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

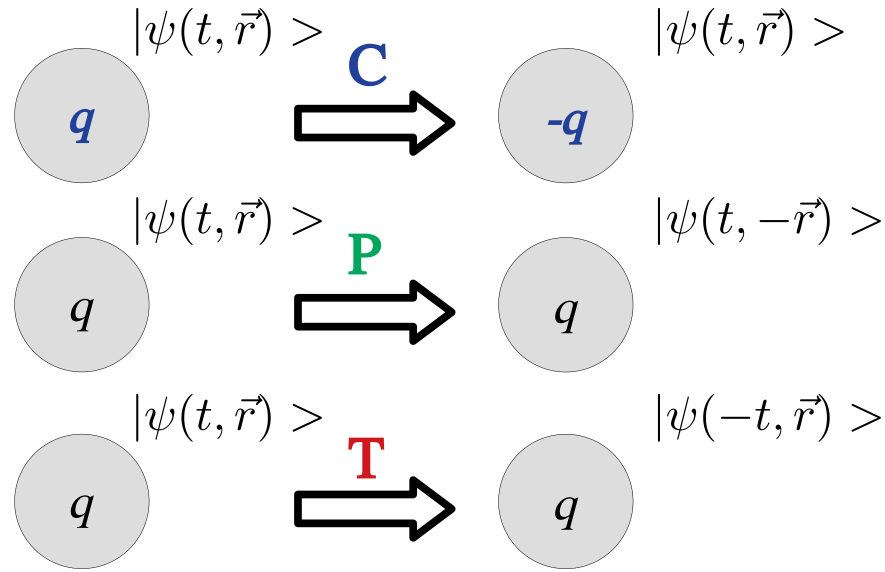
II) Analysis details and results

III) An example of remaining systematic effects

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**
     Ex : Lifetime, mass,... (except for the sign of the quantum numbers)

  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

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

$\overline{\Xi}^+$ MASS

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1321.73 ±0.08 ±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

→ 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

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II) Analysis details and results

III) An example of remaining systematic effects

IV) Current status

The ALICE detector

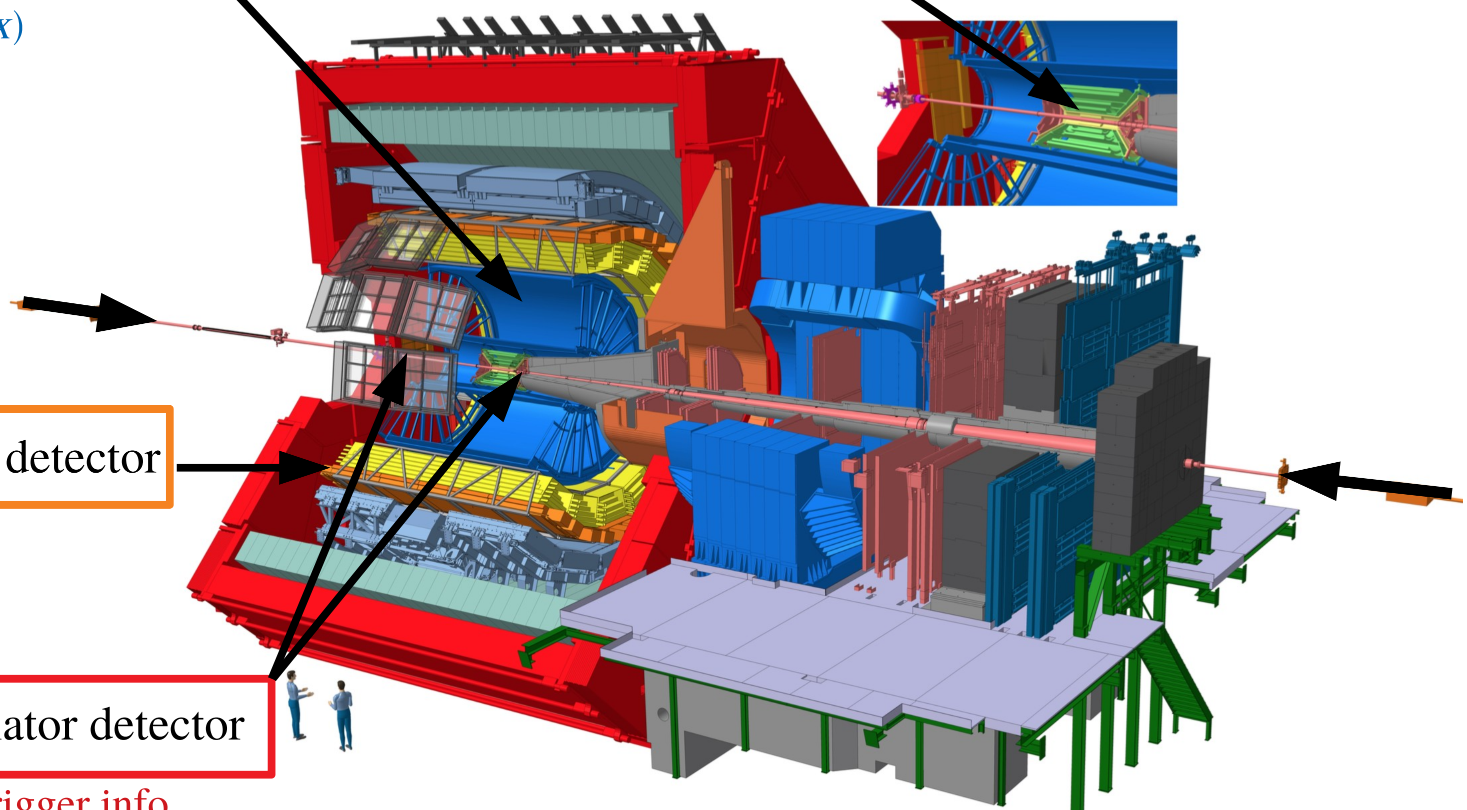
ALICE is composed of 19 detection systems

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

→ Reconstruct primary and secondary vertices

Time Projection Chamber (TPC), gaseous detector

→ Reconstruct tracks + PID ($\mathrm{d}E/\mathrm{d}x$)



Time Of Flight (TOF), gaseous detector

→ PID + OOB pile up rejection

V0, scintillator detector

→ Provide trigger info

The dataset

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

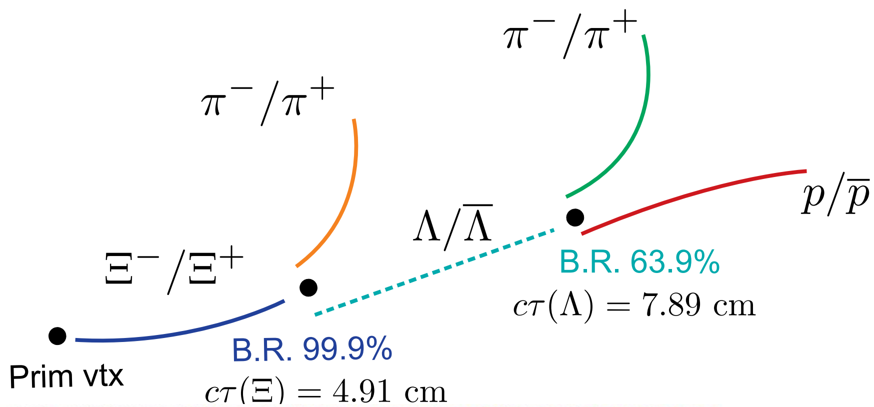
- Data :
  - ~ 2.2×10^9 pp collisions at $\sqrt{s} = 13$ TeV (LHC16 + LHC17 + LHC18)
  - Represents ~140×10^6 cascade candidates
- Event Selection :
  - ESDs,
  - Revertexing,
  - kINT7 and/or kHighV0M (MB + high multiplicity),
  - Remove in bunch (MV) and out-of-bunch pile up (OOB)
- Analysis task :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

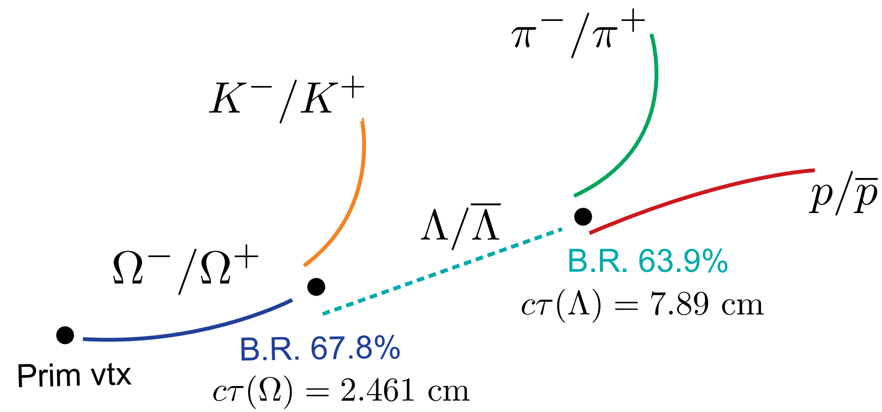
Analysis details

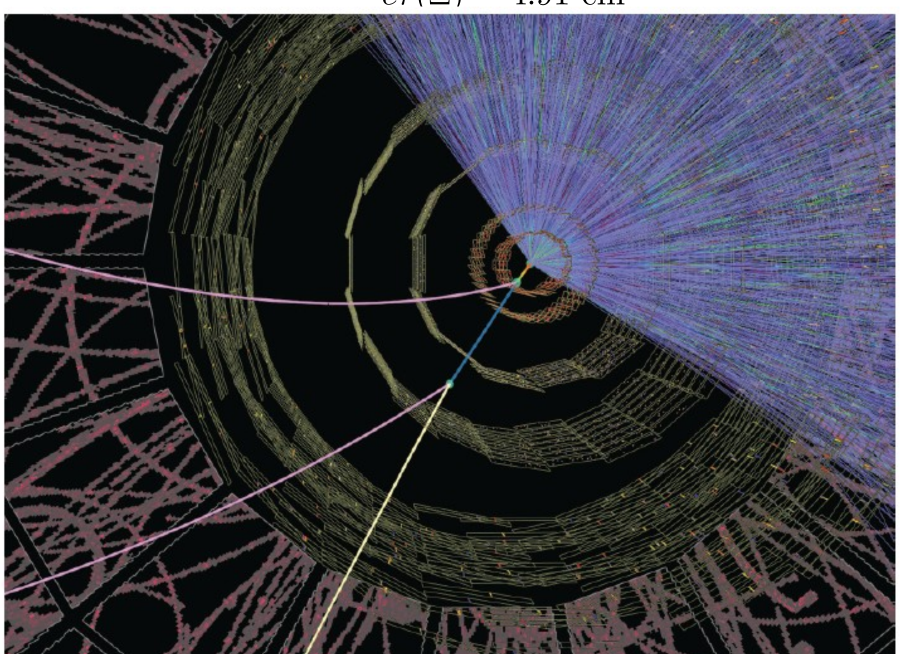
- Ξ and Ω will be studied in the following decay channel :

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

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







- 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

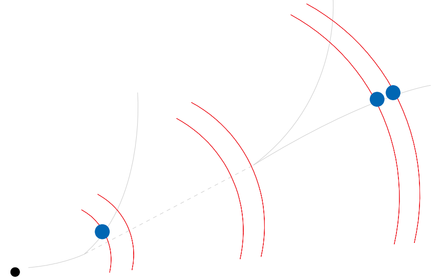
DCA Bach To PV	> 0.04 cm
DCA Casc daughters	< 1.3 cm
Casc Radius	> 0.5 cm
Casc Cos PA	> 0.97
Proper Lifetime	> 3 x 4.91 cm
Wrong PA	> 0.04

- 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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  - TPC Nbr Crossed Rows > 70
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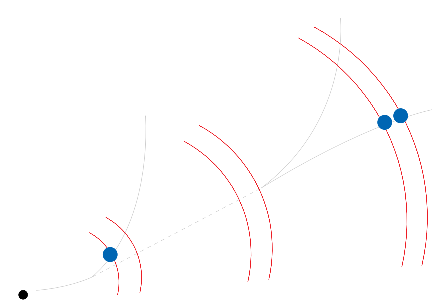
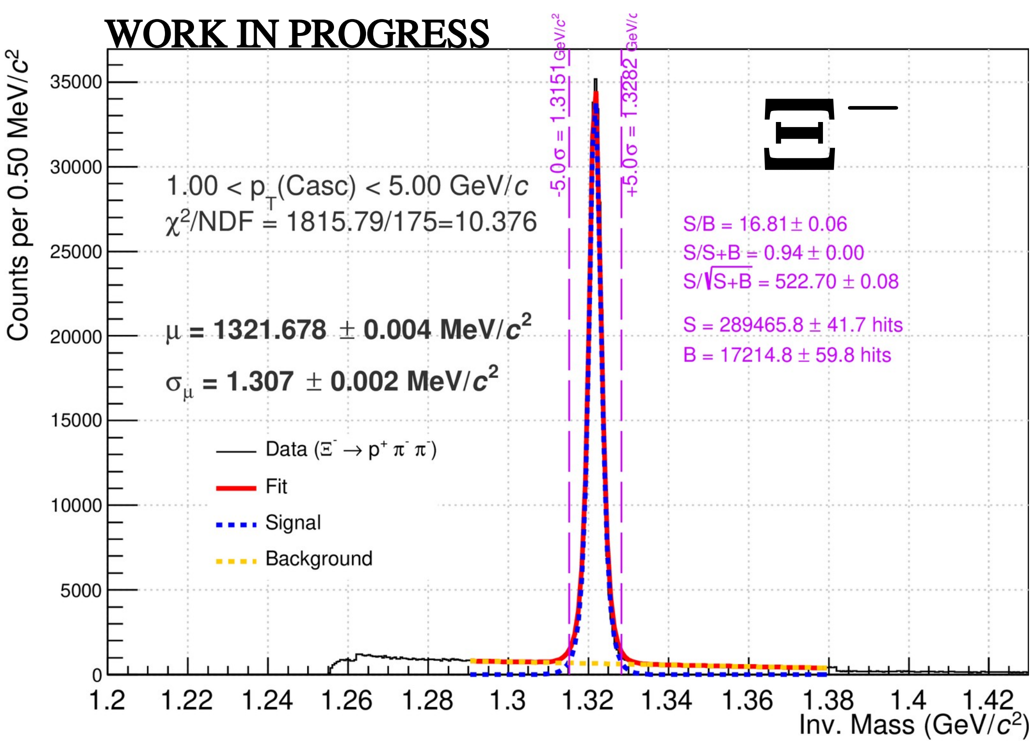
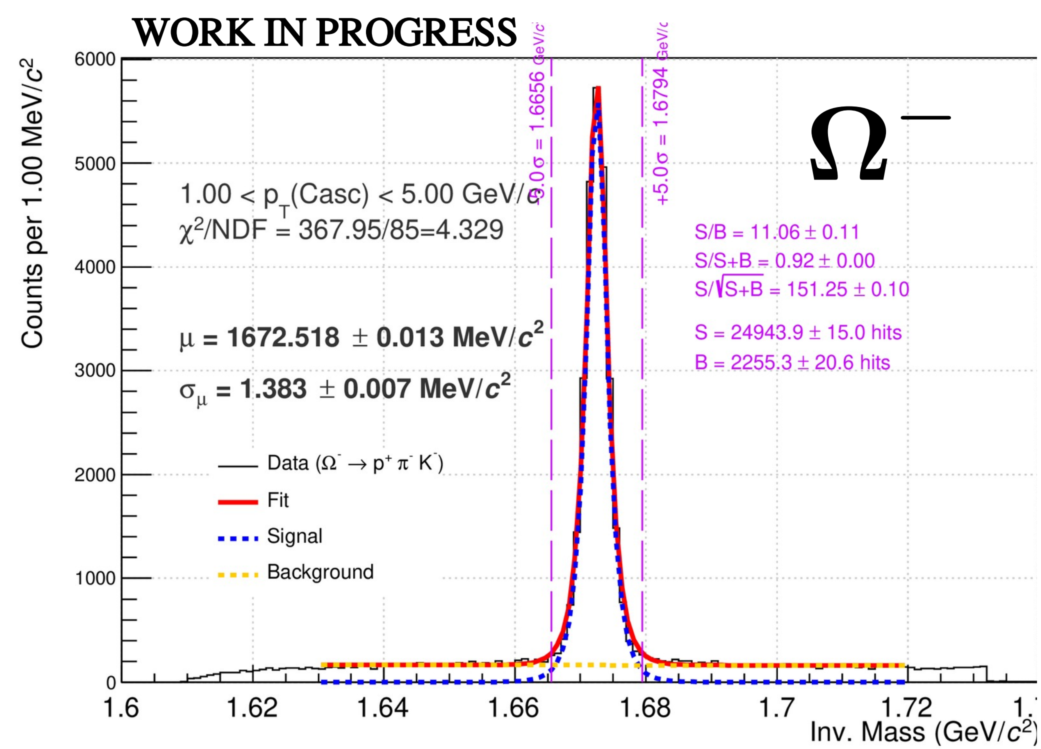


Mass extraction

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

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



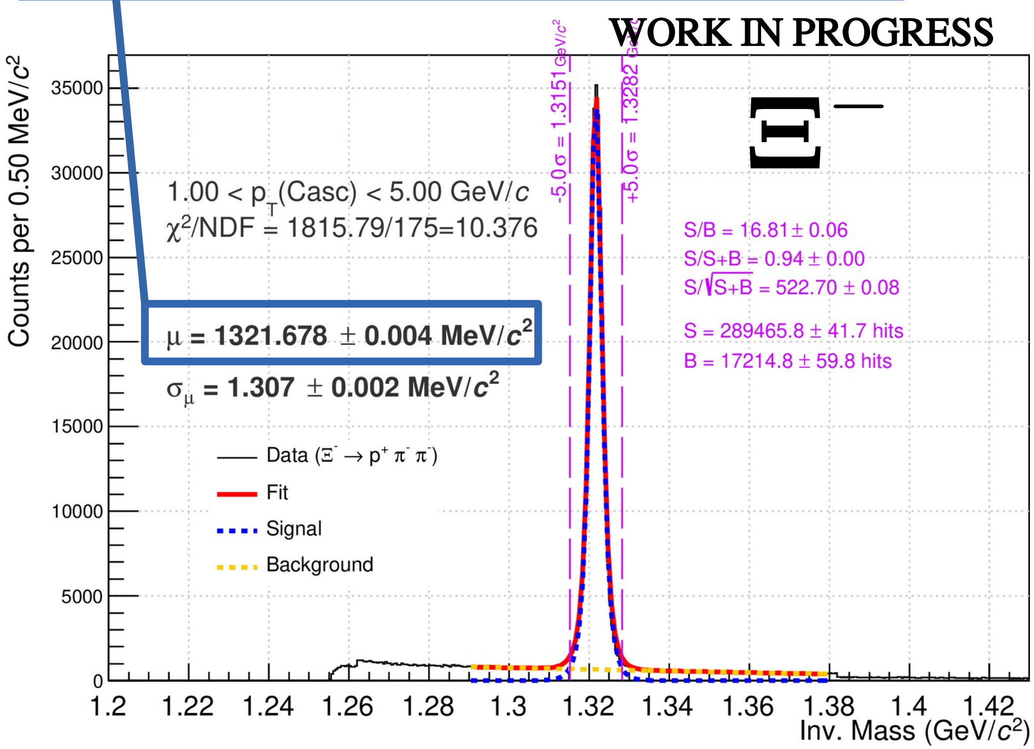


ALICE

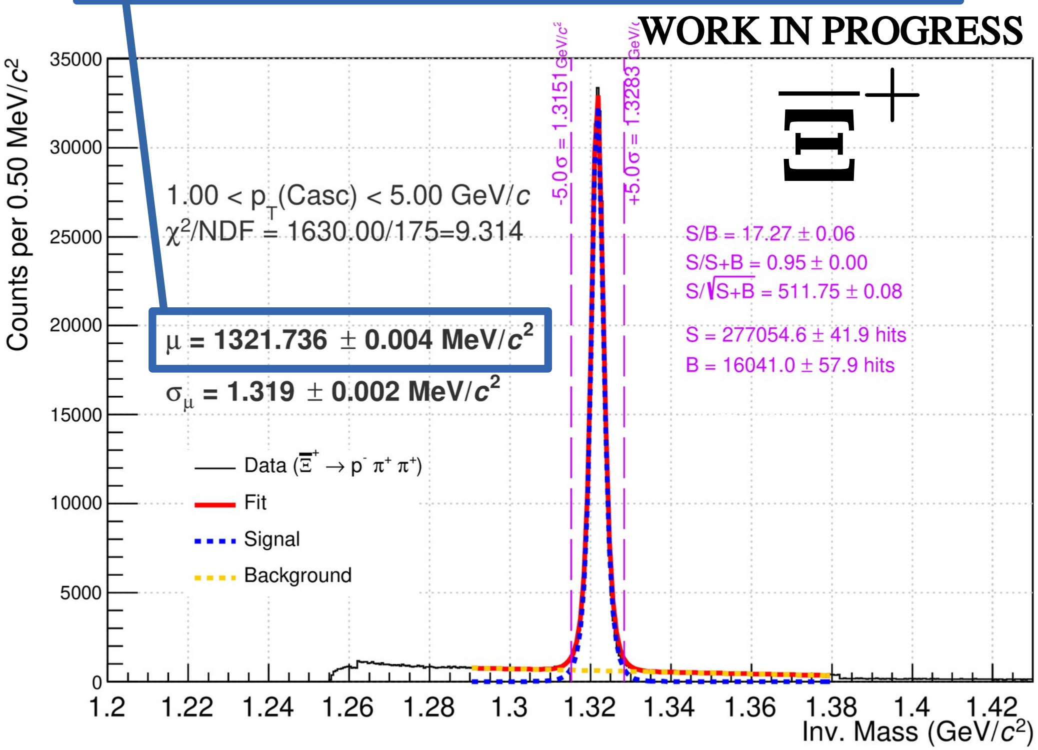
First Ξ mass measurements

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

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



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



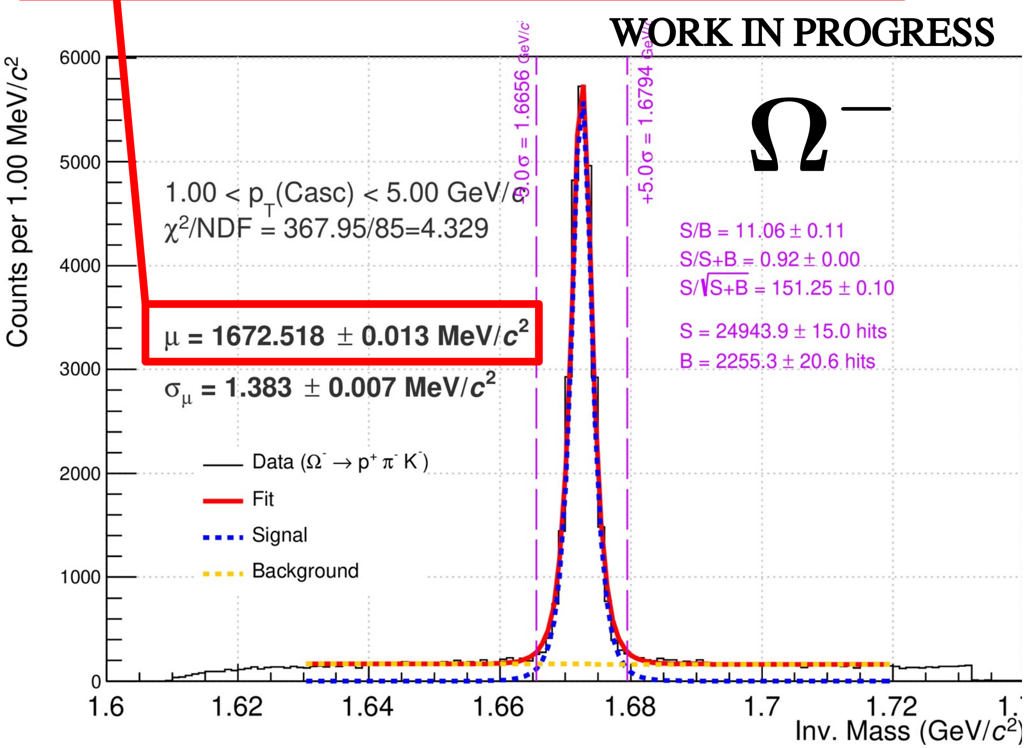
First Ω mass measurements

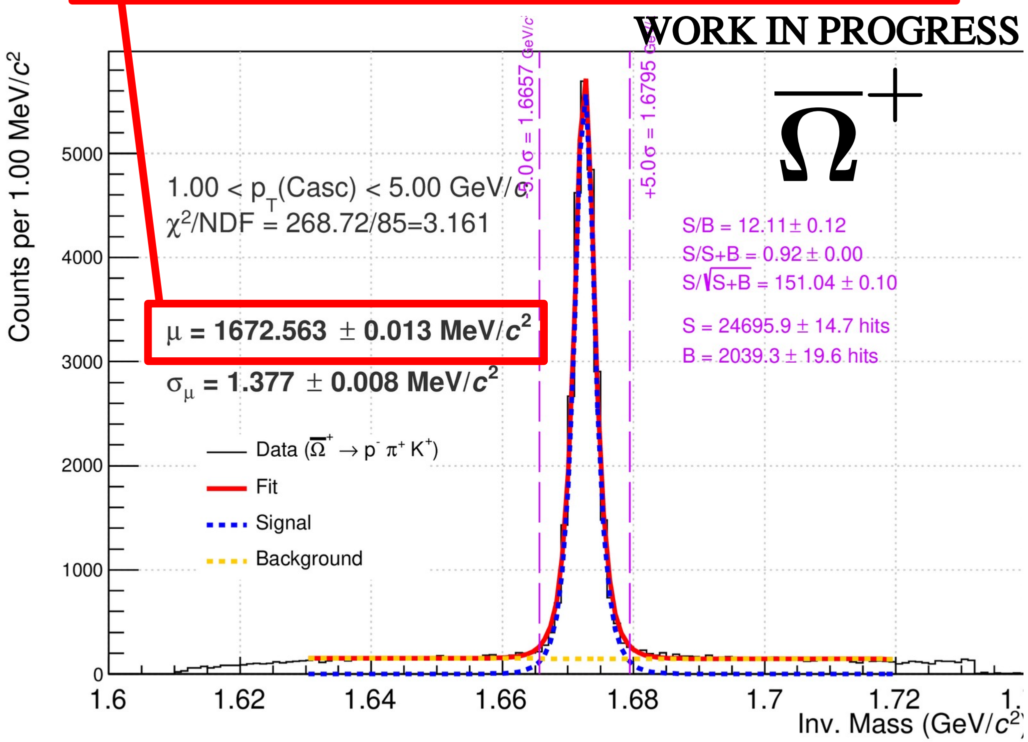
ALICE

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

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

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





ALICE

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%)
|V0 Mass – Λ Mass|	< 0.008 GeV/c^2	[0.002-0.007] (33%)

Ω^-

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

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

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Check : compare with PDG mass

- Mass values : **WORK IN PROGRESS**

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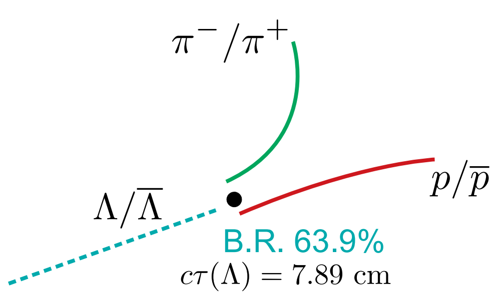
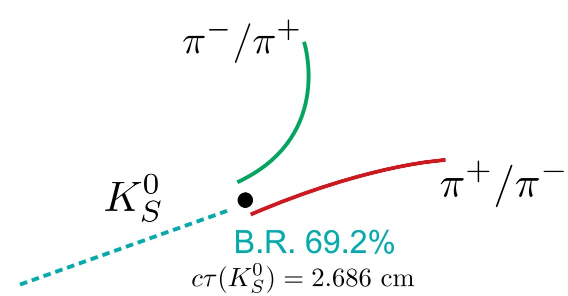
- Gap between our mass values and the PDG ones **(almost 1σ for the Ξ)**
- To check that the analysis is working properly :
  - Take a particle whose PDG mass is evaluated very precisely (σ ~ few keV/c^2),
  - Check that the mass extracted by the analysis corresponds to the PDG mass

- 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

Mass shift

- Same procedure as for the Ξ and Ω
- The extracted mass is above the PDG mass by
  - ~ 300 keV/c^2 for Λ
  - ~ 600 keV/c^2 for K0s

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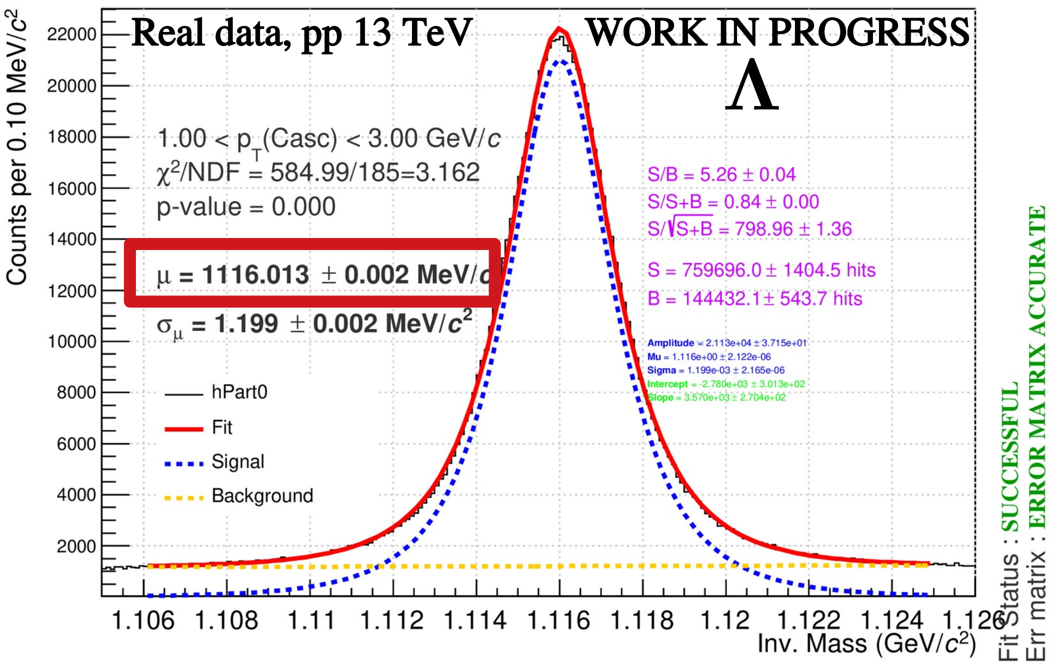
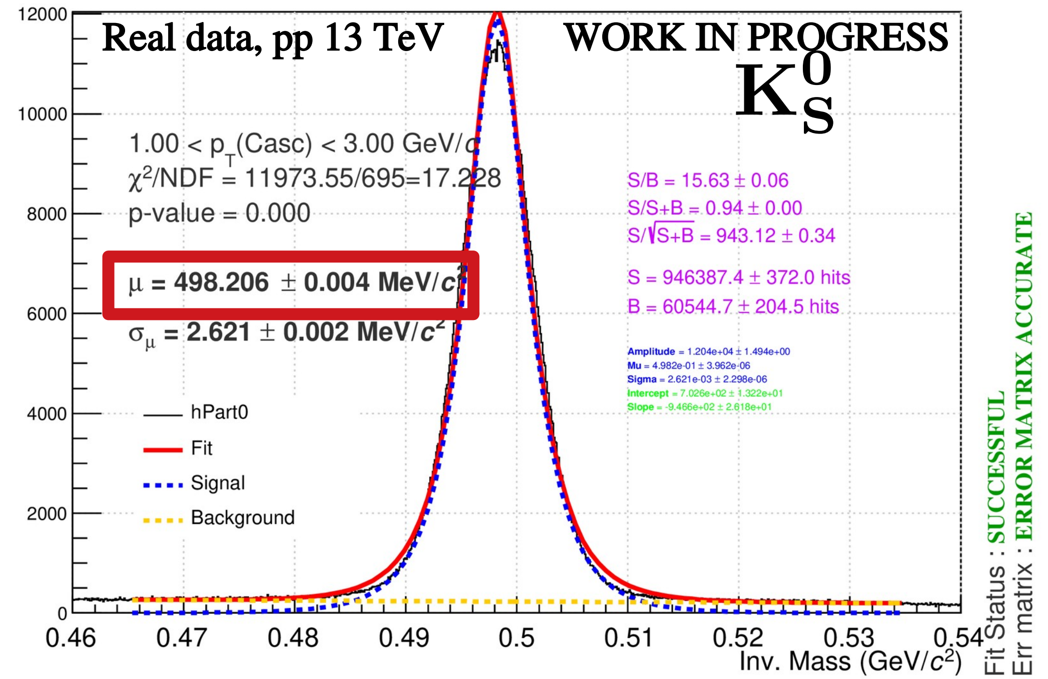
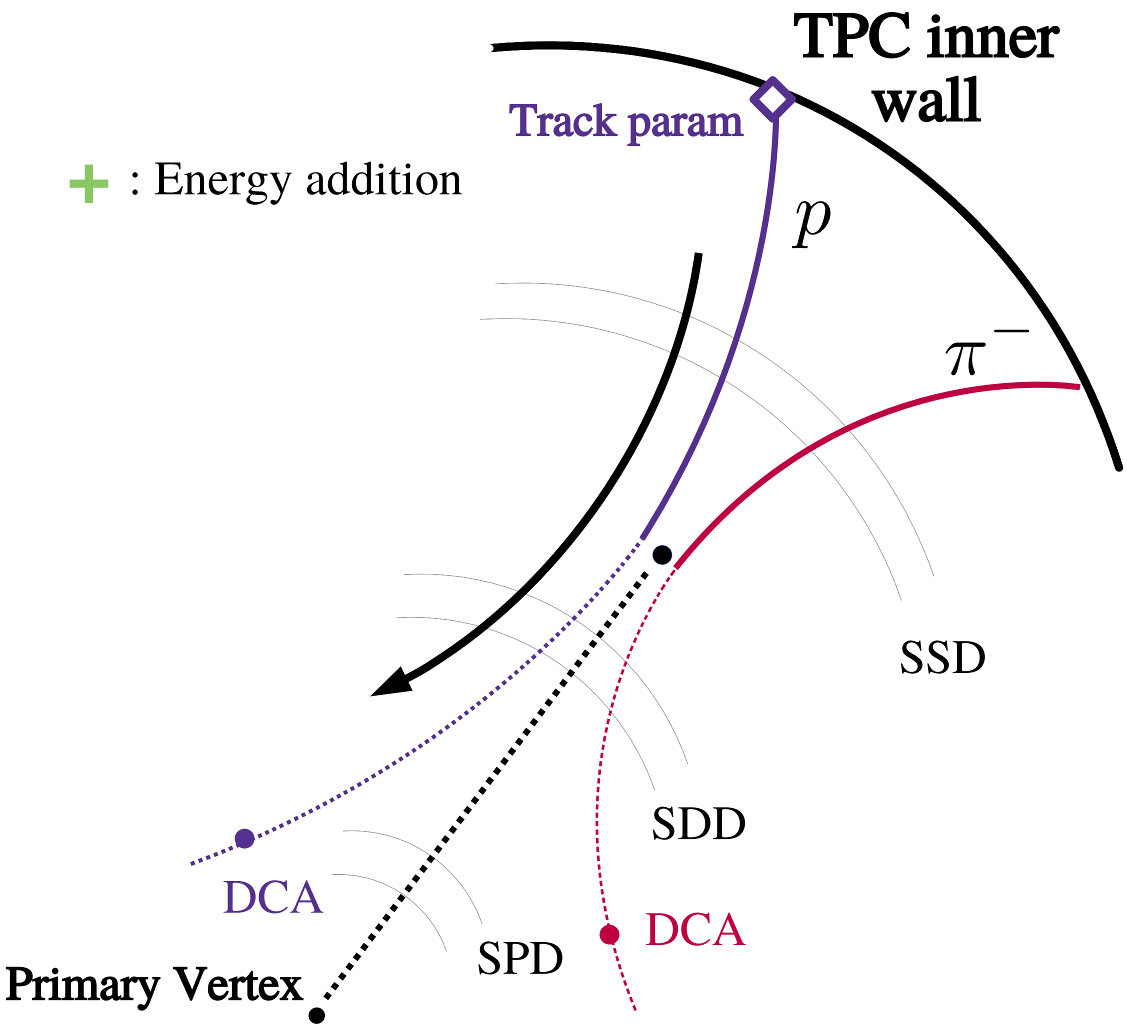




Main cause of the mass shift

- 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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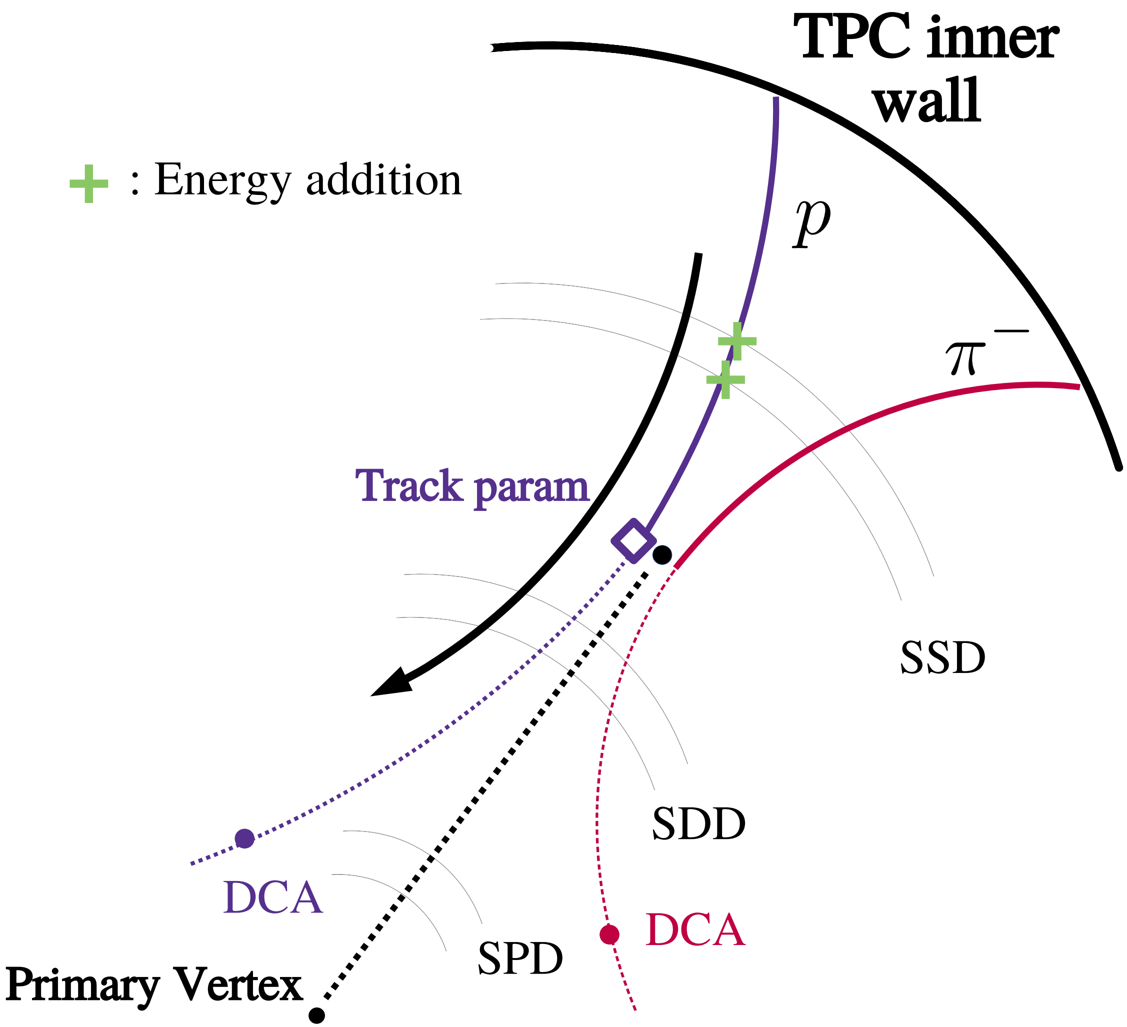

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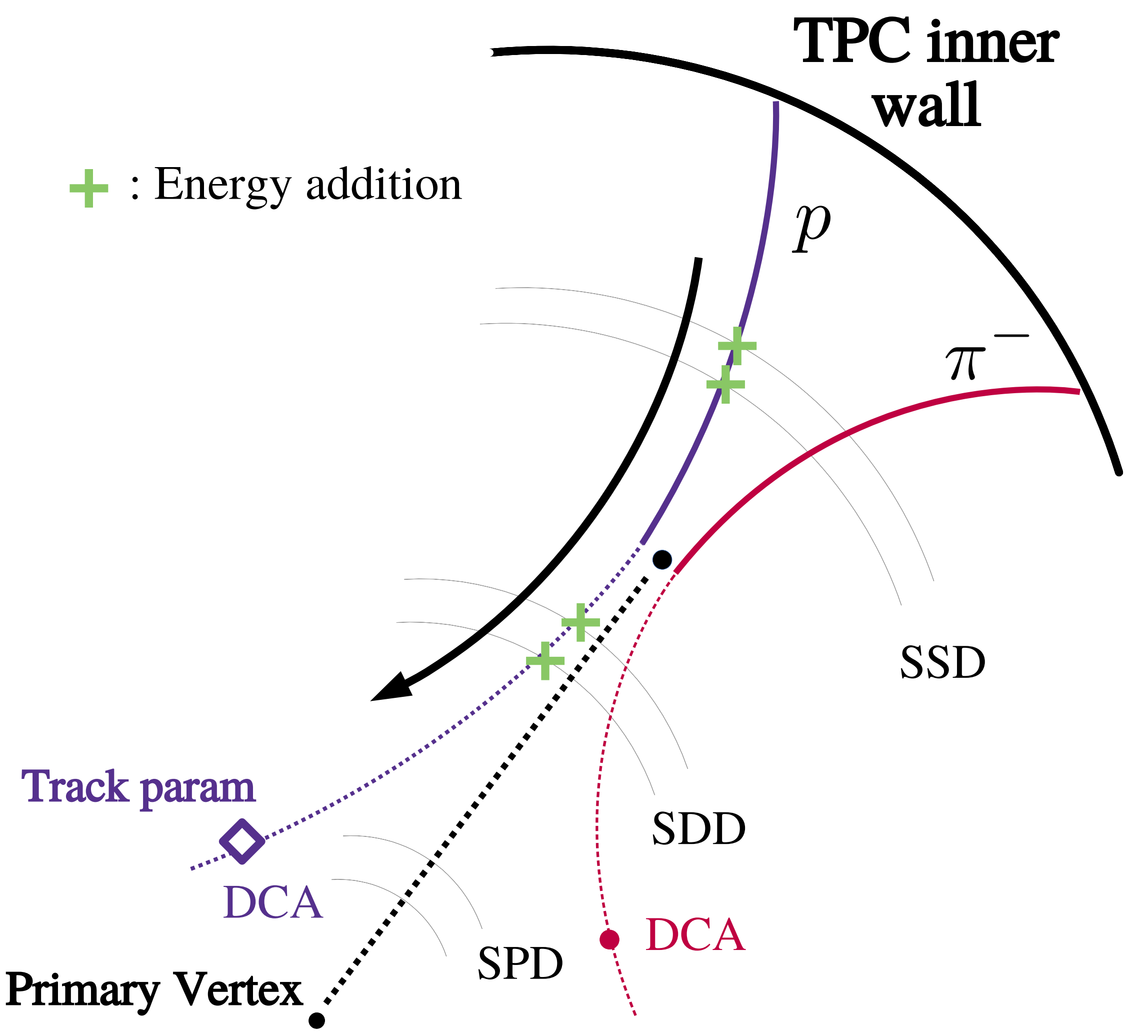

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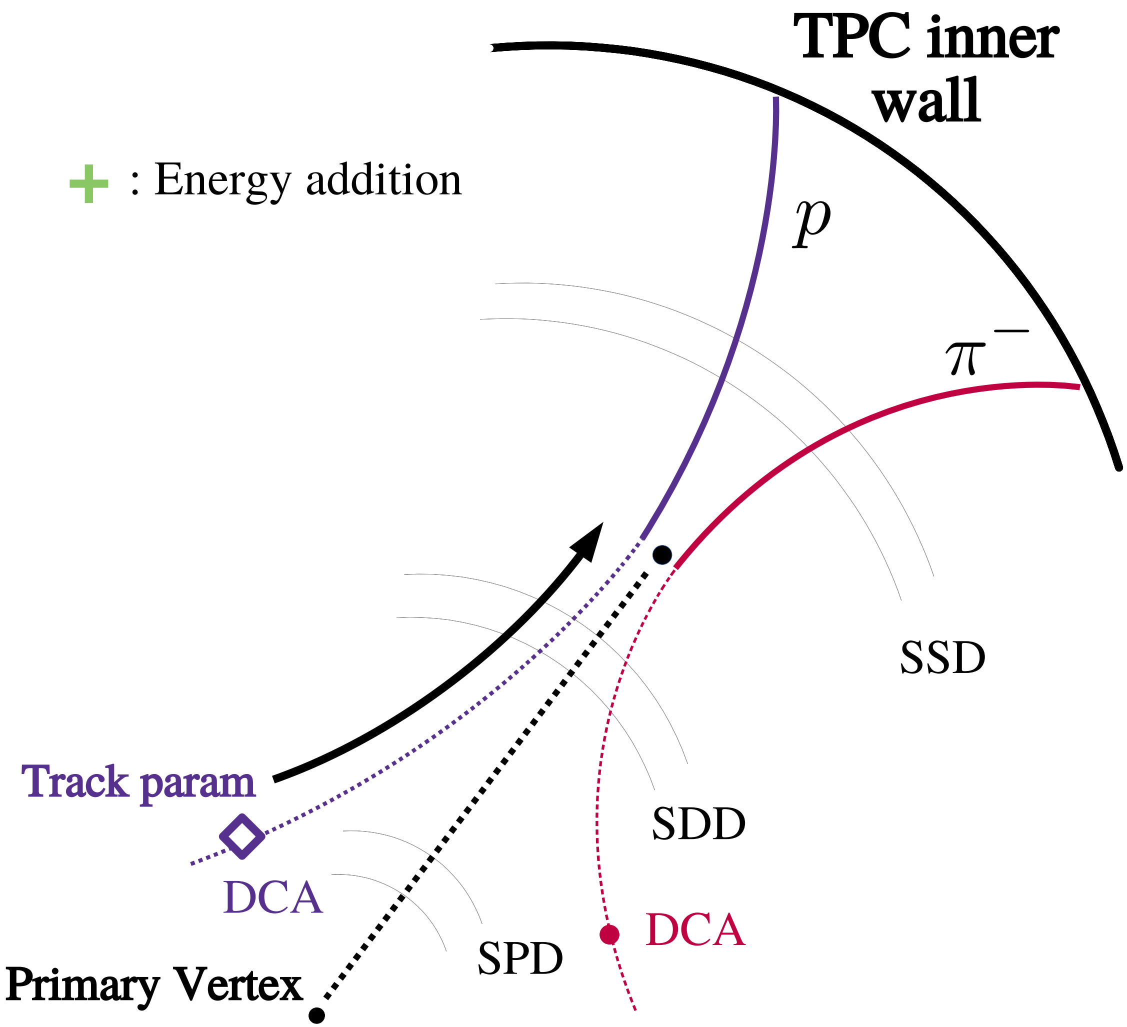

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- V0/cascade offline finding :
  - Propagate the tracks to decay point
  - Energy corrections are not redone
    - → **daughters have extra-momentum**
    - → **invariant mass is shifted**

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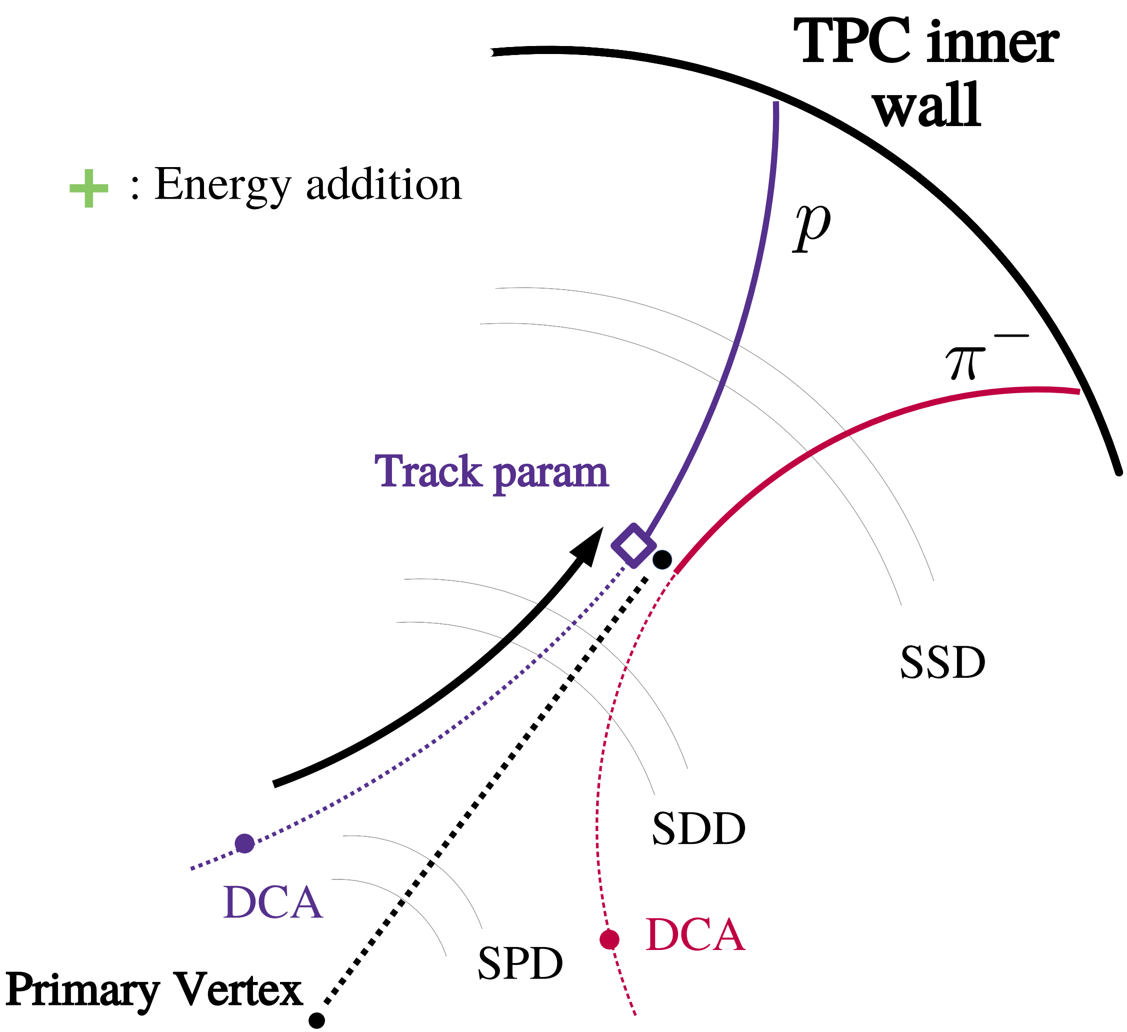

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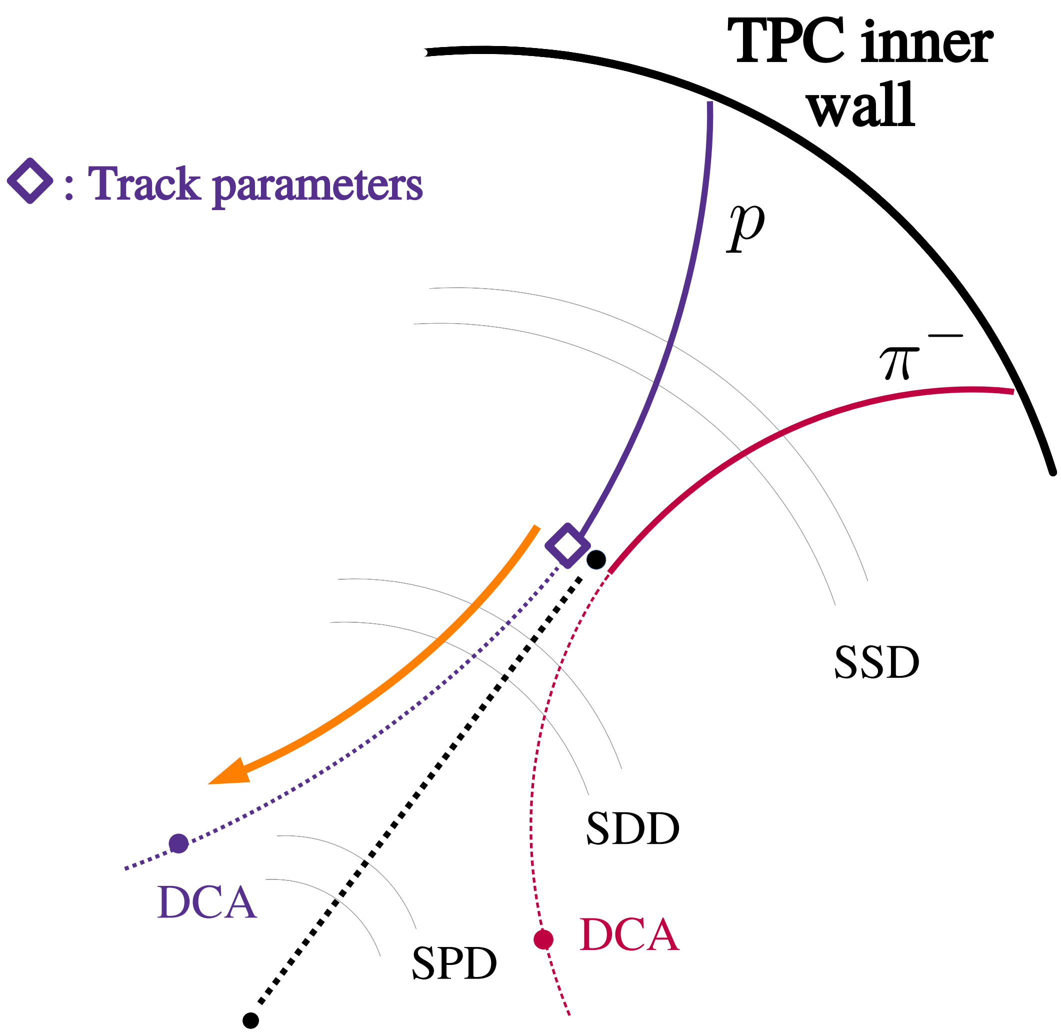
Apply retrocorrections

- 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

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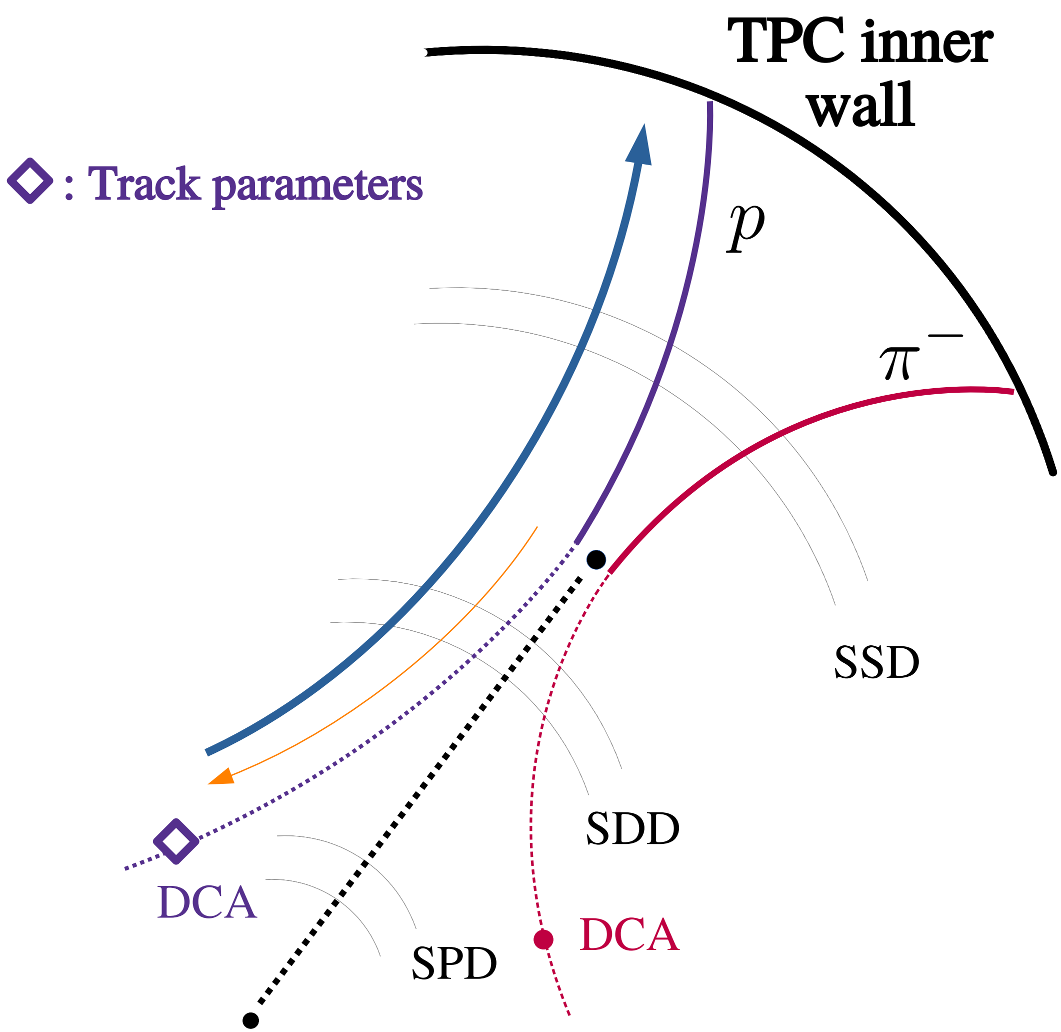

- 1st step : propagate to the DCA to PV **without** energy correction
- 2nd step : propagate to the TPC **with** energy correction (hyp : PID used during tracking)

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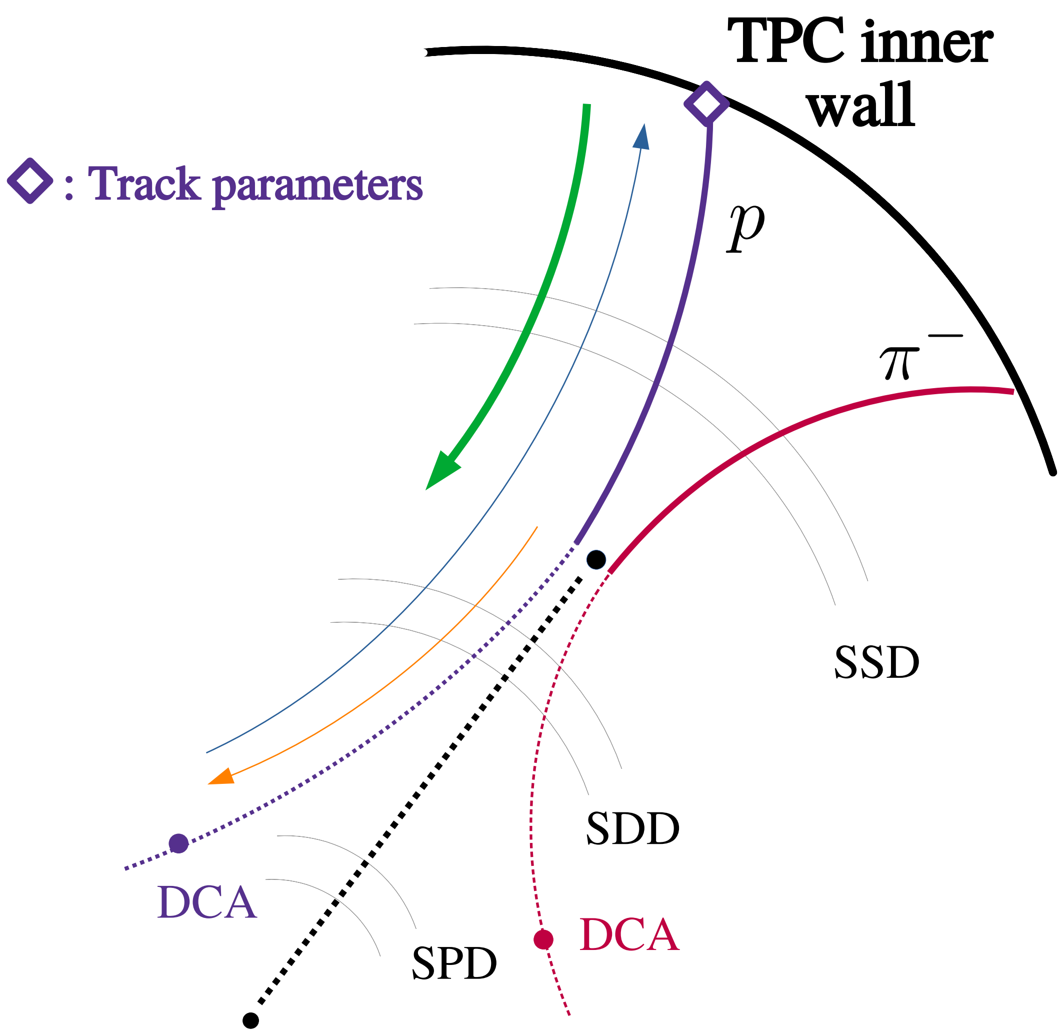

- 1st step : propagate to the DCA to PV **without** energy correction
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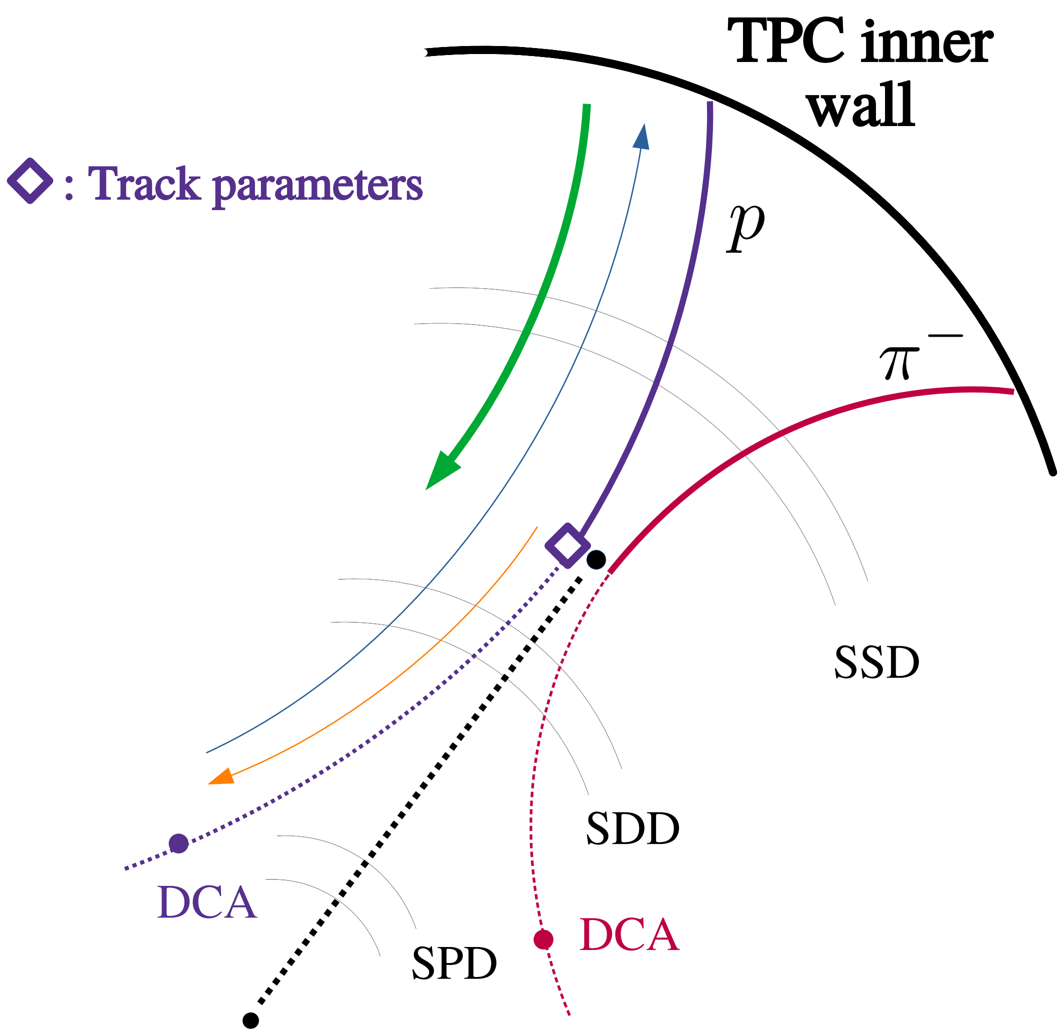

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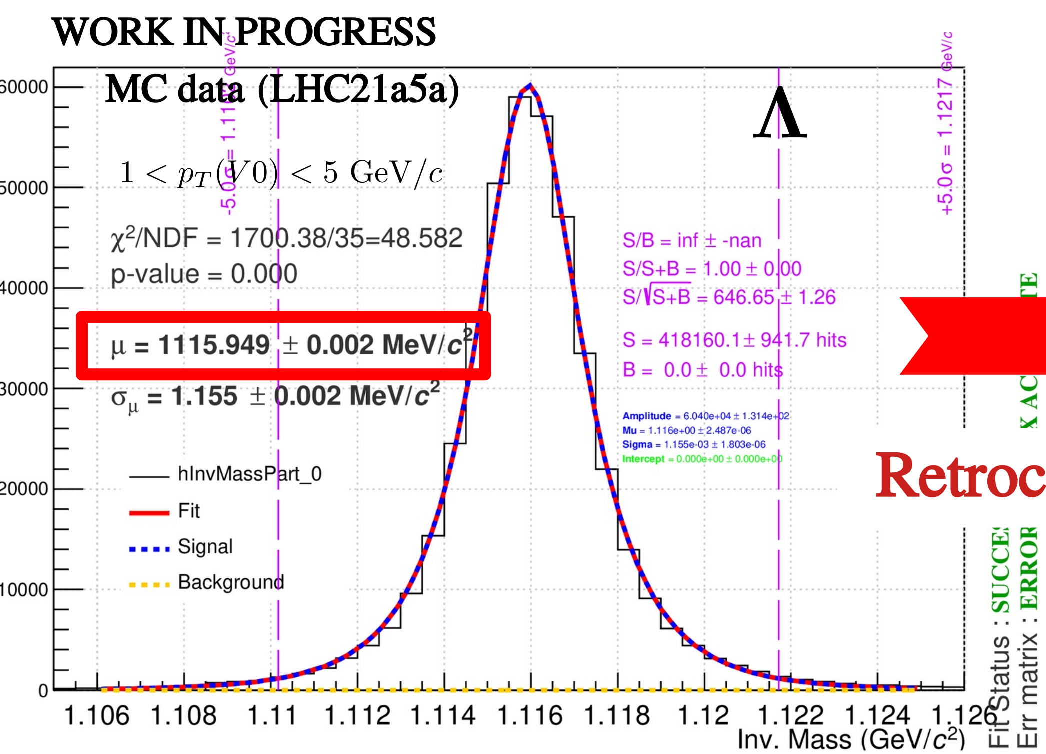
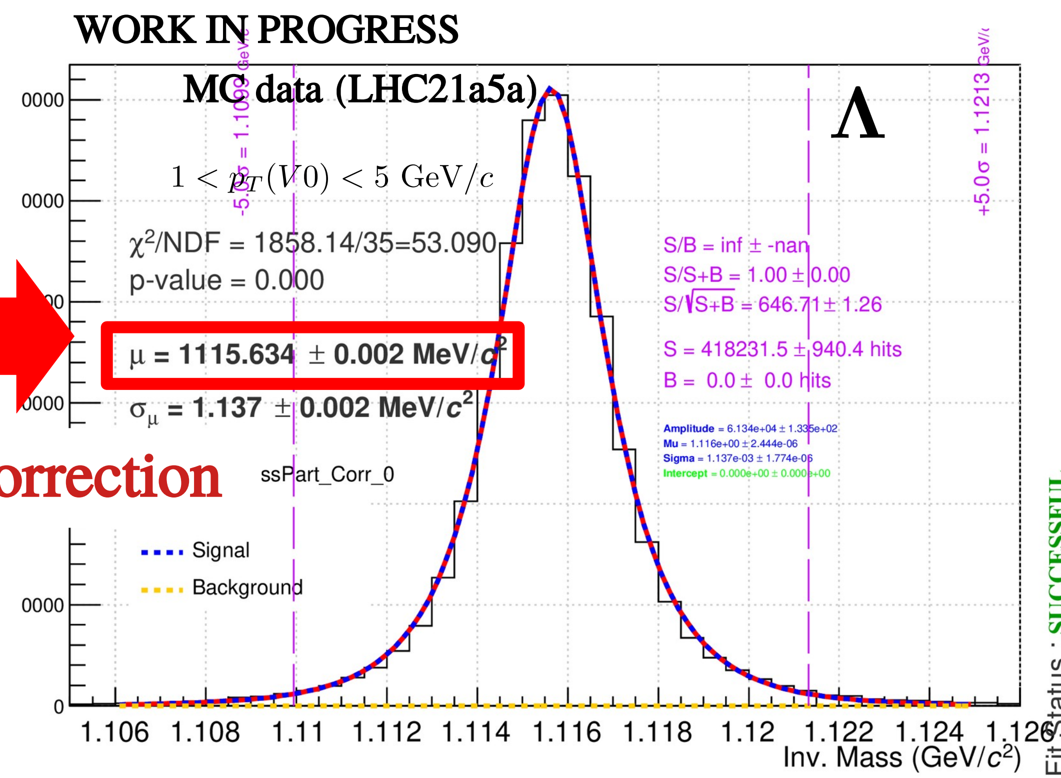
Λ Invariant mass

- 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)

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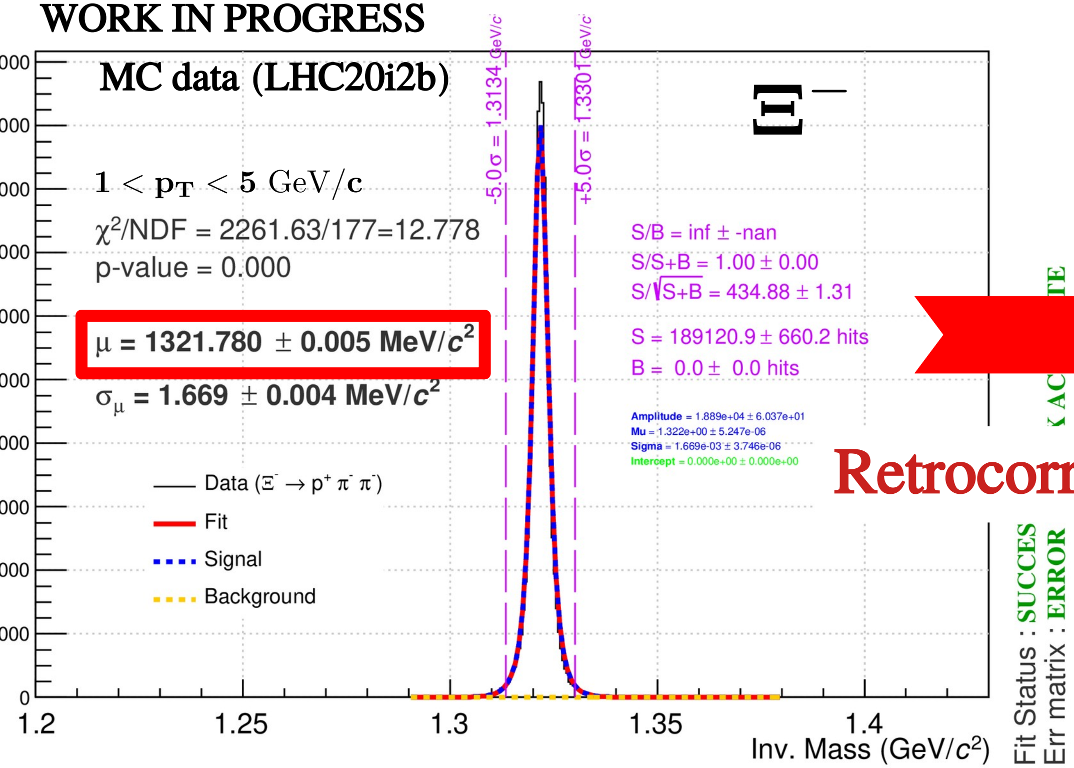
Ξ Invariant mass

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

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

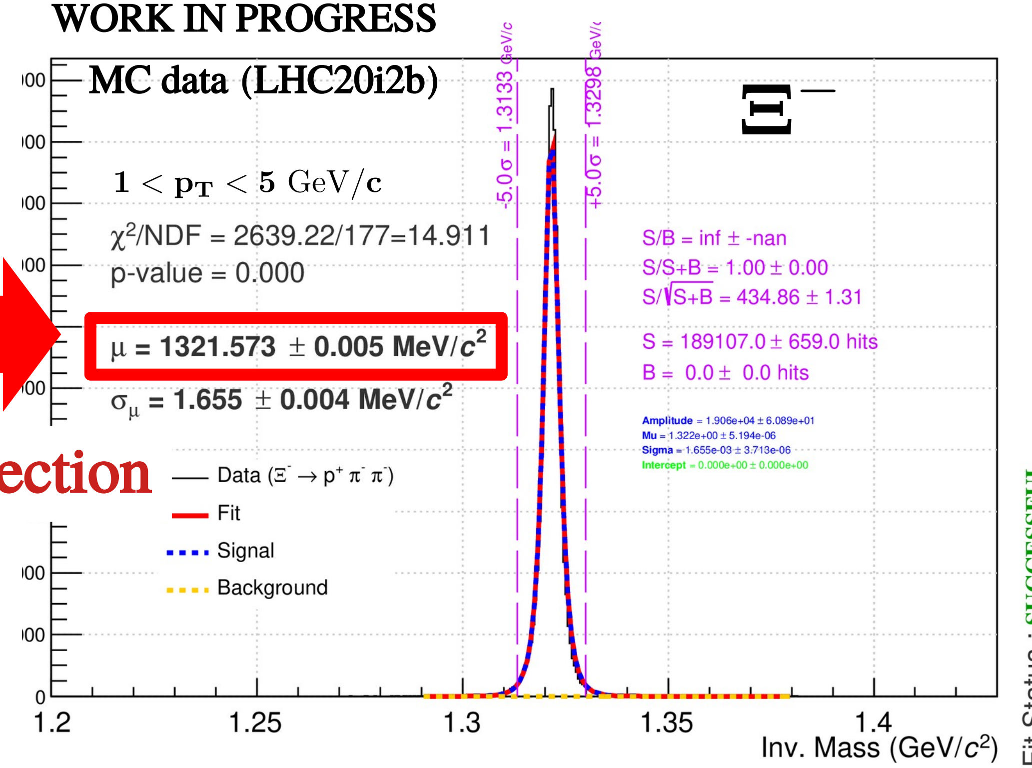
WORK IN PROGRESS



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

Retrocorrection

WORK IN PROGRESS

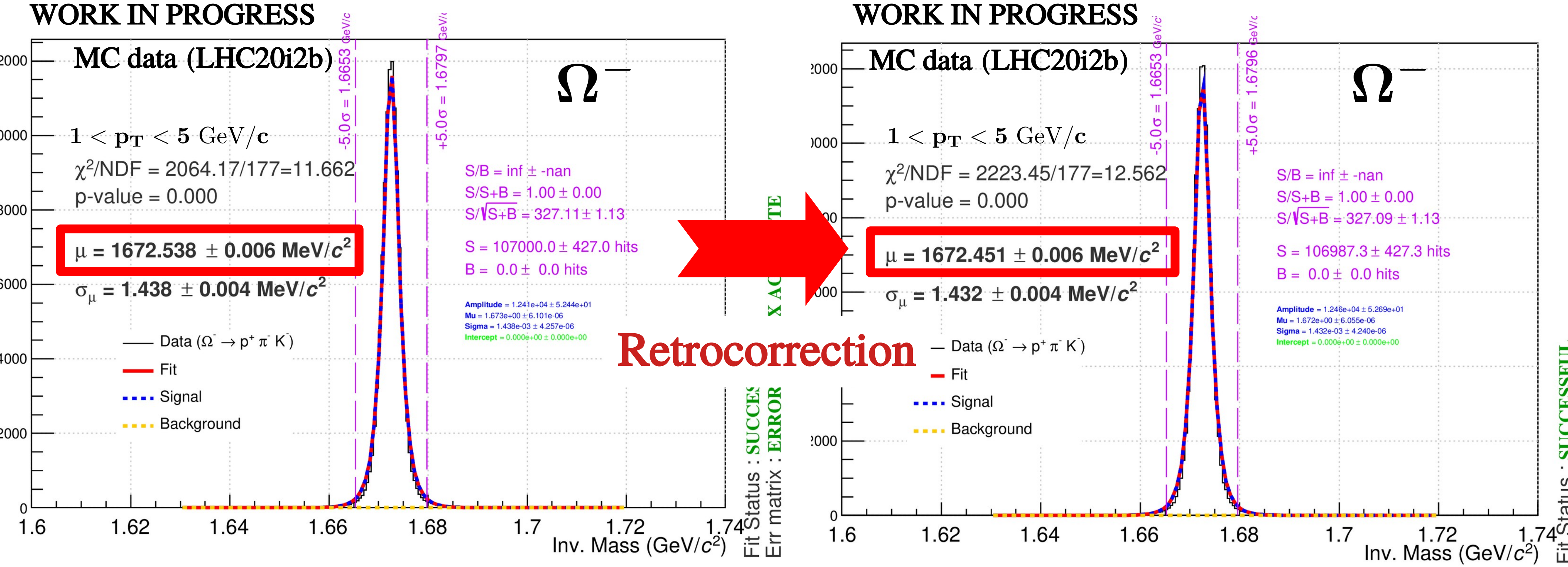


→ -137 keV shift wrt to PDG mass (injected mass)

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

- Current results :
  - 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

- A first glimpse on the complexity of such a measurement :
  - Our mass measurements have an offset wrt the PDG mass, mainly coming from extra energy addition during V0/cascade finding → corrected now

- All the systematics were not presented today :
  - Choice of the fit functions
  - B field precision
  - ...

- Next step :
  - Understand why our dE/dx retrocorrection works so well on Ω but not on Ξ

Backup slides

Systematic study strategy

- For each selection, a random number is extracted from the actual distribution of this variable in the variation range (using TUnuran)
- 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 μ_i
    → store in an histogram ➡ $\left\{ \begin{array}{l} \text{Mass} = \text{Mean} = \bar{\mu} \\ \sigma_{\text{syst}} = \text{RMS} \end{array} \right.$
  - The error on the mass σ_i
    → store in an histogram ➡ $\sigma_{\text{stat}} = \bar{\sigma}$

Systematic study strategy

- For each selection, a random number is extracted from the actual distribution of this variable in the variation range (using TUnuran)
- 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 $\Delta\mu_i/\mu_i^{\text{part}} = (\mu_i^{\overline{\text{part}}} - \mu_i^{\text{part}})/\mu_i^{\text{part}}$

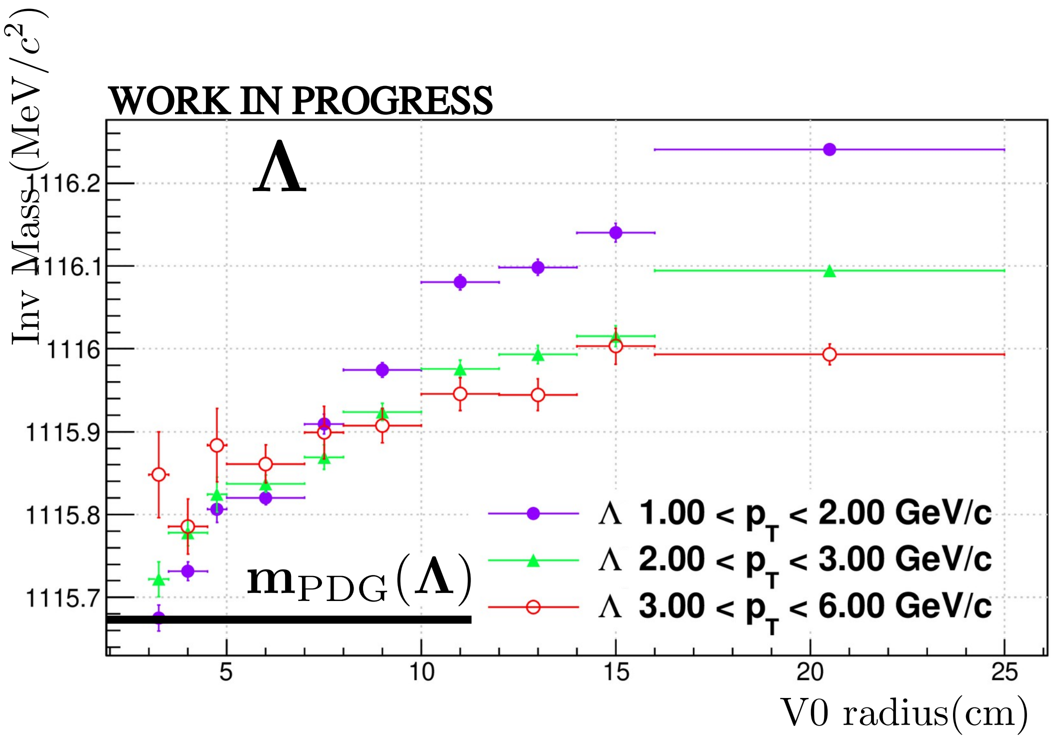
    → store in an histogram ➡
    $$\begin{cases} \frac{\Delta\text{Mass}}{\text{Mass}} = \text{Mean} = \overline{\frac{\Delta\mu_i}{\mu_i^{\text{part.}}}} \\ \sigma_{\text{syst}} = \text{RMS} \end{cases}$$
  - The error on the mass difference $\sigma_{(\mu_i^{\overline{\text{part}}} - \mu_i^{\text{part}})/\mu_i^{\text{part}}}$

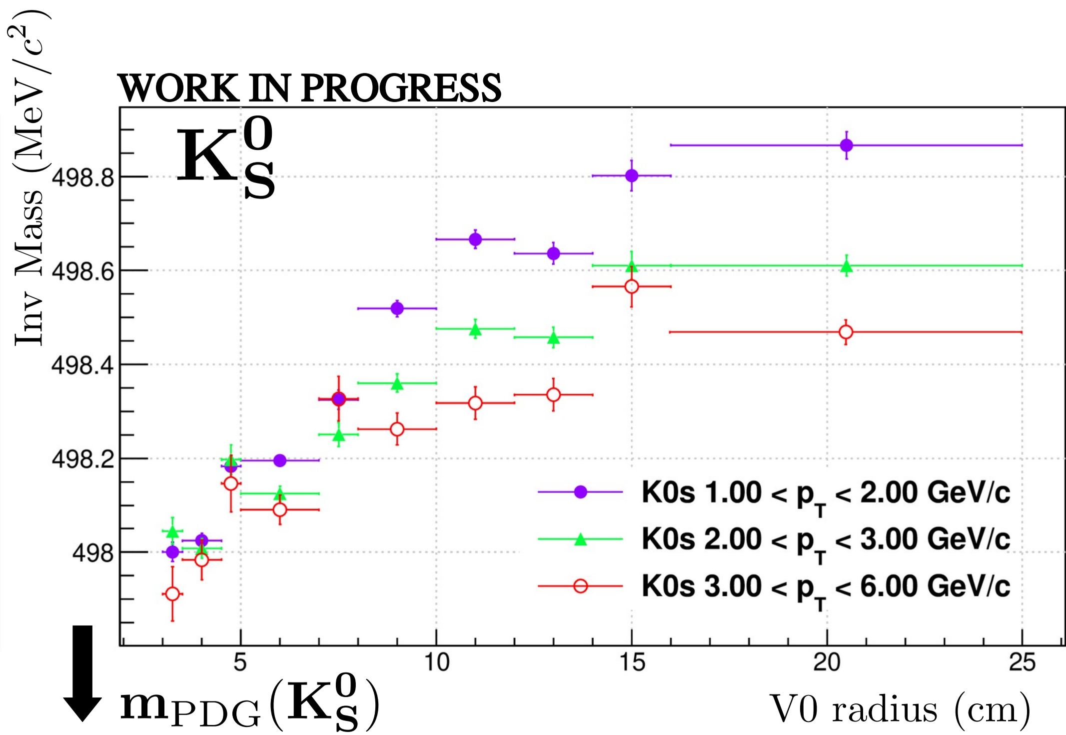
    → store in an histogram ➡ $\sigma_{\text{stat}} = \overline{\sigma}_{(\mu_i^{\overline{\text{part}}} - \mu_i^{\text{part}})/\mu_i^{\text{part}}}$

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

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

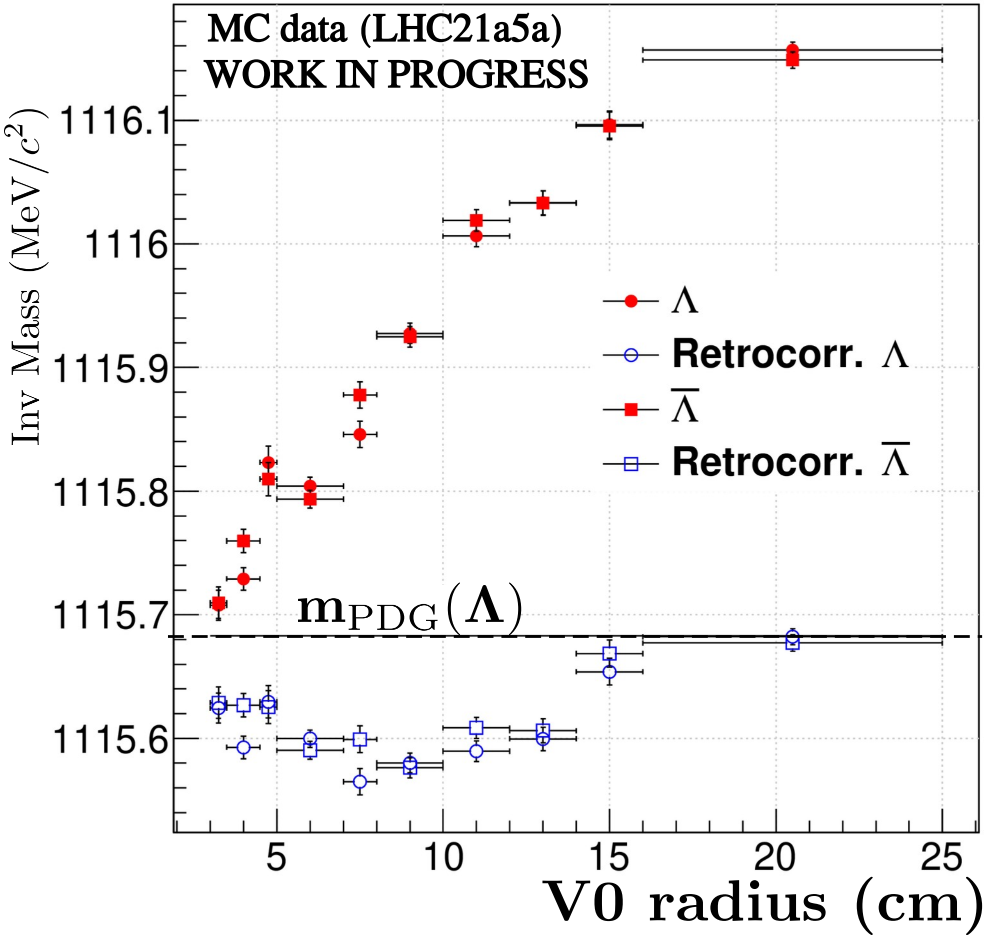




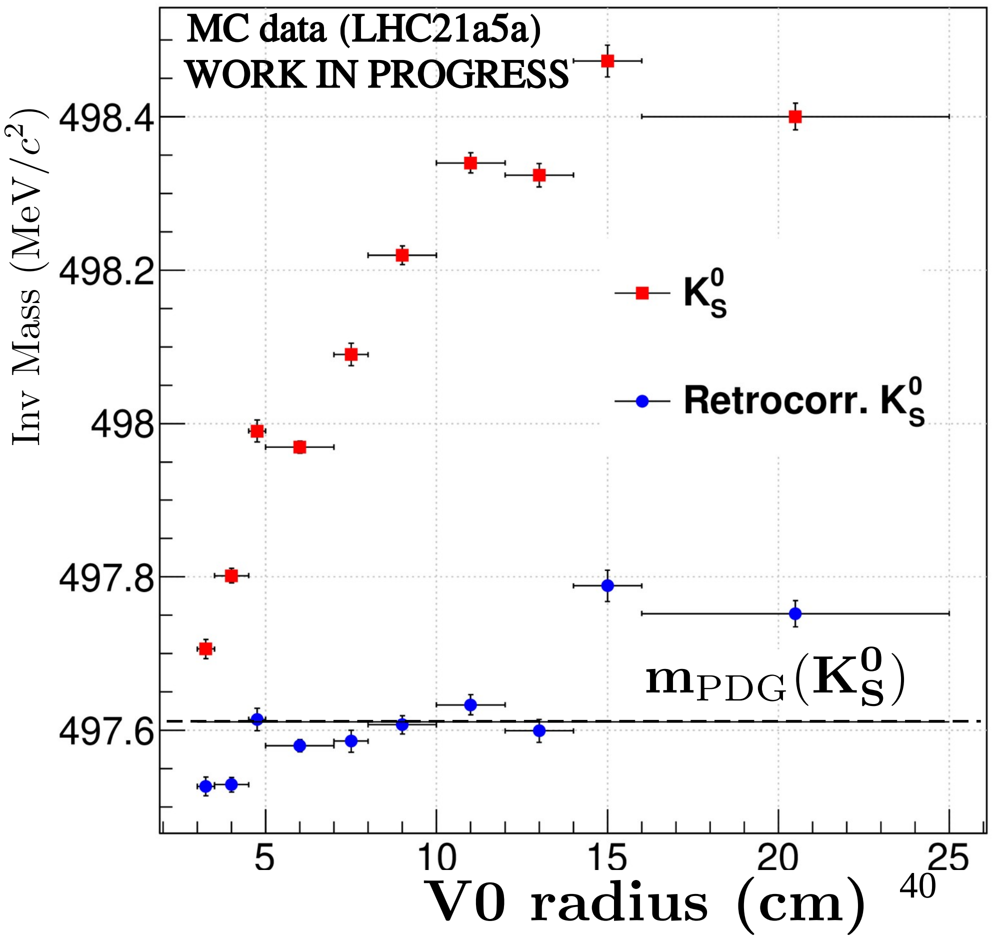
Invariant mass Vs radius

- 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/$\mathbf{c^2}$

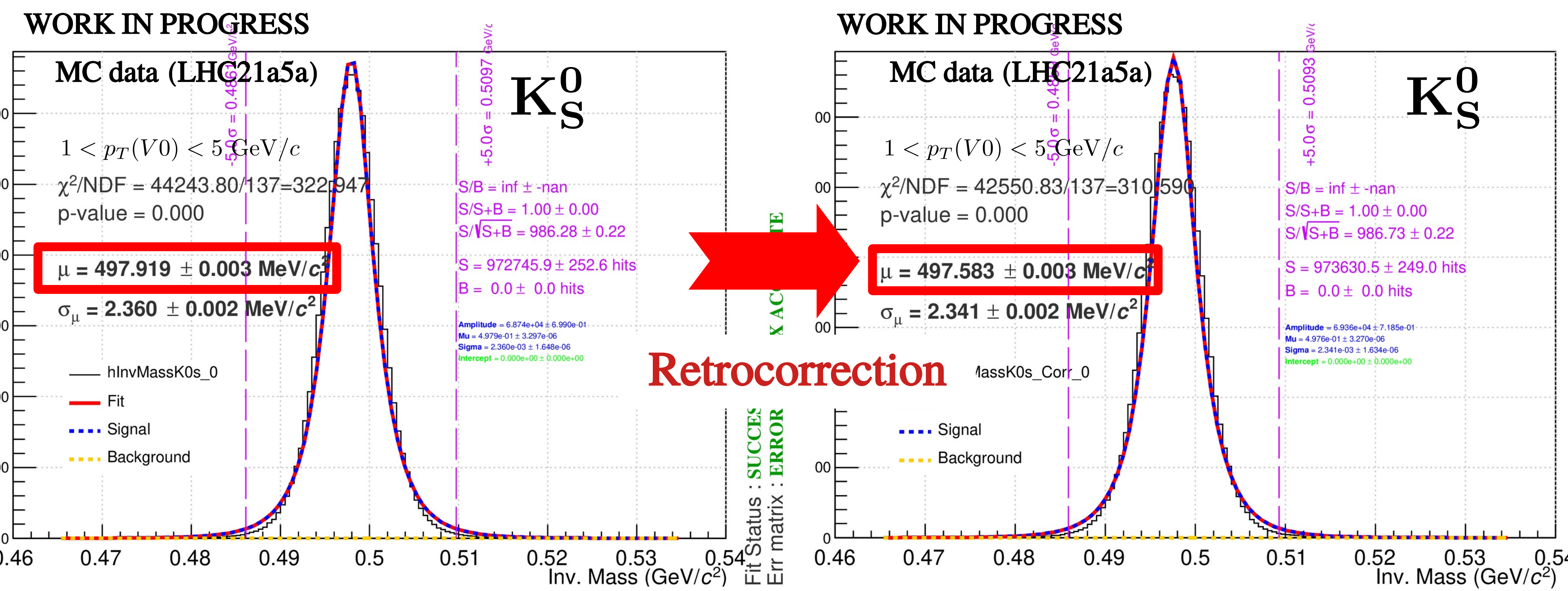


K0s Invariant mass

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

  → look at the invariant mass

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



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

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

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

Ξ selections

- Candidates are **<u>primary</u>** 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