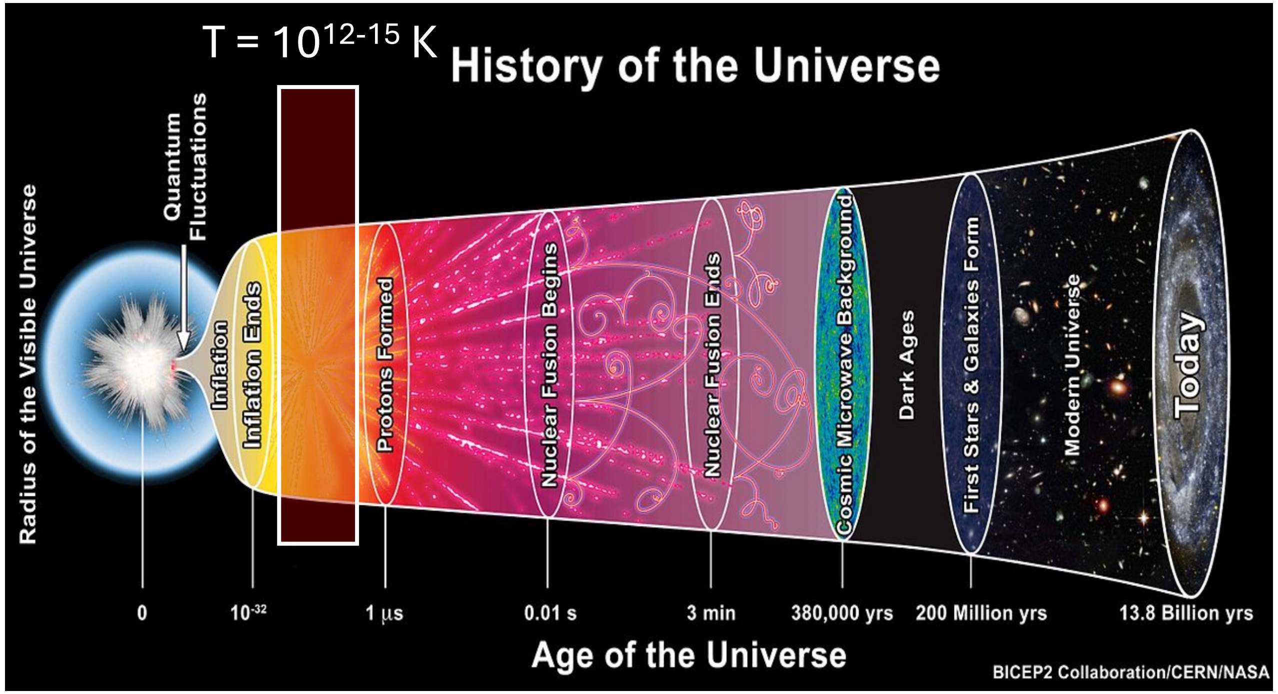
Probing identified and strange particle production using event-topology in pp collisions at $\sqrt{s} = 13$ TeV with ALICE

Dr. Rutuparna Rath
Adjunkt, IFJ PAN

IFJ PAN Seminar
29.06.2026 (Monday)

Free State of Quarks and Gluons in the Universe



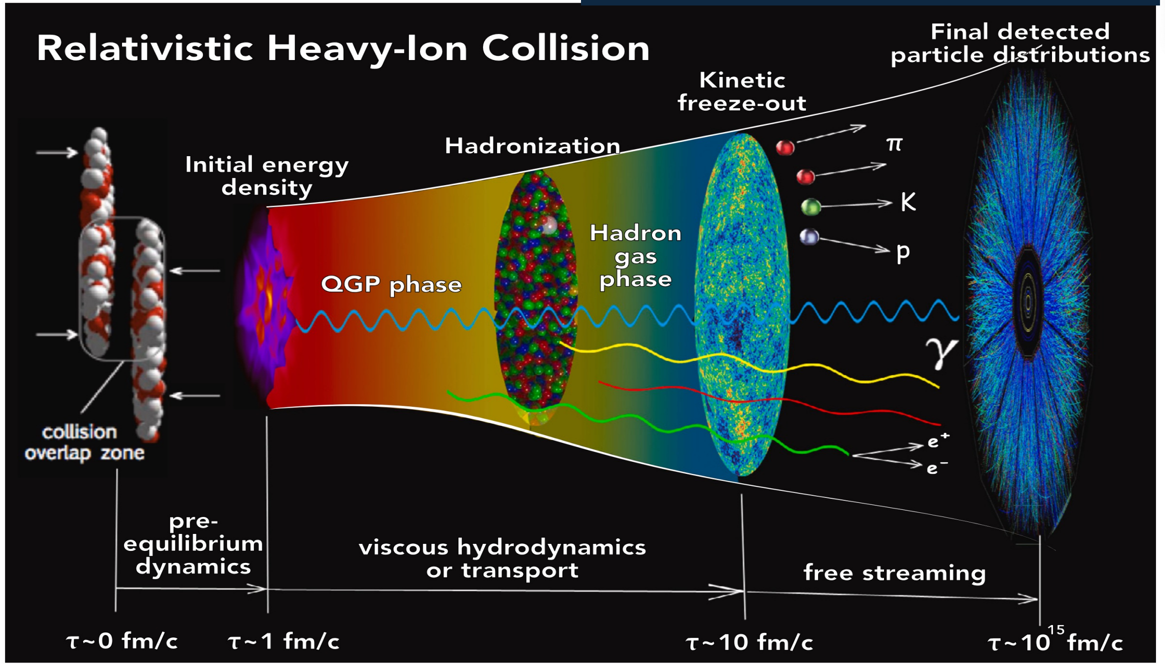
Courtesy: physics world

- Quark–Gluon Plasma (QGP) existed a few microseconds after the Big Bang
- Extreme densities and possibly deconfined quark matter may exist in the cores of neutron stars
- The early Universe belongs to the past → we cannot go back
- Neutron star cores are too far and inaccessible

The key question is: How can we create and study QGP in the laboratory?

Little Bang: Ultra-relativistic Heavy-ion Collisions

Nucl. Phys. A 1047, 122874 (2024)



- Quarks and gluons exist in nature as confined in colourless hadrons → confining property of QCD

- The strong coupling becomes weak for processes involving large momentum transfers

  → asymptotic freedom

The Quark–Gluon Plasma is formed when nuclear matter reaches extremely high temperature and energy density
→ **ultra-relativistic heavy-ion collisions**

- A phase transition is expected to occur around $T_c \sim 150 - 160$ MeV ($\sim 10^5 * T_{Sun}$)
  (Lattice QCD, PRD 90 (2014) 094503)
- u, d and s quarks are thermally produced in QGP, as $m_{u,d,s} < T_c$

How Do We Confirm QGP in Laboratory

- The QGP exists for an extremely short time and cannot be observed directly
- Need to look for observables sensitive to QGP formation

Some of them are:

- Jet quenching (energy loss in the medium)
- Collective flow (long-range correlation)
- Quarkonia suppression
- Strangeness enhancement

Why is strangeness a unique probe of the QGP?

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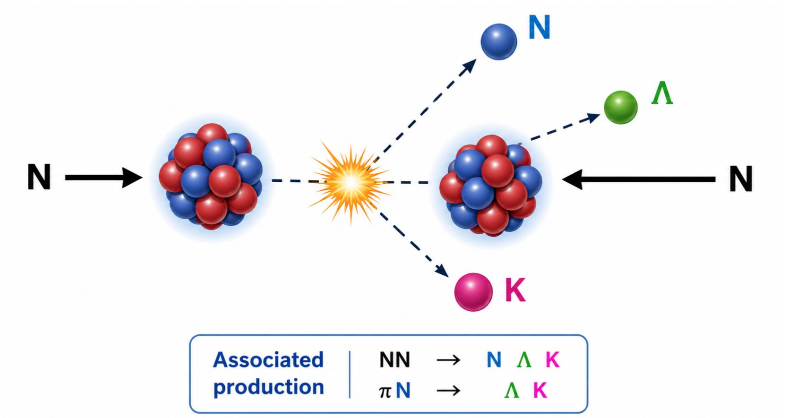
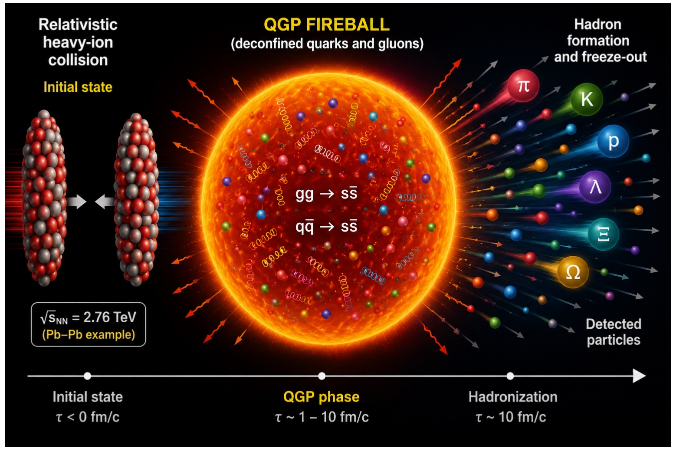
- Ordinary nuclear matter contains only u and d quarks. So, where do strange quarks come from?



Low-energy hadronic collisions



LHC Heavy-ion collisions

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Low-energy hadronic collisions

Associated production

$$NN \rightarrow N\Lambda K$$
$$\pi N \rightarrow \Lambda K$$

- Requires threshold energy
- Limited strange-particle production
- Examples: SIS18 (2-3 GeV), SPS (6-17 GeV), NA61/SHINE (5-17 GeV)

Increasing $\sqrt{s_{NN}}$

Higher gluon density and temperature

↓

Deconfined QGP medium

↓

Enhanced strange-quark production

LHC Heavy-ion collisions

Partonic production

$$gg \rightarrow s\bar{s}$$
$$q\bar{q} \rightarrow s\bar{s}$$

- Thermal production of $s\bar{s}$ pairs
- Enhanced strange-quark production
- Hadronization into K, Λ, Ξ, Ω

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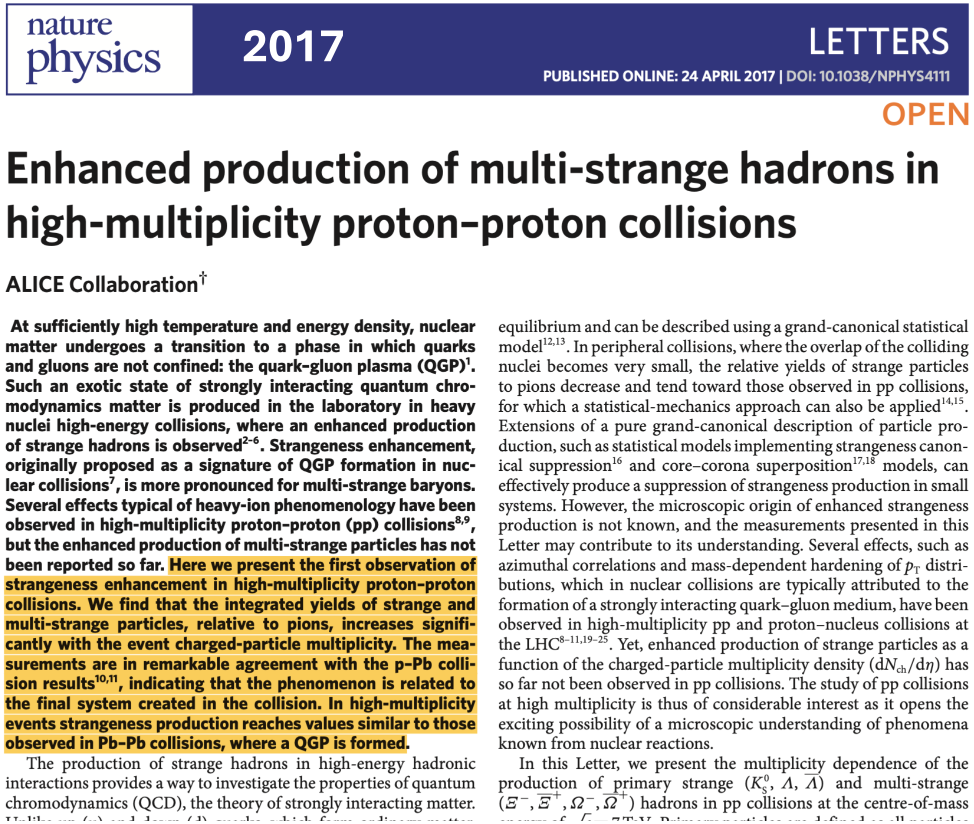
Why is strangeness a unique probe of the QGP?

- In a QGP, the hot gluon-rich medium efficiently produces strange quarks during the collision through $gg \rightarrow s\bar{s}$ and $q\bar{q} \rightarrow s\bar{s}$, T_{QGP} = 150-160 MeV is comparable to the bare mass of strange quark ~ 95 MeV, making strangeness a sensitive probe of the created QCD medium

- **Pion yields are used as non-strange reference, against which enhancement can be measured**

QGP Droplet in pp ?


nature physics | 2017 | LETTERS

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Enhanced production of multi-strange hadrons in high-multiplicity proton–proton collisions

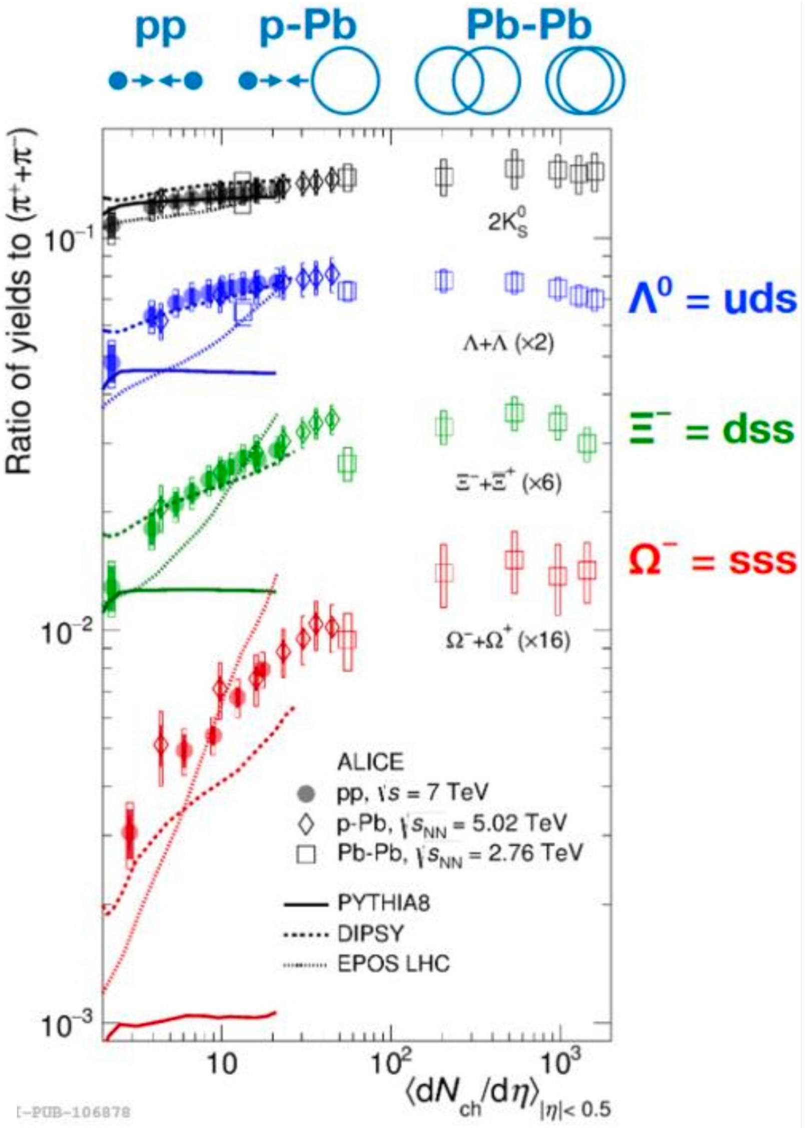
ALICE Collaboration†

At sufficiently high temperature and energy density, nuclear matter undergoes a transition to a phase in which quarks and gluons are not confined: the quark–gluon plasma (QGP)[1]. Such an exotic state of strongly interacting quantum chromodynamics matter is produced in the laboratory in heavy nuclei high-energy collisions, where an enhanced production of strange hadrons is observed[2–6]. Strangeness enhancement, originally proposed as a signature of QGP formation in nuclear collisions[7], is more pronounced for multi-strange baryons. Several effects typical of heavy-ion phenomenology have been observed in high-multiplicity proton–proton (pp) collisions[8,9], but the enhanced production of multi-strange particles has not been reported so far. Here we present the first observation of strangeness enhancement in high-multiplicity proton–proton collisions. We find that the integrated yields of strange and multi-strange particles, relative to pions, increases significantly with the event charged-particle multiplicity. The measurements are in remarkable agreement with the p–Pb collision results[10,11], indicating that the phenomenon is related to the final system created in the collision. In high-multiplicity events strangeness production reaches values similar to those observed in Pb–Pb collisions, where a QGP is formed.

The production of strange hadrons in high-energy hadronic interactions provides a way to investigate the properties of quantum chromodynamics (QCD), the theory of strongly interacting matter.

equilibrium and can be described using a grand-canonical statistical model[12,13]. In peripheral collisions, where the overlap of the colliding nuclei becomes very small, the relative yields of strange particles to pions decrease and tend toward those observed in pp collisions, for which a statistical-mechanics approach can also be applied[14,15]. Extensions of a pure grand-canonical description of particle production, such as statistical models implementing strangeness canonical suppression[16] and core–corona superposition[17,18] models, can effectively produce a suppression of strangeness production in small systems. However, the microscopic origin of enhanced strangeness production is not known, and the measurements presented in this Letter may contribute to its understanding. Several effects, such as azimuthal correlations and mass-dependent hardening of p_T distributions, which in nuclear collisions are typically attributed to the formation of a strongly interacting quark–gluon medium, have been observed in high-multiplicity pp and proton–nucleus collisions at the LHC[8–11,19–25]. Yet, enhanced production of strange particles as a function of the charged-particle multiplicity density ($dN_{ch}/d\eta$) has so far not been observed in pp collisions. The study of pp collisions at high multiplicity is thus of considerable interest as it opens the exciting possibility of a microscopic understanding of phenomena known from nuclear reactions.

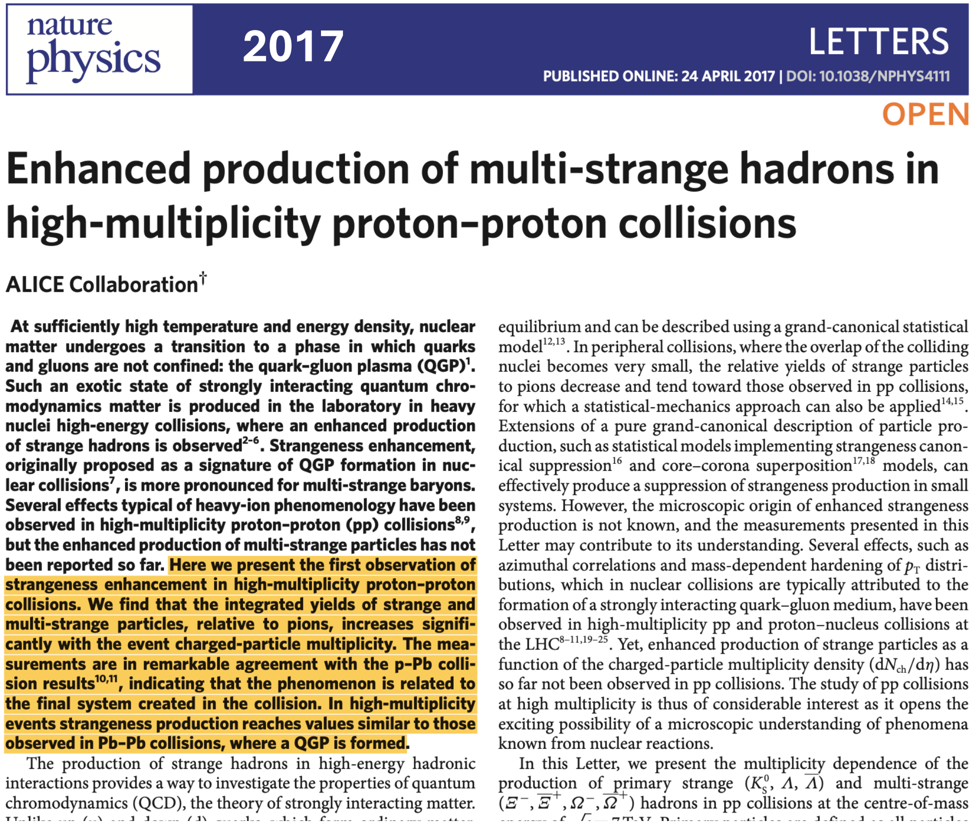
In this Letter, we present the multiplicity dependence of the production of primary strange (K^0_S, Λ, $\overline{\Lambda}$) and multi-strange (Ξ^-, $\overline{\Xi}^+$, Ω^-, $\overline{\Omega}^+$) hadrons in pp collisions at the centre-of-mass



Nature Phys 13, 535–539 (2017)

- Strangeness enhancement in high-multiplicity proton–proton reach similar values that observed for Pb-Pb collisions
- However, high-multiplicity pp events can arise from both multiple soft interactions and hard QCD processes
- **So, we need other observables to characterize such systems: differential studies**

QGP Droplet in pp ?



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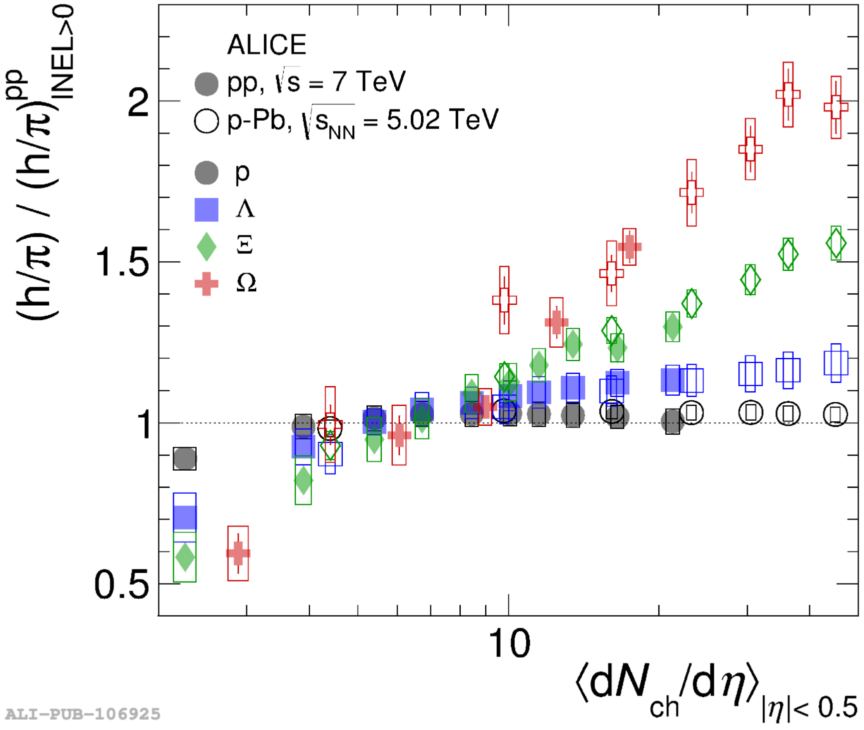

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- However, high-multiplicity pp events can arise from both multiple soft interactions and hard QCD processes
- **So, we need other observables to characterize such systems: differential studies**

Transverse Spherocity ($S_0^{p_{\rm T}=1}$)

✓ S_0 is defined using a unit vector n ($n_{\rm T}$, 0) that minimizes

$$S_0^{p_{\rm T}=1} = \frac{\pi^2}{4} \min_{\hat{n}} \left(\frac{\Sigma_i \, |\hat{p}_{T_i} \times \hat{n}|}{N_{trk}} \right)^2$$

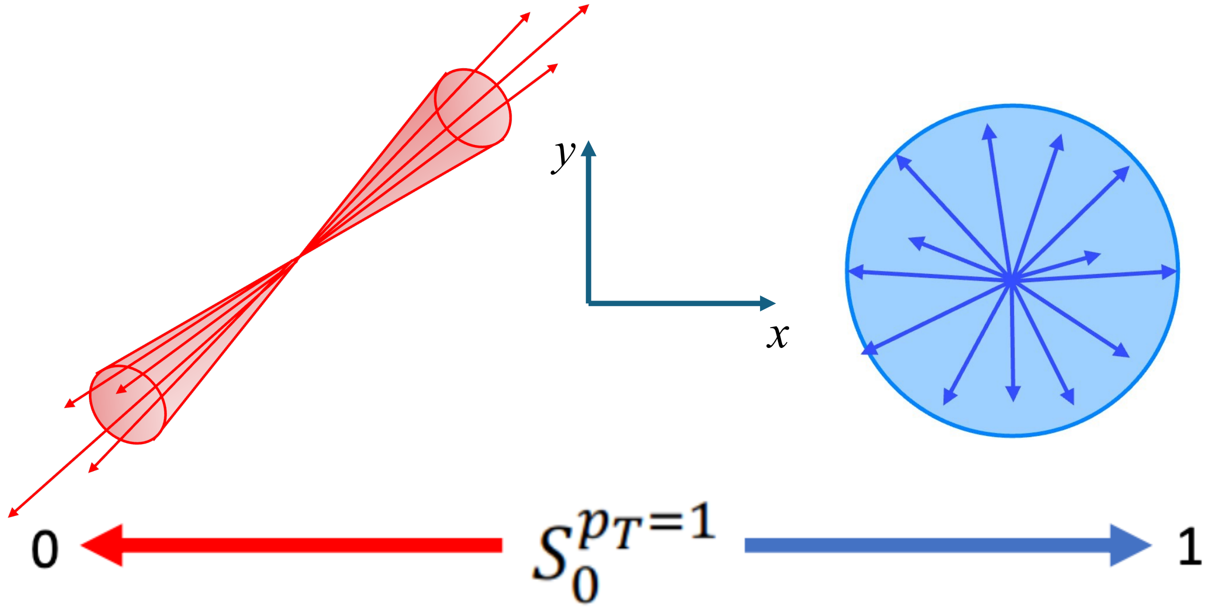
Isotropic ($S_0^{p_{\rm T}=1}$ →1):

- ✓ Azimuthally isotropic events
- ✓ Particle production is driven by multiple soft collisions

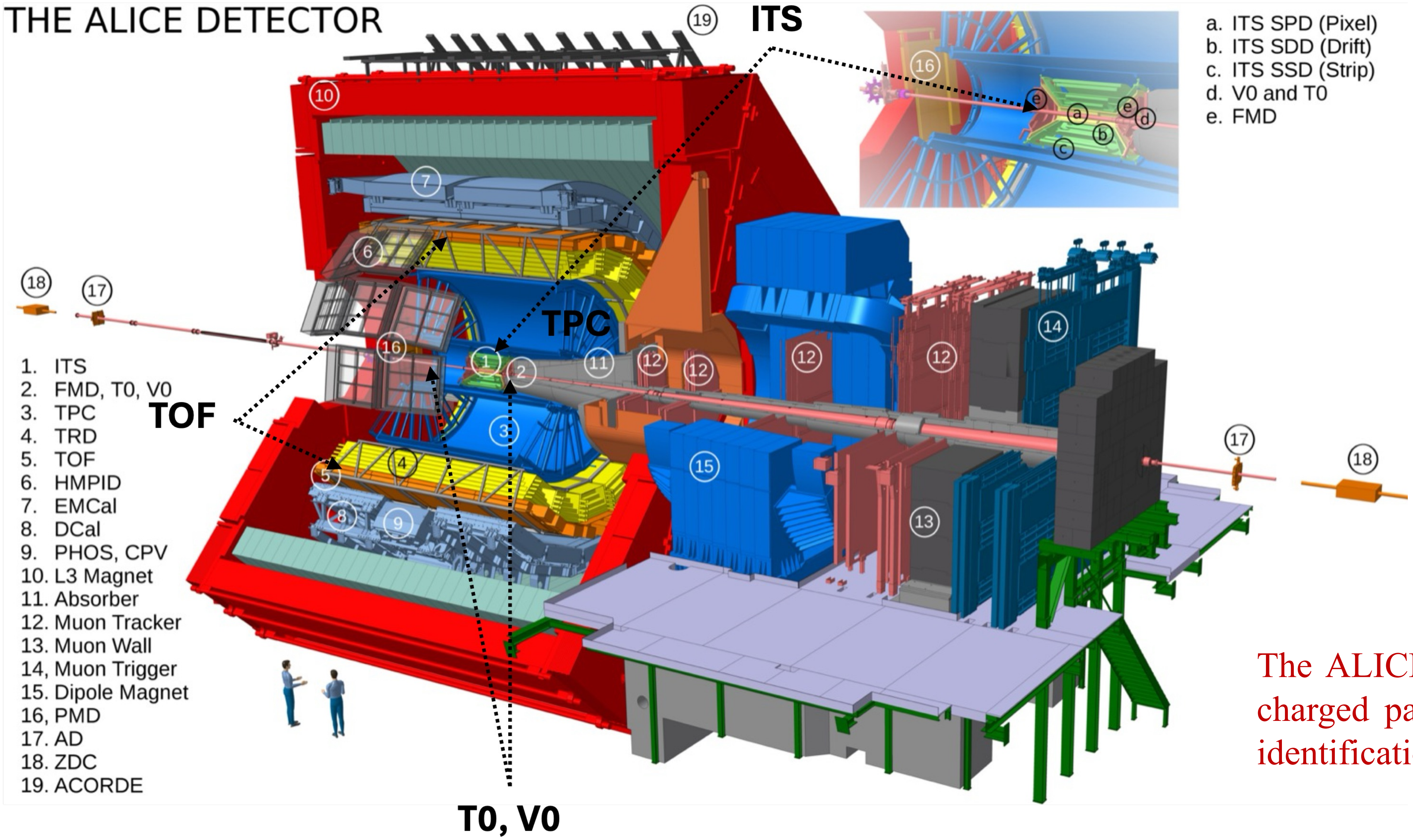
✓ S_0 can be used to disentangle the soft and hard QCD dominated processes in an event

Jet-like ($S_0^{p_{\rm T}=1}$ →0):

- ✓ Back-to-back "jet-like" events
- ✓ Particle production is primarily driven by hard physics

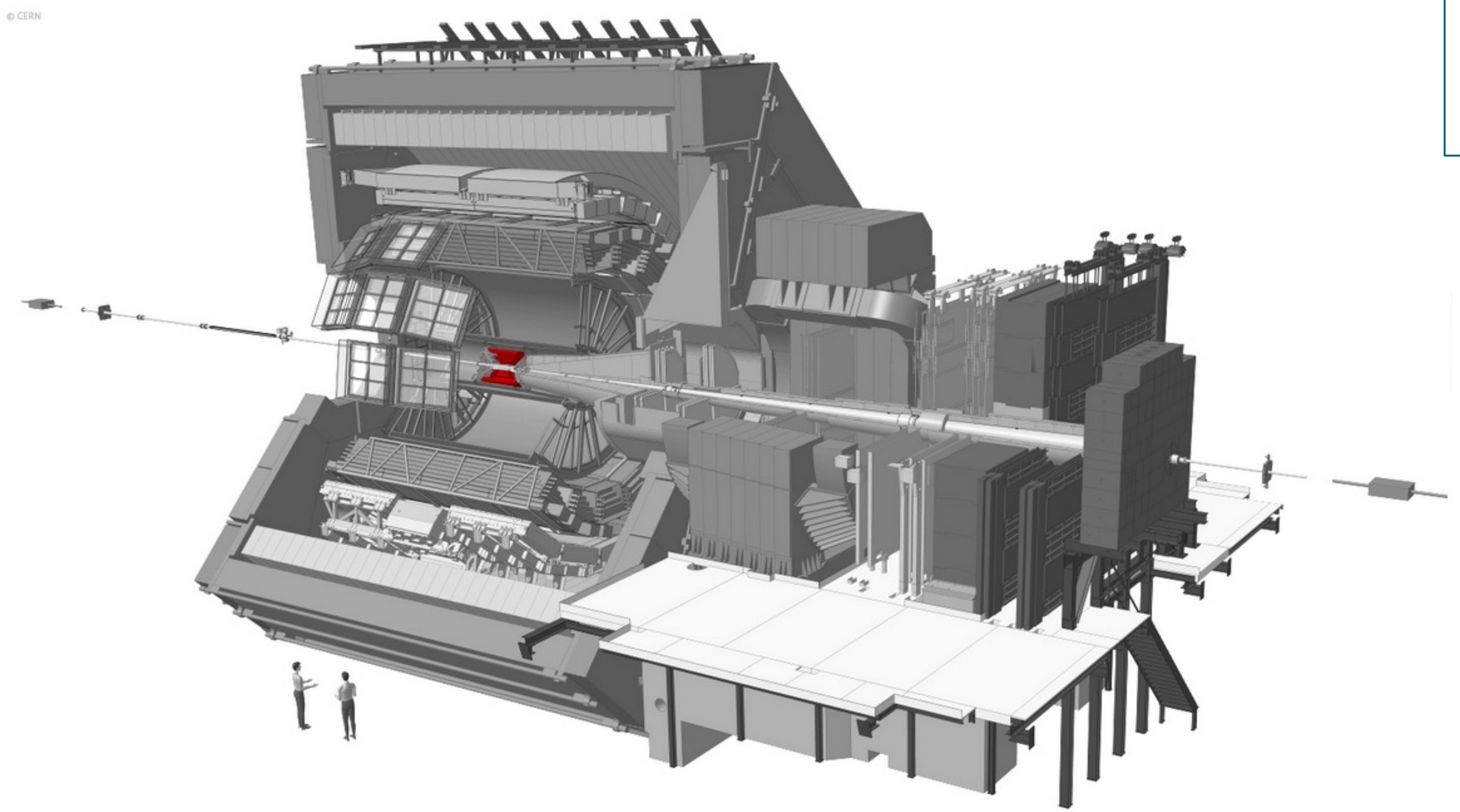


ALICE Detector



The ALICE detector is optimized for charged particle tracking and hadron identification

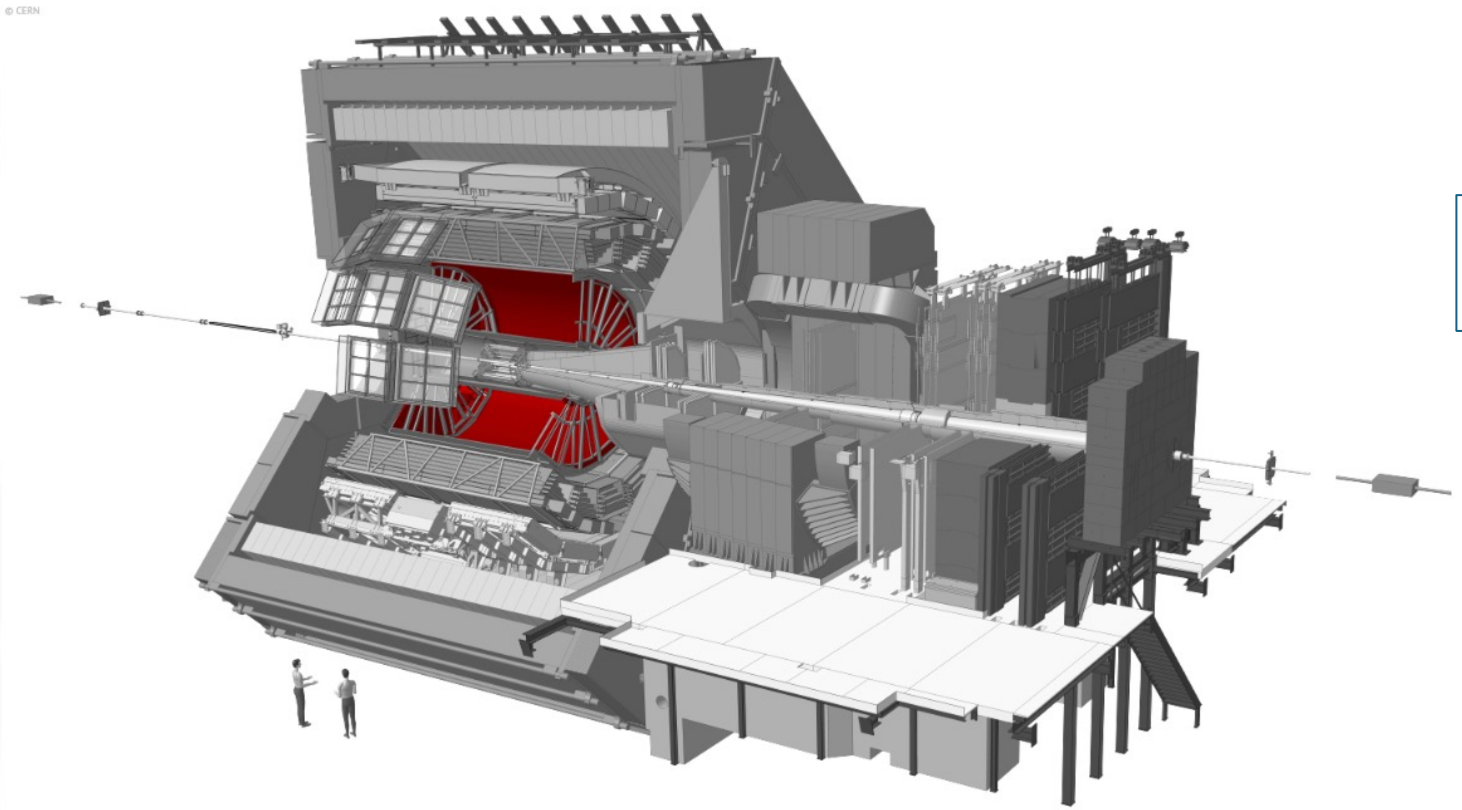
ALICE Detector- ITS



- **ITS (|η|<0.9):**
  - 6 Layers of silicon detectors
  - Trigger, vertex, and tracking

ITS = SPD + SDD + SSD

ALICE Detector- TPC



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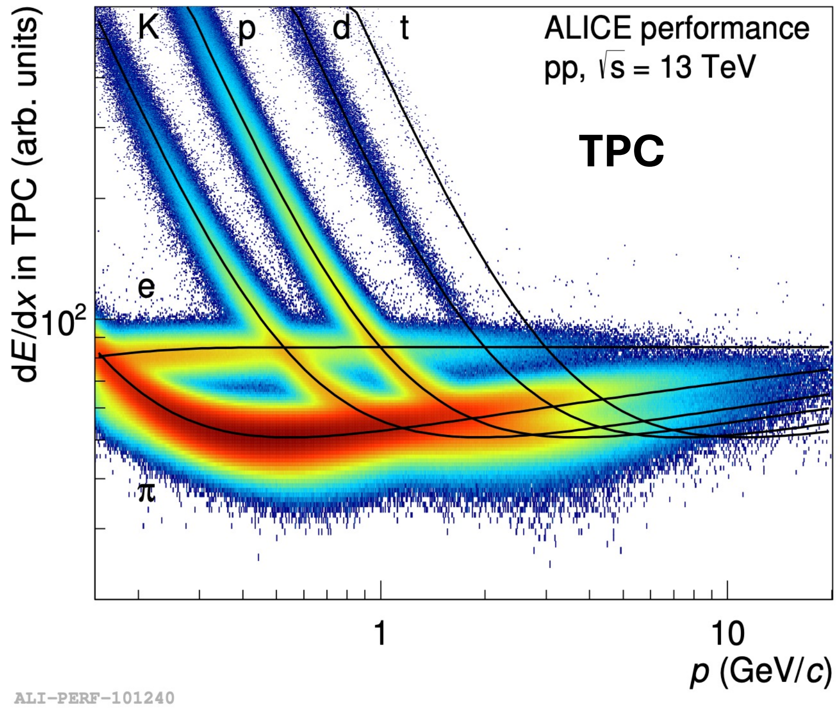
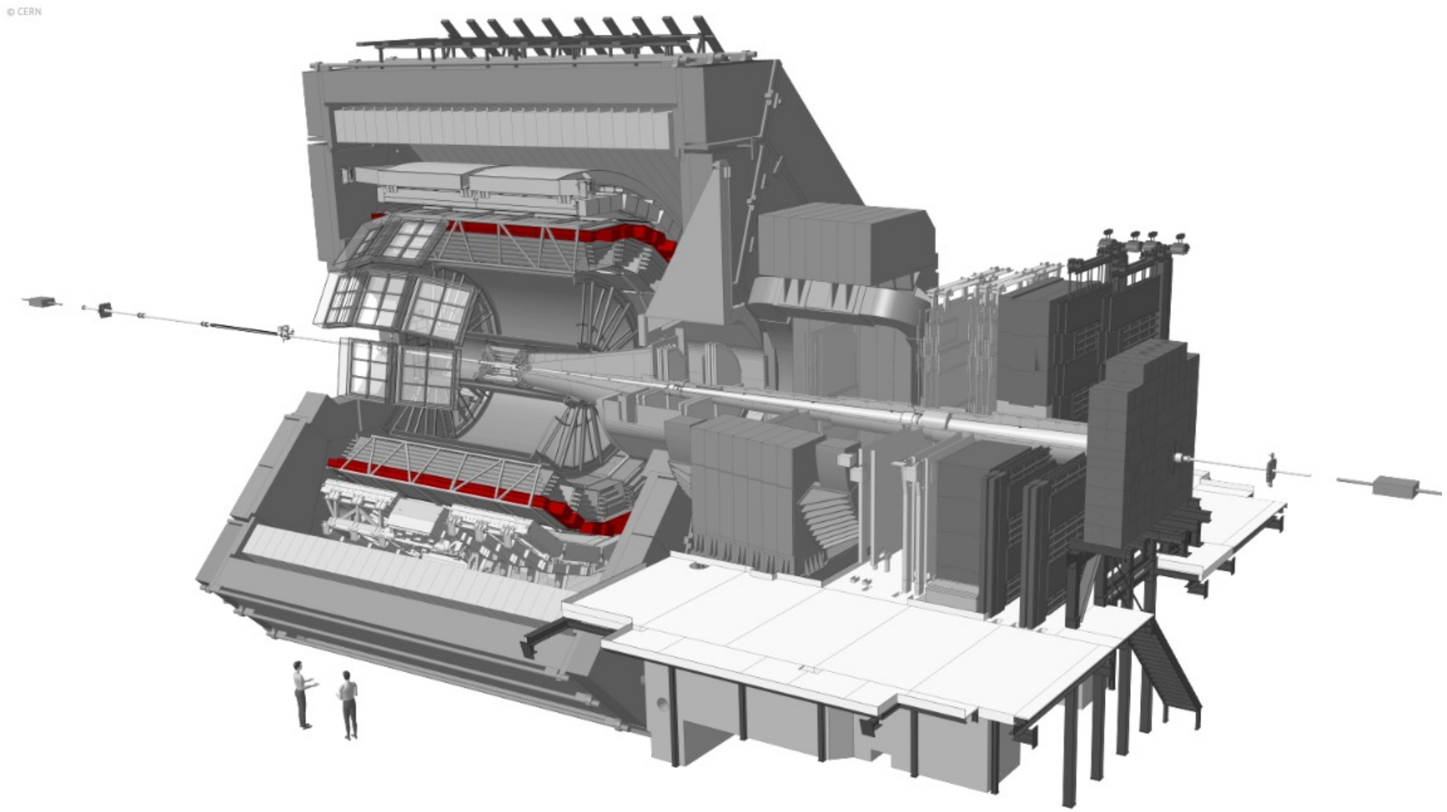
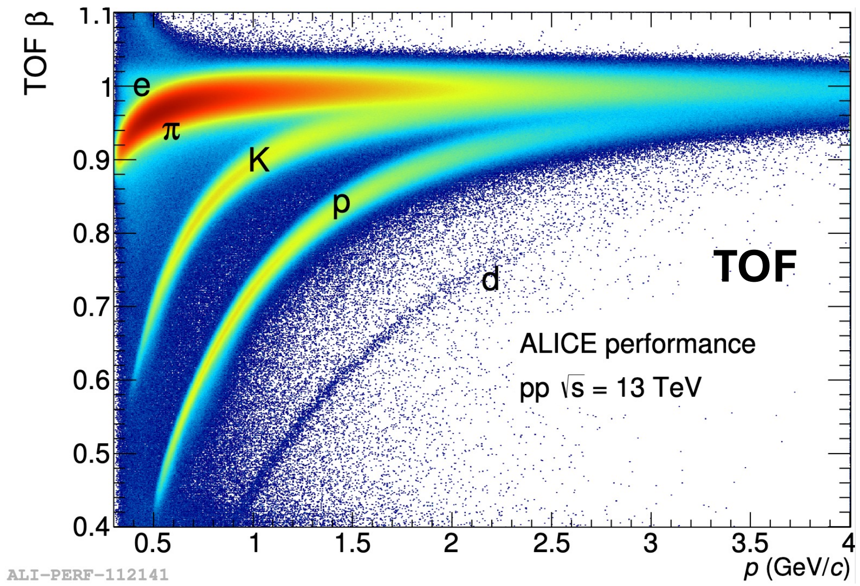
- **TPC (|η|<0.9):** Tracking, PID from specific energy loss (dE/dx)



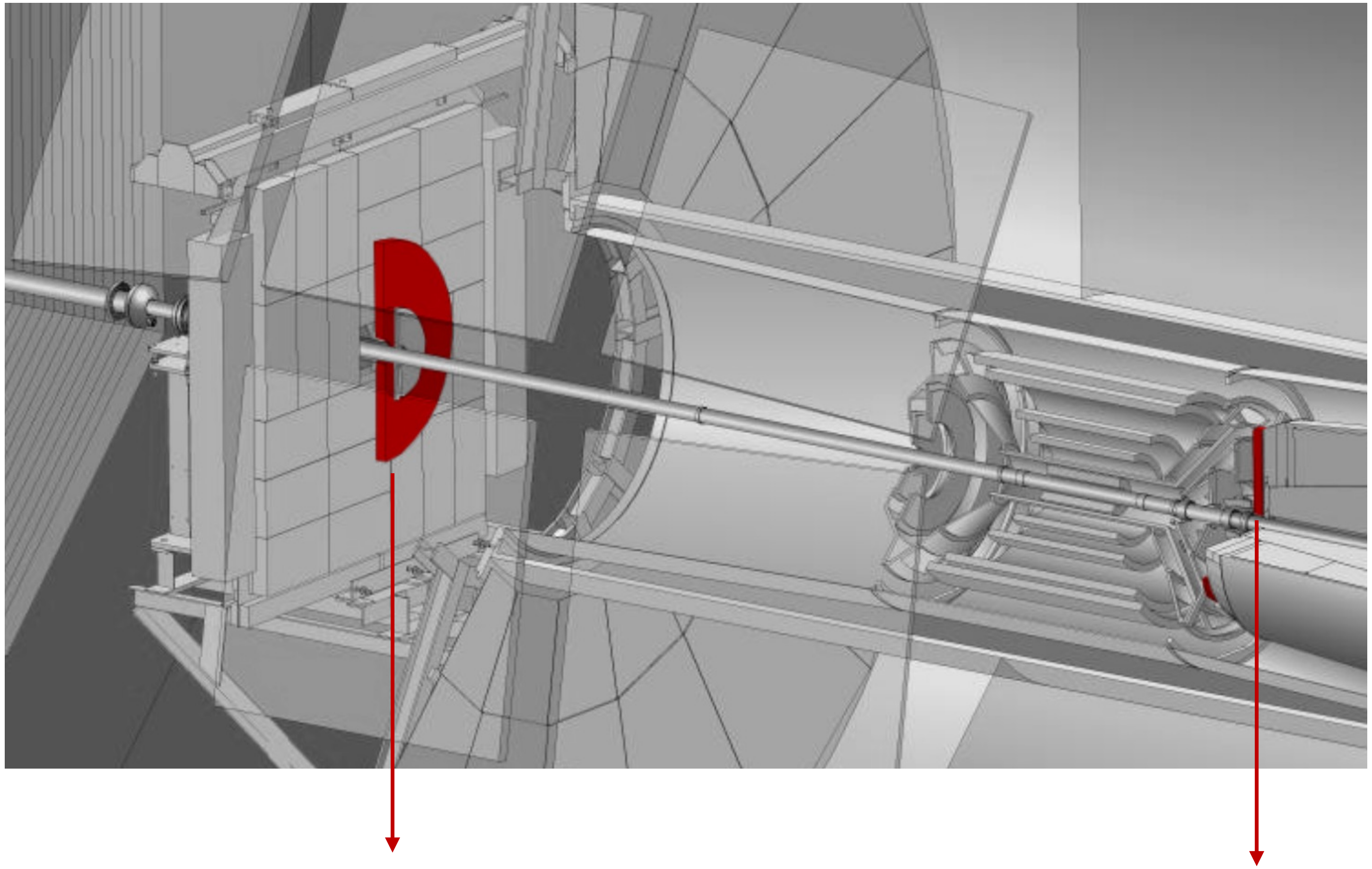
ALICE Detector- TOF



- **ITS ($|\eta|<0.9$):**
  - 6 Layers of silicon detectors
  - Trigger, vertex, and tracking
- **TPC ($|\eta|<0.9$):** Tracking, PID from specific energy loss (dE/dx)
- **TOF ($|\eta|<0.9$):**
  - Multi-gap Resistive Plate Chambers
  - PID (time-of-flight)



ALICE Detector- V0



- **ITS (|η|<0.9):**
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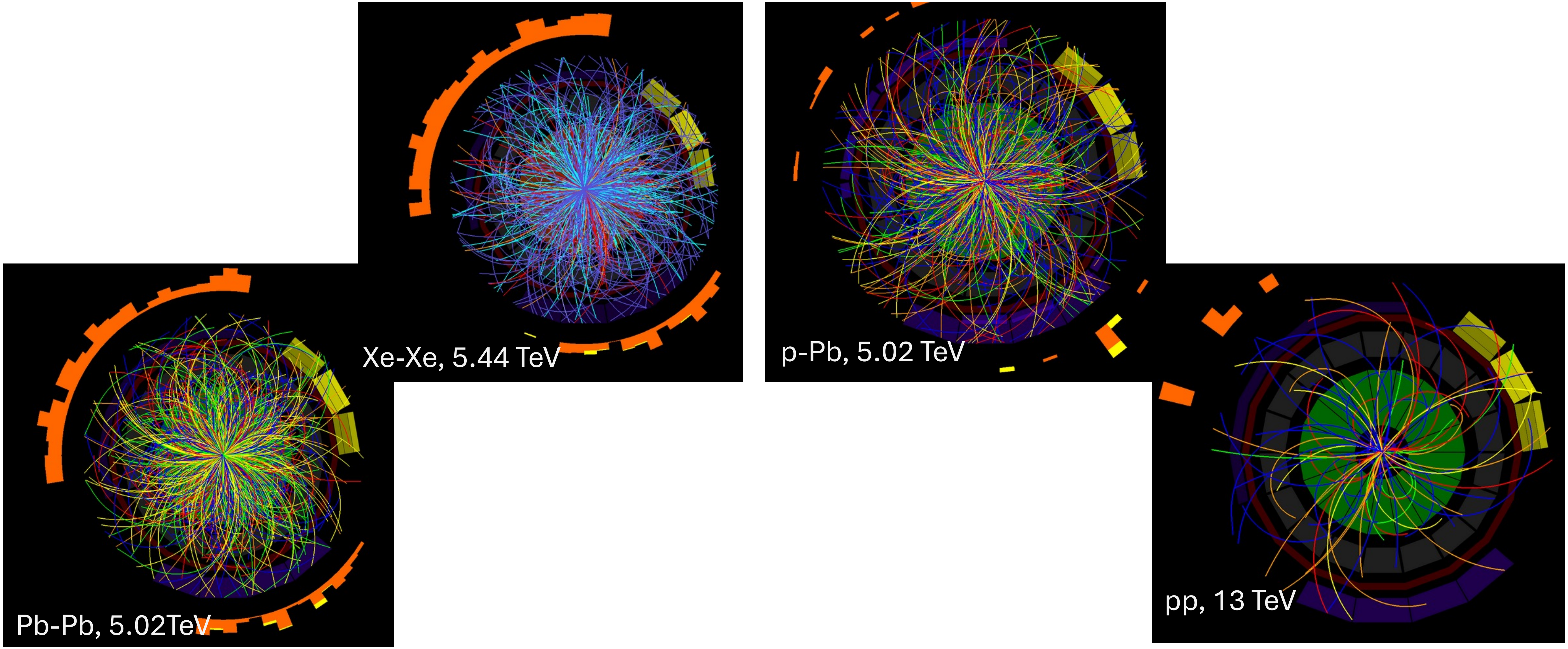
- **TOF (|η|<0.9):**
  - **Multi-gap Resistive Plate Chambers**
  - PID (time-of-flight)
- **V0 (A and C):**
  - **Segmented plastic scintillator arrays**
  - **Minimum-bias trigger and multiplicity estimator**
    - Minimum Bias: 0 – 100%
    - High Multiplicity: 0 – 1%

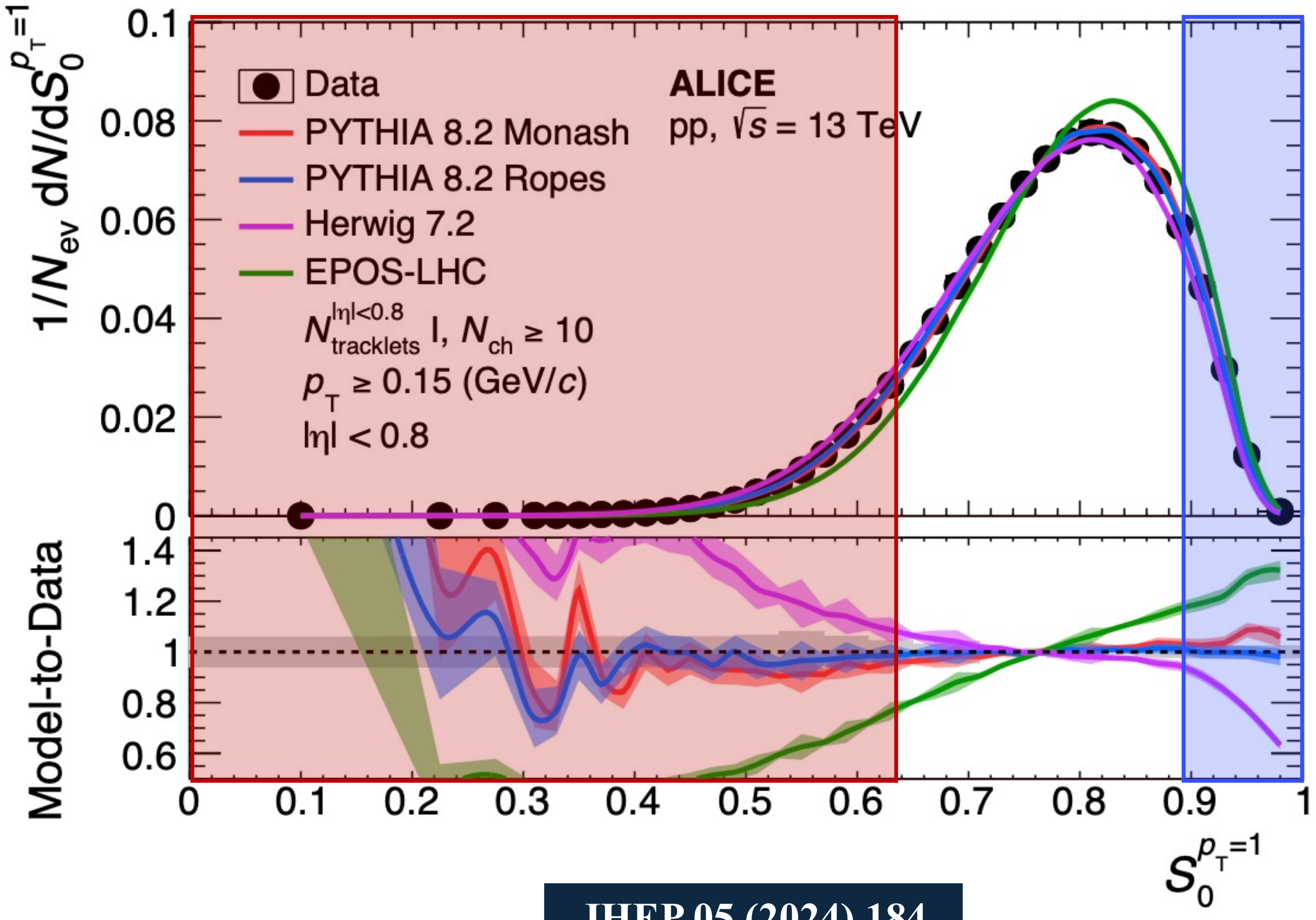
Event display



How to Select Events with $S_0^{p_{\mathrm{T}}=1}$?

$$S_0^{p_{\mathrm{T}}=1} = \frac{\pi^2}{4} \min_{\hat{n}} \left(\frac{\Sigma_i \ |\hat{p}_{T_i} \times \hat{n}|}{N_{trk}} \right)^2$$

- ✓ Classify high-multiplicity events based on event topology
  - ✓ Focus on top 1% multiplicity, where QGP-like effects arise
- ✓ Events are selected for the top (isotropic) and bottom (jet-like) 10% of the spherocity distribution
- ✓ Mid-rapidity multiplicity estimator is used to estimate multiplicity



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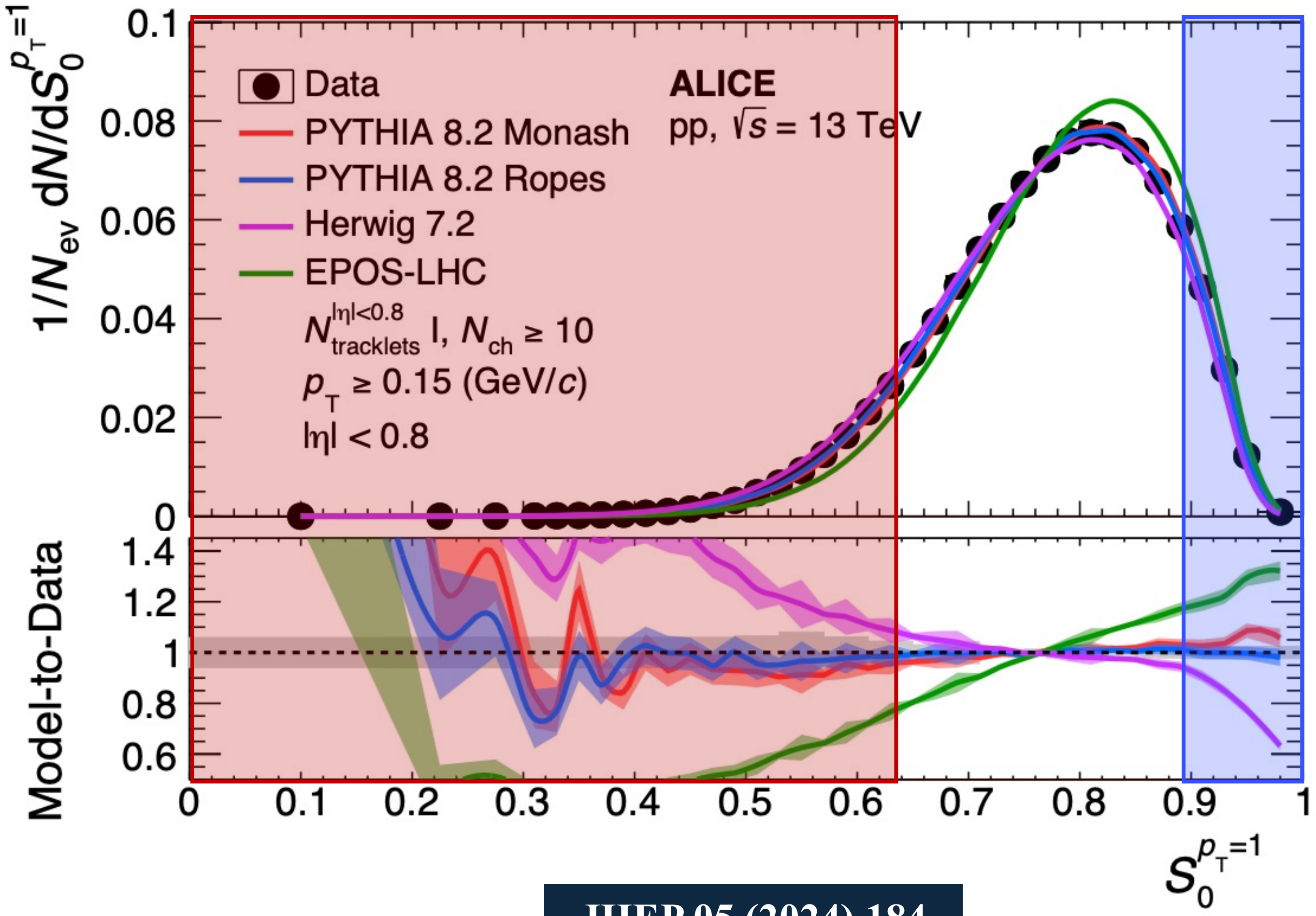
How to Select Events with $S_0^{p_T=1}$?

- ✓ PYTHIA8 (Monash, Ropes): Multipartonic interaction (MPI), Color reconnection (CR), and Lund string model for hadronization
- ✓ HERWIG: MPI, and Cluster fragmentation model for hadronization
- ✓ EPOS-LHC: Core + Corona mechanisms
- ✓ PYTHIA8 better describes the data quantitatively as compared to other MC generators



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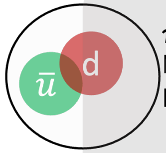
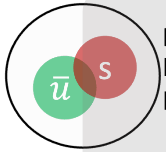
Particle Identification in ALICE

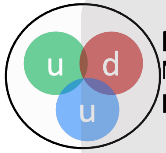
Primary hadrons



π^-
M = 140 MeV
Primary*

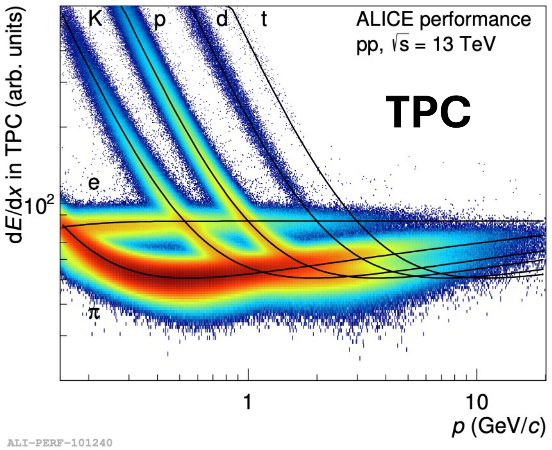


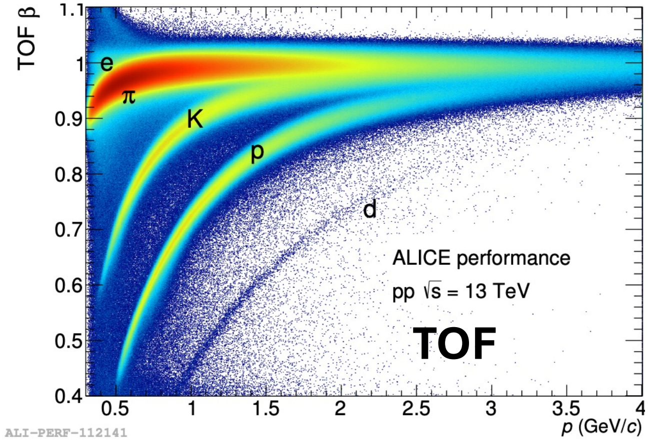
K^-
M = 494 MeV
Primary*



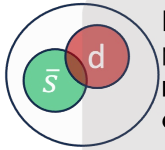
p
M = 938 MeV
Primary*

- Direct track reconstruction
- PID using TPC dE/dx and TOF timing

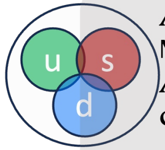




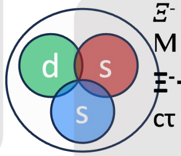
V0s and Cascade



K^0_s
M = 497 MeV
$K^0_s \rightarrow \pi^+ \pi^-$ (69.2%)
cτ → 2.68 cm



Λ
M = 1115 MeV
$\Lambda \rightarrow p\pi^-$ (63.9%)
cτ = 7.98 cm

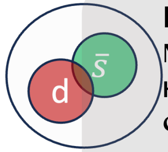


Ξ^-
M = 1322 MeV
$\Xi^- \rightarrow \Lambda\pi^-$ (99.9%)
cτ = 4.91 cm

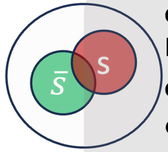
Weakly decaying particles

- Reconstructed from displaced decay topology
- Signal extracted using invariant mass

Resonance particles



K^{*0}
M = 896 MeV
$K^{*0} \rightarrow K\pi$ (66%)
cτ → 4.16 fm

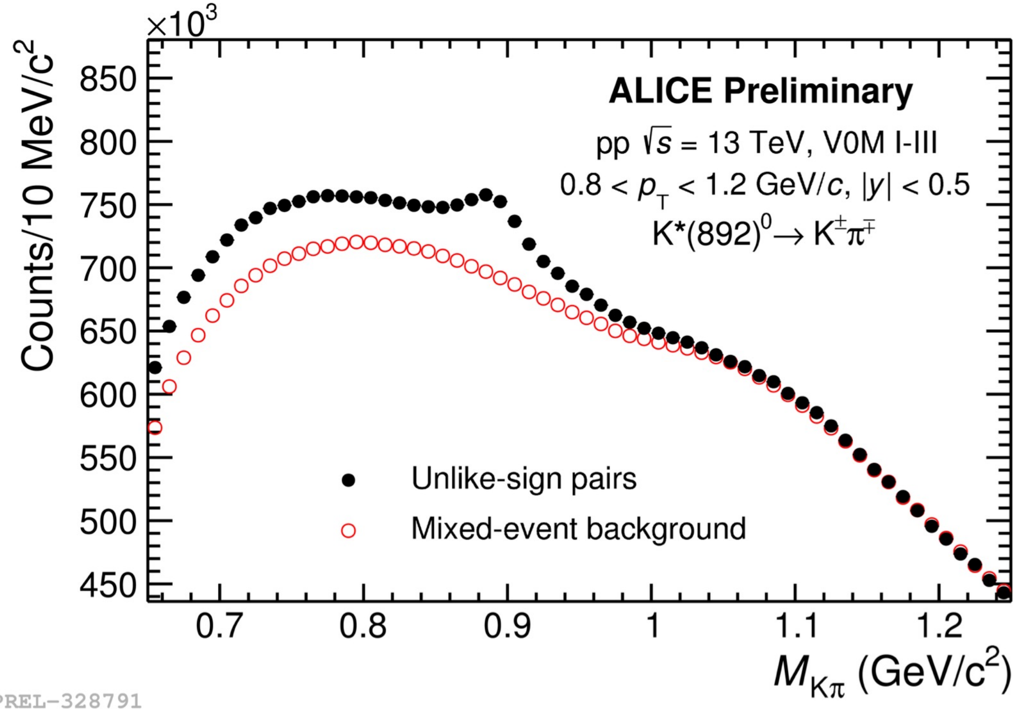


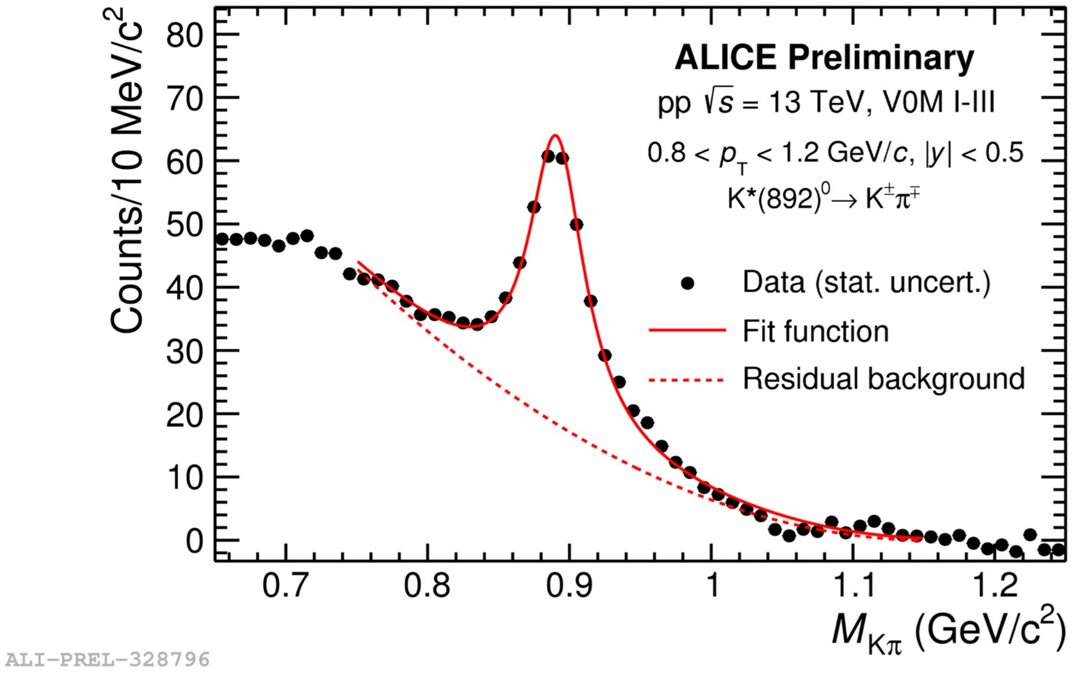
ϕ
M = 1020 MeV
$\phi \rightarrow K^+K$ (49.2%)
cτ → 45 fm

Resonances

- Reconstructed from daughter-track pairs
- Short lifetime: no displaced decay vertex
- Signal extracted from invariant-mass peaks

Signal extraction through invariant mass method in ALICE



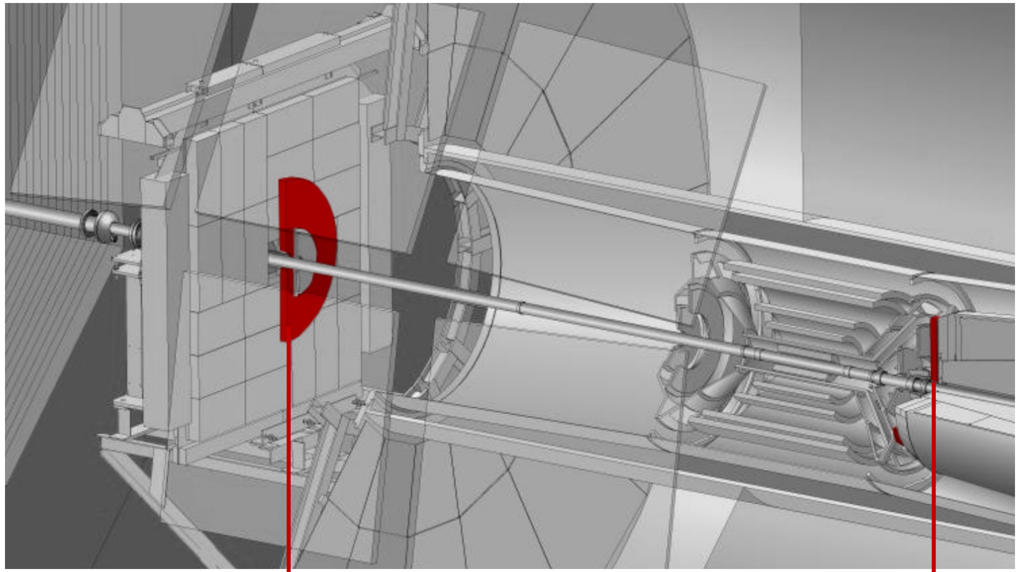


- ✓ $K^{*0} \rightarrow \pi^{\pm}K^{\mp}$ (BR 66%) channel with invariant mass study
- ✓ Uncorrelated background subtracted using event-mixing technique
- ✓ After subtraction: fit with **Breit-Wigner (signal) + 2nd order polynomial (residual background)** function

Multiplicity estimators for $S_0^{p_{\mathrm{T}}=1}$ analysis

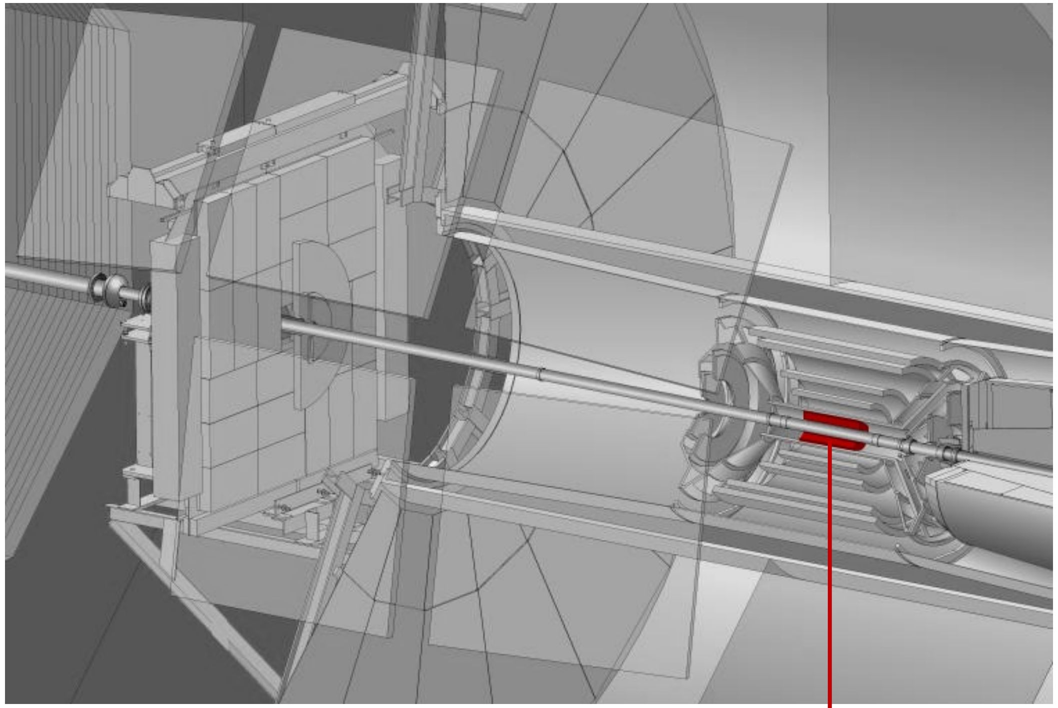
$N_{tracklets}^{|\eta|<0.8}$: **Mid-rapidity multiplicity estimator**
(SPD tracklets: $|\eta| < 0.8$)

V0M: Forward rapidity multiplicity estimator
(V0 amplitude: $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$)



V0A

V0C



SPD
(2 innermost layers of ITS)

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(SPD tracklets: $|\eta| <0.8$)

V0M: Forward rapidity multiplicity estimator
(V0 amplitude: $2.8< \eta <5.1$ and $-3.7< \eta <-1.7$)

I and I-III: 0-1% and 0-10% multiplicity class

Jet-like (0-1%) and Jet-like (0-10%): 1% and 10% selection in spherocity distribution

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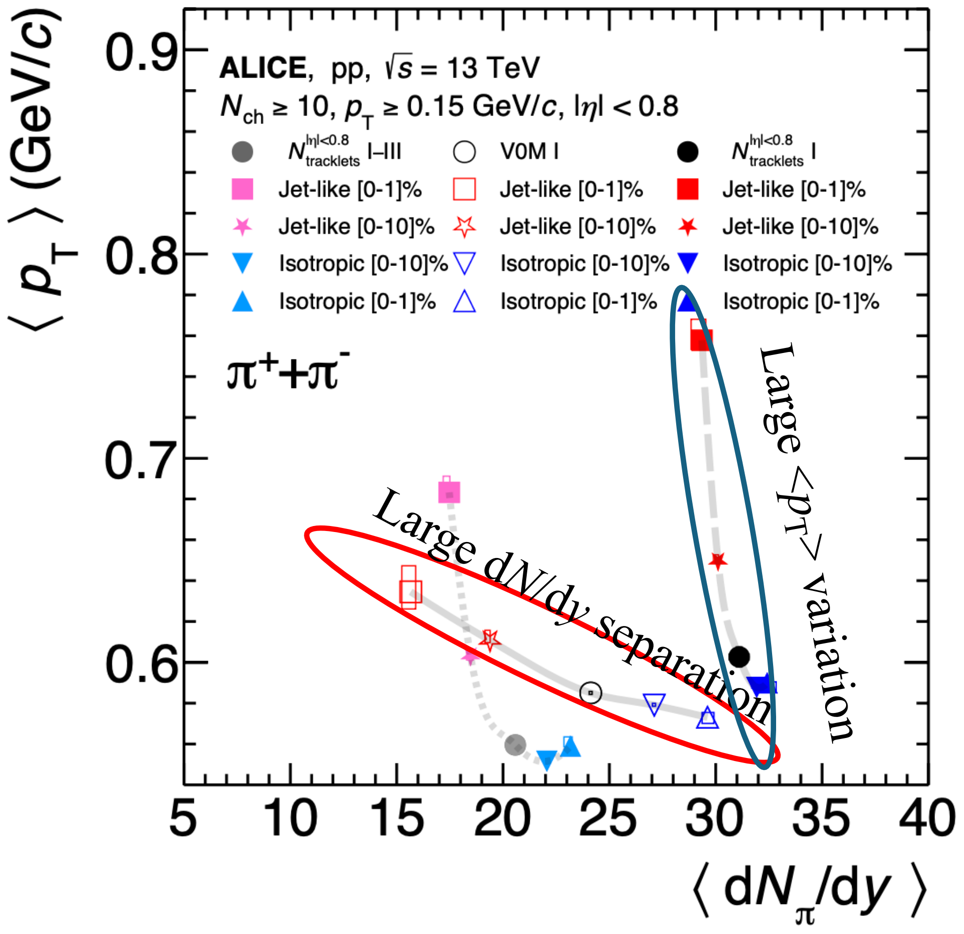

- ✓ **V0M →** change in $\langle dN_\pi/dy\rangle$
- ✓ **Broad $\langle dN_\pi/dy\rangle$ in V0M→** selection on pion multiplicity
- ✓ $N_{tracklets}^{|\eta|<0.8}$ → change in $\langle p_T\rangle$
- ✓ Primary focus is $N_{tracklets}^{|\eta|<0.8}$, where we seem to capture the jet bias in our jet-like events

Results: Transverse momentum spectra

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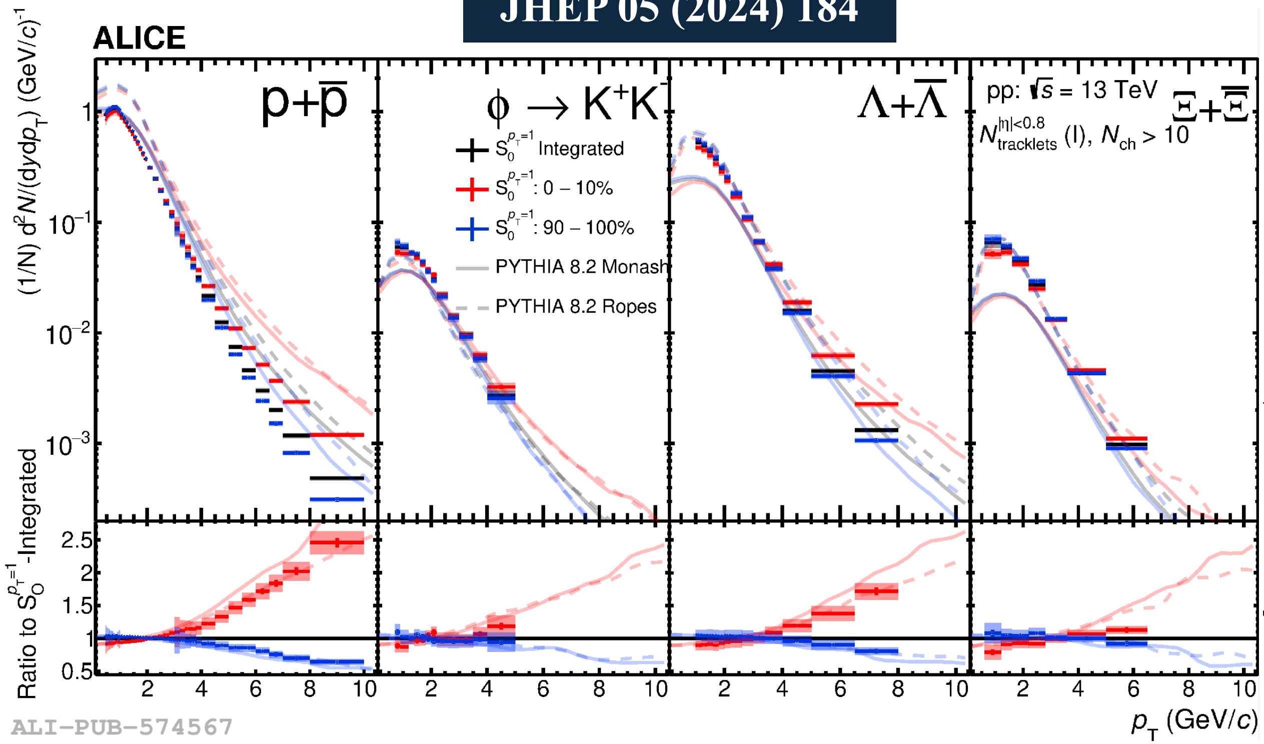
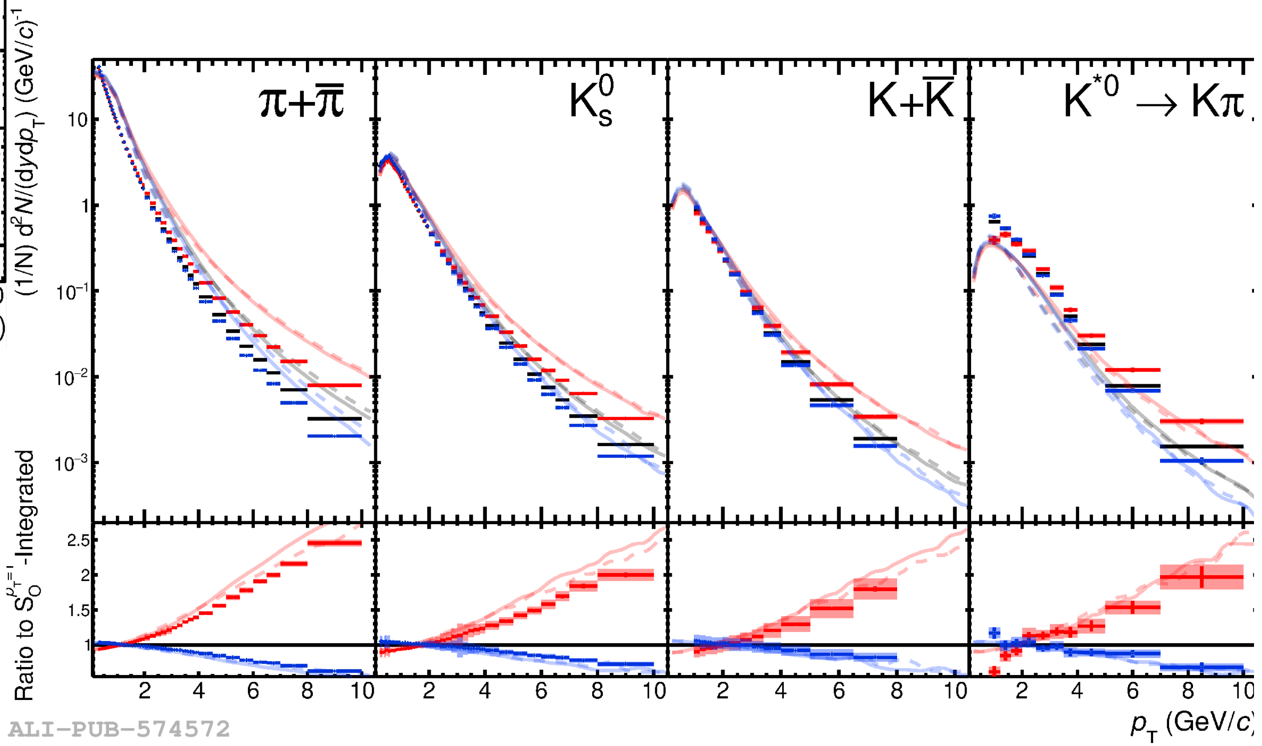


- ✓ As a function of $S_0^{p_T=1}$ event classes, the low-p_T region is dominated by isotropic events, whereas, the high-p_T region is dominated by jet-like events
- ✓ Suggests hardening of the spectra in jet-like events



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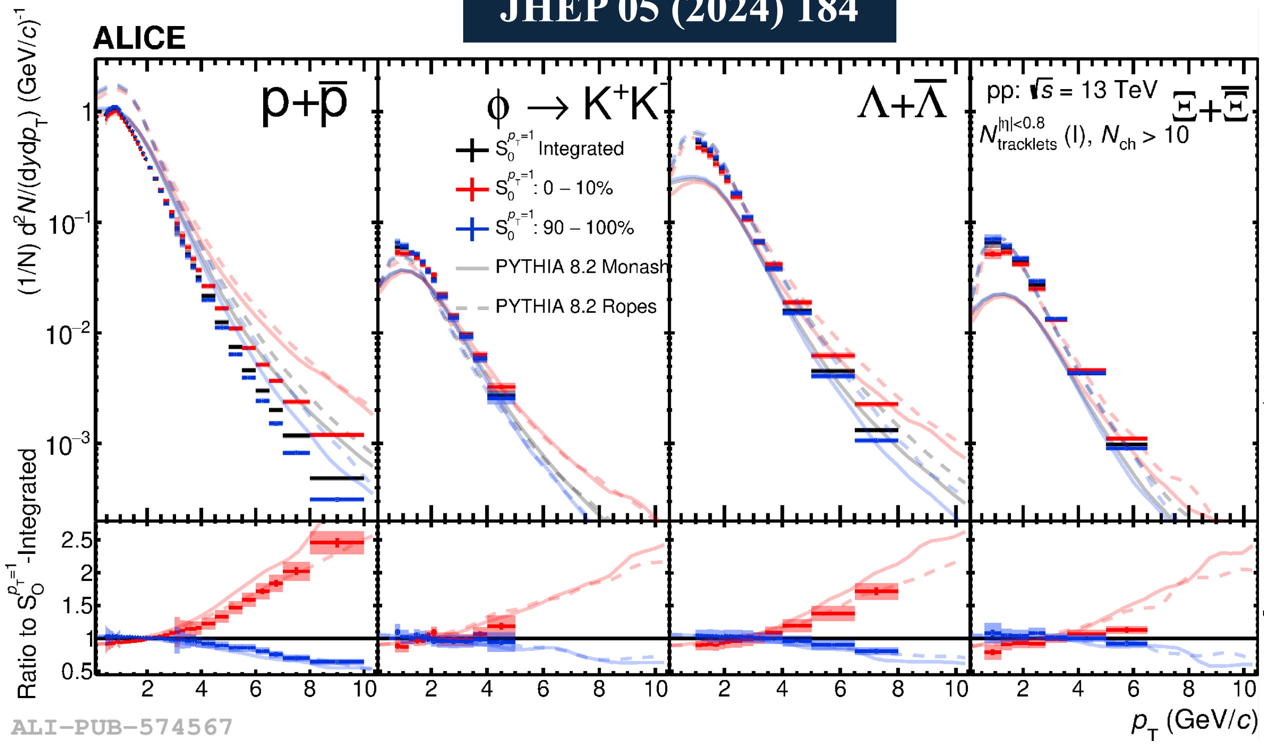

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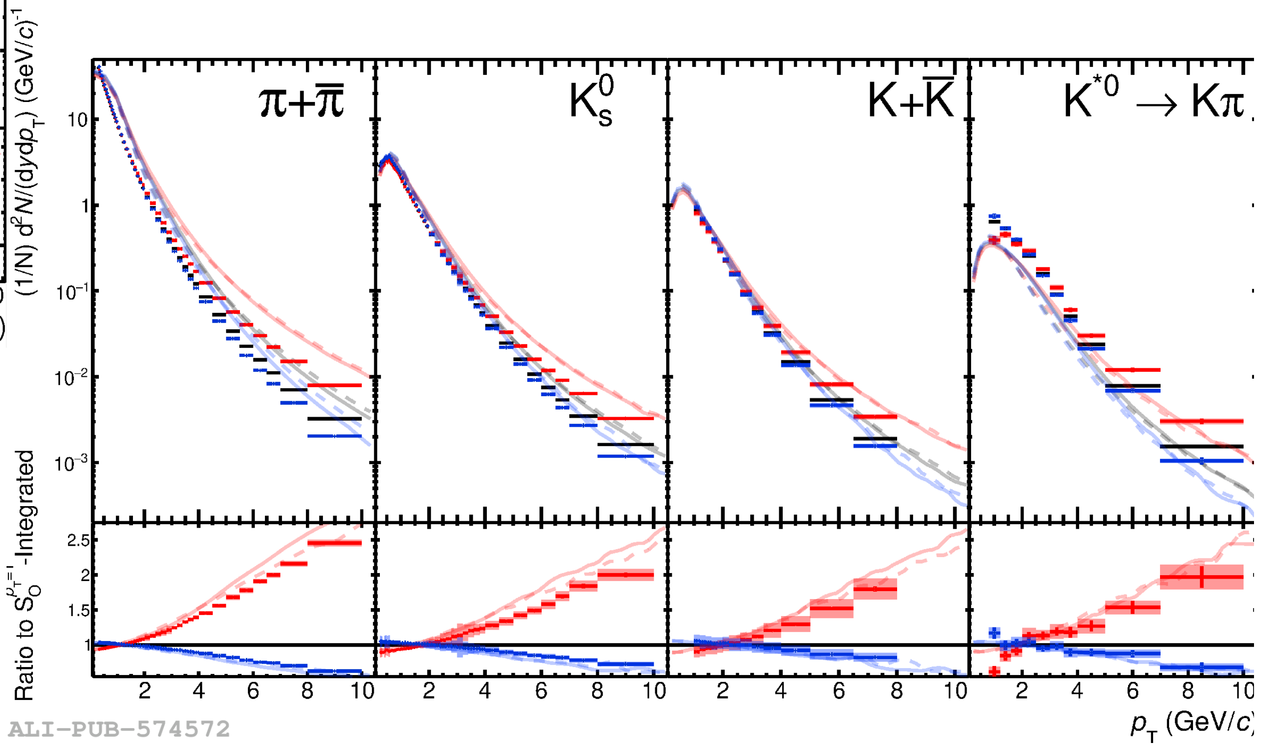
- ✓ PYTHIA8 reproduces well the ratio observed in data
- ✓ The same trends are seen for all measured particle species



Results: p_T-differential ratio to pions

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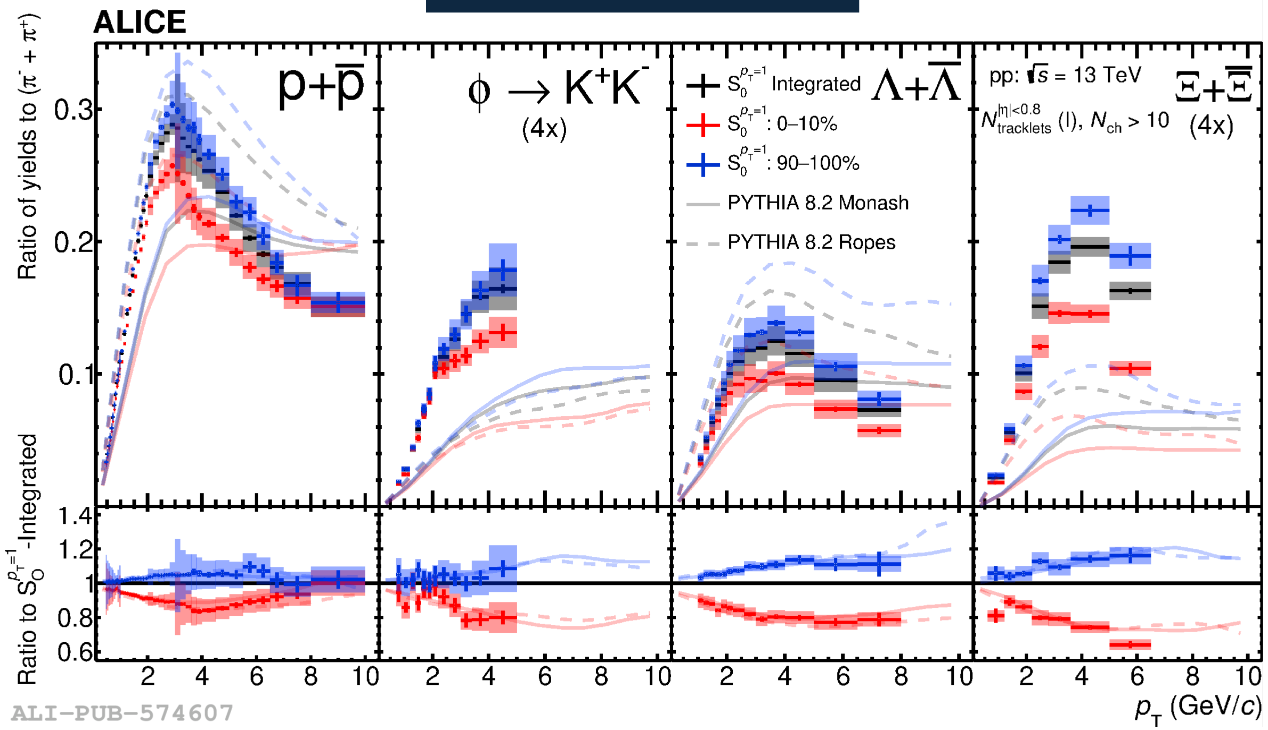
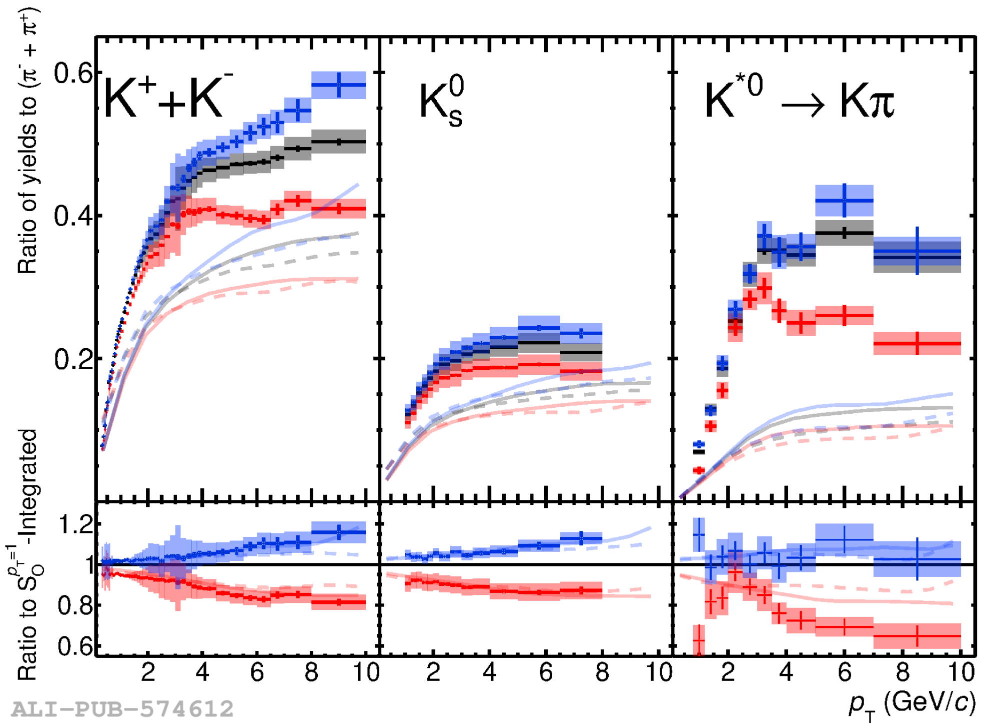


- ✓ Jet-like events demonstrate an overall decrease in the production of various particle species relative to pions → Notable suppression of strangeness



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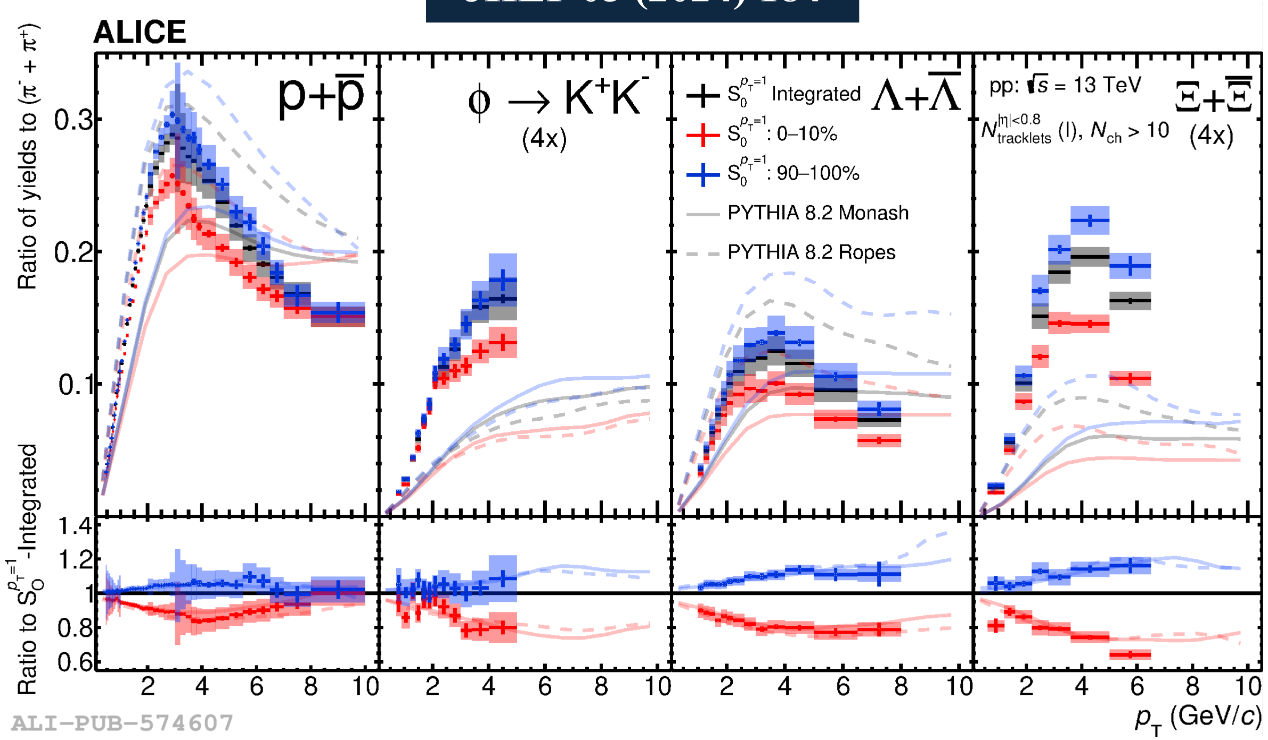

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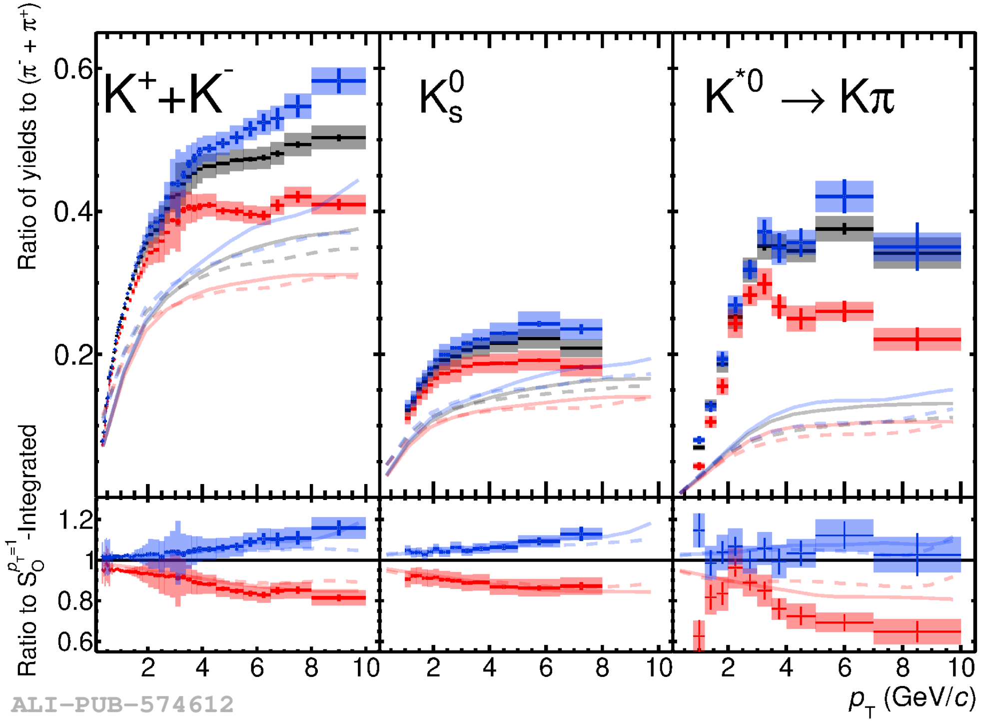
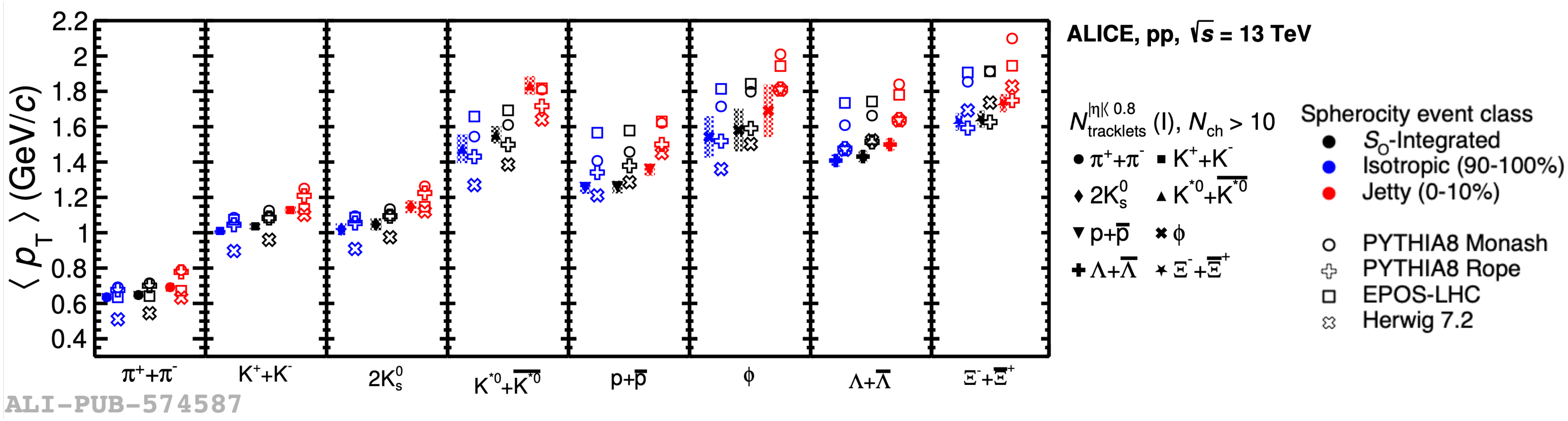


- ✓ MC models do not capture absolute trends accurately. However, all models effectively predict the interplay with high-multiplicity references

$S_0^{p_T=1}$-differential average transverse momentum ($\langle p_T \rangle$)



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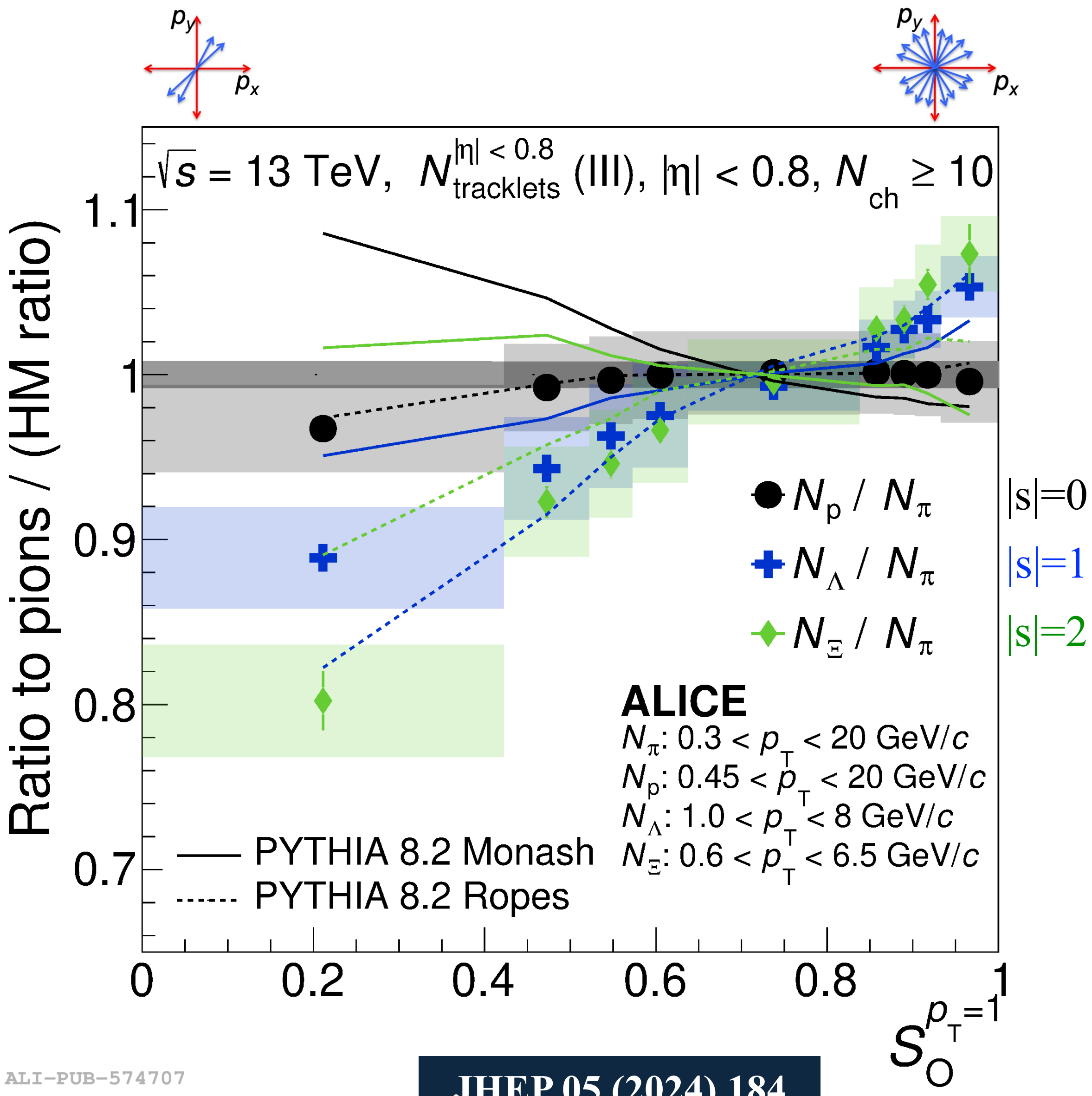
- ✓ Significant p_T-hardening observed in **jet-like** events, consistent across all the light flavor particle species
- ✓ Approximately same value of mean-p_T observed for both isotropic-like and spherocity integrated events → average high multiplicity events are mostly dominated by underlying physics processes
- ✓ Except resonances, we observe a clear mass ordering for the identified particles
- ✓ Most of the MC models predict the mean-p_T qualitatively for almost all the species

Results: Strangeness with event topology

- Substantial reduction in strange production rates observed in jet-like events
  - ✓ Proton remains mostly unaffected (S = 0)
  - ✓ Around 20% decrease observed in Ξ
  - ✓ Strangeness-based ordering

MC predictions:

- ✓ PYTHIA Ropes predicts qualitative trend, but not the strangeness ordering
- ✓ PYTHIA Monash is unable to capture trends



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MC predictions:

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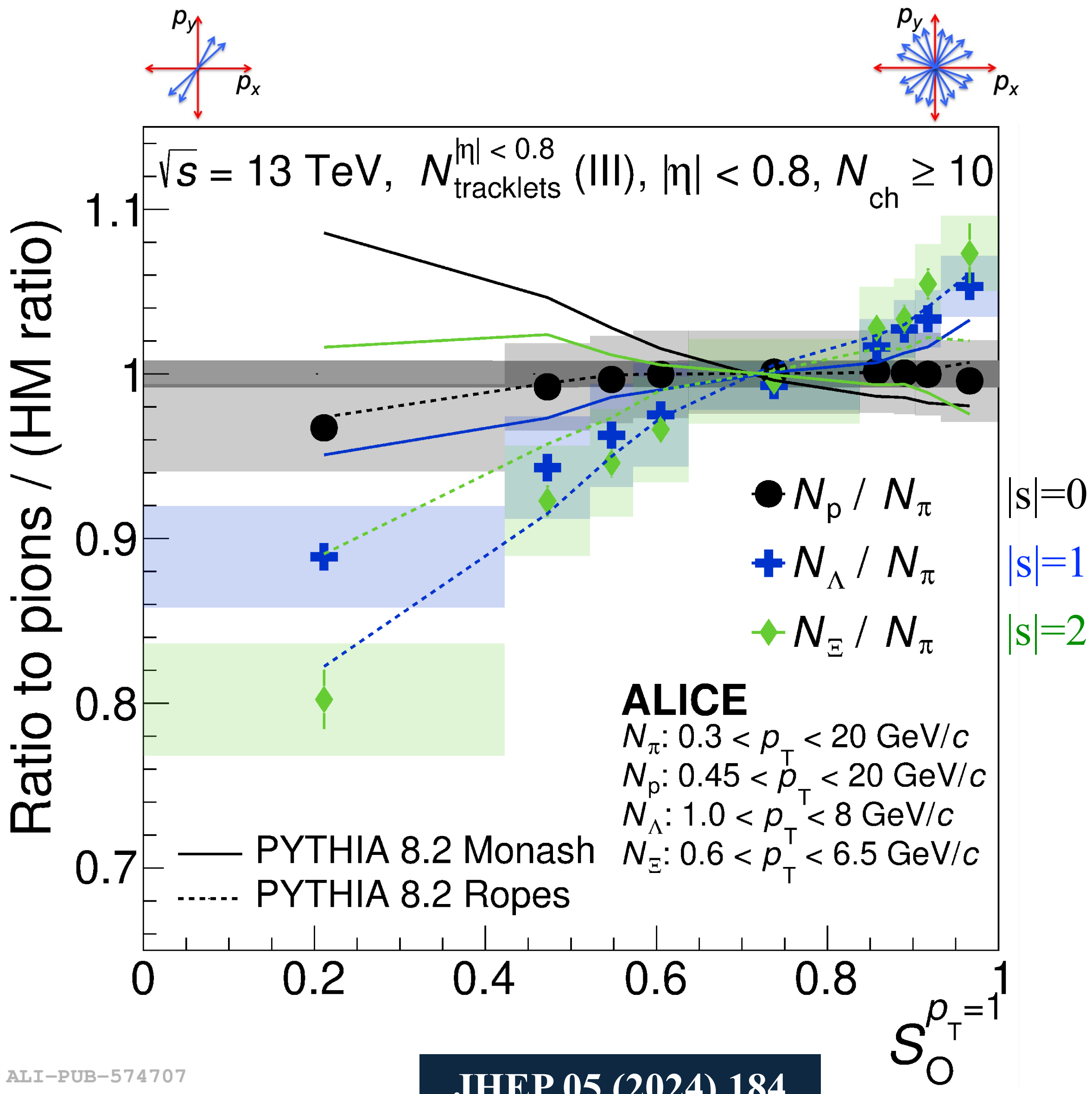
- ✓ Herwig 7.2 is unable to capture trends



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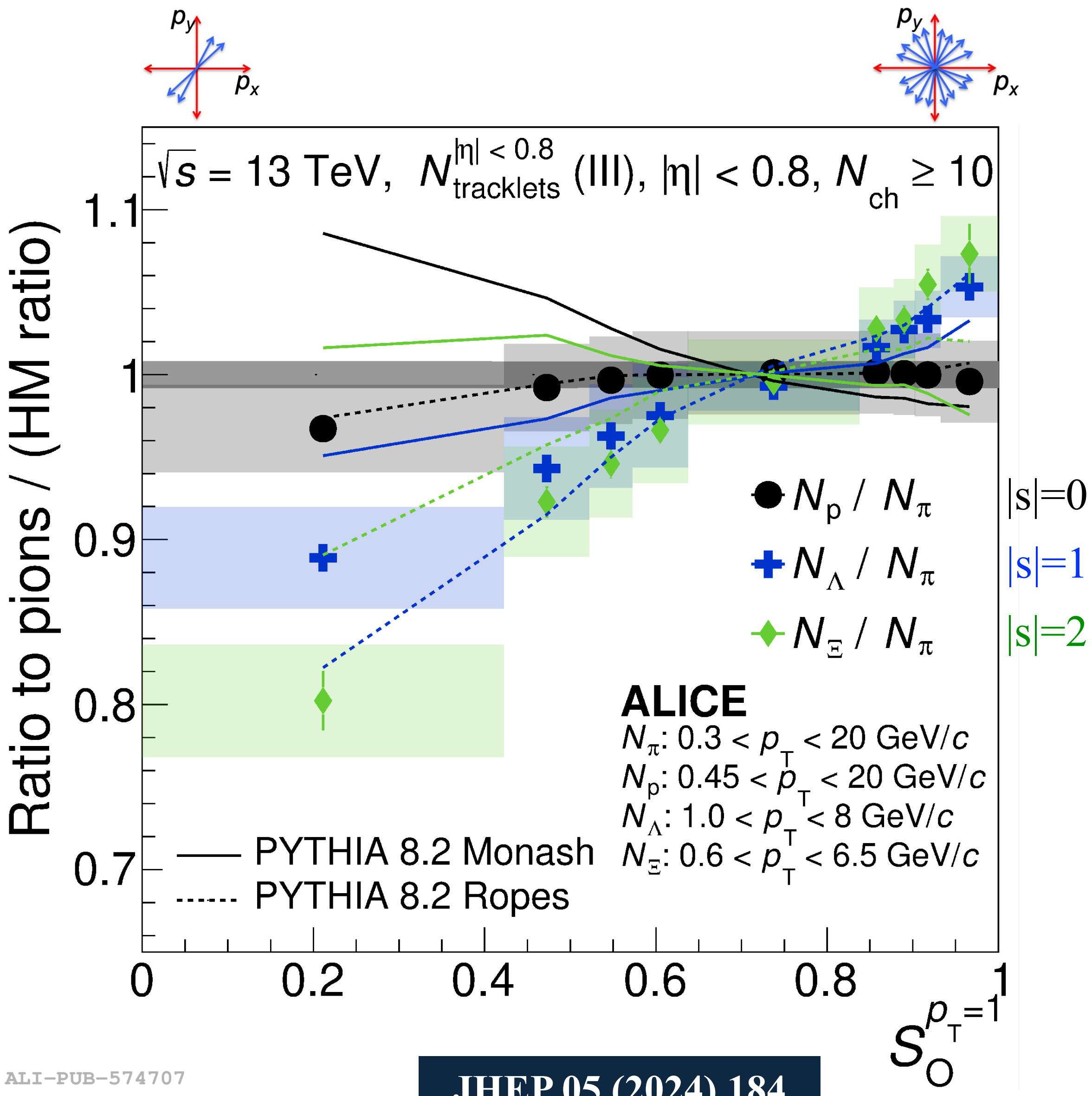
"Strangeness enhancement in pp seems to be the feature of the isotropic events"



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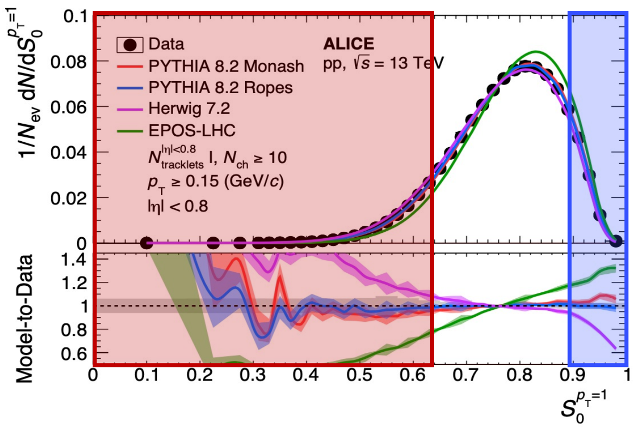
Summary

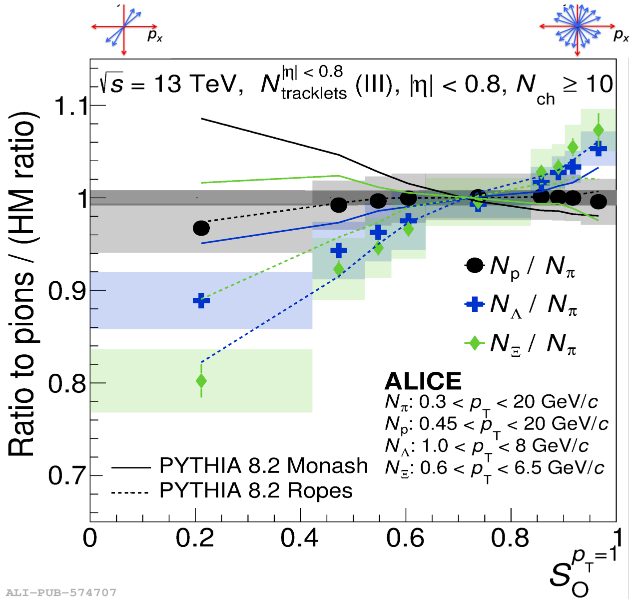
- ✓ Transverse spherocity helps to study the **events by separating the soft and hard physics processes** in small collision systems

- ✓ $\boldsymbol{S_0^{p_T=1}}$ can be used to select strangeness enhanced/suppressed events

- ✓ **Strange hadrons are suppressed in jet-like events**, with the effect increasing with strangeness content

- ✓ **Strangeness enhancement in high-multiplicity pp is mainly driven by isotropic events, not by jet-like topologies**





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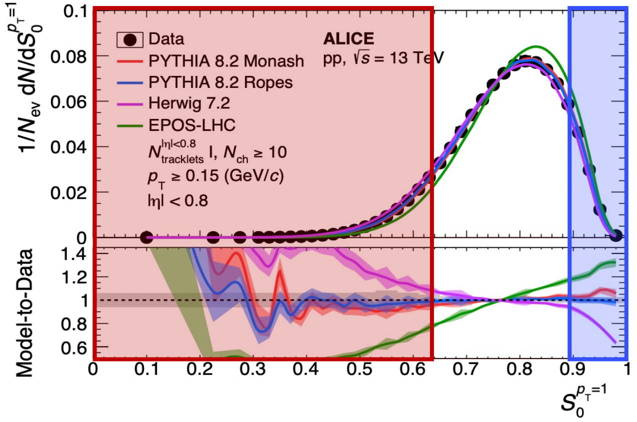
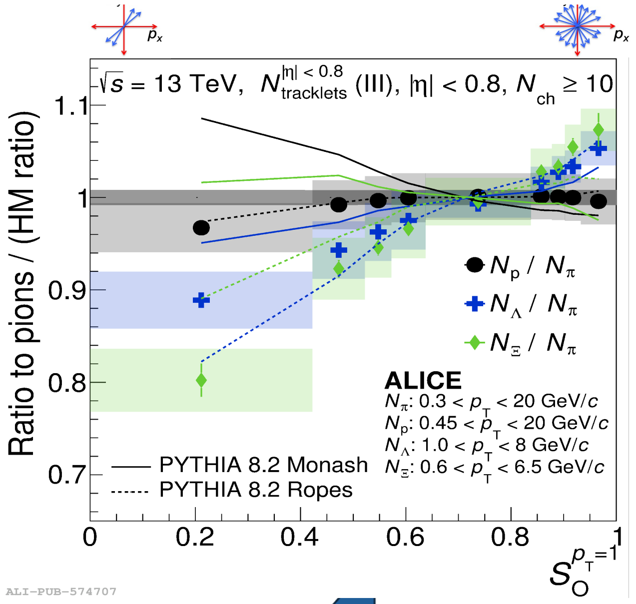
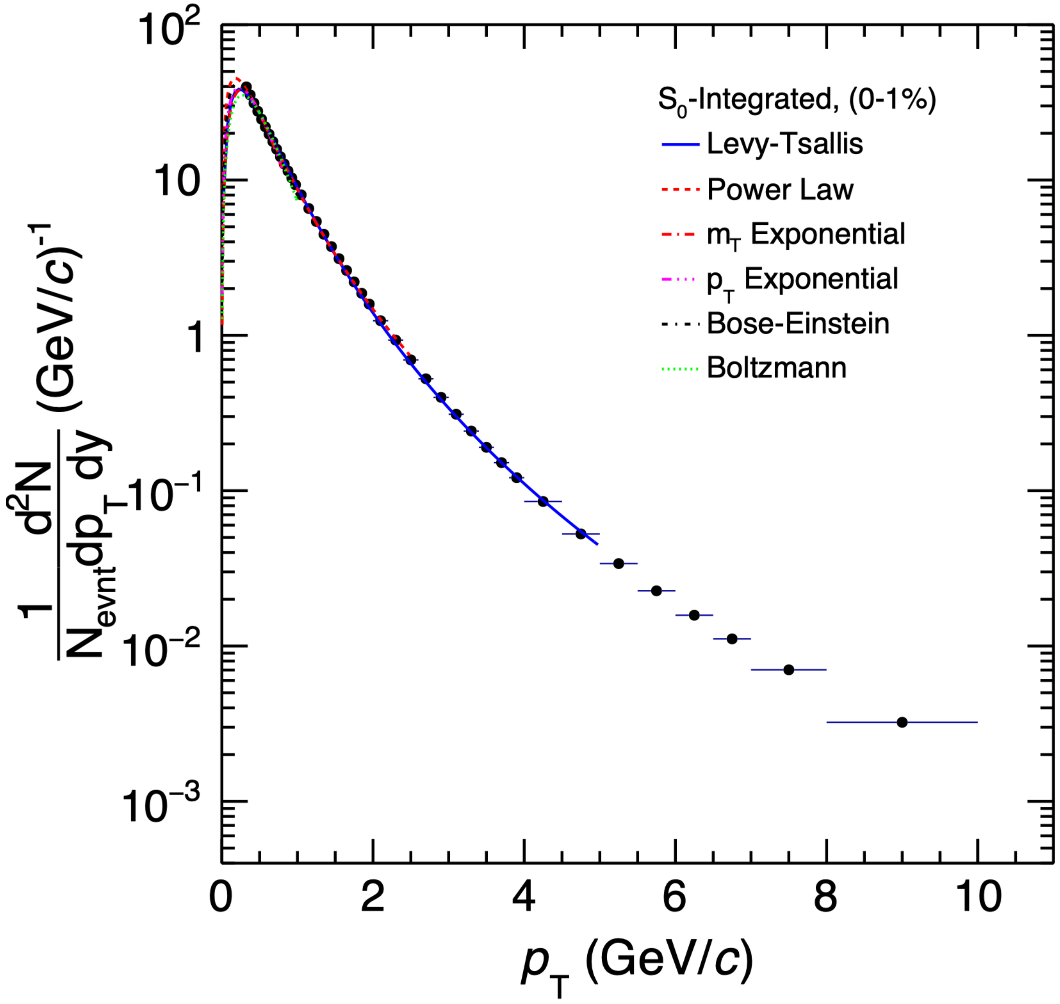


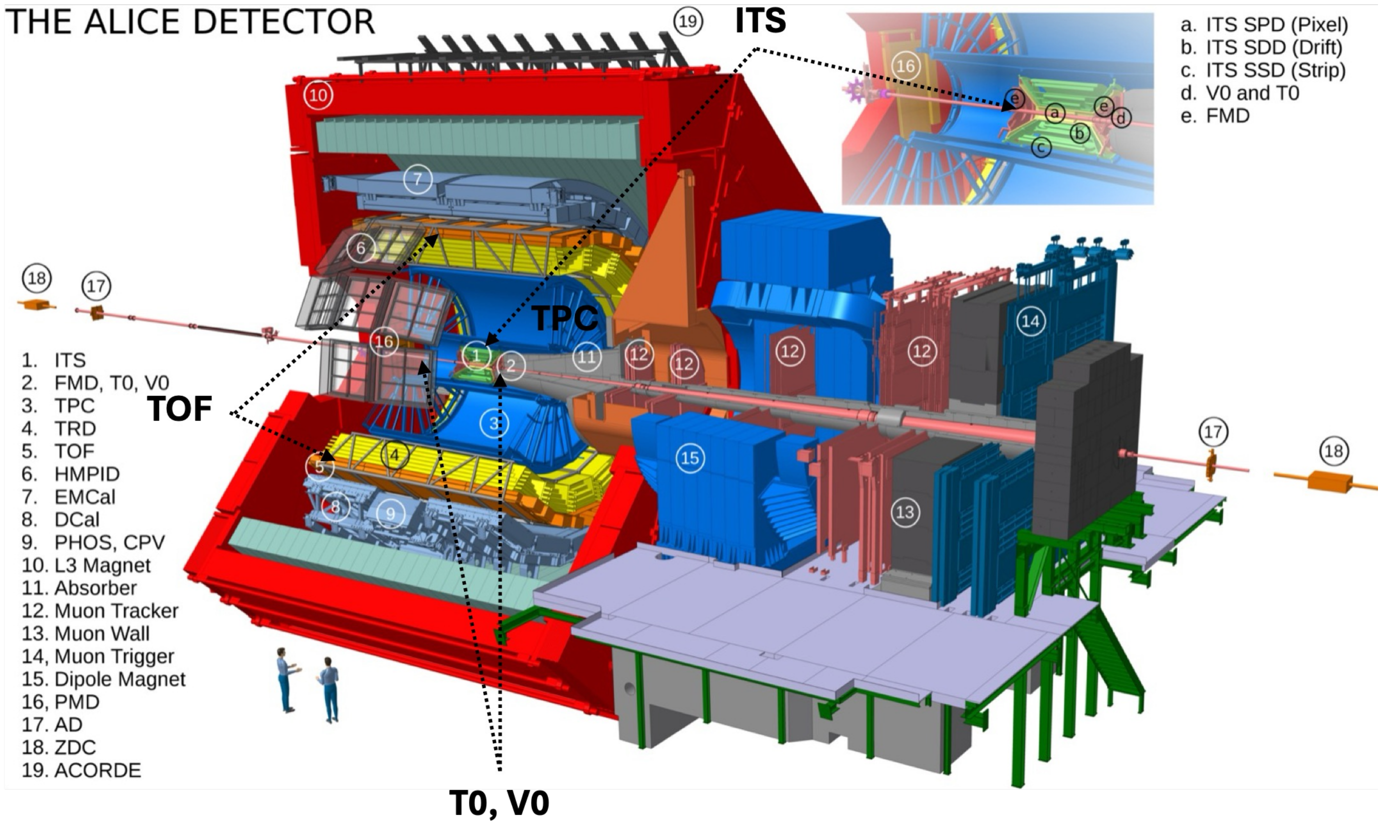


THANK YOU FOR YOUR ATTENTION…

ALICE: yield and mean-pT estimation



ALICE Detector - TPC



- **ITS ($|\eta|<0.9$):** Trigger, vertex, tracking, PID (dE/dx)
- **TPC ($|\eta|<0.9$):** Tracking, PID (dE/dx)
- **TOF ($|\eta|<0.9$):**
  - Multi-gap Resistive Plate Chambers
  - Time resolution ($\sigma_{TOF} \sim 80$ ps) , PID (time-of-flight)
- **V0 (A andC):** Min. bias trigger, multiplicity estimators
  - Minimum Bias: 0 – 100%
  - High Multiplicity: 0 – 0.1%

Kinematic variables

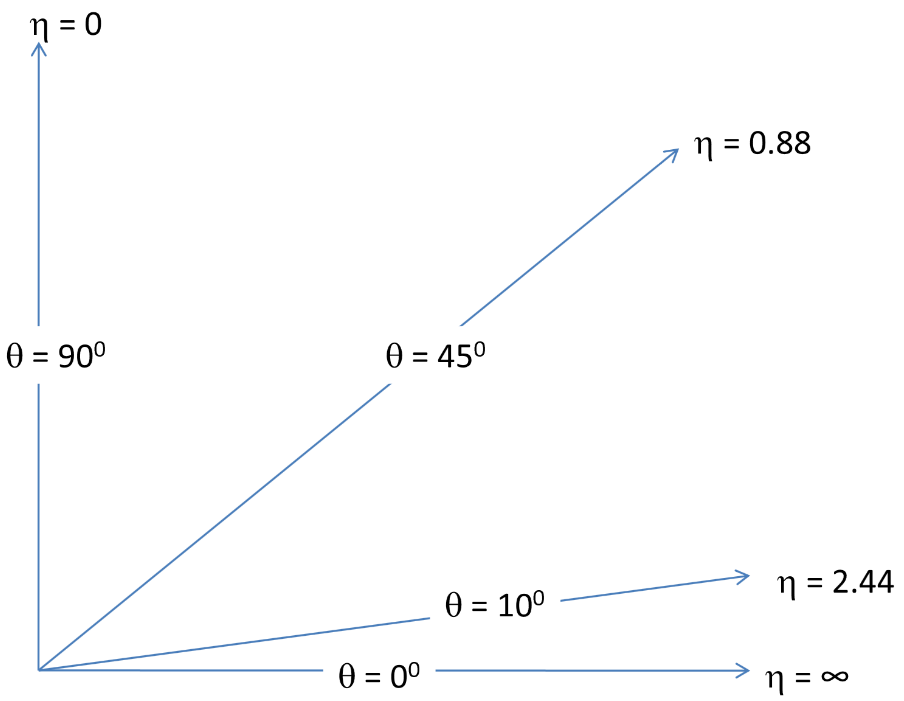
Kinematic variables used

Rapidity: $y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$

$$E = m_T \cosh y$$
$$p_z = m_T \sinh y$$
$$m_T = \sqrt{m^2 + p_T^2}$$

Pseudo-rapidity: $\eta = -\ln\left[\tan\frac{\theta}{2}\right]$

Invariant yield: $E\frac{d^3N}{dp^3} = \frac{1}{2\pi p_T}\frac{d^2N}{dp_T\,dy}$



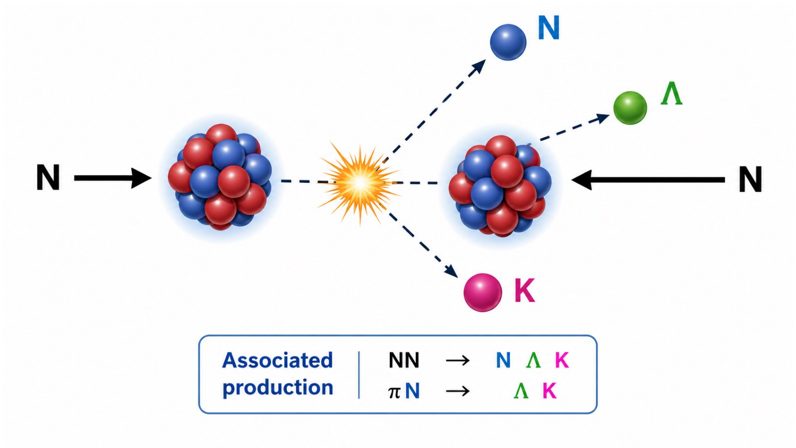
Natural units

$\hbar = c = 1$

$$1\ \text{m} = 5.07\times10^{15}\ \text{GeV}^{-1}$$
$$1\ \text{kg} = 5.62\times10^{26}\ \text{GeV}$$
$$1\ \text{s} = 1.52\times10^{24}\ \text{GeV}^{-1}$$
$$197\ \text{MeV} = 1\ \text{fm}^{-1}$$

Why is strangeness a unique probe of the QGP?

Ordinary nuclear matter contains only u and d quarks. So, where do strange quarks come from?



Increasing $\sqrt{s_{NN}}$

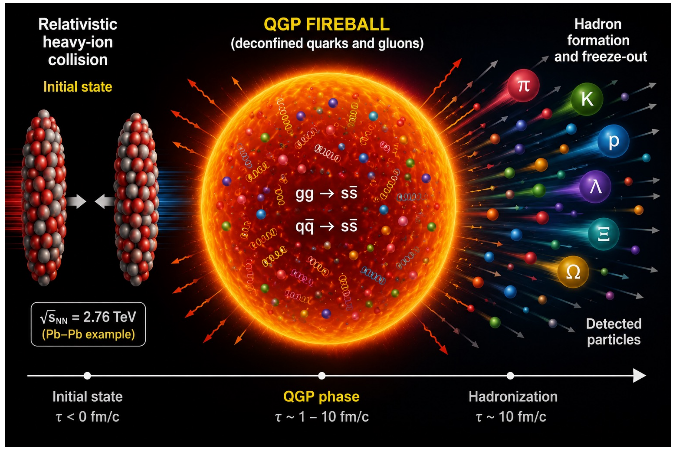
More available energy

↓

Higher gluon density

↓

Hotter medium



Low-energy hadronic collisions

Associated production
$NN \rightarrow N\Lambda K$
$\pi N \rightarrow \Lambda K$

Requires threshold energy
Rare strange-particle production

Examples: SIS18 (2-3 GeV), SPS (6-17 GeV), NA61/SHINE (5-17 GeV)

LHC Heavy-ion collisions

Partonic production
$gg \rightarrow s\bar{s}$
$q\bar{q} \rightarrow s\bar{s}$

Abundant strange-quark production
Thermal production
Hadronization

$s+\bar{s} \rightarrow K, \Lambda, \Xi, \Omega$

Key message: Strange quarks are produced during the collision itself, making them sensitive probes of the hot and dense QCD medium.