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

Gabriele Martelli
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On behalf of the LHCb collaboration

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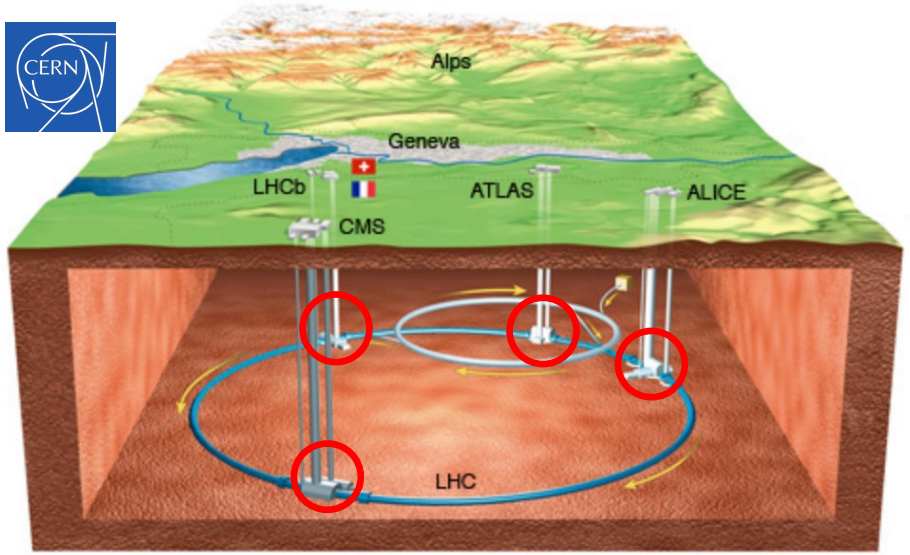
LHCb - The experiment

- 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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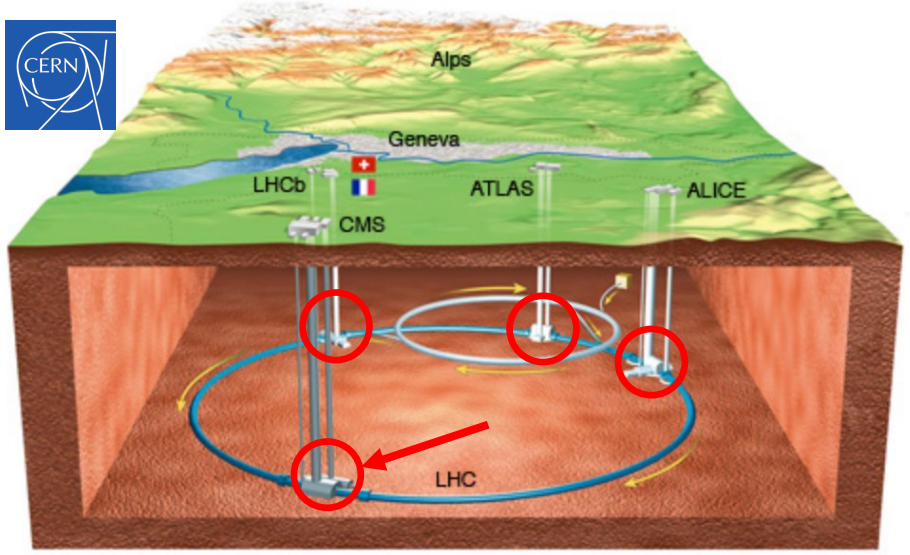
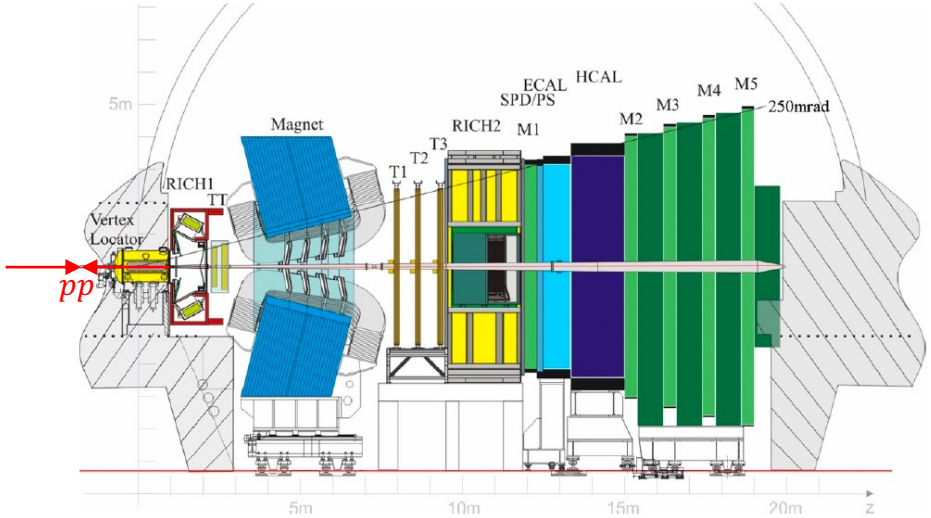
- Large Hadron Collider beauty (LHCb)
  - Investigate the quark flavour sector
    - ✓ CP violation
    - ✓ Rare decays with possible New Physics (NP) hints
  - Positioned in the forward region relative to the collision point
  - Large production $b\bar{b}$ and $c\bar{c}$ cross sections within its acceptance
    - ✓ $72(144)$ μb and $1.4(2.6)$ mb at $\sqrt{s} = 7(13)$ TeV





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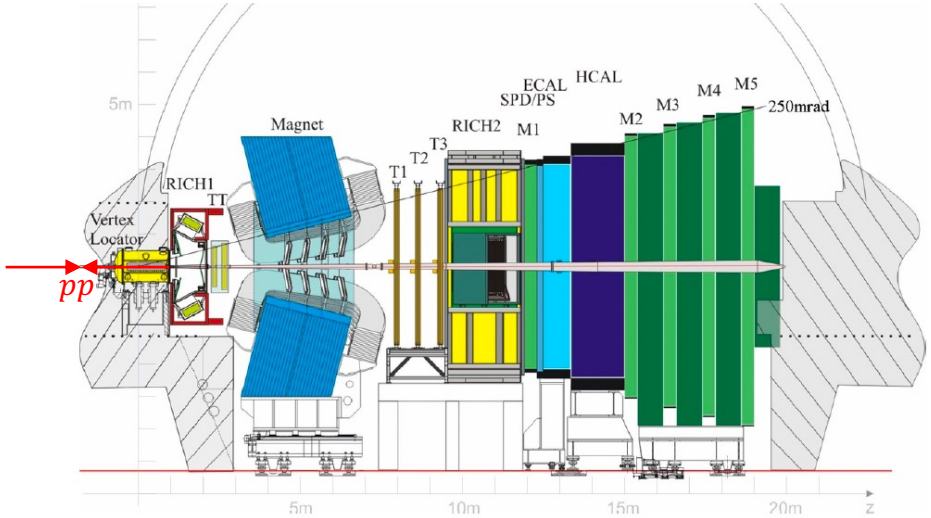
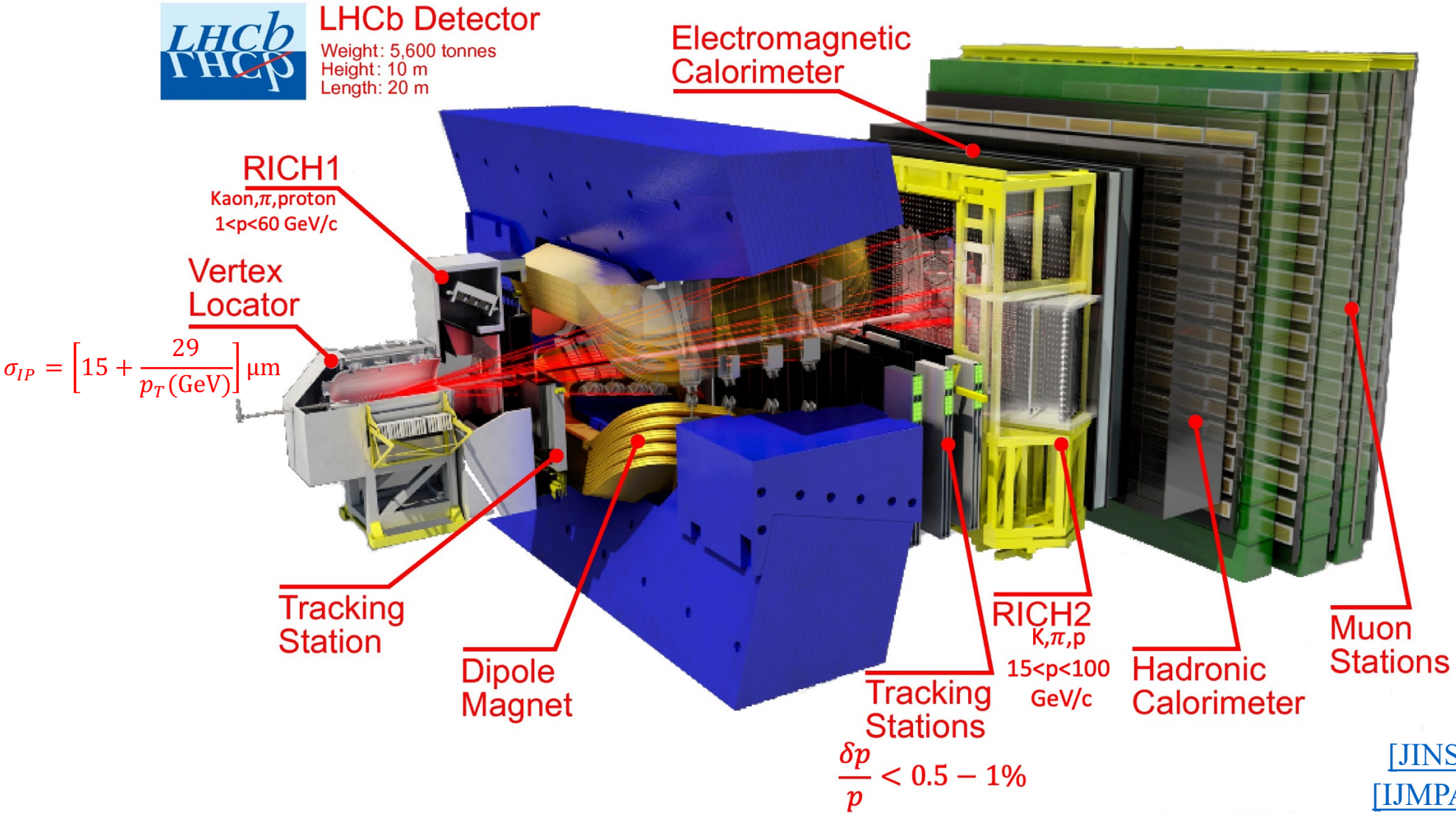
- 22 countries are involved in the collaboration
  - About 1700 scientists, engineers and technicians
  - More than 700 articles published up-to-date [https://lhcb.web.cern.ch/]



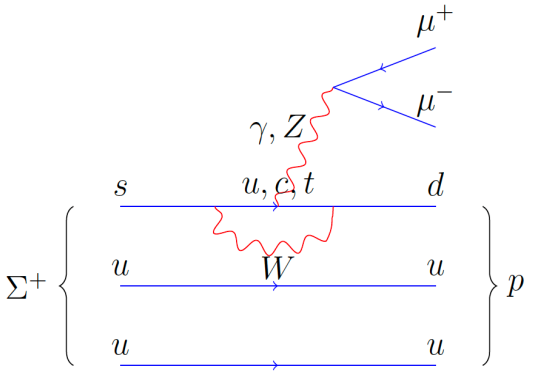
LHCb - The detector

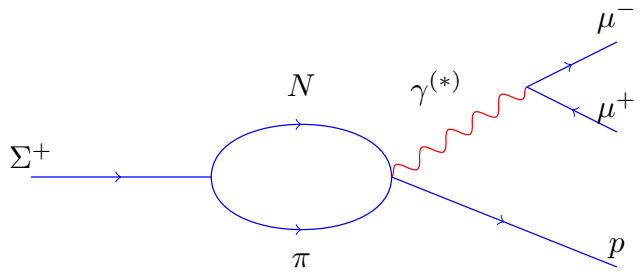


[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 1530022]

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

- $\Sigma^+ \to p\mu^+\mu^-$ is a FCNC process allowed only at loop level
  - Short distance SM $\mathcal{B}\sim\mathcal{O}(10^{-12})$
  - Dominated by long distance contributions from $\Sigma^+ \to (N\pi)^+$ decays
    $1.6 \times 10^{-8} < \mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) < 9.1 \times 10^{-8}$
    [Phys. Rev. D72 (2005) 074003]
    [JHEP 1810 (2018) 040]





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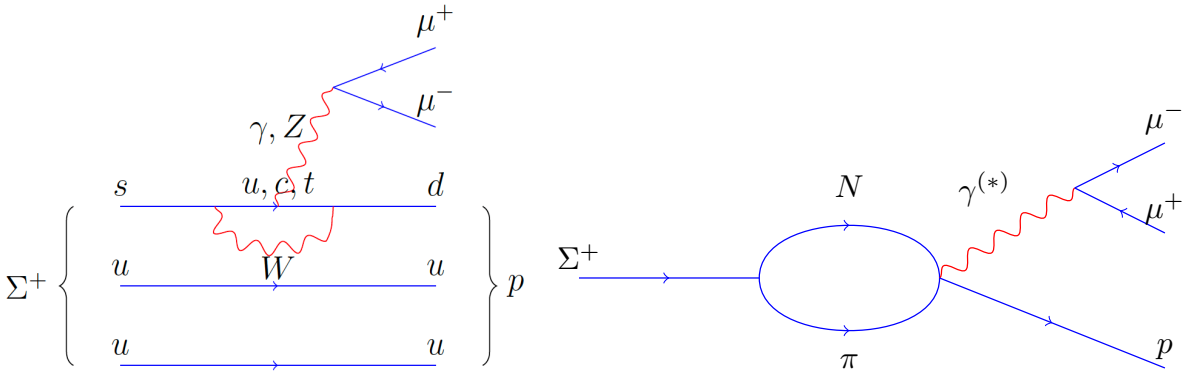

- First evidence from the HyperCP experiment
  - Three candidates observed in absence of background
  - Measured branching fraction:
    $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = \left(8.6^{+6.6}_{-5.4} \pm 5.5\right) \times 10^{-8}$
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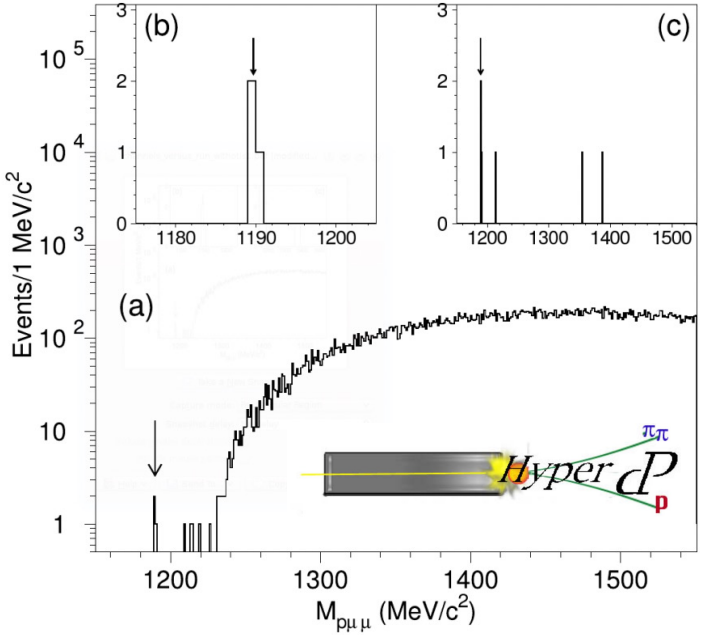

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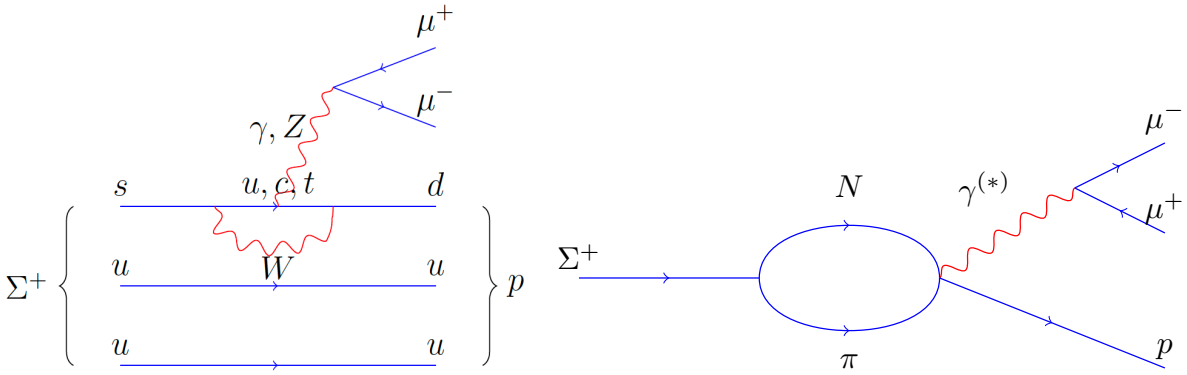

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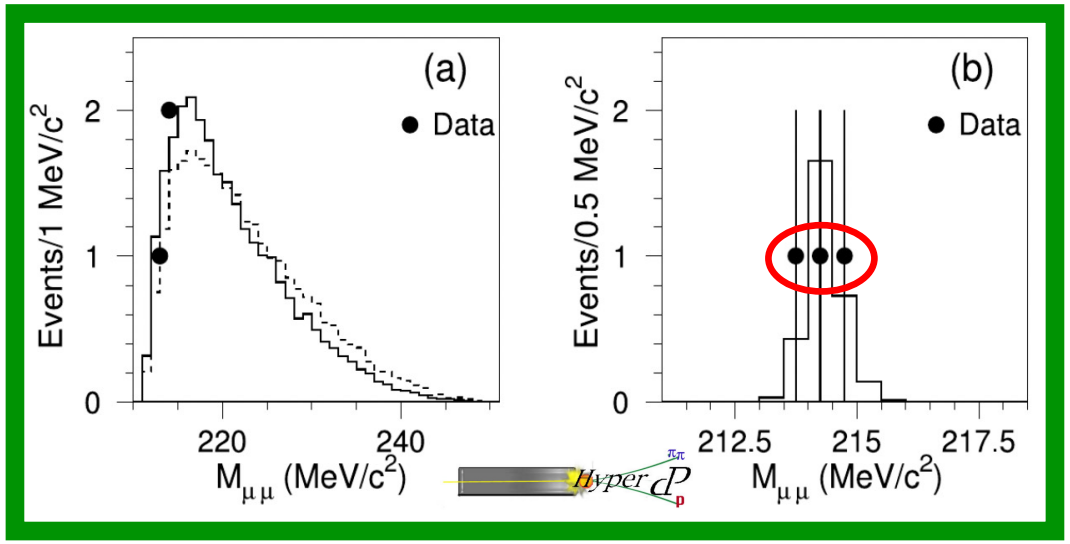
- The Anomaly
  - **Same** dimuon invariant mass for the observed candidates
  - Possible $\Sigma^+ \to pX^0(\to \mu^+\mu^-)$ decay
    $m_{X^0} = 214.3 \pm 0.5$ MeV
    $\mathcal{B}(\Sigma^+ \to pX^0(\to \mu^+\mu^-)) = (3.1^{+2.4}_{-1.9} \pm 1.5) \times 10^{-8}$



The Anomaly - Searches and interpretations

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~3 years after HyperCP

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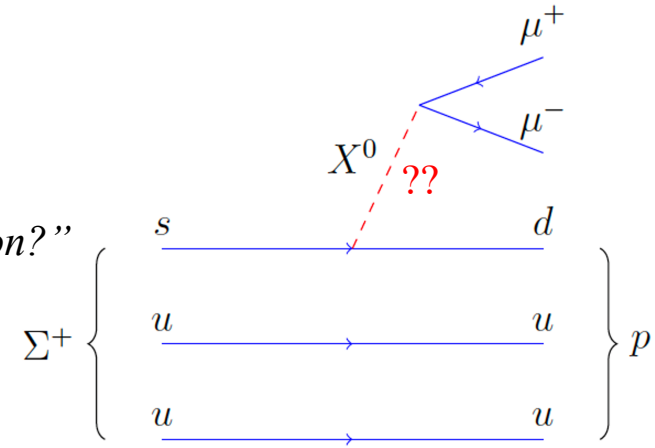

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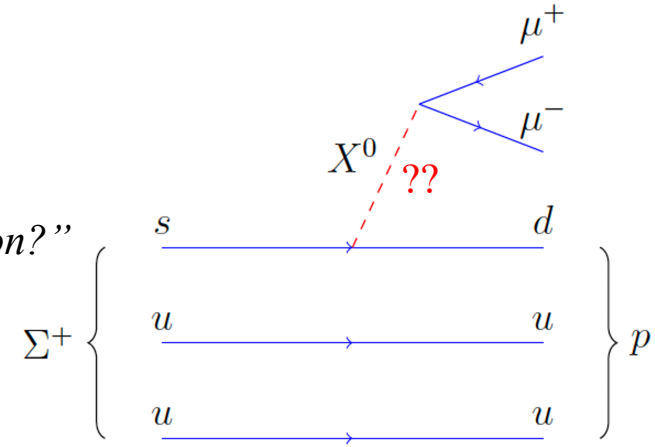

- New searches for low dimuon mass resonances

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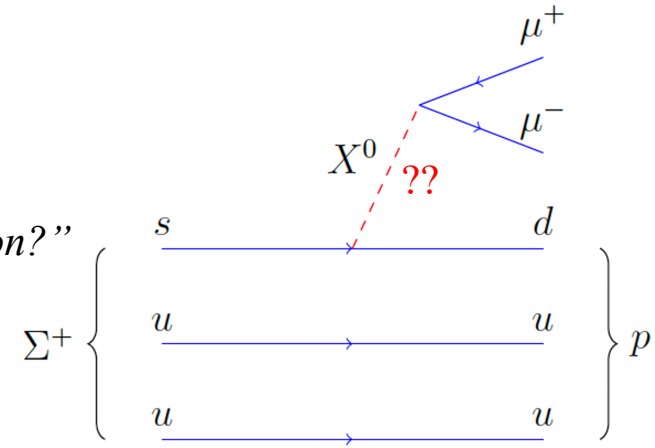

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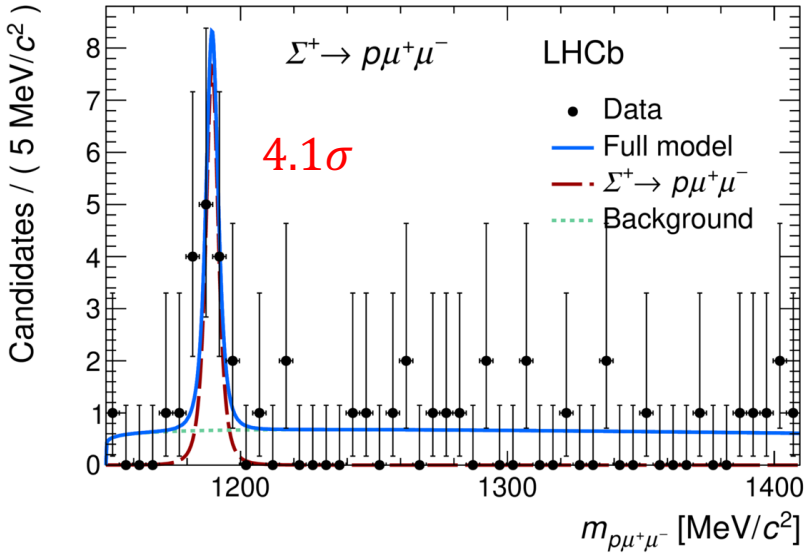
$\Sigma^+ \to p\mu^+\mu^-$ - First search at LHCb

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

- **Stronger** evidence by LHCb
  - Excess of signal candidates w.r.t. background
    $N_{\Sigma^+ \to p\mu^+\mu^-} = (10.2^{+3.9}_{-3.5})$
  - Measured branching fraction:
    $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (2.2^{+0.9+1.5}_{-0.8-1.1}) \times 10^{-8}$
  - Consistent with SM prediction



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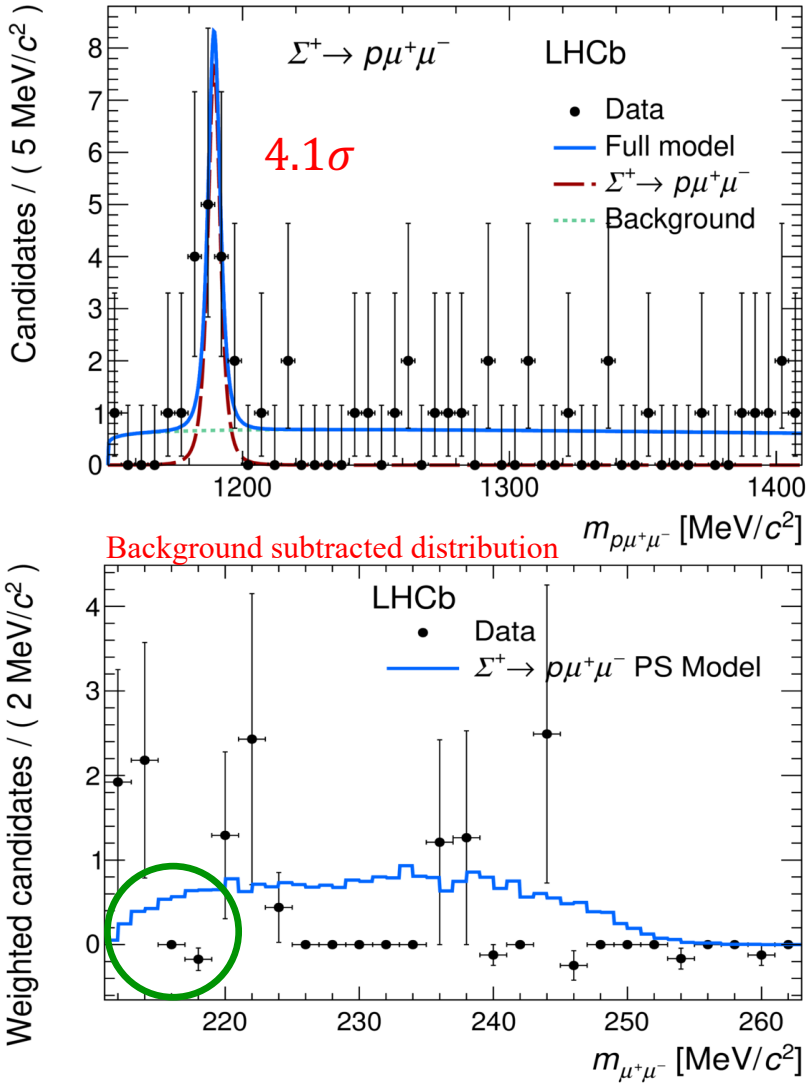
- Search for the X^0 resonance
  - No significant peak found in the $m_{\mu^+\mu^-}$ distribution
  - Upper limit at 90% C.L.
    $\mathcal{B}(\Sigma^+ \to pX^0(\to \mu^+\mu^-)) < 1.4\times10^{-8}$
  - HyperCP result central value excluded



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

  - $\Sigma^+ \to p\mu^+\mu^-$ and $\Sigma^+ \to p\gamma$ share the same form-factors

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

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

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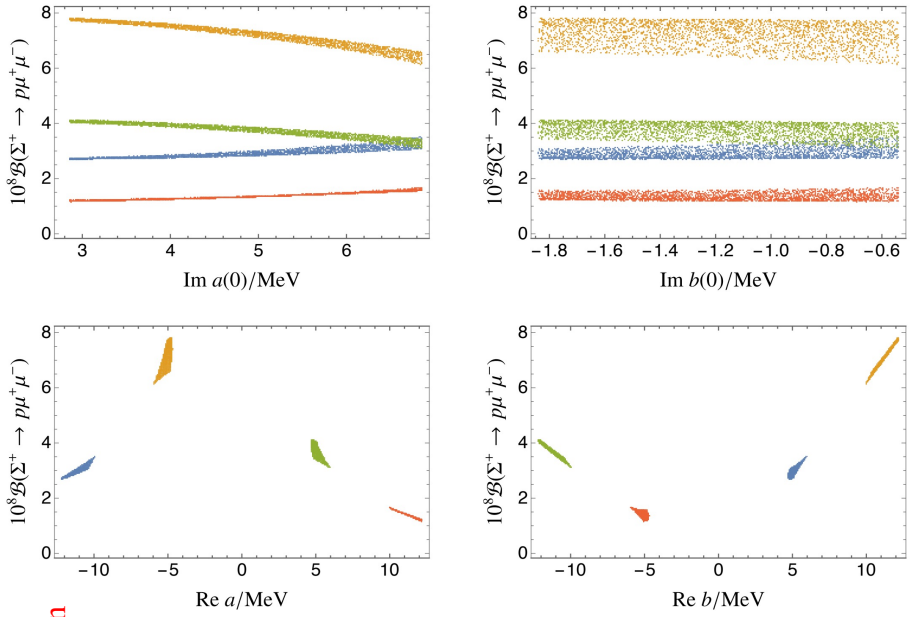
- Chiral perturbation theory (χPT)
  - Relativistic and heavy baryon approaches
  - Four-fold degeneracy in each method [arXiv:2404.15268]

Experiments should be able to solve it



	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
	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

Outline

Run 2

Observation of the $\Sigma^+ \to p\mu^+\mu^-$ rare decay at LHCb
LHCb-CONF-2024-002

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General overview
- New improvements w.r.t. Run 1
- Analysis strategy

Search for the $\Sigma^+ \to p\mu^+\mu^-$ decay
- Selection
- Fit and signal evaluation

Search for the HyperCP-like resonance
- Confirm/exclude the Anomaly

New 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

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

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` | `L0`	0.191 ± 0.011	0.459 ± 0.014
`Hlt1DiMuonNoL0` | `L0`	-	0.325 ± 0.013
`Hlt2Global` | `Hlt1Global`	0.162 ± 0.023	0.901 ± 0.012
`Hlt2DiMuonSoft` | `Hlt1Global`	-	0.804 ± 0.016
`Hlt2SigmaPMuMu` | `Hlt1Global`	-	0.485 ± 0.020
Total	0.0083 ± 0.0013	0.111 ± 0.004

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Increase in trigger efficiency from HLT

Analysis strategy

- Blind analysis technique
  - Avoid introduction of biases
  - Blinded $m_{p\mu^+\mu^-}$ region: $1173 < m_{p\mu^+\mu^-} < 1205\ \mathrm{MeV}/c^2$

Selection: Reject most of the background sources and isolate the signal candidates
- Loose preselection on kinematic variables
- Tight selection with PID variables
- Multivariate operator and optimisation

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

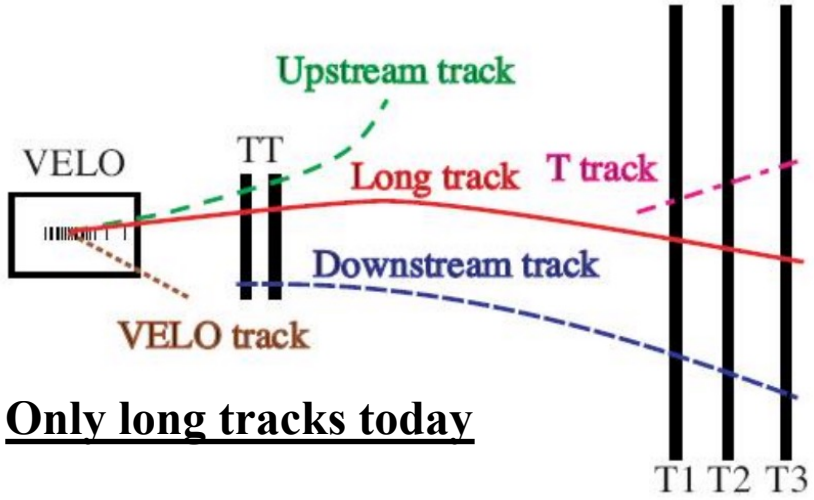
Dimuon spectrum: Look for a resonant structure
- Background subtraction with the *sPlot* method
- Scan in the $m_{\mu^+\mu^-}$ invariant mass

Selection

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

Decay products may be recostructed with

- Long tracks
- Downstream tracks



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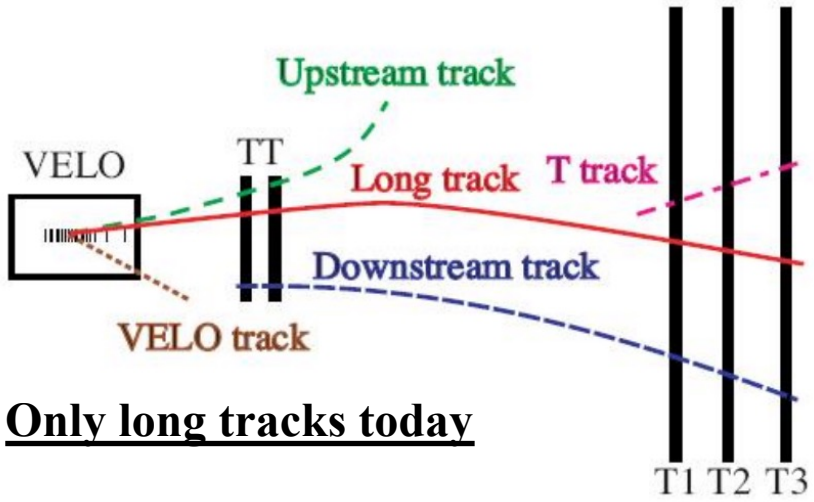

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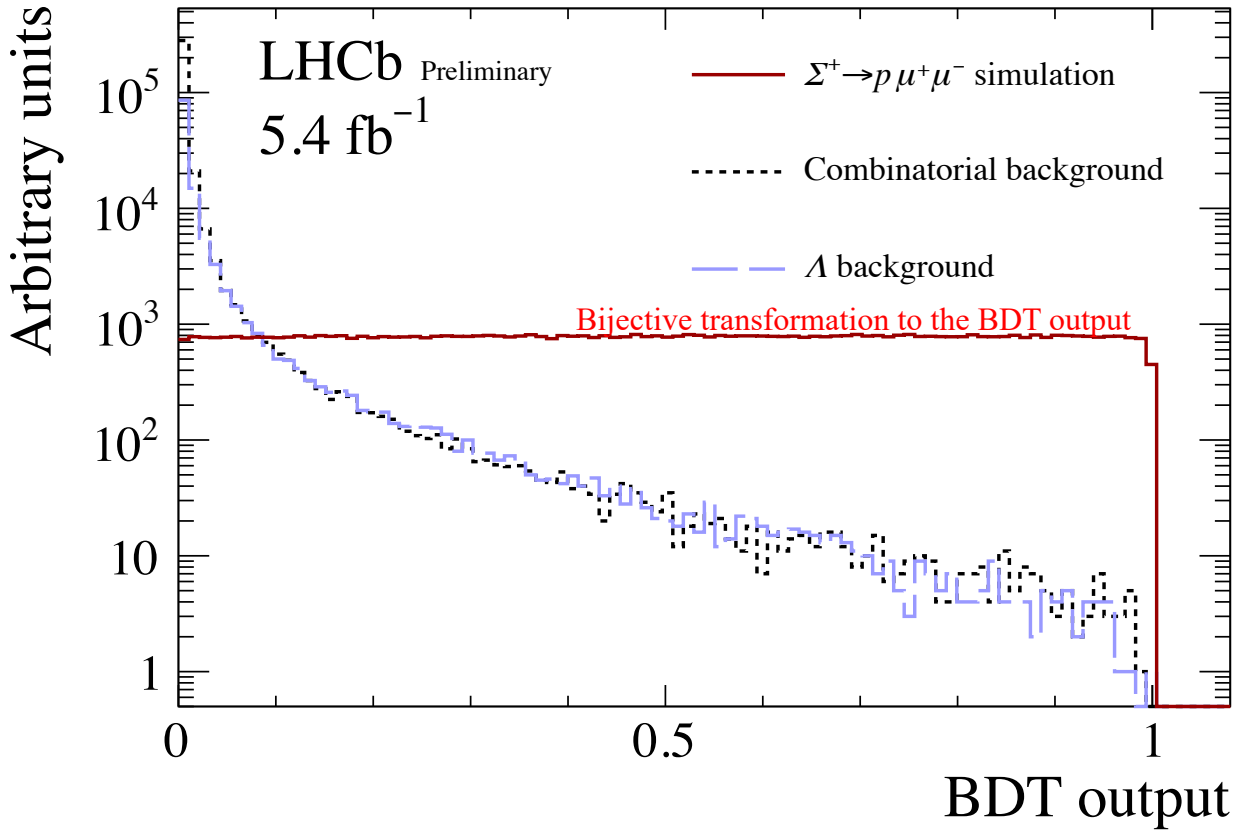
- Residual background sources
  - Combinatorial
  - $\Lambda \to p\pi^-$ decays with misID $\pi^- \to \mu^-$ with accidental μ^+

- Small q-value
  - Few modes can mimic the signal final state $(m_{\Sigma^+} - m_p - 2m_\mu) = 39.78\ \mathrm{MeV}/c^2$
  - $K^+ \to \pi^+\pi^-\pi^+$ 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
- Larger reconstructed mass w.r.t. the signal

Multivariate operator

- Final selection with a multivariate operator
  - BDT built in TMVA
  - Trained to reject combinatorial on:
    - ✓ MC signal sample
    - ✓ Sidebands in data sample
- Discriminating variables (backup slides for description)
  - $log(1 - \Sigma^+ DIRA)$
  - $\Sigma^+ \, IP\chi^2$, $DOCA$, $FD\chi^2$, $Vtx\chi^2$
  - $p \, IP\chi^2$, p_T
  - $min(\mu \, IP\chi^2)$, $min(\mu \, p_T)$
- Data divided in a Λ veto sample and a complementary one
  - Very similar distribution at high BDT values
  - A BDT requirement will reject both background sources



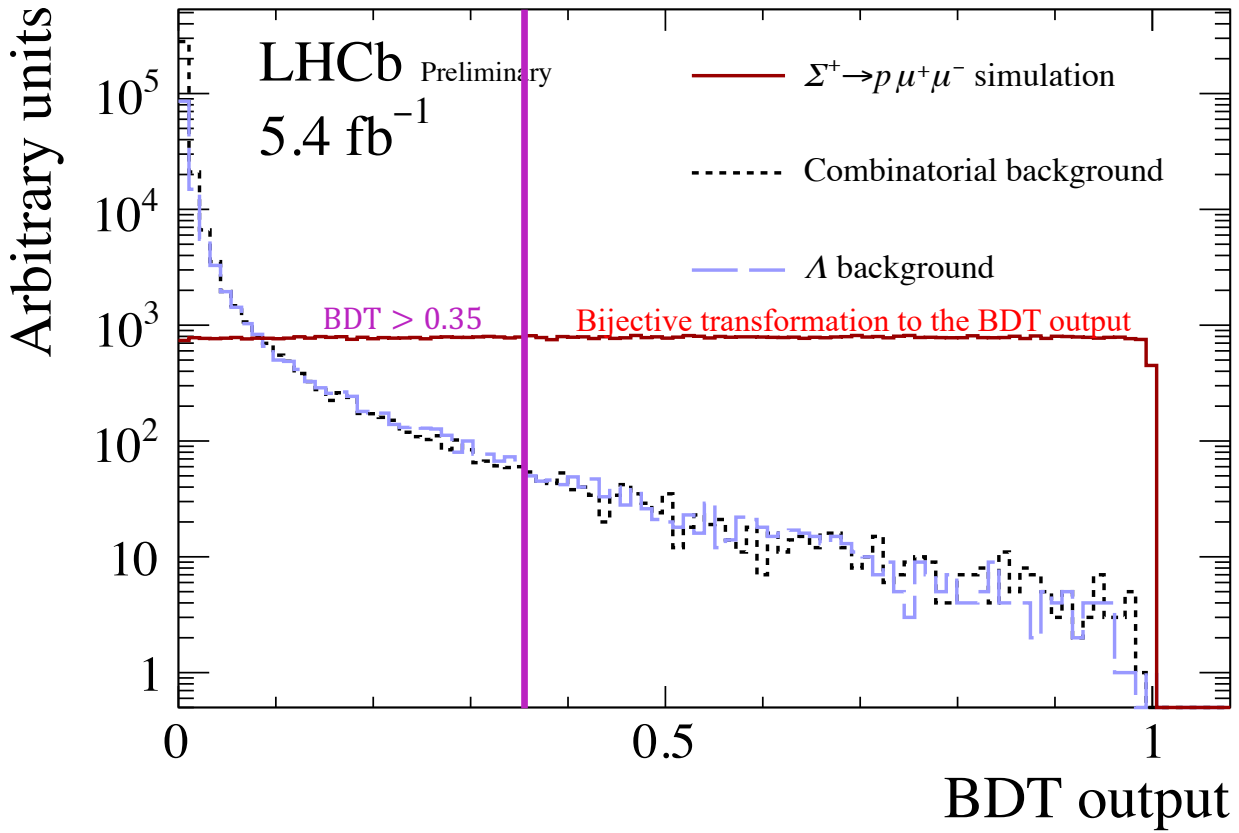
Optimisation

- Optimisation for the best chances of observation
  - Performed on:
    - ✓ MC and data samples
  - Optimal point chosen as the largest significance

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

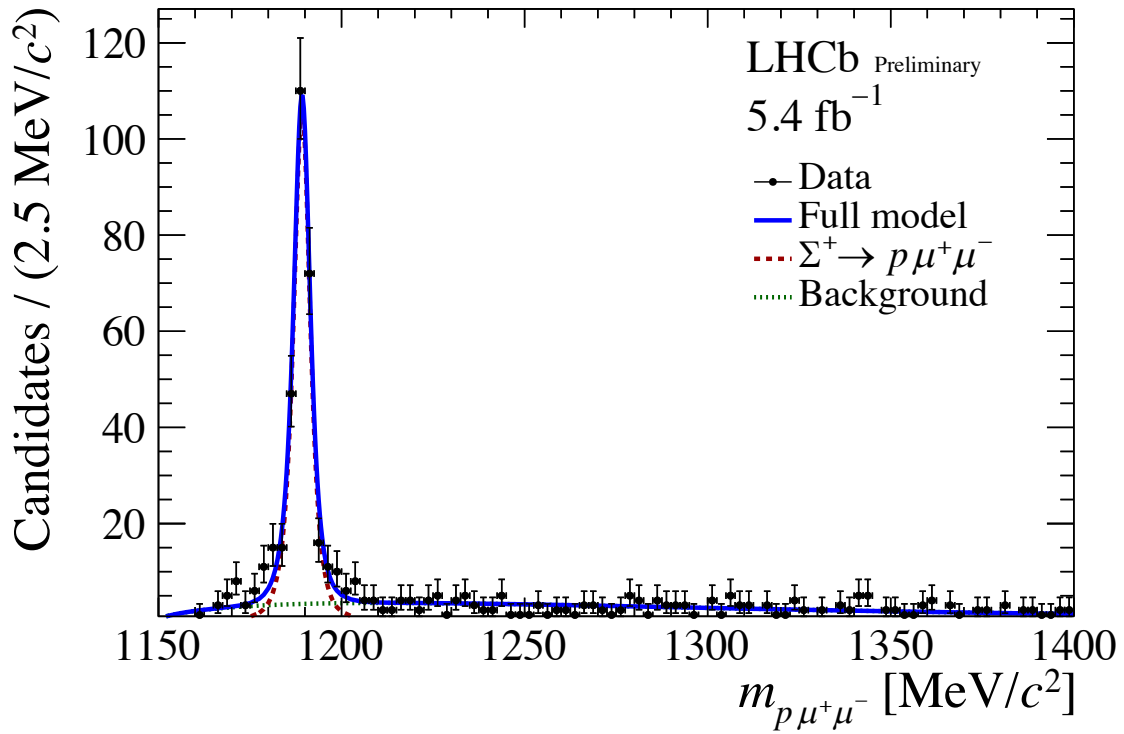
N_S = Expected signal yield
N_C = Expected combinatorial
N_Λ = Expected Λ background

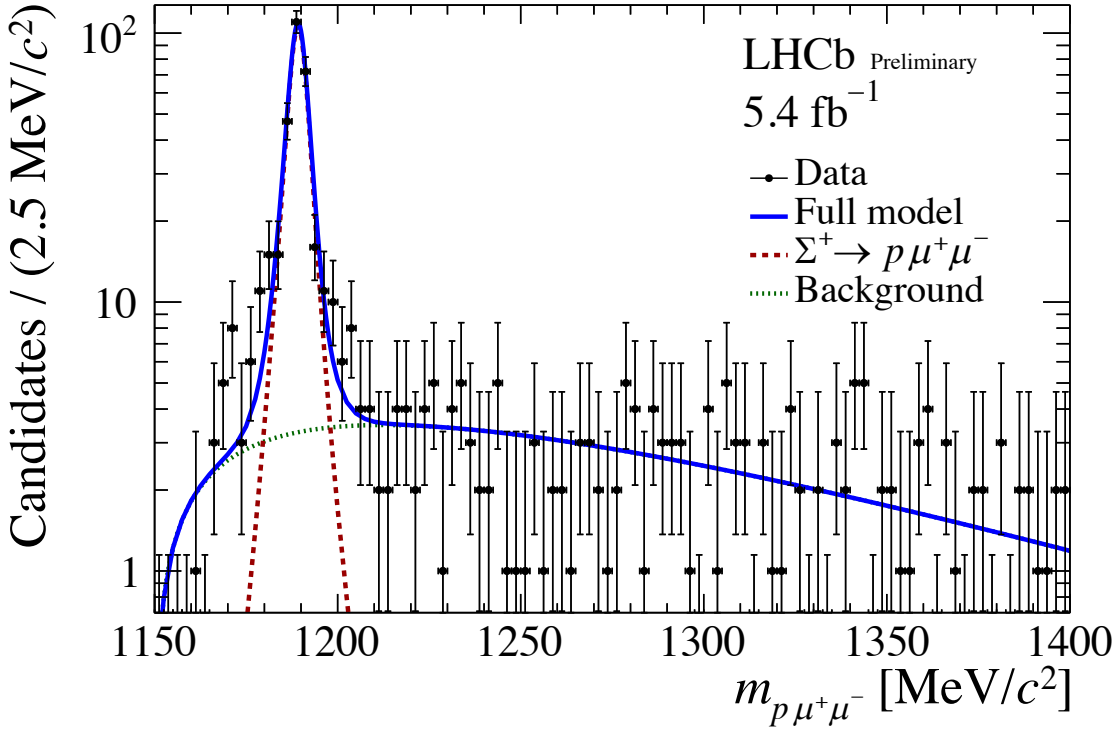
- Four dimensions
  - BDT
  - PID variables
  - Λ vetos → $\left|m_{p\pi^-} - m_\Lambda^{PDG}\right| > 6, 8, 10\ \mathrm{MeV}/c^2$



$\Sigma^+ \to p\mu^+\mu^-$ - Final fit

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





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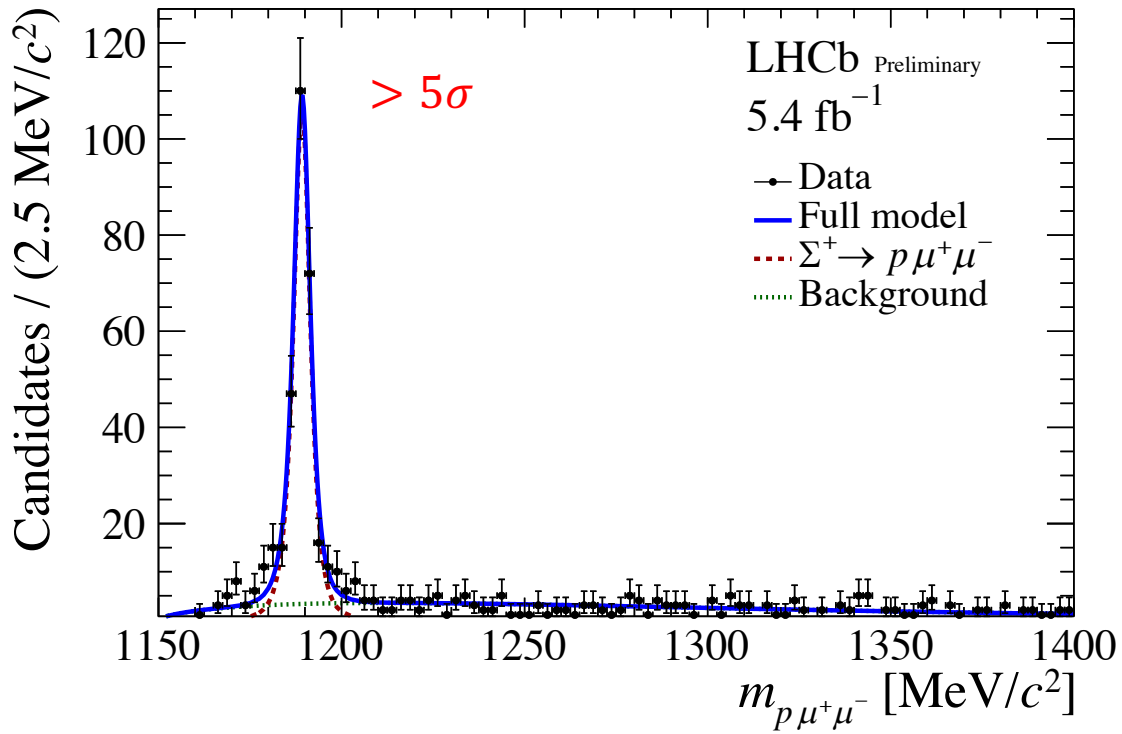
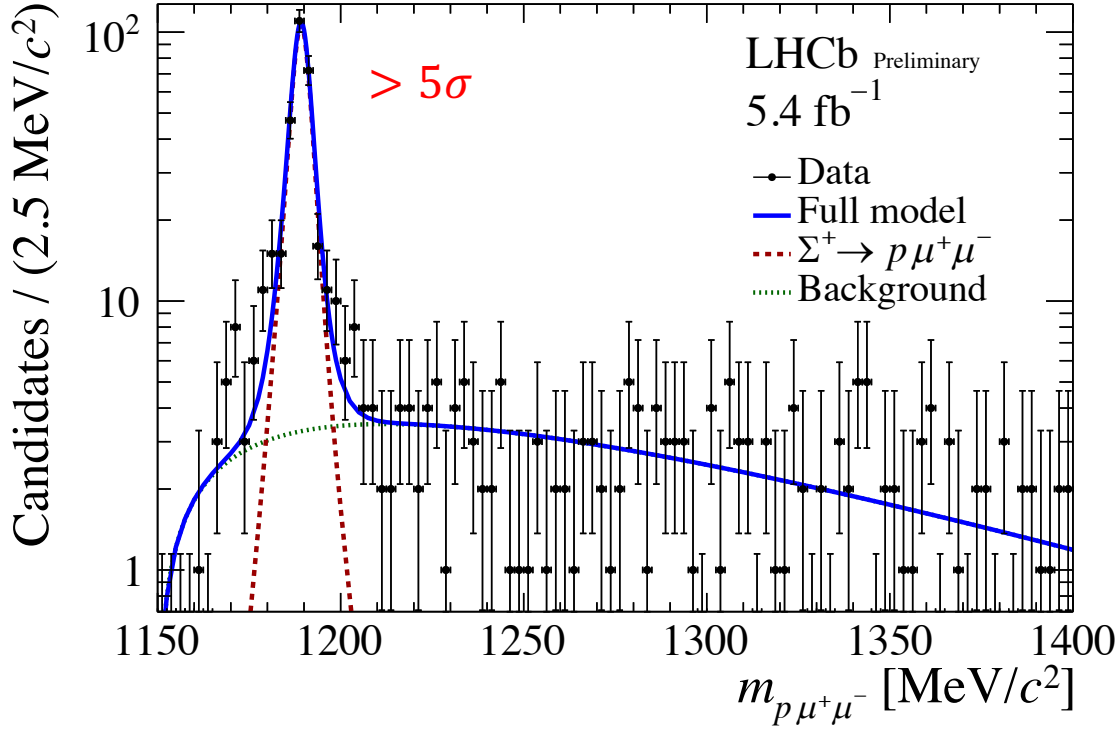
First observation with overwhelming significance

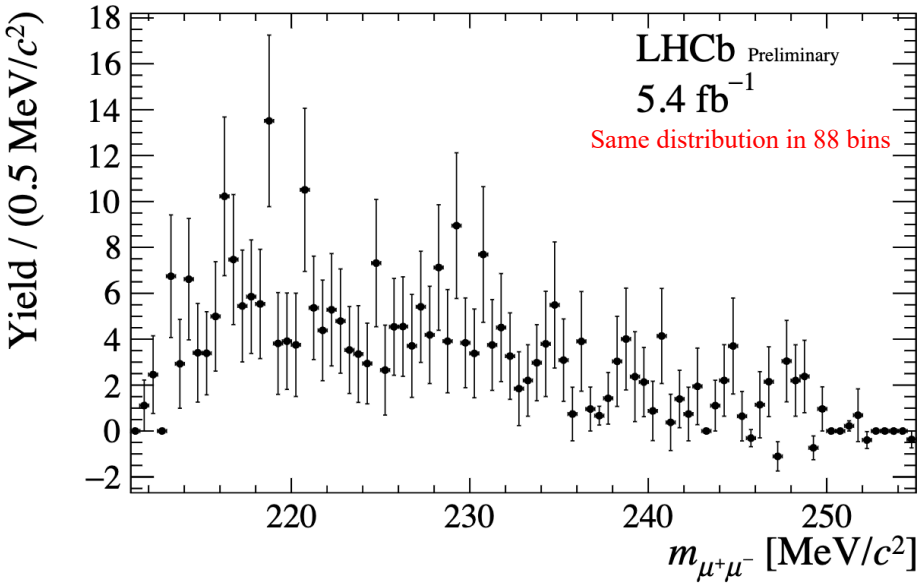


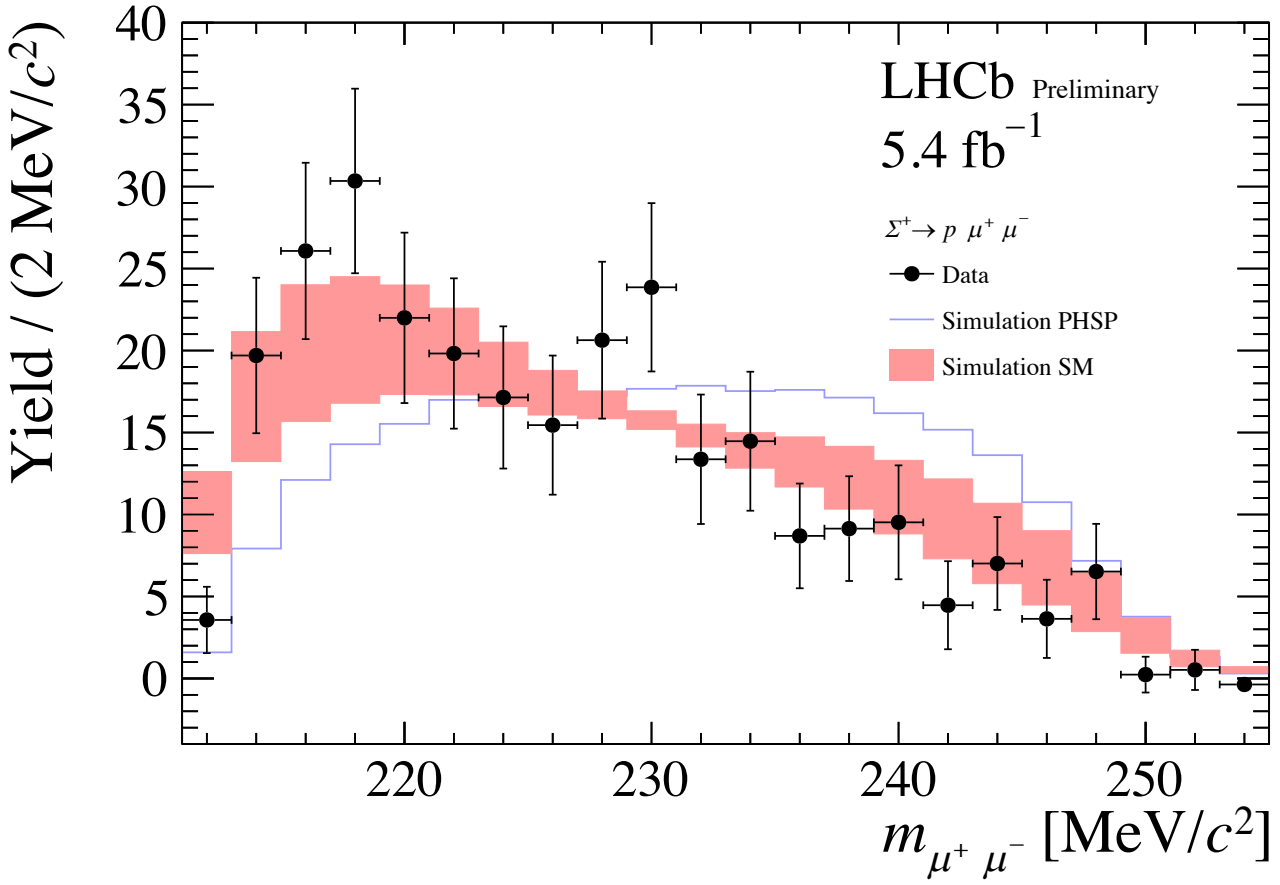


Search for HyperCP-like signals - 1/2

- Background subtraction
  - *sPlot* method using $m_{p\mu^+\mu^-}$ as discriminant variable
    - ✓ Event-by-event signal re-weight

- No significant peaking structure is visible
  - Data compared with simulated phase space
    - ✓ Simulation re-weighted according to SM amplitude
  - Good agreement found in the full $m_{\mu^+\mu^-}$ distribution

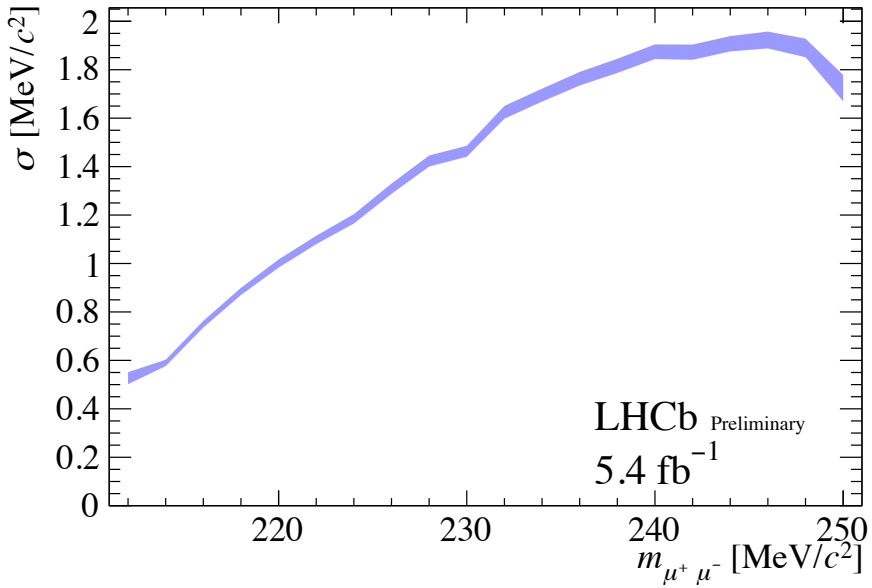


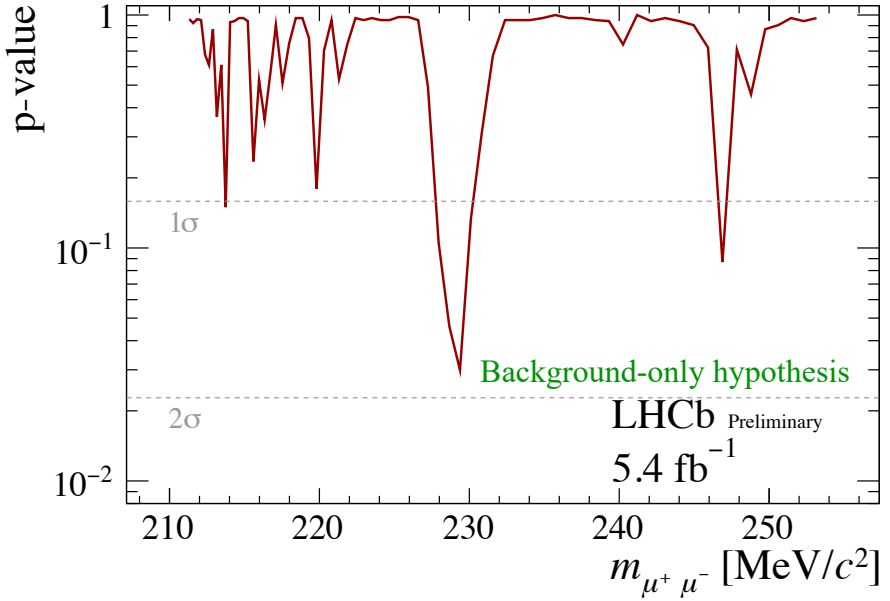


Search for HyperCP-like signals - 2/2

- Scan in the $m_{\mu^+\mu^-}$ invariant mass
  - $\pm 2\sigma_{p\mu^+\mu^-}$ around the Σ^+ mass with sidebands $[1.5\ -4.0]\sigma_{\mu^+\mu^-}$
  - Steps of $\pm 0.5\sigma_{\mu^+\mu^-}$ in signal windows of $\pm 1.5\sigma_{\mu^+\mu^-}$

- No significant structure is found and considering a putative candidate with $m_{X^0} = 214.3\ \mathrm{MeV}/c^2$:
  - The fractional contribution to all the candidates in the mass window is 3.7%
  - The difference w.r.t. to the expected background from the $m_{\mu^+\mu^-}$ sidebands is -4 events





Conclusions and outlook

- *"Observation of the $\Sigma^+ \to p\mu^+\mu^-$ rare decay at LHCb"*
  - **First** observation of the decay with significance greater than 5σ
  - Investigated the dimuon spectrum for NP resonances
    - ✓ No significant structure is found
    - ✓ HyperCP Anomaly excluded

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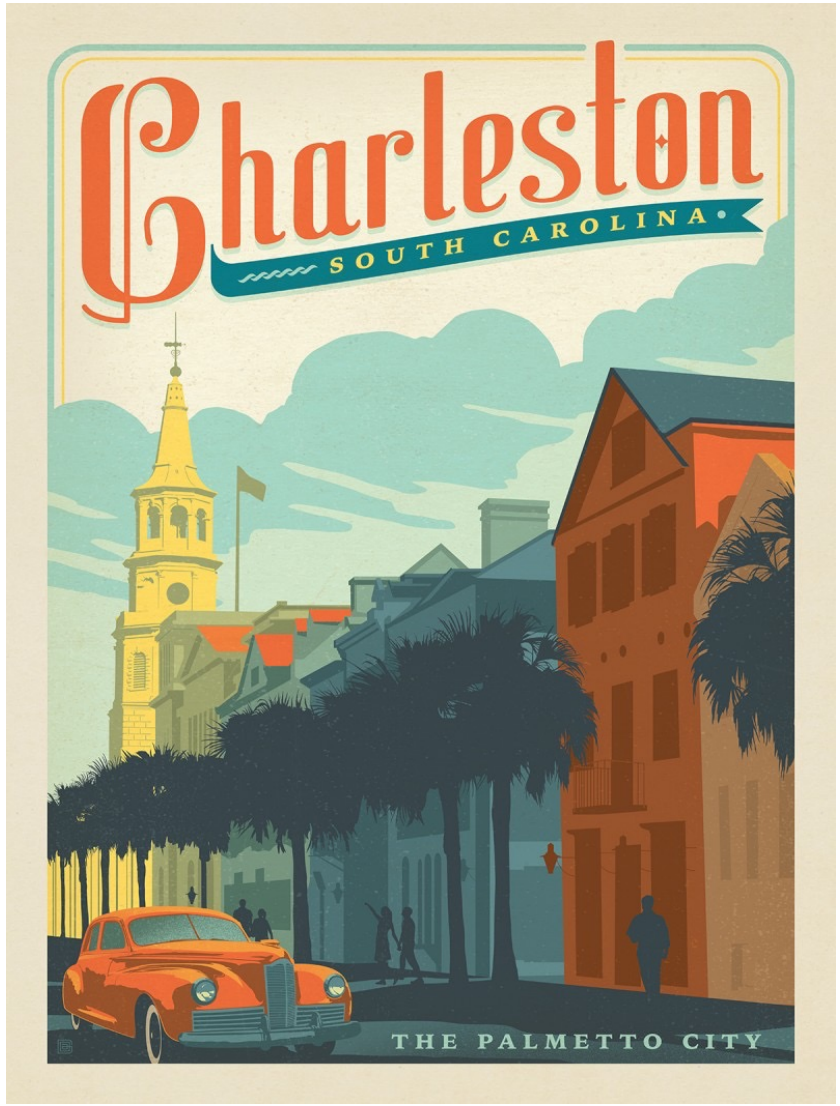
- Near future (Run 2)
  - Integrated branching fraction measurement with the $\Sigma^+ \to p\pi^0$ decay

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

- Far future (Run 2 and Run 3)
  - Large signal yield → new accessible measurements
    - ✓ Charge-parity symmetry violation
    - ✓ Forward-backward asymmetries



On behalf of the LHCb collaboration
thank you for your attention

Backup slides

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.