Evidence for the $\Sigma^+ \to p\mu^+\mu^-$ decay at LHCb

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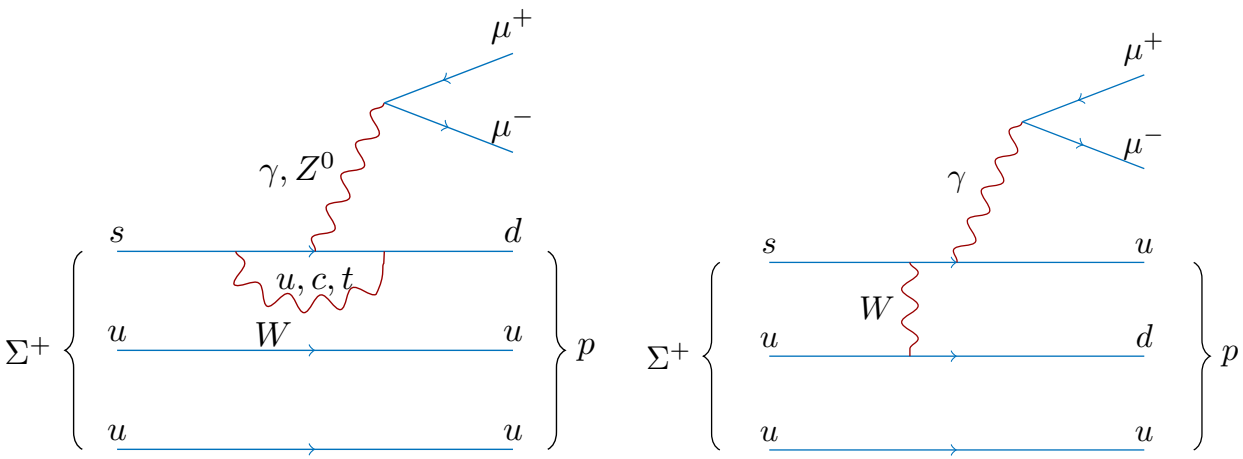
Introduction

$\Sigma^+ \to p\mu^+\mu^-$ in the Standard Model

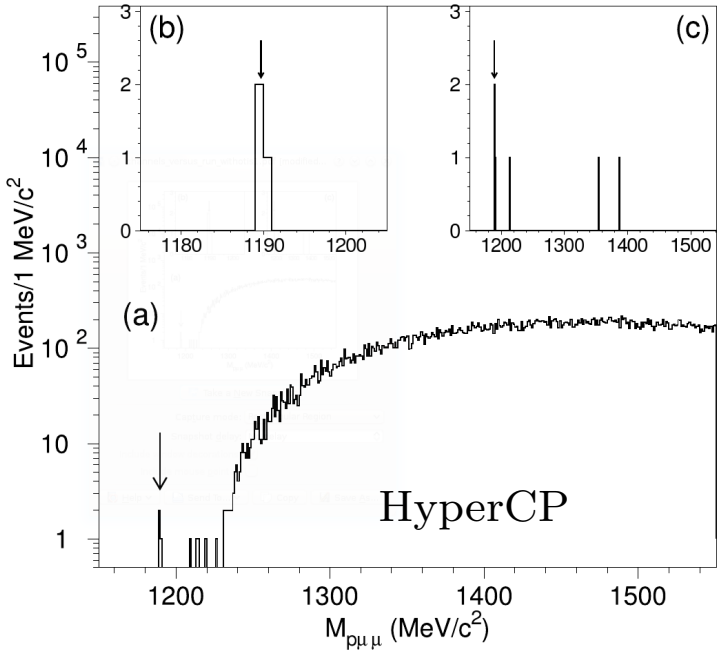
- $\Sigma^+ \to p\mu^+\mu^-$ is a very rare FCNC
- Short distance SM branching fraction is $O(10^{-12})$
- Dominated by long distance contributions:
  $1.2 \cdot 10^{-8} < \mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) < 10.2 \cdot 10^{-8}$

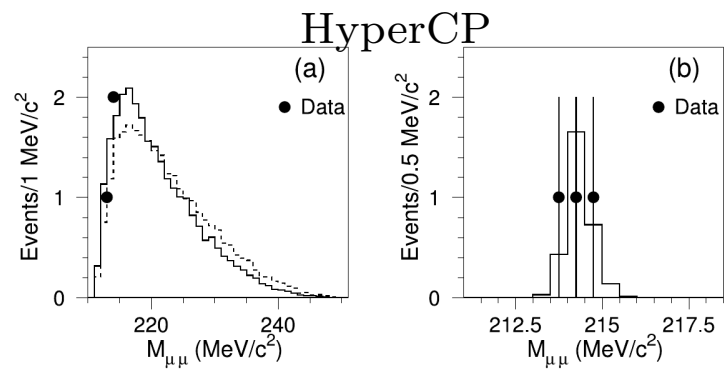
[Xiao-Gang He et al. - Phys.Rev. D72 (2005) 074003] [Xiao-Gang He et al. - JHEP 1810 (2018) 040]



The HyperCP anomaly

- Evidence found by the HyperCP experiment with 3 events in absence of background
- Measured branching fraction:
  $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \cdot 10^{-8}$
  [Phys.Rev.Lett. 94 (2005) 021801]
- All the **3** observed signal events have the same dimuon invariant mass: pointing towards a $\Sigma^+ \to pX^0(\to \mu\mu)$ decay
  with $m_{X^0} = 214.3 \pm 0.5$ MeV
  $\mathcal{B}(\Sigma^+ \to pX^0(\to \mu\mu)) = (3.1^{+2.4}_{-1.9} \pm 5.5) \cdot 10^{-8}$





Theoretical interpretations and experimental tests before LHCb

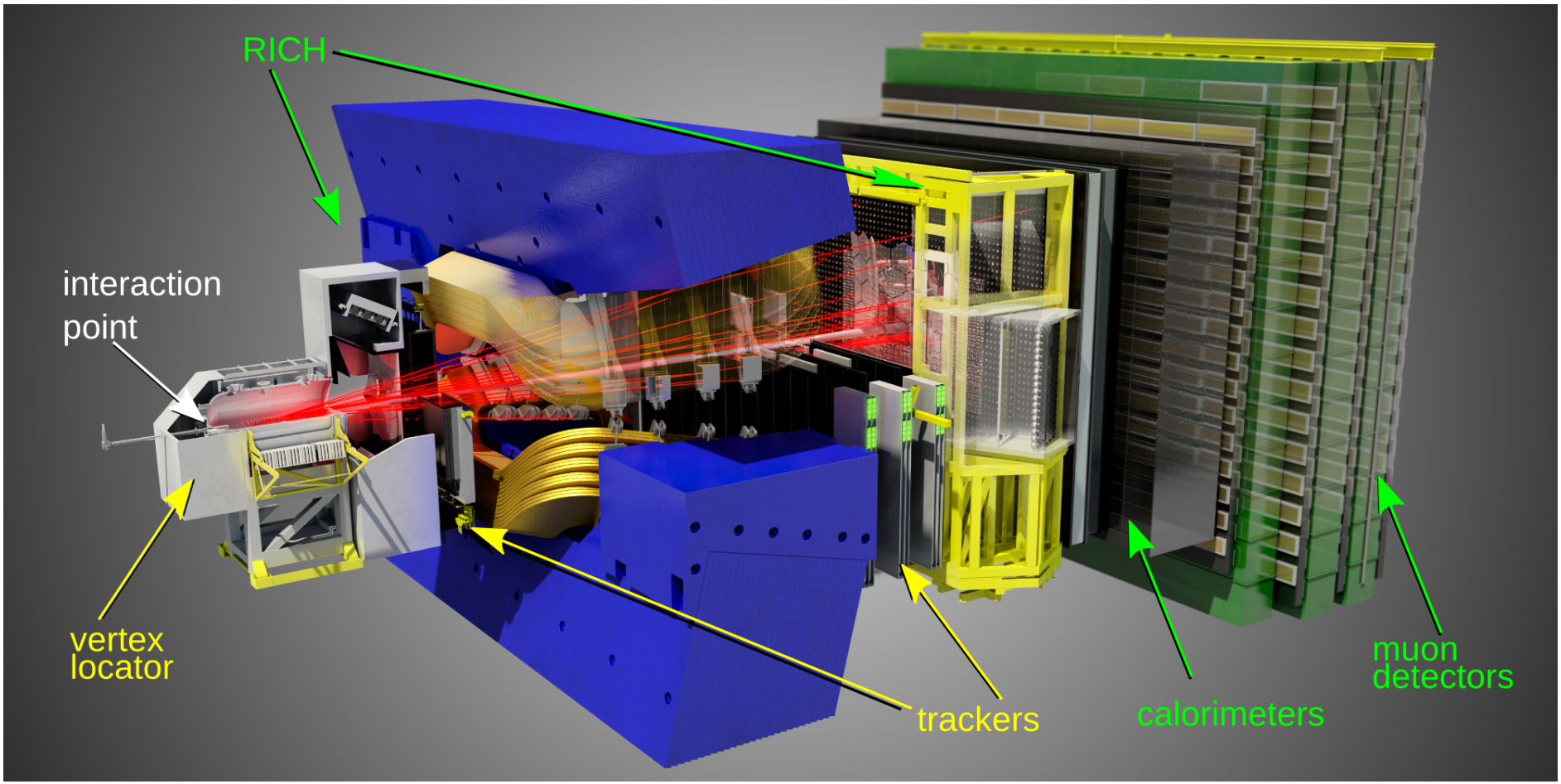
- Several interpretations were proposed
  - ⋆ Light Higgs boson [He, Tandean Valencia, PRL.98.081802 (2007)]
  - ⋆ Sgoldstino [Gorbunov, Rubakov PRD 73 035002]
  - ⋆ Many others
  - ⋆ In general pseudoscalar favoured over scalar and lifetime of order 10^{-14}s
- Many experimental searches for low mass resonances in dimuons:
  - ⋆ CLEO, E391a, D0, BaBar, Belle, KTeV, BESIII
  - ⋆ Searched also at LHCb in $B^0 \to \mu^+\mu^-\mu^+\mu^-$ and $B^0 \to K^{*0}\mu^+\mu^-$
  - ⋆ X^0 particle not confirmed
- No other search for $\Sigma^+ \to p\mu^+\mu^-$ decays

Search for $\Sigma^+ \to p\mu^+\mu^-$ at LHCb

PRL 120, 221803 - arXiv:1712.08606

- Based on full Run 1 data: 3 fb^{-1}
- Presented preliminary results at KAON2016 (LHCb-CONF-2016-013)
- Since then: added branching fraction measurement
- Slightly different working point: tighter PID and Λ veto, and looser BDT cut, following PRL review requests
- Detailed scan of the $m_{\mu^+\mu^-}$ invariant mass and limit on "HyperCP-like" signal

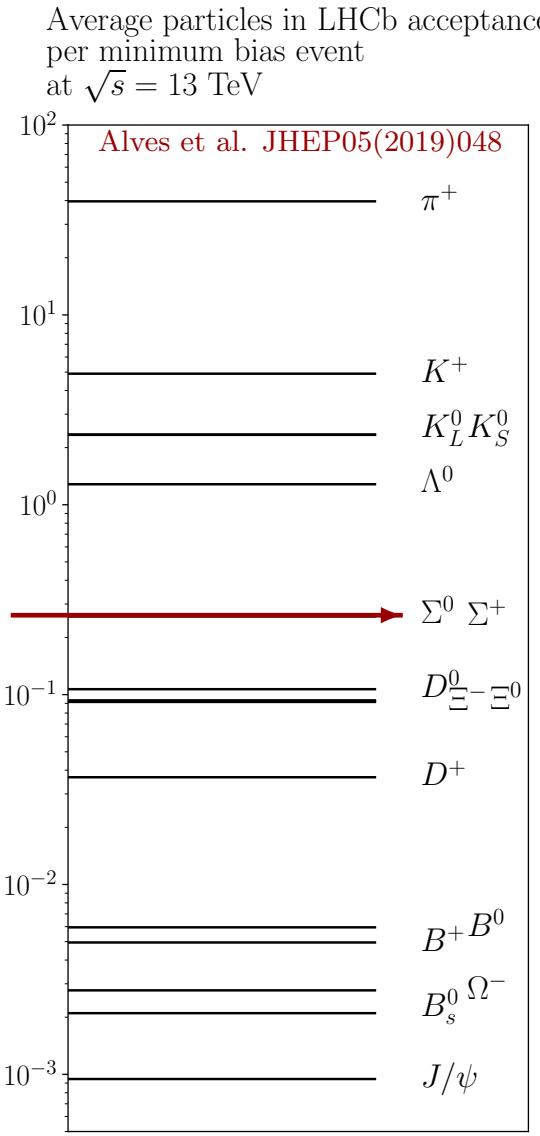
LHCb experiment



[Int. J. Mod. Phys. A 30, 1530022 (2015)]

Introduction: production at the LHC

- Huge production of Σ^+ hyperons
- About 1 in 10 min bias events has one in acceptance (compared to $\sim 10^{-3}$ B_s^0 mesons)
- Reconstruction and trigger however bring this number down



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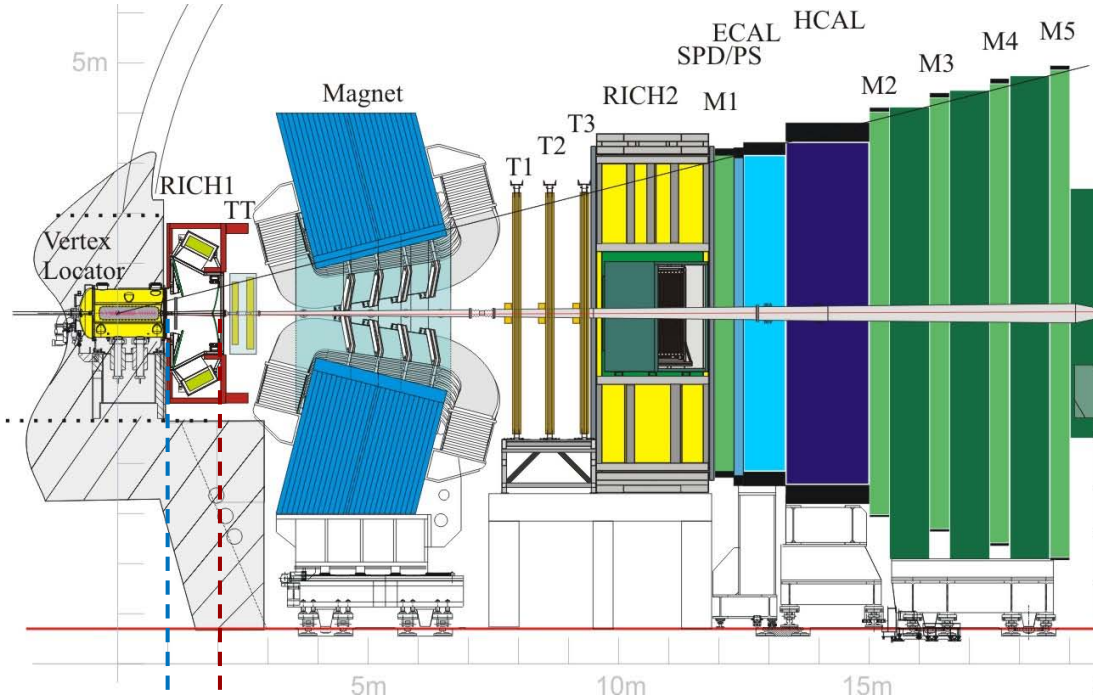
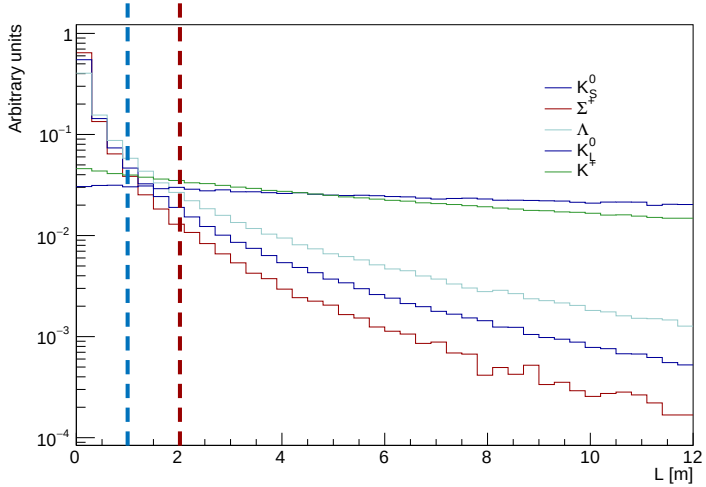
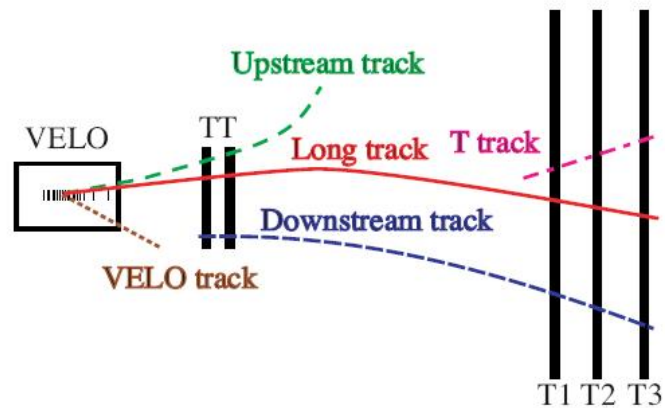
Introduction: setting the (long) stage

Reconstruction





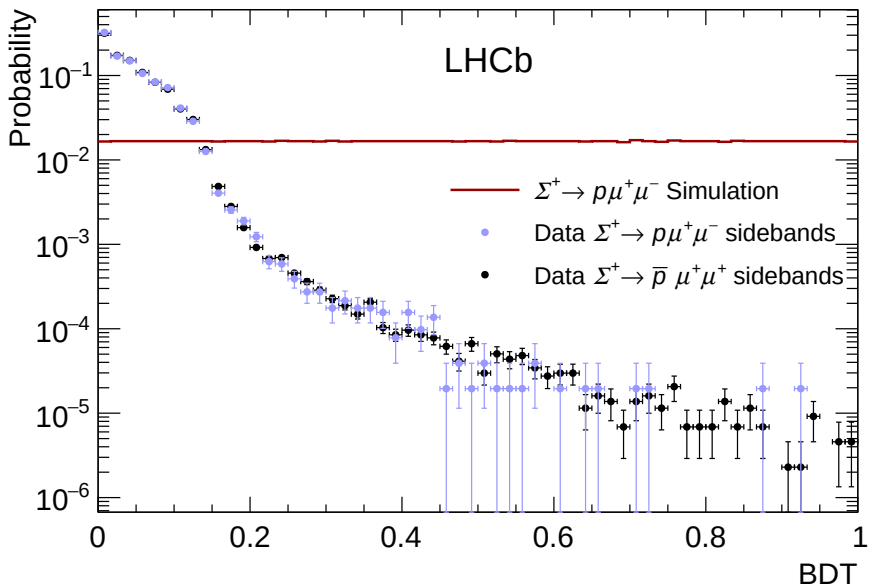
- Large lifetimes for LHCb... but the peak of an exponential is at zero!
- Different reconstruction methods for the daughter tracks



General analysis strategy

Sample and selection:

- Search with 3 fb^{-1} (full Run 1)
- Prompt decays (no displacement of the dimuon pair)
- Soft pre-selection to reduce dataset
- Cut on BDT and PID to remove most of the background
- Explicit veto of $\Lambda \to p\pi$ background, no other peaking background contributes



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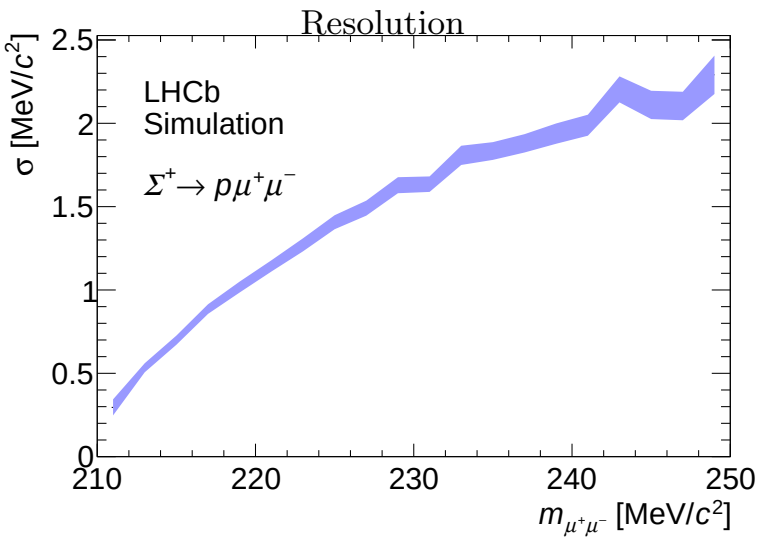
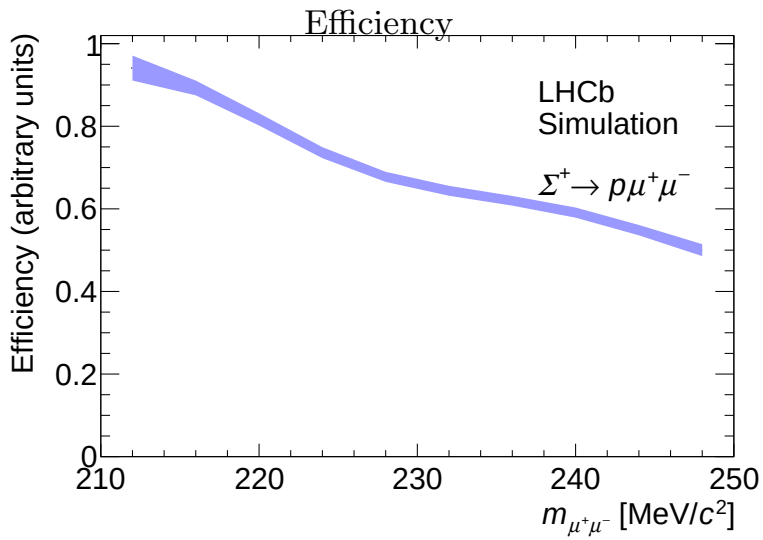
Search for an Hyper-CP like signal

- Hyper-CP signal is consistent with $\Sigma^+ \to pX^0(\to \mu\mu)$, with $m_{X^0} = 214.3 \pm 0.5$ MeV
- Mass resolution in LHCb:
  - ⋆ Raises with $m_{\mu^+\mu^-}$ departing from threshold
- Study efficiency versus $m_{\mu^+\mu^-}$: higher efficiency at small mass due to higher minimum p_T





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Normalisation

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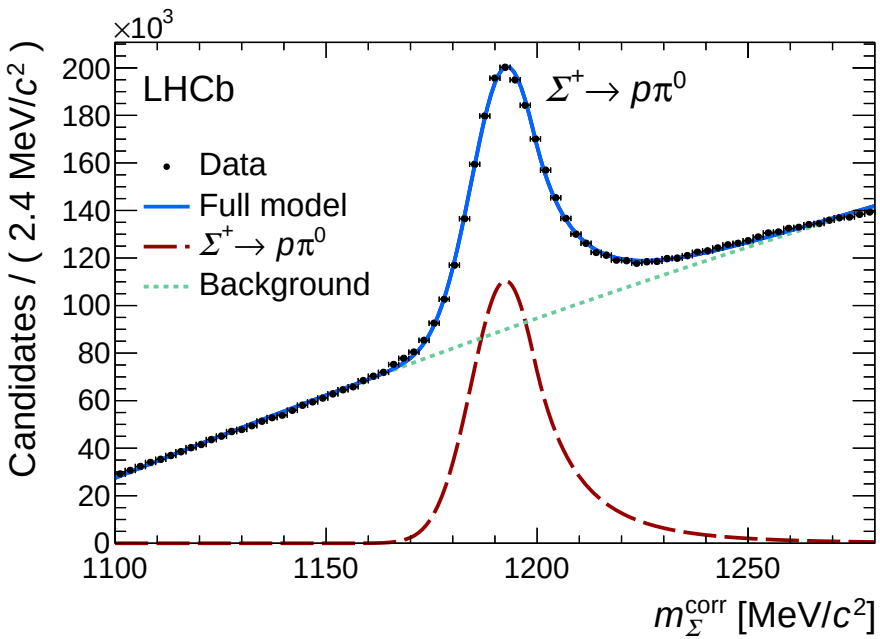
- No fully charged final state available in the Σ^+ to normalize
- Use high branching fraction $\Sigma^+ \to p\pi^0$ ($\mathcal{B} = (51.57 \pm 0.30)\%$)
- Trigger strategy: use all the events for signal and TIS-only for normalisation channel

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

Estimate of the $\Sigma^+ \to p\pi^0$ yield

- Selection for $\Sigma^+ \to p\pi^0$ with $\pi^0 \to \gamma\gamma$ (resolved clusters) from calorimeter
- $\Sigma^+ \to p\pi^0$ described as Crystal Ball function
- Background as modified Argus function
- Observed $(1171 \pm 9) \times 10^3$ candidates



Corrected mass:

$$m_\Sigma^{\text{corr}} = m_{p\gamma\gamma} - m_{\gamma\gamma} + m_{\pi^0}$$

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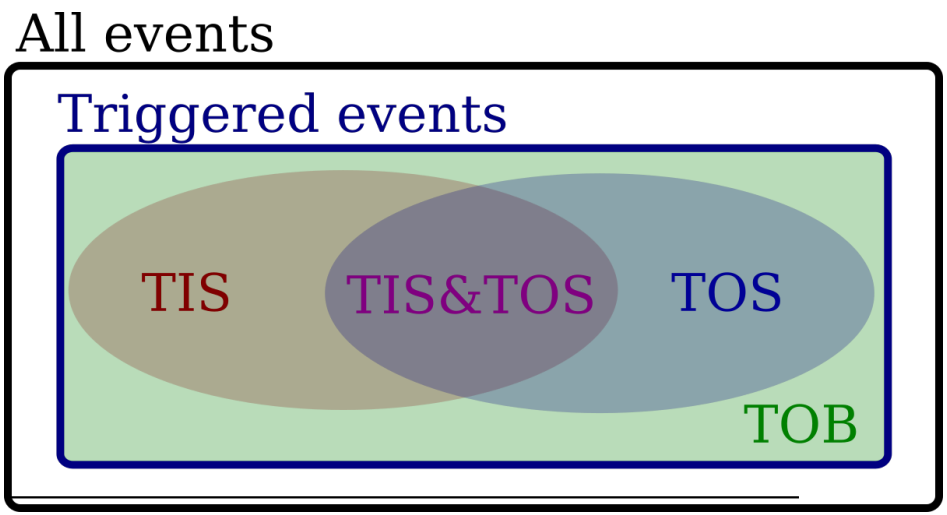
Normalisation: trigger efficiency ratio calibration

- Signal trigger efficiency measured on simulation
- Data / simulation differences calibrated with control channel using TISTOS method*
- Triggered events can be
  - Triggered On the Signal (TOS): signal is sufficient to trigger
  - Triggered Independently of the Signal (TIS): signal is not necessary to trigger
  - Triggered on both (!TIS&!TOS): measure efficiencies from this overlap
- Large fraction of TIS events: common efficiency between signal and calibration
- Calibration versus multiplicity
- Large systematic uncertainty



*Tolk, S et al. LHCb-PUB-2014-039

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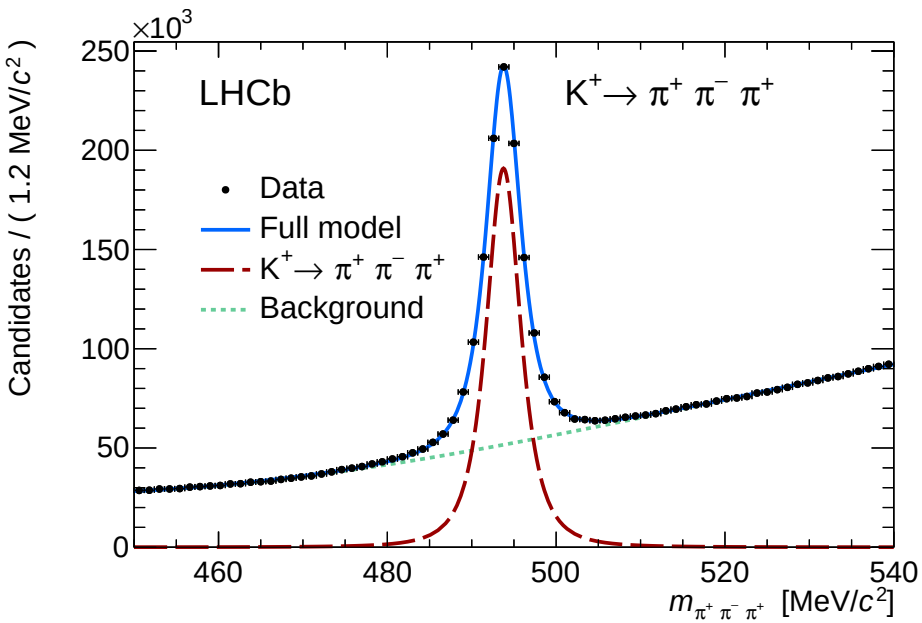
Normalisation: calibration and systematics

- Reconstruction of the π^0 calibrated with ratio of ratio of $B^+ \to J/\psi K^{*+}$ and $B^+ \to J/\psi K^+$ decays reconstructed in data.
- Muon and proton PID calibrated with control channels in data ($\Lambda \to p\pi^-$ and J/ψ): large uncertainty for soft momenta
- BDT operator calibrated with $K^+ \to \pi^+\pi^-\pi^+$ channel in data
- Signal invariant mass distribution: calibrated with $K^+ \to \pi^+\pi^-\pi^+$ in data



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Normalisation

- For full Run 1 dataset, single event sensitivity $\alpha = (2.2 \pm 1.2) \times 10^{-9}$
- Correspondent to 23 ± 20 expected events with a typical SM BR $((5 \pm 4) \times 10^{-8})$

Source	Uncertainty
Selection efficiency	1%
BDT efficiency	6%
PID efficiency ratio	28%
π^0 efficiency	10%
Trigger efficiency ratio	40%
Total	50%

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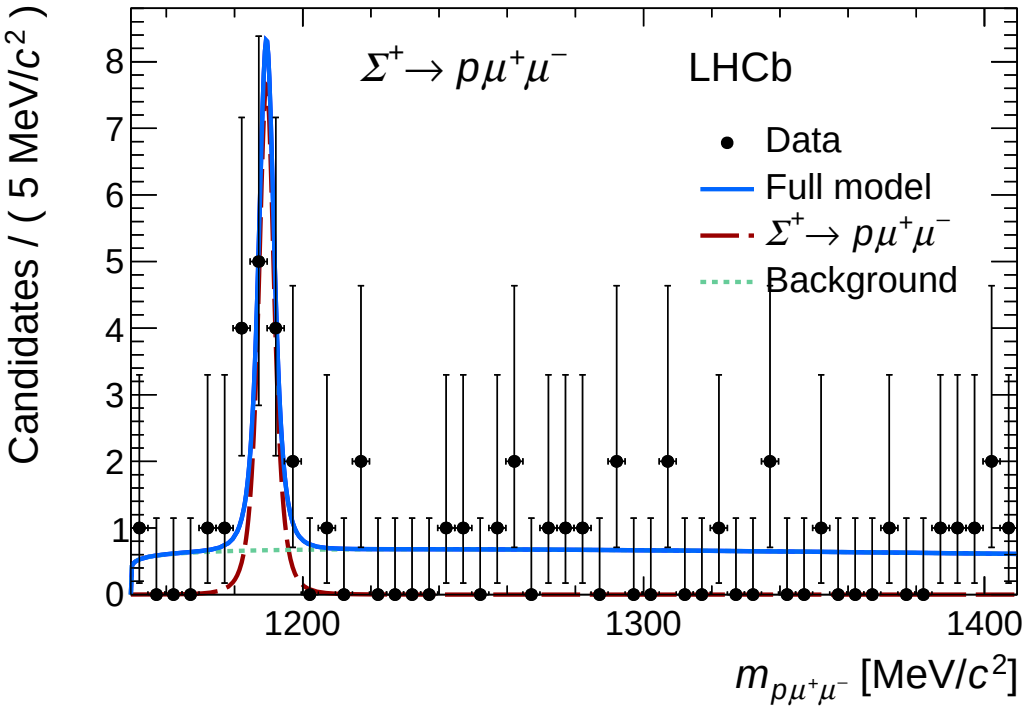
Results



Fit to $m_{p\mu^+\mu^-}$ distribution

- Hypathia function for the signal
- Modified ARGUS for background

- Excess of events w.r.t. background with a significance of $4.1\,\sigma$
- Fitted signal yield: $10.2\,^{+\,3.9}_{-\,3.5}$
- Measured branching fraction $(2.2\,^{+\,0.9\,+\,1.5}_{-\,0.8\,-\,1.1}) \times 10^{-8}$

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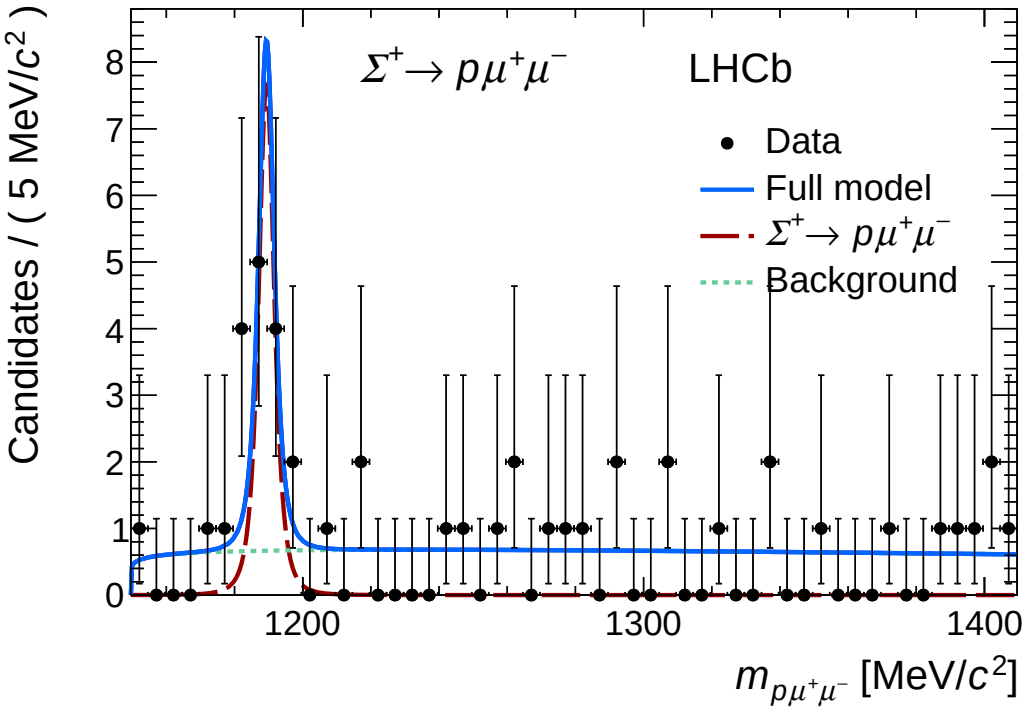
Results



Crosschecks:

- Fit repeated with tighter or looser BDT and PID cuts: signal vary consistently with signal efficiency
- Fit repeated assuming a linear function for the background, yield and significance are stable
- Candidate in final sample are about 52%/48% $\Sigma/\bar{\Sigma}$

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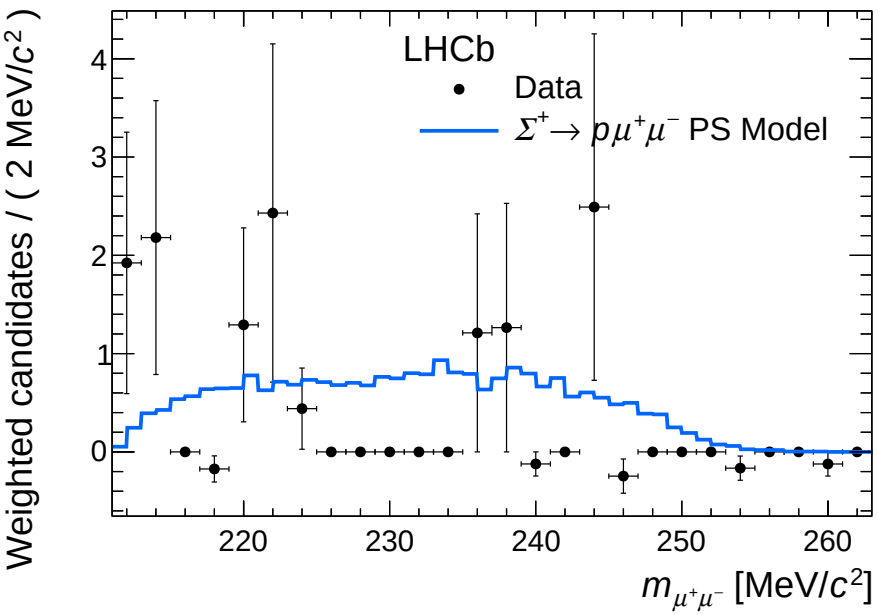
Search for an HyperCP-like signal

- Fit to $m_{p\mu^+\mu^-}$ repeated restricting the sample to events within 1.5 times the resolution from the putative particle ($m_{\mu^+\mu^-} \in [214.3 \pm 0.75]\text{MeV}/c^2$).
- No significant signal is found and a yield of $3.0\,^{+1.7}_{-1.4}$ is measured
- An upper limit on the branching fraction of the resonant channel is thus set with the CLS method
  $\mathcal{B}(\Sigma^+ \to pX^0(\to \mu^+\mu^-)) < 1.4 \times 10^{-8}$ at 90%CL
  excluding the HyperCP result (3.1×10^{-8})
- S-weighted background subtracted $m_{\mu^+\mu^-}$ distribution:



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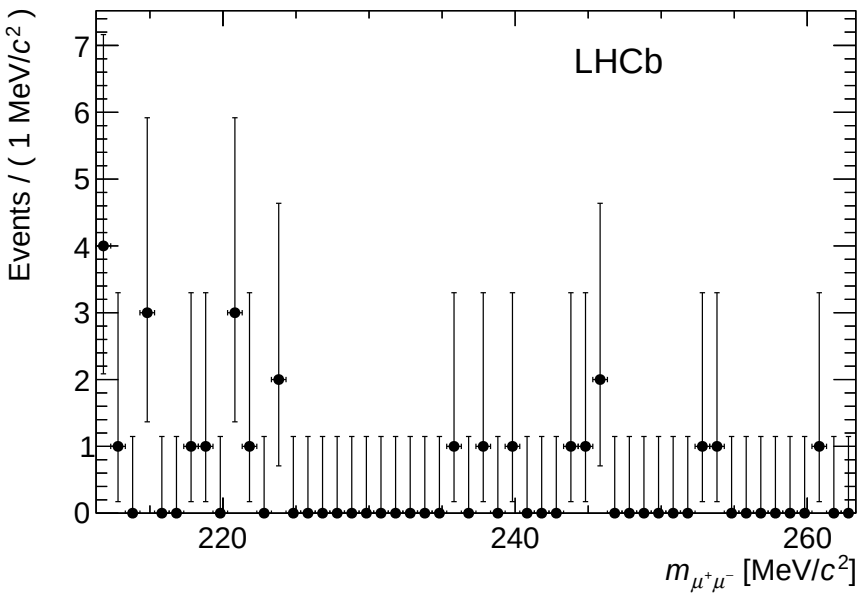
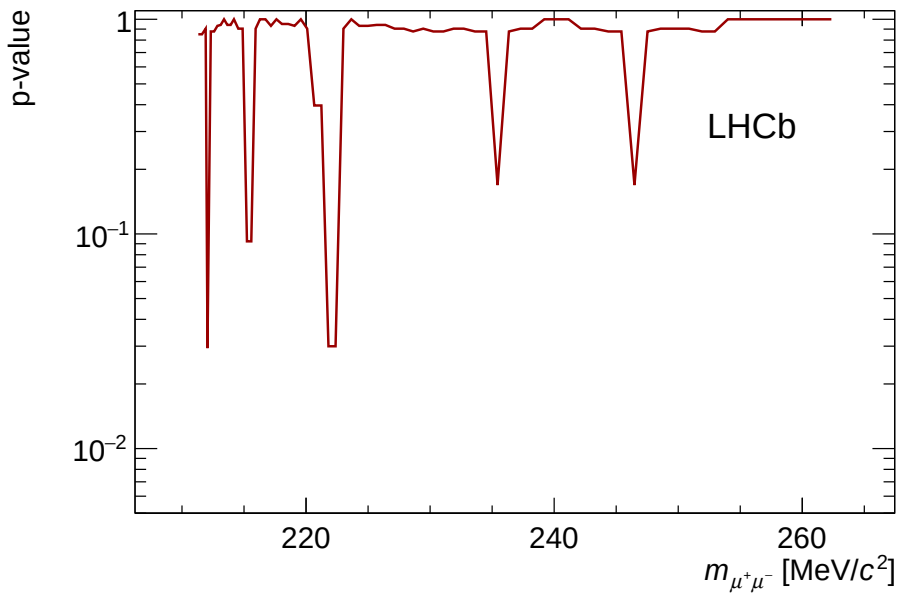
Scan of the invariant mass distribution

- Consider events within $2\sigma_{p\mu\mu}$, search for peaks in $m_{\mu^+\mu^-}$
- Scan in steps of half the resolution on $\sigma(m_{\mu^+\mu^-})$ †
- Putative signal is estimated in a window of $\pm 1.5 \times \sigma(m_{\mu^+\mu^-})$
- Background from the sidebands
- Local p-values does not show any significant signal





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†Following the method outlined in
M. Williams, J. Instrum. 10, P06002 (2015).

Prospects with Run 2

- Dedicated HLT1 and HLT2 triggers implemented in Run 2: factor 10 improvement in efficiency
- Additional factor 10 in statistics (lumi and cross-section)
- LHCb can observe and measure with good precision the $\Sigma^+ \to p\mu^+\mu^-$ branching fraction with Run 2
- Additional observables might become available [Xiao-Gang He et al. - JHEP 1810 (2018) 040]
  - ⋆ Forward backward asymmetry
  - ⋆ Differential branching fraction
  - ⋆ Direct CP violation: first time in Σ baryons!
- Upgrade data will move this to a precision observable rather than a search

Conclusions

- LHCb first in testing HyperCP-anomaly on $\Sigma^+ \to p\mu^+\mu^-$
- Improved results with respect to preliminary:
  - Strong evidence for the $\Sigma^+ \to p\mu^+\mu^-$ decay
  - Measurement of branching fraction
  - No peak in the dimuon mass distribution
  - Upper limit excluding HyperCP result
- Prospect for Run 2 include possible observation and new observables

Exciting times are ahead!

Backup