Search for Very Rare Decays at LHCb

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The University of Manchester

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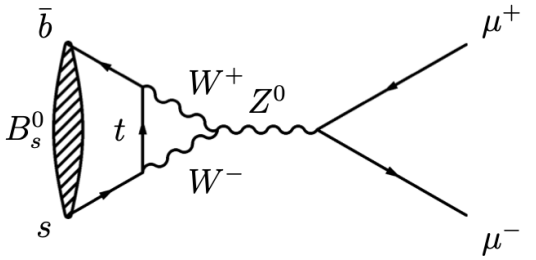
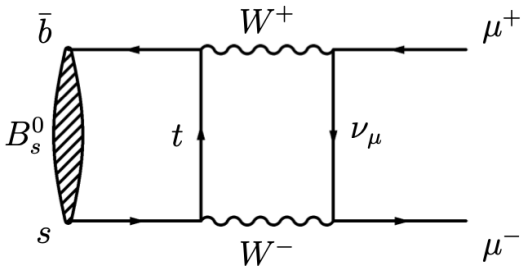
What do we mean by "very rare decays"?

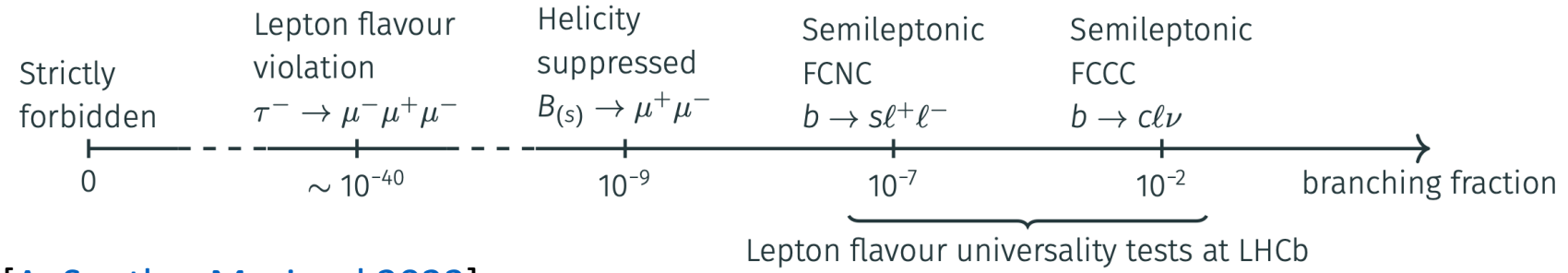
- Strongly suppressed or forbidden decays in the SM
- Include
  - FCNC processes not allowed at tree level (quantum loop diagrams, $\mathcal{B} < \mathcal{O}(10^{-7})$)
  - LFV processes ($\mathcal{B} < 10^{-40}$ in SM + ν oscillations)
- Important tests of SM
  - Sensitive to new physics contribution (Z' gauge boson, LQ, non-SM Higgs boson…)
- Mainly involving leptonic final states

$B_s^0 \to \mu^+\mu^-$





[PRD 105 (2022) 012010]



[A. Seuthe. Moriond 2023]

In this talk

- **Latest (2024) LHCb results on very rare decays**
- (Semi)leptonic decays of b mesons
  - $B_c^+ \to \pi^+\mu^+\mu^-$ [Eur. Phys. J. C 84 (2024) 468] **NEW**
  - $B_{(s)}^{*0} \to \mu^+\mu^-$ in $B_c^+ \to \pi^+\mu^+\mu^-$ decays [LHCb-CONF-2024-003] **NEW**
  - $B \to D\,\mu^+\mu^-$ [JHEP 02 (2024) 032]

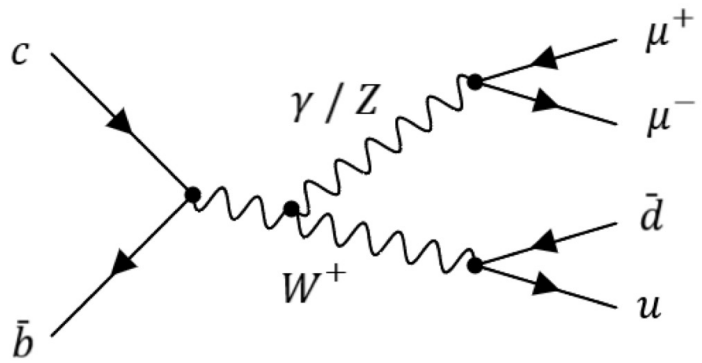
- More at LHCb
  - Dedicated talk on **LFV b decays** by Tommaso Fulghesu **NEW**
  - Dedicated talk on **radiative b-hadron decays** by Aniol Lobo Salvia ($B_s^0 \to \mu^+\mu^-\gamma$ [JHEP 07 (2024) 101])
  - Dedicated talk on **charm (very) rare decays** by Francesco Dettori

$B_c^+ \to \pi^+\mu^+\mu^-$ New

Eur. Phys. J. C 84 (2024) 468

- B_c^+ mesons made of heaviest quarks forming hadrons in the SM
- Can provide important insights into the understanting of QCD
- No theory prediction so far

Annihilation + γ/Z radiation



- May receive contribution from resonant $B_c^+ \to B_{(s)}^{*0}\pi^+$ decays (later in the talk)

- **First search** for non resonant $B_c^+ \to \pi^+\mu^+\mu^-$ decays, using **Run 1+2 dataset (9 fb^{-1})**
- Performed in intervals of $q^2 = m^2(\mu^+\mu^-)$

Decay mode		Interval
$B_c^+ \to \pi^+\mu^+\mu^-$	(low)	$0.1 < q^2 < 1.1\,\text{GeV}^2$
	(central)	$1.1 < q^2 < 8.0\,\text{GeV}^2$
	(intermediate)	$11.0 < q^2 < 12.5\,\text{GeV}^2$
	(high)	$15.0 < q^2 < 35.0\,\text{GeV}^2$
$B_c^+ \to J/\psi\,\pi^+$		$\lvert m(\mu^+\mu^-) - m_{J/\psi}\rvert < 50\,\text{MeV}$
$B_c^+ \to \psi(2S)\,\pi^+$		$\lvert m(\mu^+\mu^-) - m_{\psi(2S)}\rvert < 50\,\text{MeV}$

- $B_c^+ \to J/\psi\pi^+$ used as a control and normalisation channel

$$R_{\pi^+\mu^+\mu^-/J/\psi\pi^+} \equiv \frac{\mathcal{B}(B_c^+ \to \pi^+\mu^+\mu^-)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}$$

- BDT to suppress combinatorial background (bkg)
- PID requirements to suppress misID bkg

$B_c^+ \to \pi^+\mu^+\mu^-$ New

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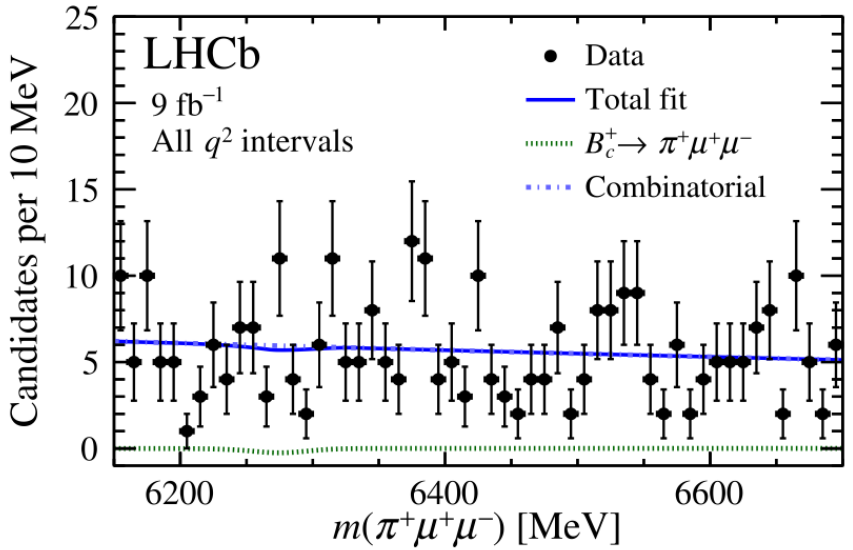
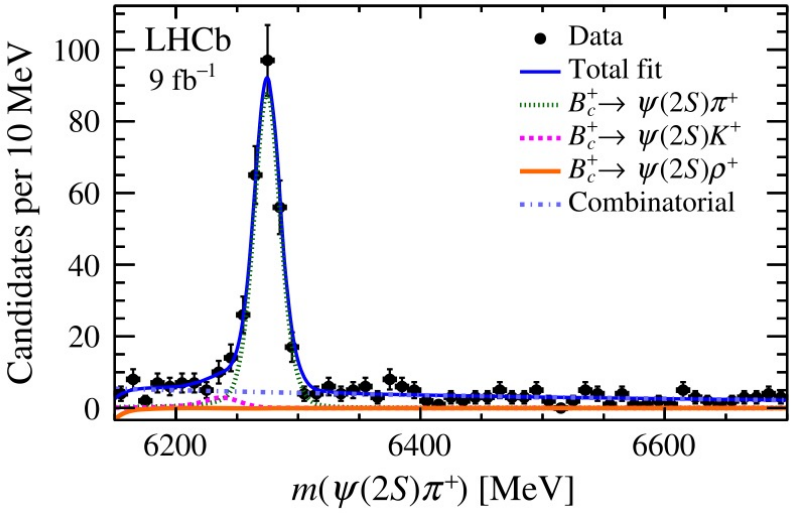
- ML fit to $m(\pi^+\mu^+\mu^-)$ in q^2 intervals
- No excess of signal events over bkg
- Upper limit evaluated using the Feldmann-Cousins method
  - $R_{\pi^+\mu^+\mu^-/J/\psi\pi^+} < 2.1 \times 10^{-4}$ at 90% CL

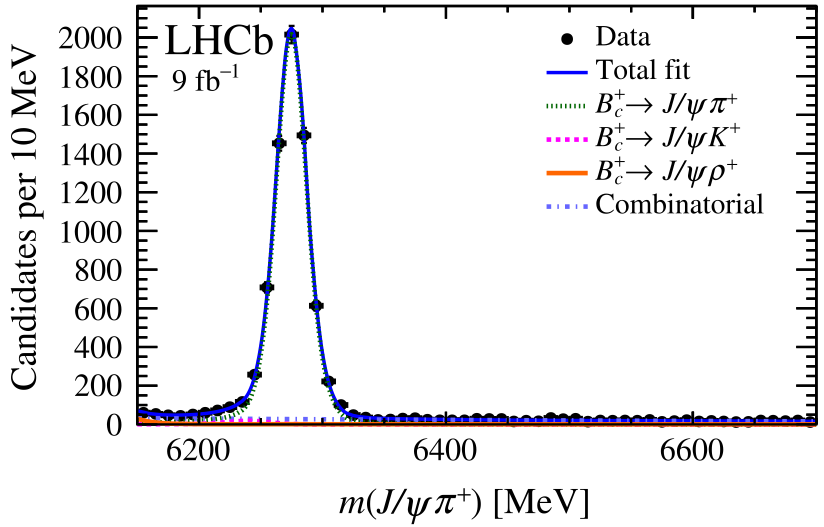


- Updated measurement of
  - $R_{\psi(2S)/J/\psi} \equiv \frac{\mathcal{B}(B_c^+ \to \psi(2S)\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} = 0.254 \pm 0.018\,(\text{stat}) \pm 0.003(\text{syst}) \pm 0.005(\text{BF})$

- **World's most precise measurement**
- Superseding previous LHCb results

[Phys. Rev. D92 (2015) 072007, Phys. Rev. D87 (2013) 071103(R)]





$B^{*0}_{(s)} \to \mu^+\mu^-$ in $B_c^+ \to \pi^+\mu^+\mu^-$ decays

New

LHCb-CONF-2024-003
LHCb-PAPER-2024-026

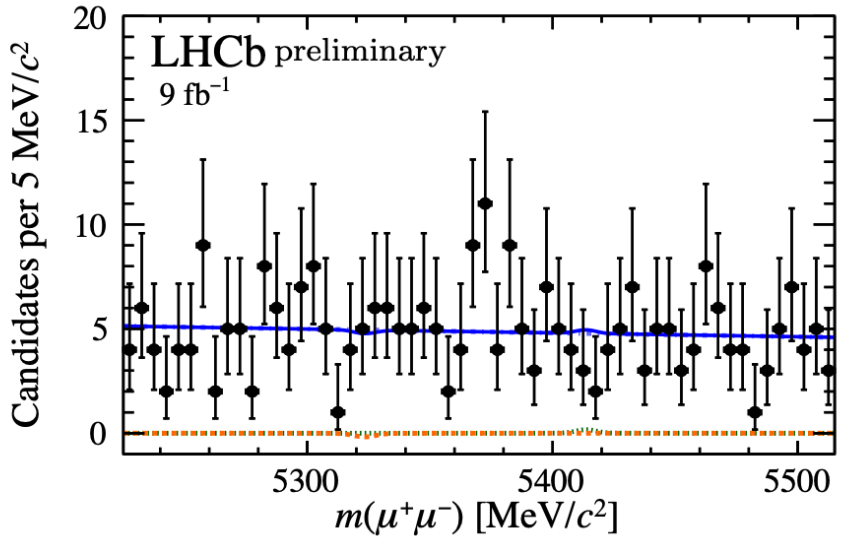
- Not affected by chirality suppression unlike $B^0_{(s)}$ decays
- Still suppressed by electromagnetic nature of the decay
- Accurate SM prediction $\mathcal{B} \sim 10^{-11}$ [PRL 116 (2016) 14, 141801]

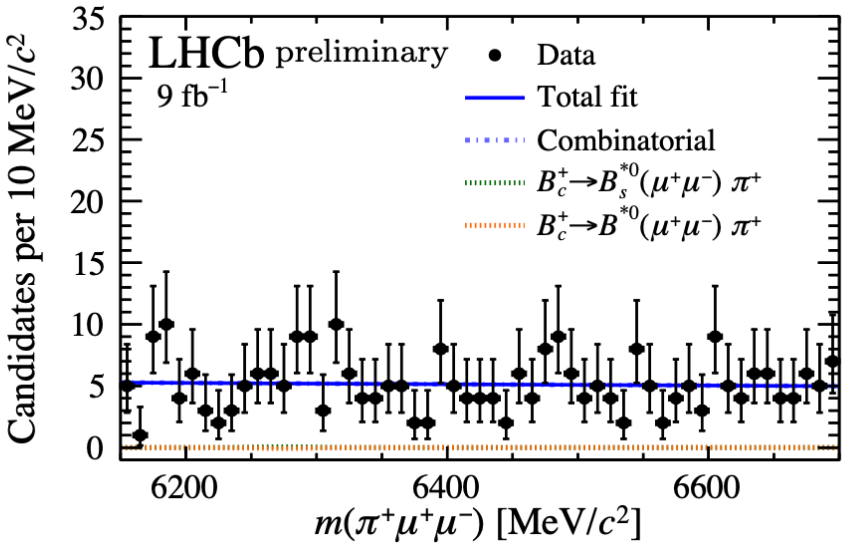
- **First search for $B^{*0} \to \mu^+\mu^-$ and $B_s^{*0} \to \mu^+\mu^-$ decays**
- Using **Run 1+2 data ($9\ \mathrm{fb}^{-1}$)**
- $B^{*0}_{(s)}$ from $B_c^+ \to B^{*0}_{(s)}(\mu^+\mu^-)\pi^+$ decays to limit bkg
  - Exploit displaced B_c^+ vertex (as for $D^{*0} \to \mu^+\mu^-$ [EPJ C83 (2023) 666])
- Similar analysis as for $B_c^+ \to \pi^+\mu^+\mu^-$
- Simultaneous ML fit to $m(\mu^+\mu^-)$ and $m(\pi^+\mu^+\mu^-)$

see Francesco's talk

$\mathcal{R}_{B^{*0}(\mu^+\mu^-)\pi^+/J/\psi\pi^+} < 3.8\ (5.2)\times10^{-5}$ at 90%(95%) CL

$\mathcal{R}_{B_s^{*0}(\mu^+\mu^-)\pi^+/J/\psi\pi^+} < 5.0\ (6.3)\times10^{-5}$ at 90%(95%)CL





$B \to D\,\mu^+\mu^-$

JHEP 02 (2024) 032

- Study of $b \to q l^+ l^-$ decays with and w/o $J/\psi \to l^+ l^-$ intermediate state
  - $B^0 \to \overline{D}^0 \mu^+\mu^-$ (a), $B^0 \to \overline{D}^0 J/\psi$ (d)
  - $B_s^0 \to \overline{D}^0 \mu^+\mu^-$ (a), $B_s^0 \to \overline{D}^0 J/\psi$ (d)

  } $\overline{D}^0 \to K^+\pi^-$

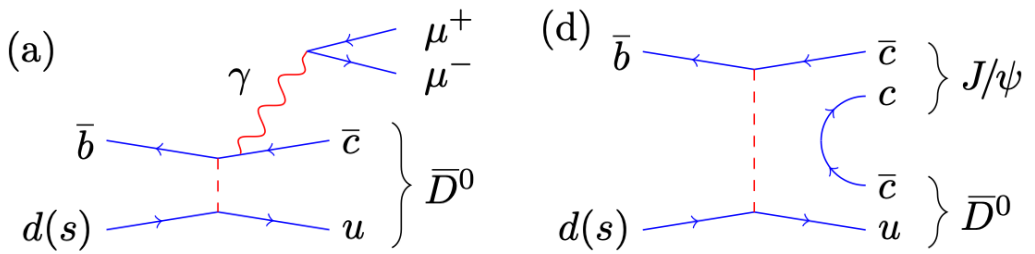
  - $B^+ \to D_s^+ \mu^+\mu^-$ (b), $B^+ \to D_s^+ J/\psi$ (e)
  - $B_c^+ \to D_s^+ \mu^+\mu^-$ (b,c), $B_c^+ \to D_s^+ J/\psi$ (e,f)

  } $D_s^+ \to K^+K^-\pi^+$

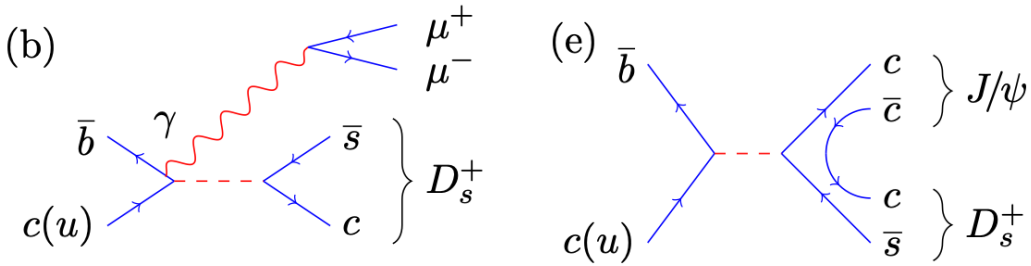
- Dominated by different modes of interaction

- Search on **Run 1+2 dataset ($9\ \mathbf{fb^{-1}}$)**
  - $q^2(\mu^+\mu^-) < 8\ \mathrm{GeV/c^2}$ to exclude J/ψ region
  - $B^0_{(s)}$ ($B^+_{(c)}$) modes normalised to $B^0 \to J/\psi K^{*0}$ ($B^+ \to J/\psi K^+$)
  - $B_c^+ \to D_s^+ \mu^+\mu^-$ normalised to $B_c^+ \to D_s^+ J/\psi$
  - PID selection + BDT against bkg

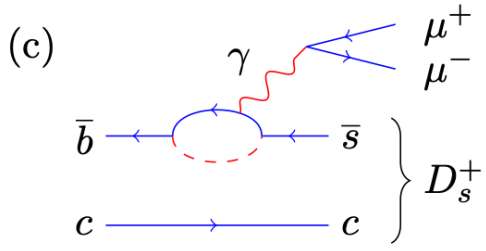
W^+ exchange



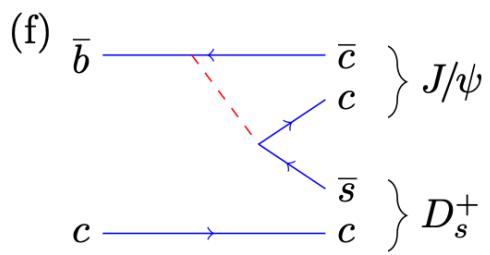
Annihilation



Penguins



Colour-suppressed



$B \to D\,\mu^+\mu^-$

JHEP 02 (2024) 032

- ML fit to inv. mass with modelling of residual misID + part. reco. bkg
- No excess of signal events observed in all modes, except for…
- **World's best upper limits** set at 95% CL

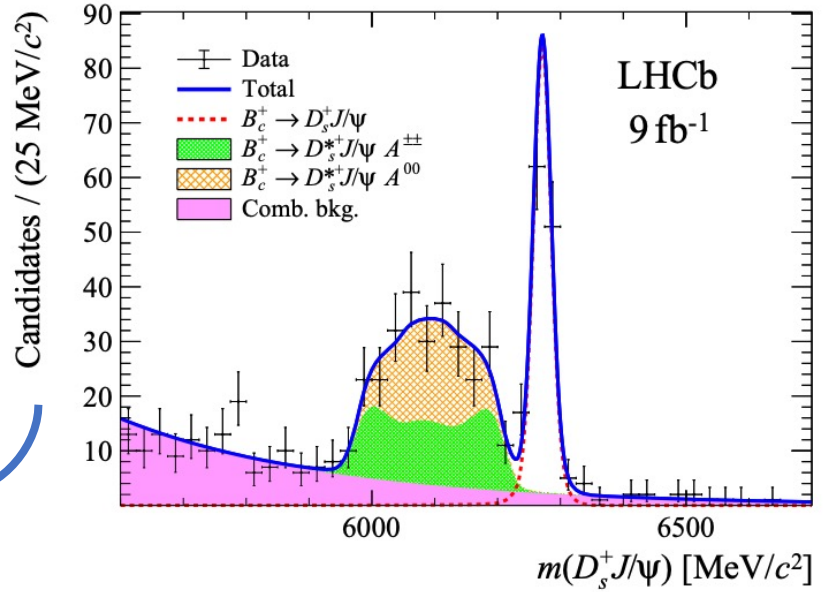
$\mathcal{B}(B^0 \to \bar{D}^0\mu^+\mu^-) < 5.1\times10^{-8}$ $\quad$ $\mathcal{B}(B^0 \to \bar{D}^0 J/\psi) < 1.1\times10^{-6}$

$\mathcal{B}(B^+ \to D_s^+\mu^+\mu^-) < 3.2\times10^{-8}$ $\quad$ $\mathcal{B}(B^+ \to D_s^+ J/\psi) < 3.5\times10^{-7}$

$\mathcal{B}(B_s^0 \to \bar{D}^0\mu^+\mu^-) < 1.6\times10^{-7}$ $\quad$ $\mathcal{B}(B_s^0 \to \bar{D}^0 J/\psi) < 1.5\times10^{-6}$

$f_c/f_u \cdot \mathcal{B}(B_c^+ \to D_s^+\mu^+\mu^-) < 9.6\times10^{-8}$

Clear peak in $B_c^+ \to D_s^+ J/\psi$



- **Most precise measurement** → $f_c/f_u \cdot \mathcal{B}(B_c^+ \to D_s^+ J/\psi) = (1.63 \pm 0.15\,(\text{stat}) \pm 0.13(\text{syst}))\times10^{-5}$
- $\mathcal{R}_{D_s^{*+}/D_s^+} = \frac{\mathcal{B}(B_c^+ \to D_s^{*+} J/\psi)}{\mathcal{B}(B_c^+ \to D_s^+ J/\psi)} = 1.91 \pm 0.20(\text{stat}) \pm 0.07(\text{syst})$
- $\Gamma_{\pm\pm}/\Gamma_{\text{tot}} = \frac{N_{A^{\pm\pm}}}{N_{A^{\pm\pm}} + N_{A^{00}}} = 0.50 \pm 0.11(\text{stat}) \pm 0.05(\text{syst})$

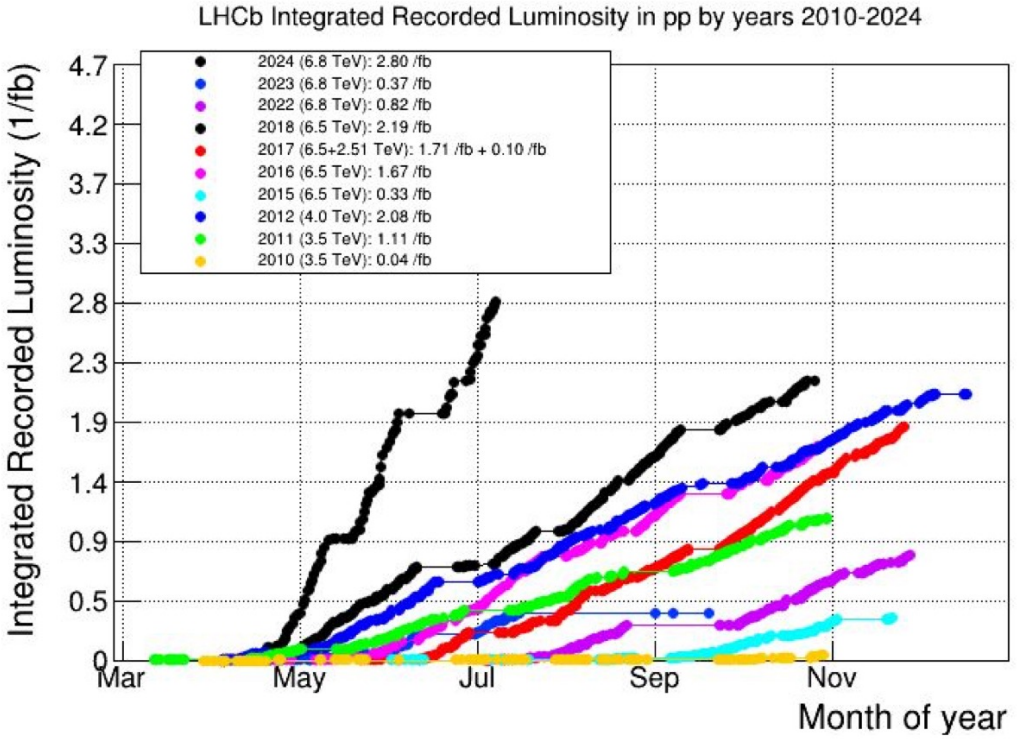
Superseding previous LHCb results [Phys. Rev. D 87, 112012]

Outlook and conclusions

- (Very) rare decays as fundamental tests of SM
- Can provide important constraints to NP models

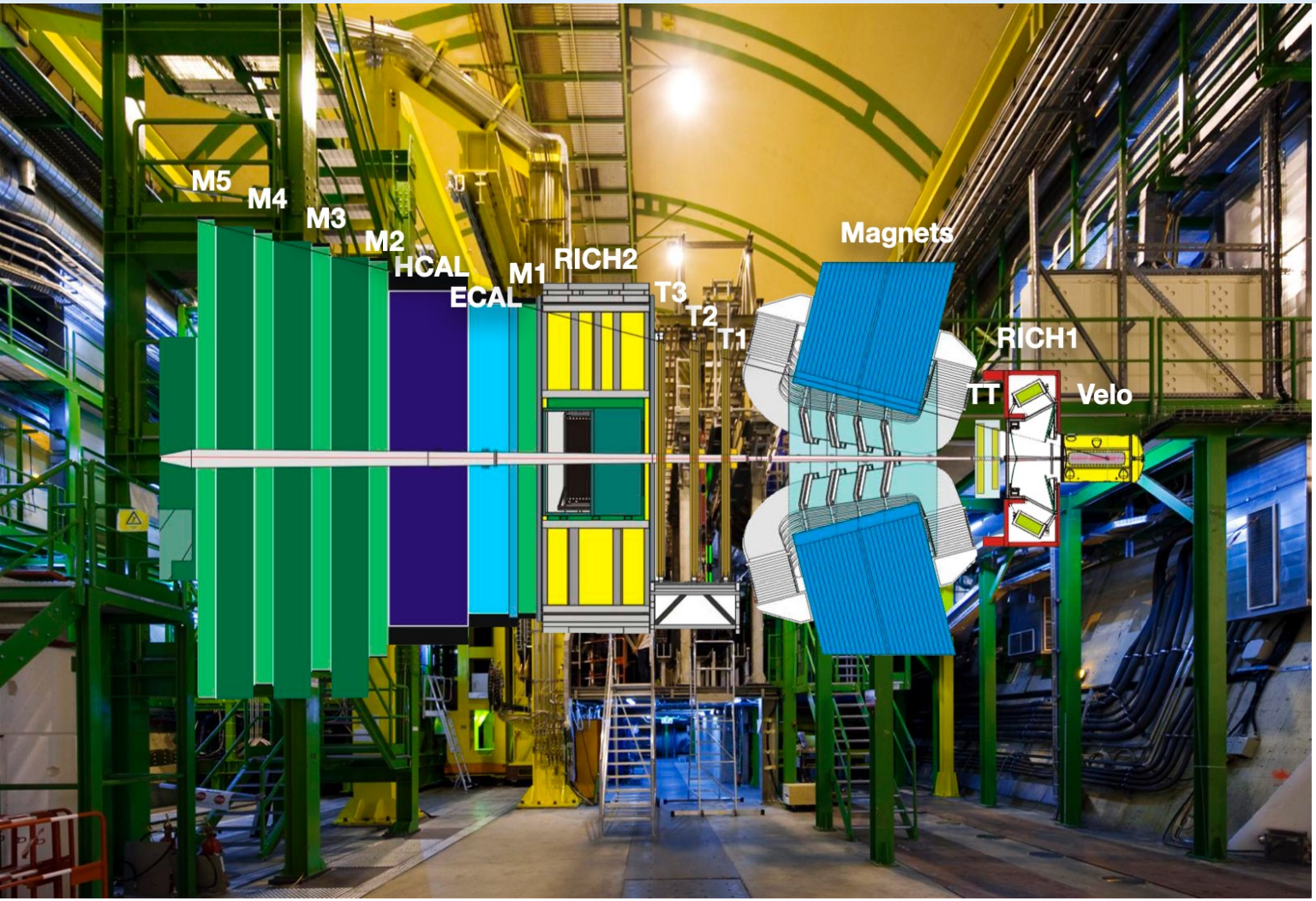
- LHCb pushing limits towards unprecedent levels
- Many other published or ongoing analyses
  - $\tau \to \mu\mu\mu$ (under internal review)
  - $\tau \to \phi\mu$ (first attempt at a hadron collider)

- Run 3 data taking happening now
  - Upgraded detector and trigger system will enhance signal acceptance
  - 5 times more luminosity expected at the end of Run 3 + 4



Backup

The LHCb detector in Run 1-2



- Single arm forward spectrometer ($2 < \eta < 5$) located at the LHC
- Excellent **particle identification** from RICH(1,2), ECAL and Muon Stations
  - $\epsilon(e \to e) \sim 90\%$ and $\epsilon(e \to h) \sim 5\%$
  - $\epsilon(K \to K) \sim 95 - 97\%$ and $\epsilon(\pi \to K) \sim 5\%$
  - $\epsilon(\mu \to \mu) \sim 97\%$ and $\epsilon(\pi \to \mu) \sim 1 - 3\%$
- Good **tracking system**
  - $\Delta p/p = 0.5\%$ at low momentum
  - Impact parameter resolution $(15 + 29\ /p_T)\mu m$

	Run 1 (2011,2012)		Run 2 (2015-2018)
$\sqrt{s}$	7 TeV	8 TeV	13 TeV
$\int \mathcal{L}\, dt$	1.0 fb^{-1}	2.0 fb^{-1}	~6 fb^{-1}

[2008 JINST 3 S08005, arXiv:1306.0249]

$B_c^+ \to \pi^+\mu^+\mu^-$

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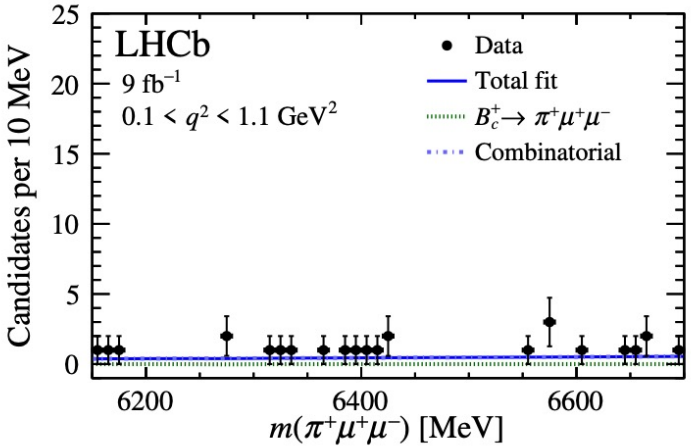
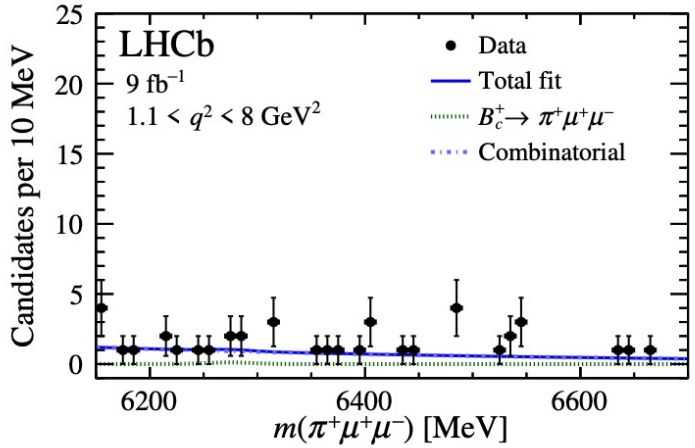
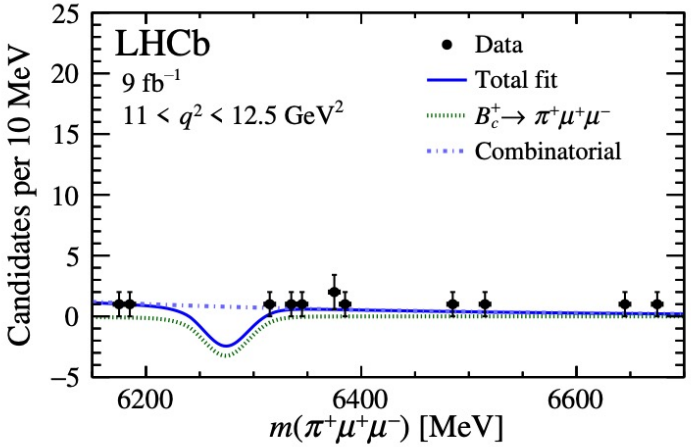
- Fit to invariant mass in the different q^2 intervals



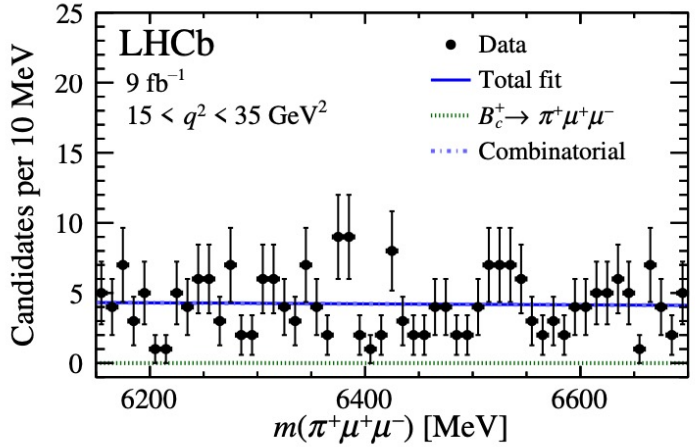
Low



Central

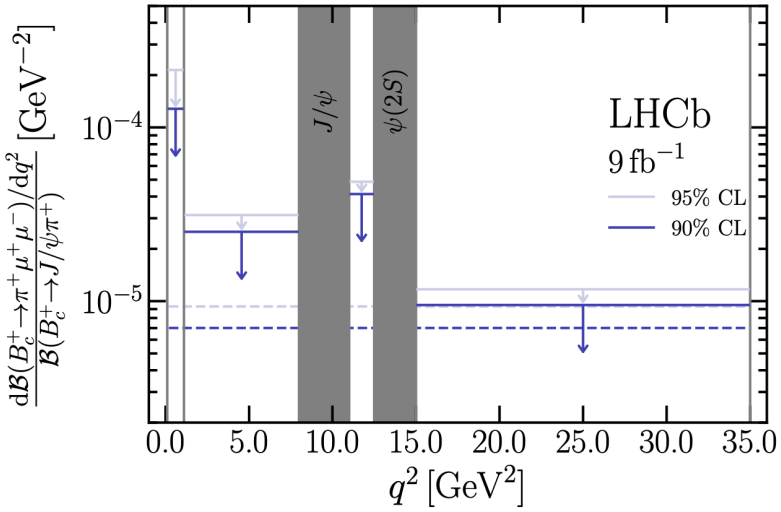


Intermediate



High

Upper limits on the normalised differential branching fraction



Final fit in $B \to D\,\mu^+\mu^-$ analysis

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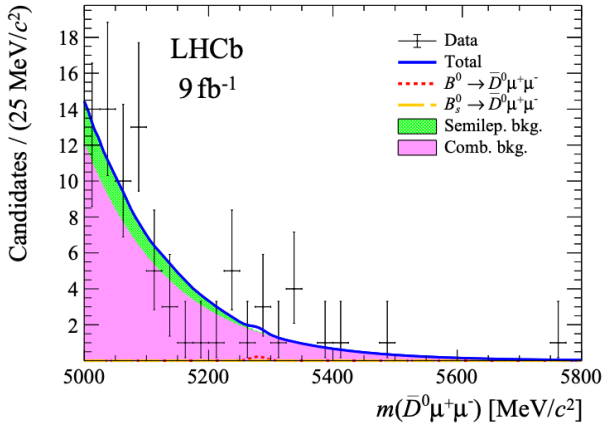
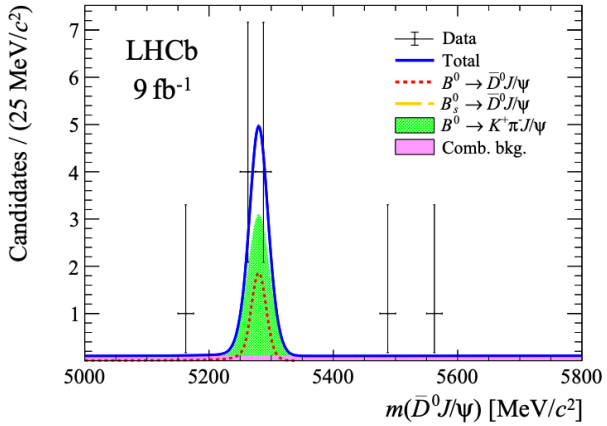
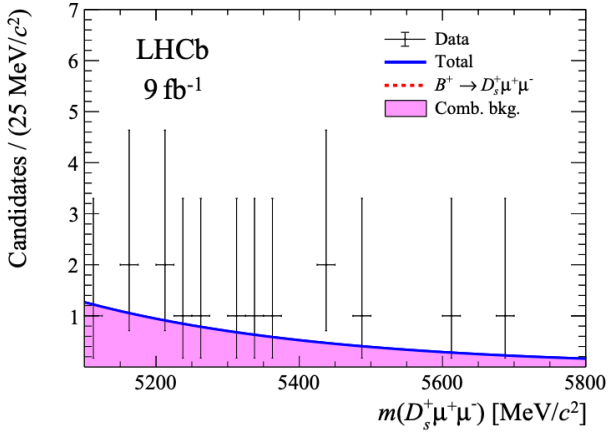
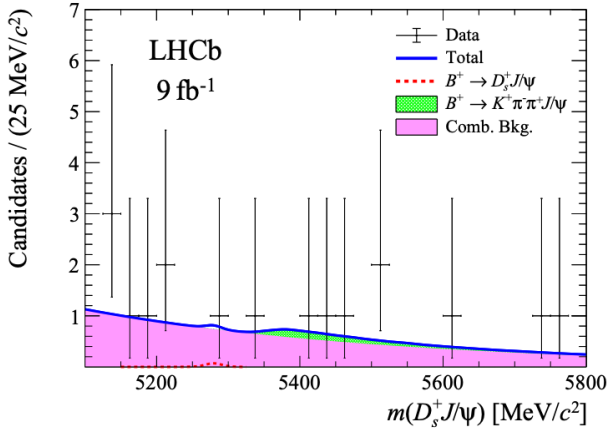
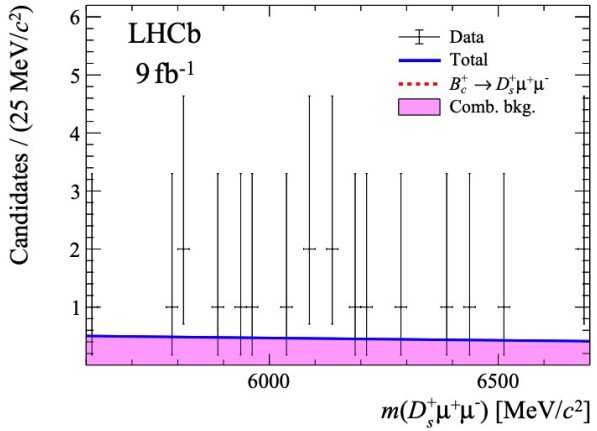
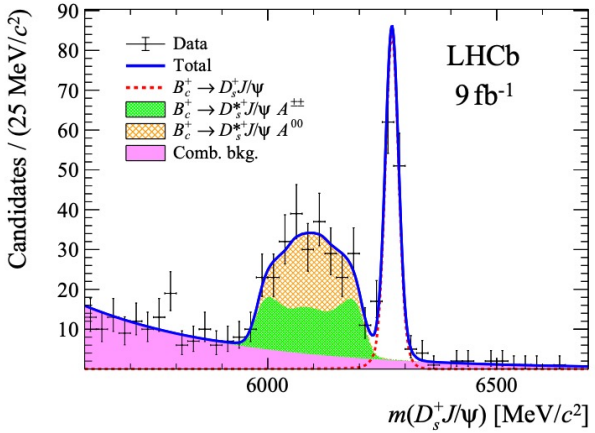








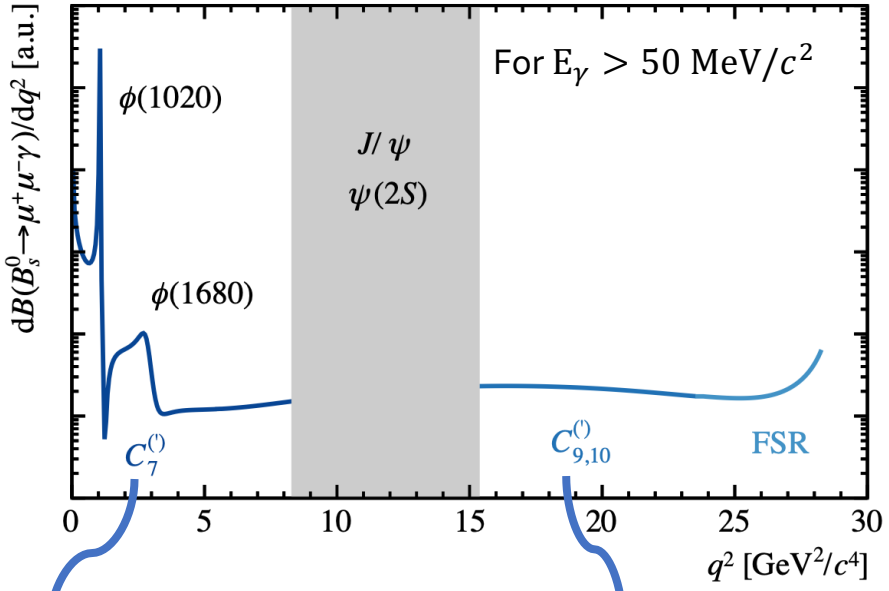




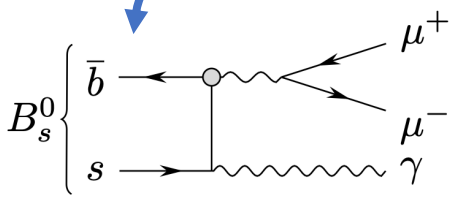
$B_s^0 \to \mu^+\mu^-\gamma$

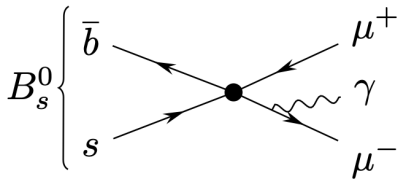
JHEP07(2024)101

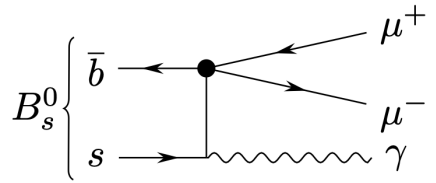
- Sensitive to a wider set of operators compared to $B_s^0 \to \mu^+\mu^-$, depending on $q^2(\mu^+\mu^-)$
- Final state γ lifting chirality suppression compensating for QED vertex
  - 👍 enhanced BF
  - 👎 local form factors describing $B_s^0 \to \gamma$ transition



- **First search with full final state reconstruction** and **first search at low q^2**
- Performed on **Run 2 data ($5.4\ \mathrm{fb}^{-1}$)** in q^2 ranges







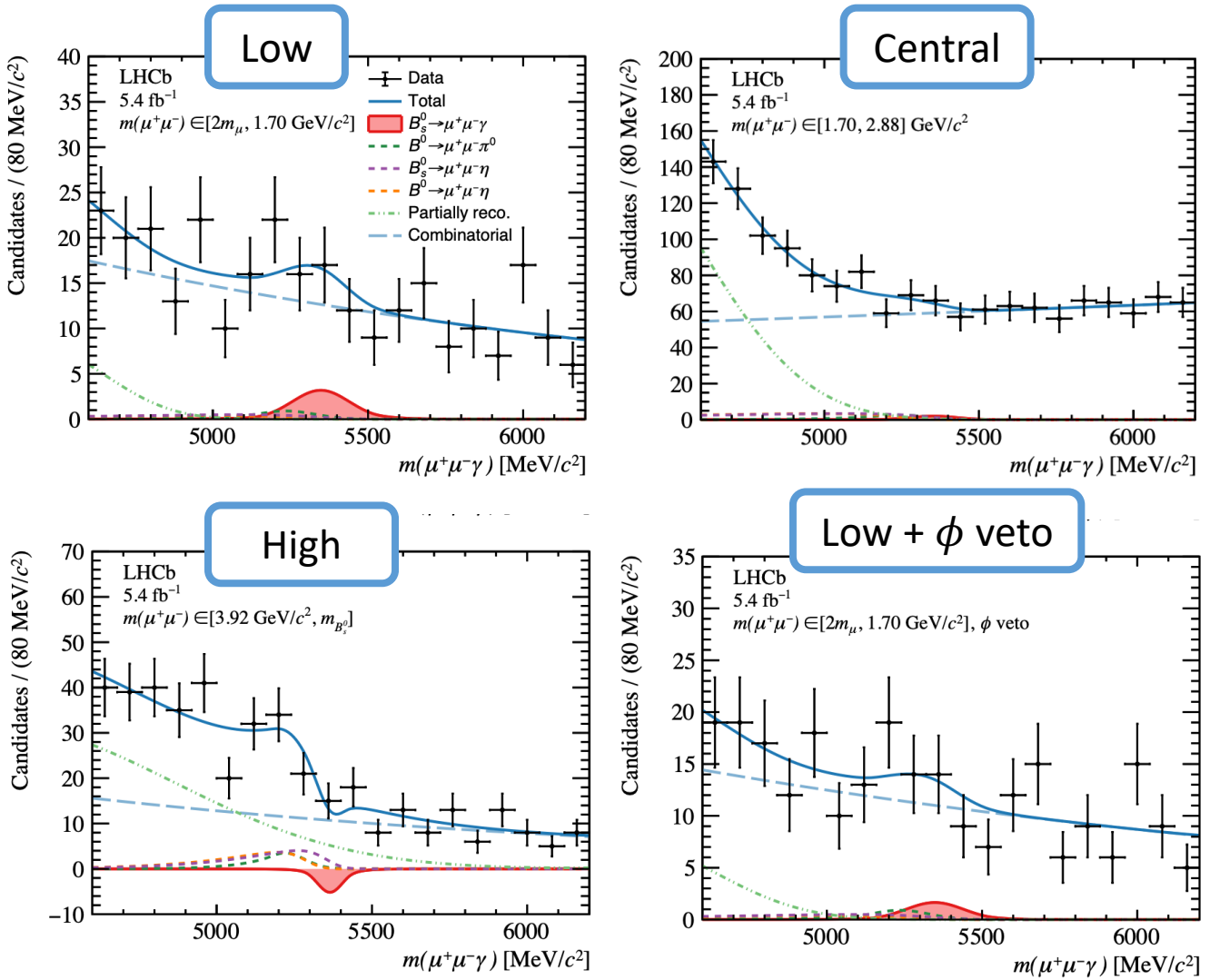
- $B_s^0 \to \phi\,(K^+K^-)\gamma$ used as a control channel in data/MC comparison
- $B_s^0 \to J/\psi(\mu^+\mu^-)\eta(\gamma\gamma)$ as a normalisation channel
- PID requirements on muons against misID bkg
- NN classifier to isolate photon clusters + "neutral" classifier against $\pi^0 \to \gamma\gamma$
- MLP classifier against combinatorial bkg

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

JHEP07(2024)101

- ML fit to $\mu^+\mu^-\gamma$ inv. mass.
  - Modelling of comb. + part.reco + peaking bkg
- No excess of signal events found
- Upper limits set at 95% using CLs method

$\mathcal{B}$ at 95%	$m(\mu^+\mu^-)$ range [GeV/c^2]
4.2×10^{-8}	$[2m_\mu, 1.70]$
7.7×10^{-8}	$[1.70, 2.88]$
4.2×10^{-8}	$[3.92, m_{B_s^0}]$
3.4×10^{-8}(*)	$[2m_\mu, 1.70]$ GeV/c^2 + ϕ veto
2.8×10^{-8}	whole



(*) complementary study with exclusion of $m(\mu^+\mu^-) \in [989.6, 1073.4]$MeV/$c^2$ as in [JHEP12(2021)078]

The LHCb detector in Run 3-4

2024 JINST 19 P05065