Rare and forbidden decays at LHCb

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on behalf of the LHCb collaboration

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Rare and forbidden decays

Decays of c and b hadrons occurring via penguin or box diagrams in the Standard Model

- FCNC processes, suppressed by small size of off-diagonal CKM elements and GIM mechanism
- Sensitive to non-Standard Model contributions
- Offer multiple tests of the SM (challenge is $\mathcal{B} \lesssim 10^{-6}$)
- Can also search for processes forbidden in SM

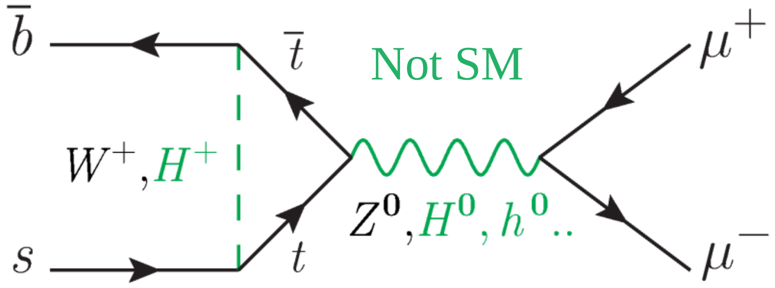
This talk

Recent results exploiting run I + II data set (9 fb^{-1}) on searches for

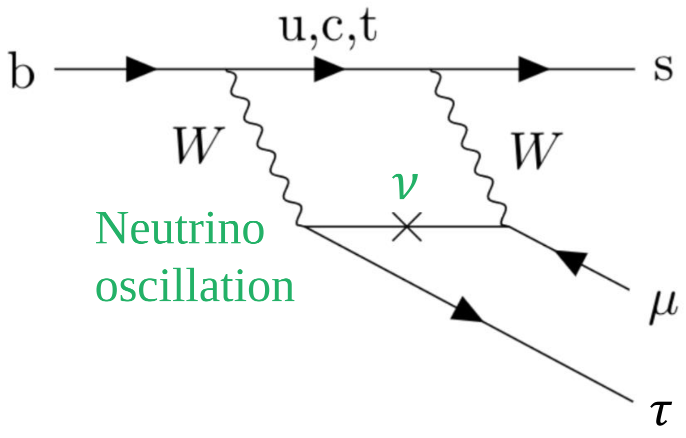
- Nonresonant $B_c^+ \to \pi^+\mu^+\mu^-$ decays EPJ.C84(2024)468
- $B_{(s)}^{*0} \to \mu^+\mu^-$ decays (new!) LHCb-CONF-2024-003
- $B_s^0 \to \phi\, \mu^\pm\tau^\mp$ decays (new!) LHCb-PAPER-2024-006

Examples from this talk

$\boldsymbol{B_s^{(*)0} \to \mu^+\mu^-}$ $\mathcal{B} \approx 10^{-9}(10^{-11})$



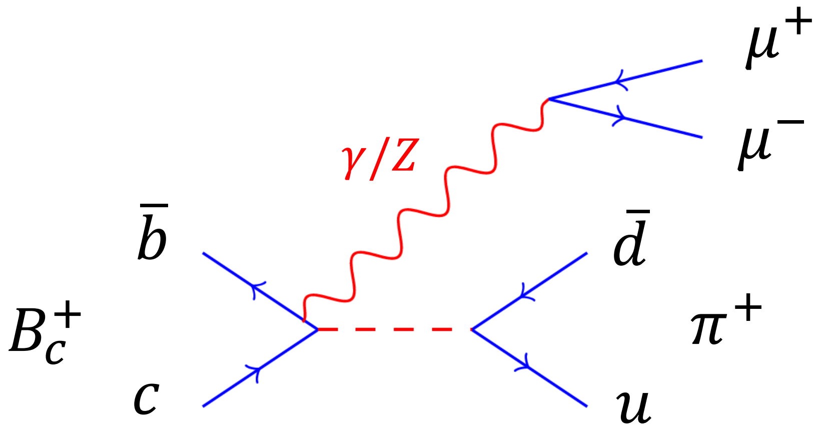
$\boldsymbol{b \to s\,\mu\,\tau}$ $\mathcal{B} \lesssim 10^{-50}$



Search for $B_c^+ \to \pi^+\mu^+\mu^-$ decays

EPJ.C84(2024)468

- Nonresonant decays occur via annihilation plus virtual γ/Z radiation
- Currently no theoretical predictions
- Studies of annihilation contributions only for $B^\pm$ EPJ.C41.173(2005) JPCS.1690.012162
- First study of pure annihilation process for B_c^+ meson decays



Analysis Strategy

- Reconstruct $B_c^+ \to \pi^+\mu^+\mu^-$ decays
- Use a BDT and PID info against combinatorial background
- BDT trained to be performant irrespective of $m(\mu^+\mu^-)$
- Sort candidates into $q^2 = m(\mu^+\mu^-)^2$ intervals excluding J/ψ and $\psi(2S)$ regions
- Perform maximum-likelihood fit to $m(B_c^+)$ in each q^2 interval

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

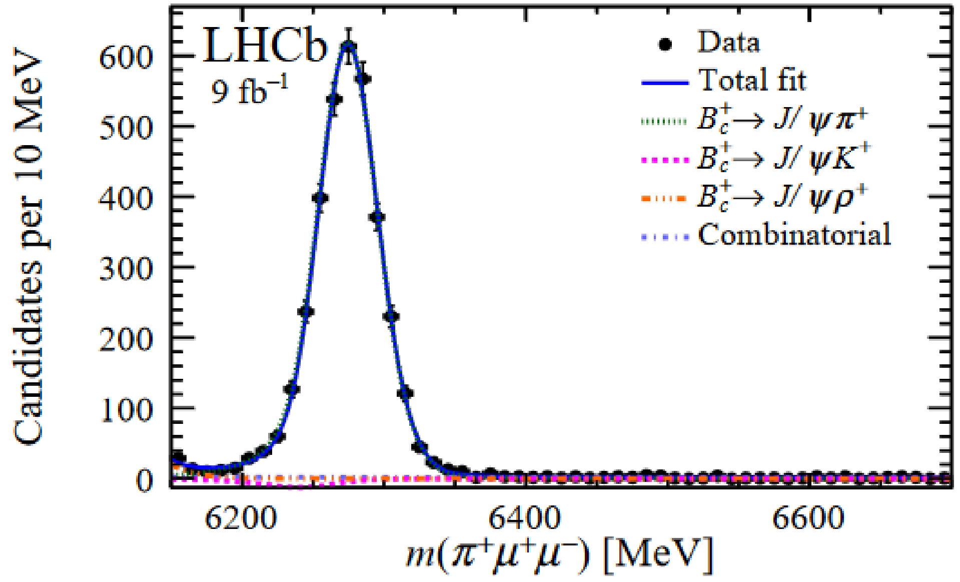
- Normalise to $B_c^+ \to J/\psi(\mu^+\mu^-)\pi^+$ decays
- Efficiencies from simulation with data/MC corrections

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

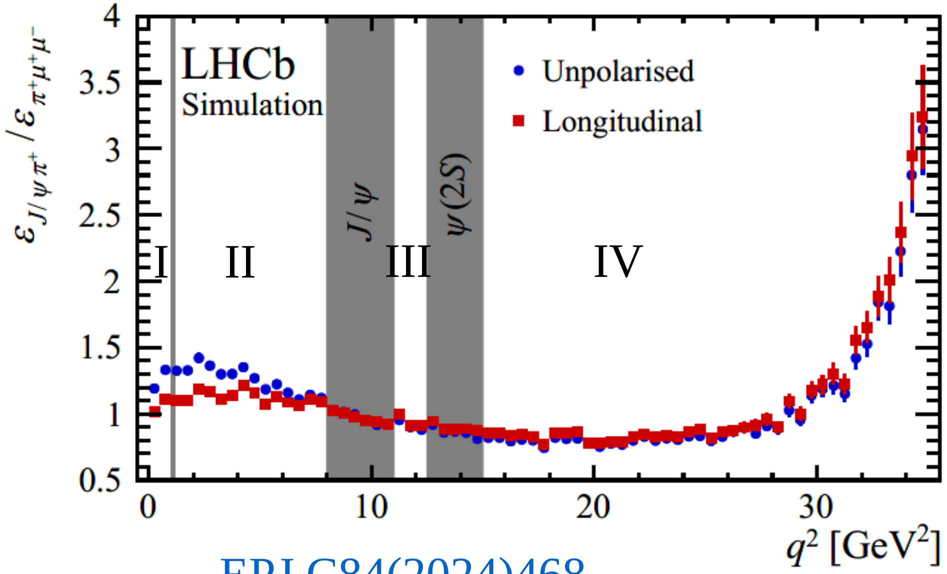
$$= \frac{N_{\pi^+\mu^+\mu^-}}{N_{J/\psi\pi^+}} \cdot \frac{\varepsilon_{J/\psi\pi^+}}{\varepsilon_{\pi^+\mu^+\mu^-}} \cdot \mathcal{B}(J/\psi \to \mu^+\mu^-)$$ Known

- Nonresonant $B_c^+ \to \pi^+\mu^+\mu^-$ simulated assuming a phase-space distribution
- Obtain model-independent results by assigning systematic uncertainty due to efficiency spread (largest syst. uncty.)
- Consider two extreme cases:
  - Dimuon system forms scalar state (unpolarised)
  - Dimuon system forms vector state (longitudinal pol.)
  - $\Rightarrow$ Difference considered as systematic uncertainty

Normalisation mode fit



Efficiency ratio as function of q^2



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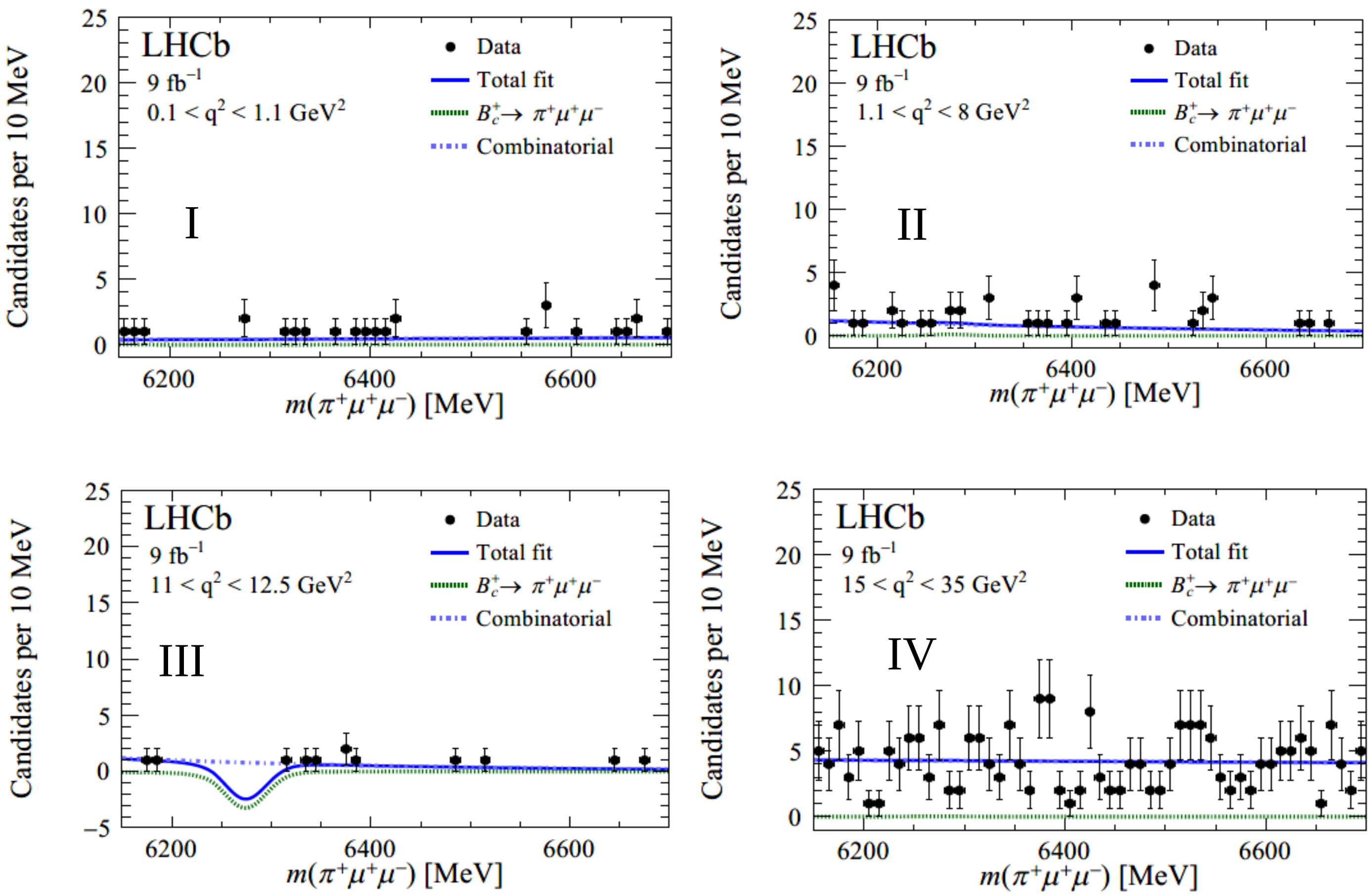
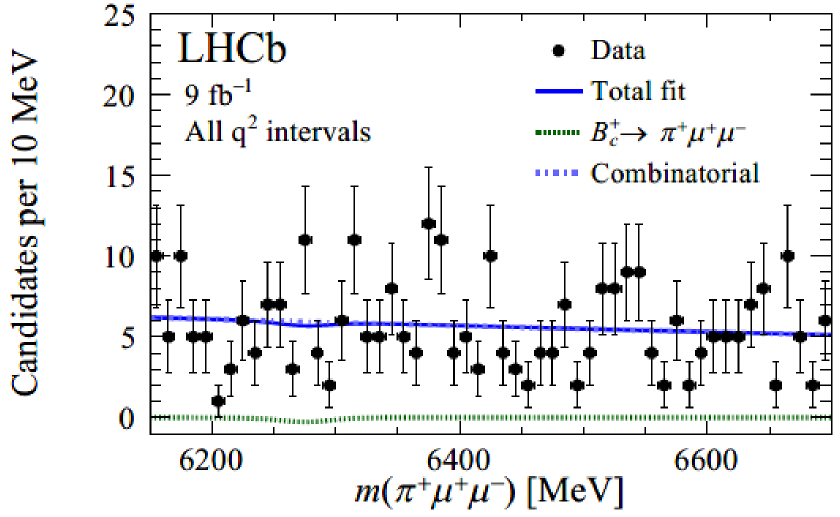
Search for $B_c^+ \to \pi^+\mu^+\mu^-$

- Fit includes signal and combinatorial background

Separate q^2 bins



All q^2 bins combined



	q^2 interval	$N_{\pi^+\mu^+\mu^-}$
I	$0.1 < q^2 < 1.1\,\text{GeV}^2$	0 ± 2
II	$1.1 < q^2 < 8.0\,\text{GeV}^2$	$1\,^{+4}_{-3}$
III	$11.0 < q^2 < 12.5\,\text{GeV}^2$	$-18\,^{+7}_{-10}$
IV	$15.0 < q^2 < 35.0\,\text{GeV}^2$	$0\,^{+8}_{-7}$
	All	$-2\,^{+9}_{-8}$

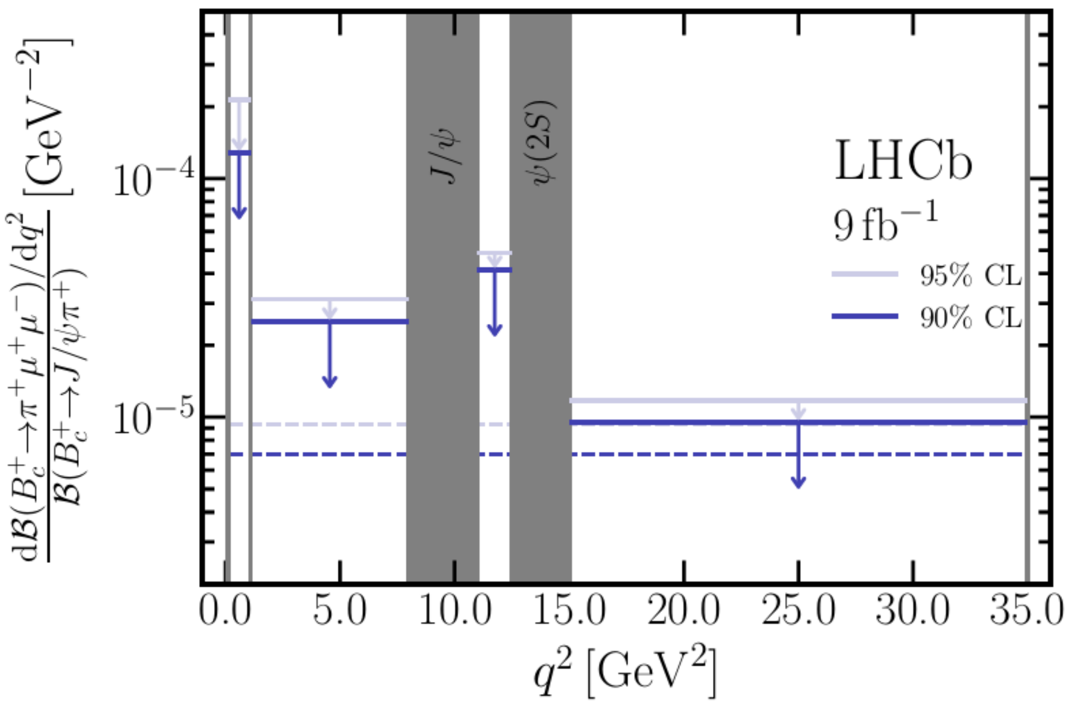
$\Rightarrow$ No signal observed in any of the q^2 bins

EPJ.C84(2024)468

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

- Systematic uncertainties included as Gaussian constraints in the fits
- Limit on branching fraction obtained for each q^2 interval and for all intervals combined following Feldman-Cousins prescription
- First limit on the nonresonant decay mode!

Limit on differential branching fraction



q^2 interval	$R_{\pi^+\mu^+\mu^-/J/\psi\pi^+}$	UL at 90% CL	UL at 95% CL
$0.1 < q^2 < 1.1\,\mathrm{GeV}^2$	$(-0.2\,^{+\,4.8\,+0.8}_{-\,3.5\,-0.7}) \times 10^{-5}$	1.3×10^{-4}	2.1×10^{-4}
$1.1 < q^2 < 8.0\,\mathrm{GeV}^2$	$(1.5\,^{+\,7.9\,+2.3}_{-\,6.4\,-1.4}) \times 10^{-5}$	1.7×10^{-4}	2.2×10^{-4}
$11.0 < q^2 < 12.5\,\mathrm{GeV}^2$	$(-28.4\,^{+10.5\,+1.4}_{-16.1\,-1.7}) \times 10^{-5}$	0.6×10^{-4}	0.7×10^{-4}
$15.0 < q^2 < 35.0\,\mathrm{GeV}^2$	$(0.2\,^{+11.5\,+3.4}_{-10.5\,-2.3}) \times 10^{-5}$	1.9×10^{-4}	2.3×10^{-4}
All	$(-3.0\,^{+15.0\,+2.4}_{-13.8\,-4.8}) \times 10^{-5}$	2.1×10^{-4}	2.7×10^{-4}

Limit for all q^2 intervals combined

EPJ.C84(2024)468

Update of $\mathcal{R}_{\psi(2S)/J/\psi}$ ratio

- Ratio of branching fractions between resonant modes used as cross check in $B_c^+ \to \pi^+\mu^+\mu^-$ search
- Performed dedicated optimisation to update previous measurement PRD.87.071103
- For optimised selection

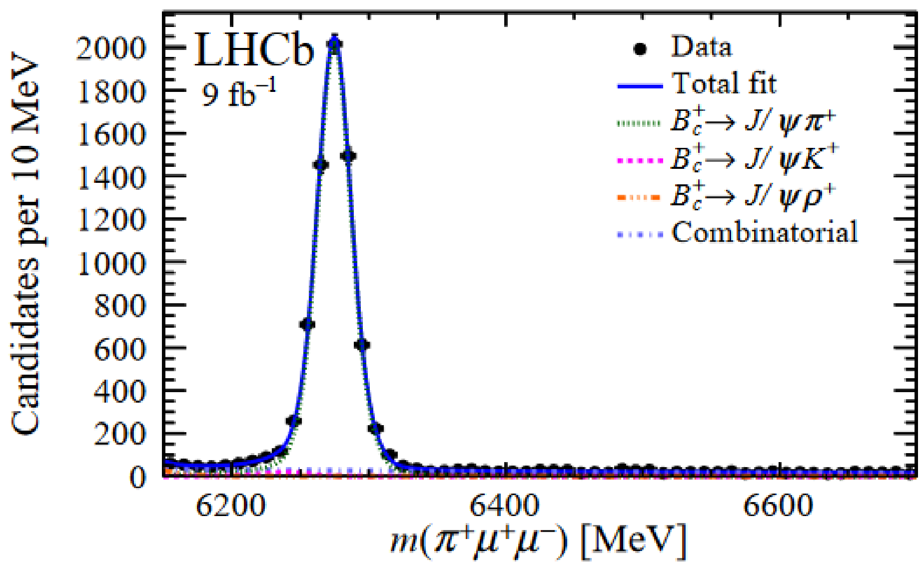
$$\frac{\mathcal{B}(B_c^+ \to \psi(2S)\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} = 0.254 \pm 0.018\,(\text{stat}) \pm 0.003\,(\text{syst}) \pm 0.005\,(\text{BF})$$

Uncertainty on $\mathcal{B}$ of leptonic decays

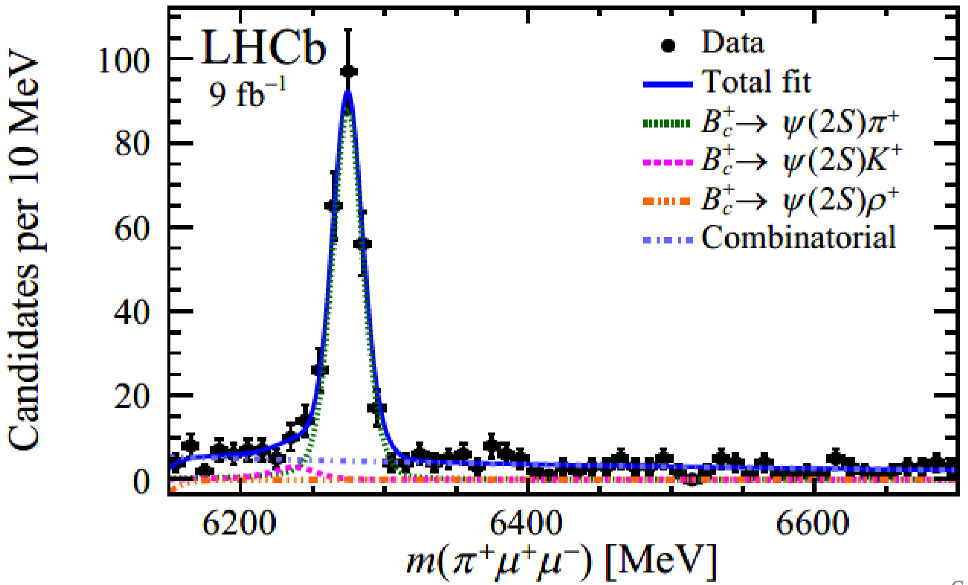
$\Rightarrow$ World's best measurement

EPJ.C84(2024)468

Normalisation mode fit



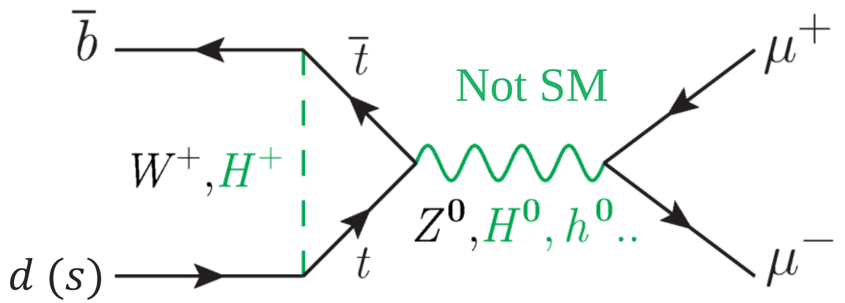
$B_c^+ \to \psi(2S)\pi^+$ fit

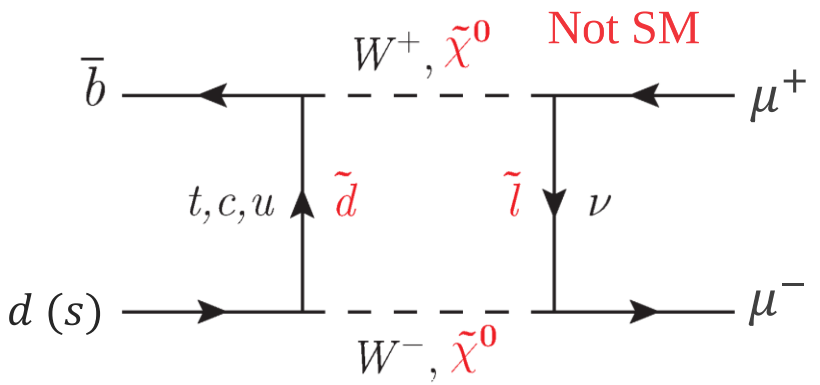


Search for $B_{(s)}^{*0} \to \mu^+\mu^-$ decays

New!
LHCb-CONF-2024-003

- $B_{(s)}^{*0} \to \mu^+\mu^-$ decays can provide constraints on Wilson coeffs. complementary to $B_{(s)}^{0} \to \mu^+\mu^-$ decays $\Rightarrow$ not helicity suppressed
- Expect $\mathcal{B}(B_s^{*0} \to \mu^+\mu^-) \lesssim 10^{-11}$ within SM PRL.116.141801
- High production rates of $B_{(s)}^{*0}$, but high background level for decays at collision point





- Most promising approach EPJ.C82(2022)459

$\Rightarrow$ Search within $B_c^+ \to B_{(s)}^{*0}\pi^+ \to \mu^+\mu^-\pi^+$ decay chain

$\Rightarrow$ Exploit displaced vertex signature to suppress background

$\Rightarrow$ Demonstrated in recent search for $D^{*0} \to \mu^+\mu^-$ decays EPJ.C83(2023)666

- No nonresonant $B_c^+ \to \pi^+\mu^+\mu^-$ background as previously shown

Search for $B^{*0}_{(s)} \to \mu^+\mu^-$ decays

Analysis Strategy

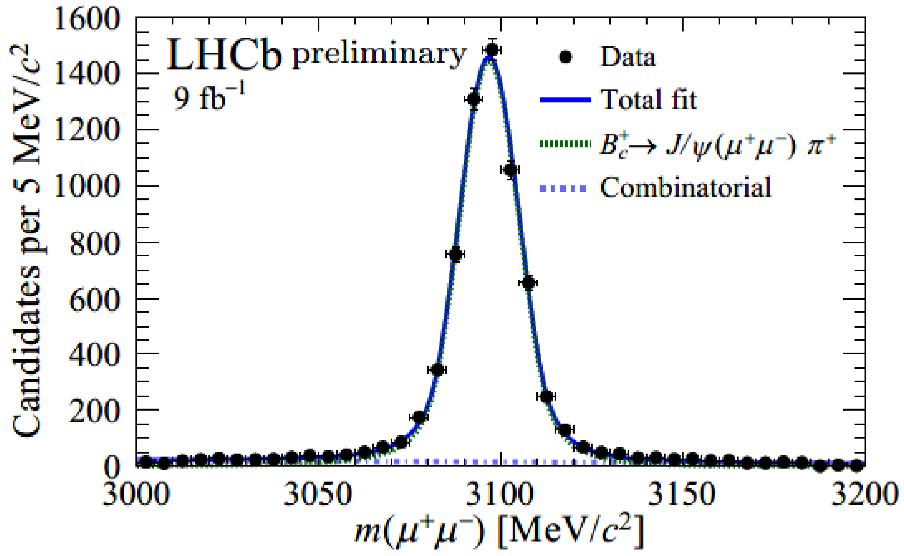
- Reconstruct $B_c^+ \to \pi^+\mu^+\mu^-$ decays
- Use BDT, angular info and PID against combinatorial bkg.
- Same BDT as for nonresonant decays, but dedicated selection
- Perform 2D ML fit to $m(\mu^+\mu^-)$ and $m(\pi^+\mu^+\mu^-)$
- Normalise to $B_c^+ \to J/\psi(\mu^+\mu^-)\pi^+$ decays
- Efficiencies from sim. corrected for data/MC discrepancies

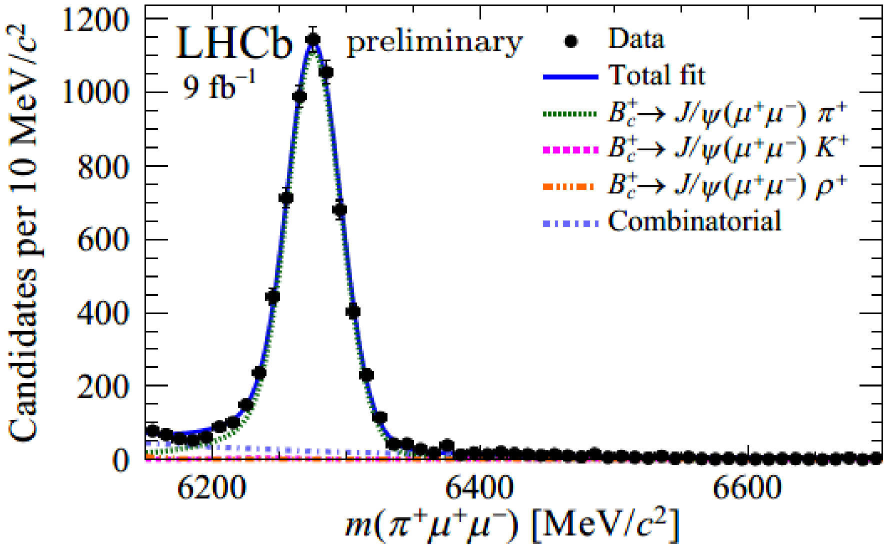
$$\mathcal{R}_{B^{*0}_{(s)}(\mu^+\mu^-)\pi^+/J/\psi\pi^+} \equiv \frac{\mathcal{B}(B_c^+ \to B^{*0}_{(s)}(\mu^+\mu^-)\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}$$

$$= \frac{N_{B^{*0}_{(s)}\pi^+}}{N_{J/\psi\pi^+}} \cdot \frac{\varepsilon_{J/\psi\pi^+}}{\varepsilon_{B^{*0}_{(s)}\pi^+}} \cdot \mathcal{B}(J/\psi \to \mu^+\mu^-)$$

Known $\mathcal{B}$

Normalisation mode fits



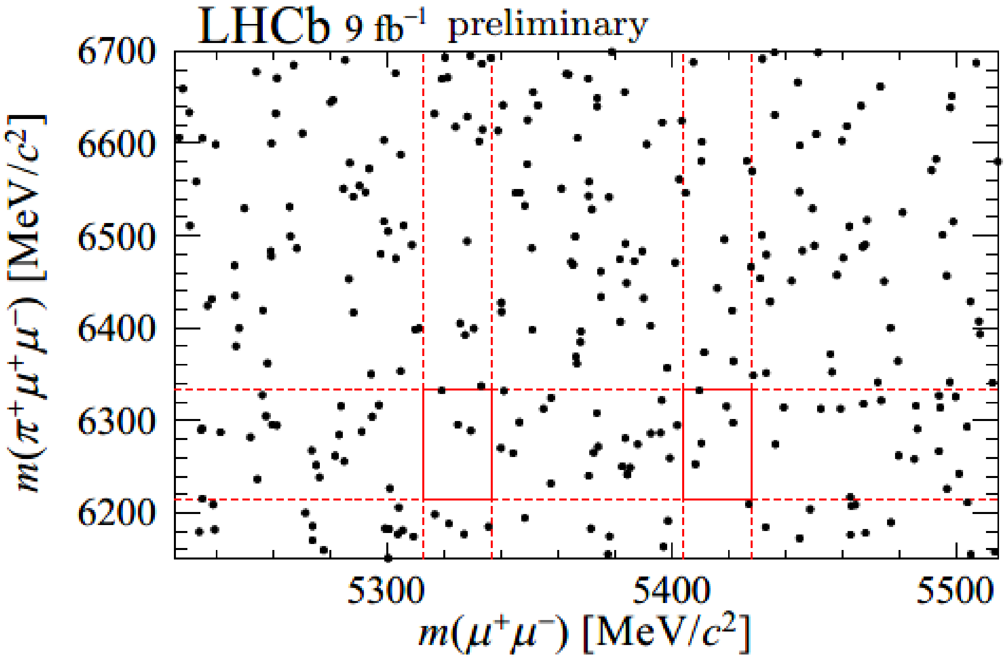


LHCb-CONF-2024-003

Search for $B_{(s)}^{*0} \to \mu^+\mu^-$ decays

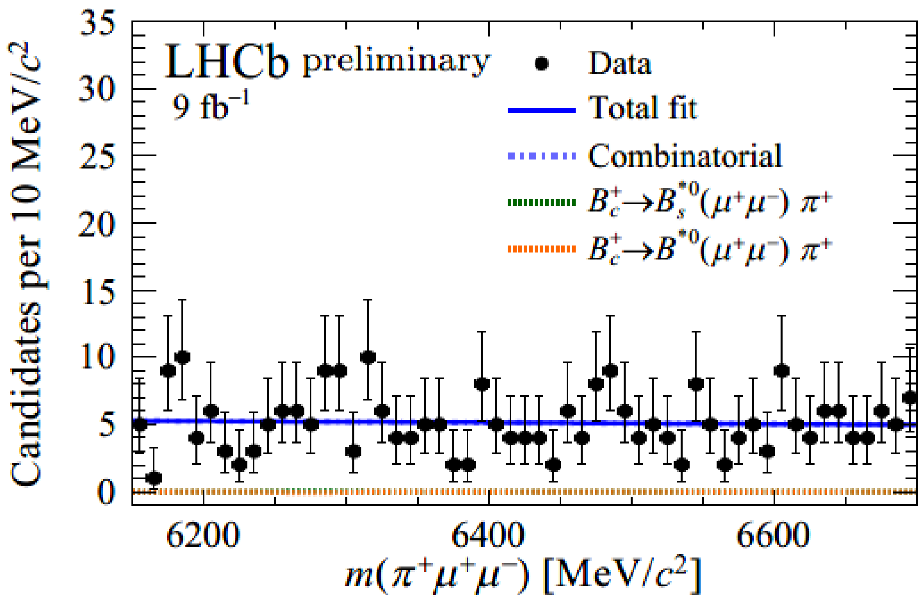
- Fit includes signal $B_c^+ \to B^{*0}(\mu^+\mu^-)\pi^+$ and $B_c^+ \to B_s^{*0}(\mu^+\mu^-)\pi^+$ decays, and combinatorial bkg.
- No statistical dependency between signal yields

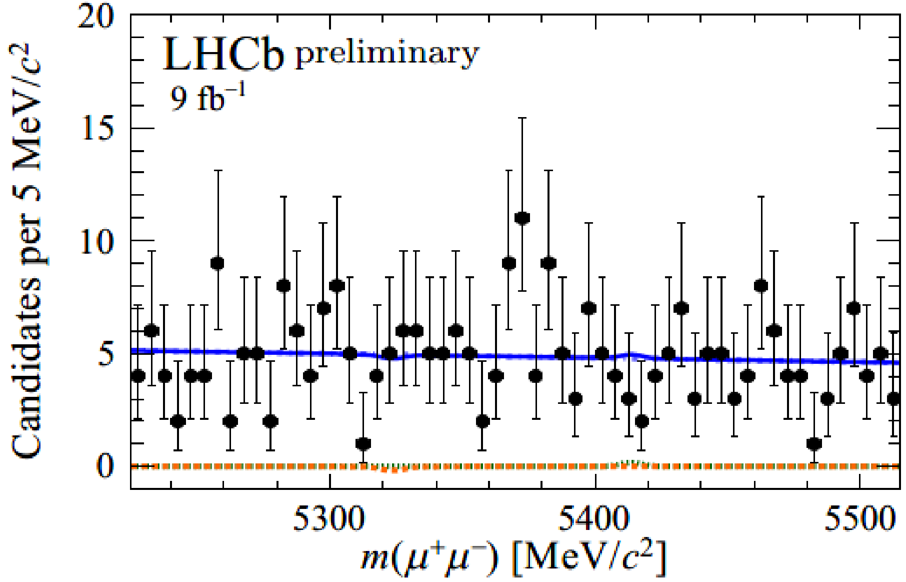
Component	Yield
$B_c^+ \to B^{*0}(\mu^+\mu^-)\pi^+$	$-0.4\,^{+1.9}_{-1.1}$
$B_c^+ \to B_s^{*0}(\mu^+\mu^-)\pi^+$	$0.4\,^{+2.2}_{-1.3}$



Number of events in 2D signal regions consistent with background-only expectation

Signal mode fit





$\Rightarrow$ No signal observed for both decay modes

LHCb-CONF-2024-003

Search for $B^{*0}_{(s)} \to \mu^+\mu^-$ decays

- Systematic uncertainties included as Gaussian constraints in signal mode fit
- Largest systematic due to data/MC discrepancies in muon impact parameters (but negligible impact)
- Results from fit to data

$$\mathcal{R}_{B^{*0}(\mu^+\mu^-)\pi^+/J/\psi\pi^+} = (-0.44^{+1.99}_{-1.12}) \times 10^{-5}$$
$$\mathcal{R}_{B_s^{*0}(\mu^+\mu^-)\pi^+/J/\psi\pi^+} = (0.43^{+2.45}_{-1.41}) \times 10^{-5}$$

$\Rightarrow$ Upper limit on branching fraction based on Feldman-Cousins method

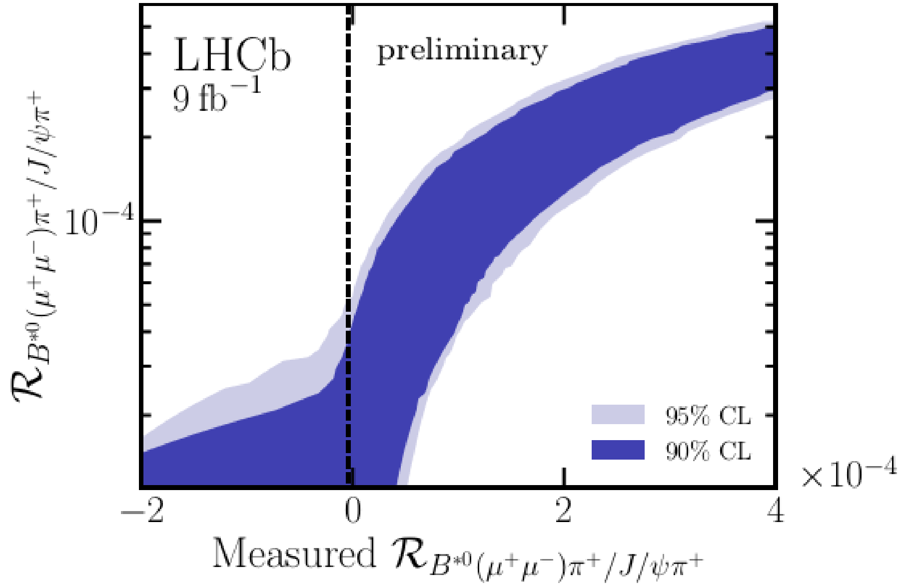
$$\mathcal{R}_{B^{*0}(\mu^+\mu^-)\pi^+/J/\psi\pi^+} < 3.8\,(5.2) \times 10^{-5} \text{ at } 90\ (95)\%\ \text{CL}$$
$$\mathcal{R}_{B_s^{*0}(\mu^+\mu^-)\pi^+/J/\psi\pi^+} < 5.0\,(6.3) \times 10^{-5} \text{ at } 90\ (95)\%\ \text{CL}$$

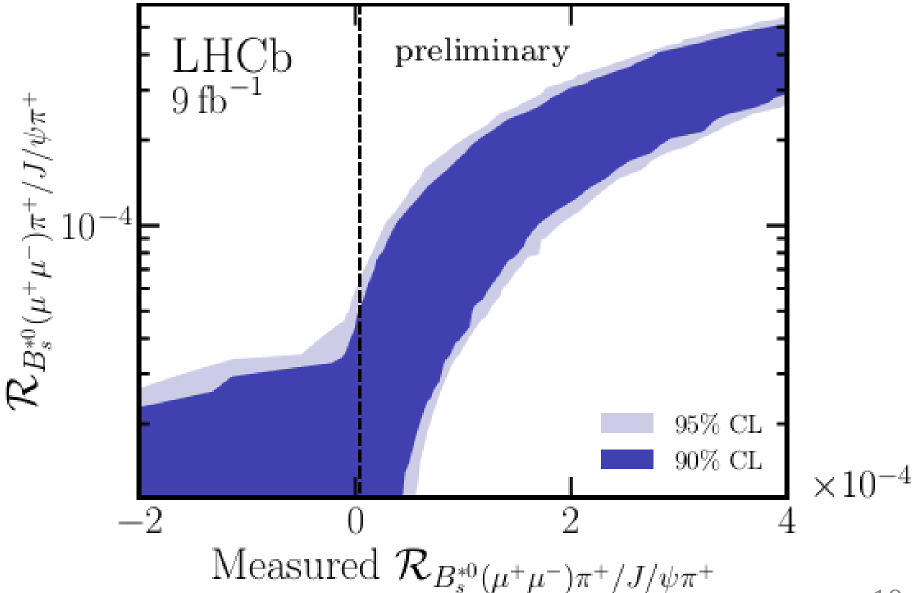
LHCb-CONF-2024-003

$\Rightarrow$ Assuming (no measurement yet)

$$\frac{\mathcal{B}(B_c^+ \to B_s^*\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} \approx \left|\frac{V_{cs}}{V_{cb}}\right|^2 \approx 0.6 \cdot 10^3 \Rightarrow \mathcal{B}(B_s^{*0} \to \mu^+\mu^-) \lesssim 10^{-7}$$

Confidence belts based on FC prescription

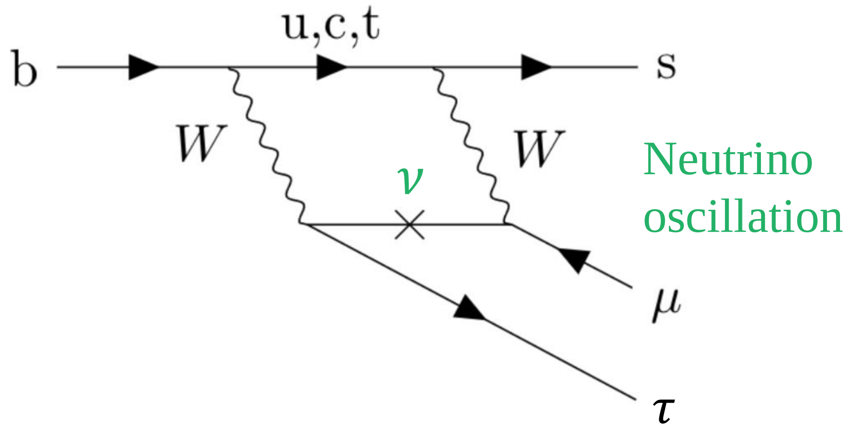




Search for $B_s^0 \to \phi\, \mu^{\pm}\tau^{\mp}$

New!
[LHCb-PAPER-2024-006]

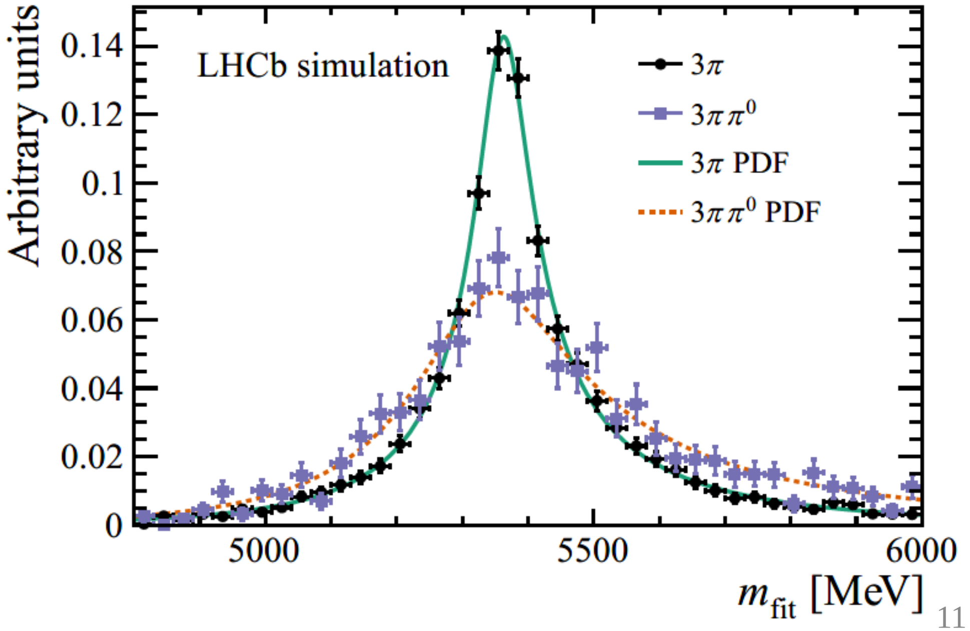
- Lepton flavour violating decay
- Possible in SM with neutrino oscillation ($\mathcal{B} \lesssim 10^{-50}$)
- First search for this decay



Analysis Strategy

- Reconstruct $B_s^0 \to \phi\ \mu^{\pm}\ \tau^{\mp}$, with $\phi \hookrightarrow K^+K^-$ and $\tau^{\mp} \hookrightarrow 3\pi^{\pm}(\pi^0)\nu_\tau$
- Reconstruct B_s^0 mass using kinematic fit constraining τ direction (using collision point, $\phi\mu^{\pm}$vertex and $3\pi^{\pm}$ vertex), τ mass and ν_τ mass
- Use a BDT against combinatorial background
- Use a second BDT against partially reconstr. b-hadron decays
- Use PID info and veto background from D decays

Reconstructed B_s^0 mass

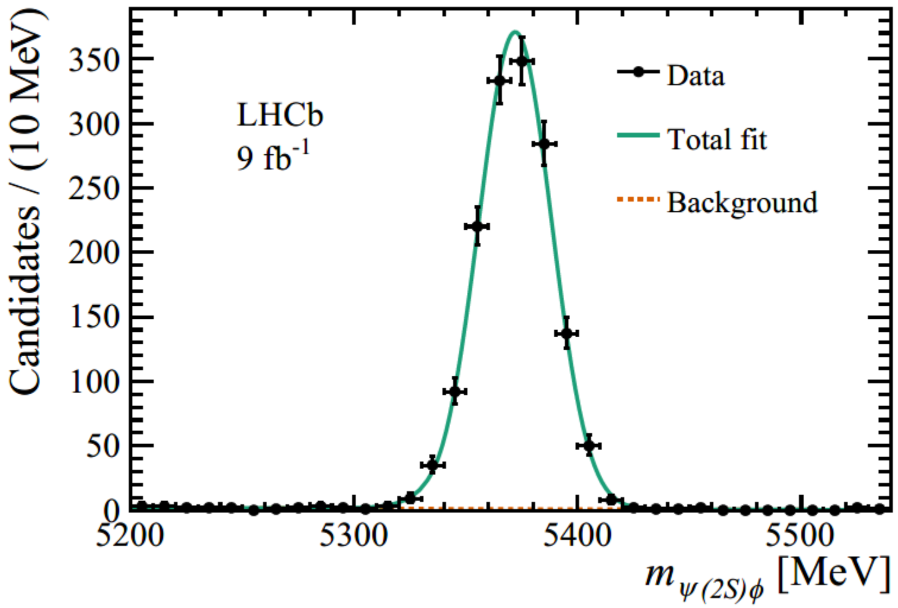


Search for $B_s^0 \to \phi\, \mu^\pm \tau^\mp$

- Normalisation mode is $B_s^0 \to \phi(K^+K^-)\, \psi(2S)(J/\psi\, \pi^+\pi^-)$
  $\hookrightarrow \mu^+\mu^-$

- Relative efficiencies from simulation with data/MC corrections
- Largest systematic uncertainty originates from known branching fractions

Normalisation mode fit



$$N_{\rm exp} = \frac{\mathcal{B}(\tau^- \to \pi^-\pi^+\pi^-\nu_\tau)}{\mathcal{B}(B_s^0 \to \psi(2S)\phi)\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)\mathcal{B}(J/\psi \to \mu^+\mu^-)}\, \varepsilon_{\rm rel.,3\pi}\, N_i(\psi(2S)\phi) \times \mathcal{B}(B_s^0 \to \phi\mu^+\tau^-)$$

LHCb-PAPER-2024-006

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

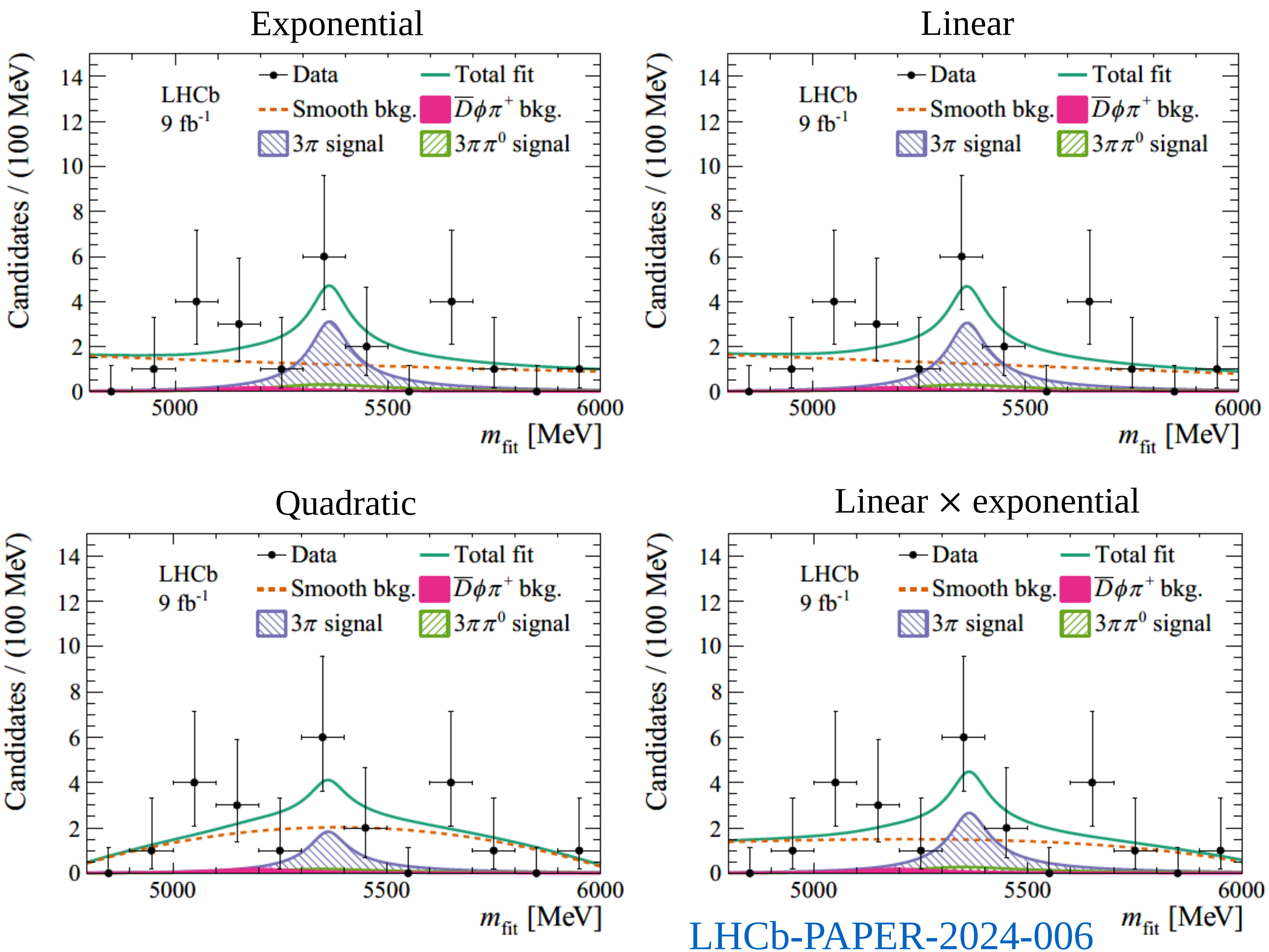
- Partially reconstructed b-hadron decays (dominant background) modelled by smooth distribution

$\Rightarrow$ Choice of model treated as discrete nuisance parameter

- Misidentified $B \to \bar{D}\phi\pi^{+}_{\to\mu^{+}}$ decays (peaking) modelled and constrained using info from simulation, control data and knowledge on inclusive $\bar{D} \to \pi^{-}\pi^{+}\pi^{-}X$ decays from BESIII

PRD107(2023)032002
PRD108(2023)032001

Signal mode fit



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$\Rightarrow$ No significant signal observed in any fit configuration

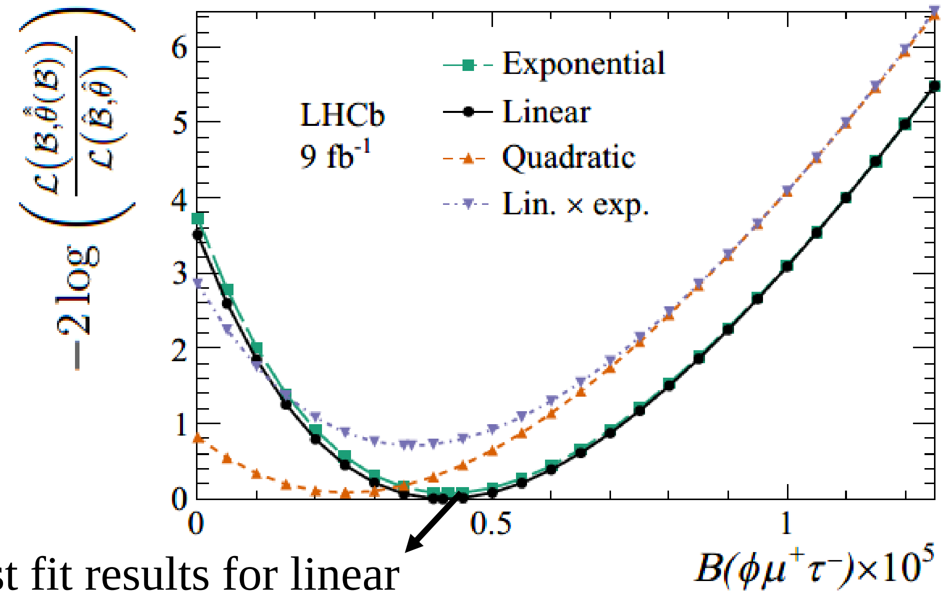
Search for $B_s^0 \to \phi\, \mu^{\pm}\tau^{\mp}$

- Systematic uncertainties included as Gaussian constraints in signal fit
- No excess observed over background-only hypothesis
- Upper limits based on Feldman-Cousins prescription

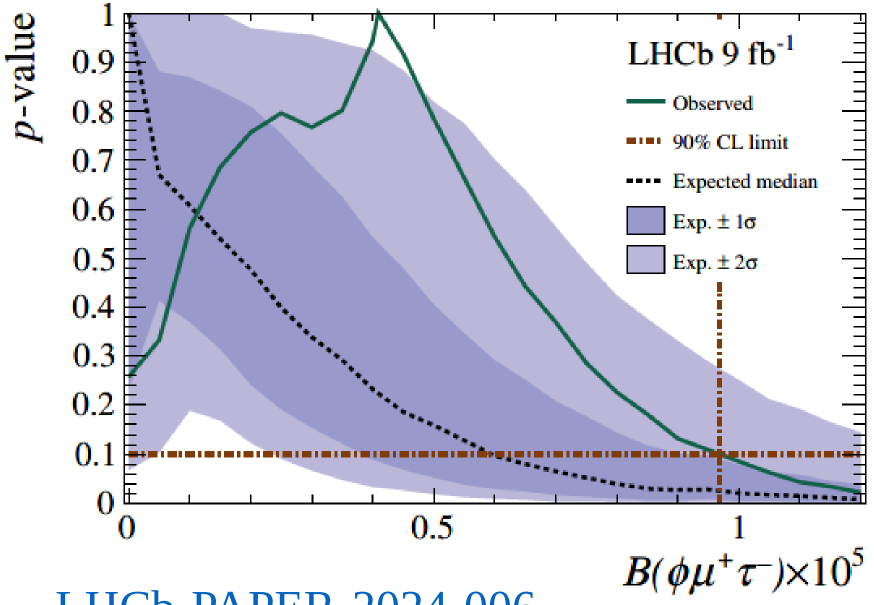
$$\mathcal{B}(B_s^0 \to \phi\mu^{\pm}\tau^{\mp}) < 1.0 \times 10^{-5} \text{ at } 90\% \text{ CL}$$
$$\mathcal{B}(B_s^0 \to \phi\mu^{\pm}\tau^{\mp}) < 1.1 \times 10^{-5} \text{ at } 95\% \text{ CL}$$

$\Rightarrow$ First upper limit on this decay mode

$\Rightarrow$ Comparable sensitivity with other $b \to s\, \tau\, \mu$ searches



Best fit results for linear model at 0.41×10^{-5}



LHCb-PAPER-2024-006

Summary and outlook

- Extremely rare and forbidden decays offer multiple constraints to non-SM contributions
- Presented three new first searches for
  - Nonresonant $B_c^+ \to \pi^+\mu^+\mu^-$ decays EPJ.C84(2024)468
  - $B_{(s)}^{*0} \to \mu^+\mu^-$ decays — New for LHCP! — LHCb-CONF-2024-003
  - $B_s^0 \to \phi\, \mu^\pm\tau^\mp$ decays — New for LHCP! — LHCb-PAPER-2024-006
- Other recent searches (not covered in this talk)
  - $B \to D\mu^+\mu^-$ decays JHEP02(2024)032
  - $\Lambda_c^+ \to p\mu^+\mu^-$ decays LHCb-PAPER-2024-005
  - $B_s^0 \to \mu^+\mu^-\gamma$ decays LHCb-PAPER-2023-045
- Still to come (exploiting run I + II):
  - $\Sigma^+ \to p\,\mu^+\mu^-$(LHCB-CONF-2024-002), $\tau \to 3\mu$, …
- LHCb Upgrade I (runs 3 - 4) started taking data (expect $\sim$50 fb^{-1} by 2032) and will continue making measurements

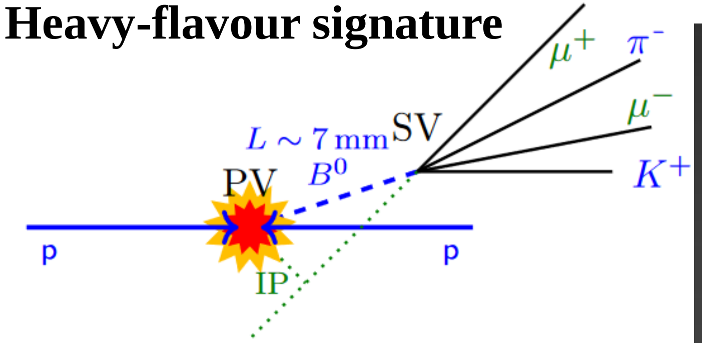
Backup

The LHCb experiment

- Single-arm forward spectrometer optimised for studies of beauty and charm hadrons
- Large cross sections: $\sigma_{b\bar{b}} \approx 280\ (500)$ μb, $\sigma_{c\bar{c}} \approx 1500\ (3000)$ μb at 7(13) TeV

JHEP10(2015)172
JHEP03(2016)159

Heavy-flavour signature



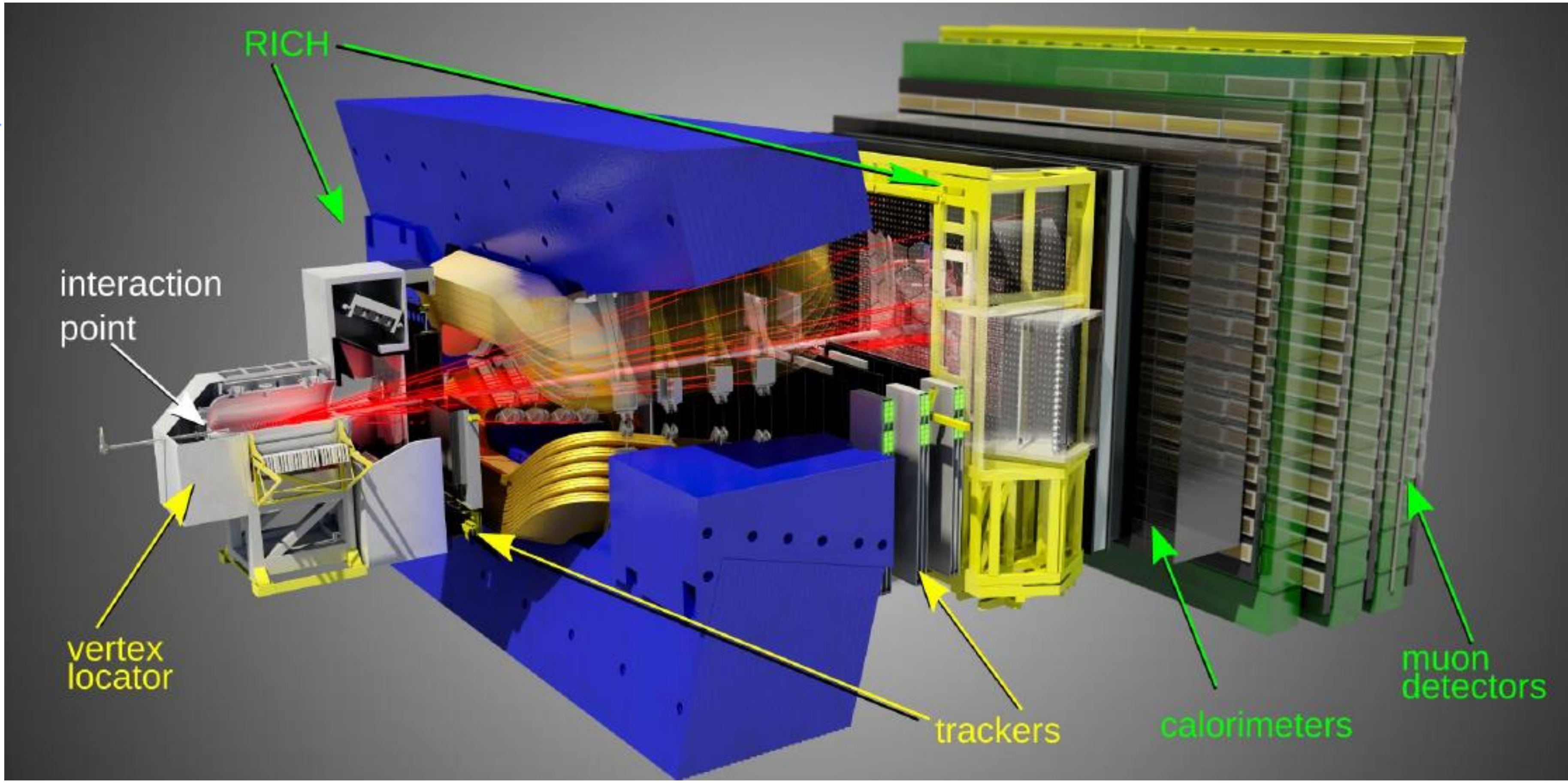
- Excellent IP resolution

~ 20μm to identify B vtx.

- Mom. res. $\frac{\Delta p}{p} = 0.5 - 1\%$
- Particle identification

$\varepsilon_{K\to K} \sim 95\%$ $\varepsilon_{\pi\to K} \sim 5\%$

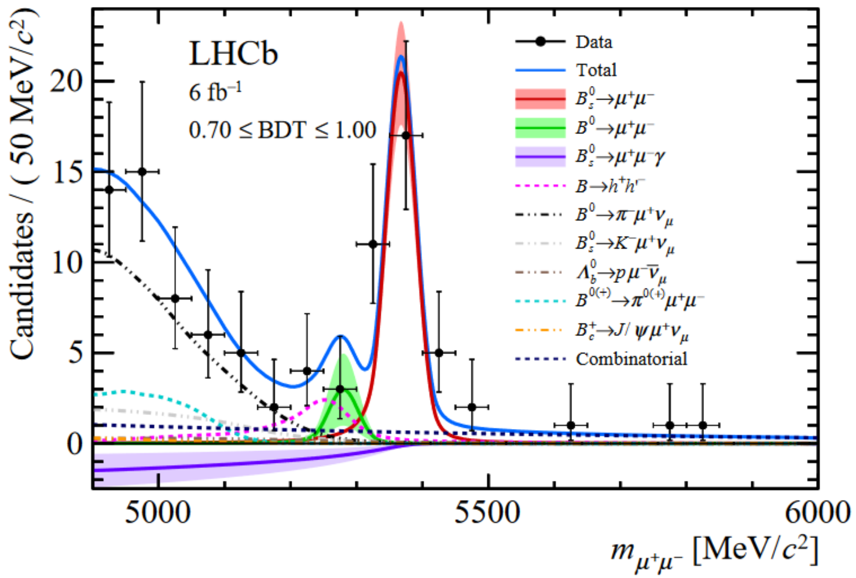
$\varepsilon_{\mu\to\mu} \sim 97\%$ $\varepsilon_{\pi\to\mu} \sim 1 - 3\%$



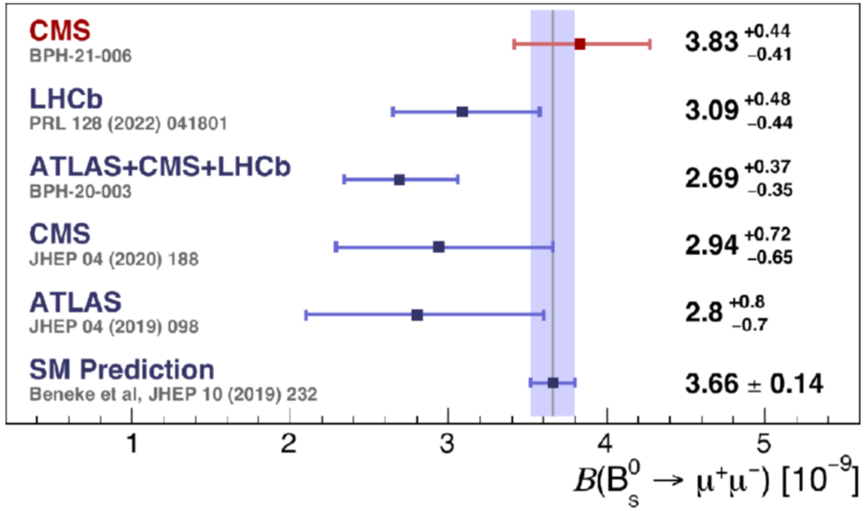
JINST(2008)3S08005

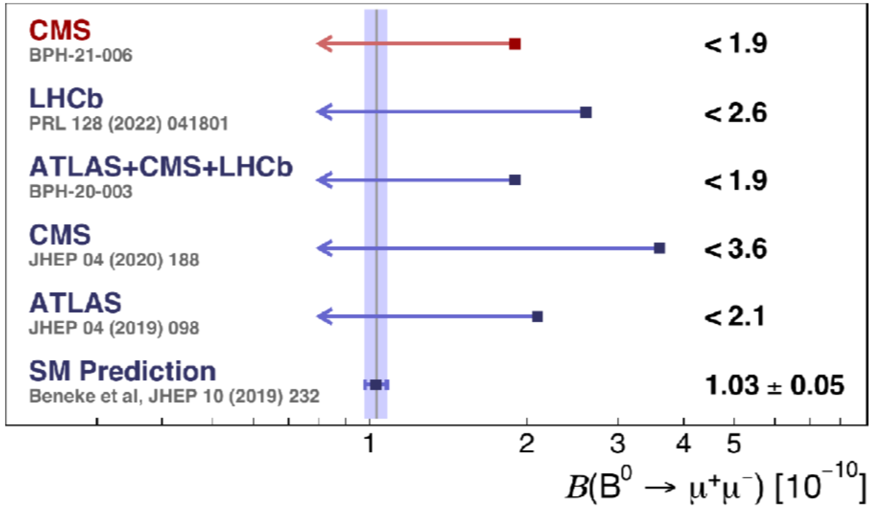
Searches for $B^0_{(s)} \to \mu^+\mu^-$ decays

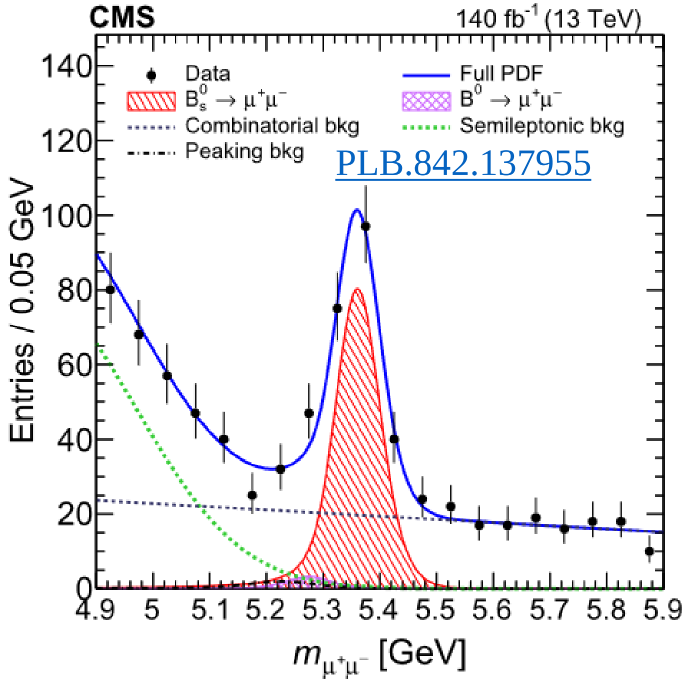
PRD.105.012010



- Helicity suppressed FCNC, precise SM predictions
- $\mathcal{B}(B^0_s \to \mu^+\mu^-)$ measured by ATLAS, CMS and LHCb
- Statistically limited, largest systematic uncertainty originates from fragmentation fraction f_s/f_d PRD.104.032005
- $B^0 \to \mu^+\mu^-$ still unobserved, but in reach

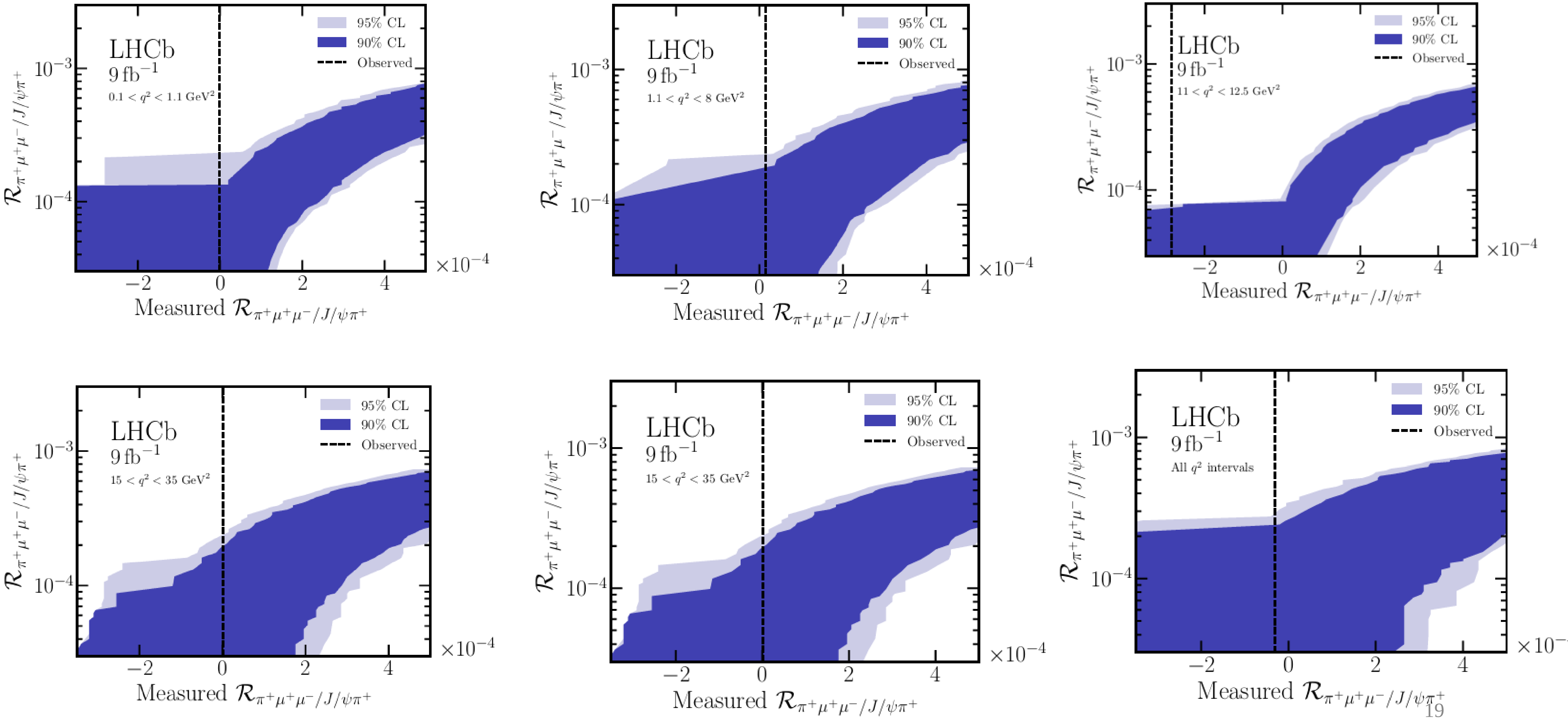






PLB.842.137955

Search for $B_c^+ \to \pi^+\mu^+\mu^-$ decays



Search for $B \to D\mu^+\mu^-$ decays

- Nonresonant signal decays selected in the range $q^2 < 8.0\ \text{GeV}^2$ to avoid all charmonium
- Charmonium region selected narrowly around J/ψ
- Yields for signal and backgrounds vary freely
- Use $B^0 \to J/\psi(\mu^+\mu^-)\ K^*(K^+\pi^-)$ for normalisation
- Keep separate fragmentation fraction f_c/f_u PRD.100.112006

$$\frac{f_c}{f_u} \cdot \mathcal{B}\left(B_c^+ \to D_s^+ J/\psi\right) = (1.63 \pm 0.15 \pm 0.13) \times 10^{-5}$$

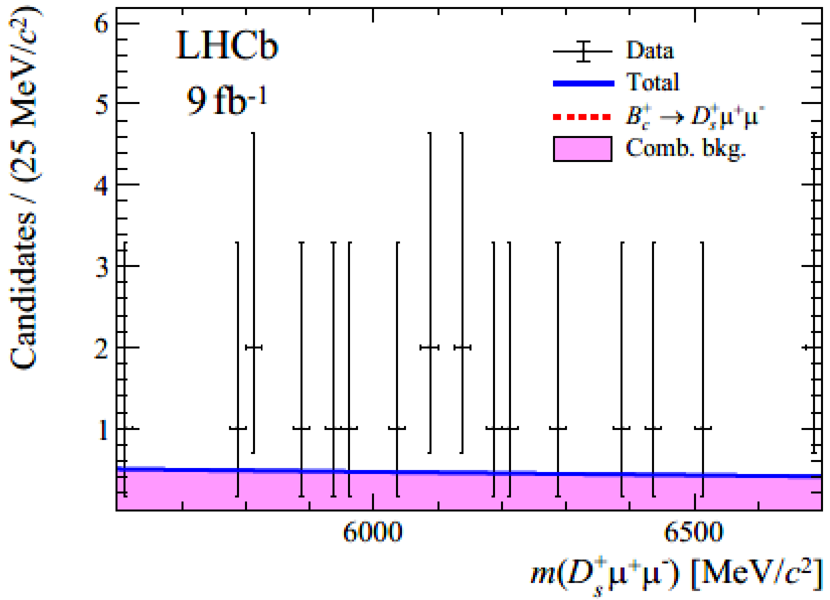
$$\frac{\mathcal{B}\left(B_c^+ \to D_s^{*+} J/\psi\right)}{\mathcal{B}\left(B_c^+ \to D_s^+ J/\psi\right)} = 1.91 \pm 0.20 \pm 0.07$$

$$\Gamma_{\pm\pm}/\Gamma_{\text{tot}} = 0.50 \pm 0.11$$

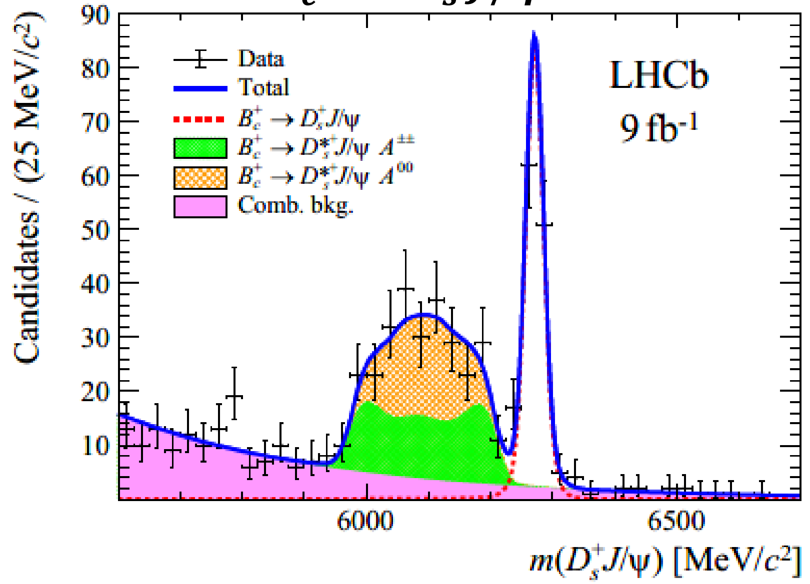
$\Rightarrow$ World's best results

JHEP02(2024)032

Nonresonant $B_c^+ \to D_s^+\mu^+\mu^-$ fit



$B_c^+ \to D_s^+ J/\psi$ fit



Search for $B \to D\mu^+\mu^-$ decays

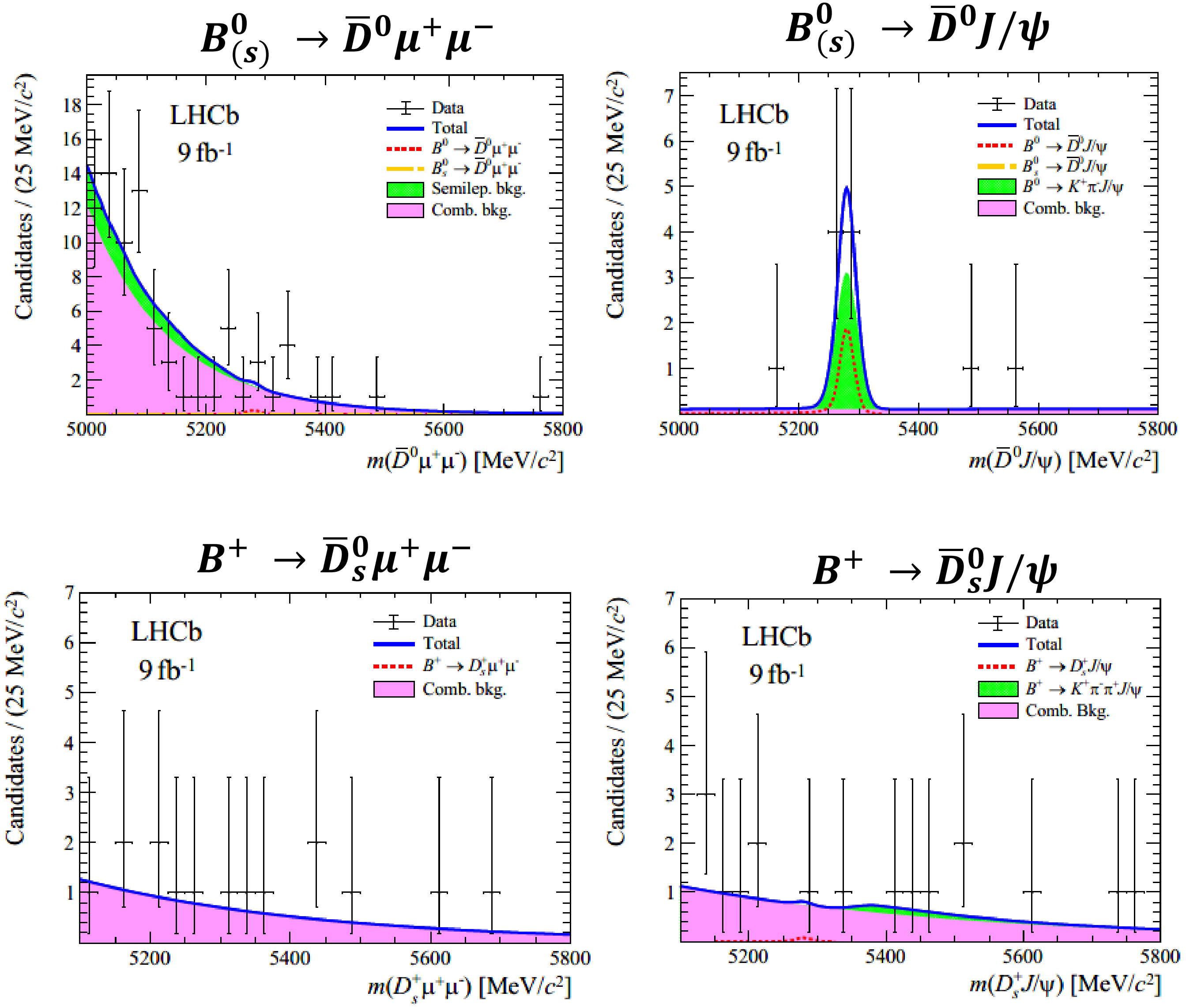
- No signal observed for all other modes

Branching fraction	Upper limits 90 % CL	95 % CL
$\mathcal{B}\left(B^0 \to \overline{D}^0\mu^+\mu^-\right)$	4.0×10^{-8}	5.1×10^{-8}
$\mathcal{B}\left(B^+ \to D_s^+\mu^+\mu^-\right)$	2.4×10^{-8}	3.2×10^{-8}
$\mathcal{B}\left(B_s^0 \to \overline{D}^0\mu^+\mu^-\right)$	1.2×10^{-7}	1.6×10^{-7}
$f_c/f_u \cdot \mathcal{B}\left(B_c^+ \to D_s^+\mu^+\mu^-\right)$	7.5×10^{-8}	9.6×10^{-8}
$\mathcal{B}\left(B^0 \to \overline{D}^0 J/\psi\right)$	9.6×10^{-7}	1.1×10^{-6}
$\mathcal{B}\left(B^+ \to D_s^+ J/\psi\right)$	2.8×10^{-7}	3.5×10^{-7}
$\mathcal{B}\left(B_s^0 \to \overline{D}^0 J/\psi\right)$	1.0×10^{-6}	1.5×10^{-6}

$\Rightarrow$ First limits or improvements ≥ 3 orders of magnitude

- SM predictions $\mathcal{O}(10^{-5} - 10^{-8})$

PRD65.2002.037504 NP.B612.2001.25 PTEP.2020.053B07



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

- SM predictions: $\mathcal{O}(10^{-8})$ (short distance) $\mathcal{O}(10^{-6})$ (long distance) JHEP09(2021)208
- Search for nonresonant decays in ranges
  - $m(\mu^+\mu^-) < 508\ \mathrm{MeV}/c^2$
  - $m(\mu^+\mu^-) > 1060\ \mathrm{MeV}/c^2$
- Normalise to $\Lambda_c^+ \to \phi(\mu^+\mu^-)\, p$ decays
- No excess observed over background-only hypothesis

$\Rightarrow$ Set upper limit extrapolated to full $m(\mu^+\mu^-)$ range (assuming phase-space distribution)

$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 7.3\ (8.2) \times 10^{-8} \text{ at } 90\%\ (95\%) \text{ CL}$$

$\Rightarrow$ Best upper limit on this decay mode

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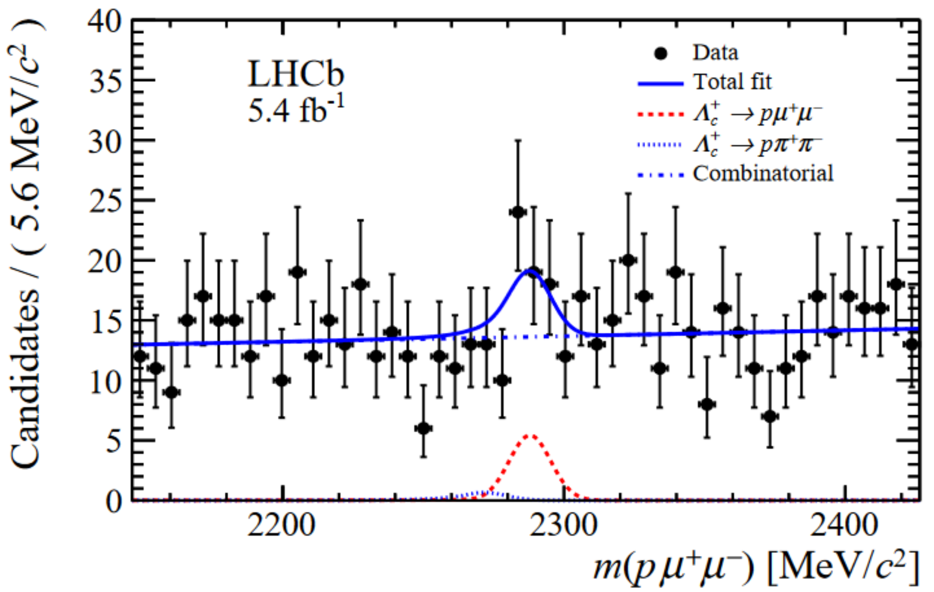
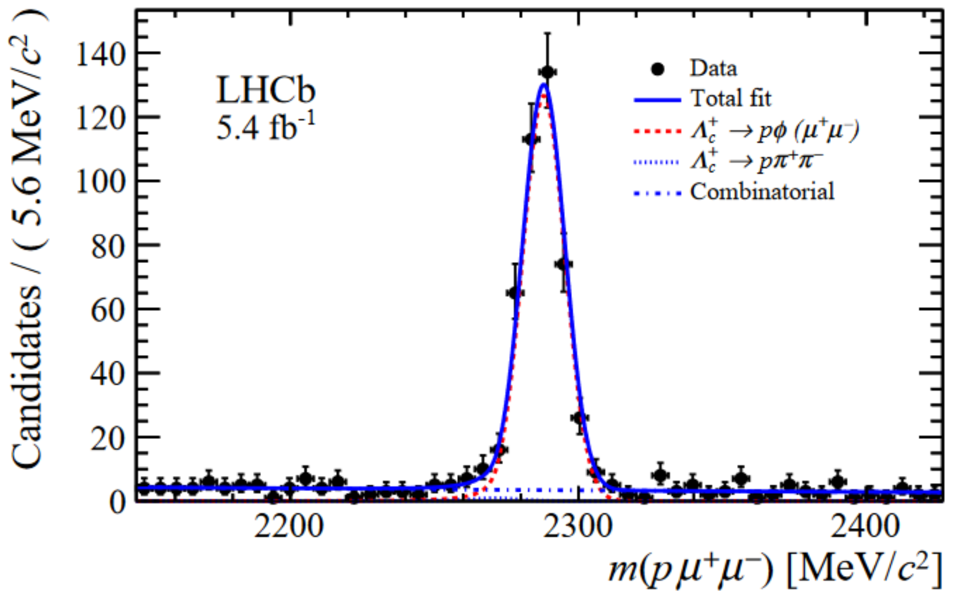
Combined $\Lambda_c^+ \to p\mu^+\mu^-$ fit



$\Lambda_c^+ \to \phi(\mu^+\mu^-)\, p$ fit



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

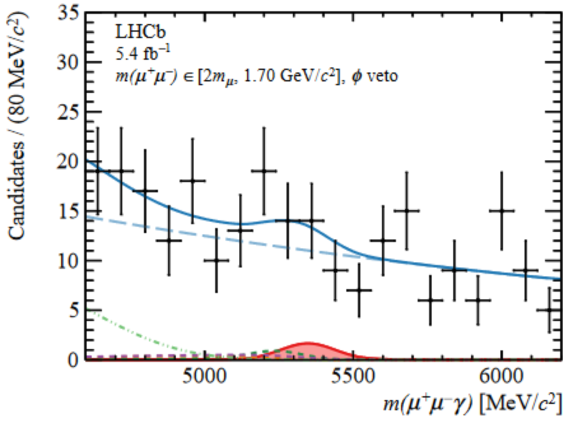
- No helicity suppression wrt. $B_s^0 \to \mu^+\mu^-$ decays, compensating for QED vertex
- SM prediction $\mathcal{O}(10^{-9})$ JHEP11(2017)184
- First search as part. reconstructed bkg. for PRL128.041801 $B_s^0 \to \mu^+\mu^-$decays at $m(\mu^+\mu^-) > 4.9\ \mathrm{GeV}/c^2$
- Reconstruct γ and perform search in three q^2 bins
- Normalise to $B_s^0 \to J/\psi\,\eta(\gamma\gamma)$ decays
- No excess observed over background-only hypothesis

$\Rightarrow$

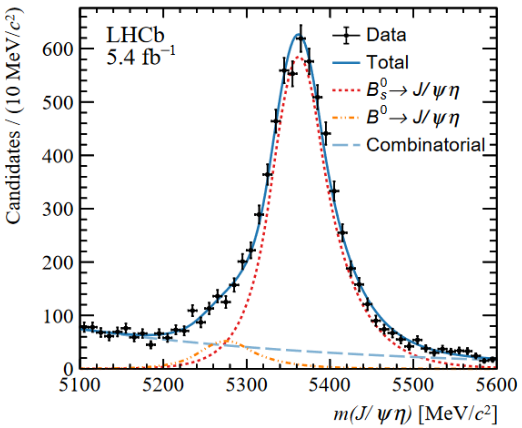
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{I}} < 3.6\,(4.2) \times 10^{-8}$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{II}} < 6.5\,(7.7) \times 10^{-8}$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{III}} < 3.4\,(4.2) \times 10^{-8}$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{I,\ with}\ \phi\ \mathrm{veto}} < 2.9\,(3.4) \times 10^{-8}$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{comb.}} < 2.5\,(2.8) \times 10^{-8}$$

$\Rightarrow$First limits at low q^2

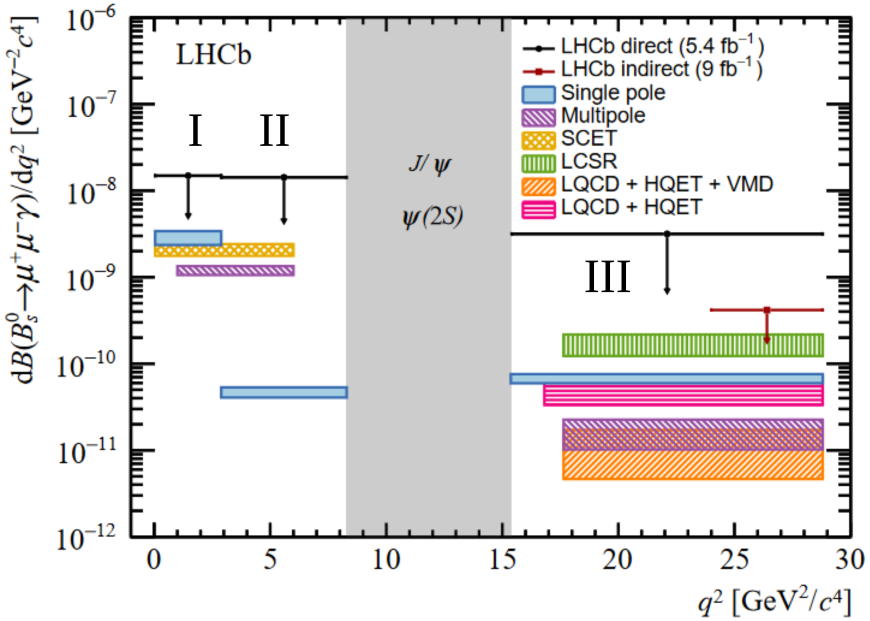
Combined signal fit



$B_s^0 \to J/\psi\,\eta$ fit



Limits and predictions on differential BF



LHCb-PAPER-2023-045

Overview of rare decays

Expected level of suppression

Expected level of suppression	Decay
10^{-5}	Radiative $b \to s\gamma$
10^{-6}	Semileptonic $b \to s\ell\ell$
10^{-9}	Helicity suppressed $B_s^0 \to \mu^+\mu^-$
	$K_S^0 \to \mu^+\mu^-$ $(\mathrm{s} \to d)$
10^{-12}	$D^0 \to \mu^+\mu^-$, long distance $(c \to u)$
10^{-19}	$D^{(*)0} \to \mu^+\mu^-$, short distance $(c \to u)$
10^{-30}	Baryon number violation
10^{-50}	Lepton flavor violation