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Measurement of Ξ^- / $\bar{\Xi}^+$ production in jets from Z boson decays with DELPHI Open Data

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[*arXiv:2607.13804*]

The 2026 International Workshop on the High Energy Circular Electron Positron Collider, 2026

1. Introduction:
LEP, DELPHI, and the legacy data

LEP and DELPHI Open Data

The Large Electron-Positron (LEP) collider is the largest electron-positron accelerator ever built.

- Two operations from 1990 to 2000: **LEP I** (1990~1995, $91.2\,\mathrm{GeV}$) and **LEP II** (1996~2000, $161{\sim}205\,\mathrm{GeV}$).
- Four detectors on LEP: **DELPHI**, ALEPH, OPAL and L3.

In 2024, **the DELPHI collaboration decided to open the data** and original software stack to the physics community **for public access** (see *DELPHI data preservation, re-use, and open access policy*) :

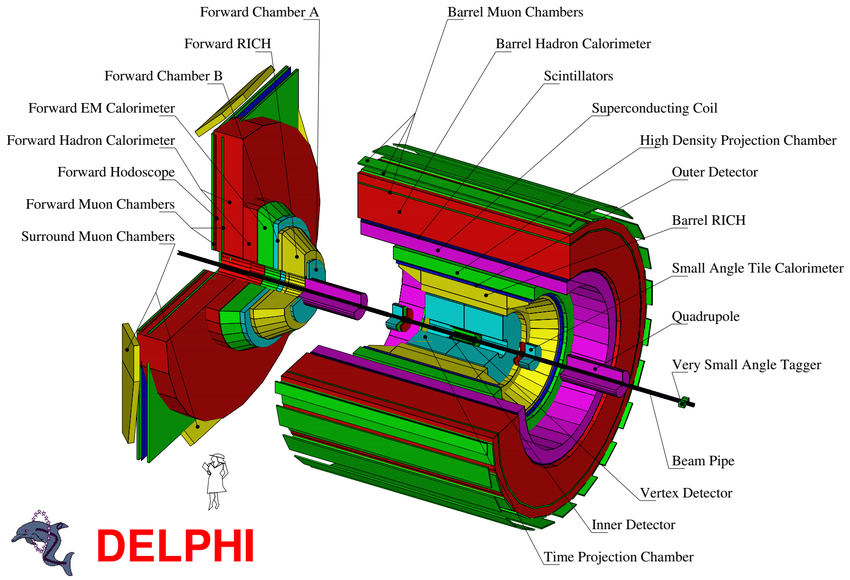
- The LEP data is:
  - The **largest e^+e^- collision data** above Z pole on the world.
  - A chance to extract **new insights from legacy data** with today's advanced theory and ideas.
  - A **unique real-data** for developing and validating analysis methods for CEPC.
  - A rare opportunity to **test modern AI/ML-based experimental techniques** on real data rather than pure simulation.

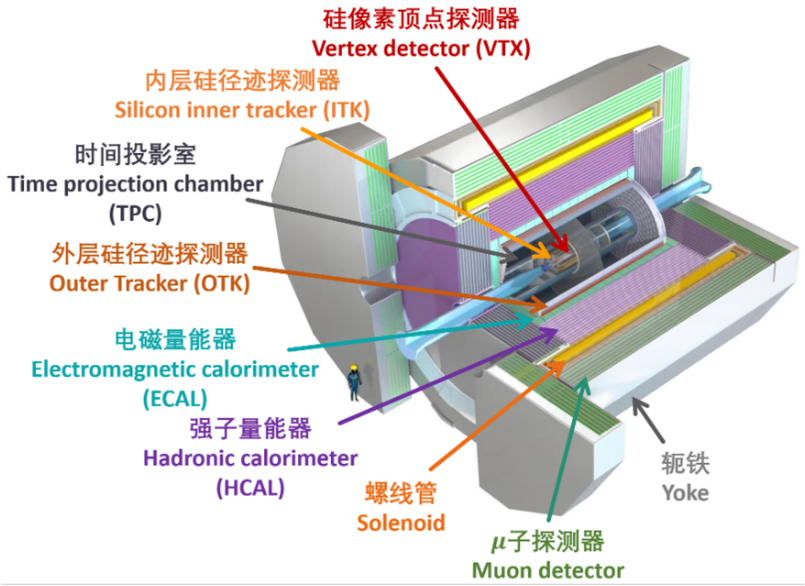
Table 2
Overview of LEP performance from 1989 to 2000. $\int \mathcal{L}dt$ is the luminosity integrated per experiment over each year and I_{tot} is the total beam current $2k_{\mathrm{b}}I_{\mathrm{b}}$. The luminosity $\mathcal{L}$ is given in units of $10^{30}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

Year	$\int \mathcal{L}dt$ (pb^{-1})	E_{b} ($\mathrm{GeV/c}^2$)	k_{b}	I_{tot} (mA)	$\mathcal{L}$
1989	1.74	45.6	4	2.6	4.3
1990	8.6	45.6	4	3.6	7
1991	18.9	45.6	4	3.7	10
1992	28.6	45.6	4/8	5.0	11.5
1993	40.0	45.6	8	5.5	19
1994	64.5	45.6	8	5.5	23.1
1995	46.1	45.6	8/12	8.4	34.1
1996	24.7	80.5 - 86	4	4.2	35.6
1997	73.4	90 - 92	4	5.2	47.0
1998	199.7	94.5	4	6.1	100
1999	253	98 - 101	4	6.2	100
2000	233.4	102 - 104	4	5.2	60

CERN-SL-2002-009-OP

A Few Minutes of CEPC/FCC-ee

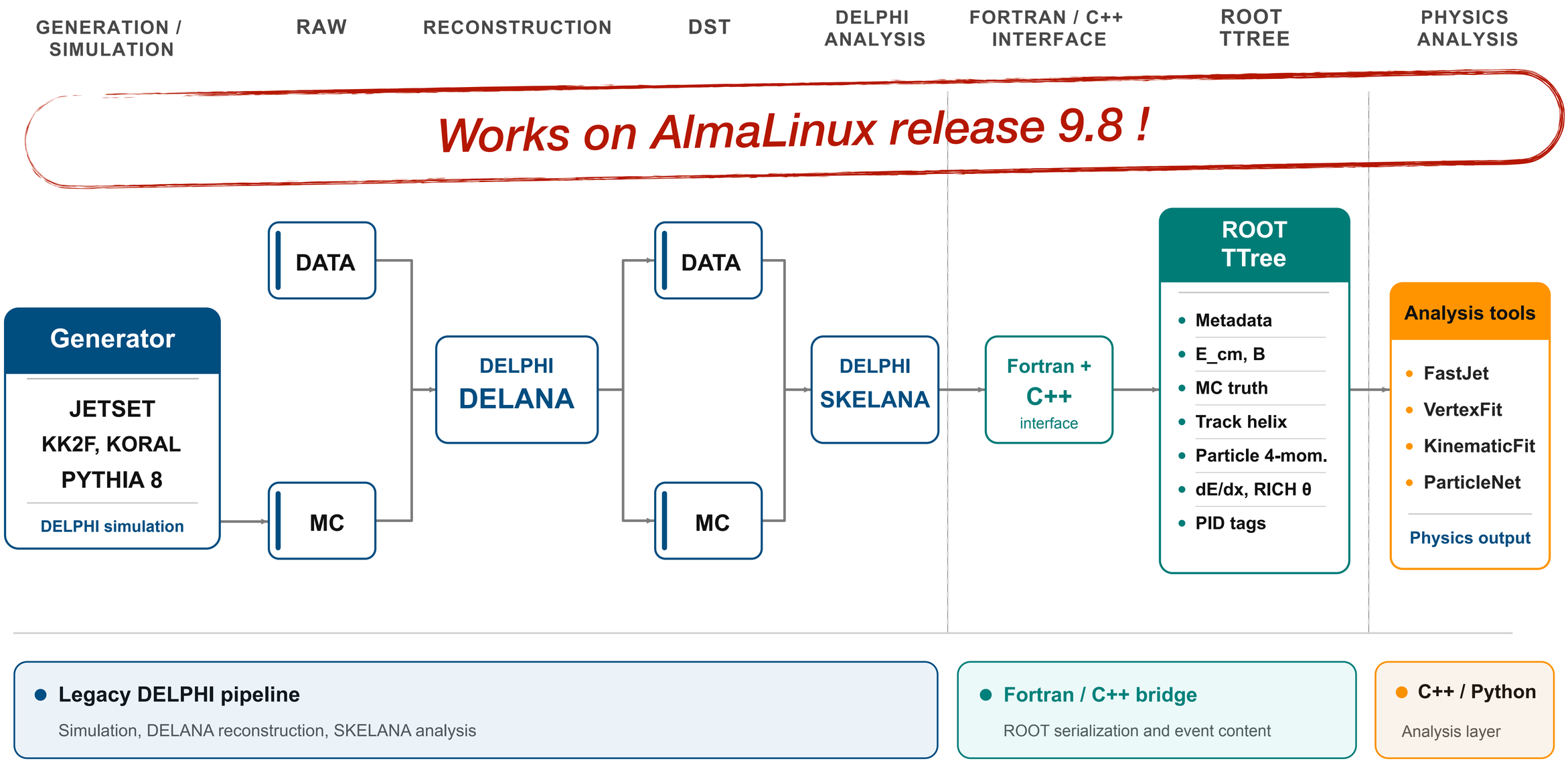




	DELPHI @ LEP	AGORA @ CEPC/FCC
Magnetic field	1.2 T	3 T
Vertex	**Inner radius**: ~63 mm	**Inner radius**: 11 mm
	Material Budget: ~1.5% X0 @ LEP1 ~3.1% X0 @ LEP2	**Material Budget**: 0.77% X0
TPC	**Single pad area**: 52.5 mm^2 **Single-point resolution**: 250 μm (rφ), 880 μm (z); **dE/dx**: ~7.4%	0.5 mm × 0.5 mm readout, Tracking: 100 μm, **dN/dx**: ~ 3%
PID	dE/dx + RICH	dN/dx + TOF
ECAL	High Density Projection Chamber: ~32%/$E^{0.5}$ ⊕ 4.3%	Glass cubic: ~3%/$E^{0.5}$ ⊕ 1%
HCAL	Iron–gas Sampling： ~112%/$E^{0.5}$ ⊕ 21%	Glass cubic: <15%/$E^{0.5}$ ⊕ 4%
Z decay data	~ 4.0 × 10^6	~ 6 × 10^{12}

See more details of DELPHI detectors in [reference list]; details of AGORA in [Costa's talk] and [arXiv:2510.05260]; Thanks to Yang Zhang for the AGORA structure diagram.

Workflow: from Legacy Fortran to Modern HEP Analysis Framework



The DST-ROOT interface is modified from *arXiv:2510.18762 [hep-ex]*

2. Physics Motivation:
Hadron Production in Jets

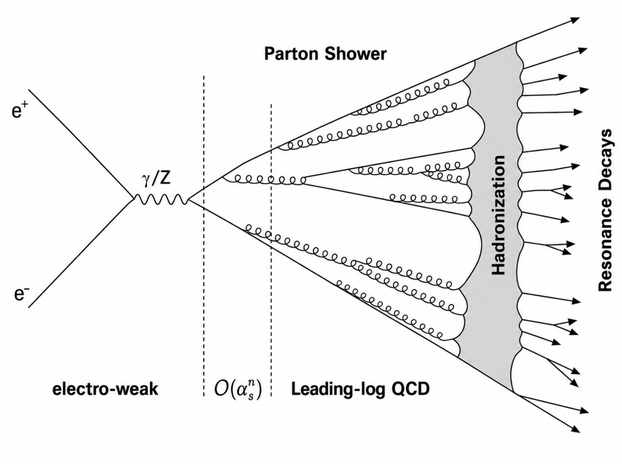
Hadron Production in Jets

- Gluon jets are expected to exhibit stronger color radiation in the perturbative parton cascade and to contain larger particle multiplicities.

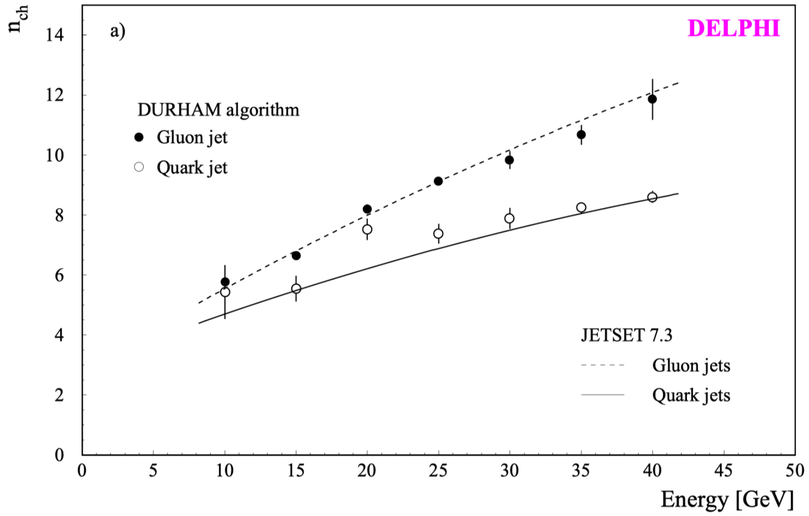
- The ratios of K_S^0 and Λ production rates in gluon and quark jets relative to the mean charged particle multiplicity,

$$\mathscr{R}_{g/q}^{h} \equiv \frac{\langle N_h \rangle_g}{\langle N_{\mathrm{ch}} \rangle_g} \Bigg/ \frac{\langle N_h \rangle_q}{\langle N_{\mathrm{ch}} \rangle_q}$$

Identified strange-particle productions in gluon jets cannot be fully understood through a general scaling.



Z.Phys.C 70 (1996) 179–196



Eur.Phys.J.C 8 (1999) 241–254

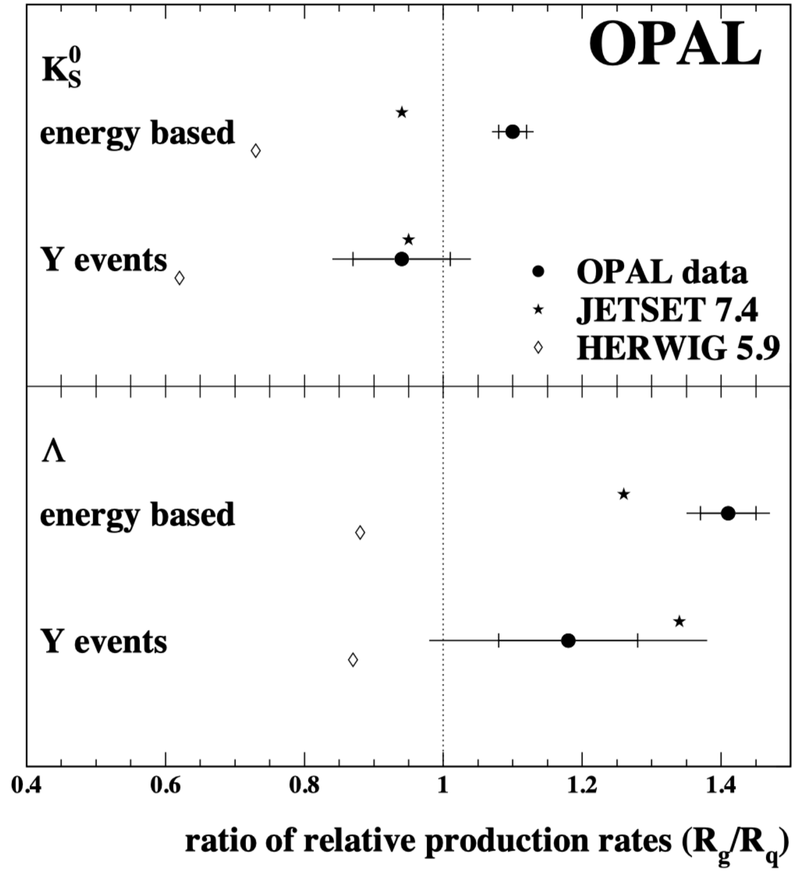


Fig. 7. The ratio of relative production rates (see text) in quark and gluon jets of K_S^0 and Λ for both analyses. The experimental statistical errors are delimited by the small vertical bars. The predictions of JETSET 7.4 and HERWIG 5.9 are also shown. The predictions of JETSET 7.3 are no more than 0.04 lower than those of JETSET 7.4

Hadron Production in Jets

The rapidity correlations between Λ baryons with other particles are observed.

There is local compensation mechanism during the production of strange quark and baryons.

The production of Ξ^- baryons in jets intrinsically involves the local compensation of strangeness and baryon number, making it a sensitive probe of non-perturbative QCD.

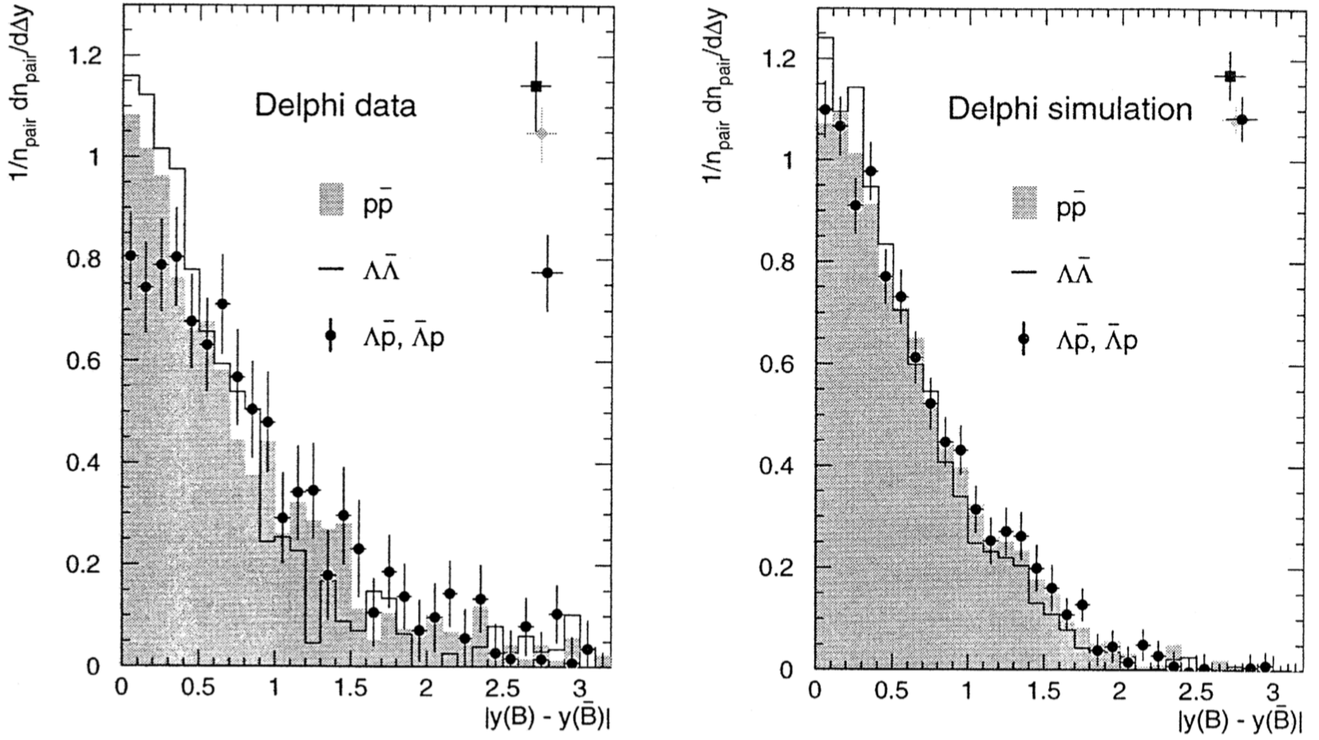
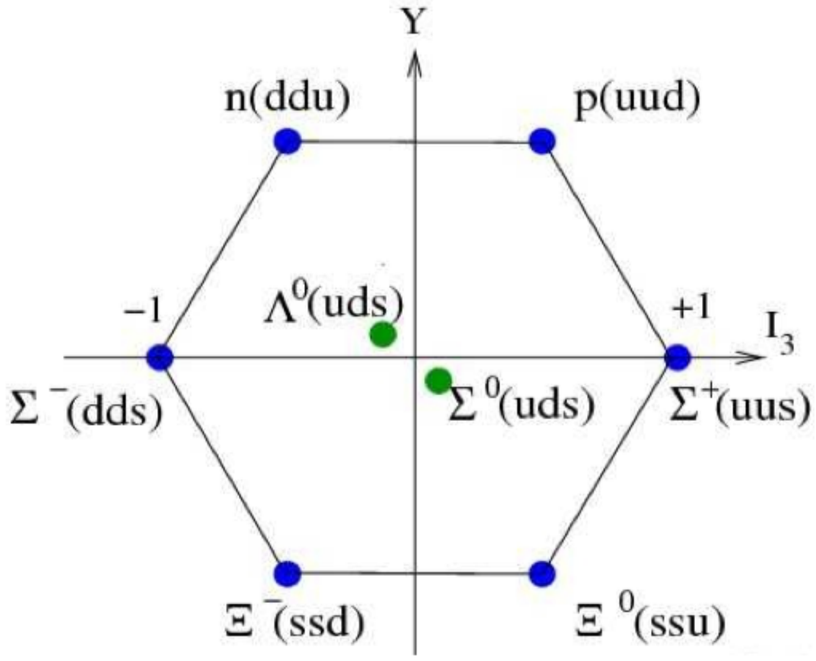


Fig. 3. Rapidity differences of baryon-antibaryon pairs for real data and full Jetset 7.3 simulation with Delphi tuning [10]. The three points with error bars on the far right of each plot show the mean values of the two leftmost bins ($|y(B) - y(\bar{B})| < 0.2$) for the three $B\bar{B}$ combinations, to show the significance of the effect.



3. Analysis:
Sample, Reconstruction & Measurement

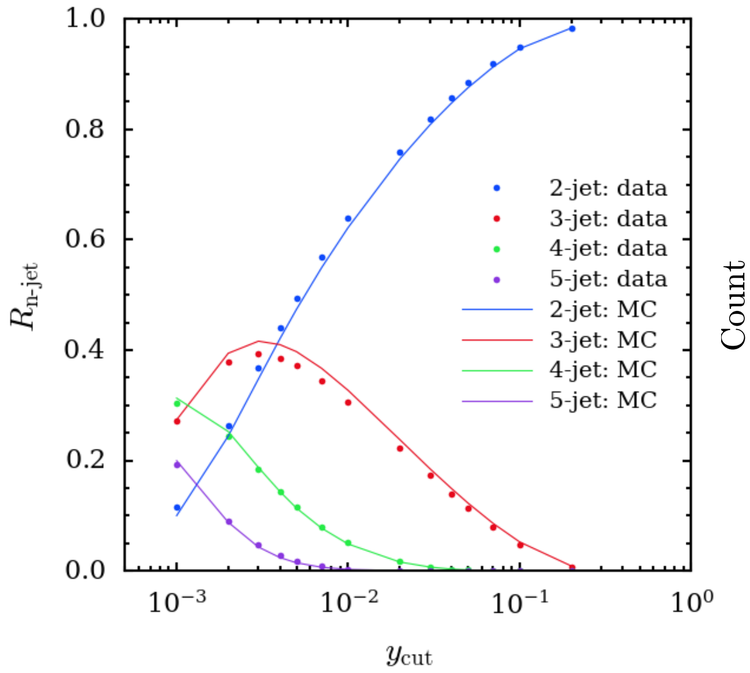
Jet Clustering: Durham Algorithm

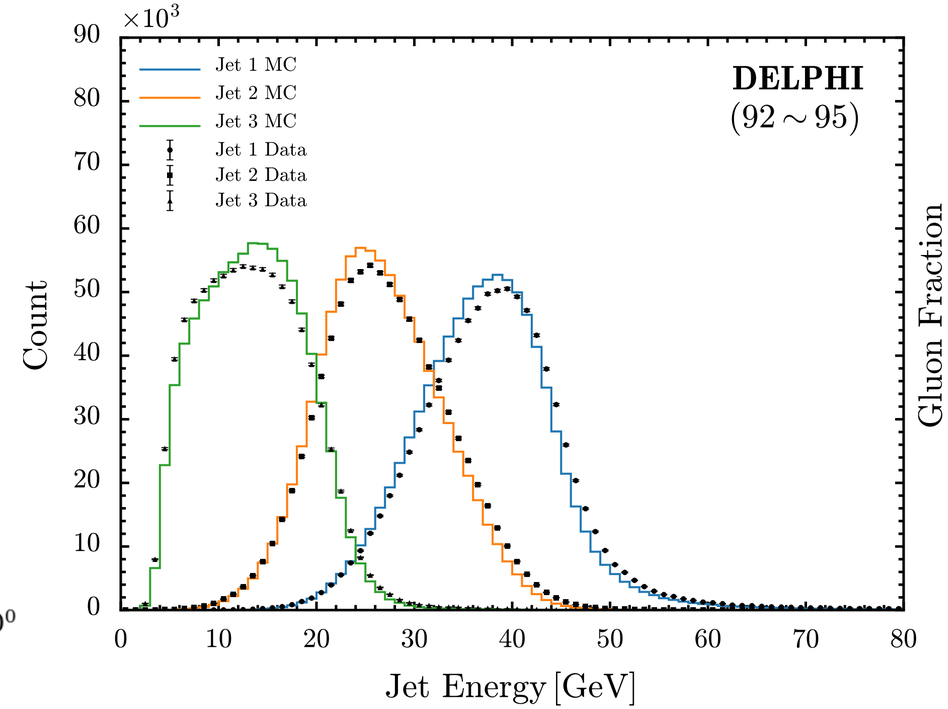
Repeat energy ranking method implemented in L3 (Phys.Lett.B 407 (1997) 389-401)/OPAL (Eur.Phys.J.C 8 (1999) 241-254).

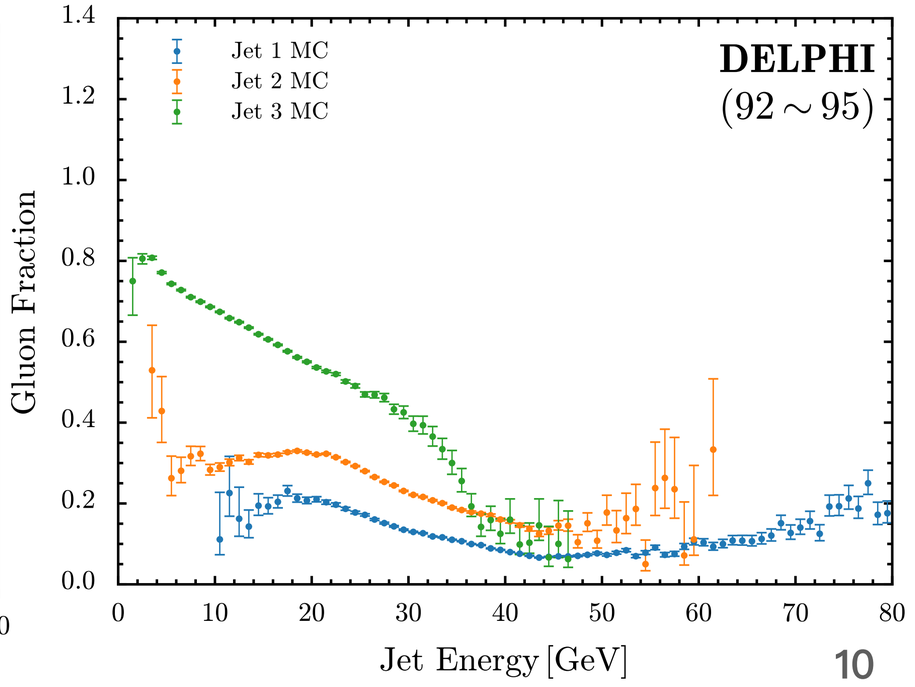
Three/Two-jet events have been selected by official cuts for **track quality** and for the **hadronic event type** as well as applying a $k_\perp$ cluster algorithm (Durham).

Durham ($k_\perp$) algorithm via FastJet: iterative pairwise clustering of all accepted charged and neutral objects.

Distance: $y_{ij} = \dfrac{2\ \min(E_i^2, E_j^2)\,(1-\cos\theta_{ij})}{Q^2}$, where $Q = \sqrt{s} = 91.2\,\mathrm{GeV}$; Jet resolution parameter: $y_{\mathrm{cut}} = 0.005$

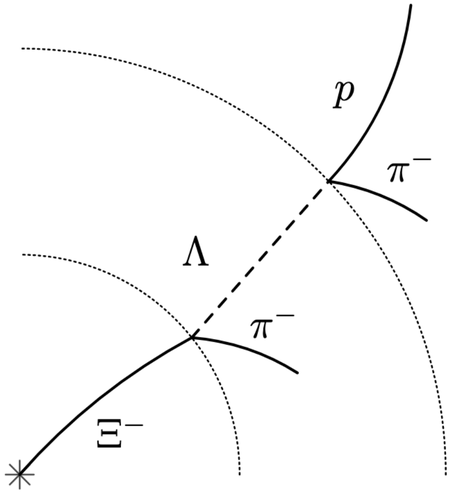


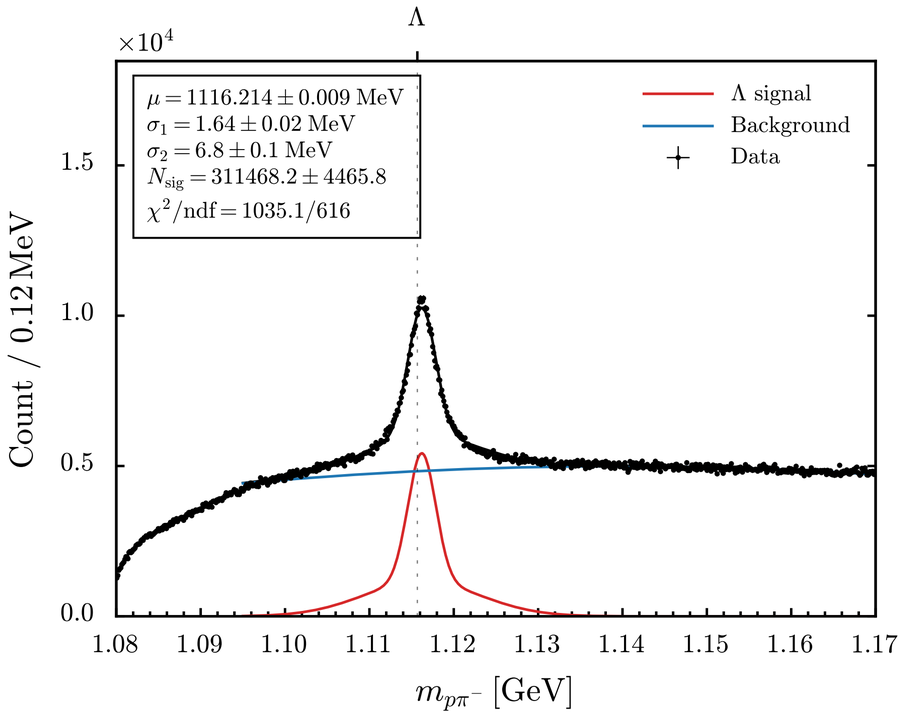




$\Xi^- \to \Lambda + \pi^-, \Lambda \to p\pi^-$ Reconstruction

- **Official V^0 selection and our repeat:**
  - All V0's, which means (done by official algorithm, Nucl.Instrum.Meth.A 378 (1996) 57-100):
    - the angle in the xy plane between the V^0 momentum and the line joining the primary to the secondary vertex: $\Delta\phi < 0.1$ rad;
    - the radial separation of the primary and secondary vertex in the XY plane is greater than twice the error on the fitted distance: $R > 2\sigma$;
    - the probability of the χ^2 fit to the secondary vertex: $P_{\chi^2} > 0.001$.
    - $\gamma \to e^+e^-$ veto: the transverse momentum of each particle of the V^0 with respect to the line of flight is greater than $0.02\,\mathrm{GeV}/c$ and the invariant mass in the e^+e^- hypothesis is more than $0.16\,\mathrm{GeV}/c^2$;
  - Considering the tracks with higher momentum as a proton, redo the vertex fit.
  - m_Λ **window:** $|m_{p\pi^-} - m_\Lambda| < 4.5\,\mathrm{MeV}$



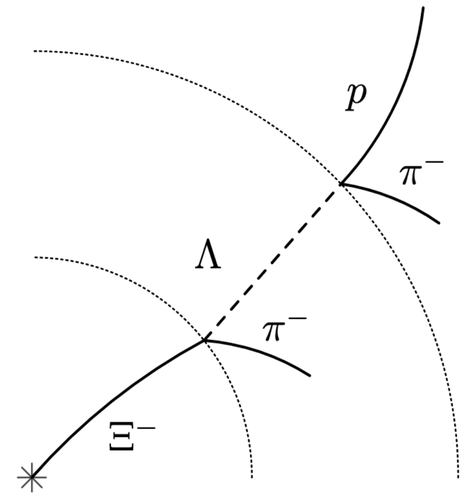


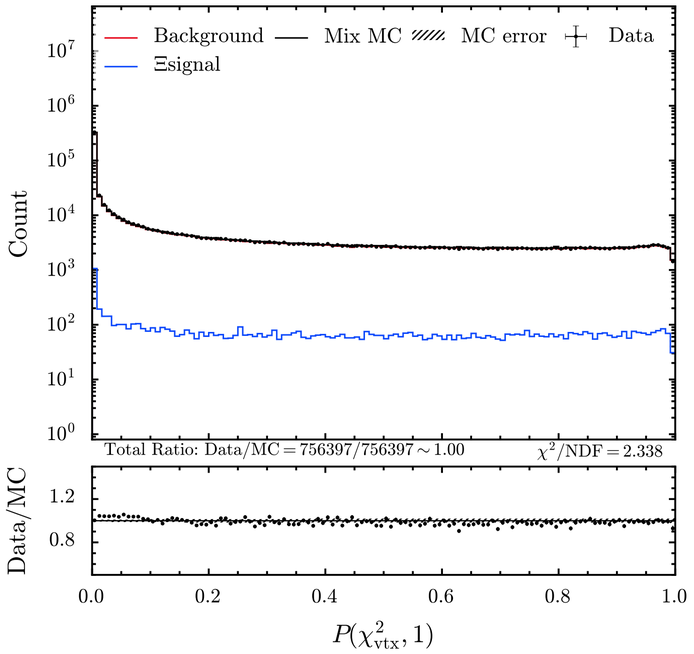
$\Xi^- \to \Lambda + \pi^-, \Lambda \to p\pi^-$ Reconstruction

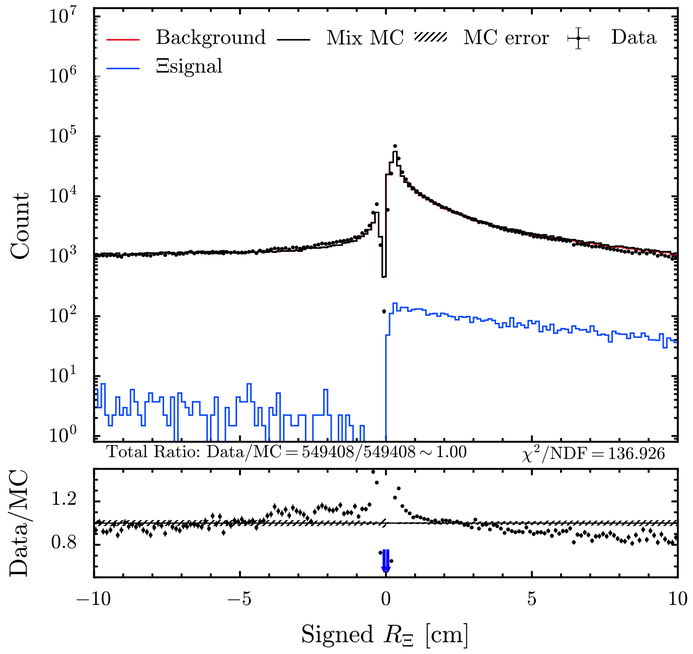
Comparing all the Λ from V0 with the other charged tracks.

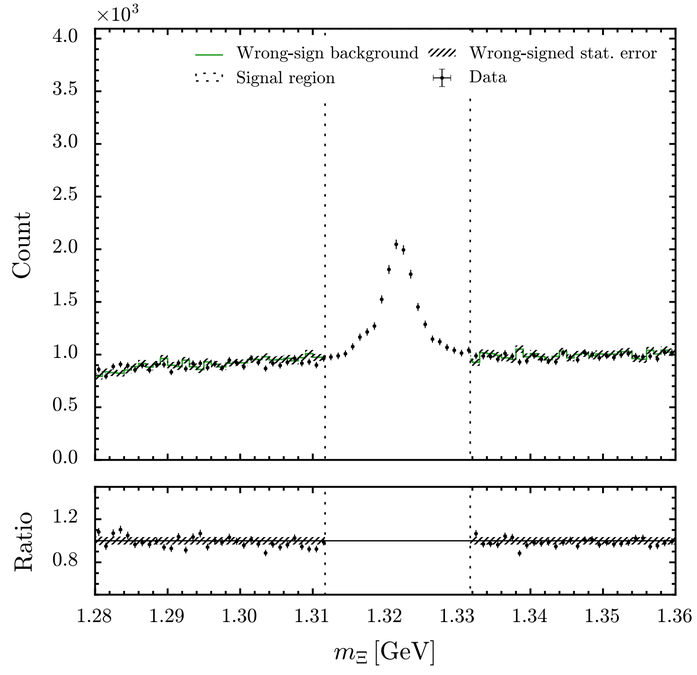
- Consider all combinations of $\Lambda + \text{track}^-$ (whose charge is required to be same with π^-_Λ).
- Calculate Ξ^- mass from Λ/Ξ^- VertexFit + Λ KinematicFit.[a)]
- A protection cut on probability of $P(\chi^2_{\text{vtx}}) > 0.001$
- Signed decay radius of Ξ^- in $R\phi$ plane: $R_\Xi = \left\{ \begin{array}{ll} +r_\Xi & \text{if } r_\Lambda > r_\Xi, \\ -r_\Xi & \text{if } r_\Lambda \leq r_\Xi, \end{array} \right\} > 0.04\,\text{cm},$

The wrong signed $\Lambda + \text{track}^+$ are considered to model the background.









a) **The vertex fit and kinematic fit program is refactored from the [BESIII software].**

$\Xi^- \to \Lambda + \pi^-, \Lambda \to p\pi^-$ Reconstruction

- Selection efficiency of Ξ is studied using truth match between generator particles and reconstructed particles in MC samples
  - $\epsilon_{\text{inc}} = \dfrac{\text{selected } \Xi \text{ that matched to truth } \Xi}{\text{all truth } \Xi}$
- DELPHI detector has limited acceptance for $\Xi^- \to \Lambda + \pi^-, \Lambda \to p\pi^-$ outside the range of $1.0 < \xi = -\ln p_\Xi / E_{\text{beam}} < 4.0$.
- Only Ξ candidates with $1.0 < \xi = -\ln p_\Xi / E_{\text{beam}} < 4.0$ are considered in the analysis.

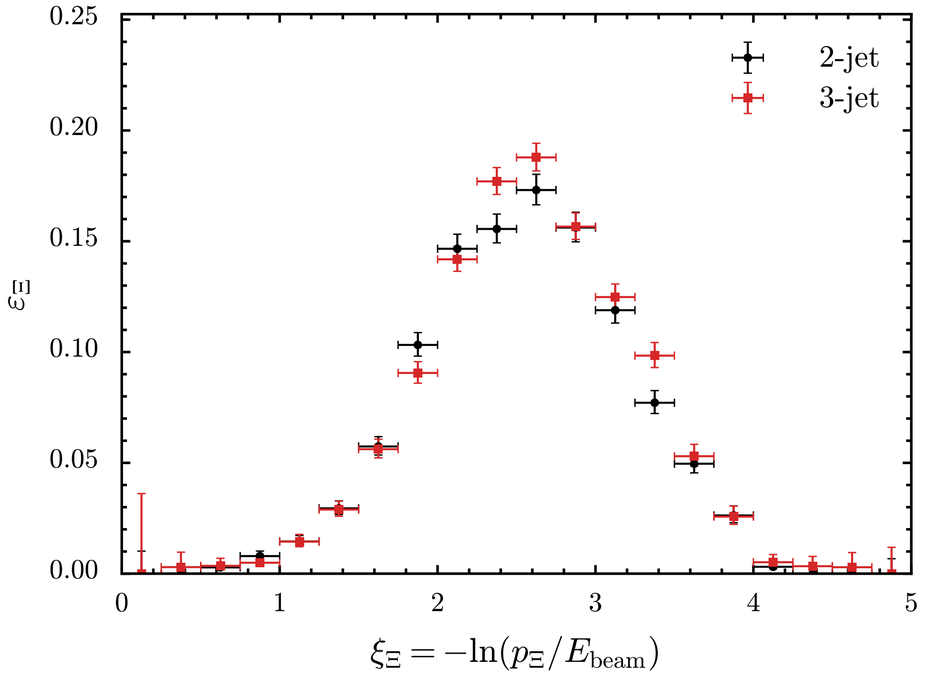


Table 4: Average efficiency of inclusive Ξ^- in 2/3-jet events.

	ε
Inclusive Z	$8.70 \pm 0.08\%$
$Z \to$ 2-Jet Events	$8.14 \pm 0.13\%$
$Z \to$ 3-Jet Events	$10.15 \pm 0.15\%$

At high momenta the loss of efficiency is due to the finite tracking volume and to the two-track separation capability of the TPC.

Extract Ξ production in jets

- **Ξ-jet assignment:** $y \equiv \dfrac{2 \cdot \min(E_{\Xi}^2, E_{\text{jet}}^2)(1-\cos\theta)}{E_{\text{vis}}^2} < 0.005$

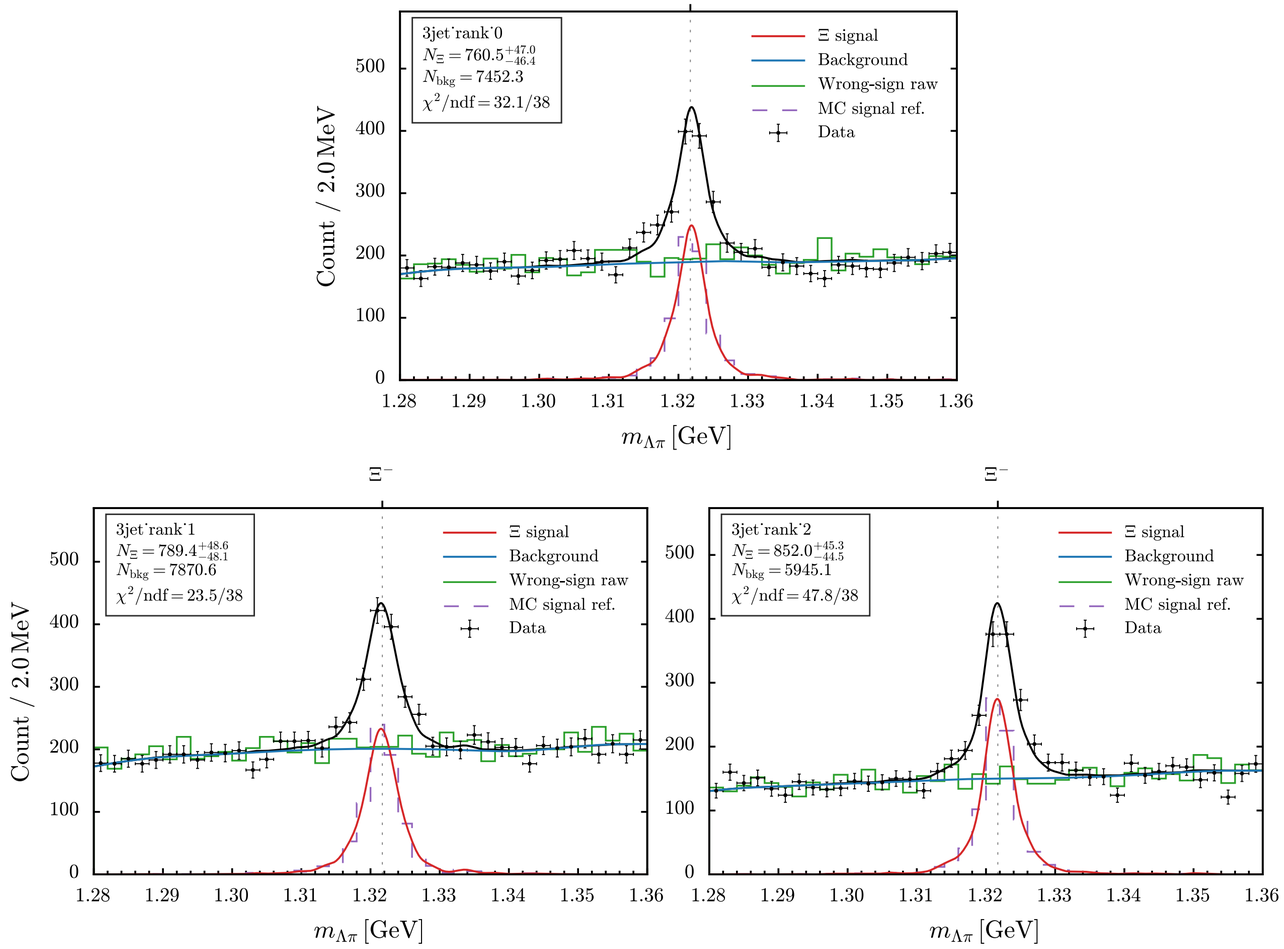
- **Extract Ξ production by fitting the Ξ mass spectrum:**
  - PDF: Kernel Density Estimation (KDE) with a Gaussian kernel.
  - Signal modeled by real mass spectrum of MC truth matched Ξ.
  - Background modeled by the wrong signed $\Lambda\pi^+$ pairs from data.

- **Efficiency Correction:**

$$\langle N_{\Xi} \rangle = \frac{1}{N_{\text{jet}}} \frac{N_{\text{obs}}}{\epsilon f_{\text{acc}}},$$

- ϵ: efficiency in acceptance range $1.0 < \xi = -\ln p_{\Xi}/E_{\text{beam}} < 4.0$ and corresponding jets.

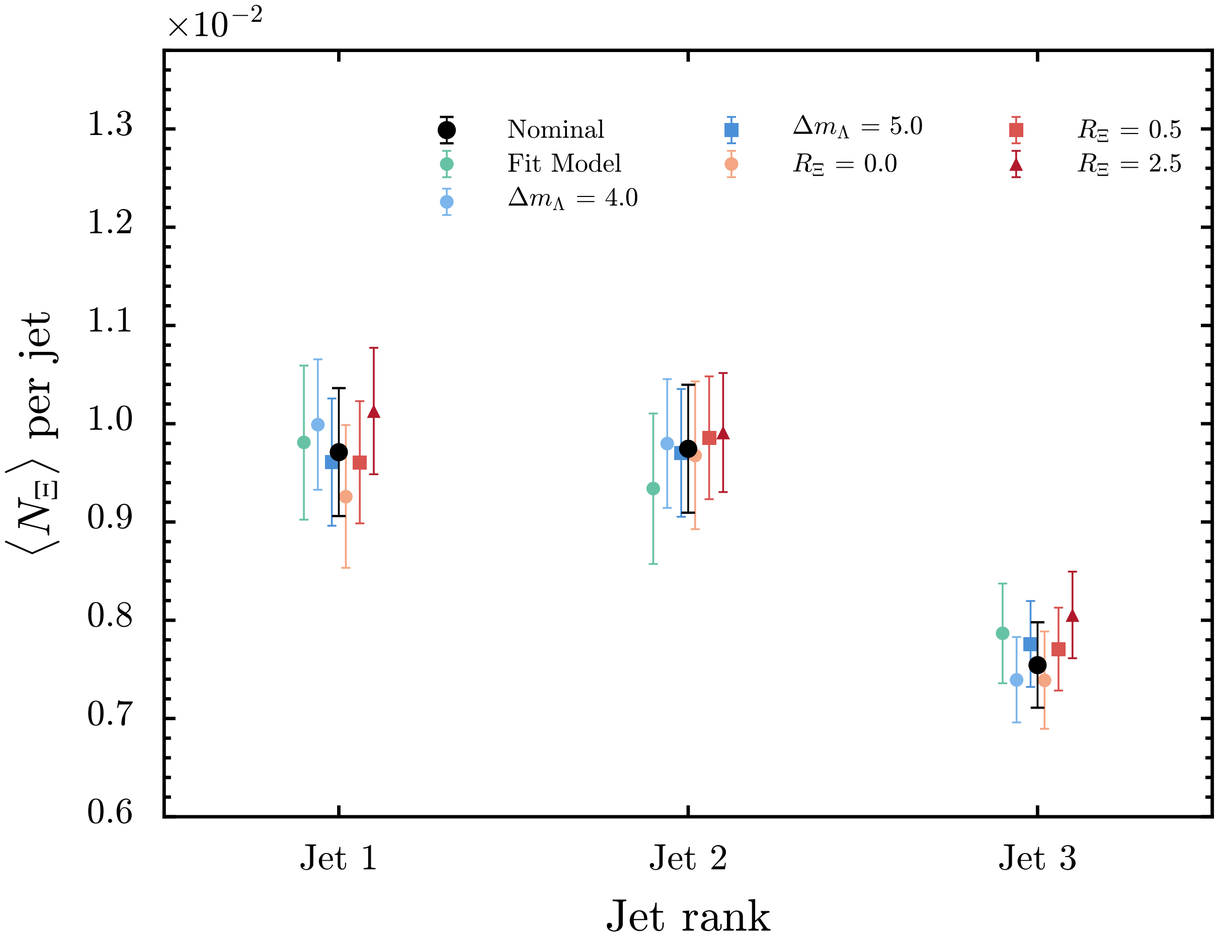
- $f_{\text{acc}} = \dfrac{N_{\text{gen}}(1.0 < \xi < 4.0)}{N_{\text{gen}}(\text{full } \xi \text{ range})}$ is estimated from the MC generator.



Fit results for Ξ production in energy-ranked jets. Each panel shows the Ξ invariant mass distribution (points) with the KDE signal template (red hatched), background (blue), and total fit (black). The green and purple histograms show the raw distributions of the wrong-signed control sample in data and MC matched Ξ candidates in MC samples.

Systematic uncertainties

- Ξ Selection:
  - m_{Λ} window: varied from $4.5\,\mathrm{MeV}$ to $4.0\,\mathrm{MeV}$ and $5.0\,\mathrm{MeV}$.
  - minimum signed decay radius of Ξ in $R\phi$-plane: varied from $0.4\,\mathrm{cm}$ to 0, 0.5 and $2.5\,\mathrm{cm}$.
  - Largest variations are considered as the systematic uncertainties.
- Fit method:
  - Fit the sideband m_{Ξ} distribution using histogram PDF of wrong signed control sample, then subtract the background from data in the signal region ($m_{\Xi} \pm 10\,\mathrm{MeV}$).
  - Half-difference between nominal & alternative fit method is assigned as systematic uncertainty.
- Acceptance:
  - an uncertainty of $50\,\%$ on the correction factor is assigned.



Results

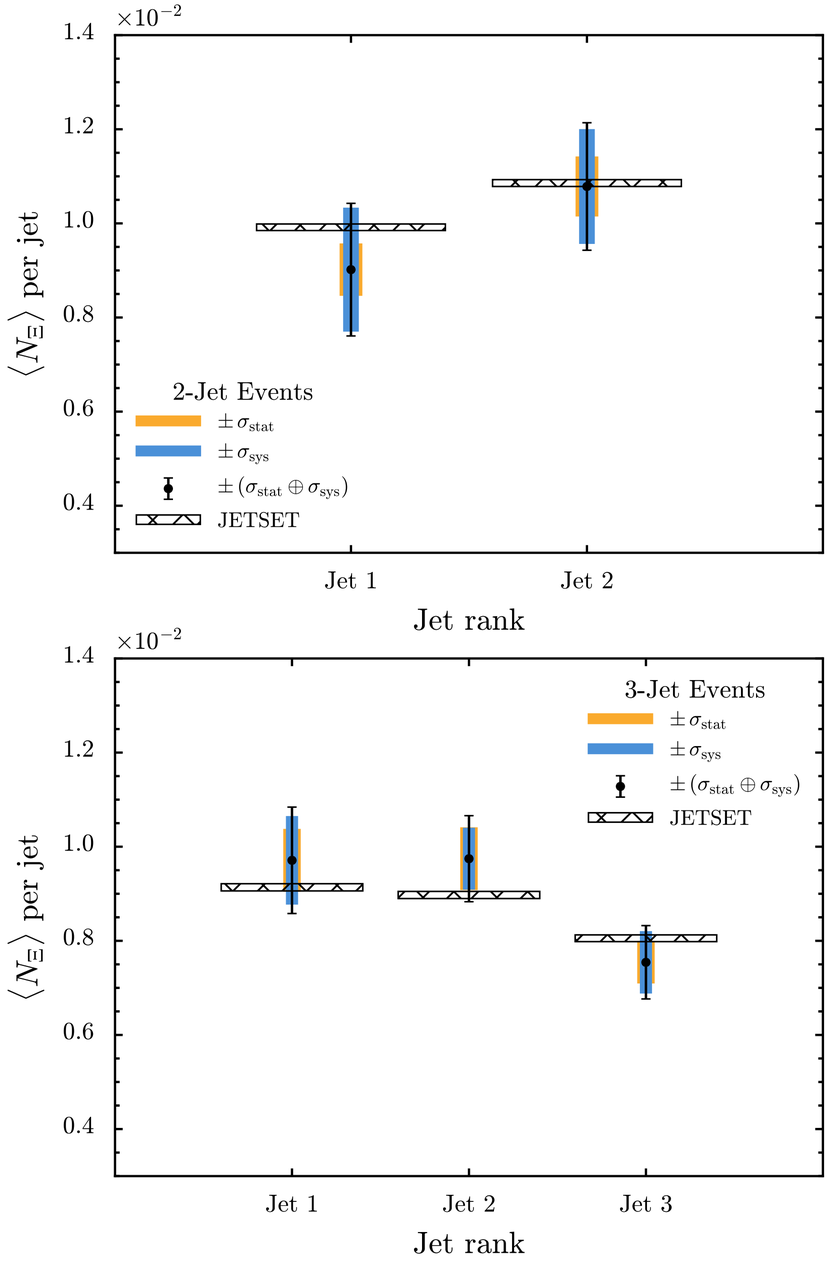
- The resulting average Ξ production in energy ranked jets:

$$\langle N_{\Xi} \rangle = \frac{1}{N_{\text{jet}}} \frac{N_{\text{obs}}}{\epsilon f_{\text{acc}}},$$

is normalized by the number of inclusive charged tracks in the corresponding jets,

$$R^{\Xi}_{\text{jet},\,k} = \langle N_{\Xi} \rangle_{\text{jet},\,k} \Big/ \langle N_{\text{ch}} \rangle_{\text{jet},\,k}$$

- The result is compatible with the prediction from the JETSET predictions.



Discussion: $\Xi^-/\bar{\Xi}^+$ production

- Production rate ($R^h_{k,\mathrm{obs}}$) of particles in a jet sample (indexed as k) can be considered as a mixture of quark and gluon-jets.

$$R^h_{k,\mathrm{obs}} = \rho_k \cdot R^h_g + (1-\rho_k) \cdot R^h_q,$$

where ρ_k is the gluon-fraction of the jet category. For 3-jet events,

$$\begin{pmatrix} R^h_{1,\mathrm{obs}} \\ R^h_{2,\mathrm{obs}} \\ R^h_{3,\mathrm{obs}} \end{pmatrix} = \begin{pmatrix} 1-\rho_1 & \rho_1 \\ 1-\rho_2 & \rho_2 \\ 1-\rho_3 & \rho_3 \end{pmatrix} \begin{pmatrix} R^h_q \\ R^h_g \end{pmatrix} \equiv A\boldsymbol{\theta}, \quad \boldsymbol{\theta} = \begin{pmatrix} R^h_q \\ R^h_g \end{pmatrix}$$

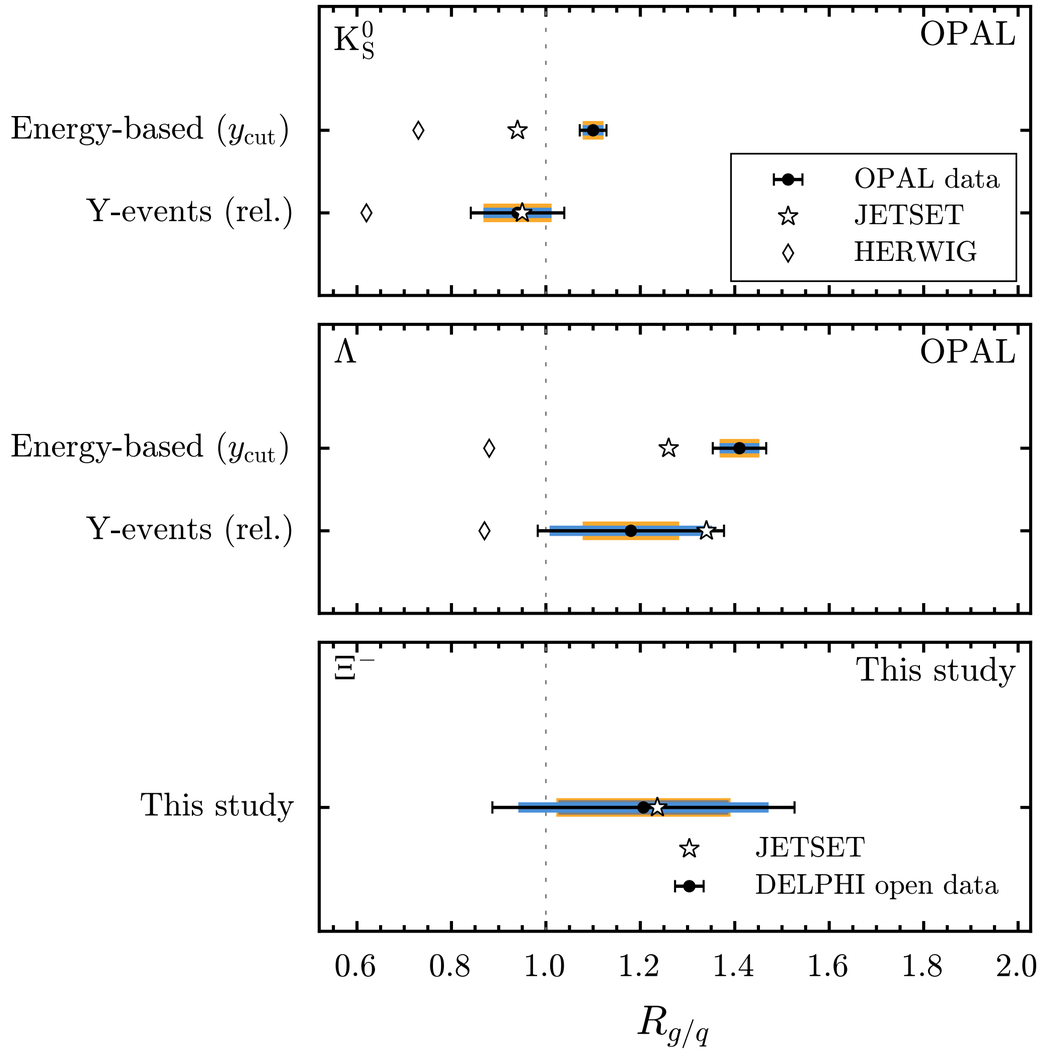
- Therefore the R^h_q and R^h_g can be derived by a χ^2-fit:

$$\chi^2 = \left(\mathbf{R}_{\mathrm{obs}} - A\boldsymbol{\theta}\right)^T V^{-1} \left(\mathbf{R}_{\mathrm{obs}} - A\boldsymbol{\theta}\right),$$

Then, the ratio $\mathscr{R}^h_{g/q} \equiv \dfrac{\langle N_h \rangle_g}{\langle N_{\mathrm{ch}} \rangle_g} \Big/ \dfrac{\langle N_h \rangle_q}{\langle N_{\mathrm{ch}} \rangle_q}$ can be derived.

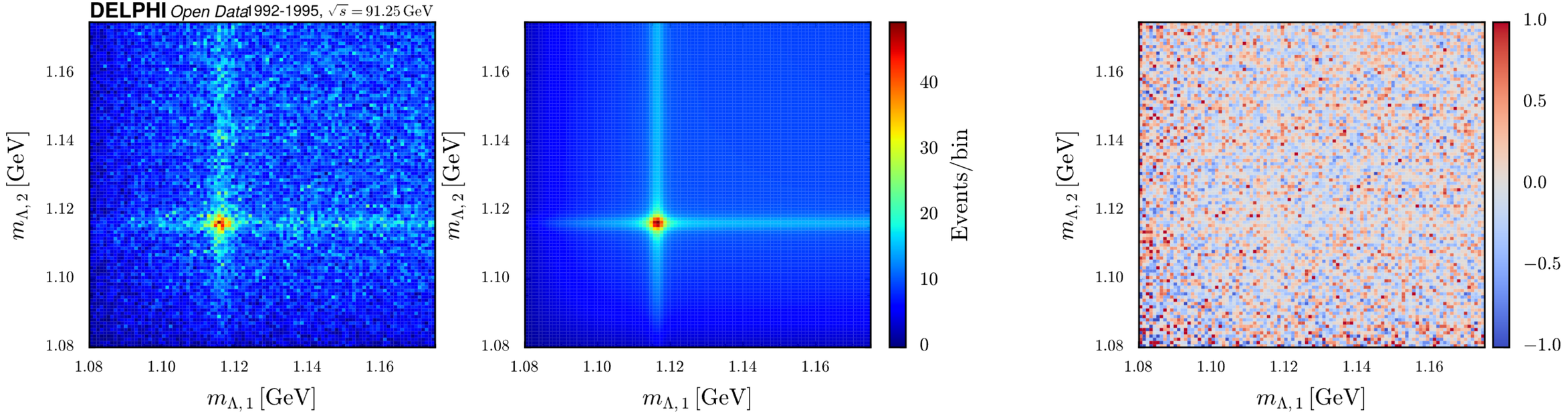
$$\mathscr{R}^{\Xi}_{gq} = 1.21 \pm 0.18(\mathrm{stat.}) \pm 0.26(\mathrm{sys.})$$

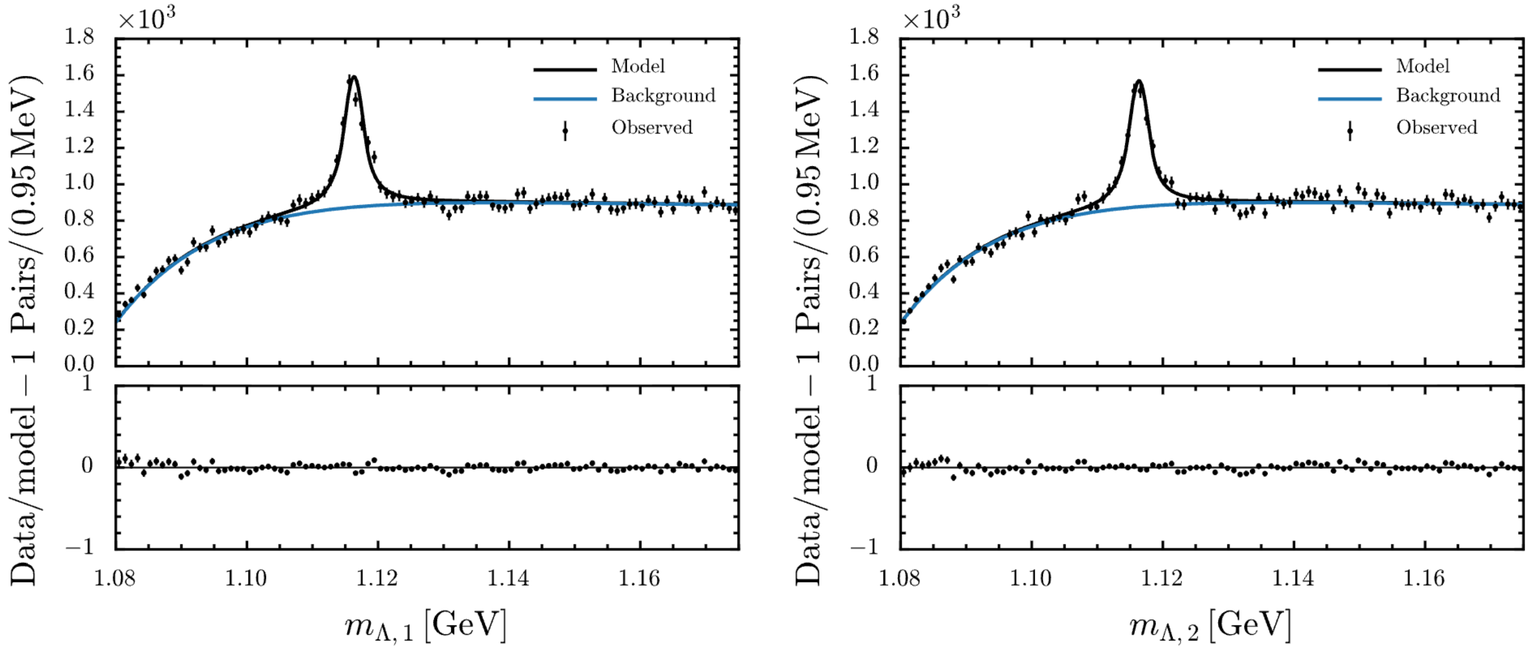
The $\mathscr{R}^{\Xi}_{g/q}$ result is consistent with the ratios of K^0_S and Λ measured by OPAL.



4. Summary & Discussion:
Ξ^-, Correlation, and More

Baryon Pair Production in Jets





From a modern perspective, coupled with:

- *new theoretical calculations*
- *phenomenological designs,*
- *new experimental technique,*

It is possible to explore more physics from legacy data !

ParticleNet for DELPHI Data

The ParticleNet is implemented on DELPHI open data, making the direct measurement of R_s possible (see [Shuo's talk] in this afternoon).

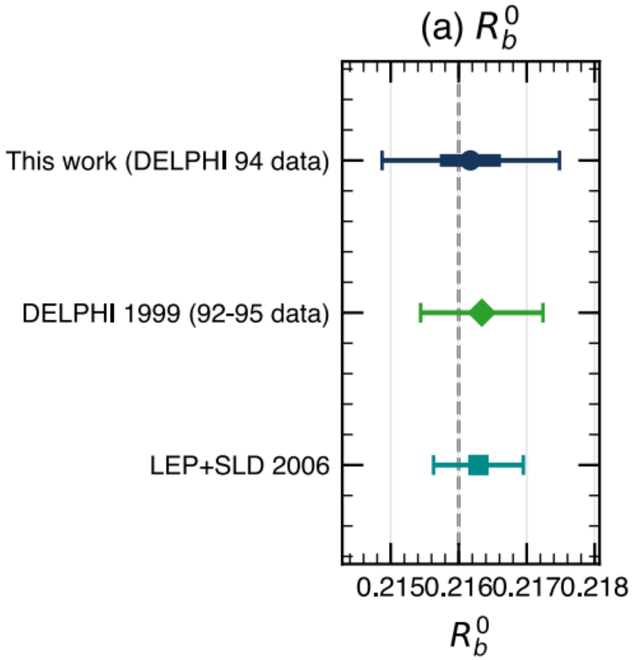
$$R_q^{\,o} = \frac{\Gamma(Z \to q\,\bar{q})}{\Gamma_{had}}$$

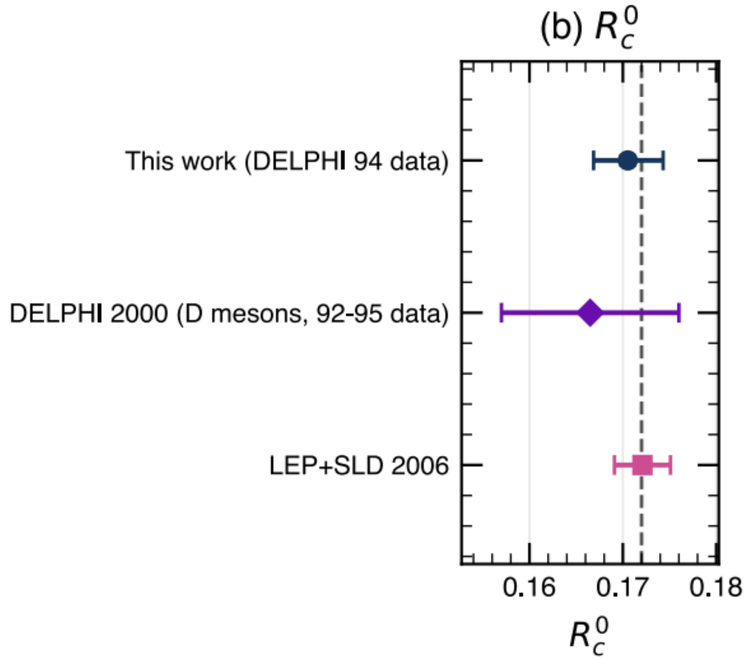
Flavor-resolved tests of the hadronic Z width

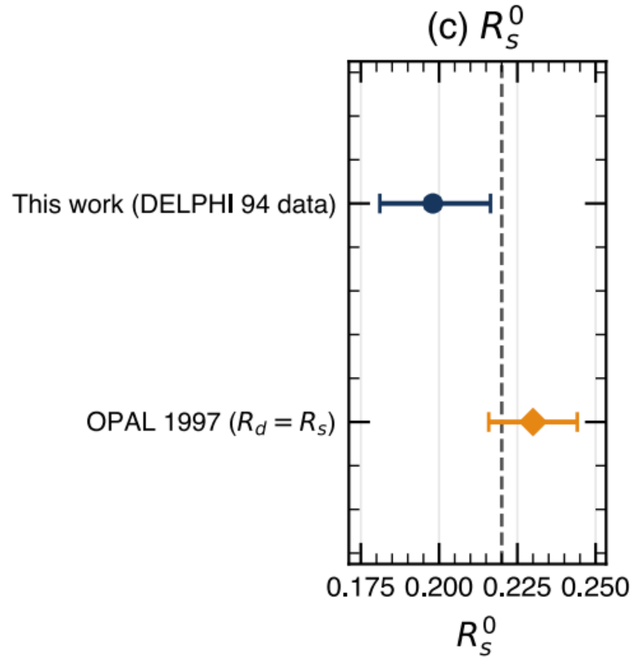
Previous benchmarks	Result
DELPHI R_b	0.21634 ± 0.00065 ± 0.00060
LEP+SLD R_b	0.21629 ± 0.00066
DELPHI R_c	0.1665 ± 0.0051 ± 0.0081
LEP+SLD R_c	0.1721 ± 0.0030
OPAL $R_{d,s}^{uds}$	0.371 ± 0.016 ± 0.016

OPAL: $R_d = R_s$, normalized to uds.

Fixing R_d instead: $R_s^{uds} = 0.392 \pm 0.043 \pm 0.045$.







Summary

- ***Data is opened & everything still work:*** The DELPHI, one of the experiments at LEP, released its full data to the public physics community.
  - Full stack of software for simulation, reconstruction, event display, usage manual and a part of internal documentations are all available.
  - The open data is readable and analyzable.
- ***A new measurement***: The ratios of $\Xi^-/\bar{\Xi}^+$ production rates in gluon and quark jets relative to the mean charged particle multiplicity is derived to be

$$\mathscr{R}_{gq}^{\Xi} = 1.21 \pm 0.18(\text{stat.}) \pm 0.26(\text{sys.})$$

  which is consistent with the JETSET expectation and OPAL result for $\mathscr{R}_{g/q}^{K_S^0}$ and $\mathscr{R}_{g/q}^{\Lambda}$, within the uncertainties.

- ***Looking forward the release of the OPAL and ALEPH data:*** triple the Z data set!
- **The legacy data in the pre-CEPC/FCC-ee time**:
  - ***A testing ground:*** new theoretical calculation; new phenomenological development; new analysis technique (see [Shuo's talk] in this afternoon).
  - **Experience** for future detector design

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Thanks for your attention

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References for the DELPHI Detector

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Overview: the Large Electron Positron Collider

The Large Electron-Positron (LEP) collider is **the largest electron-positron accelerator** ever built.

Four detectors on LEP: DELPHI, ALEPH, L3 and OPAL.

