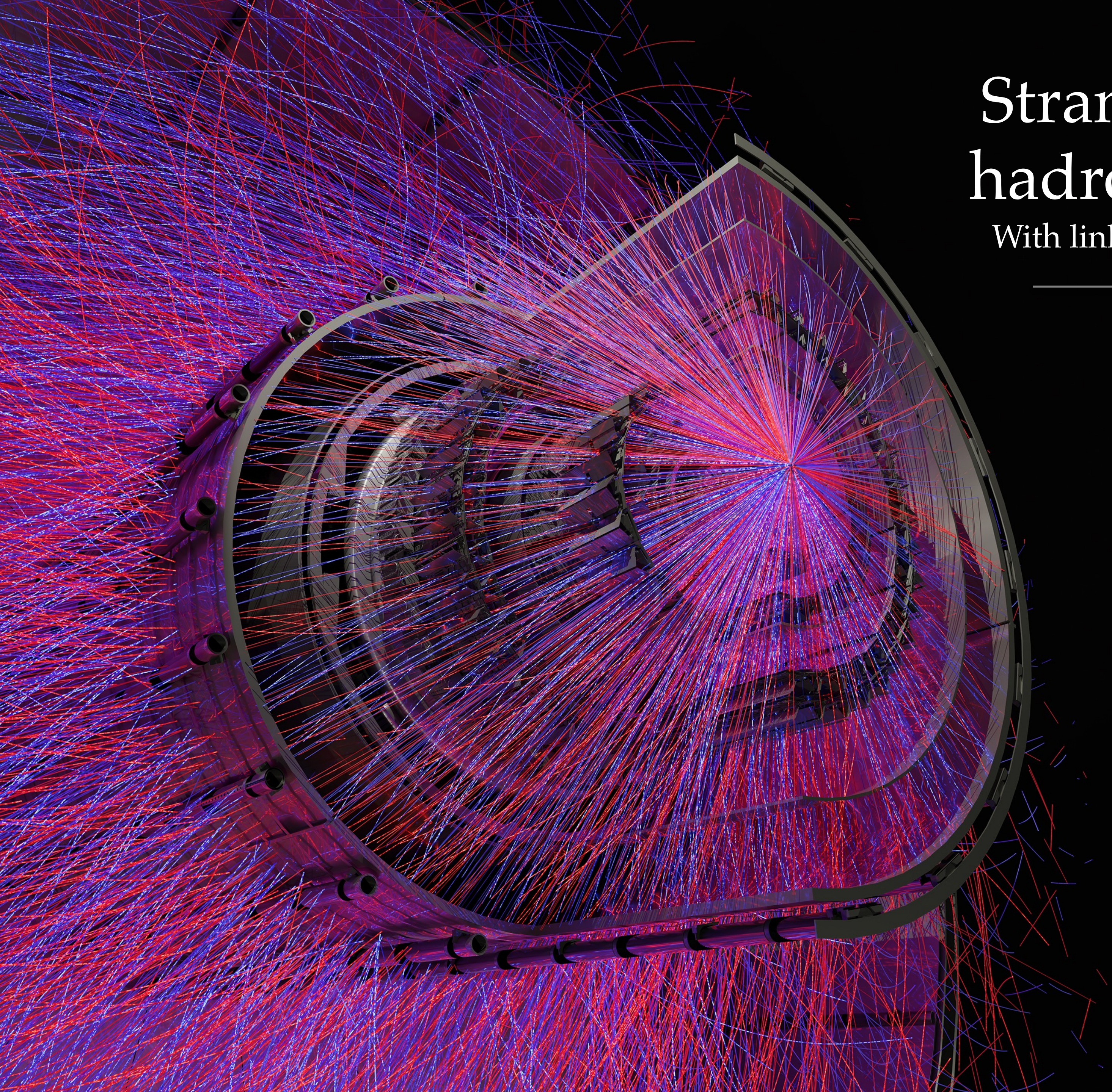


Strangeness measurements in hadronic collisions at the LHC

With links to expectations at the EIC and future programs

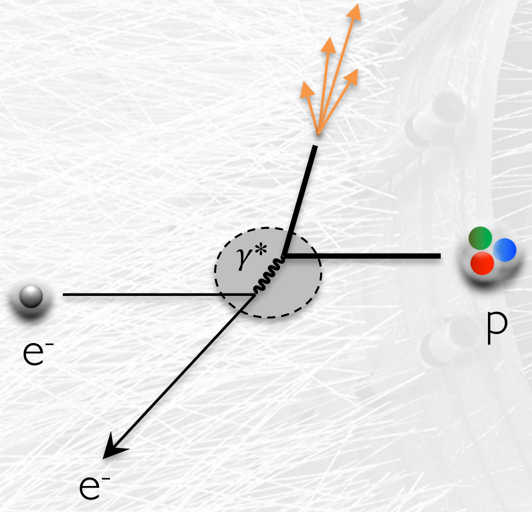
Present and future perspectives in Hadron Physics

David Dobrigkeit Chinellato

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

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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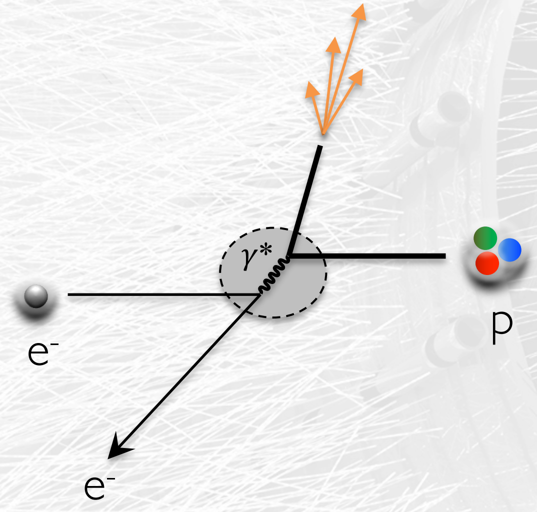

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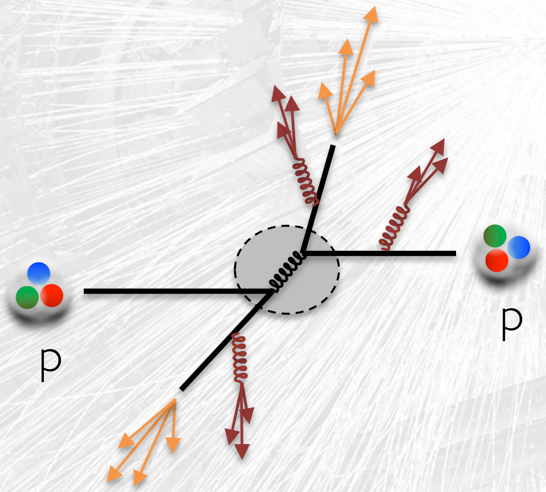
High-multiplicity pp, proton-lead collisions

hadronic



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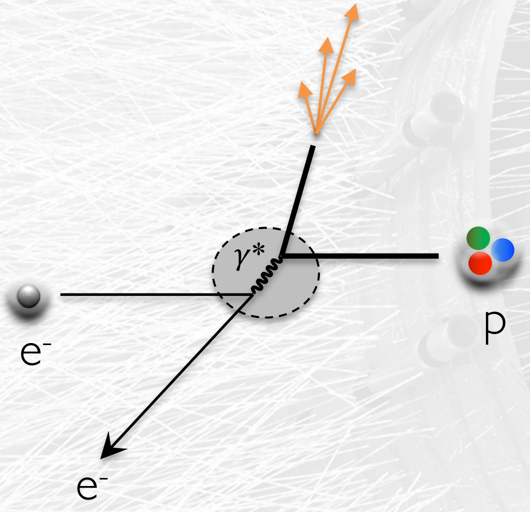

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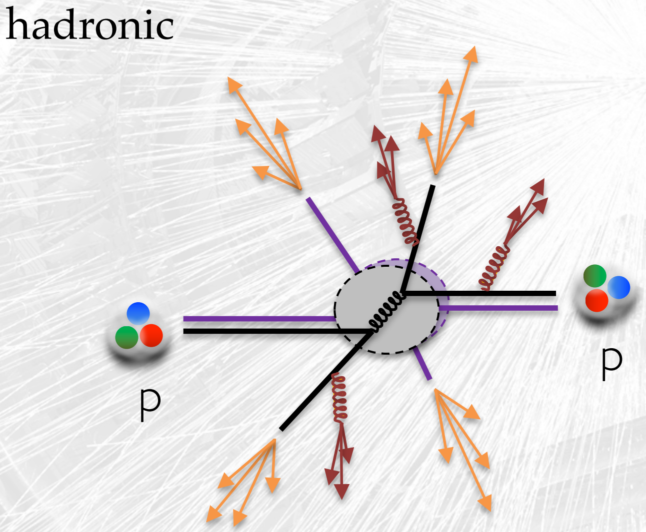

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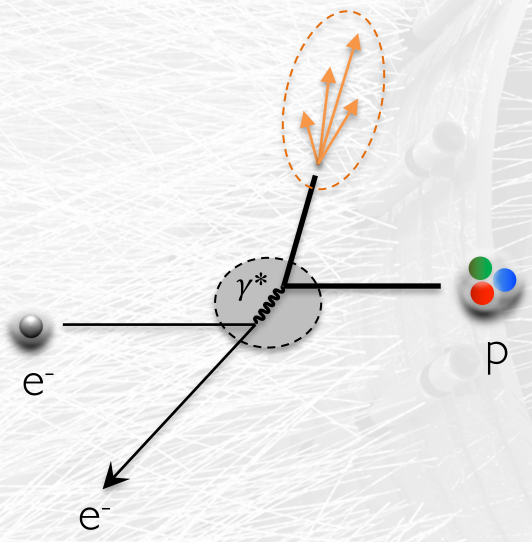

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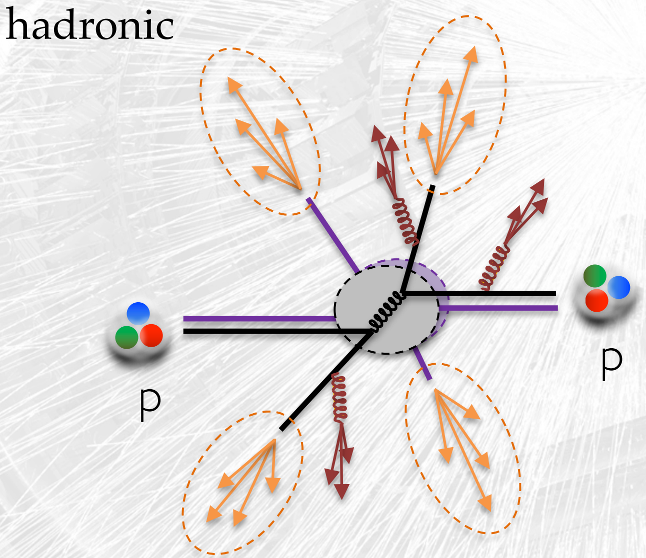

- 2 → 2 scatterings (LO QCD)
- Soft physics: initial and final state radiation, multi-parton interactions
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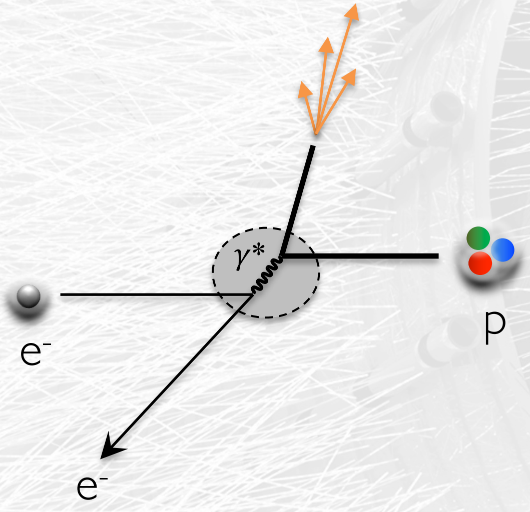
Jet universality:
Given a specific outgoing parton with a specific momentum, final hadrons are always the same

Describing electron, proton and nuclei collisions

electron-proton collisions



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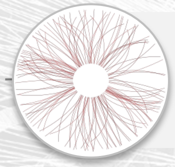

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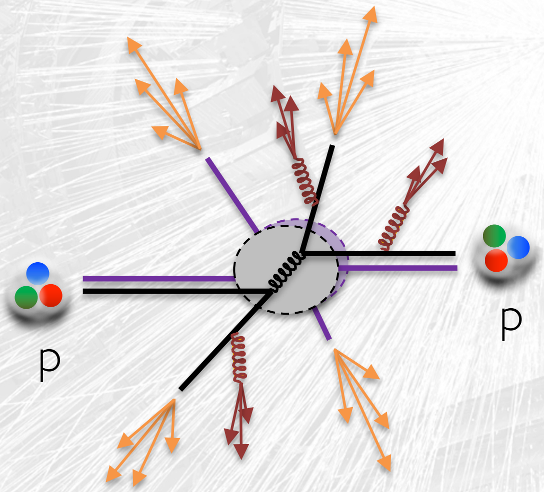

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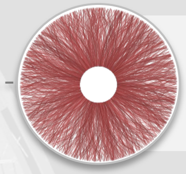
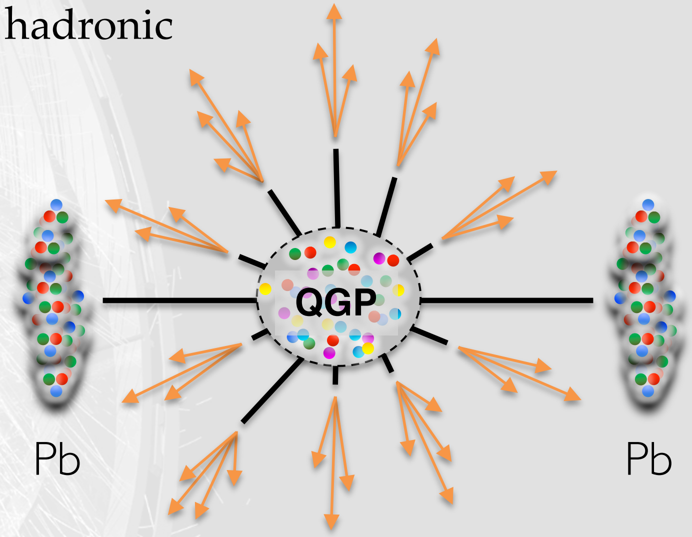
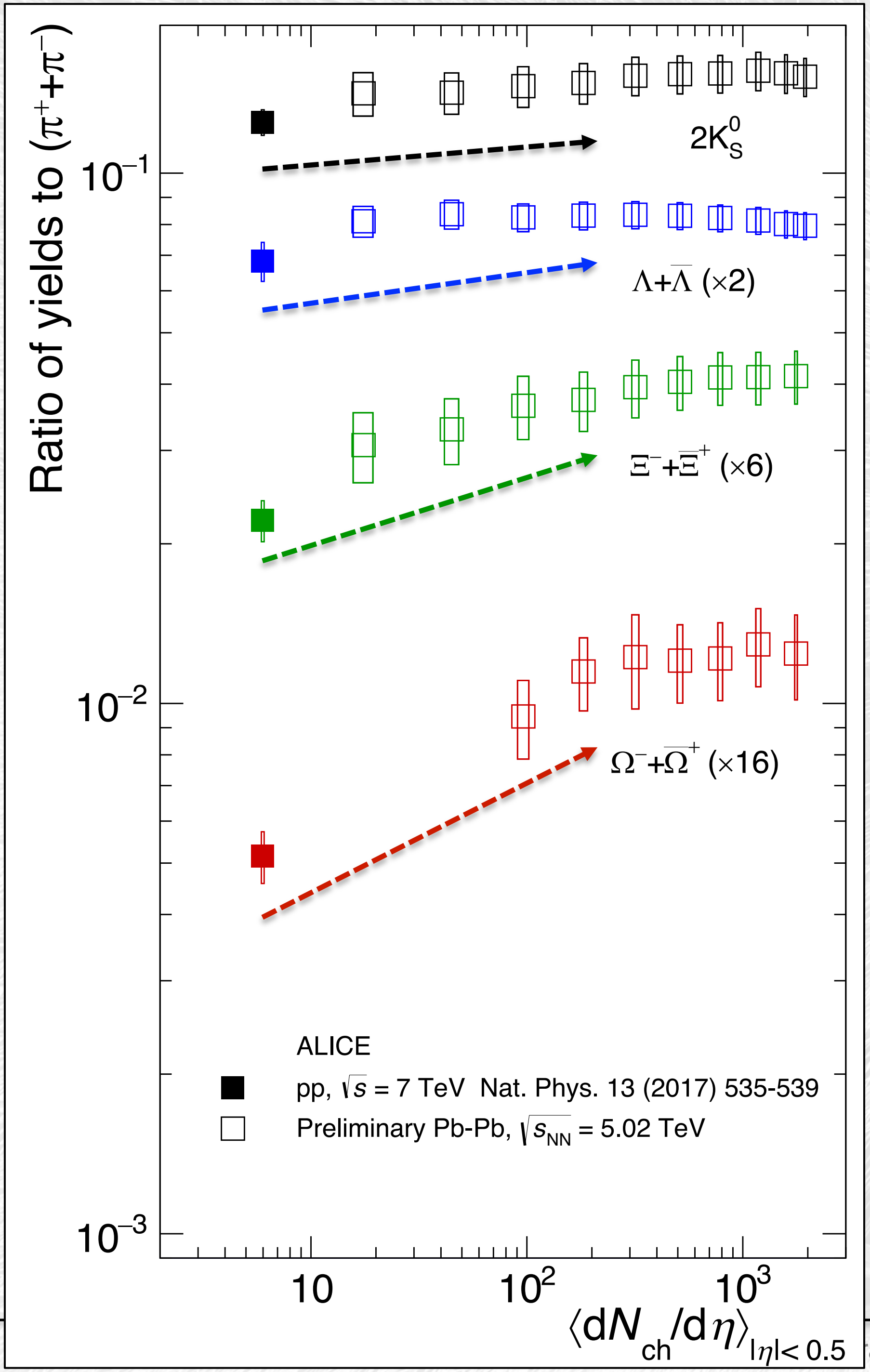


lead-lead (Pb-Pb) collisions

hadronic

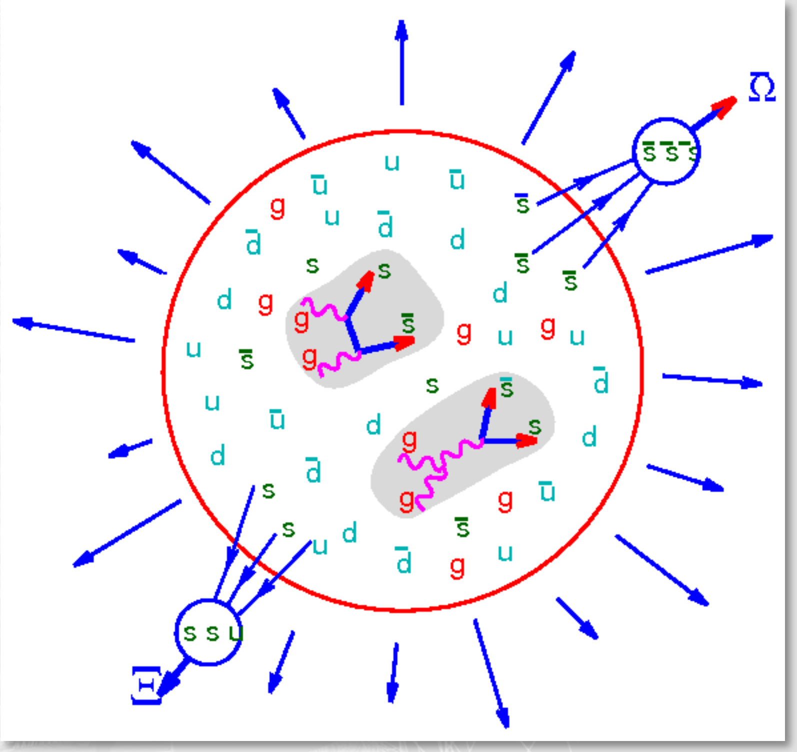


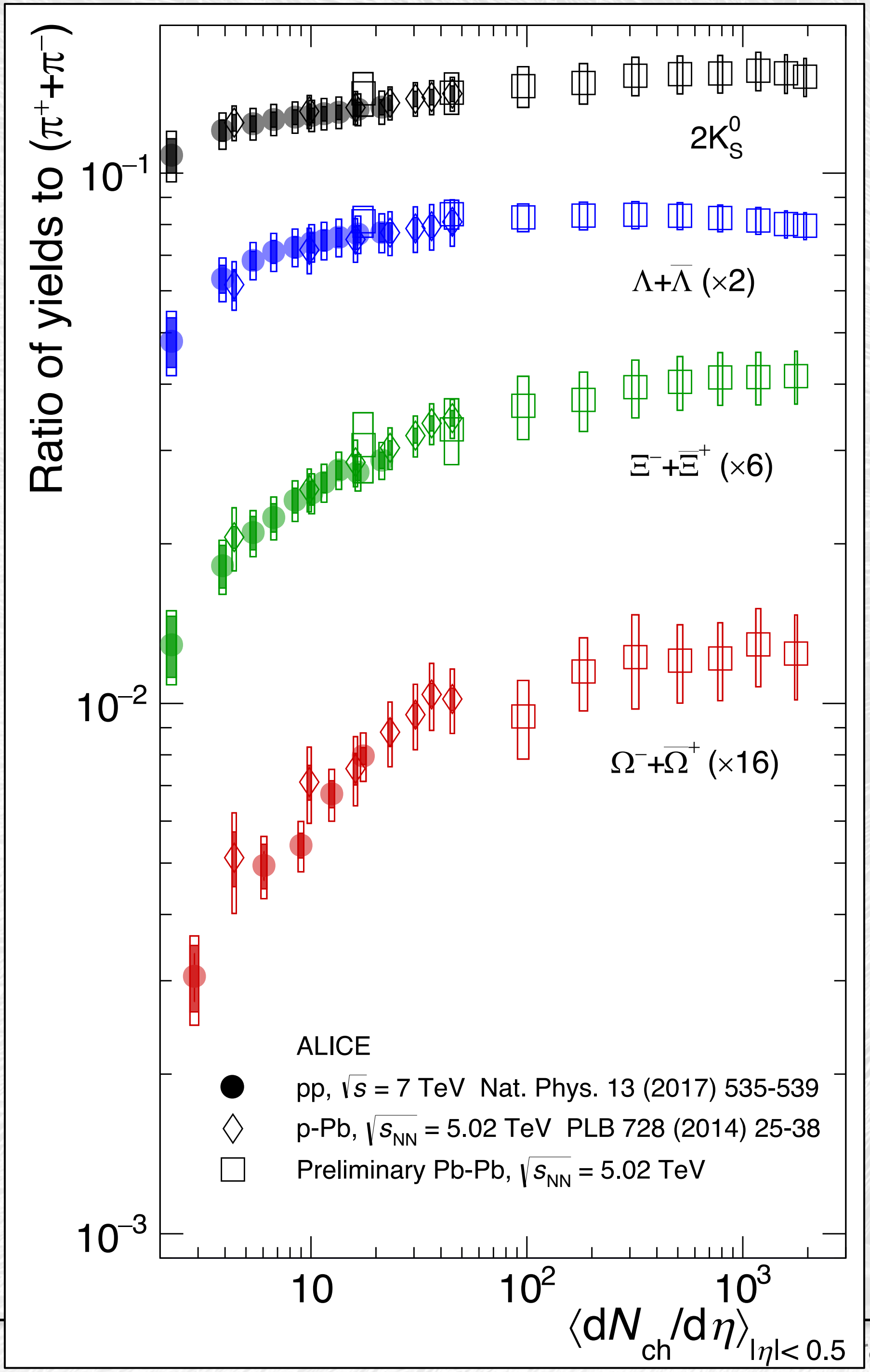
Quark-gluon plasma (QGP)
kinematically and chemically equilibrated system: hydrodynamics and statistical principles



Why strangeness?

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





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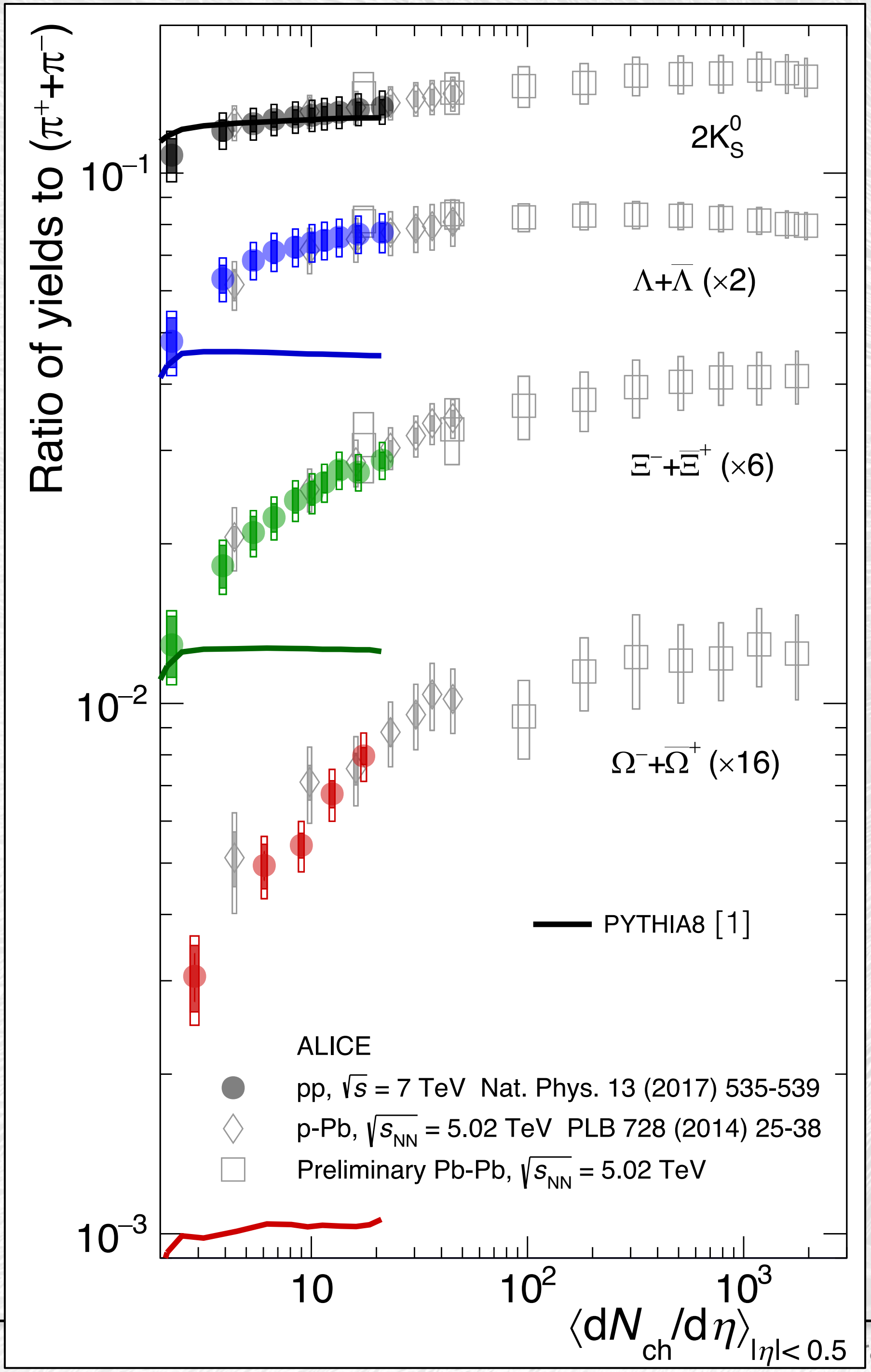

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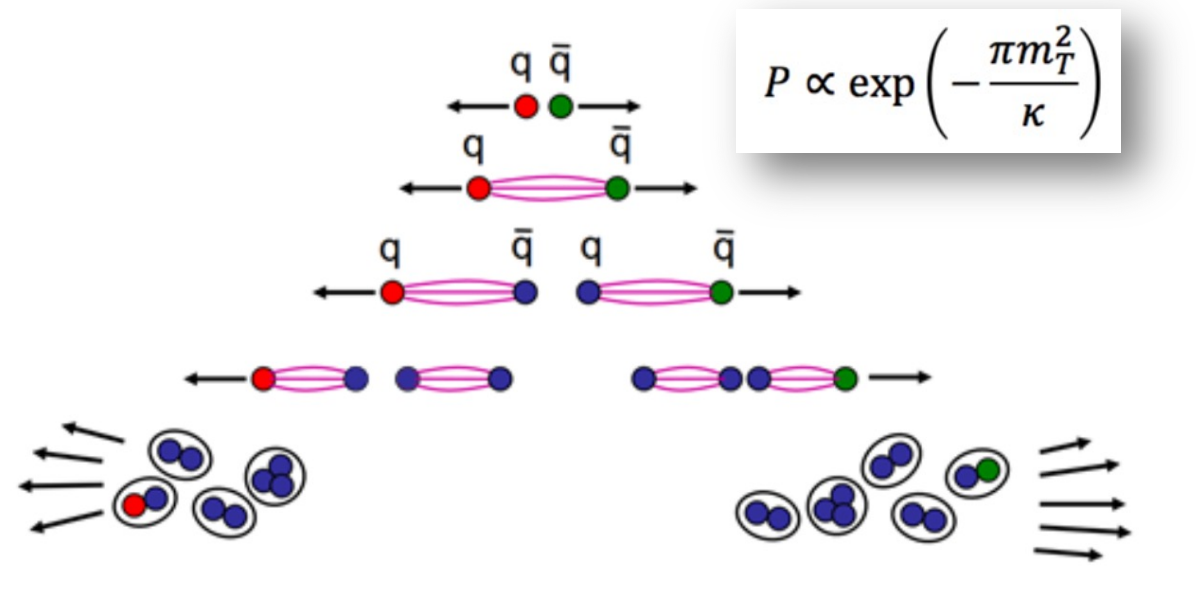
  - Production wrt to π enhanced
- Also studied in p-Pb and pp
  - Strangeness increases with multiplicity following a universal trend
- Not described by PYTHIA

  - 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

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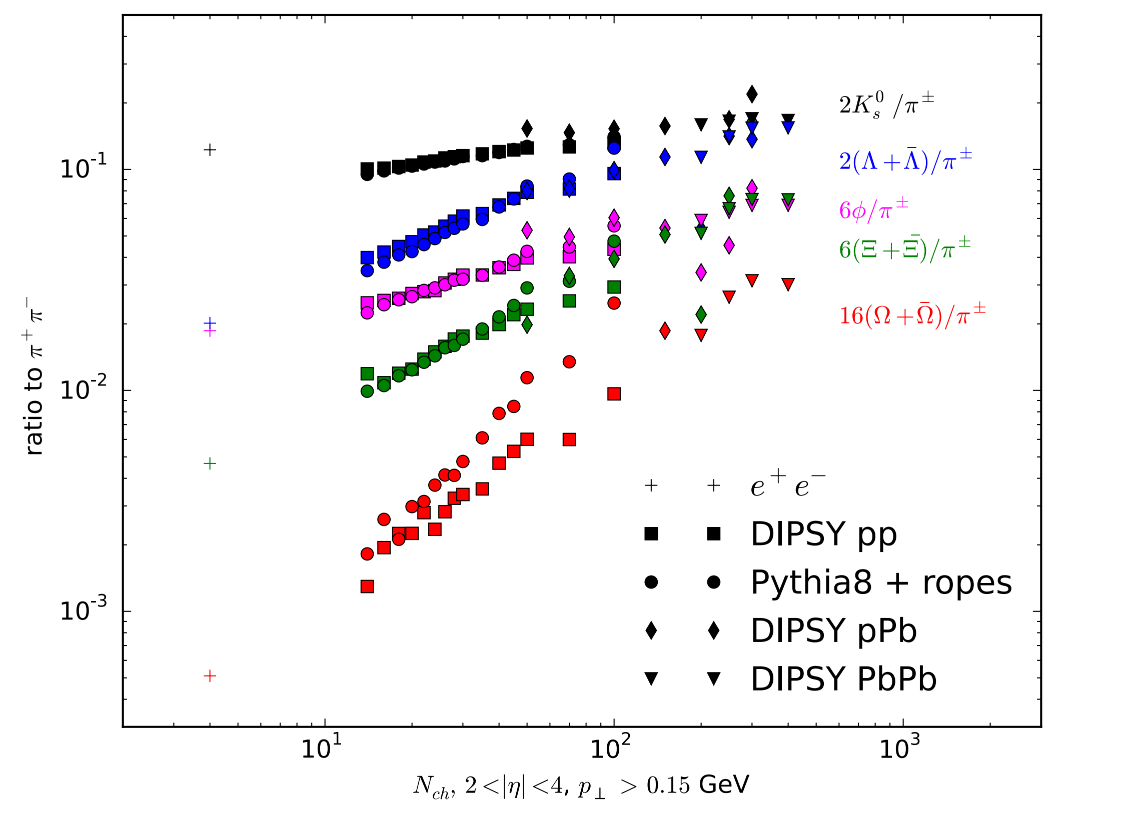
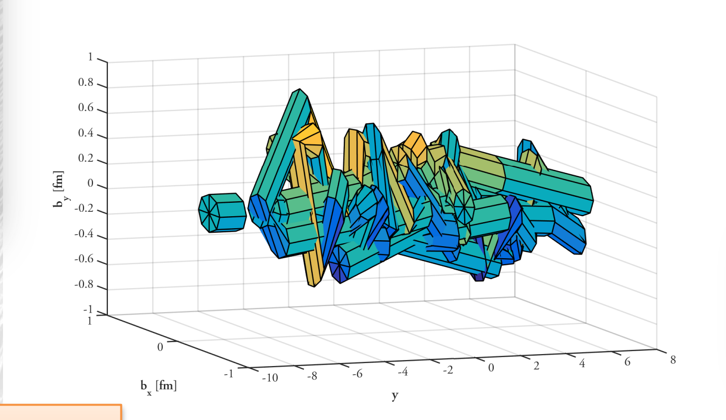


C. Bierlich,
https://indico.cern.ch/event/732345/contributions/3024828/attachments/1668639/2676025/cbierlich.pdf

- 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!



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

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

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

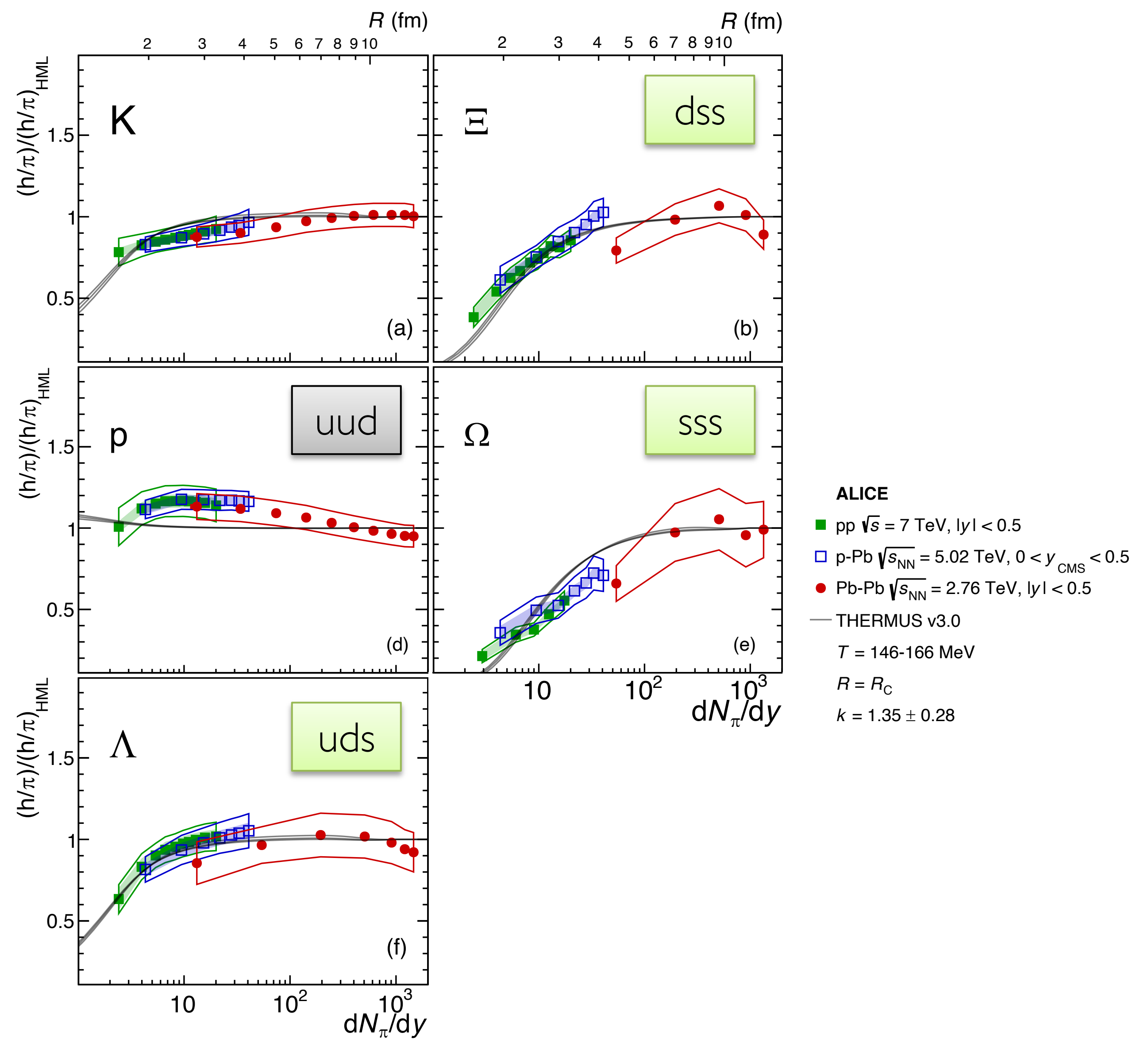
This is a **violation of jet universality**: not more of the same, but something else! → emergent phenomenon of QCD

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, $k = 1.35 \pm 0.28$
- Description OK for strangeness



ALICE, Phys. Rev. C 99, 024906

Heavy-ion perspective

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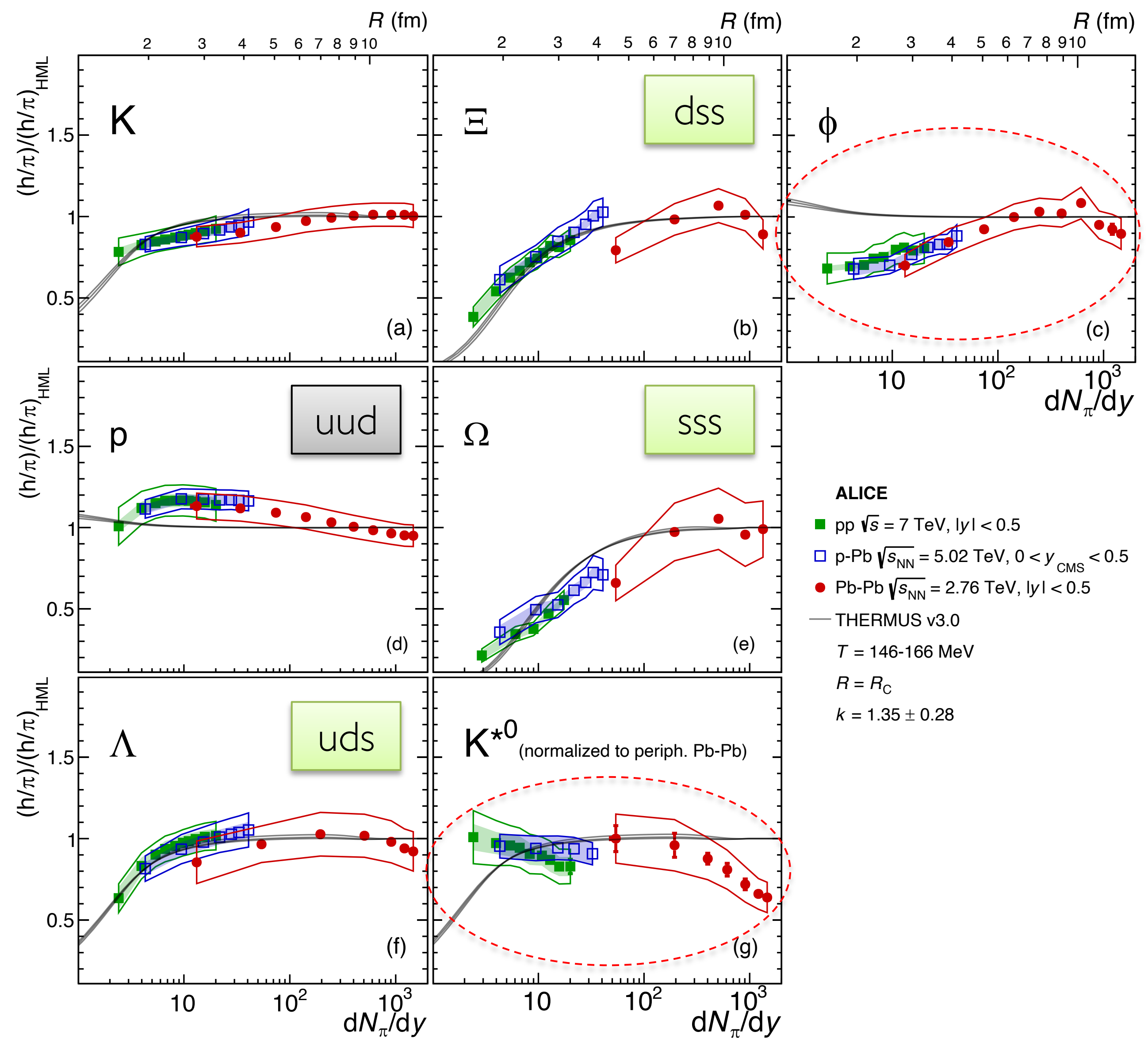
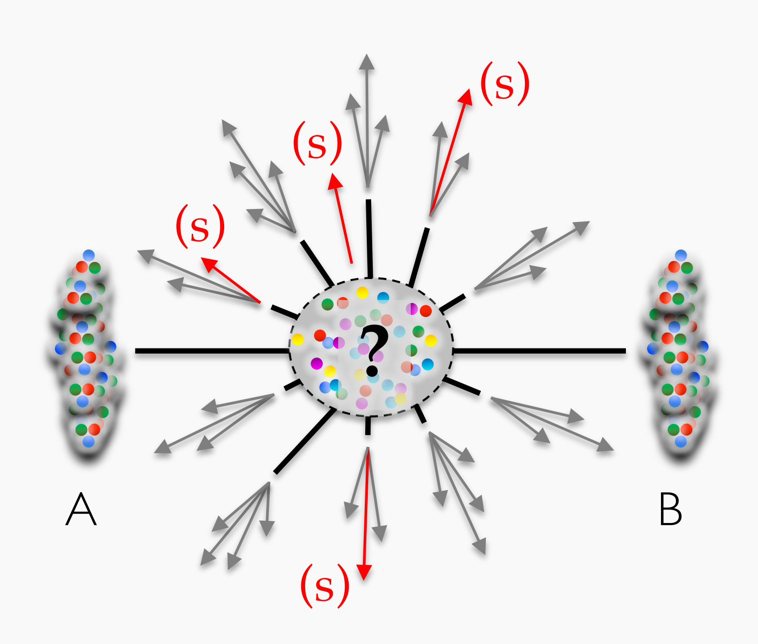


ALICE, Phys. Rev. C 99, 024906

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

Fast forward to 2024:
From discovery to experimental characterisation

Strangeness enhancement
Average yield enhancement
with respect to pions



Many additional studies performed!

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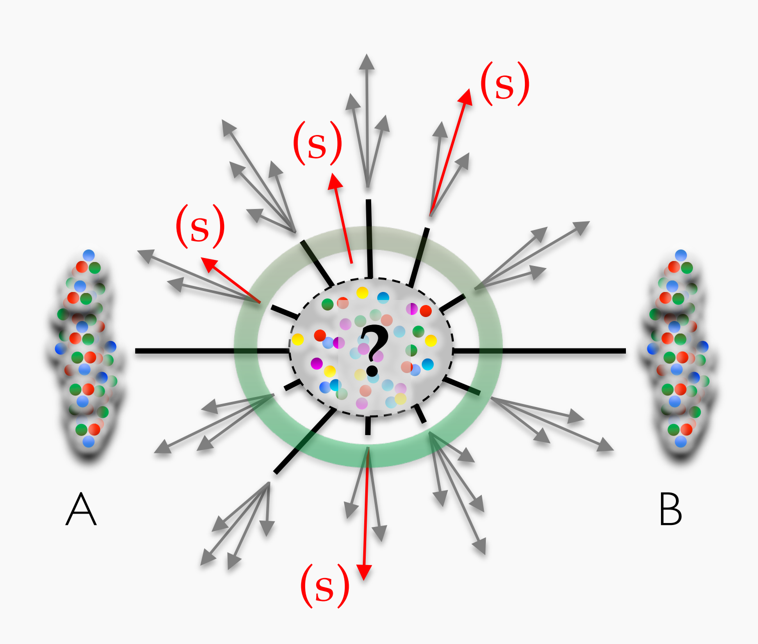
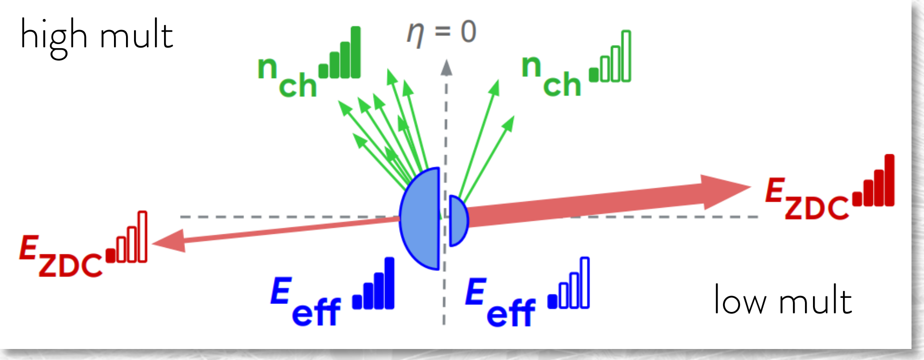
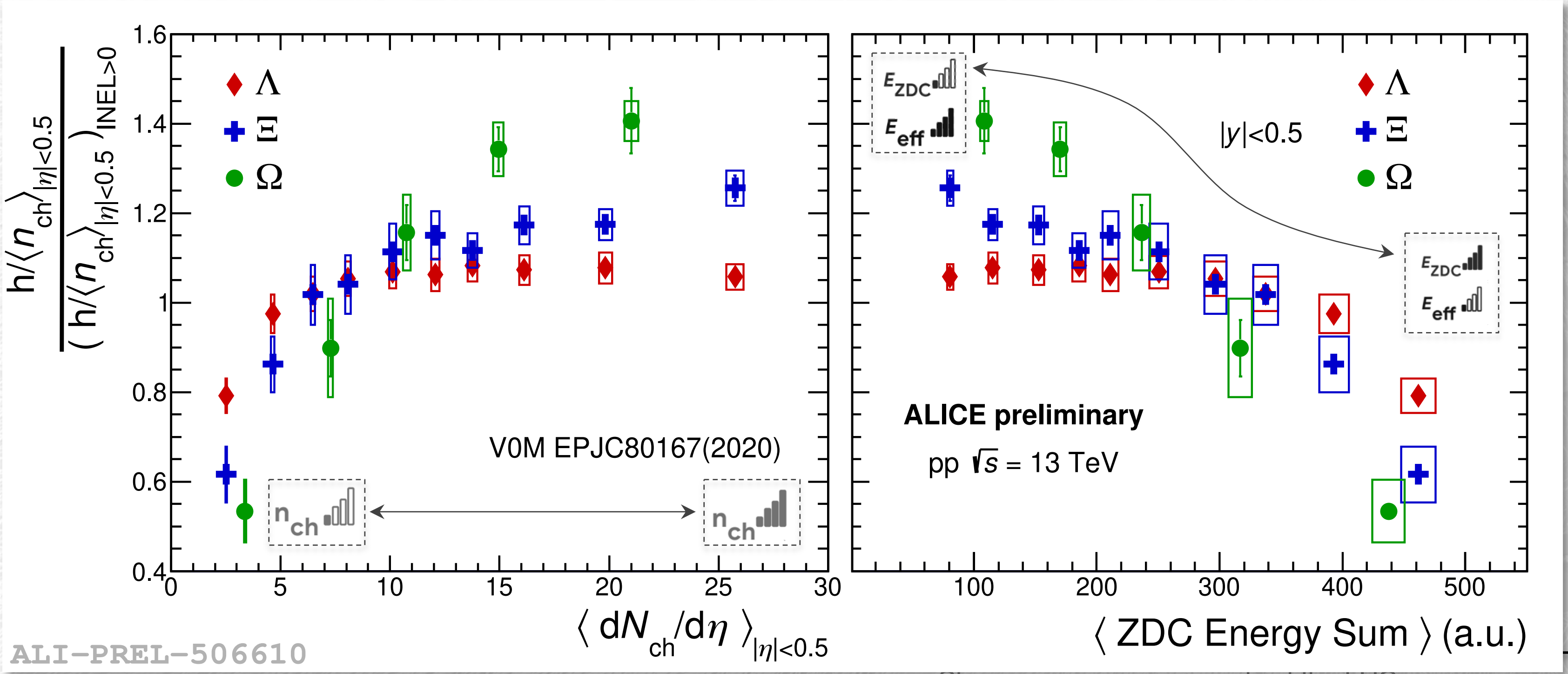
What actually *causes* strangeness enhancement?
→ **Forward selections, spherocity**



Selecting on 'effective energy': ZDC



- **Zero-degree Calorimeters**: select very very forward → inversely proportional to available energy for midrapidity processes



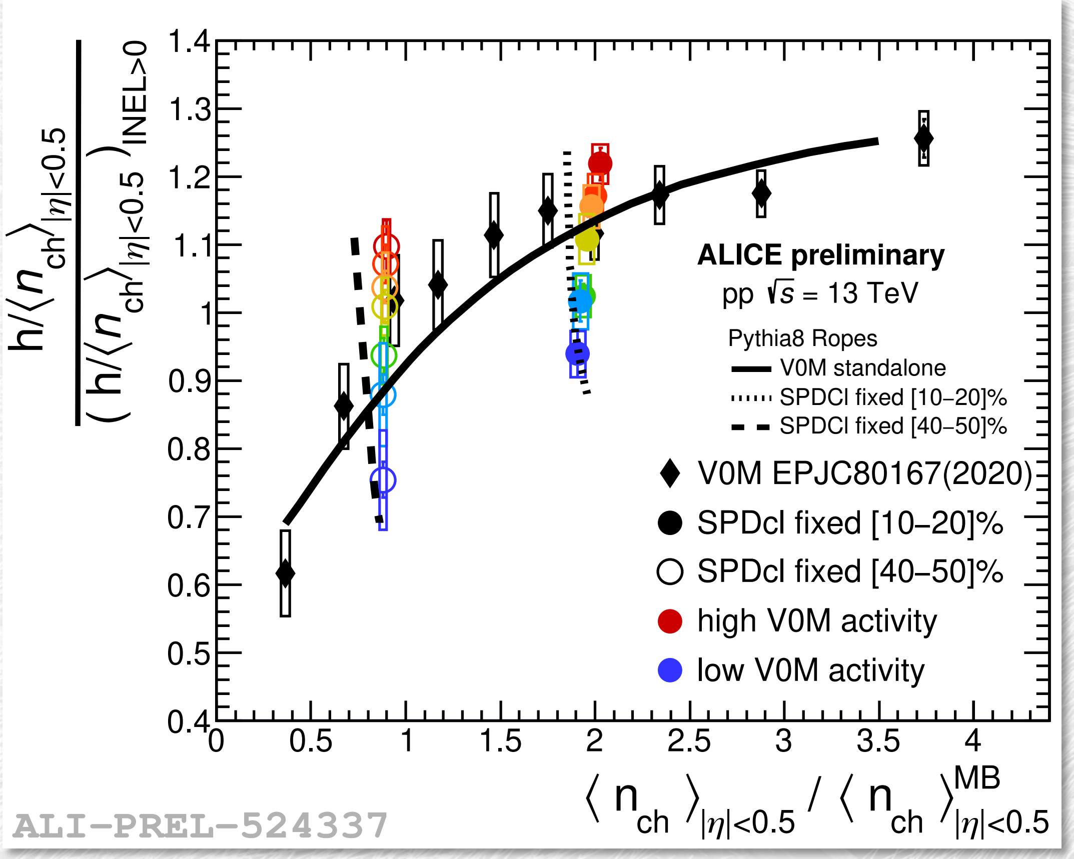
- **Important**: strangeness enhancement is decided early on in the collision (rapidity ⇆ causal disconnection)

In MPI-based models:

- N(partonic inter.) decided early
- 'final-state' factors such as colour ropes depend on N(partonic inter.)

Double-differential study:

Fixed midrapidity but different forward multiplicity



- Solid black: classical strangeness enhancement result with single V0M-based selection
- Coloured: fixed midrapidity multiplicity but varying V0M (forward) scintillator amplitude
- At fixed midrapidity multiplicity, *one can still increase the relative strangeness content by selecting in forward multiplicities*

Important:

- "local mult. drives strangeness enhancement" is incorrect
- "local mult. is correlated with strangeness enhancement" -> OK

Generally consistent with PYTHIA 8 expectation:
More MPI → more strings → rope formation → extra strangeness

+ Consistent also with other results (spherocity, etc)

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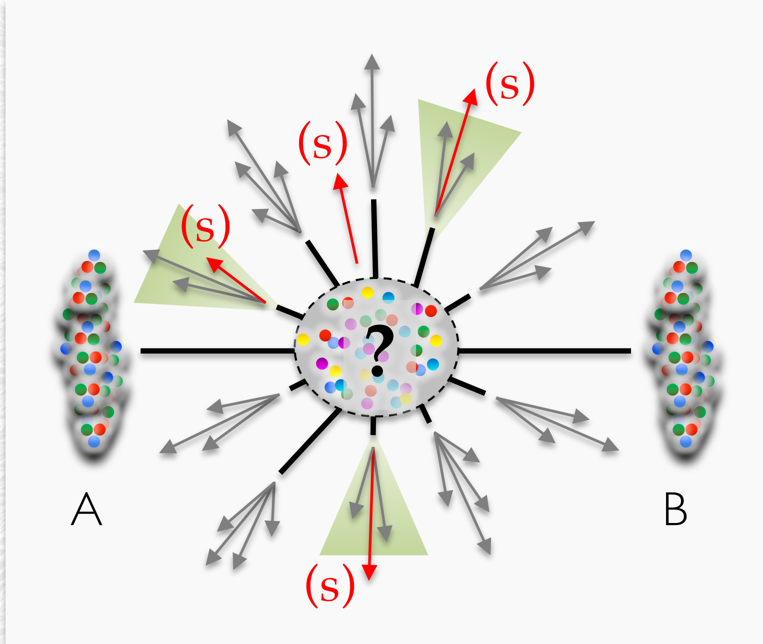

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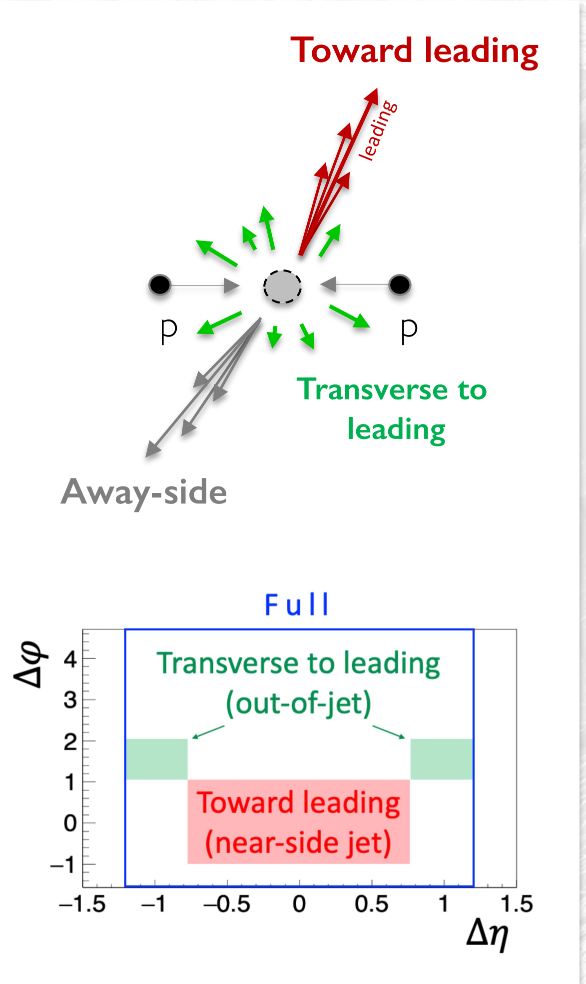
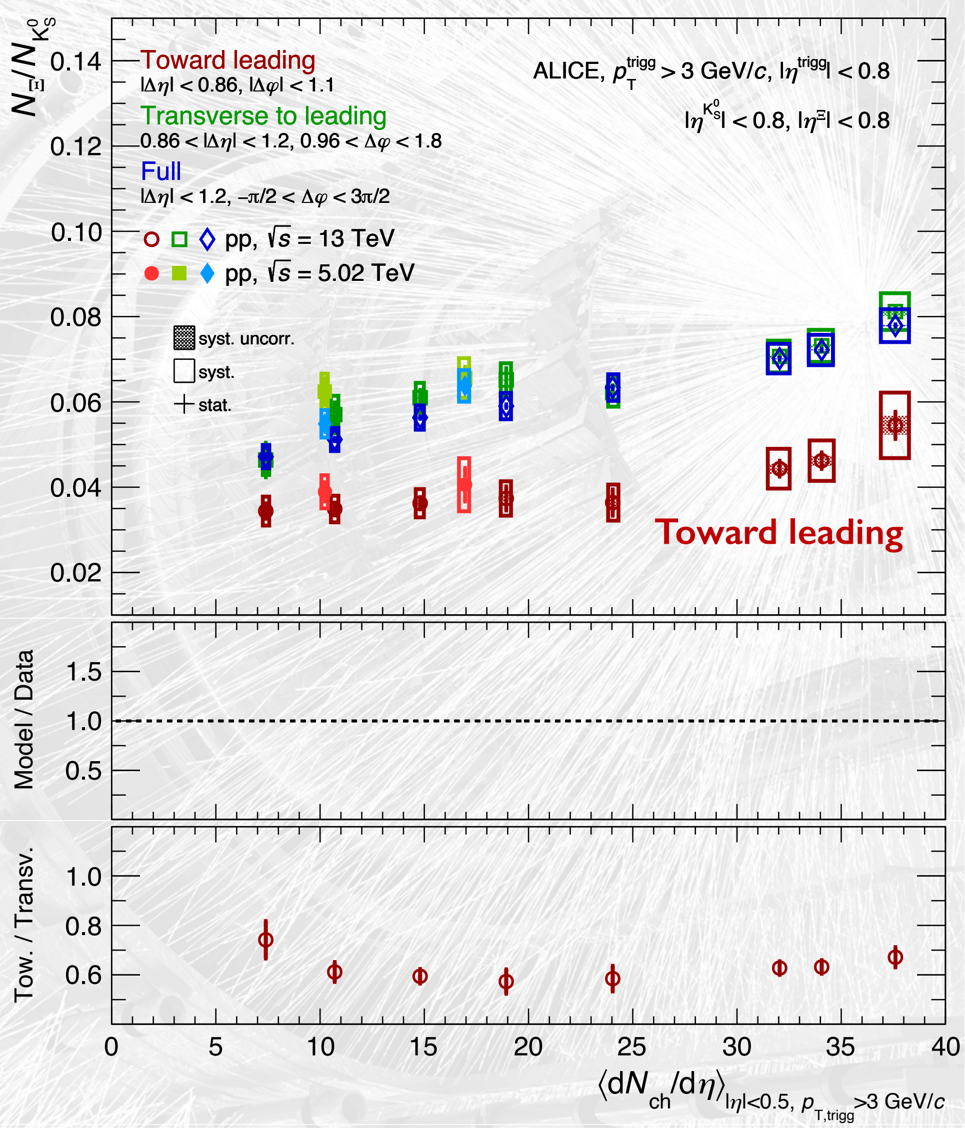
→ **R_T analysis, strangeness in jets, 2 part. corr.**

Ξ/K^0_S ratio in toward- and transverse to leading particle region





- **transverse-to-leading phase space region**: dominant contribution to the Ξ/K^0_S
- Generally compatible with high-p_T processes being less coupled to the actual increase of strangeness
- But: both contributions increase with multiplicity

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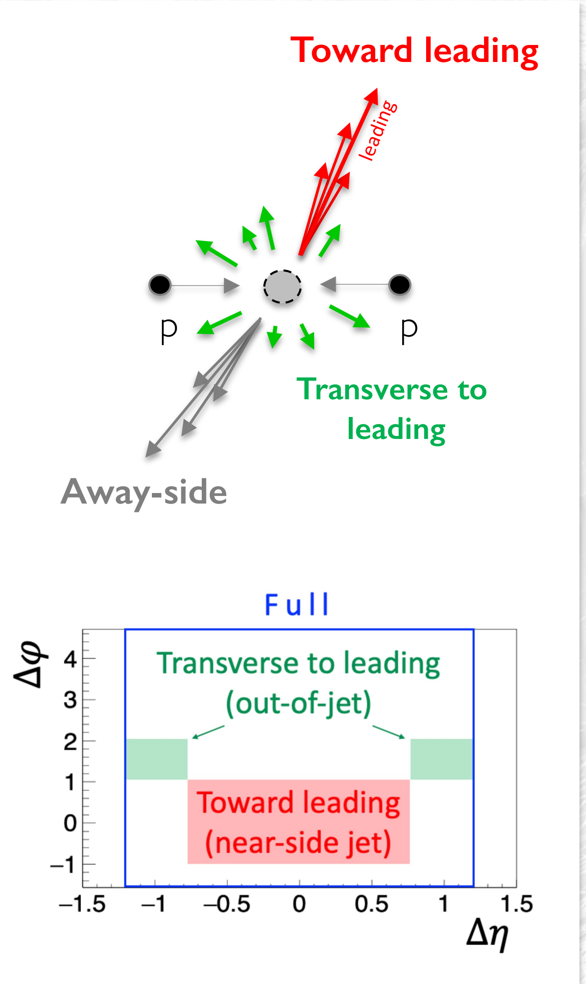

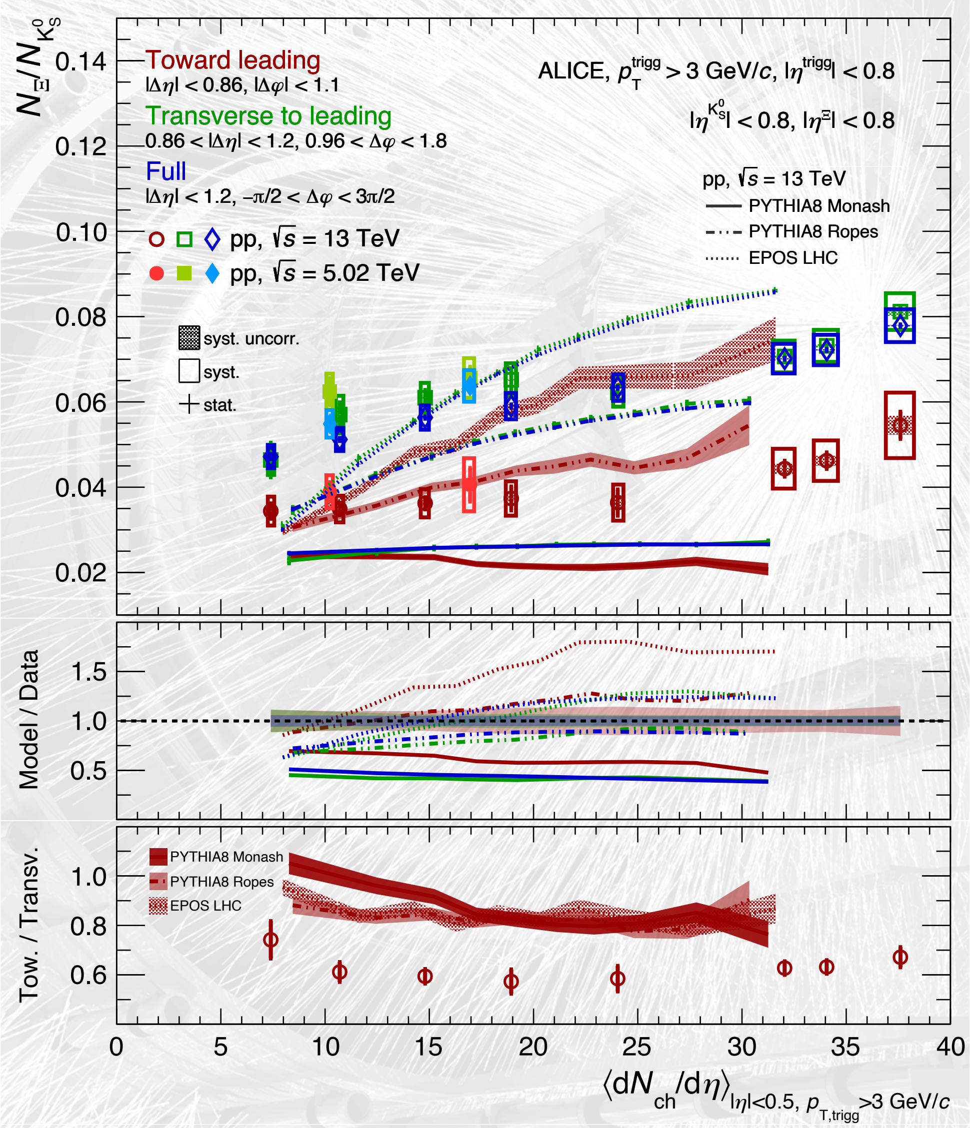

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- But: both contributions increase with multiplicity
- Monte Carlo models not in agreement with observed values, though qualitative trends similar

Progress towards quantification of strangeness enhancement phase space

Fast forward to 2024:

From discovery to experimental characterisation

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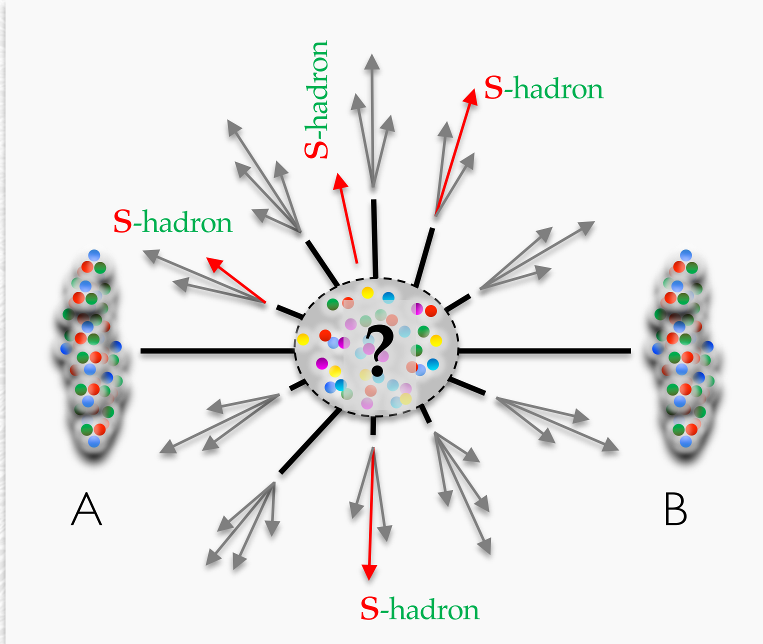
Average yield enhancement with respect to pions



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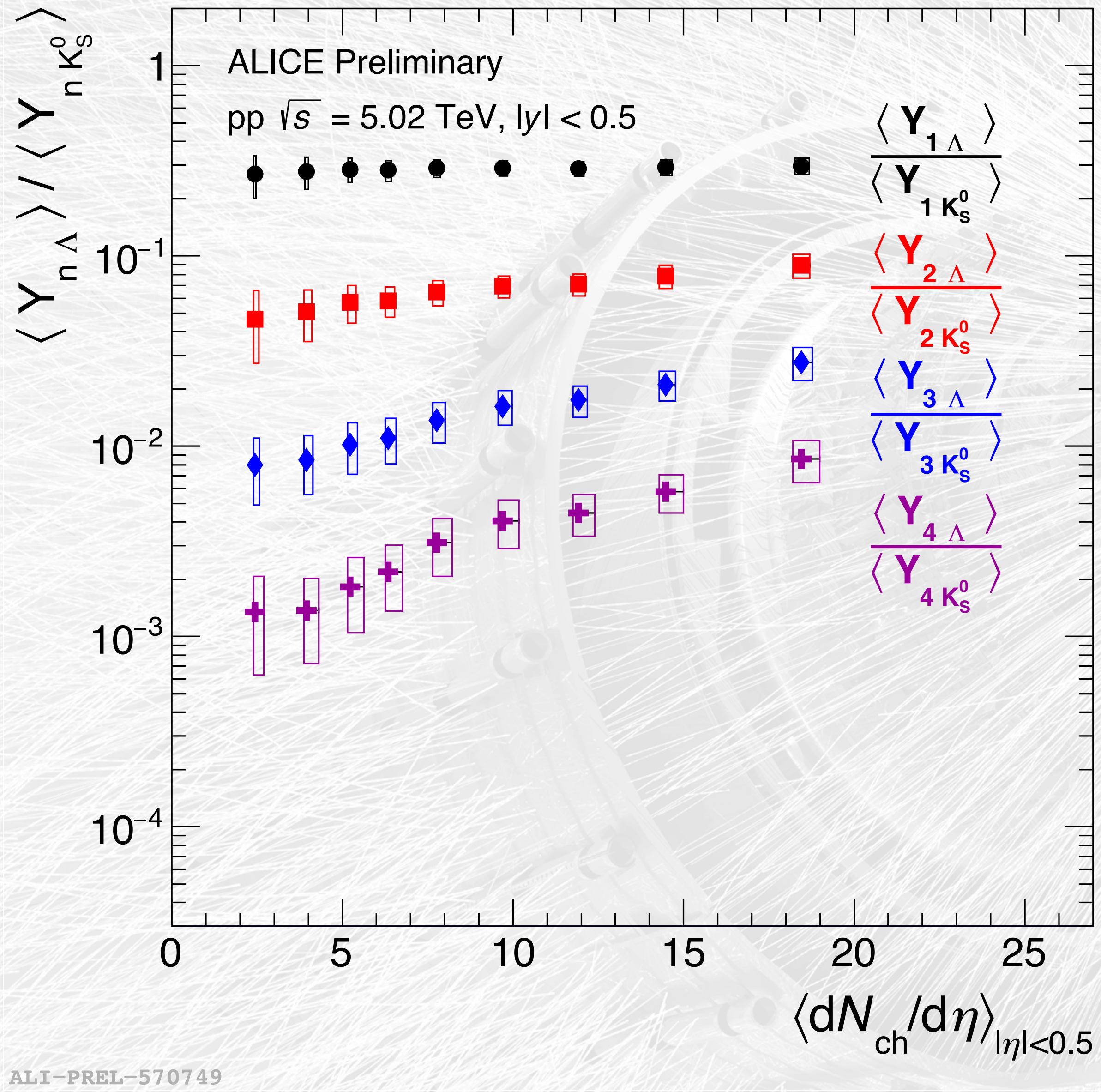
From quarks to number of s-hadrons produced E-by-E
→ P(N(s-hadron))

Production of a certain number of s-hadrons



- Multiple production of single-strange: easier to produce multiple baryons vs mesons at higher multiplicity
  - Given a certain number of strange quarks, it is easier to combine with other light quarks at higher multiplicity

Indicative of a partonic coalescence picture?

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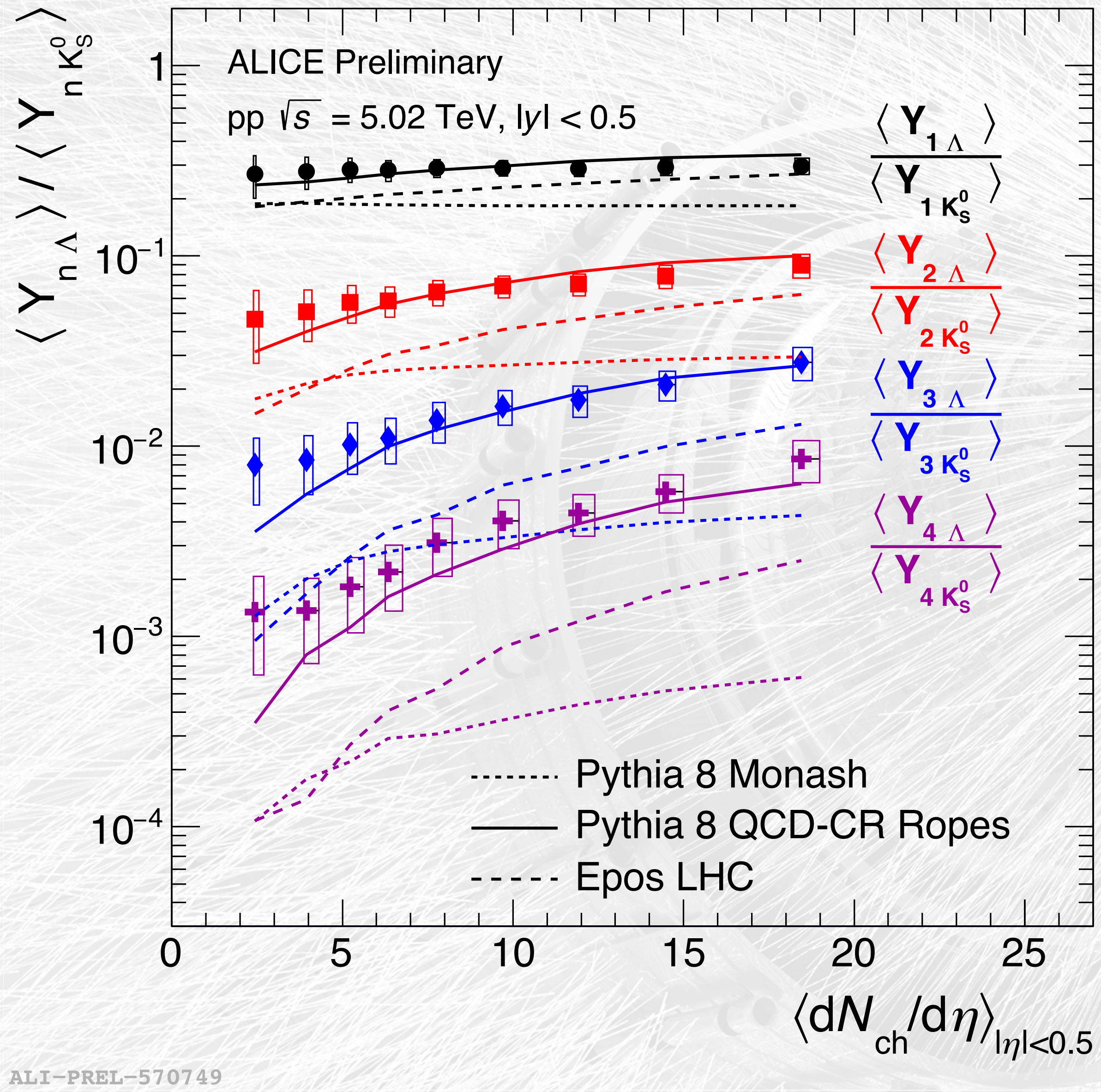

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Indicative of a partonic coalescence picture?

- Trends fairly well reproduced by PYTHIA
  - …even beyond simple averaged yields…
  - …provided colour ropes are used!

  - Begs for an attempt of following strange quantum number very precisely!

Fast forward to 2024:
From discovery to experimental characterisation

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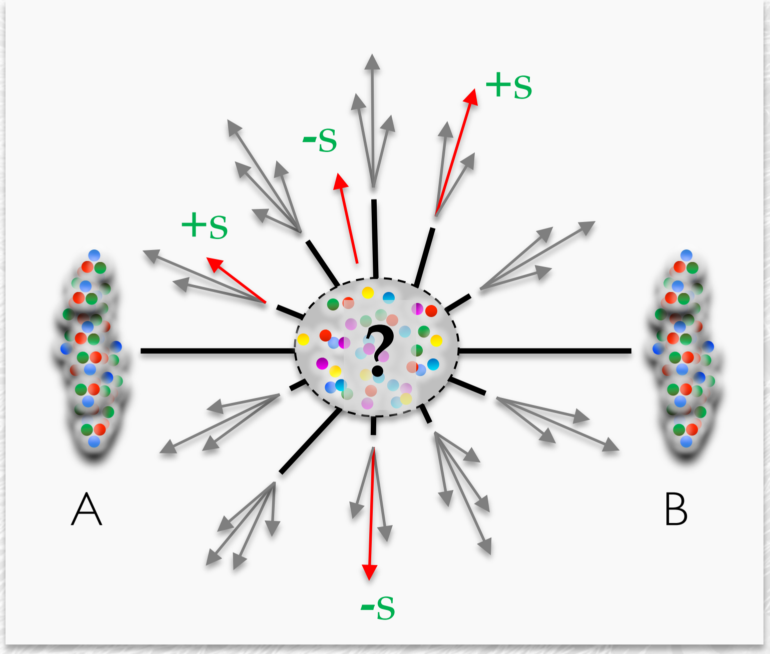
Average yield enhancement with respect to pions



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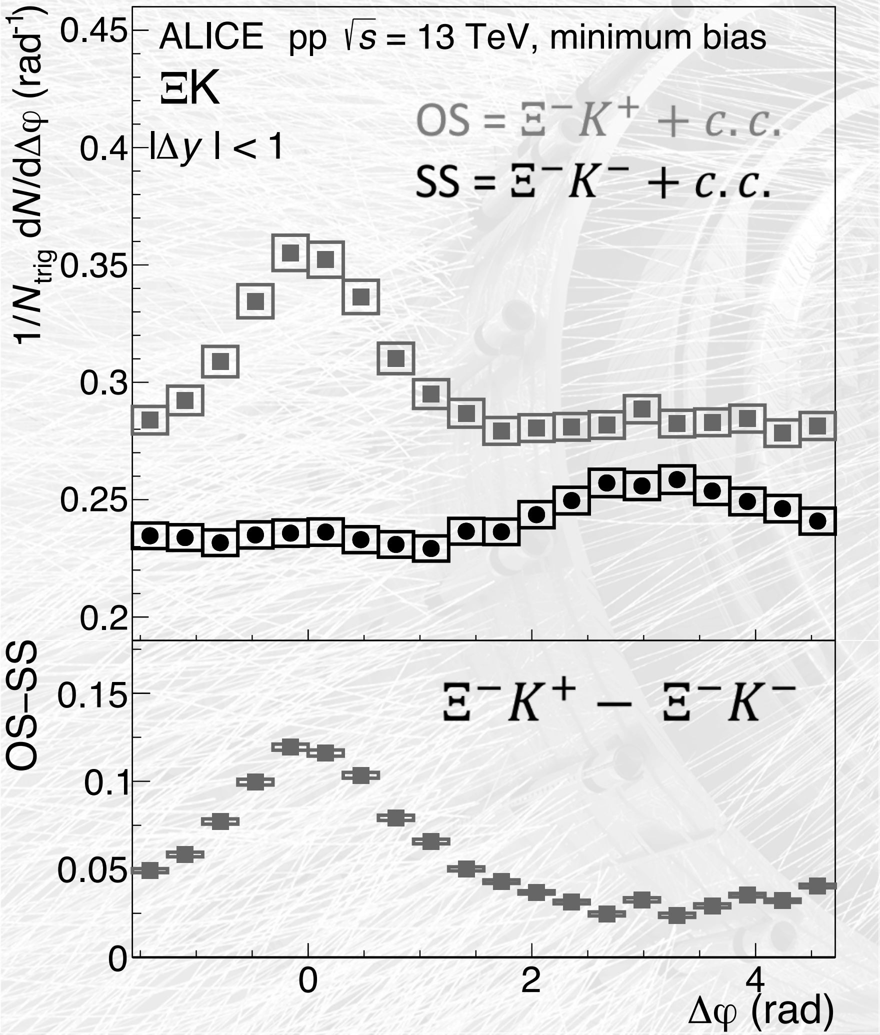
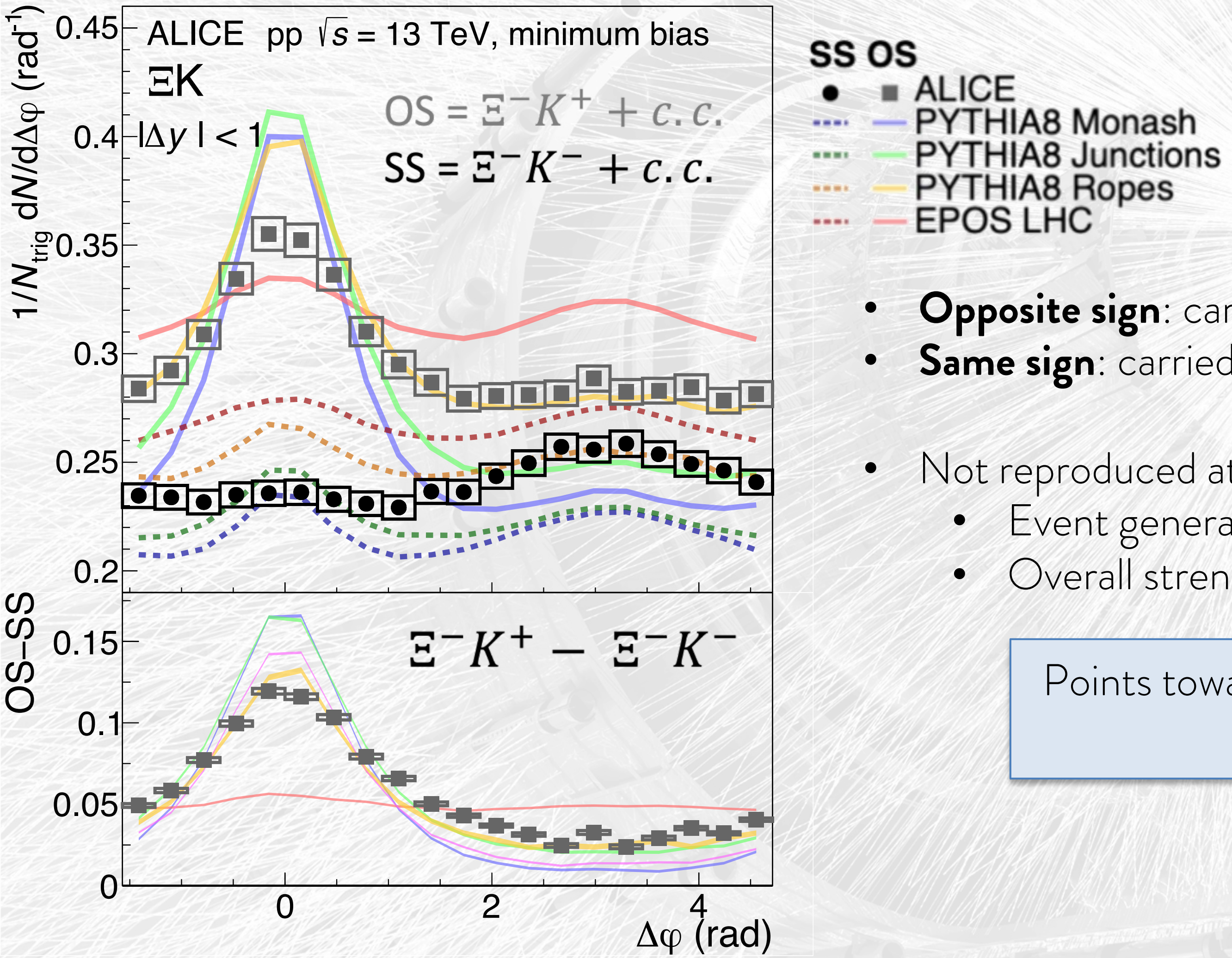
Strangeness number conservation
→ **Correlation studies**

Correlations of opposing strangeness quantum numbers



- **Opposite sign**: carried away in the same direction
- **Same sign**: carried away somewhat more significantly in the away side

Correlations of opposing strangeness quantum numbers



- **Opposite sign**: carried away in the same direction
- **Same sign**: carried away somewhat more significantly in the away side

- Not reproduced at all by event generators
  - Event generators predict same-sign peak in near side: absent in data
  - Overall strength of correlation not correct also in away side

Points towards incorrect strangeness number dynamics in the generators → more work needed!

Perspectives for the future:

Connecting elementary and complex QCD processes

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]

QGP physics: the 'solid state' study of QCD matter

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

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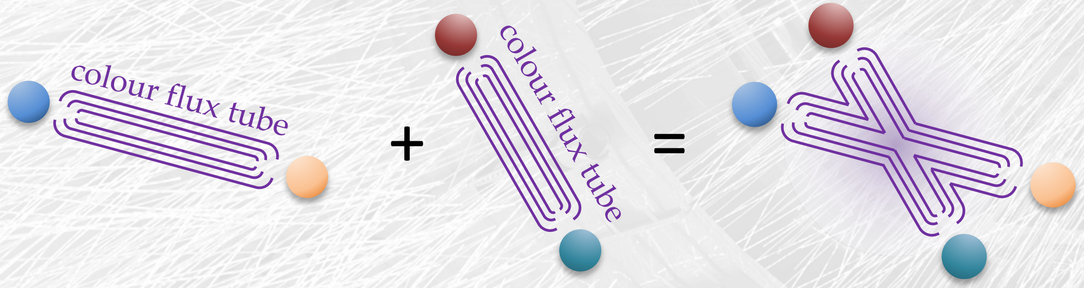

- What is **the most elementary experimental scenario** in which we can study changes in strangeness production dynamics?
- Could we **characterise strangeness hadronization** further?
- What is the role of the initial state / **strange sea quarks**?

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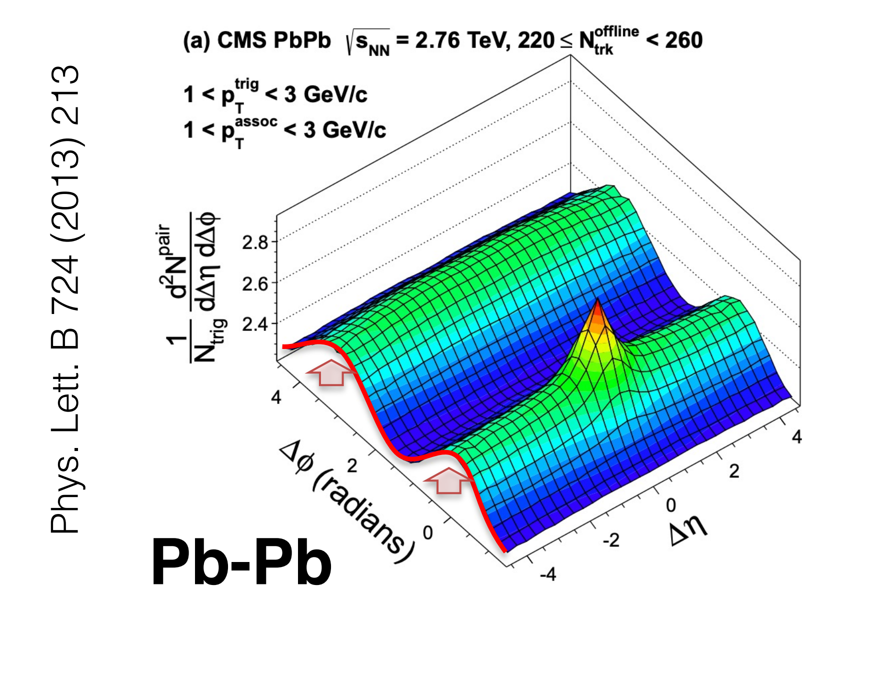
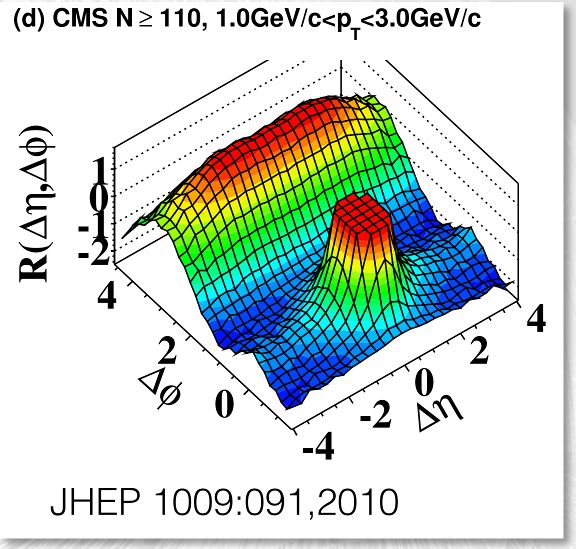
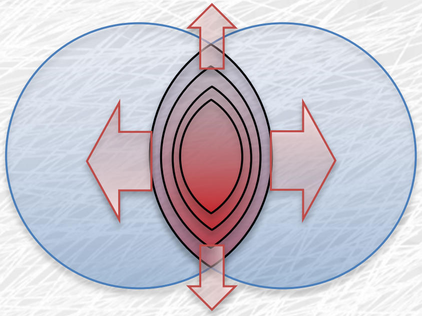
Pushing QGP signatures towards the elementary





Near-side ridge found in pp!
(see Jan Fiete's talk)
Similarly to strangeness enhancement: found in pp!
→ When does this "switch off"?

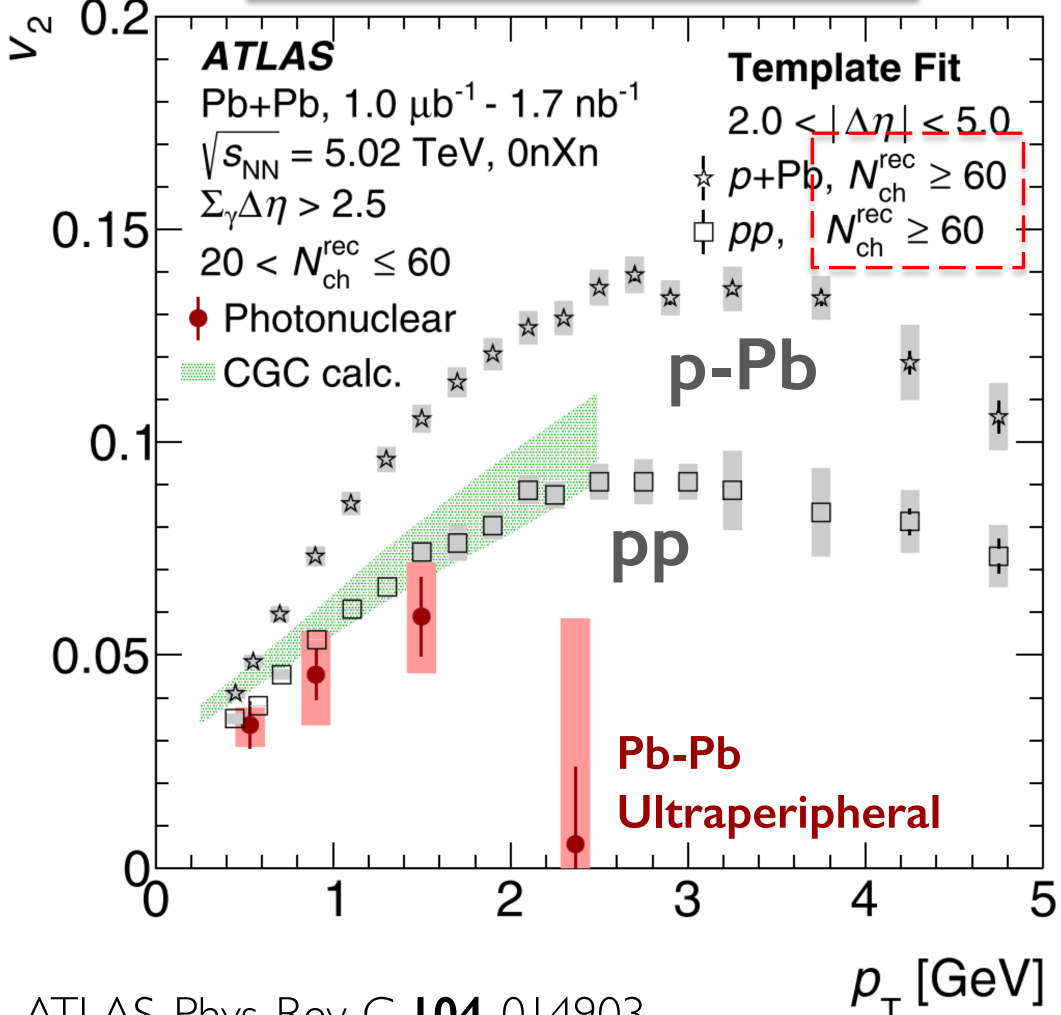


Collective expansion

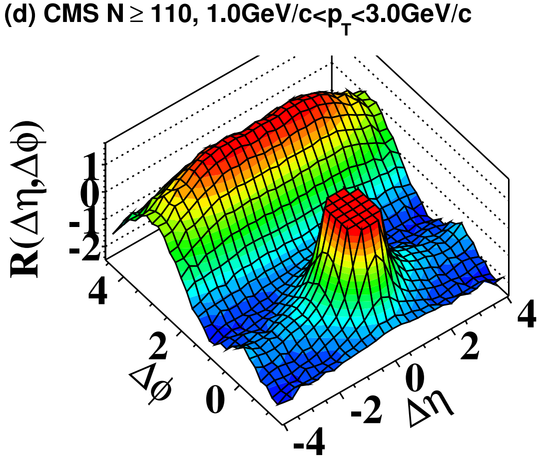
- In Pb-Pb collisions, particles are emitted with a modulation in azimuth due to collective expansion of an elliptic initial condition

Pushing QGP signatures towards the elementary

v_2: second component of fourier expansion of particle emission in phase space



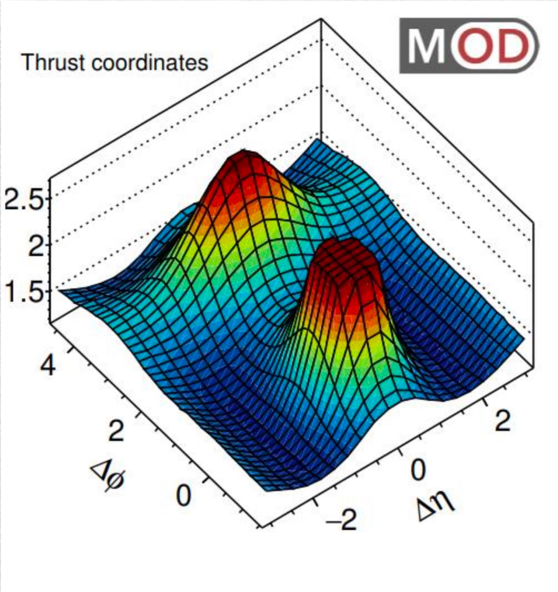
ATLAS, Phys. Rev. C **104**, 014903



JHEP 1009:091,2010

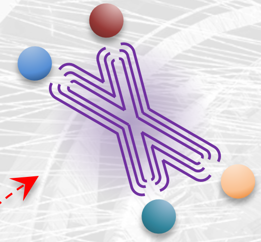
Near-side ridge found in pp!
(see Jan Fiete's talk)
Similarly to strangenes enhancement: found in pp!
→ When does this "switch off"?

- Ultra-peripheral collisions: photonuclear processes
  - High-multiplicity events selected for analysis
  - Non-zero v_2, even if lower
- Caveat: v_2 coeff. vulnerable to (residual) non-flow
- Begs the question: can we characterize these collisions?
  - What about other QGP signatures?
  - Strangeness enhancement → news soon

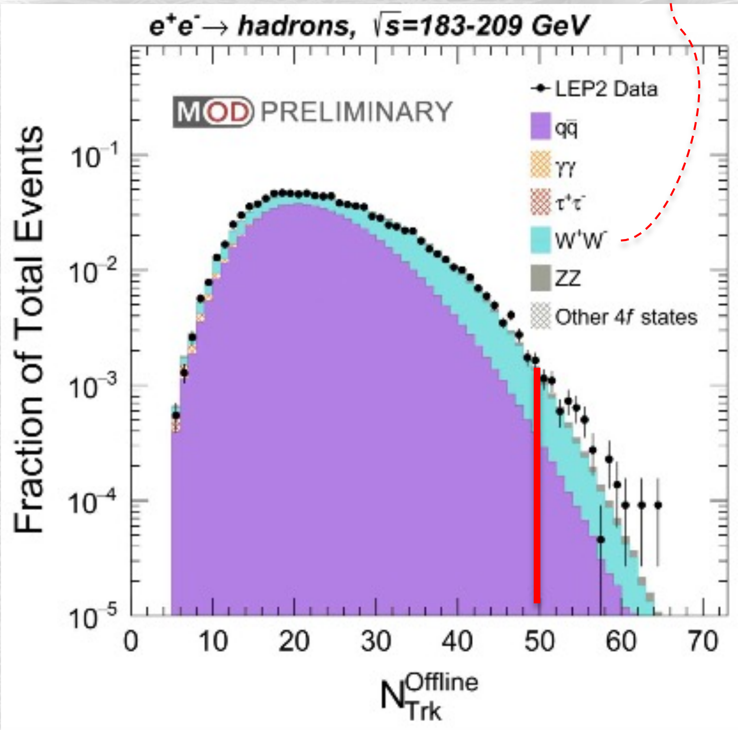


Phys. Rev. Lett. 123, 212002 (2019)

Pushing to elementary: e^+e^- and eA collisions



- Minimum-bias e^+e^- collisions: exhibit no near-side ridge
- However: e^+e^- provides access to various processes
  - High-multiplicity e^+e^- enriched with $e^+e^- \rightarrow W^+W^-$: a two-string system



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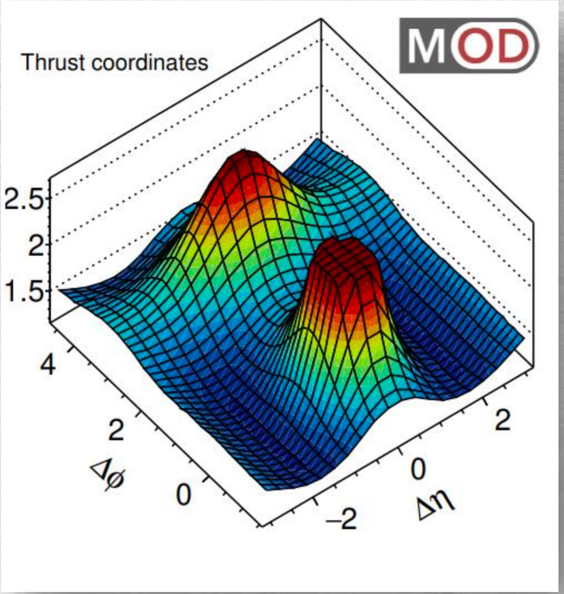
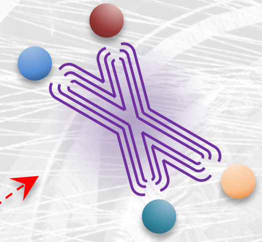
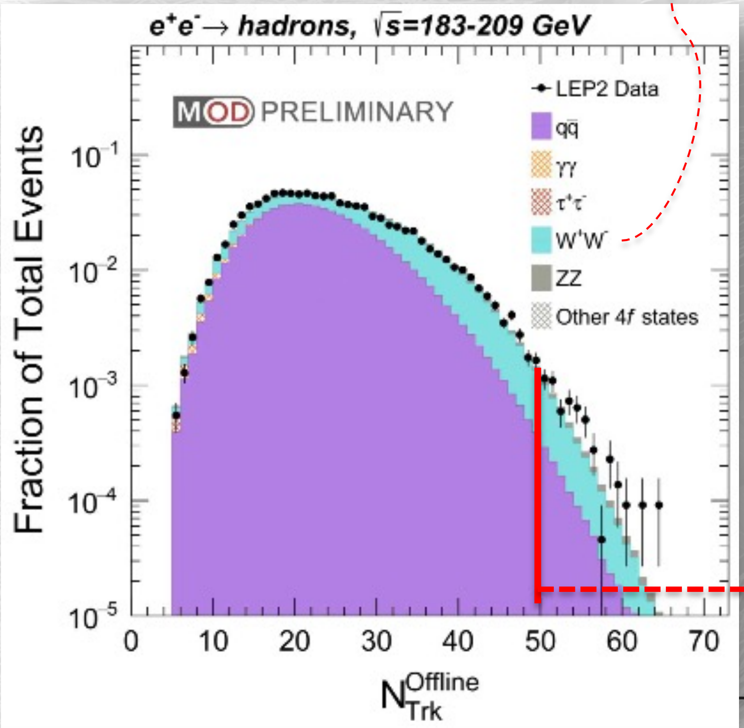
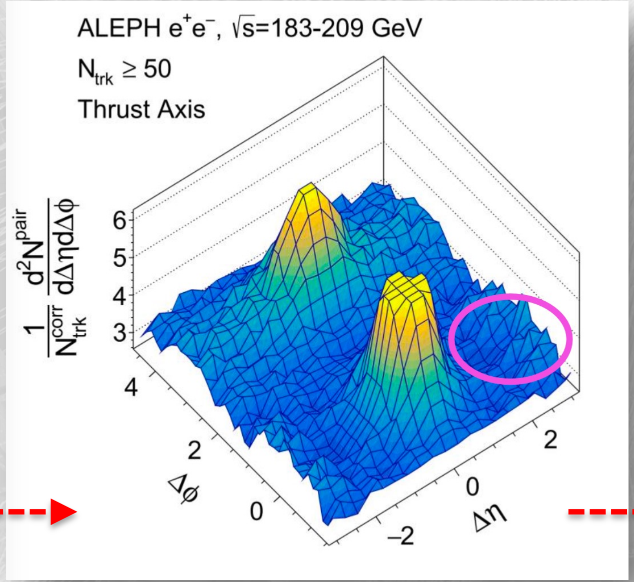


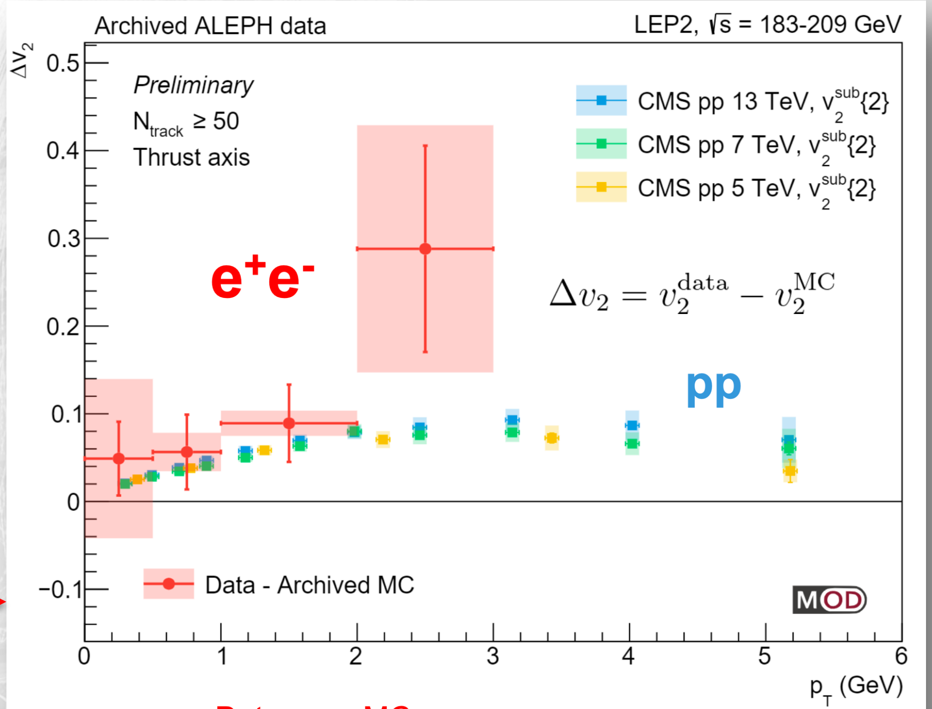
Phys. Rev. Lett. 123, 212002 (2019)



- Minimum-bias e^+e^- collisions: exhibit no near-side ridge
- However: e^+e^- provides access to various processes
  - High-multiplicity e^+e^- enriched with $e^+e^- \rightarrow W^+W^-$: a two-string system
  - Results at high multiplicity similar to pp collisions!







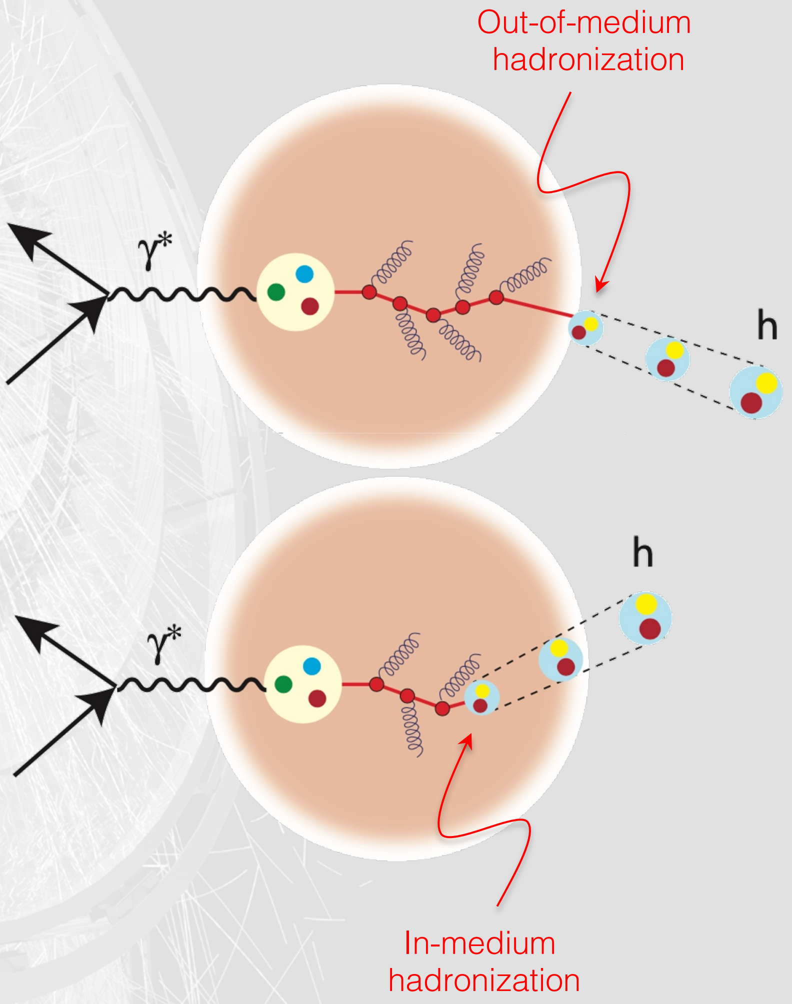
- $\Delta v_2 = v_2^{Data} - v_2^{MC}$

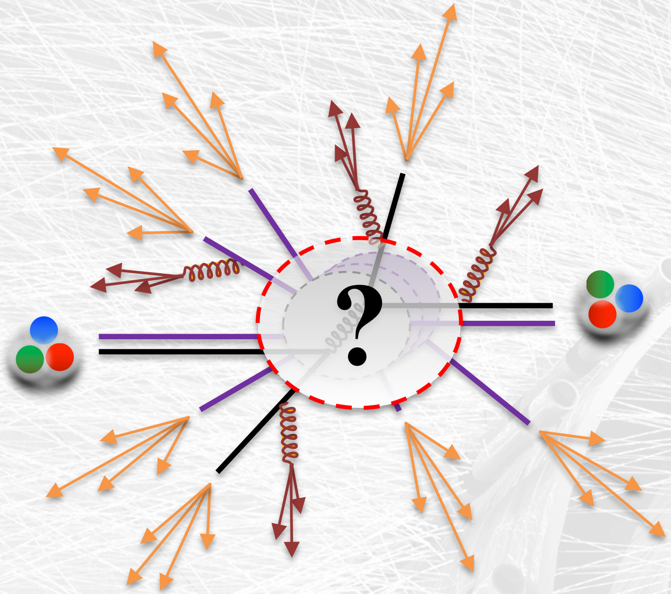
Further constraint, further knowledge: electron-ion collisions

- Probing hadronization in-medium and out-of-medium:
  - can be done cleanly at the Electron-Ion Collider (EIC)!
- Why EIC? Electron-ion collisions:
  - **single initial scattering process**, products travel through nucleus
  - **Unique control**: initial parton energy can be inferred by kinematics
  - Produced parton flavour inferred from particle identification

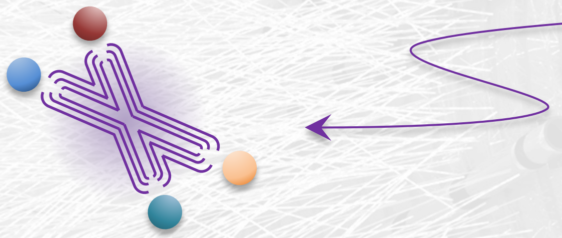
- …To answer:
  - Does a parton hadronize inside the nucleus?
  - How do quarks of different flavours hadronise? Strange, charm, beauty!
  - How does that depend on energy? Traveled path? System size?
  - → fundamental 'microscopic' knowledge of
    hadronization in vacuum or cold matter

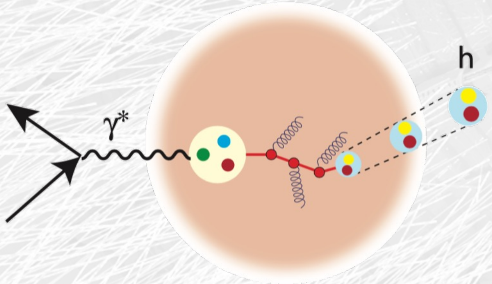
- Dramatically improve our understanding of nuclei





Summary and outlook





- There was remarkable progress in the strangeness sector in the past decade!

> From the discovery of strangeness enhancement in small systems (~2015)…
> … to the experimental characterisation of its properties: ongoing!

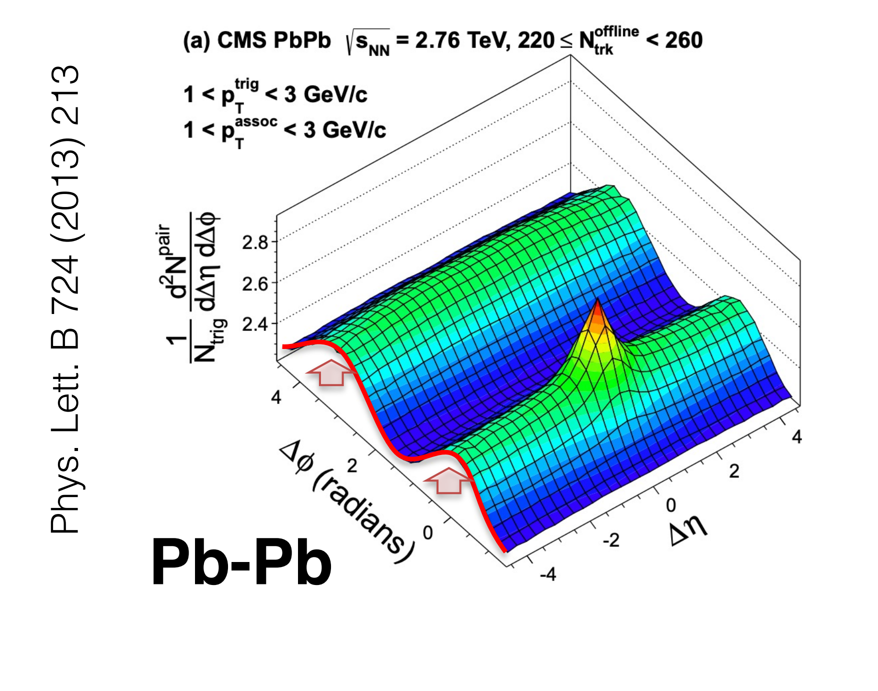
- Fundamental **building blocks of high-density QCD**: under which conditions do complex phenomena (strangeness enhancement, v_2, …) emerge?
  + **Heavy flavour studies**: interesting avenue to probe system evolution
  + investigated by a cutting edge device @LHC : ALICE 3 (see Triloki's talk)

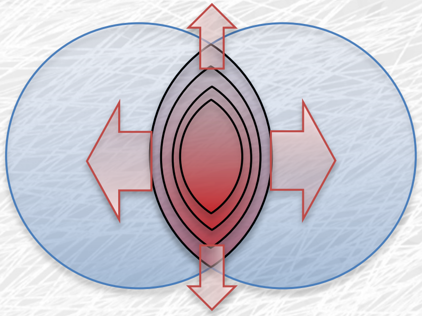
- Further fascinating facets of strangeness measurements not discussed here:
  - **Femtoscopy** (See Oton's talk)
  - **Hadron spectroscopy** (hypernuclei, etc)
- **General HI Physics**: see Jan Fiete's talk

Thank you!

Backup

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

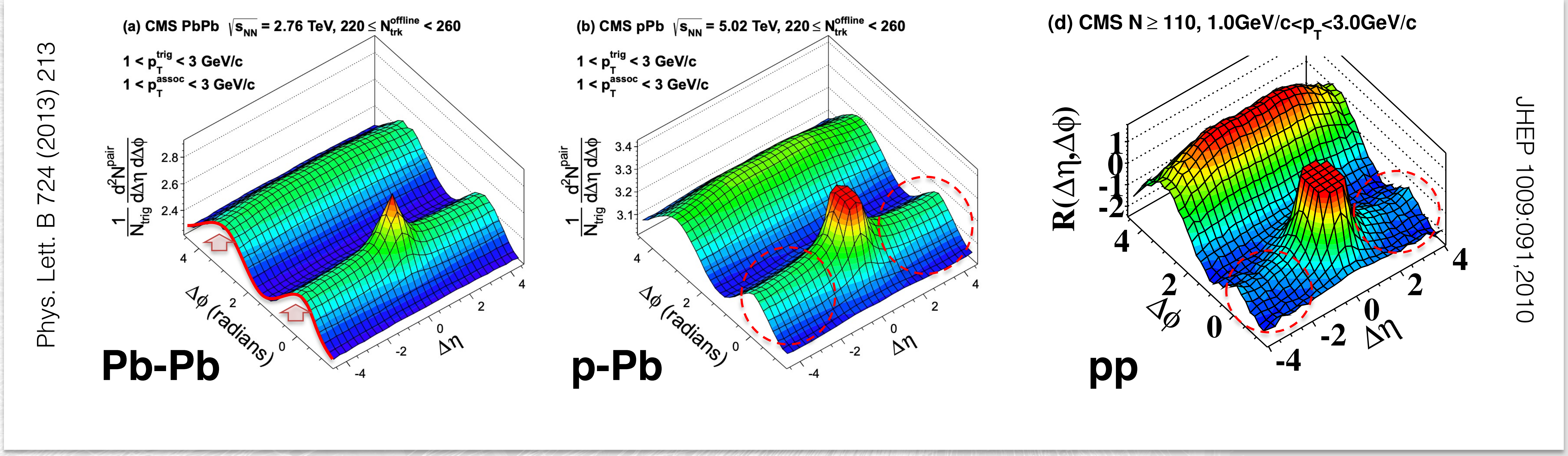


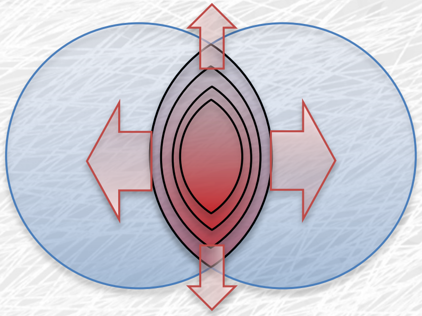


Collective expansion

- 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

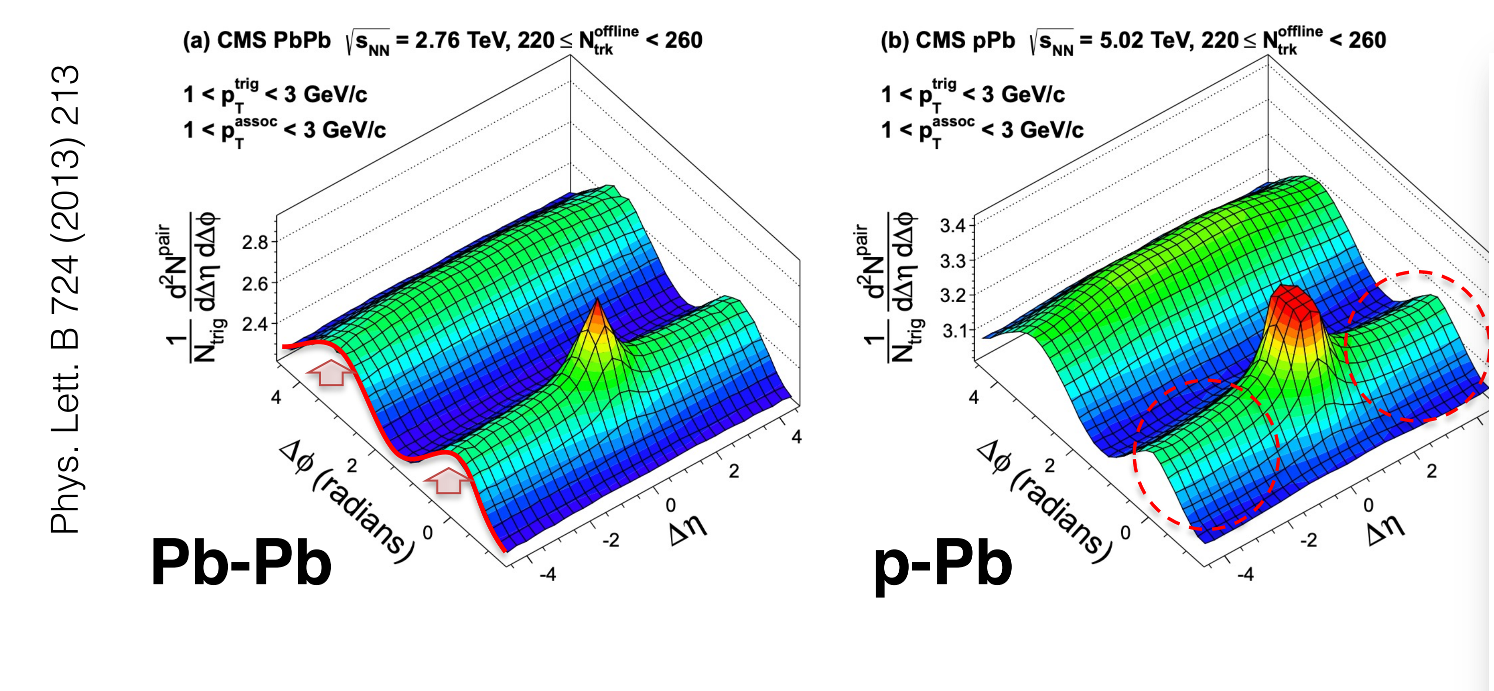


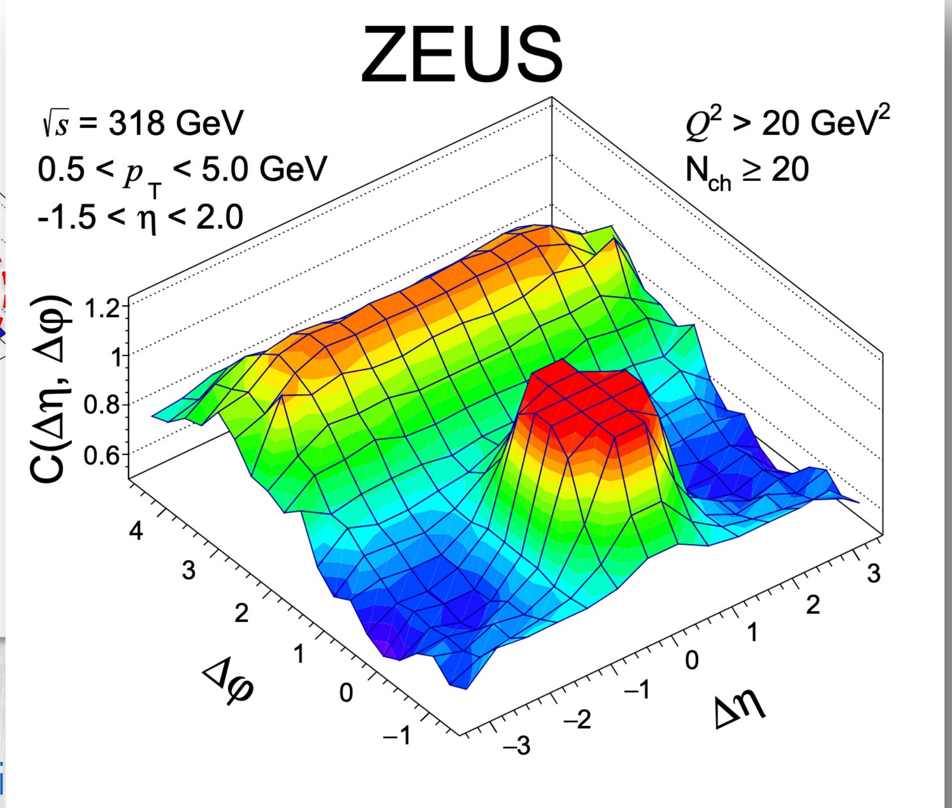


Collective expansion

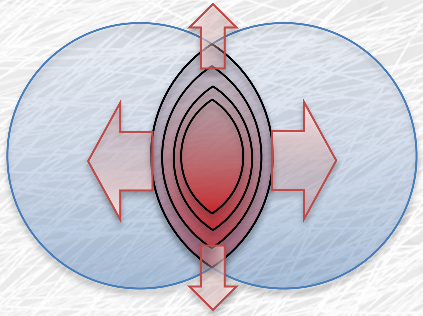
- In Pb-Pb collisions, particles are emitted with a modulation in azimuth due to collective expansion of an elliptic initial condition
- Also observed in p-Pb and pp
  - Initial condition not necessarily elliptic
  - Collective expansion also at play?
  - Under which conditions does this **not** happen?

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





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



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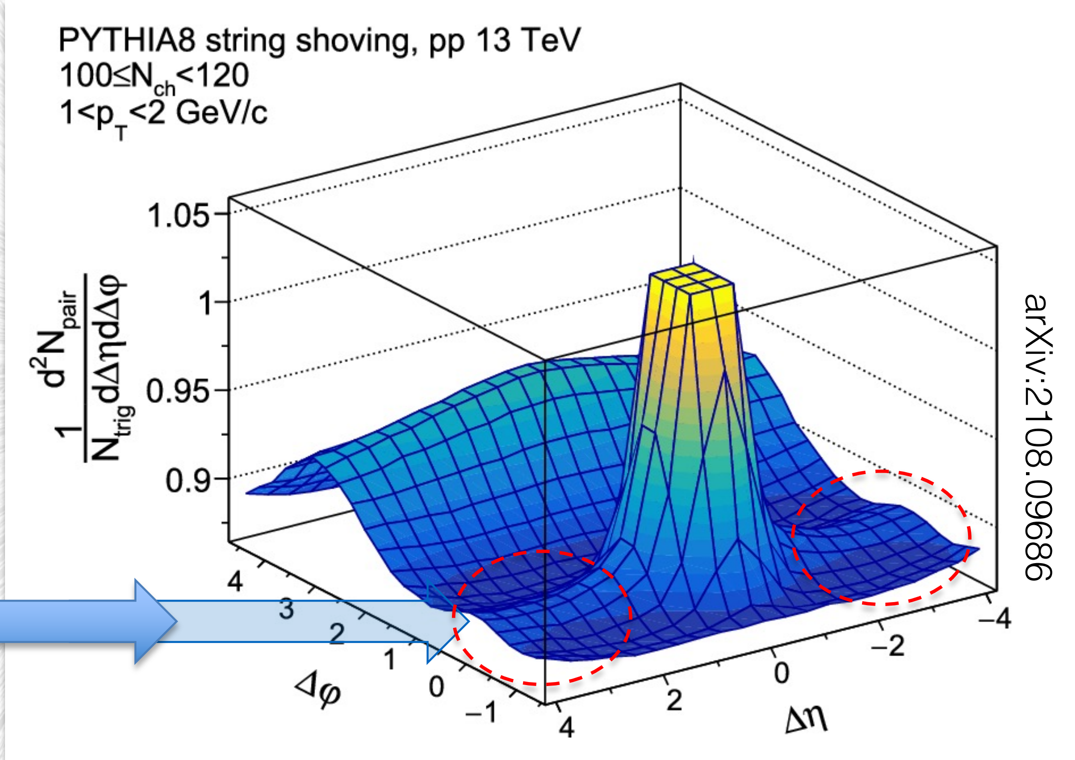
How can this be explained?

String shoving leads to collective motion

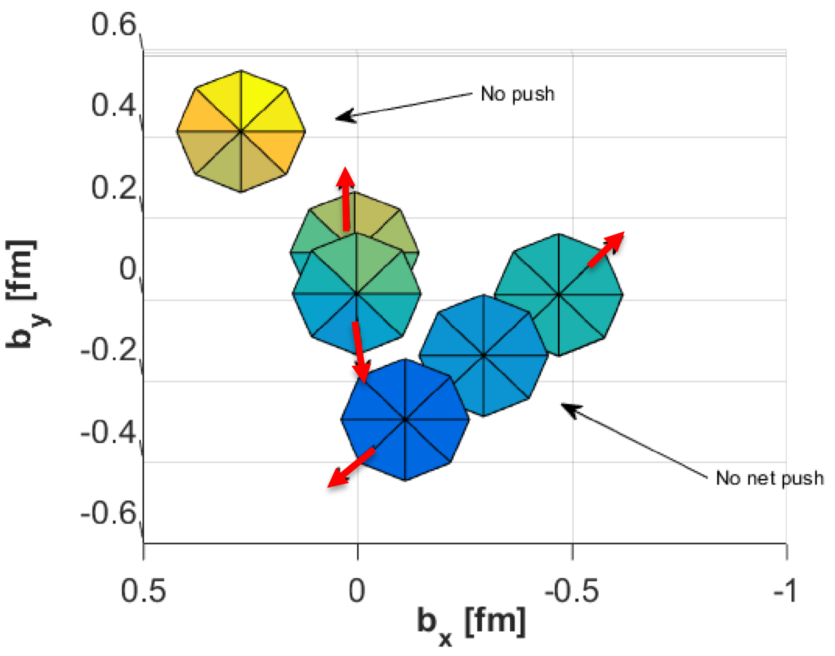
High multiplicity → many partonic interactions

Many partonic interactions → many colour strings

Many closely-packed colour strings → shoving!



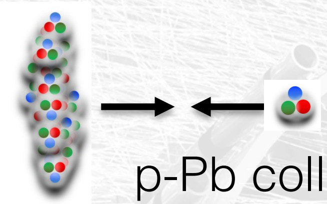
arXiv:2108.09686

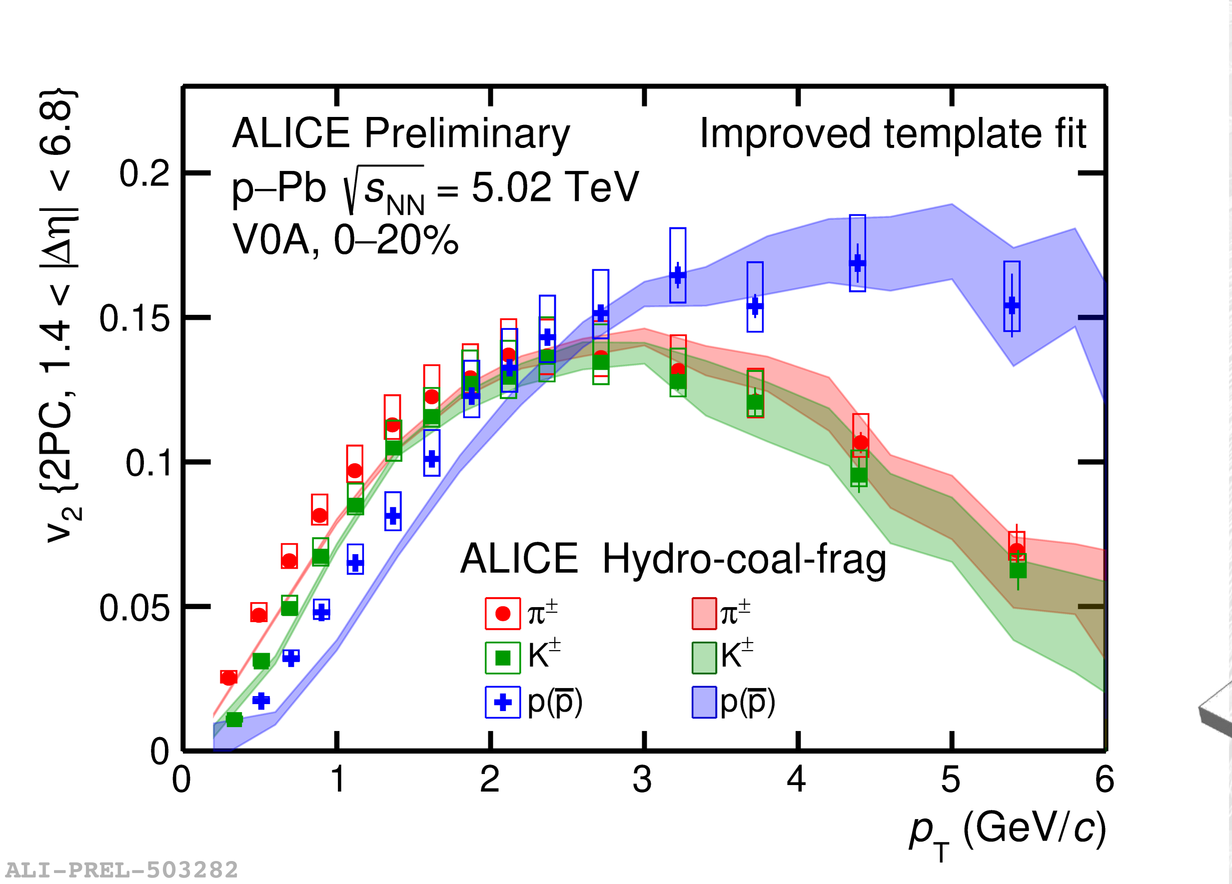


MCnet-16-48, LU-TP 16-64

- 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





- 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	✅	❌ (orange)	❌
bottomonia	❌	❌	-

Remaining puzzle:

v_2 >0 implies energy loss …

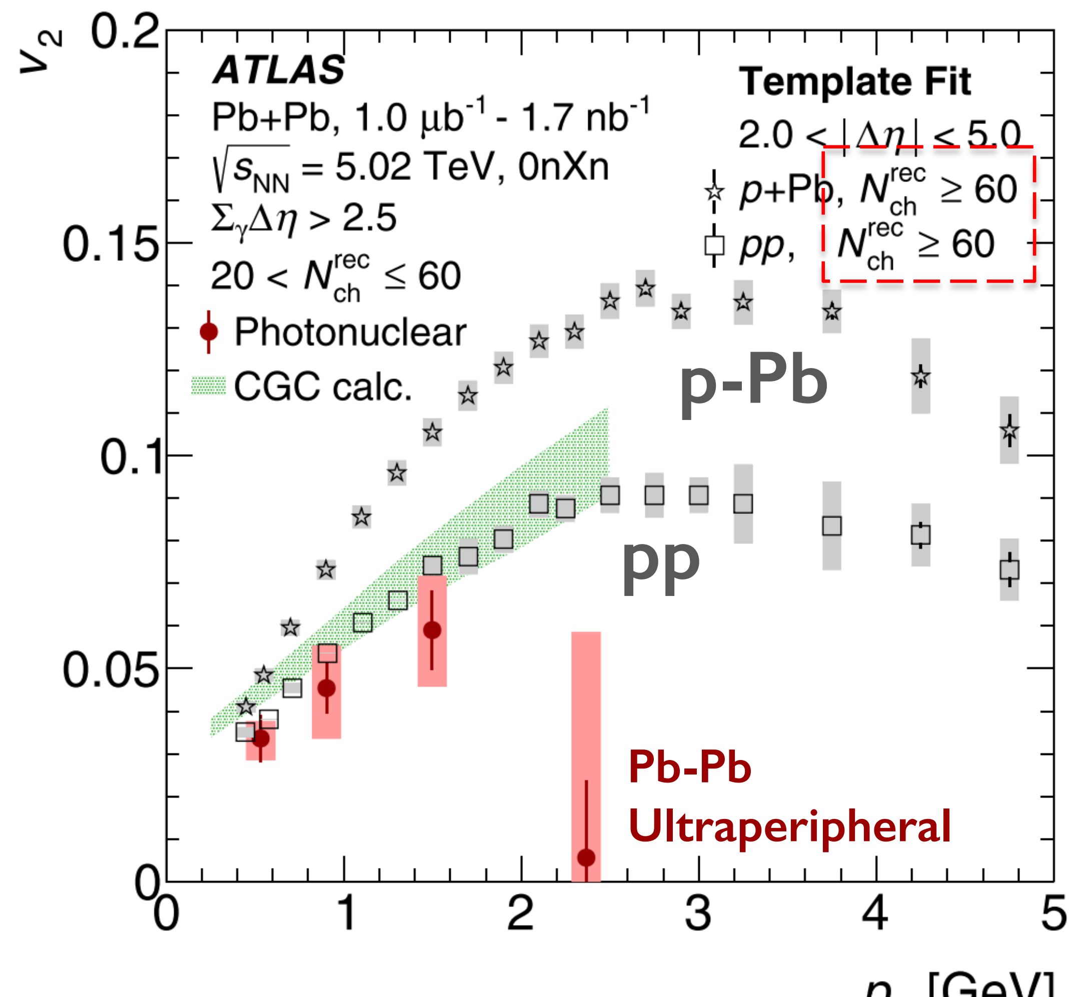
…but no jet quenching? To be solved!

Observation of non-zero flow in photo-nuclear events

→ see talk by [Sruthy Das]

✓ Specific processes

- Ultra-peripheral collisions: photonuclear processes
  - High-multiplicity events selected for analysis
  - 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
- Begs the question: can we characterize these collisions?
  - What about other QGP signatures?

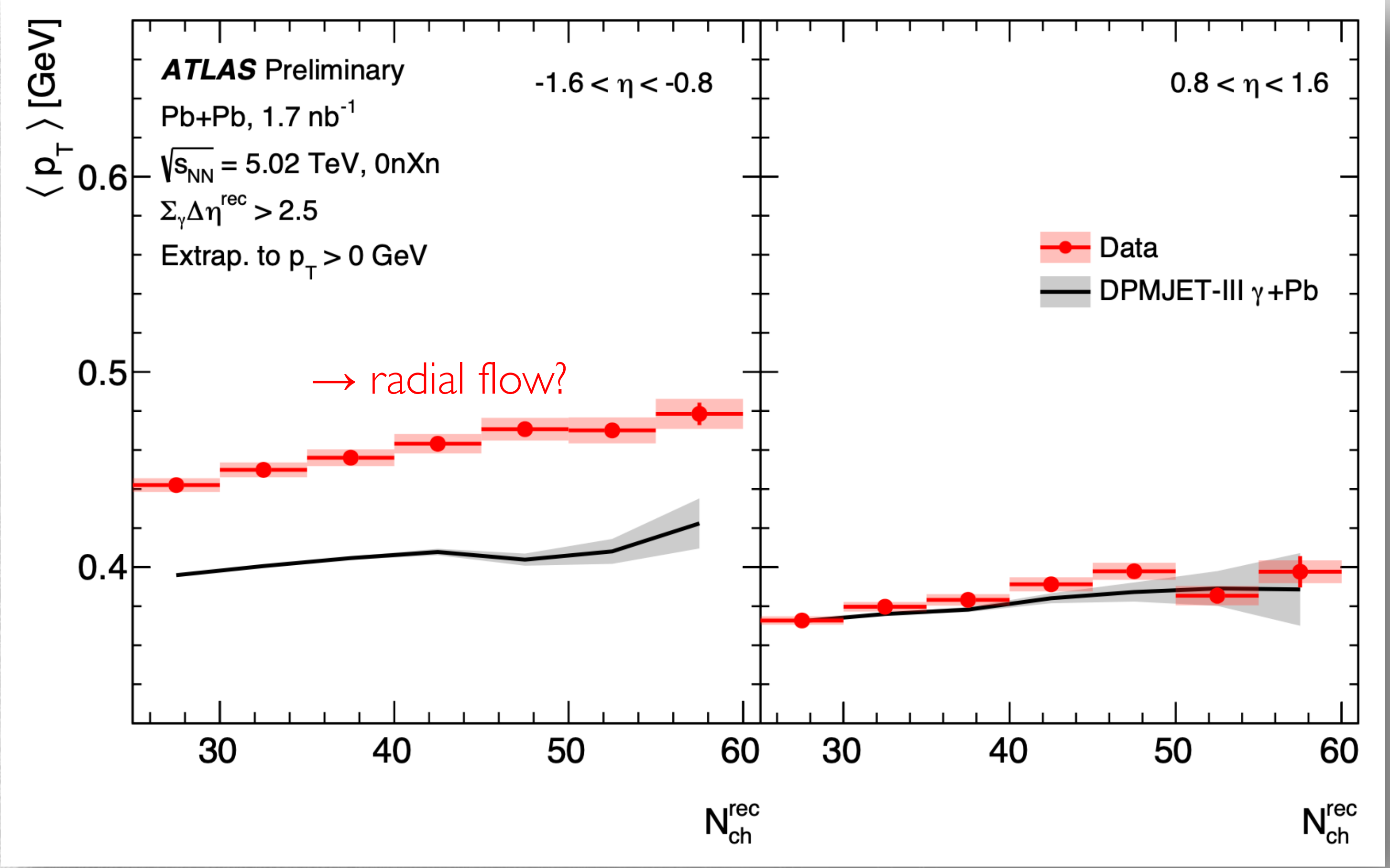


ATLAS, Phys. Rev. C **104**, 014903

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

Search for QGP signatures in photo-nuclear events

- Indications of radial flow in UPC collisions
  - In backward pseudorapidity region
  - Excess not described well by AMPT

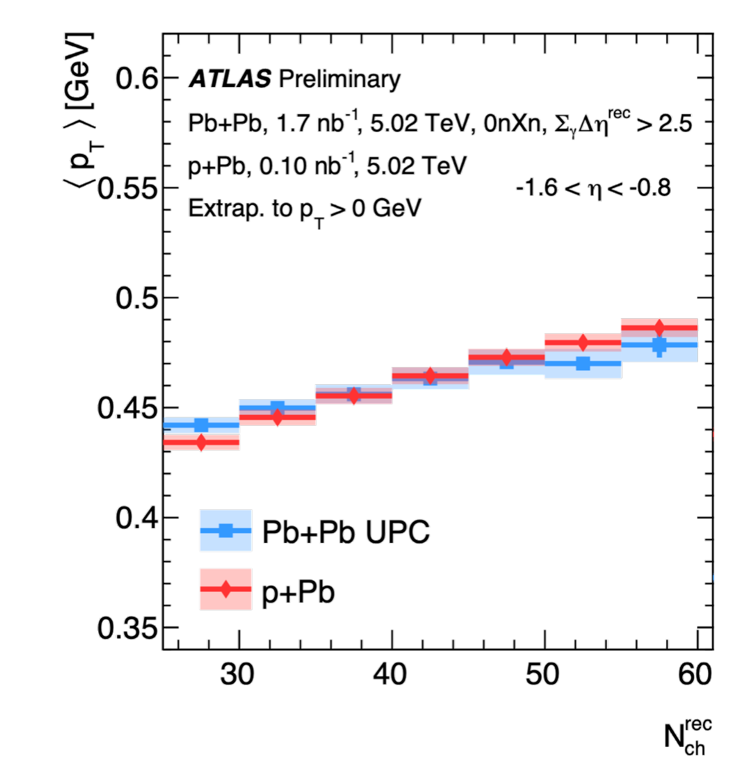


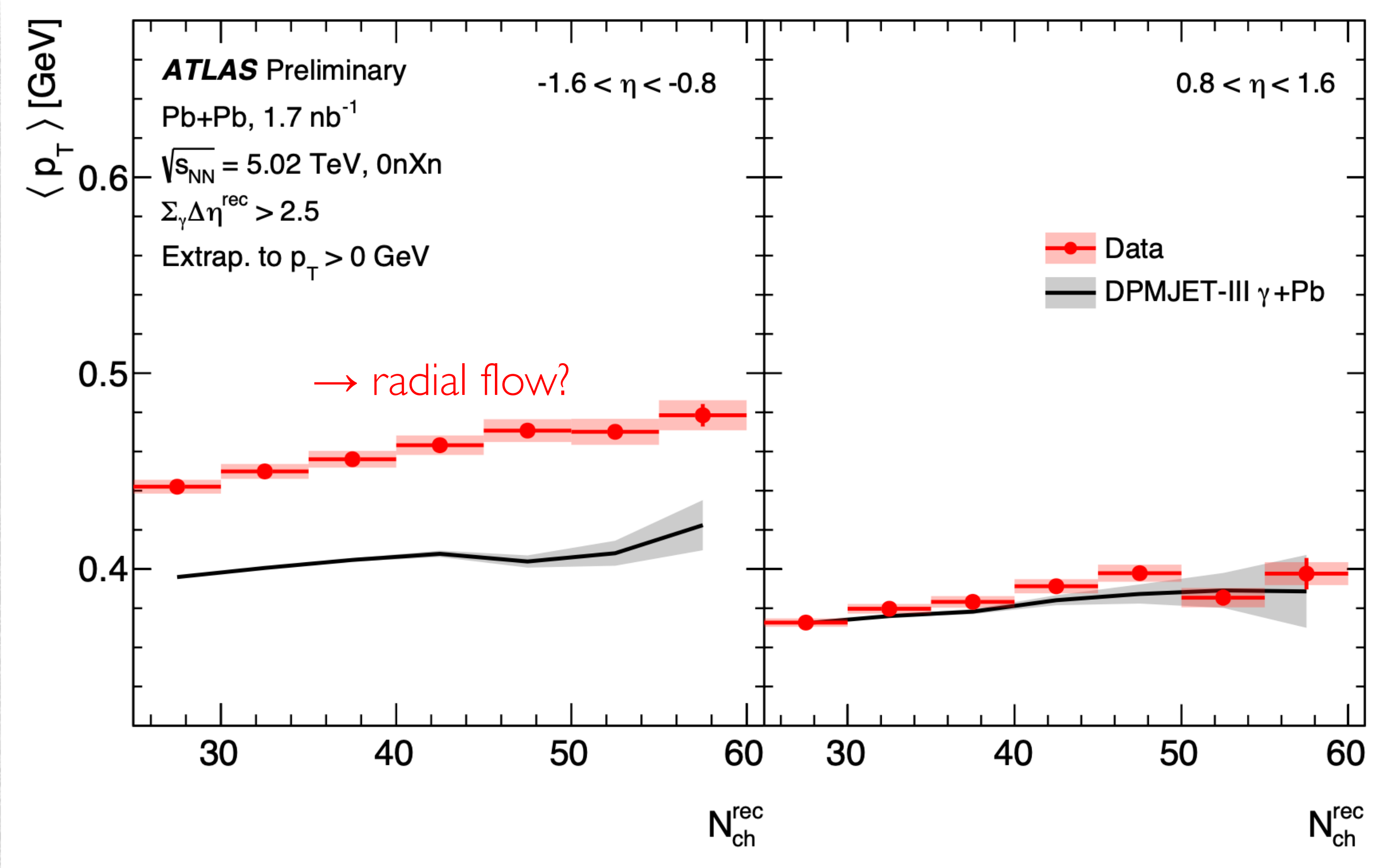
→ see talk by Sruthy Das

Search for QGP signatures in photo-nuclear events

✓ Specific processes/extremes

- Indications of radial flow in UPC collisions
  - In backward pseudorapidity region
  - Excess not described well by AMPT
- Backward η $\langle p_T \rangle$ matches p-Pb at the same multiplicities





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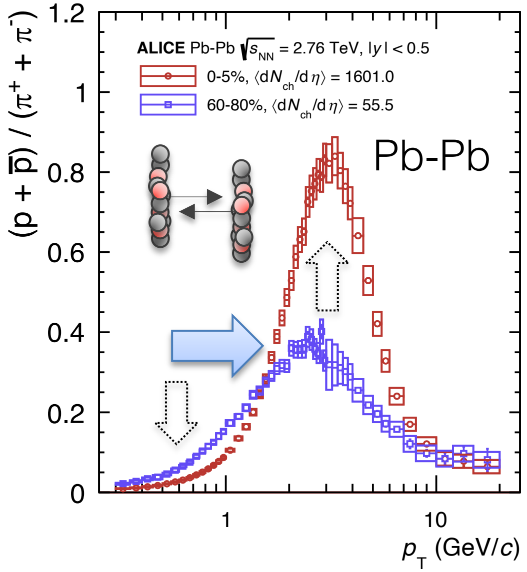
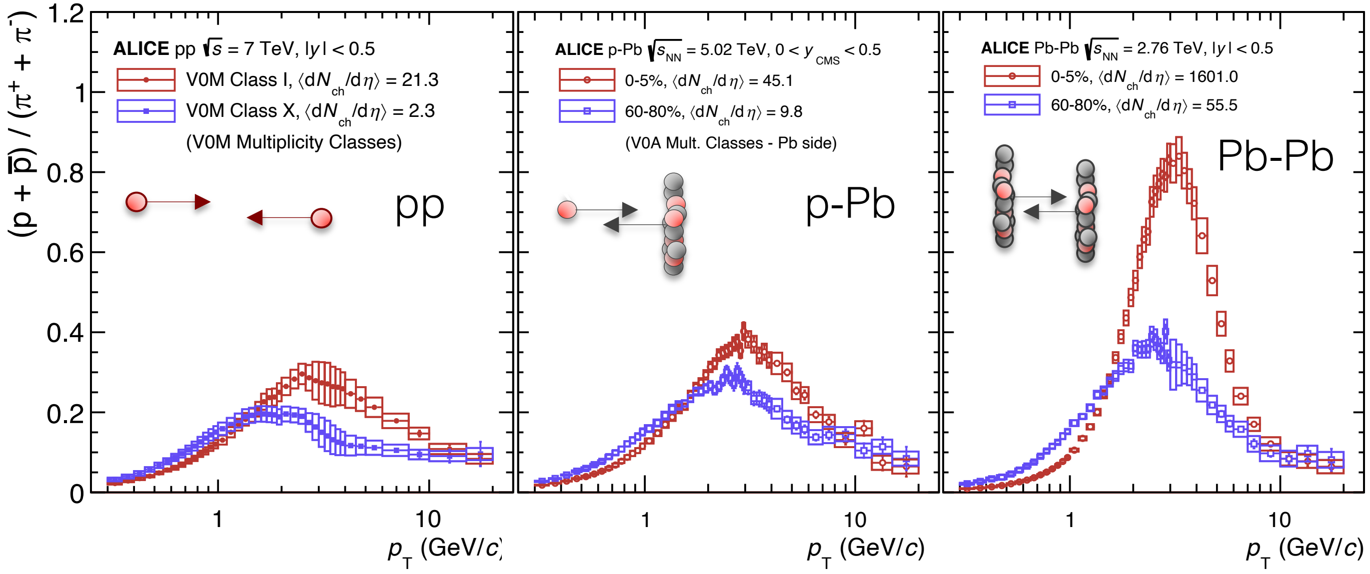
Proton to pion ratios



- 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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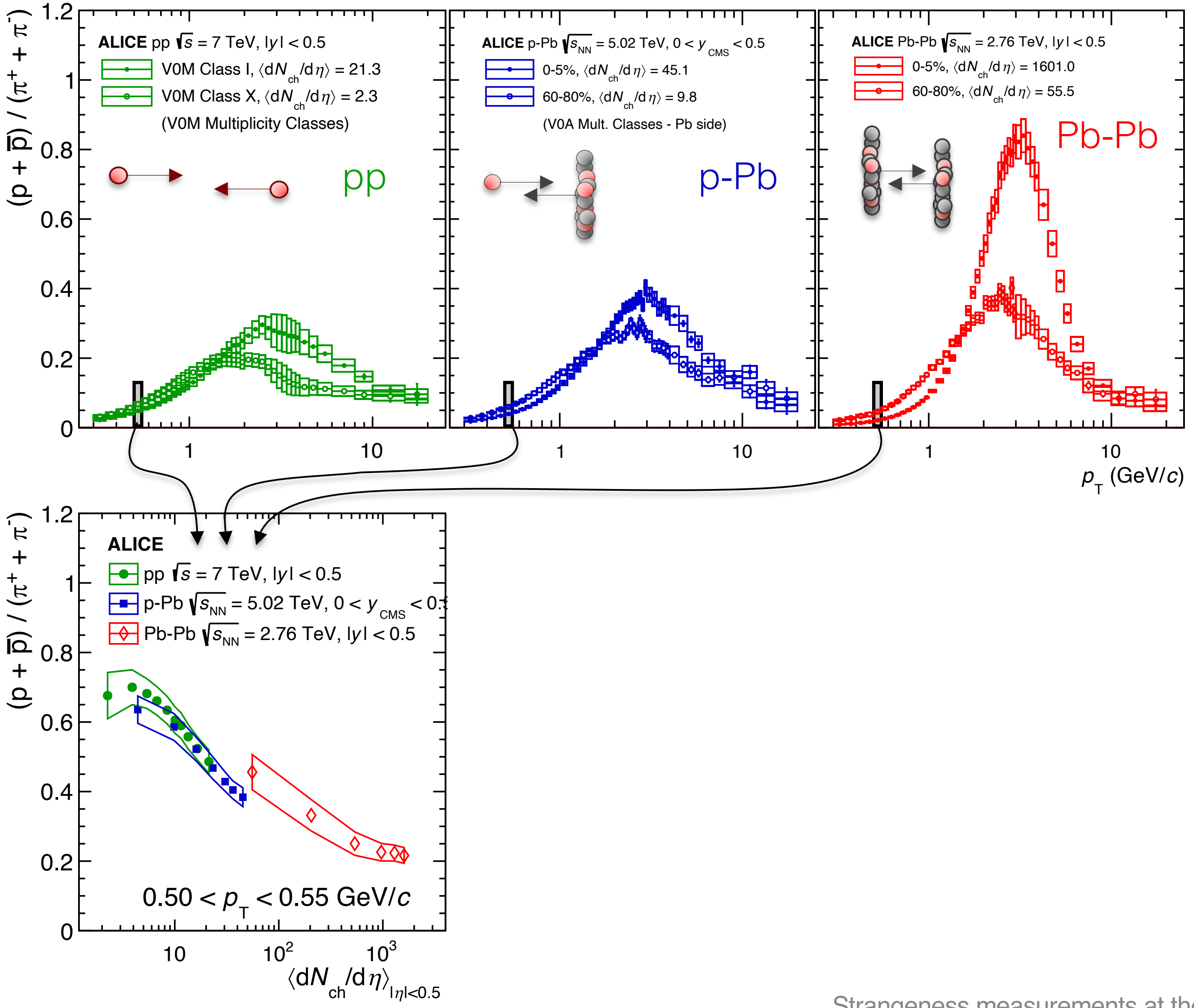

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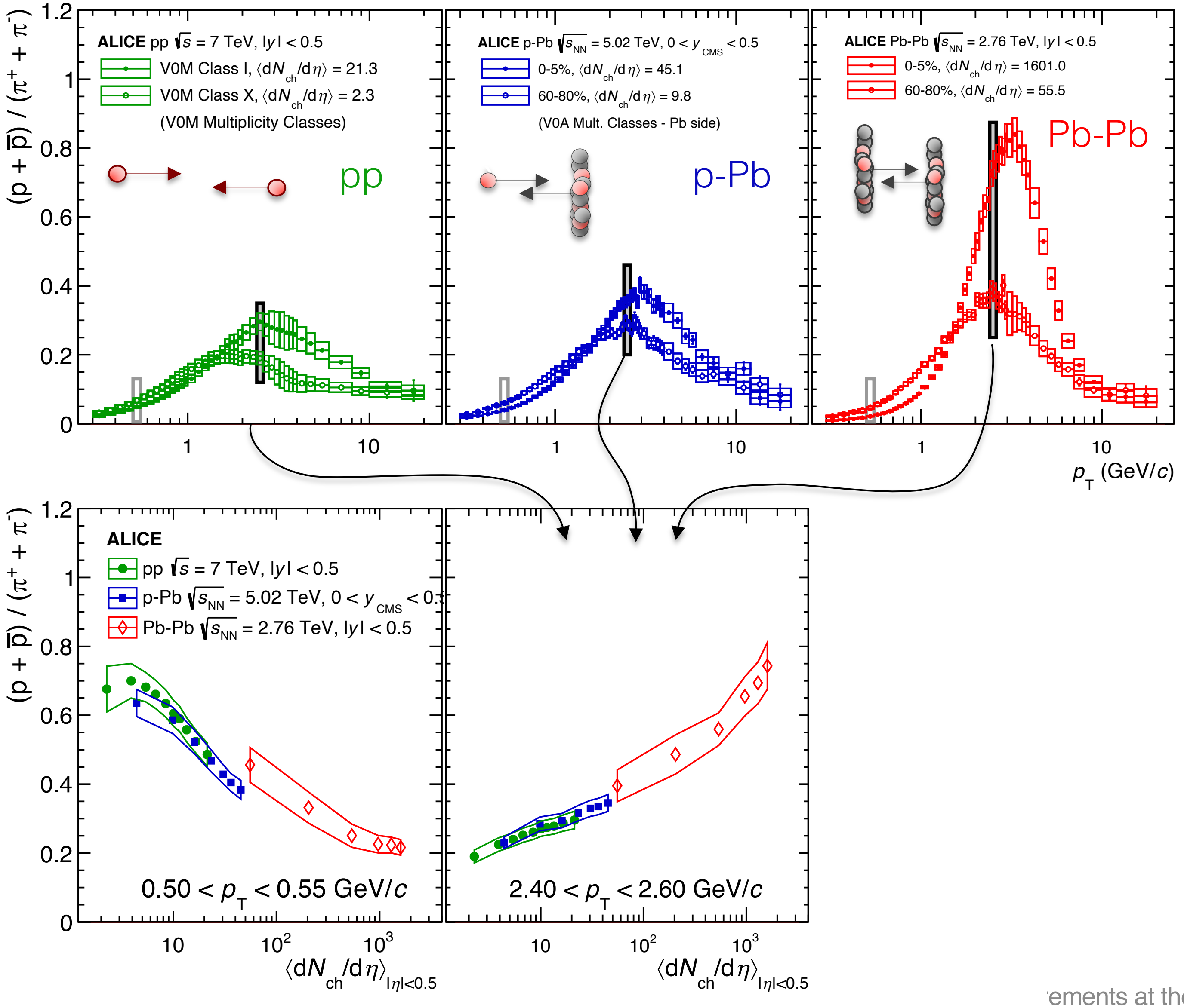

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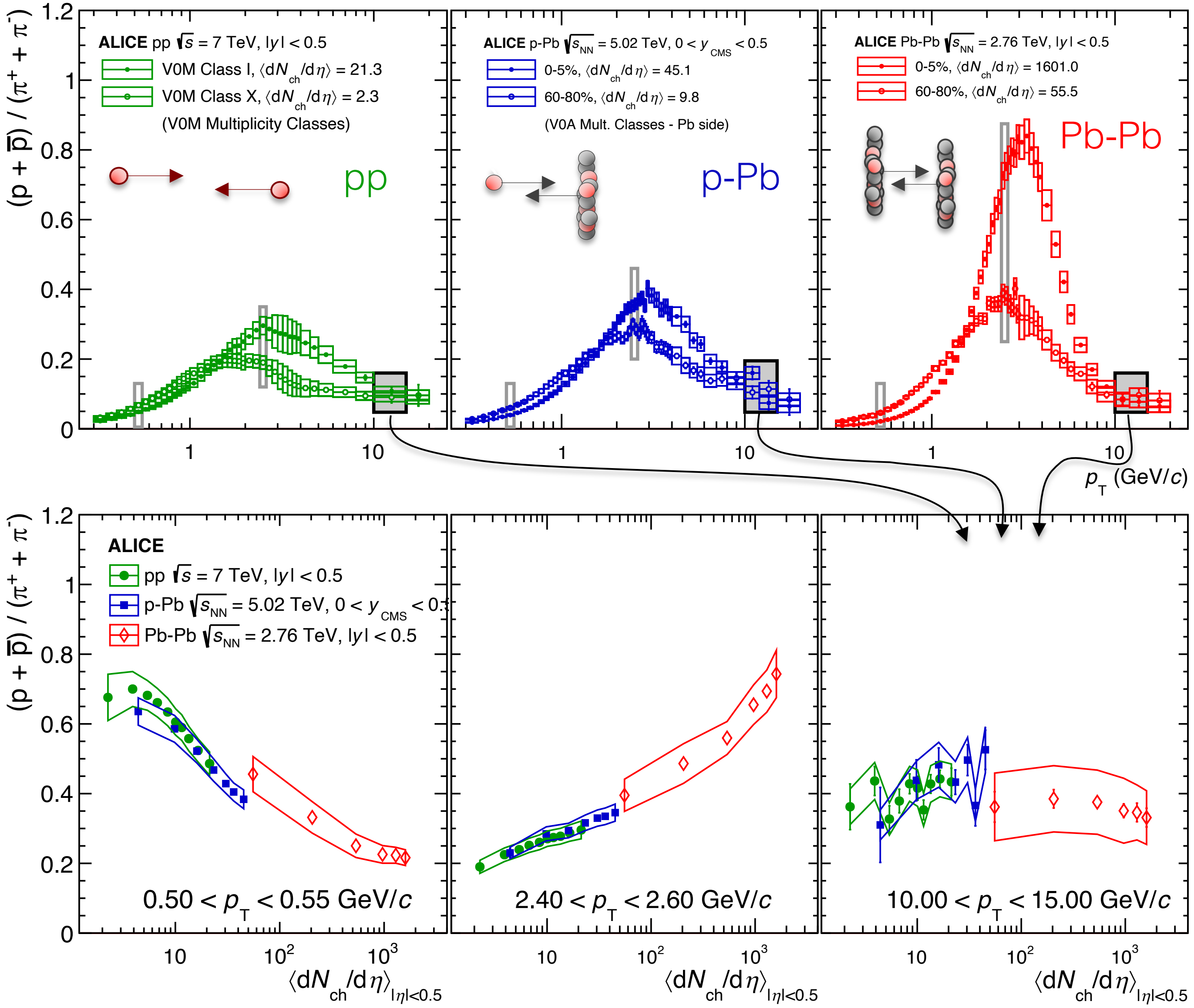
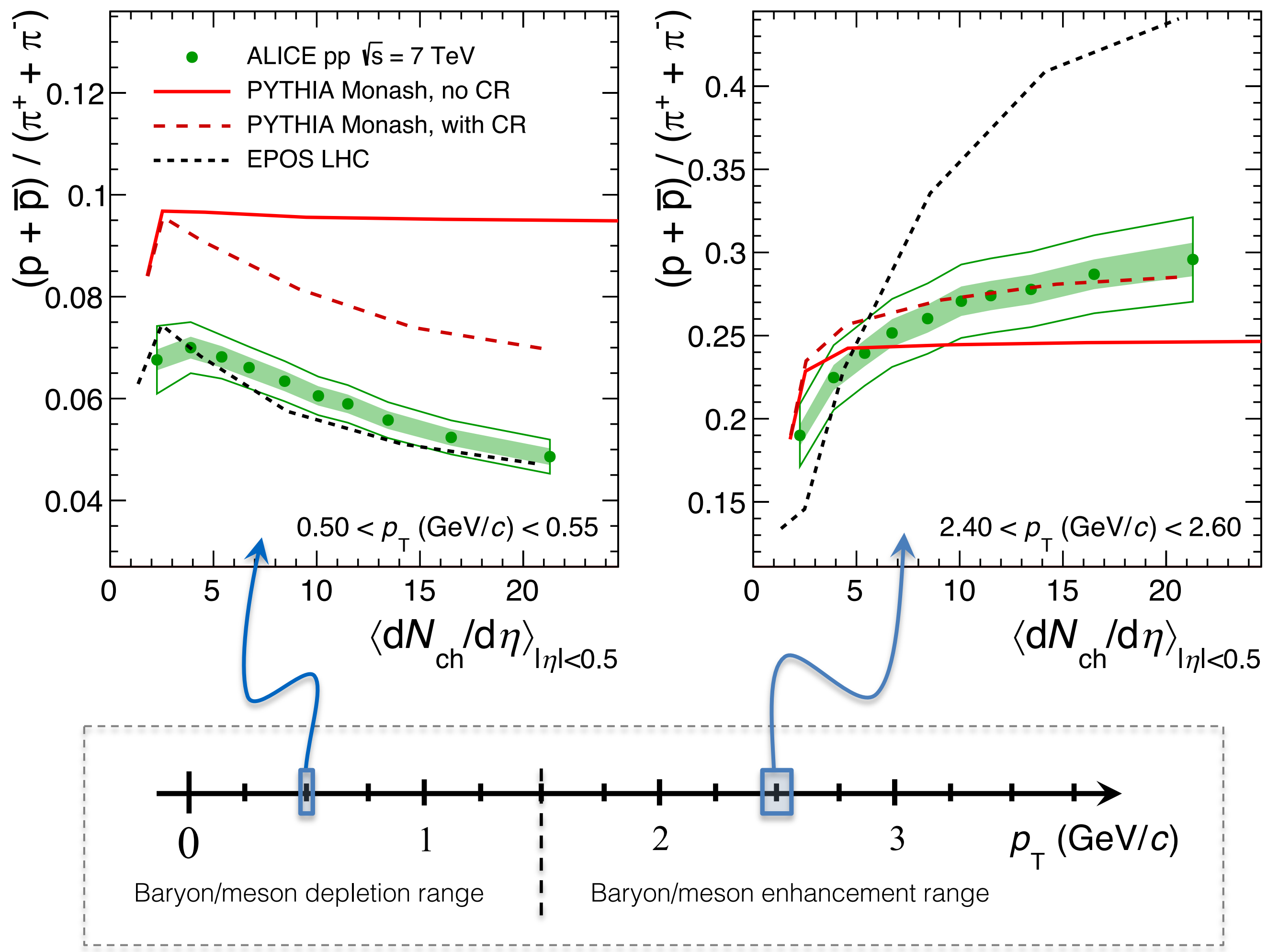


- Behavior known from Pb-Pb collisions
- Interpreted as radial flow: p are pushed to a higher momentum
  - p are pushed to higher momenta by a common velocity field
- Remarkable consistency across systems as a function of multiplicity
- high p_T: recovery of universal behavior?

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

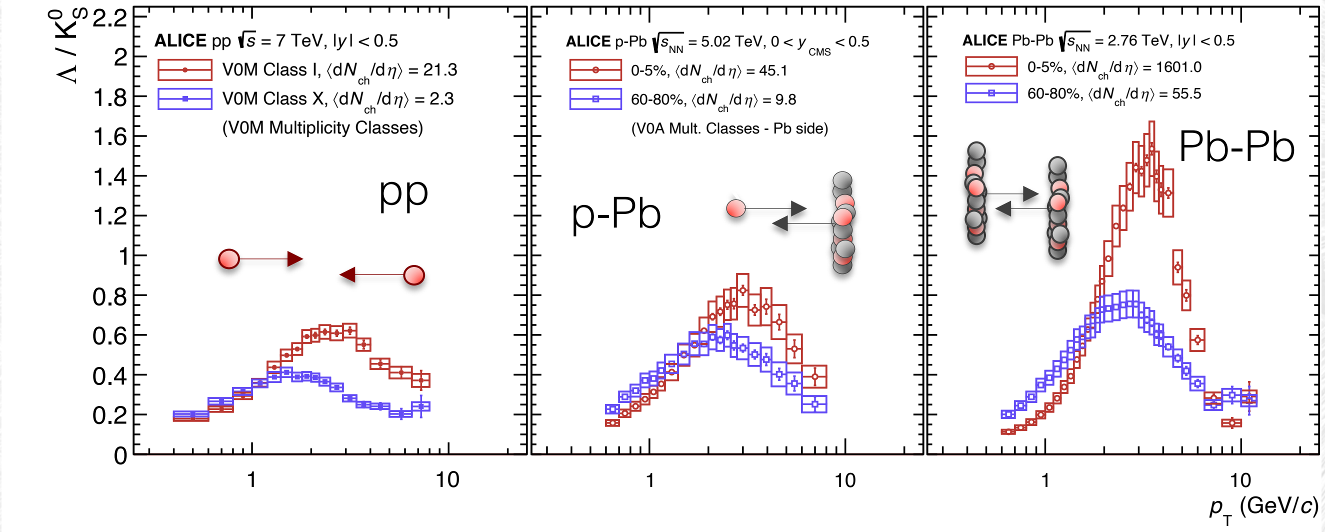
Now up to the theorists to explain via a universal mechanism

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

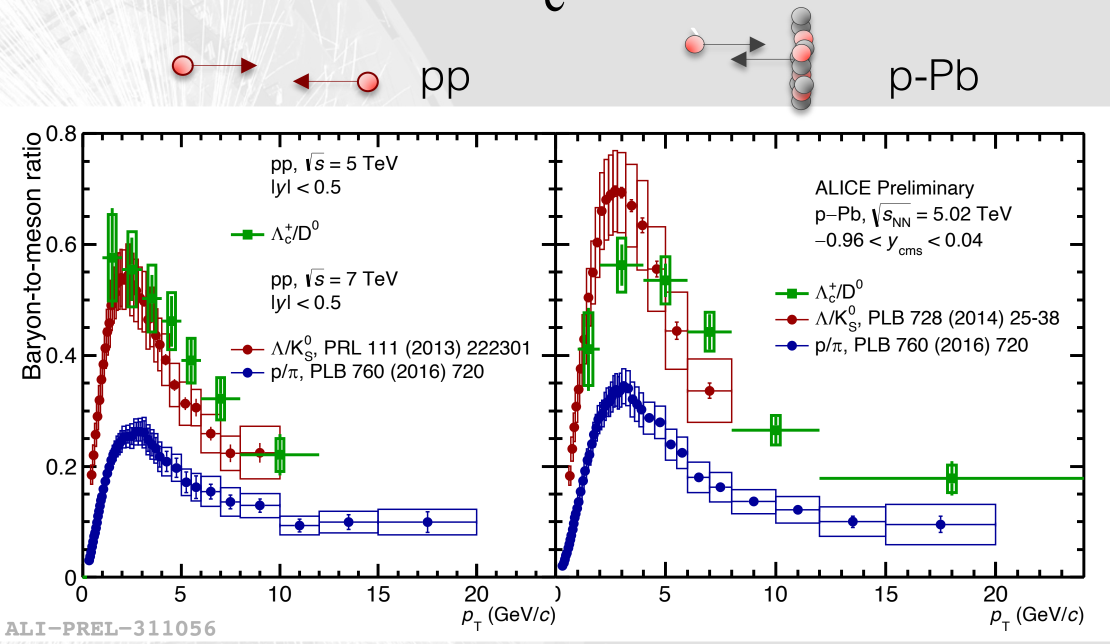
Baryon to meson ratios: strangeness + charm

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?

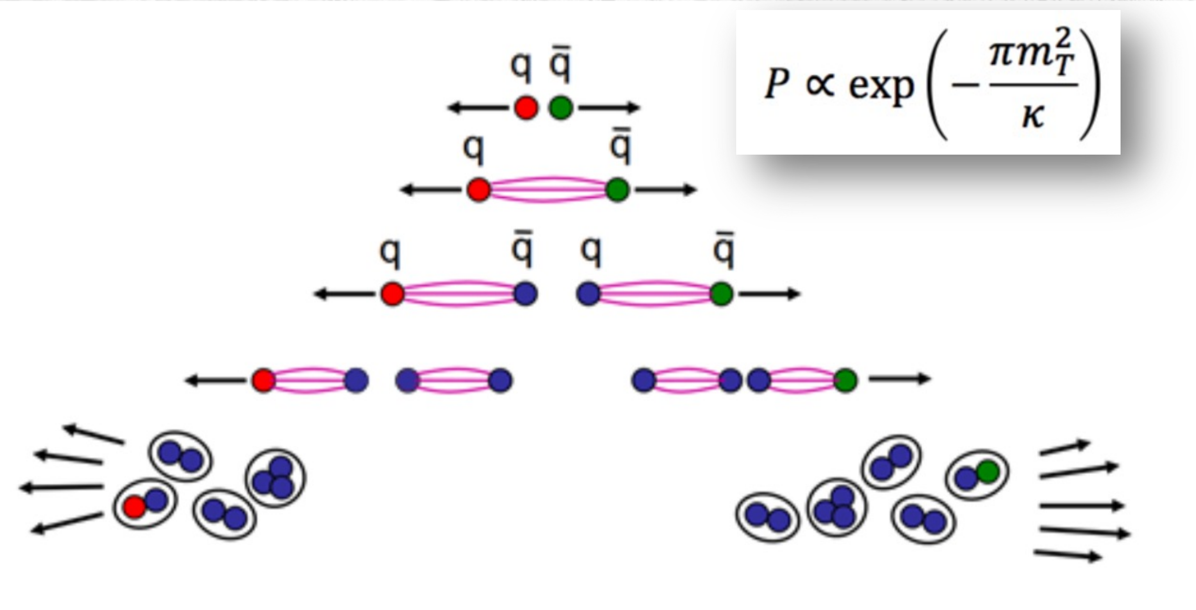
- Emergent phenomena of QCD: 'more is different' [1]

What about the synergy between the LHC and EIC?
- A hadron-hadron collider is required → effects will appear
- An electron-hadron collider is required → clean way to learn about baseline

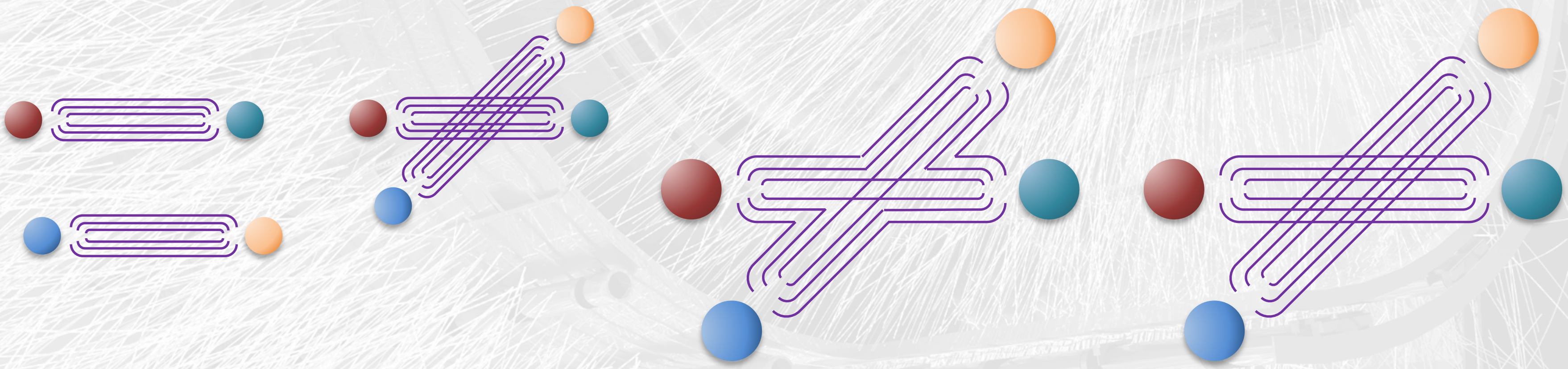
THAT'S why we are here

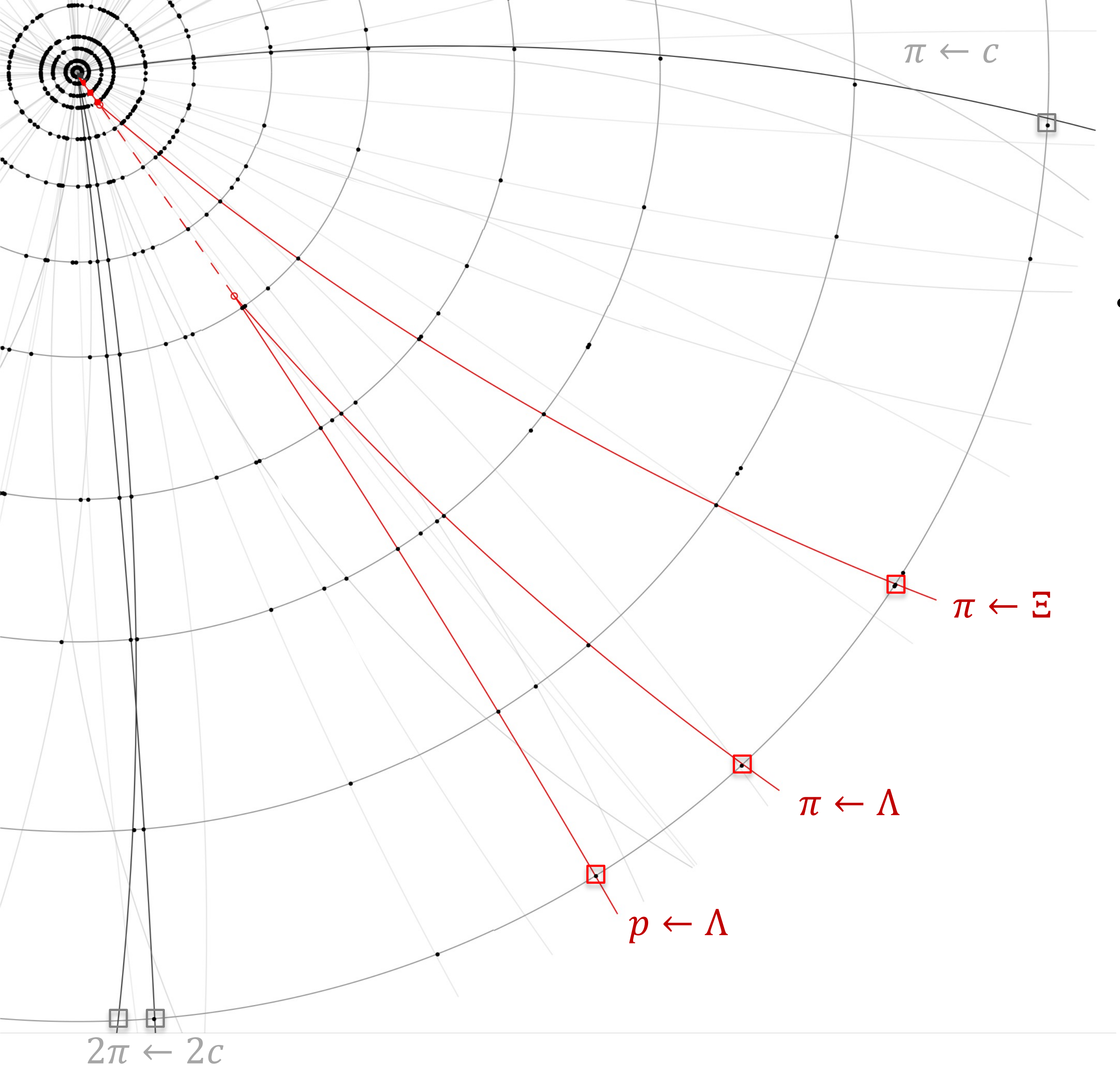
[1] **More Is Different**. P.W. **Anderson**. Science, New Series, Vol. 177, No. 4047. (Aug. 4, 1972)

Particle production in the Lund model



- 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

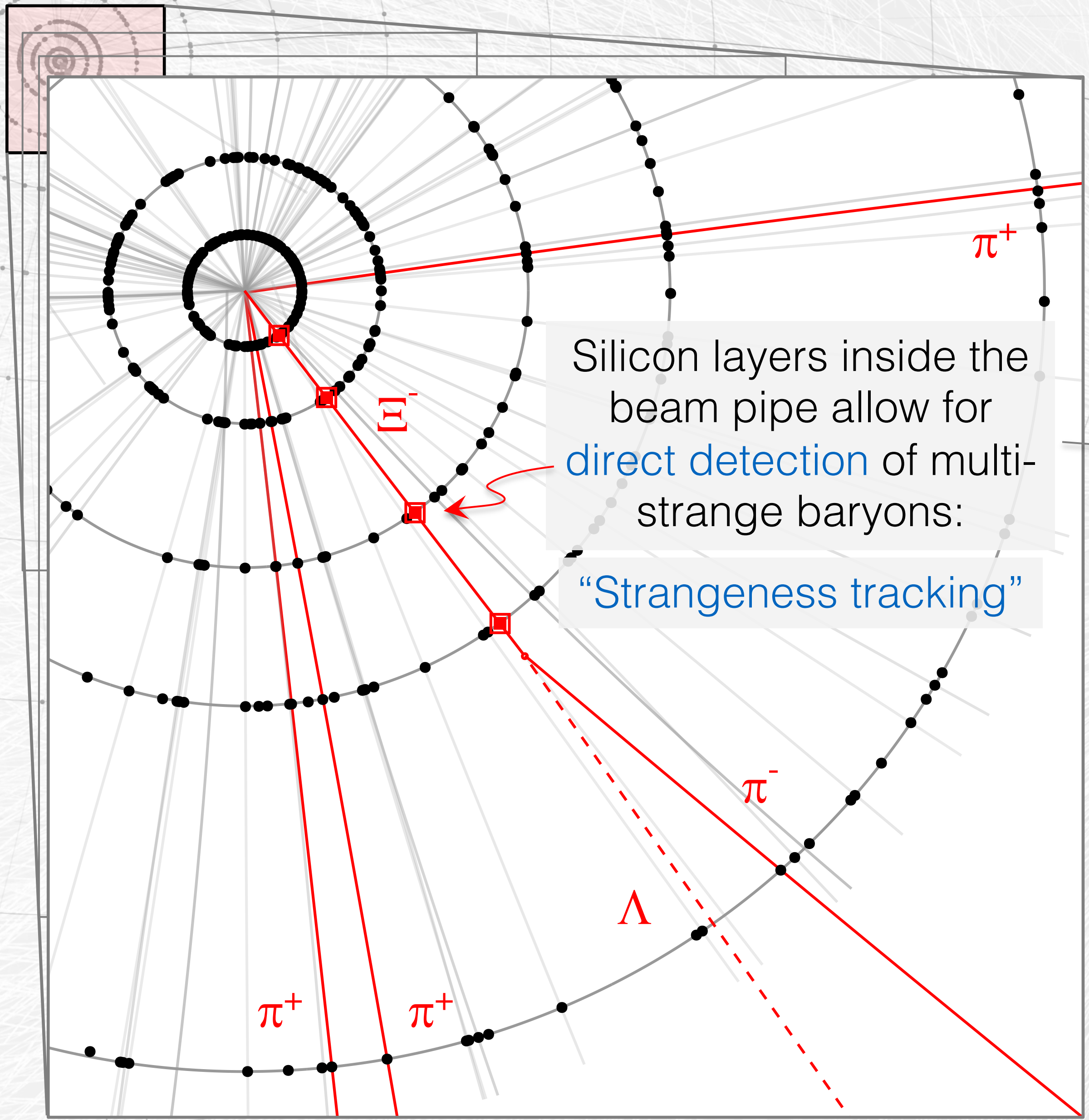




Towards strangeness tracking

- Common reconstruction: decay-daughter based
  - We can do much better with ALICE 3

Towards strangeness tracking



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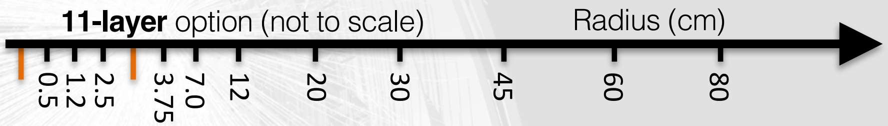

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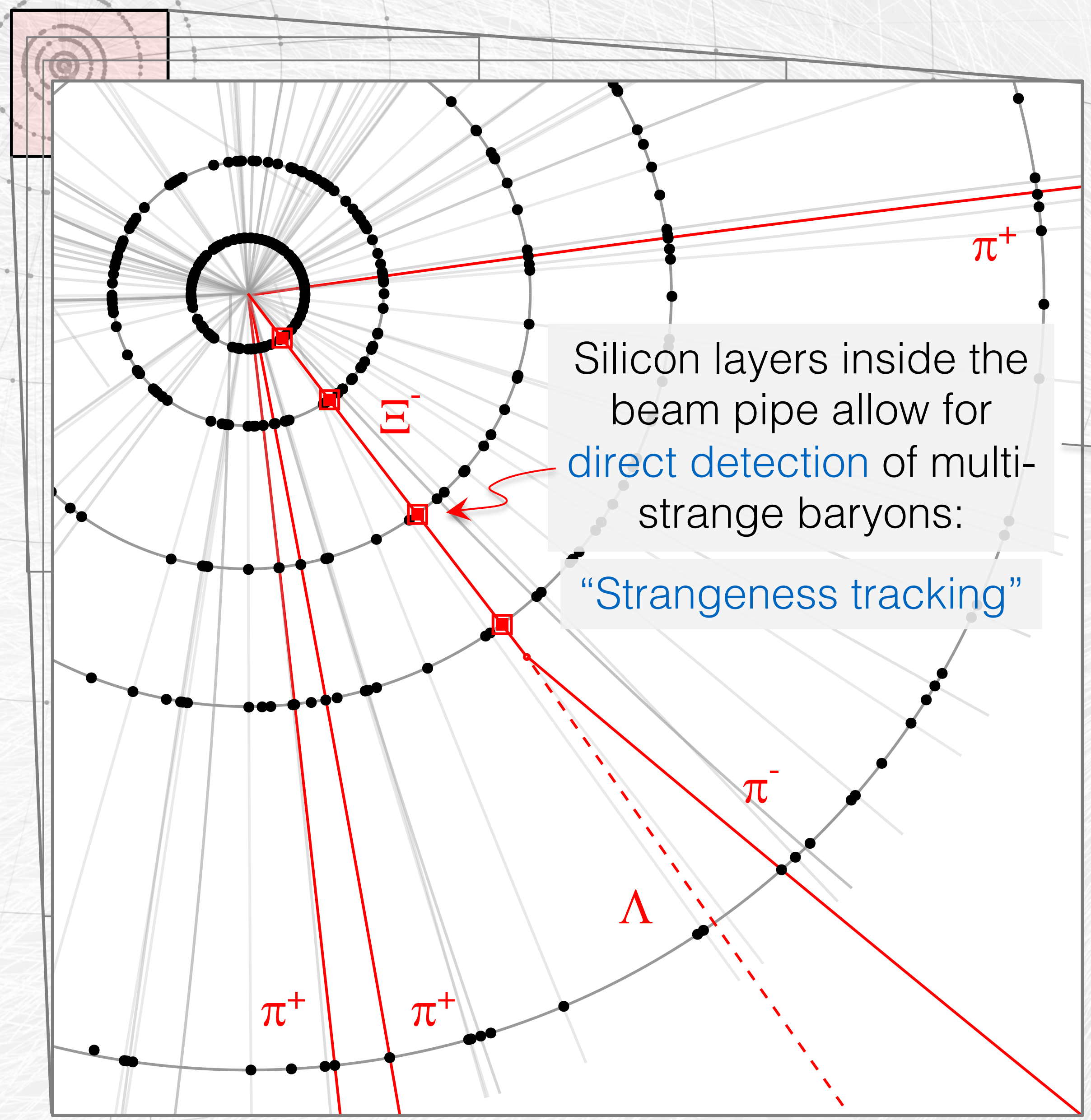
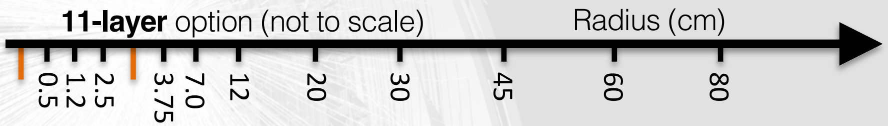
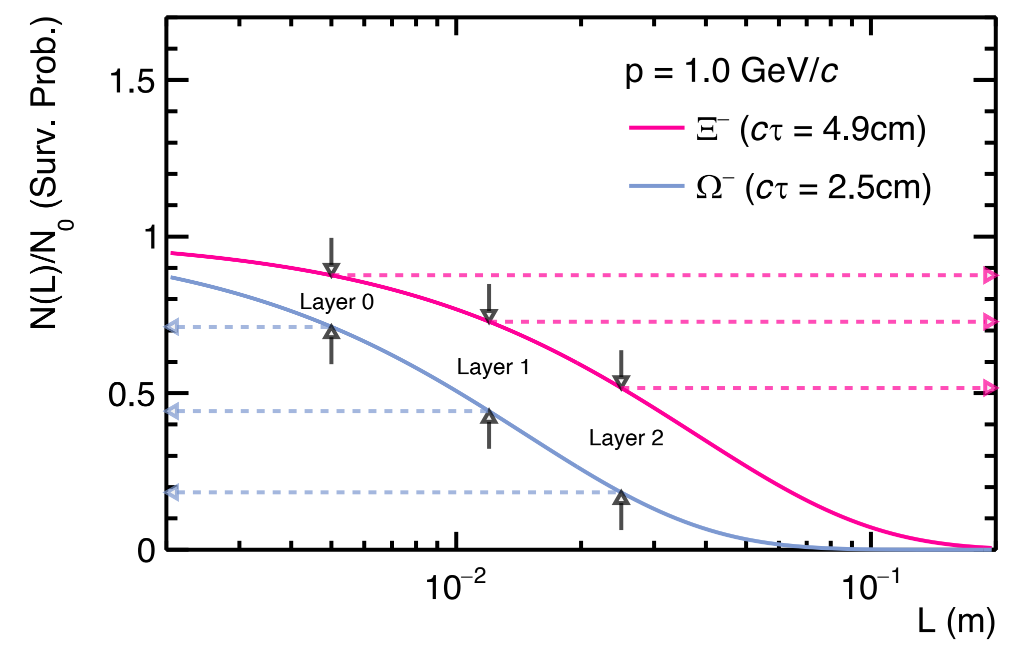


Silicon layers inside the beam pipe allow for direct detection of multi-strange baryons:

"Strangeness tracking"

- Common reconstruction: decay-daughter based
  - We can do much better with ALICE 3





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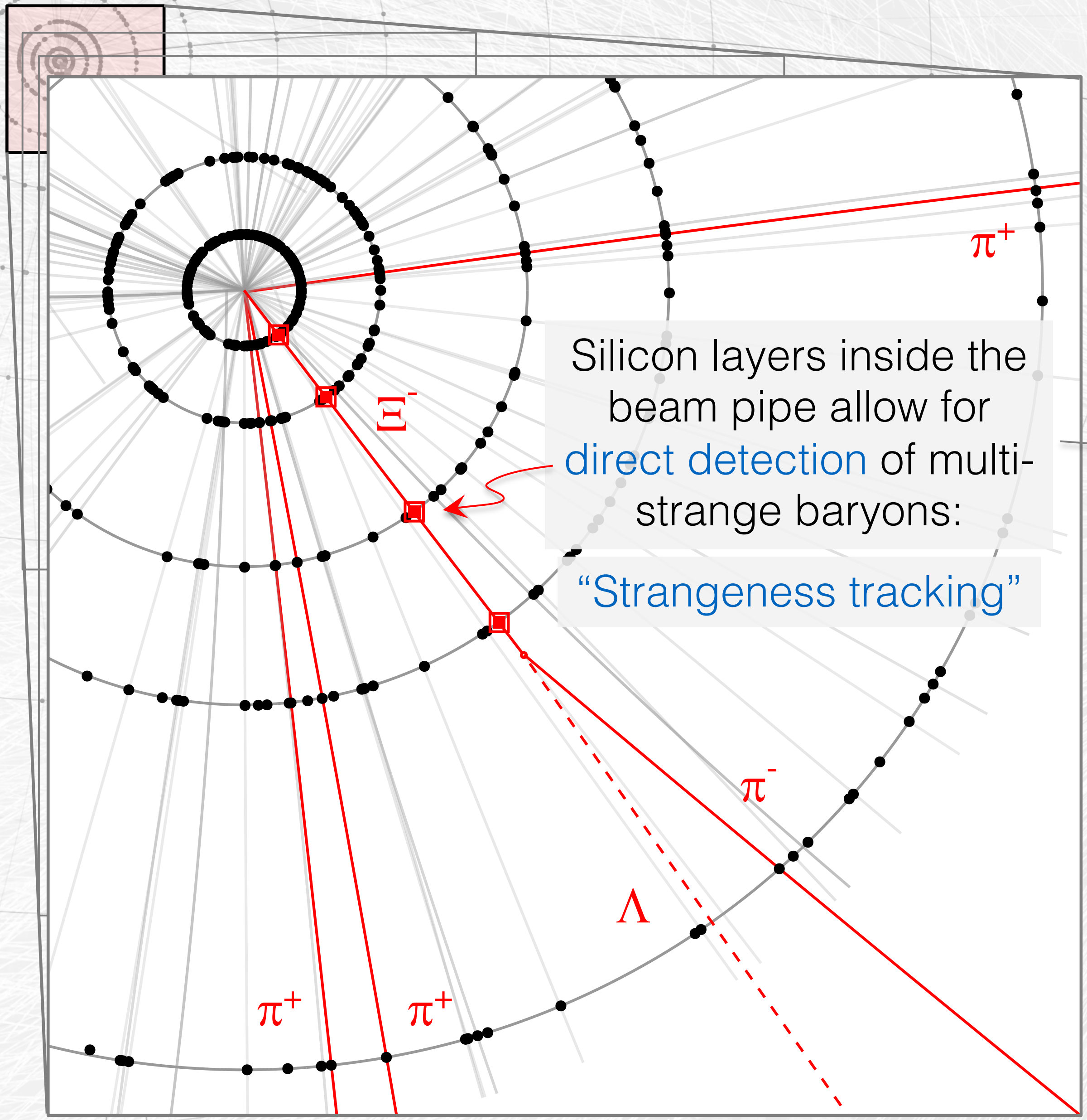
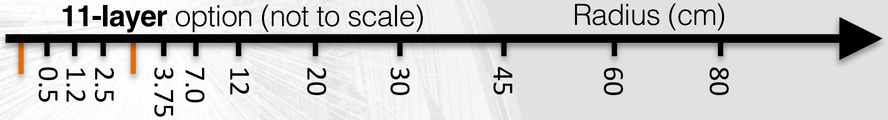
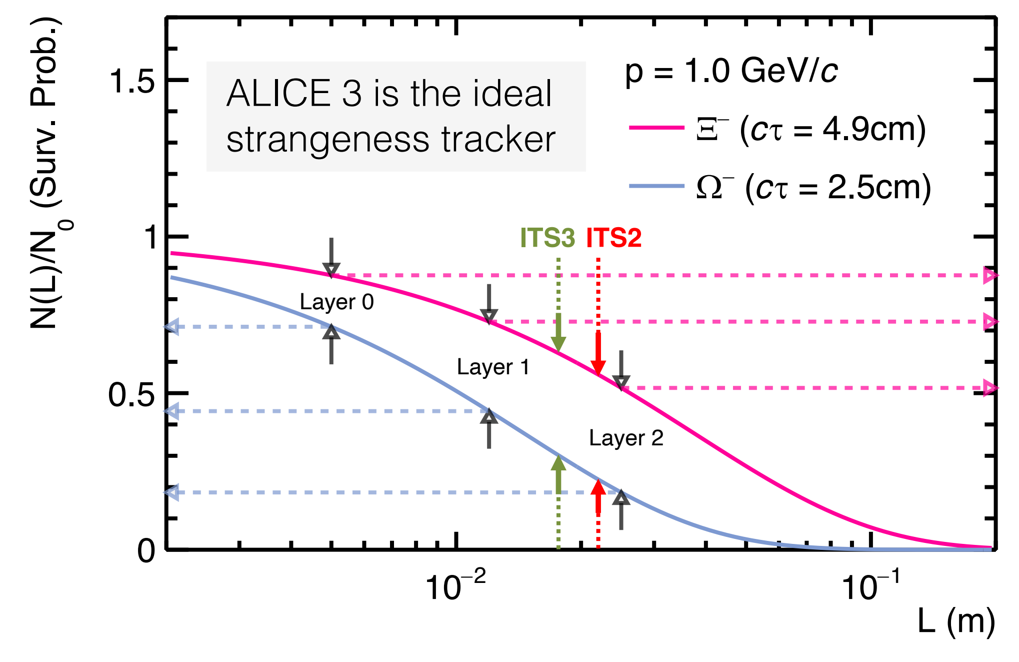
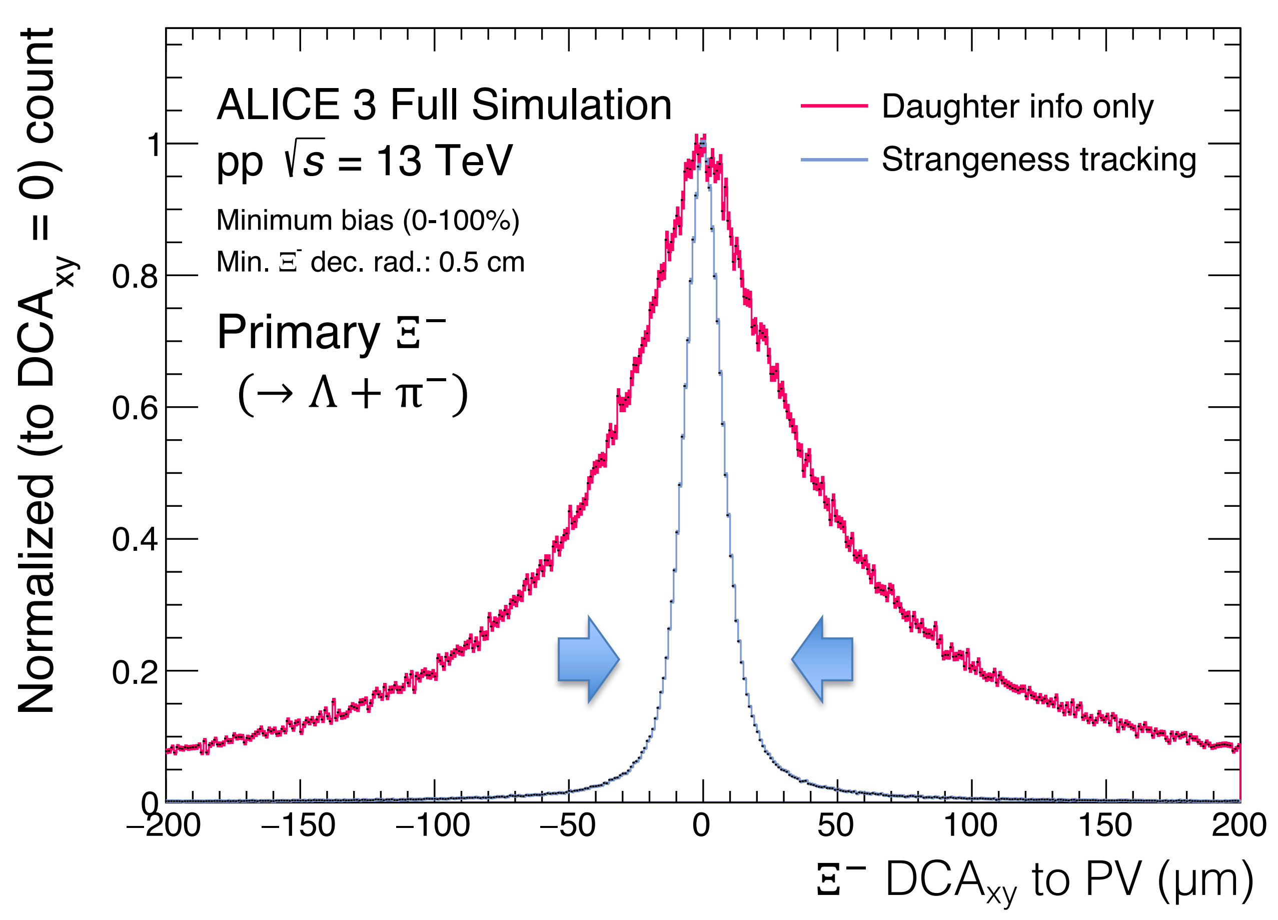






Strangeness tracking in practice: the effect

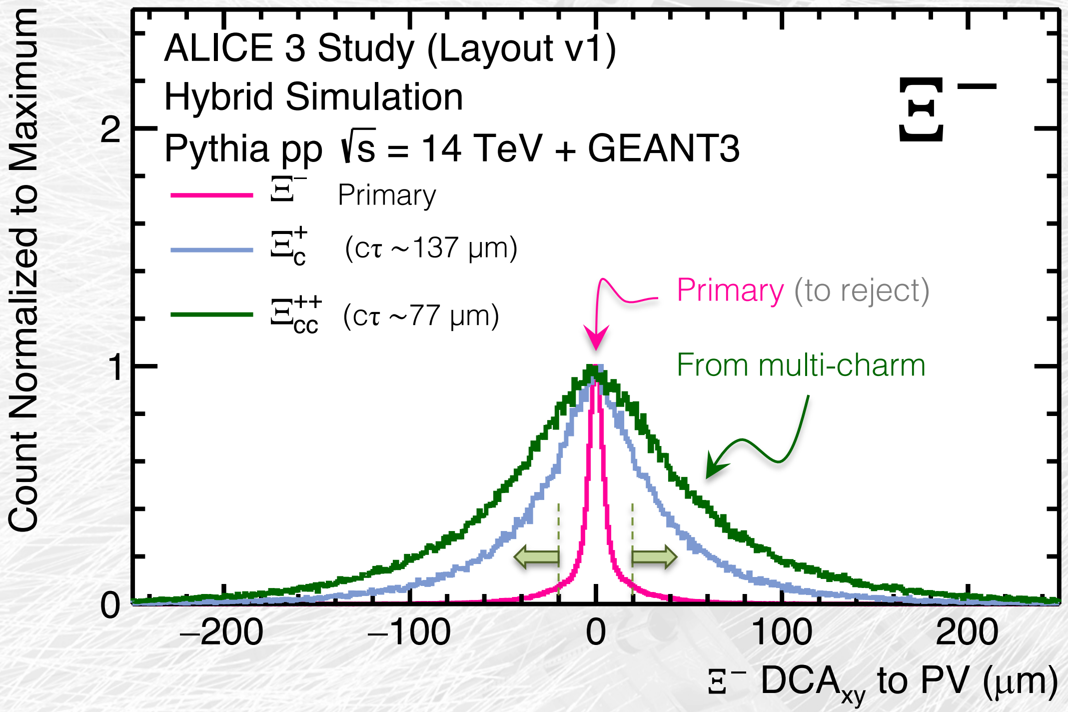
transverse impact parameter to primary vertex



- Reconstruction algorithm:
  1. Direct detection of decay products determines decay point, momenta
  2. Backward propagation determines hits to attach to trajectory
- Added hits greatly increase the primary vertex pointing accuracy: primary-like resolution!
- In practice, the best of both worlds:
  - momentum precision with (long) daughters,
  - spatial precision with primary particle hits
- Effectively also a particle identification method over a very large momentum range via invariant mass selection → improved combinatorics

Towards multi-charm: strangeness tracking the Ξ^- from Ξ_{cc}^{++}

- Improves separation power between primary and secondary Ξ^-



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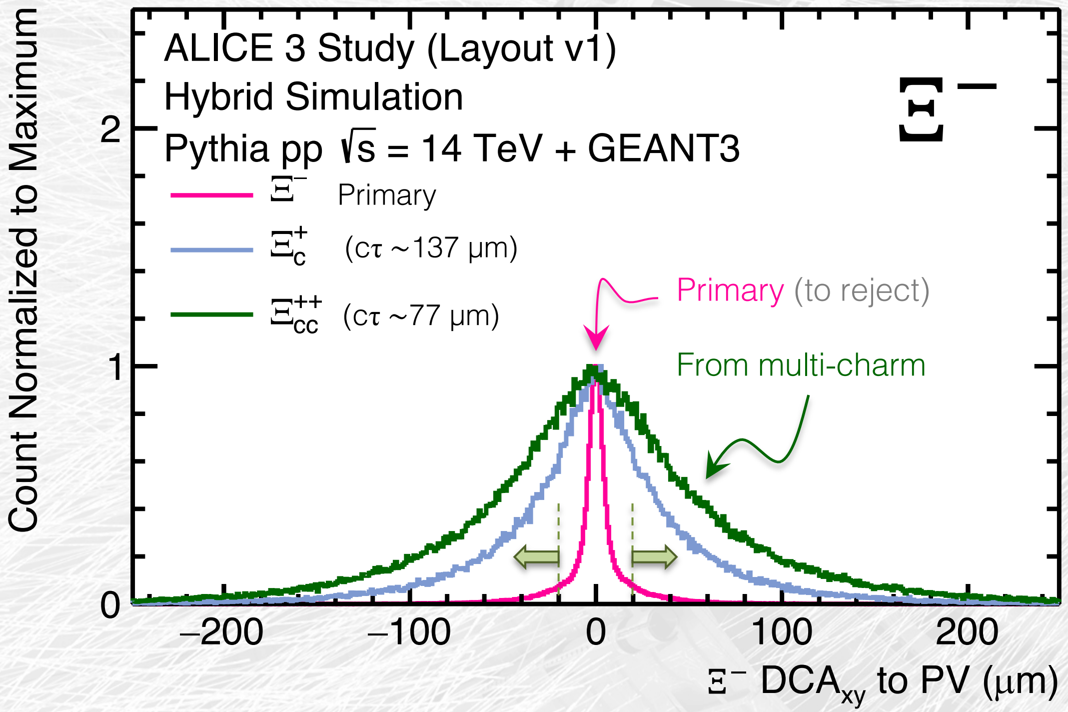

- Enormous improvement in the entire decay chain precision: Ξ_{cc}^{++} points towards primary vertex!