Search for LFU violation in Semileptonic Hyperon Decays at LHCb

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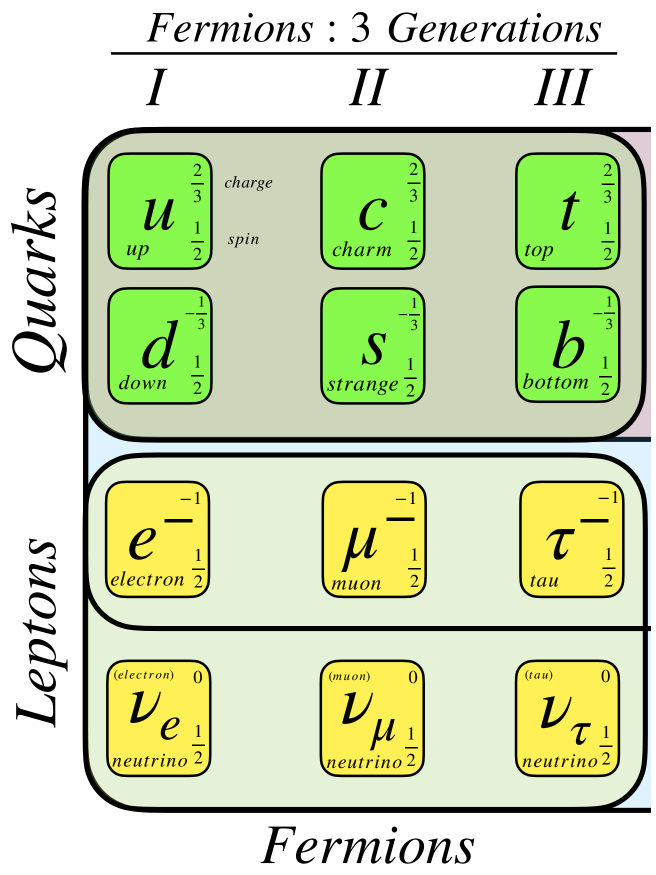
SPS MEETING
11/09/2024

Lepton Universality

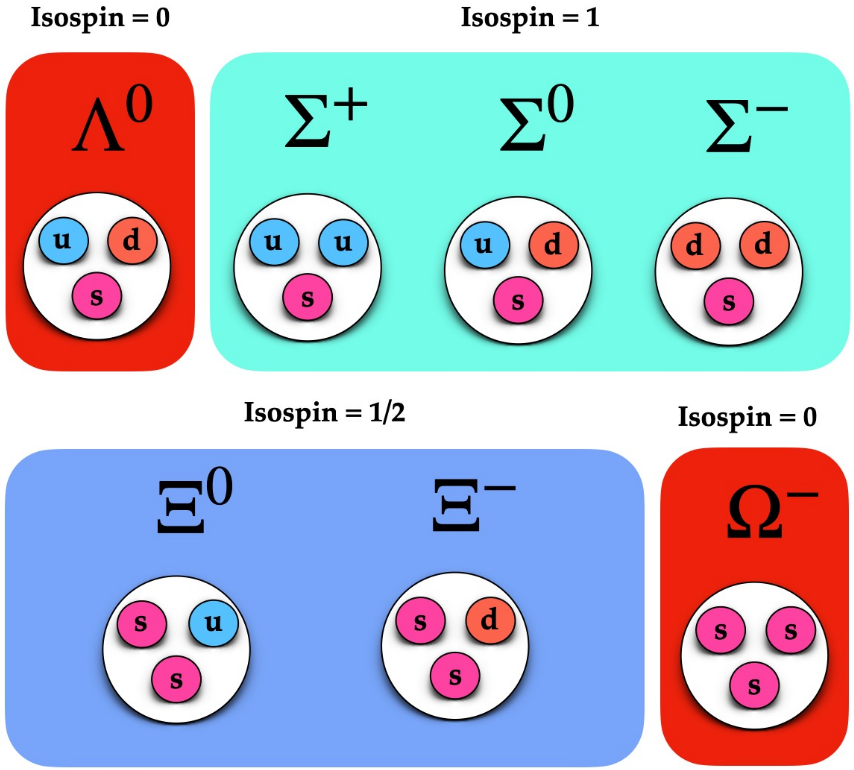


- In the SM, the **couplings** of leptons to all types of gauge bosons are **flavor-independent**. This is called Lepton Universality (LFU).

- Experimental **tests of LFU** → comparing **rates of decays** across **different lepton flavors** and looking for deviations from the expected ratios.

- A **verified violation** would point to **Beyond the Standard Model** (BSM) physics.

Hyperon Decays

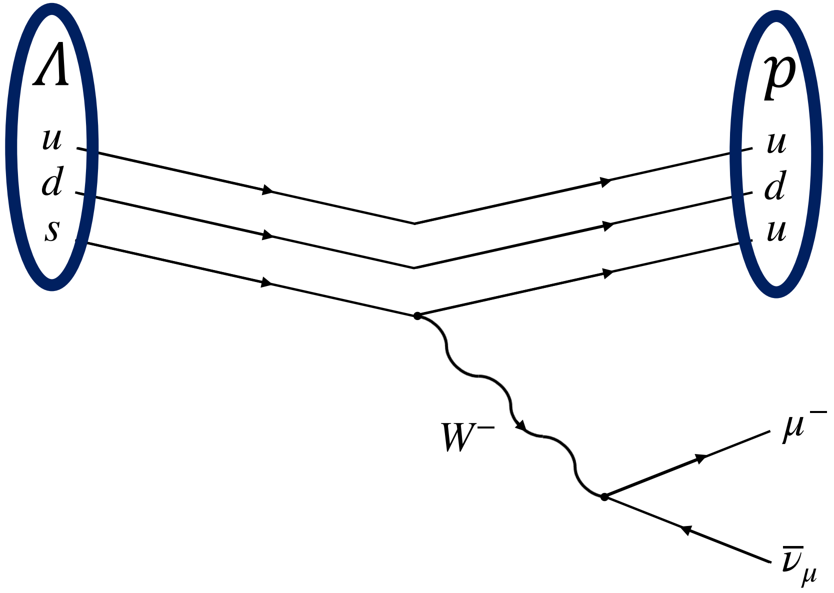


- **QCD → SU(3)-flavor symmetry** would allow the interchange of different quark flavors within hadrons. Different quark masses → This symmetry **is not exact.**

- At energy scales where the strong interaction is the predominant, **u, d, and s quarks masses are similar** → nearly interchangeable.

- **Approximate SU(3)-flavor symmetry**, particularly relevant **for hyperons**

Semileptonic Hyperon Decays



- The **LFU test observable** defined as the ratio between muon and electron modes

$$R^{\mu e} = \frac{\Gamma(B_1 \to B_2 \mu^- \bar{\nu}_\mu)}{\Gamma(B_1 \to B_2 e^- \bar{\nu}_e)}$$

is **sensitive** to non standard scalar and tensor contributions.

- In the SM, the **dependence** on the form factors is anticipated to **simplify** when considering the **ratio**.

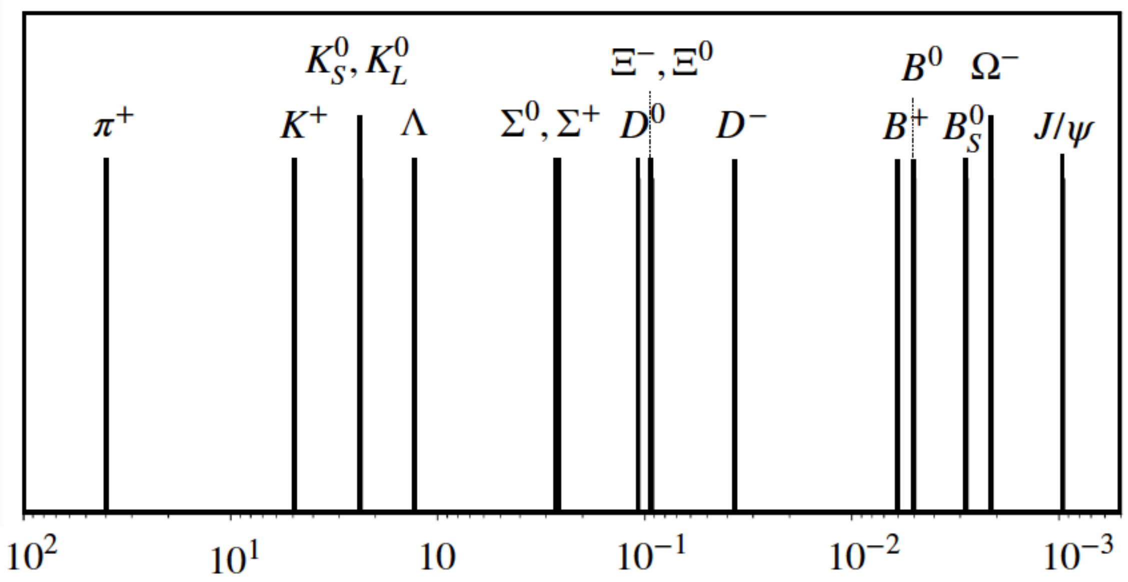
$$R^{\mu e}_{\mathrm{SM}} = \sqrt{1 - \frac{m_\mu^2}{\Delta^2}}\left(1 - \frac{9}{2}\frac{m_\mu^2}{\Delta^2} - 4\frac{m_\mu^4}{\Delta^4}\right) + \frac{15}{2}\frac{m_\mu^4}{\Delta^4}\operatorname{arctanh}\left(\sqrt{1 - \frac{m_\mu^2}{\Delta^2}}\right)$$

H.-M. Chang, M. González-Alonso, and J. Martin Camalich, "Nonstandard Semileptonic Hyperon Decays", Phys. Rev. Lett. 114 no. 16, (2015) 161802,arXiv:1412.8484 [hep-ph].

Strange physics at LHCb

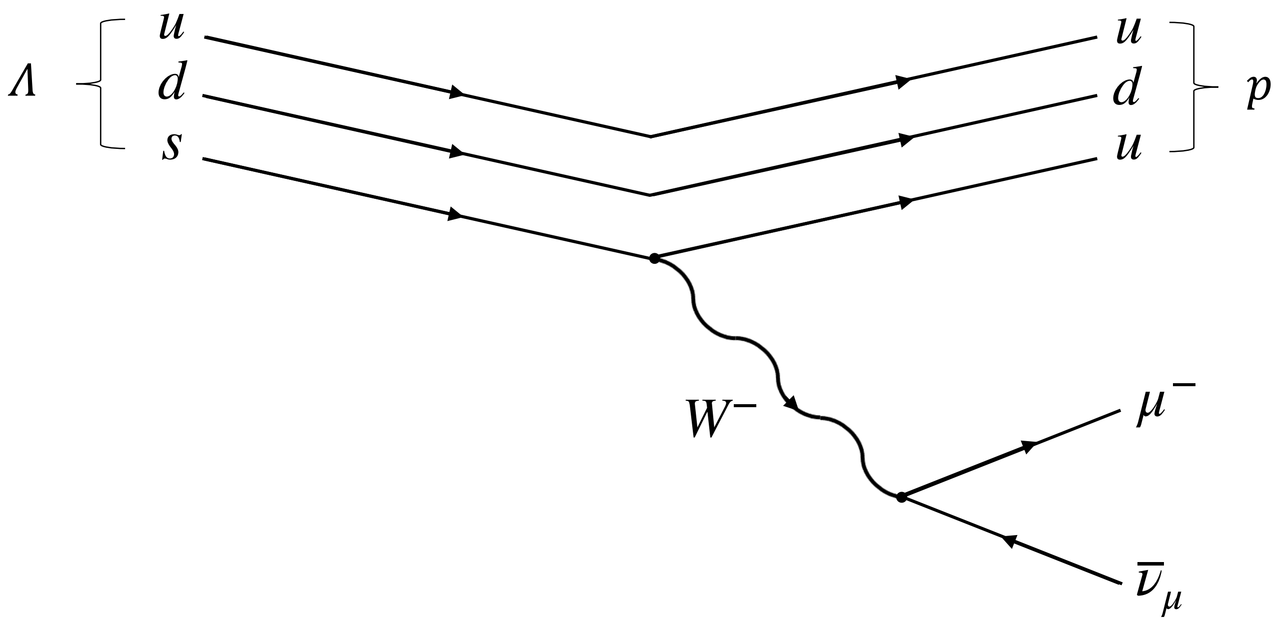
- LHCb obtained **leading strange physics measurements**, particularly searching for their rare decays, publishing best measurements in $K_S^0 \to \mu^+ \mu^-$, $K_S^0 \to \mu^+ \mu^- \mu^+ \mu^-$, and $\Sigma^+ \to p\, \mu^+ \mu^-$.

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	σ_L $\left(\frac{\text{MeV}}{c^2}\right)$	σ_D $\left(\frac{\text{MeV}}{c^2}\right)$
$K_S^0 \to \mu^+\mu^-$	1	1.0 (1.0)	1.8 (1.8)	~3.0	~8.0
$K_S^0 \to \pi^+\pi^-$	1	1.0 (0.30)	1.9 (0.91)	~2.5	~7.0
$K_S^0 \to \pi^0\mu^+\mu^-$	1	0.93 (0.93)	1.5 (1.5)	~35	~45
$K_S^0 \to \gamma\mu^+\mu^-$	1	0.85 (0.85)	1.4 (1.4)	~60	~60
$K_S^0 \to \mu^+\mu^-\mu^+\mu^-$	1	0.37 (0.37)	1.1 (1.1)	~1.0	~6.0
$K_L^0 \to \mu^+\mu^-$	~1	2.7 (2.7) $\times 10^{-3}$	0.014 (0.014)	~3.0	~7.0
$K^+ \to \pi^+\pi^+\pi^-$	~2	9.0 (0.75) $\times 10^{-3}$	41 (8.6) $\times 10^{-3}$	~1.0	~4.0
$K^+ \to \pi^+\mu^+\mu^-$	~2	6.4 (2.3) $\times 10^{-3}$	0.030 (0.014)	~1.5	~4.5
$\Sigma^+ \to p\mu^+\mu^-$	~0.13	0.28 (0.28)	0.64 (0.64)	~1.0	~3.0
$\Lambda \to p\pi^-$	~0.45	0.41 (0.075)	1.3 (0.39)	~1.5	~5.0
$\Lambda \to p\mu^-\bar{\nu}_\mu$	~0.45	0.32 (0.31)	0.88 (0.86)	-	-
$\Xi^- \to \Lambda\mu^-\bar{\nu}_\mu$	~0.04	39 (5.7) $\times 10^{-3}$	0.27 (0.09)	-	-
$\Xi^- \to \Sigma^0\mu^-\bar{\nu}_\mu$	~0.04	24 (4.9) $\times 10^{-3}$	0.21 (0.068)	-	-
$\Xi^- \to p\pi^+\pi^-$	~0.04	0.41 (0.05)	0.94 (0.20)	~3.0	~9.0
$\Xi^0 \to p\pi^-$	~0.03	1.0 (0.48)	2.0 (1.3)	~5.0	~10
$\Omega^- \to \Lambda\pi^-$	~10^{-3}	95 (6.7) $\times 10^{-3}$	0.32 (0.10)	~7.0	~20



Multiplicity of particles produced in a single pp interaction at $\sqrt{s}$ = 13 TeV within LHCb acceptance.

$\mathcal{B}\ (\Lambda \rightarrow p\ \mu^{-} \bar{\nu}_{\mu})$ measurement in LHCb



Motivation

- Improved measurement directly translates into tighter **bounds on LFU (s → u)**, since the electron mode has already been measured very precisely, $\mathcal{B}(\Lambda \rightarrow p\ e^{-}\nu_{e}) = (8.34 \pm 0.14) \times 10^{-4}$

$$\mathbf{R^{\mu e}} = \mathcal{B}\,(\Lambda \rightarrow p\,\mu^{-}\bar{\nu}_{\mu})\,/\,\mathcal{B}\,(\Lambda \rightarrow p\,e^{-}\bar{\nu}_{e})$$

$$R^{\mu e}_{prediction} = 0.153 \pm 0.008,\ R^{\mu e}_{exp} = 0.178 \pm 0.028,$$

- Best branching ratio measurement right now is from BESIII (2021):

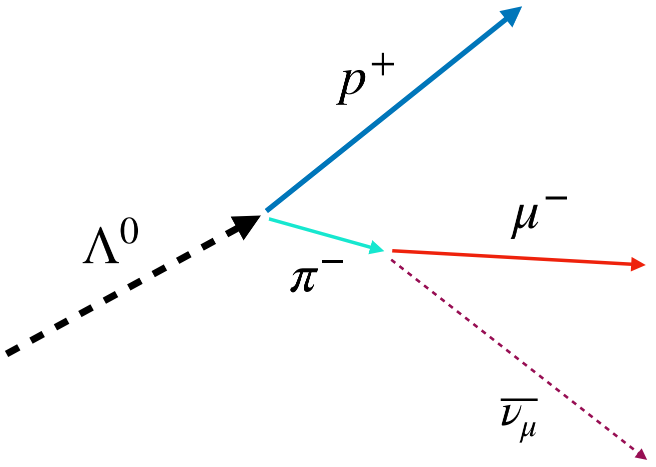
$\mathcal{B}\,(\Lambda \rightarrow p\,\mu^{-}\bar{\nu}_{\mu}) = (1.48 \pm 0.21) \times 10^{-4}$ **14.19 % Uncertainty**

<u>**The goal is to obtain a better result.**</u>

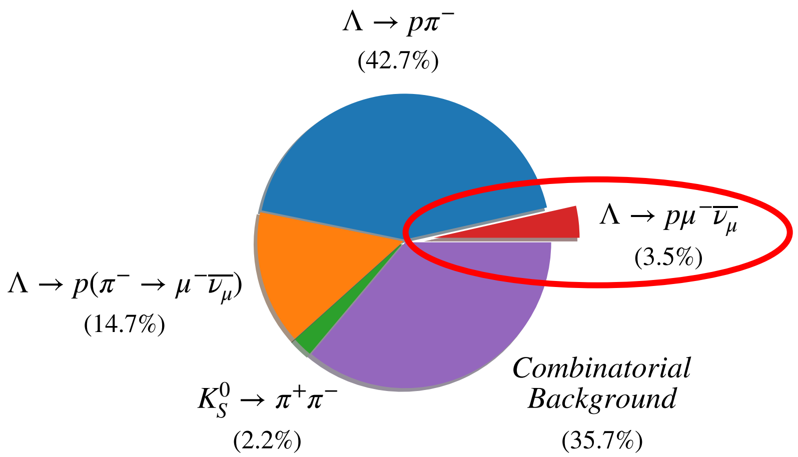
BESIII Collaboration "First Measurement of the Absolute Branching Fraction of $\Lambda \rightarrow p\,\mu^{-}\nu_{\mu}$".
In: Phys. Rev. Lett. 2019), 127, 121802

Challenges

	Λ DECAY MODES			
	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$p\pi^-$		(64.1 ± 0.5) %	
Γ_2	$n\pi^0$		(35.9 ± 0.5) %	
Γ_3	$n\gamma$		$(8.3 \pm 0.7) \times 10^{-4}$	
Γ_4	$p\pi^-\gamma$	[a]	$(8.5 \pm 1.4) \times 10^{-4}$	
Γ_5	$pe^-\overline{\nu}_e$		$(8.34 \pm 0.14) \times 10^{-4}$	
Γ_6	$p\mu^-\overline{\nu}_\mu$		$(1.51 \pm 0.19) \times 10^{-4}$	



Almost **2/3 of Λ** particles decay into a **proton and a pion**, resulting in two potential background categories:



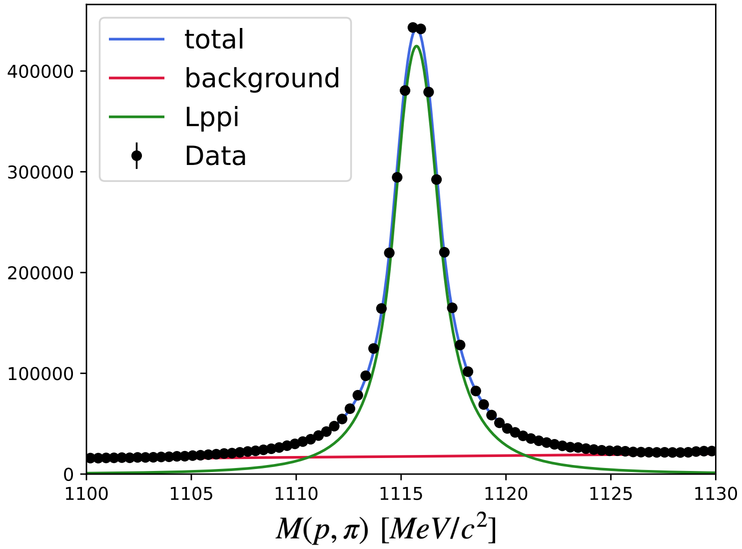
Analysis Strategy

2015 - 2018 Data

$\Lambda \to p\,\pi^-$

Normalisation Data Sample

Fit $\Lambda \to p\,\pi^-$ in Data



N $(\Lambda \to p\,\pi^-)$ and N (Λ)

Aligned Cuts

Different PID Cuts

$\mathcal{B}\,(\Lambda \to p\,\mu^-\bar{\nu}_\mu)$

$\Lambda \to p\,\mu^-\bar{\nu}_\mu$

Signal Data Sample

Design Selection

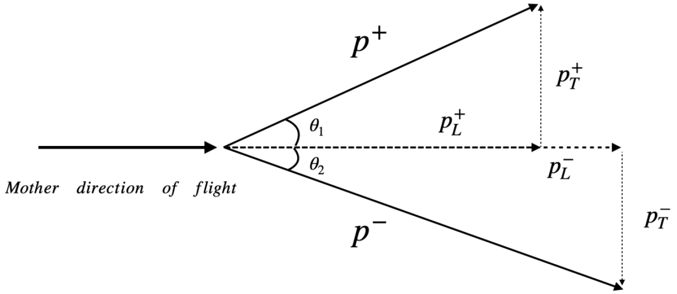
Fit Signal yield in SignalLine

N $(\Lambda \to p\,\mu^-\bar{\nu}_\mu)$

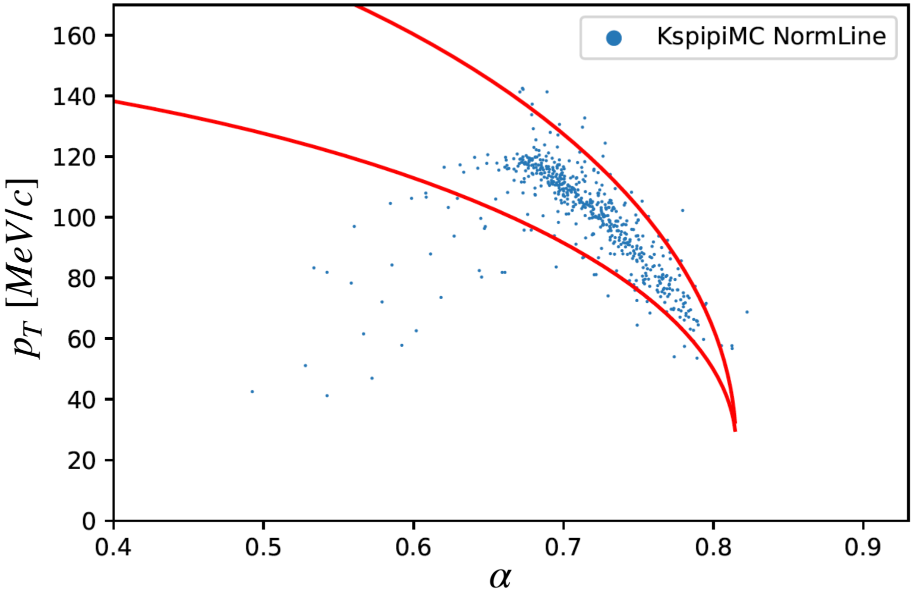
Normalization

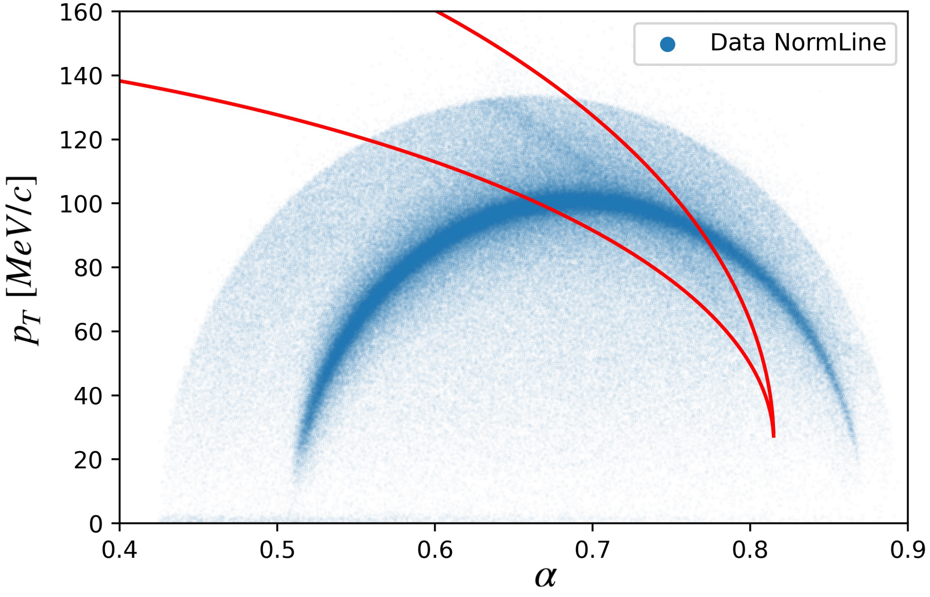
Normalization Selection

Armenteros Cut to remove $K_s^0 \to \pi^+ \pi^-$



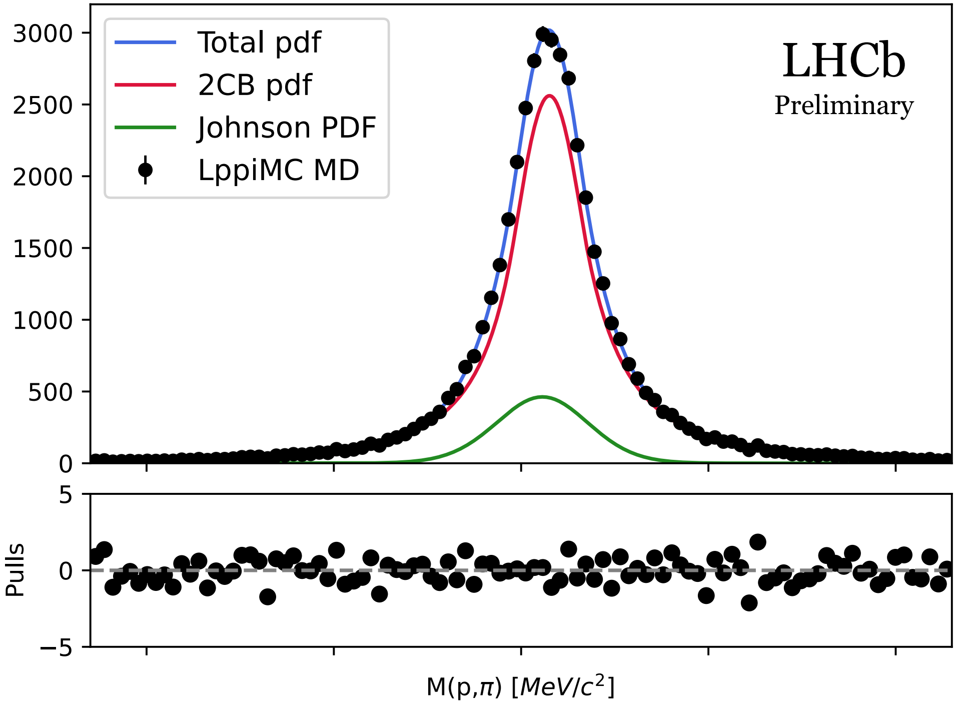
$$\alpha = \frac{p_L^+ - p_L^-}{p_L^+ + p_L^-}$$





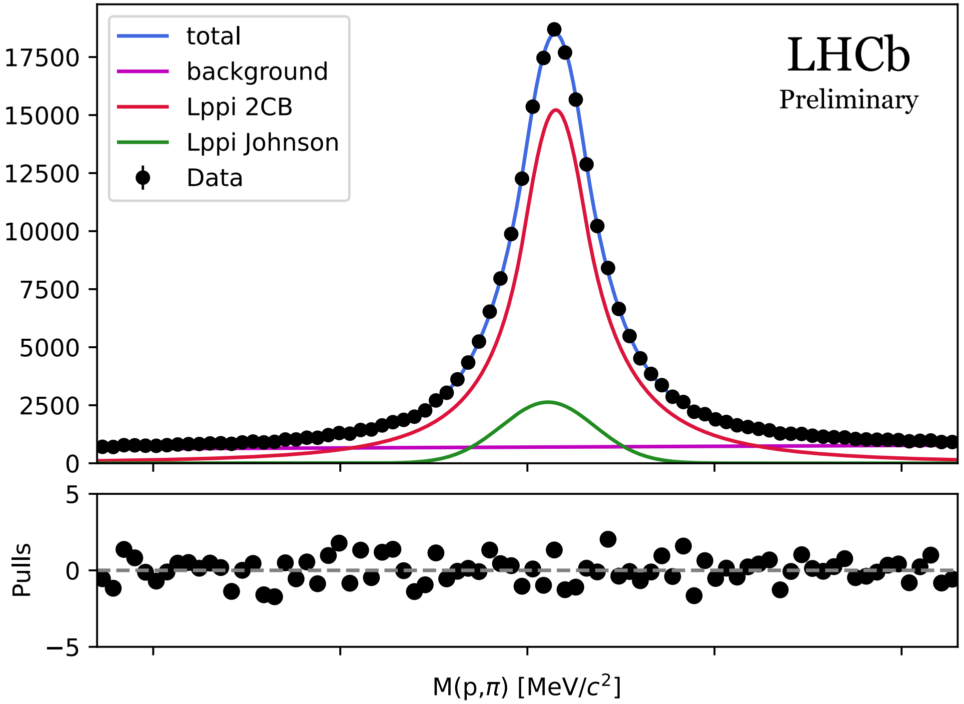
Normalization

Simulation



Pure $\Lambda \to p\,\pi^-$ MC sample

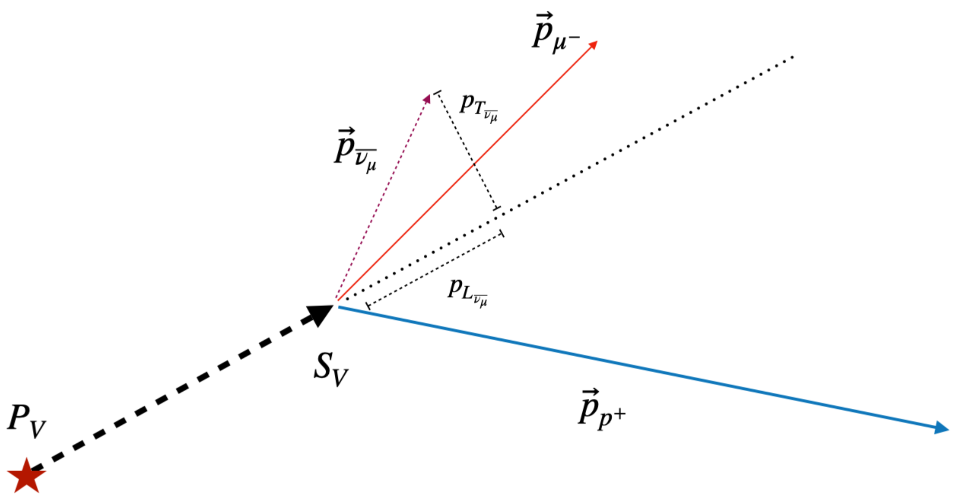
Data (NormLine)



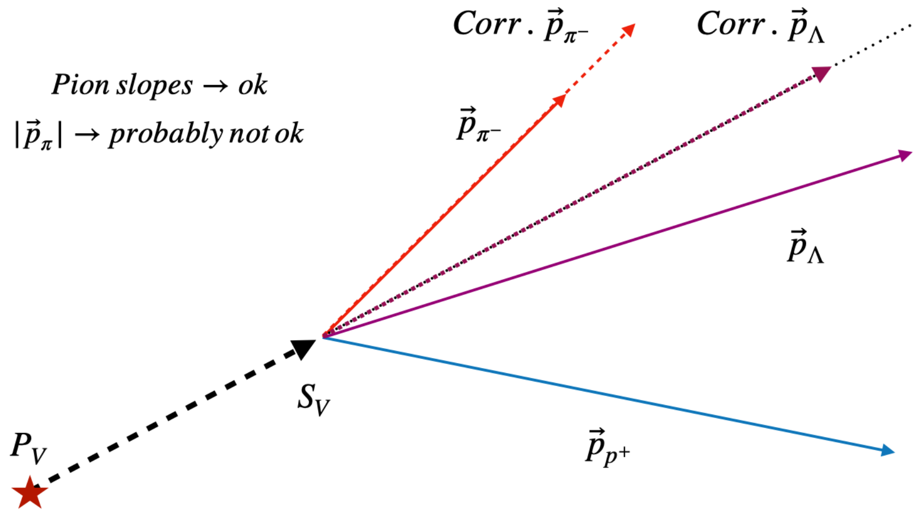
Constraint tail parameters

Signal Selection and Fit

Kinematic Strategy



Muon at VELO level



Pion at VELO level

$p_T(\nu_\mu)$: obtained from proton and muon (PTmiss)
$p_L(\nu_\mu)$: obtained by imposing Λ mass
→ **recovered neutrino momentum components**

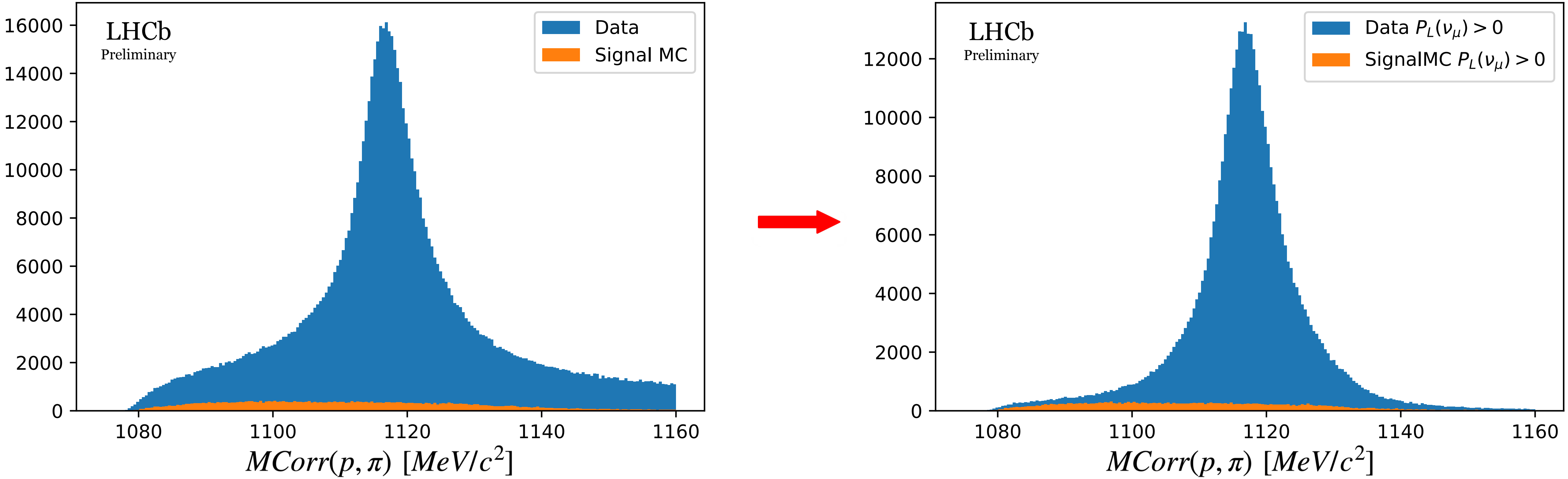
$$p_L(\nu_\mu) = \frac{E_{p\mu}.\sqrt{A^2 - M_\Lambda^2.\not{p}_T^2} - A.p'_{p\mu_z} + p'_{p\mu_z}.\not{p}_T^2}{(p'_{p\mu_z})^2 - E_{p\mu}^2}$$

If $|p_\pi|$ not ok, Λ will not point to PV.
Imposing Λ to point to PV allows to solve for $|p_\pi|$.

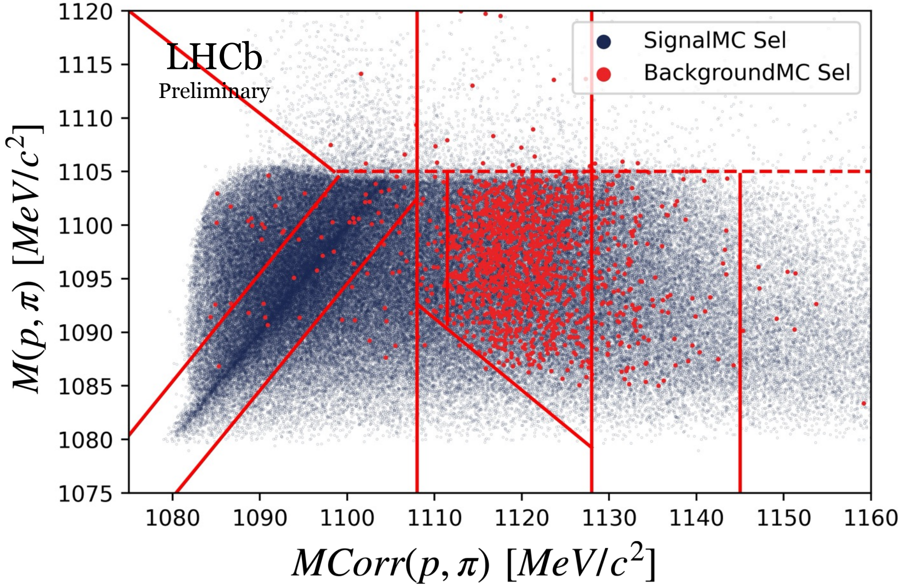
If it is a $\Lambda \to p\pi$, recomputed $M(p,\pi)$ using
the obtained value of $|p|$ will peak at Λ PDG mass.
→ **MCorr(pπ).**

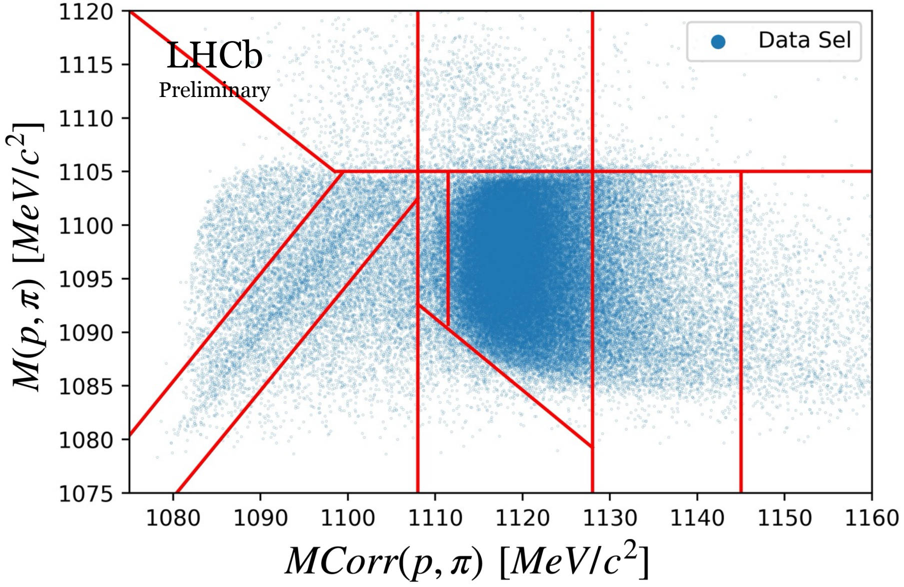
Selection

$$p_L(\nu_\mu) = \frac{E_{p\mu}.\sqrt{A^2 - M_\Lambda^2.\not{p}_T^2} - A.p'_{p\mu_z} + p'_{p\mu_z}.\not{p}_T^2}{(p'_{p\mu_z})^2 - E_{p\mu}^2}$$



2D Signal Yield Fit





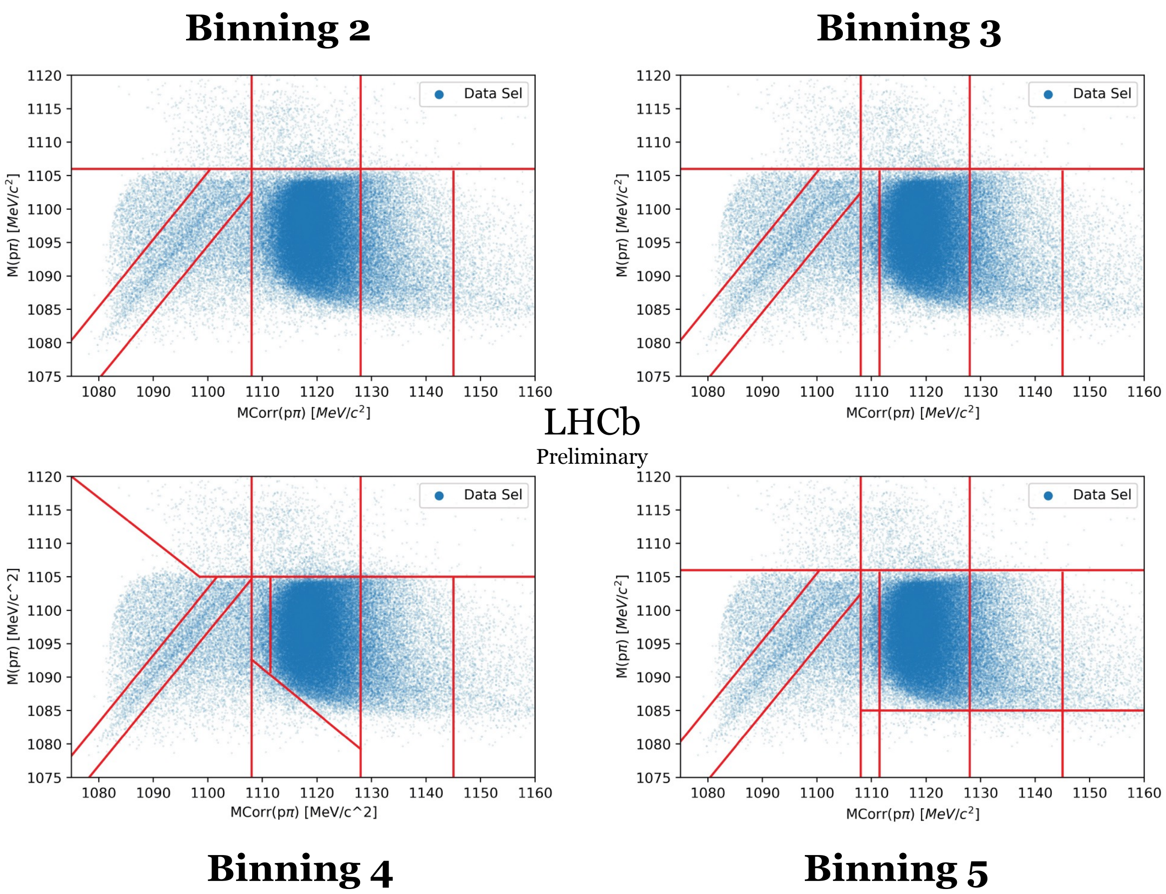
Two Dimensional fitter:

- **input: number of entries for each channel in each bin** (MC distributions as templates)
- **output: corresponding number of occurrences for each channel in the Data**.

$$\chi^2 = 2(-\mathrm{OBS} \cdot log(\mathrm{EXP}) + \mathrm{EXP}) \longrightarrow \text{Poisson distribution}$$

$$\mathrm{EXP} = f_{\Lambda \to p\mu^- \bar{\nu}_\mu} \cdot \frac{\mathcal{B}(\Lambda \to p\mu^- \bar{\nu}_\mu)}{\alpha} + f_{\Lambda \to p\pi^-} \cdot N_{\Lambda \to p\pi^-} + f_{eDIF} \cdot N_{eDIF} + f_{Comb} \cdot N_{Comb}$$

2D Signal Yield Fit



- Results using different modes and binning schemes are in good agreement.

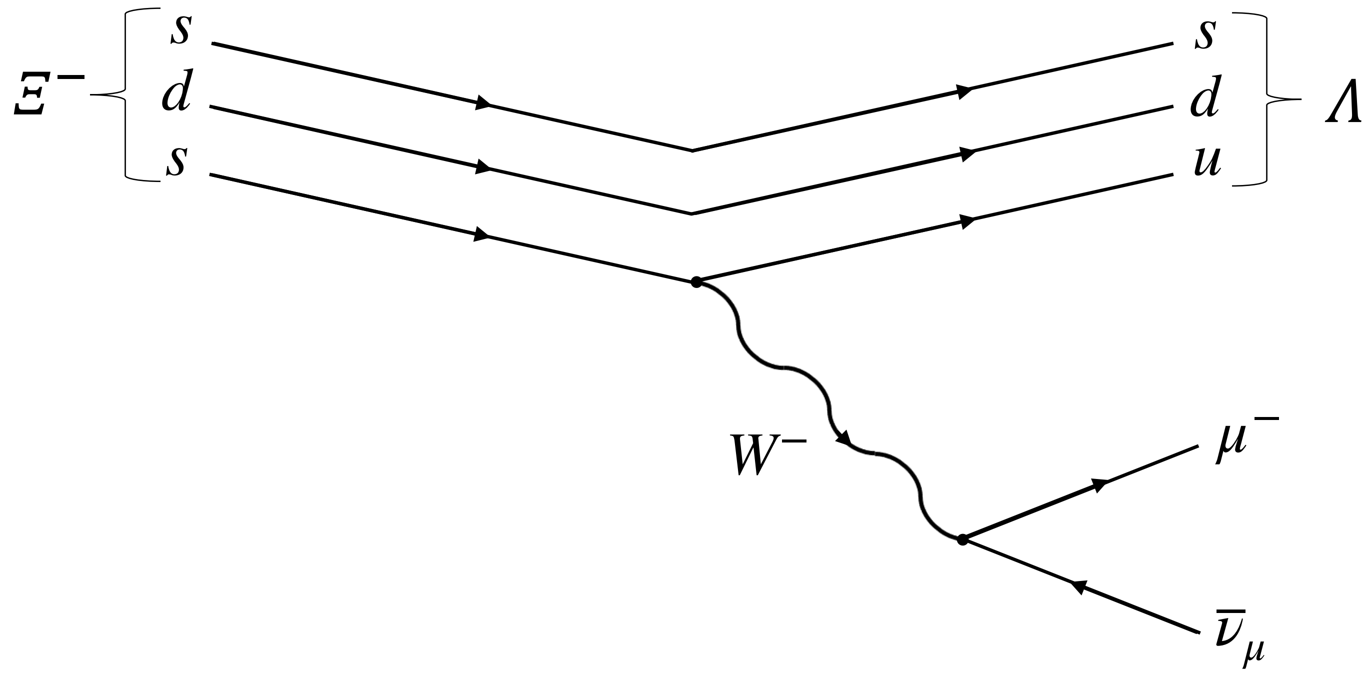
- **<u>Blinded</u> B.R. result is:**

(3.594 ± 0.055 (stat.) ± 0.182 (sys.)) x 10^{-4}

5.1 % fit systematic uncertainty
1.5 % statistics uncertainty

- Best current measurement presents a 14.2 % of uncertainty

$\mathcal{B}\,(\Xi^- \to \Lambda\,\mu^-\bar{\nu}_\mu)$ measurement in LHCb



Motivation

$\boldsymbol{\Xi^- \rightarrow \Lambda\, \mu^- \bar{\nu}_\mu}$ is a Semileptonic Hyperon Decay (SHD)

- Improved measurement directly translates into tighter **bounds on LFU (s → u)**, since the electron mode has already been measured precisely, $\mathcal{B}\,(\Xi^- \rightarrow \Lambda\, e^- \bar{\nu}_e) = (5.63 \pm 0.31) \times 10^{-4}$

$$\mathbf{R^{\mu e}} = \mathcal{B}\,(\Xi^- \rightarrow \Lambda\, \mu^- \bar{\nu}_\mu)\, /\, \mathcal{B}\,(\Xi^- \rightarrow \Lambda\, e^- \bar{\nu}_e)$$

$$R^{\mu e}_{prediction} = 0.275 \pm 0.014\ ,\ R^{\mu e}_{exp} = 0.6 \pm 0.6$$

Poor knowledge of the $\mathcal{B}\,(\Xi^- \rightarrow \Lambda\, \mu^- \bar{\nu}_\mu) = (\, 3.5^{+3.5}_{-2.2}\,) \times 10^{-4}$

Conclusions

- SHD are great candidates for testing lepton universality (accurate predictions, poor knowledge)

- LHCb can improve best current measurements for SHD branching ratios.

- $\mathcal{B}\,(\Lambda \rightarrow p\,\mu^{-}\bar{\nu}_{\mu})$ will be the first measurement and we expect to publish it soon.

- $\mathcal{B}\,(\Xi^{-} \rightarrow \Lambda\,\mu^{-}\bar{\nu}_{\mu})$ identified as the next natural step.

- These measurements will imply new constraints in $R^{\mu e}$, tighter bounds on LFU ($s \rightarrow u$)

Showing again that **LHCb is a versatile detector** that can obtain precise measurements **besides its original purpose!**

Thank you!

Back Up

LFU in SHD

- Since this is not a simple $s \to u$ quark transition, we have to consider the quarks being confined inside the baryon environment.

- Disregarding electromagnetic corrections, the amplitude for a generic semileptonic hyperon decay ($B_1(p_1) \to B_2(p_2)\, l^-(p_l)\, \bar{\nu}_l(p_\nu)$) can be separated into distinct leptonic and baryonic matrix elements. The hadronic currents are parameterizable via form factors:

$$\langle B_2(p_2)|\bar{u}\gamma_\mu s|B_1(p_1)\rangle = \bar{u}_2(p_2)\left[f_1(q^2)\gamma_\mu + \frac{f_2(q^2)}{M_1}\sigma_{\mu\nu}q^\nu + \frac{f_3(q^2)}{M_1}q_\mu\right]u_1(p_1)$$

$$\langle B_2(p_2)|\bar{u}\gamma_\mu\gamma_5 s|B_1(p_1)\rangle = \bar{u}_2(p_2)\left[g_1(q^2)\gamma_\mu + \frac{g_2(q^2)}{M_1}\sigma_{\mu\nu}q^\nu + \frac{g_3(q^2)}{M_1}q_\mu\right]\gamma_5 u_1(p_1)$$

- The approximate SU(3)-flavor symmetry present in the hyperons regulates the decay's phase space and permits a systematic expansion of observables based on the generic parameter that governs symmetry breaking

$$\delta = \frac{M_1 - M_2}{M_1}$$

H.-M. Chang, M. González-Alonso, and J. Martin Camalich, "Nonstandard Semileptonic Hyperon Decays", Phys. Rev. Lett. 114 no. 16, (2015) 161802,arXiv:1412.8484 [hep-ph].

LFU in SHD

- Expanded in δ up to next-to-leading order (NLO) and disregarding m_e the integrated ($B_1 \rightarrow B_2\, e- \bar{\nu}_e$) decay rate assuming real form factors and going to order δ^2 is given by:

$$\Gamma^{\mathrm{SM}}(B_1 \longrightarrow B_2 e^- \bar{\nu}_e) \simeq \frac{G_F^2 |V_{us}\, f_1(0)|^2 \Delta^5}{60\pi^3}\left[\left(1-\frac{3}{2}\delta\right)+3\left(1-\frac{3}{2}\delta\right)\frac{g_1(0)^2}{f_1(0)^2}-4\delta\frac{g_2(0)}{f_1(0)}\frac{g_1(0)}{f_1(0)}\right]$$

- The LFU test observable defined as the ratio between muon and electron modes

$$R^{\mu e} = \frac{\Gamma(B_1 \longrightarrow B_2 \mu^- \bar{\nu}_\mu)}{\Gamma(B_1 \longrightarrow B_2 e^- \bar{\nu}_e)}$$

is sensitive to non standard scalar and tensor contributions. Moreover, in the SM, the dependency on the form factors is anticipated to simplify when considering the ratio. Indeed, by operating at Next-to-Leading Order (NLO), we achieve:

$$R^{\mu e}_{\mathrm{SM}} = \sqrt{1-\frac{m_\mu^2}{\Delta^2}}\left(1-\frac{9}{2}\frac{m_\mu^2}{\Delta^2}-4\frac{m_\mu^4}{\Delta^4}\right)+\frac{15}{2}\frac{m_\mu^4}{\Delta^4}\mathrm{arctanh}\left(\sqrt{1-\frac{m_\mu^2}{\Delta^2}}\right) = 0.153 \pm 0.008$$

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BSM in SHD

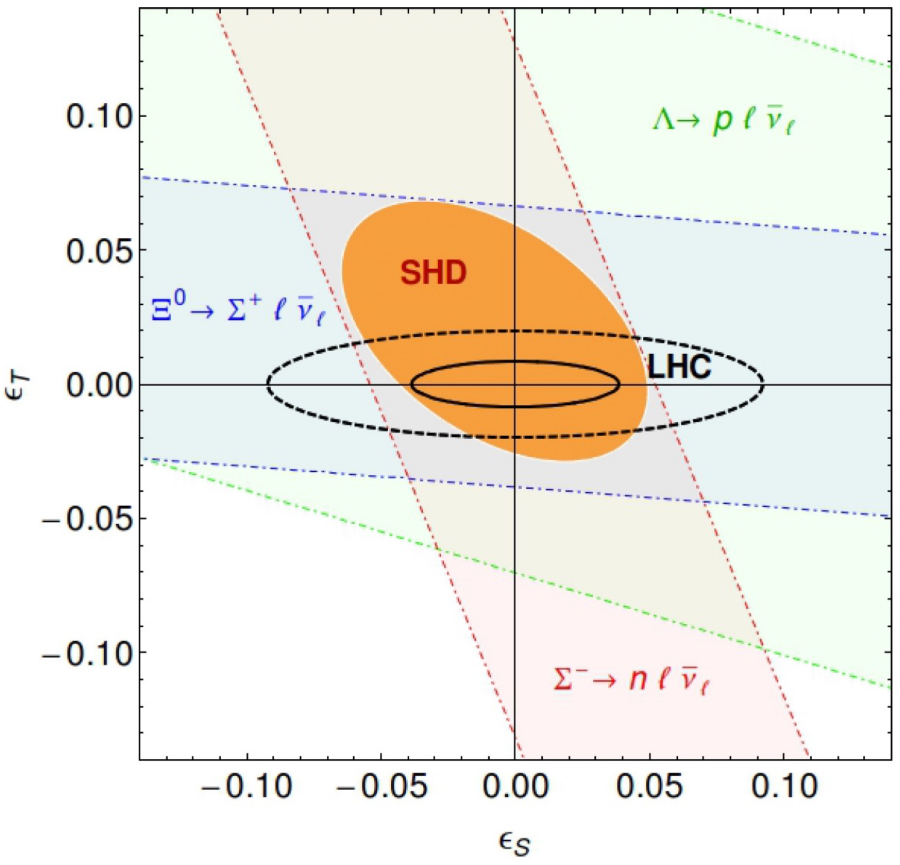


FIG. 1: 90% CL constraints on $\epsilon_{S,T}$ at $\mu = 2$ GeV from the measurements of $R^{\mu e}$ in different channels (dot-dashed lines) and combined (filled ellipse). LHC bounds obtained from CMS data at $\sqrt{s} =$ 8 TeV (7 TeV) are represented by the black solid (dashed) ellipse.

- It is useful to express the ratio of $R^{\mu e}{}_{\mathrm{NP}}$ and $R^{\mu e}{}_{\mathrm{SM}}$ encapsulating the scalar and tensor related dimensionless contributions in r_S and r_T in order to express the sensitivity to the Wilson coefficients

$$\frac{R^{\mu e}_{\mathrm{NP}}}{R^{\mu e}_{\mathrm{SM}}} = 1 + r_S \epsilon_S + r_T \epsilon_T$$

- Being the SHD sensitivity to the Wilson coefficients very channel-dependent. Given that the SM-NLO predictions, $R^{\mu e}{}_{\mathrm{SM}}$, for the various SHD modes are precise, these decays are excellent candidates for performing tests of LFU.

H.-M. Chang, M. González-Alonso, and J. Martin Camalich, “Nonstandard Semileptonic Hyperon Decays”, Phys. Rev. Lett. 114 no. 16, (2015) 161802,arXiv:1412.8484 [hep-ph].

BSM and V_{us} from SHD

- It is useful to express the ratio of $R^{\mu e}{}_{\rm NP}$ and $R^{\mu e}{}_{\rm SM}$ encapsulating the scalar and tensor related dimensionless contributions in r_S and r_T in order to express the sensitivity to the Wilson coefficients

$$\frac{R^{\mu e}_{\rm NP}}{R^{\mu e}_{\rm SM}} = 1 + r_S\epsilon_S + r_T\epsilon_T$$

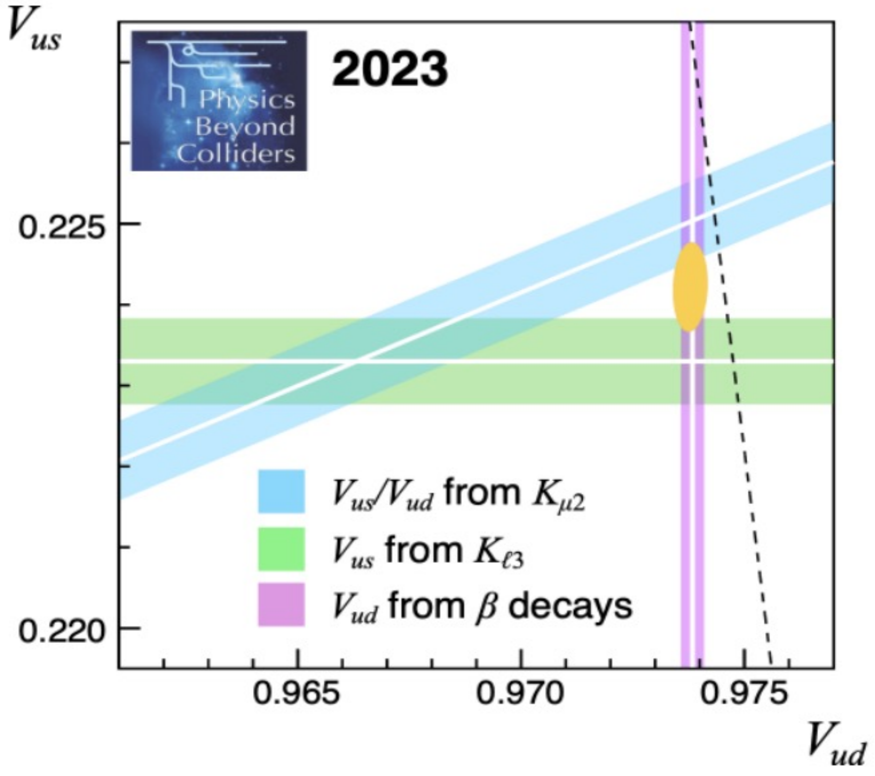
being the SHD sensitivity to the Wilson coefficients very channel-dependent. Given that the SM-NLO predictions, $R^{\mu e}{}_{\rm SM}$, for the various SHD modes are precise, these decays are excellent candidates for performing tests of LFU.

- We can also write V_{us} in terms of the form factors predicted by theory and the decay rates ratio.

$$|V_{us}|^2 \simeq \frac{\Gamma^{\rm SM}(B_1 \longrightarrow B_2\mu^-\bar{\nu}_\mu)\; 60\pi^3}{R^{\mu e}G_F^2\; f_1(0)^2\Delta^5\left[\left(1-\frac{3}{2}\delta\right)+3\left(1-\frac{3}{2}\delta\right)\frac{g_1(0)^2}{f_1(0)^2}\right]}$$

H.-M. Chang, M. González-Alonso, and J. Martin Camalich, “Nonstandard Semileptonic Hyperon Decays”, Phys. Rev. Lett. 114 no. 16, (2015) 161802,arXiv:1412.8484 [hep-ph].

V_{us}



- Strangeness changing SL decays can provide the most sensitive test of the unitarity of the CKM matrix (since $|V_{ub}|^2$ is negligible) through the relation

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

The experimental result is:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985 \pm 0.0007$$

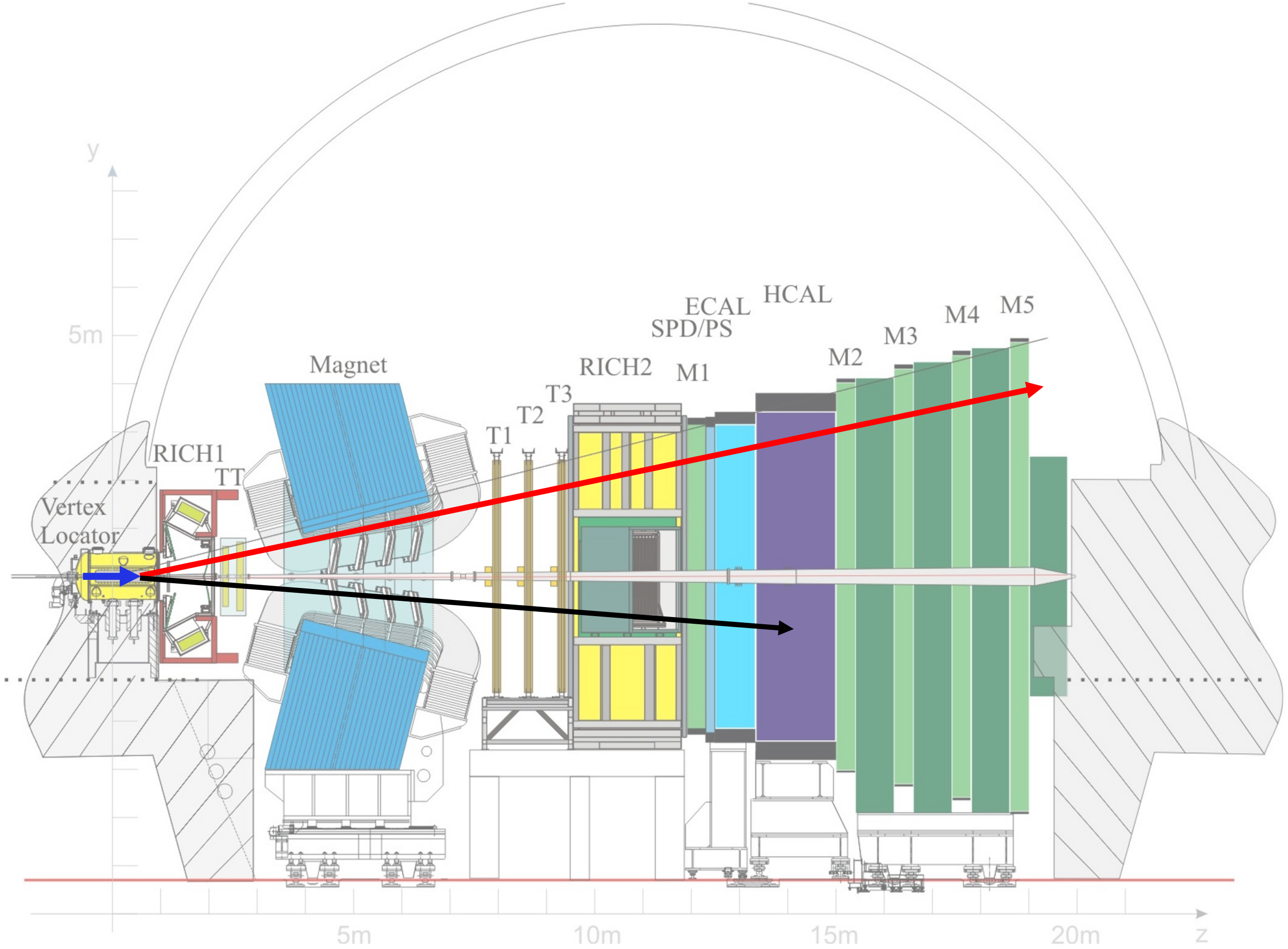
Showing a **2.2σ tension with the expected unitarity** in the first CKM row.

The measurements of V_{us} **in leptonic ($K\mu 2$) and semileptonic ($Kl3$)** kaon decays exhibit a 3σ **discrepancy.** Such a disagreement can hint towards two potential scenarios:
the existence of physics beyond the SM or a significant, yet unidentified, systematic effect within the SM itself.

Chien-Yeah Seng et al., Improved Ke3 radiative corrections sharpen the Kμ2–Kl3 discrepancy: Journal of High Energy Physics 2021.11 (Nov. 2021). doi: 10.1007/jhep11(2021)172.

LHCb

Year	Energy	Integrated Lumi
2016	13 TeV	1.67 fb^{-1}
2017	13 TeV	1.71 fb^{-1}
2018	13 TeV	2.19 fb^{-1}



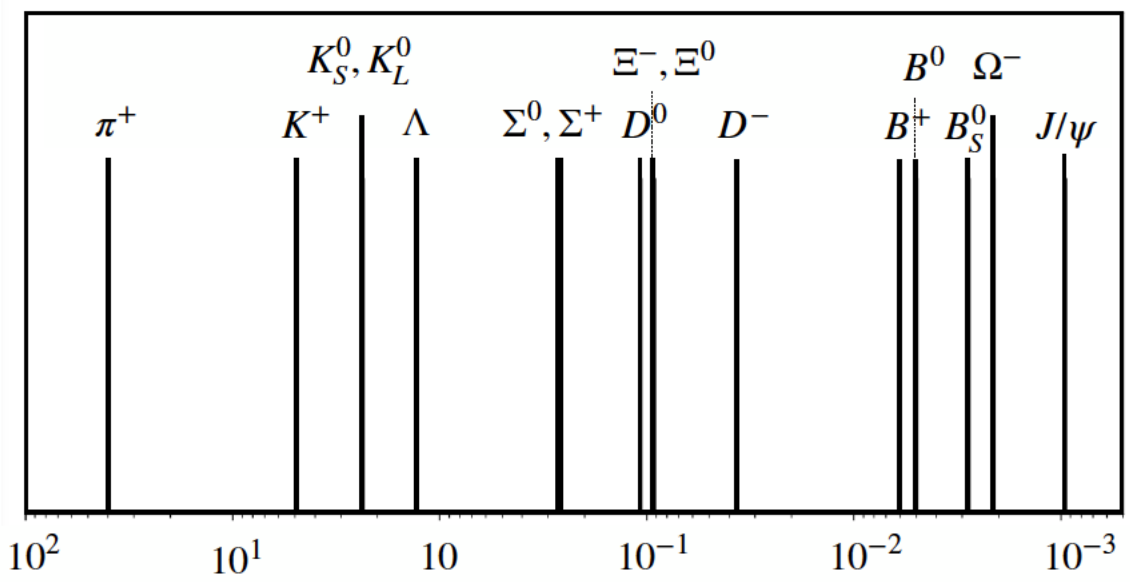
Λ
p
μ

$1.6 < \eta < 4.9$
Magnet 4 T.m

Strange physics at LHCb

- LHCb obtained leading strange physics measurements, particularly searching for their rare decays, publishing leading measurements in $K_S^0 \to \mu^+ \mu^-$, $K_S^0 \to \mu^+ \mu^- \mu^+ \mu^-$, and $\Sigma^+ \to p\, \mu^+ \mu^-$.
- In 2019 we published some prospects for measurements with strange hadrons at LHCb.

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	σ_L $\left(\frac{MeV}{c^2}\right)$	σ_D $\left(\frac{MeV}{c^2}\right)$
$K_S^0 \to \mu^+\mu^-$	1	1.0 (1.0)	1.8 (1.8)	~3.0	~8.0
$K_S^0 \to \pi^+\pi^-$	1	1.0 (0.30)	1.9 (0.91)	~2.5	~7.0
$K_S^0 \to \pi^0\mu^+\mu^-$	1	0.93 (0.93)	1.5 (1.5)	~35	~45
$K_S^0 \to \gamma\mu^+\mu^-$	1	0.85 (0.85)	1.4 (1.4)	~60	~60
$K_S^0 \to \mu^+\mu^-\mu^+\mu^-$	1	0.37 (0.37)	1.1 (1.1)	~1.0	~6.0
$K_L^0 \to \mu^+\mu^-$	~1	2.7 (2.7) $\times 10^{-3}$	0.014 (0.014)	~3.0	~7.0
$K^+ \to \pi^+\pi^+\pi^-$	~2	9.0 (0.75) $\times 10^{-3}$	41 (8.6) $\times 10^{-3}$	~1.0	~4.0
$K^+ \to \pi^+\mu^+\mu^-$	~2	6.4 (2.3) $\times 10^{-3}$	0.030 (0.014)	~1.5	~4.5
$\Sigma^+ \to p\mu^+\mu^-$	~0.13	0.28 (0.28)	0.64 (0.64)	~1.0	~3.0
$\Lambda \to p\pi^-$	~0.45	0.41 (0.075)	1.3 (0.39)	~1.5	~5.0
$\Lambda \to p\mu^-\bar{\nu}_\mu$	~0.45	0.32 (0.31)	0.88 (0.86)	-	-
$\Xi^- \to \Lambda\mu^-\bar{\nu}_\mu$	~0.04	39 (5.7) $\times 10^{-3}$	0.27 (0.09)	-	-
$\Xi^- \to \Sigma^0\mu^-\bar{\nu}_\mu$	~0.04	24 (4.9) $\times 10^{-3}$	0.21 (0.068)	-	-
$\Xi^- \to p\pi^+\pi^-$	~0.04	0.41 (0.05)	0.94 (0.20)	~3.0	~9.0
$\Xi^0 \to p\pi^-$	~0.03	1.0 (0.48)	2.0 (1.3)	~5.0	~10
$\Omega^- \to \Lambda\pi^-$	~10^{-3}	95 (6.7) $\times 10^{-3}$	0.32 (0.10)	~7.0	~20

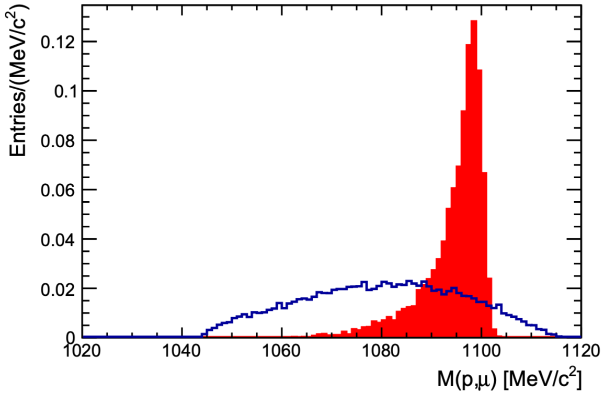


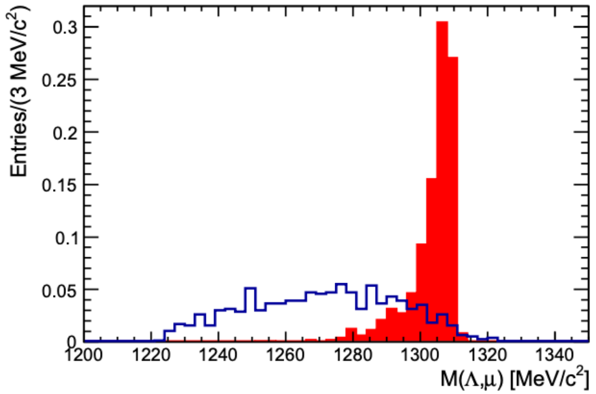
Multiplicity of particles produced in a single pp interaction at $\sqrt{s}$ = 13 TeV within LHCb acceptance.

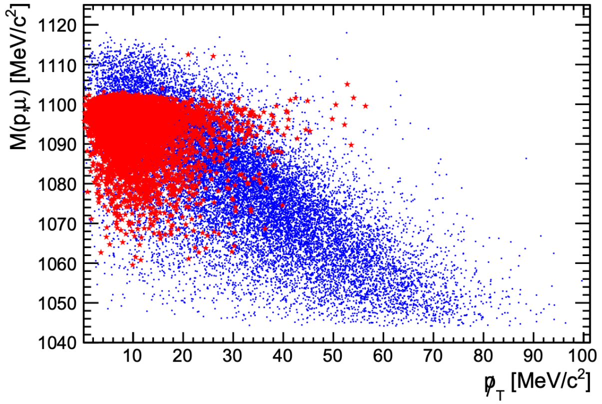
SHD Prospects in LHCb

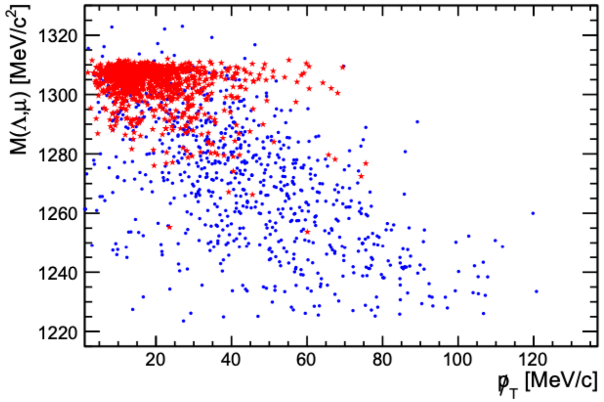
$\Lambda \rightarrow p\,\mu^{-}\bar{\nu}_{\mu}$ *vs* $\Lambda \rightarrow p\,\pi^{-}$

$\Xi^{-} \rightarrow \Lambda\,\mu^{-}\bar{\nu}_{\mu}$ *vs* $\Xi^{-} \rightarrow \Lambda\,\pi^{-}$







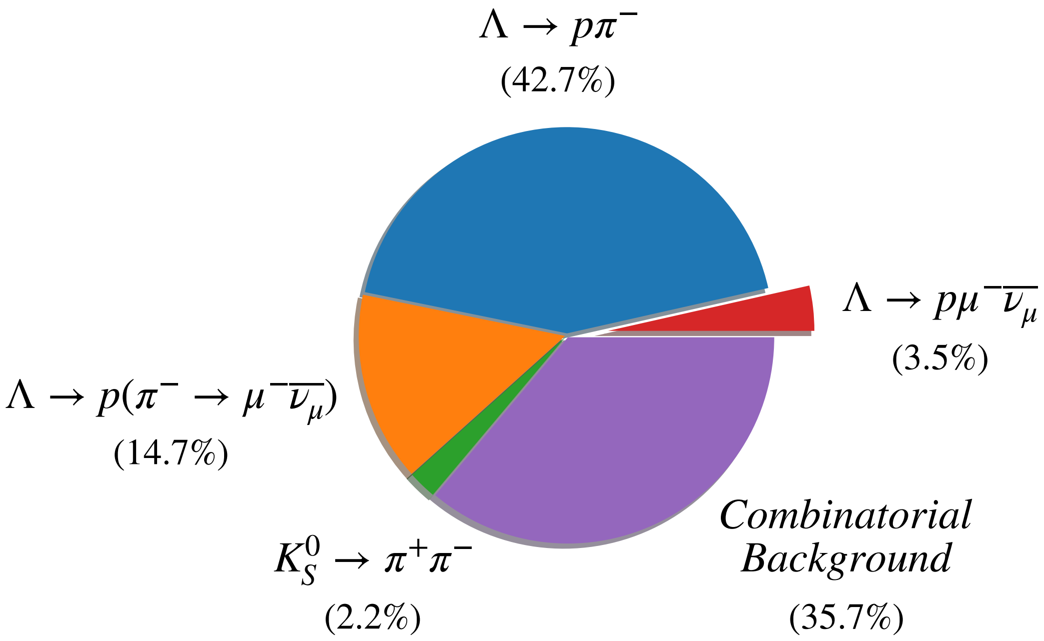


Main Challenges

Low Background Simulation (MC) Statistics

Very **tight signal stripping line** to adress the significant imbalance between the $\Lambda \to p\,\mu^- \bar{\nu}_\mu$ and $\Lambda \to p\,\pi^-$ B.R.

This implies a 10^{-5} efficiency for the background. As a consequence, generating Background MC passing the stripping line is **extremely resource-intensive** from a computational standpoint.



Even after the stripping, the signal **purity is extremely low** (3.5 %)

Our selection will be designed to increase this signal purity and remove harmful backgrounds.

Signal EvtGen MC

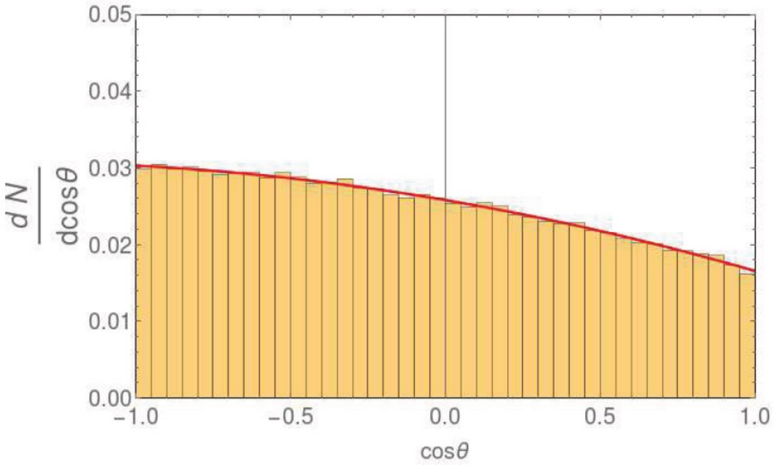
Signal (3-body decay) behaviour different from Phase Space. Specific EvtGen model needed.

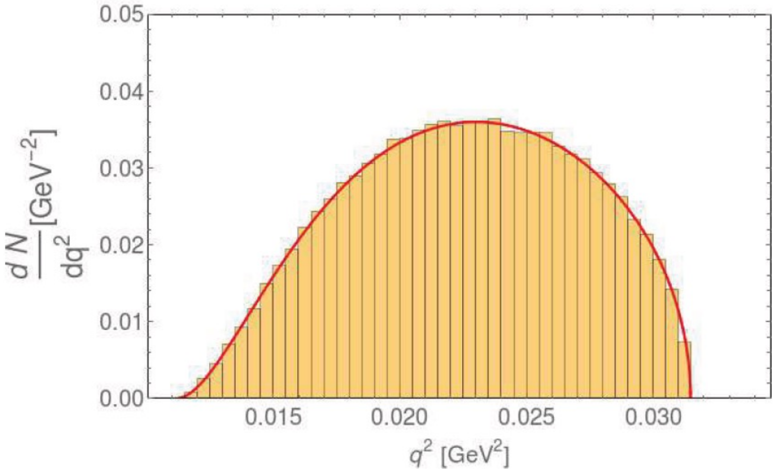
Kinematic Distributions for $B_1 \rightarrow B_2$ lepton ν

$$\frac{d\Gamma}{dq^2 d(cos\theta)} = \frac{G_F^2 f_1(0)^2 |V_{us}^2|}{(2\pi)^3}(q^2 - m_l^2)^2 \frac{q_3 \Delta^2}{16q^2}[I_1(q^2) + I_2(q^2)cos(\theta) + I_3(q^2)cos^2(\theta))]$$

EvtDecayProb allows to calculate a probability for the decay. This probability is then used in the accept-reject method.

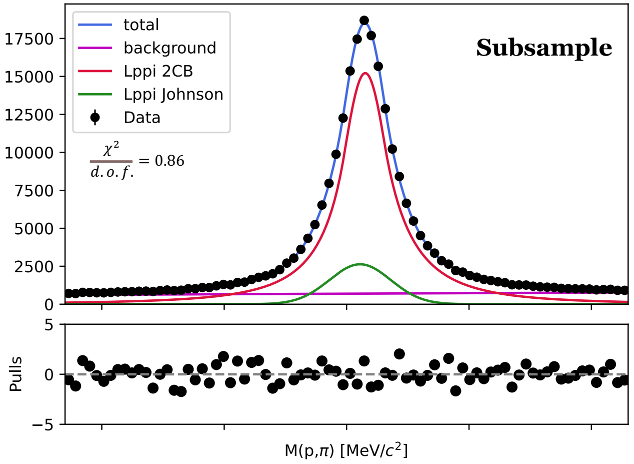
The resulting EvtGen model is called SHD**. It is written to be compatible with any Semileptonic Hyperon Decay.**



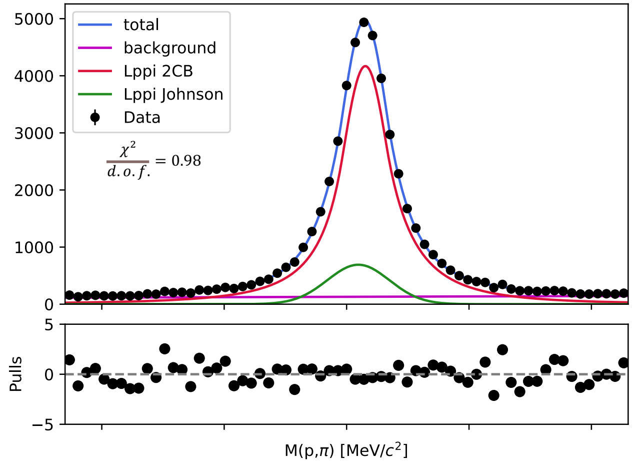


Constraint tail parameters

Data (NormLine)



Subsample



Subsample

$\Lambda \to p\,\pi^-$ Yield (NormLine)

	Magnet Down	MagnetUp
2018	17281100 ± 6400	18470700 ± 5800
2017	15408000 ± 5900	14750700 ± 8800
2016	17657000 ± 6600	15769700 ± 8800

$\Lambda \to p\,\pi^-$ Efficiency (NormLine)

	Magnet Down	MagnetUp
$\epsilon^{NormLine}_{\Lambda\to p\pi^-}$	$(1.579 \pm 0.010) \times 10^{-4}$	$(1.5708 \pm 0.0088) \times 10^{-4}$

Lambdas in Run2

Number of $\Lambda \to p\pi^-$ decays before the stripping for each year and polarity.

	Magnet Down	MagnetUp
2018	(109380 ± 690) M	(117590 ± 660) M
2017	(97530 ± 620) M	(93910 ± 530) M
2016	(111760 ± 710) M	(100390 ± 570) M

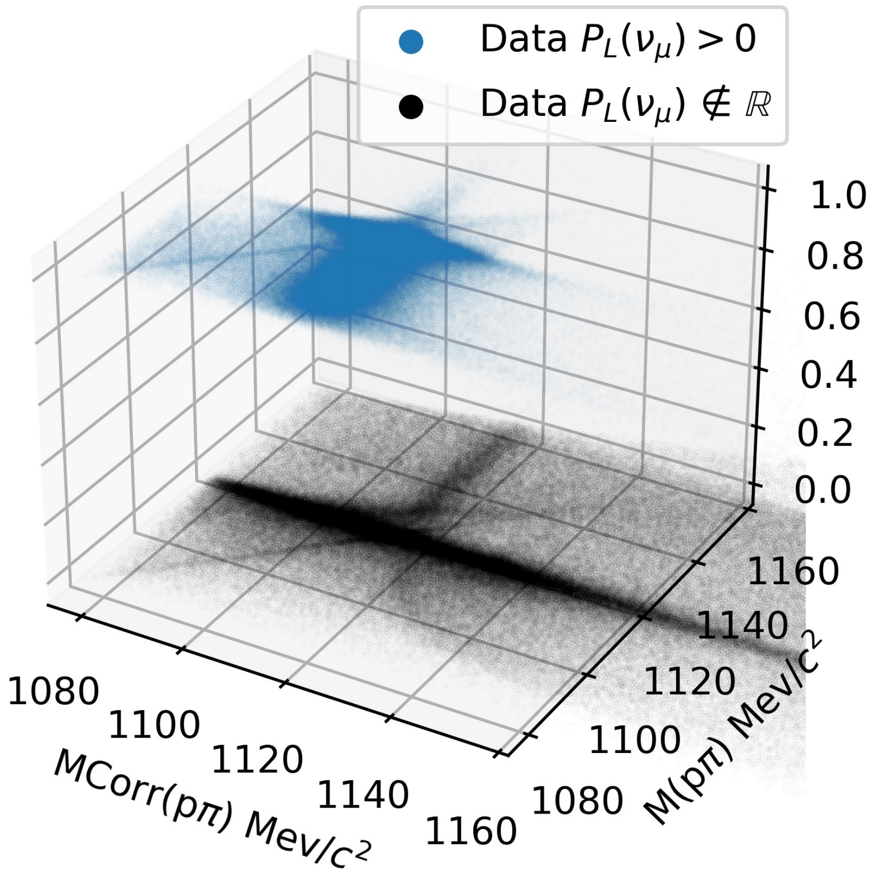
$$N_\Lambda = \frac{N_{\Lambda \to p\pi^-}}{\mathcal{B}(\Lambda \to p\pi^-)}$$

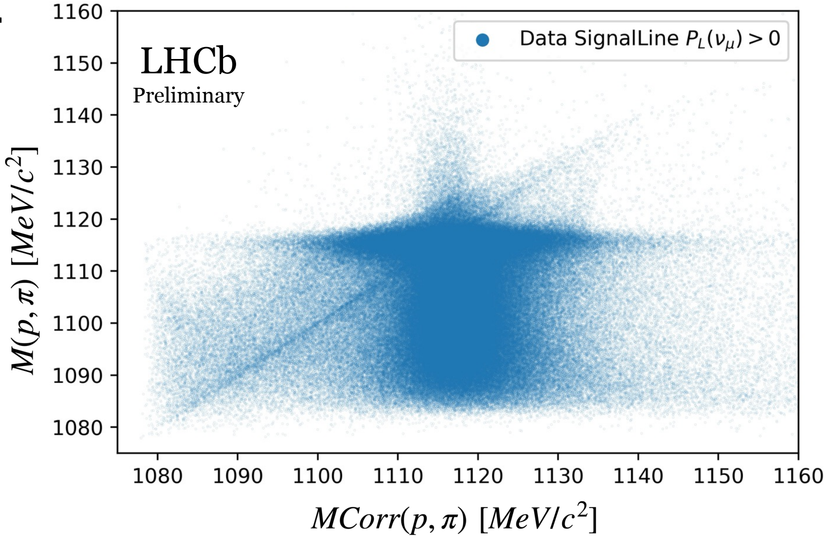
Number of Λ particles before the stripping for each year and polarity.

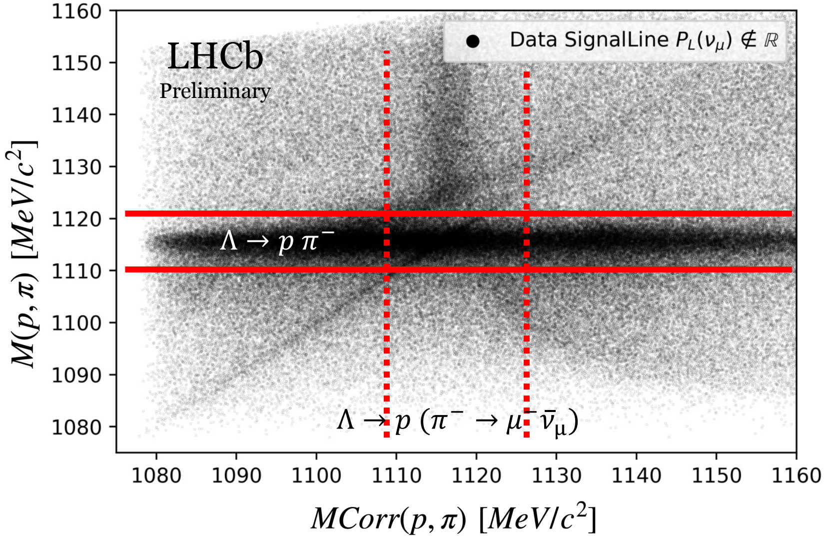
	Magnet Down	MagnetUp
2018	(171200 ± 1700) M	(184000 ± 1800) M
2017	(152600 ± 1500) M	(147000 ± 1400) M
2016	(174900 ± 1700) M	(157100 ± 1500) M

Selection

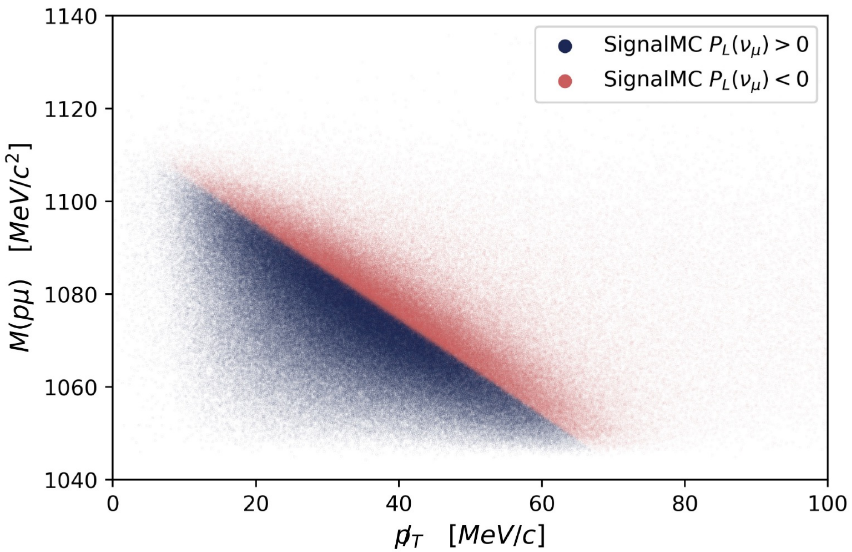
$$p_L(\nu_\mu) = \frac{E_{p\mu}\cdot\sqrt{A^2 - M_\Lambda^2 . \not{p}_T^2} - A.p'_{p\mu_z} + p'_{p\mu_z}.\not{p}_T^2}{(p'_{p\mu_z})^2 - E_{p\mu}^2}$$

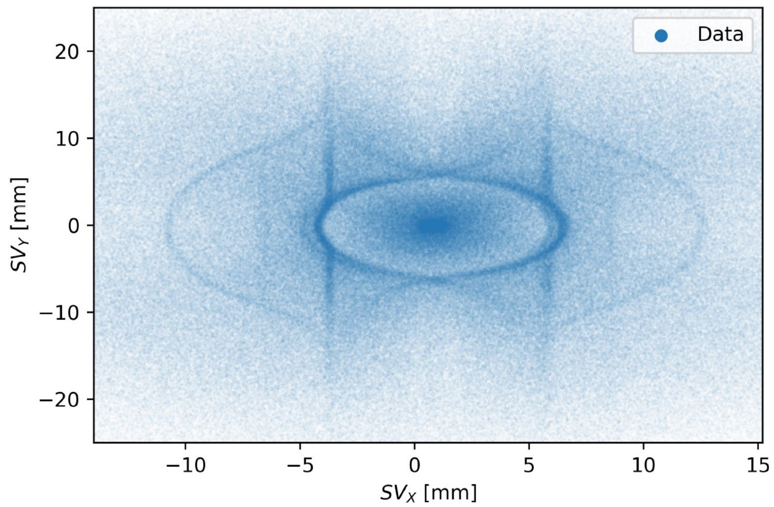


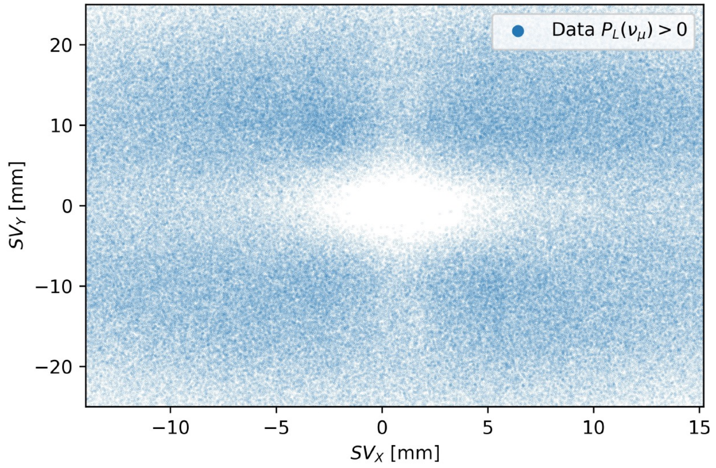




Selection





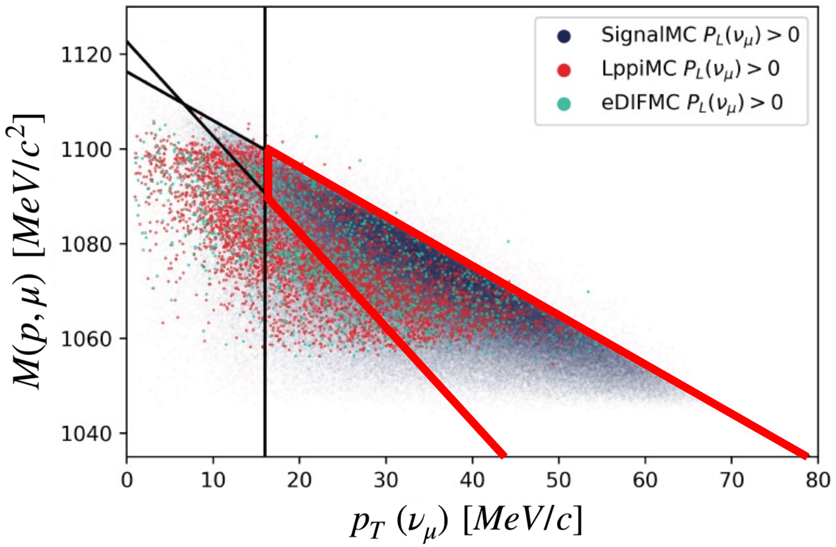


	$P_L(\nu_\mu) > 0$ **Efficiency**
Signal MC $\epsilon^{P_L(\nu_\mu)>0}_{\Lambda\to p\mu^-\bar{\nu}_\mu}$	0.63656 ± 0.00063
Lppi MC $\epsilon^{P_L(\nu_\mu)>0}_{\Lambda\to p\pi^-}$	0.7547 ± 0.0055
eDIF MC $\epsilon^{P_L(\nu_\mu)>0}_{\Lambda\to p(\pi^-\to\mu^-\bar{\nu}_\mu)}$	0.672 ± 0.011

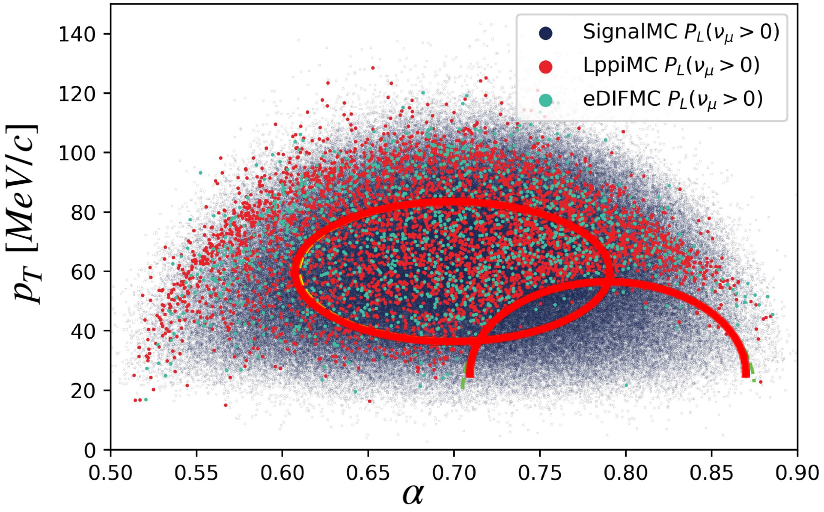
Selection

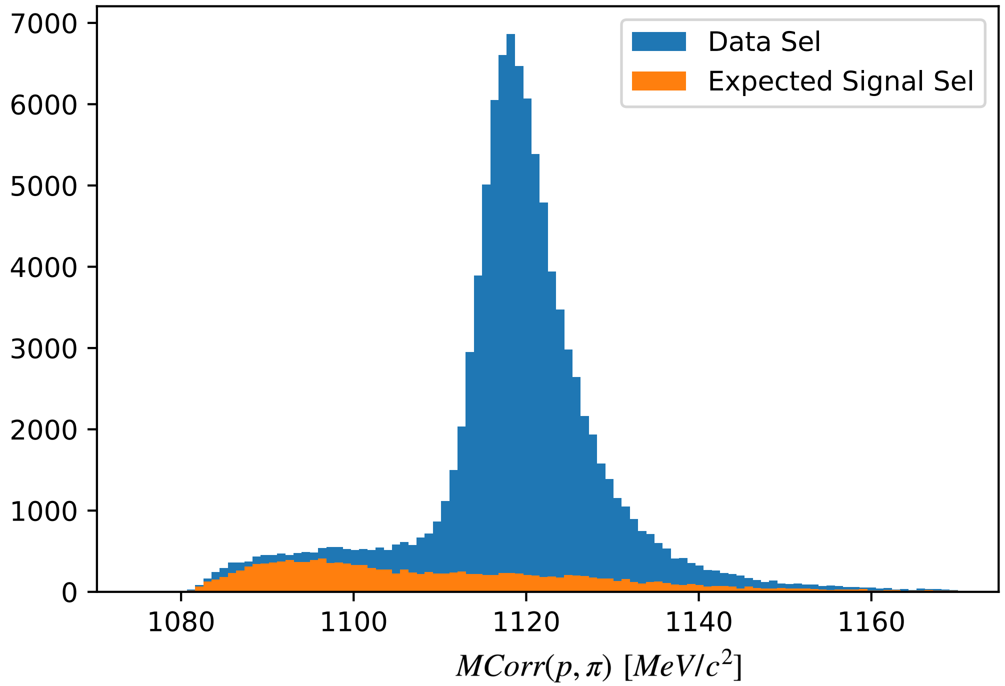
$p_L(\nu_\mu) > 0$

Sel 1



Sel 2



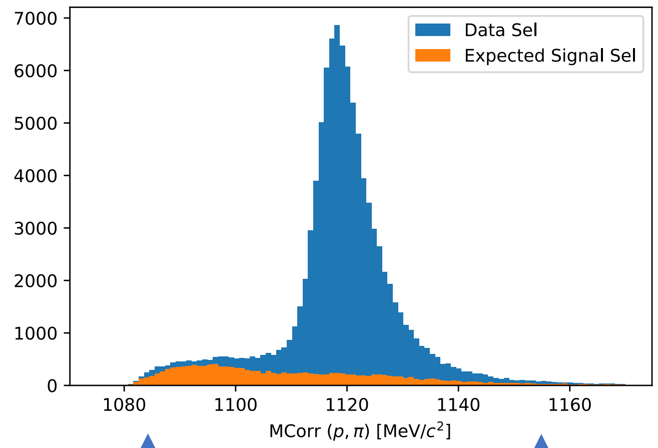


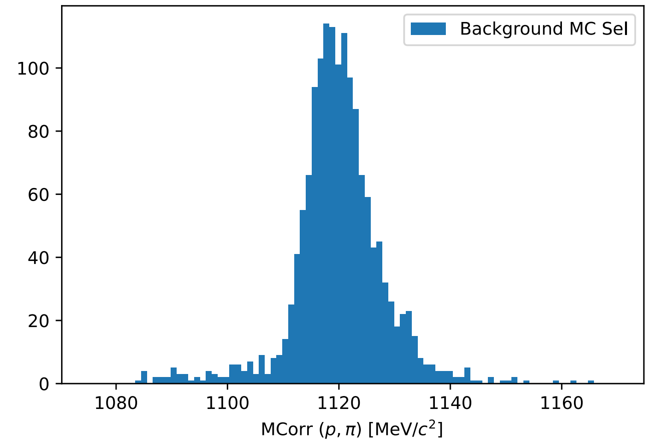
$$\epsilon^{\text{Selection}}_{\Lambda\to p\mu^-\overline{\nu}_\mu} = 0.3011 \pm 0.0015$$

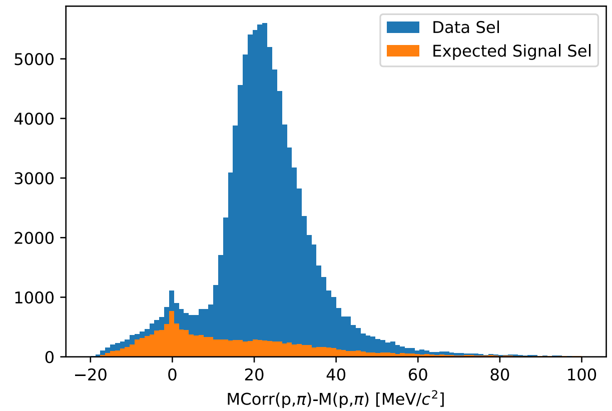
Selection

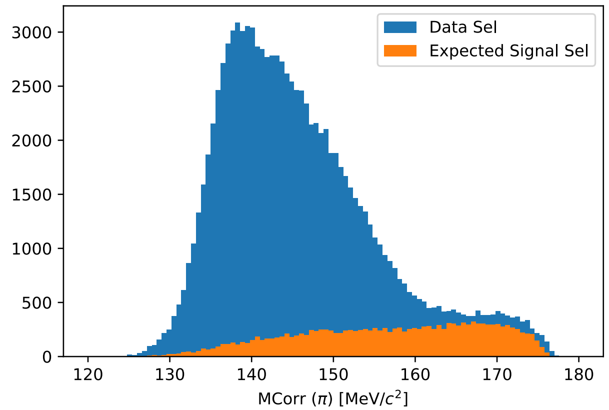
Our Selection is great removing combinatorial bkg and increasing Signal Purity.

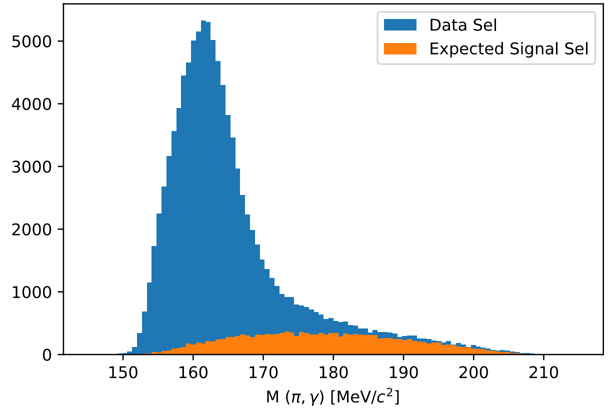
Kinematic variables under control.

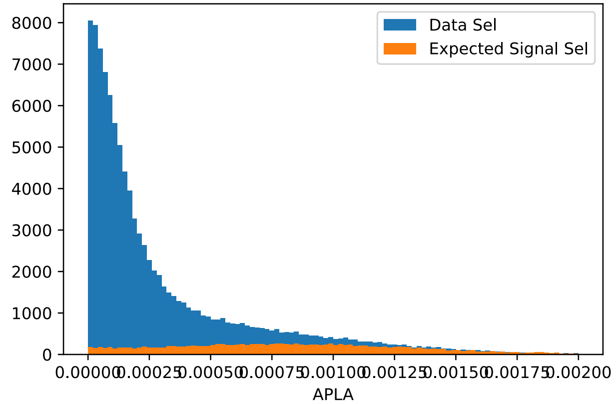








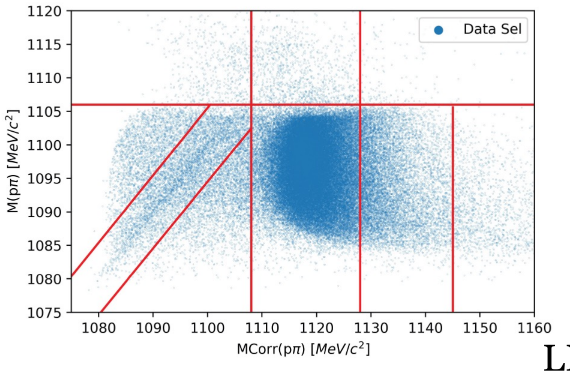




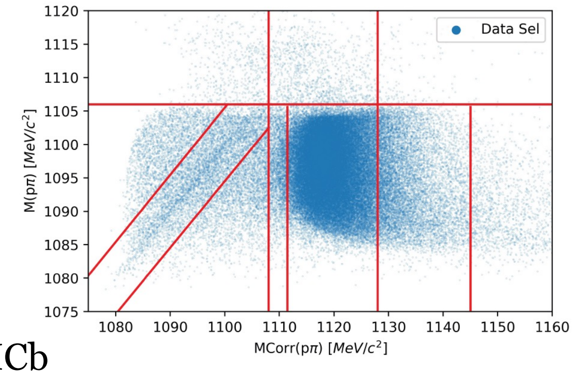
APLA= $(\mathbf{SV\text{-}PV}) \cdot (\mathbf{p}_{\text{daughter1}} \times \mathbf{p}_{\text{daughter2}})$

2D Signal Yield Fit

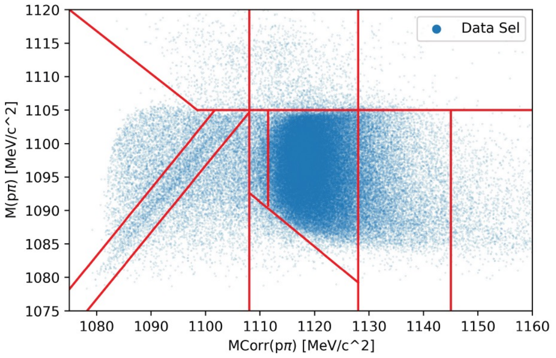
Binning 2



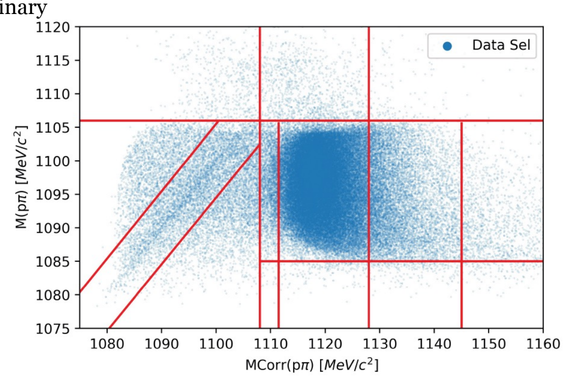
Binning 3



LHCb
Preliminary



Binning 4



Binning 5

Scheme	Merged Lppi+eDIF	Lppi,eDIF	Lppi, eDIF, CombBkg
Binning 1 ($\times 10^{-4}$)	$\mathcal{B} = 3.612 \pm 0.047$	$\mathcal{B} = 3.654 \pm 0.065$	$\mathcal{B} = 3.551 \pm 0.063$
Binning 2 ($\times 10^{-4}$)	$\mathcal{B} = 3.544 \pm 0.050$	$\mathcal{B} = 3.776 \pm 0.069$	$\mathcal{B} = 3.491 \pm 0.060$
Binning 3 ($\times 10^{-4}$)	$\mathcal{B} = 3.556 \pm 0.048$	$\mathcal{B} = 3.705 \pm 0.067$	$\mathcal{B} = 3.502 \pm 0.057$
Binning 4 ($\times 10^{-4}$)	$\mathcal{B} = 3.612 \pm 0.049$	$\mathcal{B} = 3.642 \pm 0.070$	$\mathcal{B} = \mathbf{3.594} \pm \mathbf{0.055}$
Binning 5 ($\times 10^{-4}$)	$\mathcal{B} = 3.558 \pm 0.047$	$\mathcal{B} = 3.704 \pm 0.065$	$\mathcal{B} = 3.502 \pm 0.057$

Results using different modes and binning schemes are in good agreement.

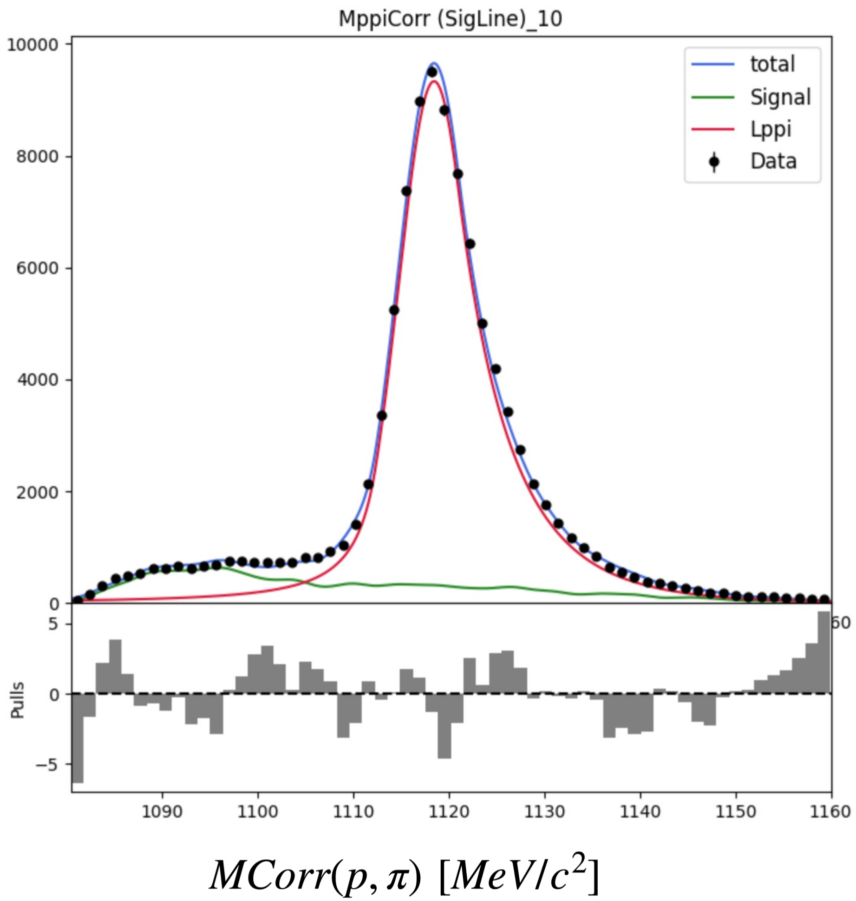
Blinded B.R. result is:

(3.594 ± 0.055 (stat.) ± 0.182 (sys.)) x 10^{-4}

5.1 % fit systematic uncertainty
1.5 % statistics uncertainty

Best current measurement presents a 14.2 % of uncertainty

1D Fit Cross-Check



Signal PDF extracted using a Kernel Density Estimation (KDE)

The Background component is fitted using a double sided Crystal Ball

Blinded B.R. result is 3.61 ± 0.10

Issues
We do not have enough statistics to know the CombBkg behaviour, even expecting a very low contribution.

Good check (reassuring)

Systematics

Analysis designed to reduce systematic uncertainties as much as possible:

- **TIS** required both for Normalization and Signal.
- **Aligned Stripping Lines cuts**. Only PID Cuts are different.
- **PIDCuts** reduced as much as possible. Selection based on kinematics.

Systematic Source	Relative Uncertainty
$\mathcal{B}\,(\Lambda \to p\,\pi^-)$	0.78 %
NormLine Fit	Negligible
PidCalib2 NormLine	1.04 %
PidCalib2 SignalLine	1.61 %
TrackCalib2	1.1 %
Signal Fit Template	Negligible
Signal Fit	5.1 %
Other sources	-

Systematic uncertainty expected 5.6 %

Prospects

The SHD sensitivity to the NP Wilson coefficients is very channel-dependent. Given that the SM-NLO predictions, $R^{\mu e}{}_{SM}$, for the various SHD modes are precise, these decays are excellent candidates for performing tests of LFU.

The general SHD can be descripted as $B_1 \to B_2\, l^- \,\bar{\nu}_l$, where B_1 is the hyperon, B_2 is the baryon in the final state and l can be any lepton flavor. The $\Delta = M_1 - M_2$ is directly related to the success of the developed strategy to separate signal and background.

The abundance of Λ particles can introduce certain disadvantages, as it requires very tight selection cuts. Consequently, generating MC simulations for $\Lambda \to p\pi^-$ and minimum bias that pass the stripping line, specifically designed to select $\Lambda \to p\mu^- \bar{\nu}_\mu$, becomes exceptionally resource intensive. However, this issue will be reduced for heavier hyperon modes.

Channel	$\mathcal{R}$	$\Delta\ (MeV/c^2)$	ϵ_L	ϵ_D	$\mathcal{B}$
$\Lambda \to p\mu^-\bar{\nu}_\mu$	~ 0.45	~ 177.41	0.32	0.88	$(1.51 \pm 0.19) \times 10^{-4}$
$\Xi^- \to \Lambda\mu^-\bar{\nu}_\mu$	~ 0.04	~ 206.03	0.039	0.27	$(3.5^{+3.5}_{-2.2}) \times 10^{-4}$
$\Xi^- \to \Sigma^0\mu^-\bar{\nu}_\mu$	~ 0.04	~ 129.07	0.024	0.21	$< 8.0 \times 10^{-4} (90\% CL)$
$\Xi^0 \to \Sigma^+\mu^-\bar{\nu}_\mu$	~ 0.04	~ 125.49	-	-	$(2.33 \pm 0.35) \times 10^{-6}$
$\Sigma^- \to n\mu^-\bar{\nu}_\mu$	~ 0.13	~ 249.80	-	-	$(4.5 \pm 0.4) \times 10^{-4}$

Prospects

The most promising channel (high available momentum for the neutrino) is $\Xi^- \rightarrow \Lambda\, \mu^- \bar{\nu}_\mu$. Its branching ratio has an uncertainty at the 100% level and the strategy can work better than for the $\Lambda \rightarrow p\mu^- \bar{\nu}_\mu$ case.

Despite having one order of magnitude less both in acceptance efficiency in the LHCb detector and in production ratio, the strategy designed for $\Lambda \rightarrow p\mu^- \bar{\nu}_\mu$ should be enough to improve its branching ratio measurement. Downstream tracks can be included if needed to enhance statistics by one order of magnitude.

Moreover, having a Λ in the final state, that will be reconstructed in the $\Lambda \rightarrow p\pi^-$ mode, will reduce significantly the combinatorial background pollution.

Additionally, $\Xi^- \rightarrow \Lambda\, \pi^-$ can be used as normalization channel. This mode has an acceptance efficiency similar to the $\Lambda \rightarrow p\pi^-$ one and we will have a huge amount of statistics for the normalization process

Strange physics at LHCb

- LHCb obtained leading strange physics measurements, particularly searching for their rare decays, publishing leading measurements in $K_S^0 \rightarrow \mu^+ \mu^-$, $K_S^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$, and $\Sigma^+ \rightarrow p \mu^+ \mu^-$.

- LHCb obtained leading strange physics measurements, particularly searching for their rare decays, publishing leading measurements in $K_S^0 \rightarrow \mu^+ \mu^-$, $K_S^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$, and $\Sigma^+ \rightarrow p \mu^+ \mu^-$.

Multiplicity of particles produced in a single pp interaction at $\sqrt{s}$ = 13 TeV within LHCb acceptance.

A. A. Alves Junior et al. "Prospects for Measurements with Strange Hadrons at LHCb". In: JHEP 05 (2019), p. 048. doi: 10.1007/JHEP05(2019)048. arXiv: 1808.03477 [hep-ex]