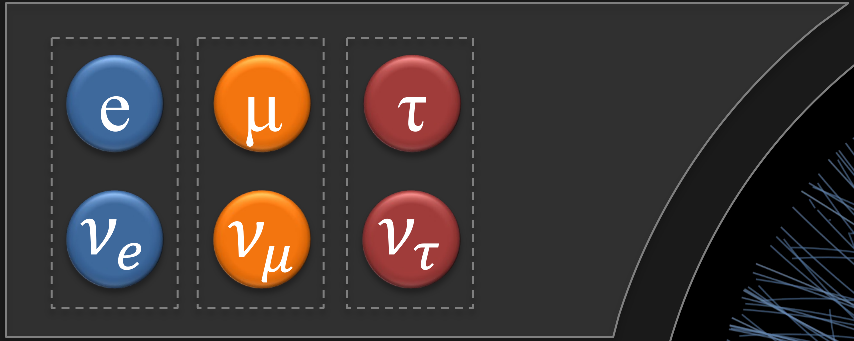
Emergent phenomena in high-density QCD matter at the LHC and beyond

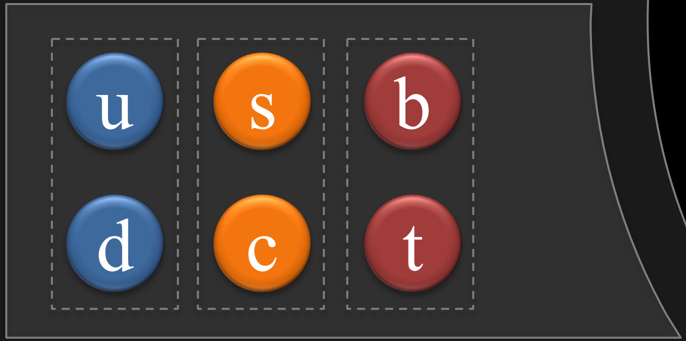
David Dobrigkeit Chinellato

Seminar at Oak Ridge National Laboratory

Constituents of matter



6 leptons

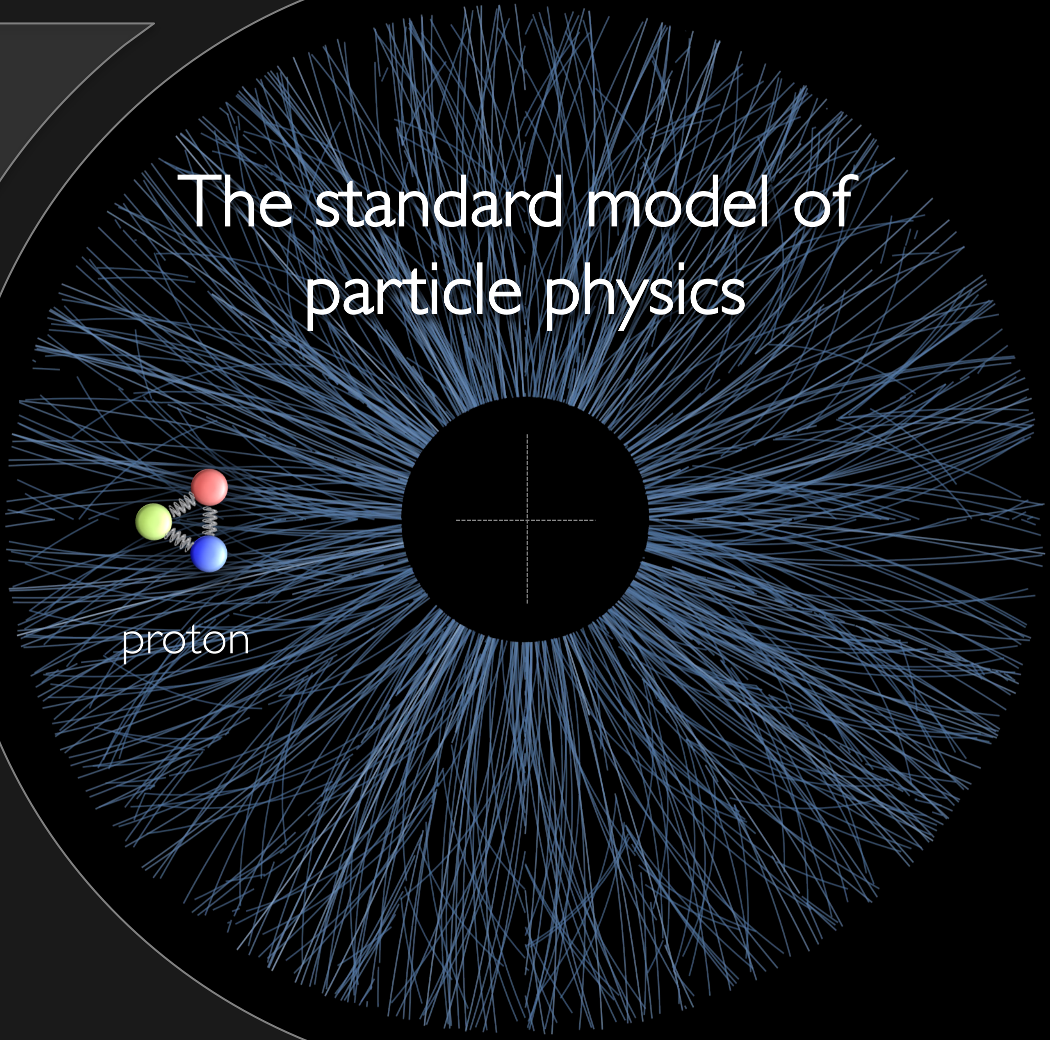


6 quarks

→ Quarks carry color charge:
Red, green, blue

→ Antiquarks carry anticolor:
cyan, magenta, yellow

The standard model of particle physics



Constituents of matter

e	μ	τ
ν_e	ν_μ	ν_τ

6 leptons

u	s	b
d	c	t

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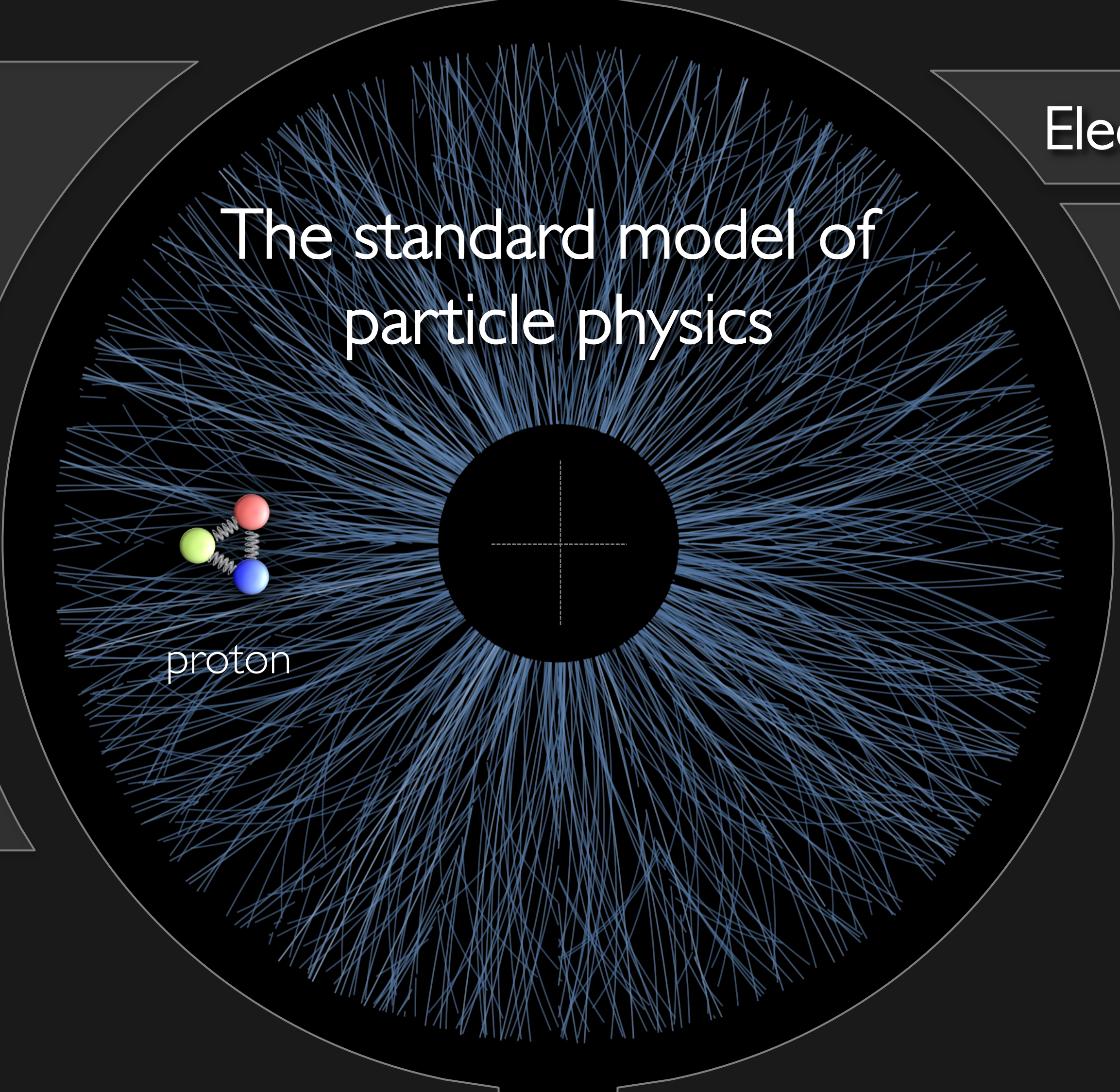

Fundamental interactions

- Electromagnetic interaction
- Weak interaction
- Strong interaction
- Gravity

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

→ Quarks may ordinarily only be found confined into colorless hadrons

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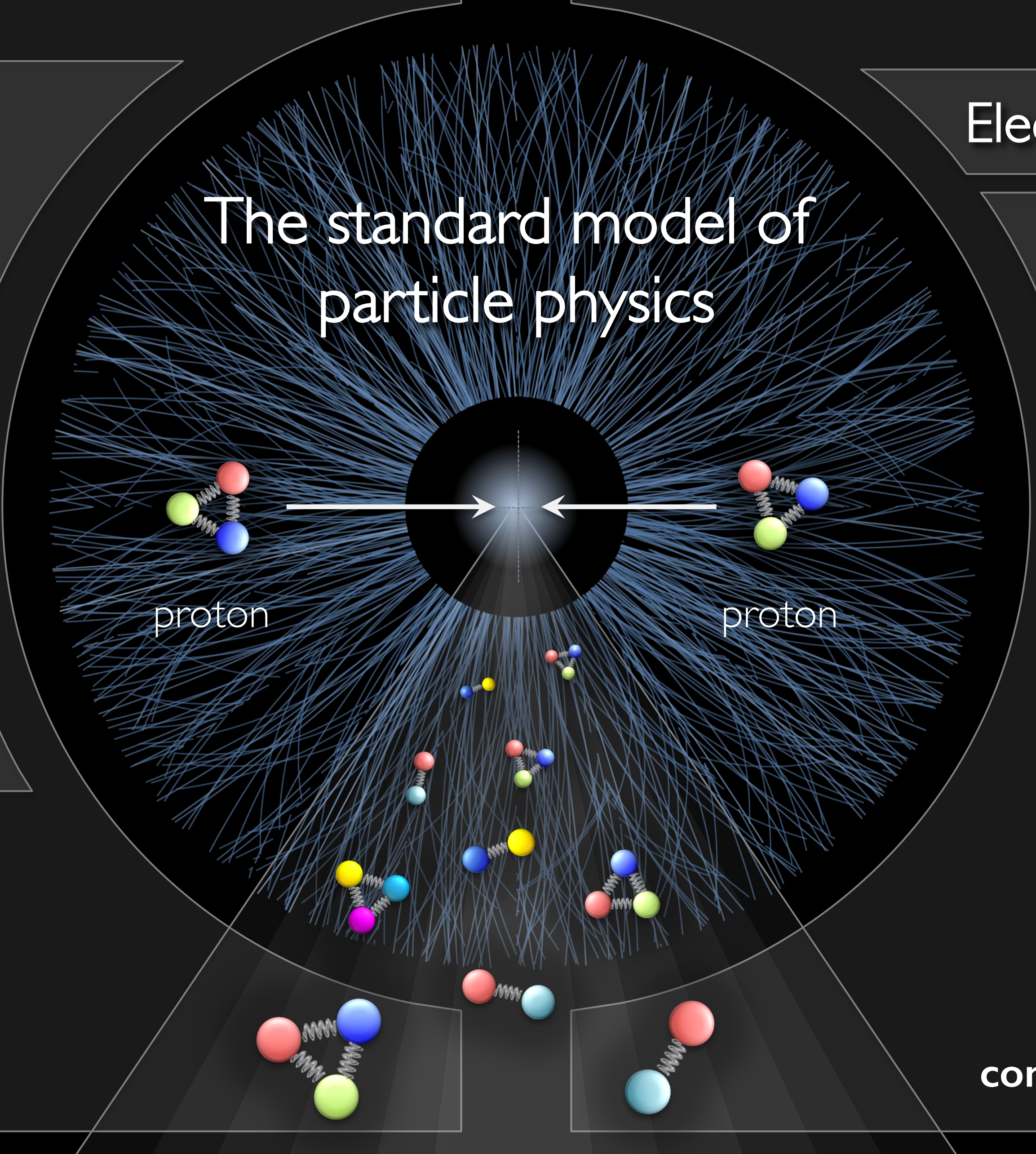

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Strong interaction

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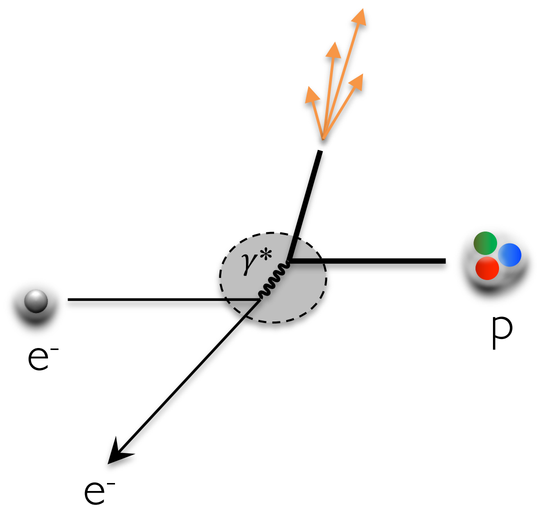
→ Quarks may ordinarily only be found confined into colorless hadrons

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

Describing electron, proton and nuclei collisions

electron-proton collisions



- QED/QCD coupling: γ^* exchange
- Single scattering in initial state
- initial parton energy can be inferred by kinematics

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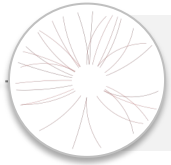

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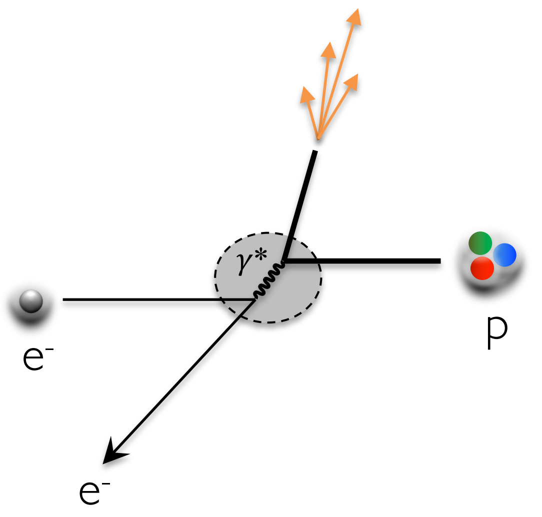

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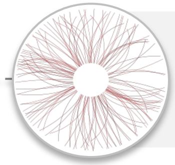
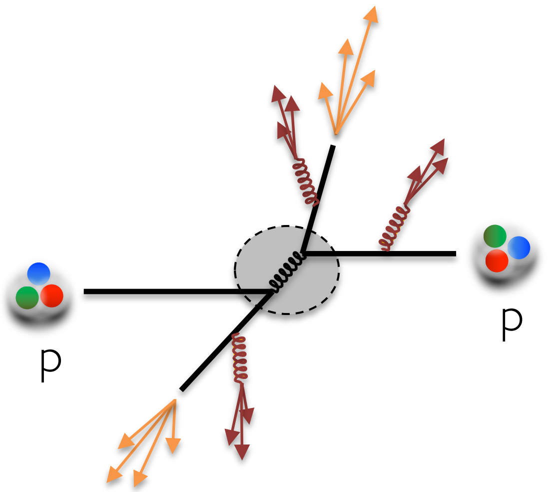


High-multiplicity pp, proton-lead collisions



- 2 → 2 scatterings (LO QCD)
- Soft physics: initial and final state radiation

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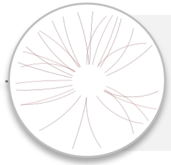

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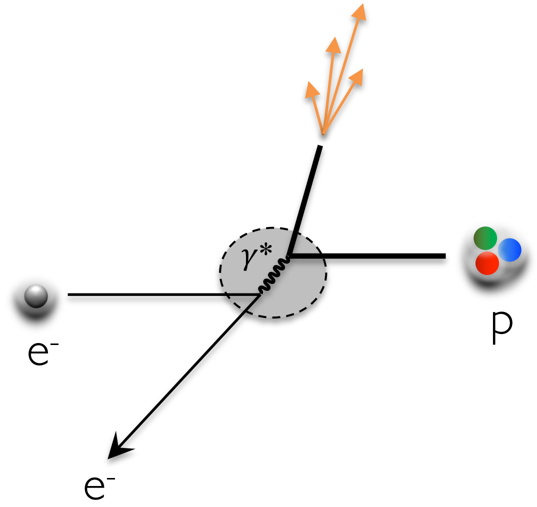

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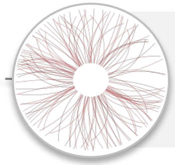

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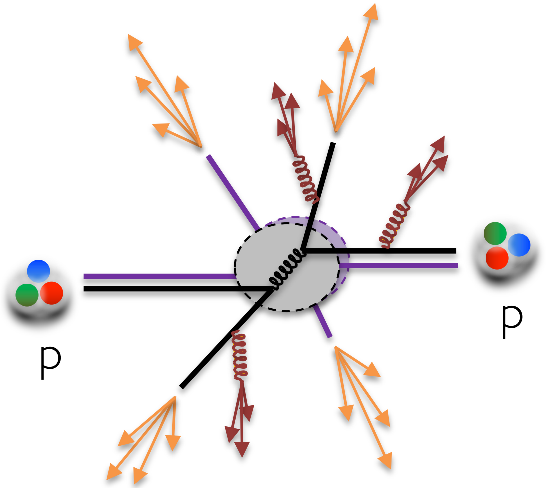

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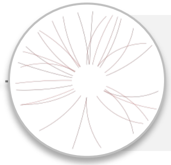

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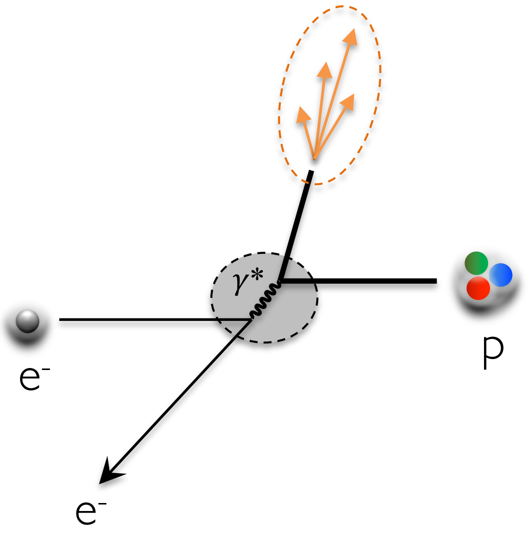

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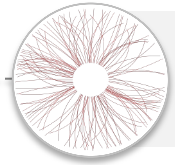

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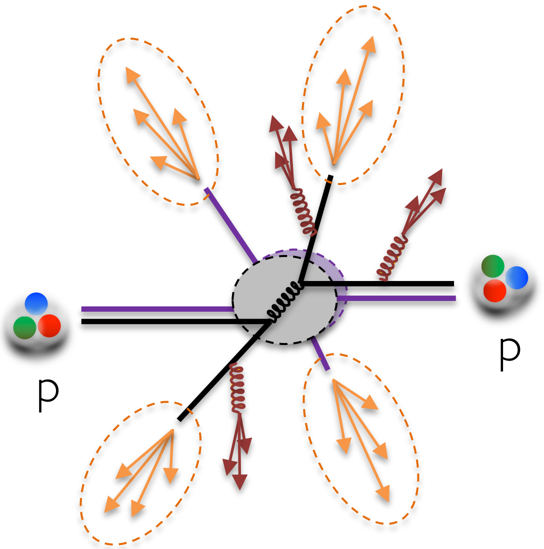

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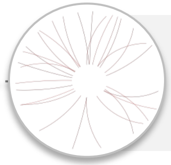
Jet universality:
Given a specific outgoing parton with a specific momentum, final hadrons are always the same

Describing electron, proton and nuclei collisions



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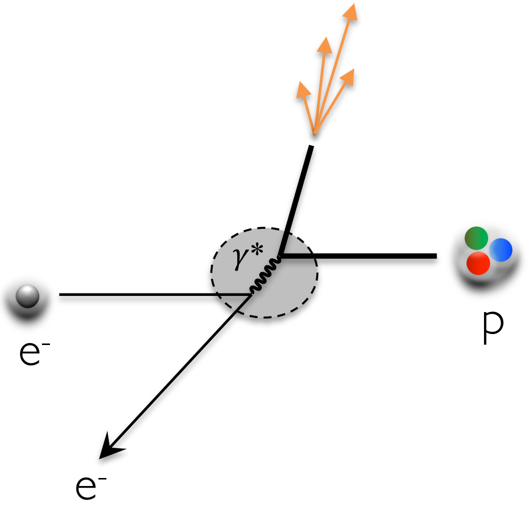

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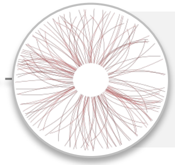

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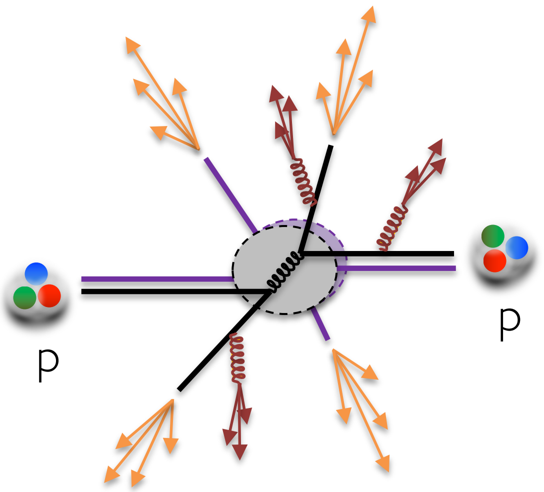

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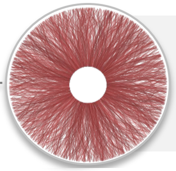
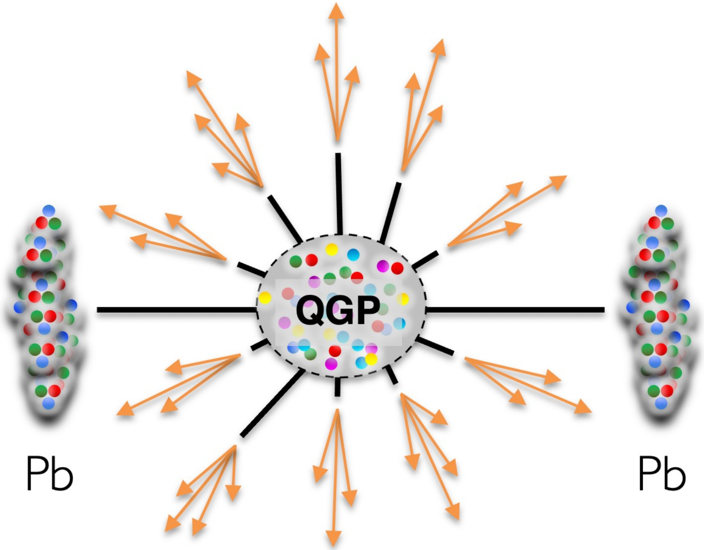
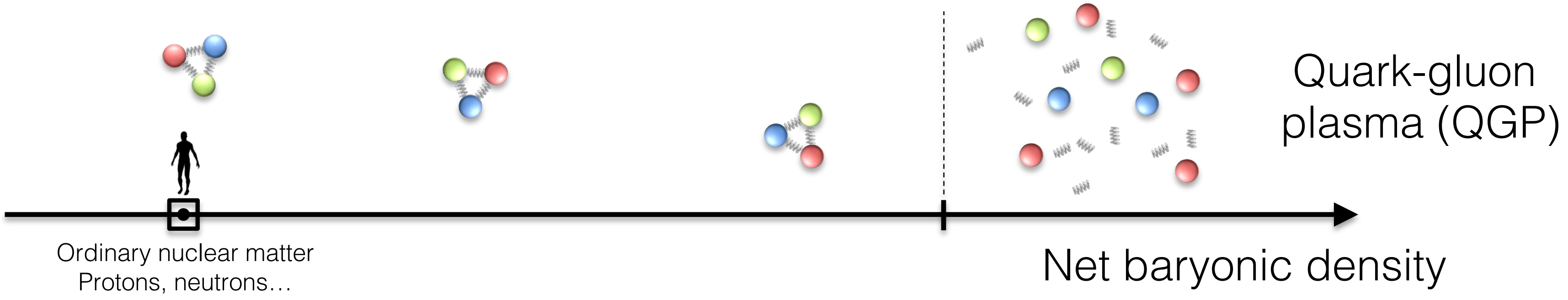


lead-lead (Pb-Pb) collisions



Quark-gluon plasma (QGP) kinematically and chemically equilibrated system: hydrodynamics and statistical principles

The phase diagram of QCD matter



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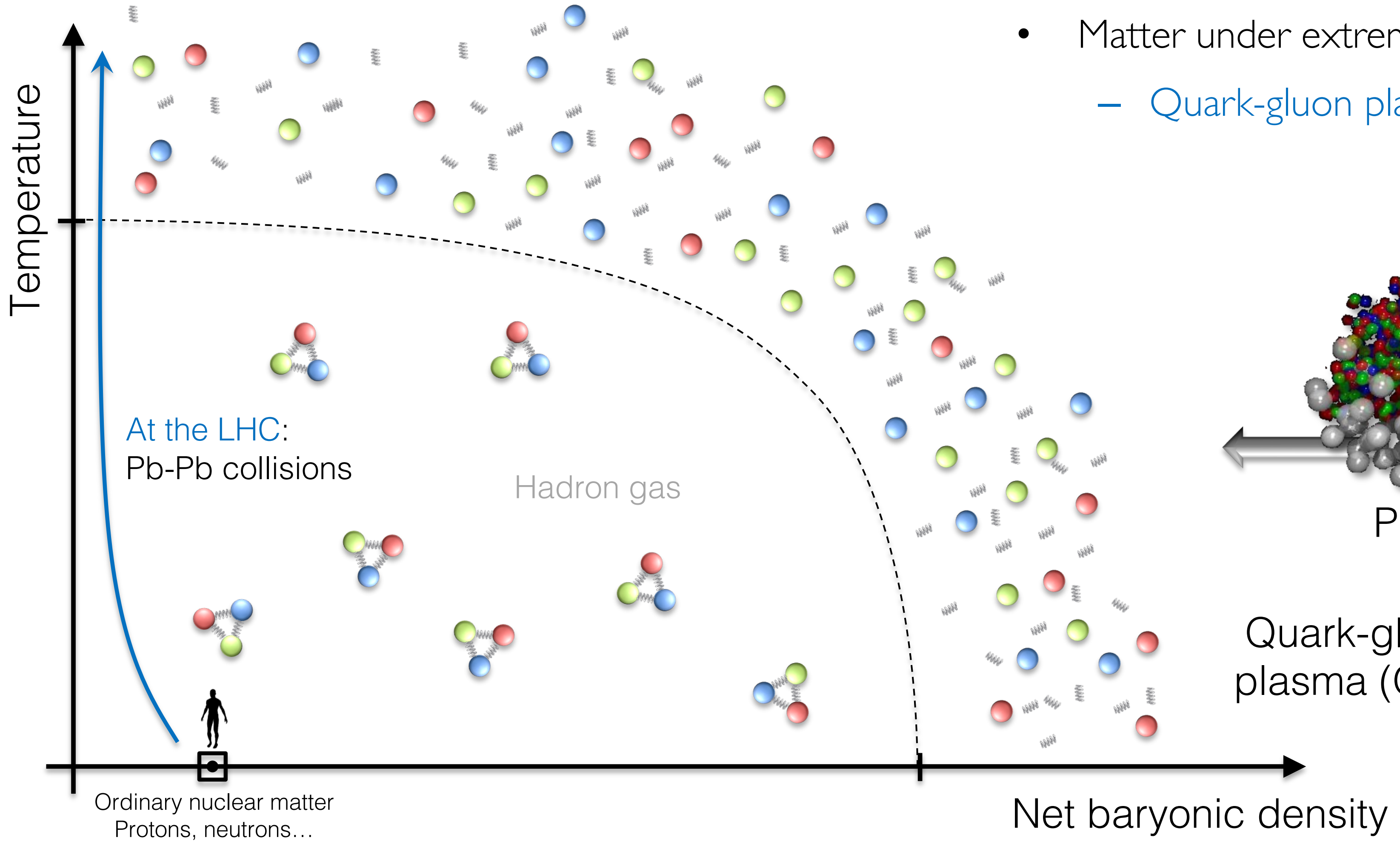
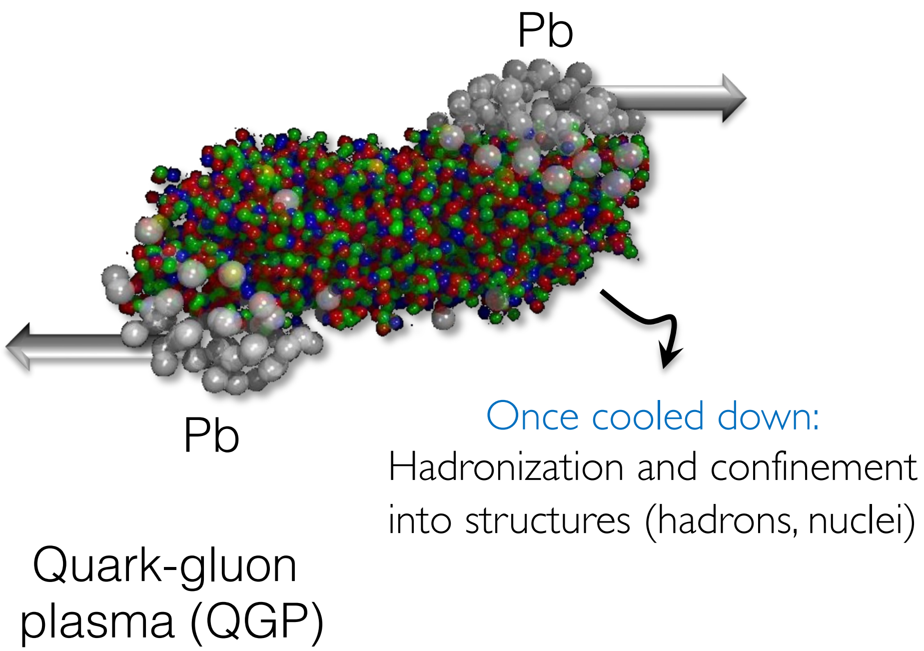


- Matter under extreme conditions:
  - Quark-gluon plasma



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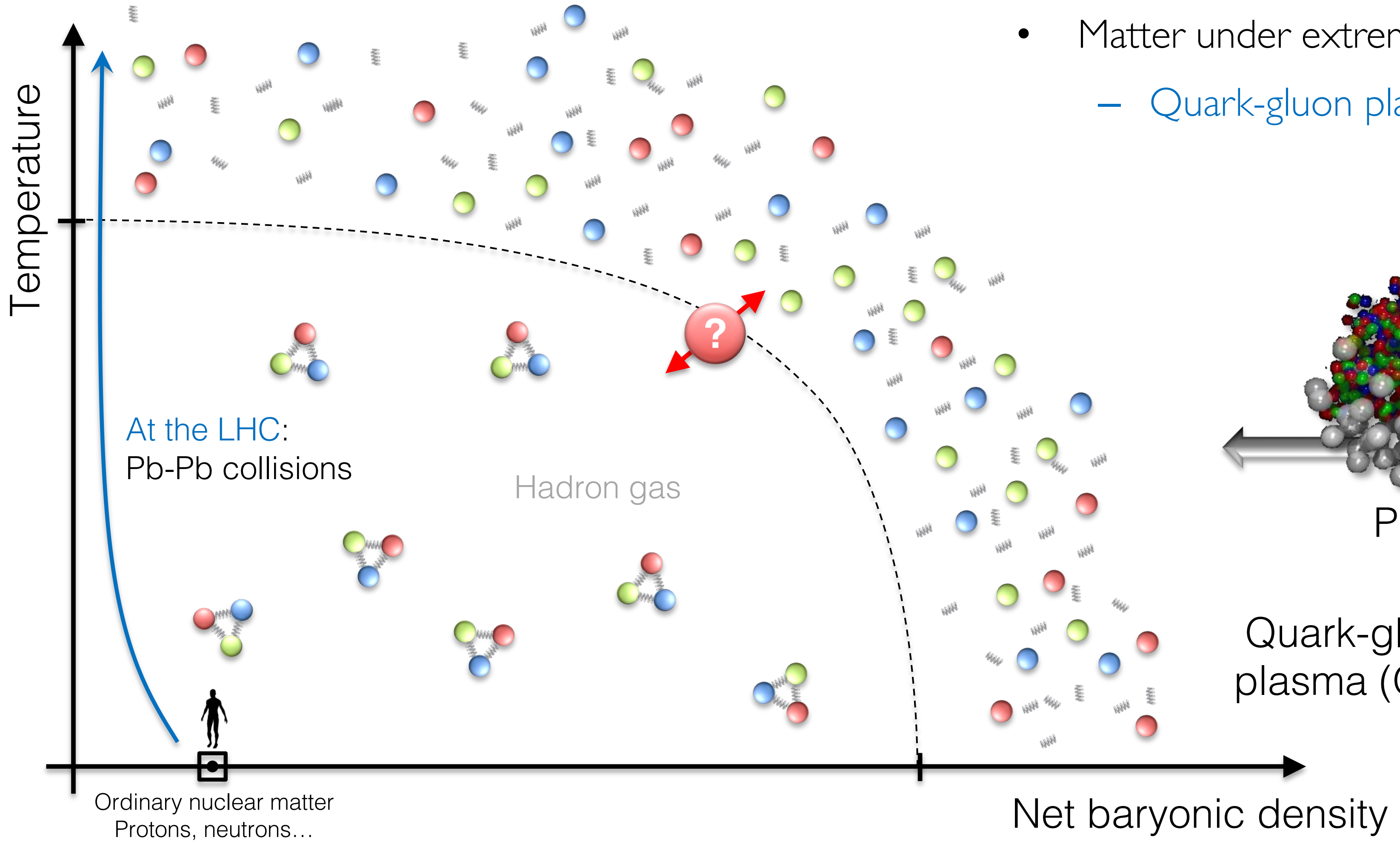

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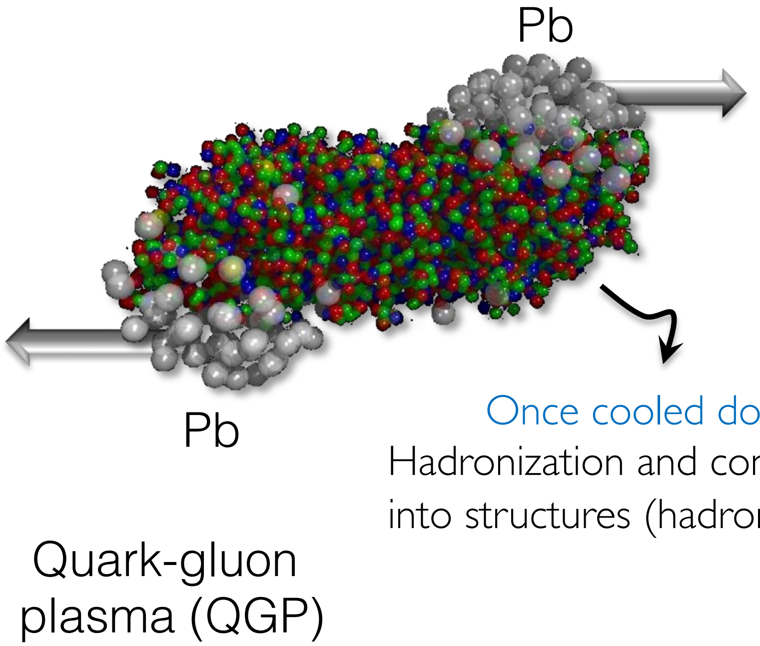
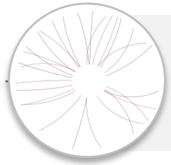


Once cooled down:
Hadronization and confinement into structures (hadrons, nuclei)

Describing electron, proton and nuclei collisions



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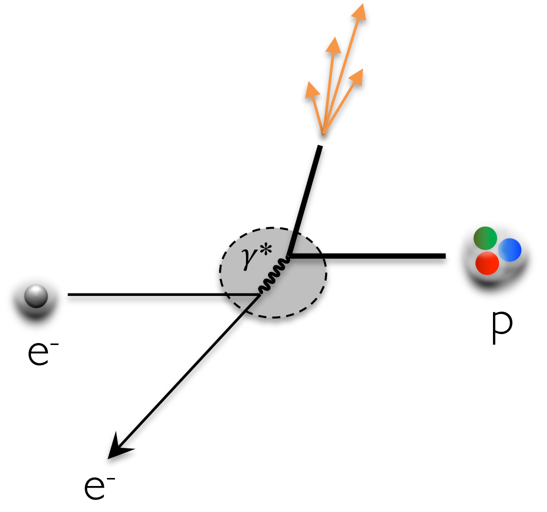

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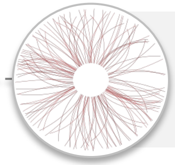

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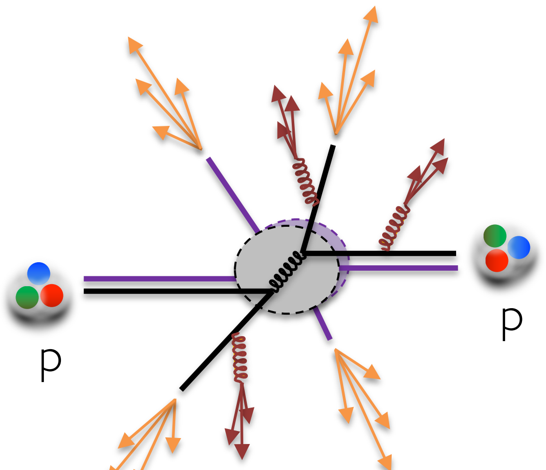

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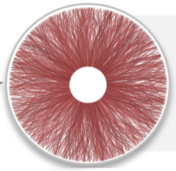

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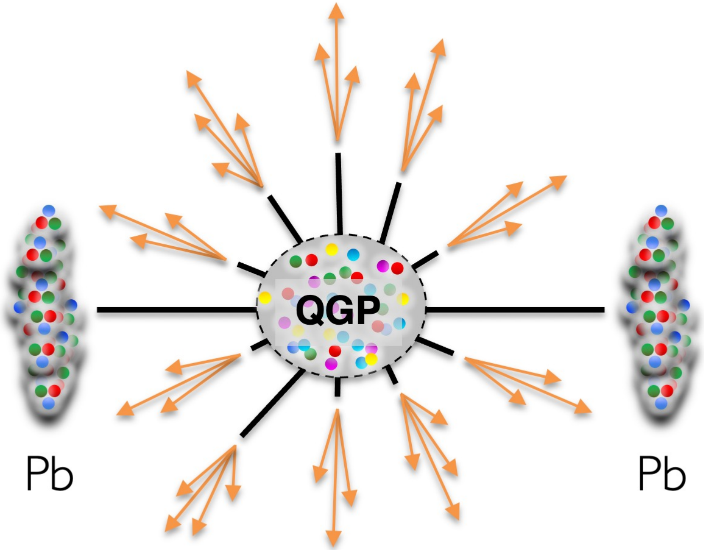
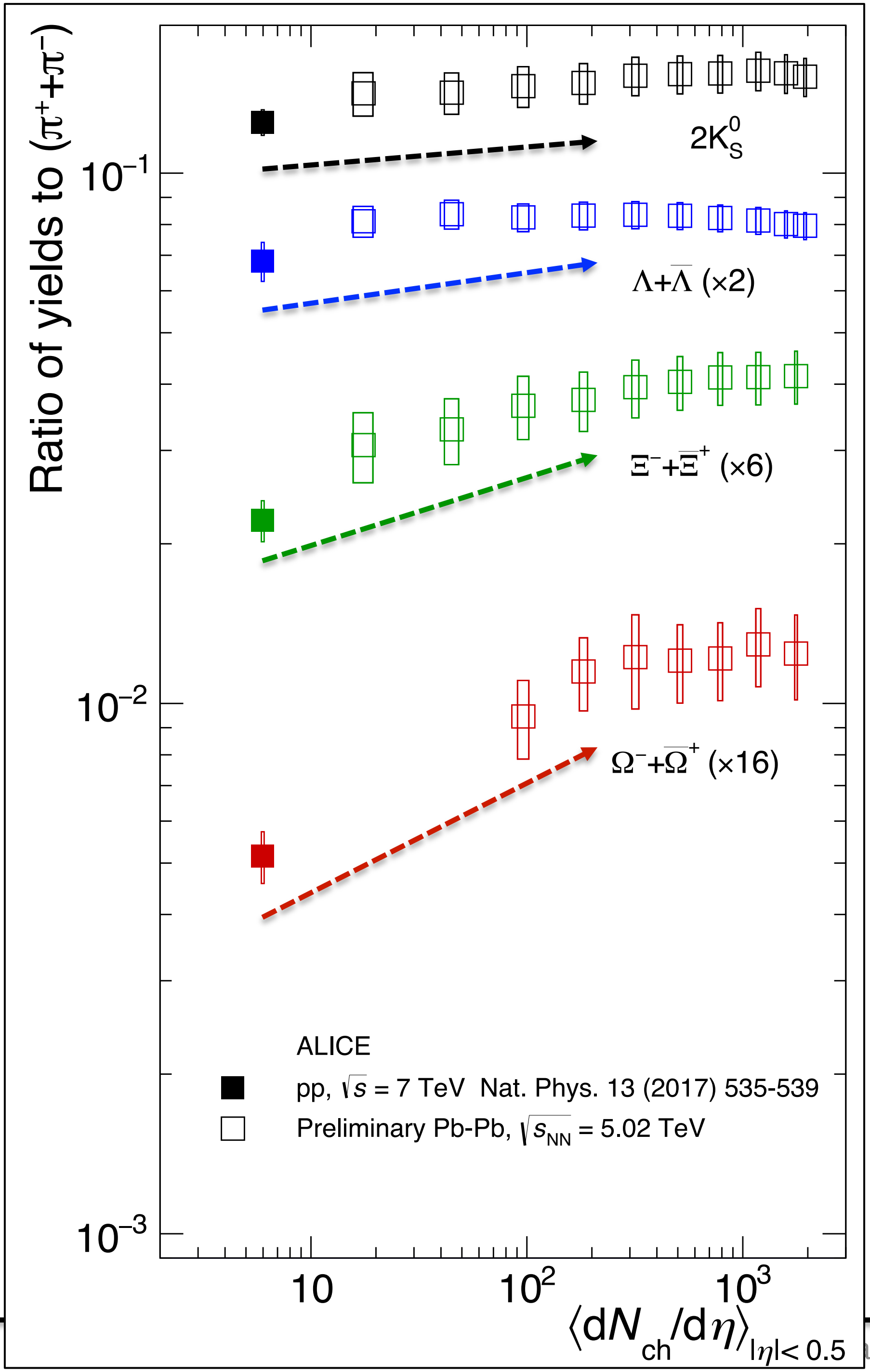
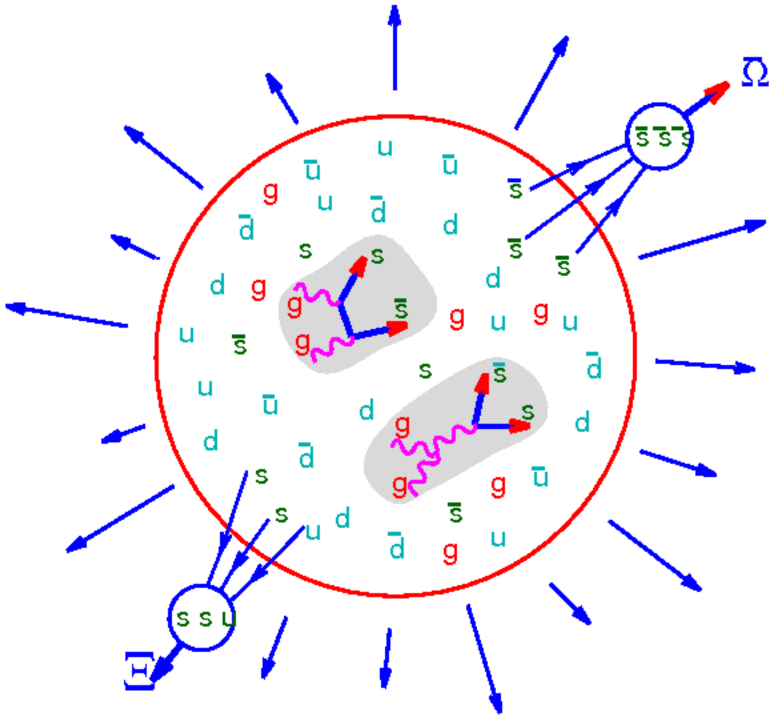


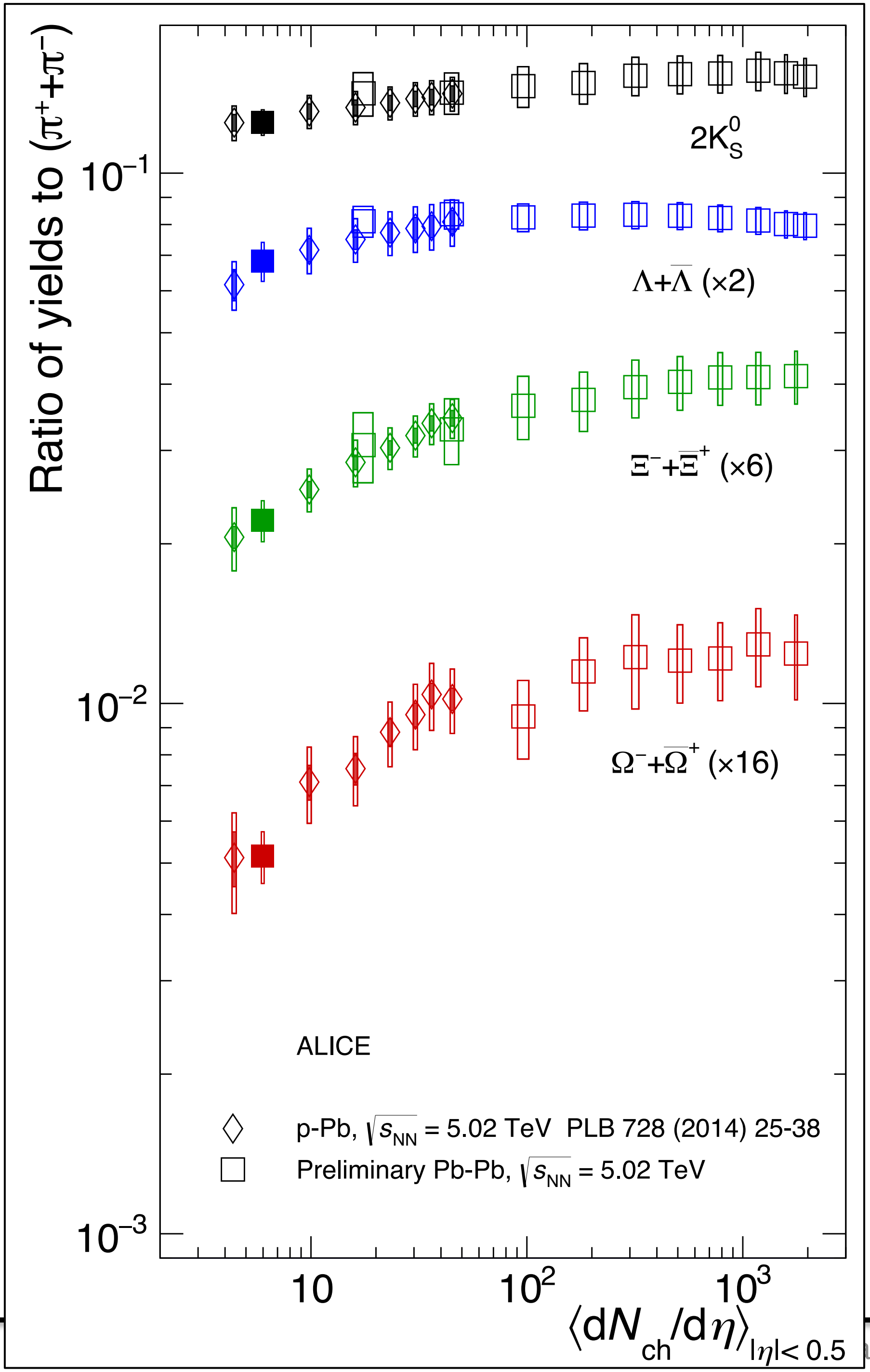
Quark-gluon plasma (QGP) kinematically and chemically equilibrated system: hydrodynamics and statistical principles

Strangeness production

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







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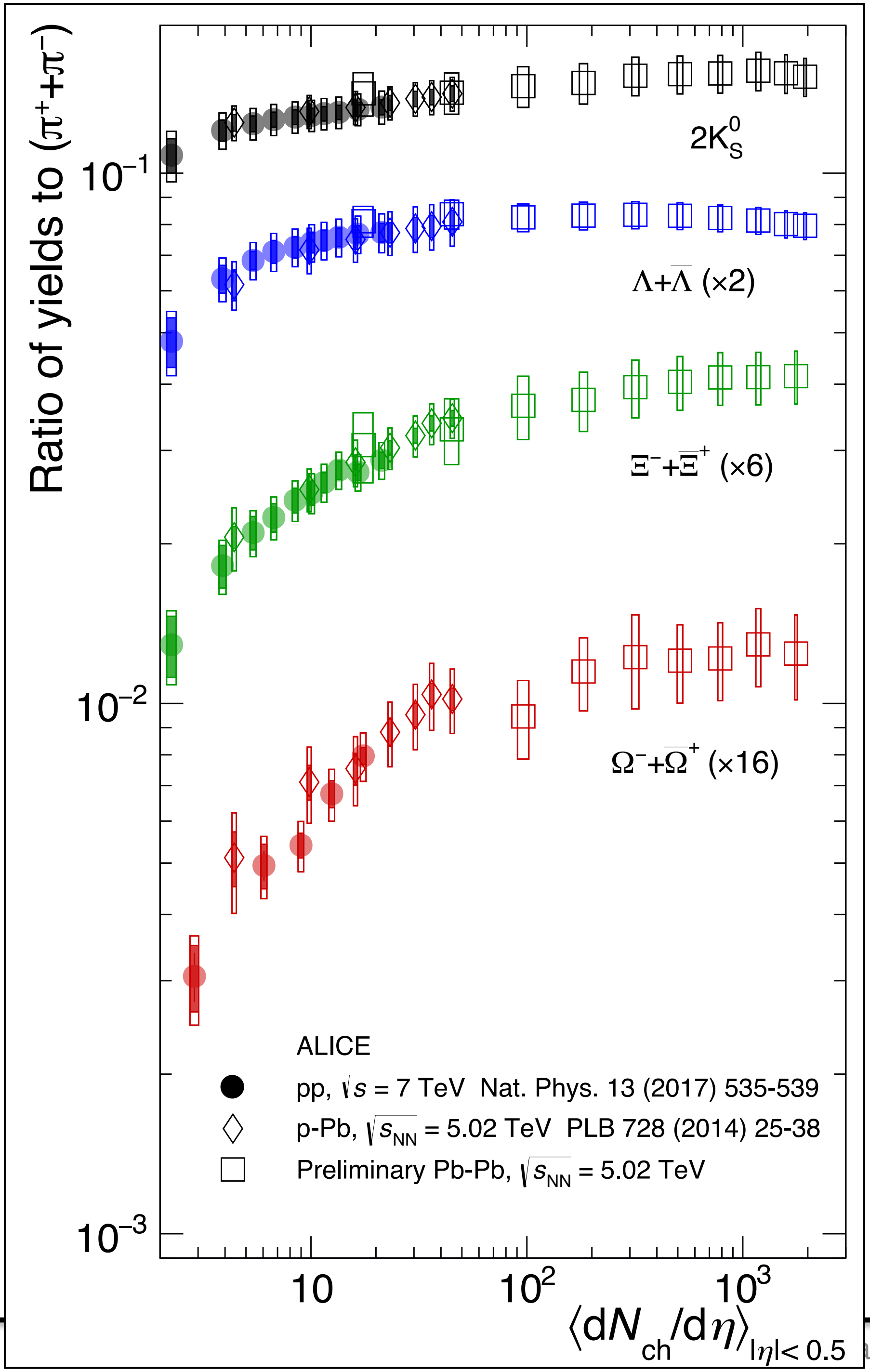
  - Strangeness increases with multiplicity following a universal trend



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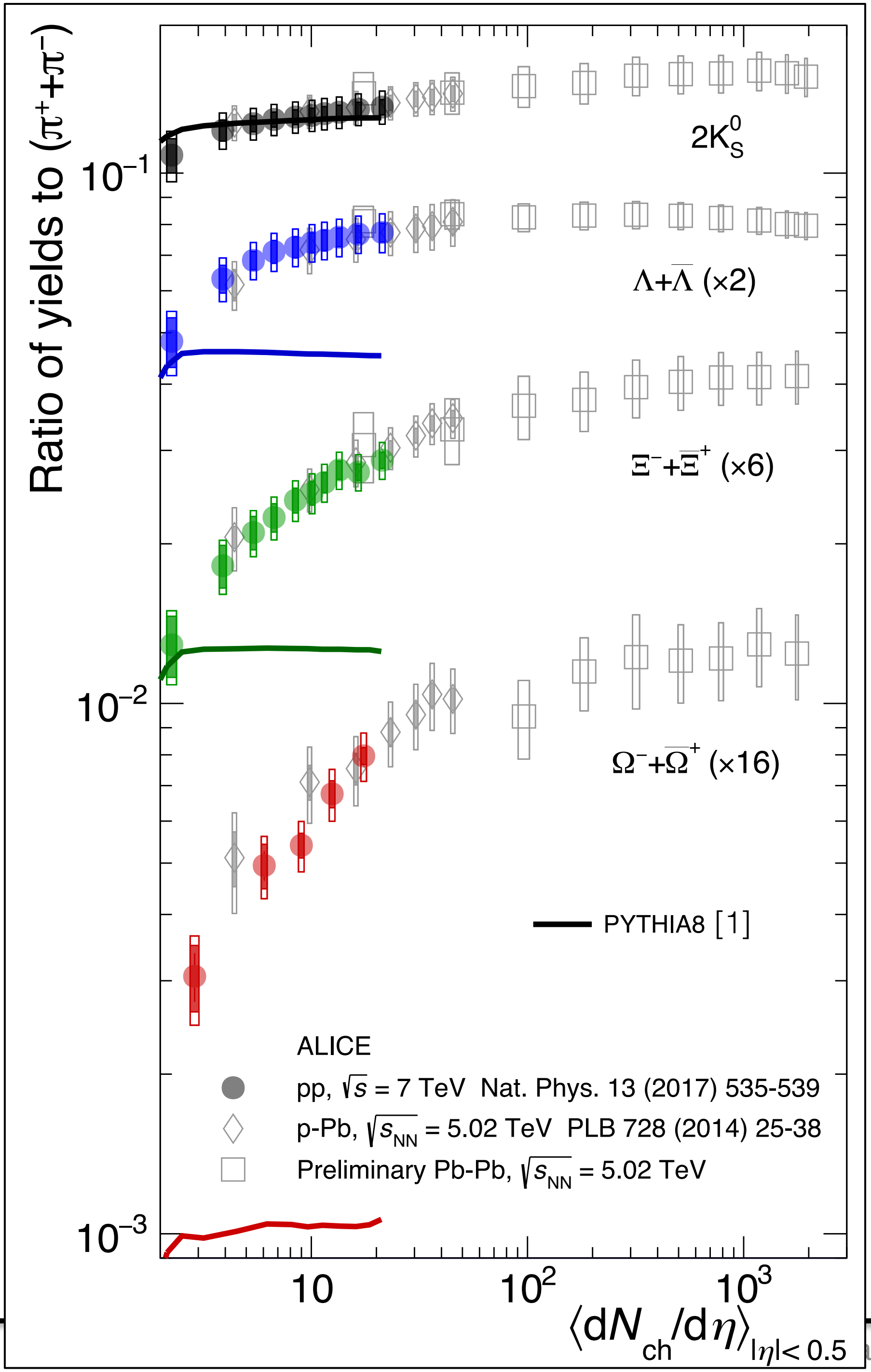

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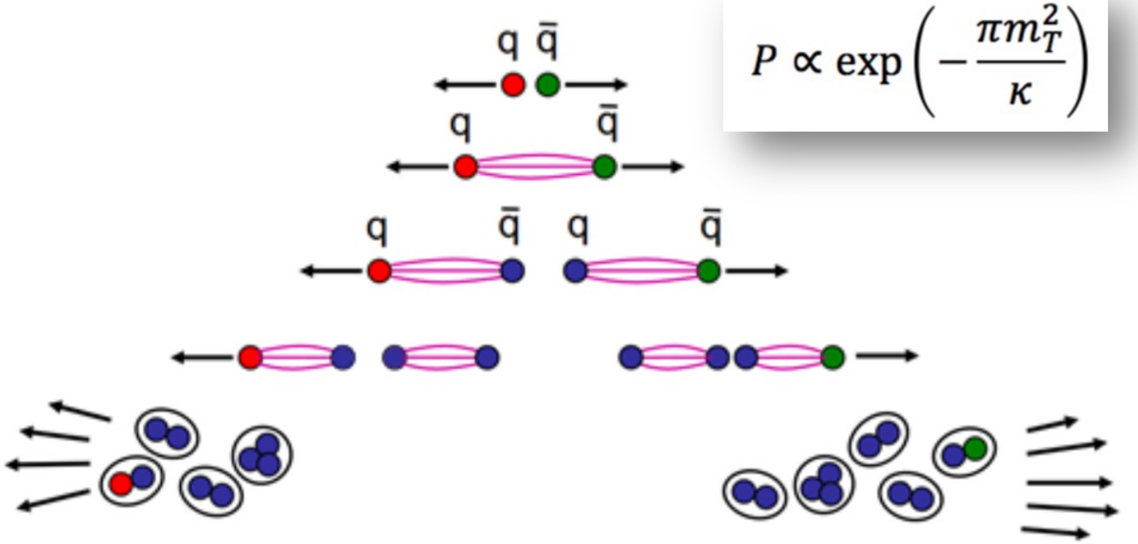
  - Production wrt to π enhanced
- Also studied in p-Pb and pp
  - Strangeness increases with multiplicity following a universal trend
- Not described by PYTHIA

- How can this be achieved?

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

Particle production in the Lund model



$$P \propto \exp\left(-\frac{\pi m_T^2}{\kappa}\right)$$

- Hadronization can be described as the breakup of color flux tubes (“strings”) with constant energy density / tension
- Standard PYTHIA with MPI: no increase of strangeness production

QCD perspective

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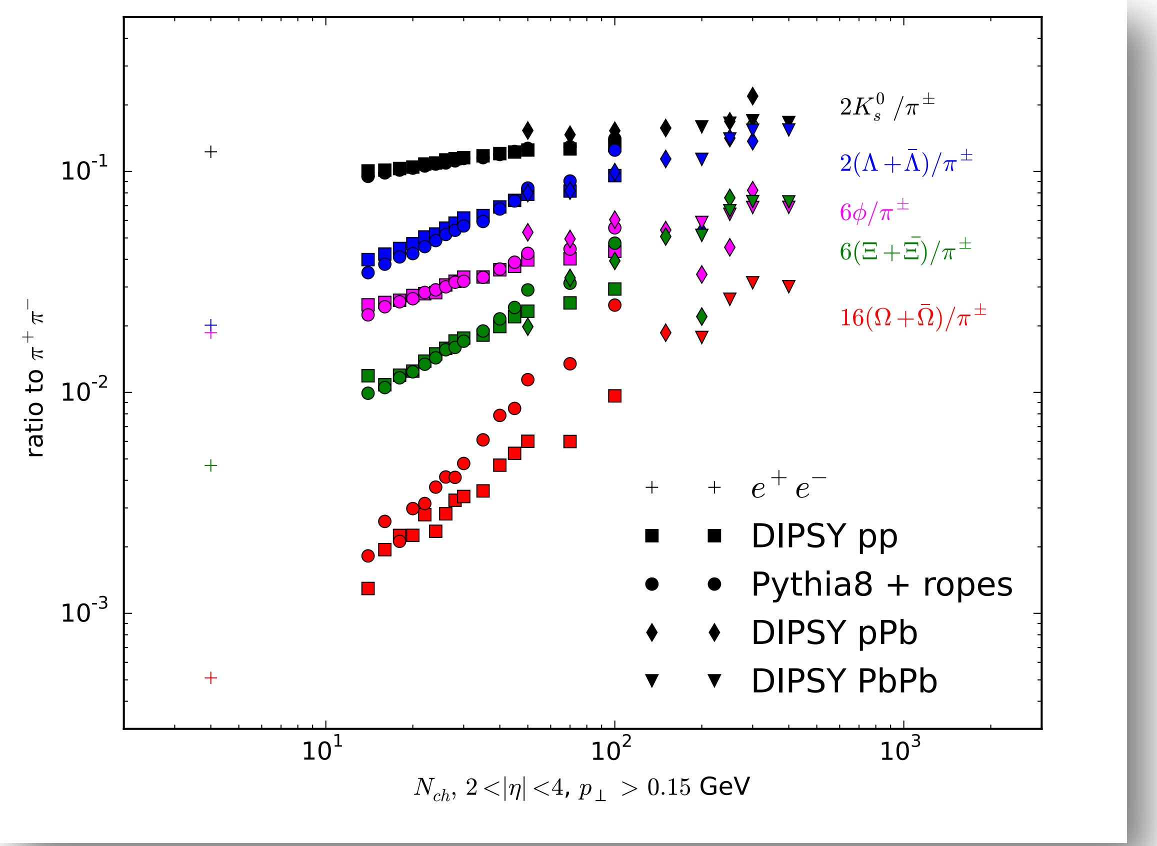
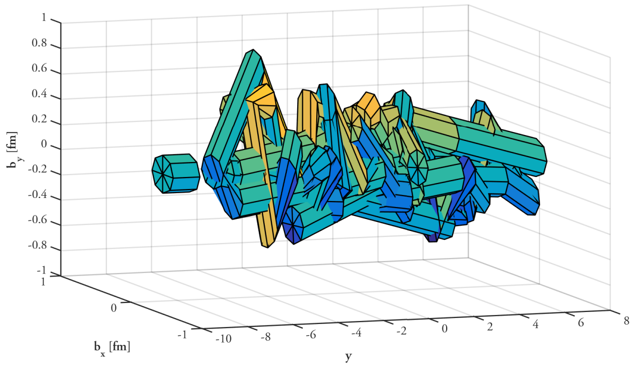


C. Bierlich, https://indico.cern.ch/event/732345/contributions/3024828/attachments/1668639/2676025/cbierlich.pdf

- Hadronization can be described as the breakup of color flux tubes ("strings") with constant energy density / tension
- Standard PYTHIA with MPI: no increase of strangeness production
- New development: in high-density conditions, strings may overlap to form color ropes
  - Increased tension → increase in s production!



$$P \propto \exp\left(-\frac{\pi m_T^2}{\kappa}\right)$$

$$\tilde{P} \propto \exp\left(-\frac{\pi m_T^2}{\tilde{\kappa}}\right)$$

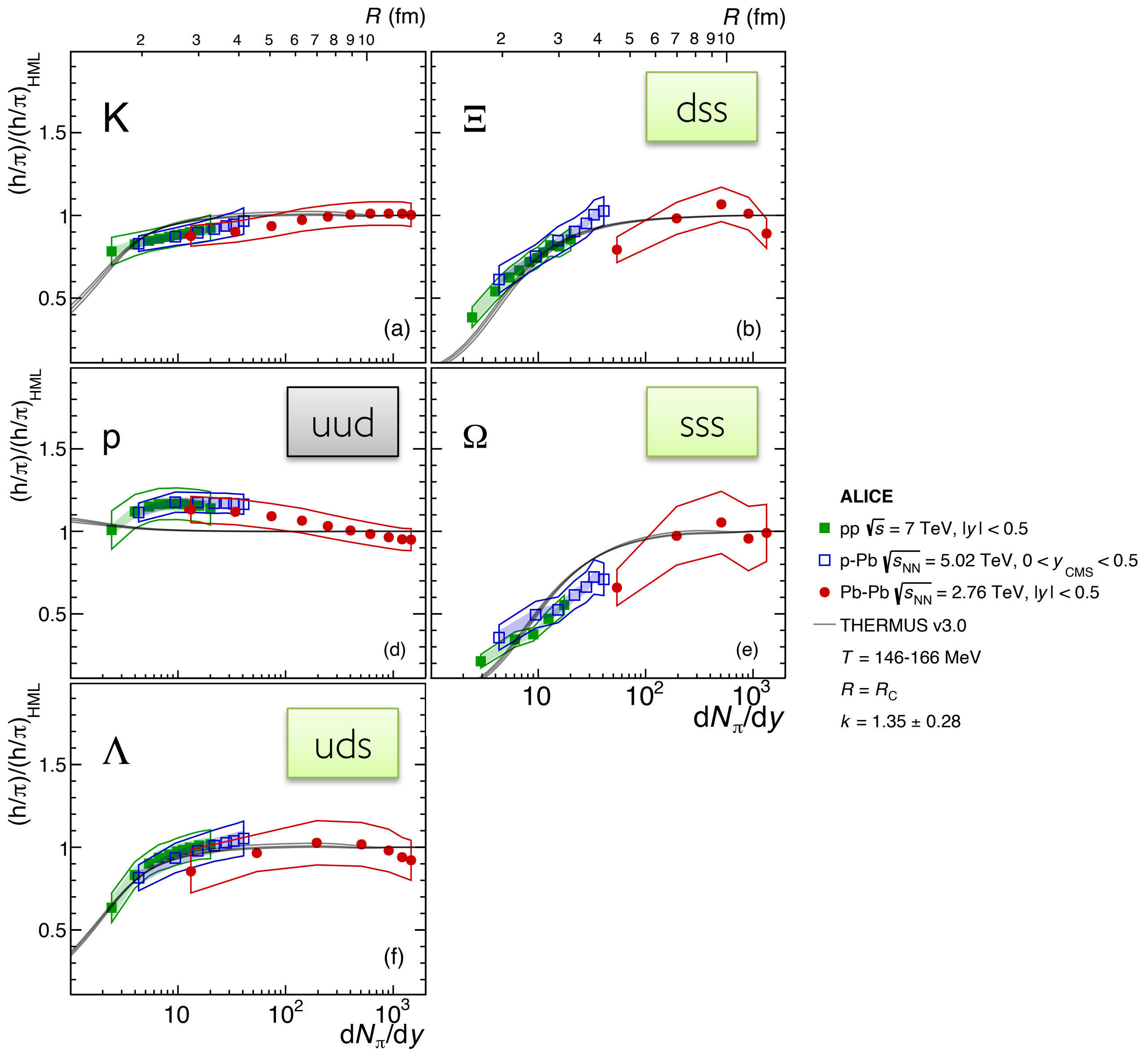
$$\tilde{\kappa} > \kappa$$

Heavy-ion perspective

The statistical hadronization picture:

Canonical suppression

- Statistical Hadronization Models (e.g. Thermus) can be used to describe relative particle species abundances
- In small systems and multiplicities:
  - strangeness must be exactly conserved
  - leads to suppression of open strangeness
- Effect depends on system size; SHM description holds over certain rapidity range *k*
  - From data, k = 1.35 ± 0.28
- Description OK for strangeness



ALICE, Phys. Rev. C 99, 024906

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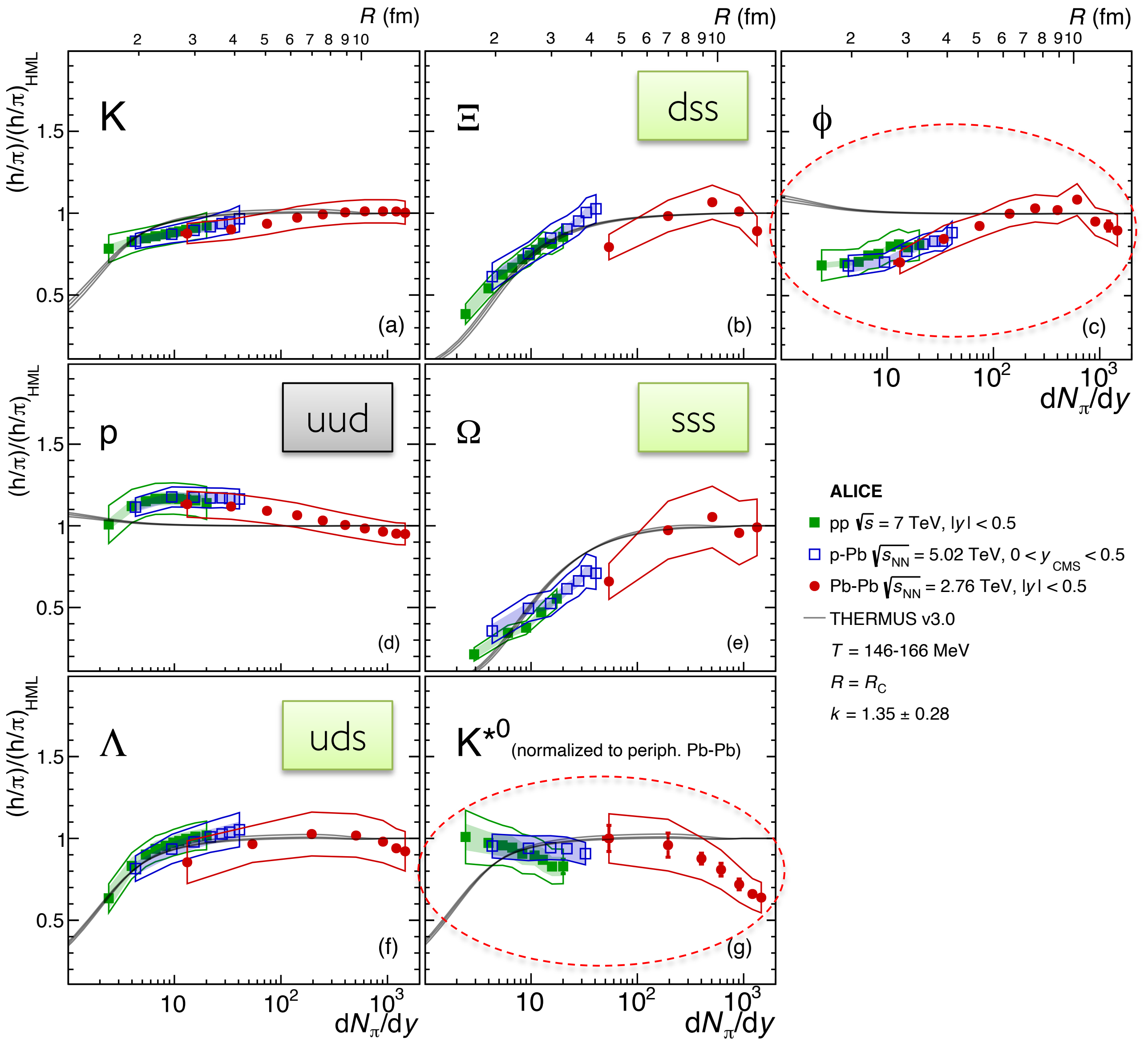
- Description OK for strangeness
  - But fails for ϕ: net strangeness zero…
  - And fails for K^{*0}: affected by post-hadronization effects (rescattering)



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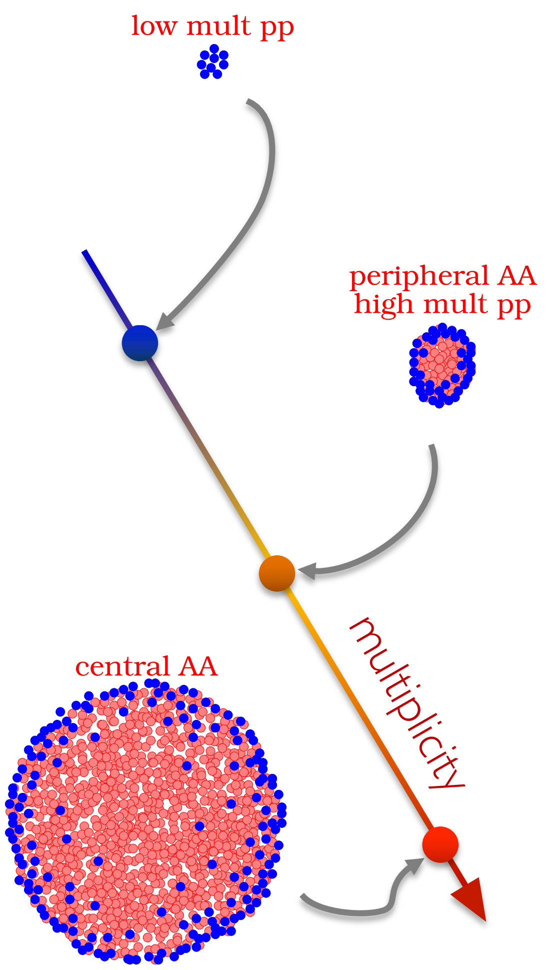
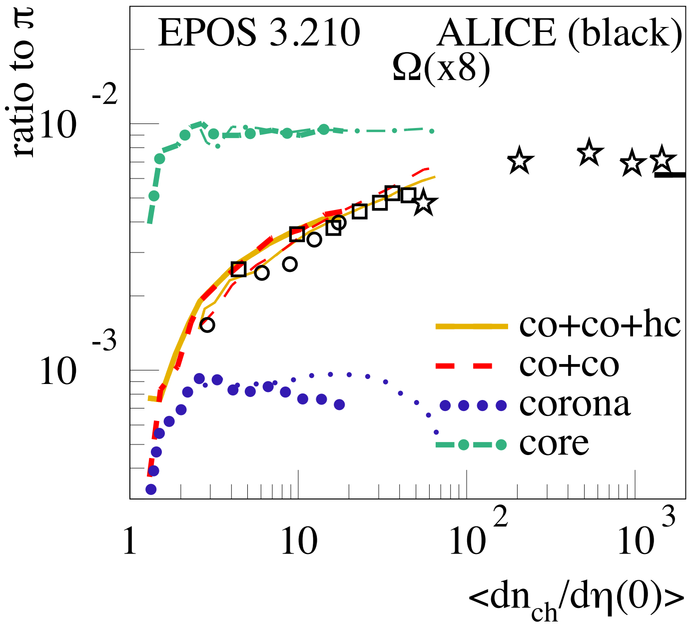
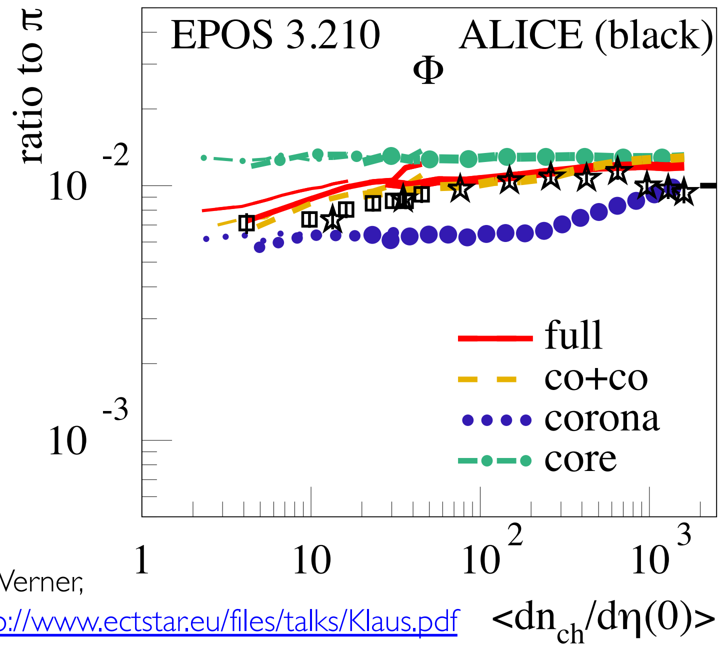
Combined / hybrid perspective

Strangeness in EPOS 3: The core-corona approach



- At time τ_0 (before hadronization) strings divided into fluid (CORE) and escaping (CORONA) according to momenta and local density
  - Corona: string fragmentation (Lund)
  - Core: from time τ_0 evolves as a viscous hydrodynamic system. Hadronization happens statistically at a common T_H
- After hadronization: hadronic cascade model (UrQMD)
  - N.B.: droplet of QGP needed

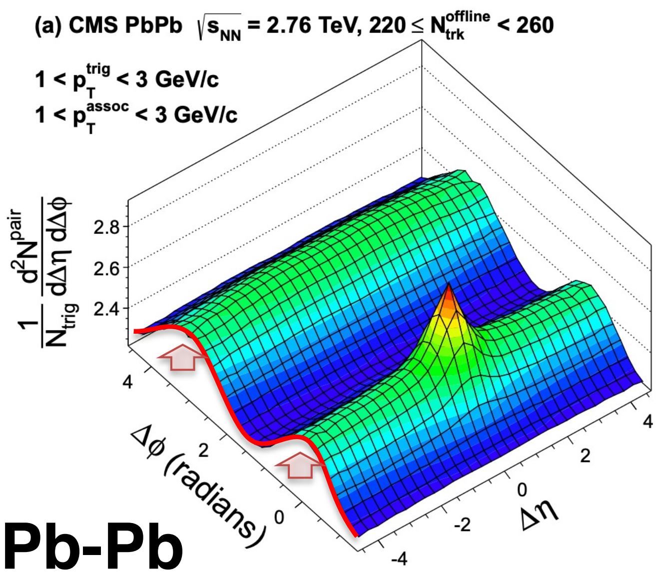




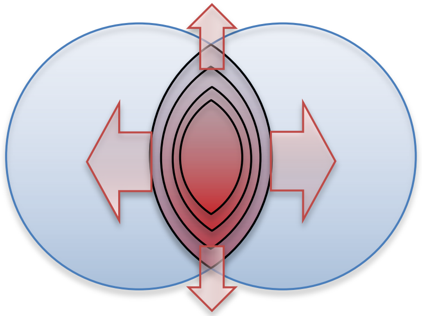
K. Werner, http://www.ectstar.eu/files/talks/Klaus.pdf

Long-range near-side particle correlations from pp to Pb-Pb

Phys. Lett. B 724 (2013) 213



Pb-Pb



Collective expansion

- In Pb-Pb collisions, particles are emitted with a modulation in azimuth due to collective expansion of an elliptic initial condition

Long-range near-side particle correlations from pp to Pb-Pb

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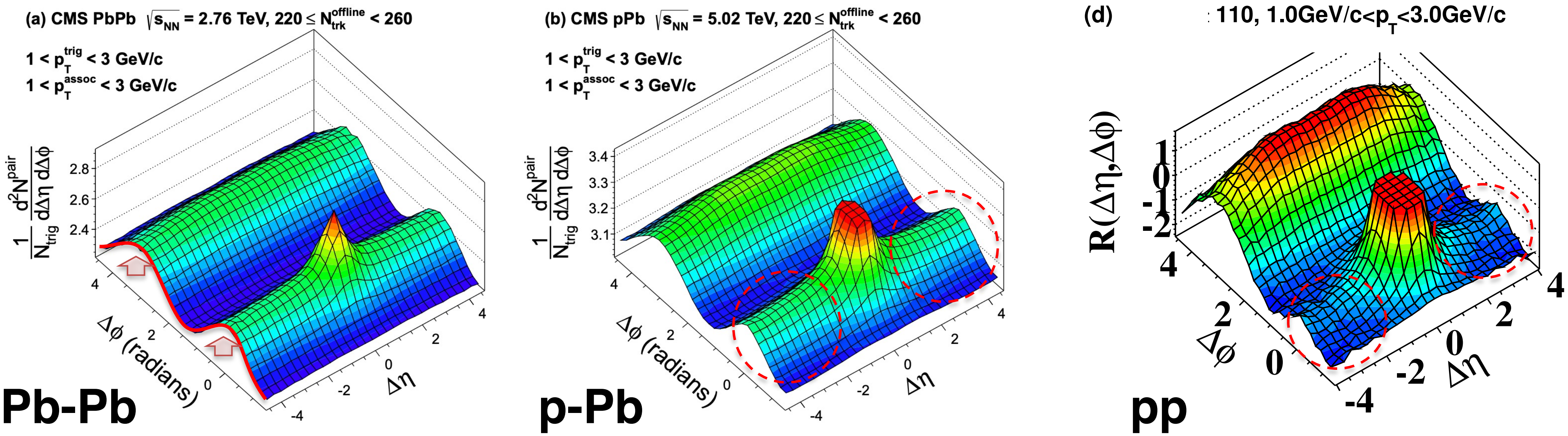
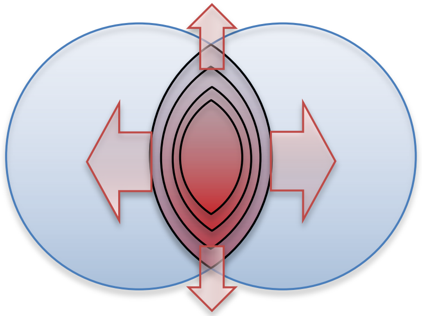


JHEP 1009:091,2010



Collective expansion

- In Pb-Pb collisions, particles are emitted with a modulation in azimuth due to collective expansion of an elliptic initial condition
- Also observed in p-Pb and pp
    - Initial condition not necessarily elliptic
    - Collective expansion also at play?
    - Under which conditions does this **not** happen?

Long-range near-side particle correlations from pp to Pb-Pb

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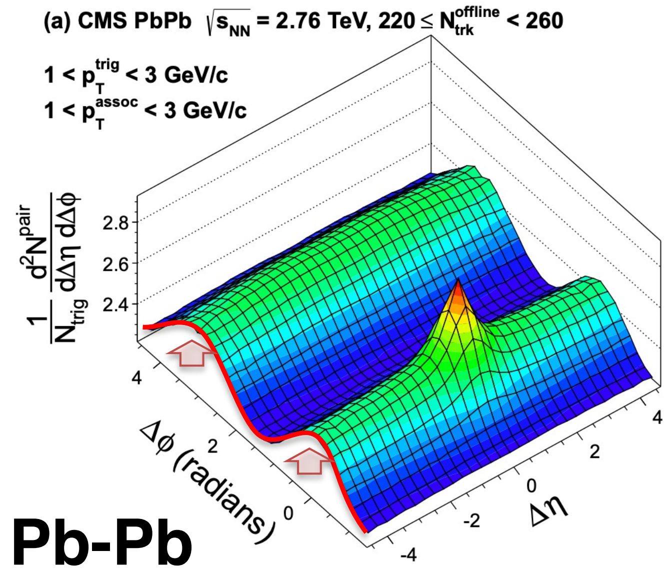
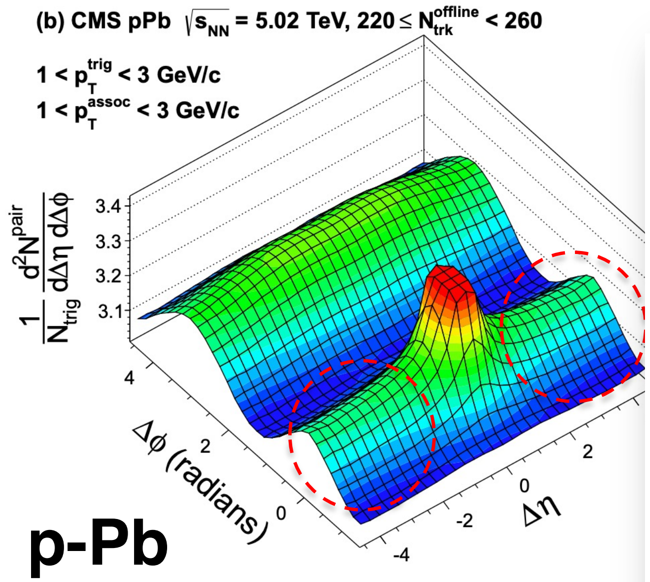
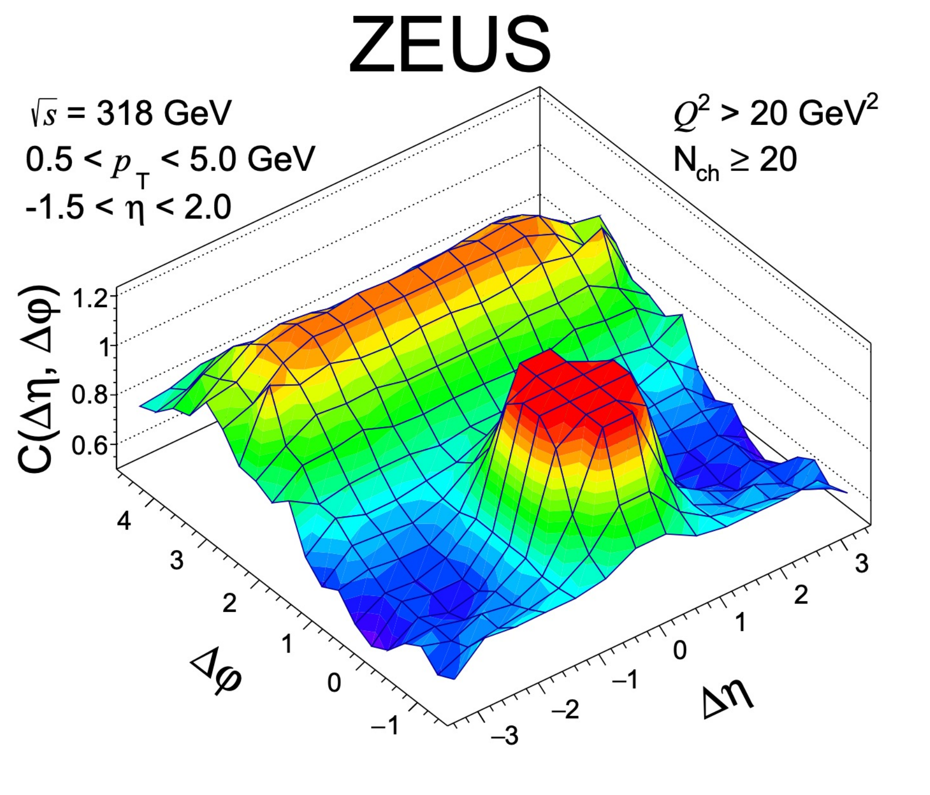
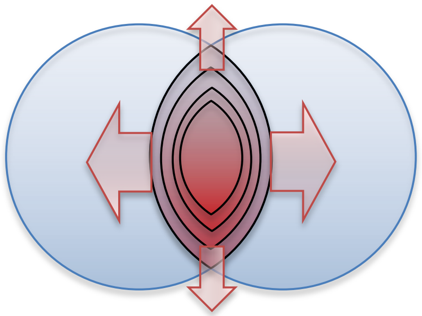






e⁻p collisions with $Q^2 > 20$ GeV^2/c^2



Collective expansion

- In Pb-Pb collisions, particles are emitted with azimuth due to collective expansion of an elli
- Also observed in p-Pb and pp
  - Initial condition not necessarily elliptic
  - Collective expansion also at play?
  - Under which conditions does this **not** happen?

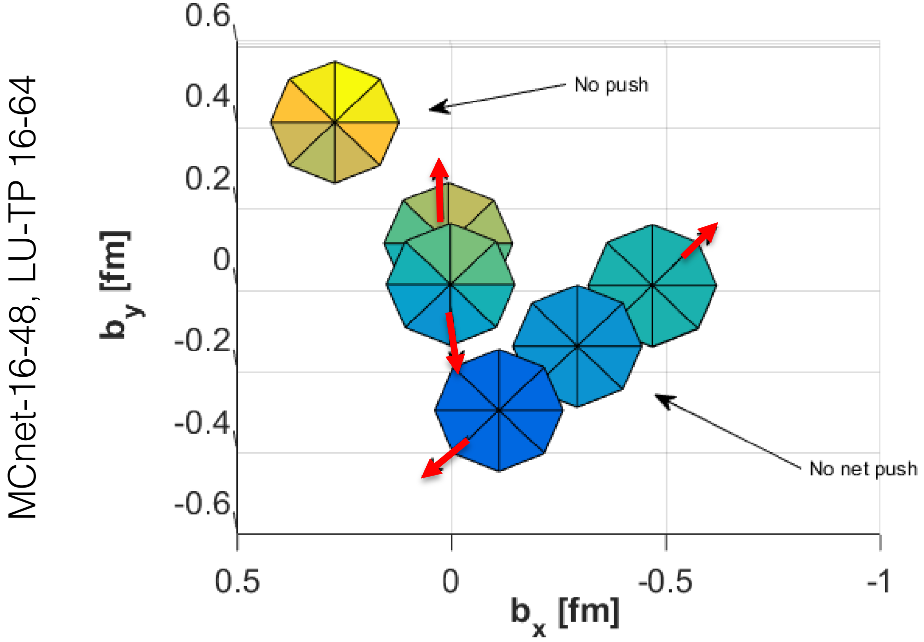
How can this be explained?

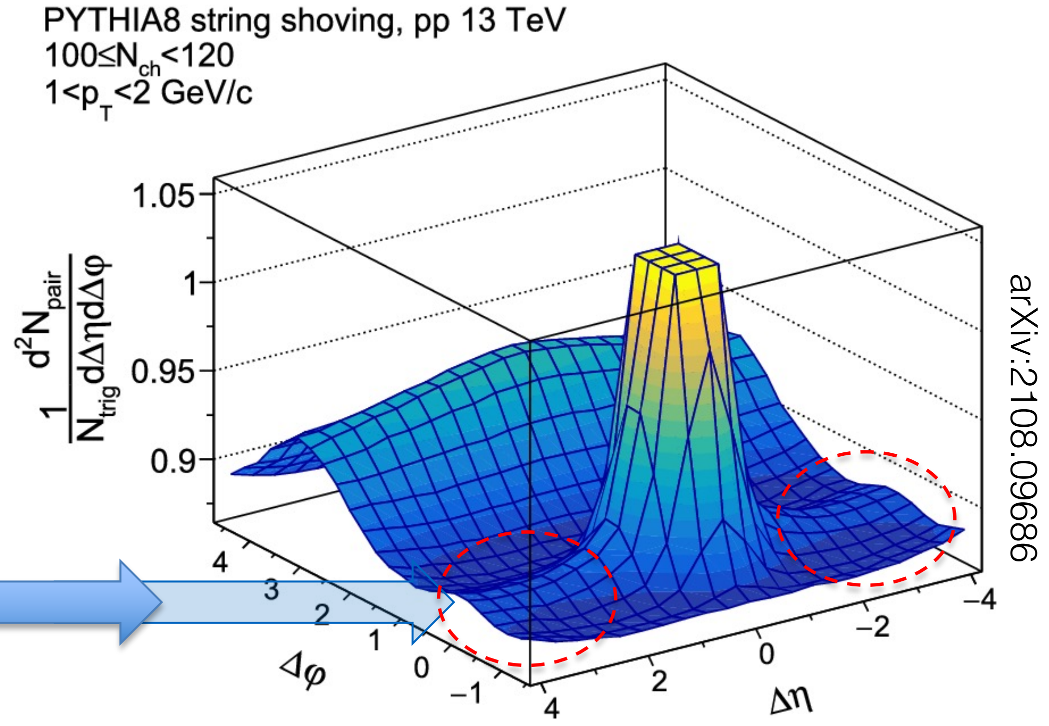
String shoving leads to collective motion

High multiplicity → many partonic interactions

Many partonic interactions → many colour strings

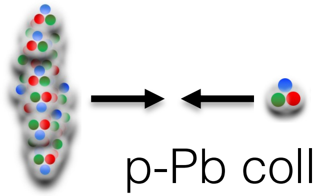
Many closely-packed colour strings → shoving!



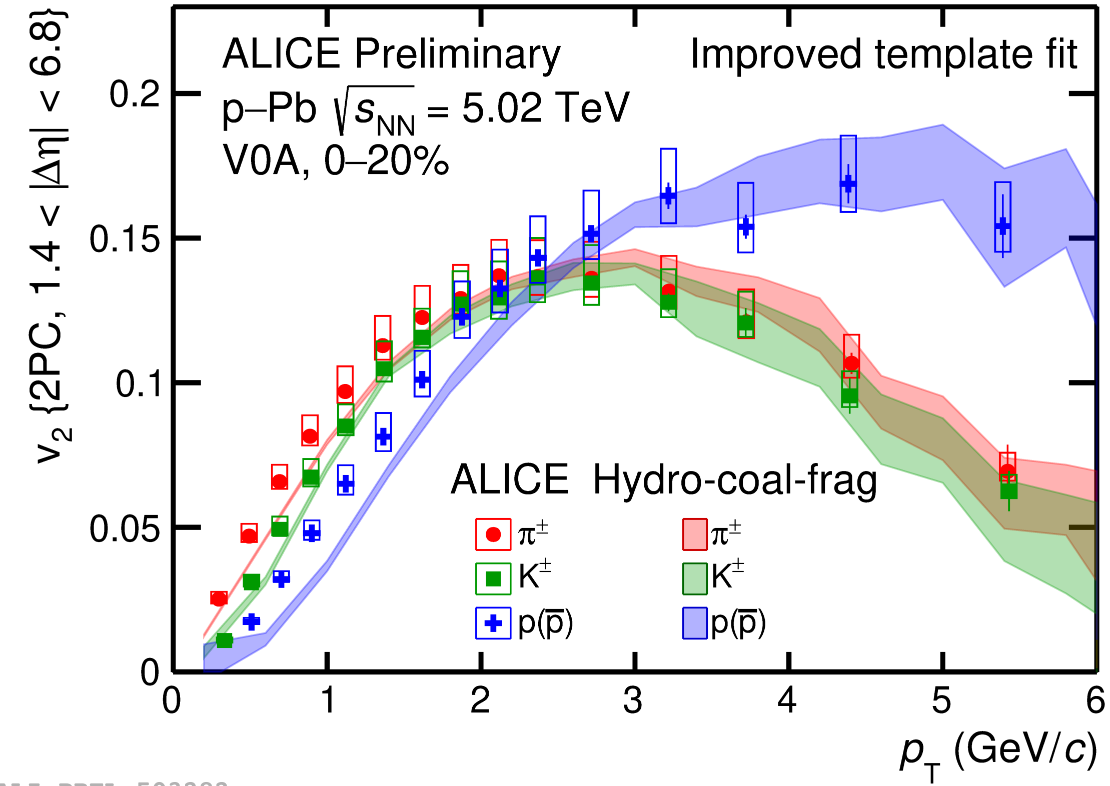


- Can now be reproduced using PYTHIA
  - Explains presence in high-multiplicity hadron-hadron collisions
  - Explains absence in electron-proton interactions
- Example of emergent QCD phenomenon
  - Should also explain Pb-Pb collectivity
  - see https://arxiv.org/abs/2010.07595

Beyond charged particles: identified particle v_2 coefficients



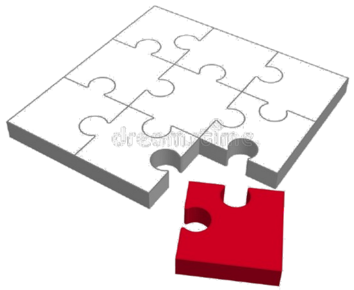
p-Pb collisions



ALI-PREL-503282

- Systematic search for identified particle flow
  - collective behaviour present: π, K, p
  - Consistent with mass ordering, particle type grouping
  - Even beyond: heavy flavour flow verified in small systems as well - except charmonia and bottom

	Pb-Pb	p-Pb	pp
open charm	✅	✅	✅
charmonia	✅	✅	❌
open bottom	✅	✖	❌
bottomonia	❌	❌	-



Remaining puzzle:

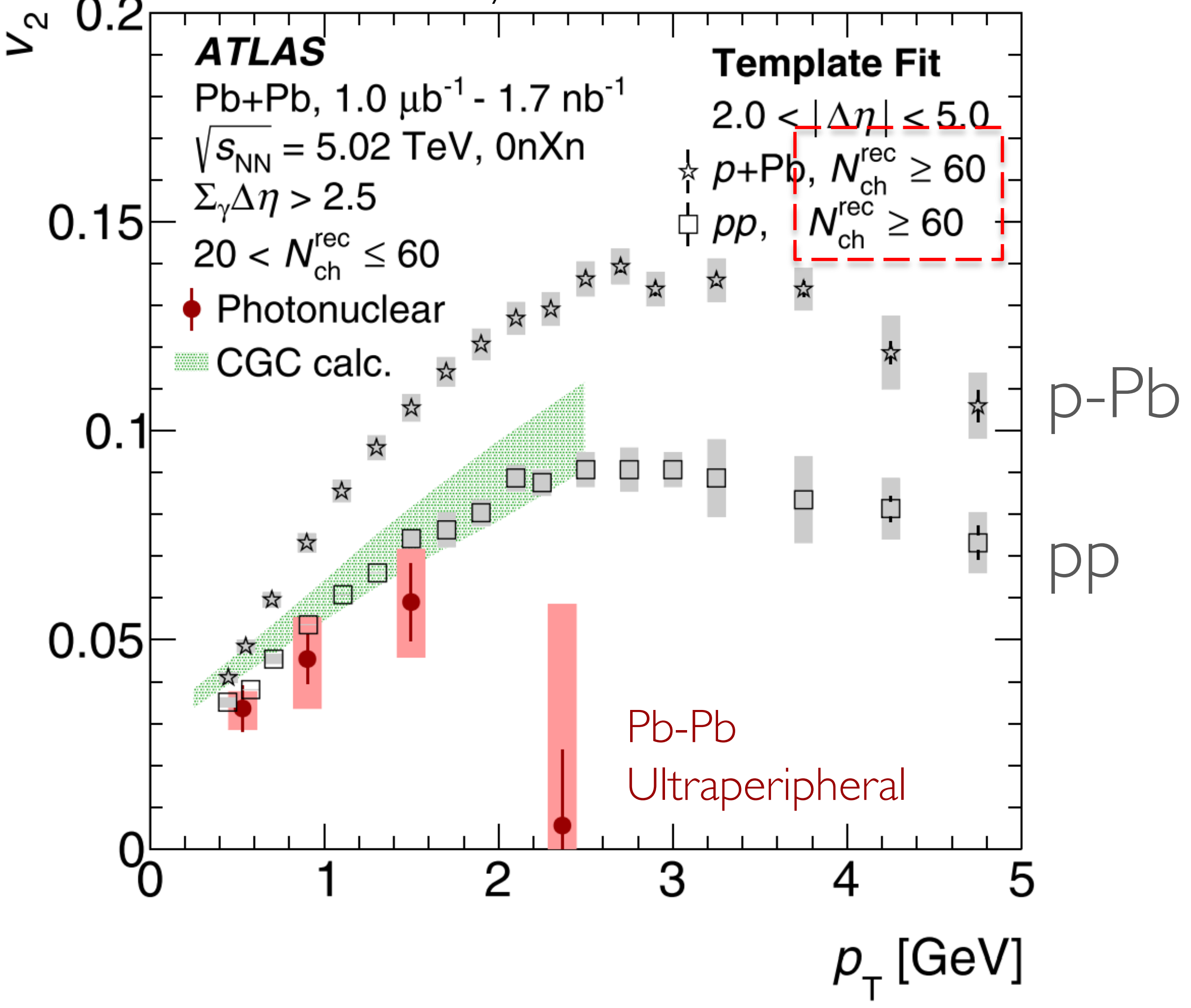
$v_2 > 0$ implies energy loss …

…but no jet quenching? To be solved!

v_2 coefficients in ultra-peripheral Pb-Pb collisions

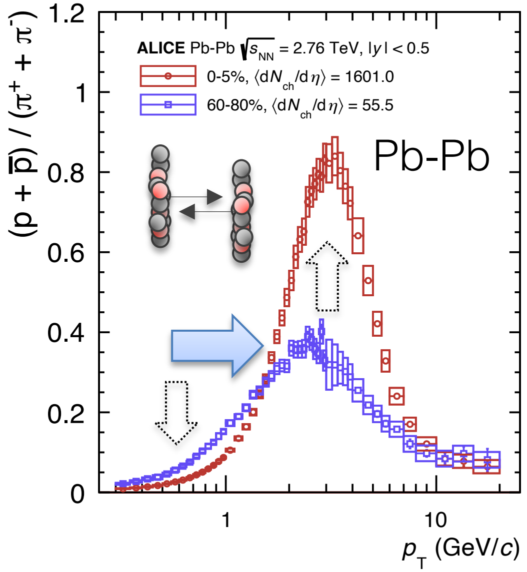
- Ultra-peripheral collisions: photonuclear processes
  - High-multiplicity events selected for analysis
  - **The plot thickens**: Non-zero v_2,
    …but lower than hadron-hadron collisions!
- Similar to result by CMS [2] in γp interactions (in p-Pb)
- Can be explained using CGC predictions [1]
- Caveat: v_2 coefficients vulnerable to (residual) non-flow
- Physics also related to electron-ion studies

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



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

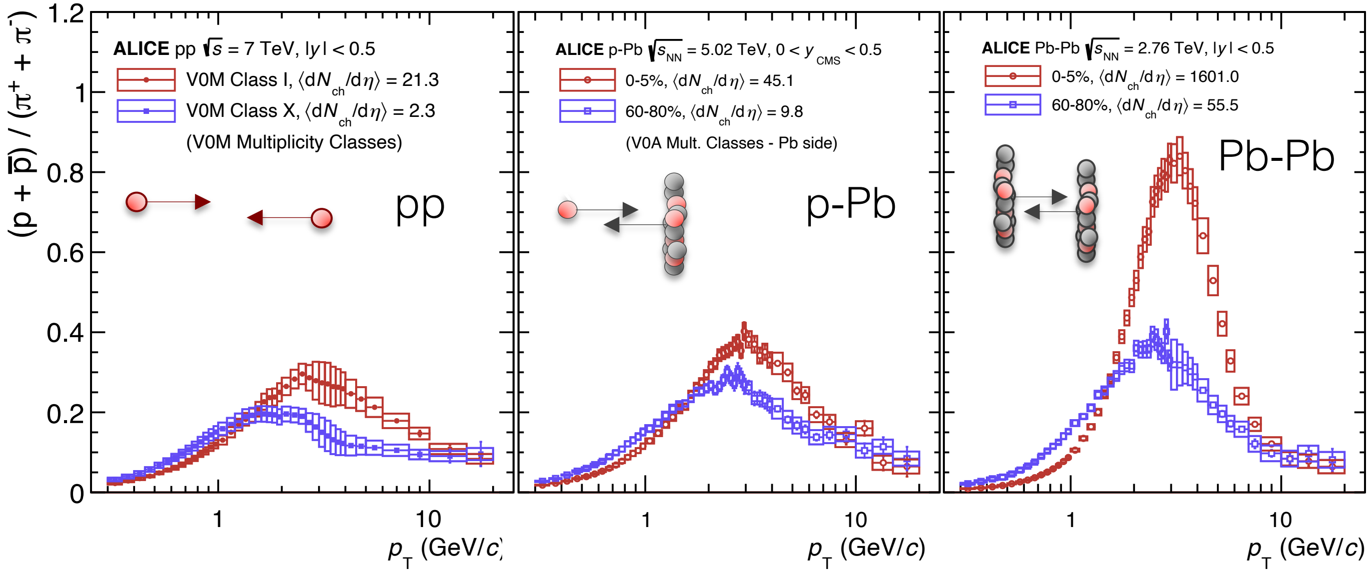
Proton to pion ratios



- Behavior known from Pb-Pb collisions
- Interpreted as radial flow: p are pushed to a higher momentum
  - p are pushed to higher momenta by a common velocity field

Proton to pion ratios

ALICE, Phys. Rev. C 99, 024906



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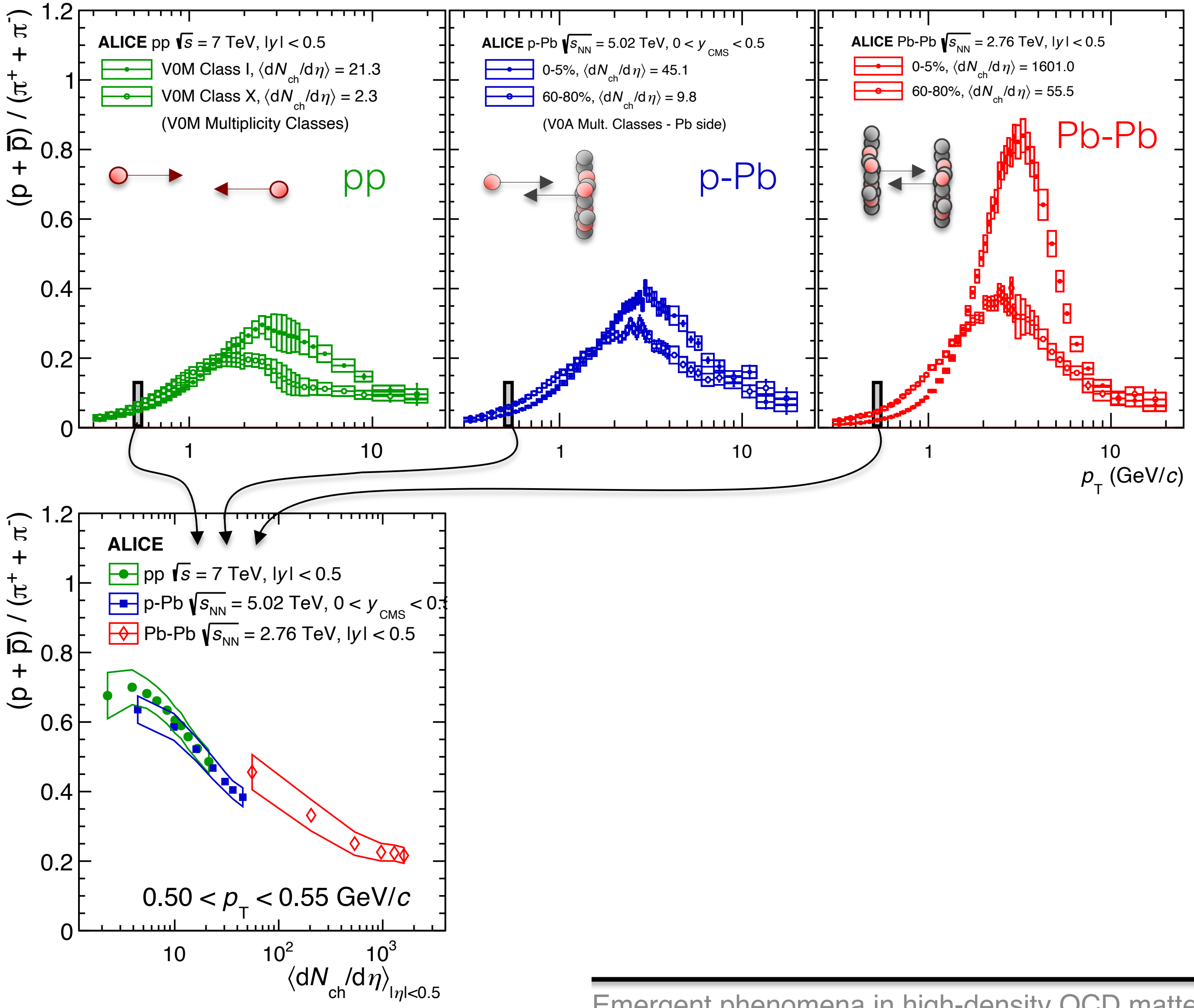

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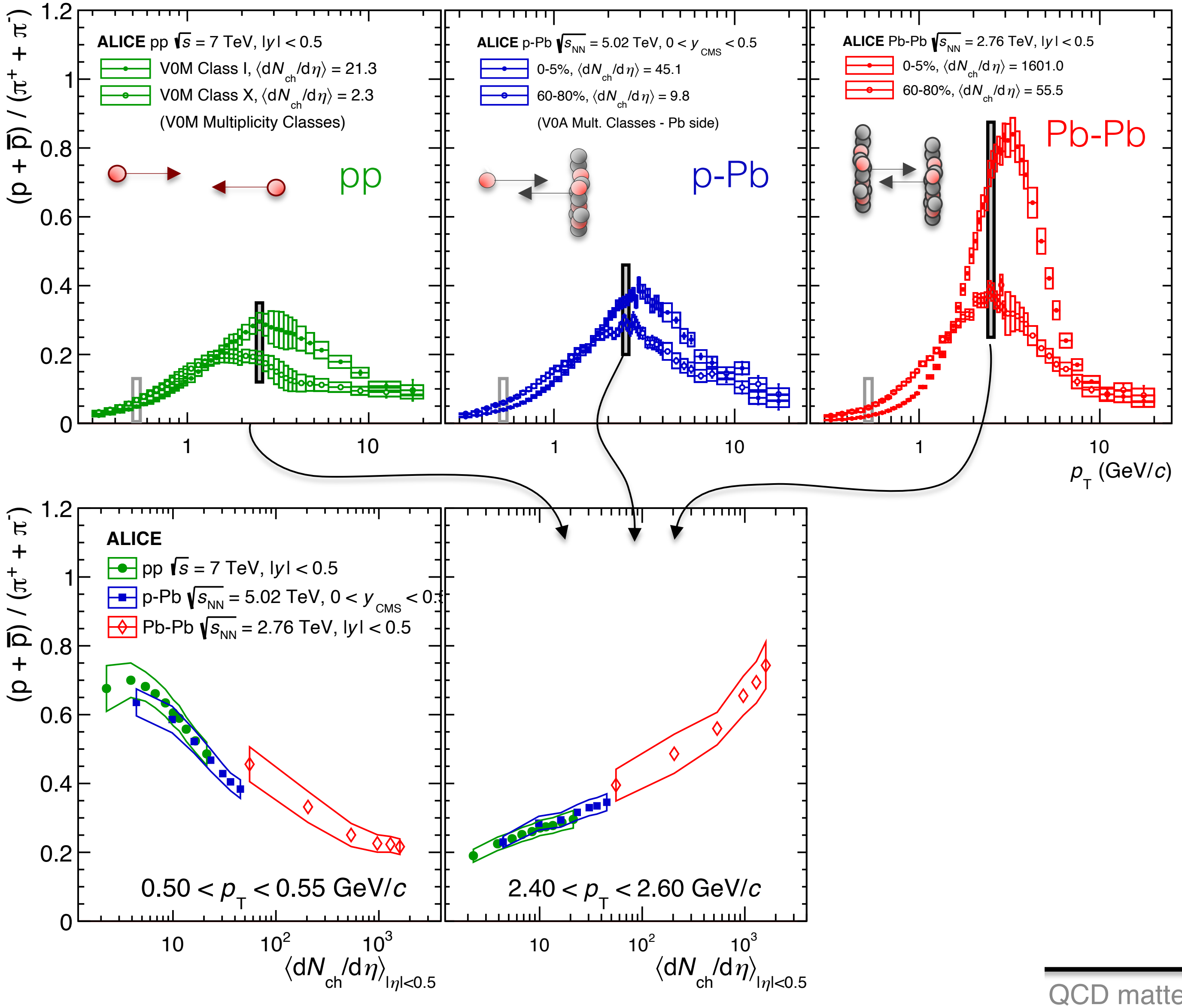

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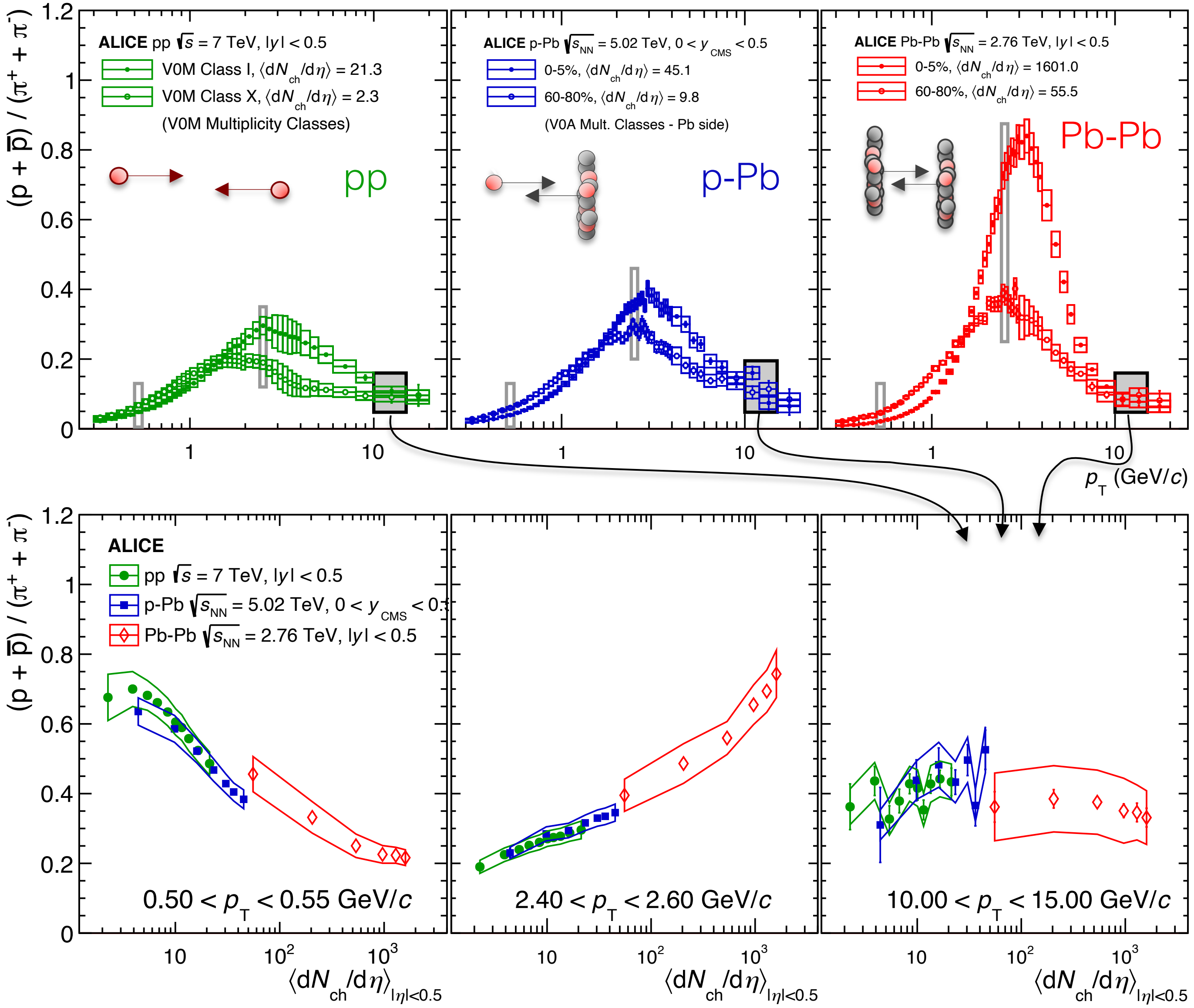
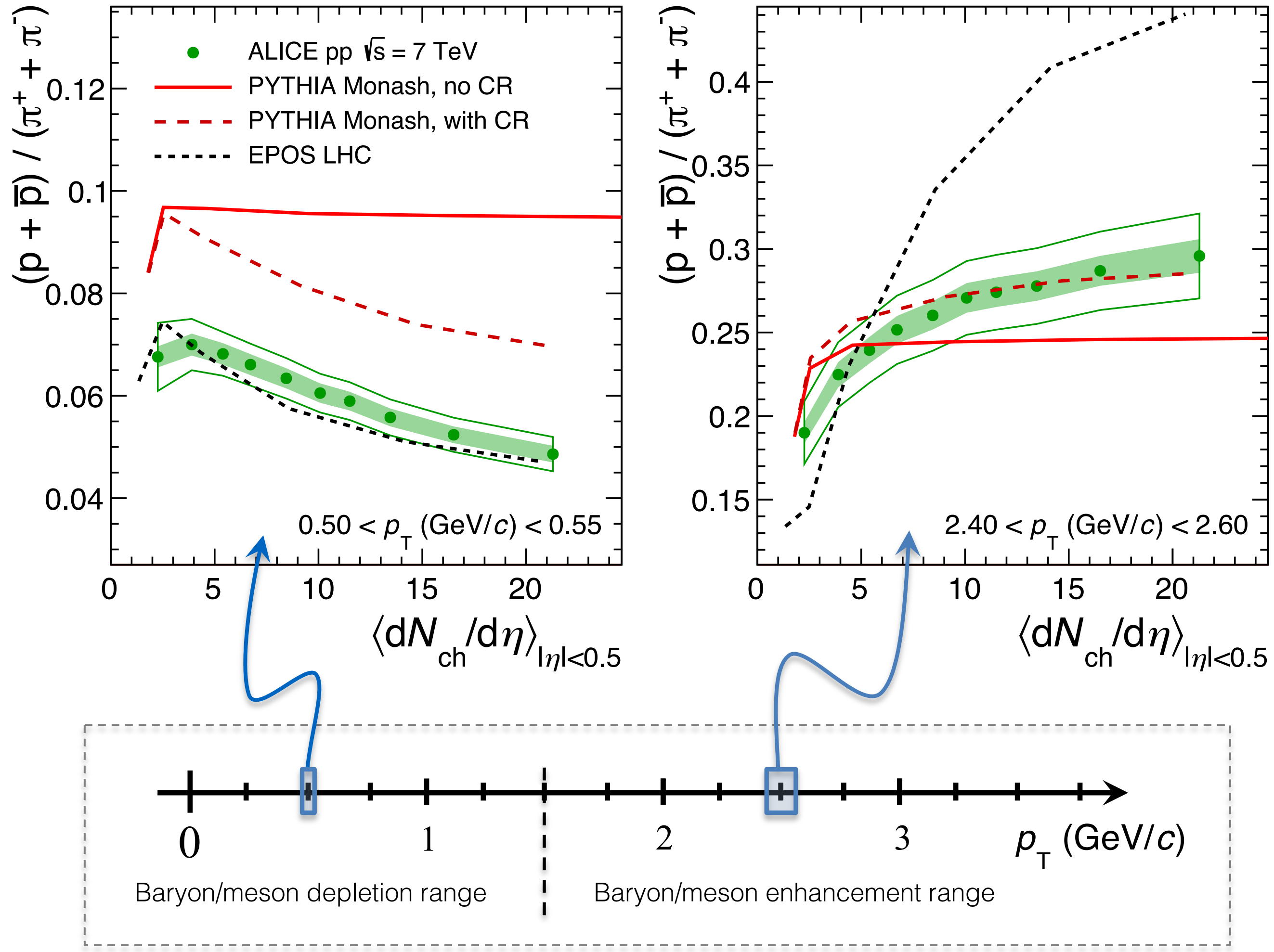


- Behavior known from Pb-Pb collisions
- Interpreted as radial flow: p are pushed to a higher momentum
  - p are pushed to higher momenta by a common velocity field
- Remarkable consistency across systems as a function of multiplicity
- high p_T: recovery of universal behavior?

Proton to pion ratios vs MC predictions

ALICE, Phys. Rev. C 99, 024906



- **Color Reconnection:**
  - Implemented in PYTHIA8 Monash; hadronizing strings may be rearranged prior to fragmentation in a multiplicity-dependent way
  - Qualitative agreement with the behavior of the data
- **Collective Radial Expansion:**
  - Present in EPOS LHC
  - Includes a QGP droplet
  - viable explanation but effect is overestimated

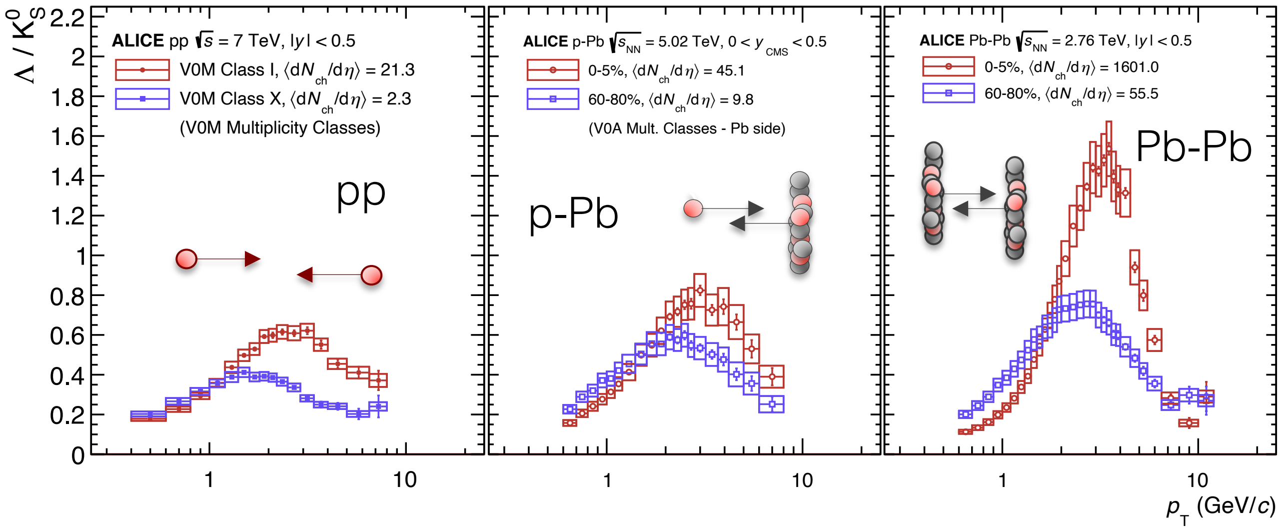
Now up to the theorists to explain via a universal mechanism

PYTHIA8 – T. Sjöstrand *et al.*, Comput. Phys. Commun. **178** (2008) 852-867
EPOS LHC – T. Pierog *et al.*, arXiv:1306.0121

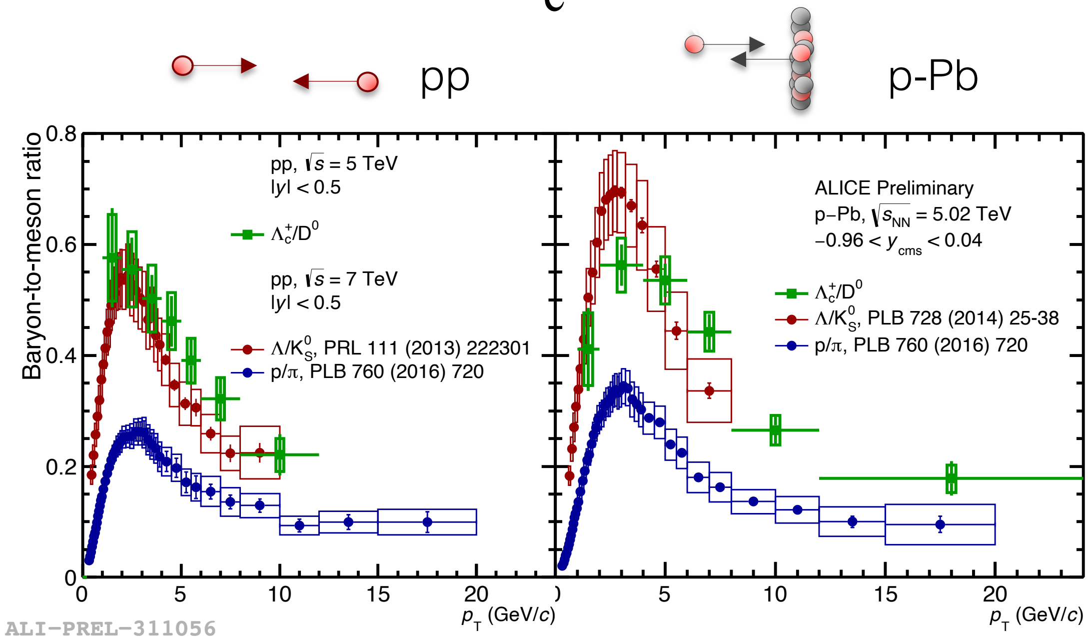
Baryon to meson ratios: strangeness + charm

Λ/K^0_S

ALICE, Phys. Rev. C 99, 024906



Λ_c/D^0



- Similarities also seen in strangeness measurements
- behavior in Λ/K^0_S ratio for all systems a function of N_{ch} only

- Also present in the charm sector
  - Universality remains a theoretical challenge

Emergent QCD phenomena versus effective descriptions

Phenomenon	Process-based, QCD-inspired explanation	Statistical mechanics-based or effective description
Strangeness enhancement	Color rope formation	Canonical suppression
Long-range correlations, baryon-to-meson ratios	String shoving	Hydrodynamical evolution / expansion

- These do not exclude each other → the ideal scenario would be a 'grand unification'

Is there a QGP in small systems? → an outdated question

Is there more in small systems than we originally thought? → Yes! Can we define the QGP more precisely?

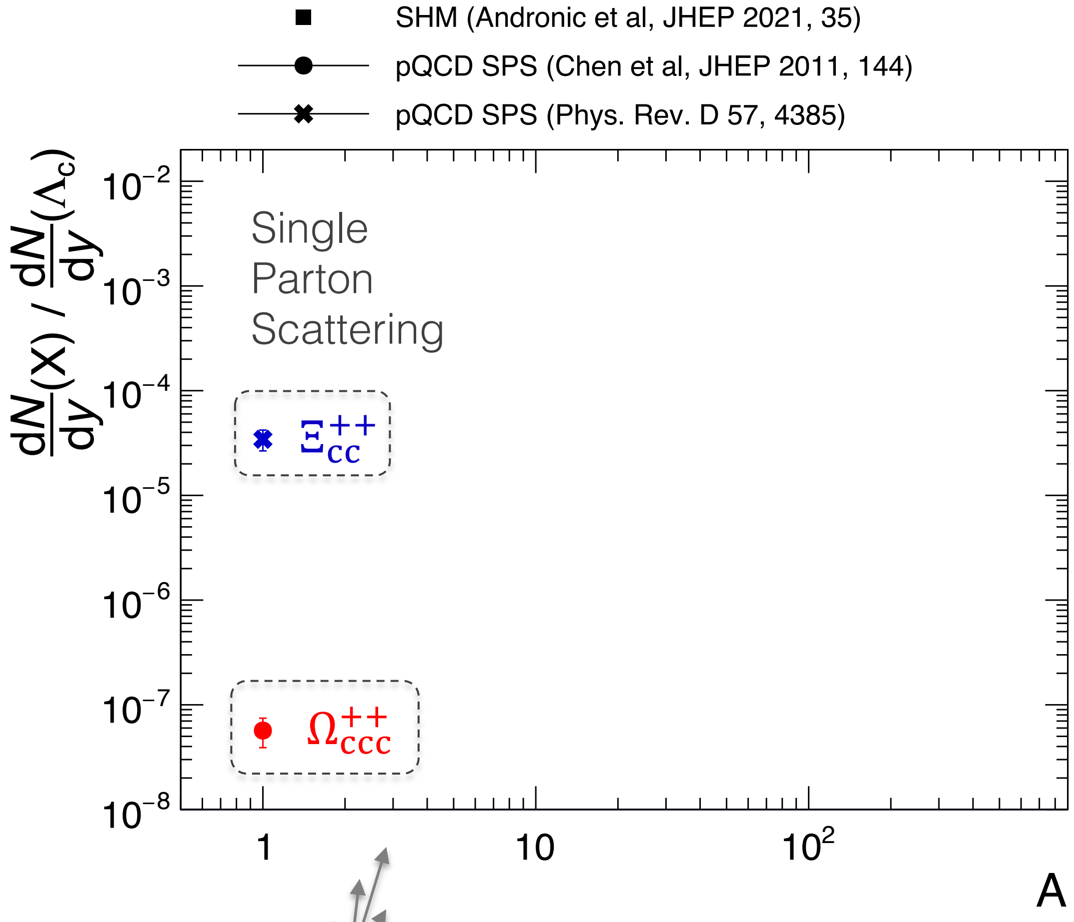
- Emergent phenomena of QCD: 'more is different' [1]

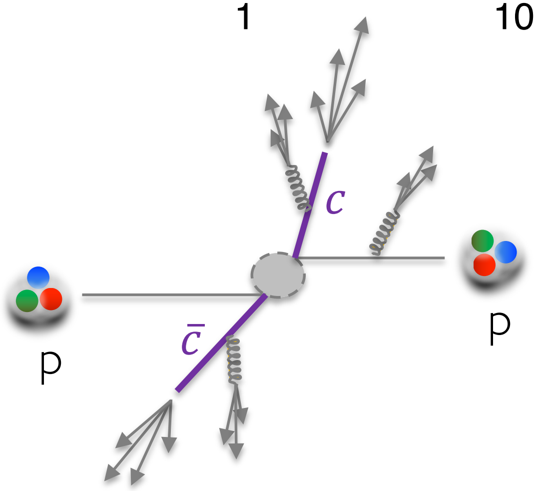
A concerted effort to understand transition between regimes:
- A hadron-hadron collider → very high-density phenomenology
- An electron-hadron collider → fundamental building blocks + onset of emergence

[1] **More Is Different**. P.W. **Anderson**. Science, New Series, Vol. 177, No. 4047. (Aug. 4, 1972)

Multi-charm baryons: from low to high density QCD

- Charm production in general: almost exclusive to hard scatterings due to large mass (~1275 MeV/c^2)
- Formation of Ξ_{cc}^{++}, Ω_{cc}^{+}, Ω_{ccc}^{++}: extremely unlikely in single parton scattering (unlike e.g. J/ψ)





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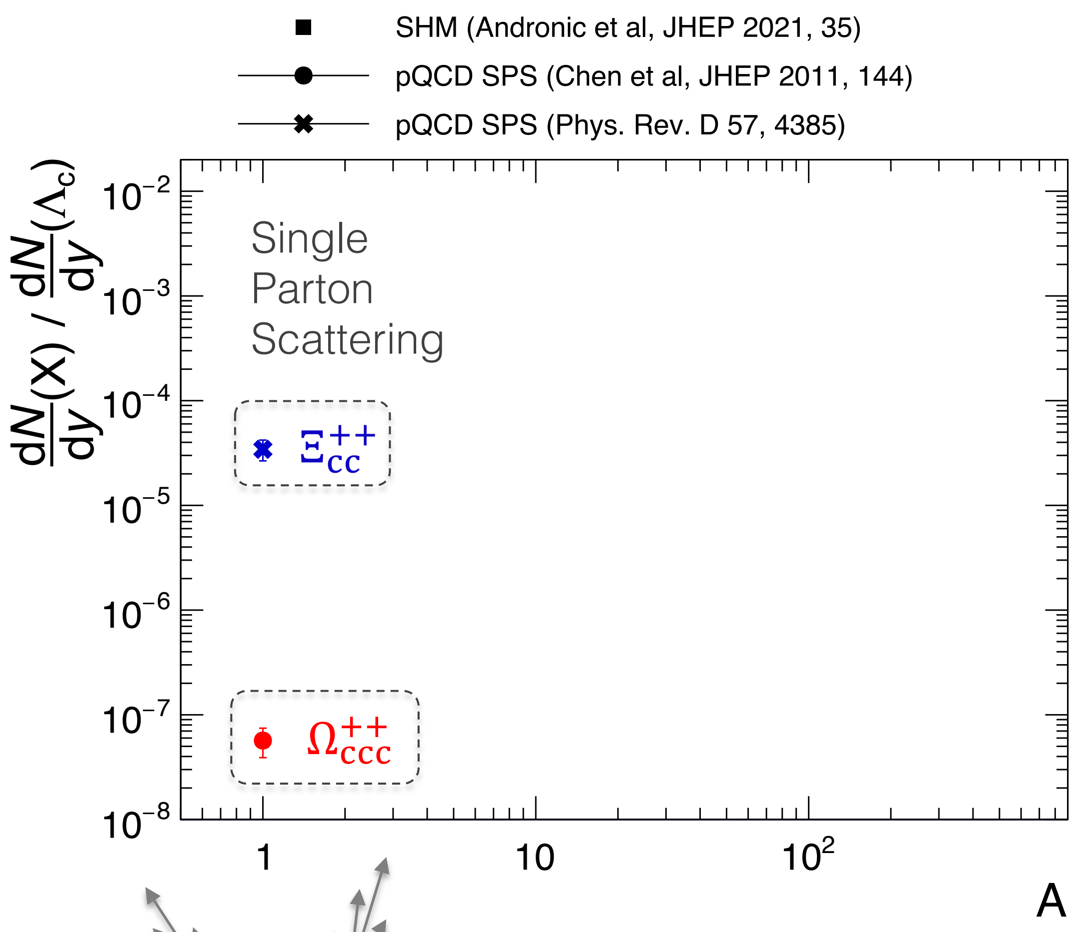

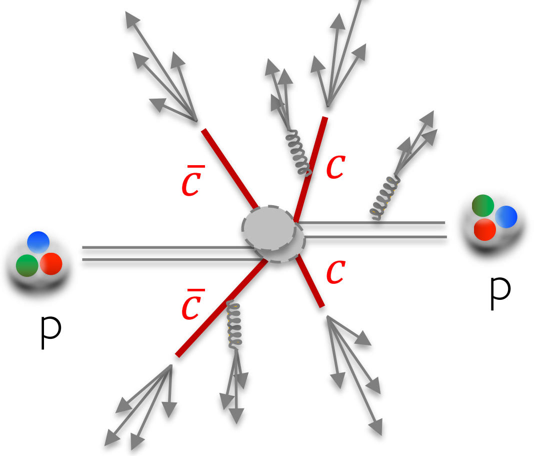

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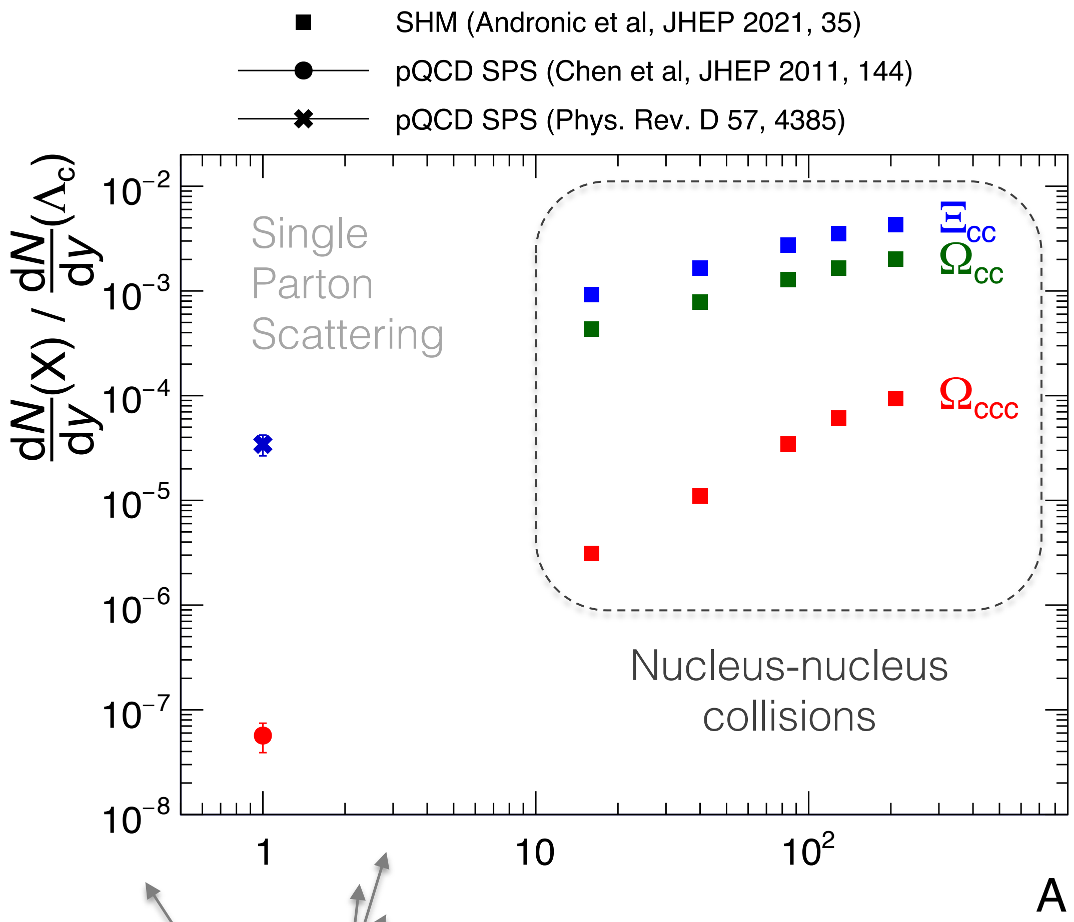
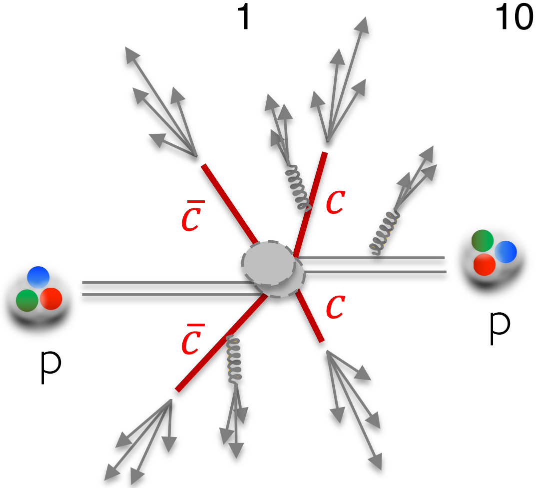
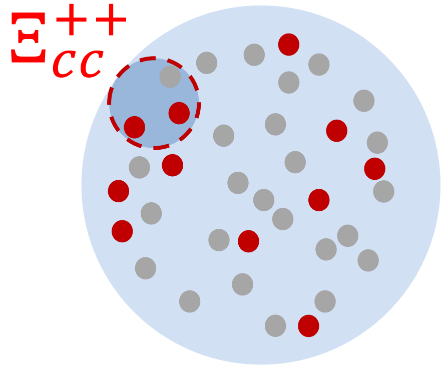
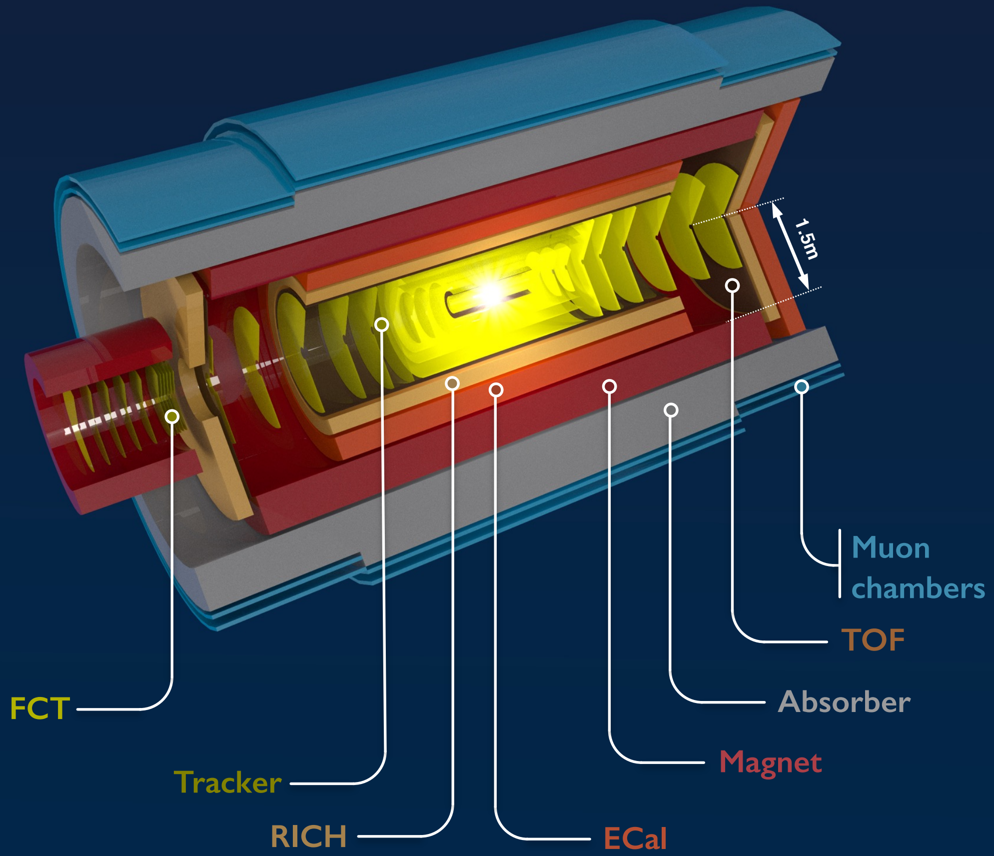
- Multi-parton interactions and multi-charm: multiple charm quarks combine into hadrons
- In nuclear collisions:
  - High density of charm quarks leads to much larger multi-charm population
  - Described by SHM (g_c) and coalescence
  - Enormous dynamic effect!







ALICE 3: a next-generation experiment for the 2030s



- All-silicon, large-acceptance tracker
  - High rate: 5x bigger luminosity, exploit LHC
  - Momentum precision of $\sigma_p/p \sim 1\%$
  - $\sim 10\%\ X_0$ overall material budget
- State-of-the-art particle identification
  - Silicon-based TOF and RICH
  - Muon identification
- Very high vertexing precision
  - First layer at 5 mm from interaction point
  - Impact parameter resolution:
    - ~10 µm at p_T ~200 MeV/c
    - ~3 µm at p_T > 1 GeV/c

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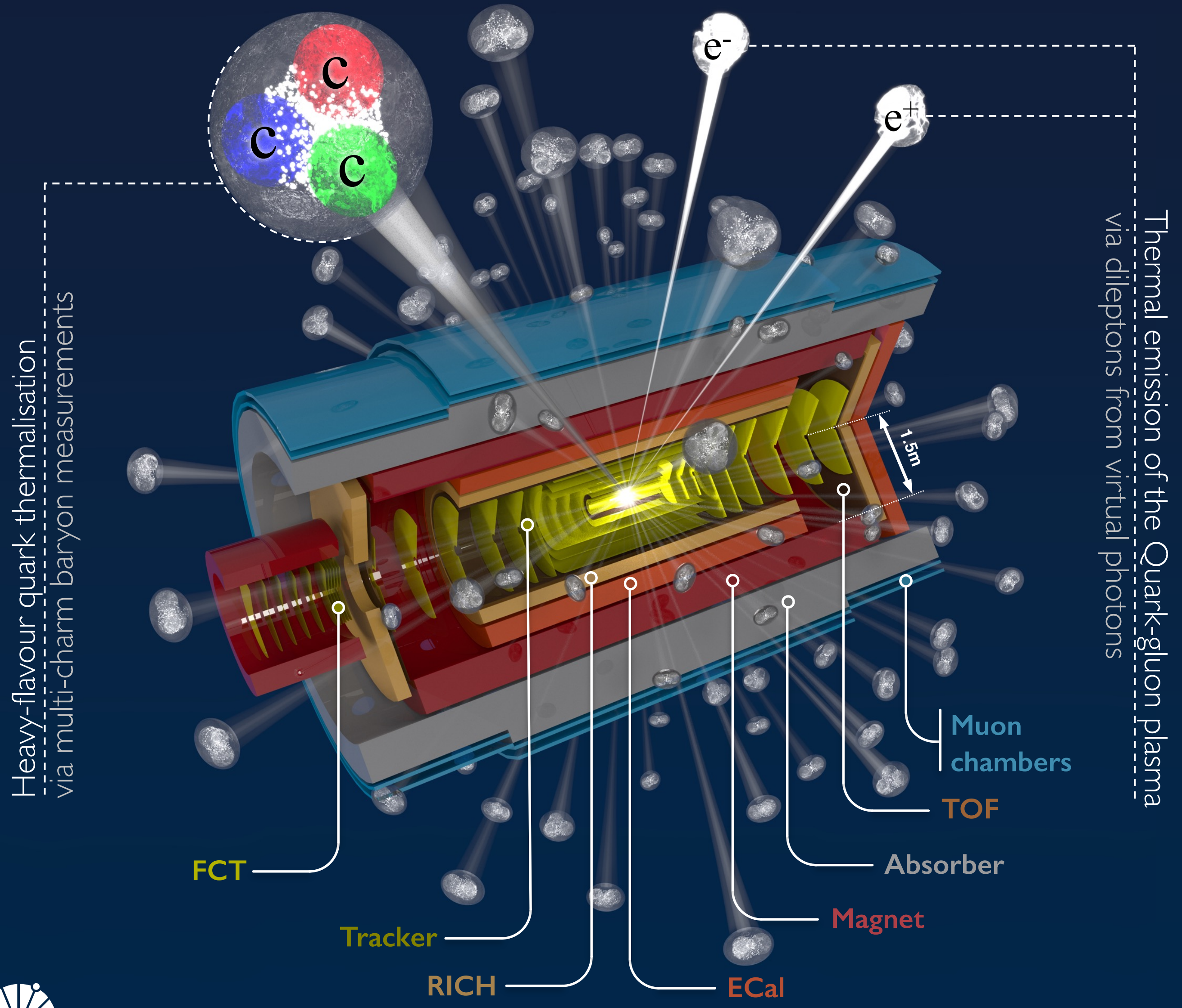

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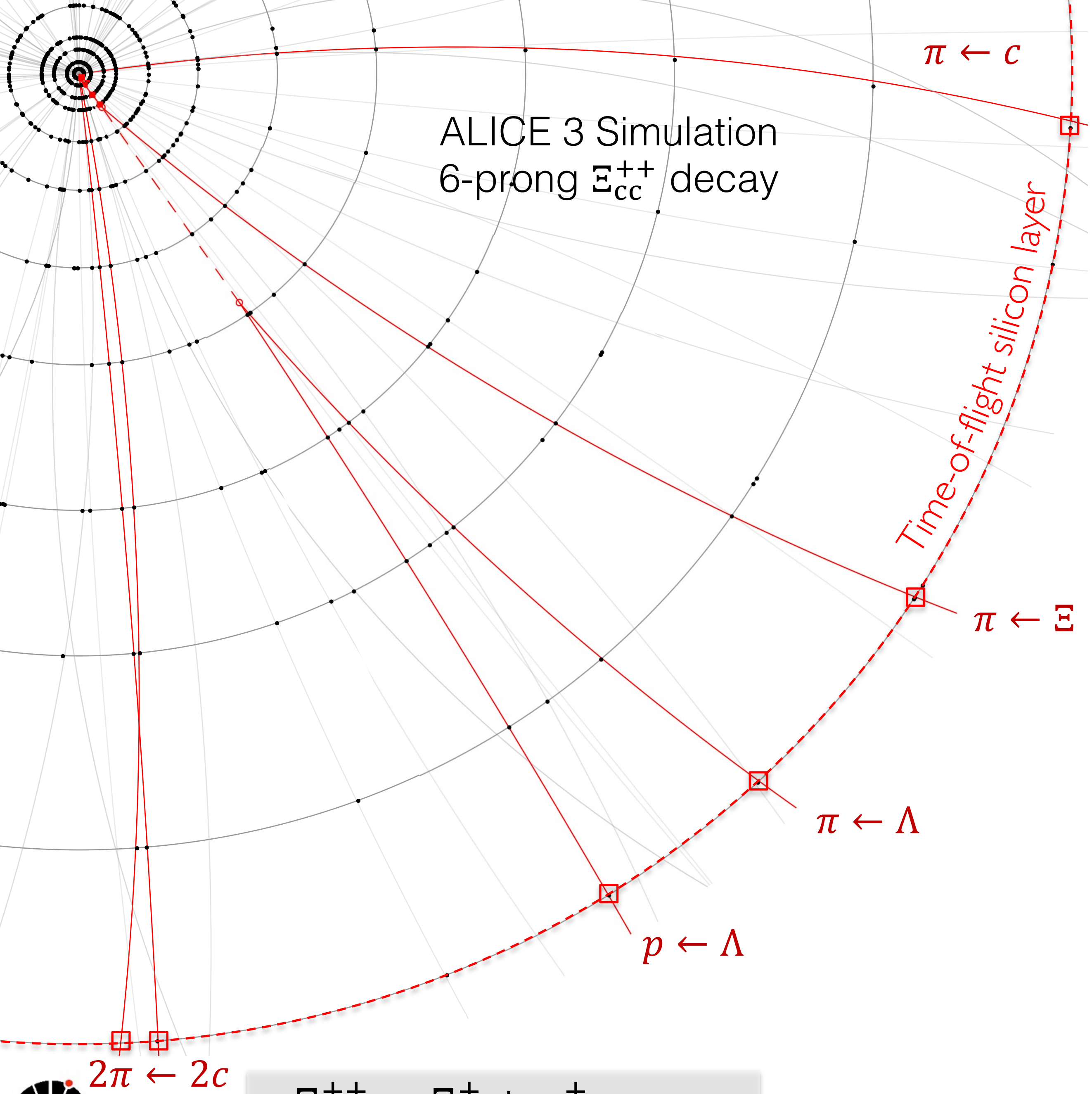
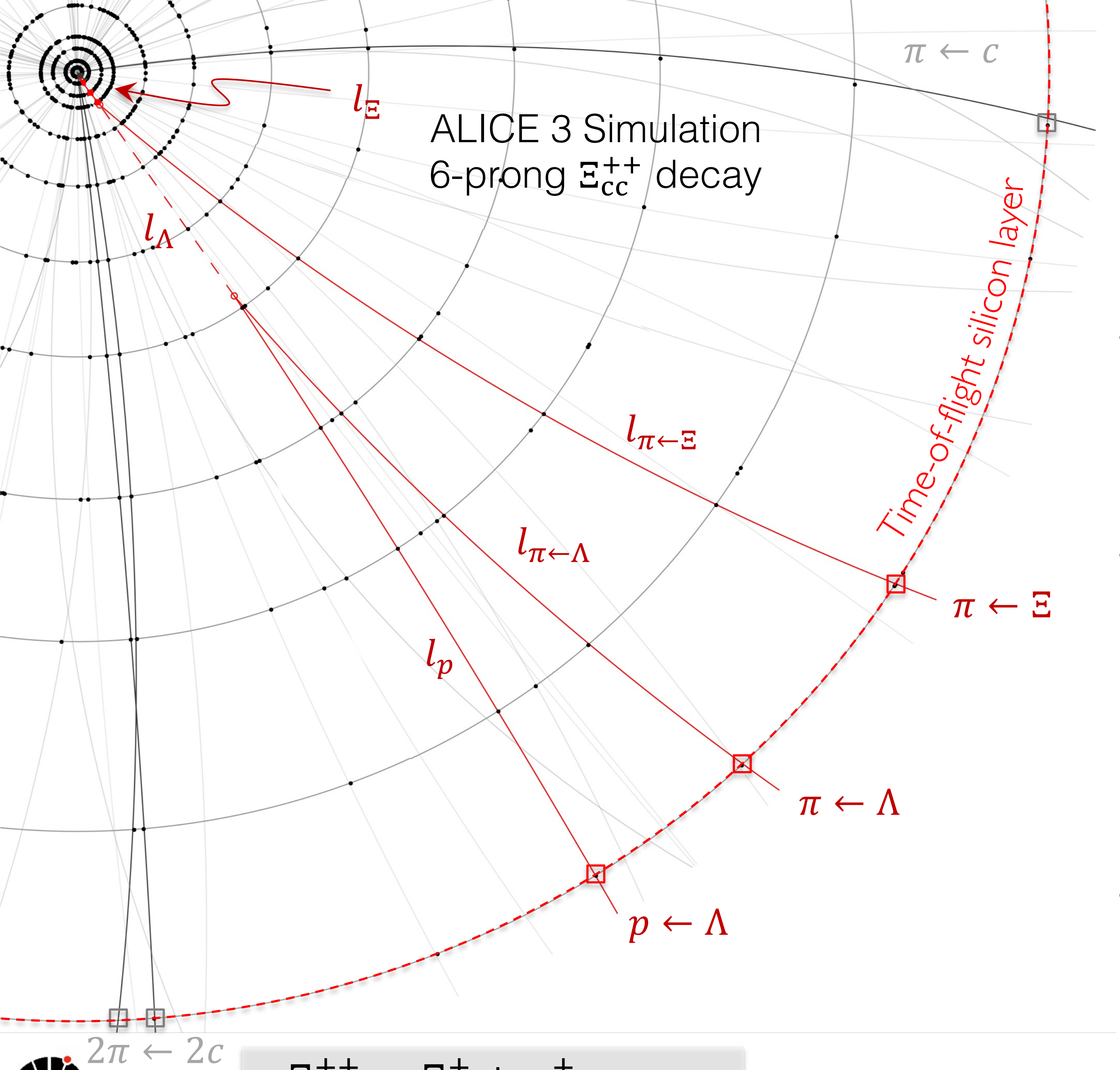
The heavy flavour angle: new frontier beyond simple thermalization

Required: new experimental techniques

The role of silicon TOF



$$\Xi_{cc}^{++} \rightarrow \Xi_c^{+} + \pi^{+}$$
$$\Xi_c^{+} \rightarrow \Xi^{-} + 2\pi^{+}$$



$$\Xi_{cc}^{++} \to \Xi_c^+ + \pi^+$$
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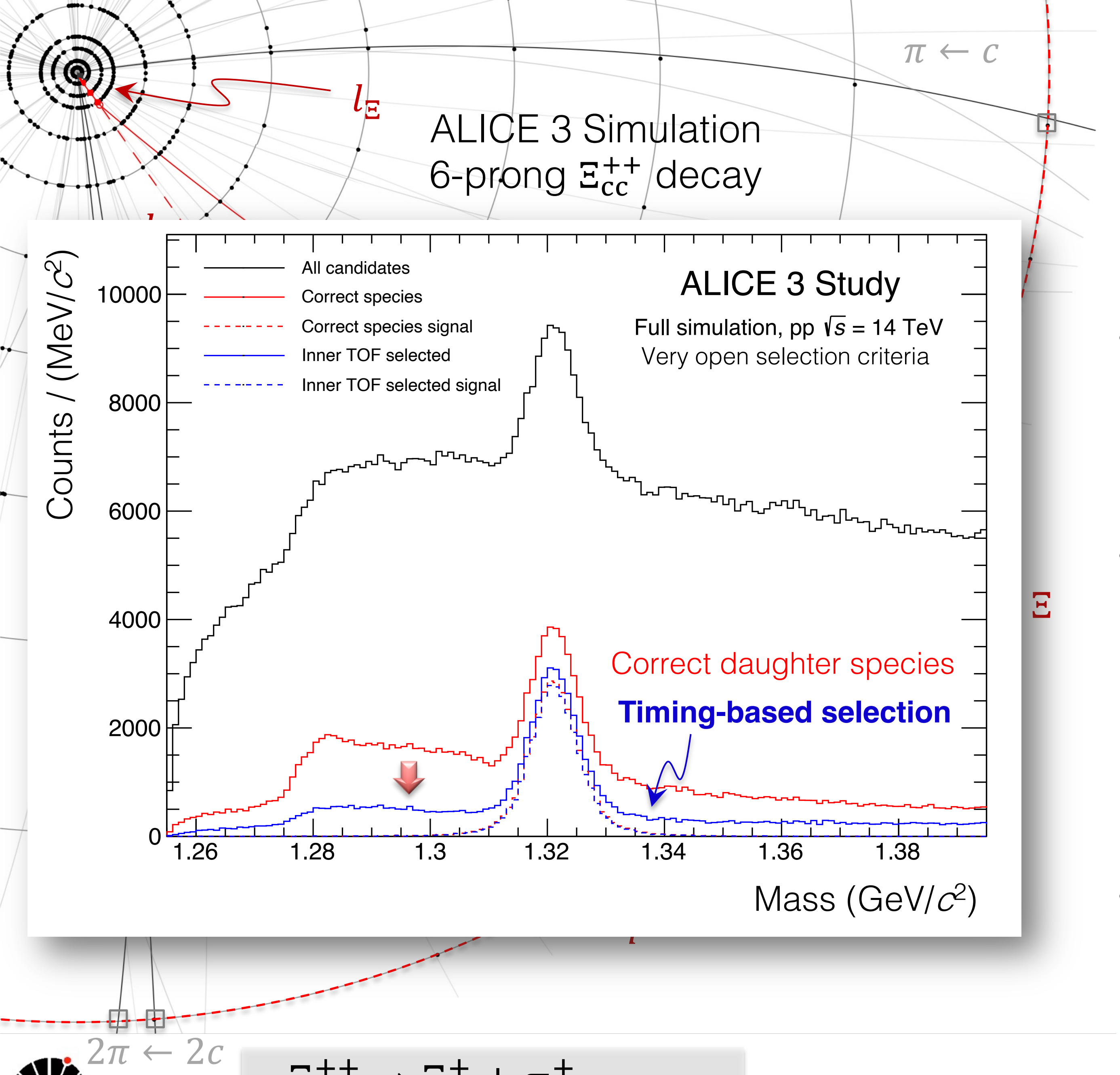
The role of silicon TOF

- ALICE 3 is expected to use state-of-the-art silicon time-of-flight detectors with 20 ps precision
  - 20 ps = 6 mm/c
  - Silicon TOF: a major new technological frontier!
- TOF identification for Ξ decay products
  - Expected time of arrival should be calculated candidate-by-candidate
  - $t = l/v$ calculated for each of the Ξ products
  - Primary pions and protons arrive earlier than those from Ξ: heavy particles travel slower!
- Don't just select π and p…
  - …select π and p that arrived late!

The role of silicon TOF



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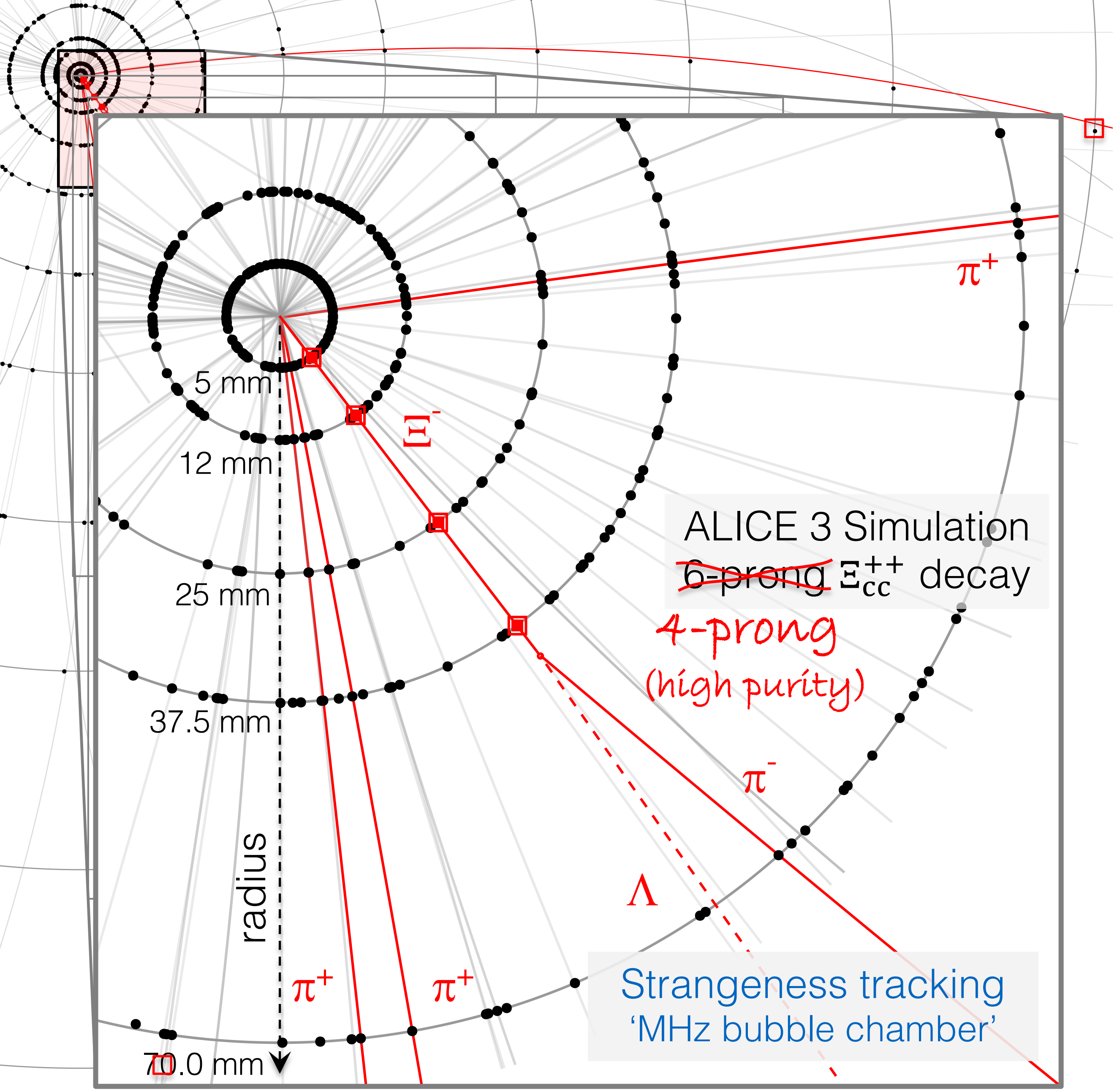
Strangeness tracking:

A Mhz-era bubble chamber technique



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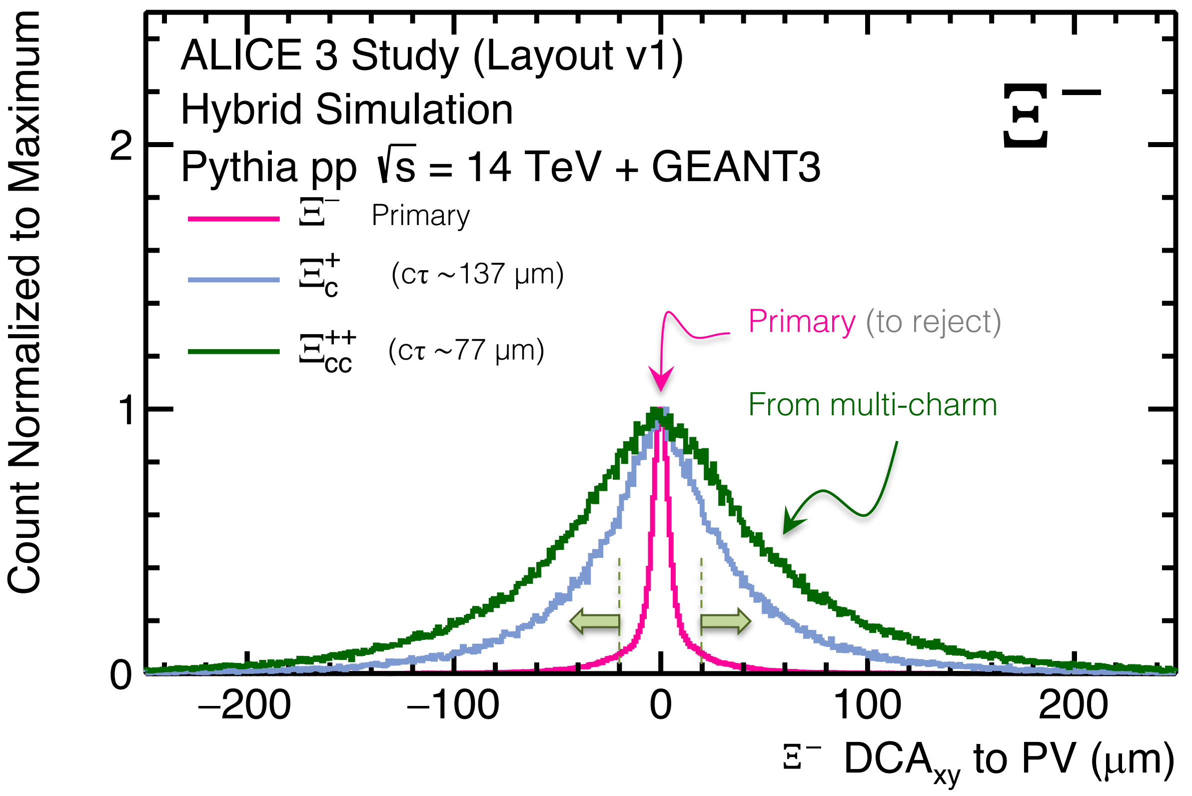
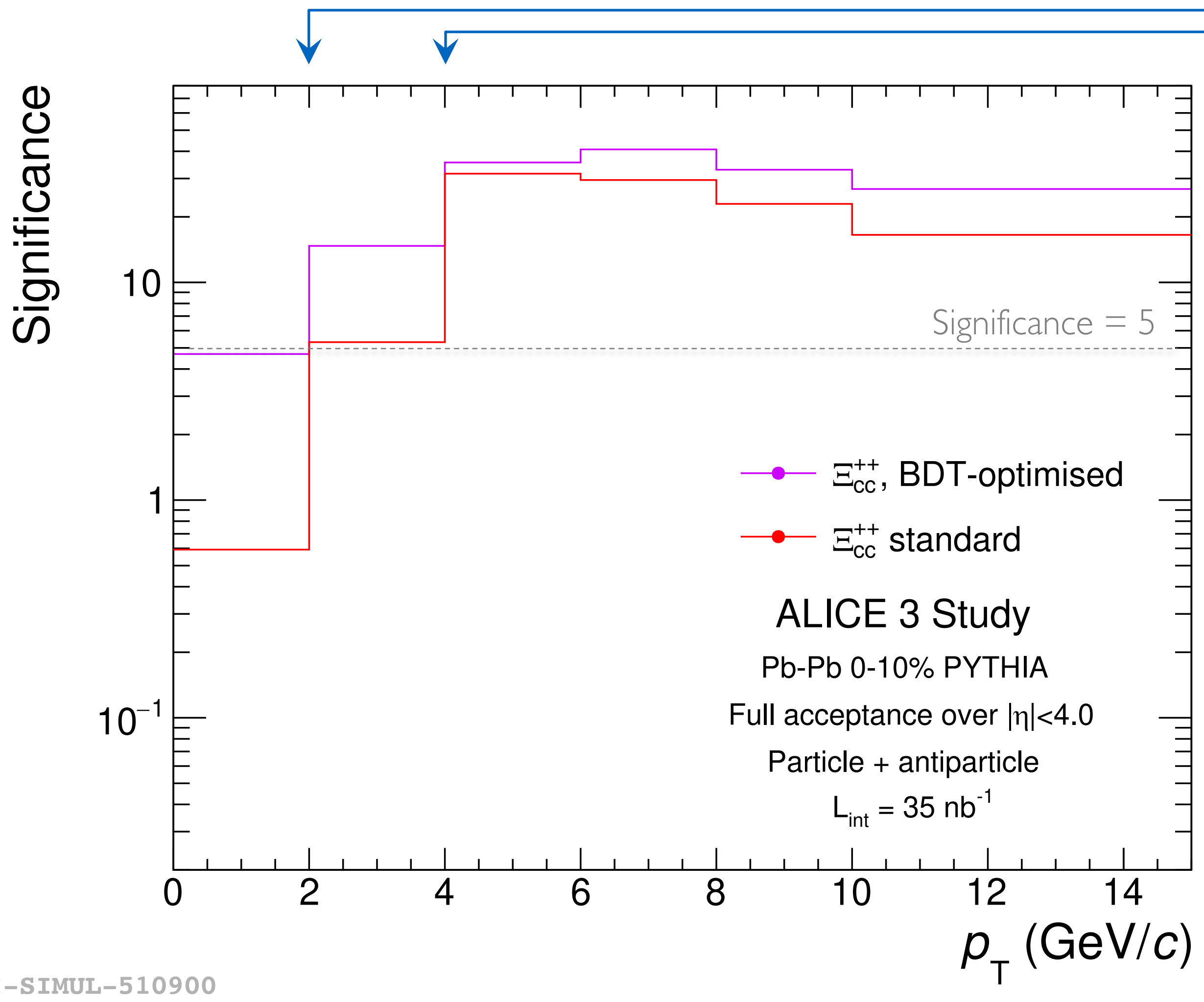
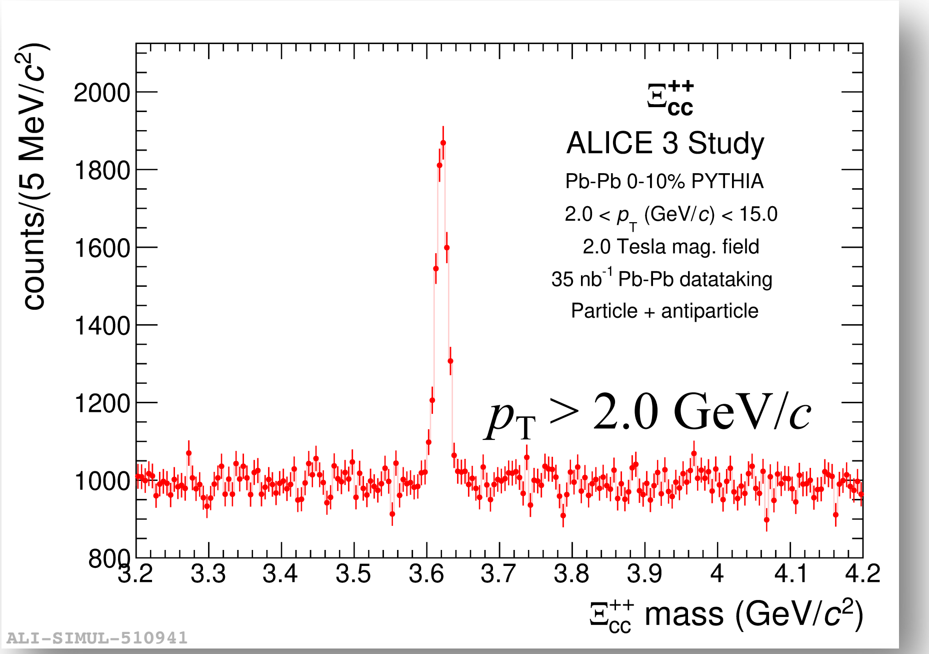
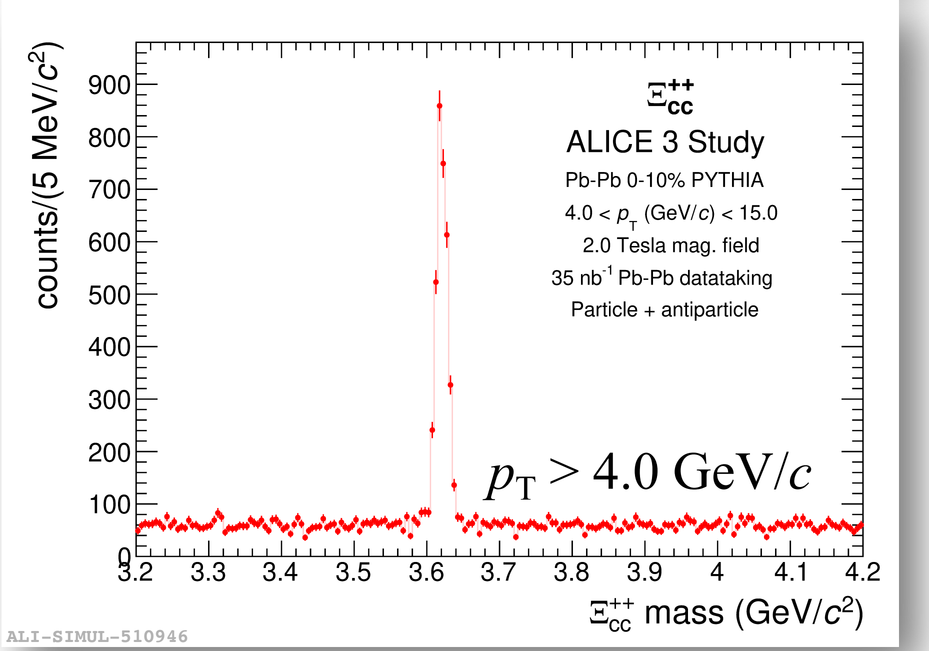


+ isolate HF secondaries
→ decisive in multi-charm analyses

Ξ_{cc}^{++}: A taste of analysis

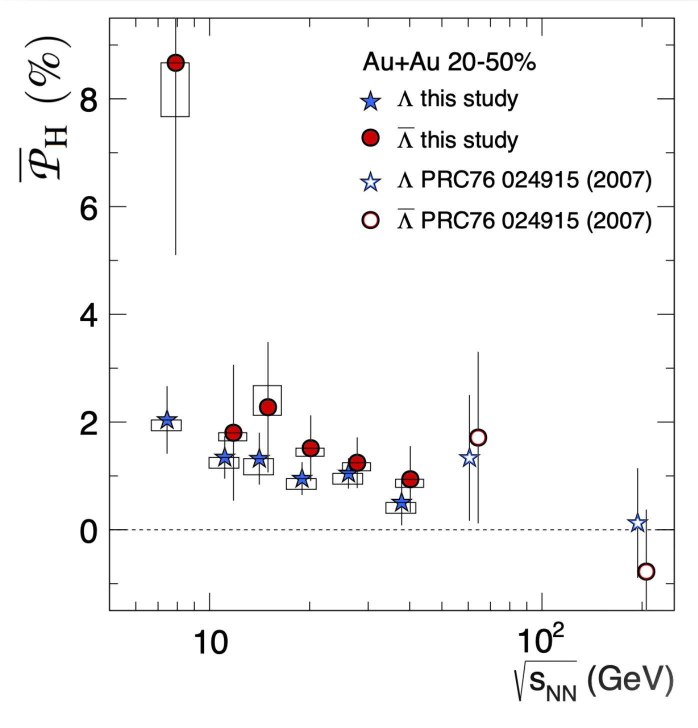






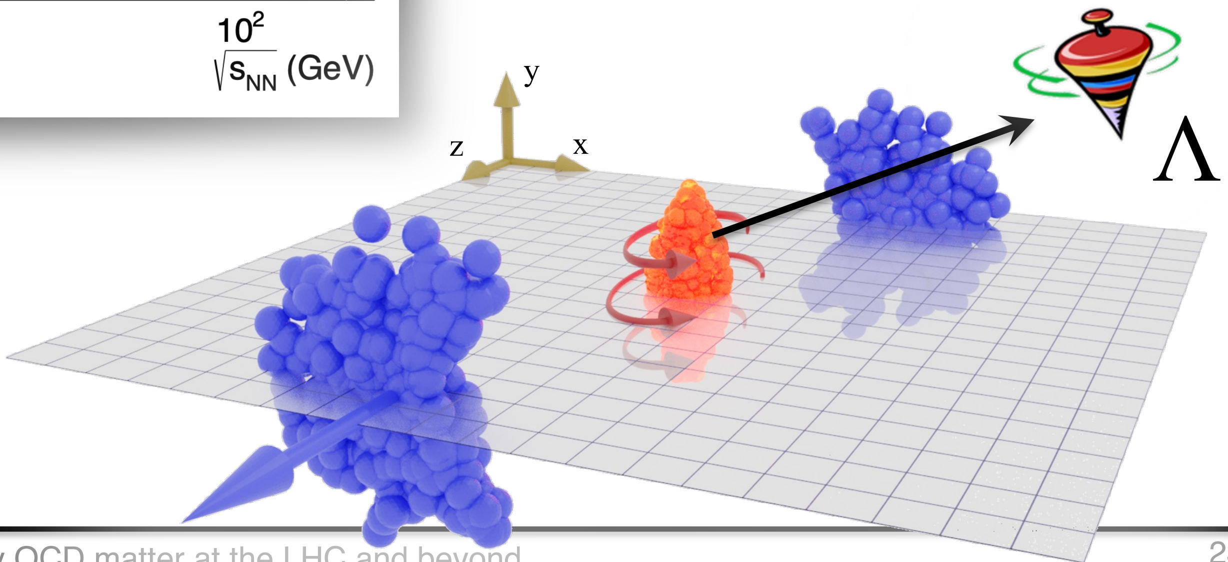
Expected Ξ_{cc}^{++} invariant mass distributions with 35 nb^{-1} of Pb-Pb data collected with ALICE 3

Λ polarization: measuring vorticity in QCD matter

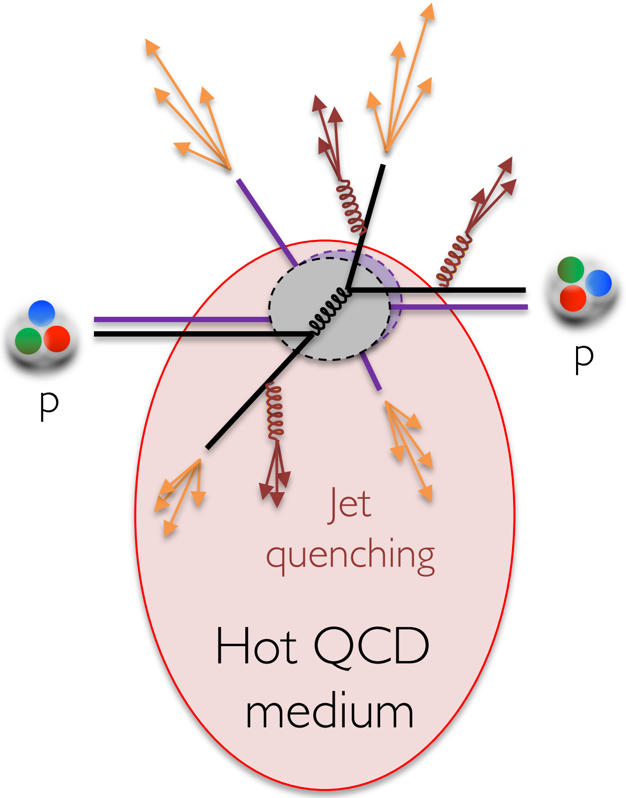


STAR Collaboration,
Nature 548, 62 (2017)

→ Lower energy advantageous:
Stronger effects!
→ also an indication of
exciting new possibilities!



Using Λ polarization to understand QCD matter



- Parton-parton scattering forms jets
- Classical nucleus-nucleus collision phenomenon: 'jet quenching' when partons travel through medium

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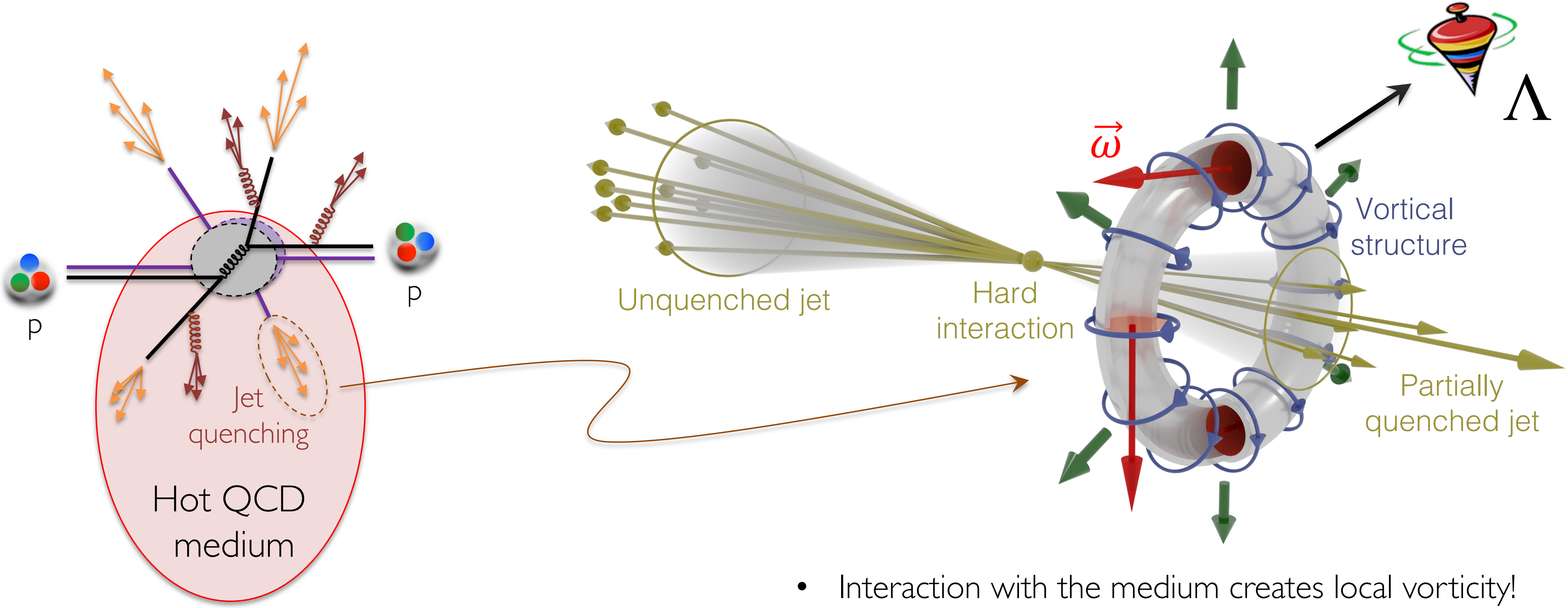

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- Interaction with the medium creates local vorticity!
- Similar to "smoke rings" → QCD matter rings
- Can be measured with Λ polarization around jet structures after system evolved [1]!

[1] W.M. Serenone, J.G.P. Barbon, D.D. Chinellato, M.A. Lisa, C. Shen, J. Takahashi, G. Torrieri, **Phys. Lett. B** 820 (2021) 136500

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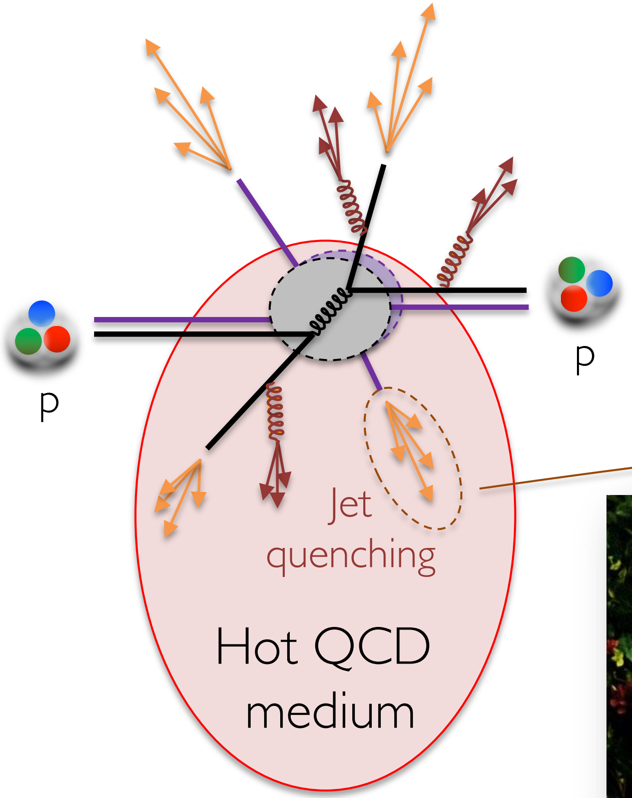

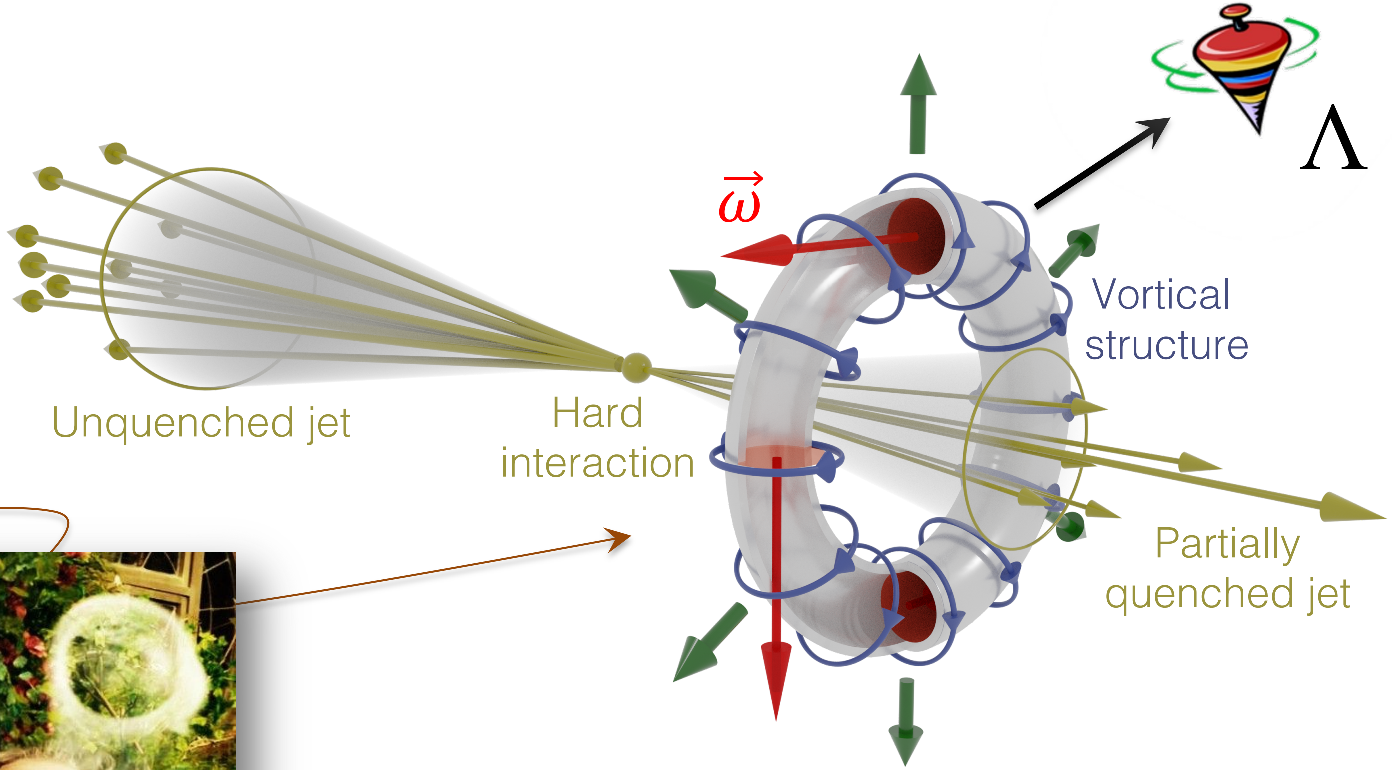

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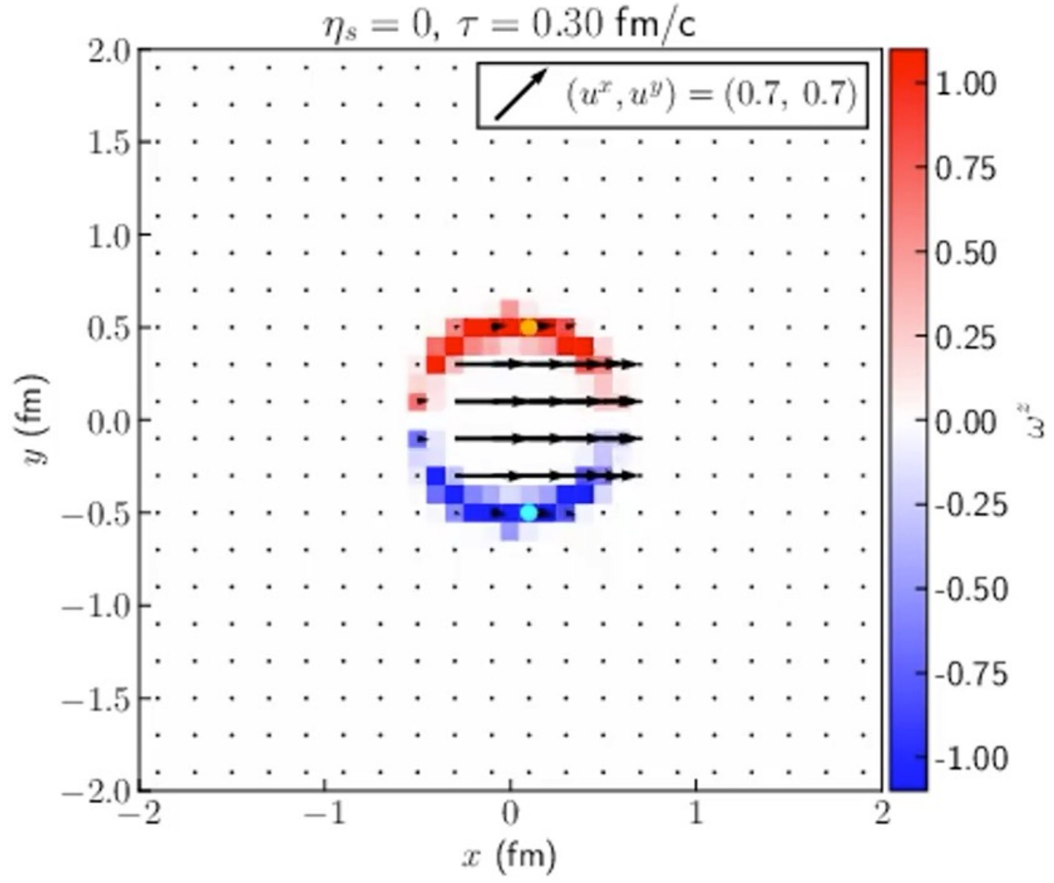
Λ polarization from thermalized jet energy

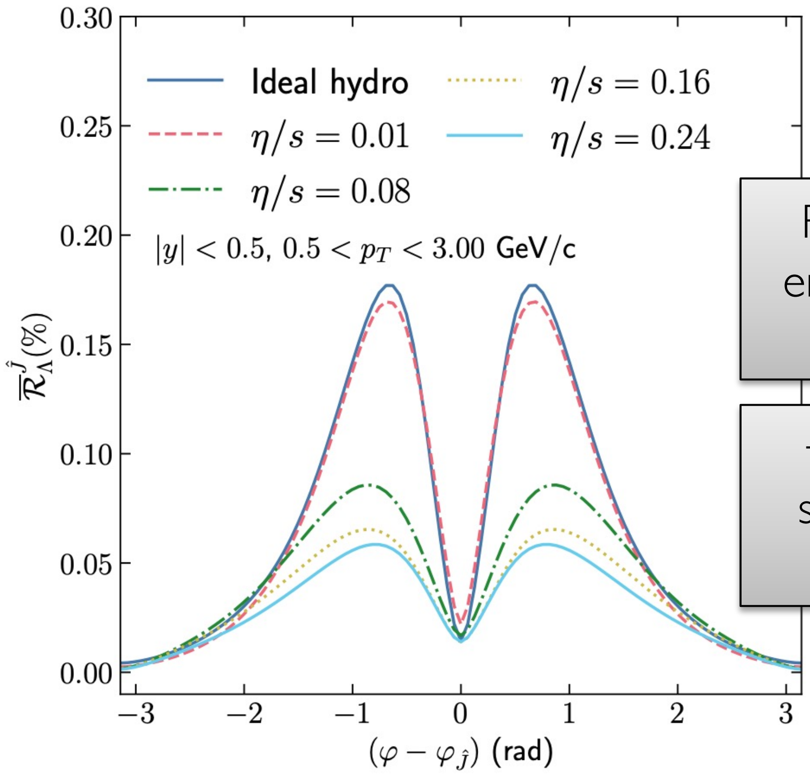


- Simulated via an initial deposition of energy and momentum in a fluid
- Evolution modeled via 3D relativistic hydrodynamics (MUSIC) at LHC energies

- We define a "ring polarization" observable:

$$\overline{\mathcal{R}}^{\hat{t}}_{\Lambda} \equiv \left\langle \frac{\vec{P}_{\Lambda} \cdot (\hat{t} \times \vec{p}_{\Lambda})}{|\hat{t} \times \vec{p}_{\Lambda}|} \right\rangle_{p_T, y}$$

$\vec{p}_{\Lambda}$: momentum
$\vec{P}_{\Lambda}$: polarization
$\hat{t}$: jet axis

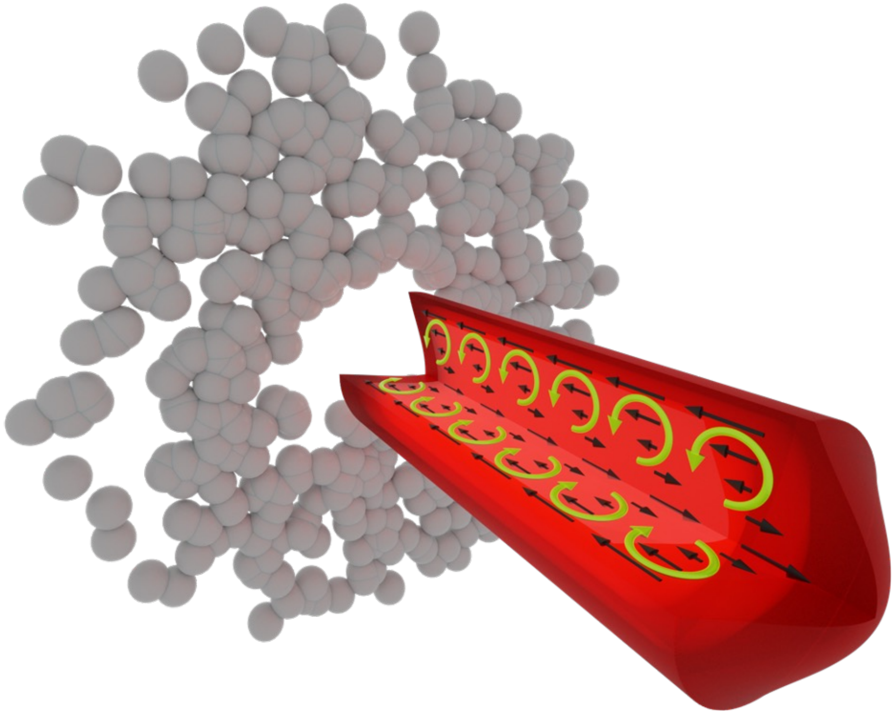


First evidence of jet energy thermalization in a medium!

+ Bonus: extremely sensitive to medium properties

View the video at: https://www.sciencedirect.com/science/article/pii/S0370269321004408?via%3Dihub

Λ polarization: other possibilities



- Proton-nucleus collisions: local vorticity induced from interactions while going through nucleus
- Similar signature (but forward in rapidity)

  …and beyond!

[1] M.A. Lista, J.G.P. Barbon, D.D. Chinellato, W.M. Serenone, C. Shen, J.Takahashi, G.Torrieri, **Phys. Rev. C** 104, 011901 (2021)

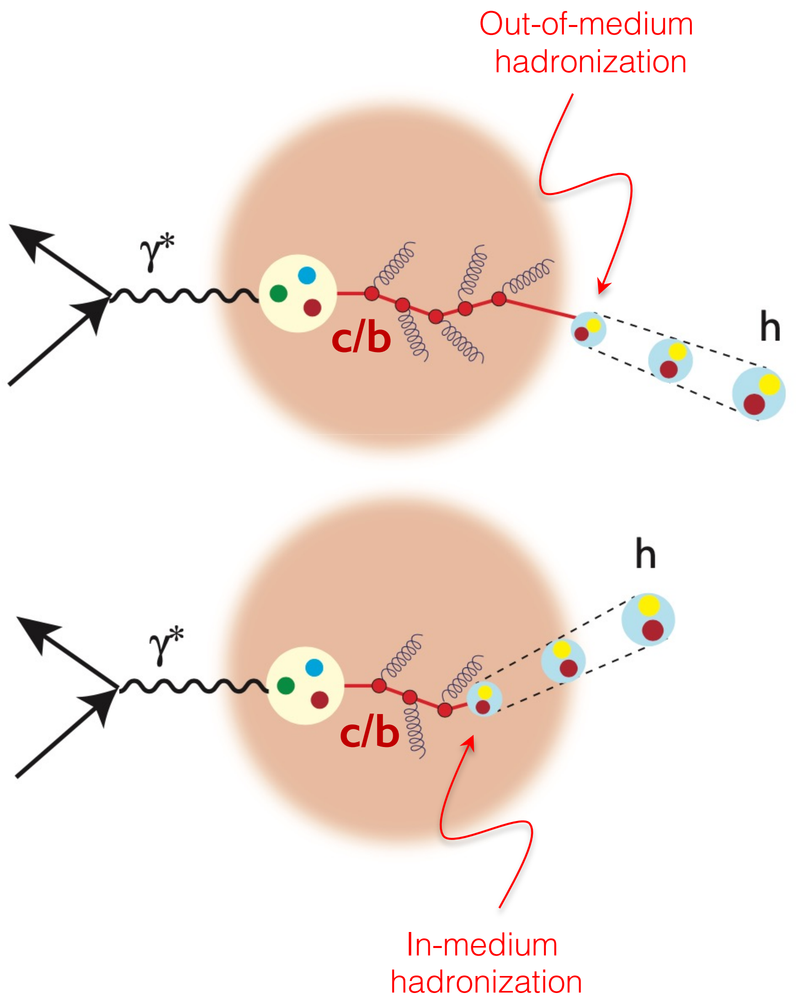
- Further studies: interact with cold nuclear matter? Differences?
  - Understand energy loss: partonic? Hadronic? Limits?
- State-of-the-art modeling and computing required!
  - …to find further key signatures that, in turn, require state-of-the-art detectors to be measured!
- Experimental requirements:
  - excellent particle identification capabilities†,
  - high luminosity,
  - high acceptance,
  - different (non-LHC, much stronger signal) energies

† E.g. timing detectors with O(10ps) resolution are important for weak decays: selection on pions and protons arriving too late for being primary particles provide unparalleled performance

Future studies of QCD matter: the EIC

- Electron-ion collisions: single initial scattering, products travel through nucleus
  - initial parton energy can be inferred by kinematics
  - Probing hadronization in-medium and out-of-medium
    - can be done cleanly at the Electron-Ion Collider (EIC)
  - Produced parton (heavy!) flavour inferred from particle identification
    - The role of heavy flavour: easy to tag!
  - Angular momentum: a new dimension to understand
    - Also relevant for understanding nuclear spin
    - Outgoing hyperon polarization could be interesting
- …To answer:
  - Does a parton hadronize inside the nucleus?
  - How does charm and beauty hadronize?
  - How does that depend on energy? Traveled path? System size?

→ towards fundamental 'microscopic' knowledge of hadronization



Summary and outlook

- We understand a lot about hot and cold QCD matter already, but …

  …there is much more to learn!

  → Hadronization of heavy flavour and jet universality?
  → Importance of nuclear structure?
  → Angular momentum in QCD matter and in the nucleus?

State-of-the-art detectors and techniques

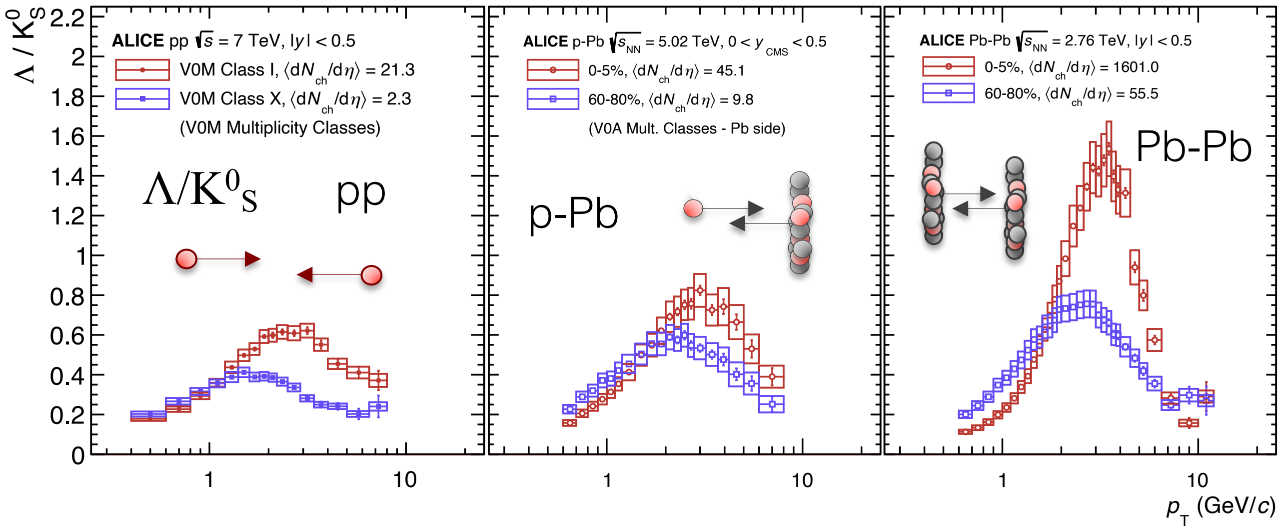
→ pave the way to state of the art physics!

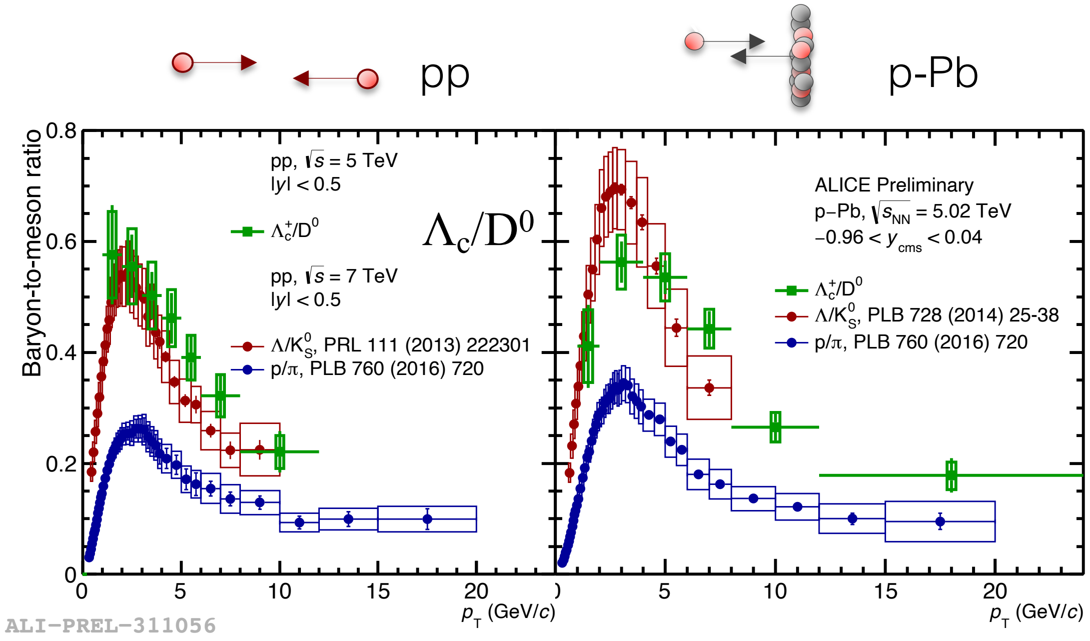
Thank you!

Backup

Baryon to meson ratios: strangeness + charm

ALICE, Phys. Rev. C 99, 024906

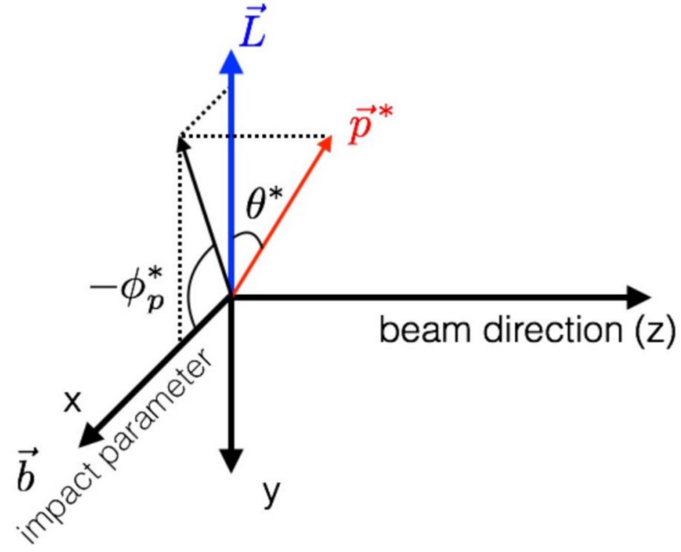




- Similarities also seen in strangeness measurements
- behavior in Λ/K^0_S ratio for all systems a function of N_{ch} only

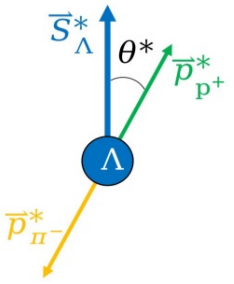
- Also present in the charm sector
  - Universality remains a theoretical challenge

The global polarization measurement



$\Lambda \rightarrow p + \pi^-$

(BR: 63.9%, cτ ~7.9 cm)



Orbital momentum is perpendicular to the reaction plane (opposite direction to y-axis - defines the polarization sign)

Angular distribution in the particle's decay rest frame:

$$\frac{dN}{d\cos\theta^*} \sim 1+\alpha_H P_H \cos\theta^*$$

Estimate particle's spin direction from self analysing weak decay

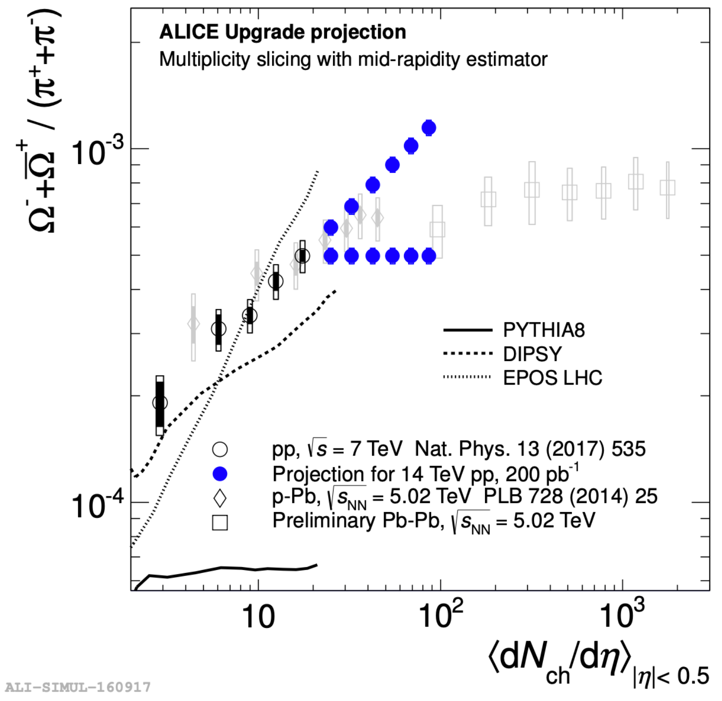
For Λ: $\alpha_H = 0.732$ / -0.758 (updated PDG value in 2020)

Global polarization observable

$$P_H = \frac{8}{\pi \alpha_H} \langle \sin(\Psi_{RP} - \phi_p^*) \rangle$$

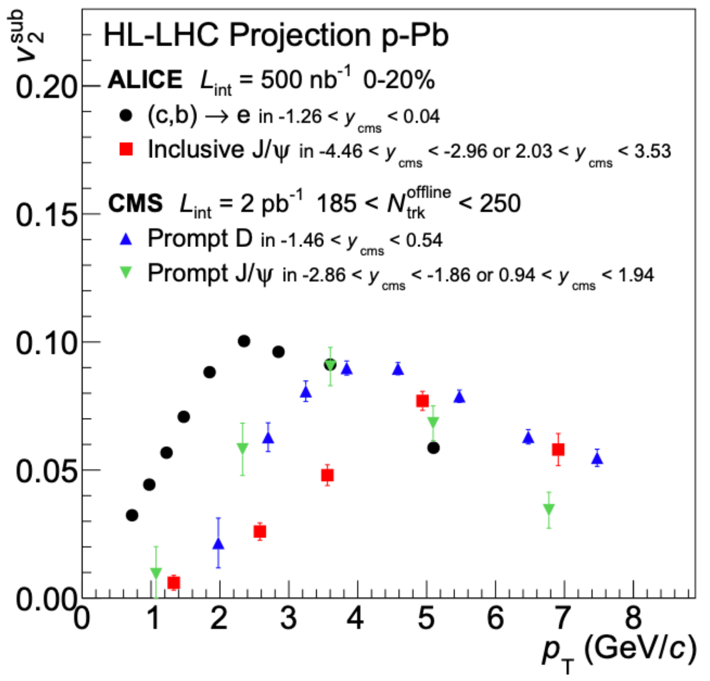
- Observable reflects P_y projection of the polarization

Small systems: future measurements at the LHC



Relatve strangeness production: Saturation in a single system

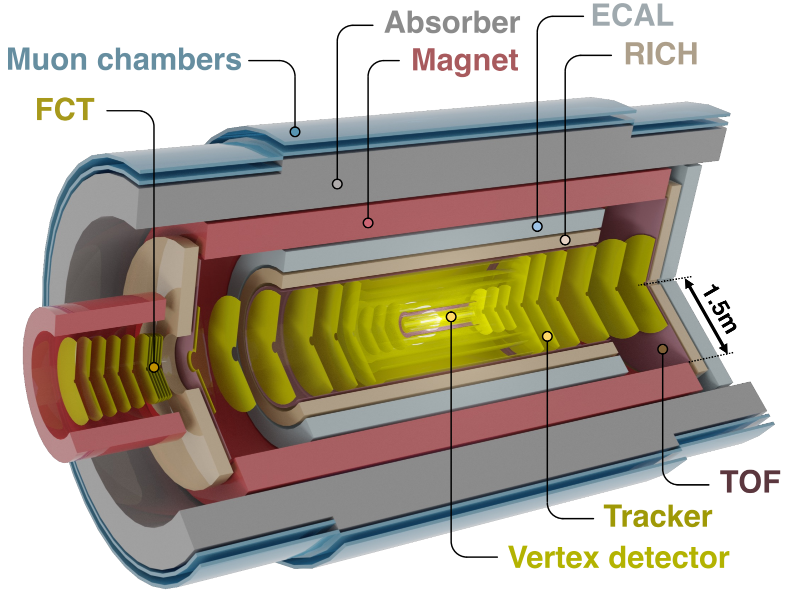
ALICE-PUBLIC-2019-001



High-precision v2 measurements (including heavy-flavour)

CERN-LPCC-2018-07

- **ALICE 3:** new detector at LHC P2: silicon tracker with large acceptance
- Emergent QCD phenomena part of physics programme



CERN-LHCC-2022-009

ALICE 3