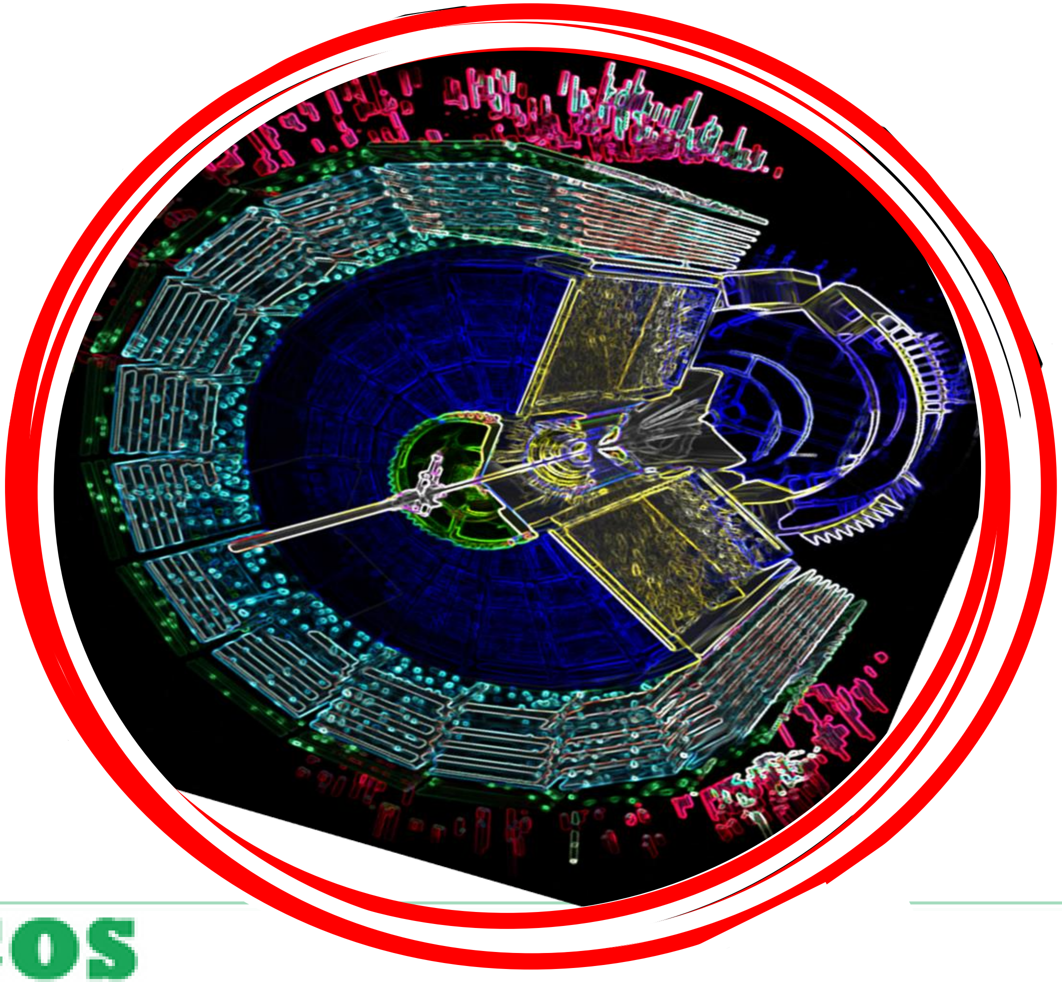
From small to large systems: Overview of Heavy-Ion Physics



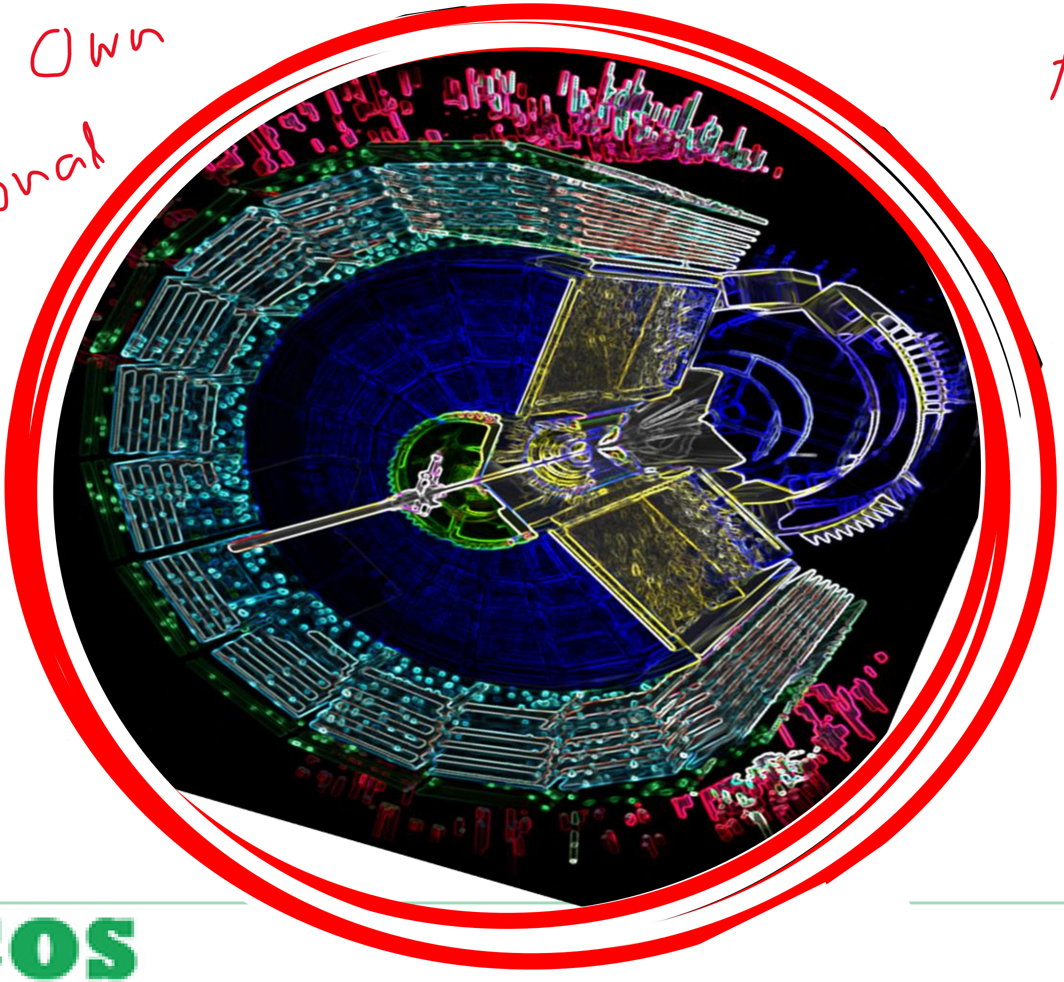
Adrian Fereydon Nassirpour
Sejong University

PASCOS 2024: 29th International Symposium on Particles, Strings and Cosmology

From small to large systems: Overview of Heavy-Ion Physics

My own Personal

Heavy Ions 4 life! :)



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Disclaimers

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My impression: SM/BSM shares a lot of consensus on what research goals to pursue

Source: John Thys/AFP via Getty Images

Disclaimers

- From my perspective, the field of heavy-ions is quite chaotic
  - Experimentally driven:
    A lot of space for model interpretation

Source: *The Thin Red Line* (1881) by Robert Gibb

Source: *The Battle of Alexander at Issus* (1529) by Albrecht Altdorfer

Outline

- Introduction & early QGP signatures
- Upset in small systems and difficulties with QCD
- Future prospects

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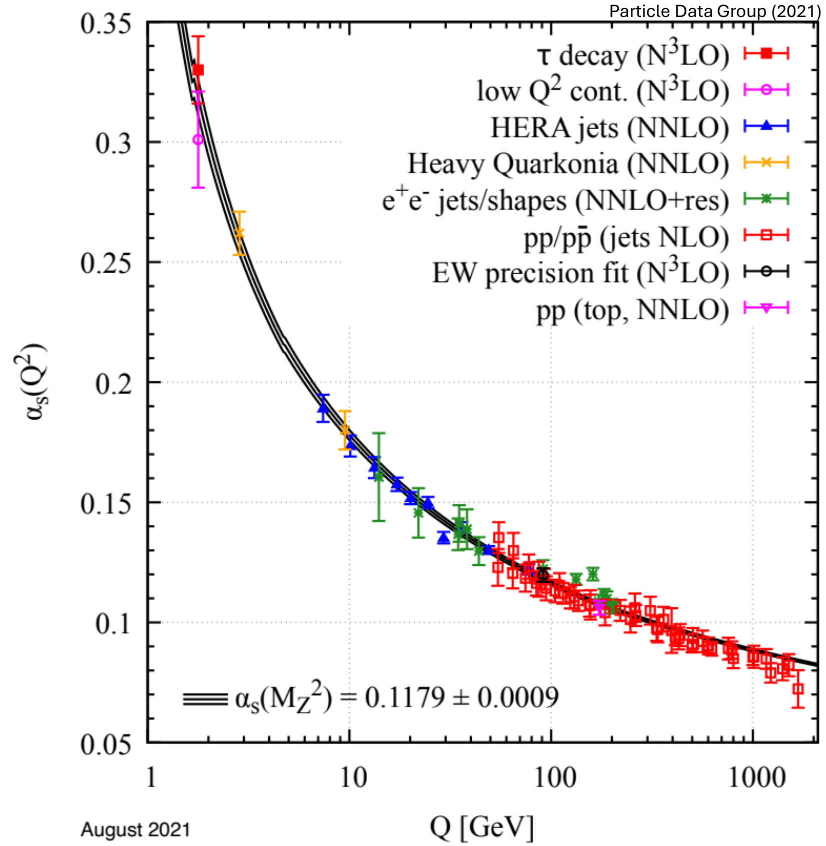
QCD & The Quark-Gluon Plasma

- Some elementary concepts: QCD
  - QCD in vacuum – Confinement
    - QCD field lines modelled as strings
    - Cornell $q\bar{q}$ potential: $V(r) = -\frac{a}{r} + \sigma r$



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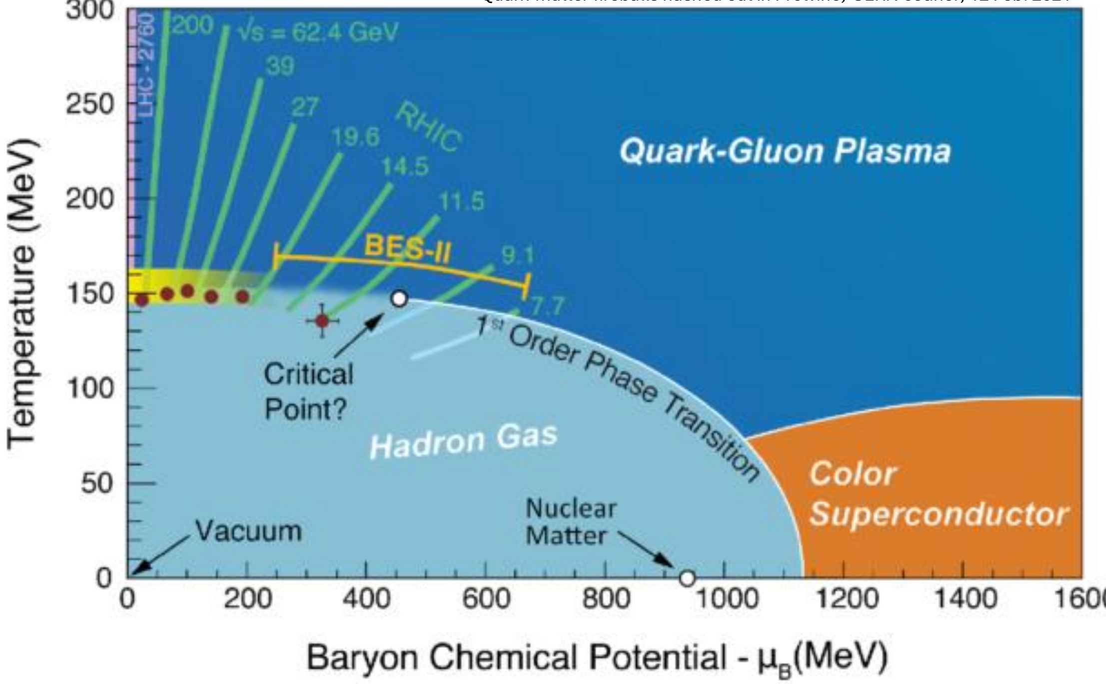
  - QCD in quark-matter – Deconfinement
    - The Quark-Gluon Plasma (QGP)
    - QCD transition: Non-perturbative in nature
      - $T = 200$ MeV, $\rightarrow E = 3k_B T = 600$ MeV $\approx 3\,\Lambda_{\text{QCD}}$

Quark-matter fireballs hashed out in Protvino, CERN courier, 12 Feb. 2021



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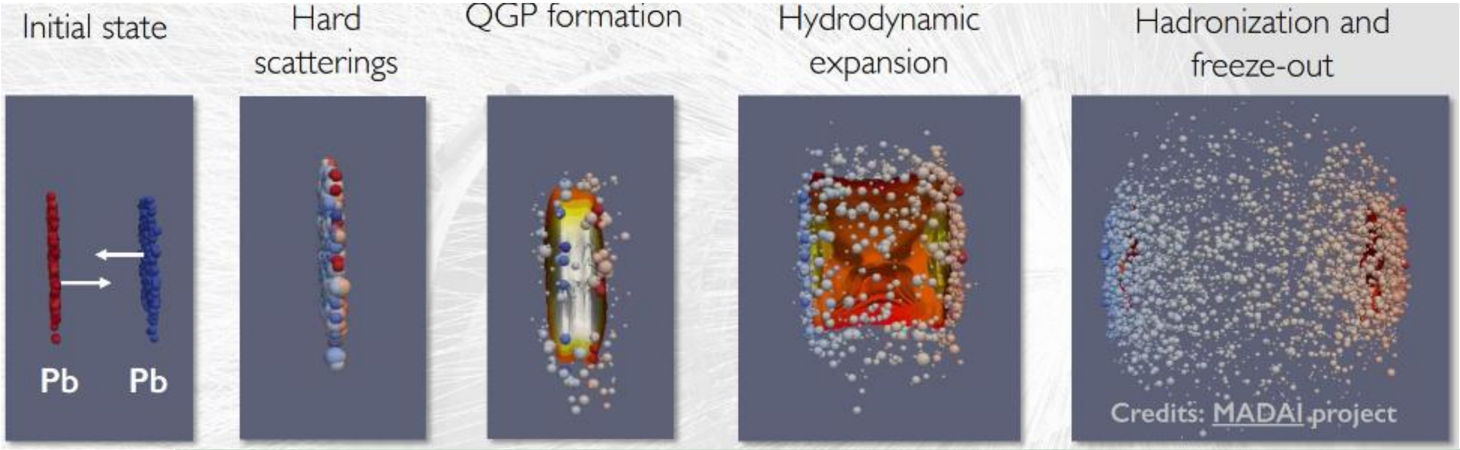
    - Heavy-Ion collisions: initial color fields evolve in different stages



Which kind of collisions can create a QGP?

- Some definitions

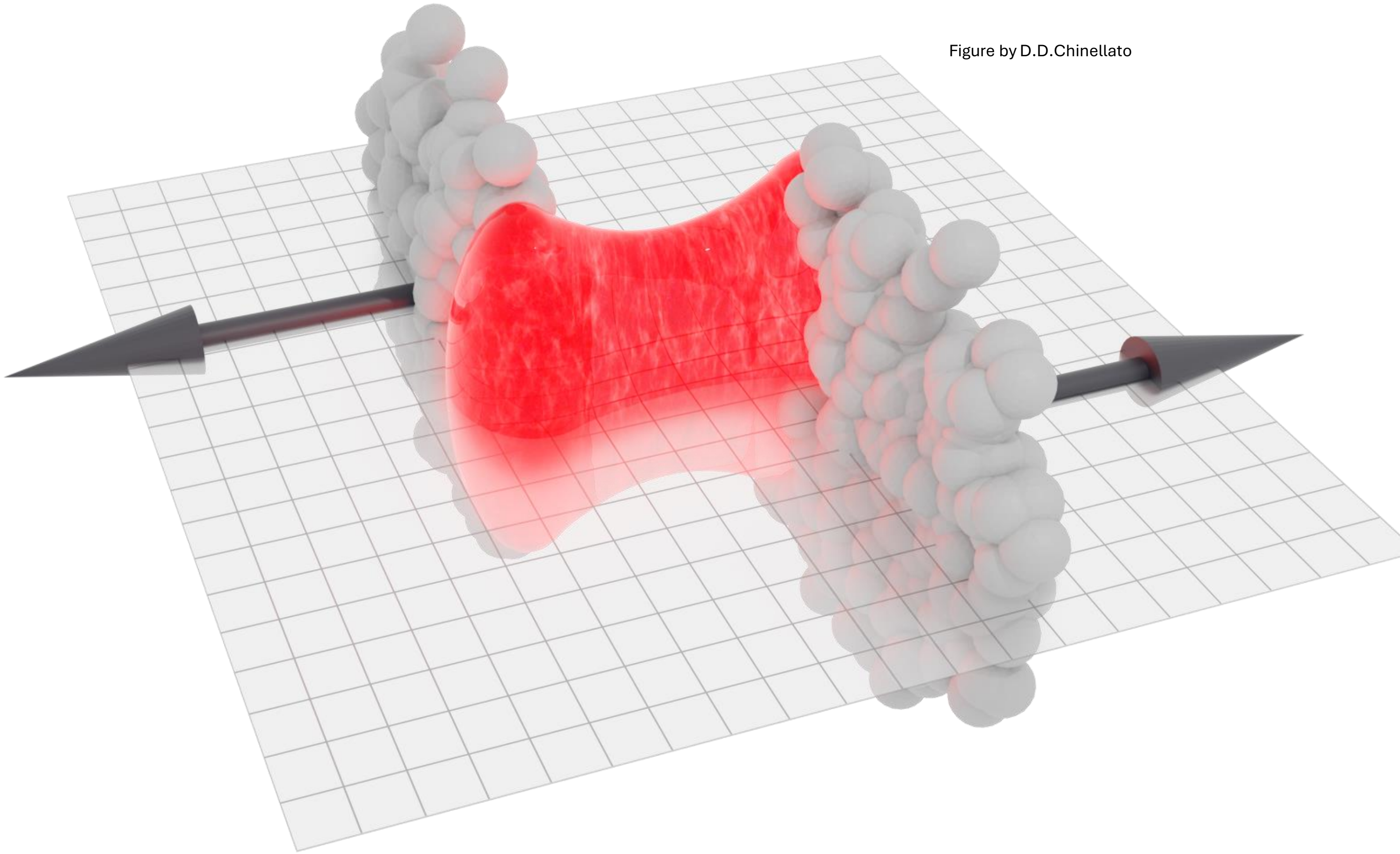


Figure by D.D.Chinellato

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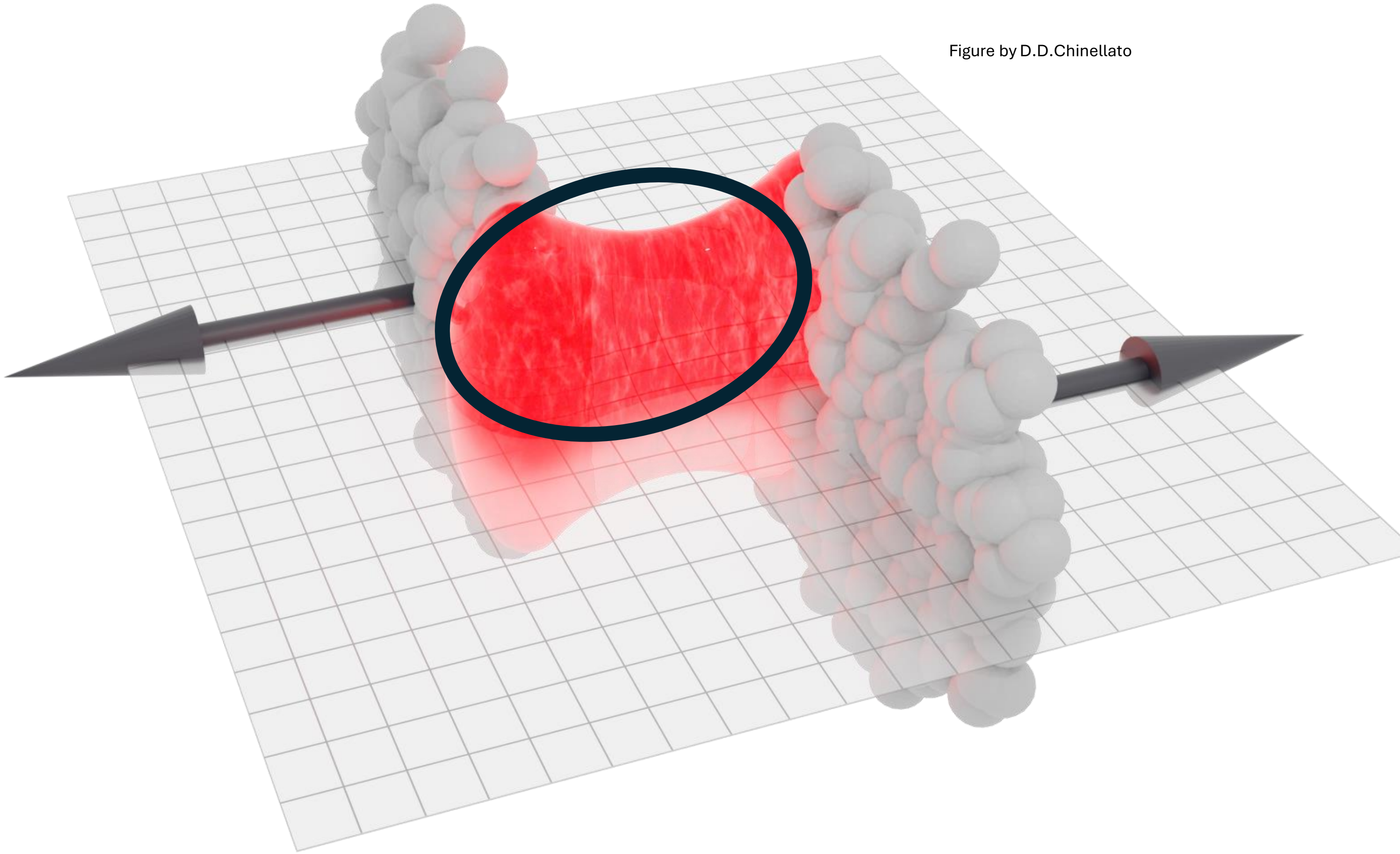

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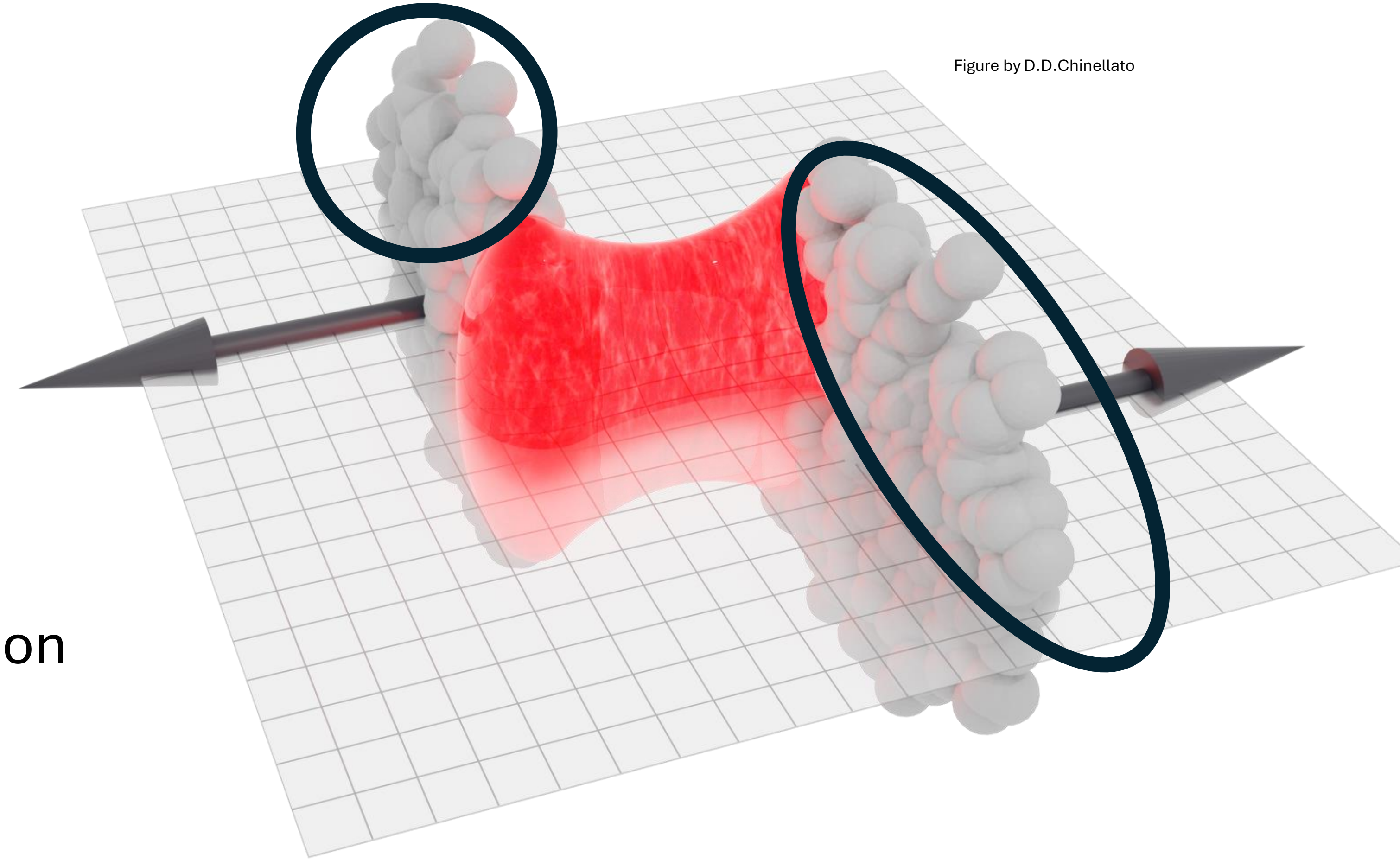

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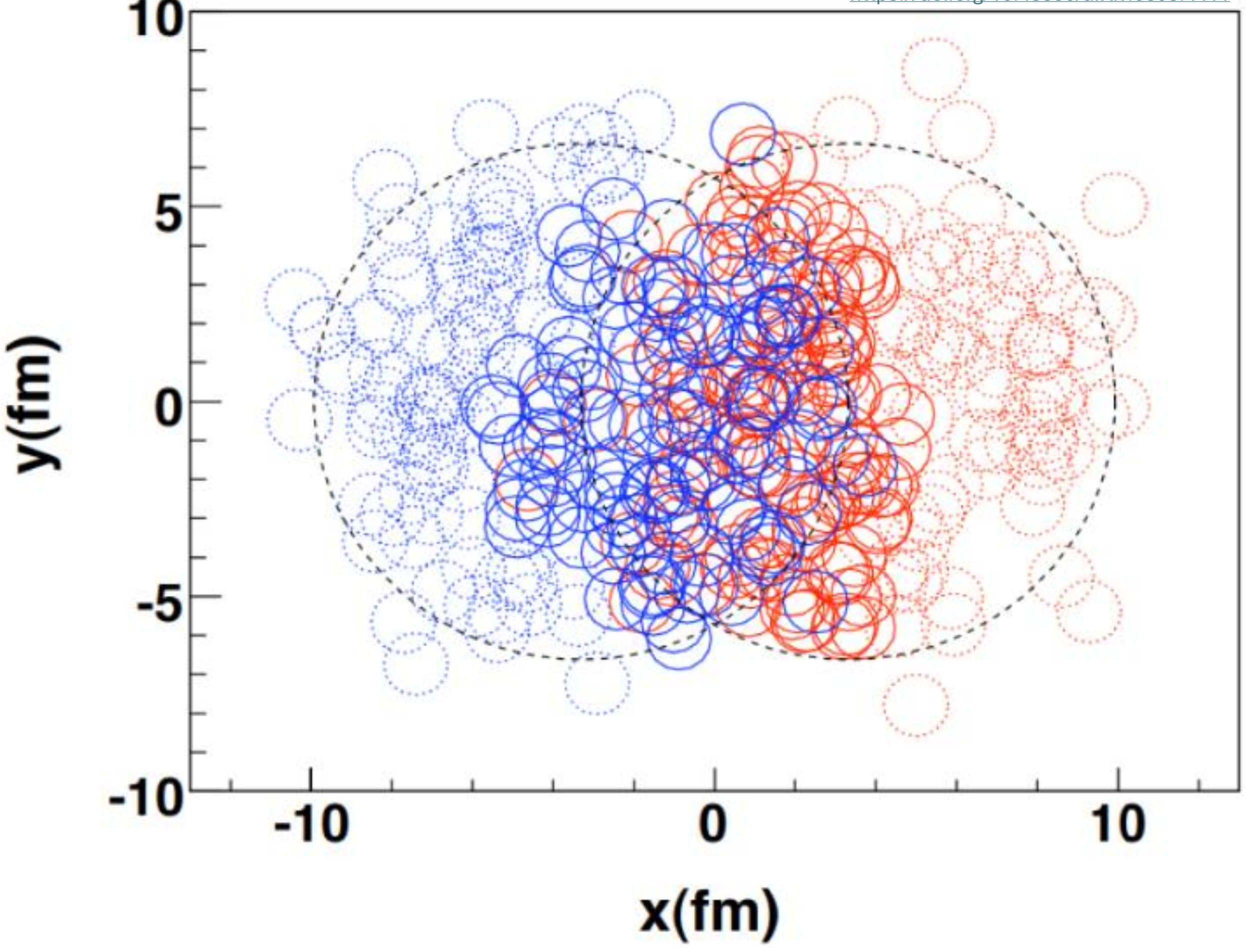
    = number of produced particles

https://doi.org/10.48550/arXiv.0805.4411



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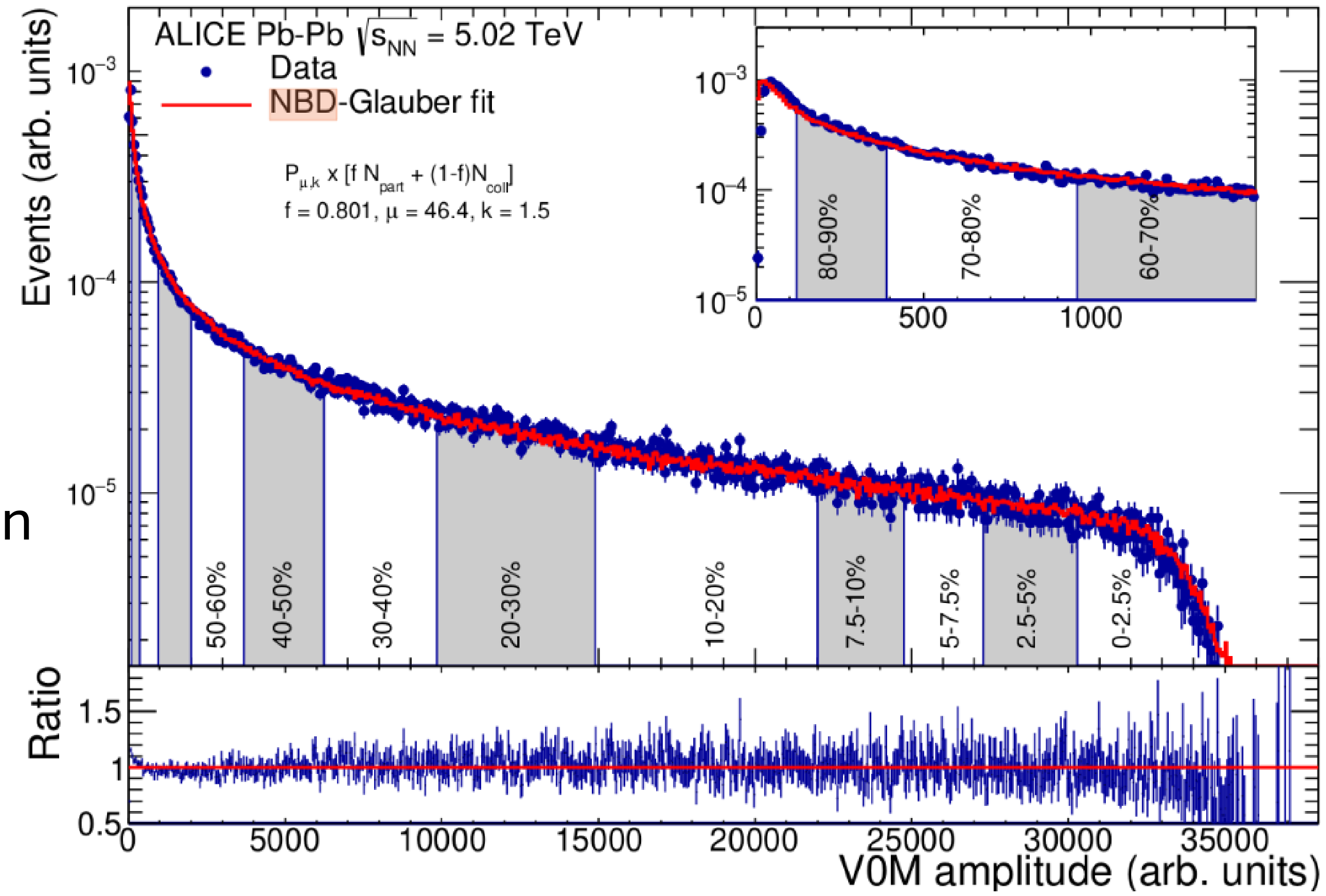
https://cds.cern.ch/record/2636623



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We generally believe that these kind of events have good theoretical conditions to produce a QGP

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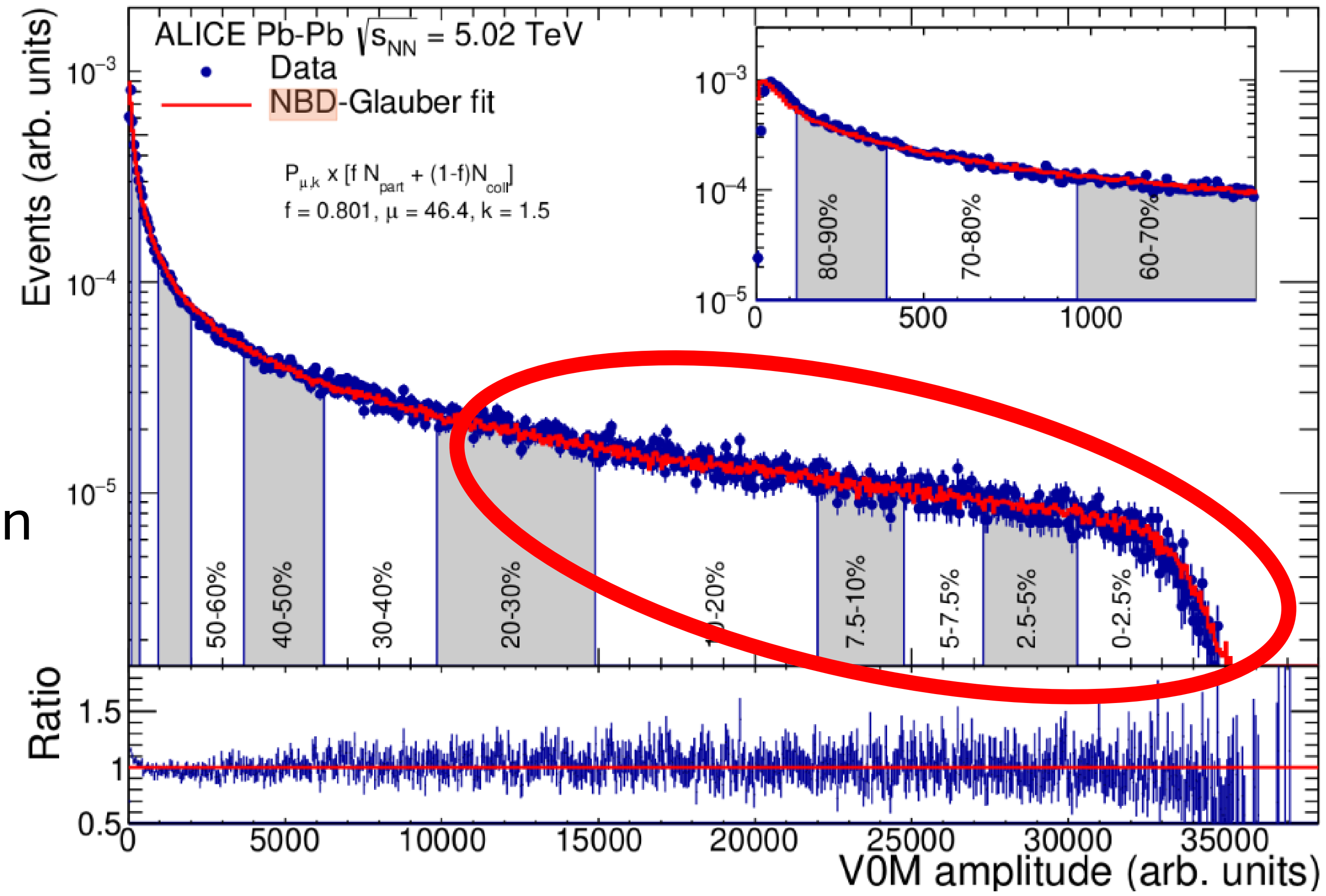

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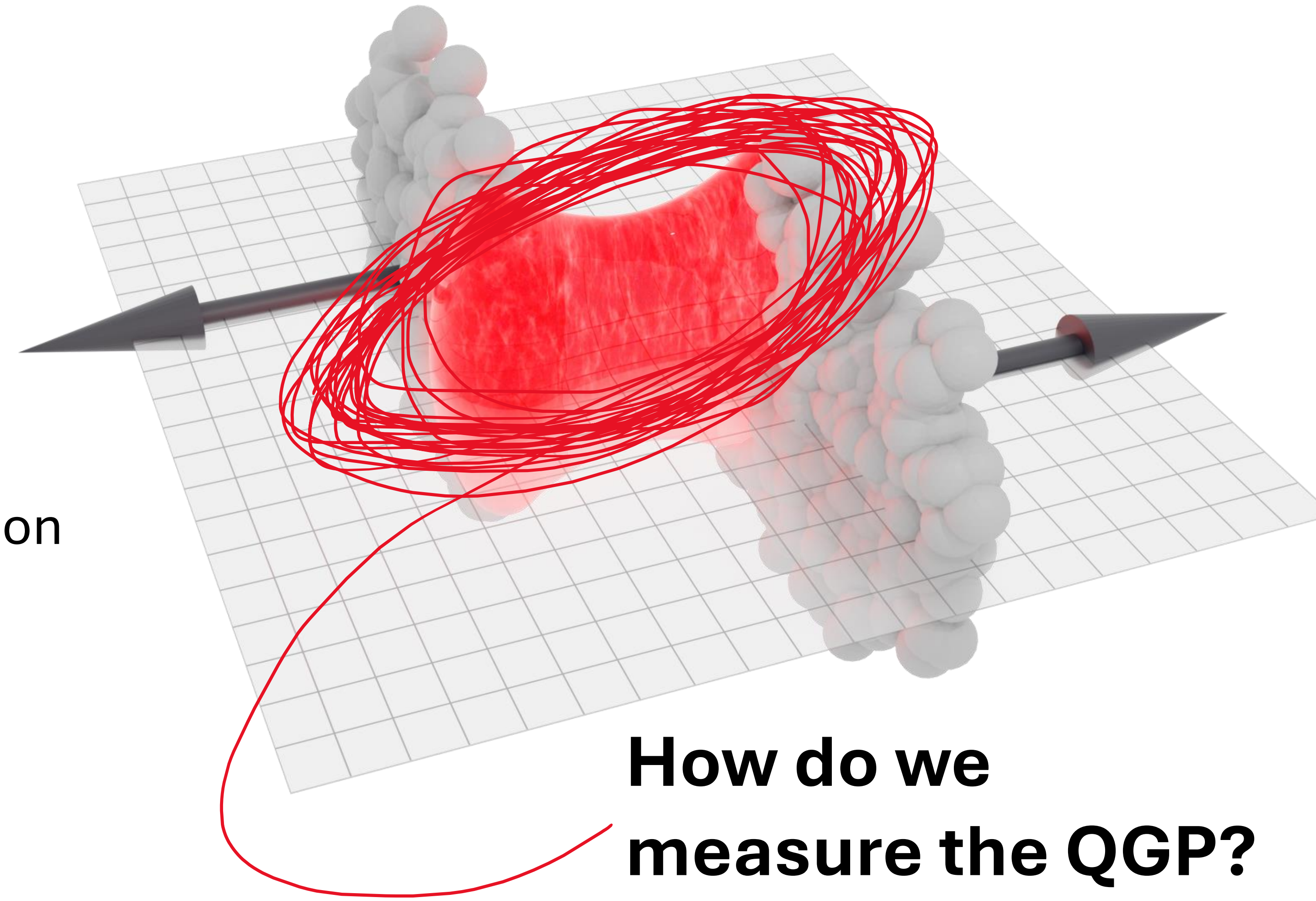


How do we measure the QGP?

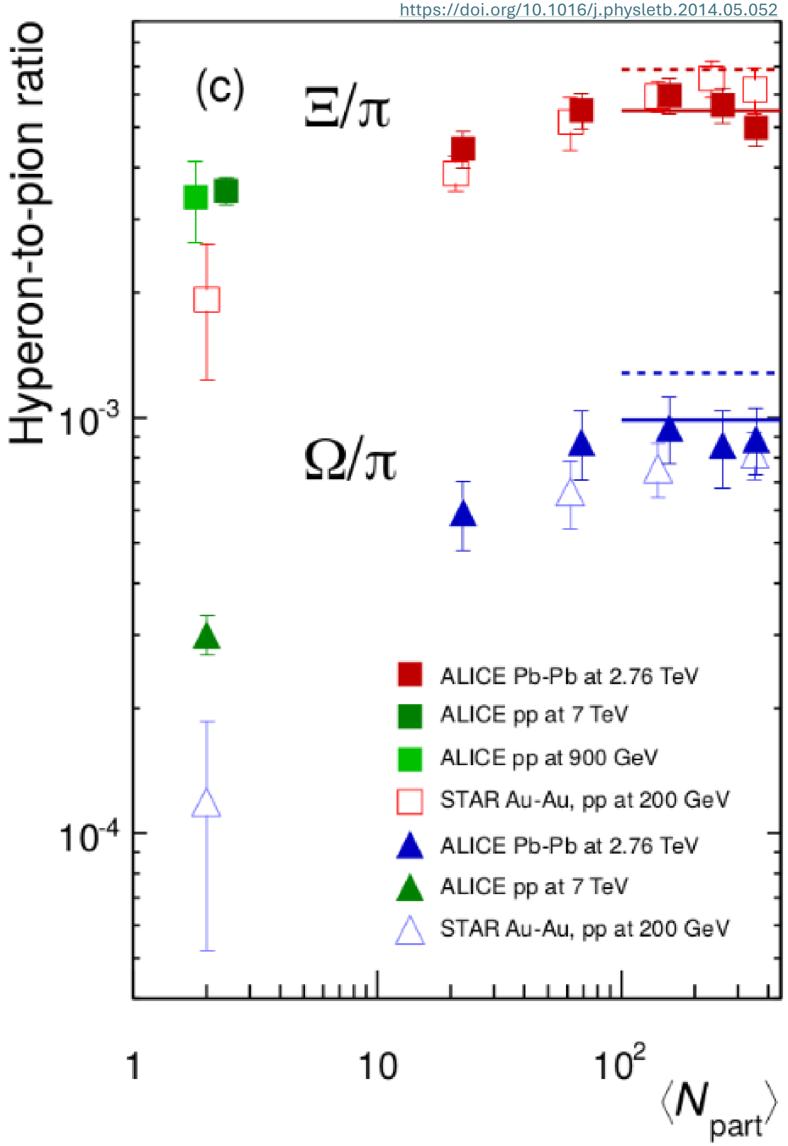
Early signatures of the QGP

- Strangeness Enhancement
  - Enhanced production of strange hadrons
    - $T_{\mathrm{QGP}} \approx m_s$ allows for thermal production

pp

Pb-Pb

https://doi.org/10.1016/j.physletb.2014.05.052



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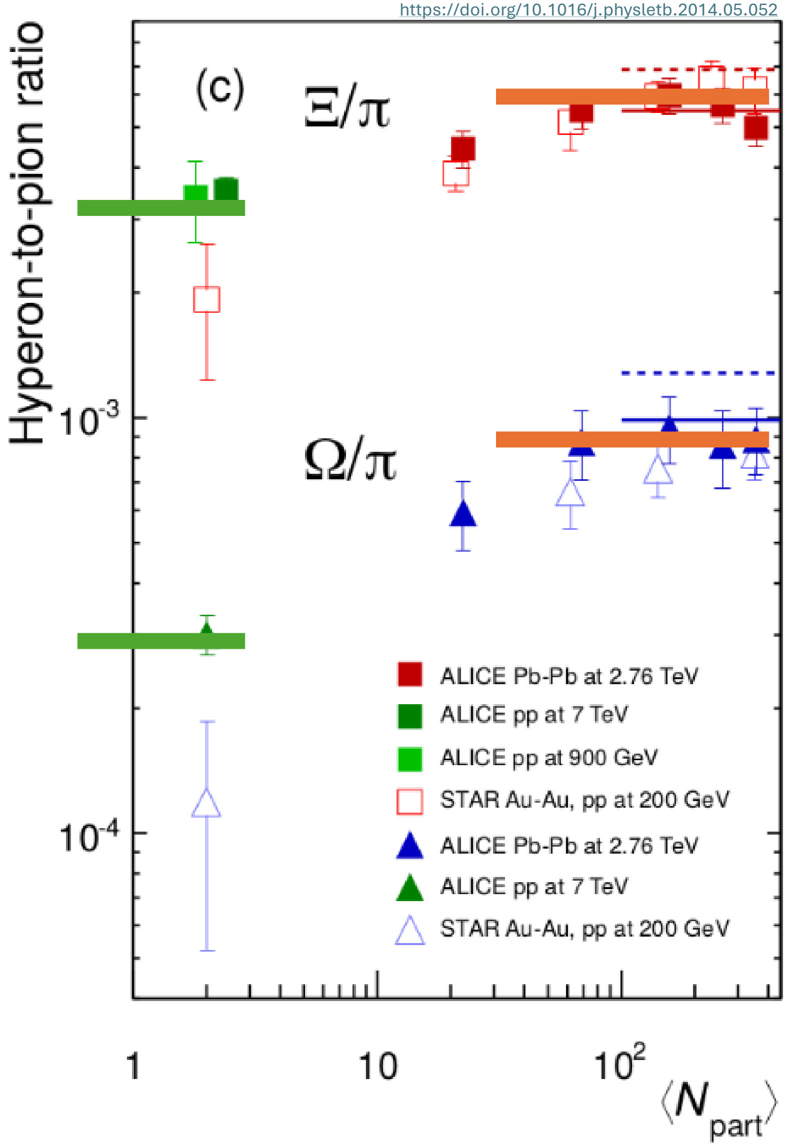

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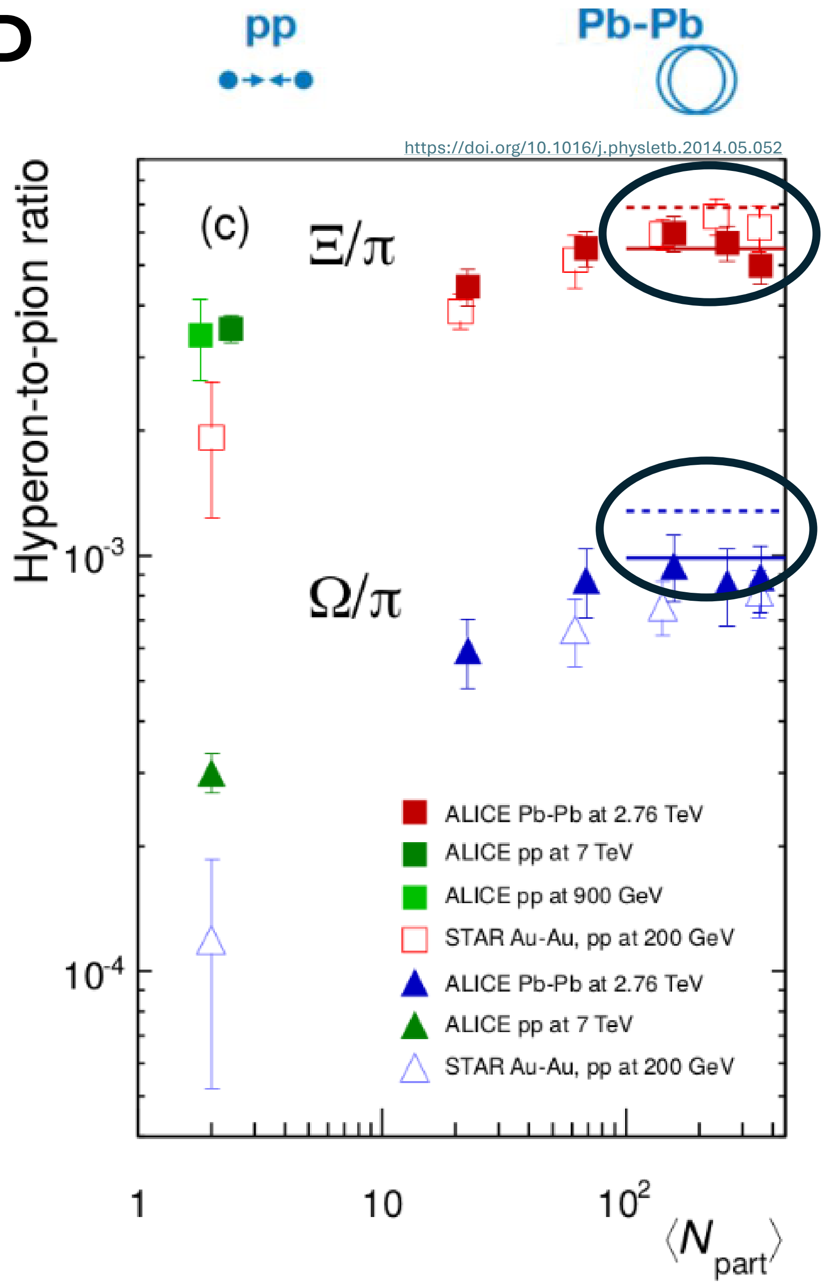

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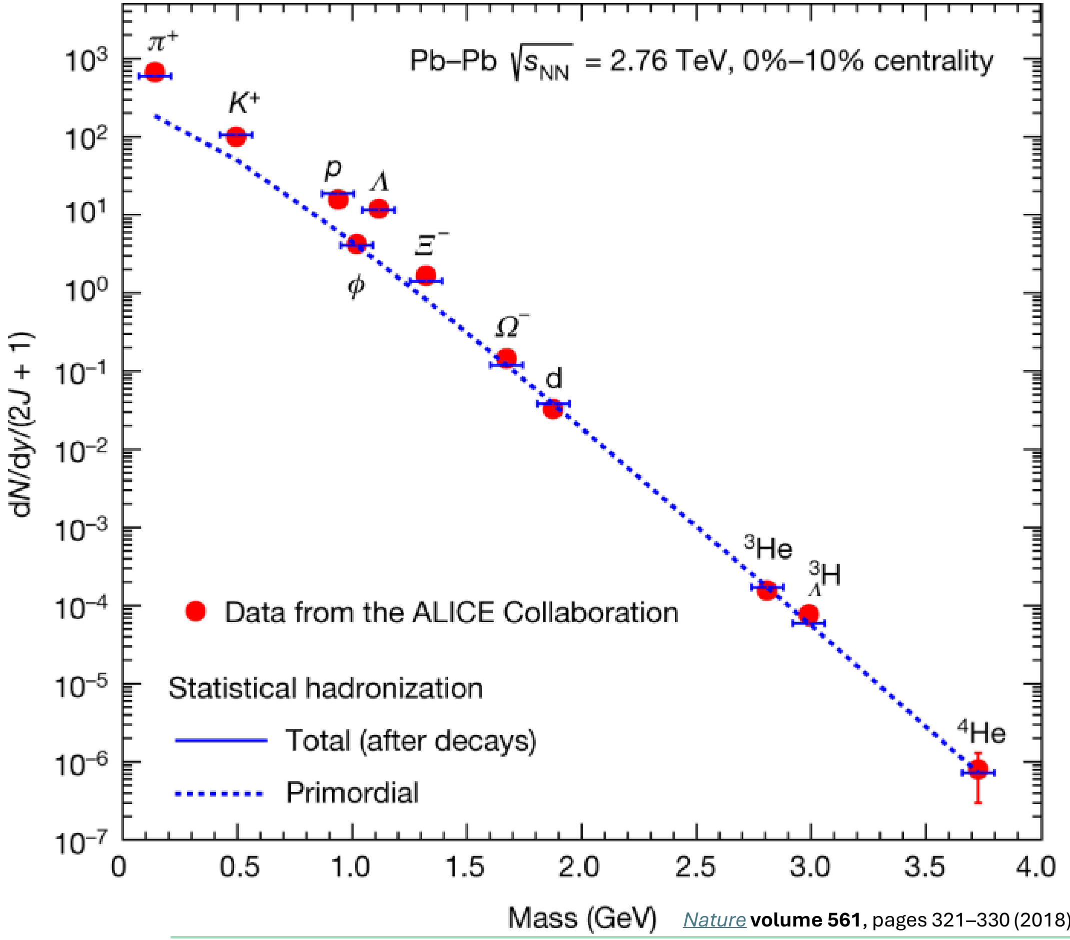
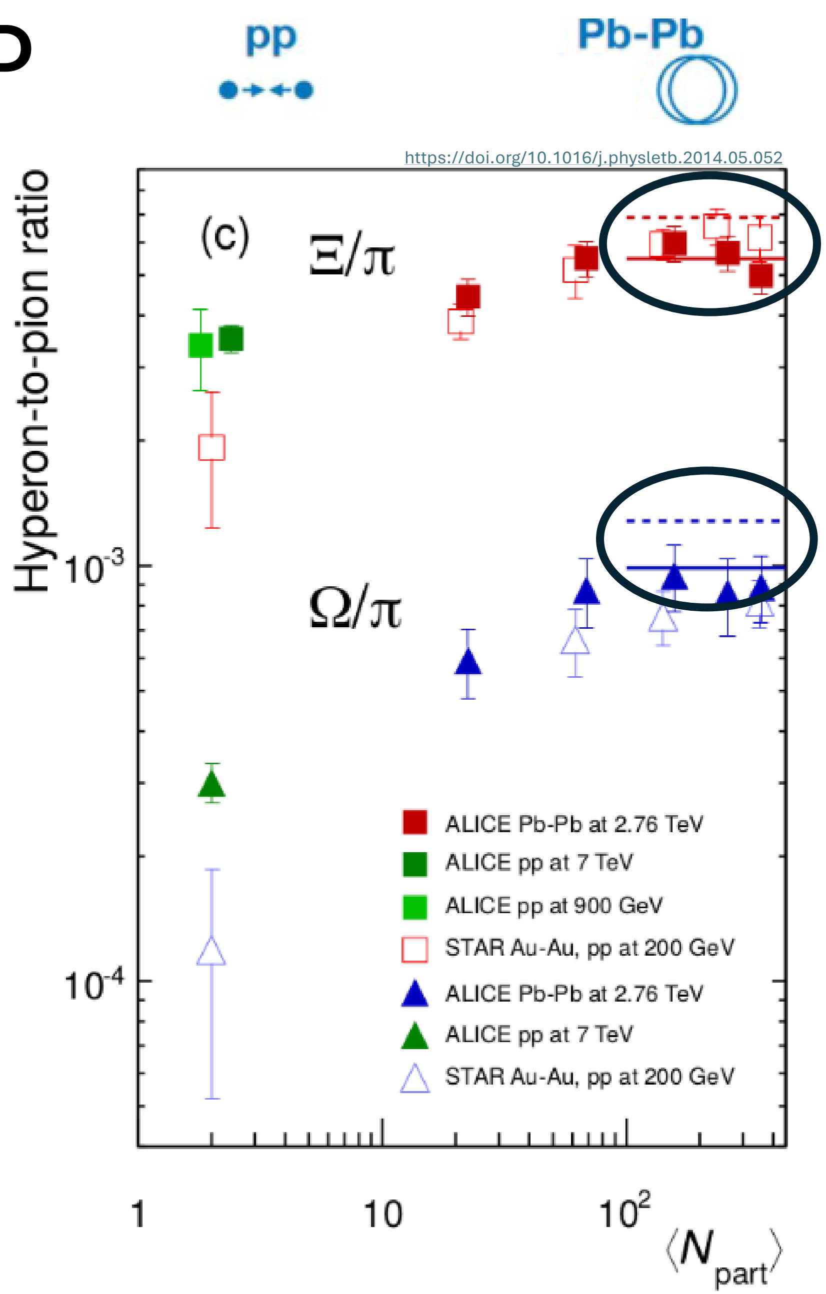


Nature **volume 561**, pages 321–330 (2018)



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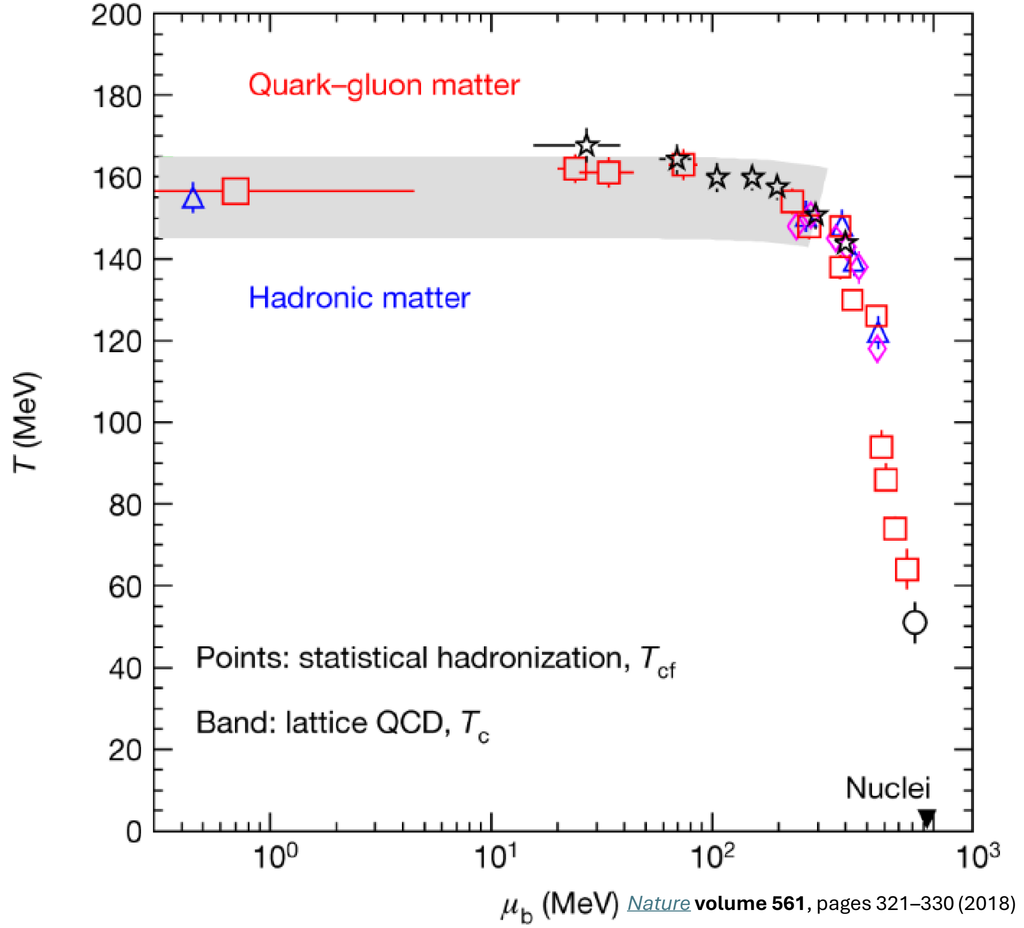

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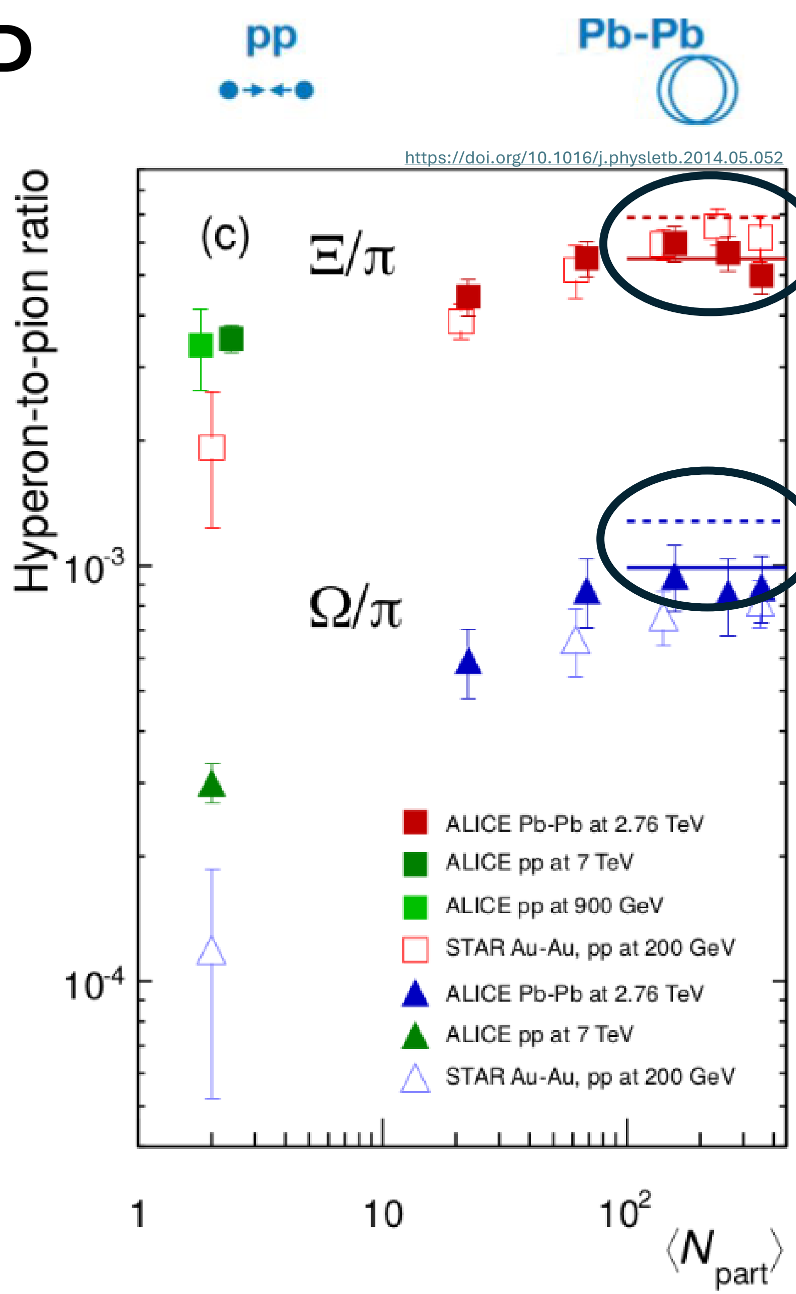

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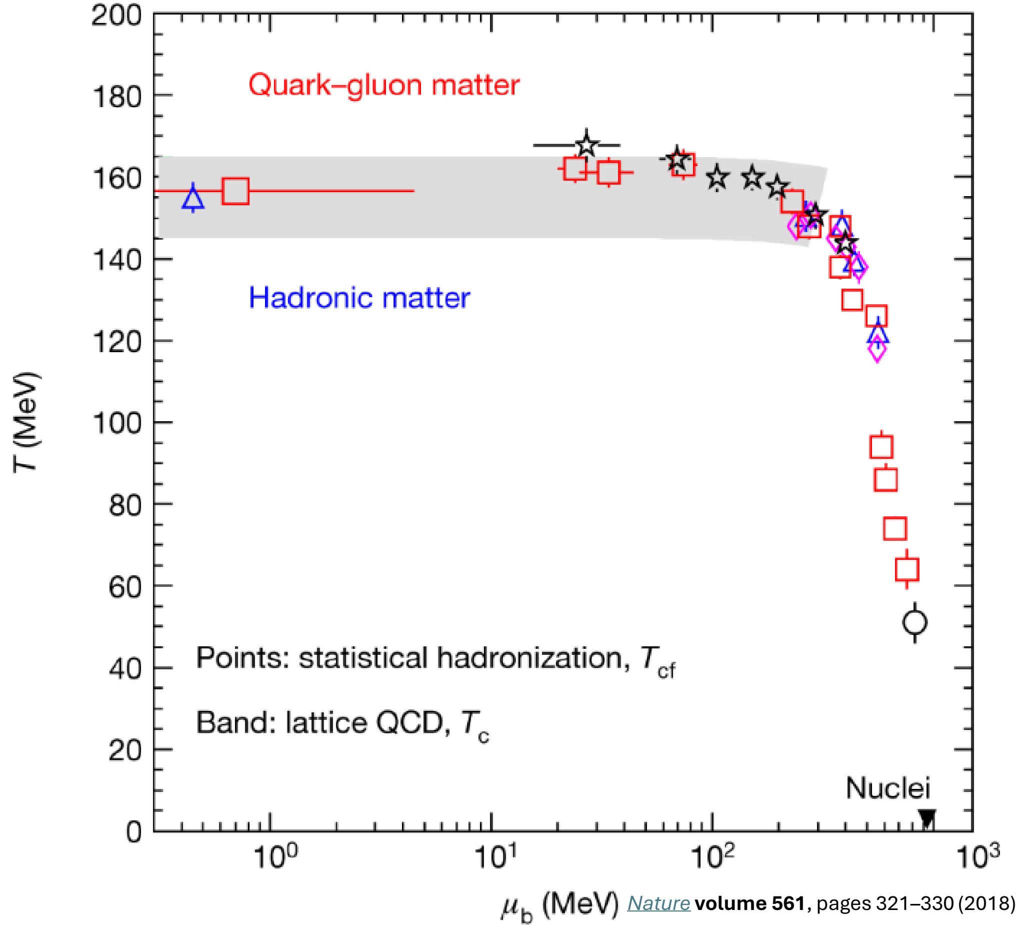

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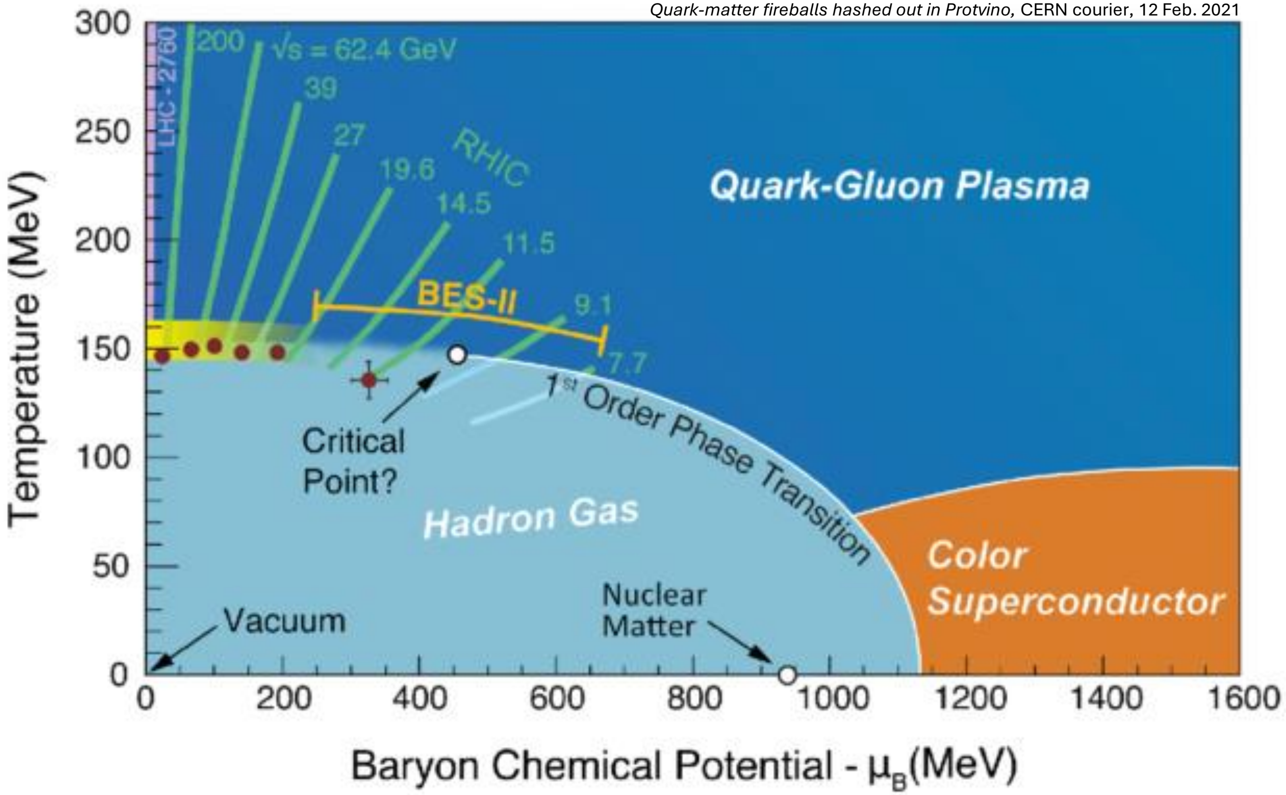
Quark-matter fireballs hashed out in Protvino, CERN courier, 12 Feb. 2021



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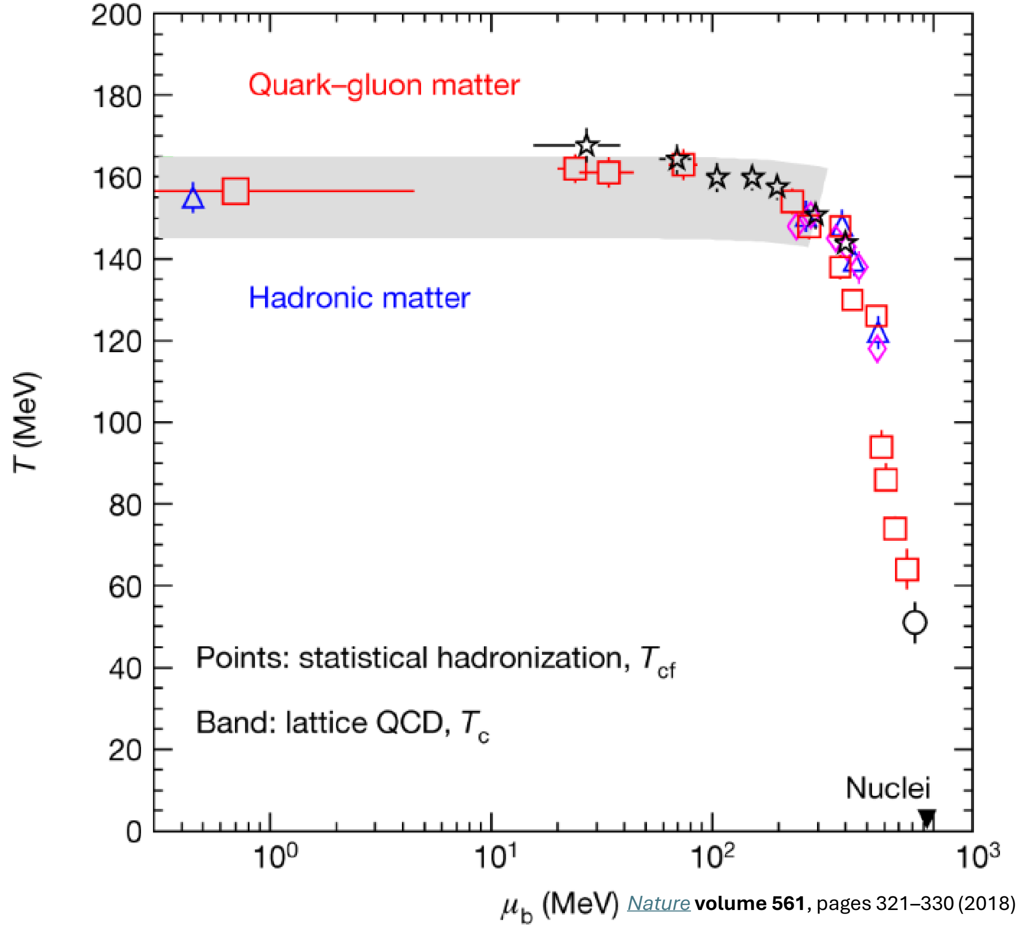

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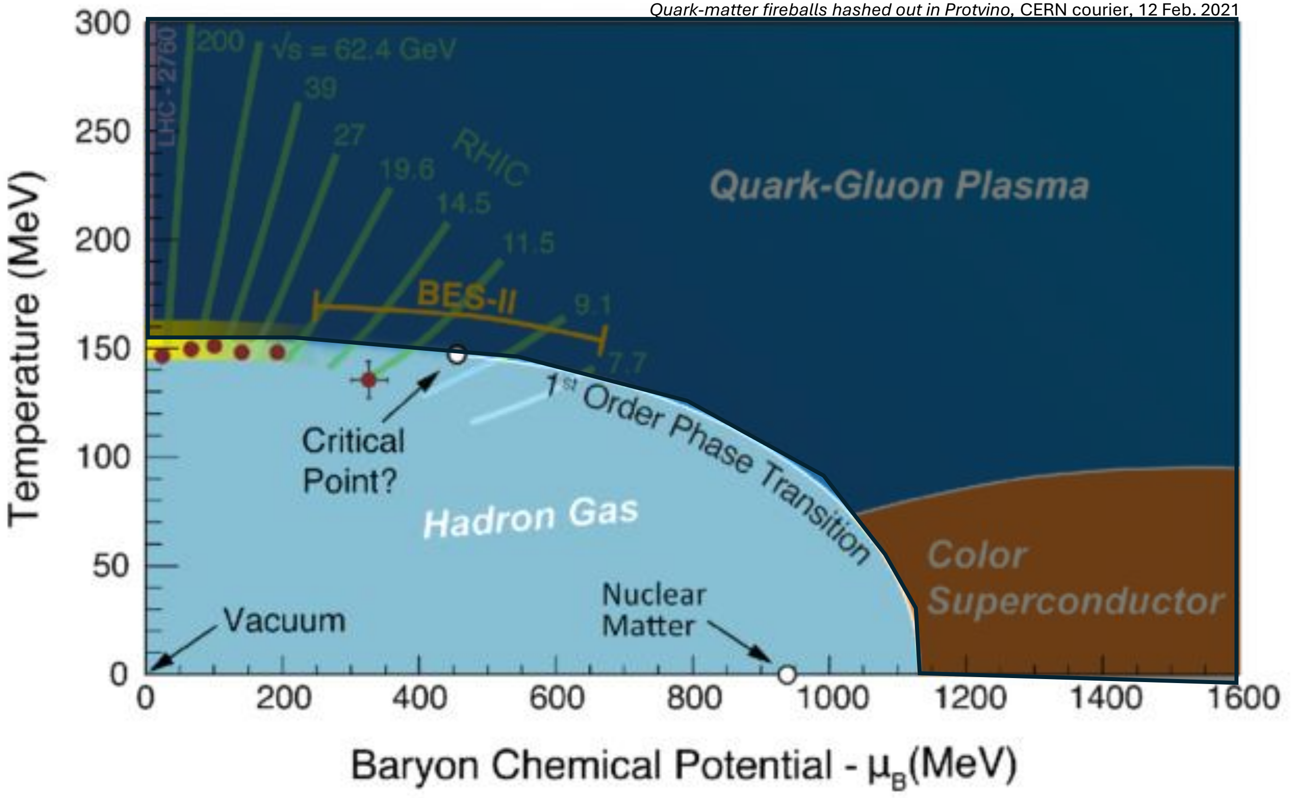

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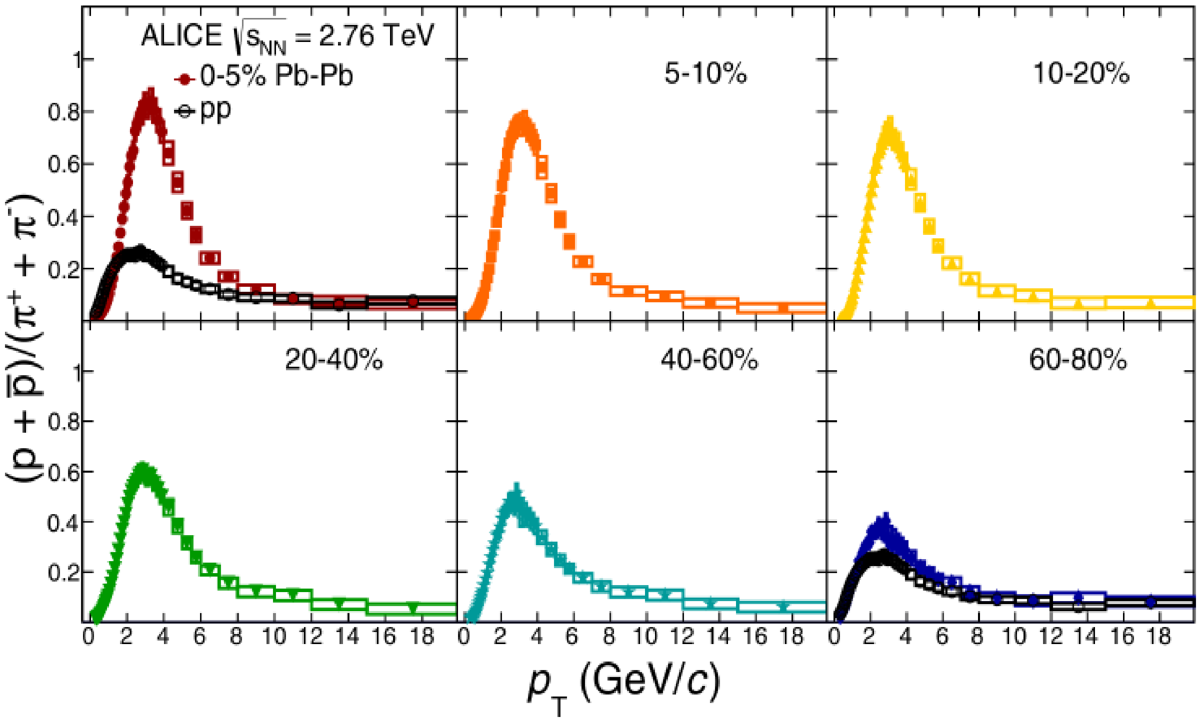
Phys. Rev.Lett. 97, 152303 (2006)



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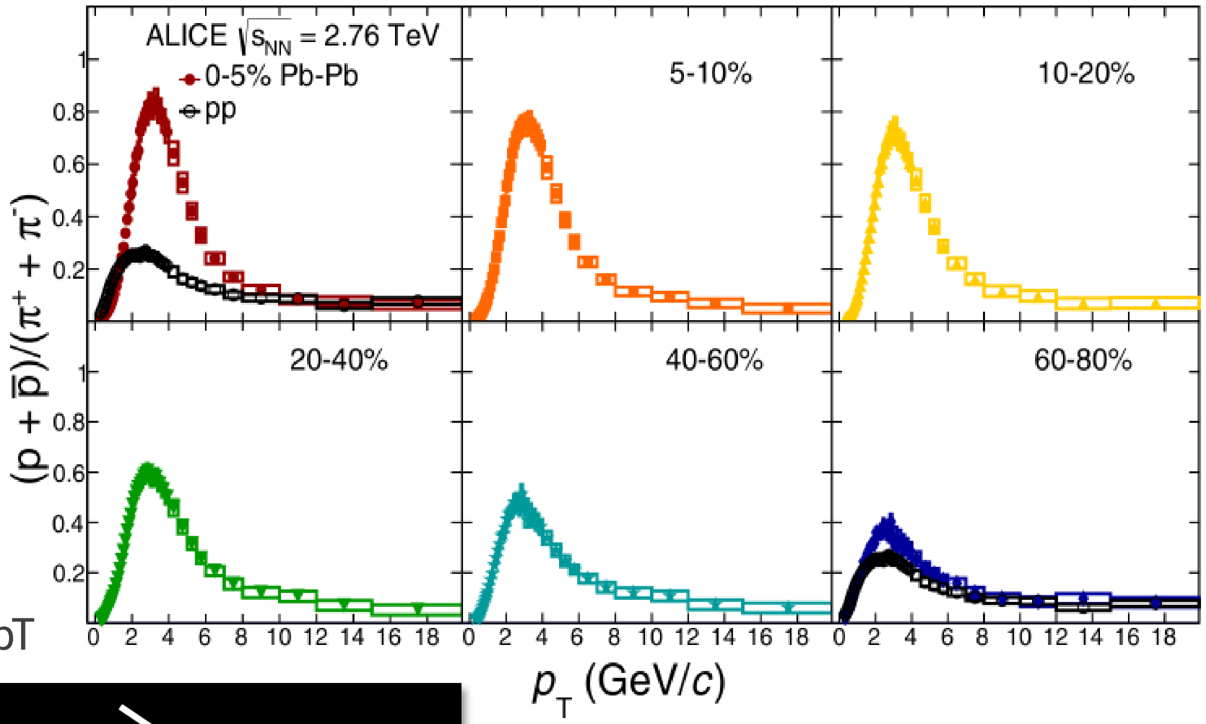
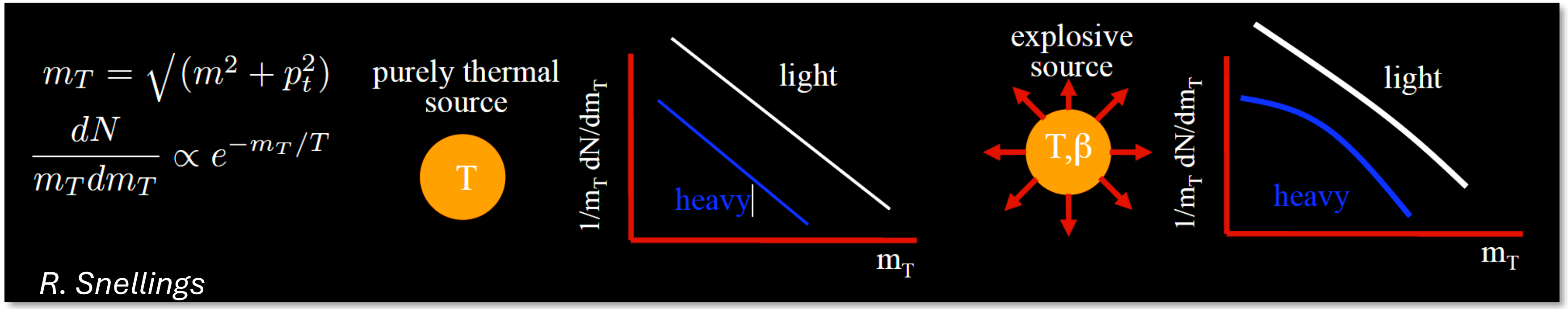


Peak is "pushed" toward high pT, while depleted at lower pT



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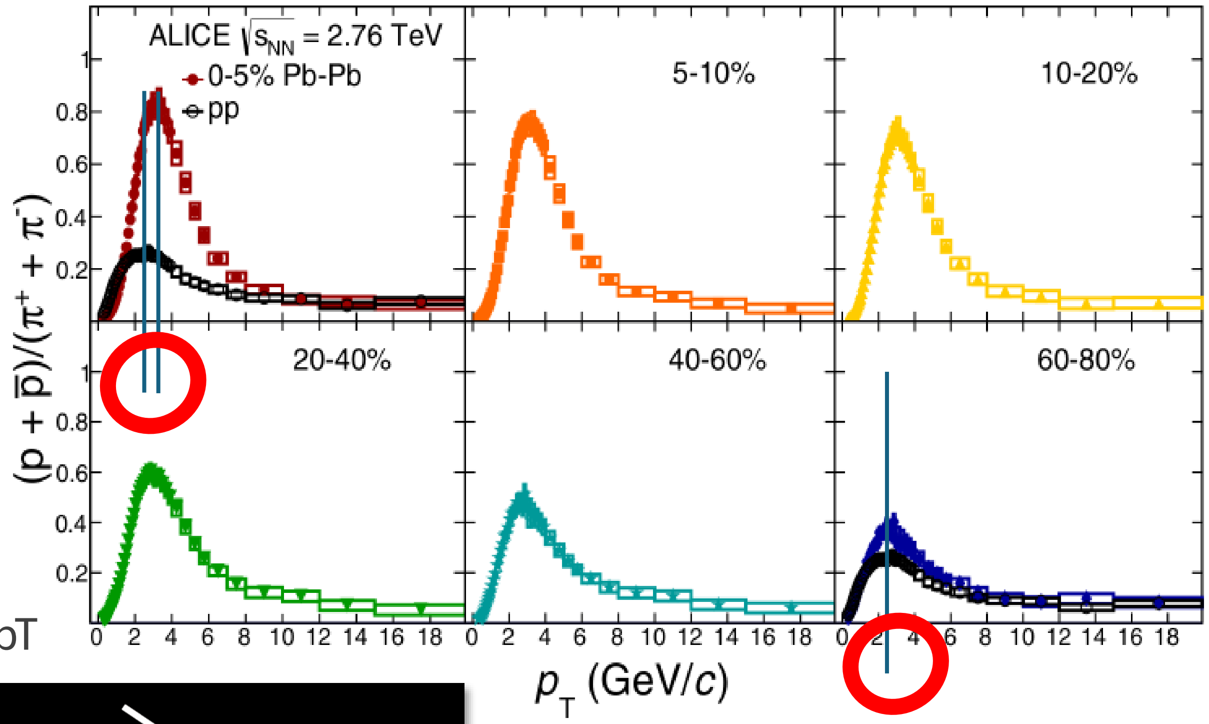

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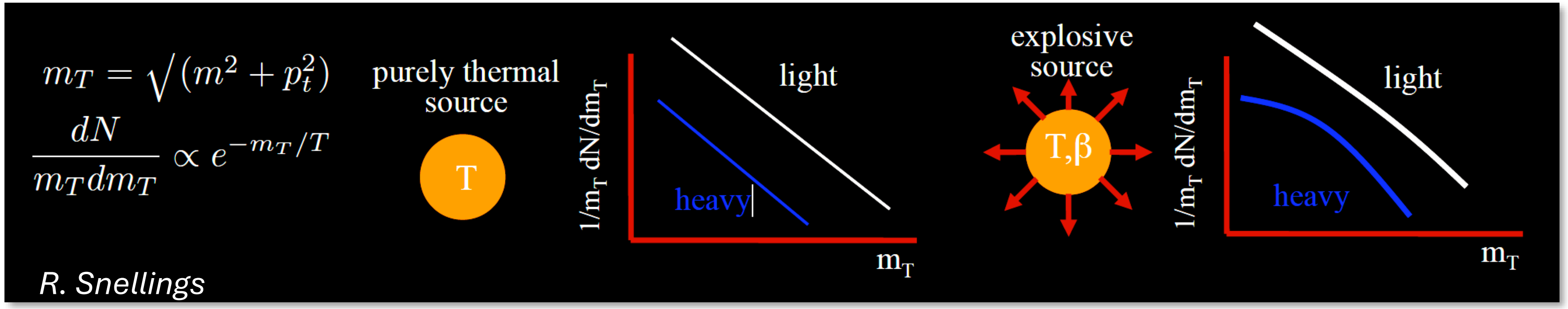

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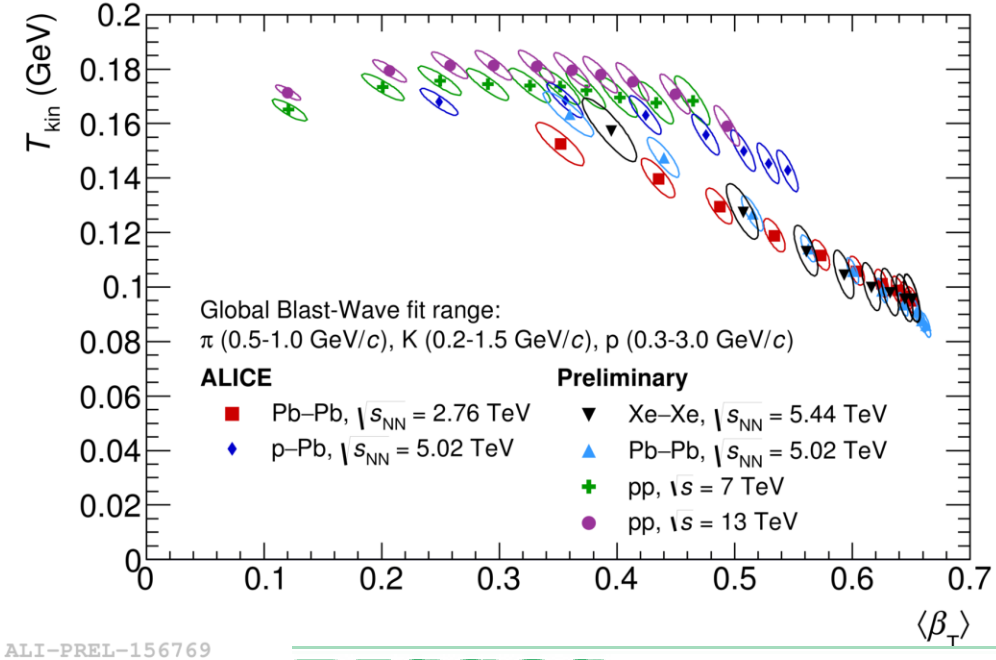

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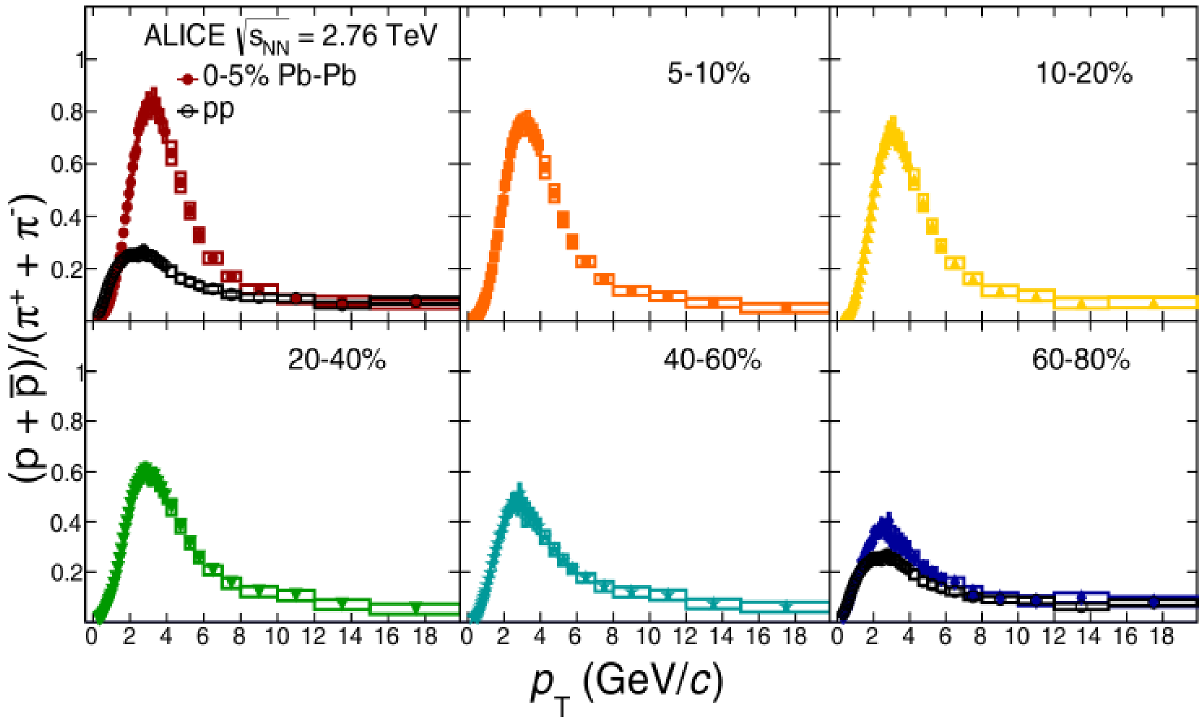

The hydrodynamical properties can be modelled by a Boltzmann-Gibbs blast-wave

- Fit to the spectra of identified pions, kaons and protons

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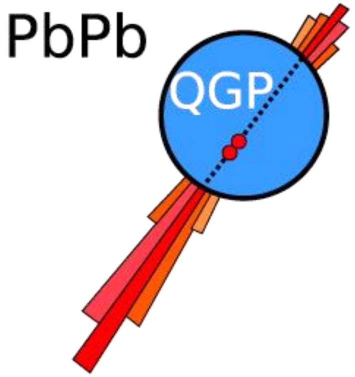
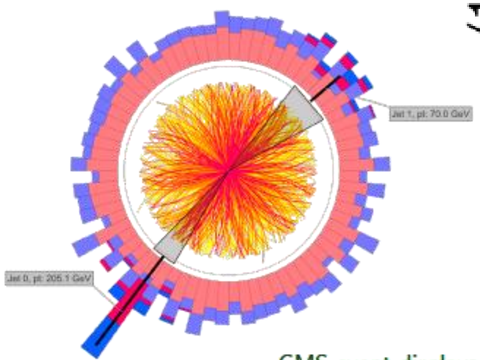
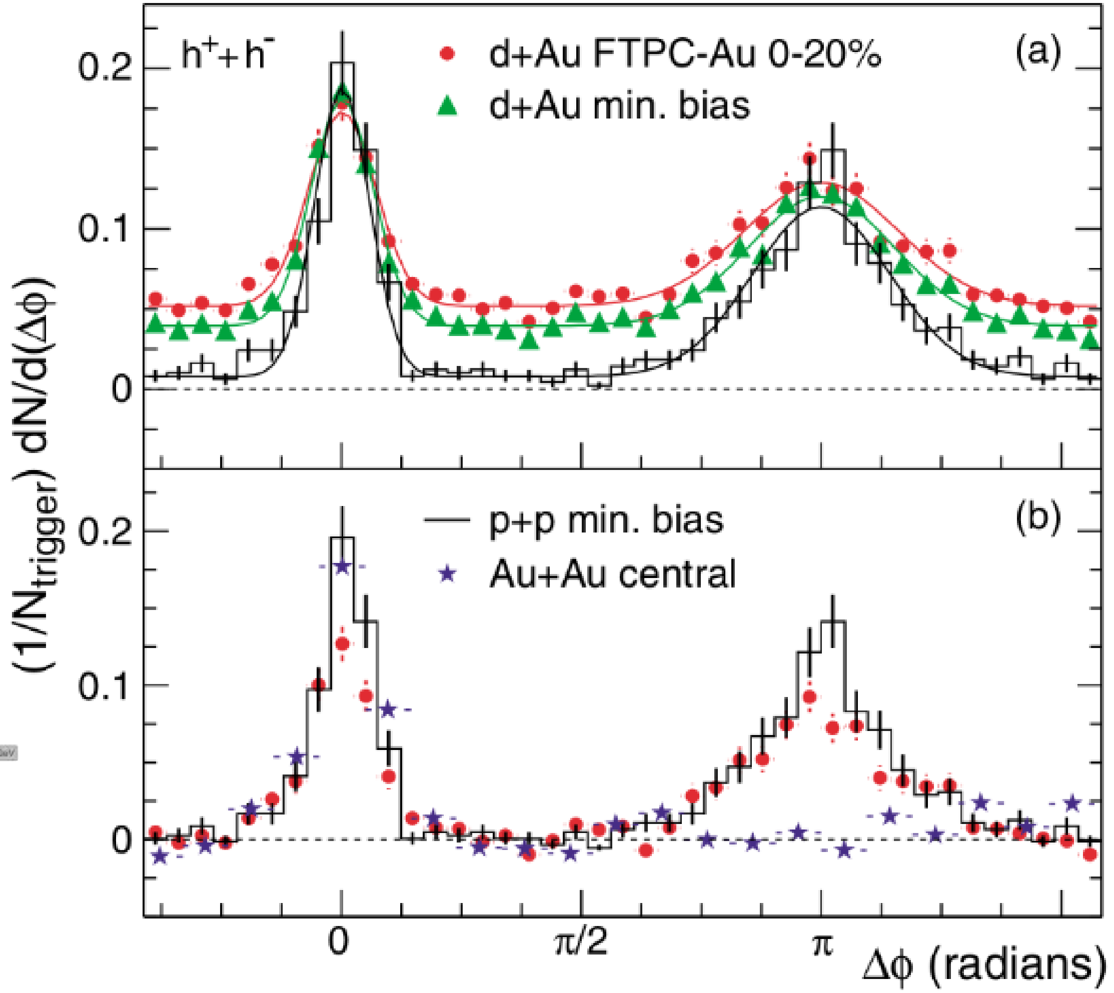




CMS event displays

Phys.Rev.Lett.91:072304,2003



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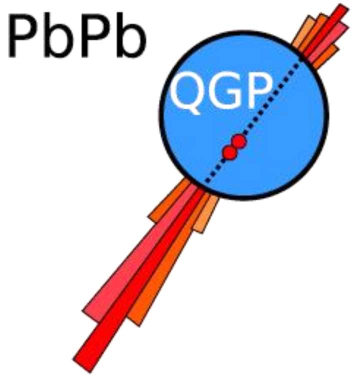

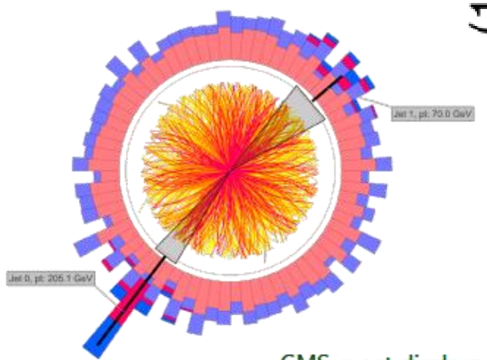

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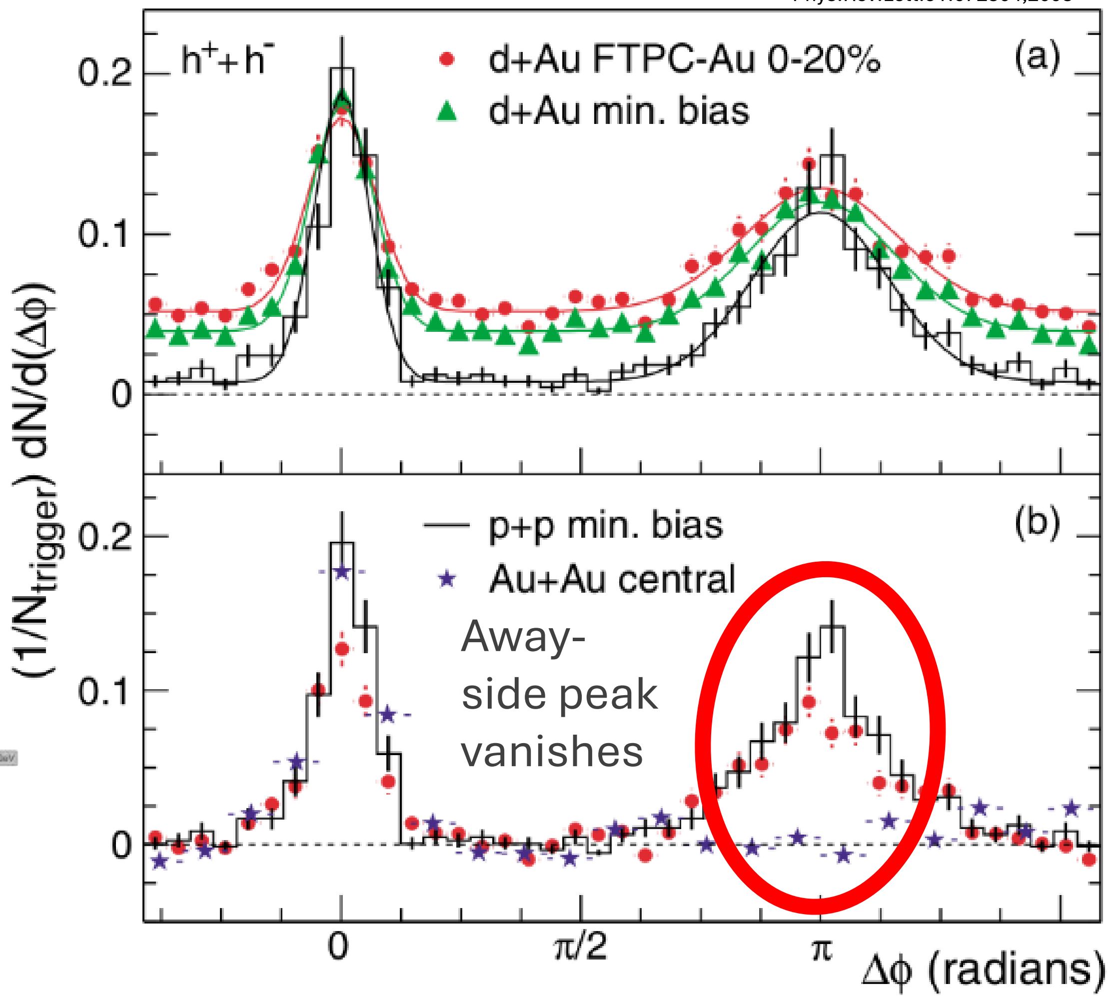

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$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

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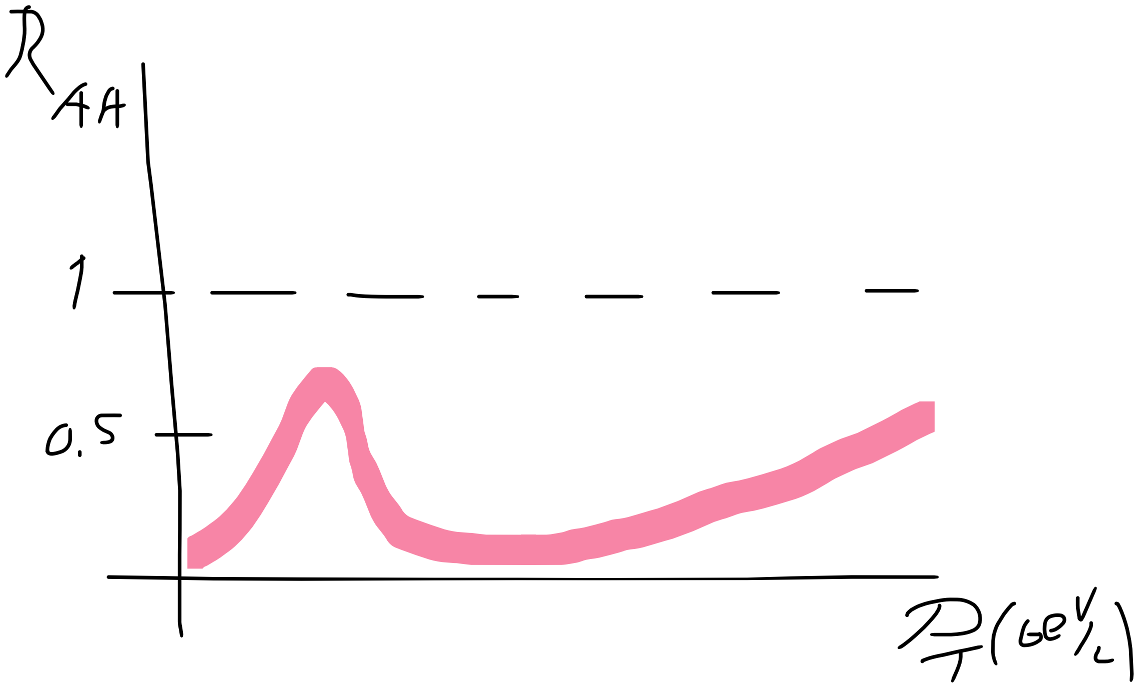

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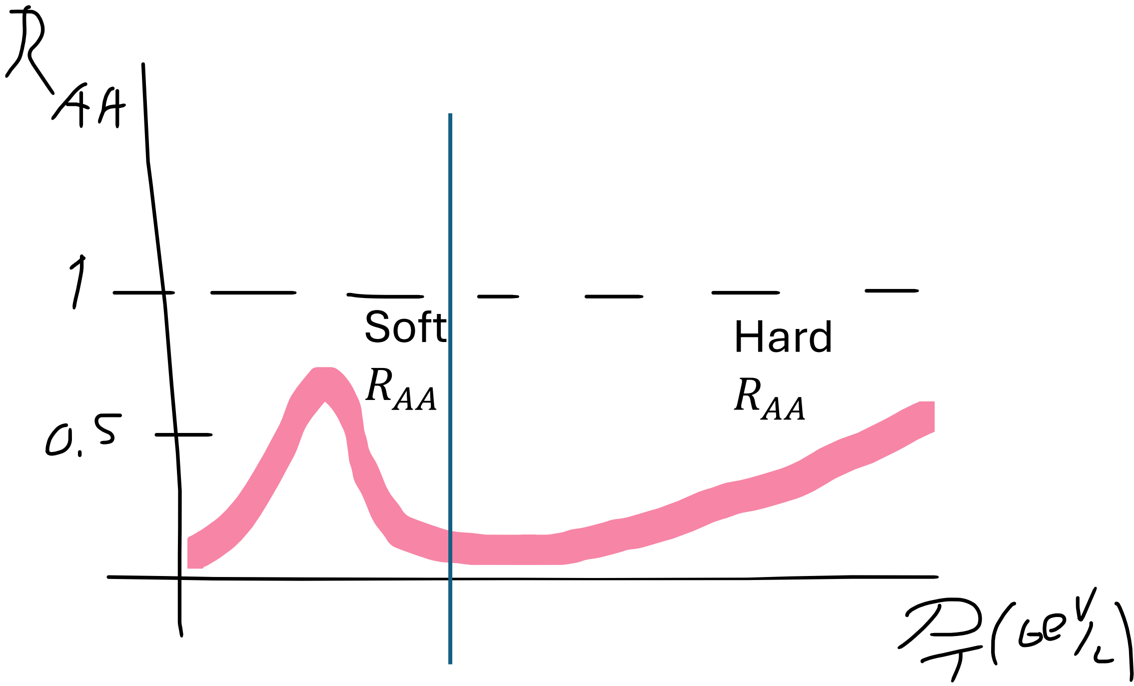

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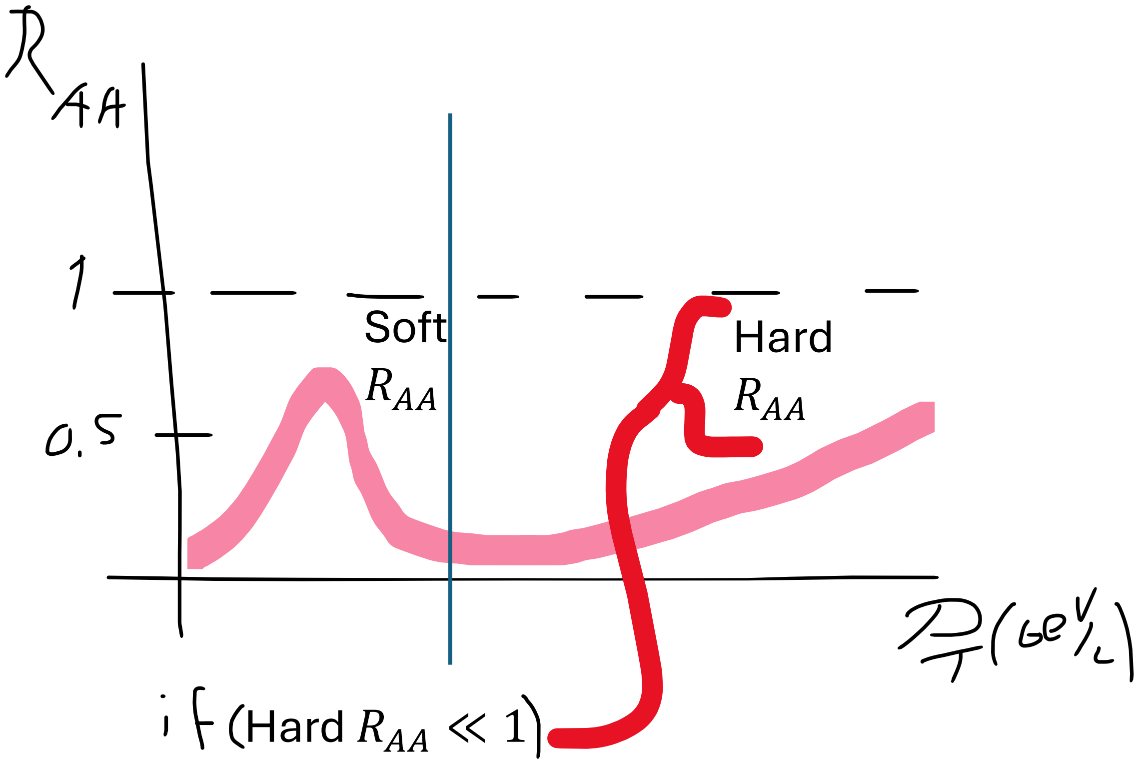

Then the hard scattered partons are being absorbed by a strongly interacting medium!

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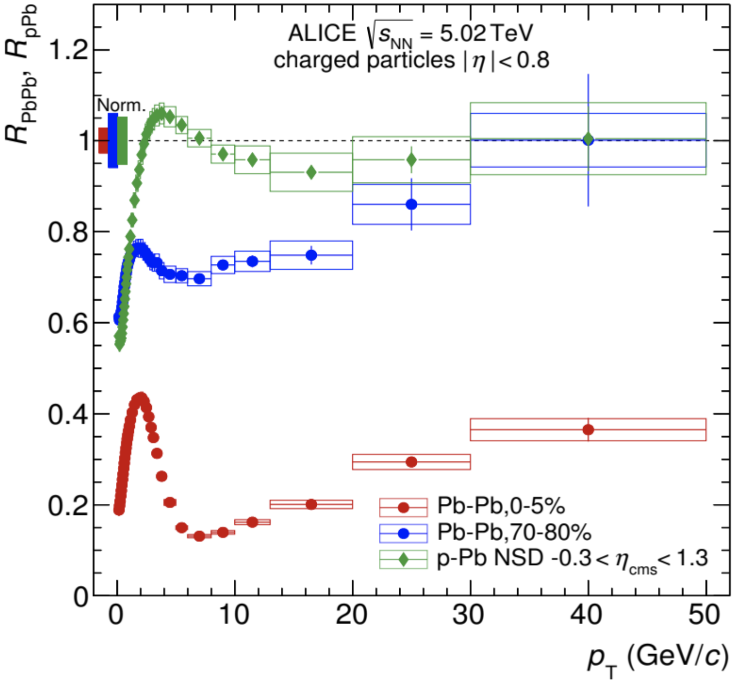
JHEP 11 (2018) 013



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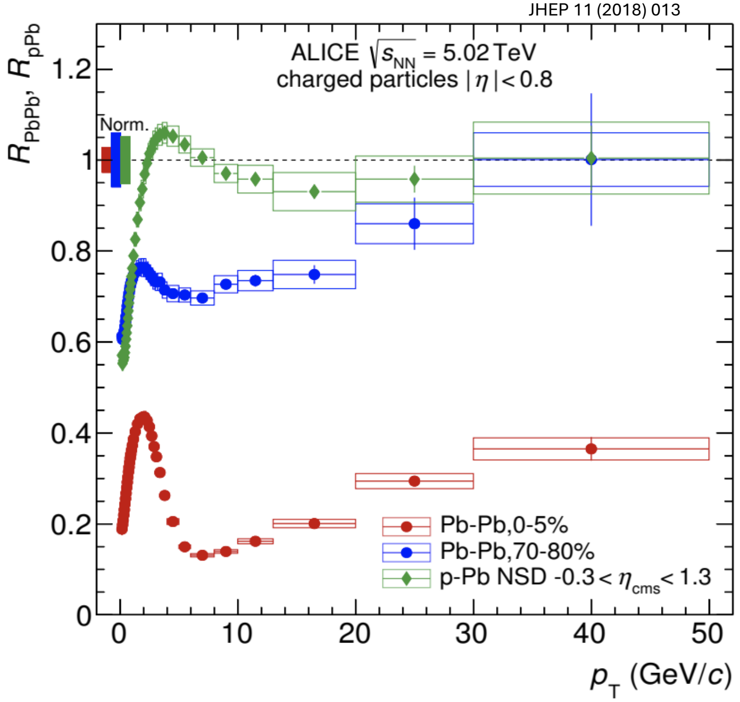

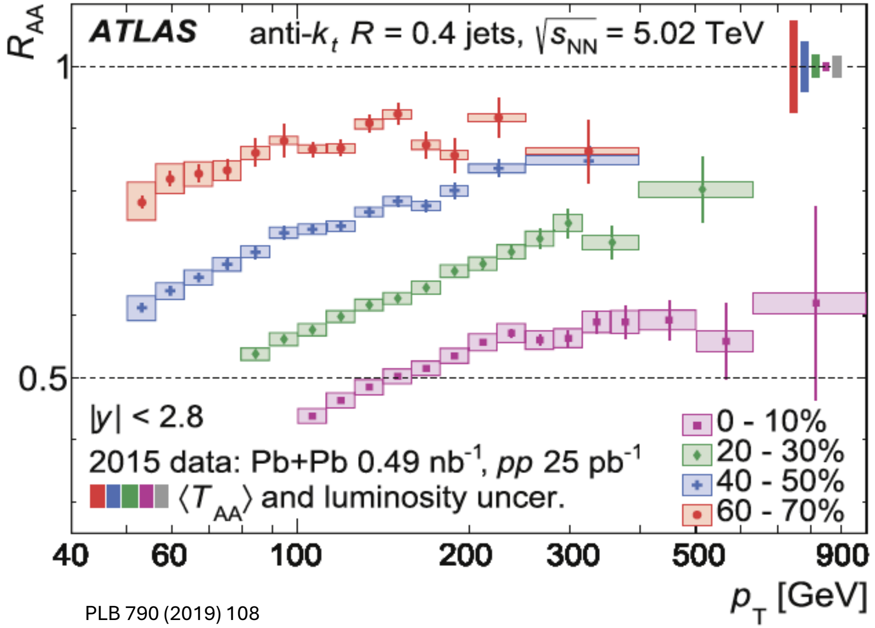

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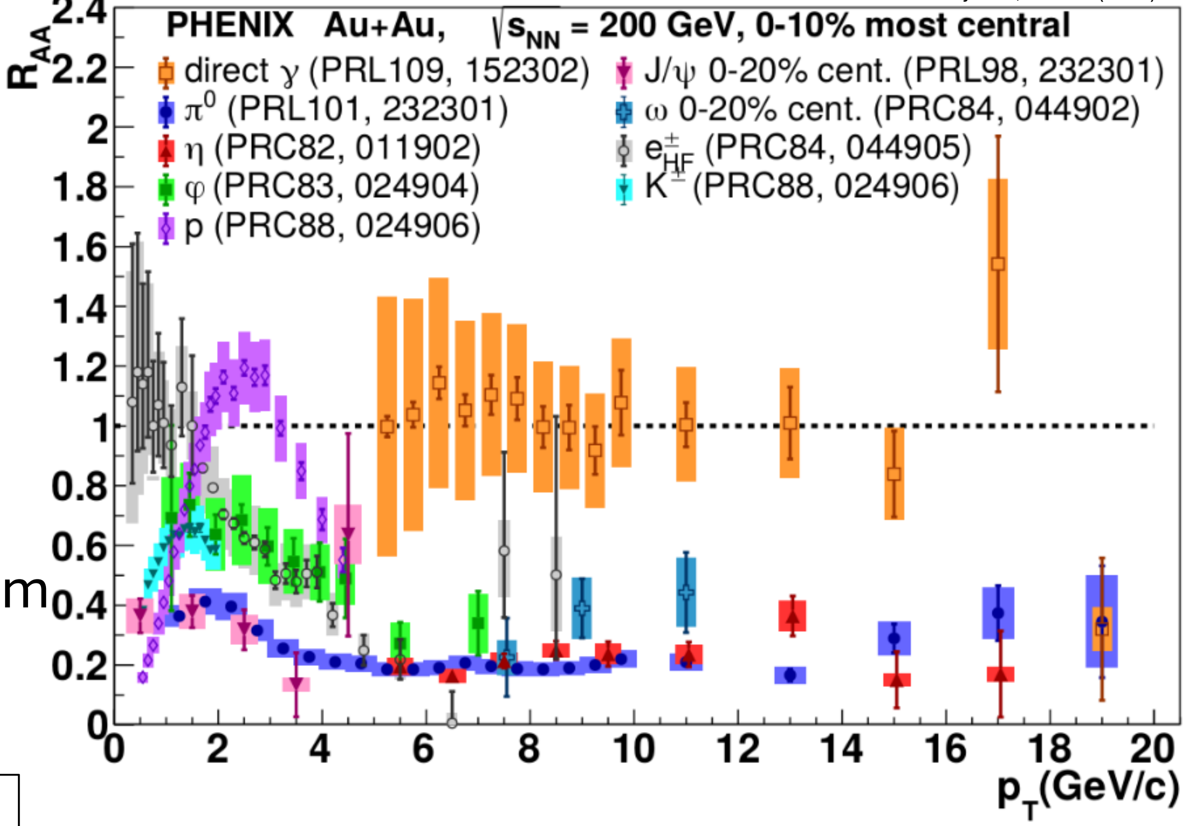
Rev. Mod. Phys. 90, 025005 (2018)



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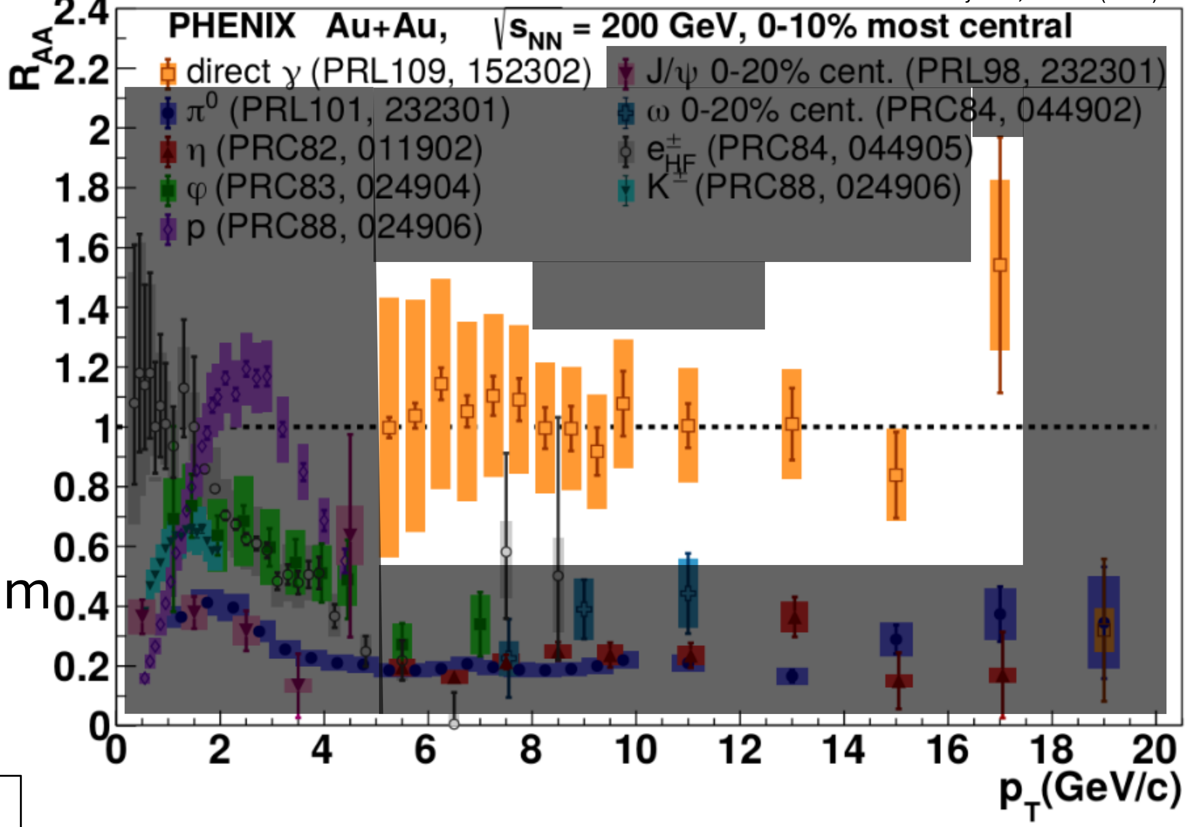
Rev. Mod. Phys. 90, 025005 (2018)



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

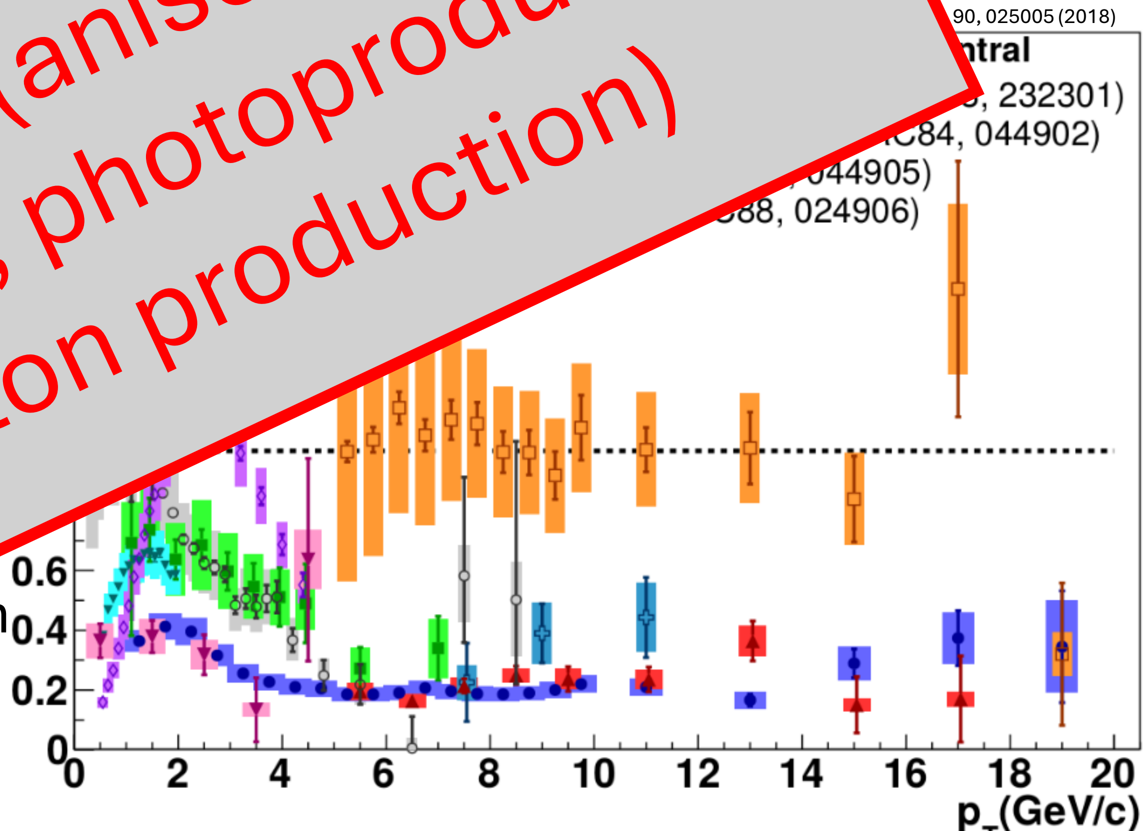
Early signatures of the QGP

- Strangeness Enhancement
  - Enhanced production of strange hadrons
    - $T_{QGP} \approx m_s$ allows for thermal produ
- Flow
  - Radial flow
    - Constant
- Jet Q

edium

edium

Several other observables (anisotropic flow, heavy flavor suppression, photoproduction, femtoscopy, di-lepton production)



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- Introduction & early QGP signatures
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QGP in proton-proton collisions?

- Are these signatures unique to heavy-ion collisions?
  - How about high-multiplicity, small collision systems?

- Some definitions: Multiplicity and Event Activity
  - The idea is to estimate pp, pA, and AA at the same charged particle densities
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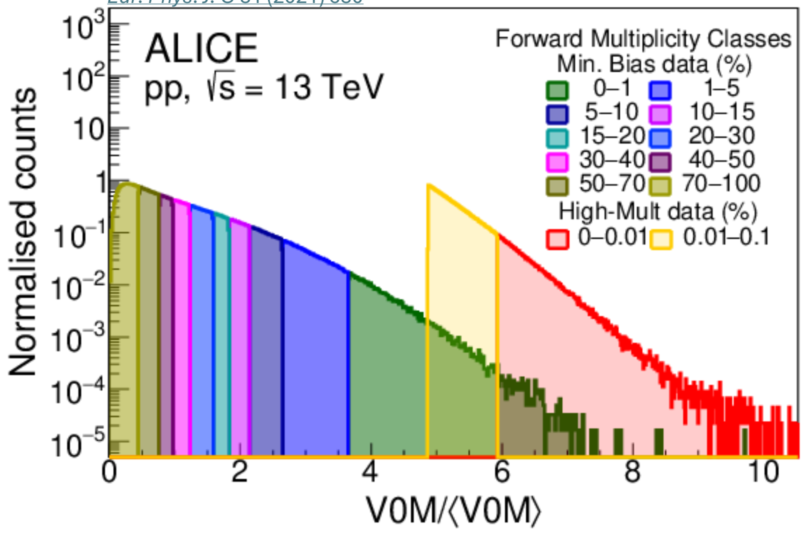
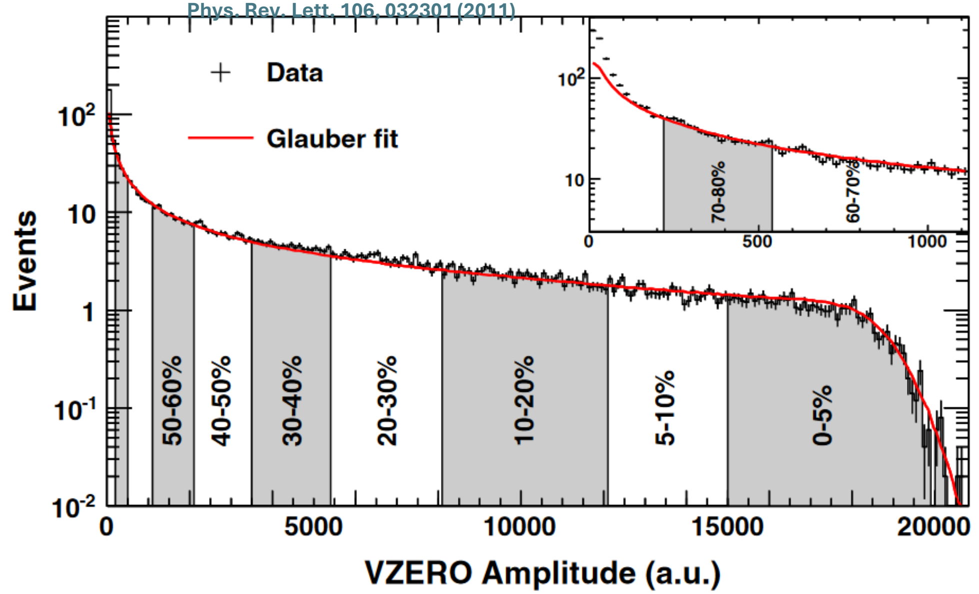
pp

Eur. Phys. J. C 81 (2021) 630



PbPb

Phys. Rev. Lett. 106, 032301 (2011)



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- Some definitions: Multiplicity and Event Activity
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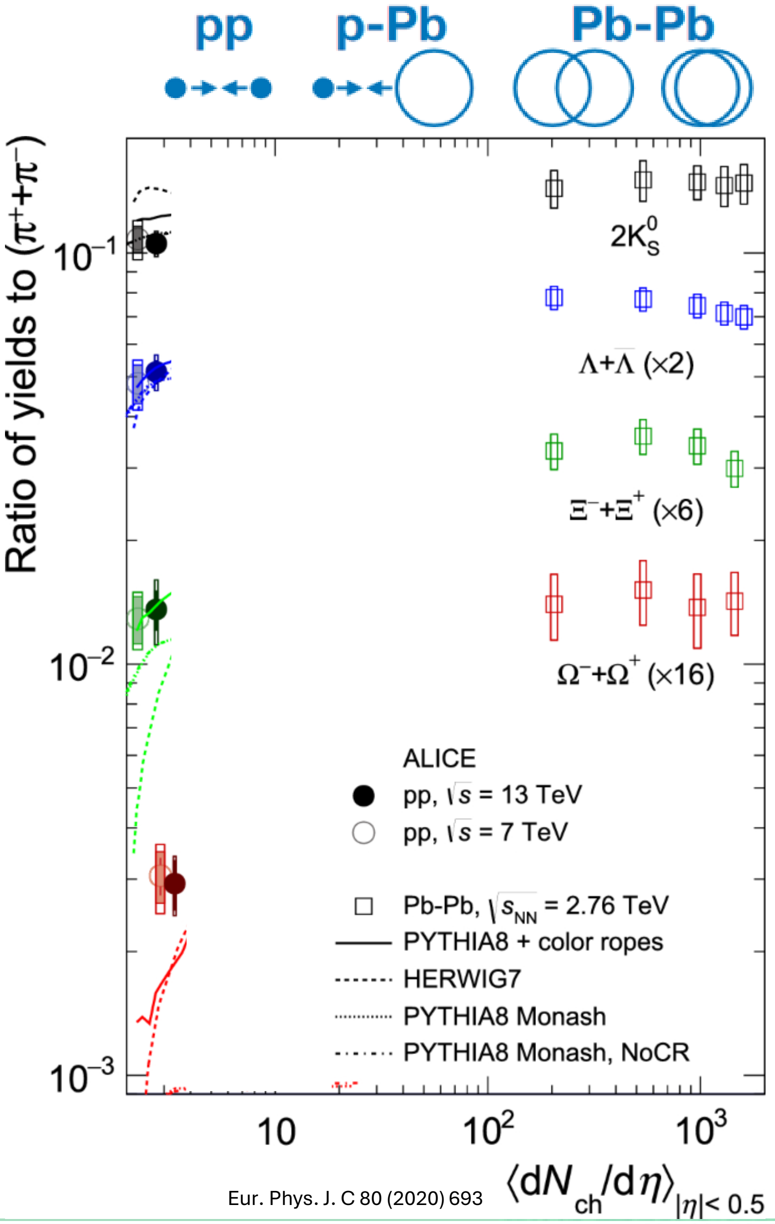
  - Multiplicity: The number of charged particles produced in each collision
- Do we see these signatures at the same charged particle densities?
  - Is the QGP sensitive to the collision system, beam energy, or the produced system?

QGP in proton-proton collisions?

- Strangeness enhancement:



Eur. Phys. J. C 80 (2020) 693

$$K_s^0 = \frac{d\bar{s} + \bar{d}s}{\sqrt{2}}$$

Λ^0 = uds

Ξ^- = dss

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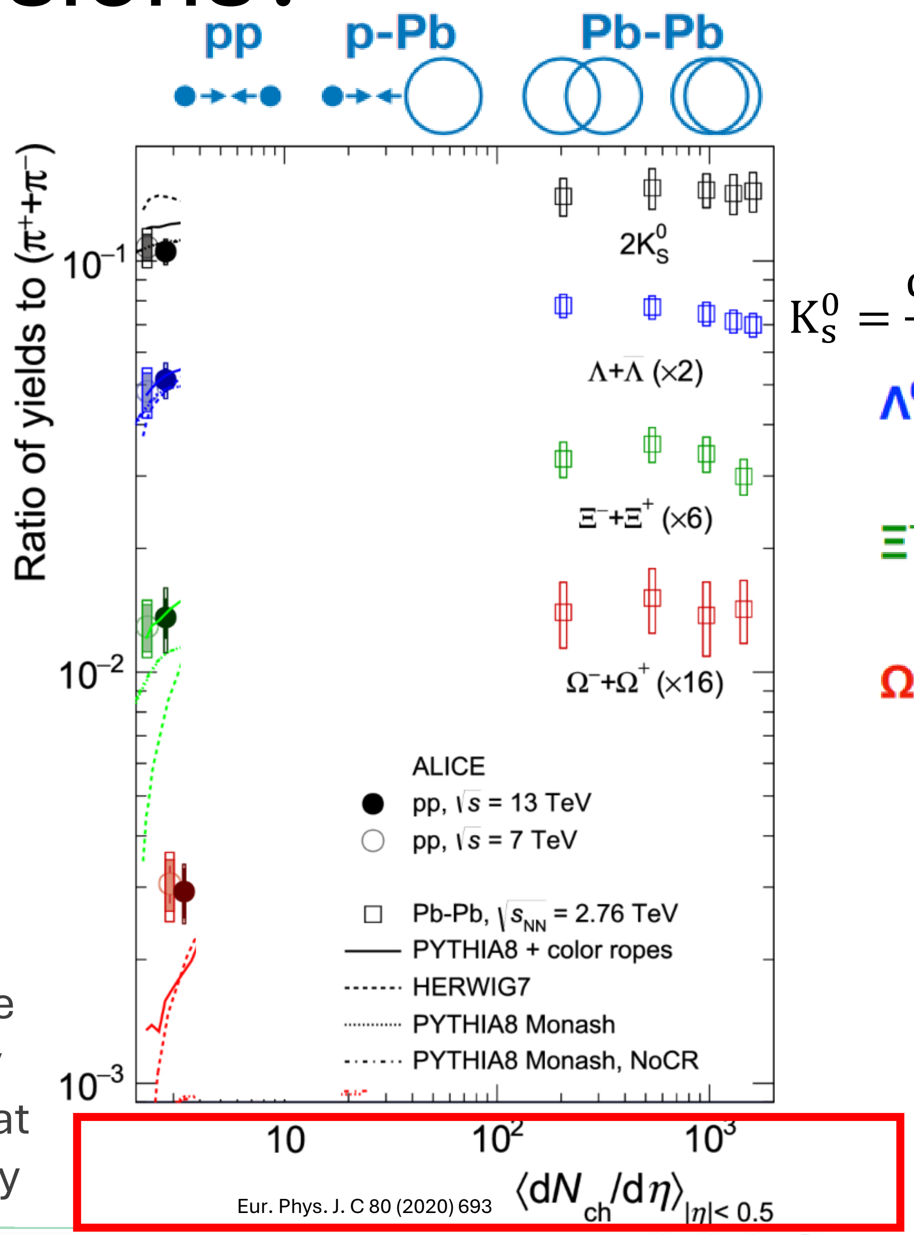

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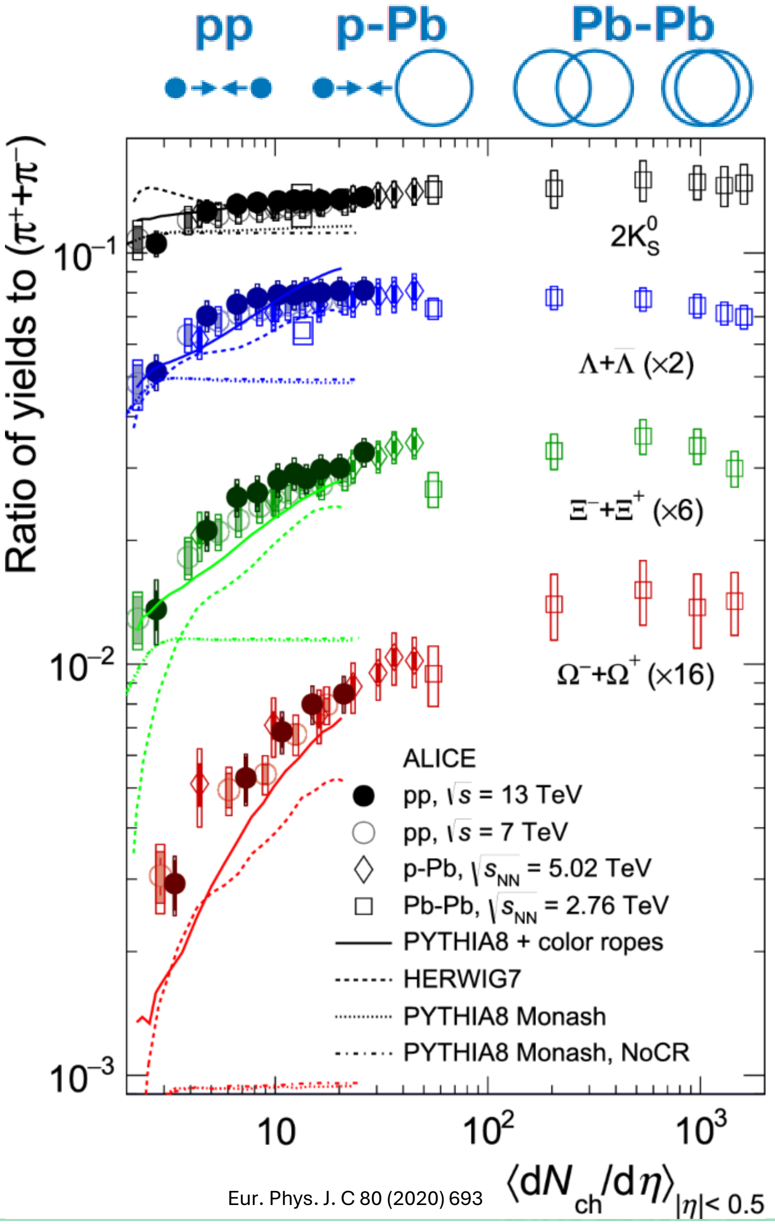
The average multiplicity measured at mid-rapidity

QGP in proton-proton collisions?

- Strangeness enhancement:
  - Actually driven in smaller systems!



Eur. Phys. J. C 80 (2020) 693

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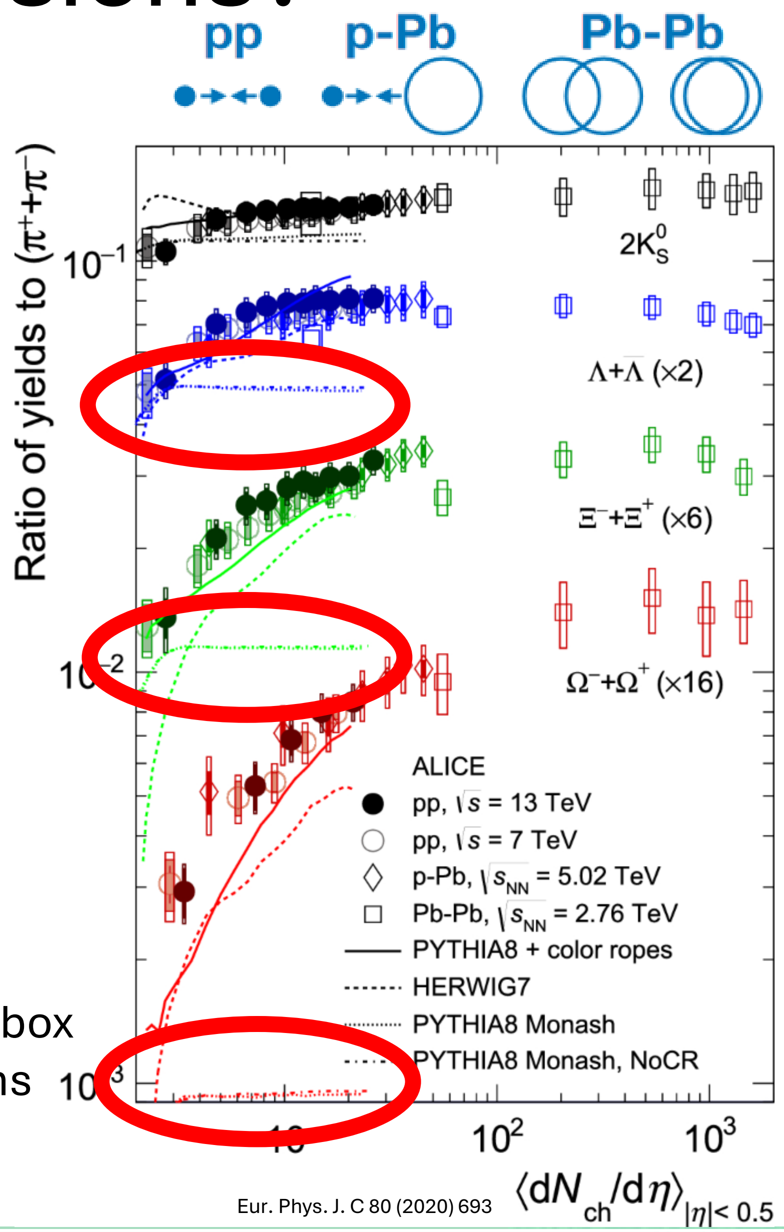

These are out-of-the box PYTHIA8.3 predictions

Eur. Phys. J. C 80 (2020) 693

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- Flow
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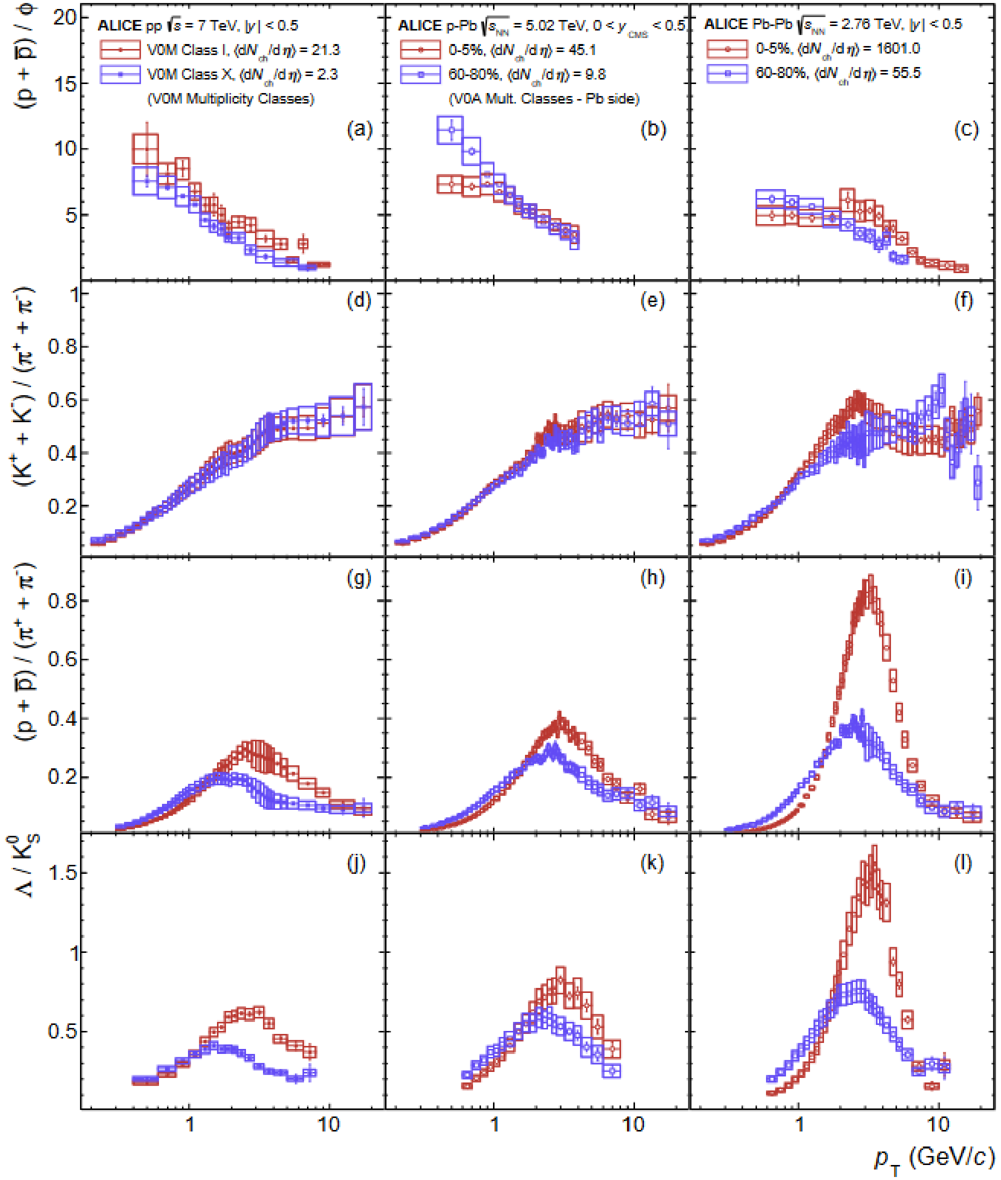
Phys. Rev. C 99, 024906 (2019)



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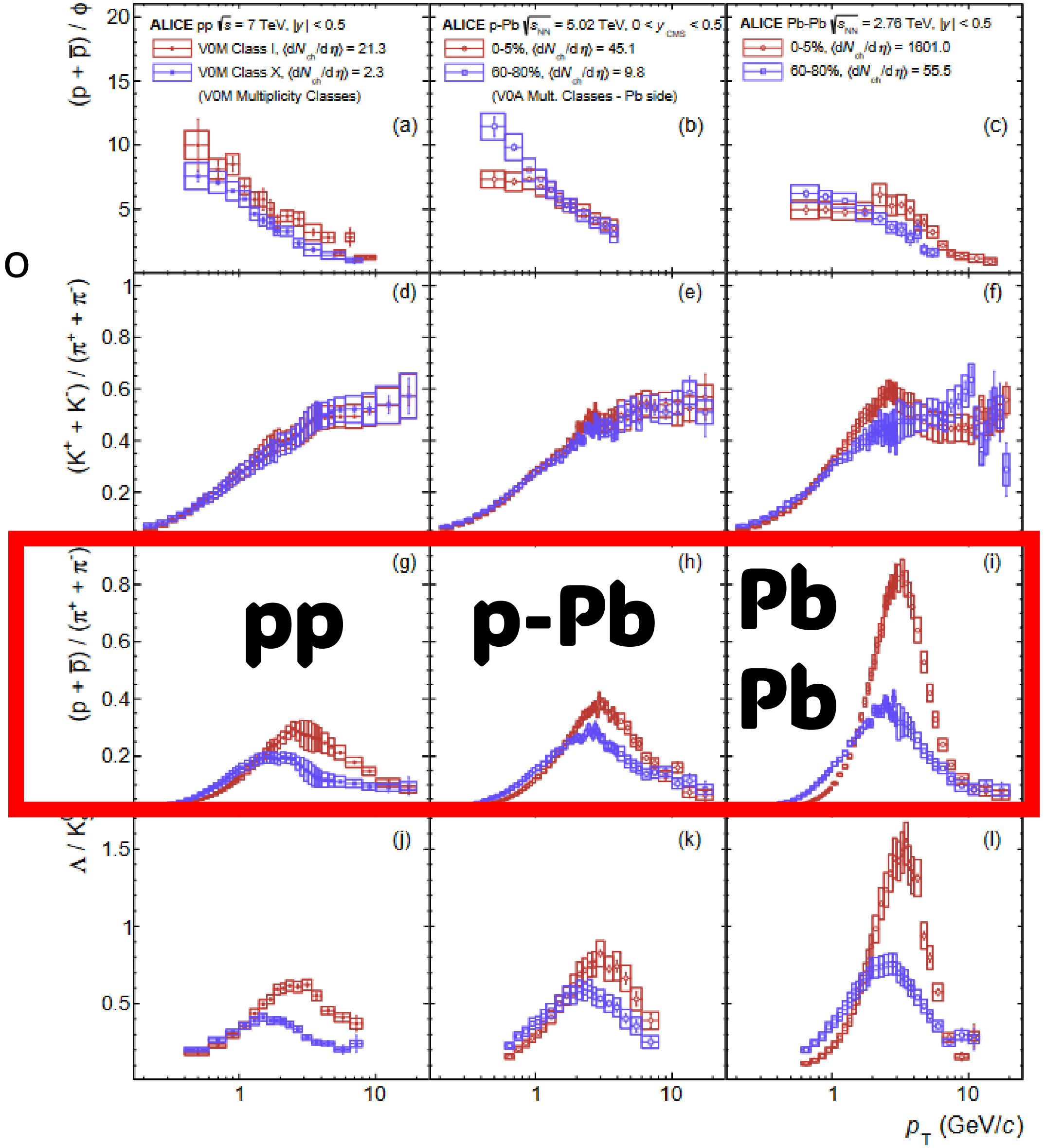
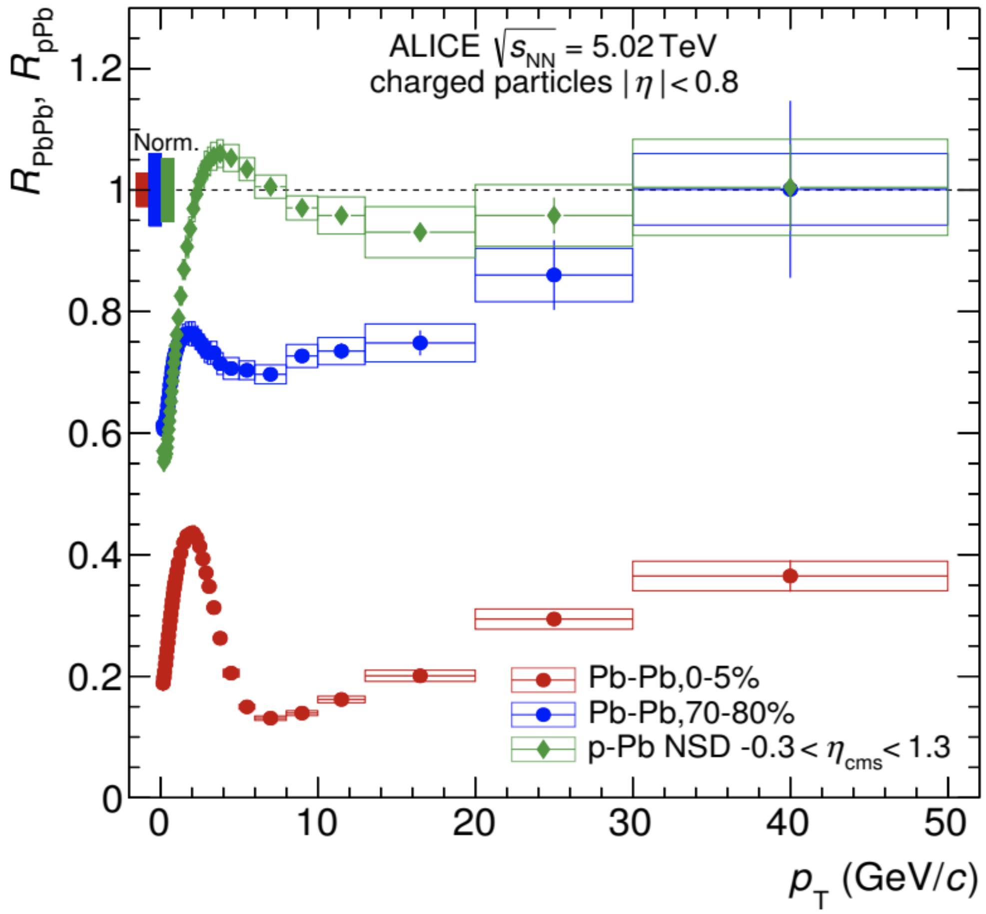


Trying to find unique AA signatures

- Energy loss and jet quenching are still not found in smaller collision systems
  - Inclusive charged hadron p-Pb showcasing no suppression effects

JHEP 11 (2018) 013



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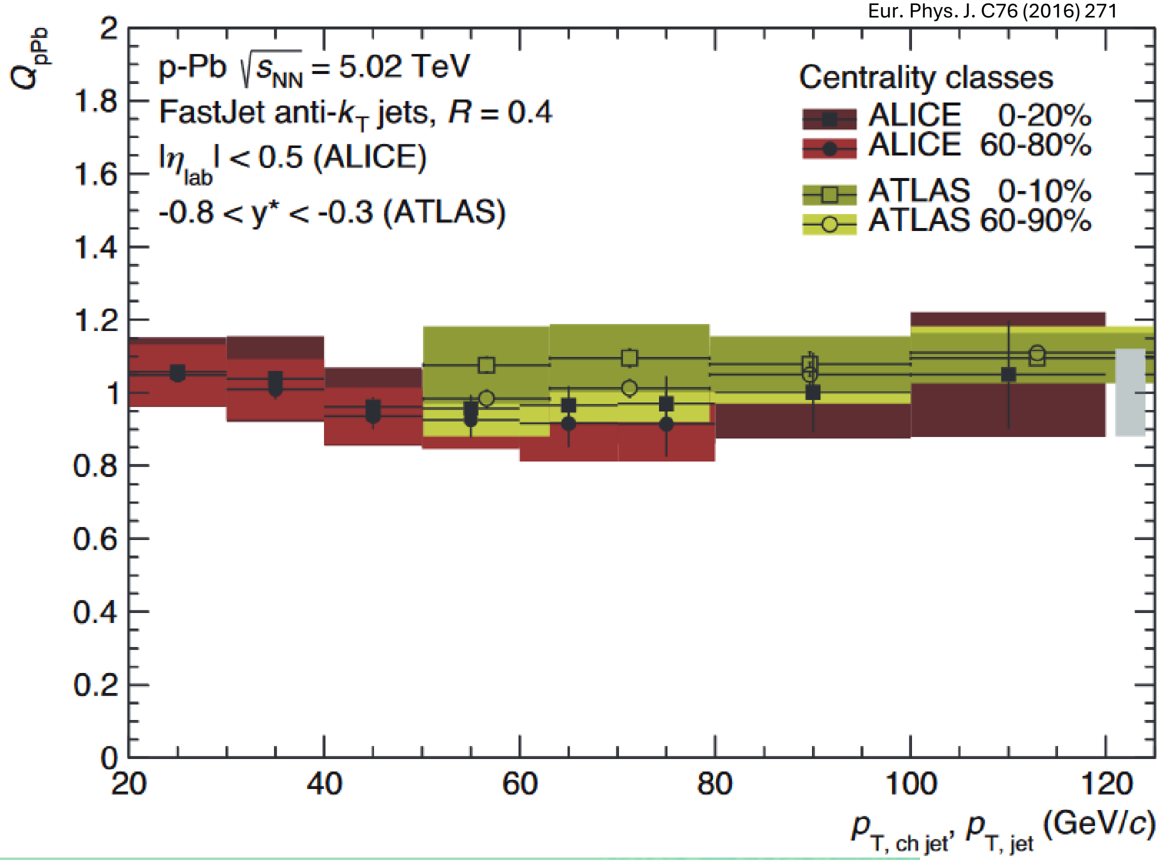
$$Q_{\mathrm{pPb}} = \frac{\mathrm{d}^2 N^c_{\mathrm{pPb}}/\mathrm{d}\eta\,\mathrm{d}p_{\mathrm{T}}}{\langle N^c_{\mathrm{coll}}\rangle \cdot \mathrm{d}^2 N_{\mathrm{pp}}/\mathrm{d}\eta\,\mathrm{d}p_{\mathrm{T}}}$$

Eur. Phys. J. C76 (2016) 271



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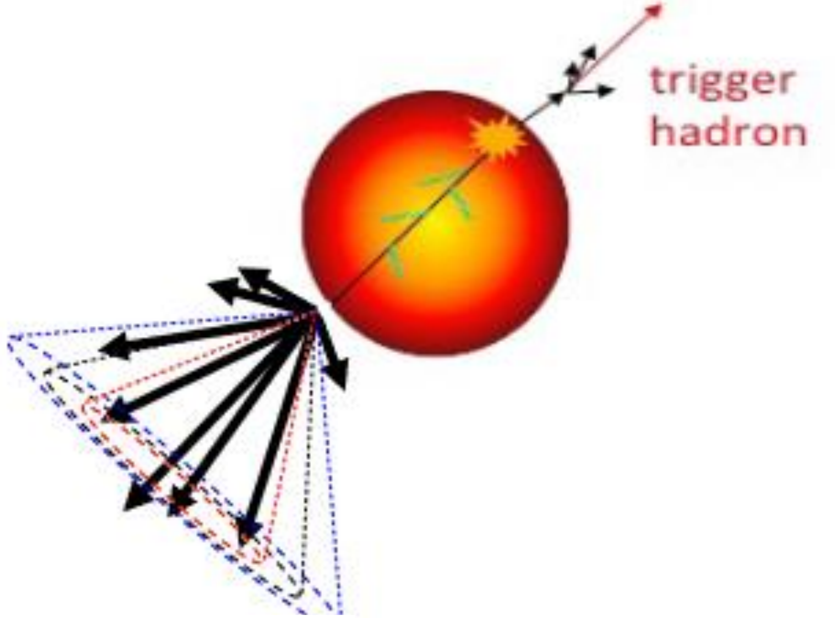

$$\frac{1}{N_{\rm trig}^{\rm pA}} \frac{{\rm d}^2 N_{\rm jet}^{\rm pA}}{{\rm d}p_{\rm T,jet}{\rm d}\Delta\varphi}\Bigg|_{p_{\rm T,trig}} = \left(\frac{1}{\sigma^{\rm pp\to h+X}} \frac{{\rm d}^2\sigma^{\rm pp\to h+jet+X}}{{\rm d}p_{\rm T,jet}{\rm d}\Delta\varphi} \right)\Bigg|_{p_{\rm T,trig}} \times \frac{T_{\rm AA}}{T_{\rm AA}}$$

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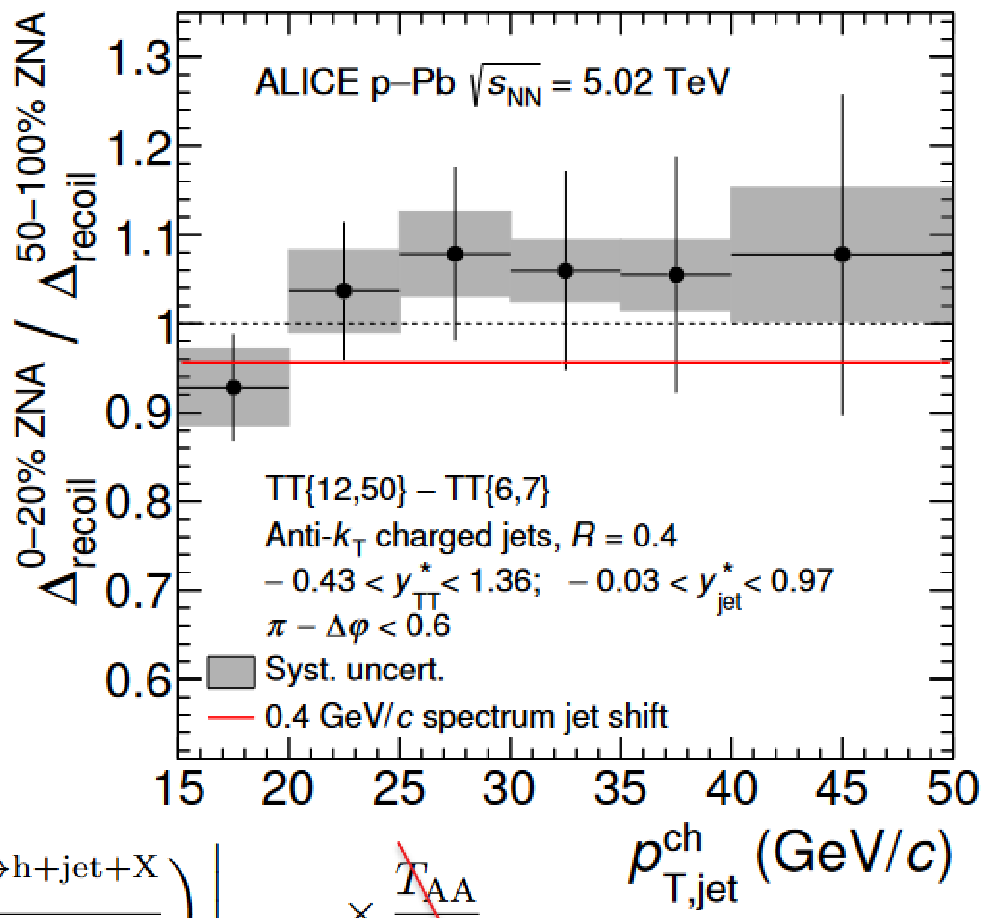
Phys. Lett. B 783 (2018) 95



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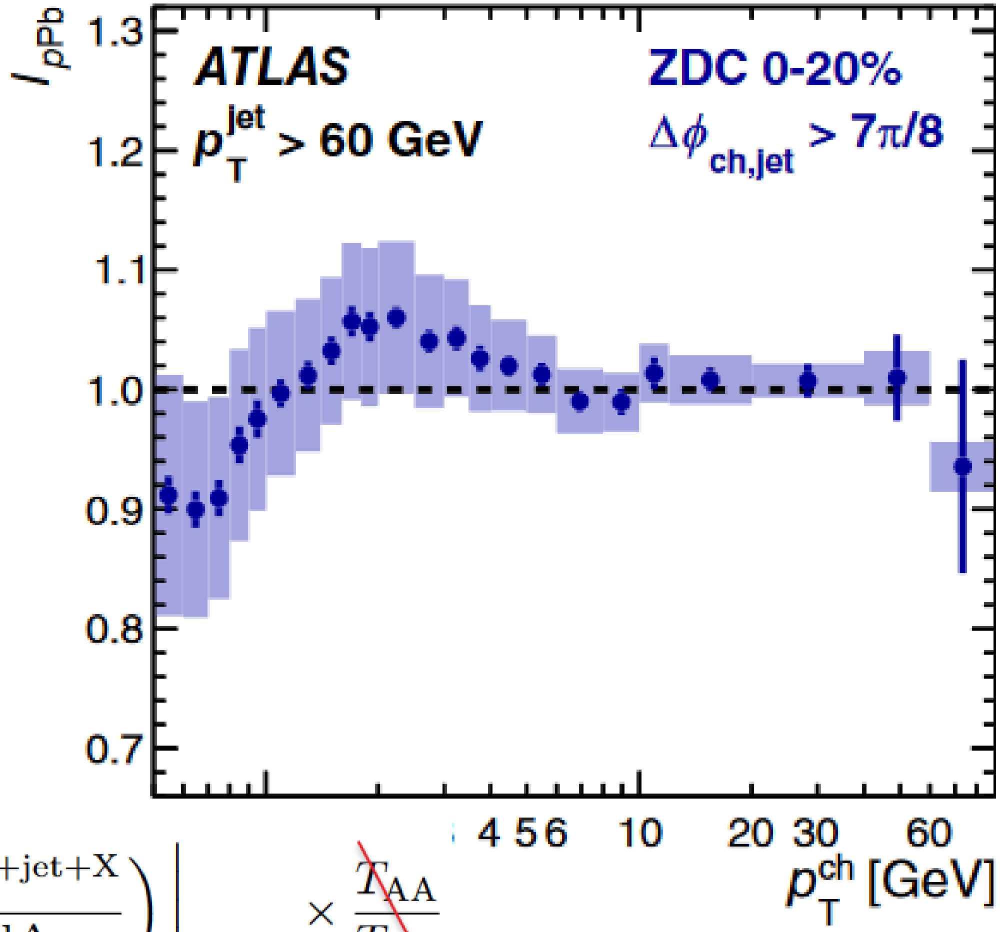
Phys. Rev. Lett. 131 (2023) 072301



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More precise & differential measurements

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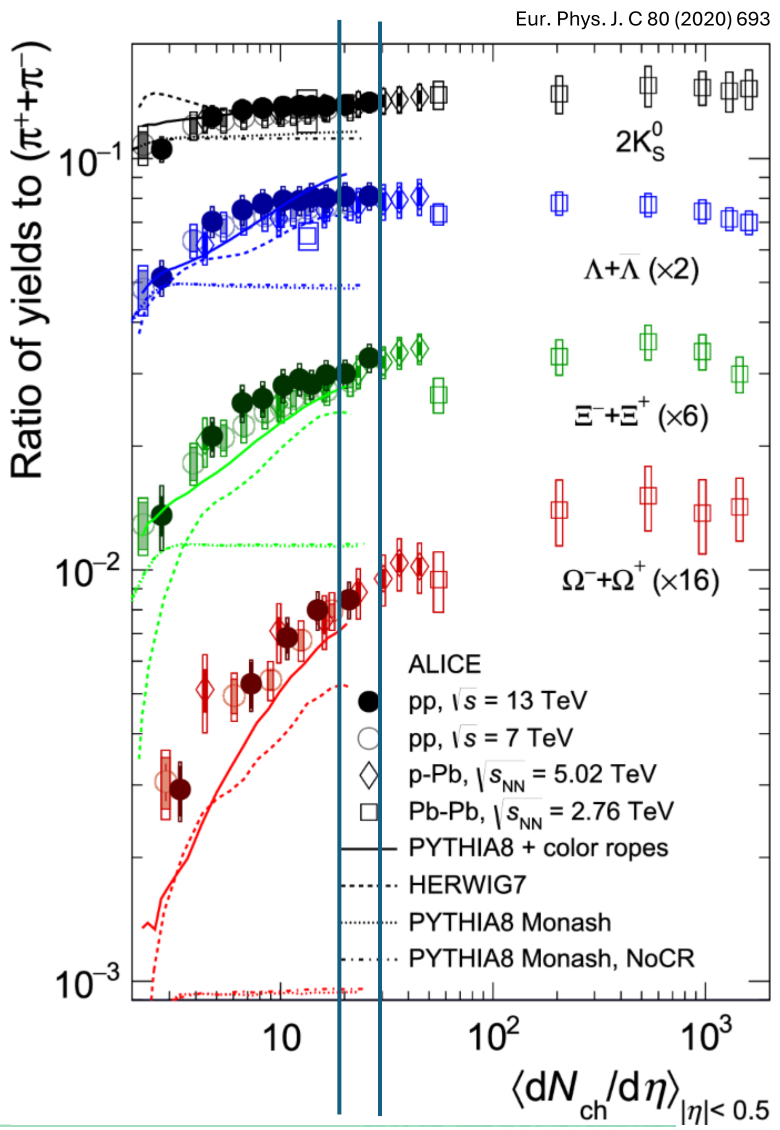

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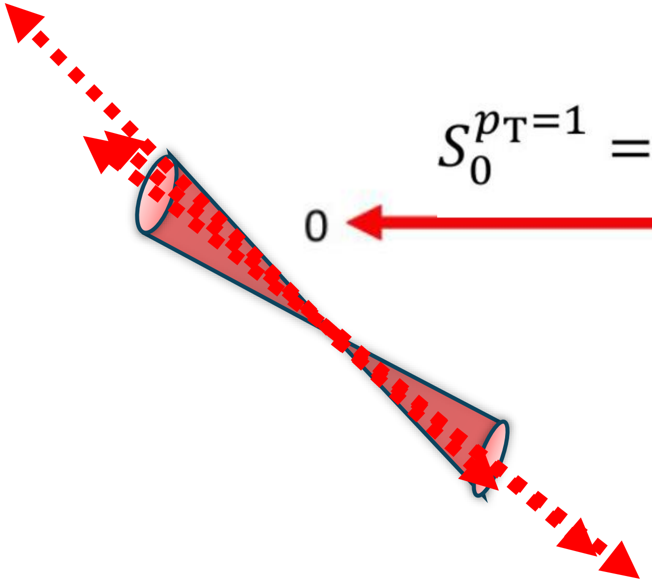
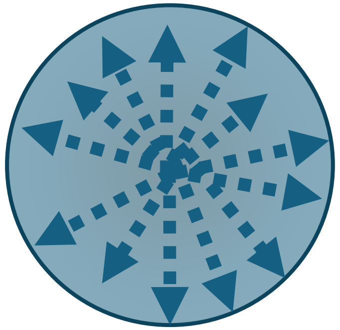
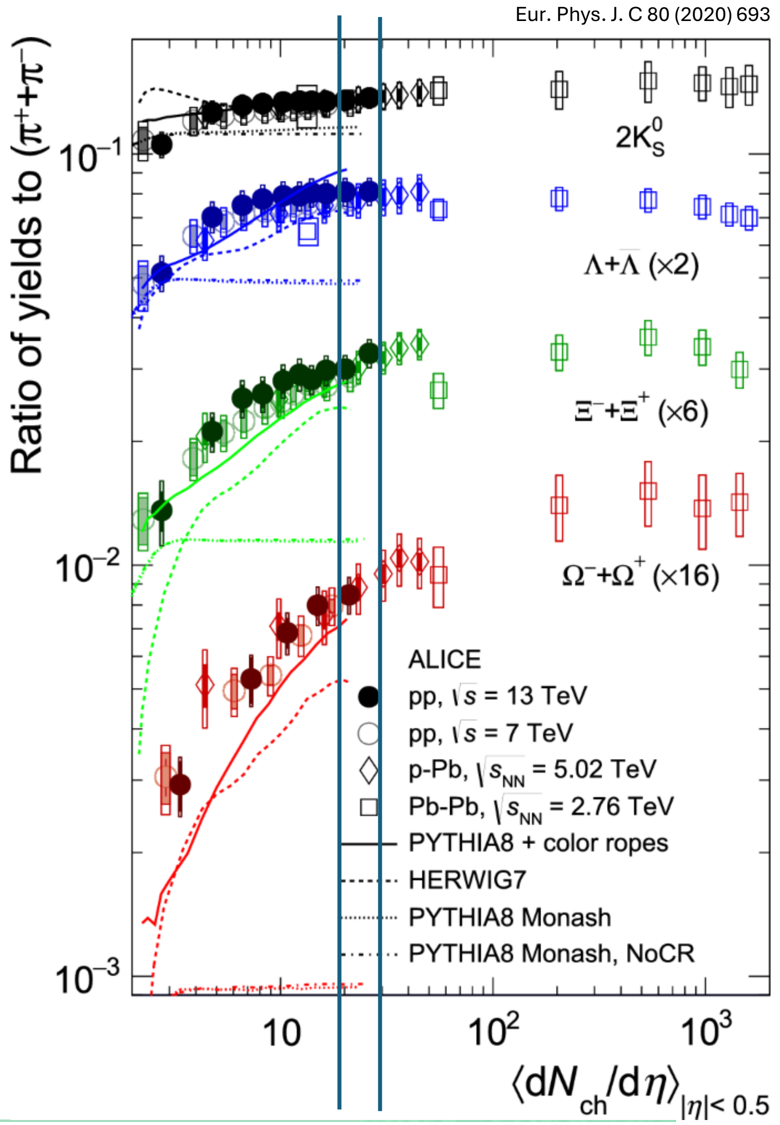


$$S_0^{p_T=1} = \frac{\pi^2}{4} \min_{\hat{n}} \sum_i \left(\frac{|\hat{p}_{T,i} \times \hat{n}|}{N_{trk}} \right)$$

0 ← → 1





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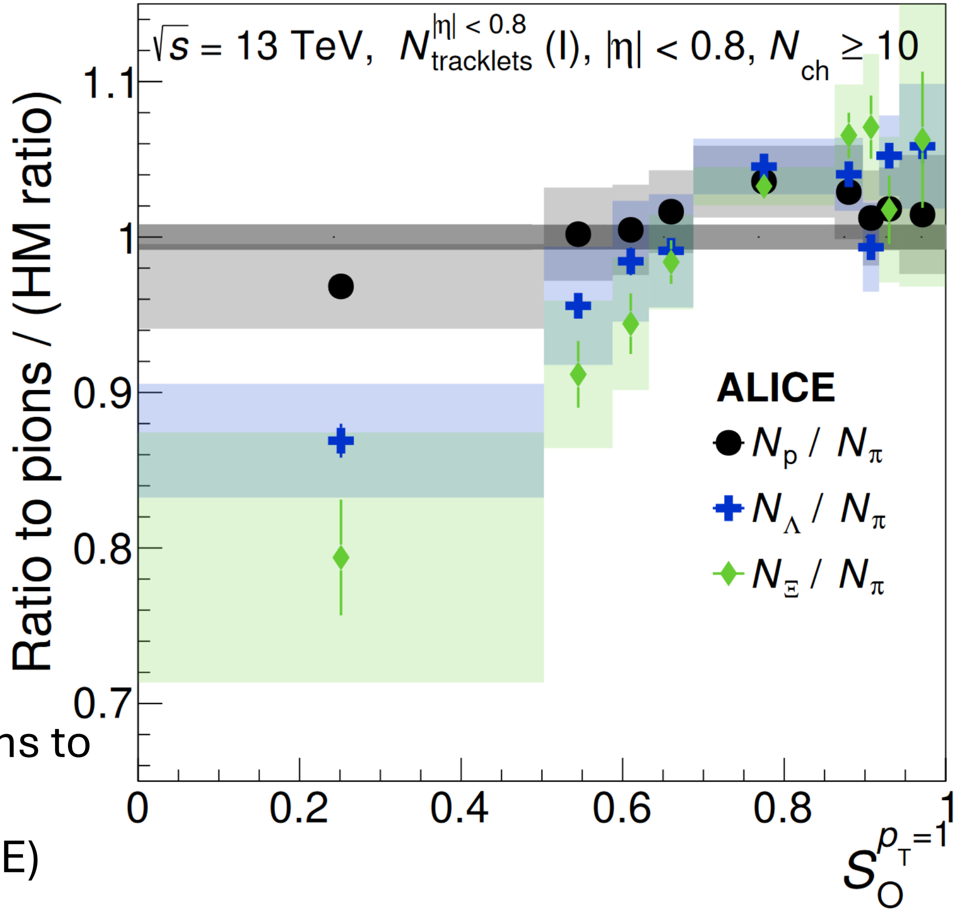

Strangeness enhancement seems to be prevalent in the underlying event (UE)

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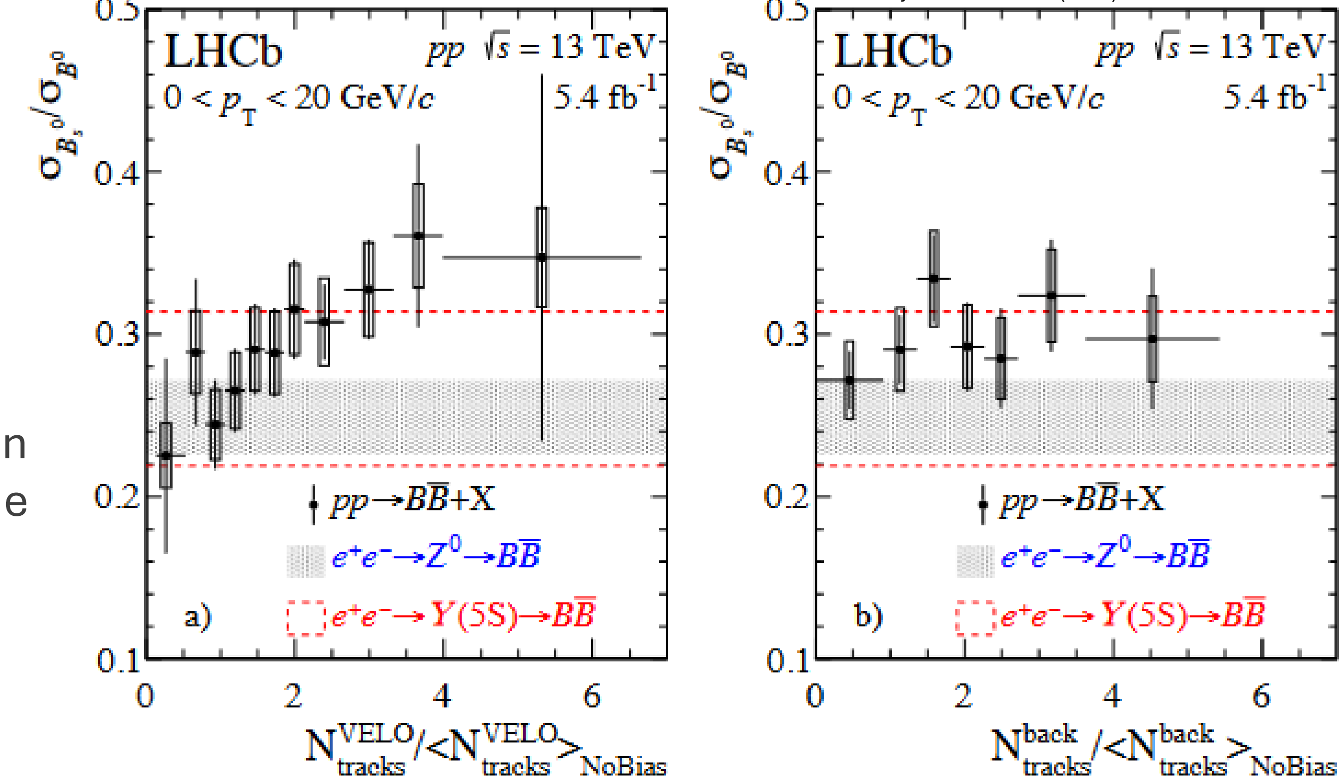
Significant enhancement of B_s/B^0 production

However, enhancement is only seen when multiplicity is measured in the same pseudorapidity region

Phys. Rev. Lett. 131 (2023) 061901



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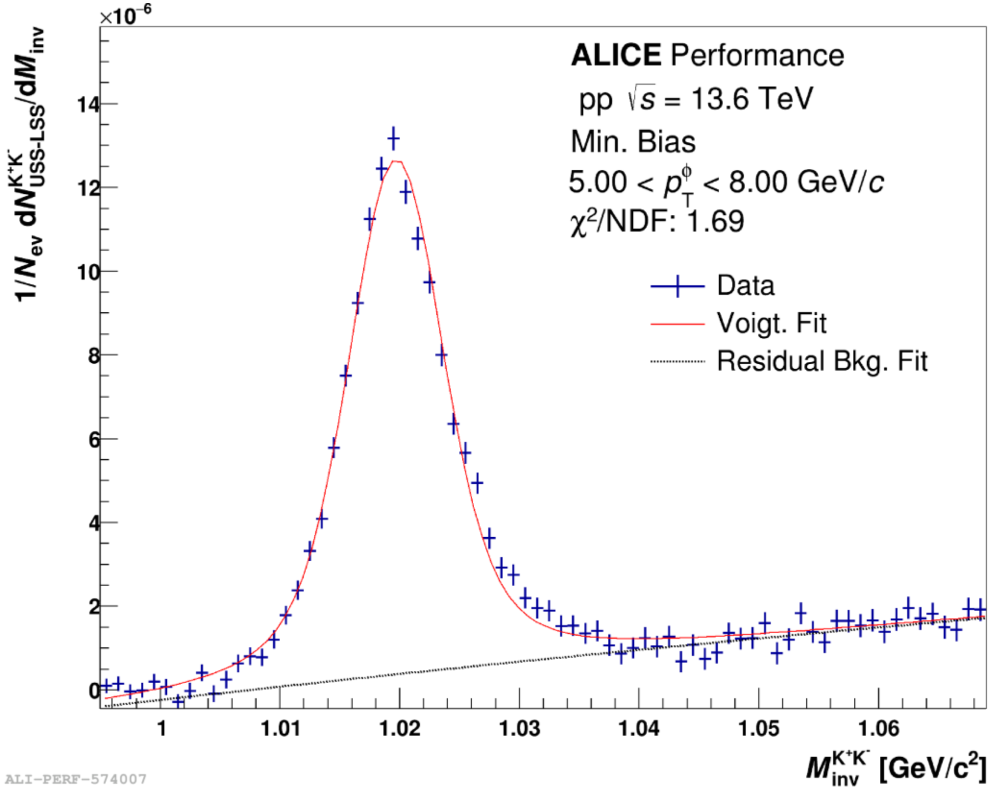
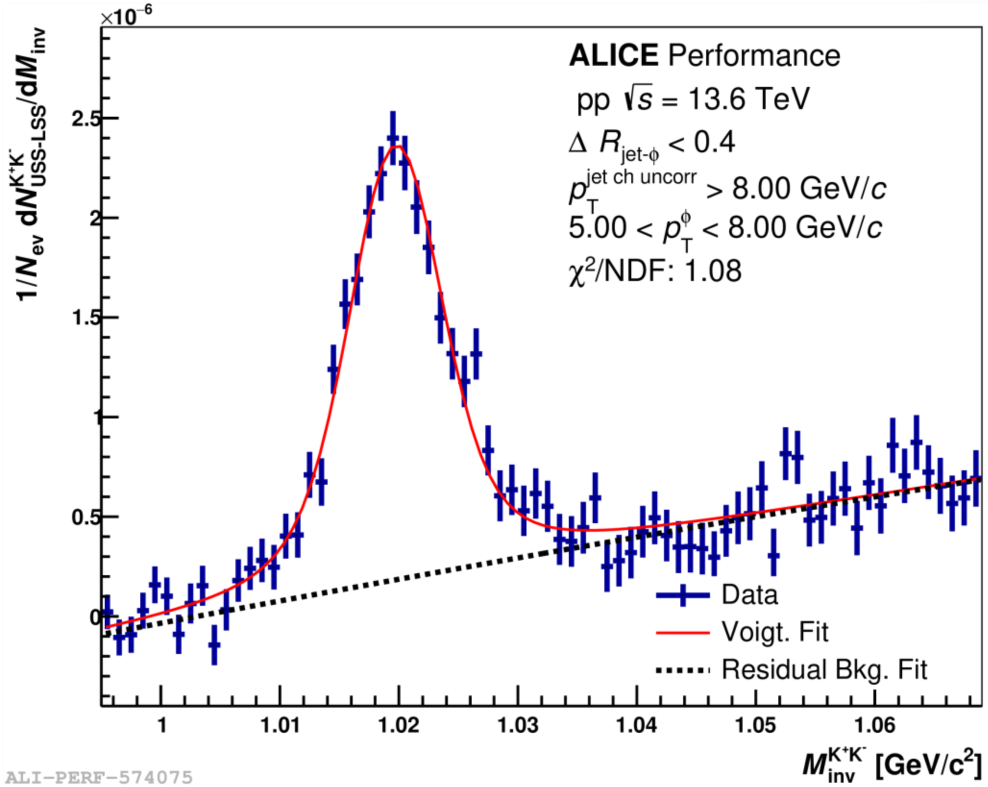
Run 3 data allows for resonance-inside jet analyses due to increased statistics, more to come!





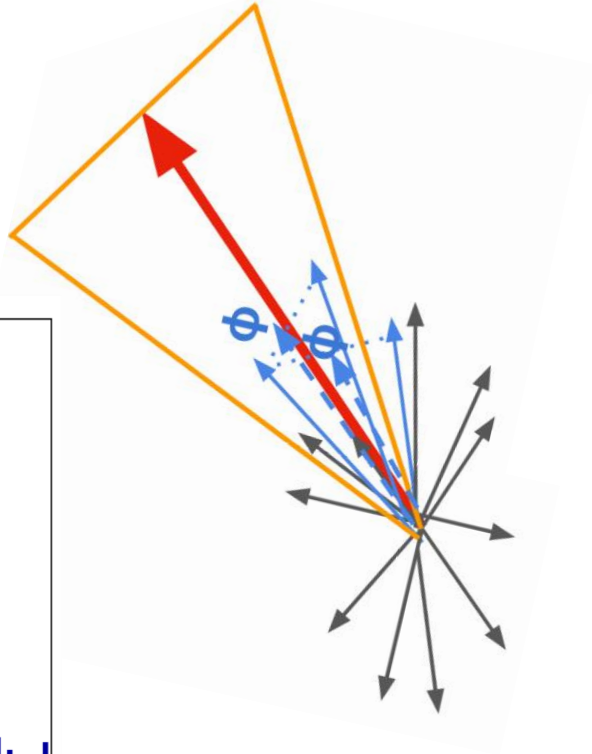
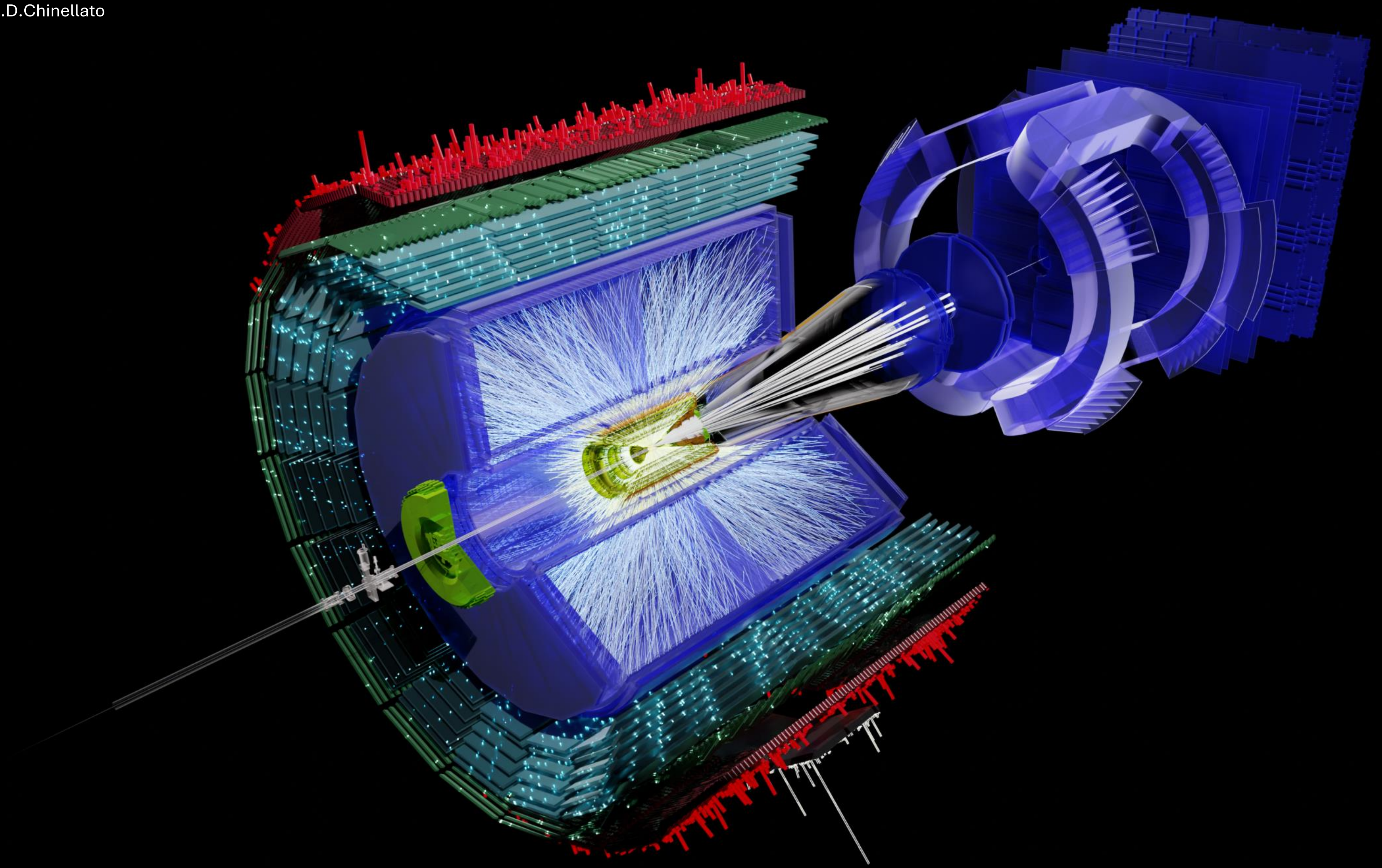


Figure by
D.D.Chinellato



ALICE

Pb – Pb Run 3

$\sqrt{s_{NN}} = 5.36$ TeV

ALICE is running
Run 3 triggerless!

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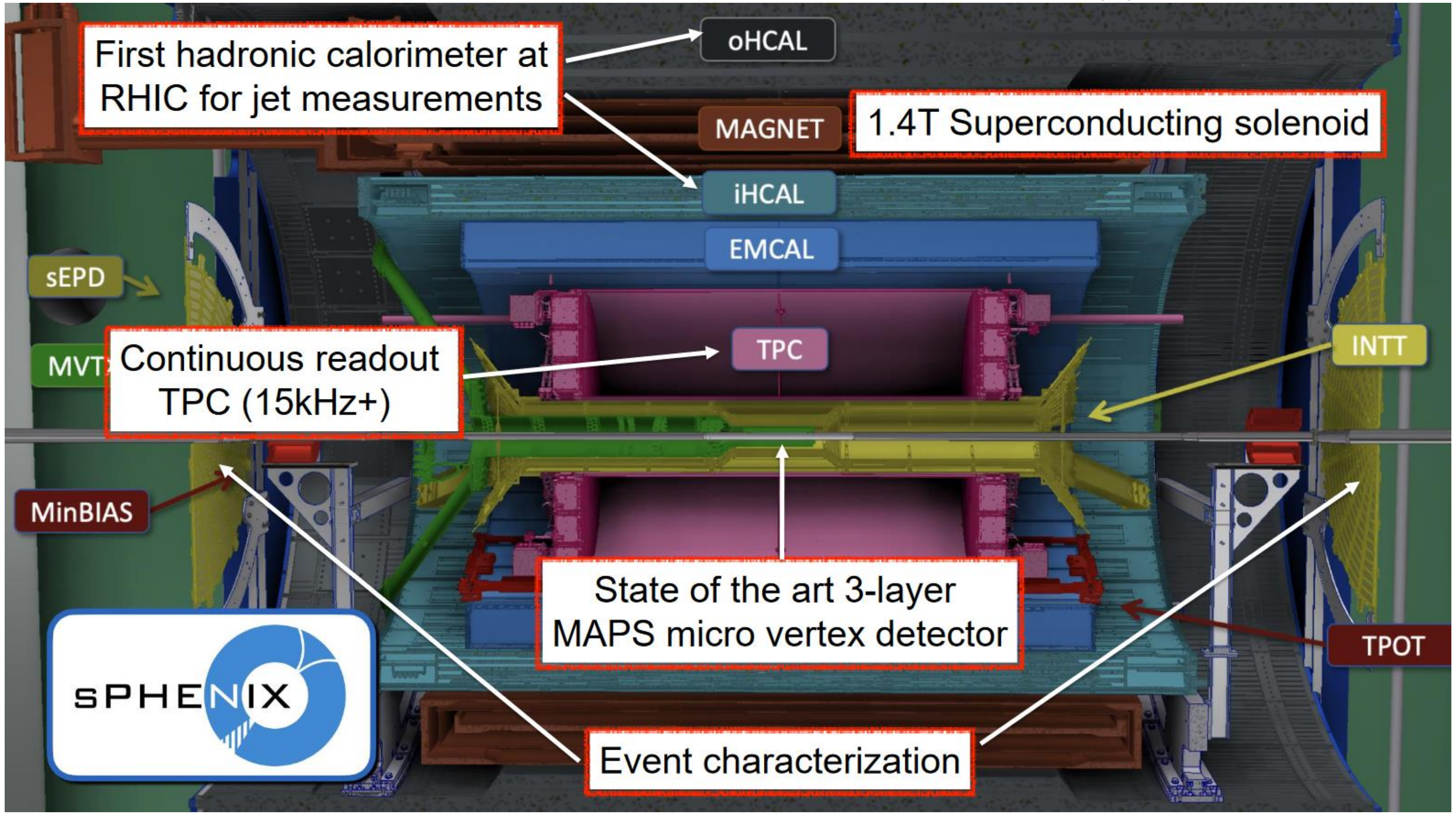
sPHENIX program:
Dedicated Jet detector!

Will be able to probe hard physics in AA collisions at RHIC

R. Nouicer, *sPHENIX highlights: First Results From sPHENIX*, SQM 2024



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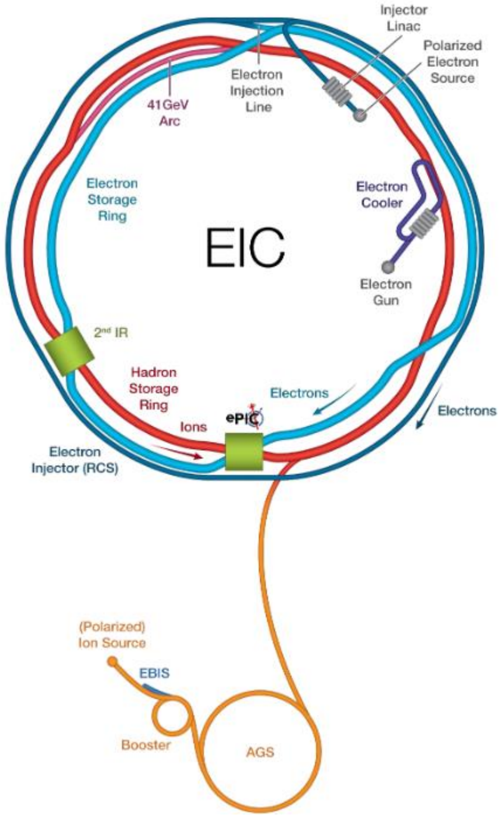

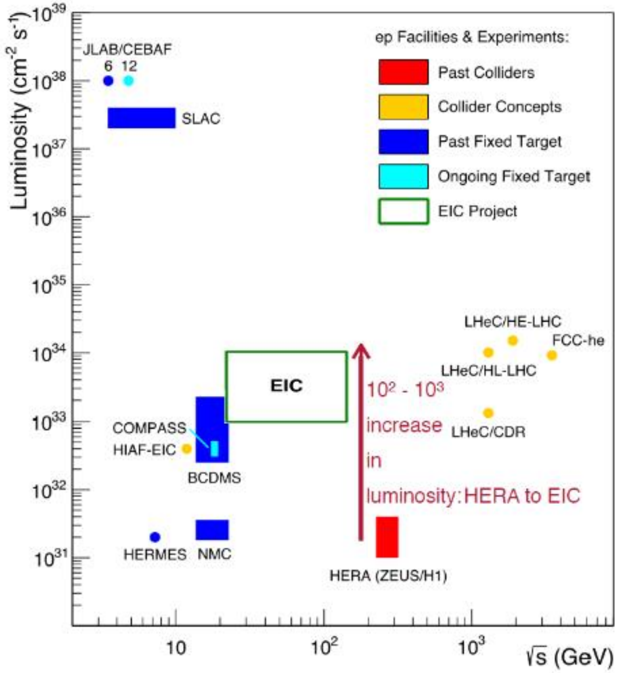

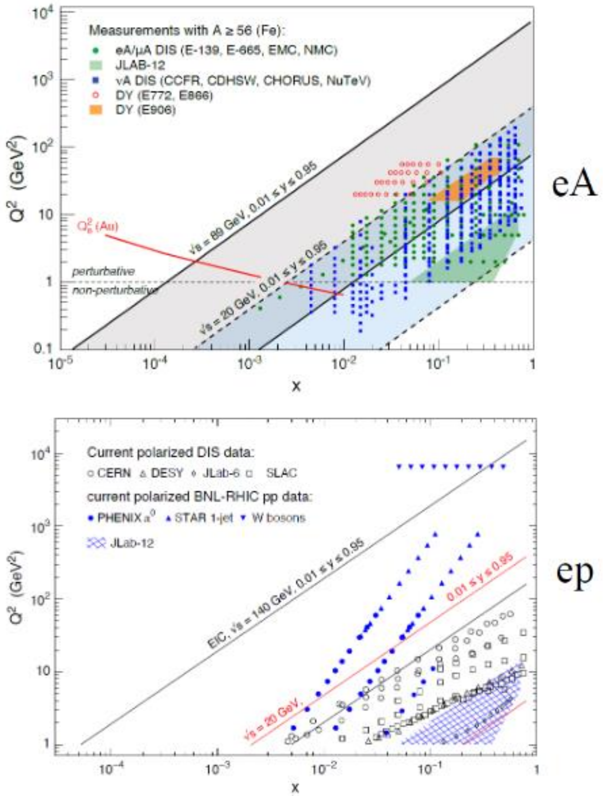

EIC:
Will be able to truly probe hard QCD phenomena

Low-x and low-Q machine

Can study QED processes between hadrons and electrons

C.M.Camacho, *Physics program and detector technologies of ePIC at EIC*, SQM 2024

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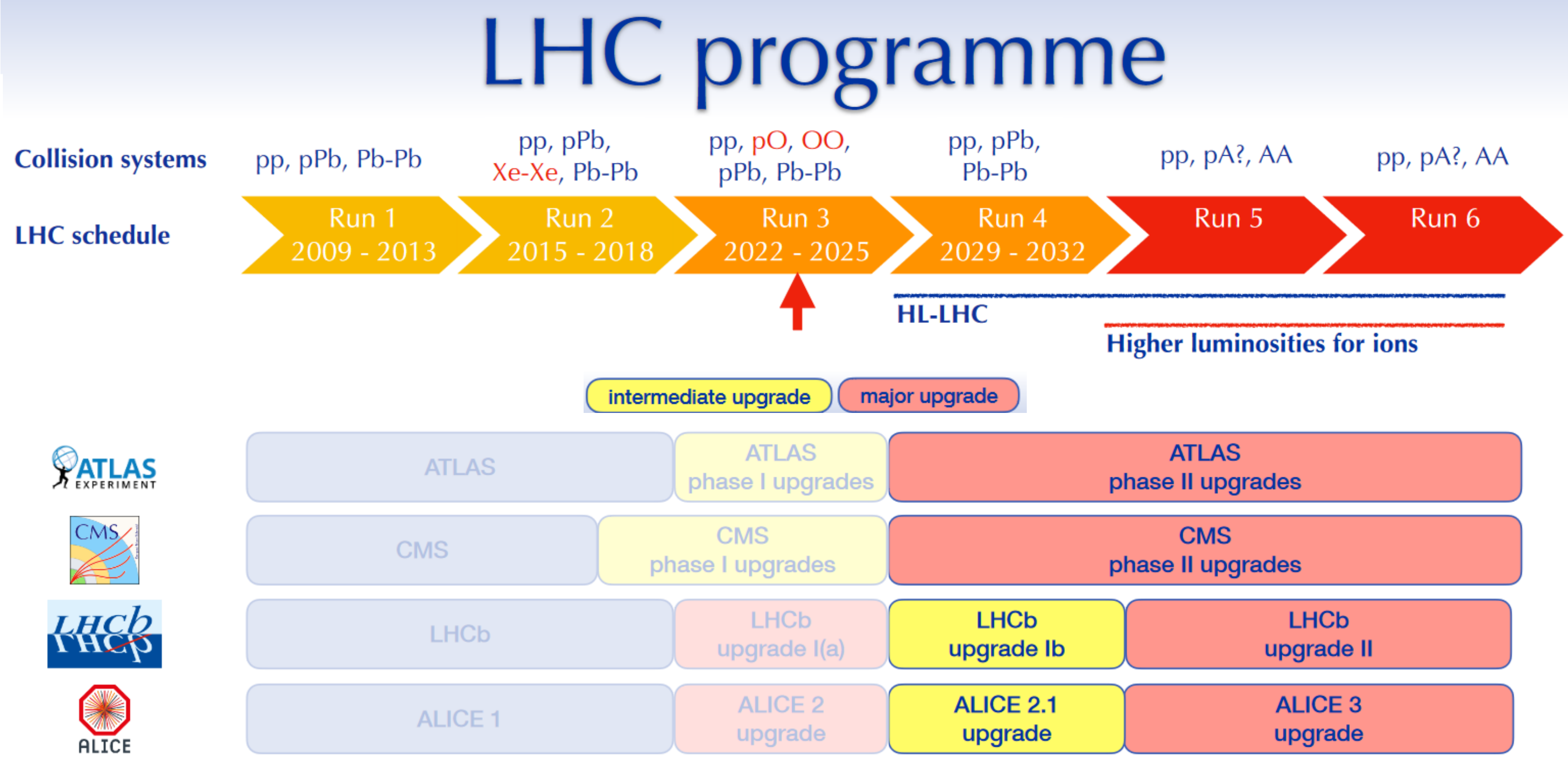
J. Klein, *LHC Upgrades*, SQM 2024



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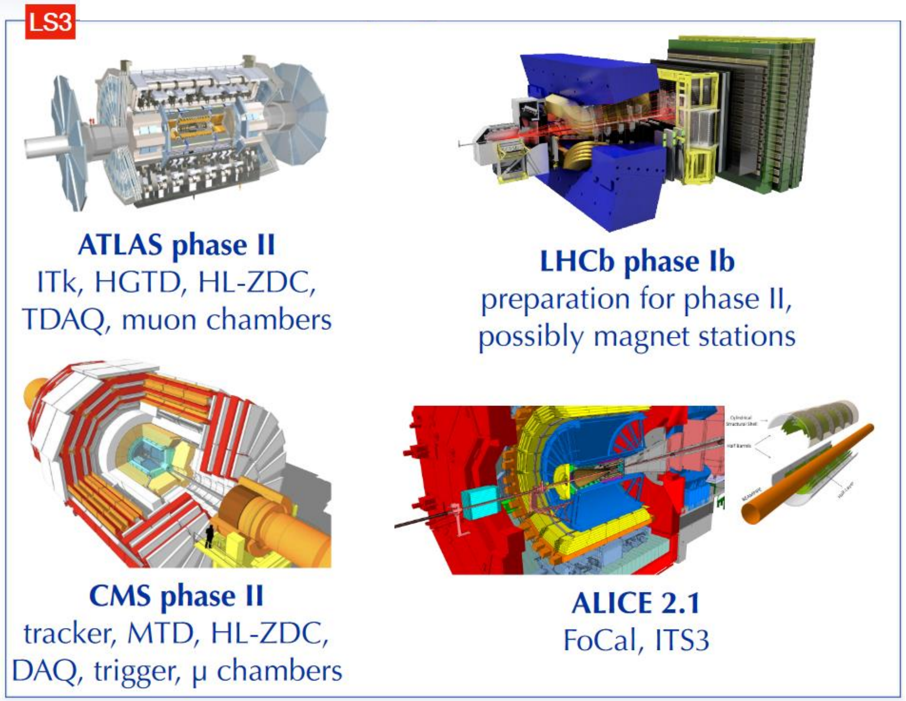

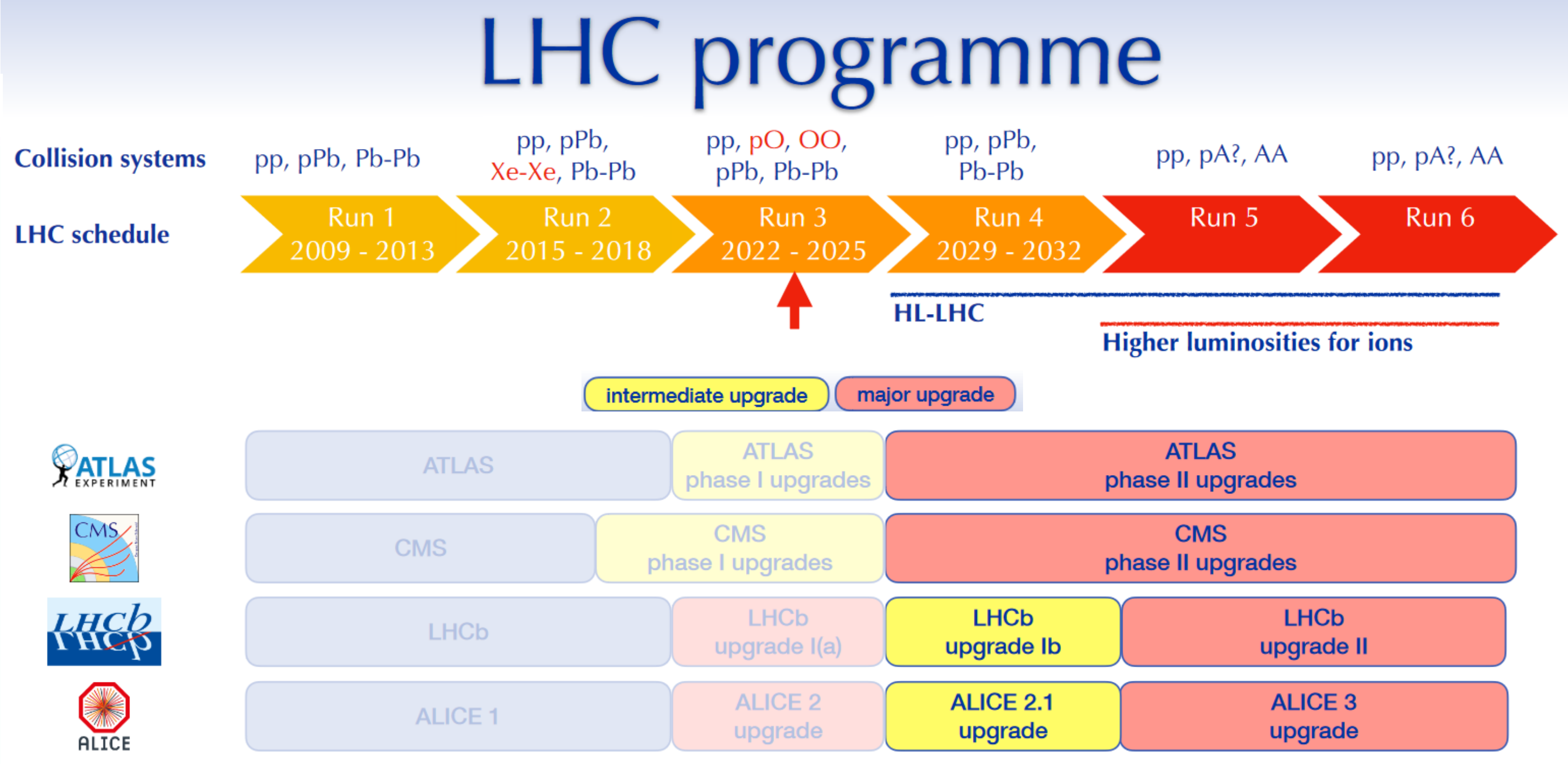

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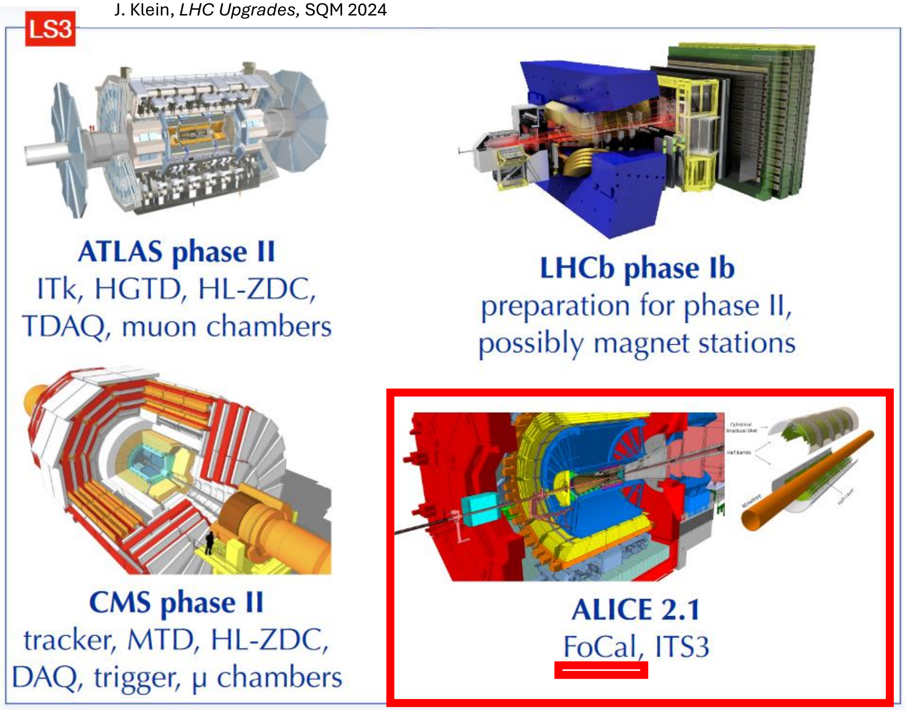
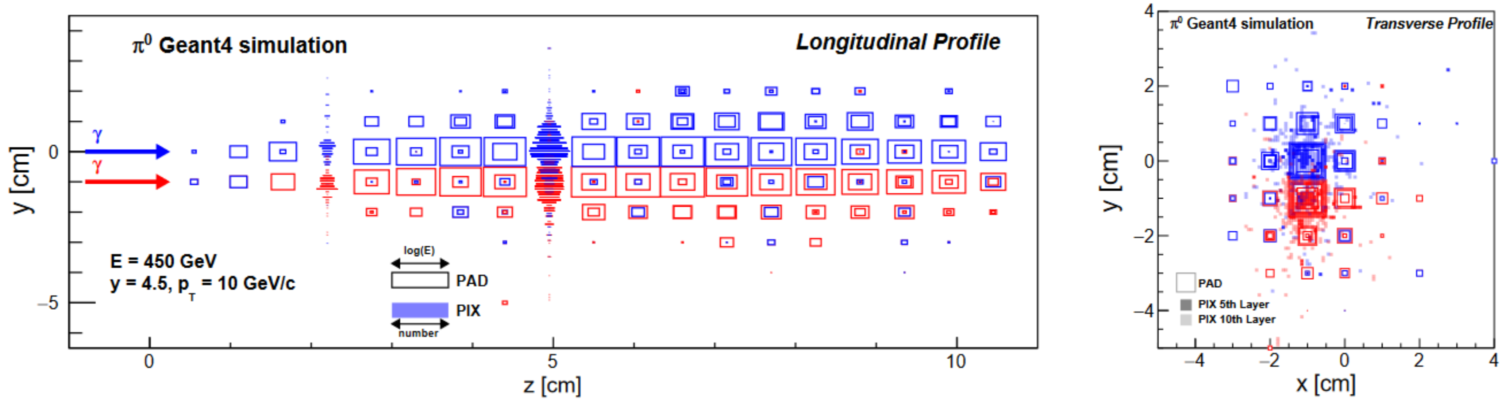
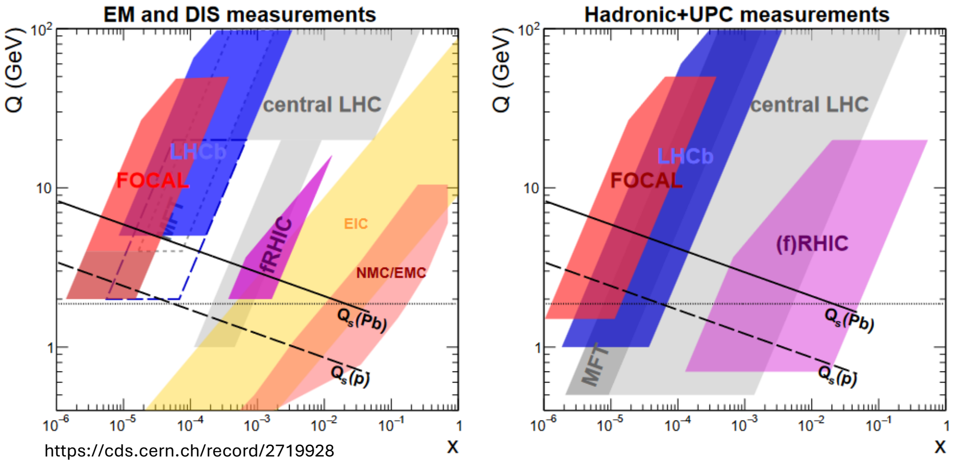


https://cds.cern.ch/record/2890281





https://cds.cern.ch/record/2719928

FoCal: Ability to probe extremely small x at large Q

Will put heavy experimental constraints on QCD

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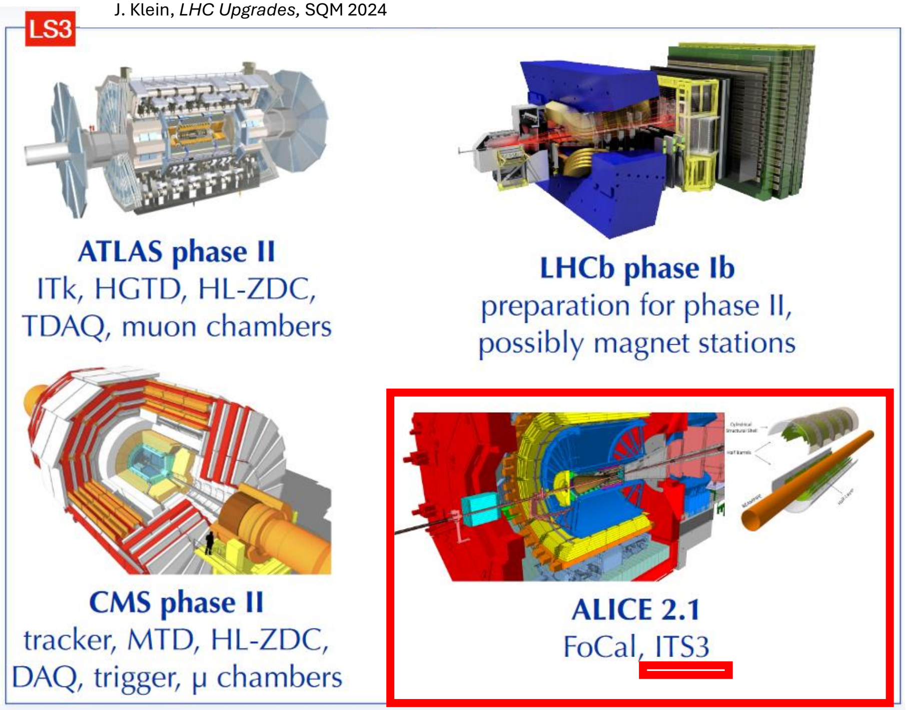
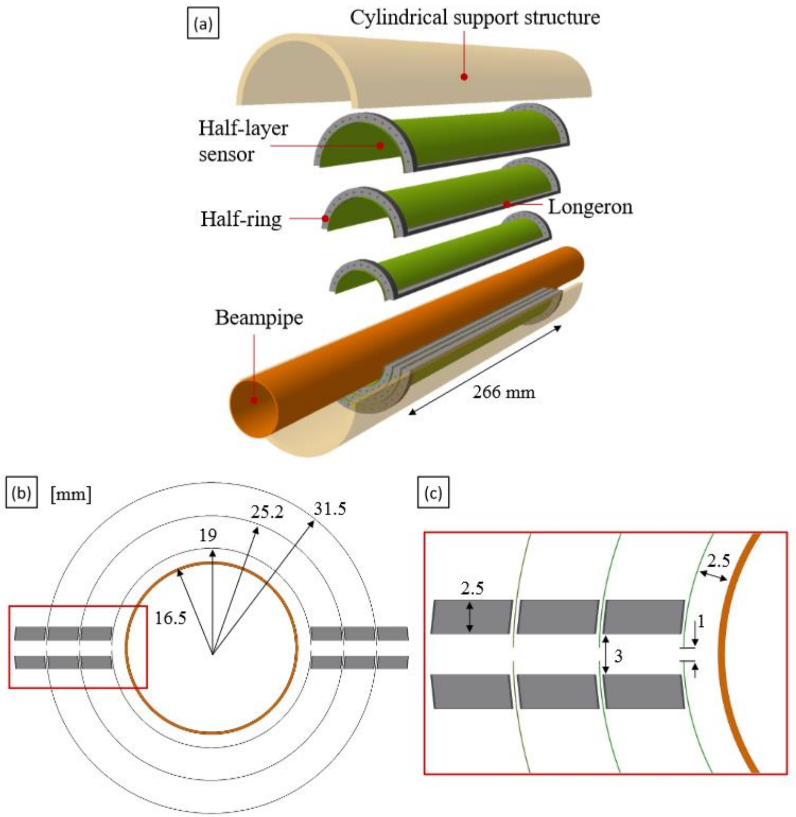
J. Klein, *LHC Upgrades*, SQM 2024



Extremely close to beampipe, 0.05% X_0 per layer

Increases tracking and momentum resolution

https://cds.cern.ch/record/2890181



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- Even in pp collisions, current implementations of QCD-inspired models cannot reproduce the observed data
  - Requires novel, heavily phenomenological features and correlations to be placed in by hand, after the initial state is generated
- Further work is performed in the field to really try to discriminate and estimate where we can “turn off” these QGP-like effects.
  - Future precision results from Run3/Run4, and eventually ALICE3, will help to elucidate the origin of these different effects