UNIVERSIDADE DA CORUÑA

First observation of $\Sigma^+ \to p\mu^+\mu^-$ decays at LHCb

XVII CPAN DAYS

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GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
UNIÓN EUROPEA
FONDO EUROPEO DE DESARROLLO REGIONAL
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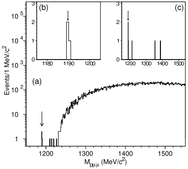
Motivation

First evidence for $\Sigma^+ \to p\mu^+\mu^-$ found by the HyperCP collaboration

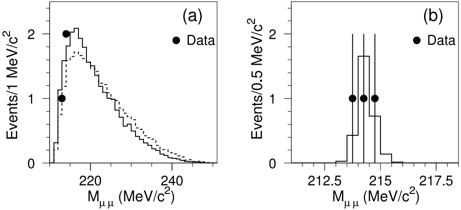
Phys. Rev. Lett. **94** (2005) 021801



3 candidates observed in the absence of background

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \times 10^{-8}$$

However, the 3 candidates were also grouped together in the dimuon mass



Probability of this occurrence estimated $< 1\%$

Anomalous $X^0 \to \mu^+\mu^-$ state suggested with $m_{X^0} = 214.3 \pm 0.5\,\text{MeV}/c^2$

Phenomenological interpretation

Several BSM hypotheses emerged in the immediate aftermath

"Sgoldstino interpretation of HyperCP events"

Phys. Rev. **D73** (2006) 035002

"On the possibility of a new boson X^0 (214 MeV) in $\Sigma^+ \to p\mu^+\mu^-$

Phys. Lett. **B632** (2006) 212-214

"Does the HyperCP Evidence for the Decay $\Sigma^+ \to p\mu^+\mu^-$ Indicate a Light Pseudoscalar Higgs Boson?"

Phys. Rev. Lett. **98** (2007) 081802

"U-boson and the HyperCP exotic events"

Phys. Lett. **B663** (2008) 400-404

Experimental searches

Several new searches for low dimuon-mass resonances

- BaBar: $\Upsilon(2S), \Upsilon(3S) \to \gamma\mu^+\mu^-$
  - Phys. Rev. Lett. **103** (2009) 081803
- Belle: $B^0 \to K^{*0}\mu^+\mu^-$, $B^0 \to \rho^0\mu^+\mu^-$
  - Phys. Rev. Lett. 105 (2010) 091801
- LHCb: $B^0 \to \mu^+\mu^-\mu^+\mu^-$
  - Phys. Rev. Lett. 110 (2013) 211801
- LHCb: $B^0 \to K^{*0}\mu^+\mu^-$
  - Phys. Rev. Lett. 115 (2015) 161802
- BESIII: $J/\psi \to \gamma\mu^+\mu^-$
  - Phys. Rev. D 93 (2016) 052005

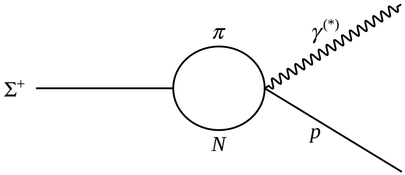
No evidence for new state found

Outline

1. Phenomenology of $\Sigma^+ \to p\mu^+\mu^-$ decays
2. Previous measurement at LHCb
3. Current measurement at LHCb
4. Future measurement at LHCb

Double-differential decay rate

Decay rate dominated by long-distance contribution



2-body transition $\Sigma^+ \to (N\pi)^+$

Followed by $(N\pi)^+ \to p\gamma^{(*)}$ rescattering

- N represents either a p or n

Double-differential decay rate in terms of dimuon-mass squared and helicity

$$A^{\mathrm{LD}}_{\mathrm{SM}}(q^2, \cos\theta_{\mu^+\mu^-}) =$$
$$e^2 G_F \left\{ \frac{-i}{q^2} \bar{u}_p [a(q^2) + \gamma_5 b(q^2)] \sigma^{\alpha\beta} q_\alpha u_\Sigma - \bar{u}_p \gamma^\beta [c(q^2) + \gamma_5 d(q^2)] u_\Sigma \right\} \bar{u}_\mu \gamma_\beta v_{\bar{\mu}}$$

Real intermediate photons only contribute to first 2 form factors

Virtual intermediate photons present in all 4

Imaginary part

$$A_{\mathrm{SM}}^{\mathrm{LD}}(q^2, \cos\theta_{\mu^+\mu^-}) =$$
$$e^2 G_F \left\{ \frac{-i}{q^2} \bar{u}_p [a(q^2) + \gamma_5 b(q^2)] \sigma^{\alpha\beta} q_\alpha u_\Sigma - \bar{u}_p \gamma^\beta [c(q^2) + \gamma_5 d(q^2)] u_\Sigma \right\} \bar{u}_\mu \gamma_\beta v_{\bar{\mu}}$$

$\Sigma^+ \to (N\pi)^+$ goes on shell

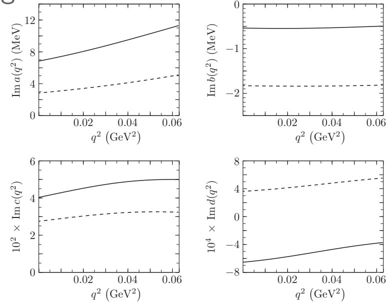
Connect to $(N\pi)^+ \to p\gamma^{(*)}$ rescattering via the optical theorem

This unitarity requirement can constrain the imaginary part

Invoke chiral perturbation theory (χPT)

Can either treat baryons as relativistic Dirac fields or heavy static sources

2-fold ambiguity emerges



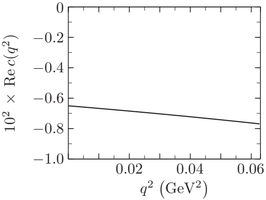
Real part

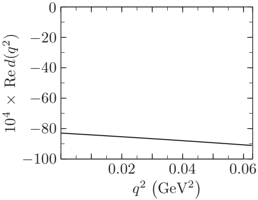
$$A_{\rm SM}^{\rm LD}(q^2,\cos\theta_{\mu^+\mu^-}) =$$
$$e^2 G_F\left\{\frac{-i}{q^2}\bar{u}_p[a(q^2)+\gamma_5 b(q^2)]\sigma^{\alpha\beta}q_\alpha u_\Sigma - \bar{u}_p\gamma^\beta[c(q^2)+\gamma_5 d(q^2)]u_\Sigma\right\}\bar{u}_\mu\gamma_\beta v_{\bar{\mu}}$$

Ideally, $c(q^2)$ and $d(q^2)$ determined by experiment

Not possible at this time

Calculate assuming vector-meson dominance





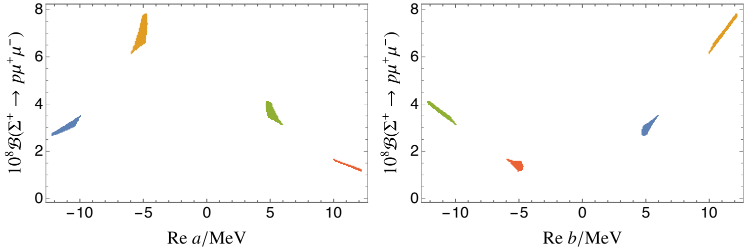
Real part

$$A_{\mathrm{SM}}^{\mathrm{LD}}(q^2, \cos\theta_{\mu^+\mu^-}) =$$
$$e^2 G_F \left\{ \frac{-i}{q^2} \bar{u}_p [a(q^2) + \gamma_5 b(q^2)] \sigma^{\alpha\beta} q_\alpha u_\Sigma - \bar{u}_p \gamma^\beta [c(q^2) + \gamma_5 d(q^2)] u_\Sigma \right\} \bar{u}_\mu \gamma_\beta v_{\bar{\mu}}$$

$a(q^2)$ and $b(q^2)$ associated with real intermediate photon
All form factors so far approximately constant in q^2
Calculation at $q^2 = 0$ should be fine
Can be determined from $\Sigma^+ \to p\gamma$ experimental results
BESIII: Phys. Rev. Lett. **130** (2023) 211901

$$\Gamma = \frac{G_F^2 e^2}{\pi} [a(0)^2 + b(0)^2] E_\gamma^3 \qquad \alpha = \frac{2\mathcal{R}e[a(0)b(0)^*]}{a(0)^2 + b(0)^2}$$

Additional 4-fold ambiguity

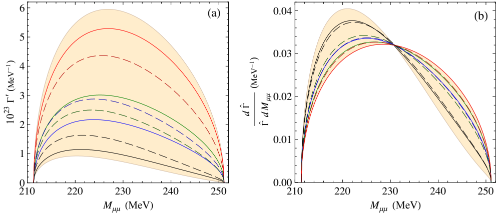


Standard model prediction

$$A_{\mathrm{SM}}^{\mathrm{LD}}(q^2, \cos\theta_{\mu^+\mu^-}) =$$

$$e^2 G_F \left\{ \frac{-i}{q^2} \bar{u}_p [a(q^2) + \gamma_5 b(q^2)] \sigma^{\alpha\beta} q_\alpha u_\Sigma - \bar{u}_p \gamma^\beta [c(q^2) + \gamma_5 d(q^2)] u_\Sigma \right\} \bar{u}_\mu \gamma_\beta v_{\bar{\mu}}$$

With all key components, integrate over phase space



Relativistic χPT

$\mathrm{Re}\, a$ (MeV)	$\mathrm{Re}\, b$ (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 χPT

$\mathrm{Re}\, a$ (MeV)	$\mathrm{Re}\, b$ (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

Setting $\mathcal{R}e(c) = \mathcal{R}e(d) = 0$ like a systematic uncertainty on theory side

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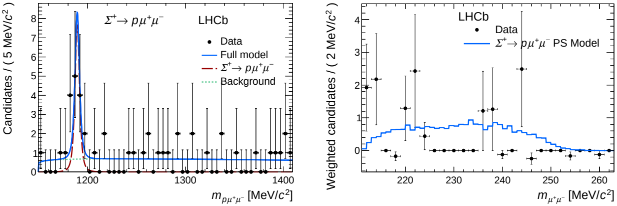
Previous measurement

Pilot analysis performed with $3\,\mathrm{fb}^{-1}$ of data taken from 2011-2012 (Run 1)

Phys. Rev. Lett. **120** (2018) 221803

No dedicated trigger



$N_{\Sigma^+\to p\mu^+\mu^-} = 10.2^{+3.9}_{-3.5}\ (4.1\sigma)$

Strongest evidence yet

Branching fraction consistent with SM prediction

$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (2.2^{+0.9+1.5}_{-0.8-1.1}) \times 10^{-8}$

Consistent with all SM predictions

No peaking structure found in dimuon mass

$\mathcal{B}(\Sigma^+ \to pX^0(\to \mu^+\mu^-)) < 1.4 \times 10^{-8}$ at 90% CL

HyperCP anomaly disfavoured

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Hyperons at LHCb

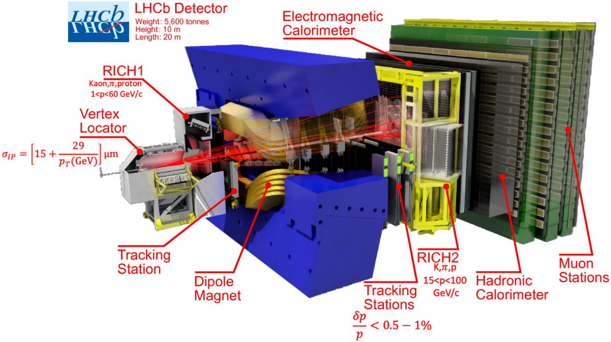
Large strange cross-section at LHC

Produced predominantly in the forward direction

- Ideal for LHCb acceptance (400 mrad)

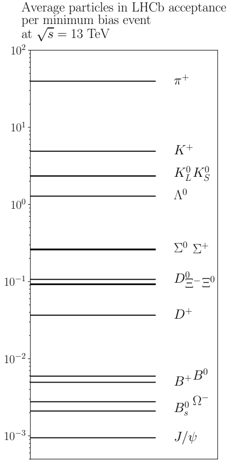
~ 1 strange hadron produced per collision

- *cf.* 10^{-3} for B_s^0 mesons

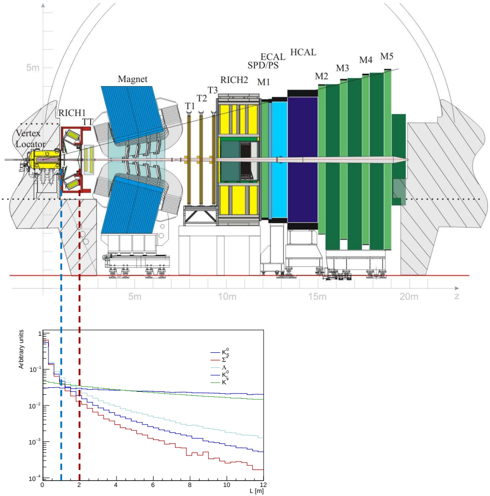


JINST 3 (2008) S08005, IJMPA 30 (2015) 1530022

JHEP **05** (2019) 048

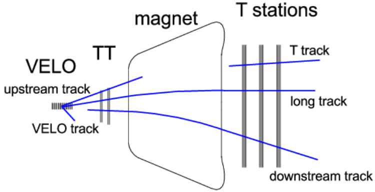


Lifetime acceptance for hyperons $\sim 50\%$



Two classes for final-state tracks

- "long"
- "downstream"



Run 1/2 efficiency limited

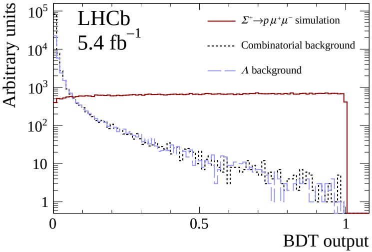
- Hardware trigger
- Muon/hadron trigger
  - $p_T > [1-5]$ GeV/c
  - Too hard for prompt hyperons

Run 2 improvement

- Soft-muon trigger

Event selection

- Analysis performed with $5.4\,\text{fb}^{-1}$ of data taken from 2016-2018 (Run 2)
- Dedicated trigger line for $\Sigma^+ \to p\mu^+\mu^-$ decays
- Measurement performed in 2 trigger categories
  - Triggered On Signal (TOS), Triggered Independently of Signal (TIS)
- Apply selection on proton and muon ID variables
- Background from $\Lambda \to p\pi^-$ and additional μ^+, π^- misidentified as μ^-
  - Apply $p\pi^-$ mass hypothesis and veto around known Λ mass
- Limited prospects for other peaking backgrounds to mimic signal
  - Small q-value, $q \equiv m_{\Sigma^+} - m_p - 2m_\mu = 39.78\,\text{MeV}/c^2$
- Combinatorial the main background otherwise
  - Suppress with Boosted Decision Tree (BDT), optimise for significance

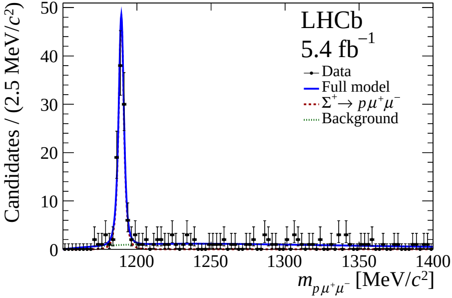


Σ^+-candidate mass fit

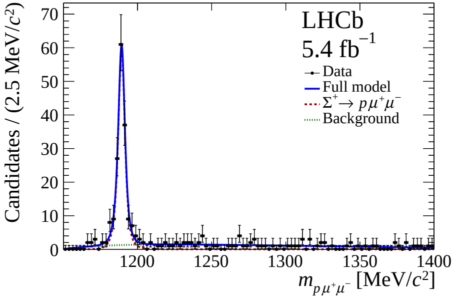
Branching fraction of $\Sigma^+ \to p\mu^+\mu^-$

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

TOS



TIS



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

More than 20 times the Run 1 yield

Overwhelming significance

First observation

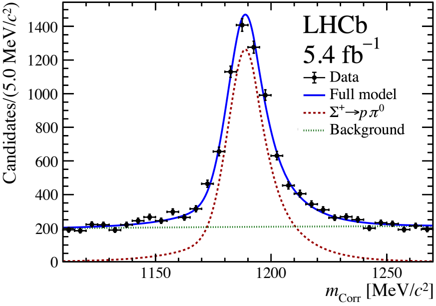
Normalisation channel

Most ideal choice, $\Sigma^+ \to p\pi^0(\to \gamma\gamma)$

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

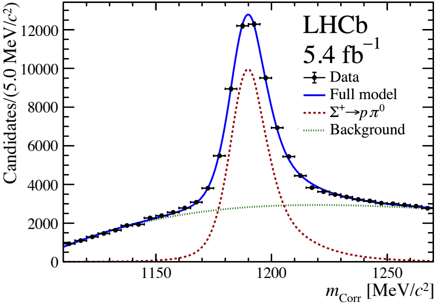
Model corrected mass, $m_{\text{Corr}} \equiv m_{p\gamma\gamma} - m_{\gamma\gamma} + m_{\pi^0}$

TOS



$N_{\Sigma^+\to p\pi^0} = (6.13 \pm 0.10) \times 10^3$

TIS



$N_{\Sigma^+\to p\pi^0} = (4.746 \pm 0.031) \times 10^4$

Efficiencies

Branching fraction of $\Sigma^+ \to p\mu^+\mu^-$

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

Efficiency of 2-body normalisation channel is straightforward

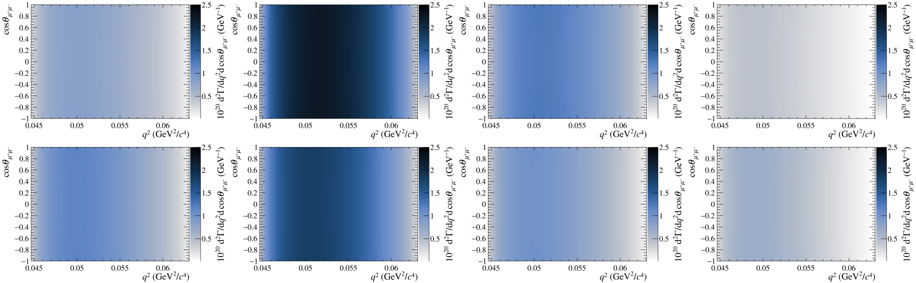
Efficiency of 3-body signal channel not so much

Simulation generated with flat phase-space model

Inclusive efficiency integrated over phase space

Needs to be weighted by physics model, but there are 8 of them

Limited choice, spread is the systematic error, $\delta\varepsilon_{\Sigma^+\to p\mu^+\mu^-} \sim 2.5\%$



Results

Rarest baryon decay ever observed

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

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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Consistent with RB4

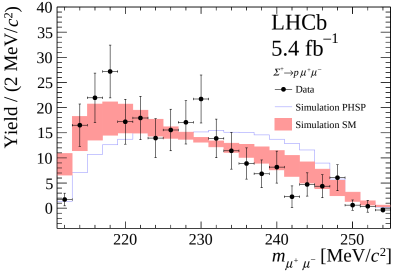
RB1 disfavoured by 3.7σ

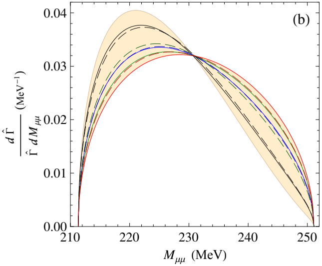
RB2 & RB3 rejected at 6.1σ

HB disfavoured by minimum of 3.1σ

RB4 qualitatively matches differential

HyperCP X^0 definitively excluded





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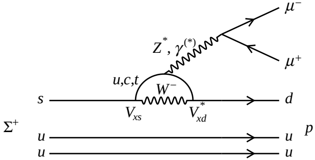
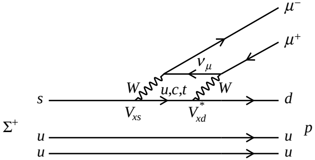
Short-distance contribution

With the SM confirmed, attention turns to BSM physics

HyperCP anomaly finished, more detailed searches needed

BSM physics expected to manifest in short-distance amplitude





$$
\begin{aligned}
A^{\mathrm{SD}}_{\mathrm{SM}}(q^2, \cos\theta_{\mu^+\mu^-}) = \\
&\frac{G_F}{\sqrt{2}}\Big\{ -\bar{u}_p\gamma^\beta[1+\gamma_5(D-F)]u_\Sigma\bar{u}_\mu\gamma_\beta(\lambda_u z_{7V} - \lambda_t y_{7V} - \gamma_5\lambda_t y_{7A})v_{\bar{\mu}} \\
&\quad + 2(D-F)\frac{m_\Sigma + m_p}{q^2 - m^2_{K^0}}\lambda_t y_{7A} m_\mu \bar{u}_p\gamma_5 u_\Sigma \bar{u}_\mu \gamma_5 v_{\bar{\mu}} \\
&\quad - \frac{i\alpha_e C_{7\gamma} m_s}{2\pi q^2} c_\sigma \bar{u}_p \sigma^{\alpha\beta}(1+\gamma_5)u_\Sigma q_\alpha \bar{u}_\mu \gamma_\beta v_{\bar{\mu}} \Big\}
\end{aligned}
$$

$\mathcal{B}^{\mathrm{SD}}_{\mathrm{SM}}(\Sigma^+ \to p\mu^+\mu^-) \sim \mathcal{O}(10^{-12})$, *cf.* $\mathcal{B}^{\mathrm{LD}}_{\mathrm{SM}}(\Sigma^+ \to p\mu^+\mu^-) \sim \mathcal{O}(10^{-8})$

However, high statistics facilitates exploration of differential quantities

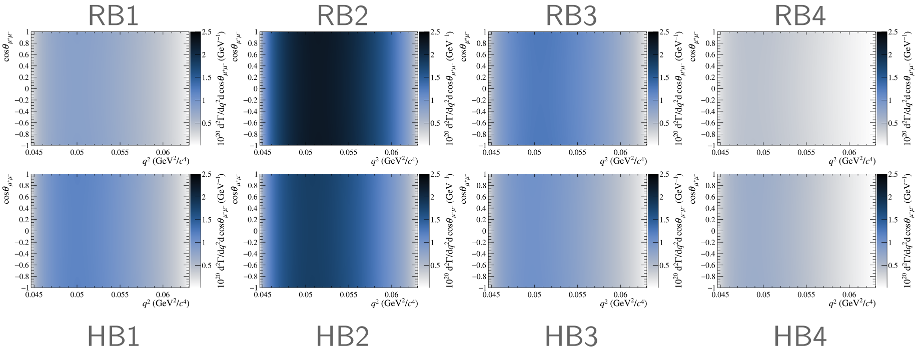
- Emergence of BSM may be more pronounced depending on phase-space region

CP-conserving observables

Experimentally measure double-differential decay rate

$$
\begin{aligned}
\frac{\mathrm{d}^2\Gamma(\Sigma^+ \to p\mu^+\mu^-)}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_{\mu^+\mu^-}} \propto & \left|A_{\mathrm{SM}}^{\mathrm{LD}}(q^2, \cos\theta_{\mu^+\mu^-}) + A_{\mathrm{SM}}^{\mathrm{SD}}(q^2, \cos\theta_{\mu^+\mu^-})\right|^2 \\
= & \left[\frac{3}{8}(1+\cos^2\theta_{\mu^+\mu^-})(1-f_L) + A_{\mathrm{FB}}\cos\theta_{\mu^+\mu^-} + \frac{3}{4} f_L \sin^2\theta_{\mu^+\mu^-}\right] \times \\
& \frac{\mathrm{d}\Gamma(\Sigma^+ \to p\mu^+\mu^-)}{\mathrm{d}q^2}
\end{aligned}
$$

Compare with theory prediction



CP-conserving observables

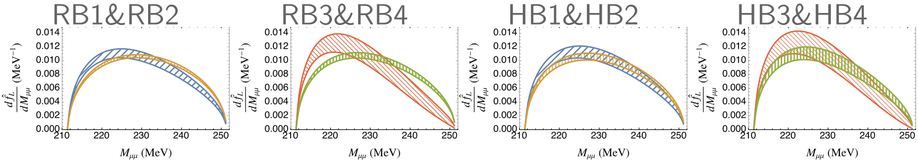
f_L: fraction of longitudinal polarisation

A_{FB}: forward-backward asymmetry

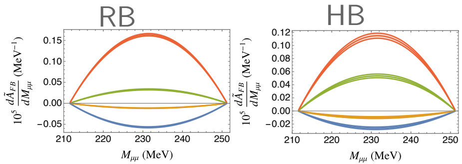
In principle, f_L and A_{FB} are functions of q^2

Will need to measure each in bins of q^2

A chance f_L structure could be visible one day



A_{FB} probably invisible though

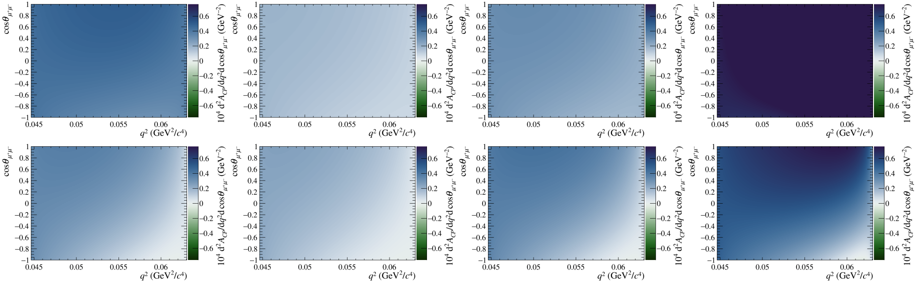


CP-violating observables

No SM prediction yet, apparently being worked on

Model implemented for Run 2 analysis, CP-conjugate all CKM elements

RB1 RB2 RB3 RB4



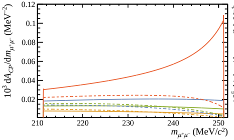
HB1 HB2 HB3 HB4

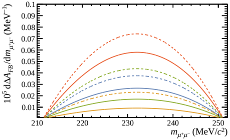
$\mathrm{d}\mathcal{A}_{CP}/\mathrm{d}q^2$

Red most likely

1% at high q^2

No events





$\mathrm{d}\Delta A_{\mathrm{FB}}/\mathrm{d}q^2$

Too small

Summary

LHCb collaboration
Observation of the very rare $\Sigma^+ \to p\mu^+\mu^-$ decay
Phys. Rev. Lett. **135** (2025) 051801