Studying particle production in high-multiplicity proton-proton and proton-lead collisions with ALICE

D.D. Chinellato for the ALICE Collaboration

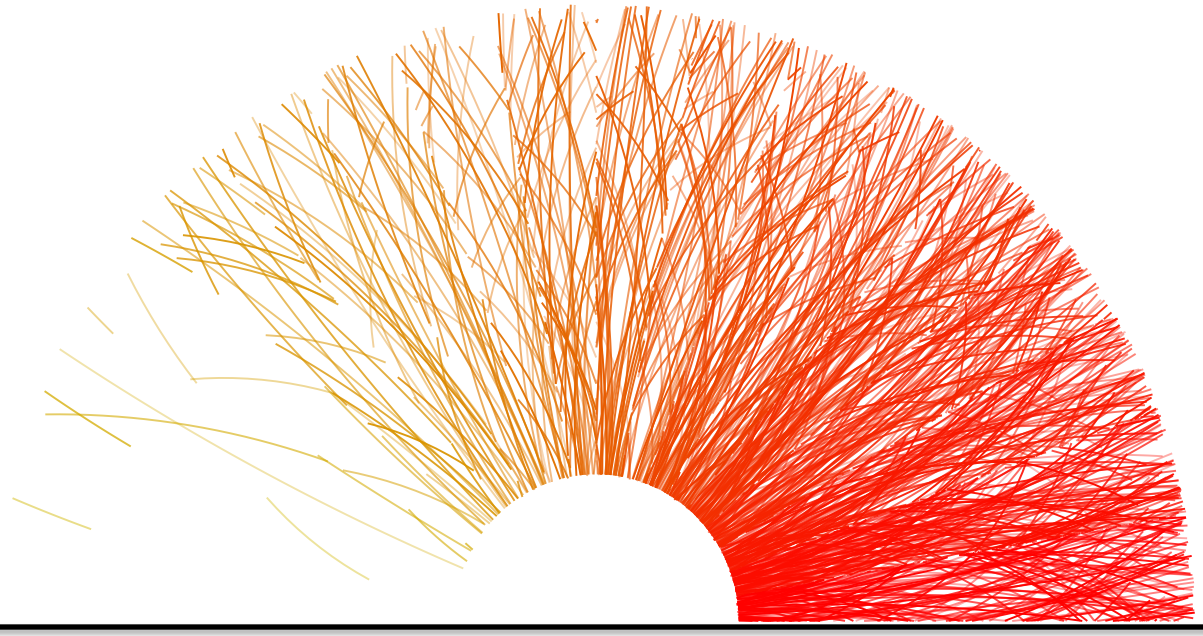
CERN EP Seminar, 19th February 2019

UNICAMP

ALICE

The role of multiplicity

High-multiplicity pp,
proton-lead collisions

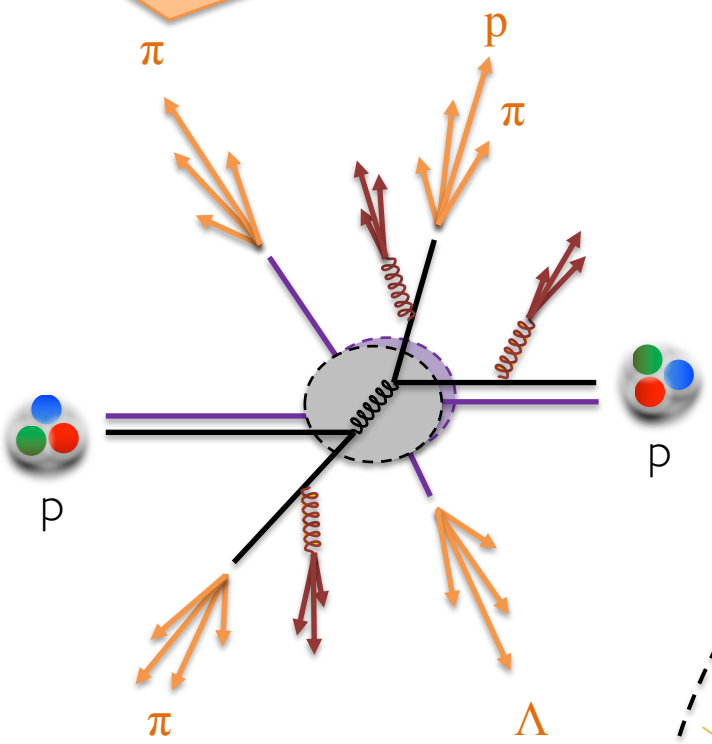


proton-proton (pp)
collisions

lead-lead (Pb-Pb)
collisions

The role of multiplicity

- 2 → 2 scatterings (LO)
- Soft physics: multi-parton interactions and initial and final state radiation
- MPI correlated via b, Q^2



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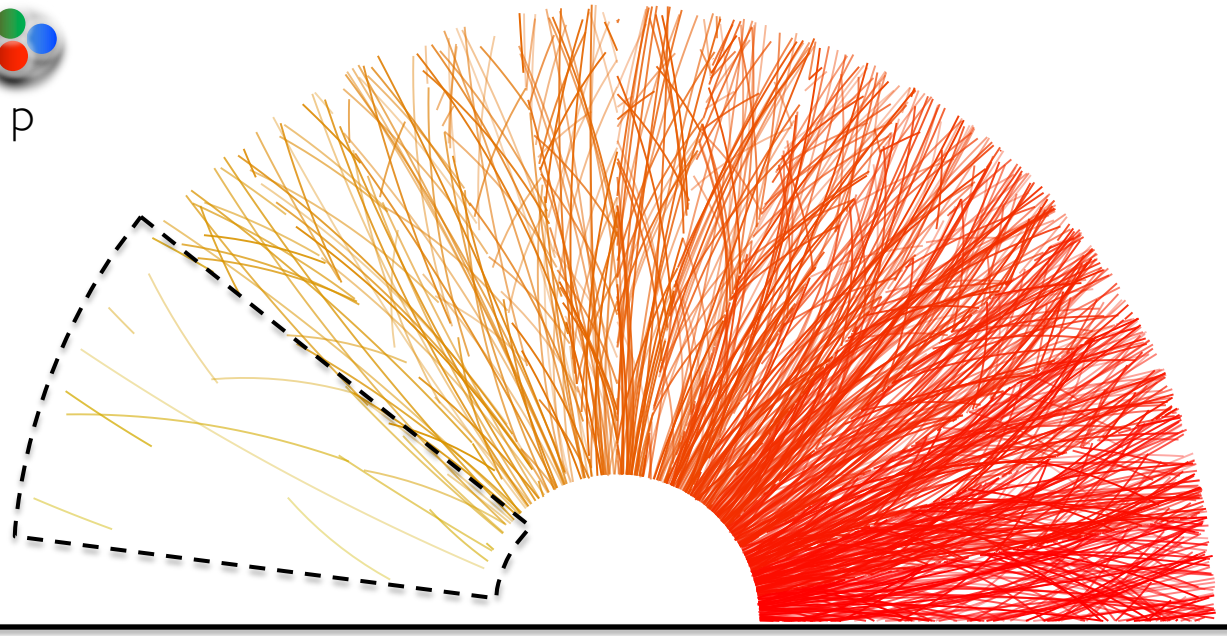

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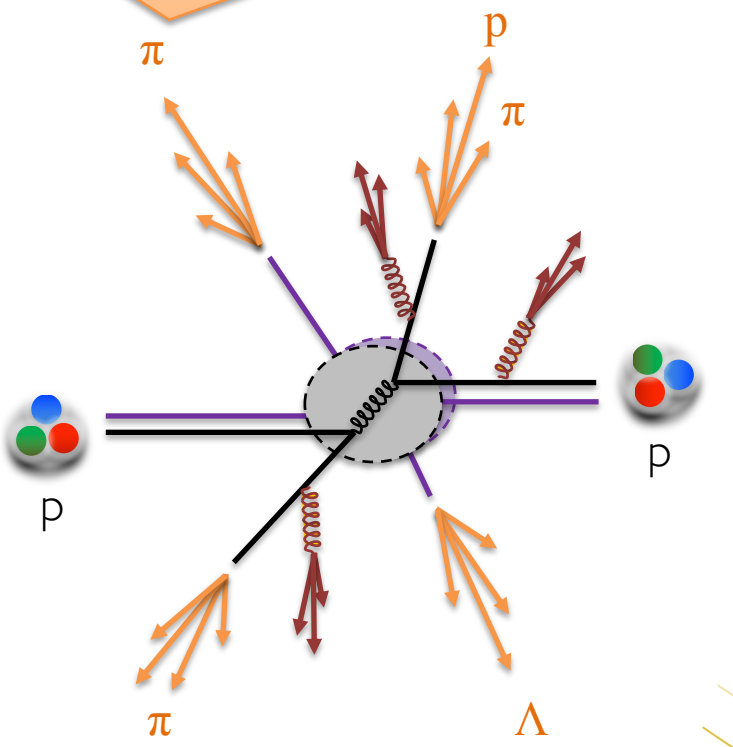
kinematically and chemically equilibrated system: hydrodynamics and statistical principles



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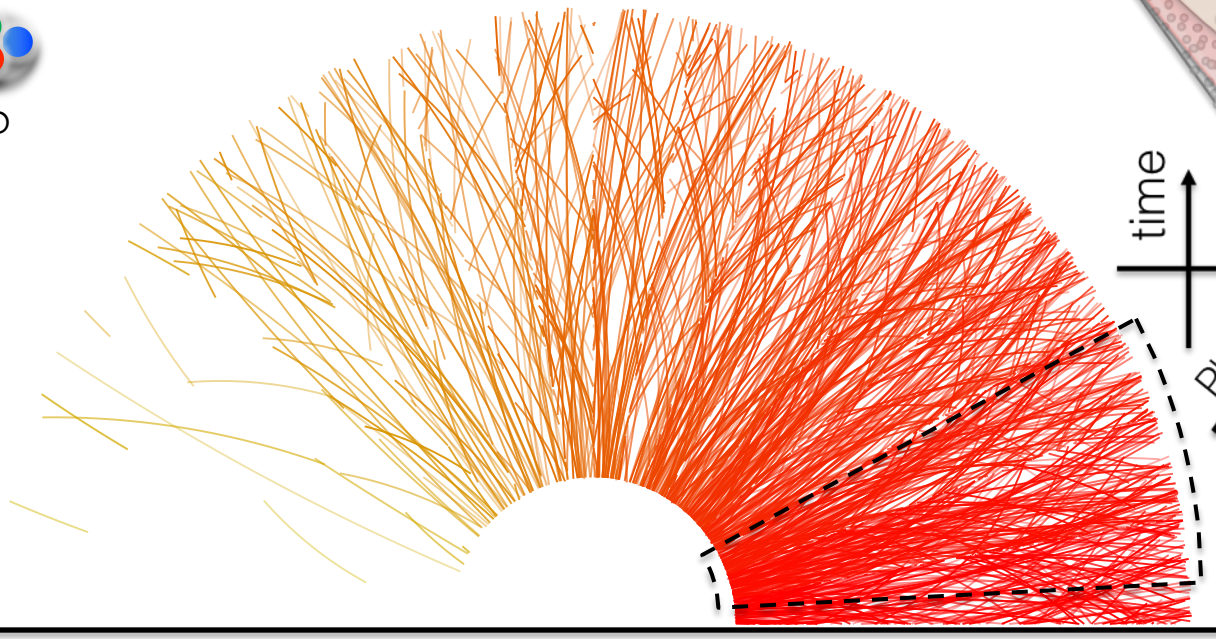

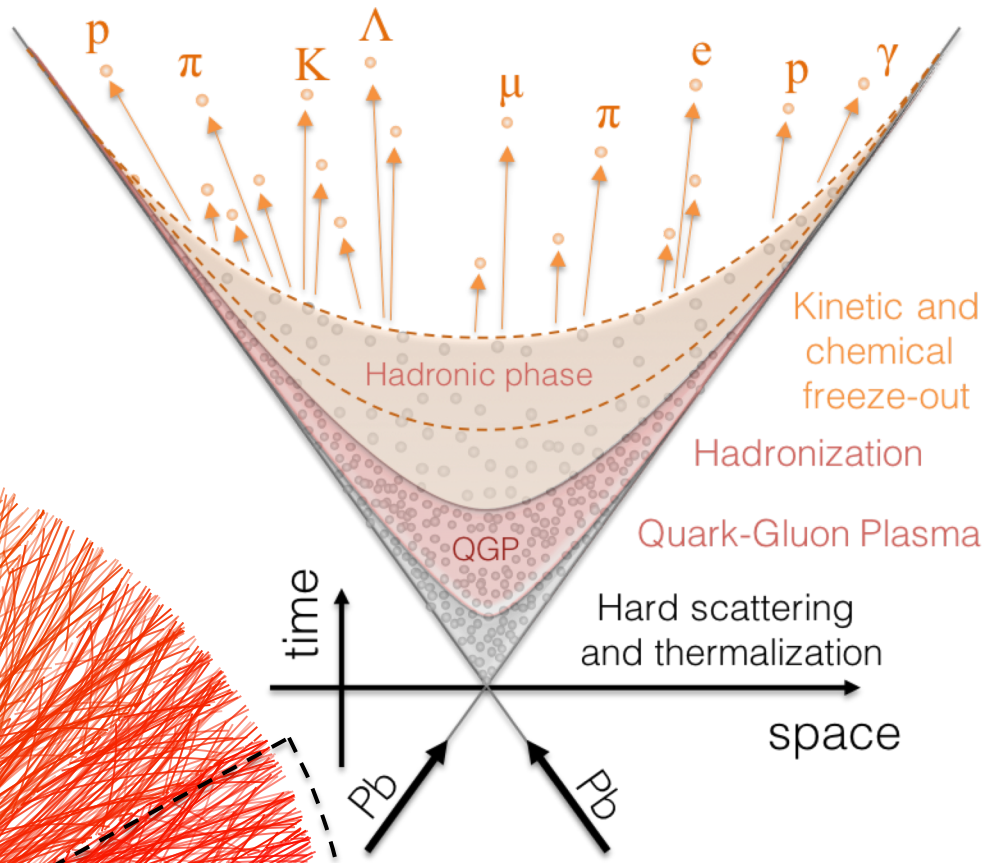

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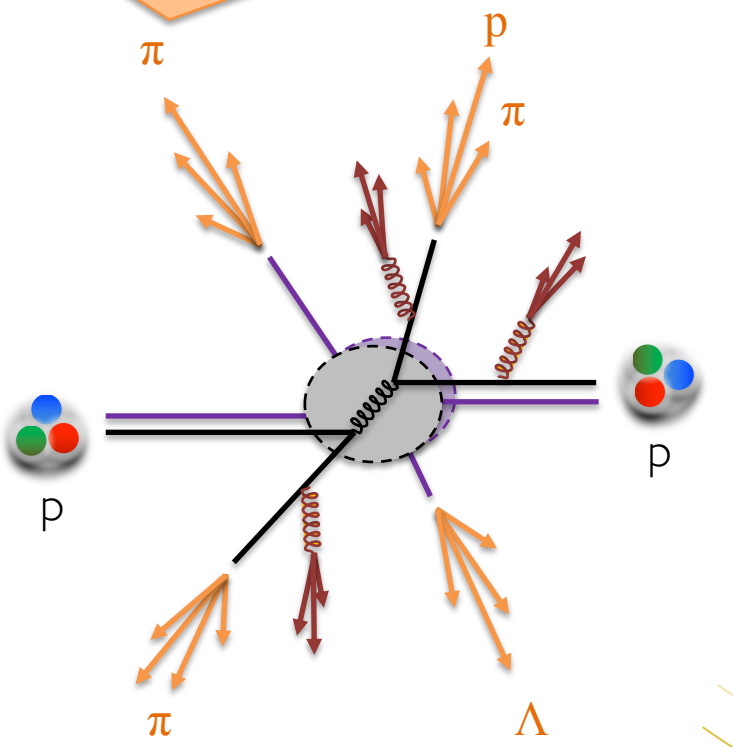
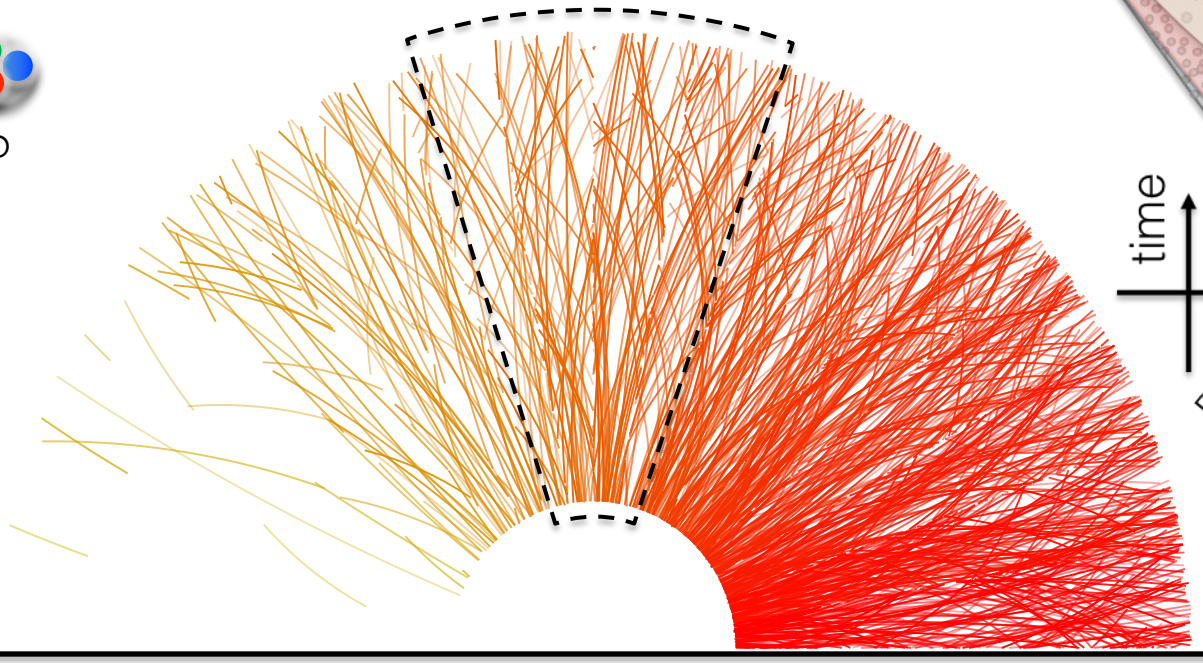


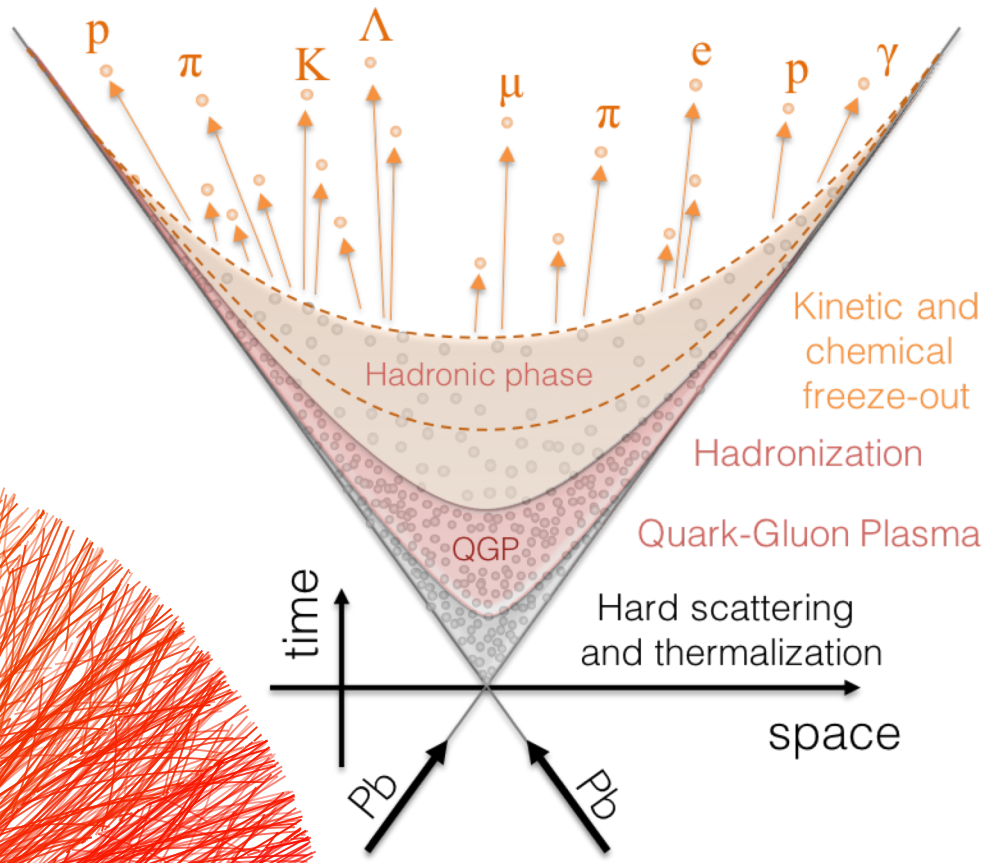
proton-proton (pp) collisions

Somewhere in between…?

High-multiplicity pp, proton-lead collisions



kinematically and chemically equilibrated system: hydrodynamics and statistical principles



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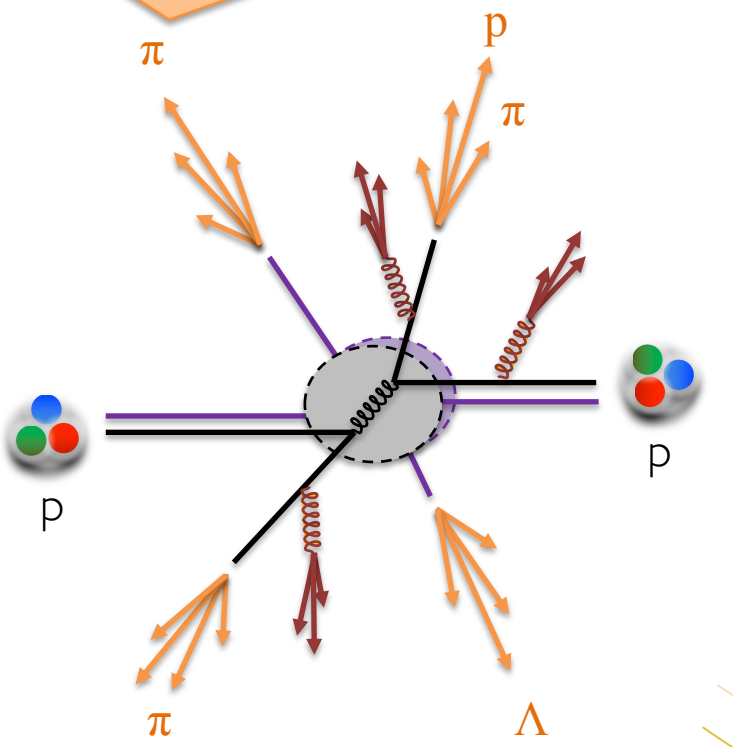

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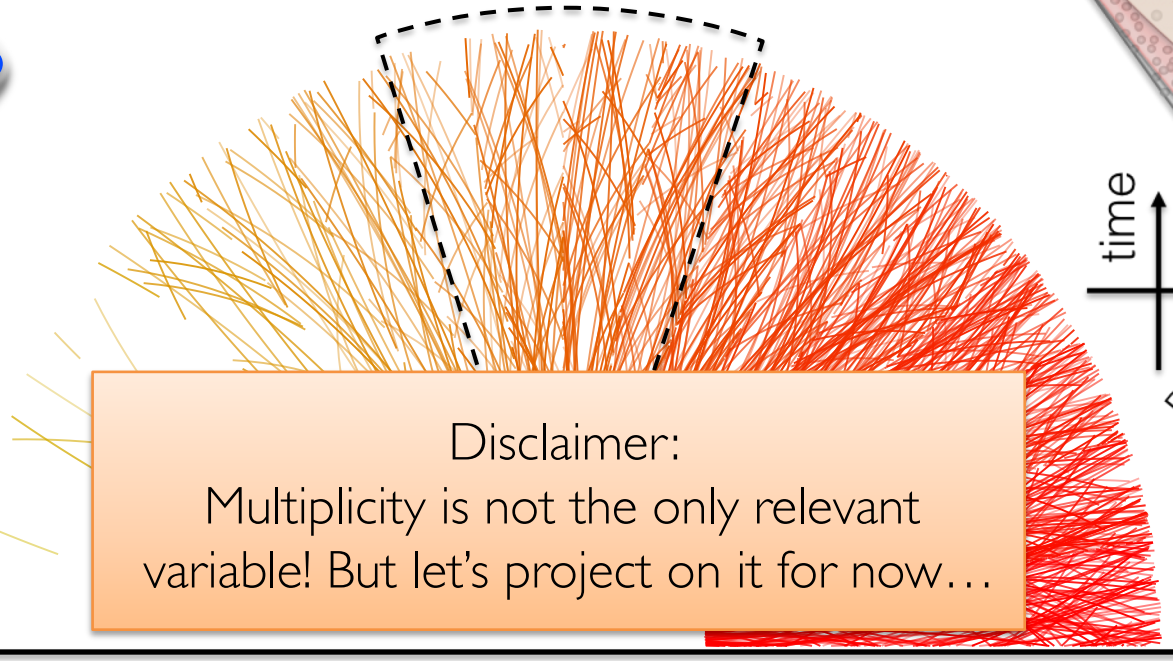
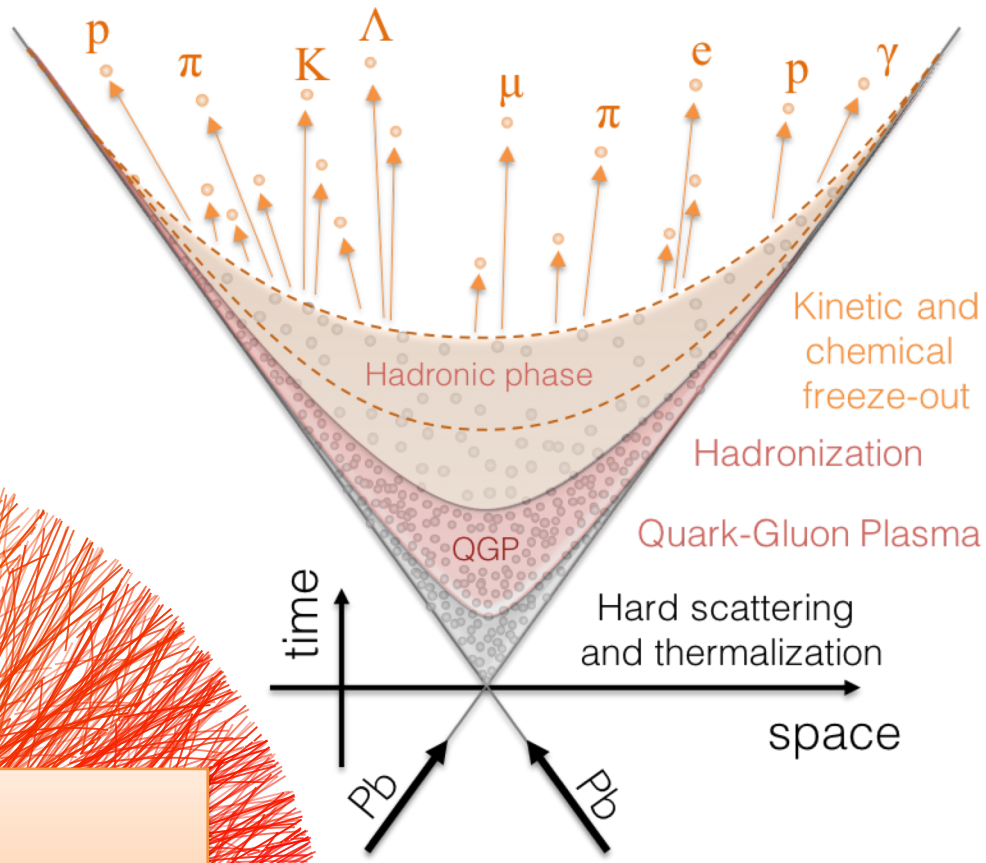


Disclaimer:
Multiplicity is not the only relevant variable! But let's project on it for now…

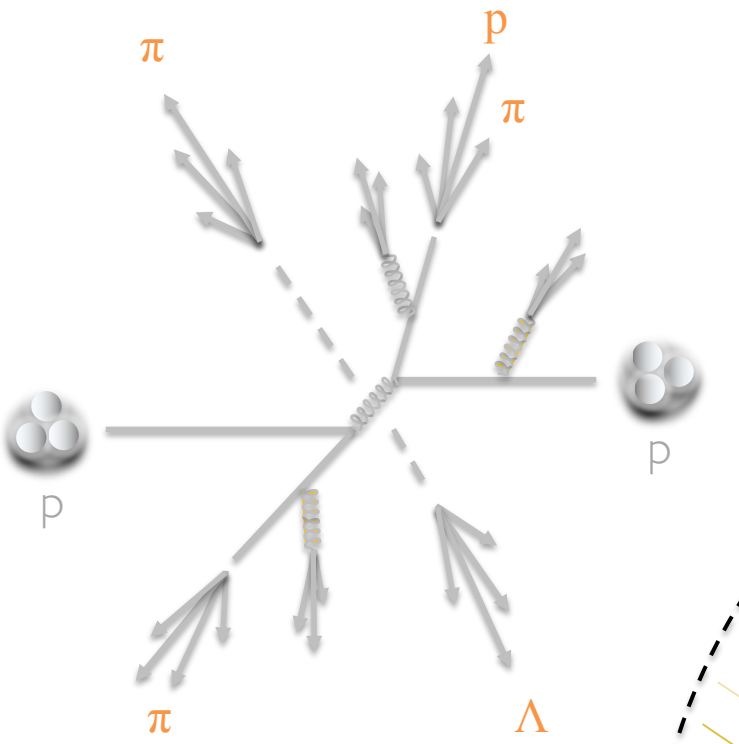
kinematically and chemically equilibrated system: hydrodynamics and statistical principles



lead-lead (Pb-Pb) collisions

The role of multiplicity

How are relative particle species abundances determined? → **chemistry**



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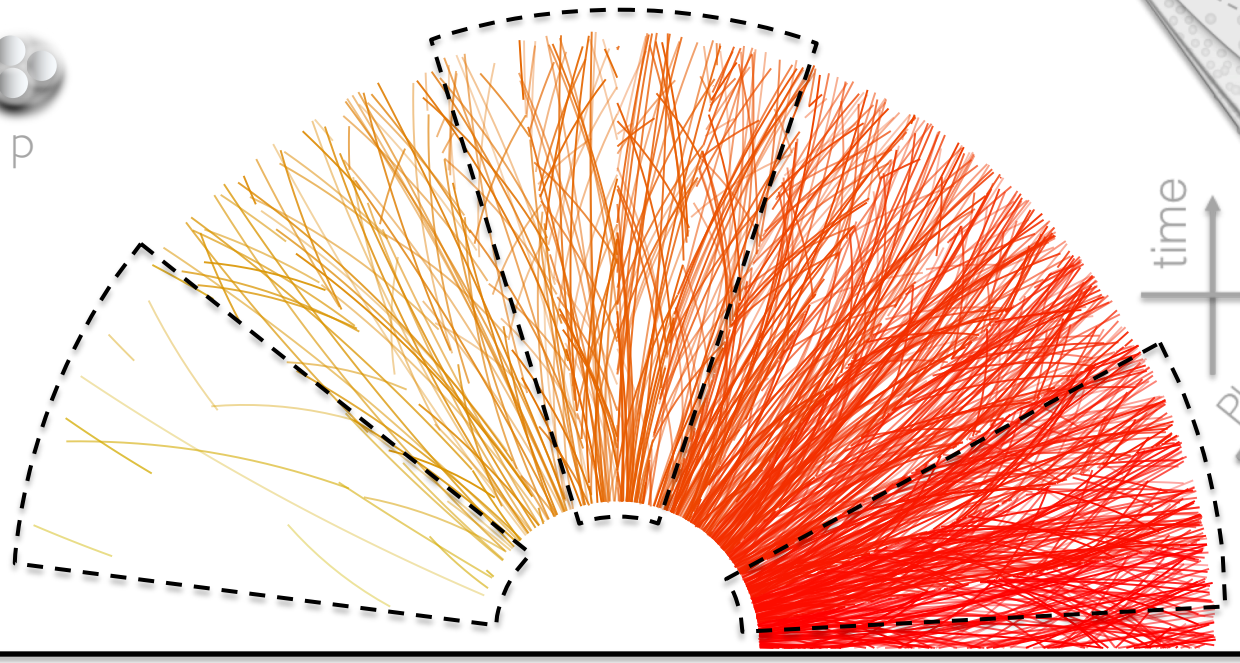
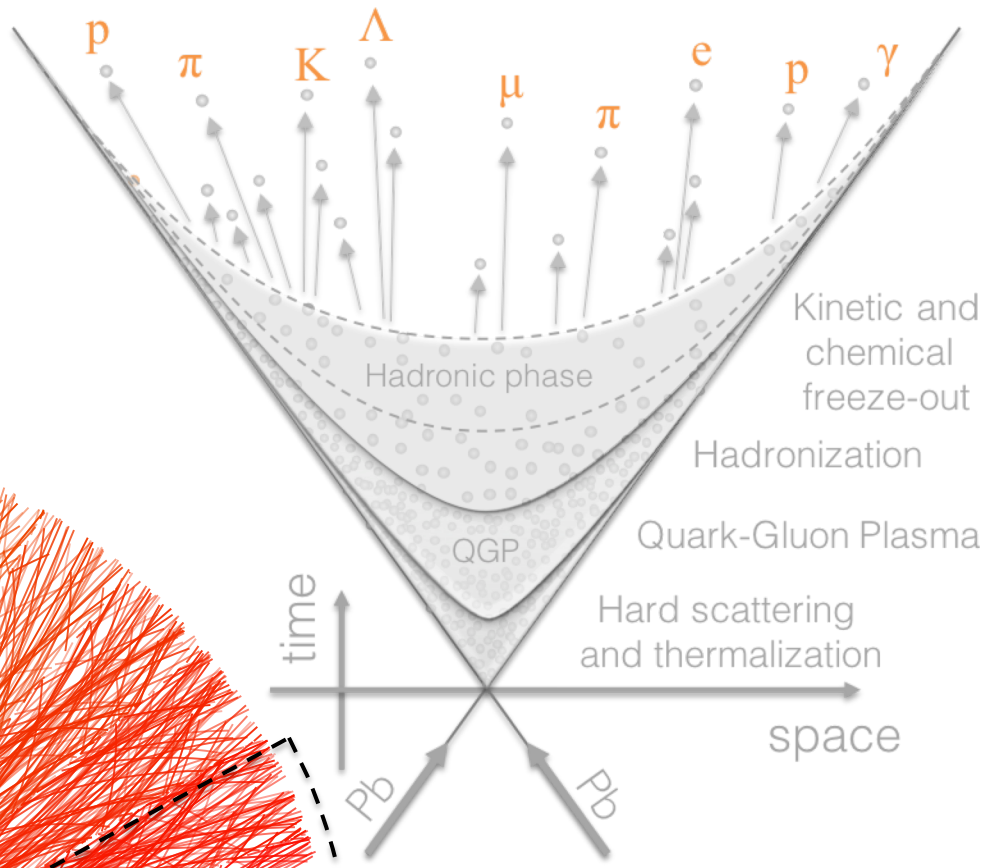


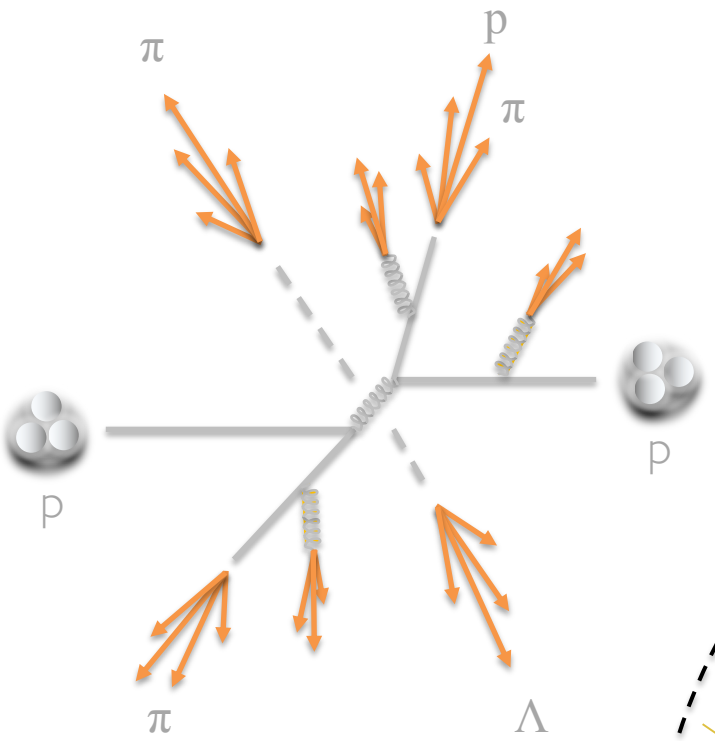


lead-lead (Pb-Pb) collisions

The role of multiplicity

How are relative particle species abundances determined? → **chemistry**

How is momentum distributed? → **kinematics**



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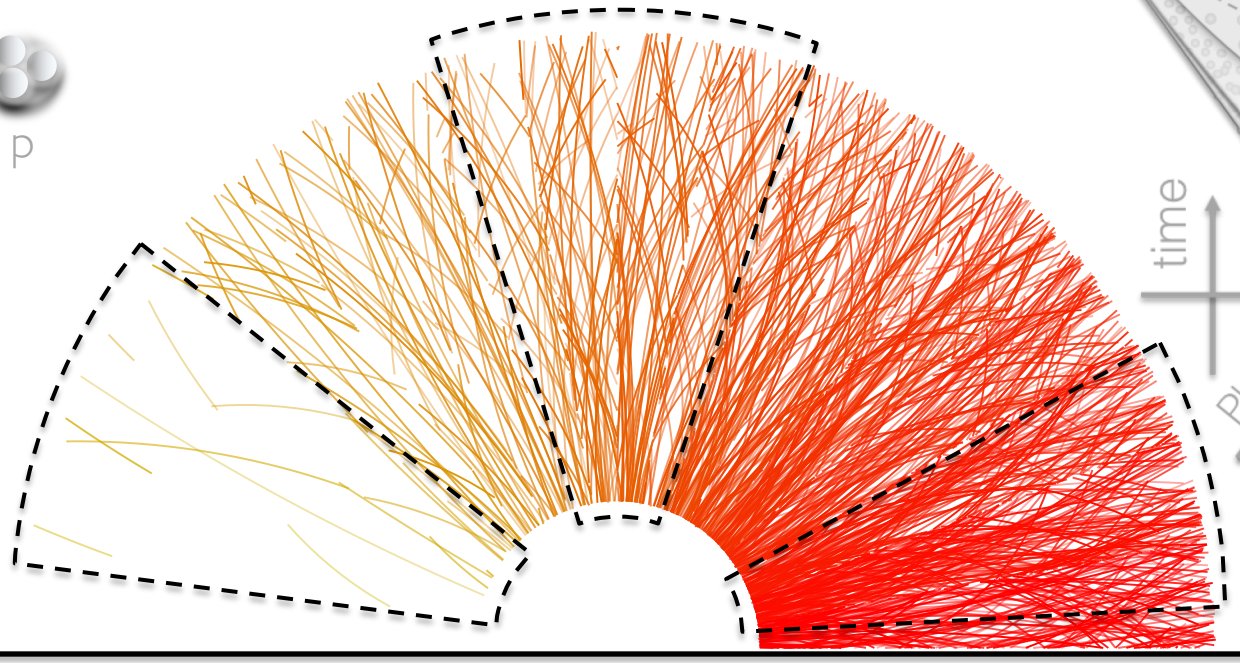
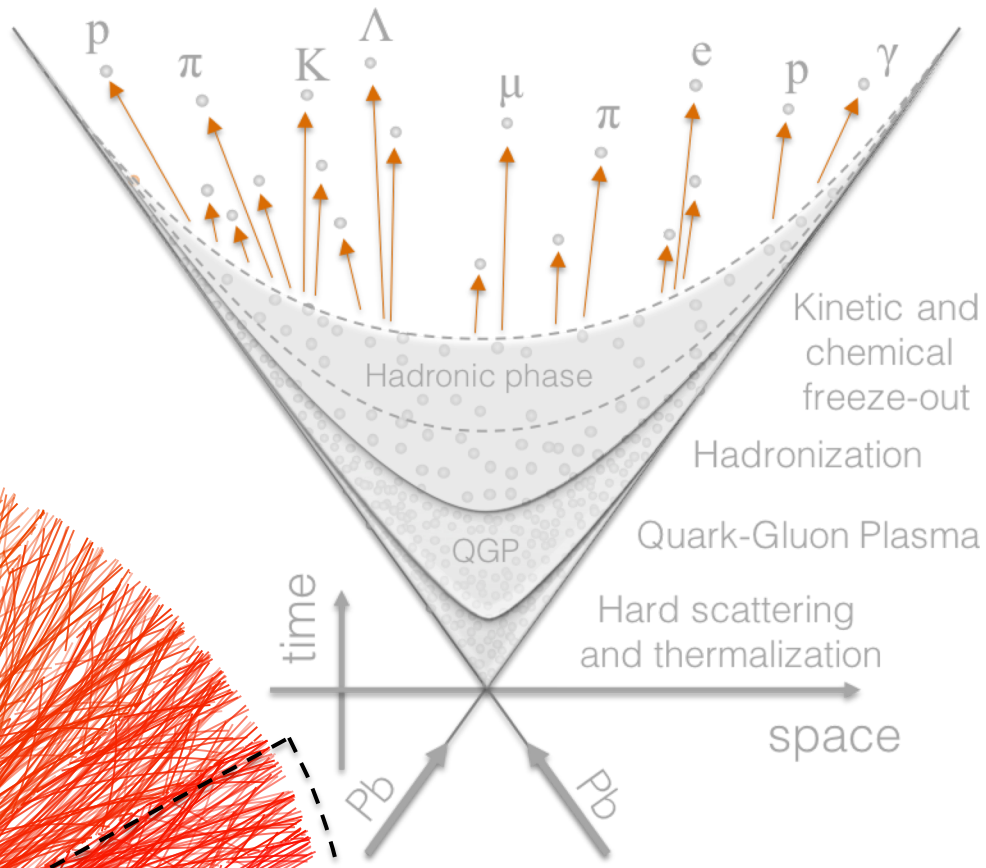
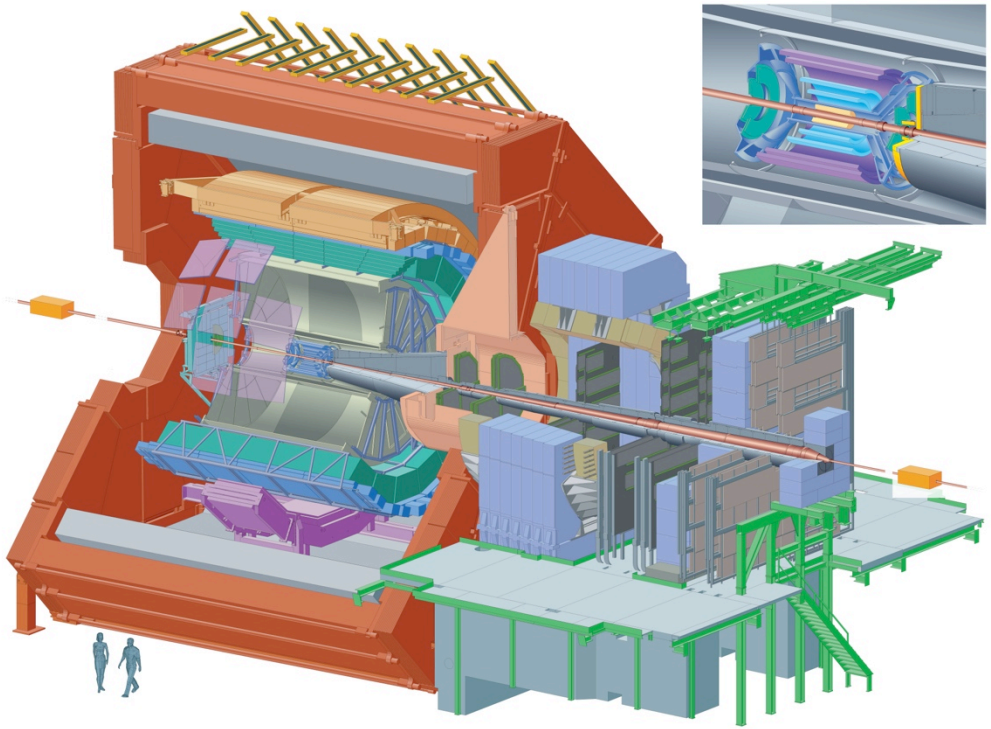




lead-lead (Pb-Pb) collisions

The ALICE Experiment at the LHC



Specificity: low-momentum tracking and particle identification in a high-multiplicity environment

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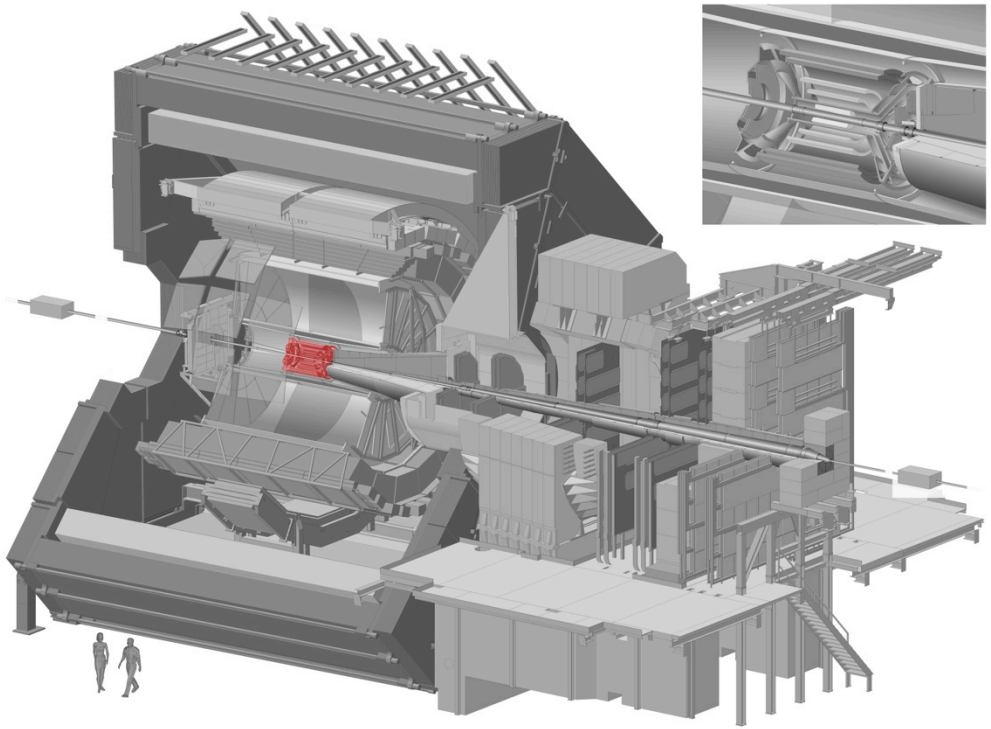
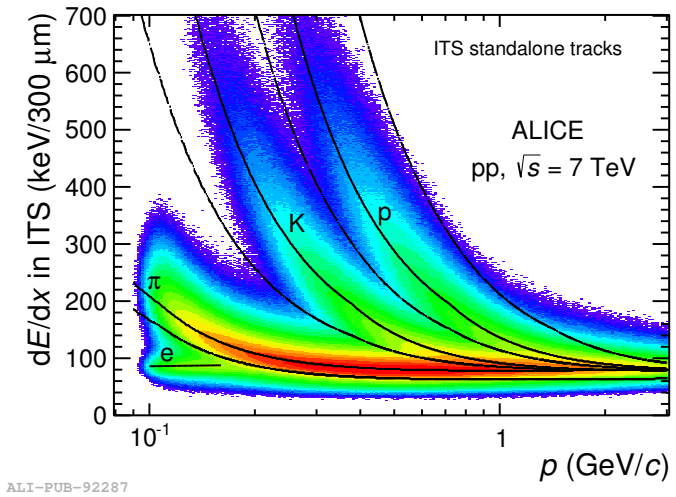
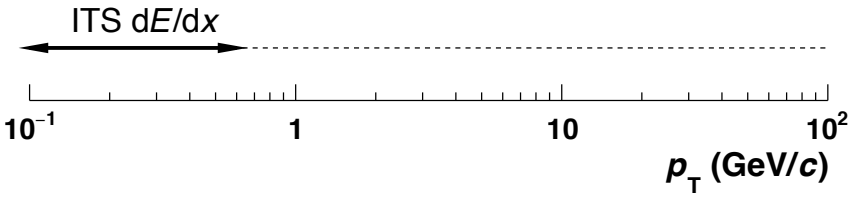


ITS ($|\eta|<0.9$)

- 6 Layers of silicon detectors
- Trigger, tracking, vertex, PID (dE/dx)





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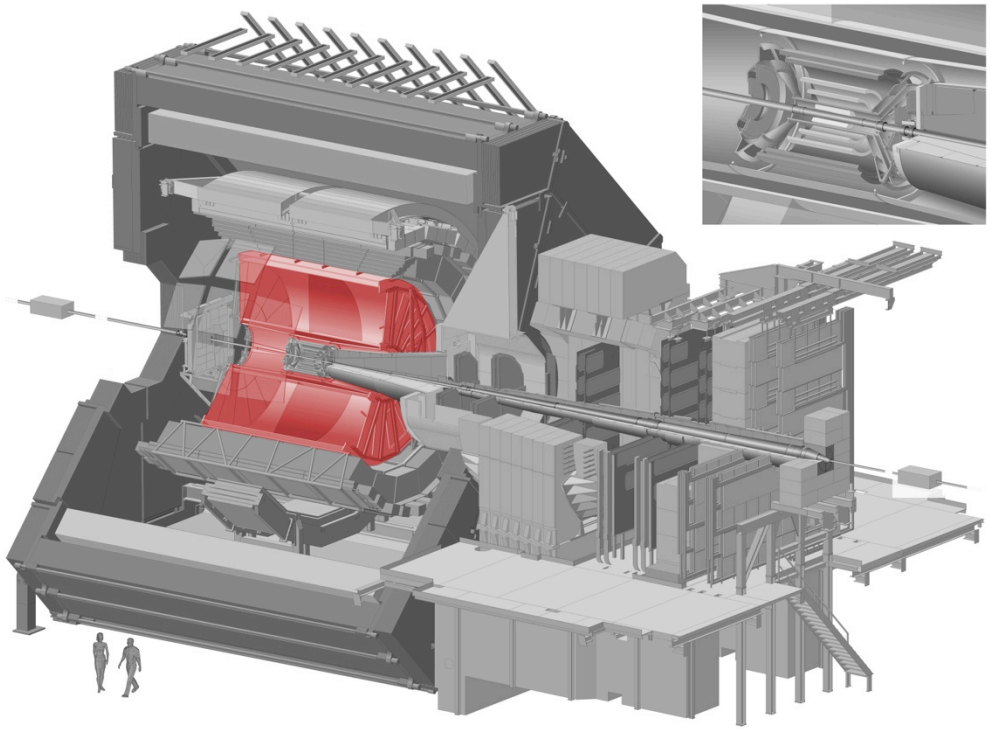

ITS ($|\eta|<0.9$)

- 6 Layers of silicon detectors
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TPC ($|\eta|<0.9$)

- Gas-filled ionization detection volume
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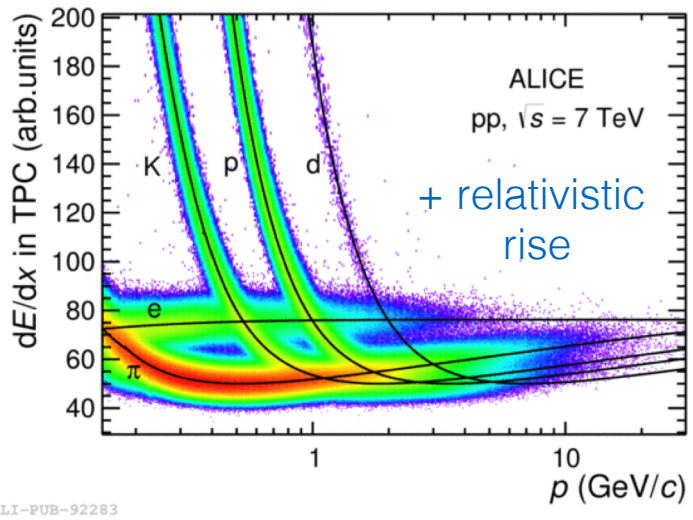

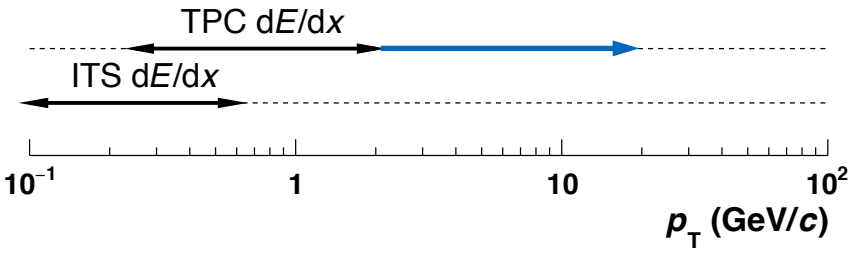

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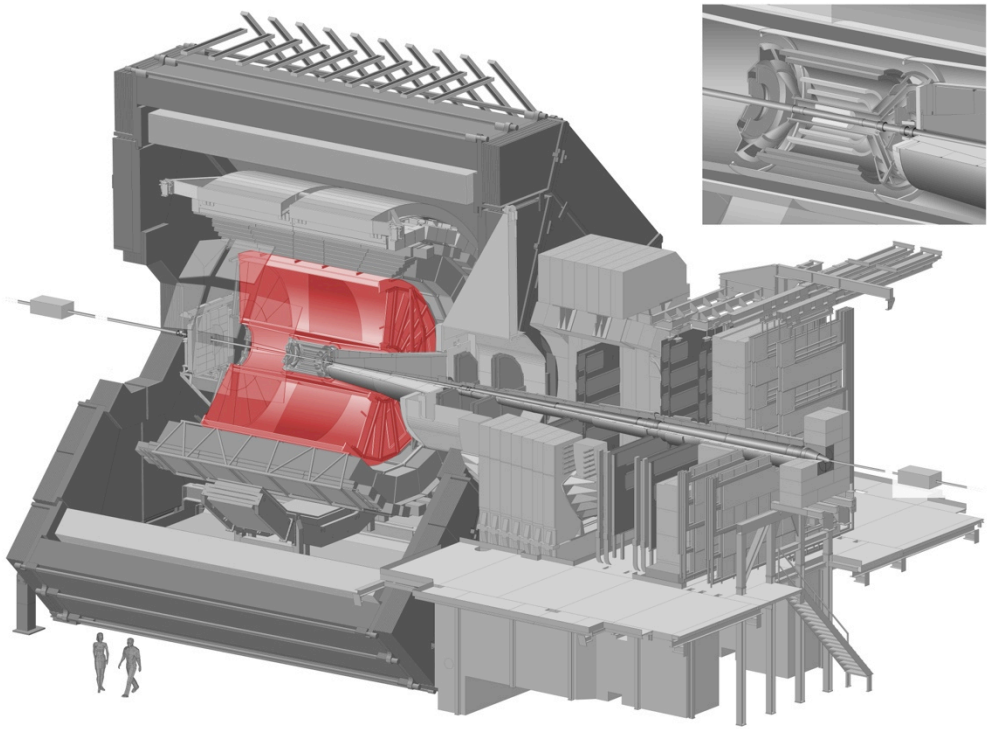

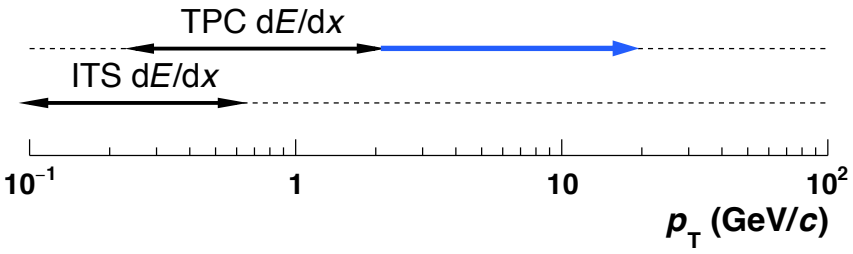

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- Trigger, tracking, vertex, PID (d*E*/d*x*)

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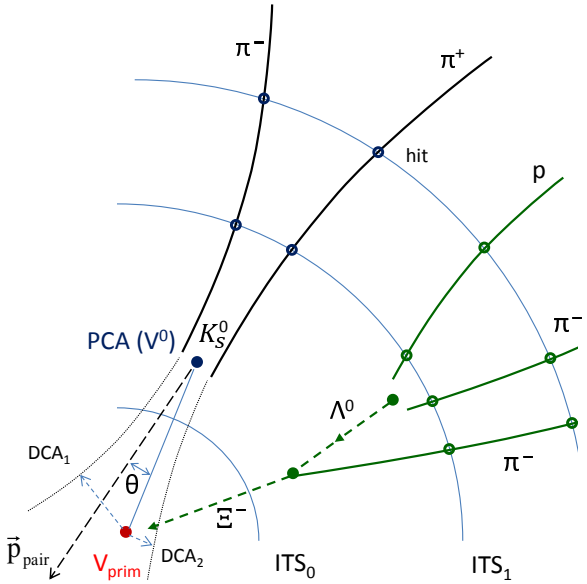
- Gas-filled ionization detection volume
- Tracking, vertex, PID (d*E*/d*x*)
- Weak decay reconstruction (topological)

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



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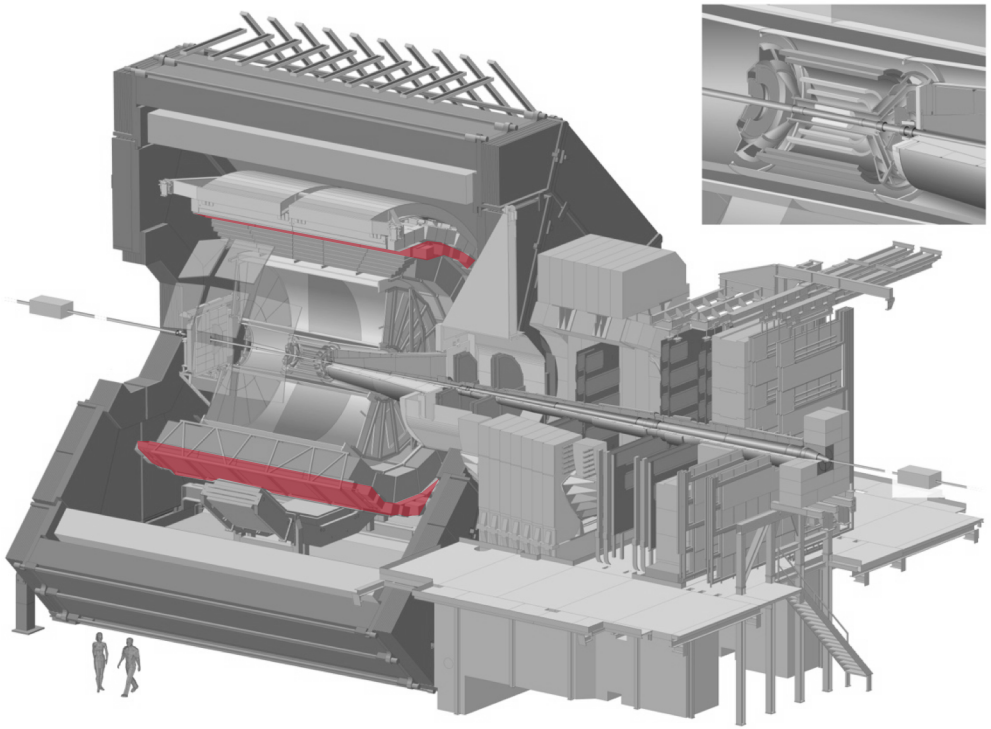

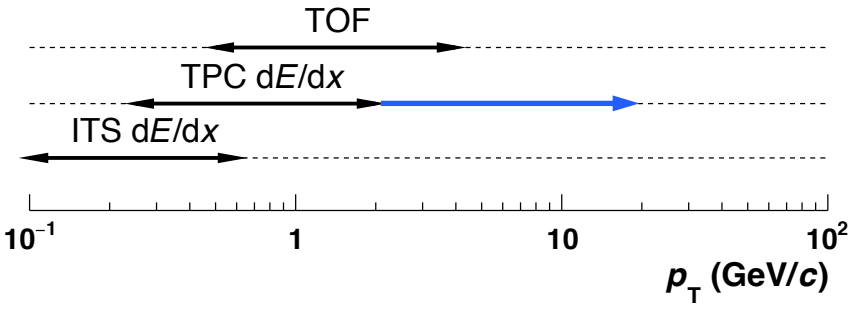

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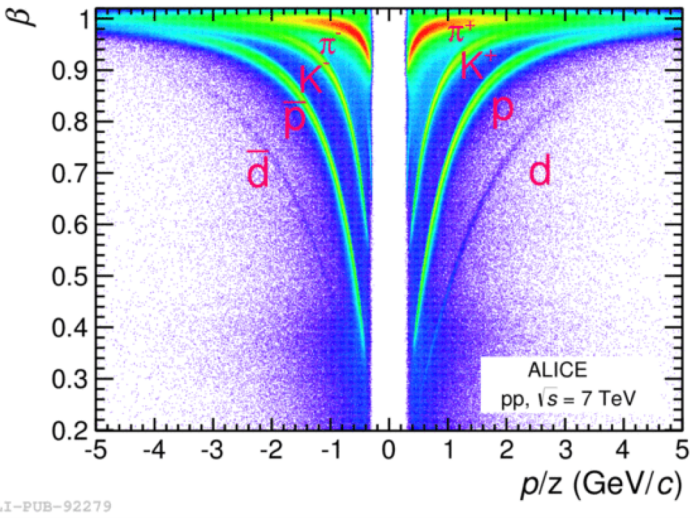
TOF (|η|<0.9)

- Multi-gap resistive plate chambers
- PID via velocity determination



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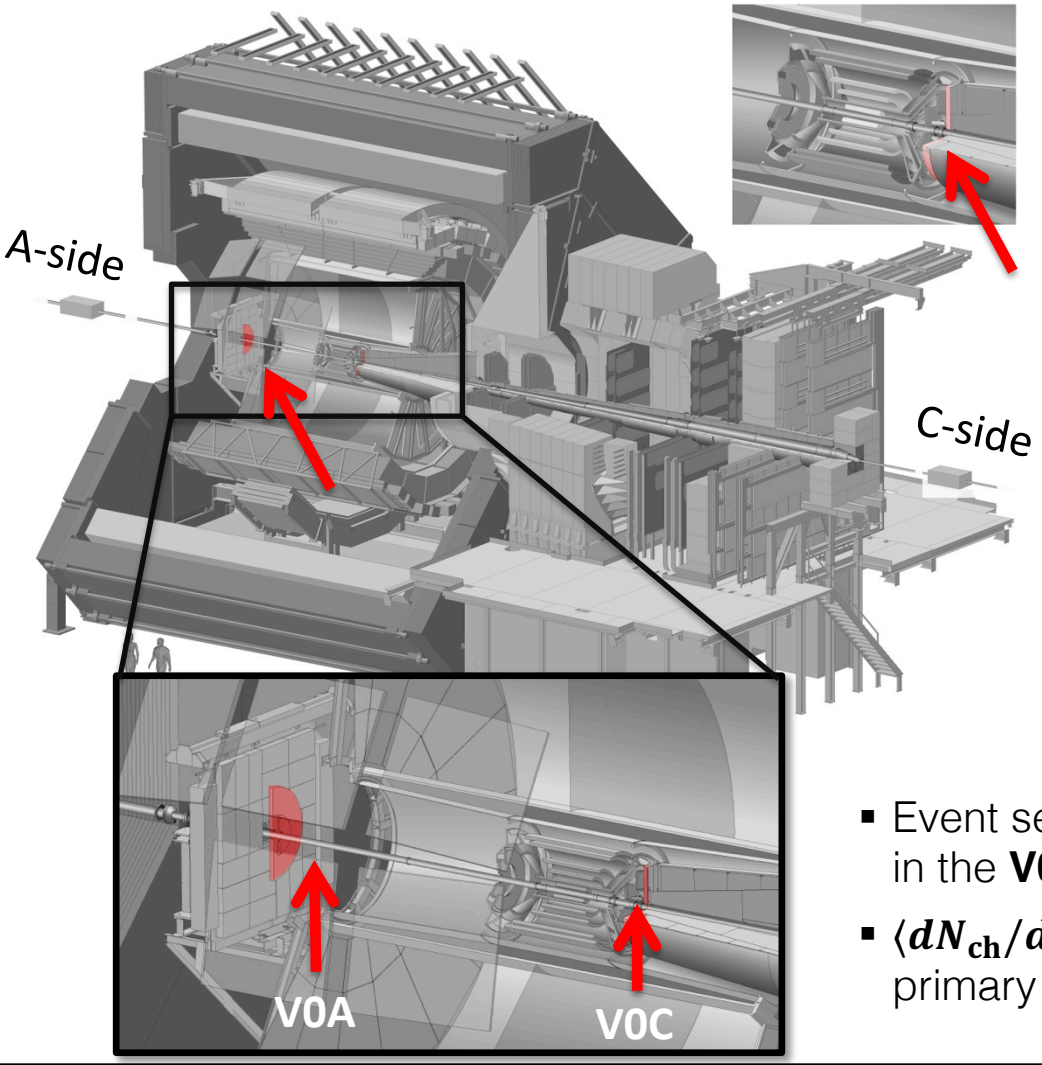

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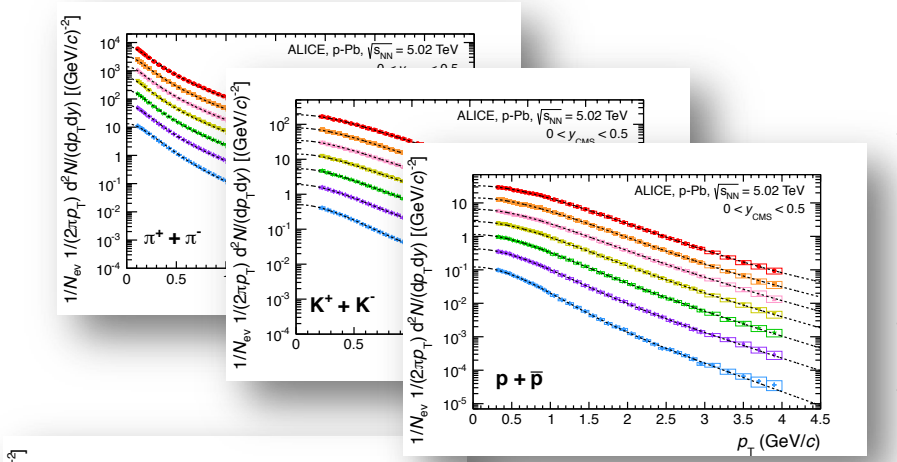
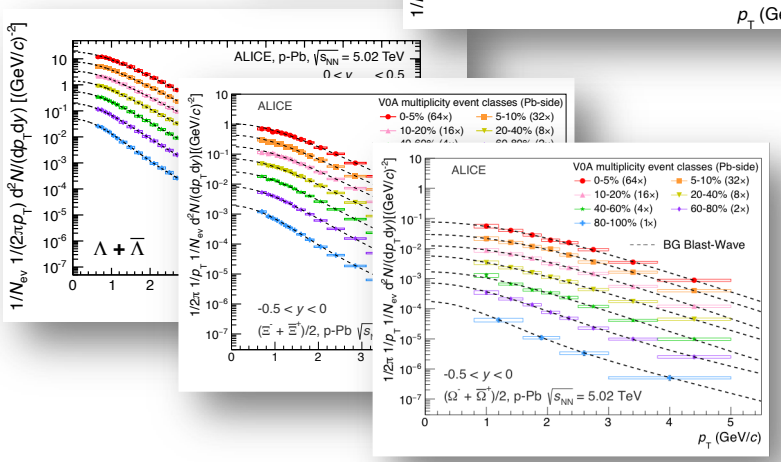
V0 [V0A ($2.8<\eta<5.1$) & V0C ($-3.7<\eta<-1.7$)]
- Forward arrays of scintillators
- Trigger, beam gas rejection
- <u>Multiplicity estimator:</u>

- Event selection based on total charge deposited in the **V0A** and **V0C** detectors ("V0M")
- $\langle dN_{\mathrm{ch}}/d\eta \rangle$ estimated as the average number of primary charged tracks in $|\eta| < 0.5$

Identified particle spectra in pp and p-Pb



Phys. Lett. B 728 (2014) 25-38



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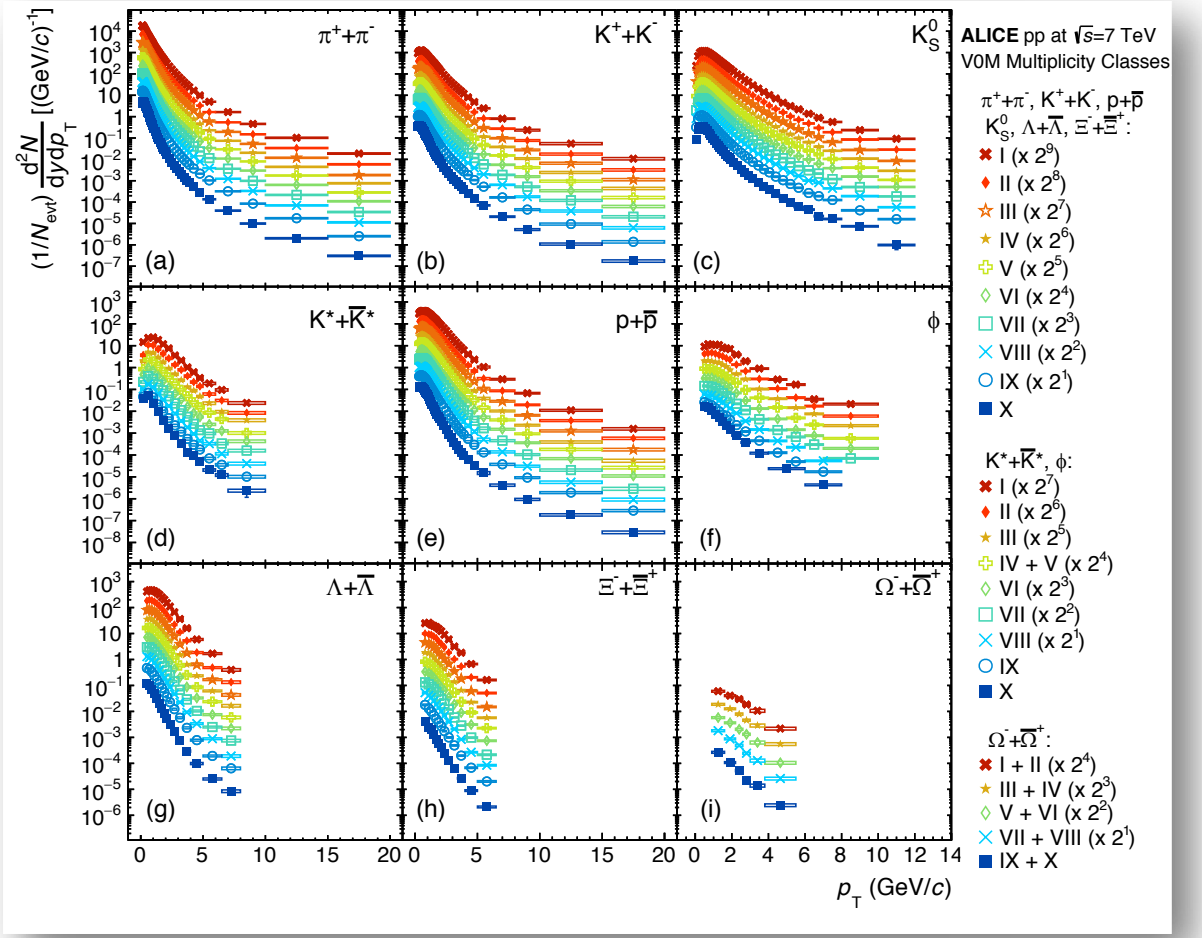
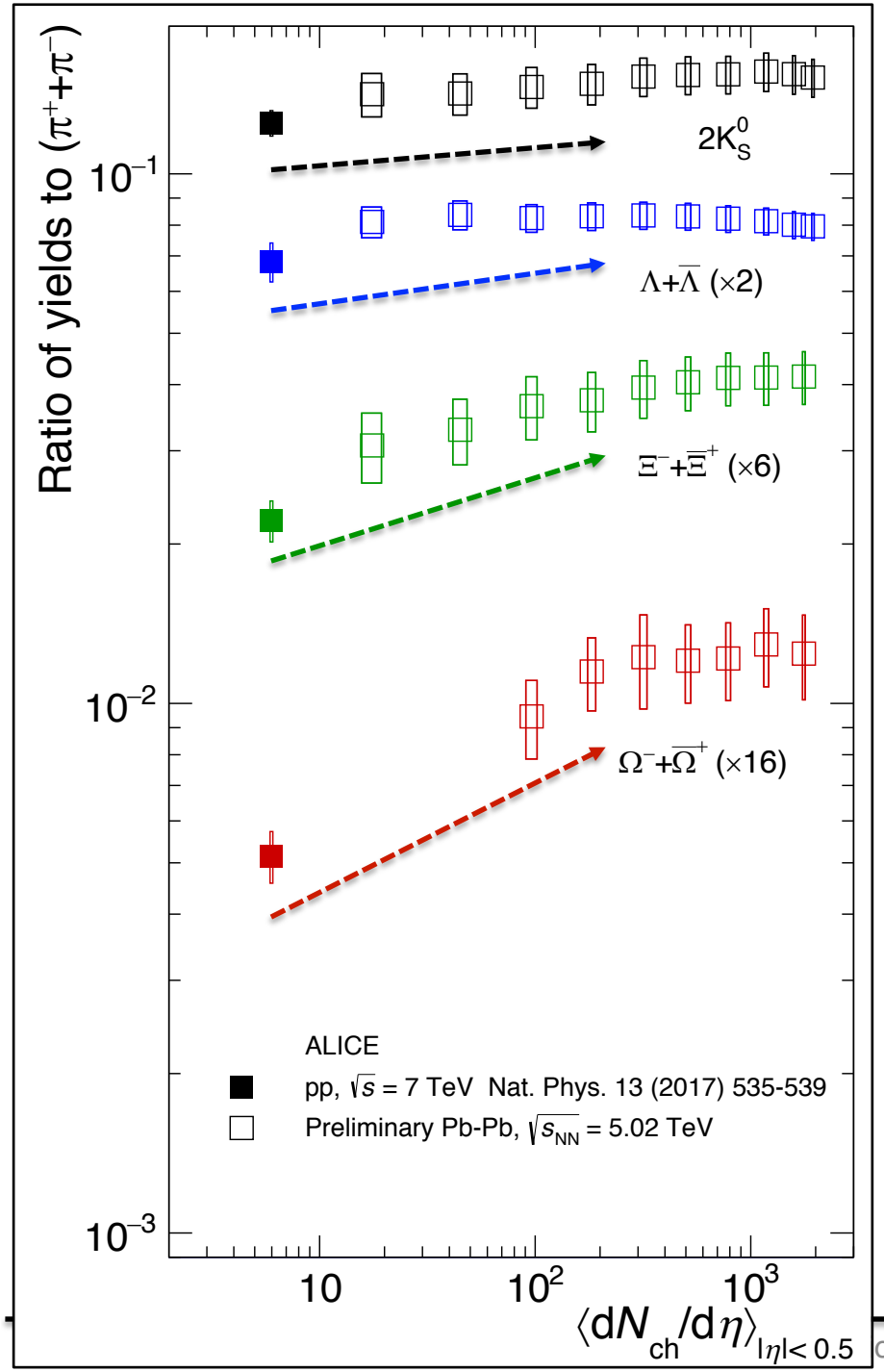


ALICE, Phys. Rev. C 99, 024906

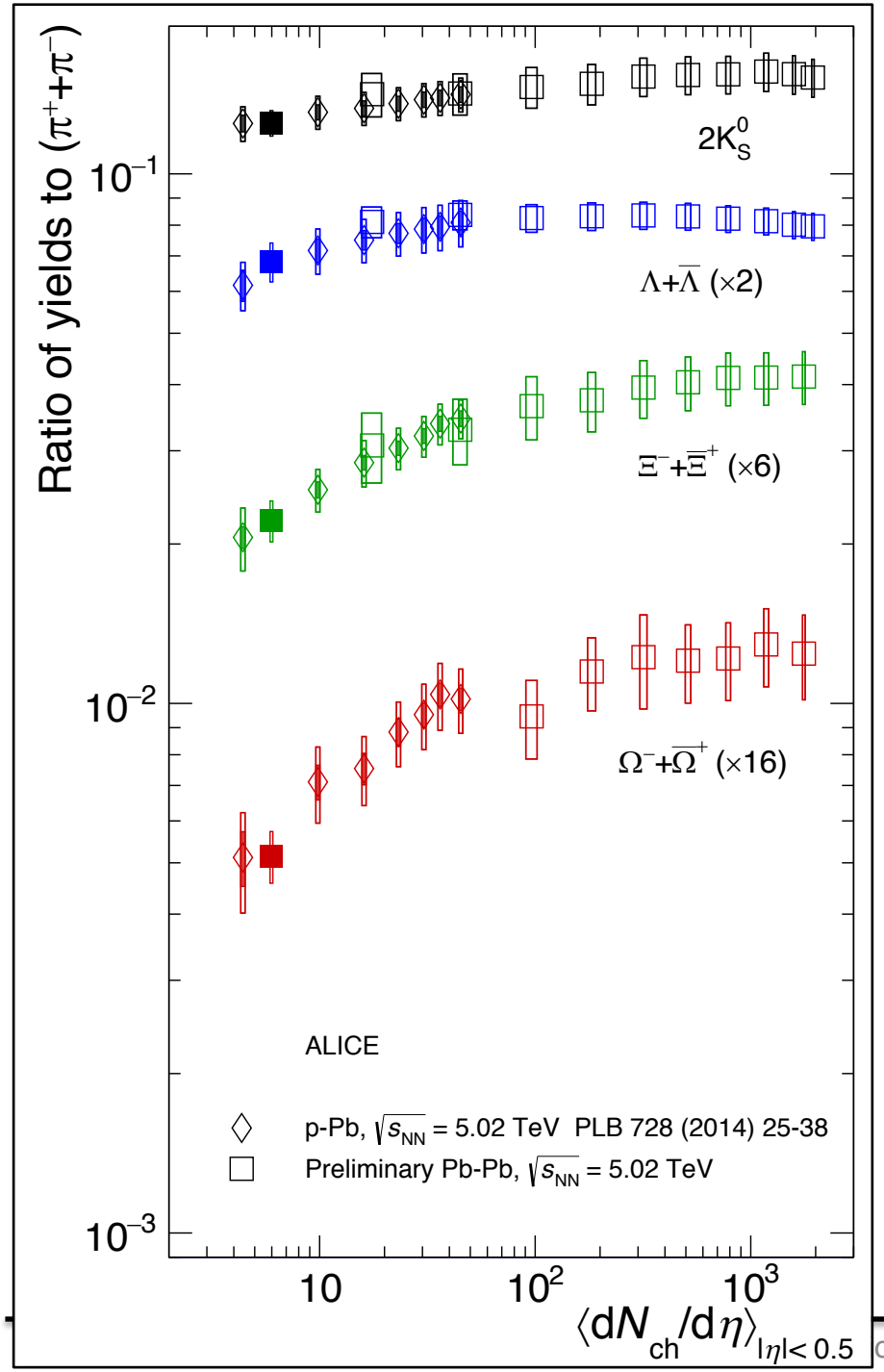
In proton-lead…

…and proton-proton: a very comprehensive set of measurements



Strangeness production

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



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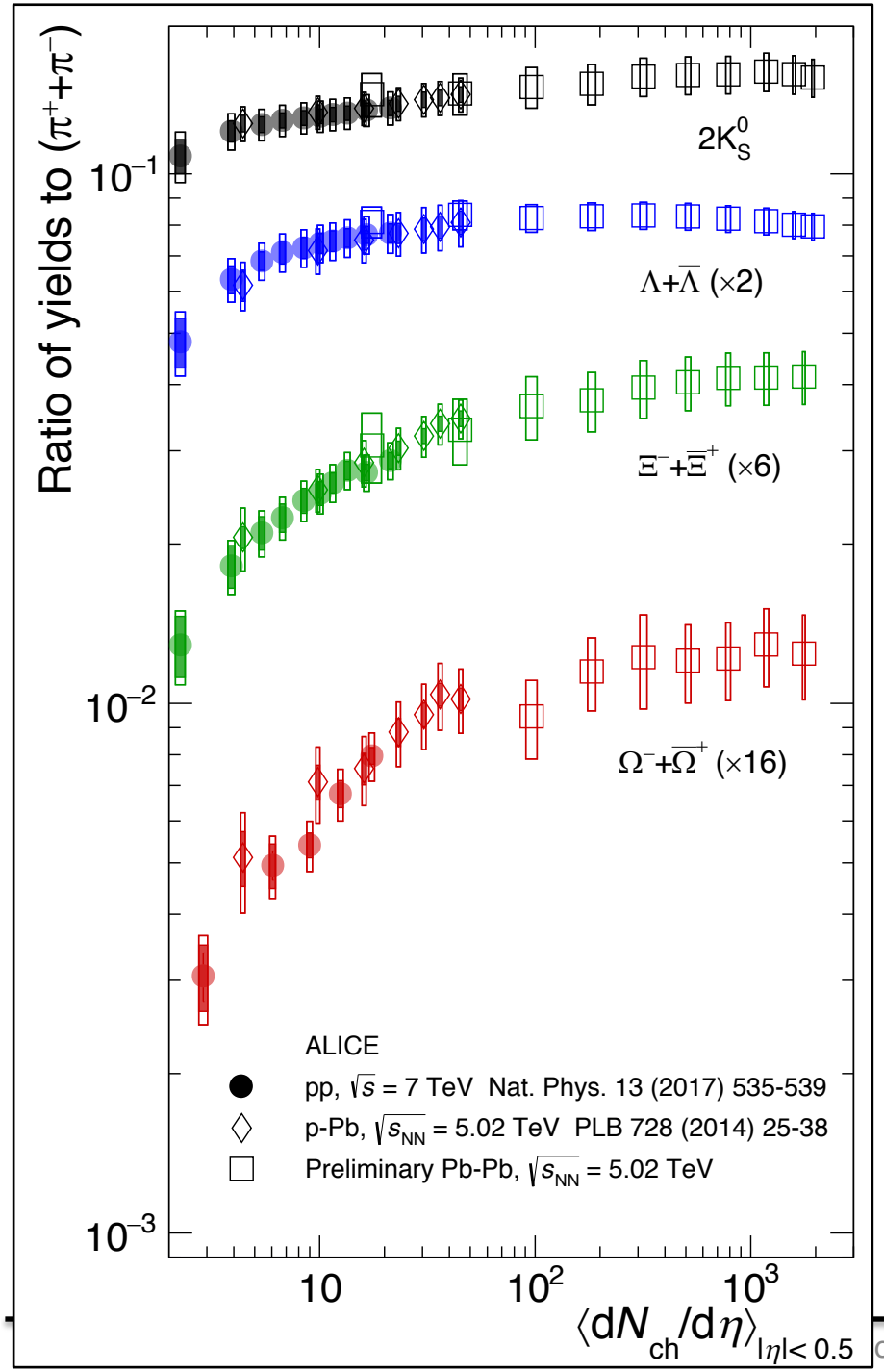
  - Strangeness increases with multiplicity following a universal trend



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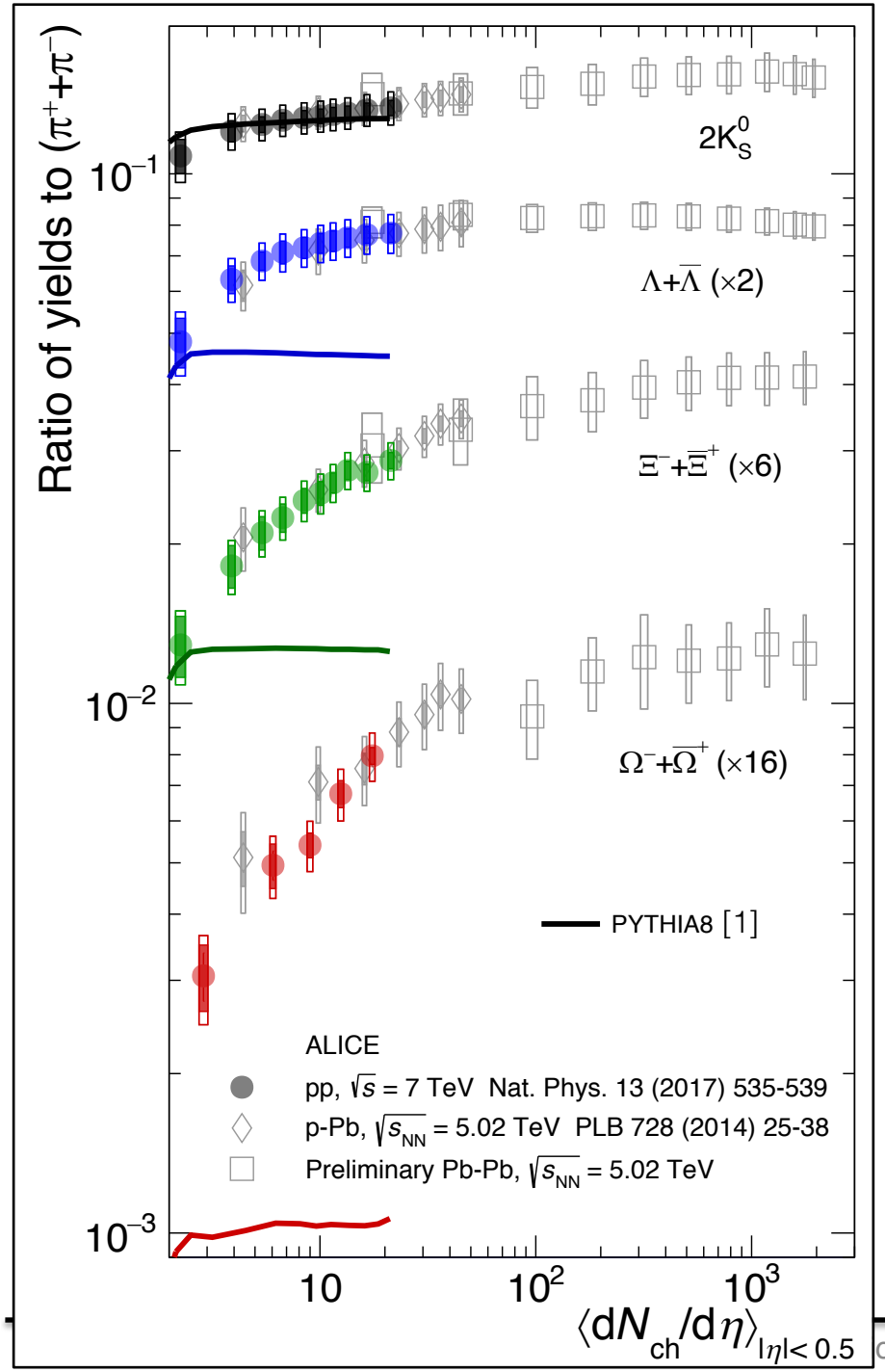

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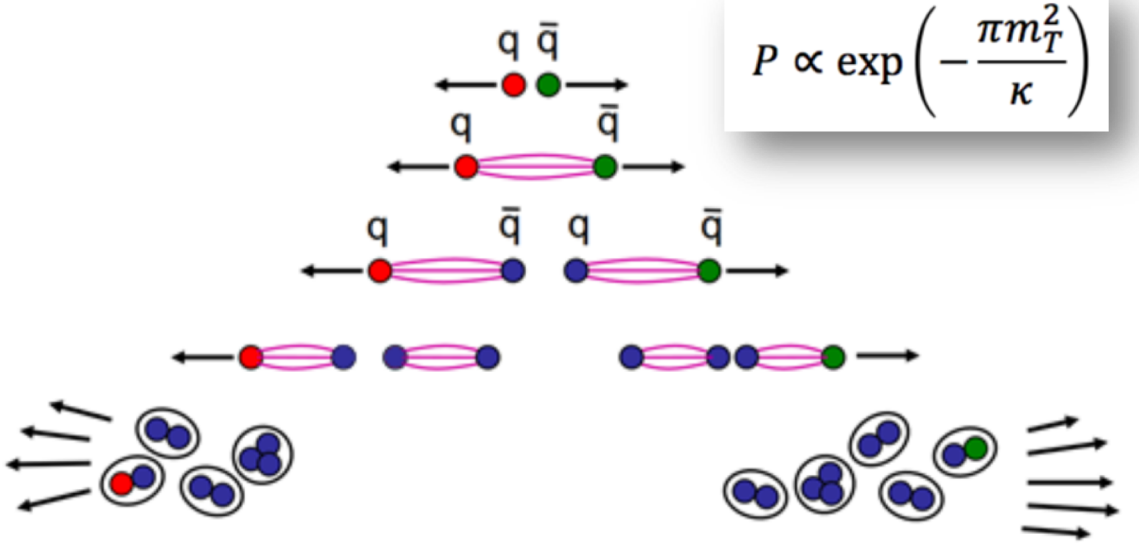
  - Production wrt to π enhanced
- Also studied in p-Pb and pp
  - Strangeness increases with multiplicity following a universal trend
- Not described by PYTHIA
  - How can this be achieved?

[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

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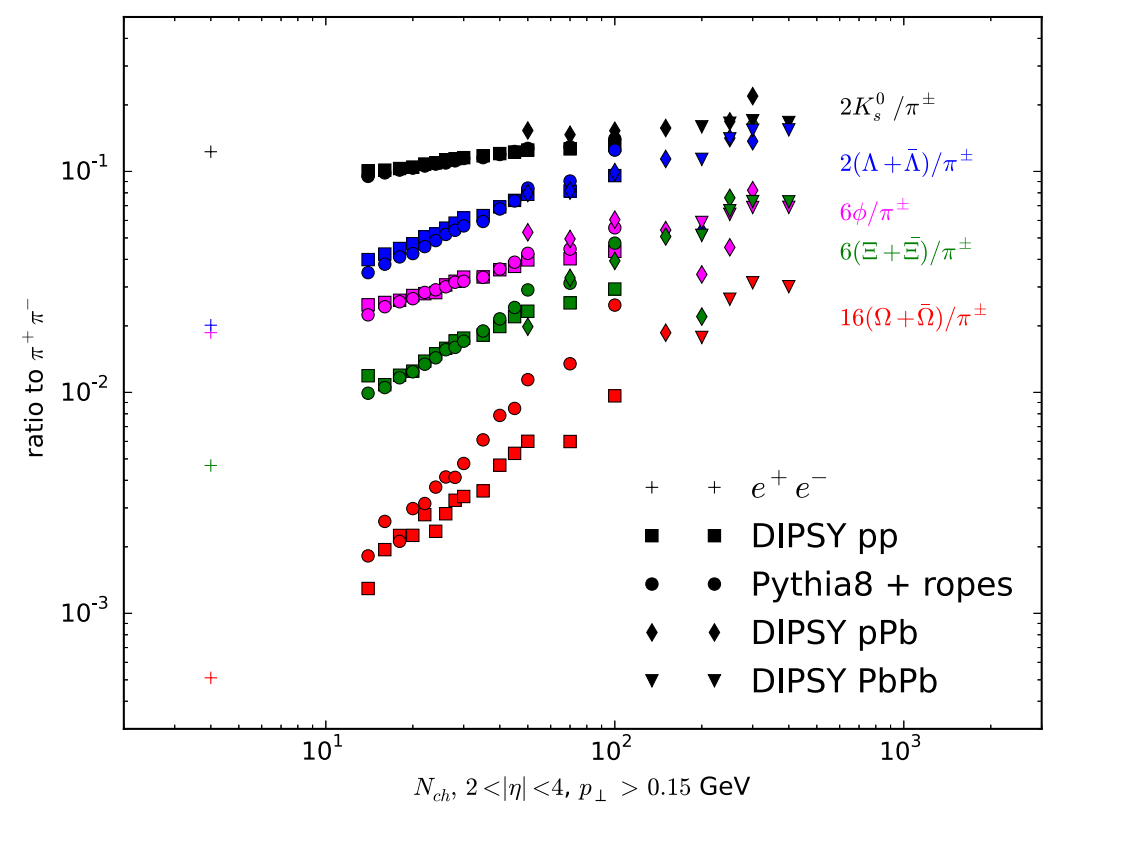
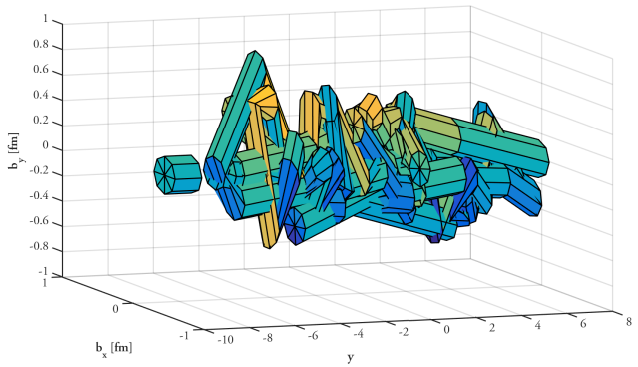


C. Bierlich,
https://indico.cern.ch/event/732345/contributions/3024828/attachments/1668639/2676025/cbierlich.pdf

- 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!



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

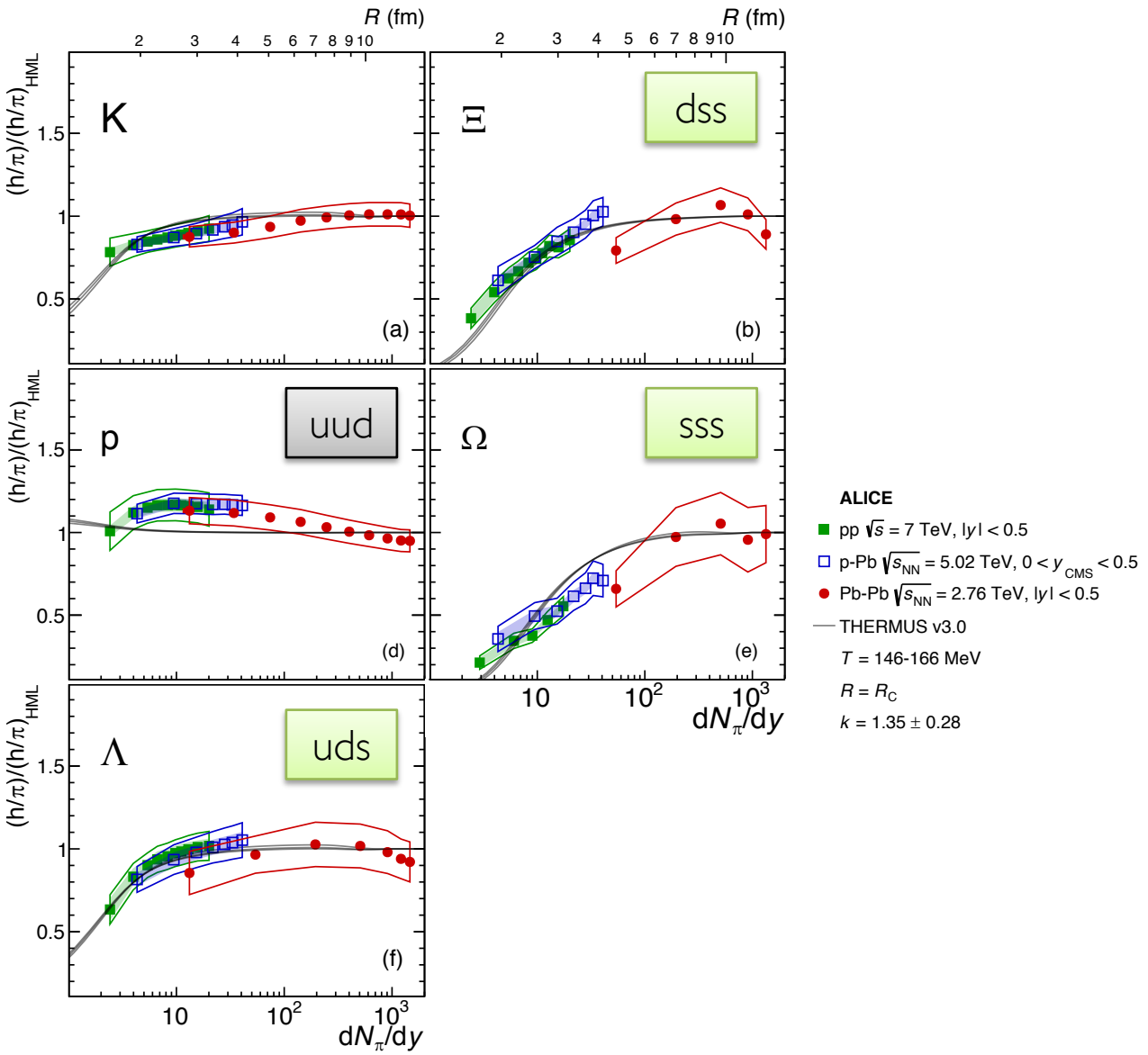
$$\tilde{P} \propto \exp\left(-\frac{\pi m_T^2}{\tilde{\kappa}}\right)$$

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

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

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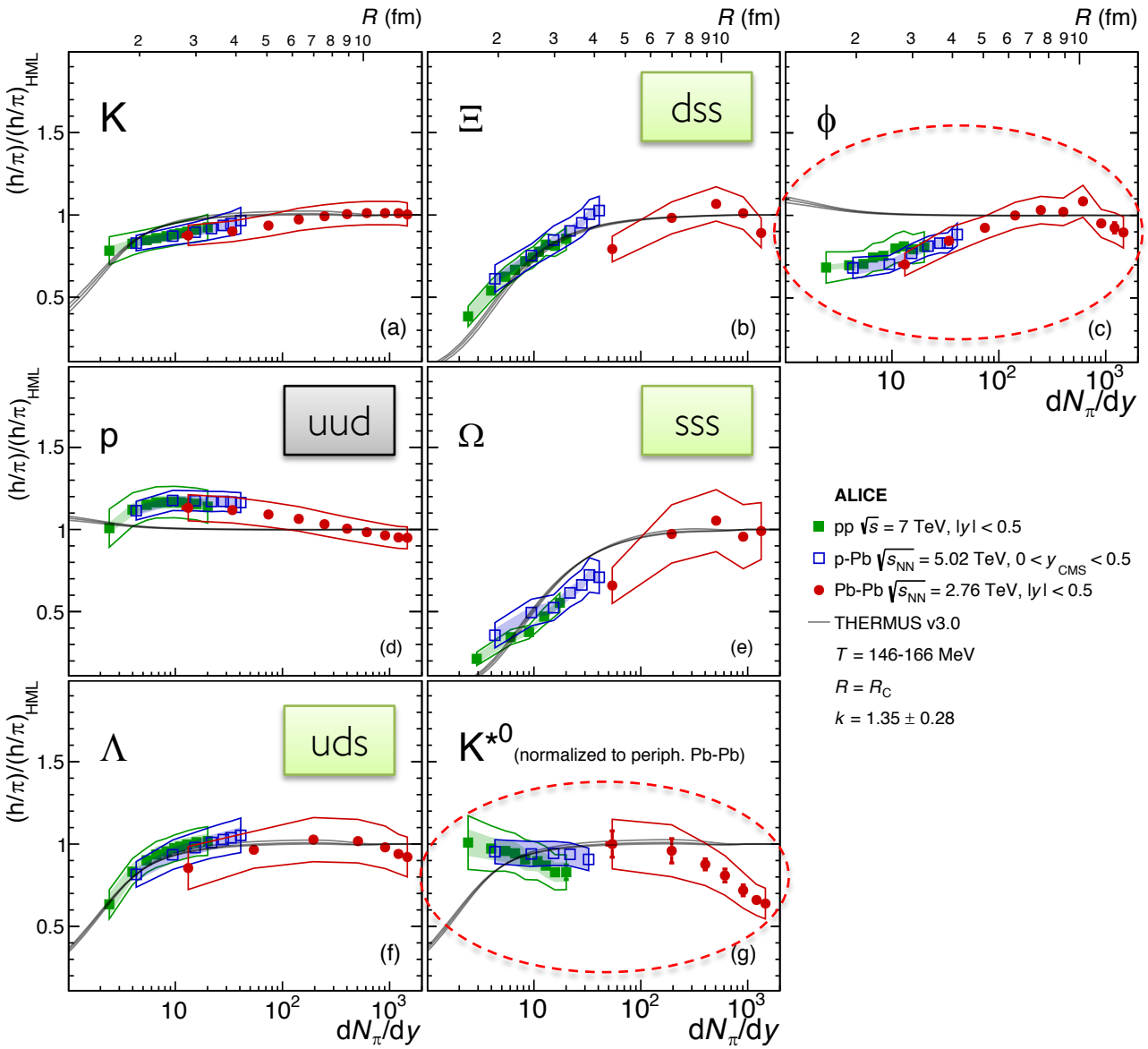
- Effect depends on system size; SHM description holds over certain rapidity range k
  - From data, $k = 1.35 \pm 0.28$
- Description OK for strangeness
  - But fails for ϕ: net strangeness zero…
  - And fails for K^{*0}: affected by post-hadronization effects (rescattering)



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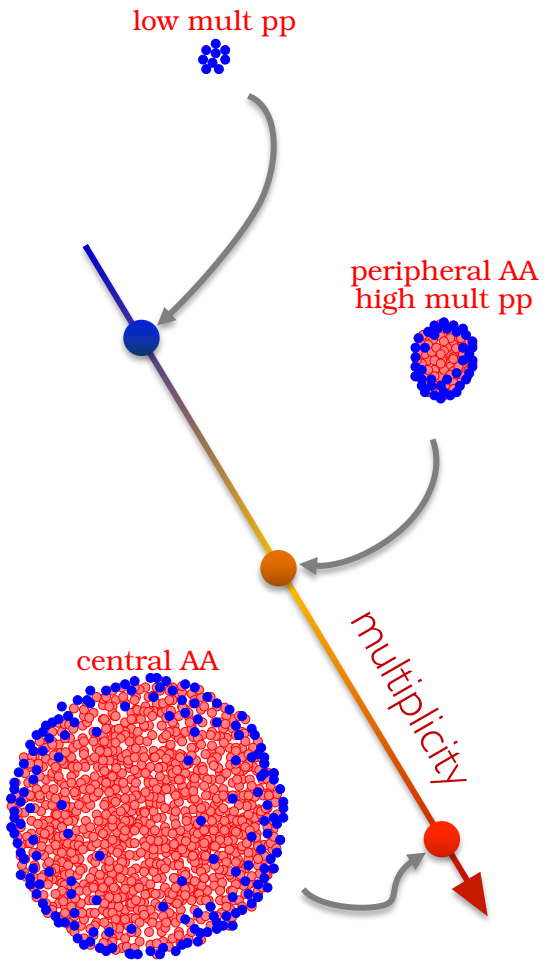
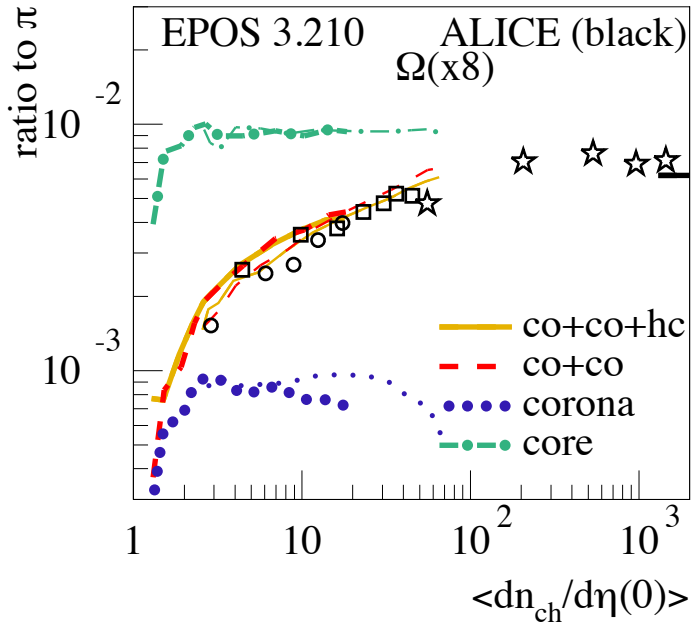
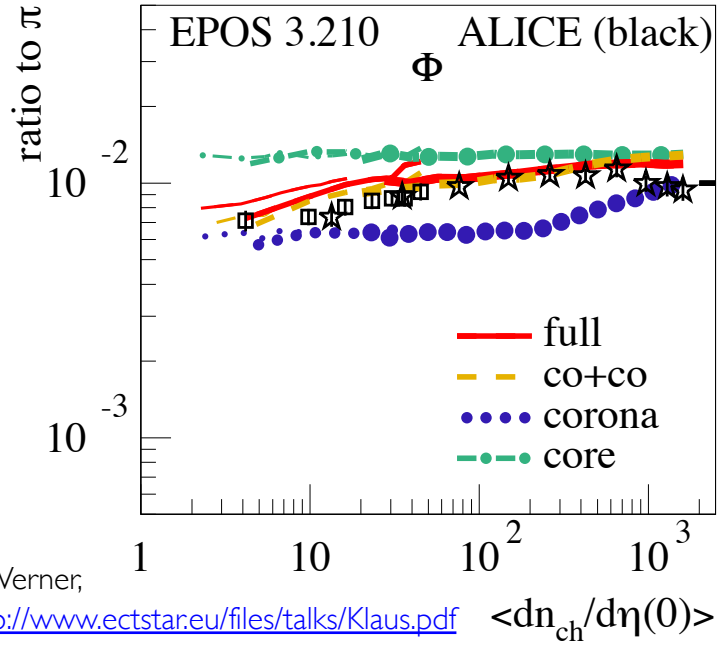
Strangeness in EPOS 3:
The core-corona approach



- Hard scattering: parton "ladders"
- 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



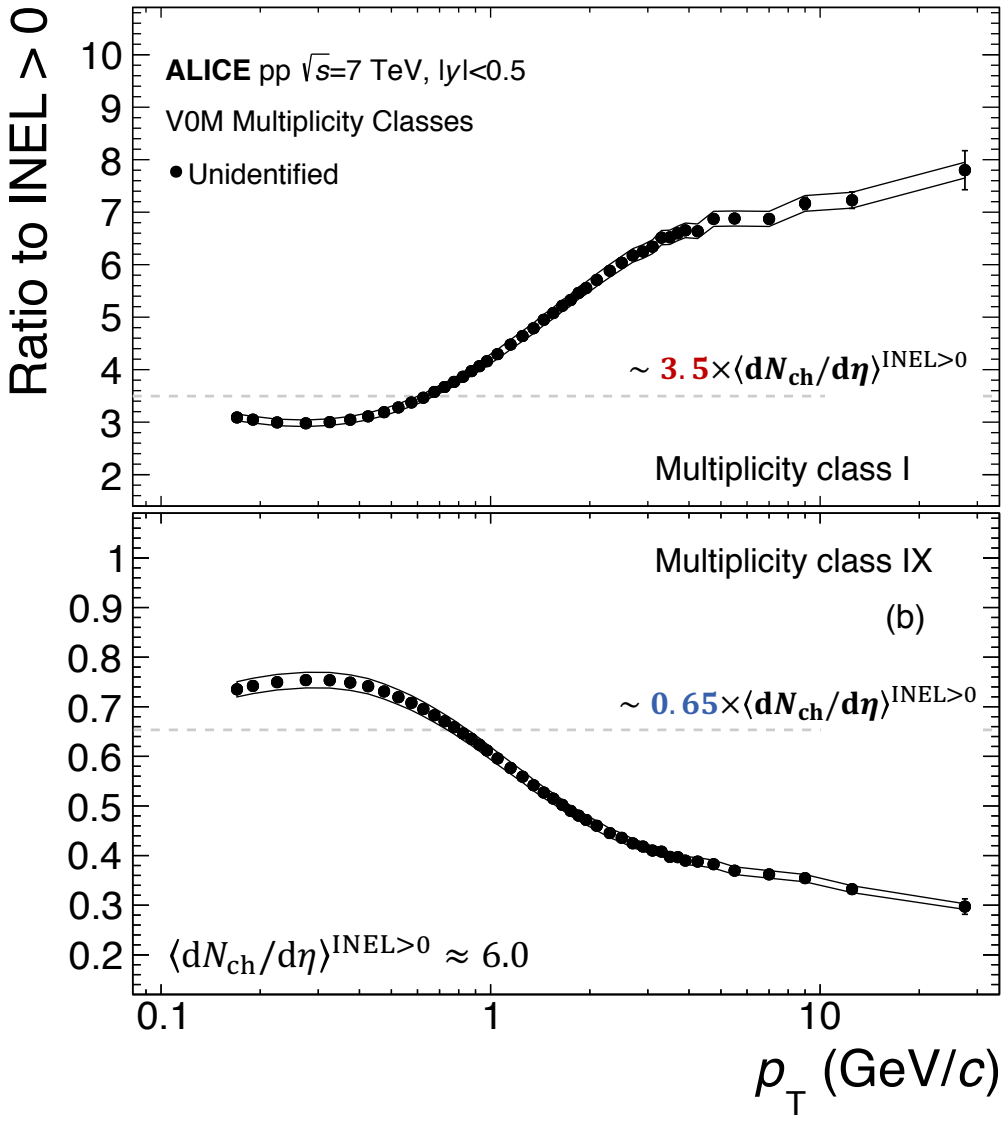


K. Werner, http://www.ectstar.eu/files/talks/Klaus.pdf

Modification of identified spectra

- Spectra become harder at higher multiplicities

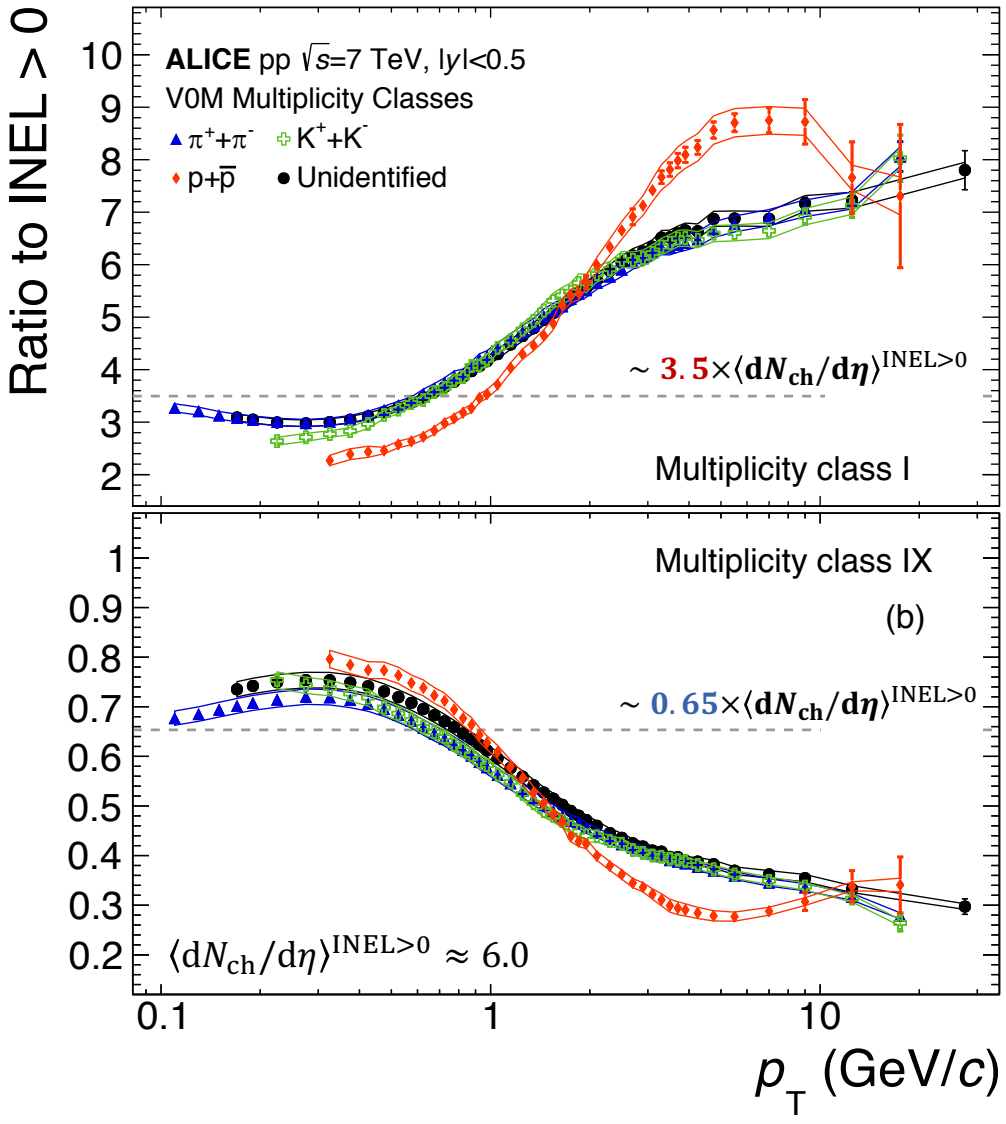
ALICE, Phys. Rev. C 99, 024906



Modification of identified spectra

- Spectra become harder at higher multiplicities
- The hardening is more pronounced for baryons than for mesons

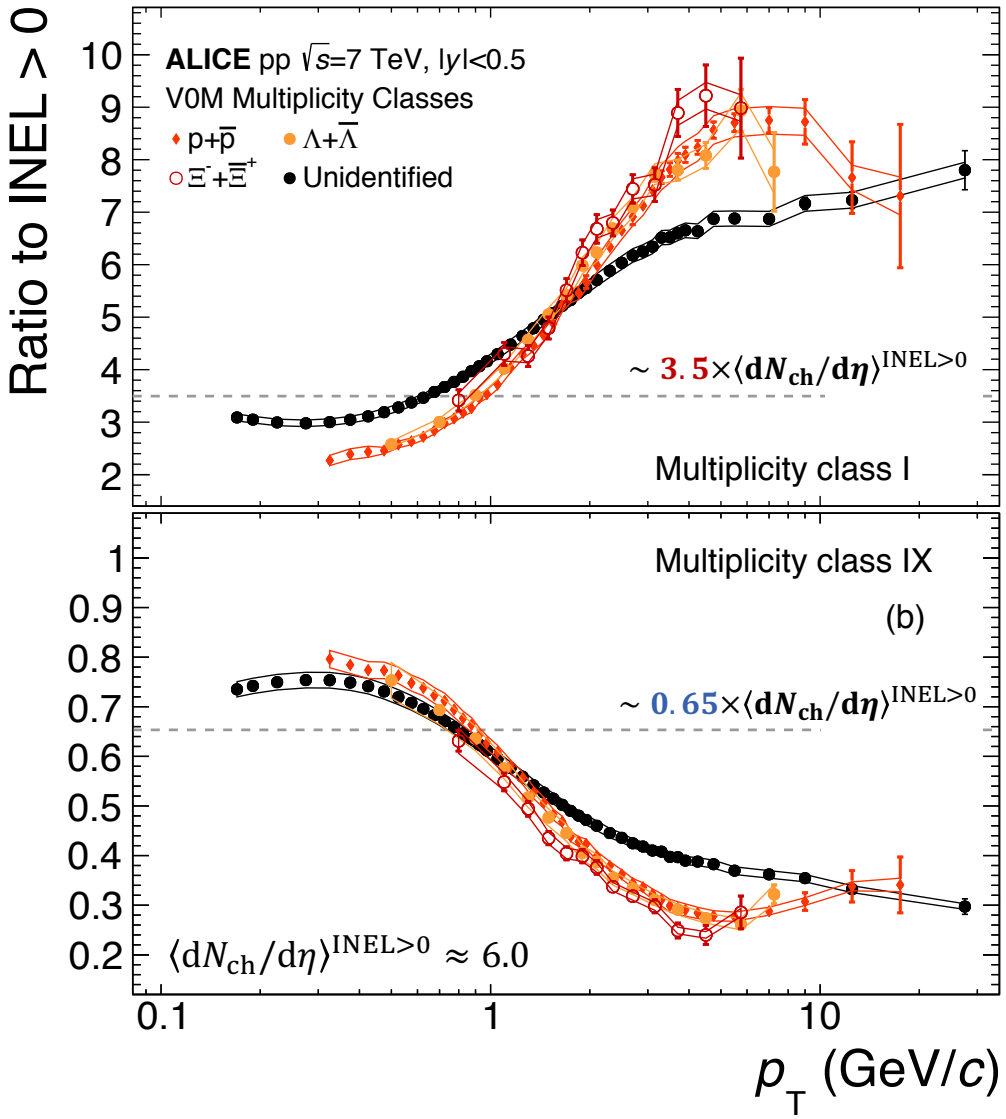
ALICE, Phys. Rev. C 99, 024906

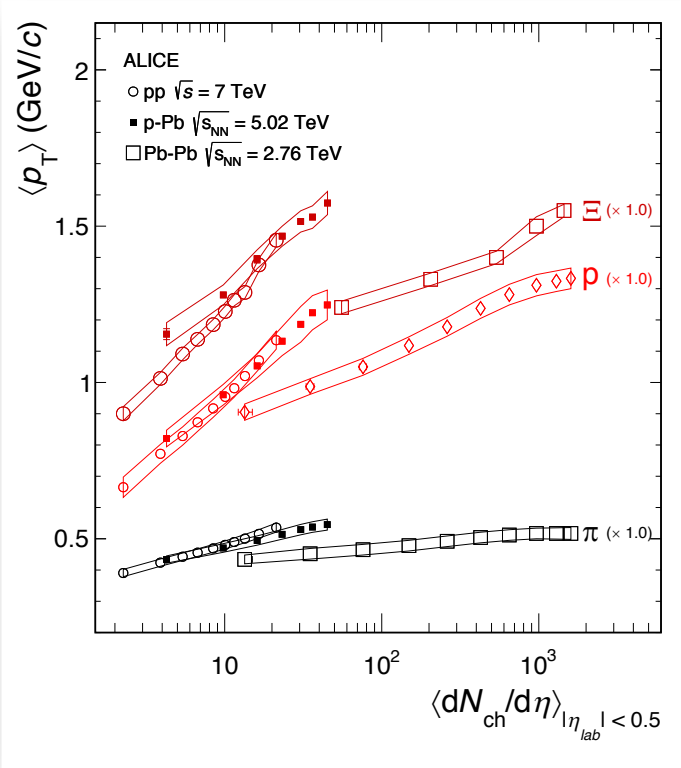


Modification of identified spectra

- Spectra become harder at higher multiplicities
- The hardening is more pronounced for baryons than for mesons
- (Multi-)strange baryons follow protons
  - Could the strangeness yield increase be a matter of $\langle p_T \rangle$?

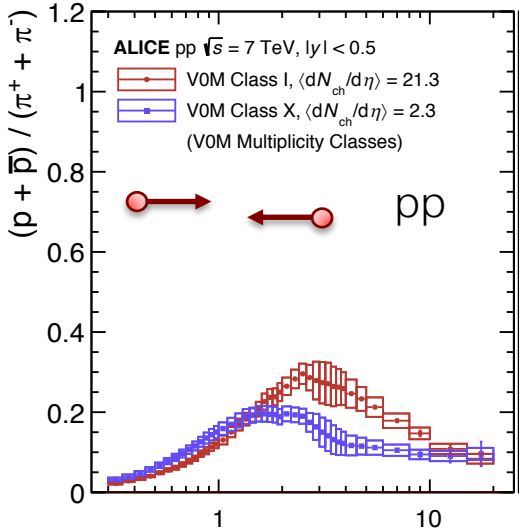
ALICE, Phys. Rev. C 99, 024906





Proton to pion ratios

ALICE, Phys. Rev. C 99, 024906



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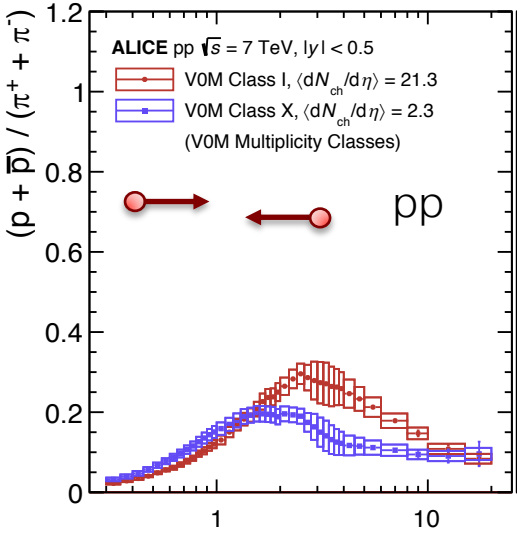

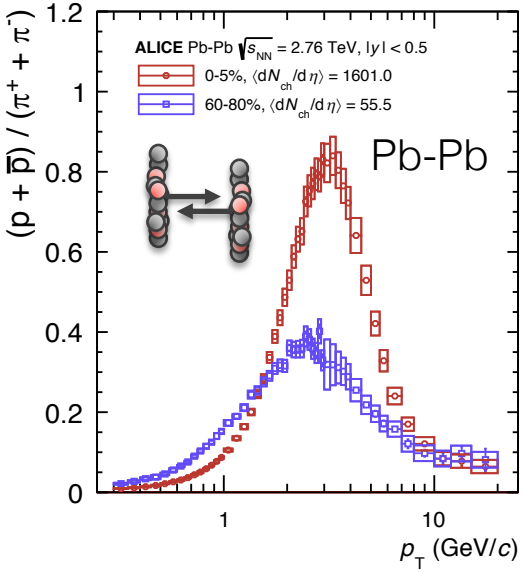

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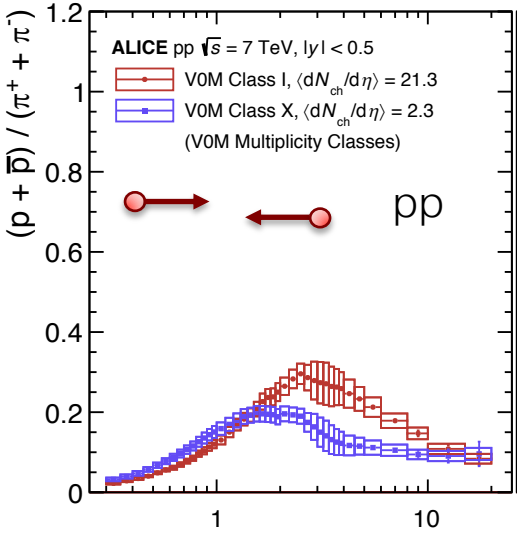

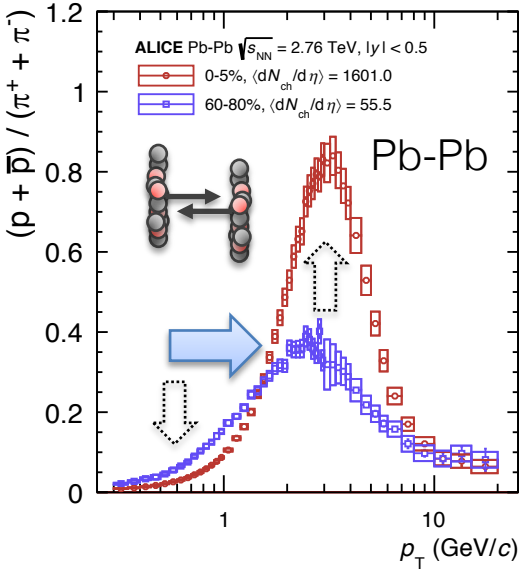

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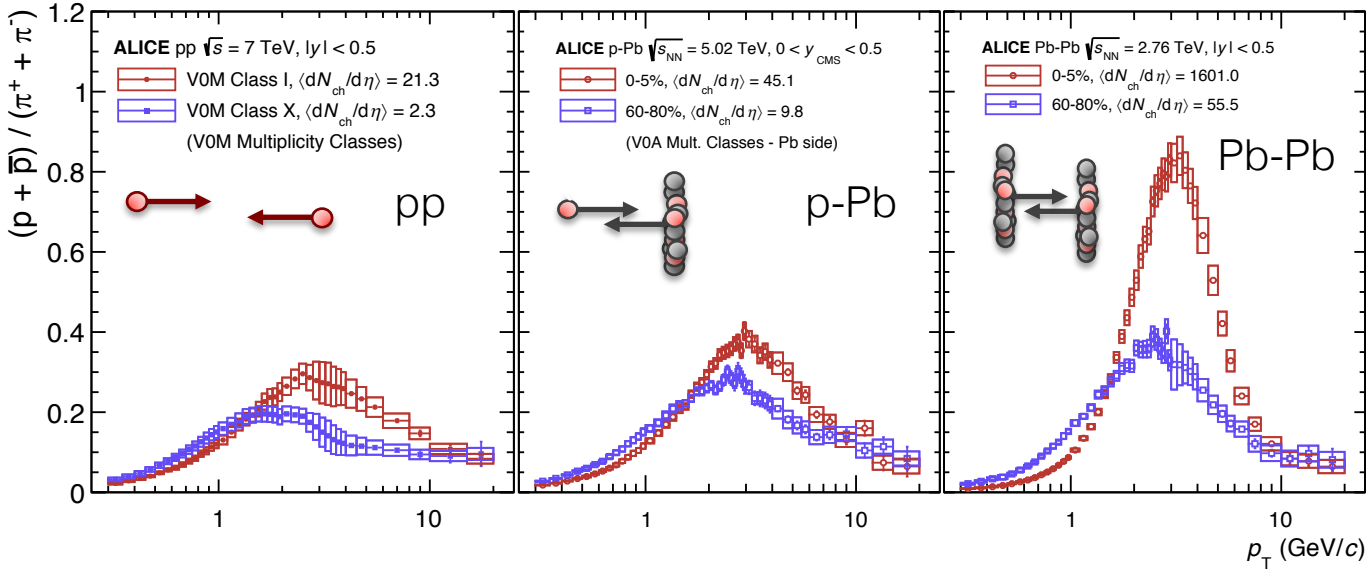

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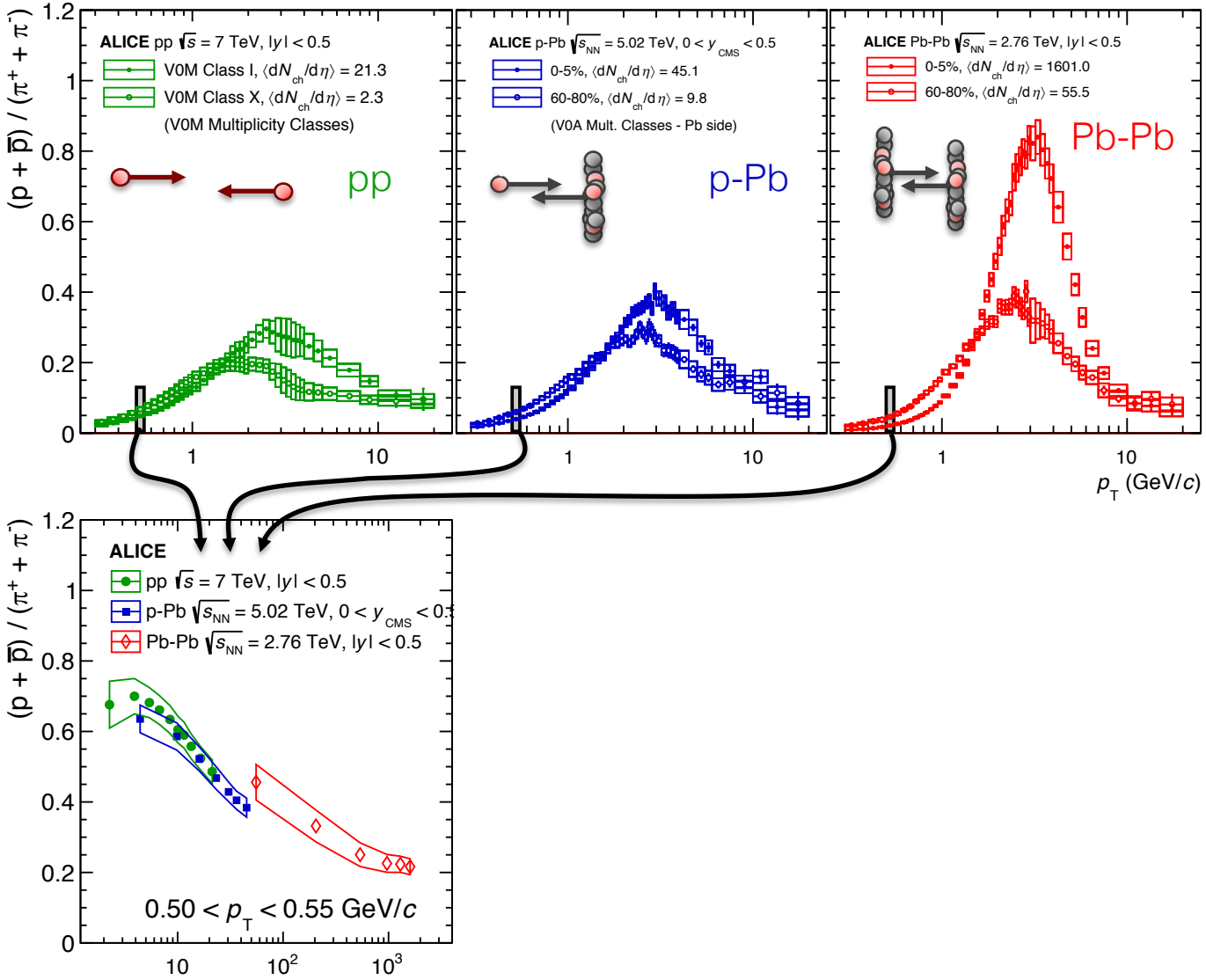

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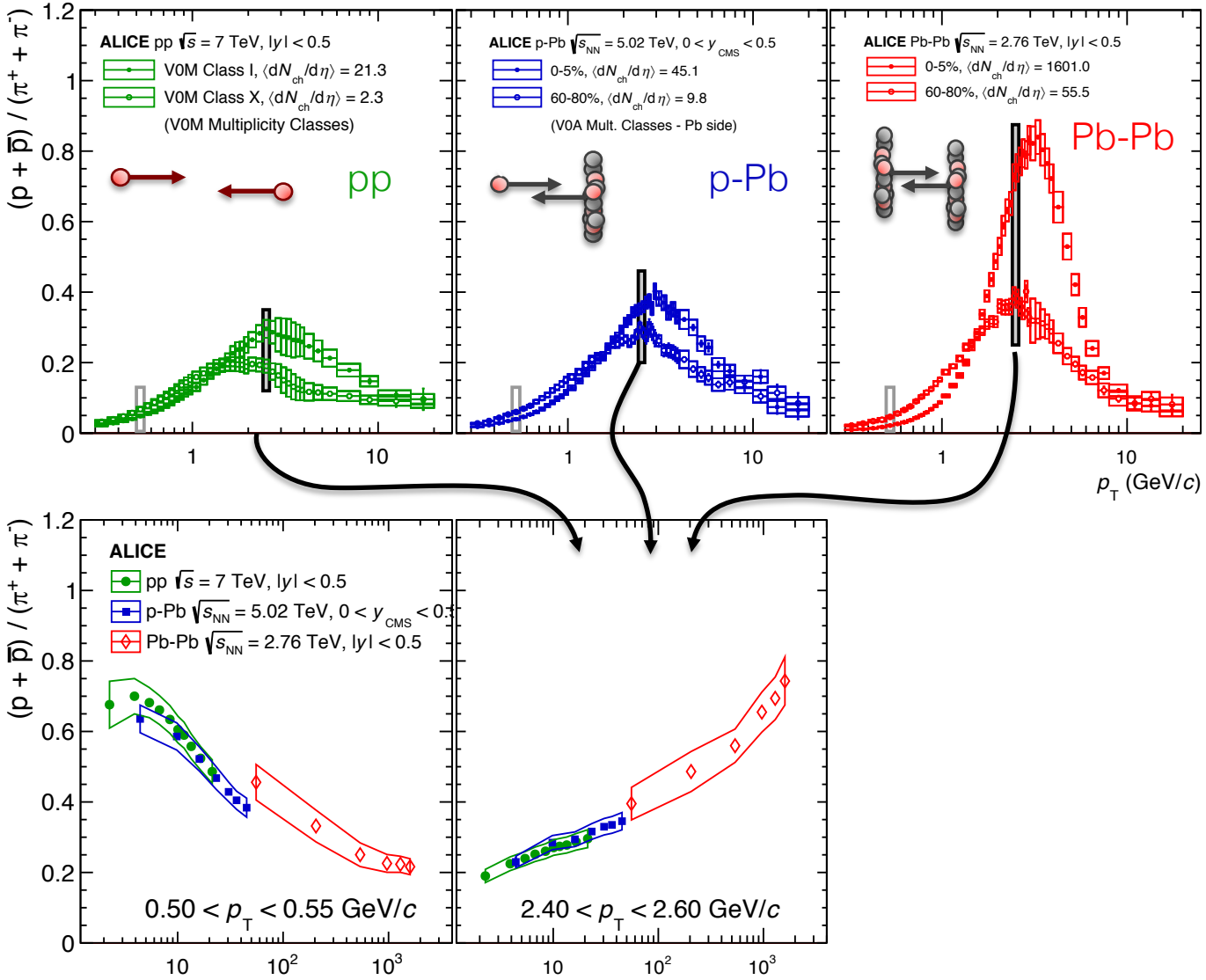

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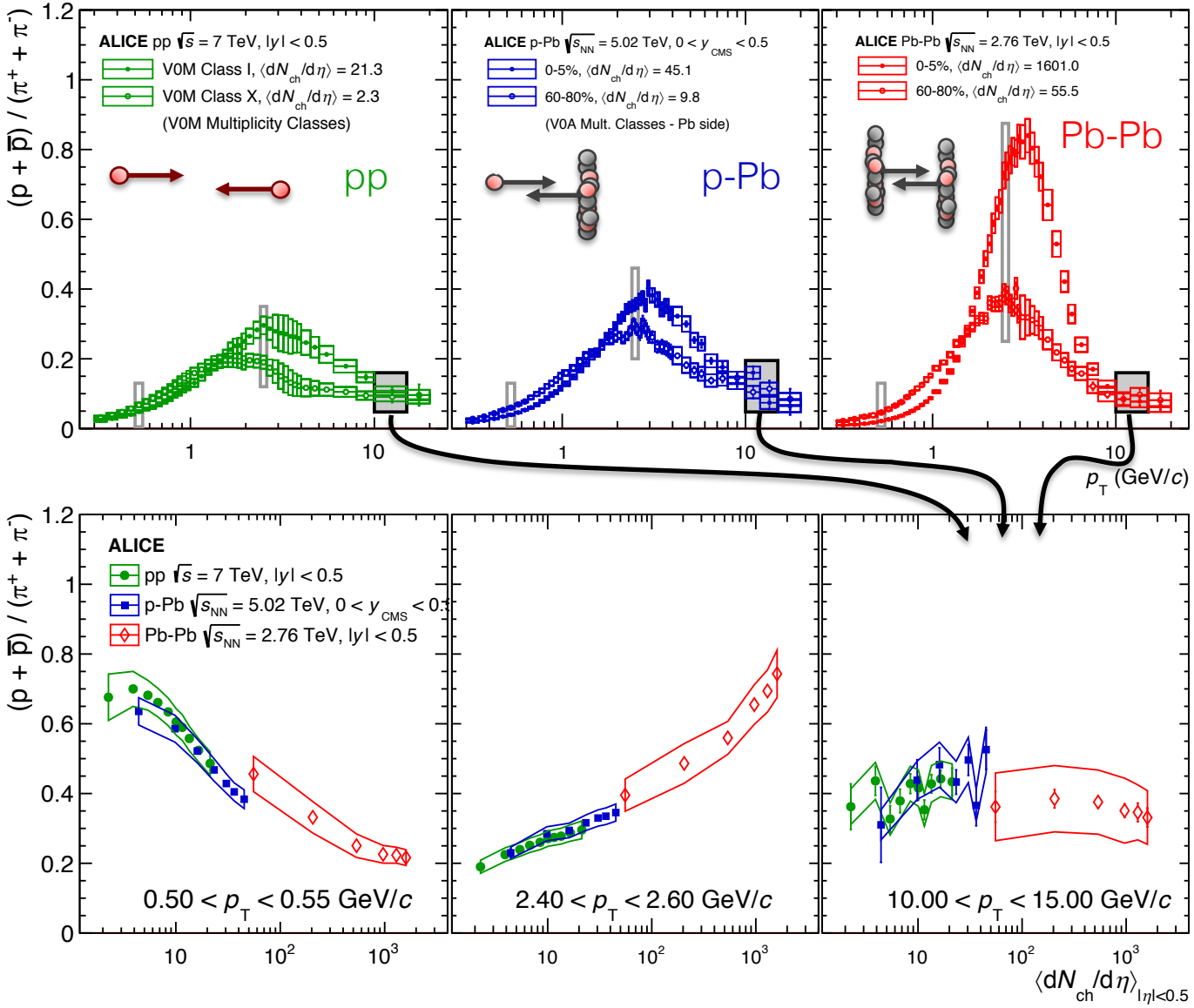

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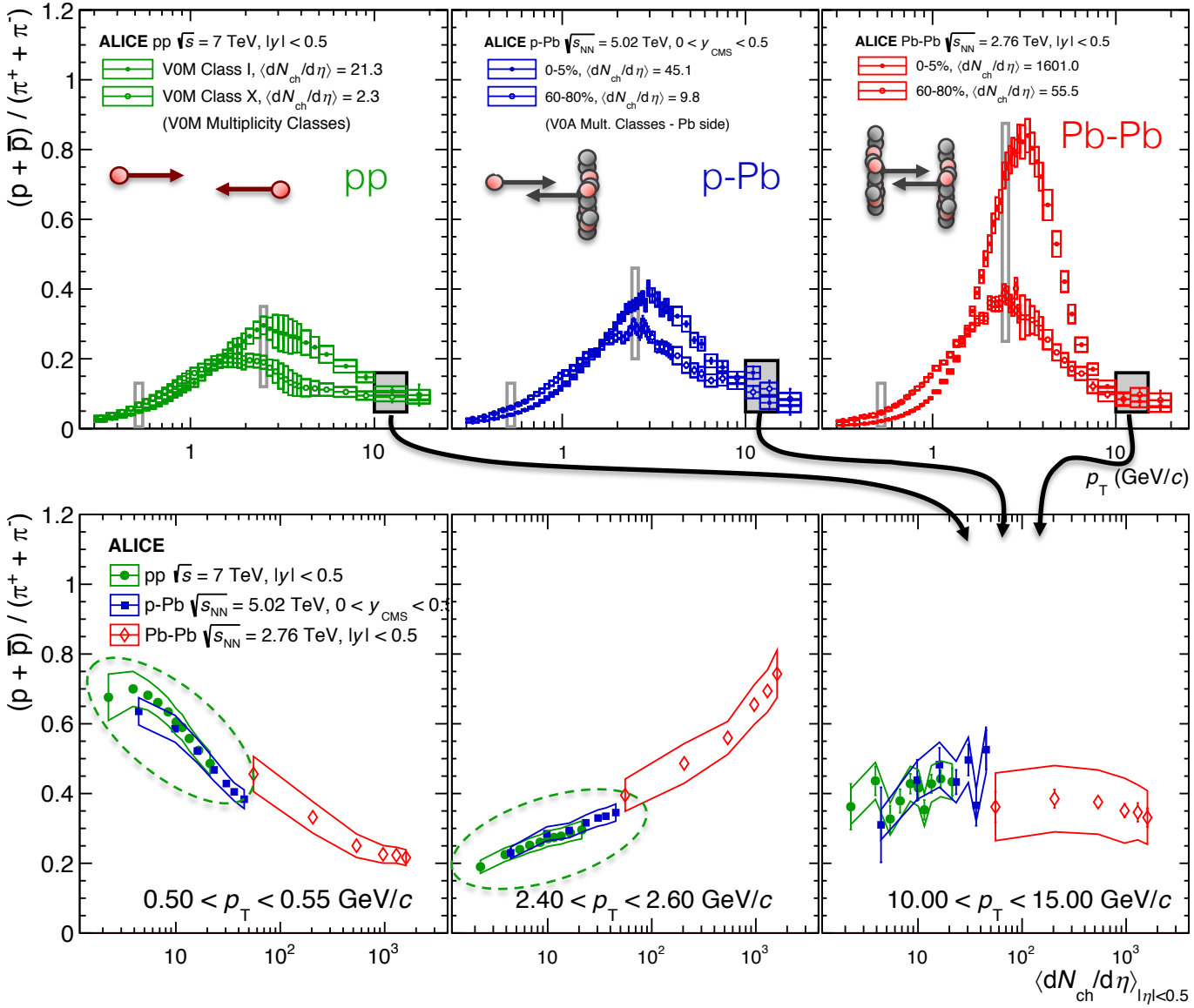
- high p_T: recovery of universal behavior?

Proton to pion ratios

ALICE, Phys. Rev. C 99, 024906



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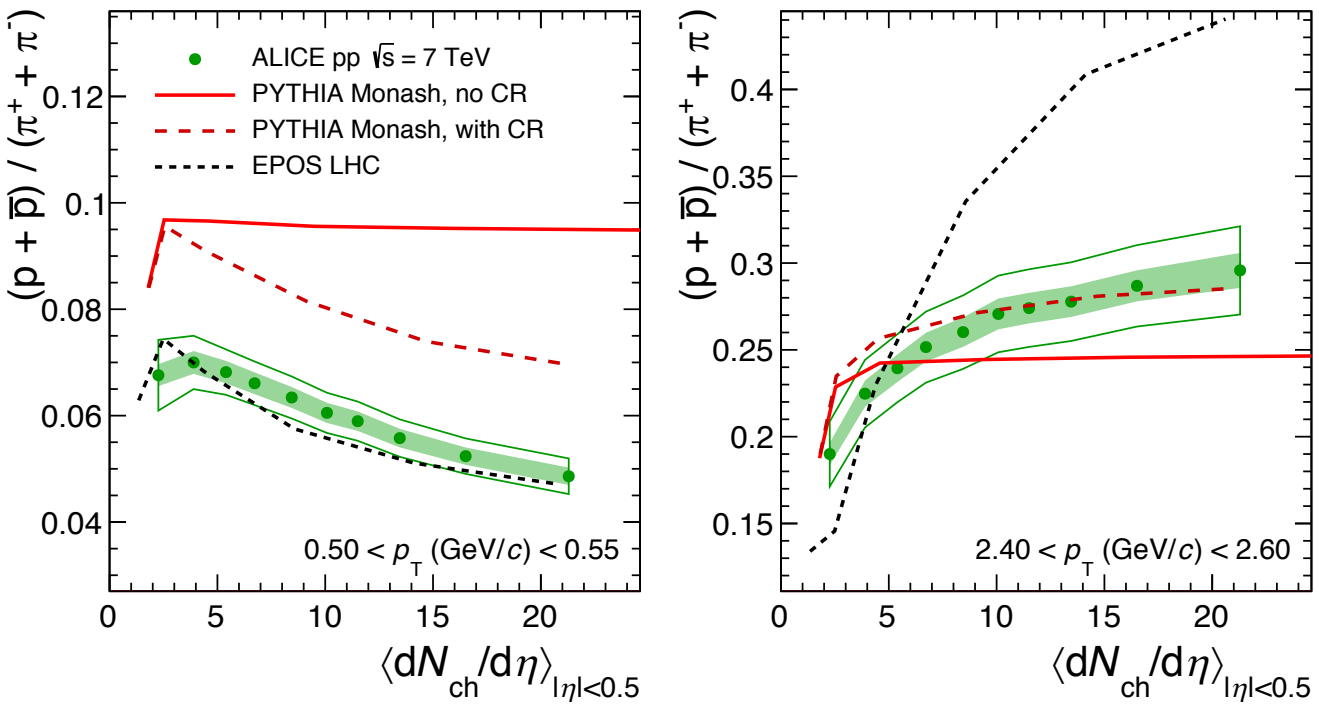
Proton to pion ratios vs MC predictions

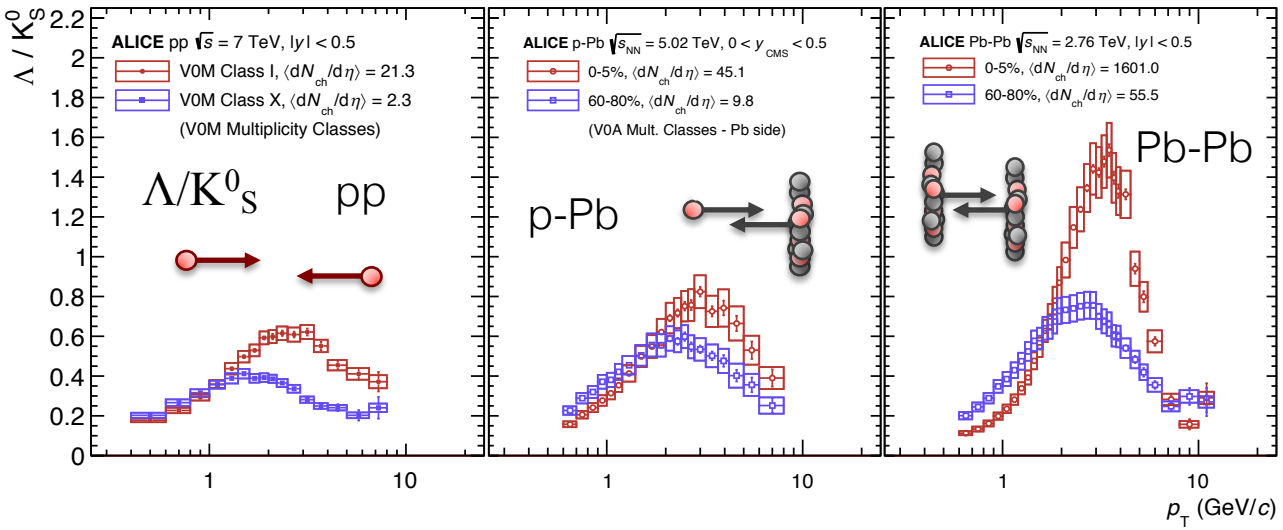
ALICE, Phys. Rev. C 99, 024906



- 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

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

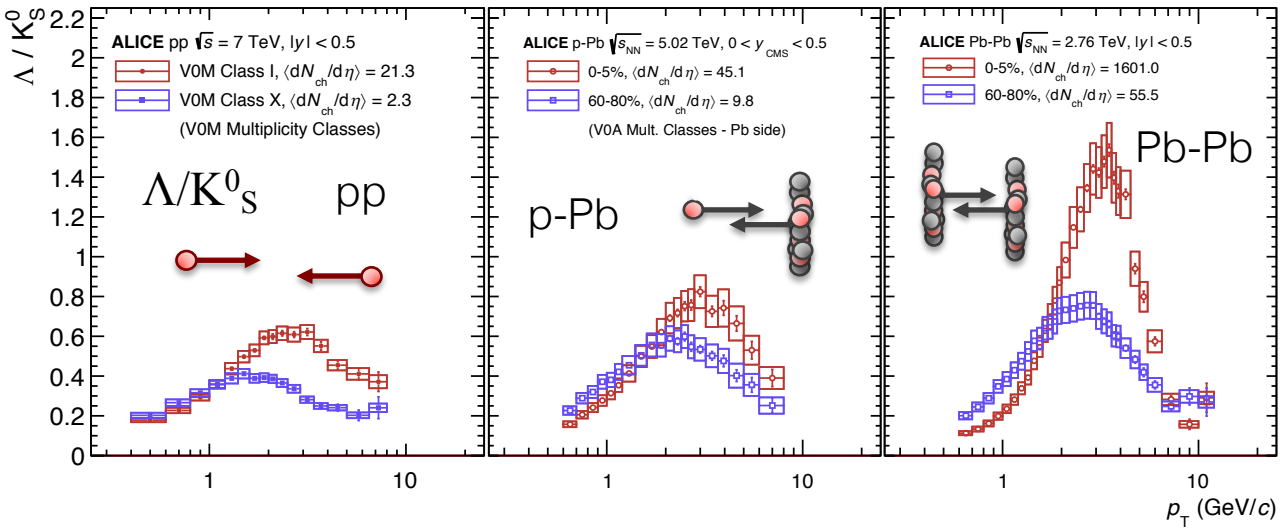
Baryon to meson ratios: strangeness



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

Baryon to meson ratios: strangeness + charm

ALICE, Phys. Rev. C 99, 024906



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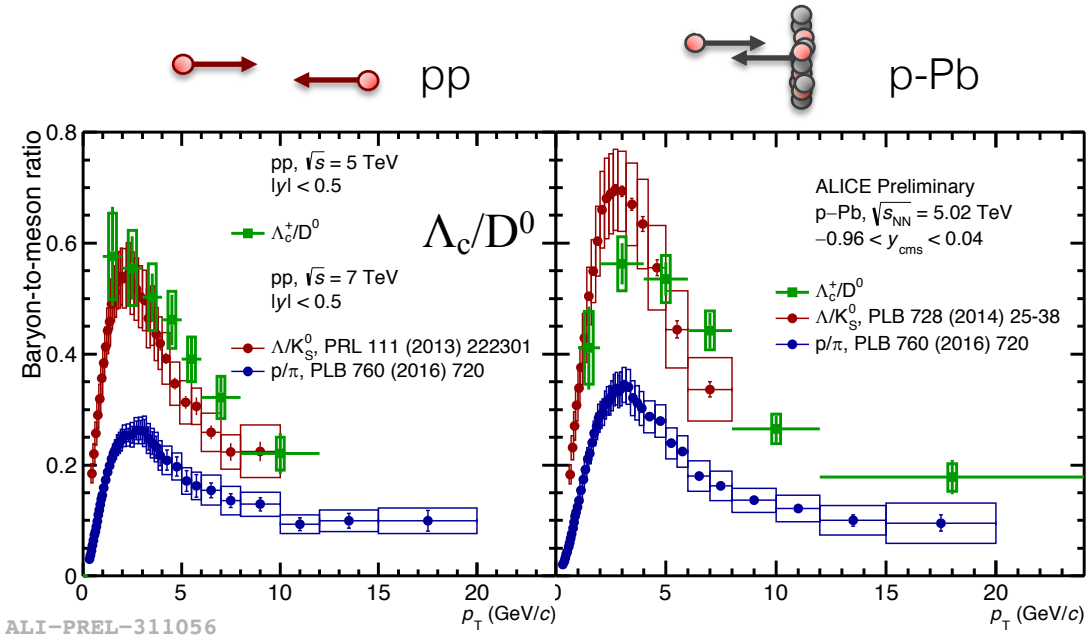
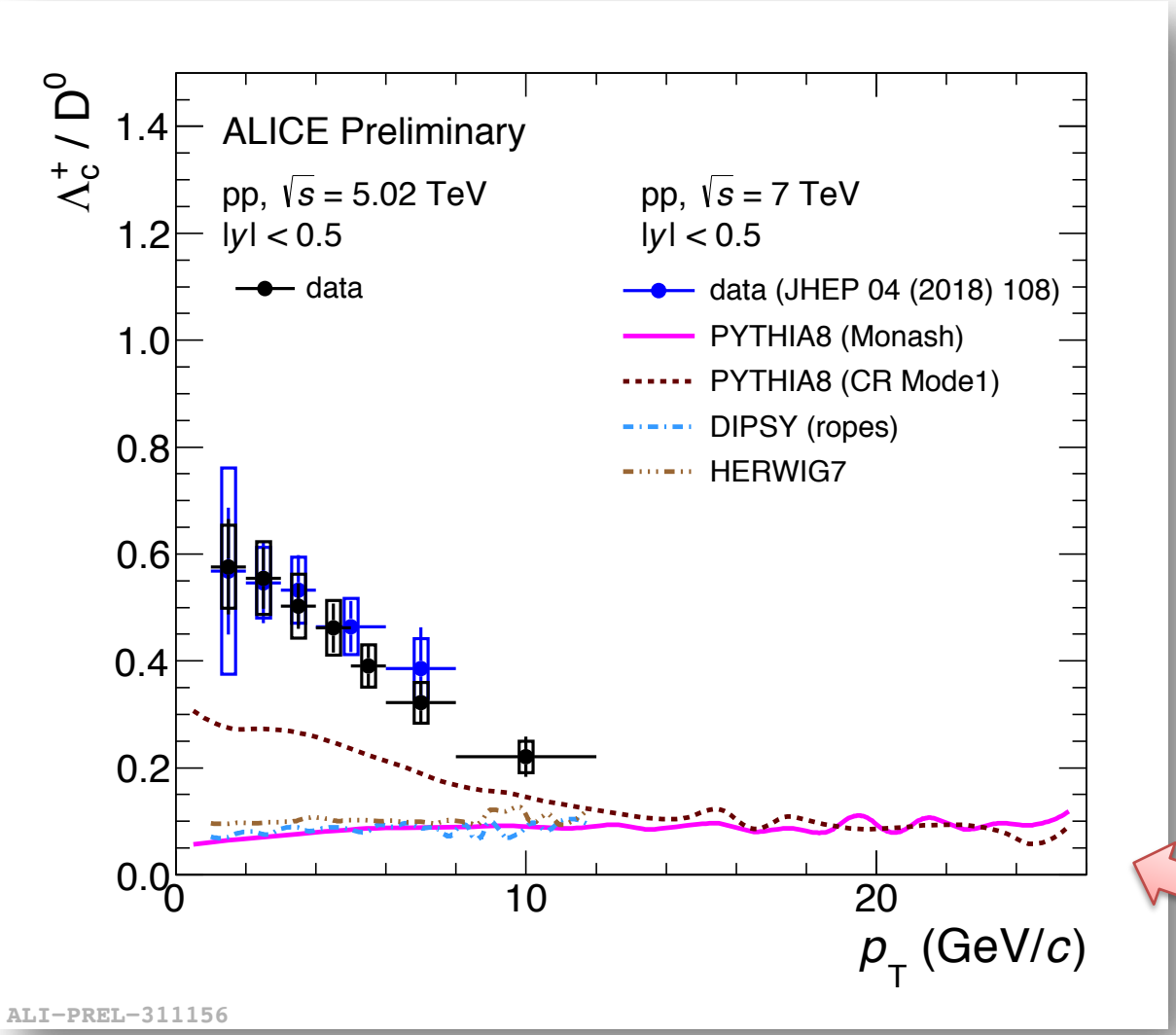
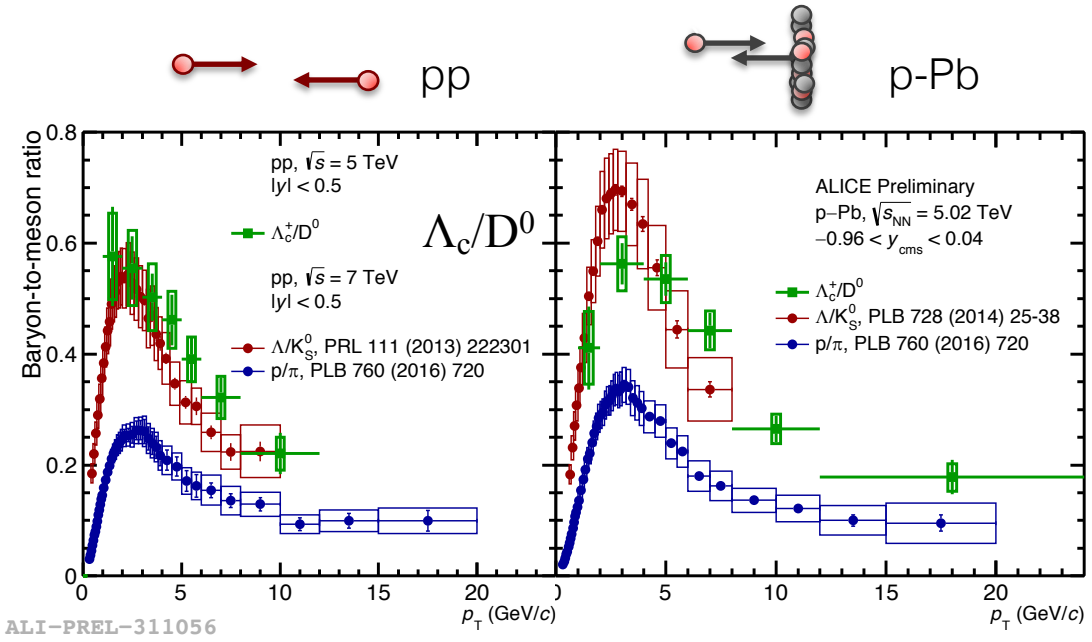


- May also be present in charm measurements in pp and p-Pb ?
  - Multiplicity-differential analysis pending…

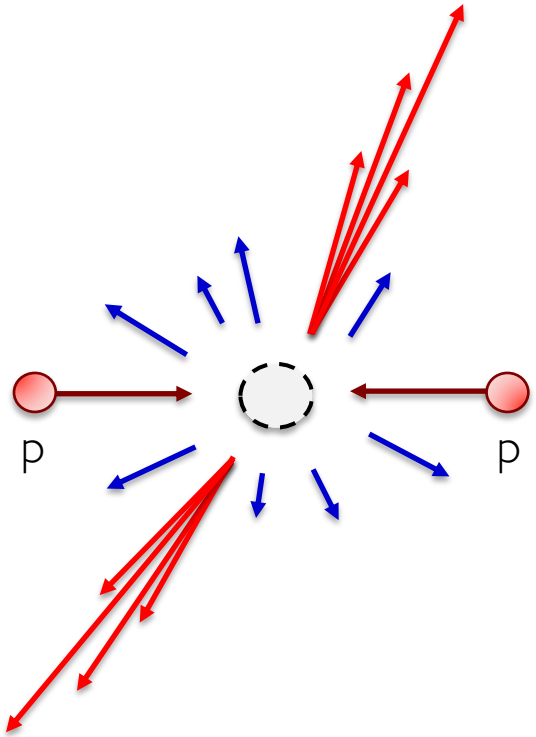
Baryon to meson ratios: strangeness + charm

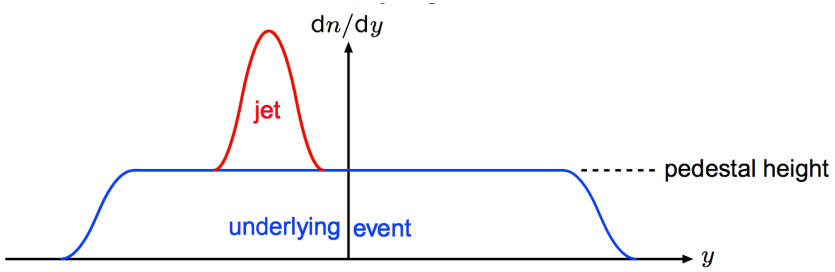




- May also be present in charm measurements in pp and p-Pb ?
  - Multiplicity-differential analysis pending…
- Charm production always produced in initial hard scattering, not in string breaking
  - Describing baryon production problematic

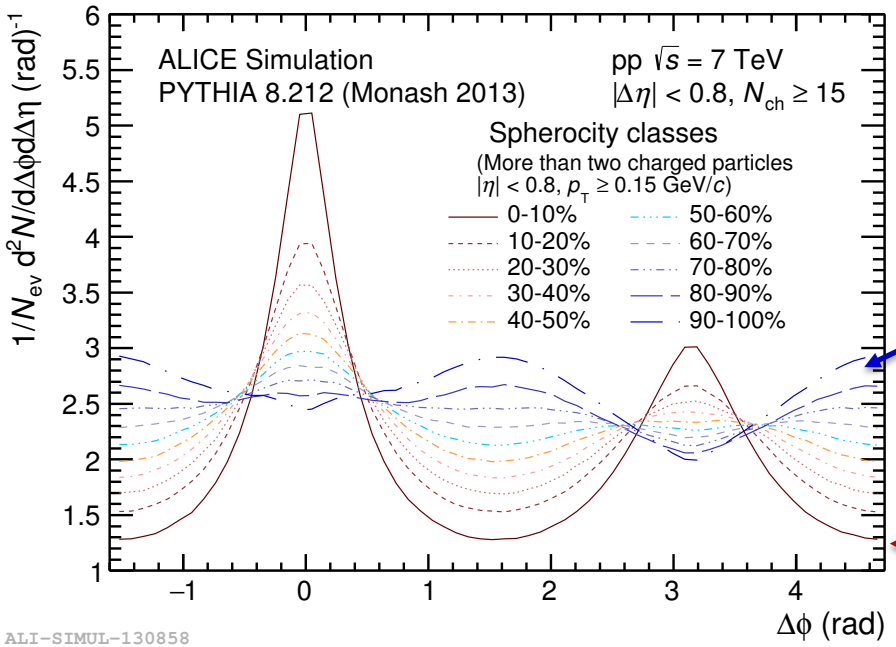
Beyond multiplicity: event shape studies

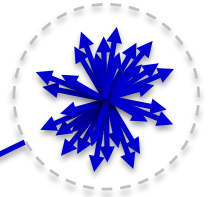




- A proton-proton interaction produces particles in
  - Jets from a (few) initial hard scattering(s)
  - A (softer) underlying event (UE): 'the rest'

- These two can be studied more closely! A possibility: spherocity S

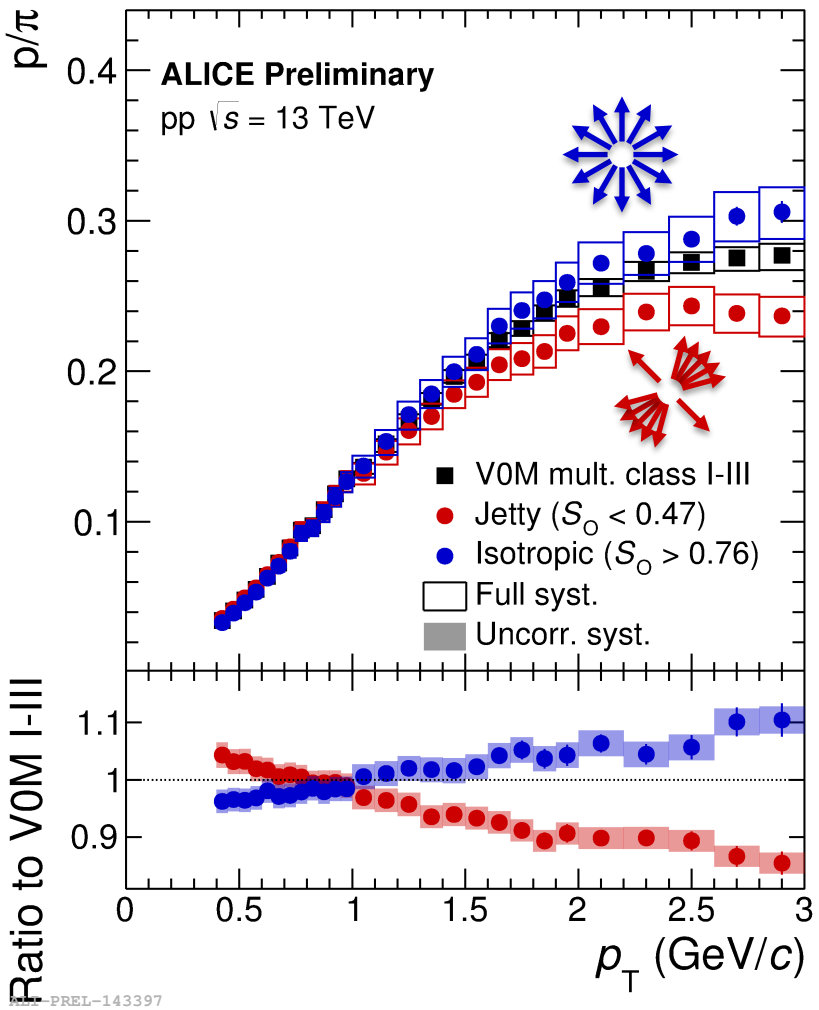




High S:
Soft QCD-like, azimuthally isotropic, enhanced UE

Low S:
Hard QCD-like, e.g. dijets

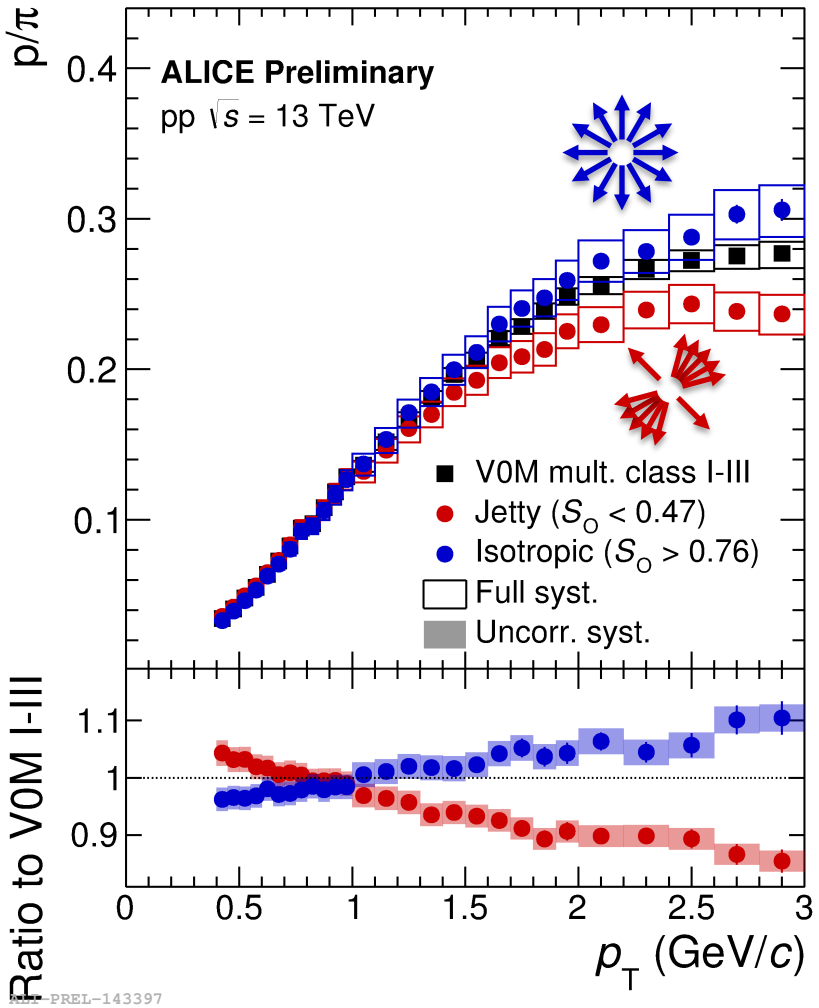
The proton-to-pion ratio in jets and the UE

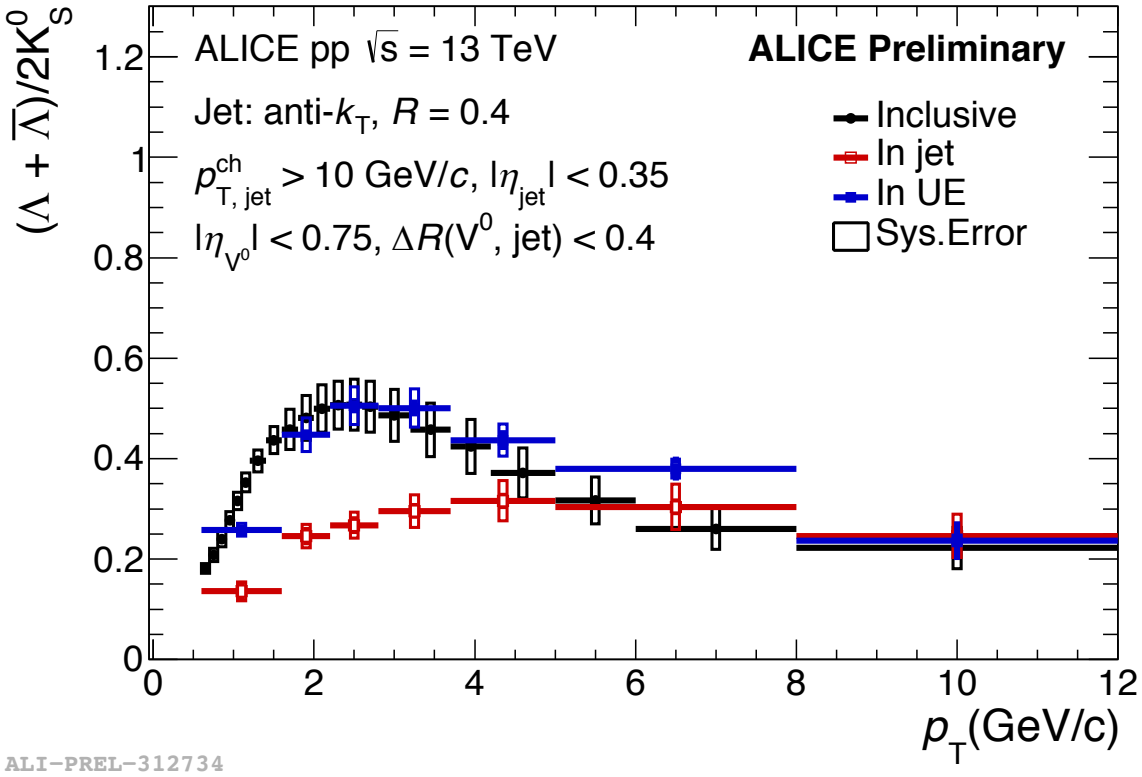


Dominated by jet-like behavior: baseline

Dominated by UE: (de/in)crease at (low/mid)-p_T?

The proton-to-pion ratio in jets and the UE



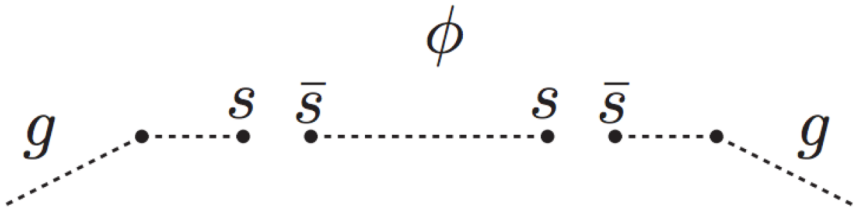


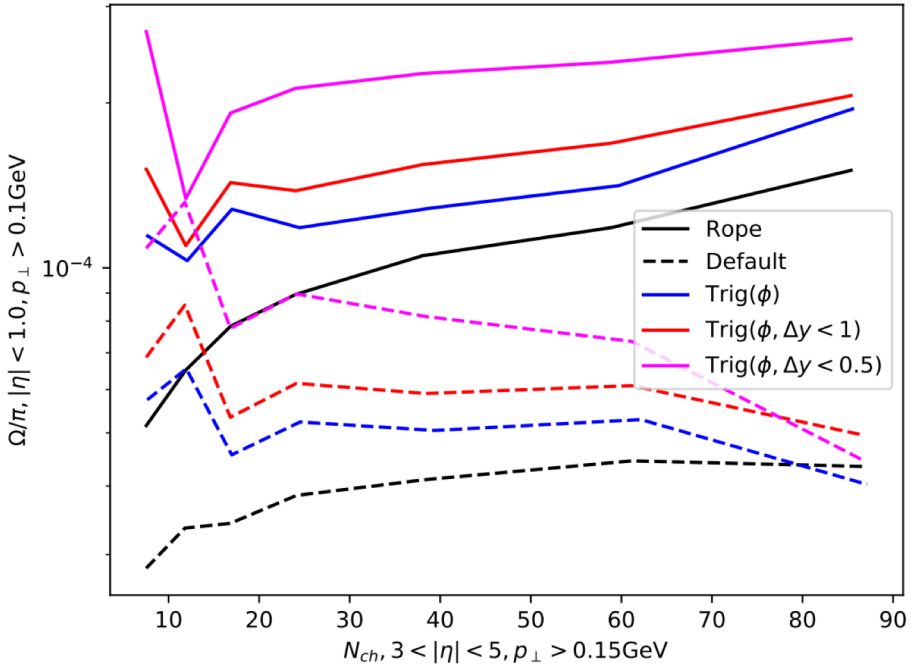
- The same idea can be explored using full jet reconstruction in pp
- Leads to consistent picture for Λ/K^0_S correlated with jets and UE:
  - Baryon/meson peak from UE dynamics
  - Constraint on phase space of relevant effect

Dominated by jet-like behavior: baseline

Dominated by UE: (de/in)crease at (low/mid) p_T?

Characterizing strangeness production



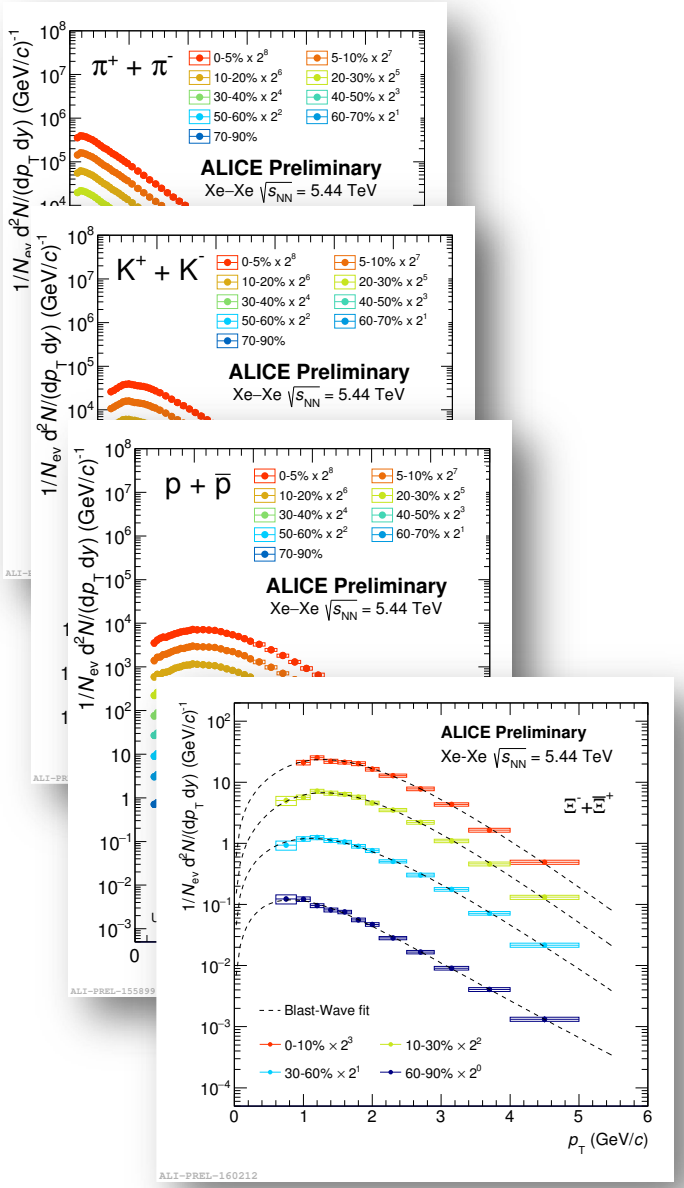


- Many effects can cause an increase in strangeness production…
  - How can we distinguish them?
- A first idea (C. Bierlich): look into e.g. the Ω/π ratio in events that contain a ϕ meson
  - Default string fragmentation: Ω suppressed
  - Ropes: increased tension, Ω enhanced
- How would other models compare?
- Other ideas?
- "Beyond multiplicity" → statistics-hungry!
  - Data is/will be there…

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

Completing the picture:

Studying Xe-Xe collisions



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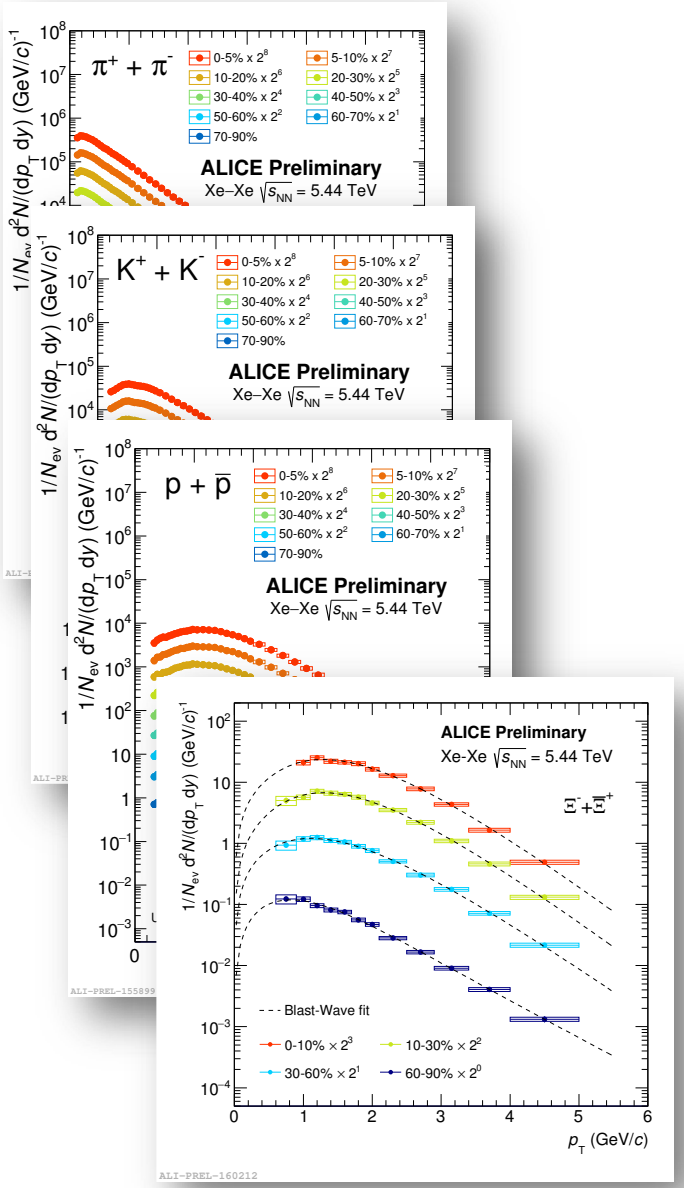

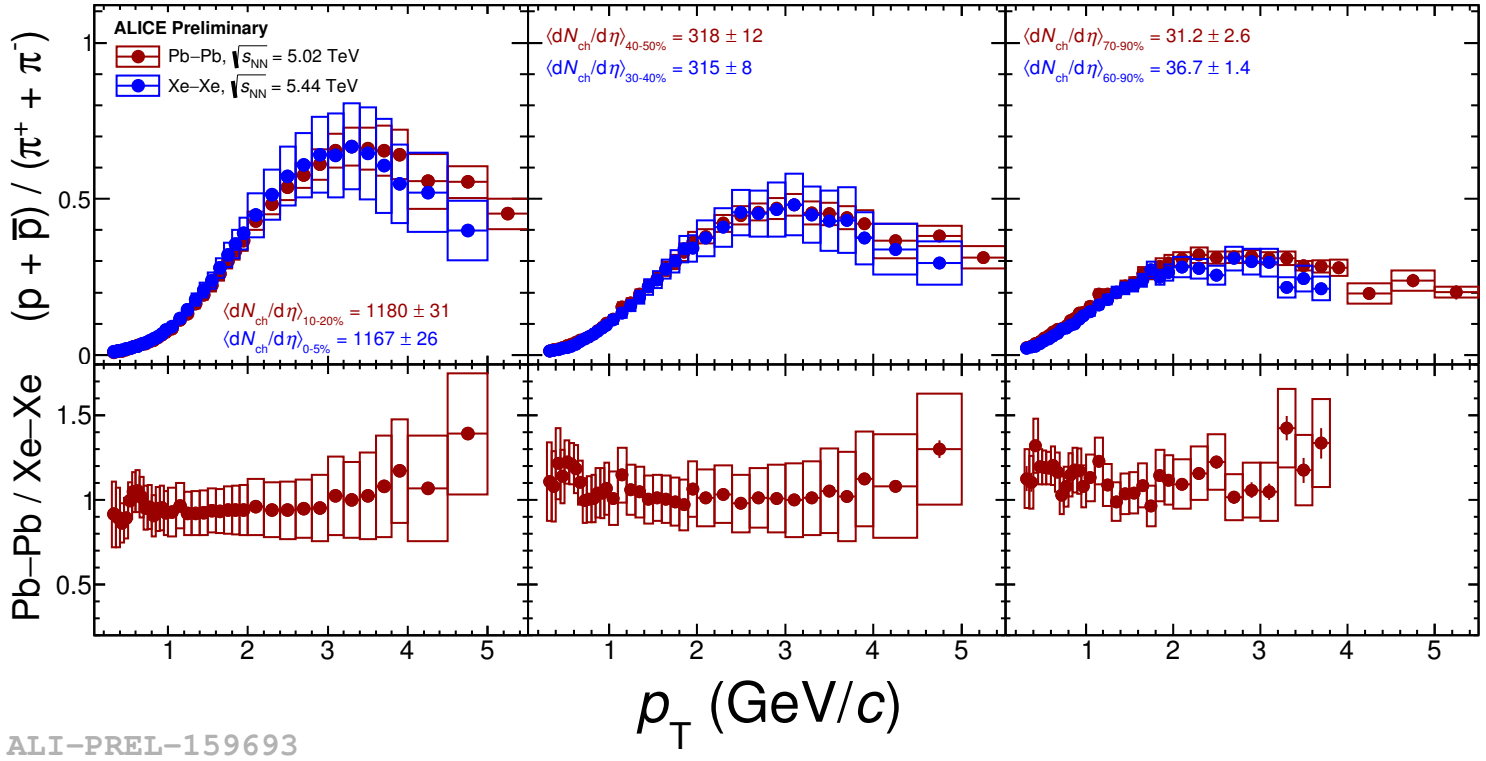

- Universality of p_T-differential ratios again confirmed
- Important piece of the puzzle: radial flow scales with $dN/d\eta$…

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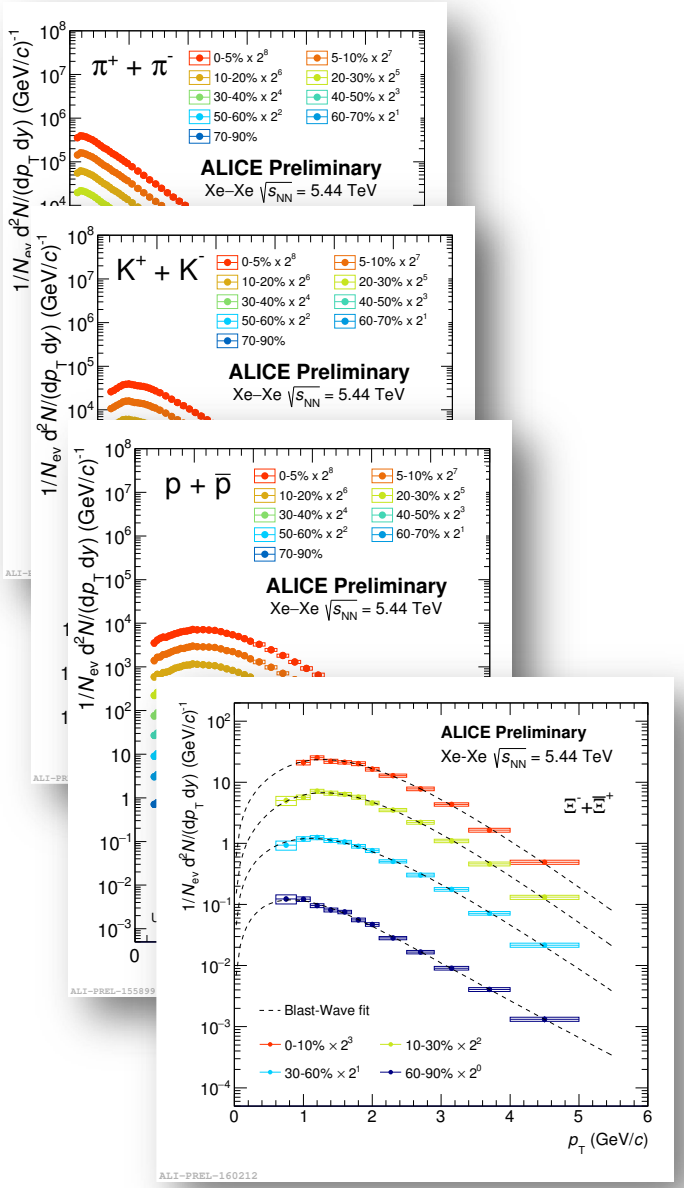

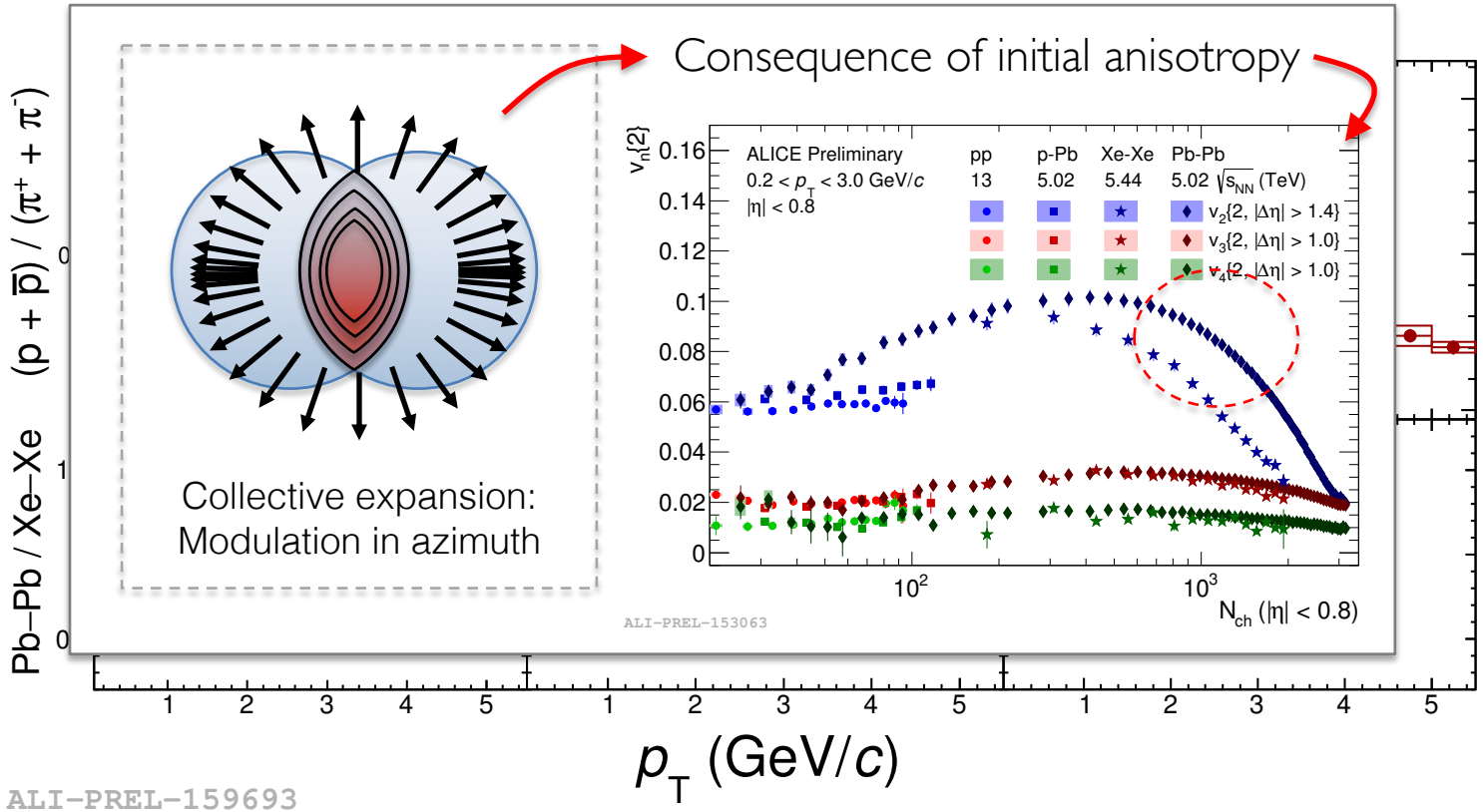

- Universality of p_T-differential ratios again confirmed
- Important piece of the puzzle: radial flow scales with $dN/d\eta$ but elliptic flow does not ?...

Completing the picture:
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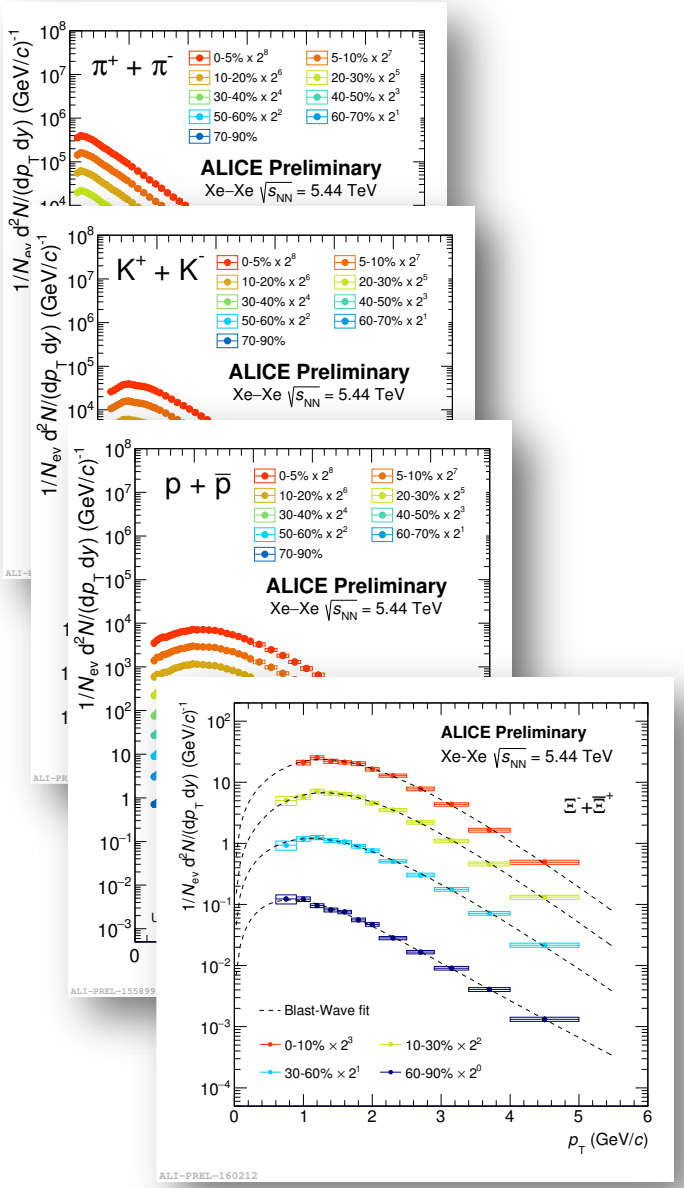

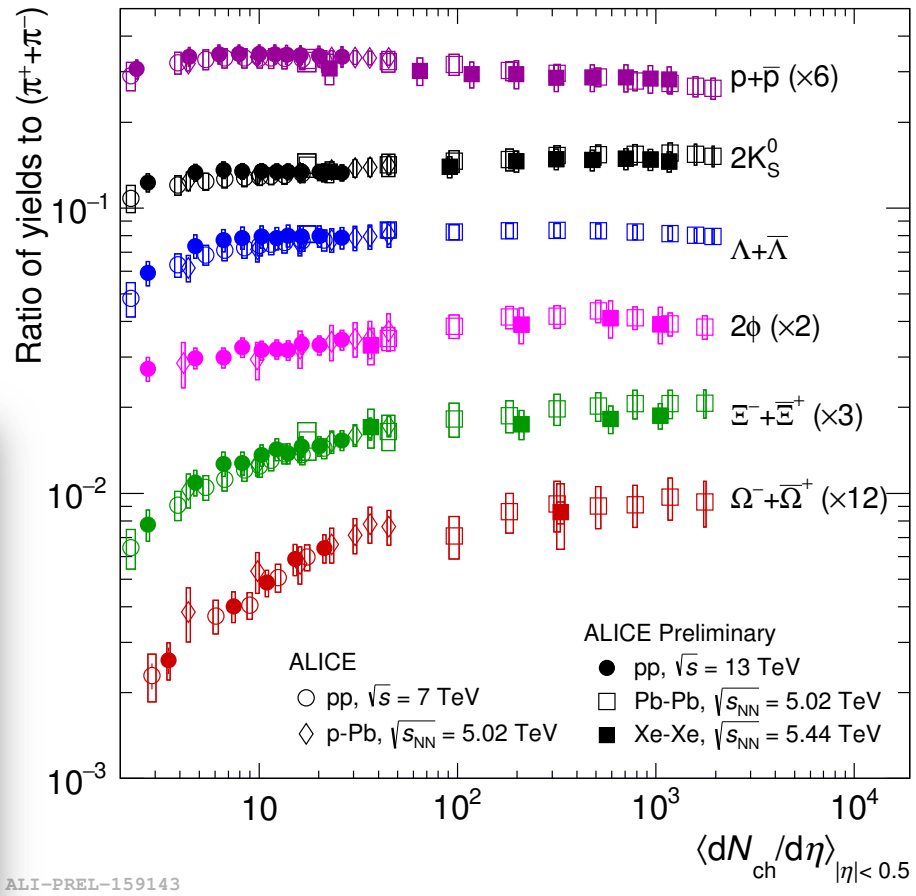

- Results from Xe-Xe at 5.44 TeV confirm that multiplicity is the key variable for relative particle abundances

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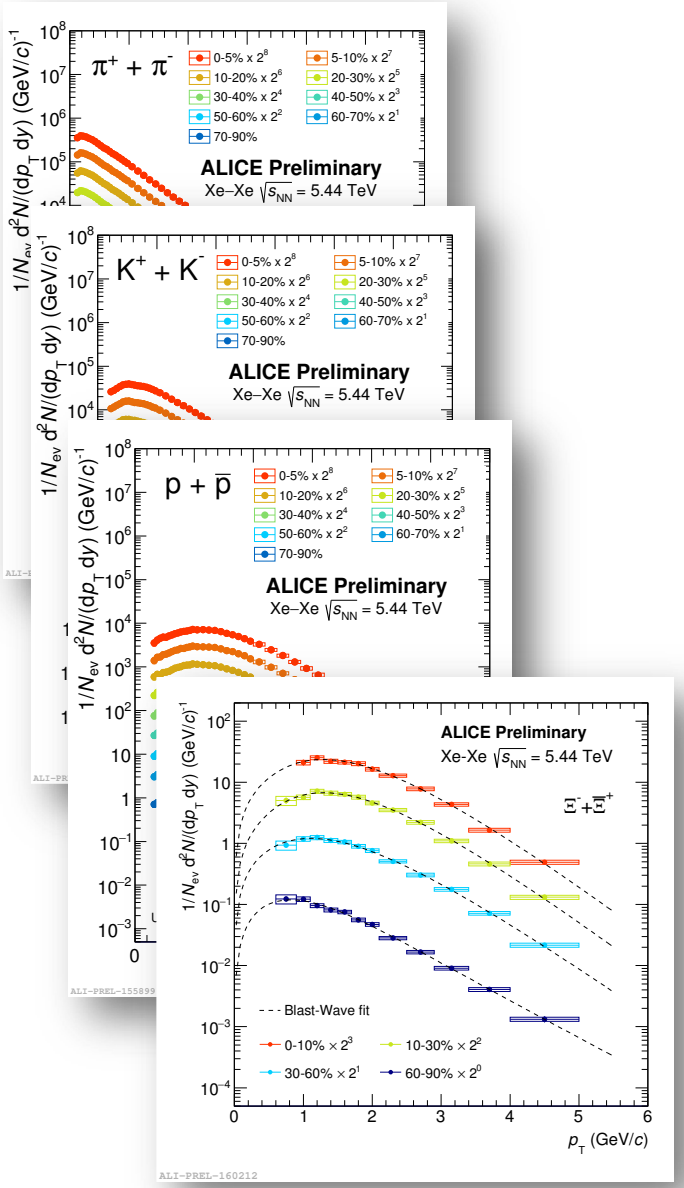
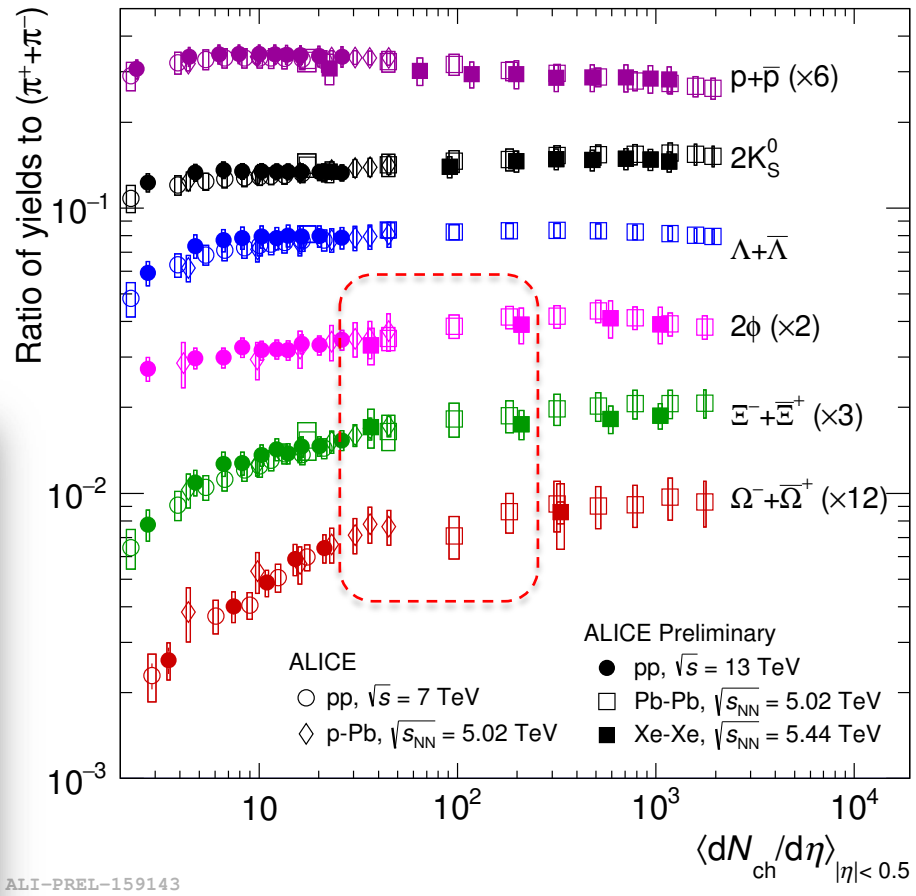
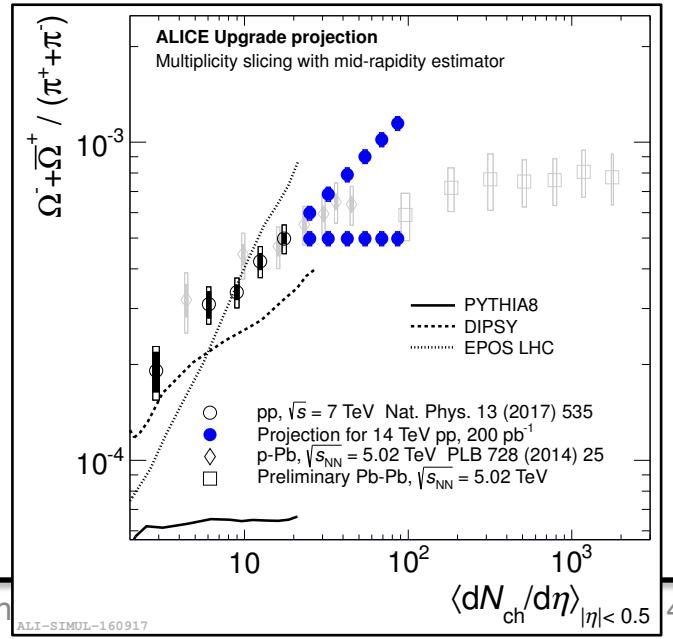
Studying Xe-Xe collisions





- Results from Xe-Xe at 5.44 TeV confirm that multiplicity is the key variable for relative particle abundances
- Can we study the onset of saturation ? *(does it always take place?)*



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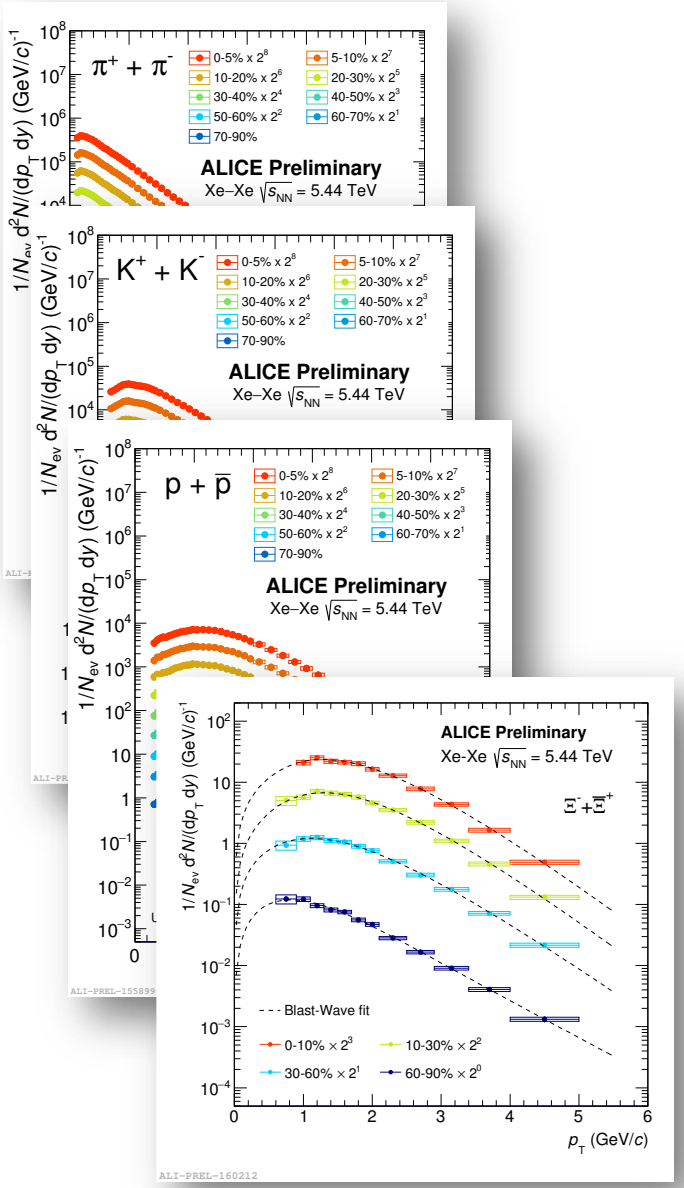

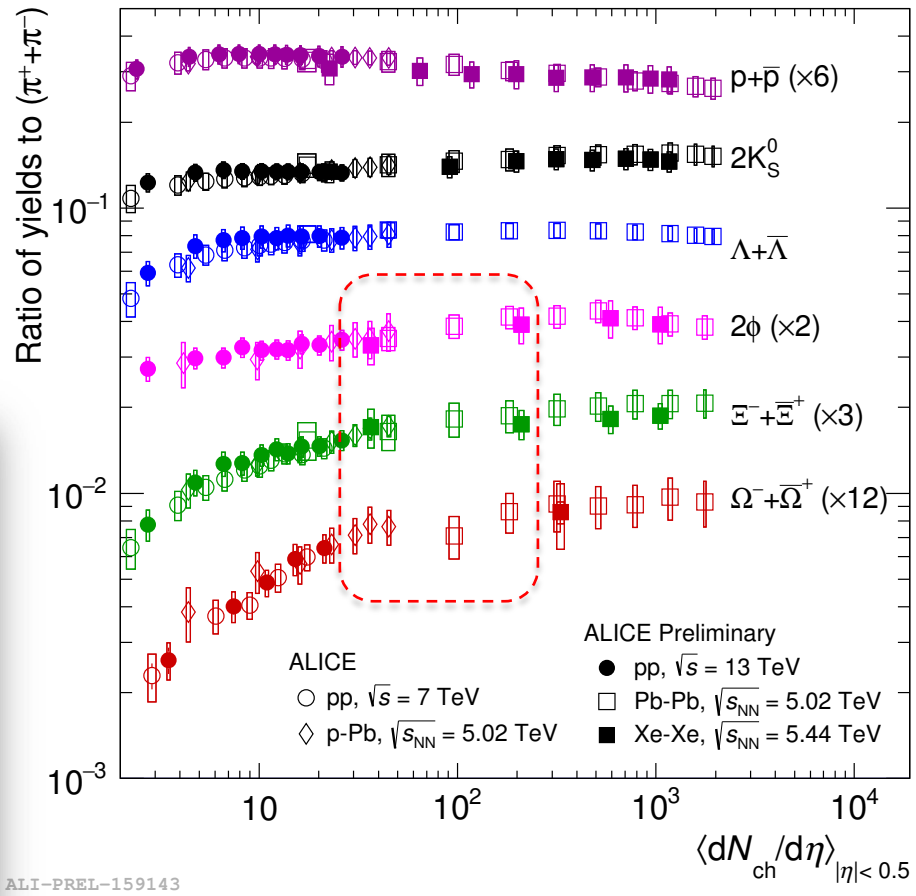

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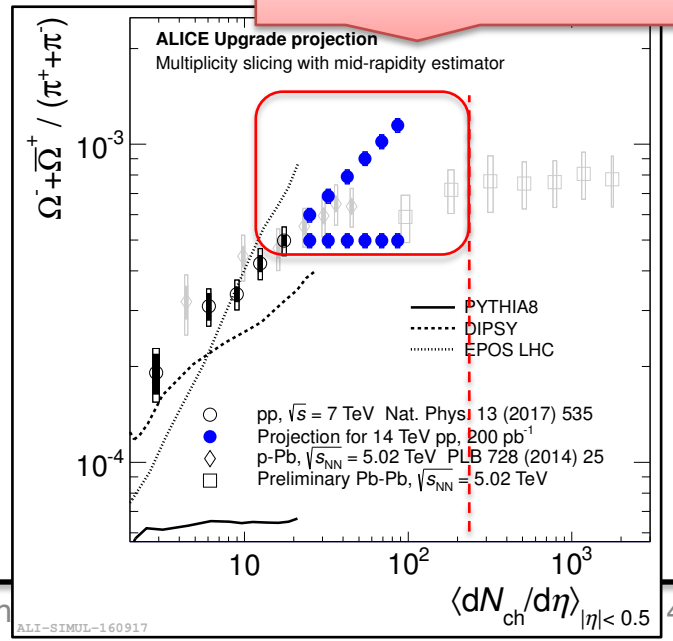
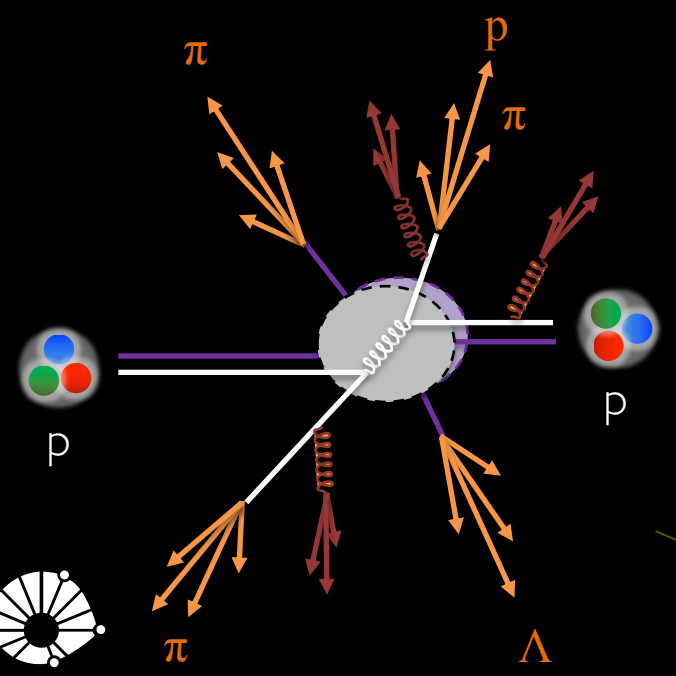
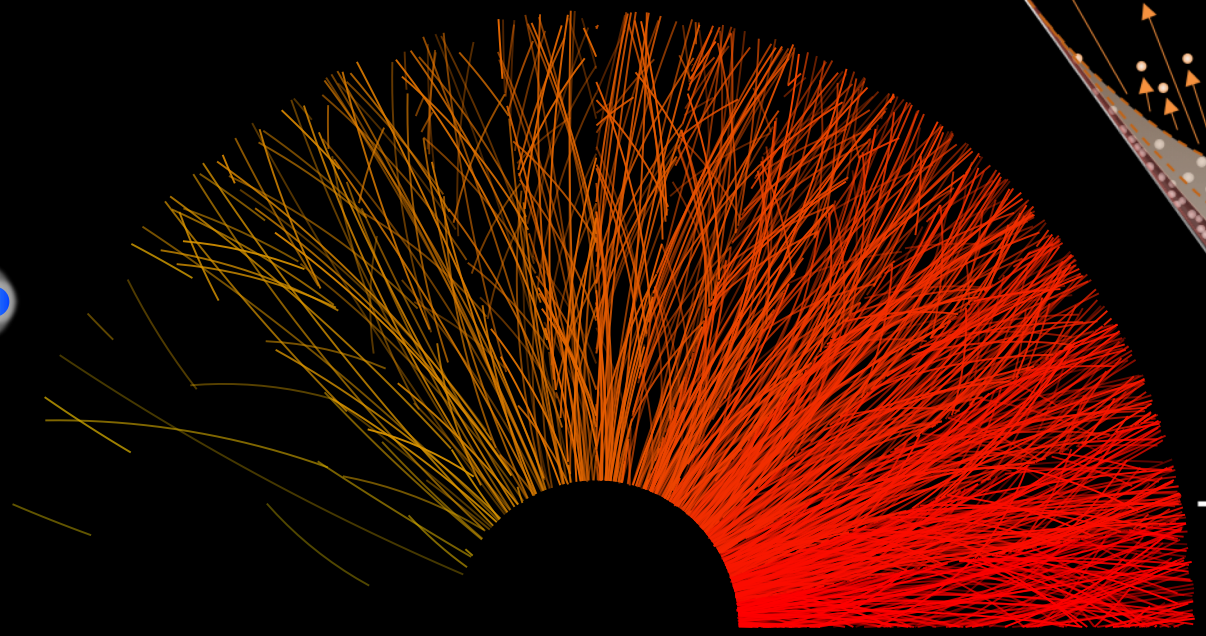
O-O collisions: Run 3+4

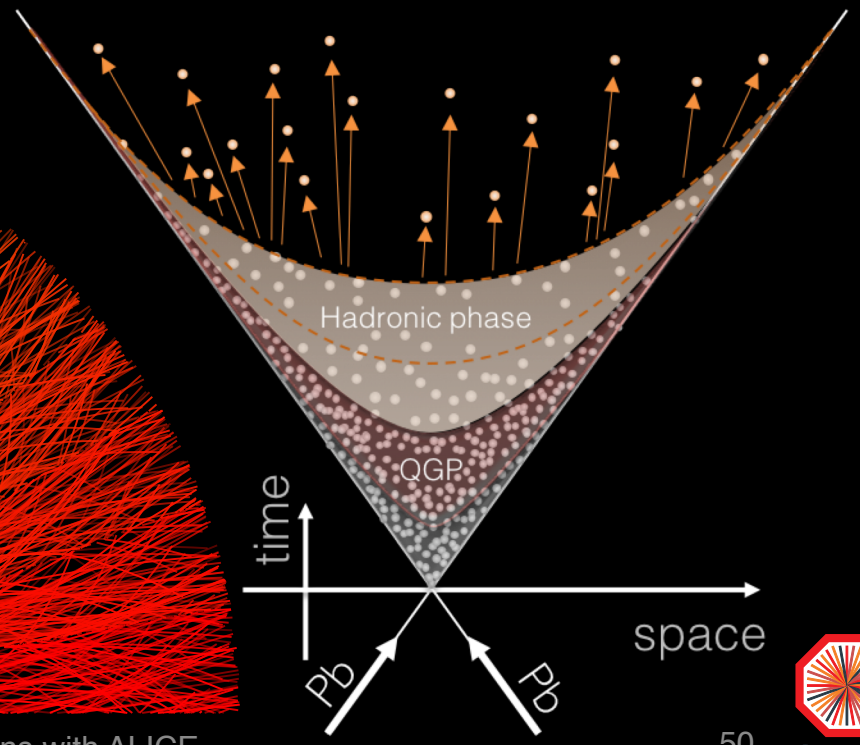


Summary and outlook

- Comprehensive measurements show: multiplicity is a key variable when comparing pp, p-Pb, Xe-Xe and Pb-Pb
  - hadrochemistry, particle ratios: similar
  - Kinematics: not necessarily
- Fundamental constraints to theory







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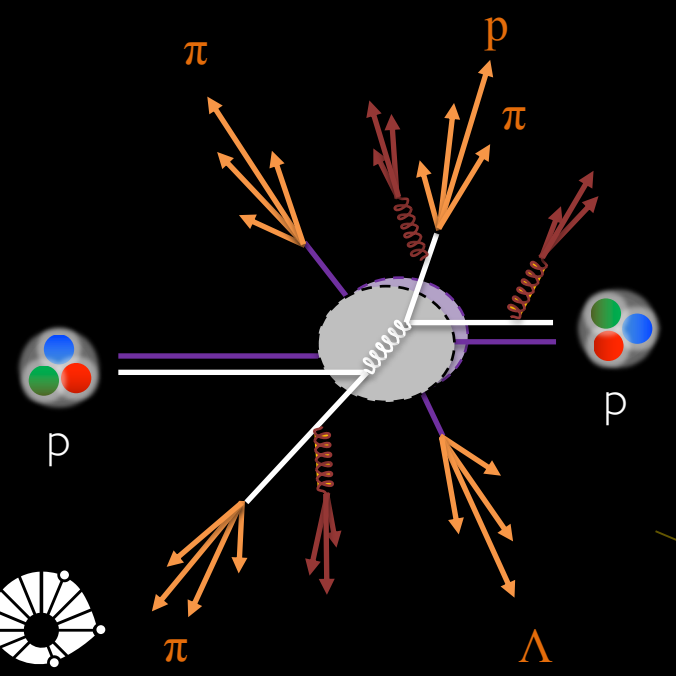
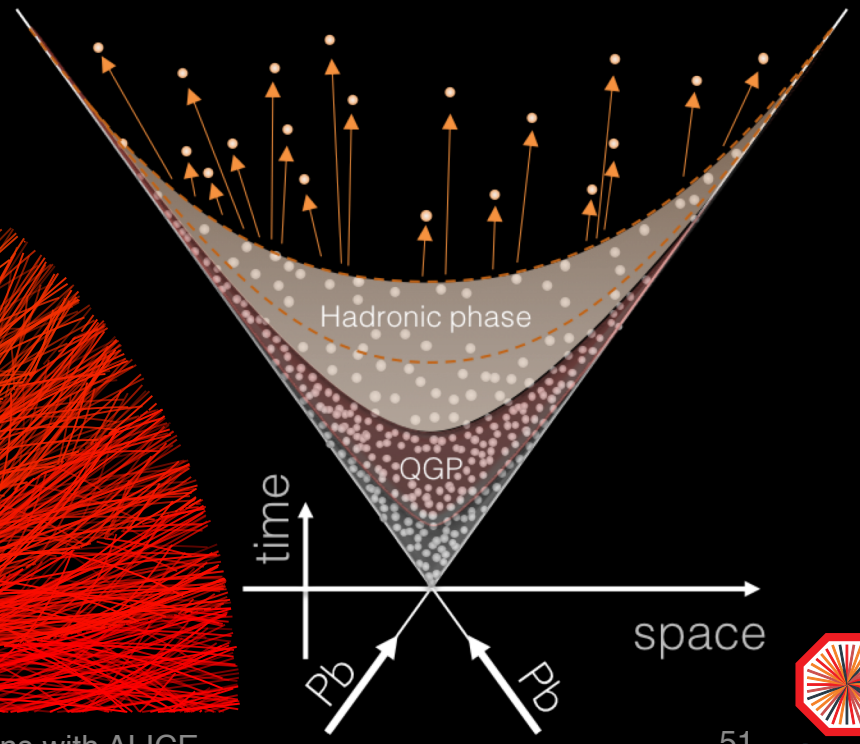
- How can models be reconciled and distinguished?
  - (To) QGP or not (to) QGP?
- More development needed: baryon production mechanisms? Consider LF and HF information together?
- A lot more ahead!





Thank you!