Production of strange particles in jets and underlying events in pp and p-Pb collisions with ALICE

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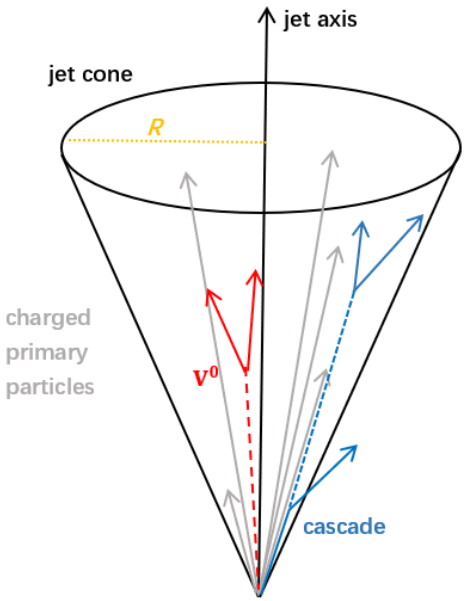
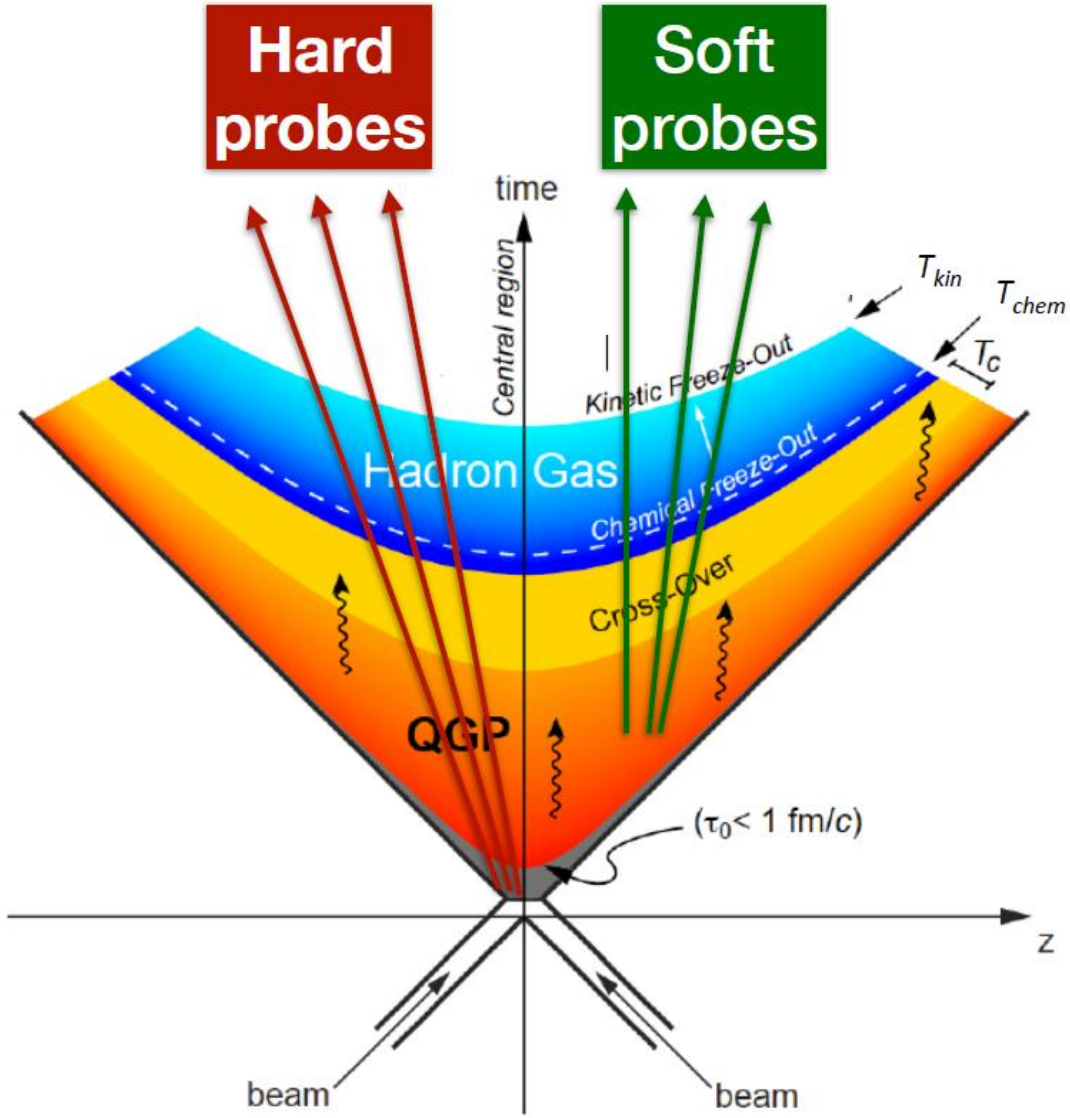
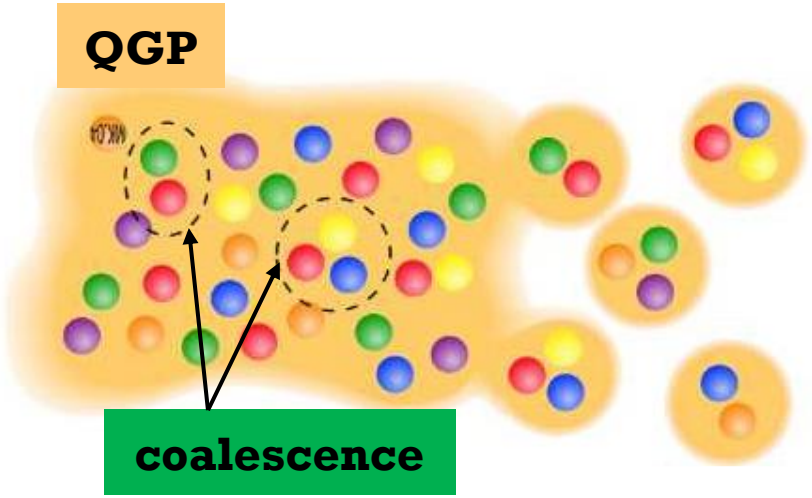


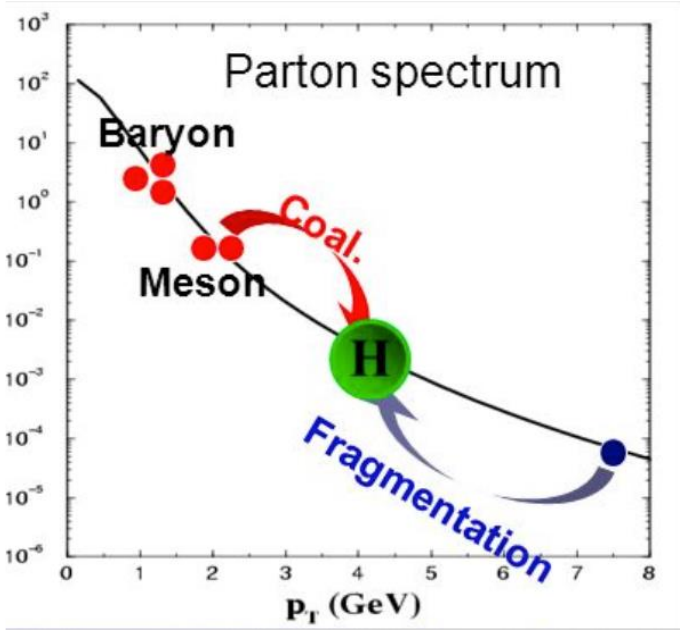
Quark gluon plasma



- **Heavy-ion collisions** probe the strongly interacting matter — the quark-gluon plasma (QGP) under extreme conditions of high temperature and energy density
- **Hard probes** created at initial stage of the collision
  - jet, heavy flavor… …
- **Soft probes** created in the “fireball”
  - Collective expansion: results in complex azimuthal structure of final state particles

Hadronization in heavy-ion collisions





- **Fragmentation** — hadrons from high p_T (hard) partons

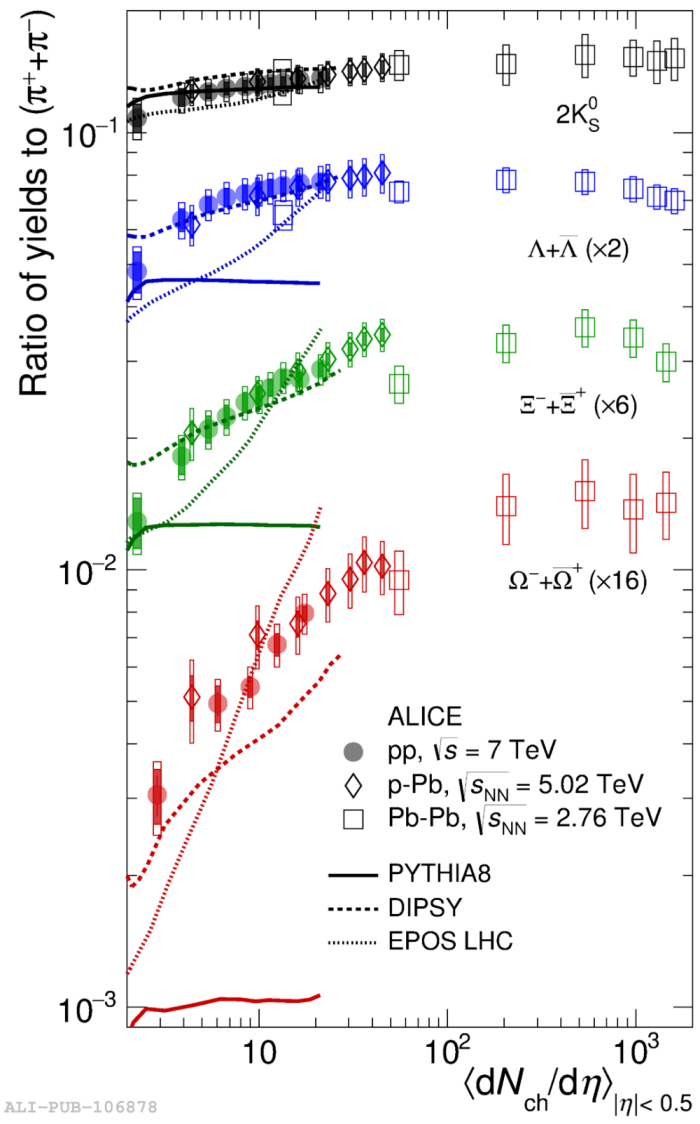
- **Coalescence/recombination** — hadron formation via (di-)quark combination in the QGP medium
  - $p_{T,\,\mathrm{hadron}} \simeq n\, p_{T,\,\mathrm{parton}}$, n = 2 (meson), 3 (baryon)
  - Sensitive to baryon and meson species
  - Baryons from lower momenta partons (denser)

Rapp et al. Phys. Lett. B655 (2007) 126

Greco et al. Phys.Rev. C92 (2015) 054904

Ko et al. Phys. Lett. B792 (2019) 132

Strangeness enhancement

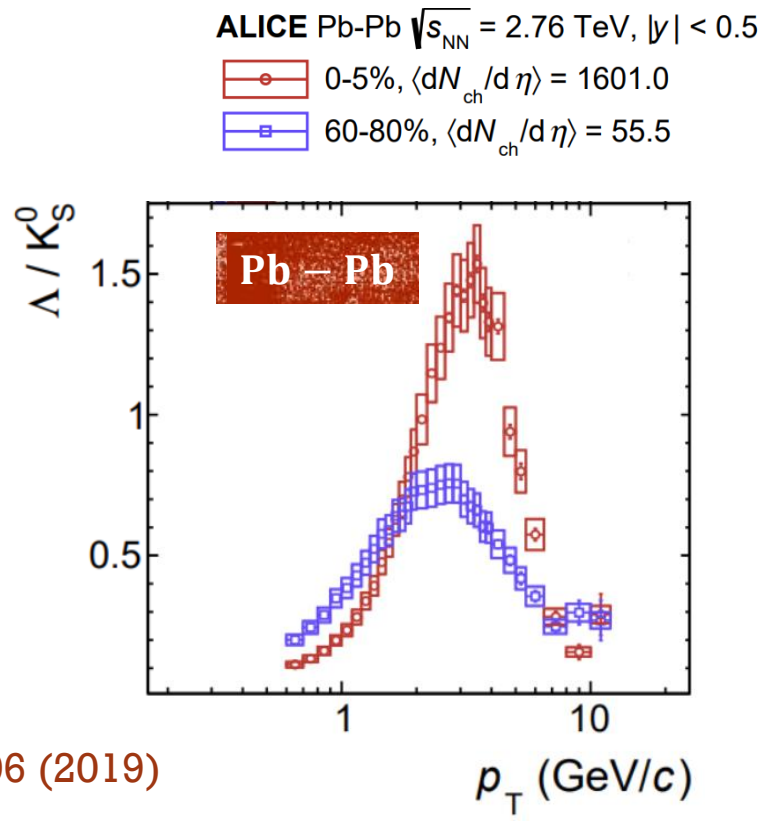


Strangeness enhancement:

- The ratio between (multi-)strange hadron and $\pi^{\pm}$ yields increases with multiplicity in pp, p-Pb and Pb-Pb collisions
- Smooth evolution with charged-particle multiplicity across different collision systems
- No dependence on the collision energy
- The enhancement is larger for particles with larger strangeness content ($\Omega > \Xi > K^0_S$)

Nature Phys. 13 (2017) 535-539, Eur. Phys. J. C 80, 167 (2020)

Baryon to meson enhancement

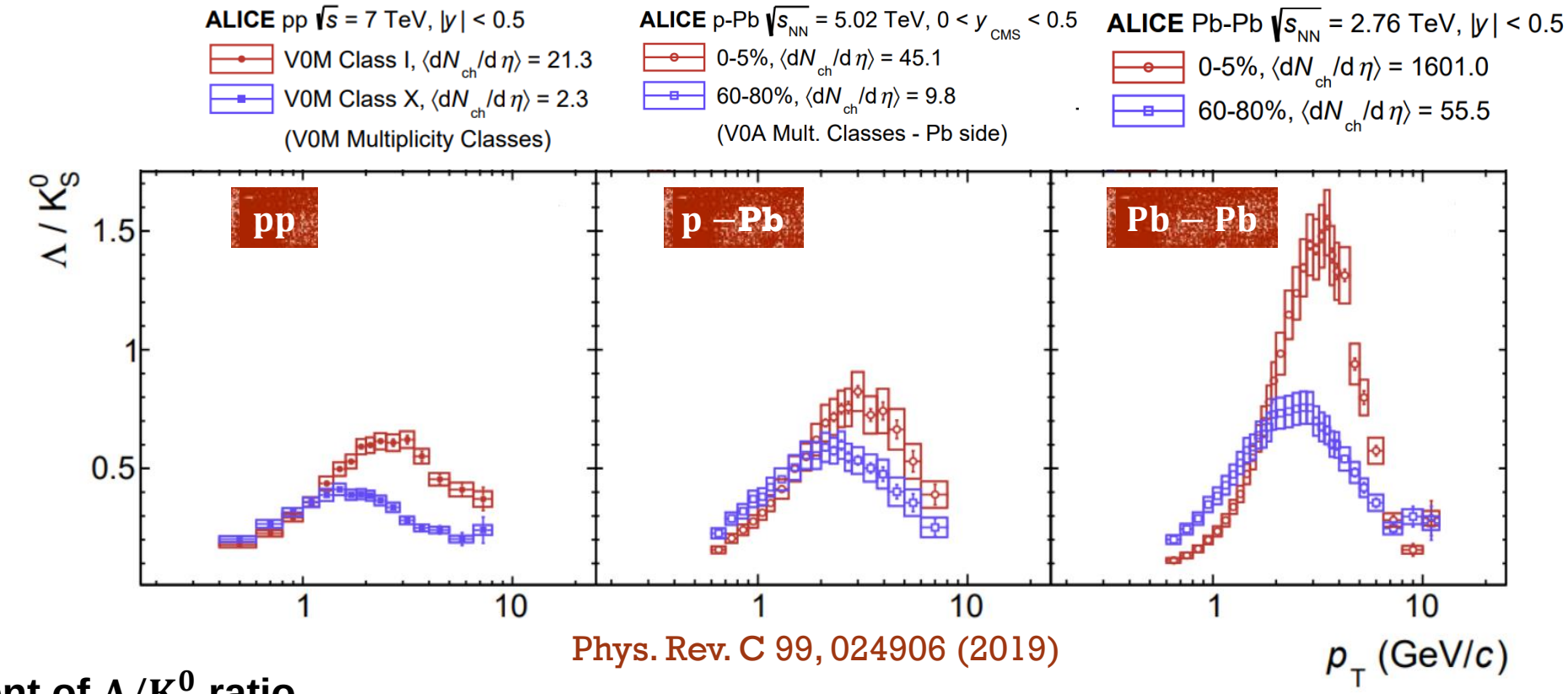


Phys. Rev. C 99, 024906 (2019)

Enhancement of Λ/K_S^0 ratio

- Baryon-to-meson ratio (Λ/K_S^0) increases at intermediate p_T in central Pb-Pb collisions w. r. t. peripheral ones
  - Interplay of radial flow and coalescence
  - Reflects QGP effects in heavy-ion collisions

Baryon to meson enhancement

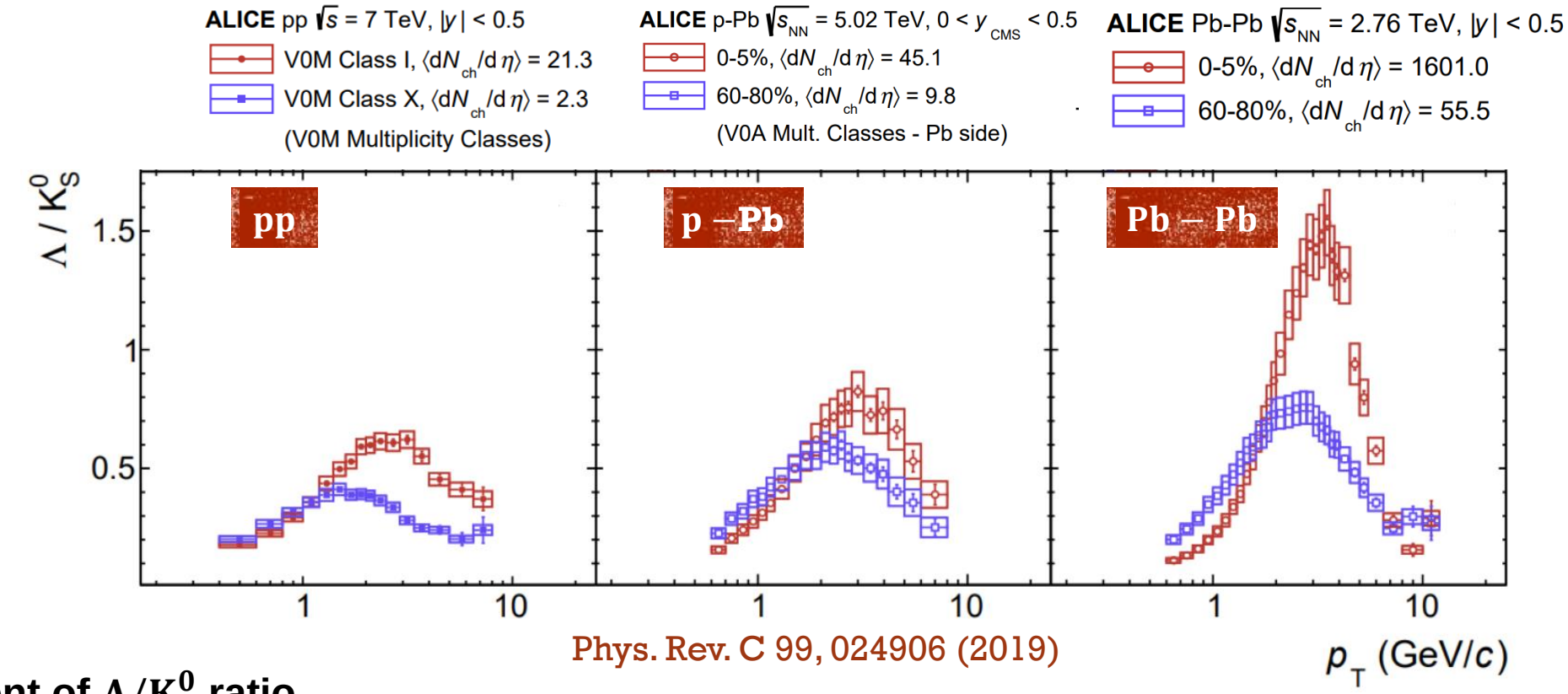


Phys. Rev. C 99, 024906 (2019)

Enhancement of $\Lambda/\mathrm{K}^0_\mathrm{S}$ ratio

- Baryon-to-meson ratio ($\Lambda/\mathrm{K}^0_\mathrm{S}$) increases at intermediate p_T in central Pb-Pb collisions w. r. t. peripheral ones
- $\Lambda/\mathrm{K}^0_\mathrm{S}$ ratio enhancement at intermediate p_T ($\sim 3\ \mathrm{GeV}/c$) in high multiplicity pp and p-Pb collisions w.r.t low multiplicity collisions
- This effect grows with $< \mathrm{d}N_\mathrm{ch}/\mathrm{d}\eta >$

Baryon to meson enhancement



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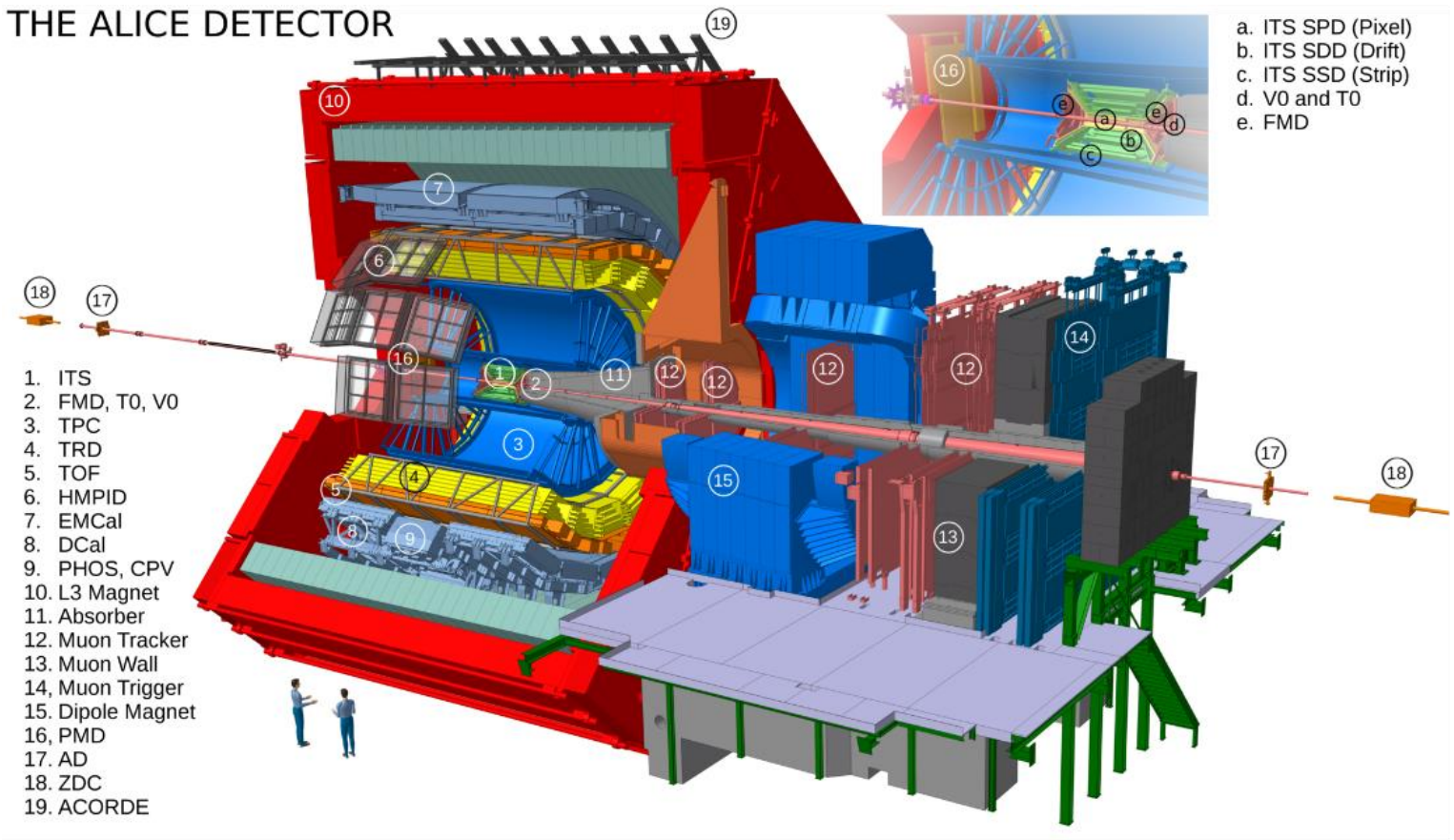
Study of strange particles in jets and the UE in pp and p-Pb collisions

Jets provide a natural reference to separate particles produced in hard processes and the underlying event

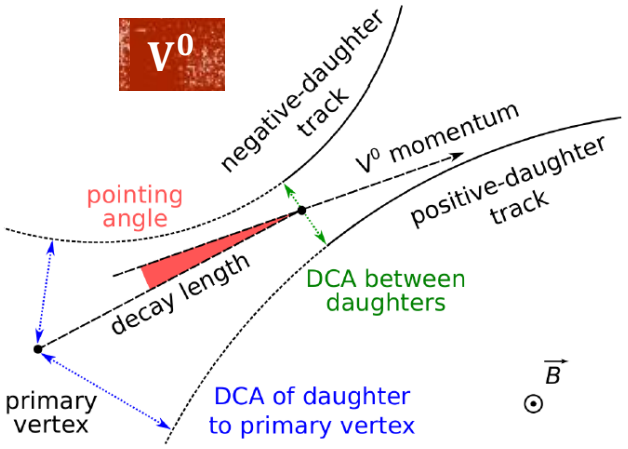
Experimental setup

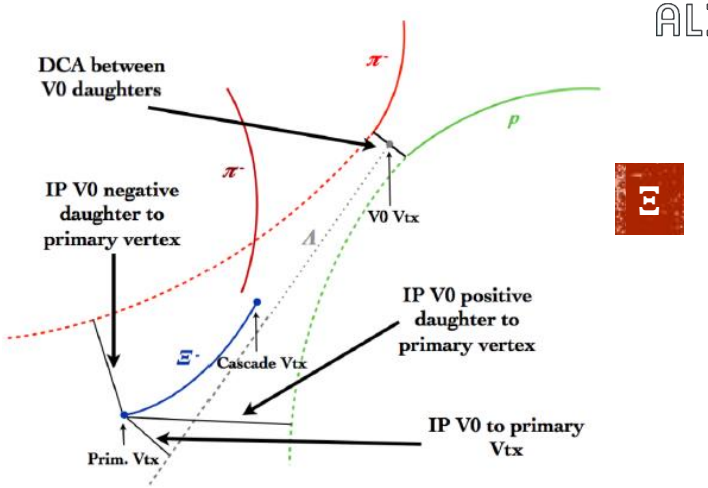


- TPC (Time Projection Chamber)
  - $|\eta|<0.9$
  - Charged particle tracking
  - Particle identification
- ITS (Inner Tracking System)
  - $|\eta|<0.9$
  - Vertex reconstruction
  - Event trigger
- V0A + V0C
  - $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$
  - Event multiplicity class determination
  - Event trigger

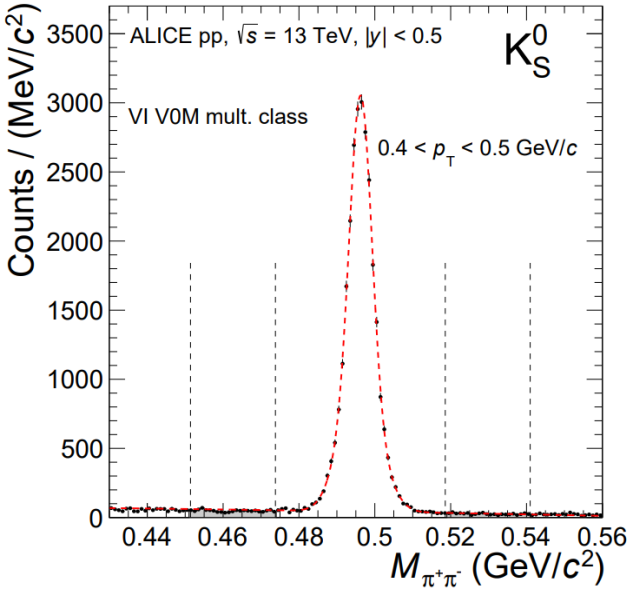
Strangeness reconstruction

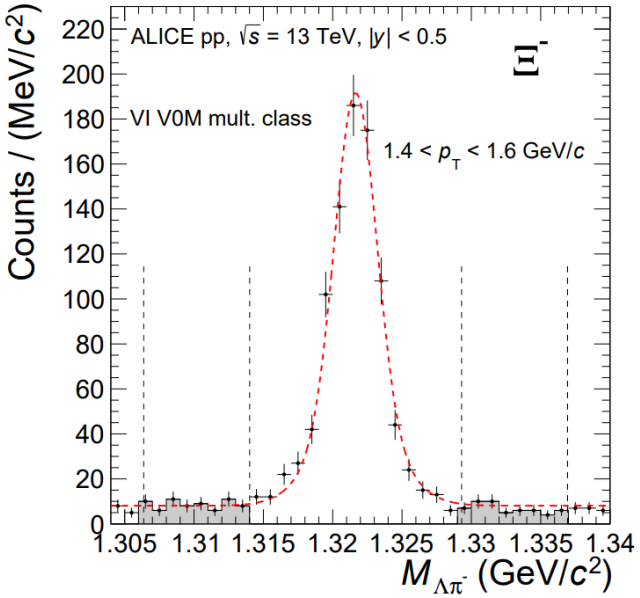
- Decay channels
  - $K_S^0 \rightarrow \pi^+ + \pi^-$ (BR 69.2%)
  - $\Lambda \rightarrow p + \pi^-$ (BR 63.9%)
  - $\Xi^- \rightarrow \Lambda + \pi^- \rightarrow p + \pi^- + \pi^-$ (BR 63.9%)





- Candidate selection
  - Pairs/triplets of tracks with proper charge-sign combination
  - Particle identification of decay tracks
  - Geometrical and kinematic selections based on decay topology





ALICE Eur. Phys. J. C80 (2020) 167

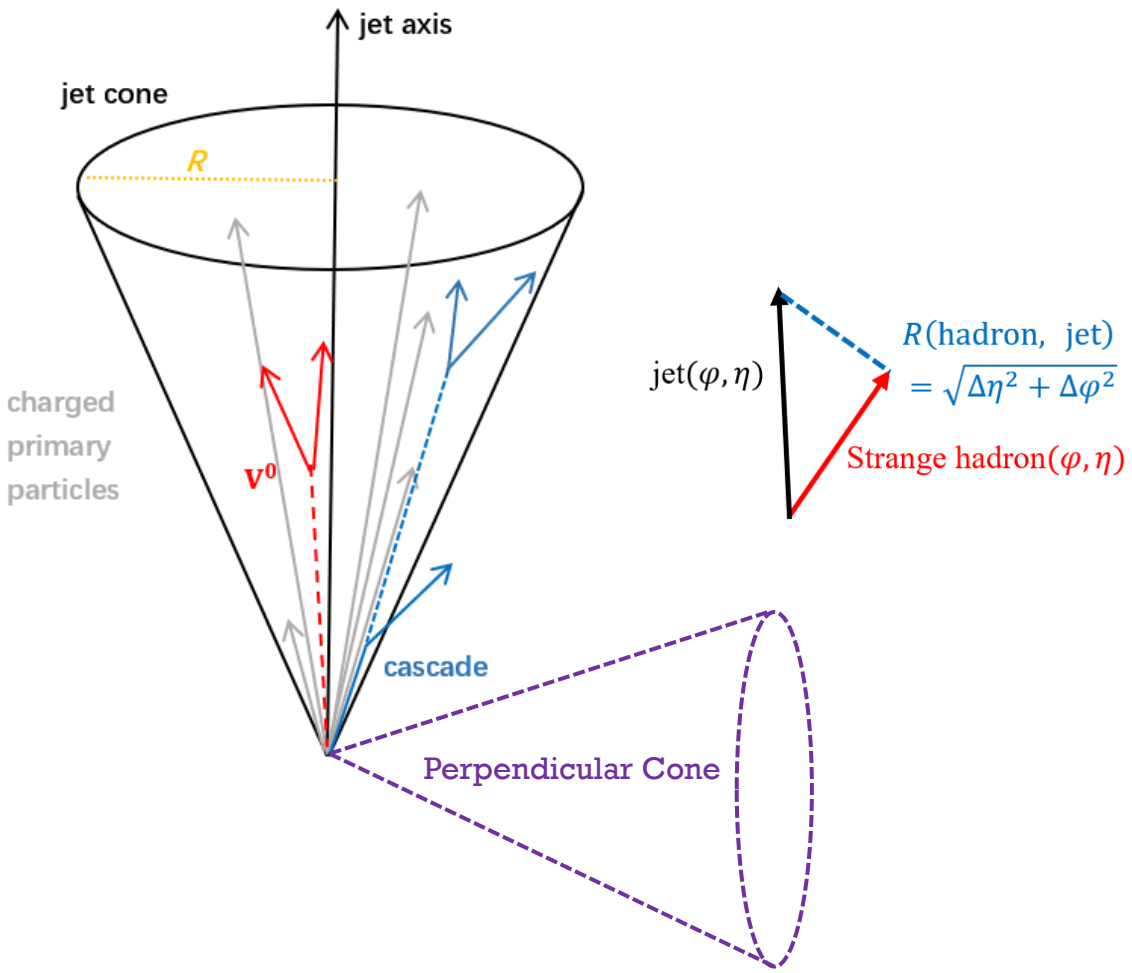
Tag hard processes using jets

- Jet reconstruction
  - Charged track selection: $|\eta| < 0.9$, $p_{\mathrm{T}} > 0.15$ GeV/c
  - Jet finder: anti-k_{T}, $R = 0.4$, $|\eta_{\mathrm{jet}}| < 0.35$, $p_{\mathrm{T,jet}} > 10$ GeV/c

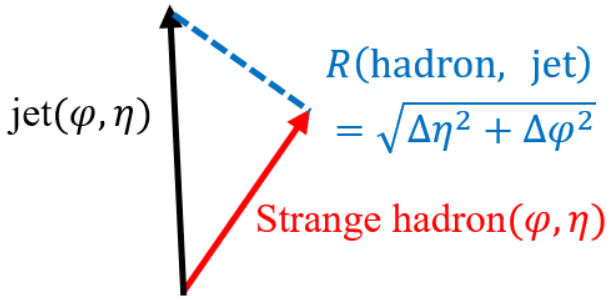
- Strangeness-jets matching
  - Strange particles found in **J**et **C**one (**JC** particles)
    - $R(\text{Strange hadron, jet})\left(=\sqrt{\Delta\eta^2+\Delta\varphi^2}\right) < 0.4$
  - Strange particles from the **U**nderlying **E**vent (**UE**) obtained with perp. cone method
  - Strange particles from jet fragmentation (**JE** particles)
    - JE = JC - UE

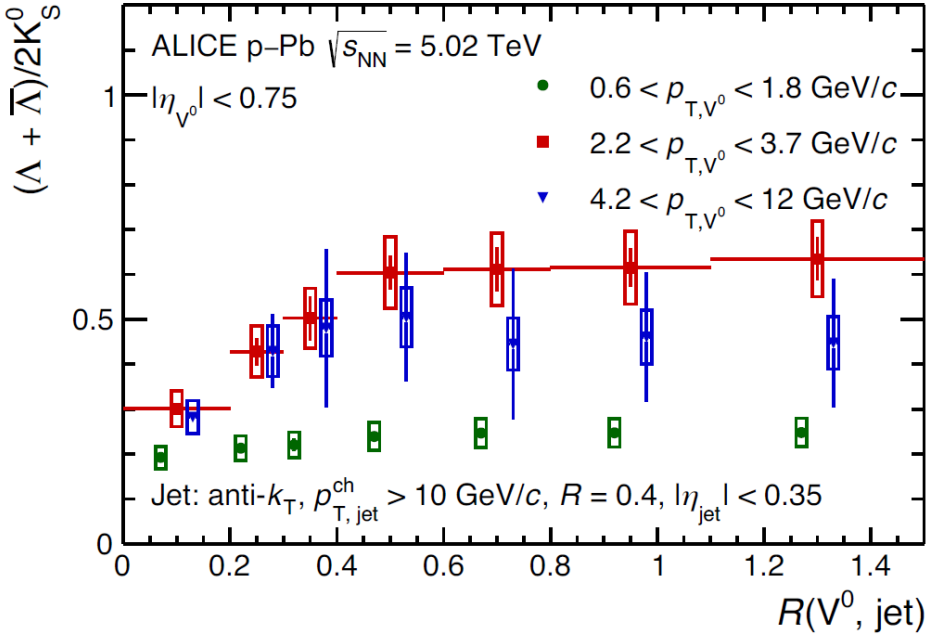
- Normalization

$$\frac{\mathrm{d}\rho}{\mathrm{d}p_{\mathrm{T}}} = \frac{1}{N_{ev}} \times \frac{1}{<\text{Acc Area}>} \times \mathrm{d}N_{\mathrm{S}}/\mathrm{d}p_{\mathrm{T}}$$



Λ/K_S^0 ratio with $R(V^0, \text{jet})$ in p-Pb collisions





Intermediate p_T

High p_T

Low p_T

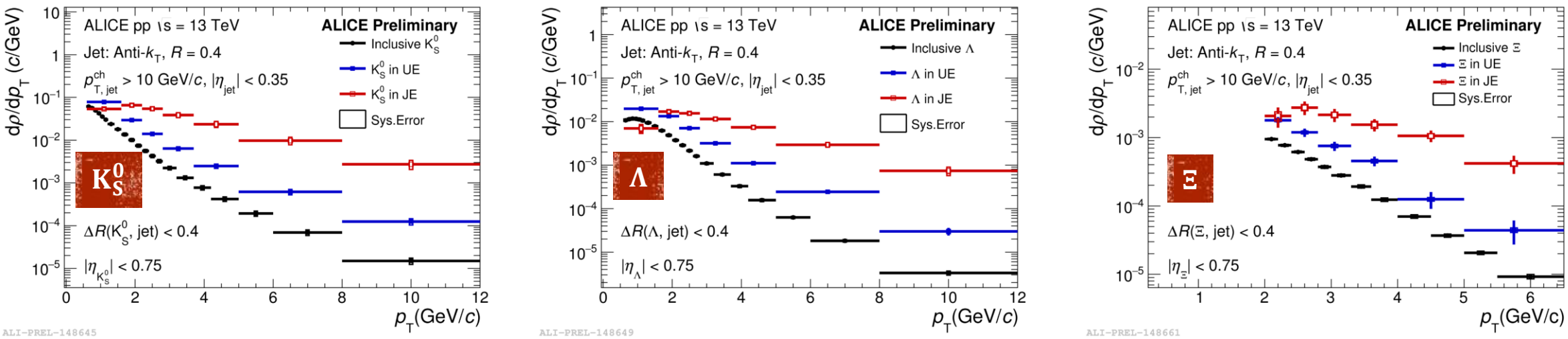
Hard process dominant → UE dominant

arXiv:2105.04890v1

Λ/K_S^0 (baryon/meson)

- Λ and K_S^0 in jet cone without UE subtraction
- The ratio at low p_T is independent of the distance to the jet axis
- The ratio at intermediate-p_T shows an increase at small $R(V^0, \text{jet})$
- For $R(V^0, \text{jet}) > 0.5$ the ratio remains constant
- Lack of enhancement close to the jet axis

Strange particle spectra

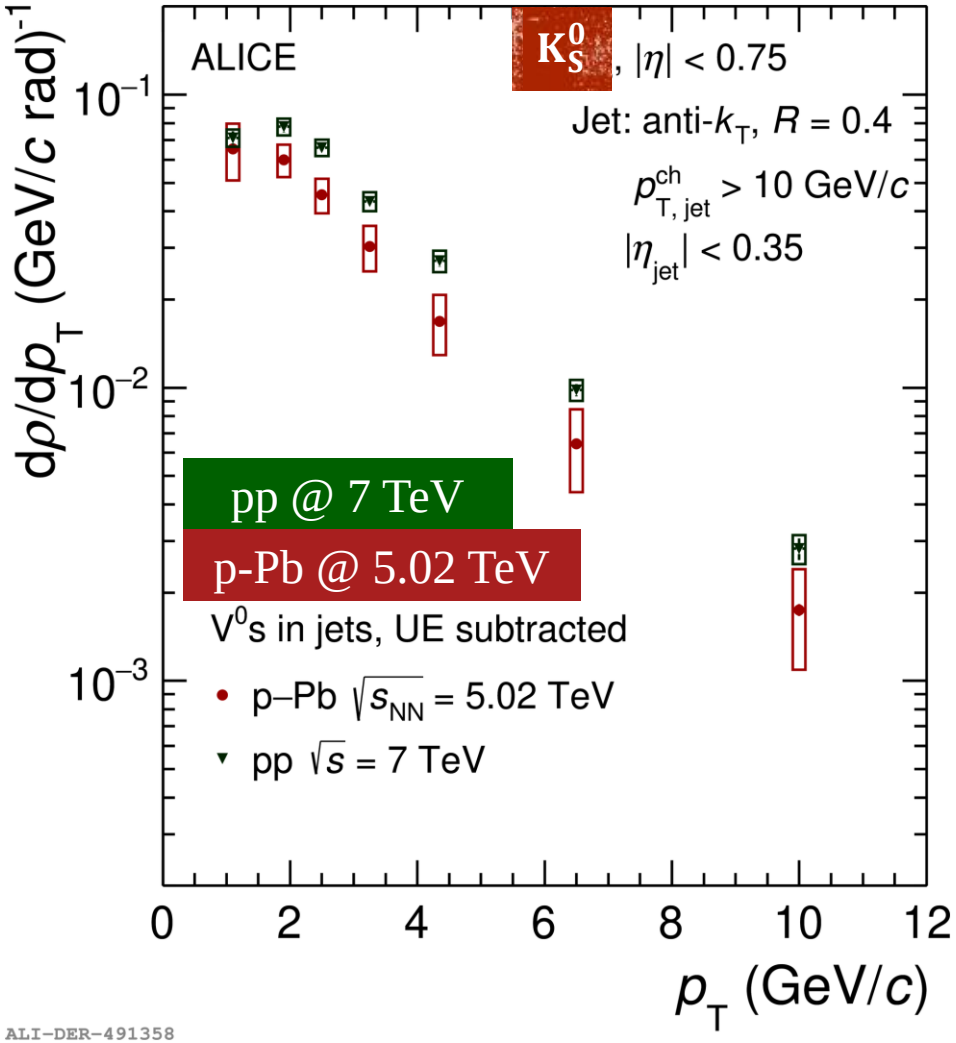


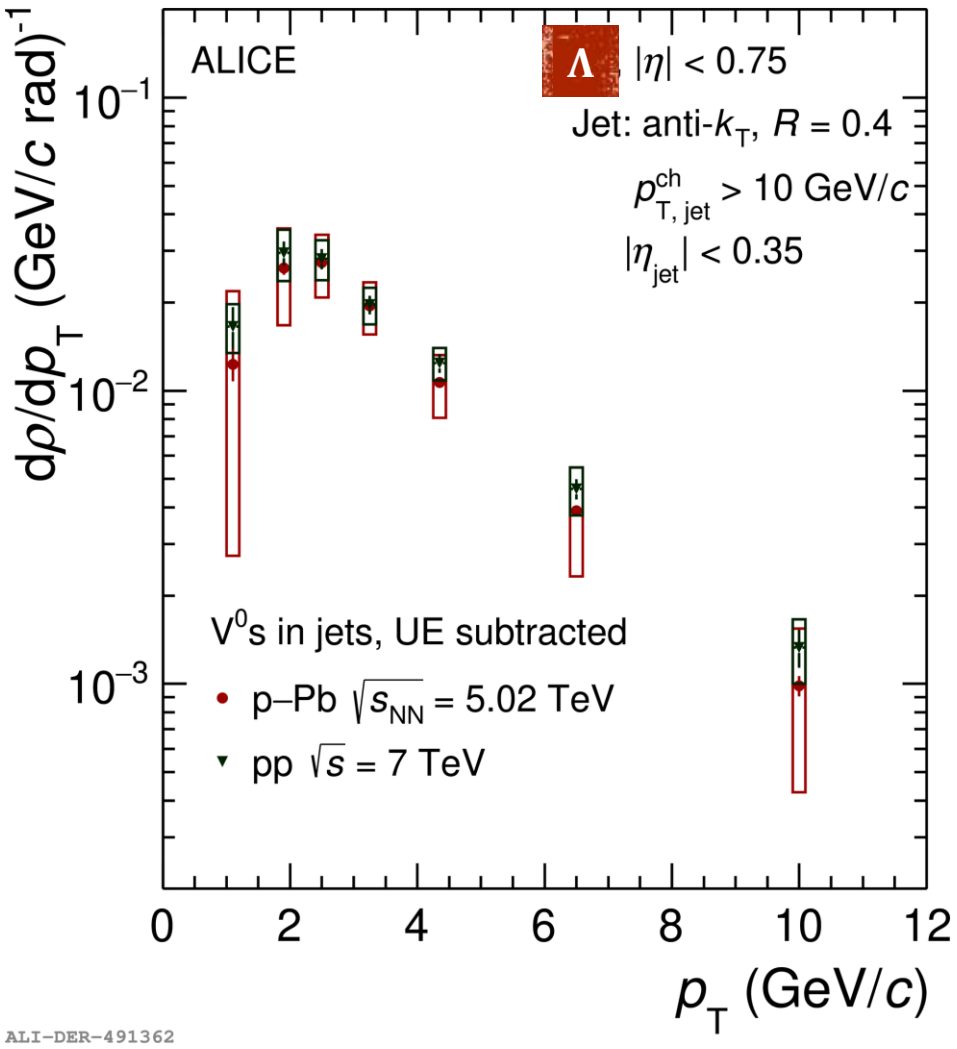
The spectra are fully corrected for instrumental effects

$$\frac{d\rho}{dp_T} = \frac{1}{N_{ev}} \times \frac{1}{< \text{Acc Area} >} \times dN_S/dp_T$$

- UE background is dominant at low p_T
- The production density of strange hadrons in jets (JE) is harder than in the underlying event (UE)
- UE distributions are harder than **inclusive** --- presence of jets biases events

K_S^0 and Λ spectra in jet in pp and p-Pb



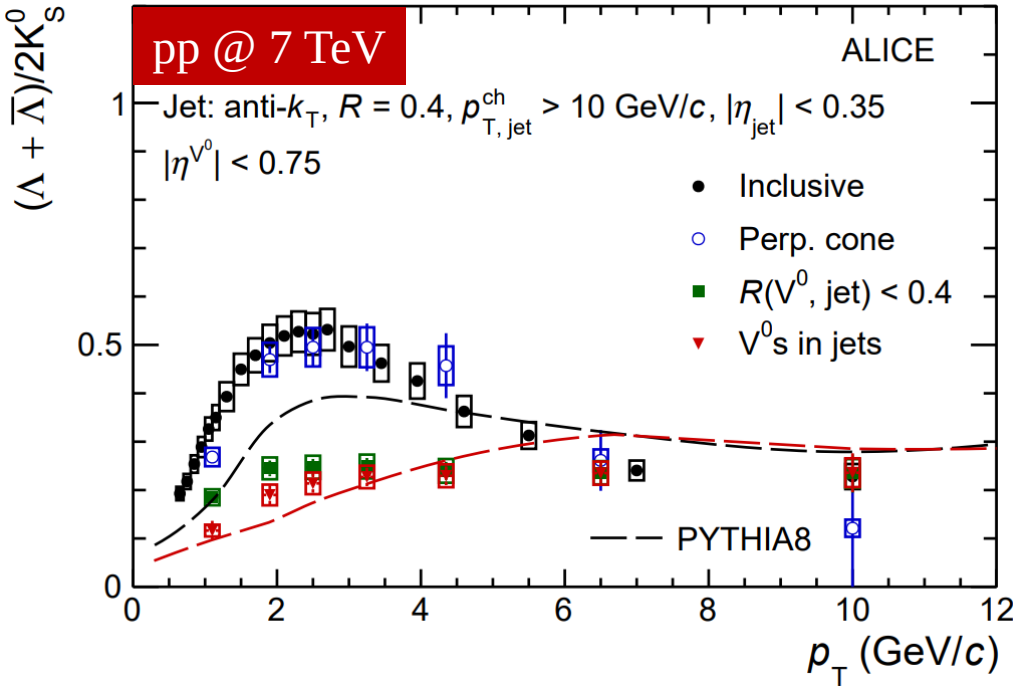


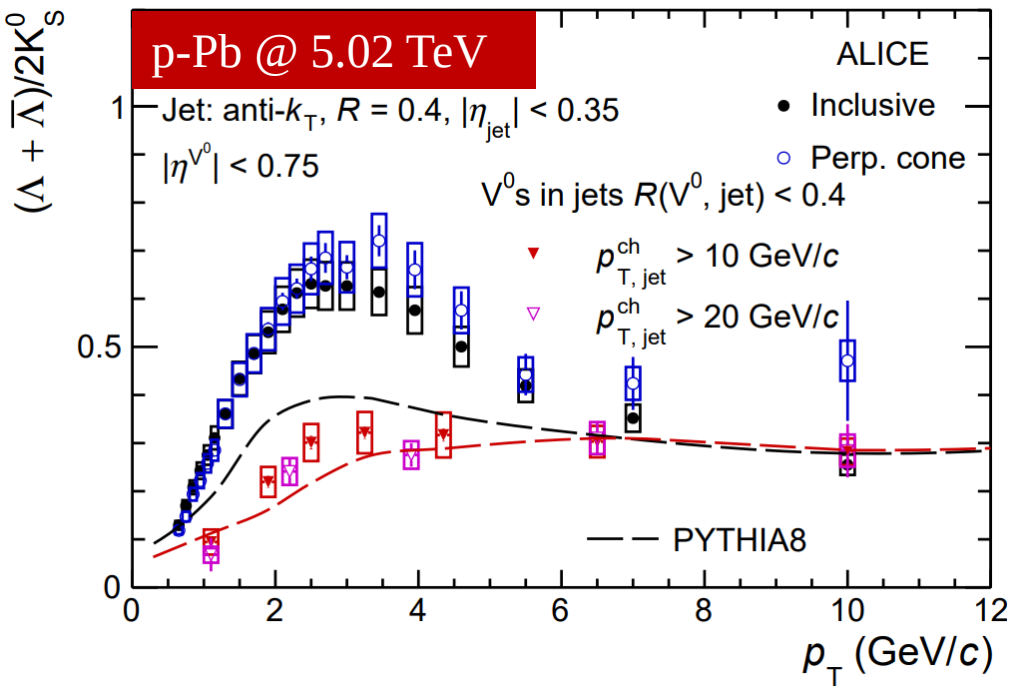
arXiv:2105.04890v1

- Weak collision system dependence for particles produced in jets

Λ/K_S^0 ratio in pp and p-Pb

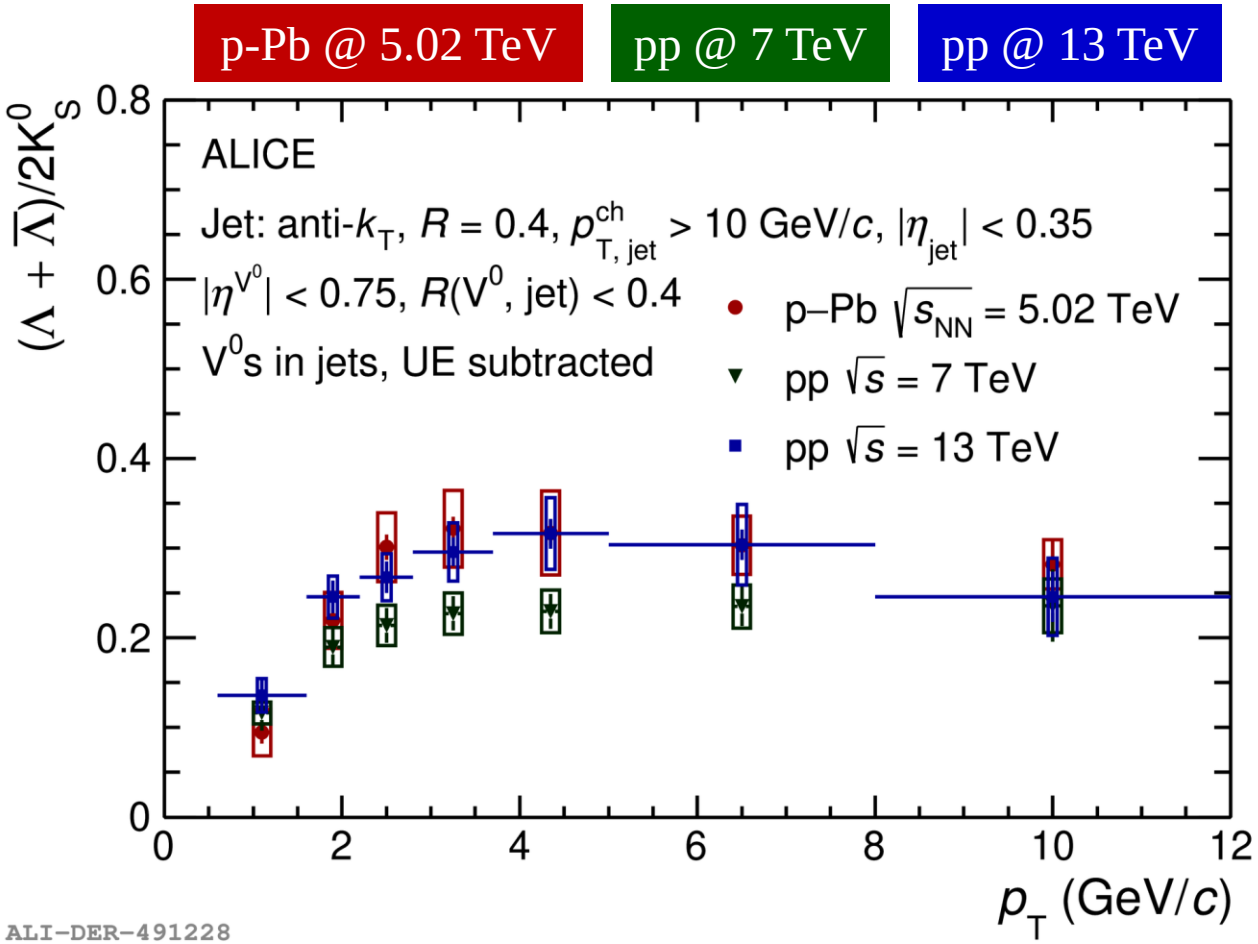
arXiv:2105.04890v1





- Ratio in jets does not show a maximum at intermediate p_T, the ratio for UE selection exhibits enhancement in $2 < p_T < 5$ GeV/c
- PYTHIA 8 hard QCD is consistent with ratio in jets but does not reproduce the inclusive ratio at low and intermediate p_T

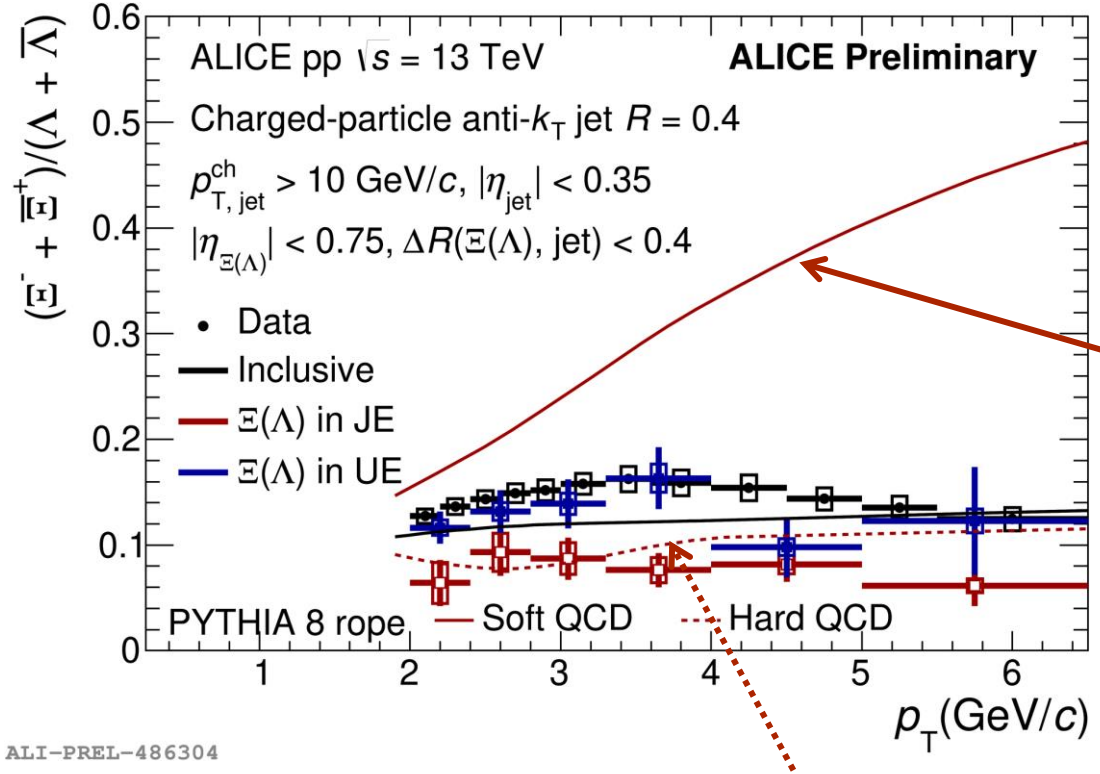
Λ/K_S^0 ratio in jet in pp and p-Pb



- In pp collisions: results at 7 TeV are consistent with those at 13 TeV within uncertainties — no (visible) energy dependence
- $< 2\sigma$ deviation at intermediate p_T between pp and p–Pb

arXiv:2105.04890v1

Ξ/Λ ratio in pp collisions



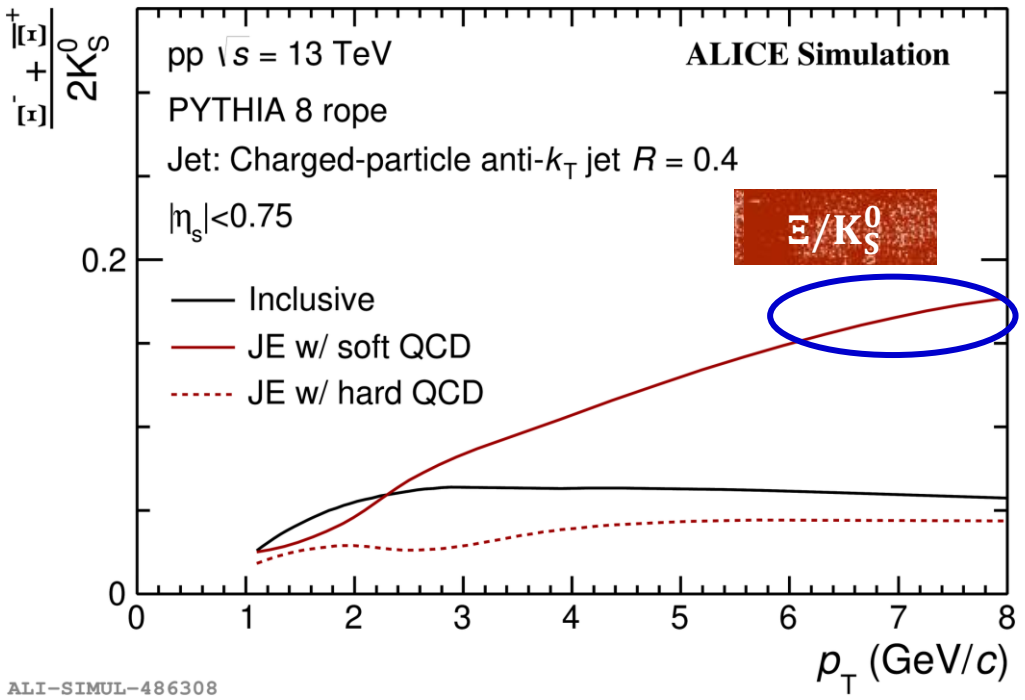
PYTHIA 8 soft QCD prediction in jets

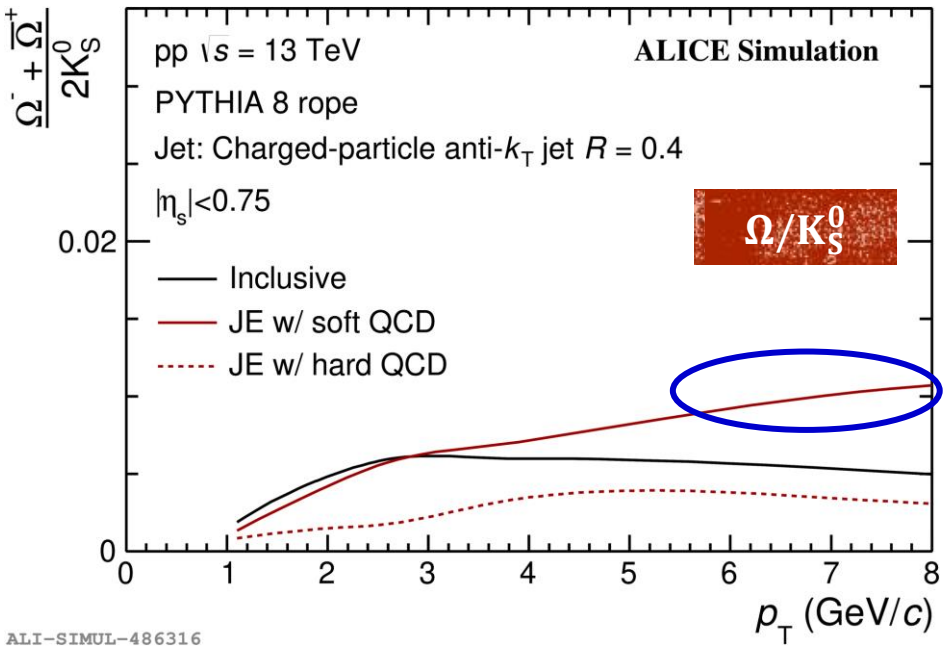
PYTHIA 8 hard QCD prediction in jets

Ξ/Λ (baryons with different strangeness content: |S|=2/|S|=1)

- UE ratio is consistent with the **inclusive** one
- Ratio in jet is almost independent of p_T
- PYTHIA 8 hard QCD generally reproduces ratio in jets
- PYTHIA 8 soft QCD shows a strong increase, inconsistent with data

Multi-strange baryon prediction in PYTHIA





baryons/meson with different strangeness content: |S|=2 (3)/|S|=1

- PYTHIA 8 soft QCD mode gives a strong increase in particle ratios at high p_T when multi-strange particles are considered, not consistent with data
- Next step extend the study to Ω-baryon

Summary

- Production of strange particles have been investigated in jets and the UE in pp and p-Pb collisions
- $\Lambda/\mathrm{K}^0_\mathrm{S}$ ratio
  - The inclusive $\Lambda/\mathrm{K}^0_\mathrm{S}$ ratio enhancement is not present within the jets, but is related to the Underlying Event (UE)
  - $\Lambda/\mathrm{K}^0_\mathrm{S}$ ratio as a function of $R(\mathrm{V}^0,\ \mathrm{jet})$: lack of enhancement close to the jet axis

  ↘ **Enhancement is not associated with the jets**
- Ξ/Λ ratio
  - The Ξ/Λ ratio in jet is almost independent of p_T

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