QGP Signals in Small Systems:

Identified Particle Spectra and Multiplicity Dependence

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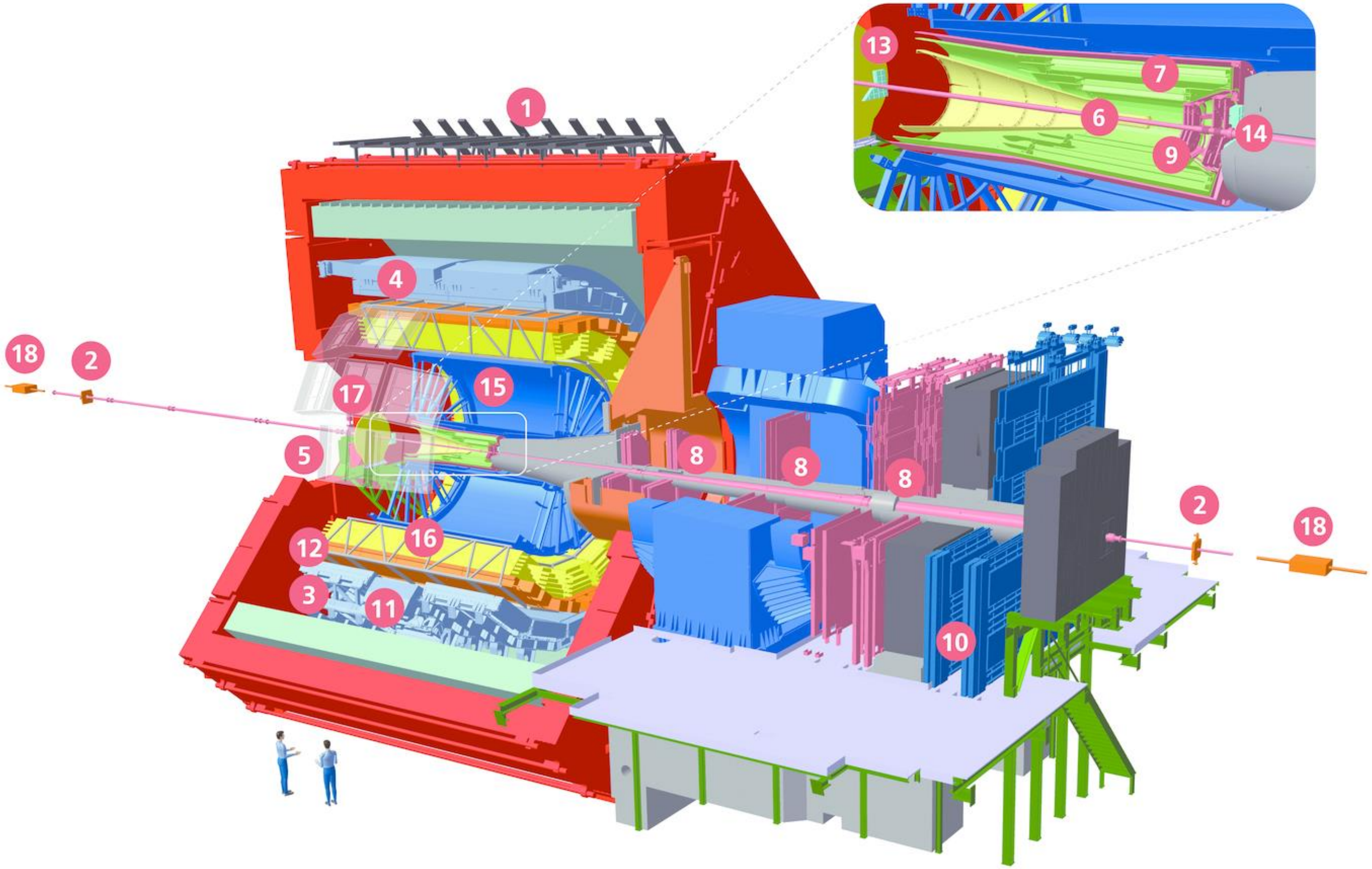
Non-perturbative and Topological Aspects of QCD
29.05.2024

Content

- Particle identification methods in ALICE
- Multiplicity estimators and biases

- Assessing MPIs in measurements
- Baryon/meson ratios
- Strangeness enhancement
- Charm sector

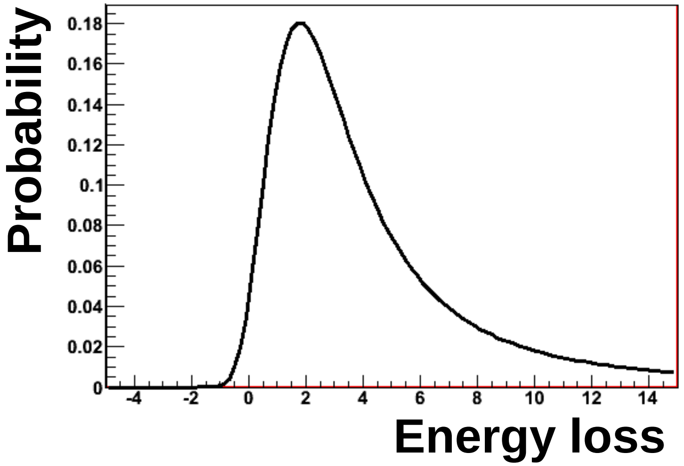


1	**ACORDE**	ALICE Cosmic Rays Detector
2	**AD**	ALICE Diffractive Detector
3	**DCal**	Di-jet Calorimeter
4	**EMCal**	Electromagnetic Calorimeter
5	**HMPID**	High Momentum Particle Identification Detector
6	**ITS-IB**	Inner Tracking System - Inner Barrel
7	**ITS-OB**	Inner Tracking System - Outer Barrel
8	**MCH**	Muon Tracking Chambers
9	**MFT**	Muon Forward Tracker
10	**MID**	Muon Identifier
11	**PHOS / CPV**	Photon Spectrometer
12	**TOF**	Time Of Flight
13	**T0+A**	Tzero + A
14	**T0+C**	Tzero + C
15	**TPC**	Time Projection Chamber
16	**TRD**	Transition Radiation Detector
17	**V0+**	Vzero + Detector
18	**ZDC**	Zero Degree Calorimeter

Methods of Particle Identification

(in ALICE)

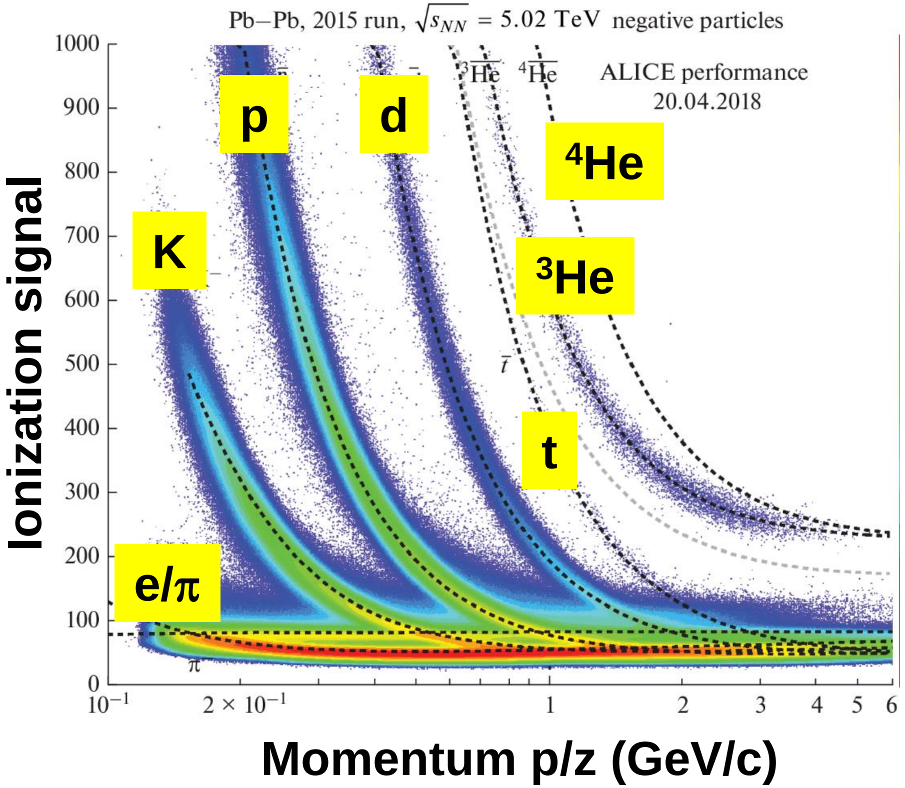
PID in TPC: Specific Energy Loss



- Particles passing through matter lose energy mainly by ionization
- Average energy loss can be calculated with the Bethe-Bloch formula

$$\left\langle -\frac{dE}{dx}\right\rangle = Kz^2\frac{Z}{A}\boxed{\frac{1}{\beta^2}}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2W_{\max}}{I^2}-\beta^2-\frac{\delta(\beta\gamma)}{2}\right]$$

- Identify particle by measuring energy deposition and momentum
  - Not necessarily unique in all regions
- Single energy loss by (primary) ionization depends on E^{-2}
  - Most of the times the energy loss is small, but small probability exists to have a large energy loss
  - Landau tail of the energy loss distribution → Truncated mean used



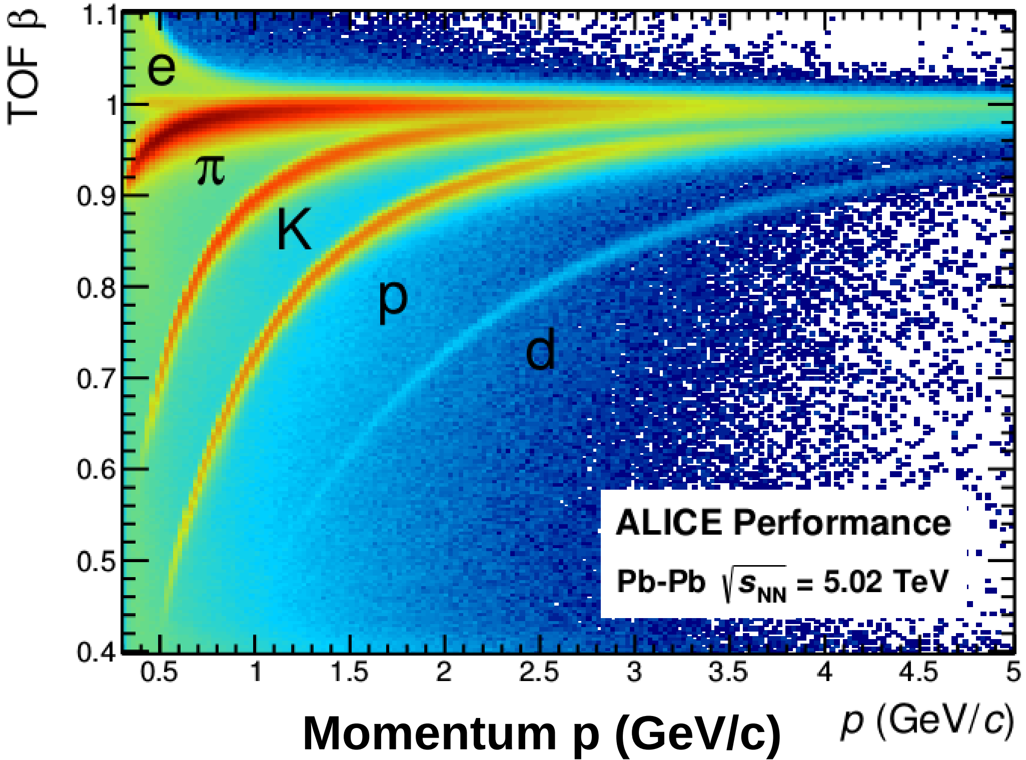
PID in TOF: Time Of Flight

- Although particles have practically speed of light, particles with same momentum have slightly different speed due to their different mass

- Precise measurement of flight time between interaction and arrival in detector allows to determine mass, and thus particle type

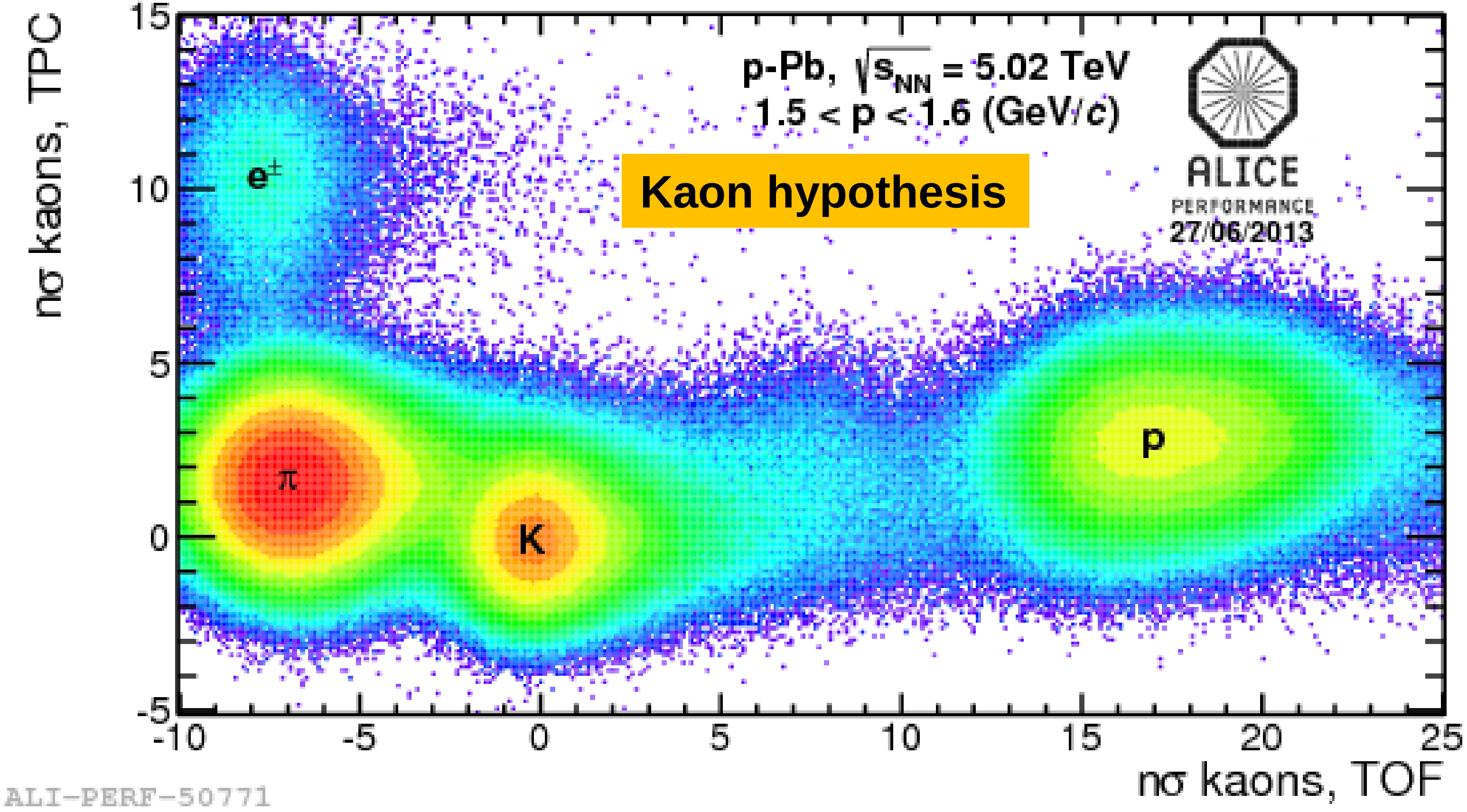
- Needed precision, e.g. for a particle with p = 3 GeV/c, flying length 3.5 m
  - t(π) ~ 12 ns | t(K) – t(π) ~ 140 ps

- Detector without drift volume needed, dispersion usually spoils time resolution
  → MRPCs (multigap resistive plate chambers)



ALI-PERF-106336

Combine PID Methods

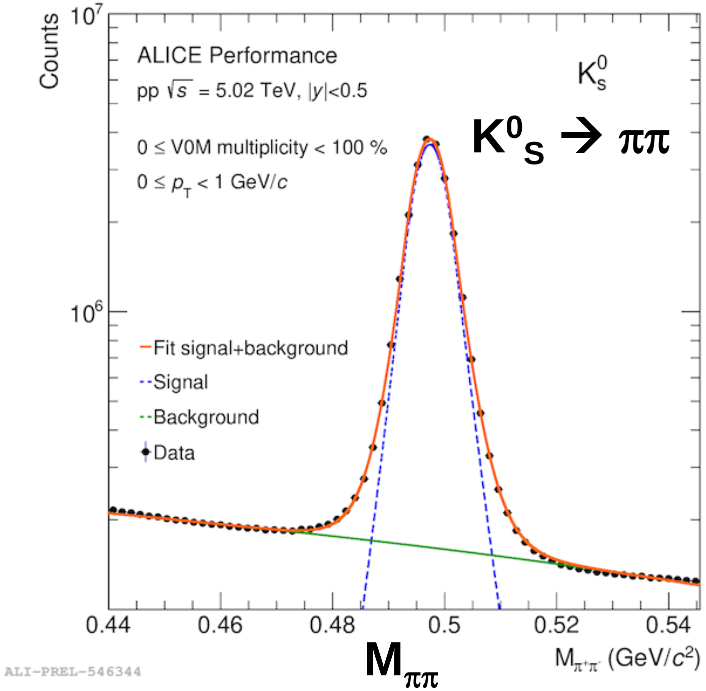


Kaon hypothesis

Invariant Mass
Topological Reconstruction

- Invariant mass of pairs of identified particles
  - Fit with Gaussian and background function
  - If needed: assess background shape with MC

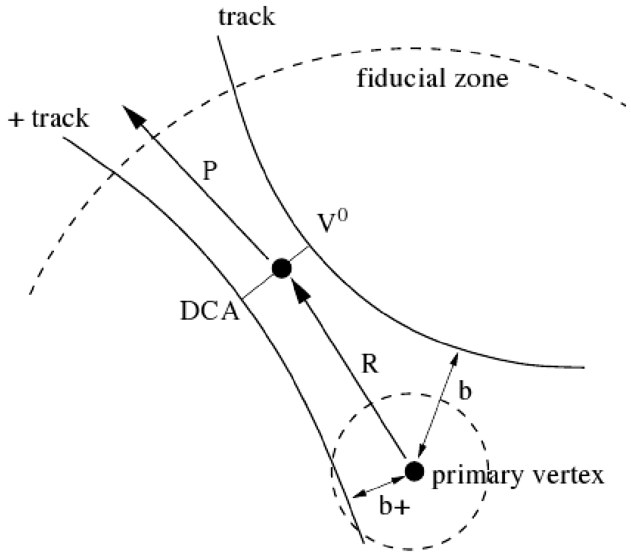
→ statistical only, not per-particle identification



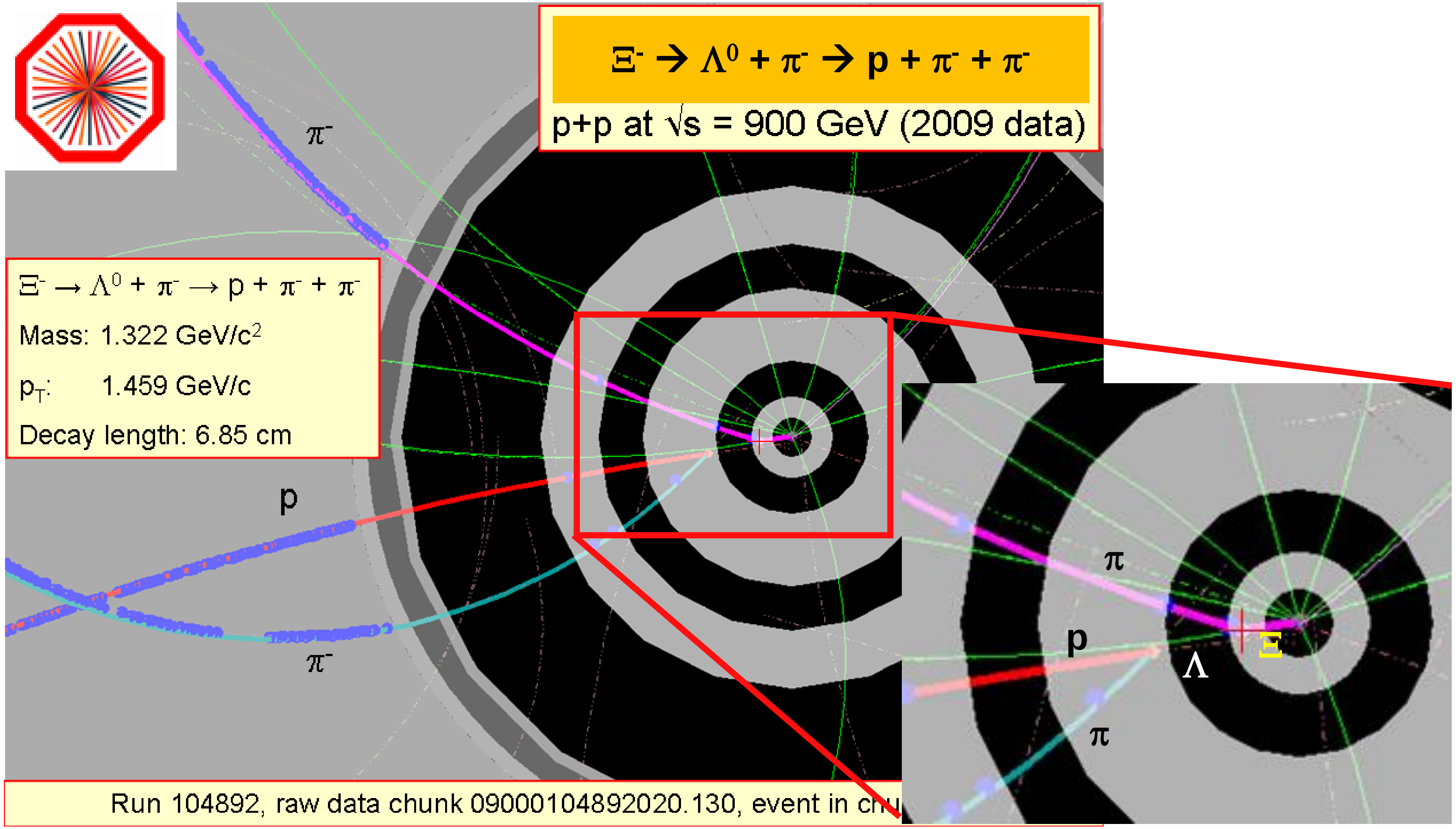
$K^0_S \rightarrow \pi\pi$

$M_{\pi\pi}$

- Displaced vertex reconstruction for long-lived particles
  - E.g. weak decays: K_0^S, Λ (called V0)
  - Exploit large DCA to primary vertex
  - Create secondary vertices
  - Check consistency with pointing back to primary



Reconstruction of a Cascade



$\Xi^- \rightarrow \Lambda^0 + \pi^- \rightarrow p + \pi^- + \pi^-$

p+p at $\sqrt{s}$ = 900 GeV (2009 data)

$\Xi^- \rightarrow \Lambda^0 + \pi^- \rightarrow p + \pi^- + \pi^-$

Mass: 1.322 GeV/c^2

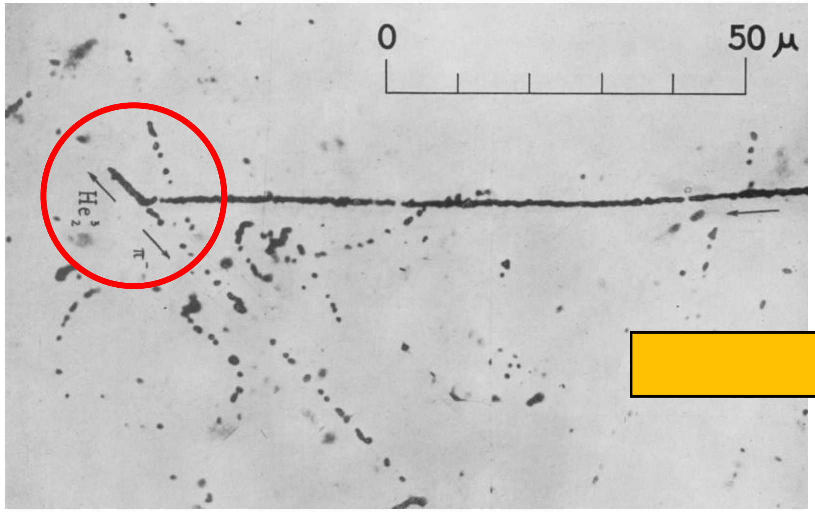
p_T: 1.459 GeV/c

Decay length: 6.85 cm

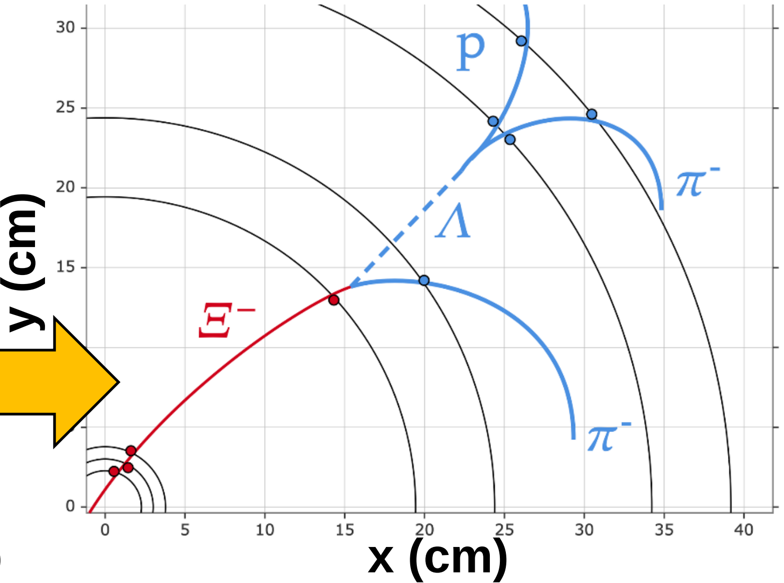
Run 104892, raw data chunk 09000104892020.130, event in chu

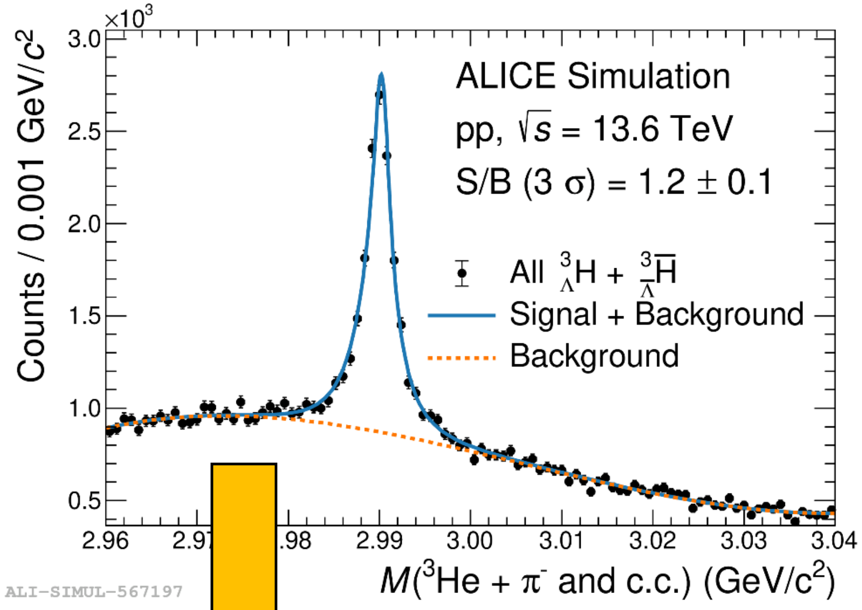
Strangeness Tracking

- Detectors closer to collision + more computing → MHz bubble chamber
- Track mother and daughter of decay
  - Cascades, hypertriton, …
  - Background significantly reduced



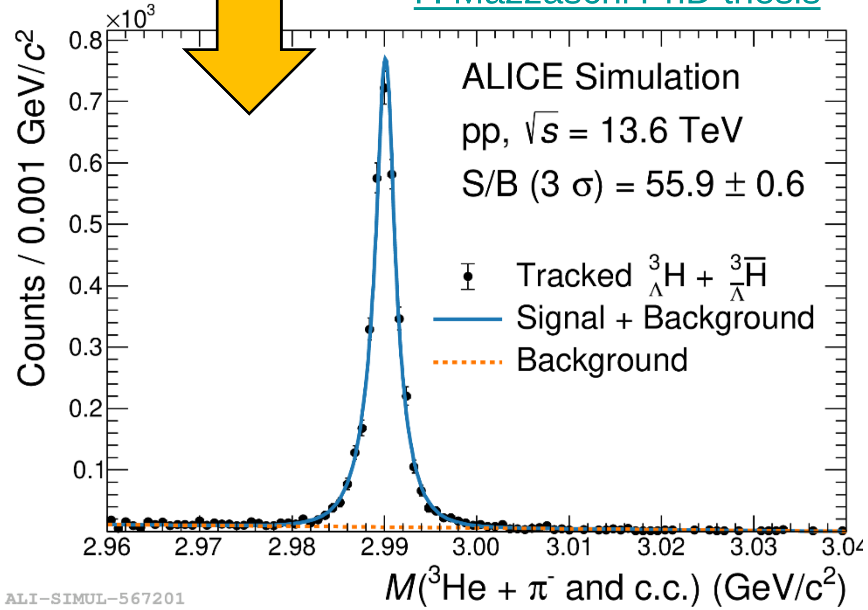
Il Nuovo Cimento (1943-1954) 11.2 (1954), pp. 210





ALI-SIMUL-567197

F. Mazzaschi PhD thesis

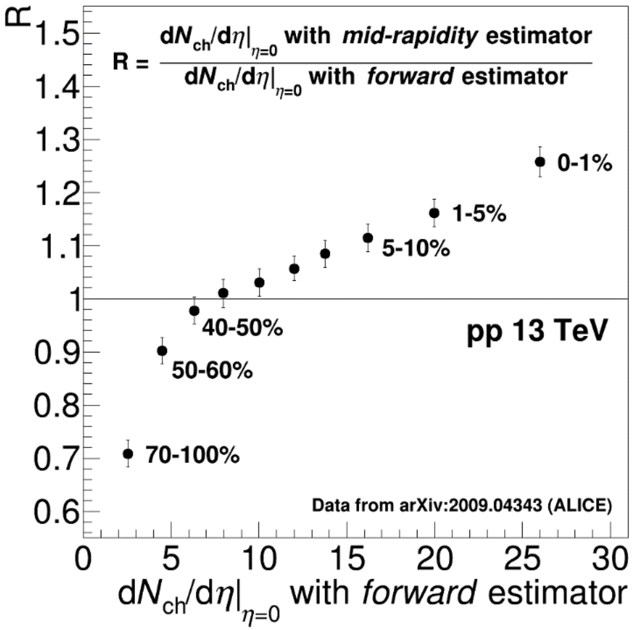


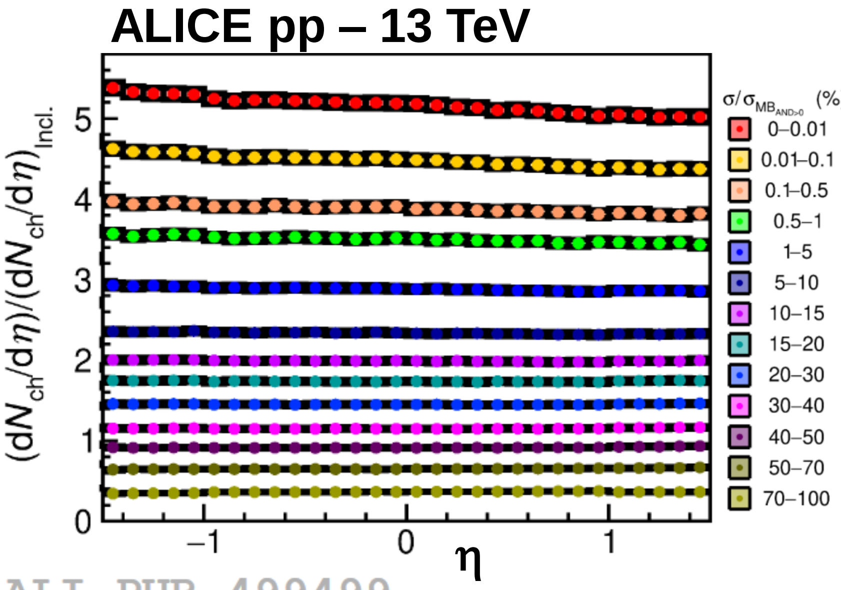
ALI-SIMUL-567201

Multiplicity Estimators

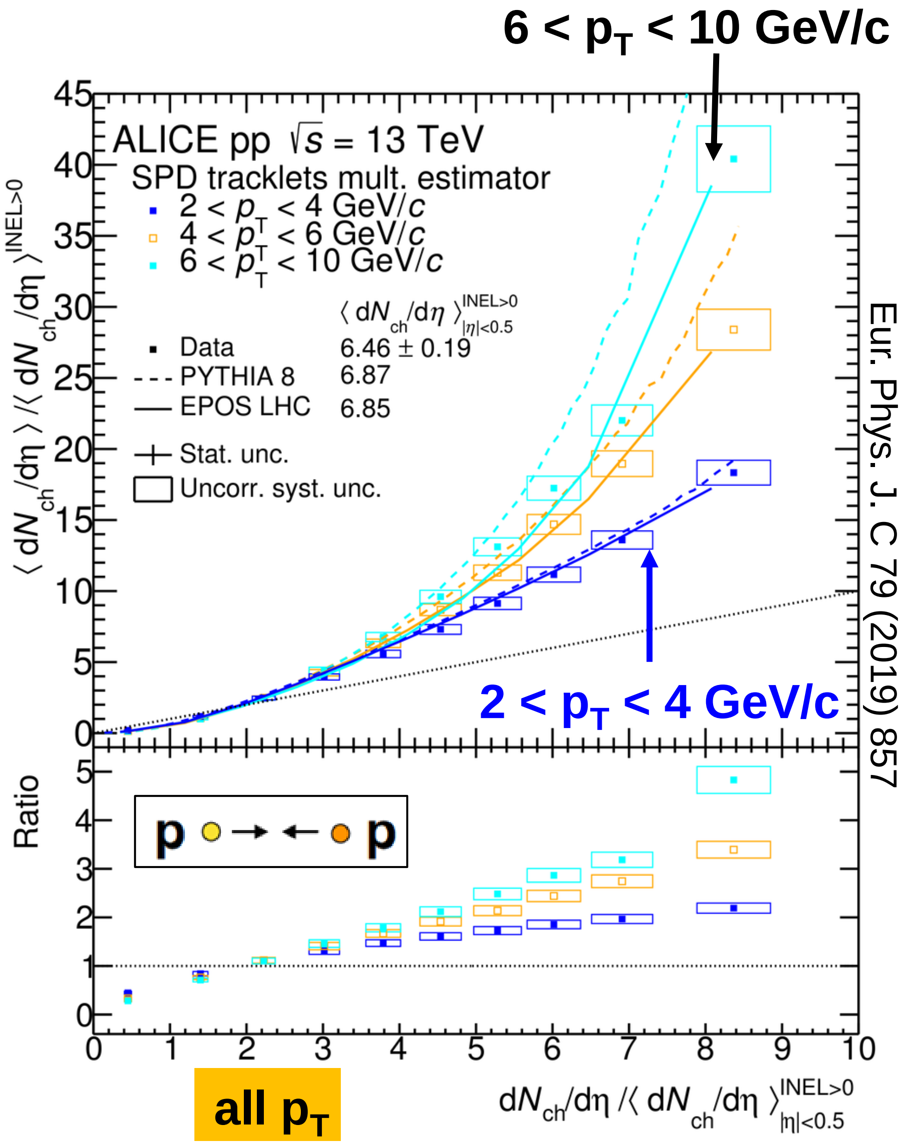
Multiplicity Estimators

- Results studied as function of multiplicity (percentile)
  - Often as self-normalized quantities
- Inherent rapidity dependence
- Inherent p_T dependence
  - Auto-correlation bias: multiplicity ↑ → parton p_T ↑





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

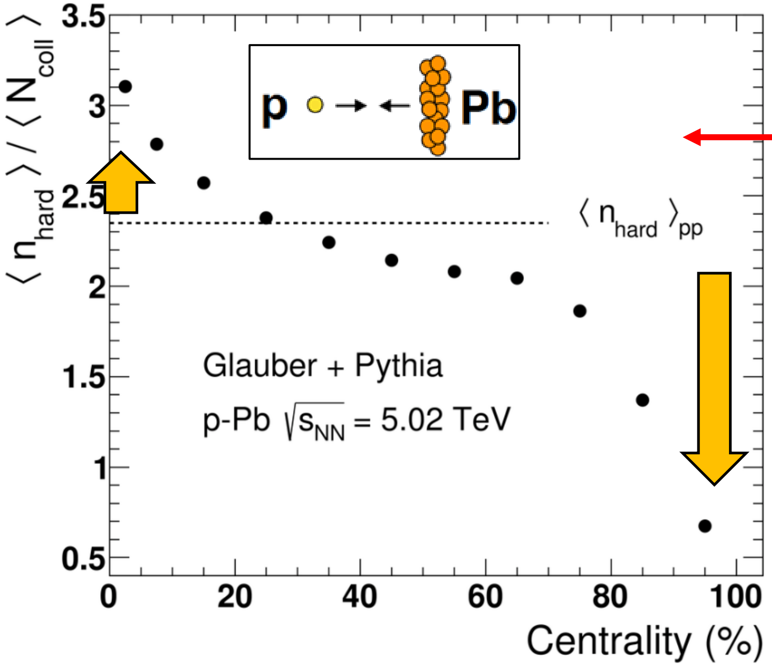


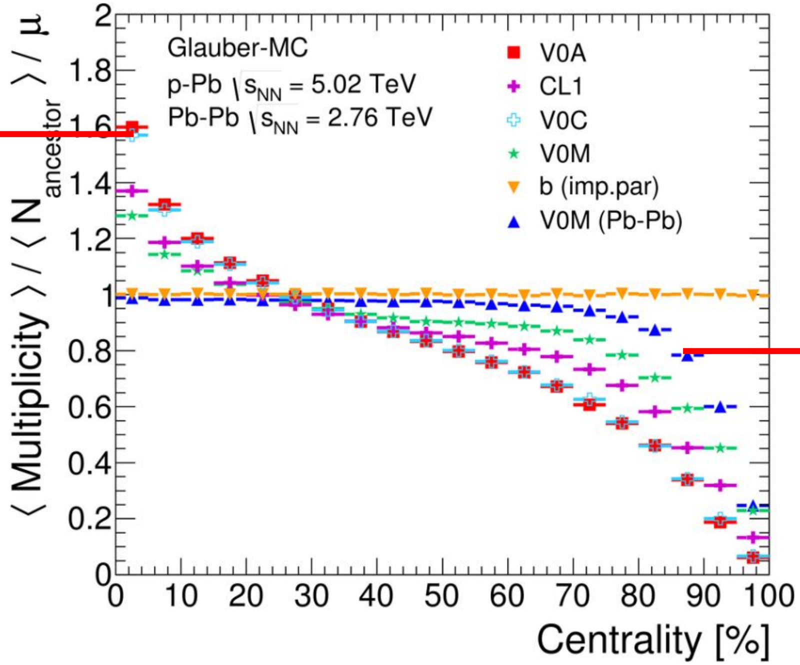
Eur. Phys. J. C 79 (2019) 857

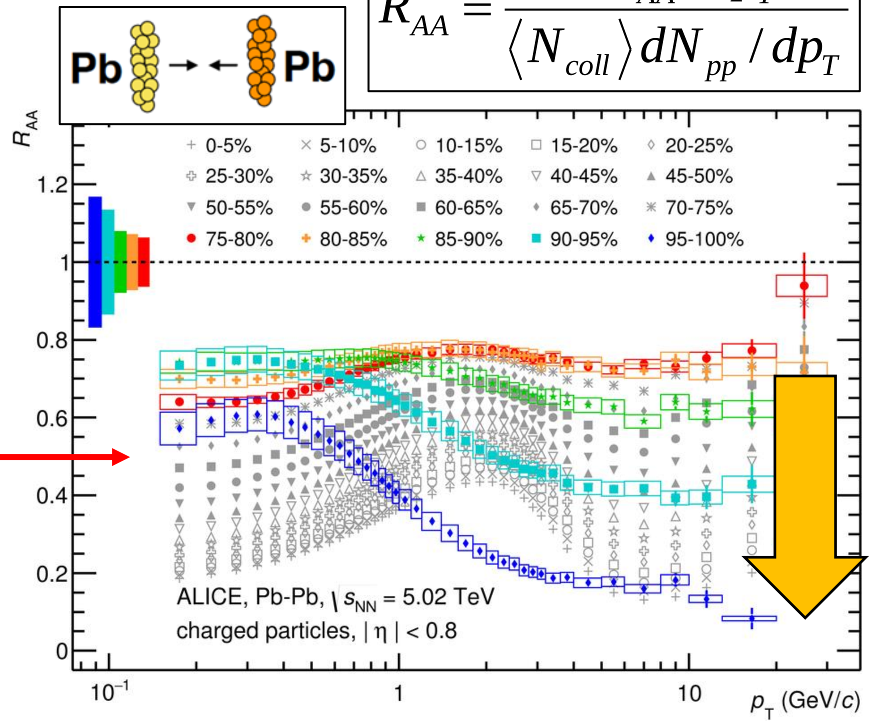
Biases

- Event slicing causes biases… in pp, p-Pb and Pb-Pb
  - on multiplicity per nucleon-nucleon interaction
  - on hard scatterings per nucleon-nucleon interaction

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







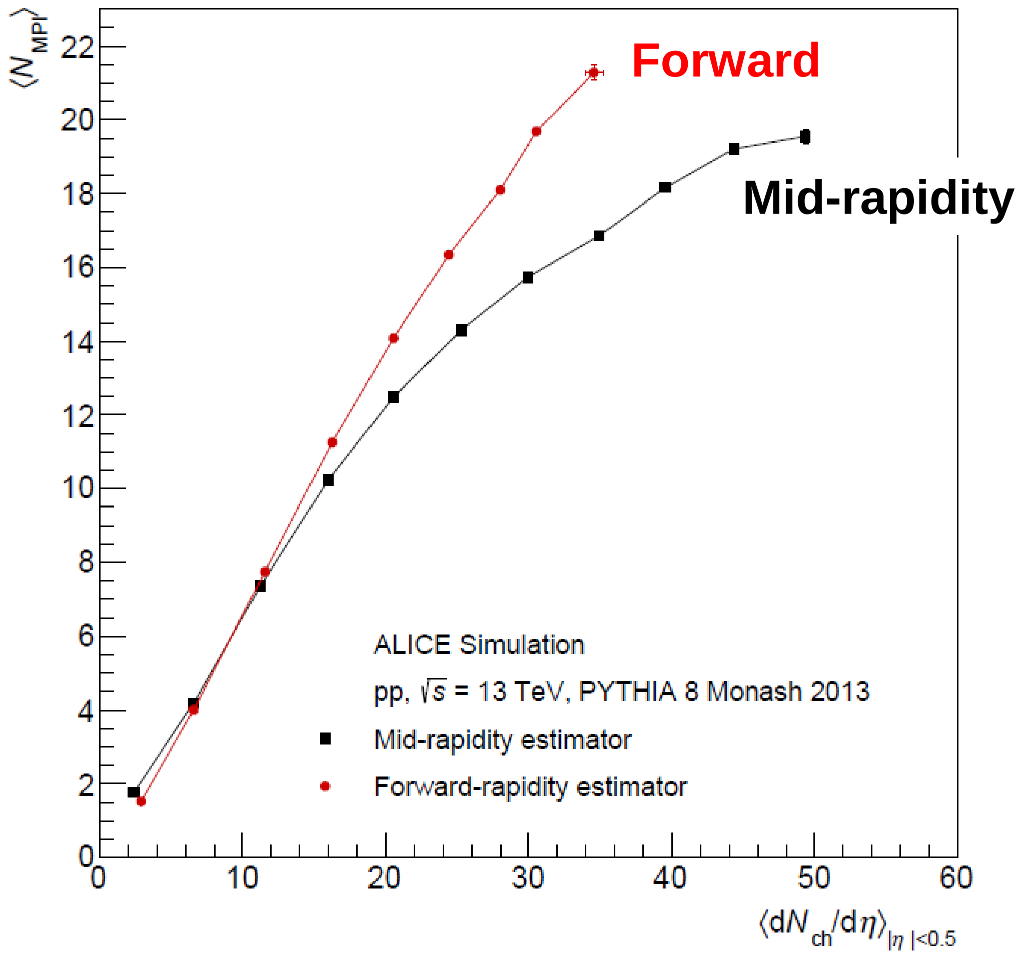
In comparisons: Biases need to be reproduced in model / Monte Carlo under study

Phys. Rev. C 91 (2015) 064905

Phys. Lett. B793 (2019) 420-432

Parton Interactions

- Multiplicity selects on MPIs, but depending on rapidity of estimator

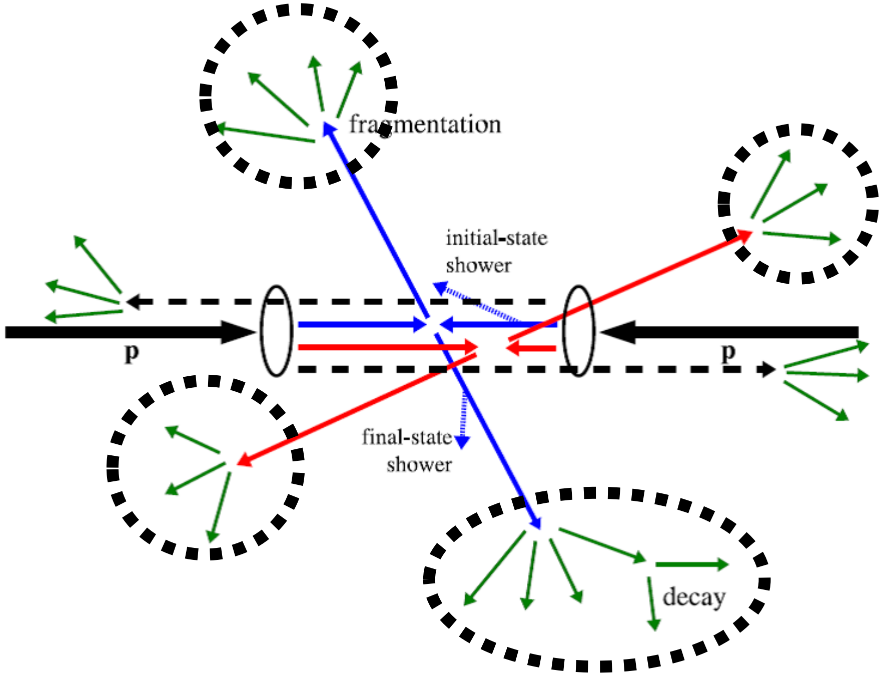


arXiv:2211.04384

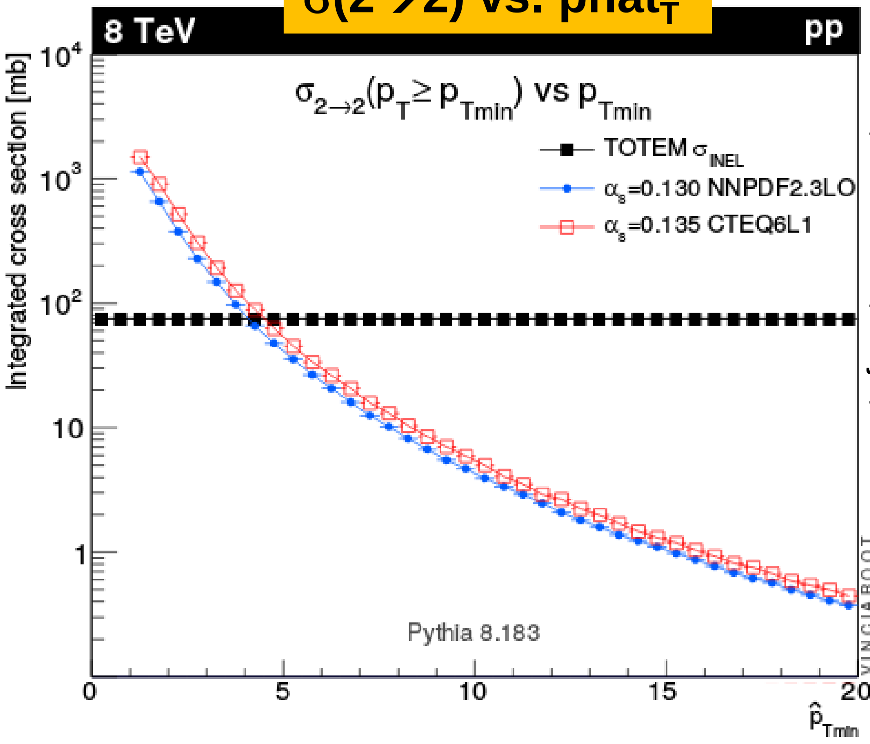
Measuring MPIs

Counting Parton Interactions with Uncorrelated Seeds

- Identify sets of particles stemming from same parton interactions (= seed)



σ(2→2) vs. phat$_T$



Skands, Carrazza, Rojo, arXiv:1404.5630

$$\left\langle N_{uncorrelated\ seeds}\right\rangle = \frac{\left\langle N_{trig}\right\rangle}{\left\langle 1 + N_{assoc,NS} + N_{assoc,AS}\right\rangle}$$

Total number of particles

trigger particle

How many particles belong "together"

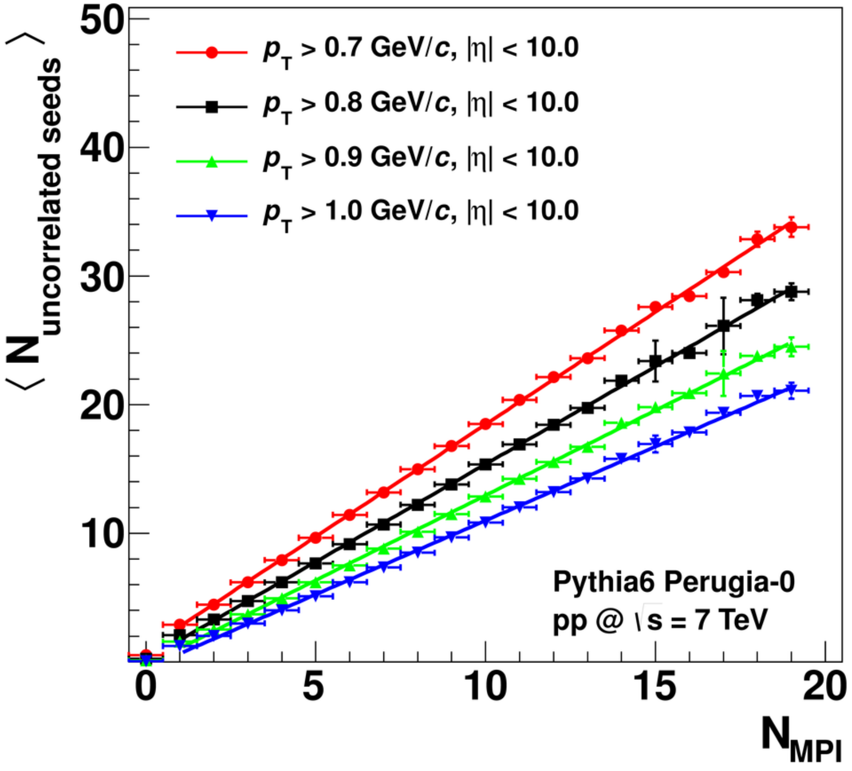
At high Q², traditional jet finding → identify each jet
At low Q², 1-2 particles → statistical approach

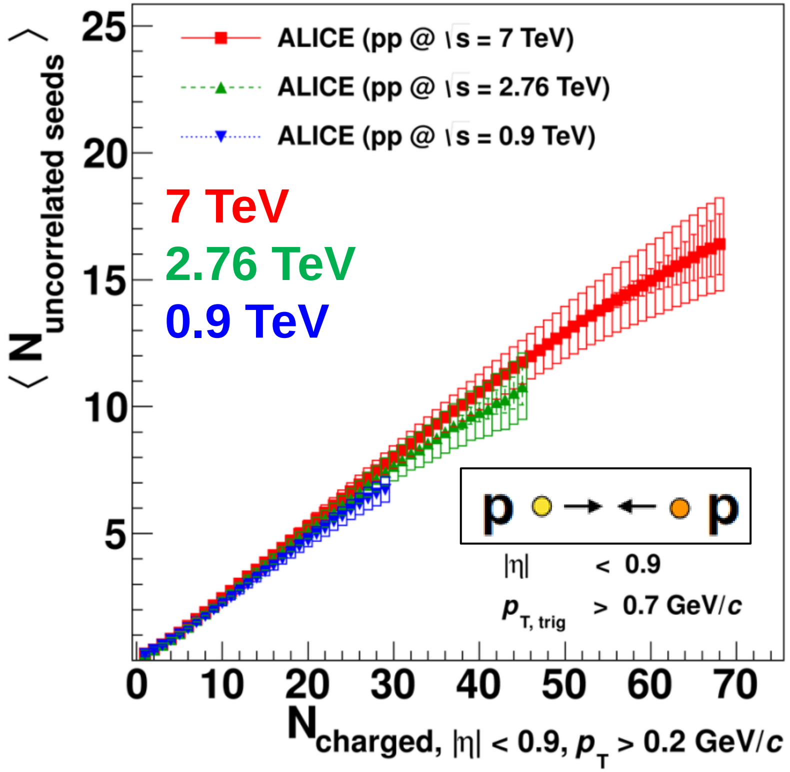
If we want to get a handle on the overall number of MPI, low Q² processes crucial

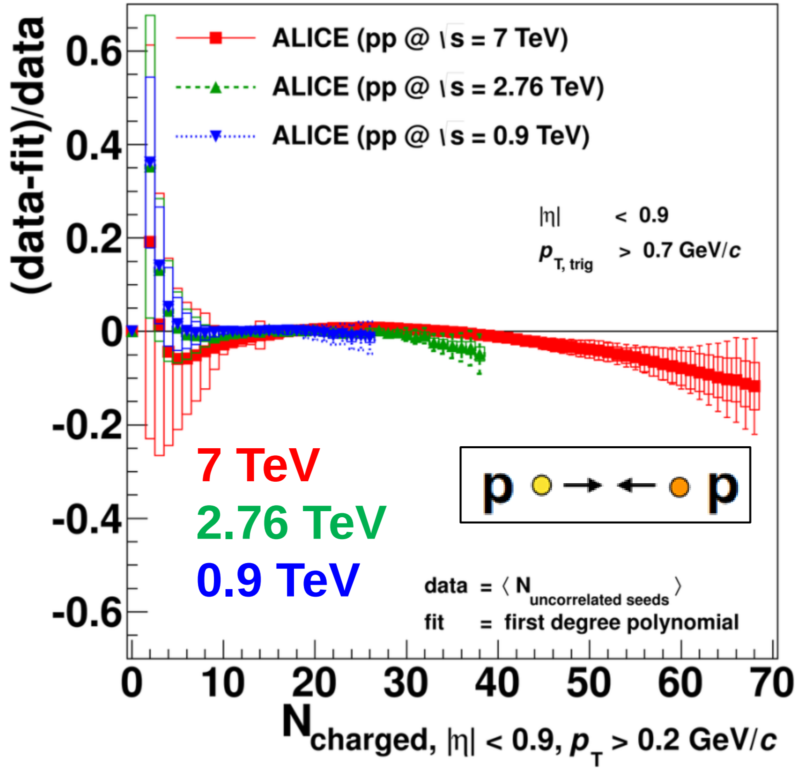
Uncorrelated Seeds

- Uncorrelated seeds (~ MPI) increase linearly with N_{ch}
- At large N_{ch}, limit of MPI?
  (i.e., larger multiplicity by fluctuation, not by additional MPI)

JHEP 09 (2013) 049





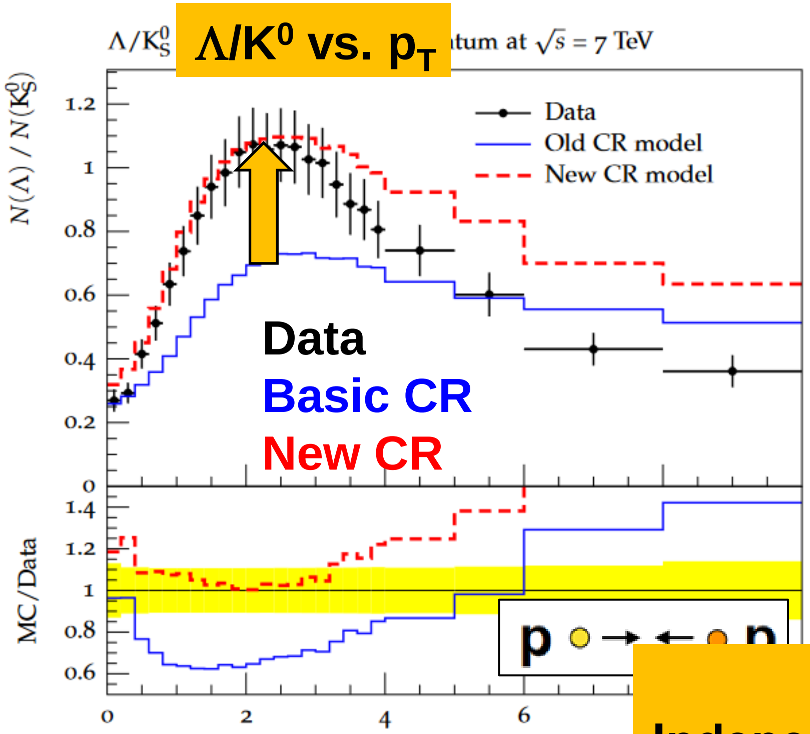


Identified Particles

Light-flavour sector

Baryon Production

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



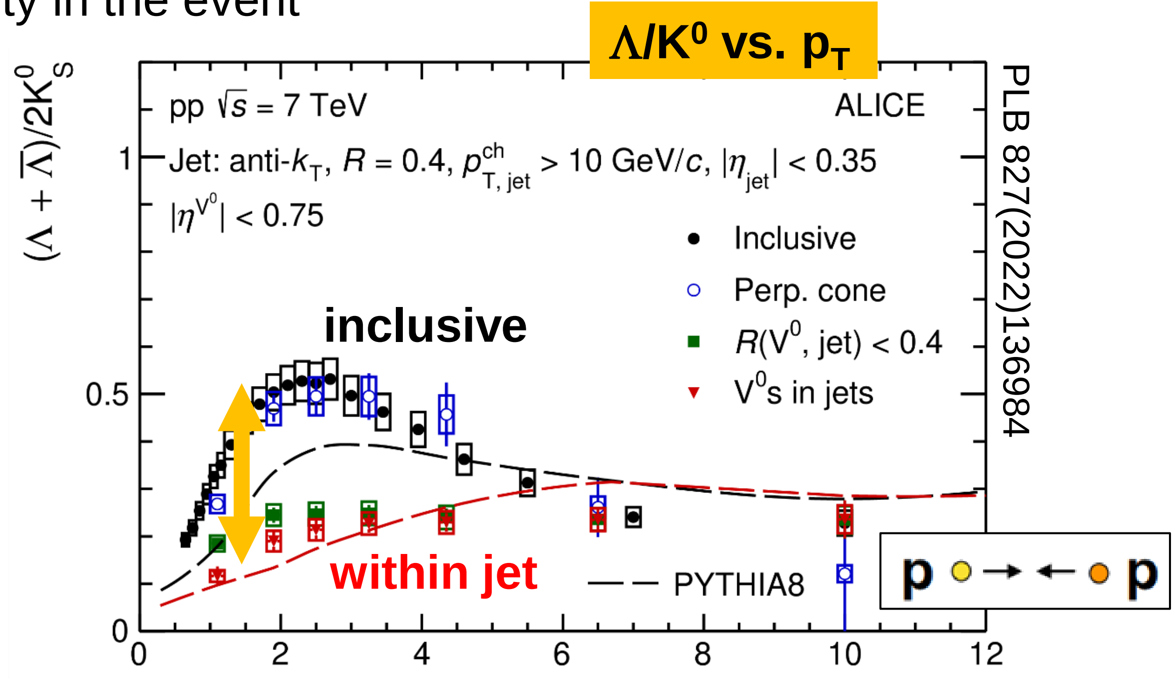
Λ/K^0 vs. p_T

Data

Basic CR

New CR

Christiansen, Skands, JHEP 08 (2015



Λ/K^0 vs. p_T

inclusive

within jet

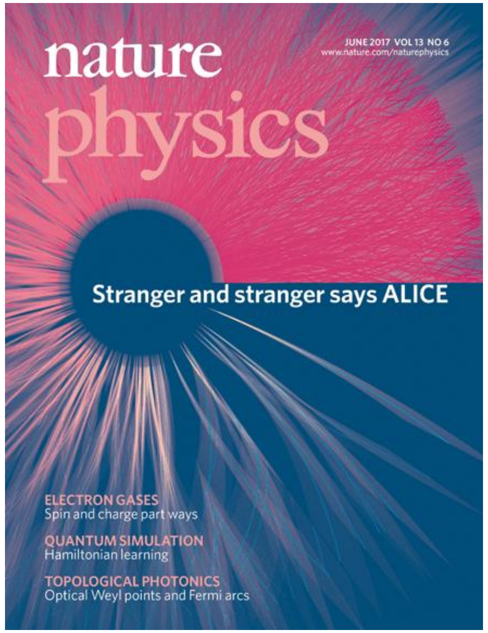
PLB 827(2022)136984

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

Strangeness Enhancement

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

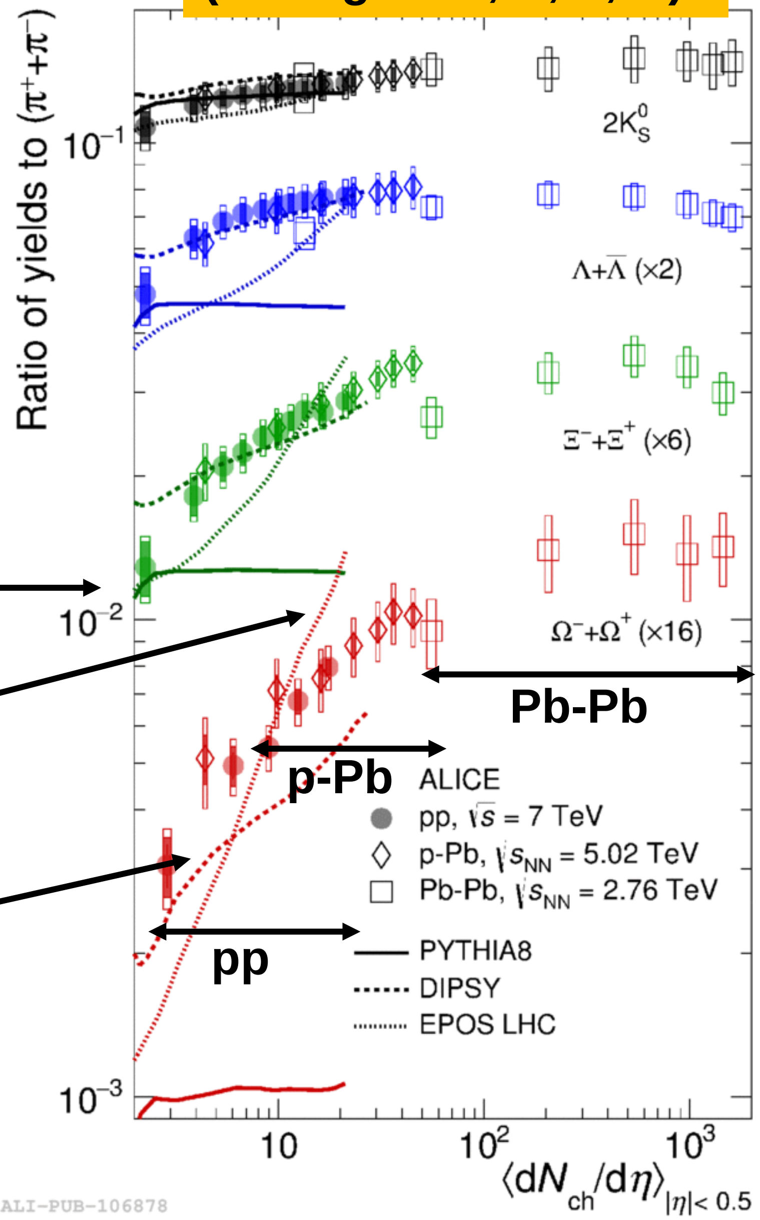
- Hadronization for strange particles density-dependent
- Strange particle production increases with multiplicity
  - K/π, Λ/π, Ξ/π, Ω/π
  - from pp, over p-Pb, to Pb-Pb



❌ Independent fragmentation

✅ EPOS (core-corona)

✅ Colour rope mechanism (DIPSY)

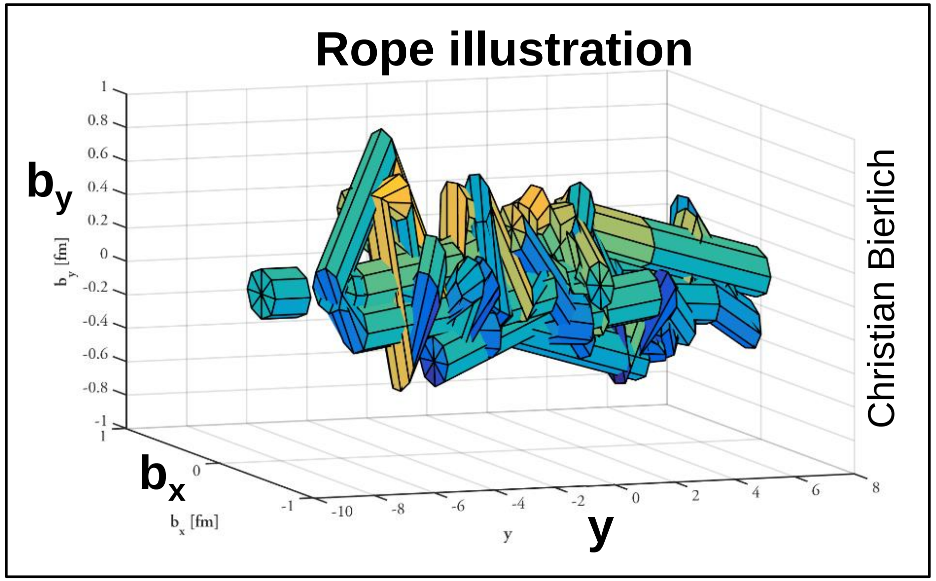


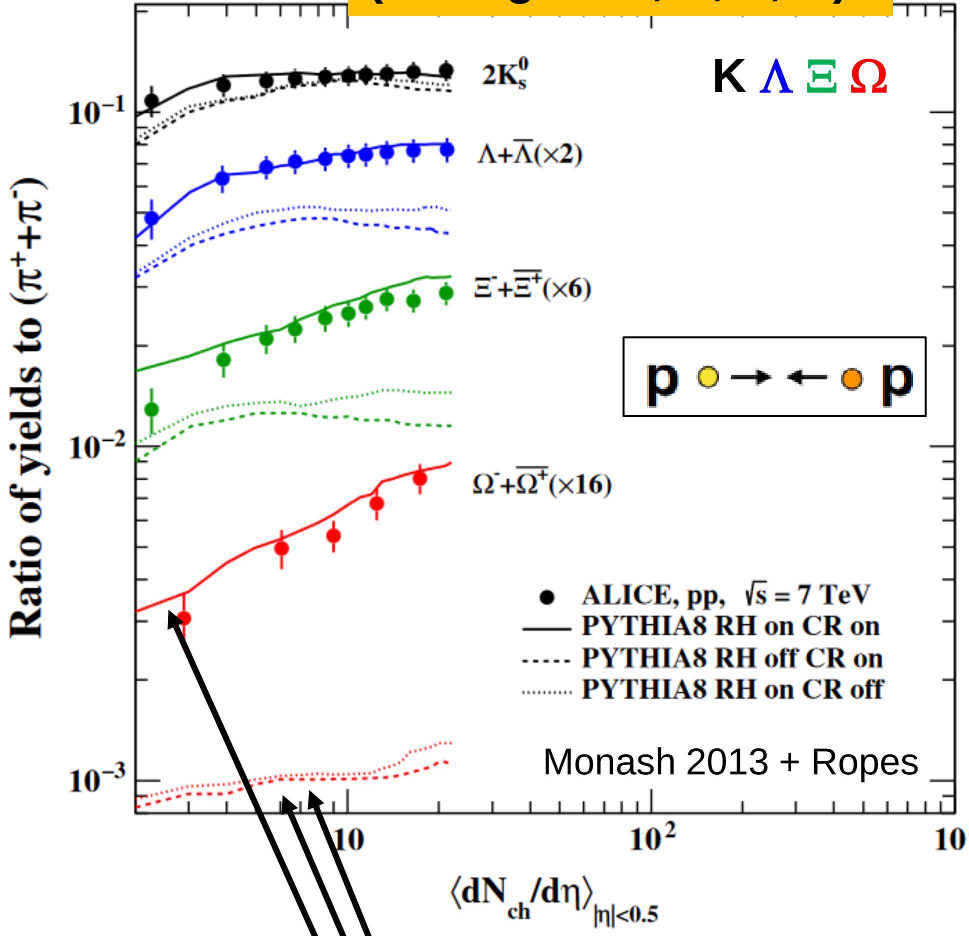
Nature Phys. 13 (2017) 535

Strangeness Enhancement (2)

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

- Colour ropes
  - Strings close in phase space hadronize together
  - Outwards pressure gradient
    → momentum perpendicular to the strings





Nayak, Pal, Dash, Phys. Rev. D 100, 074023

❌ **Colour reconnection**
❌ **Rope hadronization**
✅ **Both**

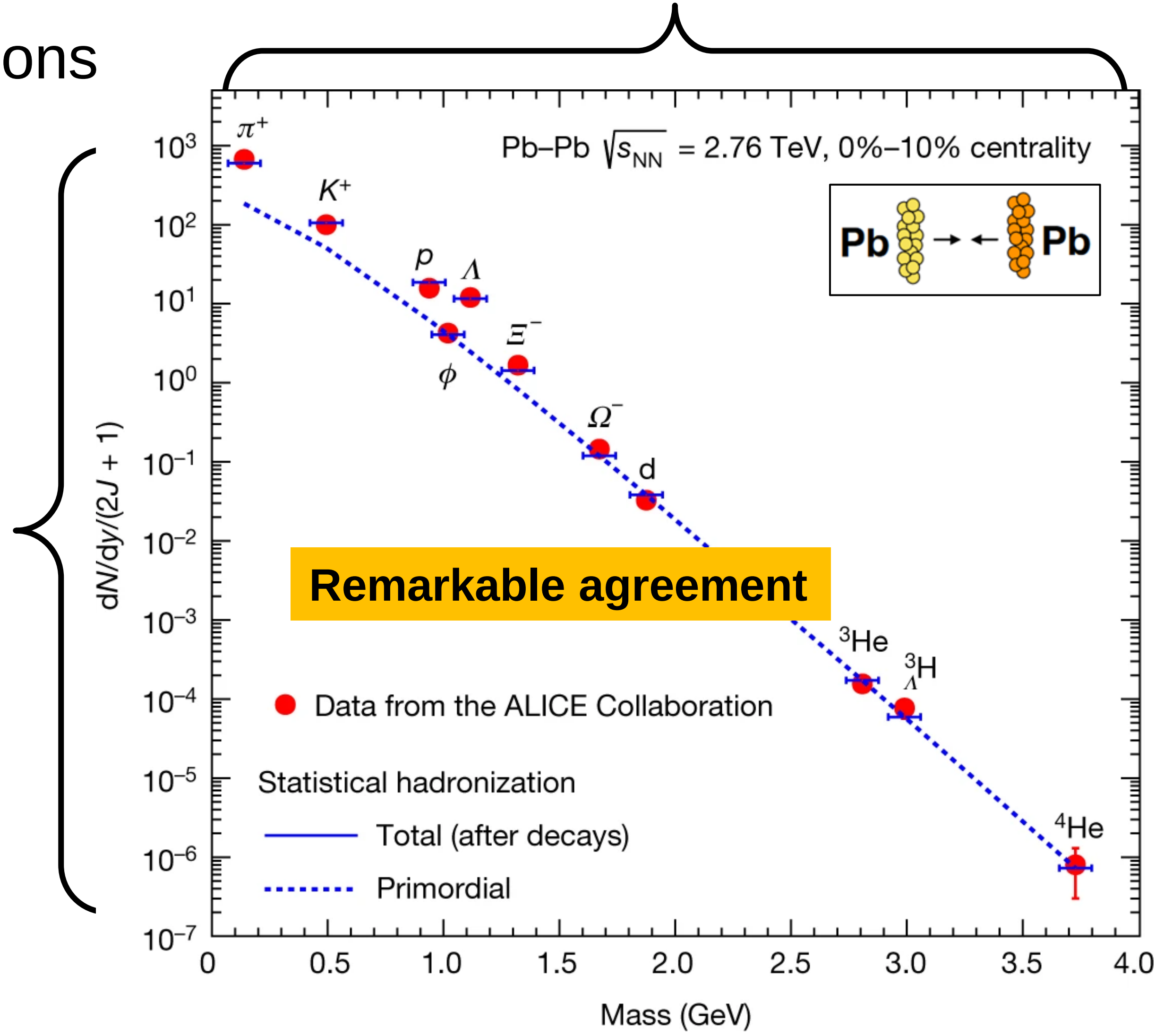
Both colour reconnection and ropes are needed

Statistical Hadronization Model (SHM)

- Relativistic ideal quantum gas of hadrons in thermal and chemical equilibrium
- 3 free parameters: V, T, μ_B
  - Particle ratios → V cancels
  - Baryochemical potential μ_B fixed by pbar/p ratio
  - → one remaining parameter T
- Central Pb-Pb
  - T = 156 ± 2 MeV
  - V ~ 5000 ± 500 fm^3
- Particle production without history
  - Macroscopic description only

11 different species

9 orders of magnitude



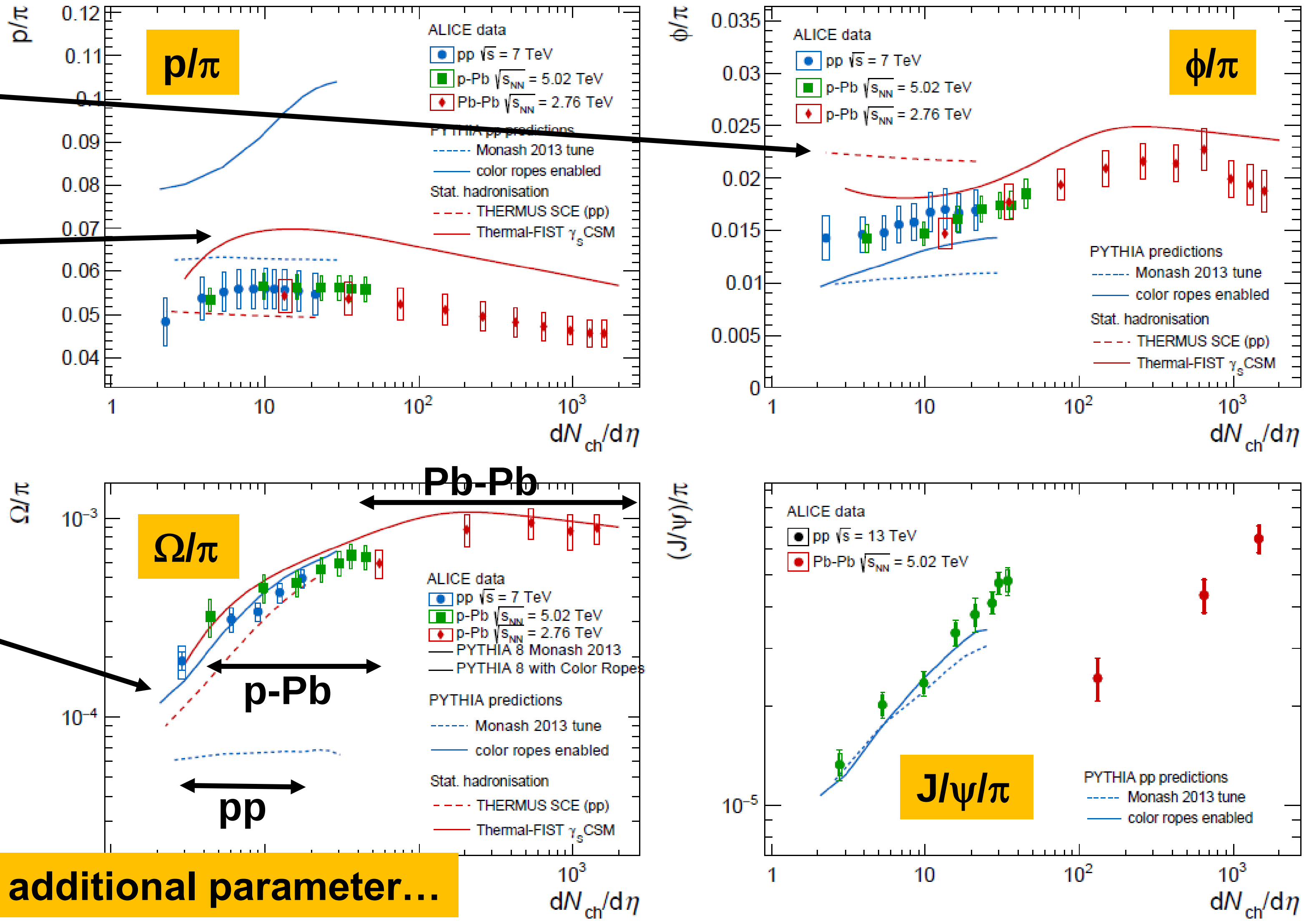
Remarkable agreement

Nature 561 (2018) 7723, 321

SHM in pp and p-Pb

arXiv:2211.04384

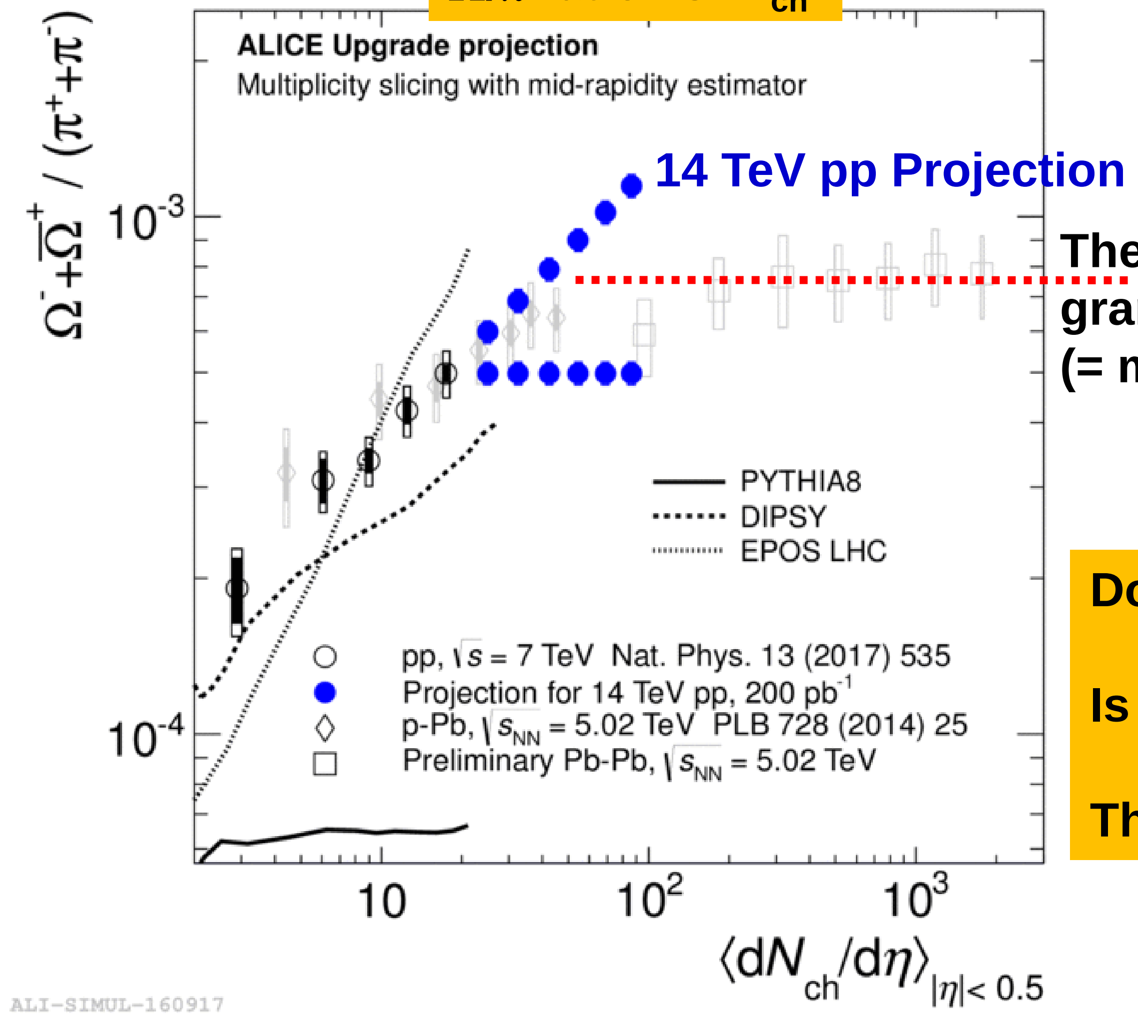
- THERMUS SCE
  - With fixed T
  - No good description
- Thermal-FIST
  - Multiplicity dependent T
  - Strangeness suppression parameter γ_S
  - Good description: ϕ/π and Ω/π
  - p/π only qualitative
- Colour ropes in Pythia
  - Successful for ϕ/π and Ω/π
  - Far off for p/π



SHM works in small systems but needs additional parameter…

Future of Strangeness Enhancement in pp

Ω/π ratio vs. N_{ch}



14 TeV pp Projection for full Run 3 sample

Thermal limit in
grand canonical ensemble
(= many body system in equilibrium)

CERN Yellow Report, arXiv:1812.06772

Does strangeness enhancement continue with same trend?

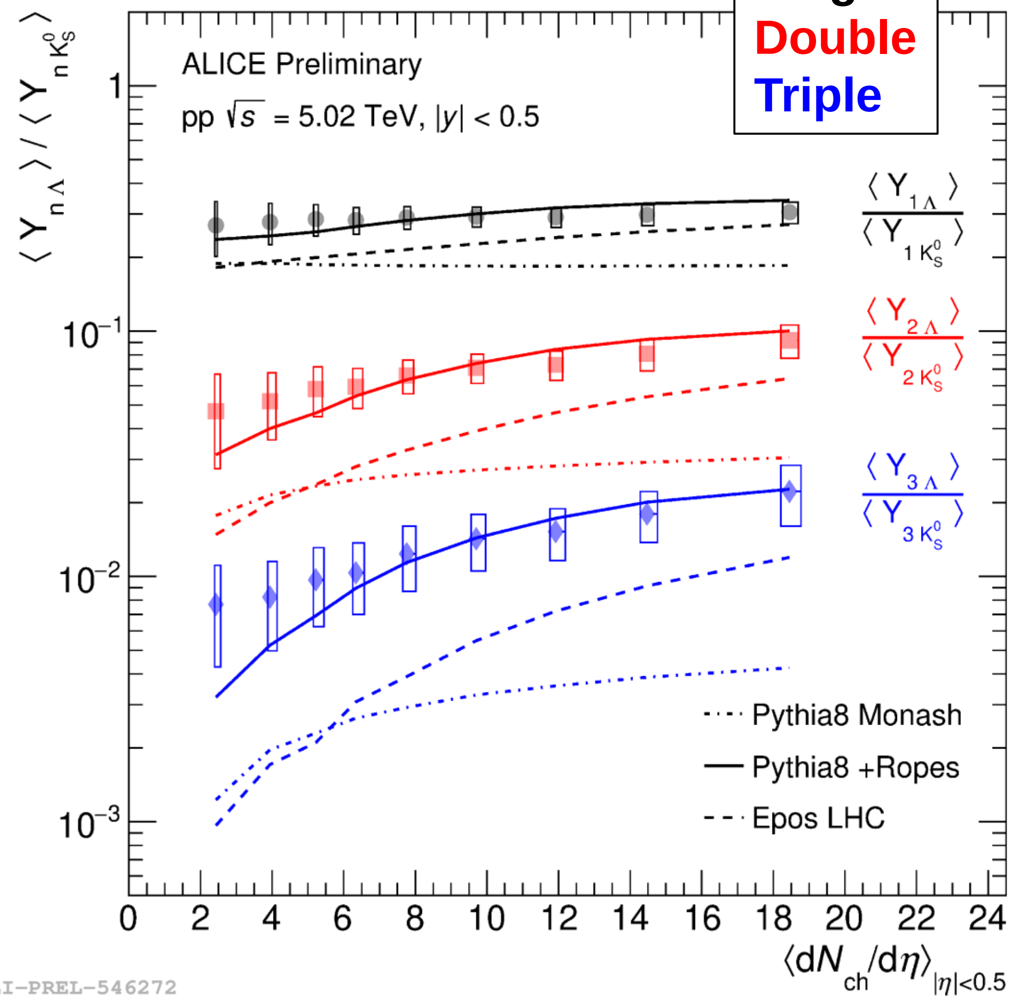
Is there a smooth connection to Pb-Pb?

Thermal limit reached or exceeded in pp?

Multiple Strange Production

- Multiple strange particle production in the same collision
  - Measured for K_0, Λ, Ξ, Ω, see e.g. QM talk

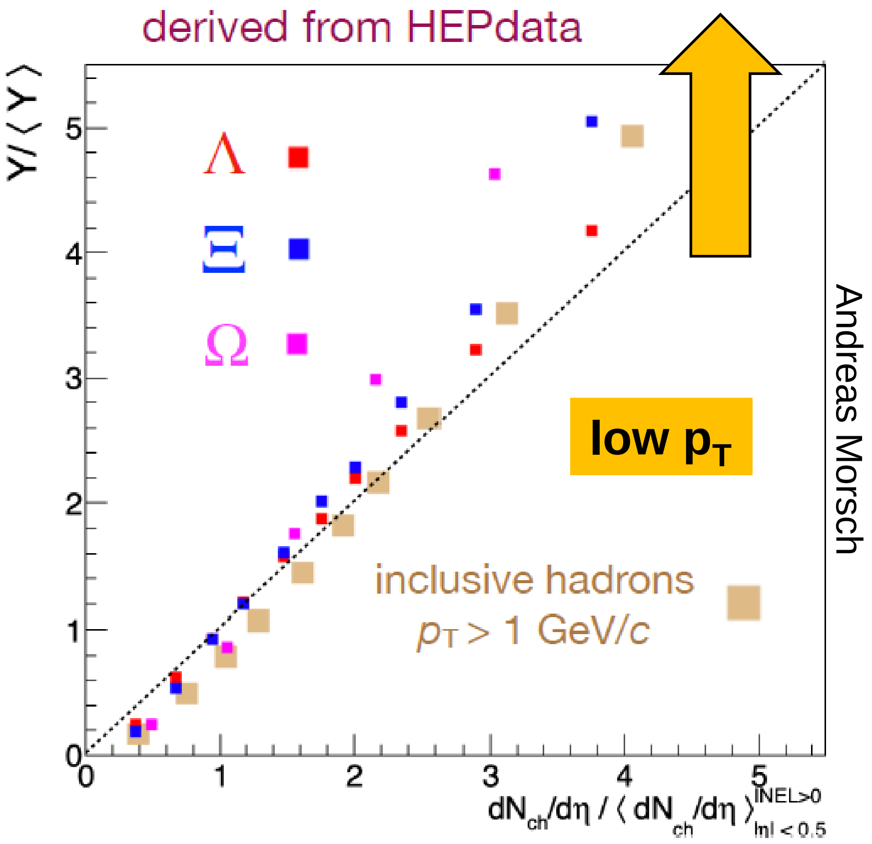
- Increase with multiplicity stronger for double or triple production
  - Strangeness-related increase *and* baryon-related increase?
  - Ropes are successful in description



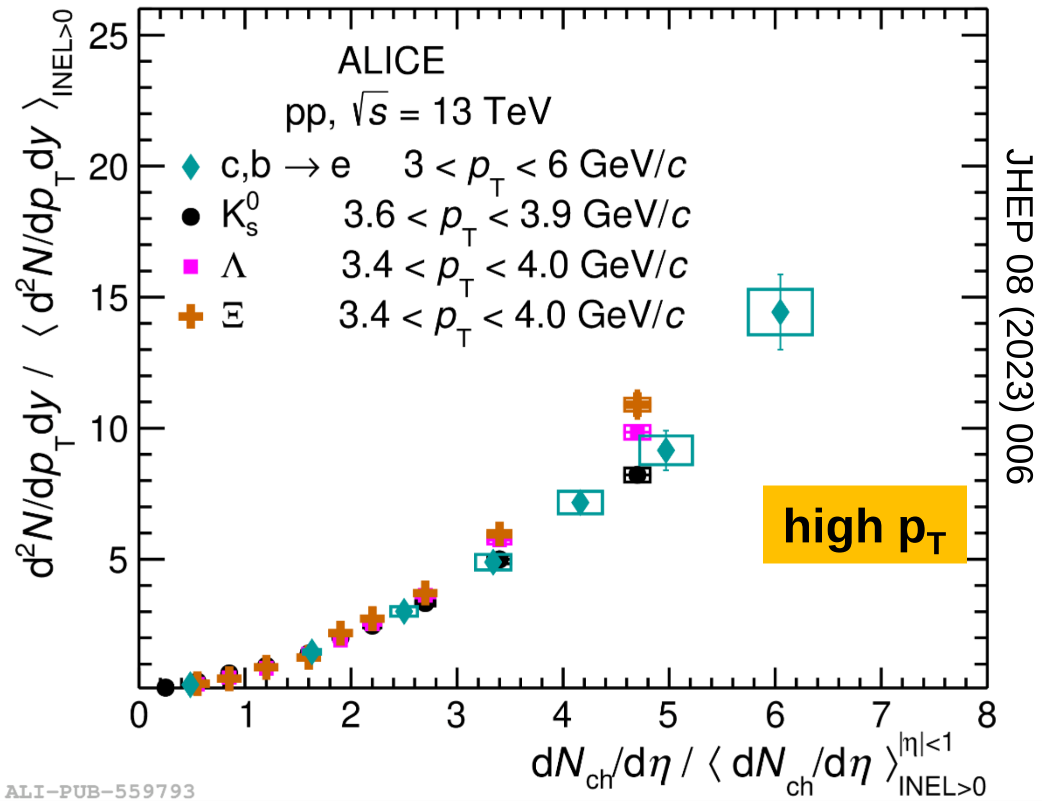
Single
Double
Triple

Species and p_T Dependence

- Low p_T and integrated yields: strangeness content dependence
- High p_T: species independent. Auto-correlation bias?



Andreas Morsch



JHEP 08 (2023) 006

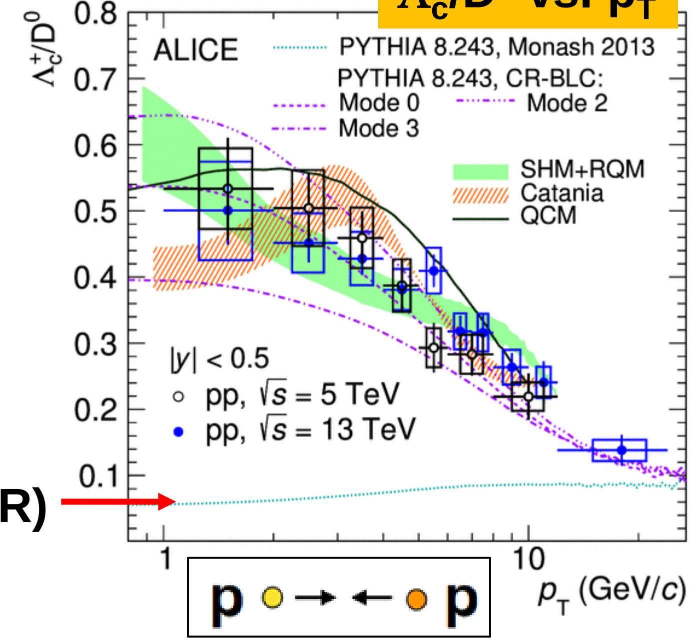
Identified Particles

Charm sector

Charm Sector

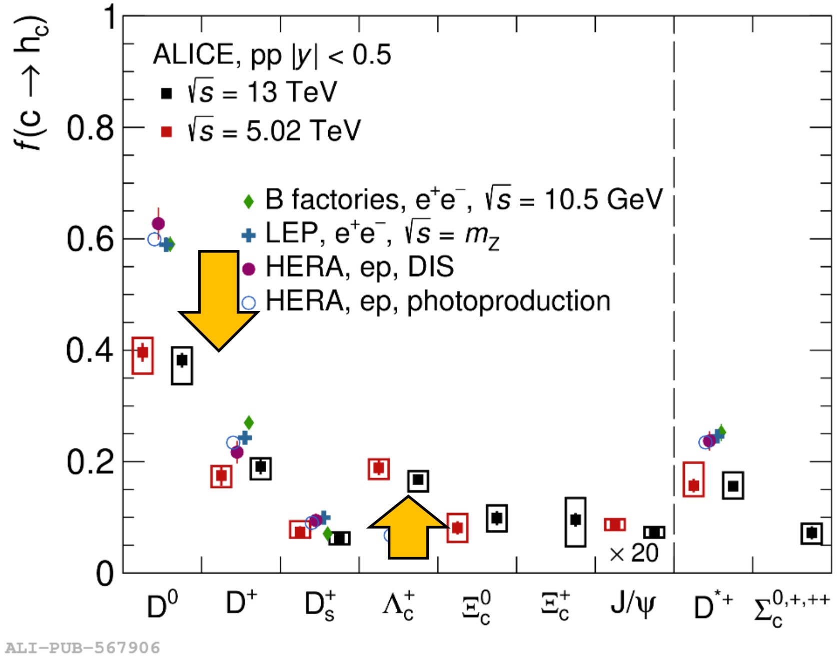
- Charm and beauty produced in hard scattering, rarely in string fragmentation
- Baryon enhancement also in charm sector
  - Λ_c/D significantly larger than e^+e^- expectation
- Pythia with reconnections beyond leading colour works well
- Significant effect on fragmentation fractions
  - Less D^0 in pp than in e^+e^- and ep
  - More Λ_c in pp than e^+e^- and ep

Λ_c/D^0 vs. p_T



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

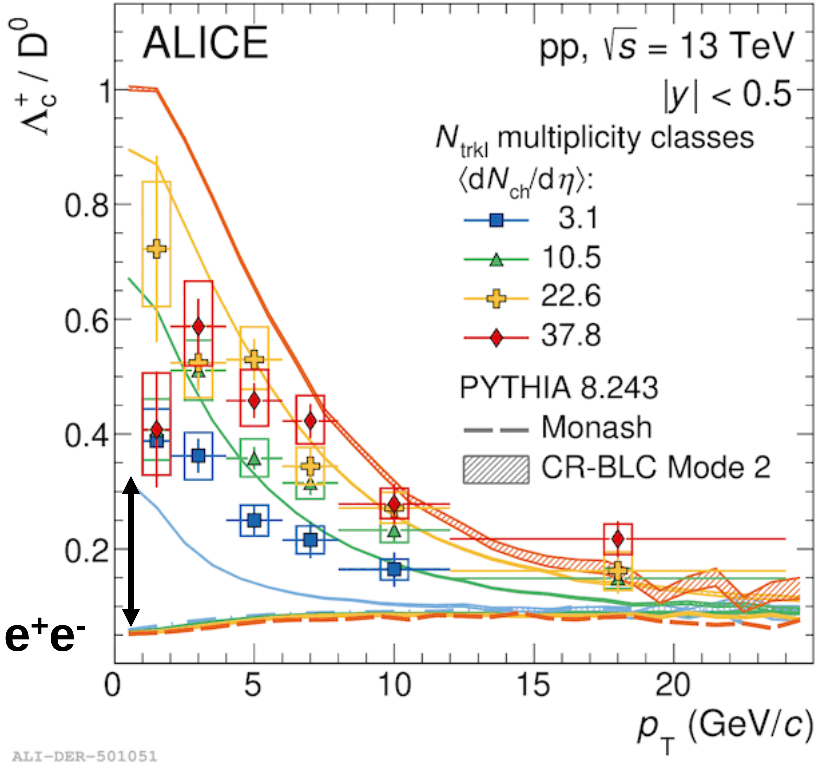
PRL128 (2022) 012001



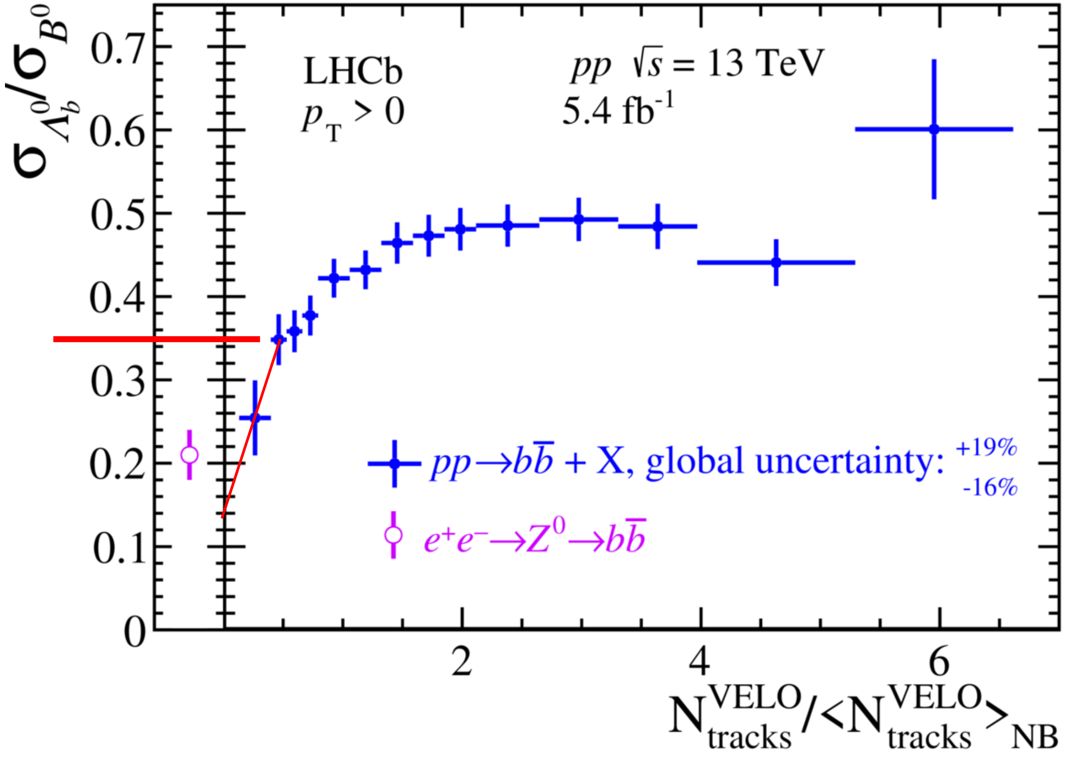
JHEP 12 (2023) 086

Low-Multiplicity pp and e^+e^-

- Λ_c/D ratio does not approach e^+e^- at low multiplicity
- Λ_b/B ratio approaches e^+e^-, depends on uncertainties at lowest point

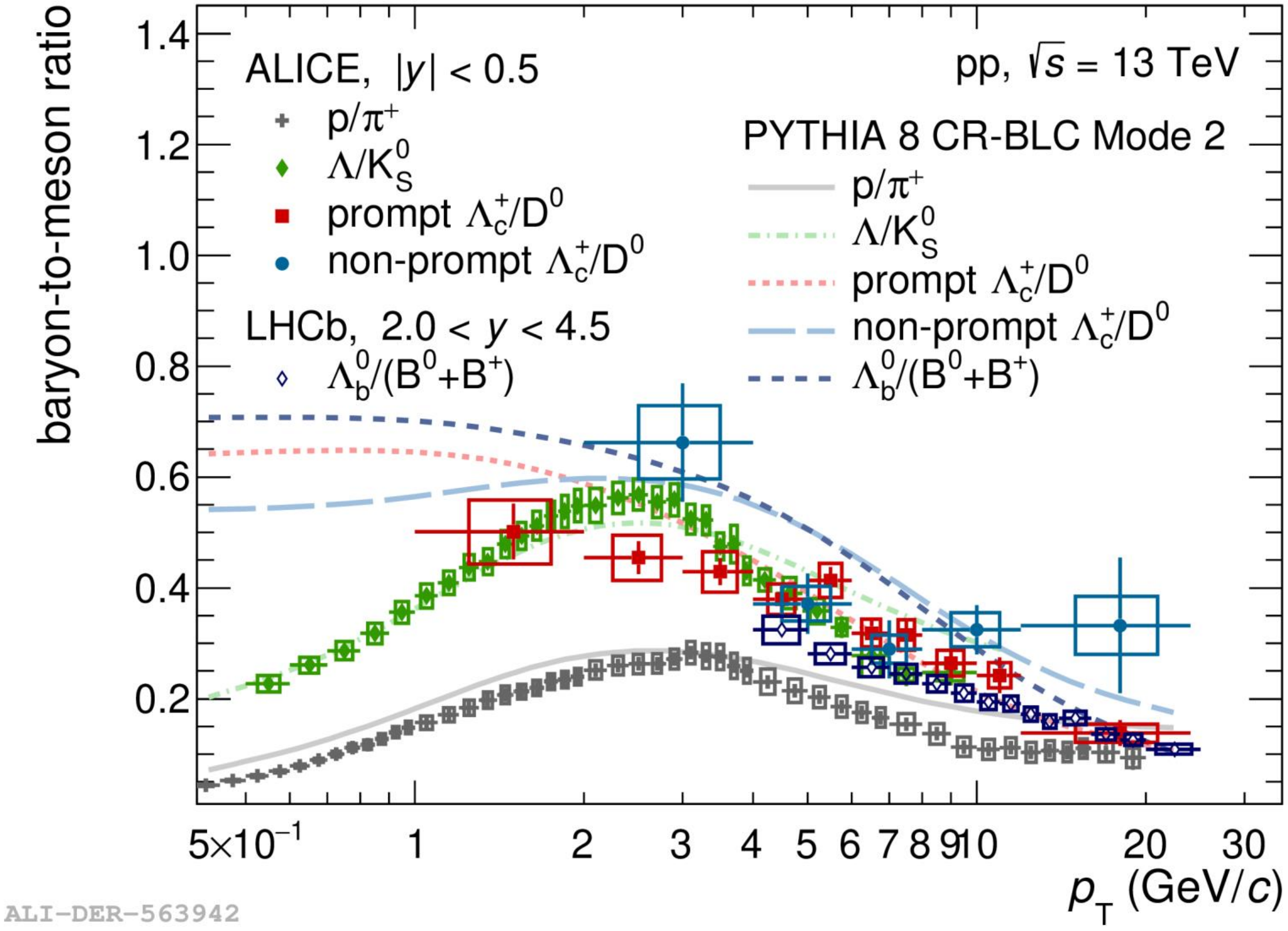


Phys. Lett. B 829 (2022) 137065



Phys. Rev. Lett. 132 (2024) 081901

A Beautiful Summary



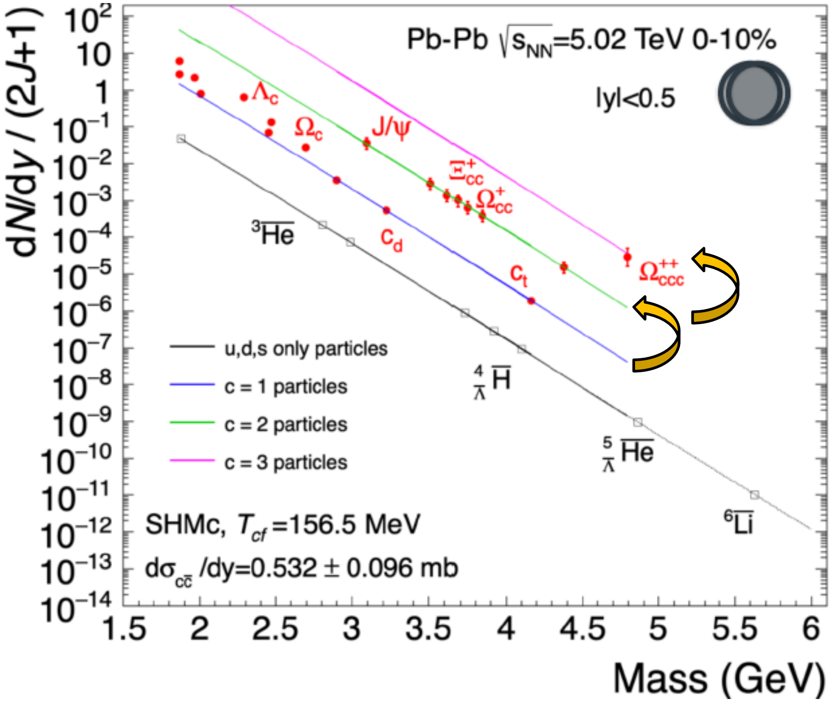
Phys. Rev. D 108, 112003 (2023)

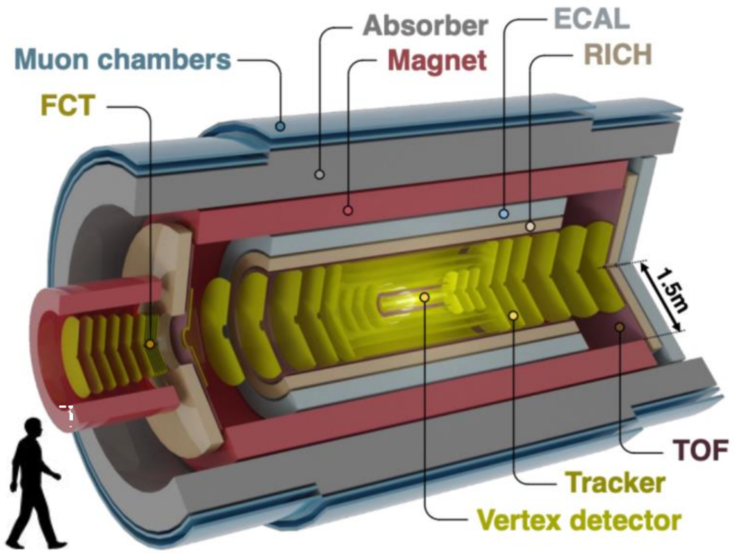
Outlook on Multi-Charm

- States with multiple charm ideal test bed for hadronization models
  - Largely enhanced in heavy ions (e.g. 100 for Ξ_{cc})
  - Measurement of Ξ_{cc}, Ω_{cc}, possibly Ω_{ccc}

$$\Xi_{CC}^{++} \to \Xi_{C}^{+}\pi^{+} \to \Xi^{-}\pi^{+}\pi^{+}\ \pi^{+} \qquad \Omega_{CC}^{+} \to \Omega_{C}^{0}\pi^{+} \to \Omega^{-}\pi^{+}\ \pi^{+}$$

  - Testing coalescence picture on quark level
- Detector proposal for LHC Run 5 (2035): ALICE 3
  - Retractable vertex detector 5 mm from beam
    - Pointing resolution 3-4 μm @ 1 GeV
    - X/X_0 ~ 0.1% per layer
  - All-silicon tracker (p_T resolution 1% @ 1 GeV)
  - Continues readout and online processing
    Pb-Pb: 35 nb^{-1} | pp 18 fb^{-1}





arXiv:2211.02491

Summary

- ALICE unique for particle identification and low p_T tracking
- Mind the biases in all comparisons

- Evolution from e^+e^- over pp and p-Pb to Pb-Pb allows new insights
  - Baryon/meson ratios, fragmentation fractions, strange & charm, multi-particle correlations

- Different hadronization concepts describe different observations
  - From colour reconnection over coalescence to statistical hadronization
  - Various mechanisms “active” in the same collision

- Challenge to find *universal* hadronization model for these complex phenomena

Thank you for your attention!

Thanks for input & discussions to: Katarina Gajdosova, Alexander Kalweit and Andreas Morsch

Backup

- Monash 2013 tune + ropes

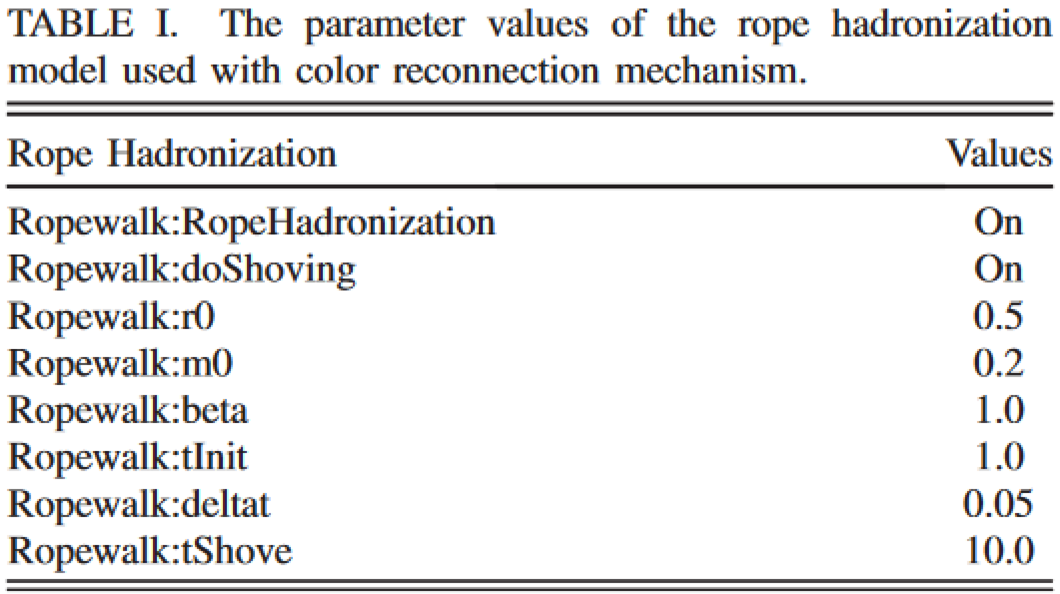
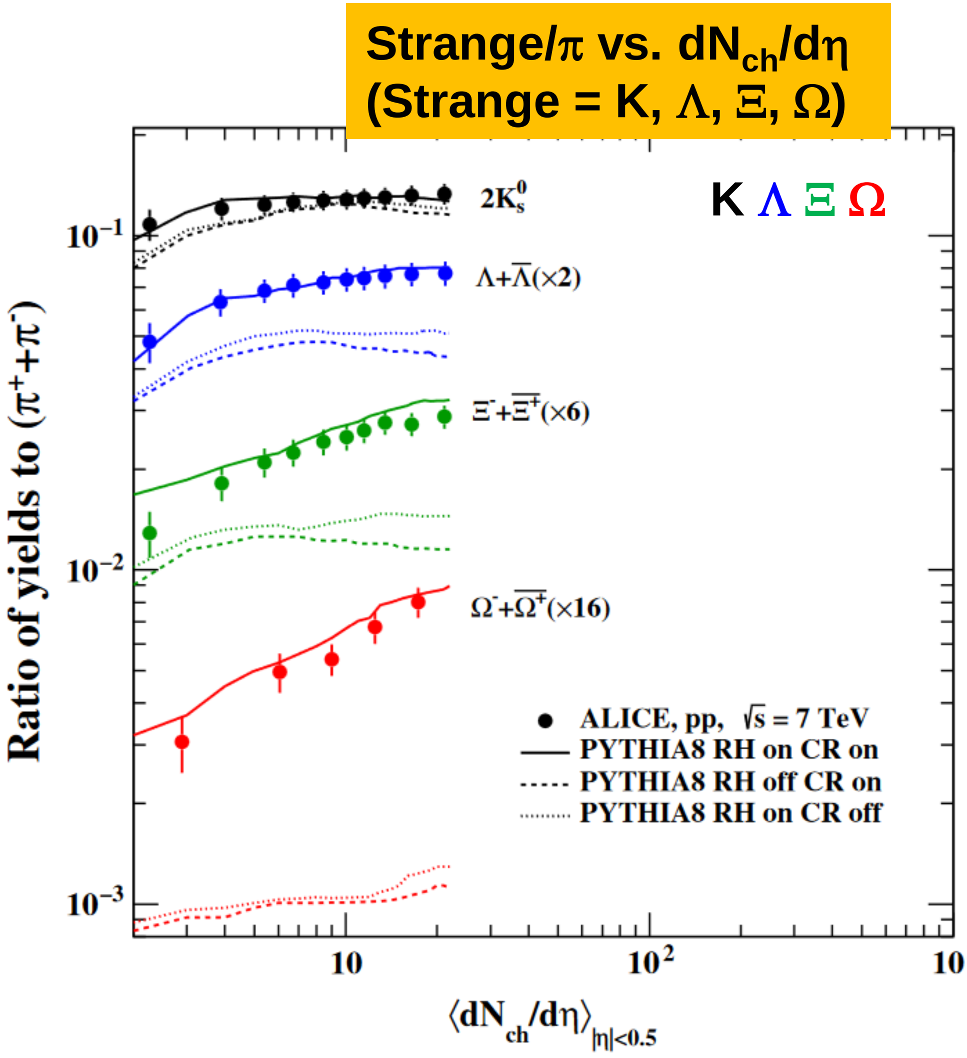


TABLE I. The parameter values of the rope hadronization model used with color reconnection mechanism.

Rope Hadronization	Values
Ropewalk:RopeHadronization	On
Ropewalk:doShoving	On
Ropewalk:r0	0.5
Ropewalk:m0	0.2
Ropewalk:beta	1.0
Ropewalk:tInit	1.0
Ropewalk:deltat	0.05
Ropewalk:tShove	10.0



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

K Λ Ξ Ω

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