CERN:

Present and Future
High-Density QCD Programme

Jan Fiete Grosse-Oetringhaus (CERN)

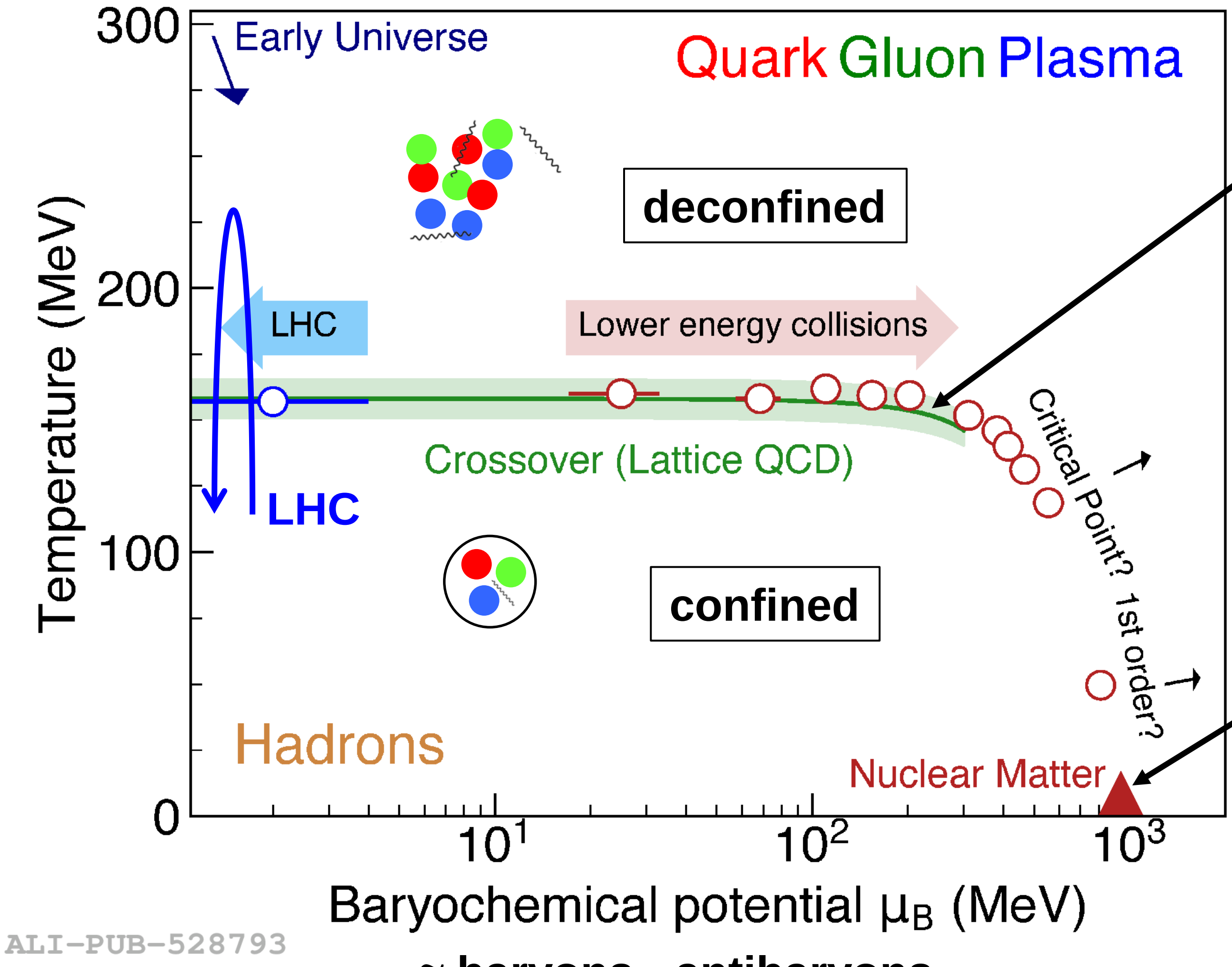
Present and future perspectives in Hadron Physics

18.06.2024

Content:
- **Key Concepts**
- **QGP Key Properties**
- **Hadronization**
- **Short-term future: Run 3 and 4**
- **Long-term future: Run 5 and 6**

Concepts

QCD Phase Diagram



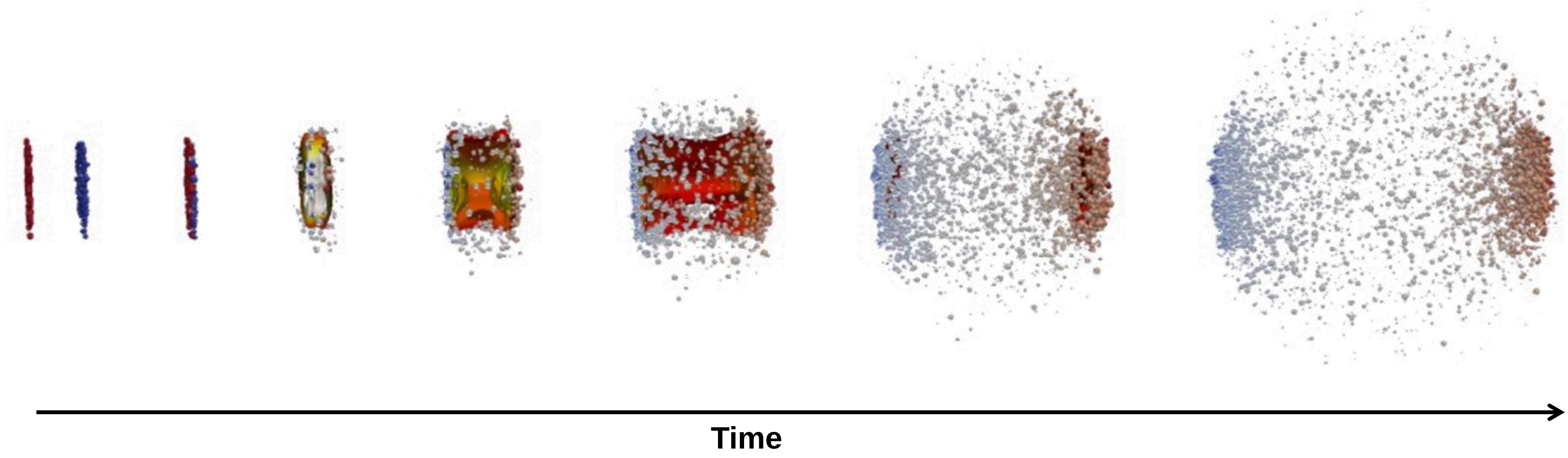
Phase transition

"We" are here

≅ baryons - antibaryons

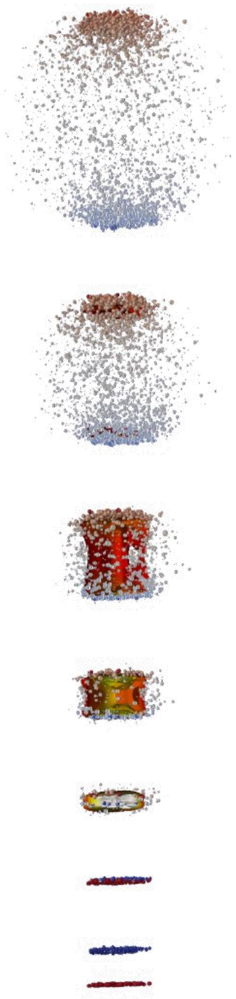
adapted from
arXiv:2211.04384

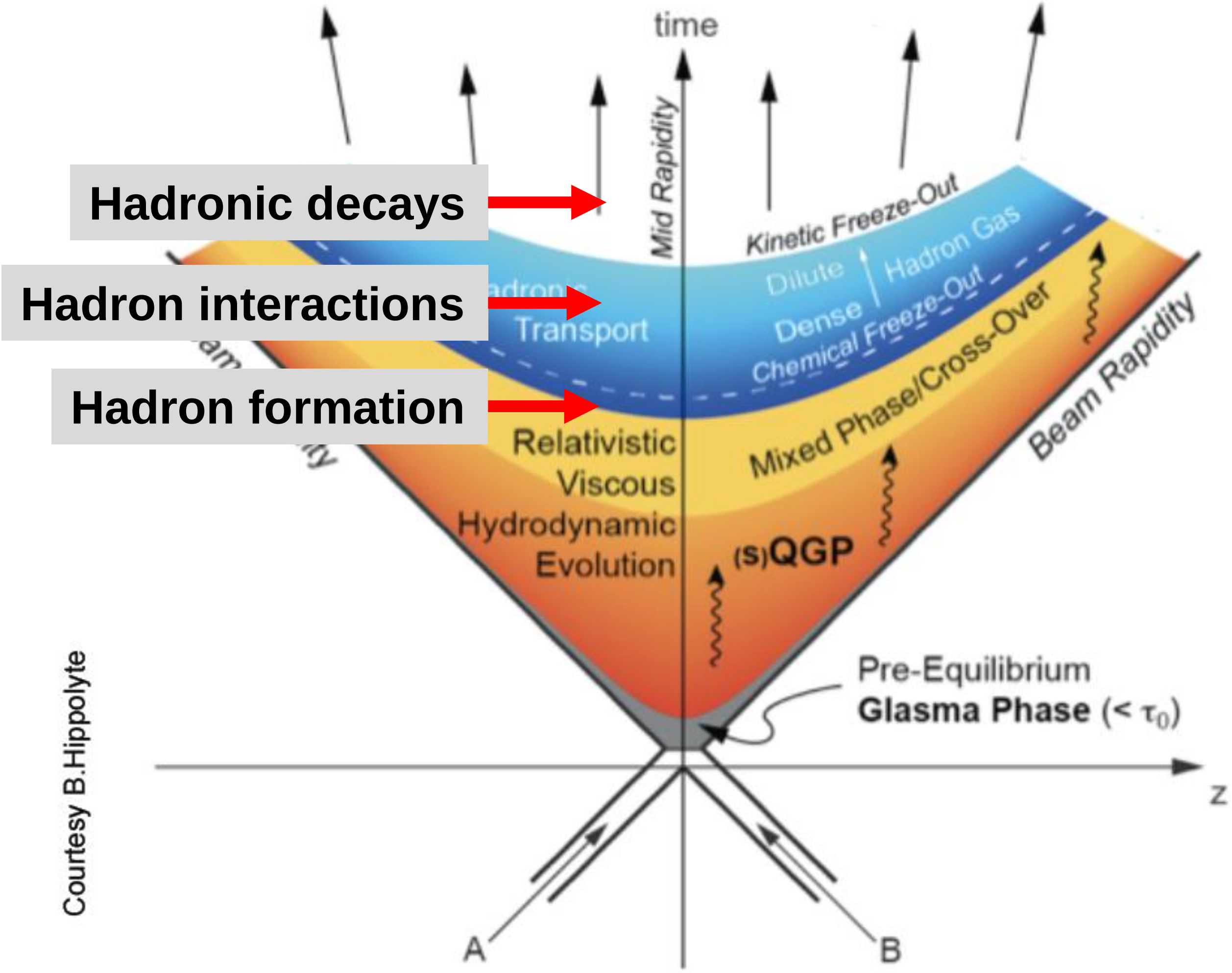
Heavy-Ion Collision, conceptually…



MADAI collaboration

Heavy-Ion Collision, conceptually…





Time

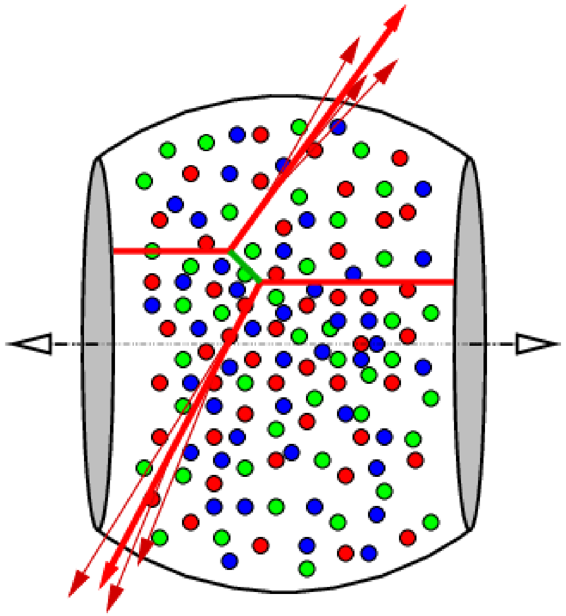
particle detection	**t = 3 cm/c**
kinetic freeze-out	**t = 10 fm/c**
chemical freeze-out hadronization	
hydrodynamic evolution	
pre-equilibrium	**t = ~1 fm/c**
collision	**t = 0 fm/c**

1 fm/c = 3 · 10^{-24} s

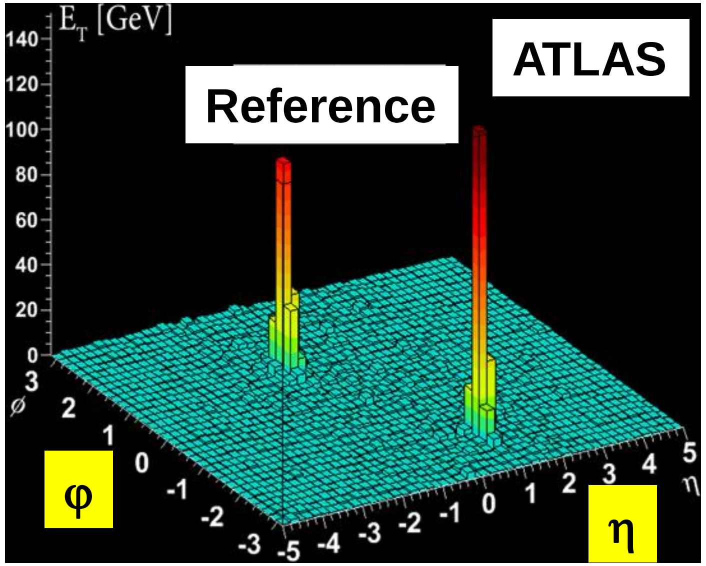
QGP Key Properties

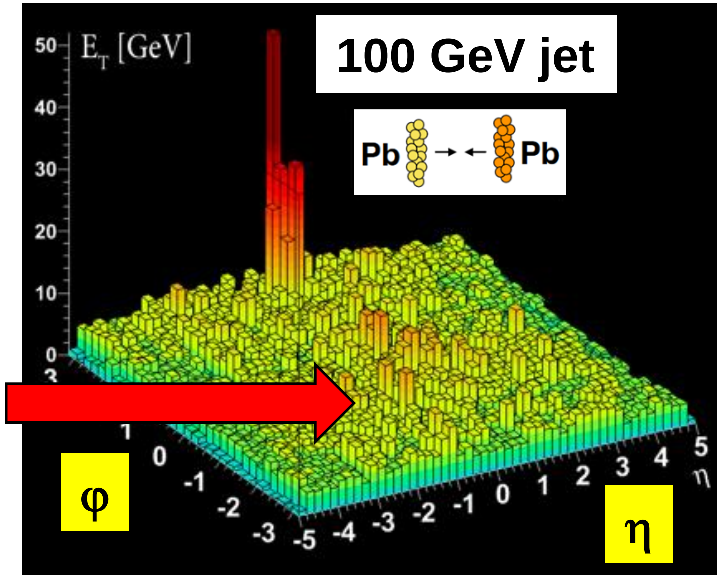
Jet Quenching

- The QGP alters jet energies
  - Radiative and collisional energy loss due to interactions of traversing parton with quarks and gluons in the medium
- Back-to-back jets significantly altered



Cartoon: E. Iancu



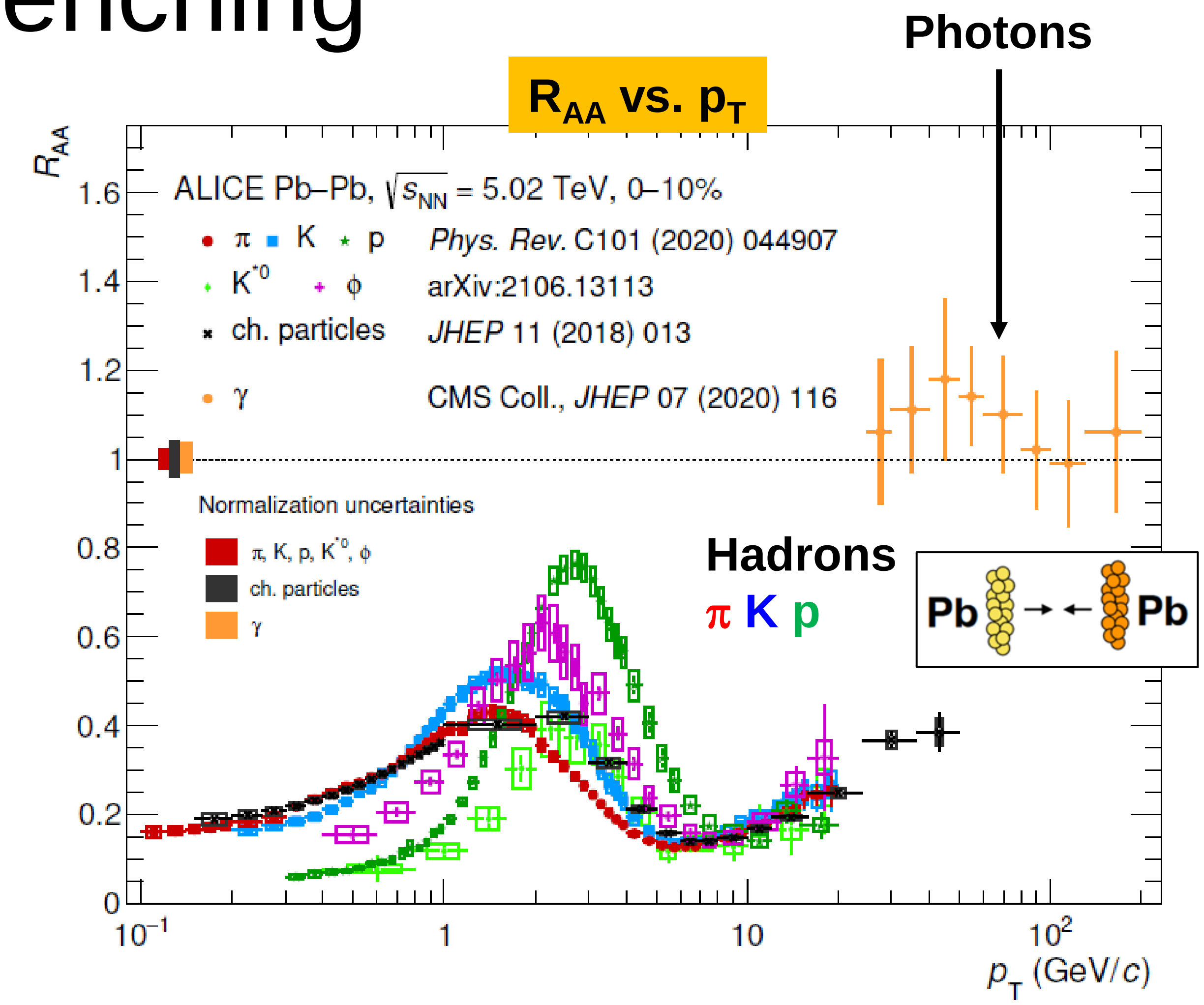


PRL105:252303,2010

970 citations!

Jet Quenching

- For all strongly interacting probes
  - Significant suppression (R_{AA} ~ 0.14)
    - Ratio of steeply falling spectra
  - Different dynamics depending on particle
    - Dependence on mass and quark content
- EW probes (γ, Z, W) not suppressed
  - Do not interact with QGP
  - Confirm correct scaling of R_{AA}
- Used to constrain QGP properties



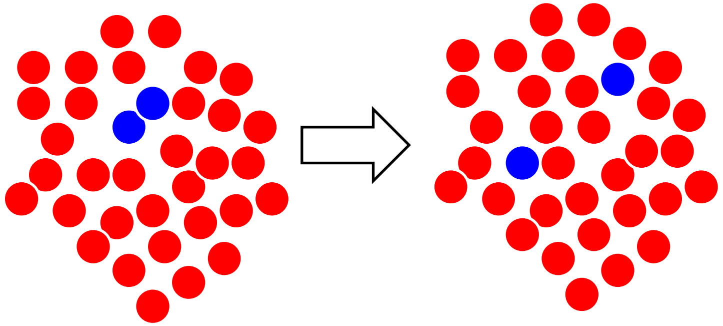
$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle dN_{pp}/dp_T}$$

→ Andres (Wednesday 9:30)

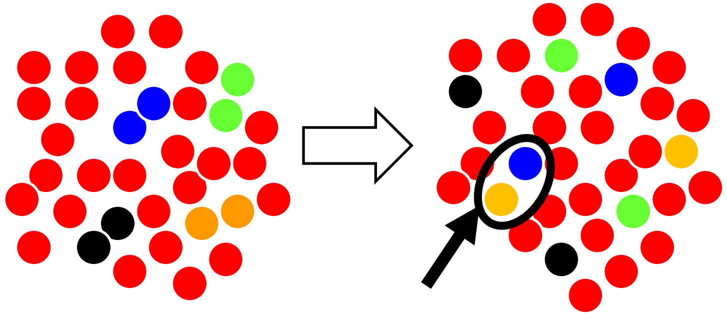
arXiv:2211.04384

J/ψ

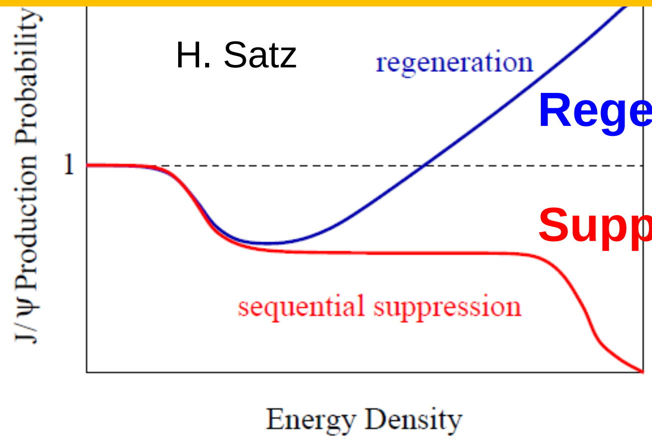
- The QGP affects bound-state formation
- Binding potential of quarkonia is modified
- ccbar produced in hard scattering does not hadronize to J/ψ in presence of medium



- Large ccbar density → regeneration

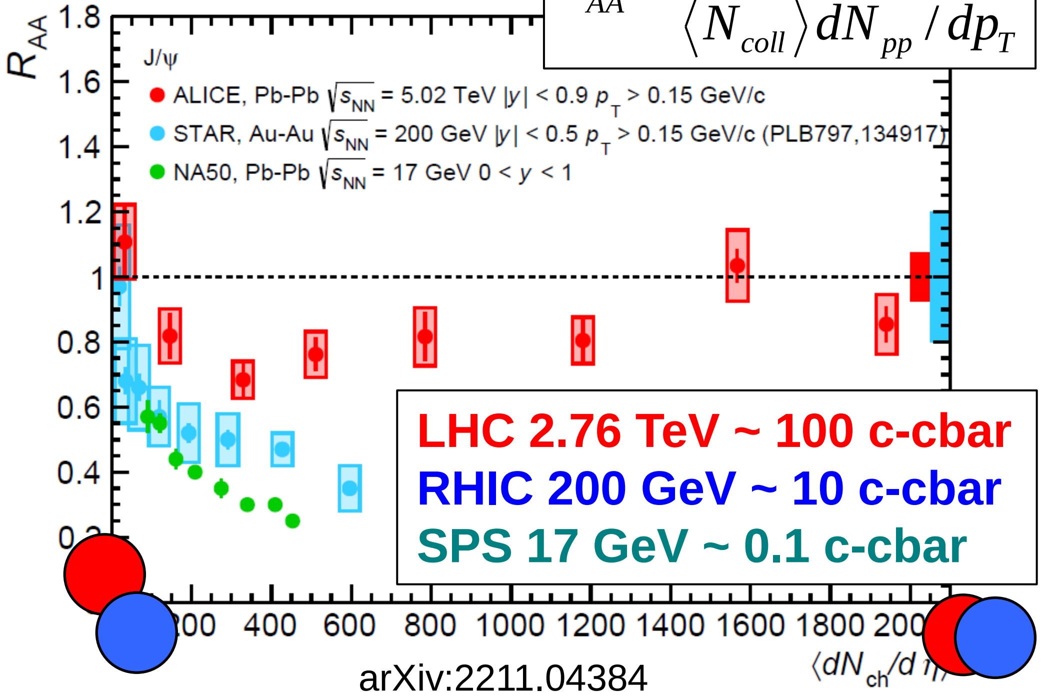


J/ψ modification vs. energy density



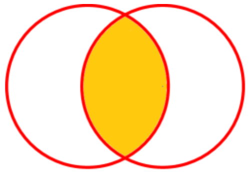
R_{AA} vs. multiplicity

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

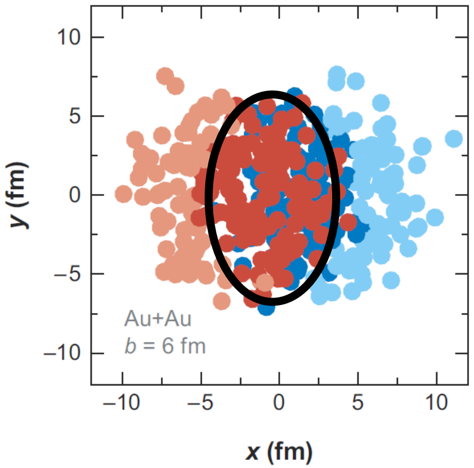


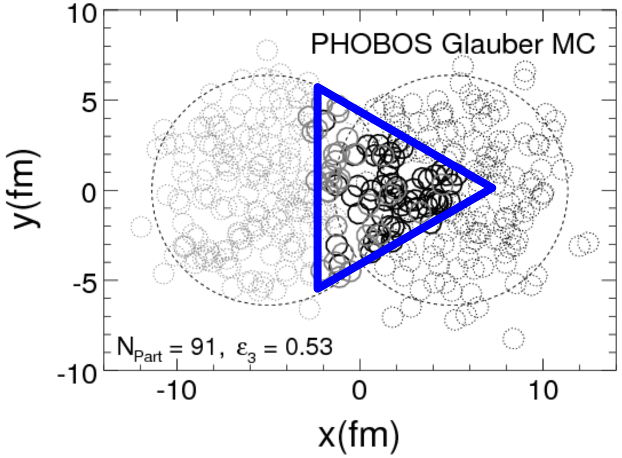
arXiv:2211.04384

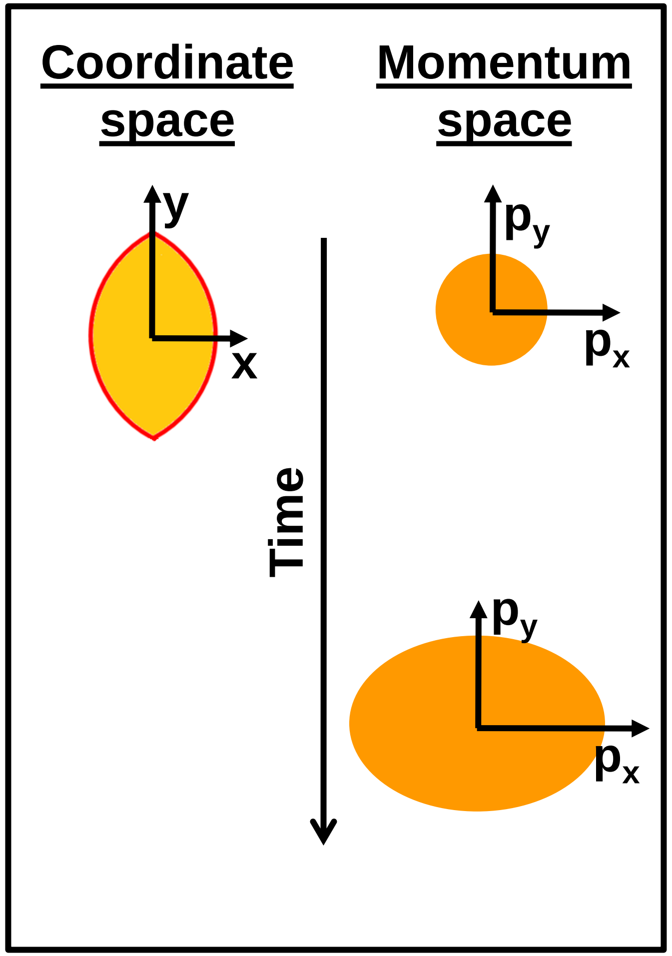
A Flowing System



- Collision zone not isotropic (coordinate space)
- Pressure gradient → momentum-space anisotropy
  - Requires reinteractions, strongly-coupled system
- Access to event-by-event fluctuations of nucleon density







- Measurable through azimuthal distribution of particles

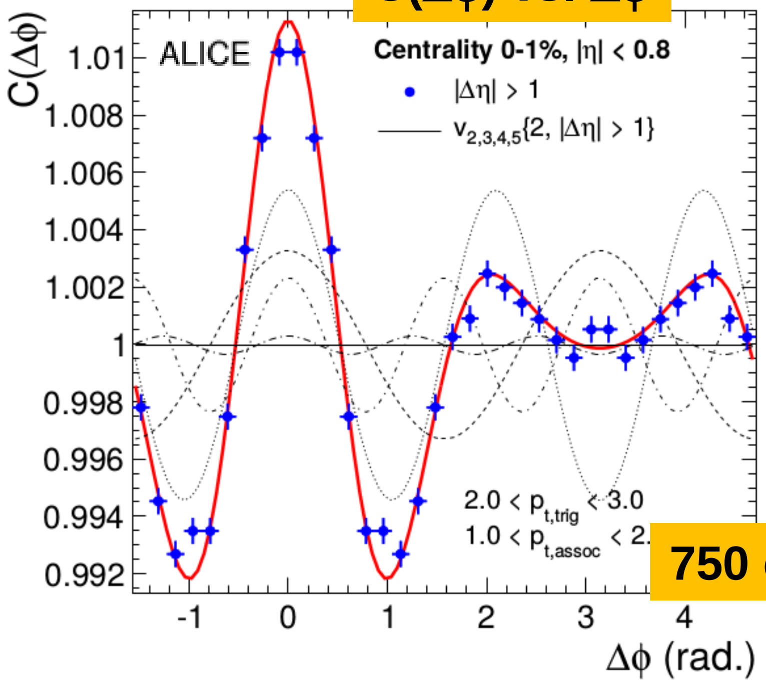
$$\frac{dN}{d\varphi} = A\left(1 + 2\sum_n v_n \cos n(\varphi - \Psi_n)\right)$$

nucl-ex/0701025, PRC81 (2010) 054905

Higher Orders

- Azimuthal distribution entirely described up to 5th order
- Finer structures can be extracted with high statistics (n = 9, at present)

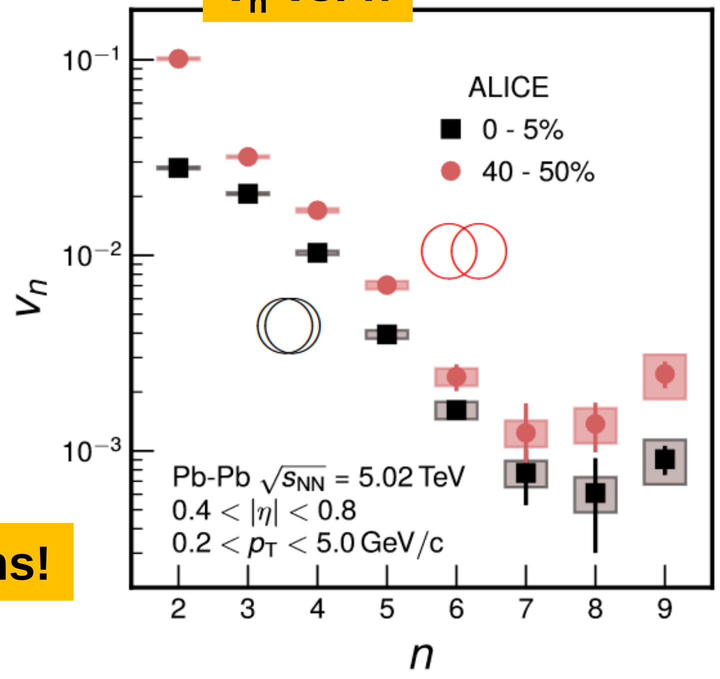
C(Δφ) vs. Δφ



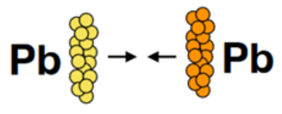
PRL107, 032301 (2011)

750 citations!

v_n vs. n



JHEP05(2020)085

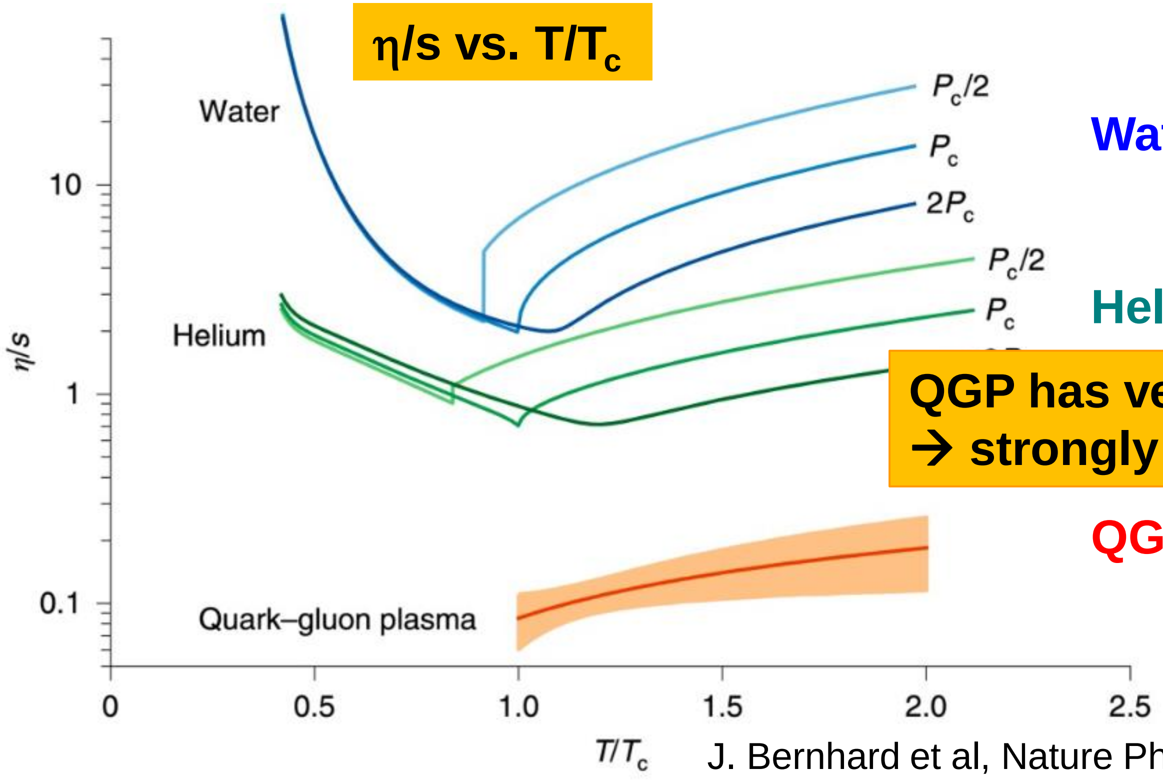


Compact description of the data
Direct link to medium transport coefficients

Transport Coefficient: Shear Viscosity

- Shear viscosity η/s washes out initial-state anisotropies
  - Large influence on higher-order flow
- Bayesian estimates for QGP medium properties

η/s vs. T/T_c



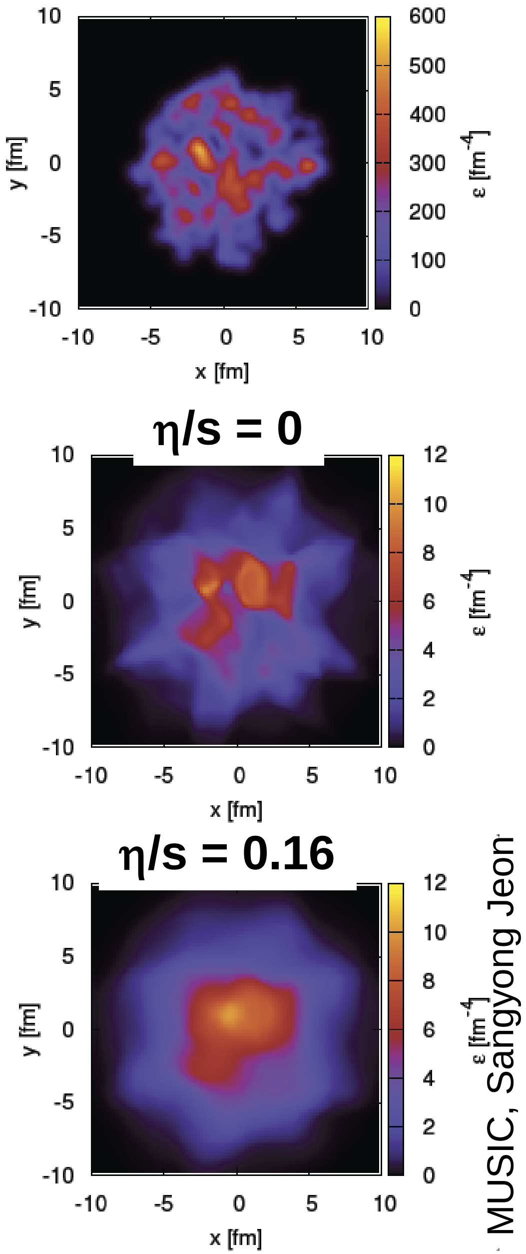
Water

Helium

QGP has very small shear viscosity → strongly coupled

QGP

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



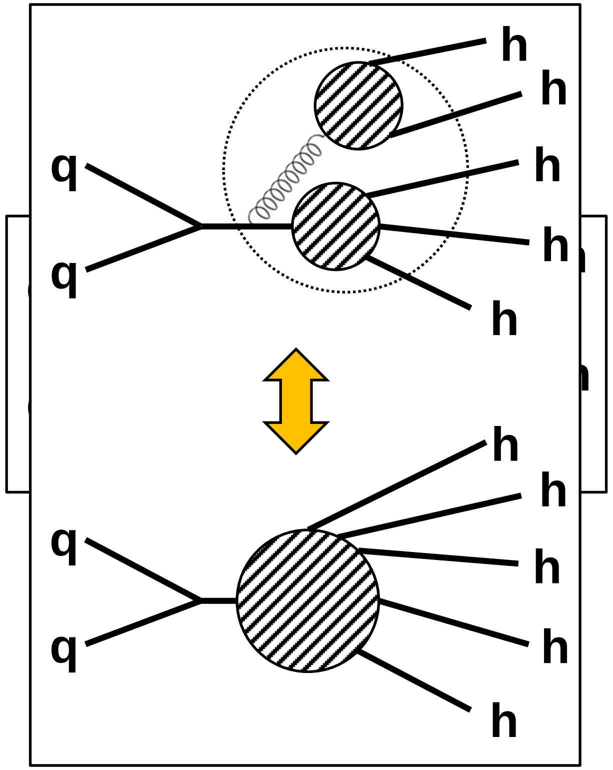
Transition from QGP to Hadrons

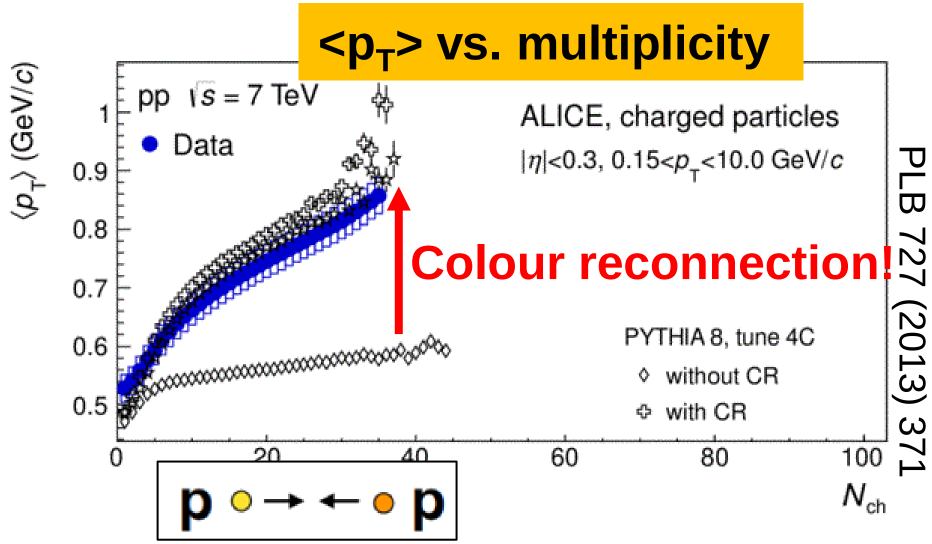
Hadronization

- Hadronization is a non-perturbative process
  - No first-principle description
  - Λ_{QCD}… but when does it begin exactly?
  - Understanding is very important, as a fundamental element of QCD
    - Affects all observables which measure hadrons
    - Needed for background estimates, including in searches
  - Experiment guides the way hand-in-hand with theory-inspired phenomenological models
- Initially: Factorized description of hadron production

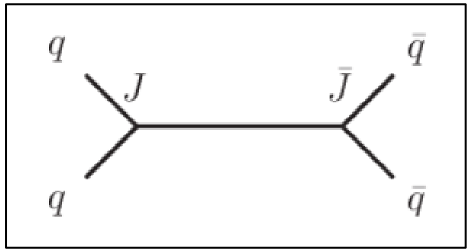
$$\sigma_{pp\to hx} = PDF(x_a,Q^2)PDF(x_b,Q^2)\otimes\sigma_{ab\to q\bar{q}}\otimes D_{q\to h}(z,Q^2)$$

  - Multiple interactions within collision combined incoherently
- But: Picture fails when multiplicity increases
  - Addition of e.g. colour reconnection needed

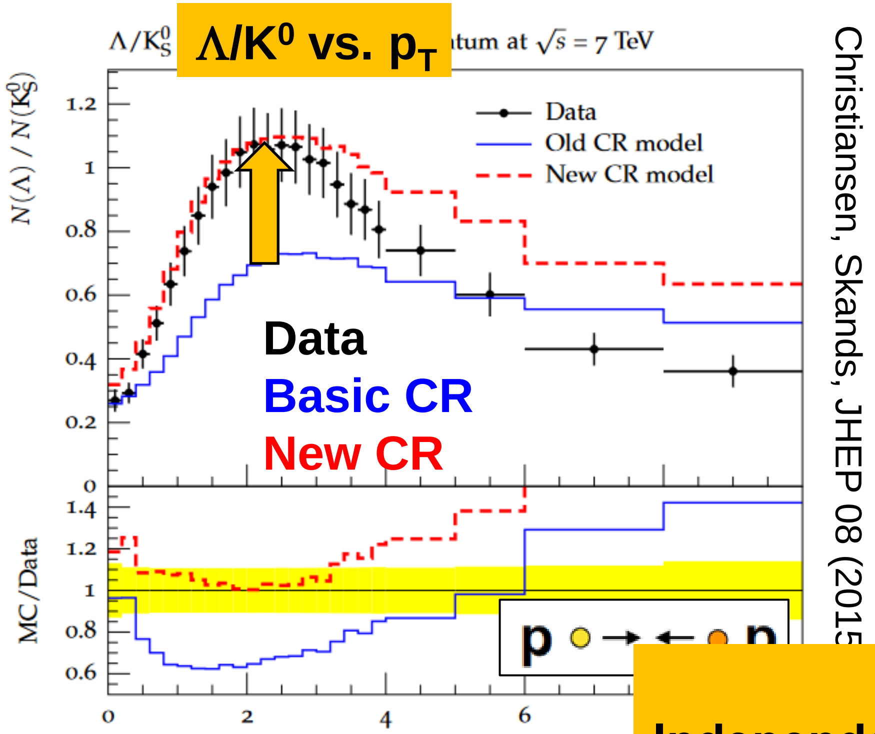


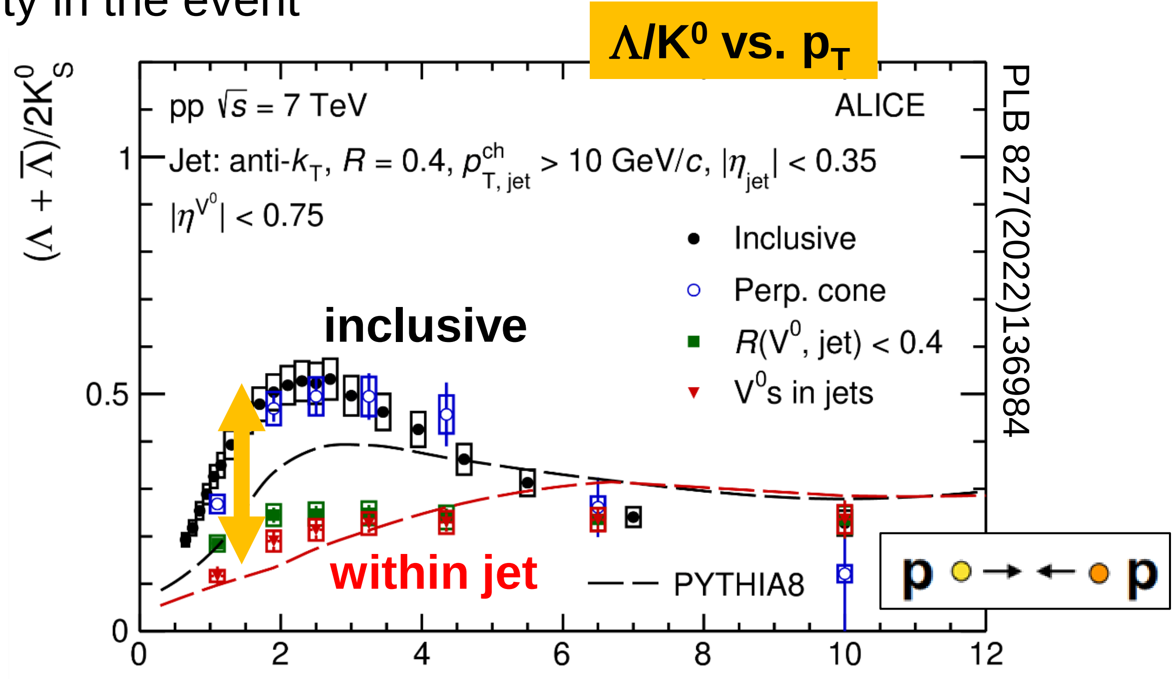


Baryon Production



- Baryon production (e.g. Λ) not described by e^+e^- inspired models
  - E.g. in Pythia, need for more than basic color reconnections (e.g. junctions, JHEP 08(2015)003)
- Baryon enhancement not visible for jet constituents
  - Fragmentation remains independent of other activity in the event





Fragmentation within jets unaltered (e^+e^- like).
Independent and "higher-order" fragmentation present in same collision

Charm Sector

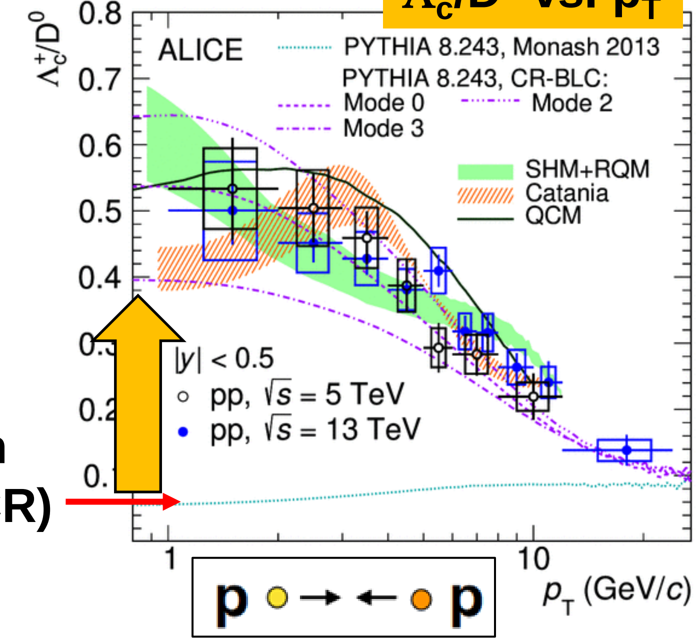
- Charm and beauty produced in hard scattering, rarely in string fragmentation

- Baryon enhancement also in charm sector
  - Surprise: Λ_c/D significantly larger than e$^+$e$^-$ expectation
  - Pythia with reconnections beyond leading colour works

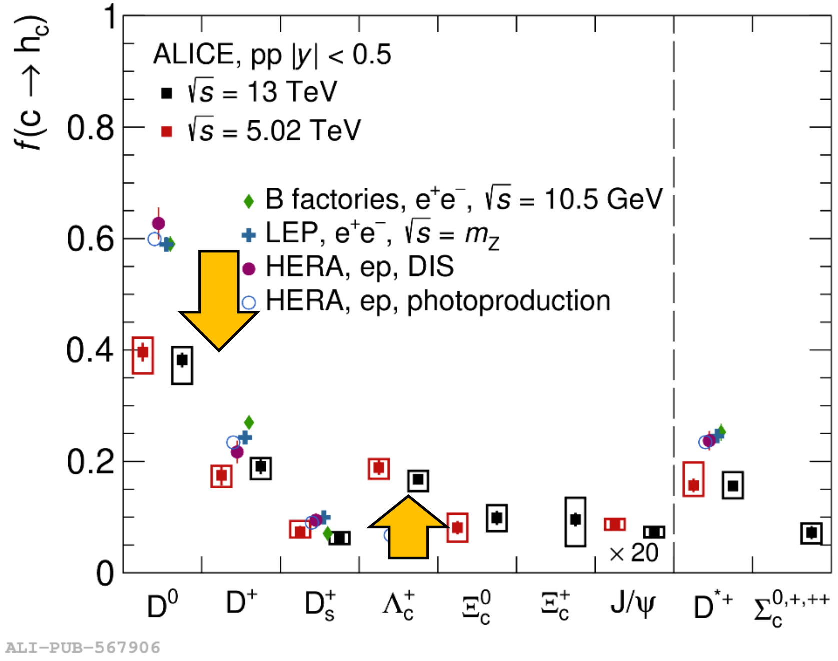
- Significant effect on fragmentation fractions
  - Less D^0 in pp than in e$^+$e$^-$ and ep
  - More Λ_c in pp than e$^+$e$^-$ and ep

Λ_c/D^0 vs. p_T

e$^+$e$^-$ expectation (including LO CR)



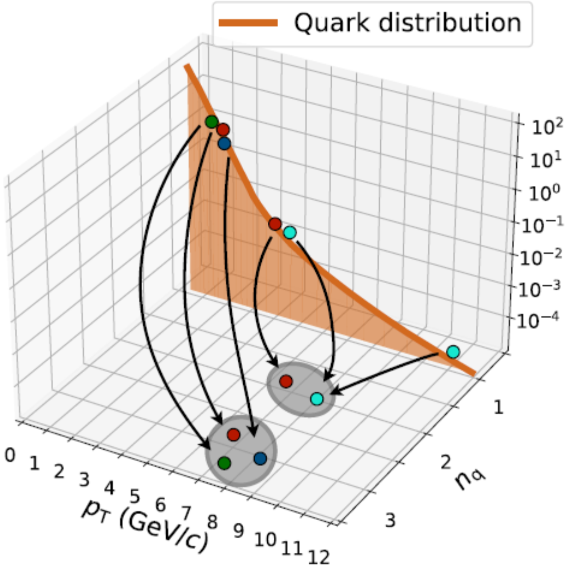
PRL128 (2022) 012001



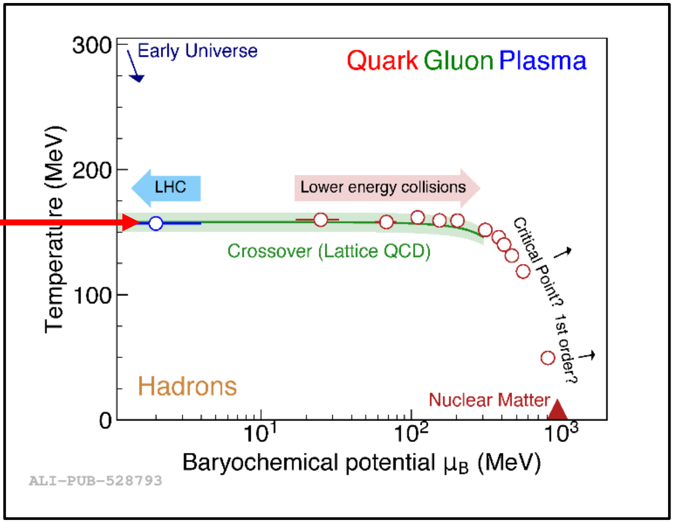
JHEP 12 (2023) 086

Coalescence and Statistical Hadronization

- Coalescence in filled phase space of quarks and gluons
  - Partons close in momentum and position space coalesce to hadrons
  - Probability is p_T dependent
  - Can be successfully applied to large objects
    - Nuclei have small binding energy and are formed late
- Statistical hadronization: Relativistic ideal quantum gas of hadrons in thermal and chemical equilibrium
  - 3 free parameters: V, T, μ_B
  - Central Pb-Pb at LHC
    - T = 156 ± 2 MeV
    - μ_B = 0.7 ± 3.8 MeV
    - V ~ 5000 ± 500 fm^3

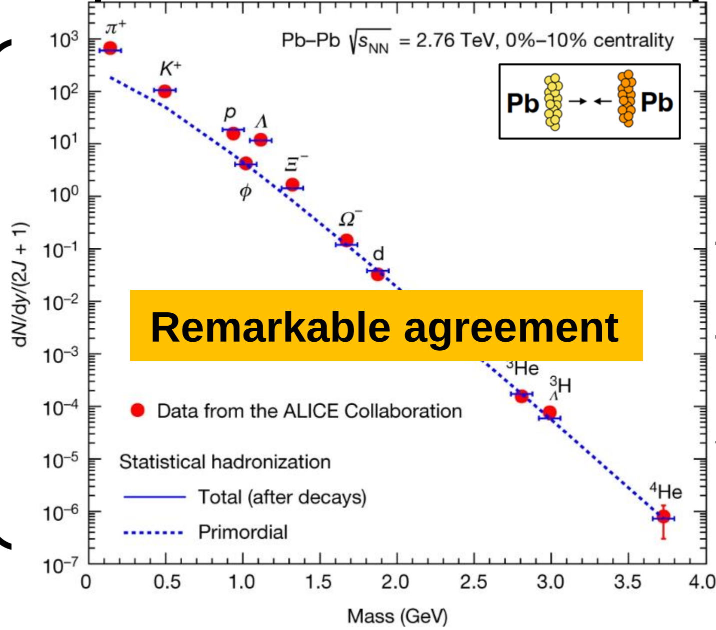


Cartoon: F. Grosa



11 different species

9 orders of magnitude

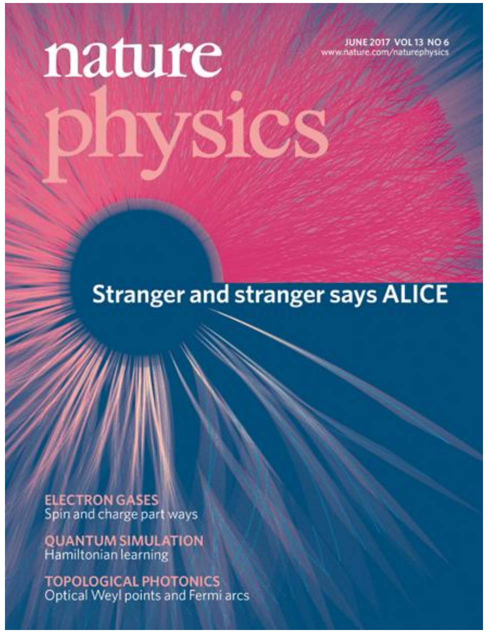


Nature 561 (2018) 7723, 321

Onset of QGP Production

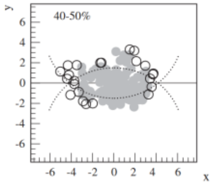
Strangeness Enhancement

- Hadronization for strange particles density-dependent
- Strange particle production increases with multiplicity
  - K/π, Λ/π, Ξ/π, Ω/π
  - from pp, over p-Pb, to Pb-Pb

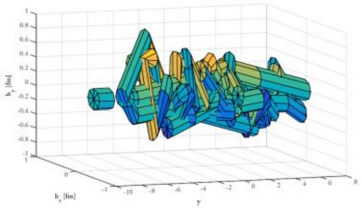


❌ Independent fragmentation
$D_{q\rightarrow h}(z,Q^2)$

✅ EPOS
(core-corona)



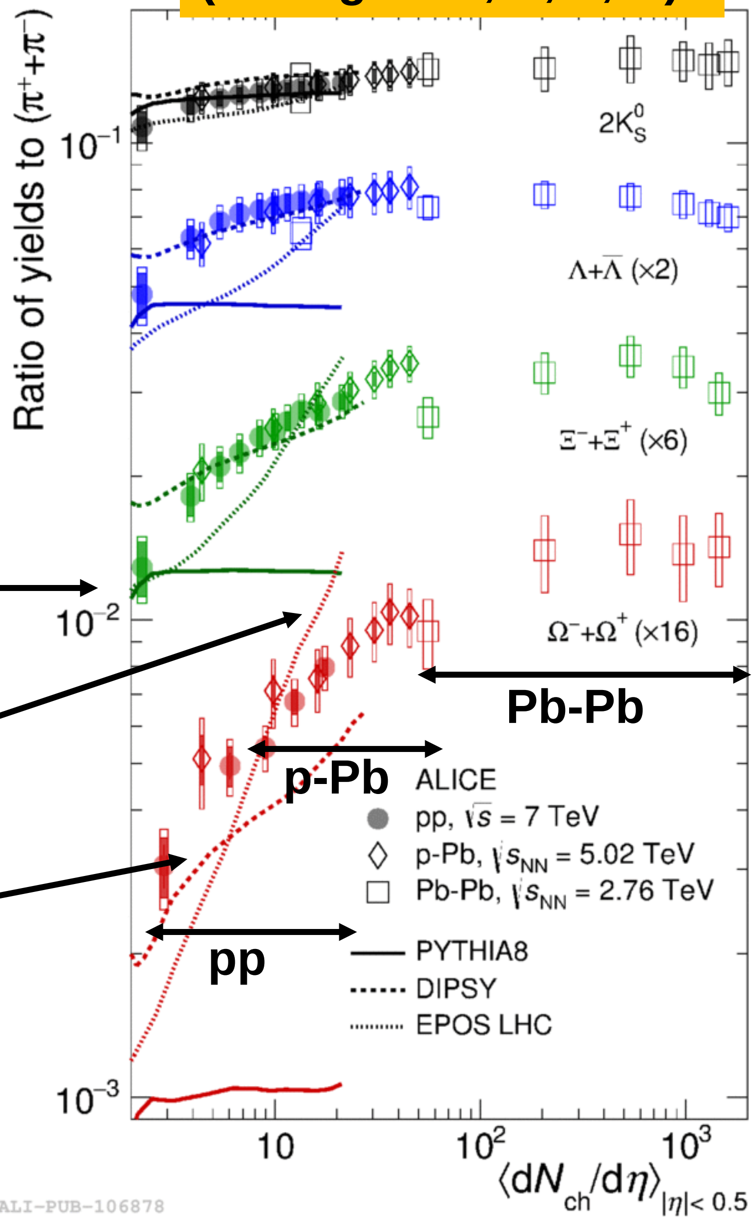
✅ Colour rope mechanism
(DIPSY)



Christian Bierlich

→ Chinellato (Tuesday 17:20)

Strange/π vs. $dN_{ch}/d\eta$
(Strange = K, Λ, Ξ, Ω)

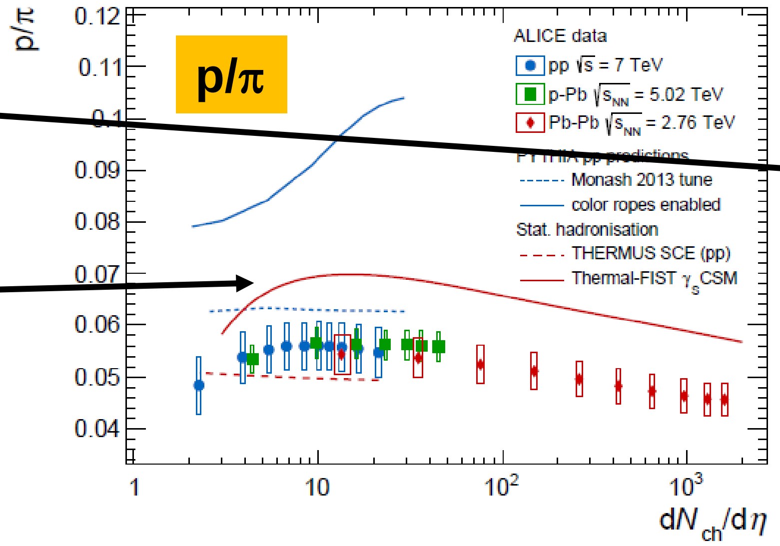


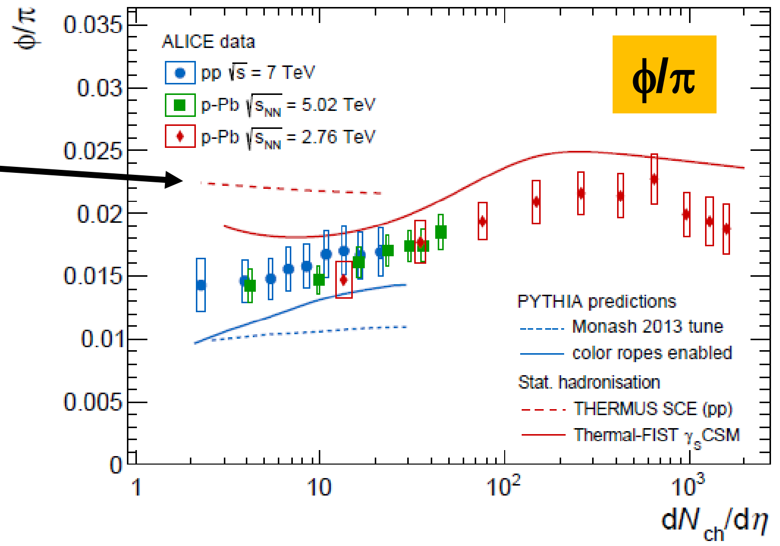
Nature Phys. 13 (2017) 535

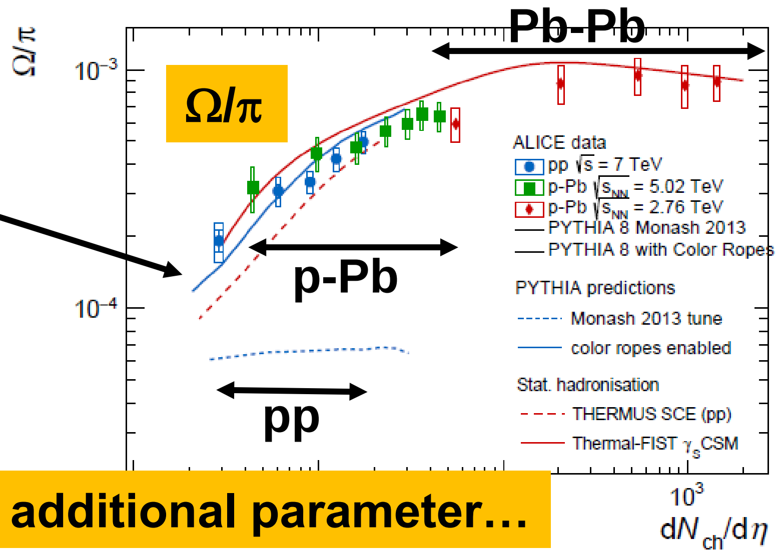
Statistical Hadronization Model in pp and p-Pb

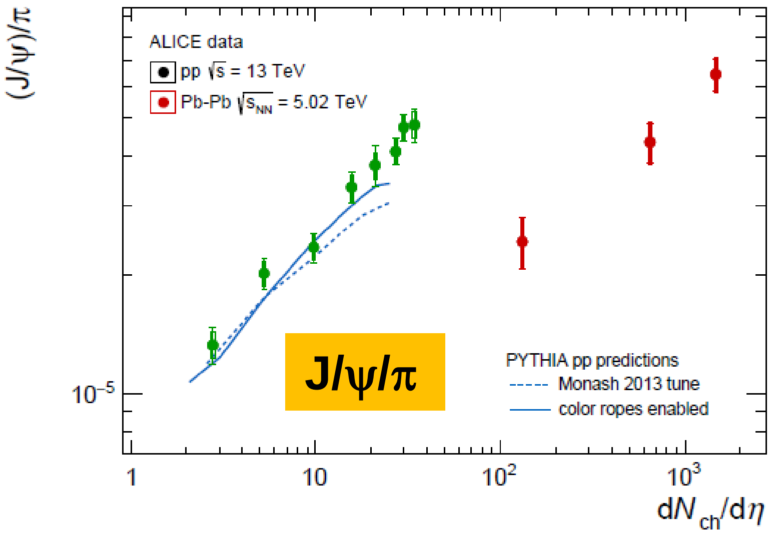
arXiv:2211.04384

- THERMUS SCE
  - With fixed T
  - No good description
- Thermal-FIST
  - Multiplicity dependent T
  - Strangeness suppression parameter γ_S
  - Good description: ϕ/π and Ω/π
  - p/π only qualitative
- Colour ropes in Pythia
  - Successful for ϕ/π and Ω/π
  - Far off for p/π





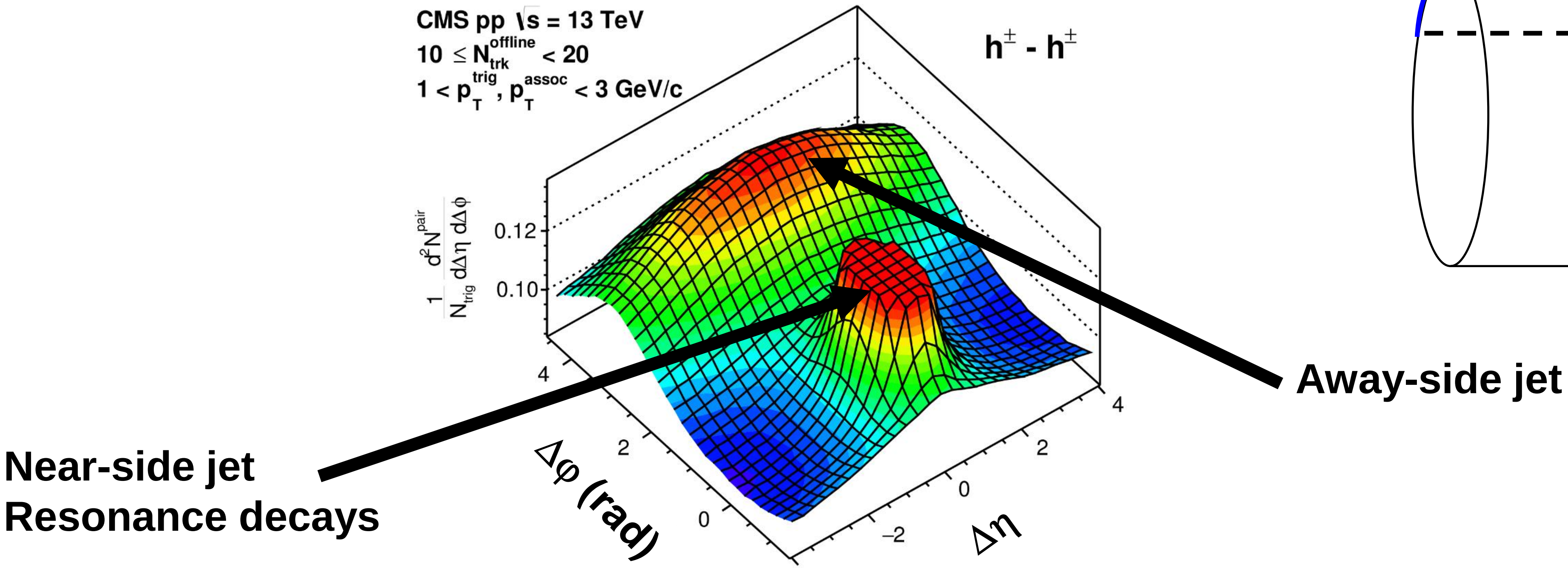


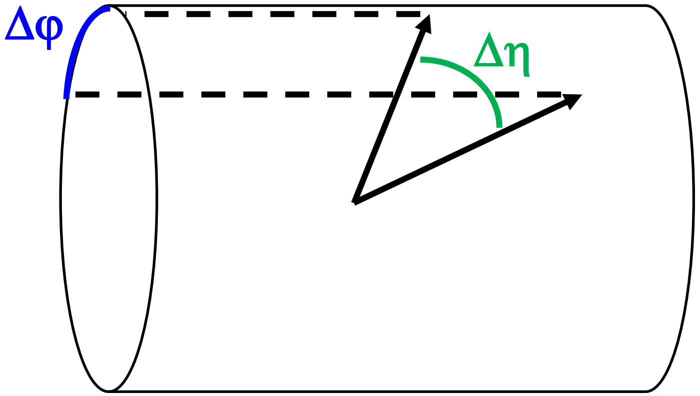


SHM works in small systems but needs additional parameter…

Collective Phenomena

- Two-particle correlations
  - "Probably density" to find second particle



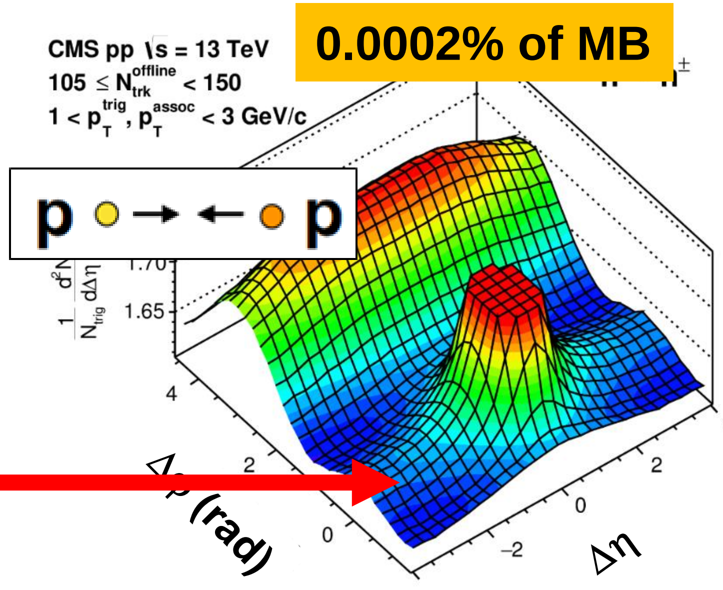


PLB 765 (2017) 193

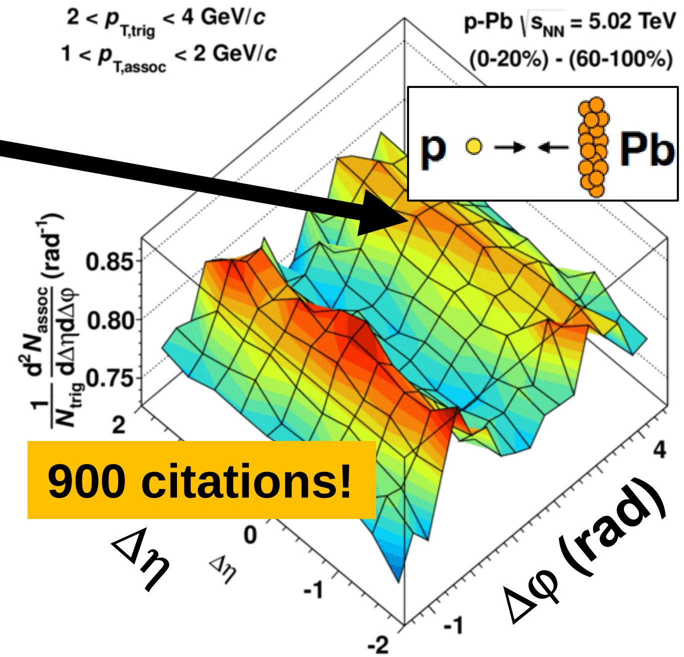
Collective Phenomena

- Two-particle correlations
  - "Probably density" to find second particle
- Striking observation of long-range ridge structures
  - First publication: JHEP 09 (2010) 091 **1200 citations!**
- Initially seen in high-multiplicity in pp and p-Pb
  - Jet subtraction procedure revealed almost symmetric away-side component
- Entire field emerged; paradigm shift
  - What is smallest system for which heavy ion "standard model" remains valid?
  - Can the standard tools for pp physics remain standard?

Intriguing interpretations involving QGP in small systems



CMS, PLB 765 (2017) 193



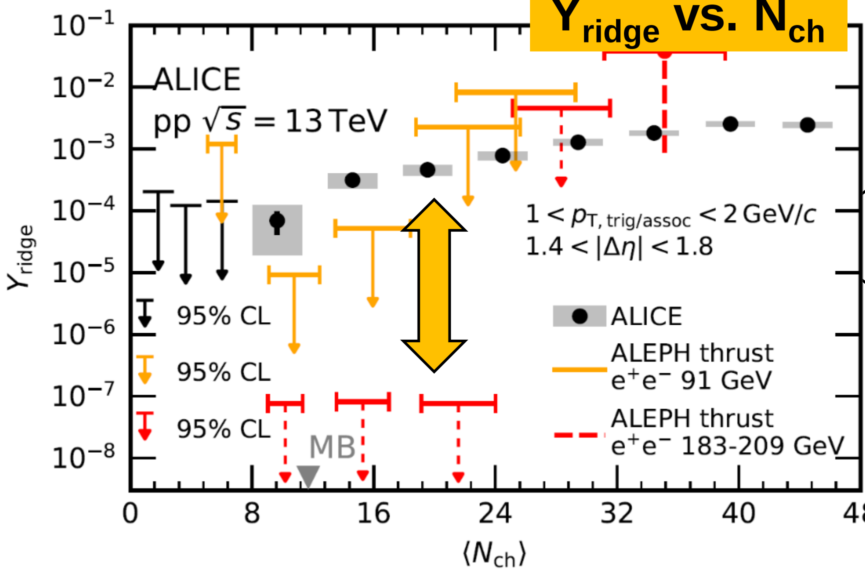
ALICE, PLB719 (2013) 29

Low-Multiplicity pp and e^+e^-

- No ridge observed in elementary e^+e^- collisions (archived ALEPH data)
- But in pp at the same multiplicity
  – Not so dense system needed for multi-particle effects

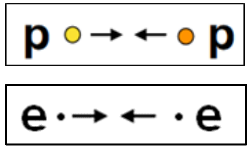
→ Mazeliauskas (Wednesday 10:00)

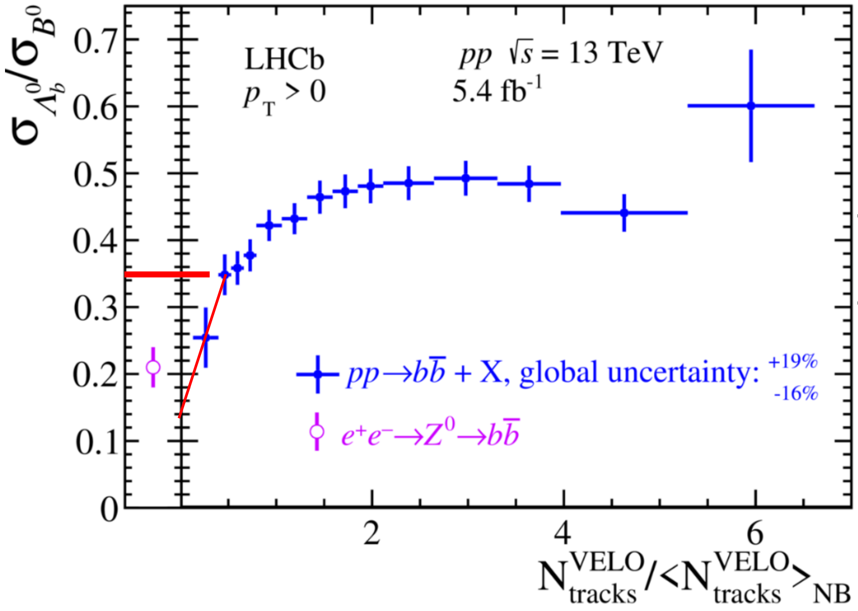
Y_{ridge} vs. N_{ch}



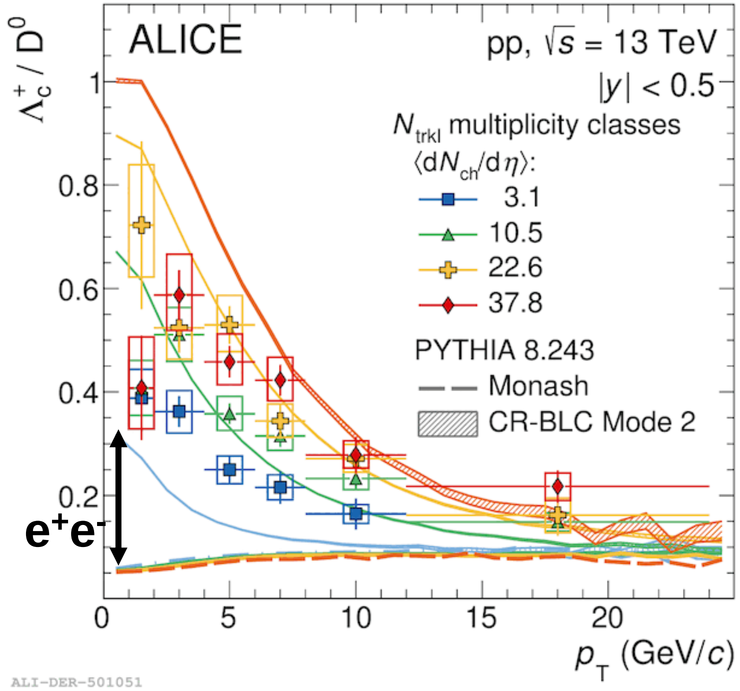
PRL132 (2024) 172302

- Open question:
  – Λ_c/D and Λ_b/B ratio





PRL132 (2024) 081901



PLB 829 (2022) 137065

Study of the Strong Interaction

Study of the Strong Force

- Femtoscopic technique for particle pairs

$$C(k^*) = \frac{N_{same}(k^*)}{N_{mixed}(k^*)} = \int S(r^*)|\Psi(r^*, k^*)|^2 d^3r$$

Correlation **Source** **Wave function**

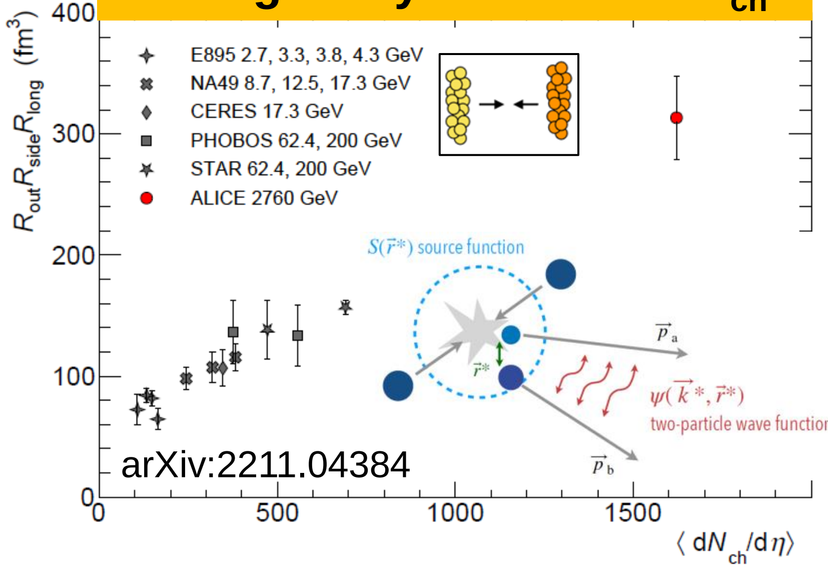
Distance r^*

$$k^* = \frac{p_a^* - p_b^*}{2}$$

- Like Hanbury Brown & Twiss interferometry
- Used to extract emitting source size in heavy ions
- If source small (e.g. pp coll.) and known, strong interaction of unstable hyperons be studied
  - pΞ, $\Lambda\Lambda$, pΩ
- Strong force needed to describe correlation
  - Lattice QCD calculations validated
    - HAL QCD: Sasaki K, et al. *Nucl. Phys. A* 998:121737 (2020)

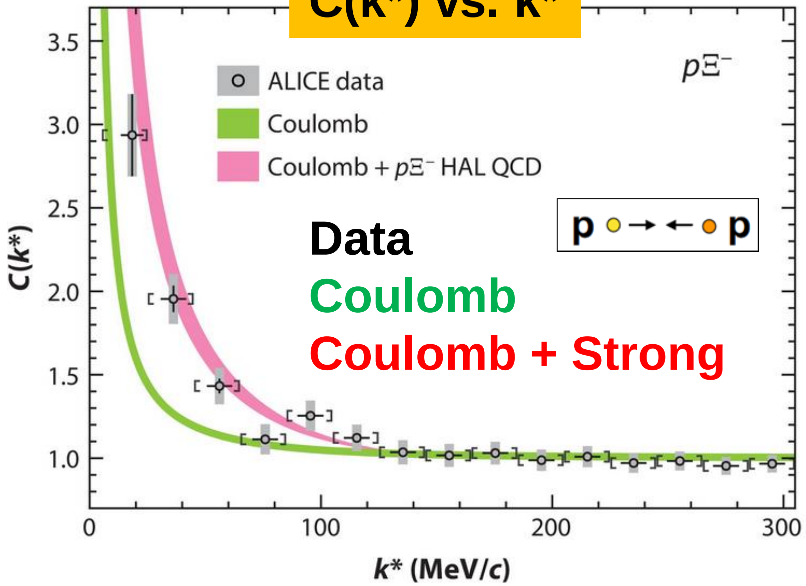
→ Vazquez Doce (Wednesday 10:30)

Homogeneity volume vs. N$_{ch}$



Cartoon: Fabrizio Grosa

C(k*) vs. k*



Fabbietti et al, Ann. Rev. Nucl. Part. Sc. 71, 377 (2021)

Short-term Future: LHC Run 3, 4

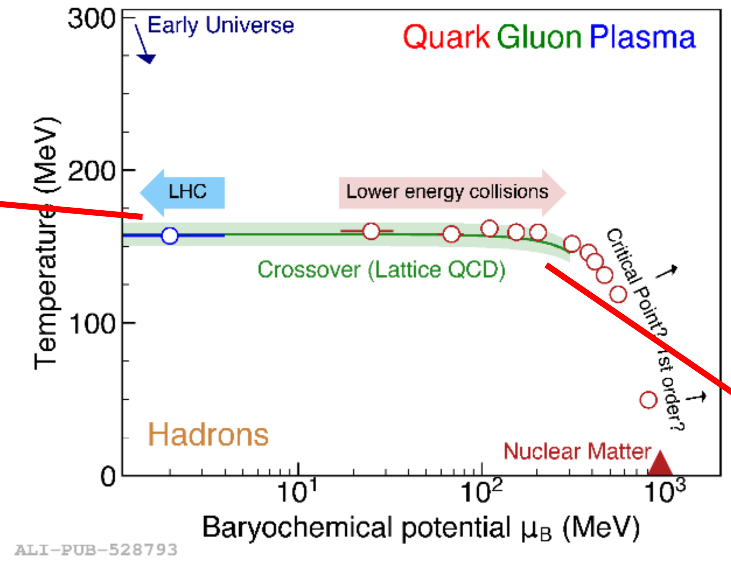
Long-term Future: LHC Run 5, 6

High-Energy Frontier

LHC + RHIC

Major upgrades completed in 2021

Major upgrades planned in 2026-28



Large-μ_B Frontier

FAIR + NICA + SPS

10 nb^{-1} Pb-Pb

10^{11} MB events

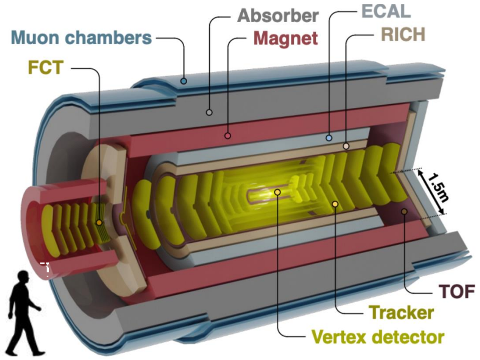
LHC 2022-32

200 pb^{-1} pp

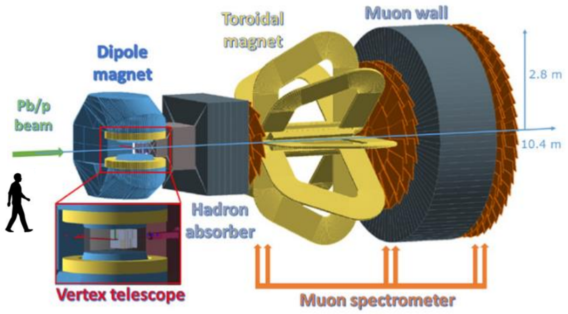
10^6 events $N_{ch} > 12 \langle N_{ch} \rangle$ (250 particles in $|\eta| < 1.5$)

LHC 2022-25

ALICE 3 (2035?)



NA60+ (2029?)

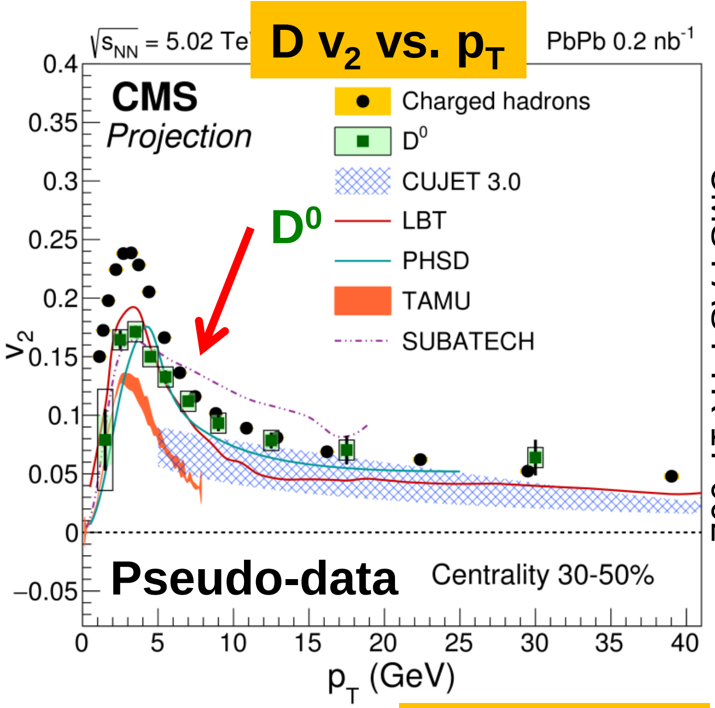


Run 3 and 4

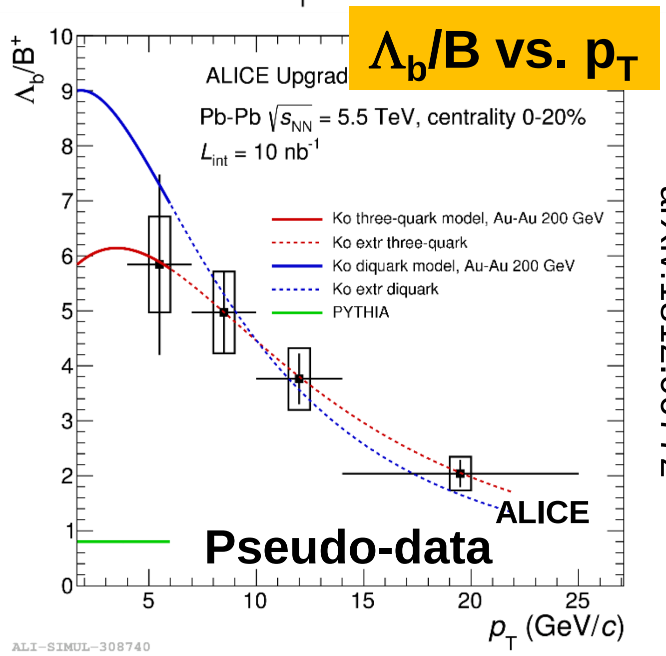
Heavy Quark Hadronization

- Do heavy quarks thermalize?
  → Charm and beauty v_2 down to $p_T = 0$
- Constrain temperature dep. of diffusion coefficient

- How does charm form in the QGP?
  - Baryon/meson ratios D_s/D, Λ_c/D, Λ_b/B
- Influence of melting and (re)generation
  - Compare states with different binding energy
- Charm cross-section to $p_T = 0$
  → reduce (re)generation model uncertainties
- Quarkonia evolution within QGP and heavy quark hadronisation, e.g. role of coalescence



CMS PAS FTR-17-002

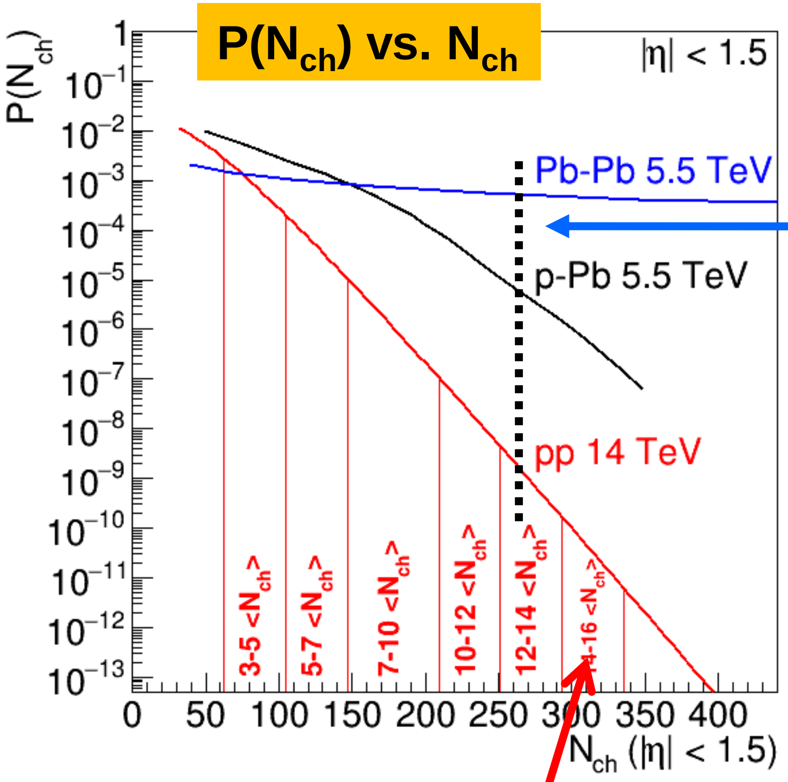


arXiv:1812.06772

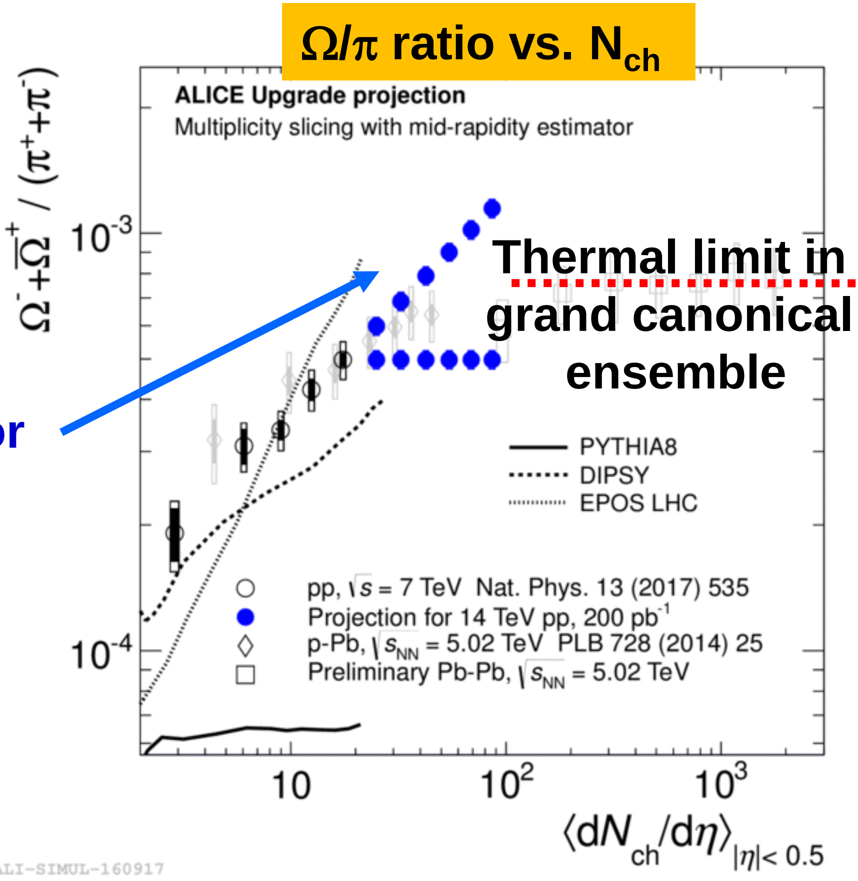
Extremely High Multiplicity Events

p → ← p

Run 3 and 4



65% central in Pb-Pb



14 TeV pp Projection for full Run 3 sample

>25k events @ 14-16 <N_{ch}>
~ 300 particles in |η| < 1.5

- **Origin of collectivity in few particle system?**
- **Does strangeness enhancement continue with same trend?**
- **Thermal limit reached or exceeded in pp?**

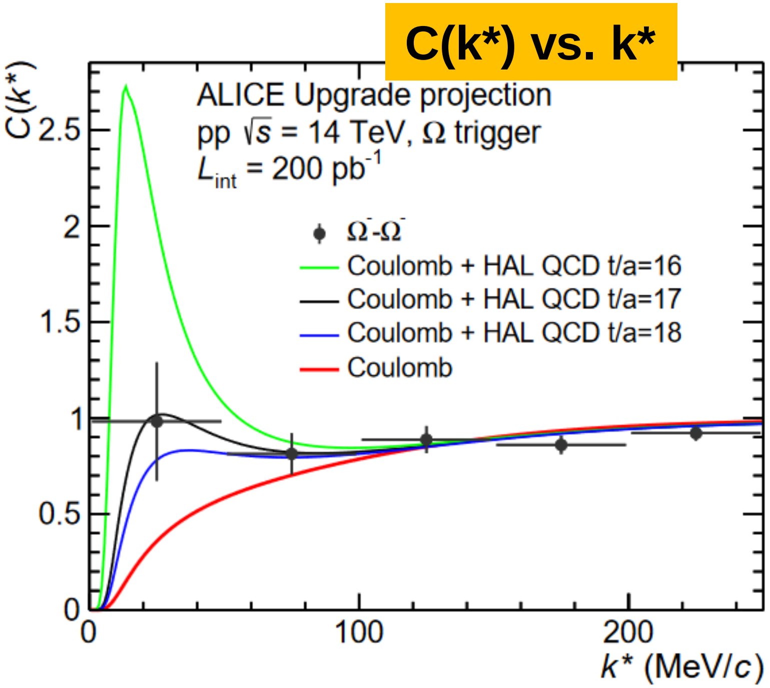
CERN Yellow Report, arXiv:1812.06772

p → ← p

Run 3 and 4

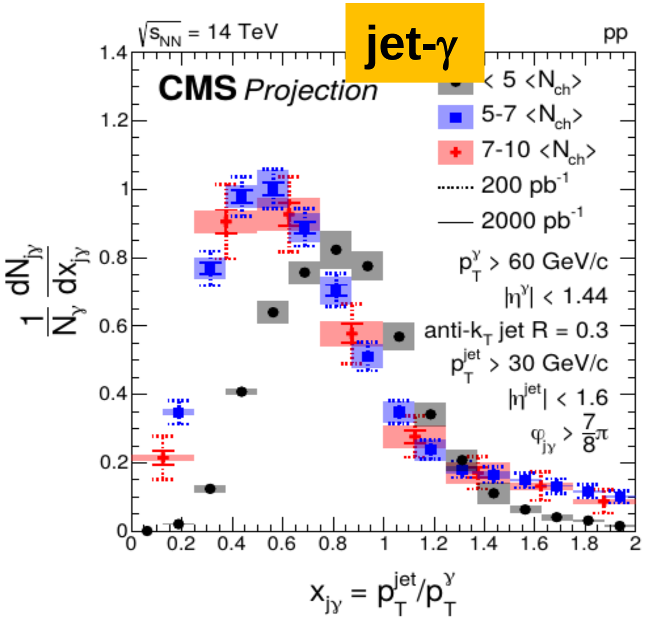
pp Programme

- Special software triggers on fully reconstructed events for hyperon correlations
  - p-Ξ, Ω-Ω, Λ-d for precise study of strong interaction

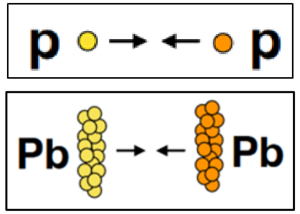


ALICE-PUBLIC-2020-005

- Energy loss in small systems
  - If v_n caused by final-state interactions, partons should lose energy
  - Energy loss through coincidence measurements → h-jet, jet-γ, jet-Z correlations



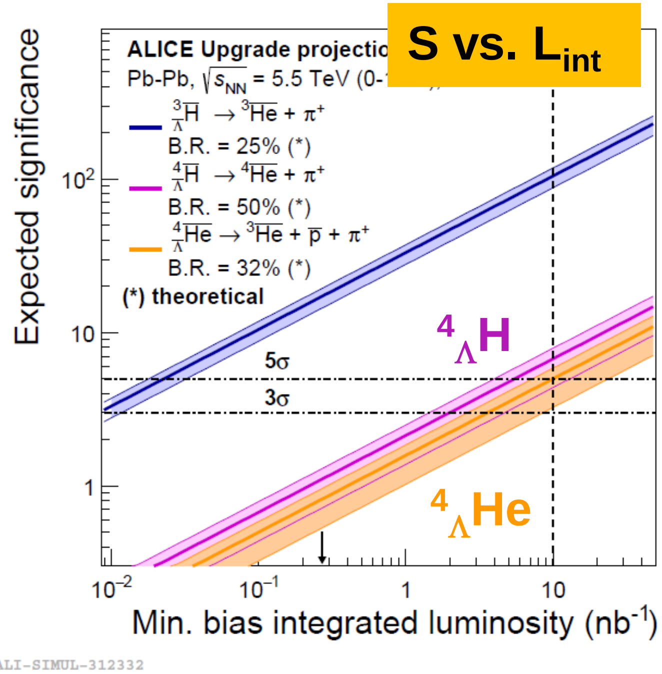
arXiv:1812.06772



Run 3 and 4

(Anti-)(hyper-)nuclei

- Precision era for (anti-)(hyper-)nuclei production
  - Abundant d, ^{3}He, $^{3}_{\Lambda}$H; > 1000 ^{4}He
  - Significance above 5σ for $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He
  - v_2 for loosely-bound objects (e.g. hypertriton)

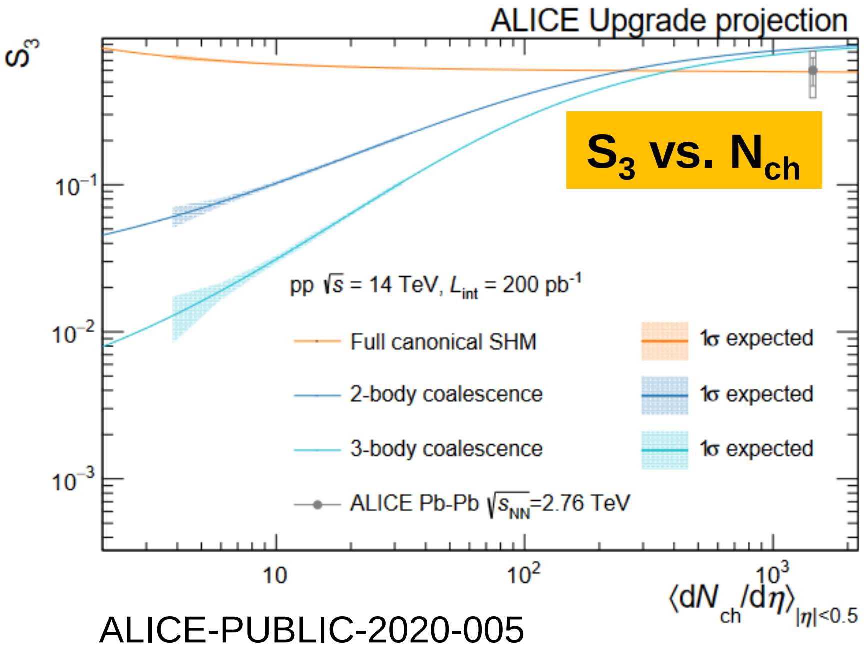


CERN YR, arXiv:1812.06772

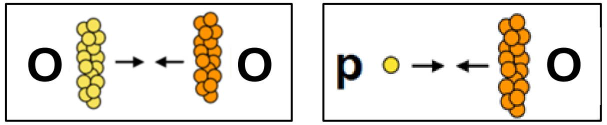
- Anti-d and anti-^{3}He data inform astrophysical background in dark matter searches (AMS)

- Production mechanism
  - (Advanced) coalescence vs. thermal model

$$S_3 = \frac{^{3}_{\Lambda}\mathrm{H}/^{3}\mathrm{He}}{\Lambda/\mathrm{p}}$$



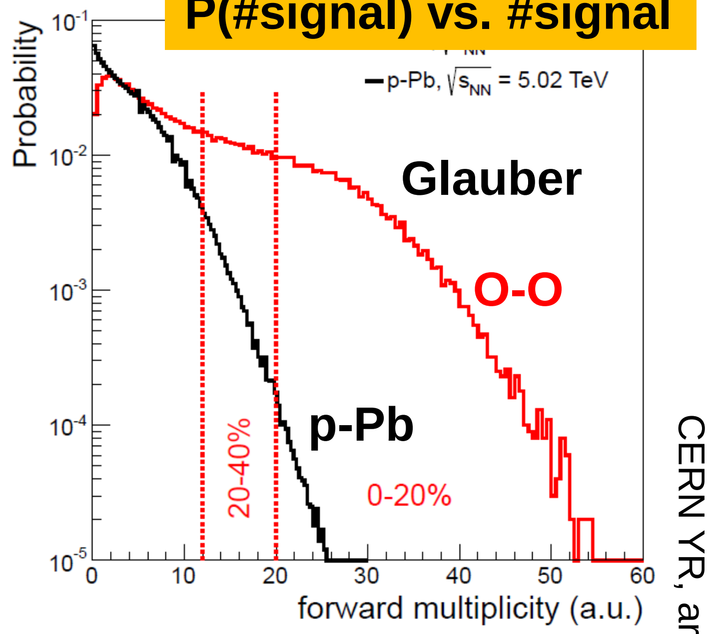
ALICE-PUBLIC-2020-005

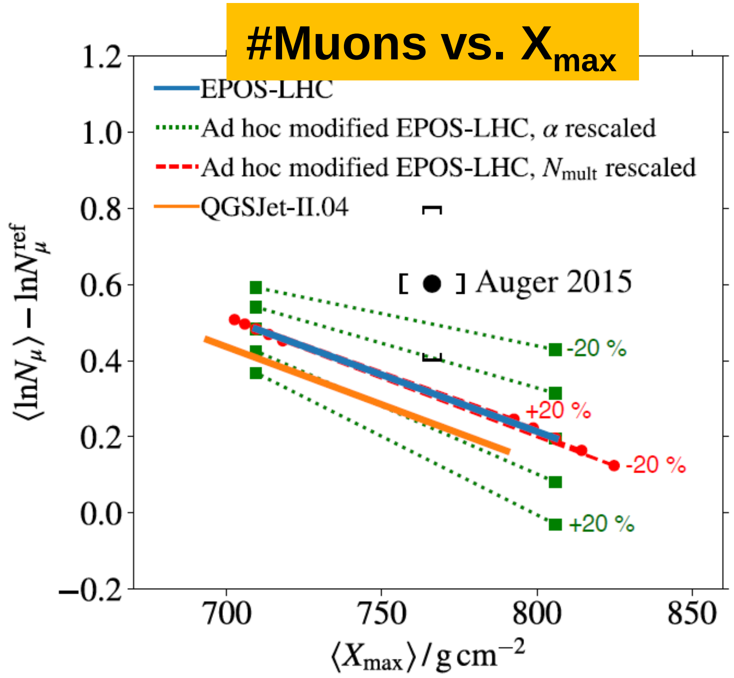


Run 3

Oxygen Run

- O-O, p-O collisions in LHC planned for July 2025
  - 3 days p-O: ALICE: p-O: 2 nb^{-1}, ~10^8 events
  - 1 day O-O: ALICE: O-O: 0.5 nb^{-1}, ~7×10^7 events
- AA geometry but N_{ch}, N_{part}, N_{coll} as p-Pb
  - Centrality shoulder allows geometry selection (N_{coll}, ε_2)
- System large enough to exhibit jet quenching
  - Critical test for energy loss for short path lengths
  - If no quenching in O-O
    → also p-Pb has insufficient energy density for quenching
- Cosmic-ray community expressed strong interest in p-O to constrain models for cosmic-ray showers
  - Muon deficit in cosmic-ray simulations mitigated by adding collective effects or strangeness
    (see e.g. arXiv:1902.08124)



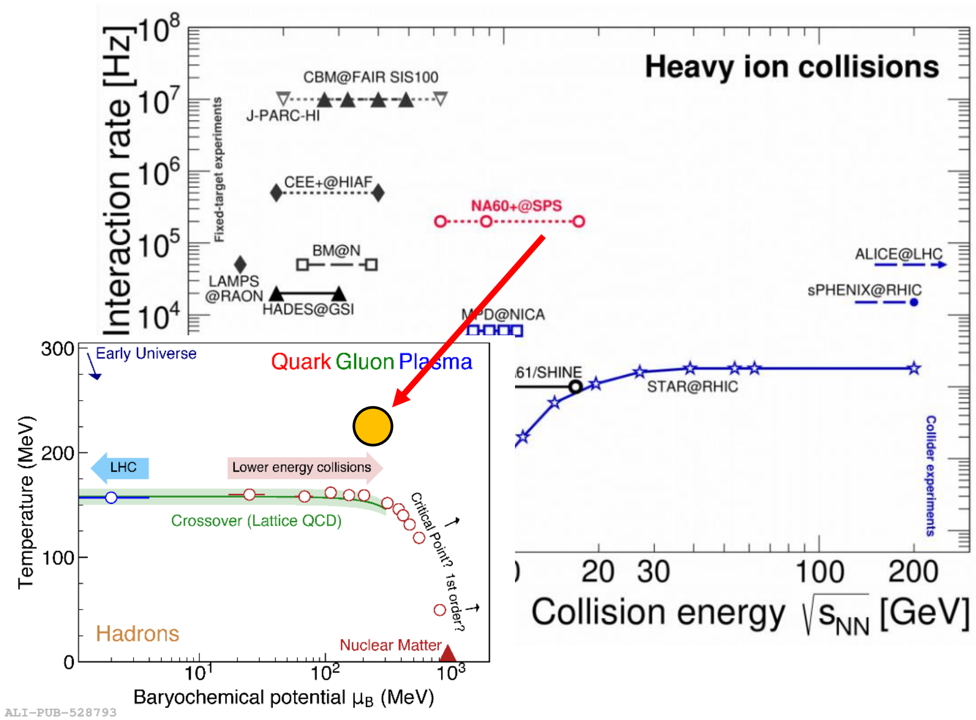


CERN YR, arXiv:1812.06772

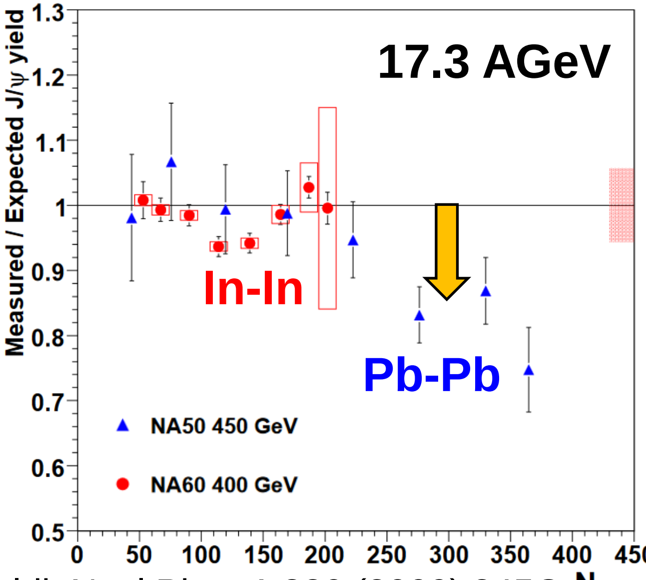
NA60+ @ SPS

Run 4 and 5

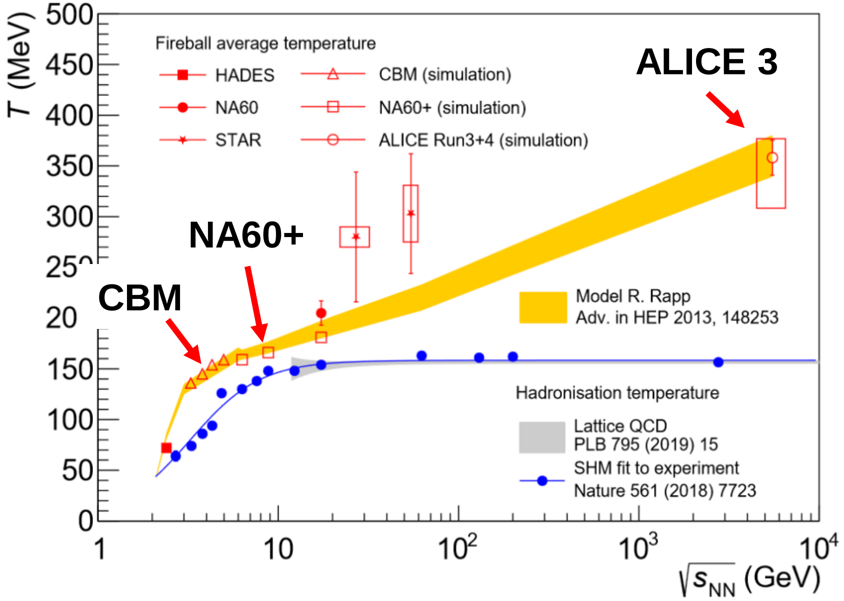
- $\sqrt{s_{NN}}$ = 6-17 GeV @ >100 kHz → QGP at high μ_B
- T through thermal dimuons → caloric curve
- Chiral symmetry restoration through ρ-a_1 mixing
- Charm hadronization
- QGP transport coefficients through open charm
- J/ψ suppression beyond CNM effects



Giacomo Alocco (NA60+)



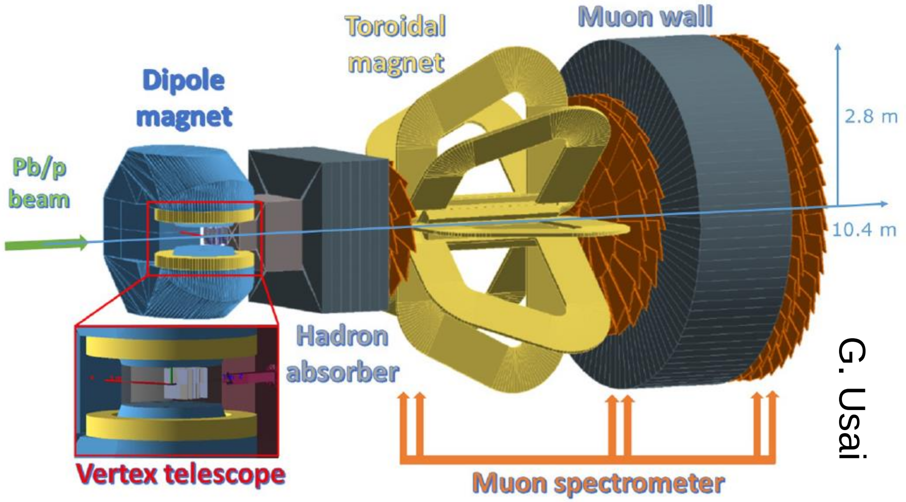
Arnaldi, Nucl.Phys.A 830 (2009) 345C



Compilation: T. Galatyuk, A. Kalweit, I. Vorobyev

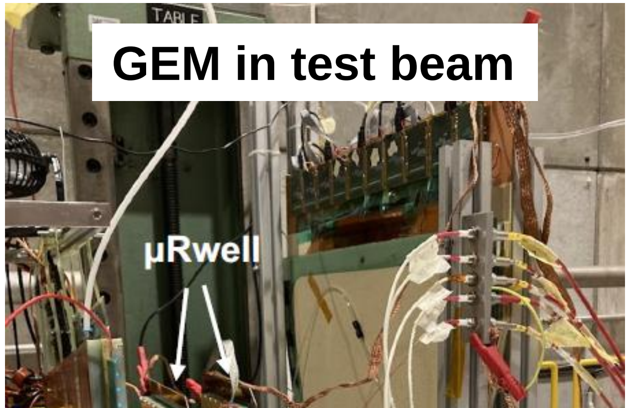
Run 4 and 5

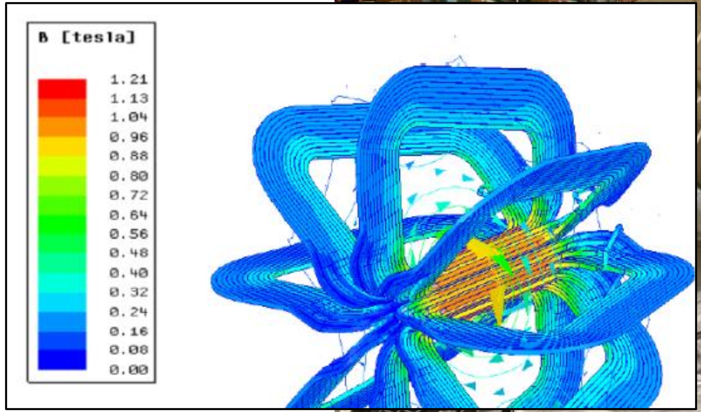
NA60+ @ SPS



G. Usai

- Significant R&D ongoing
  - Silicon detector: based on MOSAIX from ALICE ITS3 (MAPS and stitching)
  - Muon detector: prototype beam tests for design choice: GEM or MWPC
  - Toroidal magnet: 1:5 prototype built and tested
  - Trigger and reconstruction software ongoing
- Low √s p beams require secondary p from SPS
- Status & Plan
  - LoI submitted in 2022. Positive assessment by SPSC
  - Technical proposal to be submitted this year
  - Installation in LS3 (2026-2028)
  - Data taking in Run 4 and 5 (2029-2038)





ALICE 3 @ LHC

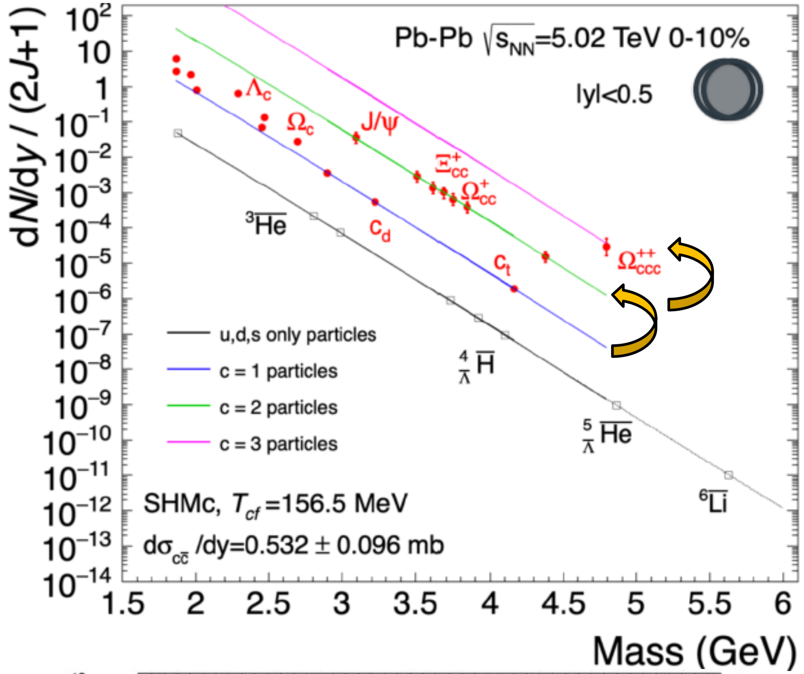
Run 5 and 6

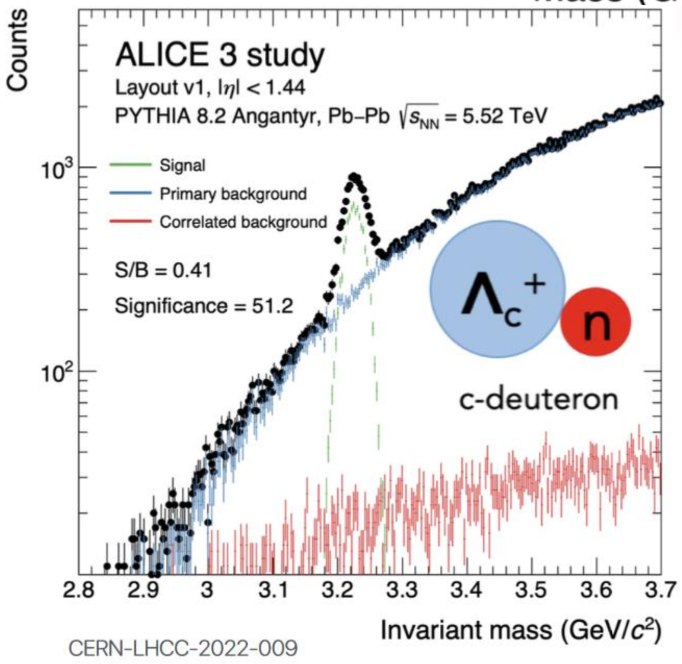
- Detector for LHC Run 5 and 6 (2035-41)
- $\sqrt{s_{NN}}$ = 5-6 TeV (PbPb, XeXe, InIn?, KrKr?)
  - Species driven by detector design and physics (no scan!)
- Thermal leptons
  - Precise medium temperature, chiral symmetry restoration
- Multiple charm (Ξ_{cc}, Ω_{cc}, …) production

$$\Xi_{cc}^{++} \to \Xi_{c}^{+}\pi^{+} \to \Xi^{-}\pi^{+}\pi^{+}\ \pi^{+} \qquad \Omega_{cc}^{+} \to \Omega_{c}^{0}\pi^{+} \to \Omega^{-}\pi^{+}\ \pi^{+}$$

  - Hadronization models; coalescence on quark level
- Heavy-quark correlations: D^0-D^0 for QGP scattering
- Quarkonia beyond S-wave: χ_c and χ_b
  - Dynamics of bound-state interactions within QGP
- Hadronic interactions and bound-state formation
  - For example: D-D* and c-deuteron
- Ultra-soft photons

→ Triloki (Monday 18:30)





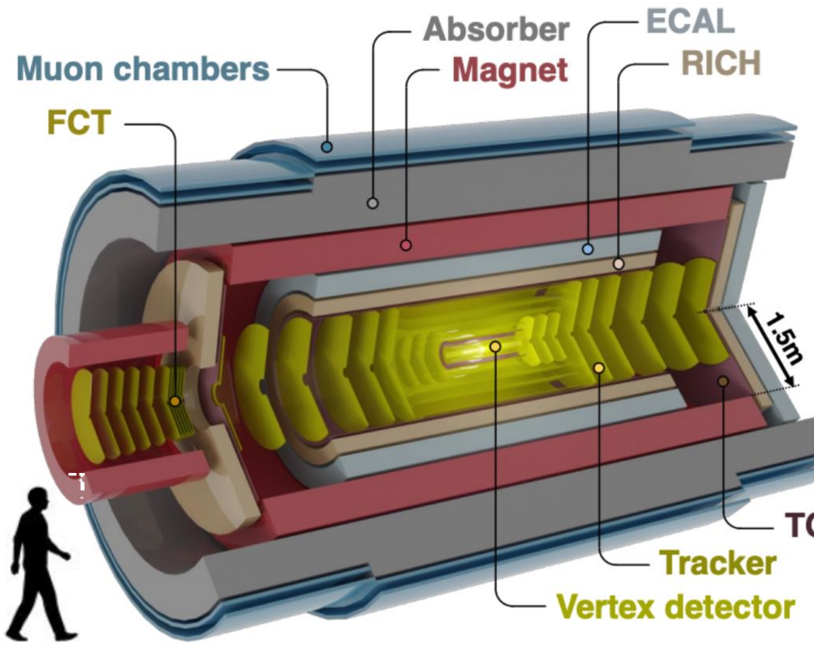
arXiv:2211.02491

ALICE 3 @ LHC

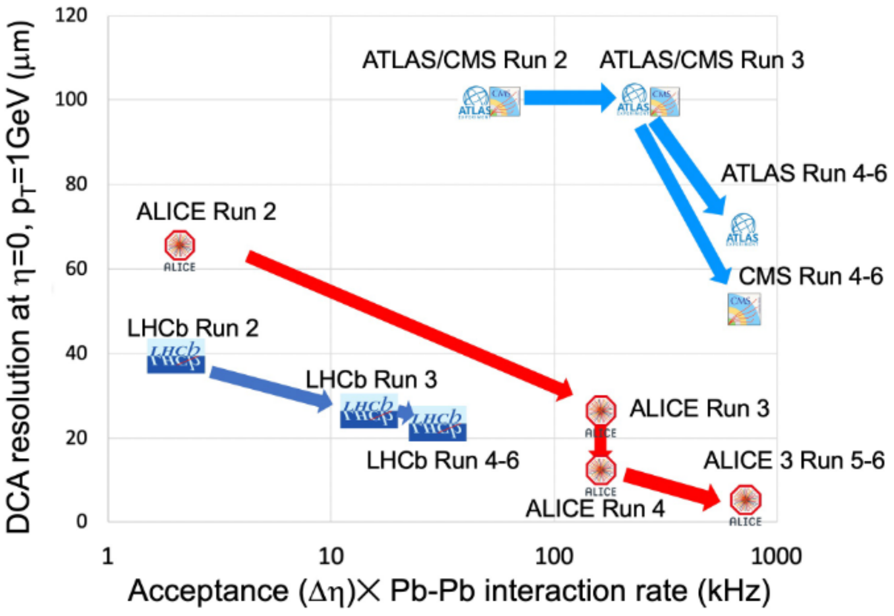
- Retractable vertex detector 5 mm from beam
  - Pointing resolution 3-4 μm @ 1 GeV
  - X/X_0 ~ 0.1% per layer
- All-silicon tracker (p_T resolution 1% @ 1 GeV)
- ECAL, RICH and muon detectors
- Continuous readout and online processing
  Pb-Pb: 35 nb^{-1} | pp 18 fb^{-1}
- Strangeness tracking: a MHz bubble chamber

- Status & Plan
  - LoI submitted in 2022. Positive assessment by LHCC
  - Scoping document to be submitted this year
  - Installation in LHC LS4 (2033-2034)
  - Data taking in LHC Run 5 and 6 (2035-2041)

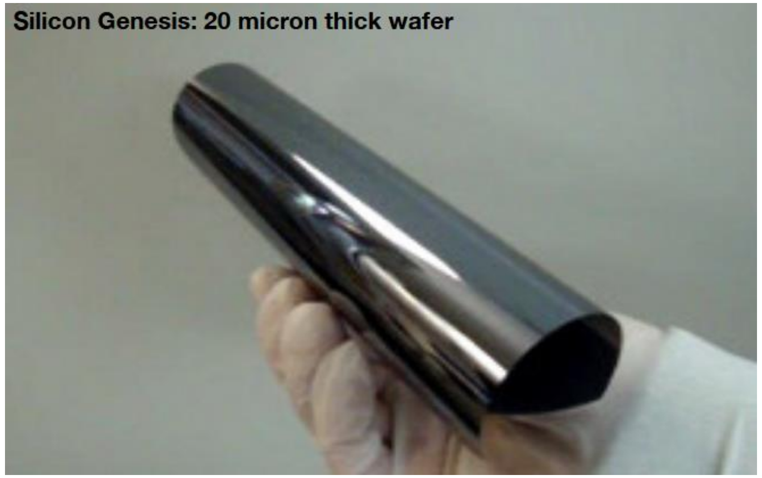
→ Triloki (Monday 18:30)



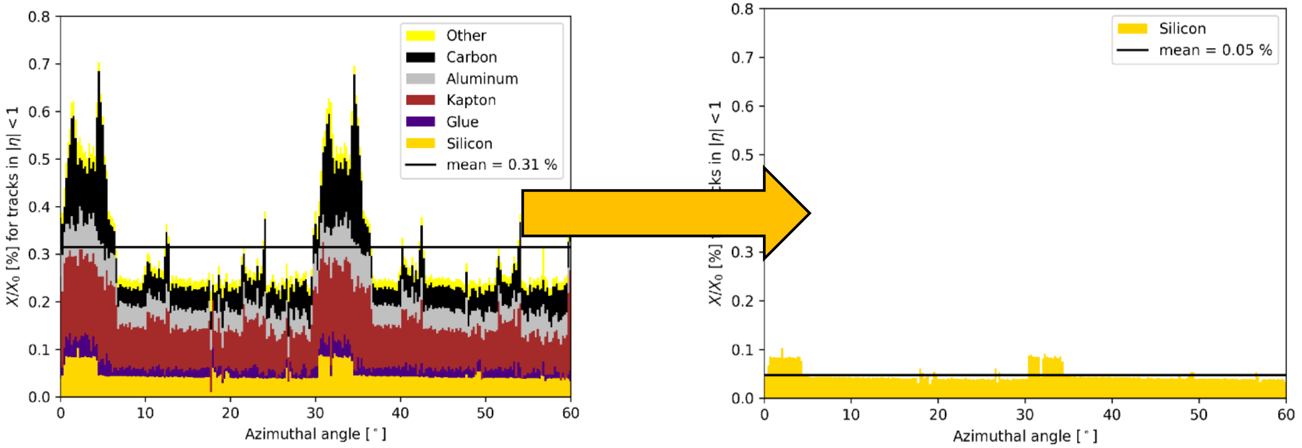
arXiv:2211.02491

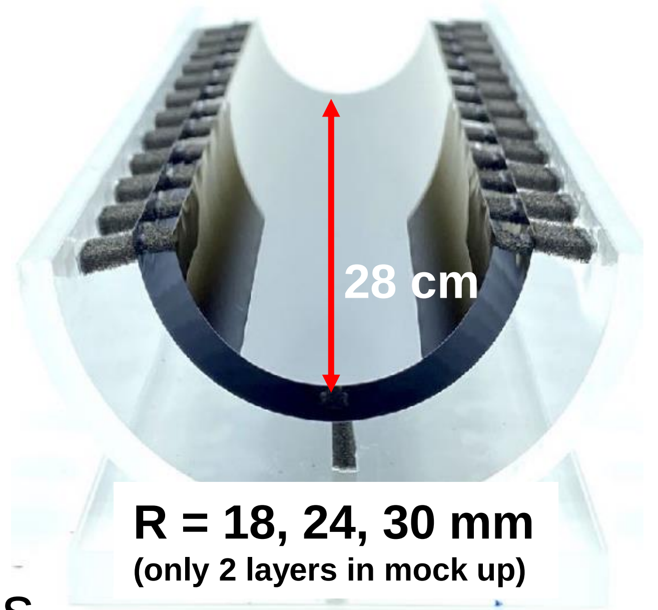


Silicon R&D



- ALICE ITS2 demonstrated: large scale (~10 m^2) use of monolithic active pixel sensors (MAPS), 50 μm thin
- Ongoing R&D for ALICE ITS3
  - Wafer-scale sensors using stitching + bending
  - "Zero-mass" detector: 0.02-0.04% X/X_0 per layer
  - Carbon foam + air cooling (power consumption < 20 mW/cm^2)

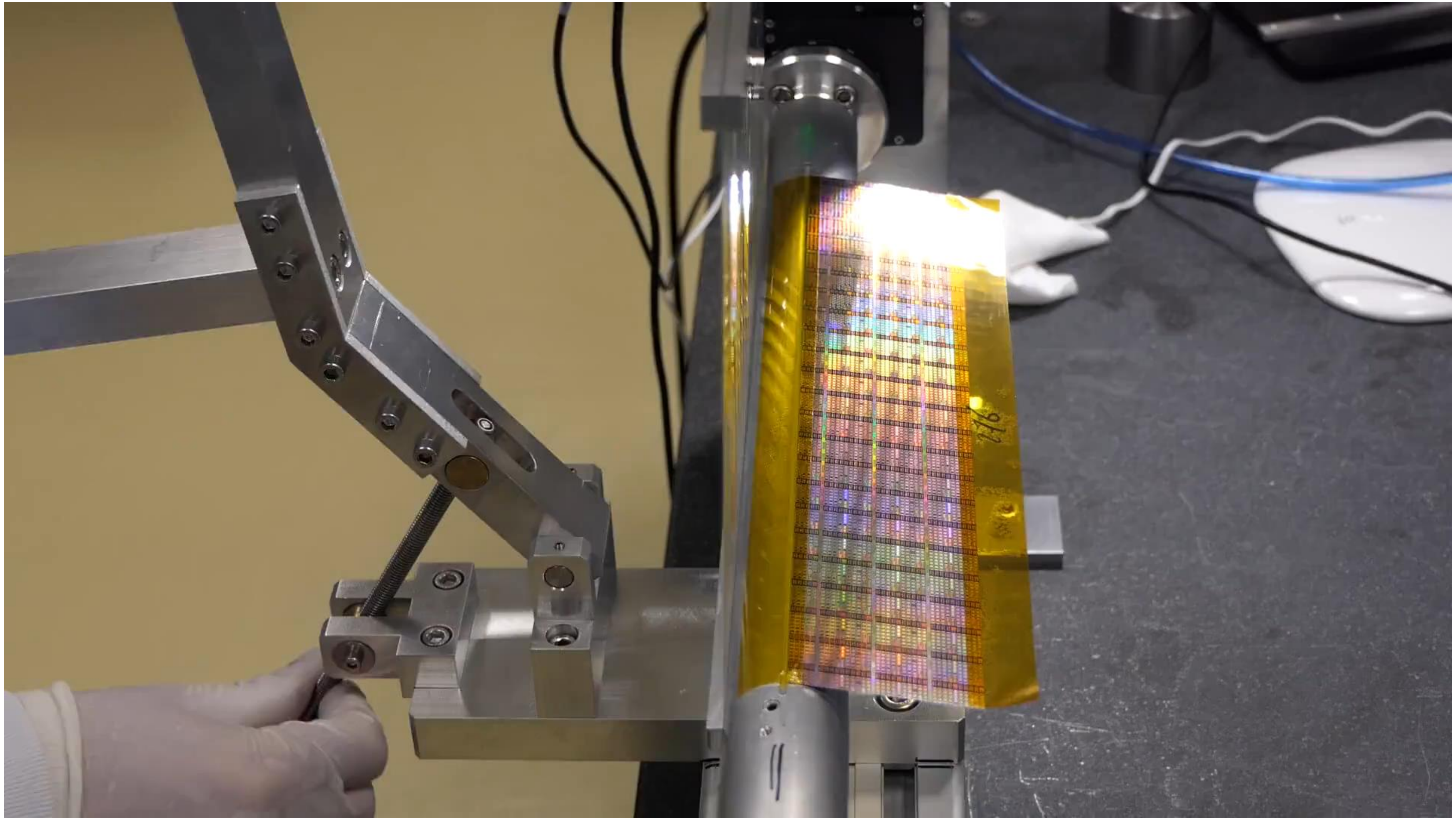




- ALICE 3 R&D for picosecond timing and radiation hardness

More details, see seminar by Magnus Mager

Bending an ITS3 Sensor



r = 18 mm !

Schedule

2021
2022
2023
2024
2025
2026
2027
2028
2029
J F M A M J J A S O N D
Run 3
Long Shutdown 3 (LS3)
ATLAS, CMS, LHCb
ALICE
NA60+
2030
2031
2032
2033
2034
2035
2036
2037
2038
Run 4
LS4
Run 5
ALICE 3
2039
2040
2041
LS5
Run 6
Last update: April 2023
Approved
Proposed
Shutdown/Technical stop
Protons physics
Ions
Commissioning with beam
Hardware commissioning

Summary

- Quark-Gluon Plasma produced in ultrarelativistic heavy-ion collisions
  - Legacy of measurements, significant precision in particular in light-flavour section
  - Detailed understanding of QGP medium properties
- Small-system observations (“collectivity”) challenge two paradigms at once
  - What is smallest system for which heavy ion “standard model” remains valid?
  - Can the standard tools for pp physics remain standard?
- Challenge to find *universal* hadronization model for these phenomena
- Future programme until end of LHC (in 2041)
  - Measure QGP dynamics with charm states
  - Study multi-charm production and temperature evolution of QGP

Thank you for your attention!