CPT Symmetry Test

Mass measurements of the Ξ(dss) and Ω(sss) with pp data collected with the ALICE detector during the LHC run II

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I) Motivations

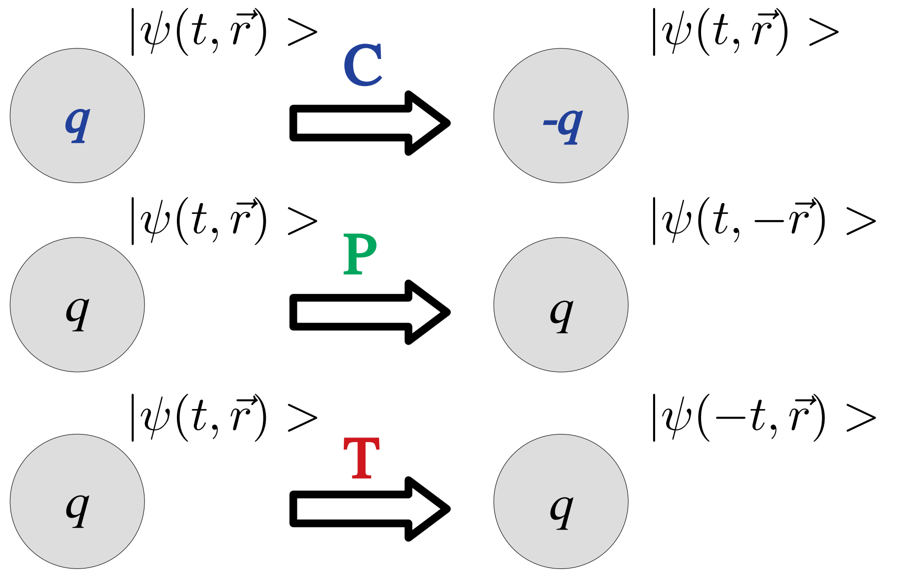
II) Analysis based on real data

III) Analysis based on MC data

IV) Current status

Motivations

- The Standard Model was initially built upon the invariance of the discrete symmetries of
  - Charge conjugation (C),
  - Parity transformation (P),
  - Time reversal (T),
  - And the combined **CPT-symmetry**



- Strong and electromagnetic interactions are invariant under these transformations

  BUT the weak interaction violates CP-symmetry → T is violated

Motivations

- Only the combined CPT-symmetry is conserved

  → 2 consequences :

  1) **Particles and antiparticles share the same fundamental properties**
     (except for the sign of the quantum numbers)
     Ex : Lifetime, mass,...

  2) **Particles and antiparticles are created in pairs**
     → contradiction with astronomical observations (matter-antimatter asymmetry)

- CP violation is too small to account for the matter-antimatter asymmetry

  → need additionnal sources of symmetry violation including CPT-symmetry violation

- It is decisive to **test CPT invariance, especially when a precision gain is possible**

Motivations

- **Previous mass measurements suffer of low statistics**

Ξ^- MASS

The fit uses the Ξ^-, $\overline{\Xi}^+$, and Ξ^0 masses and the $\Xi^- - \overline{\Xi}^+$ mass difference. It assumes that t

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	
1321.71 ± 0.07	**OUR FIT**		
$1321.70 \pm 0.08 \pm 0.05$	2478 ± 68	ABDALLAH	2006E

$\overline{\Xi}^+$ MASS

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VALUE (MeV)	*EVTS*	*DOCUMENT ID*	
1321.71 ± 0.07	**OUR FIT**		
$1321.73 \pm 0.08 \pm 0.05$	2256 ± 63	ABDALLAH	2006E

Ω^- MASS

The fit assumes the Ω^- and $\overline{\Omega}^+$ masses are the same, and averages them tc

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	
1672.45 ± 0.29	**OUR FIT**		
1672.43 ± 0.32	**OUR AVERAGE**		
1673 ± 1	100	HARTOUNI	1985
1673.0 ± 0.8	41	BAUBILLIER	1978
1671.7 ± 0.6	27	HEMINGWAY	1978

$\overline{\Omega}^+$ MASS

The fit assumes the Ω^- and $\overline{\Omega}^+$ masses are the same, and averages them toget

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	
1672.45 ± 0.29	**OUR FIT**		
1672.5 ± 0.7	**OUR AVERAGE**		
1672 ± 1	72	HARTOUNI	1985
1673.1 ± 1.0	1	FIRESTONE	1971B

$\rightarrow$ coming from the difficulty to produce as much matter as antimatter

With the **LHC**, we have an **excellent source of matter and antimatter !**

- Goal : Using the **ALICE detector**
  - Provide **new mass measurements of the Ξ and Ω**
  - And compute their mass difference to **test CPT invariance**

ALICE

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III) Analysis based on MC data

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The ALICE detector

ALICE is composed of 19 detection systems

Inner Tracking System (ITS), six layers of silicon detector (SPD, SDD, SSD)

→ Reconstruct primary and secondary vertices

Time Projection Chamber (TPC), gaseous detector (90 m3)

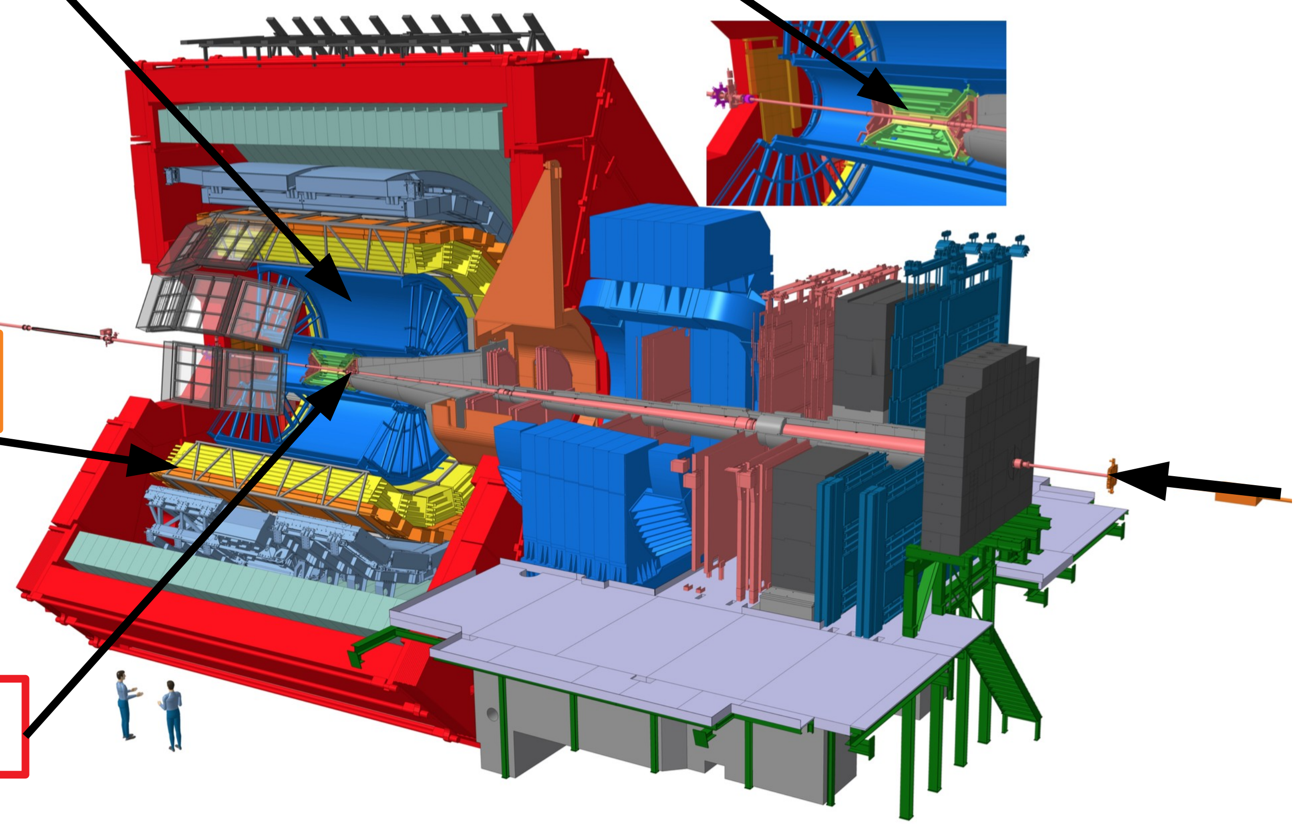
→ Reconstruct tracks + PID

Time Of Flight (TOF), gaseous detector

→ PID + OOB pile up rejection

VZERO, scintillator detector

→ Provide trigger info



The dataset

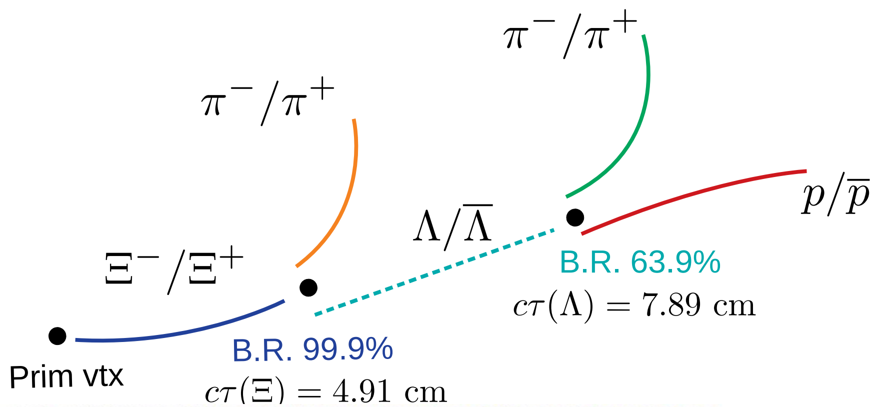
Objective : measure the mass of the Ξ and Ω, using LHC run II data

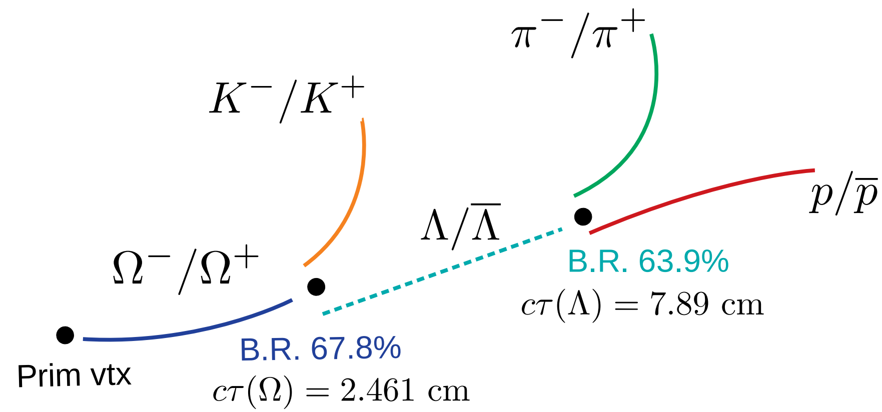
- Data :
  - ~ 2.2×10^9 pp collisions at $\sqrt{s} = 13$ TeV (LHC16 + LHC17 + LHC18)
  - Represents ~140×10^6 cascade candidates
- Event Selection :
  - ESDs,
  - Revertexing,
  - kINT7 and/or kHighV0M (MB + high multiplicity),
  - Remove in bunch (MV) and out-of-bunch pile up (OOB)
- Analysis task : https://github.com/alisw/AliPhysics/blob/master/PWGLF/STRANGENESS/Cascades/Run2/AliAnalysisTaskStrangenessVsMultiplicityRun2

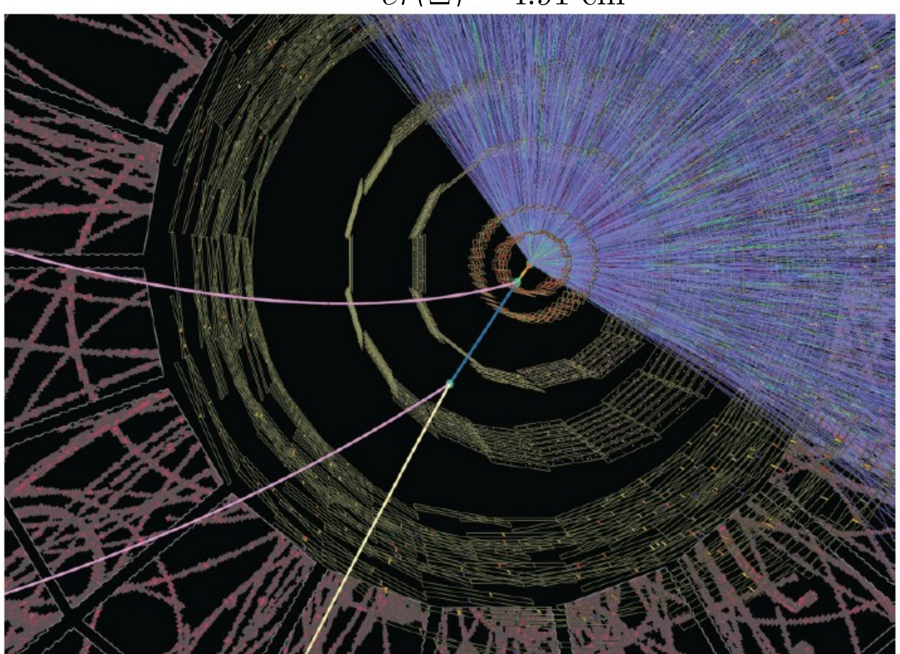
Analysis details

- Ξ and Ω will be studied in the following decay channel :

$$\begin{cases} \Xi^- \rightarrow \Lambda\,\pi^- \rightarrow p\,\pi^-\,\pi^- \\ \overline{\Xi}^+ \rightarrow \overline{\Lambda}\,\pi^+ \rightarrow \overline{p}\,\pi^+\,\pi^+ \end{cases} \qquad \begin{cases} \Omega^- \rightarrow \Lambda\,K^- \rightarrow p\,\pi^-\,K^- \\ \overline{\Omega}^+ \rightarrow \overline{\Lambda}\,K^+ \rightarrow \overline{p}\,\pi^+\,K^+ \end{cases}$$







- Ξ and Ω are distinguished from the combinatorial background using topological selections

Ξ selections

- Ξ are reconstructed using topological selections

Ξ-(Ξ+)	Cut value
|y|	< 0.5
pT	[1 ; 5] GeV/c

- Cascade selections

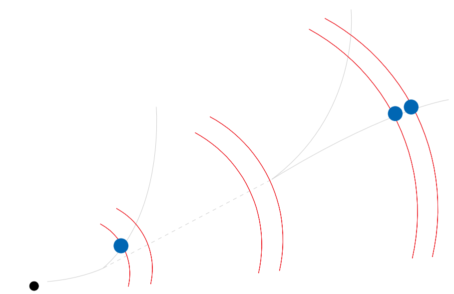
DCA Bach To PV	> 0.04 cm
DCA Casc daughters	< 1.3 cm
Casc Radius	> 0.5 cm
Casc Cos PA	> 0.97
Proper Lifetime	> 3 x 4.91 cm
Wrong PA	> 0.04

- Track selections :
  - $|\eta| < 0.8$
  - TPC refit
  - TPC Nbr Crossed Rows > 70
  - TPC PID Nsigma < 3

- V0 selections

DCA V0 to PV	> 0.04 cm
DCA Pos to PV	> 0.03 (0.04) cm
DCA Neg to PV	> 0.04 (0.03) cm
DCA V0 daughters	< 1.5 cm
V0 Radius	> 1.1 cm
V0 Cos PA	> 0.97
|V0 Mass – Λ Mass|	$< 0.008\ \mathrm{GeV}/c^2$

- ITS hit requirements
  - Bachelor : SPD 0 OR 1
  - Proton : SSD 4 OR 5



Ω selections

- Ω are reconstructed using topological selections

Ω-(Ω+)	Cut value
|y|	< 0.5
pT	[1 ; 5] GeV/c

- Cascade selections

DCA Bach To PV	> 0.04 cm
DCA Casc daughters	< 1.3 cm
Casc Radius	> 0.5 cm
Casc Cos PA	> 0.97
|Casc Mass - Ξ Mass|	> 0.008 GeV/c2
Proper Lifetime	> 3 x 2.46 cm
Wrong PA	> 0.04

- Track selections :
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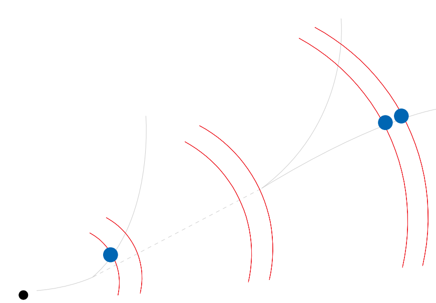
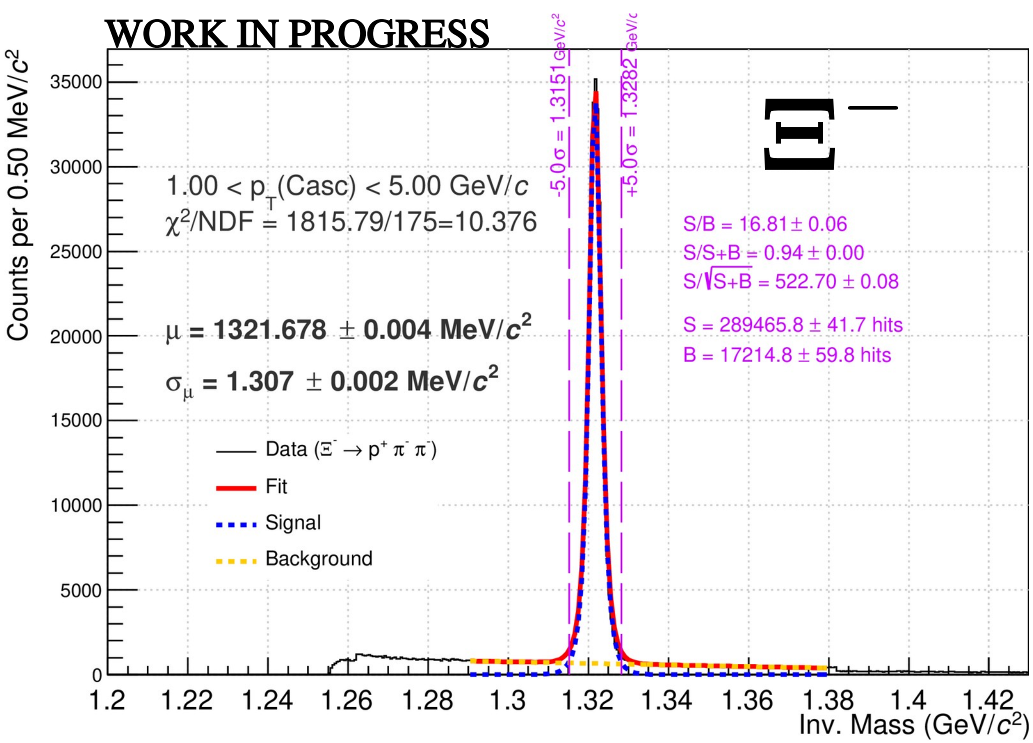
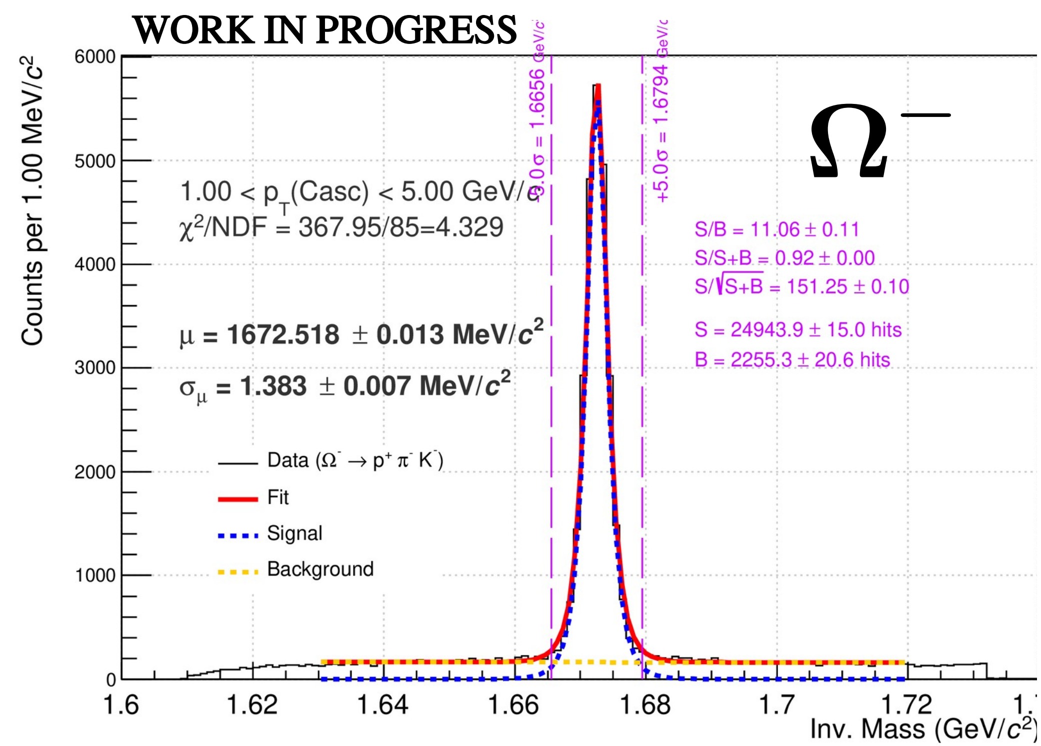


Mass extraction

- Background substraction for inv. mass analysis :
  - Fit with a *modified* Gaussian + linear function

$$\text{Modified Gaussian} = A \cdot \exp\left(-0.5u^{1+\frac{1}{1+0.5u}}\right) \quad ; \quad u = \left|\frac{x-\mu}{\sigma}\right|$$

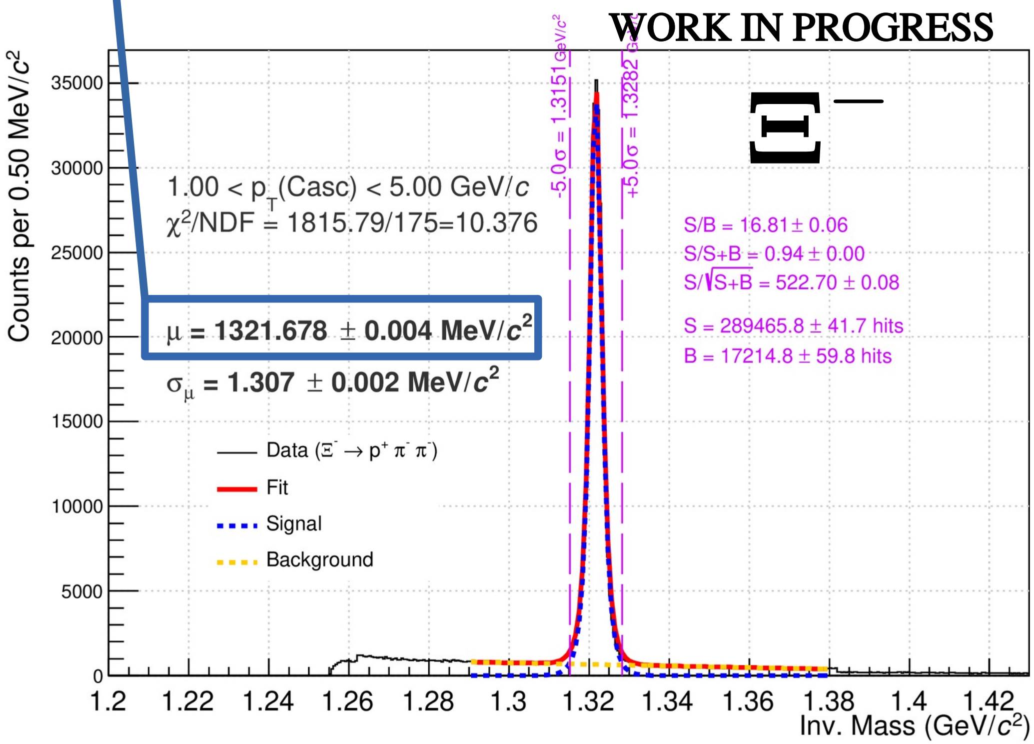




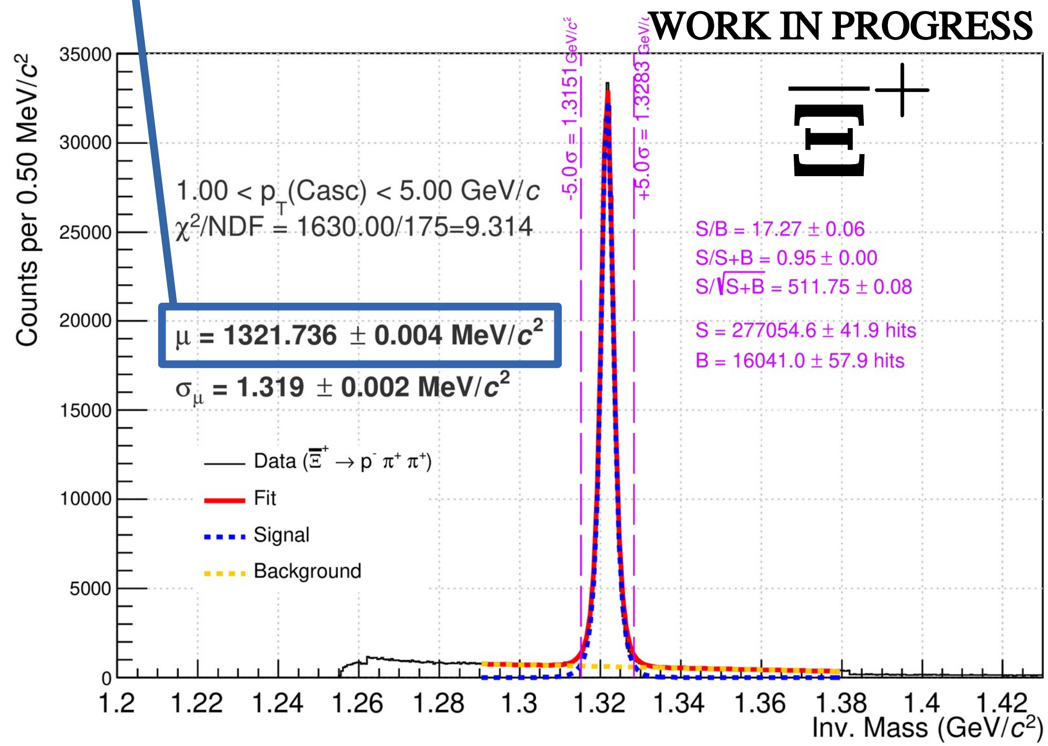
First Ξ mass measurements

$$\mathbf{M_{PDG}(\Xi) = 1321.71\varnothing \pm 0.07\varnothing\ MeV/c^2}$$

$$\mu = \mathbf{1321.678 \pm (stat.)0.004\ MeV/c^2}$$



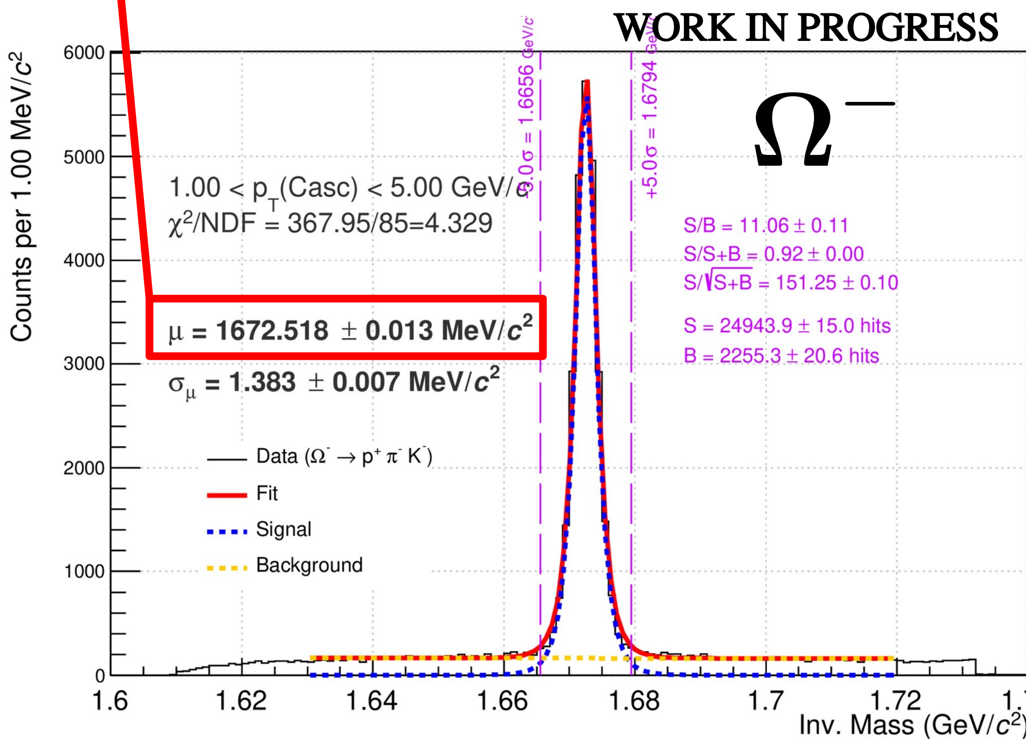
$$\mu = \mathbf{1321.736 \pm (stat.)0.004\ MeV/c^2}$$



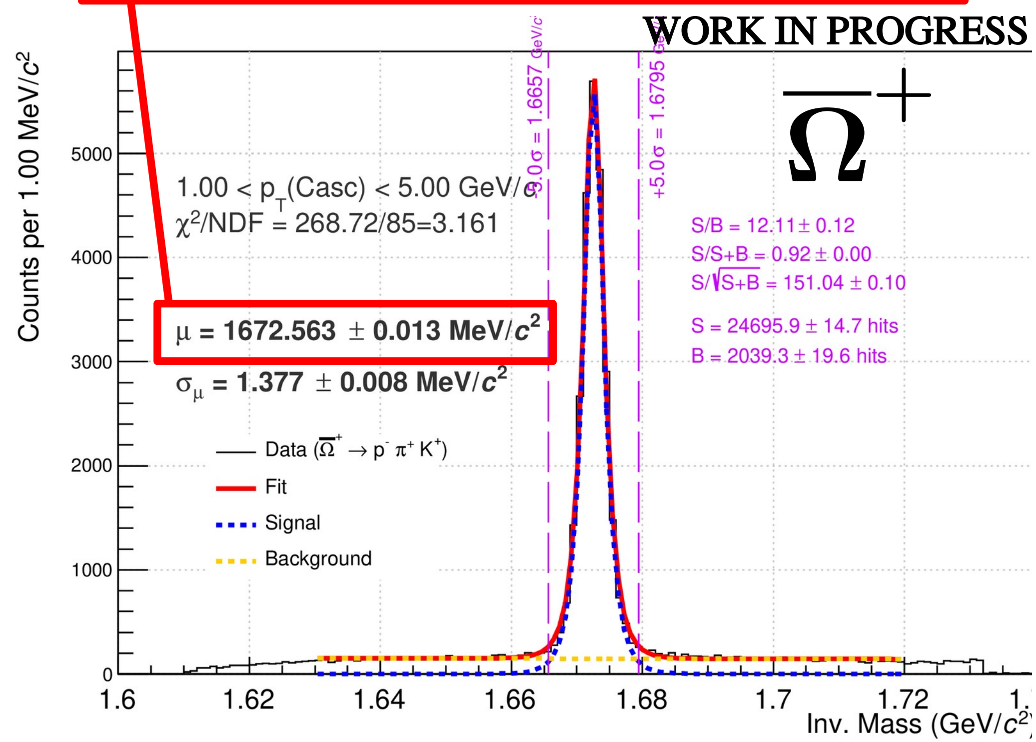
First Ω mass measurements

$$\mathbf{M_{PDG}(\Omega) = 1672.45\varnothing \pm 0.29\varnothing\ MeV/c^2}$$

$\mu = \mathbf{1672.518 \pm (stat.)0.013\ MeV/c^2}$



$\mu = \mathbf{1672.563 \pm (stat.)0.013\ MeV/c^2}$



Systematic effects

- **Main source of systematic uncertainties :**
  - Topological selections
  - TPC selections
- **Quantification of systematic uncertainties :**
  - Vary these selections (14 selections)
  - Observe how the extracted mass and the error are distributed over 20 000 different set of selections

Variables	Default values	Range (Signal variation)
DCA Bach To PV	> 0.04 cm	[0.05–0.2] (19%)
DCA Casc daughters	< 1.3 cm	[0.4-1.2] (22%)
Casc Radius	> 0.5 cm	[0.5–1.6] (21%)
Casc Cos PA	> 0.97	[0.97-0.999] (55%)
Proper Lifetime	> 3 x 2.46 cm	[2.5-5] (27%)
DCA V0 to PV	> 0.04 cm	[0.06-0.2] (18%)
DCA Pos to PV	> 0.03 (0.04) cm	[0.04-0.5] (28%)
DCA Neg to PV	> 0.04 (0.03) cm	[0.04-0.5](29%)
DCA V0 daughters	< 1.5 cm	[0.4-1.2] (32%)
V0 Radius	> 1.1 cm	[1.2-5] (17%)
V0 Cos PA	> 0.97	[0.97-0.998] (50%)
$\lvert$V0 Mass – Λ Mass$\rvert$	< 0.008 GeV/c^2	[0.002-0.007] (33%)

Ω^-

TPC Min Nbr Cr Rows	> 70	[90-110] (17%)
TPC PID	$< 3\sigma$	[1-3] (15%)

Systematic study strategy

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- For each set of selections i, we extract :

    - The measured mass μ_i
      → store in an histogram ➡

$$\begin{cases} \text{Mass} = \text{Mean} = \bar{\mu} \\ \sigma_{\text{syst}} = \text{RMS} \end{cases}$$

    - The error on the mass σ_i
      → store in an histogram ➡

$$\sigma_{\text{stat}} = \bar{\sigma}$$

ALICE

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- The new set of selections (14 selections) is then used to obtain the inv. mass distribution of the particle of interest (Ξ, Ω)
- This procedure is repeated 20 000 times
- For each set of selections i, we extract :
  - The measured mass difference $\Delta\mu_i/\mu_i^{\text{part}} = (\mu_i^{\overline{\text{part}}} - \mu_i^{\text{part}})/\mu_i^{\text{part}}$

    → store in an histogram ➡

$$\begin{cases} \frac{\Delta\text{Mass}}{\text{Mass}} = \text{Mean} = \overline{\frac{\Delta\mu_i}{\mu_i^{\text{part.}}}} \\ \sigma_{\text{syst}} = \text{RMS} \end{cases}$$

  - The error on the mass difference $\sigma_{(\mu_i^{\overline{\text{part}}} - \mu_i^{\text{part}})/\mu_i^{\text{part}}}$

    → store in an histogram ➡ $\sigma_{\text{stat}} = \overline{\sigma}_{(\mu_i^{\overline{\text{part}}} - \mu_i^{\text{part}})/\mu_i^{\text{part}}}$

Systematic study results

- Mass values : **WORK IN PROGRESS**

Particle	Mass (MeV/c^2)	Tot Uncert. (MeV/c^2)	Stat. Uncert. (MeV/c^2)	Syst. Uncert. (MeV/c^2)	PDG Mass (MeV/c^2)	PDG Tot Uncert. (MeV/c^2)
Ξ	1321.774	**0.013**	0.005	0.012	1321.71	**0.07**
Ω	1672.596	**0.022**	0.015	0.017	1672.45	**0.29**

  - Improve current PDG mass values by a factor ~5.5 for Ξ and ~13 for Ω

- Test CPT-invariance : mass difference values **WORK IN PROGRESS**

Particle	Mass diff. ($\times 10^{-5}$)	Tot Uncert. ($\times 10^{-5}$)	Stat. Uncert. ($\times 10^{-5}$)	Syst. Uncert. ($\times 10^{-5}$)	PDG Mass diff($\times 10^{-5}$)	PDG Tot Uncert ($\times 10^{-5}$)
Ξ	4.35	**1.01**	0.71	0.72	2.5	**8.7**
Ω	-0.44	**2.20**	1.75	1.32	1.44	**7.98**

  - Improve current PDG mass diff. values by a factor ~9 for Ξ and 3.7 for Ω
  - Mass difference ~ 0 : CPT still valid

Check : compare with PDG mass

- Mass values : **WORK IN PROGRESS**

Particle	Mass (MeV/c^2)	Tot Uncert. (MeV/c^2)	Stat. Uncert. (MeV/c^2)	Syst. Uncert. (MeV/c^2)	PDG Mass (MeV/c^2)	PDG Tot Uncert. (MeV/c^2)
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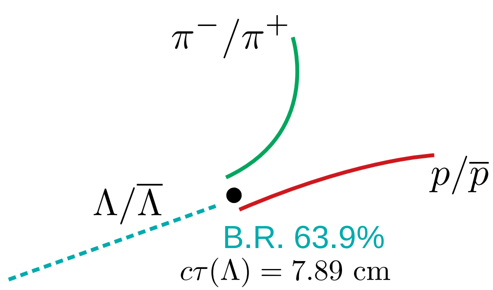
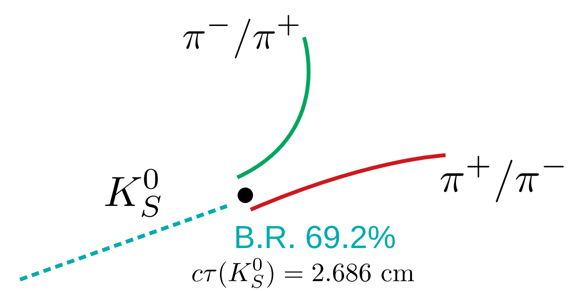
- Gap between our mass values and the PDG ones **(almost 1σ for the Ξ)**
- To check that the analysis is working properly :
  - Take a particle whose PDG mass is evaluated very precisely (σ ~ few keV/c^2),
  - Check that the mass extracted by the analysis corresponds to the PDG mass

- Here, this check will be done using Λ and K0s

$$m_{\mathrm{PDG}}(\Lambda) = 1115.683 \pm 0.006 \ \mathrm{MeV}/c^2 \qquad m_{\mathrm{PDG}}(K^0_S) = 497.611 \pm 0.013 \ \mathrm{MeV}/c^2$$





V0 candidate selections

- Candidates are **Λ, anti-Λ and K0s**

- V0 selections

Variables	Cut
Rapidity	< 0.5
Pt	[1; 5] GeV/c

- Track Selections

TPC refit	kTRUE
TPC PID N Sigma	< 3 σ
Nbr crossed rows	> 70
η	< 0.8

- Topological selections

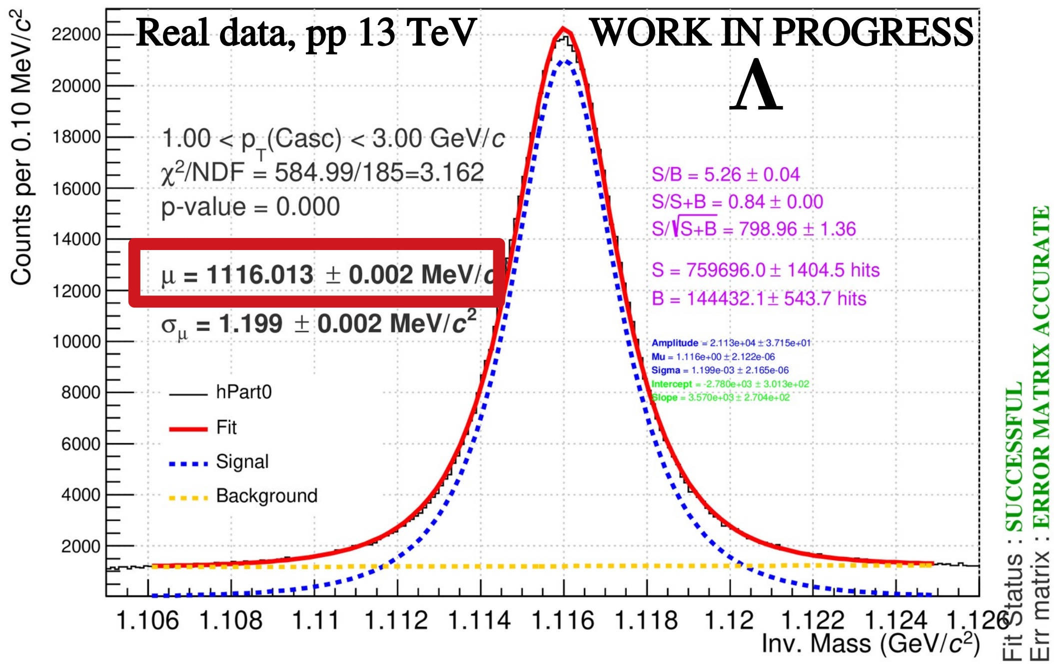
Variables	Cut Λ (K0s)
DCA V0 daughters	< 1.5 (1.0)
V0 Radius	> 0.5 cm
V0 Cos PA	> 0.97
V0 Lifetime	< 3x7.89 (3x2.686) cm
DCA V0 to PV	< 1 (0.06) cm
DCA Pos to PV	> 0.06 cm
DCA Neg to PV	> 0.06 cm

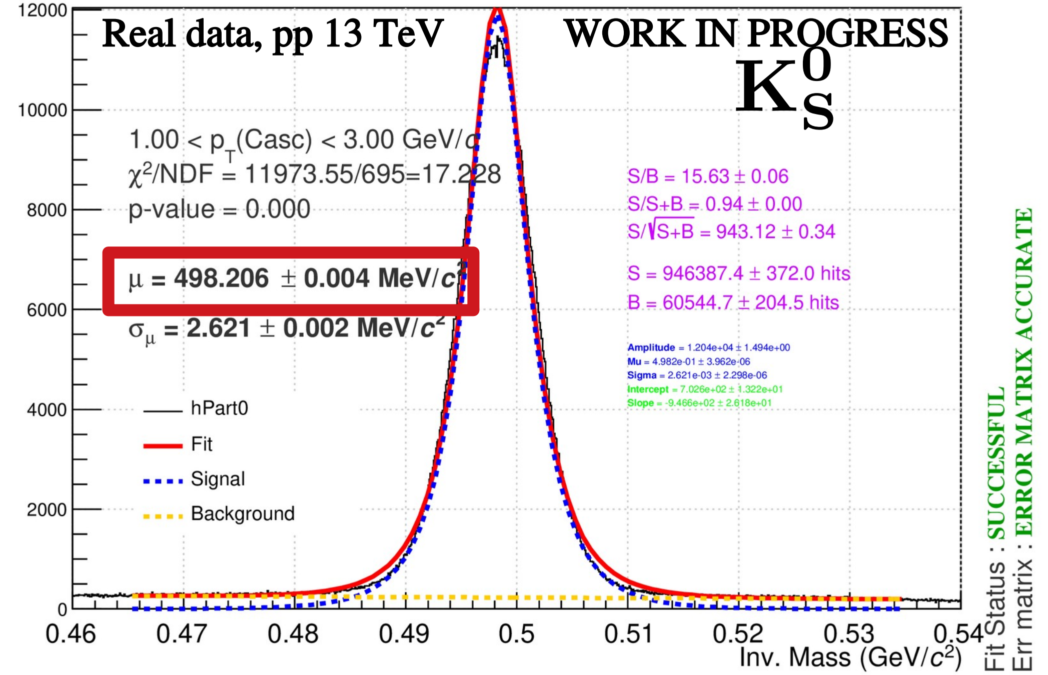
ALICE

Mass shift

- Same procedure as for the Ξ and Ω
- The extracted mass is above the PDG mass by
  - ~ 300 keV/c² for Λ
  - ~ 600 keV/c² for K0s

$$\mathbf{m}_{\mathrm{PDG}}(\boldsymbol{\Lambda}) = \mathbf{1115.683 \pm 0.006}\ \mathrm{MeV}/\mathbf{c^2} \qquad \mathbf{m}_{\mathrm{PDG}}(\mathbf{K^0_S}) = \mathbf{497.611 \pm 0.013}\ \mathrm{MeV}/\mathbf{c^2}$$





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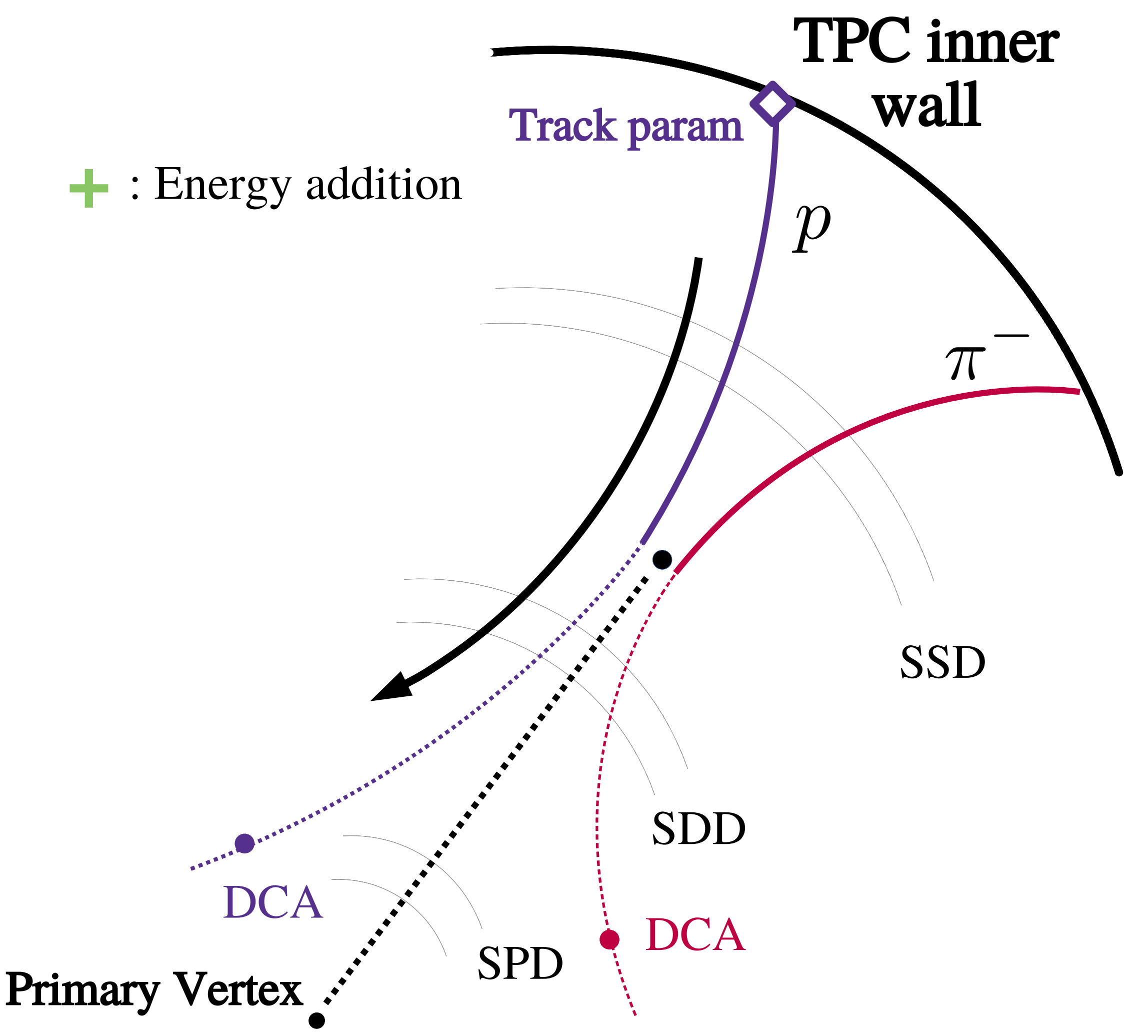
Main cause of the mass shift

- Once all tracks are reconstructed, they are **propagated to their point of closest approach to the primary vertex** (= hypothesis that all the tracks are primaries)
- In the propagation, corrections on the energy loss (based on PID used for tracking) are applied :



- **Inward propagation** (TPC→PV) :
  - → add energy
- Outward propagation (PV→TPC):
  - → subtract energy

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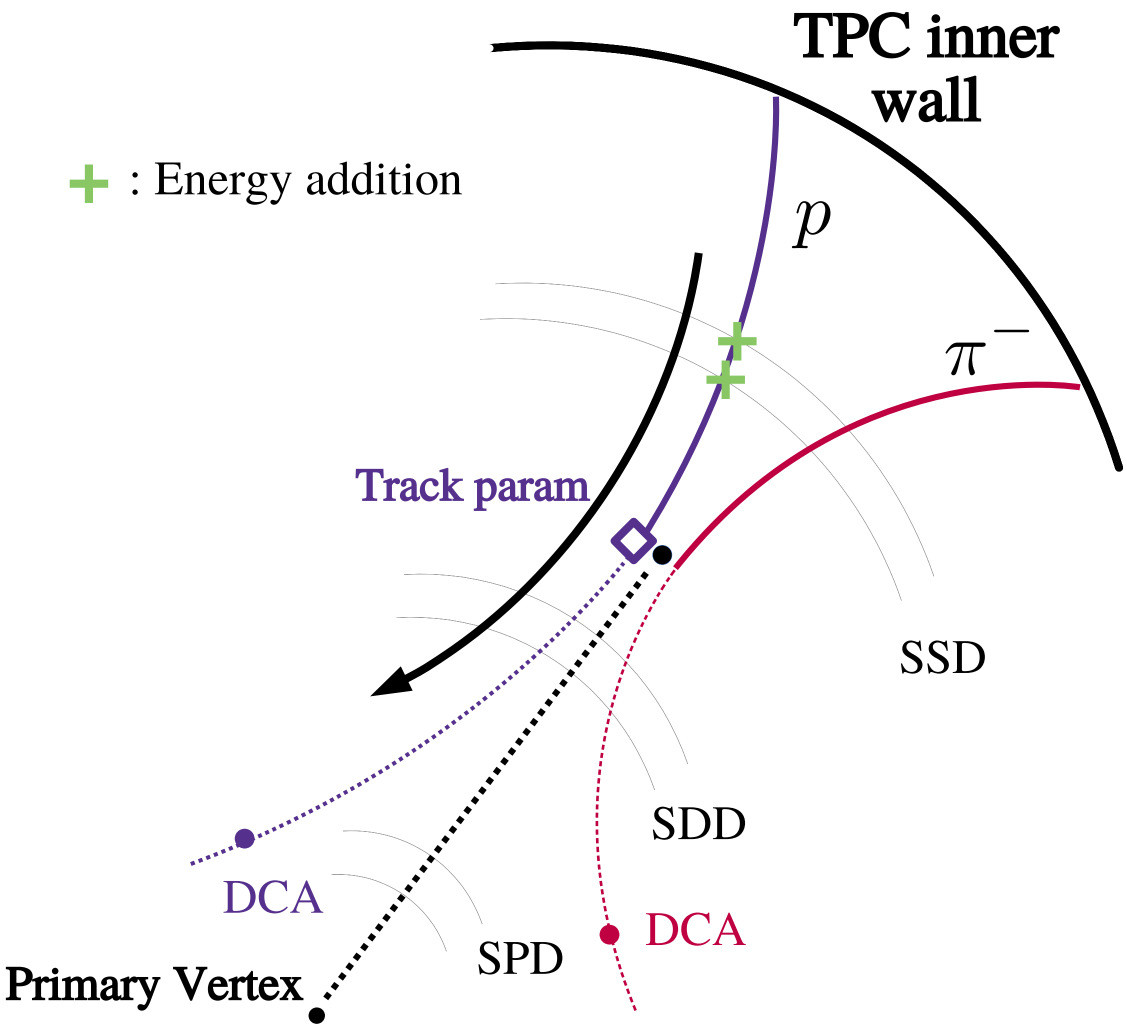

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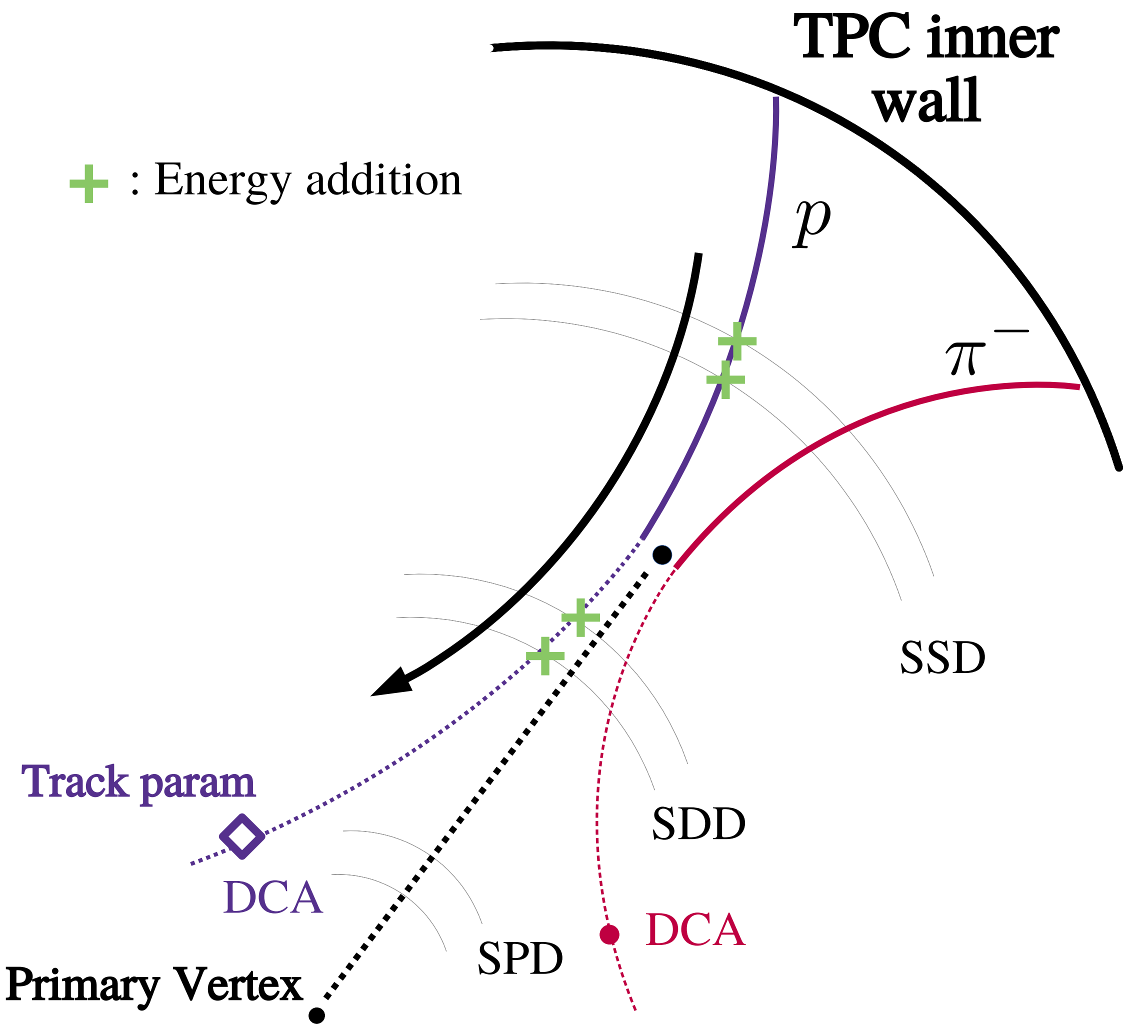

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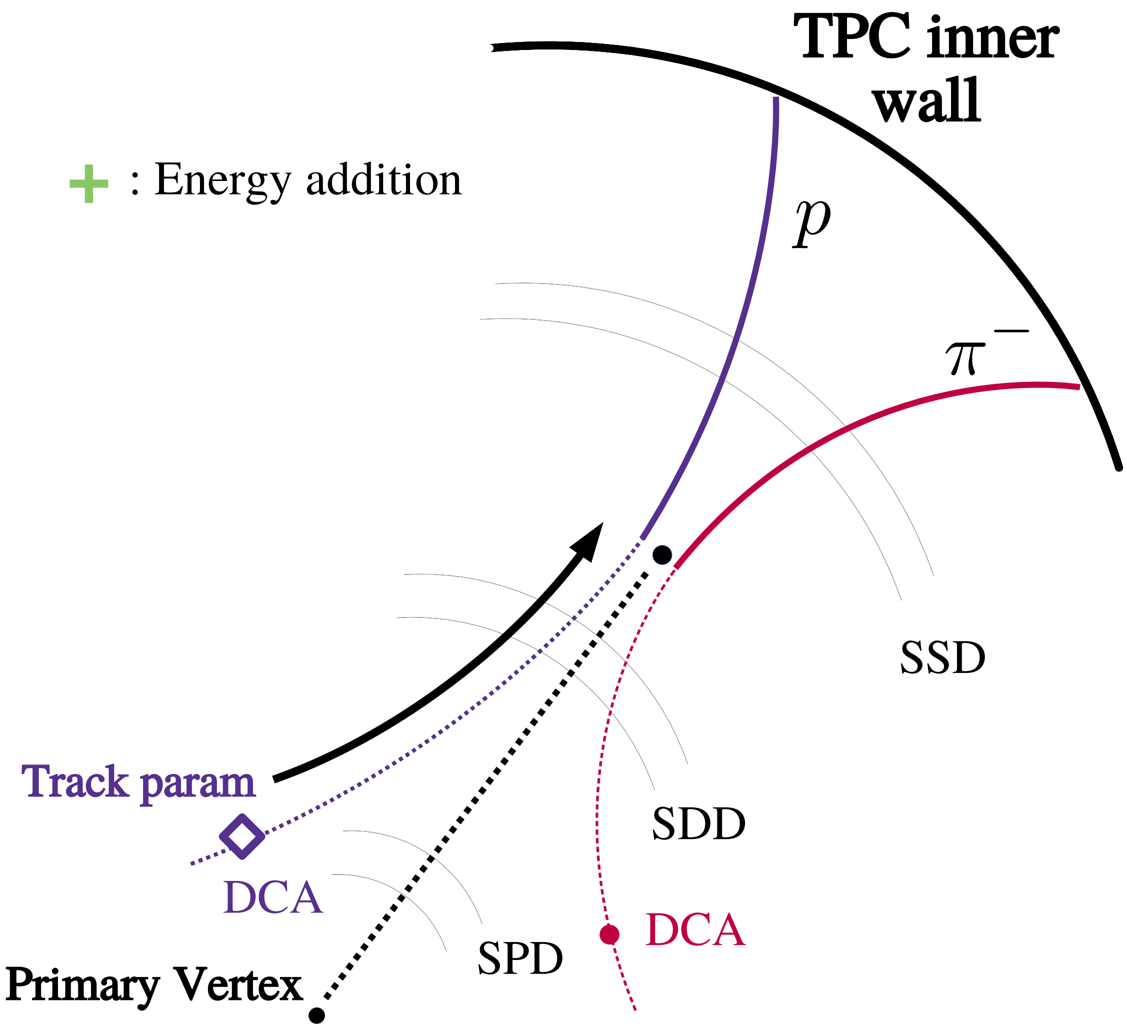

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- V0/cascade offline finding :
  - Propagate the tracks to decay point
  - Energy corrections are not redone
    - → **daughters have extra-momentum**
    - → **invariant mass is shifted**

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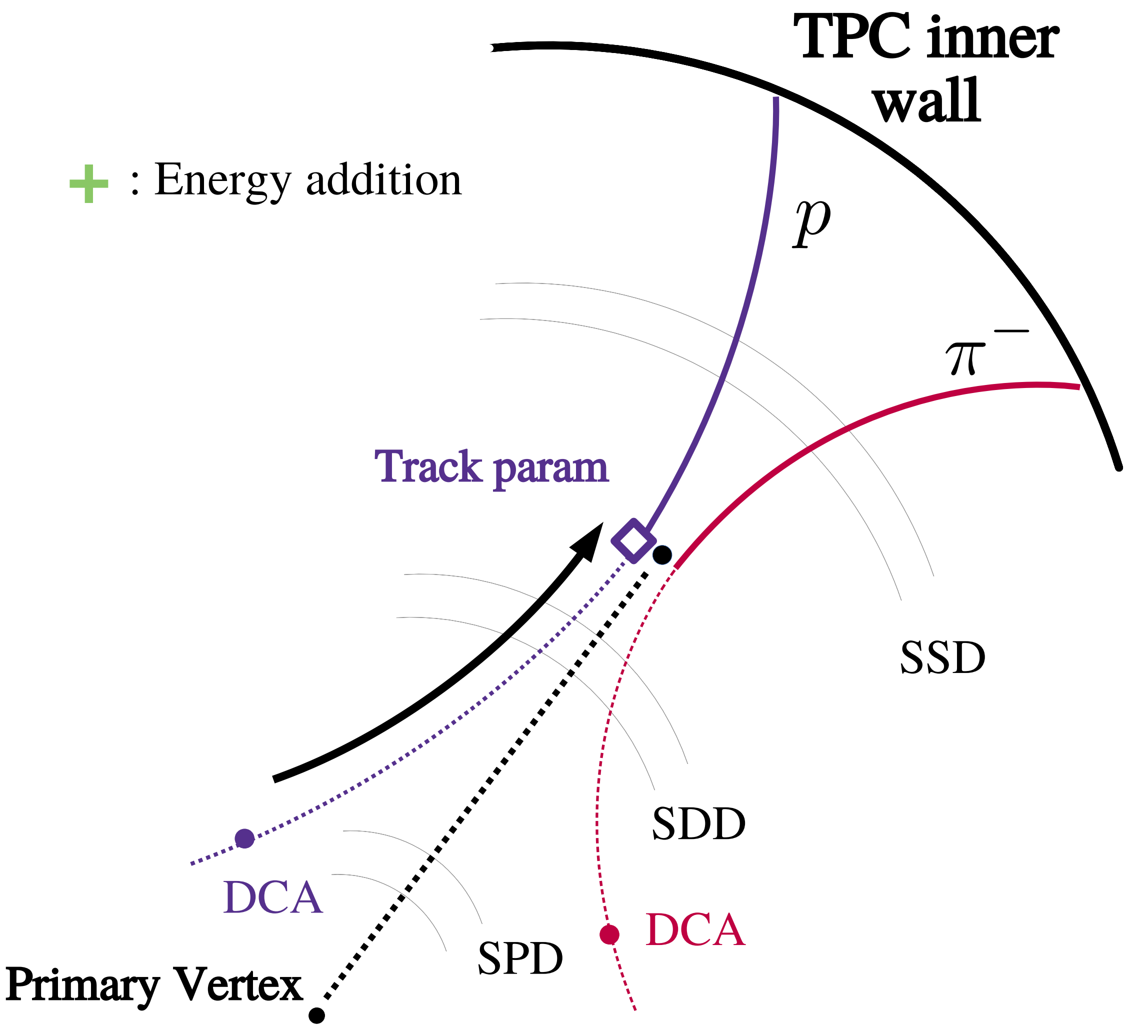

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ALICE

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ALICE

The dataset

Objective : Correct for extra energy loss correction, using a MC sample.

- 2 MC samples :
  - General purpose, anchored on LHC18m (LHC21a5a)
  - Enriched in Ξ and Ω, anchored on LHC18i (LHC20i2b)
- Event Selection :
  - ESDs,
  - Revertexing,
  - kINT7 and/or kHighV0M (MB + high multiplicity),
  - Remove in bunch (MV) and out-of-bunch pile up (OOB)
- Analysis task : https://github.com/alisw/AliPhysics/blob/master/PWGLF/STRANGENESS/Cascades/Run2/AliAnalysisTaskStrangenessVsMultiplicityRun2

Candidate selections

- Candidates are **primary Λ, anti-Λ and K0s**

- V0 selections

Variables	Cut
Rapidity	< 0.5
Pt	[1; 5] GeV/c
MC association	YES

- Track Selections

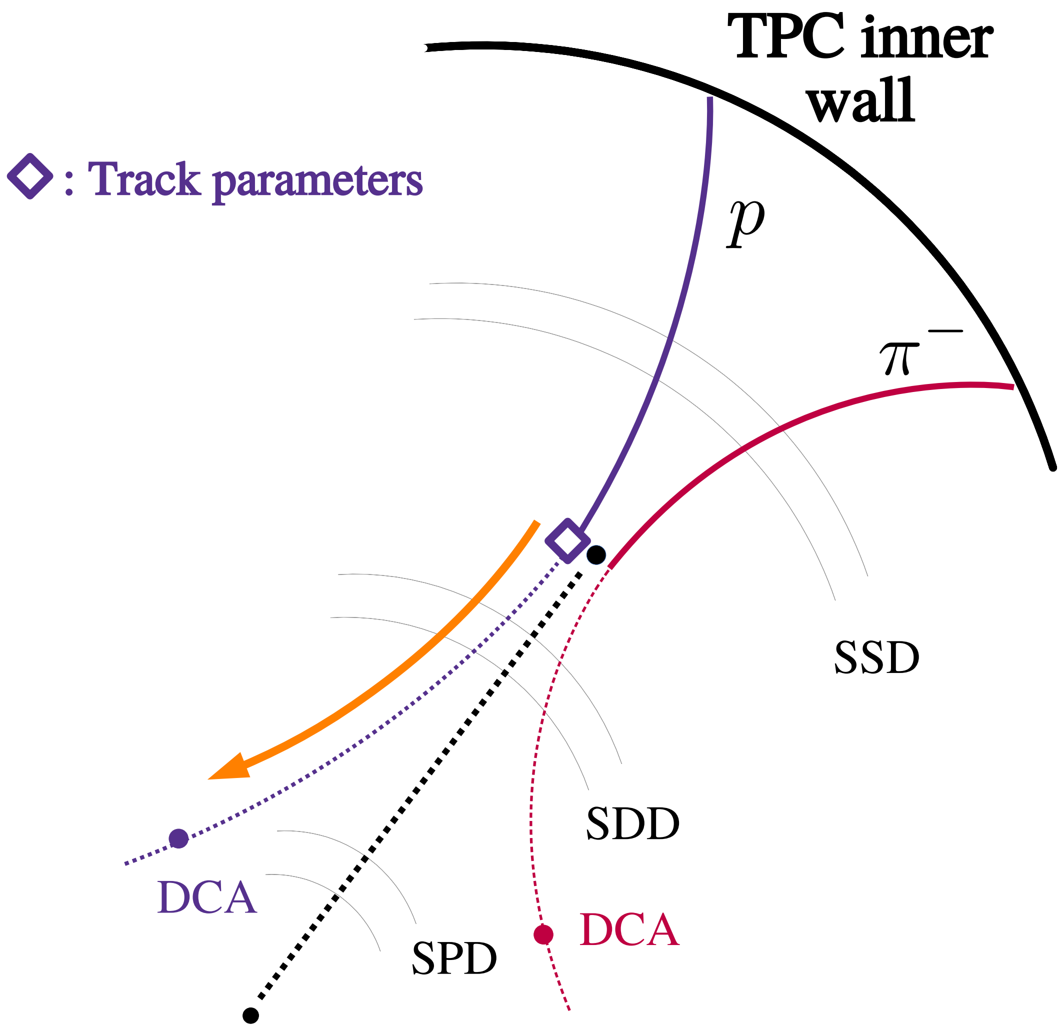
TPC refit	kTRUE
TPC PID N Sigma	< 3 σ
Nbr crossed rows	> 70
η	< 0.8

- Topological selections

Variables	Cut Λ (K0s)
DCA V0 daughters	< 1.5 (1.0)
V0 Radius	> 0.5 cm
V0 Cos PA	> 0.97
V0 Lifetime	< 3*7.89 (3*2.686) cm
DCA V0 to PV	< 1 (0.06) cm
DCA Pos to PV	> 0,06 cm
DCA Neg to PV	> 0.06 cm

Apply retrocorrections

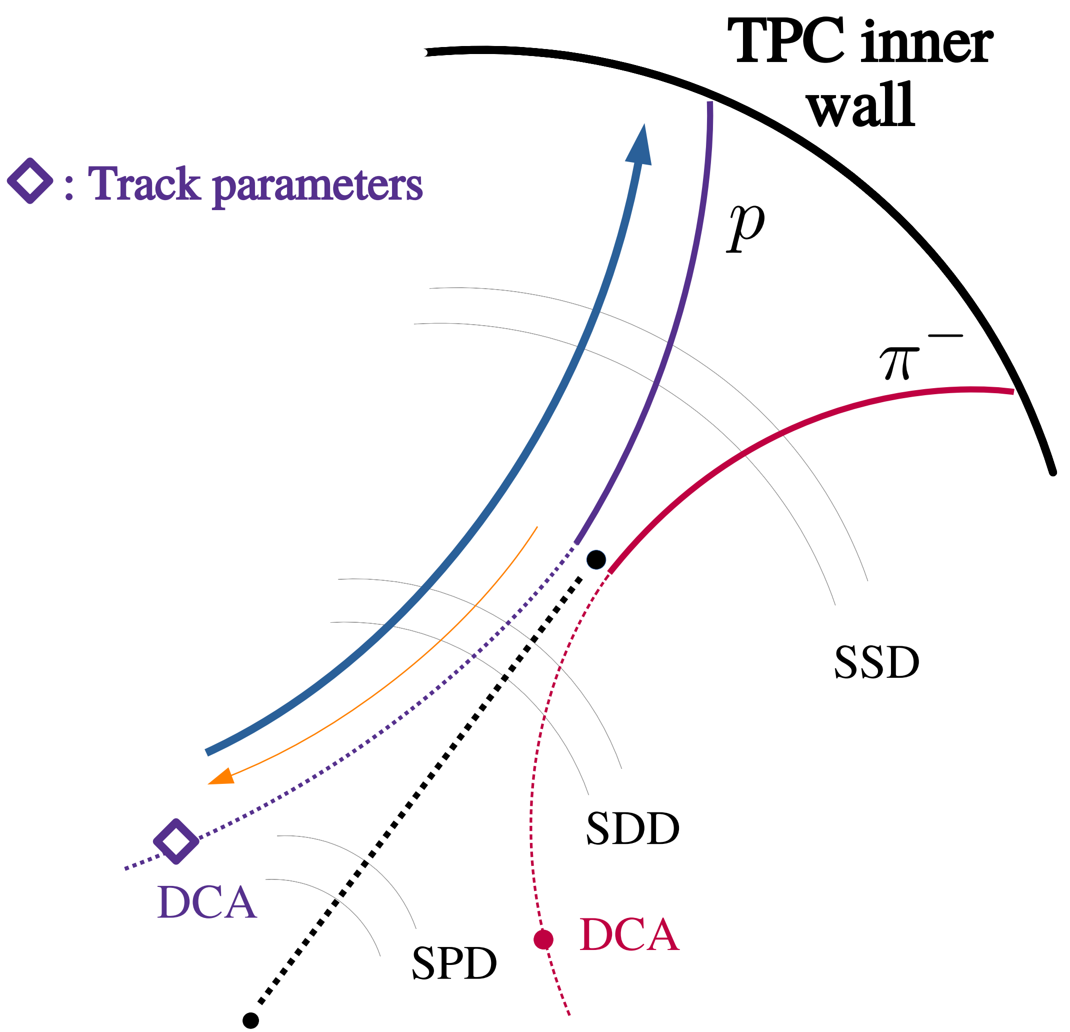
- Redo track propagation with the appropriate energy loss correction
  - Propagate the track to the inner wall of the TPC (w/ energy correction)
  - Go back to the decay point, applying energy correction w/ the correct PID assumption



- 1st step : propagate to the DCA to PV **without** energy correction

Apply retrocorrections

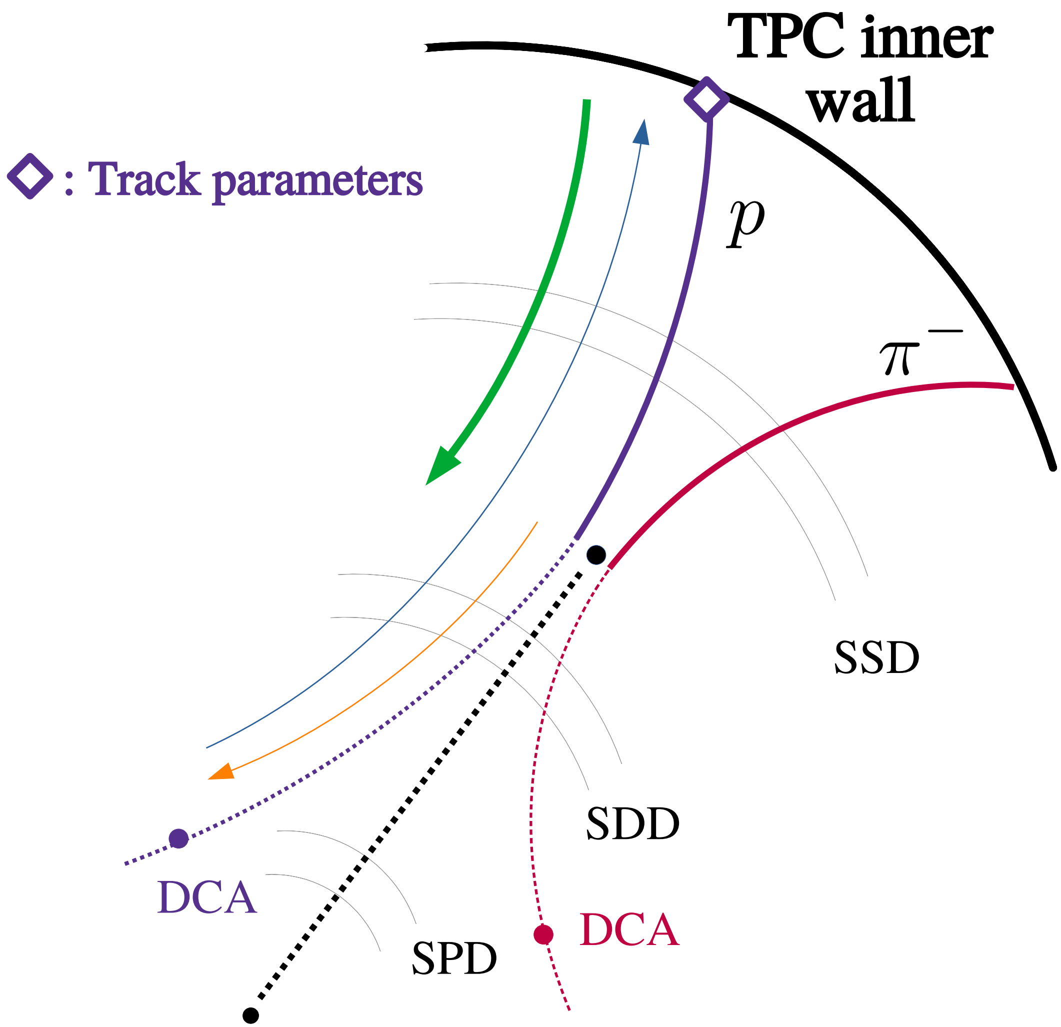
- Redo track propagation with the appropriate energy loss correction
  - Propagate the track to the inner wall of the TPC (w/ energy correction)
  - Go back to the decay point, applying energy correction w/ the correct PID assumption



- 1st step : propagate to the DCA to PV **without** energy correction
- 2nd step : propagate to the TPC **with** energy correction (hyp : PID used during tracking)

Apply retrocorrections

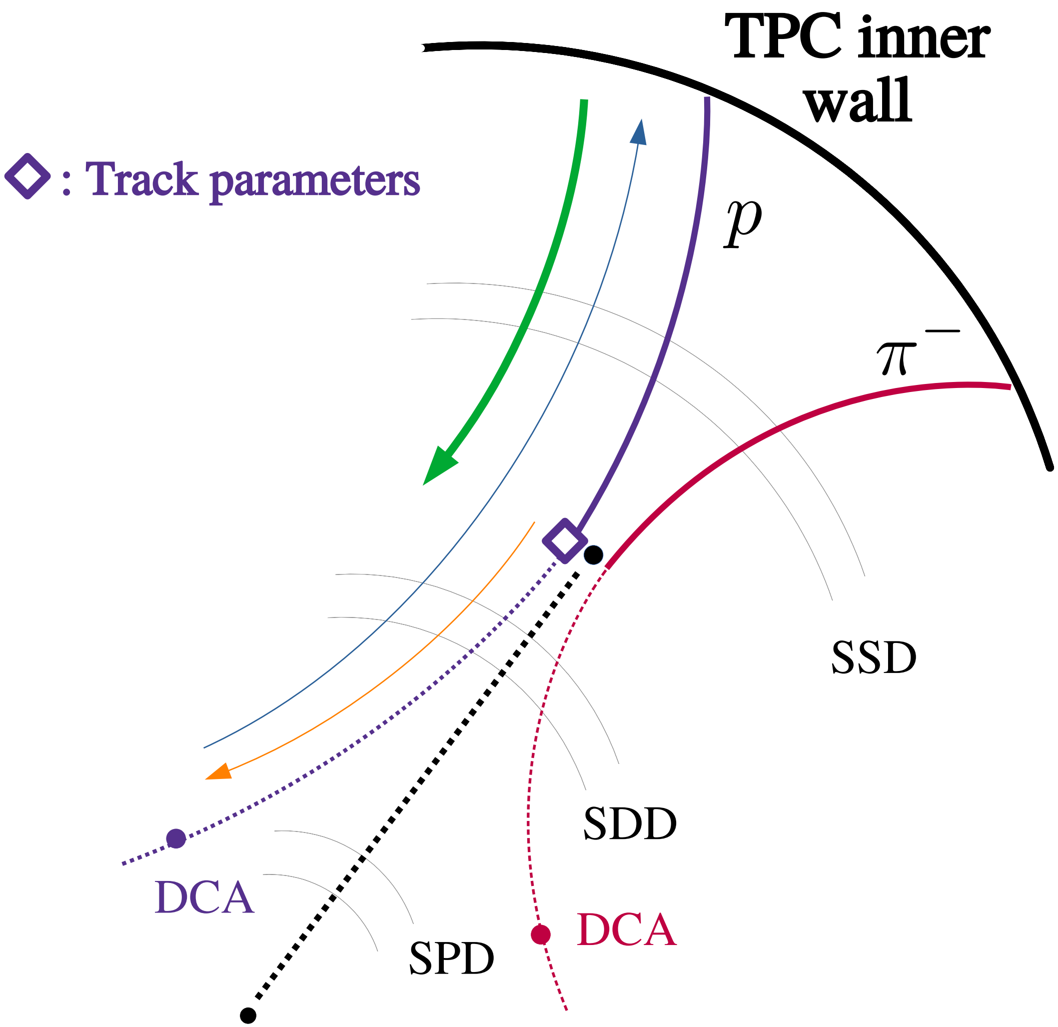
- Redo track propagation with the appropriate energy loss correction
  - **Propagate the track to the inner wall of the TPC** (w/ energy correction)
  - **Go back to the decay point**, applying energy correction w/ the correct PID assumption



- 1st step : propagate to the DCA to PV **without** energy correction
- 2nd step : propagate to the TPC **with** energy correction (hyp : PID used during tracking)
- 3rd step : propagate back to decay point **with** energy correction (hyp : correct PID)

Apply retrocorrections

- Redo track propagation with the appropriate energy loss correction
  - Propagate the track to the inner wall of the TPC (w/ energy correction)
  - Go back to the decay point, applying energy correction w/ the correct PID assumption



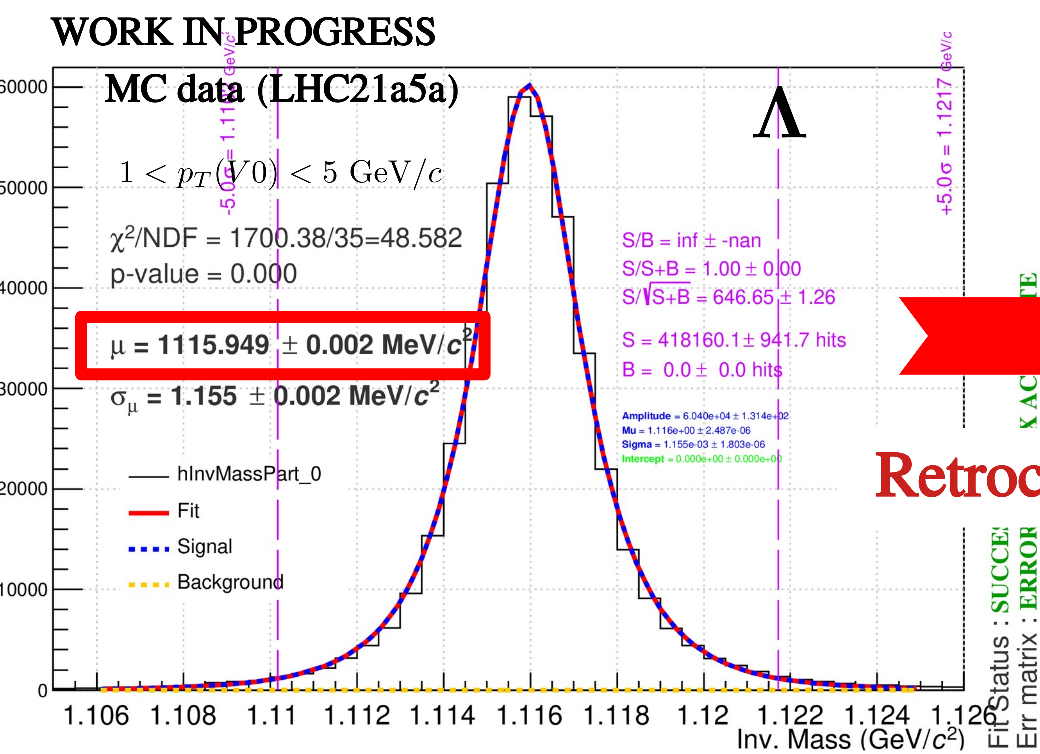
- 1st step : propagate to the DCA to PV **without** energy correction
- 2nd step : propagate to the TPC **with** energy correction (hyp : PID used during tracking)
- 3rd step : propagate back to decay point **with** energy correction (hyp : correct PID)

Λ Invariant mass

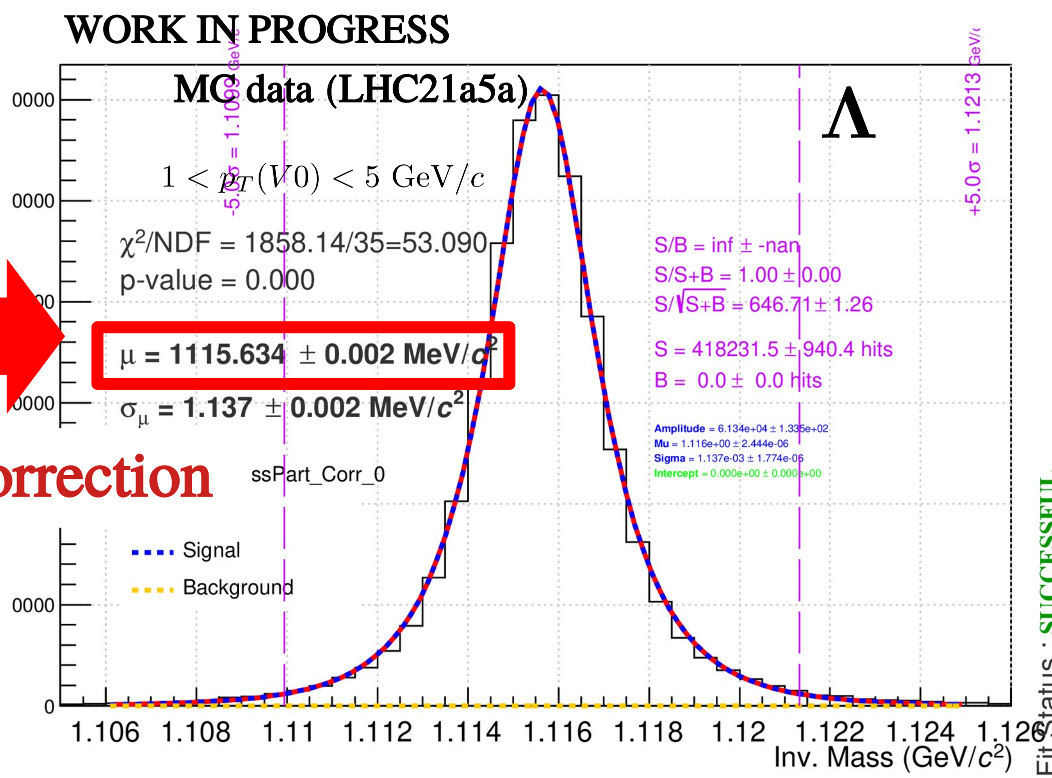
- To get an idea whether or not these corrections are going in the right direction

  → look at the invariant mass

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



Retrocorrection



→ 266 keV shift wrt to PDG mass (injected mass)

→ -49 keV shift wrt to PDG mass (injected mass)

I) Motivations

II) Analysis based on real data

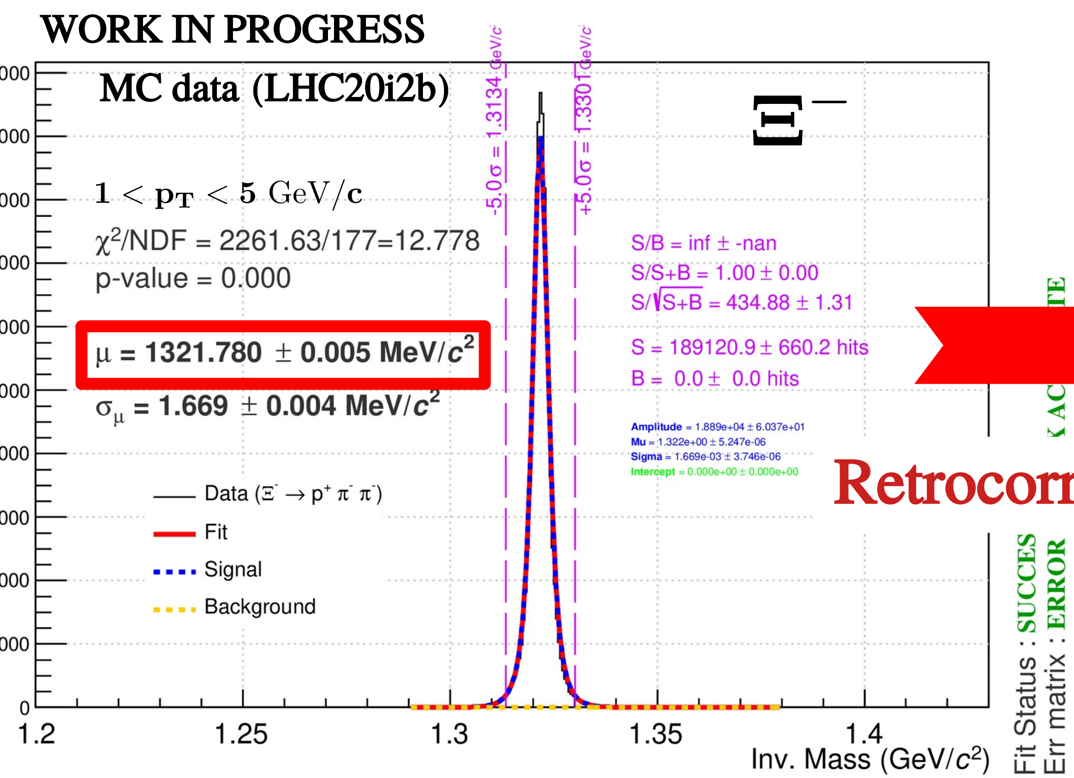
III) Analysis based on MC data

IV) Current status

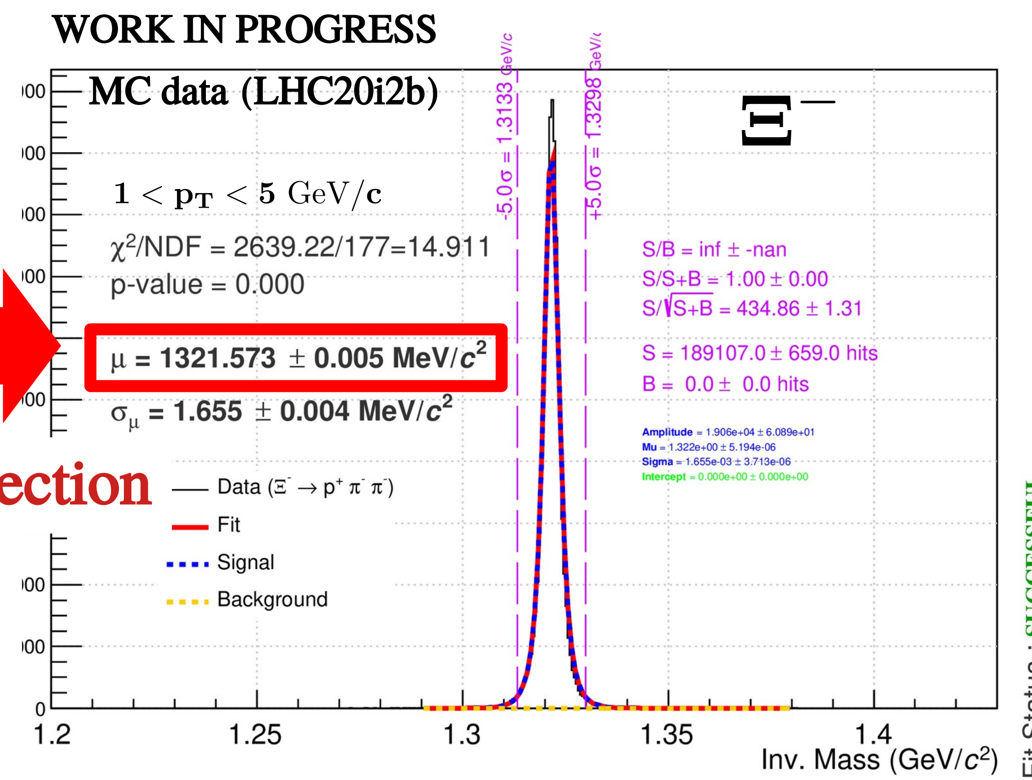
Ξ Invariant mass

- Look at dE/dx retrocorrection applied on cascades
- **In MC data (LHC20i2b) :**

$$\mathbf{m_{PDG}(\Xi) = 1321.71 \pm 0.07\ MeV/c^2}$$



Retrocorrection



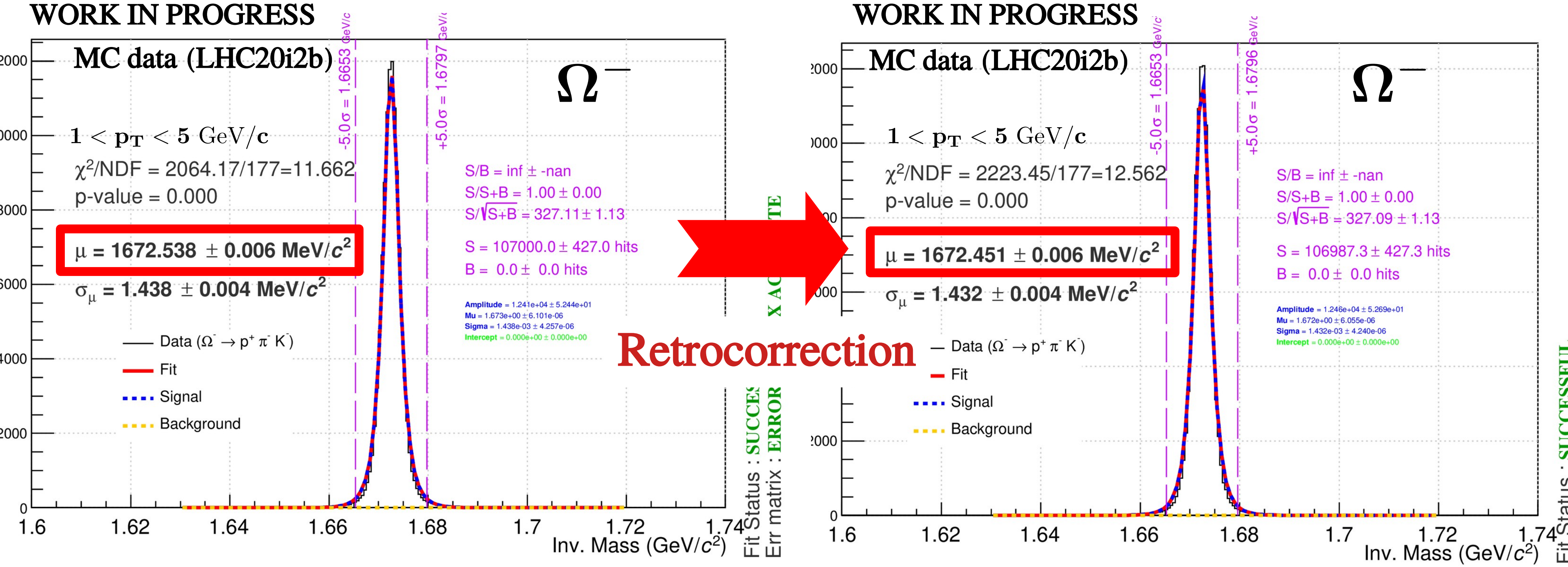
→ +70 keV shift wrt to PDG mass (injected mass)

→ -137 keV shift wrt to PDG mass (injected mass)

Ω Invariant mass

- Look at dE/dx retrocorrection applied on cascades
- **In MC data (LHC20i2b) :**

$$\mathbf{m_{PDG}(\Omega) = 1672.45 \pm 0.23 \ \mathrm{MeV}/c^2}$$



→ +88 keV shift wrt to PDG mass (injected mass)

→ +1 keV shift wrt to PDG mass (injected mass)

Conclusion

- On real data :
  - Improve PDG mass and mass difference values by at least a factor 5 and 3 respectively
  - Mass difference ~ 0 : CPT still valid but further constrained

- On MC data :
  - Our mass measurements have an offset wrt the PDG mass, whatever the particle of interest (K0s, Λ, Ξ, Ω)
  - This mass shift mainly comes from extra energy addition during V0/cascade finding $\rightarrow$ corrected now

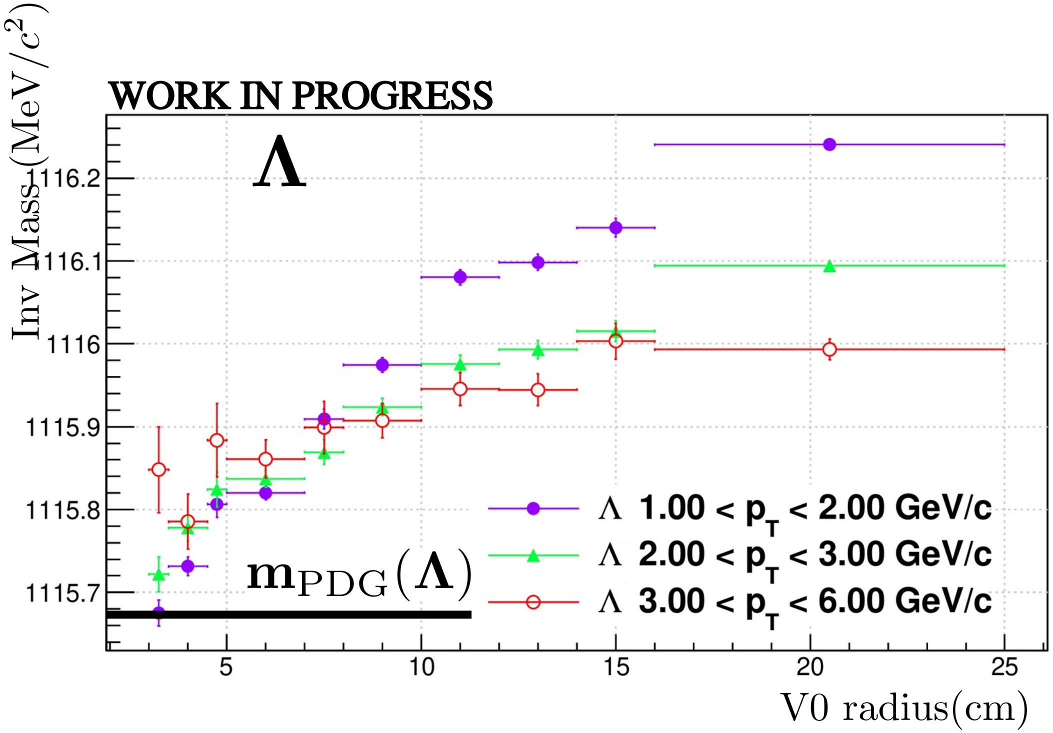
- Next step :
  - Understand why our $\mathrm{d}E/\mathrm{d}x$ retrocorrection works so well on Ω but not on Ξ

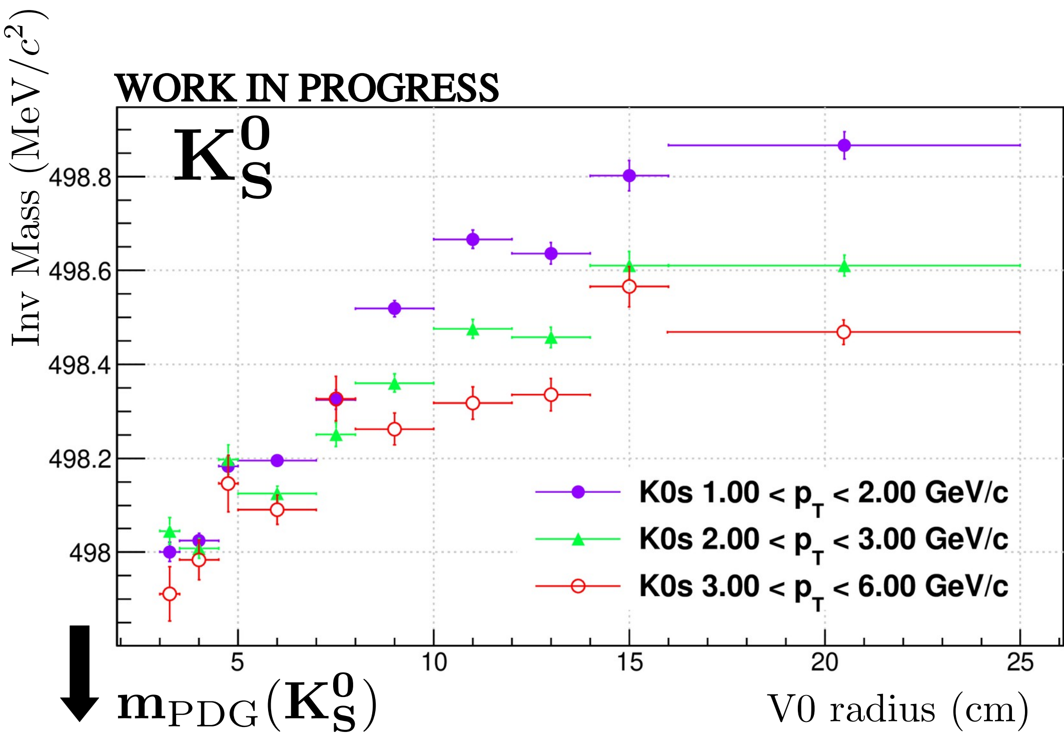
Backup slides

Dependence of the mass shift

- The gap between the extracted mass and the PDG mass seems to depend on :
    - Radial position of the decay point
    - The transverse momentum

$\mathbf{m_{PDG}(\Lambda) = 1115.683 \pm 0.006}$ MeV$/\mathbf{c^2}$ $\mathbf{m_{PDG}(K^0_S) = 497.611 \pm 0.013}$ MeV$/\mathbf{c^2}$



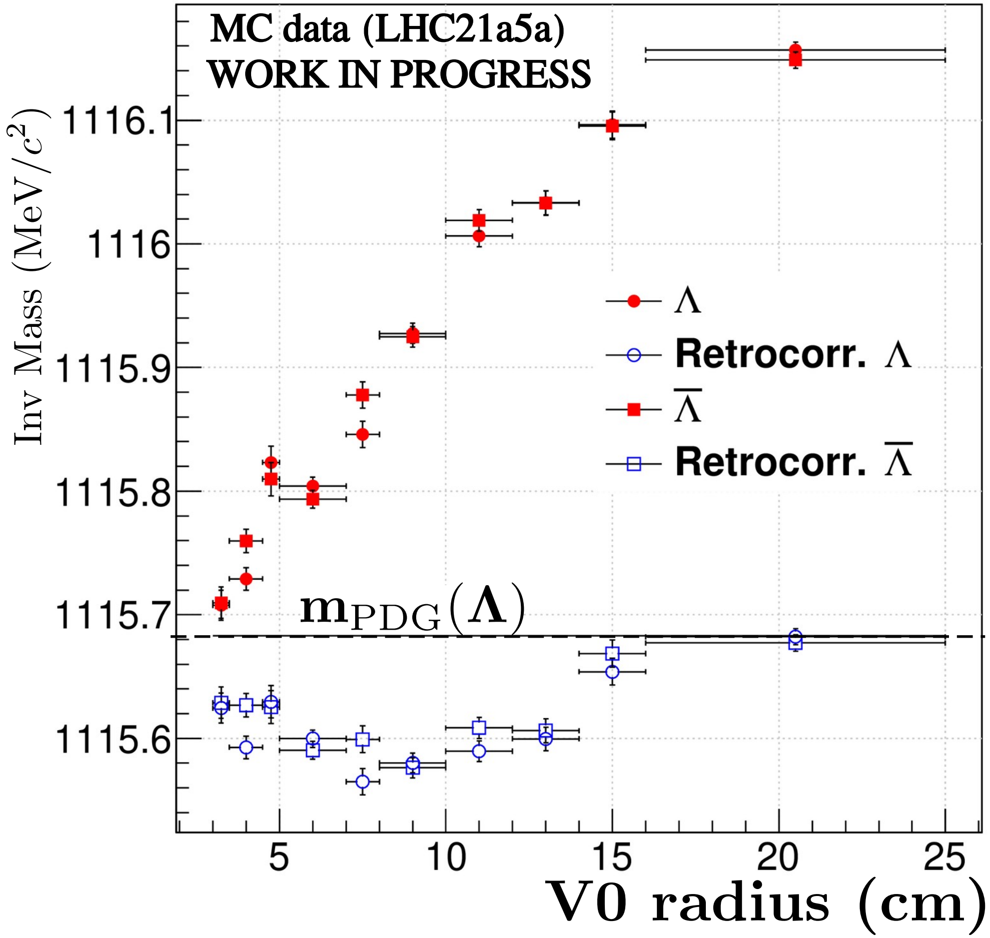


Invariant mass Vs radius

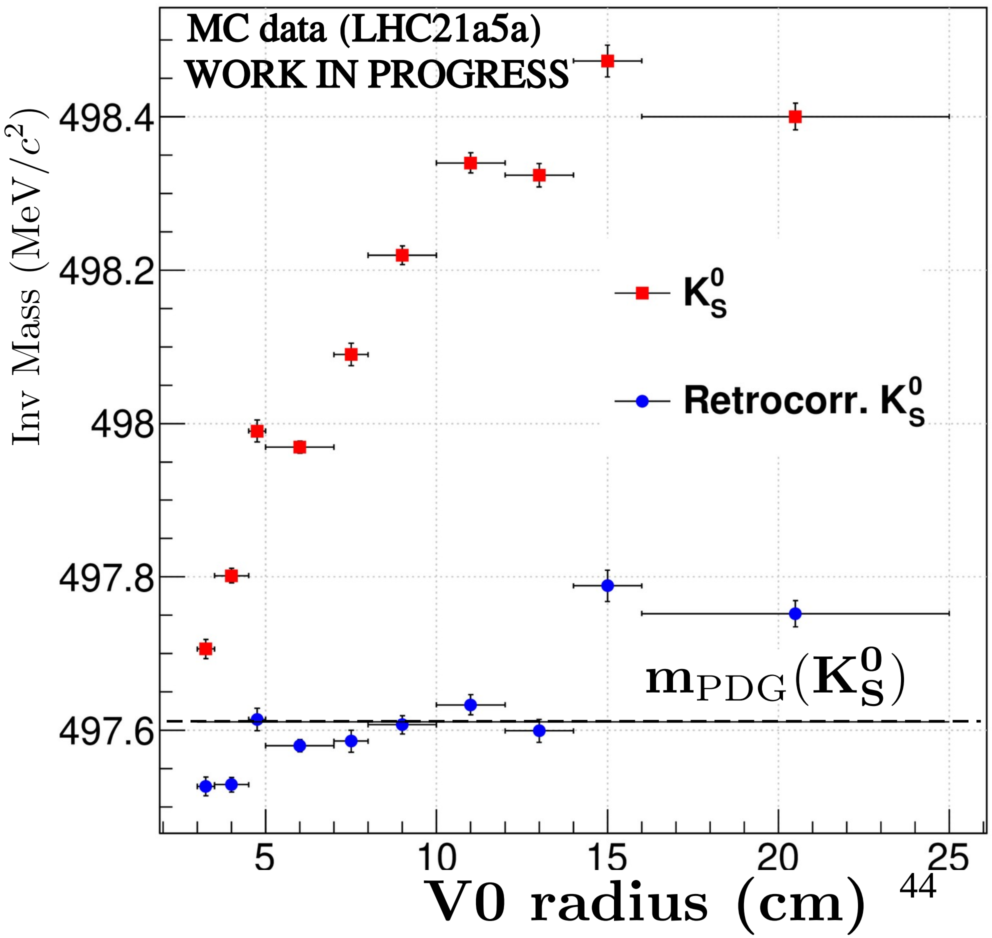
- The mass shift is dependent on the radial position of the V0

  → with retrocorrections, we'd expect the trend to be less pronounced

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



$\mathbf{m_{PDG}(K^0_S) = 497.611 \pm 0.013}$ MeV/$\mathbf{c^2}$

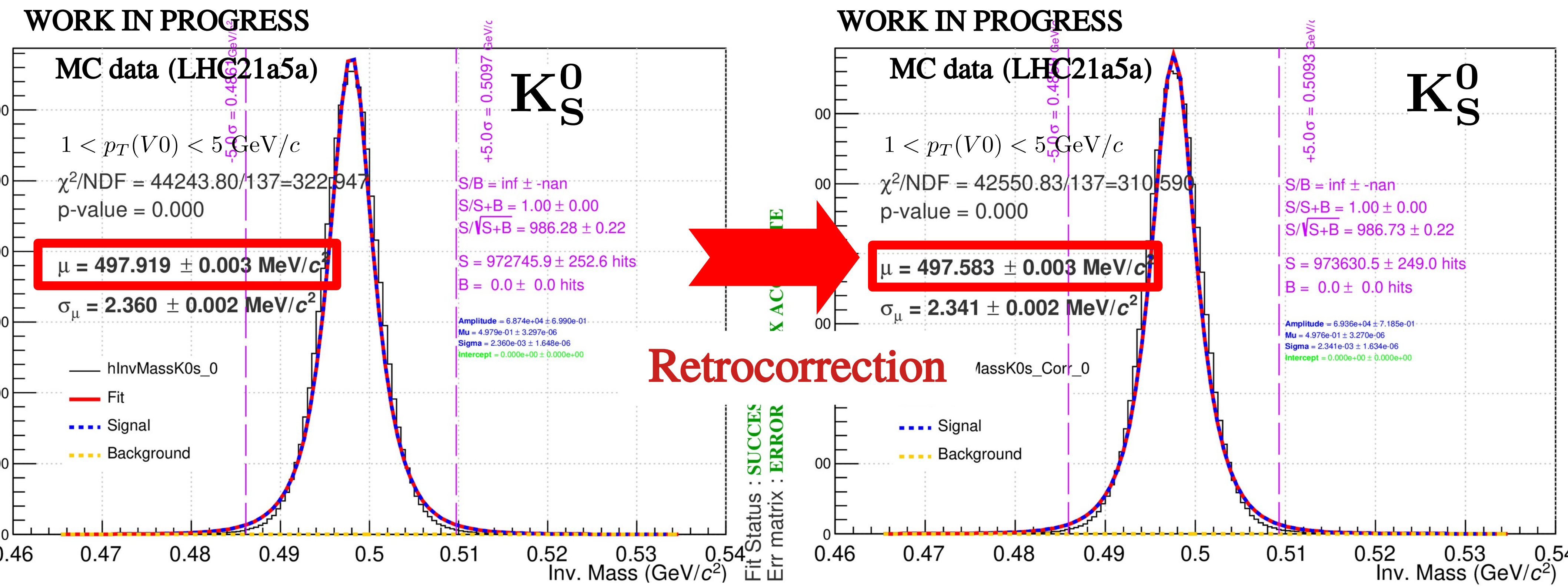


K0s Invariant mass

- To get an idea whether or not these corrections are going in the right direction

  → look at the invariant mass

$$\mathbf{m_{PDG}(K^0_S) = 497.611 \pm 0.013\ MeV/c^2}$$



→ 308 keV shift wrt to PDG mass (injected mass)

→ -28 keV shift wrt to PDG mass (injected mass)

Ξ selections

- Candidates are **primary** Ξ

Ξ-(Ξ+)	Cut value
|y|	< 0.5
pT	[1 ; 5] GeV/c
MC association	YES

- Cascade selections

DCA Bach To PV	> 0.04 cm
DCA Casc daughters	< 1.3 cm
Casc Radius	> 0.5 cm
Casc Cos PA	> 0.97
Proper Lifetime	> 3 x 4.91 cm
Wrong PA	> 0.04

- Track selections :
  - $|\eta| < 0.8$
  - TPC refit
  - TPC Nbr Crossed Rows > 70
  - TPC PID Nsigma < 3

- V0 selections

DCA V0 to PV	> 0.04 cm
DCA Pos to PV	> 0.03 (0.04) cm
DCA Neg to PV	> 0.04 (0.03) cm
DCA V0 daughters	< 1.5 cm
V0 Radius	> 1.1 cm
V0 Cos PA	> 0.97
|V0 Mass – Λ Mass|	< 0.008 GeV/c2

Ω selections

- Candidates are **primary Ω**

Ω-(Ω+)	Cut value
|y|	< 0.5
pT	[1 ; 5] GeV/c
MC association	YES

- Cascade selections

DCA Bach To PV	> 0.04 cm
DCA Casc daughters	< 1.3 cm
Casc Radius	> 0.5 cm
Casc Cos PA	> 0.97
|Casc Mass - Ξ Mass|	> 0.008 GeV/c2
Proper Lifetime	> 3 x 2.46 cm
Wrong PA	> 0.04

- V0 selections

DCA V0 to PV	> 0.04 cm
DCA Pos to PV	> 0.03 (0.04) cm
DCA Neg to PV	> 0.04 (0.03) cm
DCA V0 daughters	< 1.5 cm
V0 Radius	> 1.1 cm
V0 Cos PA	> 0.97
|V0 Mass - Λ Mass|	< 0.008 GeV/c2

- Track selections :
  - $|\eta| < 0.8$
  - TPC refit
  - TPC Nbr Crossed Rows > 70
  - TPC PID Nsigma < 3