ICHEP 2024

Testing CPT symmetry

High precision mass measurements of multi-strange baryons with ALICE

Romain Schotter, on behalf of the ALICE Collaboration
Austrian Academy of Sciences and SMI

Testing CPT symmetry: why does it (anti-)matter?

ALICE

Among all the discrete symmetries, only the *combined* **CPT symmetry** is an exact symmetry of Nature

- **Charge conjugation (C)**
- **Parity transformation (P)**
- **Time reversal (T)**

→ ***2 consequences:***

1. Matter and anti-matter share the same fundamental properties
(mass, lifetime,...)

2. Matter and anti-matter exist in equal amounts
→ contradiction with astronomical observations

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A violation of CPT symmetry could explain the matter/anti-matter imbalance in the Universe

The most stringent *(indirect)* test of the CPT symmetry involves the K^0-$\overline{K}^0$ mixing process

$$|M(\mathrm{K}^0) - M(\overline{\mathrm{K}}^0)|/M_{\mathrm{avg.}} < 6 \times 10^{-19}$$

Phys. Rev. D 86, 010001 (2012)

$$|\Gamma(\mathrm{K}^0) - \Gamma(\overline{\mathrm{K}}^0)|/\Gamma_{\mathrm{avg.}} = (8 \pm 8) \times 10^{-18}$$

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In the **multi-strange baryon** sector, the ***only*** mass difference measurements **date back to** { **18 years ago** for Ξ; **26 years ago** for Ω }
and rely on **small statistics**

$$M(\Xi^-) - M(\overline{\Xi}^+)/M_{avg.} = (-2.5 \pm 8.7) \times 10^{-5}$$

Events: 2478(2256) *DELPHI,* Phys. Lett. B 639, 179–191 (2006)

$$M(\Omega^-) - M(\overline{\Omega}^+)/M_{avg.} = (-1.44 \pm 7.98) \times 10^{-5}$$

Events: 6323(2607) *E756,* Phys. Rev. D 58, 072002 (1998)

Precision mass measurement: why does it matter?

- **Hadron masses are essential physical ingredients** to Lattice QCD (lQCD)

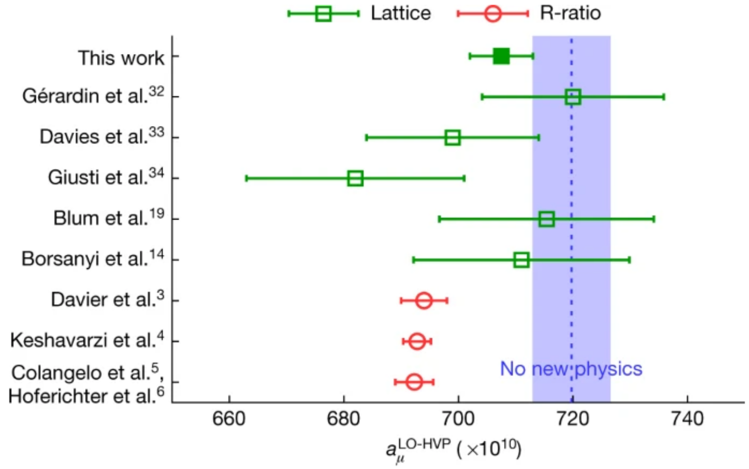
- *Example:* **prediction of the anomalous magnetic moment of the muon**

$$a_\mu = \frac{g_\mu - 2}{2} \qquad a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + \boxed{a_\mu^{\mathrm{hadrons}}}$$
$$= 116\ 591\ 810(1)(\underline{40})(18) \times 10^{-11}$$

- ***Promising approach:*** **ab-initio lQCD simulations**

  → Physical scale is set using 3 hadron ***masses*** as anchor points: $\pi^\pm$, $K^\pm$ and a **multi-strange baryon** (Ξ or Ω)

Borsanyi, Fodor, Guenther, et al.
Nature 593, 51–55 (2021)



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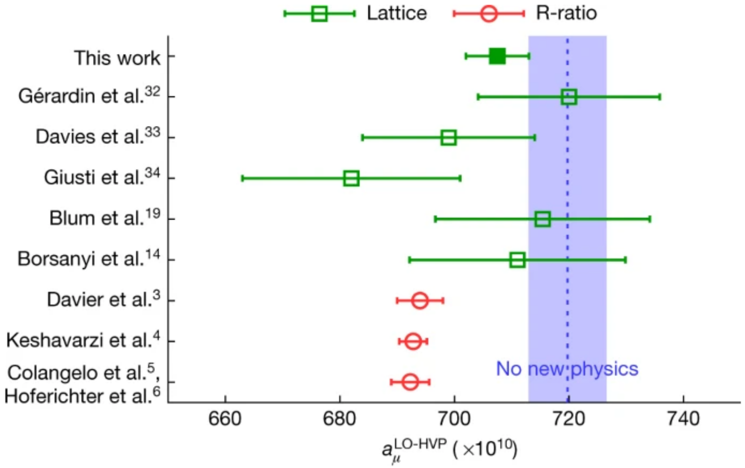


- ***Promising approach:*** **ab-initio lQCD simulations**

  → Physical scale is set using 3 hadron ***masses*** as anchor points: π±, K± and a **multi-strange baryon** (**Ξ** or **Ω**)

- In the **multi-strange baryon** sector, last mass measurements date back to { **18 years ago** for Ξ / **39 years ago** for Ω } and rely on ***small statistics***

$$M(\Xi^-) = 1321.70 \pm ({\rm stat.})0.08 \pm ({\rm syst.})0.05\ {\rm MeV}/c^2, \quad \text{Events: } 2478$$
$$M(\overline{\Xi}^+) = 1321.73 \pm ({\rm stat.})0.08 \pm ({\rm syst.})0.05\ {\rm MeV}/c^2, \quad \text{Events: } 2256$$

DELPHI, Phys. Lett. B 639, 179–191 (2006)

$$M(\Omega^-) = 1673 \pm 1\ {\rm MeV}/c^2, \quad \text{Events: } 100$$
$$M(\overline{\Omega}^+) = 1672 \pm 1\ {\rm MeV}/c^2, \quad \text{Events: } 72$$

Hartouni et al., Phys. Rev. Lett. 54, 628–630 (1985)

Towards more precise values for $\Xi^{\pm}$ and $\Omega^{\pm}$

- Previous mass and mass difference measurements are **between 18 to 39 years old**, and suffer from **limited statistics**

  → Reconstructing multi-strange baryons requires *excellent* detection capabilities

- All the data collected during the LHC Run 2 by ALICE in pp at $\sqrt{s}$ = 13 TeV

  → **2 400 000 (Ξ^{-}+$\overline{\Xi}^{+}$)** and **130 000 (Ω^{-}+$\overline{\Omega}^{+}$)** candidates, with little background

  → unique opportunity to

Objectives:

1. provide **new mass measurements of the $\Xi^{\pm}$ and $\Omega^{\pm}$**,

2. extract **mass difference between matter and anti-matter**
→ *direct* test of the CPT symmetry

The ALICE set-up during the LHC Run 2

Inner Tracking System (ITS-1), six layers of silicon detectors

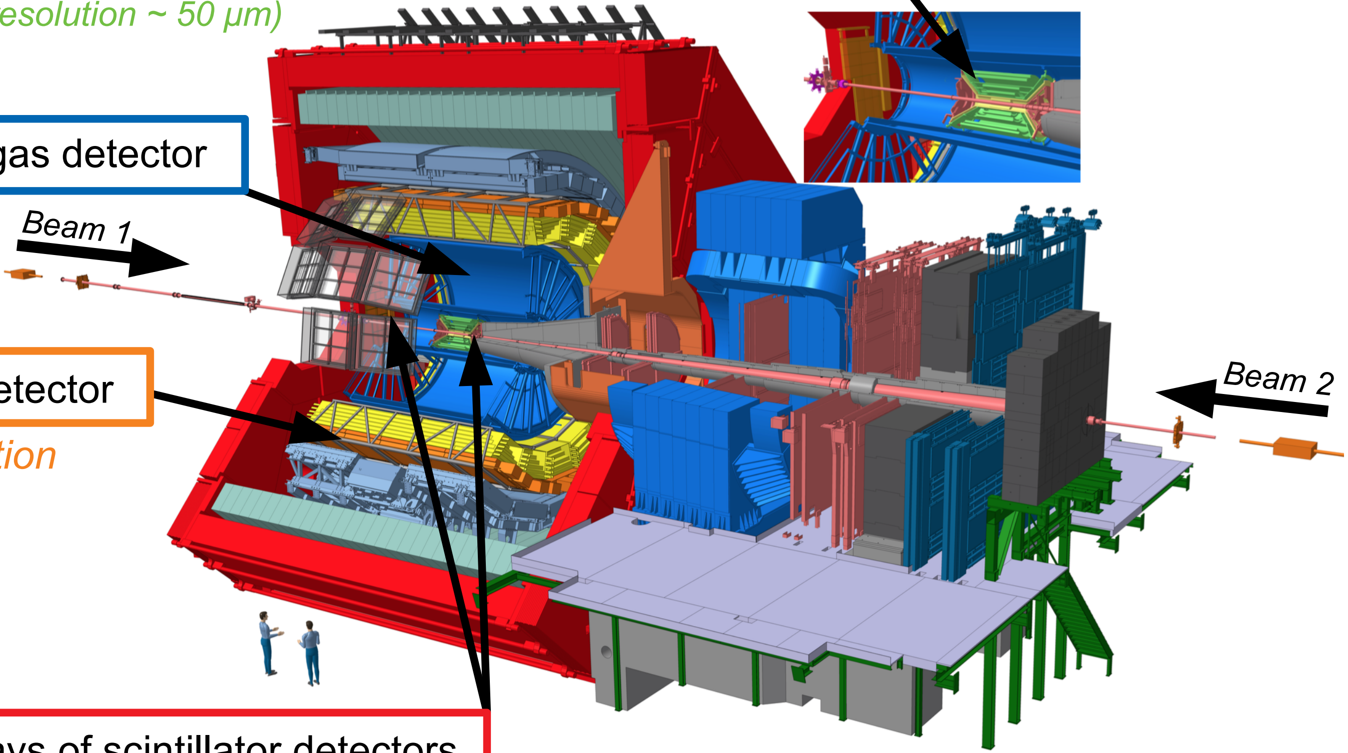
→ *Tracking*
→ *Vertexing (resolution ~ 50 μm)*
→ *Triggering*

Time Projection Chamber (TPC), gas detector

→ *Main tracking device (Δp/p ~ 1%)*
→ *Robust PID (dE/dx)*

Time-Of-Flight (TOF), gas detector

→ *Out-of-bunch pile up rejection*



V0: V0A and **V0C**, two arrays of scintillator detectors

→ *Triggering, multiplicity estimation at forward rapidity*

Dataset and data analysis

All **pp collisions at √*s* = 13 TeV**, collected during the LHC Run 2, are exploited

→ ***2.2 x 10^9 minimum-bias events***

The Ξ and Ω are studied in their characteristic ***cascade*** decay channel:

$$\begin{cases} \Xi^- \rightarrow \Lambda\ \pi^- \rightarrow \mathrm{p}\ \pi^-\ \pi^- \\ \overline{\Xi}^+ \rightarrow \overline{\Lambda}\ \pi^+ \rightarrow \overline{\mathrm{p}}\ \pi^+\ \pi^+ \end{cases}$$

$$c\tau(\Xi^{\pm}) = 4.91\ \mathrm{cm}$$

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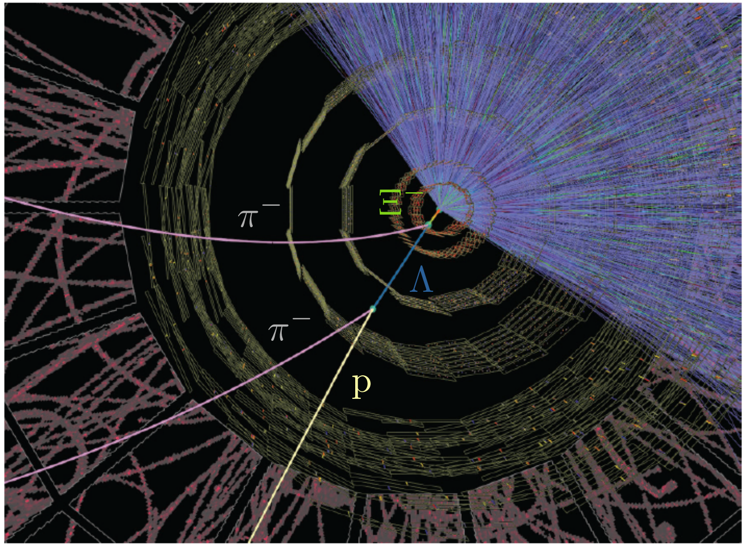

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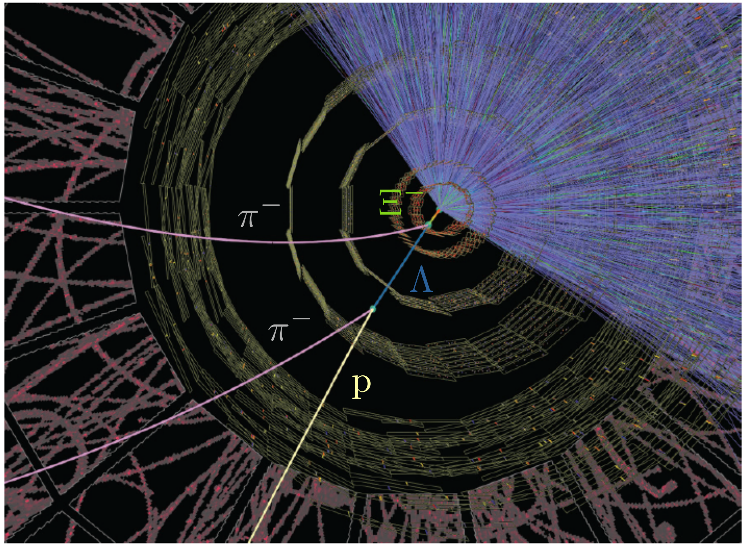


To distinguish the Ξ and Ω from the combinatorial background:
→ **topological reconstruction**

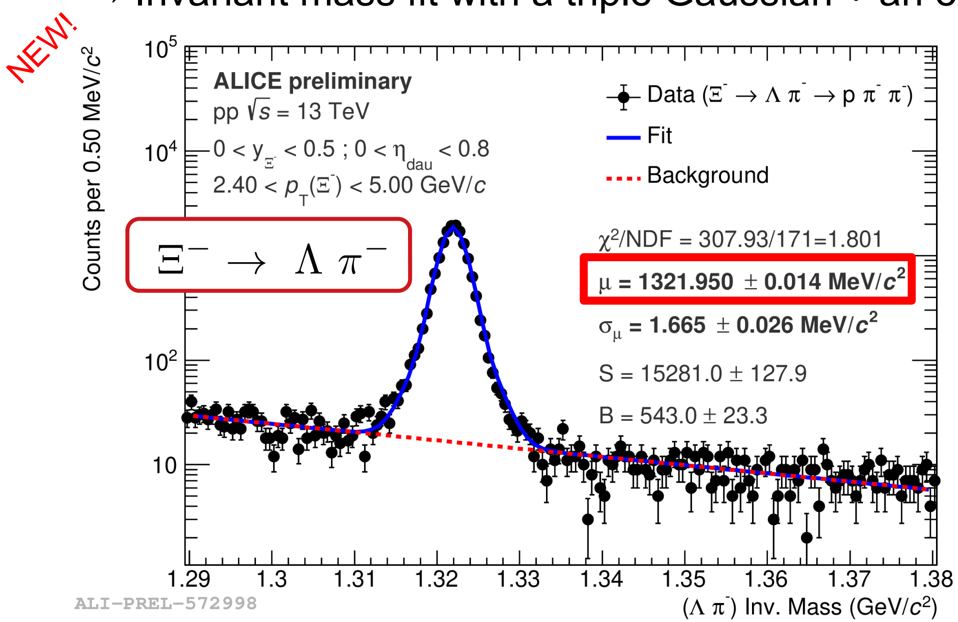
- Selections based on the geometry (vertex position, impact parameters,...) and kinematics (p_T, rapidity,...) of the decay
- PID for each decay daughter

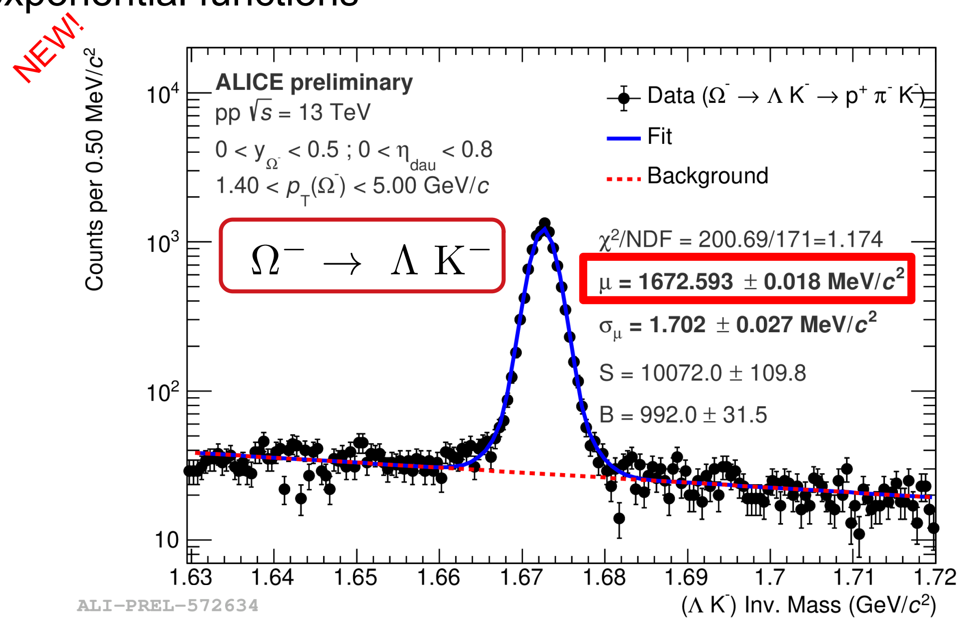
These selections have been tuned in order to reach a high level of purity

Mass extraction principle

Statistical identification of Ξ and Ω using an invariant mass analysis

→ Invariant mass fit with a triple Gaussian + an exponential functions





- **Extracted mass** (μ)
  = centre of the inv. mass peak
  = mean of the triple Gaussian functions

- **High purity sample** (~ 95% for Ξ and ~90% for Ω)
  → good control over the background shape

Summary of the systematic uncertainties

- **Topological and track selections** → Repeat analysis with 20 000 different set of selections

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Non-dominant
< 20 keV/c^2

Final results: $\Xi^{\pm}$ mass values

Final results rely on **~30 000 ($\Xi^{-}+\overline{\Xi}^{+}$)** and **~20 000 ($\Omega^{-}+\overline{\Omega}^{+}$)**, with 96% and 90% purities respectively

Out of the initial 2 400 000 ($\Xi^{-}+\overline{\Xi}^{+}$) and 130 000 ($\Omega^{-}+\overline{\Omega}^{+}$) candidates

DELPHI, *Phys. Lett. B 639, 179–191 (2006)*

$$M(\Xi^{-}) = 1321.70 \pm (\text{stat.})0.08 \pm (\text{syst.})0.05\ \text{MeV}/c^2$$

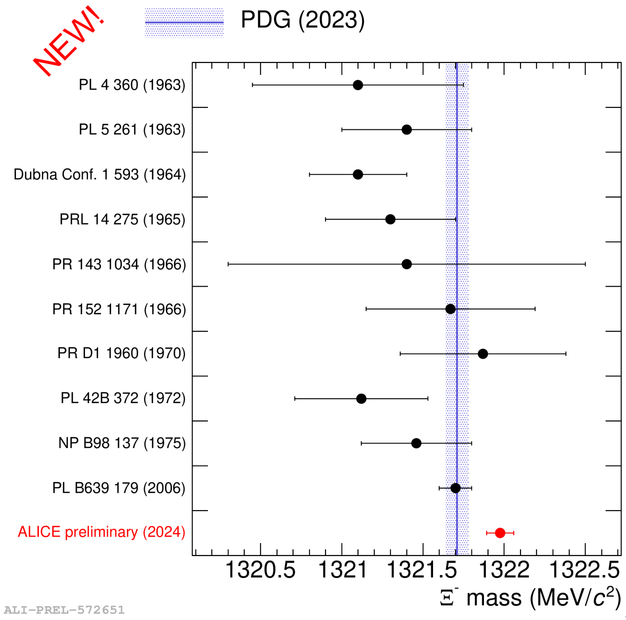
$$M(\overline{\Xi}^{+}) = 1321.73 \pm (\text{stat.})0.08 \pm (\text{syst.})0.05\ \text{MeV}/c^2$$

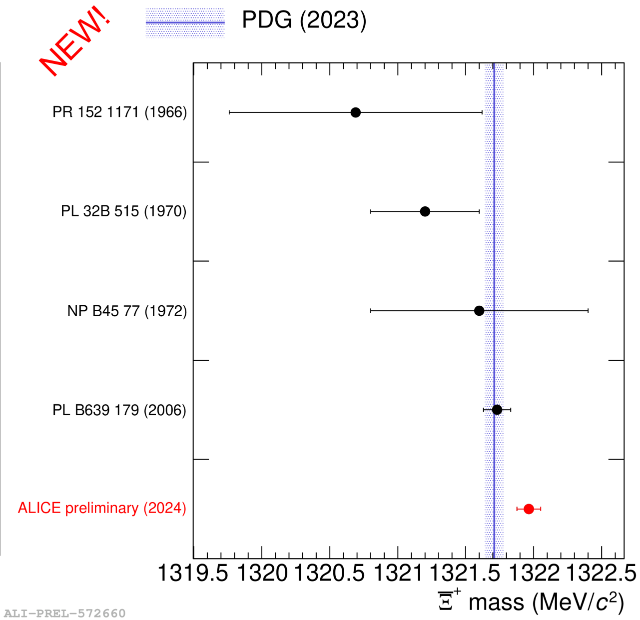
ALICE preliminary

$$M(\Xi^{-}) = 1321.975 \pm (\text{stat.})0.026 \pm (\text{syst.})0.078\ \text{MeV}/c^2$$

$$M(\overline{\Xi}^{+}) = 1321.964 \pm (\text{stat.})0.024 \pm (\text{syst.})0.083\ \text{MeV}/c^2$$

- Precision is **now dominated by** the **systematic uncertainties**
- **Improve previous mass measurements by 15% for Ξ**
- Ξ^{-} and c.c. masses are 2.5σ (~250 keV/c^2) larger than the PDG mass





Final results: $\Omega^{\pm}$ mass values

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$$M(\Omega^-) = 1673 \pm (\text{tot.})1\ \text{MeV}/c^2$$

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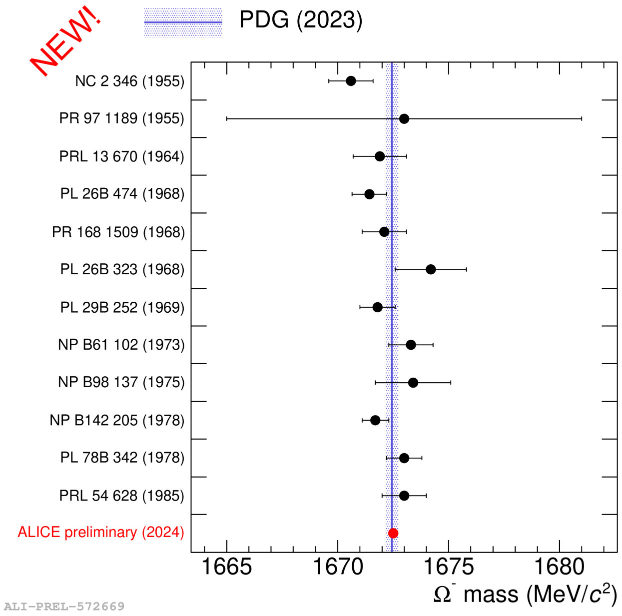
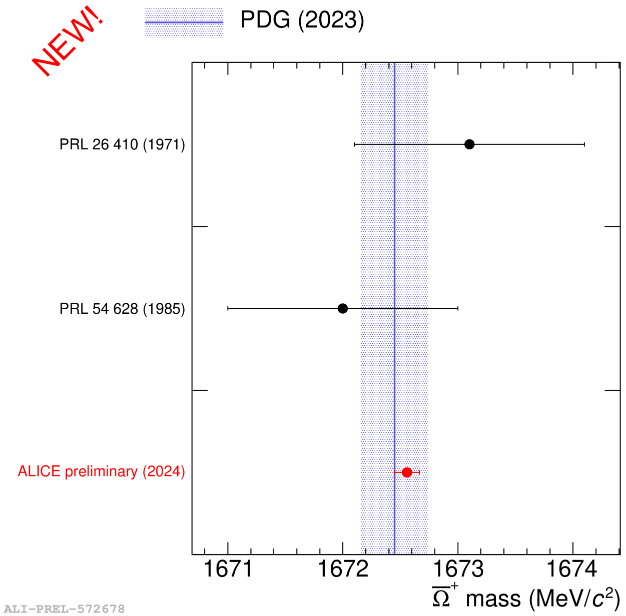
ALICE preliminary

$$M(\Omega^-) = 1672.511 \pm (\text{stat.})0.033 \pm (\text{syst.})0.102\ \text{MeV}/c^2$$

$$M(\overline{\Omega}^+) = 1672.555 \pm (\text{stat.})0.034 \pm (\text{syst.})0.102\ \text{MeV}/c^2$$

- Precision is **now dominated by** the **systematic uncertainties**
- **10-fold improvement on the Ω mass values**
- Mass is consistent with the PDG mass





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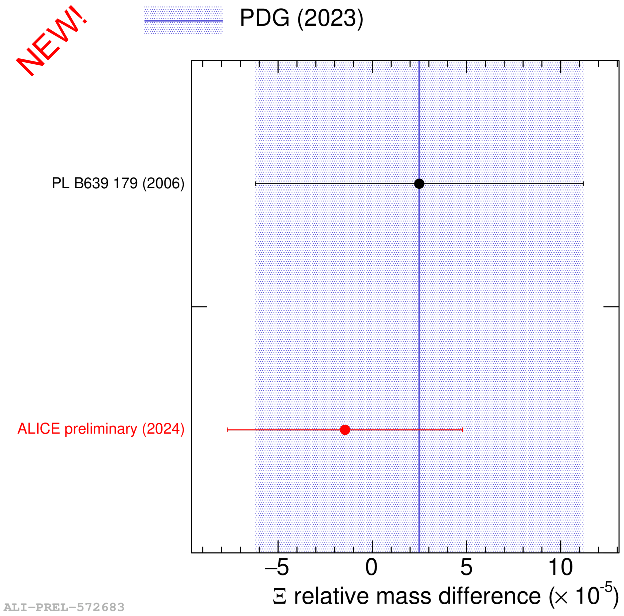
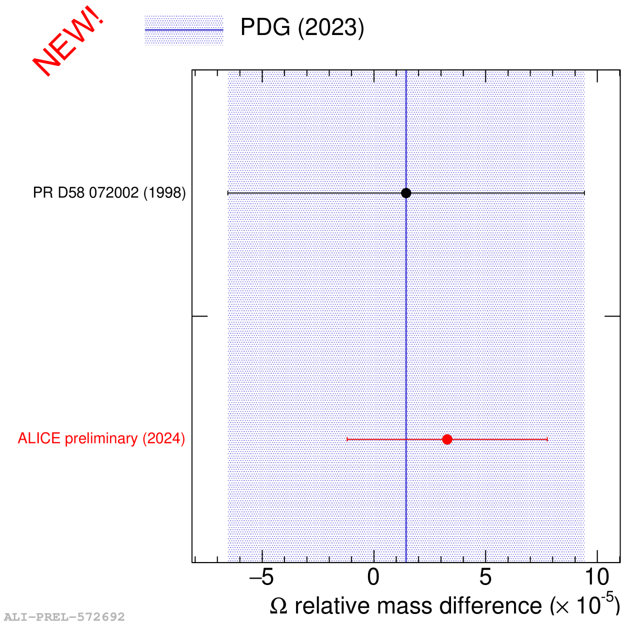
$$M(\overline{\Omega}^{+}) - M(\Omega^{-})/M_{\text{avg.}} = (3.28 \pm 4.47) \times 10^{-5}$$

- **Improve previous mass diff. measurements by 40%** for Ξ **and a factor 2** for Ω

- The mass difference values are compatible with 0

  → present results still consistent with CPT symmetry





Conclusion

High-precision mass and mass difference measurements of Ξ^-, $\overline{\Xi}^+$, Ω^-, $\overline{\Omega}^+$ have been shown

ALICE preliminary

$$M(\Xi^-) = 1321.975 \pm 0.083 \text{ MeV}/c^2$$
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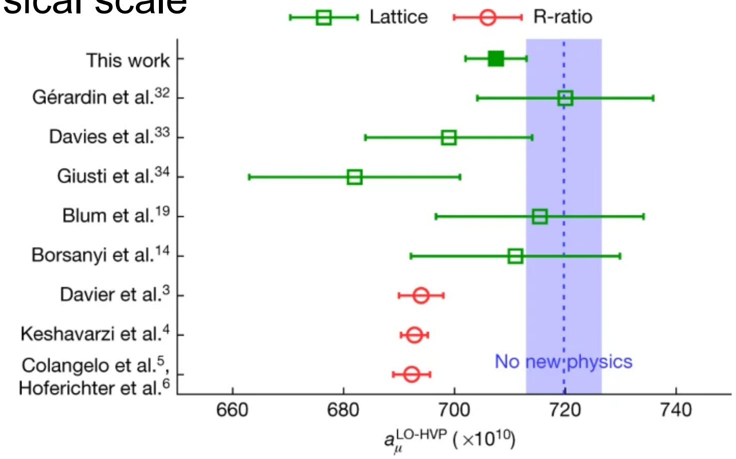
$$\mathrm{M}(\overline{\Omega}^+) - M(\Omega^-)/M_{\text{avg.}} = (3.28 \pm 4.47) \times 10^{-5}$$

- Agreement within 2.5σ of ALICE measurements with previous values
- **15% improvement** and **10-fold improvement** on the ***mass values*** of Ξ and Ω respectively
- **40% improvement** and **2-fold improvement** on the ***mass diff. values*** of Ξ and Ω respectively

→ **World most precise measurements**

Outlook: physics consequences

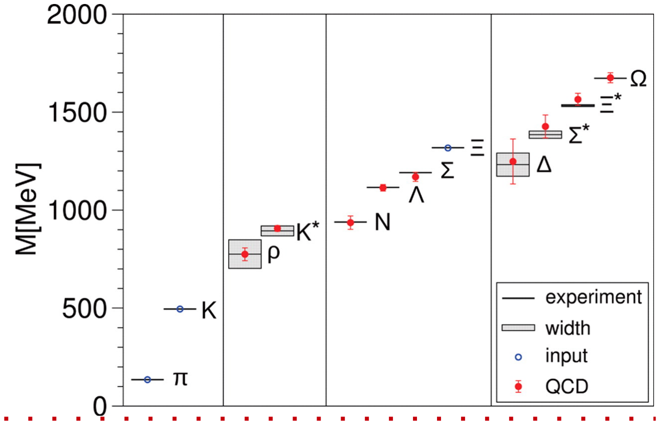
- Results are **consistent with CPT symmetry**, and further *constrained its validity*
- Lattice QCD (lQCD) uses the Ξ or Ω masses to set the physical scale



→ Improve input to lQCD calculations

For the anomalous magnetic moment of the muon, our Ω mass measurements lead *all uncertainties from the physical input* to be negligible

Borsanyi, Fodor, Guenther, et al.
Nature 593, 51–55 (2021)



→ Constrain lQCD predicted hadron mass spectrum

Predicted and measured hadron spectrum still need to be consistent if our updated and more precise Ξ mass values are used as anchor points

Dürr et al.
Science 322,1224-1227 (2008)

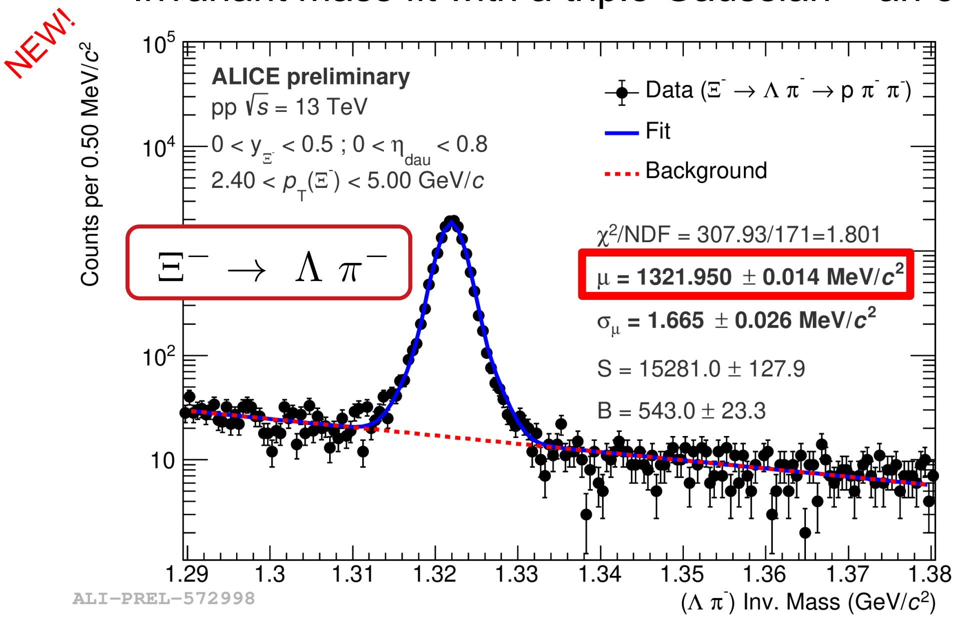
Thank you!

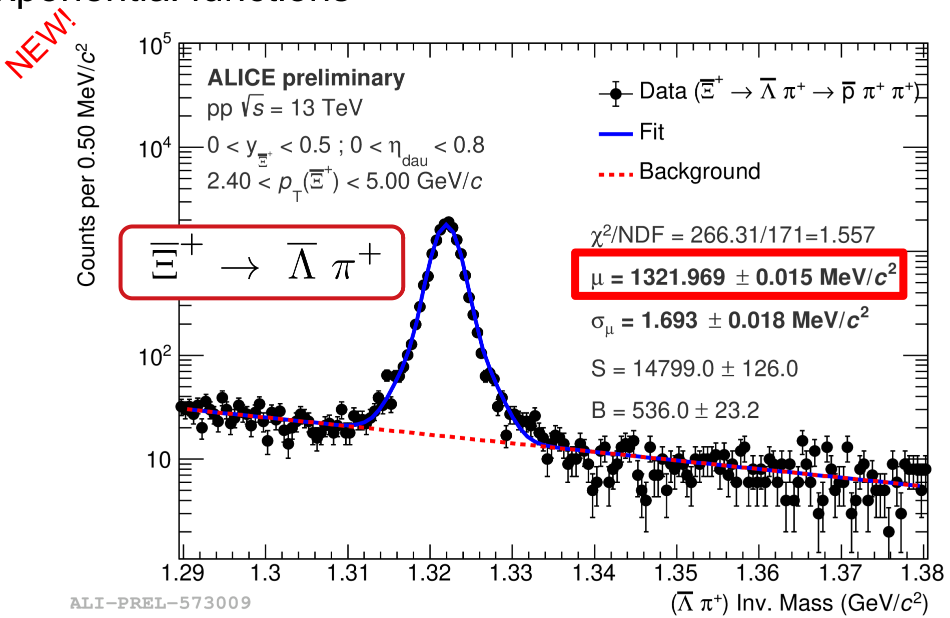
Backup slides

Mass extraction principle

Statistical identification of Ξ and Ω using an invariant mass analysis

→ Invariant mass fit with a triple Gaussian + an exponential functions





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  → good control over the background shape

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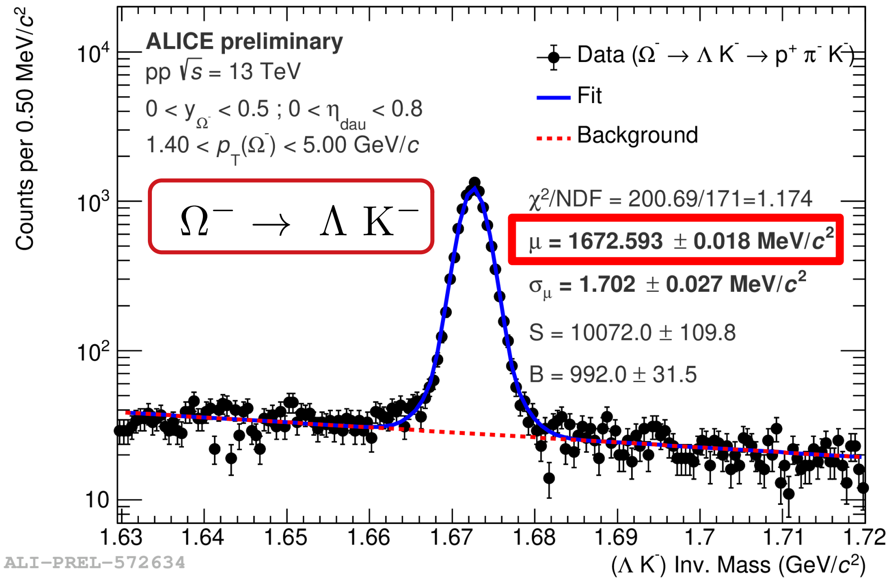
NEW!



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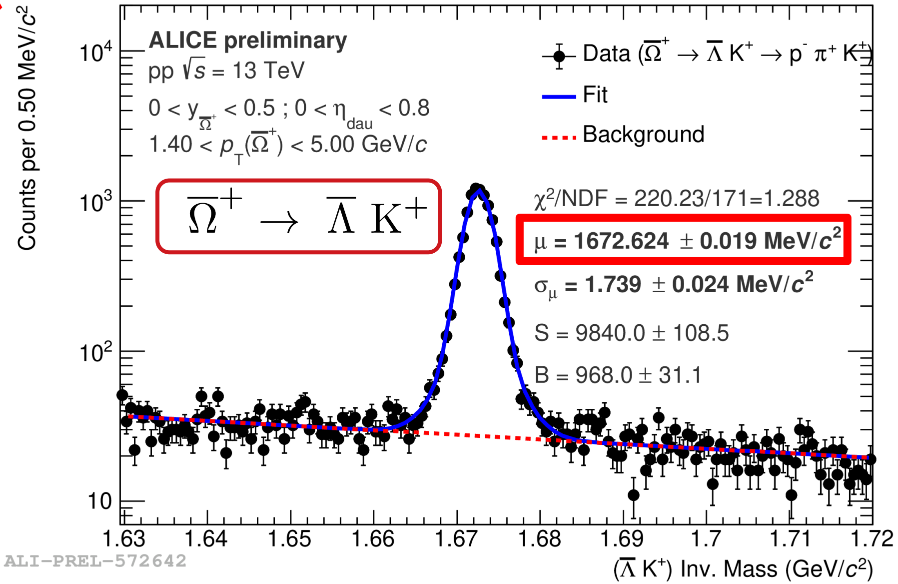

- **Extracted mass** (μ)

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- **High purity sample** (~ 90%)

  → good control over the background shape

Validation of the measurements

Validate the measurement using other strange hadrons as standard candles

$$\begin{cases} K^0_S \rightarrow \pi^+ \pi^- \\ \Lambda \rightarrow p^+ \pi^- \\ \overline{\Lambda} \rightarrow \overline{p}^- \pi^+ \end{cases}$$

- The Λ, $\overline{\Lambda}$ and K^0_S **masses are known very precisely** (σ ~ few keV/c^2)
- They can be reconstructed in their **characteristic V0 decay** topology, using topological selections

Decay	Measured mass (MeV/c^2)	PDG mass (MeV/c^2)
$K^0_S \rightarrow \pi^+\pi^-$	497.604 ± 0.257	497.611 ± 0.013
$\Lambda \rightarrow p\pi^-$	1115.775 ± 0.066	1115.683 ± 0.006
$\overline{\Lambda} \rightarrow \overline{p}\pi^+$	1115.775 ± 0.065	

The measured mass of Λ, $\overline{\Lambda}$ and K^0_S are in **good agreement with PDG values**

Decay	Measured mass difference ($\times 10^{-5}$)	PDG mass difference ($\times 10^{-5}$)
$\Lambda \rightarrow p\pi^-$	0.02 ± 2.33	0.1 ± 1.1

Measured mass difference between Λ and $\overline{\Lambda}$ is **compatible with 0**

Validation of the mass extraction

The measurement is repeated on ***simulated data*** (MC) to evaluate the global performance of the mass reconstruction

→ **compare reconstructed mass and injected mass** (= PDG mass).

Decay	$\Xi^- \to \Lambda\pi^-$	$\overline{\Xi}^+ \to \overline{\Lambda}\pi^+$	$\Omega^- \to \Lambda K^-$	$\overline{\Omega}^+ \to \overline{\Lambda}K^+$	
(In MeV/c^2)					
Mass in data	1321.974 ± 0.026	1321.988 ± 0.024	1672.616 ± 0.033	1672.658 ± 0.034	$M_{\mathrm{rec.}}^{\mathrm{data}}$
Mass in MC	1321.709 ± 0.040	1321.734 ± 0.042	1672.555 ± 0.021	1672.550 ± 0.019	$M_{\mathrm{rec.}}^{\mathrm{MC}}$
$M - M_{\mathrm{inj.}}$ in MC	-0.001 ± 0.040	0.024 ± 0.042	0.105 ± 0.021	0.100 ± 0.019	$\Delta M = M_{\mathrm{rec.}}^{\mathrm{MC}} - M_{\mathrm{inj.}}$
Corrected mass	1321.975 ± 0.026	1321.964 ± 0.024	1672.511 ± 0.033	1672.558 ± 0.034	$\text{Corrected mass} = M_{\mathrm{rec.}}^{\mathrm{data}} - \Delta M$

The measured mass **in simulation** does not agree with the *injected mass*

Possible origins:

- data reconstruction
- candidate selections
- mass extraction

Negligible for most measurements, but *here:*

→ **Offset in MC should be taken into account in the final results**

$$\Delta M = M_{\mathrm{rec.}}^{\mathrm{MC}} - M_{\mathrm{inj.}}$$

$$\text{Corrected mass} = M_{\mathrm{rec.}}^{\mathrm{data}} - \Delta M$$

Stability of the measurement

Check that the results are stable and do not fluctuate over time, space, pT,…

Different dependencies have been investigated:

- **Dependence on data taking periods**
- **Dependence on decay radius**
- **Dependence on azimuth angle**
- **Dependence on longitudinal momentum**
- **Dependence on opening angles**
- **Dependence on rapidity**
- **Dependence on multiplicity**

In order to ensure a stable measurement,

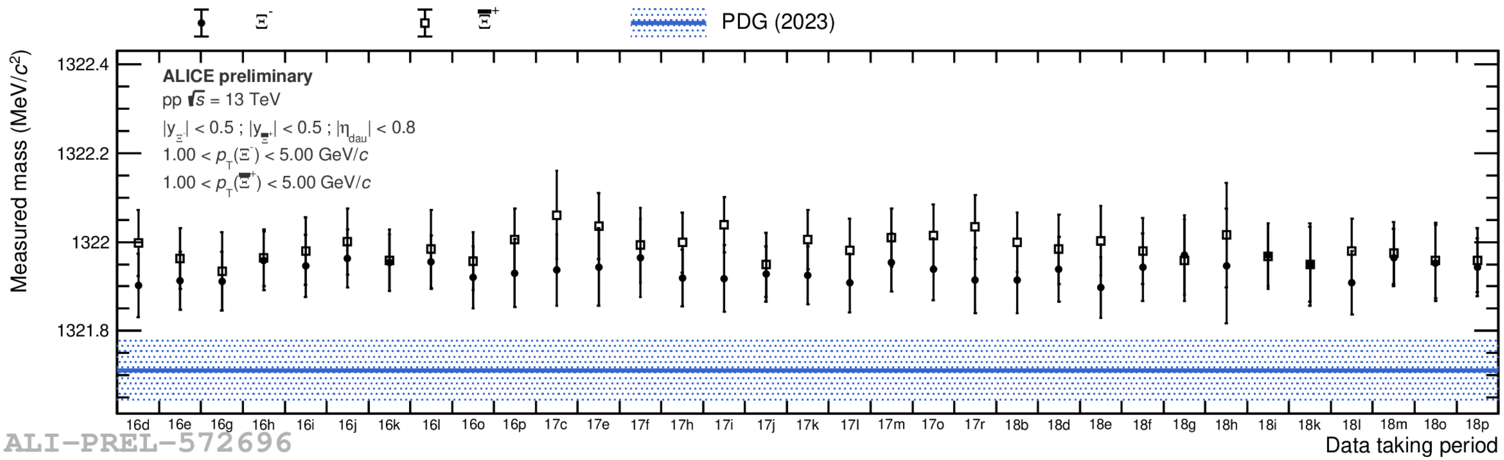
→ **focus on the region where a flat dependence is reached.**

Stability of the measurement with time

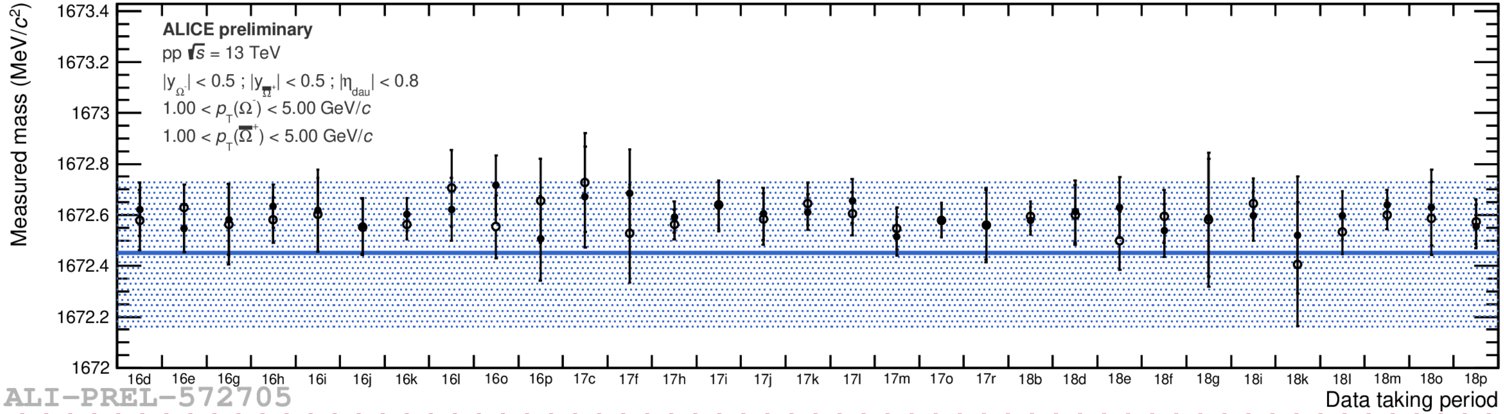
Different dependencies have been investigated:

- **Dependence on data taking periods**

NEW!



NEW!



All the measurements are **in good agreement**

Summary of the systematic uncertainties

- **Topological and track selections** → Repeat analysis with 20 000 different set of selections
- **Detector calibration** → Residual mis-calibration in azimuth between TPC sectors → **Focus solely on the A-side** (z > 0), **trend being lower**
- **Magnetic field** → Precision on the magnetic field map of 0.002 T (out of 0.5 T)
- **Detector material** → Description of the material budget in simulation

Dominant

- **p_T and opening angles biases** → p_T and op. angles selections to ensure stable measurements
- **Mass extraction procedure** → Fit functions, fitting range, invariant mass binning
- **Pile-up treatment** → Impact of out-of-bunch pile-up rejection
- **Precision on the tabulated masses** → Finite precision on the tabulated mass of the decay daughters

$$M(\pi^{\pm}) = 139.57039 \pm \mathbf{0.00018}\ \mathrm{MeV}/c^2$$
$$M(\mathrm{p}^{\pm}) = 938.27208816 \pm \mathbf{0.00000029}\ \mathrm{MeV}/c^2$$
$$M(\mathrm{K}^{\pm}) = 497.677 \pm \mathbf{0.016}\ \mathrm{MeV}/c^2$$
$$M(\Lambda) = 1115.683 \pm \mathbf{0.006}\ \mathrm{MeV}/c^2$$

- **Correction on the extracted mass** → Precision on mass offset determination in simulation → **related to the size of the MC sample**

Summary of the systematic uncertainties

Sources	Systematic uncertainties On the measured mass (MeV/c^2)			
	Ξ^-	$\overline{\Xi}^+$	Ω^-	$\overline{\Omega}^+$
Topological selections	0.024	0.028	0.027	0.034
Momentum calibration	0.029	0.017	0.084	0.081
p_T and op. angle selections	0.016	0.028	0.008	0.010
Magnetic field	0.023	0.028	0.026	0.027
Material budget	0.022	0.022	0.031	0.031
Fitting function	0.009	0.009	0.007	0.007
Fitting range	0.001	0.001	0.001	0.001
Binning	0.001	0.001	0.001	0.001
Out-of-bunch pile-up rejection	0.006	0.006	0.004	0.003
Precision on the PDG mass	0.011	0.011	0.018	0.018
MC mass offset	0.055	0.058	0.021	0.019
Total	**0.078**	**0.083**	**0.102**	**0.102**

Repeat analysis with 20 000 different set of selections

Residual mis-calibration between TPC sectors

Repeat analysis with tight and loose selections

Precision on the magnetic field map of 2 Gauss

Description of the material budget in simulation

Triple Gaussian+expo

Triple Gaussian+pol1

Bukin+expo

Bukin+pol1

Repeat analysis with 20 000 different fitting ranges

Binning: 1, 0.75, 0.5, 0.25 MeV/c²

Impact of the out-of-bunch pile-up

Finite precision on the decay daughter mass

$M(\pi^\pm) = 139.57039 \pm \mathbf{0.00018}$ MeV/c^2

$M(\mathrm{p}^\pm) = 938.27208816 \pm \mathbf{0.00000029}$ MeV/c^2

$M(\mathrm{K}^\pm) = 497.677 \pm \mathbf{0.016}$ MeV/c^2

$M(\Lambda) = 1115.683 \pm \mathbf{0.006}$ MeV/c^2

Precision on mass offset determination in simulation

→ **related to the size of the MC sample**

Total systematic uncertainty

= quadratic sum of all contributions