Rare Charm & Strange Decays @ LHCb

Liang Sun

Wuhan University

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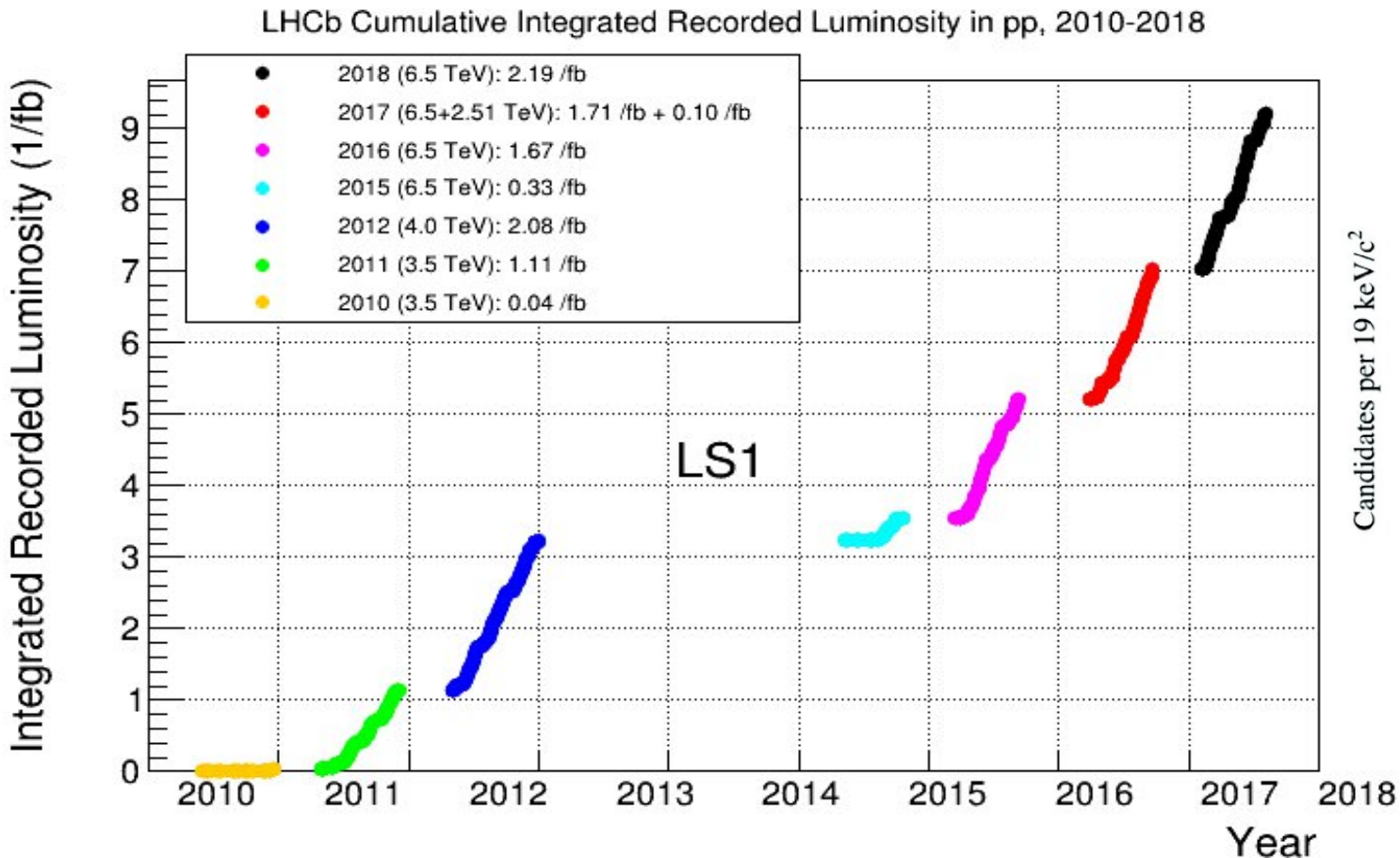
Outline

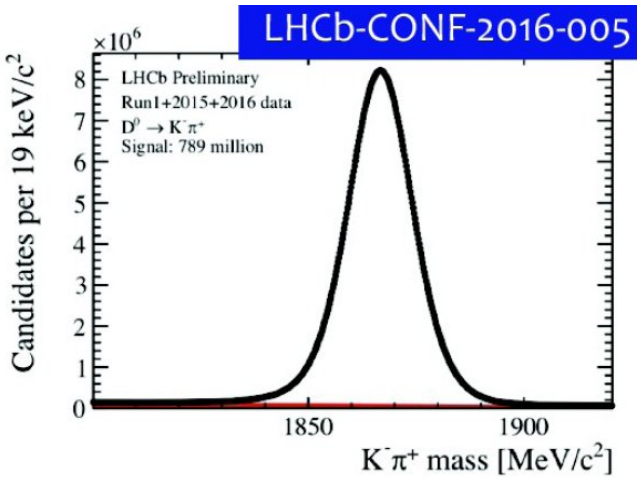
- Rare charm decays @ LHCb
- Rare strange decays @ LHCb
- Summary & prospects

LHCb: a charm factory

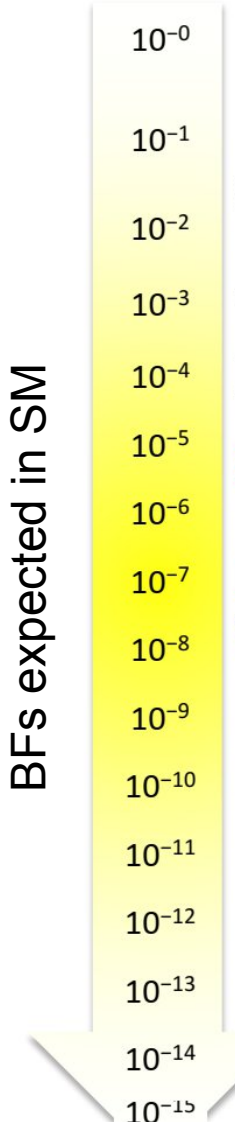
- **levelled** instantaneous luminosity of $\mathcal{L} = 4 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Run 1: $\sim 3\,\mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 7\text{-}8\,\mathrm{TeV}$
- Run 2: $\sim 6\,\mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$
- $\sigma(pp \to Q\bar{Q}X) \propto \sqrt{s} \Rightarrow$ 4x b- and c-hadrons in Run 2

More than 1B of $D^0 \to K^-\pi^+$ events reconstructed with full LHCb data sample





Summary of charm decays



Charm provide a unique environment for testing the SM rare/forbidden decays and searching for NP

Complementary information to B and K sectors with down-type quarks

Cabibbo favor

Single Cabibbo suppressed

Doubly Cabibbo suppressed

Radiative decays

$D^0 \to K^{*0}\gamma/\phi\gamma/\omega\gamma/\rho\gamma$

$D^+_{(s)} \to K^{*+}\gamma/\rho^+\gamma$

Long distance:
Vector meson Dominance (SM)

$D^{0+} \to \gamma\gamma/VV'(l^+l^-)/\ hV(l^+l^-)/\ hh'V(l^+l^-)$

Rare decays

Short distance FCNC (SM+NP)

$D^{0/+} \to \gamma\gamma/Vl^+l^-/hl^+l^-/hh'l^+l^-$

$D^0 \to \mu^+\mu^-/e^+e^-$

$D \to (hh)\mu^+\mu^+/(hh)e^+e^+$

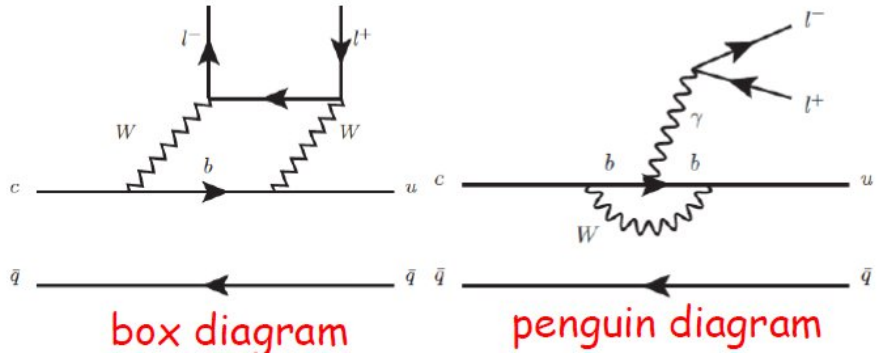
$D \to (h)\mu^+e^-$

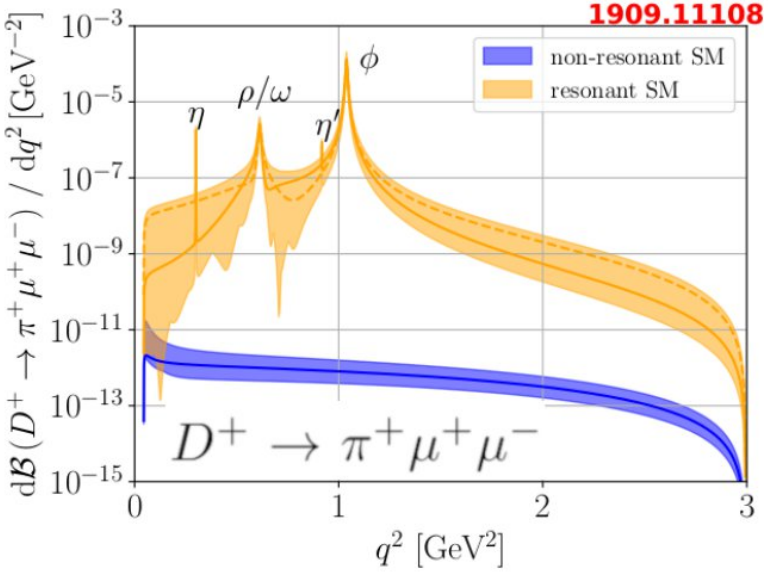
$D \to (h)pe^-$

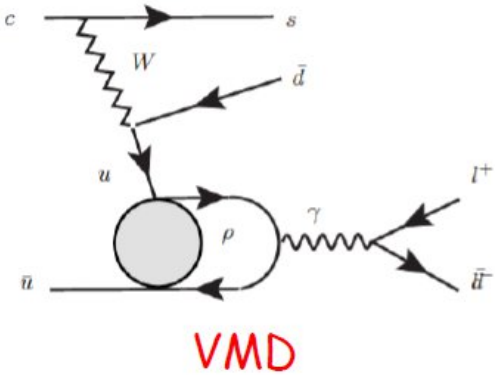
(NP)
Forbidden decays: LNV, LFV, BNV

Flavor **C**hanging **N**eutral **C**urrents

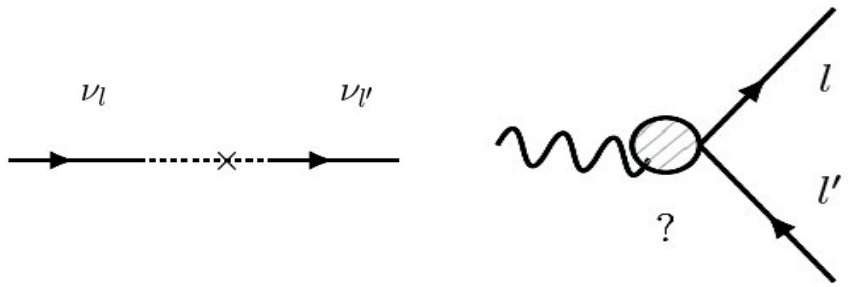
- Forbidden at tree level in SM, only allowed in loop and box diagrams
  - Strongly suppressed due to GIM cancellation:
  - BF ~O(10^{-9})
- $D \to X\ell^+\ell^-$ dominated by Long-Distance contributions
  - Vector Meson dominance (VMD)
  - BF ~O(10^{-6})
- No VMD in $D \to X\nu\bar{\nu}$





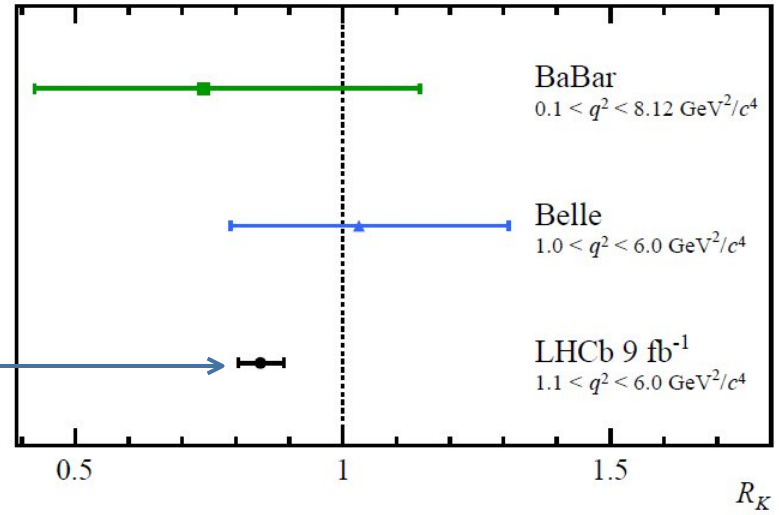


Lepton Flavor Violation

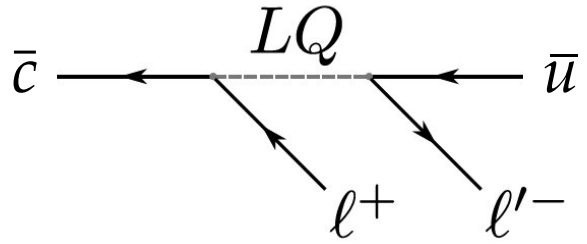


- LFV exists in neutrino oscillation
- Observation of charged LFV (cLFV) decays will be a clear sign for NP
- Lepton flavor non-universality closely related to cLFV
  - LHCb recently reported 3.1σ tension with SM in $b \to s\ell^+\ell^-$

    [Nature Phys. 18 (2022) 3, 277]



- BSM models (lepto-quark, Z', etc.) may induce cLFV and enhance BF up to O(10^{-5})

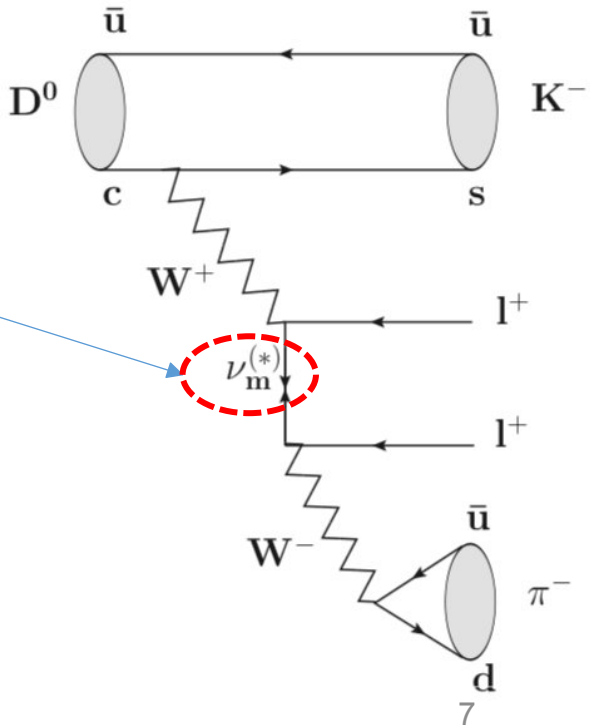


Lepton Number Violation

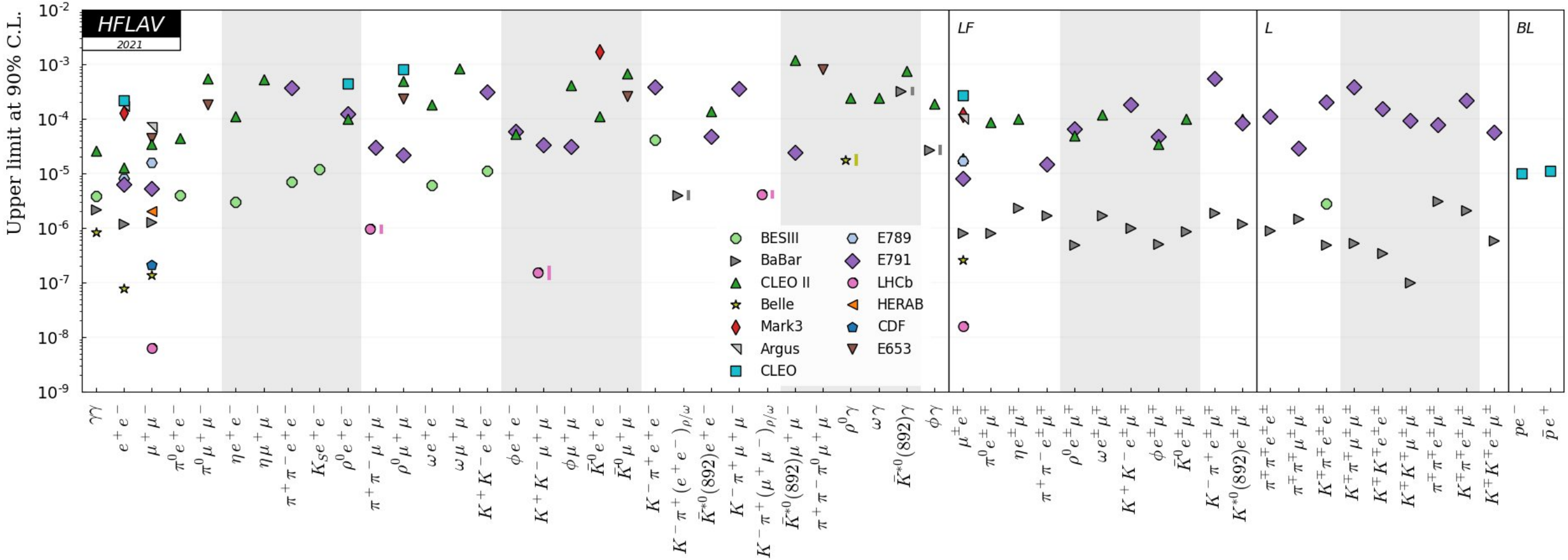
- **L**epton **N**umber **V**iolation ($\Delta L \neq 0$) is forbidden in SM
- Neutrino oscillation $\rightarrow m_\nu \neq 0 \rightarrow$ New Physics needed to explain mass origin
- Nature of neutrino: Dirac or Majorana (ν_{m})?
- Majorana neutrino can lead to $\Delta L = 2$ LNV processes
- LNV is introduced in many NP models:
  - 4th quark generation, SO(10) SUSY GUT, exotic Higgs, etc.
- LNV processes have been widely searched for in τ, K, D, and B decays

$$\begin{pmatrix} \nu_\uparrow \\ \nu_\downarrow \\ \bar{\nu}_\uparrow \\ \bar{\nu}_\downarrow \end{pmatrix} \quad \text{or} \quad \begin{pmatrix} \nu_\uparrow \\ \nu_\downarrow \end{pmatrix}$$

Dirac Majorana

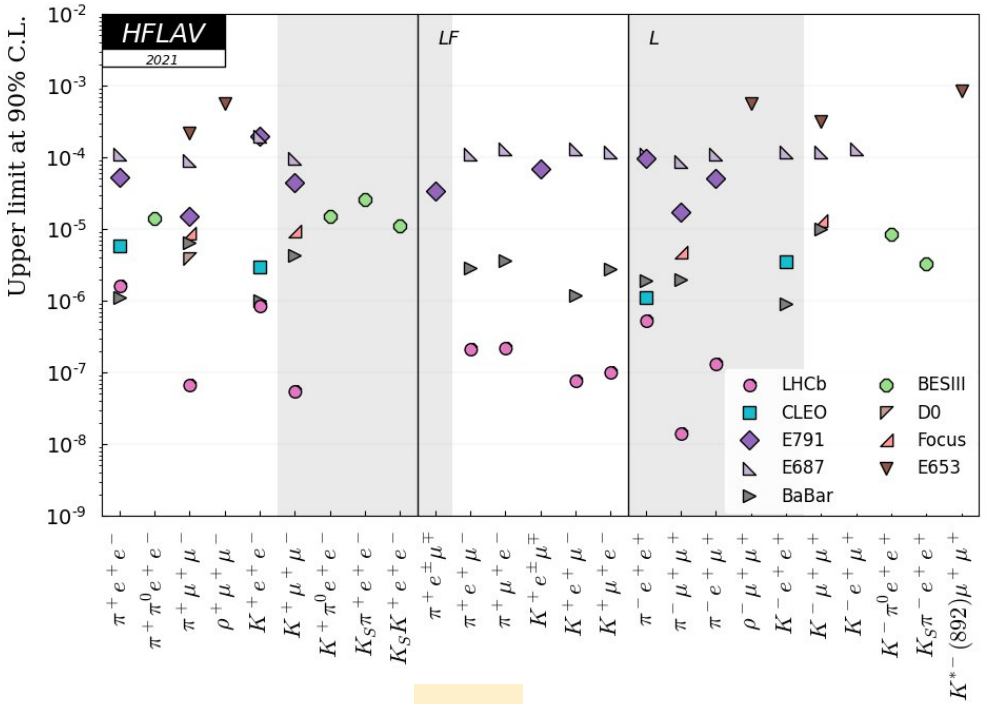


Results on rare charm decays (D^0)

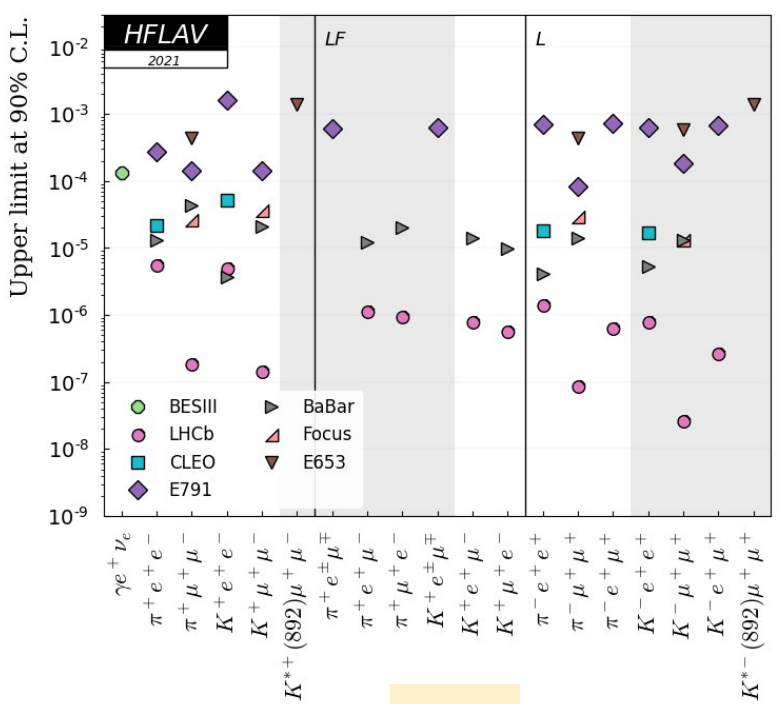


https://hflav-eos.web.cern.ch/hflav-eos/charm/rare/Spring2021/rare_charm.html

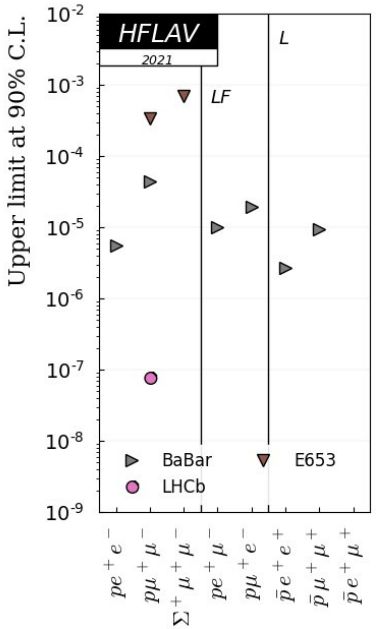
Results on rare charm decays



D^+



D_s^+



Λ_c^+

https://hflav-eos.web.cern.ch/hflav-eos/charm/rare/Spring2021/rare_charm.html

Search for $D^+_{(s)} \to h^\pm \ell^+ \ell^{(\prime)\mp}$ decays

- 25 decays

  LFV & LNV included

- Normalized with $D^+_{(s)} \to \phi(\ell\ell)\pi^+$

$D^+ \to \pi^+\mu^+\mu^-$ $D^+ \to \pi^+e^+e^-$ $D^+ \to K^+e^+e^-$ $D_s^+ \to \pi^+e^+\mu^-$ $D_s^+ \to K^+\mu^+e^-$

$D^+ \to \pi^-\mu^+\mu^+$ $D^+ \to \pi^-e^+e^+$ $D_s^+ \to \pi^+\mu^+\mu^-$ $D_s^+ \to \pi^+e^+e^-$ $D_s^+ \to K^-\mu^+e^+$

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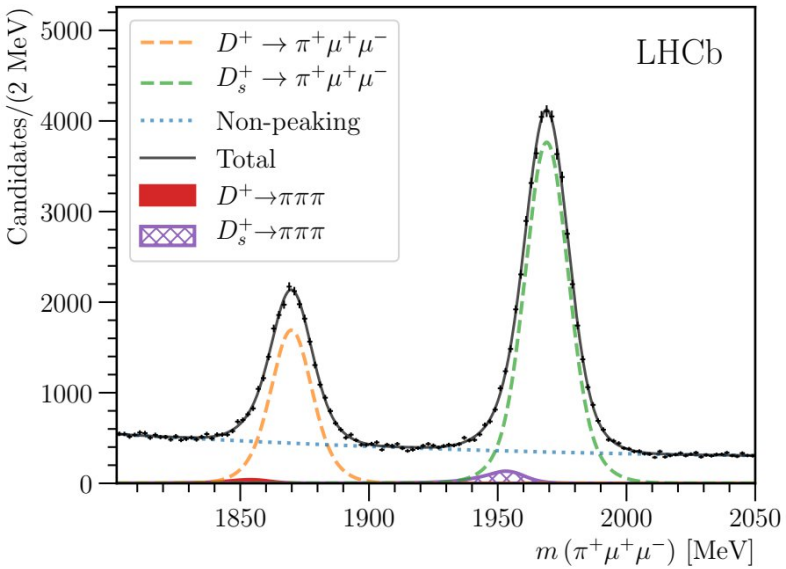
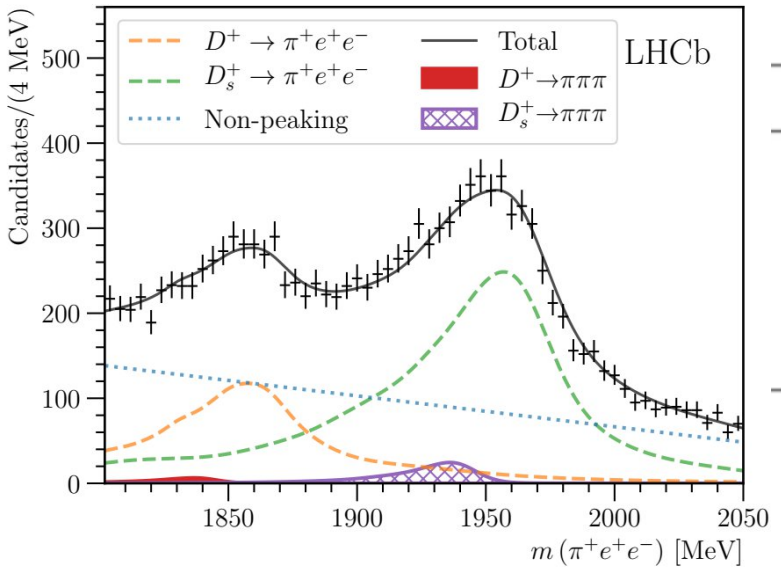
$D^+ \to \pi^+e^+\mu^-$ $D^+ \to K^+e^+\mu^-$ $D_s^+ \to \pi^-\mu^+e^+$ $D_s^+ \to K^-\mu^+\mu^+$ $D_s^+ \to K^-e^+e^+$

Allowed in the SM, Forbidden in the SM

- Analysis based on 2016 dataset (1.7 fb^{-1})

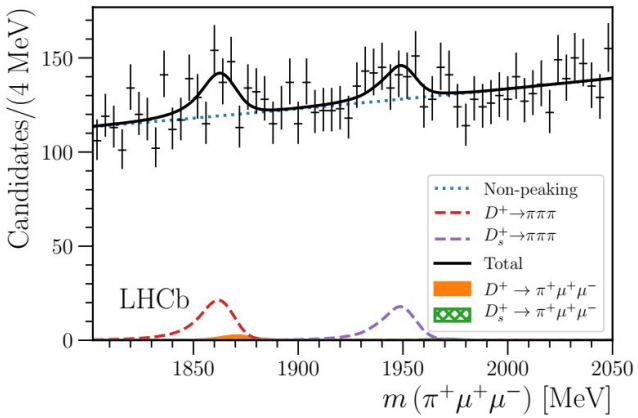


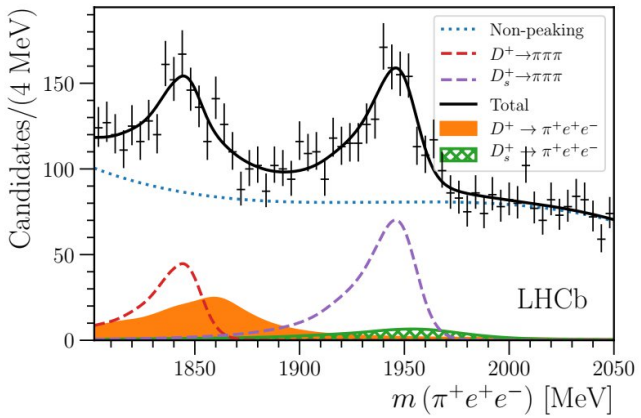


Channel	Fitted yield
$D^+ \to (\phi \to \mu^-\mu^+)\,\pi^+$	18 100±340
$D^+ \to (\phi \to e^-e^+)\,\pi^+$	2160±180
$D_s^+ \to (\phi \to \mu^-\mu^+)\,\pi^+$	42 000±400
$D_s^+ \to (\phi \to e^-e^+)\,\pi^+$	5320±180

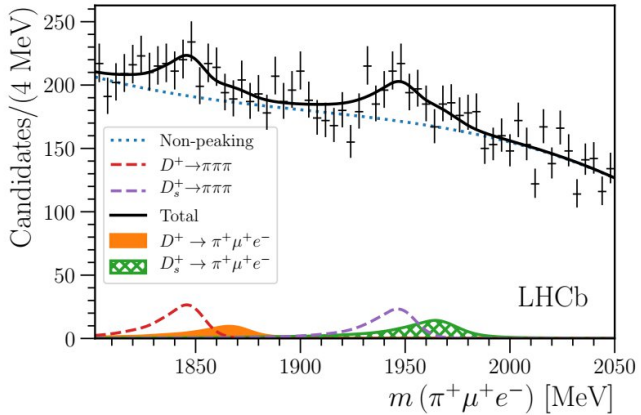
Search for $D^+_{(s)} \to h^\pm \ell^+ \ell^{(\prime)\mp}$ decays

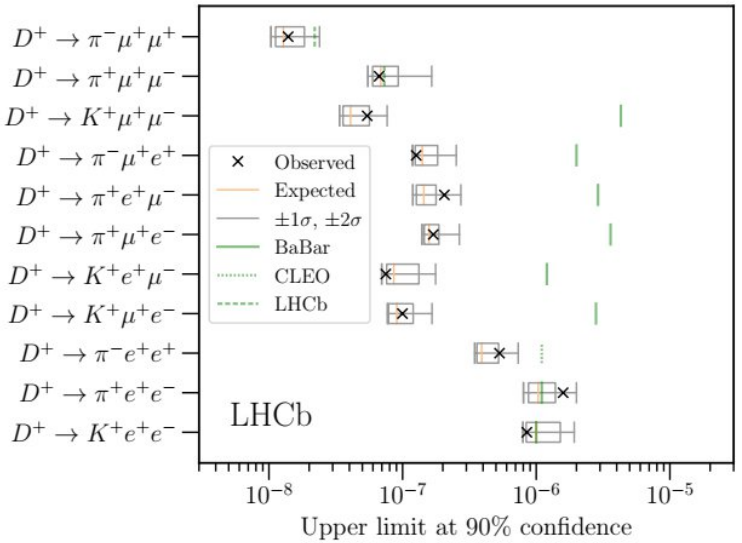
- No signal observed, BF limits are set down to $\mathcal{O}(10^{-8})$
- Results improve the prior world's best by up to a factor of 500

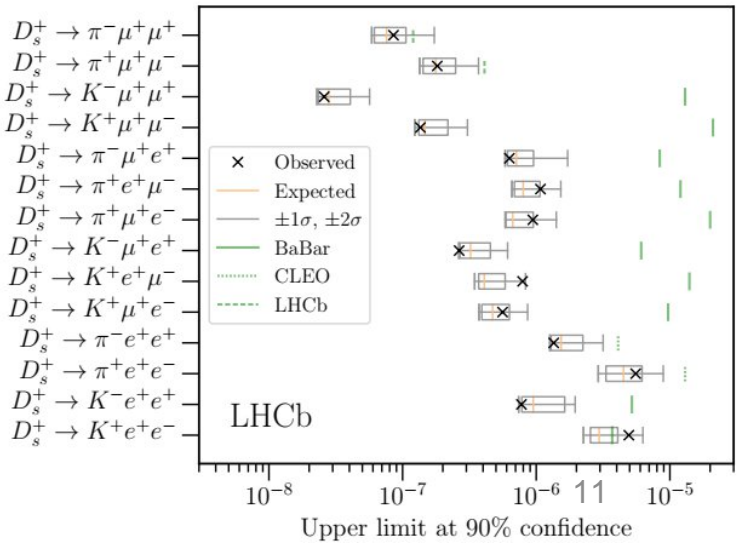




Regions dominated by resonances in dilepton mass spectrum are vetoed







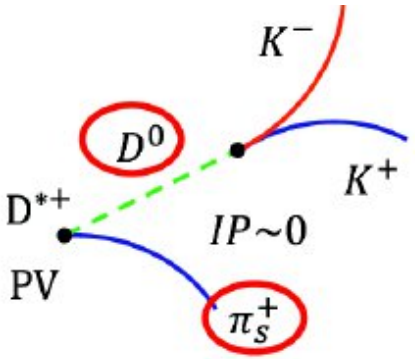
CPV and angular analysis in $D^0 \to hh\mu^+\mu^-$

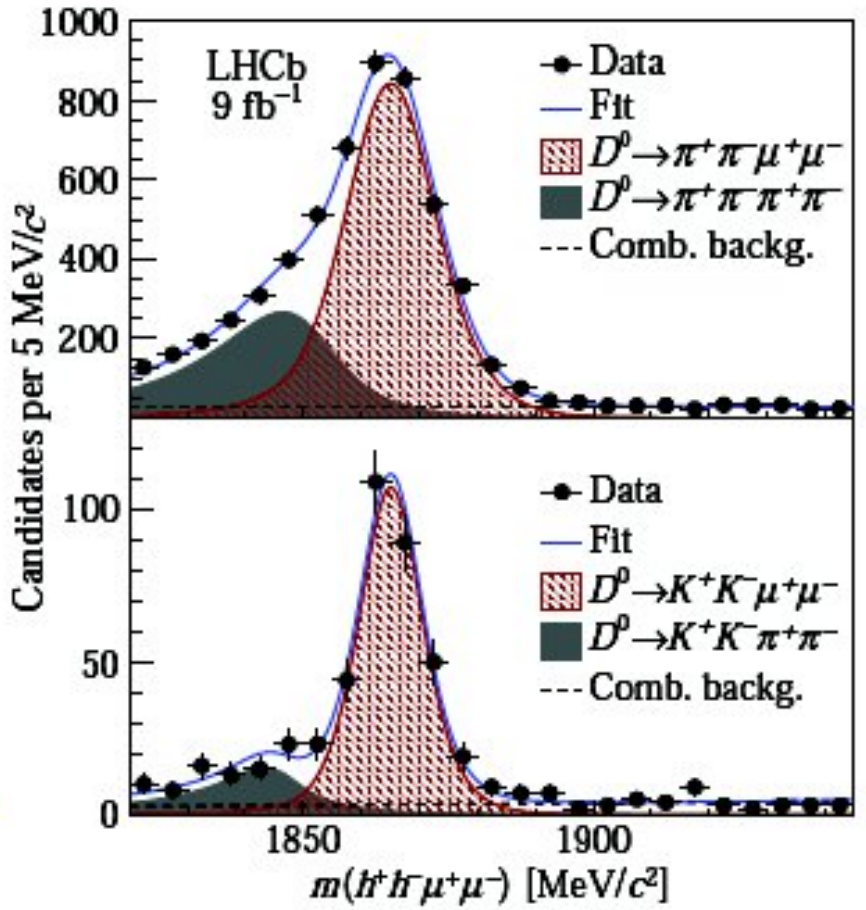
- Rarest charm meson decays observed, dominated by resonant contributions

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) \sim 9.6 \times 10^{-7}$$
$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) \sim 1.5 \times 10^{-7}$$

- First full angular analysis with 9 fb^{-1} data
- D^0 selected from flavor specific $D^{*+} \to D^0\pi^+$

$$N(D^0 \to \pi^+\pi^-\mu^+\mu^-) \sim 3500$$
$$N(D^0 \to K^+K^-\mu^+\mu^-) \sim 300$$

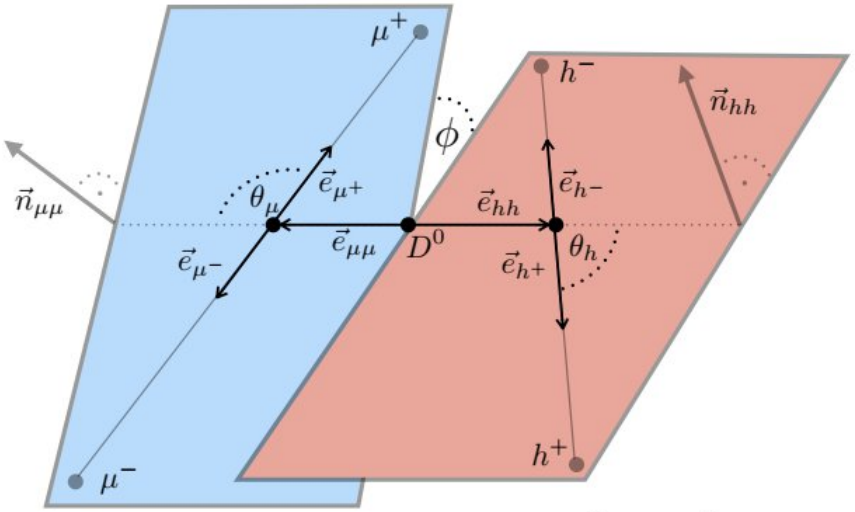




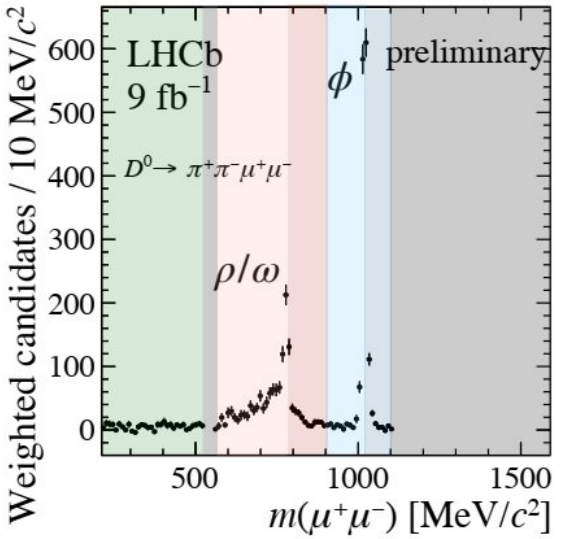
Differential decay rate in $D^0 \to hh\mu^+\mu^-$

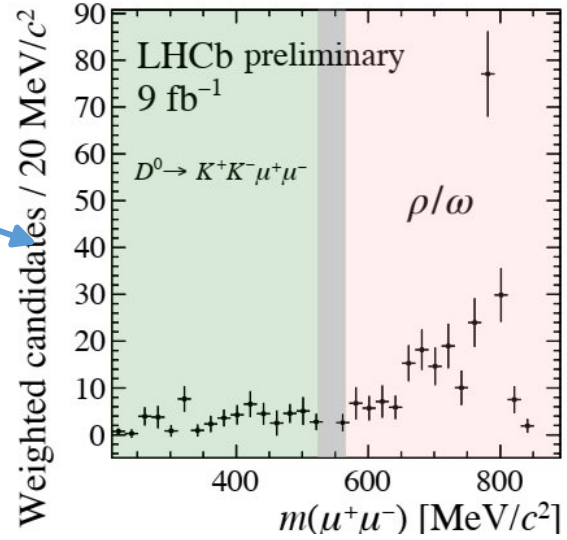
$$\frac{d\Gamma}{d\cos\theta_\mu d\cos\theta_h d\phi} = I_1 + I_2\cdot\cos 2\theta_\mu + I_3\cdot\sin^2 2\theta_\mu\cos 2\phi + I_4\cdot\sin 2\theta_\mu\cos\phi + I_5\cdot\sin\theta_\mu\cos\phi + I_6\cdot\cos\theta_\mu + I_7\cdot\sin\theta_\mu\sin\phi + I_8\cdot\sin 2\theta_\mu\sin\phi + I_9\cdot\sin^2\theta_\mu\sin 2\phi$$

I_5, I_6, I_7 clean null tests!



$$p^2 = m^2(h^+h^-)$$
$$q^2 = m^2(\mu^+\mu^-)$$





- Measure p^2, $\cos\theta_h$ integrated $\langle I_i\rangle$ separately for $D^0/\overline{D}^0$ in **q² bins**

$$\langle I_{2,3,6,9}\rangle(q^2) = \frac{1}{\Gamma}\int_{4m_h}^{p^2_{max}} dp^2 \int_{-1}^{1} d\cos\theta_h\, I_{2,3,6,9}$$

$$\langle I_{4,5,7,8}\rangle(q^2) = \frac{1}{\Gamma}\int_{4m_h}^{p^2_{max}} dp^2 \left[\int_{-1}^{0} d\cos\theta_h - \int_{0}^{1} d\cos\theta_h\right] I_{4,5,7,8}$$

$$\langle S_i\rangle = \frac{1}{2}\left[\langle I_i\rangle + (-)\langle\overline{I}_i\rangle\right] \qquad \langle S_{5,6,7}\rangle \overset{SM}{=} 0$$

$$\langle A_i\rangle = \frac{1}{2}\left[\langle I_i\rangle - (+)\langle\overline{I}_i\rangle\right] \qquad \langle A_i\rangle \overset{SM}{=} 0$$

i=2,..,9

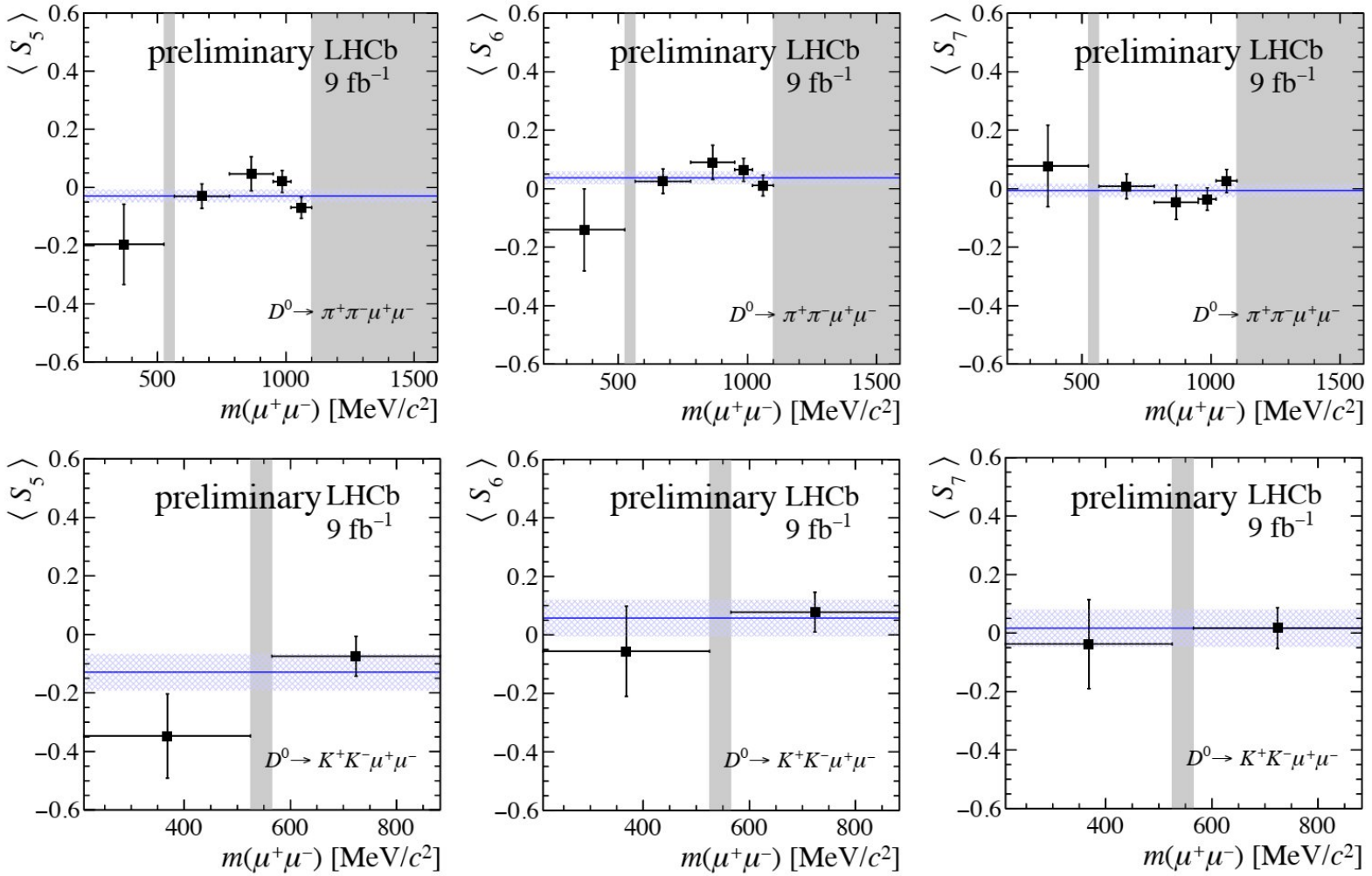
for CP even (CP odd) coefficients

2,3,4,7 (5,6,8,9)

Flavor-averaged observables $\langle S_i \rangle$

- Shown examples: SM null tests $\langle S_{5,6,7} \rangle$ $[\langle S_6 \rangle \sim A_{FB}]$

From D. Mitzel's talk @ 11th workshop on "Implications of LHCb measurements and future prospects"



agreement with SM predictions
[JHEP 04 135 (2013), PRD 98, 035041(2018)]

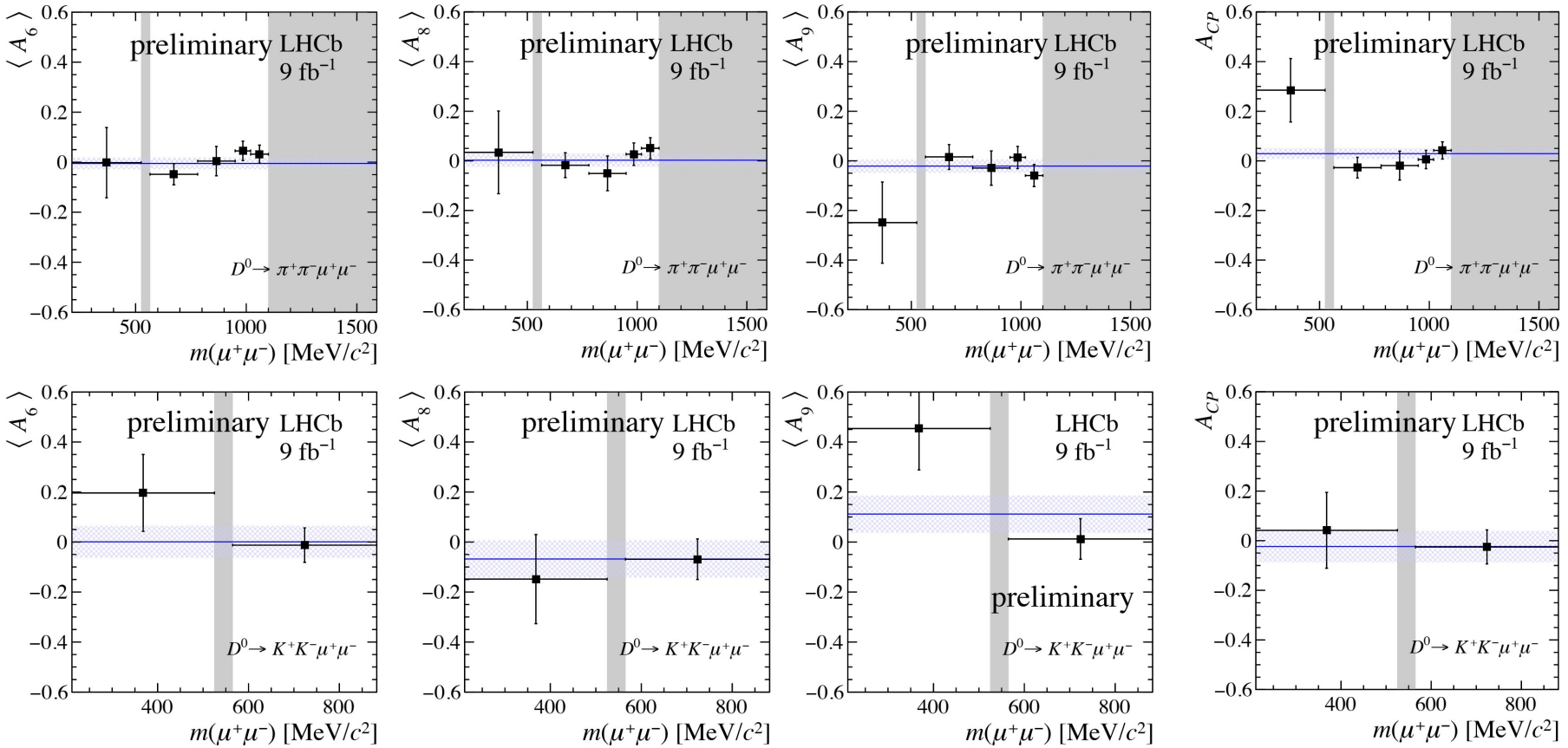
PRL 128 (2022) 221801

CP asymmetries $\langle A_i \rangle$

$$A_{CP} = \frac{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) - \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) + \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}$$

From D. Mitzel's talk @ 11th workshop on "Implications of LHCb measurements and future prospects"

- Shown: $\langle A_6 \rangle$ [$\langle A_6 \rangle \sim A_{FB}^{CP}$], $\langle A_{8,9} \rangle$ [triple-product-asym.] & A_{CP}



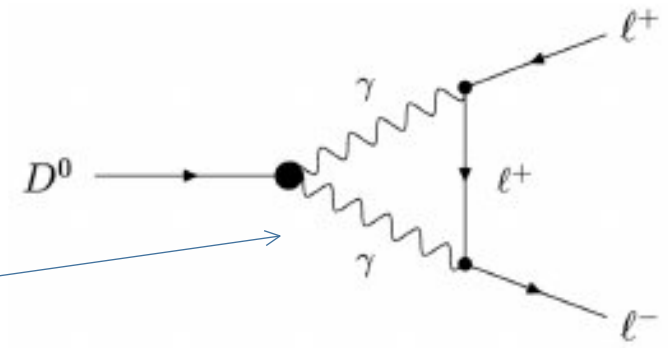
- overall agreement wrt. to SM hypothesis considering A_{CP}, $\langle A_{2-9} \rangle$ & $\langle S_{5,6,7} \rangle$:

$D^0 \to \pi^+\pi^-\mu^+\mu^-$	p = 79% (0.3σ)
$D^0 \to K^+K^-\mu^+\mu^-$	p = 0.8% (2.7σ) preliminary

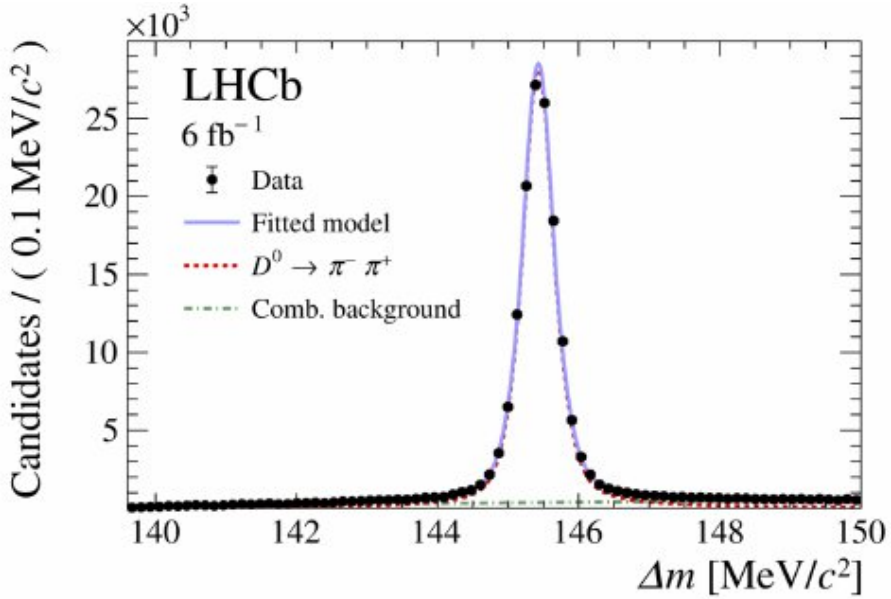
consistent with SM

arXiv:2212.11203

Search for $D^0 \to \mu^+\mu^-$



- Short-distance contribution from $c \to u\ell\ell$ (FCNC) highly suppressed: Br~10^{-18}
- Long-distance from a two-photon intermediate state: Br < 10^{-13}
- Dataset: full Runs1+2 9 fb^{-1}
- D^0 candidates from $D^{*+} \to D^0\pi^+$
- Normalization channels: $D^0 \to K^-\pi^+, \pi^+\pi^-$
- BDT trained to suppress combinatorial backgrounds



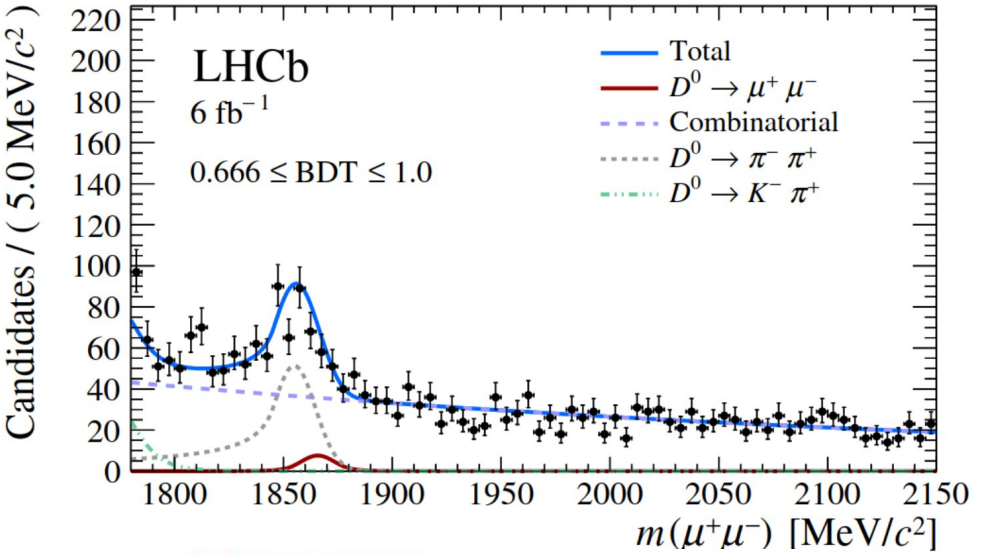
arXiv:2212.11203

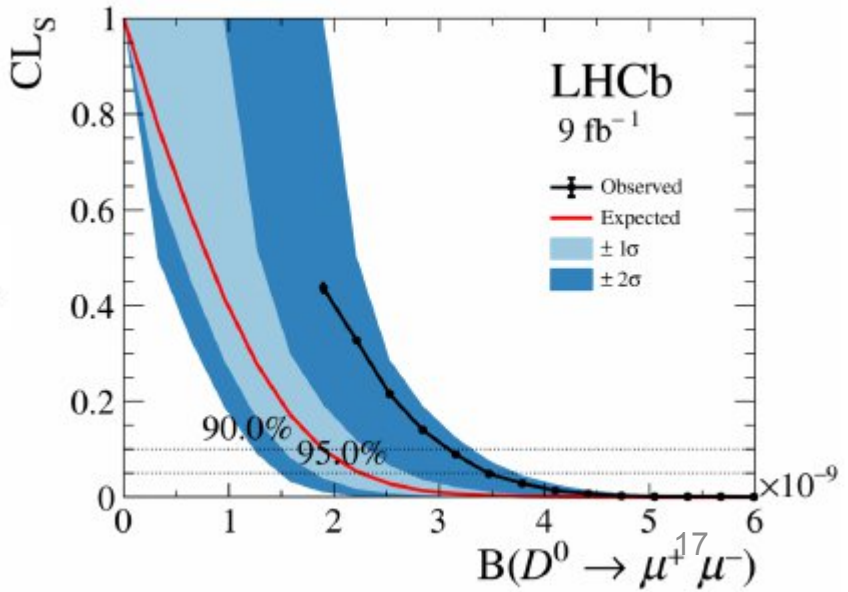
Search for $D^0 \to \mu^+\mu^-$: results

- Peaking backgrounds from $D^0 \to h\pi$ are carefully calibrated using MC & control samples
  - $K\pi$: $\mu\mu$ mass sideband
  - $\pi\pi$: $D^+_{(s)} \to \pi\pi\pi$ decays
- Final yield: $N\left(D^0 \to \mu\mu\right) = 79 \pm 45$
- Upper limits are set:

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

A factor of 2 improvement!





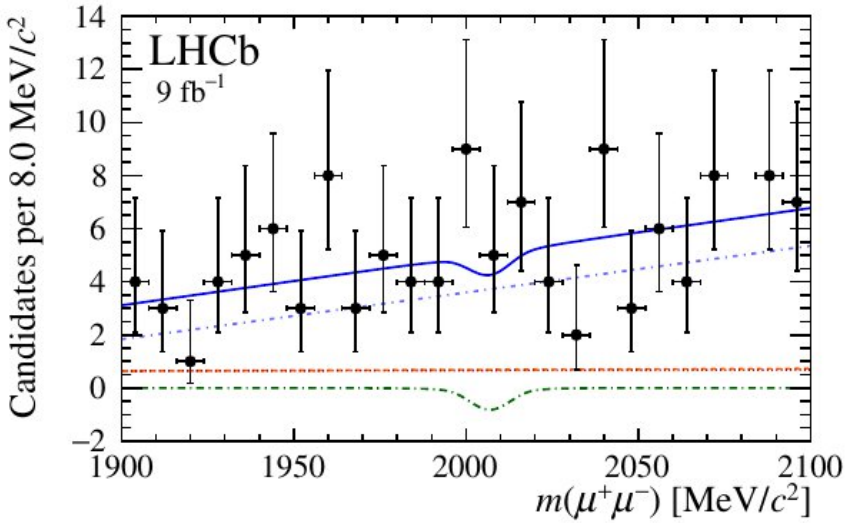
arXiv:2304.01981

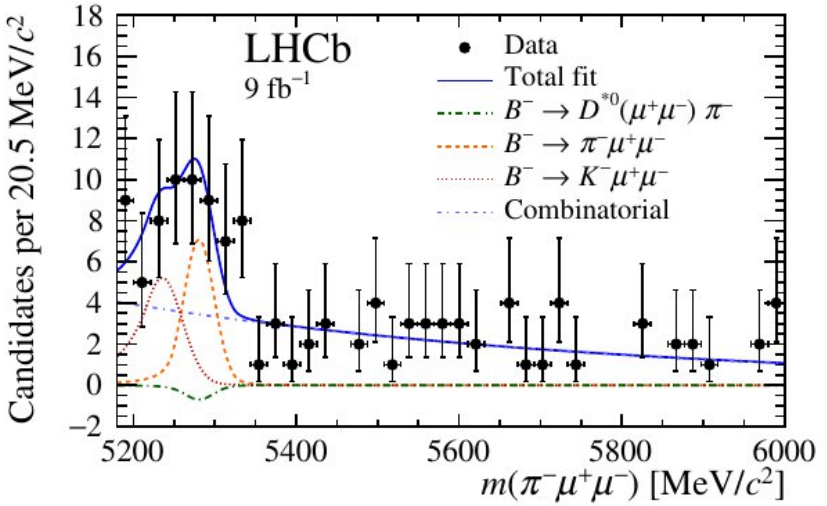
Search for $D^{*0} \to \mu^+\mu^-$ in B decay

- Leptonic D* decays offer a complementary approach to constraining Wilson coefficients
- Highly suppressed in SM: BF ~10^{-18}
- Search in the decay chain of $B^- \to D^{*0}(\to \mu^+\mu^-)\pi^-$
- Normalization channel: $B^- \to J/\psi(\to \mu^+\mu^-)K^-$
- First search:

$$\varepsilon_{J/\psi K^-}/\varepsilon_{D^{*0}\pi^-} \quad 1.21 \pm 0.03$$
$$N_{J/\psi K^-} \quad (2316 \pm 8) \times 10^3$$

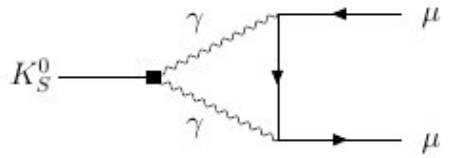
$$\mathcal{B}(D^{*0} \to \mu^+\mu^-) < 2.6 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

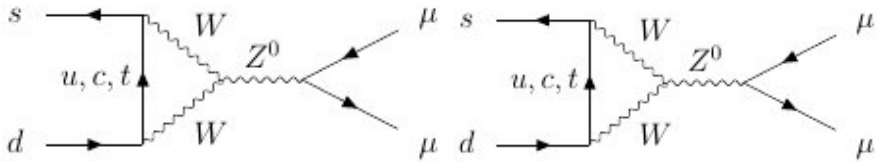




PRL 125, 231801 (2020)

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



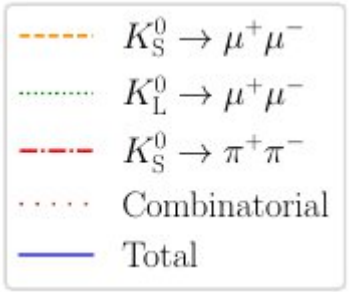


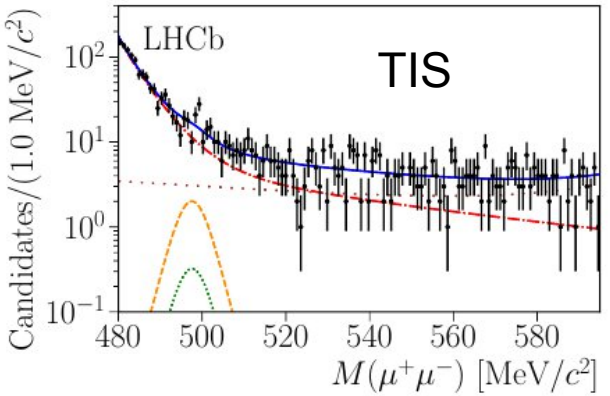
- Expected:

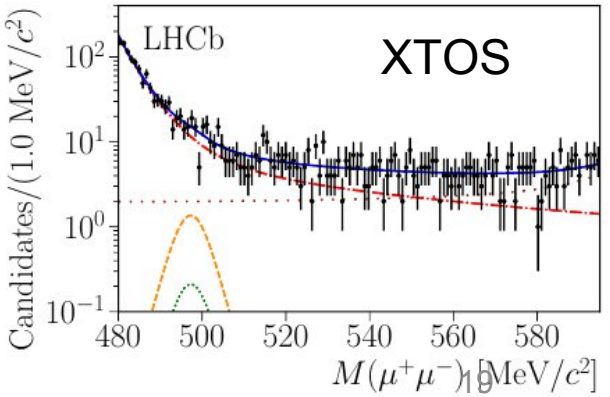
$$\mathcal{B}(K_L^0 \to \mu^+\bar{\mu}^-)_{SM} = (6.85 \pm 0.80_{LD} \pm 0.06_{SD}) \times 10^{-9}$$

- Sensitive to NP contributions
- Dedicated software trigger in Run2
- Normalized to $K_S^0 \to \pi^+\pi^-$
- Combined results from Runs1-2:

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







arXiv:2212.04977

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

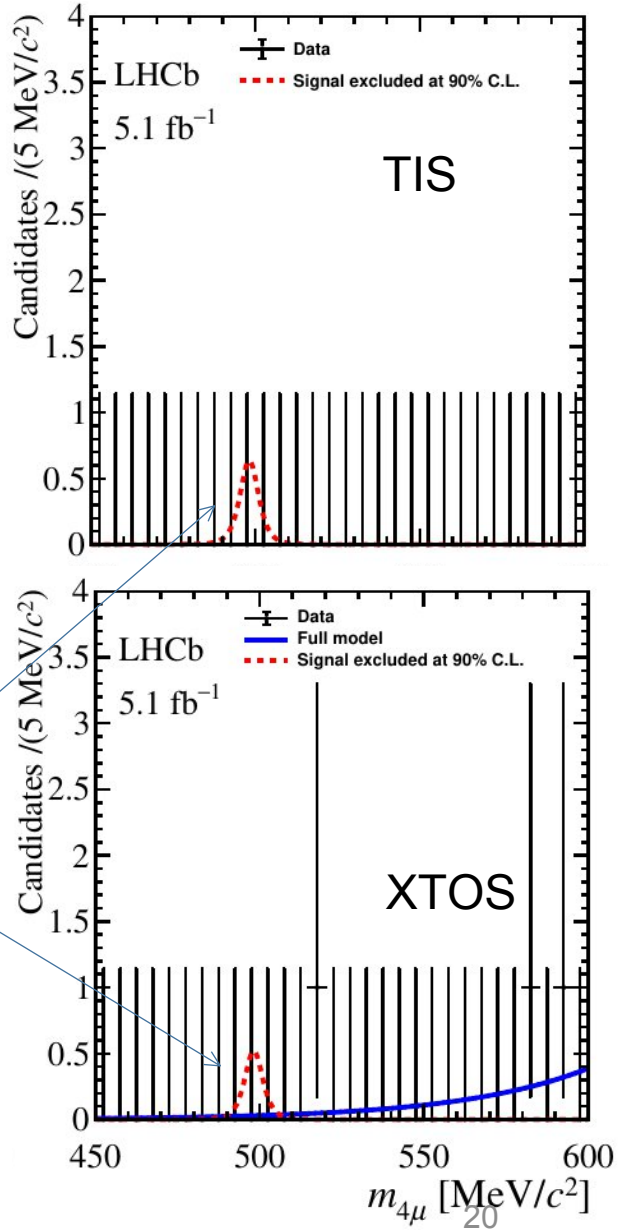
- Expected:

$$\mathcal{B}(K^0_{\rm S} \to \mu^+\mu^-\mu^+\mu^-)_{\rm SM} \sim (1\text{–}4) \times 10^{-14}.$$

$$\mathcal{B}(K^0_{\rm L} \to \mu^+\mu^-\mu^+\mu^-)_{\rm SM} \sim (4\text{–}9) \times 10^{-13}.$$

- LHCb acceptance for K^0_L ~0.2% of K^0_S
- Normalized to $K^0_S \to \pi^+\pi^-$
- No events found in the signal mass window
- ULs @ 90% CL using 5.1 fb^{-1} Run2:

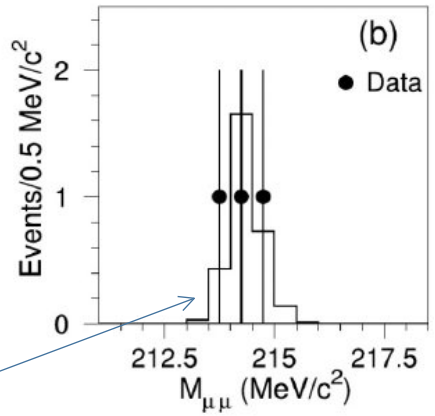
$$\mathcal{B}(K^0_{\rm S} \to \mu^+\mu^-\mu^+\mu^-) < 5.1 \times 10^{-12},$$
$$\mathcal{B}(K^0_{\rm L} \to \mu^+\mu^-\mu^+\mu^-) < 2.3 \times 10^{-9},$$

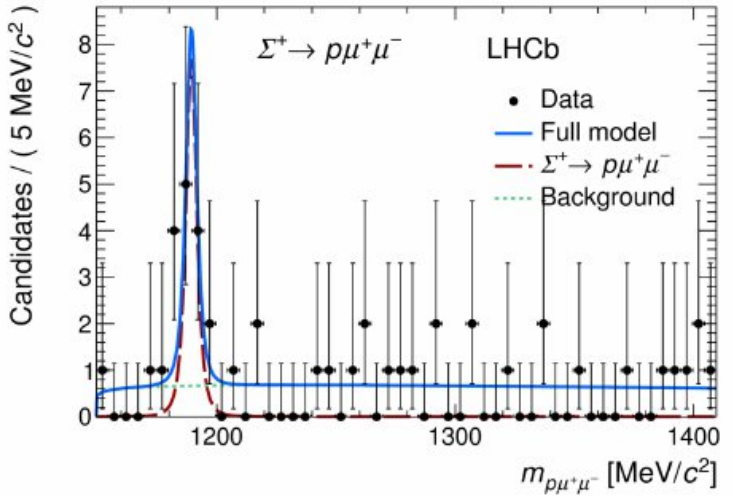


PRL 120, 221803 (2018)

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

3 fb^{-1} @ 7,8 TeV

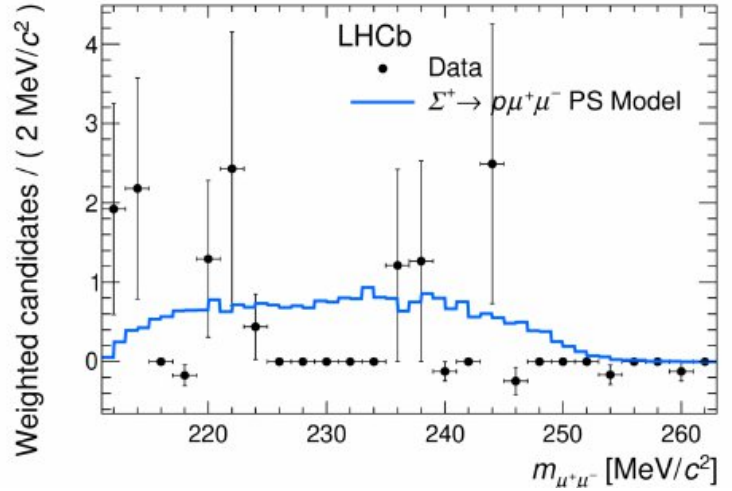




- A s → d FCNC process, LD contribution dominated
- Evidence from HyperCP [PRL 94 021801 (2005)]:

  $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \times 10^{-8}$

  - Three candidates found with $m_{X^0} = 214.3 \pm 0.5$ MeV
- LHCb uses $\Sigma^0 \to p\pi^0(\gamma\gamma)$ as norm channel
  - $N_{\Sigma^+ \to p\pi^0} = (1171 \pm 9) \times 10^3$
- Observed $\Sigma^+ \to p\mu^+\mu^-$ candidates evaluated by fitting $m_{p\mu^+\mu^-}$
  - $N_{\Sigma^+ \to p\mu^+\mu^-} = (10.2^{+3.9}_{-3.5})$
  - Measured $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (2.2^{+0.9+1.5}_{-0.8-1.1}) \times 10^{-8}$
- No significant peak found in the dimuon invariant mass distribution
  - $\mathcal{B}(\Sigma^+ \to pX^0(\to \mu^+\mu^-)) < 1.4 \times 10^{-8}$ at 90% CL
  - HyperCP result excluded



Run 2 analysis ongoing

LHCb prospects for rare charm decays

Mode	Upgrade ($50\,\mathrm{fb}^{-1}$)	Upgrade II ($300\,\mathrm{fb}^{-1}$)
$D^0 \to \mu^+\mu^-$	4.2×10^{-10}	1.3×10^{-10}
$D^+ \to \pi^+\mu^+\mu^-$	10^{-8}	3×10^{-9}
$D_s^+ \to K^+\mu^+\mu^-$	10^{-8}	3×10^{-9}
$\Lambda \to p\mu\mu$	1.1×10^{-8}	4.4×10^{-9}
$D^0 \to e\mu$	10^{-9}	4.1×10^{-9}

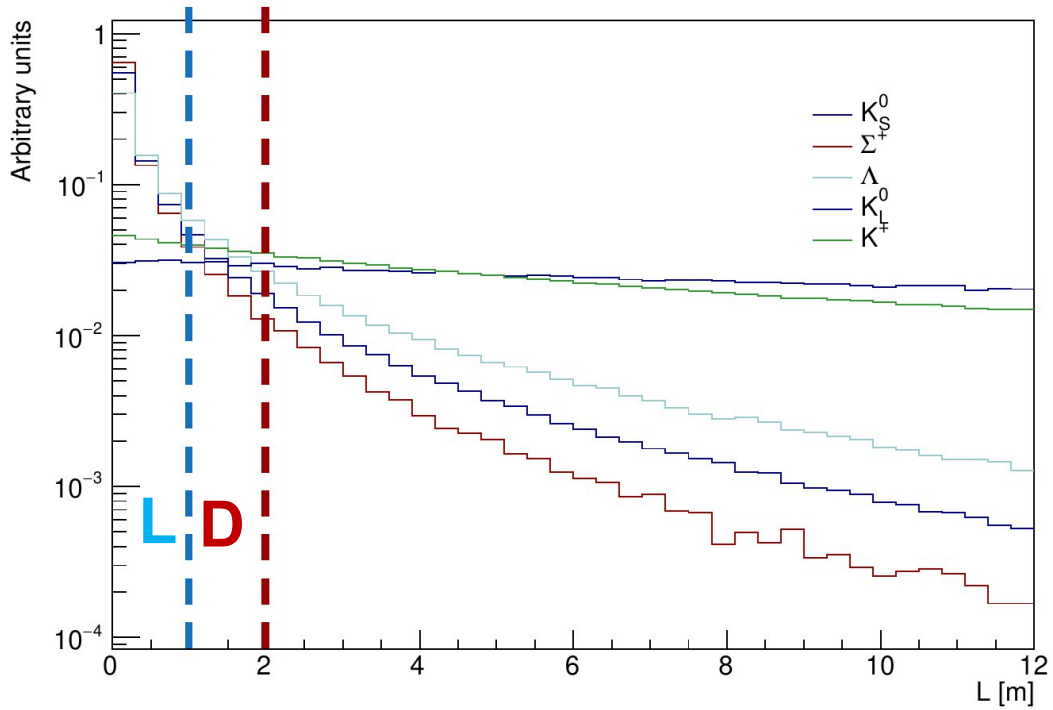
Mode	Upgrade ($50\,\mathrm{fb}^{-1}$)	Upgrade II ($300\,\mathrm{fb}^{-1}$)
$D^+ \to \pi^+\mu^+\mu^-$	0.2%	0.08%
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	1%	0.4%
$D^0 \to K^-\pi^+\mu^+\mu^-$	0.3%	0.13%
$D^0 \to K^+\pi^-\mu^+\mu^-$	12%	5%
$D^0 \to K^+K^-\mu^+\mu^-$	4%	1.7%

A. Contu, Towards the Ultimate Precision in Flavour Physics, Durham, United Kingdom, 2 - 4 Apr 2019

Prospects for measurements with strange hadrons at LHCb

arXiv:1808.03477

A. A. Alves Junior[1], M. O. Bettler[2], A. Brea Rodríguez[1], A. Casais Vidal[1], V. Chobanova[1], X. Cid Vidal[1], A. Contu[3], G. D'Ambrosio[4], J. Dalseno[1], F. Dettori[5], V.V. Gligorov[6], G. Graziani[7], D. Guadagnoli[8], T. Kitahara[9,10], C. Lazzeroni[11], M. Lucio Martínez[1], M. Moulson[12], C. Marín Benito[13], J. Martín Camalich[14,15], D. Martínez Santos[1], J. Prisciandaro [1], A. Puig Navarro[16], M. Ramos Pernas[1], V. Renaudin[13], A. Sergi[11], K. A. Zarebski[11]



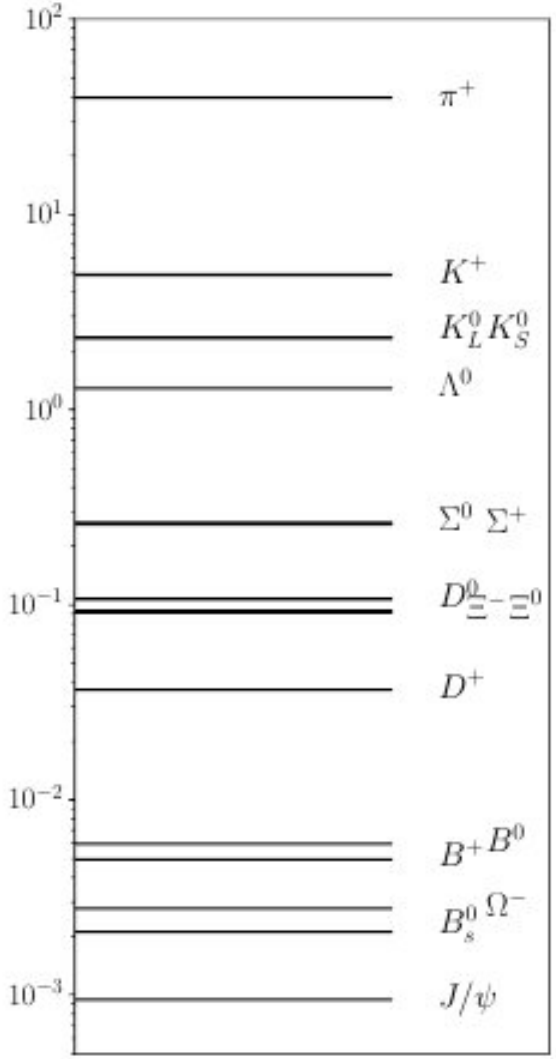


Figure 1: Multiplicity of particles produced in a single pp interaction at $\sqrt{s} = 13$ TeV within LHCb acceptance.

Summary

- Thanks to overwhelming statistics & superb detector performance, LHCb has been dominating the searches for rare charm &strange decays into all-track final states
- Still great potentials to be explored, e.g.
  - Di-electron channels
  - Radiative charm decays
  - Semileptonic charm decays
  - Decays of $D^*_{(s)}$ from B
- Expectation of improved ULs or observations

  in the Run3 era and beyond!