Production of strange particles in jets in p–p, p–Pb and Pb–Pb collisions measured with ALICE

Vít Kučera[1]

[1]Inha University

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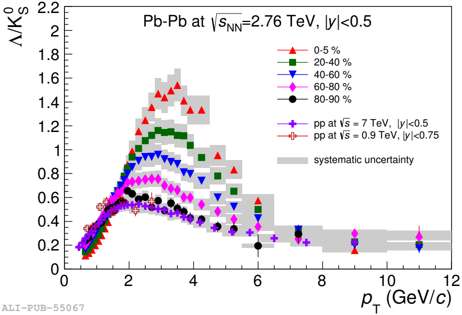
Motivation for PID in jets

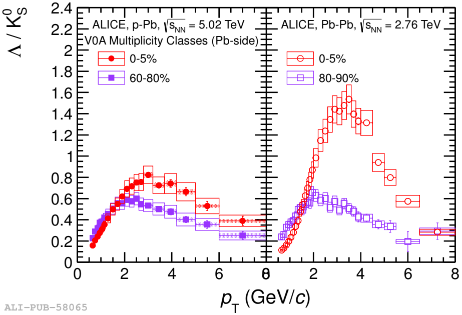
- Baryon-to-meson ratio is enhanced in A–A and p–A collisions (RHIC, LHC).
- This phenomenon cannot be explained by fragmentation in vacuum.
- What is the effect of QGP on hadronization mechanism(s) in jets?
- What are the mechanisms (parton recombination)?

Pb–Pb



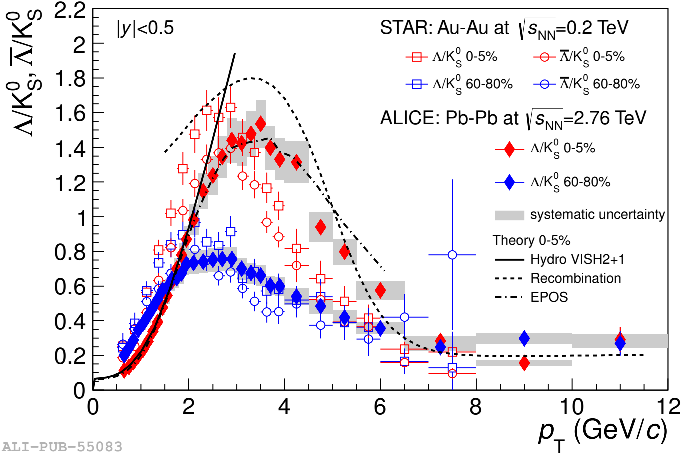
Phys. Rev. Lett. **111** (2013) 222301

p–Pb Pb–Pb



Physics Letters B **728** (2014) 25–38

Comparison of data with models



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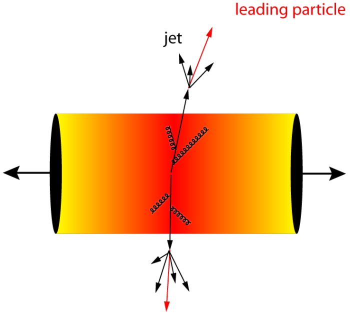
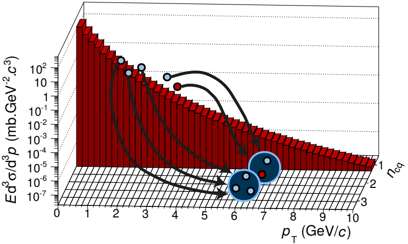
Motivation for PID in jets

We aim to understand the origin(s) of the Λ/K^0_S enhancement by separating hadrons produced in hard processes (jets) from hadrons produced in soft processes (underlying event).

Is the baryon-to-meson ratio enhanced due to the collective effects in the plasma (parton recombination, radial flow, . . .) or is it (also) due to a modification of the jet fragmentation in the medium?

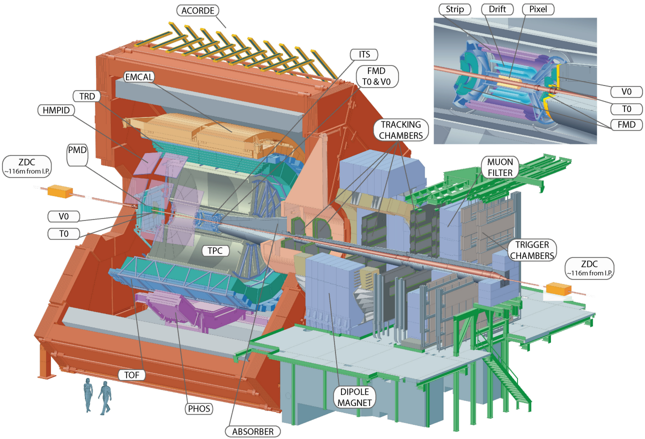
- jet fragmentation
  A high-p_T parton from hard scattering fragments into hadrons.
- parton recombination
  Multiple partons cluster together to form a hadron.





ALICE

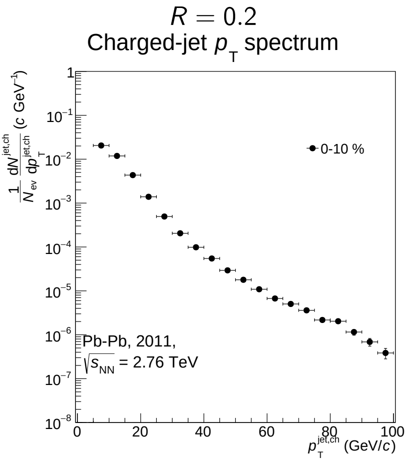
- collisions studied: p–p at $\sqrt{s} = 7$ TeV, p–Pb at $\sqrt{s_{NN}} = 5.02$ TeV, Pb–Pb at $\sqrt{s_{NN}} = 2.76$ TeV
- tracking of charged particles by ITS & TPC in magnetic field of 0.5 T
- centrality estimated from the multiplicity of charged particles in the detectors at forward and backward pseudorapidities

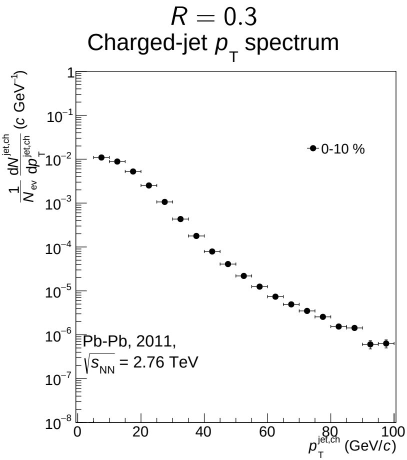


Analysis of charged jets

- track selection
  - charged primary particles
  - $p_\mathrm{T}^\mathrm{track} > 150\,\mathrm{MeV}/c$
  - uniform in $\phi \times \eta$, $|\eta_\mathrm{track}| < 0.9$
- raw-jet reconstruction
  - anti-k_t algorithm
  - resolution parameter $R = 0.2, (0.3, 0.4)$
- subtraction of average soft background
  - average background density ρ estimated from the median k_t cluster
  - $p_\mathrm{T}^\mathrm{jet,ch,corr} = p_\mathrm{T}^\mathrm{jet,ch,raw} - \rho A_\mathrm{jet,ch}$, (where $A_\mathrm{jet,ch}$ is jet area)
- signal-jet selection (good candidates for hard scattering)
  - ${p_\mathrm{T}}^\mathrm{leading\ track} > 5\,\mathrm{GeV}/c$ (only Pb–Pb)
  - $A_\mathrm{jet,ch} > 0.6\pi R^2$
- further $p_\mathrm{T}^\mathrm{jet,ch}$ corrections
  - background anisotropy (intra-event p_T fluctuations)
  - detector response

Jet spectra





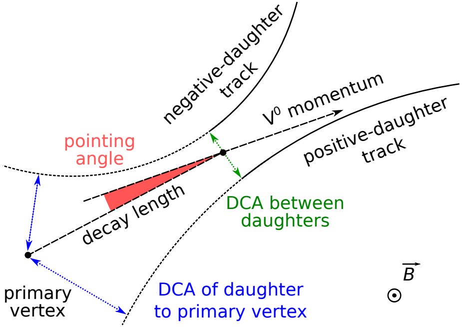
Larger $R \Rightarrow$ harder spectrum (but softer jets at a given p_T^{jet}).

Analysis of neutral strange particles

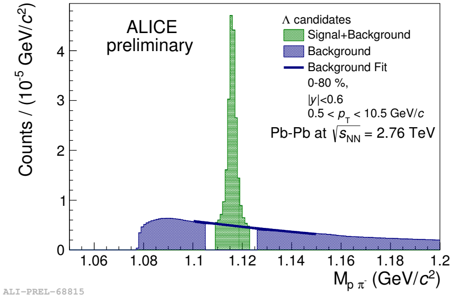
Strange neutral particles decaying into two charged daughter particles

- meson $K^0_S \to \pi^+ + \pi^-$ (BR 69 %)
- baryon $\Lambda \to p + \pi^-$ (BR 64 %)

Mother V^0 particle reconstructed using topology of its V-shaped decay.



Combinatorial background suppressed by cuts on decay parameters.
Signal yield extracted from the invariant-mass distribution.



Strange particles in jets

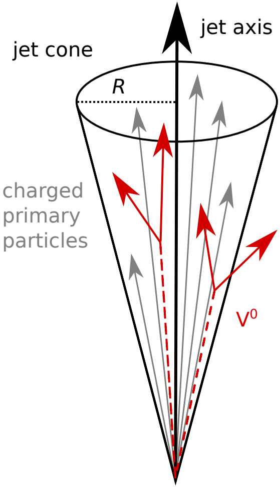
Analysis steps

- V^0 candidate selection
- candidate–jet matching (V^0s in jet cones)

$$\sqrt{(\phi_{V^0} - \phi_{jet,ch})^2 + (\eta_{V^0} - \eta_{jet,ch})^2} < R,$$

$$|\eta_{jet,ch}|^{max} < |\eta_{V^0}|^{max} - R$$

- candidate–UE matching (V^0s in events without selected jets with $p_T^{jet,ch} > 5$ GeV/c)
- signal extraction (invariant-mass distribution)
- efficiency correction (in jet cones, in UE)
- subtraction of V^0s in UE
- subtraction of V^0s coming from decays of jet constituents ($\Xi \rightarrow \Lambda$), i.e. "feed-down" correction

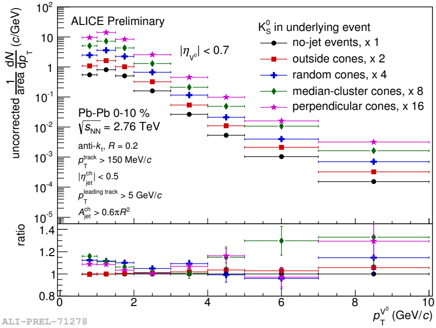


Estimation of V^0s in the underlying event

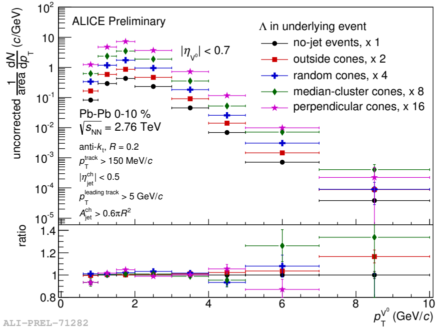
- no-jet events: V^0s in events with no selected jets
- outside cones: V^0s outside jet cones
- random cones: V^0s in a randomly oriented cone
- median-cluster cones: V^0s in the cone of the median k_t-cluster
- perpendicular cones: V^0s in cones perpendicular to the jet in azimuth

Methods differ in regions, events, statistics, efficiency.

K^0_S



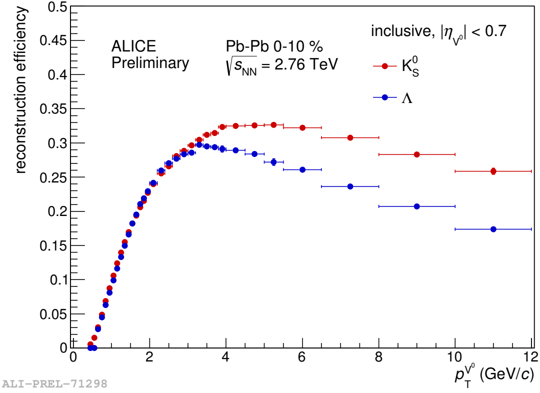
Λ



Reconstruction efficiency of V^0 particles

- Reconstruction efficiency depends strongly on $p_T^{V^0}$ and η_{V^0}.
- Shape of the measured η_{V^0} distribution depends on the selection criteria.
- Not enough statistics to apply efficiency correction in 2D ($p_T^{V^0} \times \eta_{V^0}$).

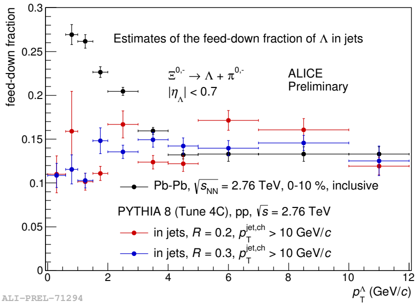
$\Rightarrow$ Efficiency of inclusive V^0s is scaled (in 2D) to get efficiency in jet cones and UE (in 1D).

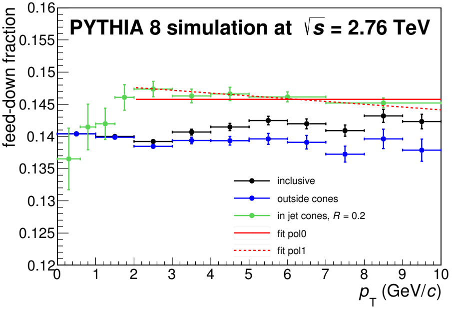


Feed-down in jets

Feed-down fraction of Λ in jets estimated from:

- inclusive Λ (Pb–Pb-like),
- jets generated by PYTHIA 8 (p–p-like).





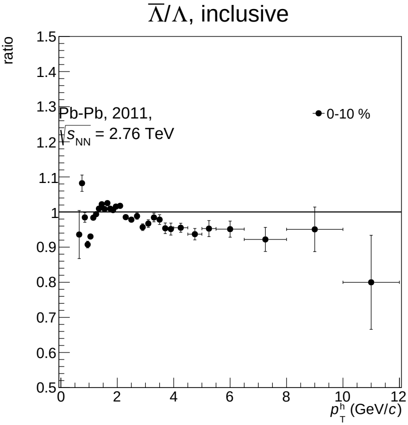
Estimation of systematic uncertainties

The systematic uncertainties are studied for the following sources:

- reconstruction efficiency of V^0s (selection cuts applied on V^0 candidates),
- signal extraction (fitting parameters),
- subtraction of spectra of V^0s in UE (5 methods),
- subtraction of feed-down in jets (inclusive vs PYTHIA),
- material budget (detector model),
- fluctuations of UE (jet embedding).

Open issue: Λ–$\overline{\Lambda}$ asymmetry

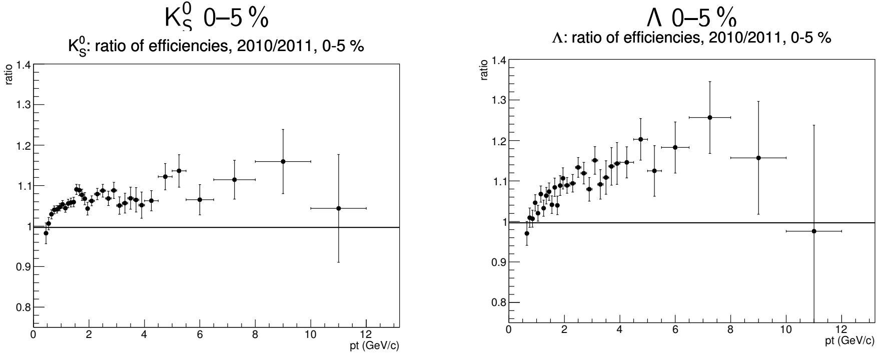
Discrepancy between inclusive spectra of Λ and $\overline{\Lambda}$.



Strong dependence on the polarity of magnetic field and the sign of η.
Additional 6 % (symmetric) considered as systematics.

Open issue: discrepancy in MC between runs 2010, 2011

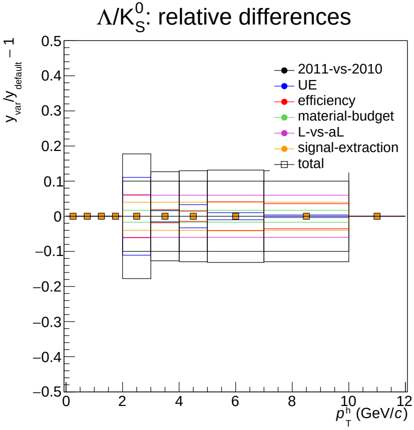
Differences in spectra traced back to the reconstruction efficiencies.



Effects of $\lesssim 10\,\%$ for K^0_S, $\lesssim 20\,\%$ for Λ, partially cancel out in Λ/K^0_S.
Observed also in other analyses (charged-particle spectra, correlations).
Additional 10 % (symmetric) considered as systematics.

Systematics: combined

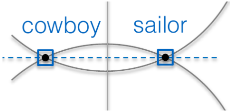
$$R = 0.2,\ p_{\mathrm{T}}^{\mathrm{jet,ch}} > 10\,\mathrm{GeV}/c,\ (\Lambda + \overline{\Lambda})/2\mathrm{K}^0_{\mathrm{S}}$$



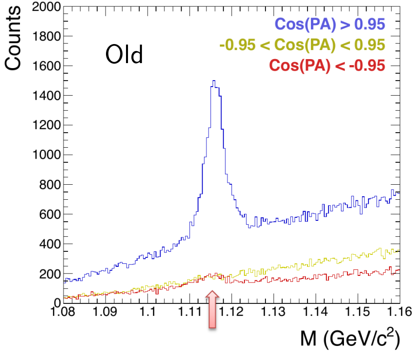
Uncertainties from different sources (except feed-down) are combined in squares and considered symmetric.

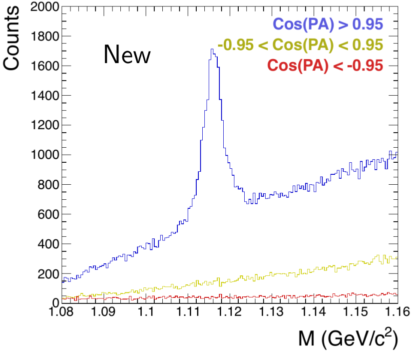
V^0 vertexer problem

- There may be two candidates for the point of closest approach ("cowboy/sailor" configuration).



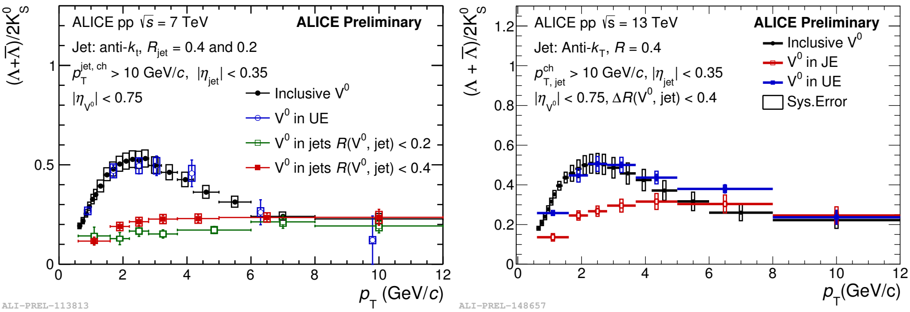
- Old vertexer: sailor misidentified as cowboy $\rightarrow$ CPA ≈ -1 $\rightarrow$ rejected.
- New vertexer: Select the point with the smallest DCA calculated in 3D.





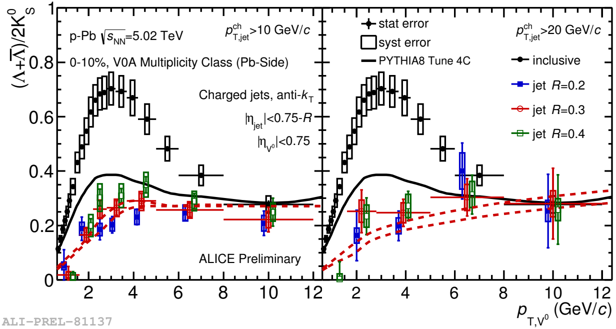
- $\Rightarrow$ Better MC–real data matching.
- Cause of loosing sailors with the old vertexer still unclear.

Λ/K^0_S ratio in jets in p–p at $\sqrt{s} = 7$ TeV and 13 TeV



- The ratio in UE is consistent with the inclusive ratio.
- The ratio in jets is clearly different from the inclusive ratio at low and intermediate $p_T^{V^0}$.
- A slight increase of the ratio in jets with increasing R.

Λ/K^0_S ratio in jets in p–Pb at $\sqrt{s_{NN}} = 5.02$ TeV
(high-multiplicity collisions, 0–10 %)

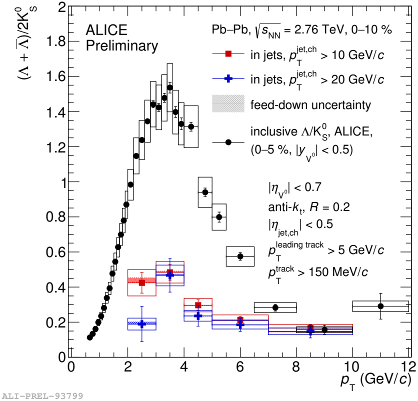


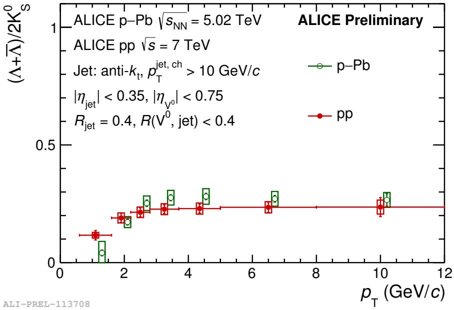
The ratio in jets

- is clearly different from the inclusive ratio at low and intermediate $p_T^{V^0}$,
- is different from the inclusive ratio in PYTHIA (black line),
- is similar to the ratios in PYTHIA jets (red dashed lines),
- shows no significant dependence on $p_T^{\text{jet,ch}}$ and a slight dependence on R.

Λ/K^0_S ratio in jets in Pb–Pb at $\sqrt{s_{NN}} = 2.76$ TeV

(7.4×10^6 central collisions, 0–10 %)





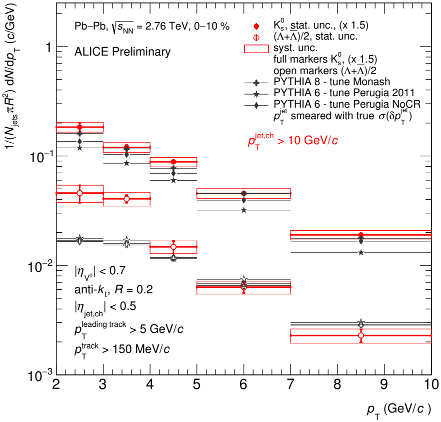
The ratio in jets

- is clearly different from the inclusive ratio at low and intermediate $p_T^{V^0}$,
- shows no significant dependence on $p_T^{jet,ch}$,
- is consistent with the ratio in jets in p–Pb and p–p at $p_T^{V^0} > 4$ GeV/c.

K^0_S, Λ spectra in jets in Pb–Pb

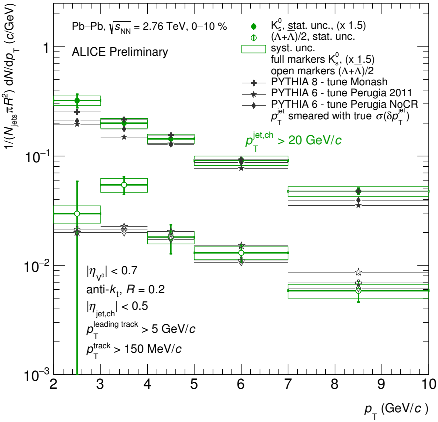
comparison to PYTHIA smeared with $p_T^{jet,ch}$ fluctuations

$p_T^{jet,ch} > 10\,\mathrm{GeV}/c$



ALI-PREL-112798

$p_T^{jet,ch} > 20\,\mathrm{GeV}/c$



ALI-PREL-112802

- Same slopes of spectra from measurement and from PYTHIA.
- Enhancement for Λ at $p_T^{V^0} < 4\,\mathrm{GeV}/c$.

Summary and outlook

ALICE has performed the first measurement of the Λ/K^0_S ratio in charged jets in p–p, p–Pb and Pb–Pb collisions at the LHC.

Results

- In every collision system, the Λ/K^0_S ratio in jets is significantly smaller than the inclusive ratio (and the UE).
- The Λ/K^0_S ratios in jets are consistent within uncertainties in all collision systems for $p_T^{V^0} > 4\,\mathrm{GeV}/c$.
- The dominant source of the enhancement are soft processes associated with collective behaviour.
- A potential modification of jet fragmentation seems to be restricted to the region $p_T^{V^0} < 4\,\mathrm{GeV}/c$ and manifest by an enhancement of the Λ yields.

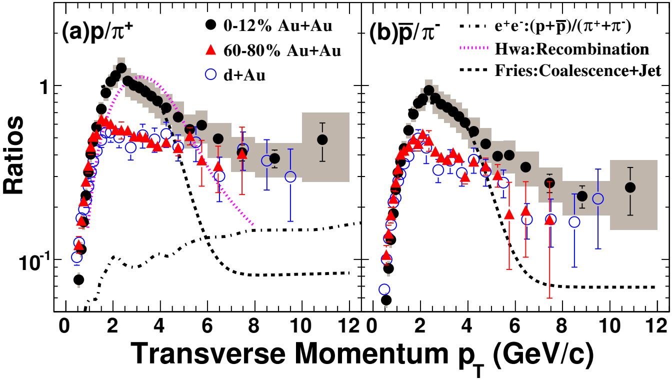
Outlook

- Solve the 2011/2010 issue.
- Comparison with more models (JEWEL).

Thank you for your attention.

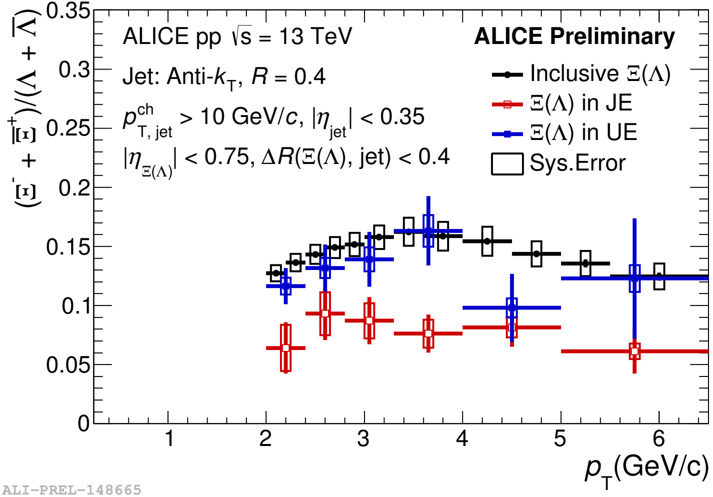
Backup

p/π ratio in Au–Au at $\sqrt{s_{NN}} = 200$ GeV



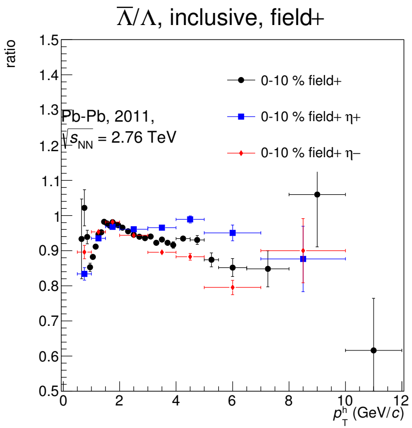
Phys. Rev. Lett. **97** (2006) 152301

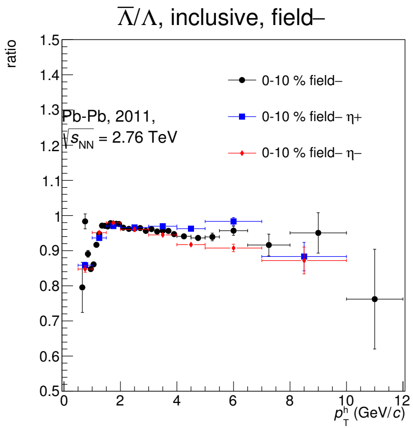
Ξ/Λ ratio in jets in p–p at $\sqrt{s_{NN}} = 13$ TeV



Pengyao Cui for the ALICE Collaboration, Quark Matter 2018

Details on the $\Lambda/\overline{\Lambda}$ discrepancy





V^0 candidate selection

Cut variable	Value
Daughter tracks	
TPC refit	`true`
type of production vertex	not `kKink`
DCA to the primary vertex	≥ 0.1 cm
DCA between daughters	$\leq 1\sigma_{\mathrm{TPC}}$
$\lvert\eta\rvert$	≤ 0.8
V^0 candidate	
reconstruction method	offline
cosine of the pointing angle (CPA)	≥ 0.998
radius of the decay vertex	5–100 cm
$\lvert\eta\rvert$	≤ 0.7
transverse proper lifetime	$\leq 5\tau$
Armenteros–Podolanski cut (K^0_S)	$p_T{}^{\mathrm{Arm.}} \geq 0.2\lvert\alpha^{\mathrm{Arm.}}\rvert$

Jet algorithms

A sequential recombination jet finder is defined according to this general scheme:

1. $\forall\, i, j$: calculate distances d_{ij} and d_{iB} (NB $k_t \equiv p_T$):

$$d_{ij} = \min\left(k_{t,i}^{2p}, k_{t,j}^{2p}\right) \frac{\Delta_{ij}^2}{R^2}, \quad \Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2\,, \quad d_{iB} = k_{t,i}^{2p}$$

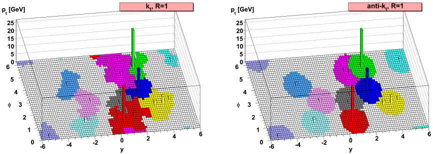
2. Find $d_{\min}$:

$$d_{\min} = \min\left(d_{ij}, d_{iB}\right).$$

   - If $\exists\, i, j : d_{\min} = d_{ij}$, merge particles i and j into a single particle and combine their momenta.
   - If $\exists\, i : d_{\min} = d_{iB}$, declare particle i to be a final jet and remove it from the list.

These steps are repeated until no particles are left.

$$p = \begin{cases} 1 & k_t \text{ (background estimation)} \\ 0 & \text{Cambridge/Aachen} \\ -1 & \text{anti-}k_t \text{ (signal jets)} \end{cases}$$



Matteo Cacciari et al. JHEP **0804** (2008) 063

Background in Pb–Pb

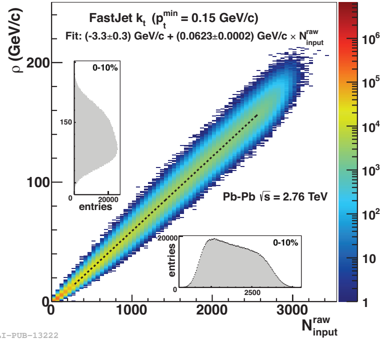
Production of soft particles by underlying-event processes.

average background density ρ:

- k_t jets w/o 2 hardest

each event: $\rho = \text{median}\left\{p_T^{\text{jet}}/A_{\text{jet}}\right\}$

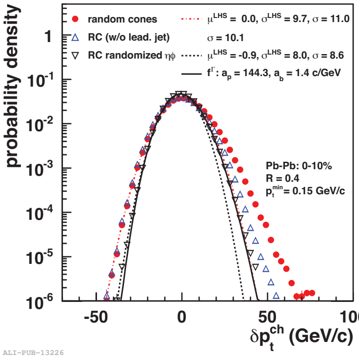
each jet: $p_{T,\text{jet}}^{\text{corrected}} = p_{T,\text{jet}}^{\text{raw}} - \rho A_{\text{jet}}$



ALICE, JHEP **1203** (2012) 053

ρ anisotropy in events (fluctuations):

- $\delta p_T = p_{T,\text{probe}}^{\text{raw}} - \rho A_{\text{probe}}$
- response matrix $\rightarrow$ deconvolution



ibid.

Scaling of the reconstruction efficiency

- ϵ — reconstruction efficiency of inclusive particles
- ϵ_s — reconstruction efficiency of particles of interest (scaled ϵ)
- a_s — yield of associated particles of interest
- g_s — yield of generated particles of interest
- m — uncorrected yield of measured particles (candidates) of interest
- t — yield of true (corrected) particles of interest
- P — signal purity

Signal extraction in JC, UE (assume that $P_{\text{inclusive}}(p_{\text{T}}^{\text{V}^0}, \eta_{\text{V}^0})$ is the same as for V^0s of interest):

$$m(p_{\text{T}}^{\text{V}^0}, \eta_{\text{V}^0}) = m_{\text{raw}}(p_{\text{T}}^{\text{V}^0}, \eta_{\text{V}^0})|_{\text{peak region}} \cdot P_{\text{inclusive}}(p_{\text{T}}^{\text{V}^0}, \eta_{\text{V}^0})|_{\text{peak region}}$$

Efficiency calculation:

$$a_s \equiv m, \quad \sigma_{a_s} \equiv 0, \qquad g_s = a_s/\epsilon$$

$$\frac{1}{\epsilon_s(p_{\text{T}}^{\text{V}^0})} = \frac{\sum_{\eta_{\text{V}^0 i}} g_s(\eta_{\text{V}^0 i}, p_{\text{T}}^{\text{V}^0})}{\sum_{\eta_{\text{V}^0 j}} a_s(\eta_{\text{V}^0 j}, p_{\text{T}}^{\text{V}^0})} = \sum_{\eta_{\text{V}^0 i}} \frac{a_s(\eta_{\text{V}^0 i}, p_{\text{T}}^{\text{V}^0})}{\sum_{\eta_{\text{V}^0 j}} a_s(\eta_{\text{V}^0 j}, p_{\text{T}}^{\text{V}^0})} \frac{1}{\epsilon(\eta_{\text{V}^0 i}, p_{\text{T}}^{\text{V}^0})}$$

Spectra correction:

$$t = m/\epsilon_s$$