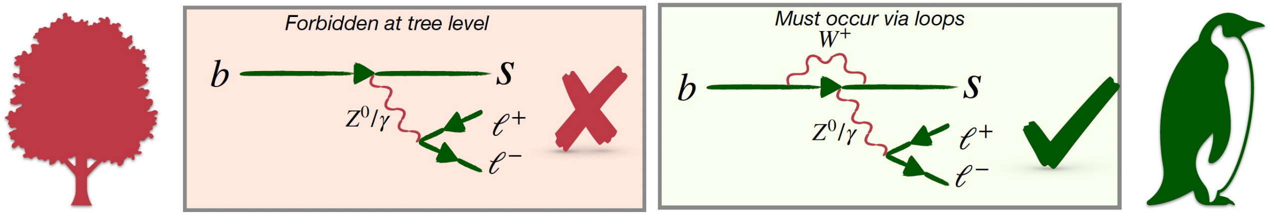
Observation of the very rare $\Sigma^+ \to p\mu^+\mu^-$ decay at LHCb

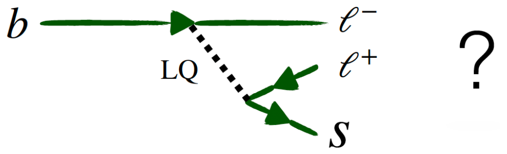
Gabriele Martelli
Istituto Nazionale di Fisica Nucleare - Sezione di Perugia
On behalf of the LHCb collaboration

TU Dortmund, 17 July 2025
Particle Physics Seminar

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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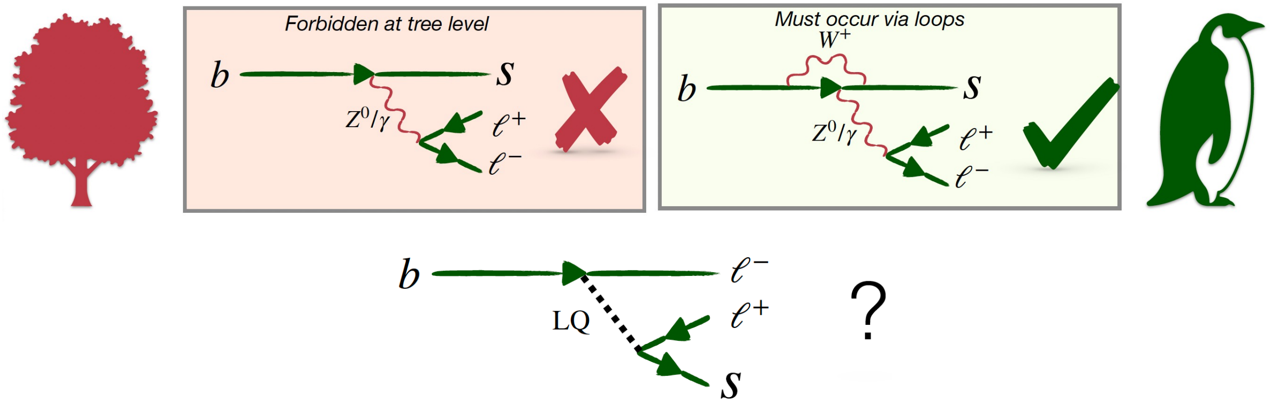

Look for deviations from SM predictions

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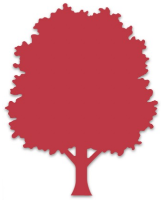
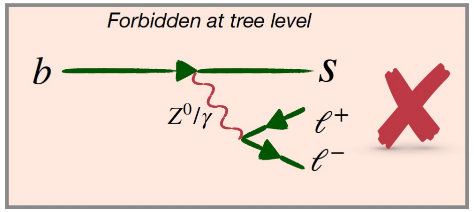
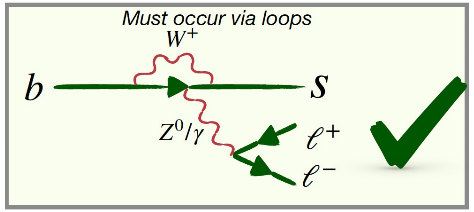
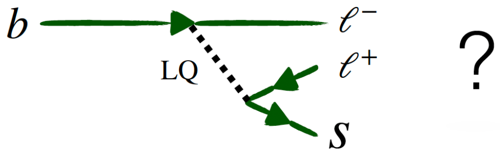


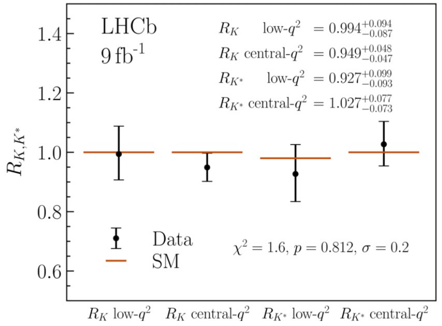


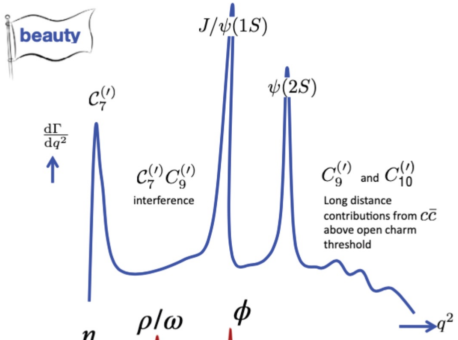


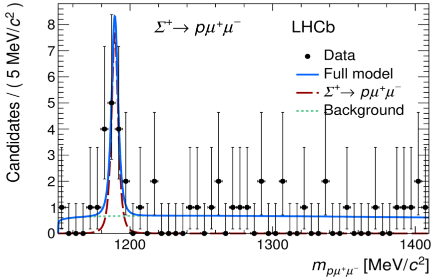


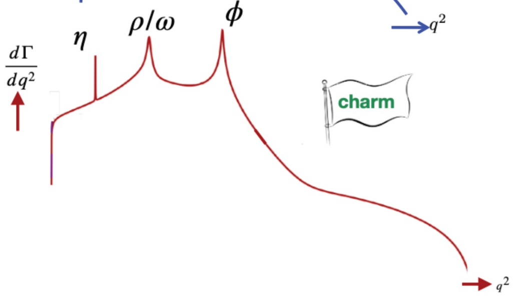
Look for deviations from SM predictions

- Exstensive programme at *LHCb*
  - Search for (very) rare or forbidden modes
  - Branching Fractions ($\mathcal{B}$) measurements
  - CP violation
  - Null tests in the SM
    [https://lbfence.cern.ch/alcm/public/analysis]



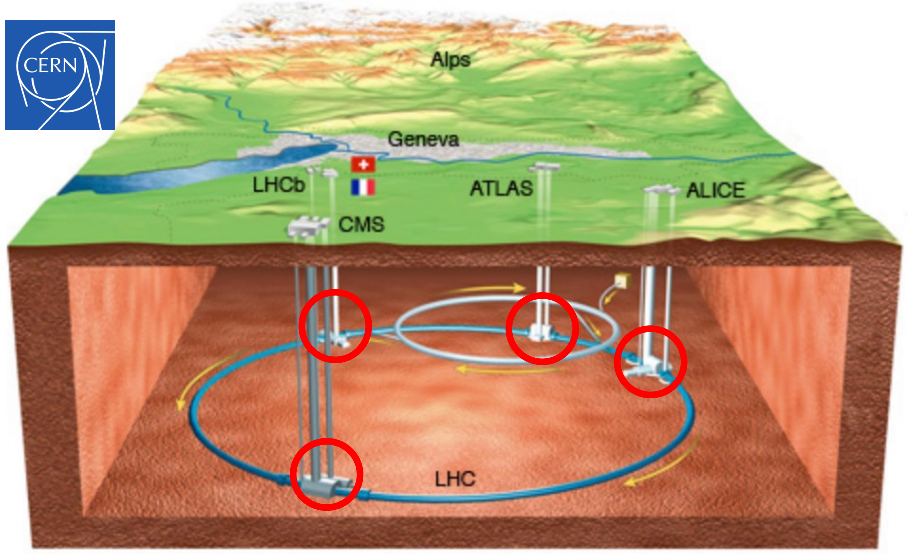






LHCb – The experiment

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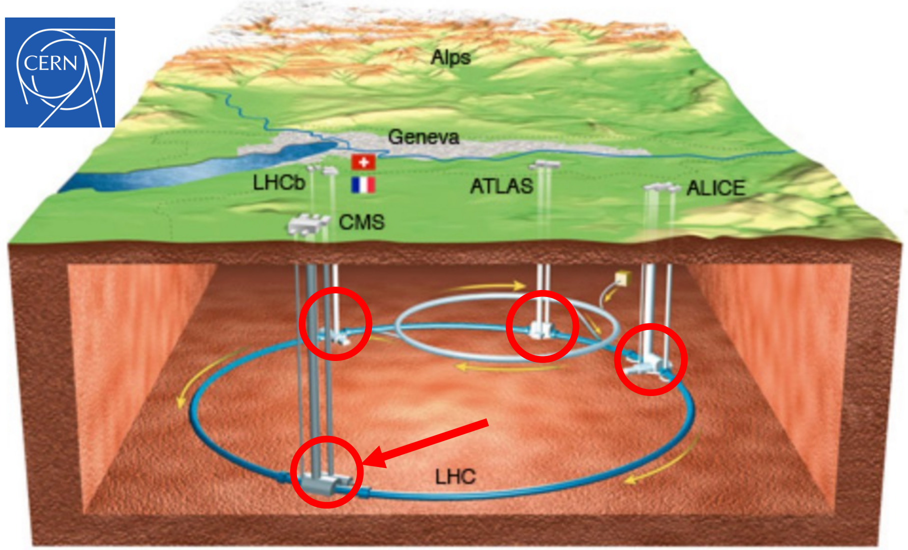
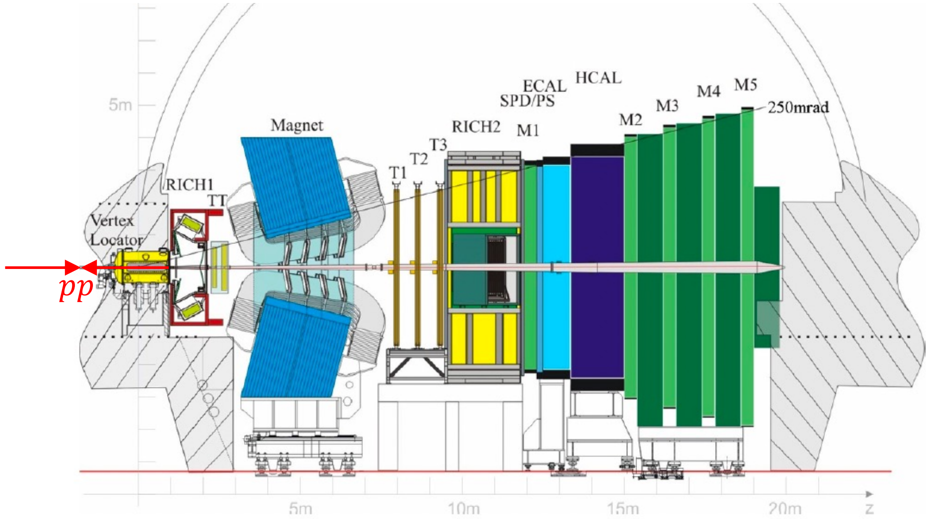
- ➤ Large Hadron Collider beauty (*LHCb*)
  - Investigate the quark flavour sector
    - ✓ CP violation
    - ✓ Rare decays with possible NP hints
  - Positioned in the forward region relative to the collision point
  - Large production $b\bar{b}$ and $c\bar{c}$ cross sections within its acceptance
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





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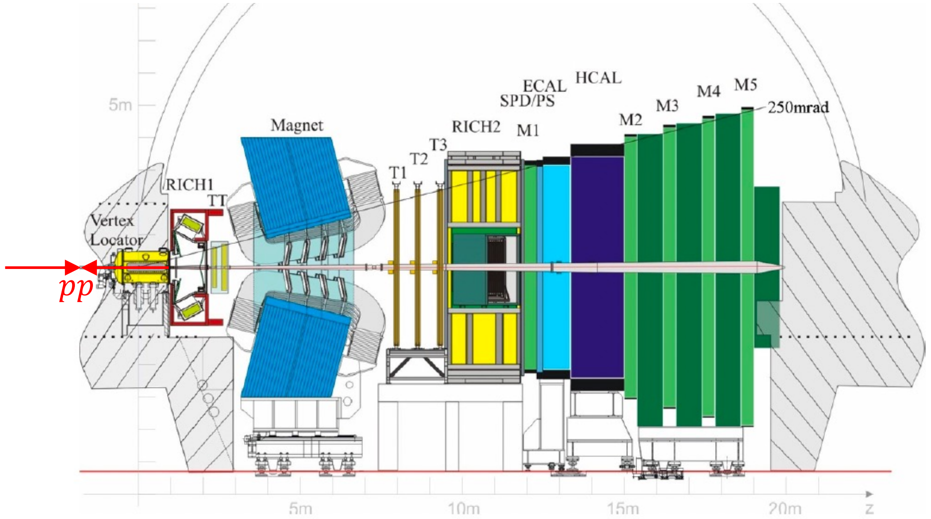
    - ✓ Not just *beauty* and *charm* …
- ➤ 22 countries are involved in the collaboration
  - About 1700 scientists, engineers and technicians
  - More than 700 articles published up-to-date [https://lhcb.web.cern.ch/]



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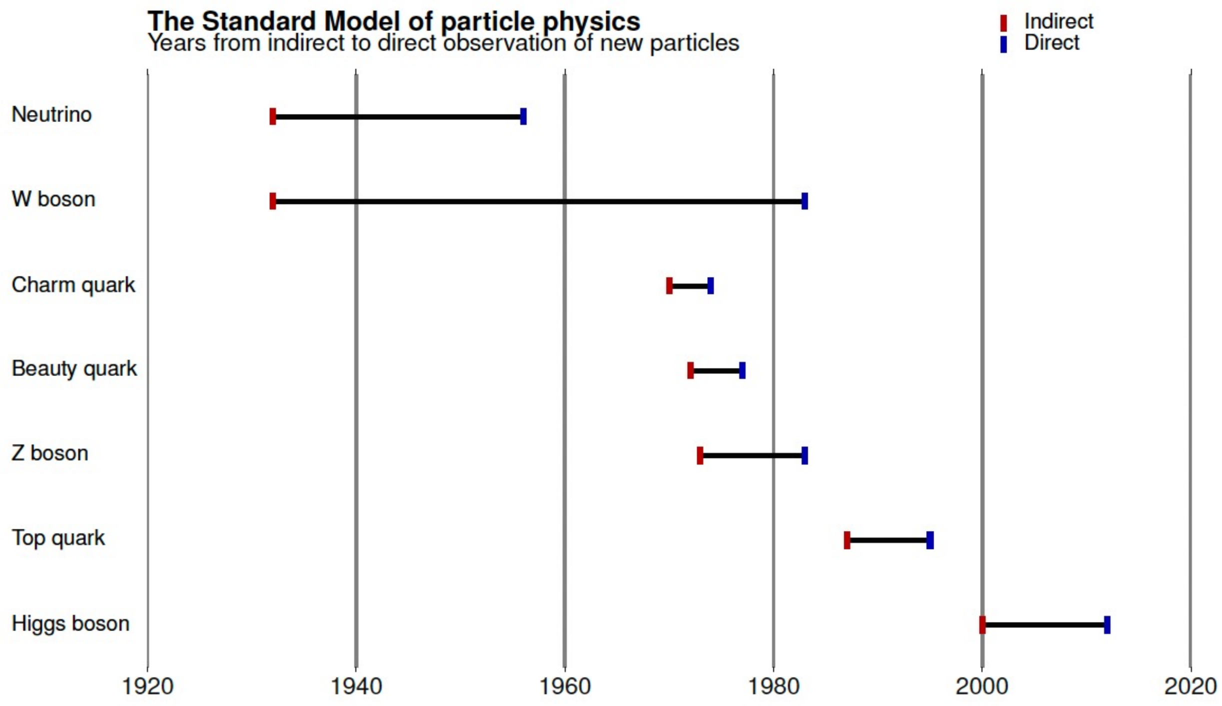

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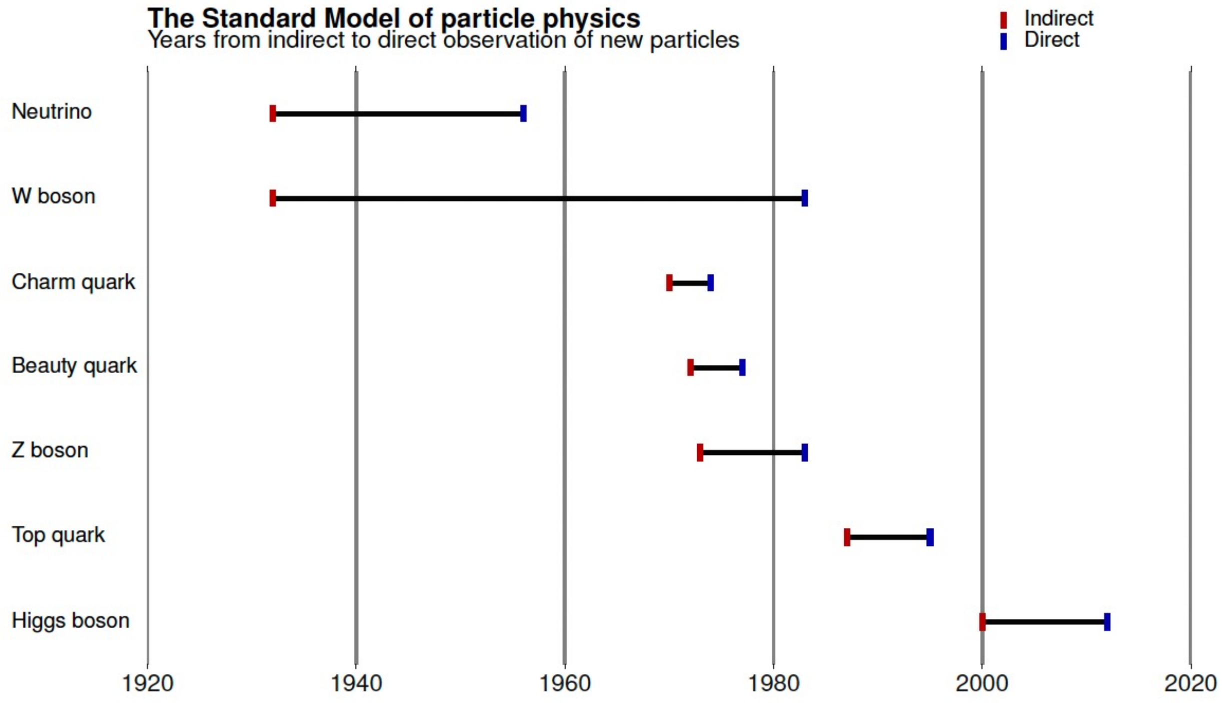
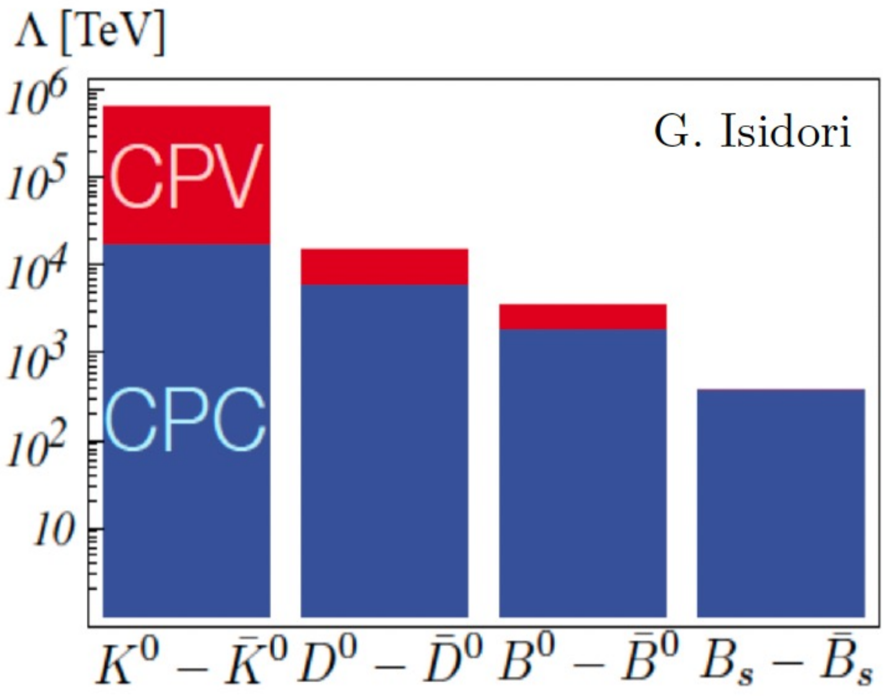
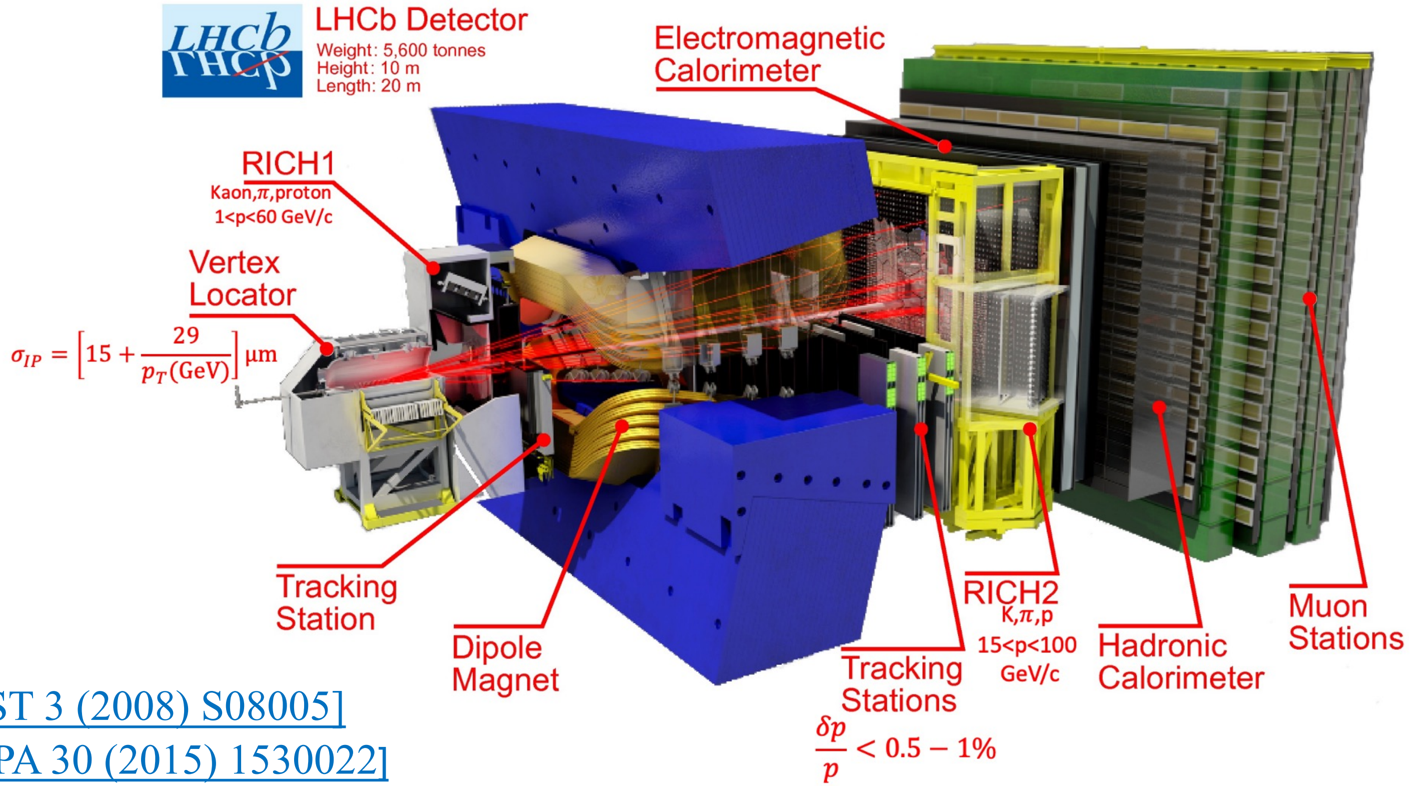
  - Still the sector with higher (indirect) energy reach
  - Rare decays and CPV sensitive to possible new dynamics





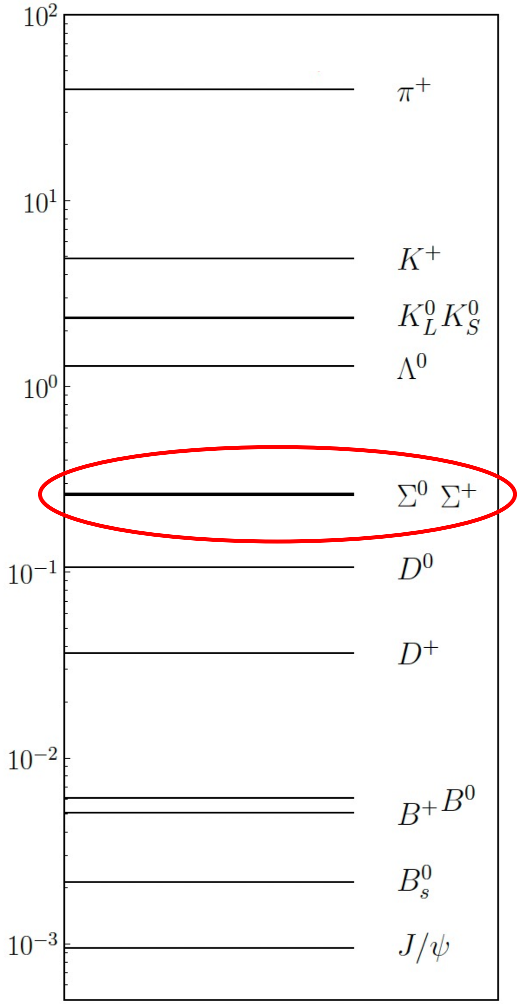
Strange – Presence in the tunnel

➤ **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 this number down …

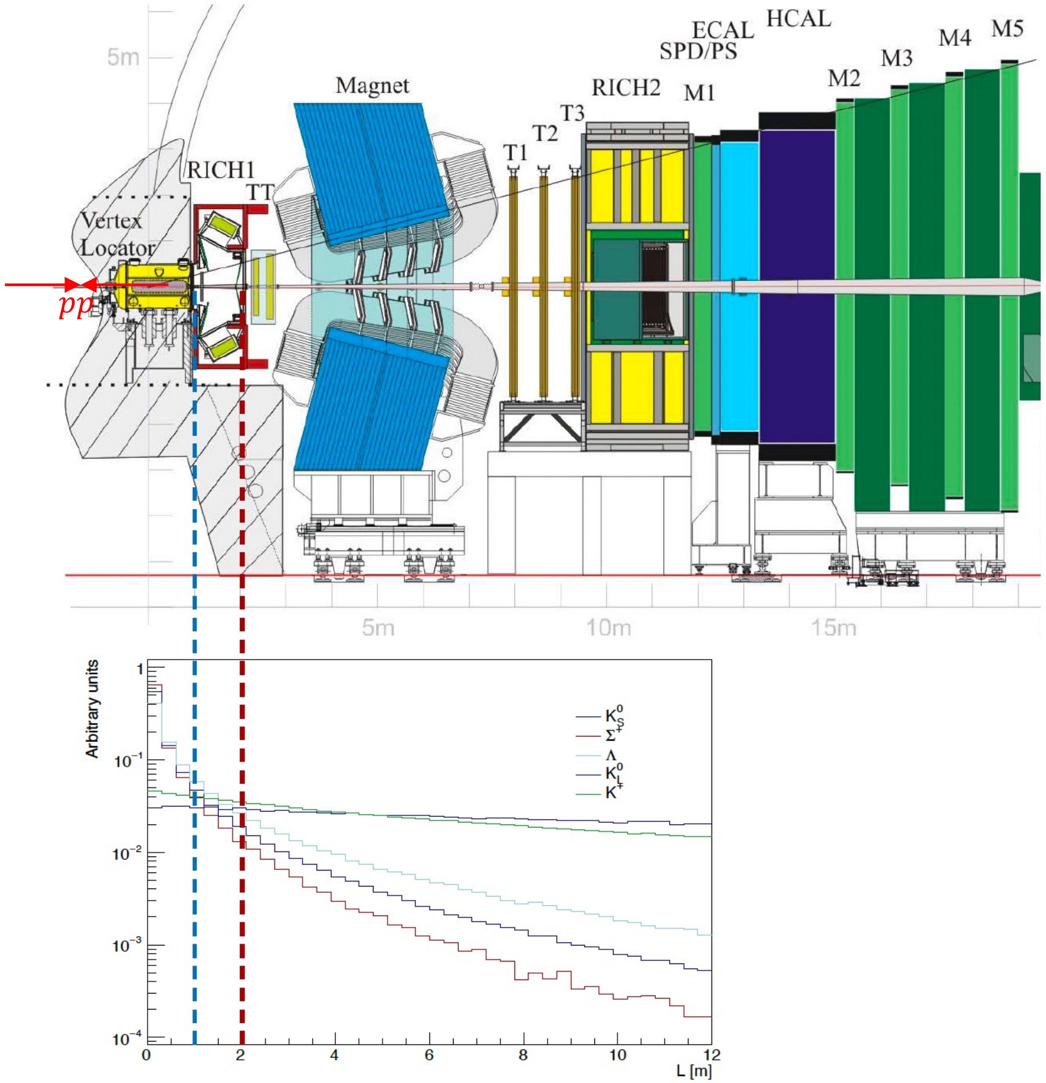


[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 1530022]

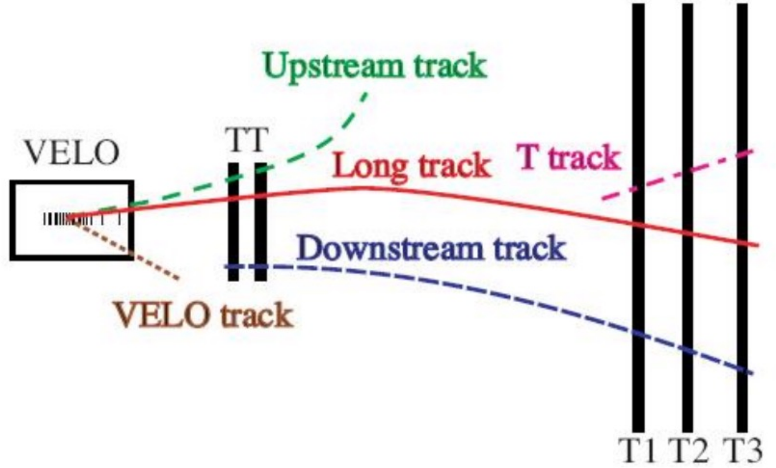
Average particles in LHCb acceptance per minimum bias event at $\sqrt{s}$ = 13 TeV [arXiv:1808.03477]



Strange – Setting the (long) stage



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



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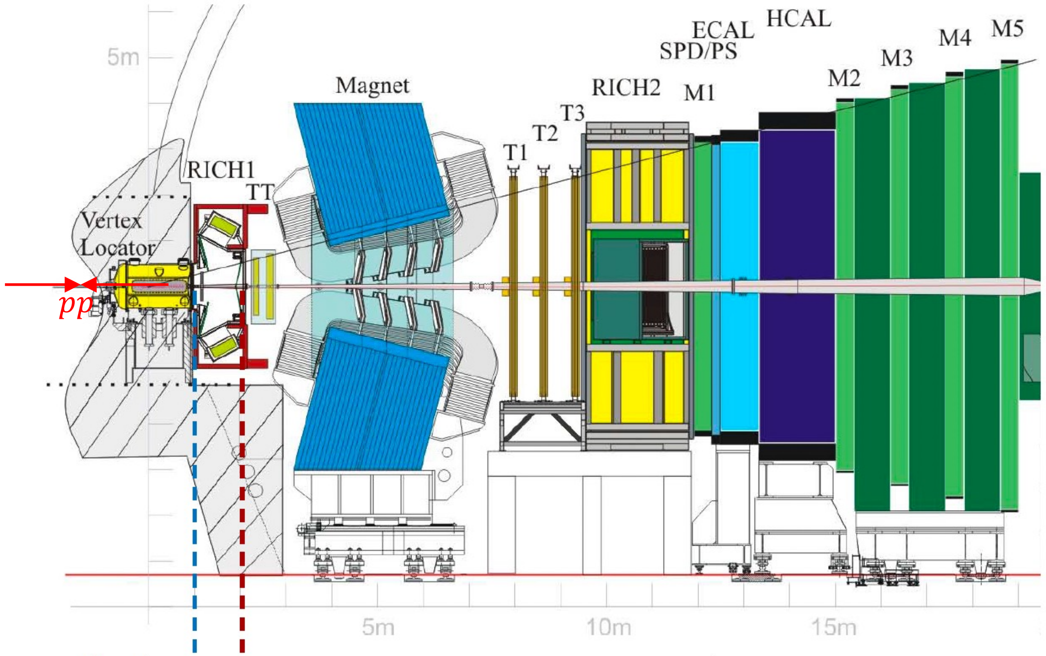

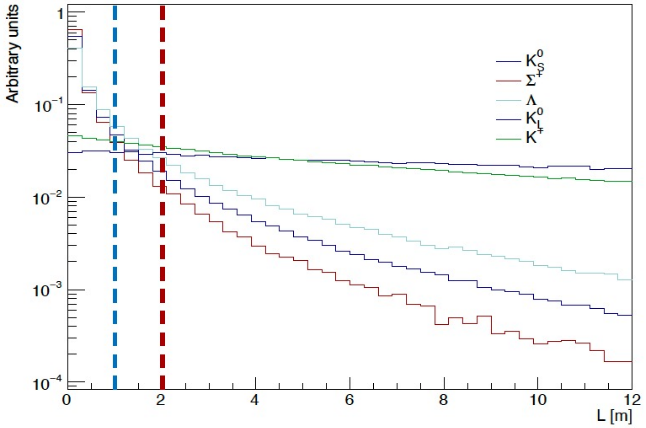

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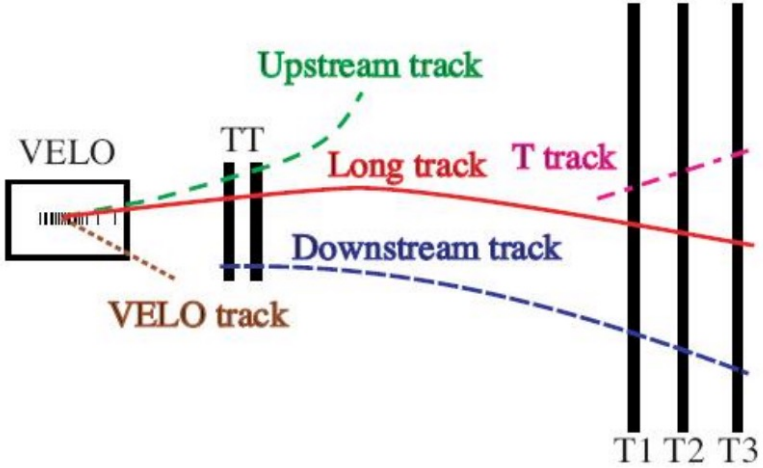

- Efficiency limited by hardware trigger → designed for heavy flavours
  - Muon/hadron Level-0 (L0) trigger require $p_T > [1-5]$ GeV
    Too hard for primary strange hadrons!!
- Software trigger **highly** customisable
  - Dedicated lines already in 2012 → Run 1
  - Dedicate software reconstruction for soft muons since 2016 → Run 2

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

$$A^{\text{LD}}_{\Sigma^+\to p\mu^+\mu^-}(q^2,\cos\theta_{\mu^+\mu^-}) = \{-iq_\alpha \bar{u}_p[a(q^2)+\gamma_5 b(q^2)]\sigma^{\alpha\beta}u_\Sigma - \bar{u}_p\gamma^\beta[c(q^2)+\gamma_5 d(q^2)]u_\Sigma\}\bar{u}_\mu\gamma_\beta v_{\bar{\mu}}$$

- $\Sigma^+ \to p\mu^+\mu^-$ is a very rare FCNC process
  - Short distance SM $\mathcal{B}\sim\mathcal{O}(10^{-12})$
  - Dominated by long distance contributions from $\Sigma^+ \to (N\pi)^+$ decays
    $1.6\times10^{-8} < \mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) < 9.1\times10^{-8}$
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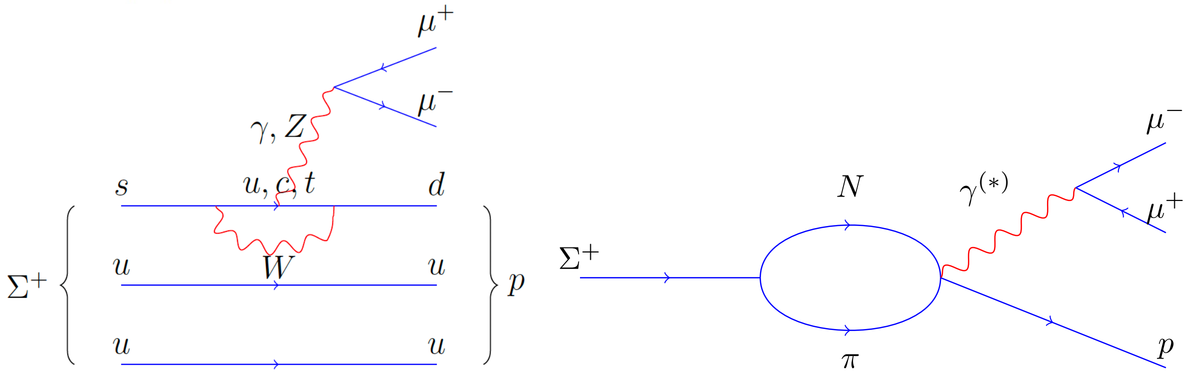

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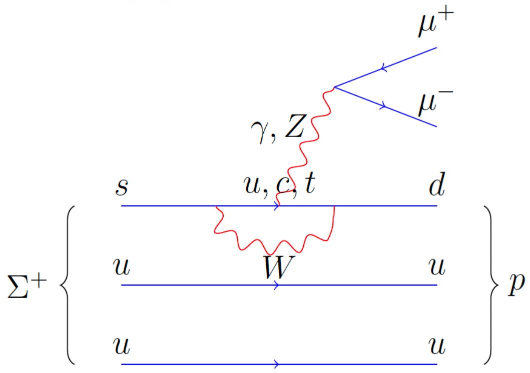

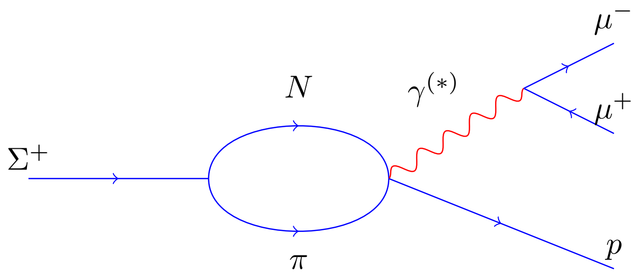

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  - Three candidates observed in absence of background
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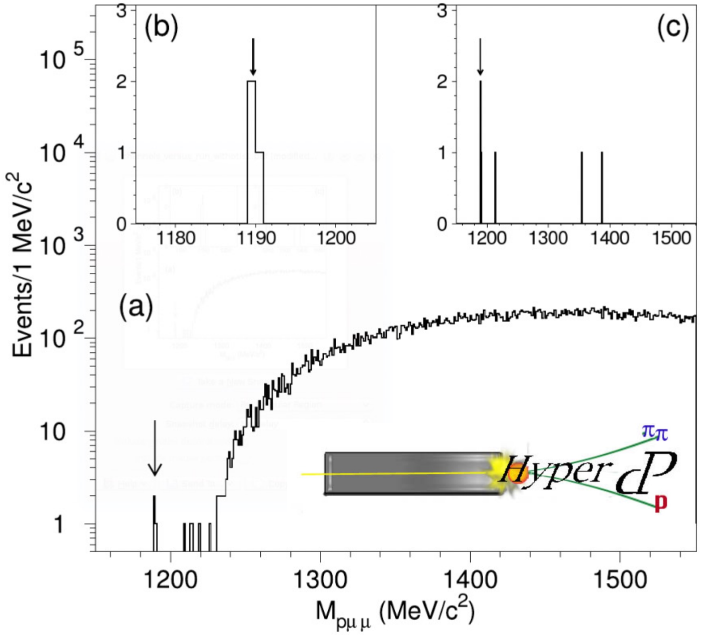

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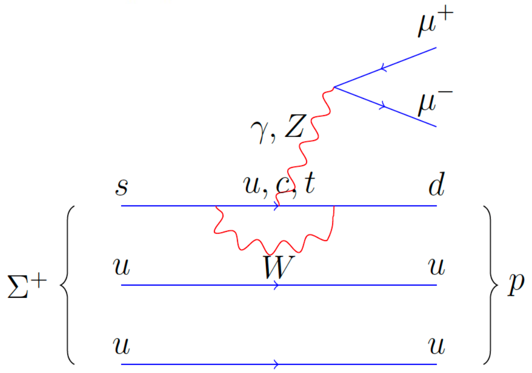

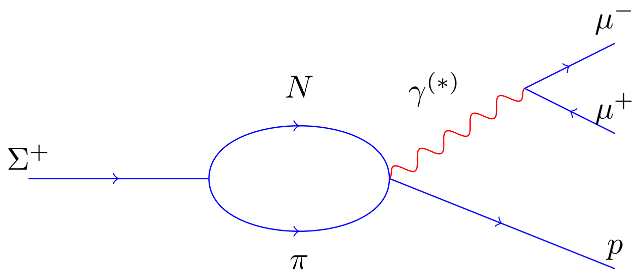

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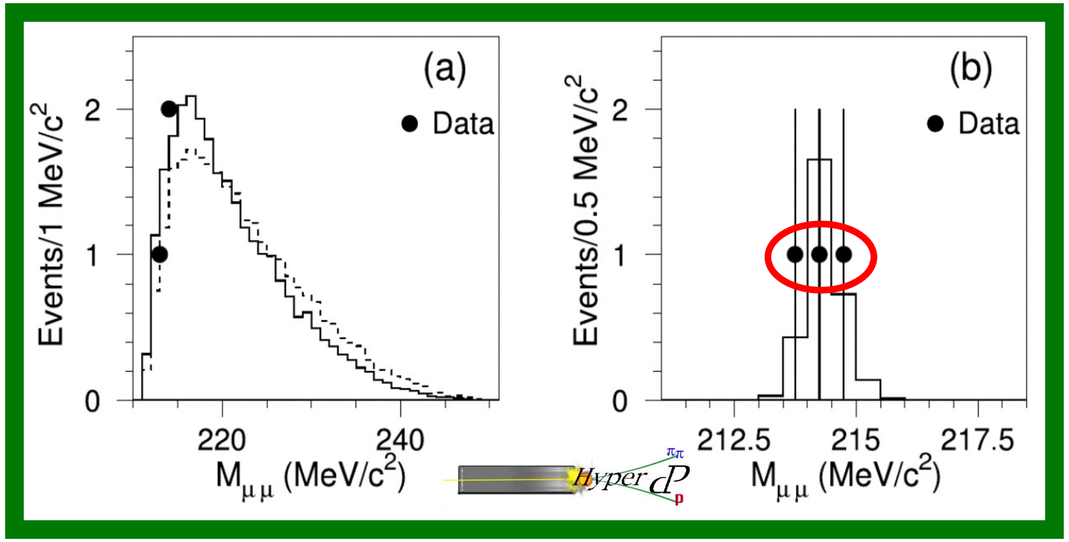
- The Anomaly
  - **Same** dimuon invariant mass for the observed candidates
  - Possible $\Sigma^+ \to pX^0(\to \mu^+\mu^-)$ decay

    $m_{X^0} = 214.3 \pm 0.5$ MeV

    $\mathcal{B}(\Sigma^+ \to pX^0(\to \mu^+\mu^-)) = (3.1^{+2.4}_{-1.9} \pm 1.5)\times10^{-8}$



The Anomaly – Searches and interpretations

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

~3 years after HyperCP

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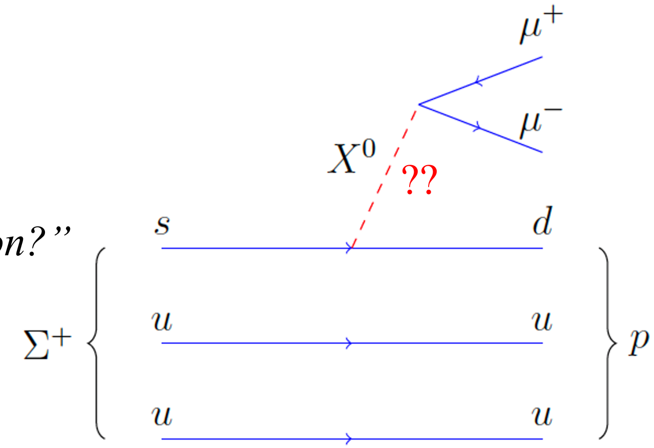

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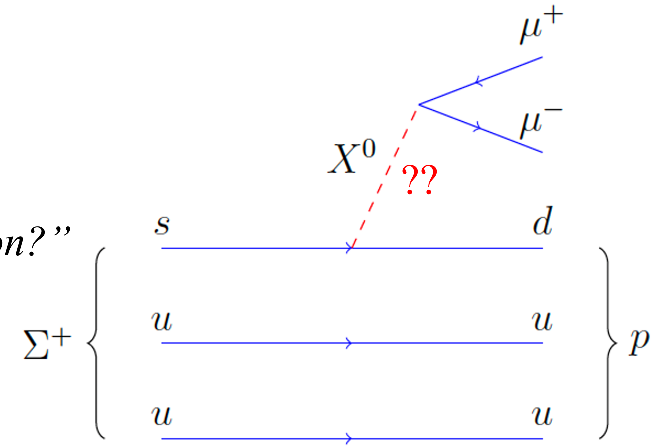

- New searches for low dimuon mass resonances

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LHCb: $B^0 \to \mu^+\mu^-\mu^+\mu^-$
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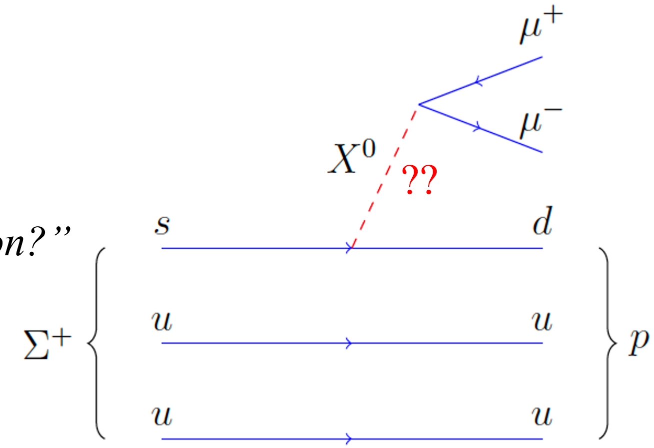

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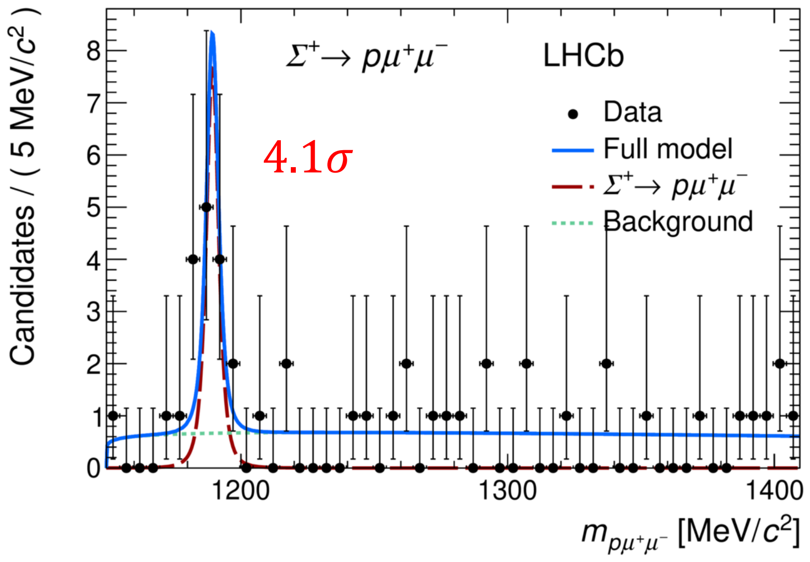
$\Sigma^+ \to p\mu^+\mu^-$ – First search at LHCb

- *"Evidence for the rare decay $\Sigma^+ \to p\mu^+\mu^-$"*
  - Run 1 dataset
    $\sqrt{s} = 7, 8$ TeV, $\mathcal{L} = 3.0\ \text{fb}^{-1}$
    [Phys. Rev. Lett. 120 (2018) 221803]

- **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:
    $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = \left(2.2^{+0.9+1.5}_{-0.8-1.1}\right)\times10^{-8}$
  - Consistent with SM prediction



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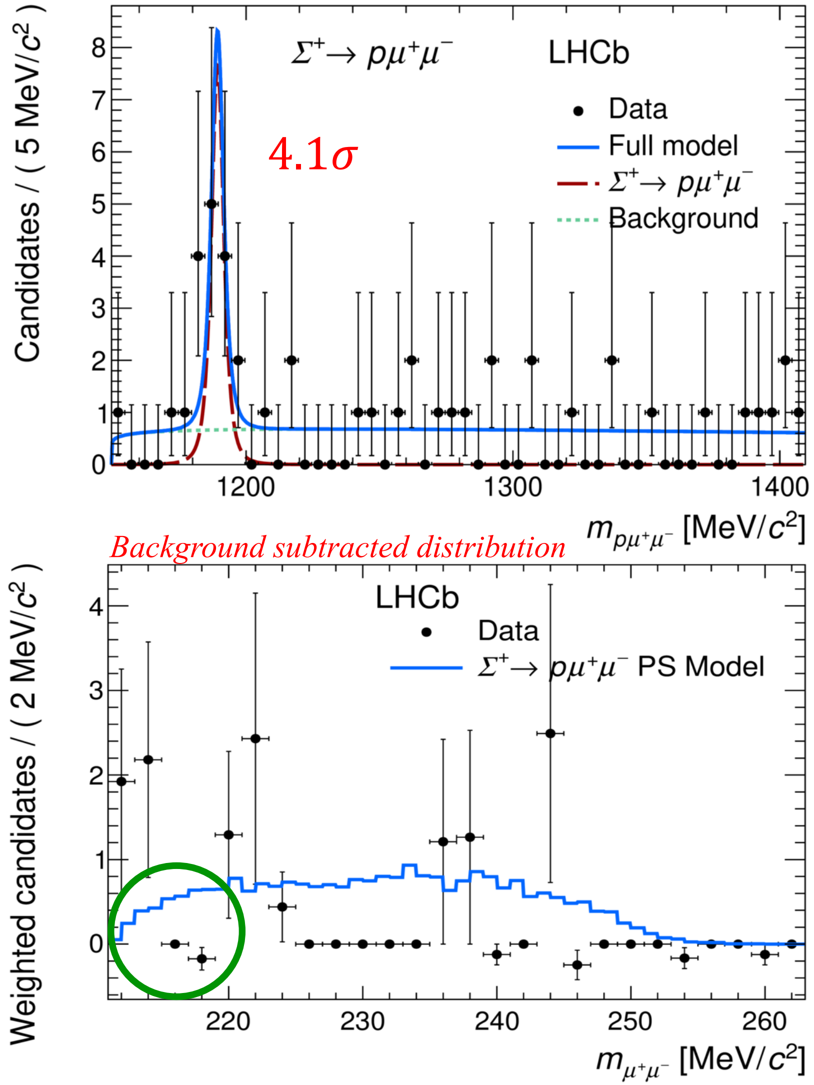
  - Consistent with SM prediction
- Search for HyperCP-like resonances
  - No peak structures found
  - Set upper limit at 90% C.L.
    $\mathcal{B}(\Sigma^+ \to pX^0(\to \mu^+\mu^-)) < 1.4 \times 10^{-8}$
  - HyperCP anomaly **disfavored**



$\Sigma^+ \to p\mu^+\mu^-$ – Additional theory interest

- **New** $\Sigma^+ \to p\gamma$ results by BESIII [Phys. Rev. Lett. 130 (2023) 211901]

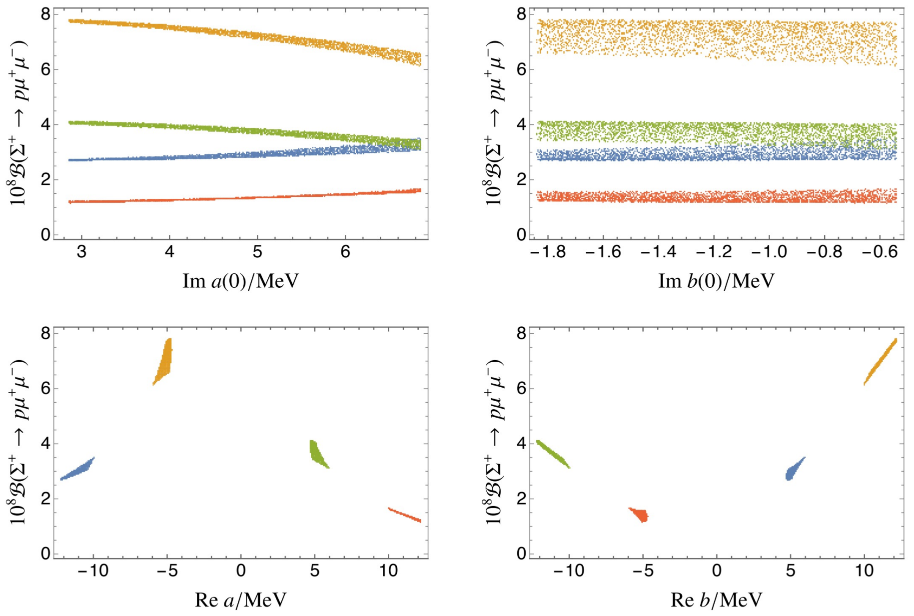
Parameter	BESIII	PDG
$\mathcal{B}\,(10^{-3})$	$0.996 \pm 0.021 \pm 0.018$	1.23 ± 0.05
α	$-0.651 \pm 0.056 \pm 0.020$	-0.76 ± 0.08

  - Dominant SM prediction of $\Sigma^+ \to p\mu^+\mu^-$ based on $\Sigma^+ \to p\gamma$

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

Decay asymmetry parameter

  - $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-)$ prediction will change with latest input



$\Sigma^+ \to p\mu^+\mu^-$ – Additional theory interest

- **New** $\Sigma^+ \to p\gamma$ results by 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

  - Dominant SM prediction of $\Sigma^+ \to p\mu^+\mu^-$ based on $\Sigma^+ \to p\gamma$

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

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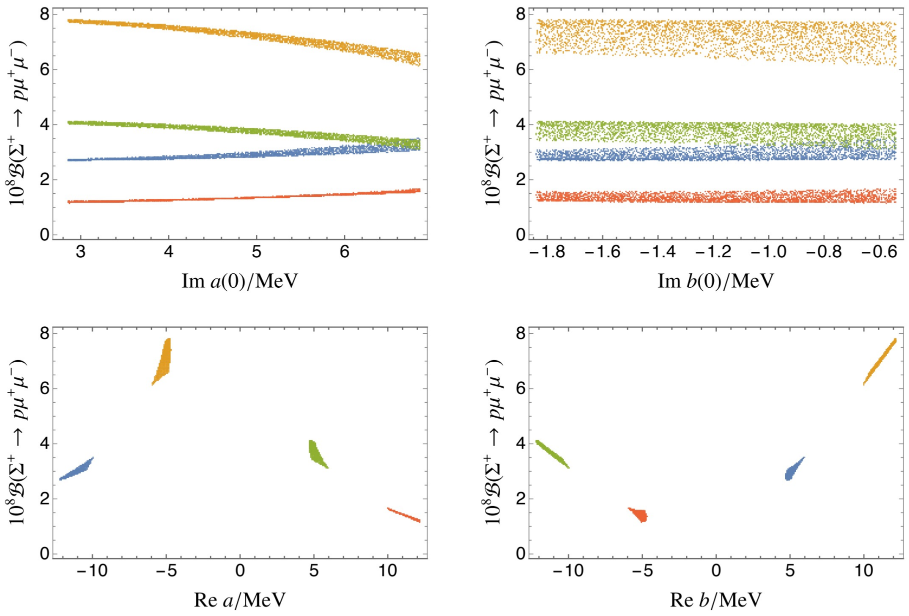
- Chiral perturbation theory (χPT)
  - Relativistic and heavy baryon approaches
  - Four-fold degeneracy in each method [arXiv:2404.15268]



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

Istituto Nazionale di Fisica Nucleare
Sezione di Perugia

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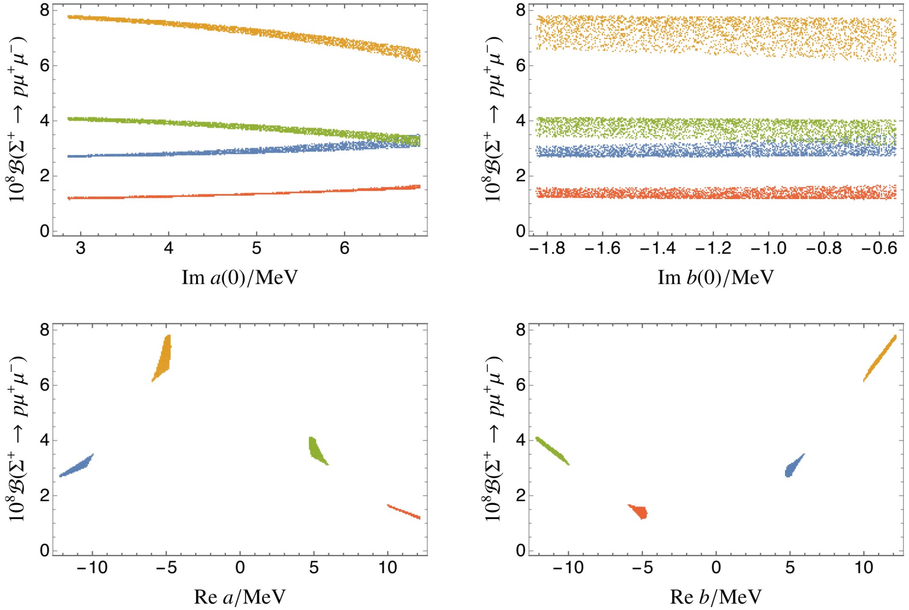
- Chiral perturbation theory (χPT)
  - Relativistic and heavy baryon approaches
  - Four-fold degeneracy in each method [arXiv:2404.15268]

Experiments should be able to solve it



Relativistic baryon

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Heavy baryon

Re a (MeV)	Re b (MeV)	$10^8\,\mathcal{B}_{\mu\mu}$	$10^8\,\mathcal{B}_{\mu\mu}^{\text{Re}(c,d)=0}$
-9.74 ± 0.54	6.17 ± 0.74	3.7 ± 0.5	2.7 ± 0.3
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Outline of the day

Run 2

Observation of the very rare $\Sigma^+ \to p\mu^+\mu^-$ decay
[arXiv:2504.06096]
Scheduled to be pubblished **July 29th** on PRL

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Introduction
- Run 2 improvements
- Analysis strategy

Search for the $\Sigma^+ \to p\mu^+\mu^-$ decay
- Selection
- Signal evaluation

Branching fraction measurement
- Normalisation with the $\Sigma^+ \to p\pi^0$ decay
- Final calculations

Search for NP resonances
- Confirm/exclude the HyperCP anomaly

Conclusions
- Interpretations
- Summary


CERN COURIER
VOLUME 64 NUMBER 4 JULY/AUGUST 2024
NEWS DIGEST
Rarest hyperon decay
The LHCb collaboration has reported the observation of $\Sigma^+ \to p\mu^+\mu^-$, the rarest known hyperon decay (LHCb-CONF-2024-002). In addition to observing a large peak at the Σ^+ mass containing 279 ± 19 events, the collaboration compared the background-subtracted $\mu^+\mu^-$ mass spectrum with different simulations. Interest in the $\Sigma^+ \to p\mu^+\mu^-$ dimu… mass spectrum arose after the

SCI NEWS
CERN Physicists Observe Rarest Hyperon Decay
…ws Staff
…a particle containing three quarks, …on and neutron, including one or …e quarks. Physicists with the LHCb …n at CERN's Large Hadron Collider …ey have observed the hyperon decay …n proton-proton collisions.

CERN
LHCb investigates the rare Σ+→pμ+μ- decay
The rarest hyperon decay ever observed
The LHCb detector (Image: M. Brice/CERN)

Run 2 improvements

- **Increase in statistics**
  - Run 1 → $\sqrt{s} = 7, 8$ TeV, $\mathcal{L} = 3.0$ fb^{-1}
  - Run 2 → $\sqrt{s} = 13$ TeV, $\mathcal{L} = 5.4$ fb^{-1}
    - ✓ Factor ~**4** larger w.r.t. previous analysis
    - ✓ Larger MC samples

- **Increase in performances**
  - Run 1 → Highly prescaled minimum bias data
  - Run 2 → Dedicated trigger lines
    - ✓ Gain of a factor ~**13** in signal efficiency
  - Improved PID performance on protons and muons

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New accessible measurements

- Differential branching fraction vs dimuon mass
- Forward-backward asymmetry in the decay
- Σ^+ and $\bar{\Sigma}^-$ polarisations
- "Direct" CP violation measurement

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

Analysis strategy

- Blind analysis technique
  - Avoid introduction of biases
  - Blinded $m_{p\mu^+\mu^-}$ signal region around the Σ^+ known mass value ($m_{\Sigma^+} = 1189.37\ \mathrm{MeV}/c^2$)

1) **Selection**: Reject most of the background sources and isolate the signal candidates
   - Loose preselection - kinematic variables
   - Tight selection - PID variables
   - Final selection - multivariate operator and optimisation

2) **Fit**: Estimate the signal candidates
   - Unblinding and fit to the full $m_{p\mu^+\mu^-}$ distribution

2.1) **Dimuon spectrum**: Look for a resonant structure
   - Background subtraction with the *sPlot* method
   - Scan in the $m_{\mu^+\mu^-}$ spectrum

3) **Normalisation**: Measurement of the integrated branching fraction
   - Normalised to the $\Sigma^+ \to p\pi^0$ decay

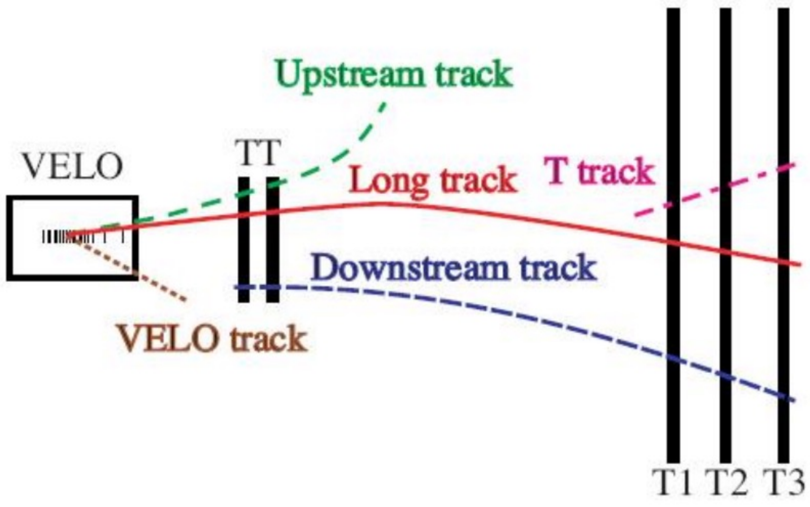
$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = \frac{\varepsilon_{\Sigma^+\to p\pi^0}}{\varepsilon_{\Sigma^+\to p\mu^+\mu^-}} \frac{\mathcal{B}(\Sigma^+\to p\pi^0)}{N_{\Sigma^+\to p\pi^0}} \cdot N_{\Sigma^+\to p\mu^+\mu^-}$$

Signal selection – First steps

$\tau_{\Sigma^+} = (8.018 \pm 0.026)\times 10^{-11}$ s

Decay products may be recostructed with

- Long tracks
- Downstream tracks



Loose preselection

- Kinematic variables
- Reduce the dataset size

Tight selection

- PID variables

Signal selection – First steps

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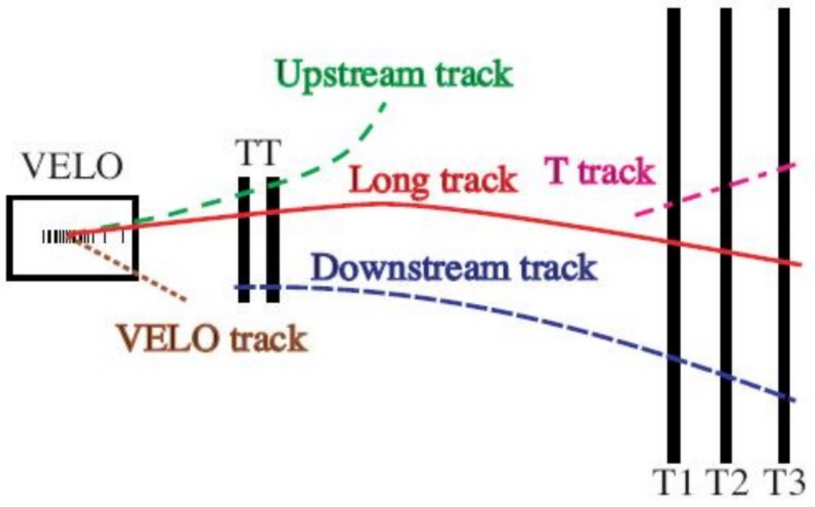


Loose preselection
- Kinematic variables
- Reduce the dataset size

Tight selection
- PID variables

➤ Residual background sources
- Combinatorial
- $\Lambda \to p\pi^-$ decays with misID $\pi^- \to \mu^-$ plus an accidental μ^+

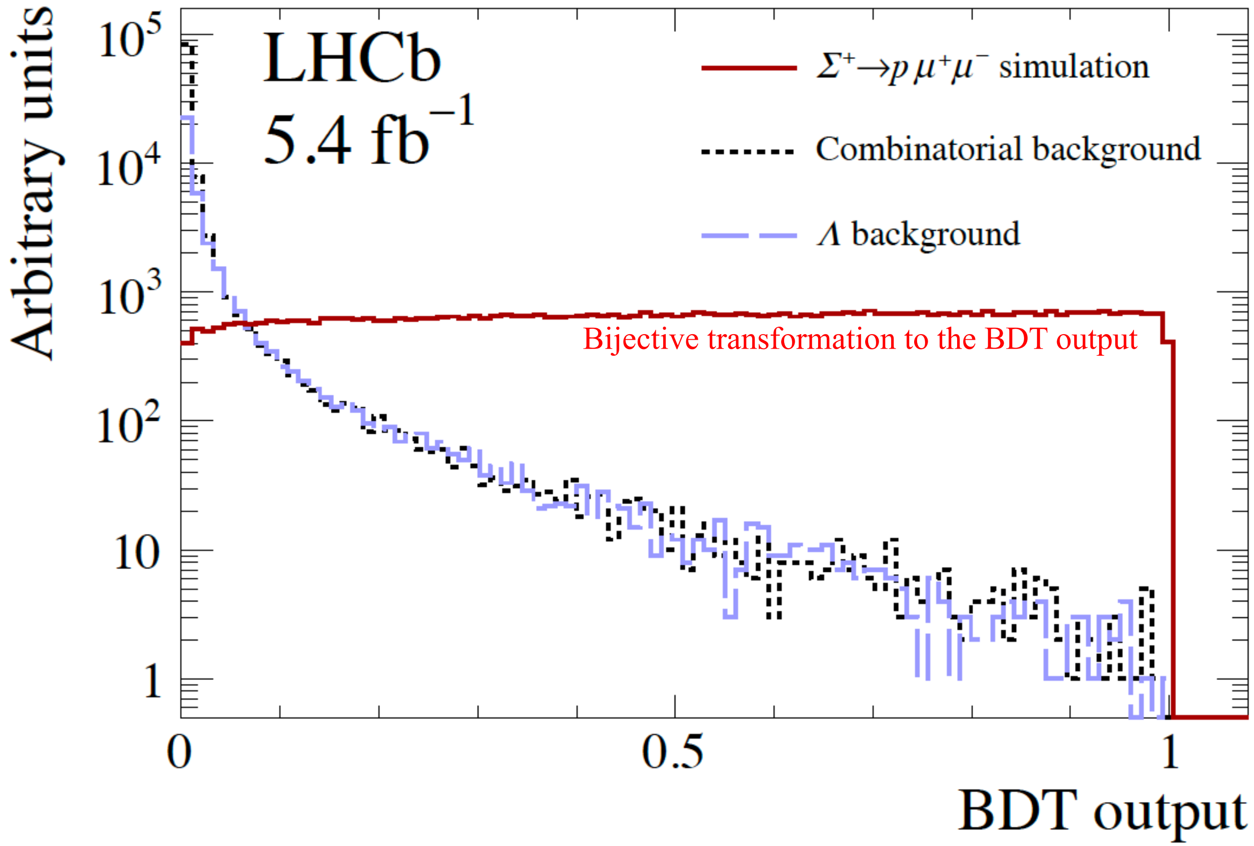
➤ Small q-value
- Few modes can mimic the signal final state
  $\left(m_{\Sigma^+} - m_p - 2m_\mu\right) = 39.78\ \mathrm{MeV}/c^2$
- $K^+ \to \pi^+\pi^-\pi^+$ and $K^+ \to \pi^+\mu^+\mu^-$ decays
  Mass peak shifter higher w.r.t. the signal
- No other baryon decays with a final state proton

Signal selection – Multivariate operator

- Final selection based on a multivariate operator
  - BDT built in TMVA
  - Trained to reject combinatorial
    MC signal sample
    Sidebands in data sample

- Discriminating variables
  - Σ^+ – $IP\chi^2$, DOCA, $FD\chi^2$, $Vtx\chi^2$, $\log(1 - DIRA)$
  - Proton – $IP\chi^2$, p_T
  - Muons – $\min(\mu\, IP\chi^2)$, $\min(\mu\, p_T)$

- Data divided in a Λ veto sample and a complementary one
  - Very similar distribution at high BDT values
  - A requirement will reject both background sources



Signal selection – Optimisation

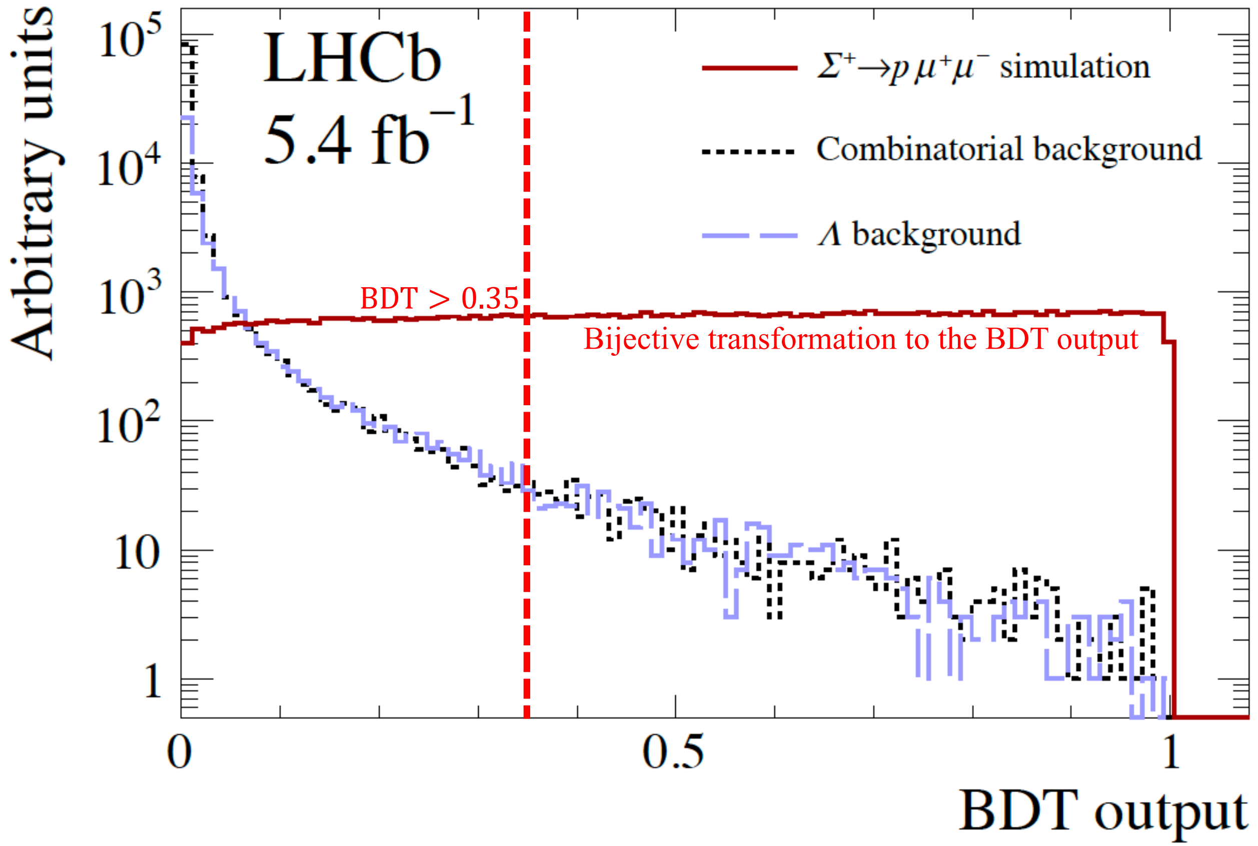
- Optimisation for the best chances of observation
  - Significance chosen as Figure of Merit (FoM)

$$\mathcal{S} = \frac{N_S}{\sqrt{N_S + (N_C + N_\Lambda)}}$$

N_S = Expected signal yield from MC
N_C = Expected combinatorial from Data
N_Λ = Expected Λ candidates from Data

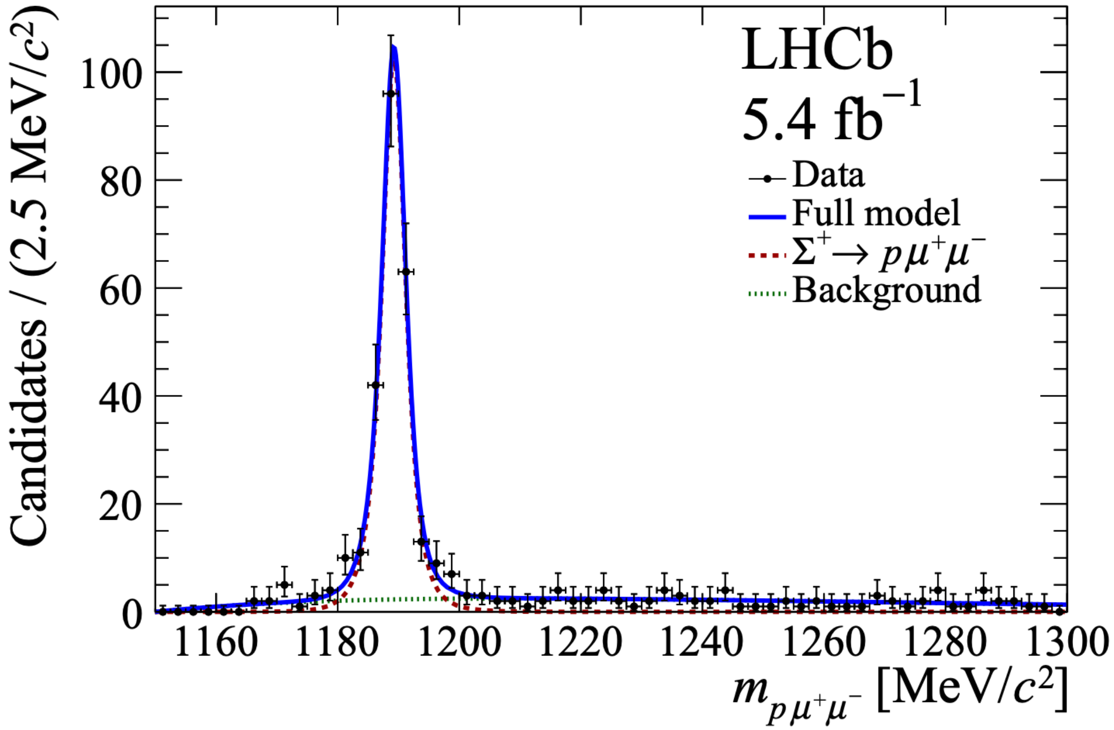
Optimal point chosen as the **largest** significance

- Four dimensions
  - BDT
  - PID variables
  - Λ vetos $\rightarrow \left|m_{p\pi^-} - m_\Lambda^{PDG}\right| > 6, 8, 10\ \mathrm{MeV}/c^2$



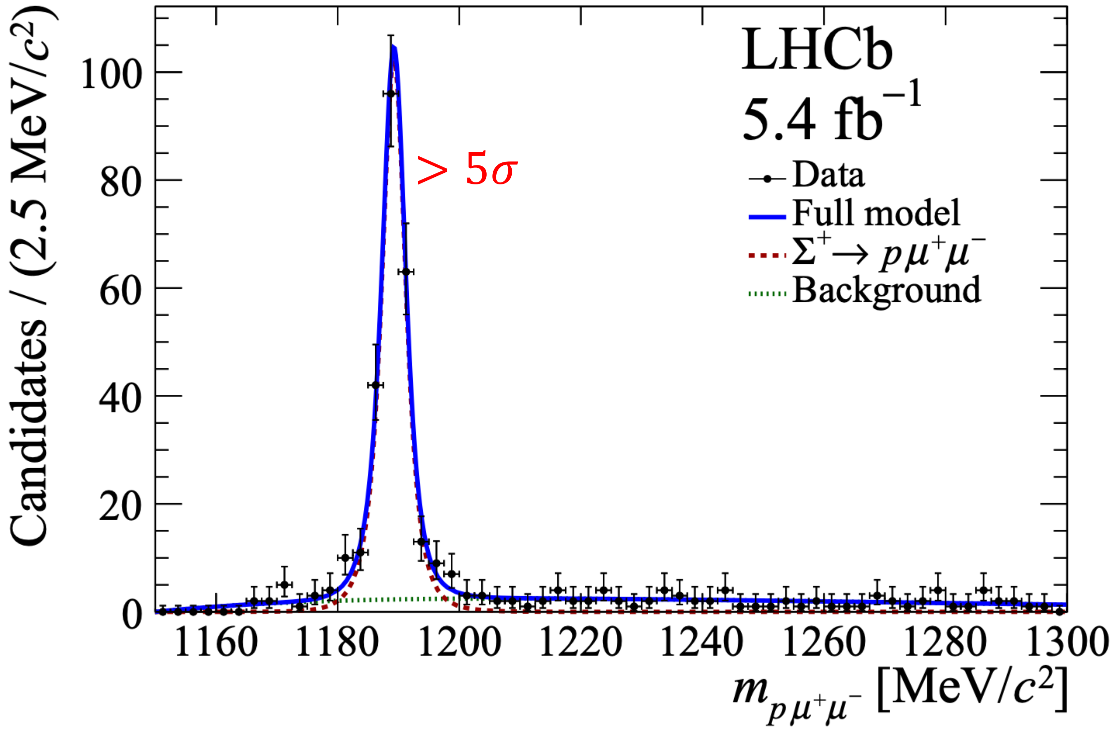
$\Sigma^+ \rightarrow p\mu^+\mu^-$ – Observation

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



$\Sigma^+ \to p\mu^+\mu^-$ – Observation

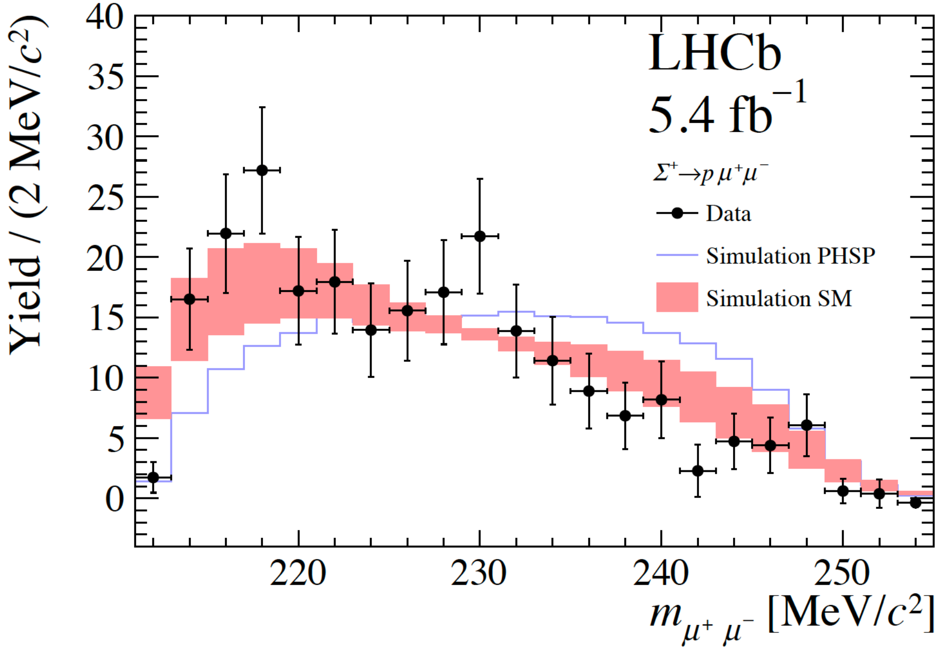
- Extended maximum likelihood fit to the final sample
  - $\Sigma^+ \to p\mu^+\mu^-$ parametrized by an Hypatia function
    $N_{\Sigma^+\to p\mu^+\mu^-} = 279 \pm 19$
  - Background by a modified Argus function



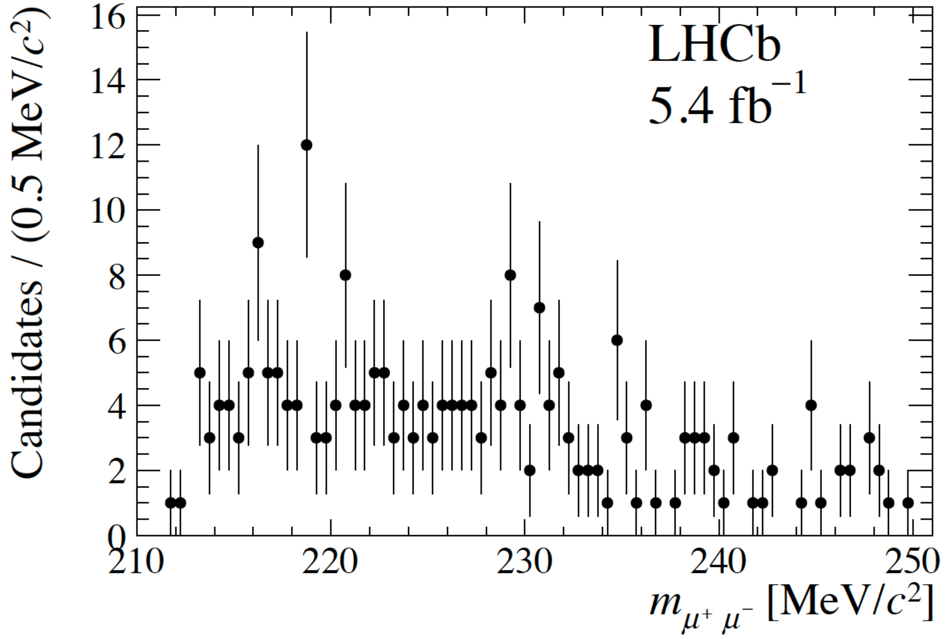
Clear **first** observation
Large signal w.r.t. small background

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

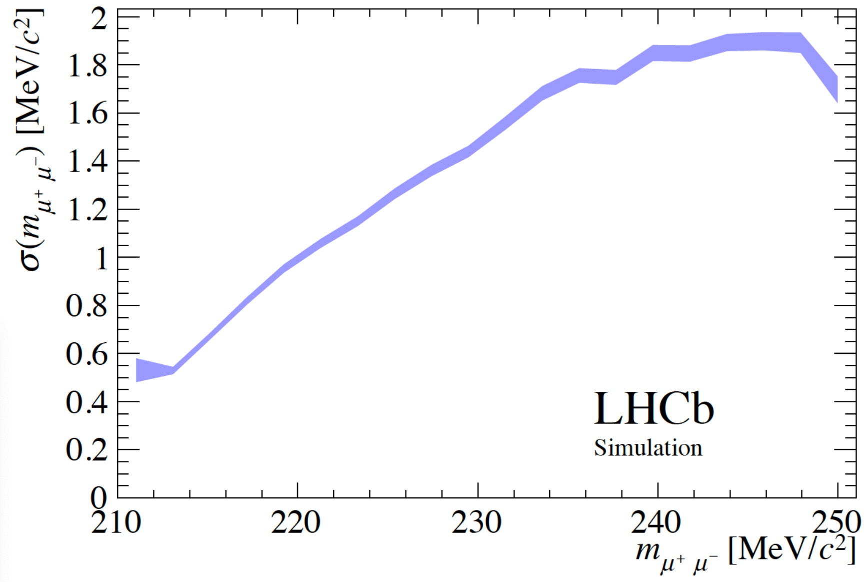


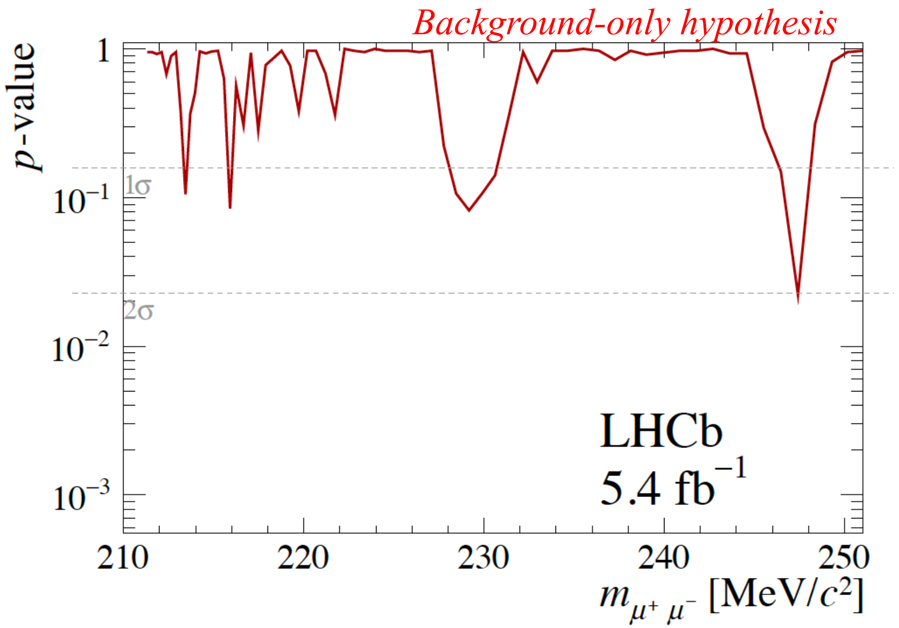
Same distribution in 88 bins



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 $m_{X^0} = 214.3\ \text{MeV}/c^2$
  - HyperCP anomaly excluded





Normalisation – Choosing the mode

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

- 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
    $\mathcal{B}(\Sigma^+ \to p\pi^0) = (51.77 \pm 0.30)\%$

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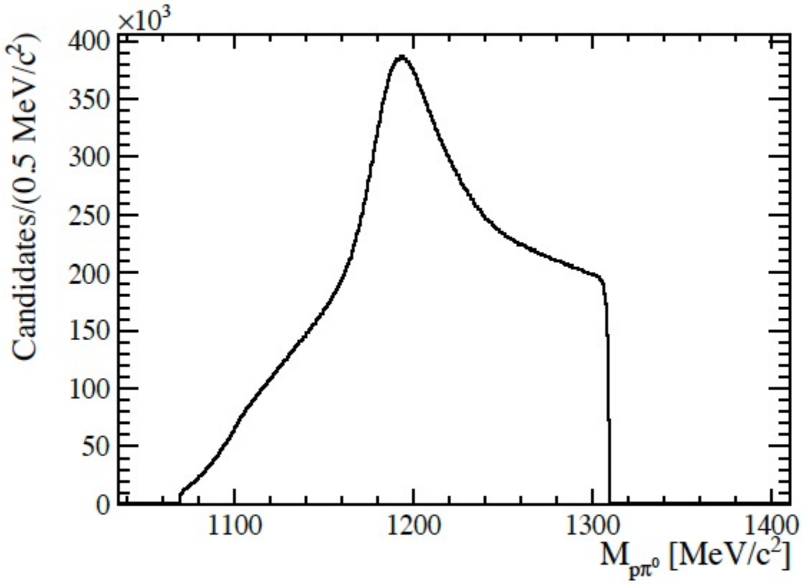
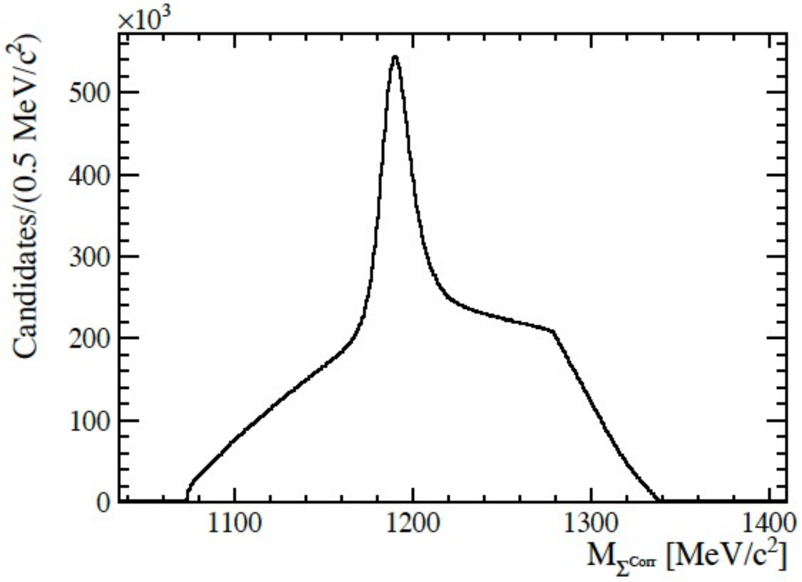
    $\mathcal{B}(\Sigma^+ \to p\pi^0) = (51.77 \pm 0.30)\%$

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

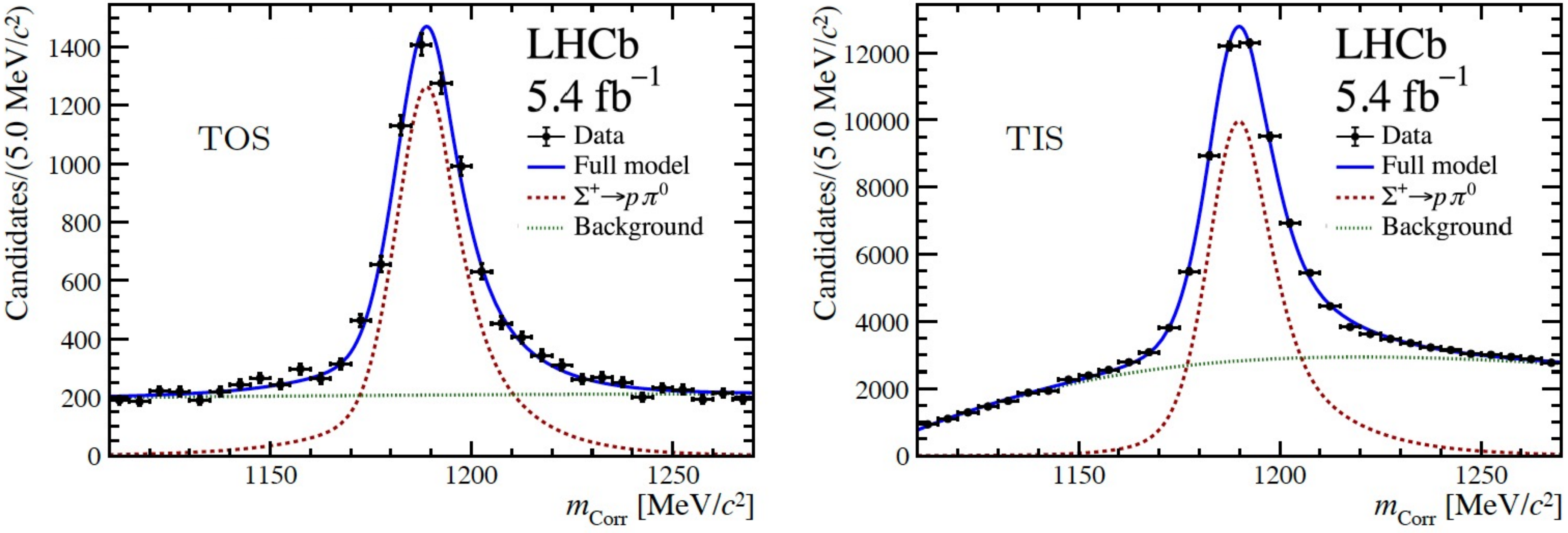
- Observed limited resolution on $m_{\gamma\gamma}$ in data after selection → PID and kinematic variables
  - Poor resolution of the photons energy deposits in the calorimeter
  - $\Sigma^+ \to p\pi^0$ mass corrected by adjusting for the PDG value of the π^0





Normalisation – Final fit

- Extended maximum likelihood fit
  - $\Sigma^+ \to p\pi^0$ parametrized by double-sided Crystal Ball function
    Trigger On Signal (TOS) → $N_{\Sigma^+\to p\pi^0} = 6132 \pm 105$
    Trigger Independent from Signal (TIS) → $N_{\Sigma^+\to p\pi^0} = 47456 \pm 307$
  - Background (mainly combinatorial) by second degree Chebyshev polynomial function



Normalisation – Efficiencies

- Taking into account TIS and TOS categories

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = \mathcal{B}(\Sigma^+ \to p\pi^0) \cdot \frac{\varepsilon^{NoTrig}_{\Sigma^+\to p\pi^0}}{\varepsilon^{NoTrig}_{\Sigma^+\to p\mu^+\mu^-}} \cdot \left(\frac{\varepsilon^{TIS}_{\Sigma^+\to p\pi^0}}{\varepsilon^{TIS}_{\Sigma^+\to p\mu^+\mu^-}} \cdot \frac{N^{TIS}_{\Sigma^+\to p\mu^+\mu^-}}{N^{TIS}_{\Sigma^+\to p\pi^0}} + \frac{\varepsilon^{TOS}_{\Sigma^+\to p\pi^0}}{\varepsilon^{TOS}_{\Sigma^+\to p\mu^+\mu^-}} \cdot \frac{N^{TOS}_{\Sigma^+\to p\mu^+\mu^-}}{N^{TOS}_{\Sigma^+\to p\pi^0}} \right)$$

- Very small efficiencies → order 10^{-5} for signal and 10^{-11} for normalisation
  - Muon trigger calibration with $K^+ \to \pi^+\pi^-\pi^+$ with two pions decayed in flight in muons
    ~ 20% systematic uncertainty of method validation
  - Hadron and TIS trigger calibrations with $\Sigma^+ \to p\pi^0$ and TISTOS method
  - PID and tracking calibration with control channels in data
  - π^0 reconstruction calibration with $B^+ \to J/\psi K^{*+}(\to K^+\pi^0)$ and $B^+ \to J/\psi K^+$ decays
    ~ 7% systematic uncertainty from branching fractions

- Single event sensitivity → $(1.65^{+0.09+0.41}_{-0.16-0.41})\times10^{-10}$ (TOS) – $(6.81^{+0.29+0.85}_{-0.25-0.85})\times10^{-11}$ (TIS)
  - Corresponding to $\mathcal{O}(10^{14})$ Σ^+ baryons produced in *LHCb*

Normalisation – Results

- Measured branching fraction(s)
  - TOS → $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (1.59^{+0.19+0.40}_{-0.23-0.40}) \times 10^{-8}$
  - TIS → $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (1.05^{+0.10+0.13}_{-0.10-0.13}) \times 10^{-8}$

- Combined result

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

- Combined result with Run1

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (1.09 \pm 0.17) \times 10^{-8}$$

- **Question**: How rare is this rare decay?
  - Let's compare the result with the theory …

Normalisation – Interpretations

- Evaluation of the the *z-score*

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

- Considerations:
  - Minimum exclusion of $\mathbf{6.2\sigma}$ for the smaller $|\Re[a(0)]|$
  - Negative $\Re[a(0)]$ disfavoured at a minimum of $\mathbf{3.7\sigma}$
  - Heavy baryon
    $\Re[a(0)]$ large and positive disfavoured at $\mathbf{3.1\sigma}$
  - Relativistic baryon
    Disfavoured at $\mathbf{3.7\sigma}$ 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

Summary …

➤ *"Measurement of the branching fraction of the $\Sigma^+ \to p\mu^+\mu^-$ rare decay at LHCb"* [arXiv:2504.06096]

- **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**
- Scheduled to be pubblished **July 29th** on PRL

Recently selected for inclusion in
the American Physical Society outreach to the press

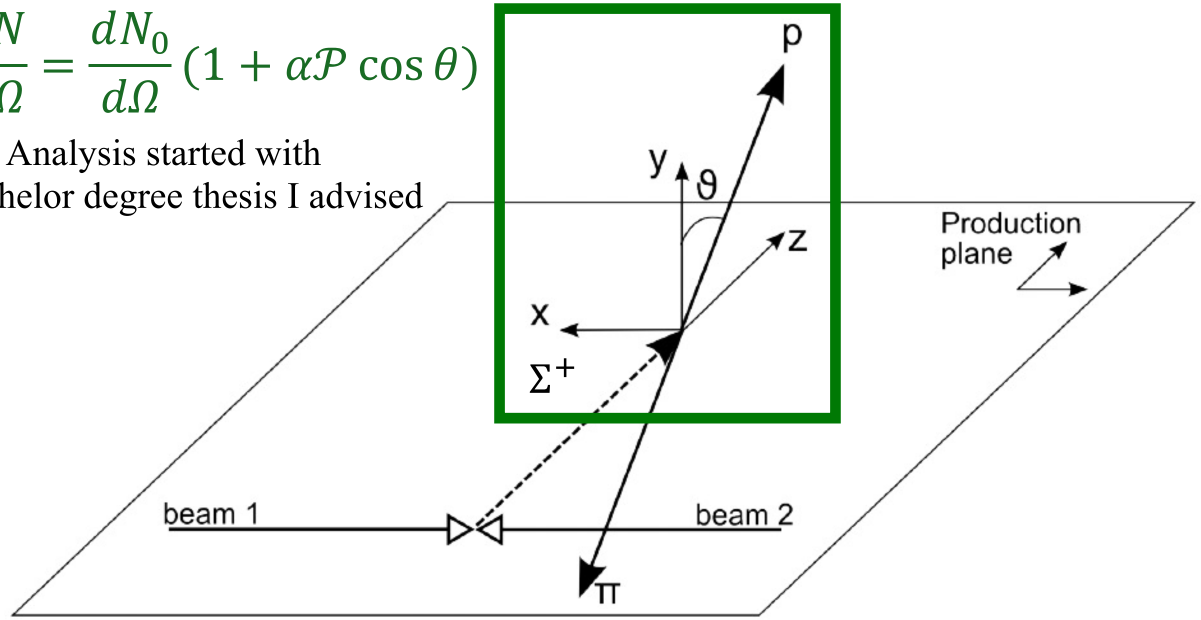
… and future prospects

- Future prospects (**Run 2** but also **Run 3**)
  - Large signal yield → new accessible measurements

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 advised



Differential branching fraction vs dimuon mass

"Direct" CP violation measurement

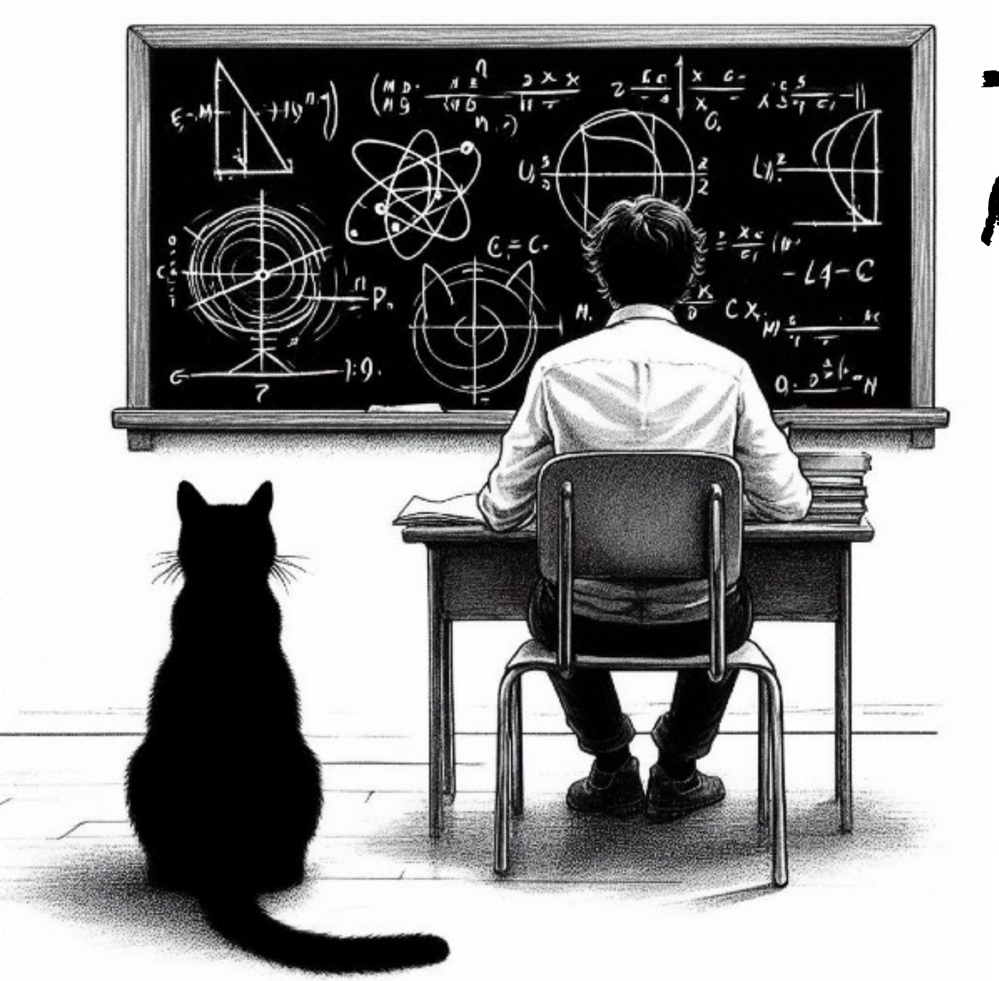
$$\mathcal{A}_{CP} = \frac{\mathcal{B}(\Sigma^{+} \to p\mu^{+}\mu^{-}) - \mathcal{B}(\bar{\Sigma}^{-} \to \bar{p}\mu^{+}\mu^{-})}{\mathcal{B}(\Sigma^{+} \to p\mu^{+}\mu^{-}) + \mathcal{B}(\bar{\Sigma}^{-} \to \bar{p}\mu^{+}\mu^{-})}$$

Main part of the second paper
Analysis started

Forward-backward asymmetry

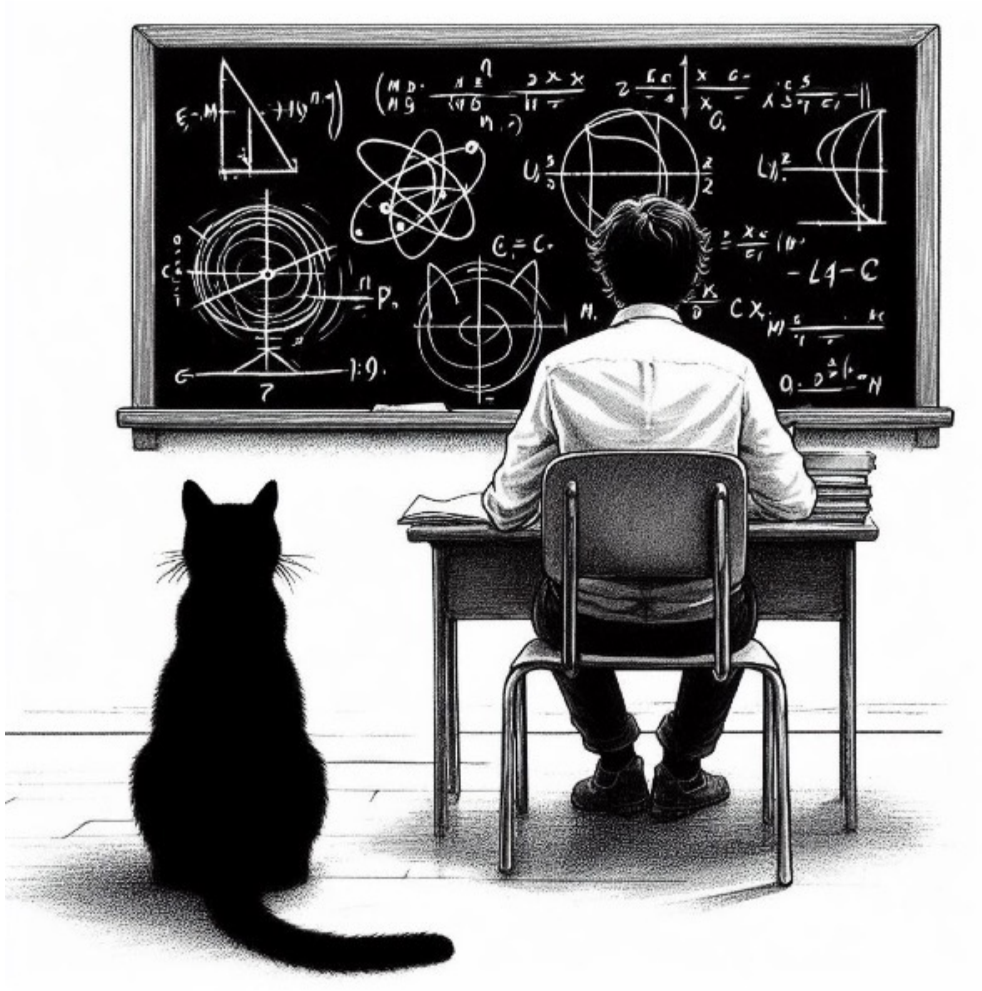
$$A_{FB} = \frac{N_{\Sigma^{+}\to p\mu^{+}\mu^{-}}(F) - N_{\Sigma^{+}\to p\mu^{+}\mu^{-}}(B)}{N_{\Sigma^{+}\to p\mu^{+}\mu^{-}}(F) + N_{\Sigma^{+}\to p\mu^{+}\mu^{-}}(B)}$$

Analysis started with
a Master degree thesis I'm advising



Thank you for your attention
Many thanks to Johannes and Dominik for inviting me

Backup slides



Run2 dedicated trigger

- Run 1: "take what is there"
  - Analyse data already collected with very small efficiency

- Run 2 improvements for strange physics [LHCb-PUB-2017-023]:
  - HLT1: Complementary forward tracking lowered down to 80 MeV for muon tracks
    Generic **Hlt1DiMuonNoL0** for soft dimuons **not** requiring only **L0Muon** or **L0Dimuon** triggered events in input
  - HLT2: Generic **Hlt2DiMuonSoft** for soft dimuons
    Dedicated **Hlt2RareStrangeSigmaPMuMu** for $\Sigma^+ \to p\mu^+\mu^-$ decays

Efficiency	$\Sigma \to p\mu^+\mu^-$	
L0	0.269 ± 0.006	
	Run 1	Run 2
Hlt1Global $\vert$ L0	0.191 ± 0.011	0.459 ± 0.014
Hlt1DiMuonNoL0 $\vert$ L0	-	0.325 ± 0.013
Hlt2Global $\vert$ Hlt1Global	0.162 ± 0.023	0.901 ± 0.012
Hlt2DiMuonSoft $\vert$ Hlt1Global	-	0.804 ± 0.016
Hlt2SigmaPMuMu $\vert$ Hlt1Global	-	0.485 ± 0.020
Total	0.0083 ± 0.0013	0.111 ± 0.004

BDT discriminating variables

- Summary
  - $IP\chi^2$ - The difference in the vertex-fit χ^2 of a given PV reconstructed with and without the particle being considered;
  - $DOCA$ - The maximum distance of closest approach between any pair of the three daughter tracks;
  - $FD\chi^2$ - The flight distance of the mother particle from the primary vertex divided by its uncertainty;
  - $DIRA$ - The angle between the mother particle momentum and the lines joining the primary and the decay vertex;
  - $Vtx\chi^2$ - The χ^2 of the vertex fit.

TIS and TOS trigger categories