Search for new physics at LHCb

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Report content

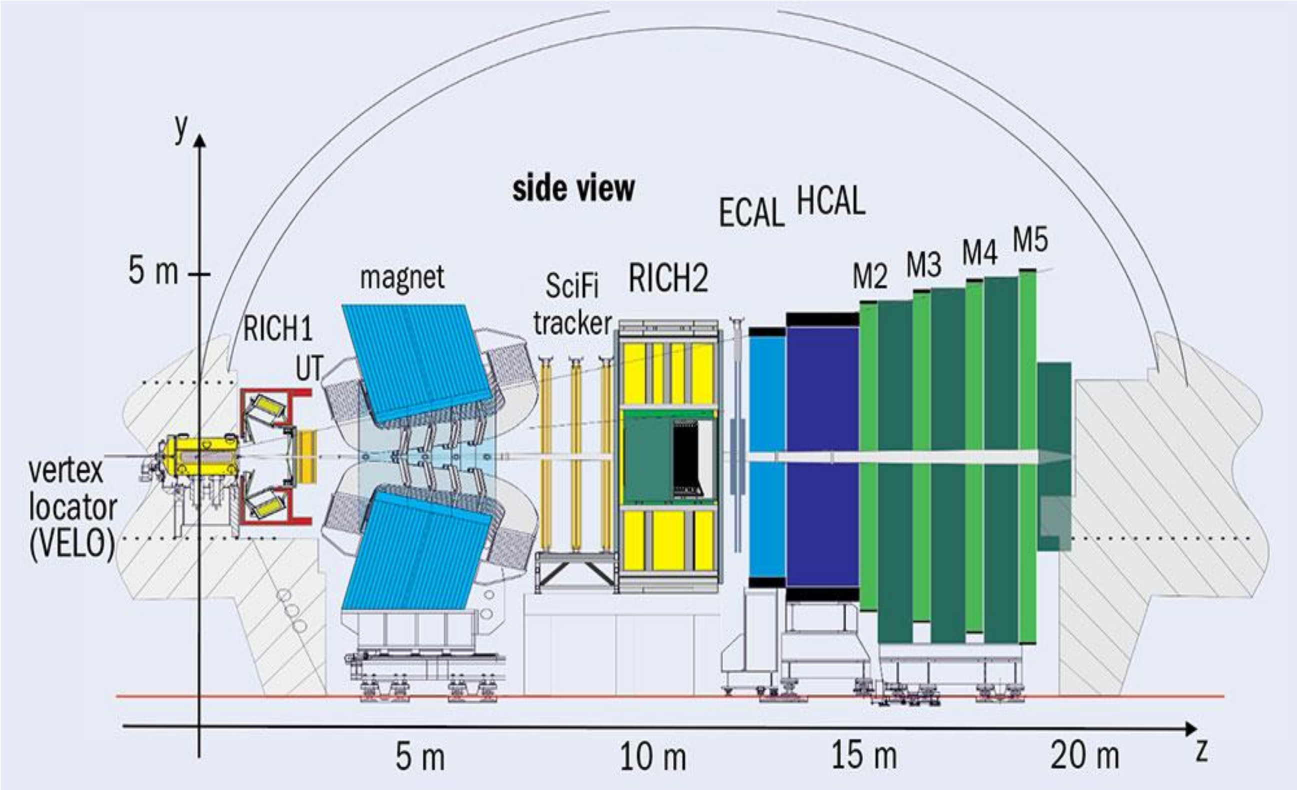
- Mainly focus on the results related with Charm and LHCb typical

• D CPV Searches

• Rare decay (including LFV)

• LFU test results

LHCb detector



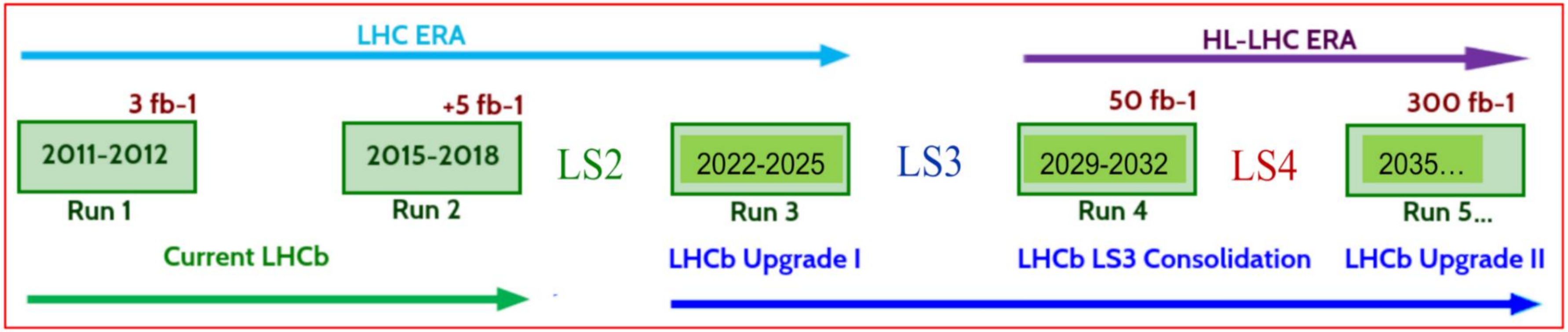
- 优秀的顶点、径迹重建和粒子鉴别等性能，灵活高效的在线触发系统

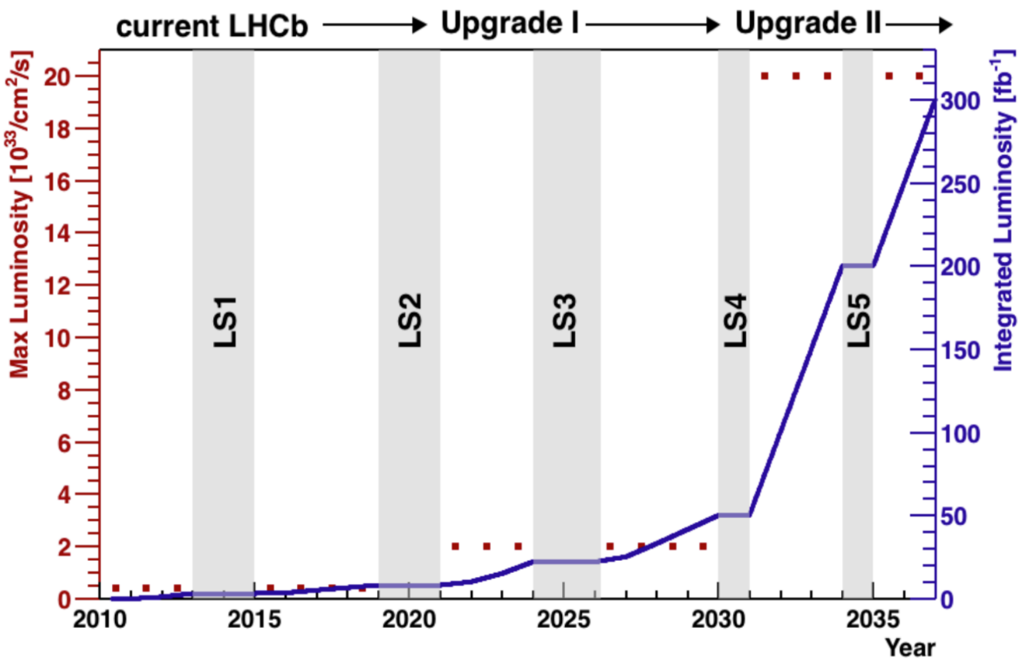
- 单臂前向的谱仪，对应于前向η范围2<η<5。在LHC上专门用于重味物理。

  - LHC pp对撞中，$b\bar{b}$强子对在前向和后向相对于束流方向（Z-方向）的小极角上产生。

- 包括一个高精度的径迹探测系统、两个环形的切伦科夫探测器、一个量能器系统和一个μ子探测器。

Data taking





- LHCb Run-I（2010-12）： 3 fb^{-1}的 7/8 TeV 的pp对撞数据
  Run-II（2015-18）： 6 fb^{-1} 13TeV的pp对撞数据
- 预计在RunIII（2022-24）采集约 30 fb^{-1}的13 TeV 的pp数据

D CPV search results

Search for CPV in $D^+_{(s)} \to K^-K^+K^+$ decays

- For the charm, CPV are very small: direct CPV (*i.e.* in the decay) can occur only for Cabibbo-suppressed (CS) decays, expected at $O(10^{-3})$.
- For doubly Cabibbo-suppressed (DCS) decays, CPV is essentially forbidden, thus its observation would indicate a manifestation of BSM physics.
- To date there is only one observation of CPV in the charm sector, through the difference of *CPV* in $\boldsymbol{D^0 \to K^+K^-}$ **and** $\boldsymbol{D^0 \to \pi^+\pi^-}$. $\boxed{\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}}$
- thus important to extend to different charm-hadron species decaying into a broad range of final states, including not only CS but also DCS decays
- A model-independent search for direct CPV in the Dalitz plots of the **CS** $\boldsymbol{D_s^+ \to K^-K^+K^+}$ **and DCS** $\boldsymbol{D^+ \to K^-K^+K^+}$ **decays**

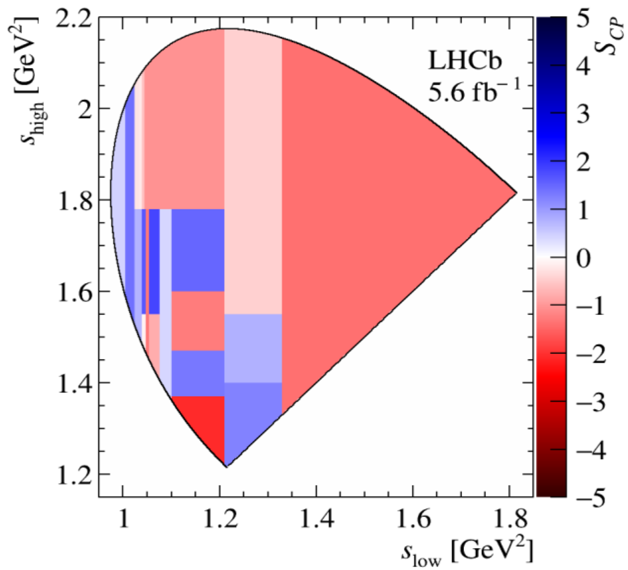
  - with 5.6 fb^{-1} Run-II data
- Divide the Dalitz plot in 2D bins and computing, for each bin, the significance of the difference in the numbers of $\boldsymbol{D^+_{(s)}}$ candidates and $\boldsymbol{D^-_{(s)}}$ candidates,

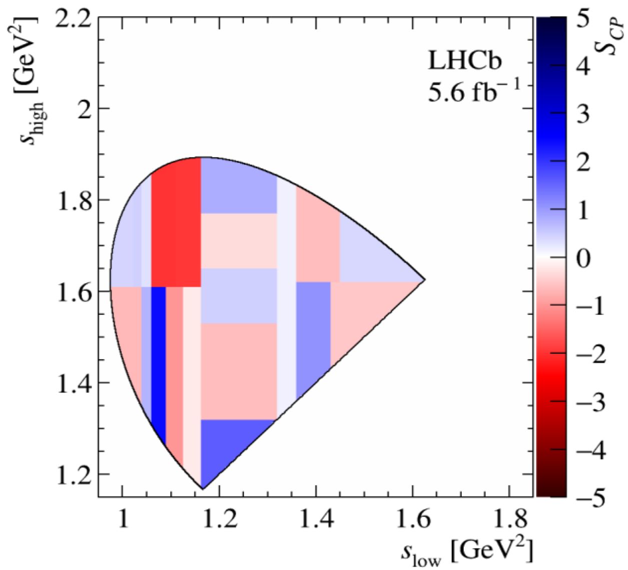
JHEP 07 (2023) 067

Search for CPV violation in $D^+_{(s)} \to K^-K^+K^+$ decays

- binned model-independent technique used, local *CP* observable S_{CP}

$$\mathcal{S}^i_{CP} = \frac{N^i(D^+_{(s)}) - \alpha N^i(D^-_{(s)})}{\sqrt{\alpha(\delta^2_{N^i(D^+_{(s)})} + \delta^2_{N^i(D^-_{(s)})})}}, \quad \text{with } \alpha = \frac{\sum_i N^i(D^+_{(s)})}{\sum_i N^i(D^-_{(s)})},$$





S_{CP} across the Dalitz plot for (left) $D^+_{(s)} \to K^-K^+K^+$ and (right) $D^+ \to K^-K^+K^+$ signal candidates using 21 bins

- Results (p-values): 13.3% for $D_s^+ \to K^-K^+K^+$ and 31.6% for $D^+ \to K^-K^+K^+$; No evidence for CP violation is found.
- The first search for CP violation in the CS channel $D_s^+ \to K^-K^+K^+$ and in the DCS channel $D^+ \to K^-K^+K^+$

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Search for CPV in the phase-space of $D^0 \to \pi^+\pi^-\pi^0$

- Multi-body charm decays provide a powerful tool to probe CPV. In these decays, PS-dependent local CP asymmetries can arise from the interference among intermediate resonances
- Studies of these local asymmetries provide additional sensitivity to observation of CPV, complementing studies of PS integrated asymmetries and two-body decays.

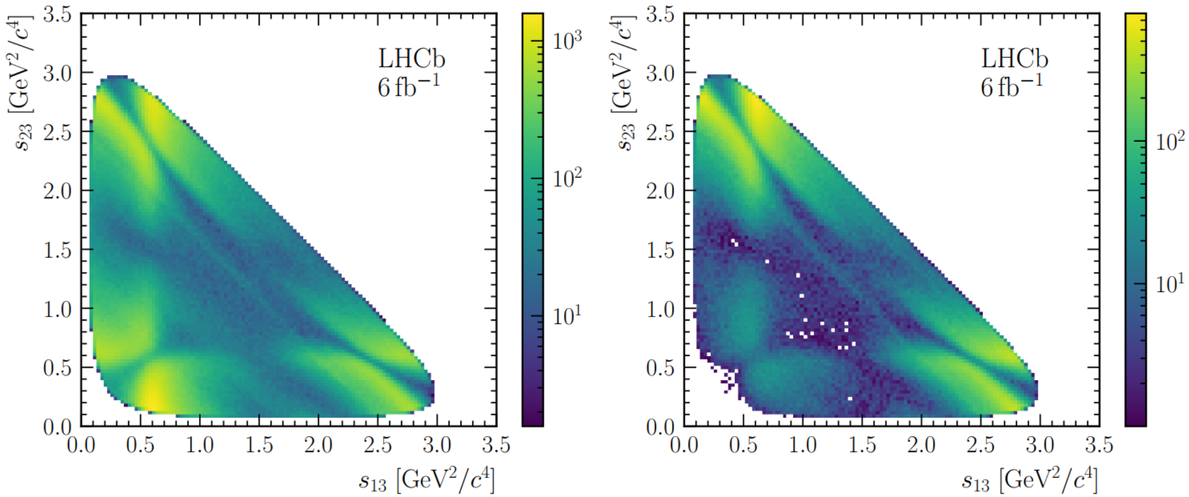

Figure 2: Dalitz plots for the background-subtracted signal samples for (left) the resolved and (right) merged π^0 categories, with the two $m^2(\pi^\pm\pi^0)$ variables chosen for the projection. The three $\rho^{\pm,0}$ resonances dominate the phase space.

- Use 2015 to 2018 data, 6 fb^{-1}
- flavour-tagged $D^0 \to \pi^+\pi^-\pi^0$ is obtained by selecting $D^{*+} \to D^0(\pi^+\pi^-\pi^0)\,\pi^+$

- **no evidence is found for *CPV* in localised regions of the PS**

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Rare decay searches

(including LFV)

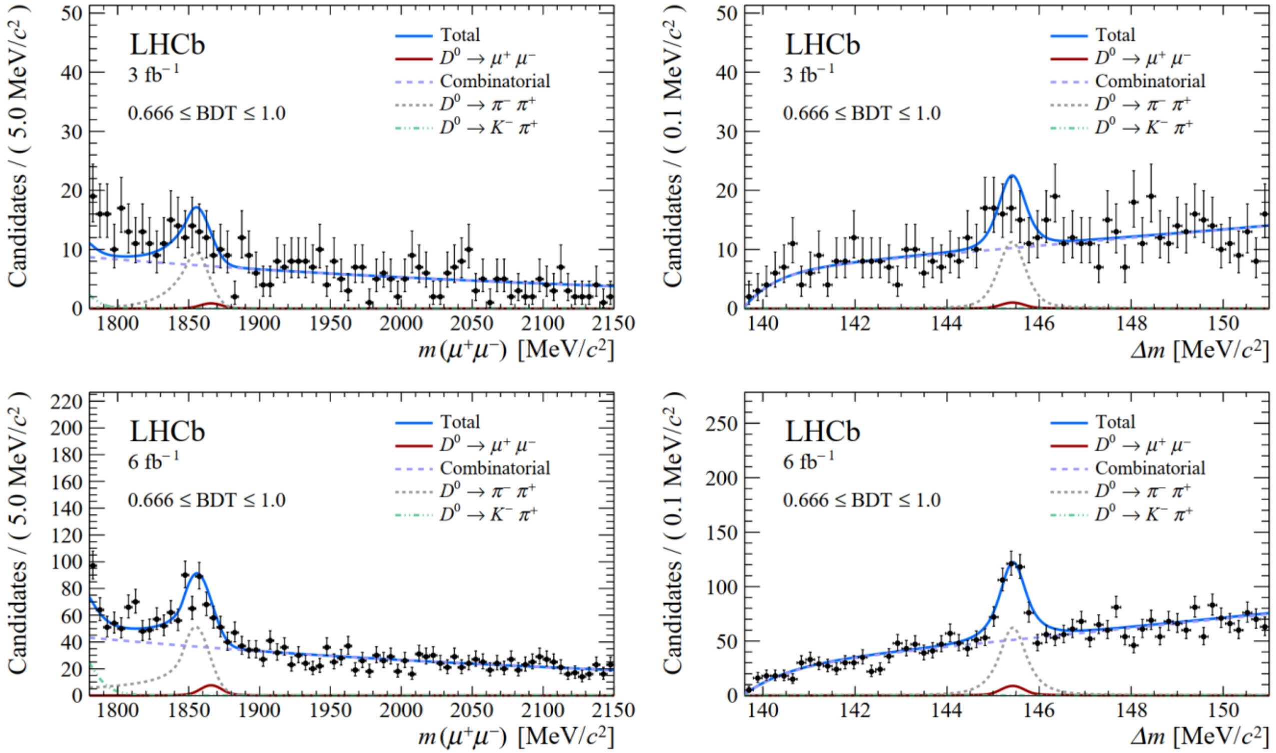
Search for $D^0 \to \mu^+\mu^-$

- It is among the most interesting charm-hadrons decays, being fully leptonic and additionally suppressed by helicity reasons.
- SM short-distance contribution extremely suppressed： 10^{-18}； long-distance contribution： 10^{-13}
- However the rate can be enhanced in many NP models:
  - new particles could mediate the $D^0 \to \mu^+\mu^-$ decay at tree level.
  - SUSY models with R-parity symmetry violation would allow tree level contributions
- The rate is correlated to the rate of D^0 - $\overline{D}^0$ mixing in many NP models. This is of uttermost importance given the recent first observation of the mass difference between neutral charm-meson eigen-states

PRL 131 (2023) 041804

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

- Searched for using $D^{*+} \to D^0\pi^-$ decays, as this improves the background rejection and allows the yield of the decay to be obtained Charge conjugate processes are implied throughout.



- 2-D fit to the $m(\mu^+\mu^-)$, and the mass difference between the D^{*+} and D^0: Δm
- for the most sensitive BDT interval

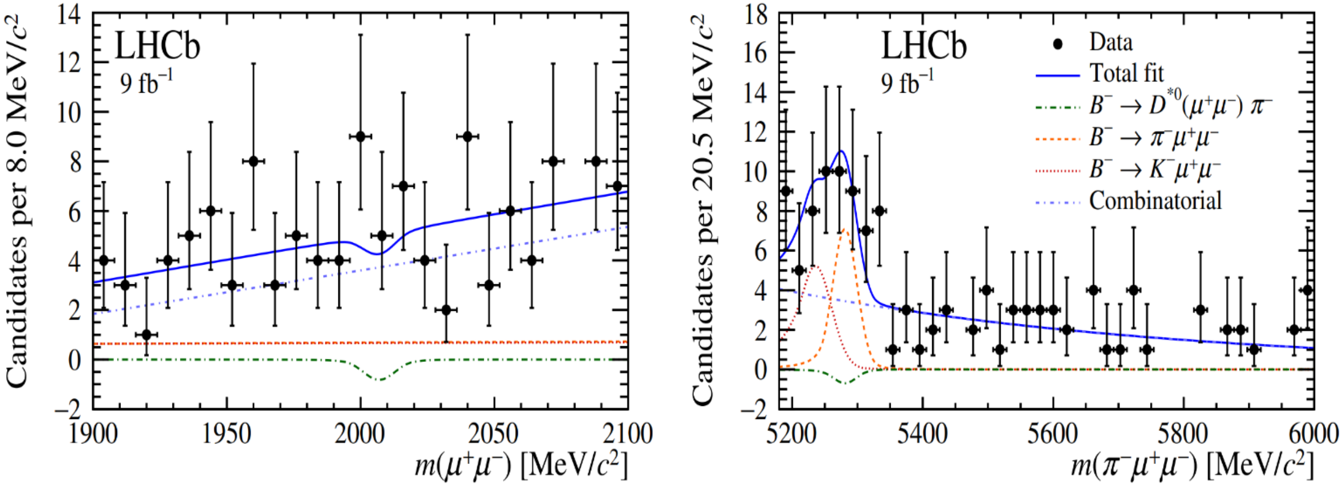
$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 3.1\,(3.5) \times 10^{-9} \text{ at } 90\ (95)\%\ \text{CL}\ .$$

- Most stringent limit on the relevant FCNC couplings in the charm sector, allowing to set additional constraints on NP

PRL 131 (2023) 041804

Search for $D^*(2007)^0 \to \mu^+\mu^-$ in $B^- \to \pi^-\mu^+\mu^-$

- First search for a rare charm-meson decay exploiting production via B decay
- The most promising approach appears to be with the $B^- \to \pi^- D^{*0}(\mu^+\mu^-)$ decay chain since the displaced vertex and exclusive final state provide powerful background rejection capabilities.



Reconstructed (left) $\mu^+\mu^-$ and (right) $\pi^-\mu^+\mu^-$ mass for the selected candidates,

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

- The first search for a rare charm-meson decay exploiting its production in B-meson decays. the most stringent limit on D^{*0} decays to leptonic final states.

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

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

- They are FCNC process that has not yet been observed. In SM its decay rate is highly suppressed, with an expected branching fraction:

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

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

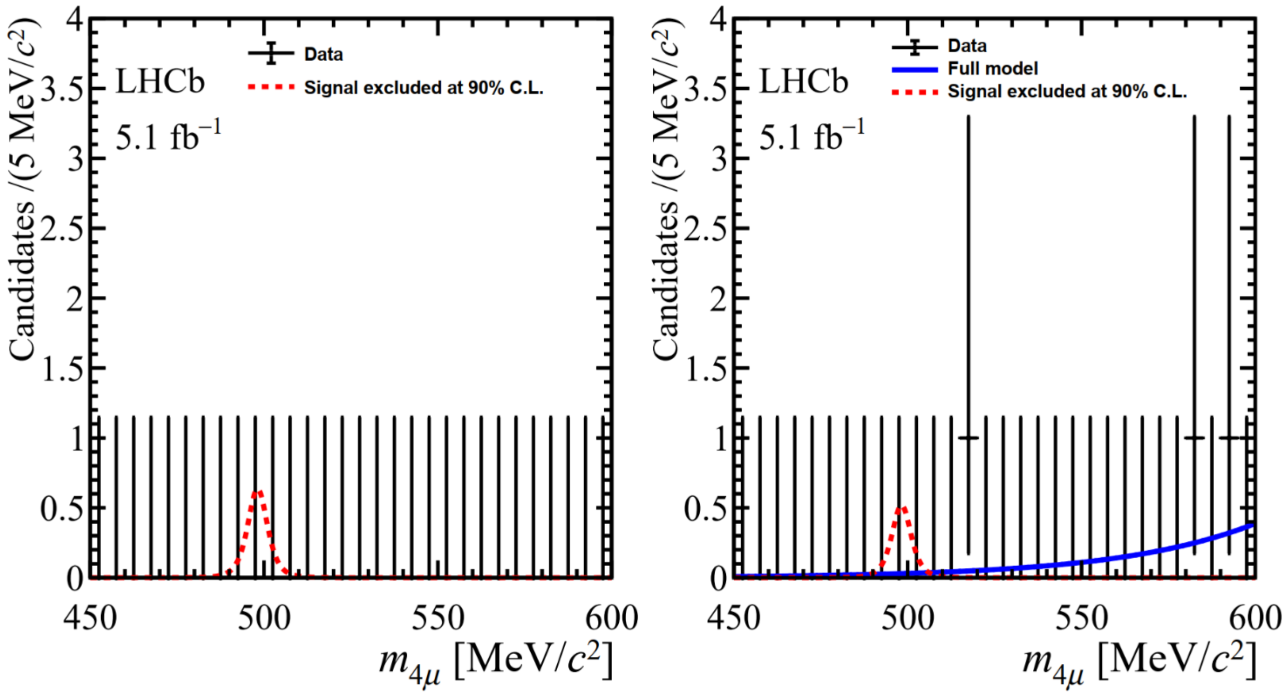
- BSM can lead to large enhancements of $B(K^0_{S(L)} \to \mu^+\mu^-\mu^+\mu^-)$. For instance, proposed **dark-sector scenarios** can enhance the BR by up to $\sim 2 \times 10^{-12}$

- To date, no direct experimental search of these decays has been performed.

- The analysis data(13 TeV, 5.1 fb^{-1}) sample is split according to the L0 hardware trigger decision: **TIS and xTOS**; $K^0_S \to \pi^+\pi^-$ as normalization

PRD108 (2023) L031102

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



$\mu^+\mu^-\mu^+\mu^-$ candidates in the (left) xTOS trigger category, and (right) TIS trigger category.

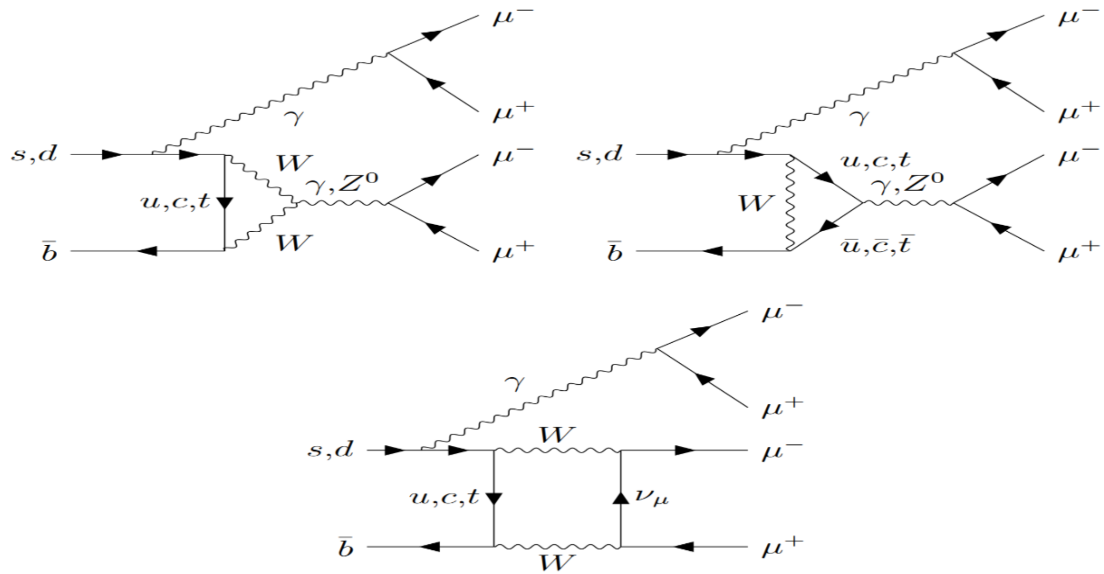
$$\boxed{\begin{aligned}\mathcal{B}(K^0_S \to \mu^+\mu^-\mu^+\mu^-) &< 5.1\times 10^{-12},\\ \mathcal{B}(K^0_L \to \mu^+\mu^-\mu^+\mu^-) &< 2.3\times 10^{-9},\end{aligned}}$$

PRD108 (2023) L031102

Search for the rare decays $B_s^0 \to \mu^+\mu^-\mu^+\mu^-$ and $B^0 \to \mu^+\mu^-\mu^+\mu^-$

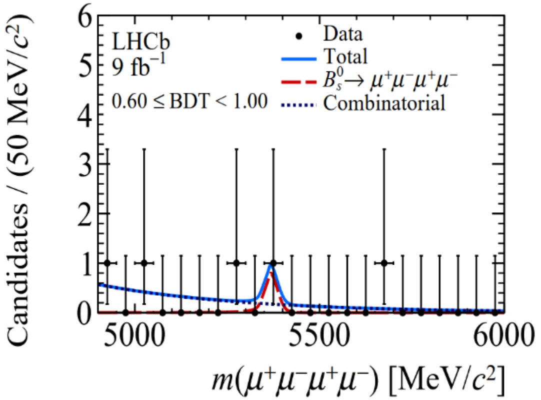
- Highly suppressed in SM: BR ($B^0 \to 4\mu$)~ 10^{-12}, BR($B_s^0 \to 4\mu$)~ 10^{-10}
- For example, decays via scalar and pseudoscalar Sgoldstino particles into a pair of dimuons in the MSSM may lead to significant enhancements of the BRs
- Furthermore, the decays into a pair of dimuons mediated by BSM light narrow scalars, $B^0_{(s)} \to a(\mu^+\mu^-)a(\mu^+\mu^-)$, naturally occur in the extensions of SM

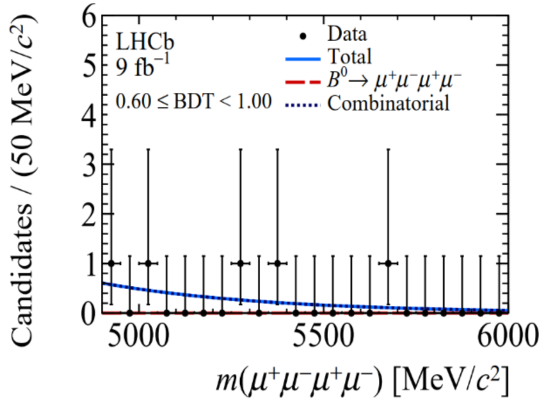
- In particular, such models can account for the long-standing tension of the anomalous magnetic dipole moment of the muon, as well as the widely discussed anomalies in transitions



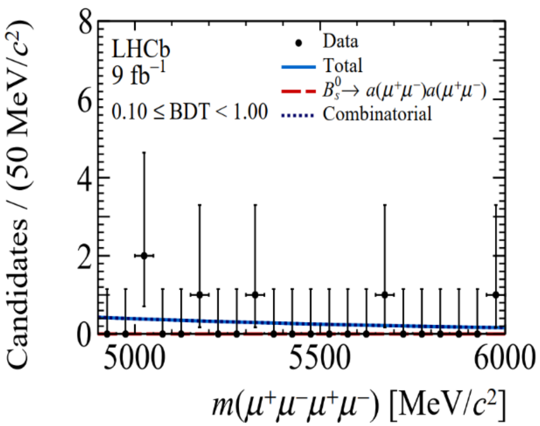
Search for the rare decays $B_s^0 \to \mu^+\mu^-\mu^+\mu^-$ and $B^0 \to \mu^+\mu^-\mu^+\mu^-$

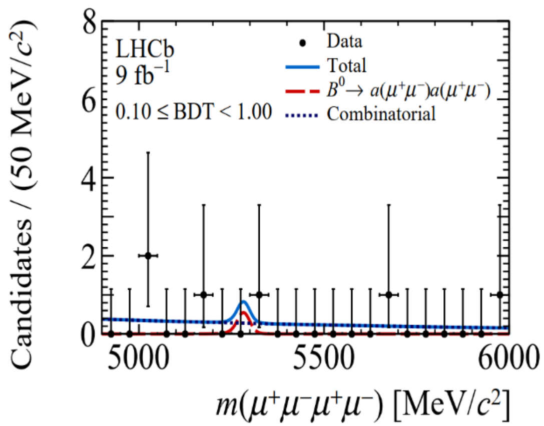
- No evidence for the six signal decay modes, with the most significant excesses found in the $B^0_{(s)} \to J/\psi(\mu^+\mu^-)\mu^+\mu^-$ searches, amounting to 2σ





$$
\begin{aligned}
&\mathcal{B}\left(B_s^0 \to \mu^+\mu^-\mu^+\mu^-\right) && < 8.6 \times 10^{-10}\,,\\
&\mathcal{B}\left(B^0 \to \mu^+\mu^-\mu^+\mu^-\right) && < 1.8 \times 10^{-10}\,,\\
&\mathcal{B}\left(B_s^0 \to a\left(\mu^+\mu^-\right) a\left(\mu^+\mu^-\right)\right) && < 5.8 \times 10^{-10}\,,\\
&\mathcal{B}\left(B^0 \to a\left(\mu^+\mu^-\right) a\left(\mu^+\mu^-\right)\right) && < 2.3 \times 10^{-10}\,,\\
&\mathcal{B}\left(B_s^0 \to J/\psi\left(\mu^+\mu^-\right) \mu^+\mu^-\right) && < 2.6 \times 10^{-9}\,,\\
&\mathcal{B}\left(B^0 \to J/\psi\left(\mu^+\mu^-\right) \mu^+\mu^-\right) && < 1.0 \times 10^{-9}\,.
\end{aligned}
$$





- The most stringent limits on each of the six decays

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The baryon and lepton number violating decays $B_s^0 \to p\mu^-$ and $B^0 \to p\mu^-$

- Matter-antimatter asymmetry is a serious challenge to our understanding of nature. Proposed three necessary conditions to produce such a large matter-antimatter asymmetry, **one of which is baryon number violation.**
- Various violation processes have been searched for in τ , Λ, D, J/ψ, and B decays by the CLEO, CLAS, BESIII and BABAR experiments, but no evidence has been found so far.

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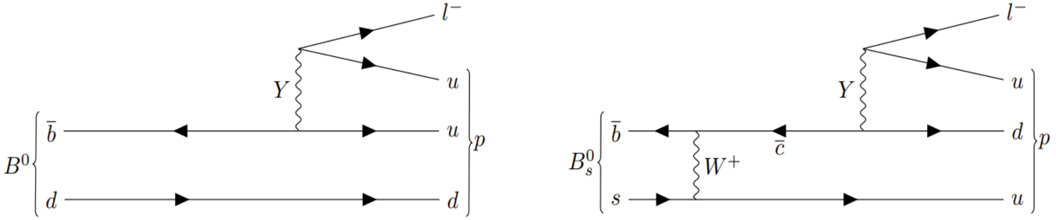
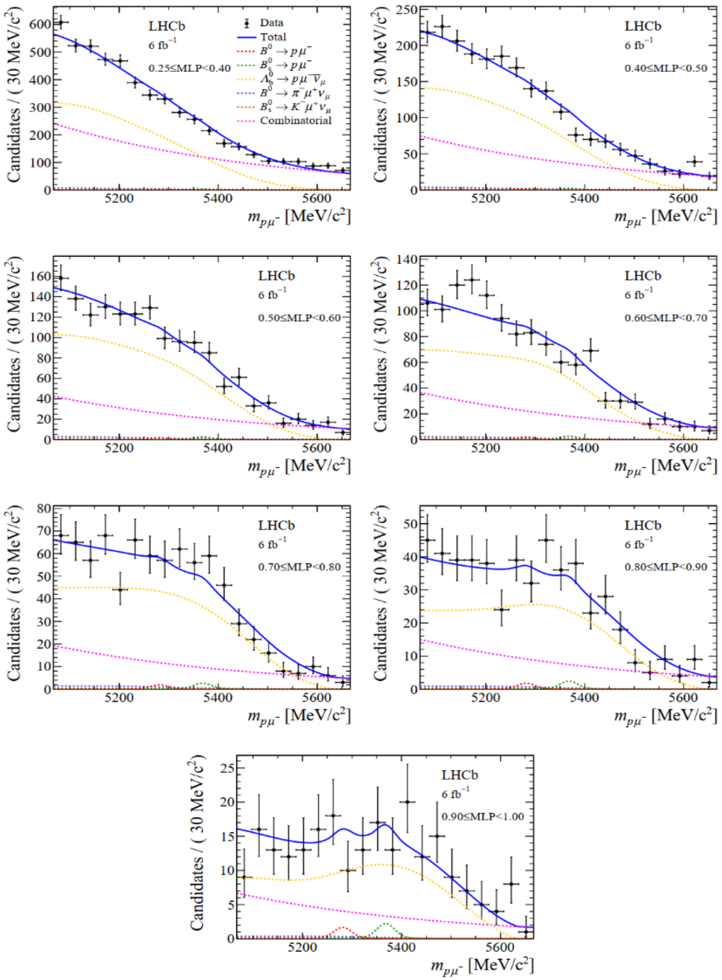
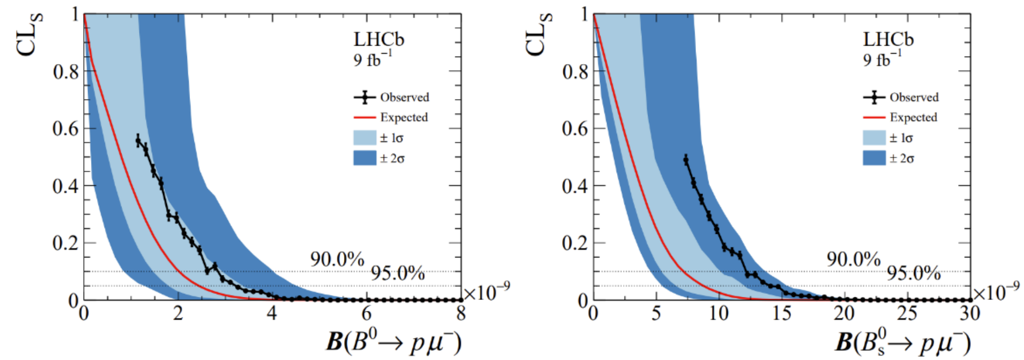


Figure 1: Hypothetical Feynman diagrams of $B^0_{(s)} \to p\ell^-$ mediated by a hypothetical Y boson.

The baryon and lepton number violating decays $B_s^0 \to p\mu^-$ and $B^0 \to p\mu^-$

- Mass distribution of signal candidates for Run 2 samples in regions of MLP.





- Results from the CLs scan used to obtain the limit on BR($B^0 \to p\mu^-$) and BR($B_s^0 \to p\mu^-$)
- the first upper limits on these decays

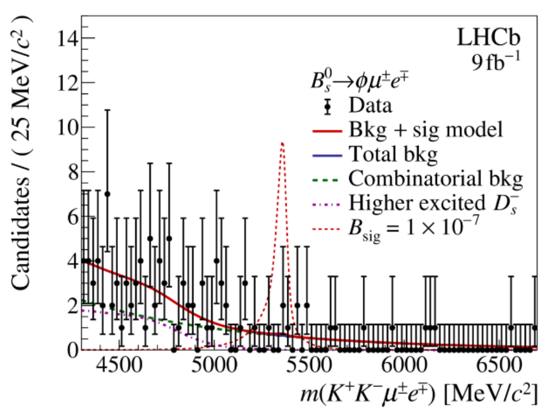
Channel	Expected	Observed
$B^0 \to p\mu^-$	$1.9\ (2.4) \times 10^{-9}$	$2.6\ (3.1) \times 10^{-9}$
$B^0_s \to p\mu^-$	$7.0\ (8.6) \times 10^{-9}$	$12.1\ (14.0) \times 10^{-9}$

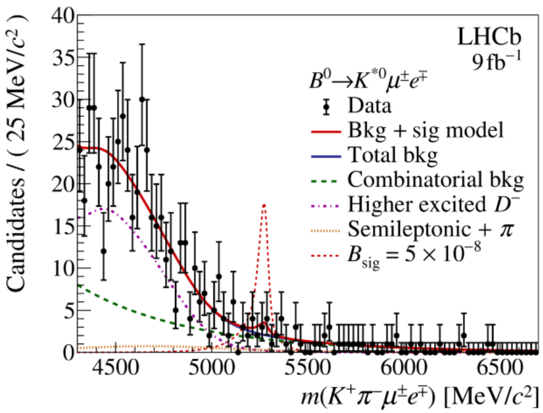
arXiv:2210.10412

LFV decays $B_s^0 \to \phi\mu^\pm e^\mp$, $B^0 \to K^{*0}\mu^\pm e^\mp$

- An observation of LFV decays involving charged leptons would constitute a clear and unambiguous sign of New Physics
  - Specific NP scenarios that can induce LFV b-hadron decays include models with scalar or vector leptoquarks and models with additional *Z'* bosons
- the flavour anomalies in rare $b \to sl^+l^-$ also make LFV important, as lepton flavour non-universality is closely connected with LFV

$$\mathcal{B}(B^0 \to K^{*0}\mu^+e^-) < \ 5.7 \times 10^{-9}(6.9 \times 10^{-9}),$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^-e^+) < \ 6.8 \times 10^{-9}(7.9 \times 10^{-9}),$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^\pm e^\mp) < 10.1 \times 10^{-9}(11.7 \times 10^{-9}),$$
$$\mathcal{B}(B_s^0 \to \phi\mu^\pm e^\mp) < 16.0 \times 10^{-9}(19.8 \times 10^{-9})$$



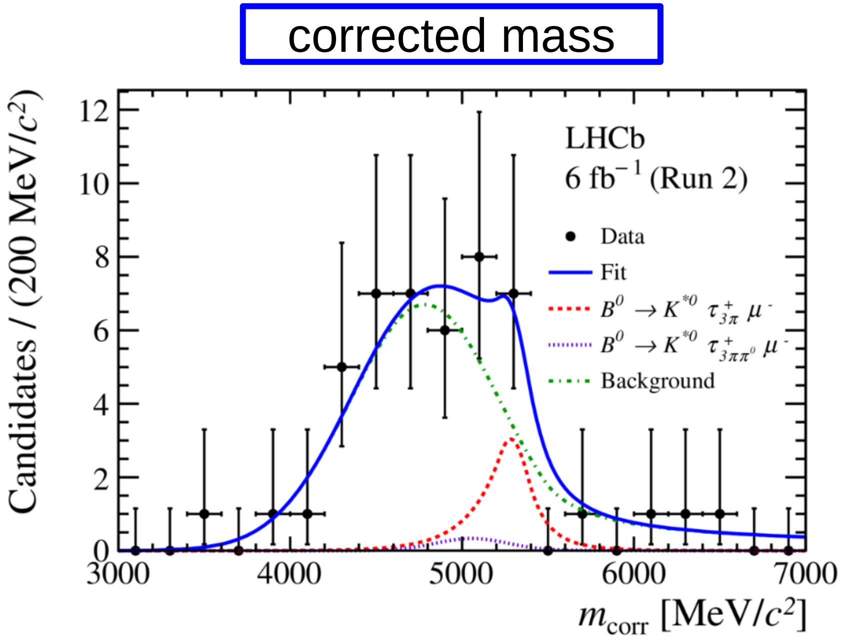


- The world's most stringent limits to date

arXiv:2207.04005

LFV decays $B^0 \to K^{*0}\mu^{\pm}\tau^{\mp}$

- Not ever investigated by any prior experiment



BR($B^0 \to K^{*0}\mu^-\tau^+$) <1.0(1.2)$\times 10^{-5}$, BR($B^0 \to K^{*0}\mu^+\tau^-$) <8.2(9.8) $\times 10^{-6}$

- The world's most stringent limits to date

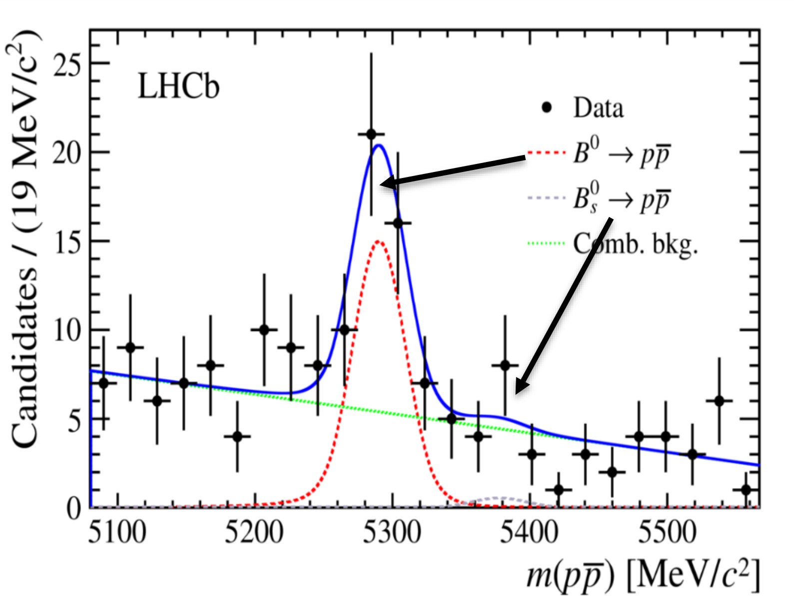
arXiv:2209.09846

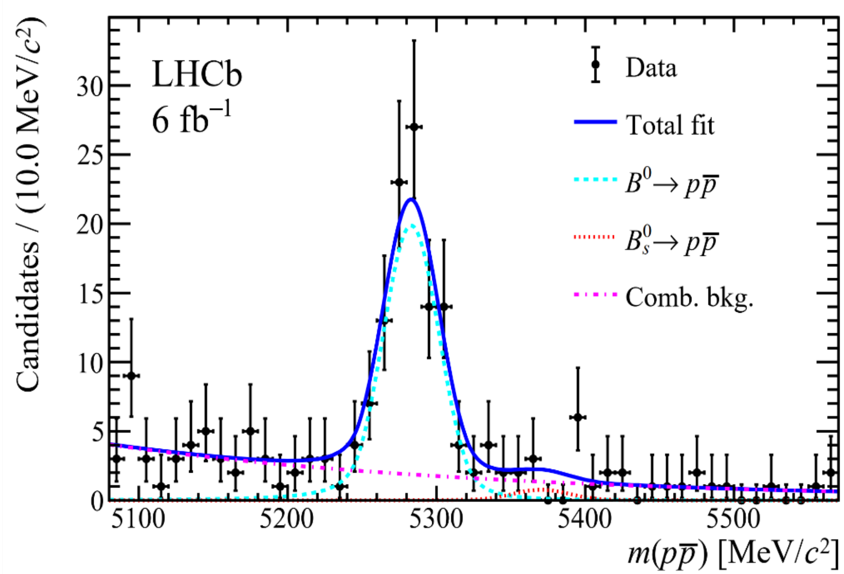
Search for the rare hadronic decay $B_s^0 \to p\bar{p}$

- To date only three charmless two-body baryonic decays have been observed, namely the $B^+ \to p\,\bar{\Lambda}(1520)$, $B^+ \to p\,\bar{\Lambda}$ and $B^0 \to p\bar{p}$ modes.

- Run-I result:

  BR($B^0 \to p\bar{p}$)= $(1.25\pm0.27\pm0.18)\times10^{-8}$





arXiv:2206.06673

Search for the rare hadronic decay $B_s^0 \to p\bar{p}$

- No statistically significant excess of the decay is observed.

The 90% (95%) upper limit on the $B_s^0 \to p\bar{p}$ decay branching fraction is set at

$$\boxed{\mathcal{B}(B_s^0 \to p\bar{p}) < 4.4\ (5.1) \times 10^{-9} \text{ at } 90\%\ (95\%) \text{ CL.}}$$

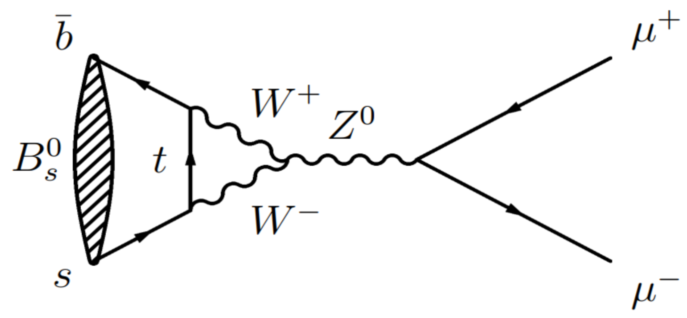
- Using the measured quantities and the equation below, the branching fraction of the ($B^0 \to p\bar{p}$) decay is measured more precisely to be:

$$\mathcal{B}(B^0_{(s)} \to p\bar{p}) = \frac{N(B^0_{(s)} \to p\bar{p})}{N(B^0 \to K^+\pi^-)} \times \frac{\varepsilon_{B^0 \to K^+\pi^-}}{\varepsilon_{B^0_{(s)} \to p\bar{p}}} \times \mathcal{B}(B^0 \to K^+\pi^-) \times \frac{f_d}{f_{d(s)}}, \qquad (1)$$

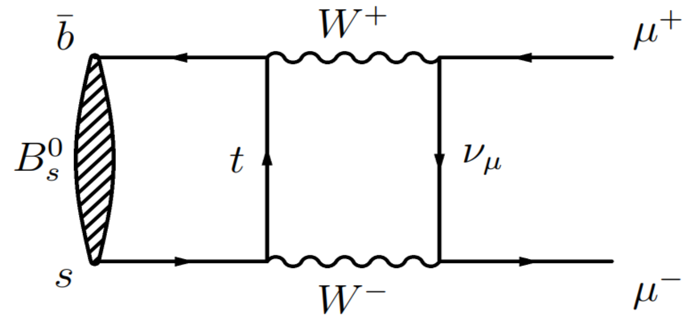
$$\mathcal{B}(B^0 \to p\bar{p}) = (1.27 \pm 0.15 \pm 0.05 \pm 0.04) \times 10^{-8},$$

arXiv:2206.06673

Measurement of $B_s^0 \to \mu^+\mu^-$ and search for $B^0 \to \mu^+\mu^-$, $B_s^0 \to \mu^+\mu^-\gamma$

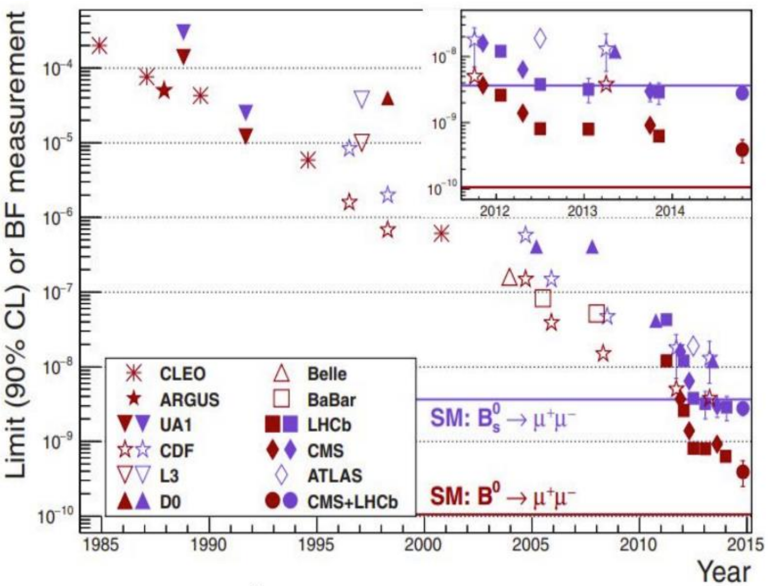


(a)



(b)

- Highly suppressed in SM, (i)Cabibbo suppressed, (ii)Helicity suppressed
- Extremely rare in SM ($B_s^0 \to \mu^+\mu^-$ ~(3.66±0.14) $\times 10^{-9}$, $B^0 \to \mu^+\mu^-$ ~(1.03±0.05) × 10^{-9}).
- powerful probes for detecting deviations from the SM due to new physics contributions mediated, for instance, by heavy *Z'* gauge bosons, leptoquarks or non-SM Higgs bosons

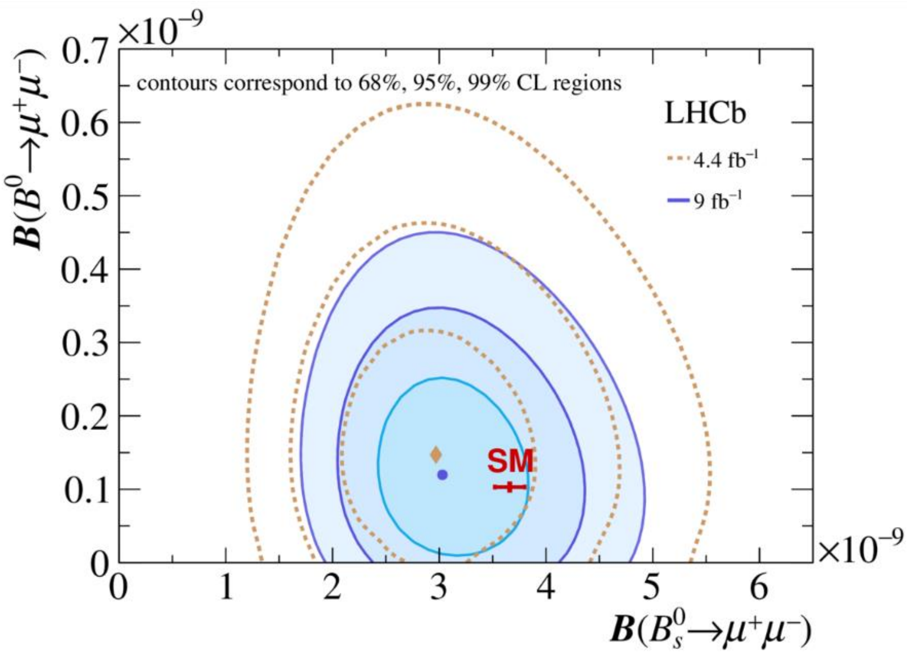


Phys. Rev. Lett. 128, (2022) 041801

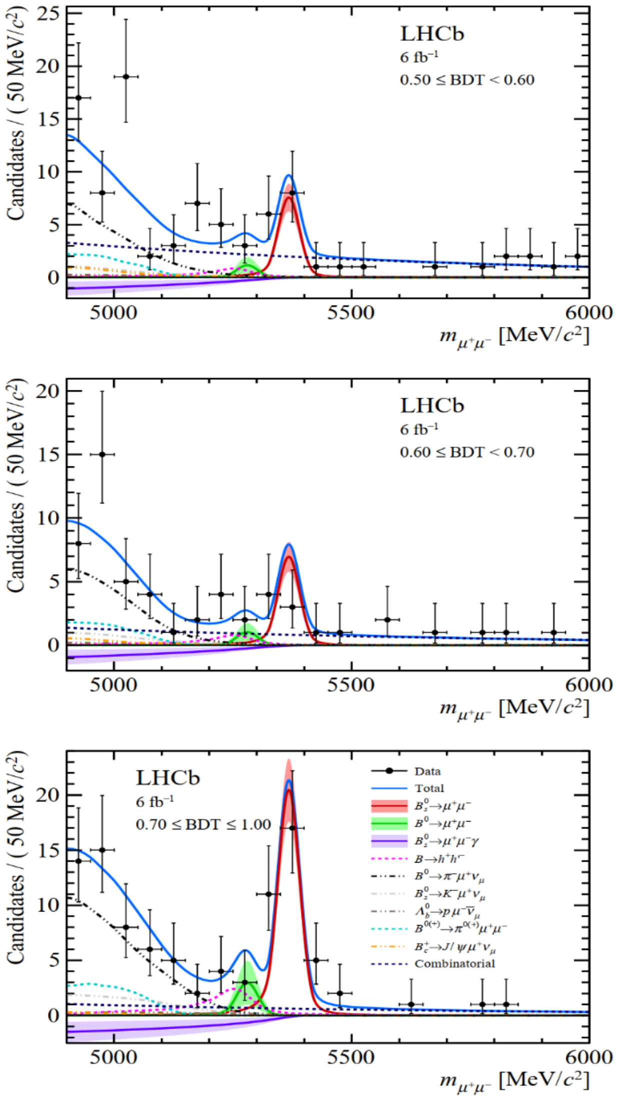
Phys. Rev. D105 (2022) 012010

LHCb Run 1 + Run 2, $B_s^0 \to \mu^+\mu^-$

- Branching ratios, consistent with SM:



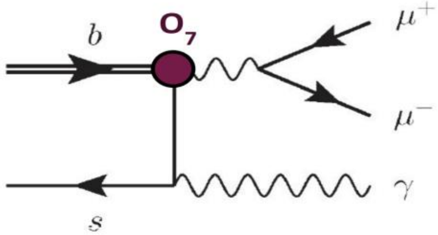
- Systematic uncertainties of $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ are dominated by the uncertainty on *fs/fd* (3%) and the knowledge of the background from specific processes (9%), respectively.

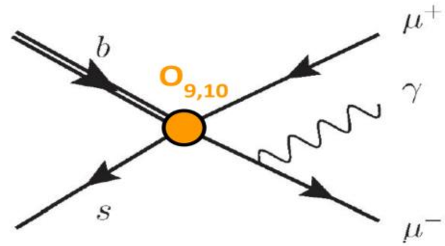


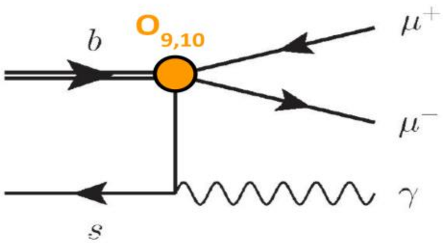
Phys. Rev. Lett. 128, (2022) 041801 Phys. Rev. D105 (2022) 012010

Search for $B_s^0 \to \mu^+\mu^-\gamma$

- Compared to the $B_s^0 \to \mu^+\mu^-$ amplitude, the additional suppression arising from the photon is compensated by no longer helicity suppressed, increasing the total predicted BR
- The $B_s^0 \to \mu^+\mu^-\gamma$ process is a powerful probe of SM, being sensitive to C7 , C9 and C10, While $B_s^0 \to \mu^+\mu^-$ is only sensitive to C10



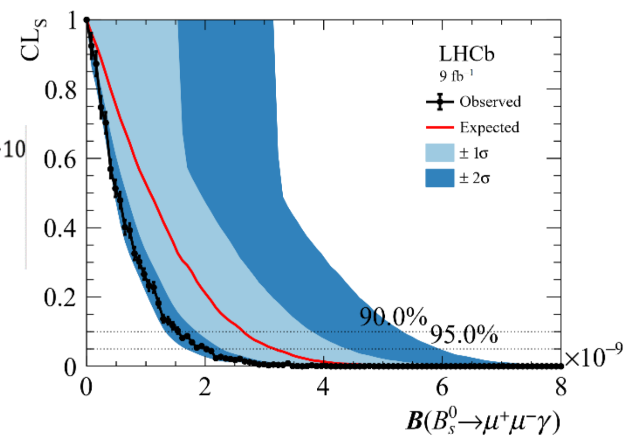




- Indirect search:

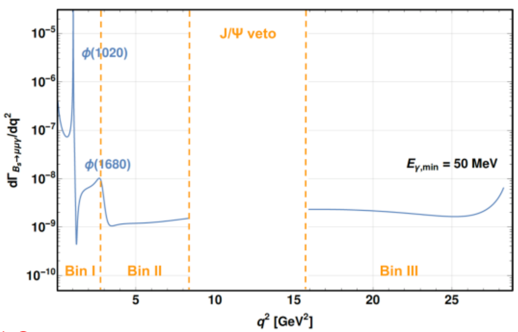
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < (8.90 \pm 0.98) \times 10^{-10}$$

$$q^2 \in [15.84, 28.27] GeV^2/c^4$$



- Direct search (coming very soon):

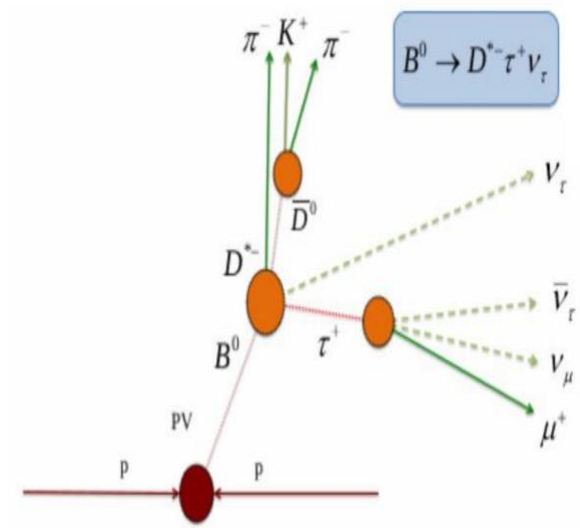
- Direct photon search first time
- Probe low q^2 regions for the first time



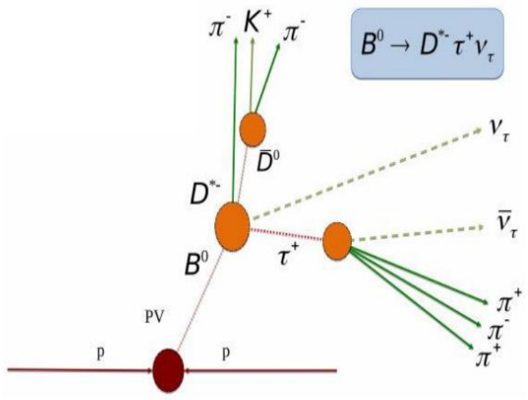
Phys. Rev. Lett. 128, (2022) 041801 Phys. Rev. D105 (2022) 012010

LFU tests

R(D$^{(*)}$) measurements



$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\mu\nu_\mu)}$$



Muonic $\tau \to \mu\bar{\nu}\nu$:

- Large statistics
- Study of τ and μ modes in one dataset
- measure R(D) and R(D*) simultaneously

Hadronic $\tau \to \pi\pi\pi(\pi^0)\bar{\nu}$:

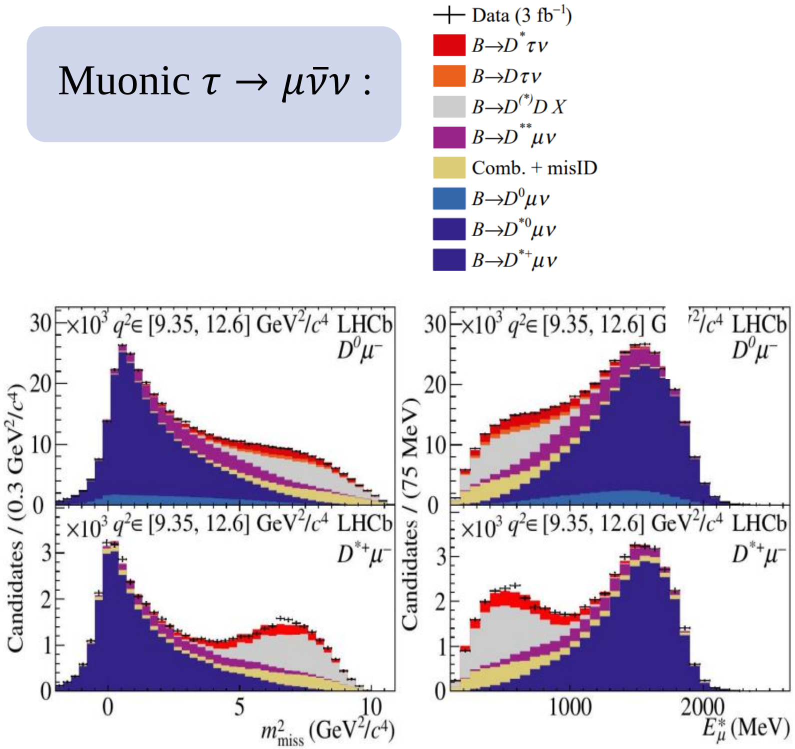
- Relatively high purity
- External BR measurement for normalization
- Decay vertex of τ well measured to suppress dominant backgrounds
- 3π dynamics important for the separation of $B \to$ D∗DX backgrounds

arXiv:2302.02886

arXiv:2305.01463

R(D$^{(*)}$) measurements

Muonic $\tau \to \mu\bar{\nu}\nu$:



Using Run-I 3 fb^{-1} data:

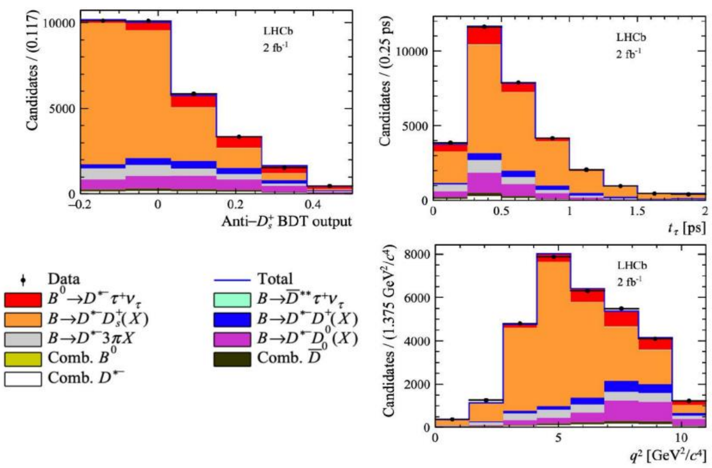
$R(D^*)$ = 0.281±0.018 (stat.) ±0.024(syst.)

$R(D)$ = 0.441±0.060 (stat.) ±0.066(syst.)

$\rho = -0.43$

1.9σ deviation from SM

Hadronic $\tau \to \pi\pi\pi(\pi^0)\bar{\nu}$:



Using Run1+2 5 fb^{-1} data:

$R(D^*)$=0.257±0.012(stat.)±0.014(syst.)±0.012(ext.)

Agreement w/ SM <1σ

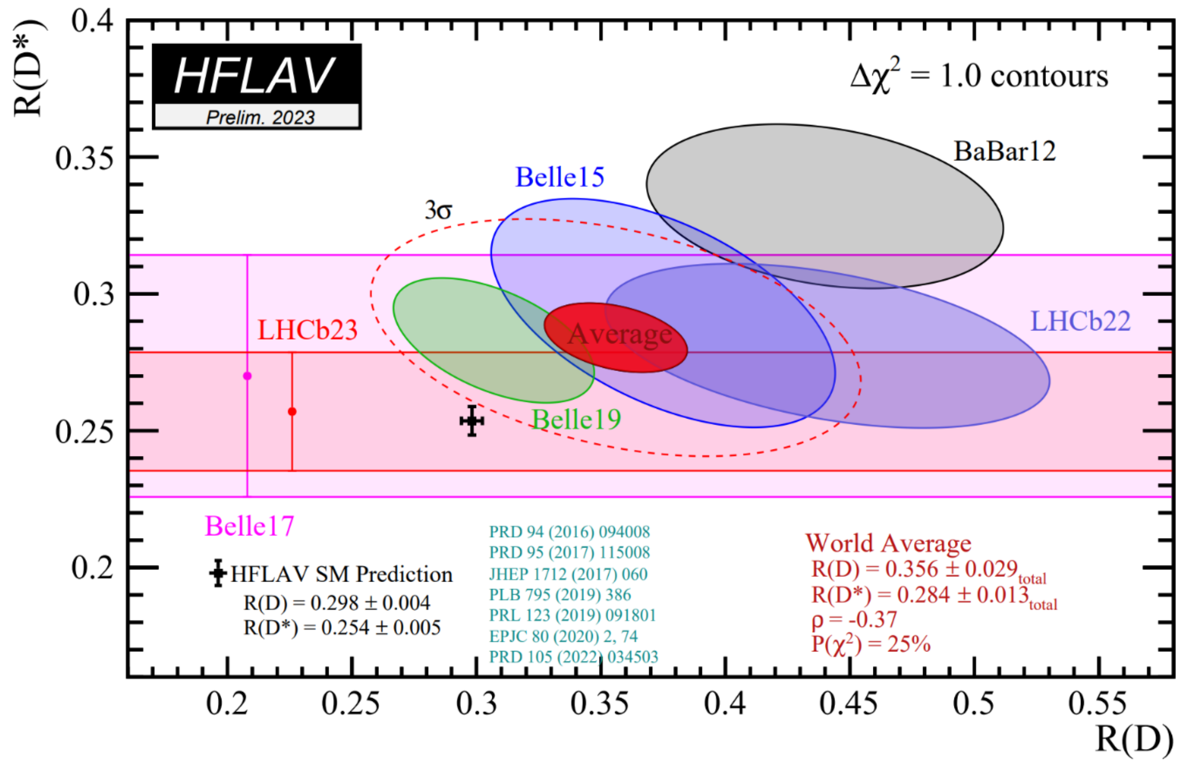
arXiv:2302.02886

arXiv:2305.01463

Updated $R(D^*)$ world averages

- Updates with inclusion o two new results (LHCb22 LHCb23)
  - $R(D^*) = 0.284 \pm 0.013$
  - $R(D) \ = 0.356 \pm 0.029$

- Deviation from SM for combined $R(D) - R(D^*)$ now moves from 3.3σ to 3.2σ



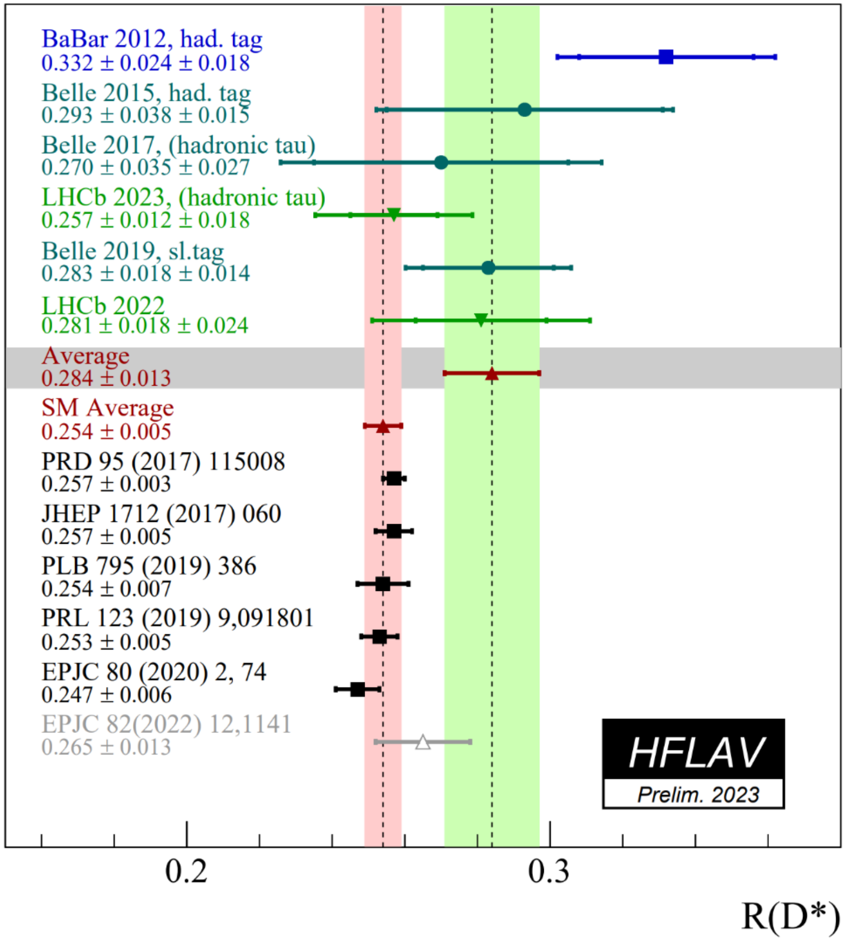
- **Recent BESIII measurements on $D_{(s)} \to 3\pi X$ could be helpful in understanding double-charm backgrounds in hadronic $R(D^*)$ measurements**

arXiv:2212.13072
arXiv:2301.03214

Updated R(D*) world averages

- Updates with inclusion of two new results (LHCb22, LHCb23)
  - R(D*) = 0.284±0.013
  - R(D) = 0.356±0.029

- Deviation from SM for combined R(D∗) now at 1.9σ



arXiv:2212.13072
arXiv:2301.03214

- **Recent BESIII measurements on $D_{(s)} \to 3\pi X$ could be helpful in understanding double-charm backgrounds in hadronic R(D*) measurements**

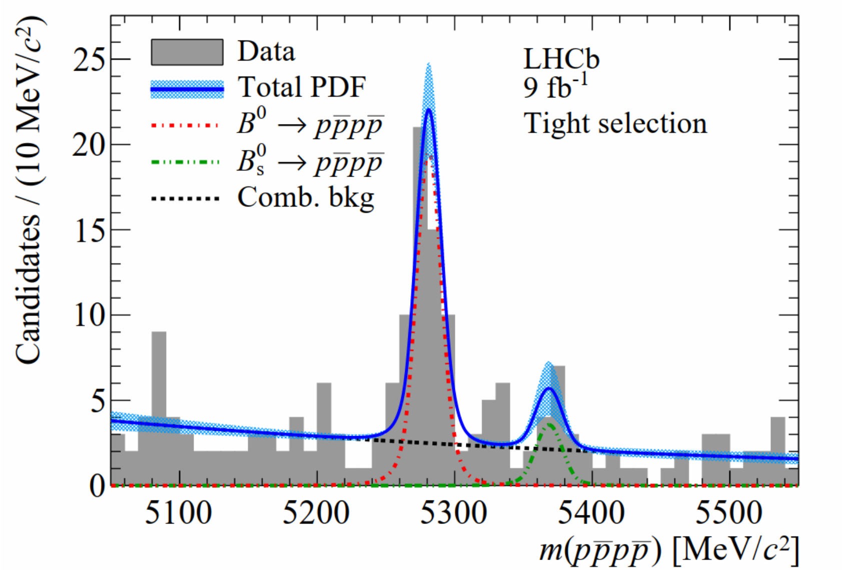
Summary

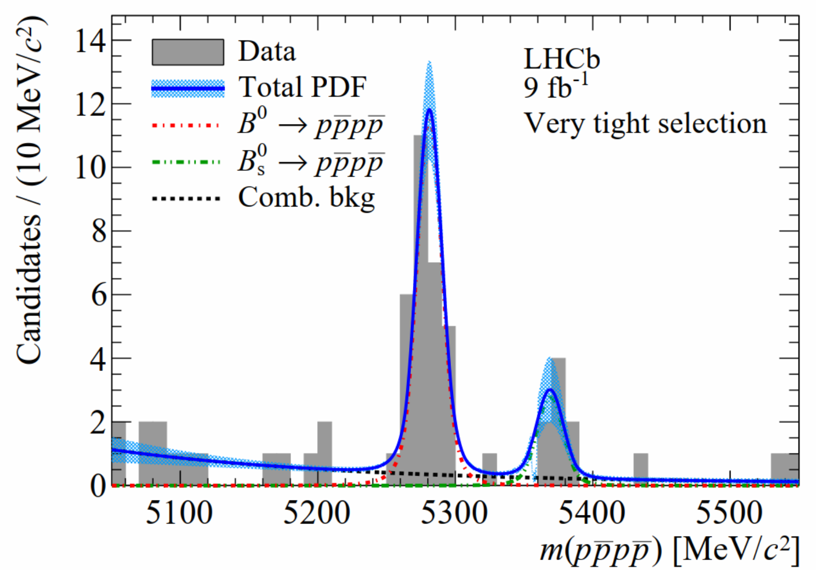
- LHCb is in fact a charm factory as well
- High statistics and excellent detector performance allow for high precision measurements on charm CP, rare decays, etc.
- Still more charm results in the pipeline with full Run1+2 data; and new data (Run3) has started
- Complementary and cross-check with BESIII in many aspects.

谢谢大家！

The rare hadronic decay $B^0_{(s)} \to p\bar{p}p\bar{p}$

- No reliable theoretical prediction for $B^0_{(s)} \to p\bar{p}p\bar{p}$ decays for now, a first measurement of the corresponding BR would allow to better understand the underlying dynamics
- The BRs of multi-body baryonic decay modes may be significantly increased due to a threshold enhancement effect in the baryon-antibaryon invariant mass, while two-body baryonic decays (such as $B^0_{(s)} \to p\bar{p}$) are suppressed
- B^0 / B^0_s: significance of 9.3σ and 4.0σ

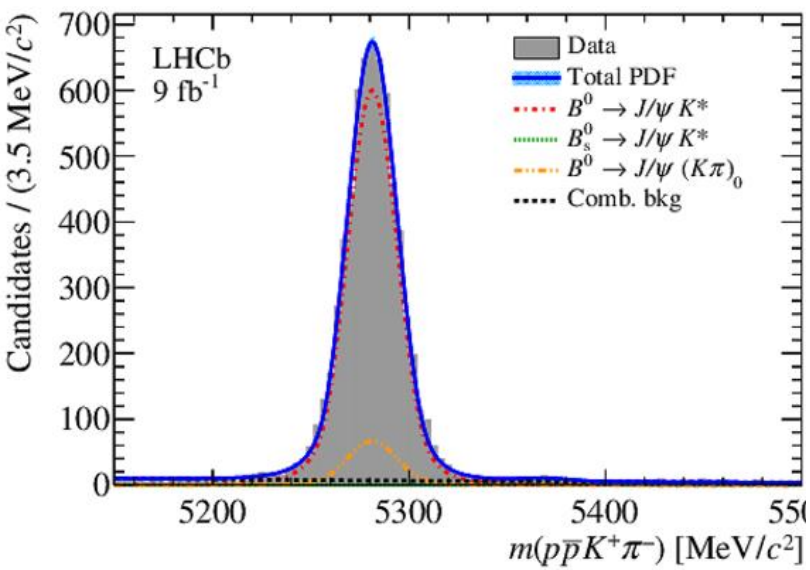


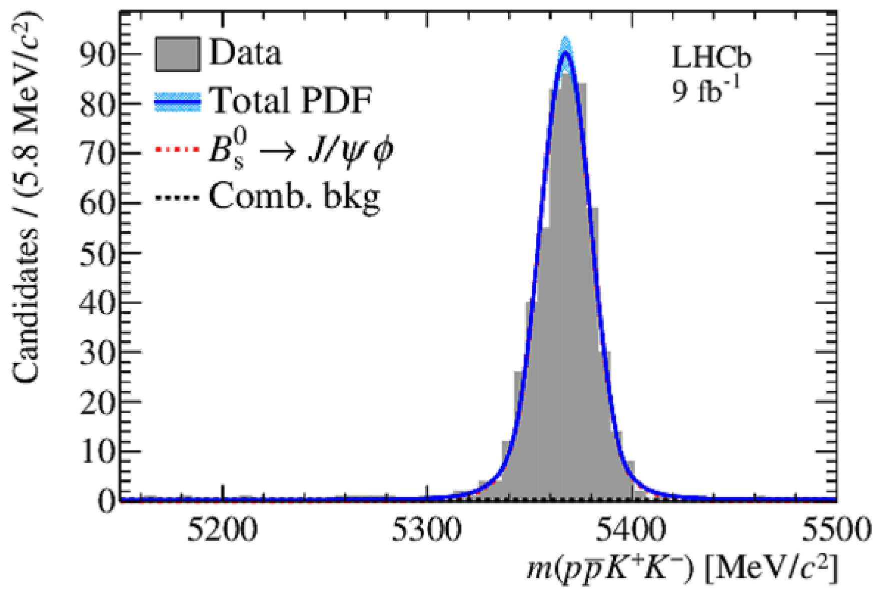


arXiv:2211.08847

The rare hadronic decay $B^0_{(s)} \to p\bar{p}p\bar{p}$

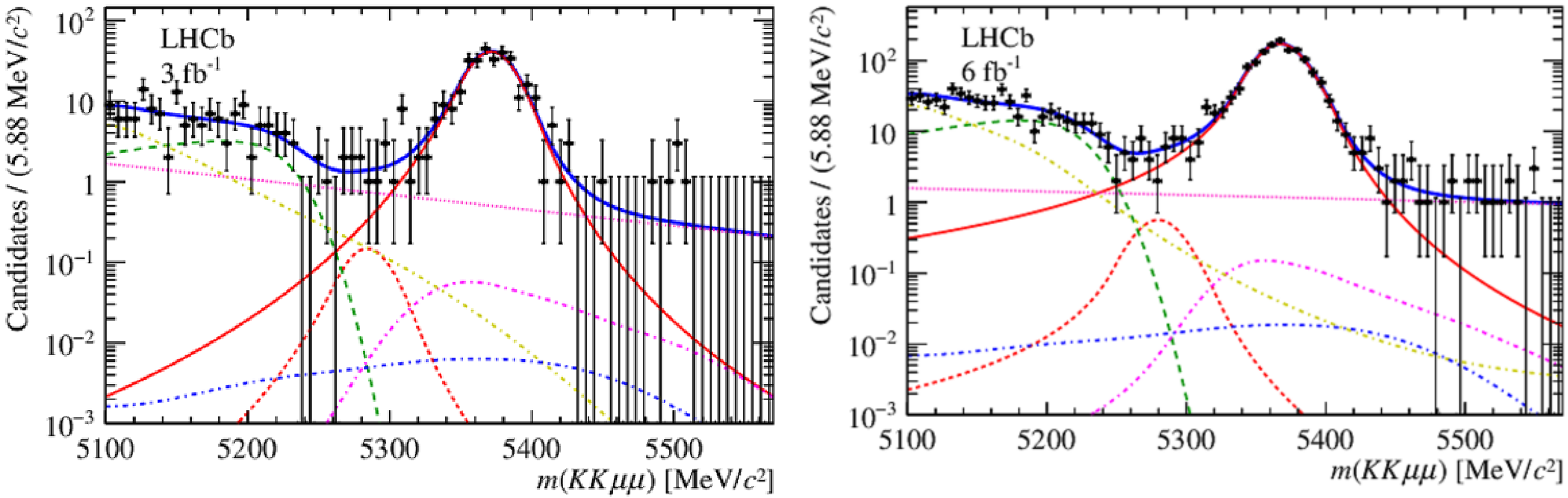
- The branching fractions are measured relative to the topologically similar normalisation decays： $B^0 \to J/\psi(\to p\bar{p})K^{*0}(\to K\pi)$ and $B^0_s \to J/\psi(\to p\bar{p})\phi(\to KK)$
- Results: BR($B^0 \to p\bar{p}p\bar{p}$)= $(2.2\pm0.4\pm0.1)\times10^{-8}$ and BR($B^0_s \to p\bar{p}p\bar{p}$)= $(2.2\pm1.0\pm0.2)\times10^{-8}$





arXiv:2211.08847

Search for the $B^0 \to \varphi\mu^+\mu^-$



- No statistically significant excess of the decay $B^0 \to \varphi\mu^+\mu^-$
- An upper limit on its BR excluding the φ and charmonium regions in the dimuon spectrum, relative to that of the decay $B_s^0 \to \varphi\mu^+\mu^-$ is determined to be 4.4×10^{-3} at a 90% CL.
- Using the LHCb measurement of $\mathrm{B}(B_s^0 \to \varphi\mu^+\mu^-)$, an upper limit on $\mathrm{B}(B^0 \to \varphi\mu^+\mu^-)$ in the full q^2 range is set to be 3.2×10^{-9} at a 90% CL, which is compatible with the SM prediction.

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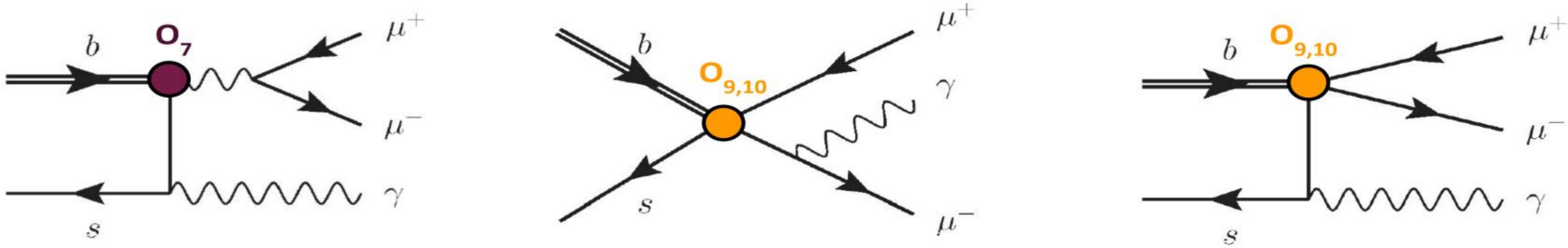
Search for $B_s^0 \to \mu^+\mu^-\gamma$

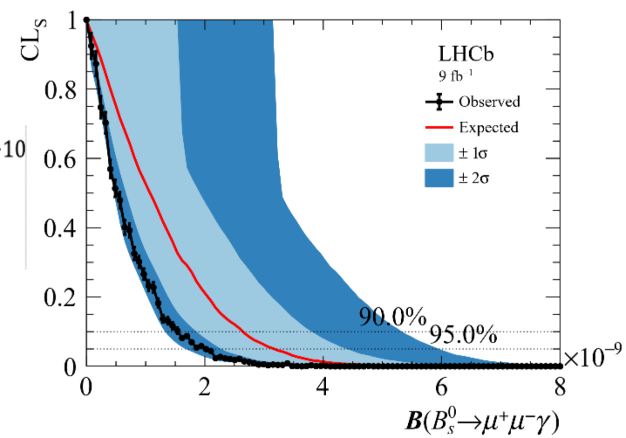
- Compared to the $B_s^0 \to \mu^+\mu^-$ amplitude, the additional suppression arising from the photon is compensated by no longer helicity suppressed, increasing the total predicted BR
- The $B_s^0 \to \mu^+\mu^-\gamma$ process is a powerful probe of SM, being sensitive to C7 , C9 and C10, While $B_s^0 \to \mu^+\mu^-$ is only sensitive to C10



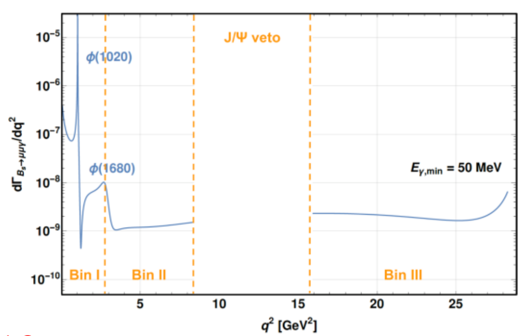
- Indirect search:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < (8.90 \pm 0.98) \times 10^{-10}$$

$$q^2 \in [15.84, 28.27] GeV^2/c^4$$



- Direct search (coming very soon):
  - Direct photon search first time
  - Probe low q^2 regions for the first time



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