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

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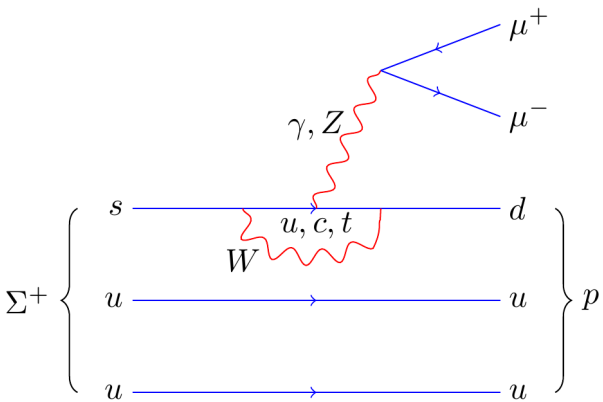
Introduction

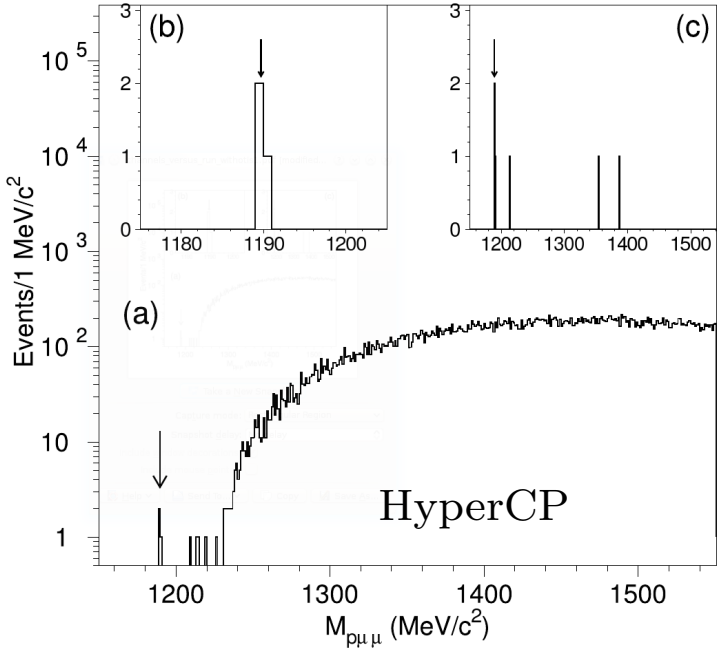
$\Sigma^+ \to p\mu^+\mu^-$ in the Standard Model

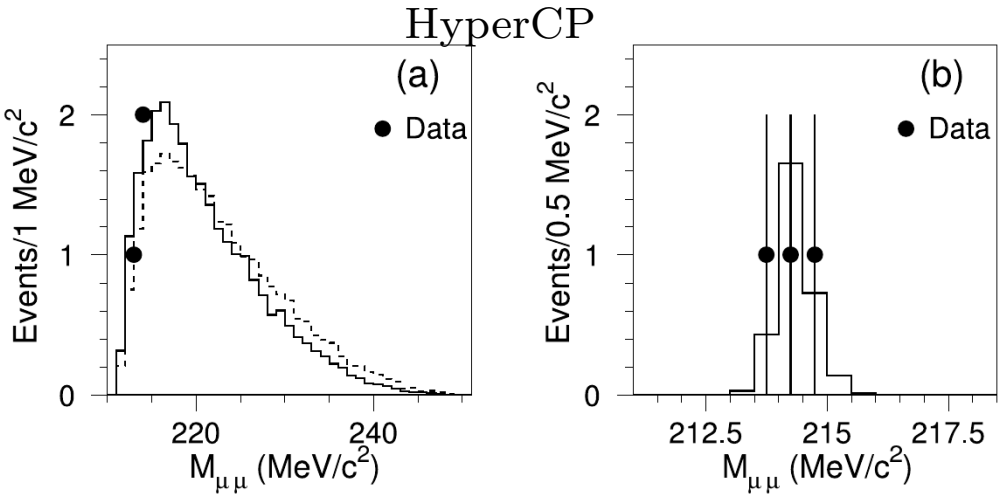
- $\Sigma^+ \to p\mu^+\mu^-$ is a very rare FCNC
- Short distance SM branching fraction is $O(10^{-12})$
- Dominated by long distance contributions:
  $1.6 \cdot 10^{-8} < \mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) < 9.0 \cdot 10^{-8}$ [He et al. - Phys.Rev. D72 (2005) 074003]



The HyperCP evidence

- An evidence for this decay was found by the HyperCP experiment with 3 events in absence of background
- Measured branching fraction is:
  $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \cdot 10^{-8}$
  [Phys.Rev.Lett. 94 (2005) 021801]
- This evidence had wide relevance since all the **3** observed signal events have the same dimuon invariant mass: pointing towards a
  $\Sigma^+ \to pX^0(\to \mu\mu)$ decay
  $\mathcal{B}(\Sigma^+ \to pX^0(\to \mu\mu)) = (3.1^{+2.4}_{-1.9} \pm 5.5) \cdot 10^{-8}$

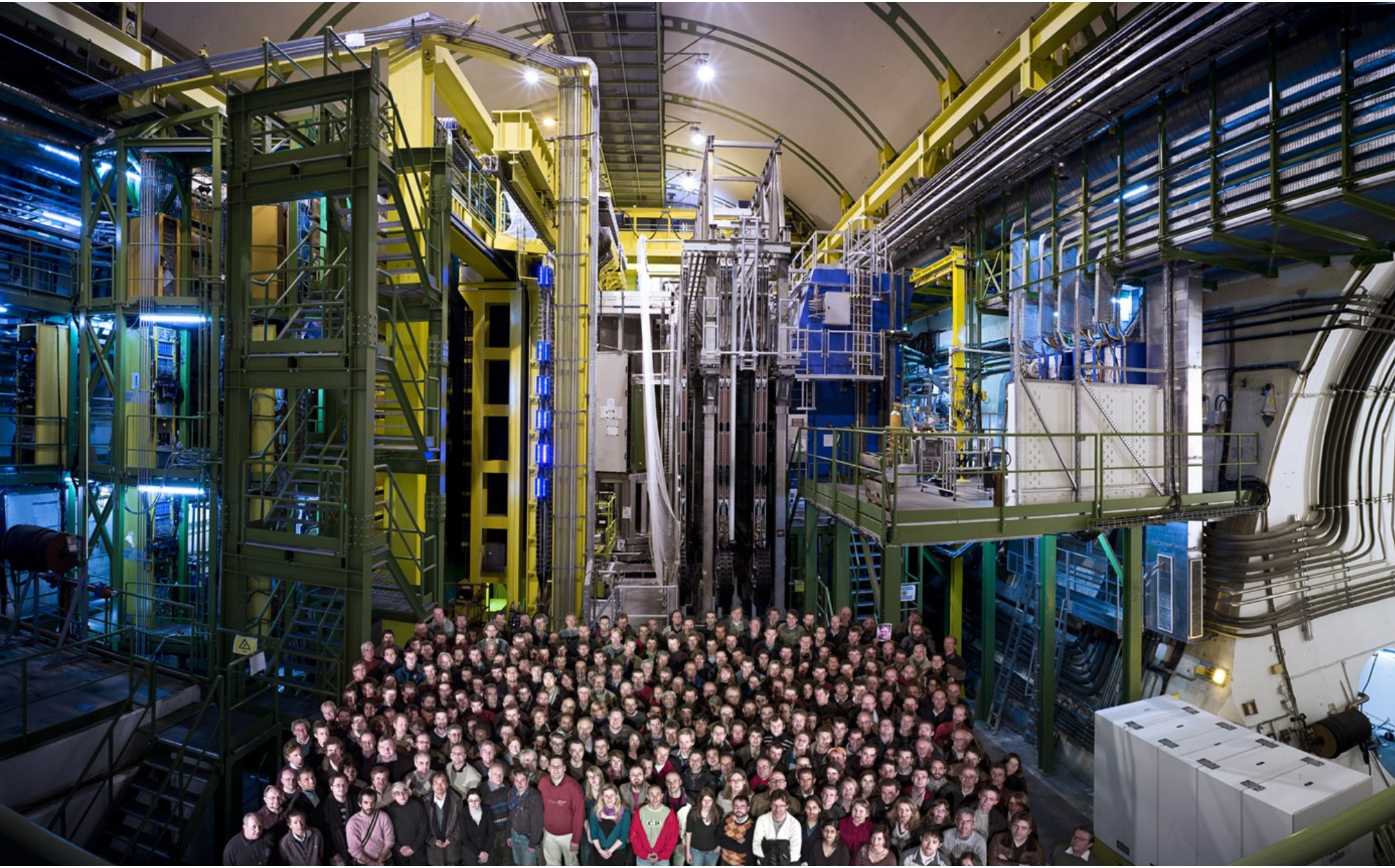




Theoretical interpretations and experimental status

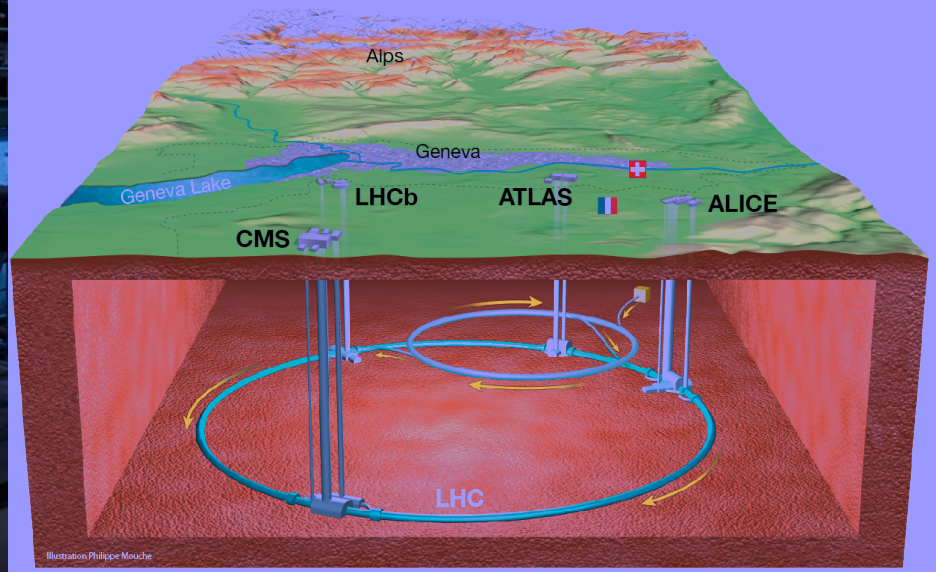
- Several interpretations were proposed
  - ⋆ Light Higgs boson [He, Tandean Valencia, PRL.98.081802 (2007)]
  - ⋆ Sgoldstino [Gorbunov, Rubakov PRD 73 035002]
  - ⋆ Many others
  - ⋆ In general pseudoscalar favoured over scalar and lifetime of order 10^{-14}s
- Many experimental searches for low mass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

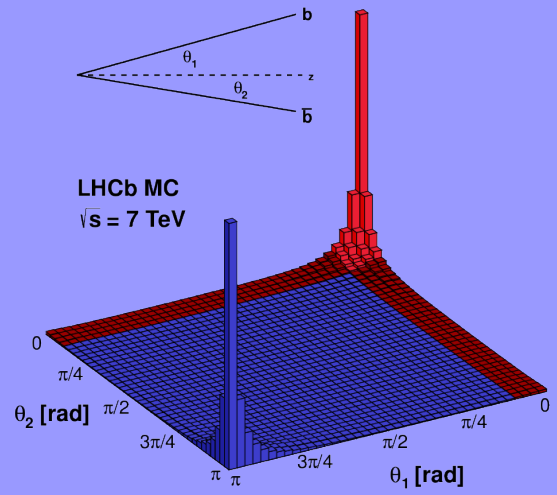
LHCb experiment



LHCb experiment

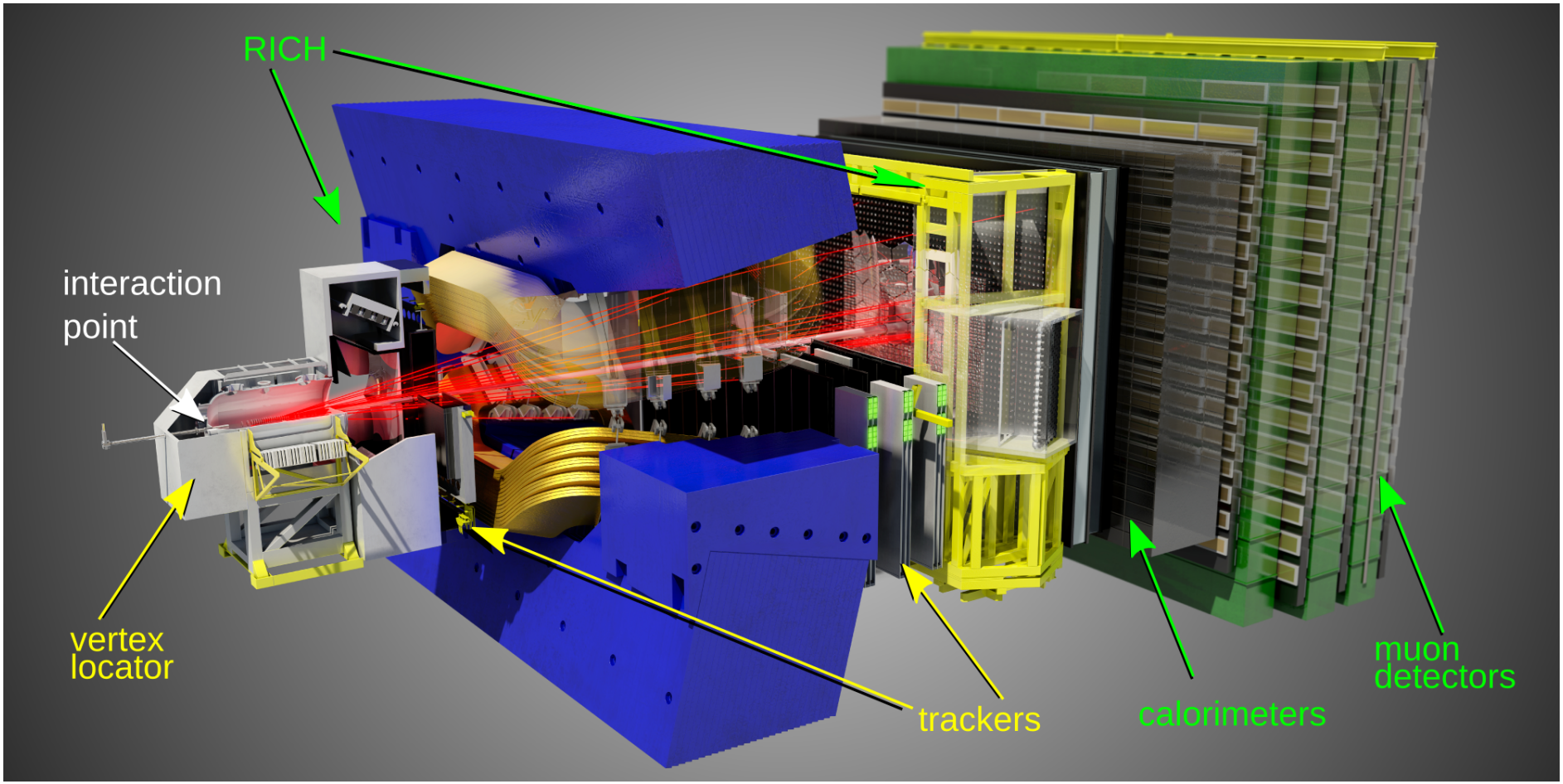
- 1075 members, from 68 institutes in 17 countries (September 2014)
- Dedicated experiment for precision measurements of CP violation and rare decays
- *Beautiful*, *charming*, *strange* physics program





- pp collisions at $\sqrt{s} = 7, 8(13)$ TeV in RunI (RunII)
- $b\bar{b}$ quark pairs produced correlated in the forward region
- Luminosity of $4 \times 10^{32} cm^{-2} s^{-1}$

LHCb detector



Excellent vertex and IP resolution

- $\sigma(IP) \simeq 24\mu$m at $p_{\mathrm{T}} = 2$ GeV/c
- $\sigma_{\mathrm{BV}} \simeq 16\mu$m in x, y

Very good momentum resolution

- $\sigma(p)/p = 0.4\% - 0.6\%$ for $p \in (0, 100)$ GeV/c
- $\sigma(m_B) \sim 24$ MeV for two body decays

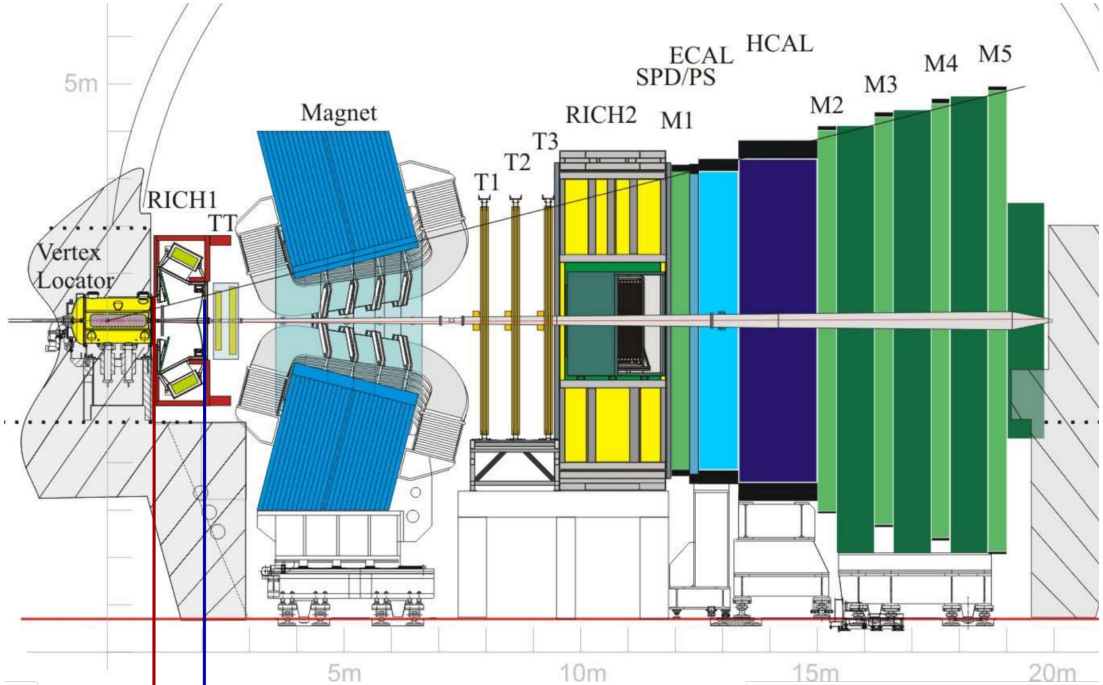
Muon identification

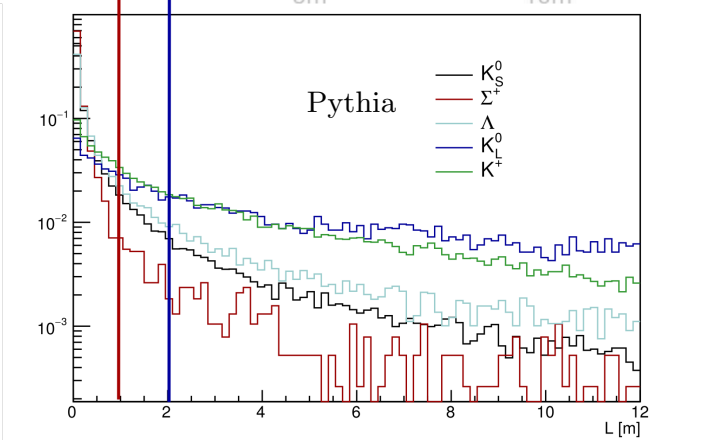
- $\varepsilon_\mu = 98\%$, $\varepsilon_{\pi\to\mu} = 0.6\%$, $\varepsilon_{K\to\mu} = 0.3\%$, $\varepsilon_{p\to\mu} = 0.3\%$

Trigger

- $\varepsilon_\mu = 90\%$

Setting the (long) stage





- Huge strange hadrons production cross-section at LHCb
- Large lifetimes for LHCb... but the peak of an exponential is at zero!

General analysis strategy

1. Soft pre-selection to reduce dataset
2. Cut on BDT and PID to remove most of the background
3. Search for $\Sigma^+ \to p\mu^+\mu^-$ decays:
   - ⋆ Search around Σ mass window for SM signal
     $\to$ If peak is found, look at $\mu\mu$ invariant mass
4. Normalize branching fraction to $\Sigma^+ \to p\pi^0$ decays

Sample and selection:

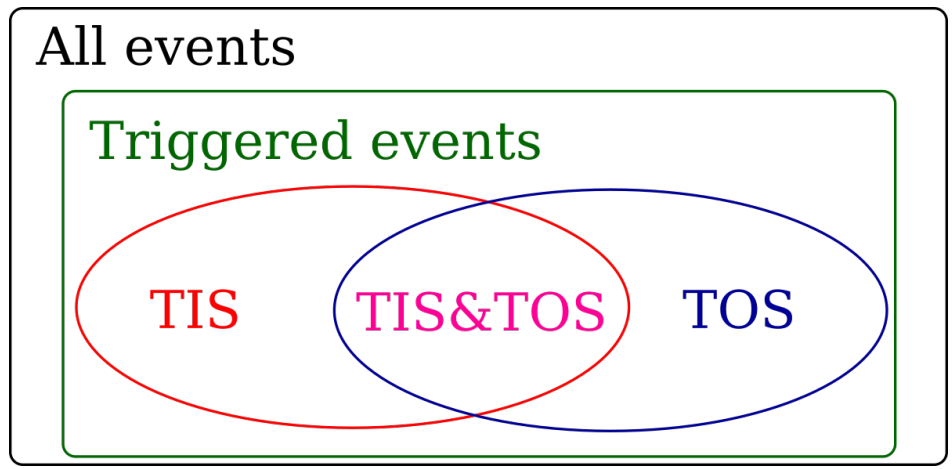
- Full 2011+2012 statistics, luminosity 3 fb^{-1}
- Selections for final states: $\Sigma^+ \to p\mu^+\mu^-$, $\Sigma^+ \to \bar{p}\mu^+\mu^+$, $\Sigma^+ \to p\pi^0$, $K^+ \to \pi^+\pi^-\pi^+$
- Decays reconstructed with long tracks (i.e. decays in VELO)
- Prompt decays

Datasets strategy

- Very soft signal to be triggered
- Two trigger strategies:
  1. Full - all events are retained, for search purposes, no normalisation
  2. TIS - for normalization purposes (sub sample)

TIS events and the TISTOS method

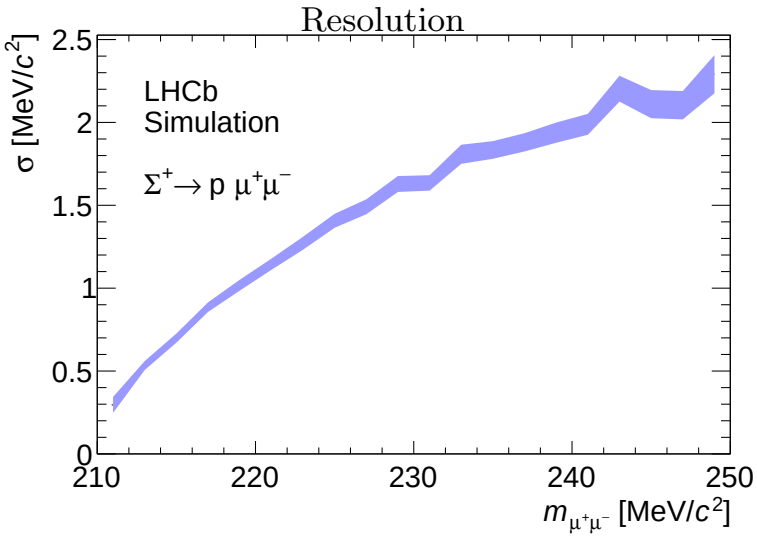
- Triggered events can be
  - ⋆ Triggered On the Signal (TOS)
    - the signal is sufficient to trigger
  - ⋆ Triggered Independently of the Signal (TIS)
    - the signal is not necessary to trigger
  - ⋆ Triggered on both (!TIS&!TOS)
- Events can be TIS and TOS
- Overal can be used to measure trigger efficiencies

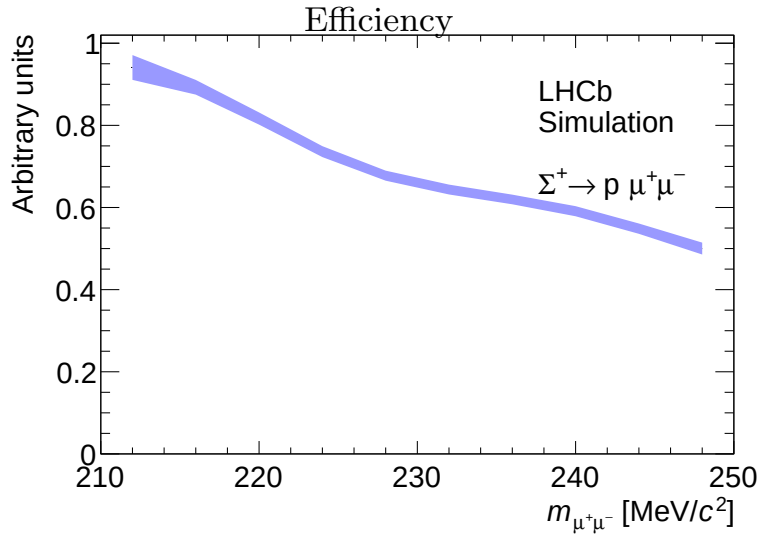


Tolk, S et al. LHCb-PUB-2014-039

Search for an Hyper-CP like signal

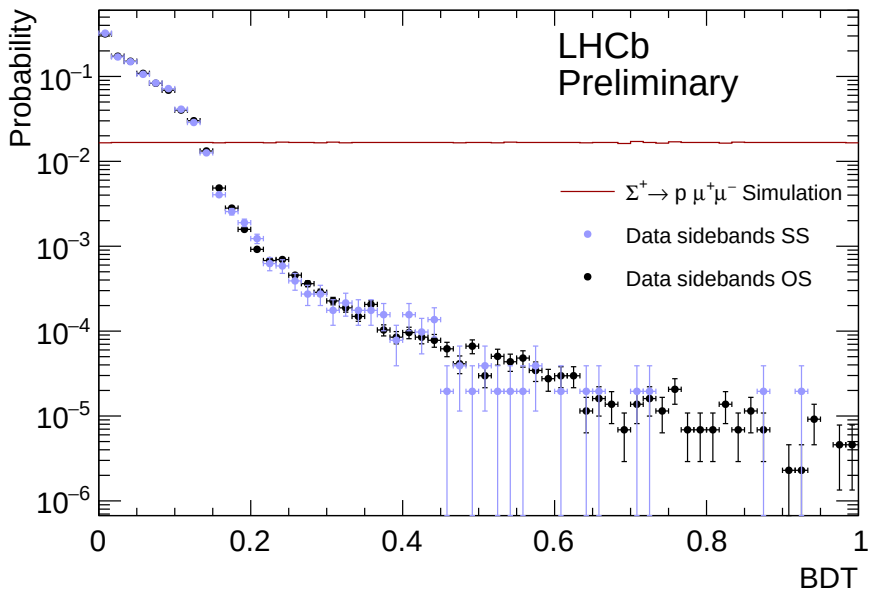
- Hyper-CP signal is consistent with $\Sigma^+ \to pX^0(\to \mu\mu)$, with $m_{X^0} = 214.3 \pm 0.5$ MeV
- Mass resolution in LHCb:
  - Raises with $m_{\mu^+\mu^-}$ departing from threshold
- Study efficiency versus $m_{\mu^+\mu^-}$: higher efficiency at small mass due to higher minimum p_T





Multivariate selection: BDT

- BDT aiming at rejecting combinatorial background
- Training on signal MC sample and background from data same-sign sidebands ($\Sigma^+ \to \bar{p}\mu^+\mu^+$)
- Common geometric and kinematic variables: pointing, IP, p_{T} and isolations, ...



Fit to the invariant mass distribution

- Signal shape described as Hypatia function used with fixed parameters (only mean and resolution floating)*
  - Resolution and mean calibrated with $K^+ \to \pi^+\pi^-\pi^+$ Data/MC ratio
  - Signal resolution left free to vary in the fit with gaussian constraint in final fits

- Background described as modified ARGUS function

$$f(m, m_0, p, c) = m \left(\frac{m^2}{m_0^2} - 1 \right)^p e^{c \frac{m}{m_0}} \quad (1)$$

where m_0 is the threshold mass typically of the order of the sum of the daughters masses; p and c are free parameters.

*D. Martinez Santos, F. Dupertuis, Nucl.Instrum.Meth. A764 (2014) 150-155

Normalisation

- No fully charged final state available in the Σ^+ to normalize the branching fraction
- Use high branching fraction $\Sigma^+ \to p\pi^0$

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

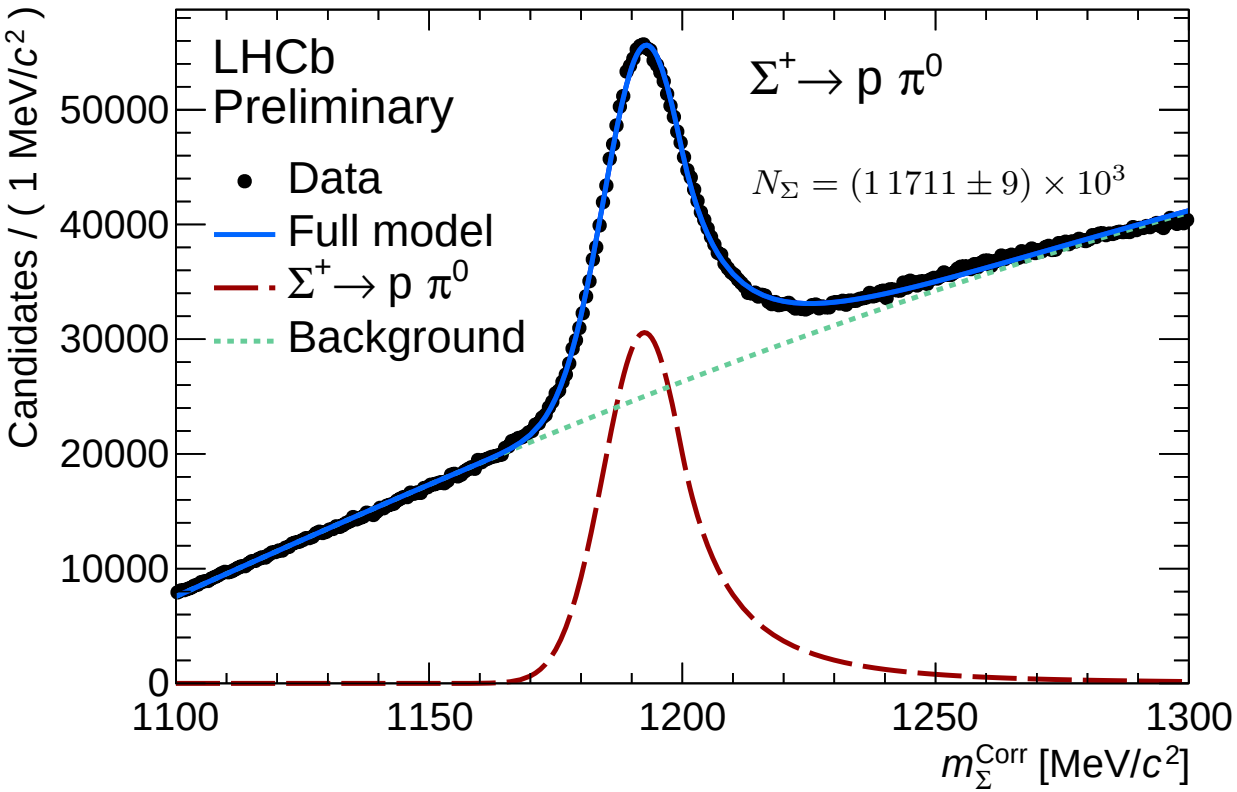
- Selection for $\Sigma^+ \to p\pi^0$ with $\pi^0 \to \gamma\gamma$ (resolved clusters) from calorimeter
- Branching fraction $\mathcal{B} = (51.57 \pm 0.30)\%$

For full RunI dataset, only TIS:

- Single event sensitivity $\alpha_{TIS} = (1.1 \pm 0.6) \times 10^{-8}$
- Correspondent to 4.6 ± 4.2 expected events in the TIS sample with a SM branching fraction

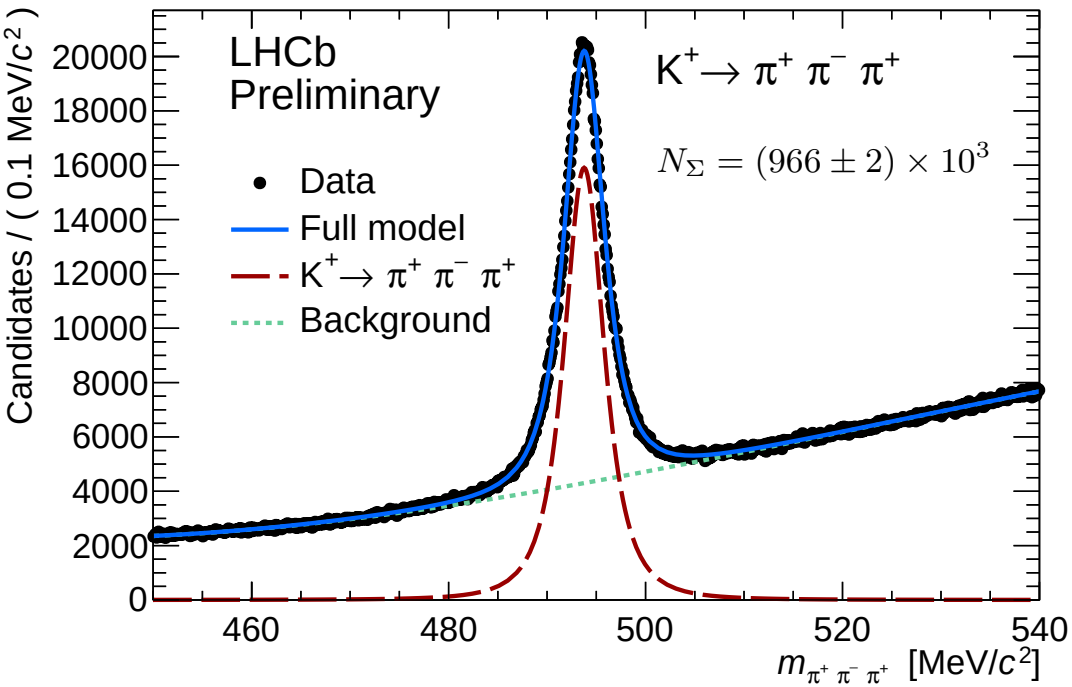
Normalisation with $\Sigma^+ \to p\pi^0$

- Fit to corrected mass: $m_\Sigma - m_{\pi^0} + m_{\pi^0}^{PDG}$
- Single Crystal-Ball pdf with right tail for the signal
- Modified Argus (with threshold on the left) for the background



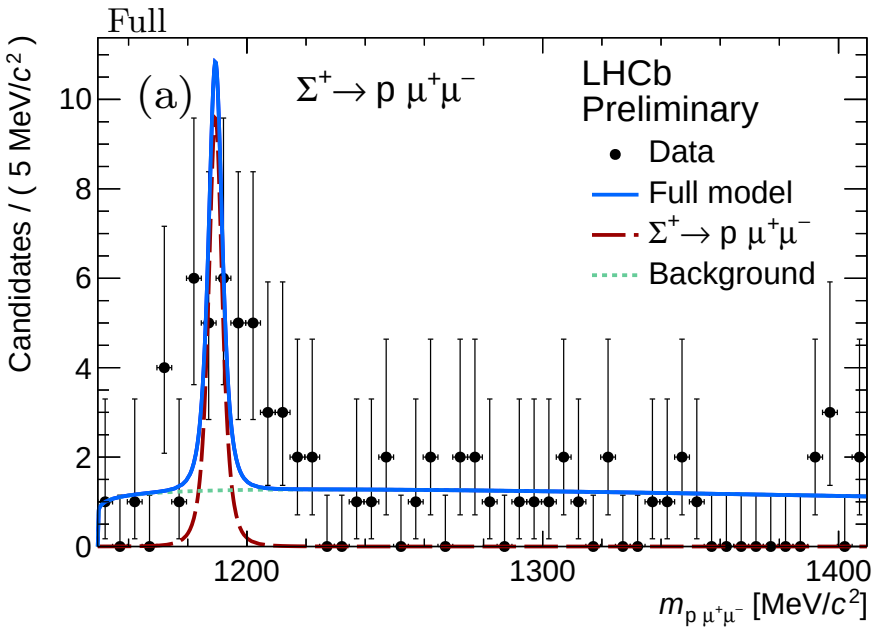
Normalisation systematics

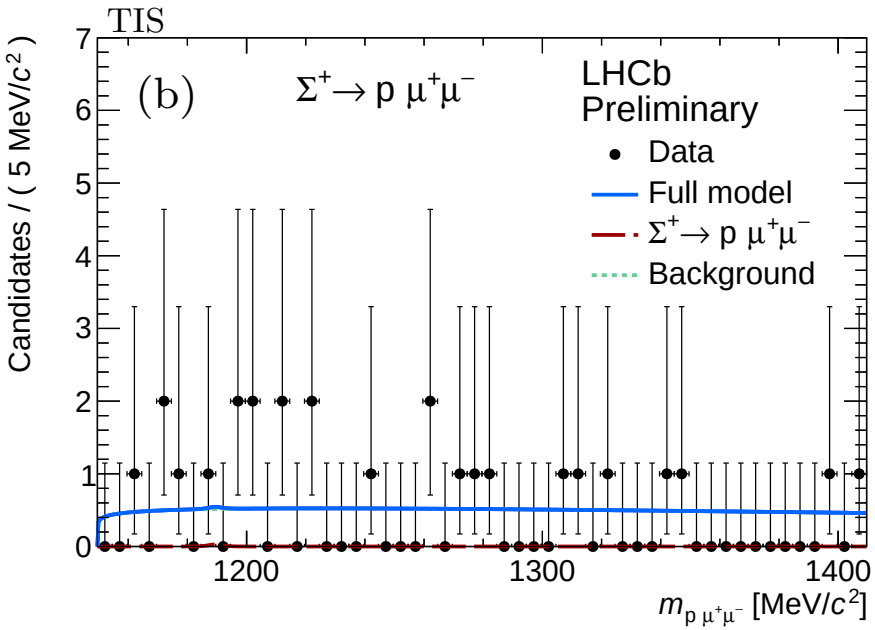
- TIS Trigger efficiency calibrated with large $K^+ \to \pi^+\pi^-\pi^+$ sample and TISTOS method
- Reconstruction of the π^0 calibrated with ratio of ratio of $B^+ \to J/\psi K^{*+}(\to K^+\pi^0)$ and $B^+ \to J/\psi K^+$ decays reconstructed in data.
- Particle identification calibrated with control channels in data ($\Lambda \to p\pi^-$ and J/ψ)
- BDT operator calibrated with $K^+ \to \pi^+\pi^-\pi^+$ channel in data



Selection Data-MC differences	1.4%
Calibration of BDT efficiency	6.4%
Calibration of PID efficiency	20%
Calibration of the π^0 efficiency	10%
Calibration of the TIS efficiency	30%
Total	43%

Results

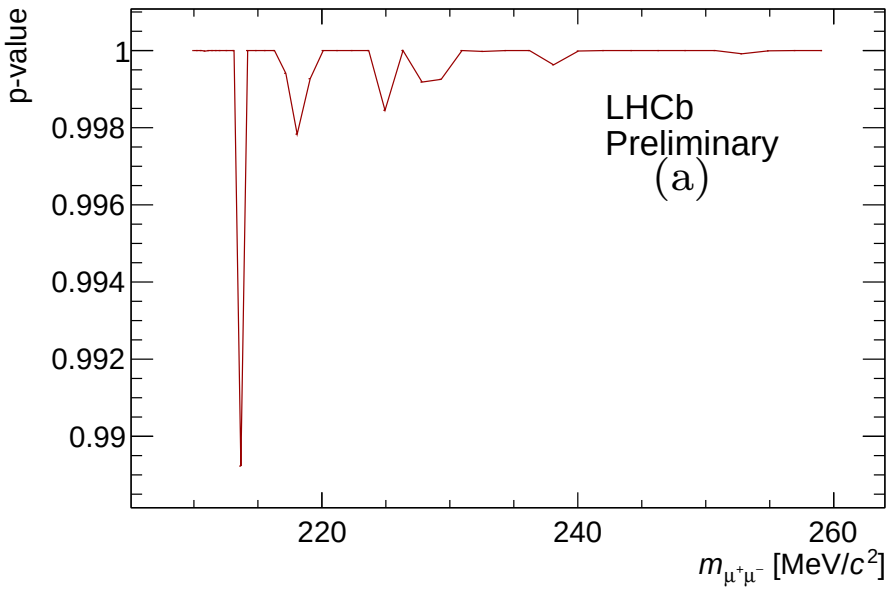


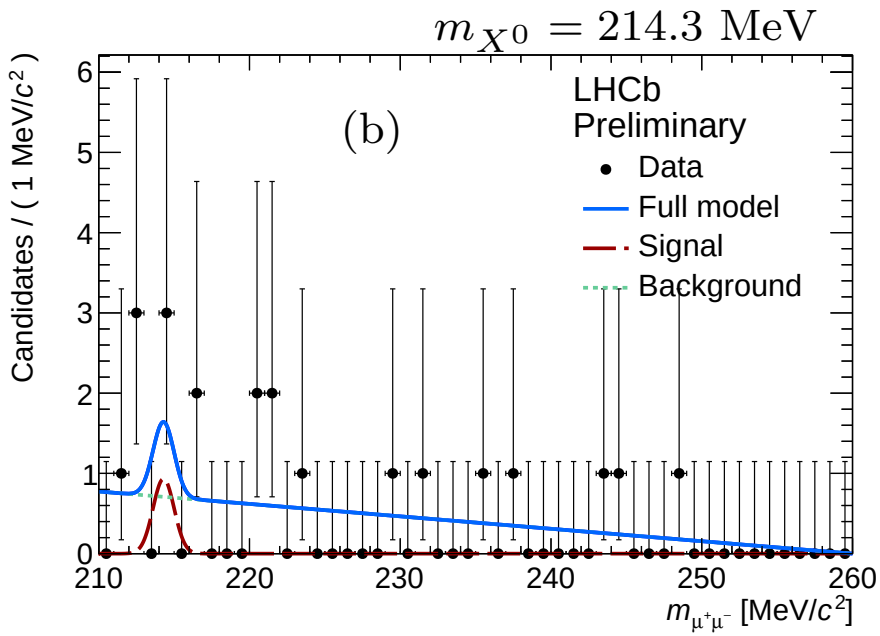


- Excess of events w.r.t. background with a significance of 4.0σ
- Fitted signal yield: $12.9^{+5.1}_{-4.2}$
- No excess of events in the TIS sub-sample
- Upper limit with CLS method: $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) < 6.3 \times 10^{-8}$ at 95% CL

Results: analysis of the dimuon mass

- Consider candidates within 2σ from the Σ mass in the full selection
- Scan dimuon invariant mass for possible peaks
- Fit with gaussian of known mass and resolution
- No significant peak found
- Most significant at 213.7 MeV (but not significant)
- Fit at $m_{X^0} = 214.3$ MeV yields 1.6 ± 1.9 events corresponding to a fraction 0.078 ± 0.092 of the total seen signal





Discussion of the results

LHCb-CONF-2016-013

- Found signal only in the full sample:
  most of the seen events have only one of the three trigger stage not being TIS
- Full detailed study of $\Sigma^+ \to p\mu^+\mu^-$ trigger efficiency is under way
- The main conclusions are anyway independent of absolute normalisation:
  - Evidence of $\Sigma^+ \to p\mu^+\mu^-$ decay
  - SM-like distribution of the dimuon invariant mass
  - Limit on the possible contribution of an additional particle

Summary and conclusions

- Search for the $\Sigma^+ \to p\mu^+\mu^-$ decay fundamental to cross-check HyperCP evidence
- First study of rare strange baryon at LHC
- Sensitivity in the 10^{-8} range
- Clear evidence of the $\Sigma^+ \to p\mu^+\mu^-$ decay
- Upper limits on branching fractions from TIS events
- No peaks in the dimuon invariant mass: SM once again
- Run II will fortunately not have these problems thanks to new dedicated trigger lines
- Conference Note LHCb-CONF-2016-013 will be public in few days

Backup