Searches for New Physics at LHCb

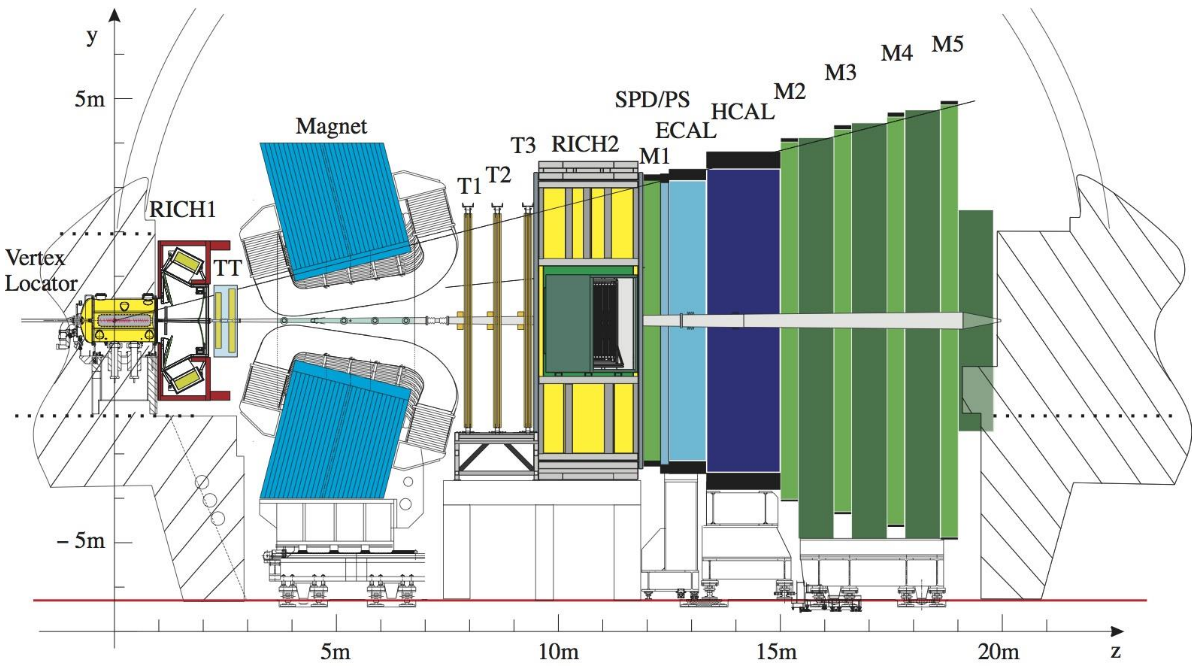
谢跃红，华中师范大学

BESIII新物理研讨会， 杭州，2024年8月26-28日

Outline

- LHCb experiment
- Dark sector: dark photon, dark scalar, ALP, sterile neutrino, LLP
- Rare and forbidden K, D, B decays: LFV, LNV, BNV, FCNC, LFUV
- Summary

LHCb Experiment



LHCb合作组

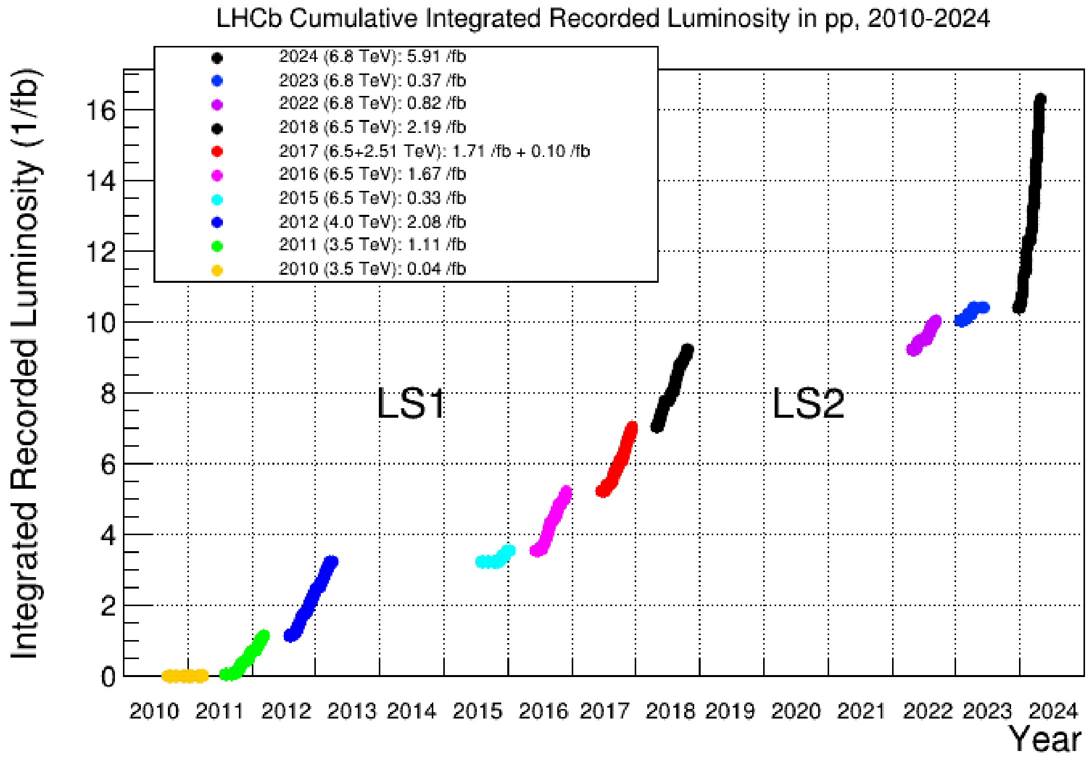
22个国家，99家单位，1698名成员

中国单位：

清华大学，华中师范大学，中国科学院大学，武汉大学，高能所, 华南师范大学，湖南大学，北京大学，兰州大学

- **理解正反物质不对称** (重味强子衰变中的CP破坏)
- **间接寻找新物理效应** (稀有衰变、轻子普适性检验)
- **理解强相互作用机制** (强子性质、新强子态)
- **前向区域的物理研究** (电弱物理、重离子物理、QCD、新物理直接寻找)

LHCb pp collision data taking



第一运行期：Run 1（2011-2012），3 fb^{-1}

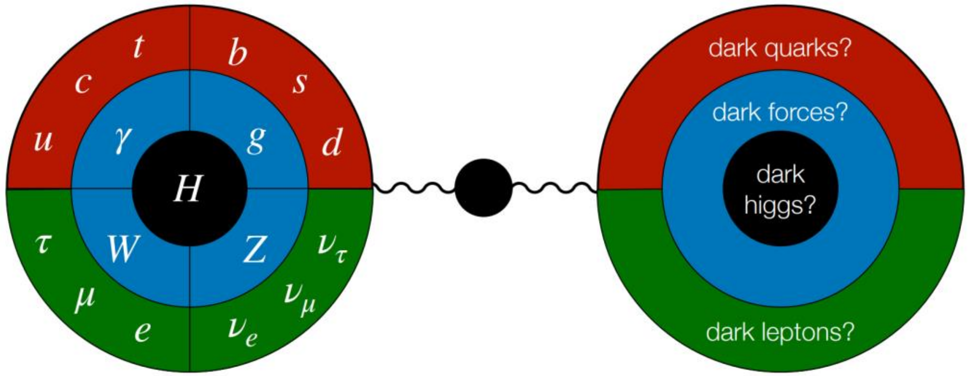
第二运行期：Run 2（2015-2018），6 fb^{-1}

第三运行期：Run 3（2022-　　　），Ongoing

Portals to the dark sector

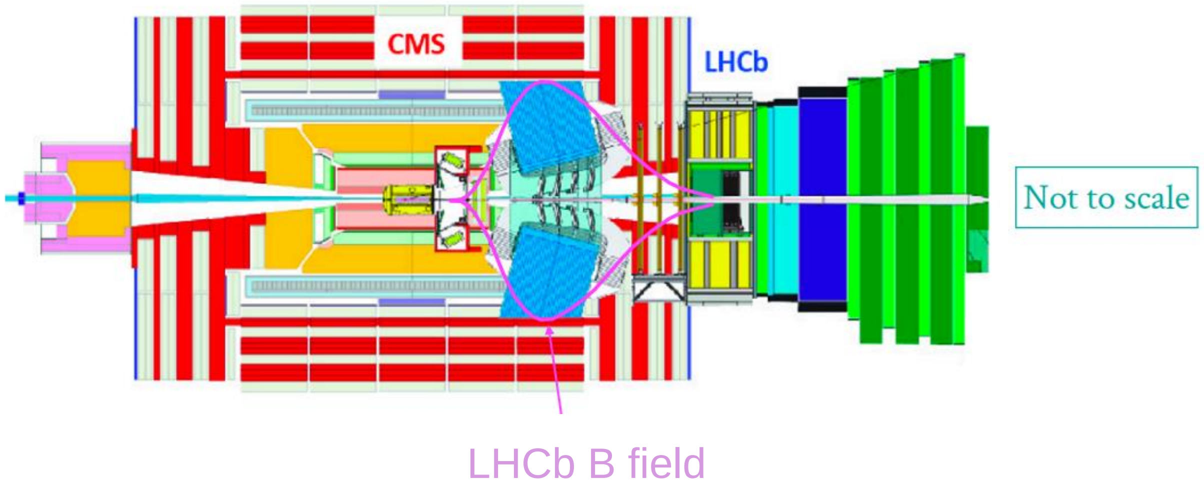
Four portals: new particles [arXiv: 2209.04761]

- Dark photons
- Higgs portal scalars
- Sterile neutrinos
- Axion-like-particles coupling to photons, fermions, gluons

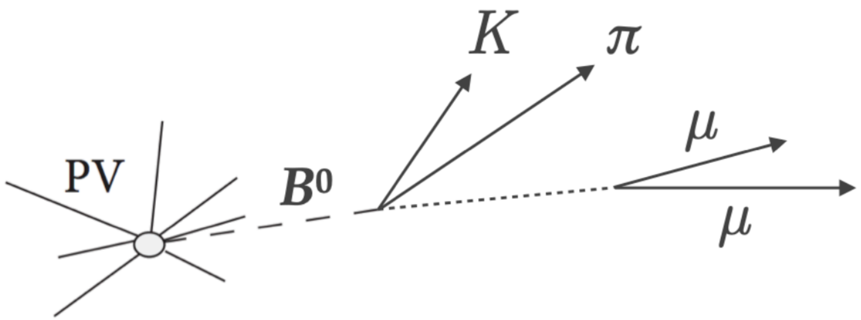


Dark physics at LHCb

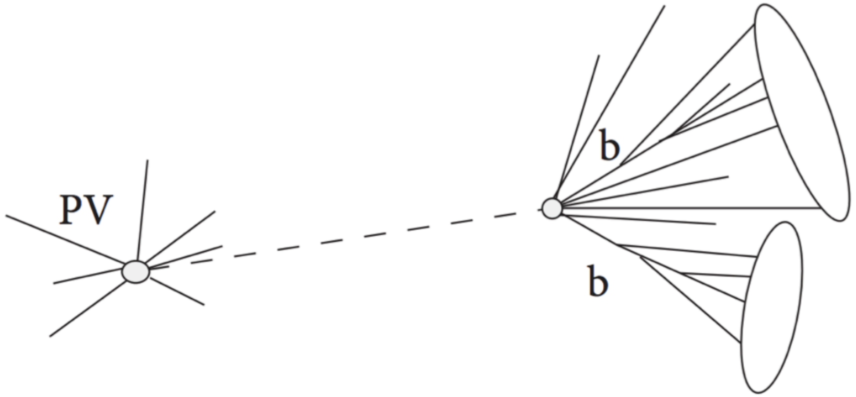
Soft trigger and forward acceptance → light mass and low lifetime



Produced in heavy-flavor decays



Produced in *pp* collisions

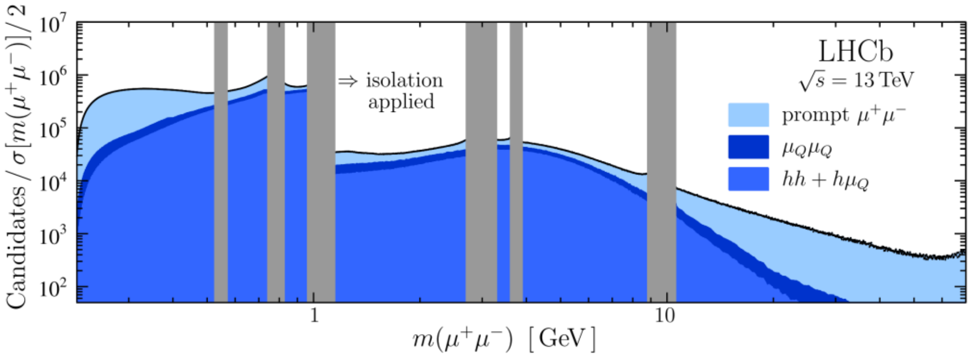


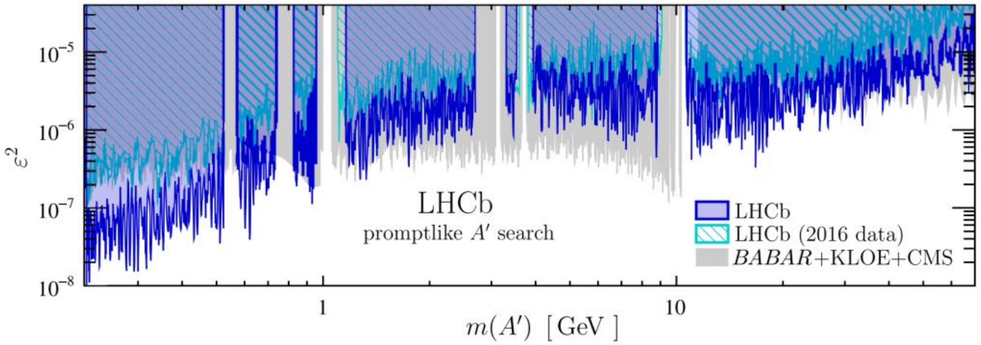
Dark photons: $A' \to \mu^+\mu^-$

PRL 124 (2020) 041801

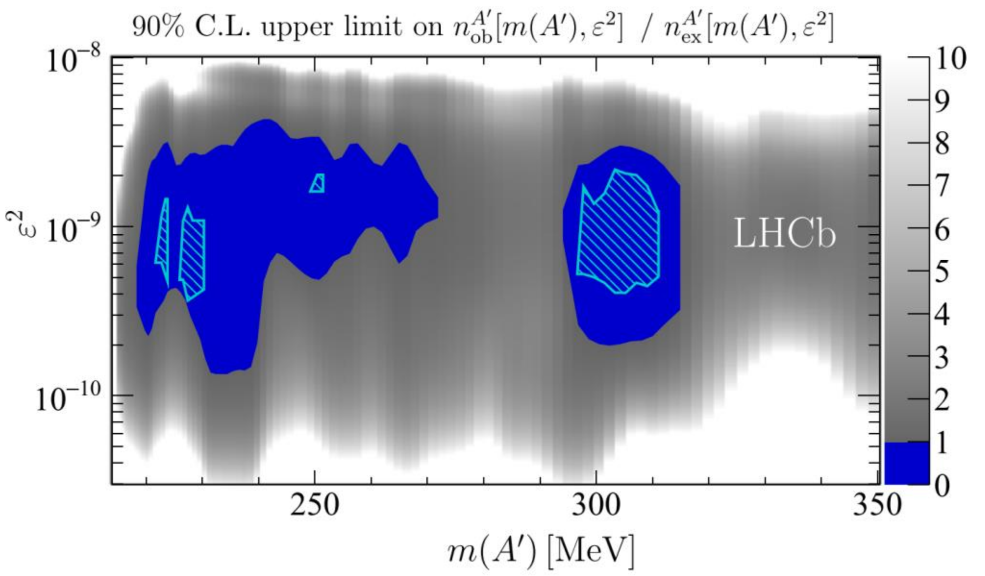
- Searches for prompt-like ($\tau \sim 0$) and long-lived ($\tau \sim \mathcal{O}(1)$ ps) dark photons using Run 2 data
- Kinetic mixing of the dark photon A' with off-shell photon γ^*, with coupling $\alpha' = \varepsilon^2 \alpha_{\text{EM}}$
- Normalize $A' \to \mu^+\mu^-$ to $\gamma^* \to \mu^+\mu^-$

Prompt search





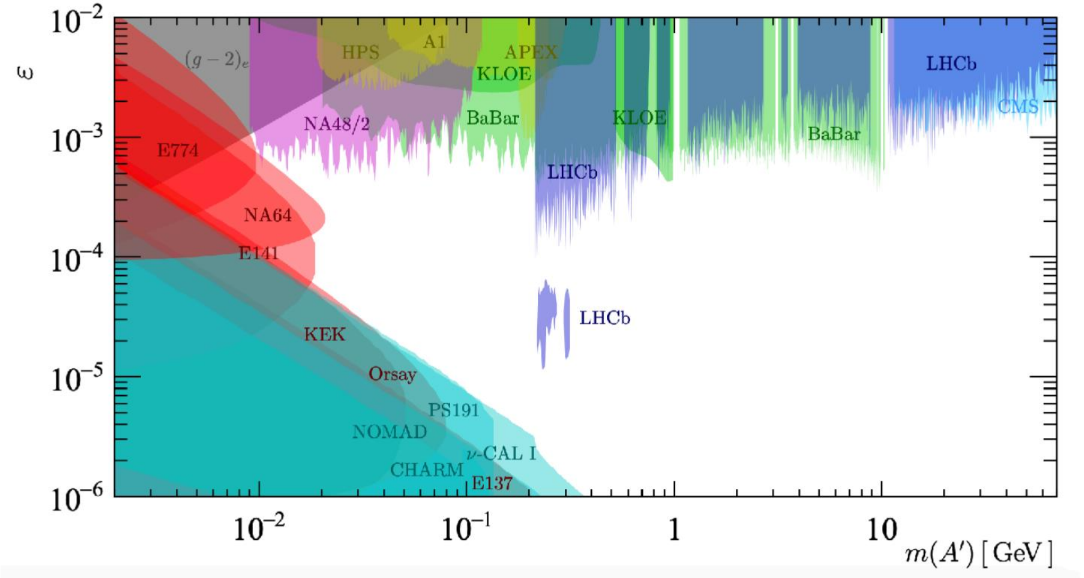
Displaced search



Dark photons: $A' \to \mu^+\mu^-$

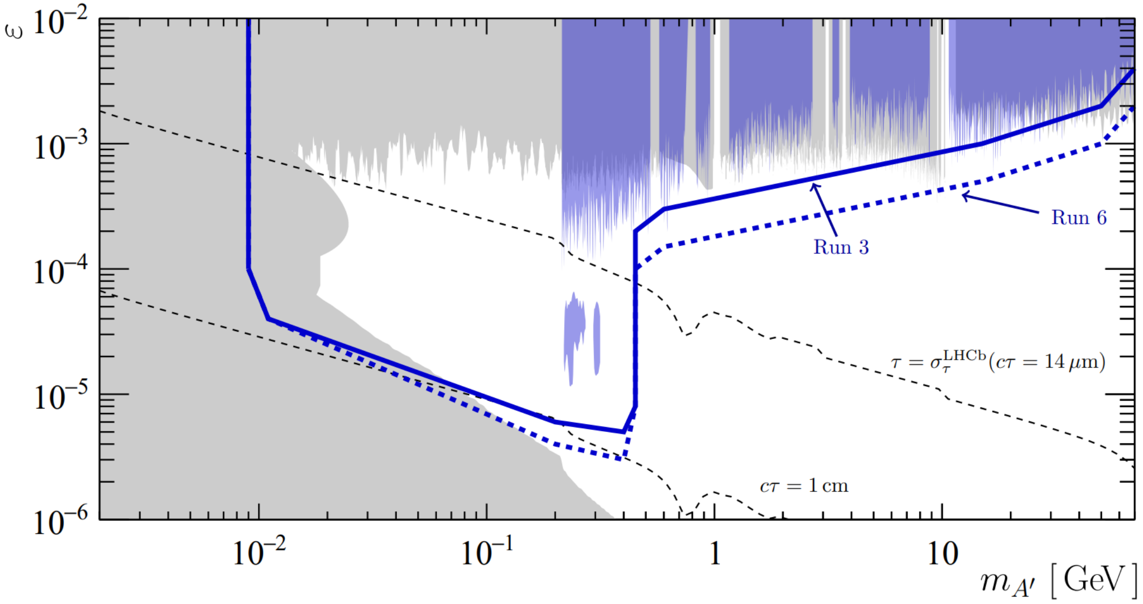
PRL 124 (2020) 041801

- Prompt search in large range: $2m(\mu) < m(\mu\mu) < m(Z)$
- Displaced search in sensitive region $214 < m(\mu\mu) < 350$ MeV



arXiv:2203.07408

Future prospect

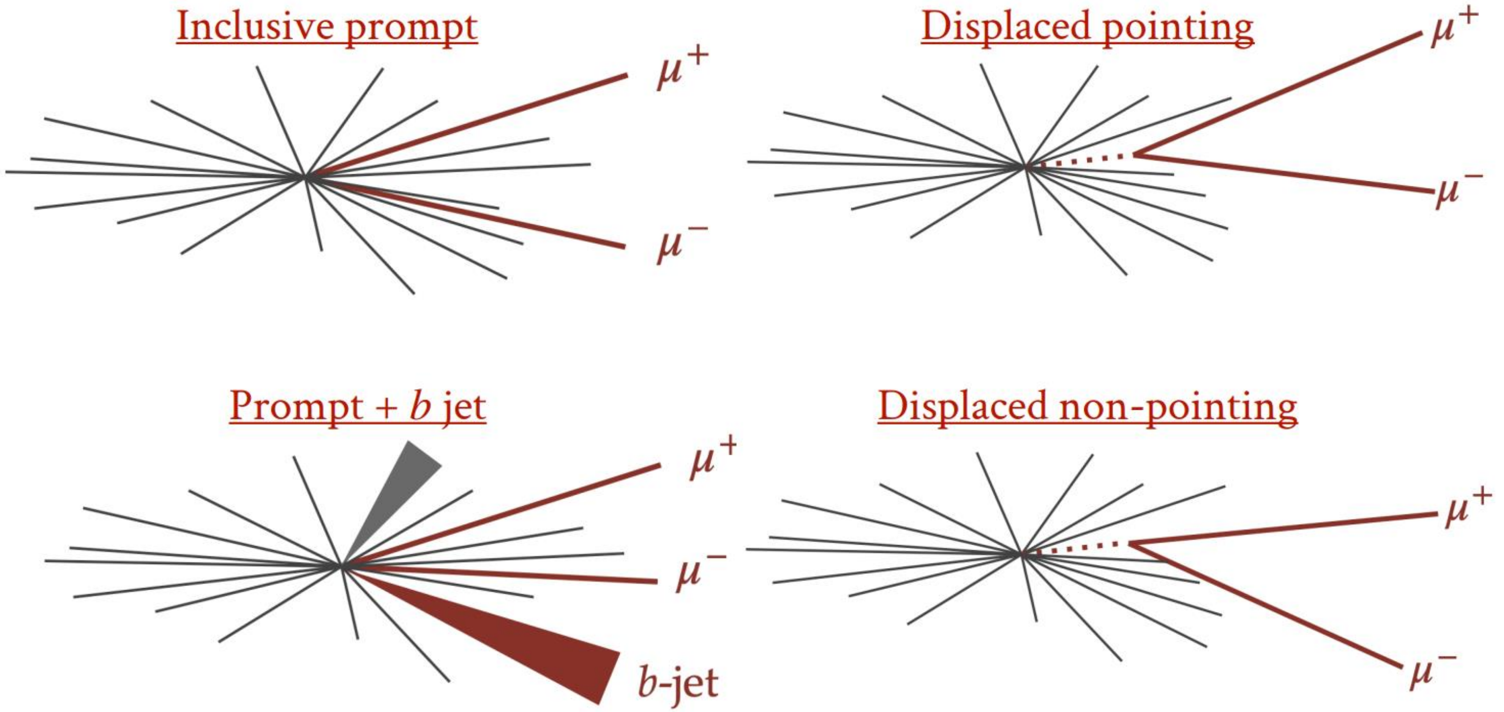


Search for low mass $X \to \mu^+\mu^-$

JHEP 10 (2020) 156

- Probe additional dark-sector particles, dropping the assumption of kinetic mixing with γ^*

- No isolation requirements
- Non-zero width considered

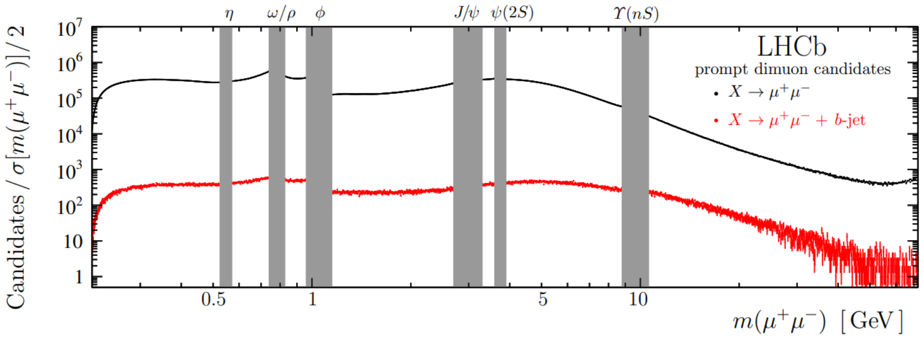


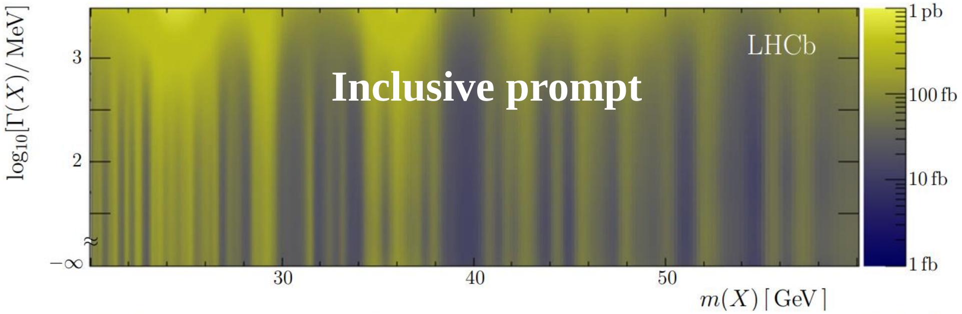
- Non-zero width considered

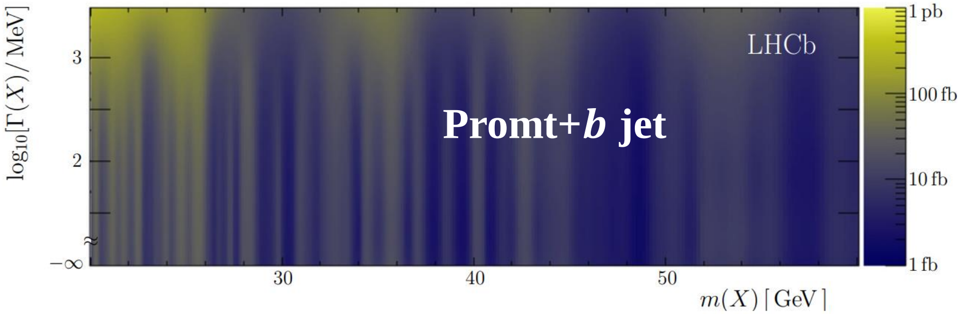
Model-independent limits: $X \to \mu^+\mu^-$

JHEP 10 (2020) 156

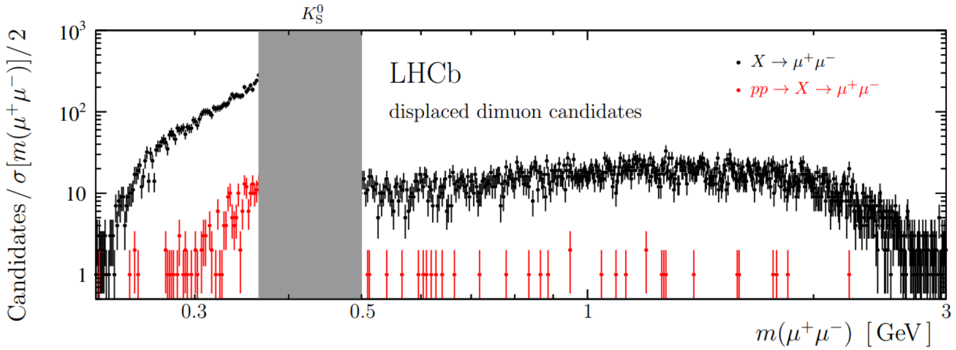
Prompt search

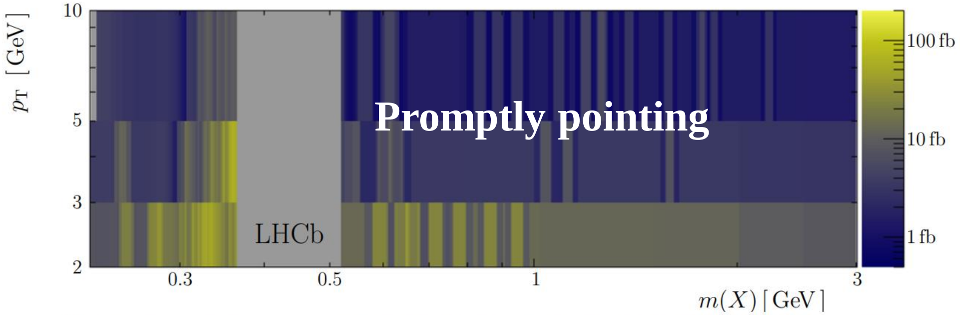


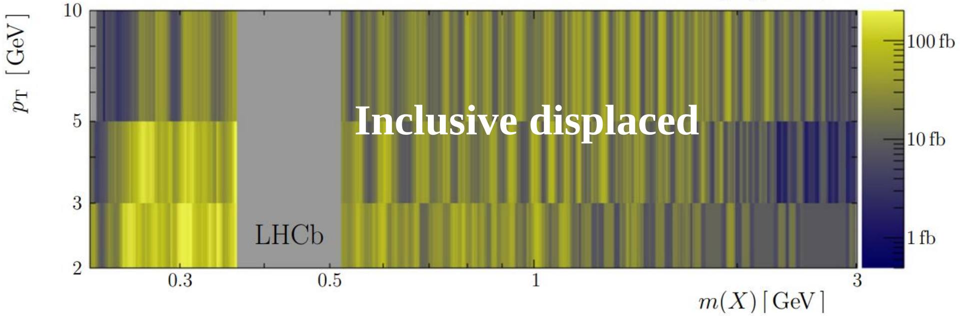




Displaced search





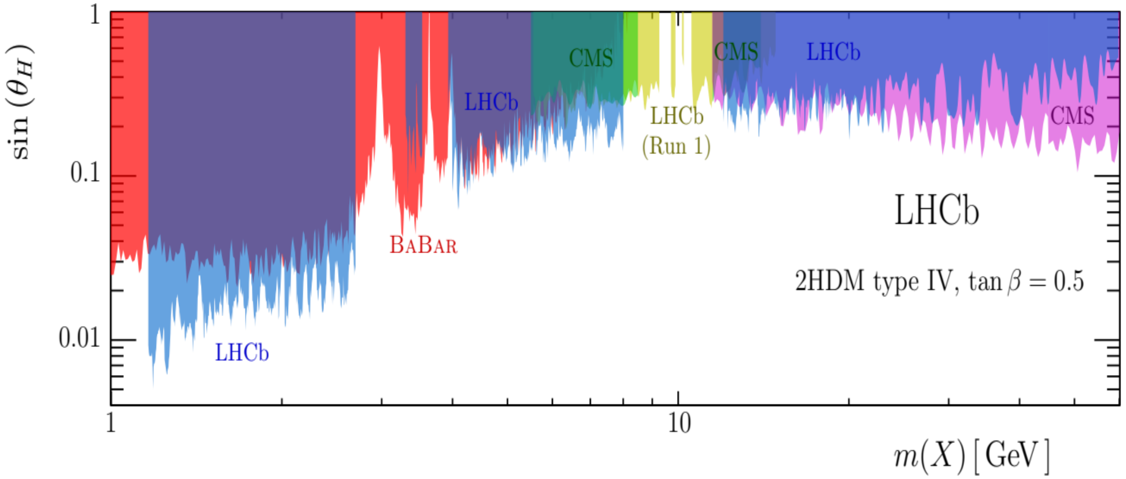


Model-dependent limits: $X \to \mu^+\mu^-$

JHEP 10 (2020) 156

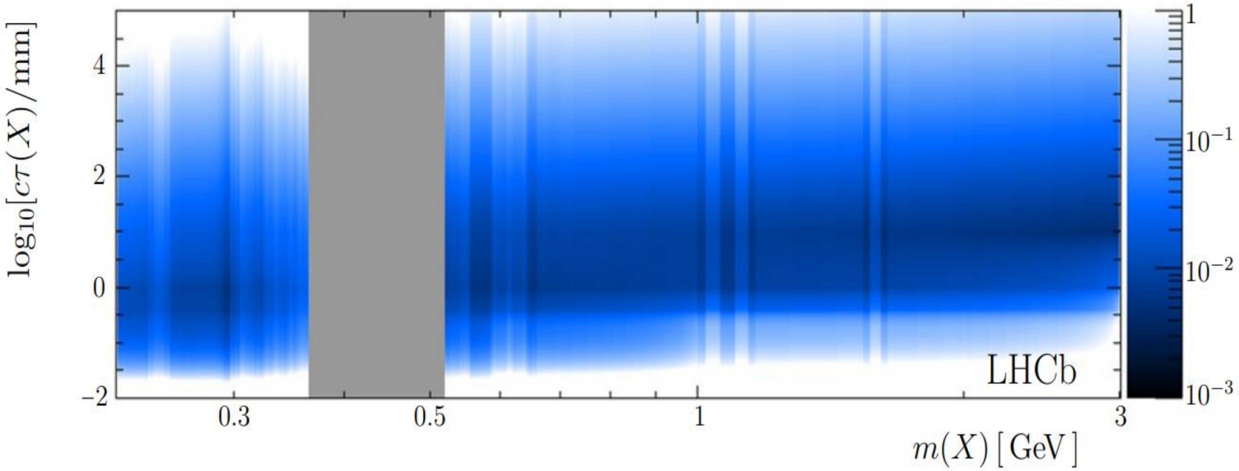
- Limits on X-H mixing angle in two-Higgs doublet models with a complex singlet X (2HDM+S), from prompt search results

$$q\bar{q} \to X \to f\bar{f}$$



- Limits on γ-$Z_{\rm HV}$ kinetic mixing strength in Hidden-Valley scenario with a heavy HV boson $Z_{\rm HV}$, from displaced search results

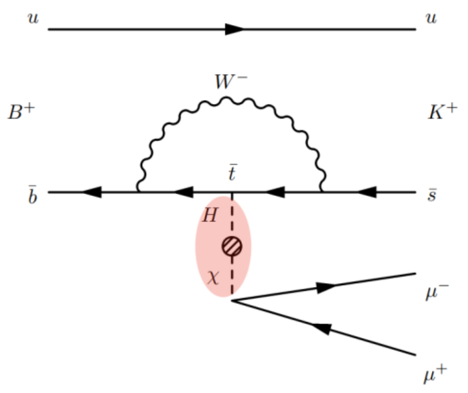
$$q\bar{q} \to Z_{\rm HV} \to q_{\rm HV}\bar{q}_{\rm HV} \to N_\omega \omega_{\rm HV} + N_\eta \eta_{\rm HV}$$
$$\omega_{\rm HV} \to f\bar{f}$$

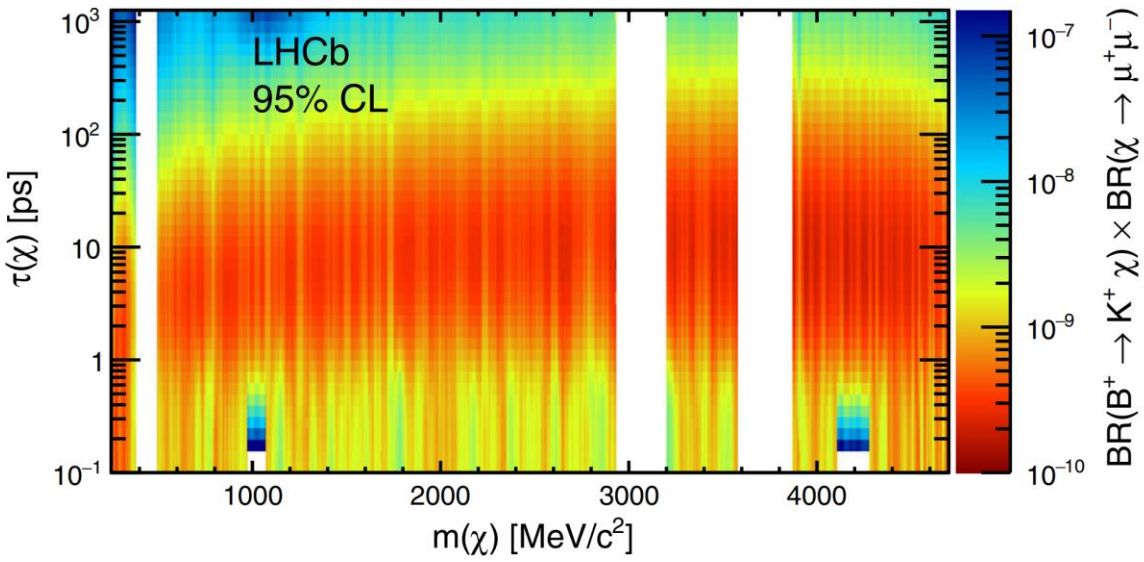


Higgs-like particles in B decays

PRD 95 (2017) 071101

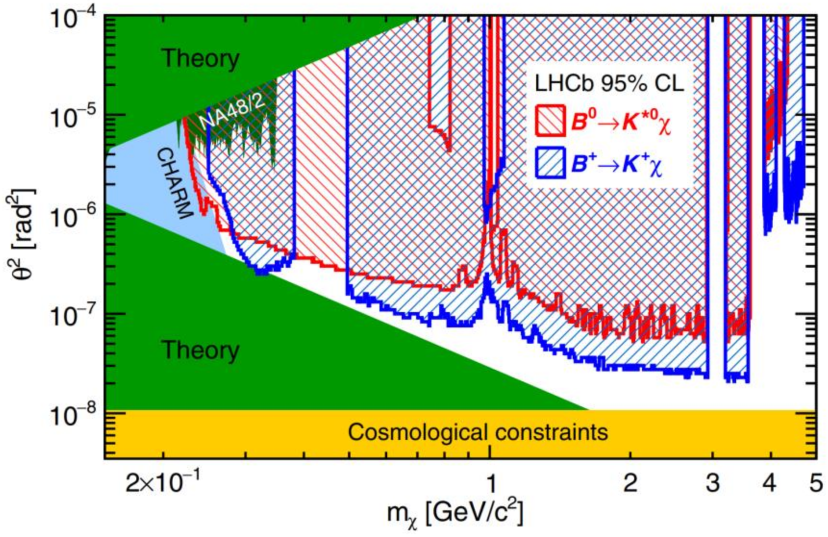
- Search for long-lived scalar decay $\chi \to \mu^+\mu^-$ in $b \to s$ decays using Run 1 data



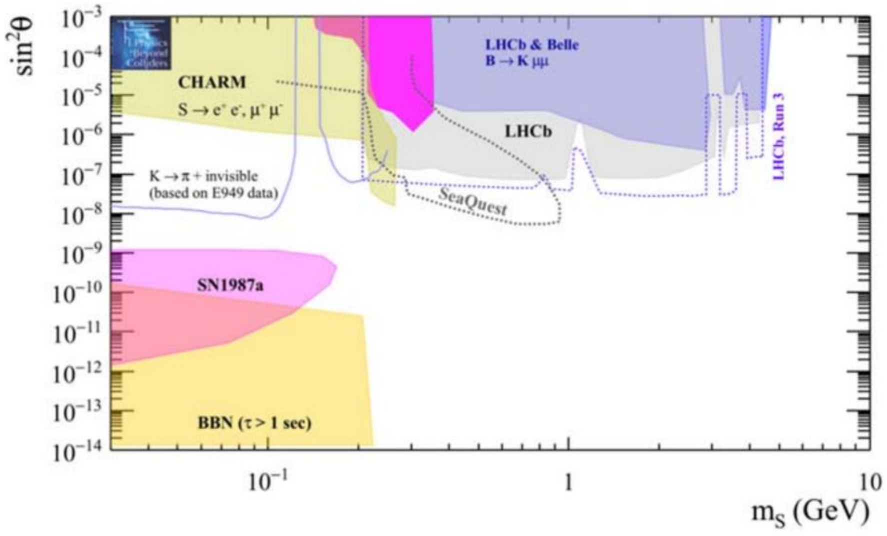


Higgs-like particles in *B* decays

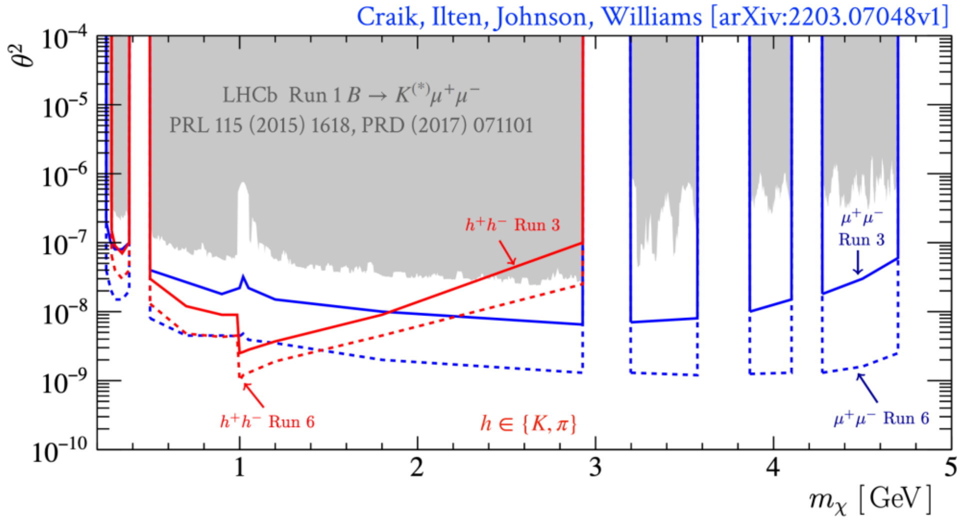
PRD 95 (2017) 071101



J. Phys. G 47 (2020) 010501



Future prospect

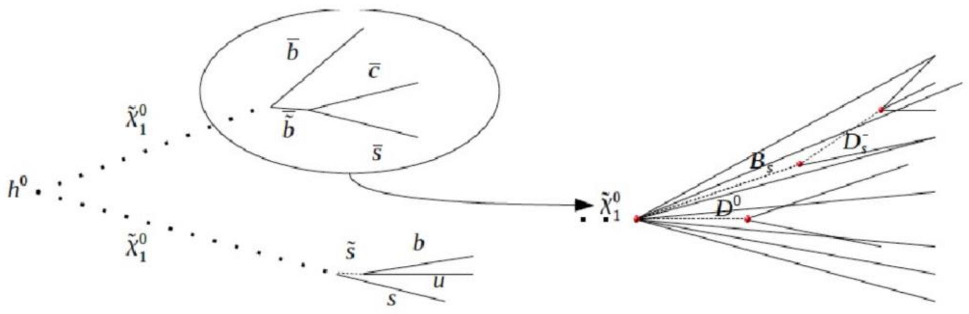


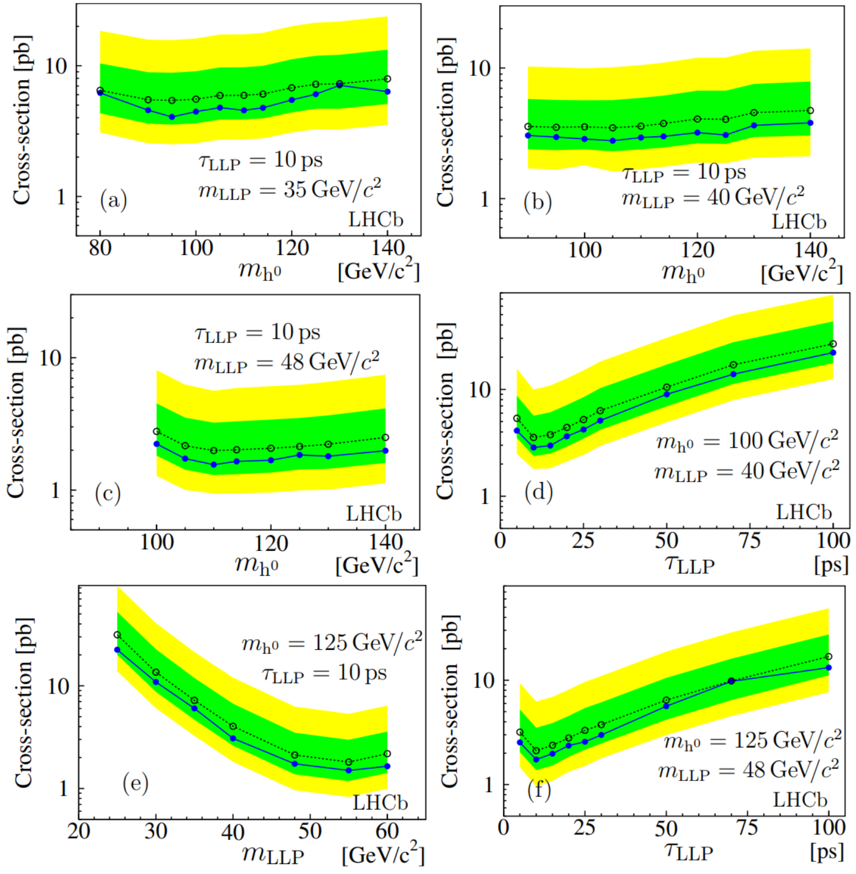
Higgs-like particle to neutral LLP pair

EPJC 76 (2016) 664

- Limits on cross section of a Higgs-like boson decaying to two long-lived particles (neutralinos), each decaying into 3 quarks, using Run 1 data

Pair of displaced high-multiplicity vertices



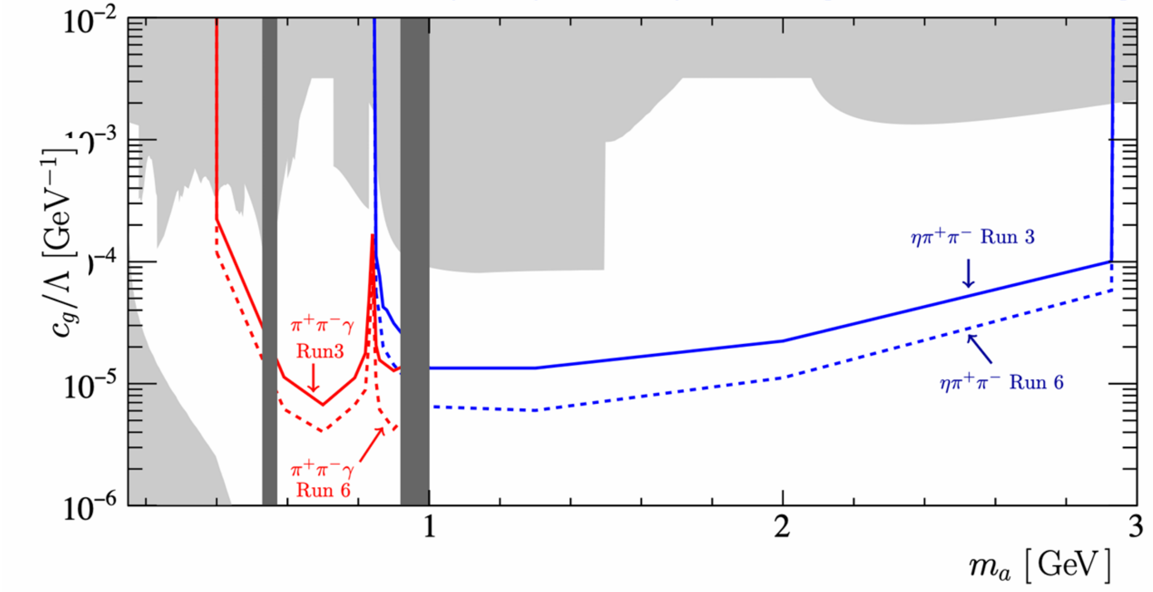


Future prospect of ALP search

- Search for short-lived axion-like-particle decays: $a \to \pi\pi(\gamma, \eta), a \to \gamma\gamma$

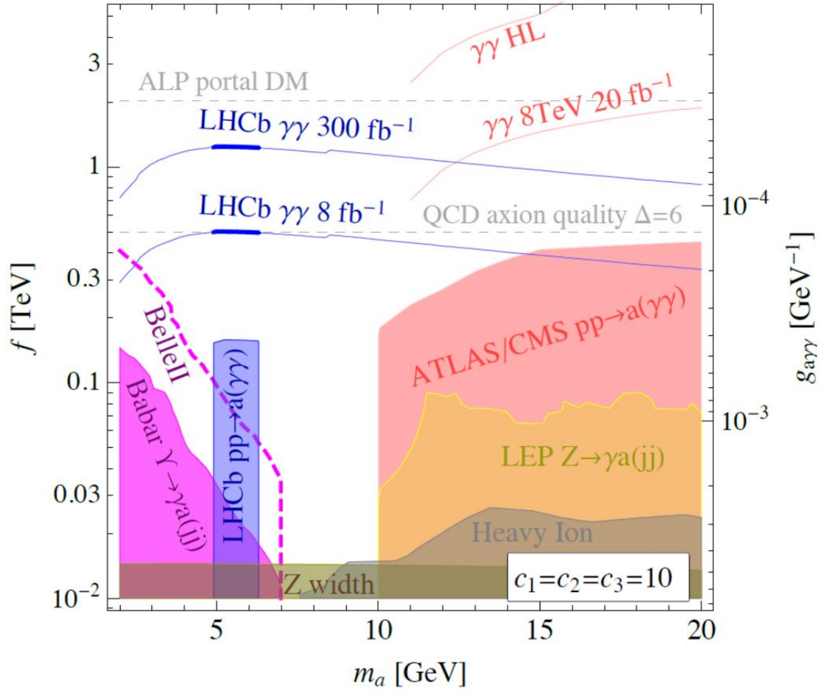
Searched for in $B \to K^{(*)}a$

Craik, Ilten, Johnson, Williams [arXiv:2203.07048v1]



Produced in gg fusion

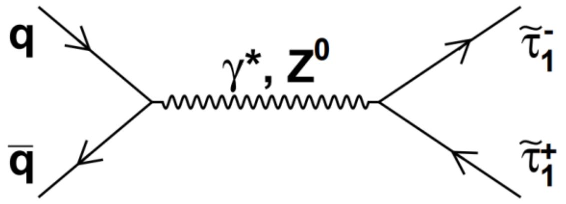
JHEP 01 (2019) 113



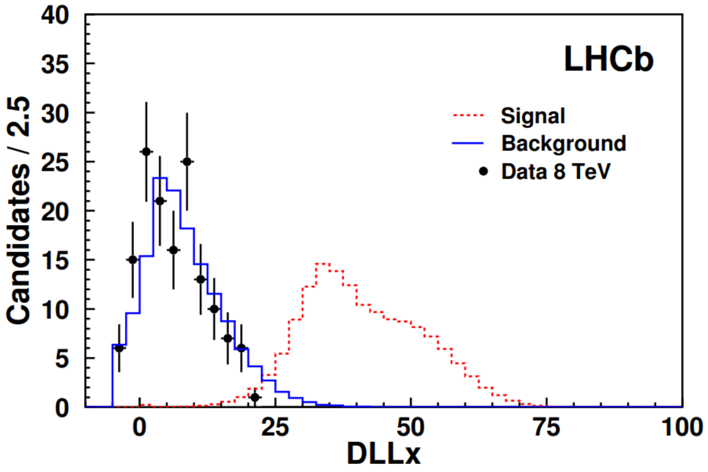
Search for pair of long-lived particles

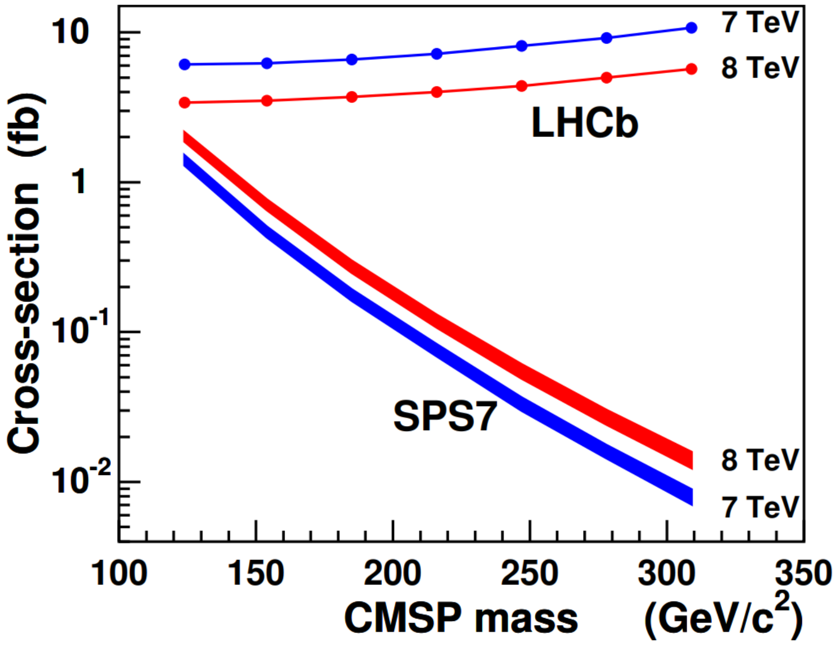
EPJC 75 (2015) 595

- Limits on cross section of pair of charged massive stable particles using ring imaging Cherenkov detectors



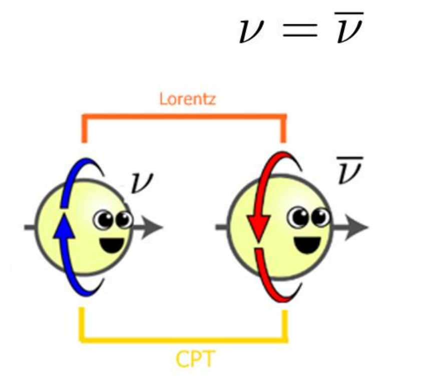
Separation of LLPs and muons

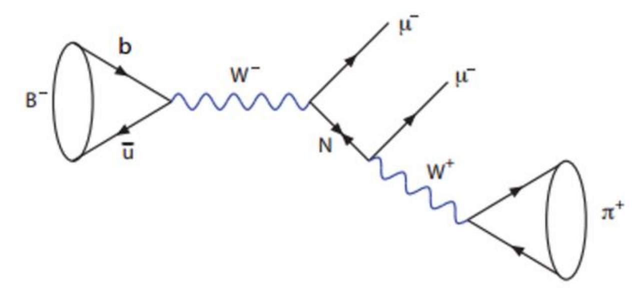


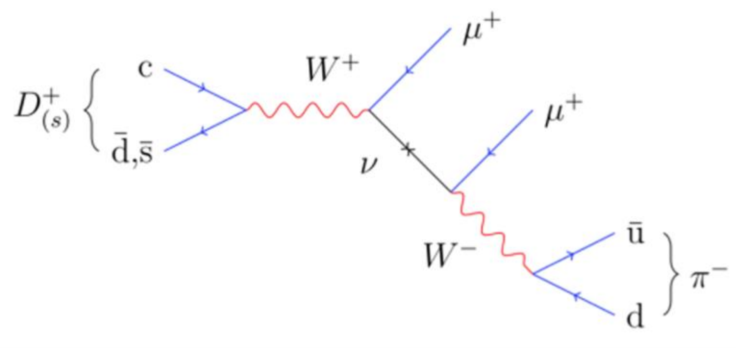


Search for Majorana neutrinos

- Limits on BFs of B and D decays to final states with a same-sign muon pair mediated by a Majorana neutrino, using Run 1 data



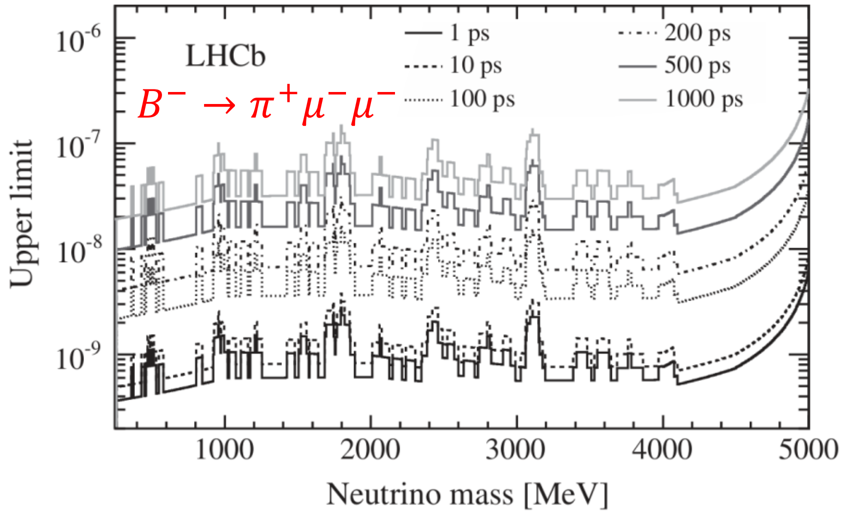




$\mathcal{B}(B^- \to \pi^+\mu^-\mu^-) < 4 \times 10^{-9}$ @ 90% CL
PRL 122 (2015) 131802

$\mathcal{B}\left(B^- \to D^0\pi^+\mu^-\mu^-\right) < 1.6 \times 10^{-6}$ @ 95% CL
PRD 85 (2012) 112004

$\mathcal{B}(D_s^- \to \pi^+\mu^-\mu^-) < 1.2 \times 10^{-7}$ @ 90% CL
PLB 124 (2013) 203



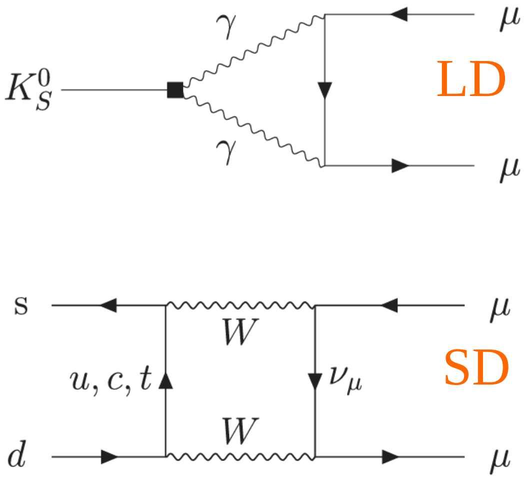
Search for $K_S^0 \to \mu^+\mu^-$

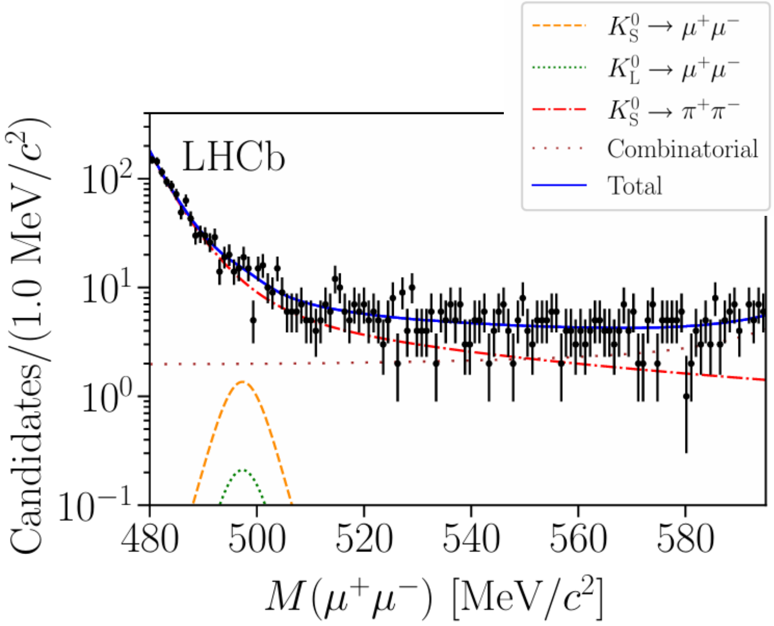
PRL 125 (2020) 231801

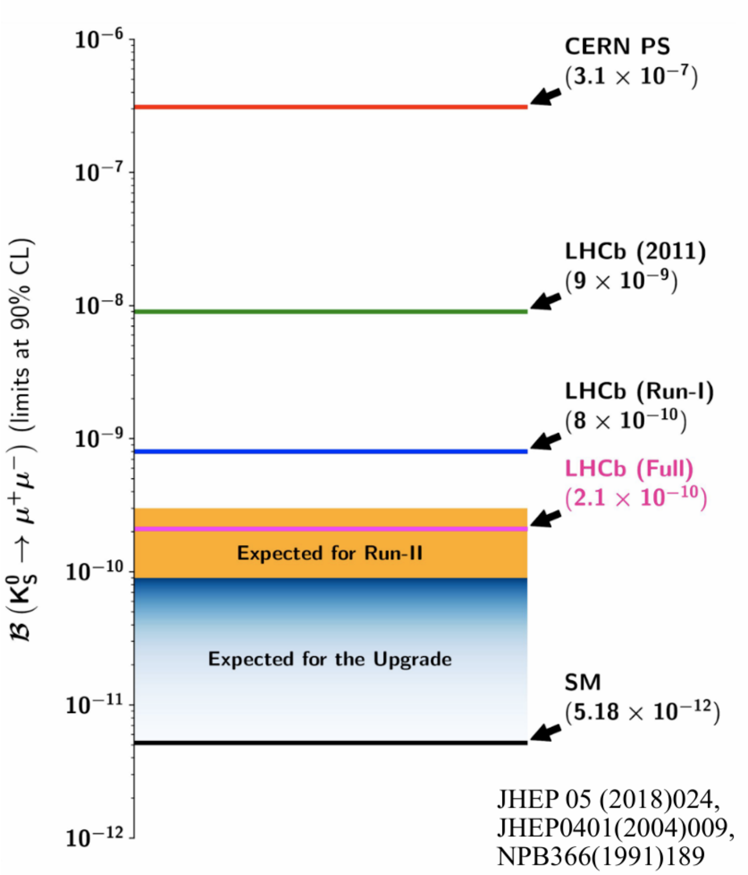
- **Limit on BF of $K_S^0 \to \mu^+\mu^-$ using Run 2 data**

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

SM prediction dominated by LD contribution
$\mathcal{B}(K_S^0 \to \mu^+\mu^-) = (5.18 \pm 1.50(\mathrm{SD}) \pm 0.02(\mathrm{LD})) \times 10^{-12}$







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

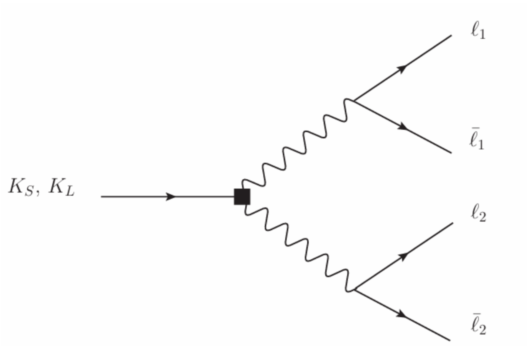
PRD 108 (2023) L031102

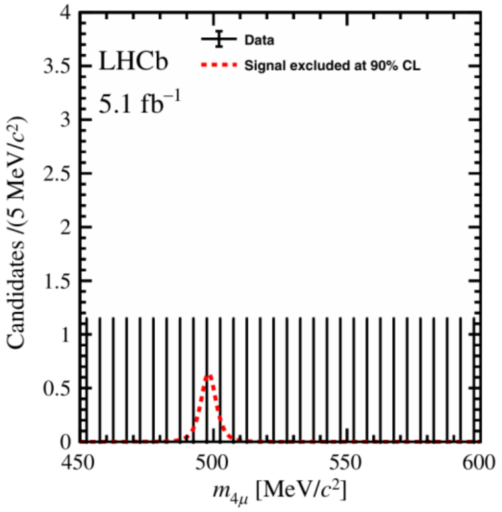
- **Limits on BFs of $K^0_{S/L} \to \mu^+\mu^-\mu^+\mu^-$ using Run 2 data**

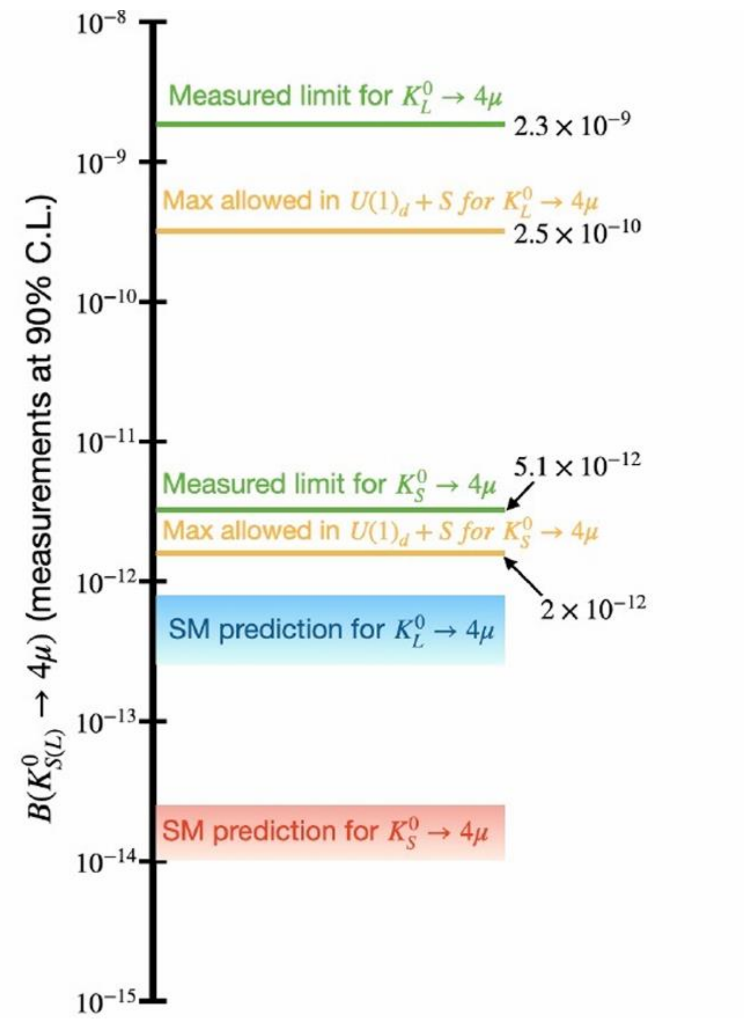
$$\mathcal{B}(K^0_S \to \mu^+\mu^-\mu^+\mu^-) < 5.1 \times 10^{-12} \text{ @ 90\% CL}$$
$$\mathcal{B}(K^0_L \to \mu^+\mu^-\mu^+\mu^-) < 2.3 \times 10^{-9} \text{ @ 90\% CL}$$

SM prediction dominated by LD contribution

$$\mathcal{B}\left(K^0_{S(L)} \to \mu^+\mu^-\mu^+\mu^-\right) \sim 10^{-14}(10^{-13})$$







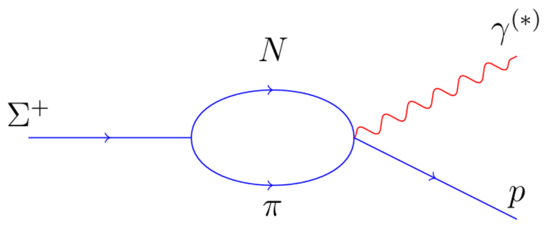
Observation of $\Sigma^+ \to p\mu^+\mu^-$

LHCb-CONF-2024-002

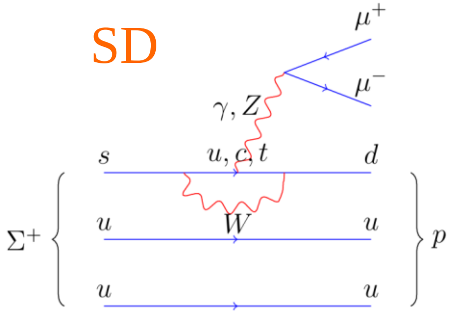
- **279 ± 19 signals observed in Run 2 data, no $\mu^+\mu^-$ structure around 214.3 MeV**

SM prediction dominated by LD contribution
$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) \sim 10^{-8}$

LD

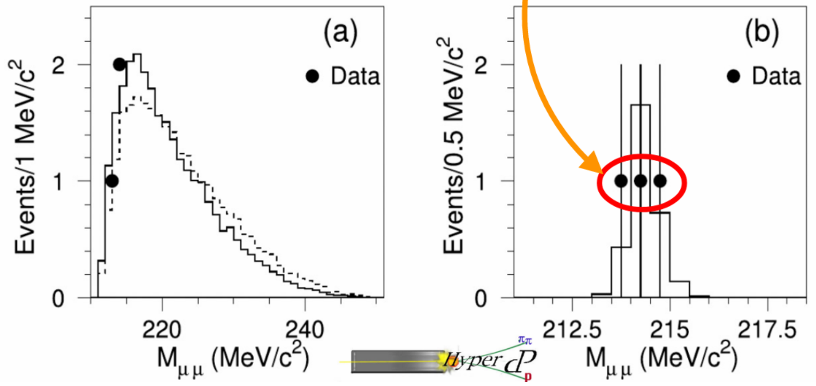


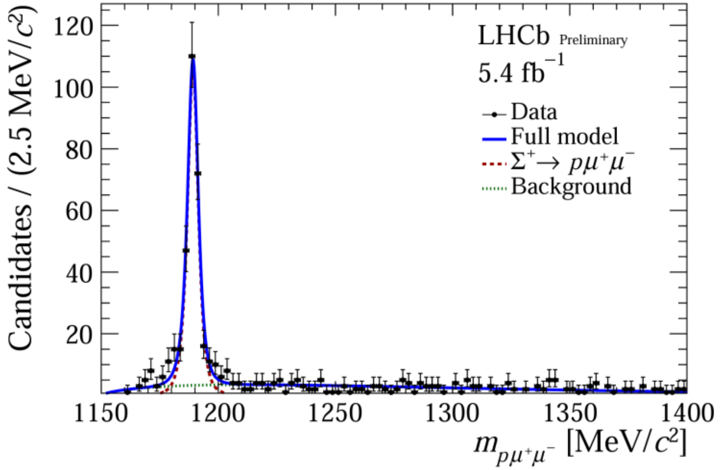
SD

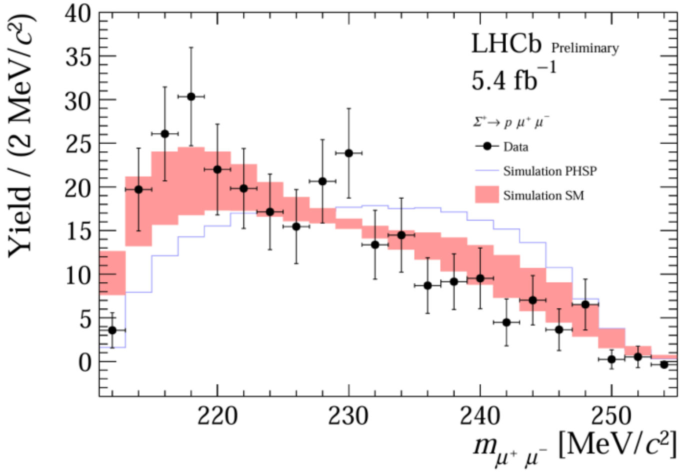


- HyperCP anomaly

X_0= 214.3 ± 0.5 MeV? Dark Boson?







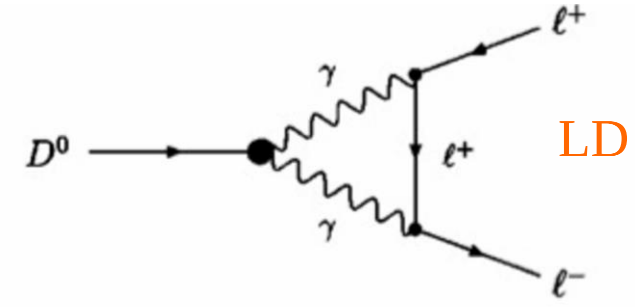
Search for $D^0 \to \mu^+\mu^-$

PRL 131 (2023) 041804

- **Limit on BF of $D^0 \to \mu^+\mu^-$ with $D^{*+} \to D^0\pi^+$, using Run 2 data**

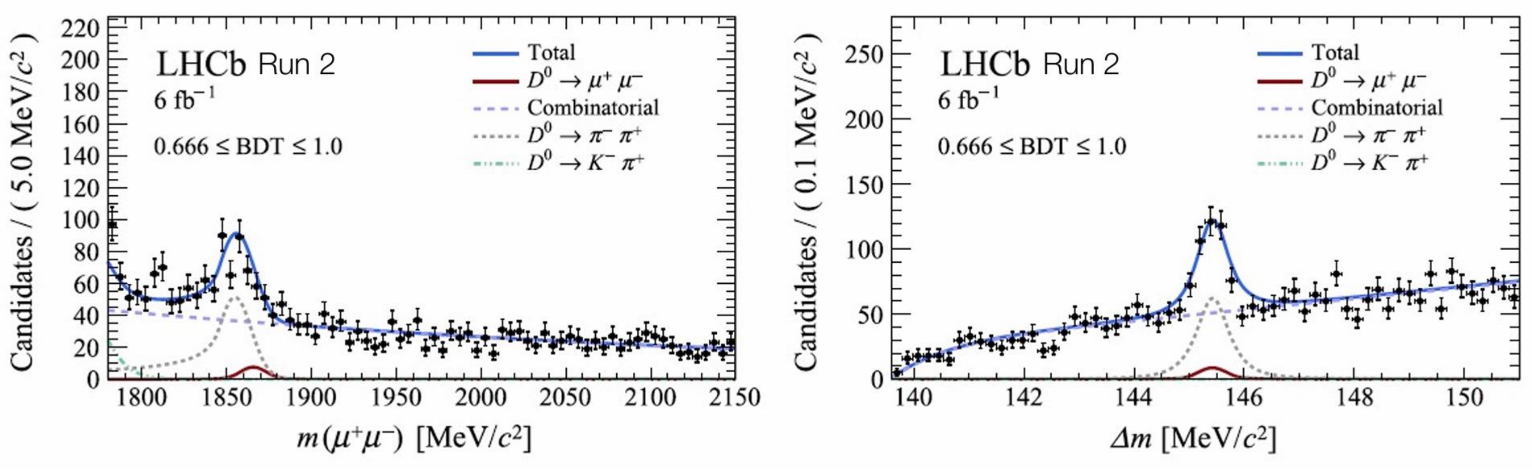
$\mathcal{B}(D^0 \to \mu^+\mu^-) < 3.1 \times 10^{-9}$ @ 90% CL

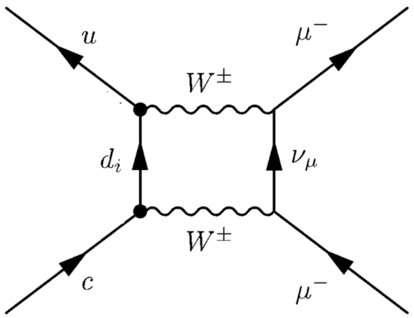
SM prediction dominated by LD contribution
$\mathcal{B}(D^0 \to \mu^+\mu^-) \sim 10^{-11}$



LD

$m(\mu\mu)$ $\Delta m = m(\mu\mu\pi^+) - m(\mu\mu)$



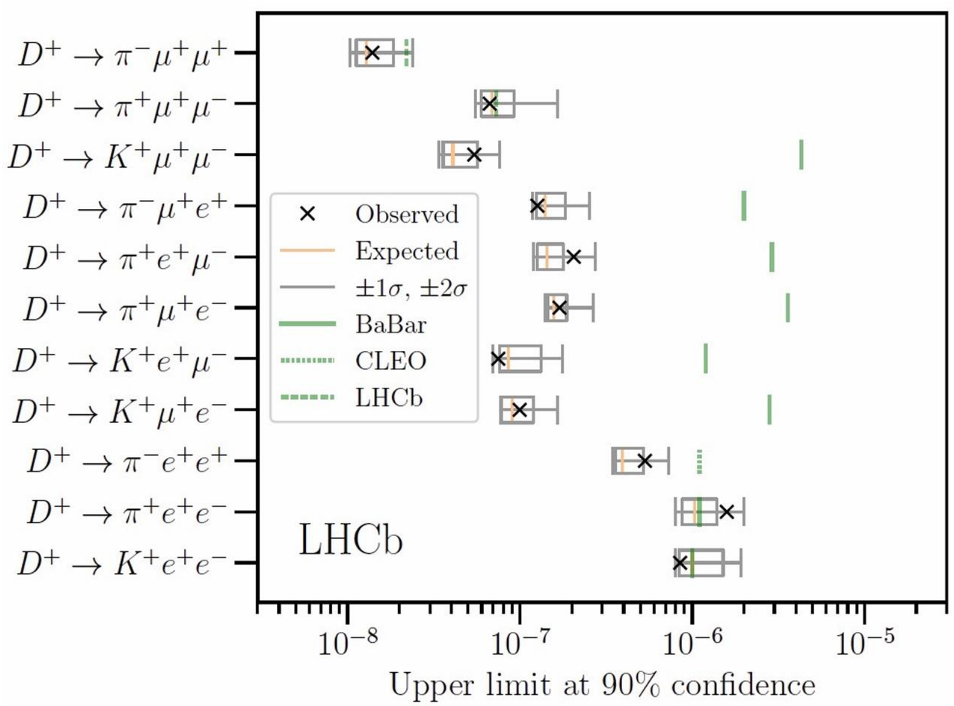


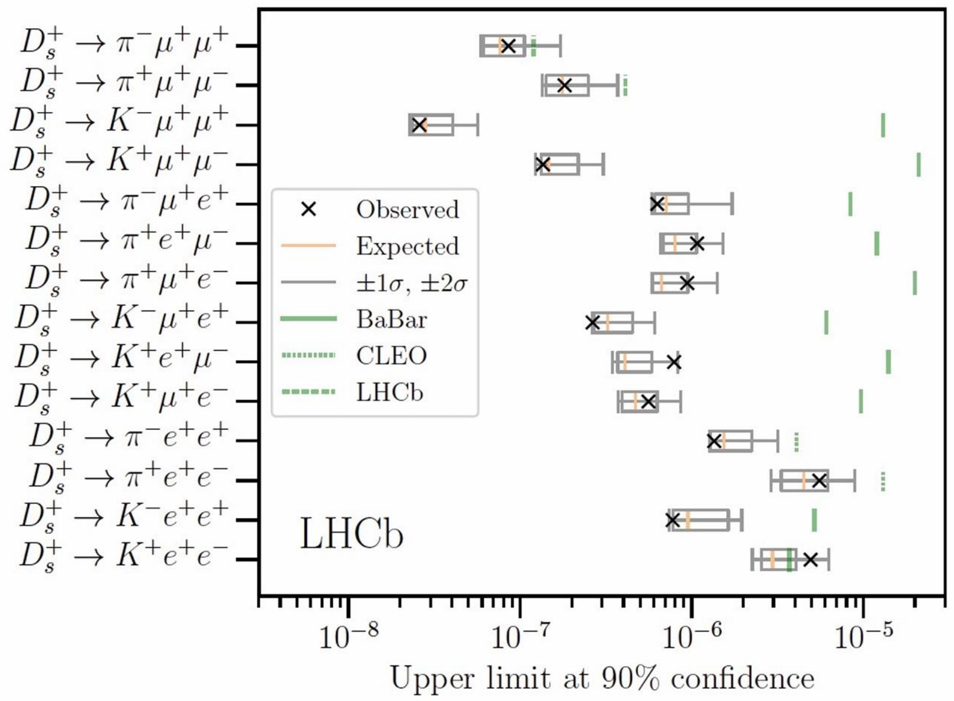
SD

25 rare and forbidden $D^+_{(s)}$ decays

JHEP 06 (2021) 044

- **Limits for FCNC, LFV and LNV decays between 1.4×10^{-8} and 6.4×10^{-6}, using 2016 data**





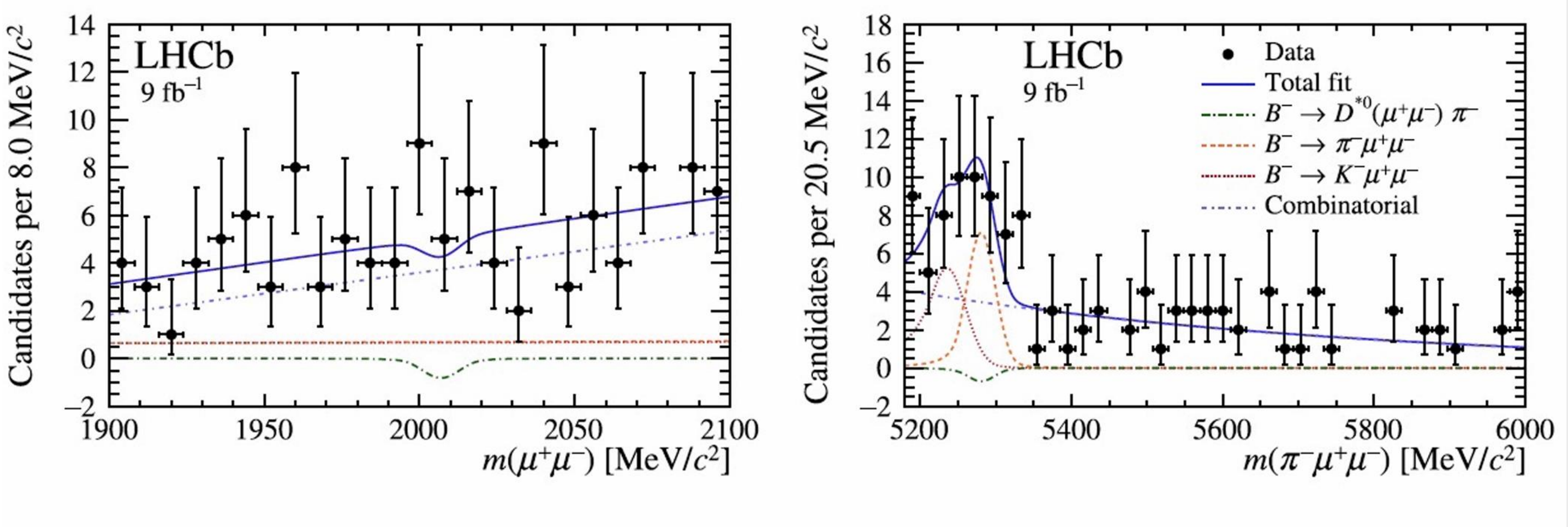
Search for $D^{*0} \to \mu^+\mu^-$

EPJC 83 (2023) 666

- **Limit using Run 2 data, with $B^- \to D^{*0}\pi^-$ as source of D^{*0}**

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

SM prediction highly suppressed due to large strong decay width
$\mathcal{B}(D^{*0} \to \mu^+\mu^-) \sim 10^{-19}$



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

arXiv:2407.11474

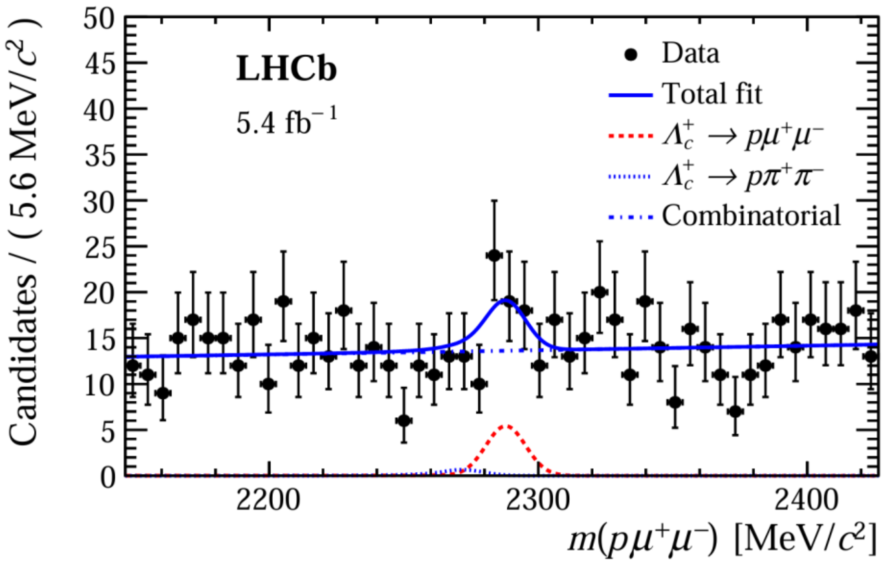
- Limit for $m(\mu^+\mu^-) < 508$ MeV or $m(\mu^+\mu^-) > 1060$ MeV, using Run 2 data

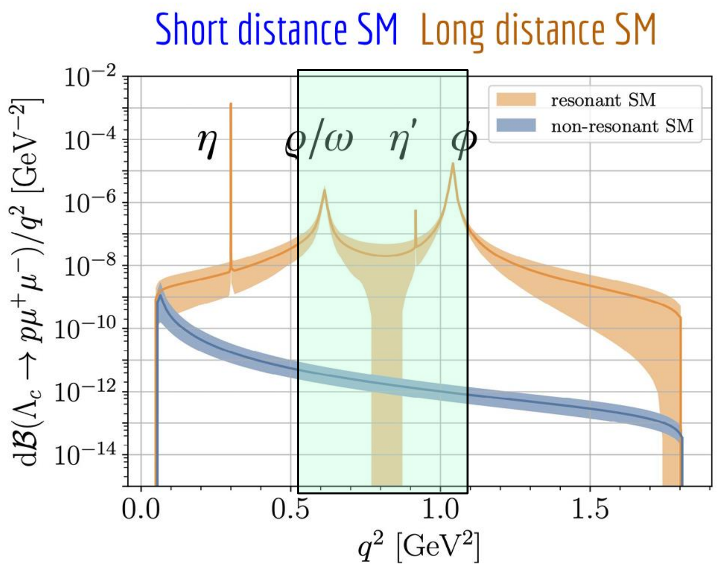
$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 2.9 \times 10^{-8}$ @ 90% CL

SM prediction dominated by LD contribution

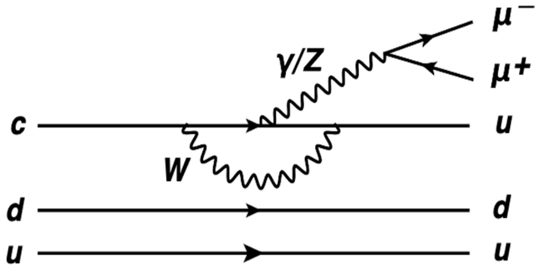
$\mathcal{B}_{\mathrm{SD}}(\Lambda_c^+ \to p\mu^+\mu^-) \sim 10^{-8}$

$\mathcal{B}_{\mathrm{LD}}(\Lambda_c^+ \to p\mu^+\mu^-) \sim 10^{-6}$





JHEP 09, 208 (2021)



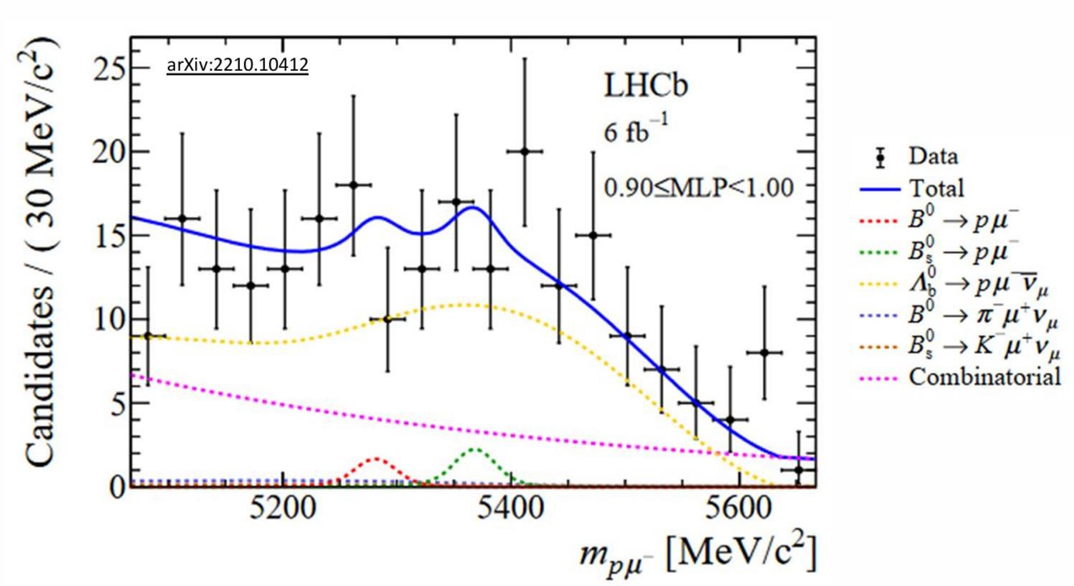
SD

$B^0_{(s)} \to p\mu^-$

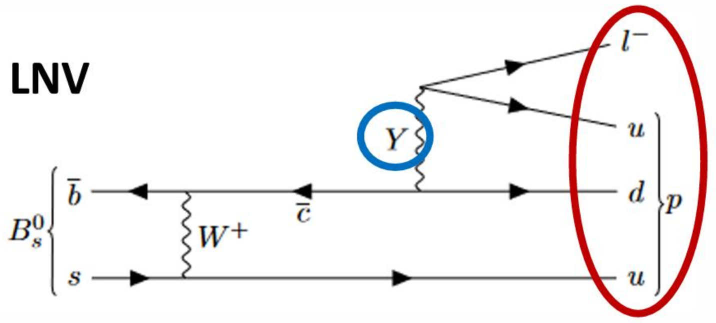
PRD 108 (2023) 012021

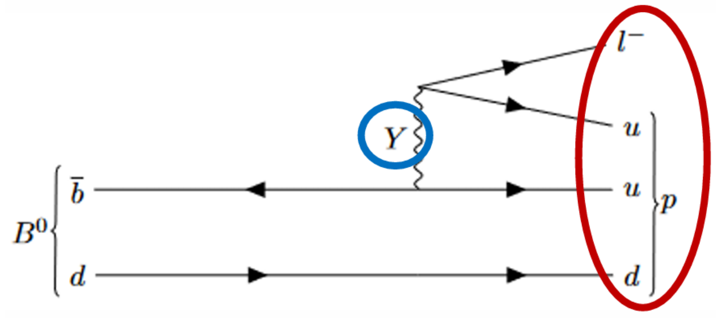
- Limits on BFs using Run 2 data

$$\mathcal{B}(B^0 \to p\mu^-) < 2.6 \times 10^{-9} \quad @\ 90\%\ \text{CL}$$
$$\mathcal{B}(B^0_s \to p\mu^-) < 12.1 \times 10^{-9} \quad @\ 90\%\ \text{CL}$$



LNV



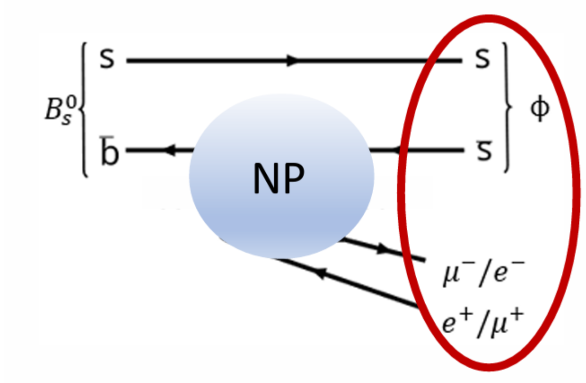


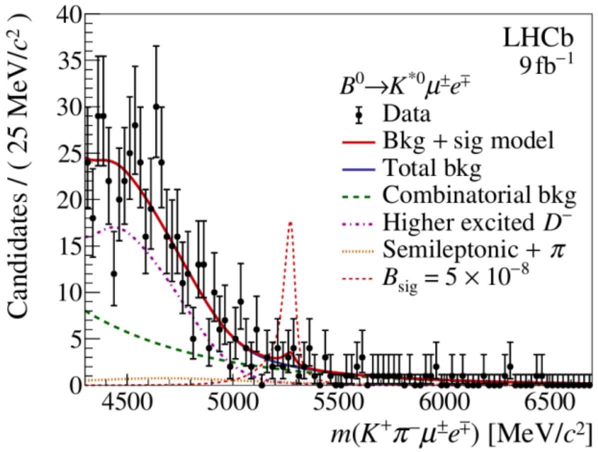
$B^0 \to K^{*0}\mu^\pm e^\mp$ and $B_s^0 \to \phi\mu^\pm e^\mp$

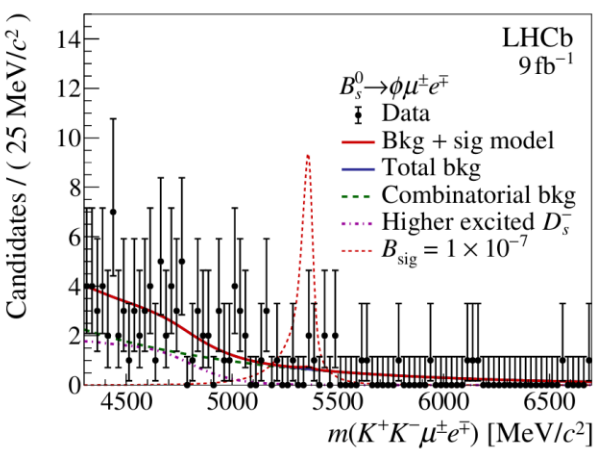
JHEP 06 (2023) 073

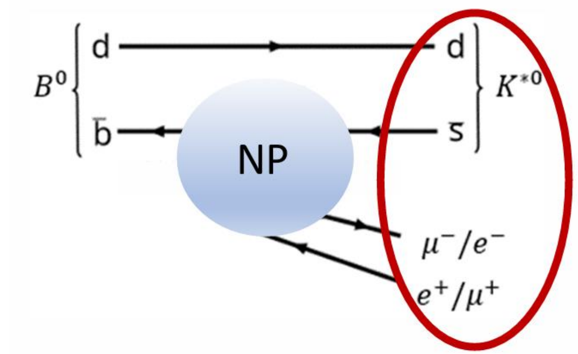
- **Limits on BFs using Run 2 data**

$$\mathcal{B}\left(B^0 \to K^{*0}\mu^\pm e^\mp\right) < 10.1 \times 10^{-9} \quad @\ 90\%\ \mathrm{CL}$$
$$\mathcal{B}\left(B_s^0 \to \phi\mu^\pm e^\mp\right) < 16.0 \times 10^{-9} \quad @\ 90\%\ \mathrm{CL}$$







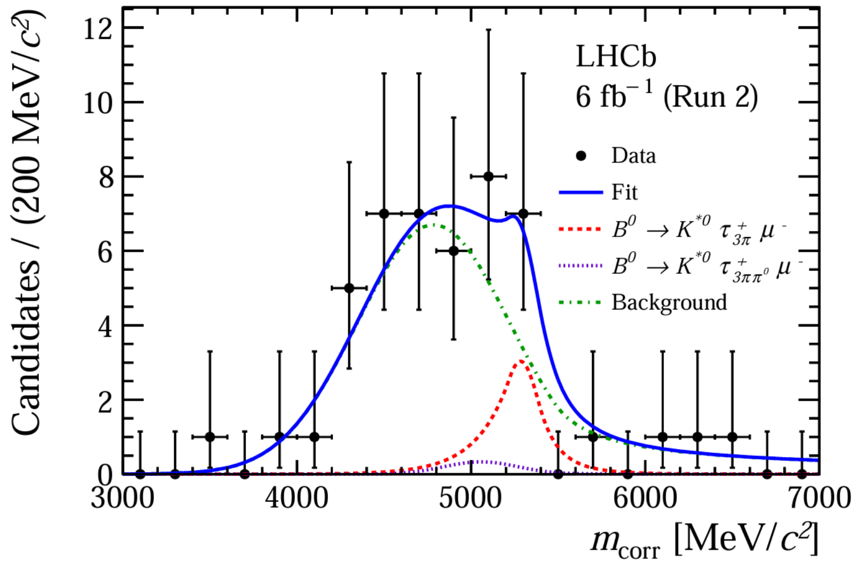


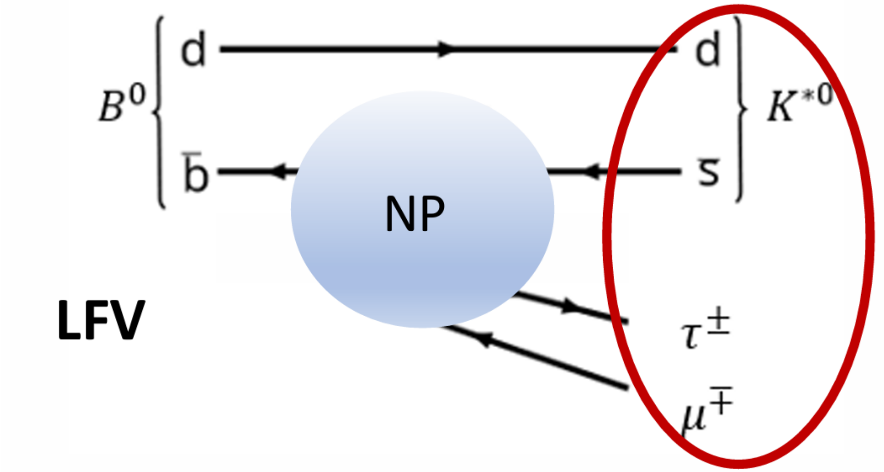
$B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$

JHEP 06 (2023) 143

- First limits on BF using Run 2 data, with $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$

$$\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0 \times 10^{-5} \quad @\ 90\%\ \text{CL}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^-\mu^+) < 8.2 \times 10^{-6} \quad @\ 90\%\ \text{CL}$$





$$m_{corr} = \sqrt{p_\perp^2 + m_{K^*\tau\mu}^2} + p_\perp$$

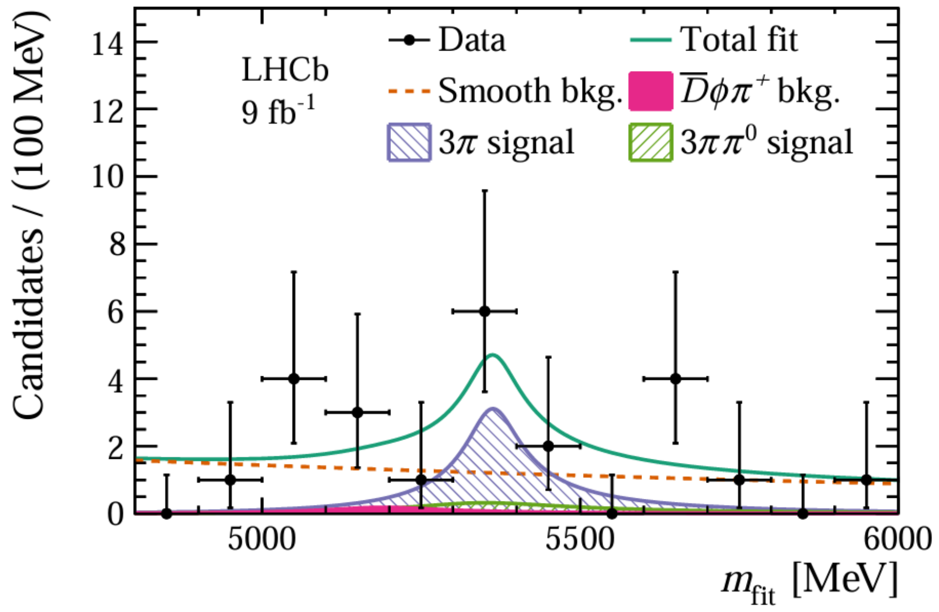
missing momentum perpendicular to B^0 direction

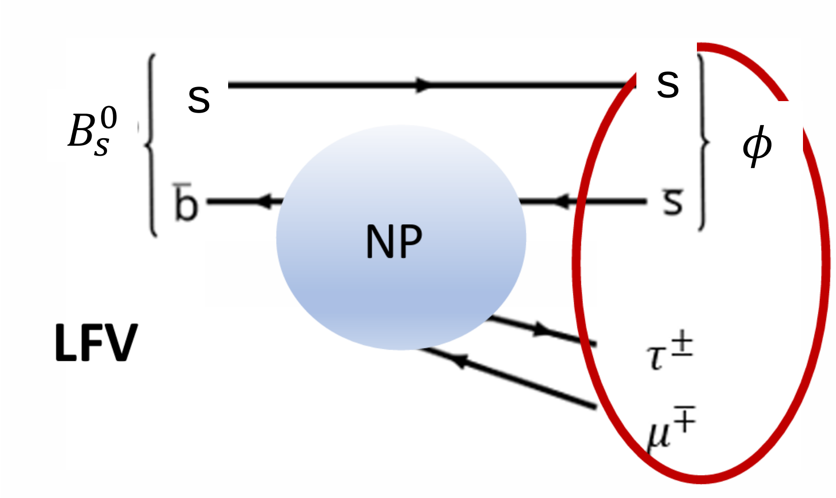
$B_s^0 \to \phi\tau^{\pm}\mu^{\mp}$

arXiv: 2405.13103

- **Limit on BF using Run 2 data, with $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$**

$\mathcal{B}(B_s^0 \to \phi\tau^{\pm}\mu^{\mp}) < 1.0 \times 10^{-5}$ @ 90% CL





$m_{\rm fit}$ calculated using PV and SV constraints

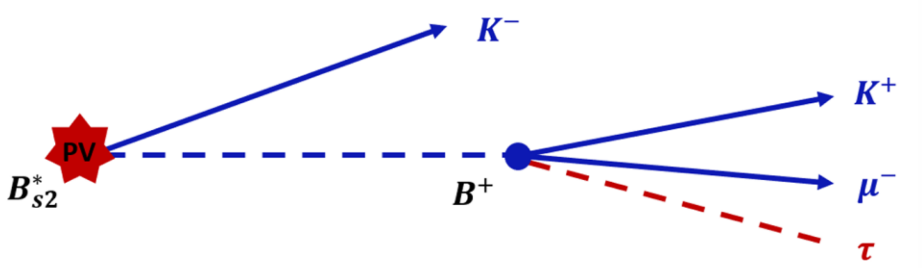
$B^+ \to K^+\tau^+\mu^-$ using B_{s2}^* decays

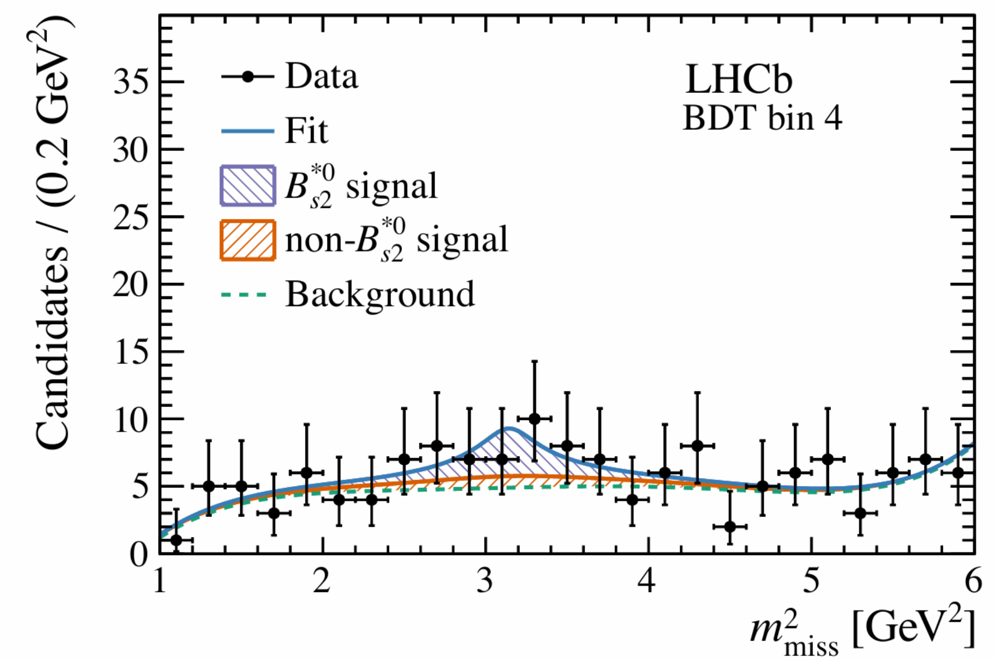
JHEP 06 (2020) 129

- Limits on BF using Run 2 data, with inclusive τ reconstruction

$\mathcal{B}(B^+ \to K^+\tau^+\mu^-) < 3.9 \times 10^{-5}$ @ 90% CL

Belle result
$\mathcal{B}(B^+ \to K^+\tau^+\mu^-) < 0.59 \times 10^{-5}$ @ 90% CL





$m_{\rm miss}$ calculated using PV and SV constraints

More LFV results

$\mathcal{B}(B^+ \to K^+\mu^-e^-) < 7.0 \times 10^{-9}$ @ 90% CL, PRL 123 (2019) 241802
$\mathcal{B}(B^+ \to K^+\mu^+e^-) < 6.4 \times 10^{-9}$ @ 90% CL, PRL 123 (2019) 241802

$\mathcal{B}\left(B^0 \to \mu^\pm\tau^\mp\right) < 1.4 \times 10^{-5}$ @ 95% CL, PRL 123 (2019) 211801
$\mathcal{B}\left(B_s^0 \to \mu^\pm\tau^\mp\right) < 4.2 \times 10^{-5}$ @ 95% CL, PRL 123 (2019) 211801

$\mathcal{B}\left(B^0 \to e^\pm\mu^\mp\right) < 1.0 \times 10^{-9}$ @ 95% CL, JHEP 03 (2018) 078

$\mathcal{B}\left(D^0 \to e^\pm\mu^\mp\right) < 4.6 \times 10^{-8}$ @ 90% CL, PLB 754 (2016) 167

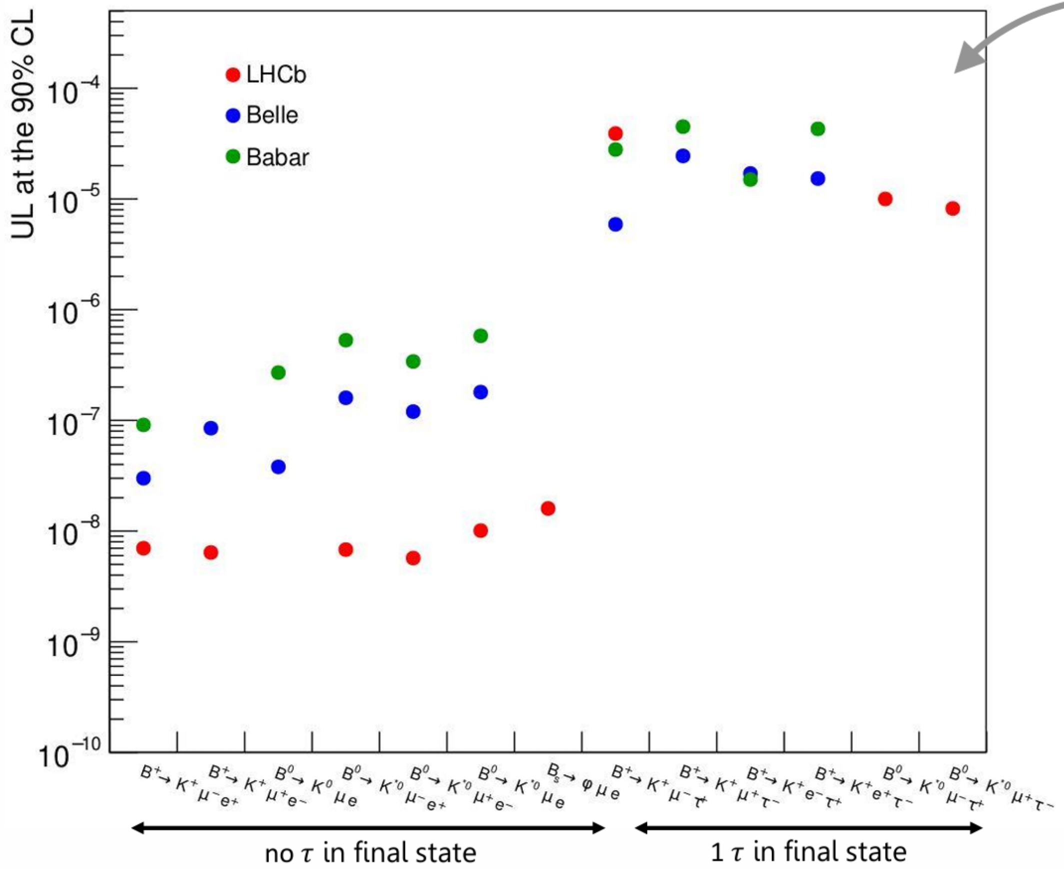
$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 3.9 \times 10^{-5}$ @ 90% CL, JHEP 02 (2015) 121

Summary of LFV in B decays

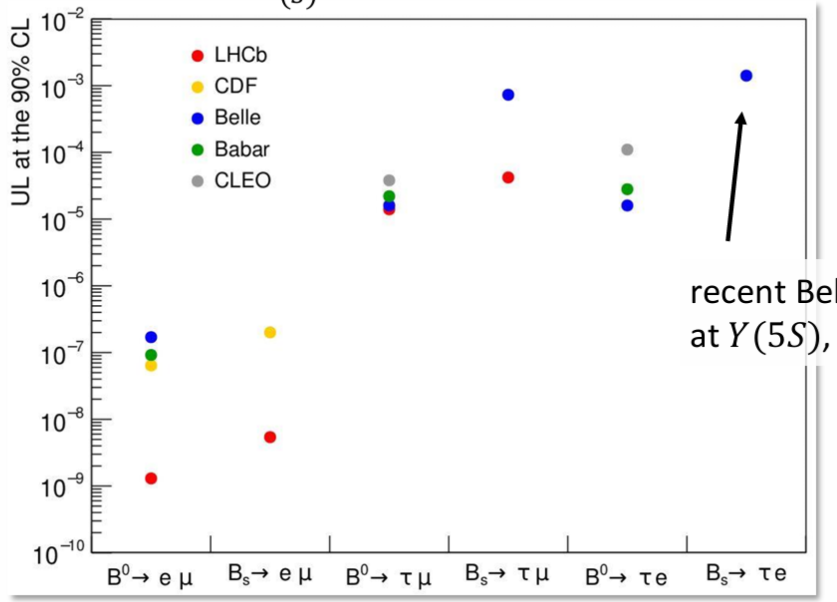
pp vs e^+e^- enviroments

- When τ replaces e or μ, LHCb looses $\geq O(10^3)$ sensitivity; B-factories pay $\sim O(10^2)$
- When no τ, LHCb benefits from very large $b\bar{b}$ prod cross-section

Experimental status of $b \to s\, l\, l'$ searches



$B_{(s)} \to l\, l'$ searches

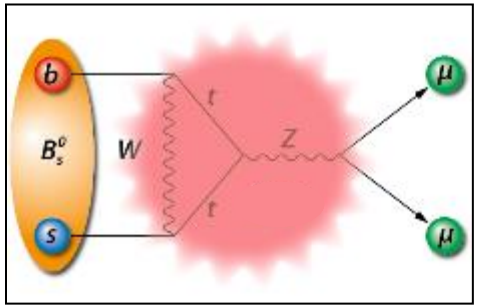


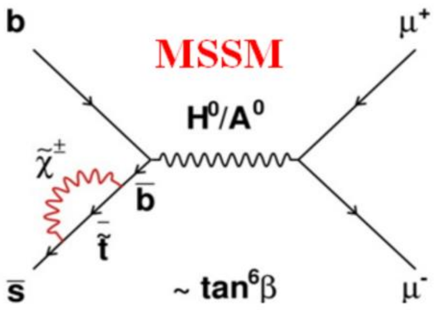
recent Belle measurement at $\Upsilon(5S)$, 2301.10989

$B^0_{(s)} \to \mu^+\mu^-$

- **Very rare in the SM, sensitive to NP**
  - FCNC and helicity suppression

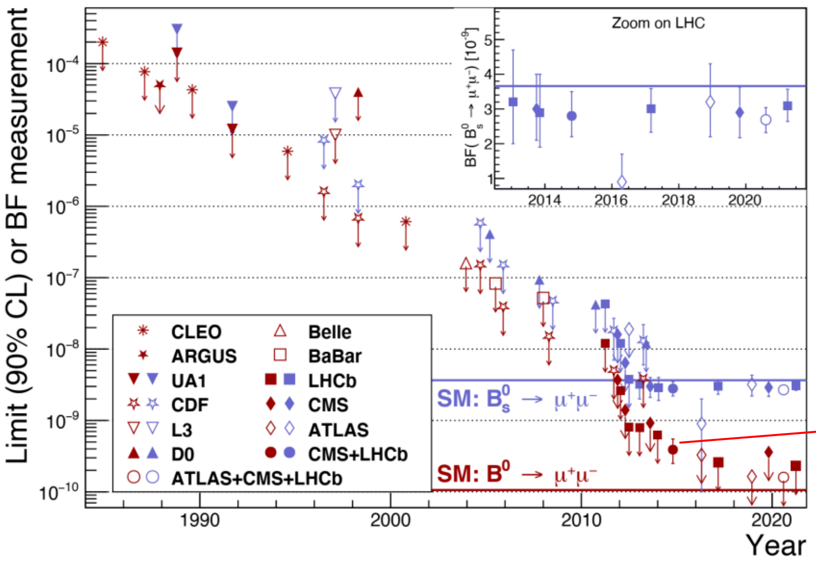
$\mathcal{B}^{SM}(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$
$\mathcal{B}^{SM}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$

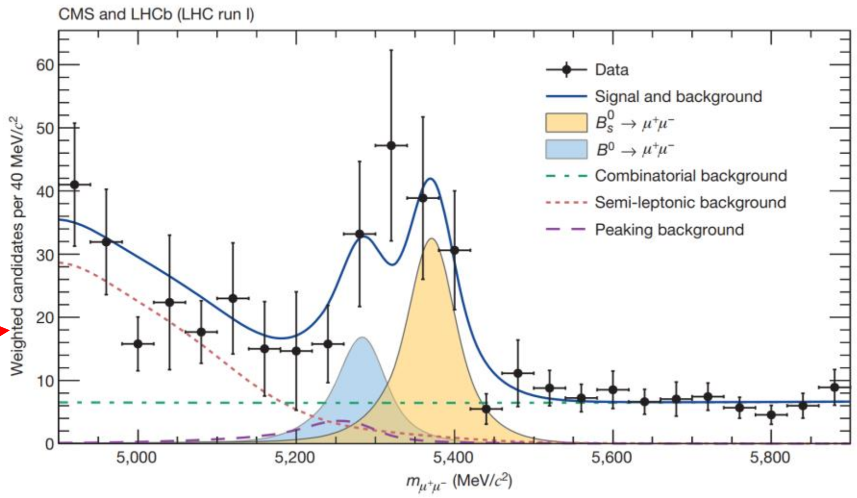




- **$B^0_s \to \mu^+\mu^-$ observed by LHCb and CMS in 2015** Nature 522 (2015) 68

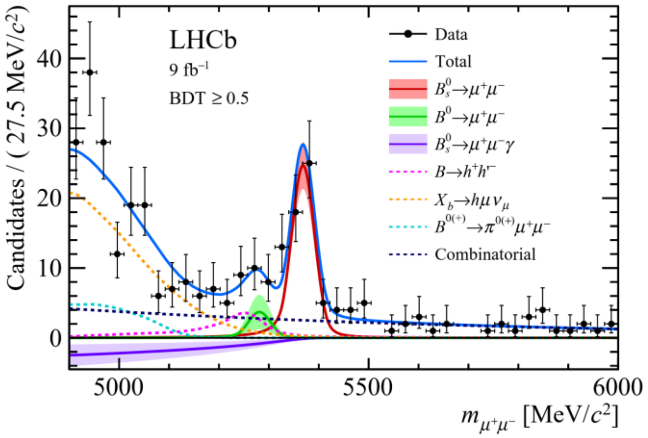
$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$



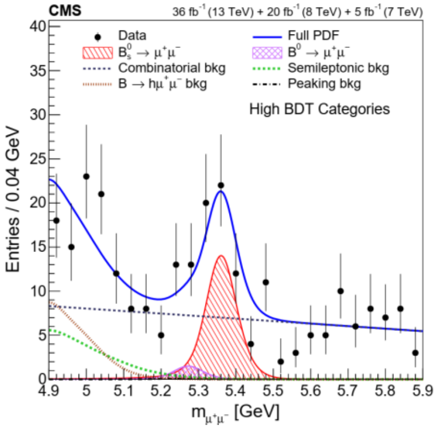


$B^0_{(s)} \to \mu^+\mu^-$

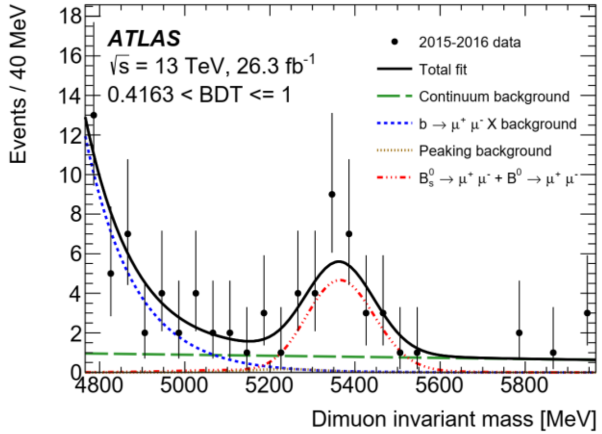
PRL 128 (2022) 04801

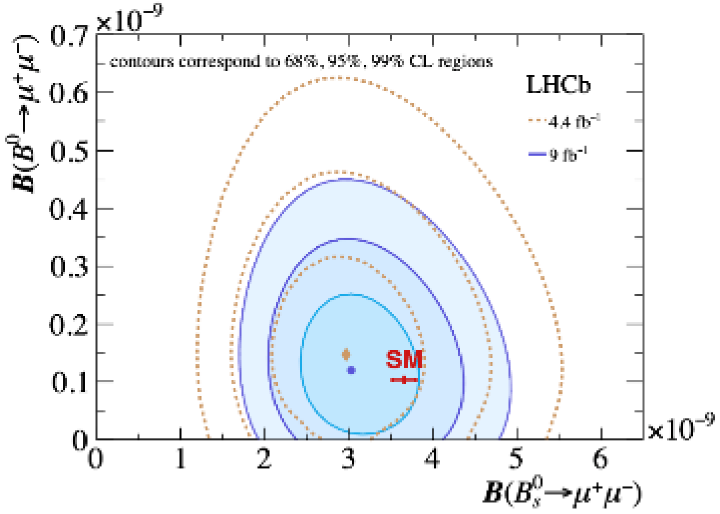


JHEP 04 (2020) 188



JHEP 04 (2019) 098





	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	$\mathcal{B}(B^0 \to \mu^+\mu^-)$
LHCb (11-18)	$\left(3.09^{+0.46}_{-0.43}{}^{+0.15}_{-0.11}\right) \times 10^{-9}$	$< 2.6 \times 10^{-10}$
CMS (11-16)	$(2.9 \pm 0.7 \pm 0.2) \times 10^{-9}$	$< 3.6 \times 10^{-10}$
ATLAS (11-16)	$\left(2.8^{+0.8}_{-0.7}\right) \times 10^{-9}$	$< 2.1 \times 10^{-10}$
SM	$(3.66 \pm 0.14) \times 10^{-9}$	$(1.03 \pm 0.05) \times 10^{-9}$

$B^0_{(s)} \to \tau^+\tau^-$

PRL 118 (2017) 251802

- **Limits on BF using Run 2 data, with $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$**

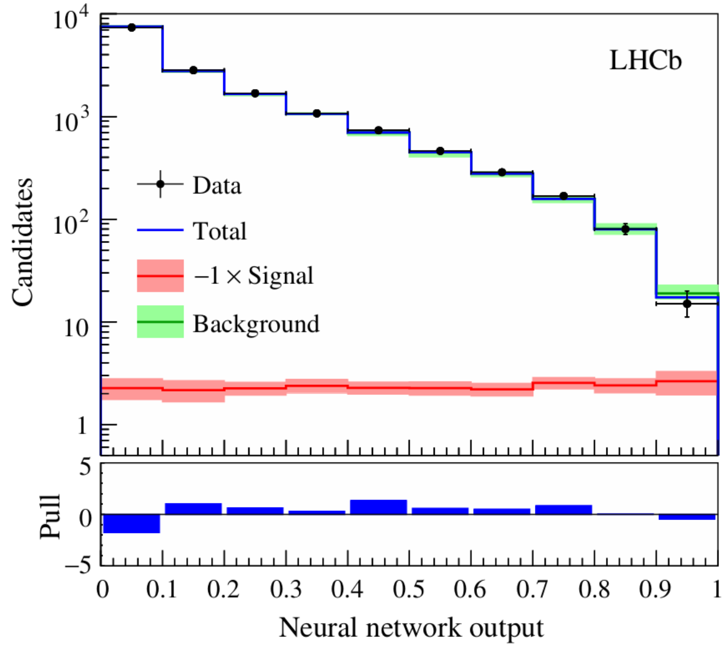
$\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3}$ @ 95% CL

$\mathcal{B}(B^0_s \to \tau^+\tau^-) < 6.8 \times 10^{-3}$ @ 95% CL

SM predictions

$\mathcal{B}(B^0 \to \tau^+\tau^-) = (2.22 \pm 0.18) \times 10^{-8}$

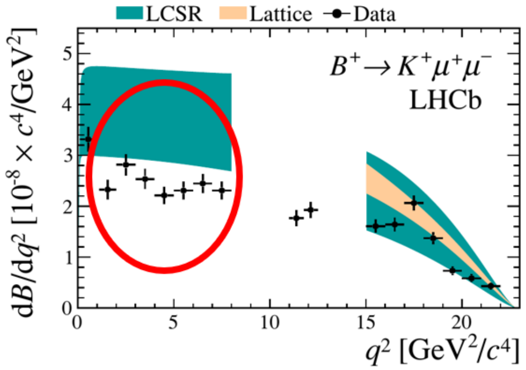
$\mathcal{B}(B^0_s \to \tau^+\tau^-) = (7.73 \pm 0.49) \times 10^{-7}$



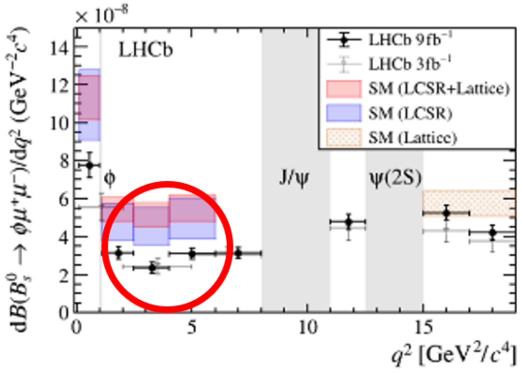
$b \to s\mu^+\mu^-$ BFs

- Data below SM predictions in low q^2 regions
- Hadronic uncertainties difficult to estimate (FFs, nonlocal contributions)

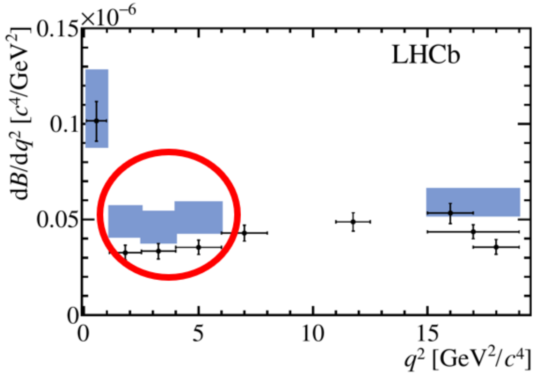
$B^+ \to K^+\mu^+\mu^-$ JHEP 06(2014)133



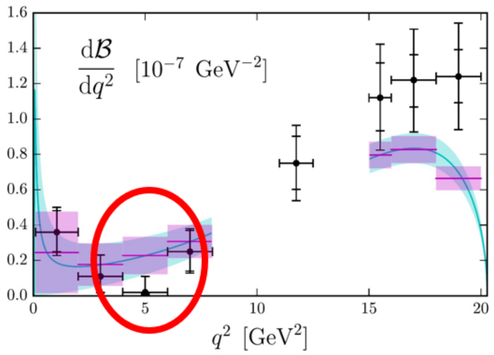
$B_s^0 \to \phi\mu^+\mu^-$ PRL 127 (2021) 151801



$B^0 \to K^{*0}\mu^+\mu^-$ JHEP 04(2017)142

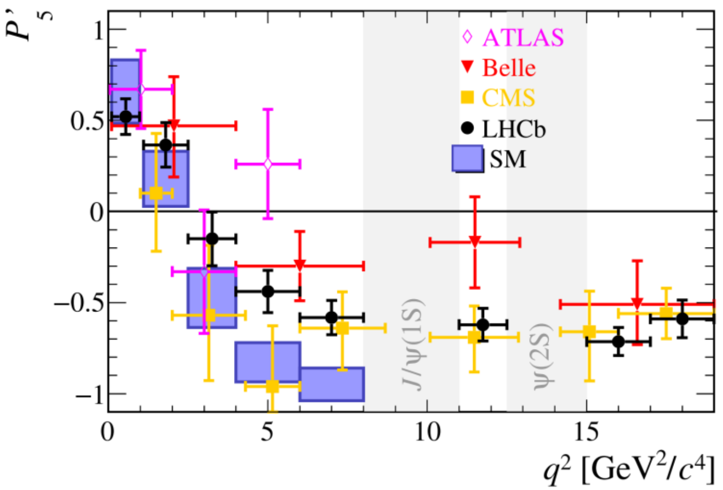


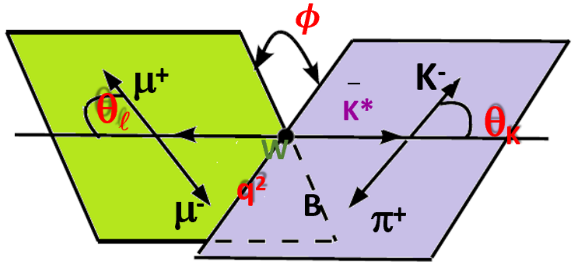
$\Lambda_b^0 \to \Lambda^0\mu^+\mu^-$ JHEP 06(2015)115



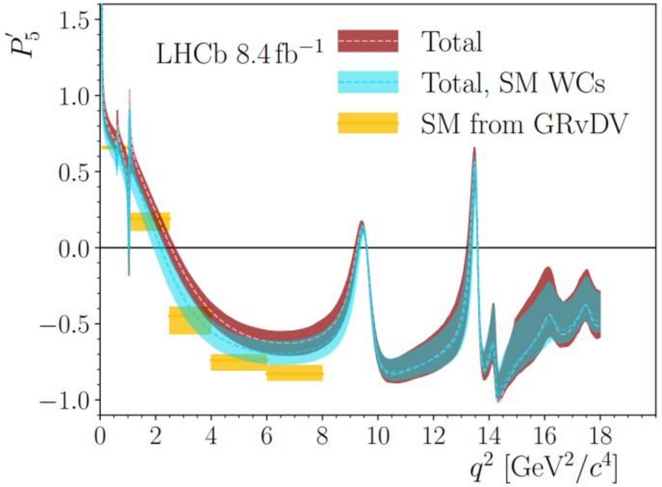
$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis

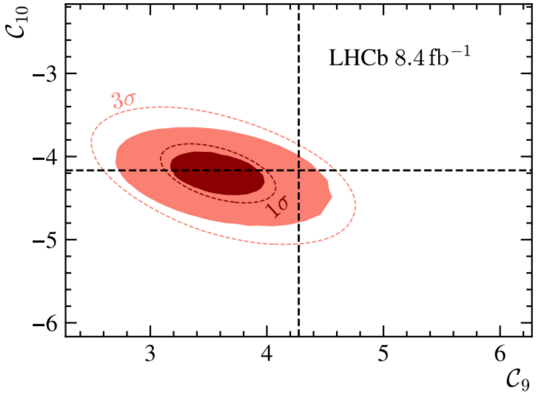
- **Broadly consistent with SM, with exception of P'_5 in low q^2 region:** **~3σ effect** PRL 125 (2020) 011802





- **Data-driven analysis of non-local contribution: 2.1σ deviation from SM** arXiv:1405.17347



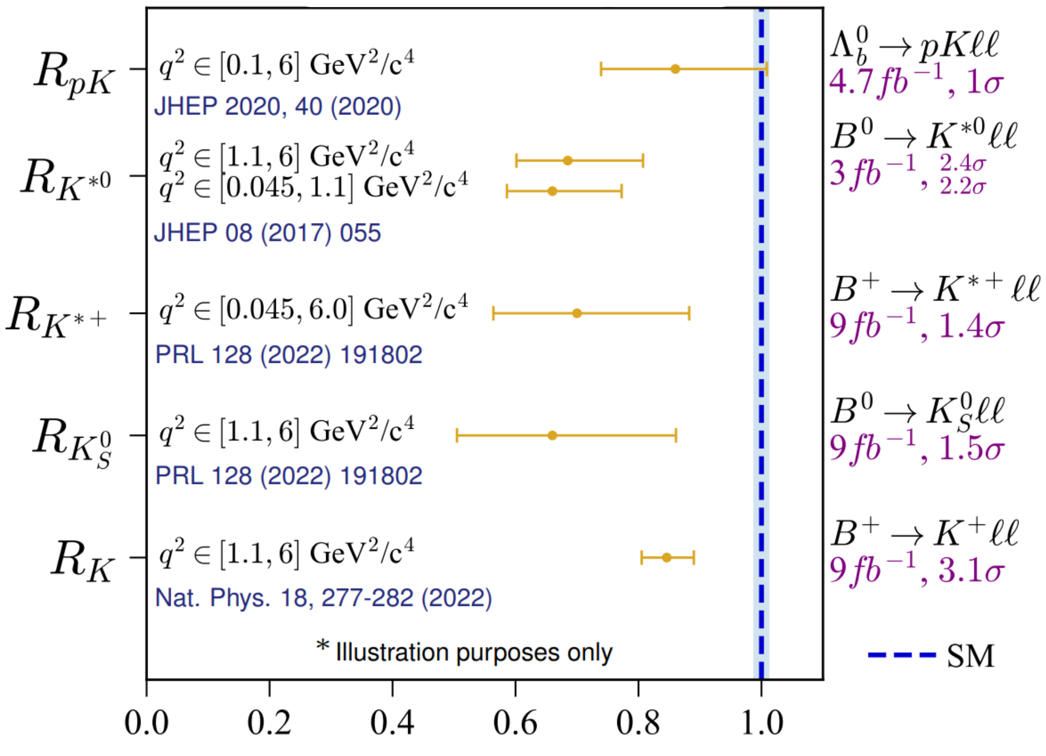


$R(K^{(*)})$

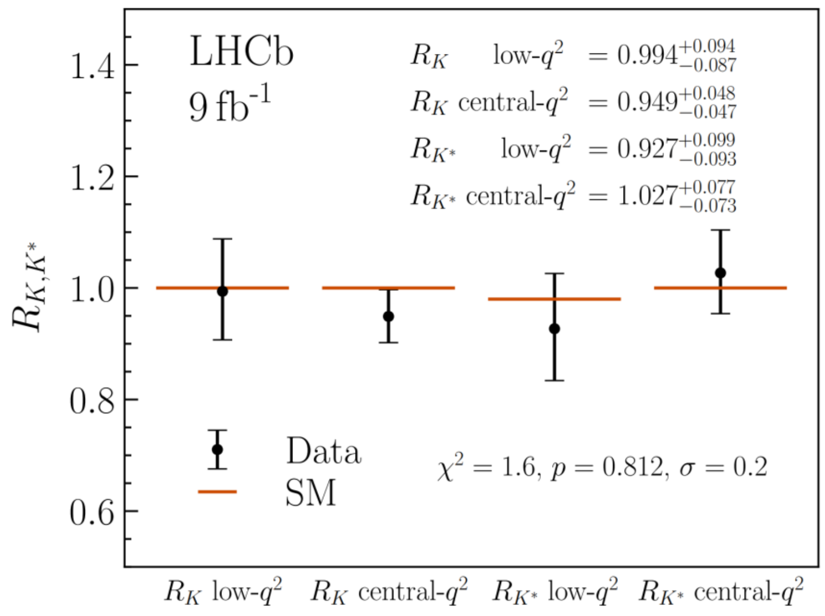
- **Test of lepton flavour universality in $b \to sl^+l^-$ ($l = e, \mu$) decays**

$$R_X = \frac{\mathcal{B}(H_b \to X\mu^+\mu^-)}{\mathcal{B}(H_b \to Xe^+e^-)}$$

2022年前

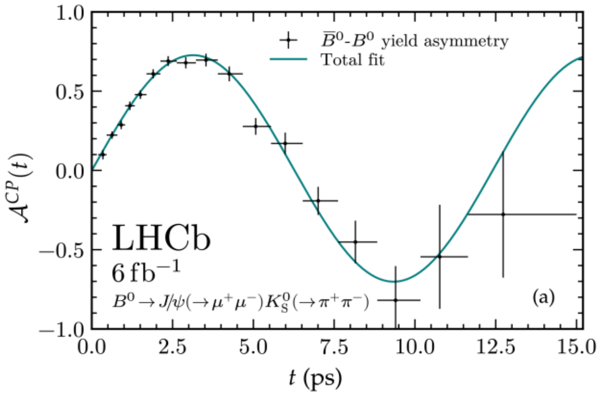


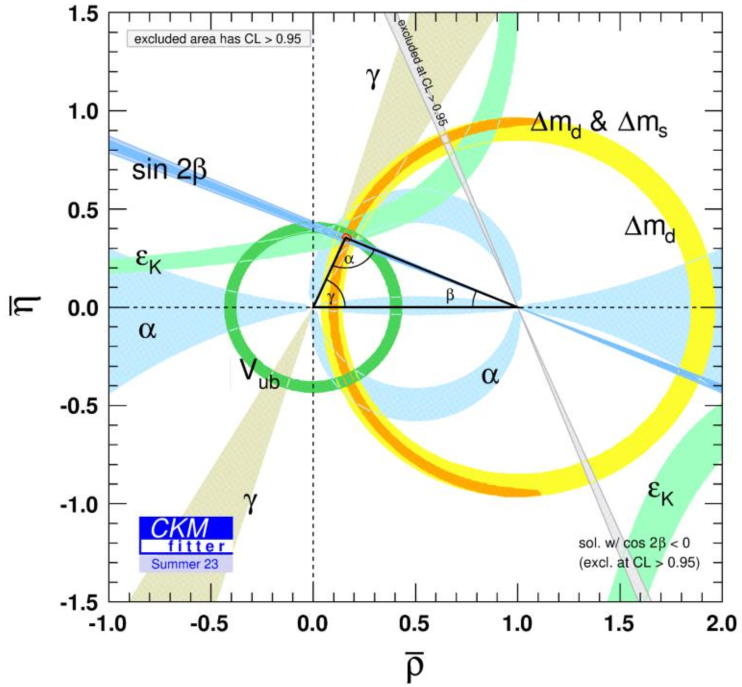
PRL 131 (2023) 051803

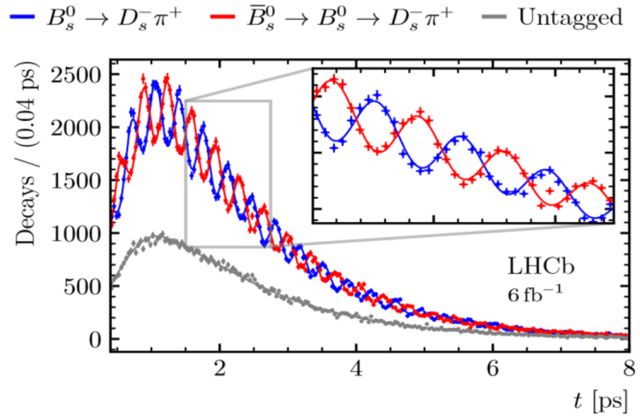


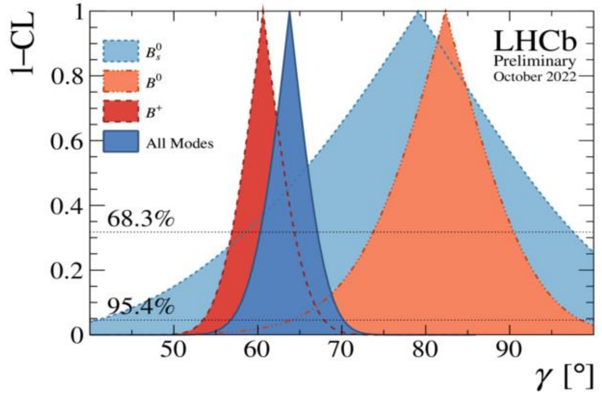
CP violation: the big picture

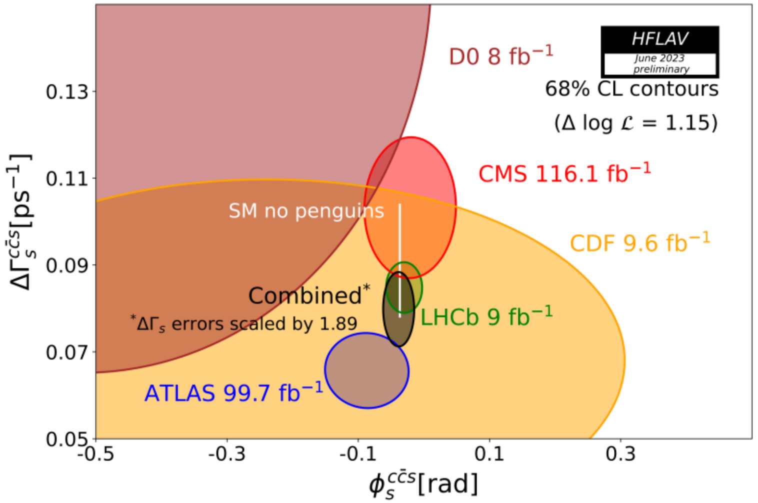
- CKM theory has passed very stringent tests and seems to work well …





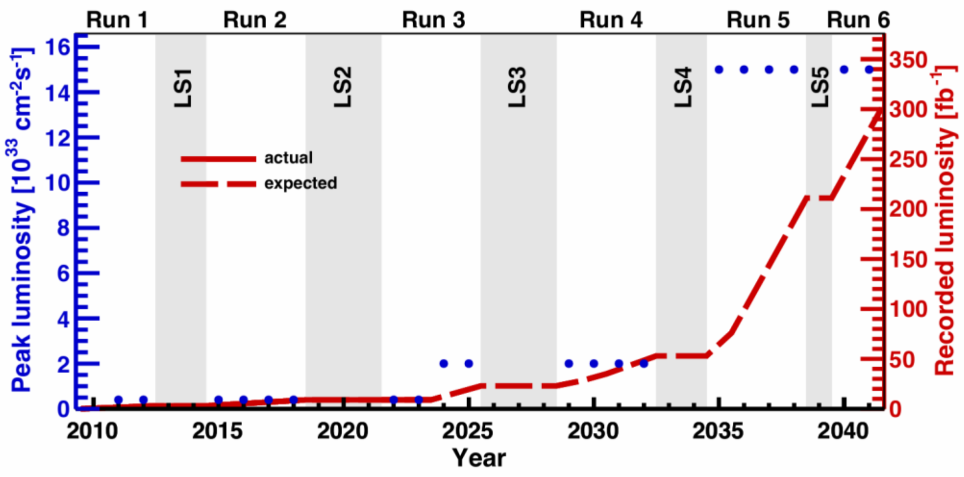






Summary

- LHCb is a general-purpose detector with a very broad physics program covering
  - Precision measurements of CP violation to test CKM unitarity
  - Indirect search for new physics effects in rare and forbidden decays
  - Direct search for new particle both from pp collisions and from B decays
- Many topics not covered: EDM/MDM, CPT violation, strong CPV, $R(D^{(*)})$, photon polarization in $b \to s\gamma$, …
- Looking forward to exciting results from LHCb Run 3, 4, …



Hidden Valley

Slide from Matthew Strassle