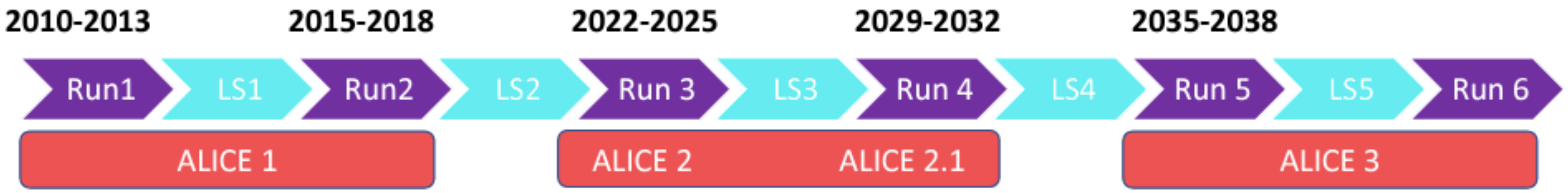
Highlights from the ALICE Experiment

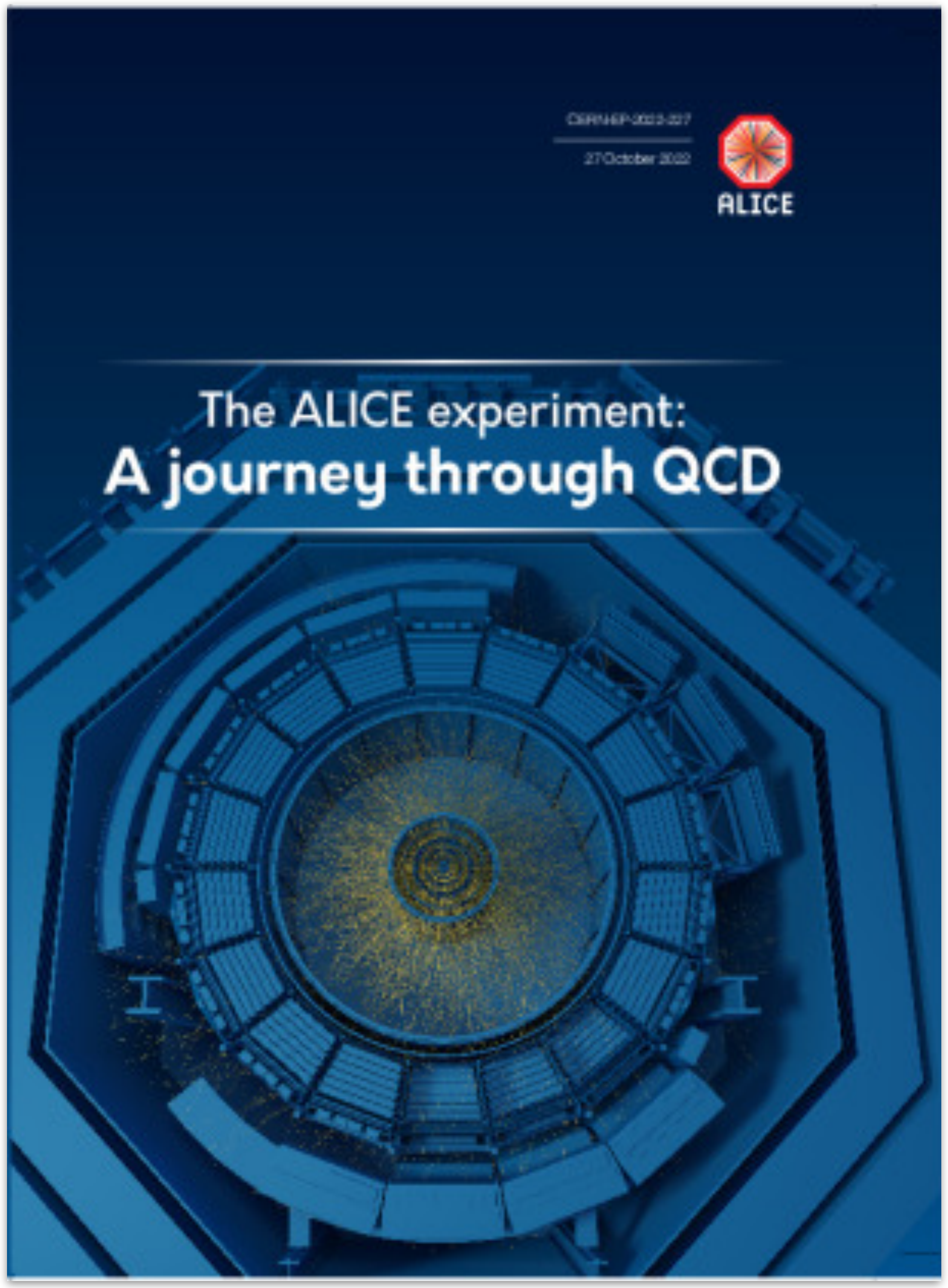
Lake Louise Winter Institute 2023

Hannah Bossi (Yale) for the ALICE Collaboration

Outline: A journey through QCD

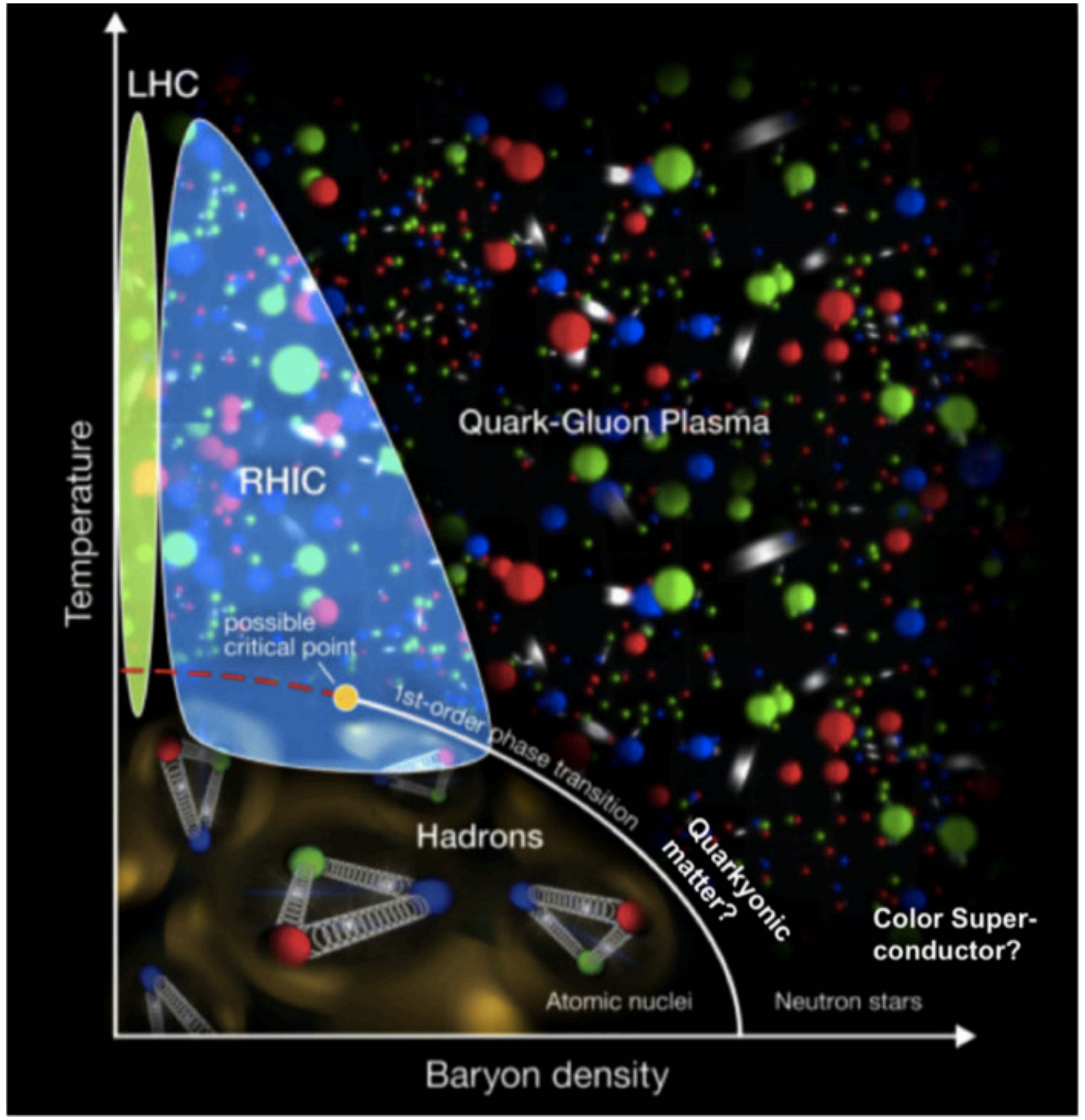


arXiv:2211:04384 ~ 400 pages



- Introduction to hot QCD
- Selected Physics Highlights from Run 1 and 2 of the LHC
  - Macroscopic properties of the QGP
  - Dynamical Properties of the QGP
  - Parton interactions with the QGP
- ALICE in Run 3 and beyond!

QCD Phase Diagram



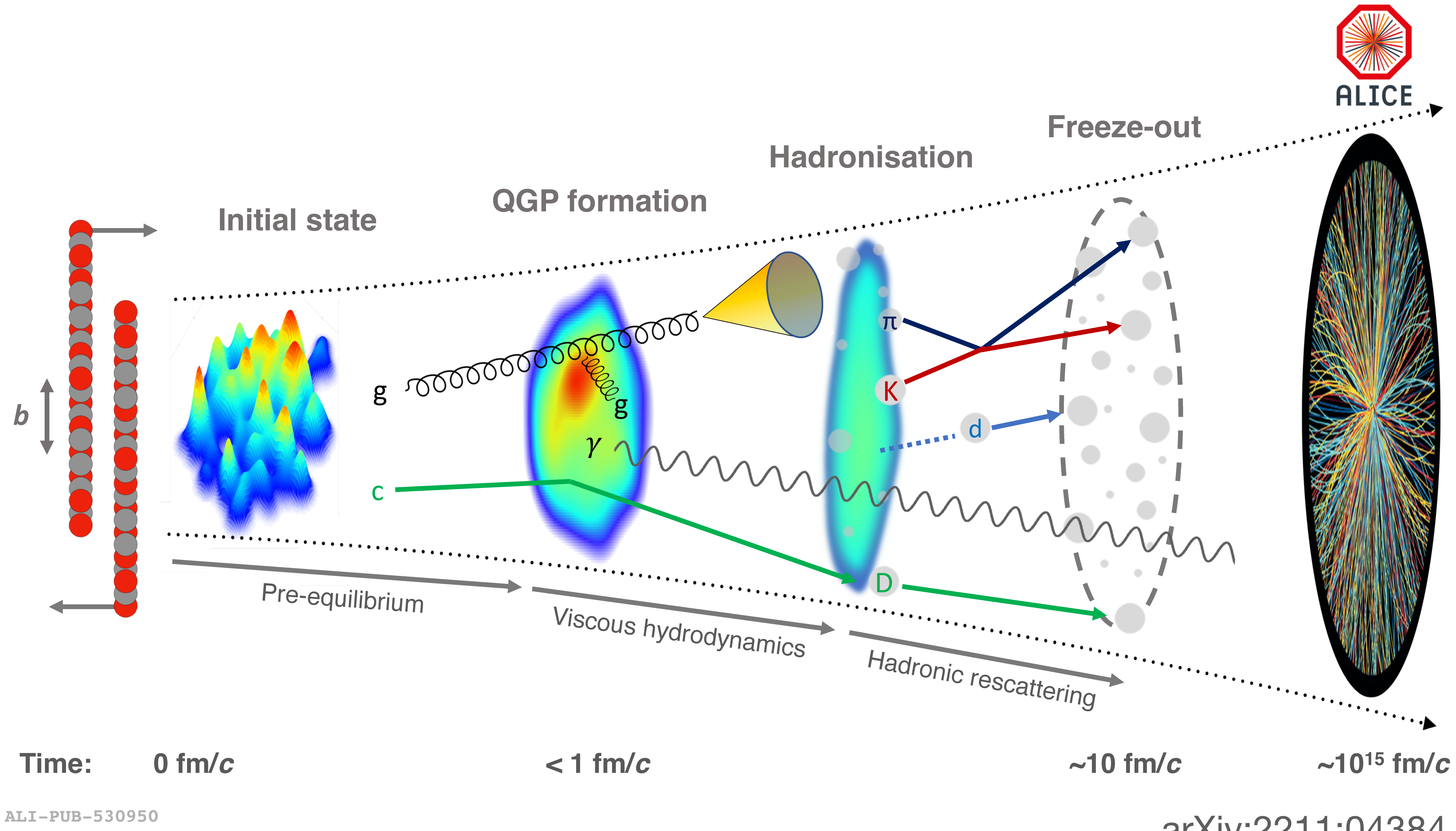
When temperature becomes hot enough QCD matter becomes a deconfined state of quarks and gluons called the **Quark-Gluon Plasma (QGP)**

Similar conditions are thought to have existed just a few μs after Big Bang.

Lattice QCD predicts smooth crossover at $\mu_{\mathrm{B}} = 0$ and $T_c \sim 150$ MeV.

Can experimentally reproduce these extreme conditions with heavy-ion collisions at RHIC and LHC!!

Evolution of a Heavy-Ion Collision



arXiv:2211:04384

QGP follows a hydrodynamical evolution, expands and cools, then hadronizes.

These hadrons free stream and are measured in the ALICE detector!

Use different probes to collect information about each stage of the collision!

Full picture allows us to characterize the QGP and provides a rich lab for studying QCD!

A Large Ion Collider Experiment

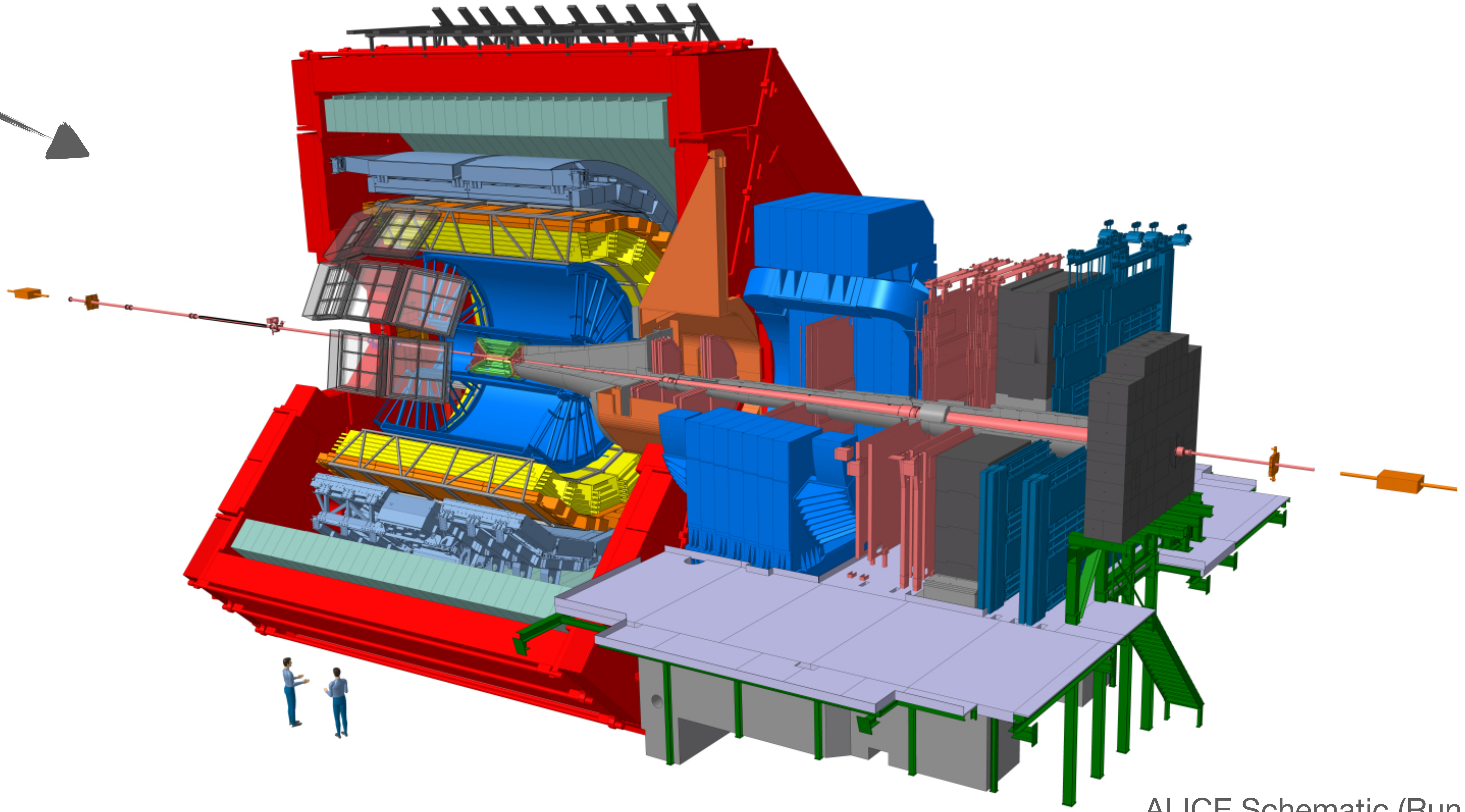
The Large Hadron Collider, CERN

Located 56 m below surface at P2 of the LHC.

Optimized for precise tracking and PID in high-multiplicity environments!

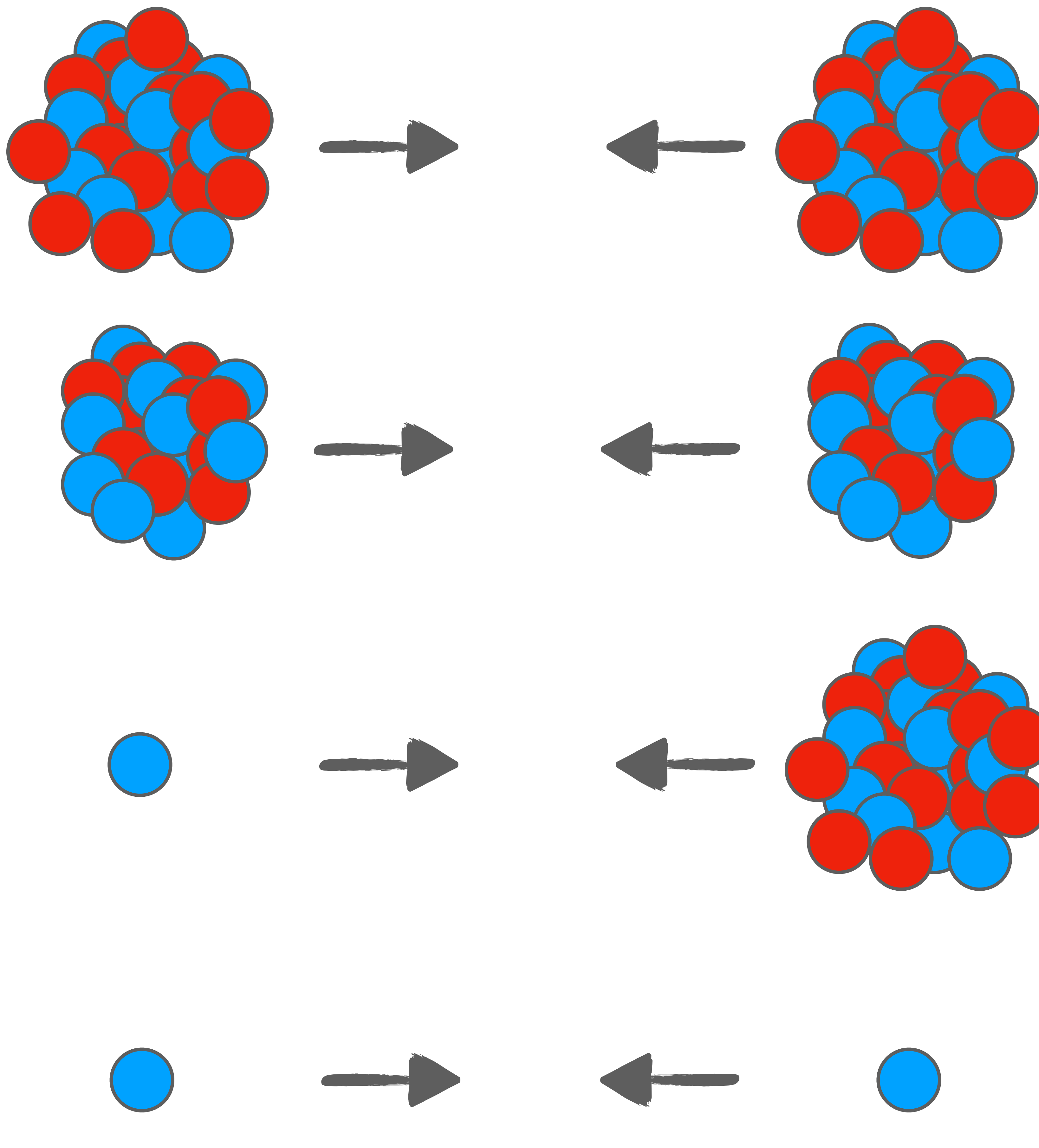
Many sub-detectors!

- Inner Tracking System
- Time Projection Chamber
- Transition Radiation Detector
- Time of Flight
- Electromagnetic Calorimeter


ALICE Schematic (Run 2)

ALICE Collision Systems

ALICE studies both small and large collision systems!



Pb—Pb: Pb^{208} collided at $\sqrt{s_{NN}} = 2.76, 5.02, 5.36$ TeV

→ Study the QGP

Xe—Xe: Xe^{129} collided at $\sqrt{s_{NN}} = 5.44$ TeV

→ Study the system-size dependence of QGP effects

p—Pb: collided at $\sqrt{s_{NN}} = 5.02 , 8.16$ TeV

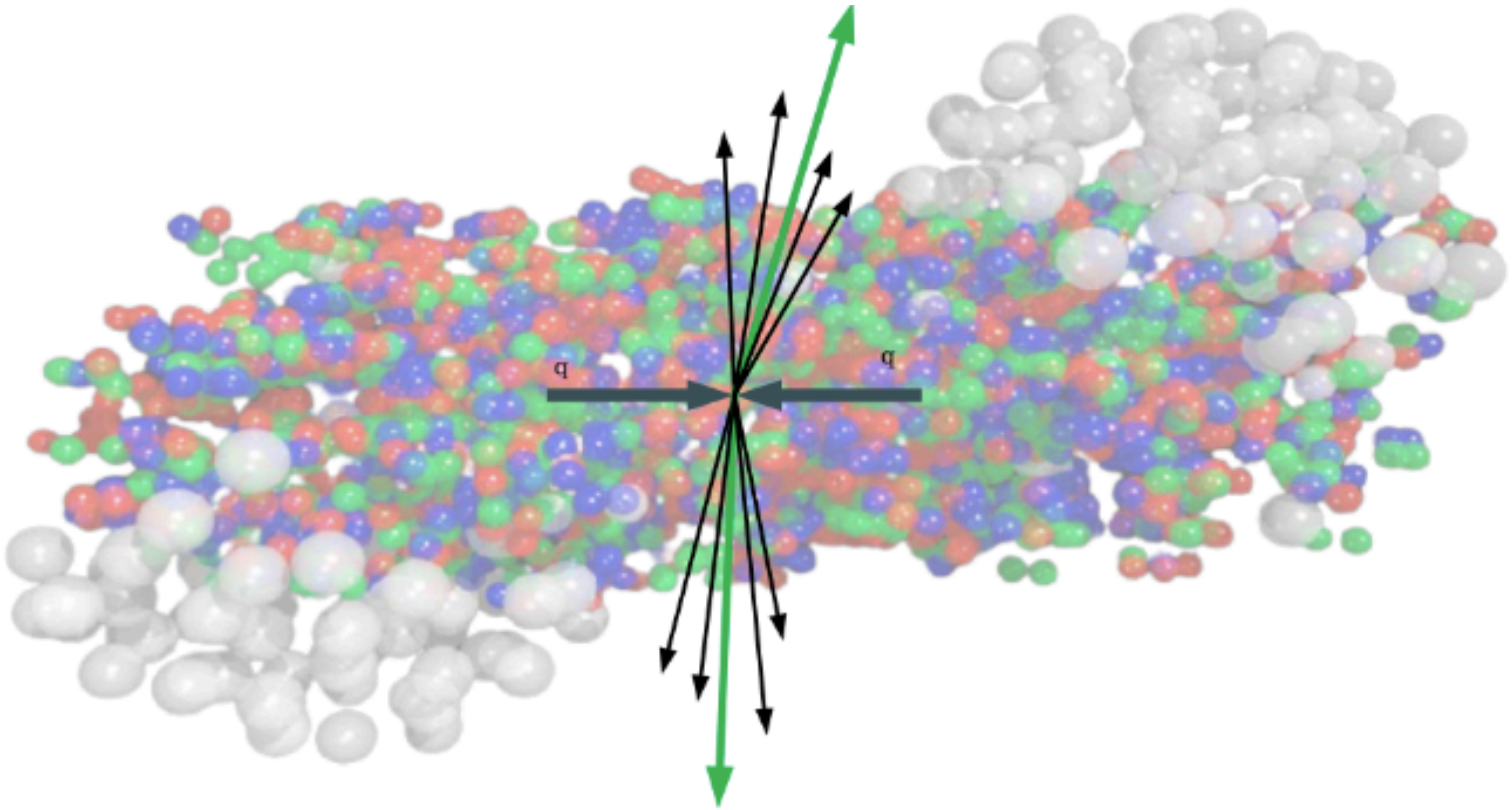
→ Study cold nuclear matter

p—p: collided at $\sqrt{s} = 0.9 , 2.76 , 5.02 , 7 , 8 , 13$ TeV

→ Precision studies of QCD

Focus today on Pb—Pb, but some other results also shown!

Probes of the QGP



Soft Probes: hadronization products of the QGP medium

→ collective properties of QGP

Hard Probes: products of early-stage hard scattering that interact with the QGP medium.

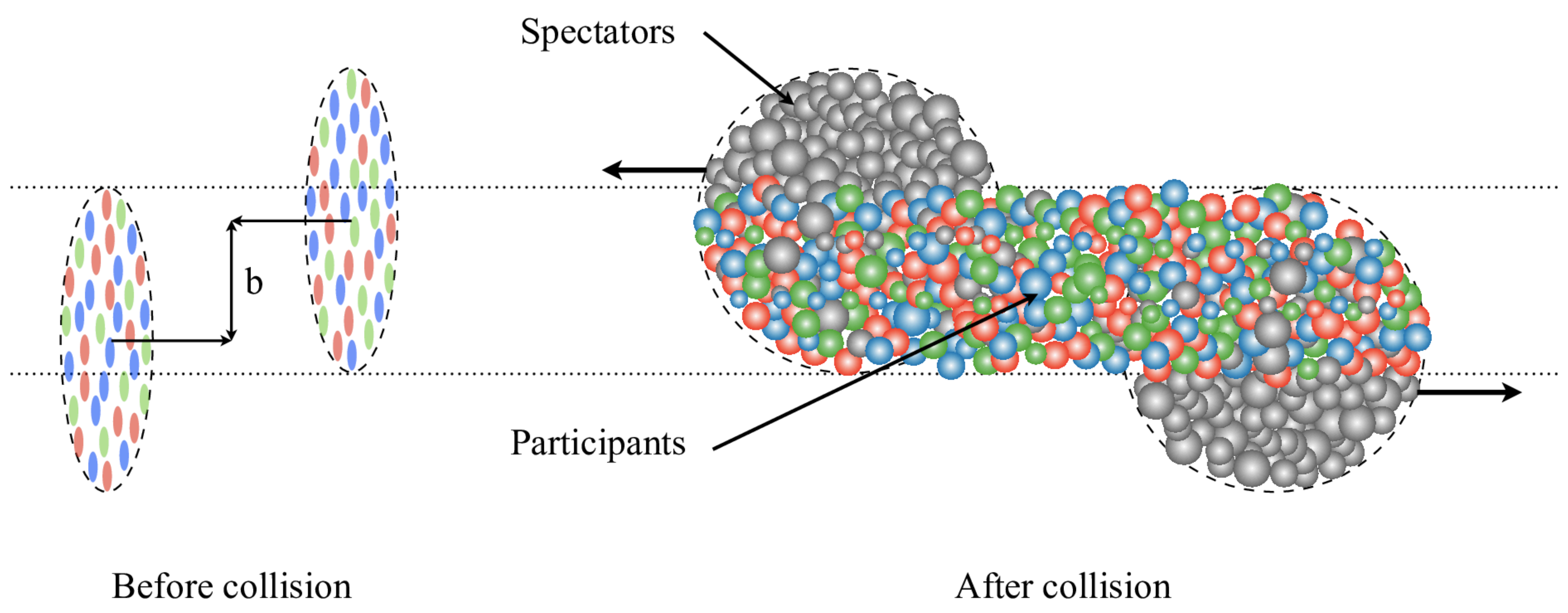
→ dynamical properties of QGP

Electroweak Probes: probes that have a long mean free path relative to the size of the QGP (negligible interactions)

→ effects of different stages of QGP formation

Common to use pp collisions as a reference system, where difference is attributed to the QGP.

Geometry of a heavy-ion collision



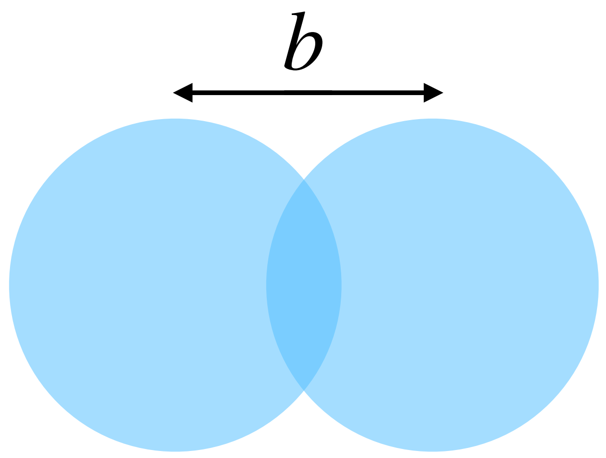
Ions will collide with a random impact parameter *b*.

Characteristics of the QGP expected to vary depending on *b*.

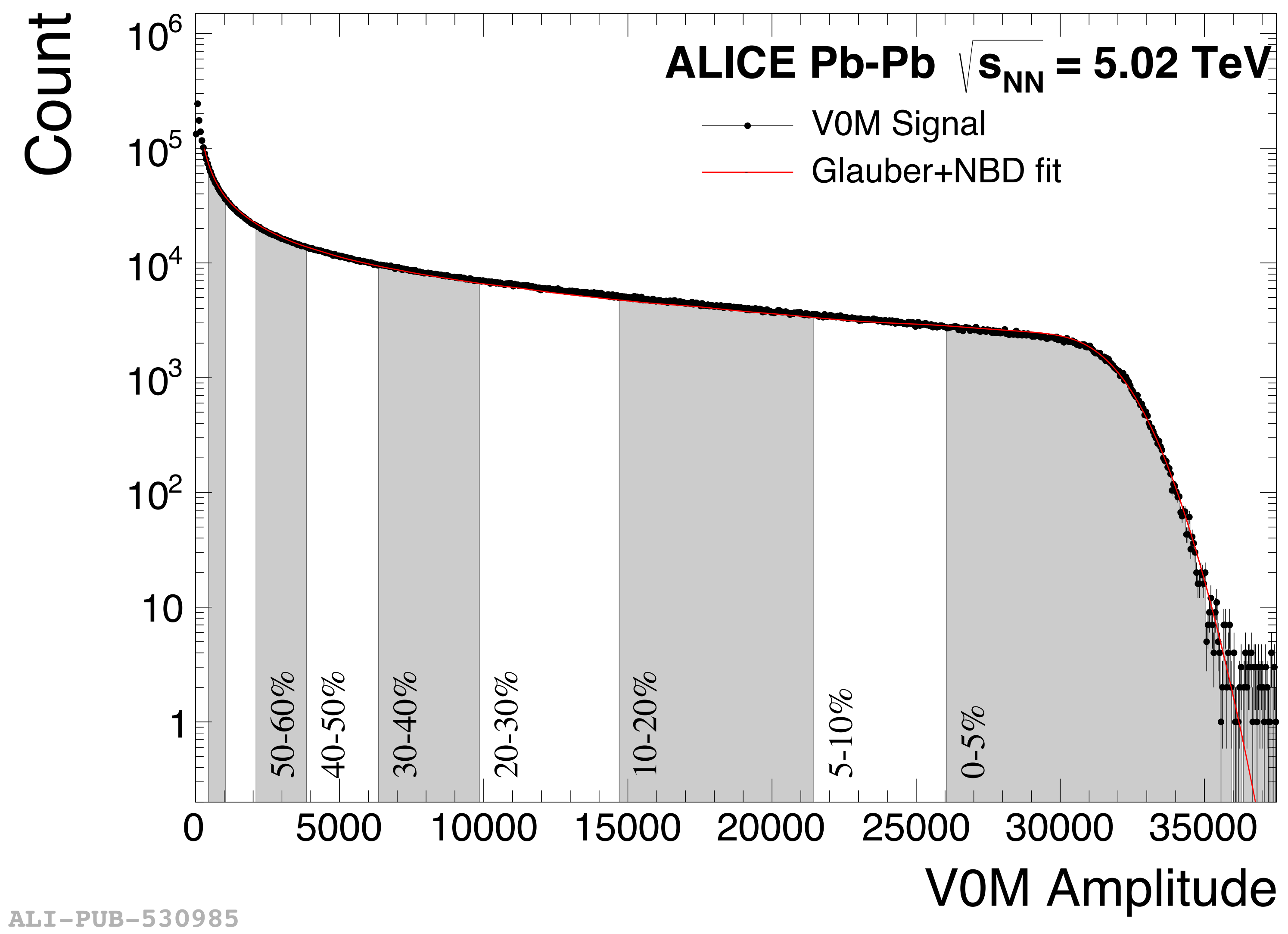
Want to analyze events with similar *b*.

In experiment, use charged particle multiplicity as a proxy for *b* - group into "centrality classes".

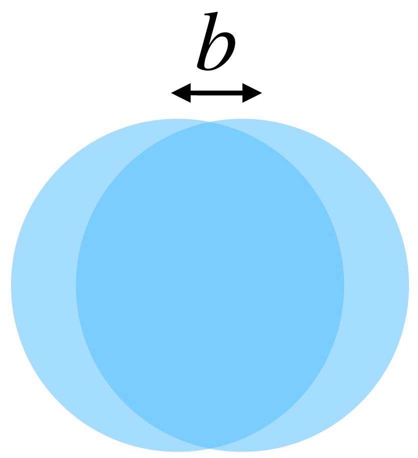
arXiv:2211:04384



Peripheral



More particles produced



Central

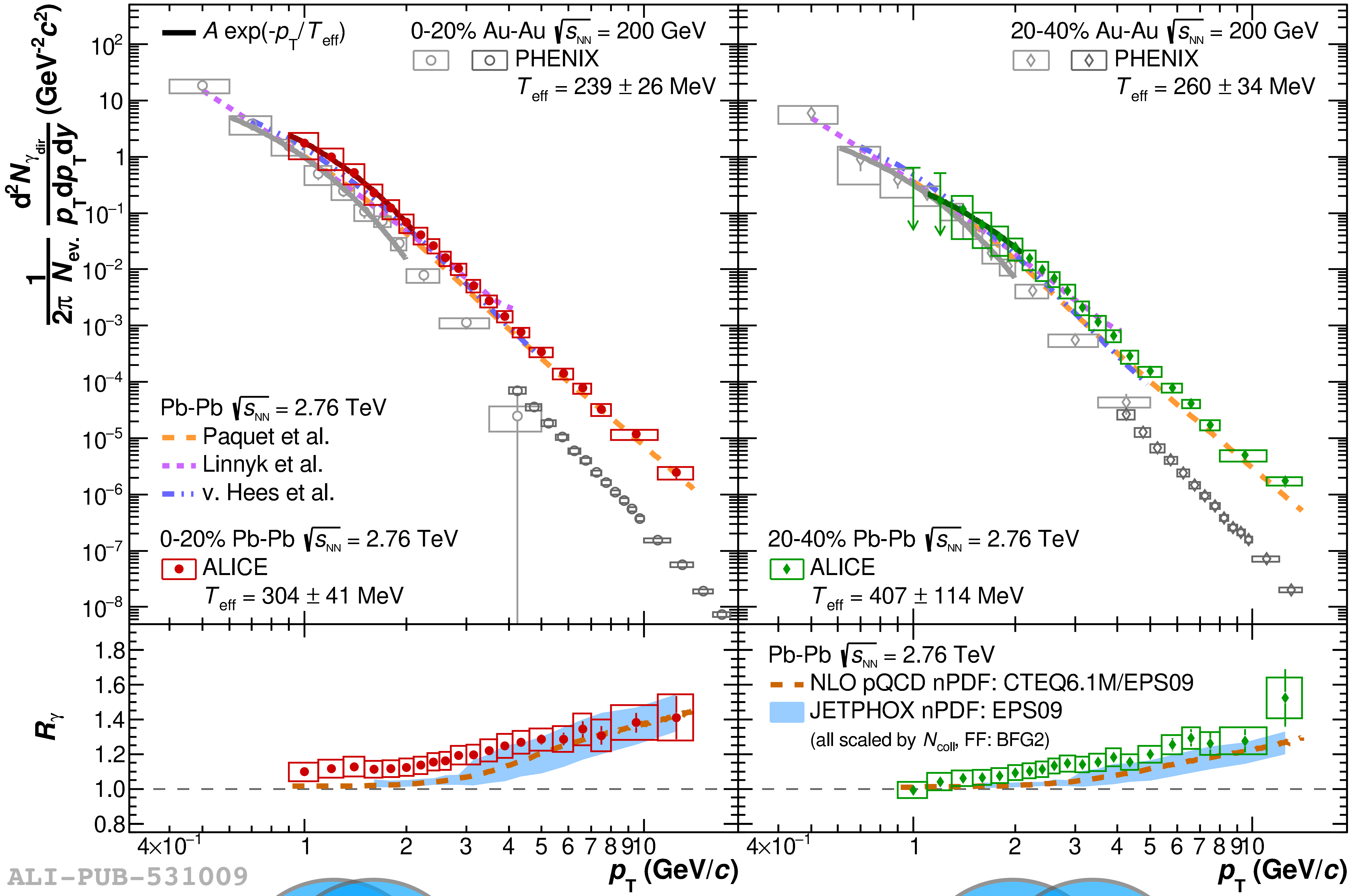
Effective temperature of the QGP

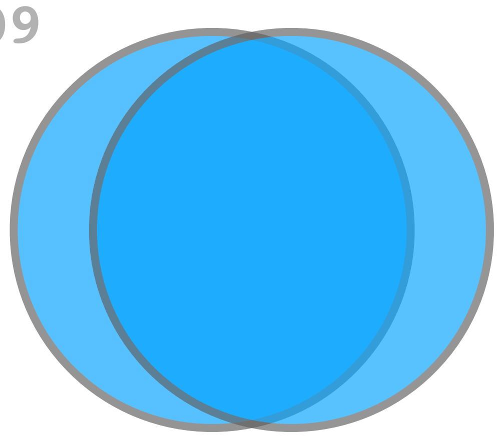
At low p_T the direct photon spectrum is dominated by thermal photons radiated during QGP evolution

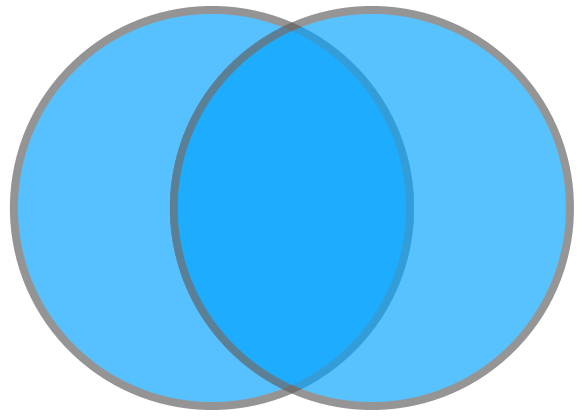
Can be used to get an effective temperature via exponential fit (solid lines)

In central collisions, $T_{\mathrm{eff}} = 304 \pm 41$ MeV well above critical temperature ($T_c \sim 150$ MeV)!

Phys. Lett. B 754 (2016) 235-248   arXiv:2211:04384

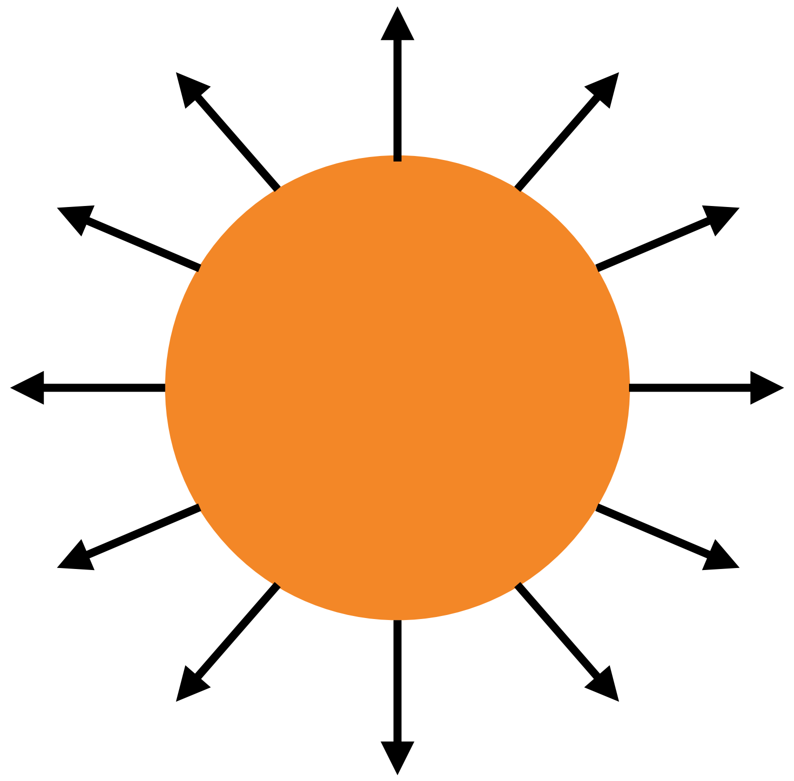






Radial and Anisotropic Flow

Bulk Viscosity

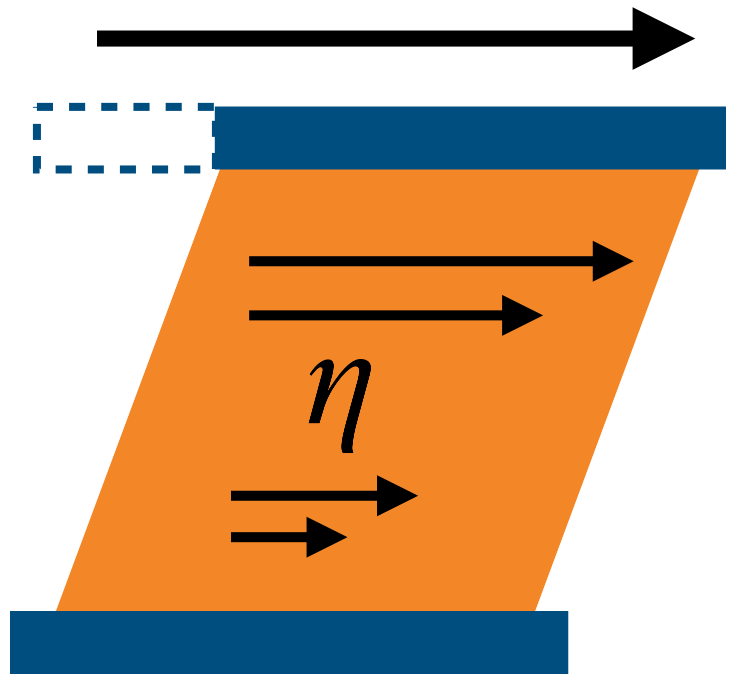


Radial Flow

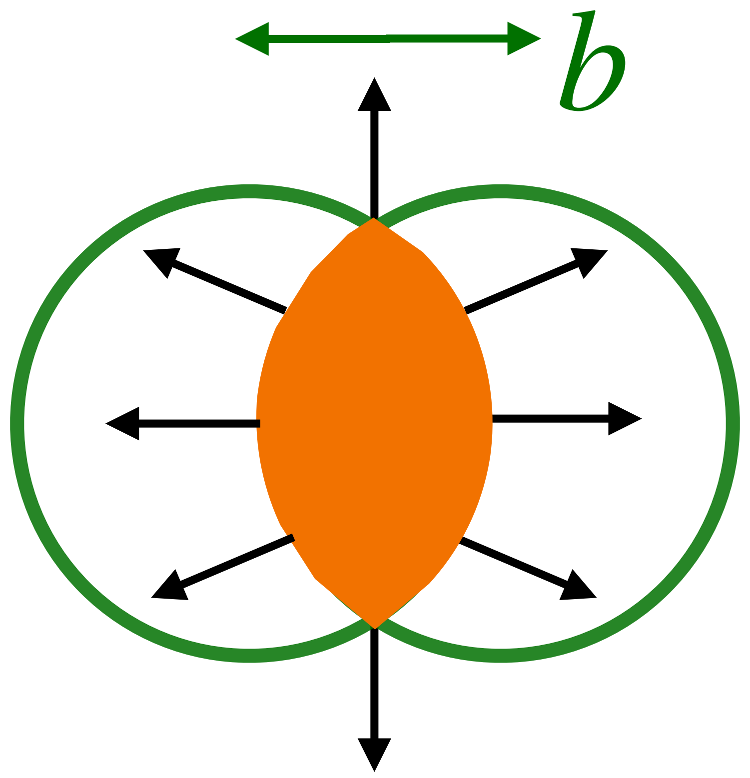
Probe of the bulk viscosity of the QGP.

Greater pressure at the center of the QGP than the outskirts results in *radial flow*.

→ Quantified with the $\langle p_{\mathrm{T}} \rangle$



Shear Viscosity



Anisotropic Flow

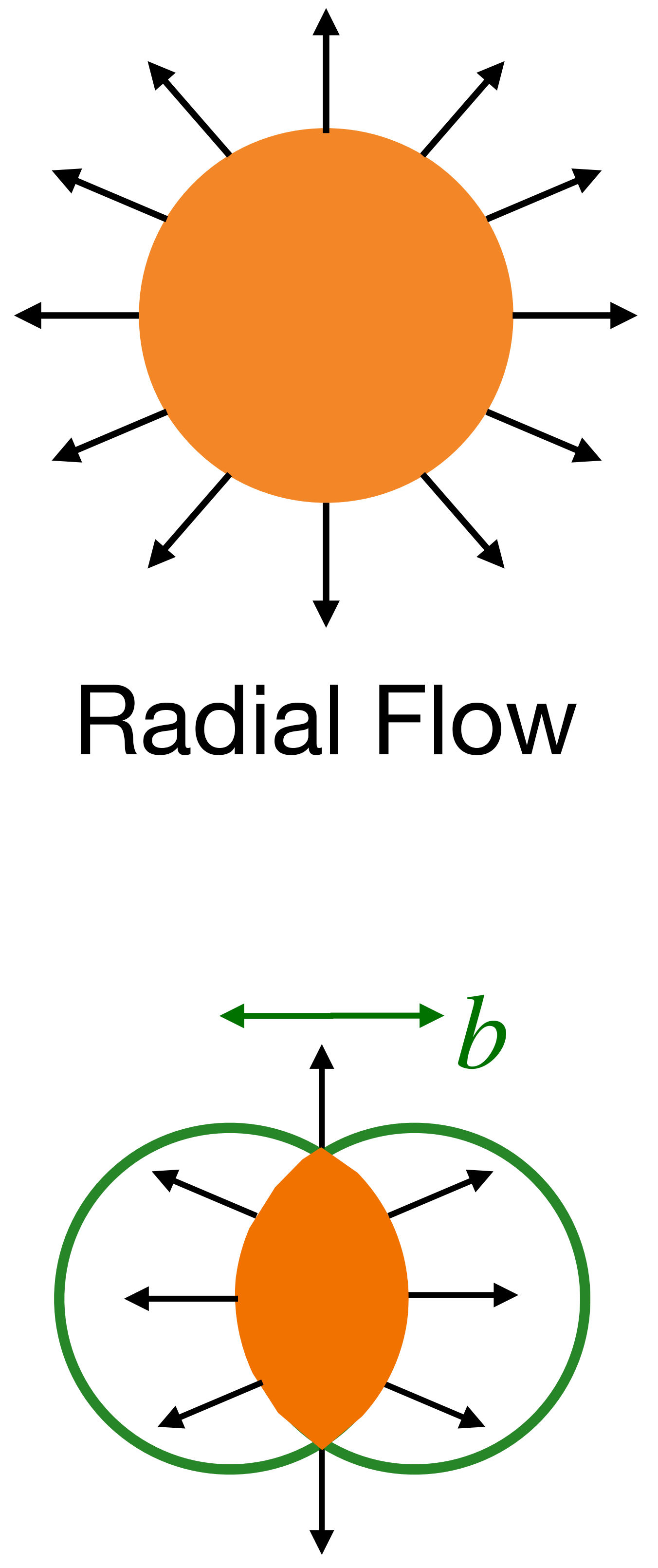
Probe of the shear viscosity of the QGP.

Spatial anisotropies in the initial state create strong pressure gradients that result in *anisotropic flow*.

→ Quantified with the Fourier coefficients (v_{n})

$$\frac{dN}{d\Delta\varphi} \propto (1 + 2\sum_{n=1}^{\infty} v_n cos(n(\varphi - \Psi_n)))$$

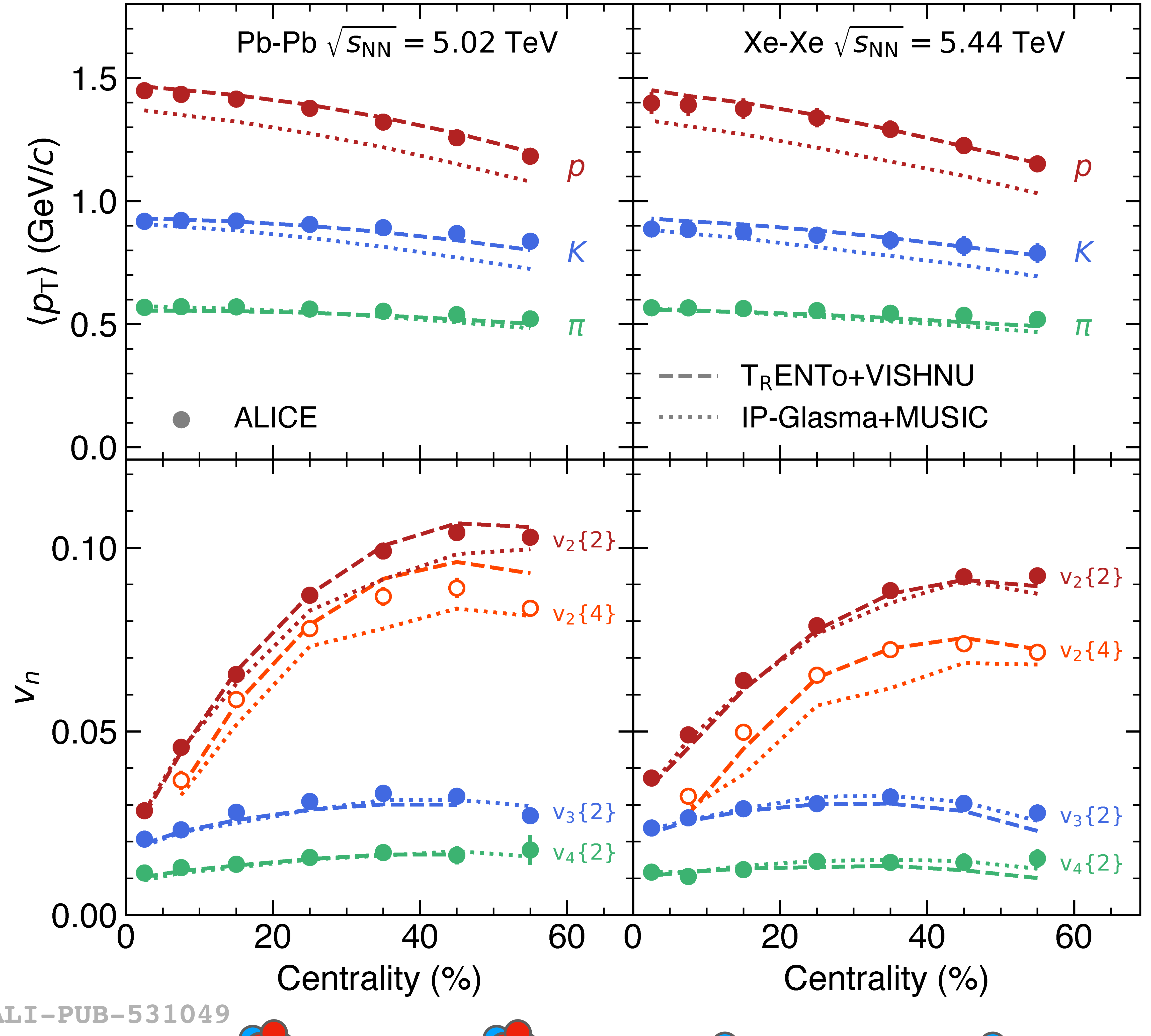
Radial and Anisotropic Flow



Radial Flow

Anisotropic Flow

arXiv:2211:04384



Higher mass particles have higher $\langle p_T \rangle$ due to boost from radial flow

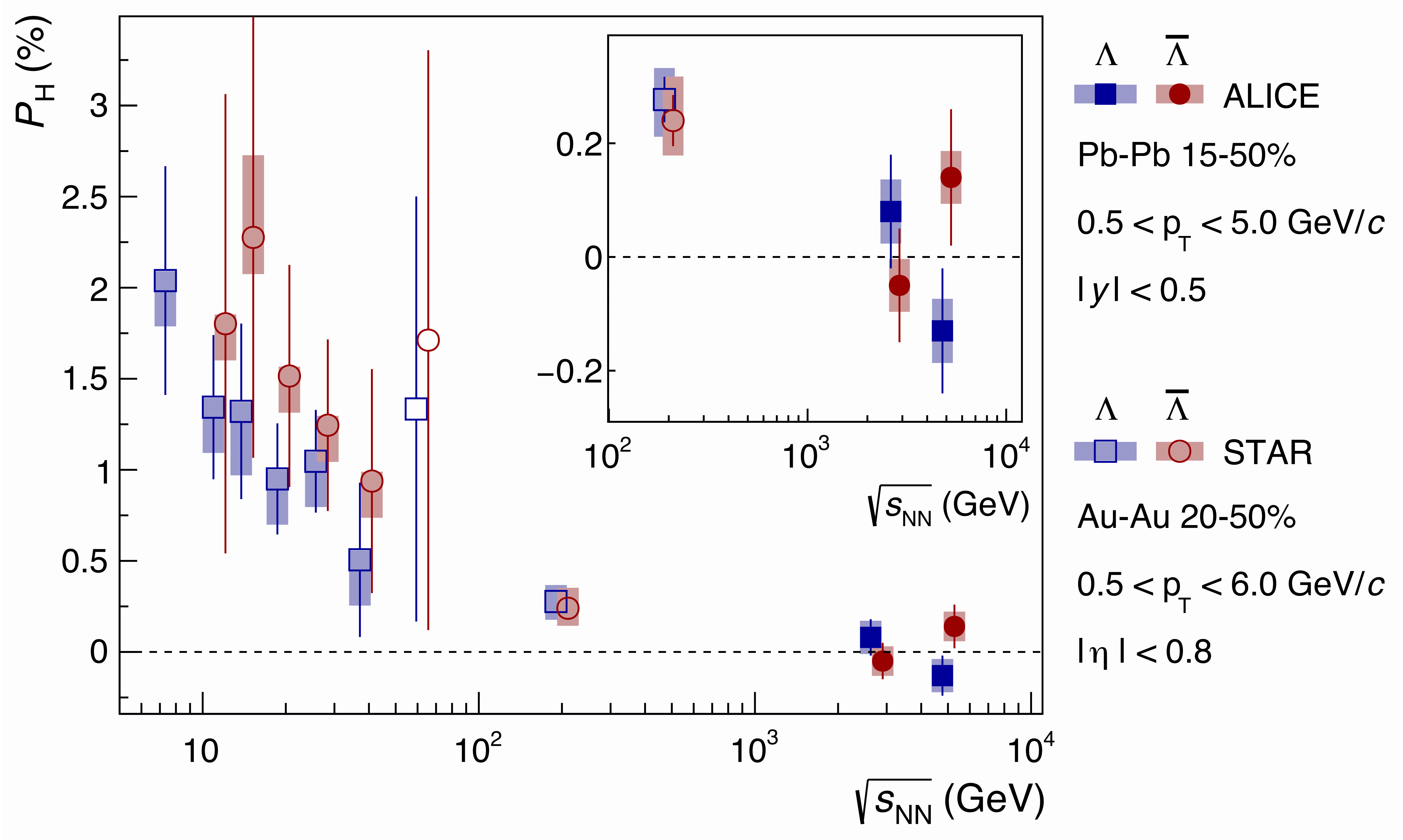
Comparing with Xe—Xe probes system-size dependence

Global radial and anisotropic flow described by hydrodynamics.

The most vortical fluid

Angular momentum of incoming nuclei results in polarization with respect to the reaction plane direction.

arXiv:2211:04384 Phys. Rev. C 101, 044611

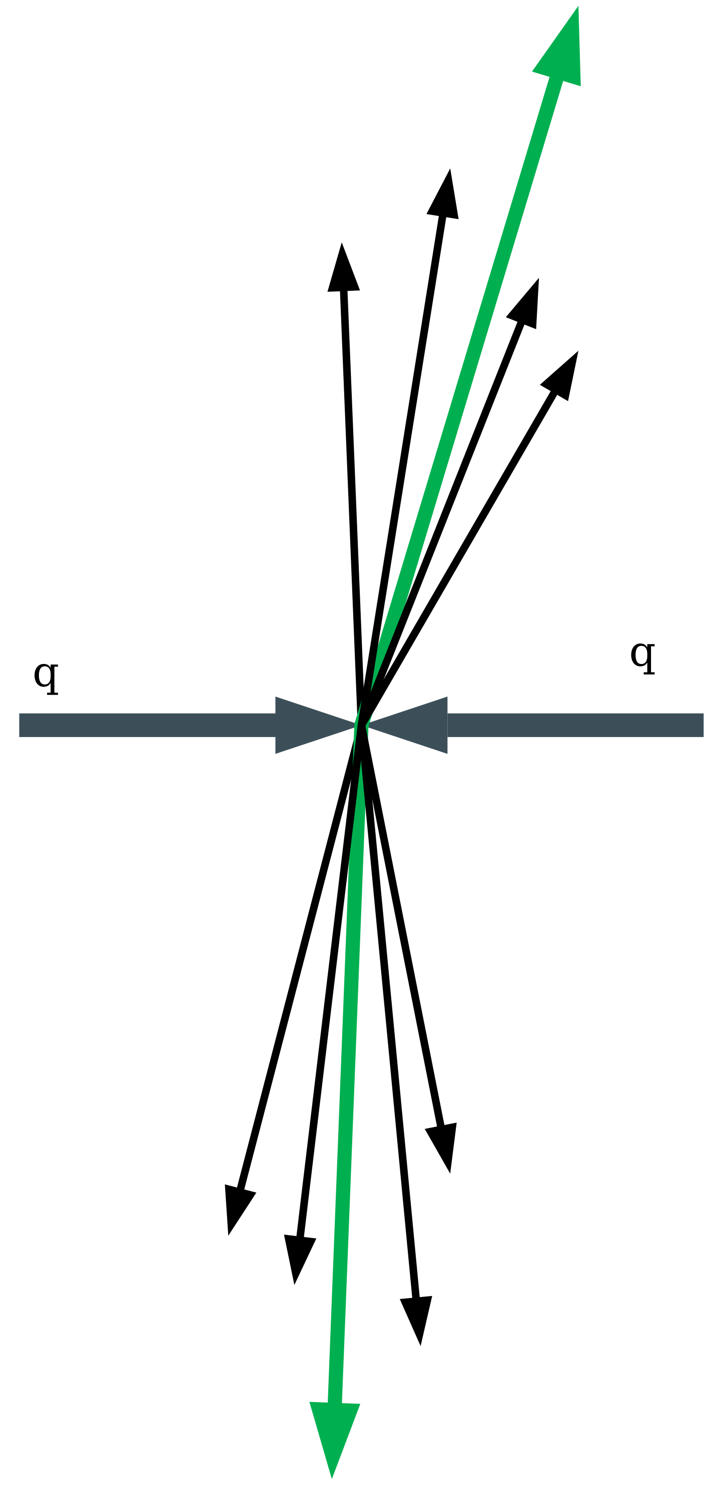


Measure average global hyperon polarization, P_{H}, using angular distribution of (anti-)protons from hyperon decays

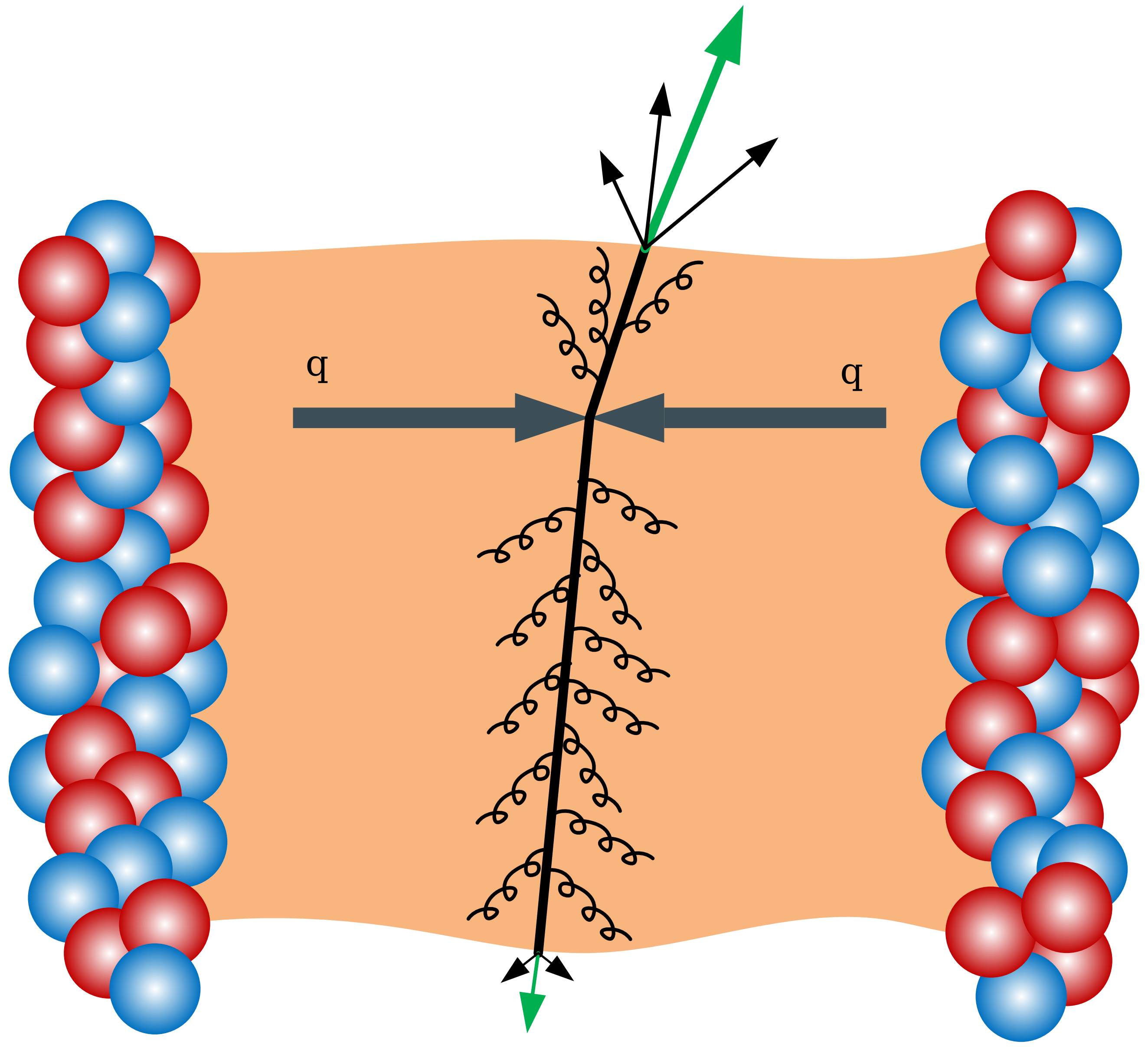
Values consistent with 0 at ALICE, confirms general trend of polarization decreasing with increasing collision energy.

Will benefit from increased statistics available in Run 3 of the LHC!

Parton energy loss via jets



p+p



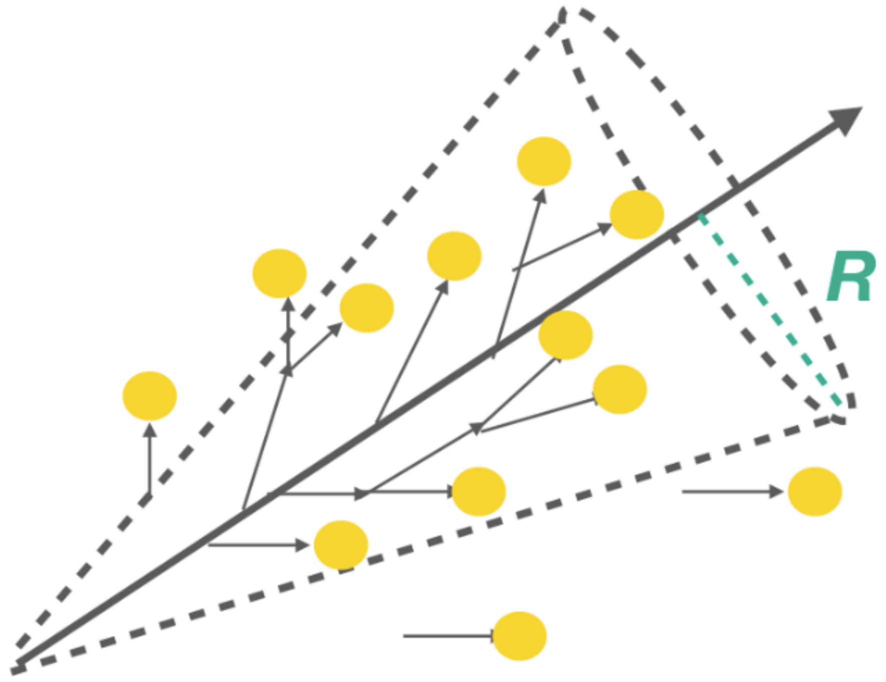
A+A

Hard scatterings during the collision form high-p_{T} partons that fragment then hadronize to form a narrow cone of particles called a *jet*.

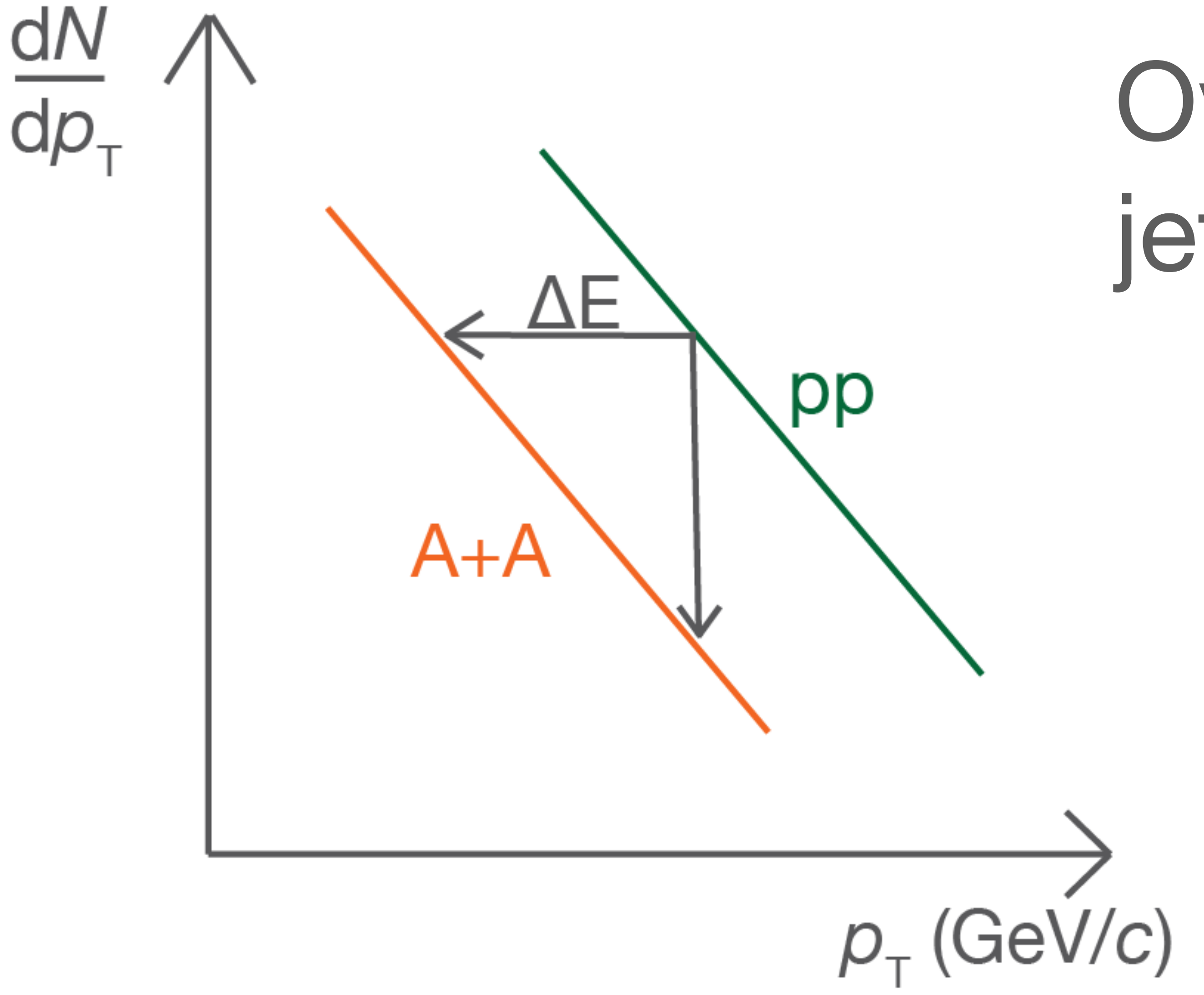
In heavy-ion collisions, parton loses energy via QCD interactions with QGP → jet quenching

Hard scattering process happens early in collision before QGP formation.

Jets probe the full evolution of the QGP!



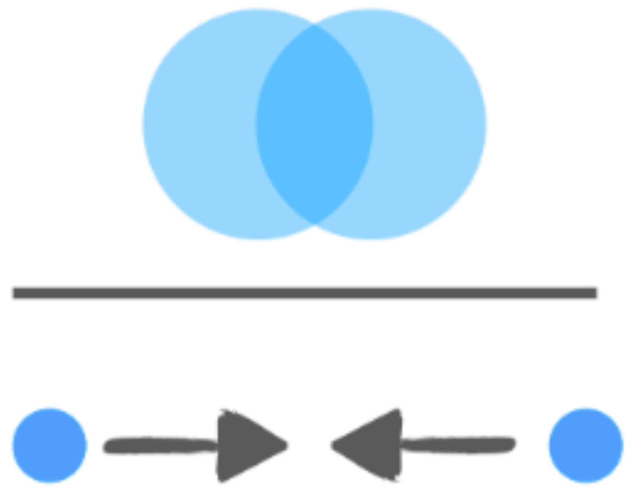
High-p_{T} hadrons and jet suppression



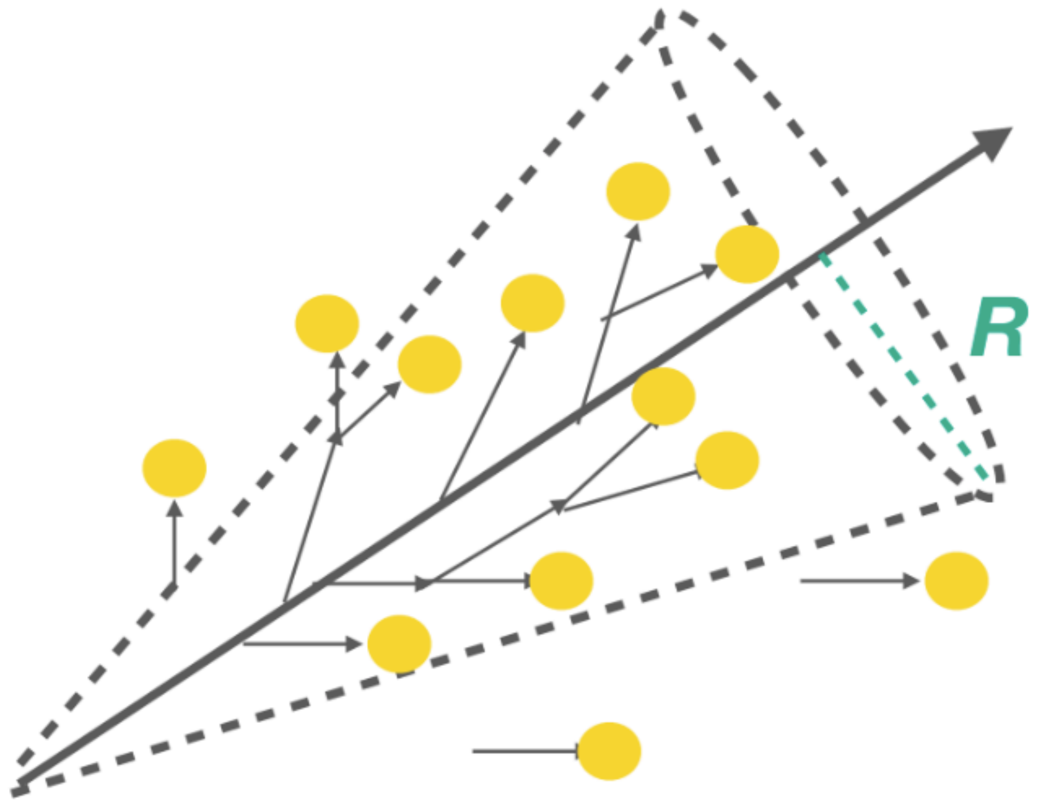
Overall energy loss leads to a suppression of jet yields in Pb—Pb.

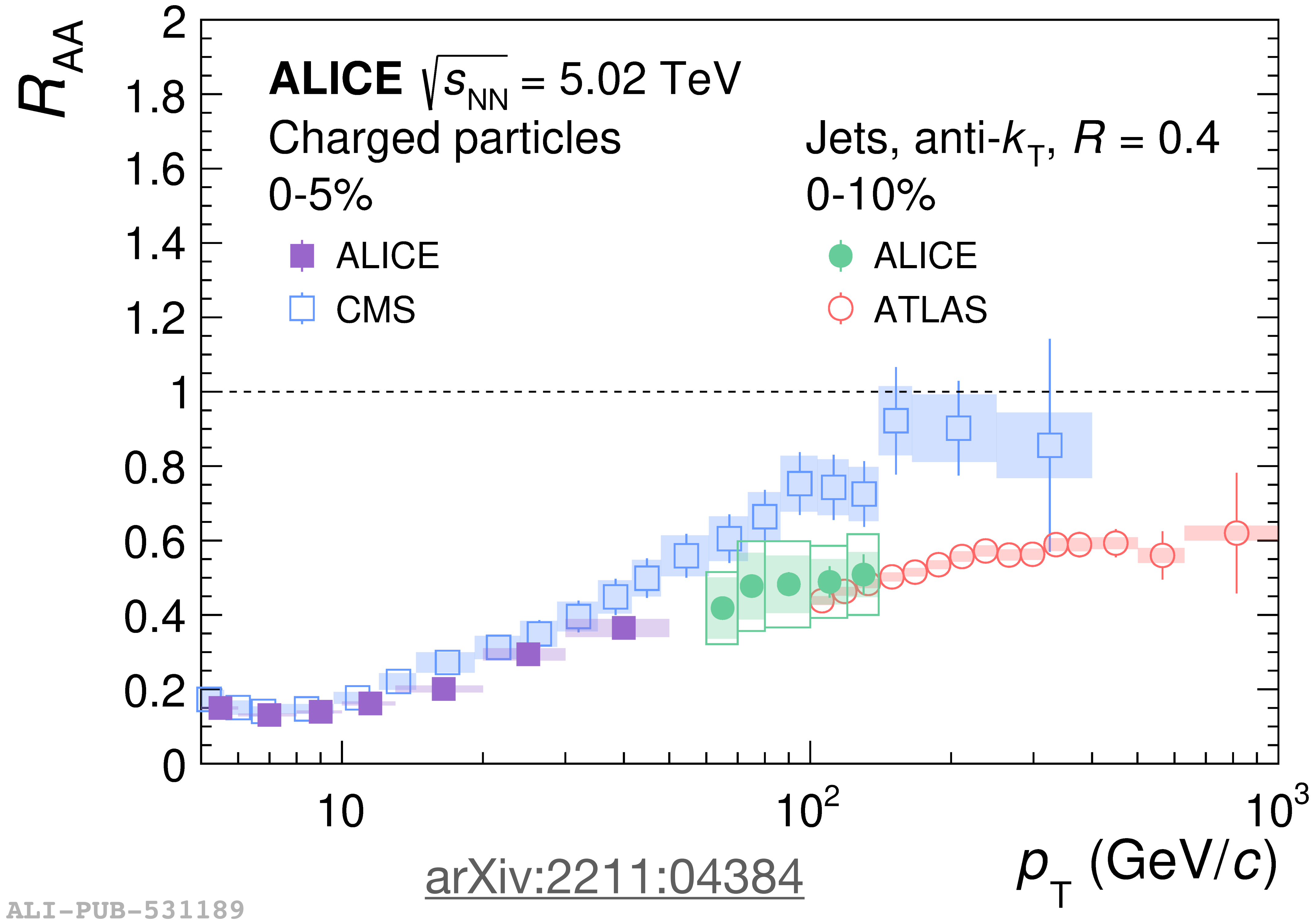
→ Quantified with

$$R_{\mathrm{AA}} = \frac{\left.\frac{1}{N_{\mathrm{event}}}\frac{d^2N_{\mathrm{jet}}^{\mathrm{PbPb}}}{dp_{\mathrm{T}}dy}\right|_{\mathrm{cent}}}{\langle T_{\mathrm{AA}}\rangle \frac{d^2\sigma_{\mathrm{jet}}^{\mathrm{pp}}}{dp_T dy}} =$$



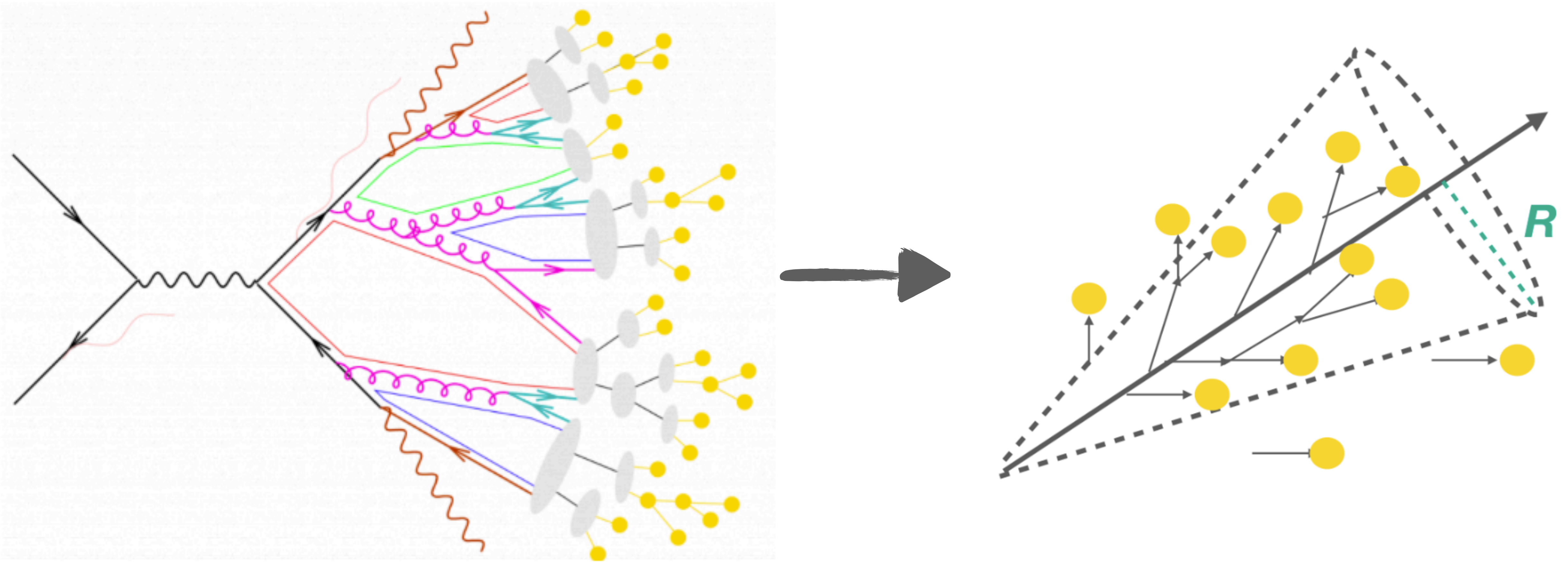
Observed suppression of charged hadrons and jets over broad range in p_{T}





arXiv:2211:04384

Dependence of jet suppression on *R*

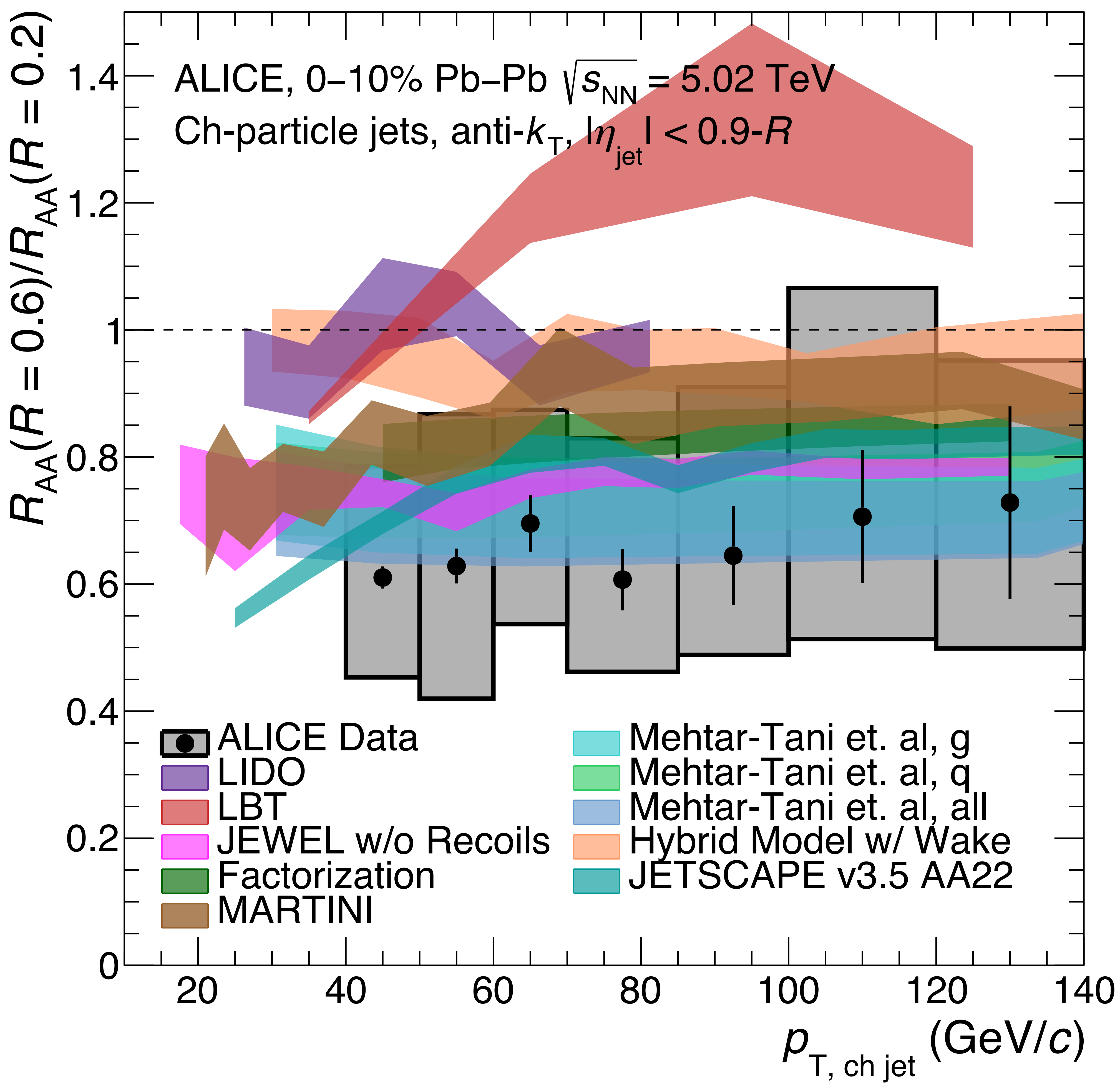


Jets are defined with a given cone-size *R*, controls how much of the shower is contained within the jet

Can compare the suppression of wider jets (R = 0.6) to narrower jets (R = 0.2).

General agreement with theoretical predictions!

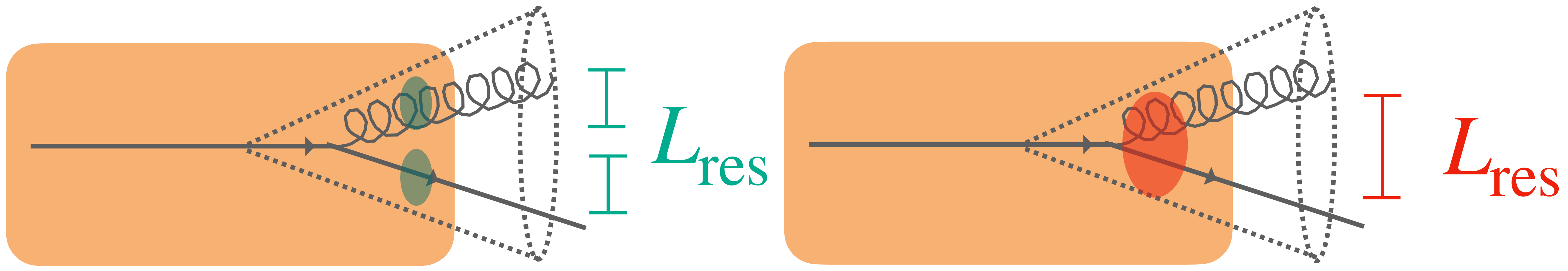
arXiv:2208.14492



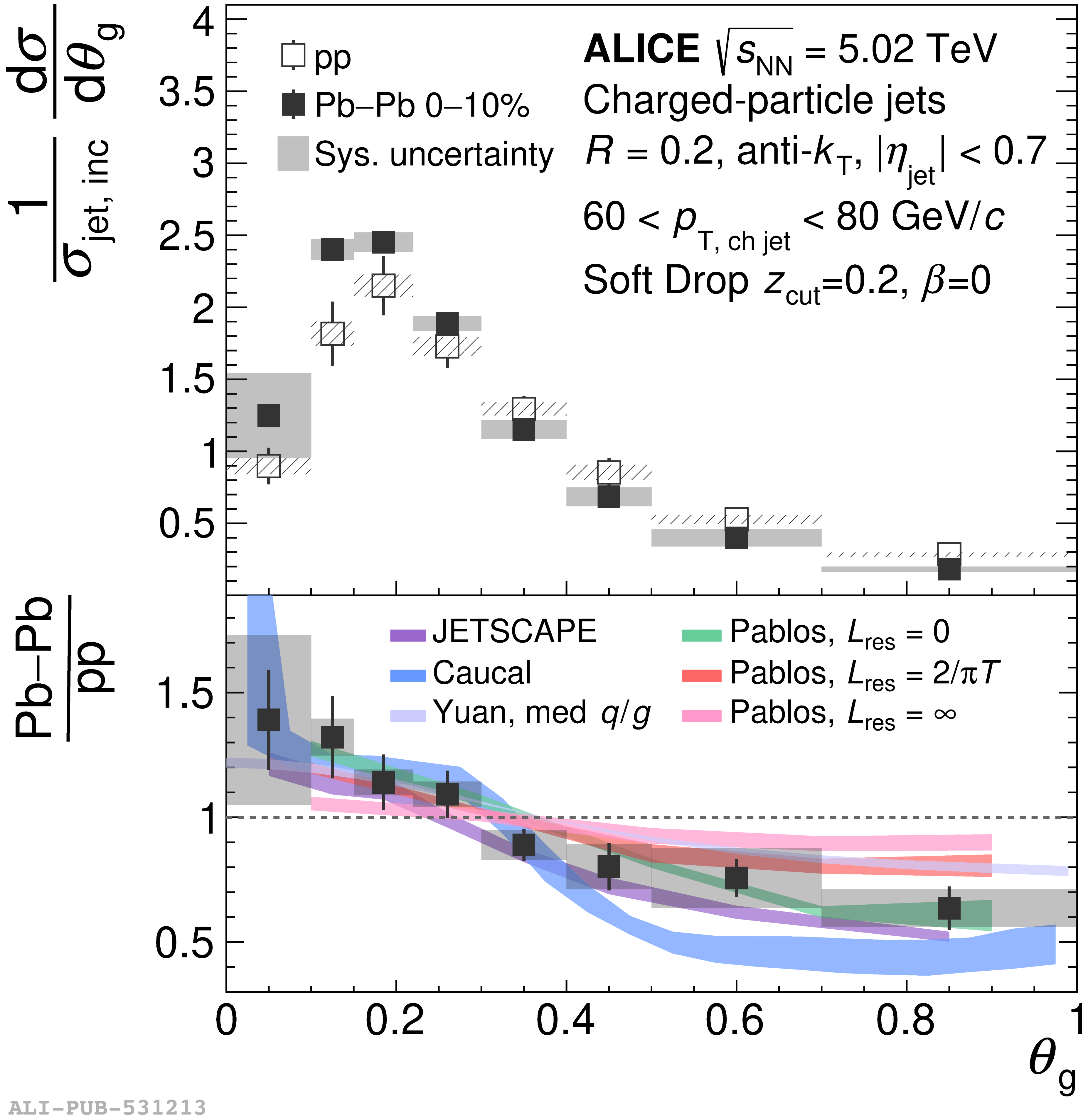
Wider jets lose more energy in the QGP!

Resolution length of the QGP

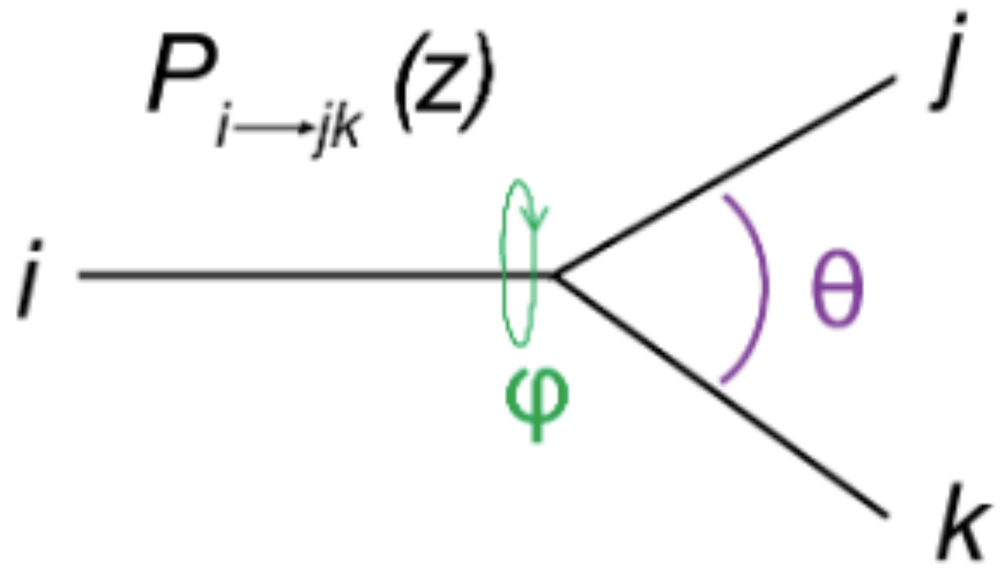
QGP is expected to have a resolution length over which it could resolve the color (sub)structure of the jet



Phys. Rev. Lett. 128 (2022) 102001



Probed via looking at suppression of angle between subjets, θ_g



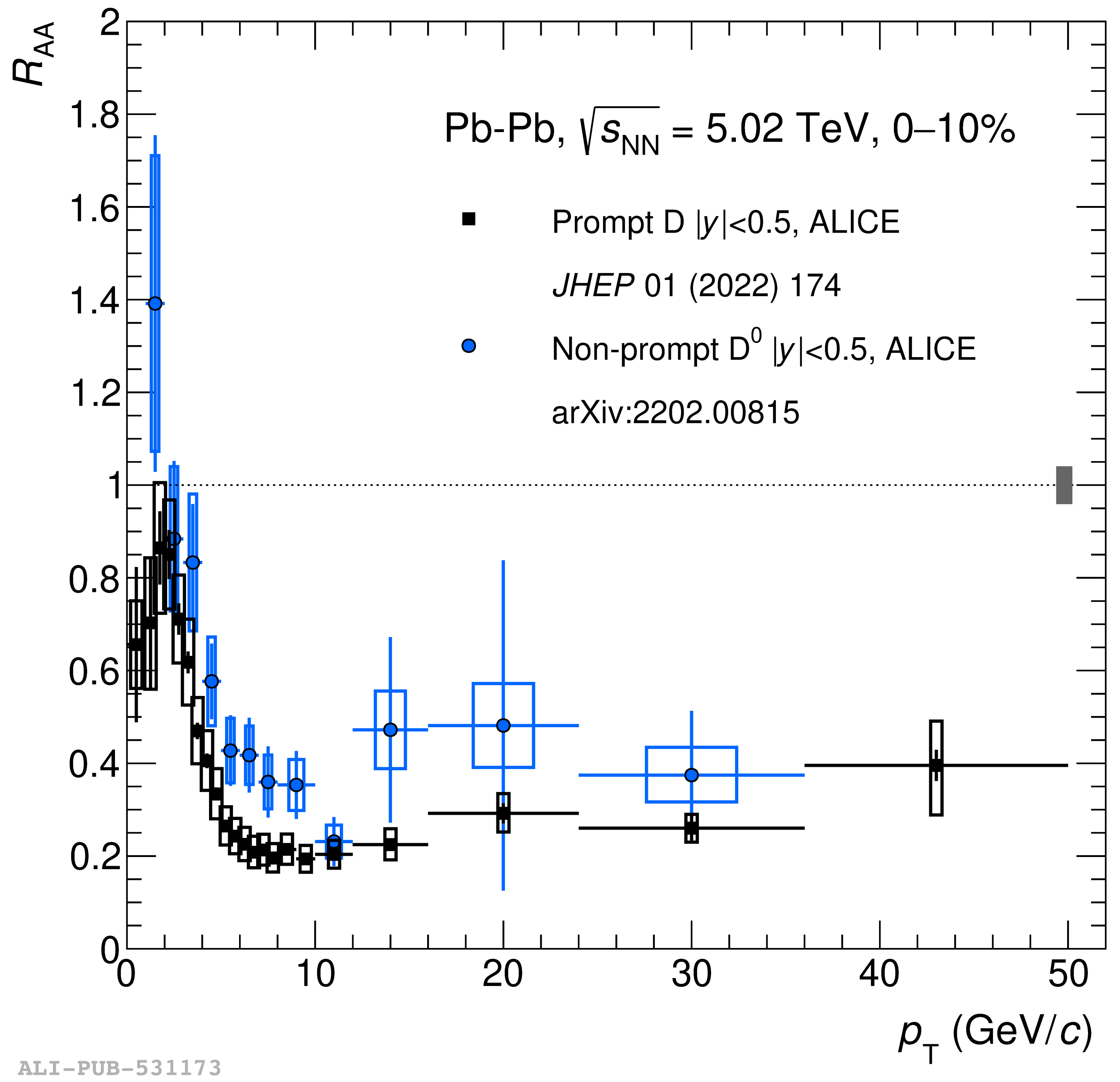
Wider jets are more suppressed, could be indicative of QGP resolving prongs within the jet!

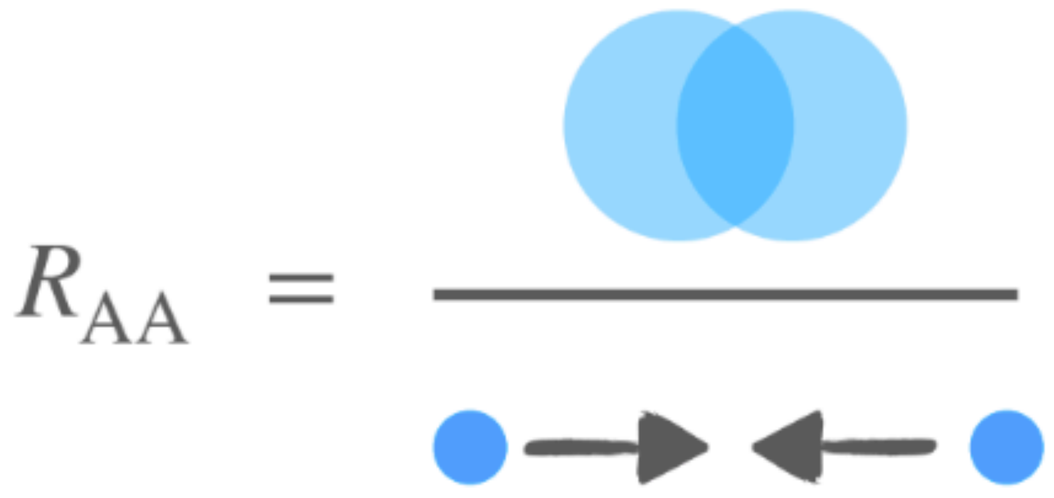
Mass dependence of energy loss

Measurements of heavy quarks and their decays can probe the mass dependence of energy loss!

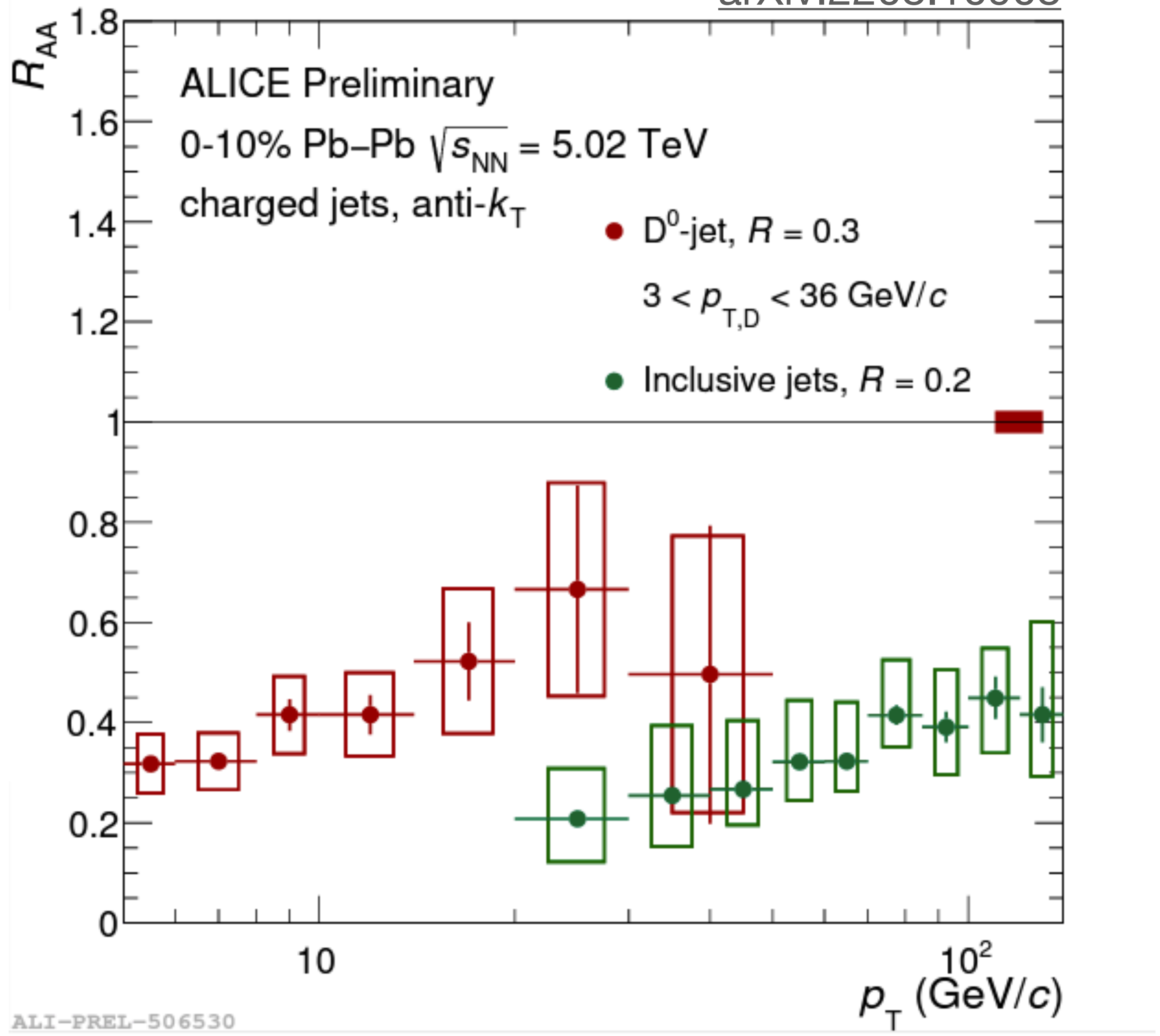
arXiv:2211:04384

Prompt: JHEP 01 (2022) 174 Non-Prompt: JHEP 12 (2022) 126





arXiv:2208.10908



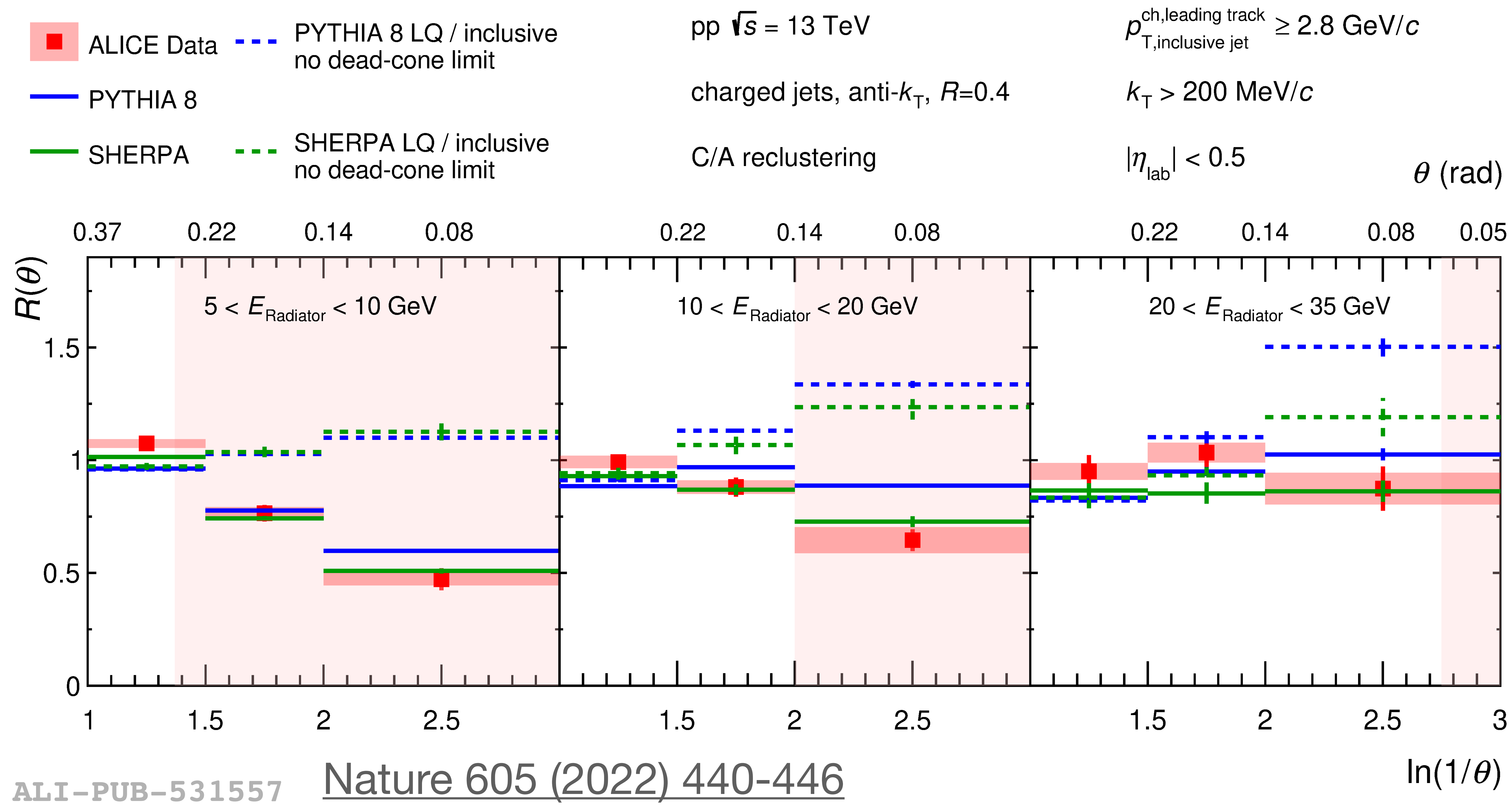
D mesons from bottom less suppressed than those from charm.

D^0 tagged jets (mostly charm quark initiated) less suppressed than inclusive jets (mostly gluon-initiated)

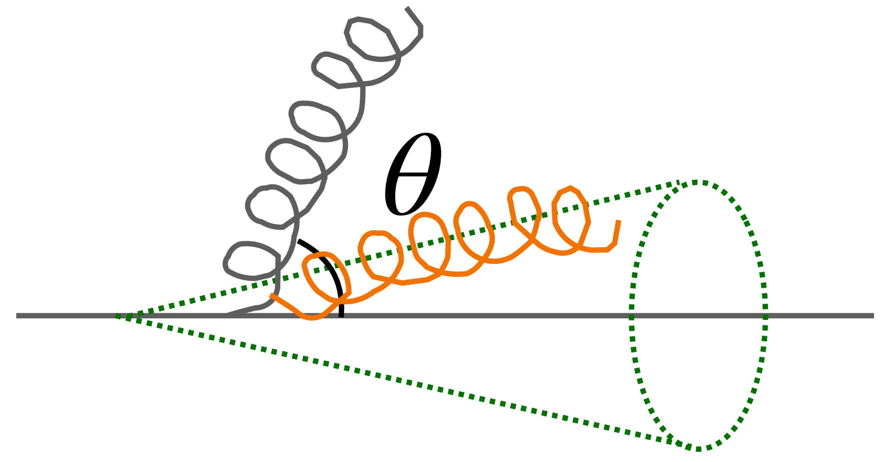
Dead-cone effect

→ QCD effect where the pattern of the parton shower is expected to depend on the mass of the initiating parton.

Pb—Pb results could be sensitive to the dead-cone effect.



ALI-PUB-531557 Nature 605 (2022) 440-446



Vacuum emissions suppressed in a cone of $\theta_0 = m/E$

Could help isolate medium-induced emissions that would not be suppressed! arXiv:2211.11789

Direct observation of dead-cone in pp collisions!! Could play a role in Pb—Pb.

Quarkonium suppression

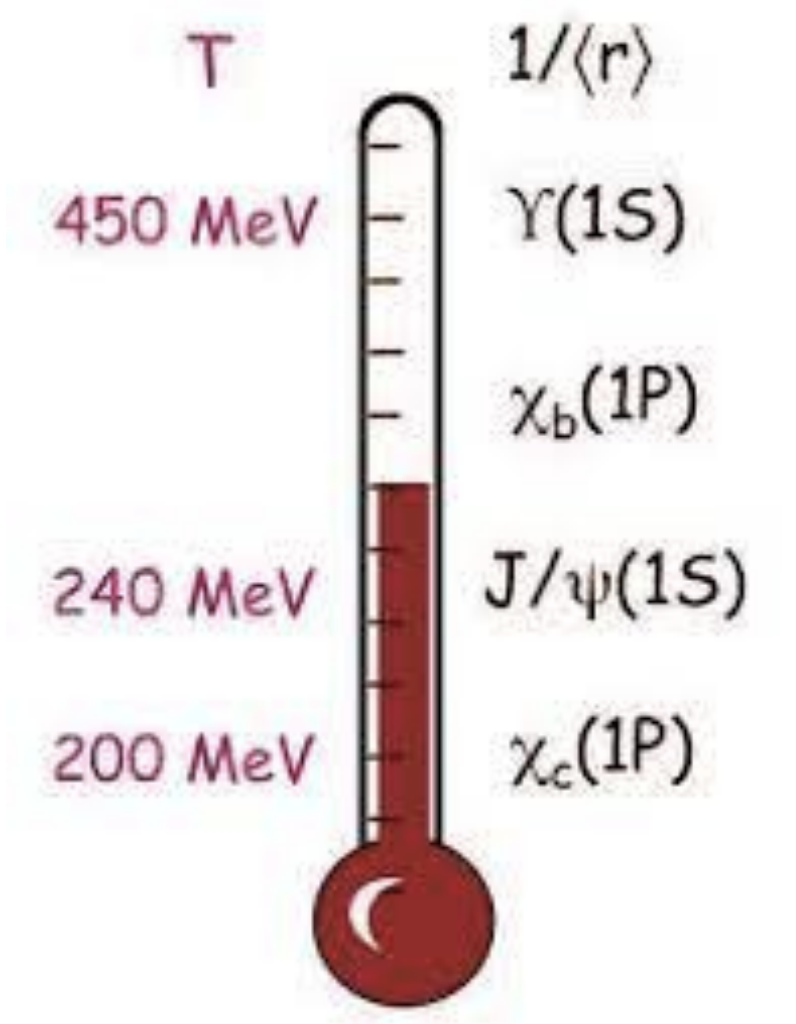
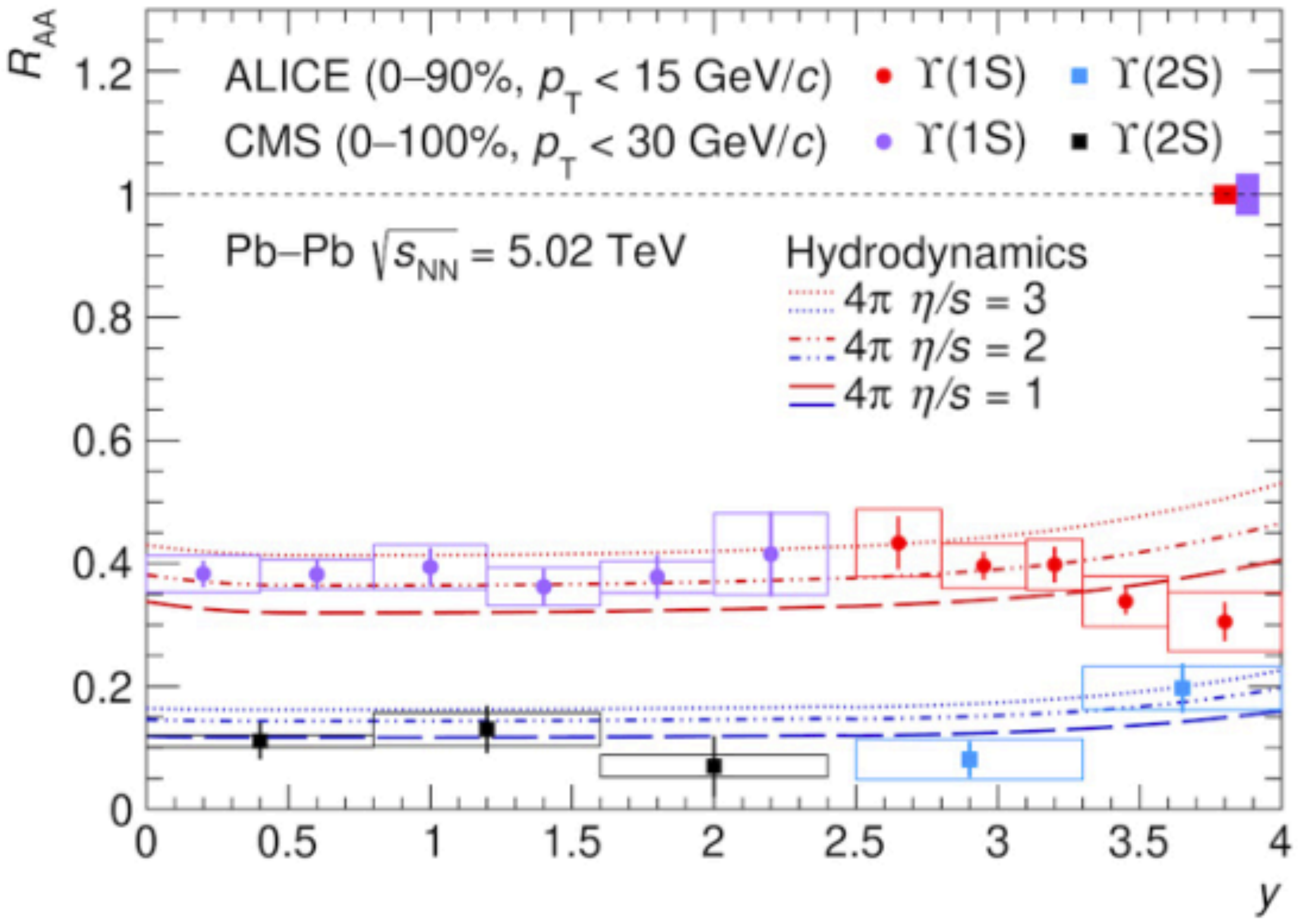


Image Credit: Agnes Mocsy

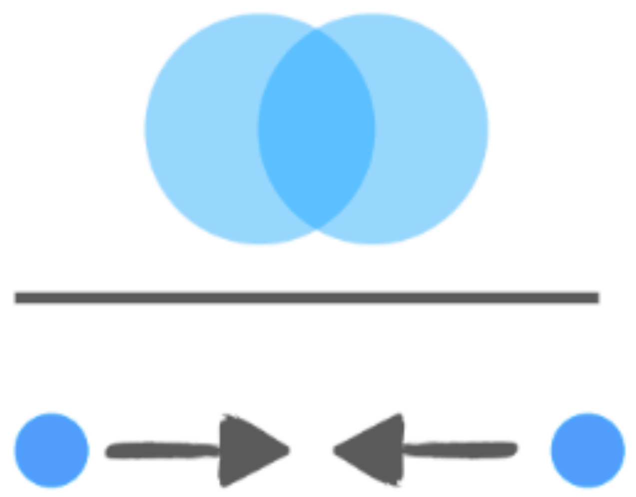
Quarkonia (bound $q\bar{q}$ states) expected to melt in a sequential fashion as the temperature increases.

→ Results in states with lower binding energy being more suppressed. (Quantify via R_{AA})

Phys. Lett. B 822 (2021) 136579

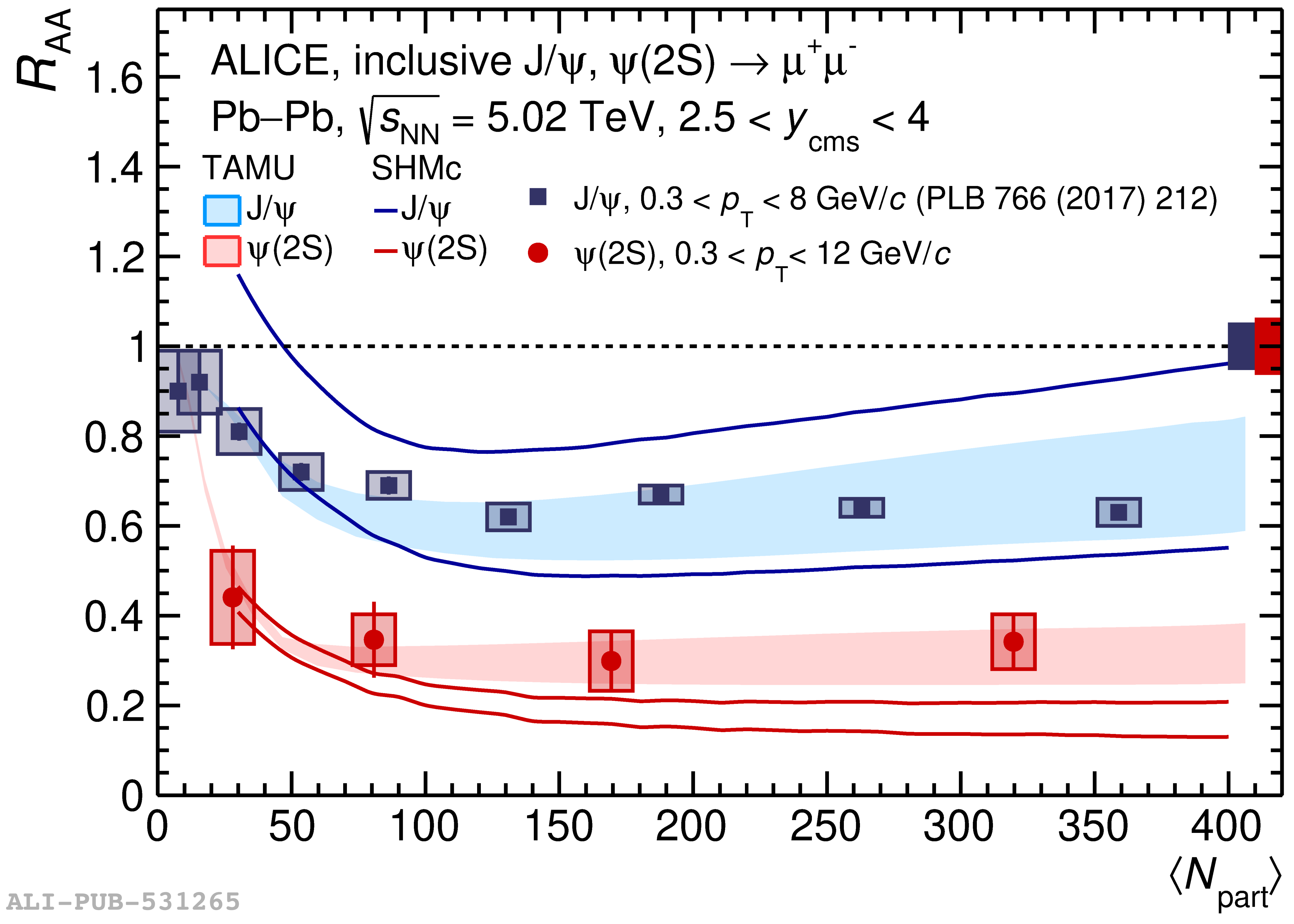


Bottomonium ($b\bar{b}$) states exhibit sequential suppression!

$R_{\mathrm{AA}} =$ 

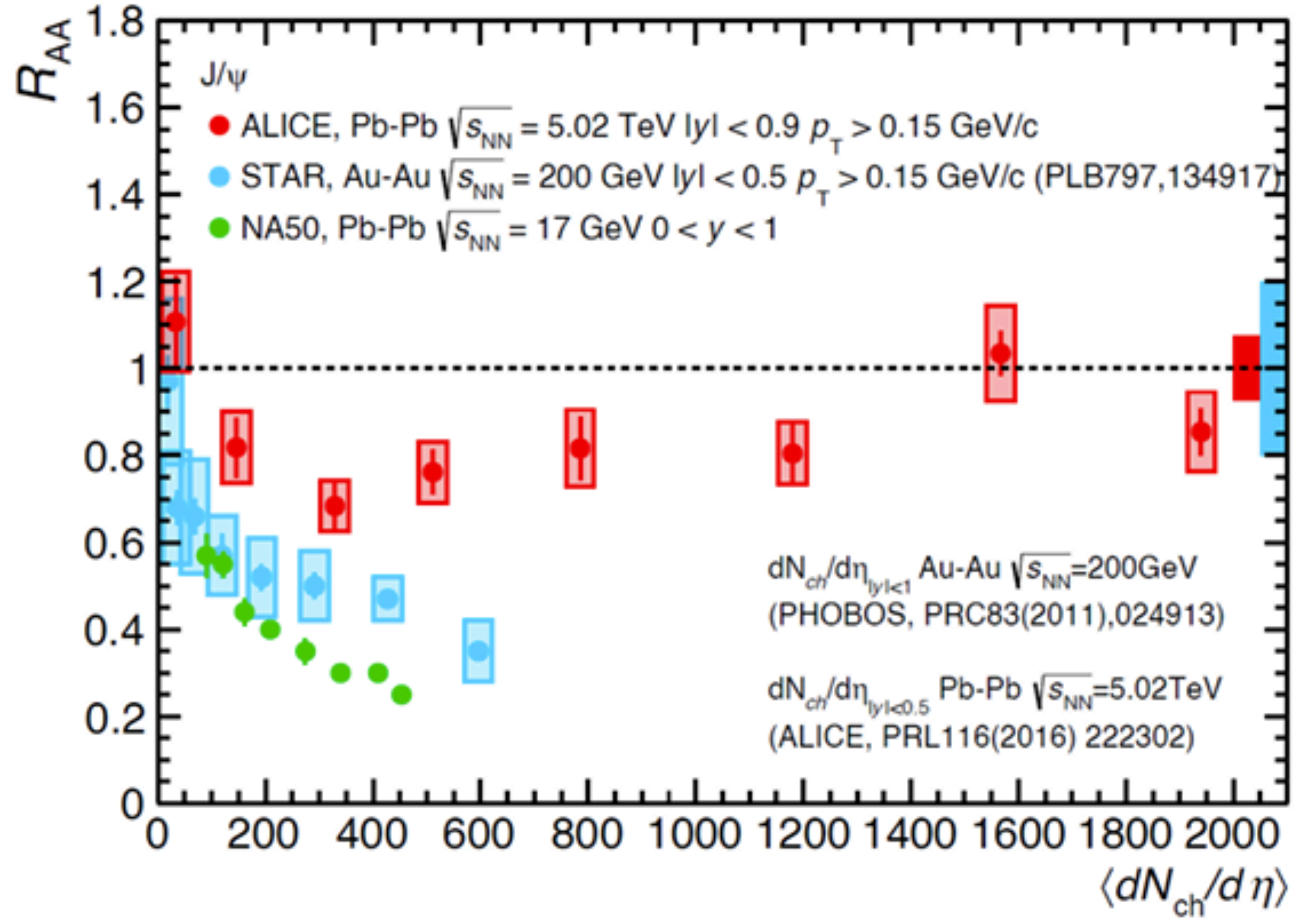
Quarkonium suppression and regeneration

arXiv:2210.08893 $J/\psi \rightarrow \mu^+\mu^-$



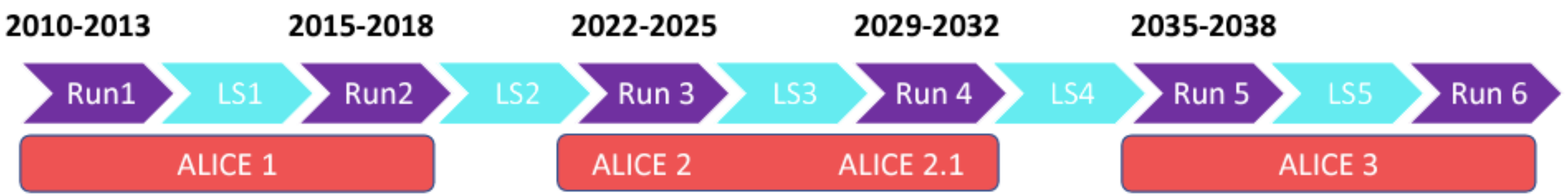
Charmonium ($c\bar{c}$) states exhibit sequential suppression!

$J/\psi \rightarrow e^+e^-$ arXiv:2211:04384

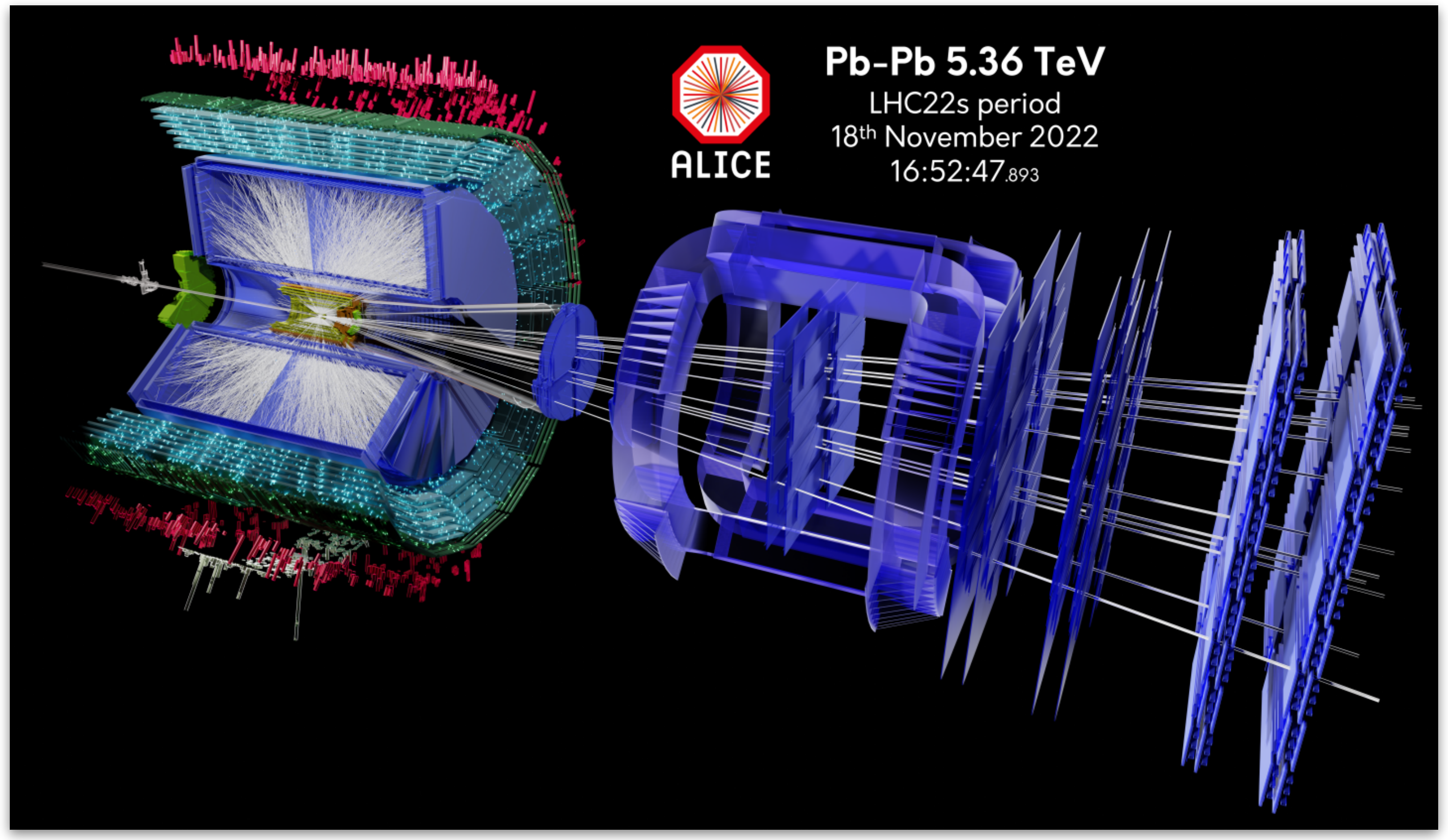


Comparing degree of suppression to RHIC, indicates regeneration effects at LHC where un-correlated quarks recombine.

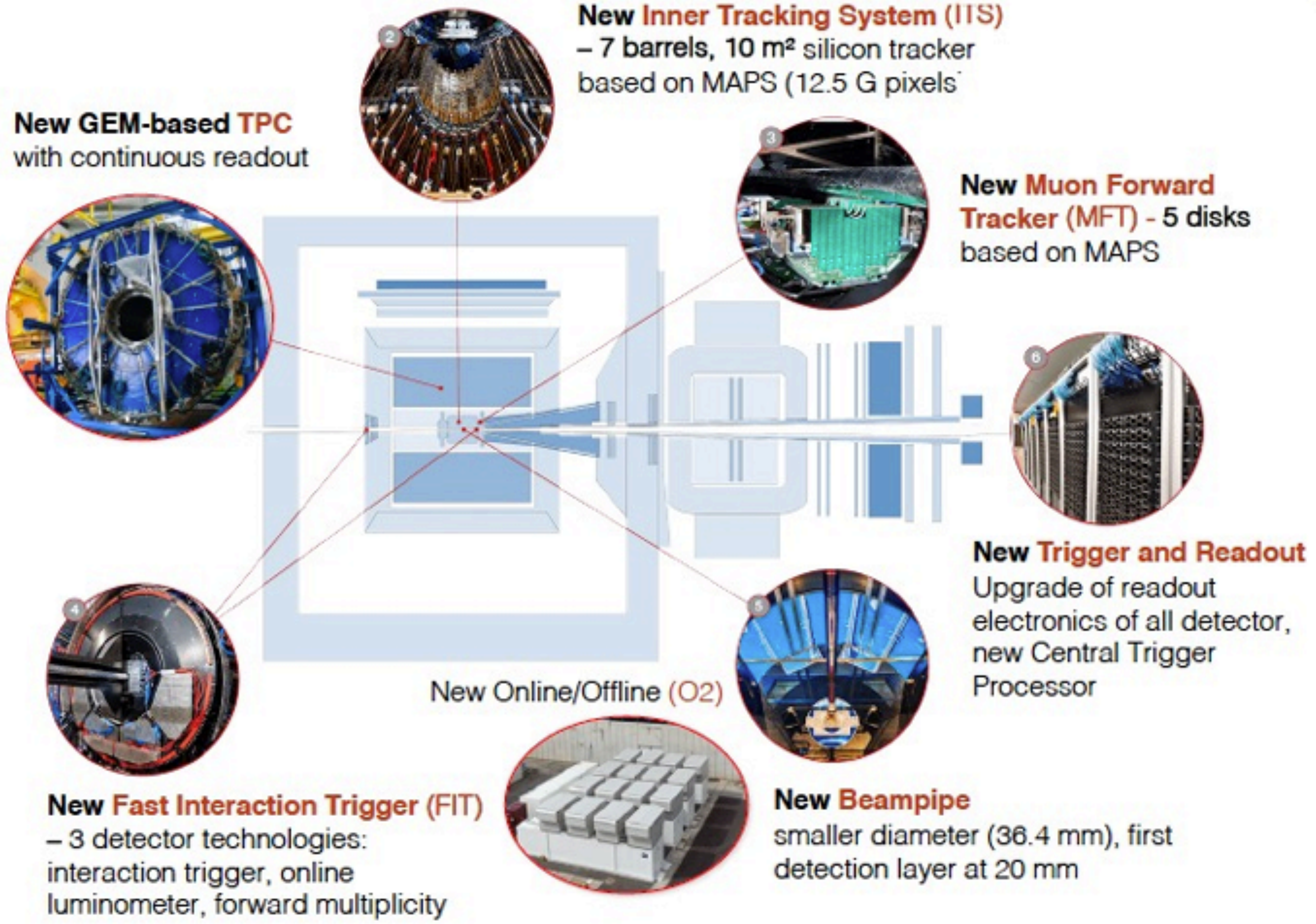
ALICE in Run 3



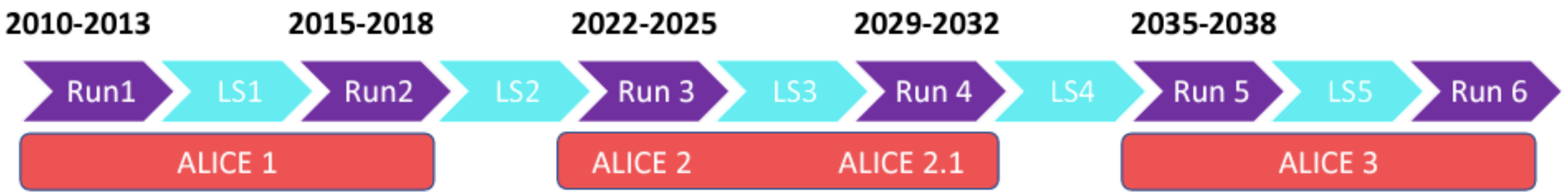
We are here!



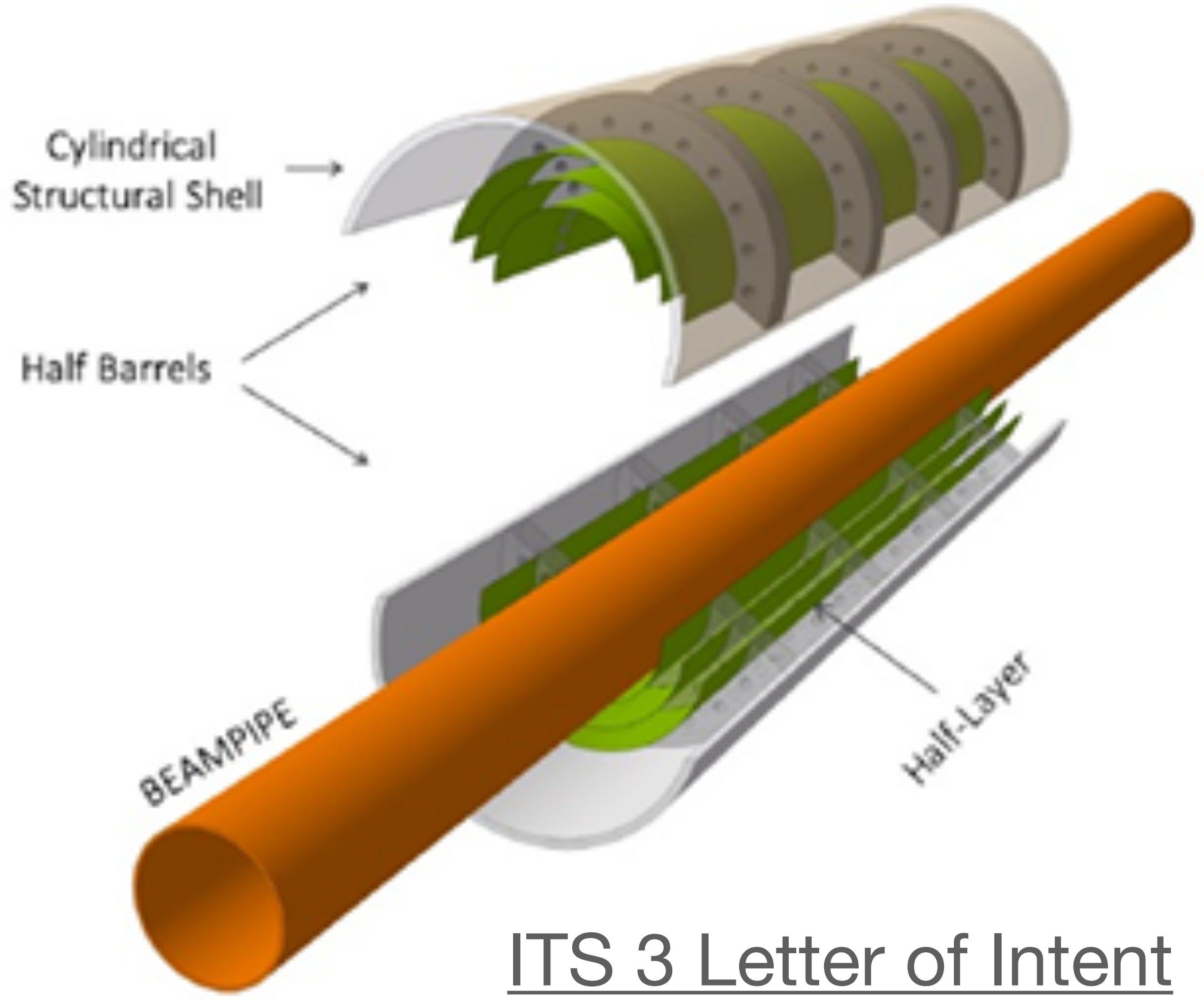
First heavy-ion collisions of Run 3 recorded in November 2022



Upgrades in Long Shutdown 3



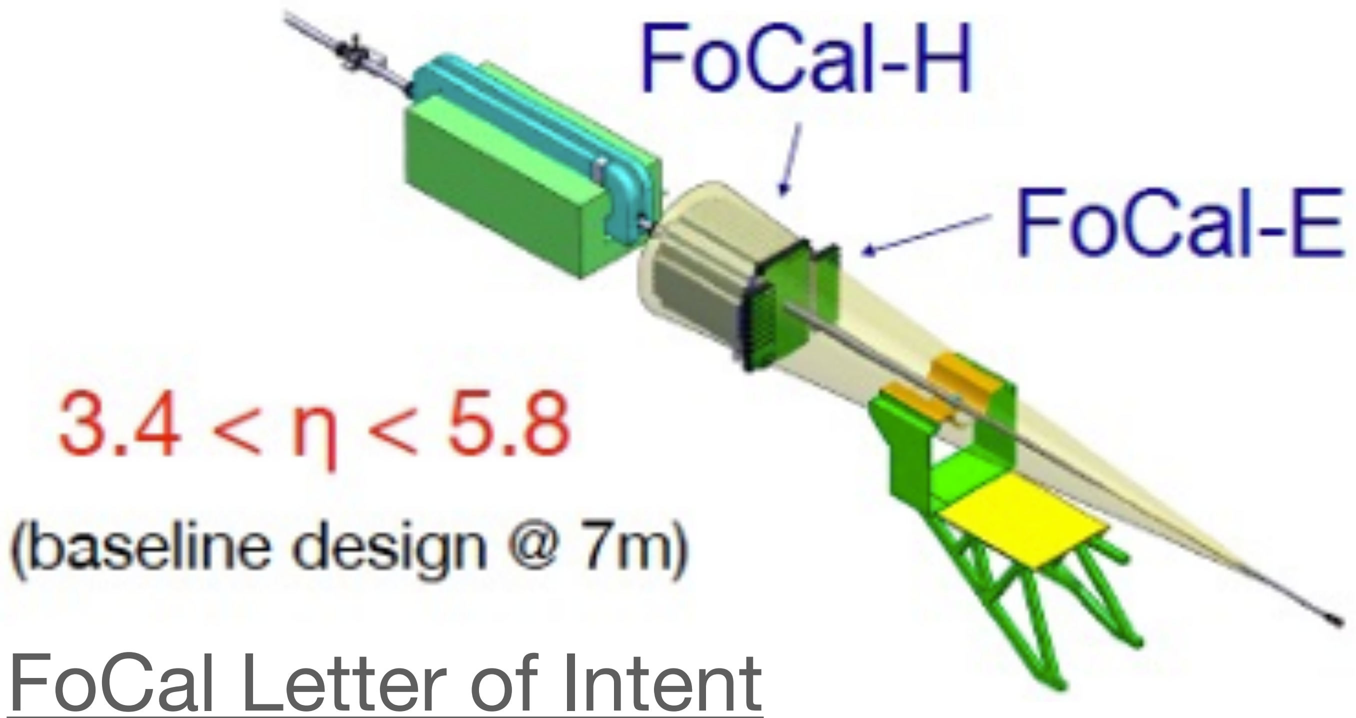
ITS-3



ITS 3 Letter of Intent

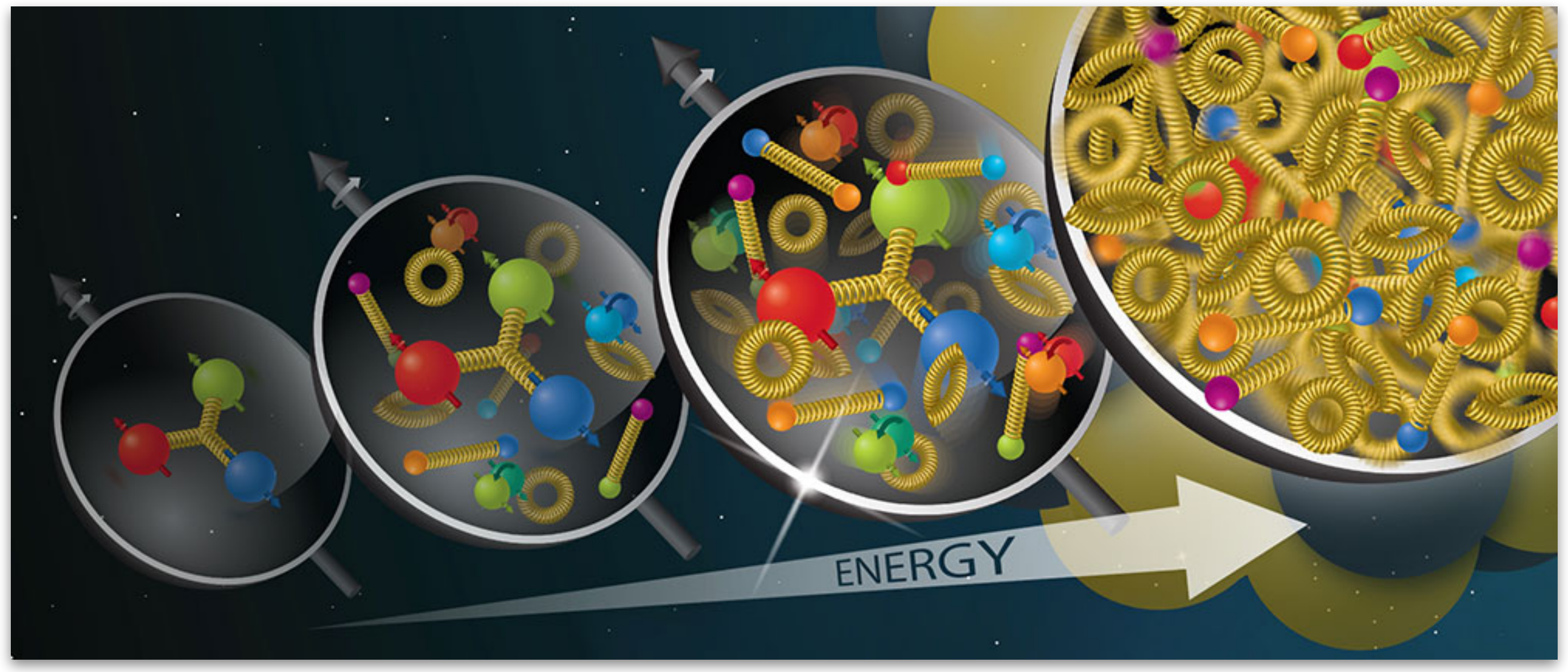
More precise tracking with less material budget. Good for heavy-flavor measurements.

Forward Calorimeter (FoCal)



FoCal Letter of Intent

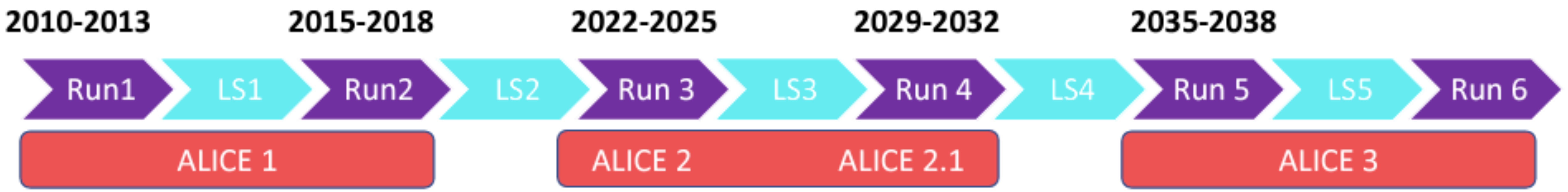
Explore gluon saturation at low-x with forward direct photons



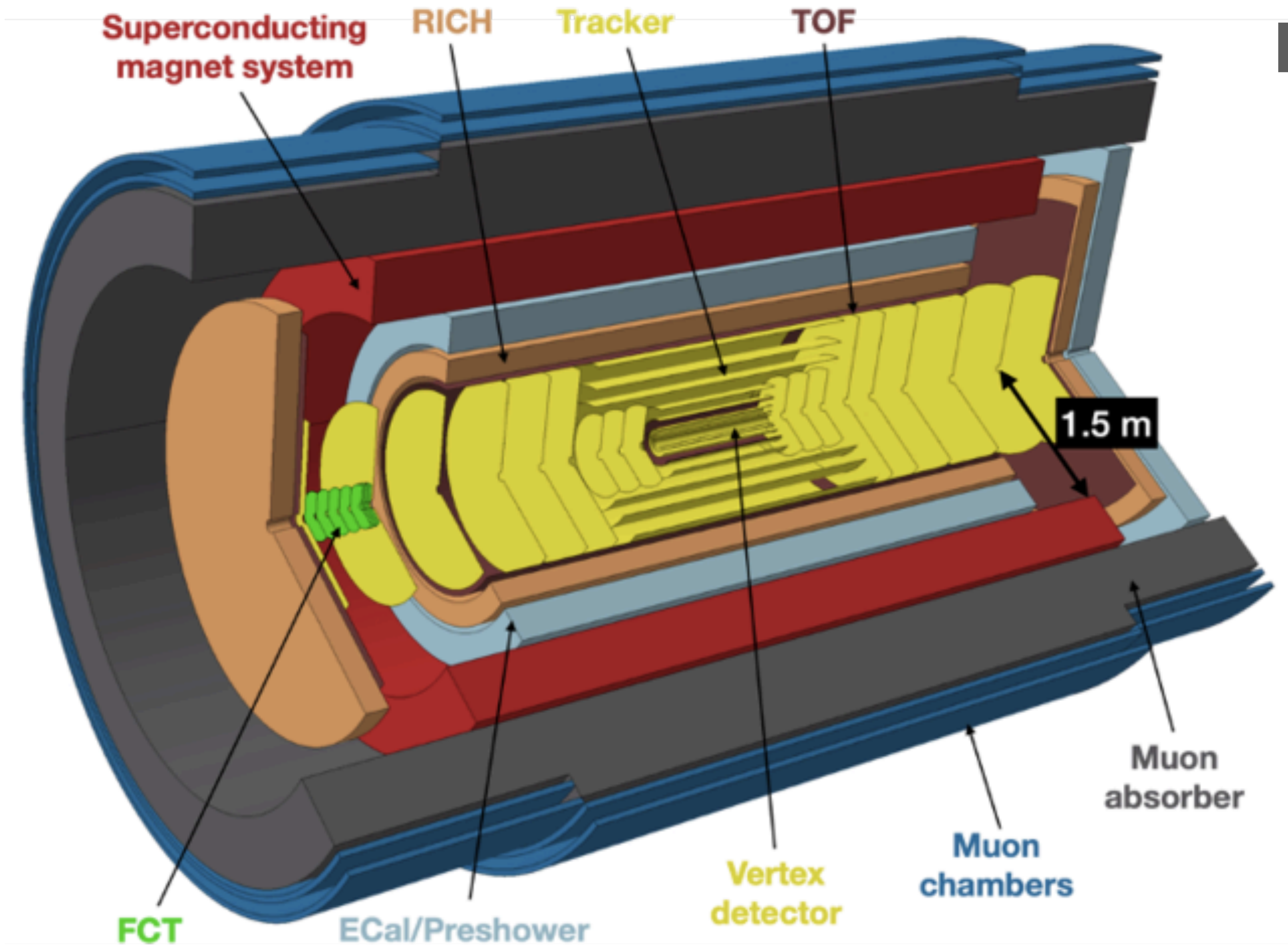
High-x → Low-x

Complements future studies at the **E**lectron **I**on **C**ollider (EIC)!

ALICE 3



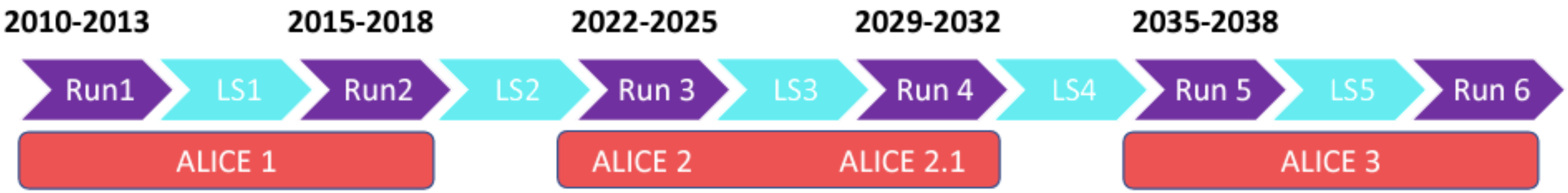
ALICE 3 Letter of Intent



New detector!

- Superconducting magnet
- Much larger acceptance $|\eta| < 4$
- New silicon-based Time of Flight detectors for PID

Physics of ALICE 3



How do partons transition to hadrons as the QGP cools?

What are the mechanisms for chiral symmetry restoration in the QGP?

What is the nature of parton interactions in the QGP?

Is the hadronization at the QGP-hadron phase boundary different from pp collisions?

What mechanisms drive the QGP toward equilibrium?

All of this and more will be explored by ALICE 3!

Outline: A journey through QCD

ALICE

- Introduction to hot QCD
- Selected Physics Highlights from Run 1 and 2 of the LHC
    - Macroscopic properties of the QGP
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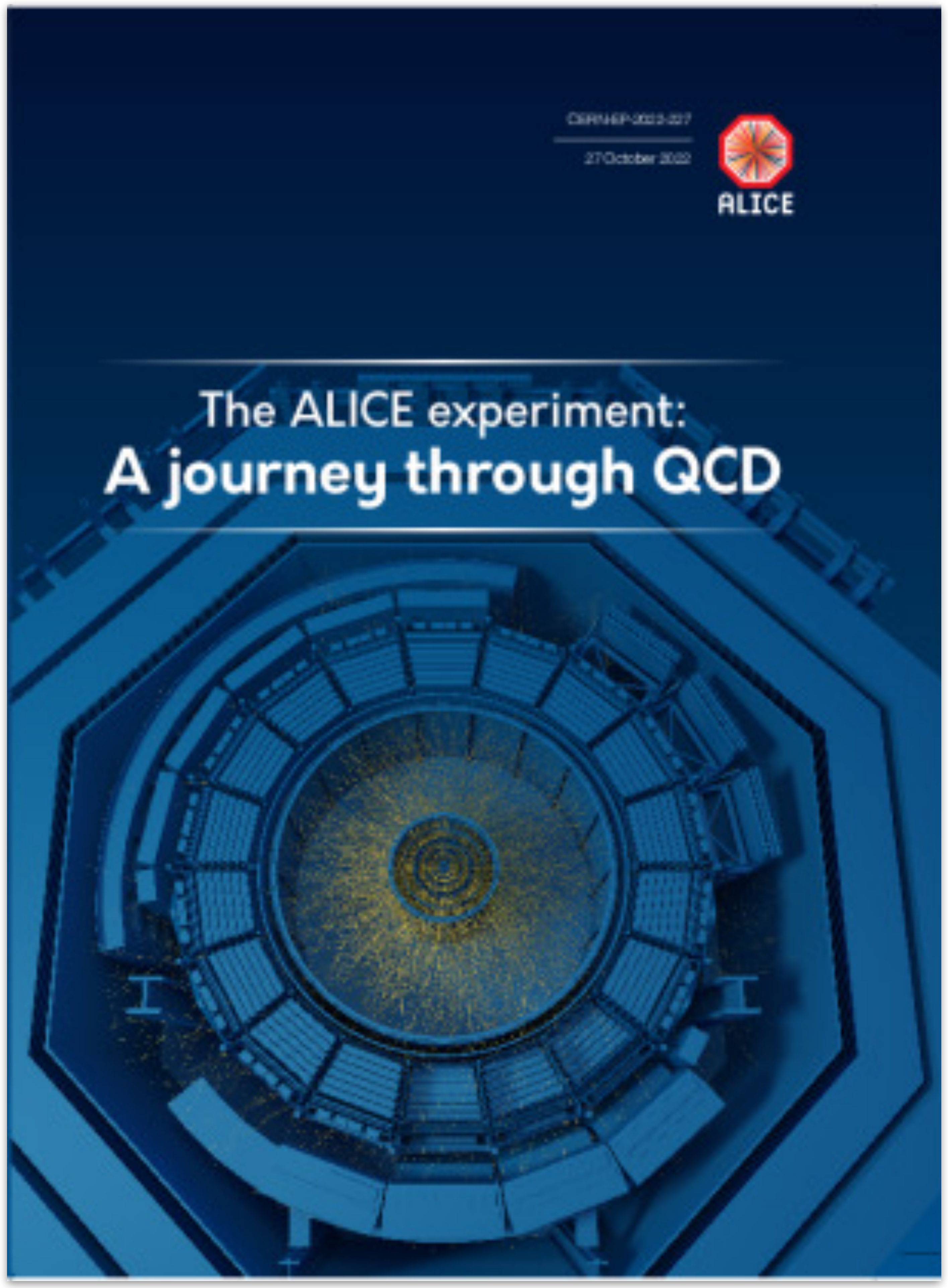
    - Parton interactions with the QGP
- ALICE in Run 3 and beyond!

The journey continues!!

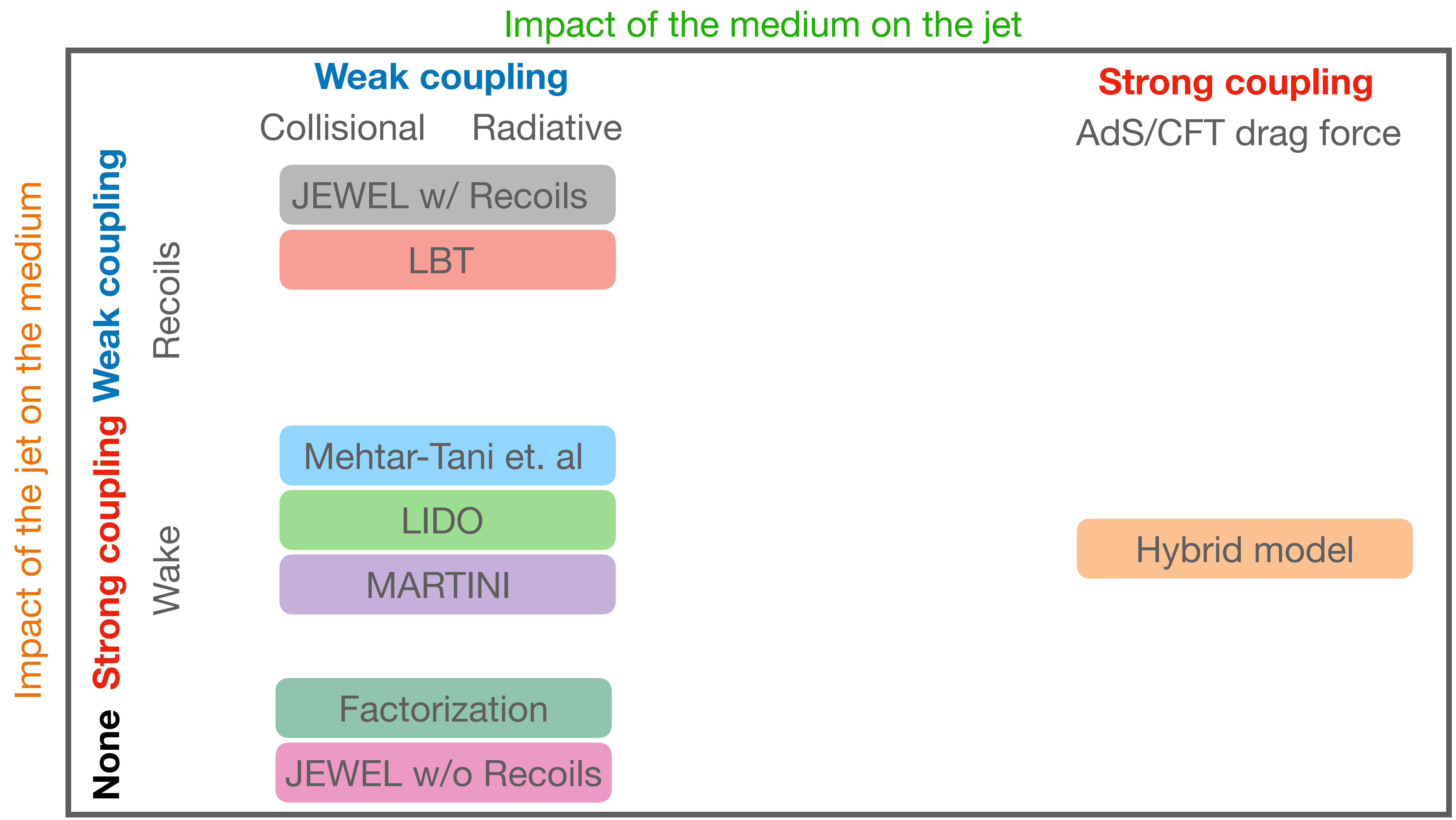


arXiv:2211:04384


ALICE
Pb-Pb 5.36 TeV
LHC22s period
18th November 2022
16:52:47.893

Backup

Jet quenching theory predictions



How do you measure direct photons?

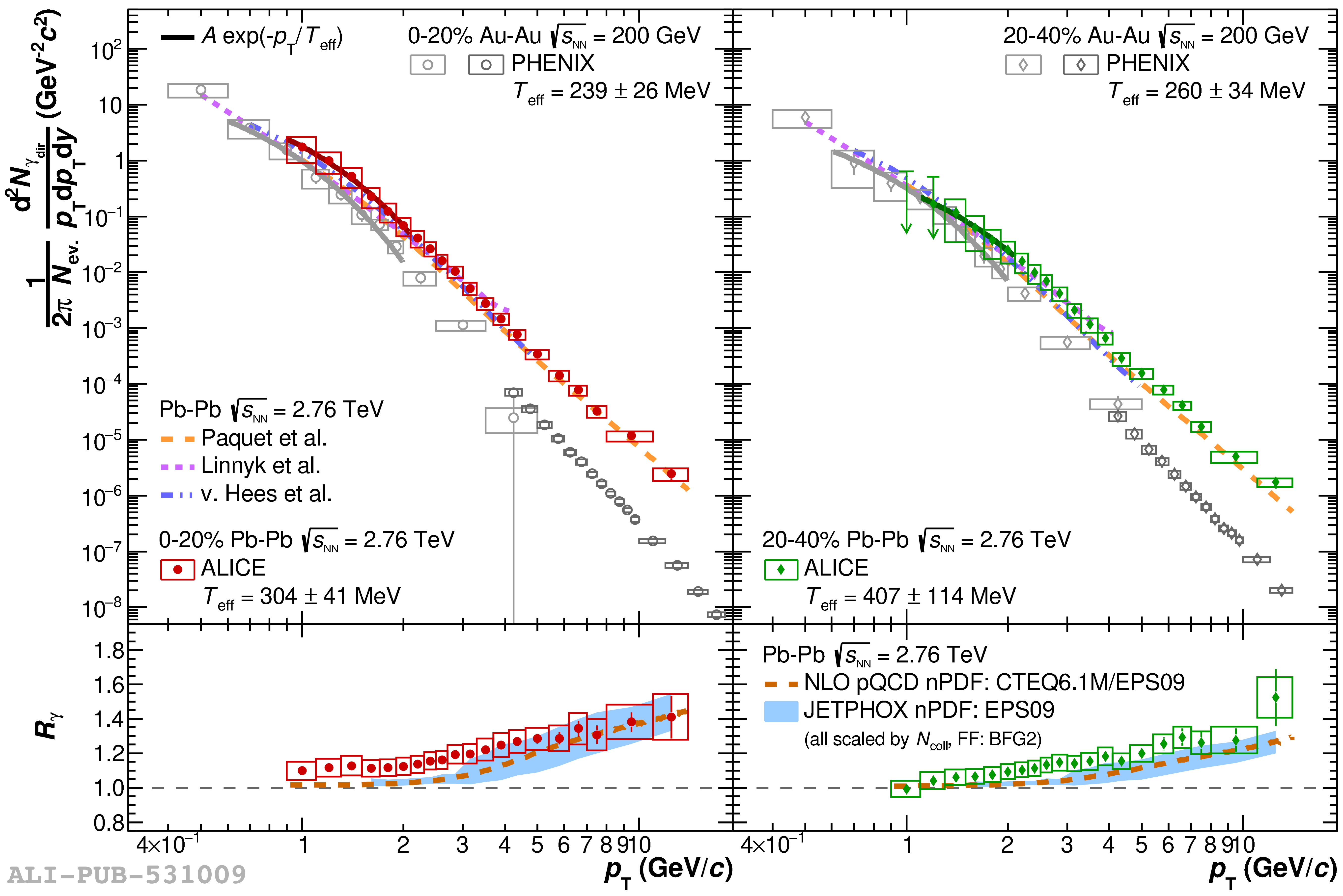
Define γ_{dir} in terms of easier to measure quantities

$$\gamma_{dir} = (1 - 1/R_\gamma)\gamma_{inc}$$

$$R_\gamma = \gamma_{inc}/\gamma_{decay}$$

Easier to measure than γ_{dir} where

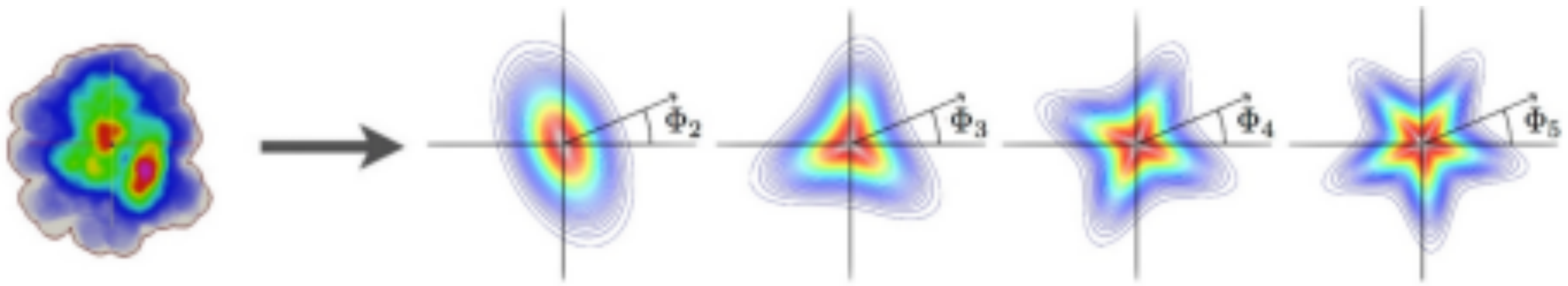
$$\gamma_{inc} = \gamma_{dir} + \gamma_{decay}$$

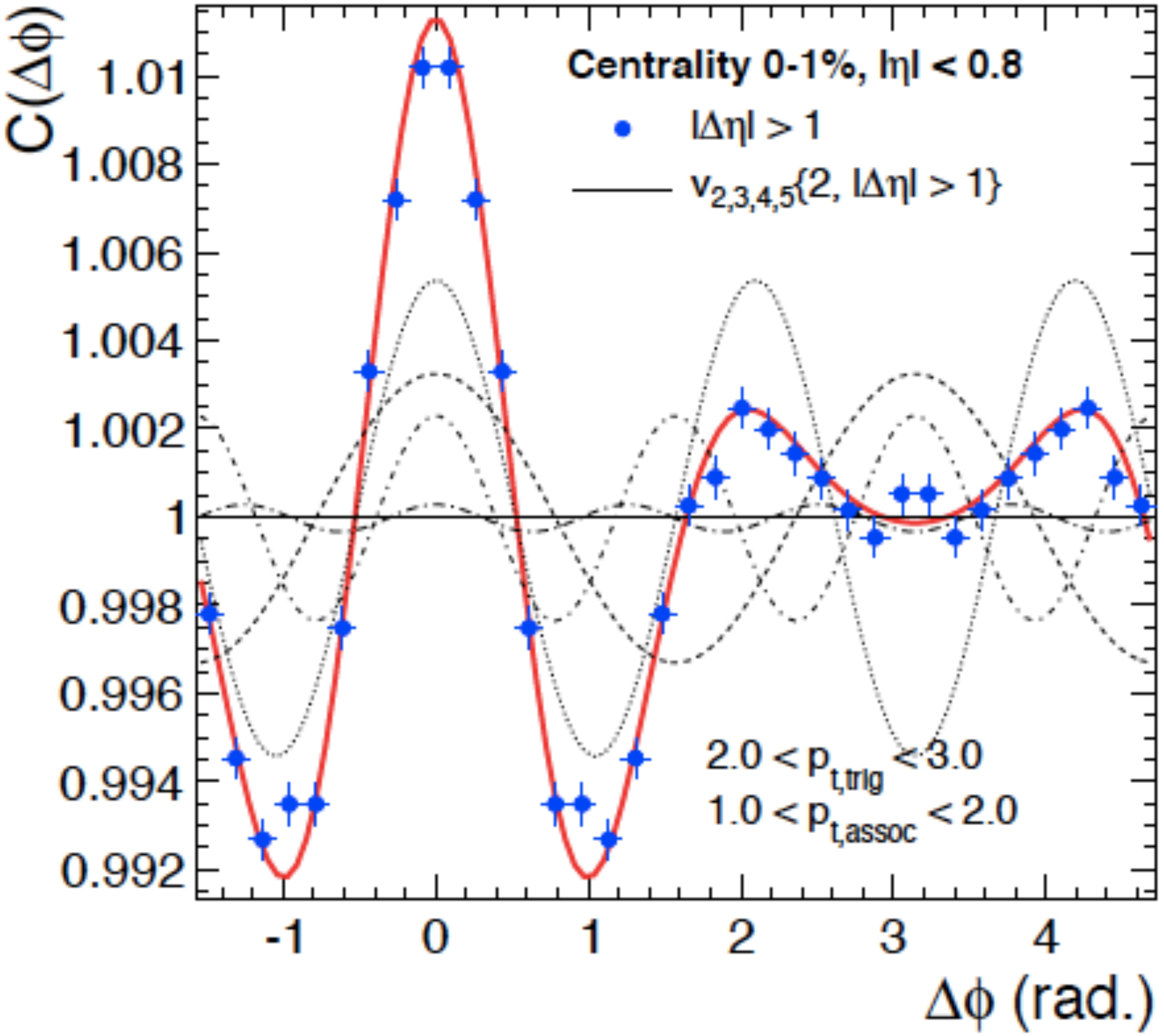


2.6σ Excess of R_γ over pQCD predictions at low p_T indicated photons emitted from QGP.

How do you measure flow?

Measure the distribution of produced particles and fit to a Fourier series.





How do you measure quarkonia?

$J/\psi, \psi(2s), \Upsilon(1s), \Upsilon(2s) \rightarrow \mu^{+}\mu^{-}$

Measure decay into muons in the muon spectrometer.

$J/\psi \rightarrow e^{+}e^{-}$

Measure decay into electrons in the central barrel.