Strange hadron production with ALICE at the LHC

Zhongbao Yin

Central China Normal University

CLHCP 2023

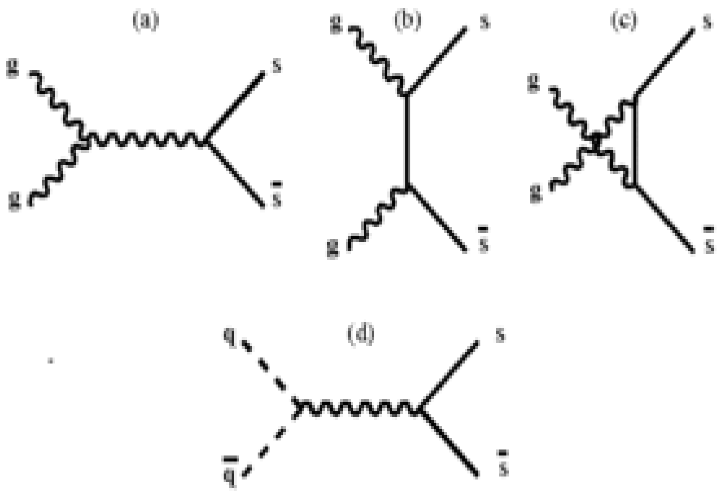
2023/11/16-20, Shanghai

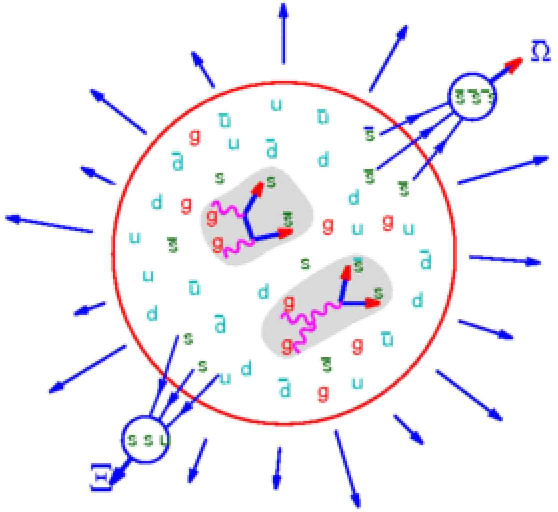
Outline

- **Why strangeness?**
- **ALICE for strangeness detection**
- **Results on strangeness production**
  - **Multiplicity dependence of strangeness production**
  - **Strangeness production in jets and underlying event**
  - **Strangeness production associated with charged hadrons**
  - **Charged particle production associated with high p_T strangeness particles**
- **Summary and outlook**

Why strangeness？

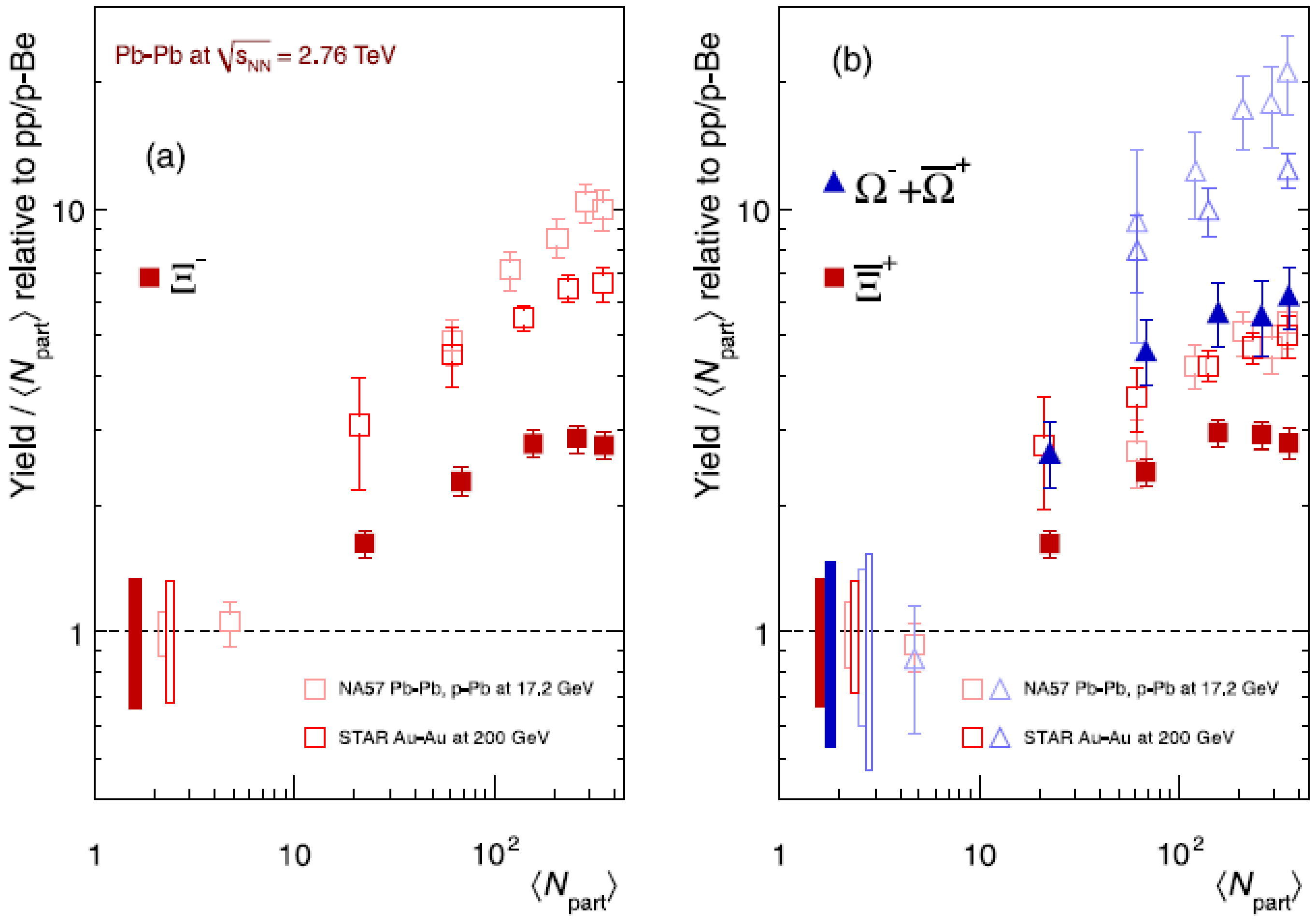
- **Enhancement of strangeness production in relativistic heavy-ion collisions relative to elementary reactions was one of the first proposed signatures of Quark-Gluon Plasma (QGP) formation [1]**
  - **Strange and anti-strange quarks can be copiously produced via gluon fusion processes in QGP, and be thermalized with the medium**
  - **These abundant thermal produced strange and anti-strange quarks can then coalesce to various strange hadrons when the temperature reaches the condition of phase transition from QGP to hadron gas**
  - **This can thus result in enhancement of strange hadron yields in heavy-ion collisions compared to pp collisions, in which a QGP of extended volume is not expected to form.**
  - **This enhancement is expected to increase with increasing strangeness content, i.e. stronger enhancement in production of multi-strange hadrons.**





【1】J. Rafelski and B. Muller, PRL 48 (1982) 1066. [Erratum: PRL 56 (1986) 2334].

Evidence of strangeness enhancement

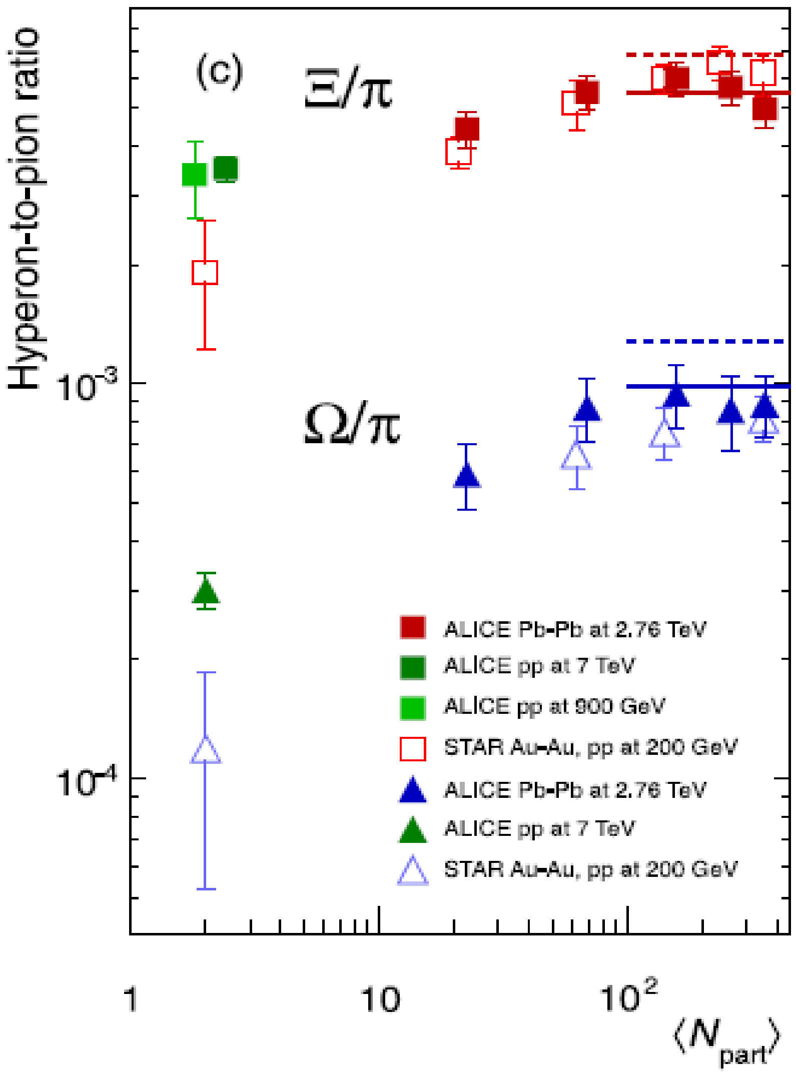


ALICE，PLB 728 (2014) 216–227；PLB 734 (2014) 409–410

- **Enhancement of strangeness production has already been observed at SPS, RHIC and LHC**
- **As expected, the enhancement increases with increasing strangeness content of the strange particle**
- **The enhancement increases with increasing number of nucleon participants, tending to saturate**
- **The enhancement weakens as collision energy increases**
  - **Due to the rapid increase of (multi-)strange hadron yields with the increasing energy in pp collisions**

Enhancement of strangeness w.r.t. pion

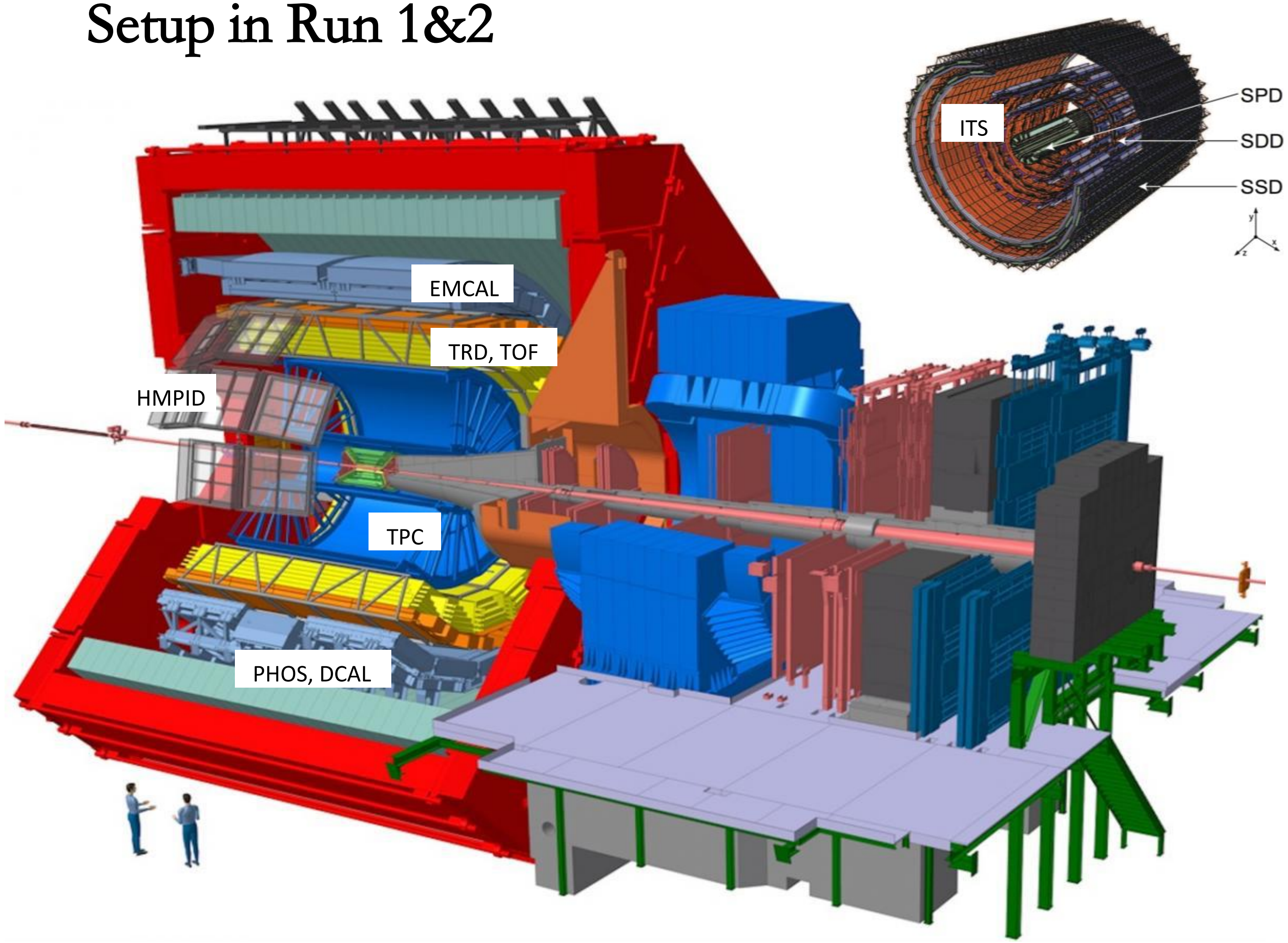
- To nail down the collision energy dependence, hyperon to pion ratio is calculated
- The hyperon to pion ratios show no energy dependence in nucleus-nucleus collisions
  - But the ratio in pp collisions does increase significantly as the collision energy increases
  - Canonical suppression weakened due to relaxation of the local strangeness conservation with increasing energy
- The hyperon to pion ratio demonstrates a significant enhancement in production of (multi)strange hadrons in nucleus-nucleus collisions relative to that in pp collisions
- When the number of participants is above 150, the ratio can be well described by grand canonical statistical hadronization model
  - Chemical freeze-out temperature： 164 MeV （solid line）， 170 MeV （dashed line）



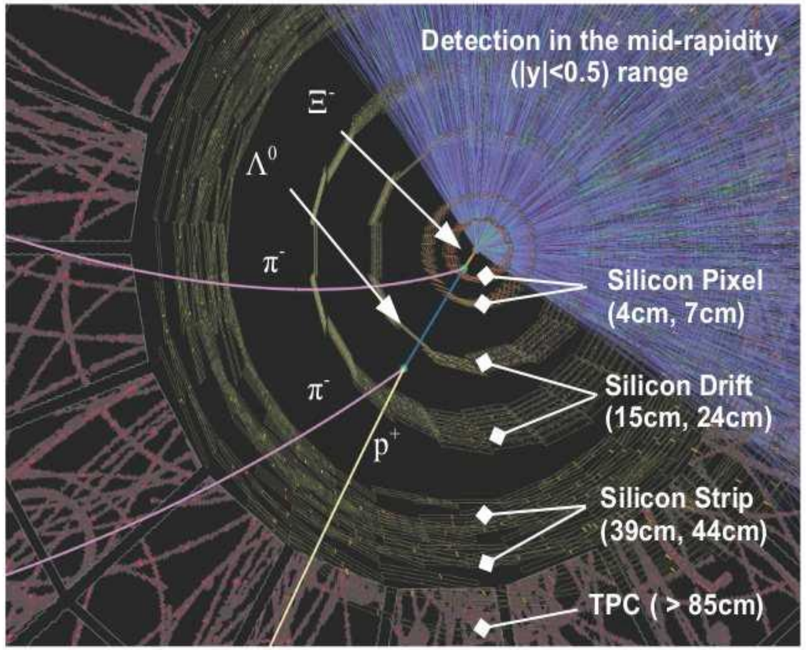
ALICE， PLB 728 (2014) 216–227； PLB 734 (2014) 409–410

ALICE for strange particle detection

Setup in Run 1&2



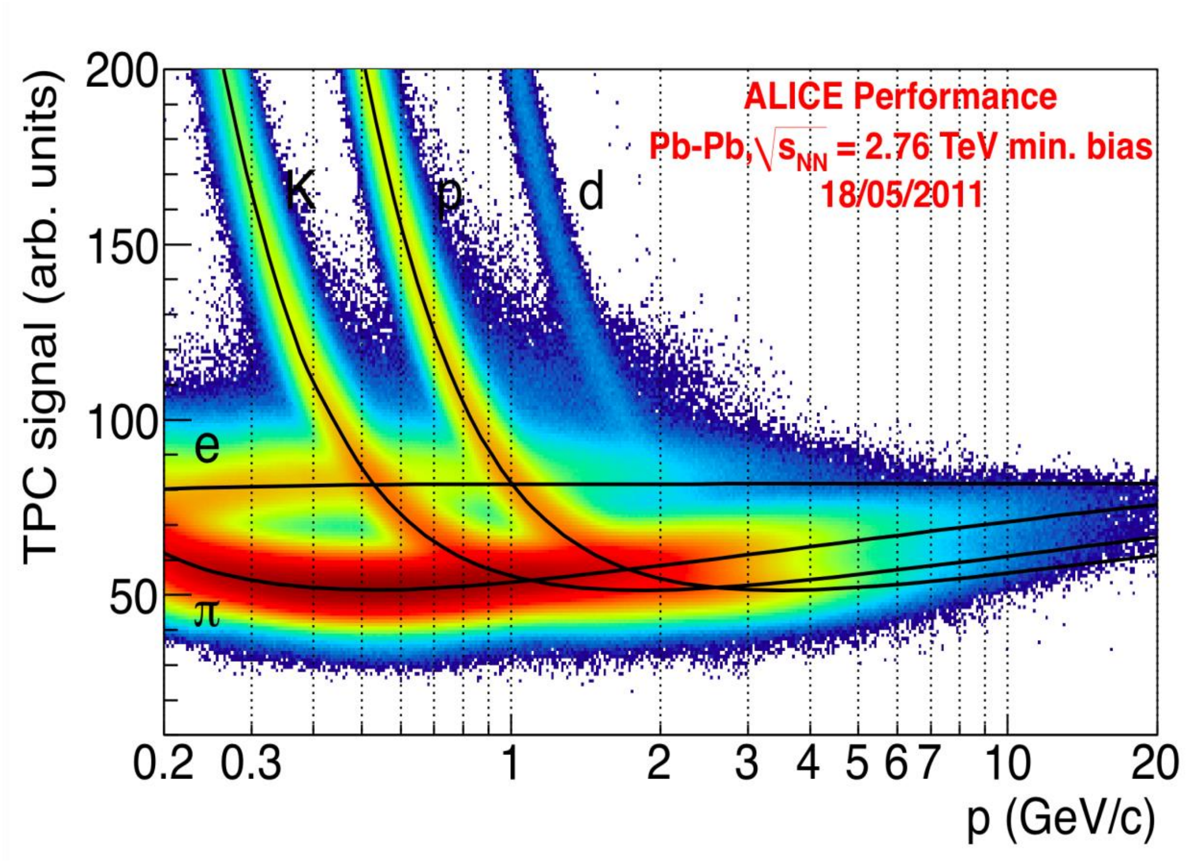
Pb-Pb 5.5TeV Hijing MC Event, not all tracks shown; Figure from Alice Physics Performance Report, Volume II (Figure IV)

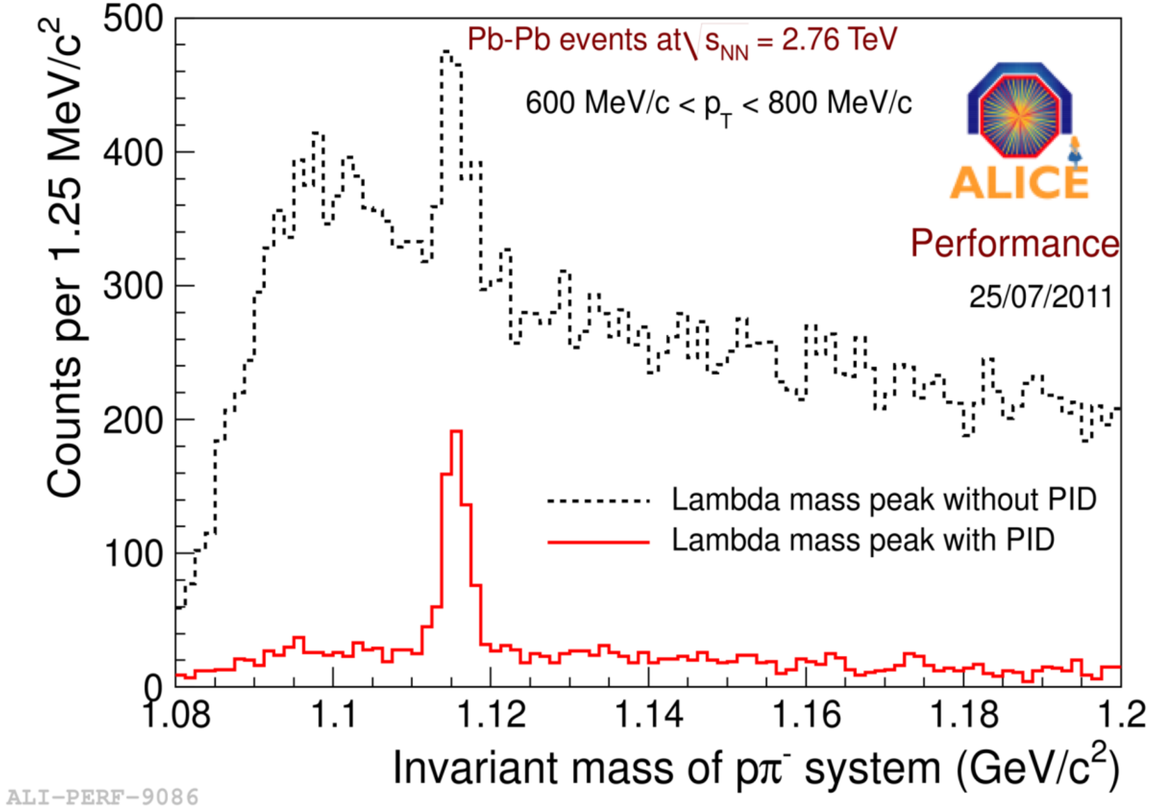


V-shape and cascade geometrical topology

$K_S^0 \to \pi^+ + \pi^-$ (B.R. 69.2%)
$\Lambda \to p + \pi^-$ (B.R. 63.9%)
$\overline{\Lambda} \to \overline{p} + \pi^+$ (B.R. 63.9%)
$\Xi^- \to \Lambda + \pi^- \to p + \pi^- + \pi^-$ (B.R. 63.9%)
$\overline{\Xi}^+ \to \overline{\Lambda} + \pi^+ \to \overline{p} + \pi^+ + \pi^+$ (B.R. 63.9%)
$\Omega^- \to \Lambda + K^- \to p + \pi^- + K^-$ (B.R. 43.3%)
$\overline{\Omega}^+ \to \overline{\Lambda} + K^+ \to \overline{p} + \pi^+ + K^+$ (B.R. 43.3%)

Charged particle identification

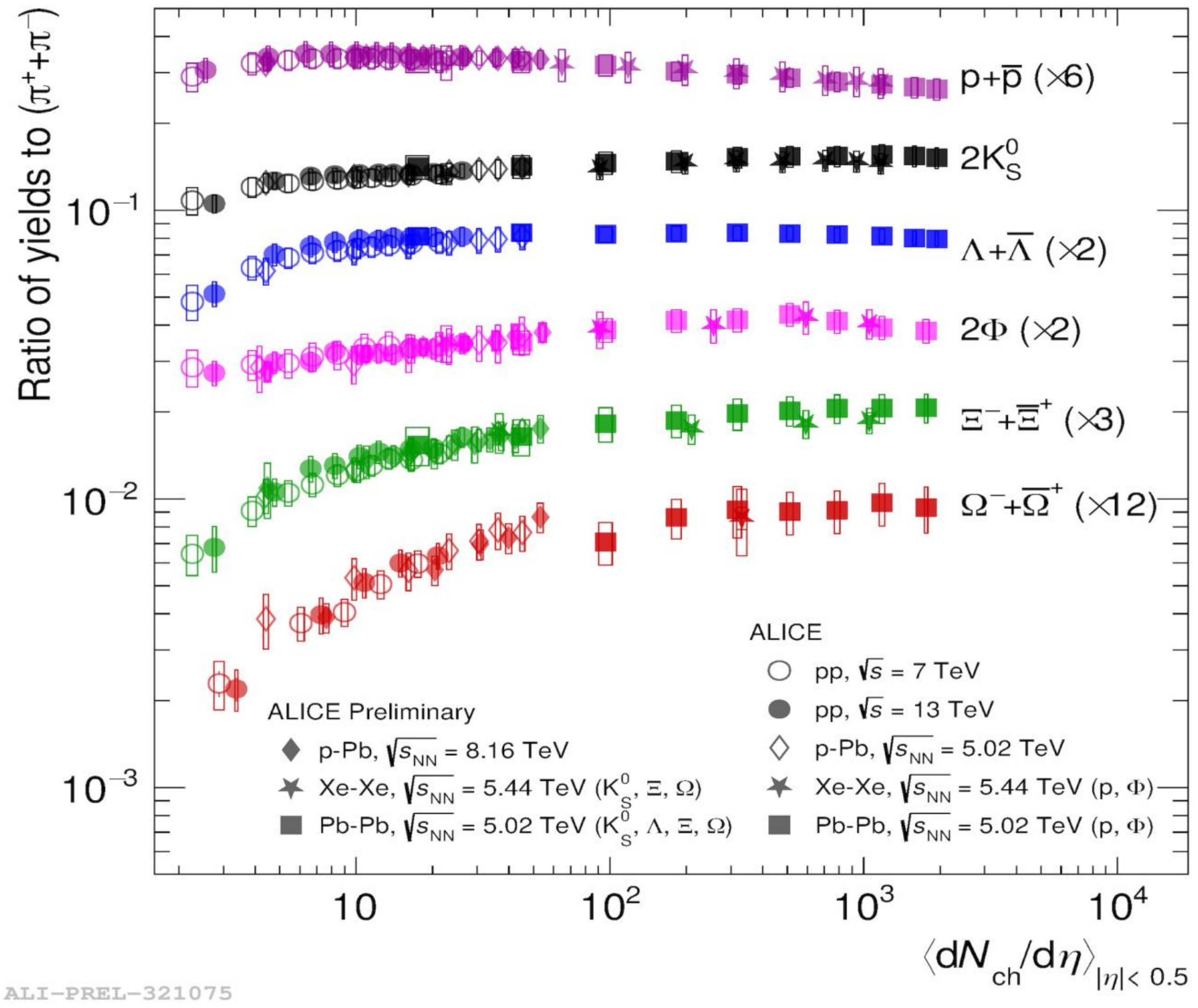




- **Daughters from their weak decays are identified with their specific energy losses (d*E*/d*x*) in TPC and time-of-flight information from TOF**

- **With the help of PID, combinatorial background can be significantly suppressed**

Multiplicity dependence of particle to pion yield ratios

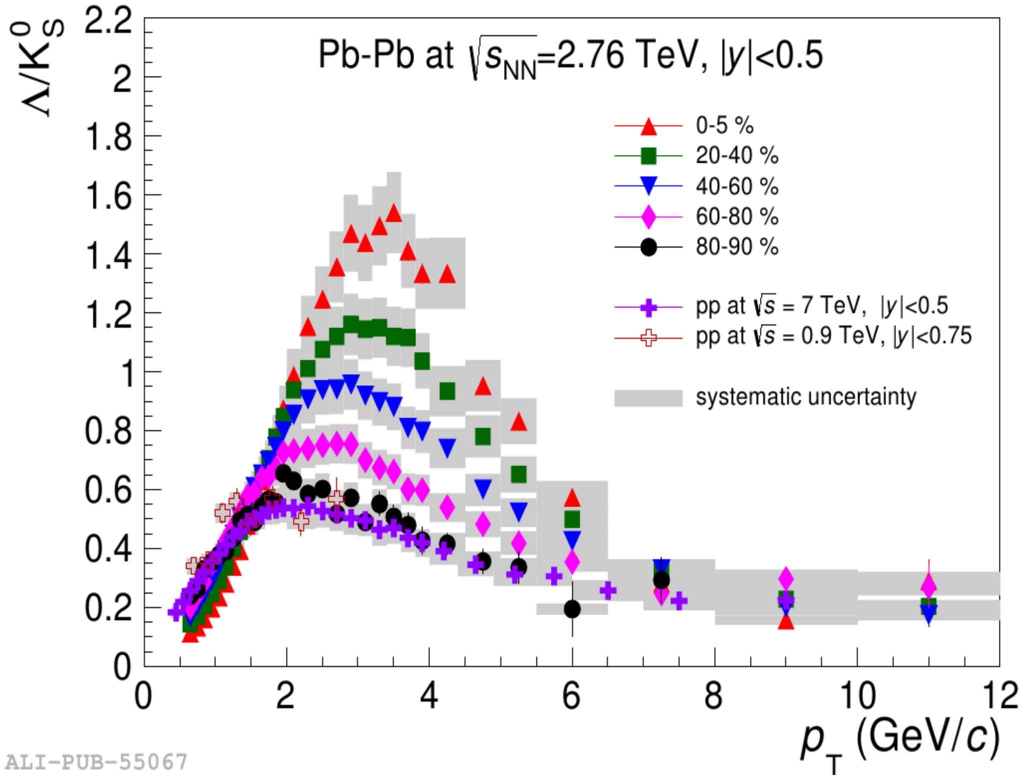


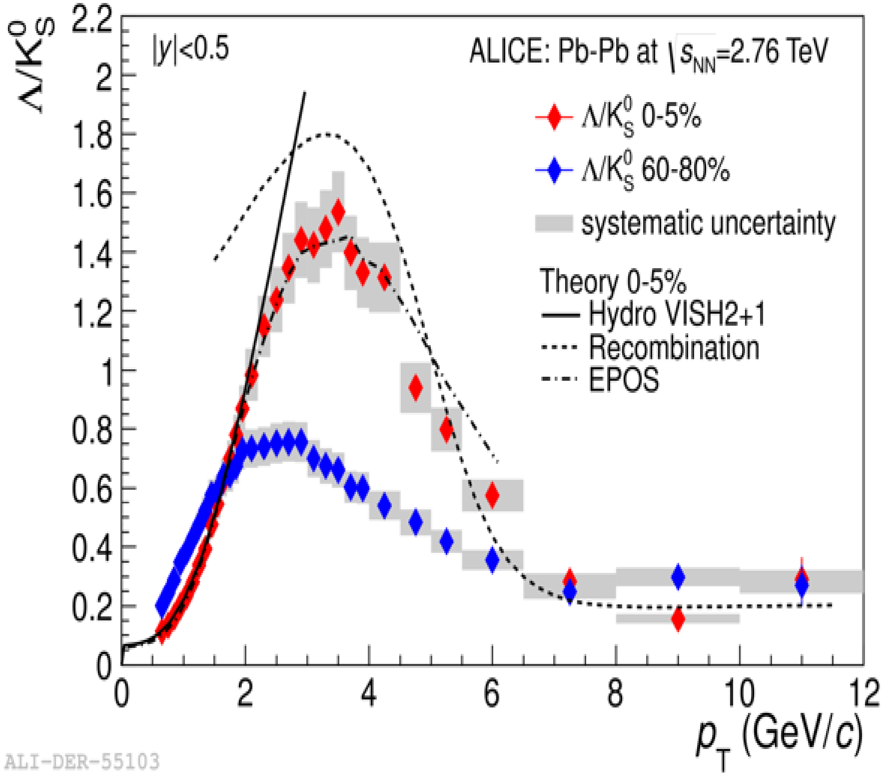
- **Ratios evolve smoothly with charged particle pseudo-rapidity density across different collision systems (pp, p-Pb, Xe-Xe and Pb-Pb)**
- **No energy dependence at LHC energies**
- **Enhancement in strangeness production increases with increasing strangeness content (Ω > Ξ > Λ~K^0_S)**
- **Strangeness enhancement originally considered as the QGP signature is also observed in small collision systems**
  - **QGP in small systems?**
  - **The same production mechanism across colliding systems?**

ALICE, Nature Phys 13, 535–539 (2017); EPJC 80, 167 (2020)

p_T dependence of baryon to meson ratio

ALICE, PRL 111 (2013) 22, 222301

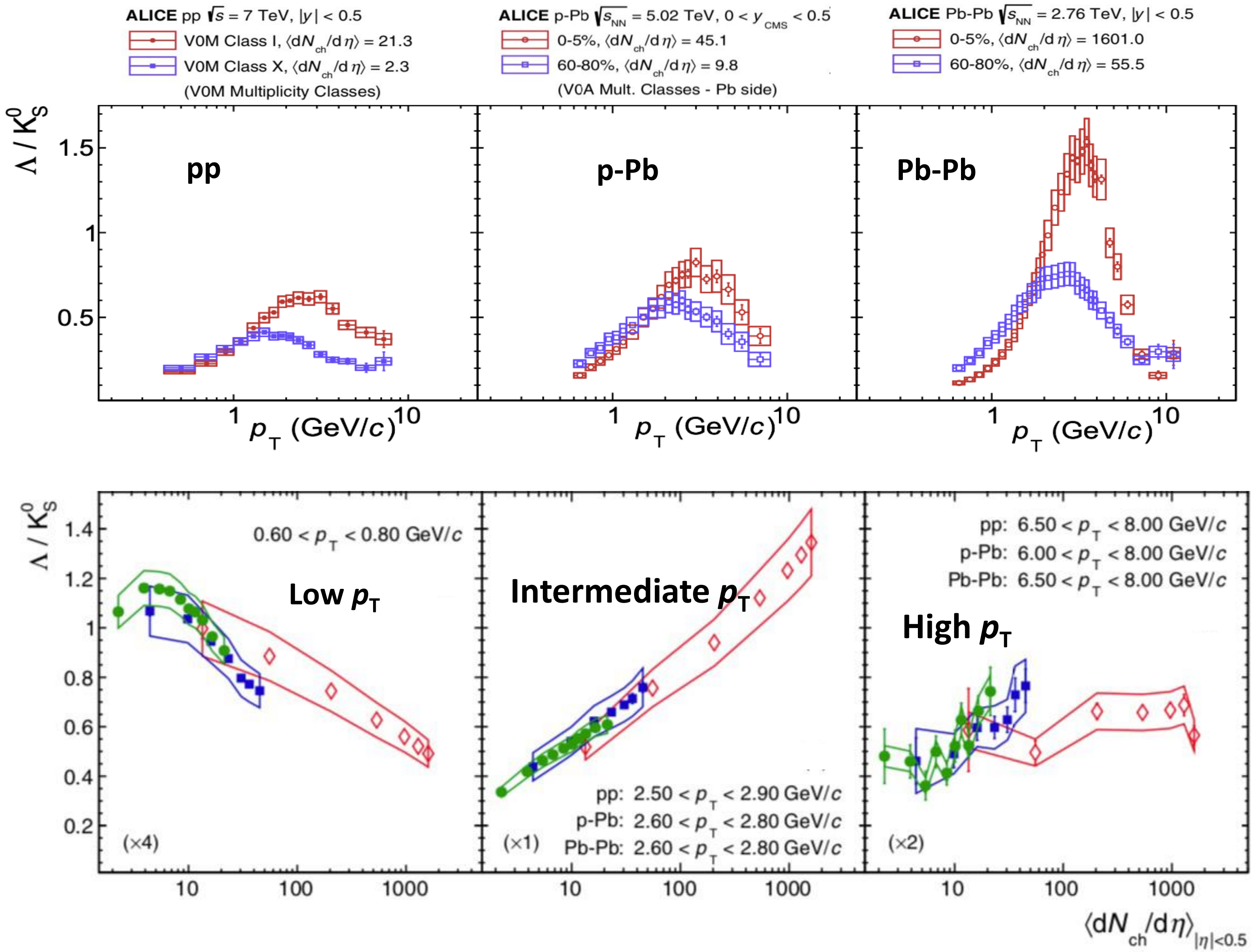




- **Ratio evolves with collision centrality**
  - **Suppression at low p_T in central collisions**
  - **Enhancement at intermediate p_T**
  - **No centrality dependence at high p_T**

- **Hydro model can only describe the low p_T region**
- **In intermediate p_T region recombination model can describe the results**

Baryon to meson ratio in small systems

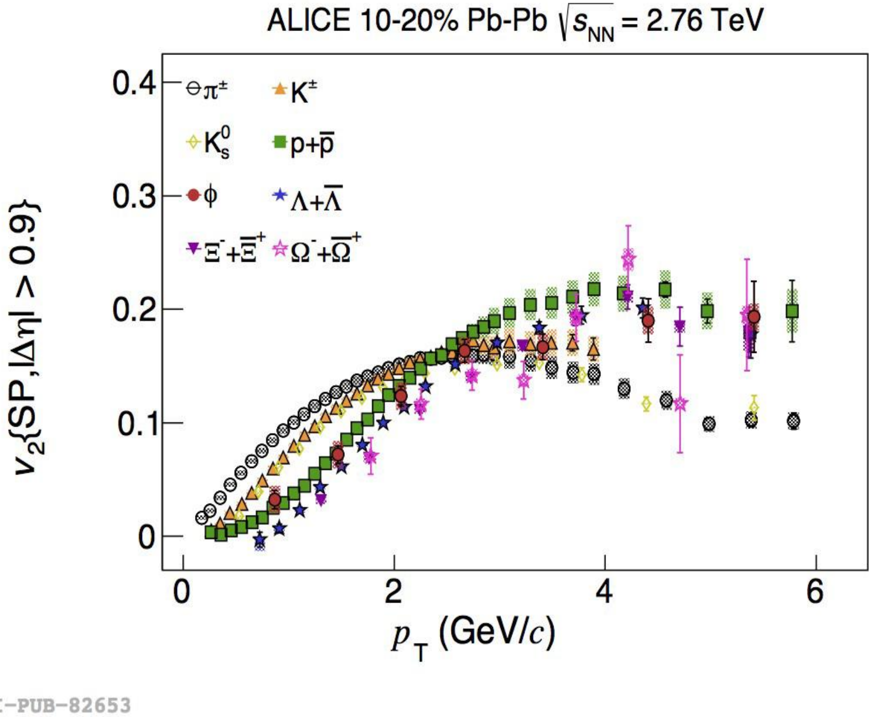


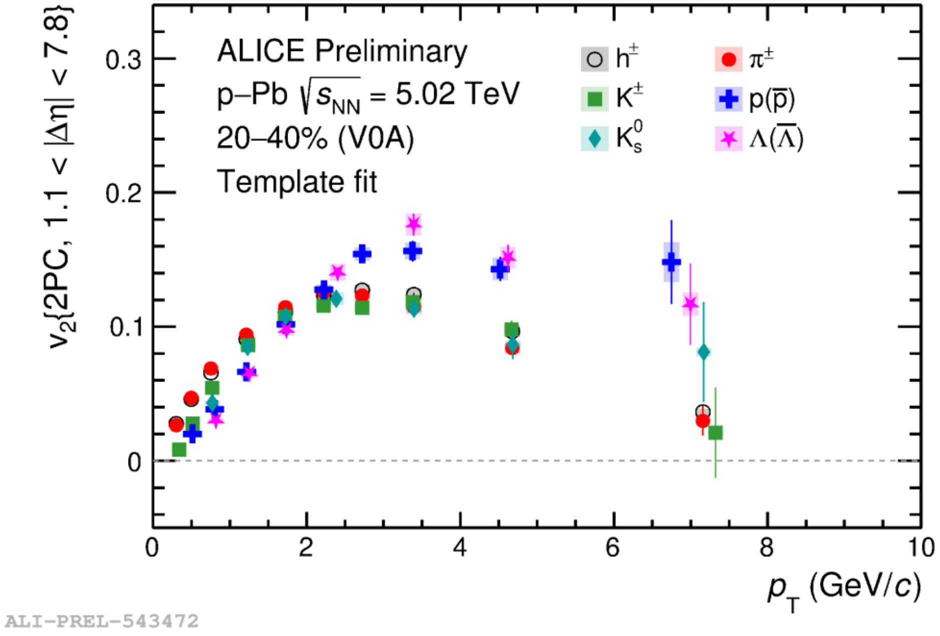
ALICE, PLB 728 (2014) 25;
PRC 99, 024906 (2019)

- **Baryon to meson ratio as a function of p_T is very much similar across different colliding systems:**
  - **Ratio increases at intermediate p_T with increasing charged particle multiplicity**
  - **Suppression at low p_T with increasing multiplicity**
  - **No dependence on multiplicity at high p_T**
- **Baryon to meson ratio evolves smoothly with multiplicity across various collision systems**
  - **Collective flow in small systems?**

Collectivity in small systems

ALICE, JHEP 06 (2015) 190; JHEP 09 (2018) 006; JHEP 05 (2023) 243





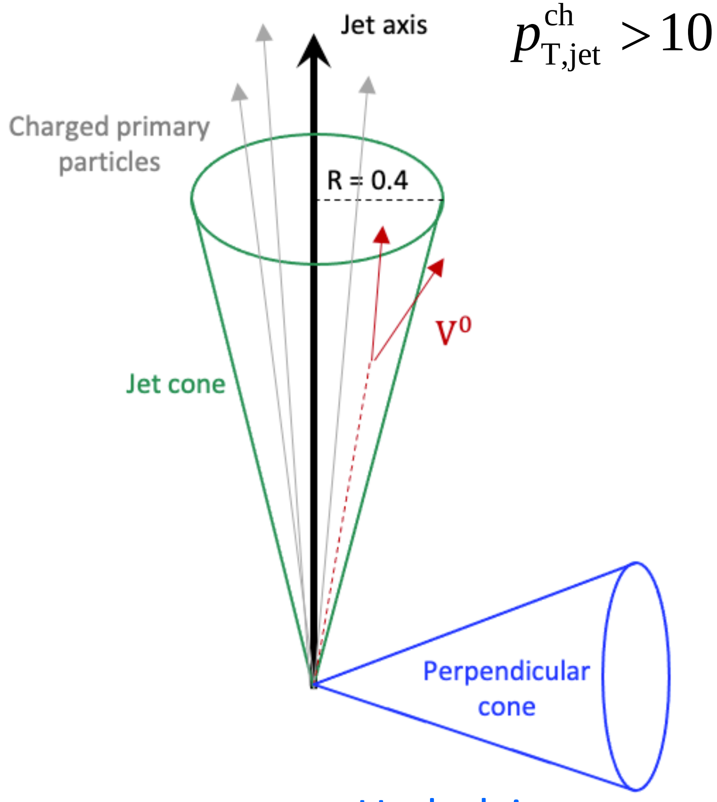
- **Similarity is observed in large and small collision systems**
- **Mass ordering of elliptic flow is observed for (multi)strange hadrons at low p_T (radial flow effect)**
- **Baryon-meson particle type grouping at intermediate p_T (partonic collectivity + recombination hadronization)**
- **Flow parameters for baryons and mesons across at about 2.5 GeV/*c***

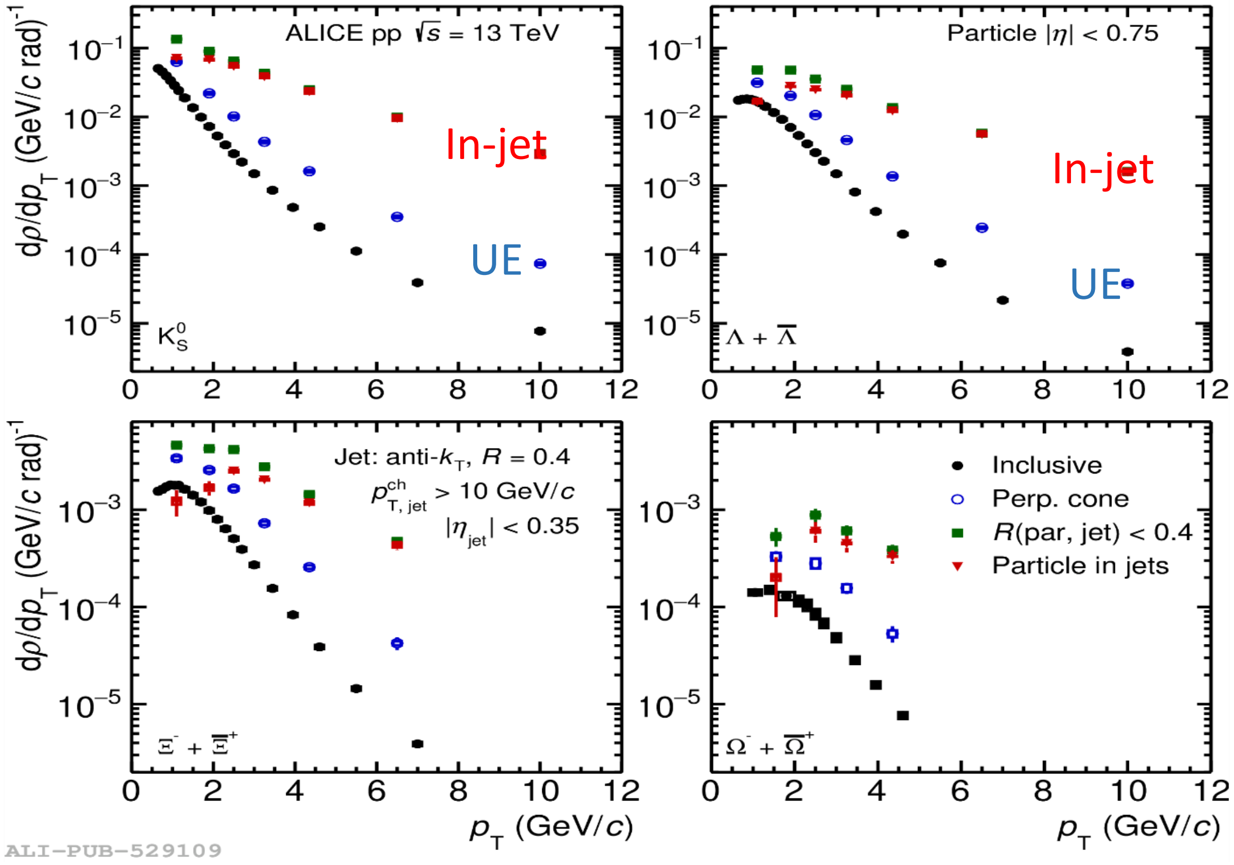
Strangeness production in jets and the underlying event

ALICE, Phys. Lett. B 827, 136984 (2022); JHEP 07 (2023) 136

Jet reconstruction algorithm: Anti-k_T

$p_{T,jet}^{ch} > 10$ GeV/c

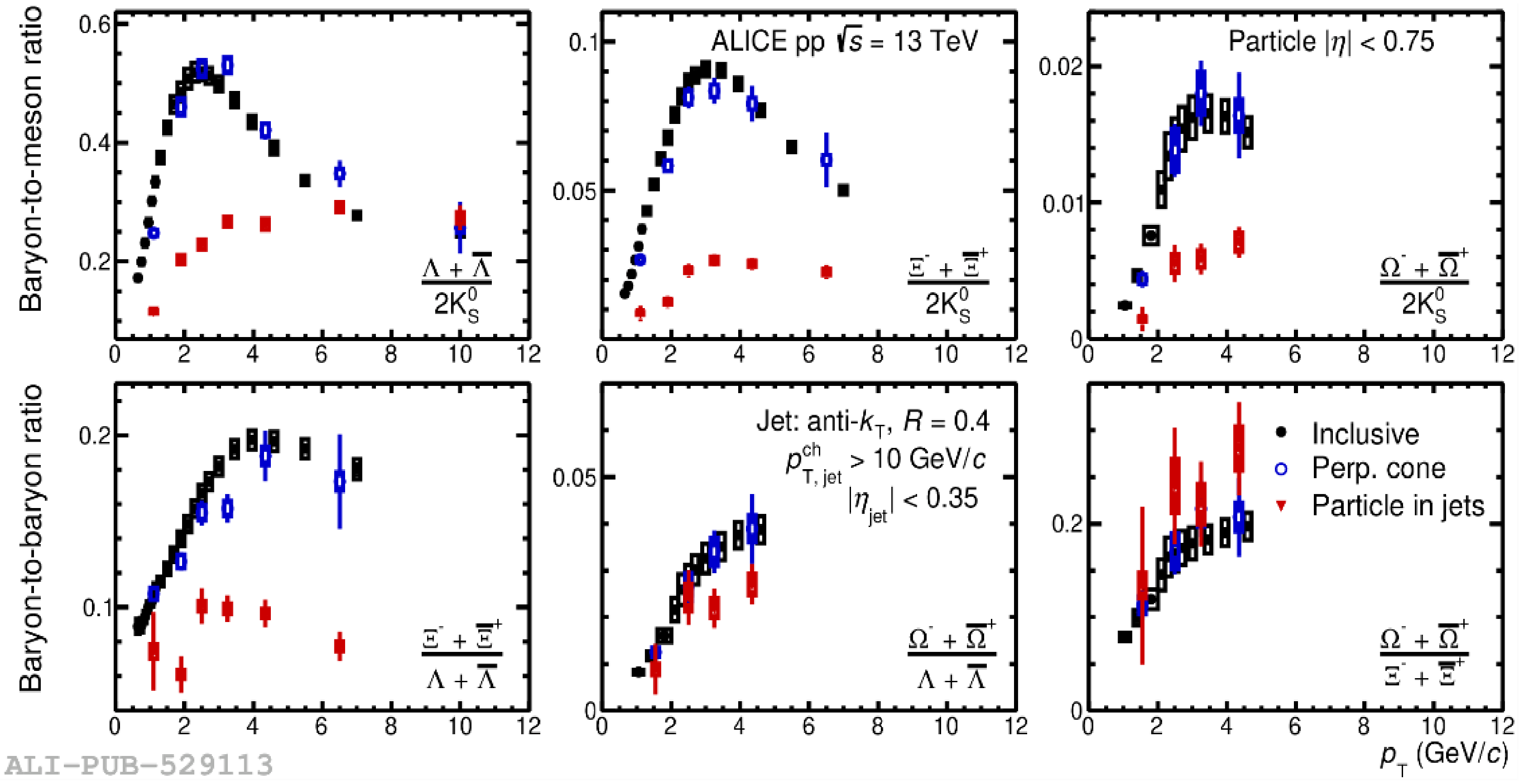




- **p_T spectra in jets are harder than that in the underlying event**
- **Similar behavior is observed in 5.02 TeV p-Pb collisions**

Particle ratios in jets and the underlying event

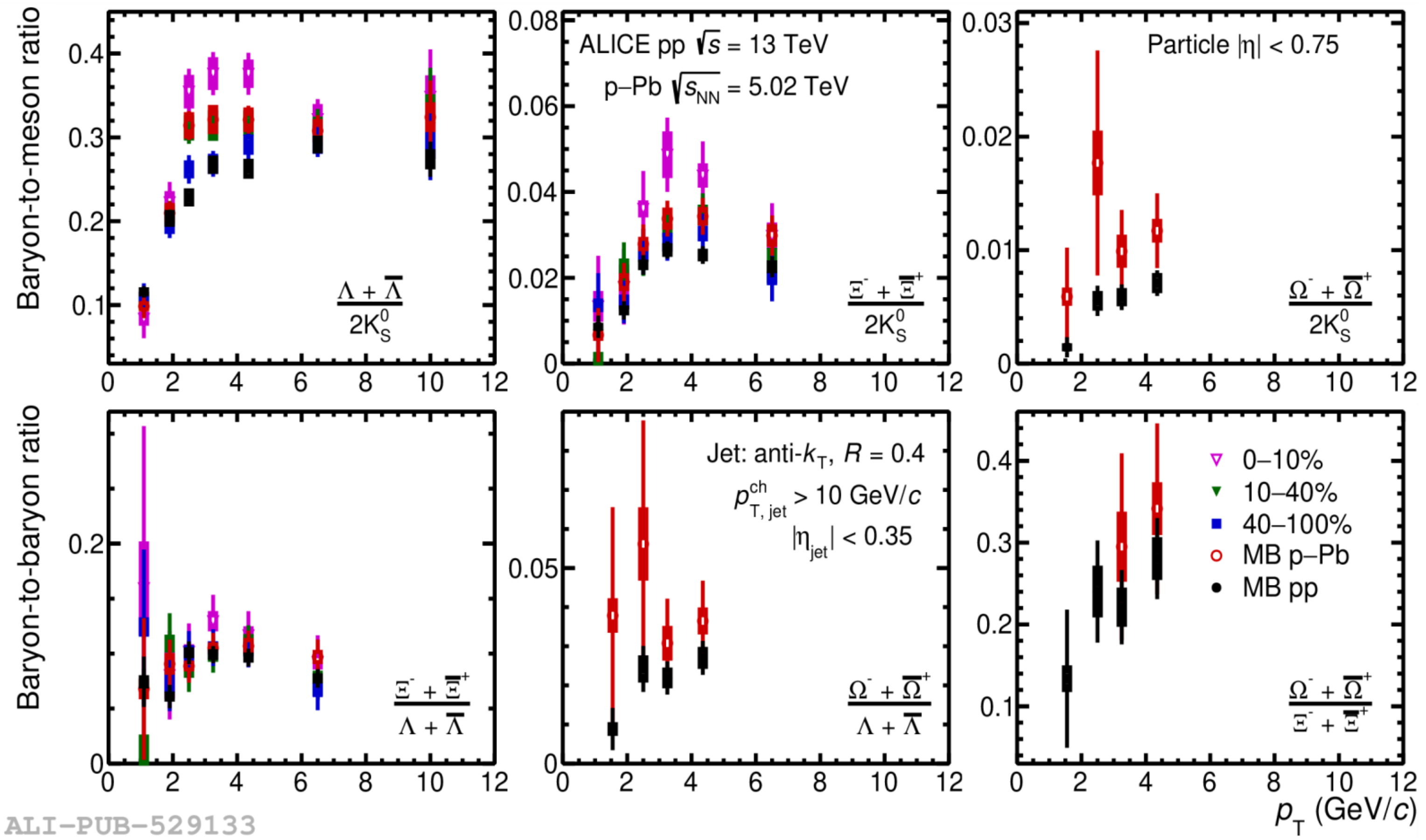
ALICE, JHEP 07 (2023) 136



- **Strange baryon to meson ratios**
  - **Ratios in the UE are consistent with that in inclusive measurement**
  - **Ratio in jets is much smaller than that in the UE**
  - **Baryon-to-meson enhancement is not due to hard parton fragmentation**
- **Strange baryon to baryon ratios**
  - **Ξ/Λ ratio in the UE agrees with that in inclusive events , and much higher than that in jets**
  - **For Ω/Λ and Ω/Ξ ratios no difference in jets and the UE within current uncertainties**

Centrality dependence of strange particle ratio in jets

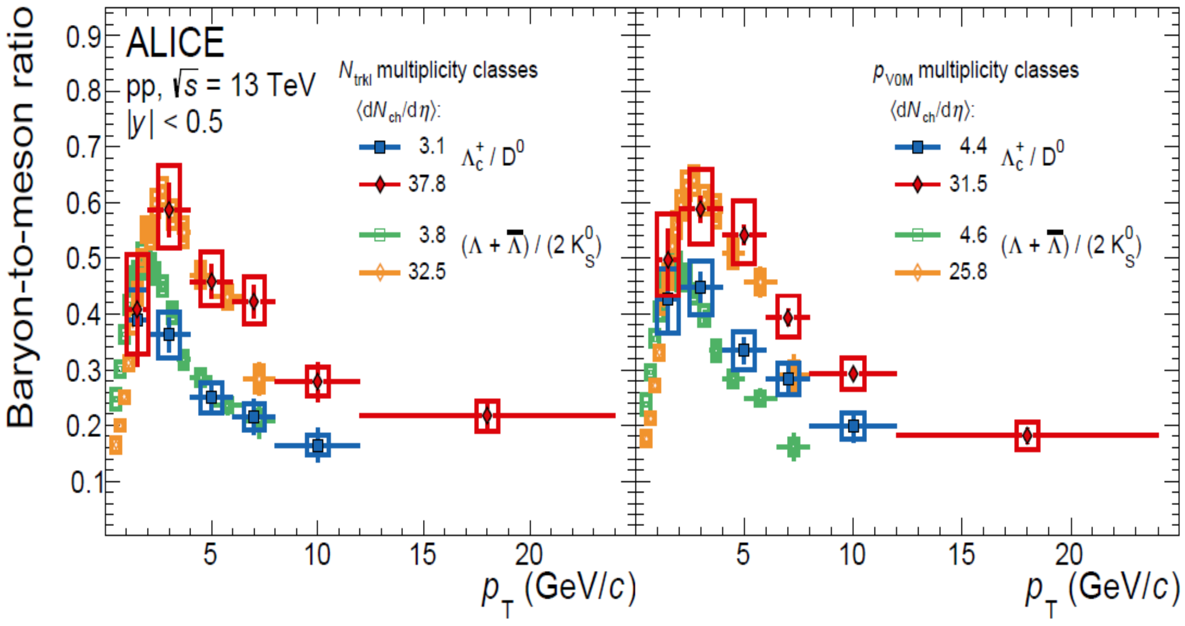
ALICE, JHEP 07 (2023) 136

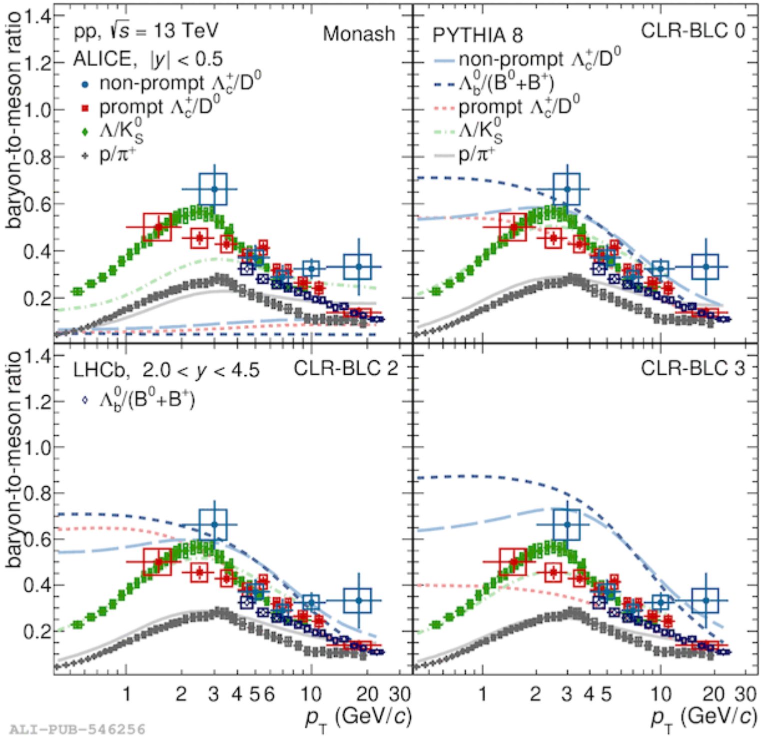


- **No centrality dependence of the ratios in jets with uncertainties unlike in the UE and inclusive measurements, where strong centrality dependence are observed**
  - **Further high precision measurements are desired to conclude**

Baryon to meson ratio: heavy-flavor sector

ALICE, Phys. Lett. B 829 (2022) 137065



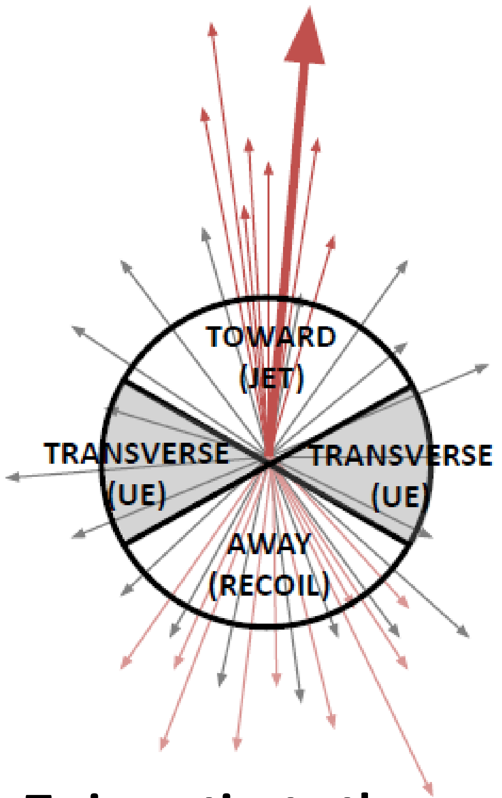


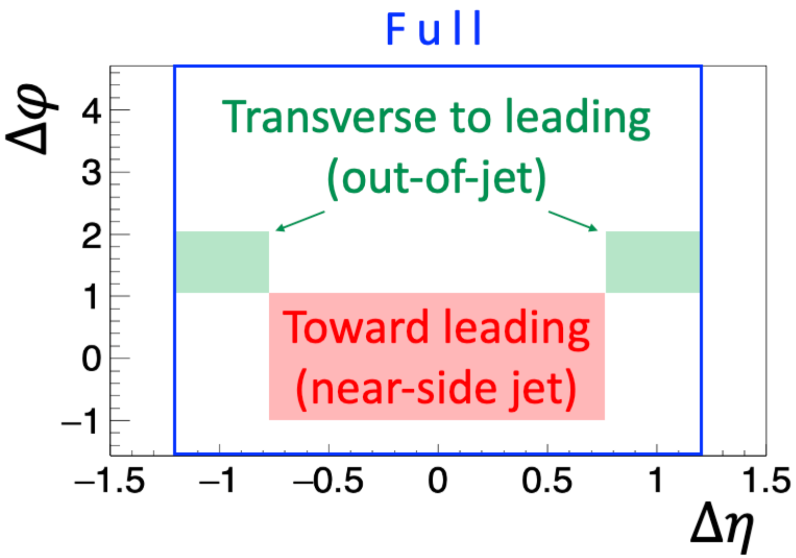
arXiv:2308.04873

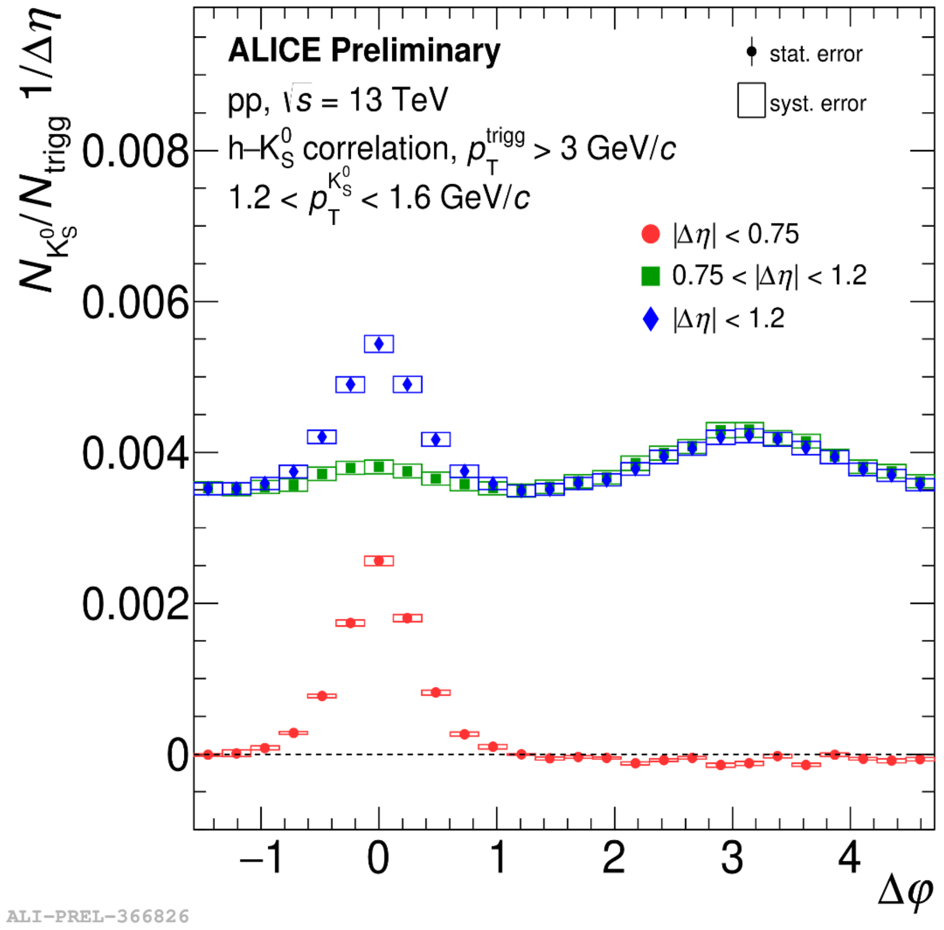
- **Baryon to meson ratio enhancement also present in beauty sector**
- **In line with expectation from color-reconnection models**

- **Charmed baryon-meson ratio also increases with increasing multiplicity at intermediate p_T**
- **p_T dependence of the charmed baryon-meson ratio shows the behavior very similar to that of strange baryon to meson ratio**
- **Heavy quarks are dominantly produced in hard scatterings in the early stage of the collisions**
  - **What is the origin of the baryon-meson ratio enhancement?**
  - **Fragmentation of hard parton from hard processes? Soft processes via recombination hadronization? Or interplay of hard and soft processes?**

Strangeness production associated with leading hadrons

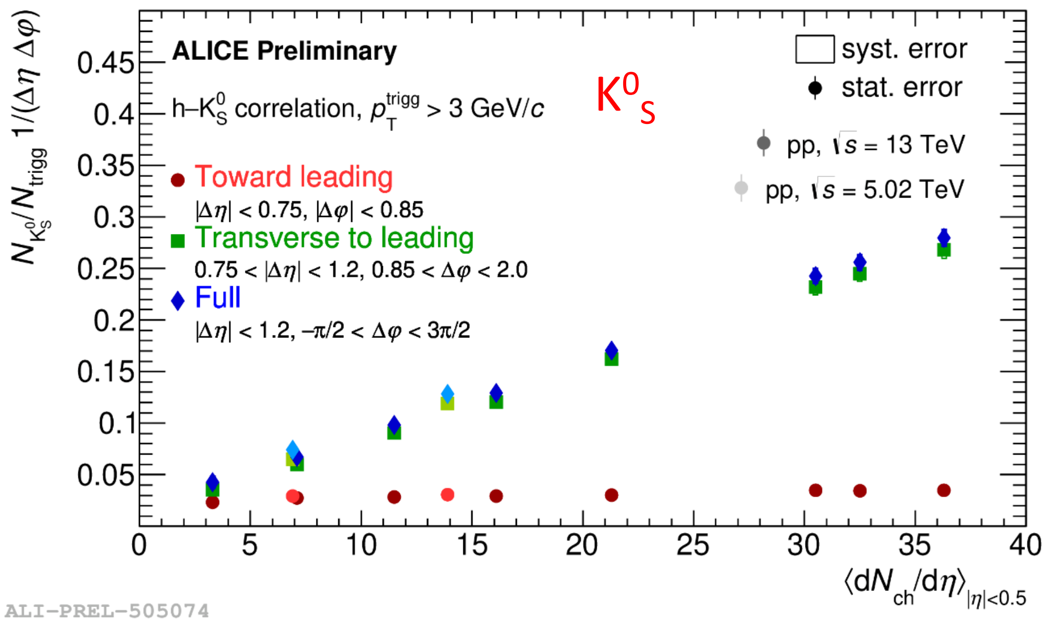


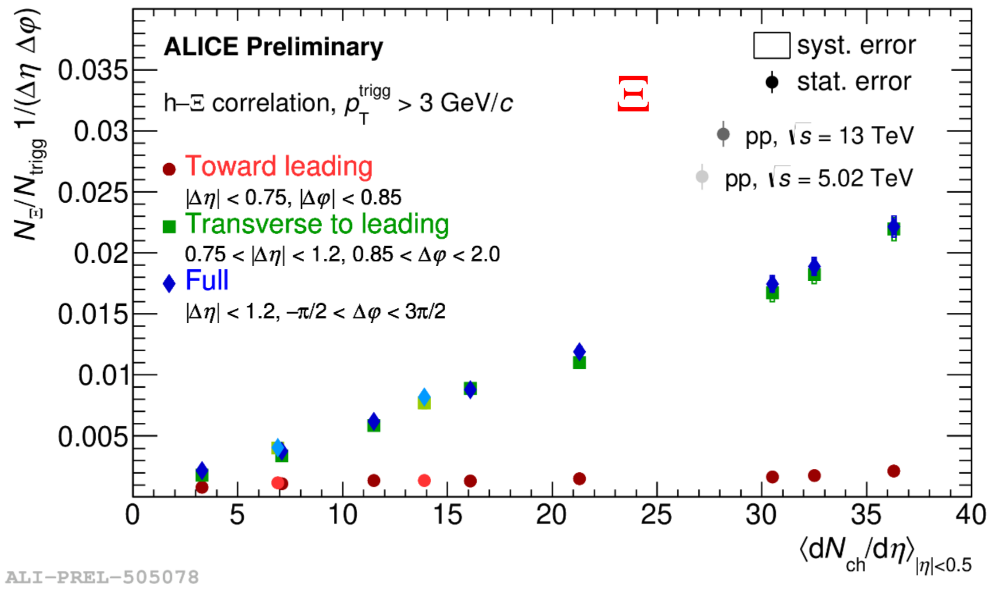




To investigate the possible contribution of low energy jets, strangeness production in and out of jets is studied via two particle correlations

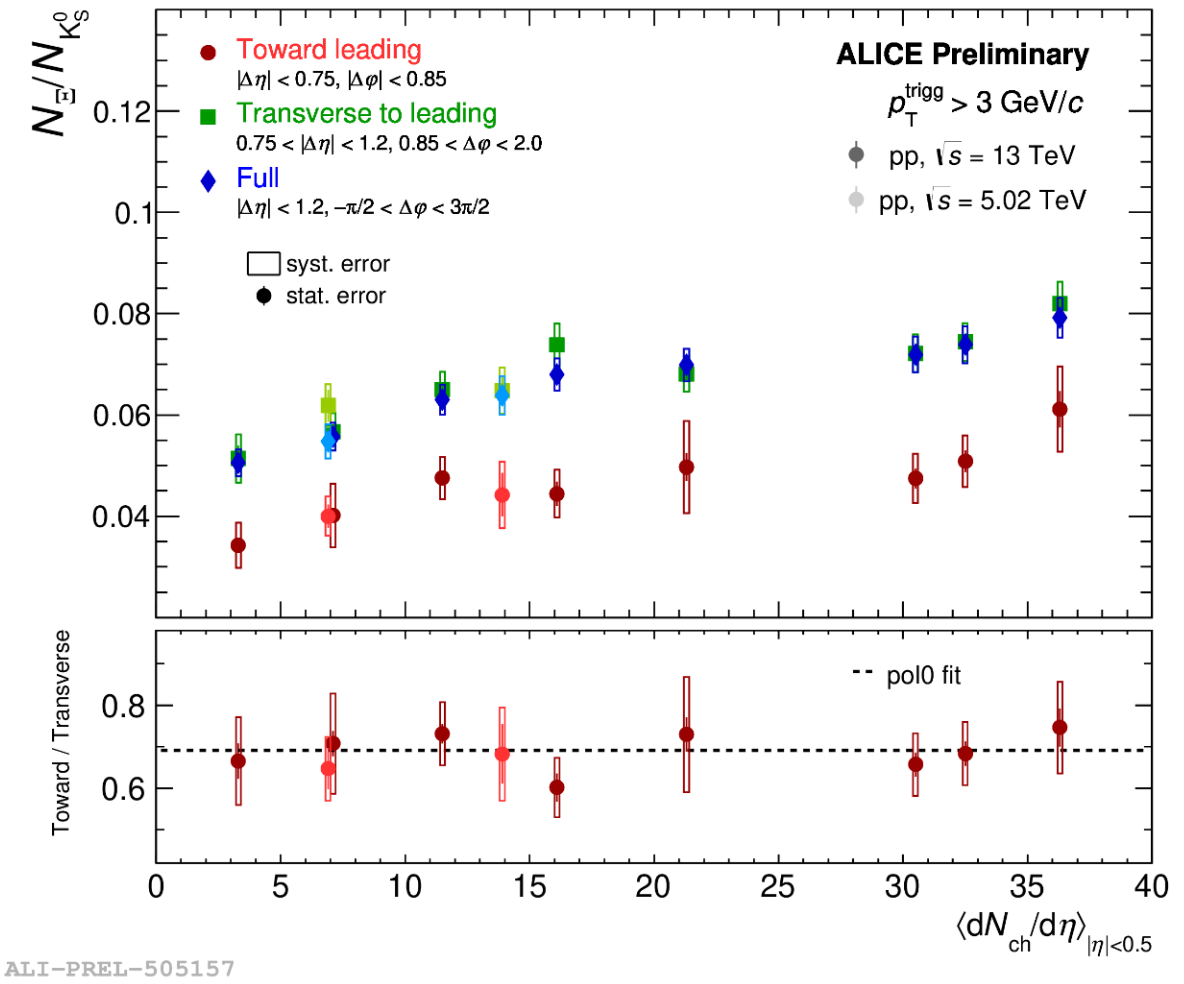
Multiplicity dependence of strangeness production toward and transverse to leading hadrons





- **(Multi-)strange hadrons are mainly produced out of jets with leading hadron of p_T > 3 GeV/*c***
- **The yields of (multi-)strange hadrons produced out of jets increase with increasing multiplicity**
- **The yields of (multi-)strange hadrons in jets show a mild dependence on the charged particle multiplicity**
- **No collision energy dependence**

Multiplicity dependence of strange baryon to meson ratio toward and transverse to leading hadrons

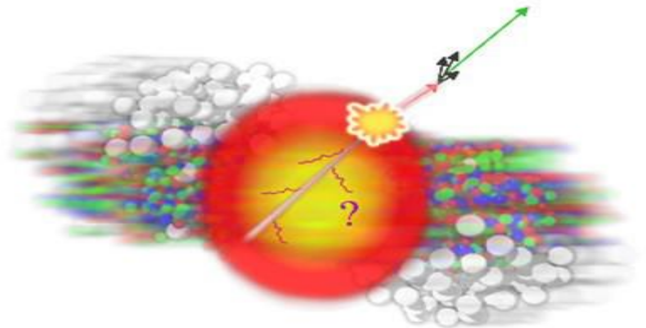


- **The ratio in the UE increases as multiplicity increases, showing a good agreement with that measured in full phase space**
- **The ratio obtained in jets also increases with increasing multiplicity, although the ratio is smaller than that in the UE**
- **However, the toward-leading and transverse-to-leading Ξ/K^0_S yield ratios show compatible increase with multiplicity**

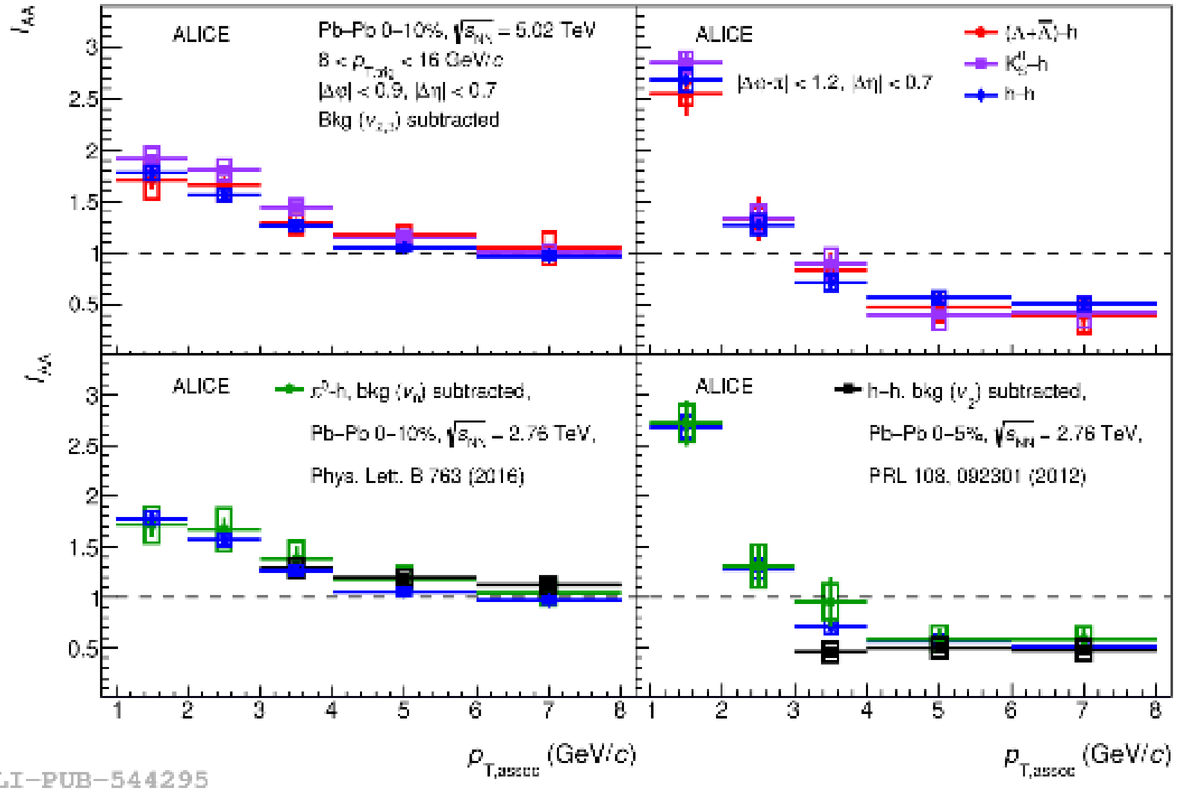
Nuclear modification factor of hadron yields associated to strange hadrons

ALICE， EPJC (2023) 83:497

- **Jet quenching in hot dense medium can be studied via di-hadron correlations**



$$I_{\mathrm{AA}} = \frac{Y^{\mathrm{AA}}}{Y^{\mathrm{pp}}}$$



- **The relative hadron production rates in quark and gluon jets seem to differ for K^0_S and Λ, with baryons produced more copiously in gluon jets**

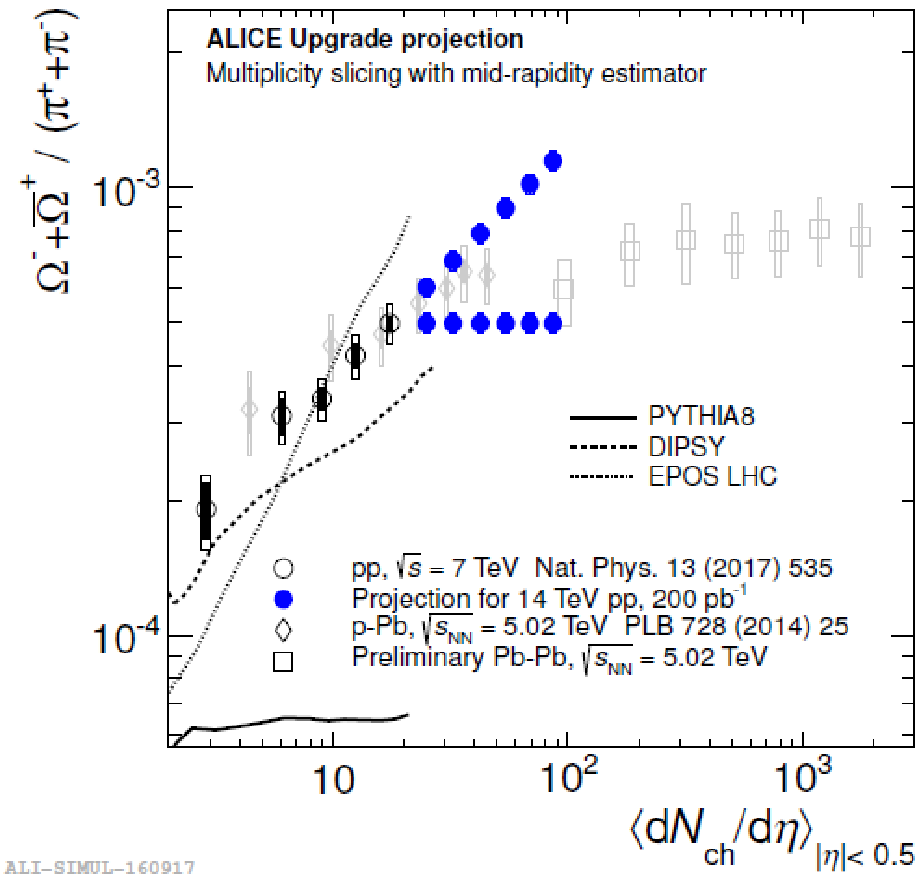
- **Away side： suppression at high p_T, whereas significant enhancement towards low p_T**
- **Near side： enhancement is also observed at low p_T**
- **No dependence on the trigger particle species: high p_T hadrons come predominantly from vacuum-like hard parton (mainly gluon) fragmentation at mid-rapidity at LHC energies**

Summary

- **Strangeness enhancement has been observed in different colliding systems and shows a smooth evolution with charged particle multiplicity**
- **Out-of-jet processes (in the UE) give the dominant contribution to strangeness production**
- **Enhancement of baryon to meson ratio at intermediate p_T are predominant by out-of-jet processes (in the UE)**
- **However, it is observed that baryon to meson ratio increases with increasing multiplicity both in and out of jets**
- **Nuclear modification factor of associated hadron yields doesn’t exhibit species dependence of high p_T triggered particles**

Outlook

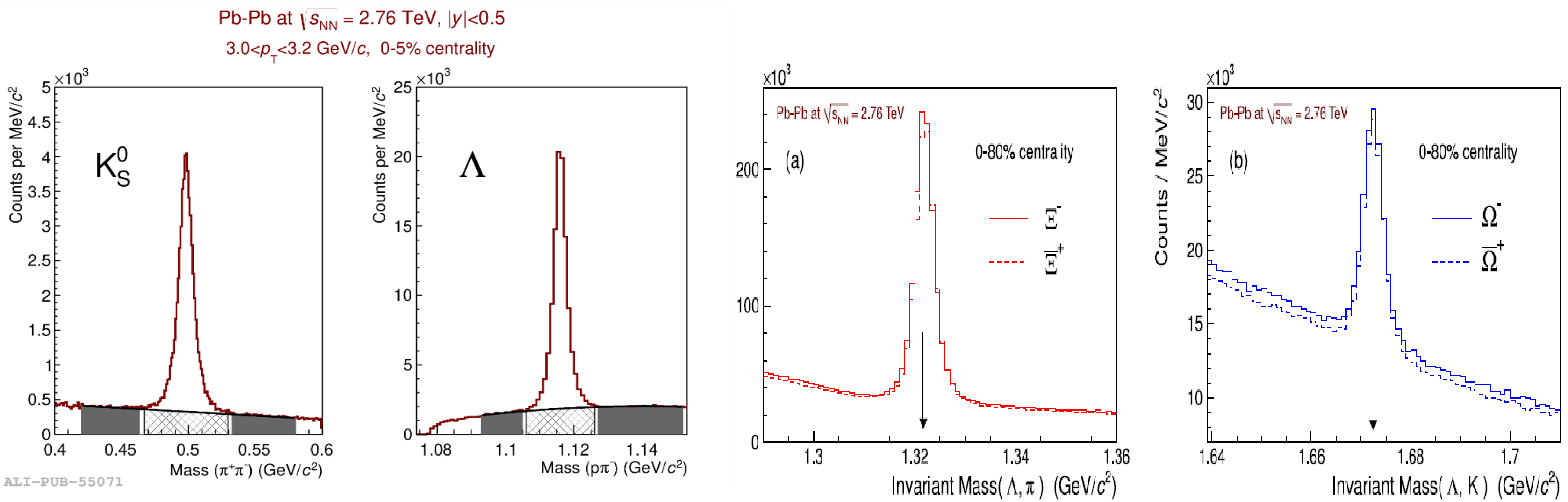
- **Studies of strangeness production in pp collisions will profit from the large amount of data that ALICE is collecting during Run 3**
  - **Statistics on $\Omega^{\pm}$ increases by a factor of 3000**
    - **Multi-strange production in and out of jets**
  - **More high precision differential measurements**
    - **Correlations between strange hadrons**
  - **Hunting for "jet quenching" effects in small collision systems**
    - **Correlations of high p_T strange and anti-strange hadrons**
  - **Hunting for new strange resonances**

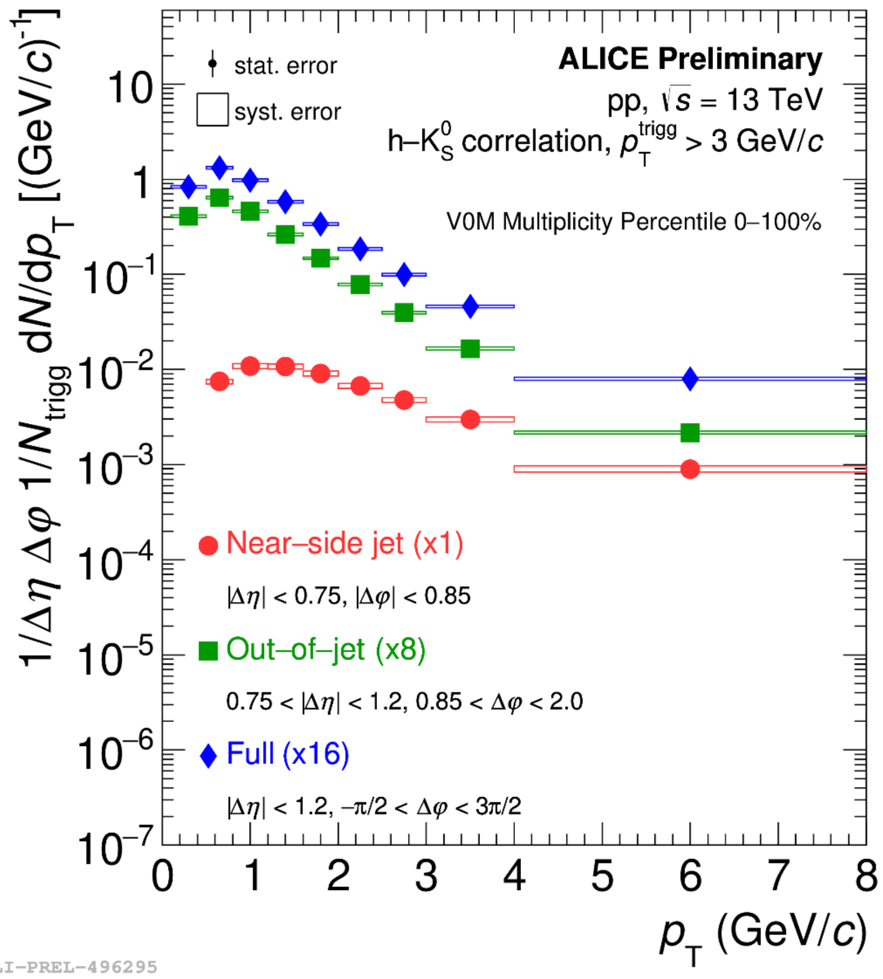


Thanks for your attention!

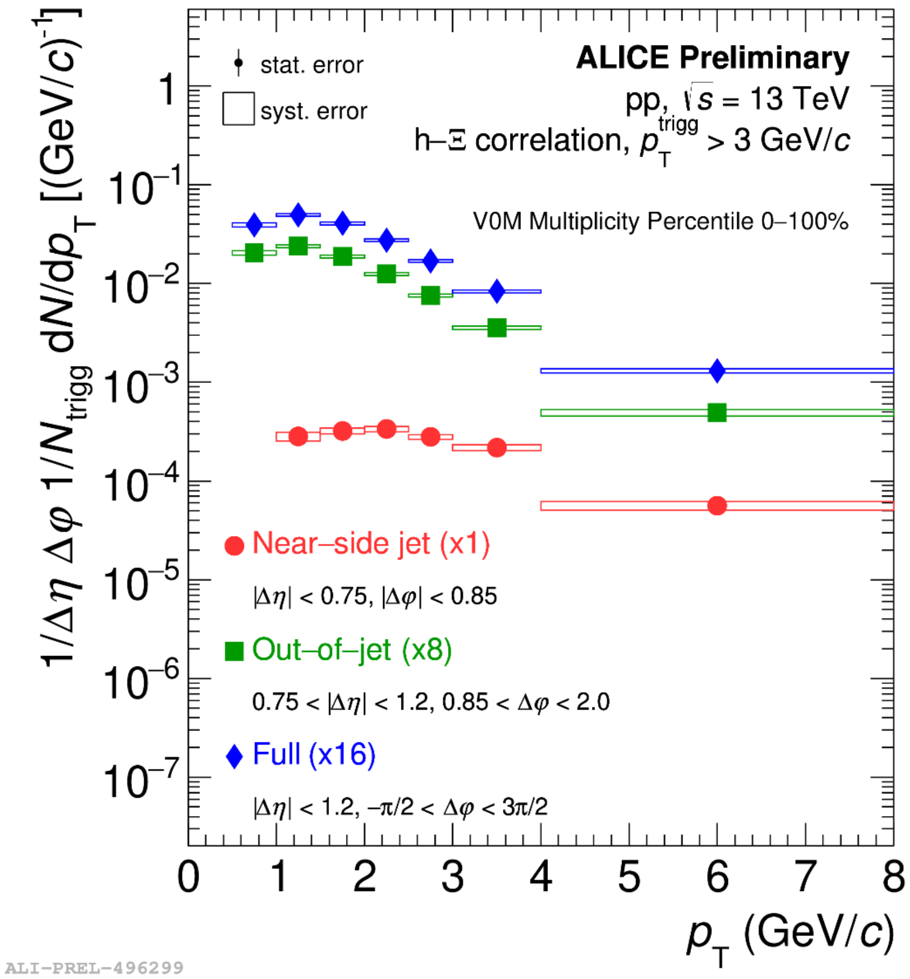
Backup

Invariant mass distribution of strange hadrons





ALICE Preliminary
pp, √s = 13 TeV
h–K0S correlation, p_T^trigg > 3 GeV/c
V0M Multiplicity Percentile 0–100%
stat. error
syst. error
Near–side jet (x1)
|Δη| < 0.75, |Δφ| < 0.85
Out–of–jet (x8)
0.75 < |Δη| < 1.2, 0.85 < Δφ < 2.0
Full (x16)
|Δη| < 1.2, −π/2 < Δφ < 3π/2
1/Δη Δφ 1/N_trigg dN/dp_T [(GeV/c)^-1]
p_T (GeV/c)
ALI-PREL-496295



ALICE Preliminary
pp, √s = 13 TeV
h–Ξ correlation, p_T^trigg > 3 GeV/c
V0M Multiplicity Percentile 0–100%
stat. error
syst. error
Near–side jet (x1)
|Δη| < 0.75, |Δφ| < 0.85
Out–of–jet (x8)
0.75 < |Δη| < 1.2, 0.85 < Δφ < 2.0
Full (x16)
|Δη| < 1.2, −π/2 < Δφ < 3π/2
1/Δη Δφ 1/N_trigg dN/dp_T [(GeV/c)^-1]
p_T (GeV/c)
ALI-PREL-496299