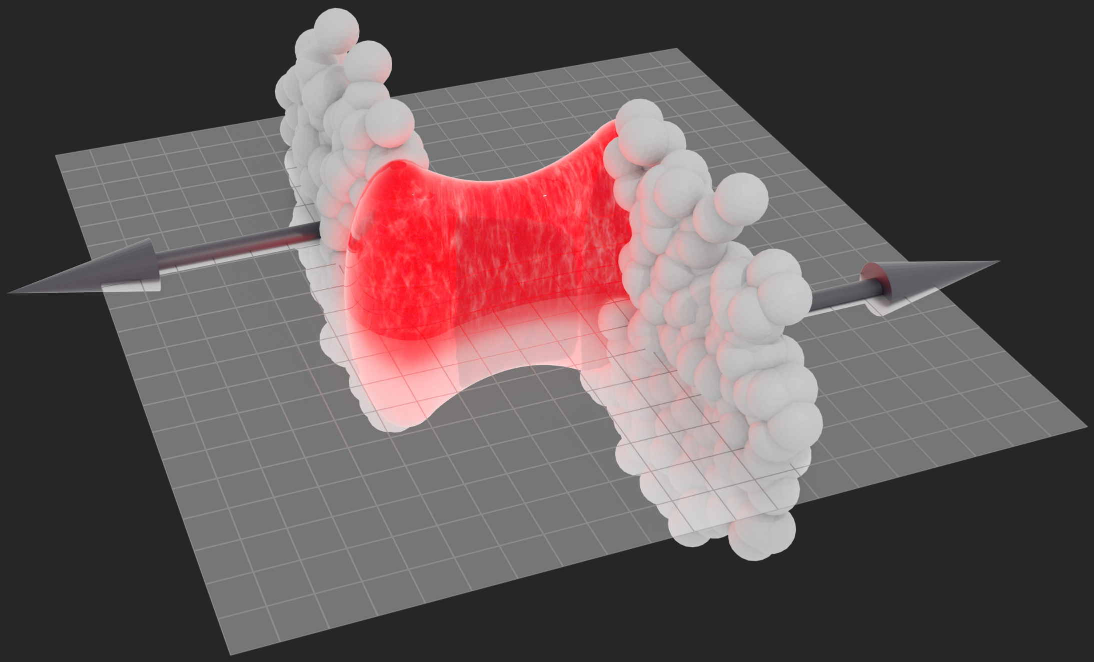
The QGP is a state of strongly-interacting matter resulting from the phase transition of nuclear/hadronic (color-neutral) matter under extreme conditions of pressure or temperature

→ the universe up to O(1-10μs) after the Big Bang

→ the properties of the QGP (have to!) emerge from the fundamental properties of the strong interaction

More is different! – P.W. Anderson

→ physics of condensed QCD matter

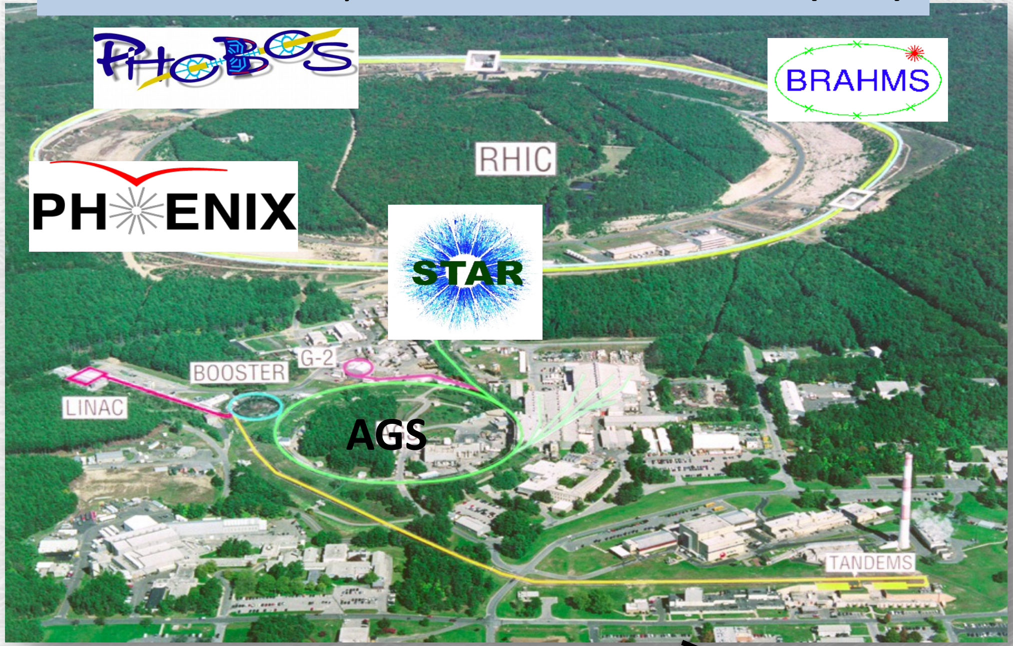


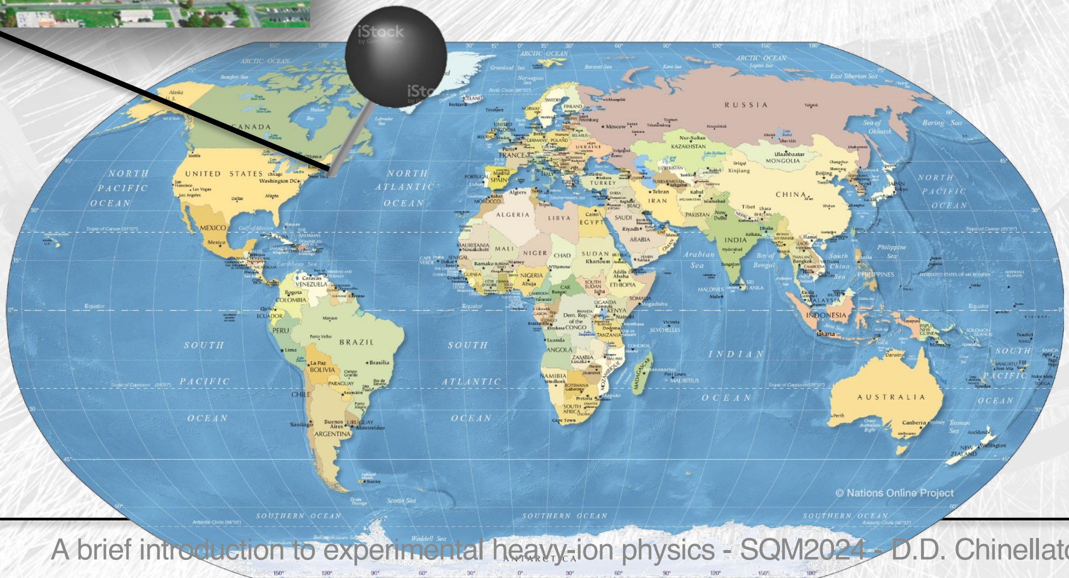
The basic question to this point:

How do I do **measurements** about the QGP and QCD at high densities?

Heavy-ion physics worldwide: present / high energy

Relativistic Heavy Ion Collider, Brookhaven (USA)





Brookhaven RHIC

- Operating since 2000
- Circumference 3.83 km, 2 rings
- Superconducting magnets
- $\sqrt{s_{NN}}$ = 3 - 200 GeV in Au-Au
- Beam energy scan I: 2010-11
- Beam energy scan II: 2019-22
- Ongoing exp: STAR

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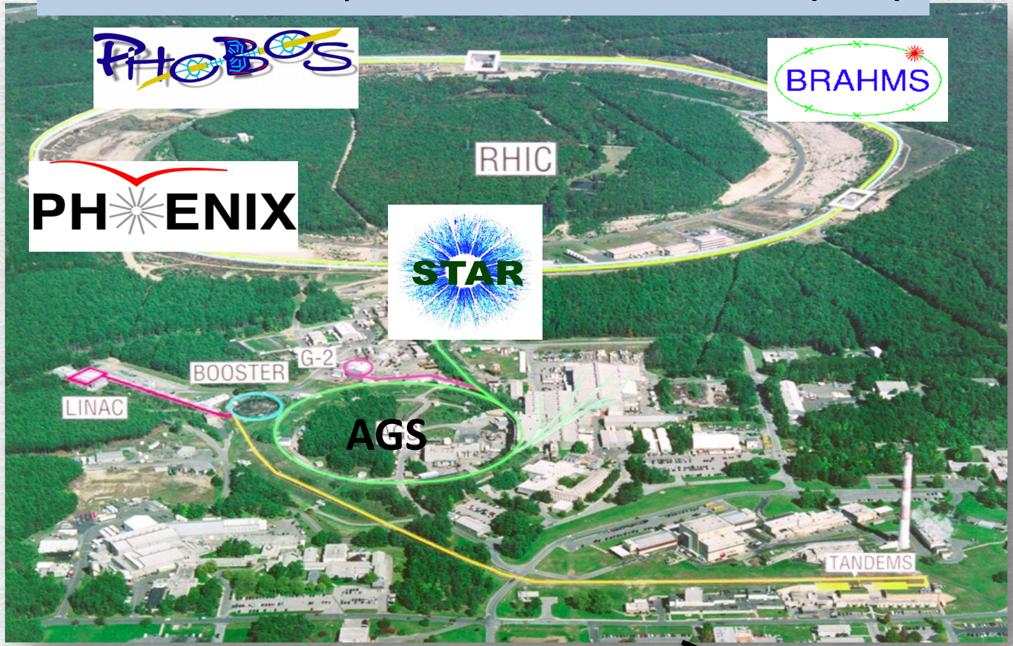
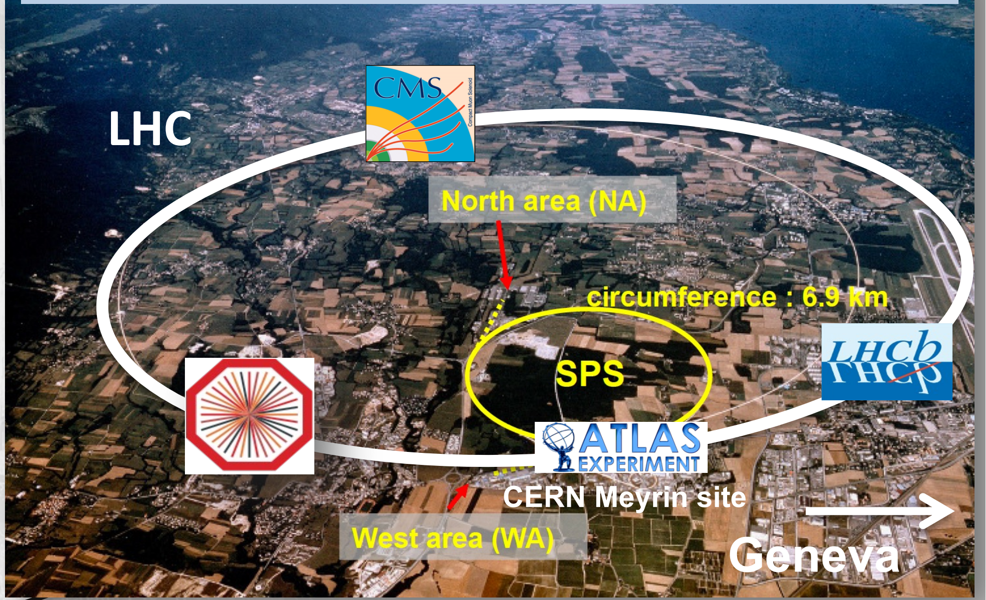


CERN SPS
- Operating since 1986
- Circumference 6.9 Km
- max p = 450 A/Z GeV
- $\sqrt{s_{NN}} < 20$ GeV
- Ongoing: NA61/Shine

Super Proton Syncrotron and Large Hadron Collider, CERN (Switzerland/France)



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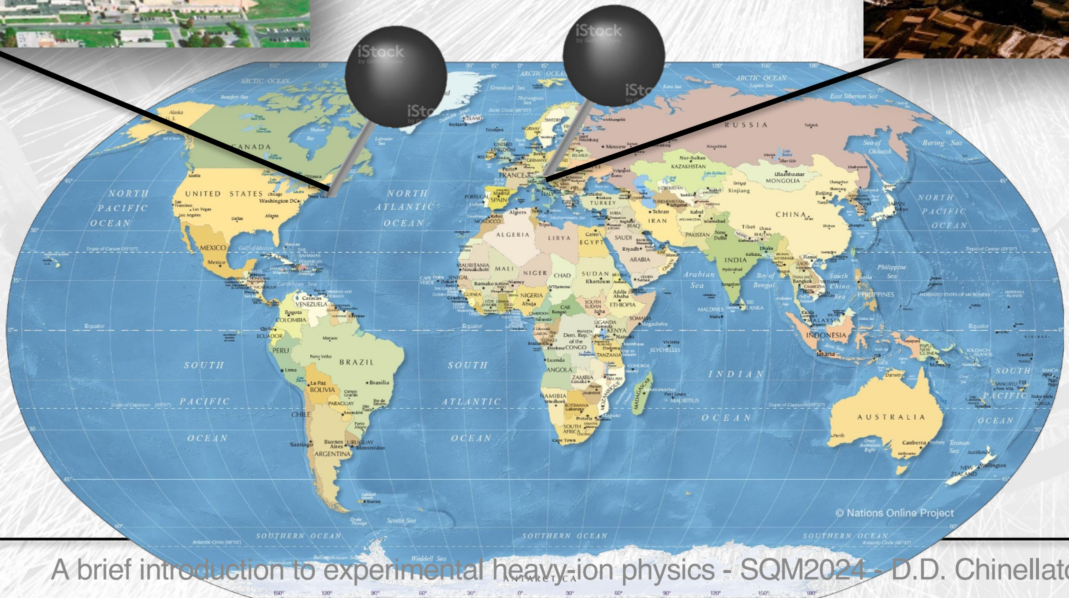
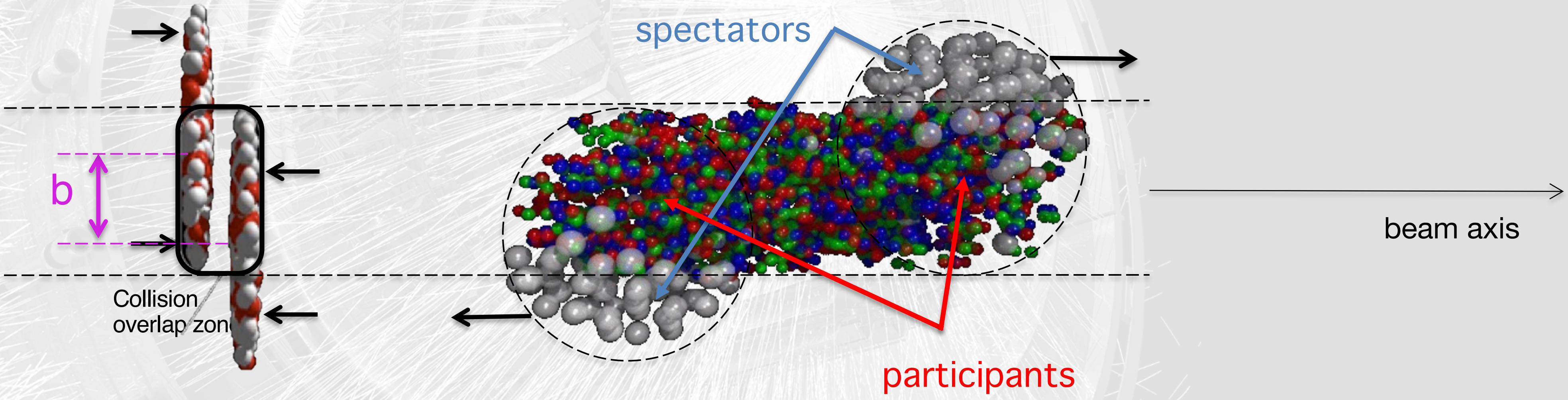


CERN LHC
- Operating since 2009
- Run III: started in 2022
- Circumference: 27 km
- B-field: 8 T, superconducting
- pp $\sqrt{s}$ = 0.9 – 13.6 TeV
- Pb-Pb $\sqrt{s_{NN}}$ = 2.76-5.5 TeV
- Main ongoing: ALICE, ATLAS, CMS, LHCb

Characterising a heavy-ion collision

We can control a posteriori the geometry of the collision by selecting in centrality.

Centrality = fraction of the total hadronic cross section of a nucleus-nucleus collision, typically expressed in percentile, and related to the impact parameter (b)

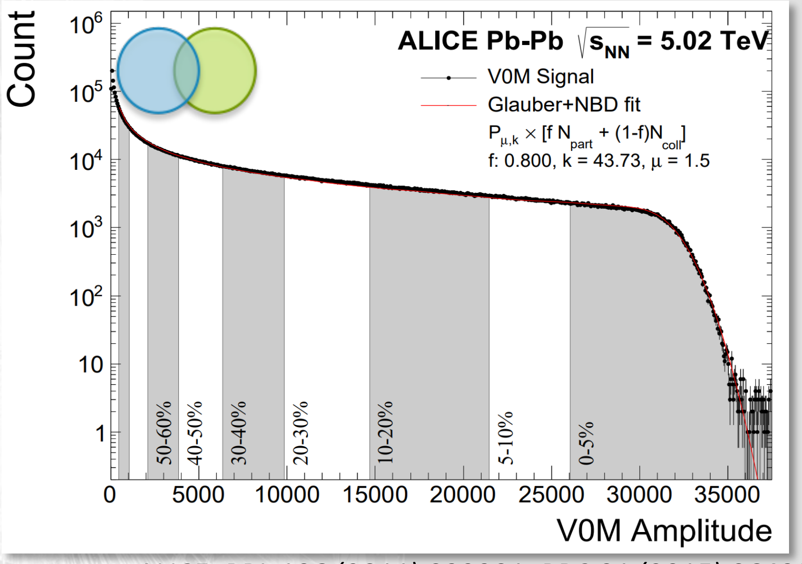


Other variables related to centrality:

- N_{coll}, number of binary nucleon-nucleon collisions
- N_{part} number of participating nucleons

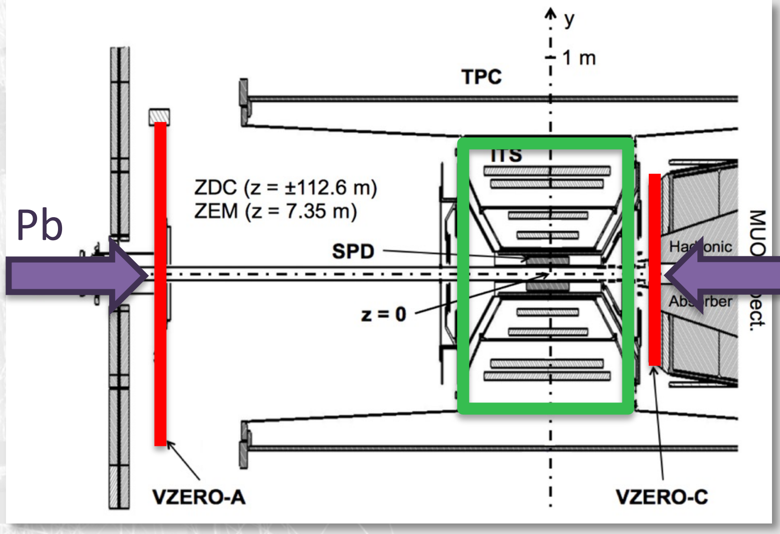
Centrality selection in heavy-ion collisions

More **central**, ie. “head-on” collisions
→ smaller impact parameter
→ larger overlap region
→ more participants
→ more particles produced



ALICE, PRL 106 (2011) 032301, PRC 91 (2015) 064905

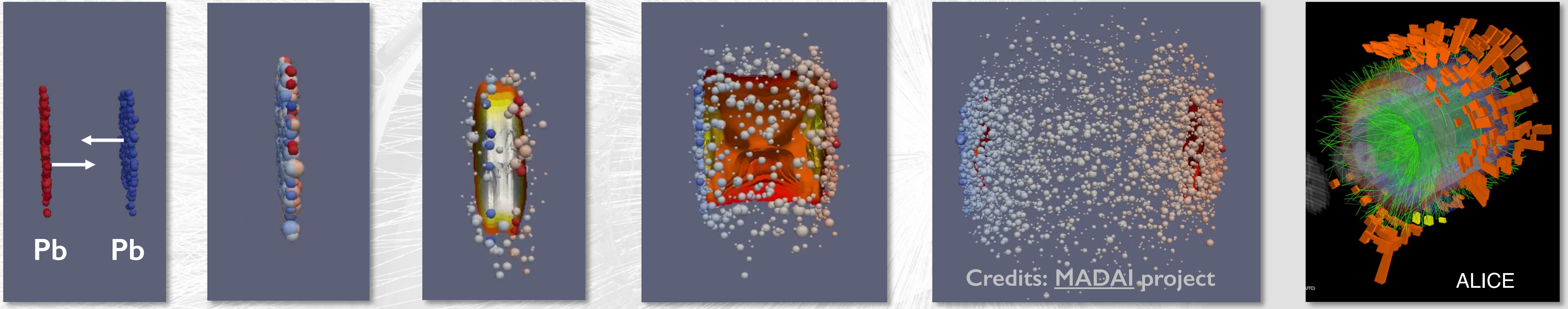
More **peripheral** collision
→ larger impact parameter
→ smaller overlap region
→ less participants
→ fewer particles produced



Centrality is determined by *counting the number of particles* (multiplicity) or *measuring the energy deposition* in a **region of phase space independent from the measurement**, to avoid biases/autocorrelations in the results.

The standard model of heavy-ion collisions

Initial state | Hard scatterings | QGP formation | Hydrodynamic expansion | Hadronization and freeze-out | Detection



Time: $\tau = 0$ → $\tau \sim 1$ fm/c → $\tau \sim 10$ fm/c → $\tau > 10$ pm/c

Temperature: T ~ 200-800 MeV [1] | T ~ 155-100 MeV [4]

$T_{c,\,lQCD} \sim$ 155-159 MeV [2,3]

No direct observation of the QGP is possible
→ rely on emerging particles as "probes"

[1] F. Gardim et al. Nature Phys. 16 (2020) 6, 615-619
[2] A. Bazavov et al., Phys. Lett. B 795 (2019)
[3] Borsaniy et al. PRL 125 (2020) 5, 052001
[4] A. Andronic et al., Nature 561 (2018) 7723, 321-330

The hadron gas phase and freeze-outs

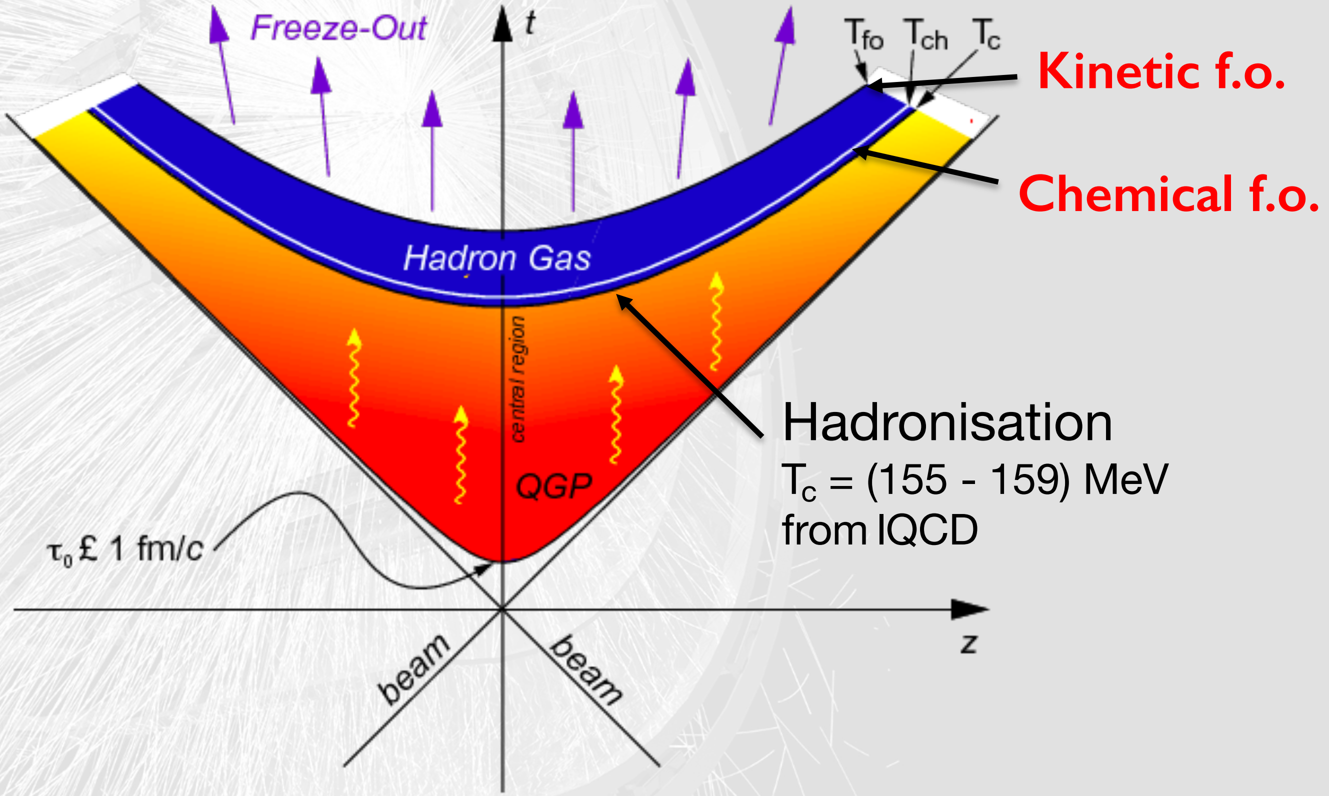
After hadronisation, the system is a hot (T< 155 MeV) and dense gas of hadrons and resonances.

Chemical freeze-out

- Inelastic collisions stop
- Relative particle abundances are fixed

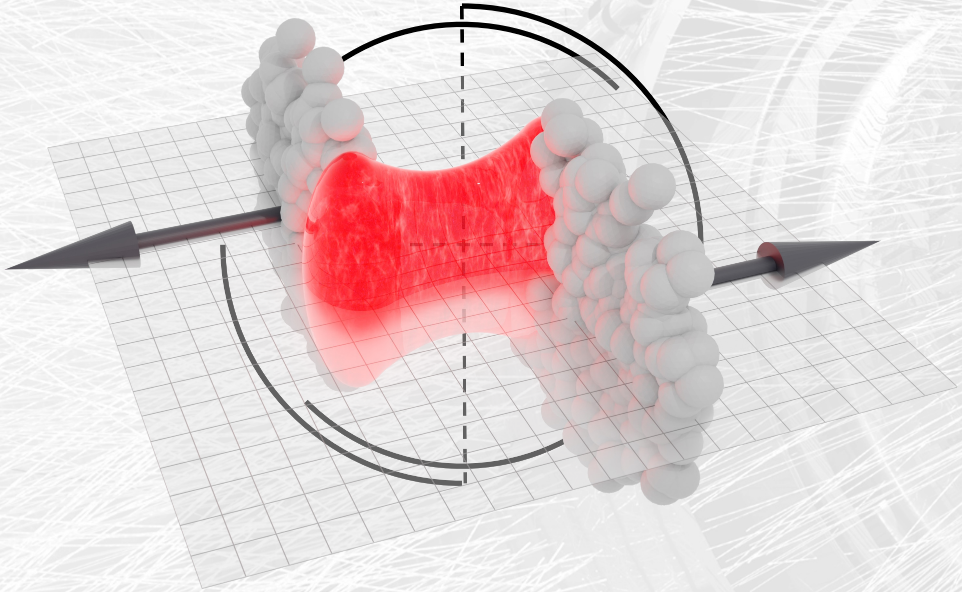
Kinetic freeze-out

- (pseudo)elastic collisions stop
- Momentum distributions are fixed



The “standard model” of quark-gluon plasma physics:

Key experimental features of a QGP in the soft sector



Soft regime:

non-perturbative, low p_T (a few GeV/c) physics

Information regarding hard scatterings mostly not recoverable / not relevant

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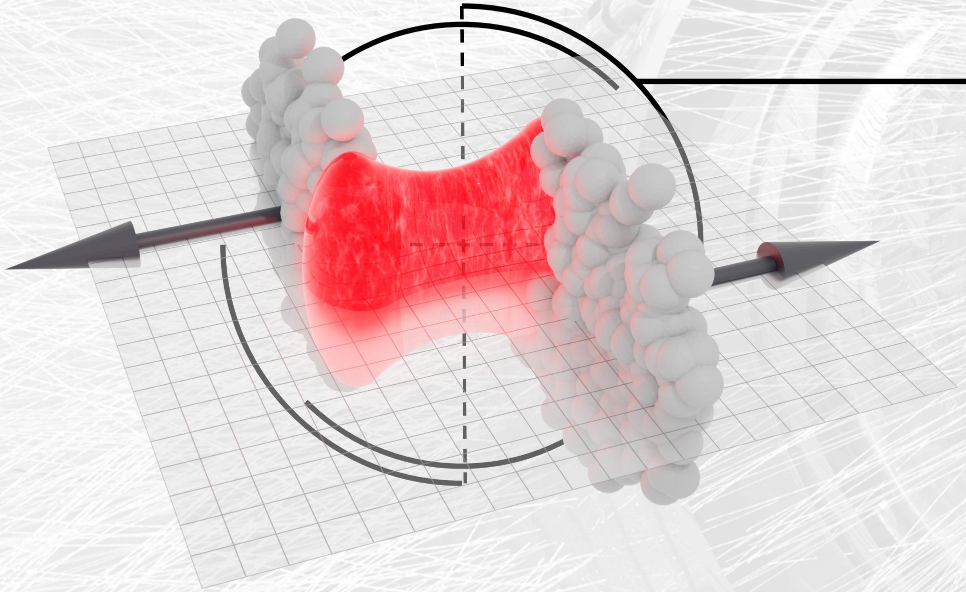

Thermal particle production

- Particle species are determined exclusively due to mass and quantum numbers of each species (‘thermal’ chemical/species spectrum)
- The proportion of states (species) conveys information about basic thermodynamic properties of the system, such as temperature
- Broadly measured via **identified particle yield measurements**
- Broadly described via statistical hadronization models (‘thermal models’)

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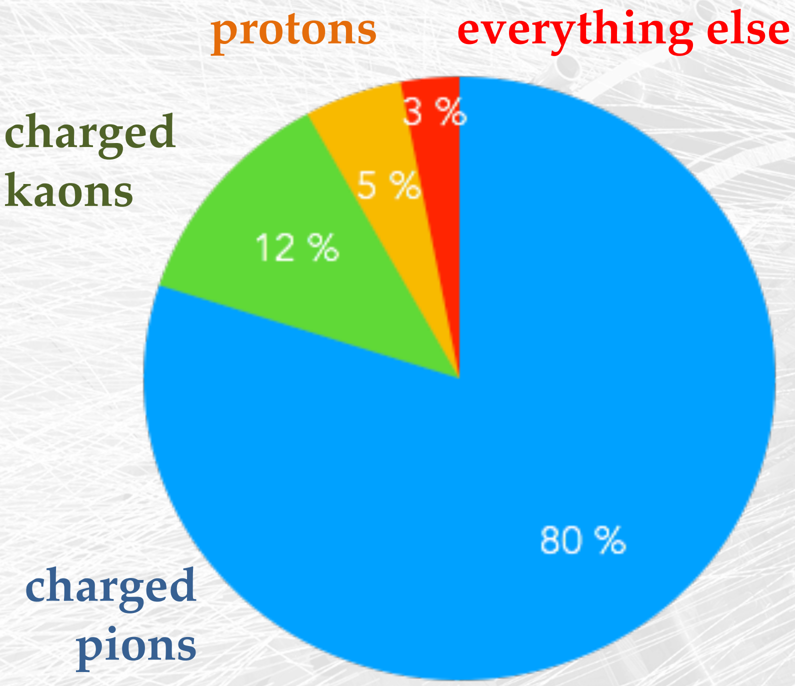
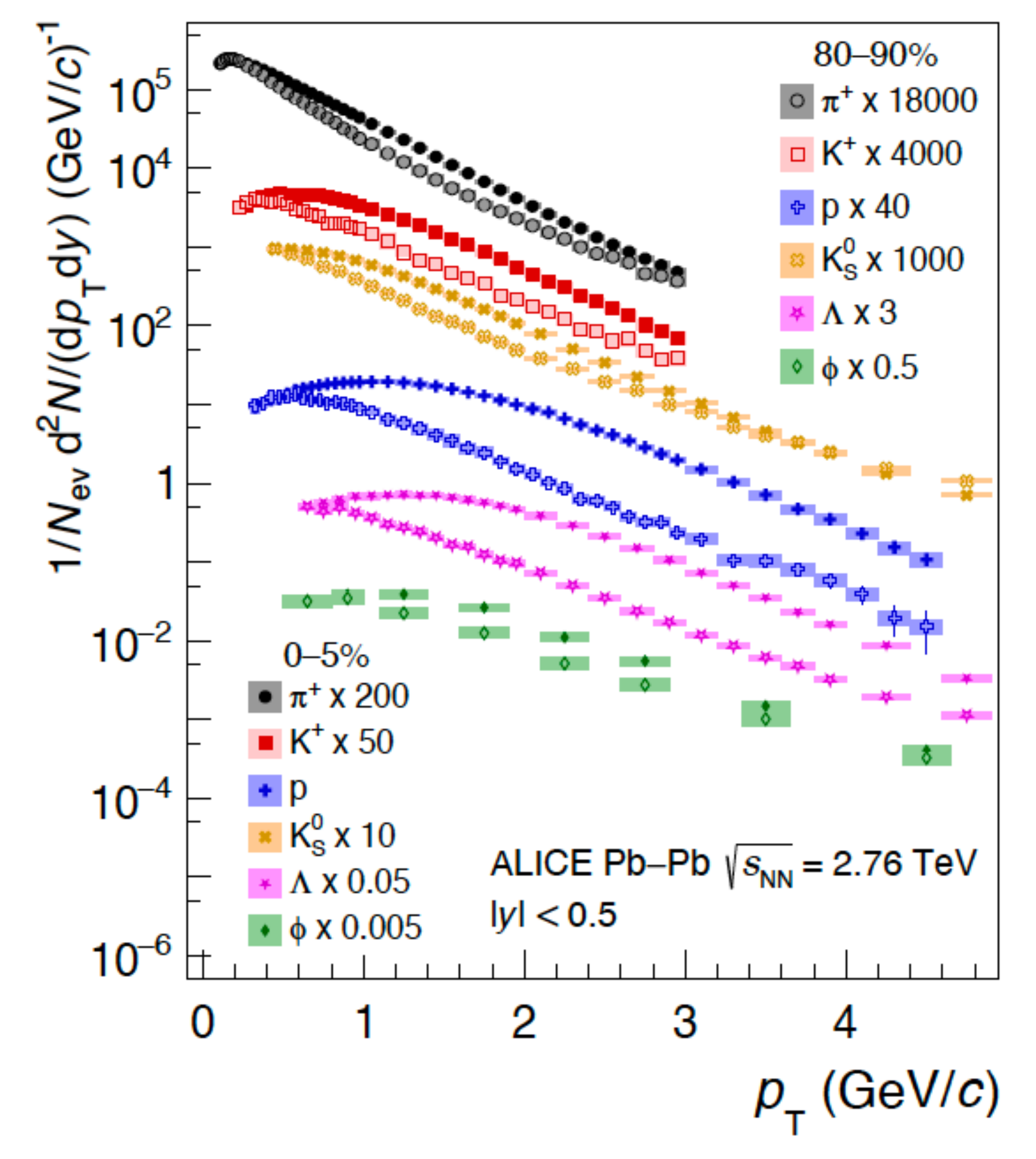
Measuring identified particle production rates





π., K and p are the most abundant hadronic species produced in the collision
→ Integrate $d^2N/(dydp_T)$ spectra over p_T to extract yields: dN/dy.

(N.B.: "dy" often denotes measurments at |y|<0.5)

Thermal particle production: statistical hadronization models

… serve to model an ideal relativistic gas of hadrons and resonances in **chemical equilibrium** (as the result of the hadronization of a QGP in thermodynamical equilibrium)

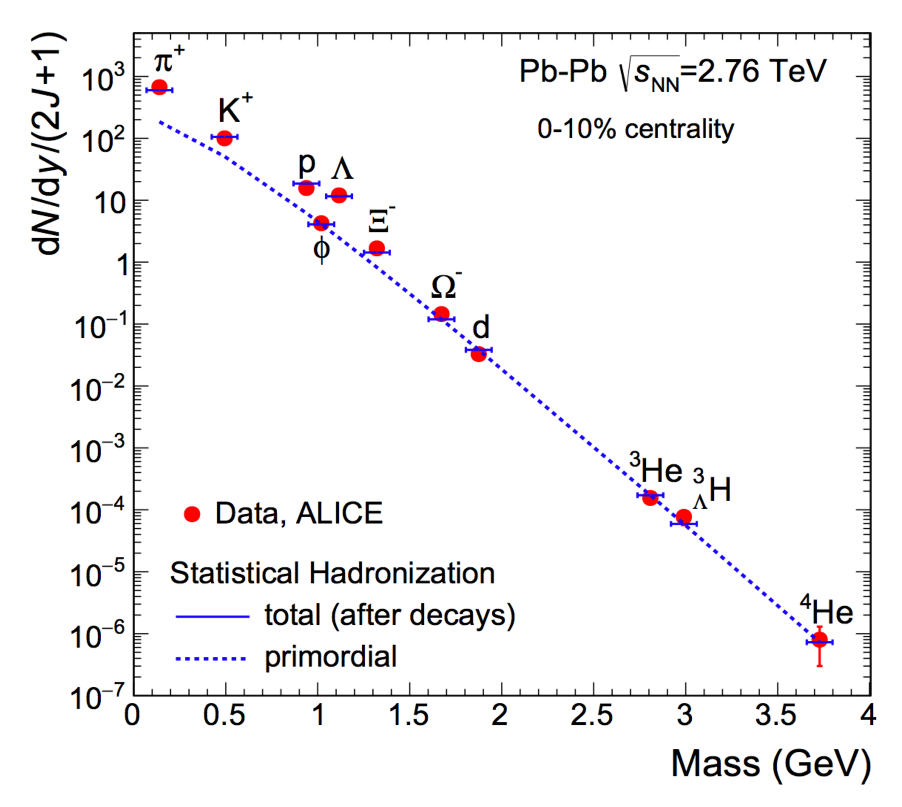
Particle abundances are obtained from the partition function of a Grand Canonical (GC) ensemble

$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i-\mu_i)/T]\pm 1}$$

where chemical potentials for quantum numbers are constrained with conservation laws.

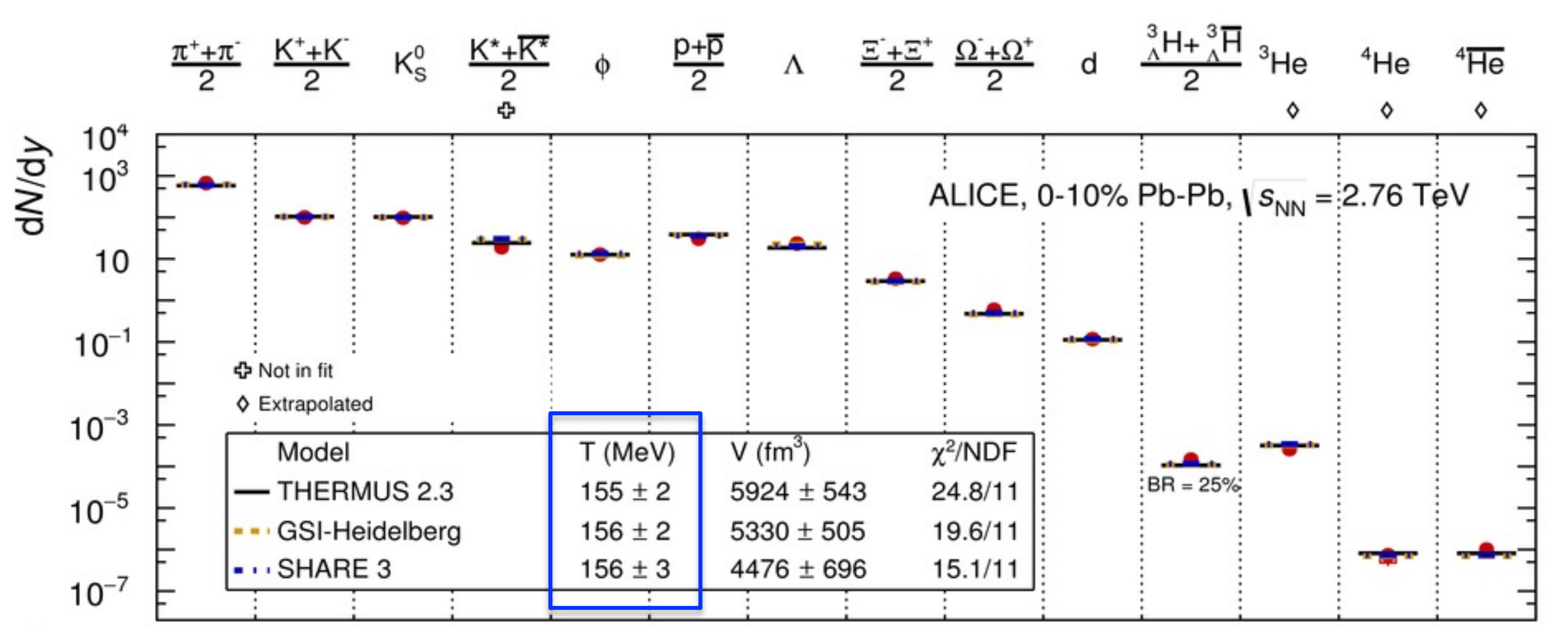
$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_{3,i} + \mu_C C_i$$

- ❑ Predict yields (see right figure) at a given temperature
- ❑ Fit measured particle yields (or ratios) to extract μ_B, T_{ch}, V.



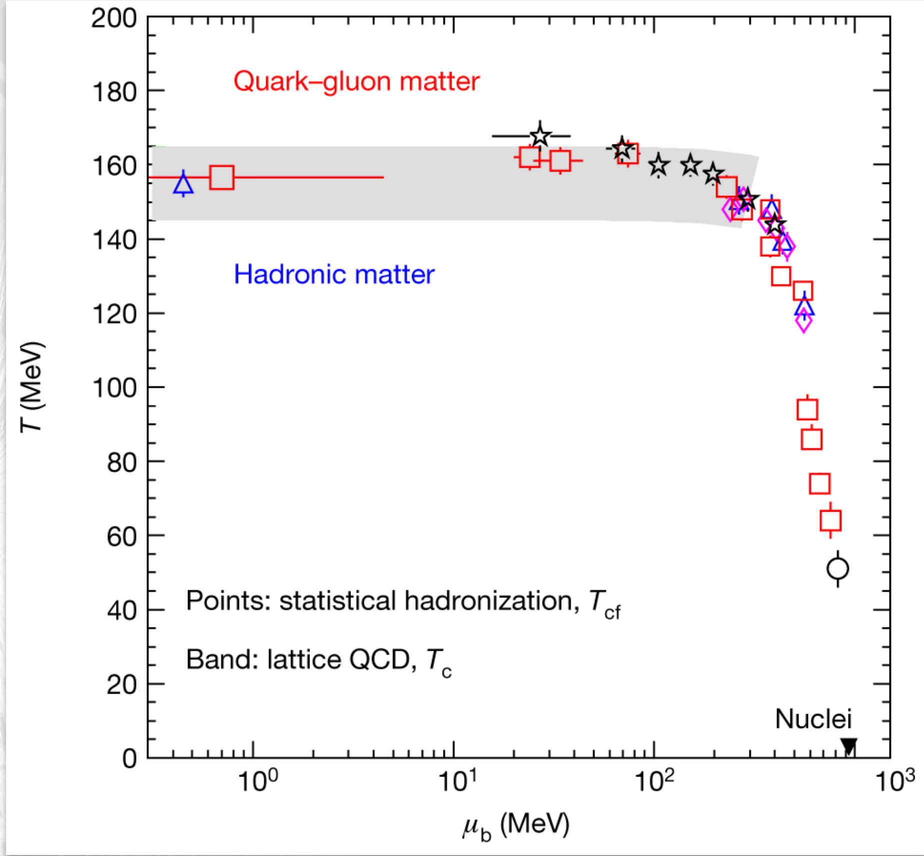
A. Andronic et al., Nature 561, 321 (2018

Chemical freeze-out temperature



Model	T (MeV)	V (fm^3)	χ^2/NDF
THERMUS 2.3	155 ± 2	5924 ± 543	24.8/11
GSI-Heidelberg	156 ± 2	5330 ± 505	19.6/11
SHARE 3	156 ± 3	4476 ± 696	15.1/11

Nature volume 561, pages 321–330 (2018)

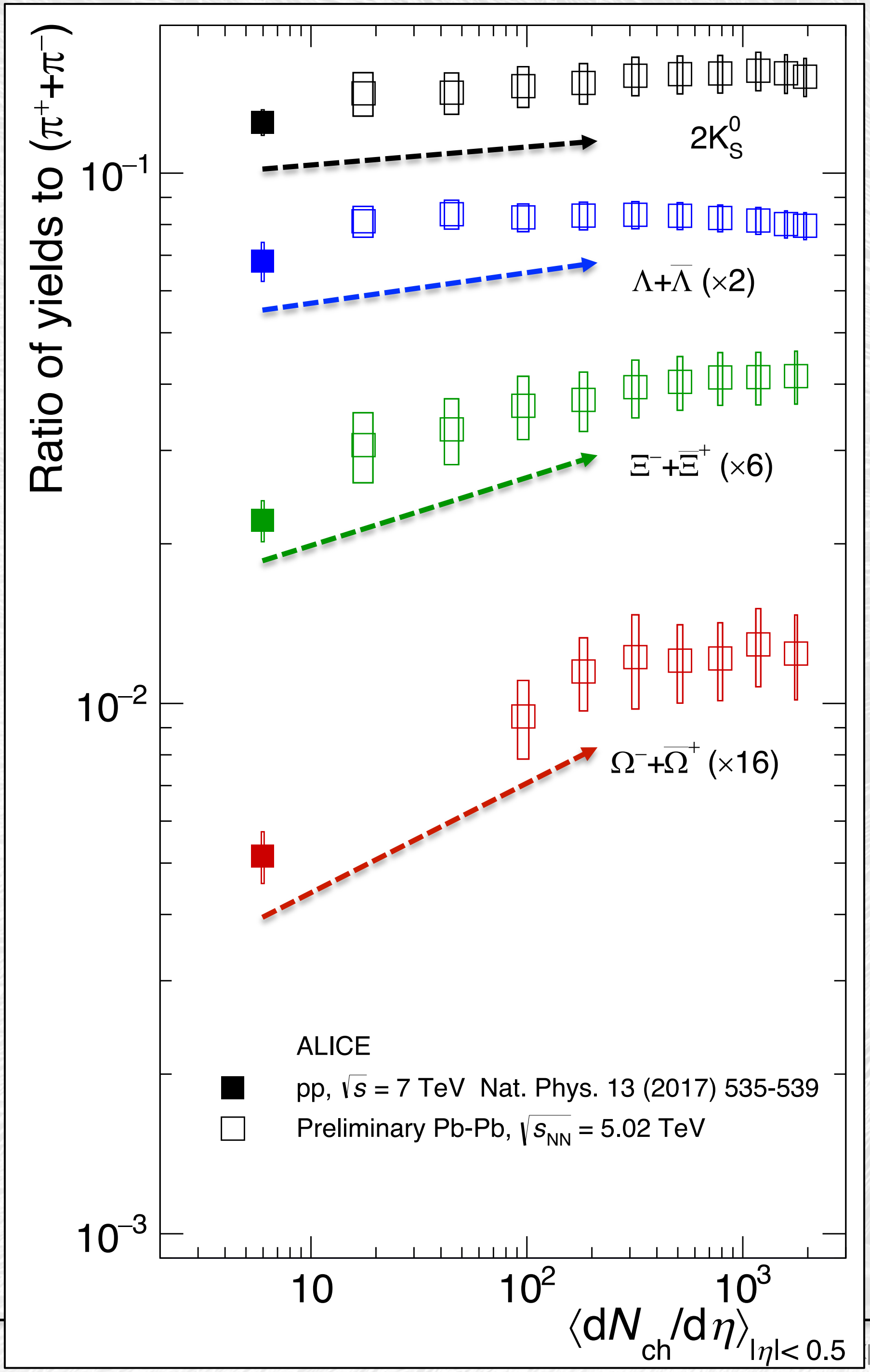


Production of (most) light-flavour hadrons (and anti-nuclei) is described (χ^2/ndf ~ 2) by thermal models with a single chemical freeze-out temperature, **T_{ch} ≈ 156 MeV**

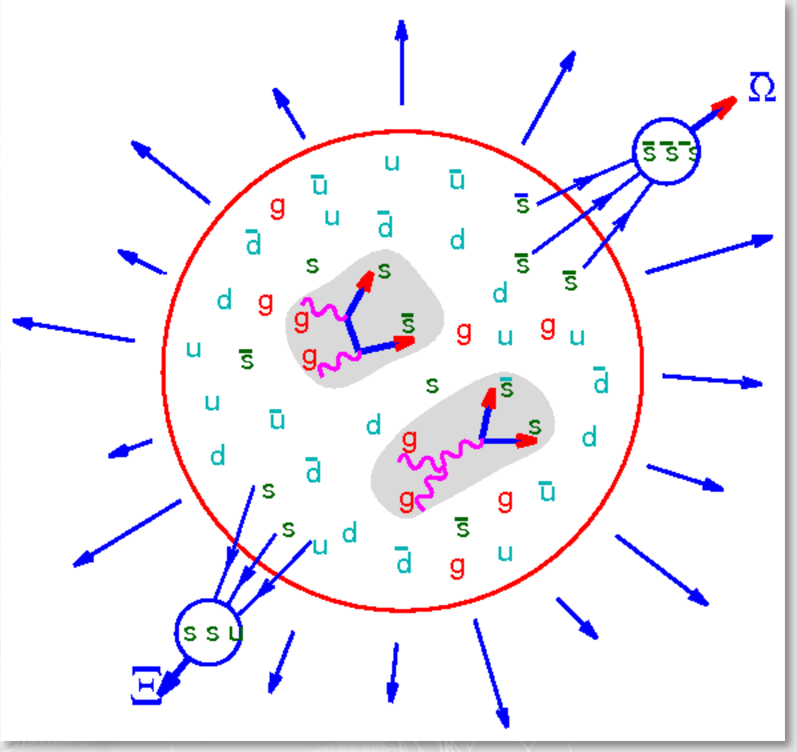
→ Approaches the critical temperature roof from lattice QCD: limiting temperature for hadrons!

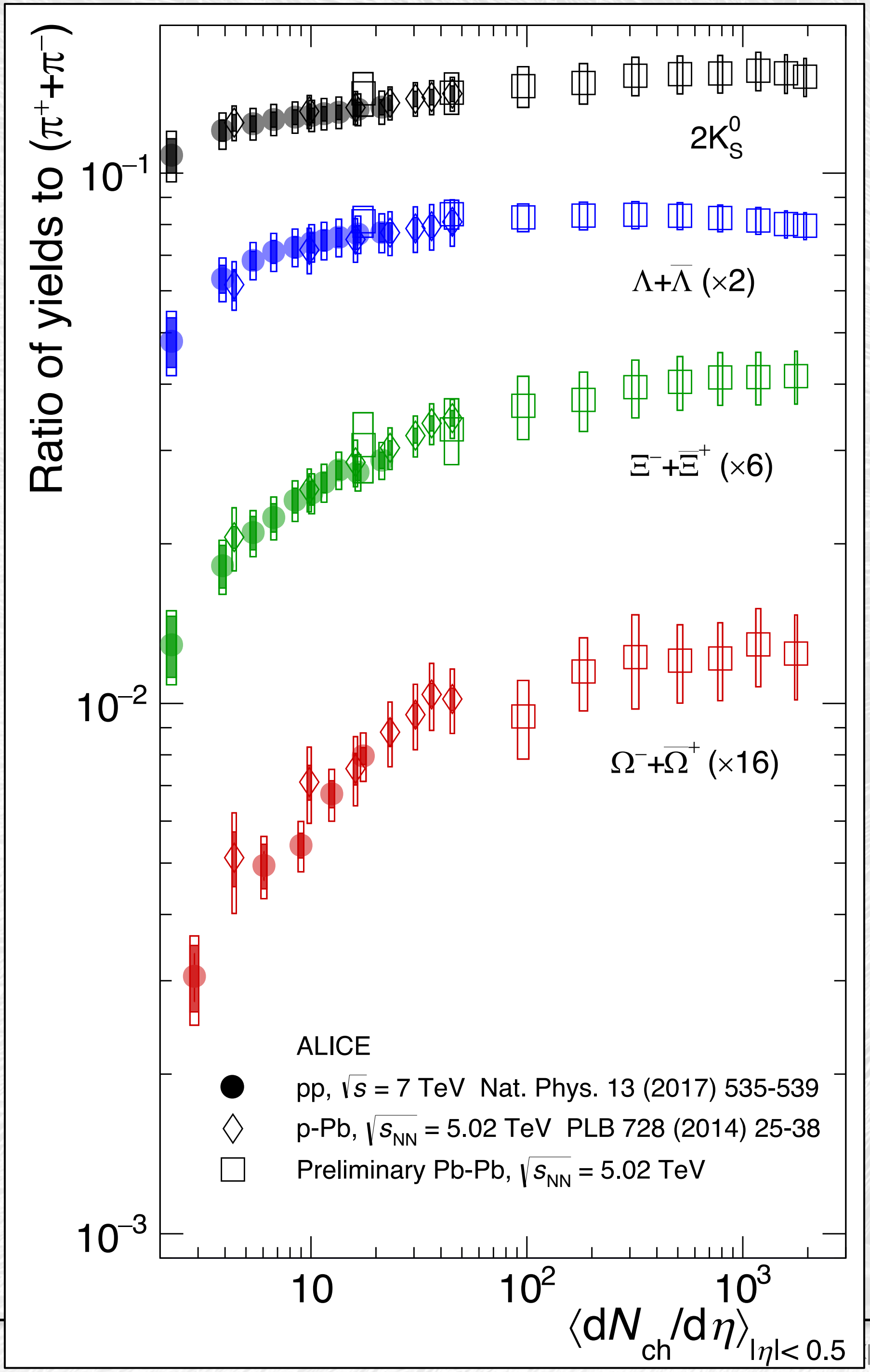
→ the success of the model in fitting yields over 10 orders of magnitude supports the picture of a system in local thermodynamical equilibrium

Strangeness production



- One of the original traces of the QGP
  - Thermal production via gluon fusion in a QGP scenario
- K^0_S, Λ (1s), Ξ (2s) and Ω (3s) in Pb-Pb at 5.02 TeV:
  - Production wrt to π enhanced





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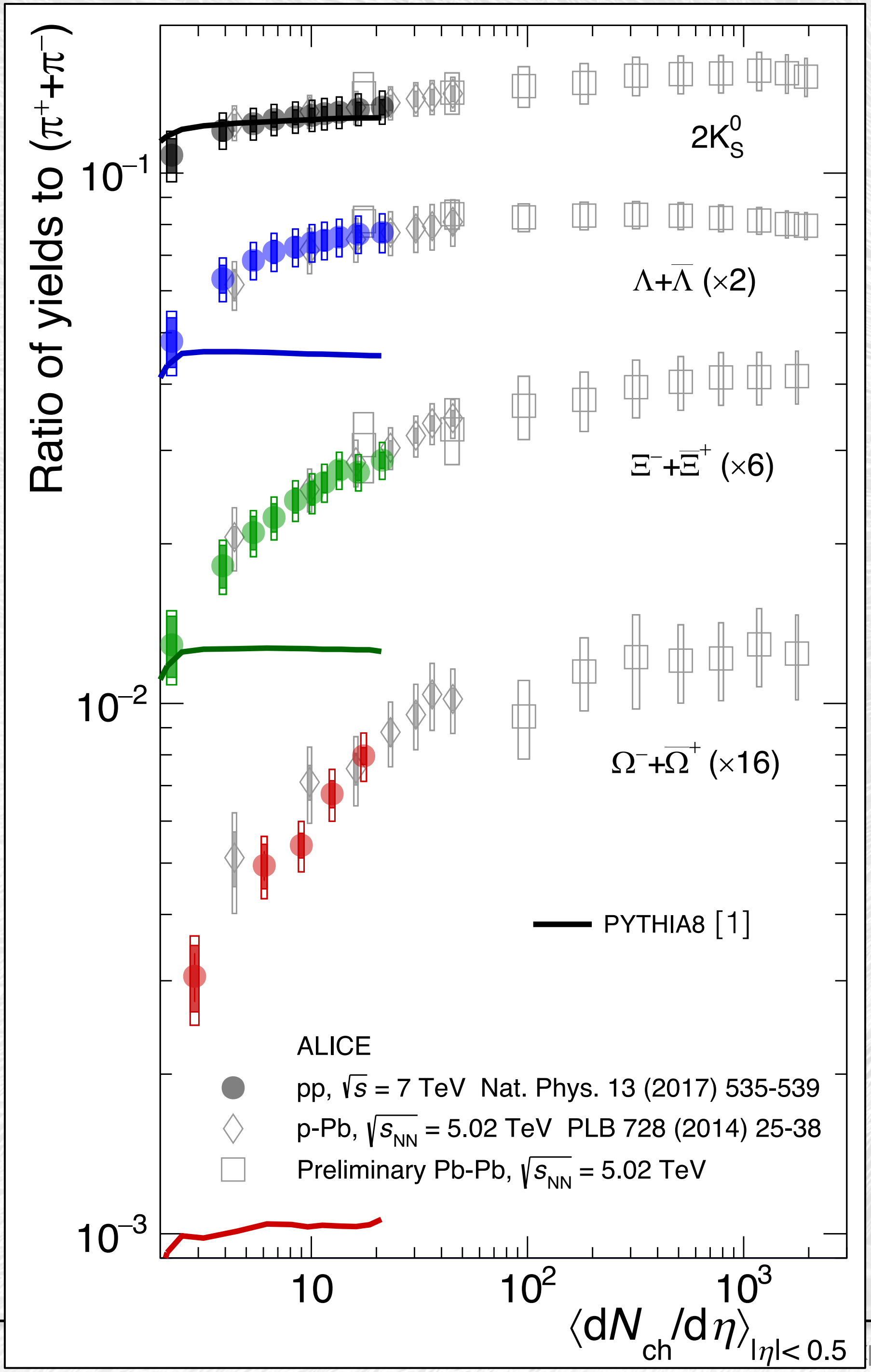
- Also studied in p-Pb and pp
  - Strangeness increases with multiplicity: a universal trend!



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  - Strangeness increases with multiplicity: a universal trend!
- Not described by event generators when published

A major milestone from the past decade in the understanding of high-density QCD physics

[1] Comput. Phys. Commun. 178 (2008) 852–867

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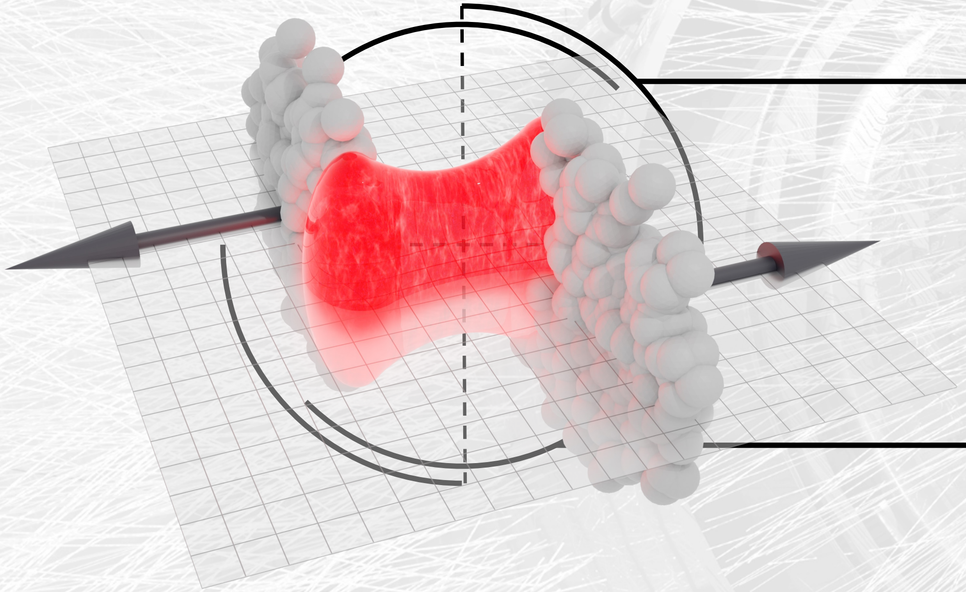

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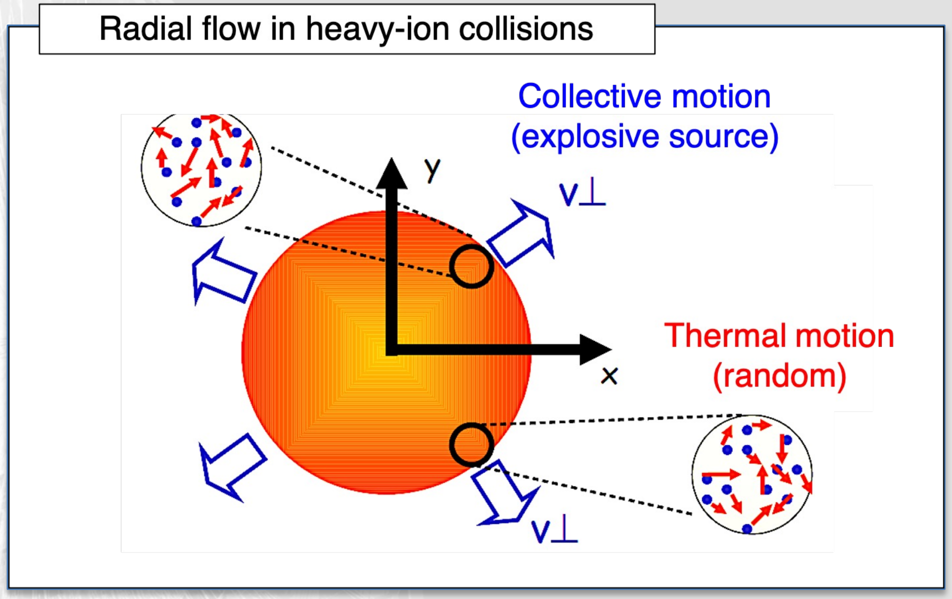
Collectively expanding medium

- The formation of a new state of strongly interacting matter will lead to many particles emitted with common properties (‘collectively’)
- The intensity of collective expansion encodes properties of the medium, e.g. energy density ⇆ pressure
- Broadly measured via **momentum measurements**
- Broadly described via hydrodynamic expansion models (‘hydro’), particle transport models

A collectively expanding fluid: radial flow

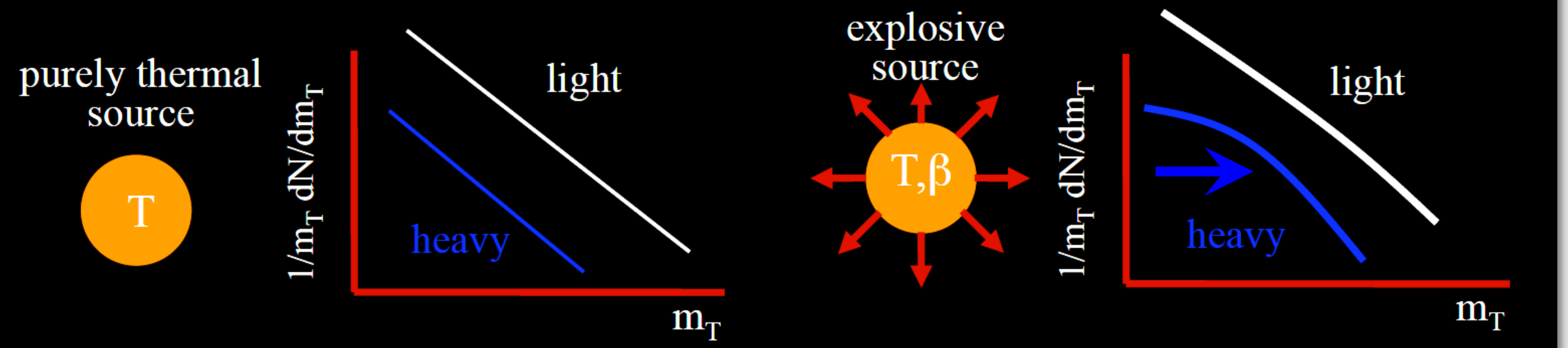
A **collective motion** is superimposed to the thermal motion of particles ⟶ the system as a **medium**

Radial flow: radial expansion of a medium in the vacuum under a common velocity field
⟶ Affects the low p_T distribution of hadrons and their ratios in a mass-dependent way
⟶ higher mass leads to higher momentum if velocity similar!



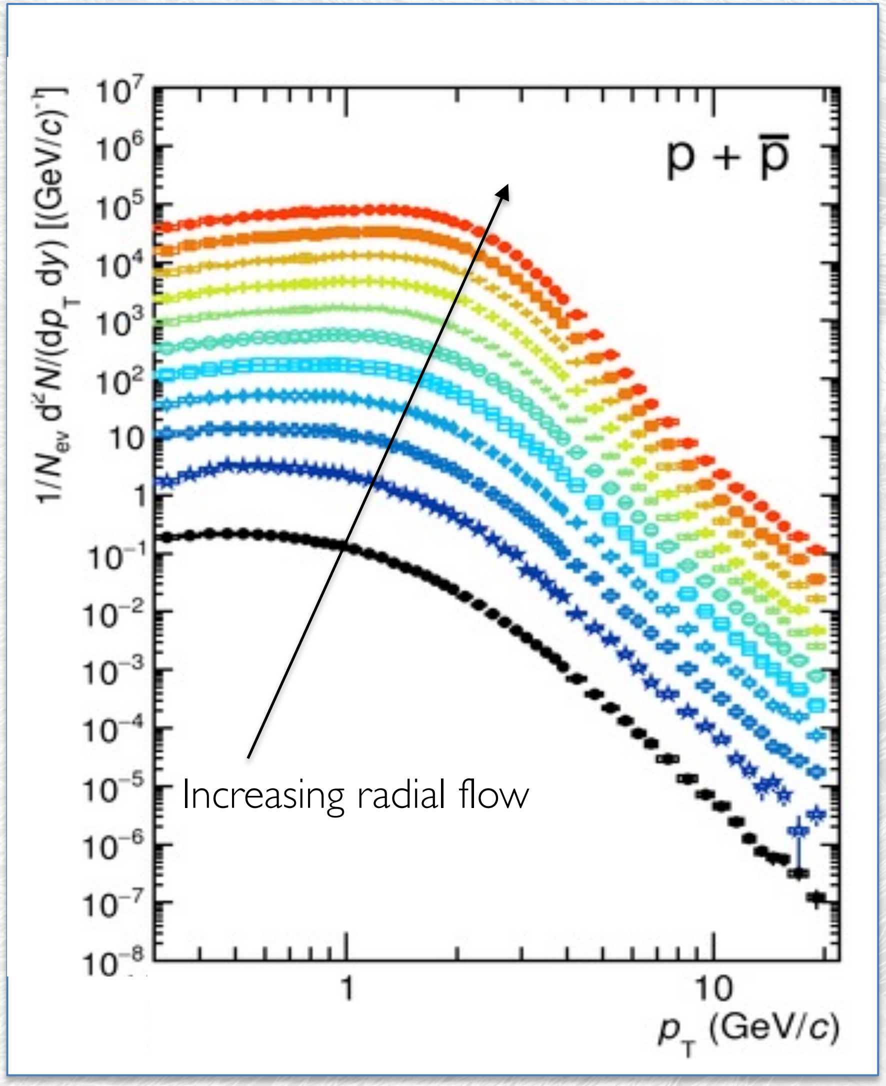
$$m_T = \sqrt{(m^2 + p_t^2)}$$

$$\frac{dN}{m_T dm_T} \propto e^{-m_T/T}$$



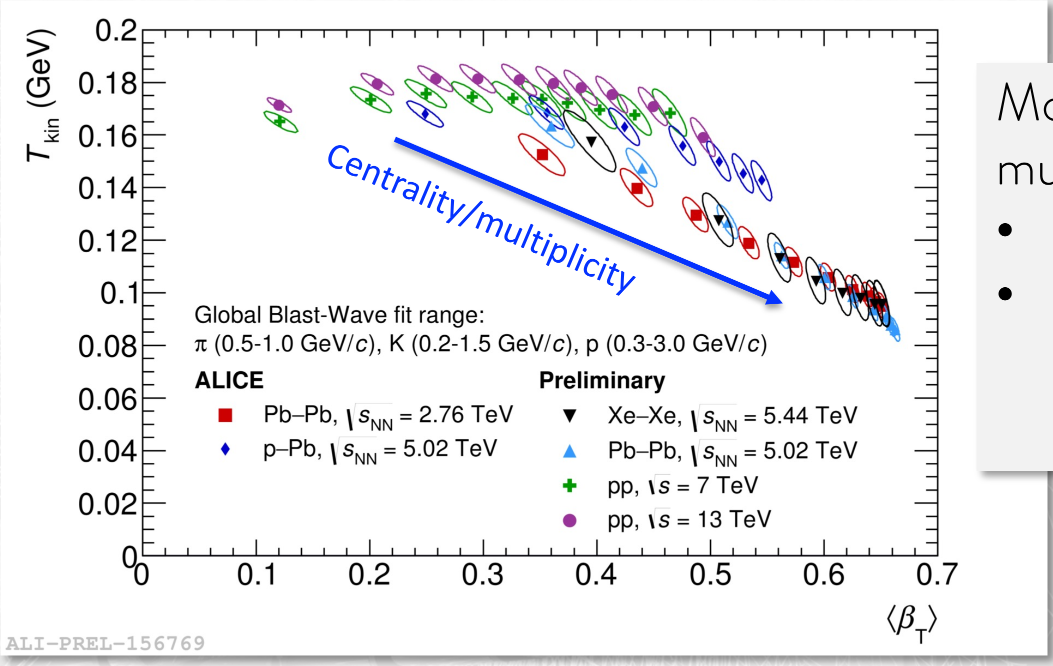
R. Snellings

Radial flow in the proton spectra



At low p_T, radial flow "pushes" particles to higher momenta
→ spectra get "harder" for more central collisions
→ mass dependence

A simplified hydrodynamical model, the Boltzmann-Gibbs blast-wave model is used to **quantify radial flow and the kinetic freeze-out temperature.**



More central (higher multiplicity) events have:

- lower T_{kin}
- higher flow velocity

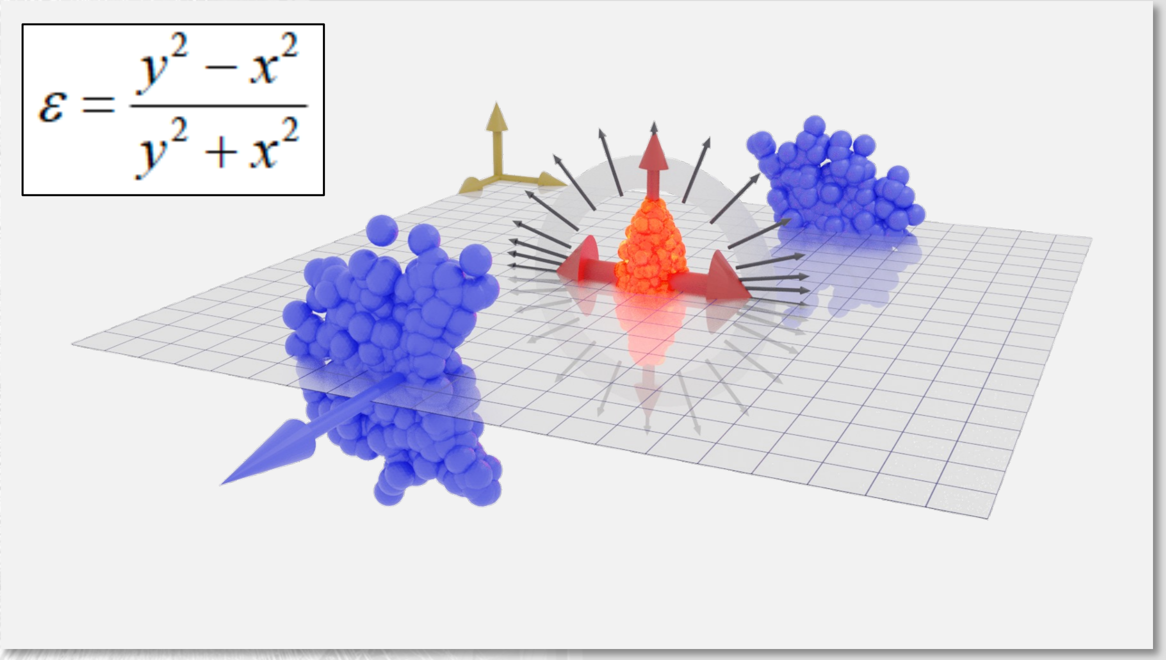
T_{kin} ~ 100-140 MeV

An expanding medium and anisotropic flow

Initial geometrical anisotropy (”almond” shape) in non-central HI collisions → eccentricity

Pressure gradients develop → more and faster particles along the reaction plane than out-of-plane

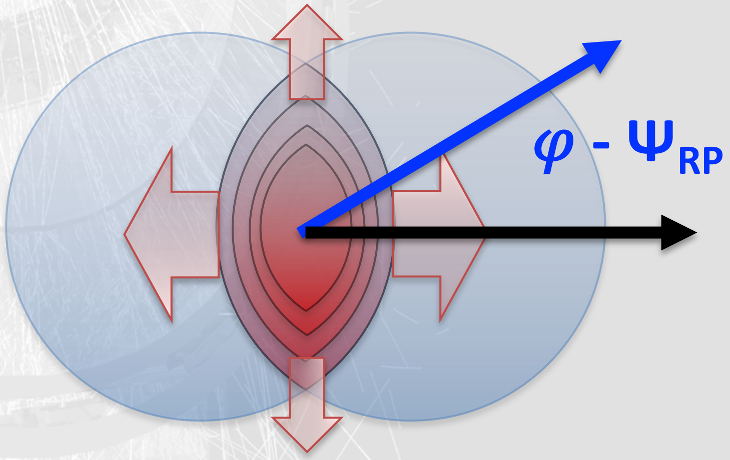
Scatterings among produced particles convert anisotropy in coordinate space into an observable momentum anisotropy
→ anisotropic flow
→ quantified by a Fourier expansion in azimuthal angle φ



$$\varepsilon = \frac{y^2 - x^2}{y^2 + x^2}$$

v_n = **harmonics**

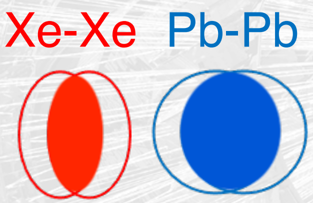
$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]\right),$$



Anisotropic flow measurements

The **strong centrality dependence** of v_2 reflects the degree of "anisotropy" in initial geometry.

Fluctuations of the initial state energy-density lead to different shapes of the overlap region
→ non-zero higher-order flow coefficients ("harmonics")



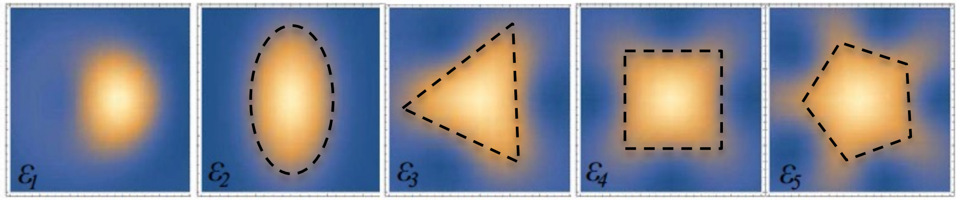
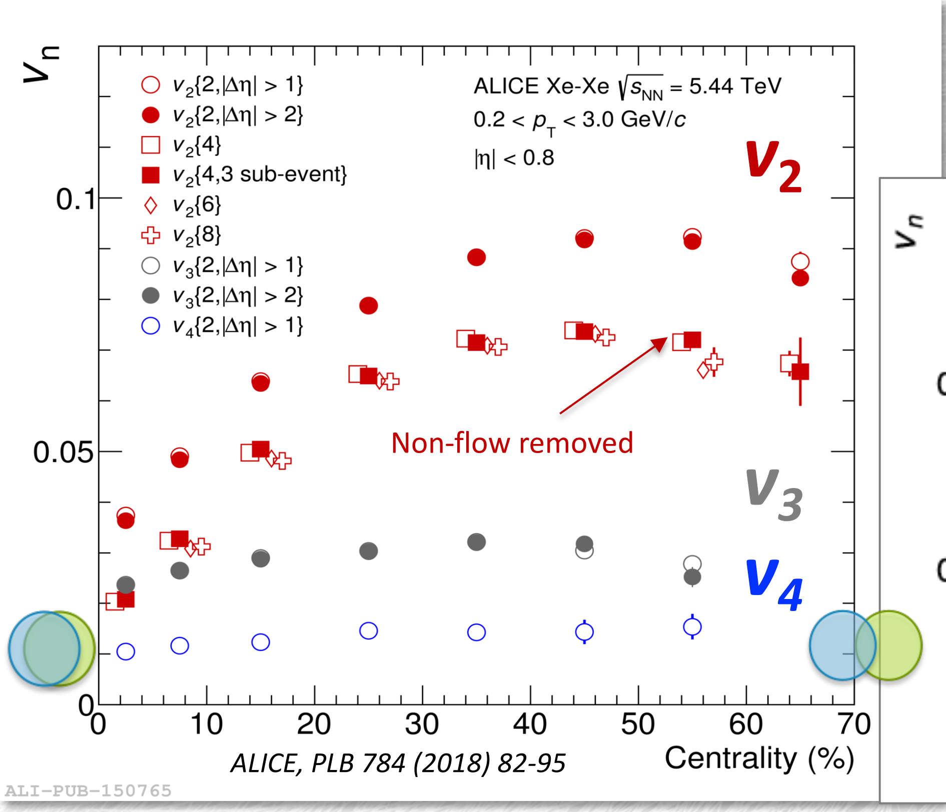
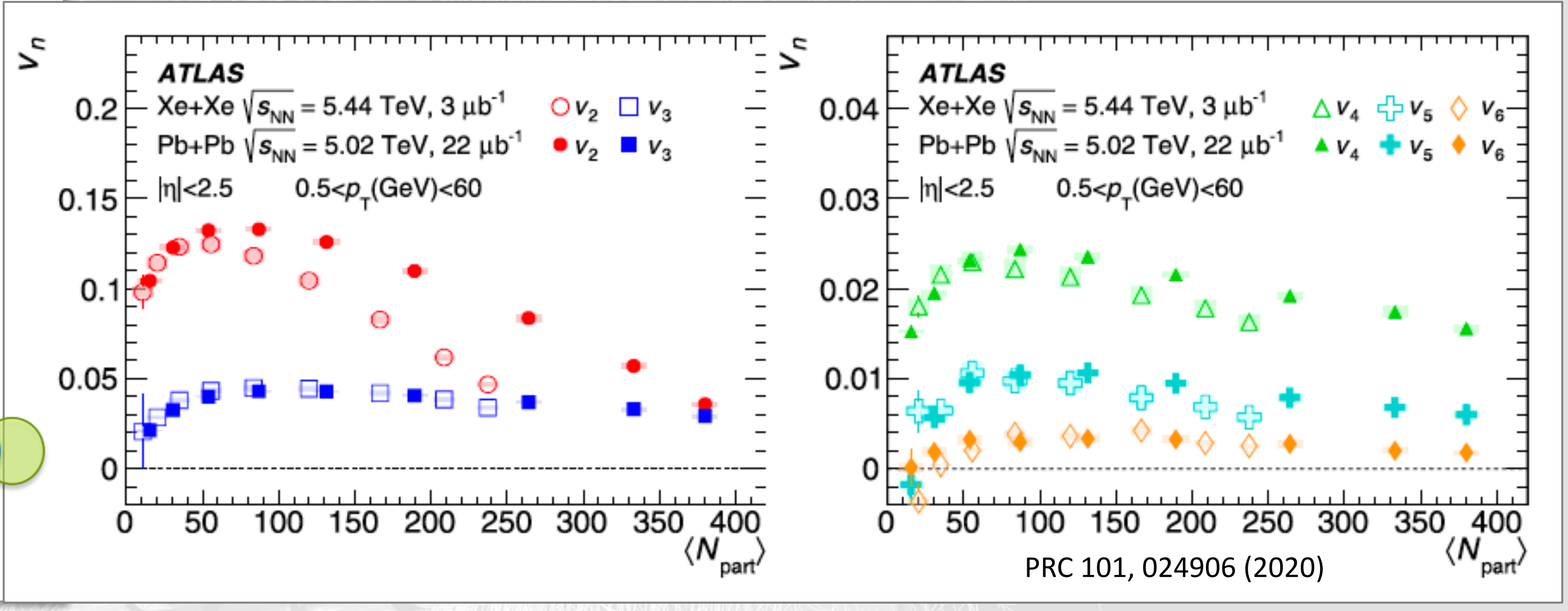


Fig. 2. (color online) Characteristic shapes of the deformed initial state density profile, corresponding to anisotropies of $\mathcal{E}_1$, $\mathcal{E}_2$, $\mathcal{E}_3$, $\mathcal{E}_4$ and $\mathcal{E}_5$ (from left to right). Li Yan 2018 Chin. Phys. C 42 042001





Hydrodynamical modeling

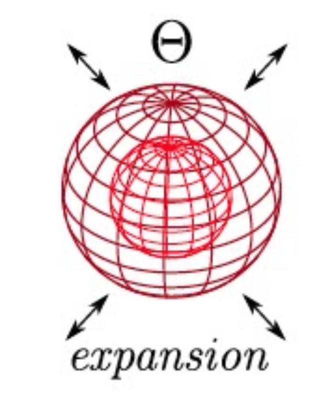
Ideal hydrodynamics

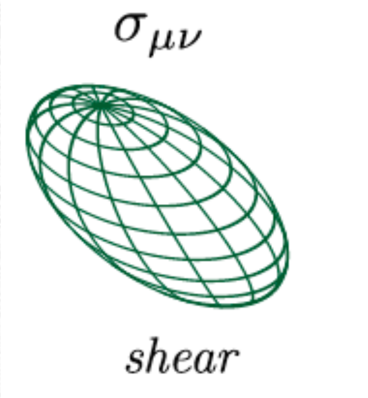
- applies to a system in local equilibrium (e.g. thermodynamical)
- requires energy and charge conservation
- system is described by energy density $\boldsymbol{\varepsilon}$, pressure P, velocity u^ν, and charge n and by 5 equation of motion, closed by one equation-of-state (EOS) $\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}(P)$
- The response of the system to external influence is controlled by the EOS

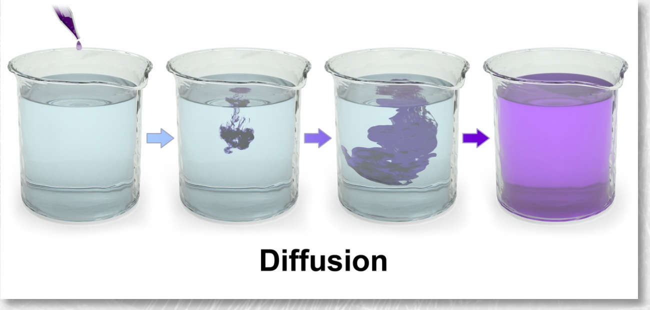
Viscous hydrodynamics

- Includes corrections for dissipative effects:
  bulk ζ and shear viscosity η, charge diffusion, κ

$$\nabla_\mu T^{\mu\nu} = 0 \qquad \nabla_\mu J^\mu_B = 0$$







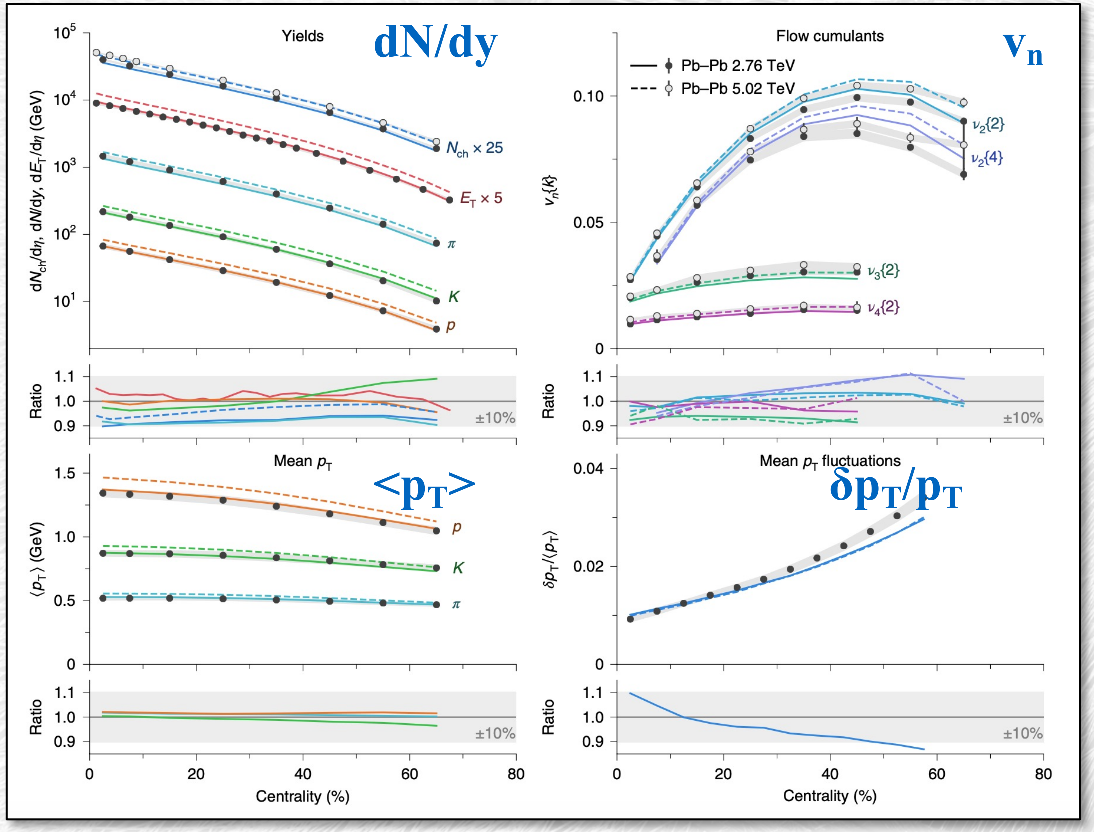
Figs. from Rezzolla and Zanotti, 2013

$$T^{\mu\nu} = \epsilon u^\mu u^\nu - (P - \zeta\Theta)\Delta^{\mu\nu} - 2\eta\sigma^{\mu\nu}$$

$$J^\mu = q u^\mu + \kappa \nabla^\mu_\perp (\mu/T)$$

Characterizing the QGP using multiple measurements

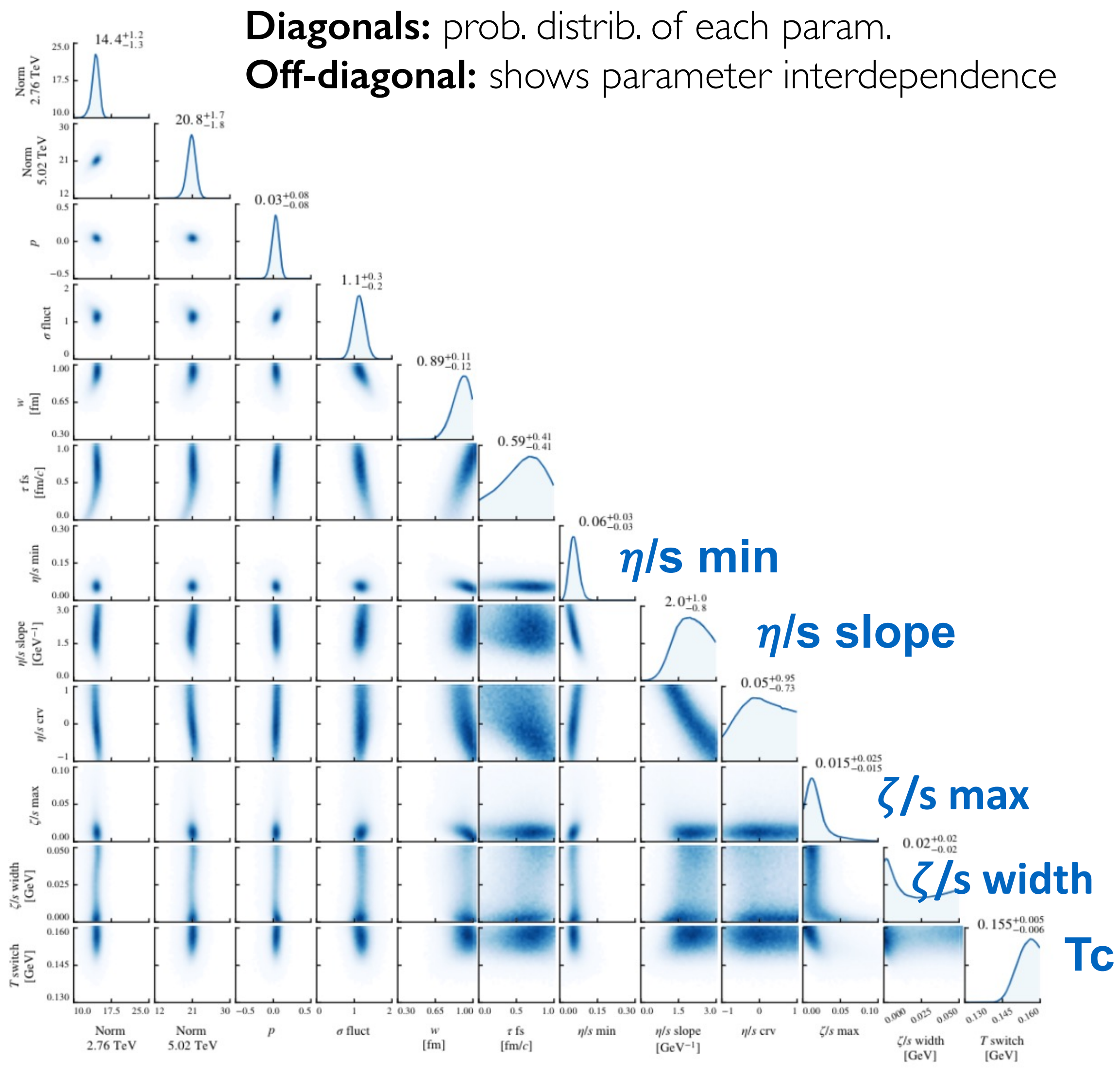
Bayesian analysis of yields, mean p_T, flow harmonics measured by ALICE has been used to **extract QGP properties**



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

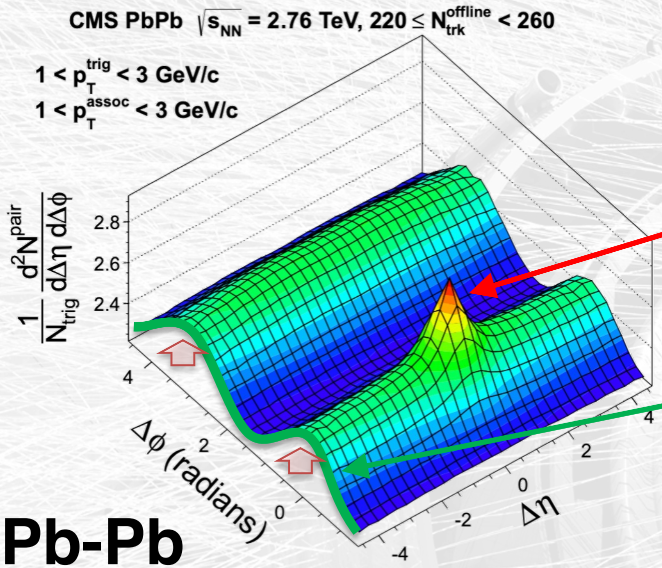
S.A. Bass et al. / Nuclear Physics A 967 (2017) 67–73

Diagonals: prob. distrib. of each param.
Off-diagonal: shows parameter interdependence



Elliptic flow across systems

Phys. Lett. B 724 (2013) 213



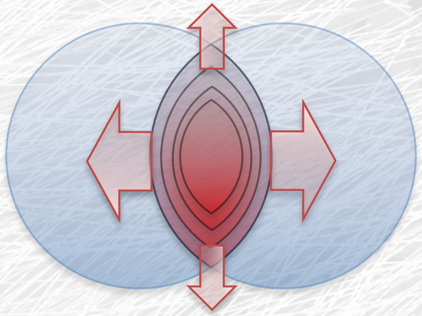
Pb-Pb

Peak at $\Delta\eta$ ~ 0:

- **short-range** correlations → **jets**

Broad "ridge" in a wide $\Delta\eta$ range:

- **long-range** correlations emerging from early times (causality) → anisotropic **flow**

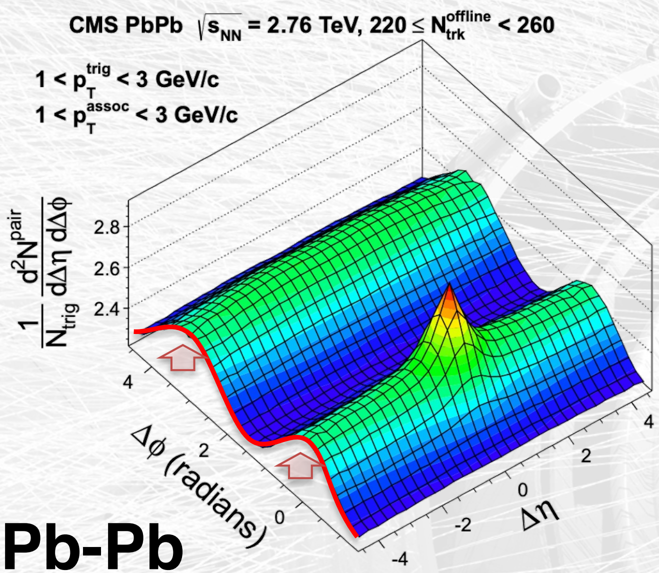


Collective expansion

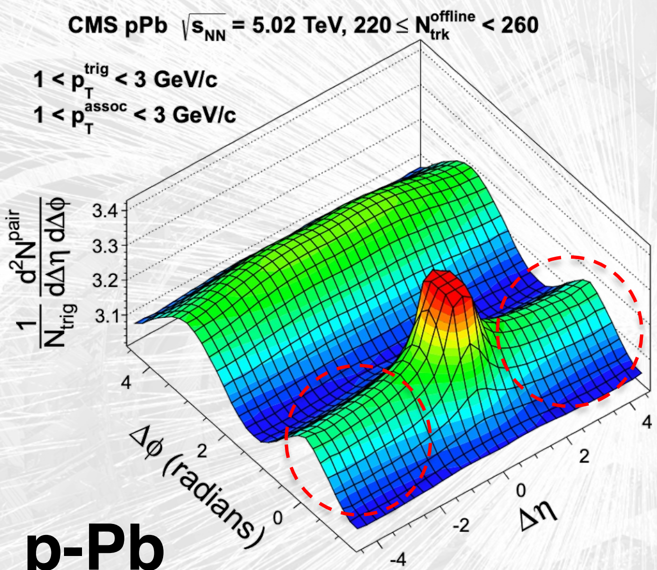
- Collective expansion can also be measured by correlating two particles in $\Delta\eta$ (difference in rapidity) and $\Delta\varphi$ (difference in azimuthal angle).

Elliptic flow across systems

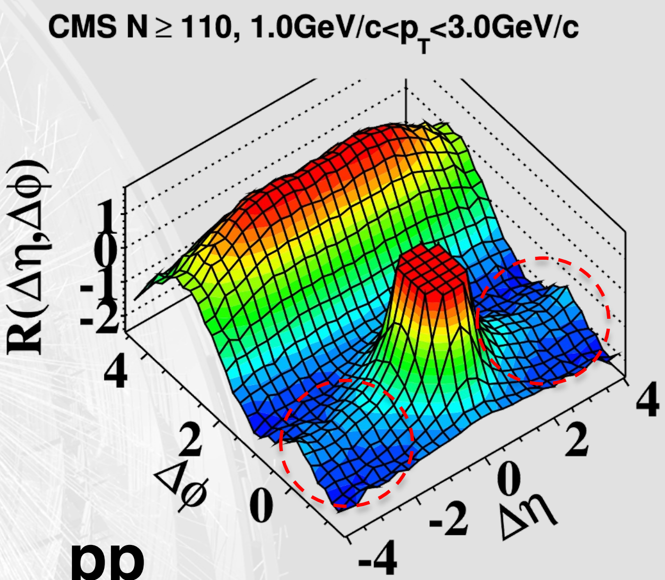
Phys. Lett. B 724 (2013) 213



Pb-Pb

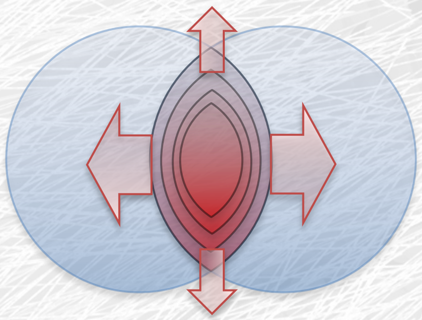


p-Pb



pp

JHEP 1009:091,2010

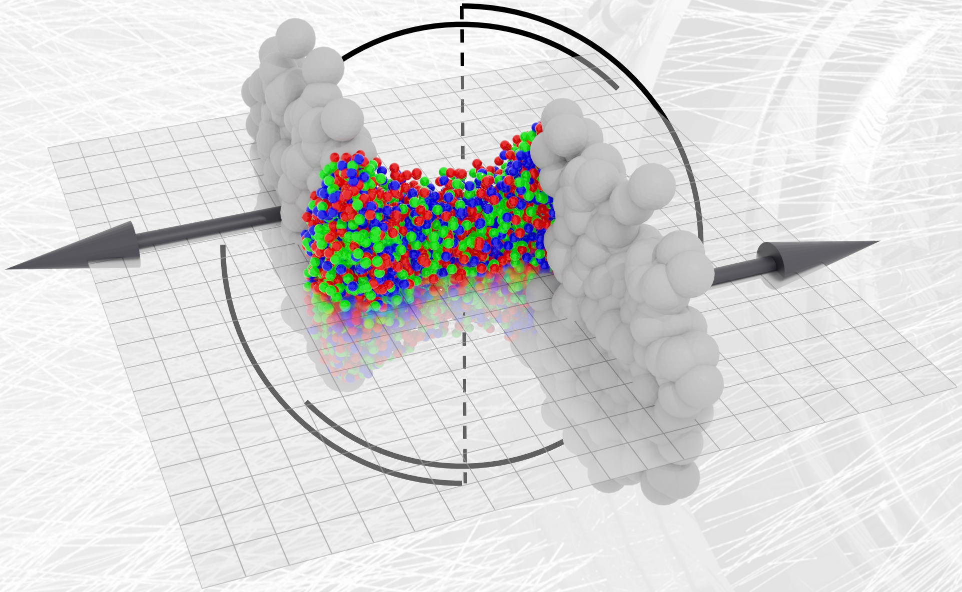


Collective expansion

- Collective expansion can also be measured by correlating two particles in $\Delta\eta$ (difference in rapidity) and $\Delta\varphi$ (difference in azimuthal angle).
- Also observed in p-Pb and pp
  - Initial condition not necessarily elliptic
  - **Experimental**: under which conditions does this **not** happen?
  - **Pheno/theory**: collective expansion also at play? Or some other (common?) phenomenon?

The “standard model” of quark-gluon plasma physics:

Key experimental features of a QGP in the hard sector



Hard regime:

perturbative, high p_{T} (many GeV/c) physics

Hard scattering-dominated, but could be modified due to presence of medium

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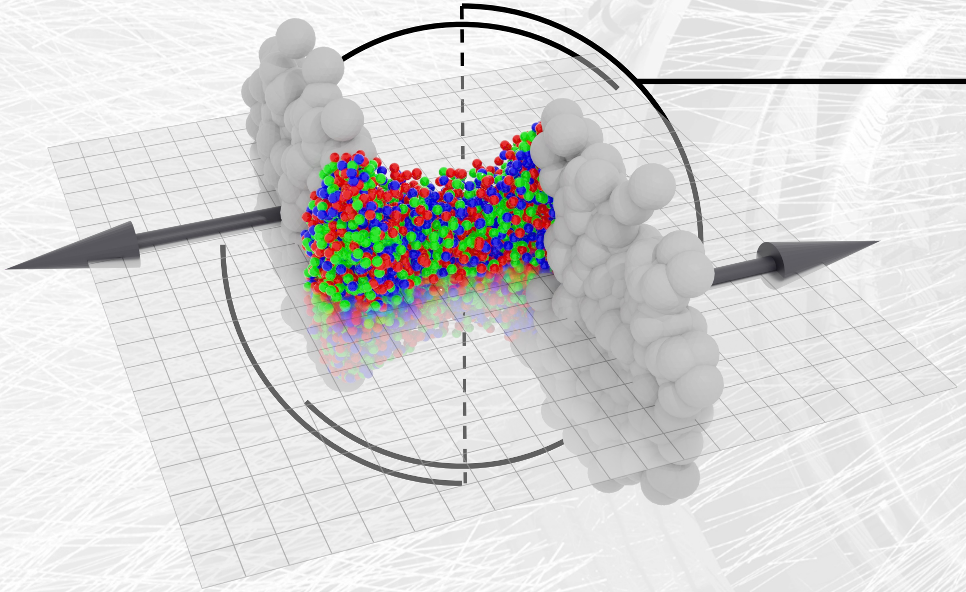

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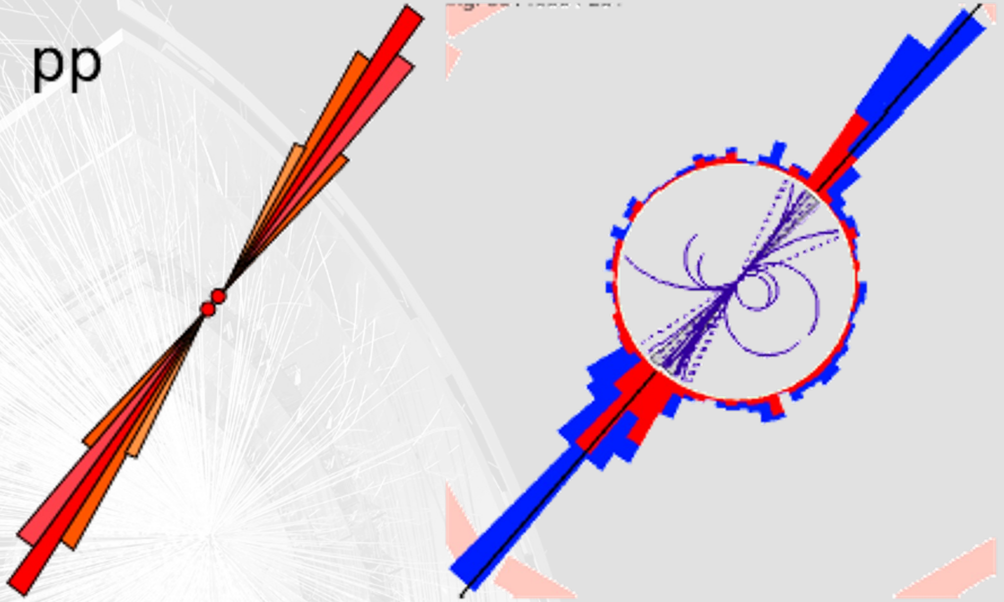
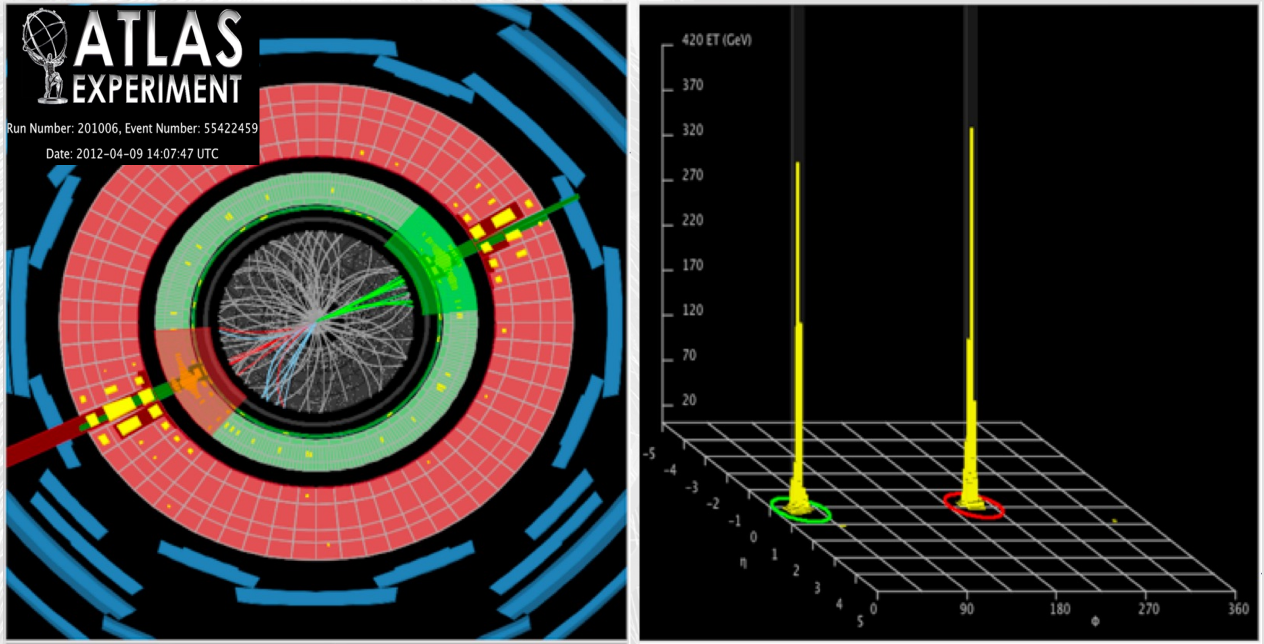
Jets

In the early stages of the collision, hard scatterings produce back-to-back recoiling partons, which fragment into collimated "sprays" of hadrons.

→ **in-vacuum fragmentation**





ATLAS, pp collision event display

Jets

In the early stages of the collision, hard scatterings produce back-to-back recoiling partons, which fragment into collimated "sprays" of hadrons.

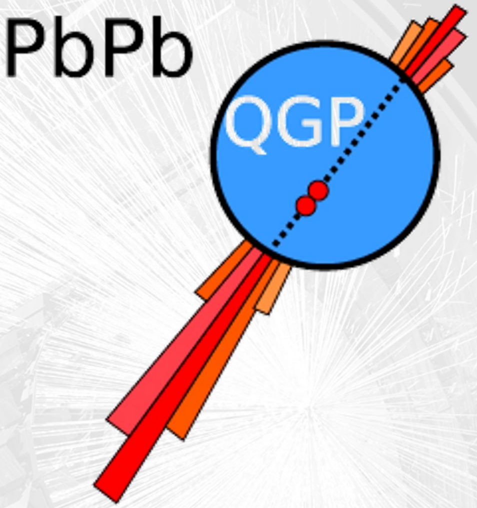
→ **in-vacuum fragmentation**

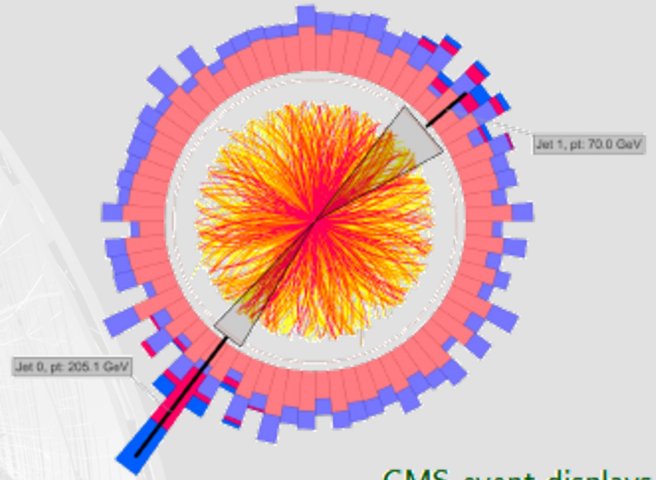
When a QGP is formed, the colored partons traverse and interact with a colored medium.

→ **in-medium fragmentation**

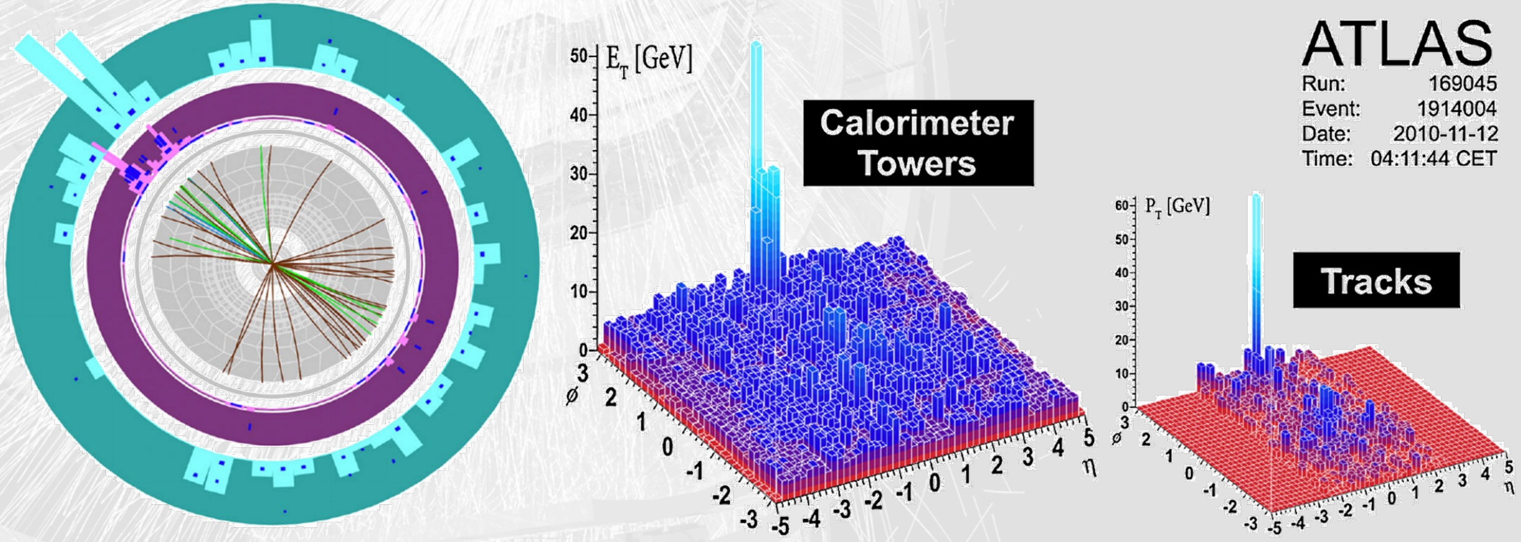
→ **jet "quenching" (energy loss)**

Goal: understand the nature of this energy loss to characterize the strongly-interacting QGP



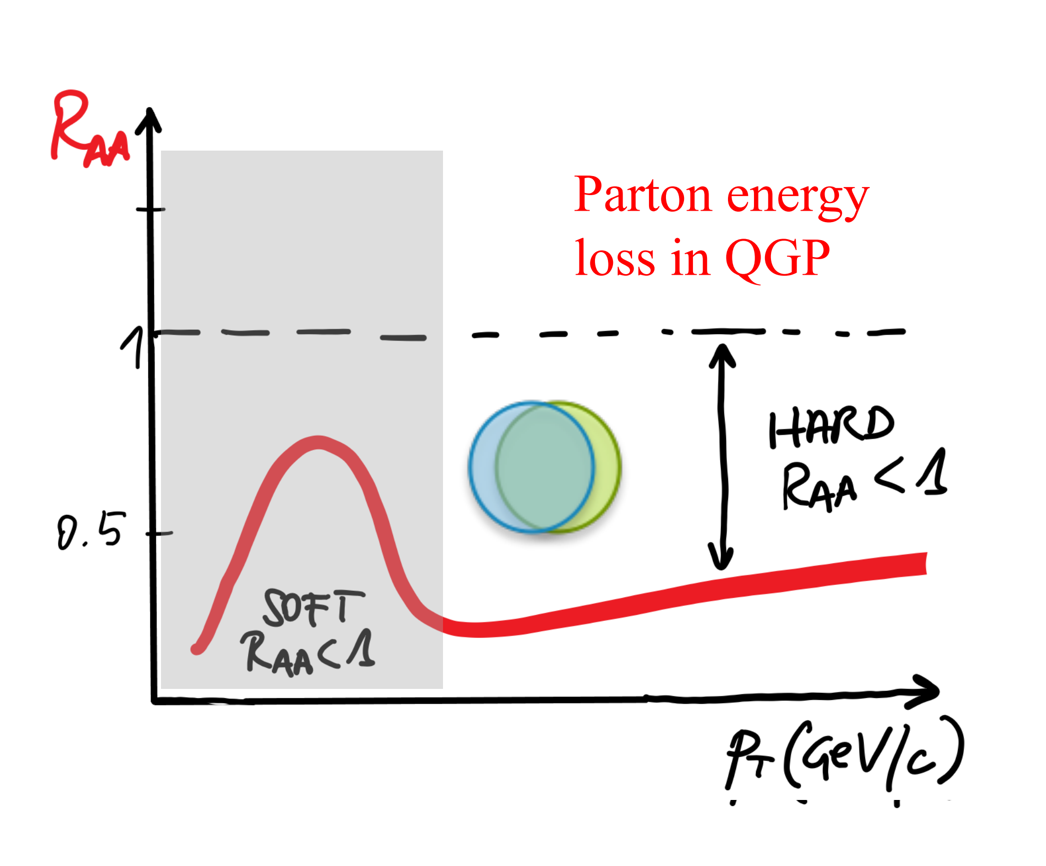


CMS event displays



The nuclear modification factor: R_{AA}

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$



If a AA collision is a incoherent superposition of independent pp collisions, the p_T spectra in AA collisions can be obtained by scaling the p_T spectra in pp collisions by the number of nucleon-nucleon collisions, N_{coll} :

$$dN_{AA}/dp_T = N_{coll} \times dN_{pp}/dp_T$$

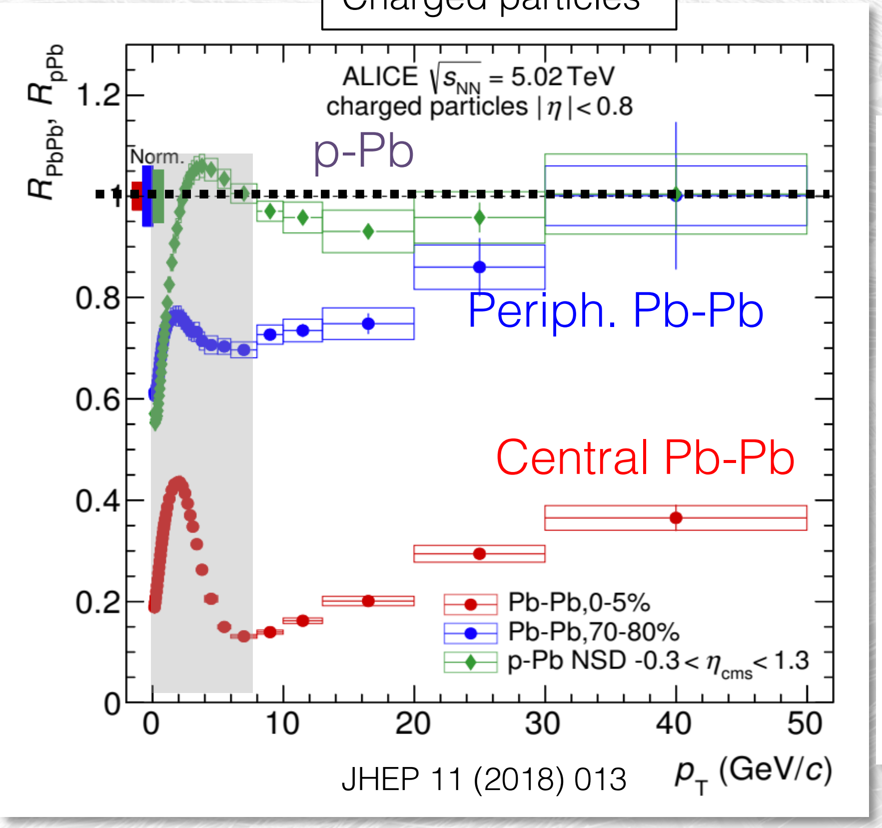
and R_{AA} = 1 at high p_T
→ the medium is transparent to the passage of partons

If R_{AA}< 1 at high p_T
→ the medium is opaque to the passage of partons
→ **parton-medium final state interactions, energy loss, modification of fragmentation in the medium**

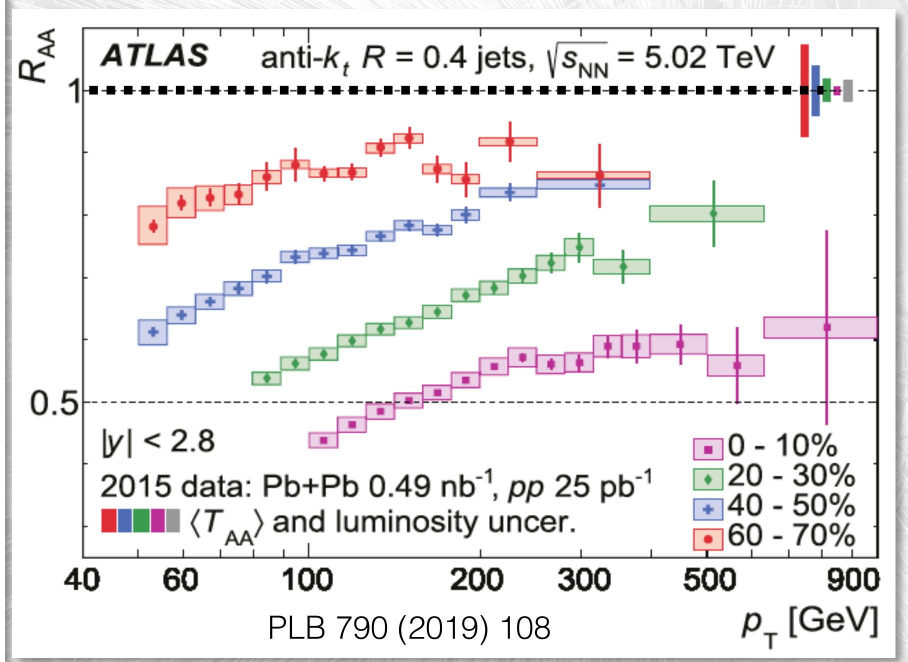
Evidence of parton energy loss in QGP

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

Charged particles



Inclusive jets



A strong suppression of **high-p_T hadrons** and **jets** is observed in central Pb-Pb collisions.

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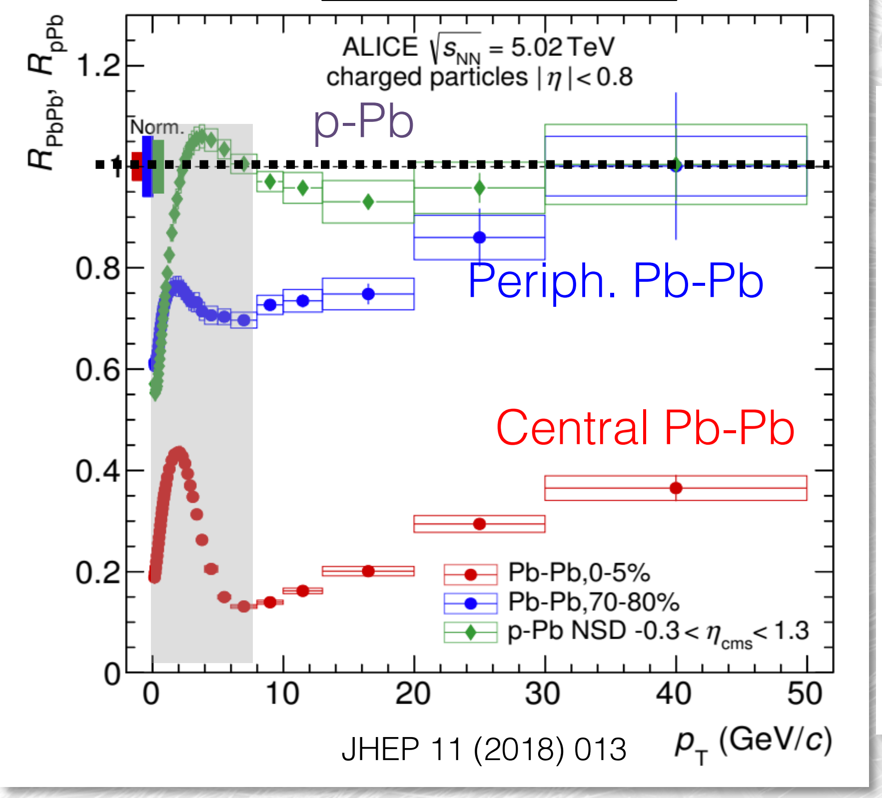
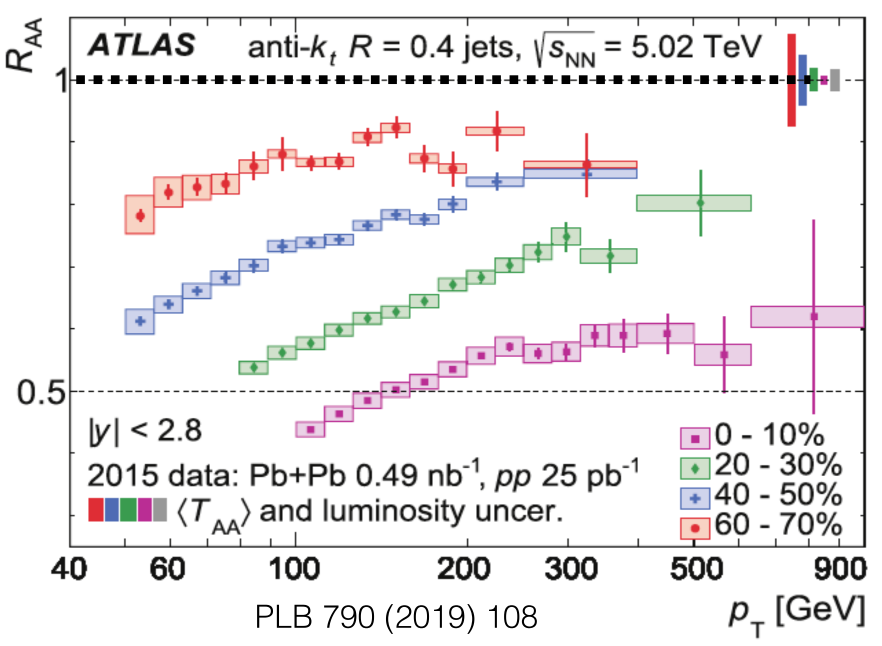
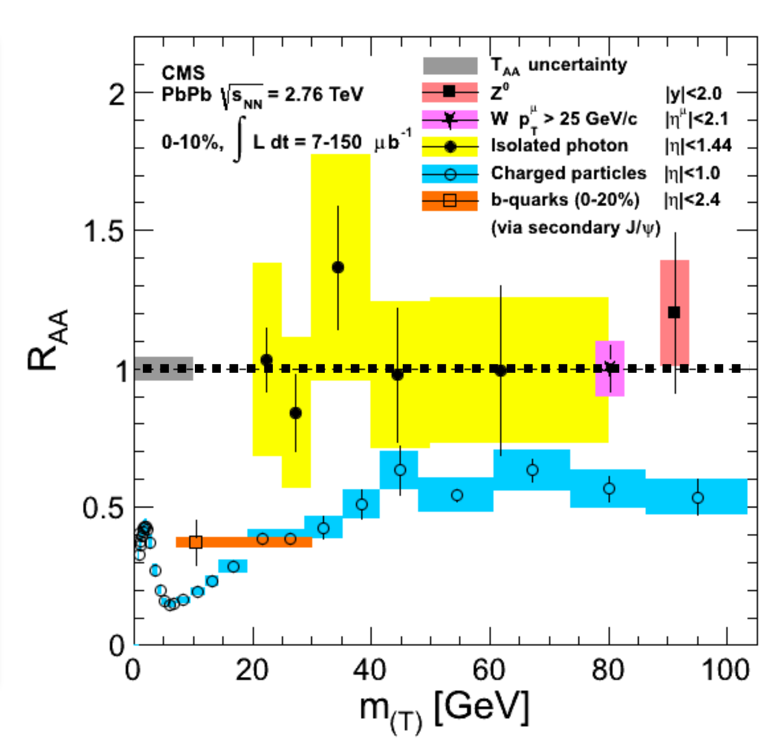


Inclusive jets



EW bosons



A strong suppression of **high-p_T hadrons** and **jets** is observed in central Pb-Pb collisions.

No suppression observed in p-Pb collisions, nor for the color-less Z bosons and photons.

→ Jet quenching is explained as **parton energy loss in a strongly interacting plasma**

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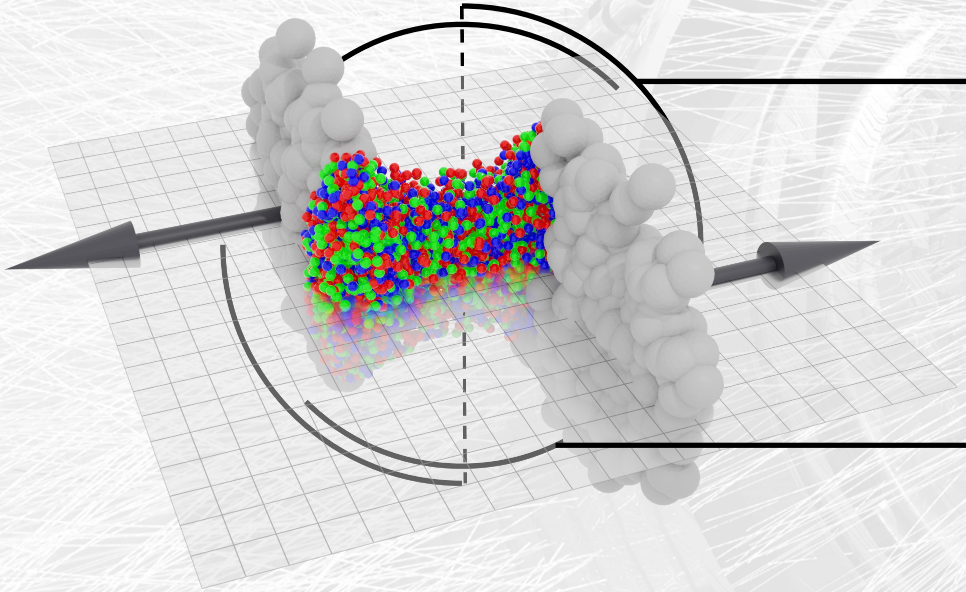

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- Broadly described by more elementary QCD (leading order any beyond, PYTHIA / Jetscape / others) + transport models

Heavy flavour quarks: charm, beauty and quarkonia

- Flavour dependence of medium interactions
- Ideal probes of the QGP: production only via hard scattering since mass much larger than medium temperature
- N.B.: not necessarily 'hard' in terms of final momentum
- Broadly measured via **heavy-flavour particle identification / tagging**
- Broadly described by more elementary QCD (leading order any beyond, PYTHIA / Jetscape / others) + transport models

Charm and beauty

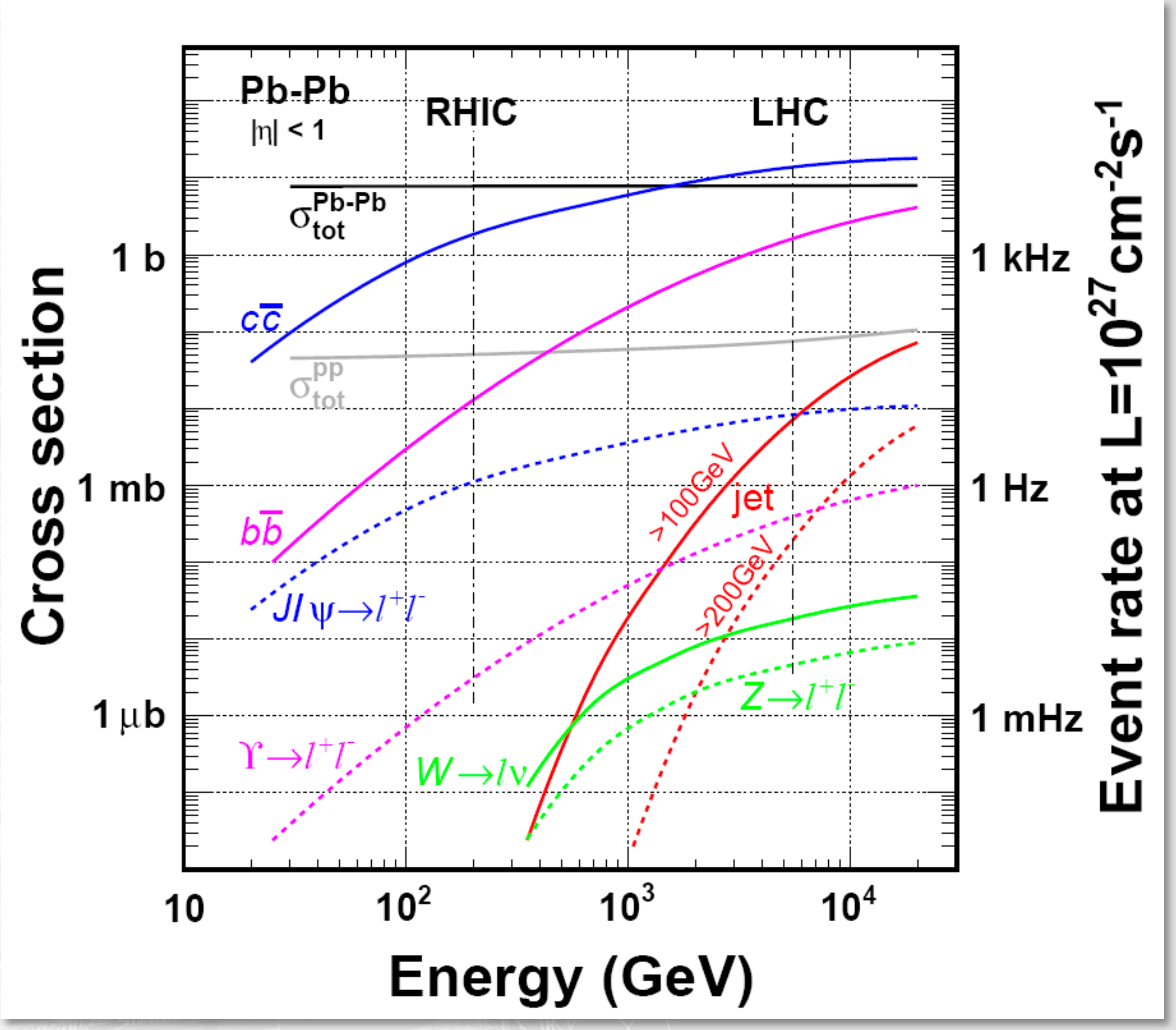
Heavy flavour quarks:

m(charm) ~ 1.3 GeV/c²

m(beauty) ~ 4.7 GeV/c²

are ideal probes of the QGP at the LHC:

- large production cross sections
- Produced in initial hard parton scatterings
- controlled values of mass and colour charge of the propagating parton
- "brownian" motion through the medium, diffusion
- sensitive to QGP hadronisation (baryon/meson)



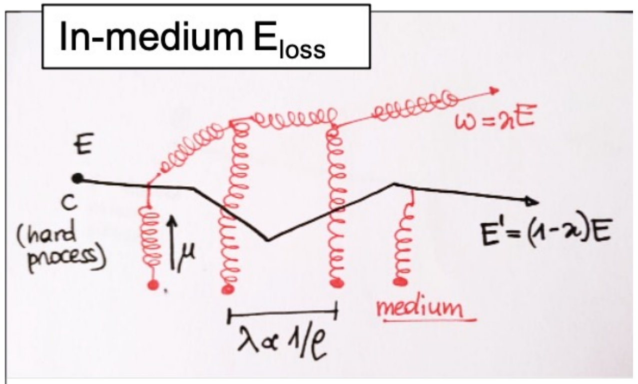
Energy loss of charm and beauty

Charm and beauty lose energy via gluon radiation + elastic collisions

Due to the large masses, radiative energy loss is subject to the dead cone effect = suppression of the gluon radiation emitted by a (slow) heavy quark at small angles, $\vartheta < \vartheta_{DC} \sim m_q/E_q$

→ hierarchy in energy loss: $\Delta E_g > \Delta E_c > \Delta E_b$

→ radiative energy loss reduced by 25% (c) and 75% (b) [μ = 1 GeV/c^2]



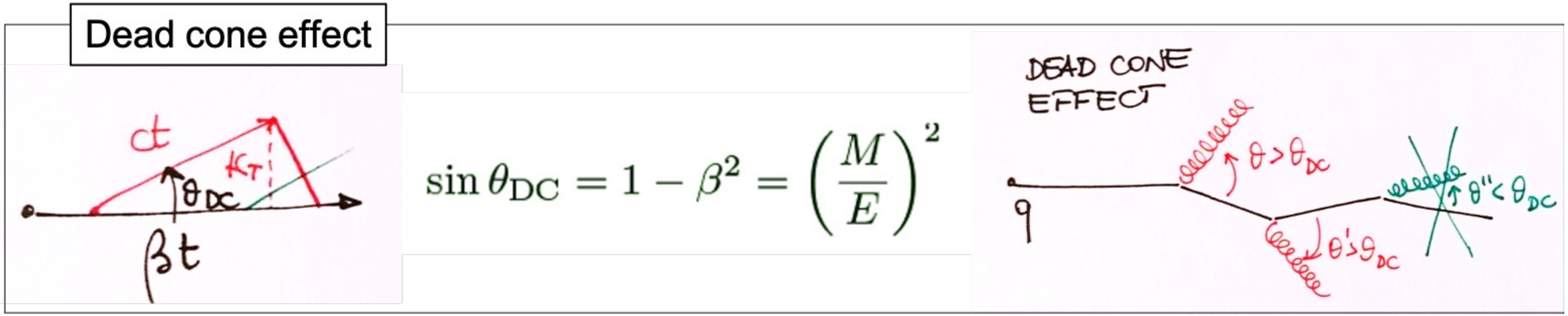
Baier-Dokshitzer-Mueller-Peigné-Schiff, Nucl. Phys. B. 483 (1997) 291

$$\langle \Delta E \rangle \propto \alpha_s C_r \hat{q} L^2$$

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

Average transverse momentum transfer

Mean free path ~1/density

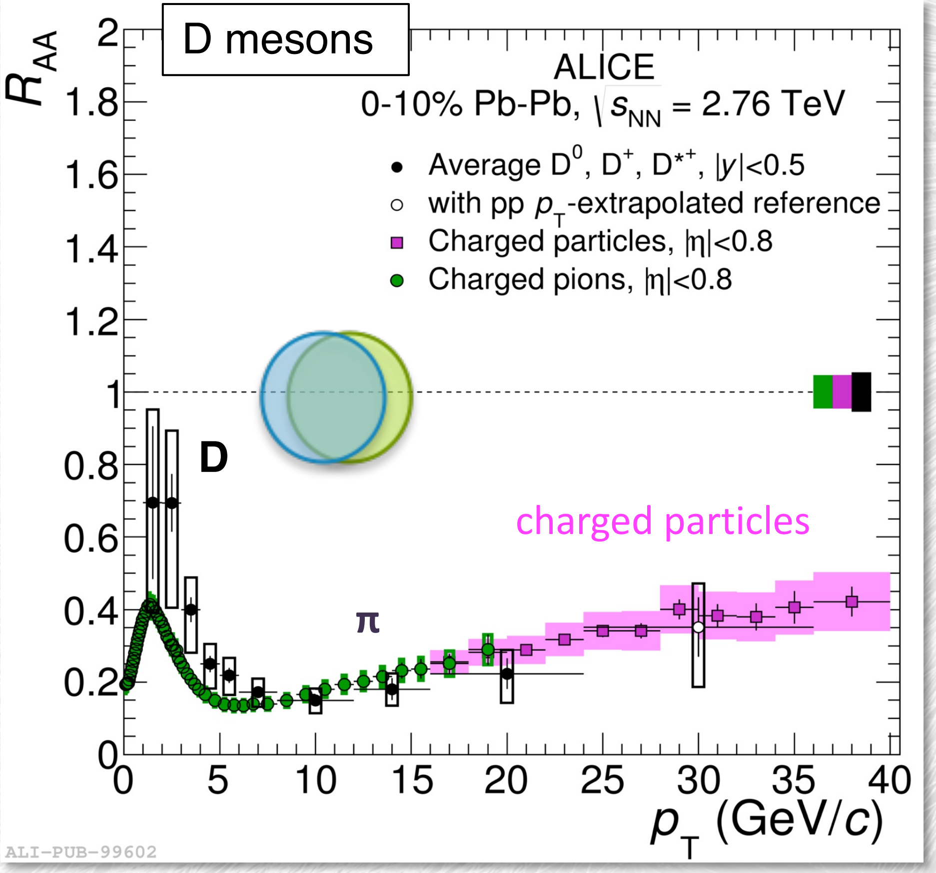


$$\sin \theta_{DC} = 1 - \beta^2 = \left(\frac{M}{E}\right)^2$$

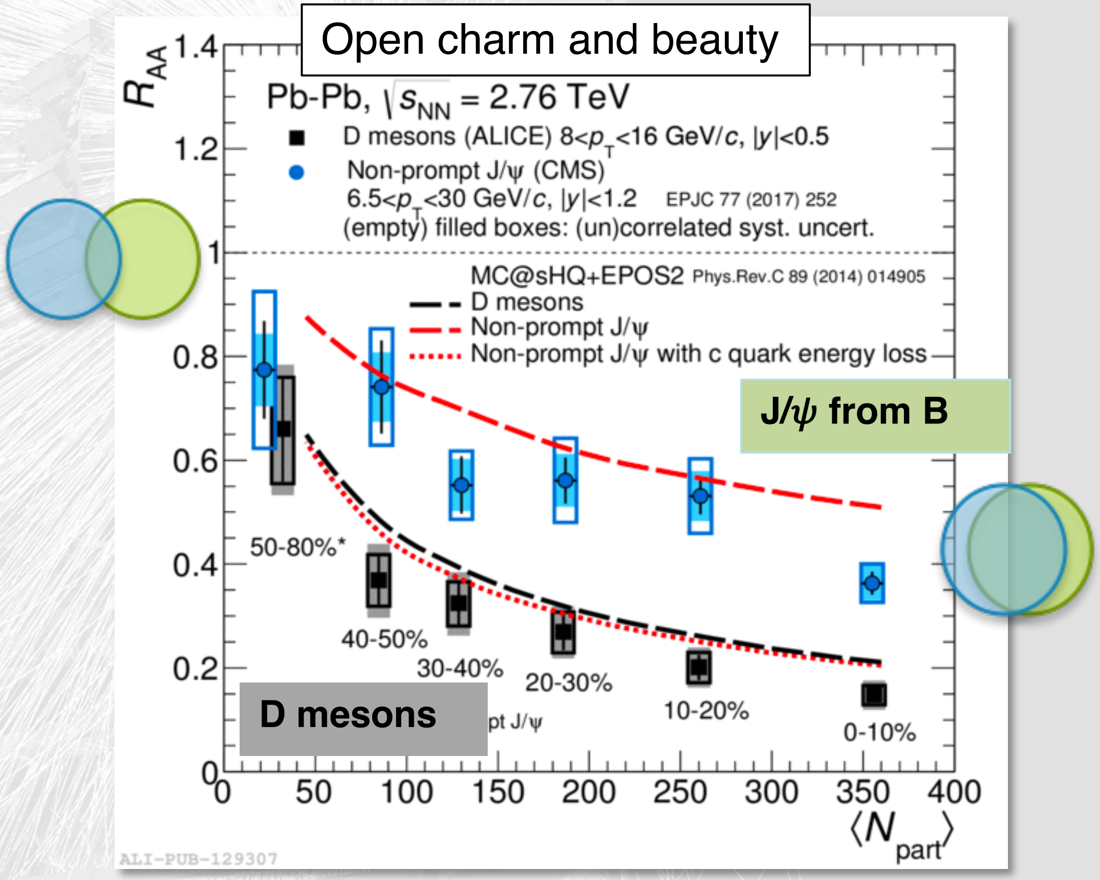
Nuclear modification of charm and beauty

A strong suppression is observed in the R_{AA} of D mesons J/psi from b decay.

J/ψ from beauty is less suppressed than D mesons from charm → $\Delta E_c > \Delta E_b$

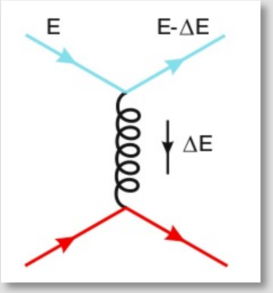


JHEP 11 (2015) 205



EPJC 77 (2017) 252

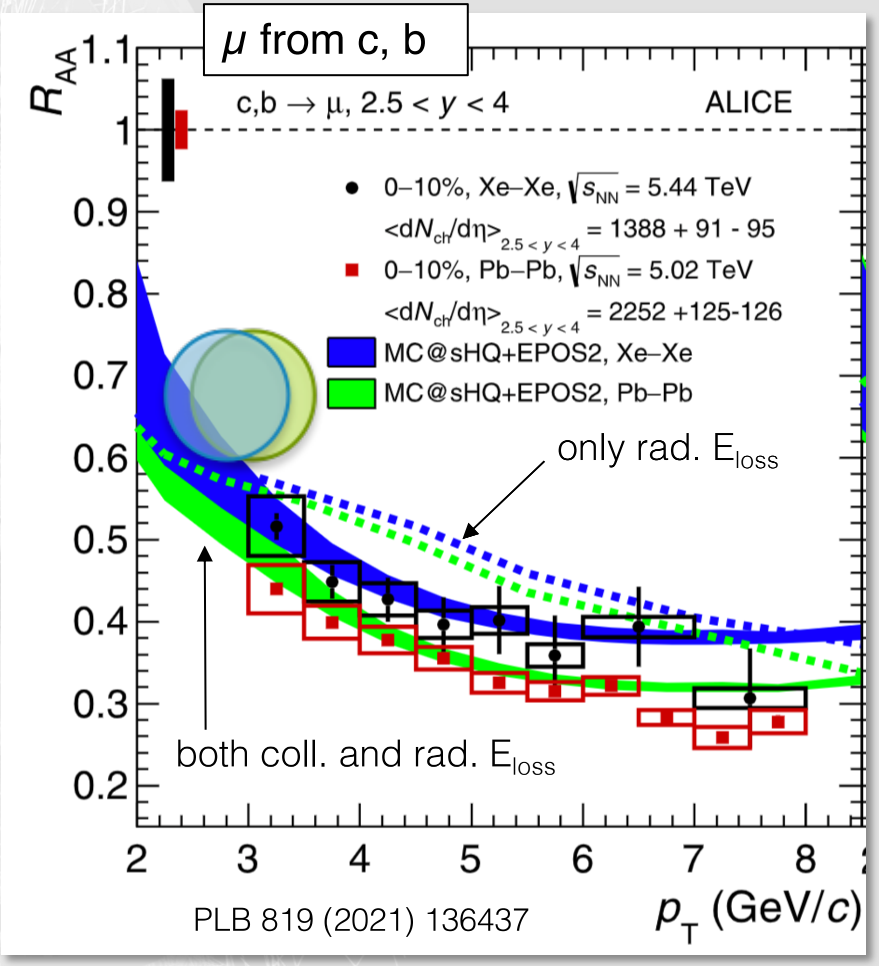
Collisional energy loss



It depends on

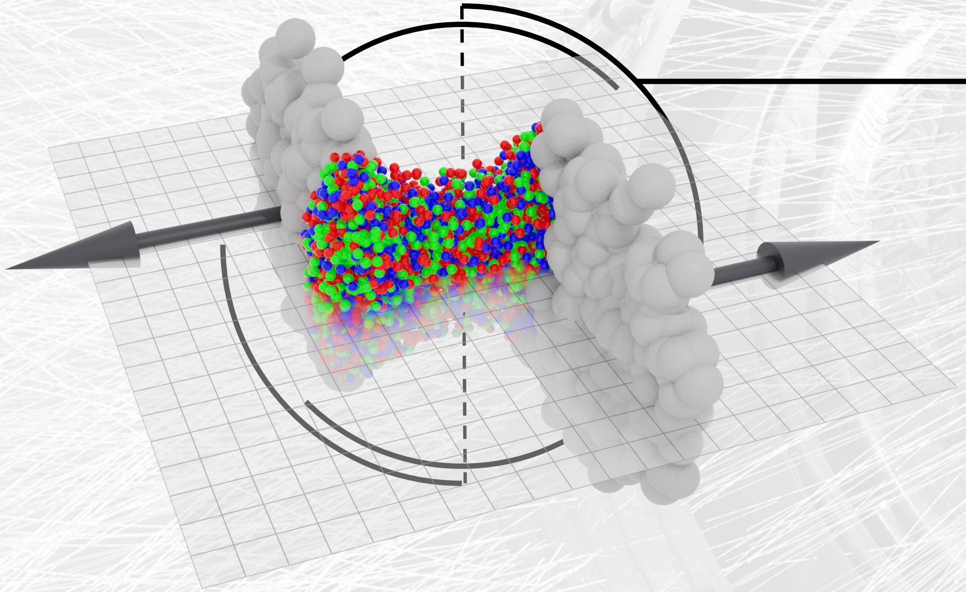
- path length through the medium, L (linearly)
- parton type
  - For light quarks $$\Delta E_{q,g} \sim \alpha_s C_R \mu^2 L \ln \frac{ET}{\mu^2}$$
  - For heavy quarks $+$ $$\alpha_s^2 T^2 C_R \mu^2 L \ln \frac{ET}{M^2}$$
- temperature of the medium, T
- mass of the heavy quark M
- average transverse momentum transfer μ in the medium

→ **Data are well described by models that include both collisional and radiative E_{loss}**



PLB 819 (2021) 136437

And beyond ...



Photon measurements
- Reveal information about QGP temperature

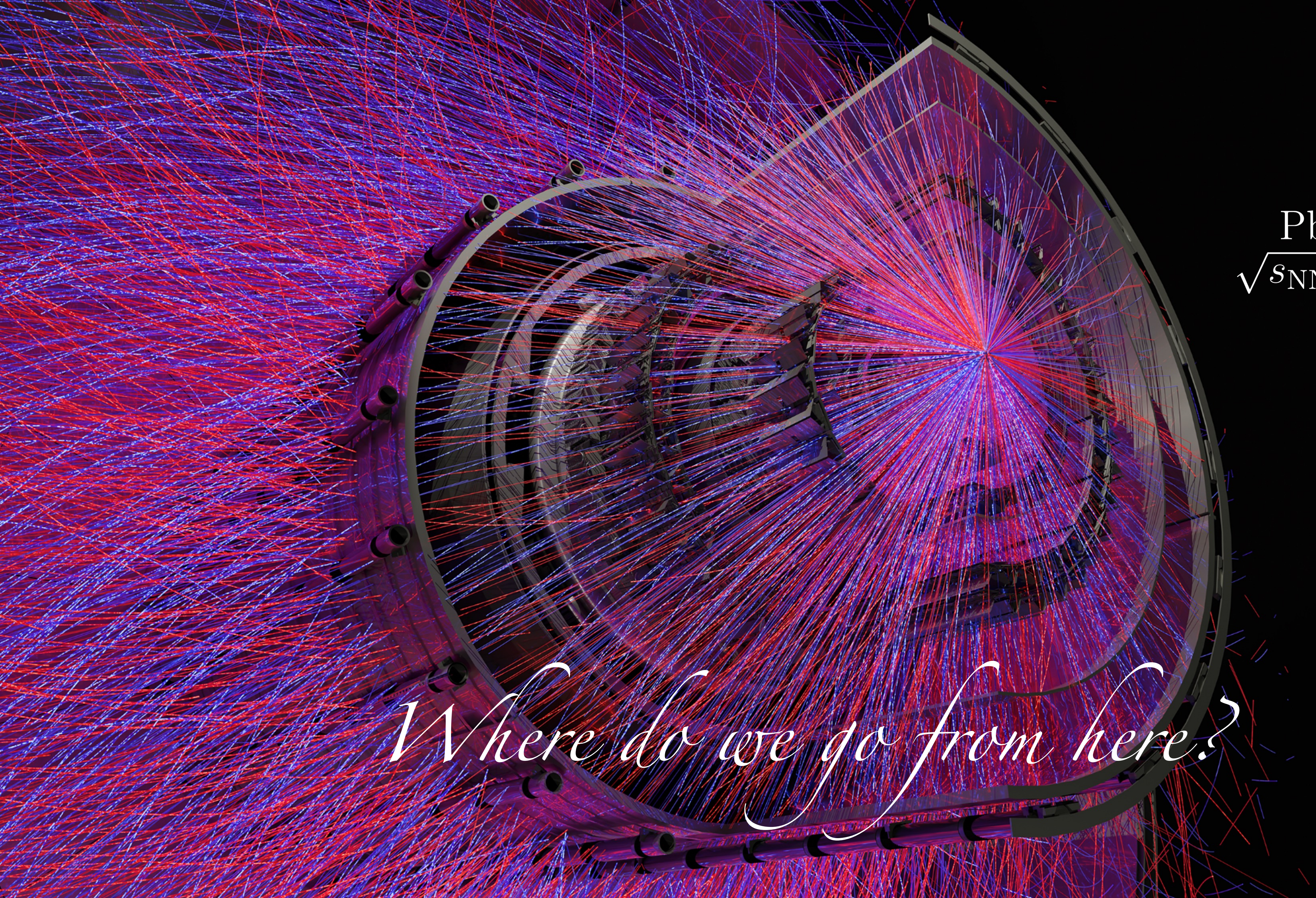
Event-by-event / correlation measurements
- Correlations in flow reveal more about origin of collectivity
- Quantum number correlations shed light on QGP dynamics

Hadron physics
- Femtoscopy as tool to study hadron-hadron interactions
- Characterisation (and formation) of heavy nuclei
- Strong connections to astrophysics and other fields

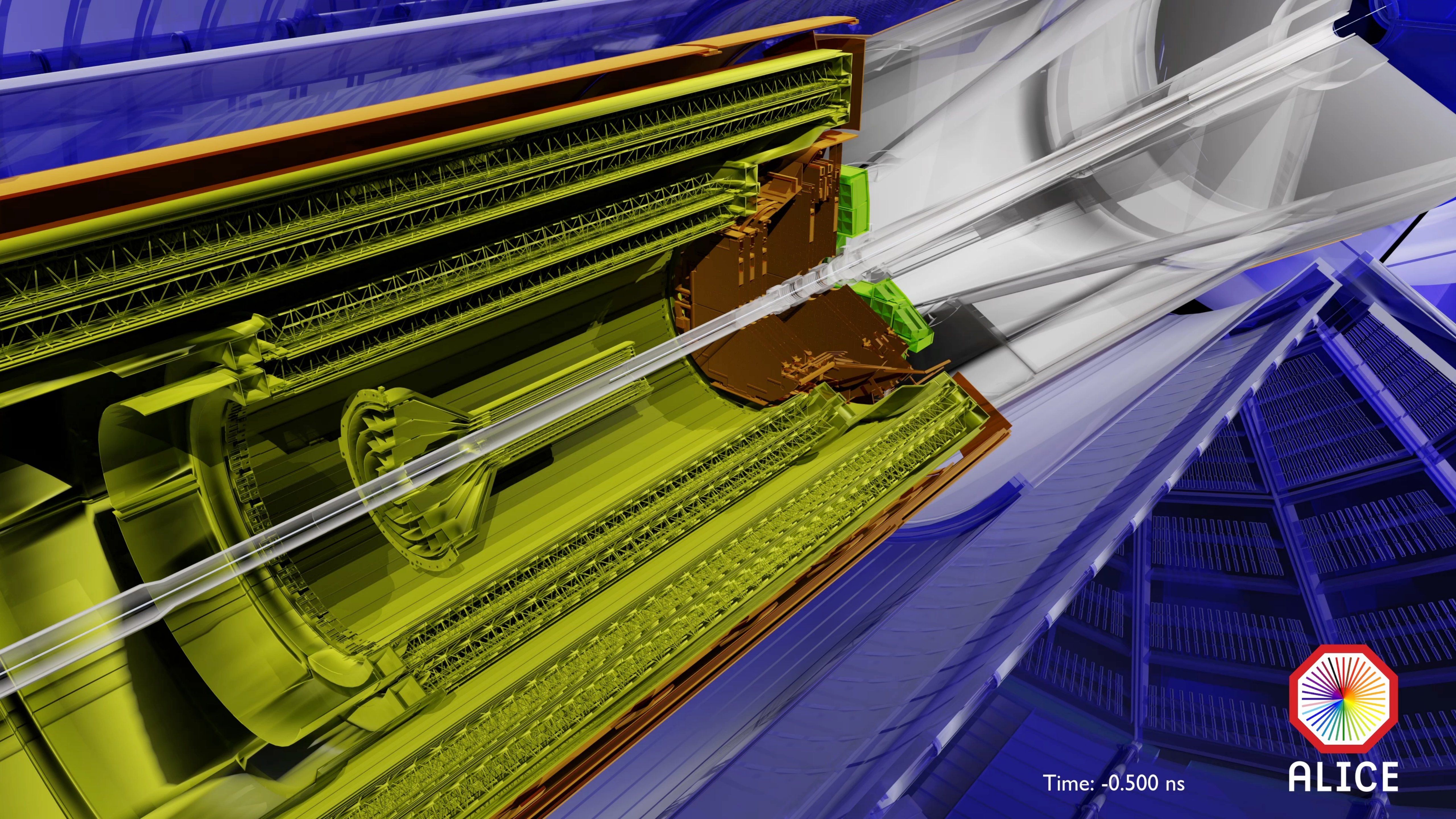
Relating traditional heavy-ion and particle physics
- Small systems studies: how do different views relate?

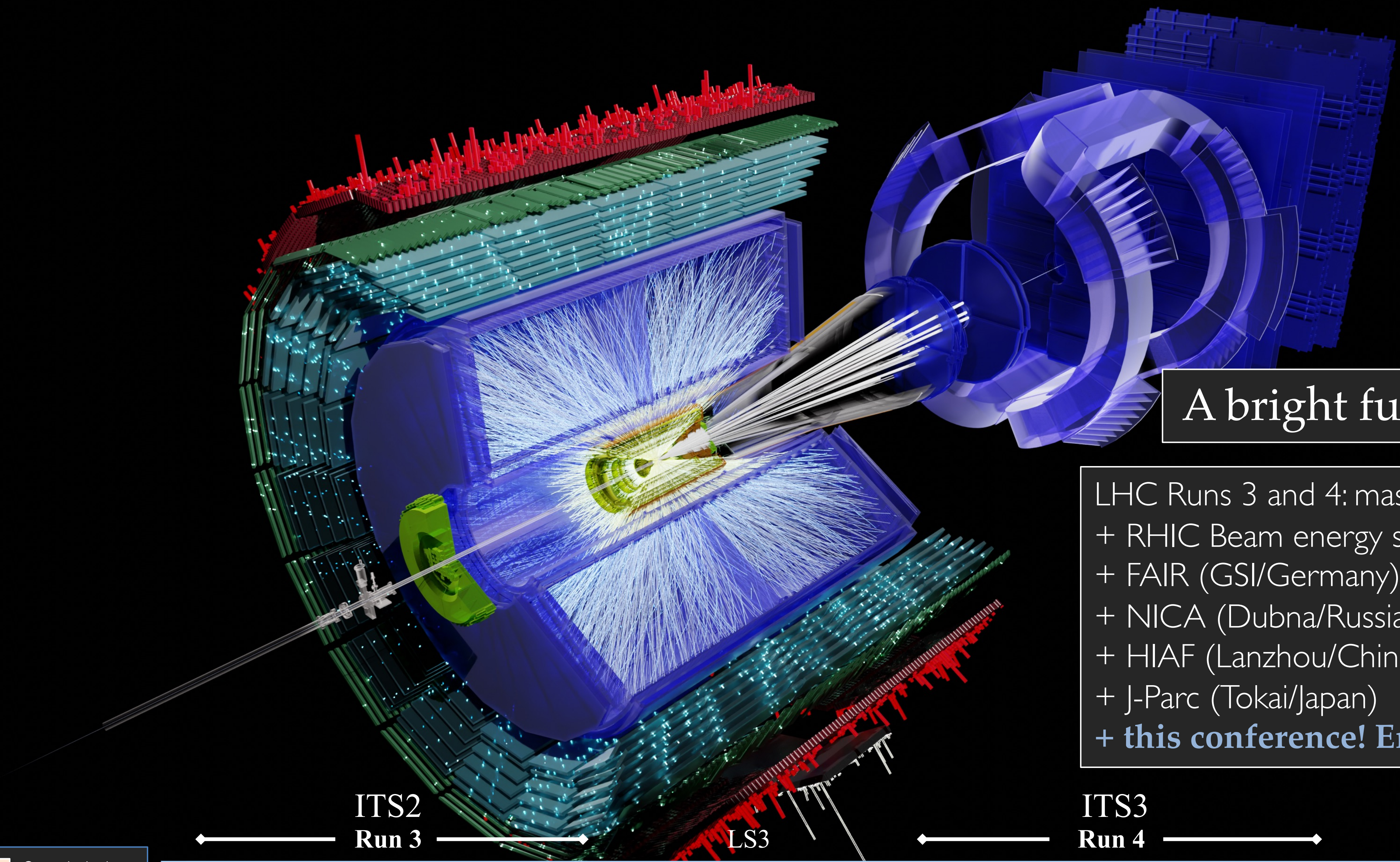
ALICE

Pb-Pb Run 2
$\sqrt{s_{\rm NN}} = 5.02$ TeV



Where do we go from here?

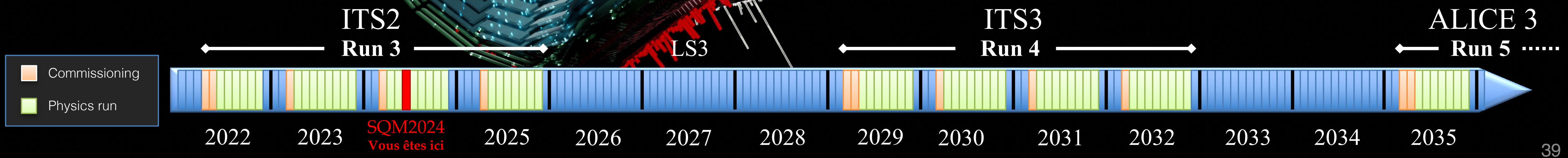

Time: -0.500 ns
ALICE

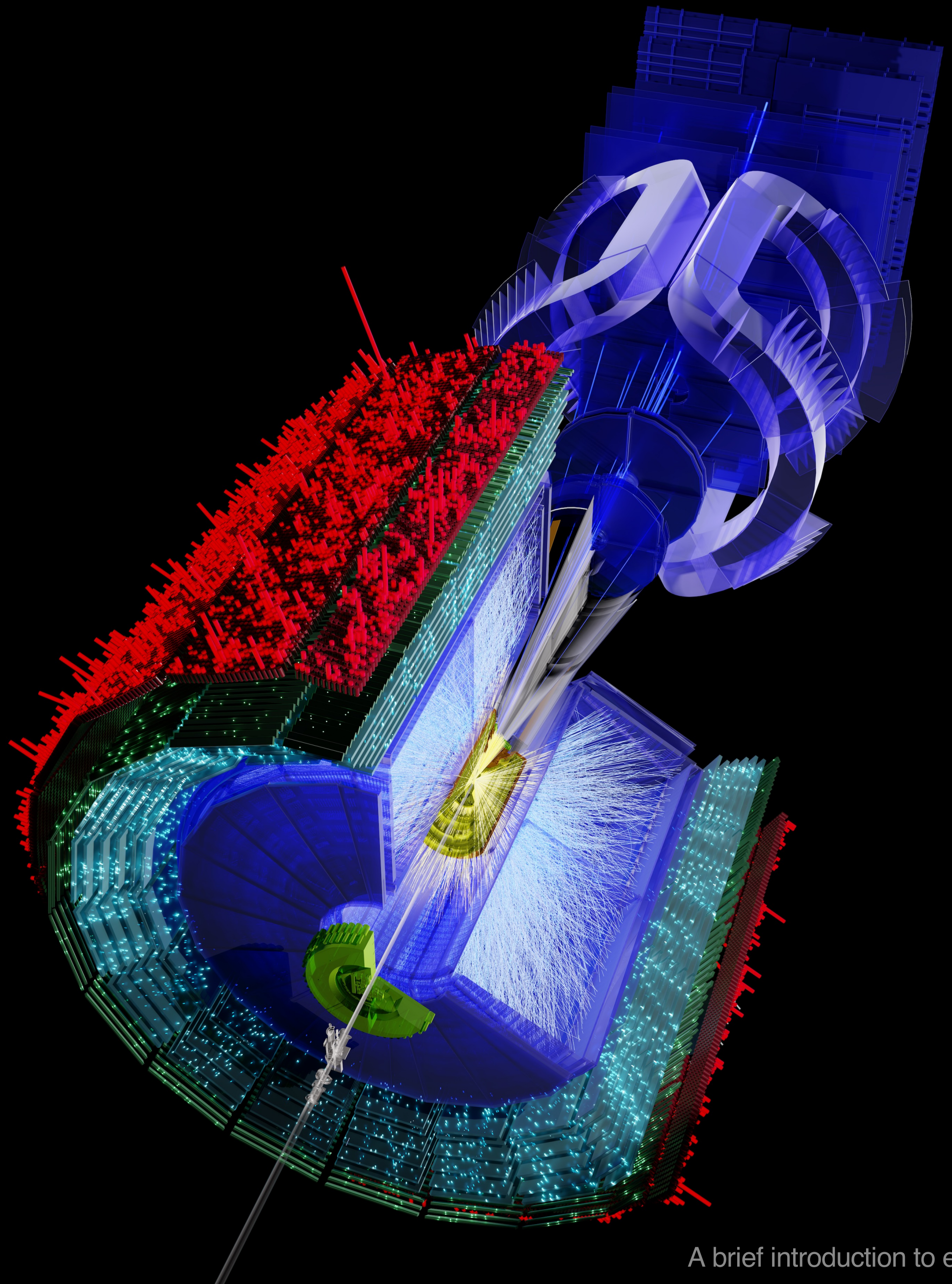


A bright future ahead !

LHC Runs 3 and 4: massive data samples
+ RHIC Beam energy scan
+ FAIR (GSI/Germany)
+ NICA (Dubna/Russia)
+ HIAF (Lanzhou/China)
+ J-Parc (Tokai/Japan)
+ this conference! Enjoy!

Thank you!





Extras

(Intermezzo: kinematic variables in collider physics)

Momentum and transverse momentum: $p = \sqrt{p_L^2 + p_T^2}$

Transverse mass: $m_T := \sqrt{m^2 + p_T^2}$

Rapidity (generalizes longitudinal velocity $\beta_L = p_L / E$): $y := \text{arctanh}\, \beta_L = \frac{1}{2} \ln \frac{1+\beta_L}{1-\beta_L} = \frac{1}{2} \ln \frac{E + p_L}{E - p_L}$

- In a collider where 2 beams of different ions: $y_{CM} = \frac{1}{2} \ln \frac{Z_1 A_2}{A_1 Z_2}$
- In fixed-target mode: $y_{CM} = (y_{\text{target}} + y_{\text{beam}})/2 = y_{\text{beam}}/2$

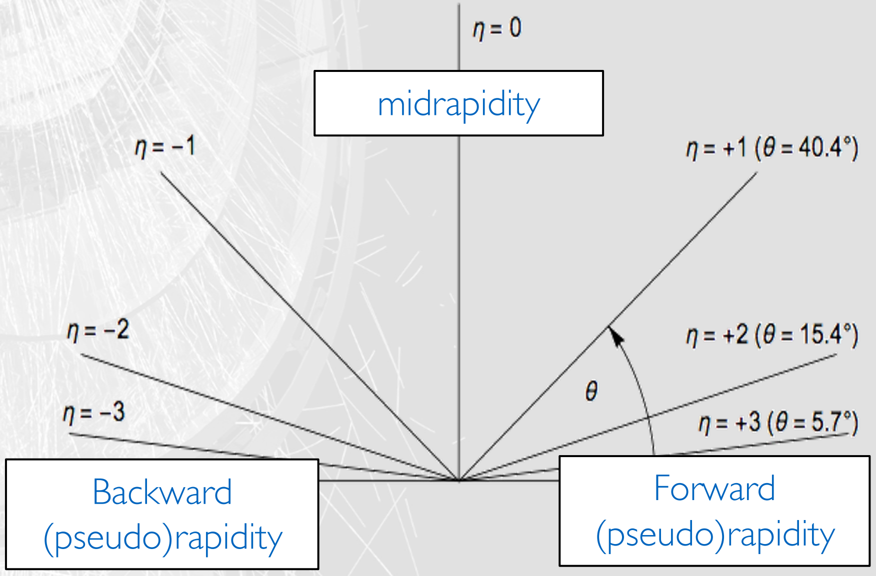
The rapidity can be approximated by pseudorapidity in the ultra-relativistic limit (p>>m):

$$y = \frac{1}{2} \ln \frac{E + p\cos\vartheta}{E - p\cos\vartheta} \overset{p \gg m}{\approx} \frac{1}{2} \ln \frac{1+\cos\vartheta}{1-\cos\vartheta} = \frac{1}{2} \ln \frac{2\cos^2\frac{\vartheta}{2}}{2\sin^2\frac{\vartheta}{2}} = -\ln\left[\tan\frac{\vartheta}{2}\right] =: \eta$$

$$\cos(2\alpha) = 2\cos^2\alpha - 1 = 1 - 2\sin^2\alpha$$

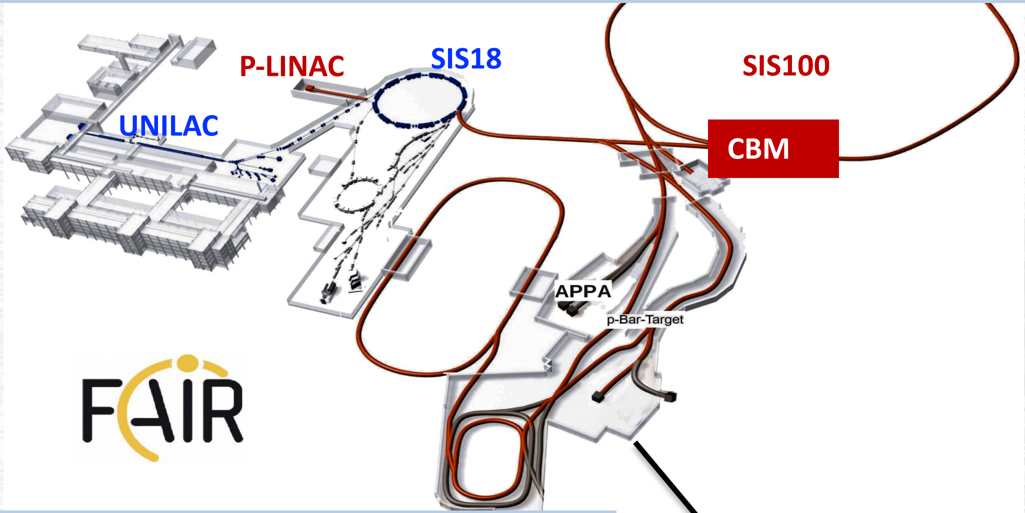
where ϑ is the angle between the direction of the beam and the particle.

In general y $\neq \eta$, especially at low momenta.

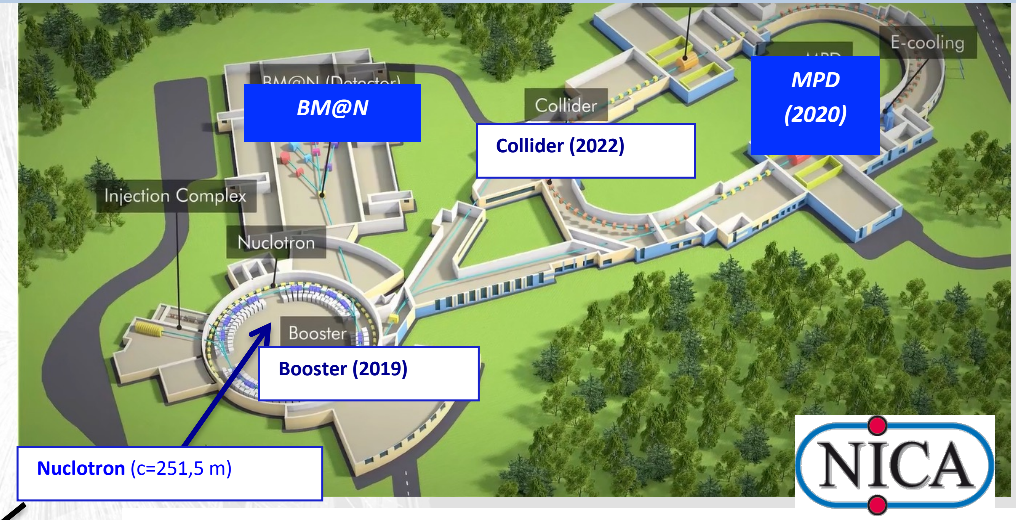


Heavy-ion physics worldwide: future / low energy

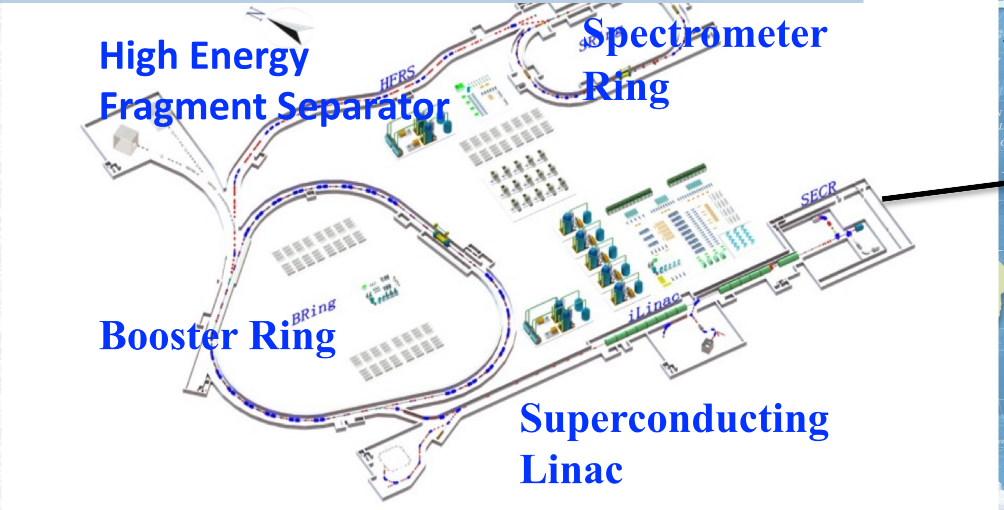
Facility for **A**ntiproton and **I**on **R**esearch, GSI, Germany

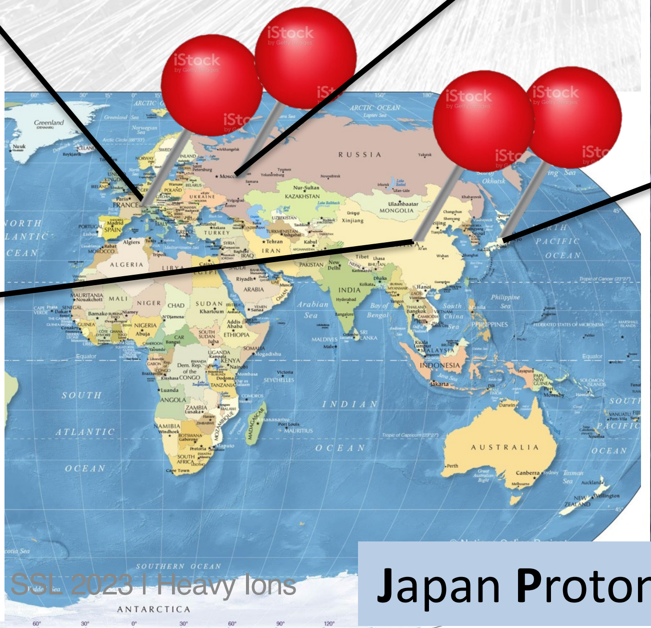


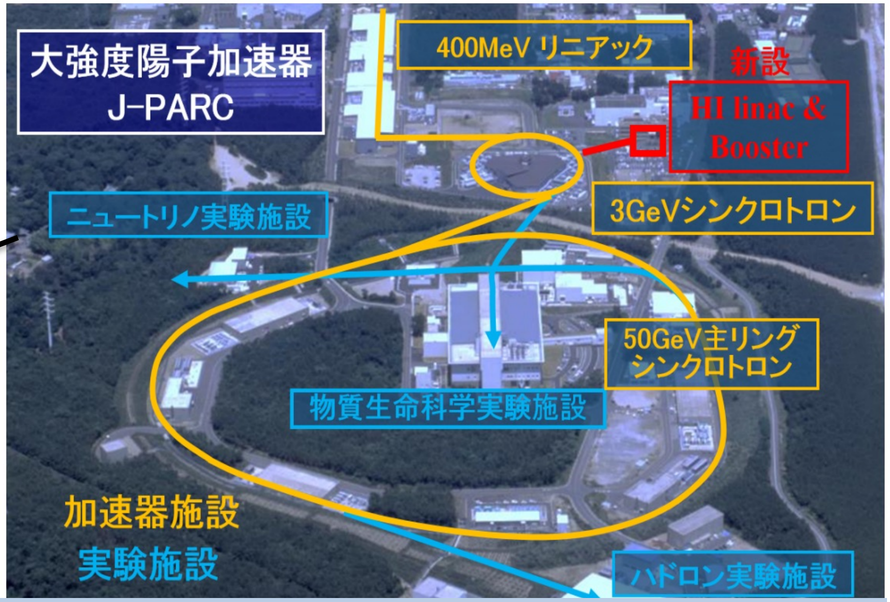
Nuclotron-based **I**on **C**ollider f**A**cility, JINR, Dubna



High-**I**ntensity Heavy Ion **A**ccelerator **F**acility, Lanzhou, China

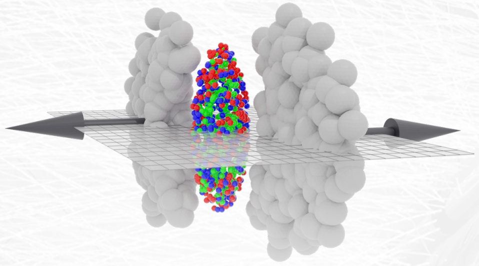


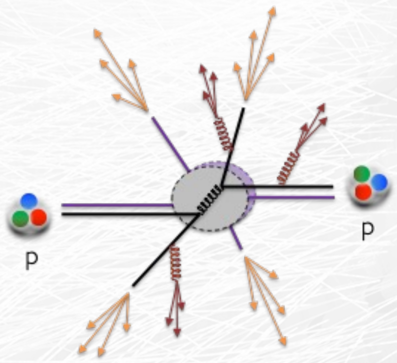


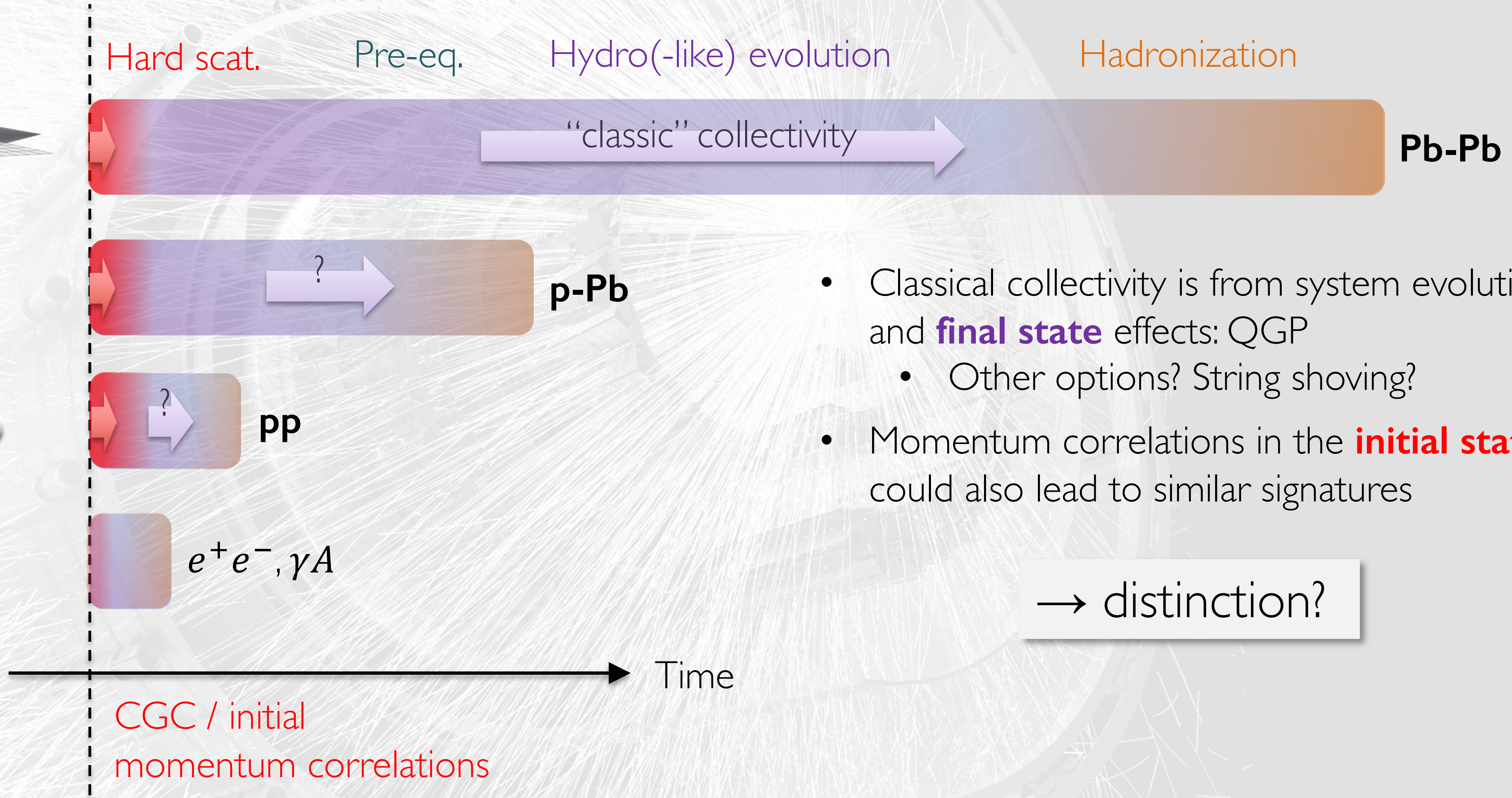


Japan **P**roton **A**ccelerator **R**esearch **C**omplex**, J**apan

Origins of collectivity and role of system evolution



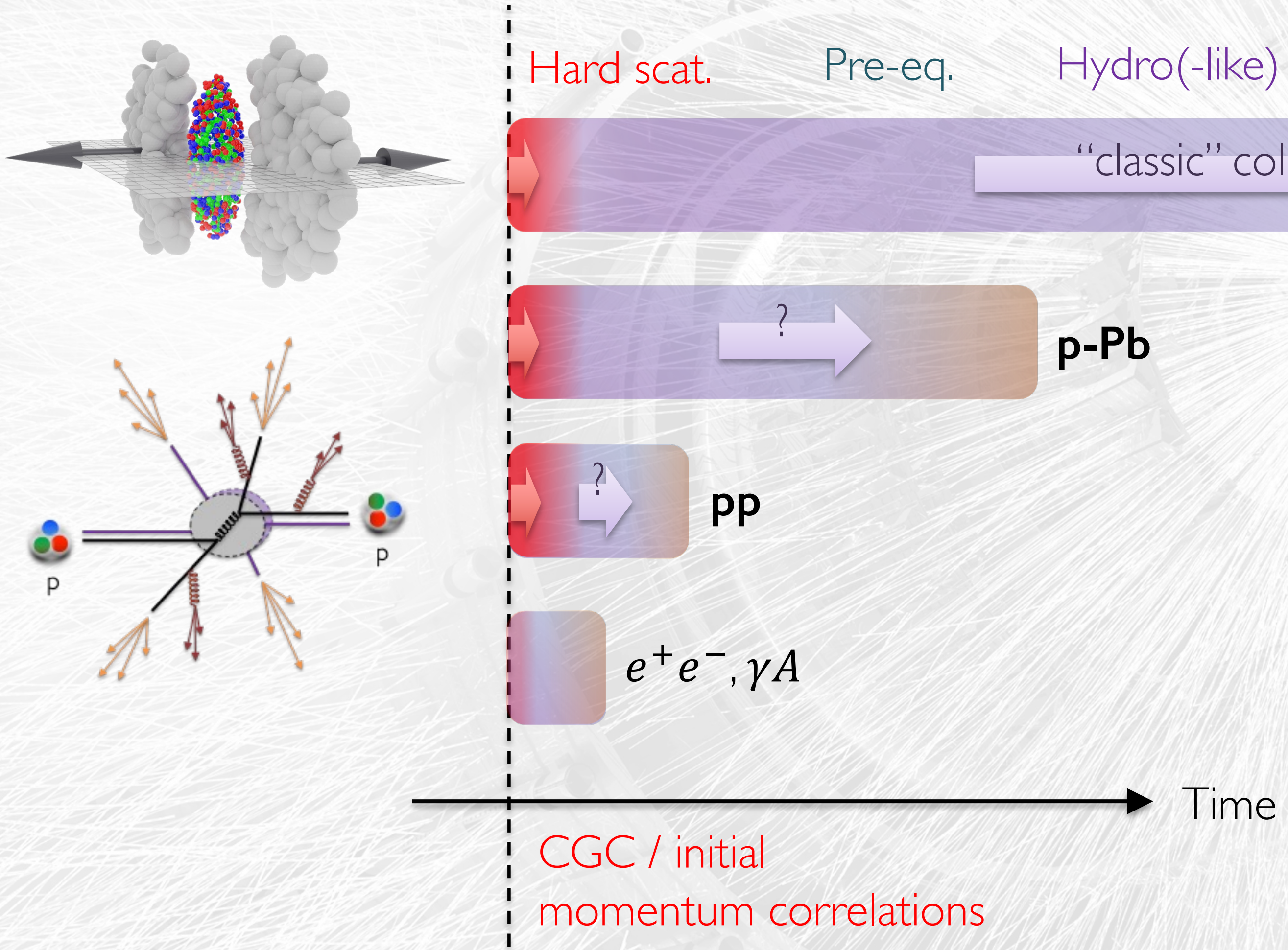




- Classical collectivity is from system evolution and **final state** effects: QGP
  - Other options? String shoving?
- Momentum correlations in the **initial state** could also lead to similar signatures

→ distinction?

Origins of collectivity and role of system evolution



- Classical collectivity is from system evolution and **final state** effects: QGP
  - Other options? String shoving?
- Momentum correlations in the **initial state** could also lead to similar signatures

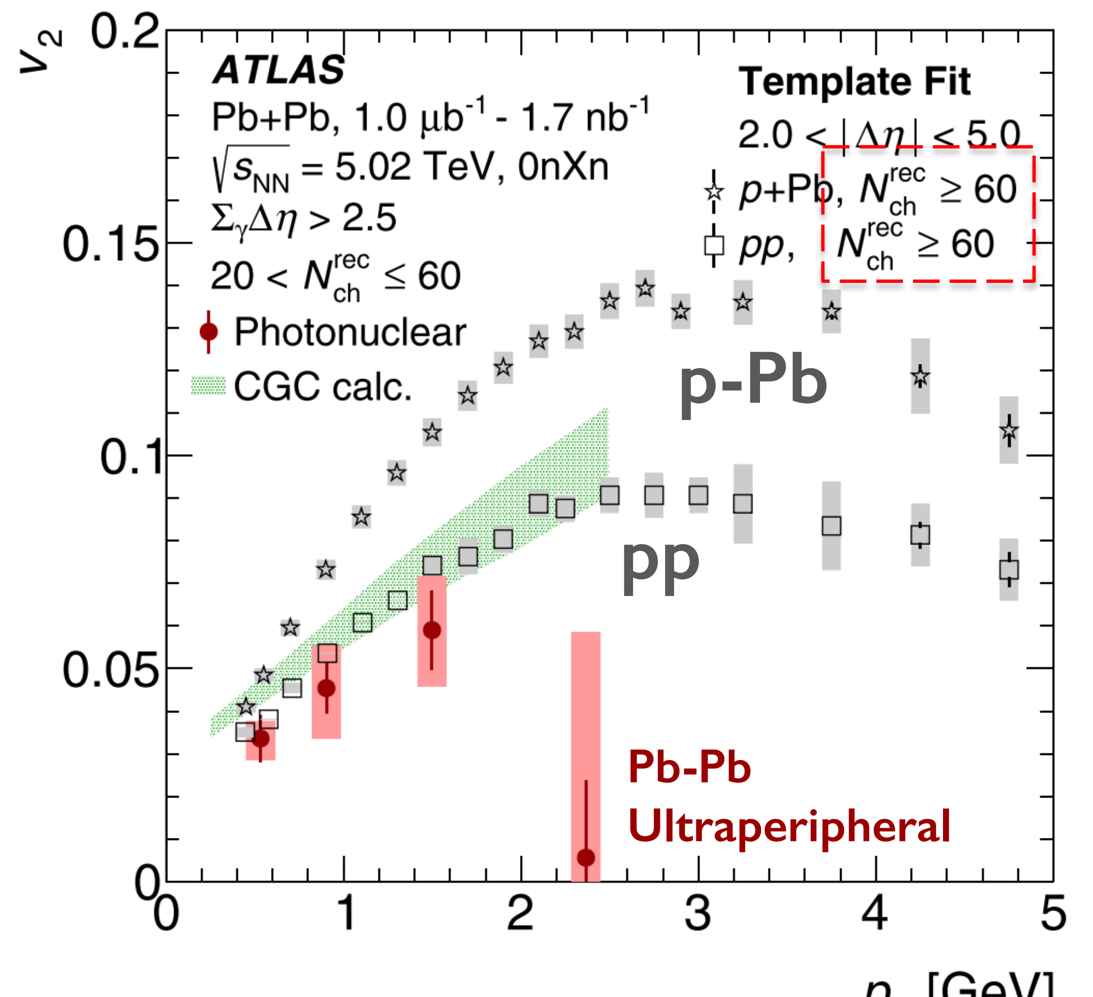
Experimentally, community focus on:

1. In-depth study of flow correlations
2. Rapidity as a tool for 3D dynamics
3. **Look for extremes: $e^+e^-, \gamma A$, BES / low E**
4. Understanding the hard/soft interplay

Observation of non-zero flow in photo-nuclear events

- Ultra-peripheral collisions: photonuclear processes
  - High-multiplicity events selected for analysis
  - Non-zero v_2,
    …but lower than hadron-hadron collisions!
- Similar to result by CMS [2] in γp interactions (in p-Pb)
- Can be explained using CGC predictions [1]
- Caveat: v_2 coefficients vulnerable to (residual) non-flow
- Begs the question: can we characterize these collisions?
  - What about other QGP signatures?

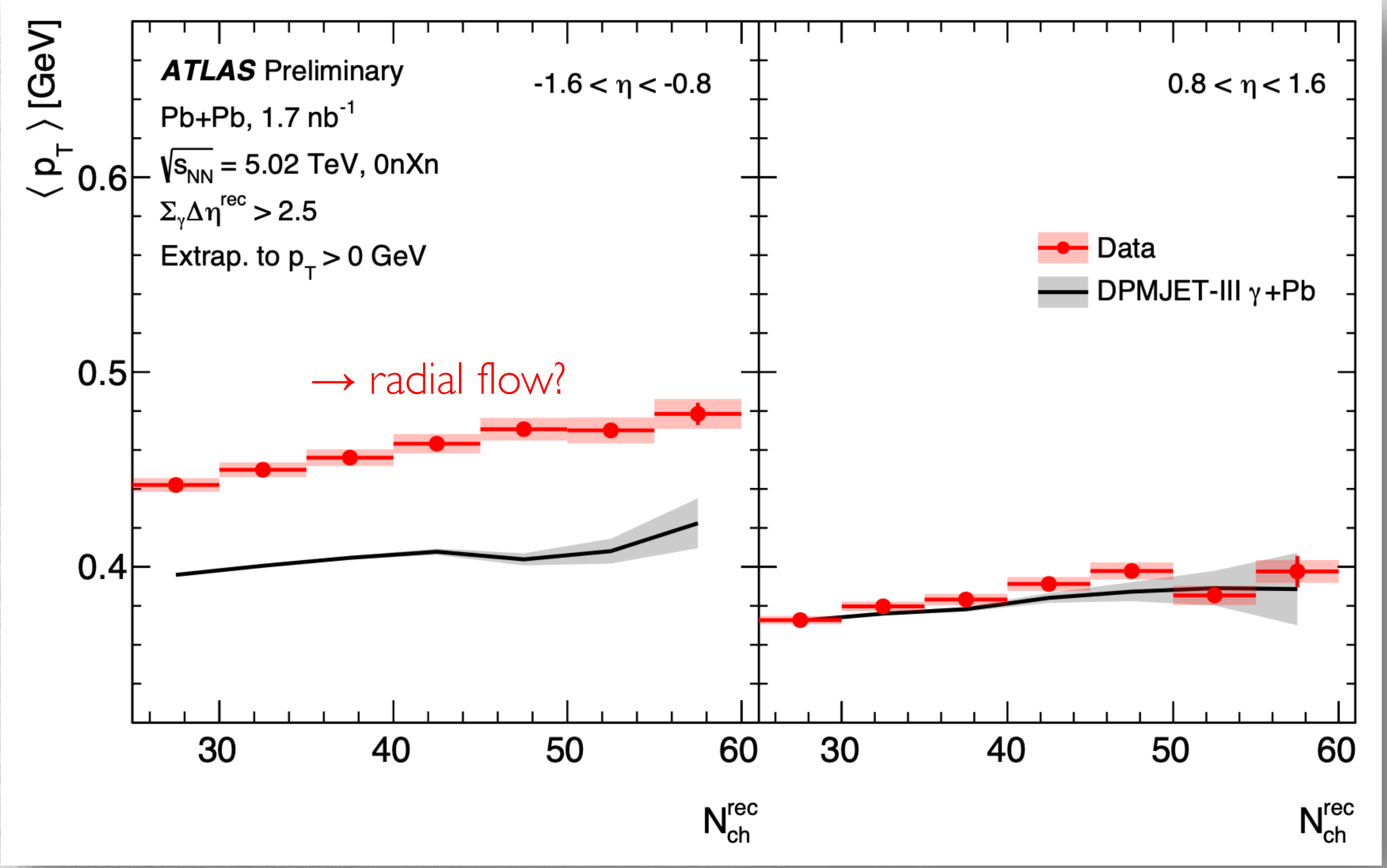
[1] Phys. Rev. D **103**, 054017
[2] https://arxiv.org/abs/2204.13486



ATLAS, Phys. Rev. C **104**, 014903

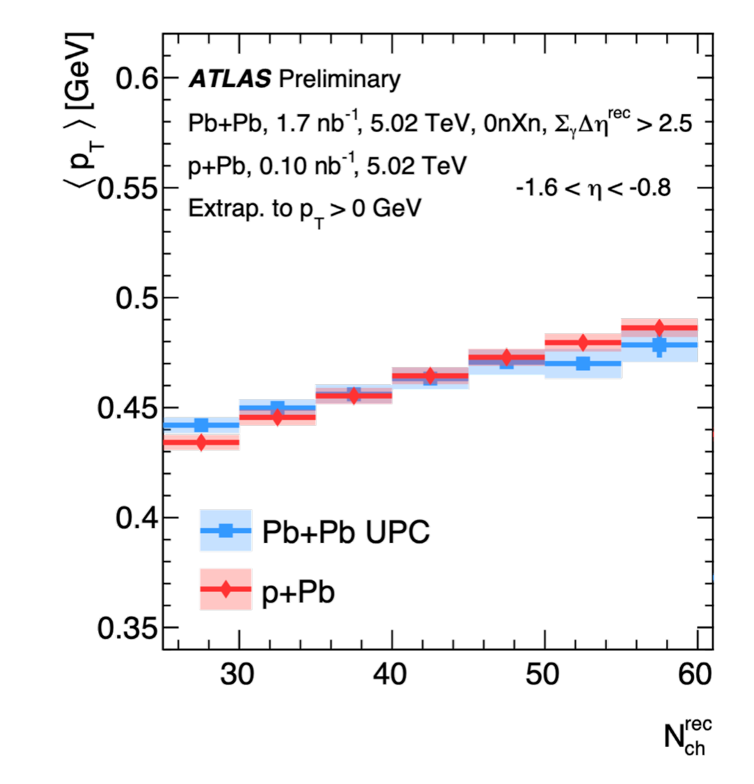
Search for QGP signatures in photo-nuclear events

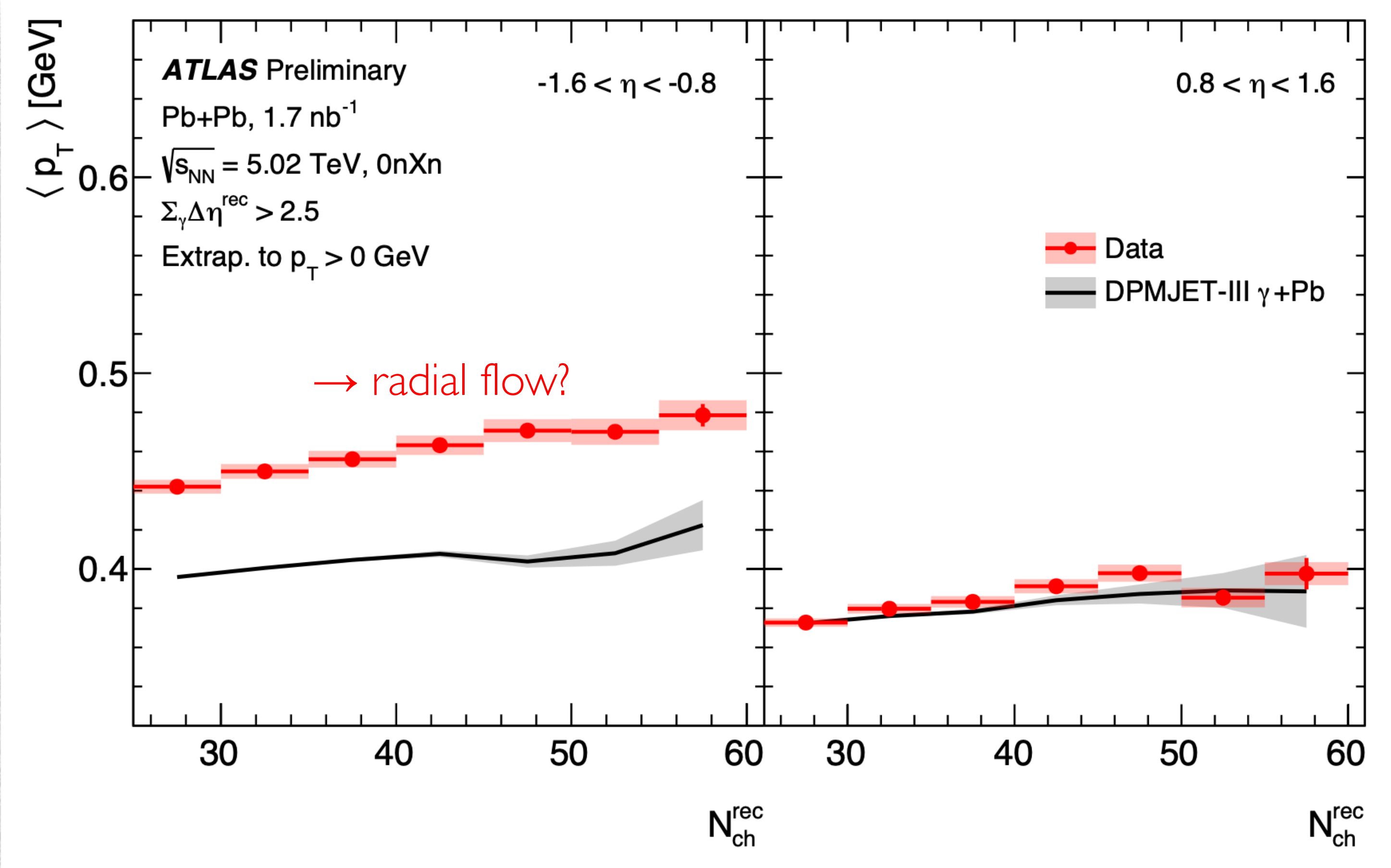
- Indications of radial flow in UPC collisions
  - In backward pseudorapidity region
  - Excess not described well by AMPT

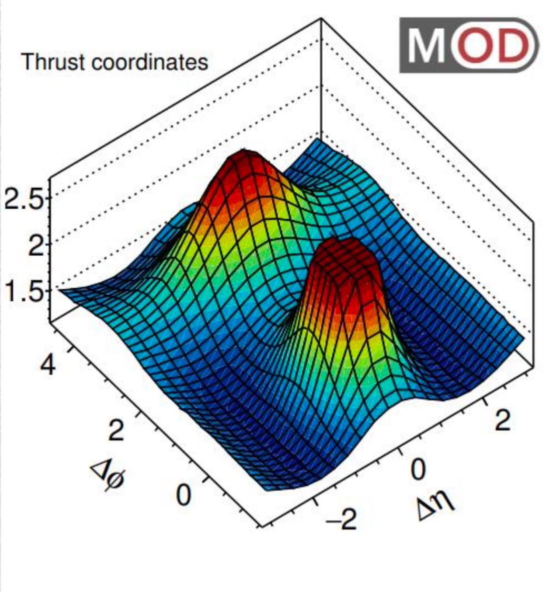


Search for QGP signatures in photo-nuclear events

- Indications of radial flow in UPC collisions
  - In backward pseudorapidity region
  - Excess not described well by AMPT
- Backward η $\langle p_T \rangle$ matches p-Pb at the same multiplicities







Phys. Rev. Lett. 123, 212002 (2019)

What about e^+e^- collisions?

- Minimum-bias e^+e^- collisions: exhibit no near-side ridge
- However: e^+e^- provides access to various processes

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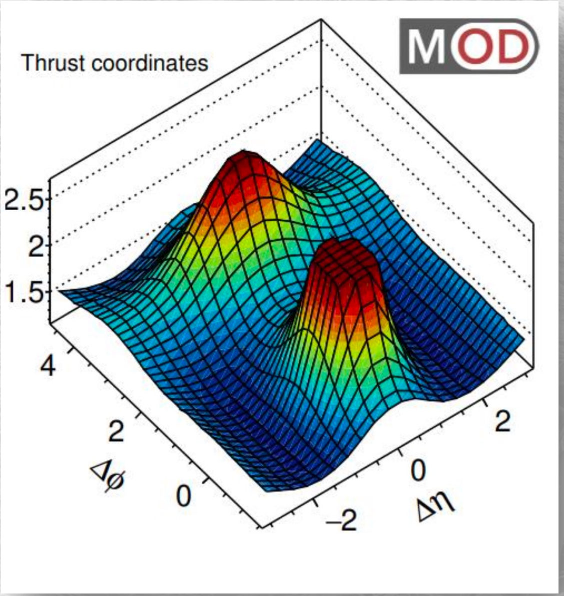

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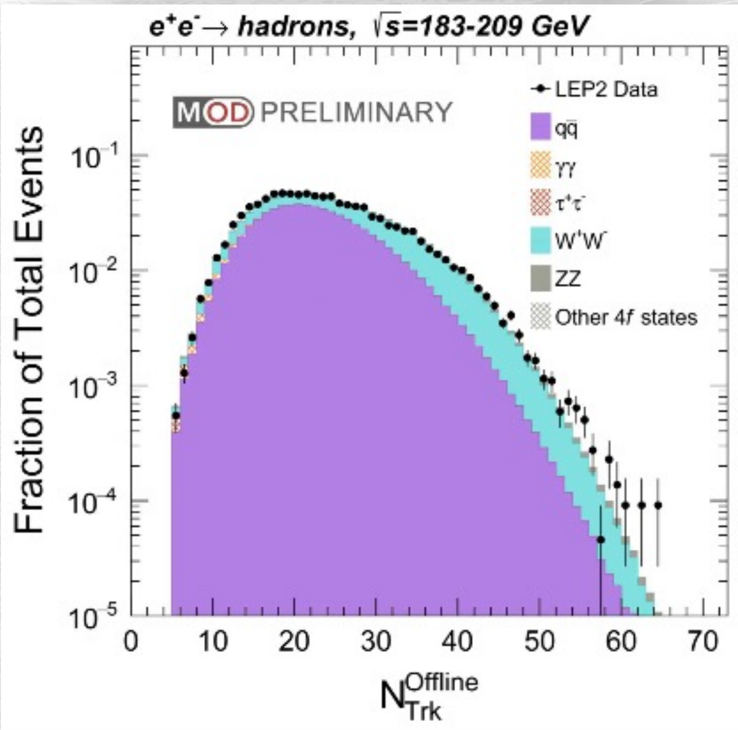

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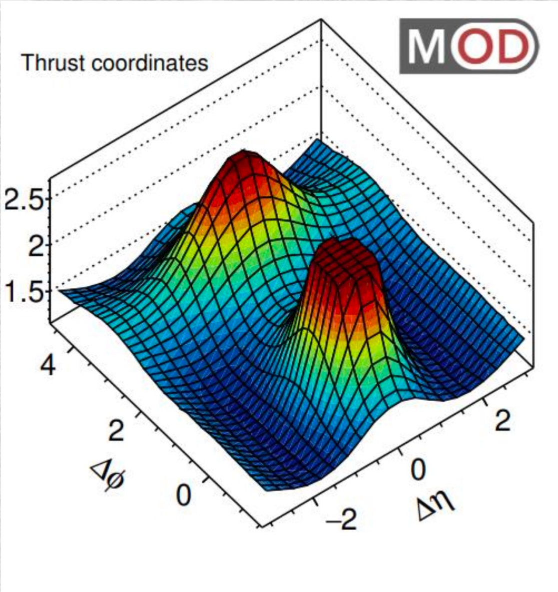

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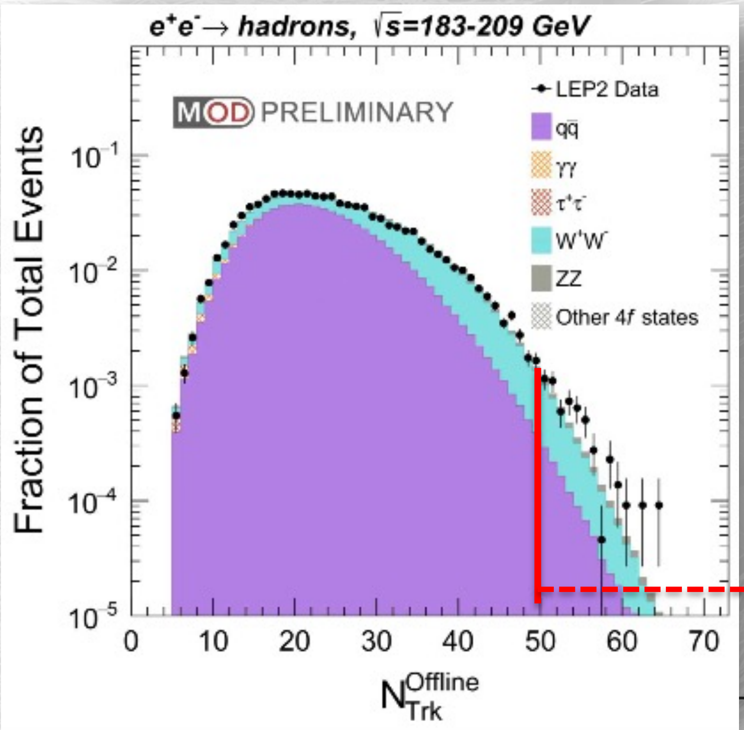

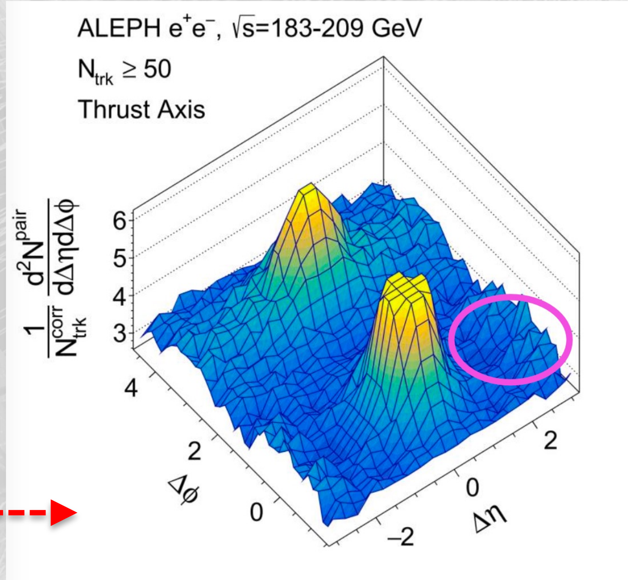

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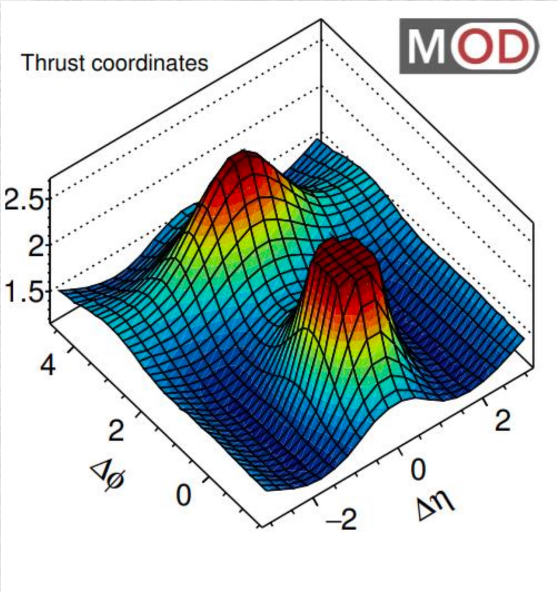
- Minimum-bias e^+e^- collisions: exhibit no near-side ridge
- However: e^+e^- provides access to various processes
  - High-multiplicity e^+e^- enriched with $e^+e^- \to W^+W^-$: a two-string system
  - Results at high multiplicity similar to pp collisions!



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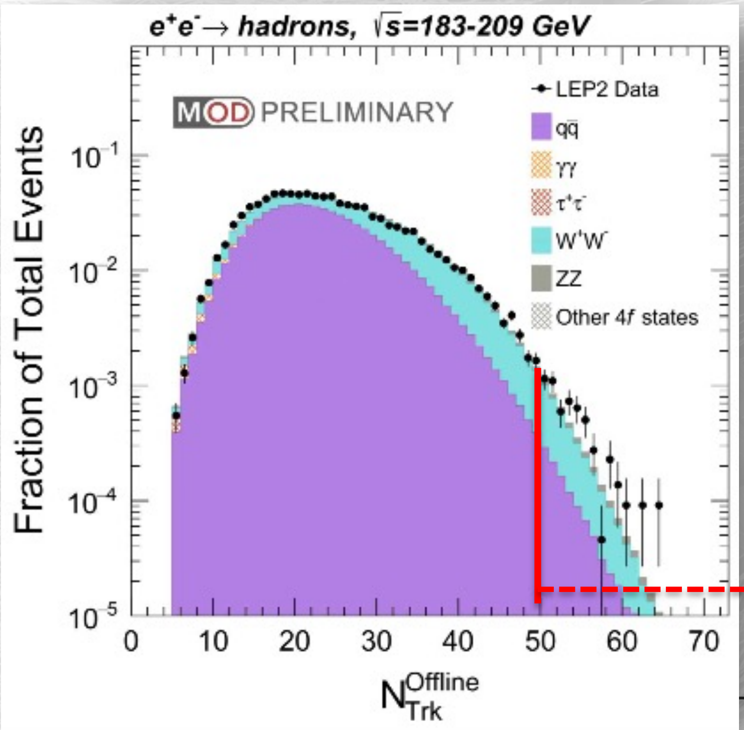
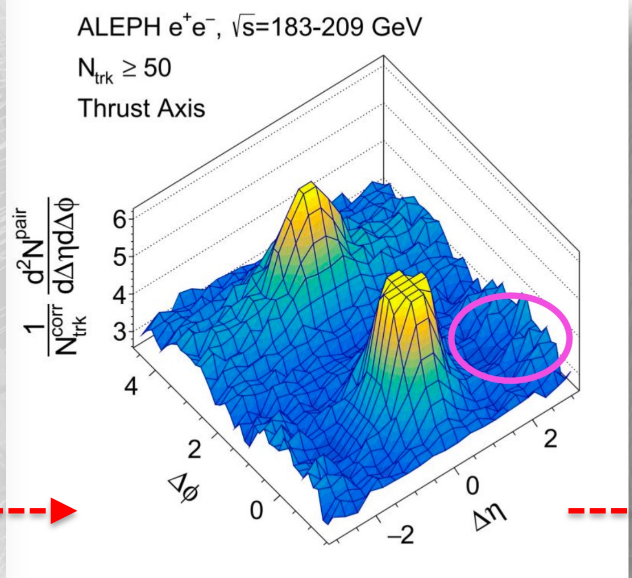
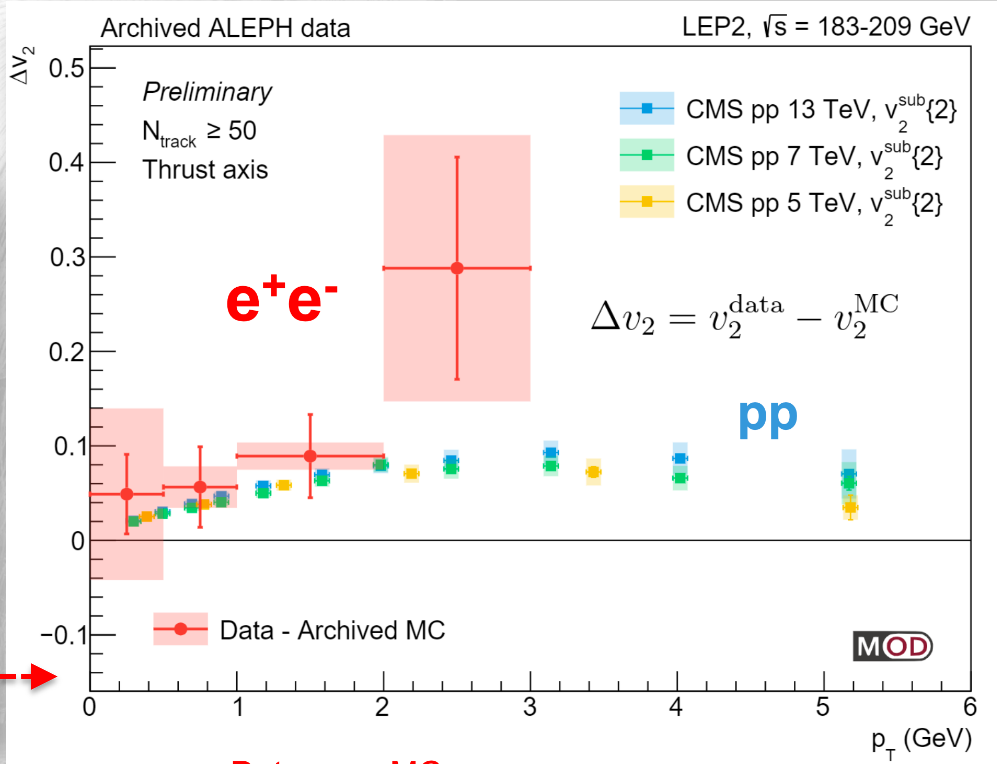


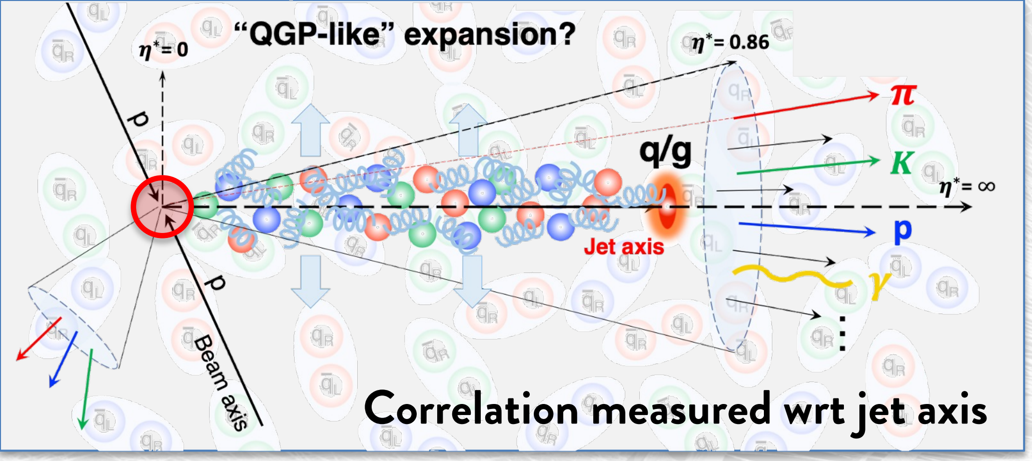


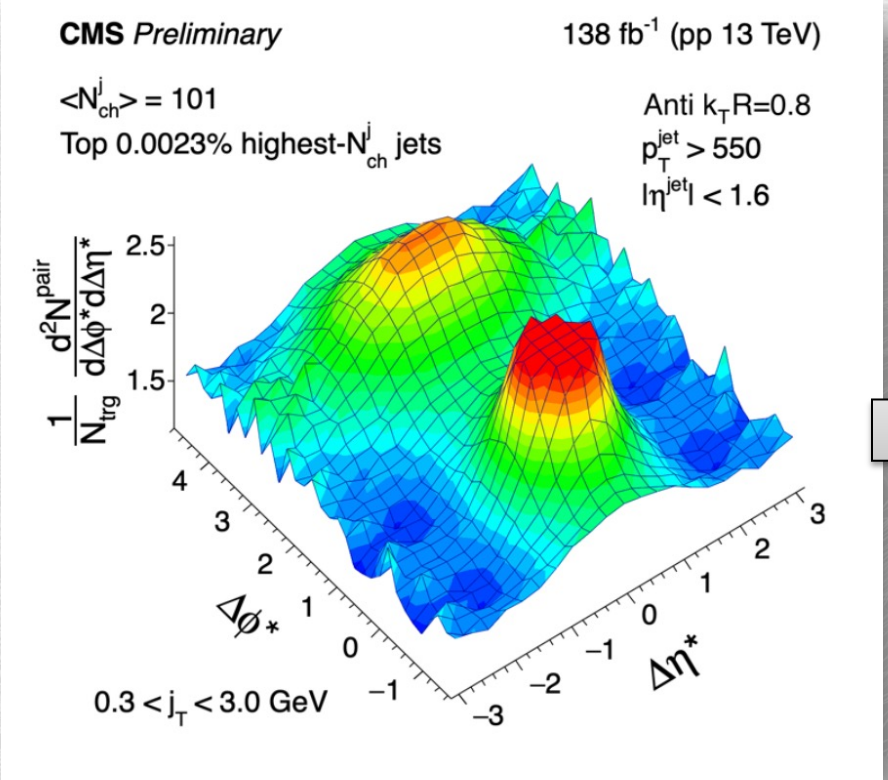


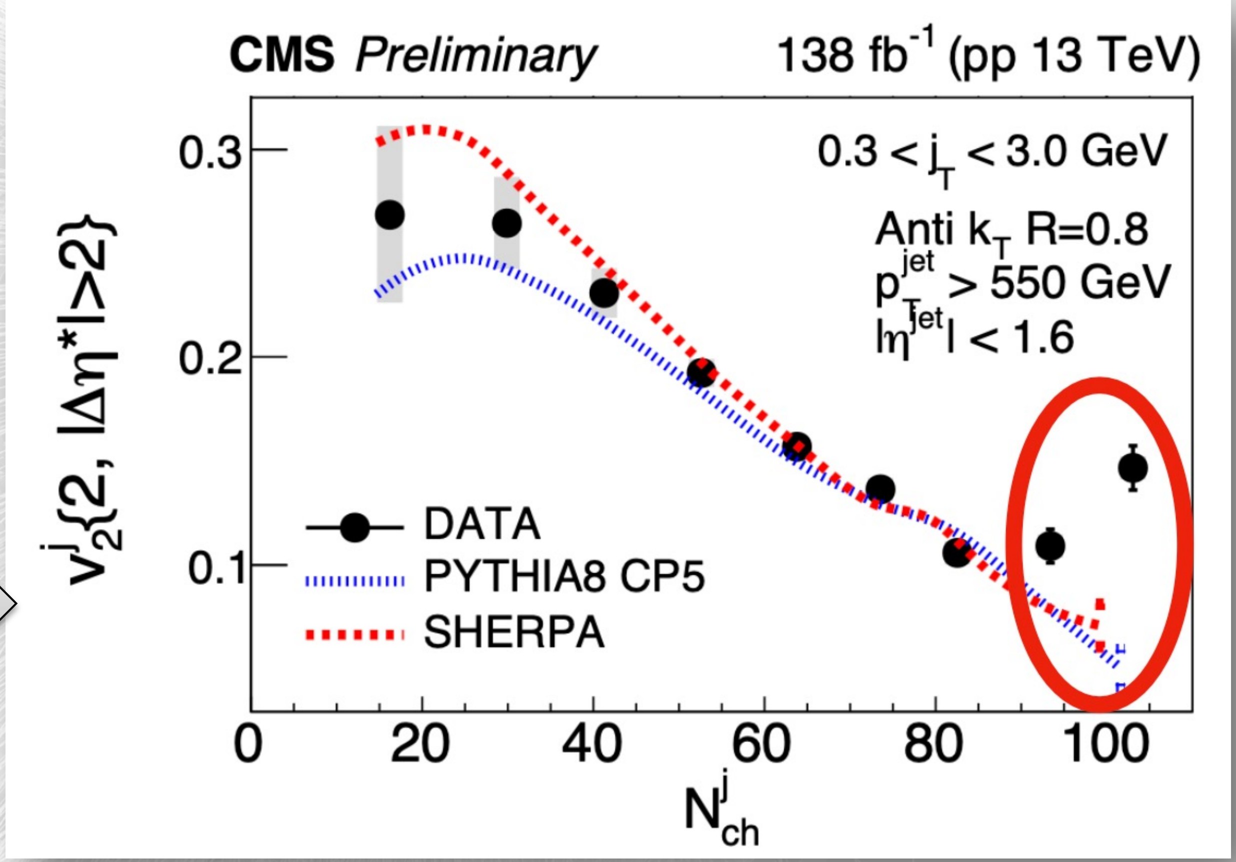
- $\Delta v_2 = v_2^{Data} - v_2^{MC}$

Flow in individual jets?

→ See talk by Parker Gardner



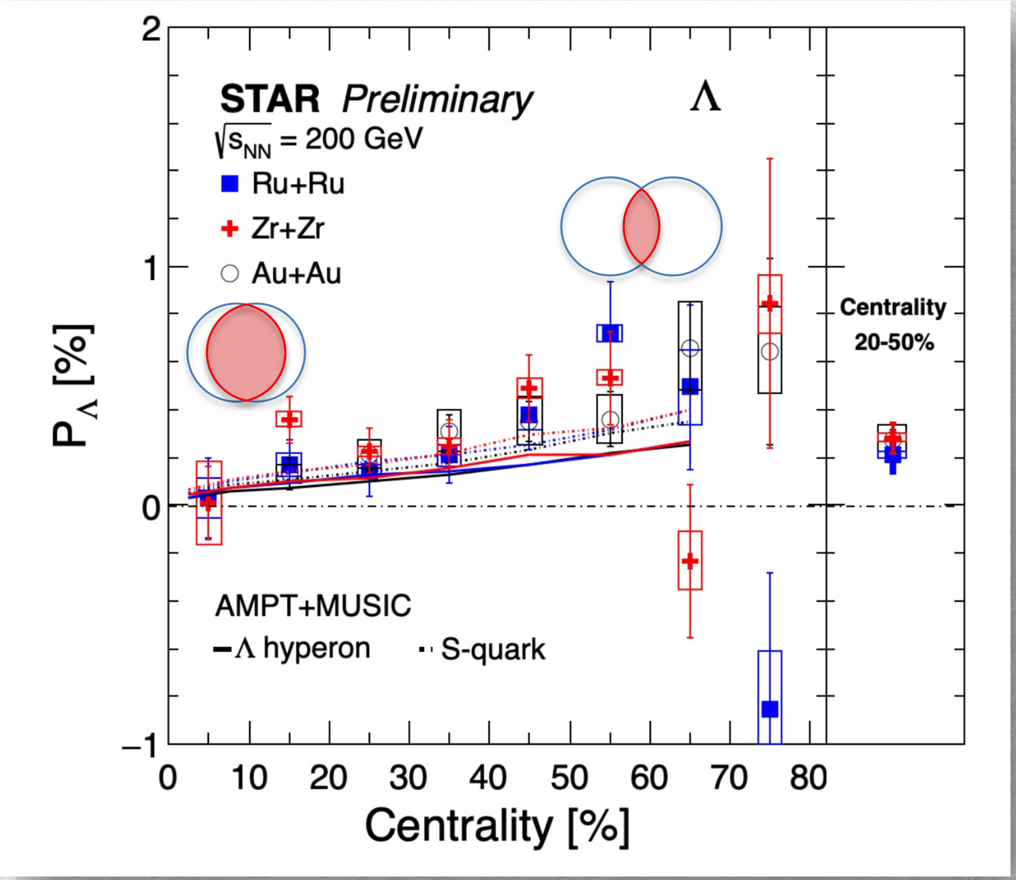


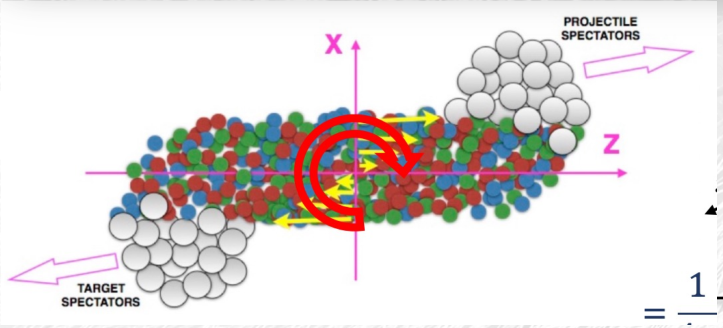


- ✓ Flow correlations
- ✓ Hard/soft interplay

- Elliptic flow with respect to jet axis anomalously high for high N^j_{ch}
- Possibly a sign of collectivity in jets?

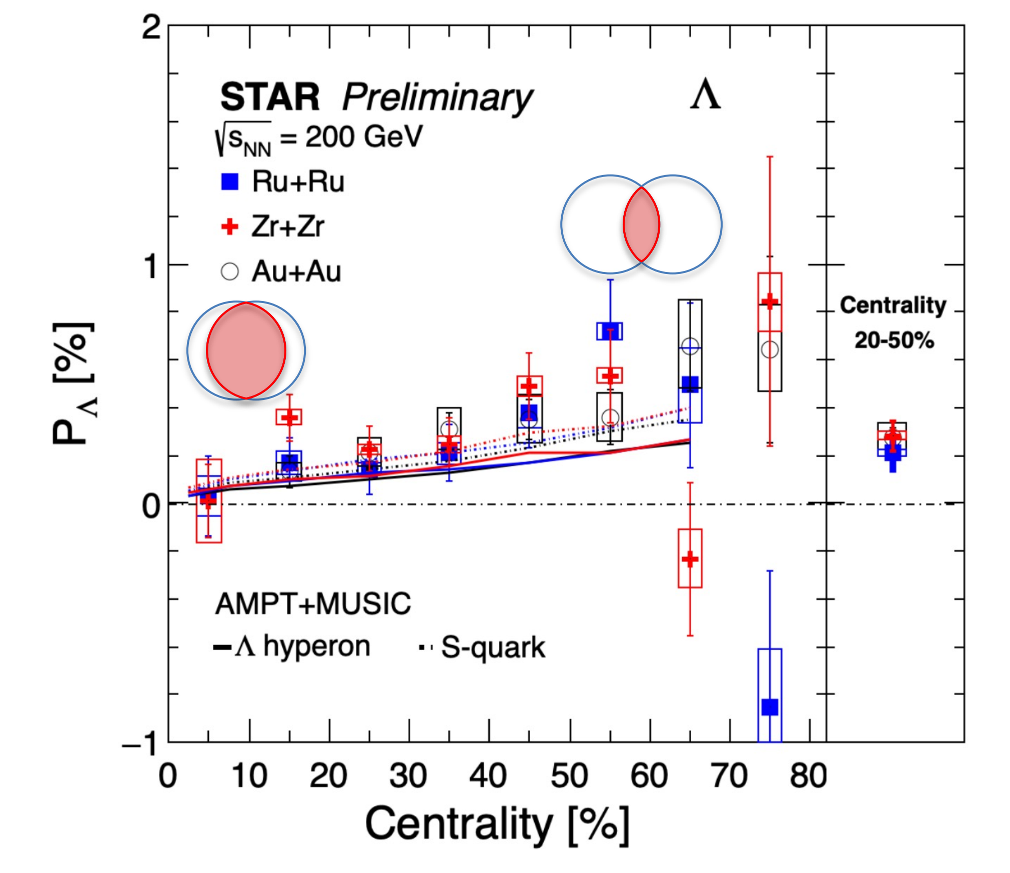
Hyperon polarization and collectivity

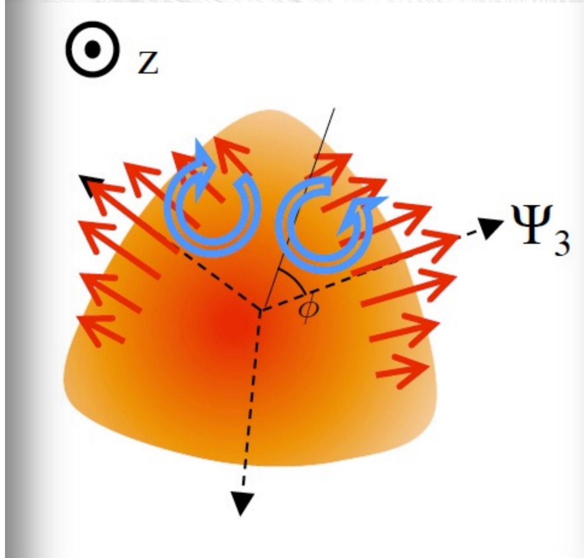


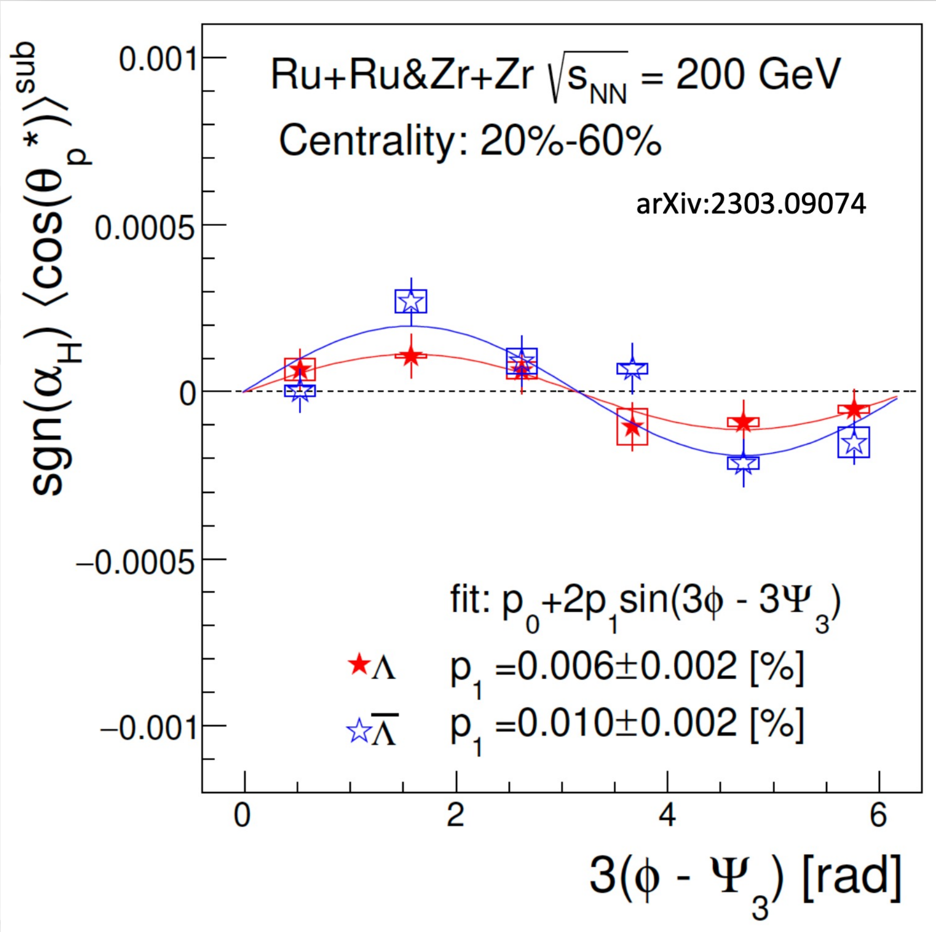


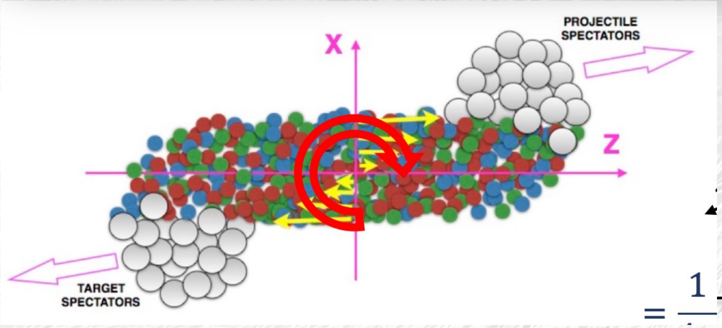
- Hydrodynamic flow impinges polarization to hyperons

Hyperon polarization and collectivity



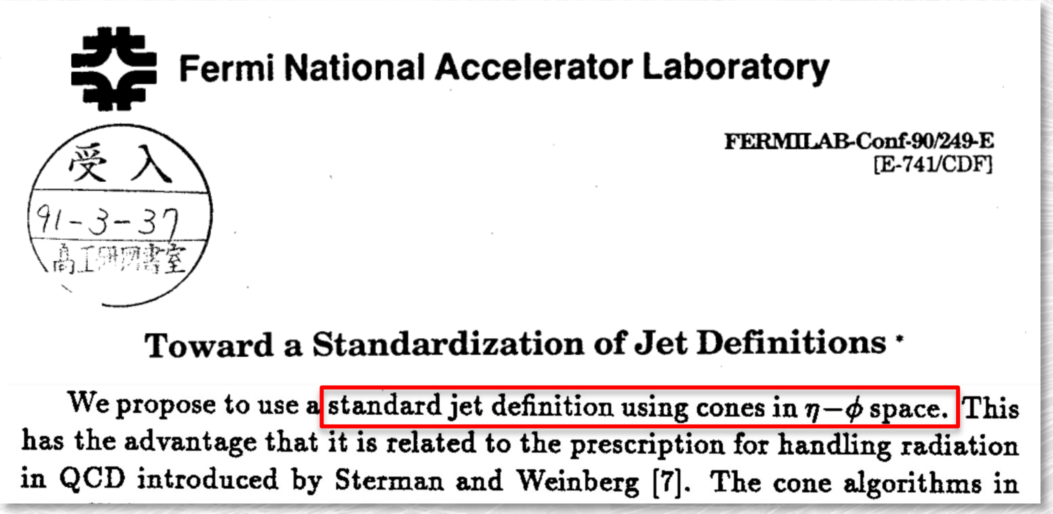






- Hydrodynamic flow impinges polarization to hyperons
- Now: first observation of polarization wrt third-order event plane
- Other directions of polarization studies being explored: hard/soft interplay and jet quenching

Studying how particles are emitted with respect to each other


Fermi National Accelerator Laboratory

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[E-741/CDF]

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高工研図書室

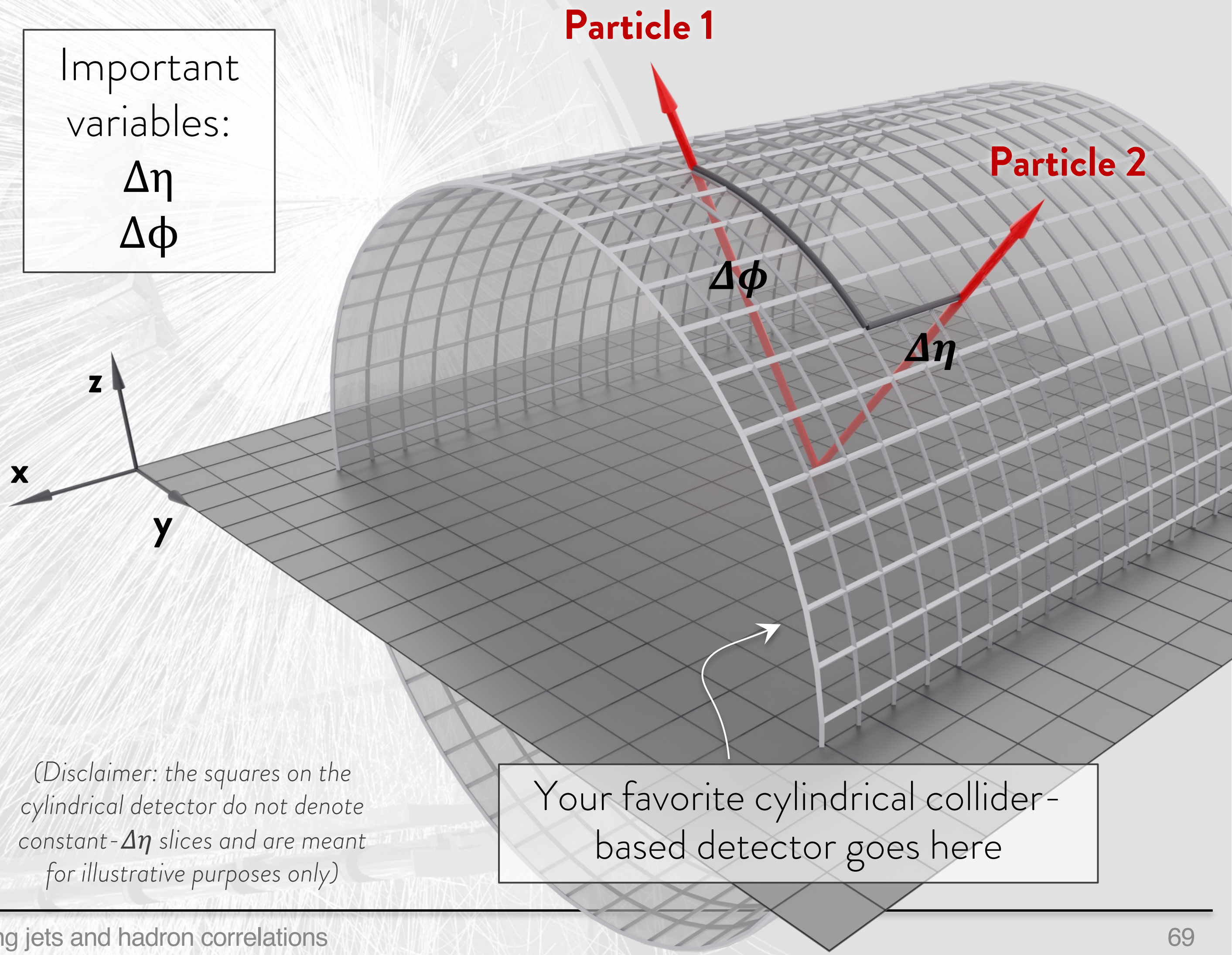
Toward a Standardization of Jet Definitions *

We propose to use a standard jet definition using cones in $\eta-\phi$ space. This has the advantage that it is related to the prescription for handling radiation in QCD introduced by Sterman and Weinberg [7]. The cone algorithms in

Important variables:

$\Delta\eta$

$\Delta\phi$

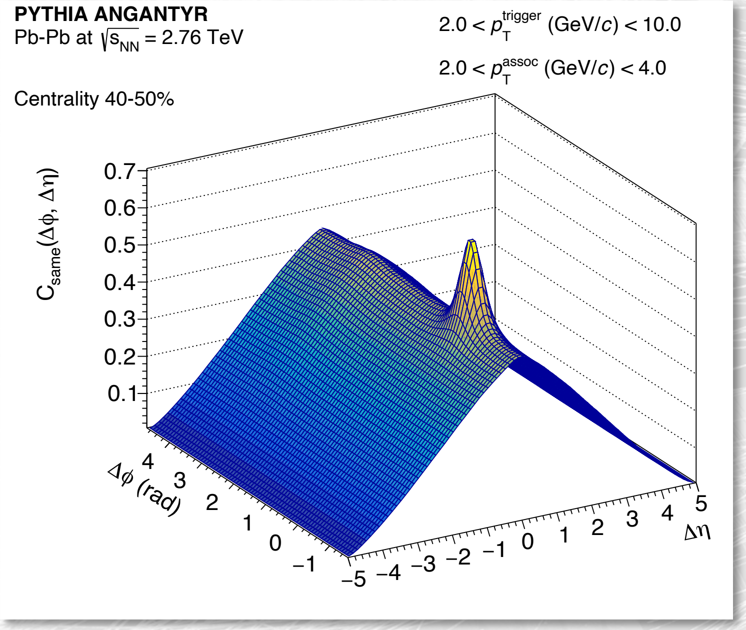


Let's attempt something slightly different:

- Let's try to look into how each particle is laid out with respect to others in $\eta - \phi$ space!
- This allows us to study jets from a different, **complementary point of view**
- ...and look at **a few other phenomena** as well

(Disclaimer: the squares on the cylindrical detector do not denote constant-$\Delta\eta$ slices and are meant for illustrative purposes only)

Two-particle correlation measurements: the basic calculation

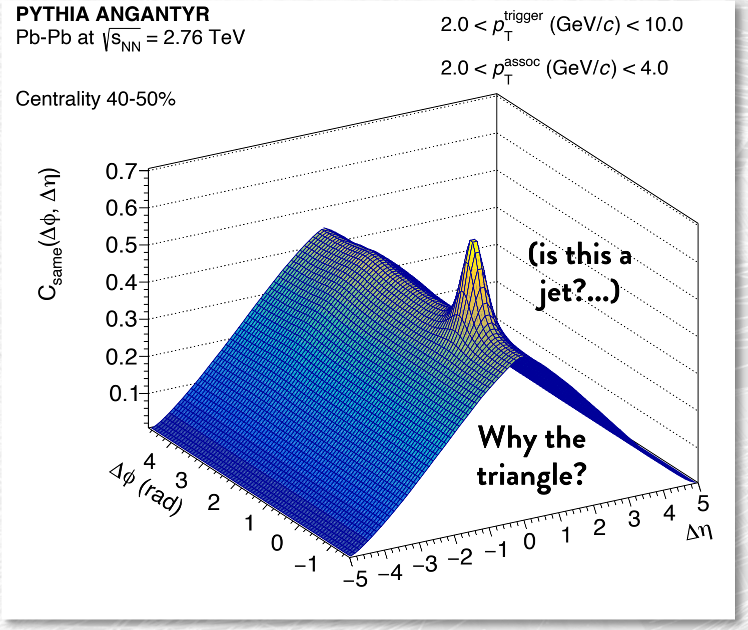


Same-event correlation function:

$C_{same}(\Delta\eta, \Delta\phi)$

How many times a certain **associated** particle was found in a certain position with respect to a **trigger** particle

Two-particle correlation measurements: the basic calculation



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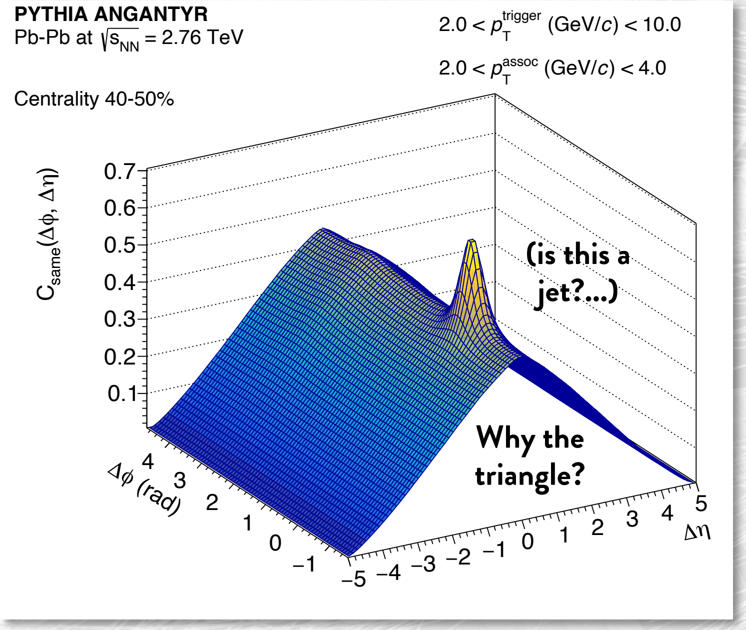
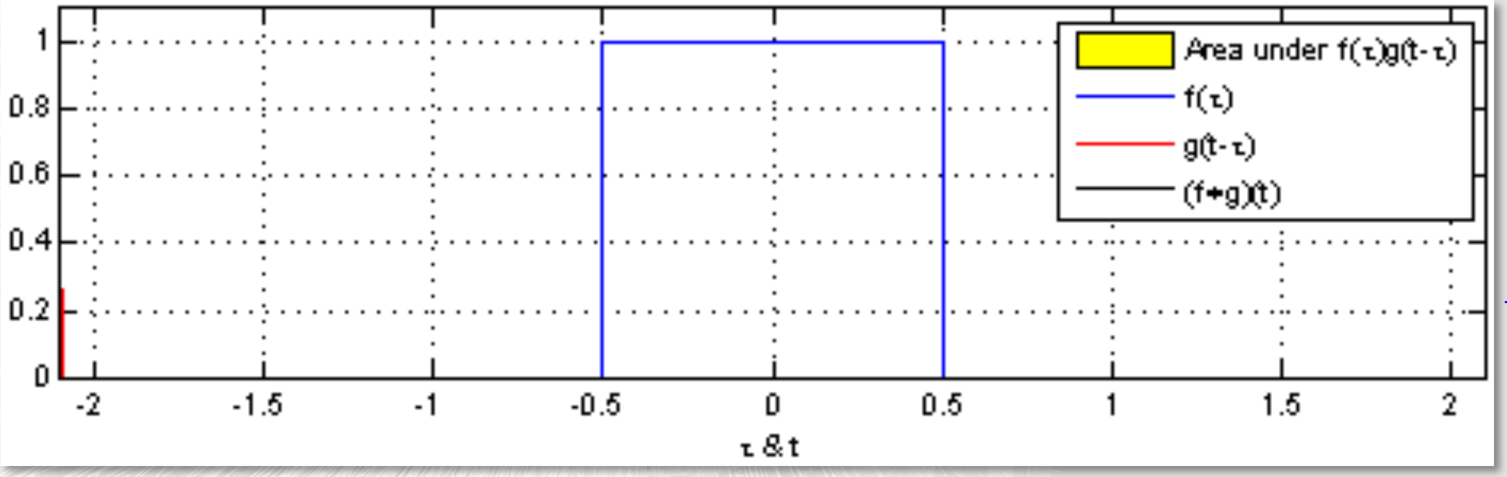




source: wikipedia

Same-event correlation function:

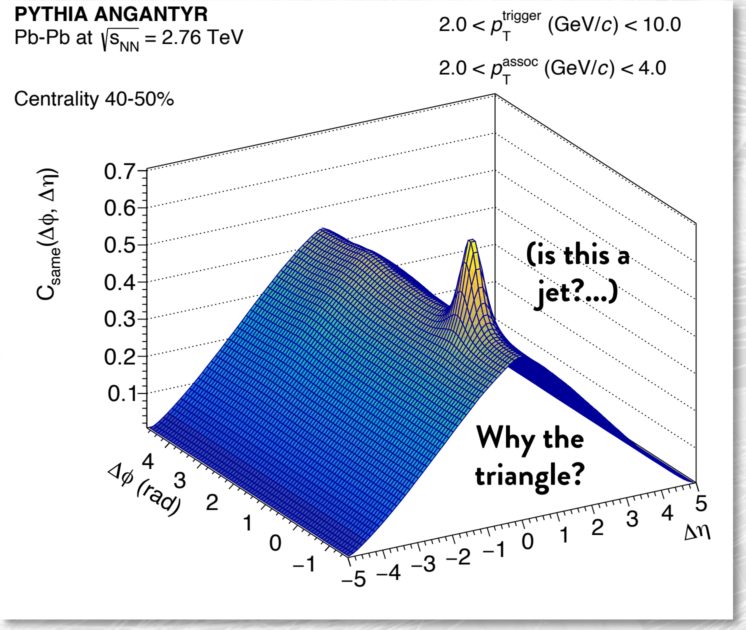
$$C_{same}(\Delta\eta, \Delta\phi)$$

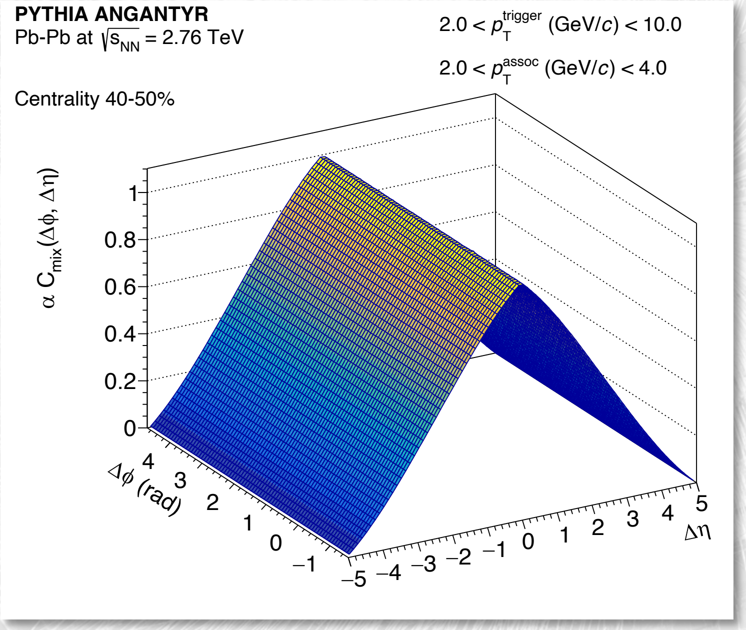
How many times a certain **associated** particle was found in a certain position with respect to a **trigger** particle

Turns out this is **an acceptance effect**.

- Whenever you have a **trigger**, a **certain region of pseudorapidity will be removed** because you ran out of detector to measure it.
- This is an effect you do not want! → correction needed
- And it is probabilistic (meaning: multiplicative...)

Two-particle correlation measurements: the basic calculation





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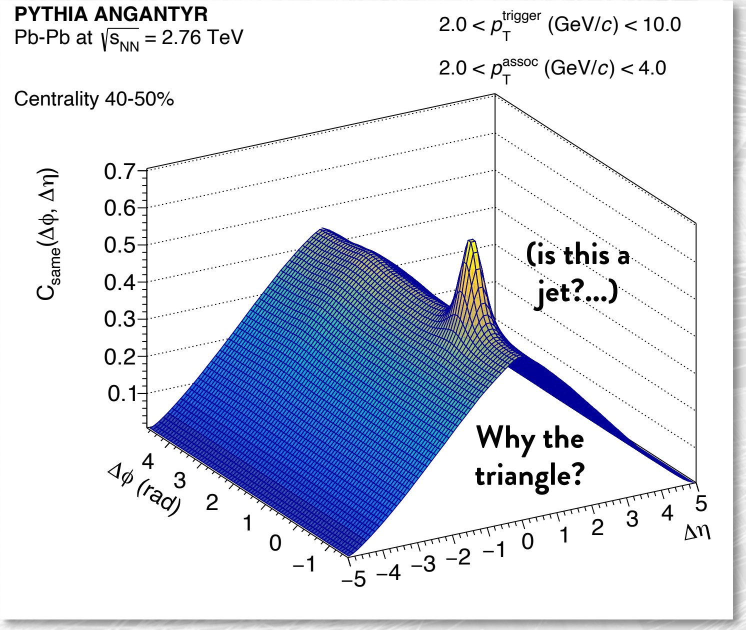
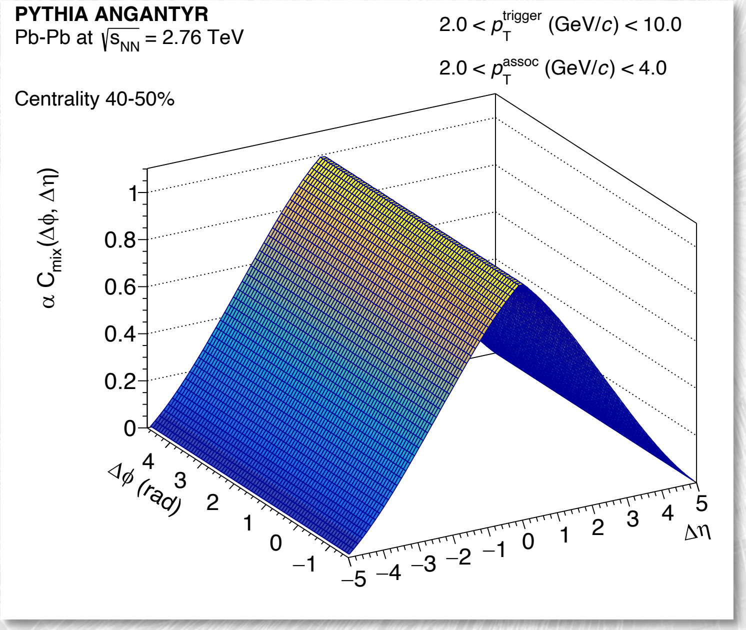
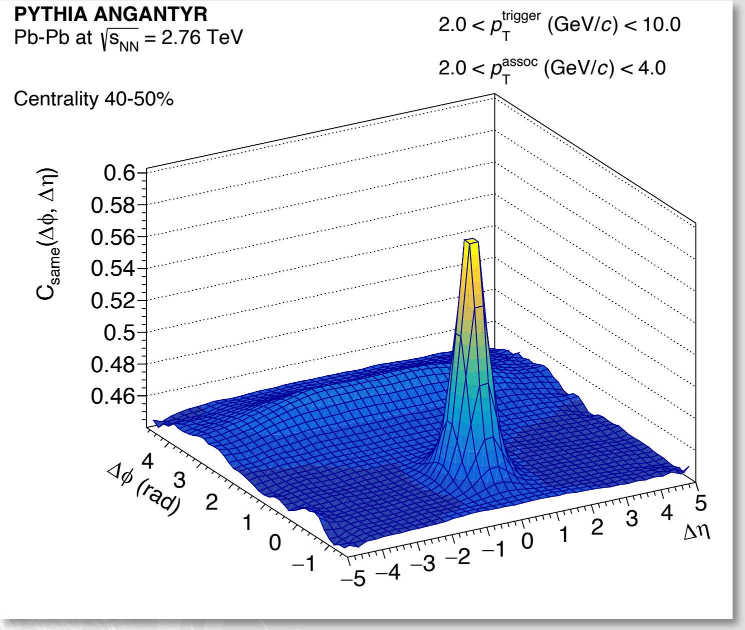
What is the probability you will miss the associated particle at a given $\Delta\eta$?

Interesting: normalized to 1 at $\Delta\eta = \Delta\phi = 0$

Two-particle correlation measurements: the basic calculation







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$C_{mixed}(\Delta\eta, \Delta\phi)$

What is the probability you will miss the associated particle at a given $\Delta\eta$?

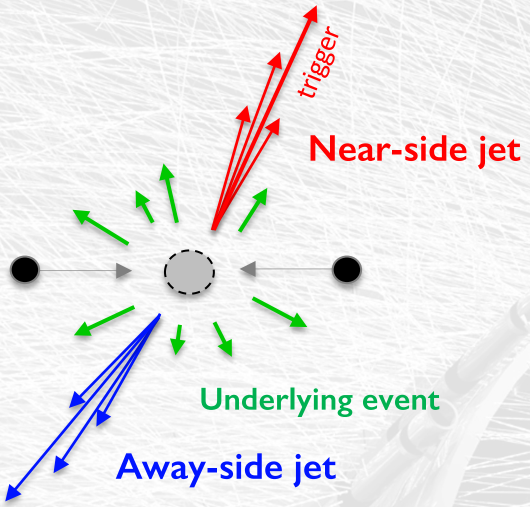
Interesting: normalized to 1 at $\Delta\eta = \Delta\phi = 0$

Corrected correlation function:

$$C(\Delta\eta, \Delta\phi) = \frac{C_{same}(\Delta\eta, \Delta\phi)}{C_{mixed}(\Delta\eta, \Delta\phi)}$$

→ *ok, that's the one!*

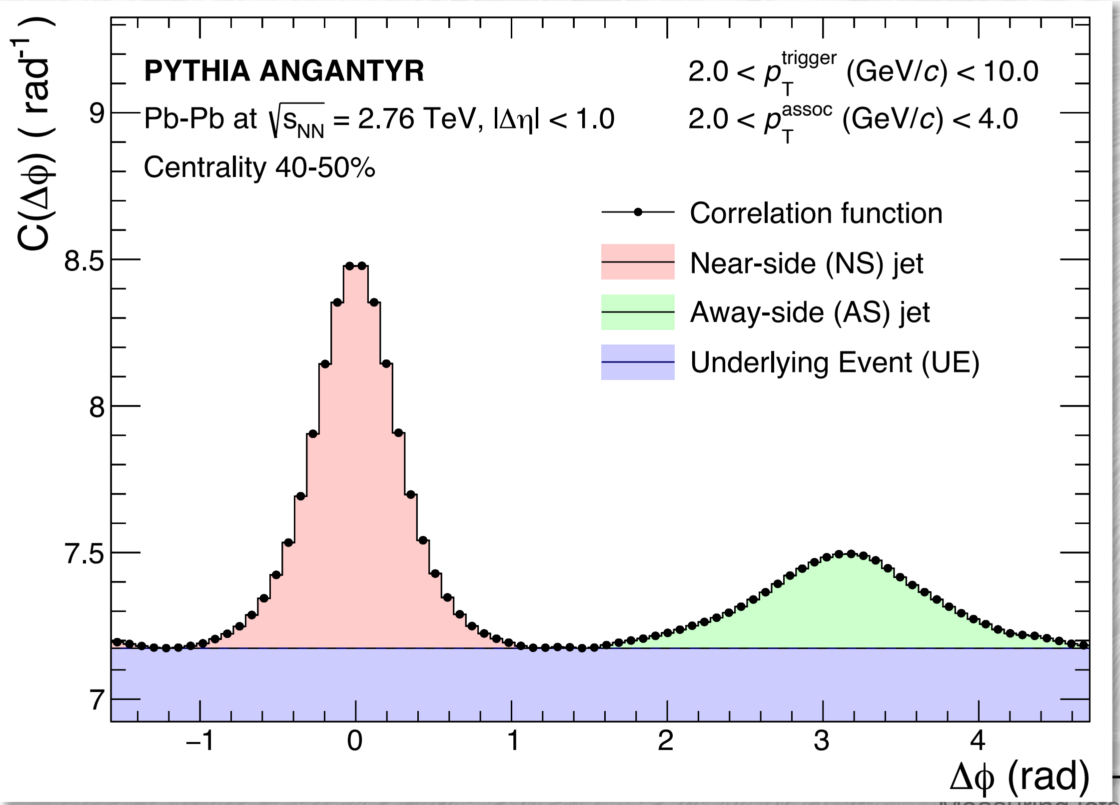
The ‘standard’ components of a correlation



→ in the *absence of collective expansion, a correlation will be comprised of:*

- **Near-side jet**: particles emitted in the same direction as your trigger particle.
- **Away-side jet**: particles emitted in exactly the opposite direction as your trigger. Needed for momentum conservation.
- **Underlying event**: a certain number of particles that is in the event but are seemingly unrelated (any random $\Delta\phi$) to your trigger particle.

Fantastically useful already!



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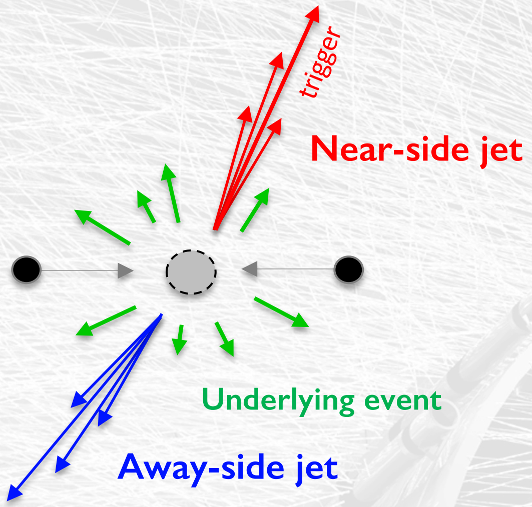

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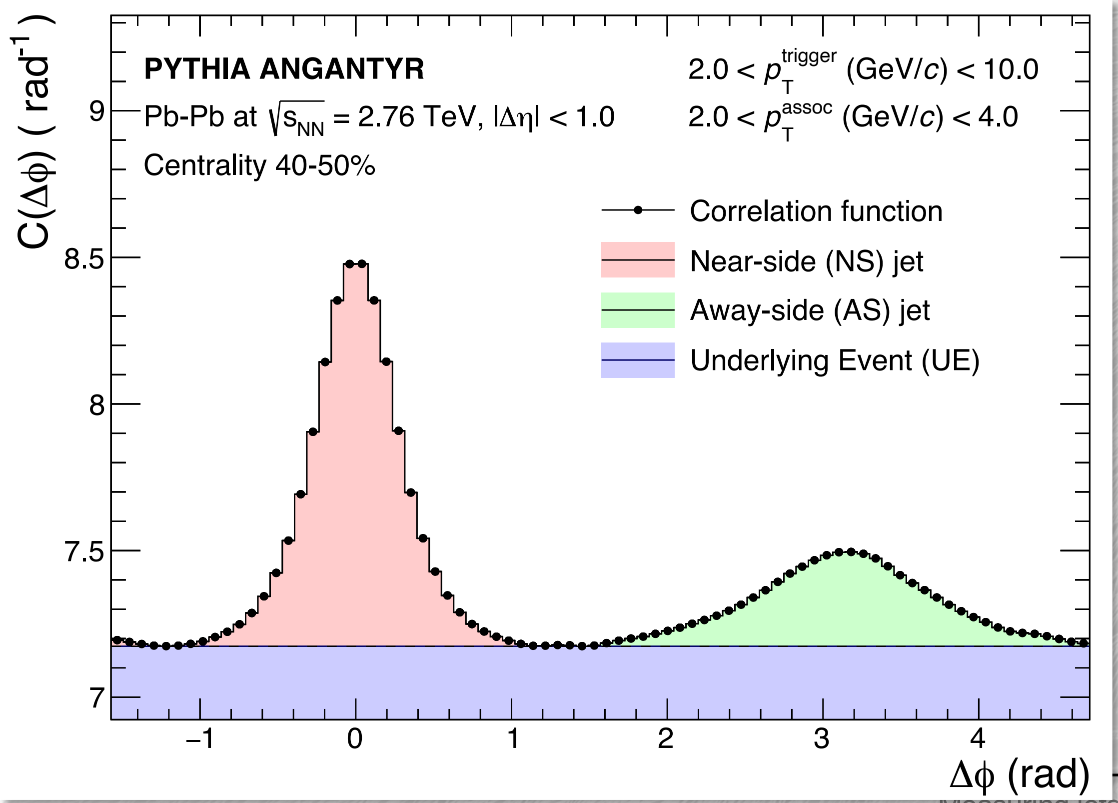
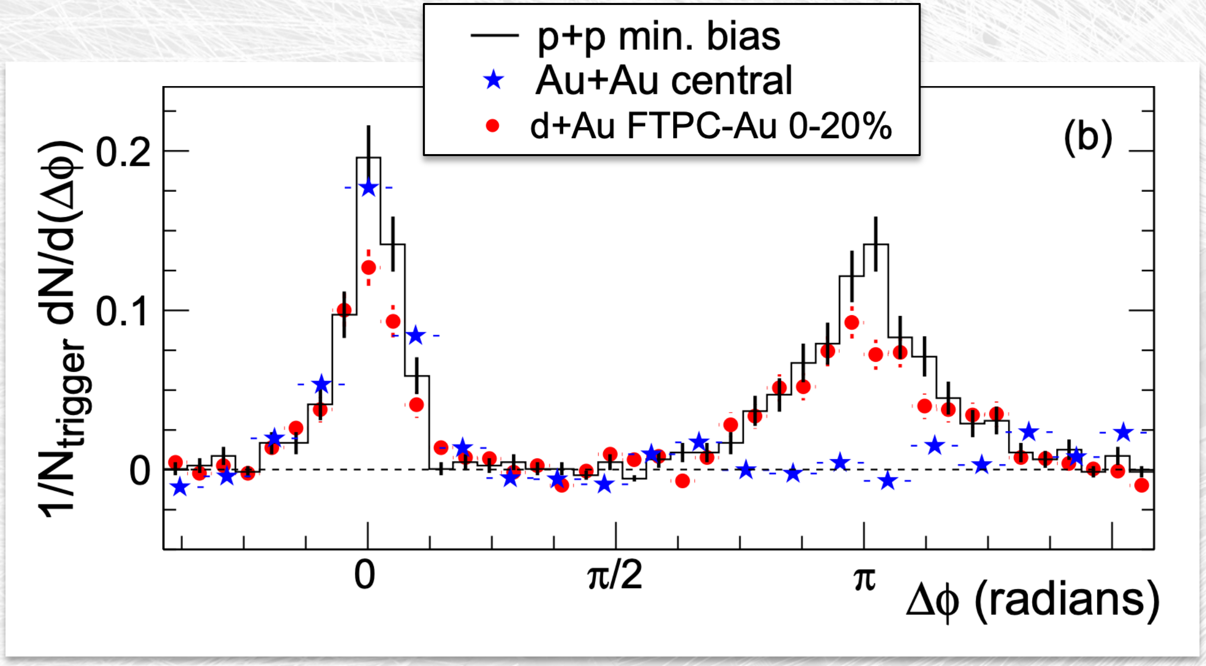


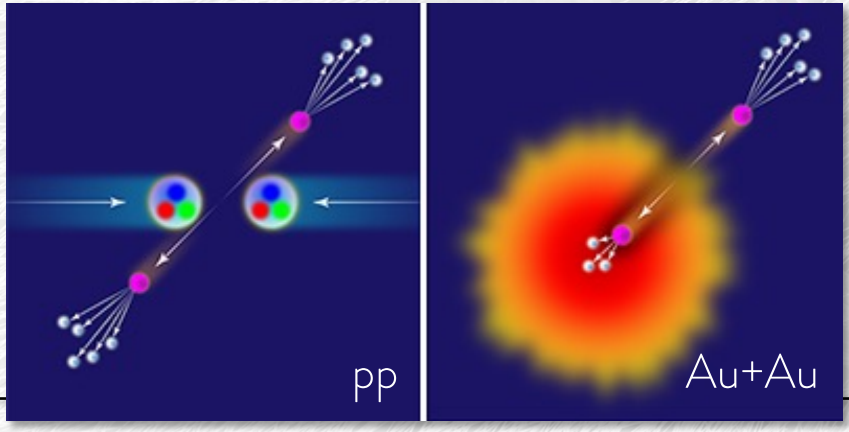
Fantastically useful already! But …

- **Warning 1**: this is an *average* emission function effectively calculated for many jet-like particle structures
- **Warning 2**: the underlying event is *not* free of jets!
- **Warning 3**: Many *resonances* decay into two particles…

The STAR observation of jet quenching (> 20 years ago!)



STAR Collab, Phys.Rev.Lett.91 (2003) 072304



This simple picture breaks down in AA:

- **The away side is missing**!
- It has been "quenched" by the medium
- QCD matter is opaque to high momentum particles
- not present in d+Au: **'cold' matter is transparent**
- An example of **complementarity** with yesterday's nuclear modification factor R_{AA} !

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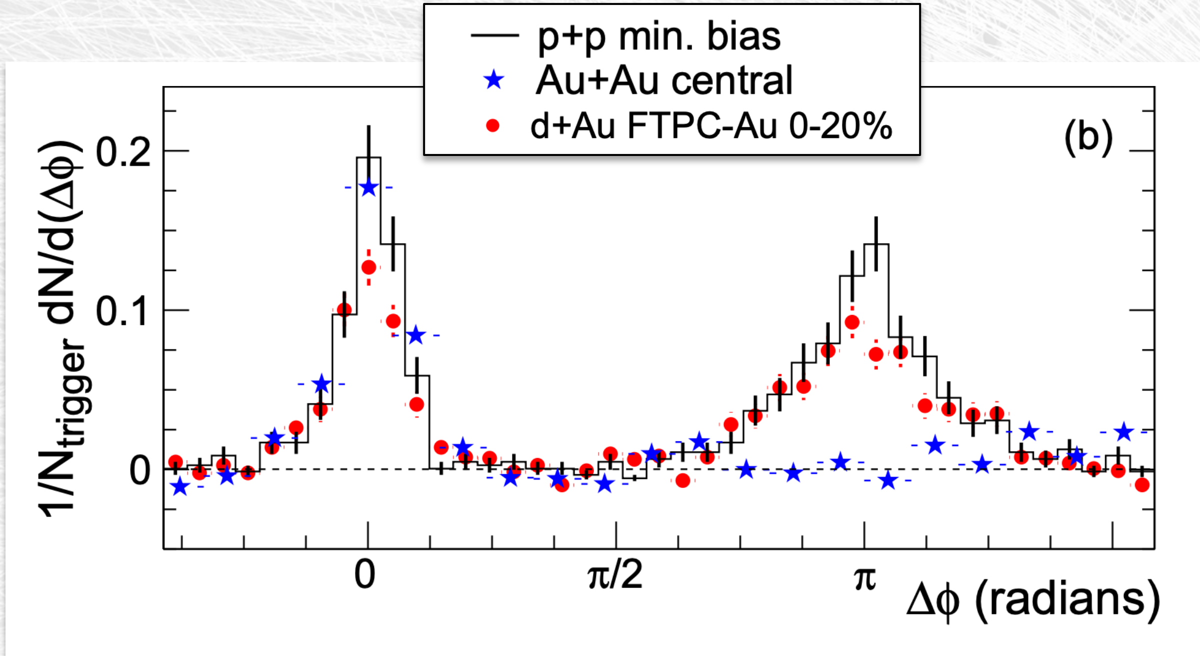

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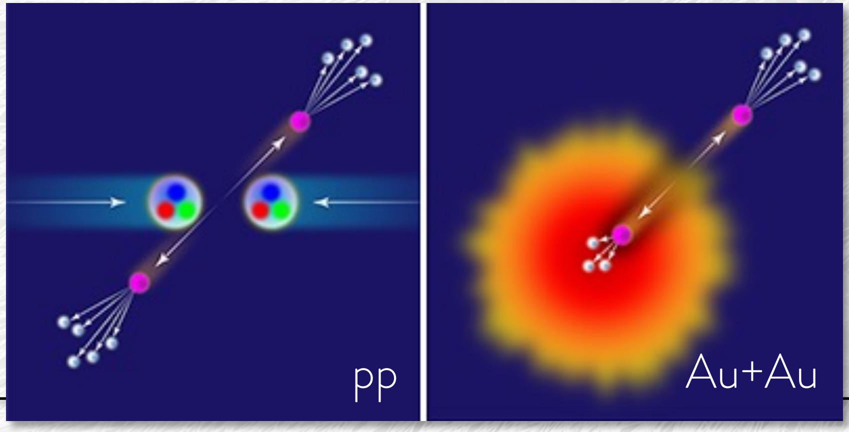

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- not present in d+Au: **'cold' matter is transparent**
- An example of **complementarity** with yesterday's nuclear modification factor R_{AA} !

However: in order to do this measurement, some background effects and correlations unrelated to jets had to be accounted for …

→ **What are those effects?**