INFN PERUGIA
Istituto Nazionale di Fisica Nucleare
Sezione di Perugia

PerAPS 2025

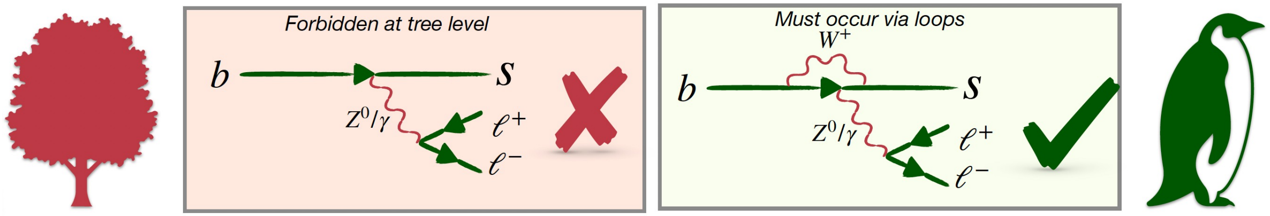
Observation of the very rare $\Sigma^+ \rightarrow p\mu^+\mu^-$ decay at LHCb

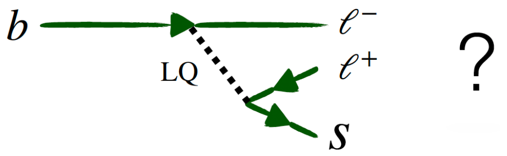
Gabriele Martelli
Istituto Nazionale di Fisica Nucleare - Sezione di Perugia
On behalf of the LHCb collaboration

University of Perugia, 08 October 2025
Perugia Advanced Physics Seminars

Why search for rare decays?

- ➤ Flavour Changing Neutral Currents (FCNC)
  - Forbidden at tree level in the Standard Model (SM)
  - Allowed only at loop level
  - New Physics (NP) contributions may enter in loops





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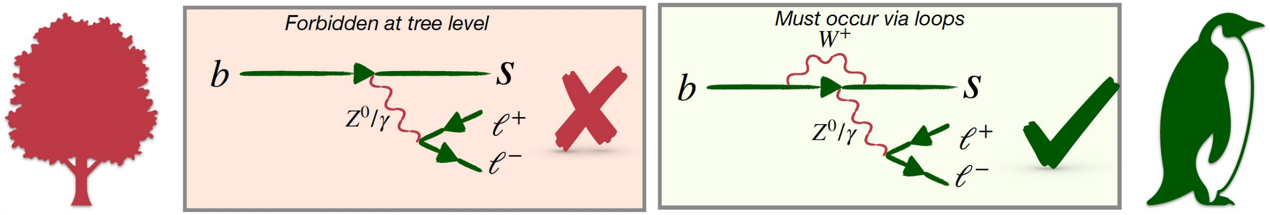
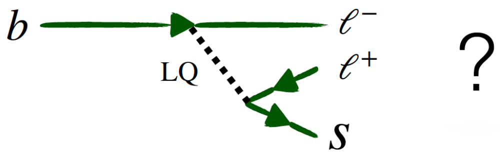


Look for deviations from SM predictions



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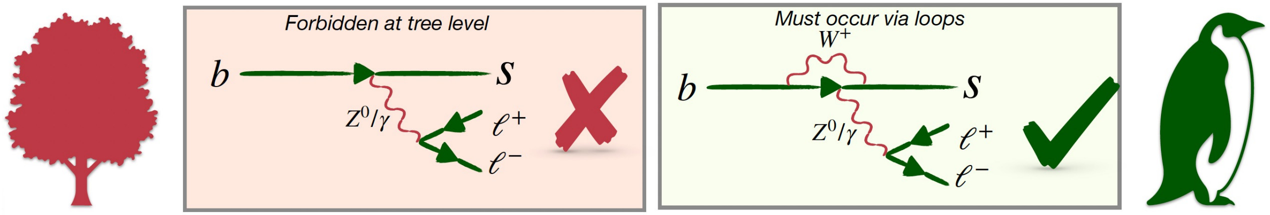
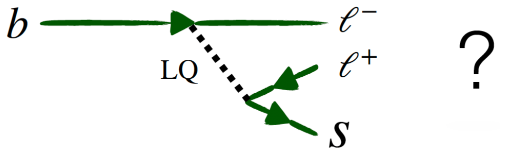
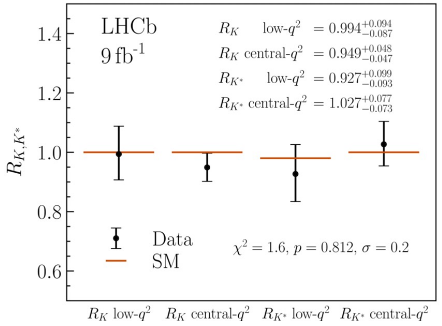


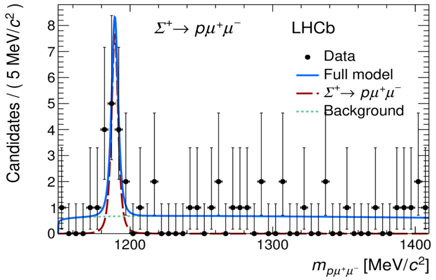


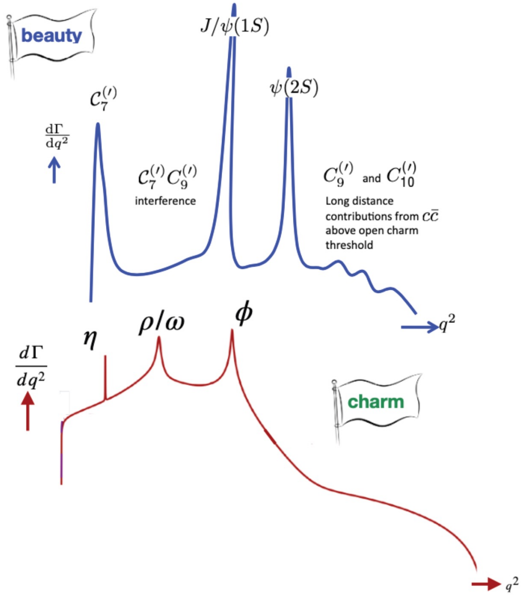
Look for deviations from SM predictions

- Exstensive programme at *LHCb*
  - Search for (very) rare or forbidden modes
  - Branching fractions measurements
  - CP violation
  - Null tests in the SM

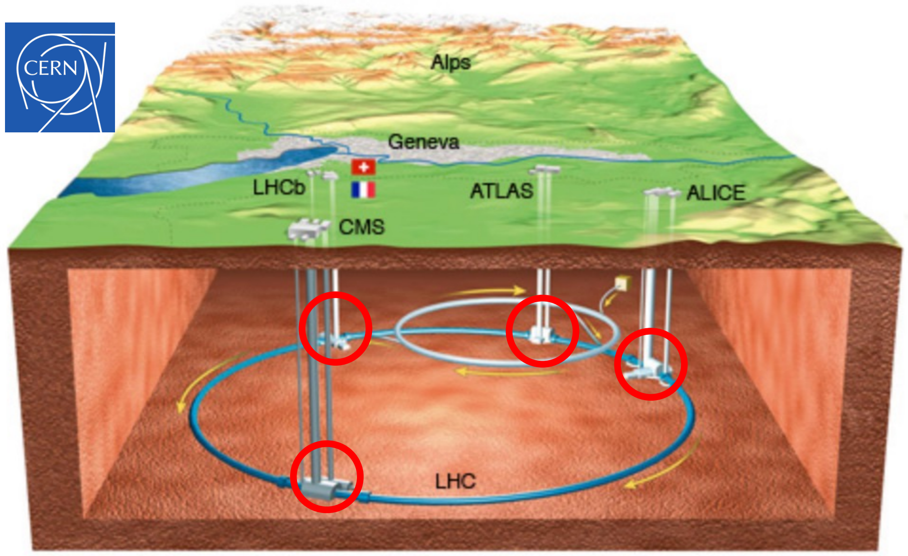
    [Published papers]







The LHCb experiment



- Large Hadron Collider (LHC)
  - Located at CERN
  - World largest particle collider
    - ✓ 26.7 km long, 100 m underground
  - Proton/heavy ion beams collide in four points

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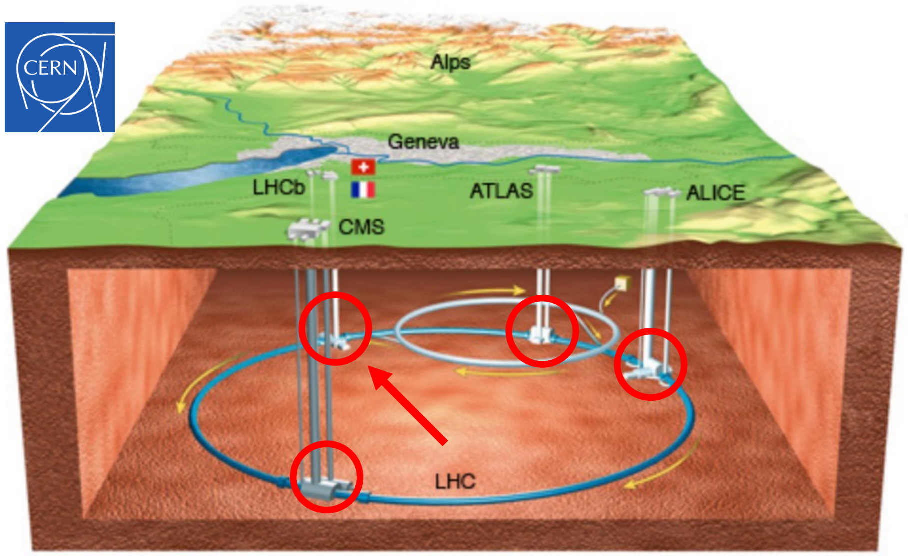
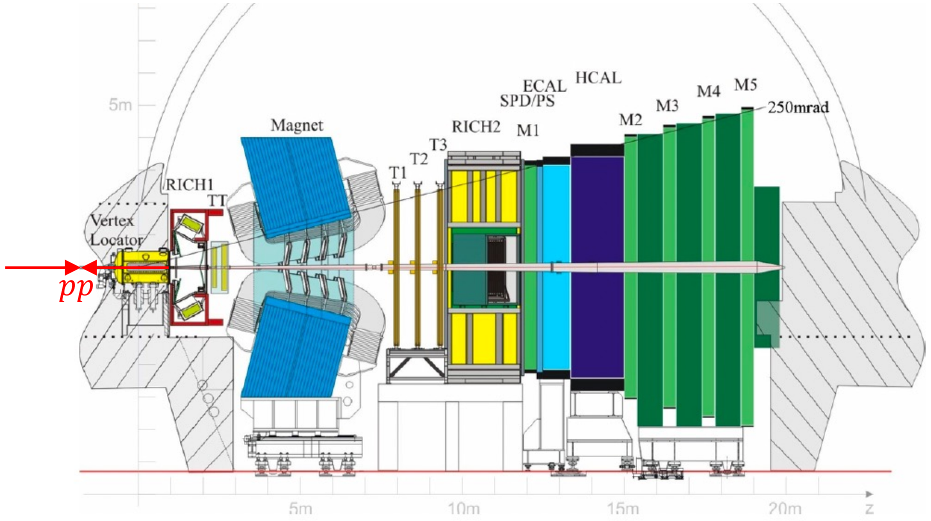
  - Investigate the quark flavour sector
  - Positioned in the forward region relative to the collision point
  - Large production $b\bar{b}$ and $c\bar{c}$ cross sections within its acceptance
    - ✓ $72(144)$ μb and $1.4(2.6)$ mb at $\sqrt{s} = 7(13)$ TeV
    - ✓ Not just *beauty* and *charm* …





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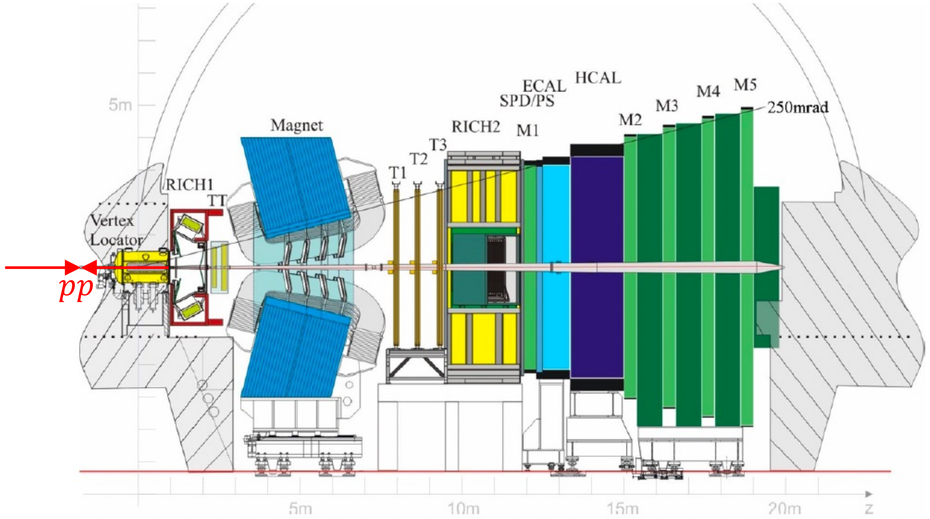
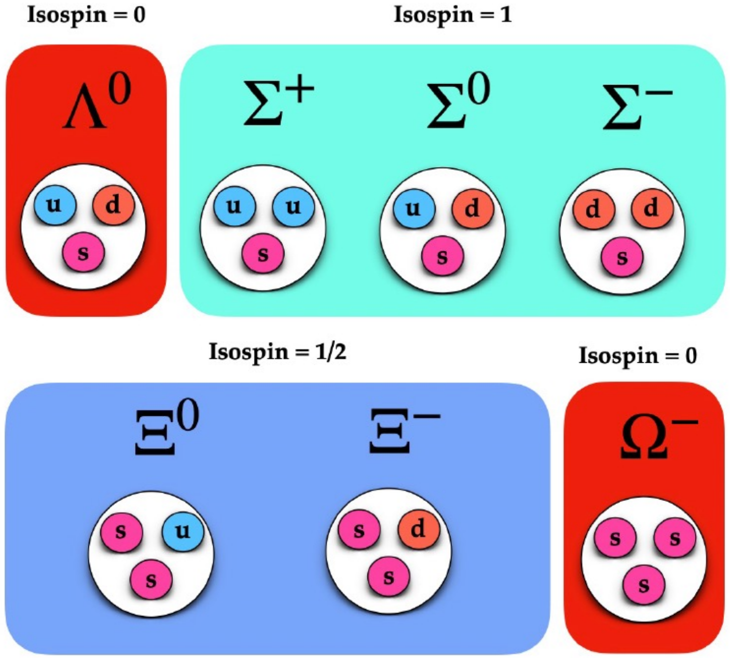
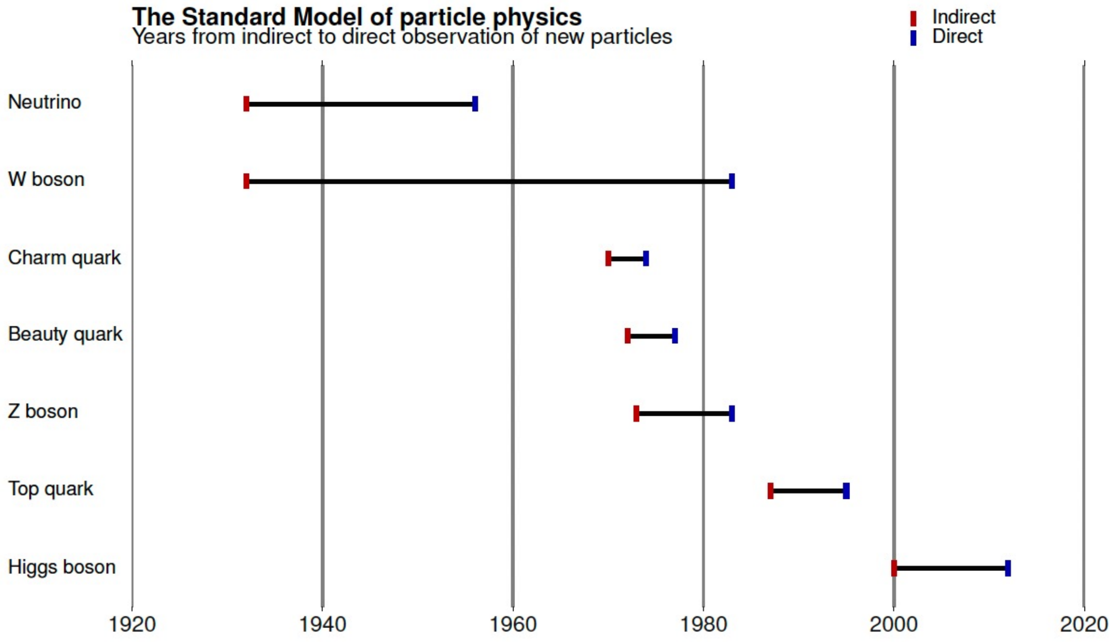
- 22 countries are involved in the collaboration
  - About 1700 scientists, engineers and technicians
  - More than 800 articles published up-to-date
    [LHCb public site]



Why hyperons?

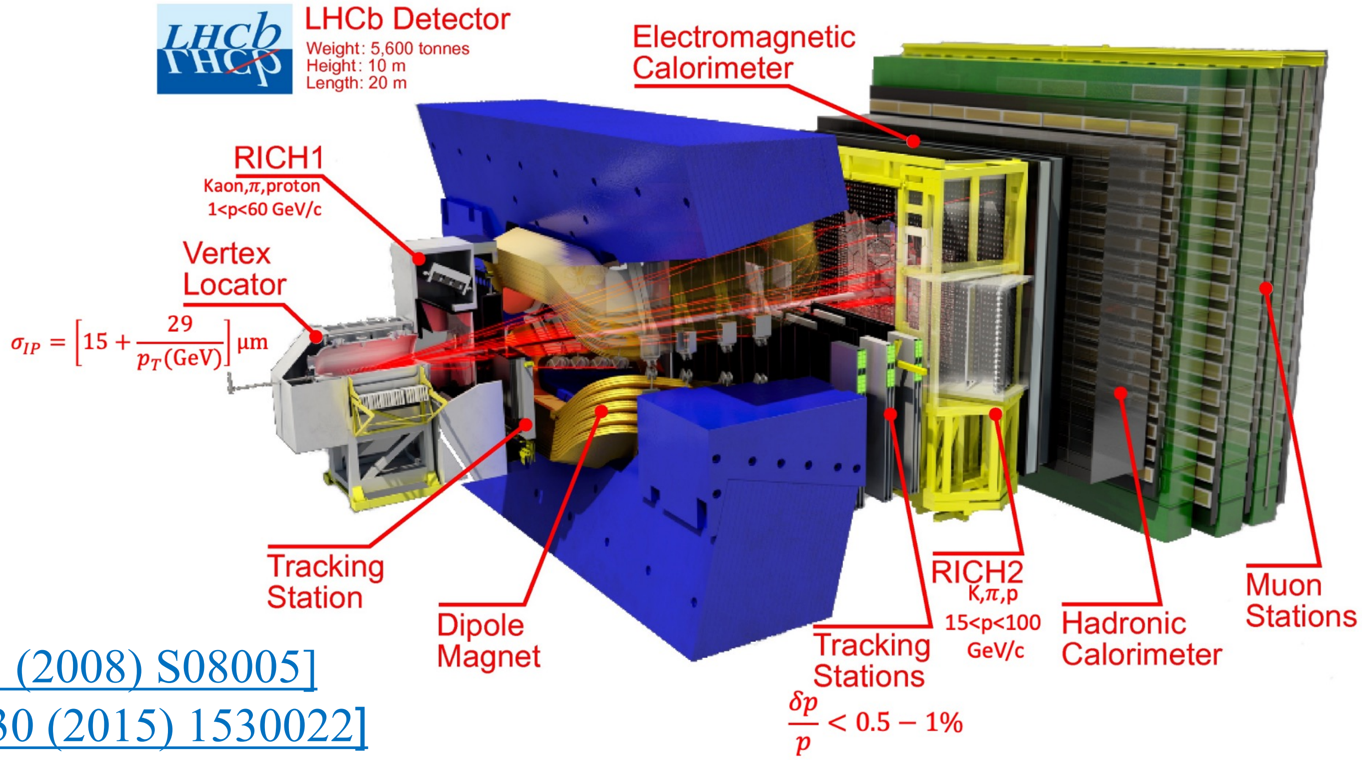
- *Strange* sector as the birth of flavour physics
  - Fostered numerous discoveries → new quarks, families and CPV
  - Complementary to *beauty* and *charm* studies
  - Still the sector with higher (indirect) energy reach
  - Rare decays and CPV sensitive to possible NP



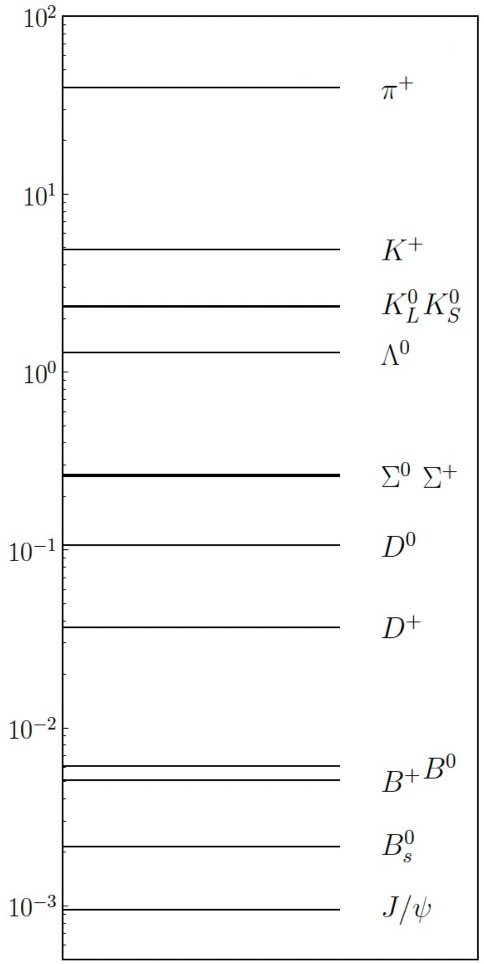


Hyperons at LHC(b)

- Huge *strange* hadrons cross-section at LHC
  - Production mostly in the forward region → perfect for *LHCb* acceptance (400 mrad)
  - About 1 *strange* hadron per collision (compared to $\sim 10^{-3}$ B_s^0 mesons)
  - However, reconstruction and trigger bring it down …



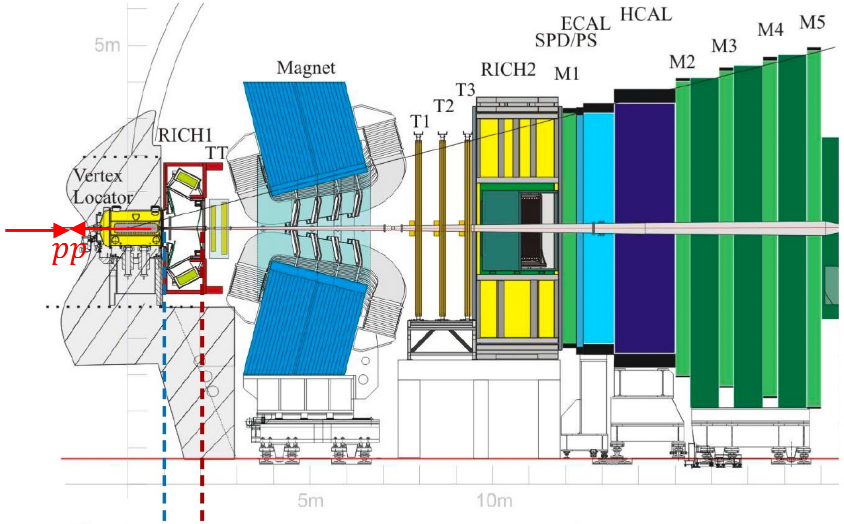
Average particles in LHCb acceptance per minimum bias event at $\sqrt{s} = 13$ TeV
[arXiv:1808.03477]

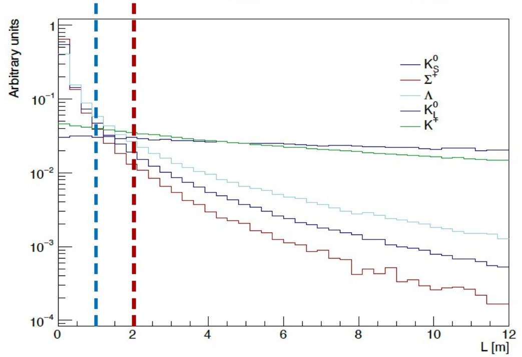


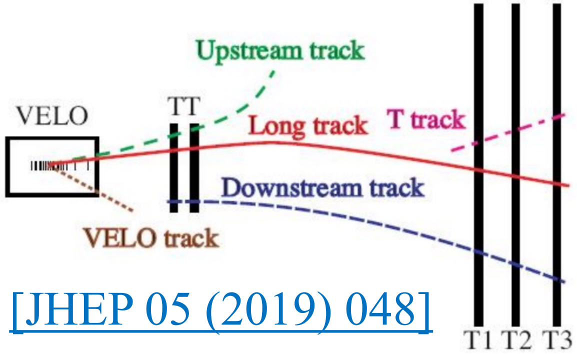
[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 1530022]

Looking for hyperons

- About 50% lifetime acceptance for hyperons
  - Different reconstruction methods for final-state tracks







[JHEP 05 (2019) 048]

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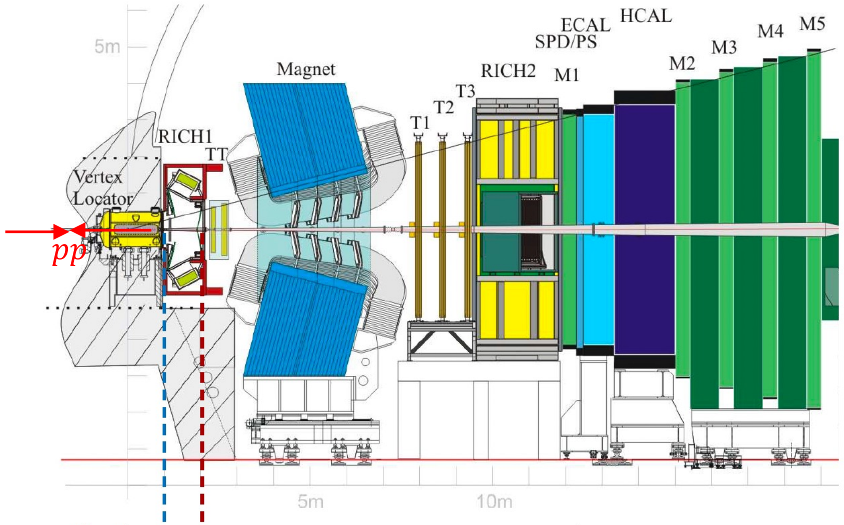

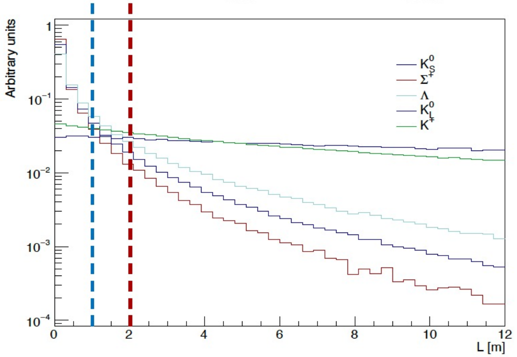

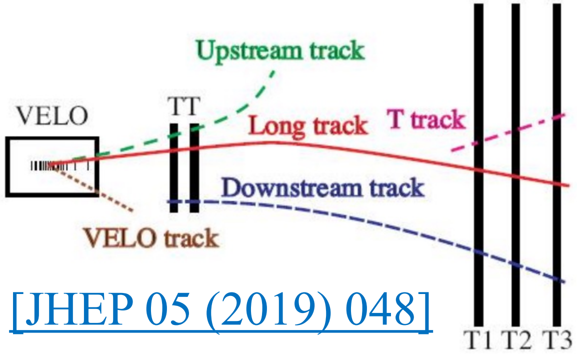

[JHEP 05 (2019) 048]

- Run 1/2 efficiency limited by L0 hardware trigger
  - Designed for heavy flavours
  - Muon/hadron trigger require $p_T > [1-5]$ GeV
    Too hard for primary hyperons

- Software HLT trigger highly customisable
  - First dedicated lines → Run 1
  - Dedicate reconstruction for soft muons → Run 2
  - Many more dedicated lines → Run 3 (Upgrade)
    No hardware trigger

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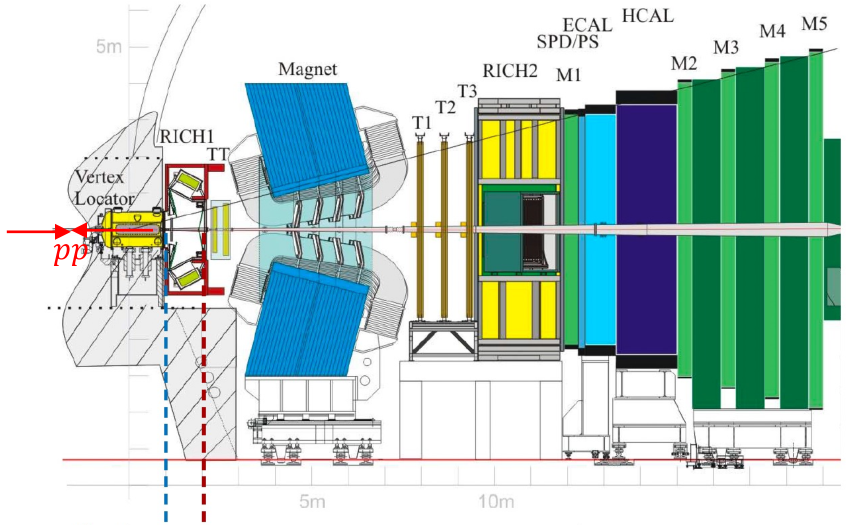

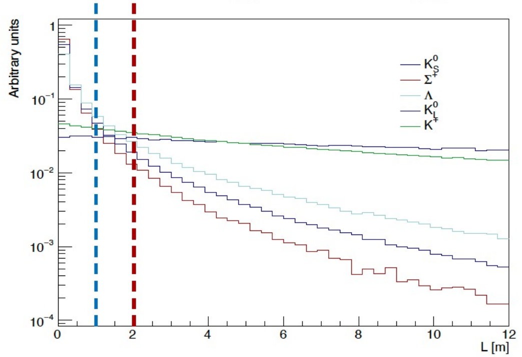

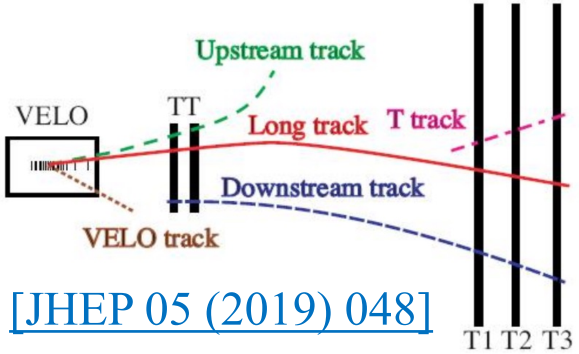

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Outline of the day
Latest results on hyperons decay at *LHCb*
"Observation of the very rare $\Sigma^+ \to p\mu^+\mu^-$ decay"
[Phys. Rev. Lett. 135 (2025) 051801]

The $\Sigma^+ \to p\mu^+\mu^-$ decay

$$\mathcal{M}_{SM}^{LD} = e^2 G_F \left[\frac{-i}{q^2}\bar{u}_p(a+\gamma_5 b)\sigma^{\kappa\nu}q_\kappa u_\Sigma - \bar{u}_p\gamma^\nu(c+\gamma_5 d)u_\Sigma\right]\bar{u}_\ell\gamma_\nu v_{\bar{\ell}}$$

- $\Sigma^+ \to p\mu^+\mu^-$ is a very rare FCNC process
  - Short distance SM $\mathcal{B}\sim\mathcal{O}(10^{-12})$
    Z-penguin, box, and photon-penguin diagrams
  - Dominated by long distance contributions
    $1.6\times10^{-8} < \mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) < 9.1\times10^{-8}$
    [Phys. Rev. D72 (2005) 074003]
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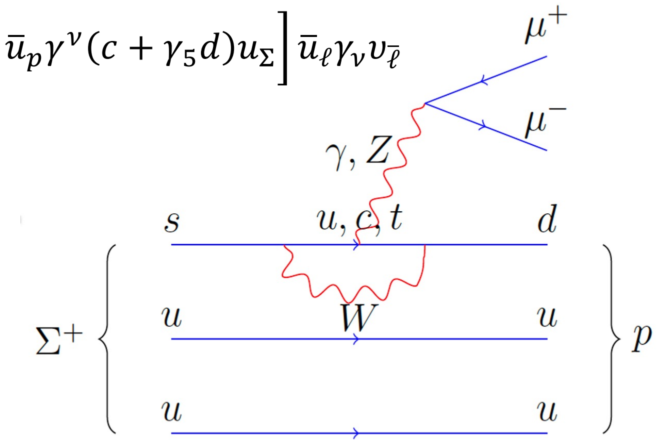

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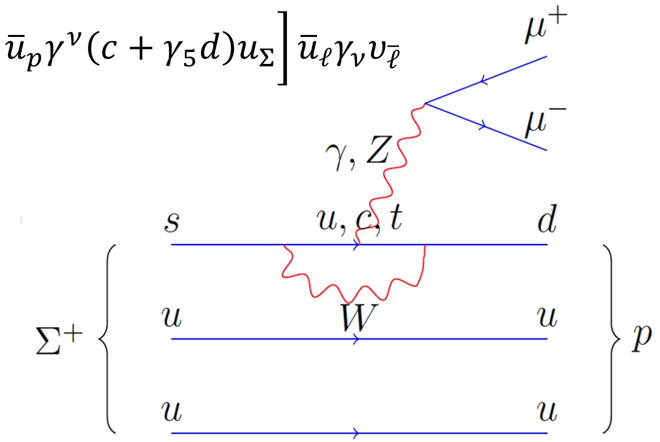

- First evidence from the HyperCP experiment
  - Three candidates observed in absence of background
  - Measured branching fraction
    $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = \left(8.6^{+6.6}_{-5.4} \pm 5.5\right)\times10^{-8}$
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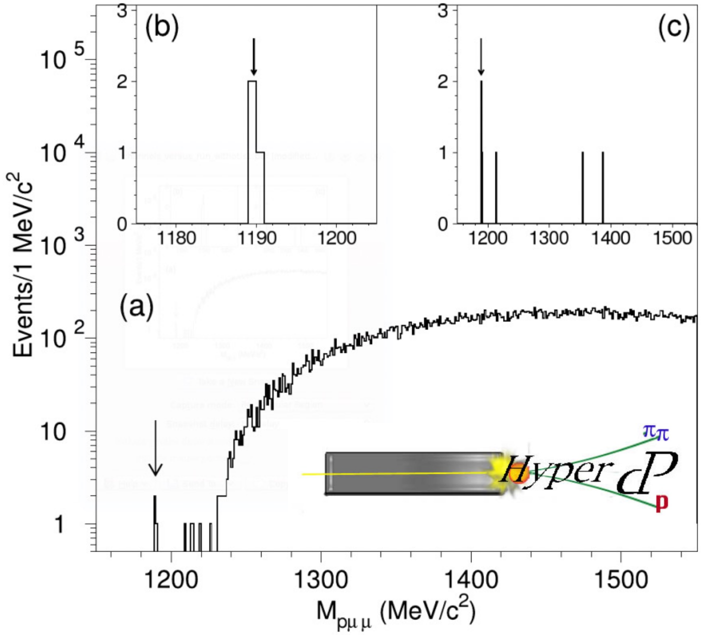

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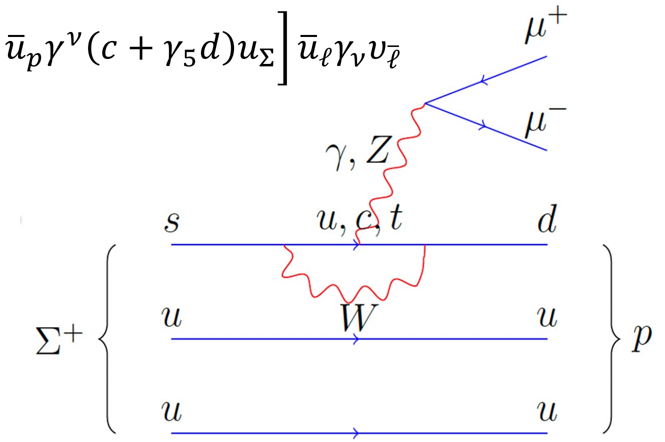

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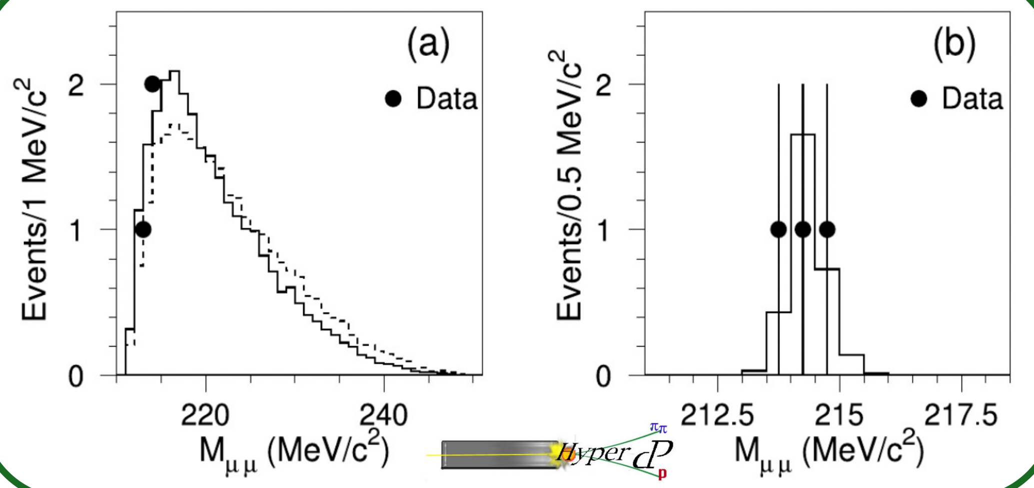
- The Anomaly
  - Same dimuon invariant mass for the observed candidates
  - Possible $\Sigma^+ \to pX^0(\to \mu^+\mu^-)$ decay $\to m_{X^0} = 214.3 \pm 0.5$ MeV



Searches and interpretations

- Many Beyond SM hypotheses → NP contributions expected only at short distance for an HyperCP-like particle

~3 years after HyperCP

"Sgoldstino interpretation of HyperCP events"
[Phys. Rev. D73 (2006) 035002]
"On the possibility of a new boson X^0 (214MeV) in $\Sigma^+ \to p\mu^+\mu^-$"
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BELLE: $B^0 \to K^{*0}\mu^+\mu^-$
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LHCb: $B^0 \to \mu^+\mu^-\mu^+\mu^-$
[Phys. Rev. Lett. 110 (2013) 211801]
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  - Run 1 dataset → $\sqrt{s} = 7,8$ TeV, $\mathcal{L} = 3.0\ \text{fb}^{-1}$
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- Stronger evidence
  - Excess of signal candidates w.r.t. background
    $N_{\Sigma^+\to p\mu^+\mu^-} = \left(10.2^{+3.9}_{-3.5}\right)$
  - Measured branching fraction
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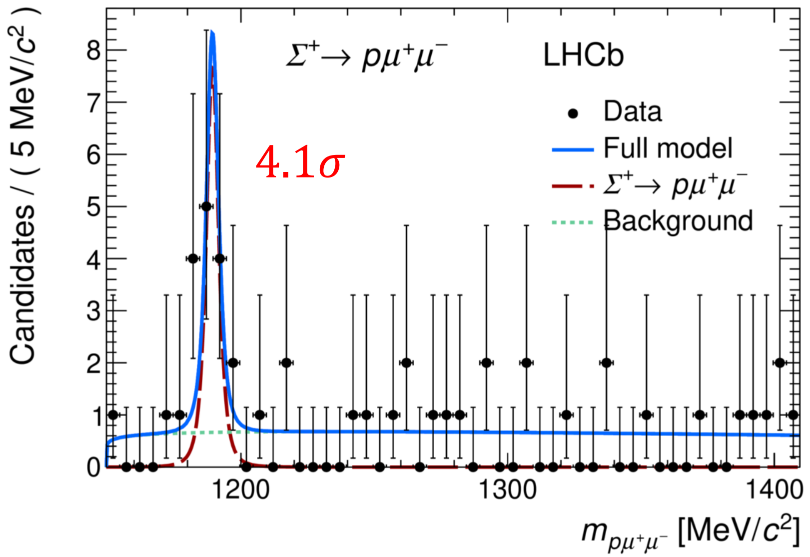

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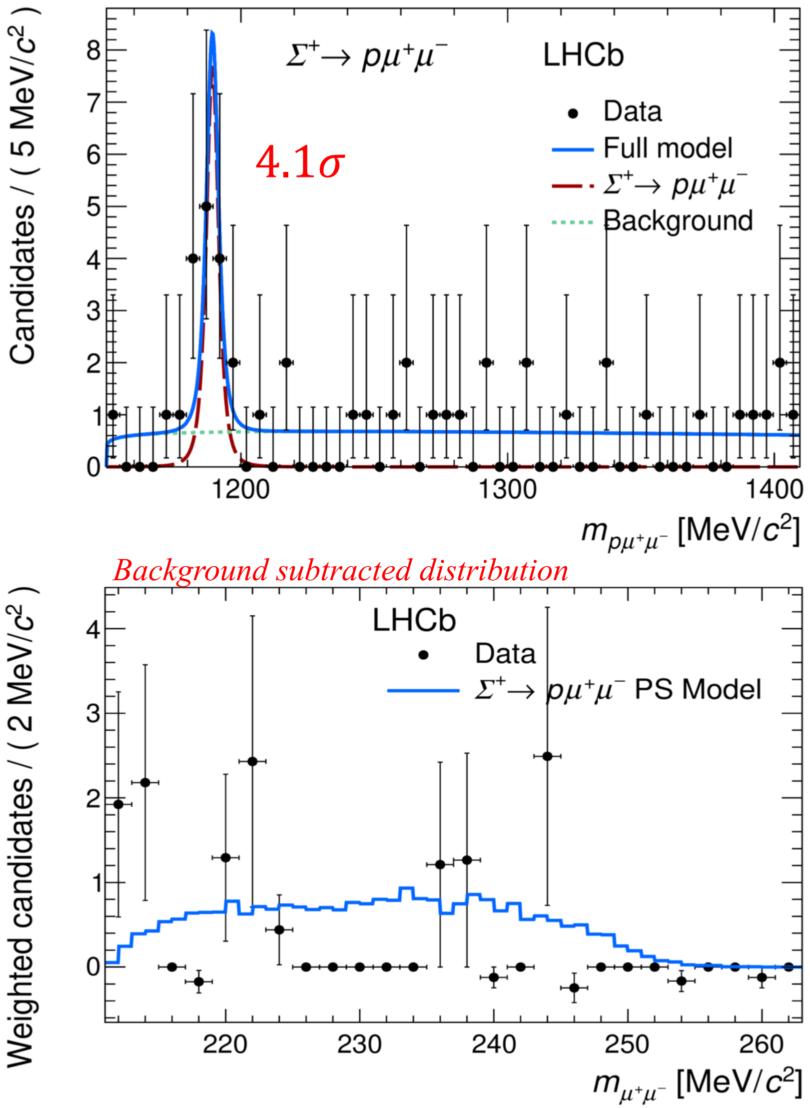
- Search for HyperCP-like resonances
  - No peak structures found
  - Set upper limit at 90% C.L.
    $\mathcal{B}(\Sigma^+ \to pX^0(\to \mu^+\mu^-)) < 1.4\times10^{-8}$
  - HyperCP anomaly disfavored



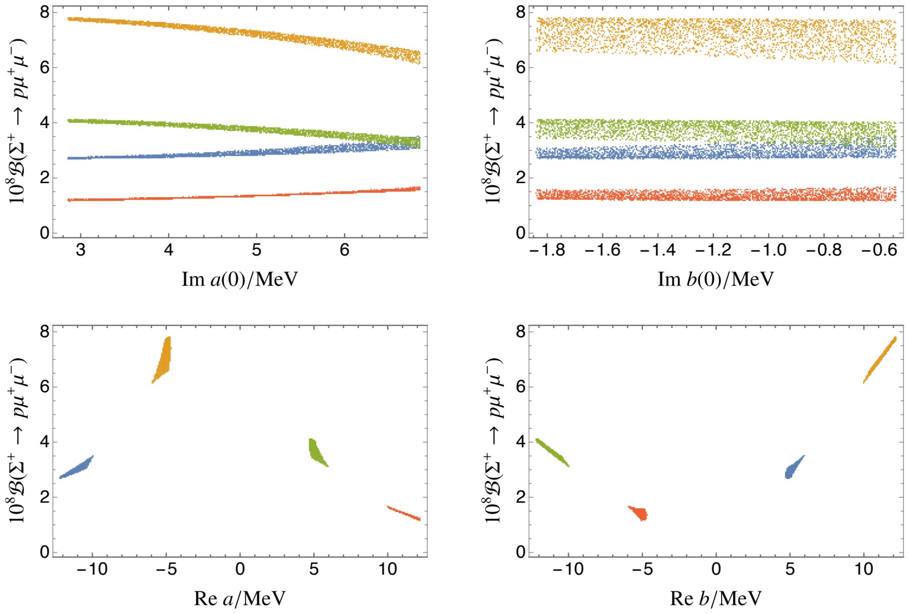
Additional theory interest

- $\Sigma^+ \to p\mu^+\mu^-$ SM prediction based on the $\Sigma^+ \to p\gamma$ decay
  - New results from BESIII [Phys. Rev. Lett. 130 (2023) 211901]

Parameter	BESIII	PDG
$\mathcal{B}\,(10^{-3})$	$0.996 \pm 0.021 \pm 0.018$	1.23 ± 0.05
α	$-0.651 \pm 0.056 \pm 0.020$	-0.76 ± 0.08

$$\Gamma = \frac{G_F^2 e^2}{\pi}(a^2 + b^2)E_\gamma^3 \qquad \alpha = \frac{2\mathcal{R}[ab^*]}{a^2 + b^2}$$

SM prediction will change with latest input



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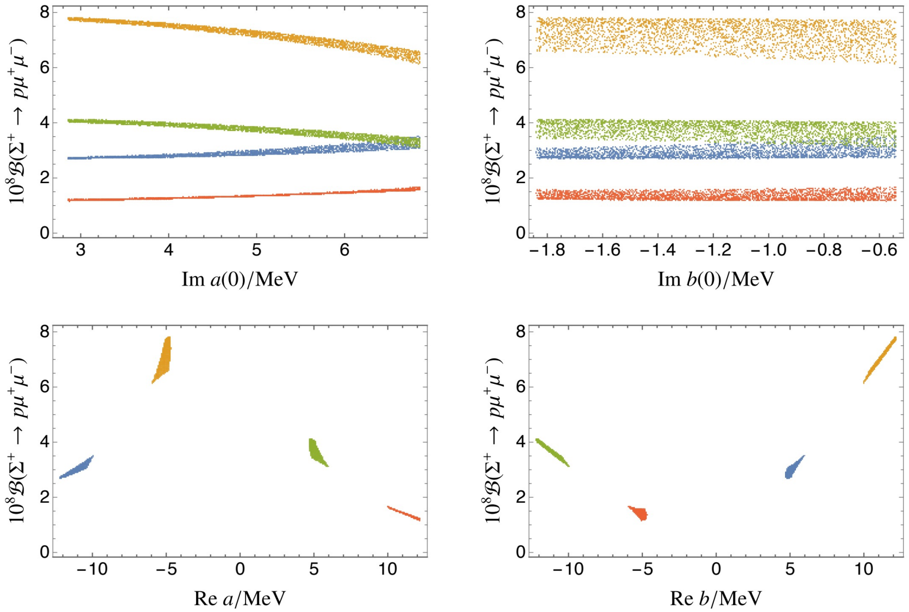
- Chiral perturbation theory (χPT)
  - Relativistic and heavy baryon approaches
  - Four-fold degeneracy in each method [arXiv:2404.15268]



Relativistic baryon

Re a (MeV)	Re b (MeV)	$10^8\,\mathcal{B}_{\mu\mu}$	$10^8\,\mathcal{B}_{\mu\mu}^{\mathrm{Re}(c,d)=0}$
-12.15 ± 0.24	4.78 ± 0.42	2.7 ± 0.2	1.8 ± 0.1
-4.78 ± 0.42	12.15 ± 0.24	7.8 ± 0.3	5.8 ± 0.2
4.78 ± 0.42	-12.15 ± 0.24	4.2 ± 0.2	5.8 ± 0.2
12.15 ± 0.24	-4.78 ± 0.42	1.2 ± 0.1	1.8 ± 0.1

Heavy baryon

Re a (MeV)	Re b (MeV)	$10^8\,\mathcal{B}_{\mu\mu}$	$10^8\,\mathcal{B}_{\mu\mu}^{\mathrm{Re}(c,d)=0}$
-9.74 ± 0.54	6.17 ± 0.74	3.7 ± 0.5	2.7 ± 0.3
-6.17 ± 0.74	9.74 ± 0.54	6.1 ± 0.5	4.5 ± 0.4
6.17 ± 0.74	-9.74 ± 0.54	3.2 ± 0.3	4.5 ± 0.4
9.74 ± 0.54	-6.17 ± 0.74	1.9 ± 0.2	2.7 ± 0.3

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Additional theory interest

- $\Sigma^+ \to p\mu^+\mu^-$ SM prediction based on the $\Sigma^+ \to p\gamma$ decay
  - New results from BESIII [Phys. Rev. Lett. 130 (2023) 211901]

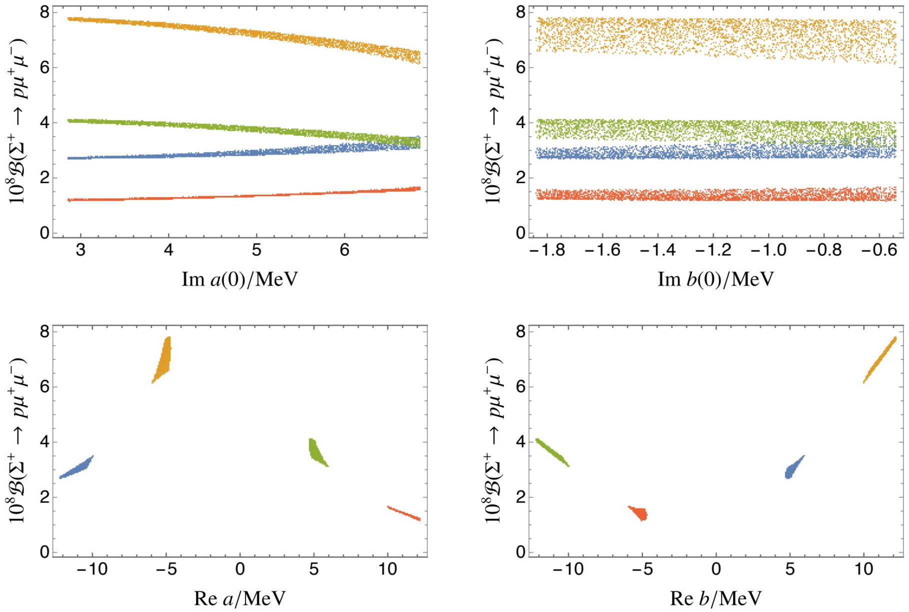
Parameter	BESIII	PDG
$\mathcal{B}\,(10^{-3})$	$0.996 \pm 0.021 \pm 0.018$	1.23 ± 0.05
α	$-0.651 \pm 0.056 \pm 0.020$	-0.76 ± 0.08

$$\Gamma = \frac{G_F^2 e^2}{\pi}(a^2 + b^2)E_\gamma^3 \qquad \alpha = \frac{2\mathcal{R}[ab^*]}{a^2 + b^2}$$

SM prediction will change with latest input

- Chiral perturbation theory (χPT)
  - Relativistic and heavy baryon approaches
  - Four-fold degeneracy in each method [arXiv:2404.15268]

Experiments should be able to solve it



	Re a (MeV)	Re b (MeV)	$10^8\,\mathcal{B}_{\mu\mu}$	$10^8\,\mathcal{B}_{\mu\mu}^{\mathrm{Re}(c,d)=0}$
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	-4.78 ± 0.42	12.15 ± 0.24	7.8 ± 0.3	5.8 ± 0.2
	4.78 ± 0.42	-12.15 ± 0.24	4.2 ± 0.2	5.8 ± 0.2
	12.15 ± 0.24	-4.78 ± 0.42	1.2 ± 0.1	1.8 ± 0.1
	Re a (MeV)	Re b (MeV)	$10^8\,\mathcal{B}_{\mu\mu}$	$10^8\,\mathcal{B}_{\mu\mu}^{\mathrm{Re}(c,d)=0}$
Heavy baryon	-9.74 ± 0.54	6.17 ± 0.74	3.7 ± 0.5	2.7 ± 0.3
	-6.17 ± 0.74	9.74 ± 0.54	6.1 ± 0.5	4.5 ± 0.4
	6.17 ± 0.74	-9.74 ± 0.54	3.2 ± 0.3	4.5 ± 0.4
	9.74 ± 0.54	-6.17 ± 0.74	1.9 ± 0.2	2.7 ± 0.3

New LHCb Run 2 analysis

- Many improvements w.r.t. previous analysis
  - Increase in statistics
    Run 1 $\rightarrow$ $\sqrt{s} = 7, 8$ TeV, $\mathcal{L} = 3.0\ \text{fb}^{-1}$
    Run 2 $\rightarrow$ $\sqrt{s} = 13$ TeV, $\mathcal{L} = 5.4\ \text{fb}^{-1}$
  - Increase in performances
    Run 1 → Highly prescaled minimum bias data
    Run 2 → Dedicated trigger lines [LHCb-PUB-2017-023]
    HLT1: Complementary forward tracking lowered down to 80 MeV for muon tracks
    Generic Hlt1DiMuonNoL0 for soft dimuons not requiring L0 triggered events in input
    HLT2: Generic Hlt2DiMuonSoft for soft dimuons
    Dedicated Hlt2RareStrangeSigmaPMuMu for $\Sigma^+ \rightarrow p\mu^+\mu^-$ decays

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New accessible measurements

$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-)$ vs dimuon mass

Forward-backward asymmetry in the decay

Σ^+ and $\bar{\Sigma}^-$ polarisations

“Direct” CP violation

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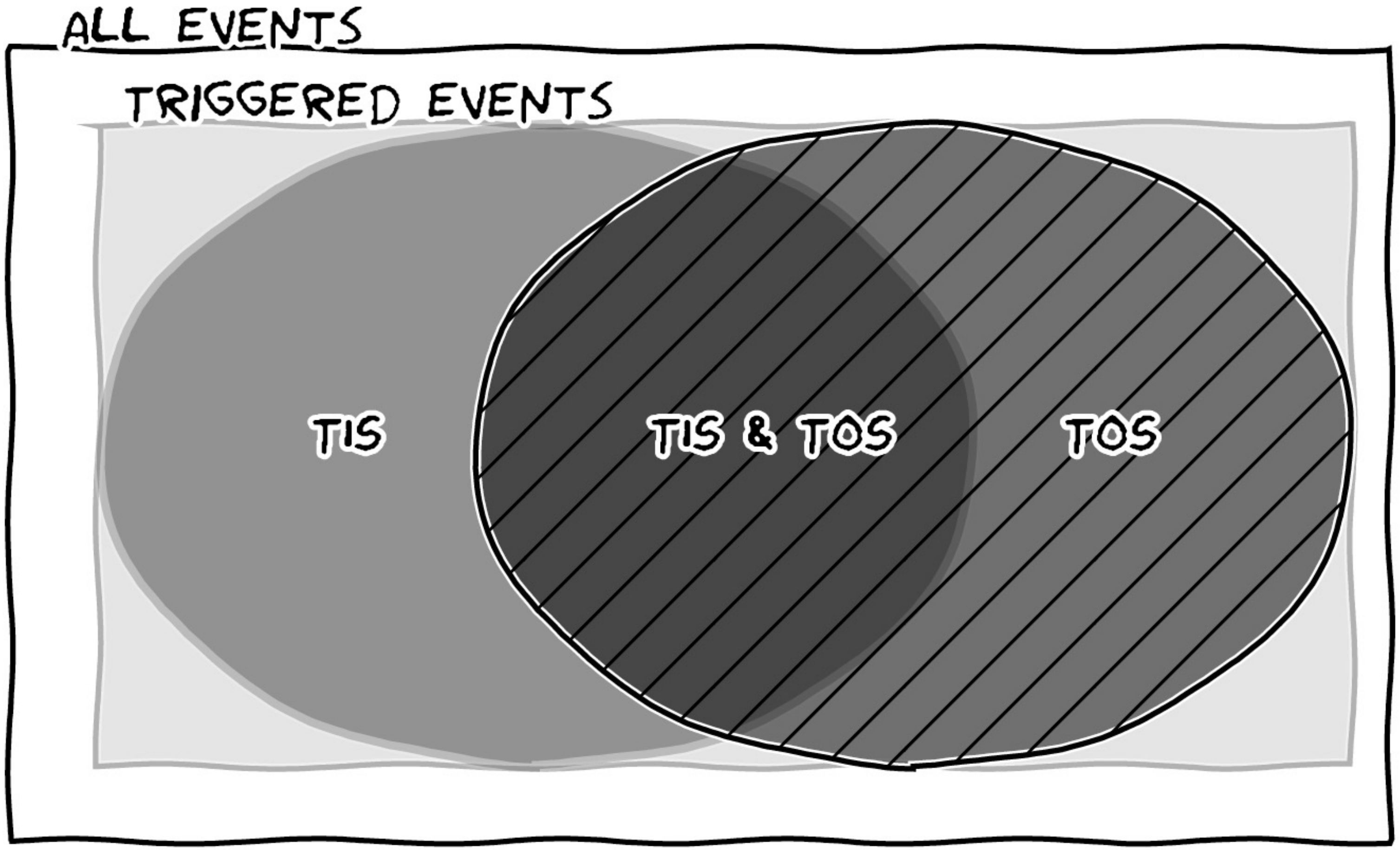
- Analysis strategy
  - Trigger → TISTOS method
  - Preselection → kinematic variables
  - Final selection → PID variables and multivariate operator
    - ✓ Optimised for smallest statistical uncertainty

Trigger

- Low trigger efficiencies in *strange* analyses
  - Use also "parasitic" events
- *LHCb* categories
  - TIS → Trigger Independently from Signal
  - TOS → Trigger On Signal
  - Overlap crucial to estimate efficiencies

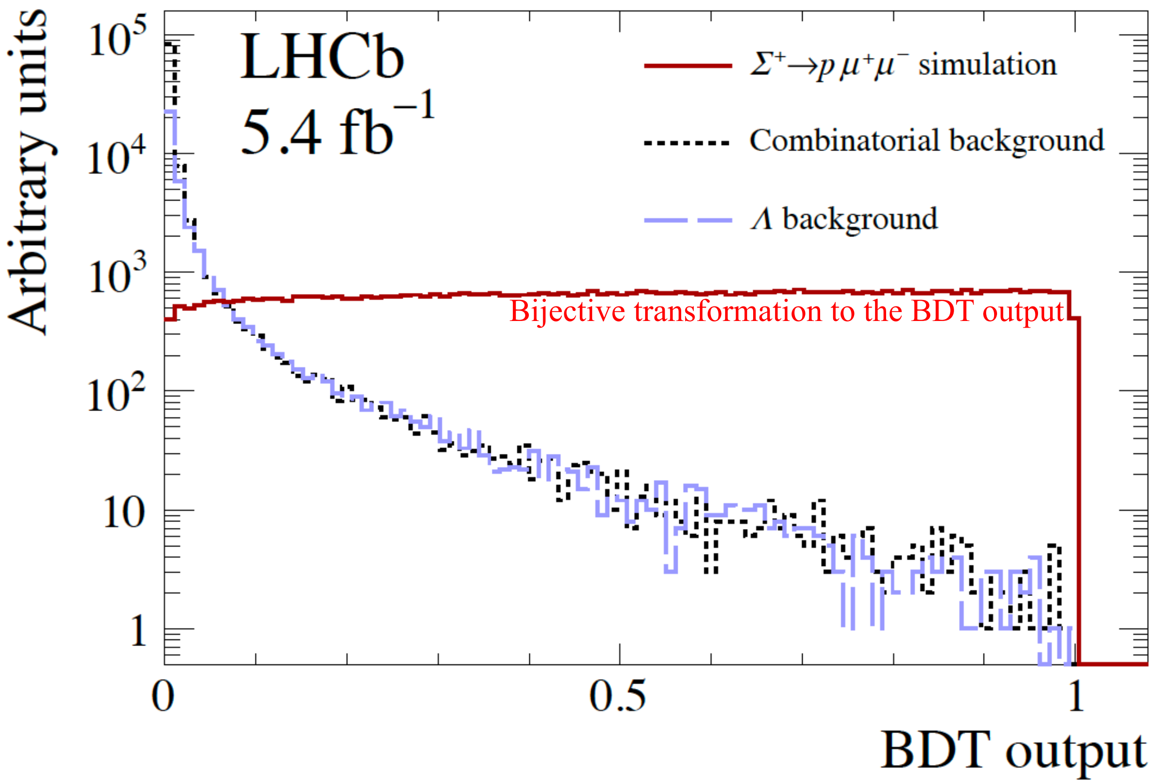
$$\varepsilon_{TOS} = \frac{N_{TIS\&TOS}}{N_{TIS}} \qquad \varepsilon_{TIS} = \frac{N_{TIS\&TOS}}{N_{TOS}}$$

TISTOS method
[LHCb-PUB-2014-039]



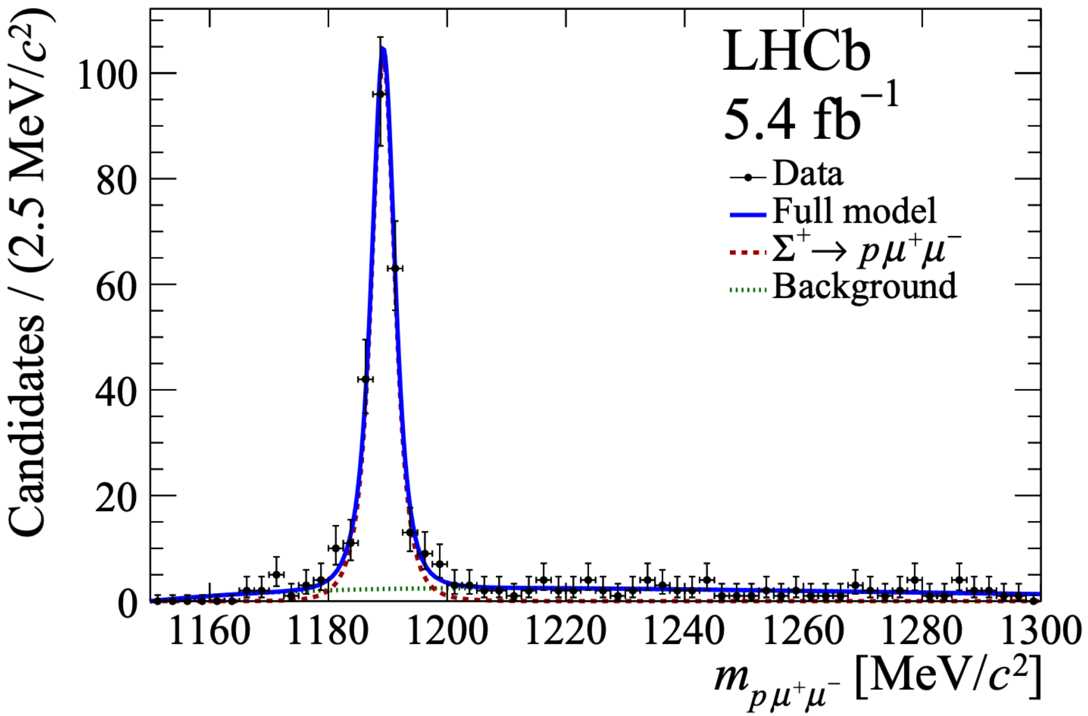
Selection

- First steps
  - Loose → Kinematic variables
  - Tight → PID variables
    - ✓ Reduce the dataset size
- Background sources
  - Combinatorial
  - $\Lambda \rightarrow p\pi^-$ decays with $\pi^- \rightarrow \mu^-$ misID plus an additional μ^+
  - Small q-value → few modes can mimic the signal final state
    $q = (m_{\Sigma^+} - m_p - 2m_\mu) = 39.78\ \mathrm{MeV}/c^2$
- Final step based on a multivariate operator
  - BDT built in TMVA
    - ✓ Trained to reject combinatorial
    - ✓ A requirement will reject both background sources



Observation of the $\Sigma^+ \to p\mu^+\mu^-$ decay

- Extended maximum likelihood fit to the final sample
  - $\Sigma^+ \to p\mu^+\mu^-$ parametrised by an Hypatia function
  - Background by a modified Argus function



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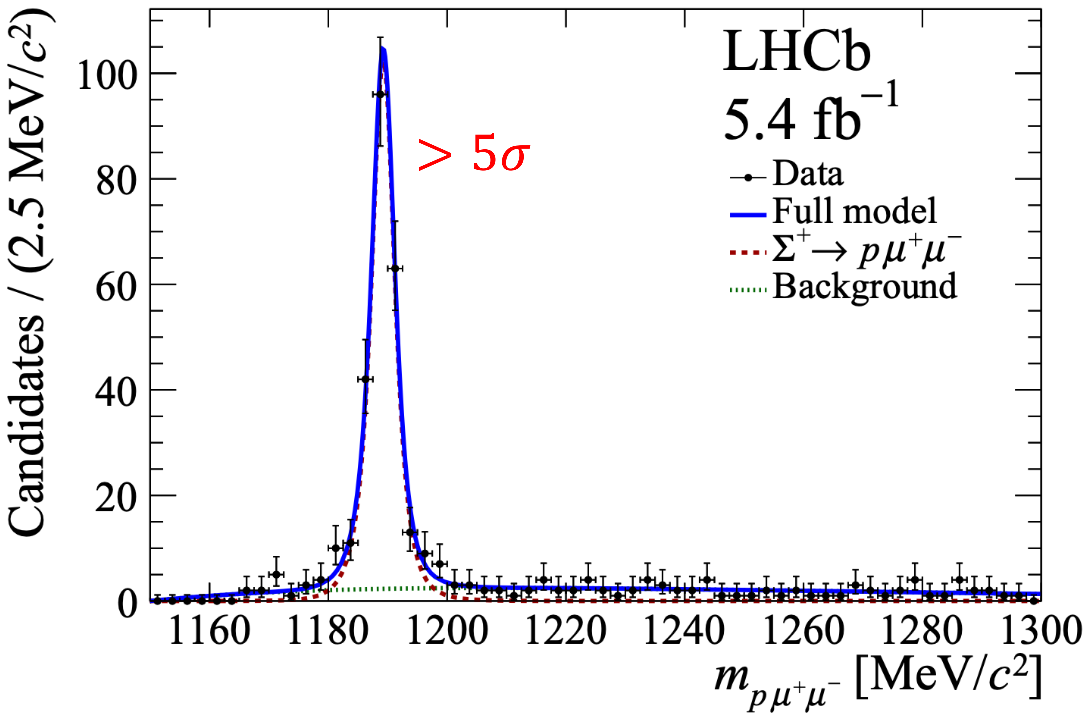
  - Background by a modified Argus function

  $N_{\Sigma^+ \to p\mu^+\mu^-} = 237 \pm 16$

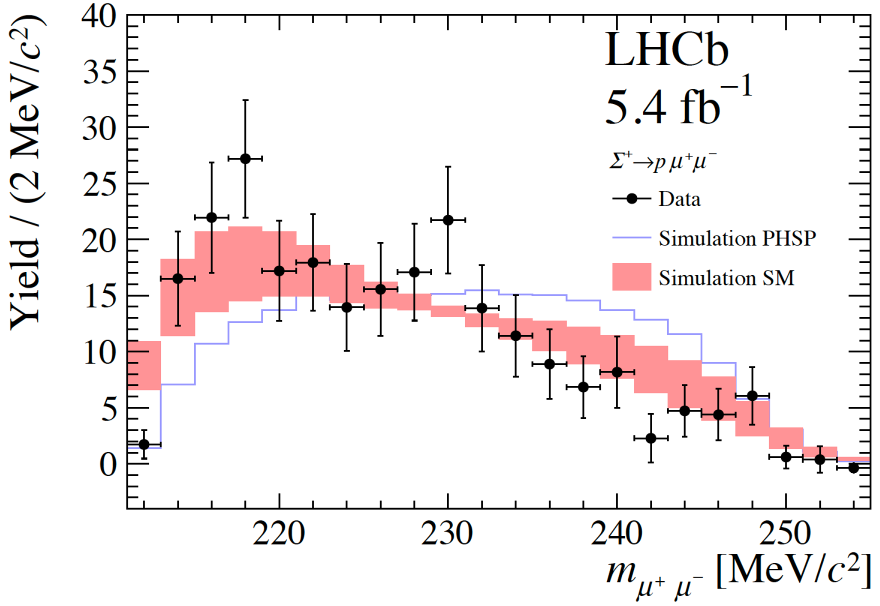


Very clear first observation
Large signal w.r.t. small background

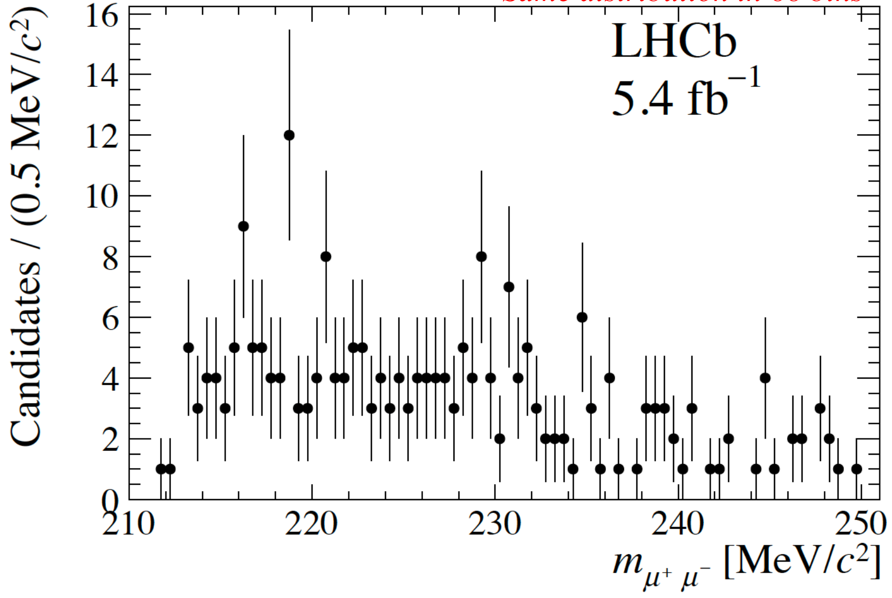
Search for the Anomaly – *sPlot*

- Background subtraction
  - Signal weights per-event derived with the *sPlot* method → cross-check with bin-by-bin fits
  - $m_{p\mu^+\mu^-}$ as discriminat variable

- No significant peaking structure is visible
  - Data compared with simulated phase space and SM prediction
  - Good agreement in the full dimuon distribution

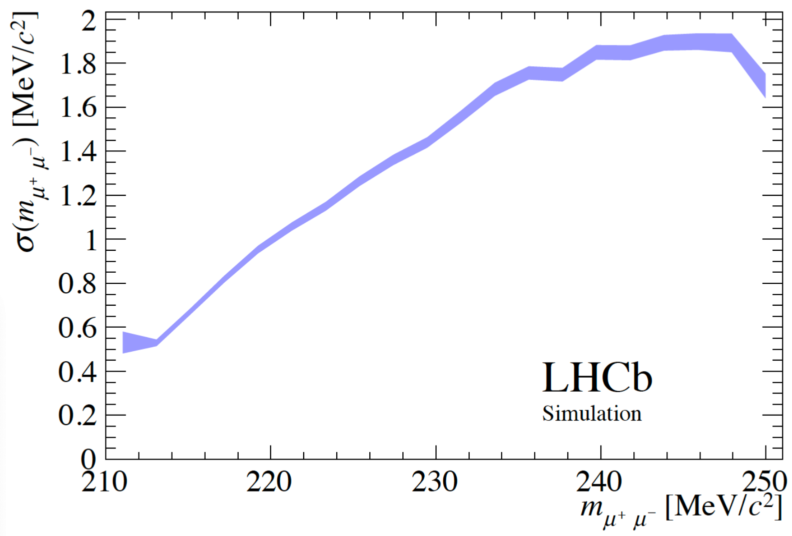


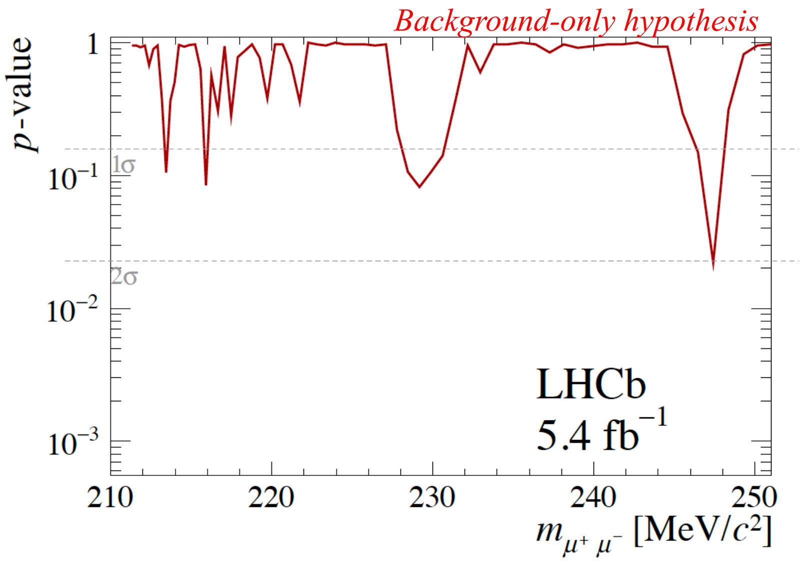
Same distribution in 88 bins



Search for the Anomaly – Scan

- Scan in the $m_{\mu^+\mu^-}$ distribution
  - Candidates in $\pm 2\sigma$ from the Σ^+ peak
  - Steps of $2\sigma_{\mu^+\mu^-}$ and signal window of $\pm 1.5\sigma_{\mu^+\mu^-}$
  - Background estimate from sidebands $[1.5\ - 4.0]\sigma_{\mu^+\mu^-}$
  - Compute p-value of a Poisson fluctuation of the background (i.e. non-resonant)
- No significant structure is found considering a putative candidate with $m_{X^0} = 214.3\ \mathrm{MeV}/c^2$
  - HyperCP anomaly excluded



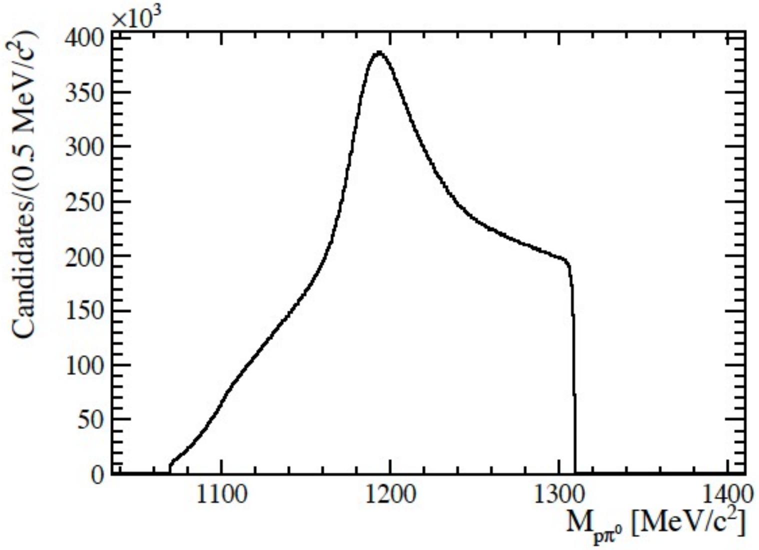


Normalisation

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = \frac{\varepsilon_{\Sigma^+\to p\pi^0}}{\varepsilon_{\Sigma^+\to p\mu^+\mu^-}} \frac{\mathcal{B}(\Sigma^+ \to p\pi^0)}{N_{\Sigma^+\to p\pi^0}} \cdot N_{\Sigma^+\to p\mu^+\mu^-}$$

- No fully charged final states of the Σ^+ available to normalise
  - $\Sigma^+ \to p\pi^0$ chosen as normalisation channel
  - Reconstructible as a charged track plus $\pi^0 \to \gamma\gamma$ in ECAL → resolved π^0 at low energies
    $\mathcal{B}(\Sigma^+ \to p\pi^0) = (51.77 \pm 0.30)\%$

- Observed limited resolution on $m_{\gamma\gamma}$ in data after selection → PID and kinematic variables
  - Poor resolution of the photons energy deposits in the calorimeter



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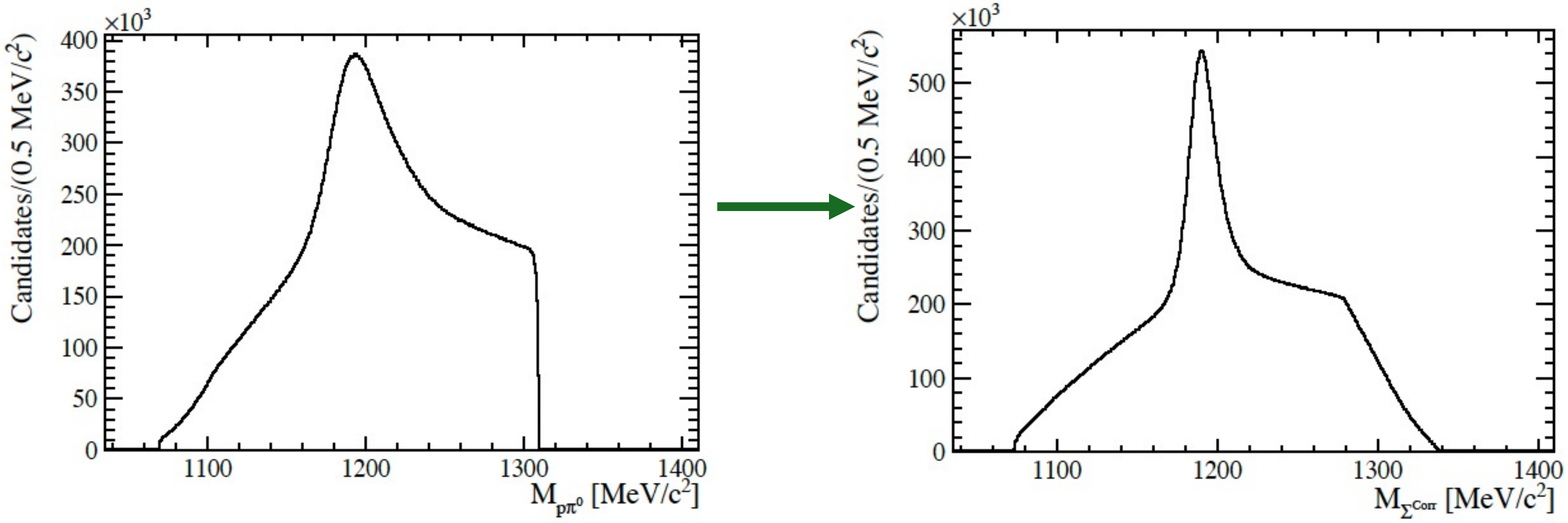
$$m_{Corr} = m_{p\gamma\gamma} - m_{\gamma\gamma} + m_{\pi^0}^{PDG}$$
$$m_{\pi^0}^{PDG} = 134.977\ \mathrm{MeV}/c^2$$

- Observed limited resolution on $m_{\gamma\gamma}$ in data after selection → PID and kinematic variables
  - Poor resolution of the photons energy deposits in the calorimeter
  - $\Sigma^+ \to p\pi^0$ mass corrected by adjusting for the PDG value of the π^0



Fit to the normalisation channel

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = \frac{\varepsilon_{\Sigma^+\to p\pi^0}}{\varepsilon_{\Sigma^+\to p\mu^+\mu^-}} \frac{\mathcal{B}(\Sigma^+ \to p\pi^0)}{N_{\Sigma^+\to p\pi^0}} \cdot N_{\Sigma^+\to p\mu^+\mu^-}$$

- Extended maximum likelihood fit to the corrected mass
  - $\Sigma^+ \to p\pi^0$ parametrised by double-sided Crystal Ball function
  - Background by second degree Chebyshev polynomial function

$$m_{Corr} = m_{p\gamma\gamma} - m_{\gamma\gamma} + m_{\pi^0}^{PDG}$$

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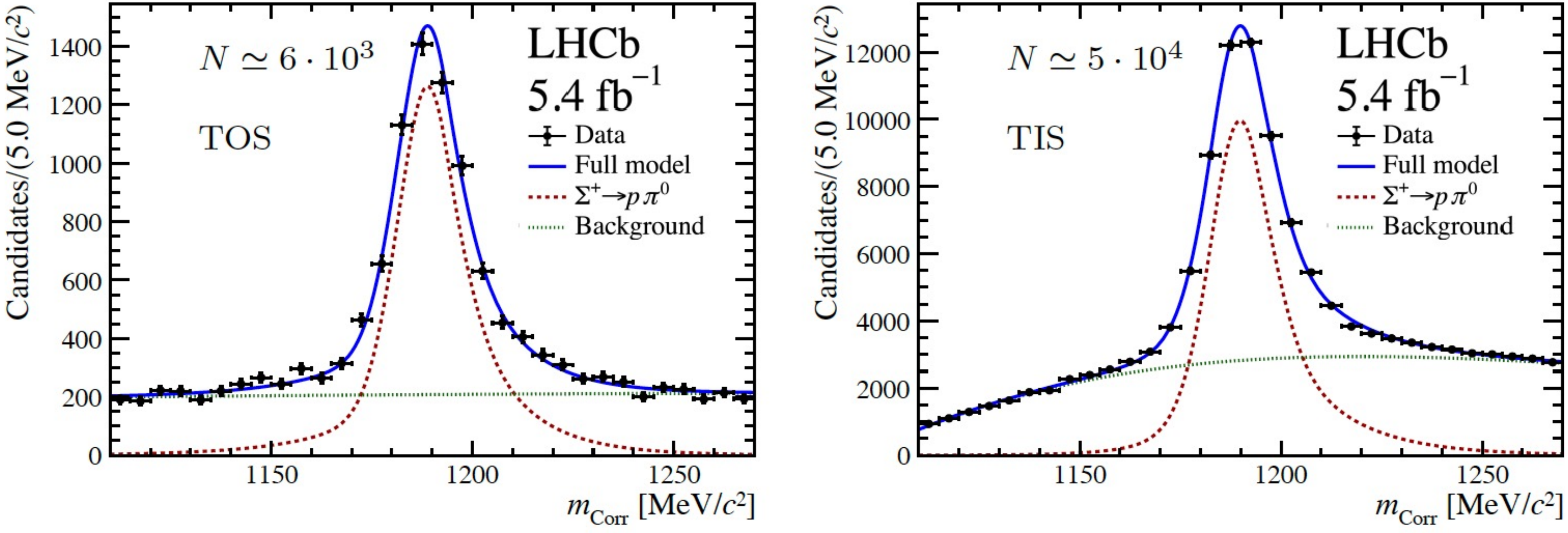


Branching fraction measurement

- Single event sensitivity
  - Divided by trigger category

    TIS → $\alpha_{TIS} = \left(6.81^{+0.29+0.85}_{-0.25-0.85}\right)\times 10^{-10}$

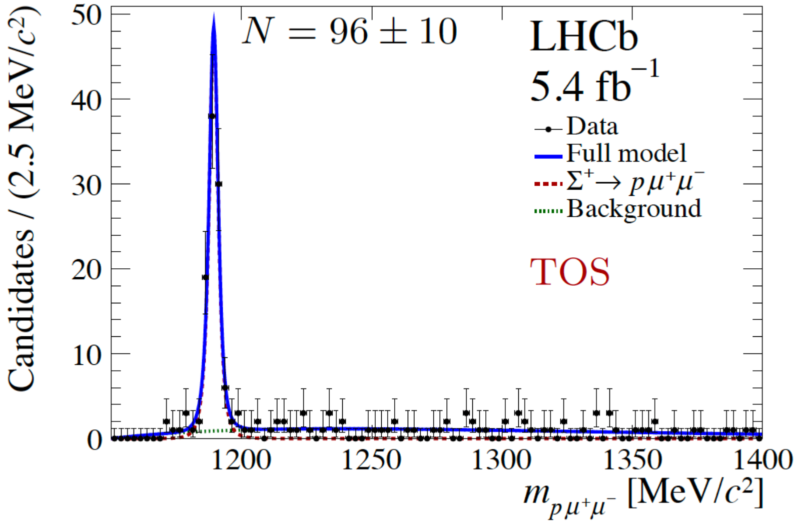
    TOS → $\alpha_{TOS} = \left(1.65^{+0.09+0.41}_{-0.16-0.41}\right)\times 10^{-10}$
  - Corresponding to $\mathcal{O}(10^{14})$ Σ^+ hyperons in *LHCb*

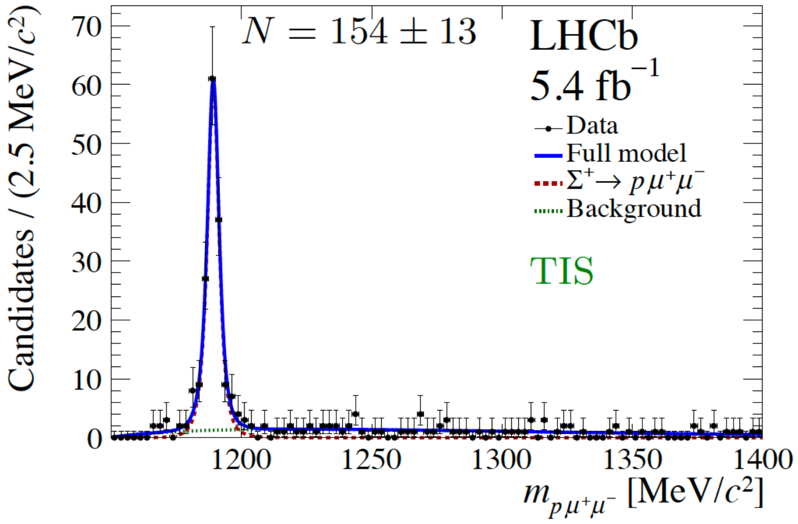
- Measured branching fraction

    TIS → $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = \left(1.05^{+0.10+0.13}_{-0.10-0.13}\right) \times 10^{-8}$

    TOS → $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = \left(1.59^{+0.19+0.40}_{-0.23-0.40}\right) \times 10^{-8}$
  - Combined result

    $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (1.08 \pm 0.17) \times 10^{-8}$





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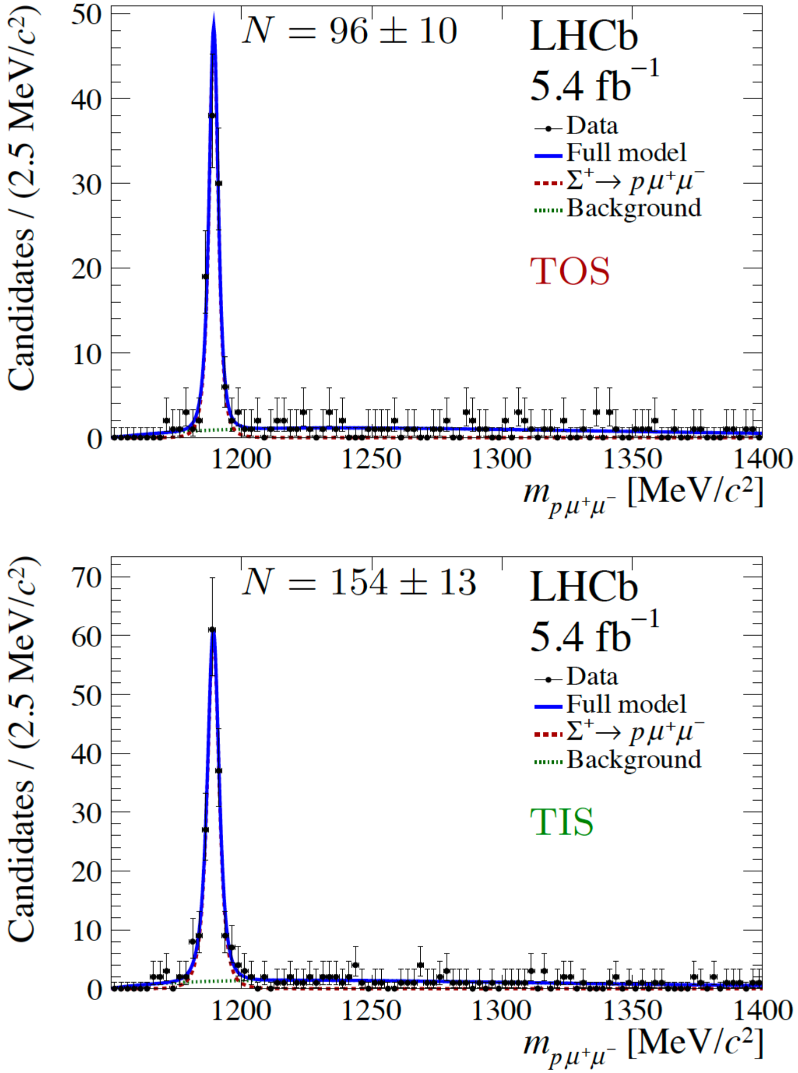
$\boxed{\text{How rare is this decay?}}$



Interpretations

- Evaluation of the the *z-score*

$$z = \frac{|\mu_{exp} - \mu_{th}|}{\sqrt{\sigma_{exp}^2 + \sigma_{th}^2}}$$

- Considerations:
  - Minimum exclusion of 6.2σ for the smaller $|\Re[a(0)]|$
  - Negative $\Re[a(0)]$ disfavoured at a minimum of 3.7σ
  - Heavy baryon
    $\Re[a(0)]$ large and positive disfavoured at 3.1σ
  - Relativistic baryon
    Disfavoured at 3.7σ for $\Re[c(q^2)] = \Re[d(q^2)] = 0$

First relativistic baryon solution is preferred
Rarest decay of a baryon ever observed!!!

	$\Re[a(0)]$ (MeV^{-1})	$\Re[b(0)]$ (MeV^{-1})	$\mathcal{B}$ (10^{-8})	z-score (σ)
Relativistic baryon	$+12.15 \pm 0.24$	-4.78 ± 0.42	1.2 ± 0.1	0.6
	-12.15 ± 0.24	$+4.78 \pm 0.42$	2.7 ± 0.2	6.2
	$+4.78 \pm 0.42$	-12.15 ± 0.24	4.2 ± 0.2	11.9
	-4.78 ± 0.42	$+12.15 \pm 0.24$	7.8 ± 0.3	19.5
Heavy baryon	$+9.74 \pm 0.54$	-6.17 ± 0.74	1.9 ± 0.2	3.1
	-9.74 ± 0.54	$+6.17 \pm 0.74$	3.7 ± 0.5	5.0
	$+6.17 \pm 0.74$	-9.74 ± 0.54	3.2 ± 0.3	6.1
	-6.17 ± 0.74	$+9.74 \pm 0.54$	6.1 ± 0.5	9.5

$\Re[c(q^2)] = \Re[d(q^2)] = 0$

	$\Re[a(0)]$ (MeV^{-1})	$\Re[b(0)]$ (MeV^{-1})	$\mathcal{B}$ (10^{-8})	z-score (σ)
Relativistic baryon	$+12.15 \pm 0.24$	-4.78 ± 0.42	1.8 ± 0.1	3.7
	-12.15 ± 0.24	$+4.78 \pm 0.42$	1.8 ± 0.1	3.7
	$+4.78 \pm 0.42$	-12.15 ± 0.24	5.8 ± 0.2	18.0
	-4.78 ± 0.42	$+12.15 \pm 0.24$	5.8 ± 0.2	18.0
Heavy baryon	$+9.74 \pm 0.54$	-6.17 ± 0.74	2.7 ± 0.3	4.7
	-9.74 ± 0.54	$+6.17 \pm 0.74$	2.7 ± 0.3	4.7
	$+6.17 \pm 0.74$	-9.74 ± 0.54	4.5 ± 0.4	7.9
	-6.17 ± 0.74	$+9.74 \pm 0.54$	4.5 ± 0.4	7.9

Conclusions …

- *“Observation of the very rare $\Sigma^+ \to p\mu^+\mu^-$ decay”* [Phys. Rev. Lett. 135 (2025) 051801]
  - First observation of the decay with overwhelming significance
  - Investigated the dimuon spectrum for NP resonances
    - ✓ No significant peak structure
    - ✓ HyperCP anomaly excluded
  - Branching fraction measurement
    $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (1.08 \pm 0.17) \times 10^{-8}$
  - Reduced ambiguities in the SM prediction
  - Rarest baryon decay ever observed

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International and national news

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INFN Link
le Scienze edizione italiana di Scientific American Link
CERN Link
PHYS.ORG Link
ANSA.it Link
LA STAMPA Link

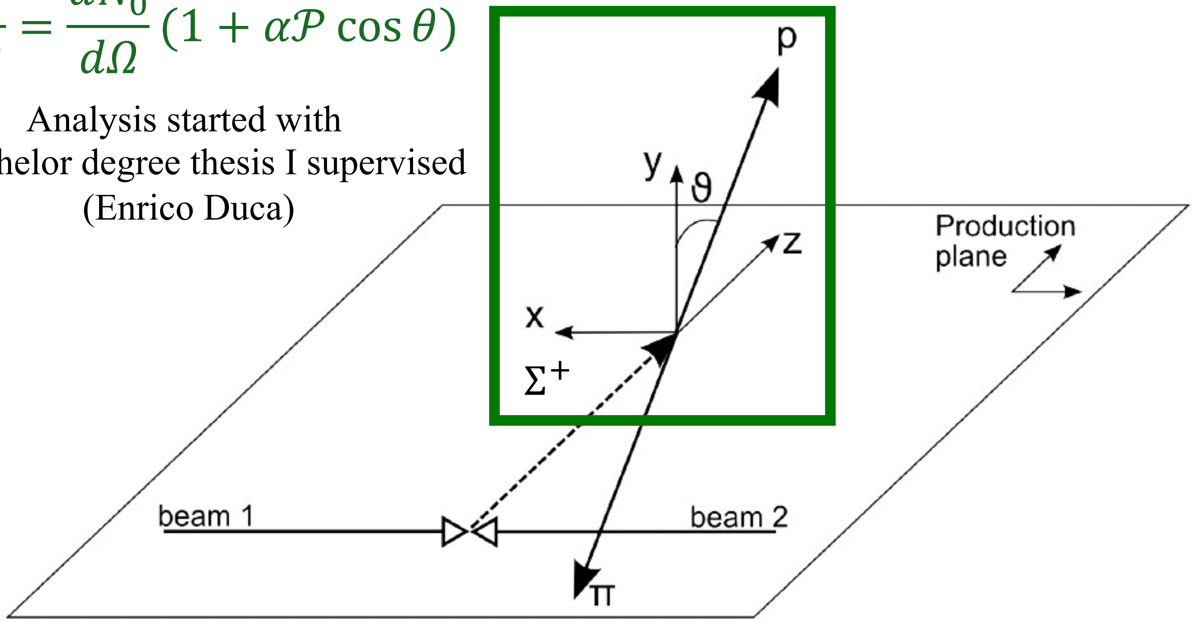
… future prospects …

- Large signal yield → new accessible measurements
  - Run 2 but also Run 3 (ongoing)

Σ^+ and $\bar{\Sigma}^-$ polarisations

$$\frac{dN}{d\Omega} = \frac{dN_0}{d\Omega}(1 + \alpha\mathcal{P}\cos\theta)$$

Analysis started with
a Bachelor degree thesis I supervised
(Enrico Duca)



Forward-backward asymmetry in the decay

$$A_{FB} = \frac{N_{\Sigma^+\to p\mu^+\mu^-}(F) - N_{\Sigma^+\to p\mu^+\mu^-}(B)}{N_{\Sigma^+\to p\mu^+\mu^-}(F) + N_{\Sigma^+\to p\mu^+\mu^-}(B)}$$

Analysis started with
a Master degree thesis I supervised
(Arianna Codovini)

Differential branching fraction vs dimuon mass
"Direct" CP violation measurement

$$\mathcal{A}_{CP} = \frac{\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) - \mathcal{B}(\bar{\Sigma}^- \to \bar{p}\mu^+\mu^-)}{\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) + \mathcal{B}(\bar{\Sigma}^- \to \bar{p}\mu^+\mu^-)}$$

Main part of an upcoming paper

… and more

- No resonant structure found in $\Sigma^+ \to p\mu^+\mu^-$
  - What about $\Sigma^+ \to pe^+e^-$?
    Not yet observed in the SM → why not search for it?
  - What about a possibile dark sector particle (e.g. Dark Photon, X17) in the decay?

$$\mathcal{L}_{A'} \supset -\epsilon \mathtt{e} \mathtt{Q}_\mathtt{f}\, \bar{\mathtt{f}} \gamma^\kappa \mathtt{f}\, A'_\kappa$$

$$\mathcal{M}_{\Sigma^+ \to pA'} = -\epsilon \mathtt{e} G_\mathrm{F}\, \bar{u}_p \left[i\sigma^{\kappa\nu} q_\kappa (a + \gamma_5 b) + (\gamma^\nu q^2 - \not{q}\, q^\nu)(c + \gamma_5 d) \right] u_\Sigma\, \varepsilon^*_\nu$$

$$\overline{|\mathcal{M}_{\Sigma^+ \to pA'}|^2} = (\epsilon \mathtt{e} G_\mathrm{F})^2 \Big\{ \big[(2\hat{\sigma}_+ + 3m^2_{A'})|a|^2 + (\hat{\sigma}_+ m^2_{A'} + 3m^4_{A'})|c|^2 + 6\,\mathtt{M}_+ m^2_{A'}\, \mathrm{Re}(a^* c) \big] \hat{\sigma}_-$$
$$+ \big[(2\hat{\sigma}_- + 3m^2_{A'})|b|^2 + (\hat{\sigma}_- m^2_{A'} + 3m^4_{A'})|d|^2 - 6\,\mathtt{M}_- m^2_{A'}\, \mathrm{Re}(b^* d) \big] \hat{\sigma}_+ \Big\}$$

$$\mathcal{B}(\Sigma^+ \to pA') = \frac{\tau_{\Sigma^+} |\mathbf{p}_{A'}|}{8\pi\, m^2_{\Sigma^+}} \overline{|\mathcal{M}_{\Sigma^+ \to pA'}|^2}$$

$$\mathcal{B}(\Sigma^+ \to pA')\, \mathcal{B}(A' \to e^+e^-) \le [1.0, 0.64] \times 10^{-9}$$

$$\mathcal{B}(\Sigma^+ \to pe^+e^-)_{\mathtt{SM}} = (7.4 \pm 0.3) \times 10^{-6}$$

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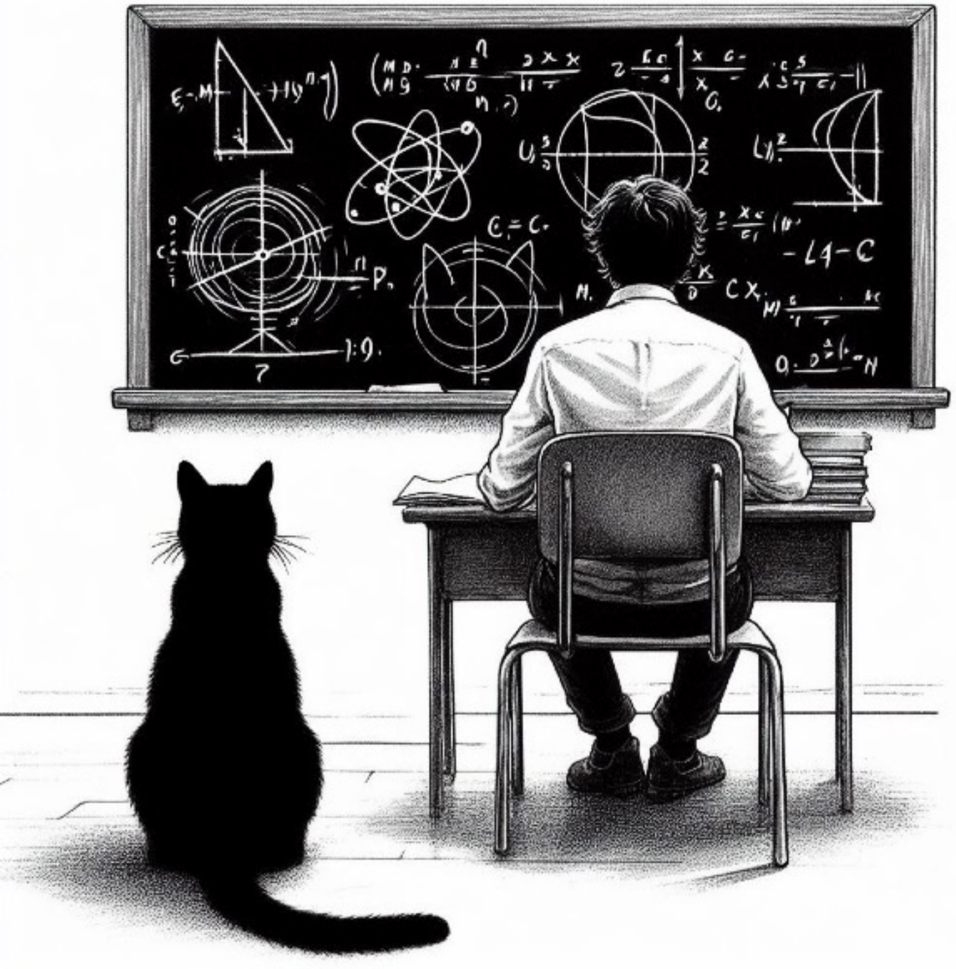
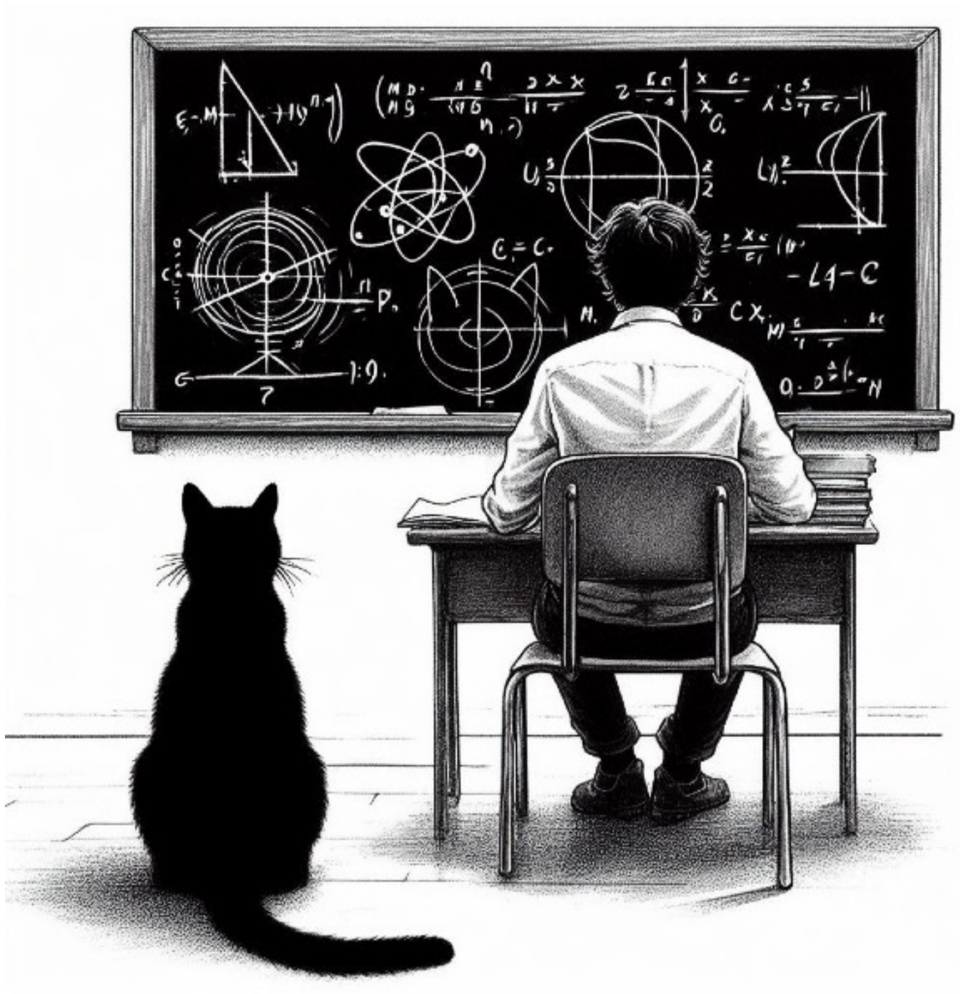
LHCb



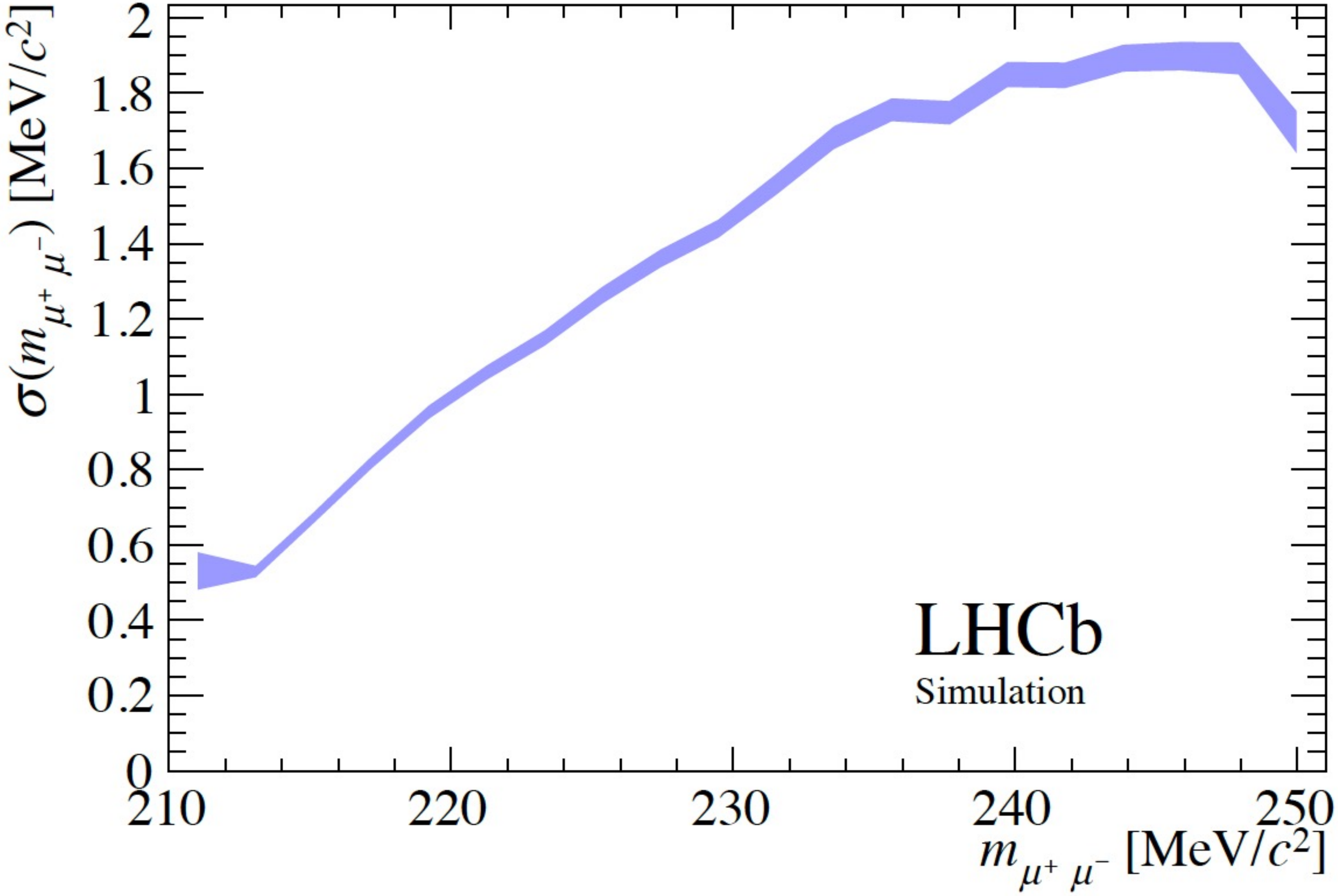
On behalf of the LHCb collaboration
thank you for your attention

Interested in a thesis or just some (physics) talk?
Email: gabriele.martelli@cern.ch
Room 2794, second floor

Backup slides



Dimuon mass resolution



Calibration of the BDT