Rare charm (and strange) decays at LHCb

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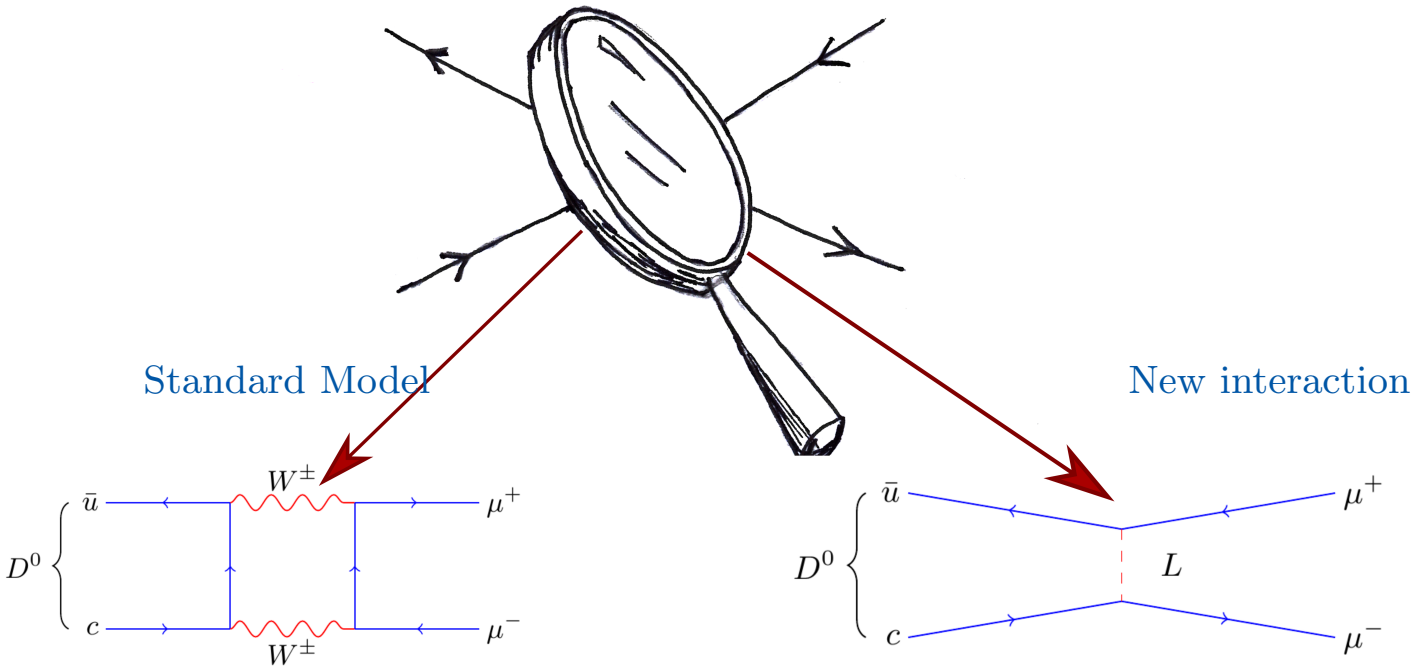
Introduction: Why search indirectly for new interactions?



- Precise predictions in the SM
- Rare phenomena → New interactions can be major contribution
- New interactions can have different symmetries from the SM
- Charm, strange and beauty probe complementary couplings

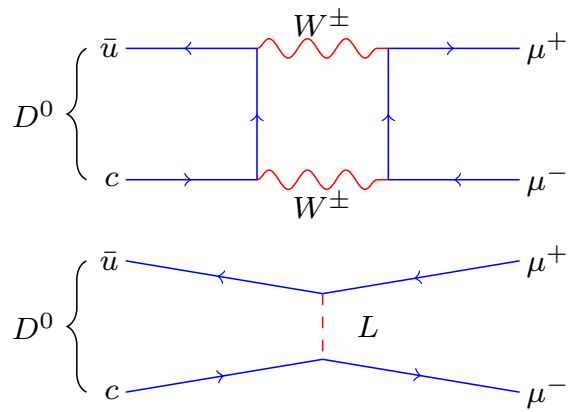
Over-constraining new interaction couplings is crucial to understand their origin

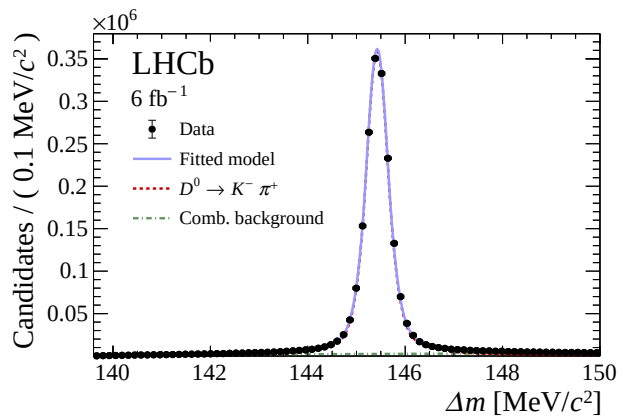
Search for the rare $D^0 \to \mu^+\mu^-$ decays

- Very rare FCNC
  - ⋆ GIM mechanism stronger in charm decays
  - ⋆ Helicity suppression
- Short distance at $\mathcal{B} \sim 10^{-18}$
- Long distance SM:
  $\mathcal{B}(D^0 \to \mu^+\mu^-) \simeq 2.7 \cdot 10^{-5} \cdot \mathcal{B}(D^0 \to \gamma\gamma) \lesssim 2.3 \cdot 10^{-11}$
  [Burdman et al.]
- Sensitivity to NP: many different models and complementary to B physics
  e.g. tree level contribution for some leptoquark model proposed for the "B anomalies"
- $\Rightarrow$ used as corner stone to constrain couplings for model building

Run1+2 analysis

- 9 fb^{-1}
- Search in $D^{*+} \to D^0\pi^+$ decays
- Double normalisation: $D^0 \to \pi^+\pi^-$ and $D^0 \to K^-\pi^+$



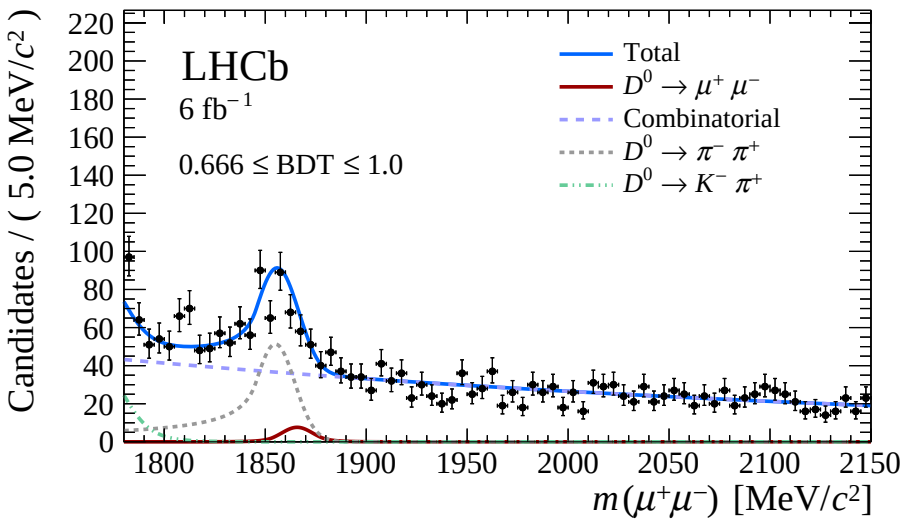


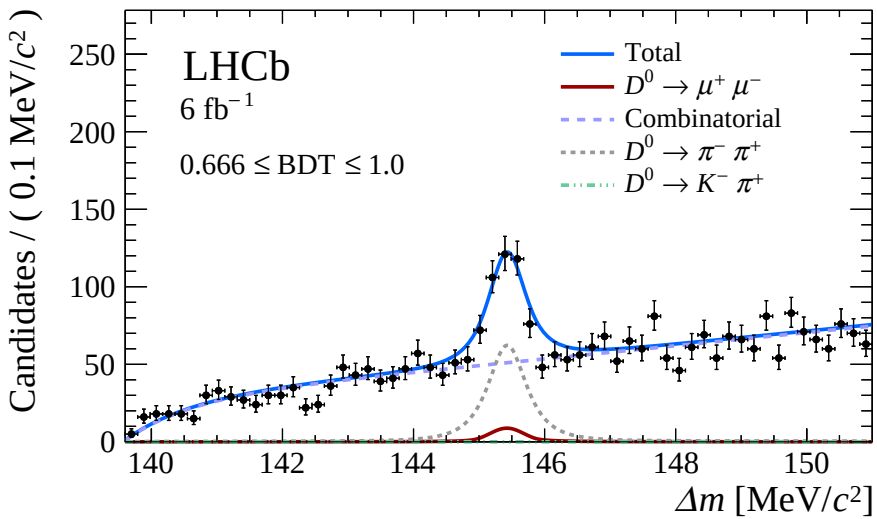
Phys. Rev. Lett. 131 (2023) 041804

Search for the rare $D^0 \to \mu^+\mu^-$ decays

Phys. Rev. Lett. 131 (2023) 041804

- Simultaneous 2-dimensional unbinned fit in 6 search regions: 2 Runs $\times$ 3 BDT intervals
- Main background: $D^{*+} \to D^0(\to \pi^+\pi^-)\pi^+$, precisely calibrated
- No excess over background
- World best upper limit

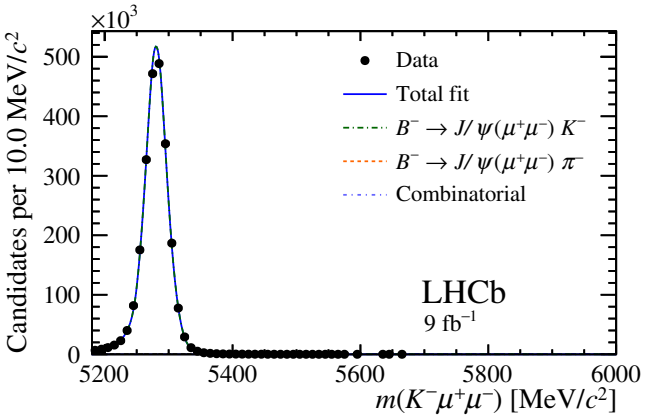




$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 3.1(3.5) \times 10^{-9} \quad \text{at } 90\% \ (95\%) \text{ CL}$$

Search for the rare $D^{*0}(2007) \to \mu^+\mu^-$ decays

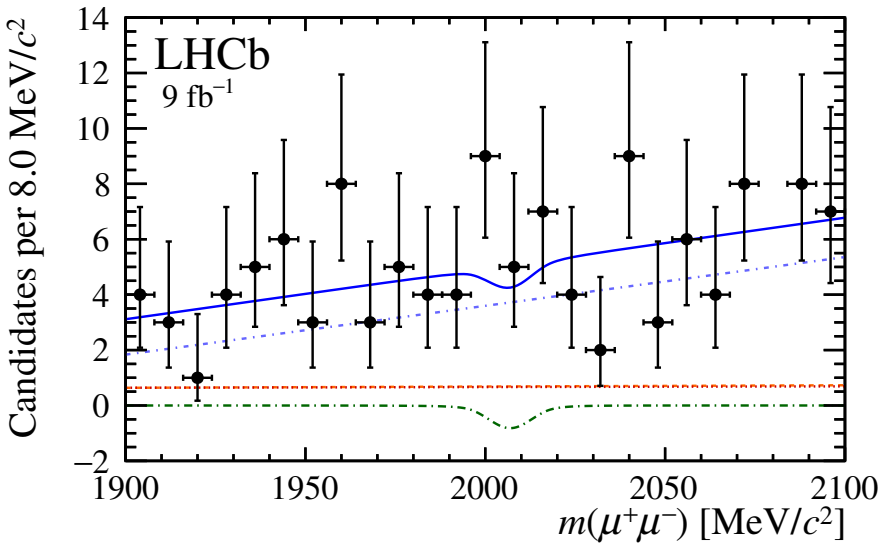
- No helicity suppression: sensitive to vector couplings
  complementary to $D^0 \to \mu^+\mu^-$
- Electromagnetic decay makes lifetime too short
  Search for $D^{*0}(2007) \to \mu^+\mu^-$ in
  $B^+ \to \pi^+ D^{*0}$ decays ($\mathcal{B} = 4.9 \times 10^{-3}$)
- Signature: reconstruct $B^+ \to \pi^+\mu^-\mu^+$ decays and search for a peak in dimuon mass
- Normalised to $B^+ \to J/\psi K^+$ decays

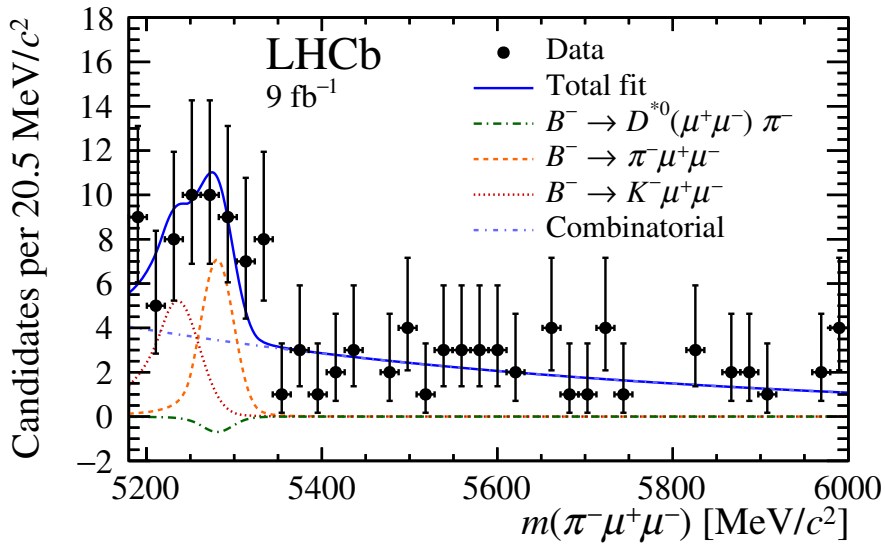


Eur. Phys. J. C 83, 666 (2023)

Search for the rare $D^{*0}(2007) \to \mu^+\mu^-$ decays

- Two-dimensional unbinned fit to the $m(\pi^-\mu^+\mu^-)$ and $m(\mu^+\mu^-)$ distributions
- Main background: combinatorial and mis-ID $B^+ \to K^+\mu^+\mu^-$





$$\mathcal{B}(D^{*0}(2007) \to \mu^+\mu^-) < 2.6(3.4) \times 10^{-8} \quad \text{at 90 (95)\% CL}$$

World first result on this channel.

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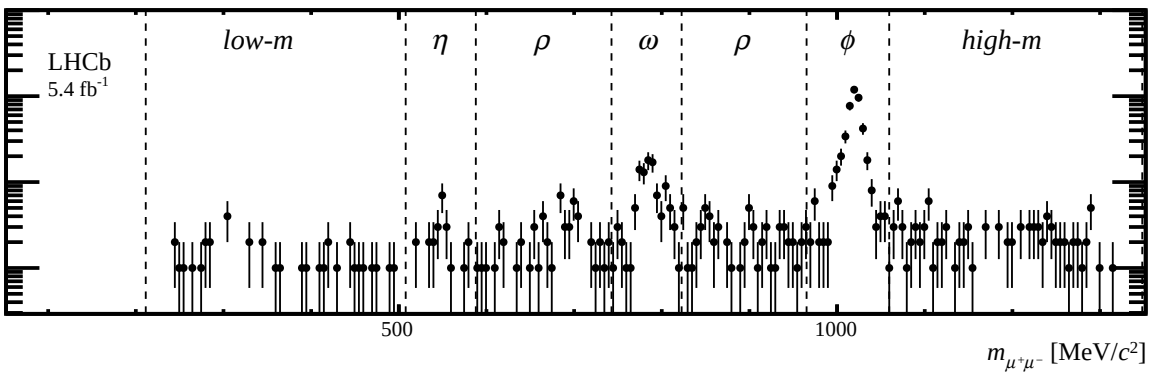
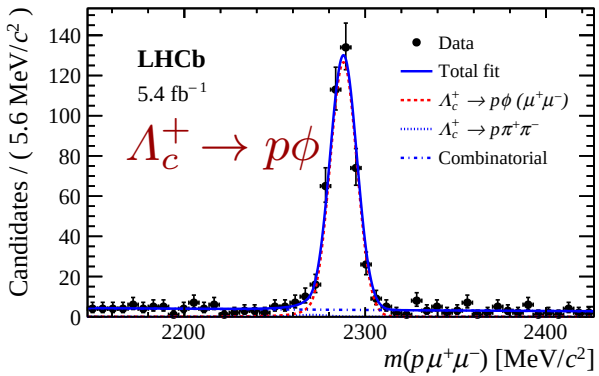
*See also a search for $B^* \to \mu^+\mu^-$ decays in $B_c^+ \to \pi^+\mu^+\mu^-$ G. Frau talk and [LHCb-PAPER-2024-026]

Search for (non-resonant) $\Lambda_c^+ \to p\mu^+\mu^-$ decays

- Non-resonant short-distance $c \to u\mu\mu$ $\mathcal{B} \sim 10^{-8}$
- ϕ, ρ, η, ω intermediate resonances
- Analysis using $5.4\,\text{fb}^{-1}$ at $13\,\text{TeV}$
- Normalised to $\Lambda_c^+ \to p\phi(\mu\mu)$
- No amplitude analysis done



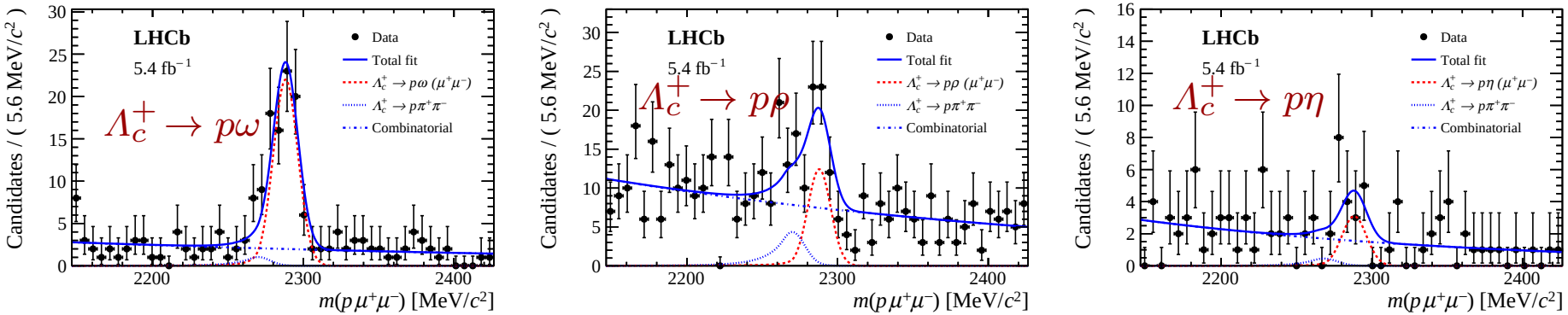


Region	Range [MeV/c^2]
low-m region	$211.32 < m_{\mu^+\mu^-} < 507.86$
high-m region	$1059.46 < m_{\mu^+\mu^-} < 1348.13$
η region	$507.86 < m_{\mu^+\mu^-} < 587.86$
ω region	$742.65 < m_{\mu^+\mu^-} < 822.65$
ρ region	$587.86 < m_{\mu^+\mu^-} < 742.65$
	or $822.65 < m_{\mu^+\mu^-} < 965.20$
ϕ region	$979.46 < m_{\mu^+\mu^-} < 1059.46$

LHCb-PAPER-2024-005 - In preparation

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

Resonant $\Lambda_c^+ \to p\omega$ ($> 7\sigma$)and $\Lambda_c^+ \to p\rho$ (5.6σ) observed and evidence (3.0σ) for $\Lambda_c^+ \to p\eta$



The corresponding branching fractions are determined to be

$$\mathcal{B}(\Lambda_c^+ \to p\omega) = (9.82 \pm 1.23\ (\text{stat.}) \pm 0.73\ (\text{syst.}) \pm 2.79\ (\text{ext.})) \times 10^{-4},$$

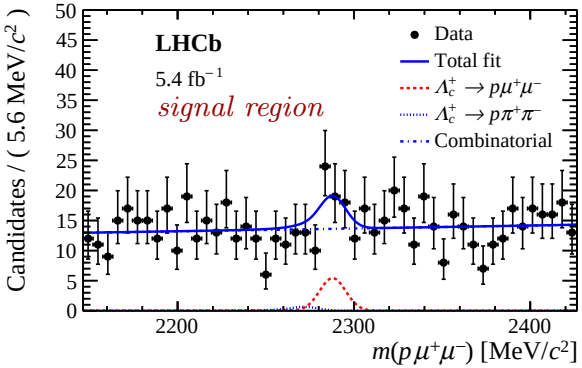
$$\mathcal{B}(\Lambda_c^+ \to p\rho) = (1.52 \pm 0.34\ (\text{stat.}) \pm 0.14\ (\text{syst.}) \pm 0.24\ (\text{ext.})) \times 10^{-3},$$

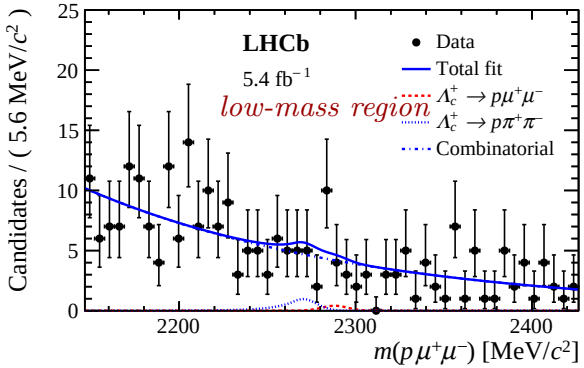
$$\mathcal{B}(\Lambda_c^+ \to p\eta) = (1.67 \pm 0.69\ (\text{stat.}) \pm 0.23\ (\text{syst.}) \pm 0.34\ (\text{ext.})) \times 10^{-3},$$

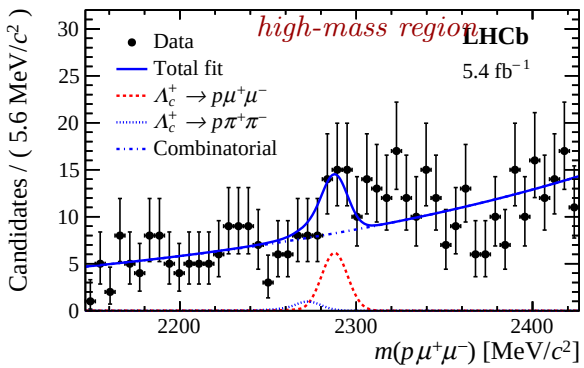
Branching fractions in the considered regions, non-resonant and interferences possibly are included.

Search for (non-resonant) $\Lambda_c^+ \to p\mu^+\mu^-$ decays

No evidence for $\Lambda_c^+ \to p\mu^+\mu^-$ decays in the non-resonant regions







$$\frac{\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-)}{\mathcal{B}(\Lambda_c^+ \to p\phi)\mathcal{B}(\phi \to \mu^+\mu^-)} < 0.09\ (0.10) \quad \text{at} \quad 90\%\ (95\%)\ \text{CL.}$$

Using the values of the branching fractions for $\Lambda_c^+ \to p\phi$ and $\phi \to \mu^+\mu^-$ decays from PDG

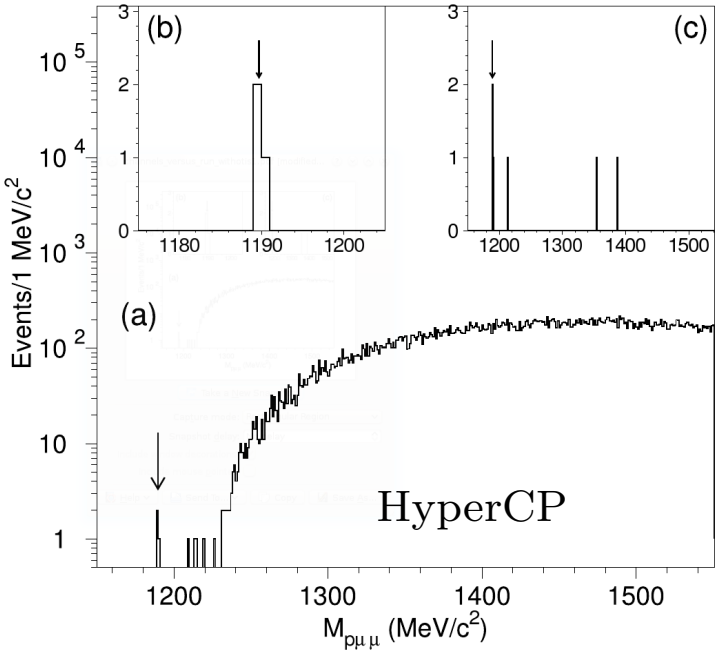
$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 2.9\ (3.2) \times 10^{-8} \quad \text{at} \quad 90\%\ (95\%)\ \text{CL.}$$

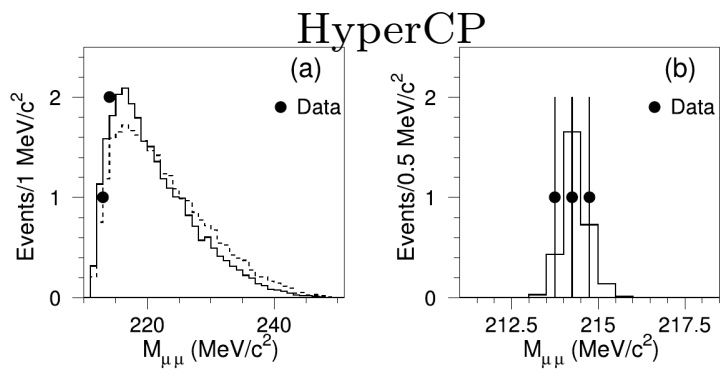
LHCb-PAPER-2024-005 - In preparation

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:
  $1.2 \cdot 10^{-8} < \mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) < 10.2 \cdot 10^{-8}$
  [Xiao-Gang He et al. - Phys.Rev. D72 (2005) 074003]
  [Xiao-Gang He et al. - JHEP 1810 (2018) 040]
- Evidence found by the HyperCP experiment with 3 events in absence of background
- Measured branching fraction was:
  $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \cdot 10^{-8}$
  [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
  $\mathcal{B}(\Sigma^+ \to pX^0(\to \mu\mu)) = (3.1^{+2.4}_{-1.9} \pm 5.5) \cdot 10^{-8}$

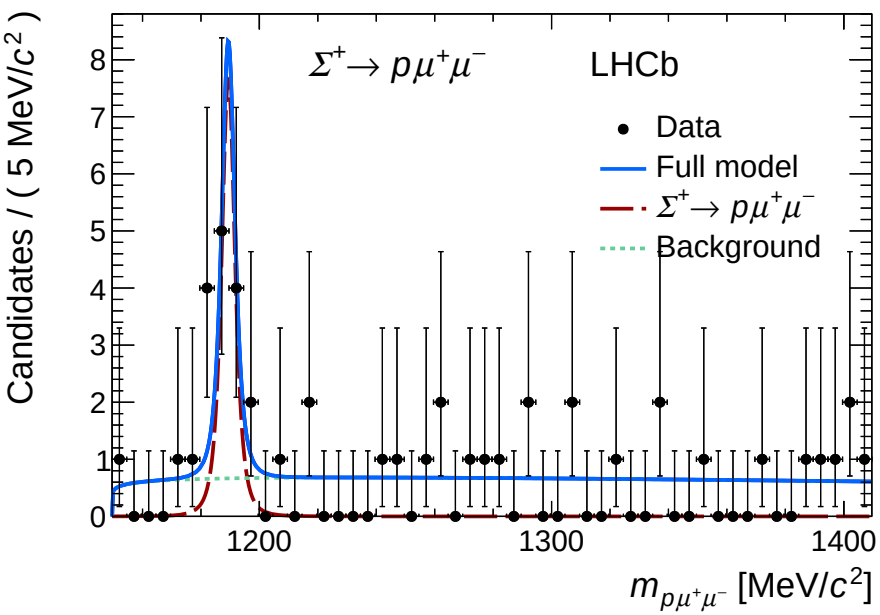




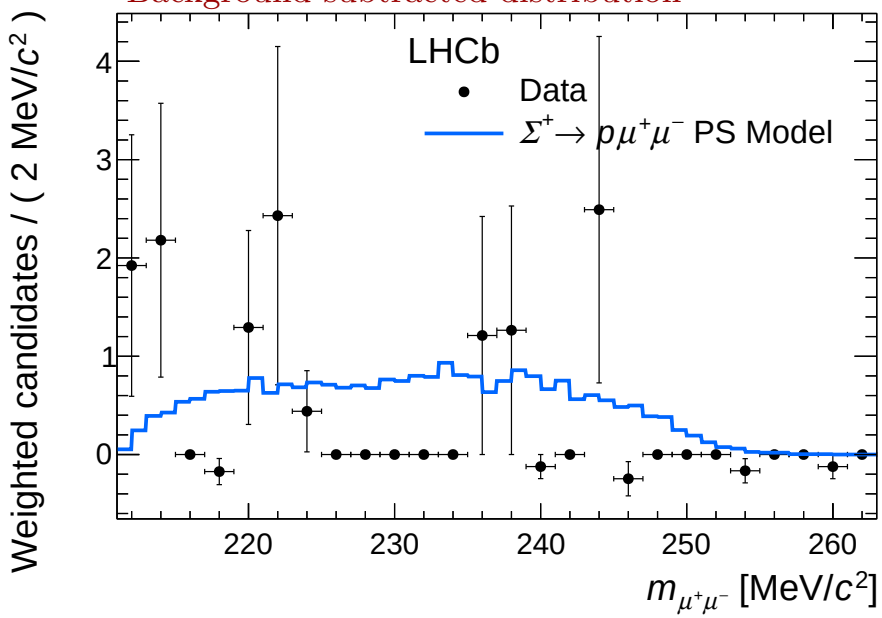
LHCb Run 1 analysis

- Σ hyperons in LHCb
  - ⋆ long lifetime and very small p_{T}, but
  - ⋆ very high production (about 1/10 of minimum bias events)
- 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 $(2.2\,^{+\,0.9\,+\,1.5}_{-\,0.8\,-\,1.1}) \times 10^{-8}$
- $\mathcal{B}(\Sigma^+ \to pX^0(\to \mu^+\mu^-)) < 1.4 \times 10^{-8}$ at 90%CL excluding the HyperCP result

PRL 120, 221803 - arXiv:1712.08606



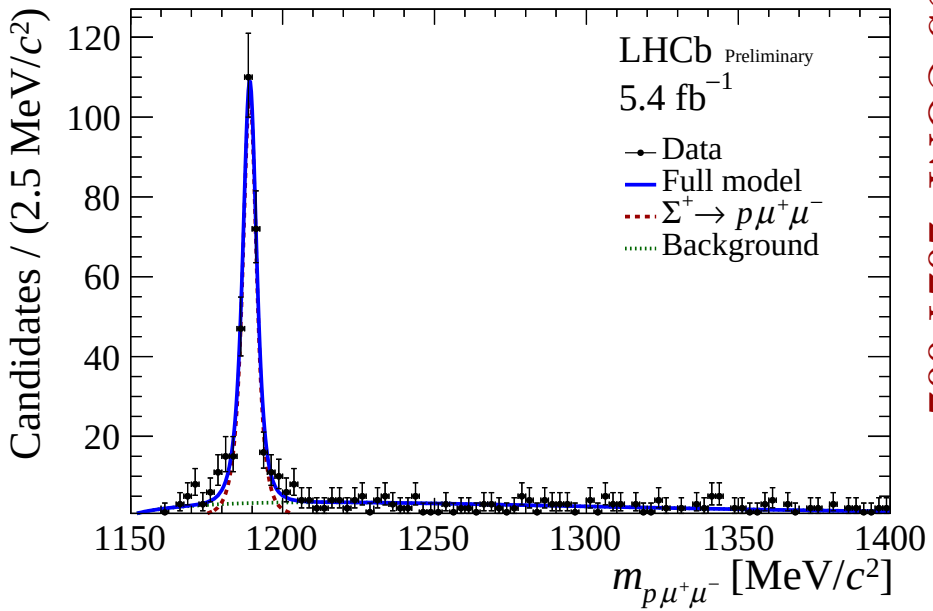
Background subtracted distribution



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

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



LHCb-CONF-2024-002

$$N(\Sigma^+ \to p\mu^+\mu^-) = 279 \pm 19$$

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

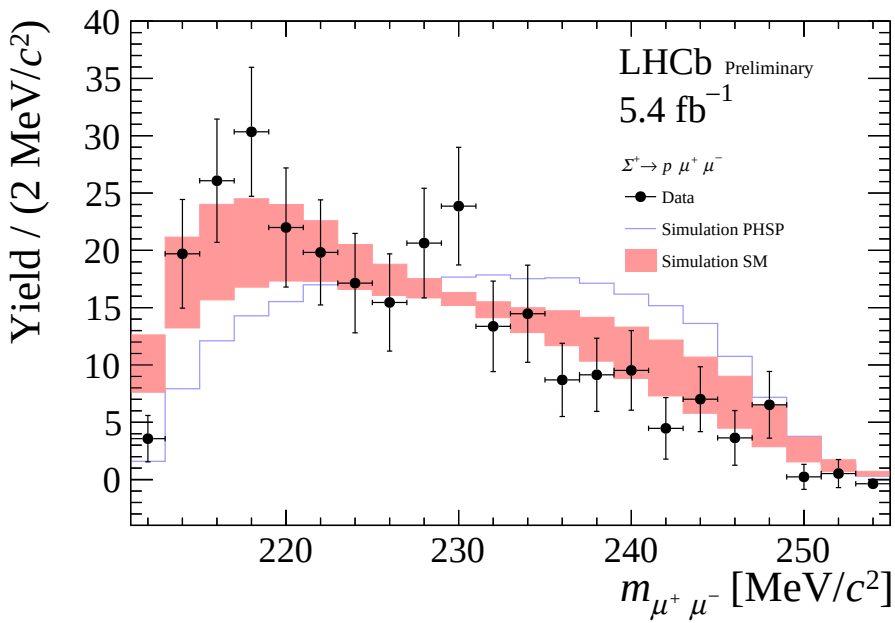
Rarest hyperon (possibly rarest baryon) decay every observed

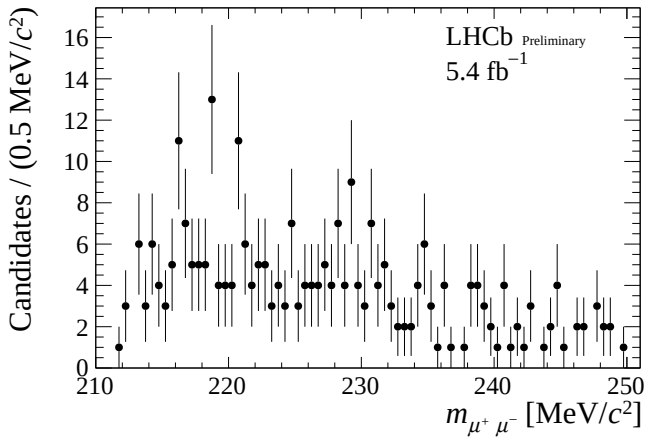
- Paper in preparation with integrated branching fraction measurement
- Possible other measurements: CP violation and forward backward asymmetry

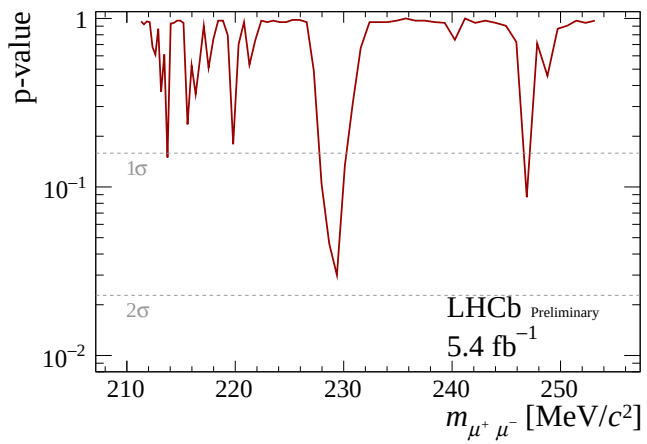
Observation of the $\Sigma^+ \to p\mu^+\mu^-$ decay

- Search for resonances in the dimuon invariant mass distribution
- No reasonance found, contribution at 214 MeV is negligible
- Distribution compatible with SM prediction

[He et al. JHEP 10 (2018) 040] [Roy et al. hep-ph/2404.15268]







LHCb-CONF-2024-002

Conclusion

- LHCb leading results on rare charm decays:
- World best limit on $D^0 \to \mu^+\mu^-$ strongly constraints NP models in their $cu\ell\ell$ couplings
- First limit on $D^{*0}(2007) \to \mu^+\mu^-$ complementary on vector currents
- Search for non-resonant $\Lambda_c^+ \to p\mu^+\mu^-$ decays and observation of resonant ones
- First observation of $\Sigma^+ \to p\mu^+\mu^-$ compatible with SM
  expanding the LHCb program to hyperons

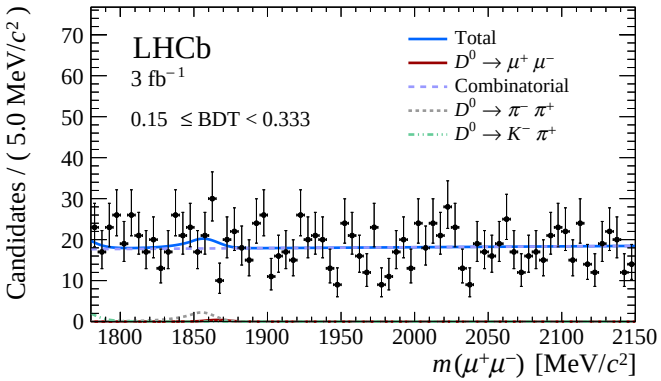
Other rare charm and strange results

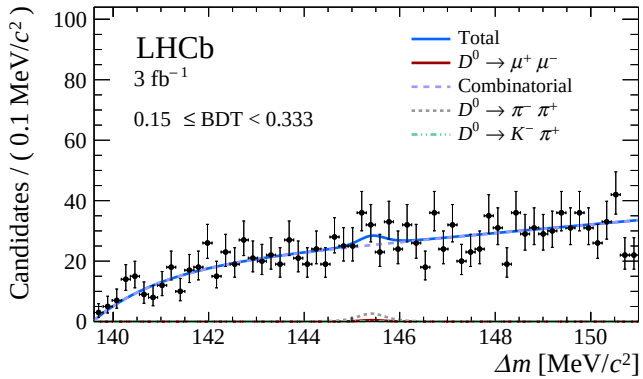
- ⋆ Search for $K^0_{S(L)} \to \mu^+\mu^-\mu^+\mu^-$ [Phys. Rev. D 108 (2023) L031102]
- ⋆ Strong constraints on the $K^0_s \to \mu^+\mu^-$ branching fraction [Phys. Rev. Lett. 125 (2020) 231801]
- ⋆ Angular Analysis of $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$ Decays and Search for CP Violation [Phys. Rev. Lett. 128 (2022) 221801]
- ⋆ Searches for 25 rare and forbidden decays of D^+ and D^+_s mesons [JHEP06(2021)044]

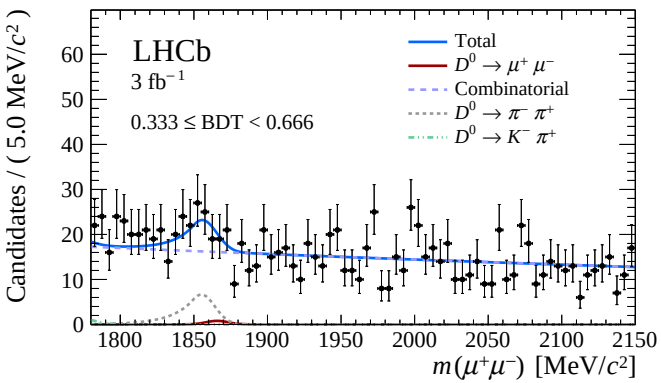
Backup slides

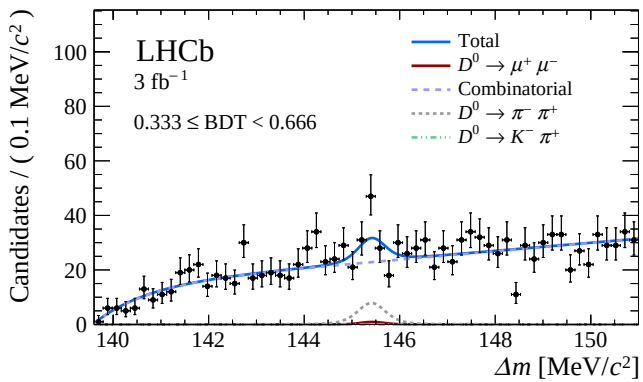
Search for the rare $D^0 \to \mu^+\mu^-$ decays

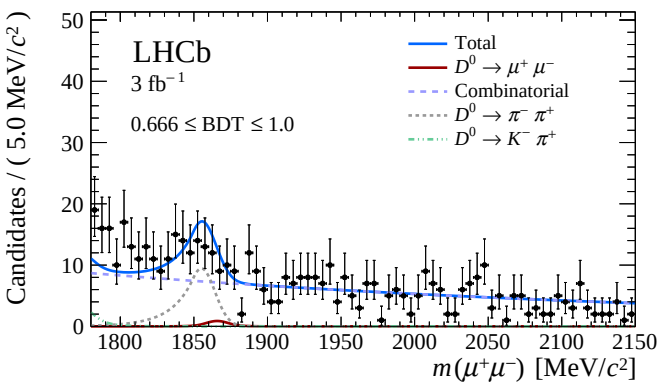
Run 1 - All BDT bins - Each cut in the signal regions of the other variable.

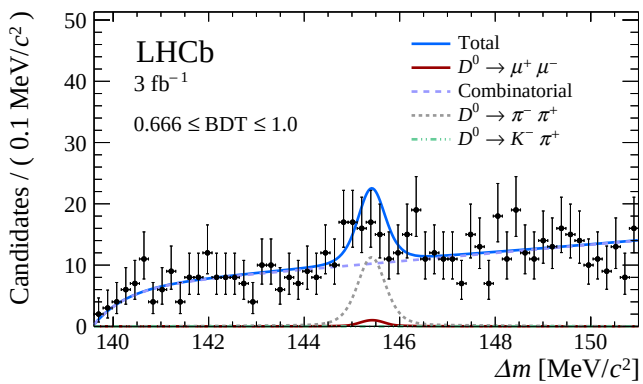












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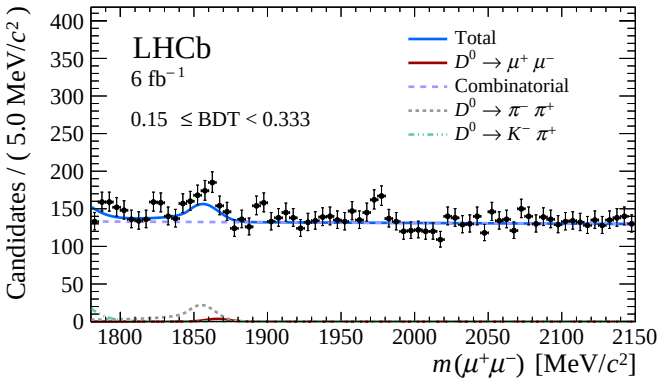
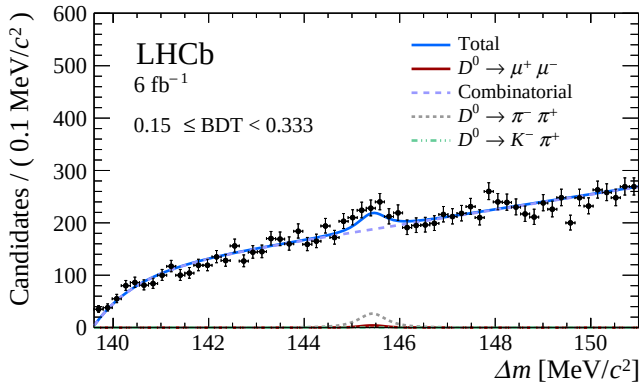
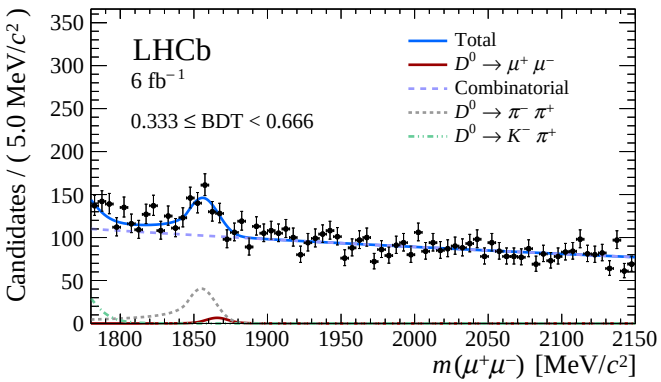
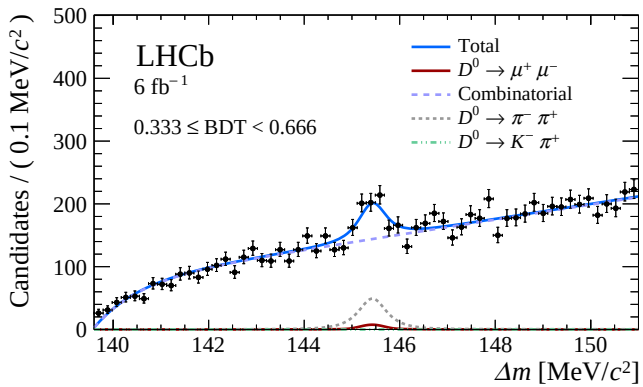
Search for the rare $D^0 \to \mu^+\mu^-$ decays

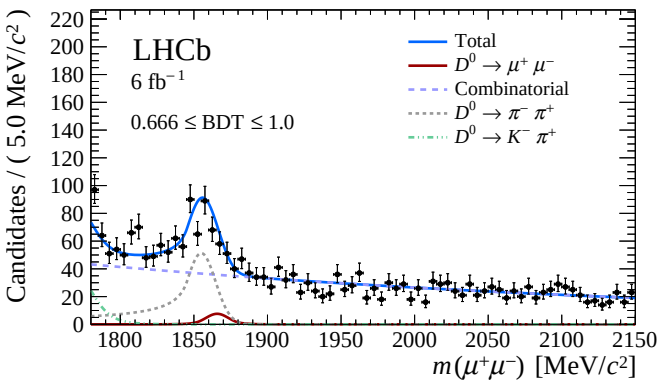
Run 2 - All BDT bins - Each cut in the signal region of the other variable.

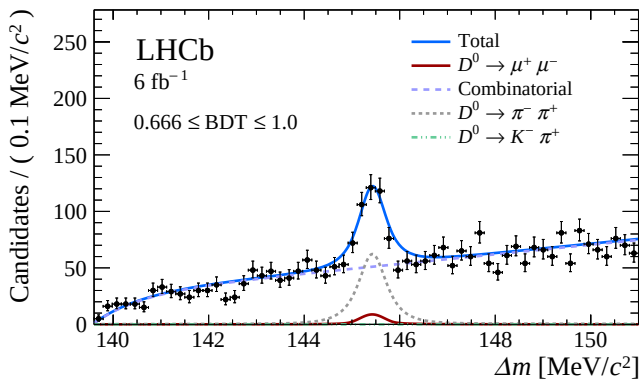












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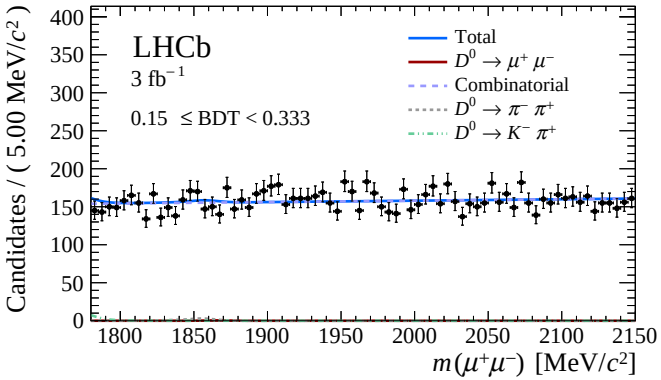
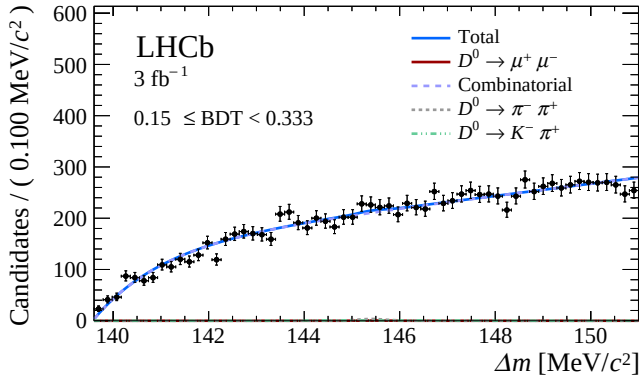
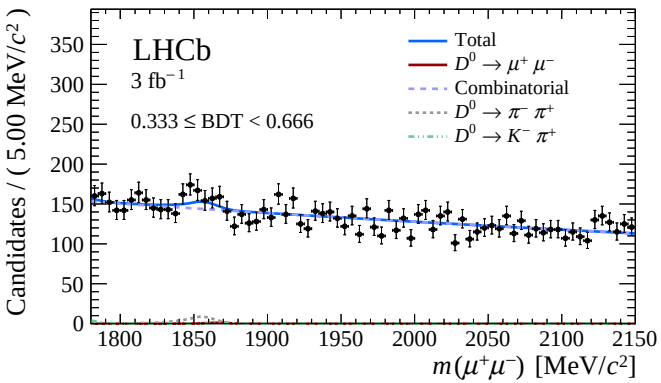
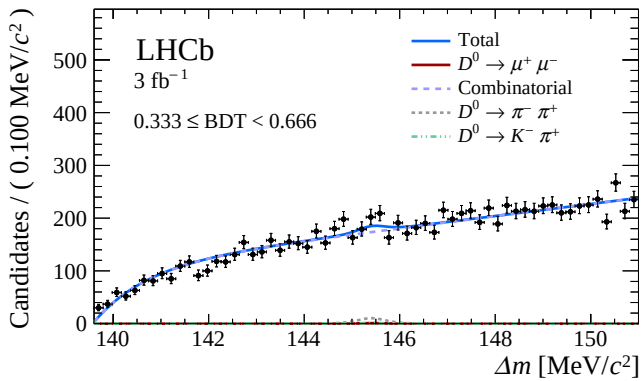
Search for the rare $D^0 \to \mu^+\mu^-$ decays

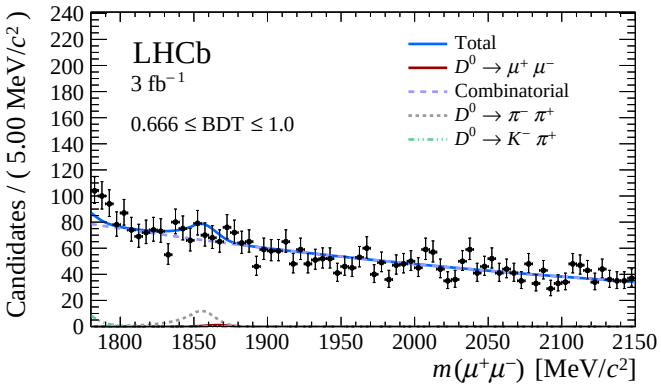
Run 1 - All BDT bins - All data.

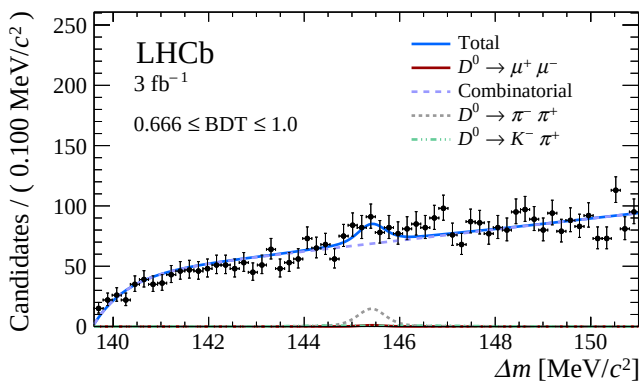












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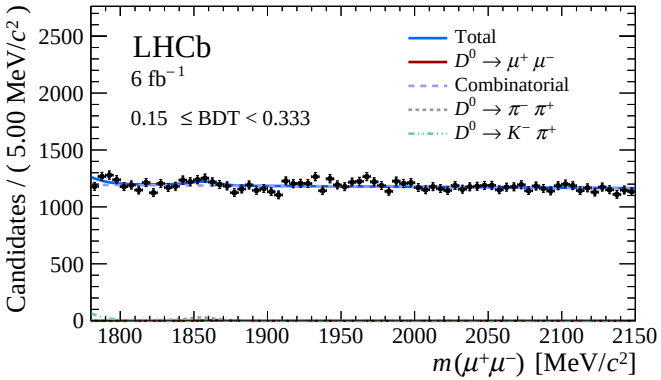
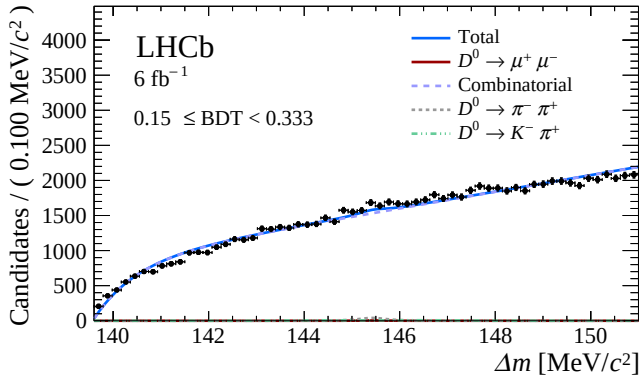
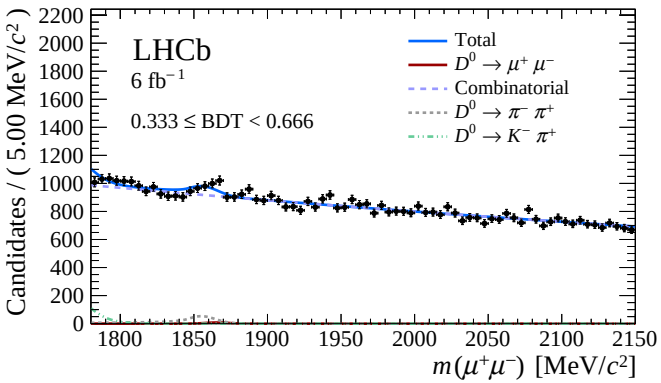
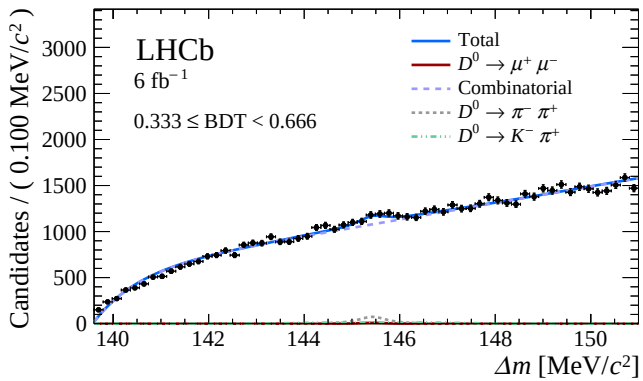
Search for the rare $D^0 \to \mu^+\mu^-$ decays

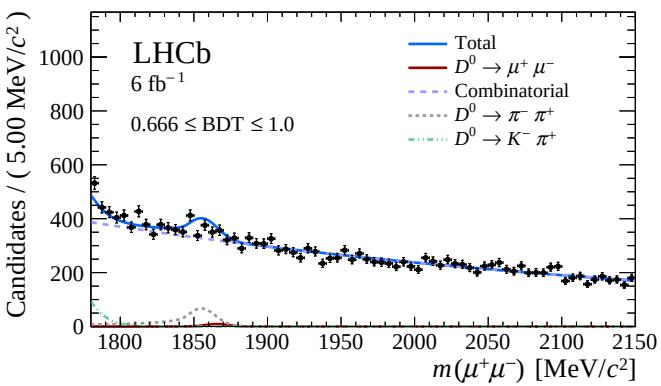
Run 2 - All BDT bins - All data.

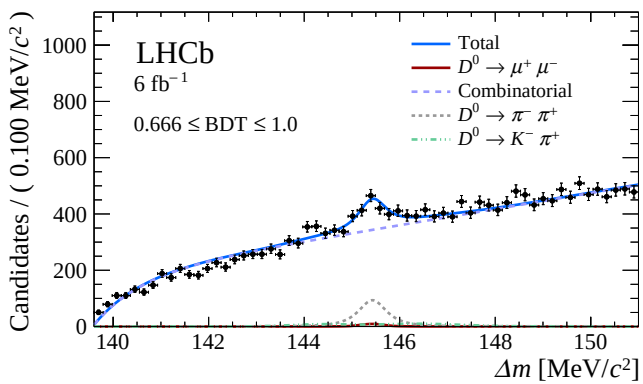






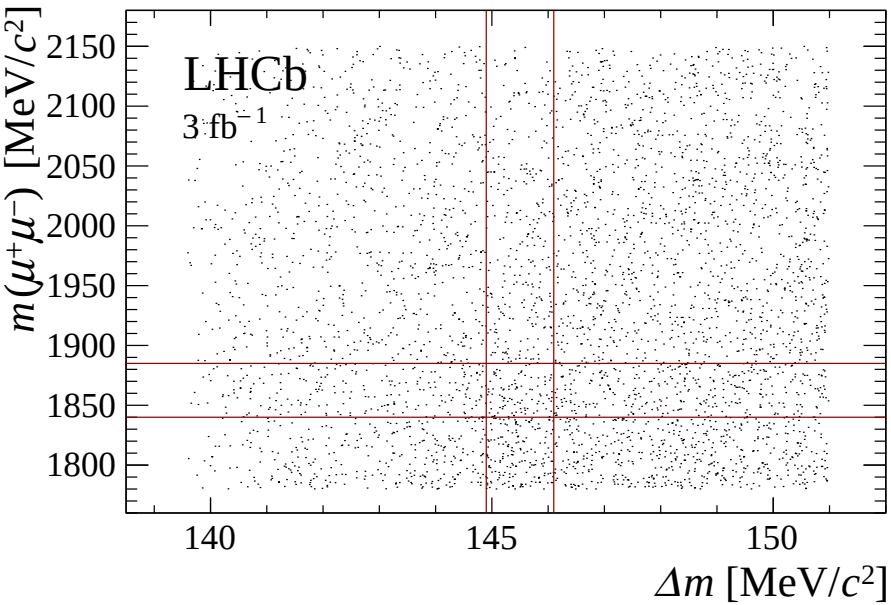


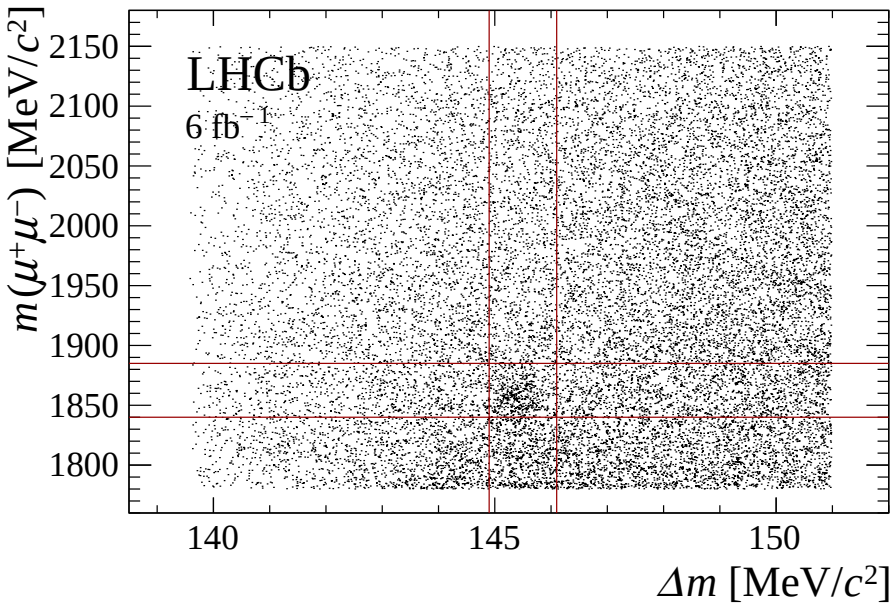




Phys. Rev. Lett. 131 (2023) 041804

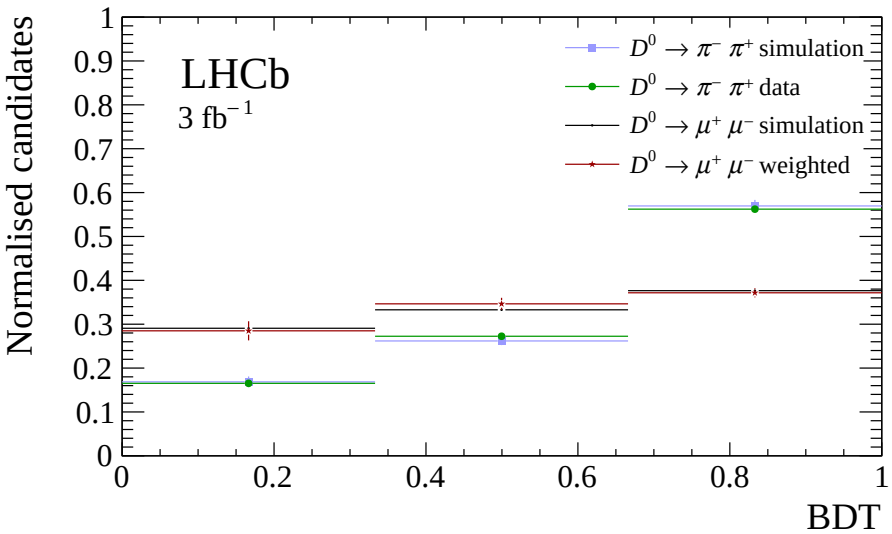
Search for the rare $D^0 \to \mu^+\mu^-$ decays

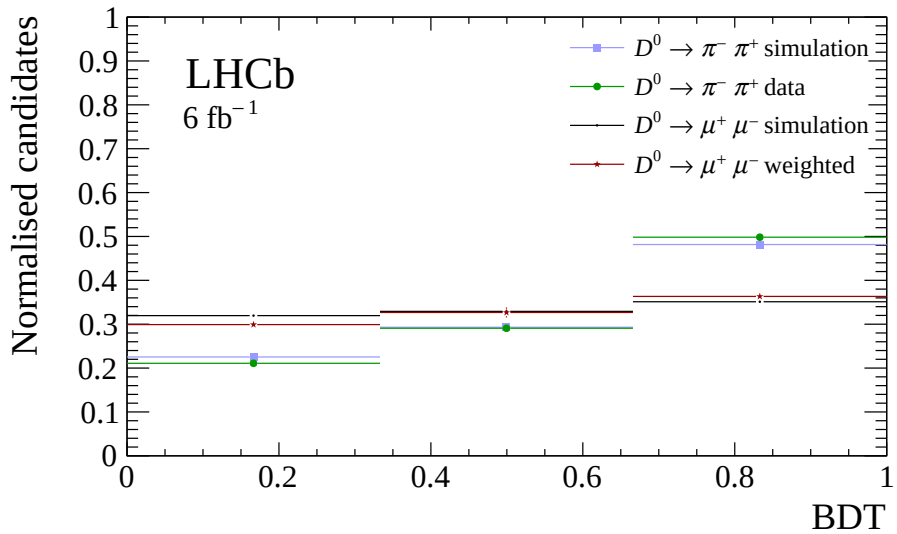


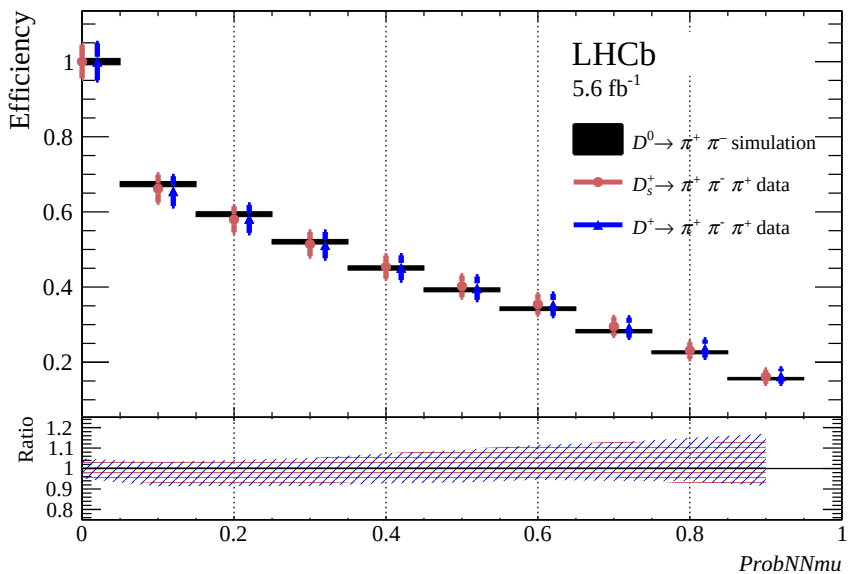


Phys. Rev. Lett. 131 (2023) 041804

Search for the rare $D^0 \to \mu^+\mu^-$ decays







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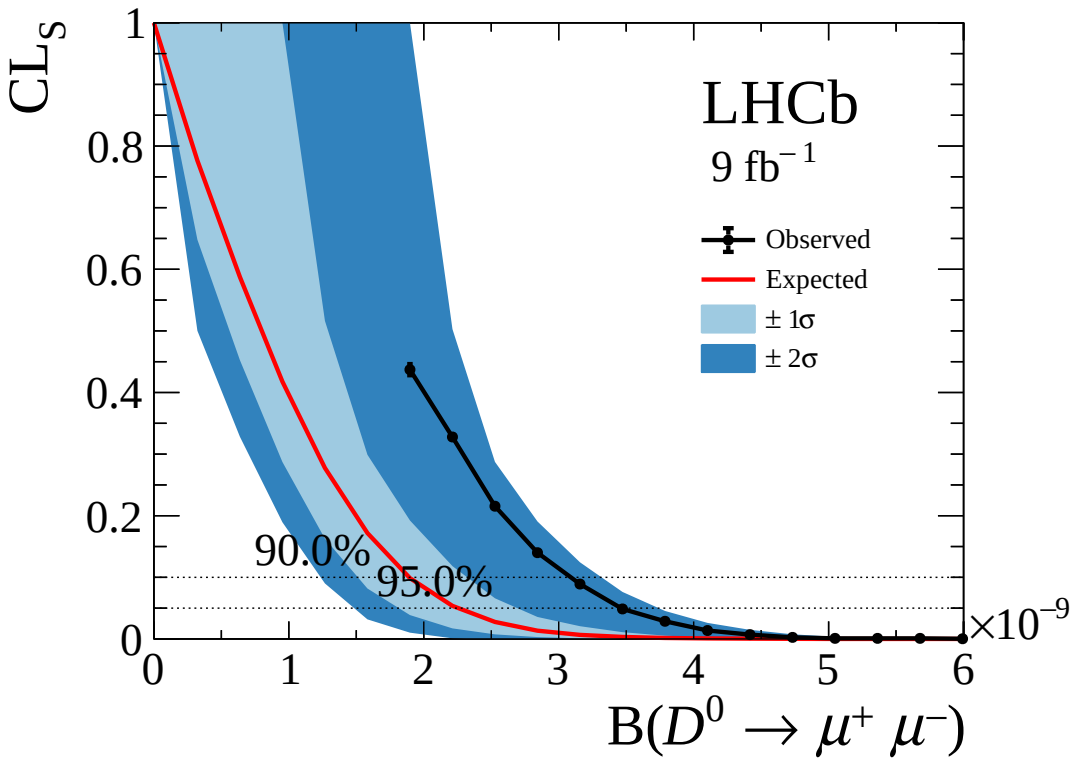
Search for the rare $D^0 \to \mu^+\mu^-$ decays



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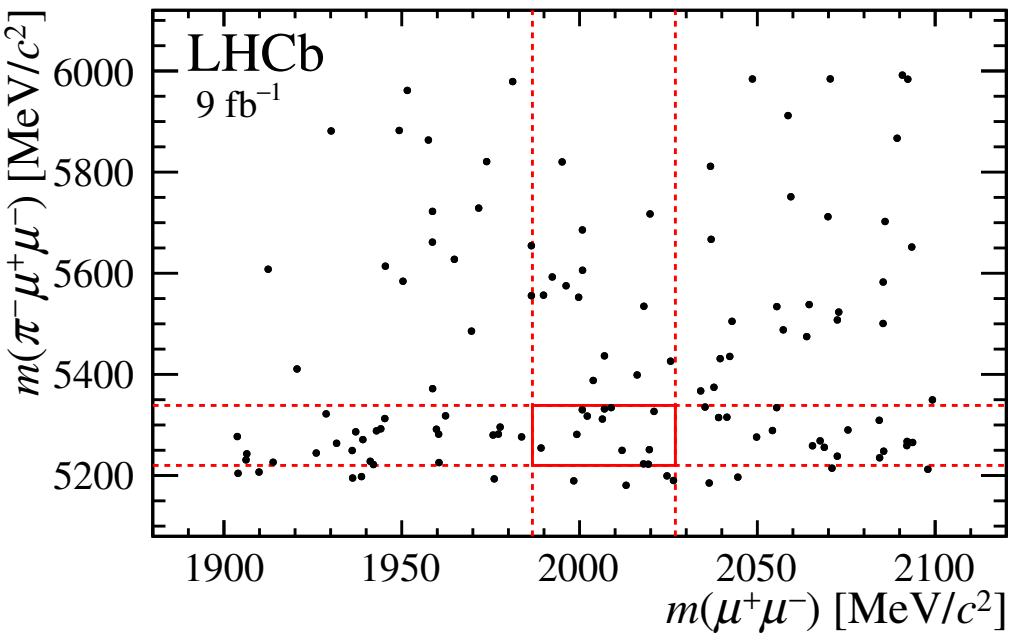
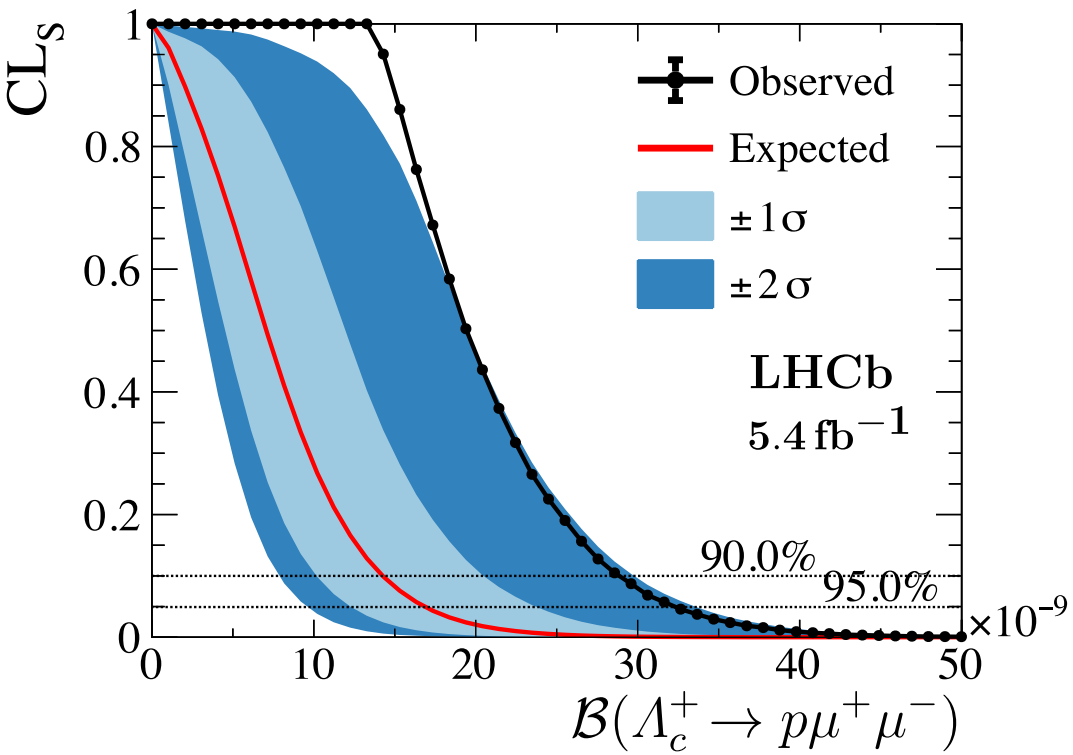
Search for the rare $D^{*0}(2007) \to \mu^+\mu^-$ decays



Eur. Phys. J. C 83, 666 (2023)

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



LHCb-PAPER-2024-005

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

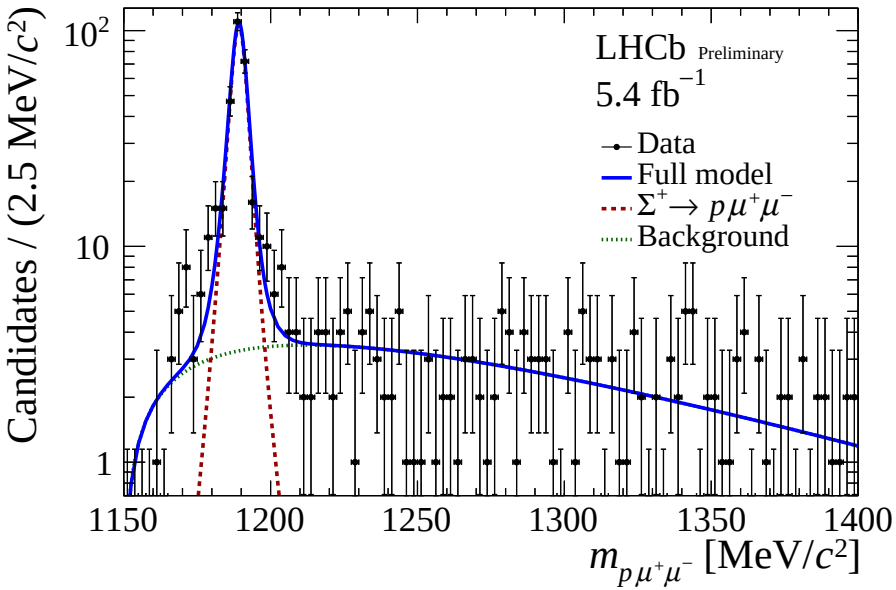
Table: Results of the fit to the $p\mu^+\mu^-$ invariant-mass distribution for various $m_{\mu\mu}$ regions. The significance of the $\Lambda_c^+ \to p\mu^+\mu^-$ component is also given.

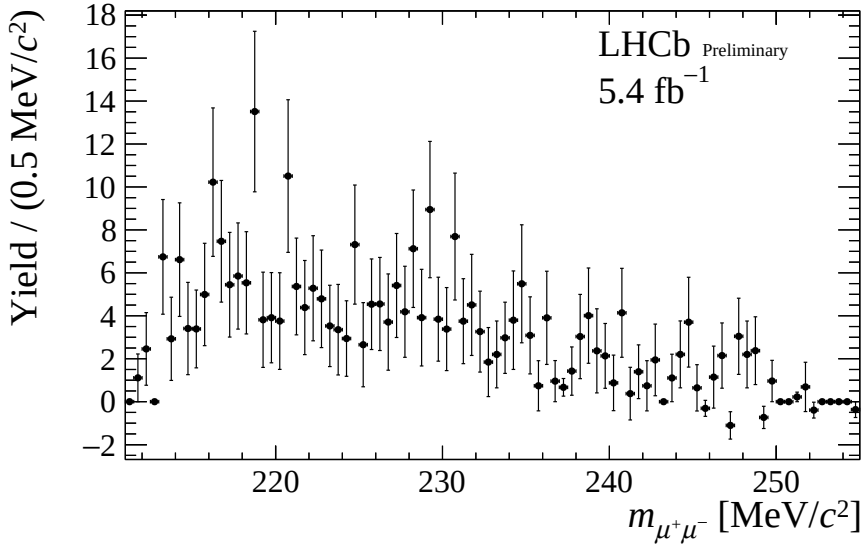
Region	$\Lambda_c^+ \to p\mu^+\mu^-$ yield	$\Lambda_c^+ \to p\pi^+\pi^-$ yield	Combinatorial yield	Significance $\Lambda_c^+ \to p\mu^+\mu^-$
signal	18 ± 10	3 ± 7	681 ± 28	2.0σ
low-m	1 ± 5	4 ± 4	241 ± 17	0.3σ
high-m	21 ± 8	4 ± 4	432 ± 22	2.8σ
η	12 ± 5	2.2 ± 1.6	84 ± 10	3.0σ
ρ	43 ± 10	20 ± 6	382 ± 22	5.6σ
ω	81 ± 10	4.8 ± 2.1	101 ± 11	$> 7\sigma$
ϕ	423 ± 22	3.8 ± 2.4	173 ± 15	$> 7\sigma$

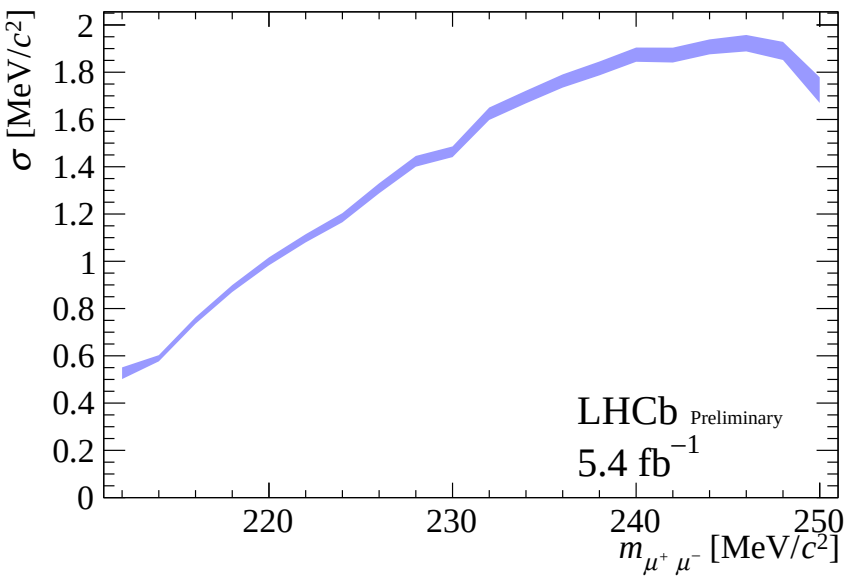
Table: Summary of systematic uncertainties for the signal regions and for the η, ρ and ω resonant regions.

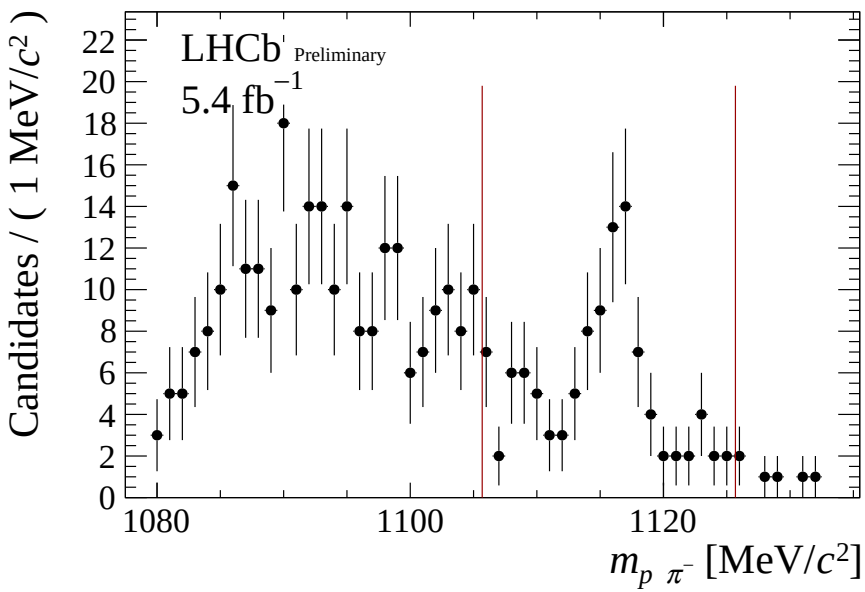
Uncertainty source [%]	*signal*	*low-m*	*high-m*	η	ρ	ω
Normalisation channel	5.3	5.3	5.3	5.3	5.3	5.3
Efficiency ratio (stat.)	5.7	8.2	6.8	12.9	5.3	4.6
Efficiency ratio (syst.)	1.7	1.7	1.7	1.7	1.7	1.7
Shape of signal	1.6	3.4	1.1	0.6	1.7	1.2
Shape of $\Lambda_c^+ \to p\pi^+\pi^-$	0.1	3.2	0.2	0.4	5.3	1.2
Shape of combinatorial	0.1	0.3	0.2	0.1	0.0	0.0
$\Lambda_c^+ \to p\pi^+\pi^-$ decay model	0.1	0.1	0.1	0.1	0.1	0.1
Fit bias	0.1	0.1	0.2	0.3	0.1	0.1
Total	8.1	11.0	8.9	14.1	9.5	7.4

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



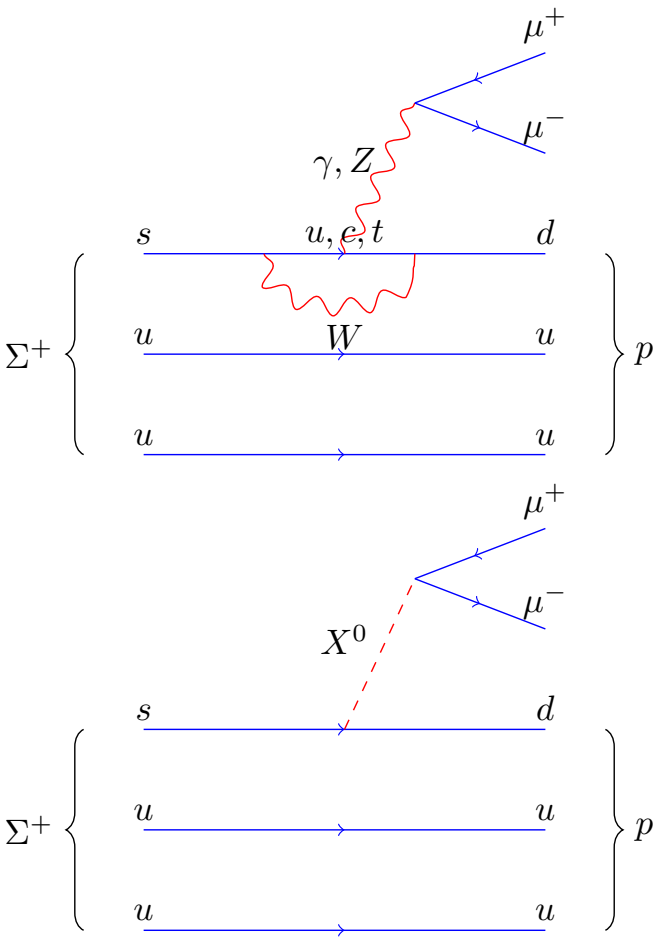


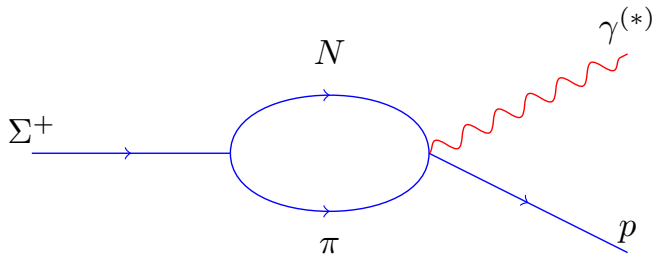




LHCb-CONF-2024-002

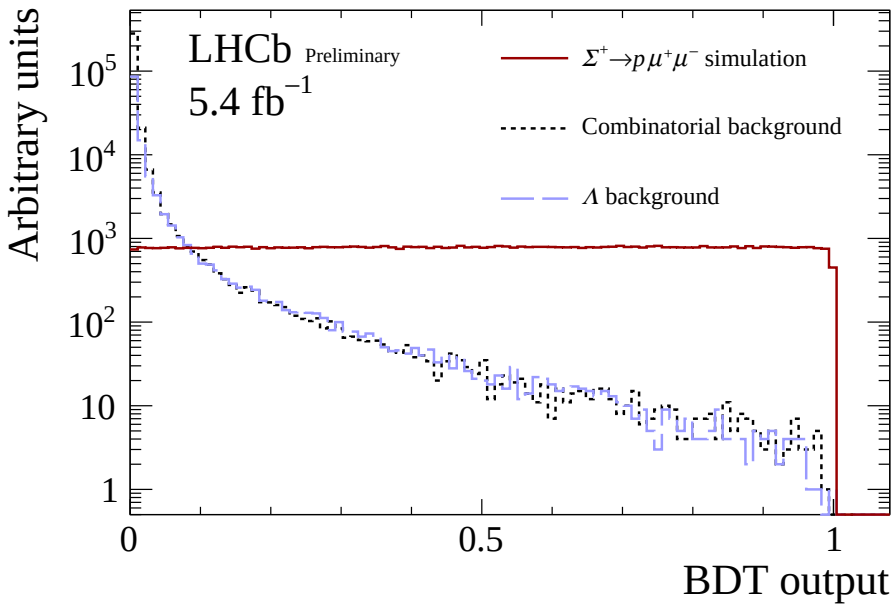
Observation of the $\Sigma^+ \to p\mu^+\mu^-$ decay





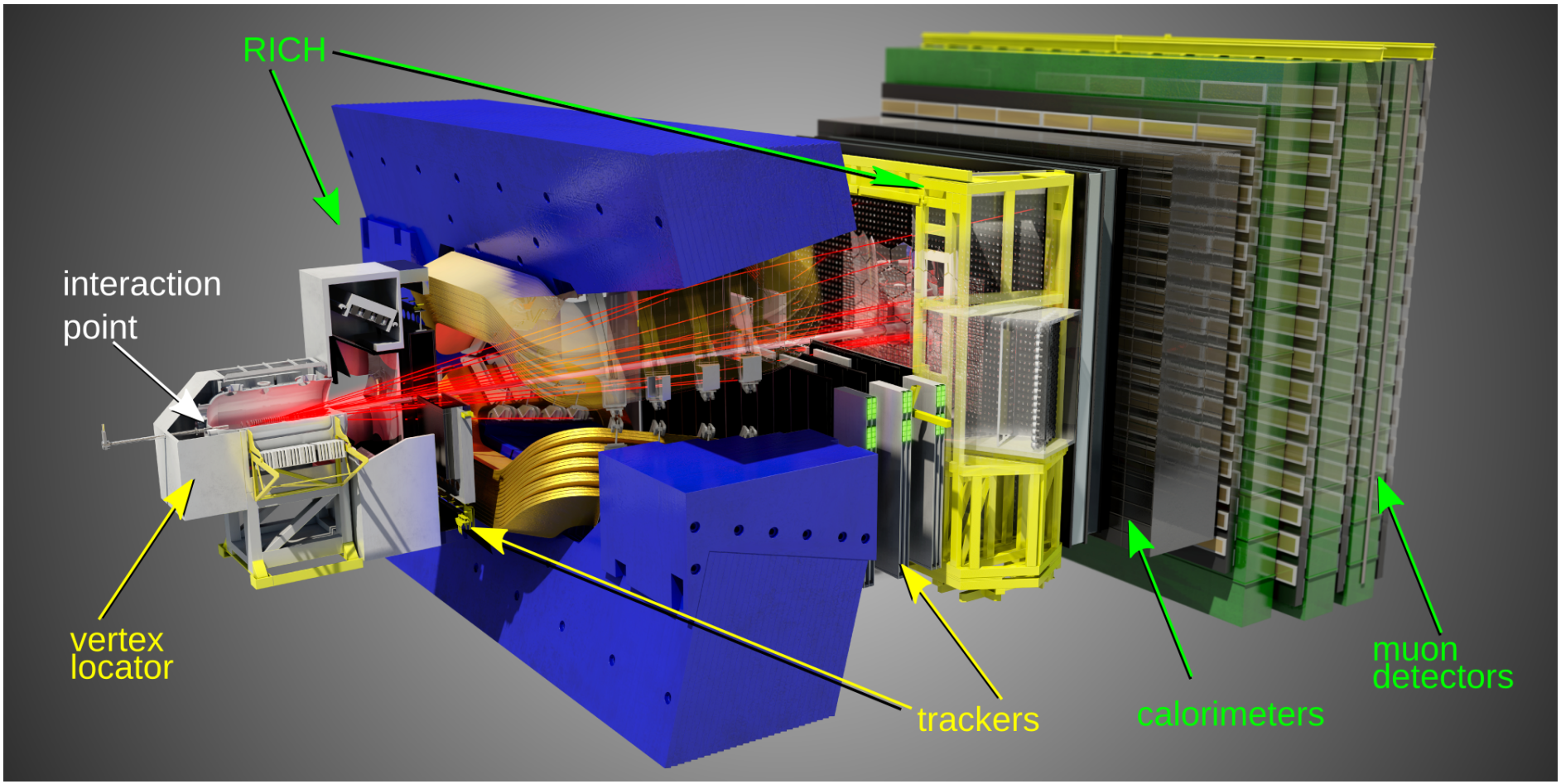
LHCb-CONF-2024-002

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



LHCb-CONF-2024-002

LHCb experiment

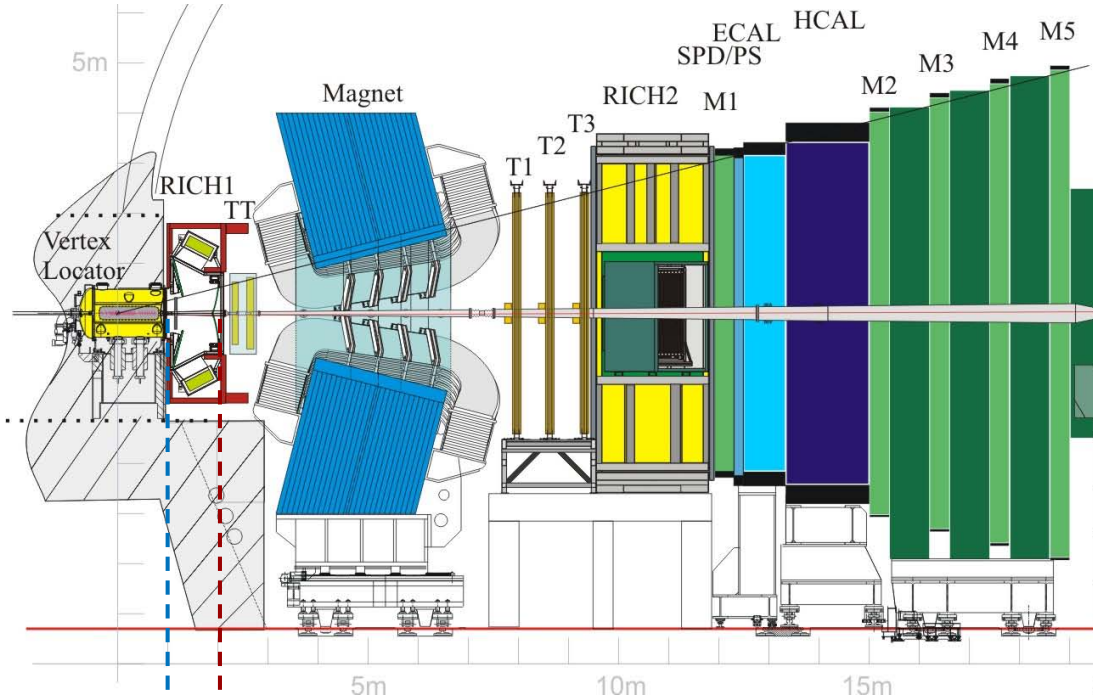


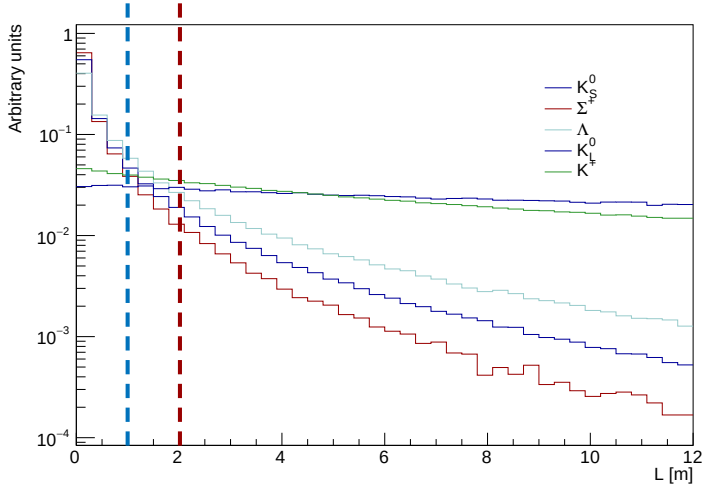
[Int. J. Mod. Phys. A 30 (2015) 1530022]

- 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

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 dedicate software reconstruction for soft muons