



SUSY related searches at LHCb

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SUSY 2023, Southampton
17th July 2023

Results in this talk:

[Phys. Rev. Lett. 128, \(2022\) 041801](#)

[Phys. Rev. D105 \(2022\) 012010](#)

[JHEP 03 \(2022\) 109](#)

[LHCb-PAPER-2022-029](#)

Introduction



- Many measurements / searches at LHCb are sensitive to SUSY models.
- Will highlight a few recent results with particular relevance:

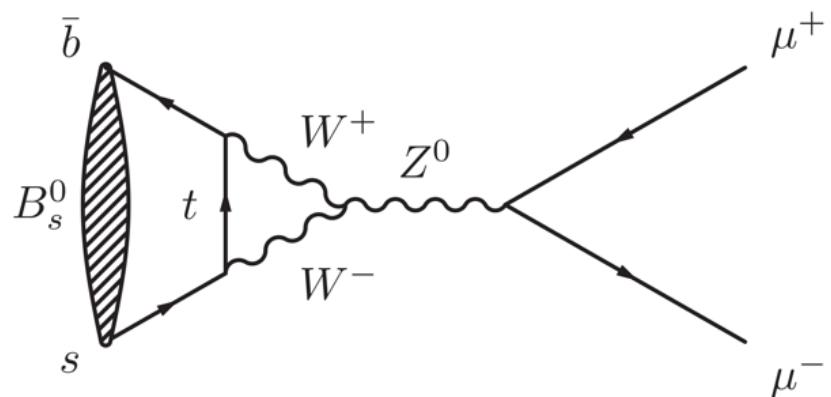
$$B_{(s)}^0 \rightarrow \mu^+ \mu^-$$

$$B_{(s)}^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$$

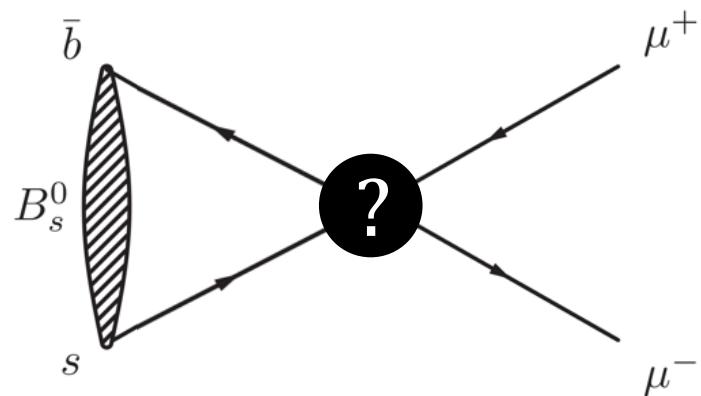
$$D^0 \rightarrow \mu^+ \mu^-$$

- Rare decays mediated by flavour changing neutral current (FCNC) transitions.

Standard Model

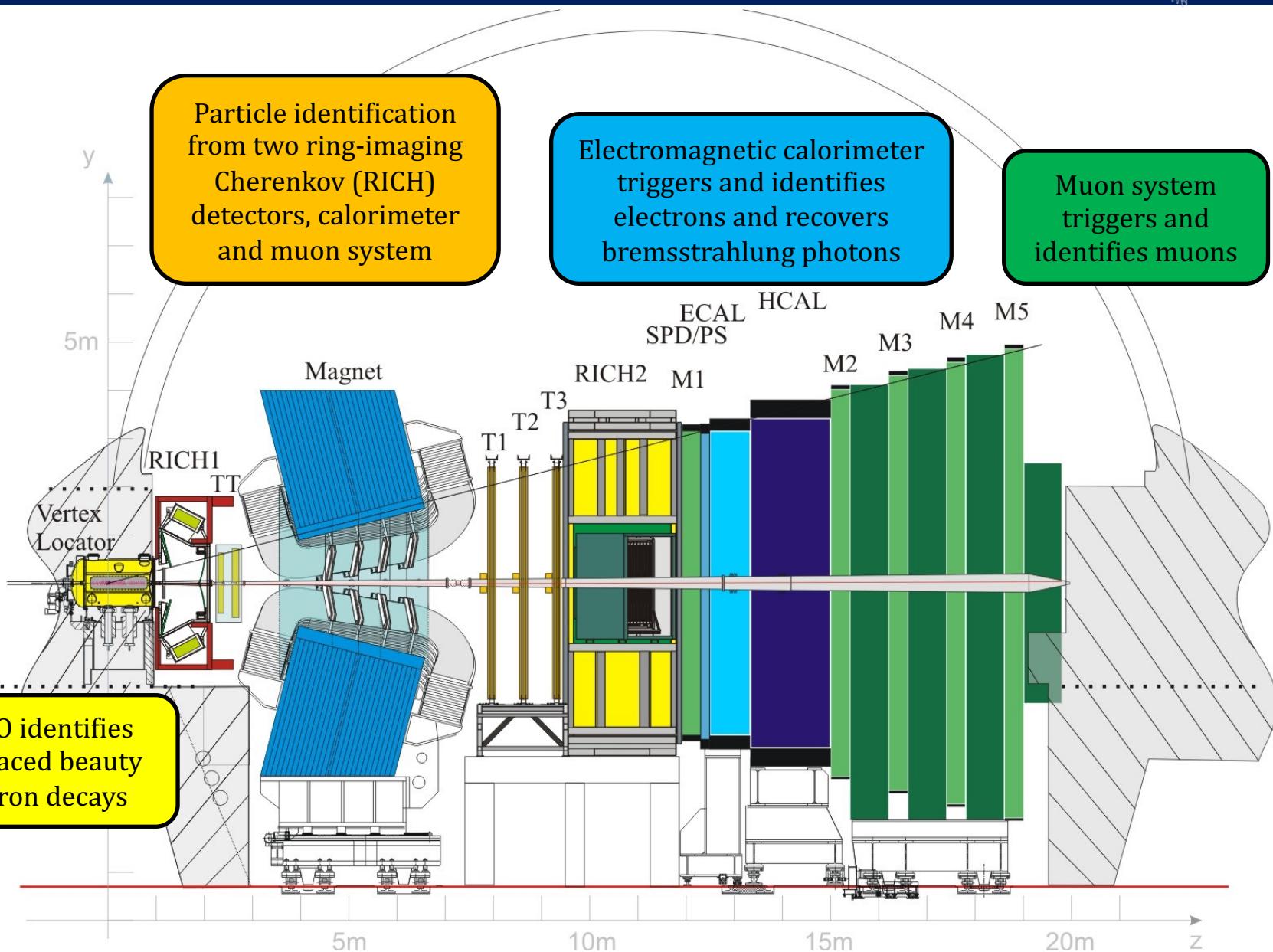


New Physics



- Forbidden at tree level in standard model → highly suppressed.
- Sensitive to new physics (inc. SUSY) at scales above direct LHC reach.

The LHCb Experiment





$$B_{(s)}^0 \rightarrow \mu^+ \mu^-$$

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

Phys. Rev. D105 (2022) 012010

Theoretical motivation

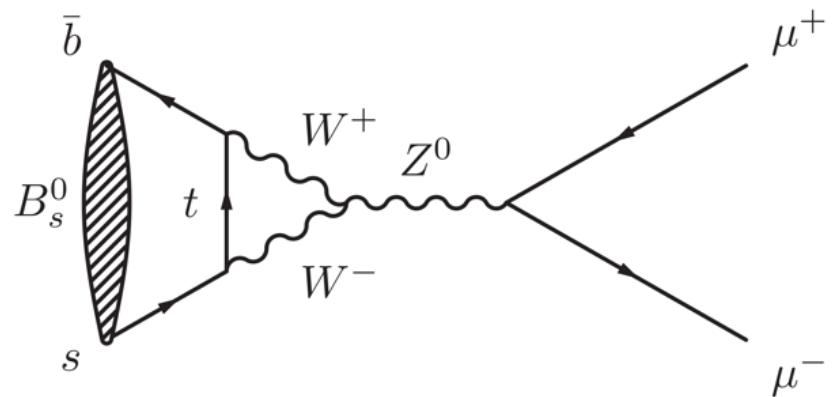


$B_{(s)}^0 \rightarrow \mu^+ \mu^-$ decays are a **FCNC** decay and **helicity suppressed** – very rare.

Matrix element factorises into (trivial) leptonic part and B_q decay constant:

$$\langle \mu\mu | Q | B_q \rangle = \langle \mu\mu | j_\mu \cdot j_q | B_q \rangle = \langle \mu\mu | j_\mu | 0 \rangle \cdot \langle 0 | j_q | B_q \rangle \sim \langle \mu\mu | j_\mu | 0 \rangle \cdot f_{B_q}$$

- Decay constant (f_{B_q}) calculated with lattice QCD to a few percent.
- Decay depends only on EW axial-vector Wilson coefficient C_{10} in SM.



Low theoretical uncertainty:

$$\text{BR}(B_s^0 \rightarrow \mu^+ \mu^-)_{\text{SM}} = (3.66 \pm 0.14) \times 10^{-9}$$

$$\text{BR}(B^0 \rightarrow \mu^+ \mu^-)_{\text{SM}} = (1.03 \pm 0.05) \times 10^{-10}$$

[C. Bobeth et.al. \(2014\)](#) + [M. Beneke, C. Bobeth, and R. Szafron \(2019\)](#)

Theoretical motivation



Sensitive to **scalar (S)** and **pseudoscalar (P)** operators:

- Extended Higgs sector (e.g. MSSM)
- Vector leptoquarks

Also NP in C_{10} or C'_{10} :

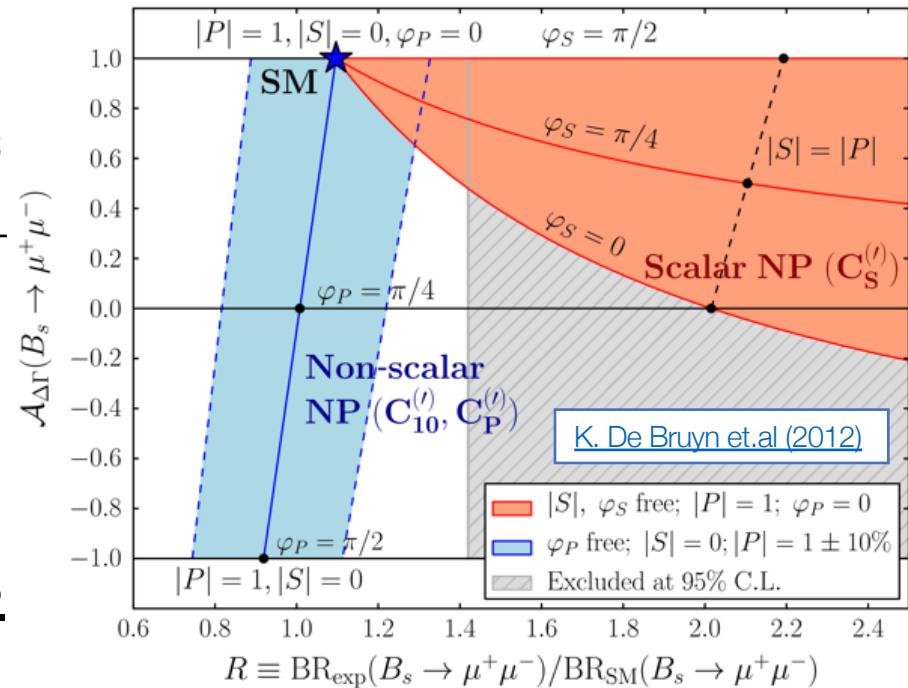
- Effective FCNC Z couplings (MSSM, partial composite, Randall-Sundrum)
- Short-distance semi-leptonic operators (Z', scalar or vector leptoquarks)

Key observables:

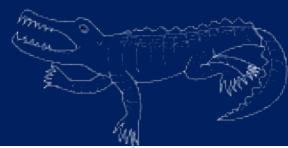
$$\frac{\text{BR}(B_q \rightarrow \mu^+ \mu^-)}{\text{BR}(B_q \rightarrow \mu^+ \mu^-)_{\text{SM}}} = \frac{|S|^2 \left(1 - \frac{4m_\mu^2}{m_{B_q}^2}\right) + |P|^2}{|C_{10}^{\text{SM}}|^2}$$

$$\mathcal{A}_{\Delta\Gamma} = \frac{\text{Re}(P^2 - S^2)}{|P|^2 + |S|^2}$$

can disentangle **scalar & pseudoscalar NP**.



Analysis strategy



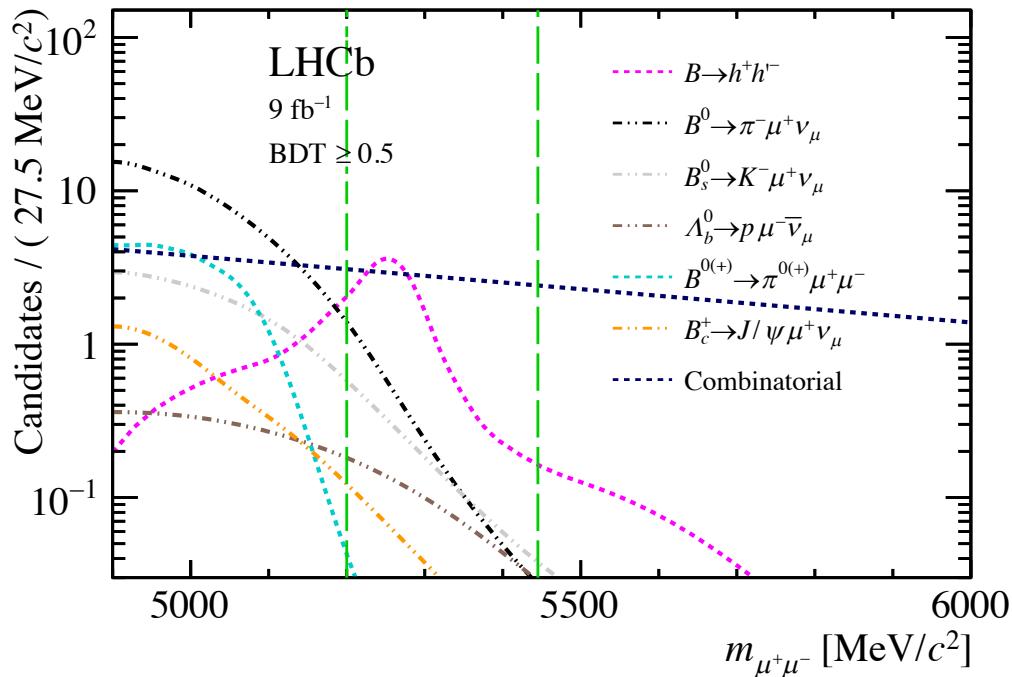
Used 2011-2018 (9 fb^{-1}) data to:

1. Measure the $B_s^0 \rightarrow \mu^+ \mu^-$ branching fraction
2. Search for $B^0 \rightarrow \mu^+ \mu^-$ and $B_s^0 \rightarrow \mu^+ \mu^- \gamma$ ($m_{\mu\mu} > 4.9 \text{ GeV}$)
3. Measure the $B_s^0 \rightarrow \mu^+ \mu^-$ effective lifetime:

$$\tau_{\mu\mu} \equiv \frac{\int_0^\infty t \langle \Gamma(B_s(t) \rightarrow \mu^+ \mu^-) \rangle dt}{\int_0^\infty \langle \Gamma(B_s(t) \rightarrow \mu^+ \mu^-) \rangle dt} \quad \mathcal{A}_{\Delta\Gamma} = \frac{(1-y_s^2)\tau_{\mu\mu} - (1+y_s^2)\tau_{B_s}}{y_s(2\tau_{B_s} - (1-y_s^2)\tau_{\mu\mu})} \quad y_s \equiv \tau_{B_s} \Delta\Gamma / 2$$

Key features:

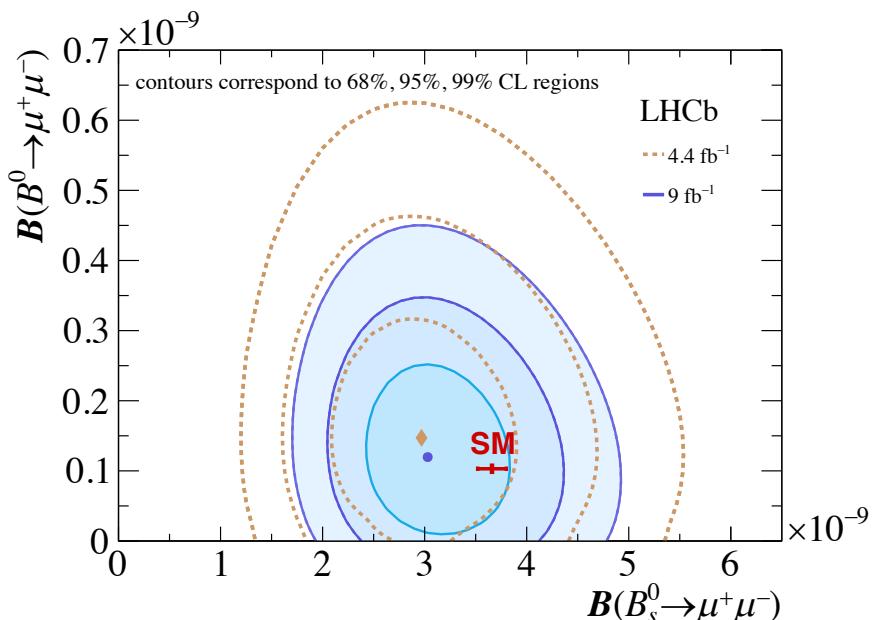
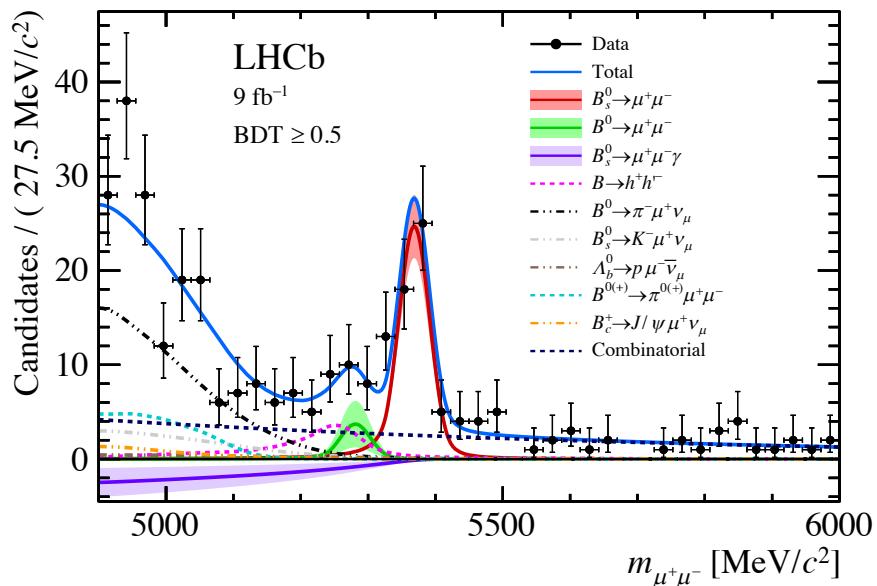
- Normalise w.r.t. $B^0 \rightarrow K^+ \pi^-$ and $B^+ \rightarrow J/\psi K^+$
- Reject physical backgrounds (esp. $B \rightarrow h^+ h^-$) using particle ID
- Reject of combinatorial background using BDT





Branching fraction

Improved measurement of $B_s^0 \rightarrow \mu^+ \mu^-$ decay but no evidence of $B^0 \rightarrow \mu^+ \mu^-$ or $B_s^0 \rightarrow \mu^+ \mu^- \gamma$ (yet!)



$$\text{BR}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.09^{+0.46}_{-0.43} {}^{+0.15}_{-0.11}) \times 10^{-9}$$

$$\text{BR}(B^0 \rightarrow \mu^+ \mu^-) < 2.6 \times 10^{-10} \text{ at 95% conf.}$$

$$\text{BR}(B_s^0 \rightarrow \mu^+ \mu^- \gamma) < 2.0 \times 10^{-9} \text{ at 95% conf.}$$

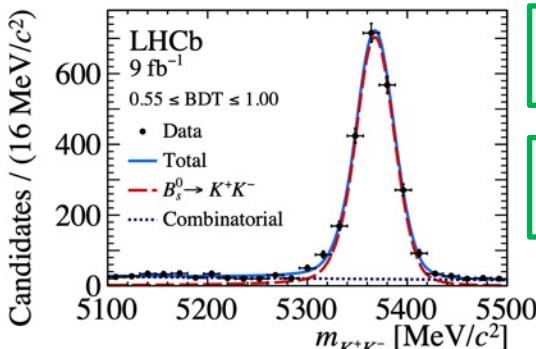
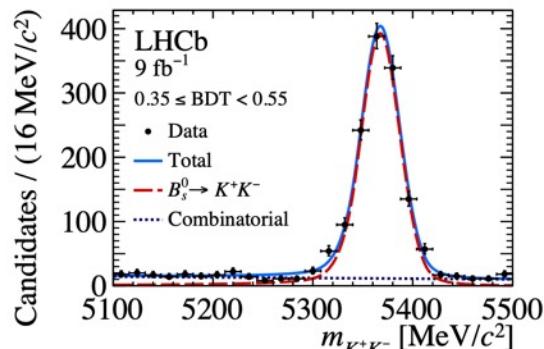
$(m_{\mu\mu} > 4.9 \text{ GeV})$



Effective lifetime

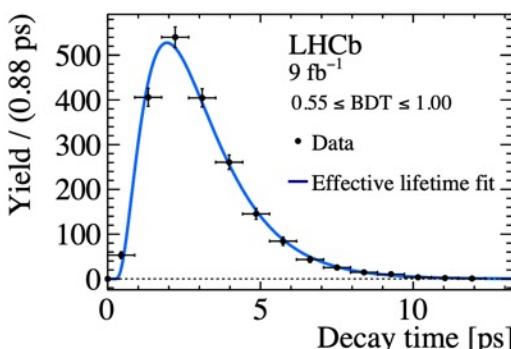
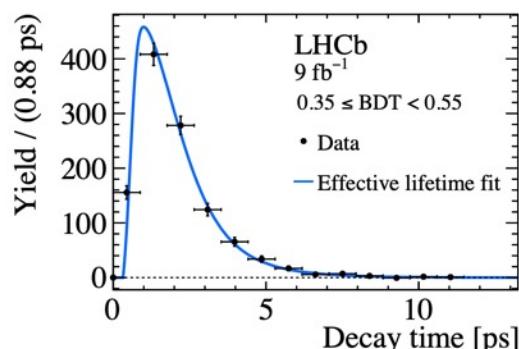
Improved measurement of the $B_s^0 \rightarrow \mu^+ \mu^-$ effective lifetime:

- Simultaneous fit to two bins of BDT (simple cut in 2017 analysis).
- Softer PID requirements as $B \rightarrow h^+ h^-$ background less problematic for B_s^0 .
- Decay time distribution extracted using *sWeights*.
- Decay time efficiency calculated from weighted simulation.
- Method validated on $B^0 \rightarrow K^+ \pi^-$ and $B_s^0 \rightarrow K^+ K^-$.



$$\tau_{B_s^0 \rightarrow K^+ K^-} = 1.435 \pm 0.026 \text{ ps}$$

$$\tau_{B^0 \rightarrow K^+ \pi^-} = 1.510 \pm 0.015 \text{ ps}$$



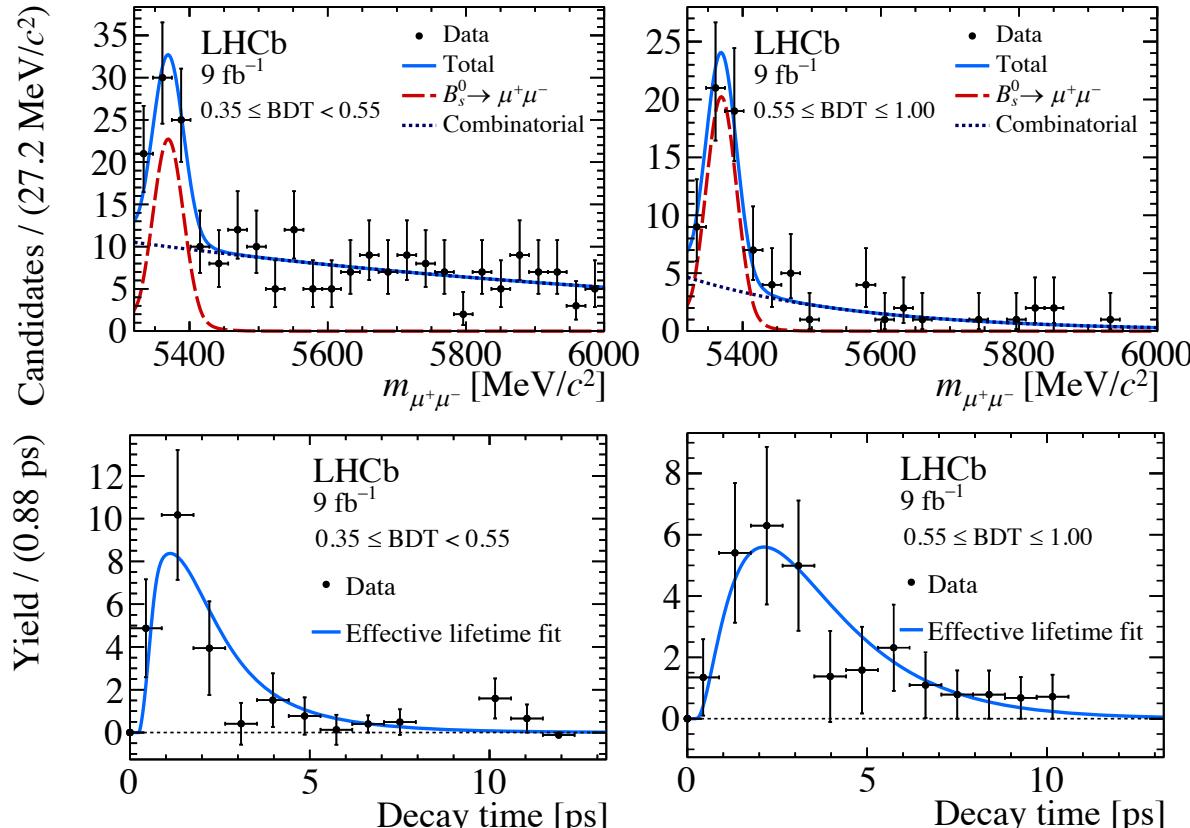
vs PDG:

$$\tau_{B_s^0 \rightarrow K^+ K^-} = 1.407 \pm 0.016 \text{ ps}$$

$$\tau_{B^0 \rightarrow K^+ \pi^-} = 1.524 \pm 0.011 \text{ ps}$$



Effective lifetime



$$\tau_{\mu\mu} = 2.07 \pm 0.29 \pm 0.03 \text{ ps}$$

Currently statistically limited but favours SM $\mathcal{A}_{\Delta\Gamma} = 1$ (SM).

Dominant systematic from $B^0 \rightarrow K^+\pi^-$ validation – will decrease with more data.



$$B_{(s)}^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$$

[JHEP 03 \(2022\) 109](#)



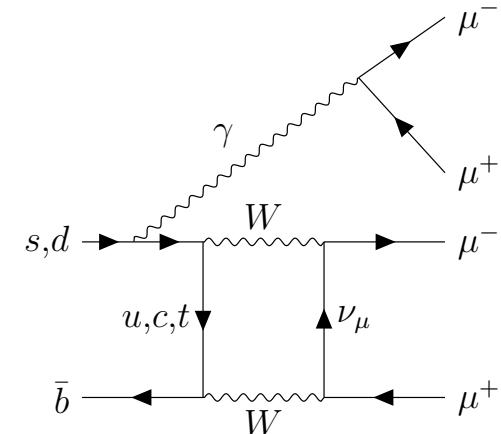
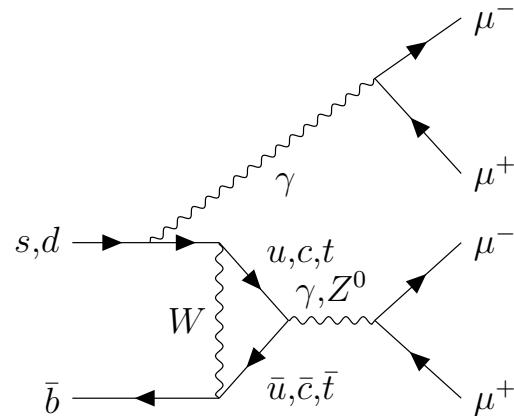
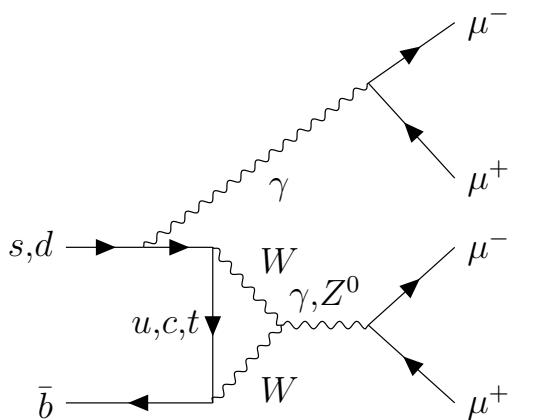
Motivation

$B_{(s)}^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ are also **FCNC** decays – helicity suppression lifted but extra virtual photon reduces rate even further.

$$\text{BR}(B_s^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-)_{\text{SM}} = (0.9 - 1.0) \times 10^{-10}$$

$$\text{BR}(B^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-)_{\text{SM}} = (0.4 - 4.0) \times 10^{-12}$$

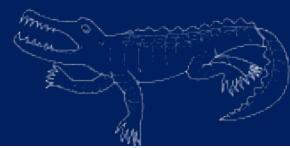
A. V. Danilina and N. V. Nikitin (2018)



Can be enhanced by NP, especially scalar and pseudoscalar sgoldstino particles in MSSM.

Also sensitive to neutral scalars explaining the muon g-2 anomaly, which appear as $B_{(s)}^0 \rightarrow a(\mu^+ \mu^-)a(\mu^+ \mu^-)$.

M. Chala, U. Egede, and M. Spannowsky (2019)



Analysis strategy

Previous limits at 95% confidence set by LHCb with Run 1 sample:

$$\text{BR}(B_s^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-) < 2.5 \times 10^{-9}$$

$$\text{BR}(B^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-) < 6.9 \times 10^{-10}$$

[LHCb Collaboration, JHEP 03 \(2017\) 001](#)

$B_{(s)}^0 \rightarrow a(\mu^+ \mu^-)a(\mu^+ \mu^-)$ decays covered by Run 1 analysis, except when m_a falls in vetoed ϕ , J/ψ , $\psi(2S)$ regions.

However, muon g-2 anomaly favours $m_a \sim 1$ GeV.

[M. Chala, U. Egede, and M. Spannowsky \(2019\)](#)

This analysis uses full Run 1 and Run 2 sample (9 fb^{-1}):

1. Update of searches for $B_s^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ and $B^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ decays
2. **New** dedicated search for $B_{(s)}^0 \rightarrow a(\mu^+ \mu^-)a(\mu^+ \mu^-)$ decays (inc. $m_a \sim 1$ GeV)
3. **New** search for $B_{(s)}^0 \rightarrow J/\psi(\mu^+ \mu^-)\mu^+ \mu^-$ decays (SM BF $\sim 10^{-13}$)



Analysis strategy

Branching fraction normalised to $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(\mu^+\mu^-)$ control mode:

$$\mathcal{B}_{sig} = \mathcal{B}_{con} \times \frac{N_{sig}}{N_{con}} \frac{f_s}{f_q} \frac{\epsilon_{con}}{\epsilon_{sig}}$$

Most systematics cancel in ratio.

Key steps:

1. Efficiency ratios w.r.t. control mode from reweighted MC
2. Control mode yield from mass fit with optimised BDT cut
3. BF's extracted using simultaneous mass fit in bins of BDT [simple BDT cut for $B_{(s)}^0 \rightarrow aa$]
4. In absence of signal, set limit using *GammaCombo*



Analysis strategy

Search for $B_s^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ and $B^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ decays vetoes:

$$\phi: \quad 950 \text{ MeV} < m_{\mu\mu} < 1090 \text{ MeV}$$

$$J/\psi: \quad |m_{\mu\mu} - m_{J/\psi}| > 100 \text{ MeV}$$

$$\psi(2S): \quad |m_{\mu\mu} - m_{\psi(2S)}| > 100 \text{ MeV}$$

for all four opposite sign muon pairs.

$B_{(s)}^0 \rightarrow a(\mu^+ \mu^-)a(\mu^+ \mu^-)$ search requires

$$|m_{ij}^2 - m_{kl}^2| < 2\sqrt{\sigma^2(m_{ij}^2) + \sigma^2(m_{kl}^2)}$$

Search for $B_{(s)}^0 \rightarrow J/\psi(\mu^+ \mu^-)\mu^+ \mu^-$ requires one dimuon pair in the J/ψ region and for the other to not fall in the ϕ region.



Efficiency evaluation

Efficiencies calculated using reweighted simulation.

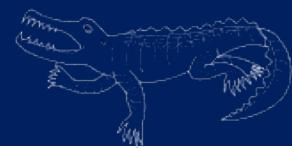
Weight calculated by comparing $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decays in data and simulation:

1. Generated B kinematics (p_T and η)
2. Generated event multiplicity
3. Reconstructed quantities (B vertex χ^2 and IP χ^2)

PID and trigger efficiencies cancel very precisely in ratio with control mode – no weights applied in these cases.

$$\epsilon = \epsilon_{\text{presel}} \cdot \epsilon_{\text{BDT}} = \frac{\sum_{\text{presel}} \omega_{\text{gen}}}{\sum_{\text{gen}} \omega_{\text{gen}}} \cdot \frac{\sum_{\text{BDT}} \omega_{\text{gen}} \omega_{\text{rec}}}{\sum_{\text{presel}} \omega_{\text{gen}} \omega_{\text{rec}}}$$

Backgrounds and Systematics



Numerous **physical backgrounds** studied:

Four muon backgrounds: $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(\mu^+\mu^-)$, $B_s^0 \rightarrow \phi(\mu^+\mu^-)\mu^+\mu^-$

Hadronic mis-ID: $H_b^0 \rightarrow \mu^+\mu^-h^+h'^-$ where $h = K, \pi, p$

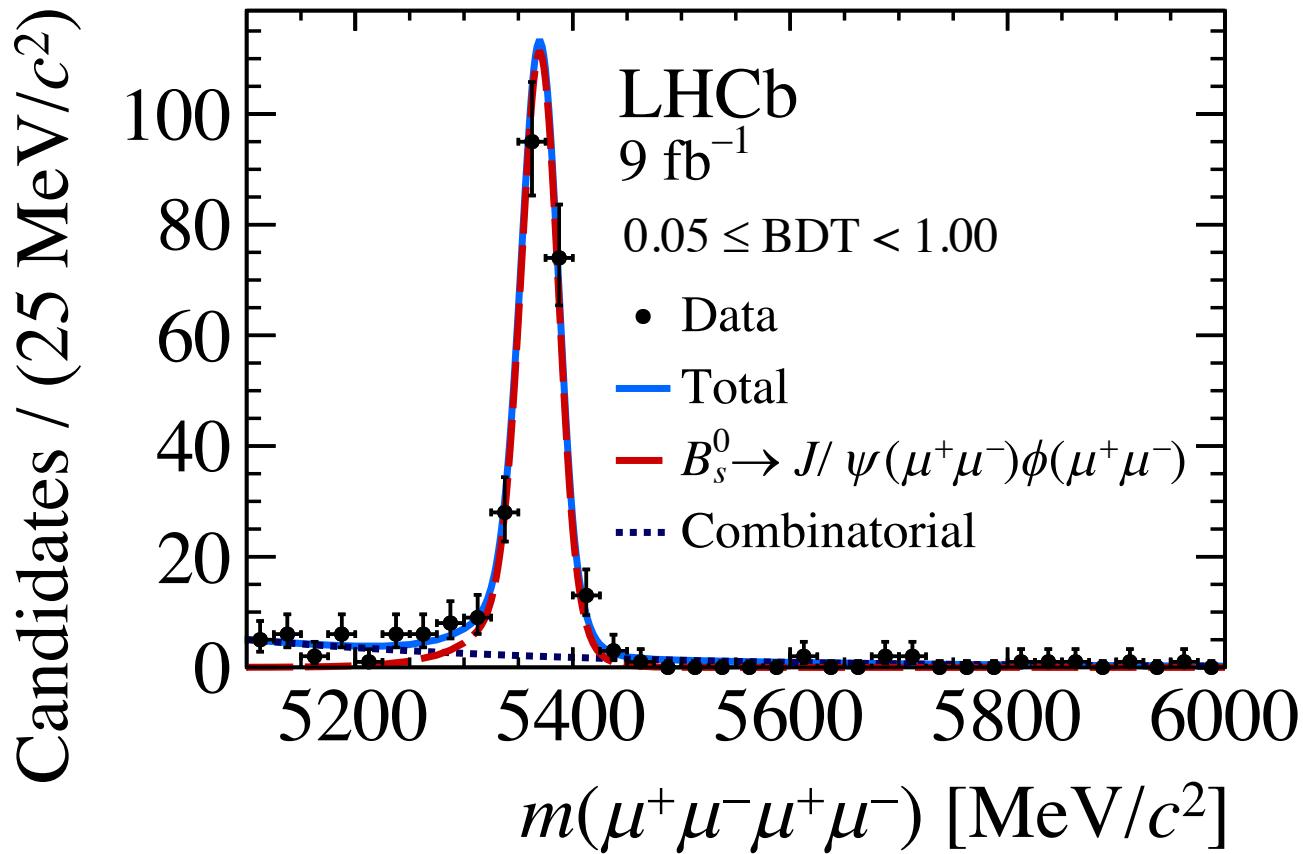
- All reduced to negligible levels by standard selection, except for $B_{(s)}^0 \rightarrow J/\psi(\mu^+\mu^-)\mu^+\mu^-$ search where some $B_{(s)}^0 \rightarrow J/\psi(\mu^+\mu^-)\pi^+\pi^-$ survives.
- Removed by stronger PID requirements on tracks not from J/ψ .

Dominant **systematic** from unknown SM decay model. However, effect on sensitivity is negligible.



Mass fits

Control mode yield extracted using invariant mass fit

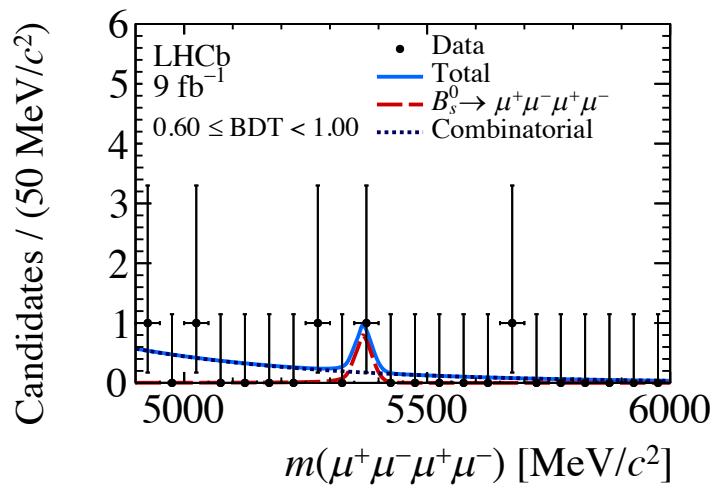
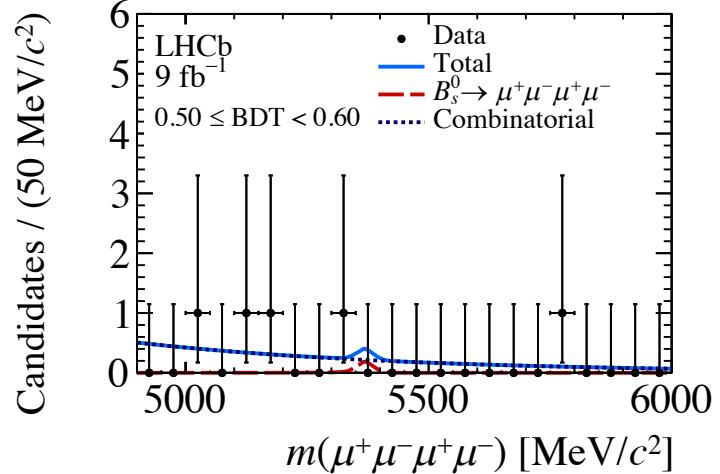
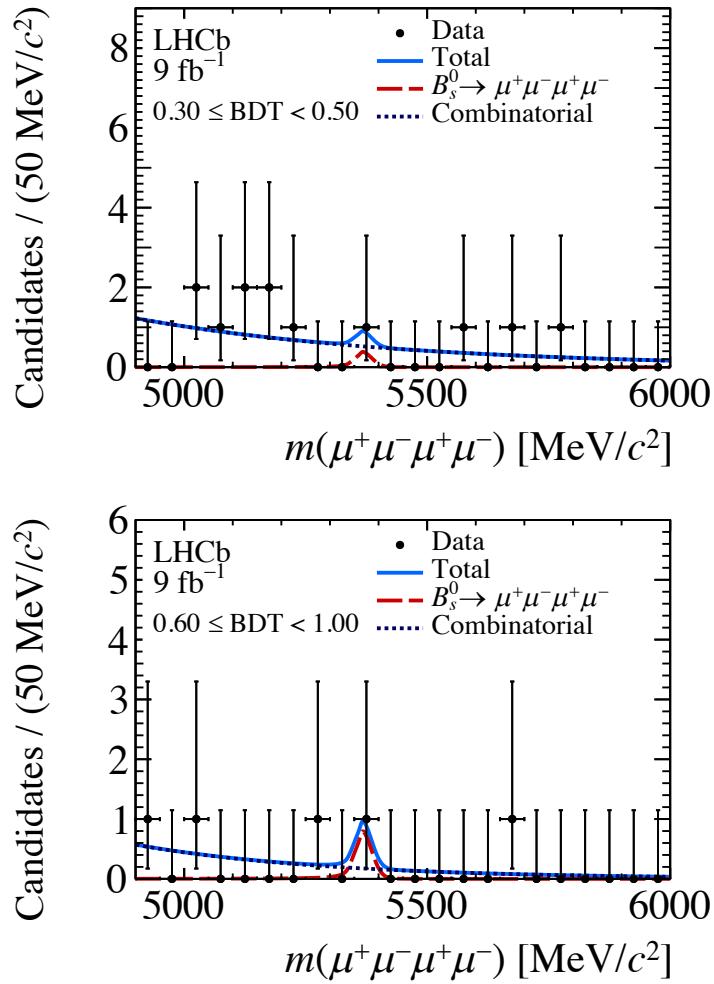
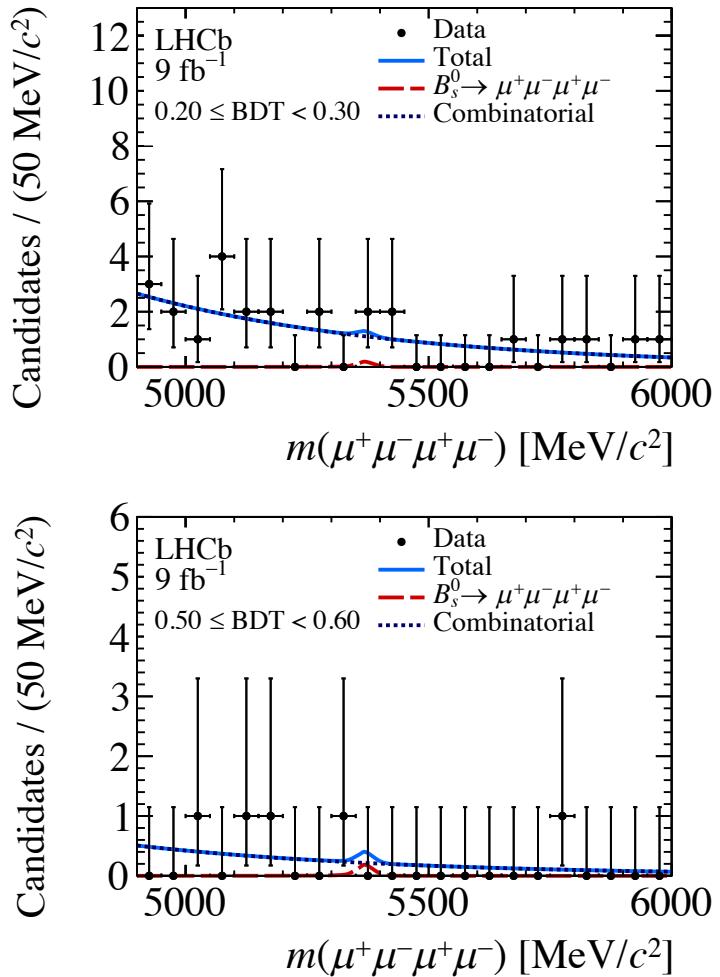


218 +/- 16 candidates.

Mass fits



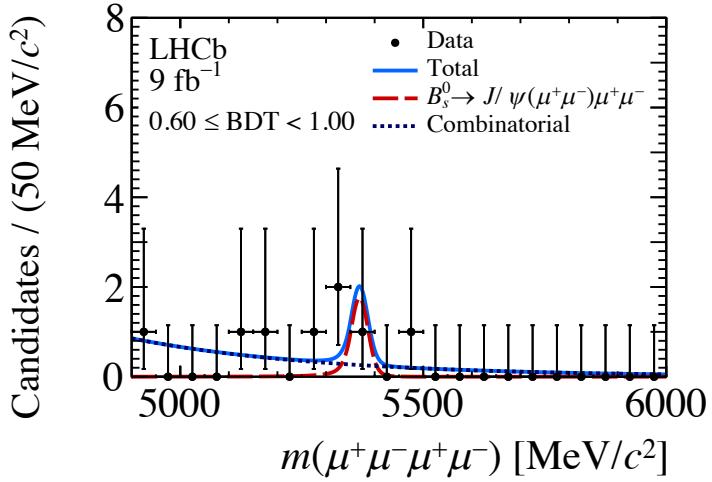
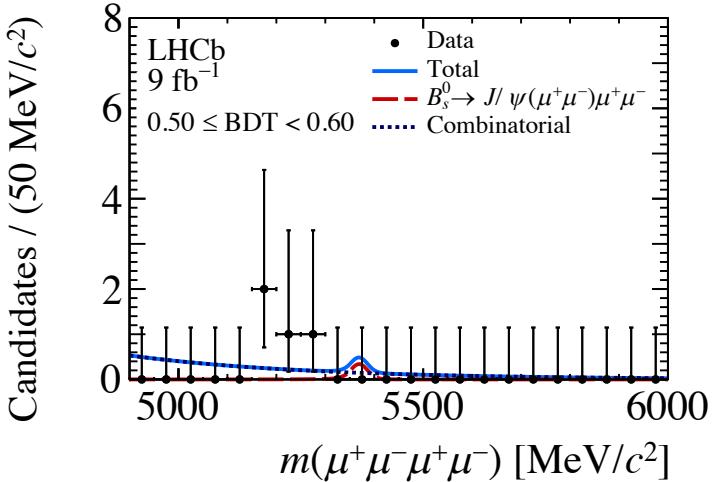
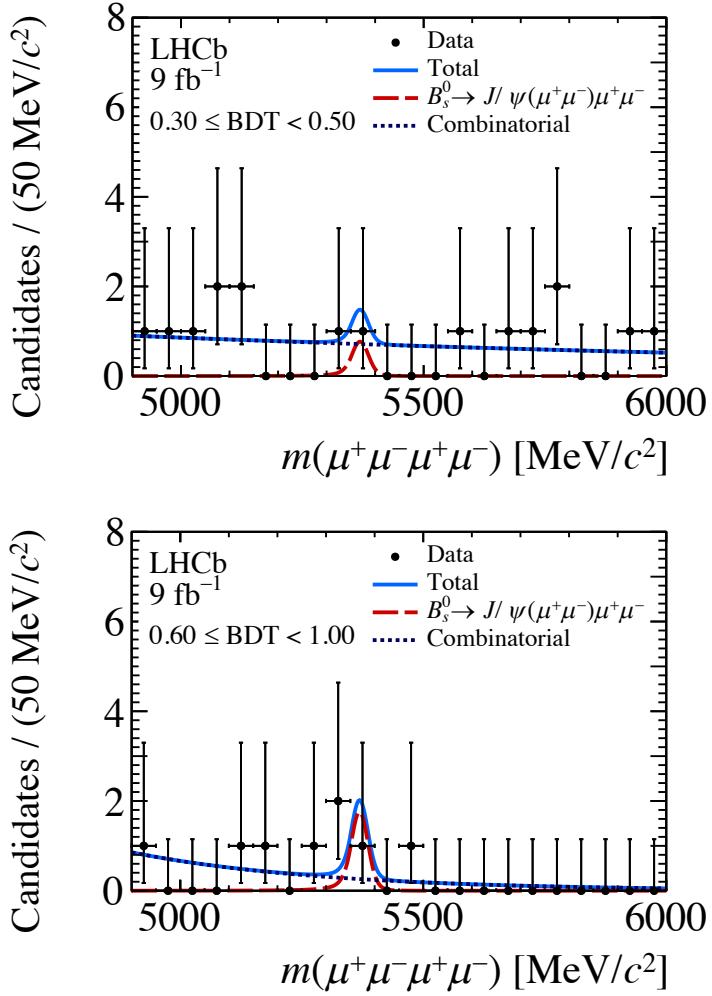
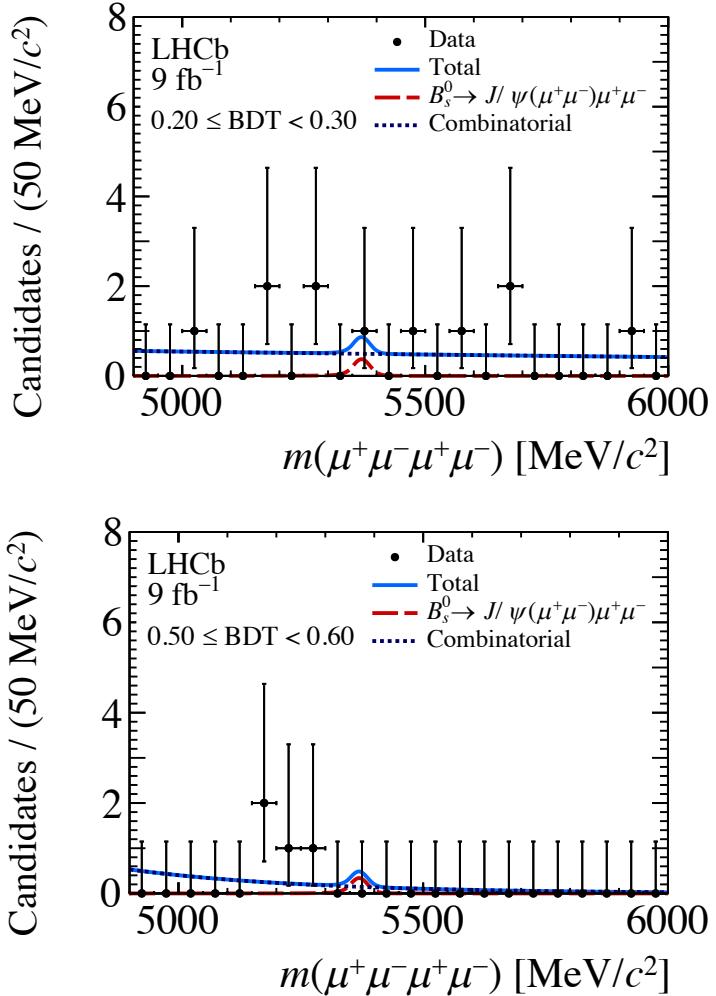
$B_{(s)}^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ BF estimated by simultaneous mass fit in four bins of BDT:





Mass fits

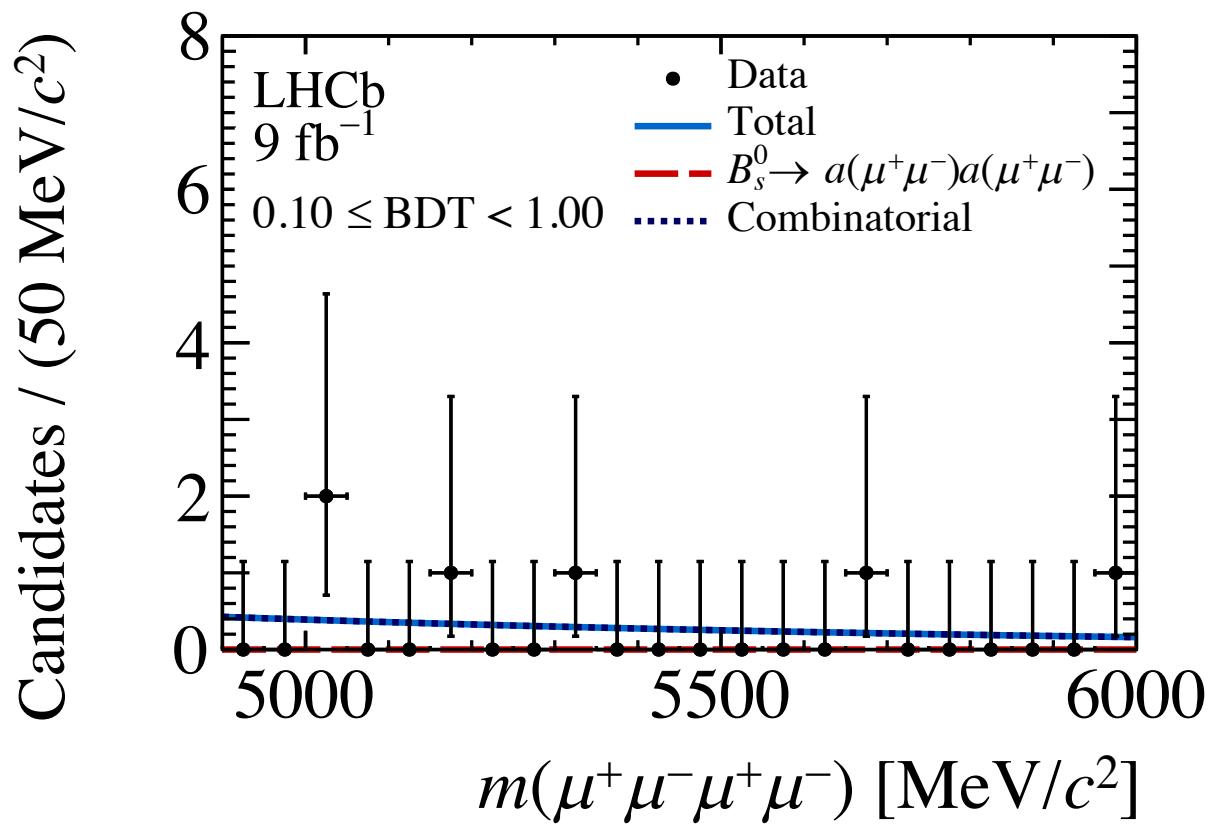
$B_{(s)}^0 \rightarrow J/\psi(\mu^+\mu^-)\mu^+\mu^-$ BF from simultaneous mass fit in four bins of BDT:





Mass fits

$B_s^0 \rightarrow a(\mu^+\mu^-)a(\mu^+\mu^-)$ BF estimated using single fit to mass after BDT cut:



Results



No significant signals observed → set limits.

$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-)$	$< 8.6 \times 10^{-10},$
$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-)$	$< 1.8 \times 10^{-10},$
$\mathcal{B}(B_s^0 \rightarrow a(\mu^+ \mu^-) a(\mu^+ \mu^-))$	$< 5.8 \times 10^{-10},$
$\mathcal{B}(B^0 \rightarrow a(\mu^+ \mu^-) a(\mu^+ \mu^-))$	$< 2.3 \times 10^{-10},$
$\mathcal{B}(B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \mu^+ \mu^-)$	$< 2.6 \times 10^{-9},$
$\mathcal{B}(B^0 \rightarrow J/\psi(\mu^+ \mu^-) \mu^+ \mu^-)$	$< 1.0 \times 10^{-9}.$

Factor 3-4 improvement in limits for main channels.

Limit on $B^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ second lowest ever achieved by LHCb.

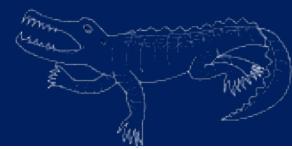
Good prospects to observe the B_s decay at the LHCb Upgrade (assuming SM).



$$D^0 \rightarrow \mu^+ \mu^-$$

[LHCb-PAPER-2022-029](#)

Motivation



- FCNC $c \rightarrow u\mu^+\mu^-$ decays unexplored compared to strange and beauty.
- Even more suppressed – precise GIM cancellation due to low down-type quark masses.

One of the most interesting decays is $D^0 \rightarrow \mu^+\mu^-$:

- SM short-distance helicity suppressed at 10^{-18} .
- Decay dominated by long-distance $D^0 \rightarrow \gamma\gamma$ contribution.

BF expected to be at least 10^{-13} .

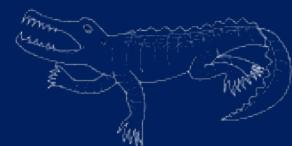
Burdman et al. (2002)

Decay insensitive to the MSSM but can be enhanced significantly in SUSY models with R-parity violation.

Previous best limit from LHCb: $\text{BR}(D^0 \rightarrow \mu^+\mu^-) < 7.6 \times 10^{-9}$ at 95% CL.

Phys. Lett. B 725 (2013) 15-24

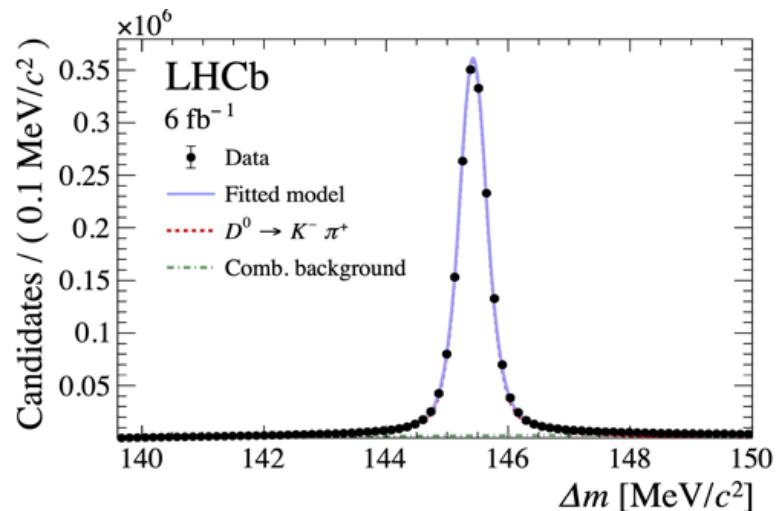
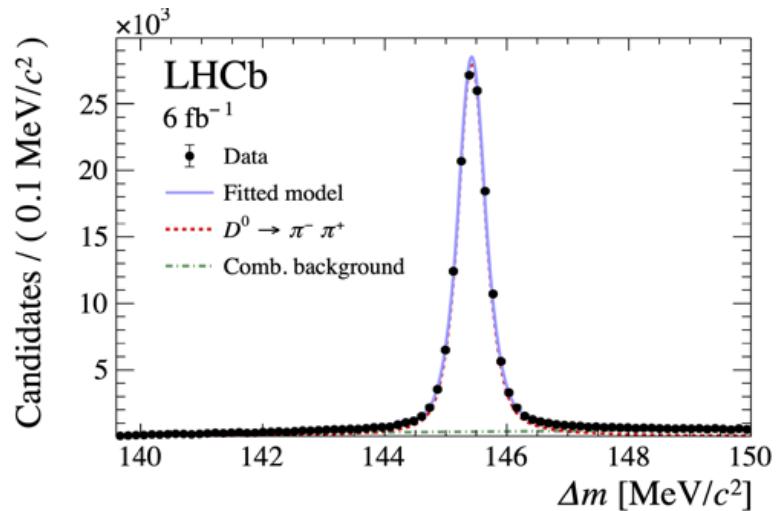
Strategy



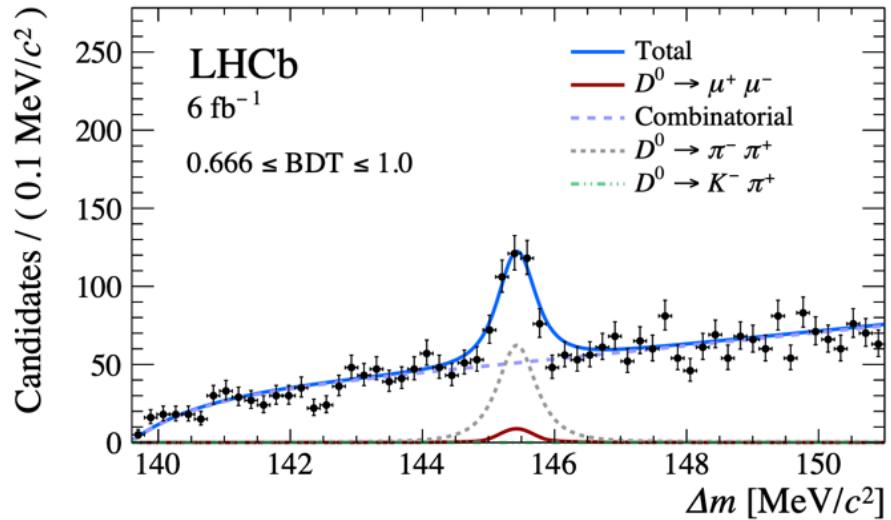
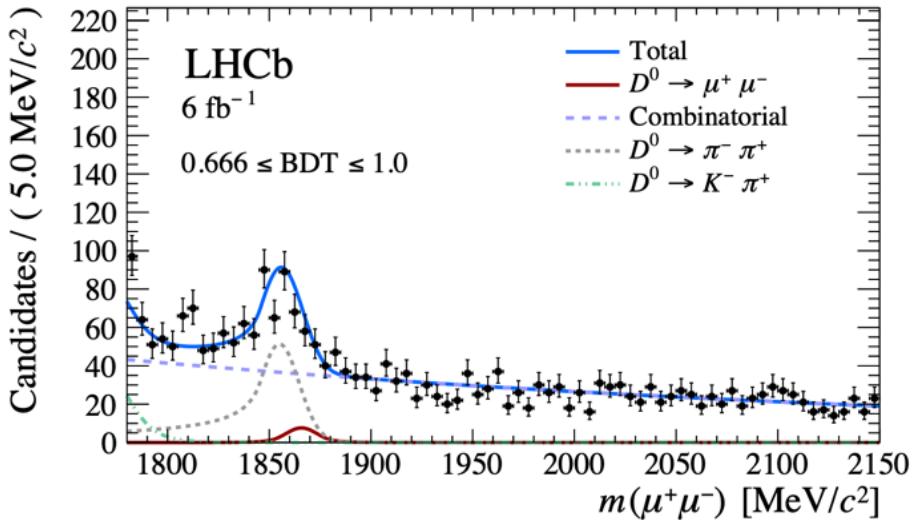
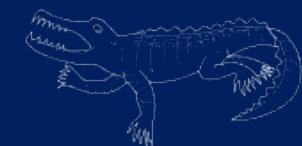
New measurement uses for 9 fb^{-1} data sample.

Search for D decays in $D^{*+} \rightarrow D^0\pi^+$:

- ✓ Improved background rejection
- ✓ 2D fit performed to $m(\mu^+\mu^-)$ and $\Delta m \equiv m(\pi^+\mu^+\mu^-) - m(\mu^+\mu^-)$.
- Search normalised to $D^0 \rightarrow K^-\pi^+$ and $D^0 \rightarrow \pi^+\pi^-$ control modes.
- BDT to reject combinatorial background.
- Hadronic background rejected by multivariate muon classifier.
- Efficiencies from reweighted simulation.
- Cross-check ratio of control mode BFs:
 - ✓ Consistent with world average.
 - ✓ Consistent across data-taking periods.



Signal search

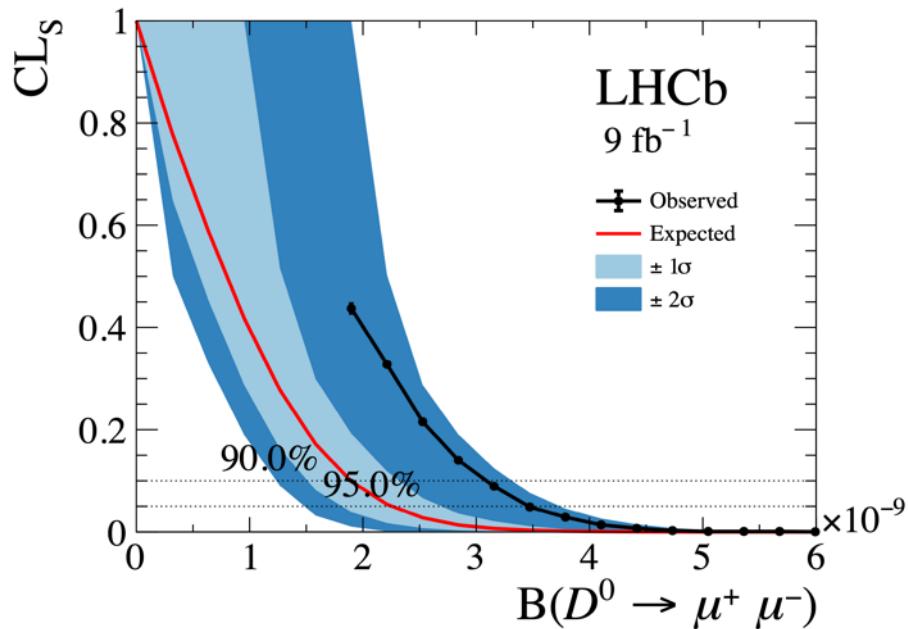


- **2D fit** to $m(\mu^+ \mu^-)$ and Δm .
- **Simultaneous fit** to three BDT regions and two data taking periods.
- **Misidentified $D^0 \rightarrow \pi^+ \pi^-$** decays constrained using simulation, cross-checked on $D^+ \rightarrow \pi^+ \pi^- \pi^+$ and $D_s^+ \rightarrow \pi^+ \pi^- \pi^+$ data samples.
- **Misidentified $D^0 \rightarrow K^- \pi^+$** decays constrained from fit to Δm with a ± 10 MeV region around the D^0 mass under the $K^- \pi^+$ hypothesis.

Results



- $\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) = (1.7 \pm 1.0) \times 10^{-9}$,
79 \pm 45 signal decays.
- p-value of 0.068, corresponding to a significance of 1.5σ .
- $\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) < 3.1(3.5) \times 10^{-9}$
at 90(95)% CL.
- BF larger than expected from background-only toys:
 $\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) < 1.9(2.3) \times 10^{-9}$
at a 90 (95)% CL.



World's most stringent limit on relevant FCNC couplings in charm

Conclusion

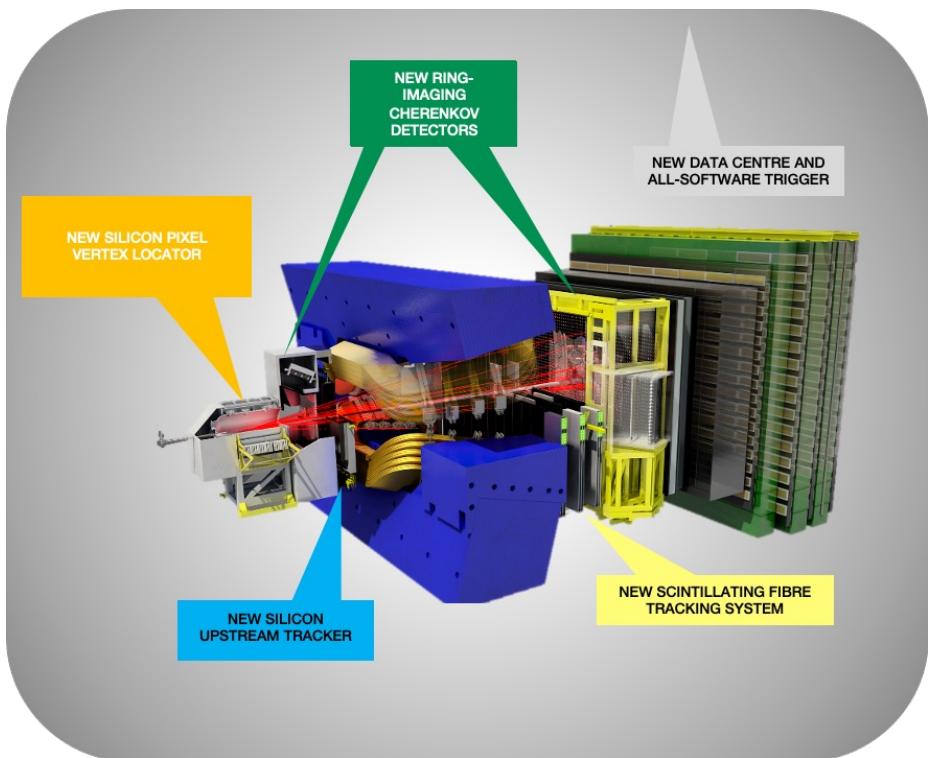


FCNC decays of beauty and charm probe a range of BSM models, with particular sensitivity to SUSY.

Full Run 1 and Run 2 LHCb 9 fb^{-1} data sample analyses of:

$$B_{(s)}^0 \rightarrow \mu^+ \mu^- (\gamma), \quad B_{(s)}^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-, \quad D^0 \rightarrow \mu^+ \mu^-$$

agree with SM, constraining BSM couplings.

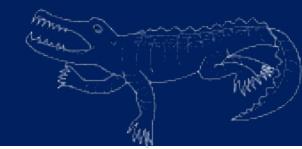


The **LHCb Upgrade** is now running!

- (Almost) all-new detector to allow readout at 30 MHz
- Full software trigger
- Data taking with five times previous rate

Larger data sample will significantly increase sensitivity and open up new measurements of FCNC decays.

Conclusion

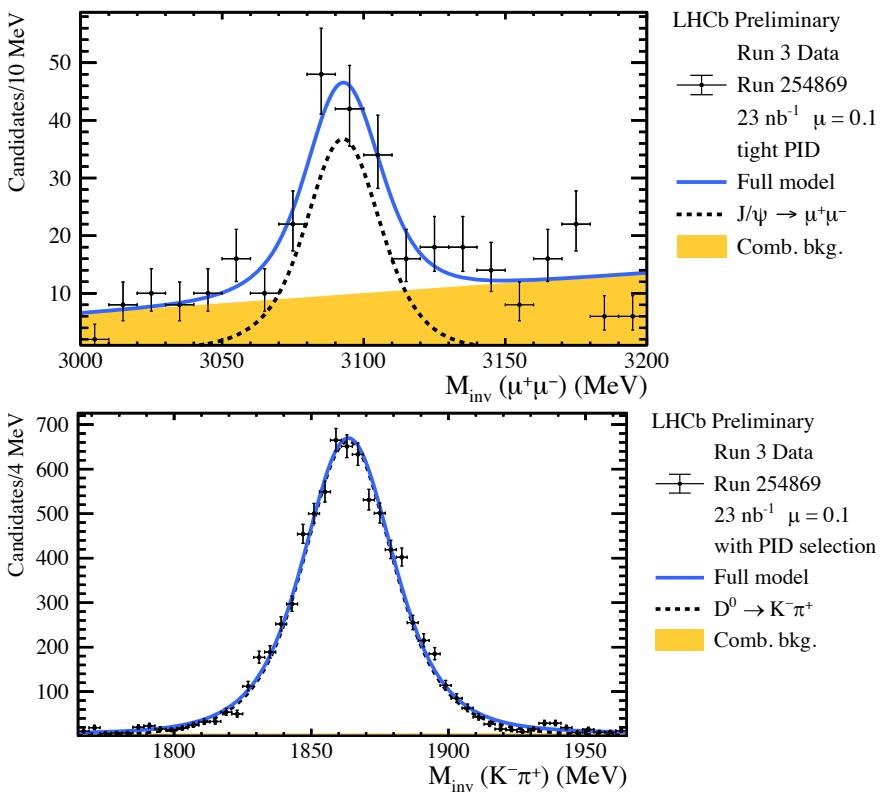


FCNC decays of beauty and charm probe a range of BSM models, with particular sensitivity to SUSY.

Full Run 1 and Run 2 LHCb 9 fb^{-1} data sample analyses of:

$$B_{(s)}^0 \rightarrow \mu^+ \mu^- (\gamma), \quad B_{(s)}^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-, \quad D^0 \rightarrow \mu^+ \mu^-$$

agree with SM, constraining BSM couplings.



The **LHCb Upgrade** is now running!

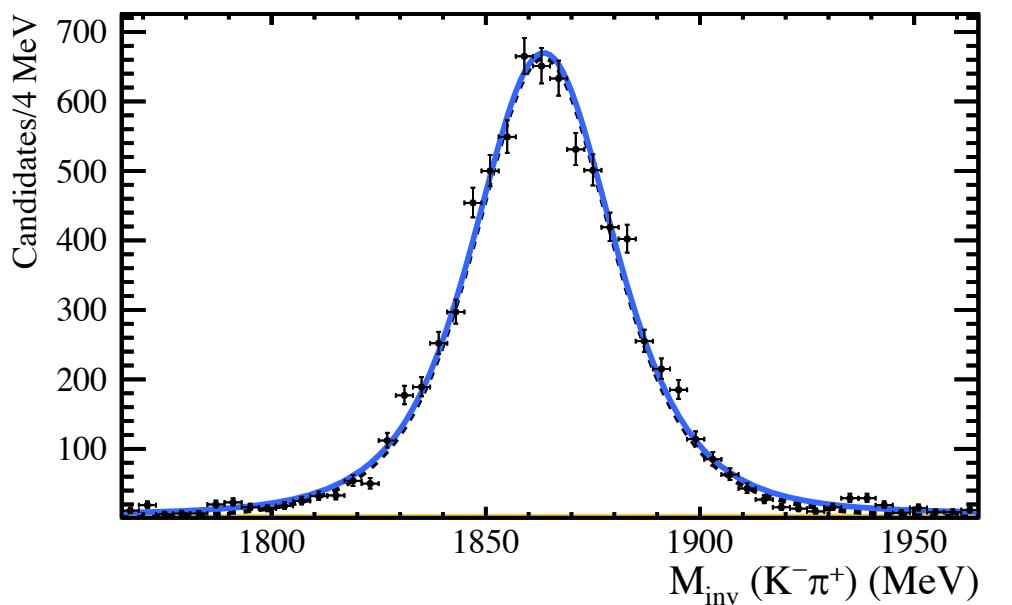
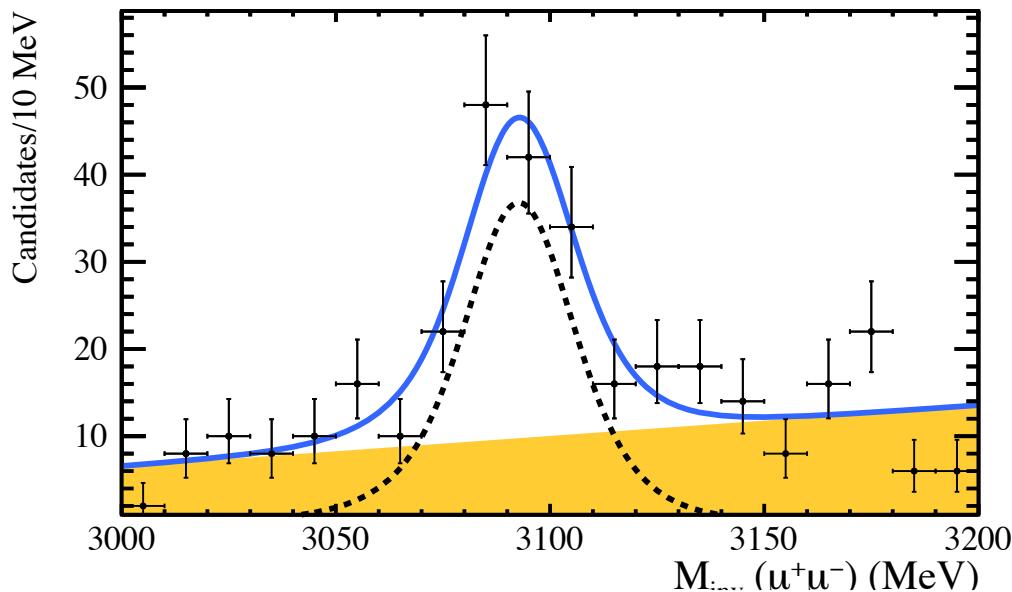
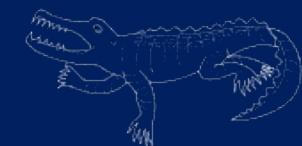
- (Almost) all-new detector to allow readout at 30 MHz
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Backup

First data!

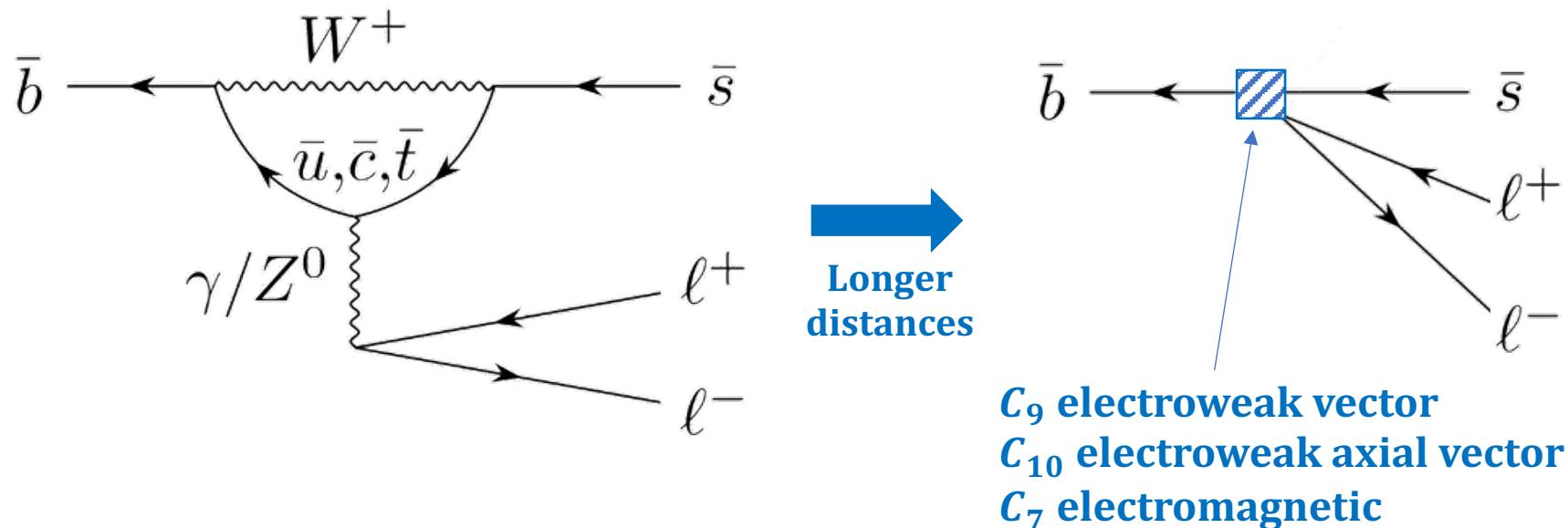


Effective Field Theory of $b \rightarrow s\ell^+\ell^-$



$b \rightarrow s\ell^+\ell^-$ transitions can be described using an **Effective Field Theory**

- zoom out to b quark scale ~ 4.8 GeV
- integrate out short distance (high energy) interactions
- short distance interactions parametrised using **Wilson Coefficients**



Effective Field Theory of $b \rightarrow s\ell^+\ell^-$



Hamiltonian defined in terms of **Wilson Coefficients** [$C_i^{(')}$] and **Operators** [$\mathcal{O}_i^{(')}$]

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (\mathcal{C}_i \mathcal{O}_i + \mathcal{C}'_i \mathcal{O}'_i)$$

- **Wilson Coefficients** encode short-distance physics (the bit we're interested in)
- **Operators** describe low-energy QCD (described using **form factors**), which have large theory uncertainties

B24mu Systematics

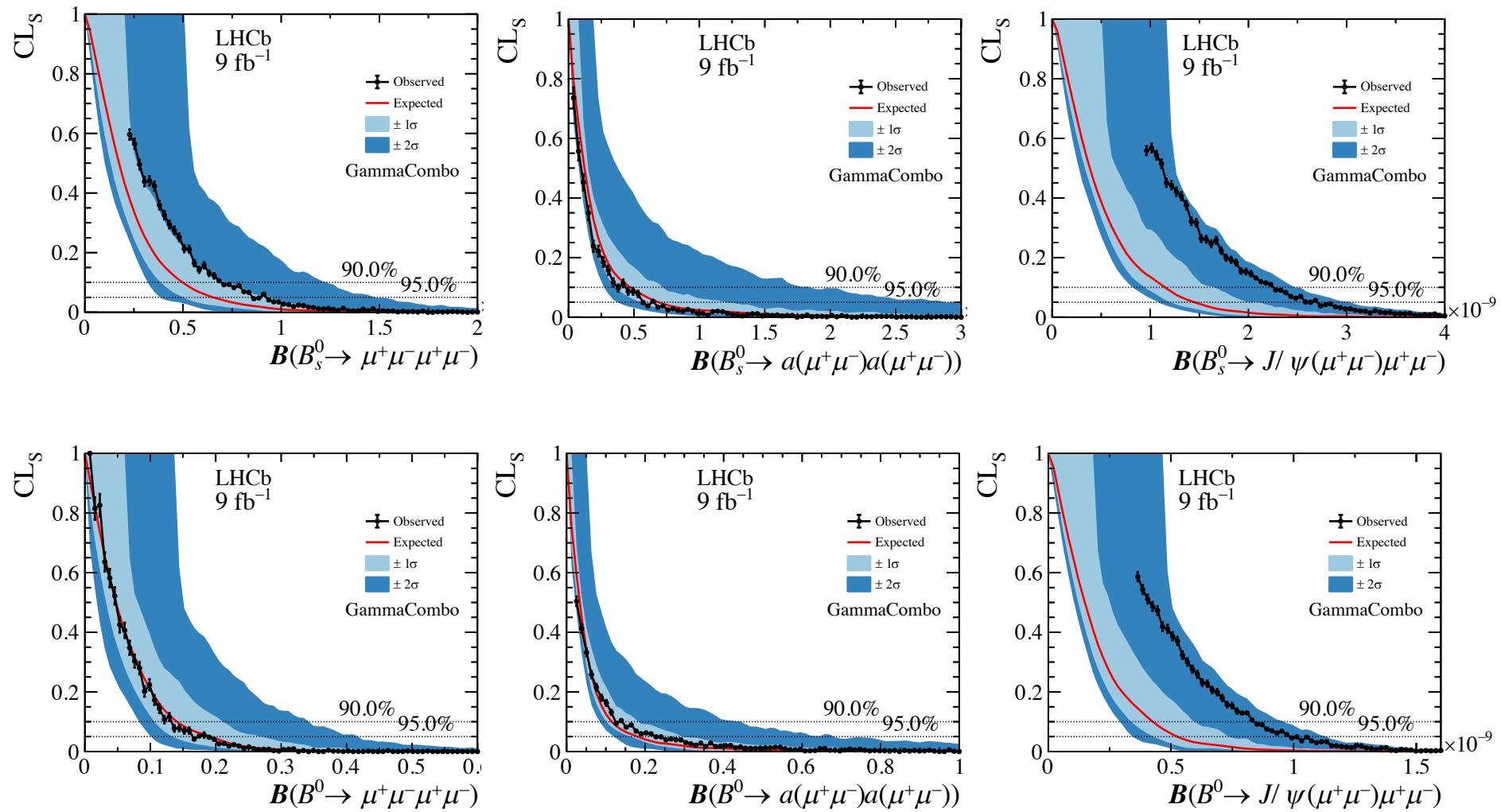


Very similar signal and control modes – most systematics cancel. Largest remaining effects:

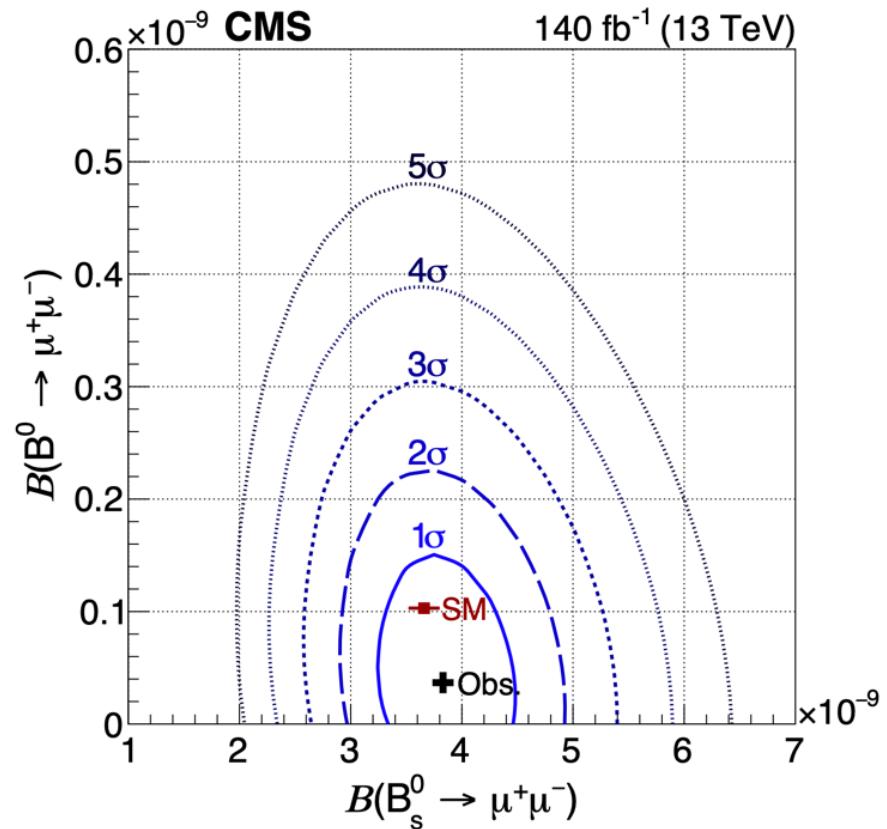
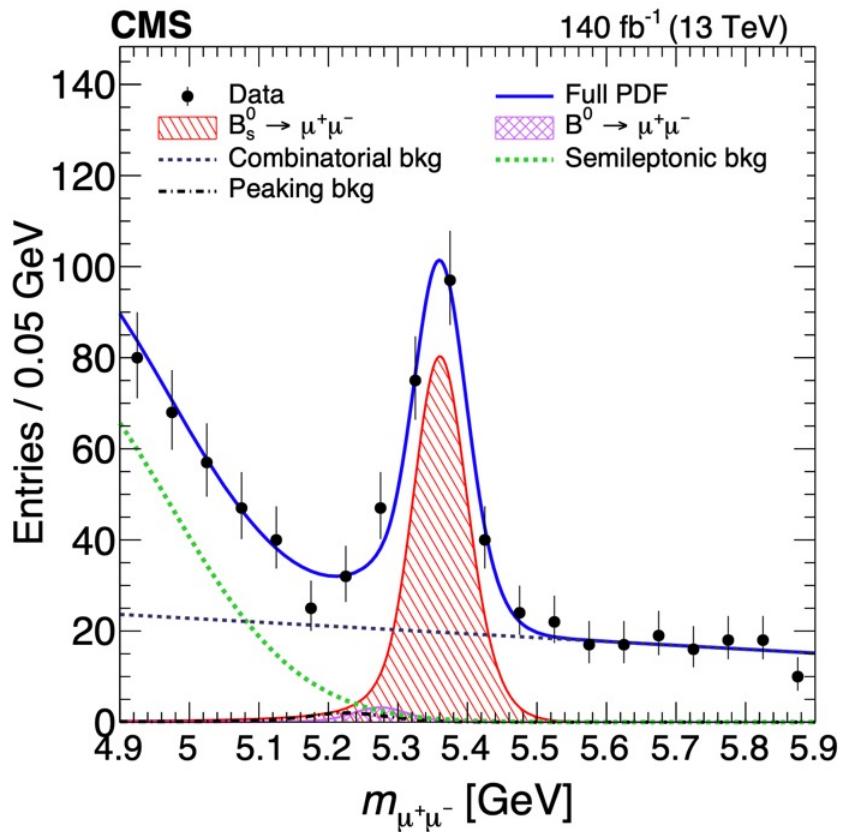
- SM decay model unknown – simulation uses phase space ($\sim 20\%$)
- Unknown effective lifetimes of B_s decays ($\sim 5\%$)
- Mismodelling of PID response in simulation ($\sim 1\text{-}2\%$)
- Mismodelling mass resolution in simulation ($< 1\%$)

Systematics have negligible effect on expected limits.

Results



Bs2mumu CMS



$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = \left[4.02^{+0.40}_{-0.38} \text{ (stat)} ^{+0.28}_{-0.23} \text{ (syst)} ^{+0.18}_{-0.15} (\mathcal{B}) \right] \times 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 1.9 \times 10^{-10} \text{ at } 95\% \text{ CL}$$

$$\tau = 1.83^{+0.23}_{-0.20} \text{ (stat)} ^{+0.04}_{-0.04} \text{ (syst)} \text{ ps.}$$