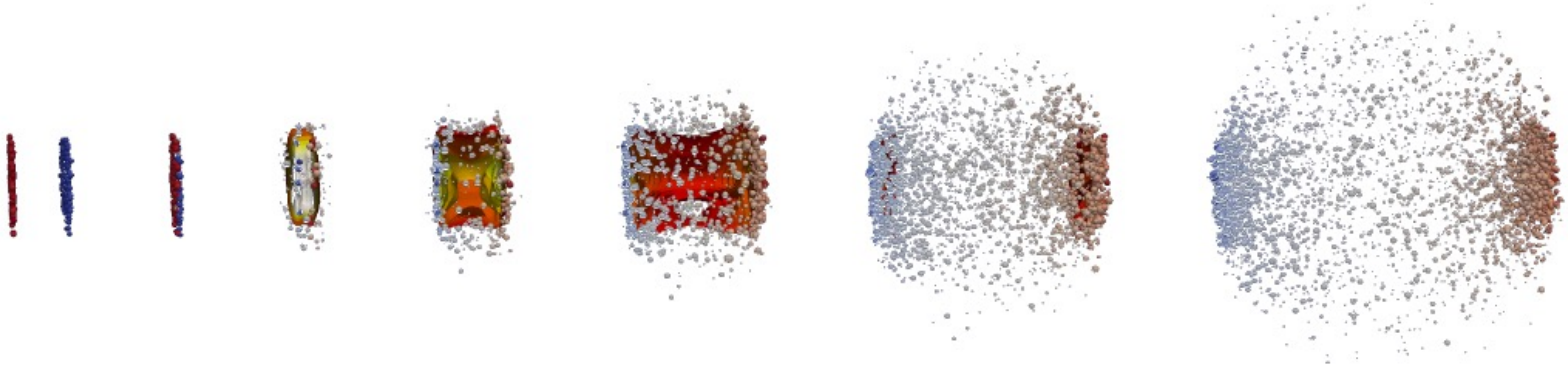
Ultra-relativistic nuclear collisions



From: MADAI collab.

Alexander Kalweit (CERN)

EPS-HEP Hamburg, 25th August 2023

Introduction

1. What is an ultra-relativistic nuclear collision?

2. Where do we do ultra-relativistic nuclear collisions?

3. What can we learn from ultra-relativistic nuclear collisions?

   → For the characteristics of the quark-gluon-plasma

   → For the (subnucleonic) structure of nuclei

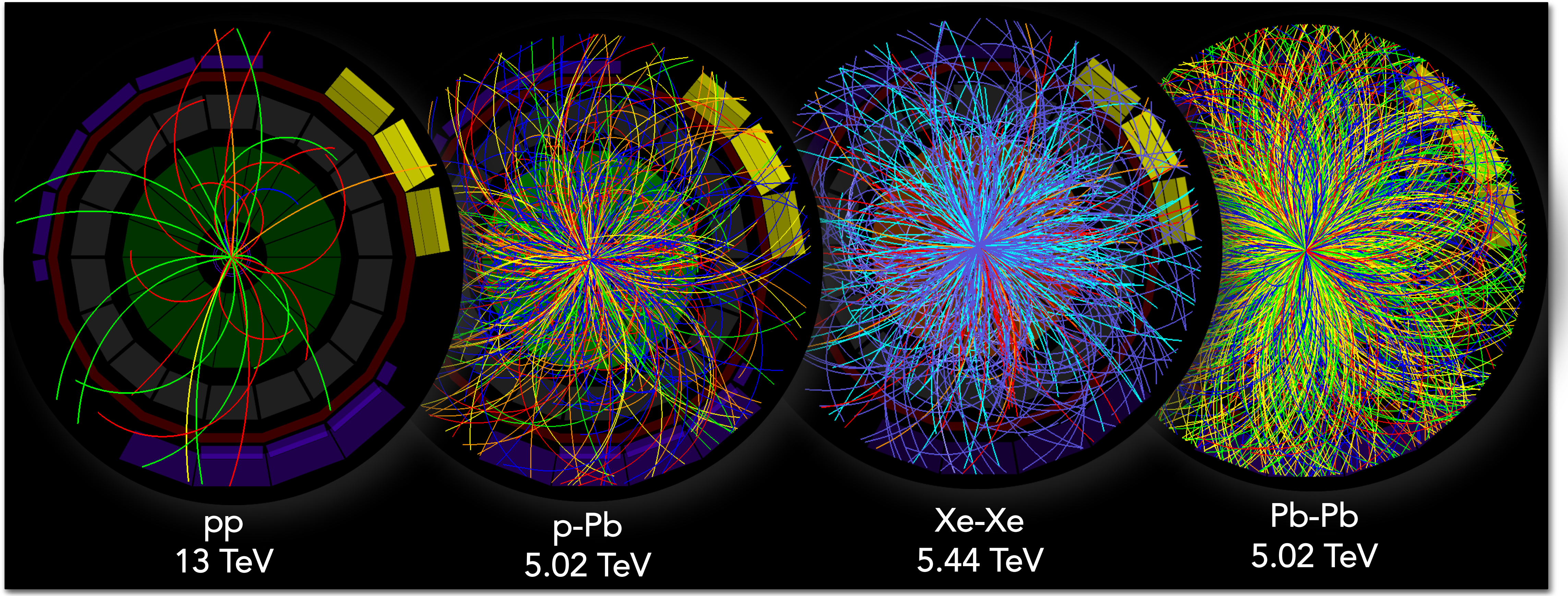
   → For astroparticle physics

→ Disclaimer: our field is diverse, based on many experiments and full of fascinating physics. In the following, I am only able to show a small personal selection.

What is an ultra-relativistic nuclear collision?

pp / p-Pb / Xe-Xe / Pb-Pb collisions

- The LHC can not only collide protons on protons, but also heavier ions.
- Approximately one month of running time is dedicated to heavy-ions each year.



Heavy-ions at the LHC

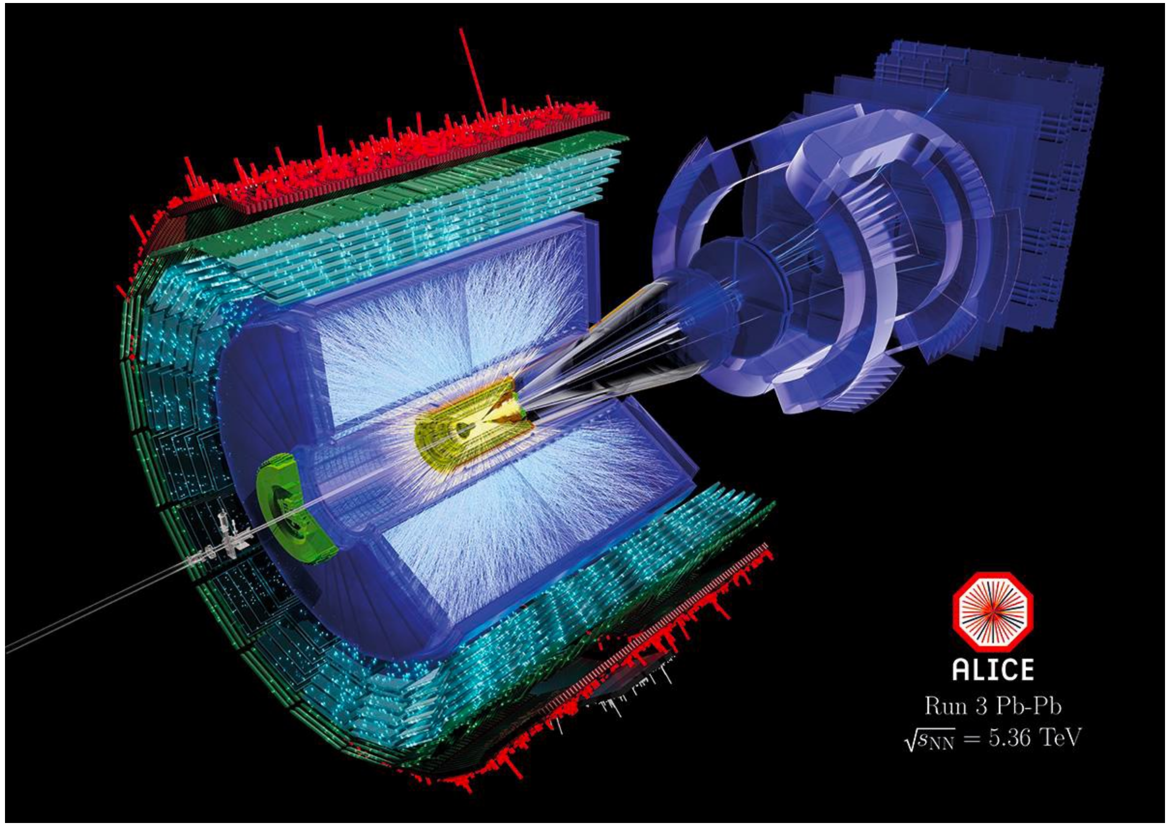
→ Energy per nucleon in a ${}^{208}_{82}$Pb-Pb collision at the LHC (Run 3):

- pp collision energy $\sqrt{s}$ = 13.6 TeV
- beam energy in pp E_{beam} = 6.8 TeV

- Beam energy per nucleon in a Pb-Pb nucleus:
  $E_{beam,PbPb}$ = 82/208 · 6.8 = 2.68 TeV

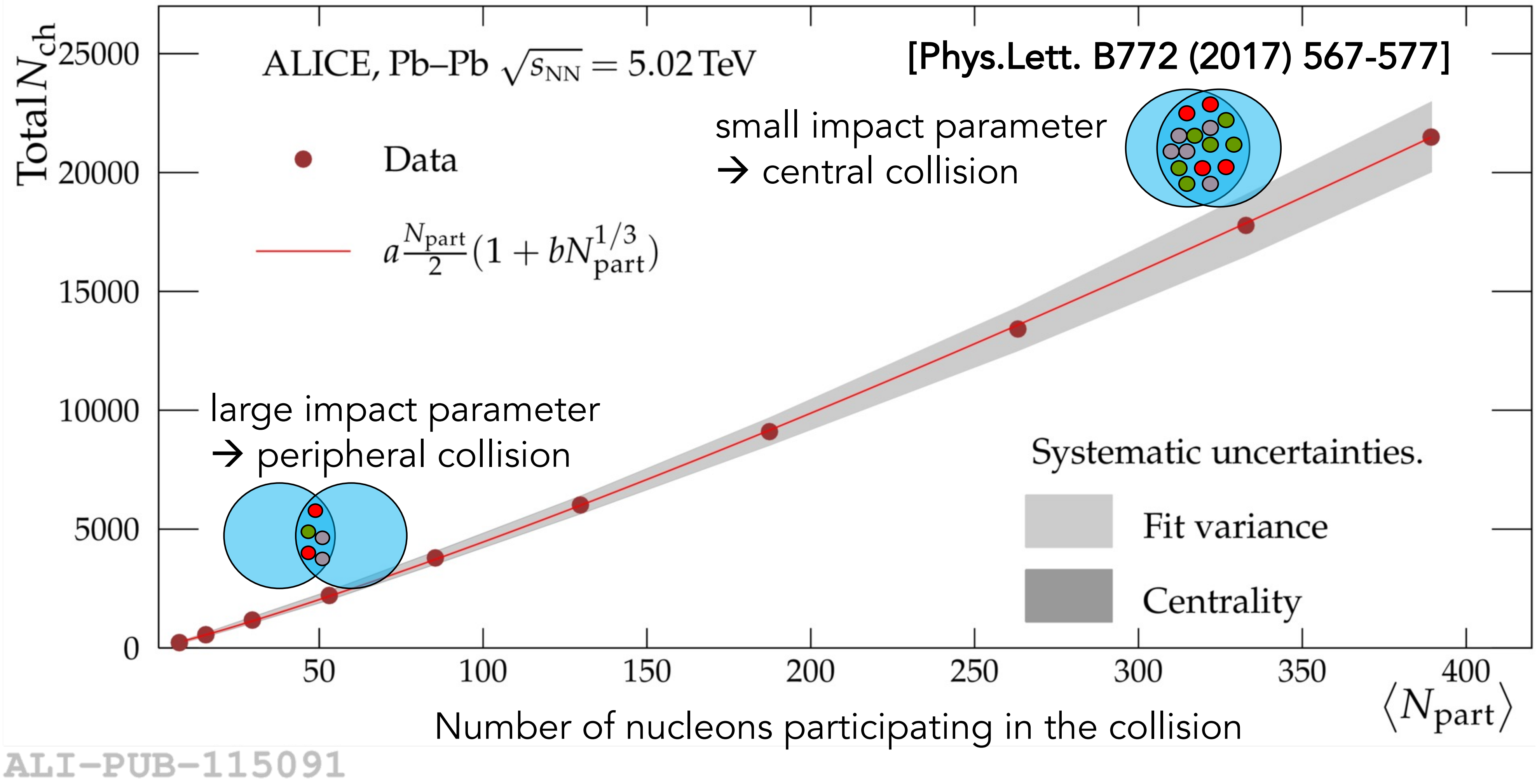
- Collision energy per nucleon-nucleon pair in Pb-Pb: $\sqrt{s_{NN}}$ = 5.36 TeV

- Total collision energy in Pb-Pb:
  $\sqrt{s} = 208 \cdot 5.36$ TeV = 1.1 PeV



→ What can we learn from these massive interactions?

Total number of charged hadrons in Pb-Pb collisions

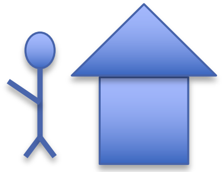


→ Collisions of heavy-ions at high energy accelerators allow the creation of several tens of thousands of hadrons (1 << N << 1mol) in local thermodynamic equilibrium in the laboratory.
→ Access to multi-body phenomena in QCD (in analogy of condensed matter physics to QED).

QGP as the asymptotic state of QCD (1)

Quark-Gluon-Plasma (QGP): at extreme temperatures and densities quarks and gluons behave quasi-free and are not localized to individual hadrons anymore.

bound quarks & gluons

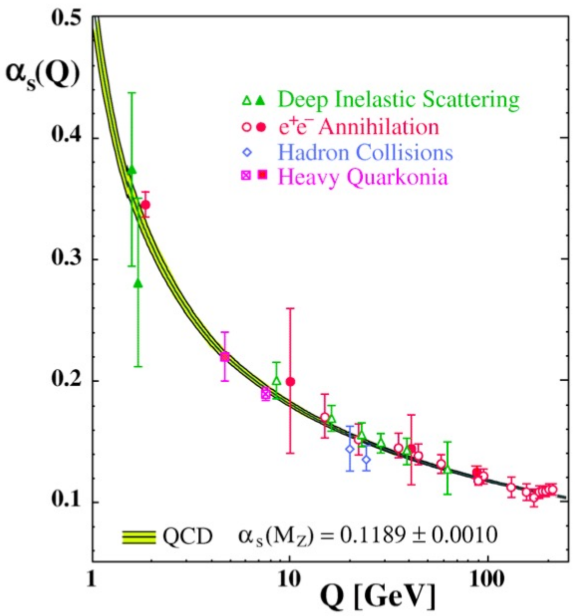


Asymptotic freedom:
free quarks & gluons

$T \to \infty$

Temperature T

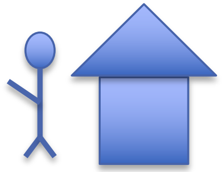
$T_0 \approx 1/40$ eV



QGP as the asymptotic state of QCD (2)

Quark-Gluon-Plasma (QGP): at extreme temperatures and densities quarks and gluons behave quasi-free and are not localized to individual hadrons anymore.

bound quarks & gluons



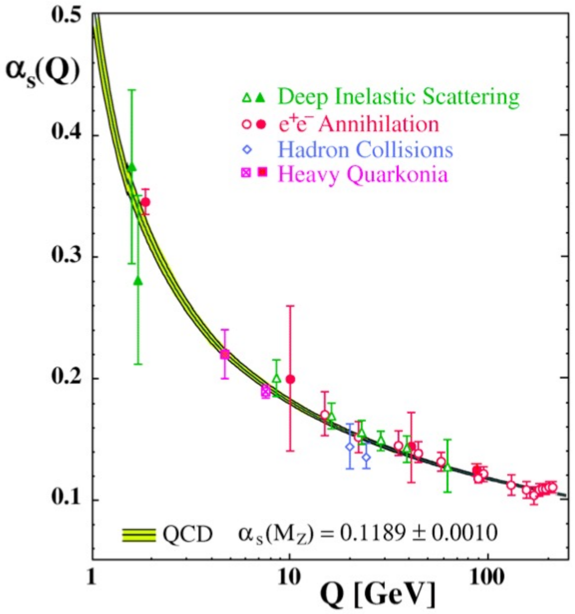
Where is the phase transition?
→ Lattice QCD

Asymptotic freedom:
free quarks & gluons

$T \rightarrow \infty$

Temperature T

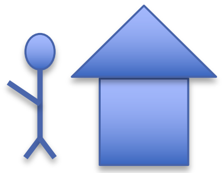
$T_0 \approx 1/40$ eV



QGP as the asymptotic state of QCD (3)

Quark-Gluon-Plasma (QGP): at extreme temperatures and densities quarks and gluons behave quasi-free and are not localized to individual hadrons anymore.

bound quarks & gluons



Where is the phase transition?
→ Lattice QCD

Asymptotic freedom:
free quarks & gluons

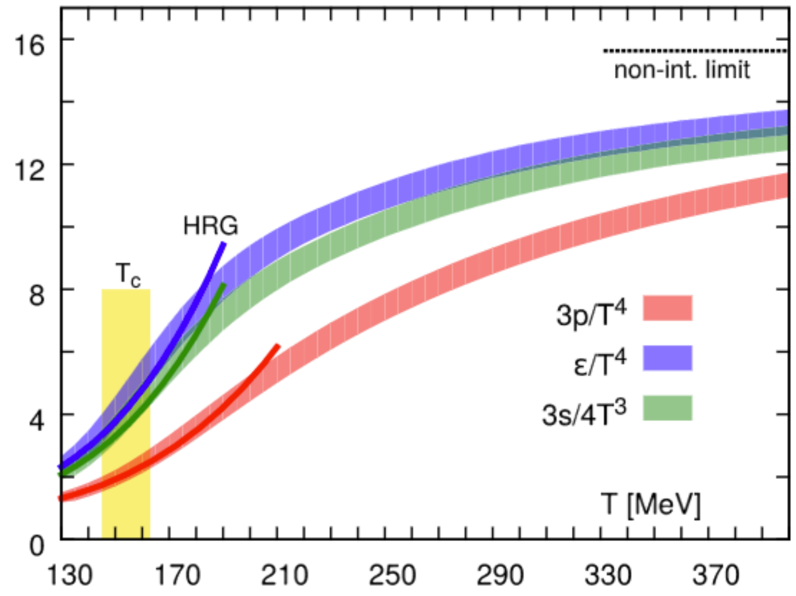
$T \rightarrow \infty$

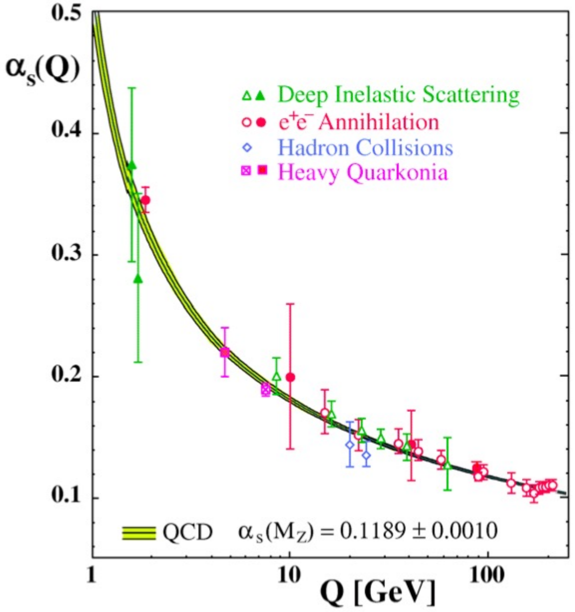
Temperature *T*

$T_0 \approx 1/40$ eV

Critical temperature
$T_c \approx 156$ MeV ≙ $1.8 \cdot 10^{12}$ K

[PRD 90 094503 (2014)]

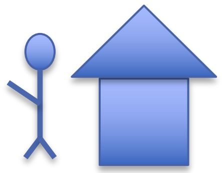




QGP as the asymptotic state of QCD (4)

Quark-Gluon-Plasma (QGP): at extreme temperatures and densities quarks and gluons behave quasi-free and are not localized to individual hadrons anymore.

bound quarks & gluons



Where is the phase transition?
→ Lattice QCD

Asymptotic freedom:
free quarks & gluons

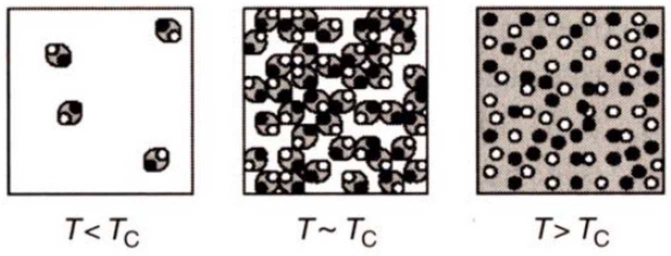
$T \rightarrow \infty$

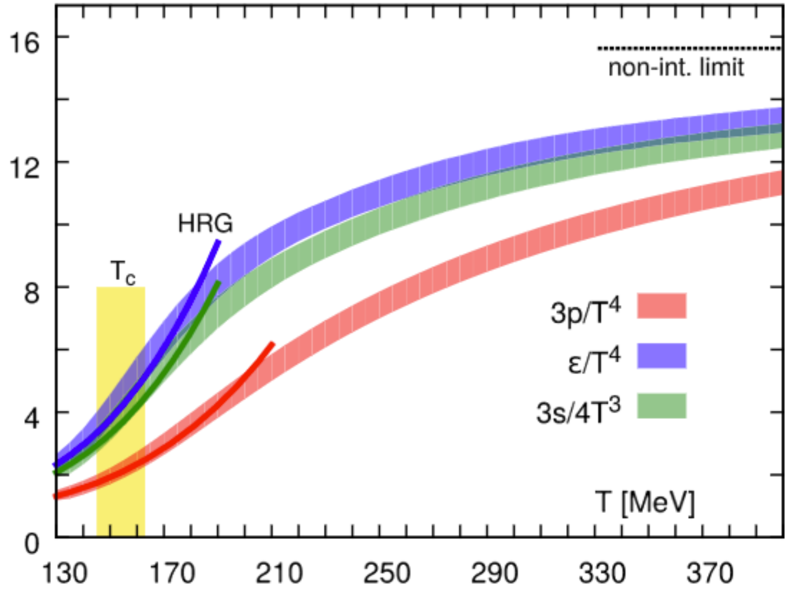
Temperature T

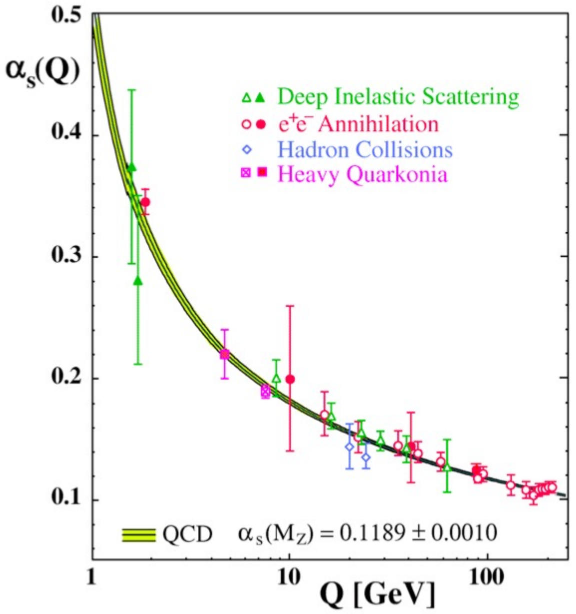
$T_0 \approx 1/40$ eV

Critical temperature
$T_c \approx 156$ MeV ≙ $1.8 \cdot 10^{12}$ K

[PRD 90 094503 (2014)]







→ Are such extreme temperatures reached in the experiment?
Yes..

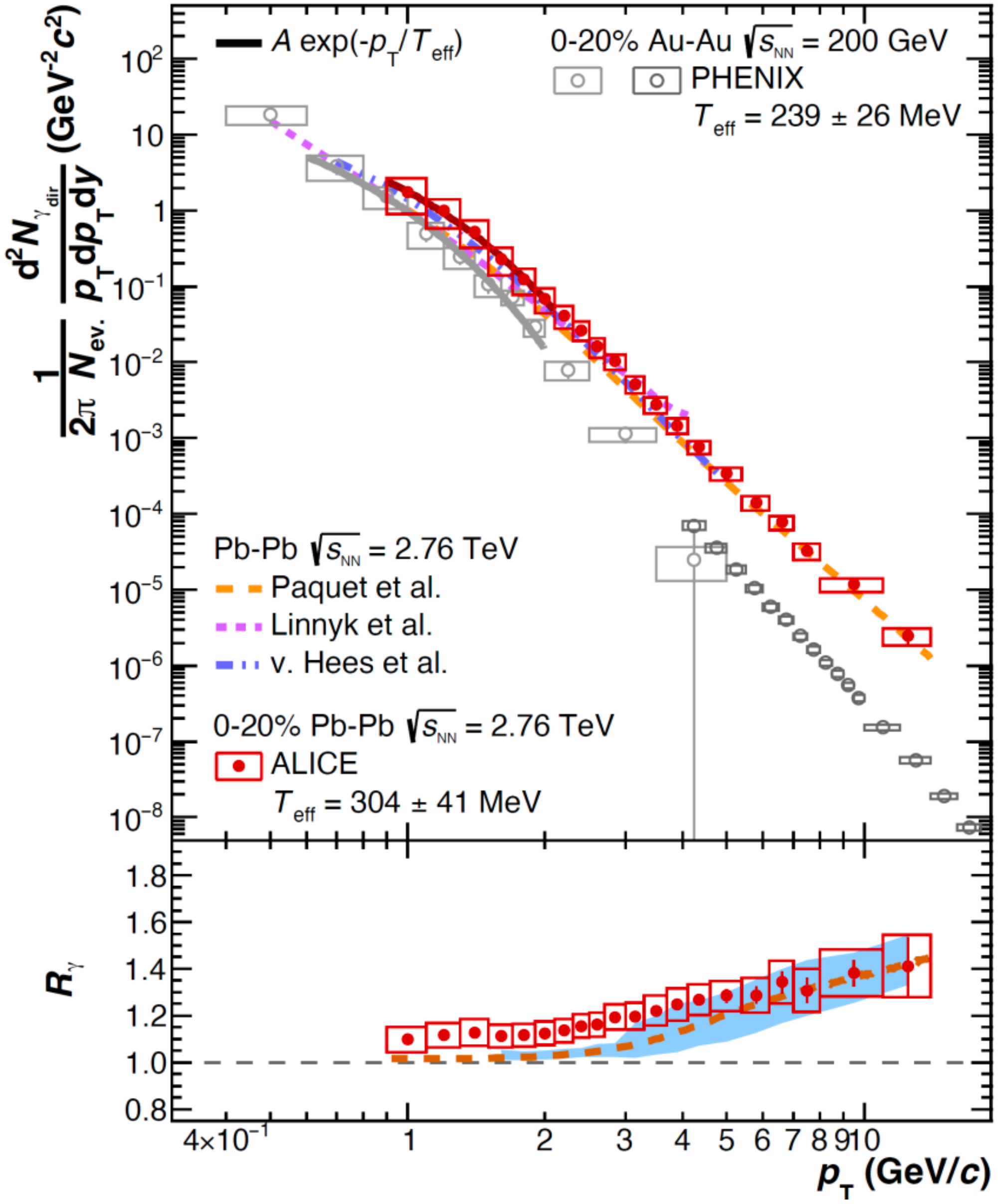
Fireball temperature

[ALICE, PLB 754 (2016) 235]

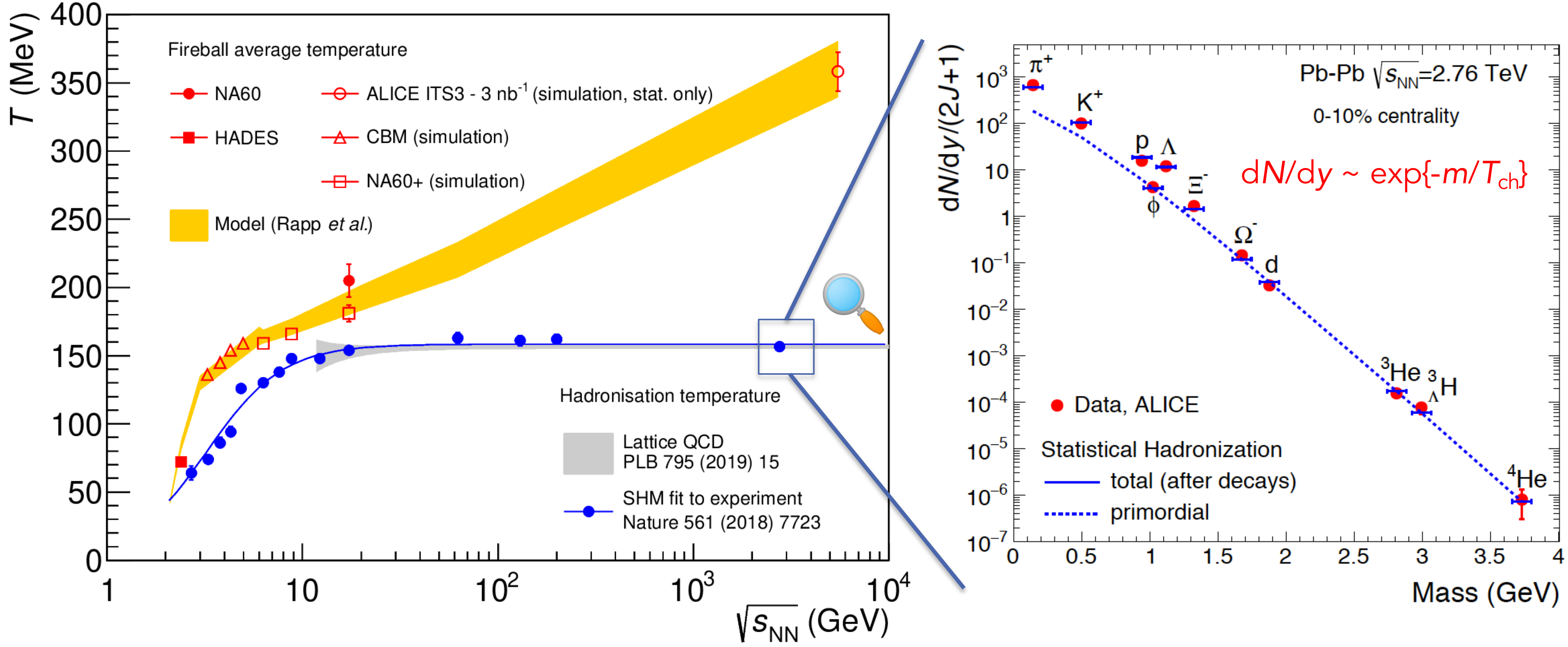
→ The effective photon temperature T_{eff} = 304 ± 41 MeV is twice larger than the critical temperature of approx. 160 MeV.

→ Ultra-relativistic nuclear collisions provide extreme conditions in terms of:

- Multiplicities
- Temperature
- Energy density



Temperatures in heavy-ion collisions



→ Systematic measurements of light flavor hadrons demonstrate that chemical freeze-out (hadronization) temperature saturates at:

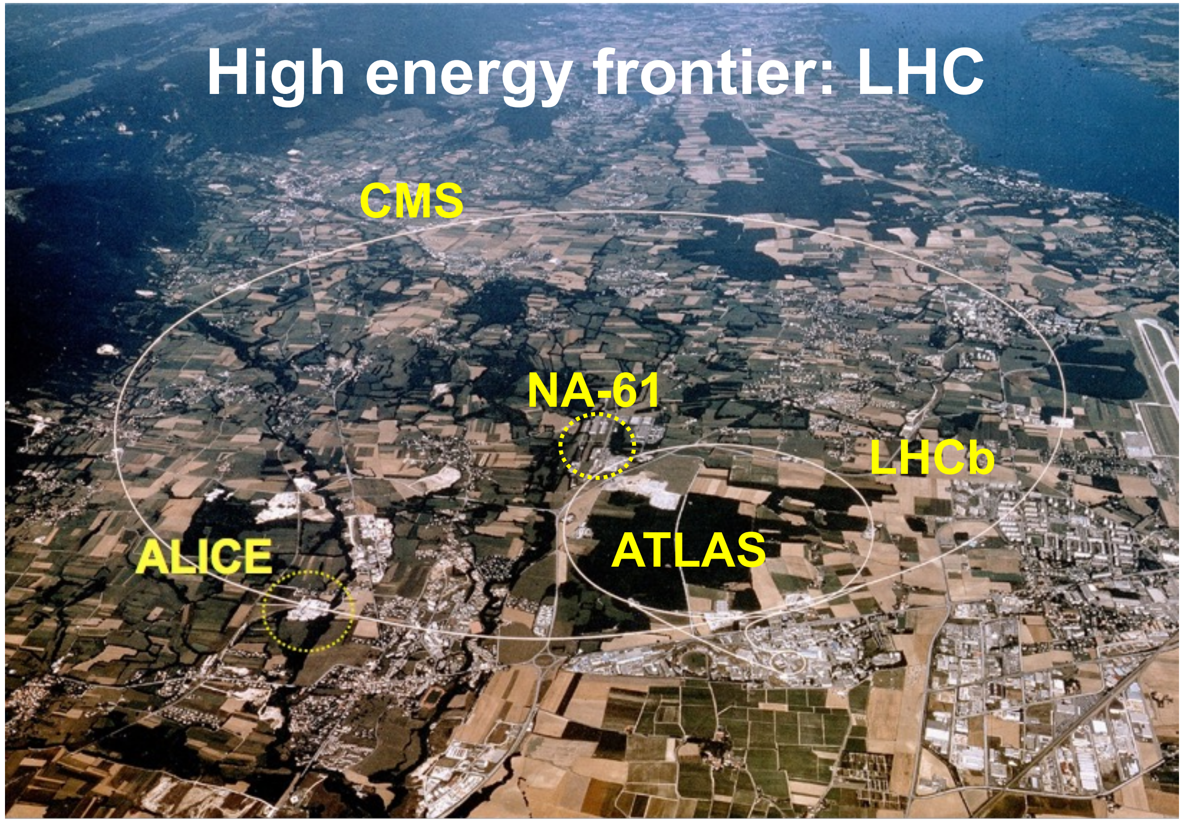
$T_{ch} \approx 156$ MeV ± 3 MeV (≙ $1.8 \cdot 10^{12}$ K)

→ In agreement with first principle Lattice QCD calculations

[Nature 561 (2018) no.7723, 321-330] [ALICE, Nucl. Phys. A 971 (2018) 1-20]

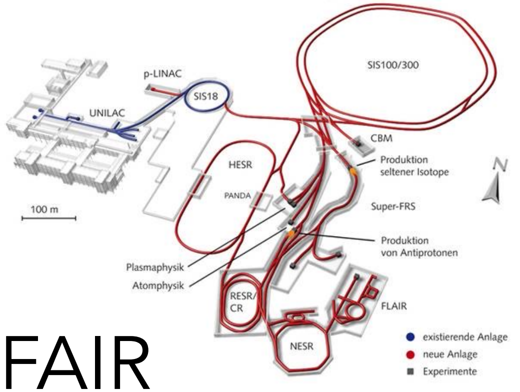
Where do we do ultra-relativistic nuclear collisions?

Heavy-ion experiments

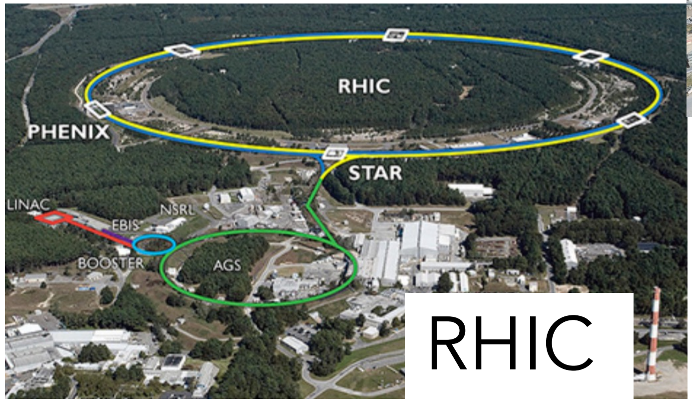


→ By now **all major LHC experiments have a heavy-ion program**: LHCb took Pb-Pb data for the first time in November 2015.

Low energy frontier: RHIC (BES), SPS
→ future facilities: FAIR (GSI), NICA



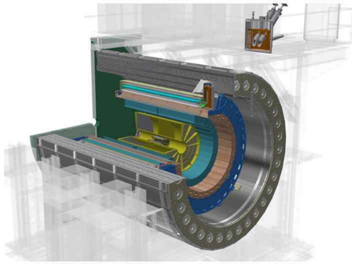
FAIR



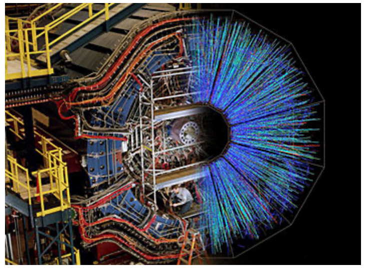
RHIC

Lower energy heavy-ion experiments

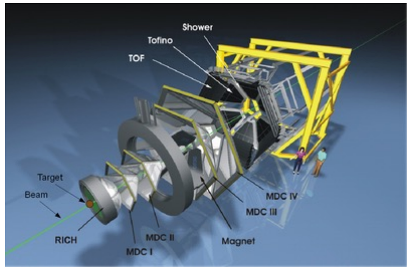
→ Existing:



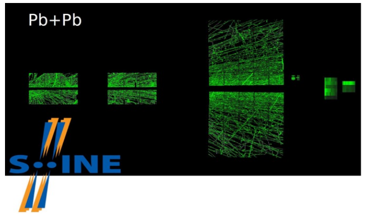
[sPHENIX]



[STAR]

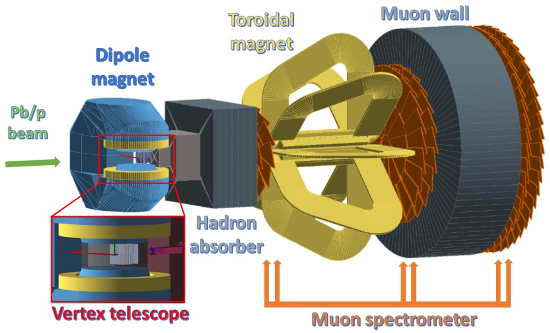


[HADES]

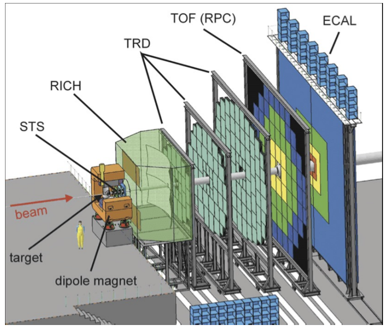


[NA-61 SHINE]

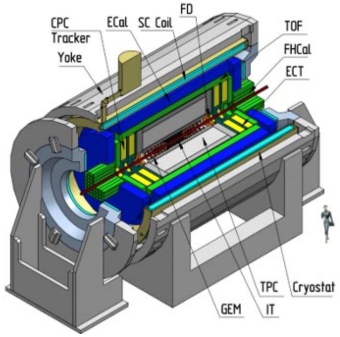
→ Planned:



[NA-60+]

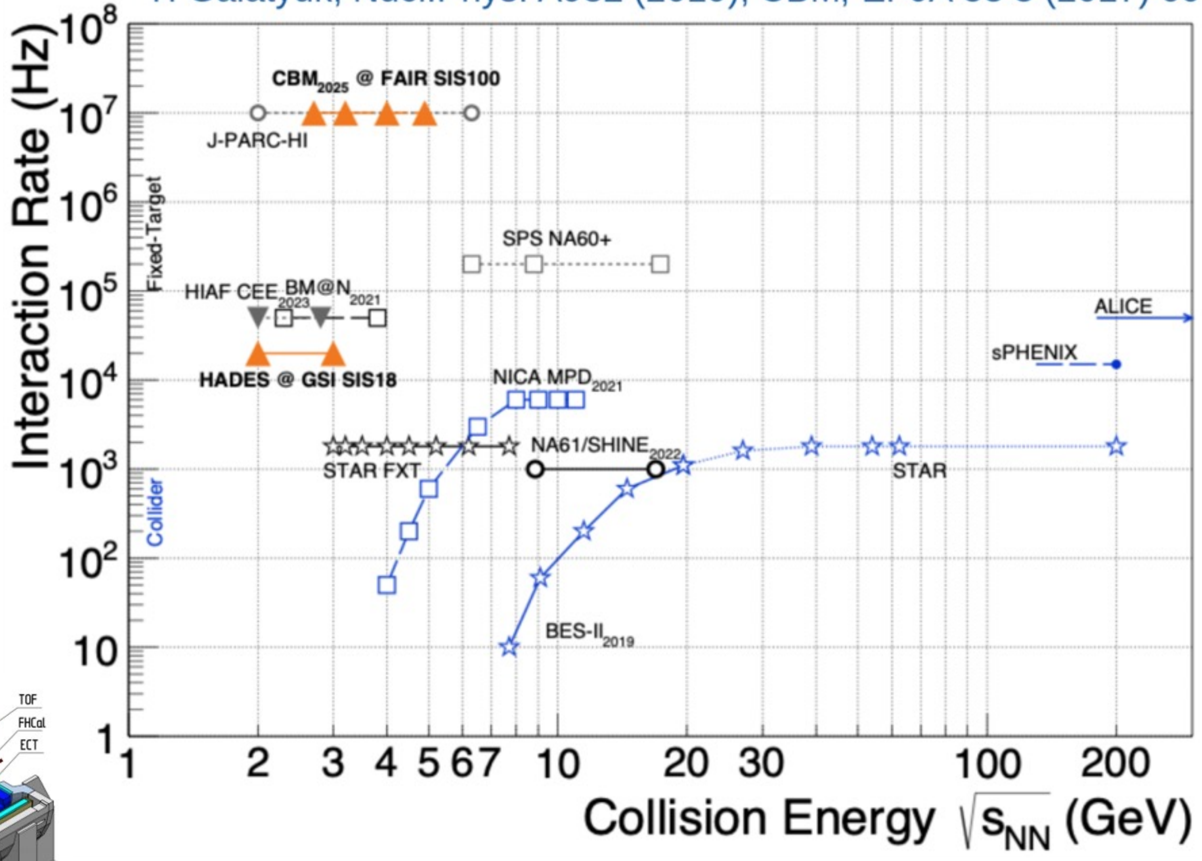


[CBM]



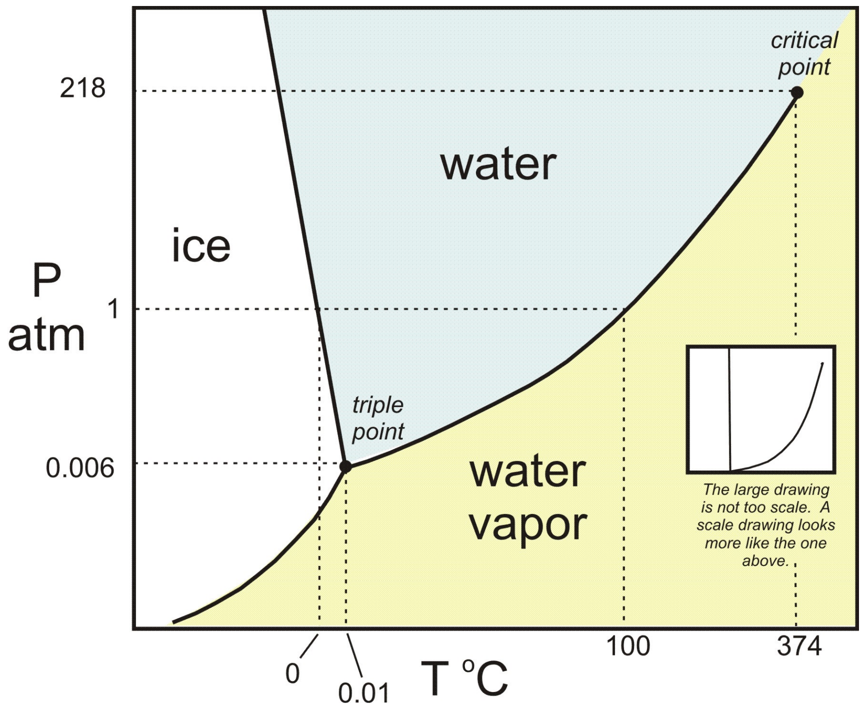
[MPD]

T. Galatyuk, Nucl.Phys. A982 (2019); CBM, EPJA 53 3 (2017) 60

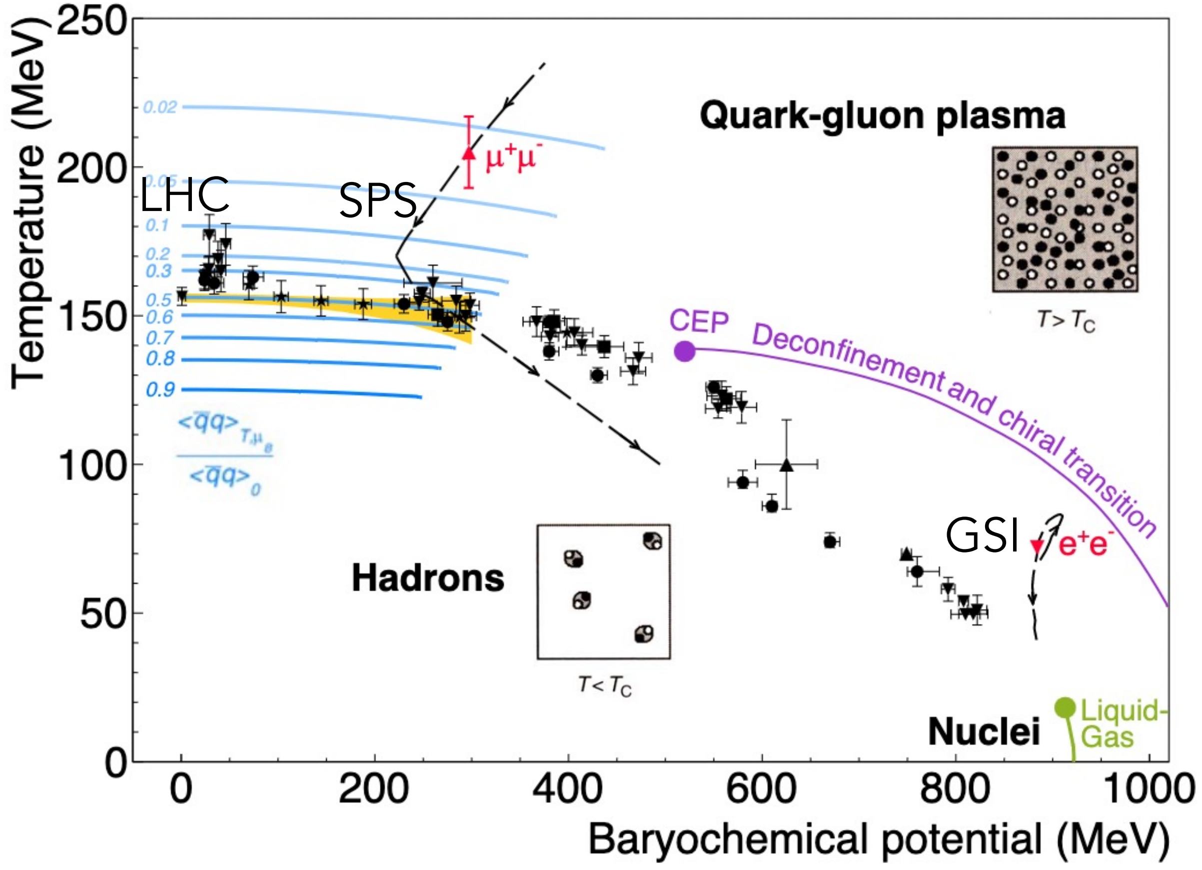


Exploring the phase diagram of QCD

- Similar to water or any other substance, also QCD has a phase diagram.
- The different facilities and experiments probe different regions of the phase diagram.



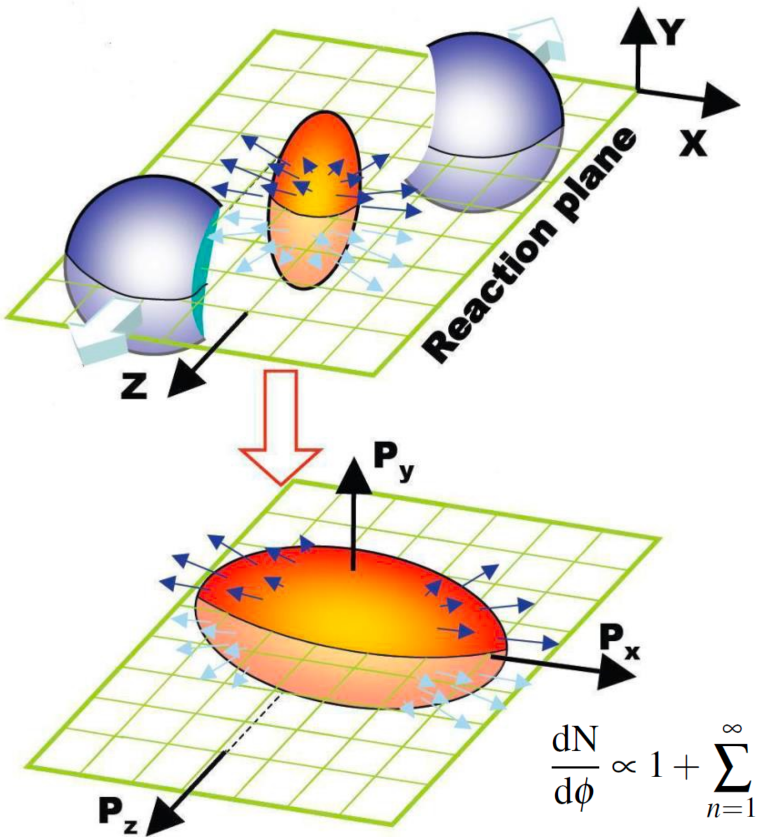
[http://serc.carleton.edu/research_education/equilibria/phaserule.html]



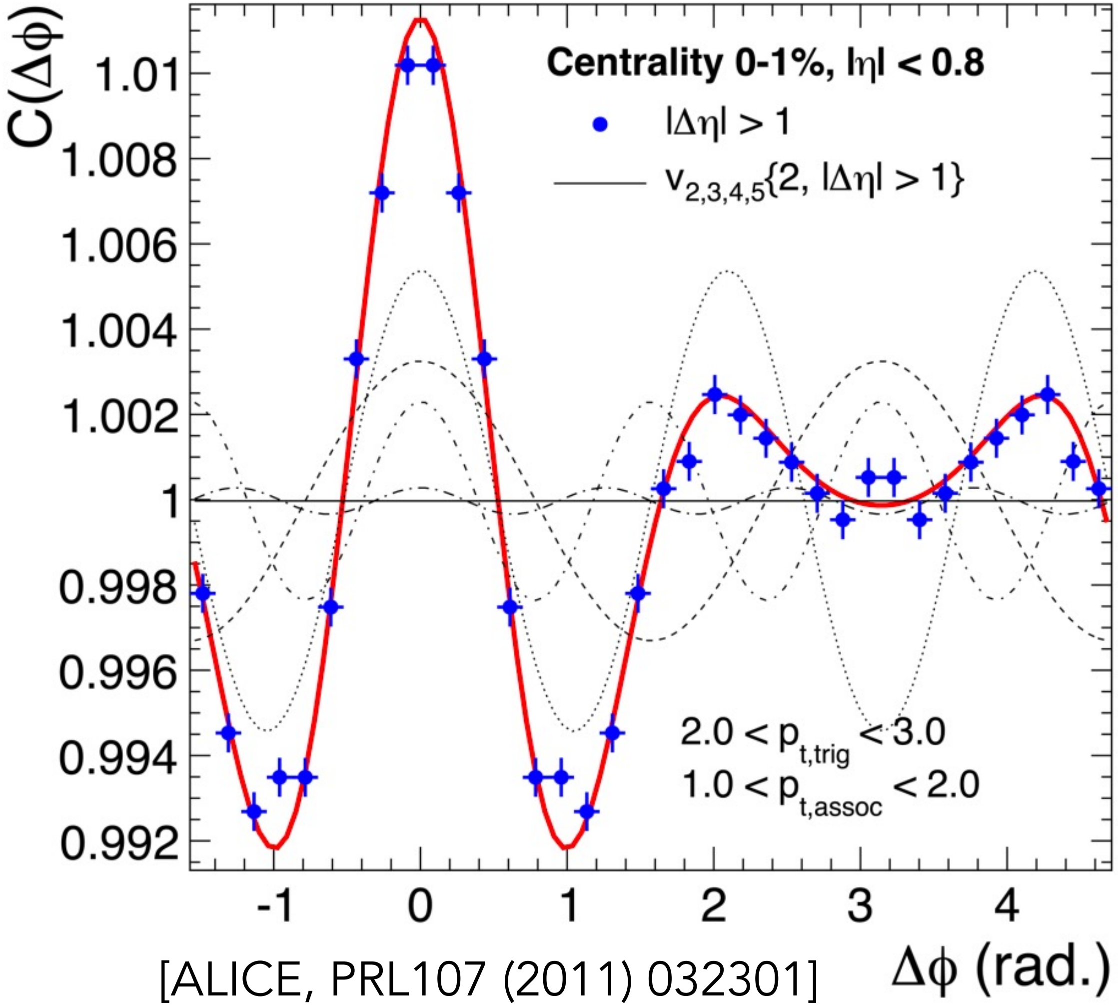
[Nature Phys. 15 (2019) 10, 1040-1045]

What can we learn from ultra-relativistic nuclear collision for the characterization of the quark-gluon-plasma?

Probing the ideal liquid (1)



$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n(p_T)\cos\left(n(\phi - \Psi_n)\right)$$

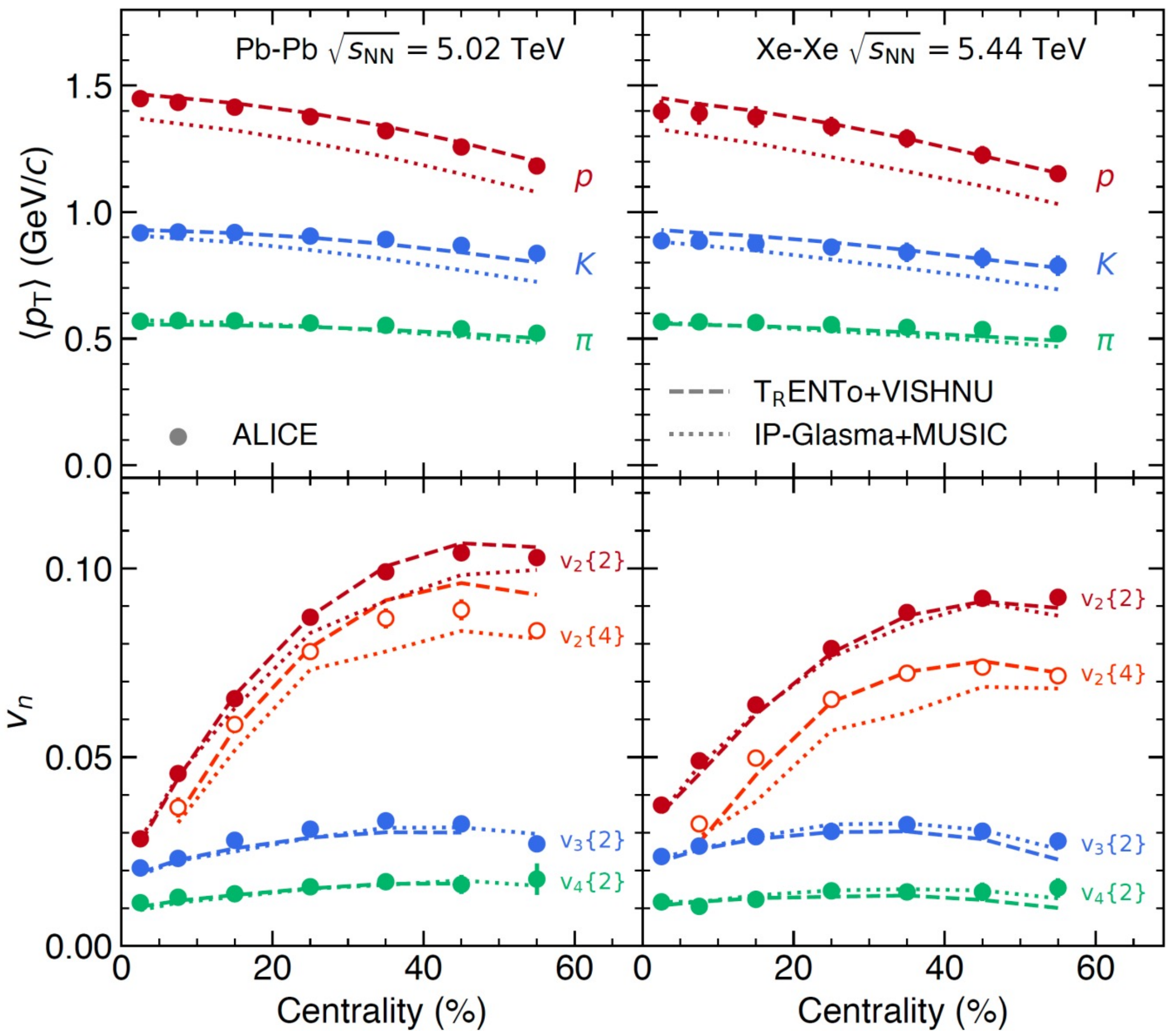


[ALICE, PRL107 (2011) 032301]

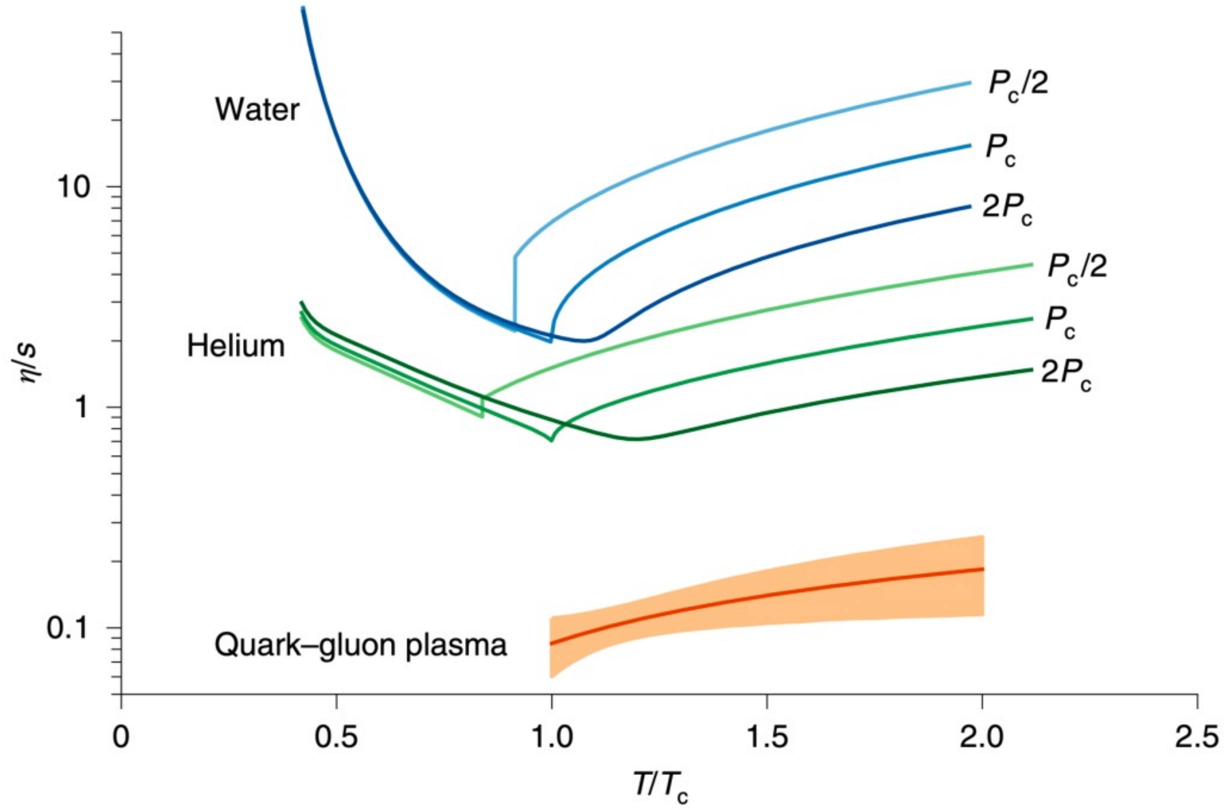
- Spatial anisotropy of the initial state induces momentum anisotropy in the final state
- Characterised by anisotropic flow coefficients v_n
- Fluctuations in the initial state lead to non-zero values of higher harmonics if they are not damped (sensitivity to the *viscosity* of the system)

Probing the ideal liquid (2)

[J. Bernhard et al, *Nature Physics* (2019)]

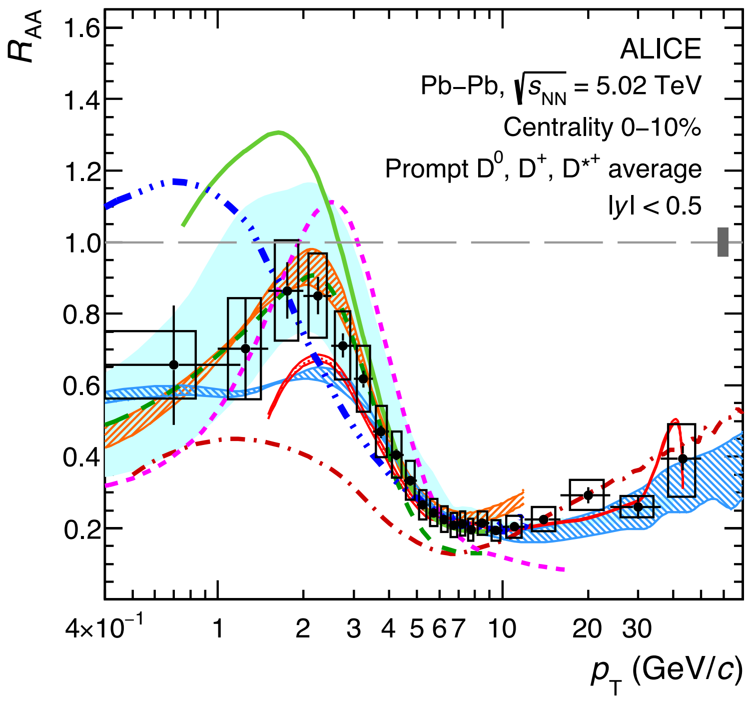


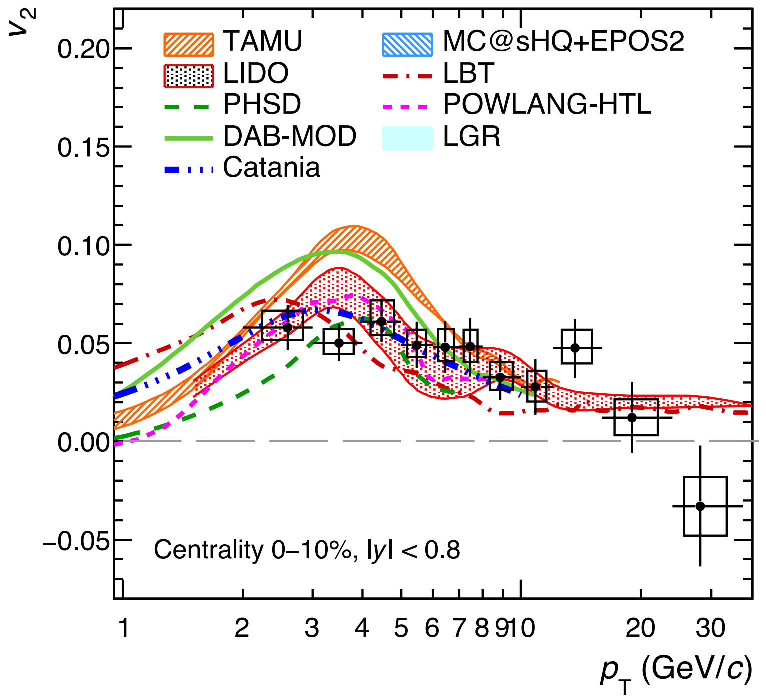
[ALICE, arXiv:2211.04384]

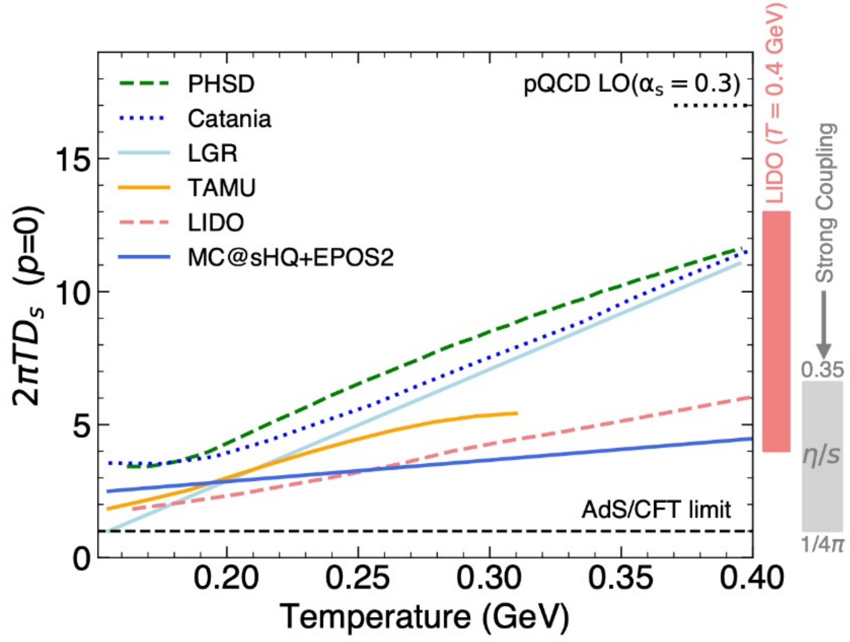


→ Radial and anisotropic expansion of QGP described by hydrodynamical equation of state with small viscosity close to the Ads/CFT limit.

Following the propagation of charm through the QGP





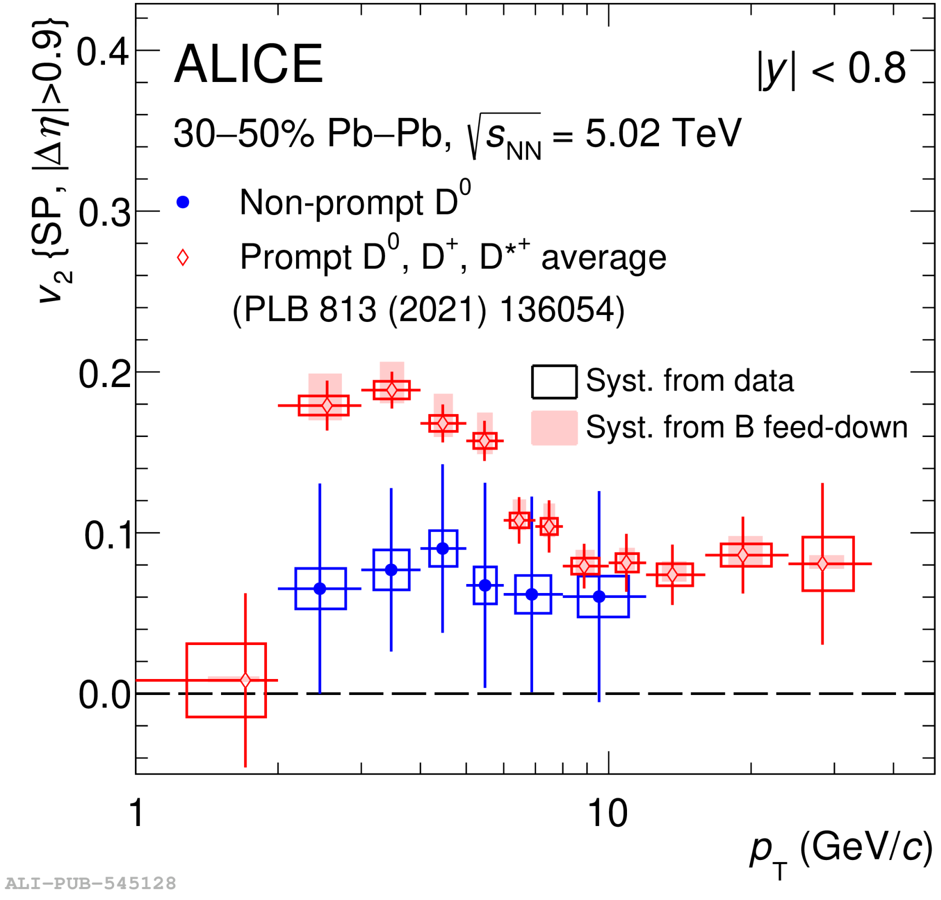


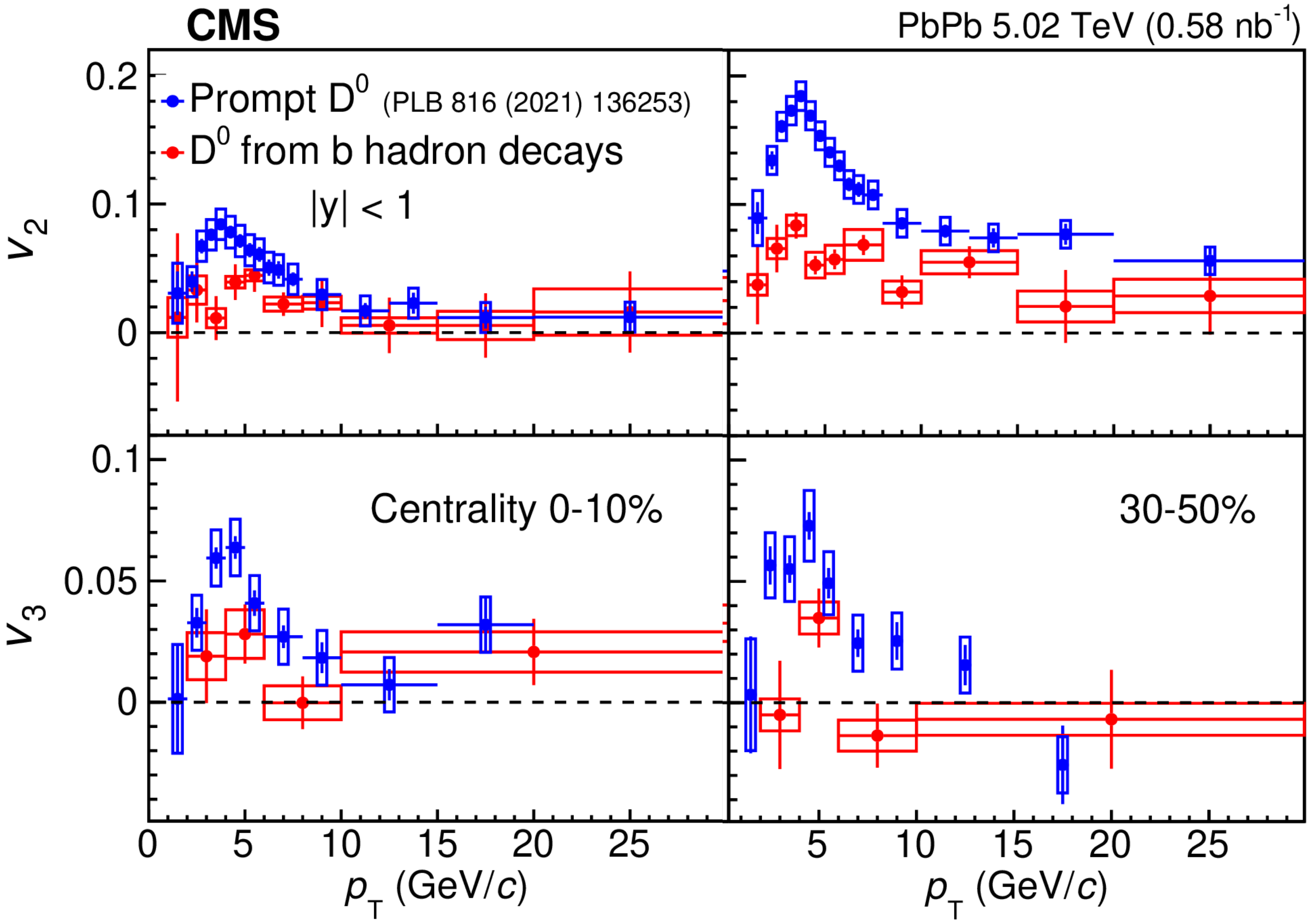
ALICE, A journey through QCD, arXiv:2211.04384

- Charm quarks are roughly 200-500 times heavier than u- or d-quarks.
- The ideal QGP probe: they are so heavy ($m_c >> T$) that they are produced only in the initial collisions, then their number is conserved → perfect tool to study diffusion, recombination, and energy loss for a *characterization of the medium.*
- Despite being so heavy, the many other light quarks give them apparently so many kicks that they participate in the medium expansion. Latest estimate on charm quark diffusion coefficient: $1.5 < 2\pi D_s T_c < 4.5$

Thermalisation of beauty?

[CMS, arXiv:2212.01636]
[ALICE, arXiv:2307.14084]





→ Different behavior for the heavier beauty quarks! They seem only partially thermalized (longer relaxation time) and thus they do show less elliptic flow than charm quarks (v_2 of B mesons < v_2 of D mesons).

Future instrumentation at the LHC

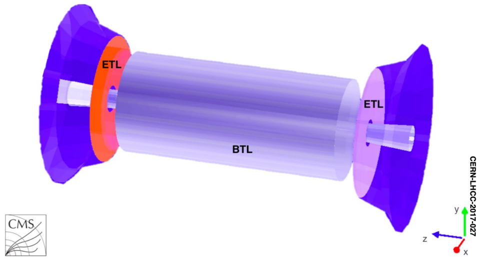
→ The heavy-ion program in ATLAS, CMS, and LHCb will naturally profit from the planned Phase II upgrades of ATLAS & LHCb and the LHCb upgrade II.

→ In addition, a dedicated heavy-ion experiment ALICE 3 is planned for installation in LS4:

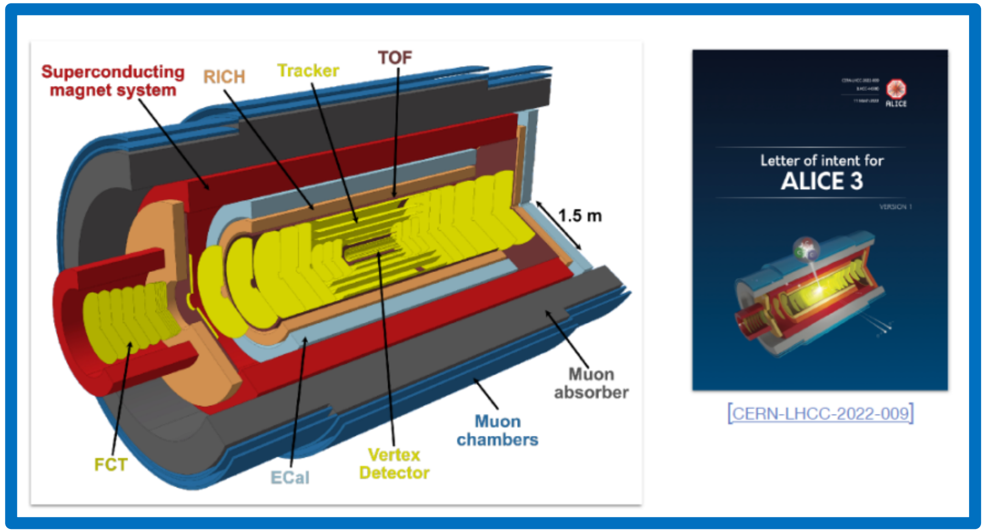
- Compact low-mass all-Si tracker, excellent vertex reconstruction and PID
- First layer is envisaged to be positioned inside the beam-pipe (5mm from interaction point).

Main physics goals: chiral symmetry restoration and thermal radiation, multi-charm hadrons, heavy-flavour transport and hadronization, exotic bound states, small systems,..

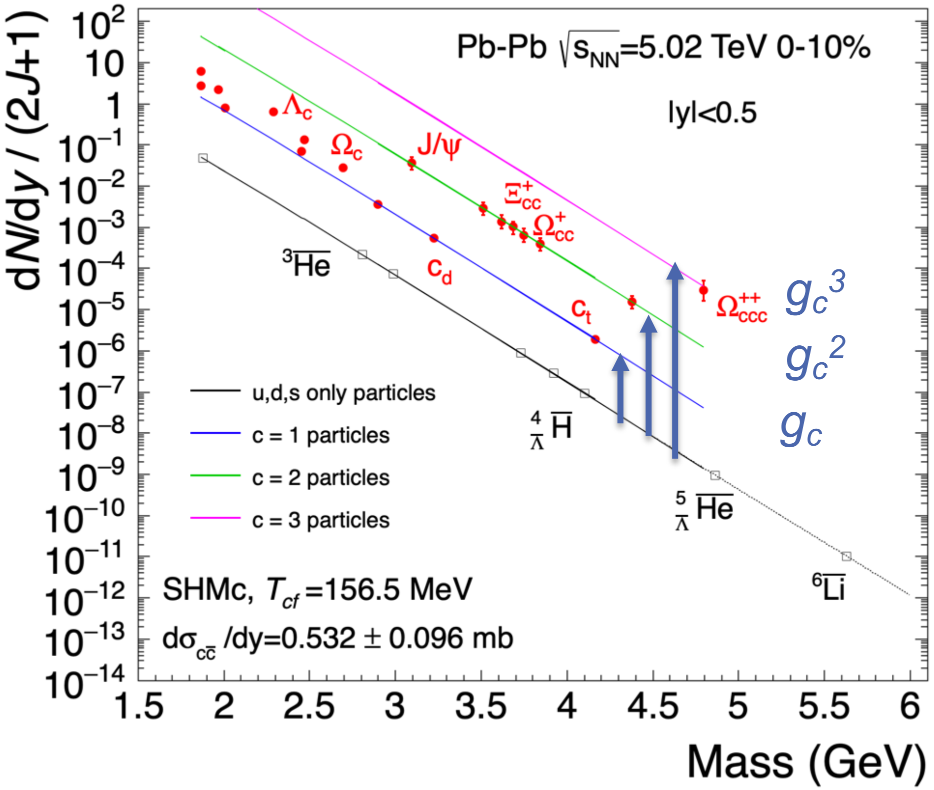
New CMS Inner Tracker



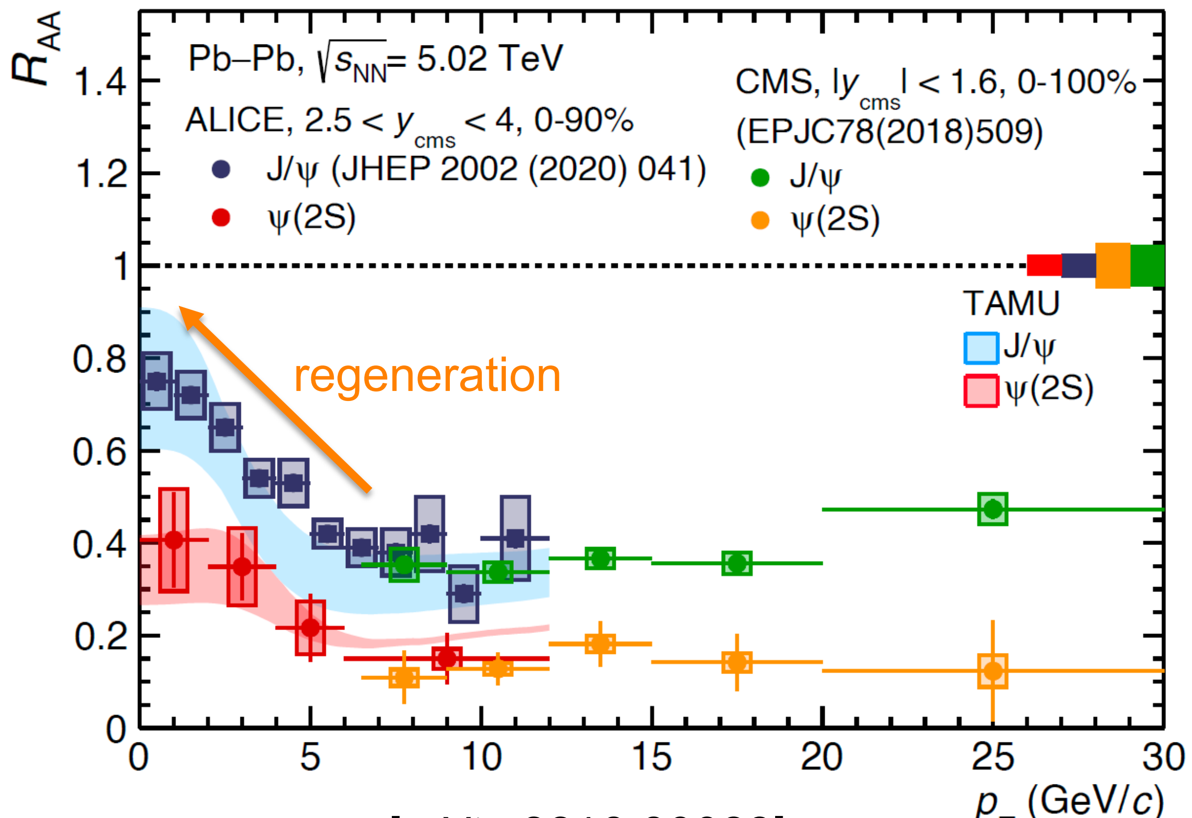
ALICE 3



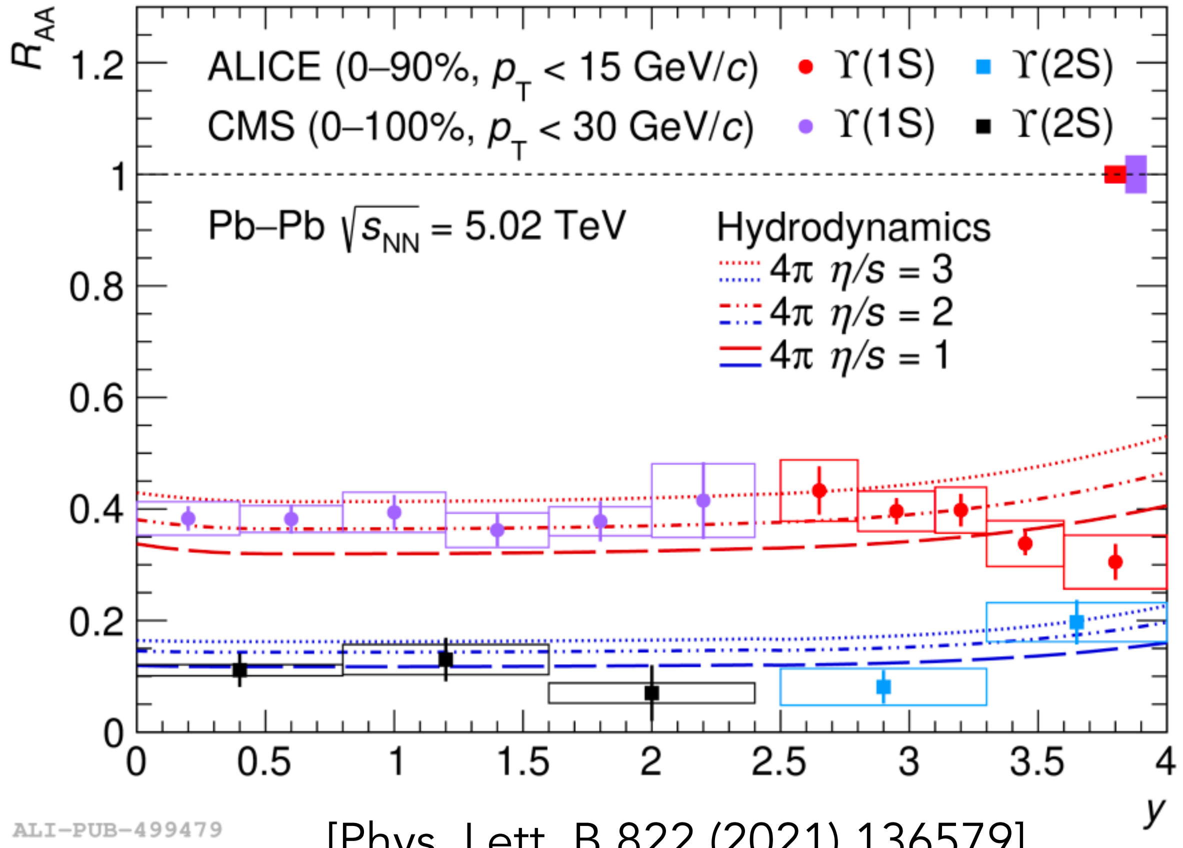
[CERN-LHCC-2022-009]



Quarkonia (1)



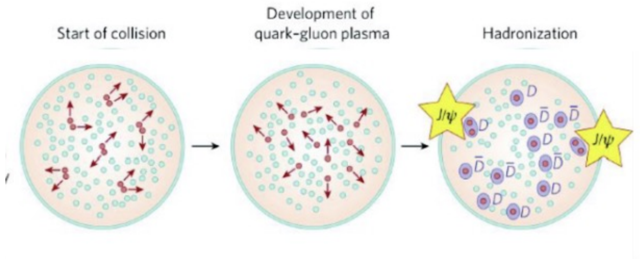
[arXiv:2210.08893]



[Phys. Lett. B 822 (2021) 136579]

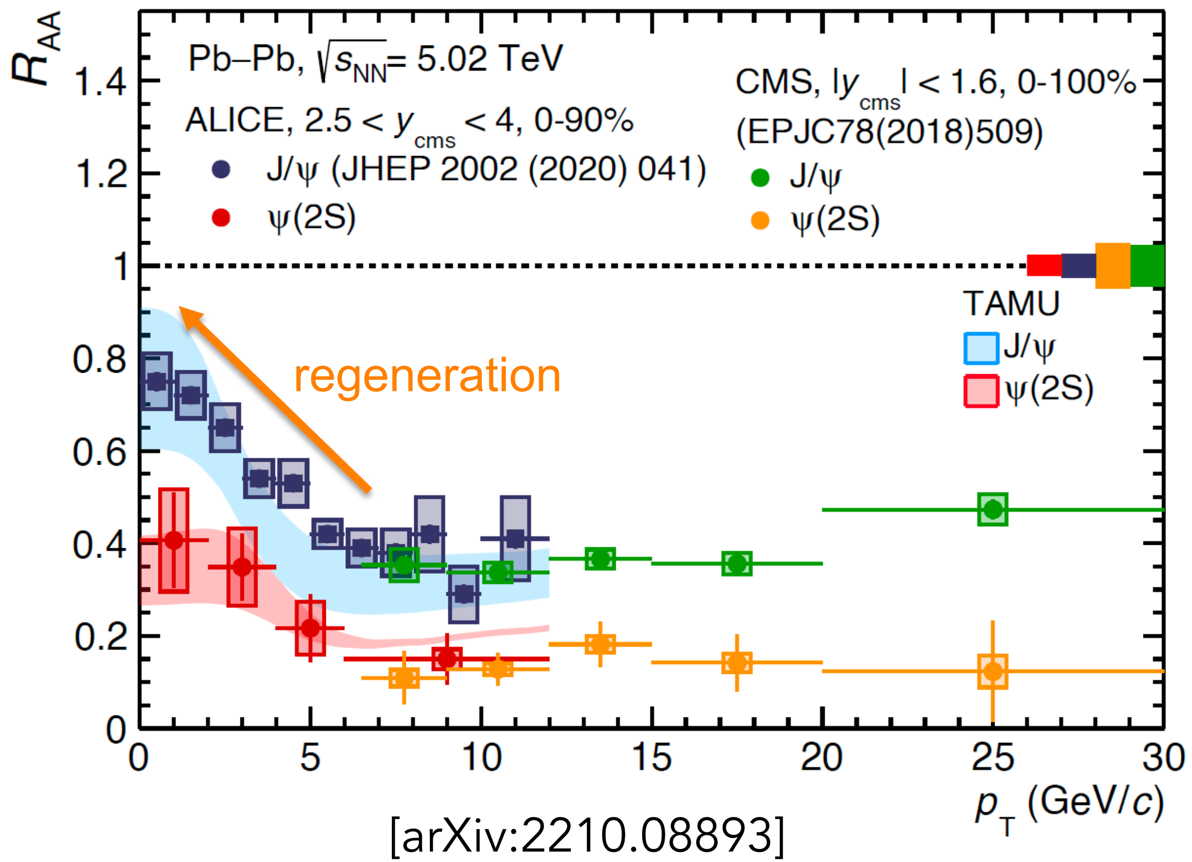
→ Charmonium: sequential suppression + regeneration effects

→ Bottomonium: sequential suppression

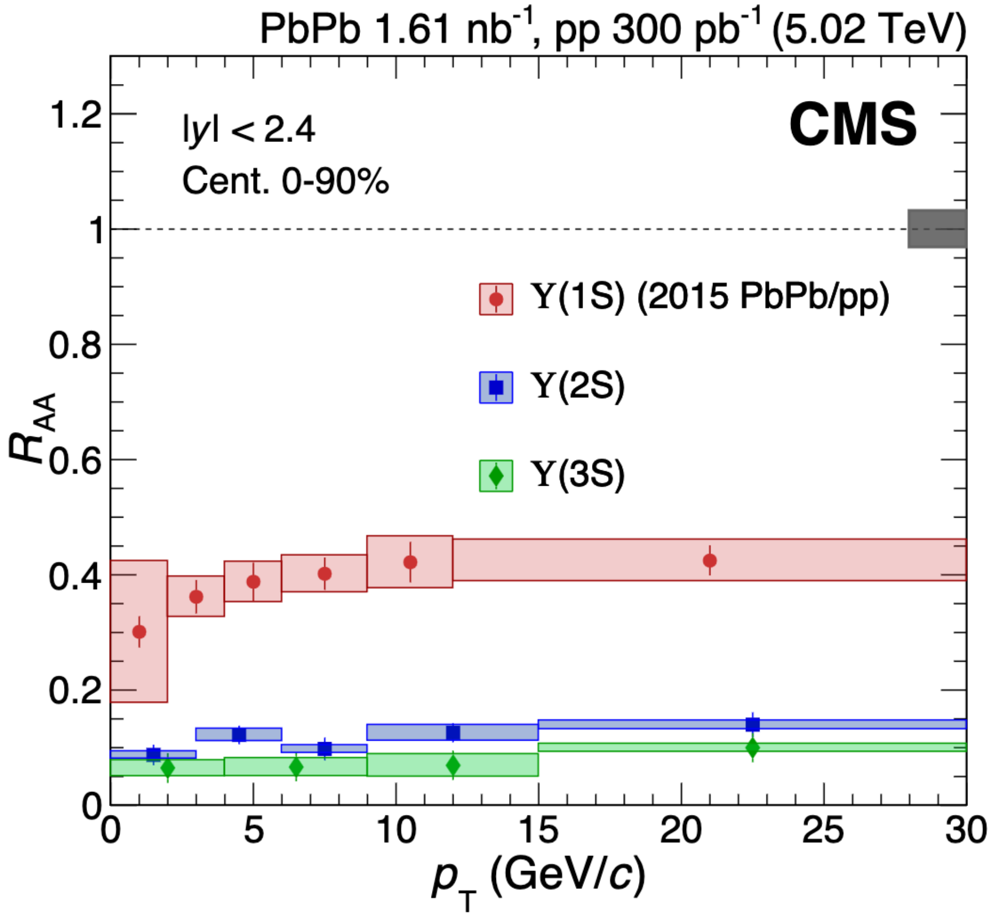


[Nature 448 (2007) 302-309]

Quarkonia (2)



[arXiv:2210.08893]



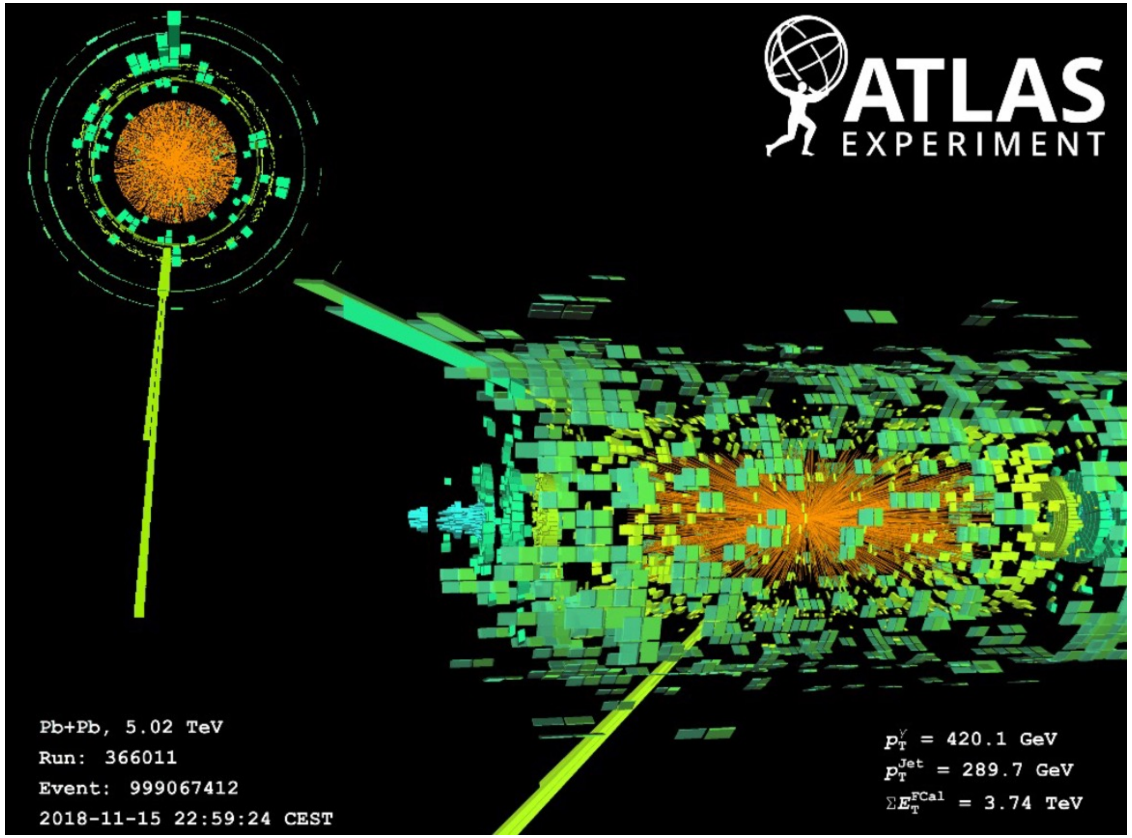
[CMS, arXiv::2303.17026v1]

→ Charmonium: sequential suppression
+ regeneration effects

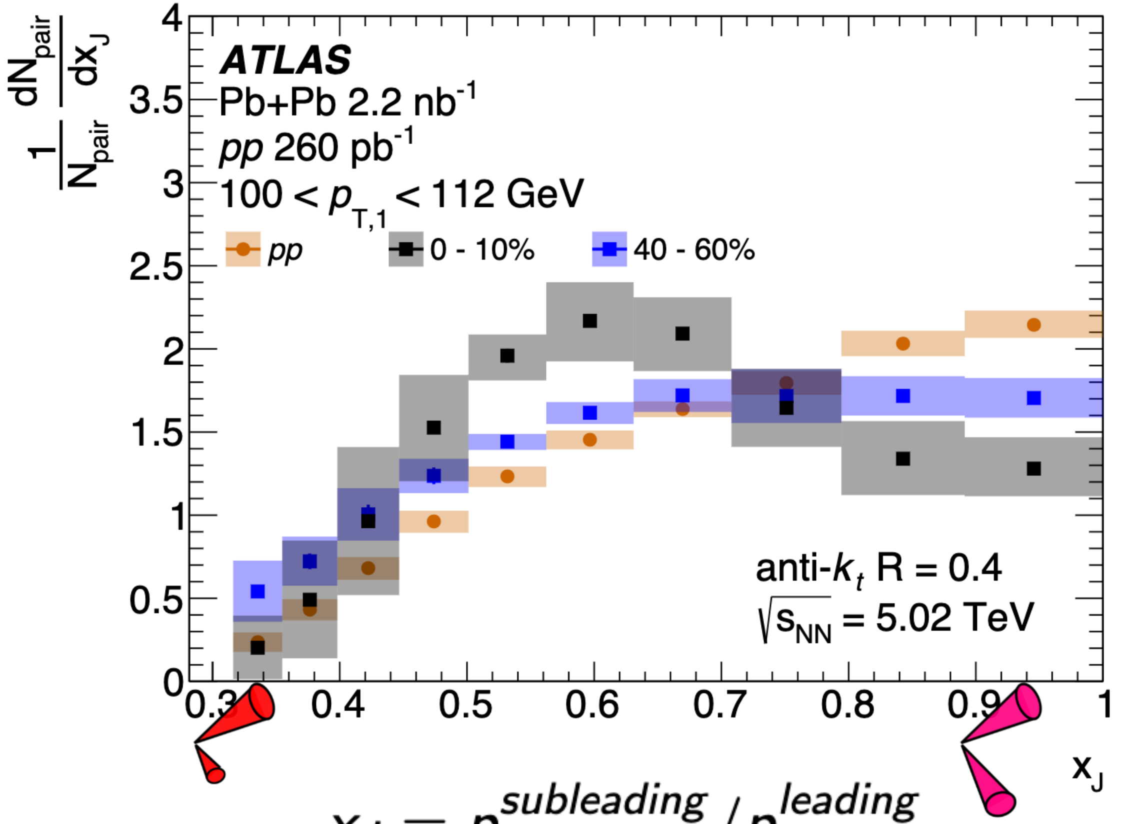
→ Bottomonium: sequential suppression → less tightly bound states are more suppressed

Energy loss and jet quenching

- Jet and high-p_T hadron suppression observed over a wide momentum range
- Explained by energy loss of hard partons interacting with QGP medium



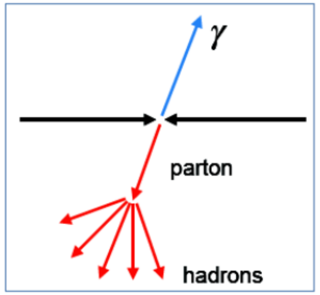
[ATLAS arXiv:2205.00682, arXiv:2302.03967]



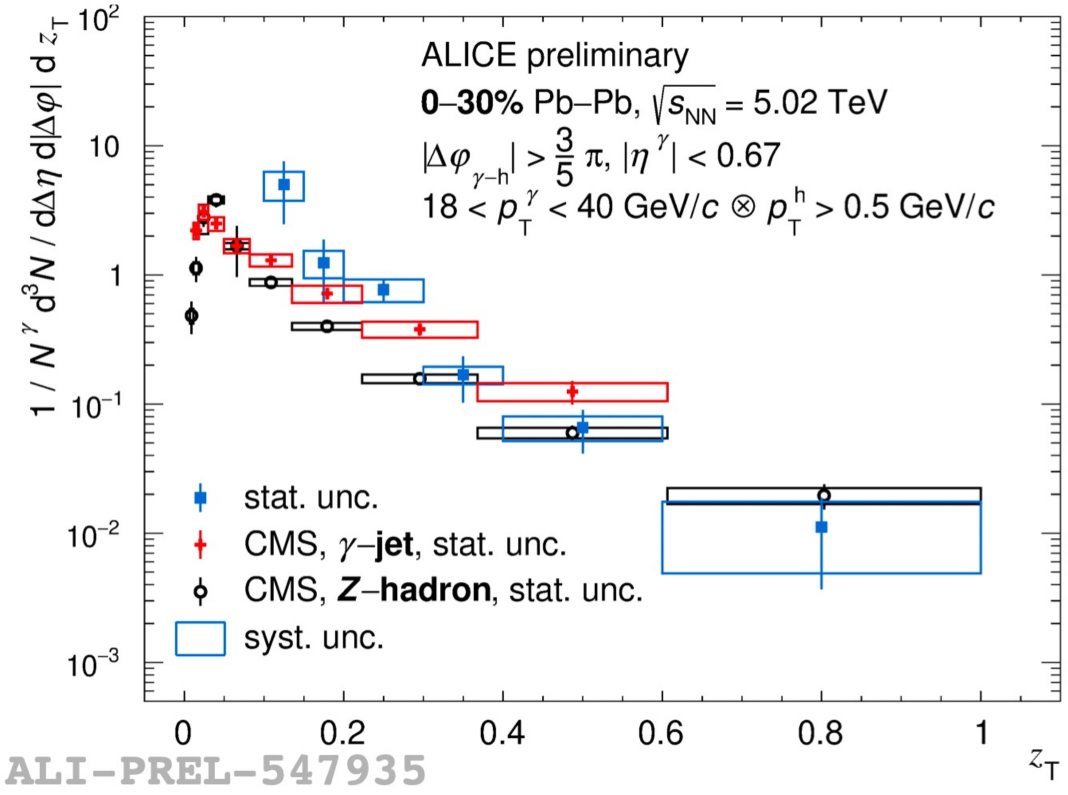
$$x_J = p_T^{subleading} / p_T^{leading}$$

Jet+photon measurements

→ Ideal probe for jet quenching measurements: Leading jet is highly energetic photon that escapes the medium without interaction.



$$z_T = \frac{p_T^h}{p_T^\gamma}$$



CMS, Phys.Rev.Lett. 121 (2018) 712301, 2018

γ–**jet**, 0–10%

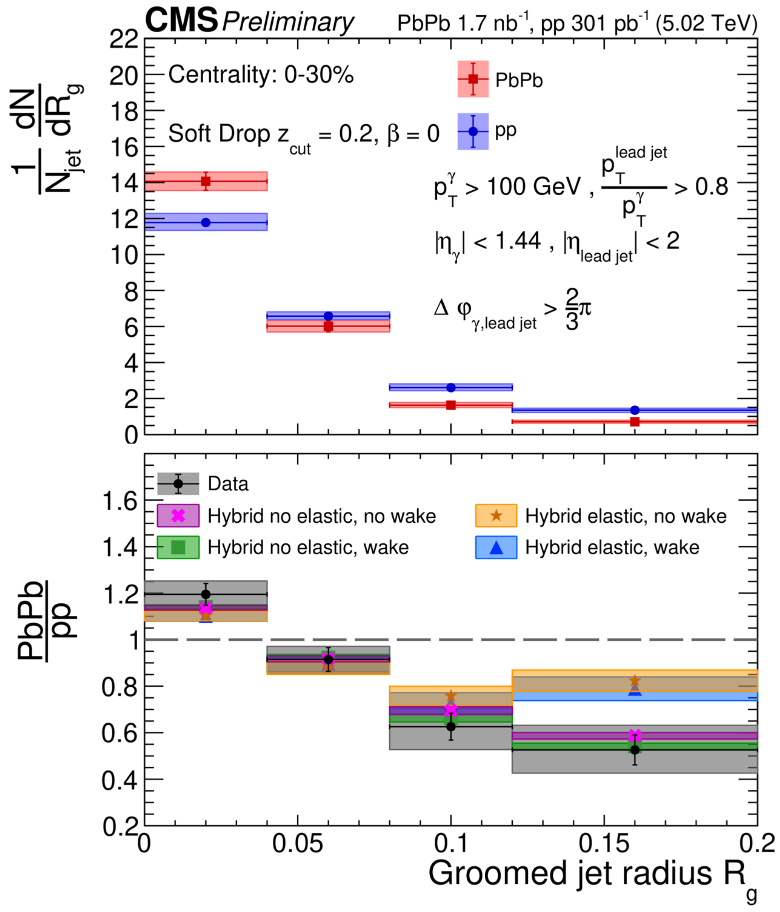
anti-k$_T$ jet R = 0.3, $p_T^{jet} > 30$ GeV/c, $|\eta^{jet}| < 1.6$

$|\Delta\varphi_{\gamma\text{-jet}}| > \frac{7}{8}\pi$, $|\eta^\gamma| < 1.44$, $p_T^\gamma > 60$ GeV/c ⊗ $p_T^h > 1$ GeV/c

CMS, Phys.Rev.Lett. 128 (2022) 122301, 2022

Z–**hadron**, 0–30%

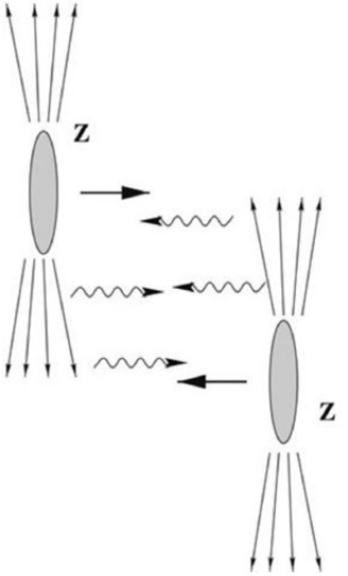
$|\Delta\varphi_{Z\text{-h}}| > \frac{7}{8}\pi$, $p_T^Z > 30$ GeV/c ⊗ $p_T^h > 1$ GeV/c

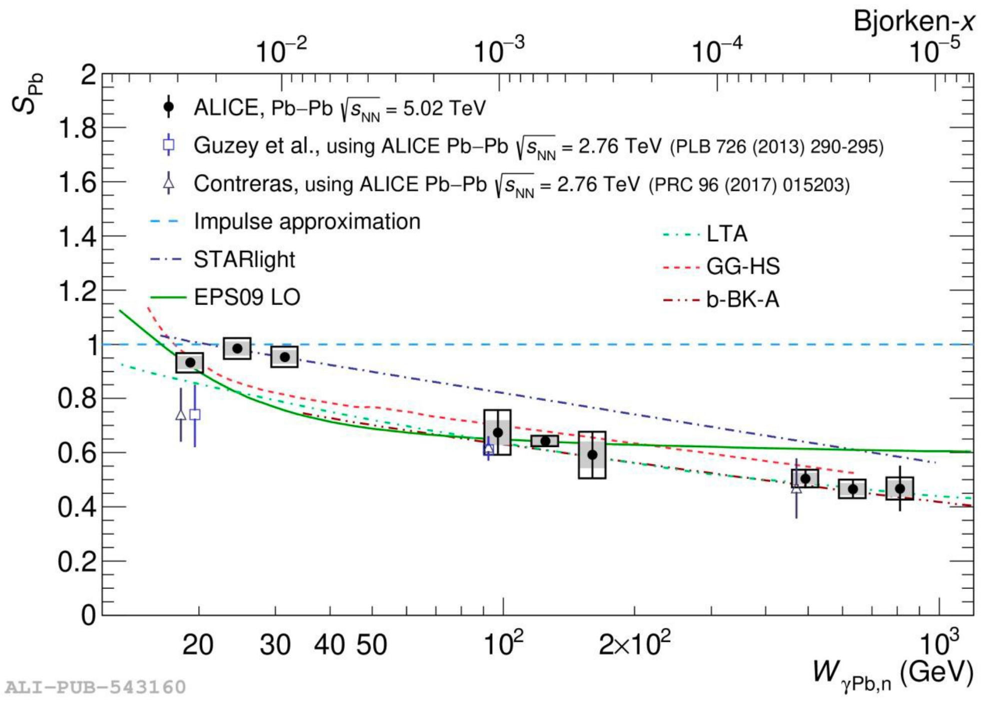


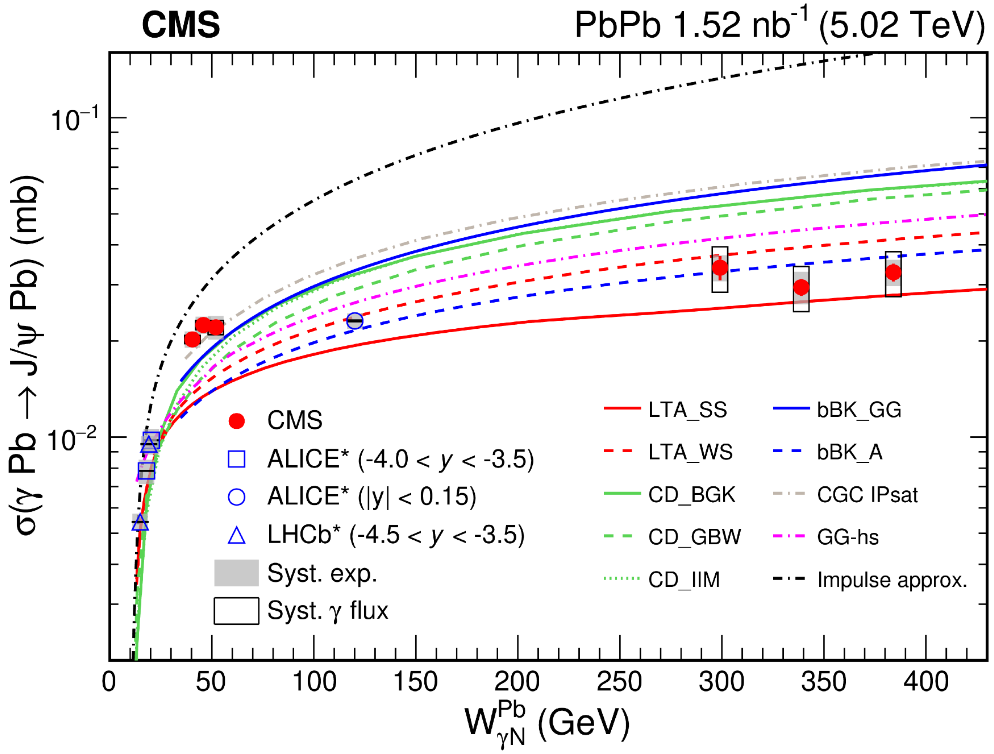
[CMS-PAS-HIN-23-001]

What can we learn from ultra-relativistic nuclear collision for the (subnucleonic) structure of nuclei?

Nuclear PDFs with ultra-peripheral collisions

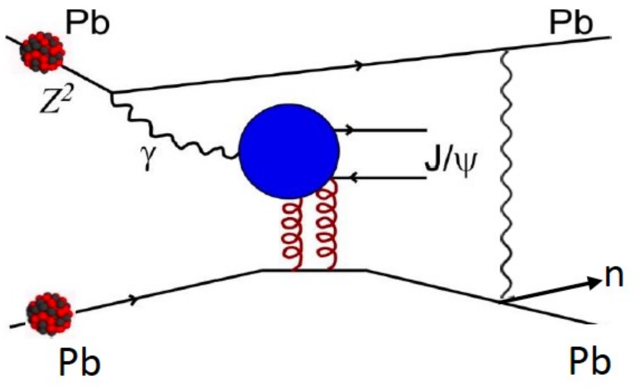






[ALICE, arXiv:2305.19060]

[CMS, arXiv2303.16984]



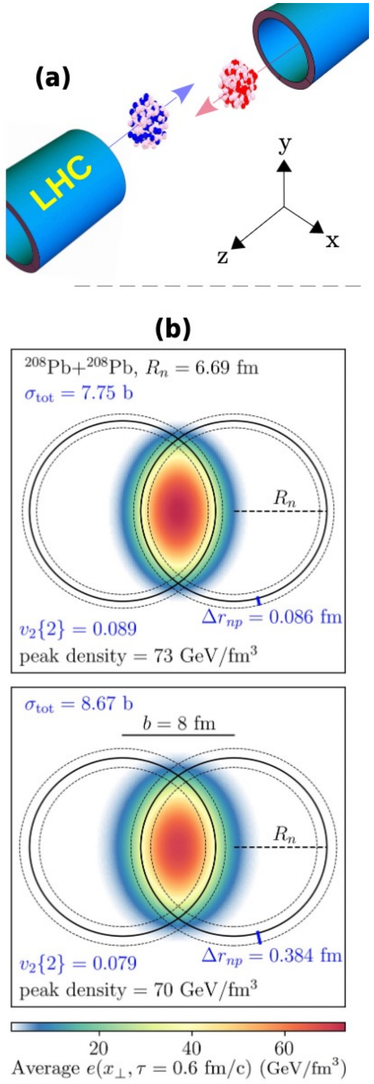
→ Coherent J/**ψ** photoproduction is probing low-x gluon PDFs in the nucleus

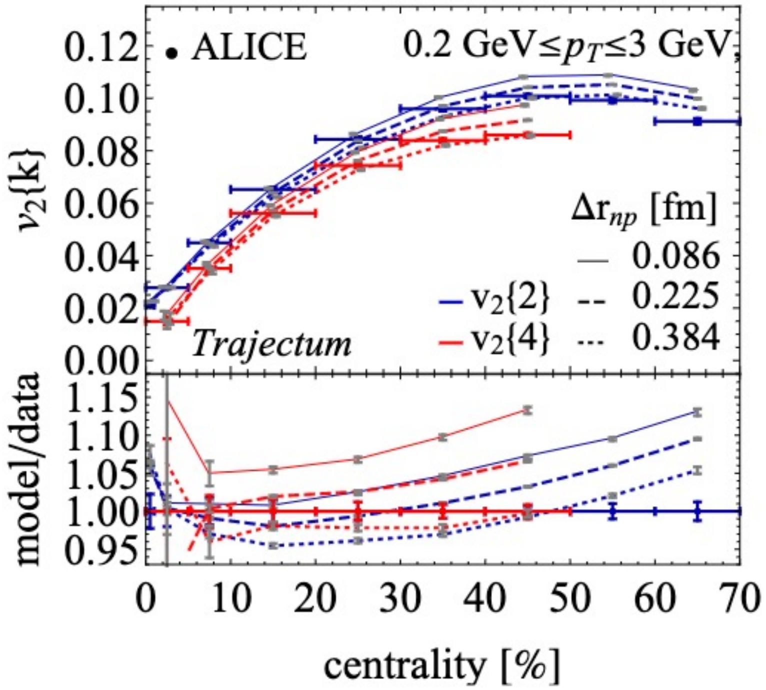
→ Comparison with the impulse approximation (no nuclear effects) allows for extraction of the gluon shadowing factor: R_g~ 0.5 at x~10^{-5}

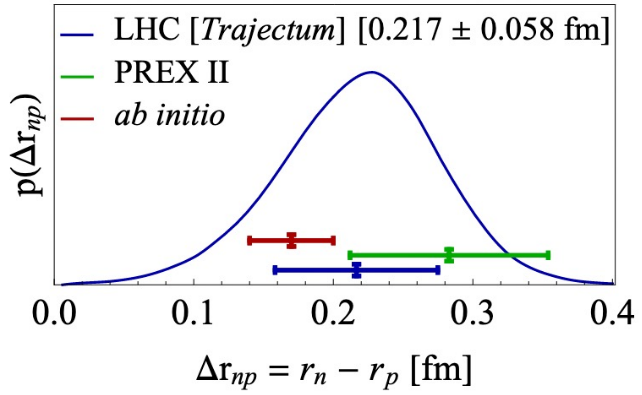
Neutron skin and nuclear deformation with v_2

- The collision deposits energy in the interaction region depending on the extent of the neutron skin of the ^{208}Pb nuclei.
- A larger neutron skin leads to a considerably larger total hadronic cross section, $\boldsymbol{\sigma}_{tot}$, and the resulting QGP is in addition more diffuse and less elliptical.
- This allows for a determination of the neutron skin with comparable precision to alternative methods and state-of-the art calculations.

[G. Giacalone et al., arXiv:2305.00015]

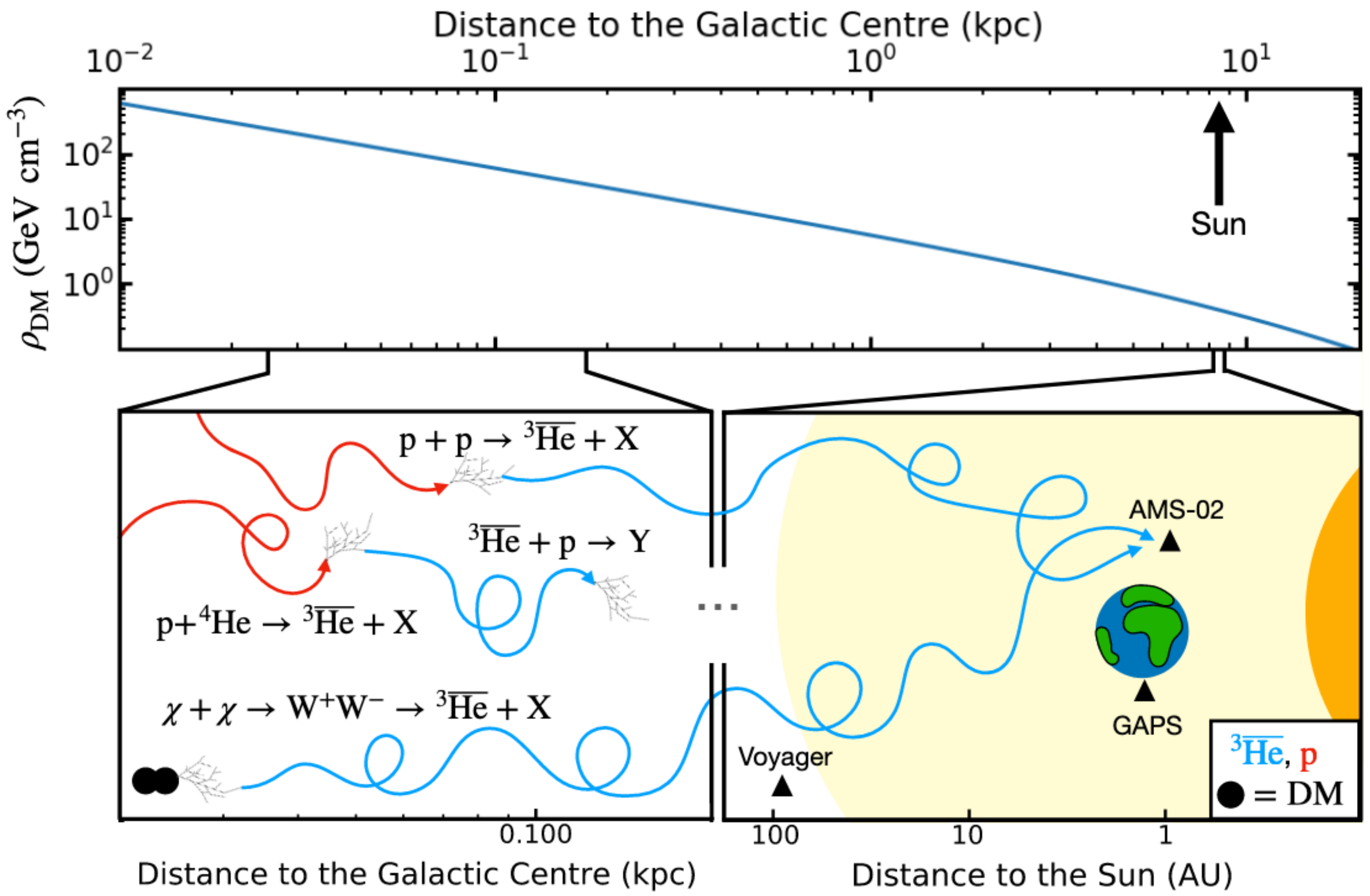




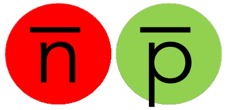


What can we learn from ultra-relativistic nuclear collision for astroparticle physics?

Search for antinuclei in space



1 kpc ≙ 3261 lightyears



anti-deuteron

anti-helium3

To-do list for collider based experiments:

- Understand antinuclei formation to model production in DM decays
- Understand antinuclei formation to model production in background reactions
- Understand interaction of antinuclei with matter to determine the transparency of the galaxy

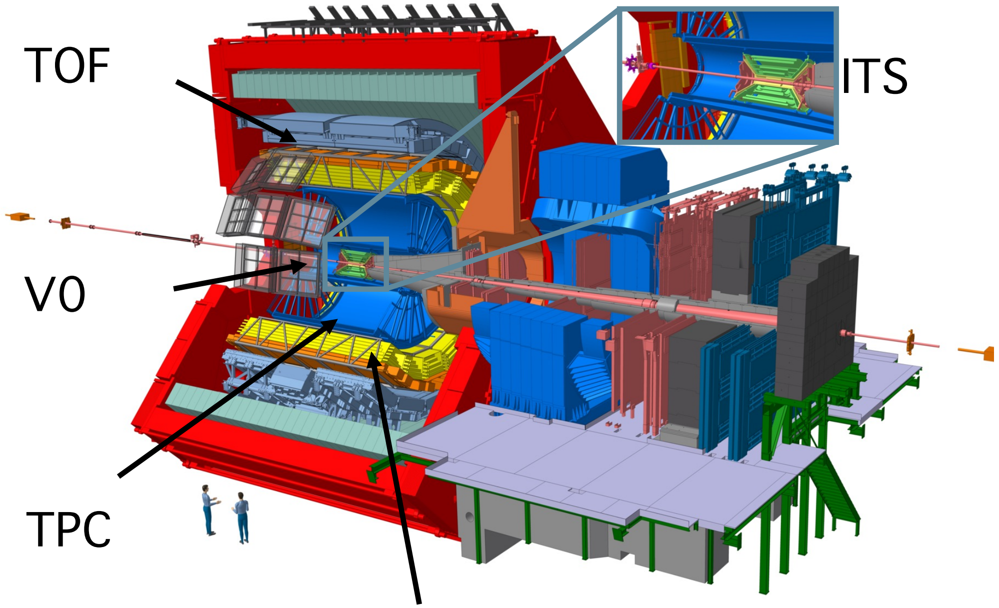
[ALICE, *Nature Phys.* 19 (2023)]

Antinuclei measurements at the LHC

ALICE

General purpose heavy-ion experiment

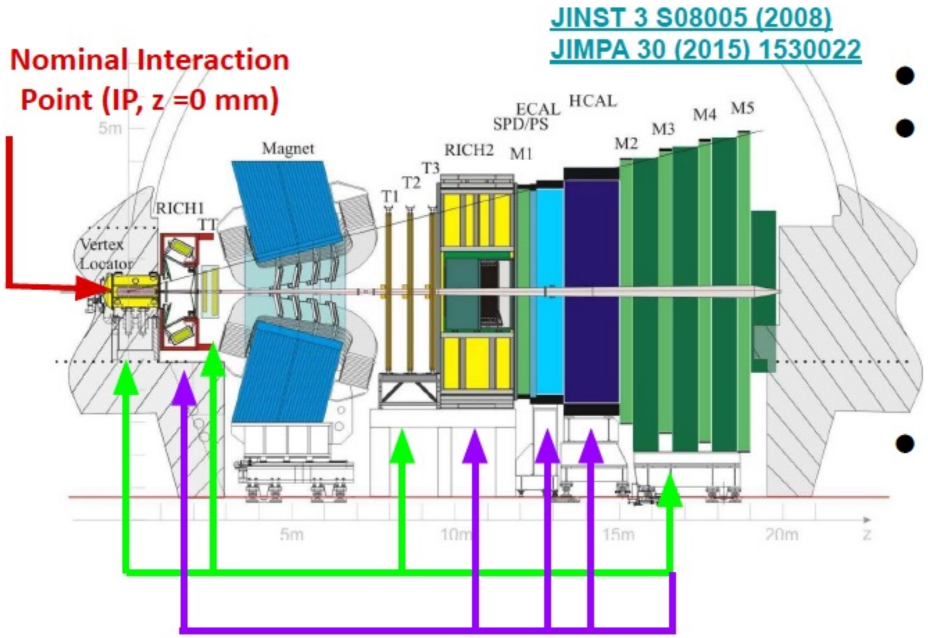
- Excellent particle identification (PID)
- pp, p-Pb and Pb-Pb at $\sqrt{s}$ up to 13 TeV
- Production cross section for $\bar{\text{p}}, \bar{\text{d}}, {}^3\overline{\text{He}}$
- Annihilation cross sections for $\bar{\text{p}}, \bar{\text{d}}, {}^3\overline{\text{He}}$



LHCb and SMOG

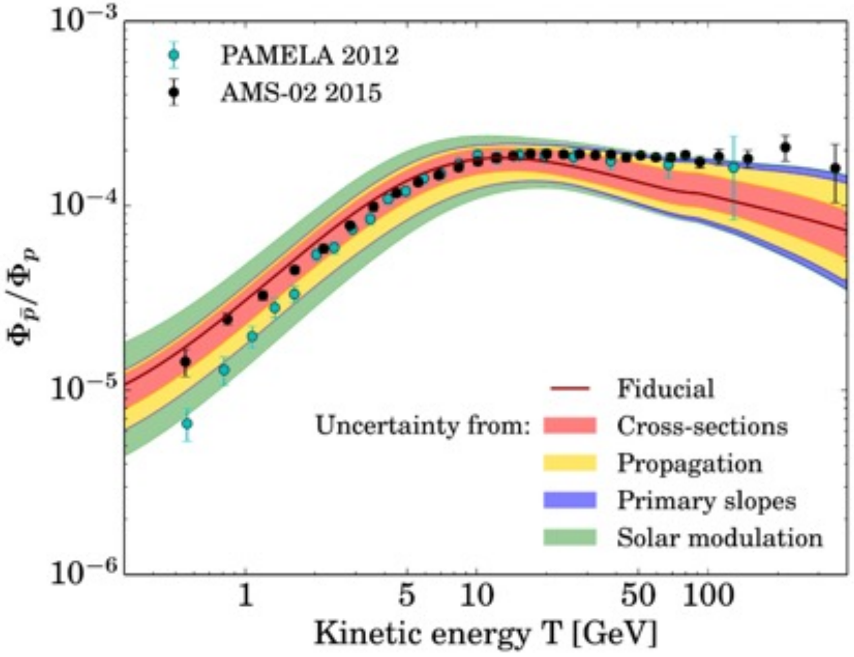
Particle Fixed target experiment with LHCb

- Excellent particle identification (PID)
- p-He at $\sqrt{s}$ =100 GeV
- Production cross section for $\bar{\text{p}}$
- Intrinsic charm (LHC Coll. PRL 122 (2019))

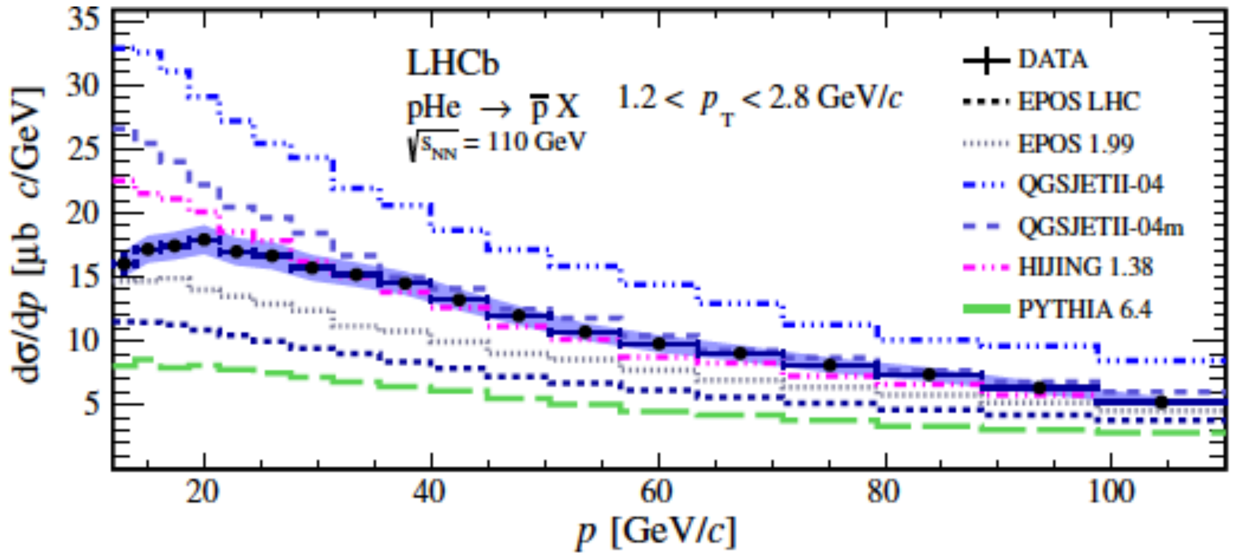


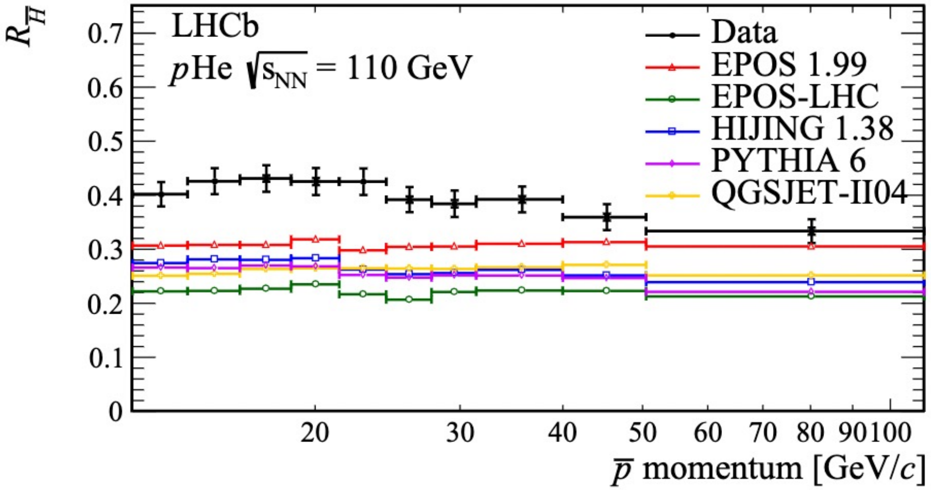
Antiprotons from cosmic rays and from SMOG

[AMS-02 coll. JCAP 09 (2015)]



[LHCb coll. PRL 121 (2018)] [LHCb, arXiv:2205.09009]





Where do these $\bar{p}$ come from?

$$R_{\bar{\Lambda}} \equiv \frac{\sigma(p\mathrm{He} \to \bar{\Lambda} X \to \bar{p}\pi^+ X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}} X)}$$

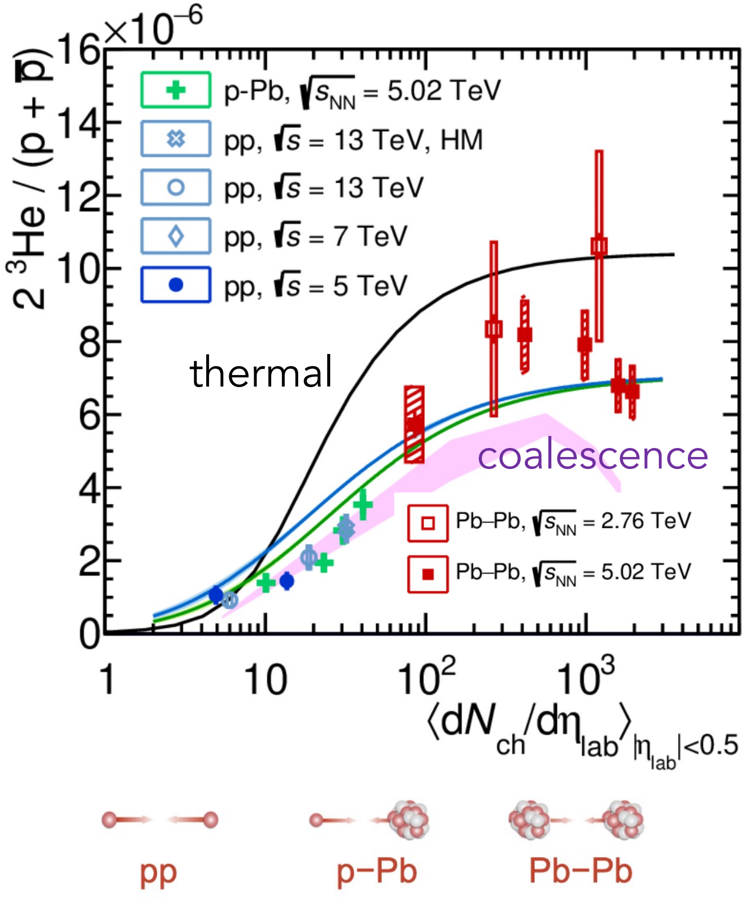
SMOG@LHCb: p+He at $\sqrt{s}$ =110 GeV
→ $\bar{p}$ cross sections for prompt and secondaries from hyperon decays

Antinuclei formation and annihilation (1)

→ Using heavy-ion collisions at the LHC as "anti-matter factory"

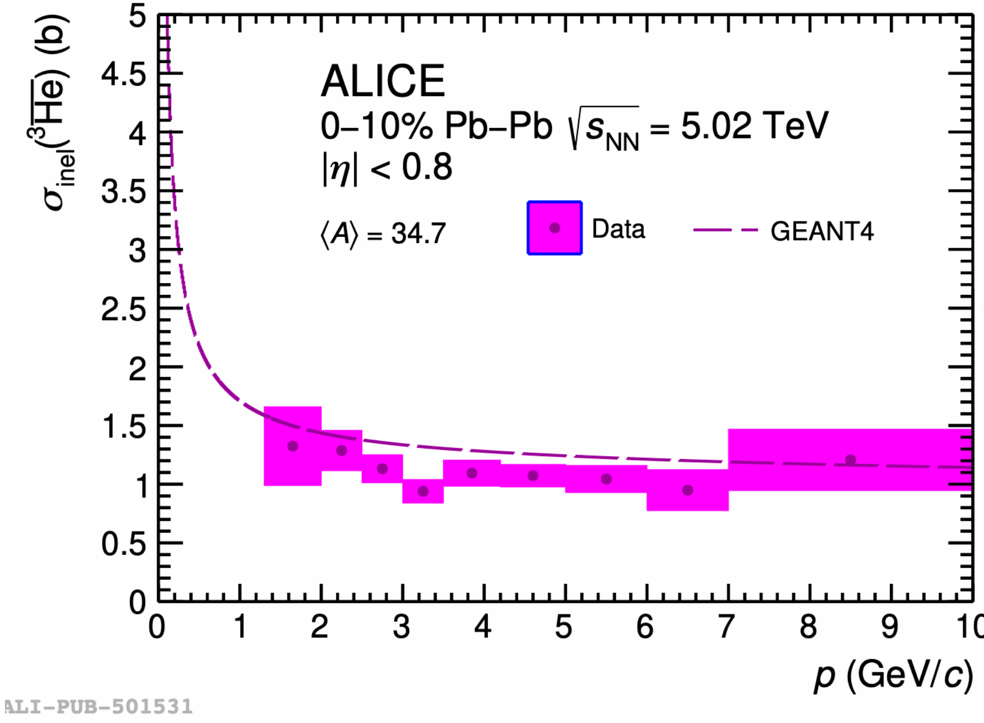
Production:

simultaneous measurement in pp and PbPb constrains mechanism!

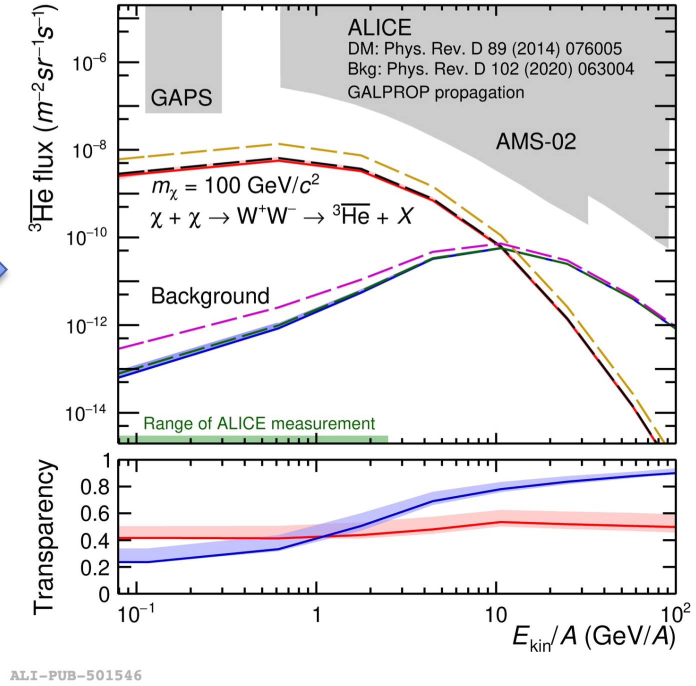


[ALICE, Phys. Rev. C 107 (2023) 064904]

Annihilation cross-section



Theoretical calculation of flux near earth



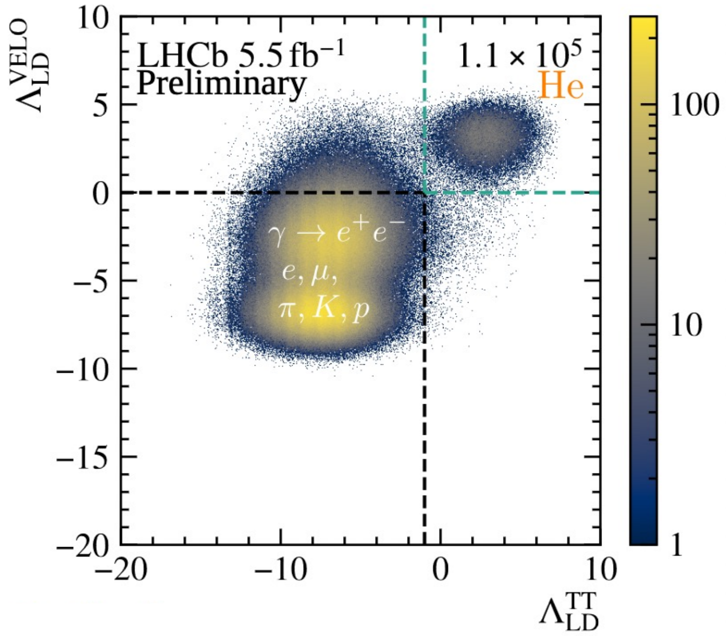
[ALICE, *Nature Phys.* 19 (2023)]

Antinuclei formation and annihilation (2)

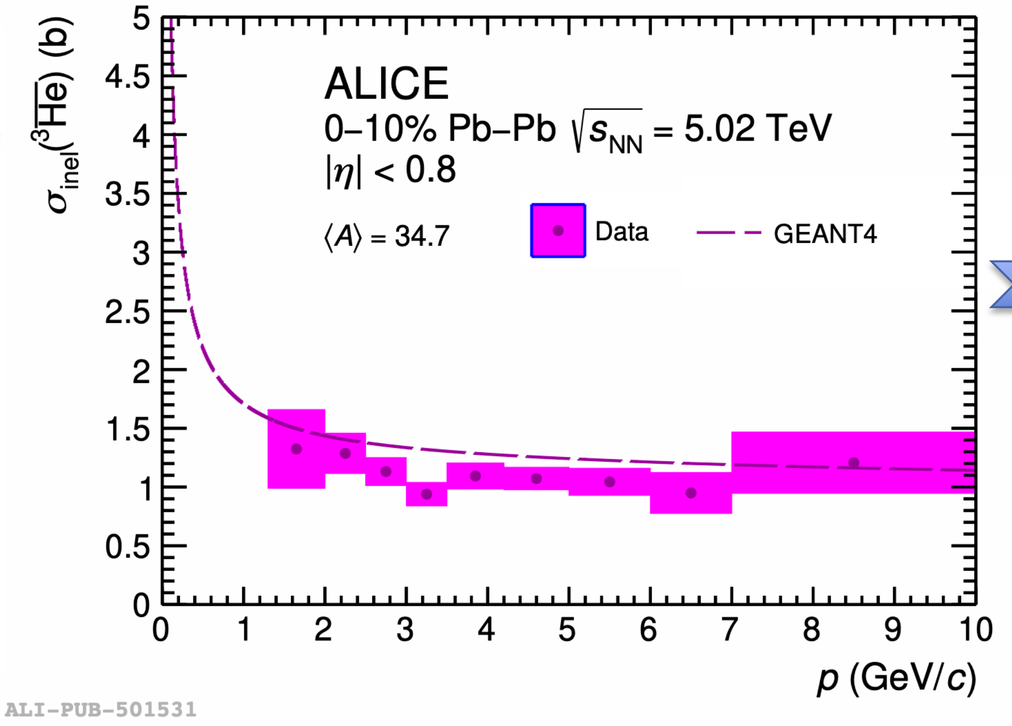
→ Using heavy-ion collisions at the LHC as "anti-matter factory"

Production:

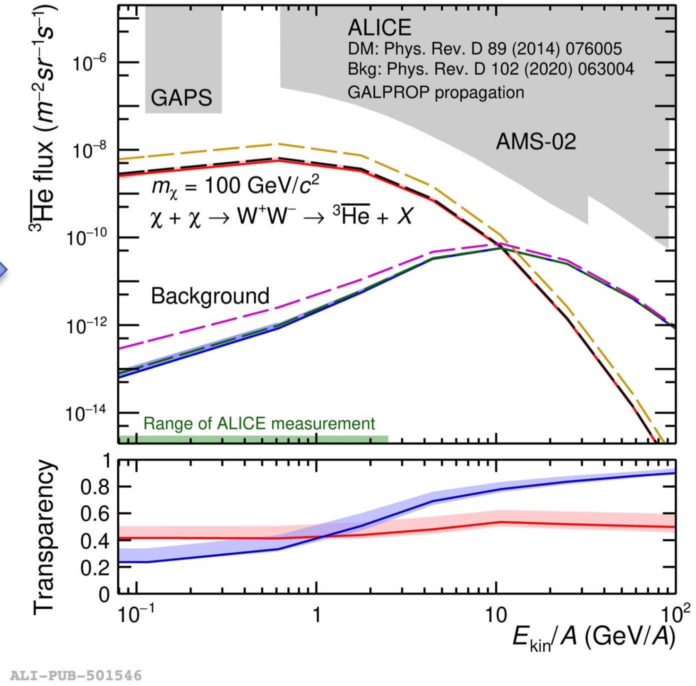
simultaneous measurement in pp and PbPb constrains mechanism!



Annihilation cross-section



Theoretical calculation of flux near earth



[ALICE, *Nature Phys.* 19 (2023)]

Summary and Outlook

Summary and outlook

- Ultra-relativistic collisions are a unique laboratory to study QCD at extreme densities.
- A World-wide program involving many facilities and collaborations is needed to study the phase diagram of QCD in all its facets.
- Characterization of the QGP enters a quantitative era (numerical determination of transport coefficients) and will reach textbook quality in the next decade.
- Along the way, many interesting and unique insights impacting the neighboring fields of nuclear and astroparticle physics have been found.