Rare strange decays at LHCb

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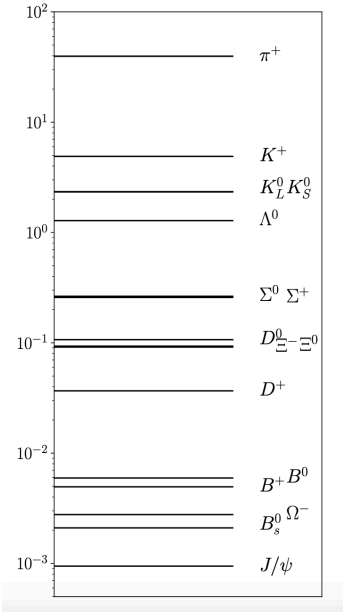
Why Strange Physics

- Kaons have shaped the SM since its inception
  - They were at the inception of the CKM matrix
- $s \to d\ell^+\ell^-$ transitions are highly suppressed in SM
  - Relevant for kaons but also strange baryons
- Involvement of strange quark pushes limits on theory predictions
  - Symmetries of QCD EFTs start to break with light mesons involving *s* quark

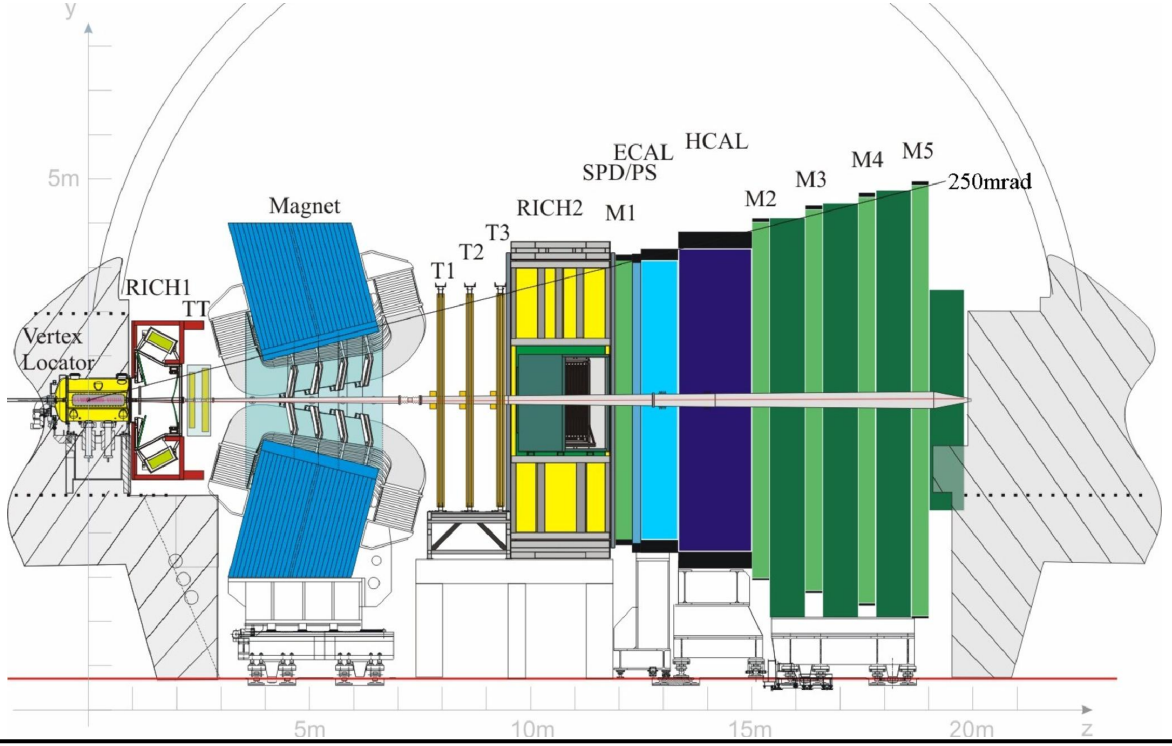
Why Strange Physics at LHCb

JHEP 05 (2019) 048

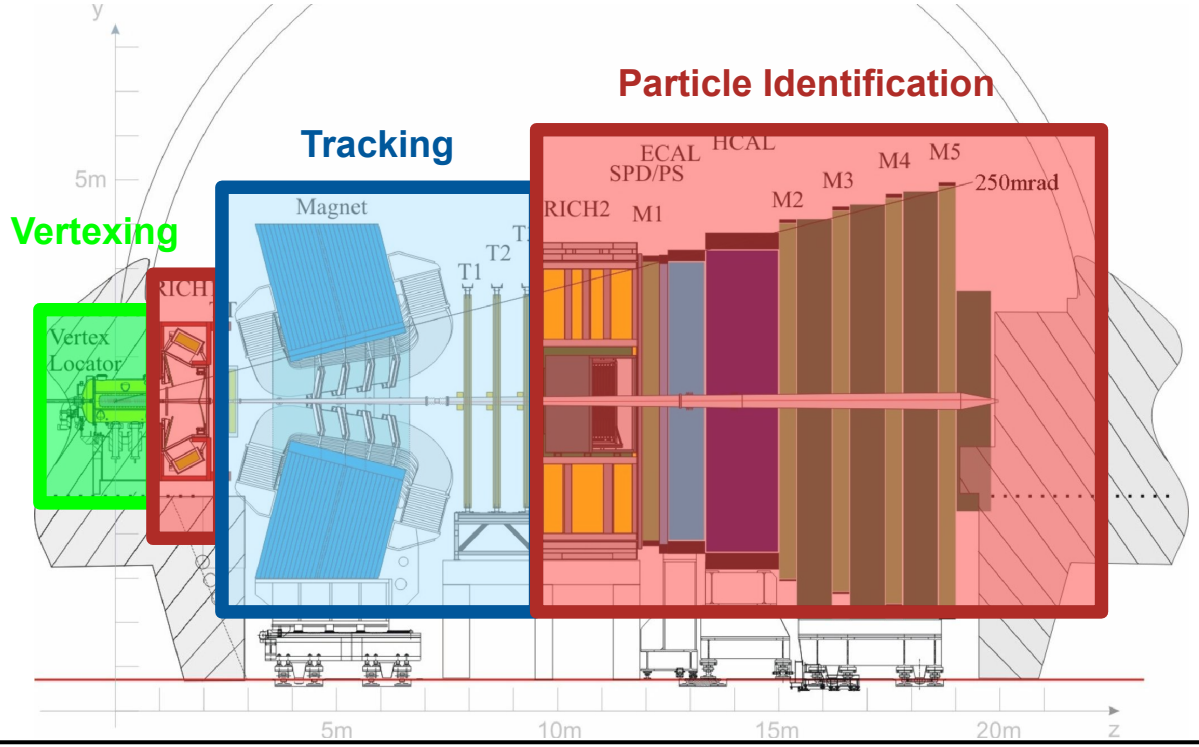


- Large production of strange hadrons at LHCb
- Very good PID + mass resolution
- Can go down to low p_T
  - Key for light mesons
  - Run 3 (2022–26) → hardware trigger removed, expected increase in efficiency
- This talk:
  - Quick review of latest $\Sigma^+ \to p\mu^+\mu^-$ result
  - Latest results on K_S^0, η and η' decays

The LHCb Experiment



The LHCb Experiment



The LHCb Experiment

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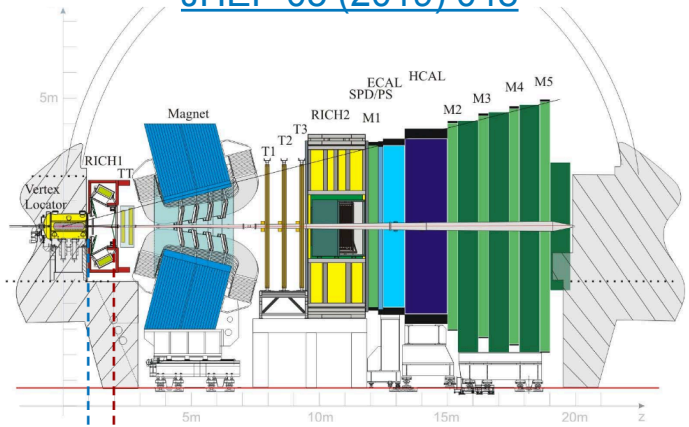
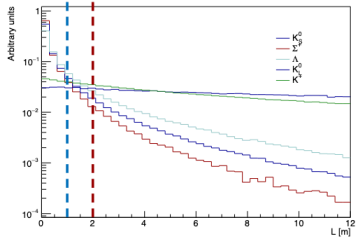


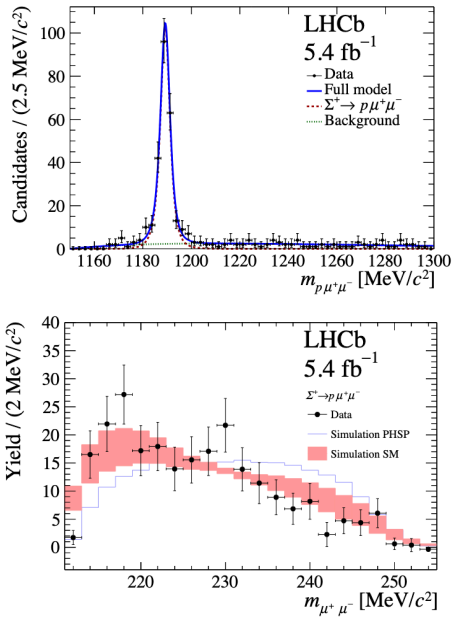


- 50% of K_S^0, Σ decay inside the VELO
- Run 1+2 (2011—18): Two-stage trigger
  - Hardware trigger selects high-pT signatures
  - Software trigger is more customizable
- Run 3 removed hardware trigger

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

Analysis Highlights

Phys. Rev. Lett. 135 (2025)

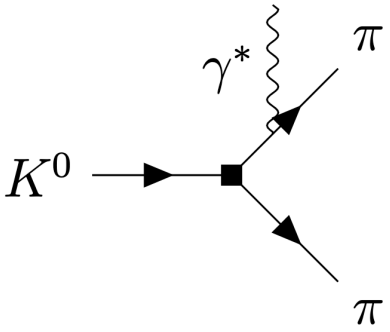


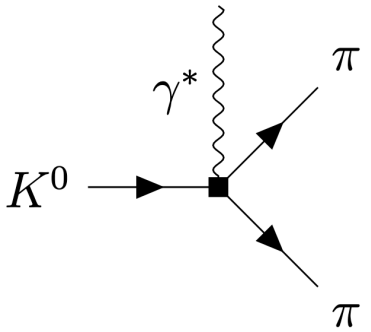
- Very rare FCNC
- Third search at LHCb
- 2016—2018 LHCb data
- Normalization to $\Sigma^+ \to p\pi^0$
- Signal observed with high significance
- No $\mu^+\mu^-$ excesses observed

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

$$K^0_{S(L)} \rightarrow \pi^+\pi^-\mu^+\mu^-$$

Motivation



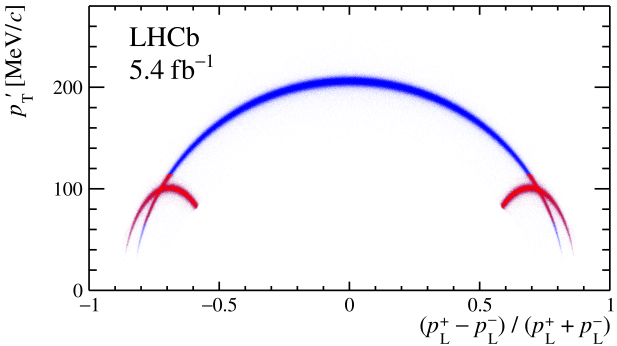


- Radiative decay with off-shell brem photon
  - $K_S^0 \to \pi^+\pi^-\gamma^*$: LD chiral terms
  - $K_L^0 \to \pi^+\pi^-\gamma^*$: CPV
- Complementary to electron mode (Eur. Phys. J C30 (2003) 33)
- Challenge: $m(K_S^0) - m(\pi^+\pi^-\mu^+\mu^-) = 7\ \mathrm{MeV/c^2}$
- 2016—2018 search (first ever)
  - First presented at KAON 2025
  - arXiv:2511.02619 — submitted to PRD

Analysis Strategy

- Normalization mode $K_S^0 \to \pi^+\pi^-$
- Looking for both K_S^0 and K_L^0 → LHCb is only competitive in K_S^0
- Search performed in two trigger categories
- Backgrounds:
  - Combinatorial (signal)
  - $\Lambda \to p\pi^-$ (norm)
- Background model challenging
  - Very close to kinematic threshold

2511.02619



Results

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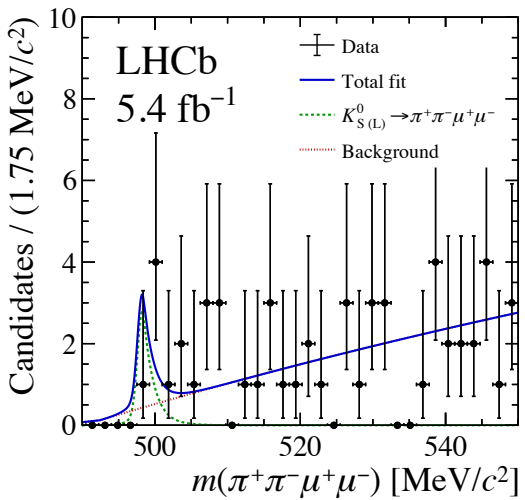


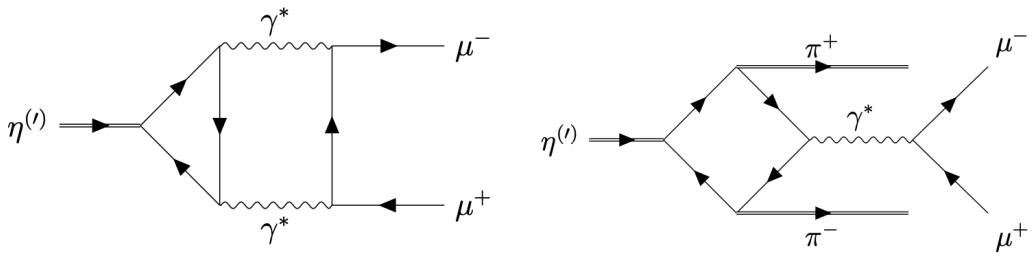
- No significant signal found
- Search performed for both K_S^0 and K_L^0
  - Difference is a lifetime acceptance factor
- Upper limits established at 90% CL

$$\mathcal{B}(K^0_{\rm S} \to \pi^+\pi^-\mu^+\mu^-) < 1.4 \times 10^{-9},$$
$$\mathcal{B}(K^0_{\rm L} \to \pi^+\pi^-\mu^+\mu^-) < 6.6 \times 10^{-7}.$$

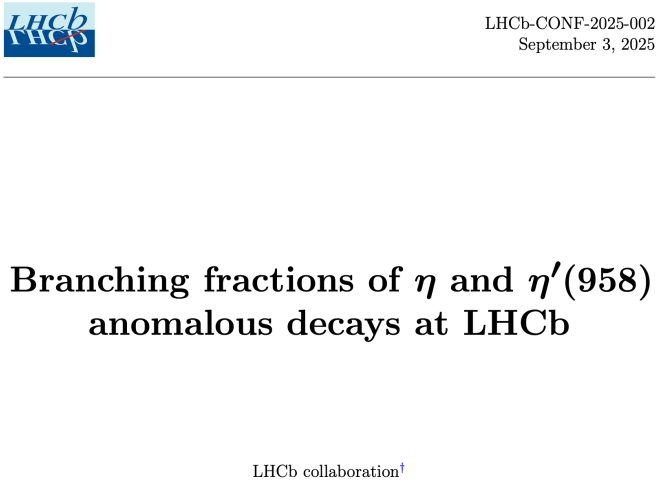
η, η’ anomalous decays

Motivation

- η, η' mesons are an admixture of *u*, *d*, *s* quarks
- Can help us inform QCD EFTs, e.g. ChPT
- BRs also important input for theory computations of transition form factors, relevant for $(g-2)_\mu$ theory calculations
- Rare decays are also subject to potential BSM mediators



Today…



- Presenting new results from η, η' searches at LHCb
  - 2016—2018 dataset
  - η, η'→(ππ)μμ
- LHCb-CONF-2025-002
- First presented at CKM Workshop in Sept.

State of the Art

15% uncertainty
Target: Update measurement

No measurements
Target: First measurement

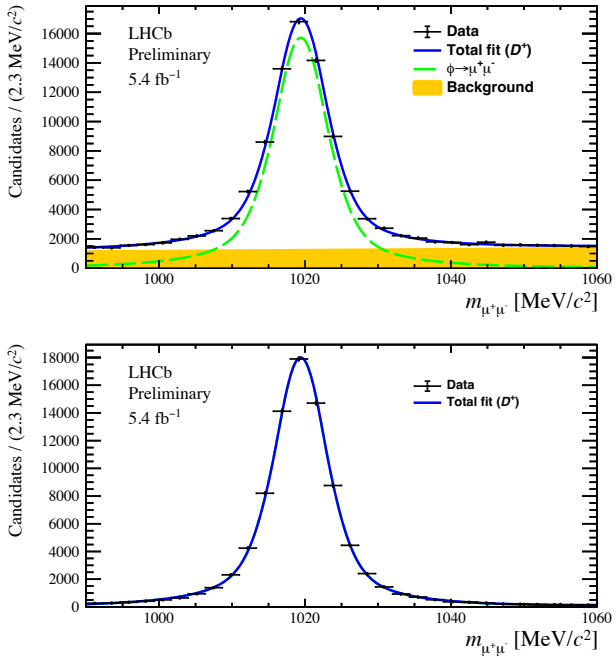
Channel	χPT Theoretical predictions	Best measurements of $\mathcal{B}$	
$\eta \to \mu^+\mu^-$	$(4.72^{+0.05}_{-0.21}) \times 10^{-6}$ JHEP 08 (2016) 108	$(5.7 \pm 0.9) \times 10^{-6}$	Phys. Rev. D 110 (2024)
$\eta' \to \mu^+\mu^-$	$(1.36^{+0.29}_{-0.26}) \times 10^{-7}$ JHEP 08 (2016) 108	—	
$\eta' \to \pi^+\pi^-\mu^+\mu^-$	$(1.57^{+0.96}_{-0.75}) \times 10^{-5}$ Eur.Phys.J.A 33 (2007)	$(2.14 \pm 0.13) \times 10^{-5}$	Phys. Rev. D 110 (2024)
$\eta \to \pi^+\pi^-\mu^+\mu^-$	$(7.5^{+4.5}_{-2.7}) \times 10^{-9}$ Eur.Phys.J.A 33 (2007)	$< 4.0 \times 10^{-7}$	2501.10130

6% uncertainty
Target: Update measurement

Tight upper limit
Target: Update result

Analysis Strategy

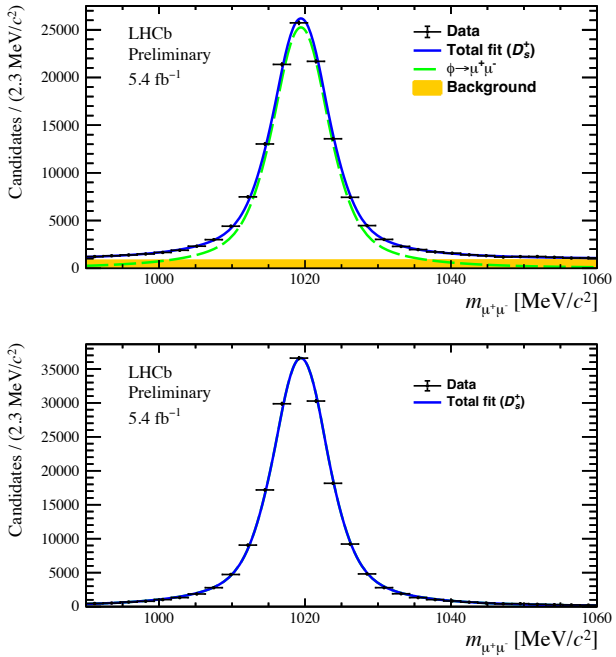
LHCb-CONF-2025-002



- η, η' taken from D meson decays
  - $D^+ \to \eta^{(\prime)}\pi^+$ & $D_s^+ \to \eta^{(\prime)}\pi^+$
- Normalization: $D_{(s)}^+ \to \phi(\mu^+\mu^-)\pi^+$
  - Same topology as $\mu^+\mu^-$ modes → excellent to align selections, including BDT
  - Two-track difference w.r.t. $\pi^+\pi^-\mu^+\mu^-$ modes
- Physical bkgs:
  - $\phi \to \mu^+\mu^-$ leaking into $\eta' \to \mu^+\mu^-$ upper masses (kinematic refit of η' mass)

Analysis Strategy (II)

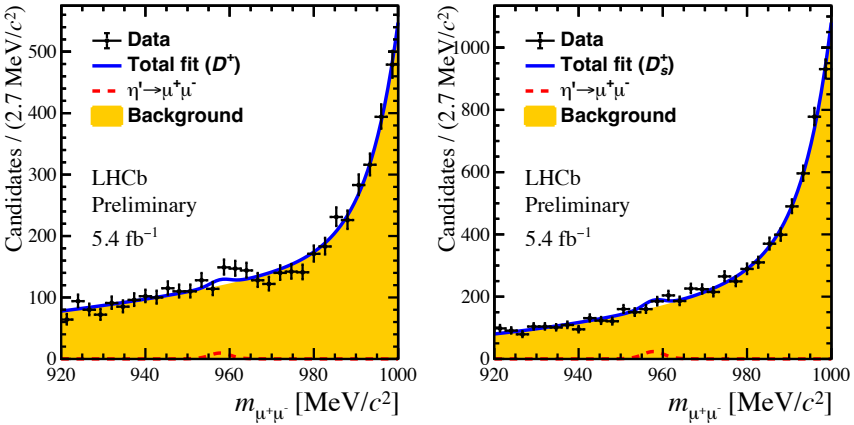
LHCb-CONF-2025-002



- $\mathrm{BR}(\phi \to \mu^+\mu^-)$ is largest source of syst. uncertainty (~5%)
- BDT to fight combinatorial background
  - Applied on $\mu^+\mu^-$ normalization modes (similar topology)
  - Not on $\pi^+\pi^-\mu^+\mu^-$ norm samples
- Simultaneous fit to both D meson modes
  - Signal → double-sided Crystal Ball
  - Bkg → exponential

Results (μμ)

LHCb-CONF-2025-002



$$\mathcal{B}(\eta' \to \mu^+\mu^-) < 1.9 \times 10^{-7},$$

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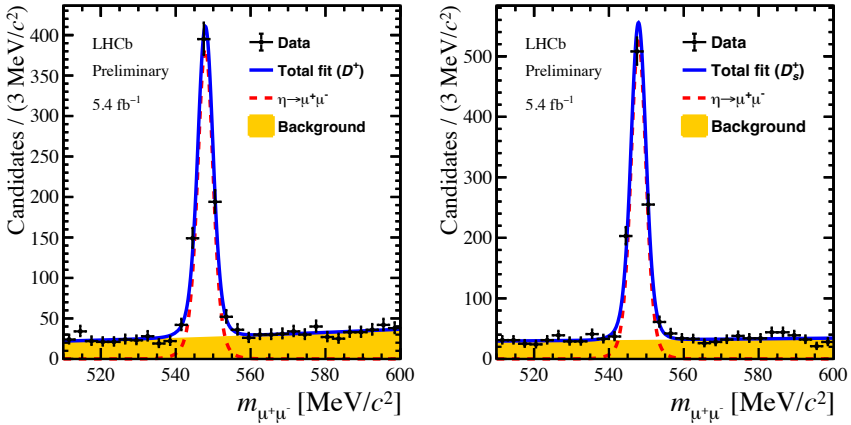
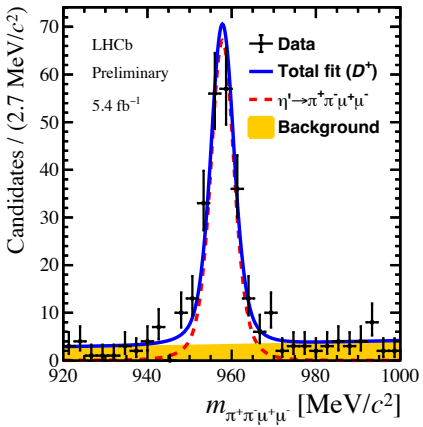
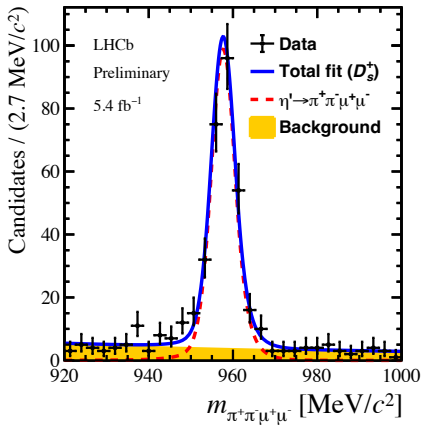


$$\mathcal{B}(\eta \to \mu^+\mu^-) = (5.30 \pm 0.14_{\,(\mathrm{stat})} \pm 0.18_{\,(\mathrm{syst})} \pm 0.26_{\phi}) \times 10^{-6},$$

Results (ππμμ)

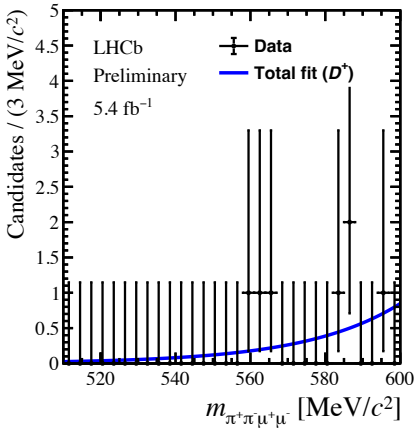
LHCb-CONF-2025-002

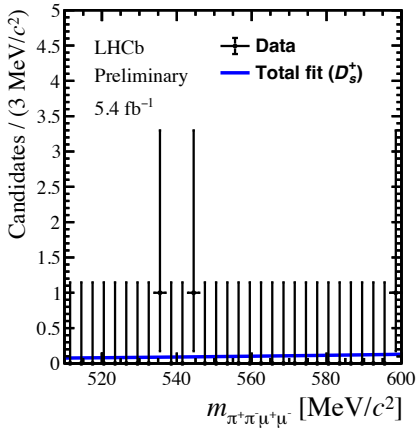




$$\mathcal{B}(\eta' \to \pi^+\pi^-\mu^+\mu^-) = (2.80 \pm 0.14_{\,(\mathrm{stat})} \pm 0.13_{\,(\mathrm{syst})} \pm 0.14_{\phi}) \times 10^{-5}.$$

LHCb-CONF-2025-002





$$\mathcal{B}(\eta \to \pi^+\pi^-\mu^+\mu^-) < 6.0 \times 10^{-7}.$$

Search for μμ excesses

- Used large statistics in $\eta' \to \pi^+\pi^-\mu^+\mu^-$ to look for $\mu^+\mu^-$ BSM resonances
- Search conducted in steps of $50\ \mathrm{MeV/c^2}$ between $m_{\mu\mu} \in (250 - 500)\ \mathrm{MeV/c^2}$
- No significant excesses found → upper limits established for each

LHCb-CONF-2025-002

$m_a\,[\mathrm{MeV}/c^2]$	250	300	350	400	450	500
$\mathcal{B}$ upper limit at 90% CL ($\times 10^{-3}$)	2.9	1.5	0.8	0.7	0.4	0.3

Towards the future

Look out for…

- Massive improvements in low-pT measurements
- New $K_S^0 \to \mu^+\mu^-$ result
  - Interest in other K_S^0 decays (electrons, LFV, $\pi^0\mu^+\mu^-$, etc.)
- New Σ results
- Run 3 could bring first evidence of $\eta' \to \mu^+\mu^-$

Conclusions

- LHCb is highly competitive in strange physics
- Only experiment providing K_S^0 results
- Can improve/update measurements of known rare decays
  - This informs QCD
  - Can veto BSM models
- We are just getting started
  - Removal of hardware trigger will allow large efficiency increases

Thank you for your attention

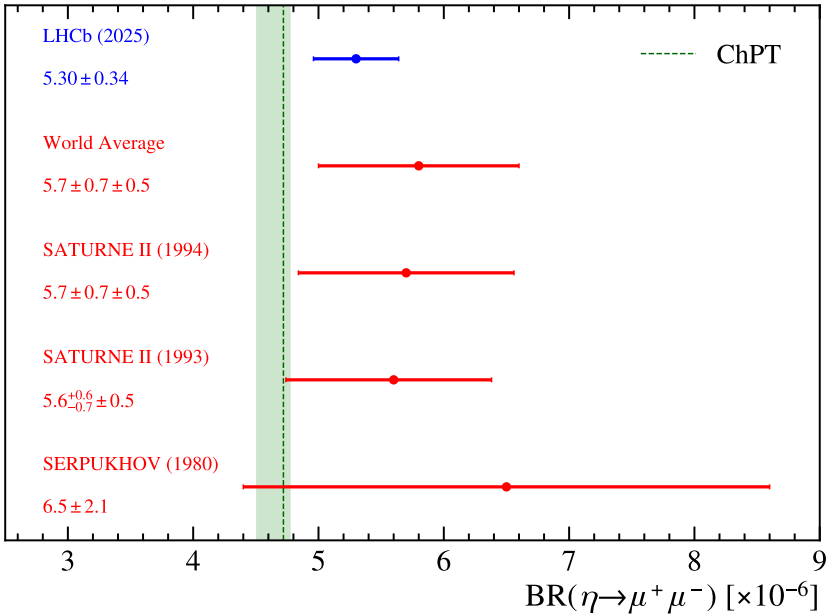
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
AGENCIA ESTATAL DE INVESTIGACIÓN
EXCELENCIA MARÍA DE MAEZTU 2024-2029
XUNTA DE GALICIA
CENTROS gusiR
Cofinanciado por la Unión Europea
Fondos Europeos

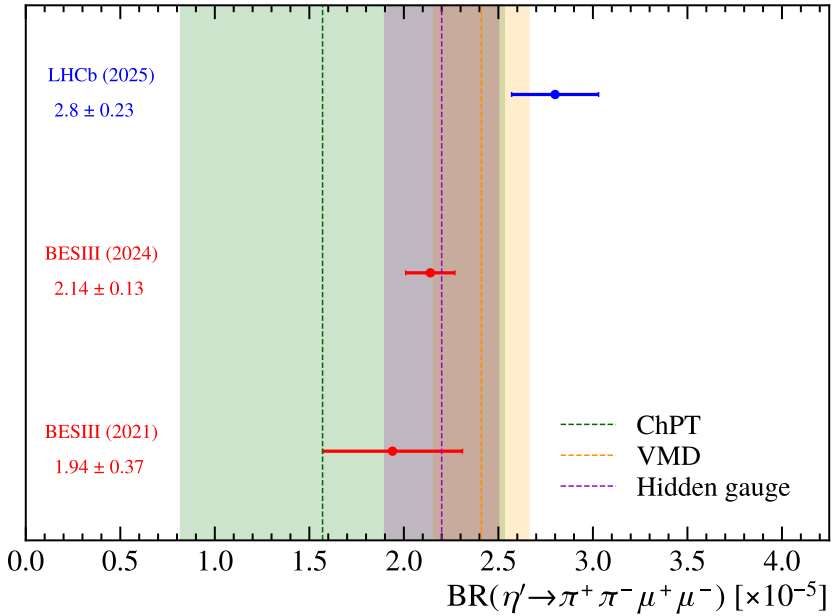
Backup

Sigma+ Motivation

- Very rare FCNC
  - Dominated by LD contributions
  - $\mathrm{BR}(\Sigma^+ \to p\mu^+\mu^-) = (1.8 - 5.8) \times 10^{-8}$ Phys.Rev.D 111 (2025) 1
- Attracted attention in the 00s when HyperCP reported first evidence, with potential hints at $\Sigma^+ \to p(X^0 \to \mu^+\mu^-)$ Phys.Rev.Lett. 94 (2005)
- LHCb has performed two searches
  - Run 1 search ($3\ \mathrm{fb}^{-1}$, Phys.Rev.Lett. 120 (2018) 22)
  - Run 2 search ($5.4\ \mathrm{fb}^{-1}$, Phys. Rev. Lett. 135 (2025))

η, η' measurements





Systematic Uncertainties

LHCb-CONF-2025-002

	$\eta \to \mu^+\mu^-$		$\eta' \to \mu^+\mu^-$		$\eta \to \pi^+\pi^-\mu^+\mu^-$		$\eta' \to \pi^+\pi^-\mu^+\mu^-$	
Source	D^+	D_s^+	D^+	D_s^+	D^+	D_s^+	D^+	D_s^+
$\frac{\mathcal{B}(D^+_{(s)}\to\phi\pi^+)}{\mathcal{B}(D^+_{(s)}\to\eta^{(\prime)}\pi^+)}$	3.4	3.4	4.5	3.5	3.4	3.4	4.5	3.5
$\mathcal{B}(\phi \to \mu^+\mu^-)$	5.1		5.1		5.1		5.1	
Trigger	0.9	0.4	0.2	0.3	5.3	1.7	2.7	1.7
BDT	0.6	1.4	4.3	1.4	—	—	0.9	1.3
PID	0.2	0.2	0.1	0.2	1.7	1.8	1.0	1.1
Tracking	2.2	2.2	2.2	2.2	3.3	3.2	3.2	3.1
Mass model	1.1		5.3		—		1.6	
Simulation size	0.4	0.5	0.8	0.9	1.1	1.9	1.5	2.9
N_{norm}	3.0	2.3	3.0	2.3	3.0	2.3	3.0	2.3
Total	7.3	7.1	9.3	7.6	9.6	8.2	8.8	7.9

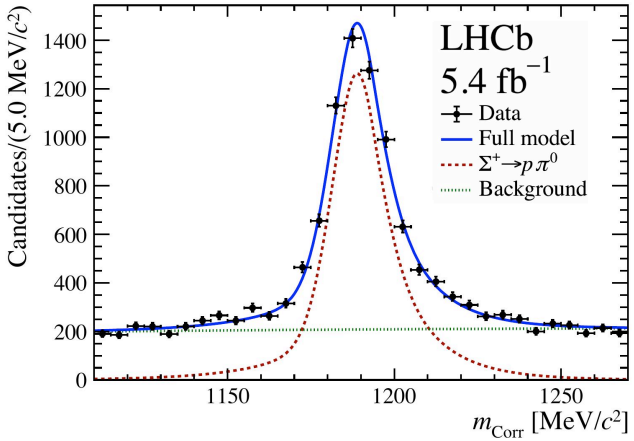
η,η' BF Computations

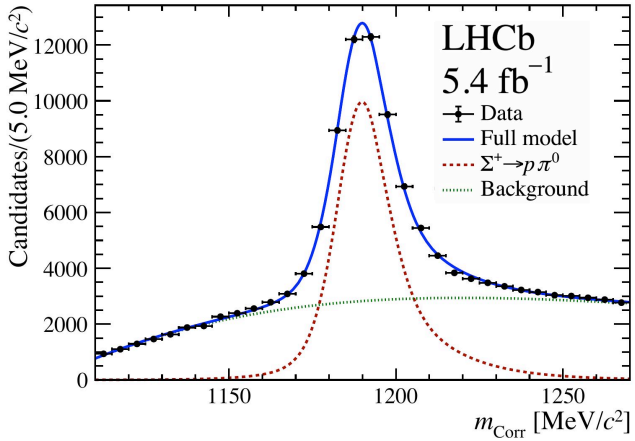
LHCb-CONF-2025-002

	$\eta \to \mu^+\mu^-$		$\eta' \to \mu^+\mu^-$	
Source	D^+	D_s^+	D^+	D_s^+
$\frac{\mathcal{B}(D^+_{(s)}\to\phi\pi^+)}{\mathcal{B}(D^+_{(s)}\to\eta^{(\prime)}\pi^+)}$	1.152 ± 0.052	2.663 ± 0.091	1.147 ± 0.052	1.139 ± 0.040
$\varepsilon_{\text{norm}}/\varepsilon_{\text{sig}}$	1.427 ± 0.011	1.384 ± 0.013	1.1039 ± 0.0039	1.0941 ± 0.0052
N_{norm} $(\times 10^3)$	90.59 ± 0.31	188.42 ± 0.46	87.22 ± 0.30	179.81 ± 0.44
α $(\times 10^{-9})$	7.25 ± 0.55	5.30 ± 0.38	4.45 ± 0.47	1.85 ± 0.16
	$\eta \to \pi^+\pi^-\mu^+\mu^-$		$\eta' \to \pi^+\pi^-\mu^+\mu^-$	
Source	D^+	D_s^+	D^+	D_s^+
$\frac{\mathcal{B}(D^+_{(s)}\to\phi\pi^+)}{\mathcal{B}(D^+_{(s)}\to\eta^{(\prime)}\pi^+)}$	1.152 ± 0.052	2.663 ± 0.091	1.147 ± 0.052	1.139 ± 0.040
$\varepsilon_{\text{norm}}/\varepsilon_{\text{sig}}$	56.66 ± 0.87	65.20 ± 0.19	26.01 ± 0.28	32.09 ± 0.60
N_{norm} $(\times 10^3)$	77.02 ± 0.36	125.52 ± 0.41	77.02 ± 0.36	125.52 ± 0.41
α $(\times 10^{-9})$	432 ± 41	418 ± 35	149 ± 13	91.0 ± 7.2

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

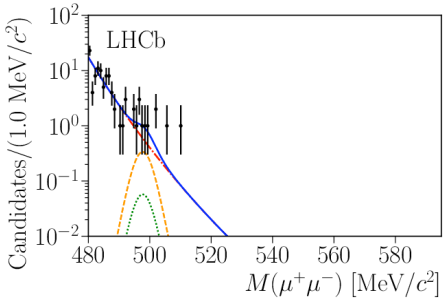
- $\Sigma^+ \to p\pi^0$ built from MinBias
- Fit to corrected mass, $m_{Corr} = m_{p\gamma\gamma} - m_{\gamma\gamma} + m_{\pi^0}^{PDG}$

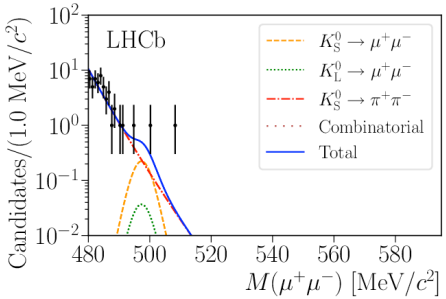




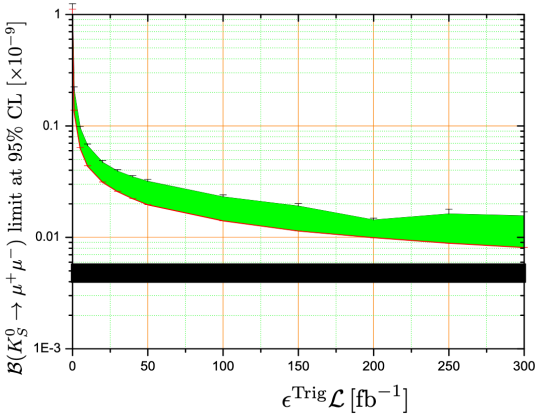
$K_S^0 \to \mu^+\mu^-$

Phys Rev. Lett. 125 (2020) 231801



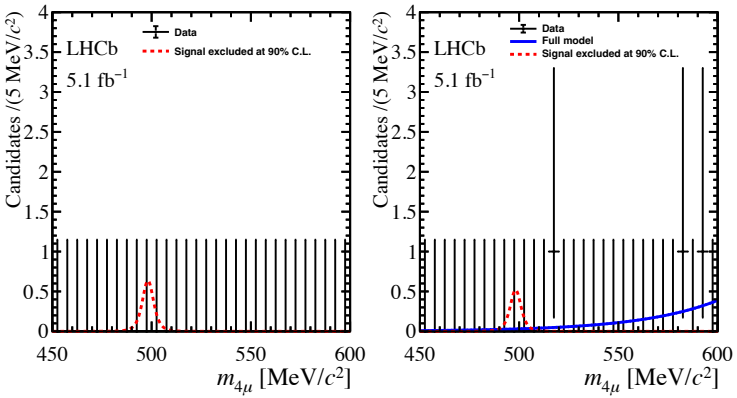


- Flagship (golden goose) of strange decays at LHCb
- Getting closer to SM prediction
- High hopes for Run 3 → software trigger is key



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

Phys Rev. D 108 (2023) L031102



- 2016—2018 search
- SM prediction around 10^{-14}
- LHCb set tight upper limit

$$\mathcal{B}(K_S^0 \to \mu^+\mu^-\mu^+\mu^-) < 5.1 \times 10^{-12},$$
$$\mathcal{B}(K_L^0 \to \mu^+\mu^-\mu^+\mu^-) < 2.3 \times 10^{-9},$$