Searches for muonic decays of excited mesons at LHCb

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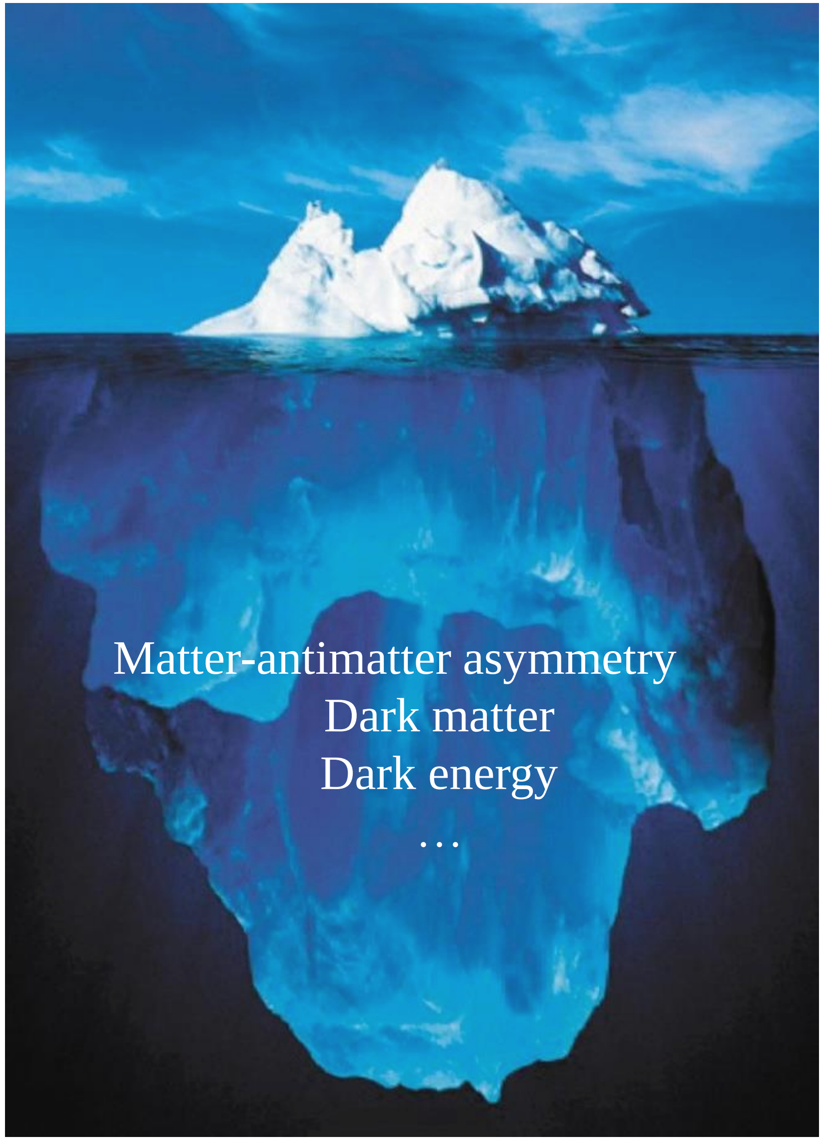
The Standard Model

- Describes three out of the four fundamental forces in nature predicting accurately thousands of measurements over many orders of magnitude in energy.

⇒ Most precisely experimentally probed theory ever but fails at providing a full-picture explanation for many cosmological observations and leaves several intrinsic questions open such as the particle hierarchy, etc.

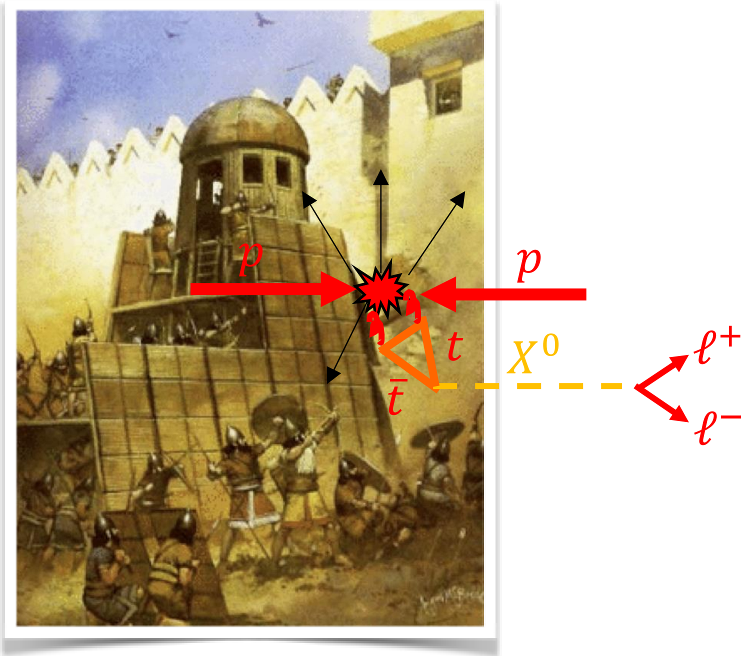
⇒ Might be an effective theory of a universal one.

⇒ Holy grail of today’s experimental particle physics is to find signatures of dynamics Beyond the Standard Model.

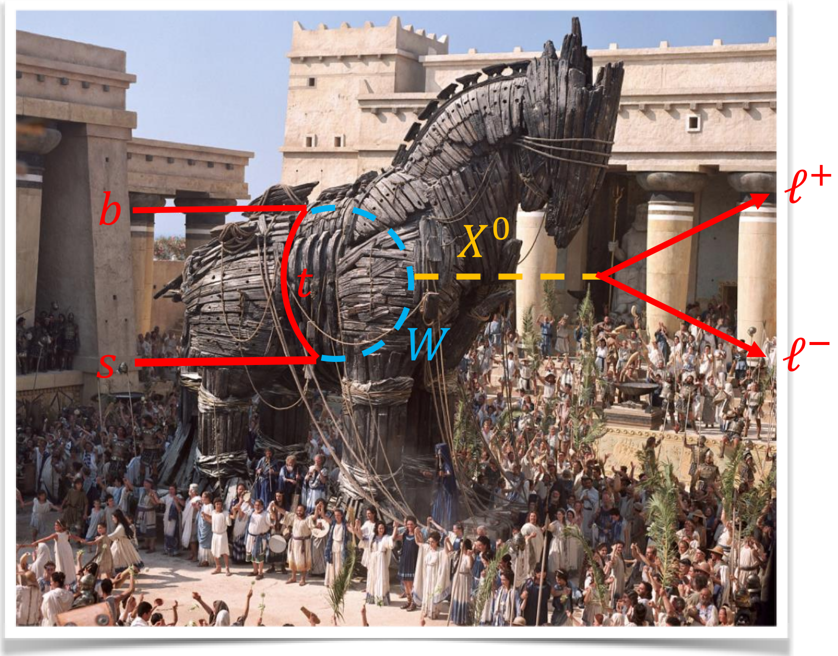


Two ways out

Energy frontier
Direct high-energy production of non-SM particles.



Intensity/precision frontier
Indirect quantum probing of massive non-SM particles in known/expected low-energy processes.



⇒ Currently no evidence for non-SM physics at the high-energy frontier

⇒ Intensity frontier offers indirect sensitivity to very high energy scales

⇒ Weak interactions of quarks offer rich opportunities for intensity frontier

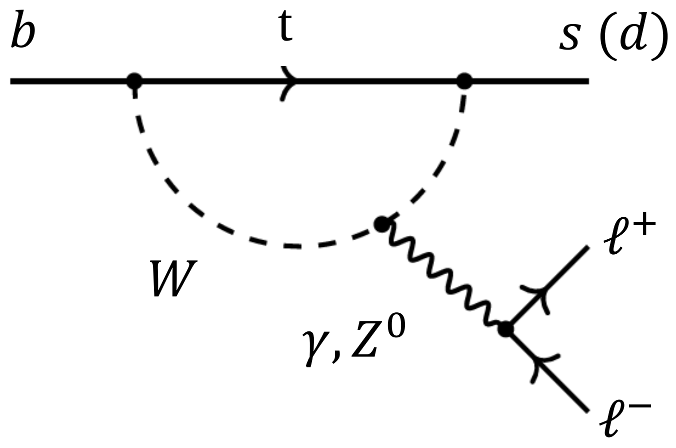
Rare charm and beauty decays

- Are Flavour Changing Neutral Currents
- Allowed in the SM only via quantum fluctuations (loops)
- Suppressed by small size of off-diagonal CKM elements and GIM mechanism
- Sensitive non-SM contributions that can alter decay rates, asymmetries and angular distributions

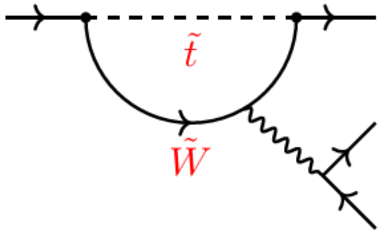
$\Rightarrow$ Offer multiple tests of symmetries of the SM

$\Rightarrow$ Challenge is $\mathcal{B} \lesssim 10^{-6}$

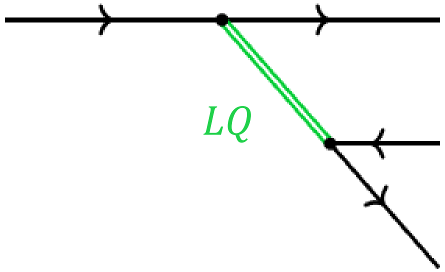
Standard Model



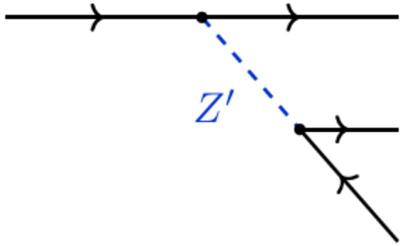
Supersymmetry



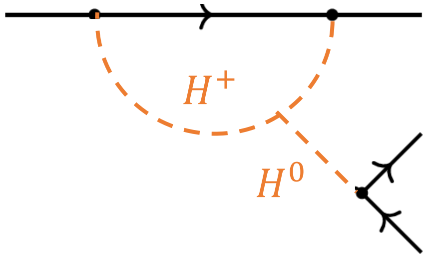
Leptoquarks



New heavy gauge bosons



Extended Higgs sector



Complementarity of BSM searches with rare decays

- Searches at the energy frontier are limited by beam energy

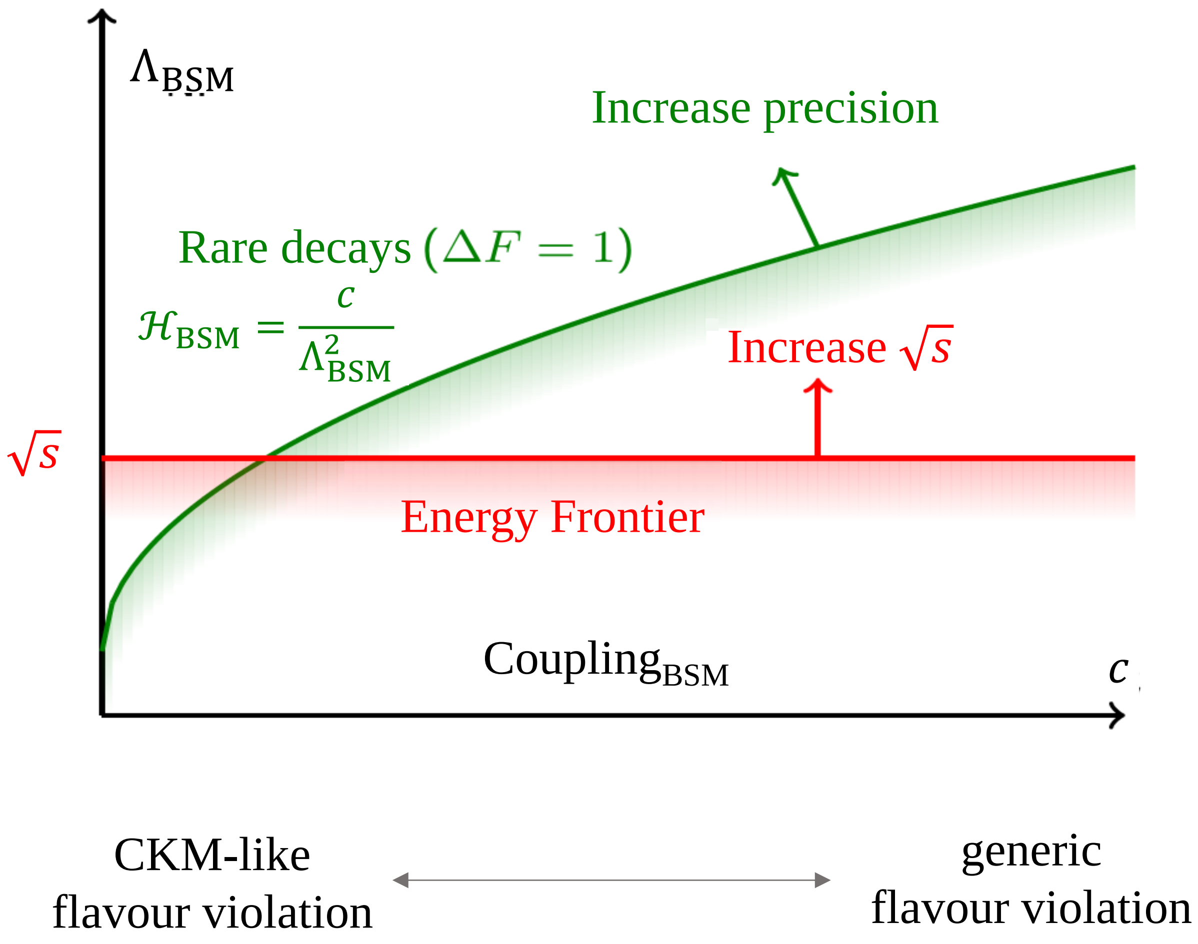
$\Rightarrow \Lambda_{\mathrm{NP}} < \sqrt{s}$

- Reach with rare decays depends on coupling and measurement precision

(assuming clean SM prediction and no limiting exp. systematics)

$\Rightarrow \Lambda_{\mathrm{NP}} \propto \frac{c}{\sqrt[4]{\mathcal{B}}} \propto \sqrt[4]{\int \mathcal{L} dt}$

Exclusion limit for BSM searches



Emerging flavour anomalies in rare B decays

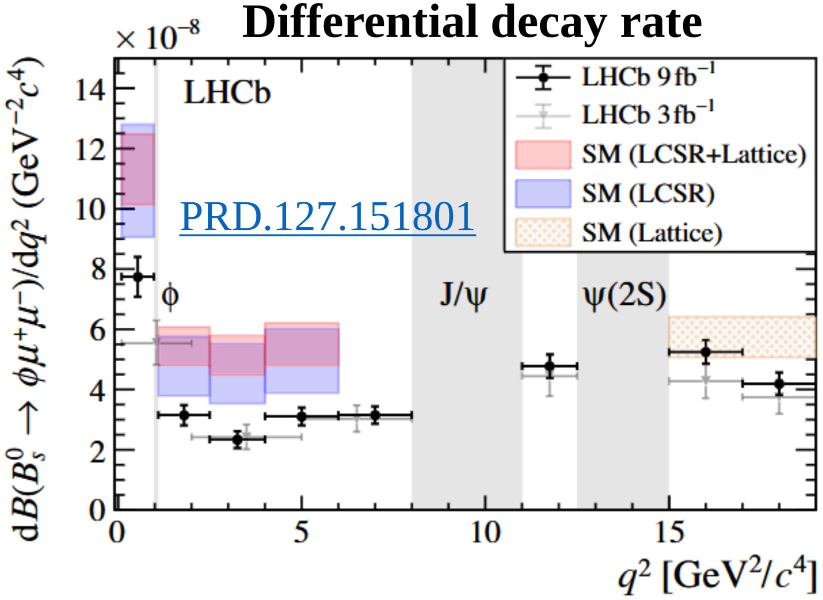
Self-consistent pattern of anomalies associated with $b \to s\ell\ell$ transitions emerging over last decade:

- Differential decay rates for $B_s^0 \to \phi\mu^+\mu^-$, $B^0 \to K^{*0}\mu^+\mu^-$, and $B^+ \to K^+\mu^+\mu^-$ show lower values than expected

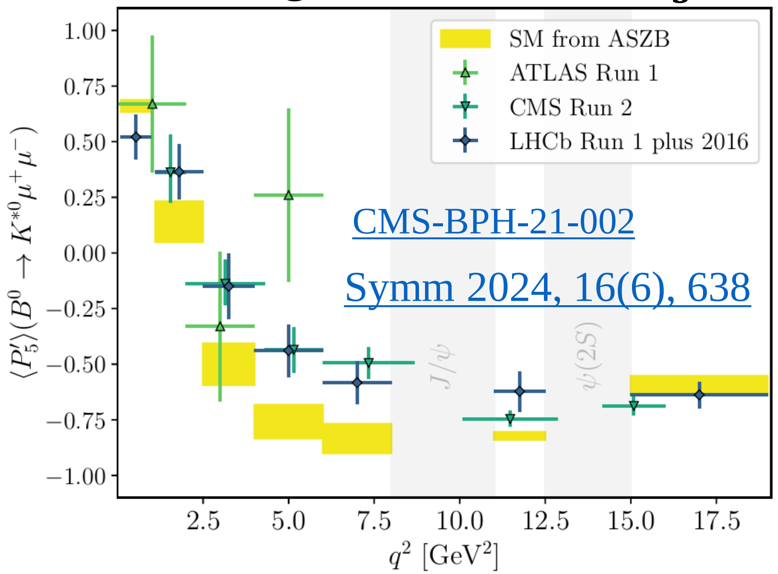
- Discrepancies in angular observables of $B^0 \to K^{*0}\mu^+\mu^-$

However, hadronic (QCD) effects affect predictions

Differential decay rate



Angular observable P_5'

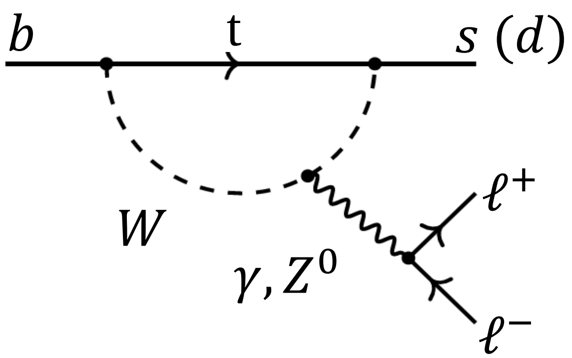


Interpreting the deviations

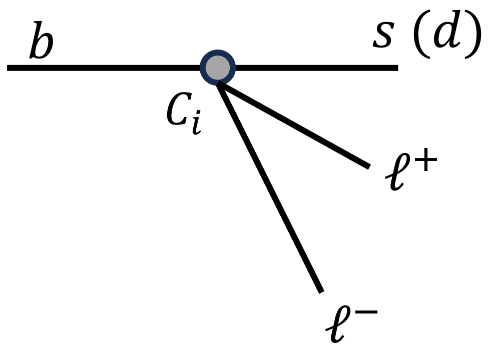
Model independent description in effective field theory

Integrate out heavy degrees of freedom
(EW scale $\gg m_b$)
$\Rightarrow$ Replace loop with effective couplings

Full theory



Effective description



Local operators

$$\mathcal{H}_{eff} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left(C_i^{\mathrm{SM}}\right) O_i$$

Wilson coefficients
(effective couplings)

$$\Delta\mathcal{H} = \frac{c}{\Lambda_{\mathrm{BSM}}^2} O_i$$

Scale of non-SM
contribution

- Rare decays allow to probe several operators $O_i^{(\mathrm{BSM})}$
- Analog description in charm sector, but different renormalisation scale (m_c)

Wilson coefficient		Current
γ-Penguin	$C_7^{(\prime)}$	Electromagnetic
EW-Penguin	$C_9^{(\prime)}$	Vector
	$C_{10}^{(\prime)}$	Axial vector
	$C_{(P)S}^{(\prime)}$	(Pseudo) scalar

$b \to s\gamma$

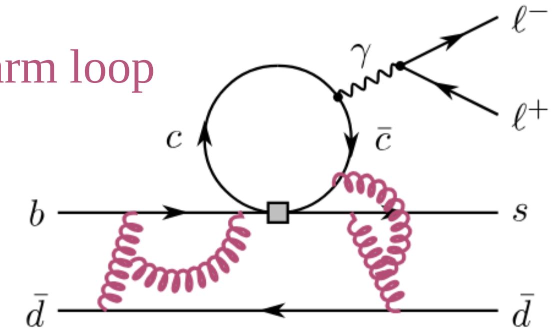
$b \to s\ell\ell$

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

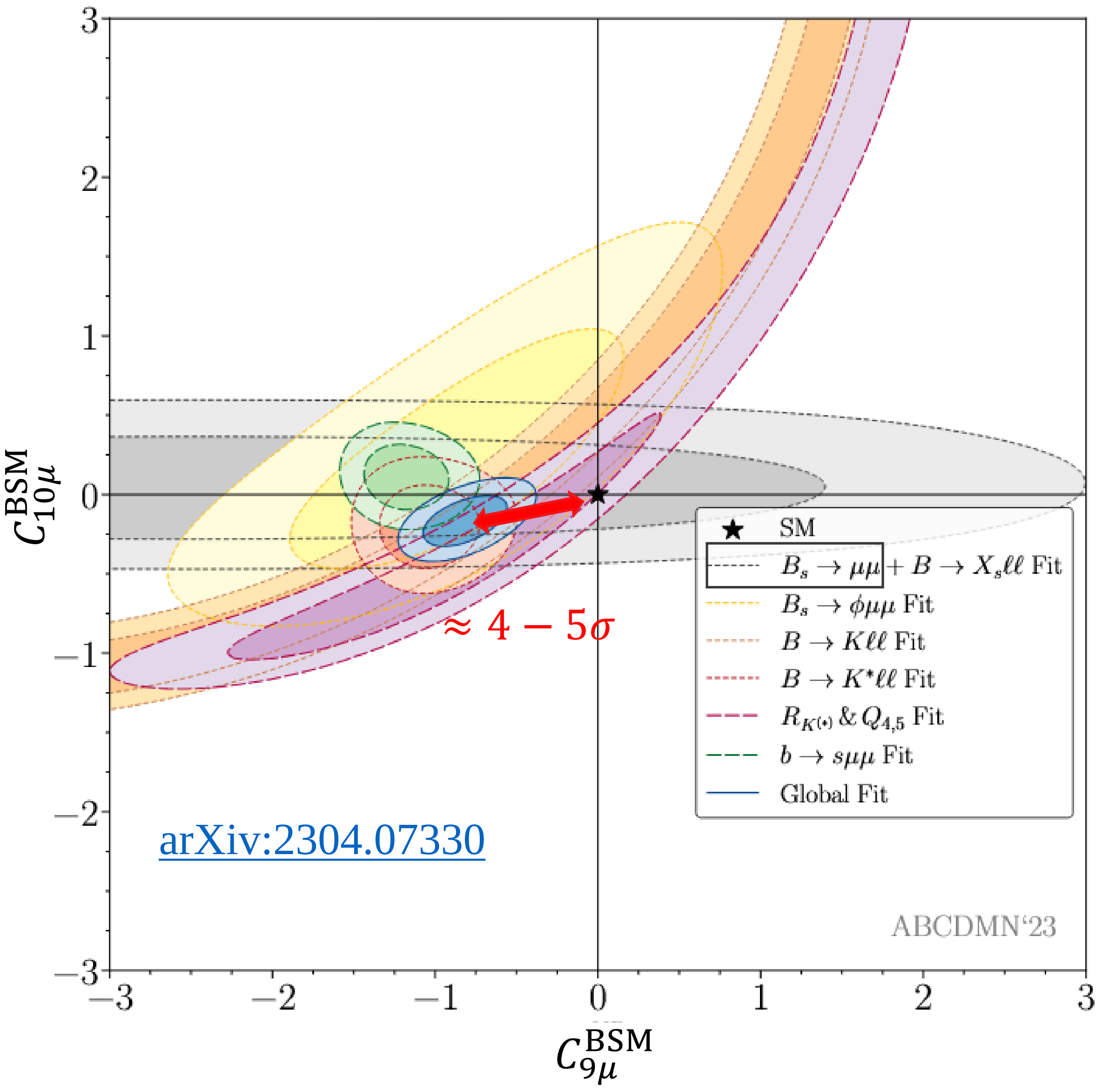
Example of global fit over all $b \to s\ell\ell$ data

- Deviation from SM at the level of $\approx 4 - 5\,\sigma$
- Non-SM contributions?
- Misunderstood QCD processes?

SM charm loop



$\Rightarrow$ Inputs from not yet observed processes can provide additional information to improve our understanding



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

- Loop, CKM and helicity suppressed
- Purely muonic final state

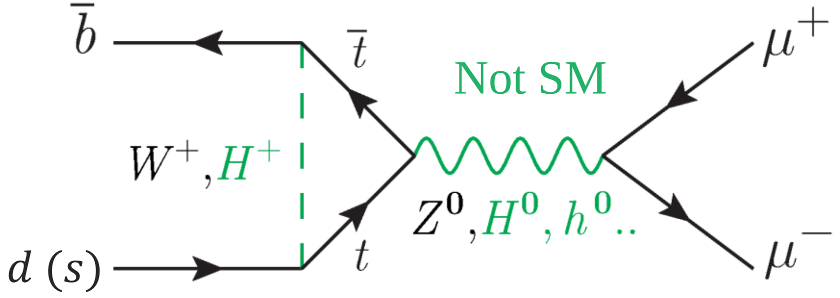
$\Rightarrow$ Theoretically and experimentally clean

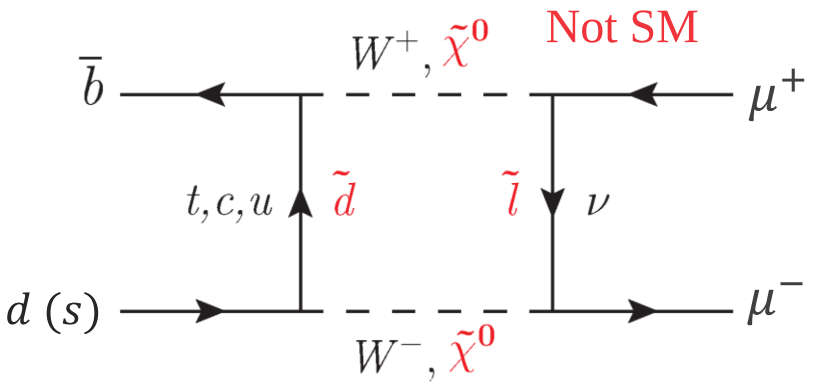
- Very clean prediction in the SM

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

JHEP10(2019)232
PRL.112.101801

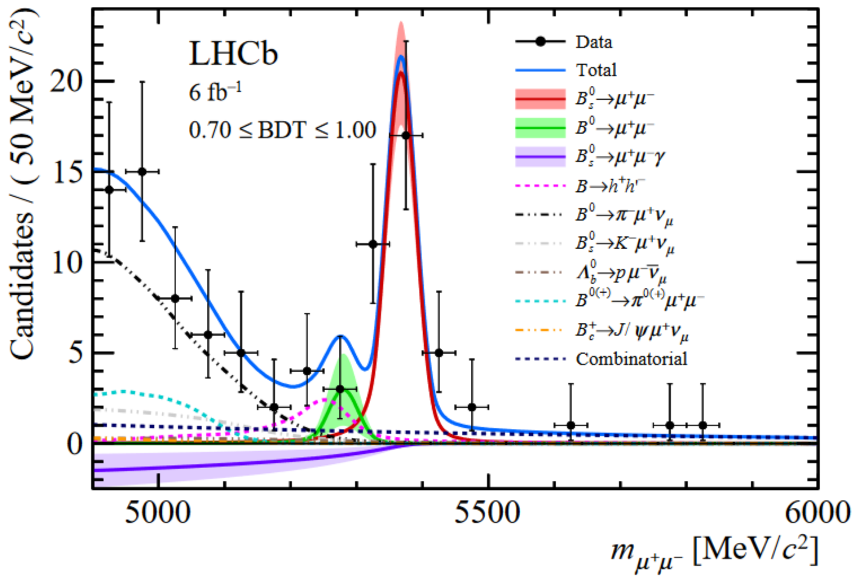
- In SM: contribution only from axial vector operator (C_{10})
- Sensitive to new (pseudo)scalar operators ($C_{(P)S}$)



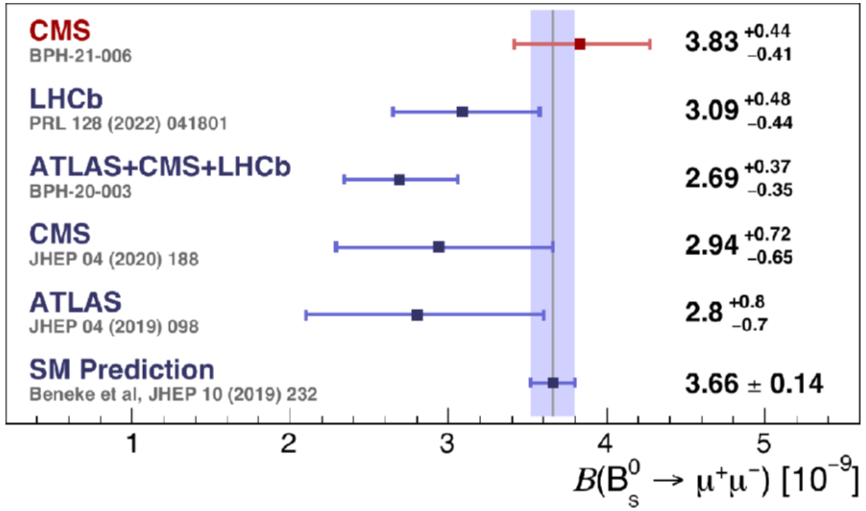


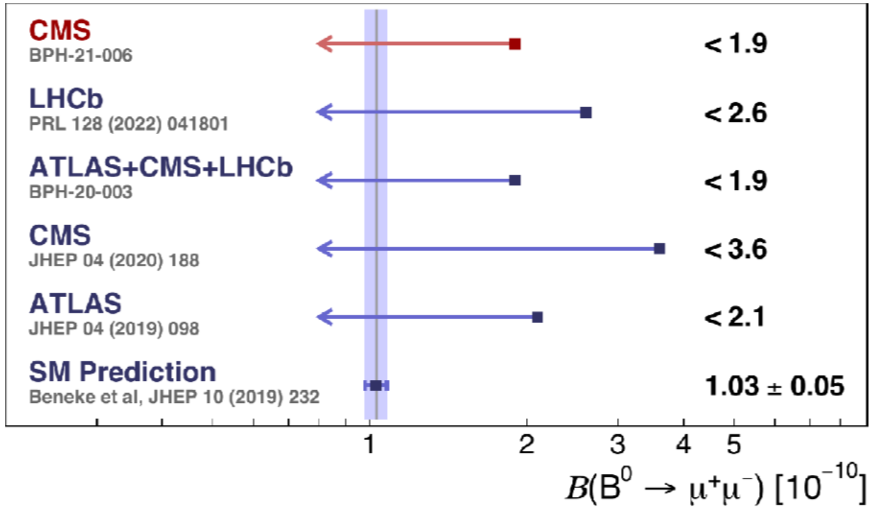
Searches for $B^0_{(s)} \to \mu^+\mu^-$ decays

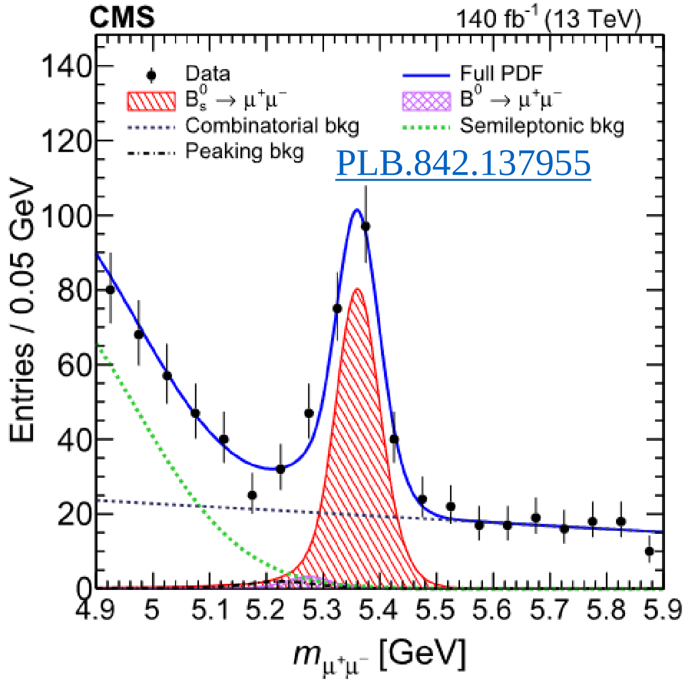
PRD.105.012010



- $\mathcal{B}(B^0_s \to \mu^+\mu^-)$ 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

Rare $D^0 \to \mu^+\mu^-$ decays

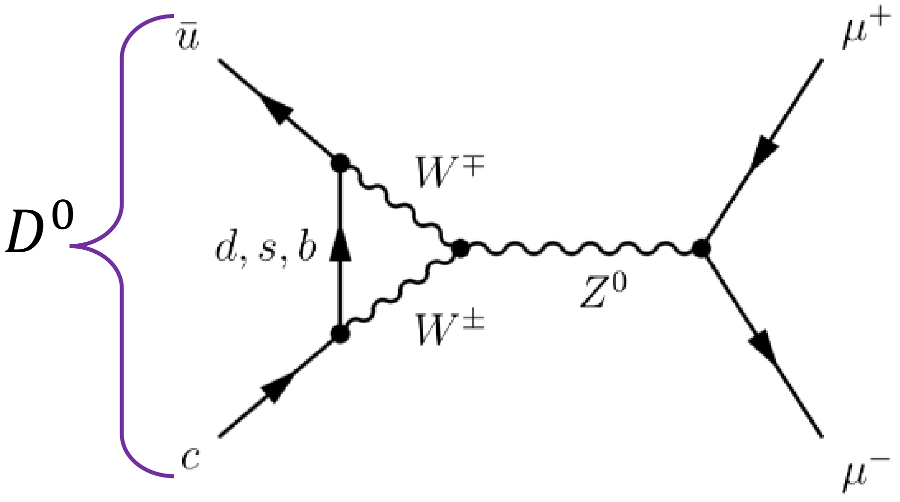
- Loop, CKM and helicity suppressed
- Large GIM suppression
- Key in constraining non-SM physics
- Receives two contributions within SM PRD.93.074001

  Short distance: $\mathcal{B}(D^0 \to \mu^+\mu^-) < 10^{-18}$ (Z-penguins, W-boxes)

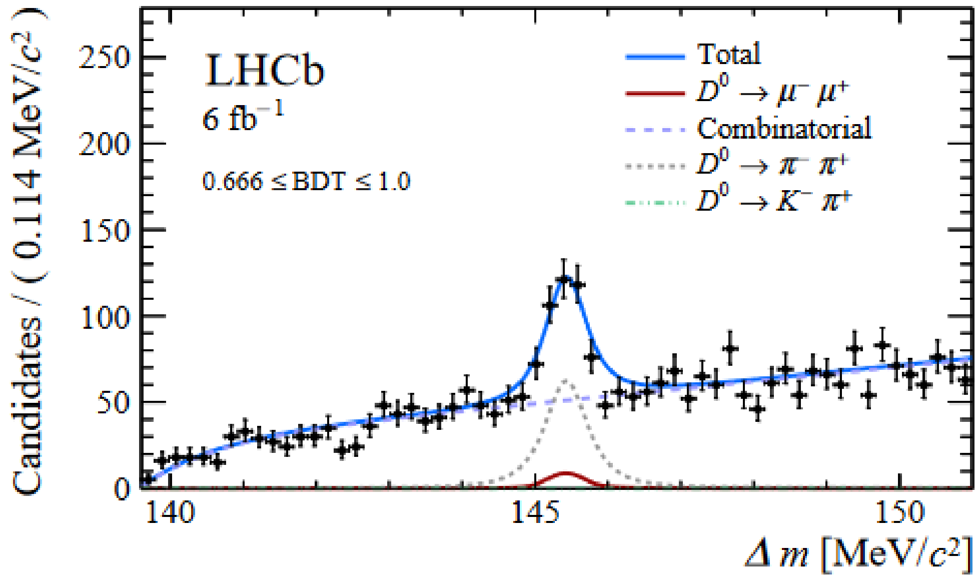
  Long distance : $\mathcal{B}(D^0 \to \mu^+\mu^-) < 10^{-11}$ ($D^0 \to \gamma\gamma$ transitions)

- Long-distance contributions more difficult to estimate
- Upper limit by LHCb (9fb^{-1})

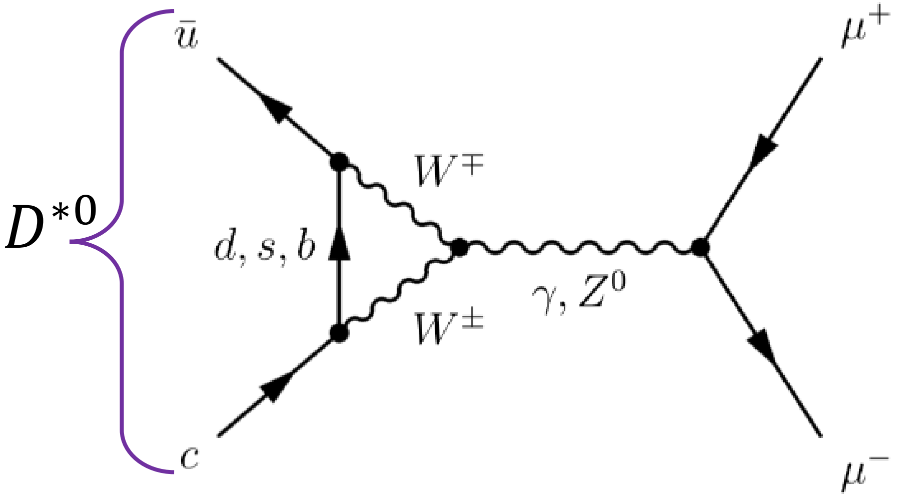
$$\boxed{\mathcal{B}(D^0 \to \mu^+\mu^-) < 3.1(3.5) \times 10^{-9} \text{ at } 90(95)\%\text{C.L.}}$$



PRL.131.041804



Rare D^{*0} and $B^{*0}_{(s)} \to \mu^+\mu^-$ decays



- Probe vector, axial vector and tensor operators

$\Rightarrow$ Provide independent probe of C_9 (if we can measure it)

- Not helicity suppressed

$\Rightarrow$ Larger partial widths (but also larger total widths)

- D^{*0} and $B^{*0}_{(s)}$ mesons decay predominantly via strong or electromagnetic interaction

$\Rightarrow$ Very small branching fractions in the SM

$$\mathcal{B}\left(B^{*0}_{(s)} \to \mu^+\mu^-\right) \lesssim 10^{-11}$$ JHEP11(2015)142

$$\mathcal{B}\left(D^{*0} \to \mu^+\mu^-\right) \lesssim 10^{-18}$$ PRL.116.141801

- High production rates of D^{*0} and $B^{*0}_{(s)}$ at the LHC

$\Rightarrow$ But background level also high for decays at collision point

$\Rightarrow$ Study experimental techniques to suppress the background

Searches for weak decays of excited mesons

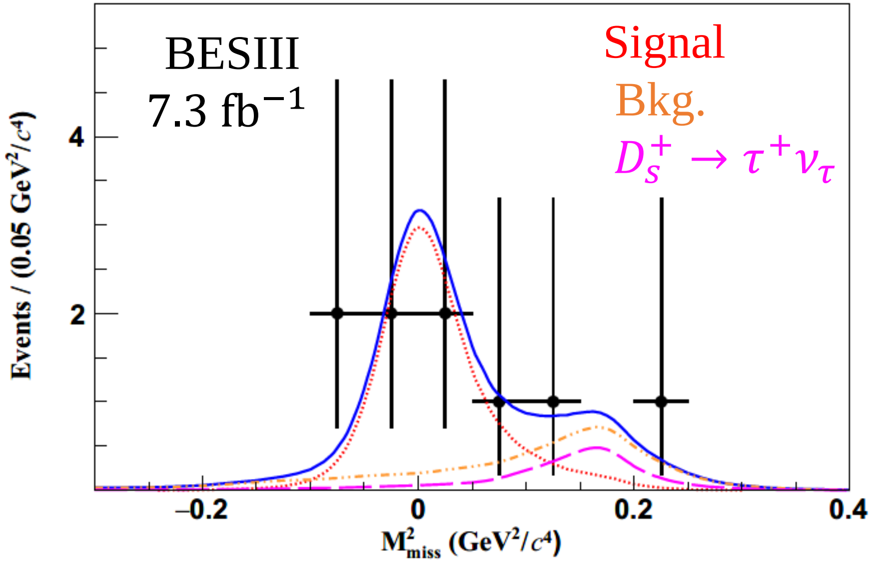
BESIII search for $D_s^{*+} \to e^+\nu_e$ (charged current)

- Doubly tagged $e^+e^- \to D_s^{*+}D_s^-$ events

$$\mathcal{B}(D_s^{*+} \to e^+\nu_e) = (2.1^{+1.2}_{-0.9\,\text{stat.}} \pm 0.2_{\text{syst.}}) \times 10^{-5}$$

- Signal significance is 2.9σ
- Agrees with SM predictions within 1σ

arXiv:2304.12159

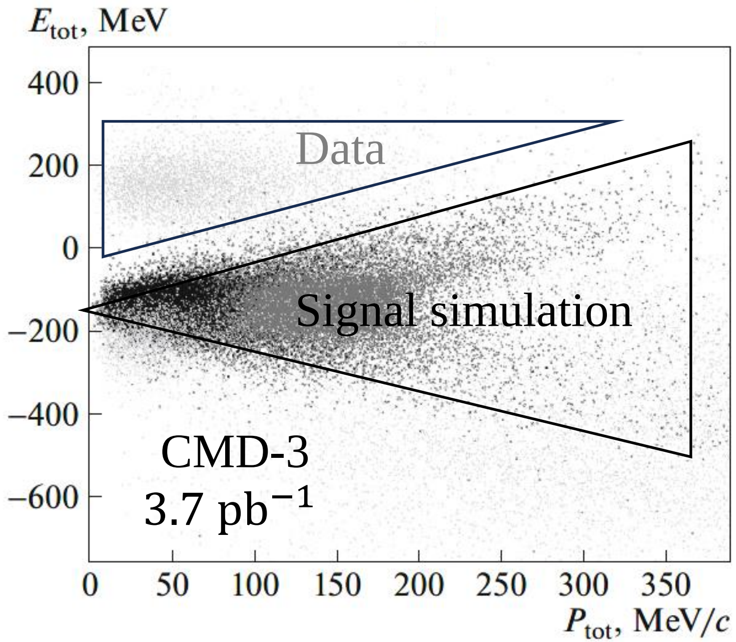


CMD-3 search for $e^+e^- \to D^{*0}$ (FCNC)

- Reconstruct $D^{*0} \to D^0\pi^0$ and $D^{*0} \to D^0\gamma$ events

$$\mathcal{B}(D^{*0} \to e^+e^-) < 1.7 \cdot 10^{-6} \text{ at 90\% C.L.}$$

PAN83.954(2020)



$\Rightarrow$ No weak decays observed ever for particles that can decay strongly or electromagnetically

Searching for the weak among the strong

Eur. Phys. J. C (2022) 82:459
https://doi.org/10.1140/epjc/s10052-022-10369-y

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Experimental Physics

Prospects for studies of $D^{*0} \to \mu^+\mu^-$ and $B^{*0}_{(s)} \to \mu^+\mu^-$ decays

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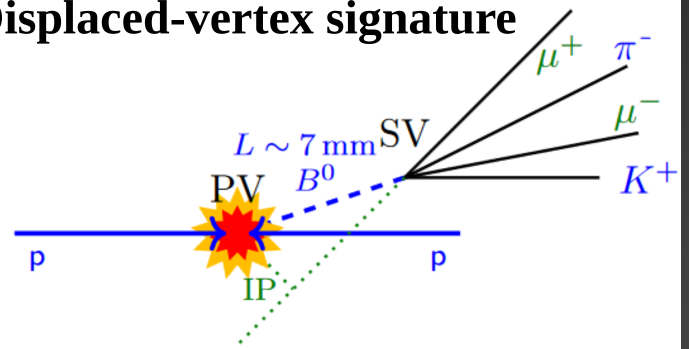
[EPJ.C82.459(2022)](EPJ.C82.459(2022))

LHCb detector in Run 1 and 2

- 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

Displaced-vertex signature



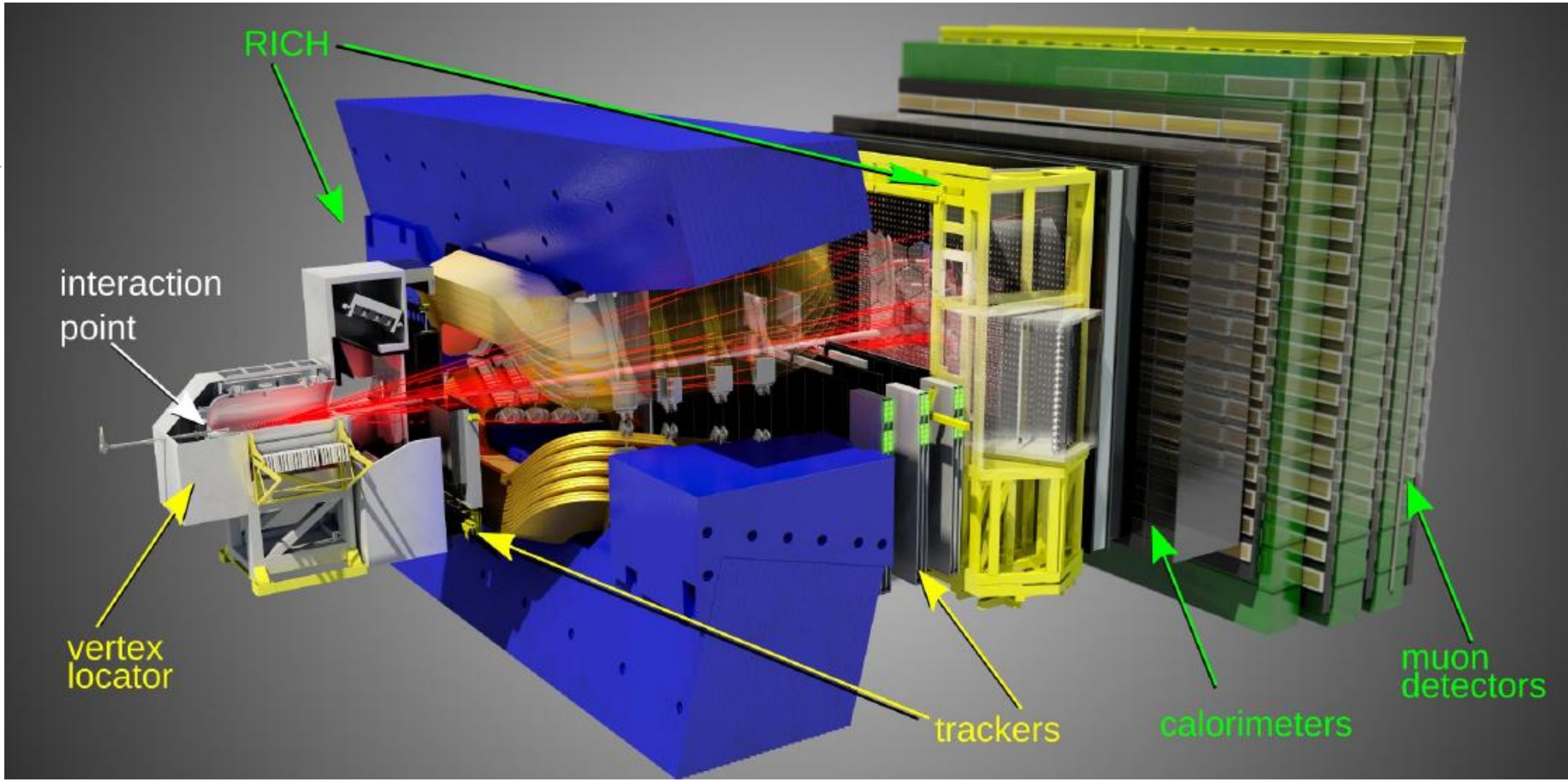
- Excellent IP resolution

~ 20μm to identify B vtx.

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

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

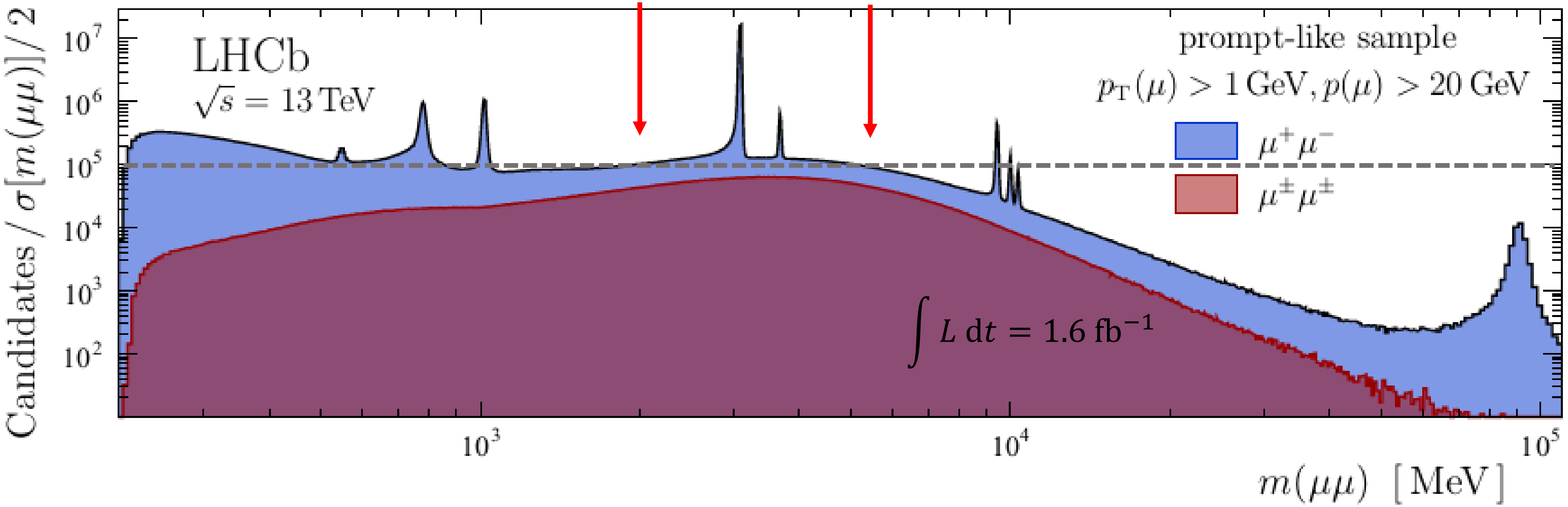
$\varepsilon_{\mu\to\mu} \sim 97\%$ $\varepsilon_{\pi\to\mu} \sim 1-3\%$



JINST(2008)3S08005

Searches exploiting prompt decays

Dark photon search
PRL120.061801



$$\mathcal{B}\left(D^{*0} \to \mu^+\mu^-\right) = \frac{N_{D^{*0}\to\mu^+\mu^-}}{N_{J/\psi\to\mu^+\mu^-}} \underbrace{\frac{\epsilon_{J/\psi\to\mu^+\mu^-}}{\epsilon_{D^{*0}\to\mu^+\mu^-}}}_{\approx 1} \frac{\boxed{\sigma_{J/\psi}}}{\boxed{\sigma_{D^{*0}}}} \boxed{\mathcal{B}\left(J/\psi \to \mu^+\mu^-\right)}$$

Known

$\alpha_{\text{SES}} \sim 10^{-11}$

$\approx \sigma(D^{*+}) \approx 800$ μb

$$= \boxed{\alpha^{\text{prompt}}_{D^{*0}\to\mu^+\mu^-} \begin{array}{l} \sim 10^{-11} (D^*) \\ \sim 10^{-10} (B^*) \end{array}} N_{D^{*0}\to\mu^+\mu^-}$$

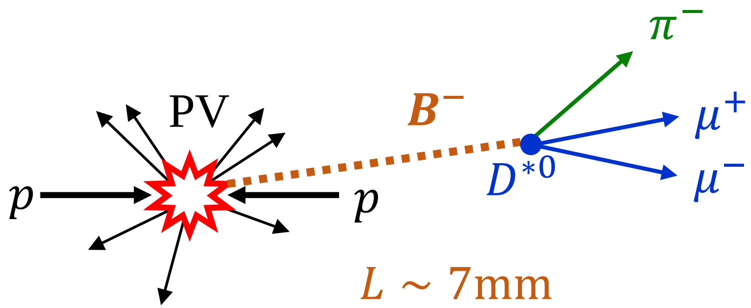
$\Rightarrow$ Searches are background dominated!

Assuming same bkg. level as for dark photon search

$$\boxed{\begin{array}{l} \mathcal{B}(D^{*0} \to \mu^+\mu^-) \lesssim 10^{-7} \\ \mathcal{B}(B^{*0}_{(s)} \to \mu^+\mu^-) \lesssim 10^{-6} \end{array}}$$

New idea

- Exploit displaced vertex signature by searching for

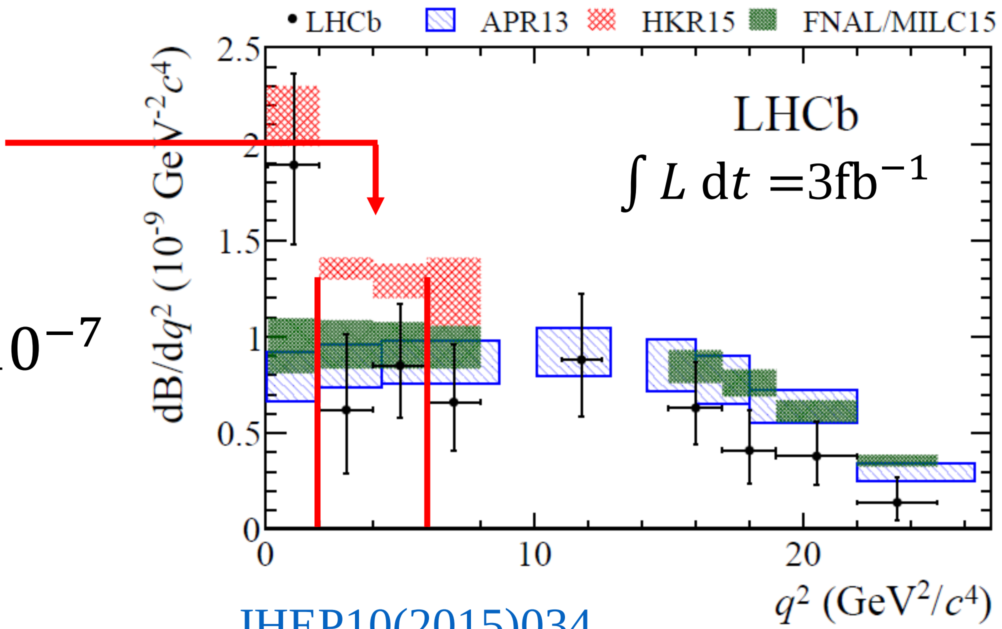


- Look at measurements of $d\mathcal{B}(B^- \to \mu^+\mu^-\pi^-)/dq^2$:

  Assume that $\mathcal{B}(B^- \to D^{*0}(\mu^+\mu^-)\,\pi^-)$ less than half the signal in the two bins around $M^2_{D^{*0}}$

  $$\Rightarrow \mathcal{B}(D^{*0} \to \mu^+\mu^-) = \frac{\mathcal{B}(B^- \to D^{*0}(\mu^+\mu^-)\,\pi^-)}{\mathcal{B}(B^- \to D^{*0}\pi^-)} \lesssim 3 \cdot 10^{-7}$$

  $\Rightarrow$ Nearly background free sample!



JHEP10(2015)034

Expected sensitivity

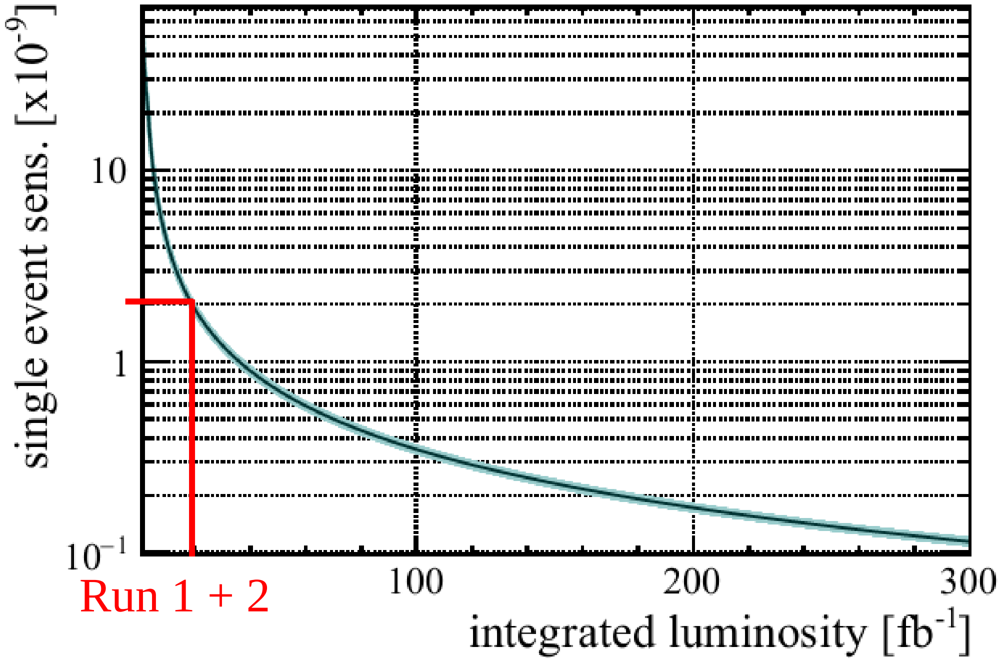
- Search for peak in the $m(\mu^+\mu^-)$ distribution of simulated $B^- \to \mu^+\mu^-\pi^-$ candidates
- Normalise to $B^- \to J/\psi(\to \mu^+\mu^-)K^-$decays

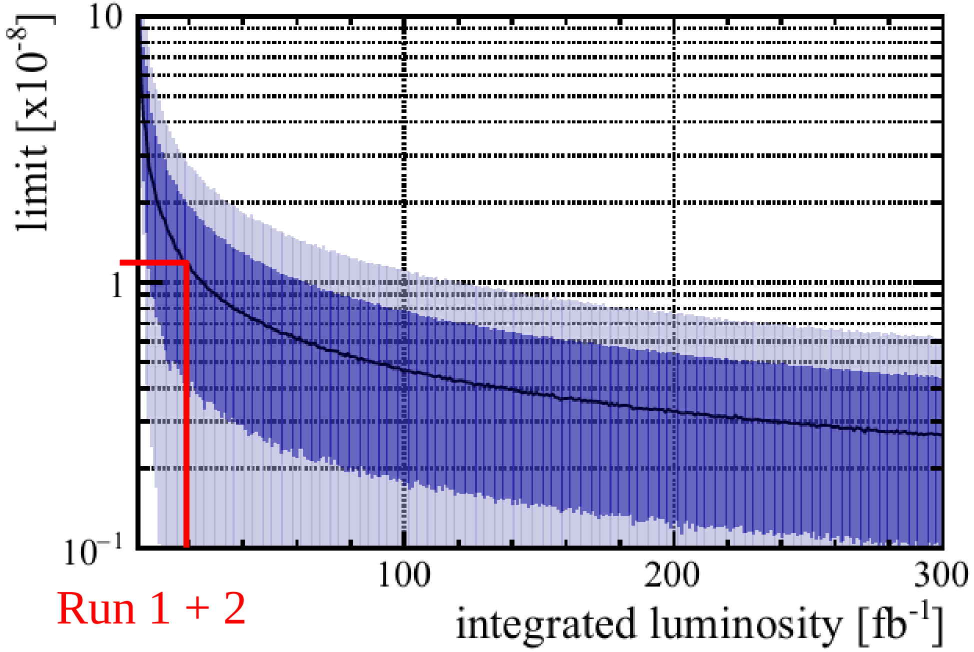
All known

$$\begin{aligned}\mathcal{B}\left(D^{*0}\to\mu^+\mu^-\right) &= \frac{N_{B^-\to D^{*0}\pi^-}}{N_{B^-\to J/\psi K^-}}\,\frac{\epsilon_{B^-\to J/\psi K^-}}{\epsilon_{B^-\to D^{*0}\pi^-}}\boxed{\frac{\mathcal{B}\left(B^-\to J/\psi K^-\right)}{\mathcal{B}\left(B^-\to D^{*0}\pi^-\right)}\mathcal{B}\left(J/\psi\to\mu^+\mu^-\right)}\\ &= \alpha_{D^{*0}\to\mu^+\mu^-}N_{B^-\to D^{*0}\pi^-}\end{aligned}$$

Single event sensitivity

Limit from simulated experiments including expected combinatorial, and non-res. $\mu^+\mu^-\pi^-$and $\mu^+\mu^-K^-$ bkg.





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

EPJ.C83.666(2023)

Analysis Strategy

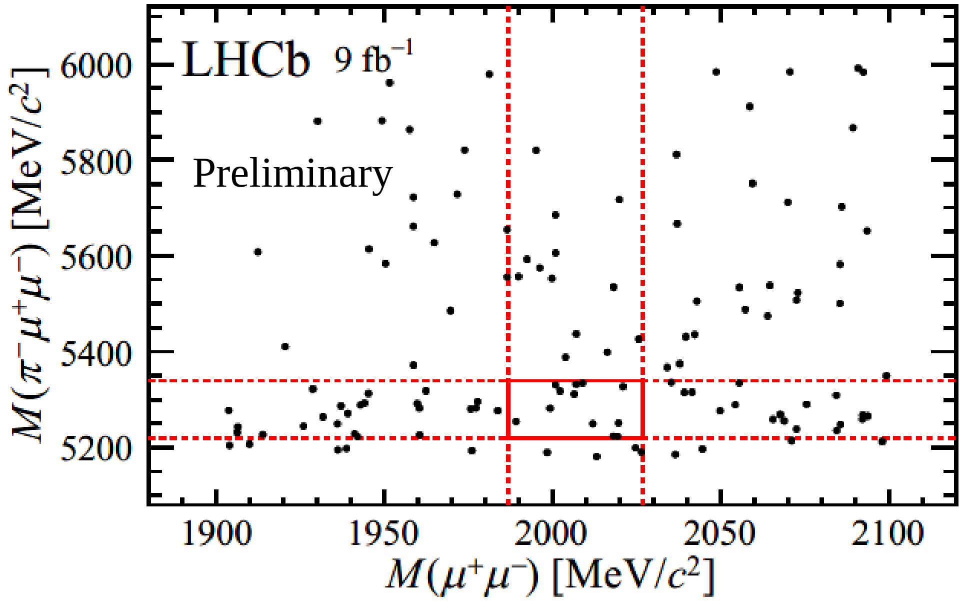
- Reconstruct $B^- \rightarrow D^{*0}(\mu^+\mu^-)\,\pi^-$ decays
- Use a BDT against combinatorial background (exploiting displaced vertex signature and kinematic properties)
- Use PID info to suppress $K \rightarrow \pi$ and $hh \rightarrow \mu\mu$ misID backgrounds
- Perform simultaneous ML fit to $m(D^{*0})$ and $m(B^-)$
- Fit includes: signal, non-resonant $B^+ \rightarrow \pi^+\mu^+\mu^-$, and misID $B^+ \rightarrow K^+\mu^+\mu^-$ decays, and combinatorial background

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

- Yields for all components vary freely in fit
- Fit converges to a slightly negative signal yield

$$N_{B^- \to D^{*0}\pi^-} = -2 \pm 3$$

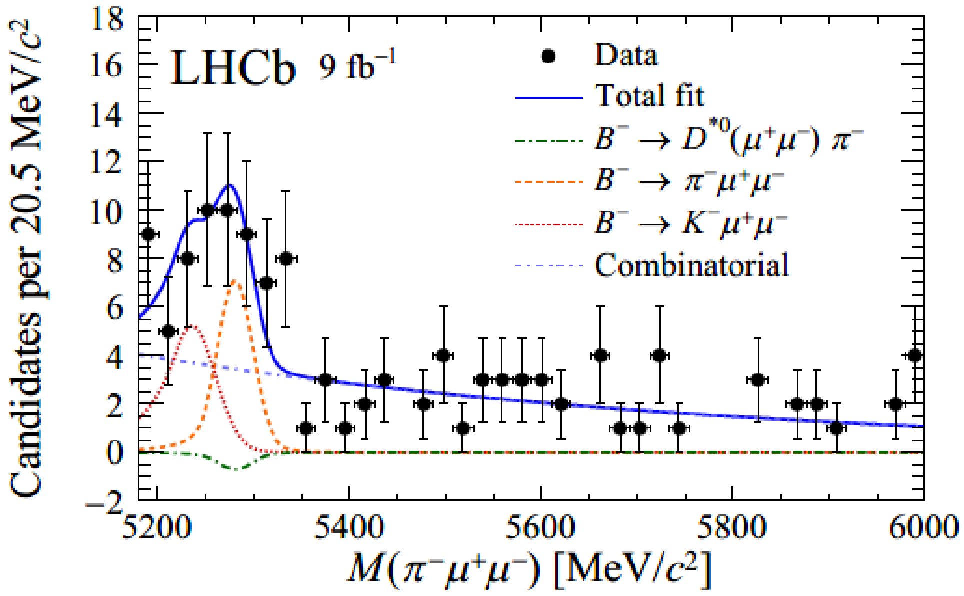
$\Rightarrow$ Attributed to under fluctuation of bkg. in sig. box

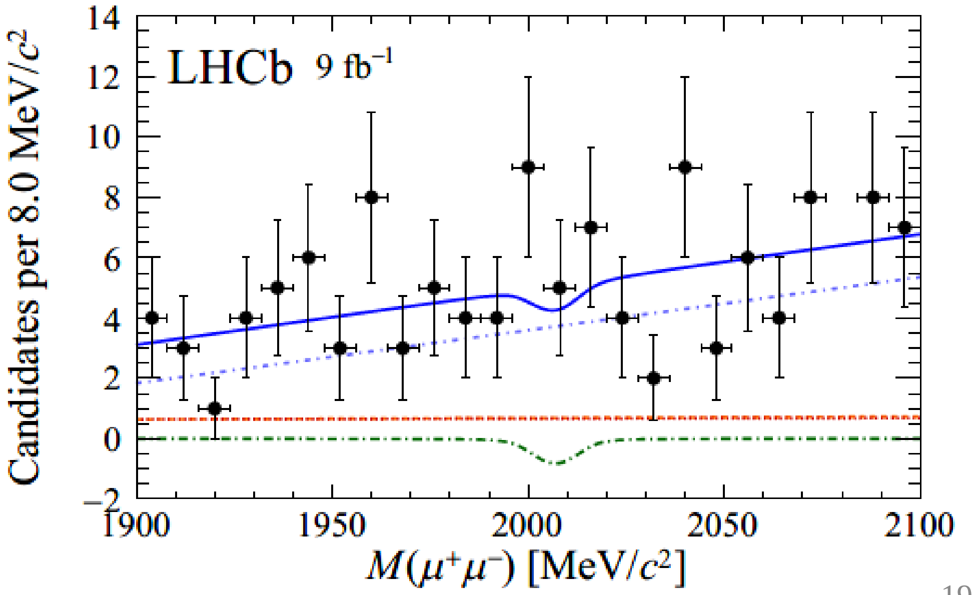


See F. Porter and I. Narsky

EPJ.C83.666(2023)

Signal mode fit





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

Signal yield $N_{B^- \to D^{*0}\pi^-}$ from fit translated into BF via

$$\mathcal{B}\left(D^{*0} \to \mu^+\mu^-\right) = \frac{N_{D^{*0}\pi^-}}{\boxed{N_{J/\psi K^-}}} \cdot \boxed{\frac{\varepsilon_{J/\psi K^-}}{\varepsilon_{D^{*0}\pi^-}}} \cdot \boxed{\frac{\mathcal{B}\left(B^- \to J/\psi K^-\right)}{\mathcal{B}\left(B^- \to D^{*0}\pi^-\right)} \cdot \mathcal{B}\left(J/\psi \to \mu^+\mu^-\right)}$$

Efficiency ratio

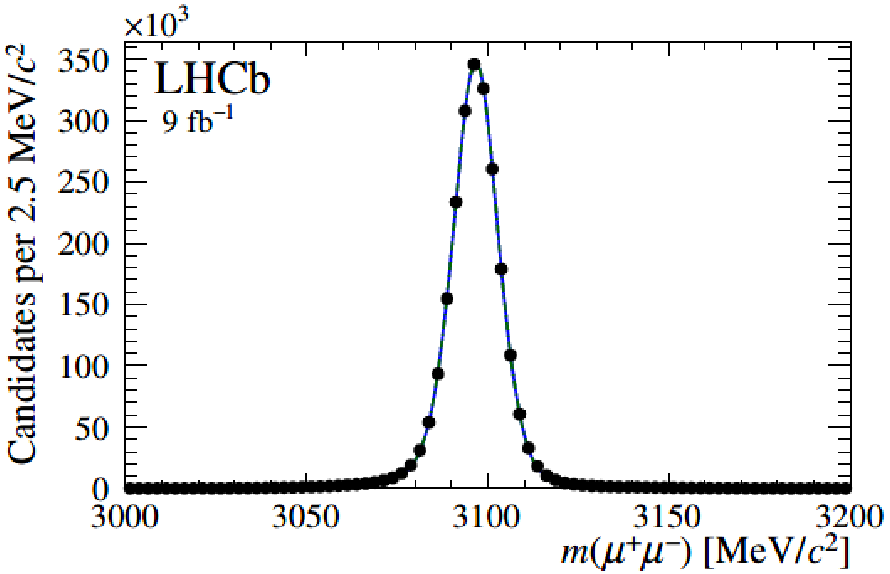
Known BFs

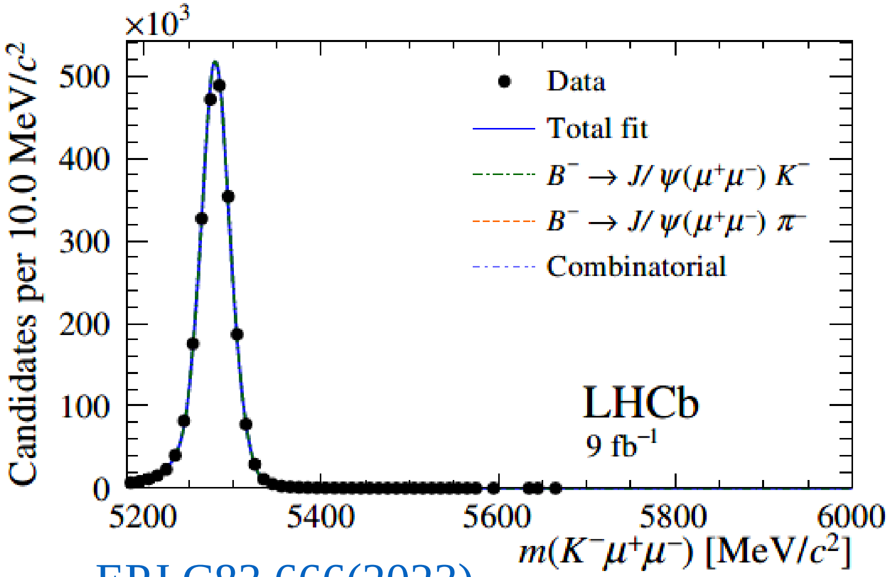
Normalisation yield

Normalisation yield from fits to $m(J/\psi)$ and $m(B^-)$ of $B^- \to J/\psi(\mu^+\mu^-)K^-$ decays

Efficiencies from sim. corrected for data/MC discrepancies

Normalisation mode fits





EPJ.C83.666(2023)

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

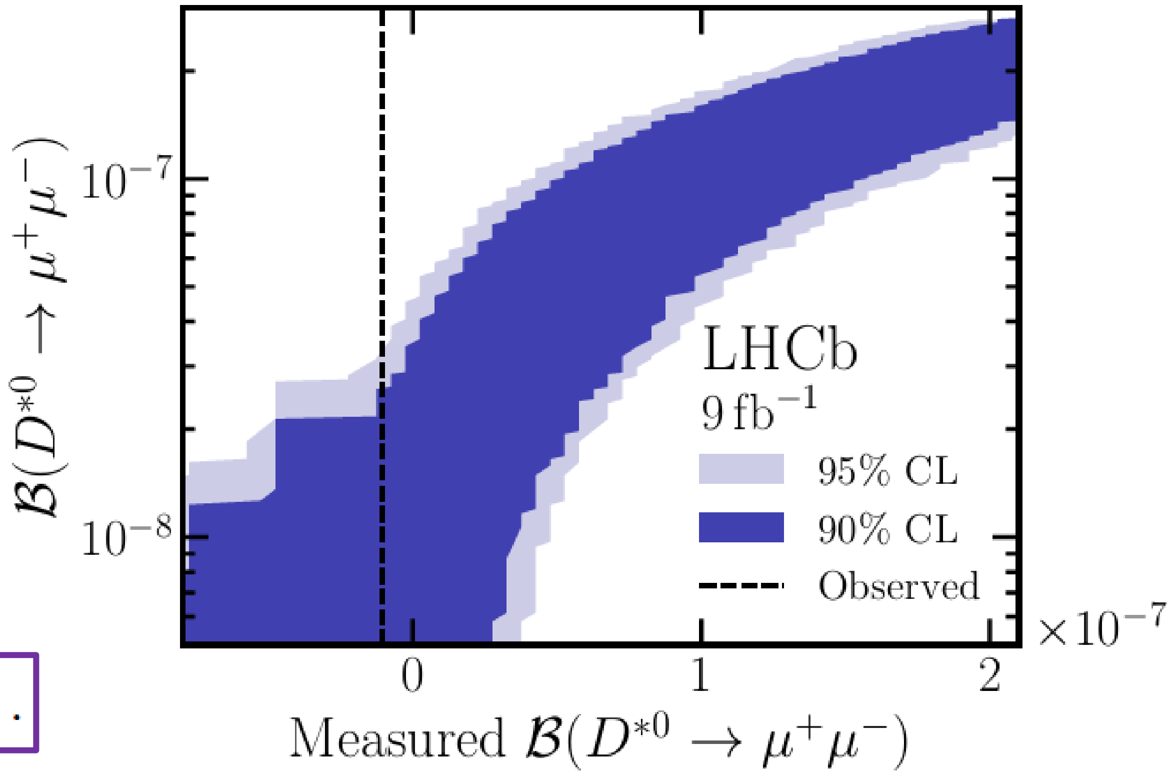
- Systematic uncertainties included as Gaussian constraints in signal mode fit
- Largest systematic originates from known BFs
- Results from fit to data

$$\mathcal{B}\,(D^{*0} \to \mu^+\mu^-) = (-1.06 \pm 1.85) \cdot 10^{-8}$$

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

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

Confidence belt based on FC prescription



EPJ.C83.666(2023)

$\Rightarrow$ Most stringent upper limit on $D^{*0} \to \ell^+\ell^-$ decays

$\Rightarrow$ First search of a rare charm-hadron decay exploiting production in beauty decays

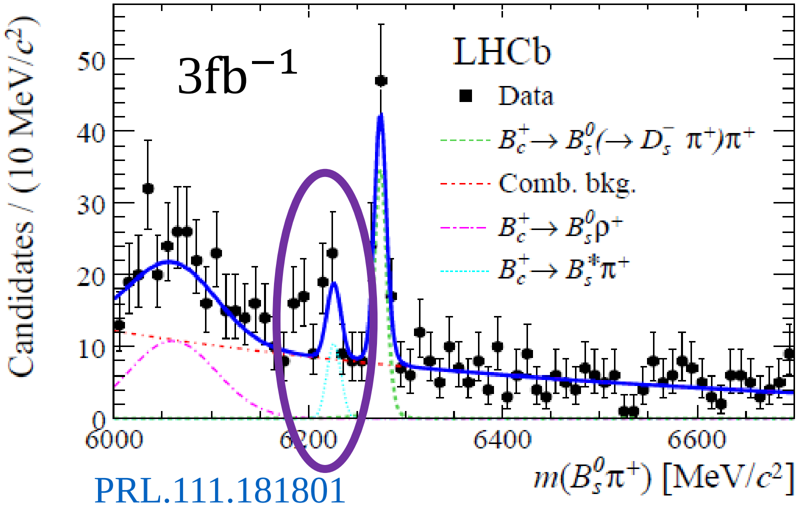
$\Rightarrow$ Confirms expectation: higher sensitivity than for prompt search

Can we search for $B_{(s)}^{*0} \to \mu^+\mu^-$ decays?

- Similarly to the D^{*0} search, most promising approach

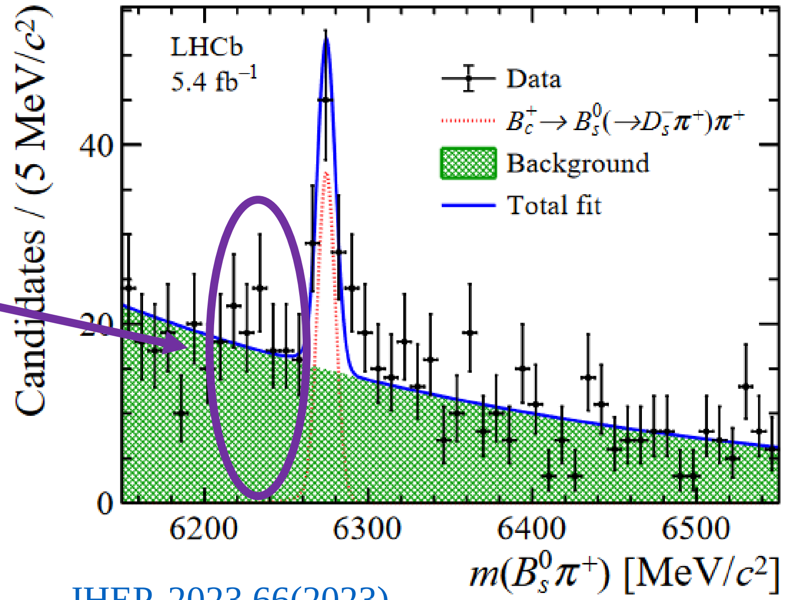
$\Rightarrow$ Search within $B_c^+ \to B_{(s)}^{*0}\pi^+$ decay chain EPJ.C82.459(2022)

$\Rightarrow$ Exploit displaced vertex signature to suppress bkg.



PRL.111.181801

- Missing ingredient: $\mathcal{B}(B_c^+ \to B_{(s)}^{*0}\pi^+)$
  - $\Rightarrow$ Possible via partial reconstruction technique
  - $\Rightarrow$ No evidence in latest analysis, but not optimised for this



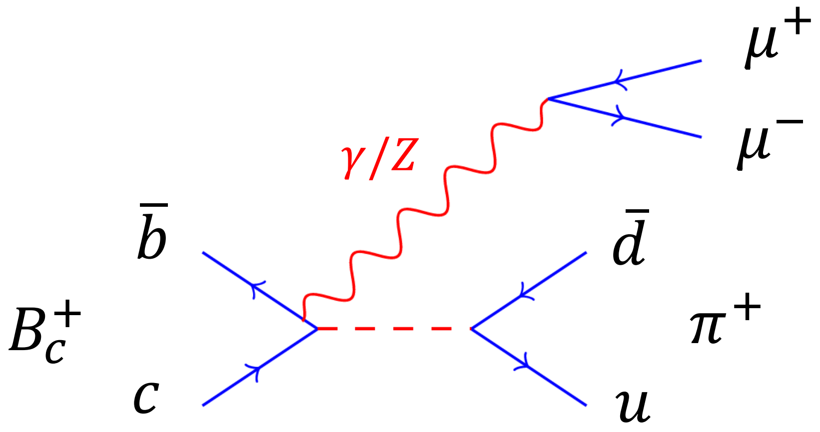
JHEP. 2023.66(2023)

Question: is there a nonresonant $B_c^+ \to \pi^+\mu^+\mu^-$ background?

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



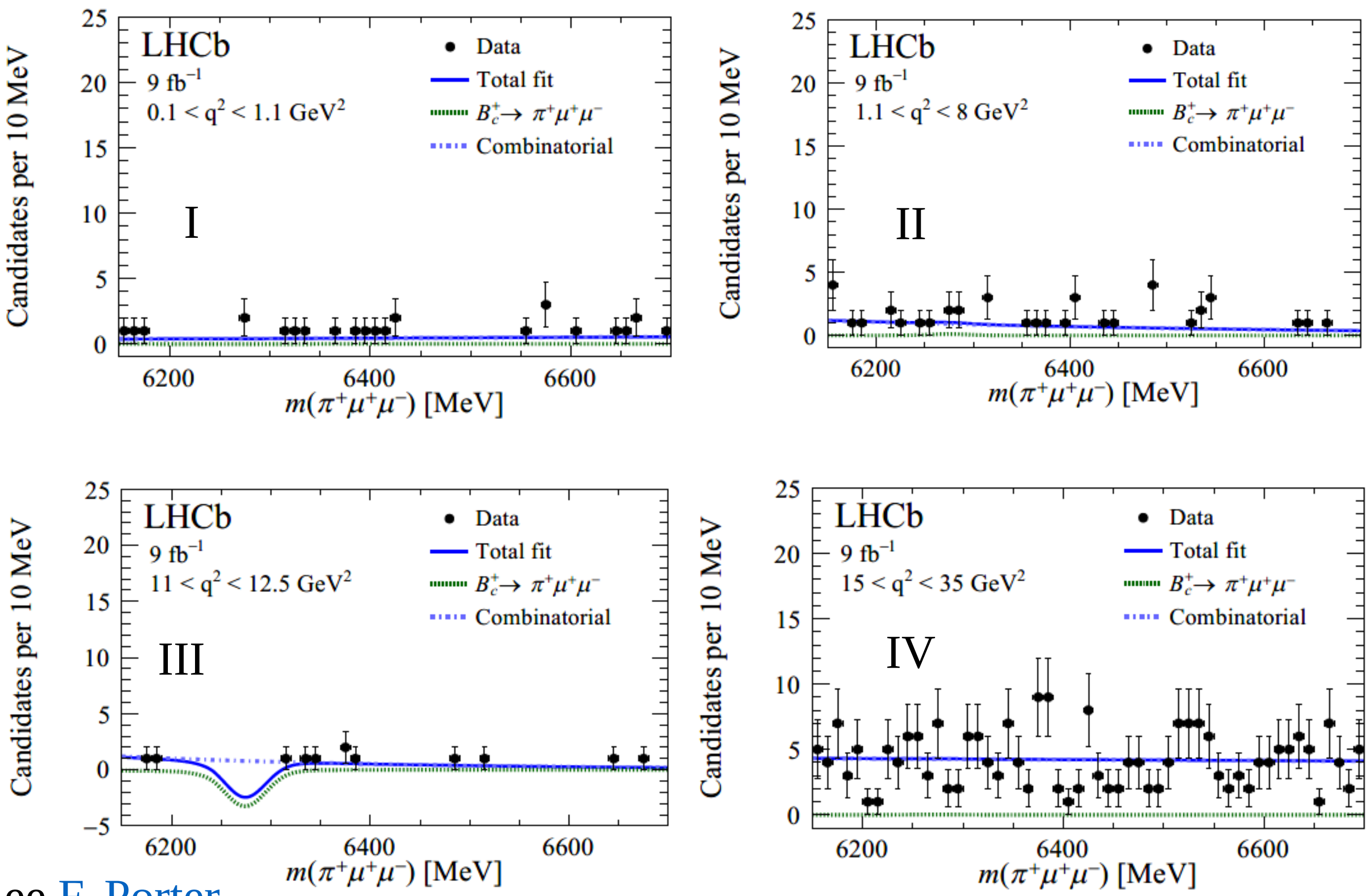
Analysis Strategy

- 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

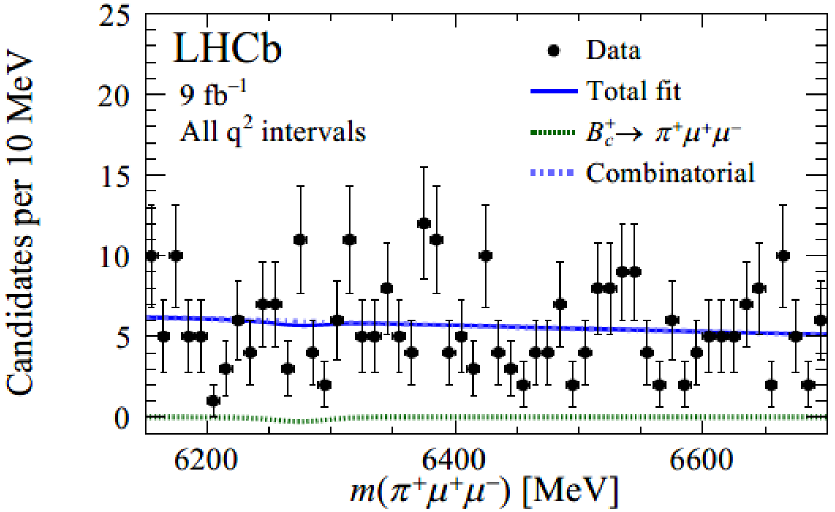
Search for $B_c^+ \to \pi^+\mu^+\mu^-$

- Fit includes signal and combinatorial background

Separate q^2 bins



All q^2 bins combined



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

See F. Porter and I. Narsky

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

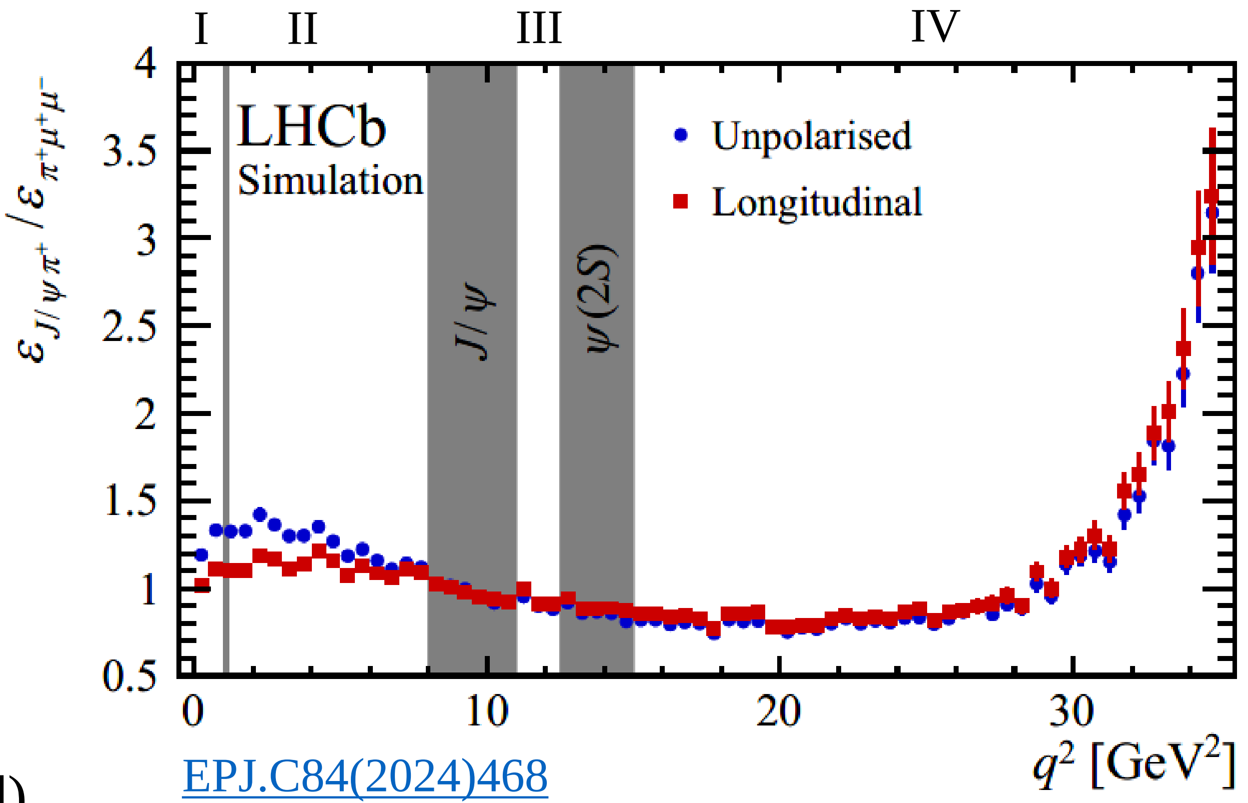
EPJ.C84(2024)468

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

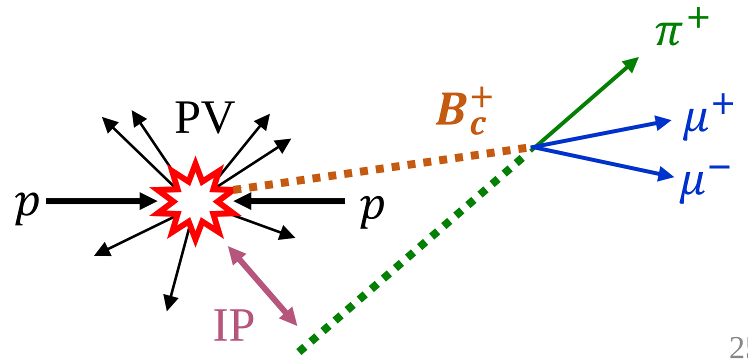
- Nonresonant $B_c^+ \to \pi^+\mu^+\mu^-$ simulated assuming a phase-space distribution
- Obtain model-independent results by assigning systematic uncertainty due to efficiency spread (largest syst. uncty.)
- Consider two extreme cases:
  - Dimuon system forms scalar state (unpolarised)
  - Dimuon system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

  $\Rightarrow$ Difference considered as systematic uncertainty

Efficiency ratio as function of q^2



EPJ.C84(2024)468



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

Normalise to $B_c^+ \to J/\psi(\mu^+\mu^-)\pi^+$ decays

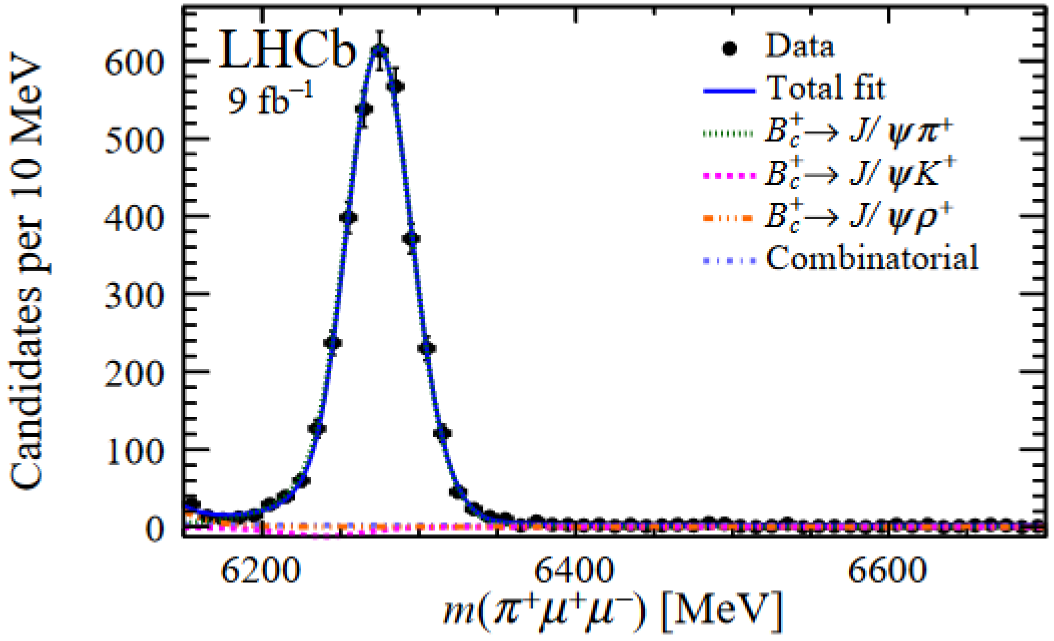
Efficiencies from simulation with data/MC corrections

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

Known

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

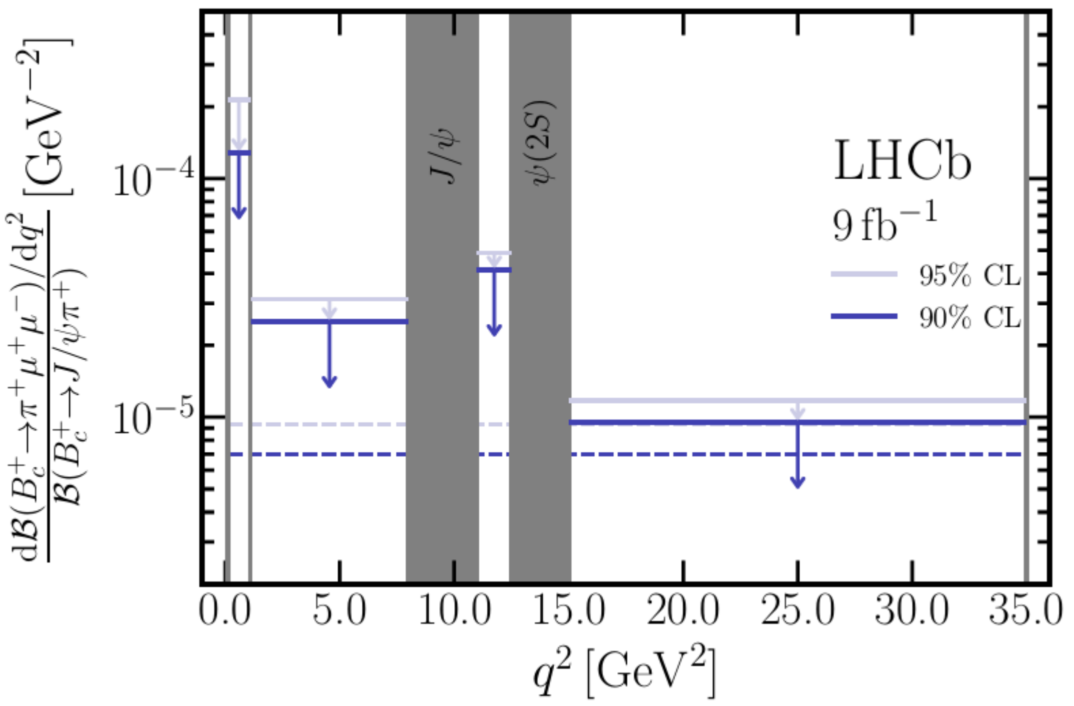
Normalisation mode fit



EPJ.C84(2024)468

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

Limit on differential branching fraction



- 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!

q^2 interval	$R_{\pi^+\mu^+\mu^-/J/\psi\pi^+}$	UL at 90% CL	UL at 95% CL
$0.1 < q^2 < 1.1\,\mathrm{GeV}^2$	$(-0.2\,^{+\,4.8}_{-\,3.5}\,^{+0.8}_{-0.7}) \times 10^{-5}$	1.3×10^{-4}	2.1×10^{-4}
$1.1 < q^2 < 8.0\,\mathrm{GeV}^2$	$(1.5\,^{+\,7.9}_{-\,6.4}\,^{+2.3}_{-1.4}) \times 10^{-5}$	1.7×10^{-4}	2.2×10^{-4}
$11.0 < q^2 < 12.5\,\mathrm{GeV}^2$	$(-28.4\,^{+10.5}_{-16.1}\,^{+1.4}_{-1.7}) \times 10^{-5}$	0.6×10^{-4}	0.7×10^{-4}
$15.0 < q^2 < 35.0\,\mathrm{GeV}^2$	$(0.2\,^{+11.5}_{-10.5}\,^{+3.4}_{-2.3}) \times 10^{-5}$	1.9×10^{-4}	2.3×10^{-4}
All	$(-3.0\,^{+15.0}_{-13.8}\,^{+2.4}_{-4.8}) \times 10^{-5}$	$\boxed{2.1\times10^{-4}}$	$\boxed{2.7\times10^{-4}}$

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

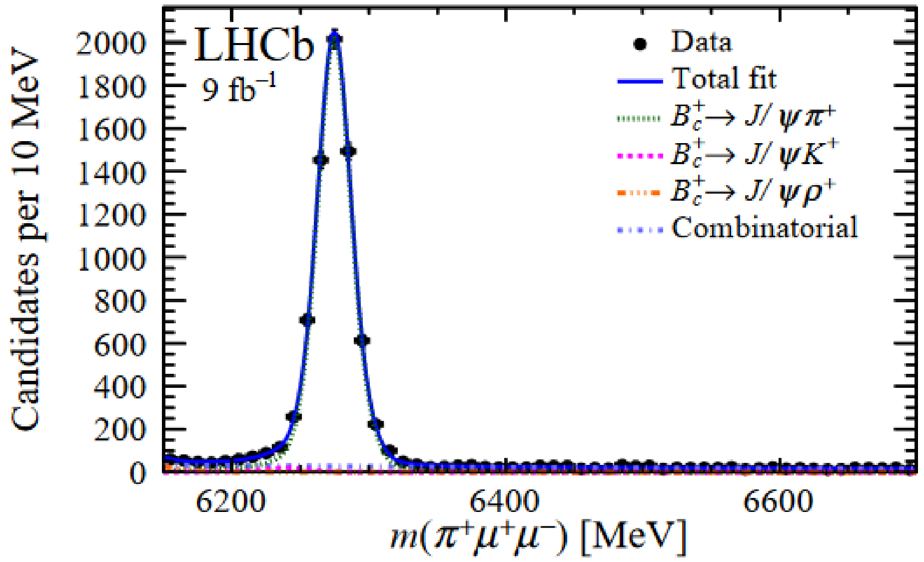
$$\frac{\mathcal{B}(B_c^+ \to \psi(2S)\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} = 0.254 \pm 0.018\,(\text{stat}) \pm 0.003\,(\text{syst}) \pm 0.005\,(\text{BF})$$

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

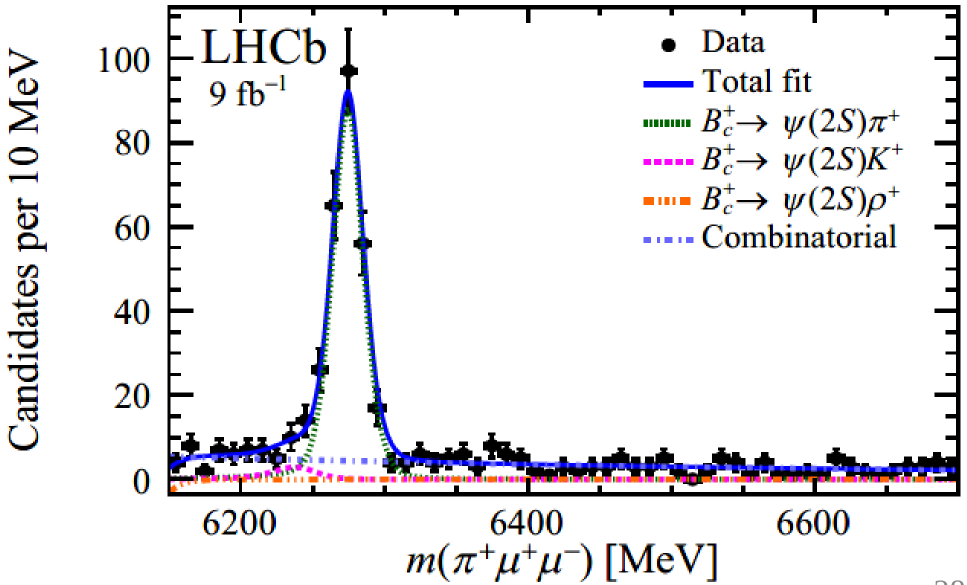
$\Rightarrow$ World's best measurement

EPJ.C84(2024)468

Normalisation mode fit



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



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

EPJ C85 (2025) 20

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 $m(\pi^+\mu^+\mu^-)$
- Fit includes

  Signal $B_c^+ \to B^{*0}(\mu^+\mu^-)\pi^+$

  Signal $B_c^+ \to B_s^{*0}(\mu^+\mu^-)\pi^+$ decays,

  and combinatorial bkg.

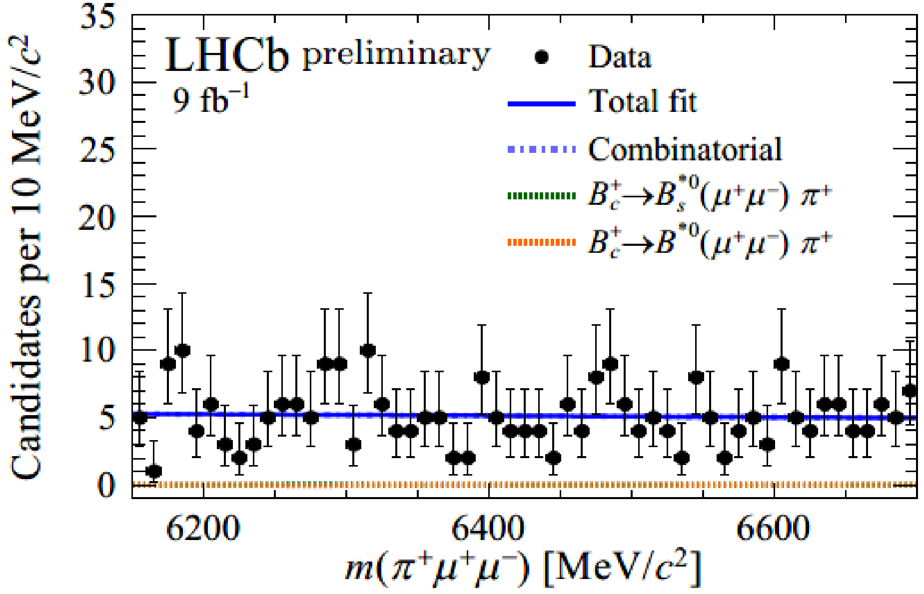
Search for $B^{*0}_{(s)} \to \mu^+\mu^-$ decays

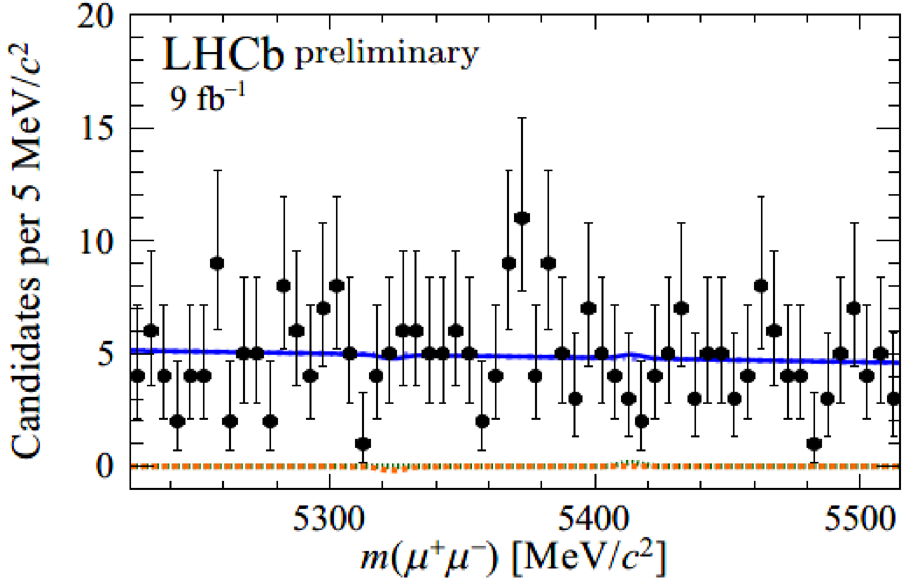
- No statistical dependency between signal yields

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

$\Rightarrow$ No signal observed for both decay modes

Signal mode fit

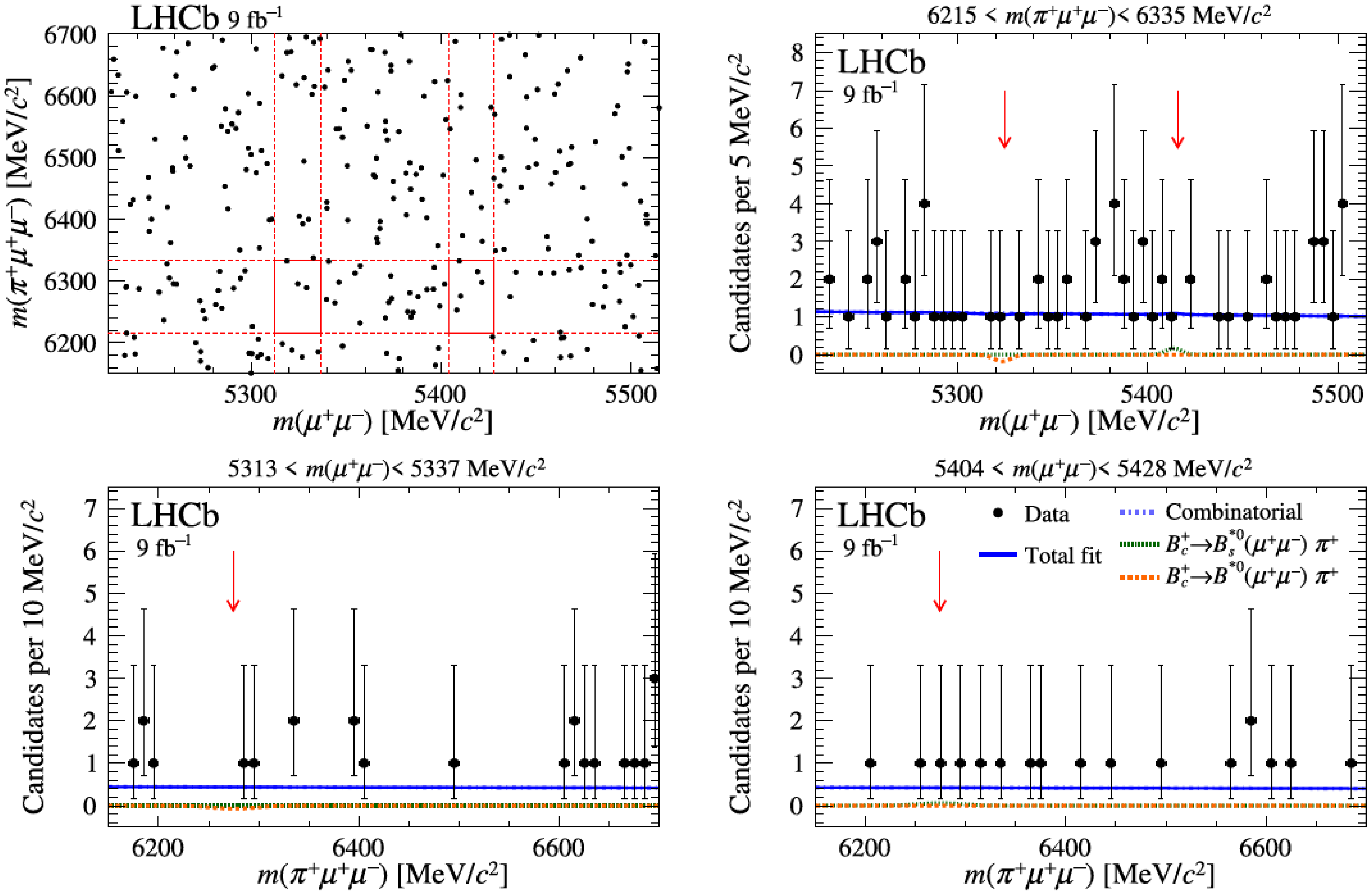




EPJ C85 (2025) 20

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

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



$\Rightarrow$ Nearly background free sample

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

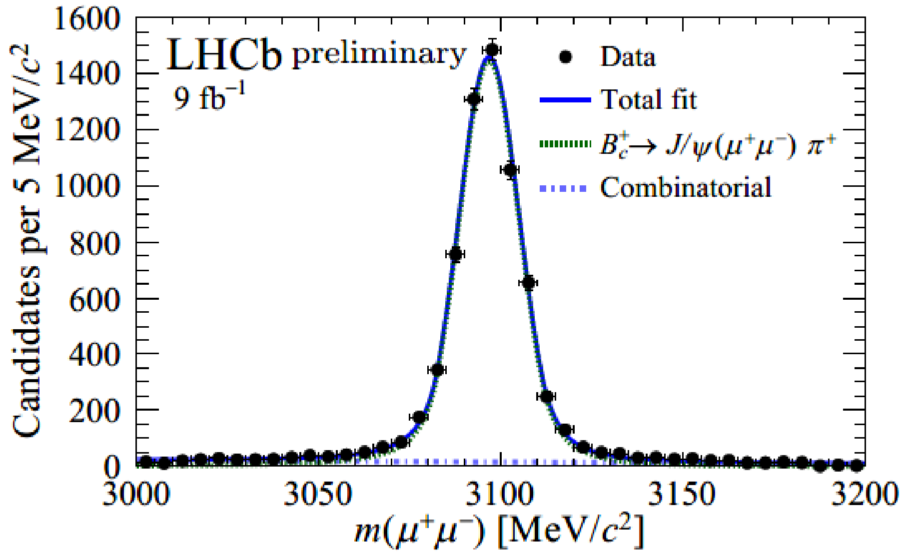
- Normalise to $B_c^+ \to J/\psi(\mu^+\mu^-)\pi^+$ decays
- Efficiencies from sim. corrected for data/MC discrepancies

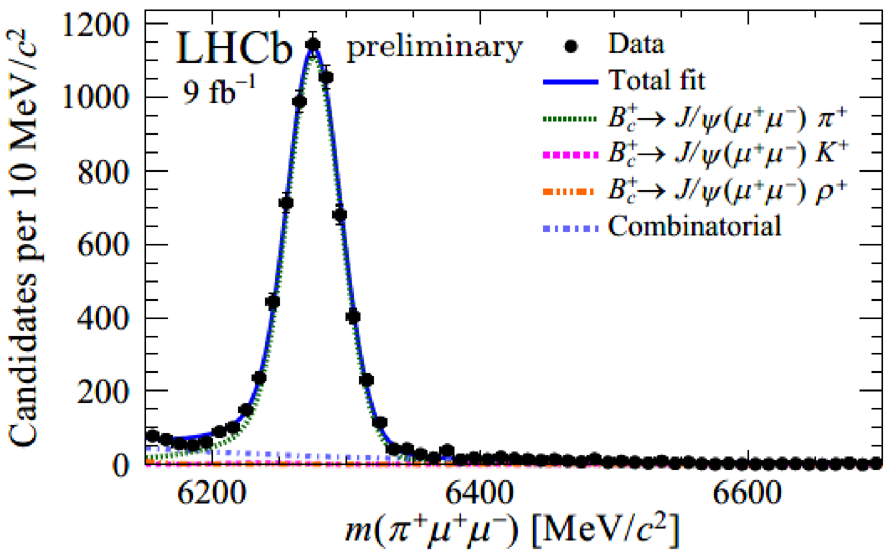
$$\mathcal{R}_{B_{(s)}^{*0}(\mu^+\mu^-)\pi^+/J/\psi\pi^+} \equiv \frac{\mathcal{B}(B_c^+ \to B_{(s)}^{*0}(\mu^+\mu^-)\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}$$

Known $\mathcal{B}$

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

Normalisation mode fits





EPJ C85 (2025) 20

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

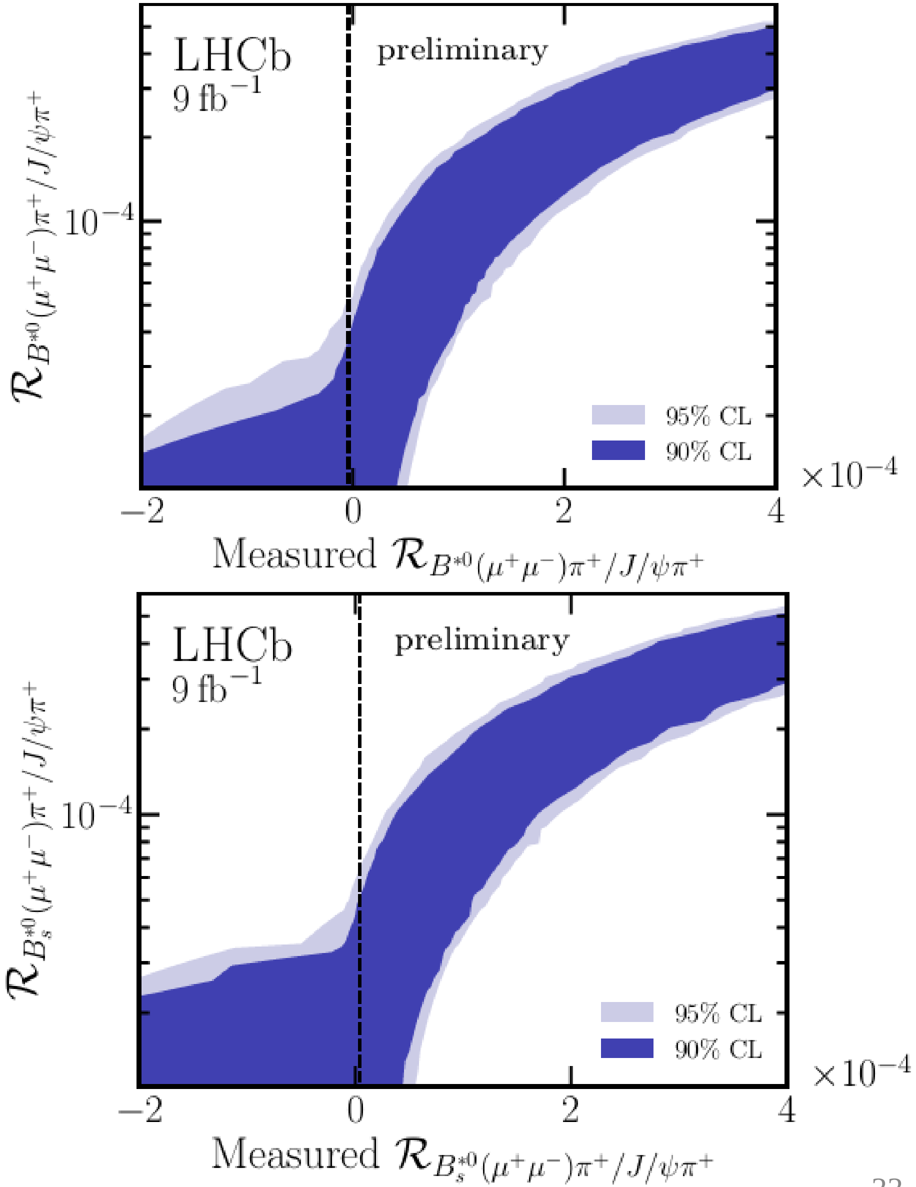
- Systematic uncertainties included as Gaussian constraints in signal mode fit
- Largest systematic due to data/MC discrepancies in muon impact parameters (but negligible impact)
- Results from fit to data

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

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

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

Confidence belts based on FC prescription



EPJ C85 (2025) 20

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

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

- No measurement yet of $\mathcal{B}(B_c^+ \to B_s^{*0}\pi^+)$ In progress!

$\Rightarrow$ Assuming

$$\boxed{\frac{\mathcal{B}(B_c^+ \to B_s^{*0}\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}} \approx \left|\frac{V_{cs}}{V_{cb}}\right|^2 \approx 6 \cdot 10^2 \Rightarrow \mathcal{B}(B_s^{*0} \to \mu^+\mu^-) \lesssim 10^{-7}$$

Missing piece

- More challenging for $\mathcal{B}(B_c^+ \to B^{*0}\pi^+)$ due to Cabibbo suppression

$\Rightarrow \mathcal{B}(B^{*0} \to \mu^+\mu^-) \lesssim 10^{-6}$

Summary and outlook

- Extremely rare $V \to \mu^+\mu^-$ decays provide complementary constraints on non-SM contributions
- New search method exploiting displaced vertex signature in exclusive hadronic B decays

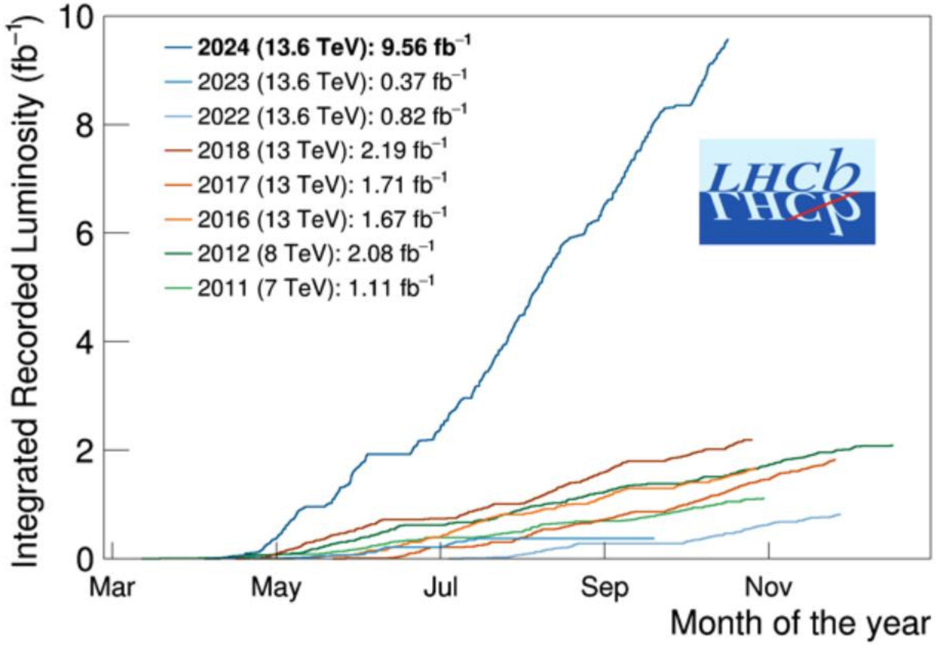
$\Rightarrow$ World first (best) upper limits with LHCb Run 1+2 (9 fb^{-1})

- Expect $\approx$ 300 fb^{-1} with Upgrade I + II (Runs 3 - 6)
- Implemented dedicated trigger lines $\Rightarrow$ higher efficiency (already in Run 3)
- Improved VELO in Upgrade I and II $\Rightarrow$ better IP resolution

$\Rightarrow$ Better trigger and reco efficiency for B_c^+

$\Rightarrow$ Good prospects although still not clear if SM level in reach

- Interesting to see what ATLAS and CMS can do



Thanks!

Backup

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

EPJ.C83.666(2023)

Table 1 Yields obtained from the fit to data described in the text, with statistical uncertainties only

Component	Yield
$B^- \to D^{*0}(\mu^+\mu^-)\pi^-$	-2 ± 3
$B^- \to \pi^-\mu^+\mu^-$	17 ± 7
$B^- \to K^-\mu^+\mu^-$	17 ± 8
Combinatorial bkg.	90 ± 13

Table 2 Input parameters used in the estimation of the $D^{*0} \to \mu^+\mu^-$ branching fraction. The uncertainties correspond to the statistical and systematic uncertainties added in quadrature

Parameter	Value
$\mathcal{B}\left(B^- \to J/\psi K^-\right)$	$(10.20 \pm 0.19) \times 10^{-4}$ [25]
$\mathcal{B}\left(B^- \to D^{*0}\pi^-\right)$	$(4.90 \pm 0.17) \times 10^{-3}$ [25]
$\mathcal{B}\left(J/\psi \to \mu^+\mu^-\right)$	$(59.61 \pm 0.33) \times 10^{-3}$ [25]
$\varepsilon_{J/\psi K^-}/\varepsilon_{D^{*0}\pi^-}$	1.21 ± 0.03
$N_{J/\psi K^-}$	$(2316 \pm 8) \times 10^3$

$$\alpha_{\text{SES}} = (6.5 \pm 0.3) \cdot 10^{-9}$$

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

EPJ.C84(2024)468

Table 3 Yields obtained from the $B_c^+ \to J/\psi\pi^+$ fits to data at the two working points as described in the text, with statistical uncertainties only

Component	$\pi^+\mu^+\mu^-$ WP	$\psi(2S)\pi^+$ WP
$B_c^+ \to J/\psi\pi^+$	3508 ± 82	6887 ± 93
$B_c^+ \to J/\psi K^+$	-81 ± 58	90 ± 43
$B_c^+ \to J/\psi\rho^+$	41 ± 11	56 ± 22
Comb. bkg.	101 ± 25	1254 ± 60

Table 4 Yields obtained from the $B_c^+ \to \psi(2S)\pi^+$ fit to data described in the text, with statistical uncertainties only

Component	Yield
$B_c^+ \to \psi(2S)\pi^+$	256 ± 18
$B_c^+ \to \psi(2S)K^+$	13 ± 10
$B_c^+ \to \psi(2S)\rho^+$	-4 ± 5
Comb. bkg.	197 ± 19

Table 5 Efficiency ratios between signal and normalisation modes. The values of $\varepsilon_{J/\psi\pi^+}/\varepsilon_{\pi^+\mu^+\mu^-}$ are provided for each q^2 interval and for all intervals combined. The uncertainty on the ratio combines statistical and systematic effects

Signal decay mode		$\varepsilon_{J/\psi\pi^+}/\varepsilon_{\pi^+\mu^+\mu^-}$
$B_c^+ \to \pi^+\mu^+\mu^-$	(low)	1.26 ± 0.24
	(central)	1.27 ± 0.18
	(intermediate)	0.91 ± 0.04
	(high)	0.86 ± 0.24
	(all)	1.01 ± 0.27
$B_c^+ \to \psi(2S)\pi^+$		0.91 ± 0.01

Table 36: External branching fractions obtained from the PDG [2].

Parameter	Value
$\mathcal{B}(J/\psi \to \mu^+\mu^-)$ $[10^{-3}]$	59.61 ± 0.33
$\mathcal{B}(\psi(2S) \to \mu^+\mu^-)$ $[10^{-3}]$	8.0 ± 0.6
$\mathcal{B}(J/\psi \to e^+e^-)$ $[10^{-3}]$	59.71 ± 0.32
$\mathcal{B}(\psi(2S) \to e^+e^-)$ $[10^{-3}]$	7.93 ± 0.17

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

EPJ C85 (2025) 20

Table 1 Yields obtained from the fit to data described in the text, with statistical uncertainties only

Component	Yield
$B_c^+ \to B^{*0}(\mu^+\mu^-)\pi^+$	$-0.4^{+1.9}_{-1.1}$
$B_c^+ \to B_s^{*0}(\mu^+\mu^-)\pi^+$	$0.4^{+2.2}_{-1.3}$
Combinatorial background	282 ± 17

$$\alpha^{\text{SES}}_{B^{*0}\pi^+} = (1.04 \pm 0.05) \cdot 10^{-5}\,,$$
$$\alpha^{\text{SES}}_{B_s^{*0}\pi^+} = (1.13 \pm 0.05) \cdot 10^{-5}\,.$$

Table 2 Input parameters used in the estimation of the ratio $\mathcal{R}_{B^{*0}_{(s)}(\mu^+\mu^-)\pi^+/J/\psi\pi^+}$. The $J/\psi \to \mu^+\mu^-$ branching fraction and its uncertainty are taken from Ref. [18]. For the $B_c^+ \to J/\psi\pi^+$ yield the uncertainties are statistical and systematic, respectively; all other uncertainties are systematic

Parameter	Value
$\mathcal{B}\left(J/\psi \to \mu^+\mu^-\right)$	$(59.61 \pm 0.33) \times 10^{-3}$
$N_{J/\psi\pi^+}$	$6213 \pm 89 \pm 27$
$\varepsilon_{J/\psi\pi^+}/\varepsilon_{B^{*0}\pi^+}$	1.09 ± 0.05
$\varepsilon_{J/\psi\pi^+}/\varepsilon_{B_s^{*0}\pi^+}$	1.18 ± 0.05

Semi-inclusive searches

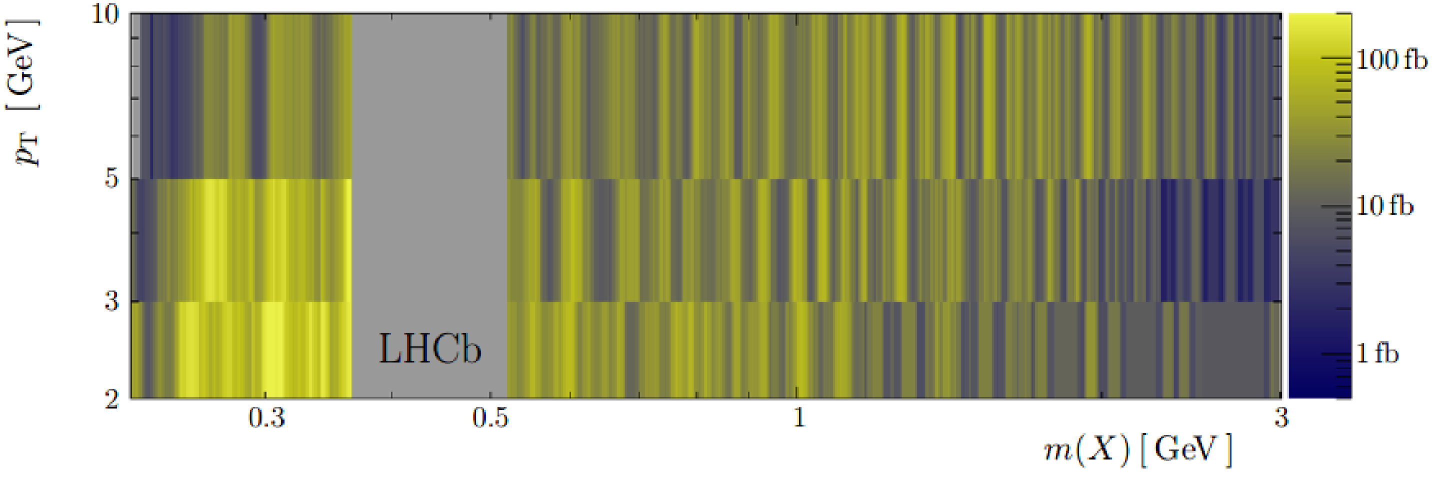
- Search for D^{*0}, $B^{*0}_{(s)} \to \mu\mu$ decays from a displaced (b-hadron) decay vertex
- Example:

$$N_{D^{*0}\to\mu^+\mu^-} = \mathcal{L}\mathcal{B}\left(D^{*0}\to\mu^+\mu^-\right)\sum_i \sigma_{B_i}\mathcal{B}\left(B_i\to D^{*0}X\right)\epsilon_{B_i\to D^{*0}X}$$

$\Rightarrow$ Production cross sections and inclusive branching fractions known for dominant $B^{\pm(0)}$ hadrons (in the D^{*0} case).

$\Rightarrow$ Analysis in principle possible, but worse dimuon mass resolution and higher irreducible backgrounds

Limit at 90% CL on $\sigma(X)\cdot\mathcal{B}(X\to\mu\mu)$ JHEP10(2020)156



$\Rightarrow$ Most likely less sensitive than exclusive searches

Search for $D^0 \rightarrow \mu^+\mu^-$ decays

- Signal mode fit performed simultaneously in 3 BDT intervals
- MisID background yields constrained based on simulation and PDG
- Results from fit

$$N_{D^0 \rightarrow \mu^+\mu^-} = 79 \pm 45$$

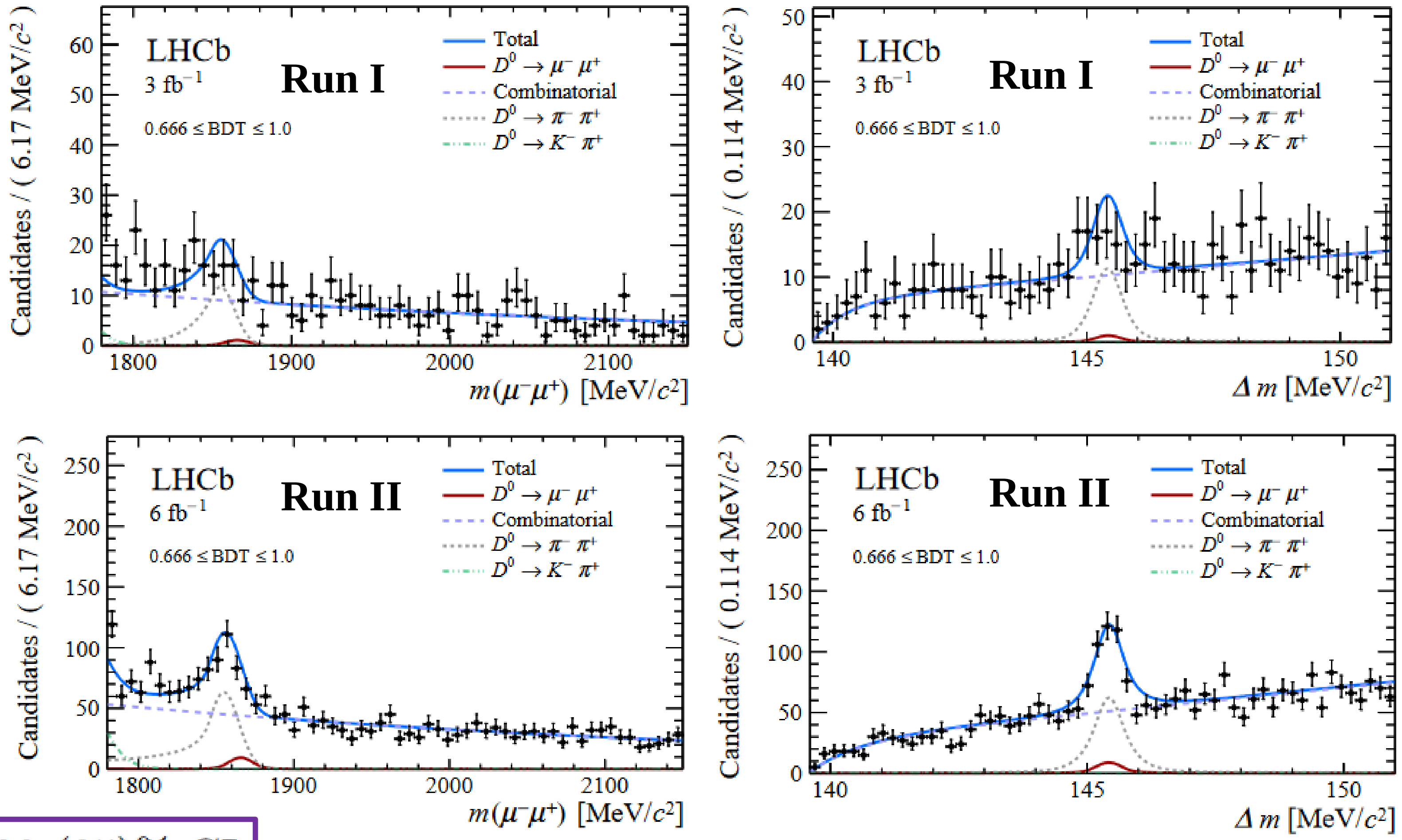
$$\Downarrow$$

$$\boxed{\mathcal{B}(D^0 \rightarrow \mu^+\mu^-) = (1.7 \pm 1.0) \cdot 10^{-9}}$$

$\Rightarrow$ Upper limit on branching fraction based on CLs method

$$\boxed{\mathcal{B}(D^0 \rightarrow \mu^+\mu^-) < 2.94\,(3.25) \times 10^{-9} \text{ at } 90\ (95)\% \text{ CL}}$$

Signal mode fit for most sensitive BDT interval



PRL.131.041804

$\Rightarrow$ Improvement by factor ≈ 2 wrt. previous result and most stringent limit of FCNC in charm sector