Rare strange decays at LHCb

Observation of the $\Sigma^+ \to p\mu^+\mu^-$ rare decay and searches for rare K^0 decays

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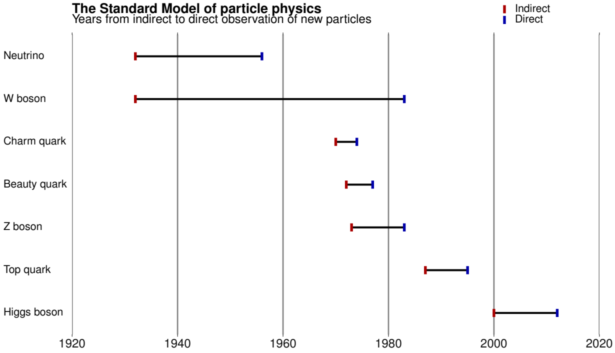
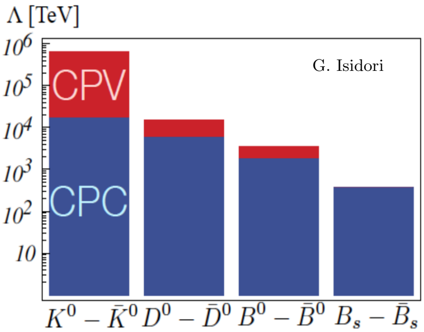
Why strange?

Strange physics as the birth of flavour physics

Fostered numerous discoveries in particle physics: new quarks, families and CPV

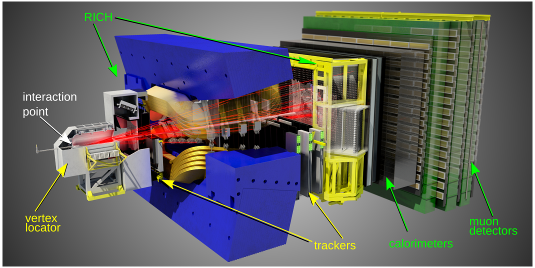
- Complementary to the more studied b and c
- Why not? Several observables have very large theory uncertainties
- Still the reign with higher (indirect) energy reach
- Rare decays and CPV sensitive to possible new dynamics



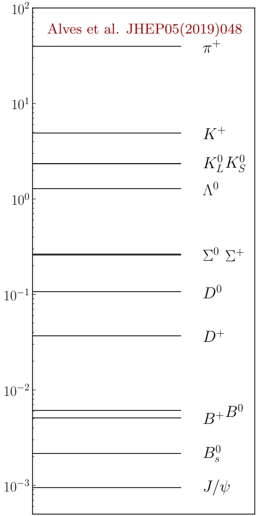


Strange hadrons at the LHC

- 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)
- Reconstruction and trigger however bring this number down
- LHCb fully instrumented in this region

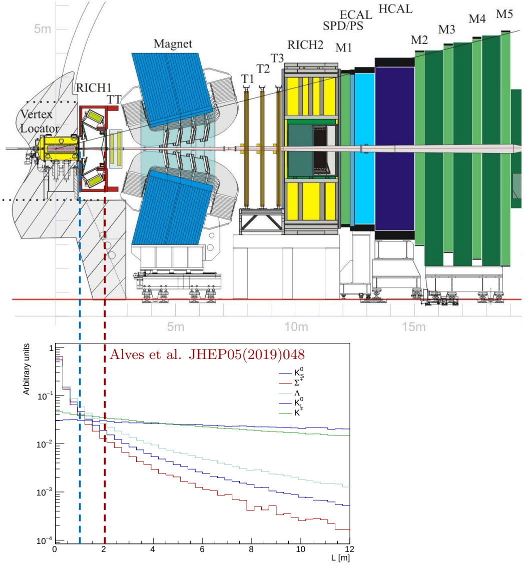


Average particles in LHCb acceptance per minimum bias event at $\sqrt{s} = 13$ TeV



Setting the (long) stage

Reconstruction and trigger of strange hadrons in LHCb Run 1-2

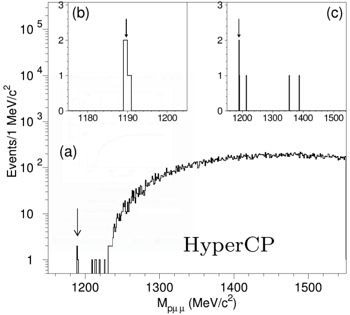


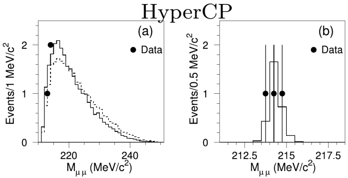
- About 50% lifetime acceptance for K_S and hyperons
- Different reconstruction methods for the daughter tracks
- Efficiency limited by hardware trigger
  - ⋆ LHCb trigger designed for heavy flavours
  - ⋆ Muon (hadron) L0 trigger require $p_T > [1-5]$GeV
  - ⋆ **Too hard for primary strange hadrons**
- Software trigger highly customisable: dedicated lines already in 2012
- Since 2016 (Run 2) dedicated software reconstruction for soft muons
- In Run 3 (Upgrade): no hardware trigger and many dedicated lines

Search for $\Sigma^+ \to p\mu^+\mu^-$ decays

The HyperCP anomaly

- $\Sigma^+ \to p\mu^+\mu^-$ is a very rare FCNC
- Short distance SM $\mathcal{B} \sim O(10^{-12})$
- Dominated by long distance contributions:
  $1.8 \cdot 10^{-8} < \mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) < 5.8 \cdot 10^{-8}$
  [Xiao-Gang He et al. - Phys.Rev. D72 (2005) 074003] [Xiao-Gang He et al. - JHEP 1810 (2018) 040] [Roy et al. , PRD111 (2025) 013003]
- Evidence found by the HyperCP experiment with 3 events in absence of background
- Measured branching fraction was:
  $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 1.5) \cdot 10^{-8}$ [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 $m^0_X = 214.3 \pm 0.5$ MeV
  $\mathcal{B}(\Sigma^+ \to pX^0(\to \mu\mu)) = (3.1^{+2.4}_{-1.9} \pm 5.5) \cdot 10^{-8}$
- Attracted considerable theoretical attention



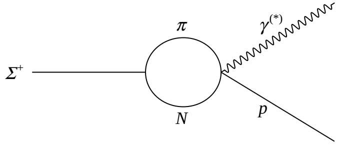


$\Sigma^+ \to p\mu^+\mu^-$: theoretical prediction

Branching fraction

Amplitude

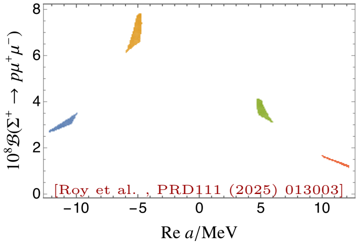
$$A^{\mathrm{LD}}_{\Sigma^+\to p\mu^+\mu^-} = \{-iq_\alpha \bar{u}_p[a(q^2) + \gamma_5 b(q^2)]\sigma^{\alpha\beta}u_\Sigma - \bar{u}_p\gamma^\beta[c(q^2) + \gamma_5 d(q^2)]u_\Sigma\}\bar{u}_\mu\gamma_\beta v_{\bar{\mu}}$$



- Dominated by long distance contributions $\Sigma \to N\pi \to p\gamma^*$
- With some assumptions a and b can be taken from $\Sigma^+ \to p\gamma$ experimental data [BESIII - Phys. Rev. Lett. 130, 211901 (2023)]
- Four-fold theoretical ambiguity
- Relativistic-baryon and heavy-baryon χPT approaches do not agree

Hence final prediction has large uncertainty:

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) \in [1.8, 5.8] \times 10^{-8}$$



Experiment can help solve the ambiguity

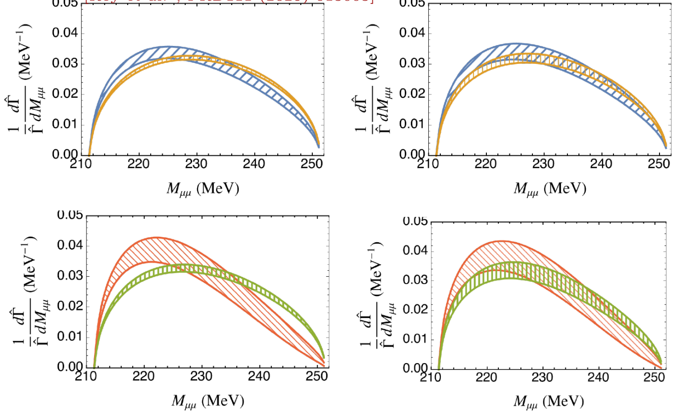
Theoretical prediction

Dimuon mass distribution

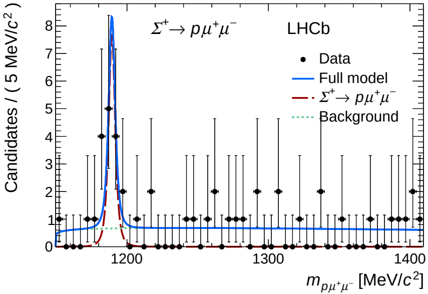
- Different predictions for the different approaches and parameter values

Additional observables: forward-backward asymmetry, CP violation

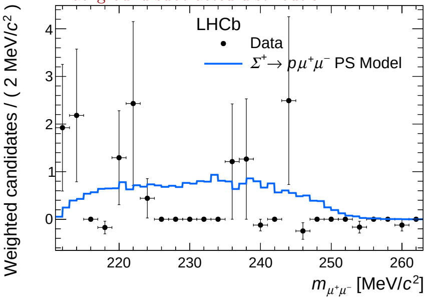
[Roy et al. , PRD111 (2025) 013003]



- LHCb Run1 analysis confirmed $\Sigma^+ \to p\mu^+\mu^-$ ($4.1\,\sigma$) decay but no dimuon structure
- Fitted signal yield: $10.2^{+3.9}_{-3.5}$
- Measured branching fraction $(2.2^{+0.9}_{-0.8}{}^{+1.5}_{-1.1}) \times 10^{-8}$
- No structure in dimuon mass



Background subtracted distribution



Today: Run 2 analysis

- Dedicated HLT1 and HLT2 lines:
  10-fold increase in trigger efficiency [LHCb-PUB-2017-023]
- Additional increase from luminosity ($5.4\,\text{fb}^{-1}$) and cross-section

[PRL 120, 221803 - arXiv:1712.08606]

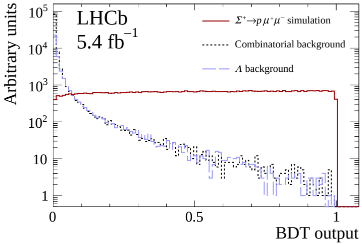
Analysis strategy

Main (and only) backgrounds:

- Combinatorial
- From $\Lambda \to p\pi^-$ with misidentified pion and an additional track: vetoed explicitly with cut on $m(p\mu^-)$
- For example $\Sigma^+ \to p\pi^+\pi^-$ is forbidden by energy conservation

Strategy

- Soft preselection
- Trigger: see later
- Final selection based on
  - ⋆ Boosted decision tree against combinatorial
  - ⋆ Strong particle identification on muons and proton
- Analysis optimised for smallest statistical uncertainty

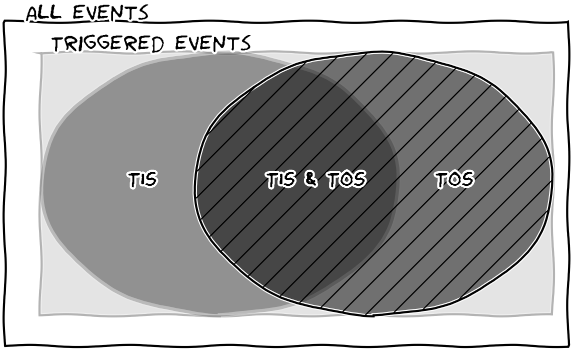


[LHCb-PAPER-2025-002 - arxiv:2504.06096 - Accepted in PRL]

Trigger strategy: TIS and TOS

- As trigger efficiencies for strange are low, all analyses use also "parasitic" events acquired due to something else in the event.
- TIS: Triggered independently of the signal
- TOS: Triggered on the signal
- Overlap crucial to estimate trigger efficiencies (TISTOS method)

$$\varepsilon_{TOS} = \frac{N_{TIS\&TOS}}{N_{TIS}}$$



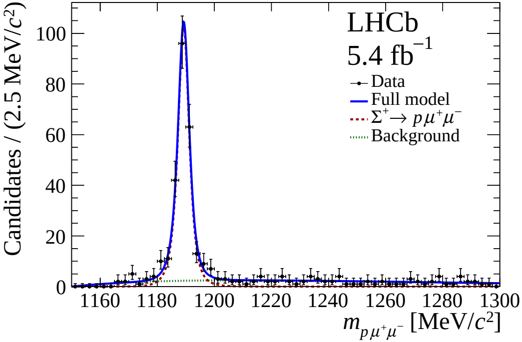
[LHCb-PAPER-2025-002 - arxiv:2504.06096 - Accepted in PRL]

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

Fit to the invariant mass distribution

- Signal described with an Hypatia function
- Modified Argus function to describe residual background

$$N(\Sigma^+ \to p\mu^+\mu^-) = 237 \pm 16$$

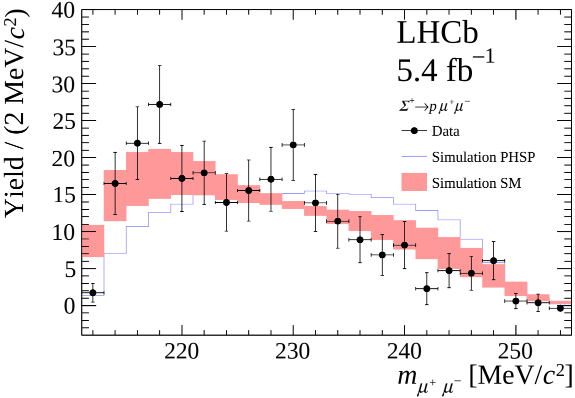


[LHCb-PAPER-2025-002 - arxiv:2504.06096 - Accepted in PRL]

Very clear first observation of the $\Sigma^+ \to p\mu^+\mu^-$ decay

Dimuon mass distribution

- Background subtraction with sPlot method (cross-check with bin-by-bin fits)
- Distribution well compatible with SM MC (not with phase-space one).
- Note: this is not efficiency corrected
- Qualitatively in agreement with lowest of SM predictions

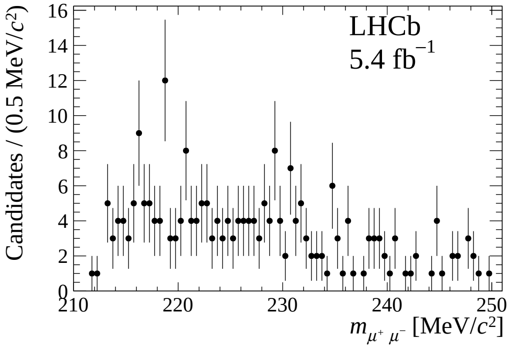


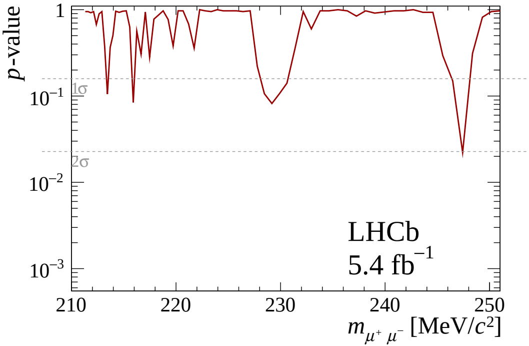
[LHCb-PAPER-2025-002 - arxiv:2504.06096 - Accepted in PRL]

Dimuon mass distribution

Search for resonances

- Scan on dimuon distribution in windows of ±1.5 times the dimuon resolution
- Contribution at 214 MeV is negligible, excluding the HyperCP anomaly





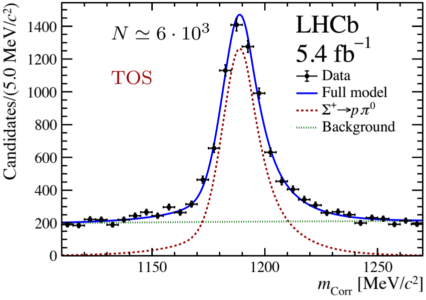
[LHCb-PAPER-2025-002 - arxiv:2504.06096 - Accepted in PRL]

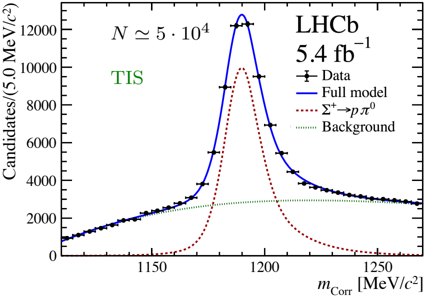
Normalisation

- $\Sigma^+ \to p\pi^0$ difficult to reconstruct at LHCb: one track and two calo clusters, no vertexing possible
- Very large abundance ($\mathcal{B} = 50\%$) makes it possible even with min-bias trigger (and only channel available...)

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

- Fit to the corrected mass $m_{\rm Corr} \equiv m_{p\gamma\gamma} - m_{\gamma\gamma} + m_{\pi^0}^{\rm PDG}$ to correct π^0 one
- Signal: sum of a Gaussian and a Crystal Ball function with power-law tails
- Background: Chebyshev second-degree polynomial
- Alternative background parametrisations show negligible change in signal yield





[LHCb-PAPER-2025-002 - arxiv:2504.06096 - Accepted in PRL]

Very small efficiencies (order 10^{-5} for signal and 10^{-11} for norm channel, including prescale)

- Muon trigger calibration with $K^+ \to \pi^+\pi^-\pi^+$ with two pions decayed in flight in muons ($\sim 20\%$ 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 sensitivities of

$$\alpha_{\rm TOS} = (1.65\,^{+\,0.09}_{-\,0.16}\,^{+\,0.41}_{-\,0.41}) \times 10^{-10} \quad \text{and} \quad \alpha_{\rm TIS} = (6.81\,^{+\,0.29}_{-\,0.25}\,^{+\,0.85}_{-\,0.85}) \times 10^{-11}$$

- Corresponding to $O(10^{14})$ Σ baryons produced in LHCb

[LHCb-PAPER-2025-002 - arxiv:2504.06096 - Accepted in PRL]

Results

The measured branching fractions are

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (1.59\,^{+\,0.19}_{-\,0.23}\,^{+\,0.40}_{-\,0.40}) \times 10^{-8} \text{ for the TOS trigger}$$
$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (1.05\,^{+\,0.10}_{-\,0.10}\,^{+\,0.13}_{-\,0.13}) \times 10^{-8} \text{ for the TIS trigger}$$

for a combined branching fraction of

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

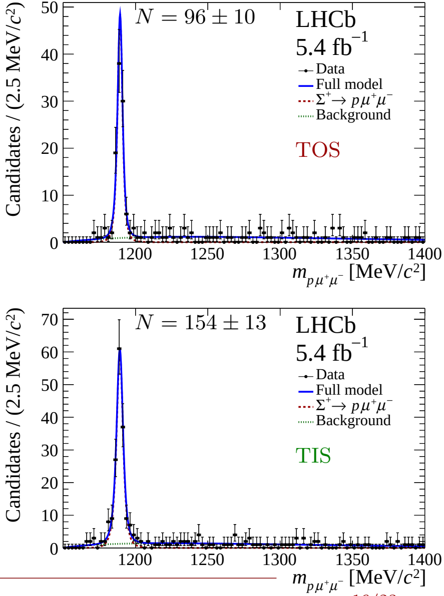
we also combine it with Run1 result ($(2.2\,^{+\,1.8}_{-\,1.3}) \times 10^{-8}$) giving

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

this result favours the lowest predicted degenerate branching fraction ([Roy et al. , PRD111 (2025) 013003]), which is also qualitatively favoured by the structure measured in the dimuon mass distribution.

In general, heavy-baryon χPT predictions are disfavoured by at least 3.1σ compared to relativistic χPT predictions.

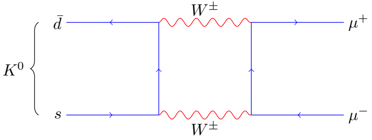
This is the rarest decay of a baryon ever observed!

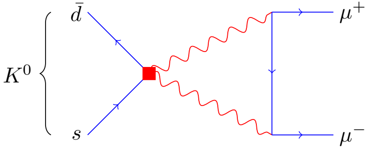


[LHCb-PAPER-2025-002 - arxiv:2504.06096 - Accepted in PRL]

- $K^0_{\rm L} \to \mu^+\mu^-$ is the "father" of flavour physics
  motivating the need for charm quark and GIM mechanism
- $K^0_S \to \mu^+\mu^-$ in addition suppressed by CPV
- SM prediction $\mathcal{B}(K^0_S \to \mu^+\mu^-) = (5.1 \pm 1.5) \cdot 10^{-12}$
  [Ecker, Pich - Nucl Phys B366 (1991)] [Isidori, Unterdorfer - JHEP 01 (2004) 009]
- Dominated by long distance contributions
- Sensitive to NP, e.g. light scalars with CP-violating Yukawa couplings
- Best limit before LHCb was $\mathcal{B}(K^0_S \to \mu^+\mu^-) < 3.1 \cdot 10^{-7}$ at 90% CL at CERN PS in 1973 [S. Gjesdal et al. PLB44(1973)217]
- Recent theoretical interest following LHCb results:
  possibility to study the interference of $K^0_{\rm L}$ and K^0_S to two muons [D'Ambrosio et al. PRL(2017)20,201802]

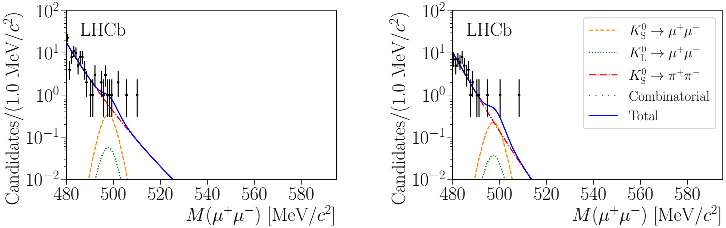
[Phys. Rev. Lett. 125, (2020) 231801]





Search for $K^0_S \to \mu^+\mu^-$ decays

- $K^0_S \to \pi^+\pi^-$: normalisation and main background
- Dedicated particle id developed
- Sensitive to the sum of K_S and K_L: K^0_L acceptance in LHCb is 10^{-3} that of K^0_S

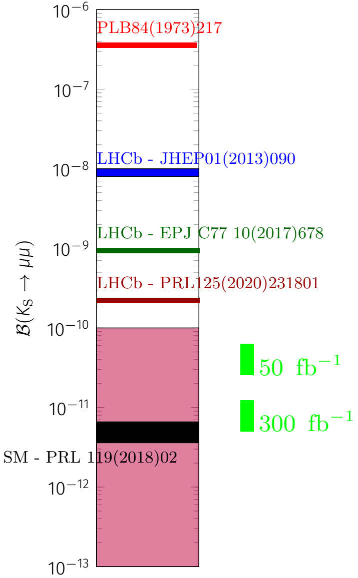


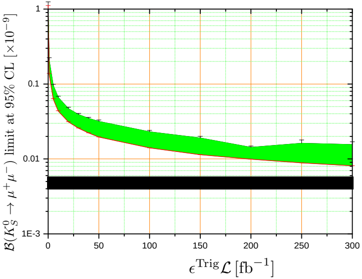
Legacy Run 2 analysis combined with Run 1 yields

$$\mathcal{B}(K^0_S \to \mu^+\mu^-) < 2.1 \times 10^{-10} \text{ at } 90\% \text{ CL}$$

[Phys. Rev. Lett. 125, (2020) 231801]

$K_S^0 \to \mu^+\mu^-$ prospects





Future sensitivity to $K_S^0 \to \mu^+\mu^-$

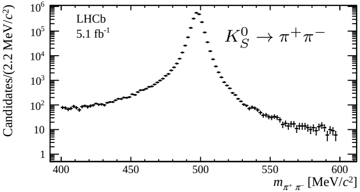
- Depends on real trigger efficiencies
- Approach interesting region in Run 3 (Upgrade)
- Probe SM in Upgrade II

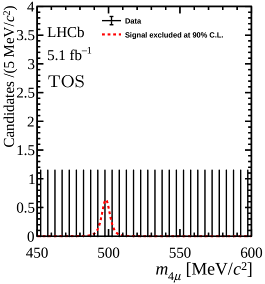
[Phys. Rev. Lett. 125, (2020) 231801]

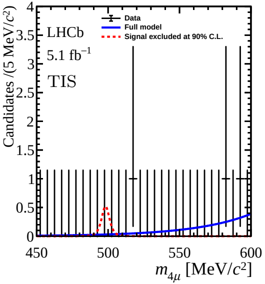
Search for $K^0_{S(L)} \to \mu^+\mu^-\mu^+\mu^-$

- Very suppressed SM at $O(10^{-14})$ for the K^0_S and $O(10^{-12})$ for the K^0_L [D'Ambrosio et al. EPJC73(2013)2678]
- New physics up to orders $O(10^{-12})$, e.g. new dark-sectors [Goudzovski et al. Rept.Prog.Phys. 86 (2023) 1, 016201] [Hostert, Pospelov Phys. Rev. D105 (2022) 015017]
- Run 2 analysis in LHCb using 5.1 fb^{-1}- Similar strategy to $K^0_S \to \mu^+\mu^-$ search
- Essentially background free search due to four muons

[Phys. Rev. D108 (2023) L031102]







Upper limits closing in on NP space

$$\mathcal{B}(K^0_S \to \mu^+\mu^-\mu^+\mu^-) < 5.1 \times 10^{-12} \qquad \mathcal{B}(K^0_L \to \mu^+\mu^-\mu^+\mu^-) < 2.3 \times 10^{-12}$$

Conclusion and outlook

- LHCb is giving new momentum to strange-hadrons physics
- First observation of $\Sigma^+ \to p\mu^+\mu^-$ very rare decay:
  rarest decay of a baryon ever observed
  large yield to measure CP violation, forward-backward asymmetry etc
- Strong limits on $K^0_S \to \mu^+\mu^-$ and $K^0_S \to \mu^+\mu^-\mu^+\mu^-$ decays
- Other analysis are presented for the first time here, or almost ready to be published:
  - ⋆ Measurement of the $\Lambda \to p\mu^-\bar{\nu}_\mu$ branching fraction (See Alexandre Brea's talk!)
  - ⋆ Search for $K^0 \to \pi^+\pi^-\mu^+\mu^-$ decays
- Many more results to come (see bibliography for further readings)

This is just the start, Run 3 analyses with increased trigger efficiency and luminosity are in progress!

Bibliography

Strange physics at LHCb

LHCb Collaboration

Papers

- Observation of the very rare $\Sigma^+ \to p\mu^+\mu^-$ decay [LHCb-PAPER-2025-002 - arxiv:2504.06096 - Accepted in PRL]
- Search for $K^0_{\mathrm{S(L)}} \to \mu^+\mu^-\mu^+\mu^-$ decays at LHCb [Phys. Rev. D108 (2023) L031102]
- Strong constraints on the $K^0_S \to \mu^+\mu^-$ branching fraction [Phys. Rev. Lett. 125, (2020) 231801]
- Evidence for the rare decay $\Sigma^+ \to p\mu^+\mu^-$ [Phys. Rev. Lett. 120, 221803 (2018)] [LHCb-PAPER-2017-049] [hep-ex/1712.08606]
- Improved limit on the branching fraction of the rare decay $K^0_S \to \mu^+\mu^-$ [LHCb-PAPER-2017-009] [hep-ex/1706.00758] [Eur. Phys. J. C, 77 10 (2017) 678]
- Search for the CP-violating strong decays $\eta \to \pi^+\pi^-$ and $\eta' \to \pi^+\pi^-$ [LHCb-PAPER-2016-046] [hep-ex/1610.03666] [Physics Letters B 764 (2017) 233-240]
- Search for the rare decay $K^0_S \to \mu^+\mu^-$ [LHCb-PAPER-2012-023] [hep-ex/1209.4029] [JHEP 01 (2013) 090]

Public notes

- Physics case for an LHCb Upgrade II [LHCB-PUB-2018-009][arXiv/1808.08865]
- Low p_T dimuon triggers at LHCb in Run 2 [LHCb-PUB-2017-023]
- Sensitivity of LHCb and its upgrade in the measurement of $\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-)$ [LHCb-PUB-2016-017]
- Feasibility study of $K^0_S \to \pi^+\pi^-e^+e^-$ at LHCb [LHCb-PUB-2016-016]
- A method to study long lived charged particles at LHCb [LHCb-PUB-2014-032]

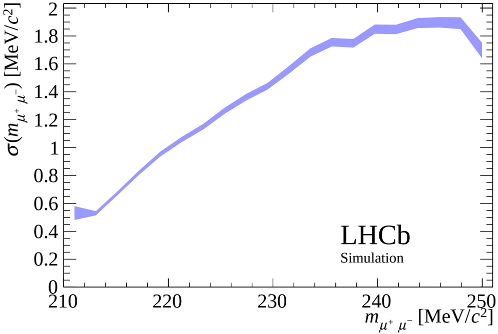
Others

- Aebischer et al. “Kaon Physics: A Cornerstone for Future Discoveries” [arXiv/2503.22256] - Input to the European Strategy of Particle Physics
- Anzivino et al. “Workshop summary: Kaons@CERN 2023” [Eur.Phys.J.C 84 (2024) 4, 377]
- Goudzovski et al. “New physics searches at kaon and hyperon factories” [Rept.Prog.Phys. 86 (2023) 1, 016201]
- Alves A. A. et al. “Prospects for Measurements with Strange Hadrons at LHCb” [JHEP05(2019)048]
- Borsato et al. “The strange side of LHCb” [Phys. Rev. D 99, 055017 (2019)]

I wait for you in Cagliari for CKM!

Backup slides

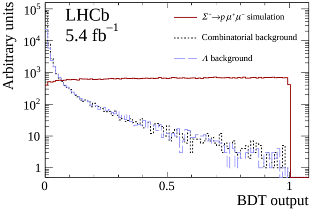
Resolution on dimuon mass versus the mass itself

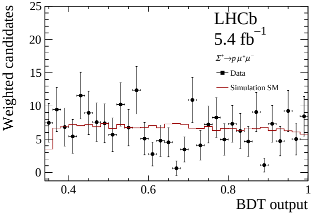


[LHCb-PAPER-2025-002 - arxiv:2504.06096 - Accepted in PRL]

[LHCb-PAPER-2025-002 - arxiv:2504.06096 - Accepted in PRL]

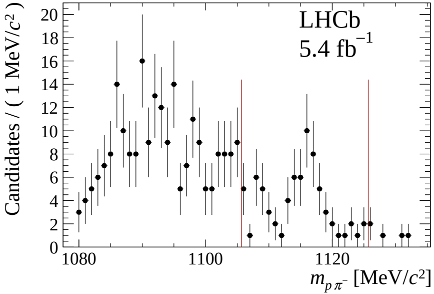
Calibration of the BDT classifier





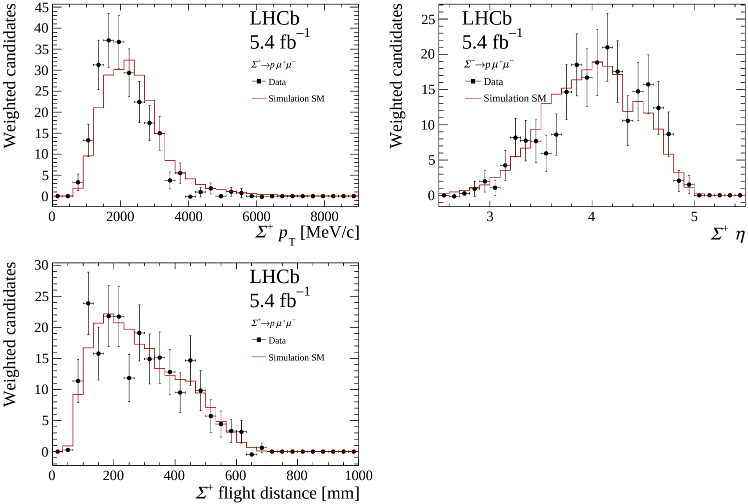
Observation of the $\Sigma^+ \to p\mu^+\mu^-$ decay

Distribution of the $p\mu^-$ invariant mass in the $p\pi$ mass hypothesis, without the Λ veto



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

Variable distribution for the $\Sigma^+ \to p\mu^+\mu^-$ decays in data and simulation

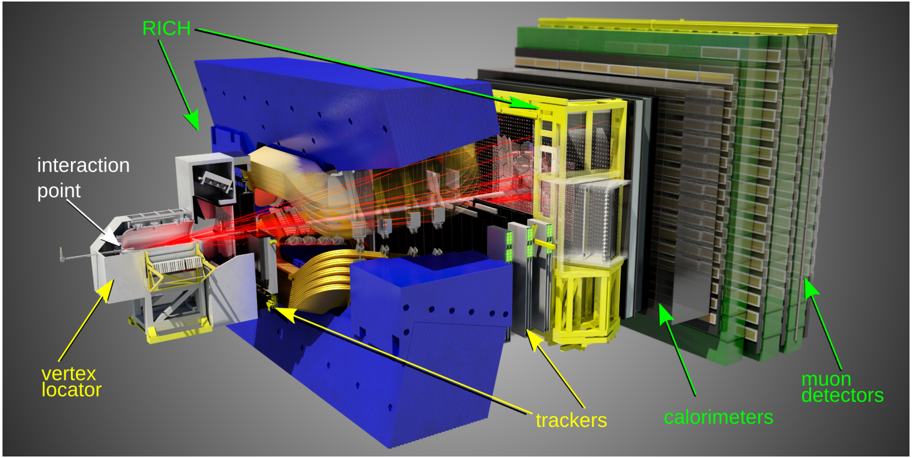


[LHCb-PAPER-2025-002 - arxiv:2504.06096 - Accepted in PRL]

Detailed L0 trigger strategy:

- TOS sample
  - $\Sigma^+ \to p\mu^+\mu^-$ signal triggered on the muons (L0Muon) OR on the proton (L0Hadron)
  - $\Sigma^+ \to p\pi^0$ triggered on the proton (L0Hadron)
- TIS sample
  - Both $\Sigma^+ \to p\mu^+\mu^-$ and $\Sigma^+ \to p\pi^0$ are triggered TIS

LHCb experiment



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

- pp collisions at $\sqrt{s} = 7, 8, 13$ TeV
- 3 (6) fb^{-1} in Run 1 (Run 2)
- Dedicated to b- and c-hadrons physics