Rare decays and searches for exotic signatures at LHCb: Purely leptonic decays

Titus Mombächer on behalf of the LHCb collaboration

IGFAE, Universidade de Santiago de Compostela

Moriond QCD 2021

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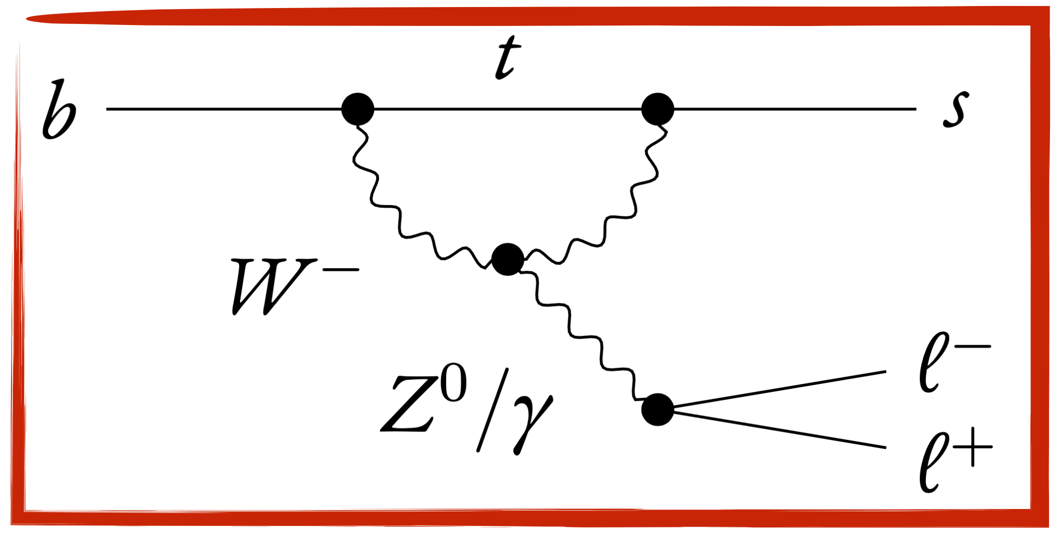
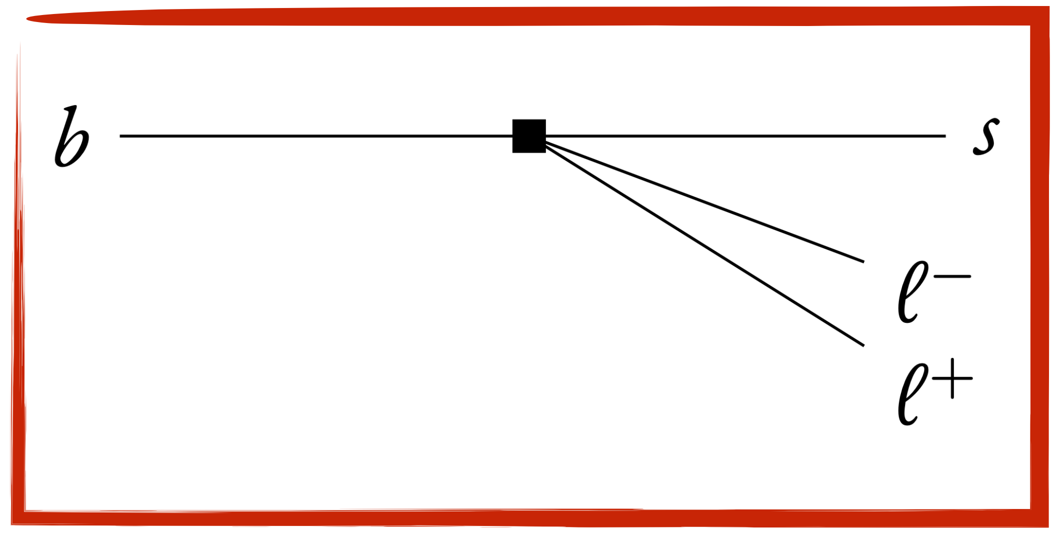
titus.mombacher@cern.ch

Rare decays - indirect searches for New Physics (NP)

- Series of deviations wrt Standard Model (SM) in $b \to s\ell\ell$ measurements
- Effective Field Theory: **consistent pattern** with modification of muonic C_9 (vector) and C_{10} (axial-vector) couplings



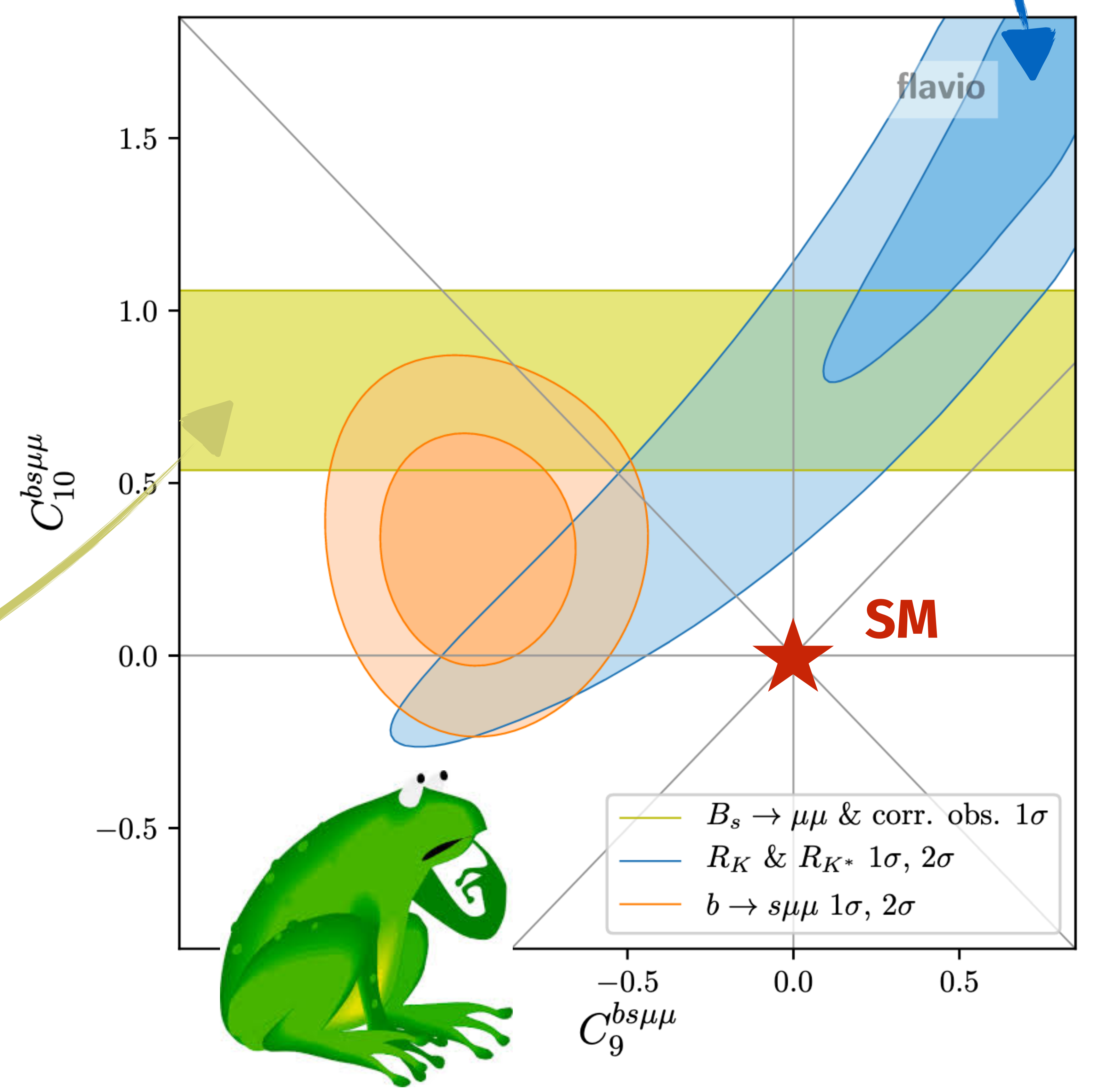


- **$B^0_{(s)} \to \ell^+\ell^-$ sensitive to C_{10} in SM**
  - FCNC and helicity suppressed
  - NP scalar or pseudo-scalar contributions would lift helicity suppression

Today!

See talk by Davide

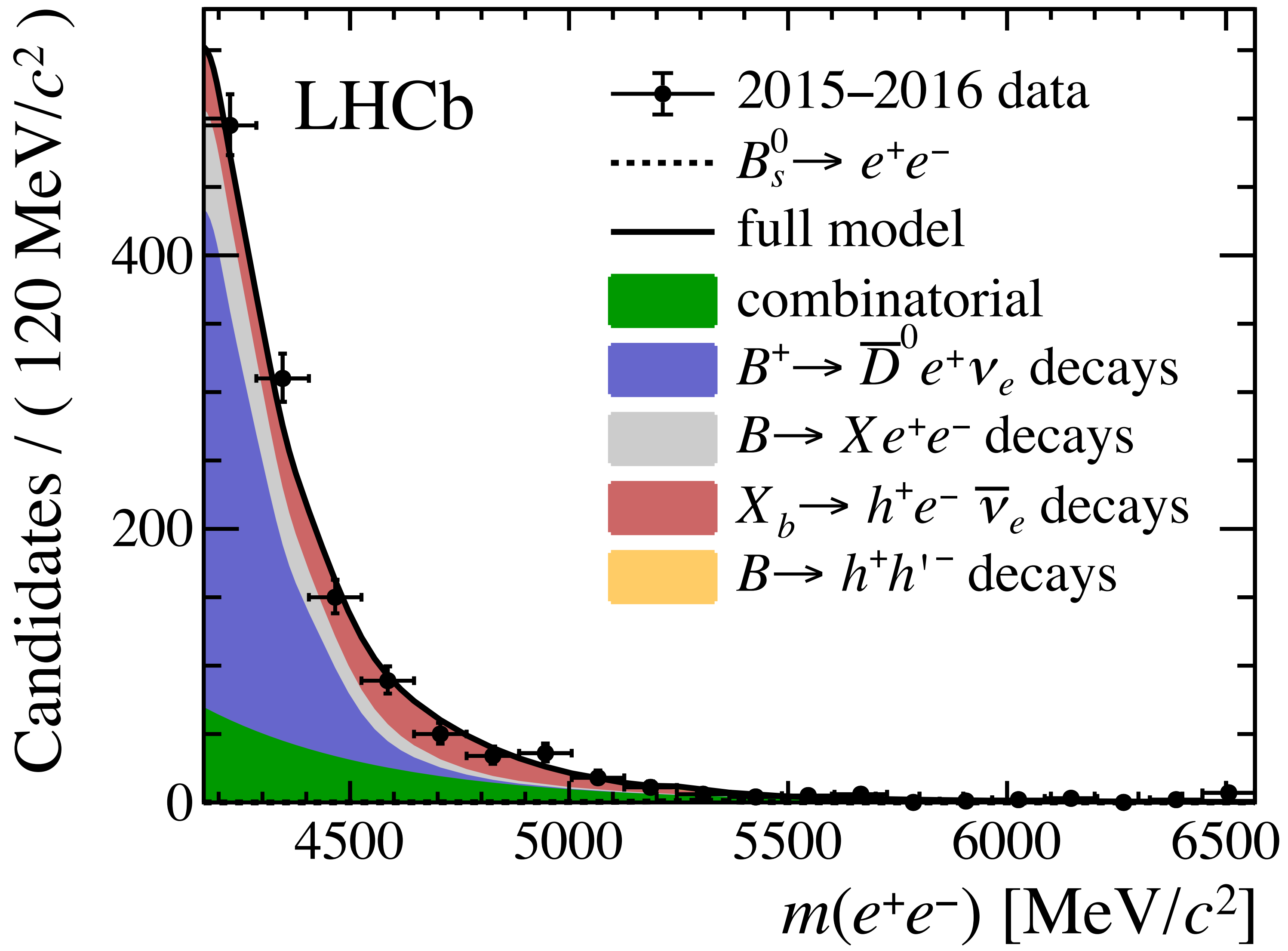
[P. Stangl, La Thuile 2021*]



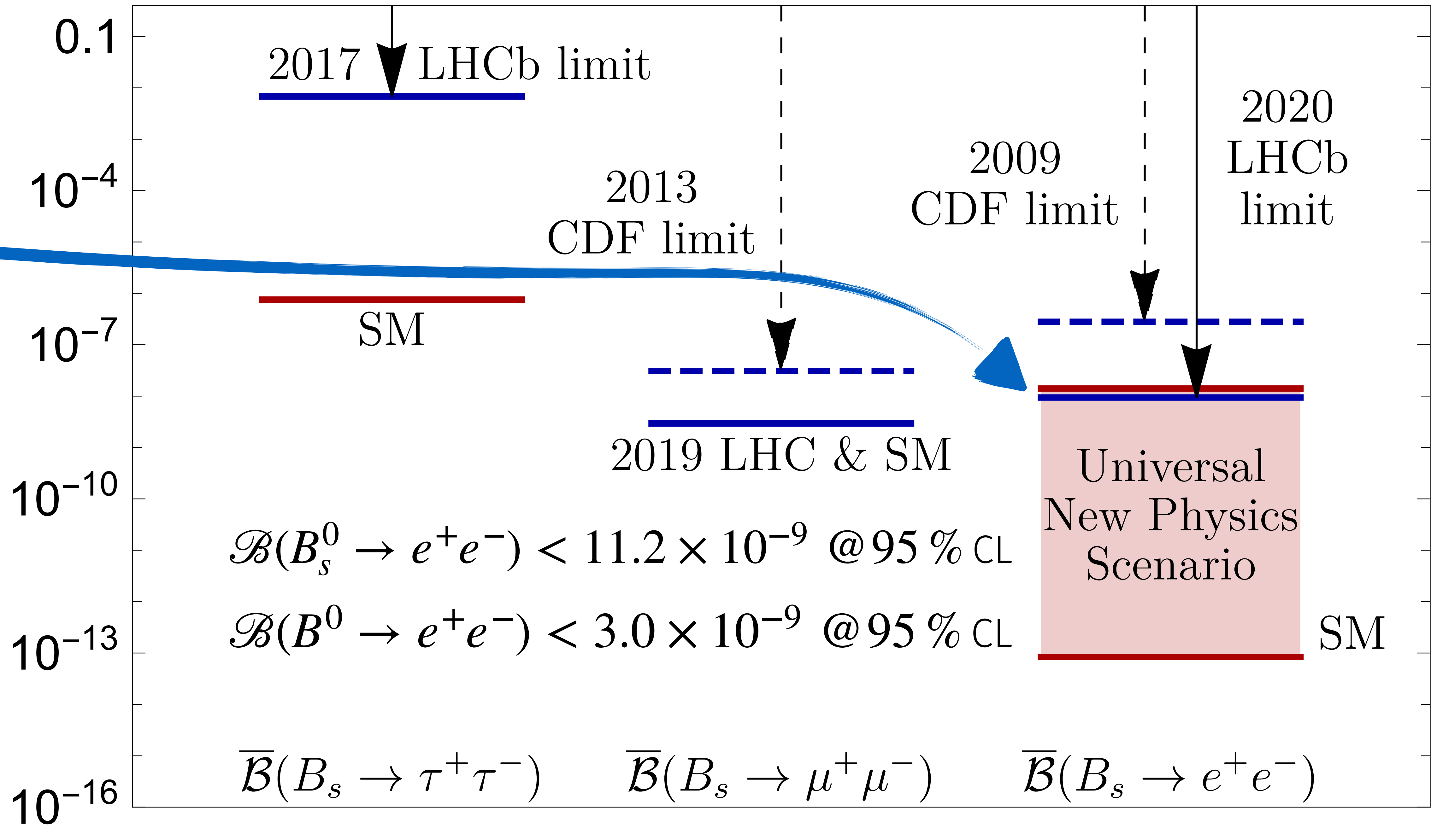
* updated in [arXiv:2103.13370], similar global fits by others, e.g. Marcel later

State of the art in $B^0_{(s)} \to \ell^+\ell^-$ processes

[PRL 124 (2020) 211802]



[Fleischer et al., JHEP 05 (2017) 156]



Good sensitivity due to

- large data set
- clean displaced B vertex signature

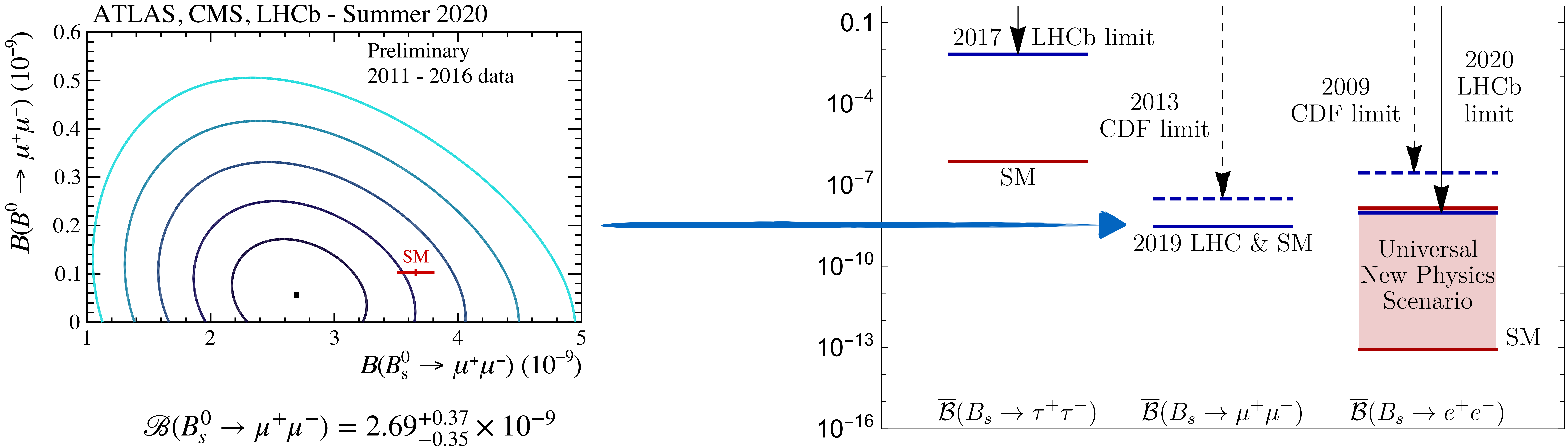
Exploit bremsstrahlung effects in the detector to suppress misID decays.

$B^0_{(s)} \to e^+e^-$ decays become sensitive to New Physics scenarios

State of the art in $B^0_{(s)} \to \ell^+\ell^-$ processes

[LHCb-CONF-2020-002, CMS PAS BPH-20-003, ATLAS-CONF-2020-049]

[Fleischer et al., JHEP 05 (2017) 156]



$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 2.69^{+0.37}_{-0.35} \times 10^{-9}$$

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

Entering precision regime with $B^0_{(s)} \to \mu^+\mu^-$ decays

New LHCb measurement of $B^0_{(s)} \to \mu^+\mu^-(\gamma)$

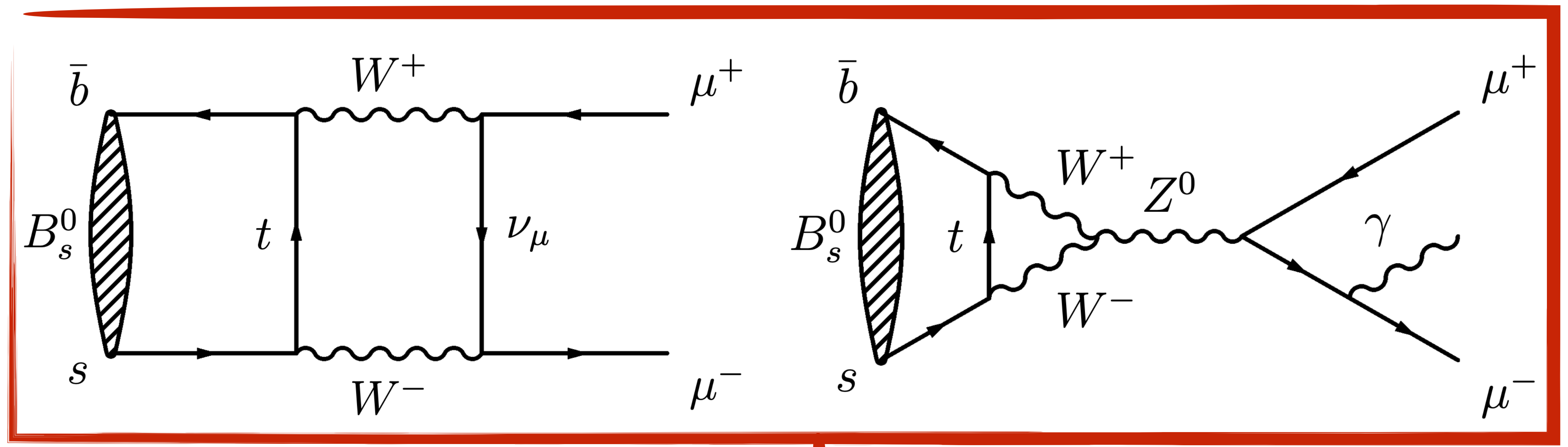
- Very clean theory predictions

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

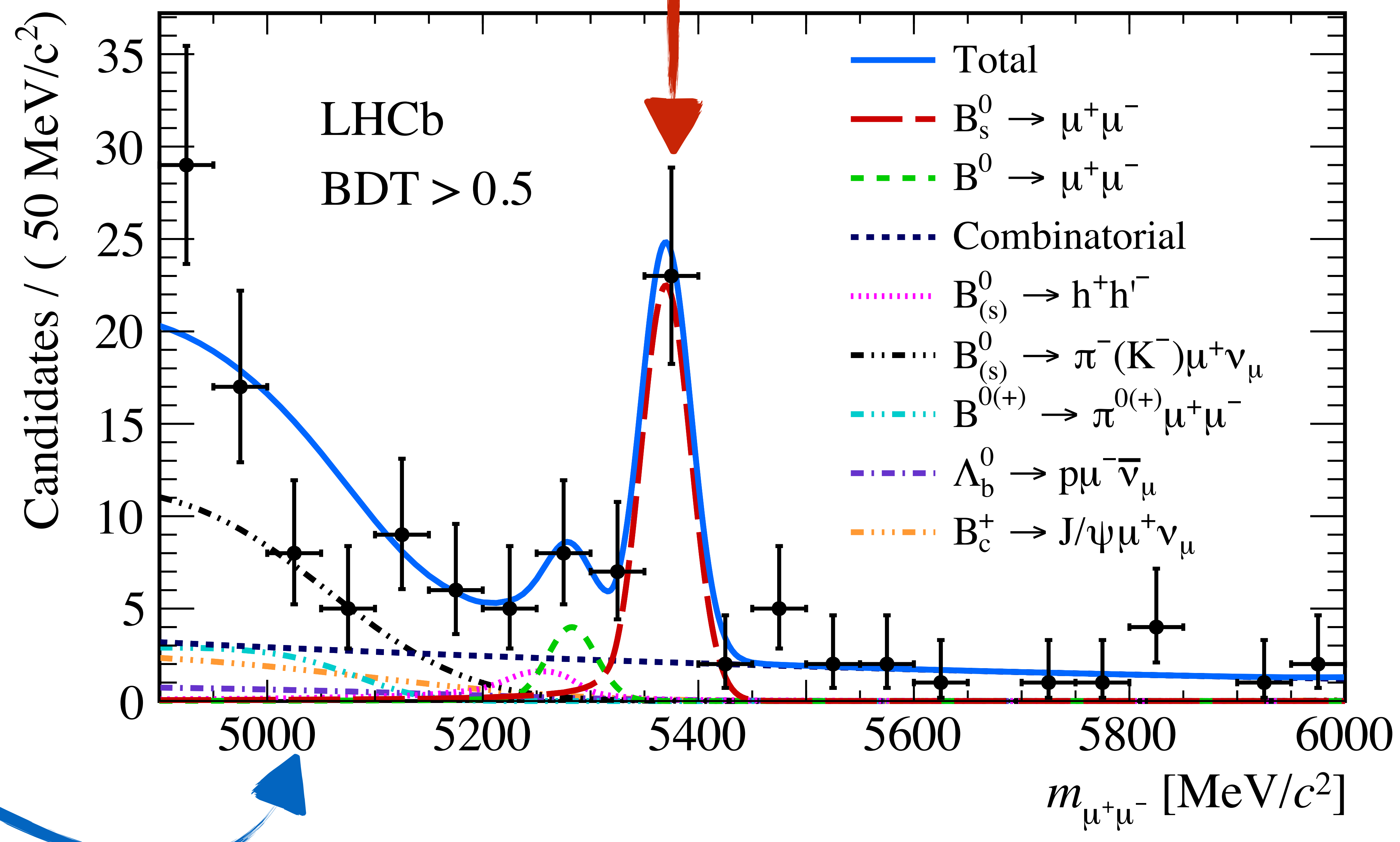
  $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$

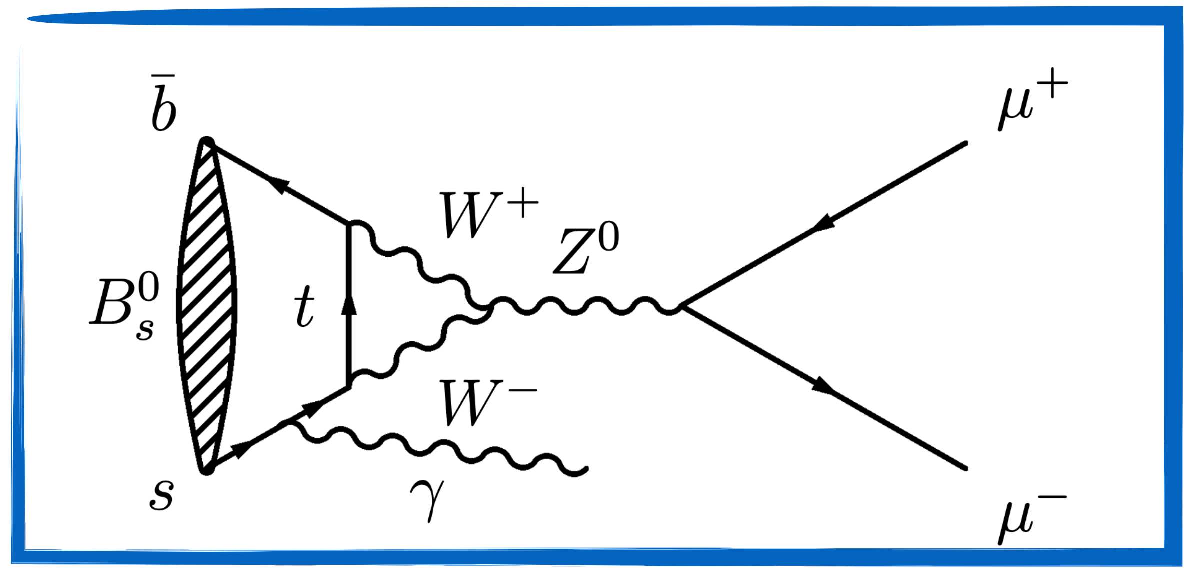
  [Beneke et al., JHEP10 (2019) 232]

- Add new observable:
  - Initial state radiation measurement at low mass
  - $\mathcal{B}(B^0_s \to \mu^+\mu^-\gamma)_{m_{\mu^+\mu^-} > 4.9\,\mathrm{GeV}/c^2} \approx 10^{-10}$ [Kozachuk et al., PRD 97 (2018) 053007]
  - Only experimental limit $\mathcal{B}(B^0 \to \mu^+\mu^-\gamma) < 1.6 \times 10^{-7}$ at 90% CL by BaBar [PRD 77 (2008) 011104]



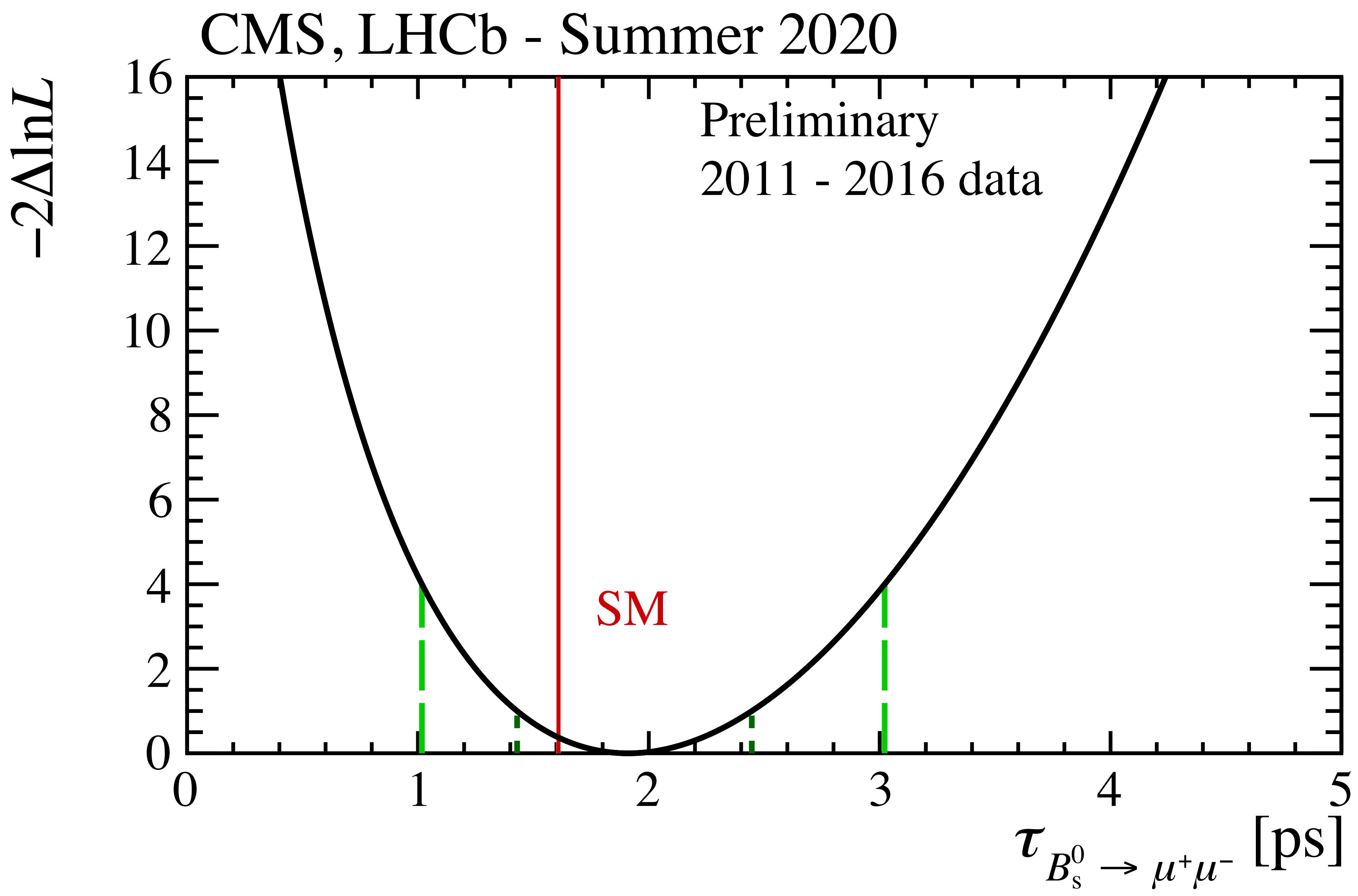
[PRL 118 (2017) 191801]





New LHCb measurement of $B^0_{(s)} \to \mu^+\mu^-(\gamma)$

- Only heavy B^0_s eigenstate (CP-odd) can decay to $\mu^+\mu^-$ in the SM
- Sizeable decay width difference in B^0_s system:
  - $\tau_{\mu\mu} = 1.62$ ps (CP-odd) vs. 1.42 ps (CP-even, light B^0_s)
  - Access to CP structure of $B^0_s \to \mu^+\mu^-$ decays via effective lifetime
- Combinations of LHCb and CMS:
  - $\tau_{\mu\mu} = 1.91^{+0.37}_{-0.35}$ ps

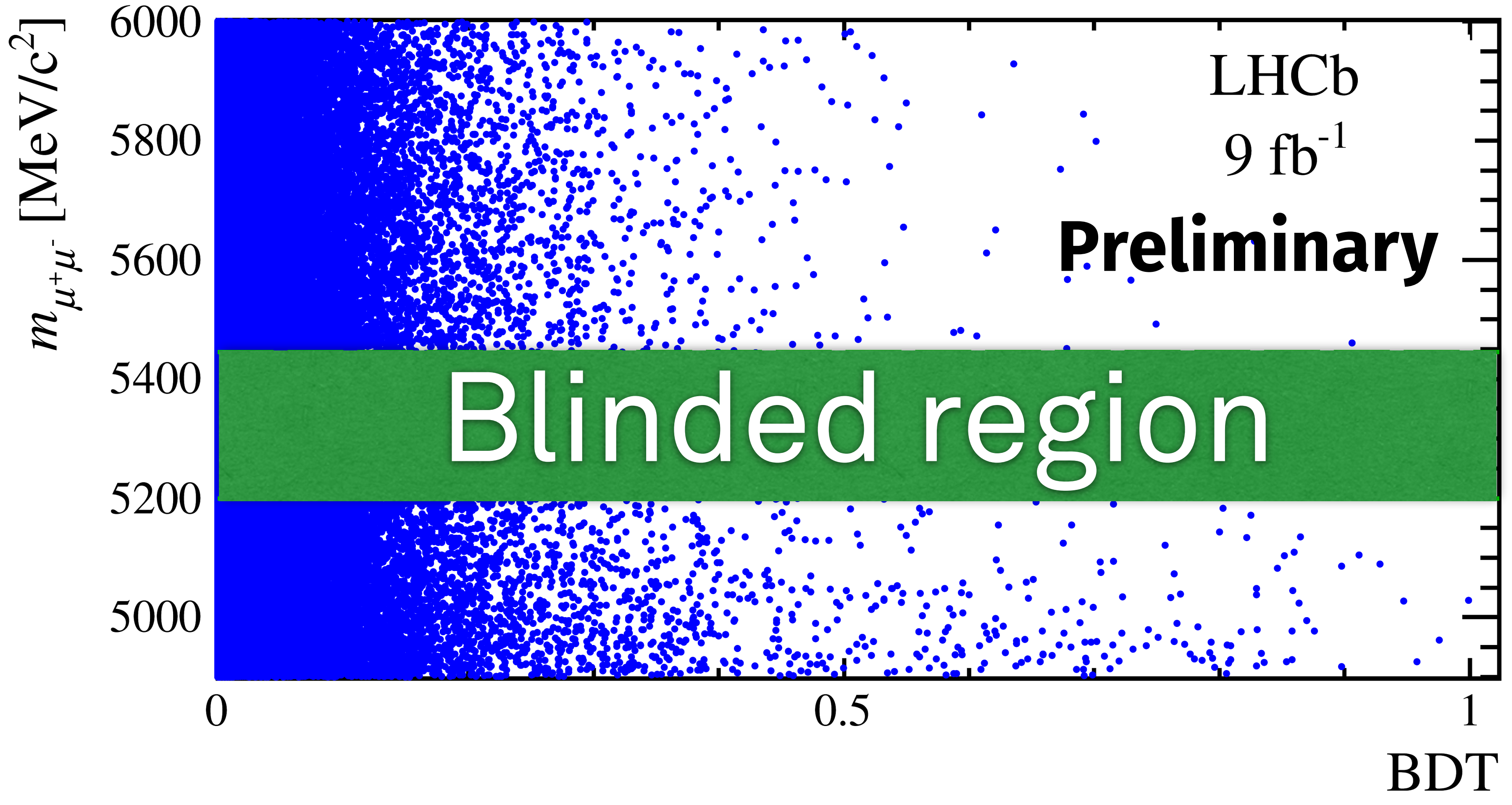


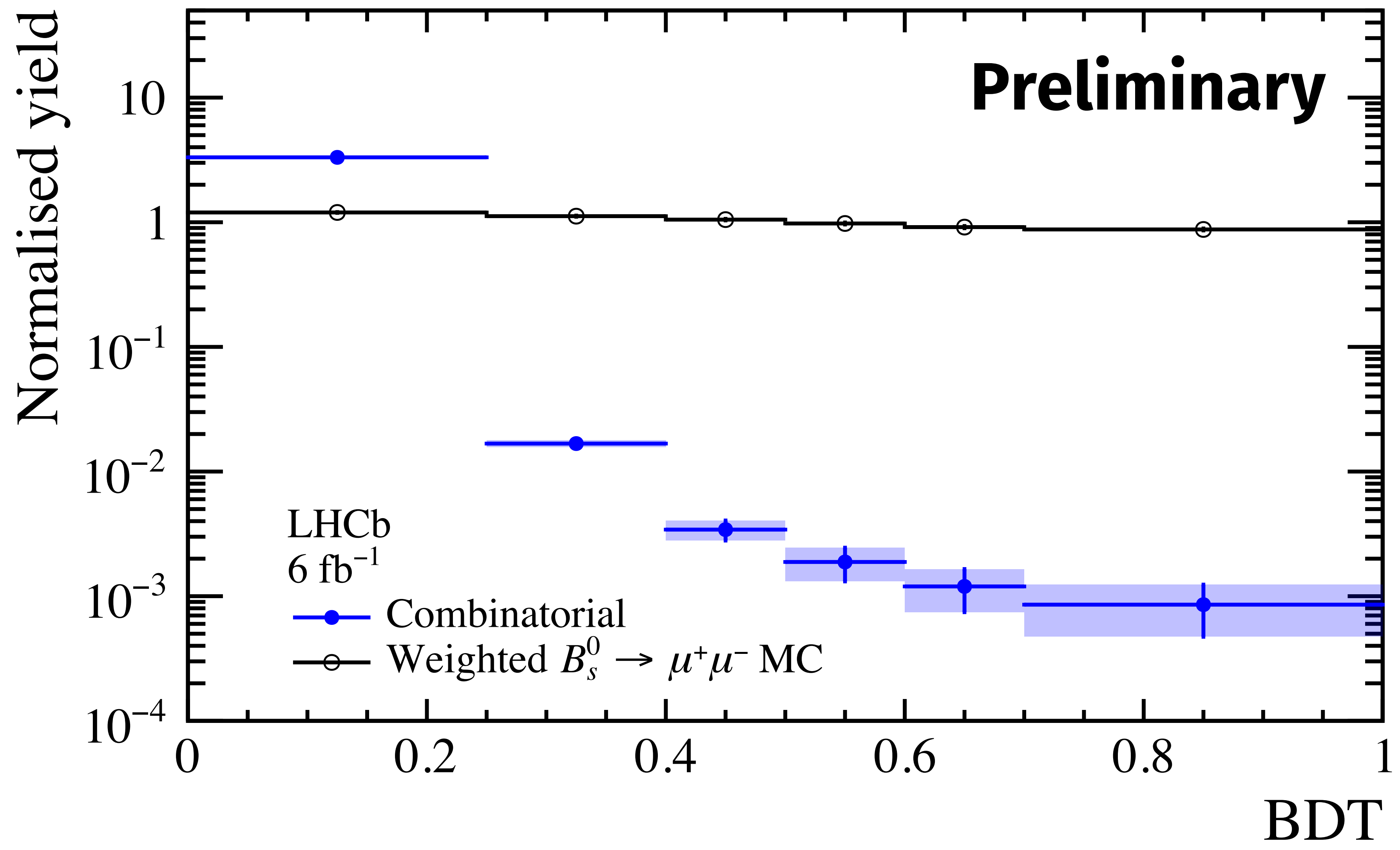
[LHCb-CONF-2020-002, CMS PAS BPH-20-003]

More statistics necessary to distinguish B^0_s eigenstates

Analysis strategy

- Use full Run 1+2 LHCb data set $(3\,\mathrm{fb}^{-1} + 6\,\mathrm{fb}^{-1})$
  $\rightarrow$ double previous data set
- Selection unchanged
  - Search in $m_{\mu^+\mu^-} \in [4.9, 6.0]\,\mathrm{GeV}/c^2$
  - $B_s^0 \rightarrow \mu^+\mu^-\gamma$ with untagged ISR in lower mass sideband
- Dominant background: two muon combinatorics
  - Separation from signal: $m_{\mu^+\mu^-}$ and BDT trained on two-body kinematics and topology
  - Suppress misidentified backgrounds with strong particle identification
  - Enhance sensitivity by fitting multiple BDT regions





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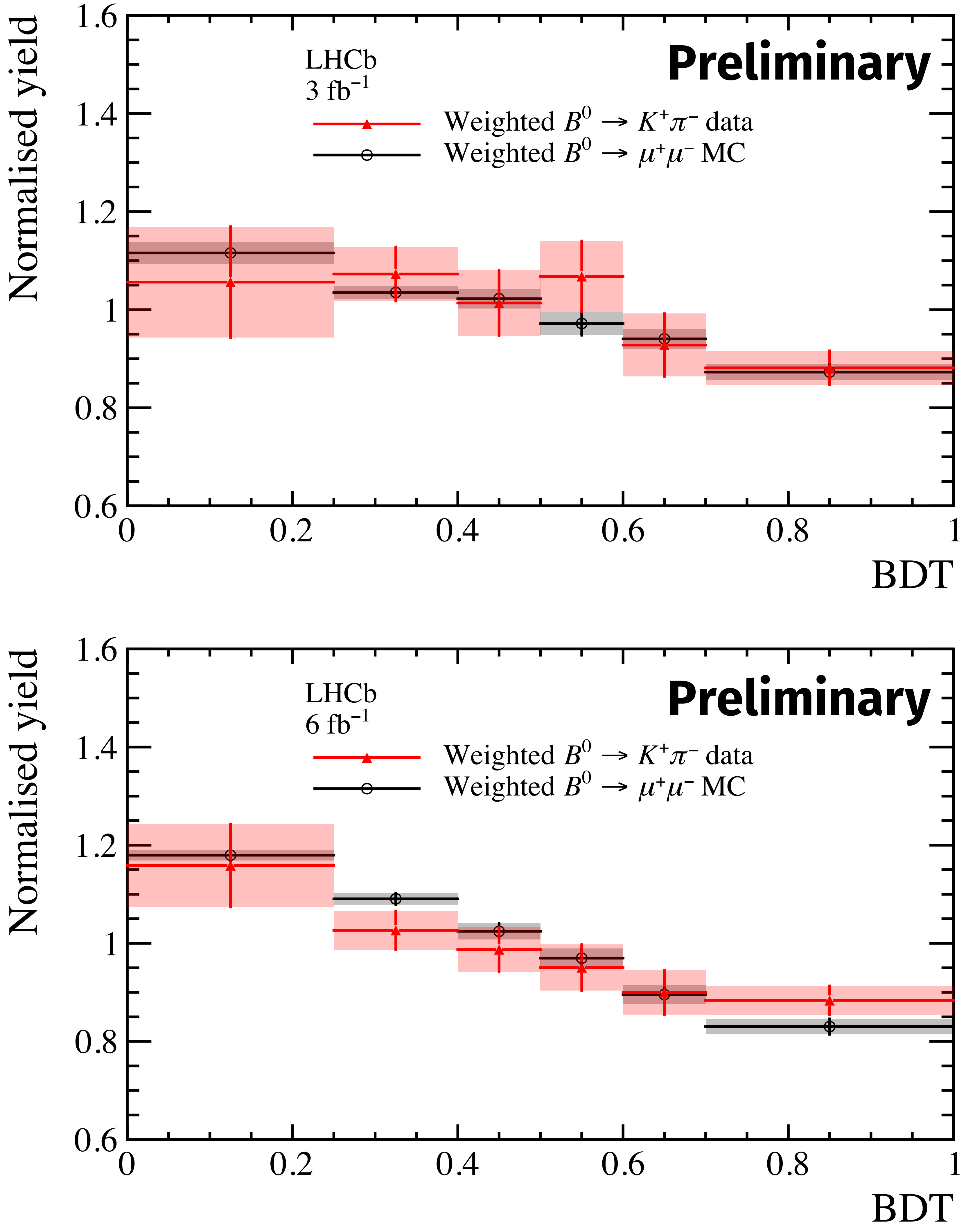
Signal calibration

- New BDT calibration:
  - Correct simulation in B kinematics, detector occupancy, Particle identification, Trigger
  - Good agreement with direct calibration with $B \to hh'$ decays in data, drastically reduces uncertainties
- Mass calibration data control modes:
  - Peak position from $B^0 \to K^+\pi^-$ and $B_s^0 \to K^+K^-$
  - Mass resolution interpolated from dimuon resonances



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Normalisation

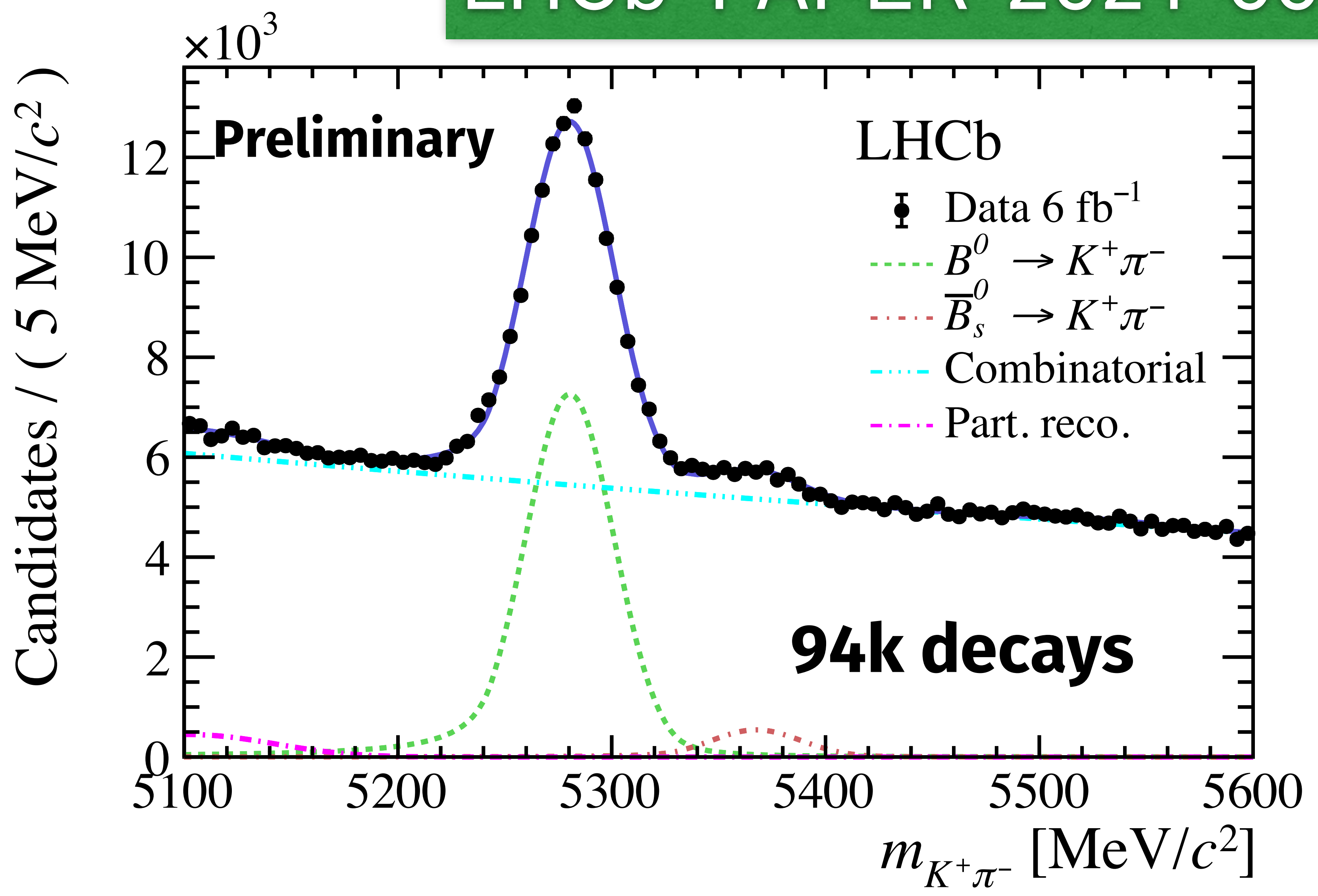
- Measure relative to normalisation modes:

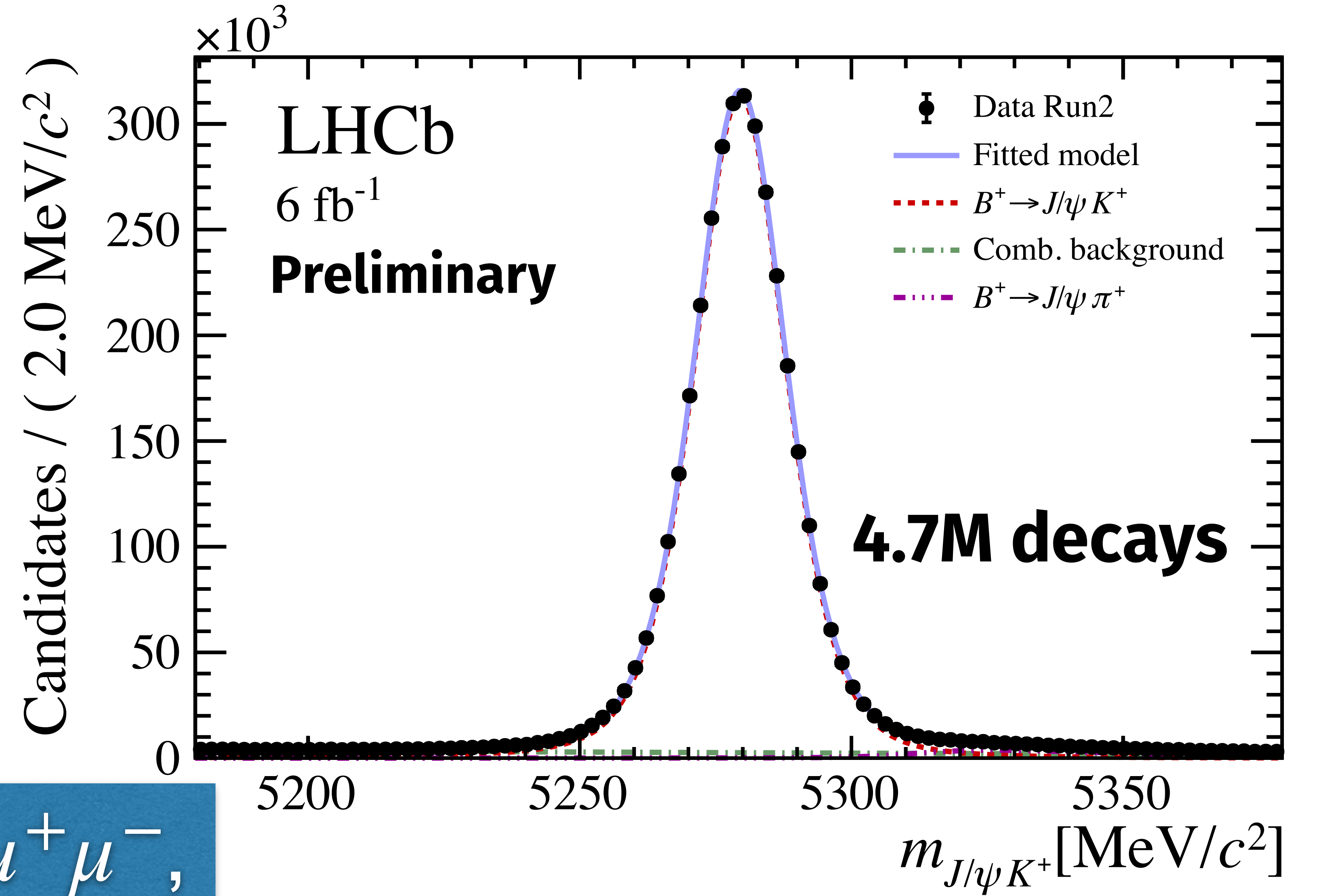
$$\mathscr{B}(\text{sig}) = \frac{f_{\text{sig}}}{f_d} \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}} \frac{N_{\text{sig}}}{N_{\text{norm}}} \mathscr{B}(\text{norm}) = \alpha_{\text{sig}} N_{\text{sig}}$$

- Two normalisation modes: $B^+ \to J/\psi(\mu^+\mu^-)K^+$, $B^0 \to K^+\pi^-$

  $\to$ find excellent agreement between the two normalisations

- **Use new LHCb combination of fragmentation fractions ratio**
  - Improves uncertainty from $\approx 6\,\%$ to $\approx 3\,\%$ [arXiv:2103.06810]
  - $f_s/f_d\,(13\ \text{TeV}) = 0.254 \pm 0.008$
  - $\dfrac{f_s/f_d\,(13\ \text{TeV})}{f_s/f_d\,(7\ \text{TeV})} = 1.064 \pm 0.007$





Expect $147 \pm 8\ B_s^0 \to \mu^+\mu^-$, $16 \pm 1\ B^0 \to \mu^+\mu^-$,
$\approx 3\ B_s^0 \to \mu^+\mu^-\gamma\ @\ m_{\mu^+\mu^-} > 4.9$ GeV

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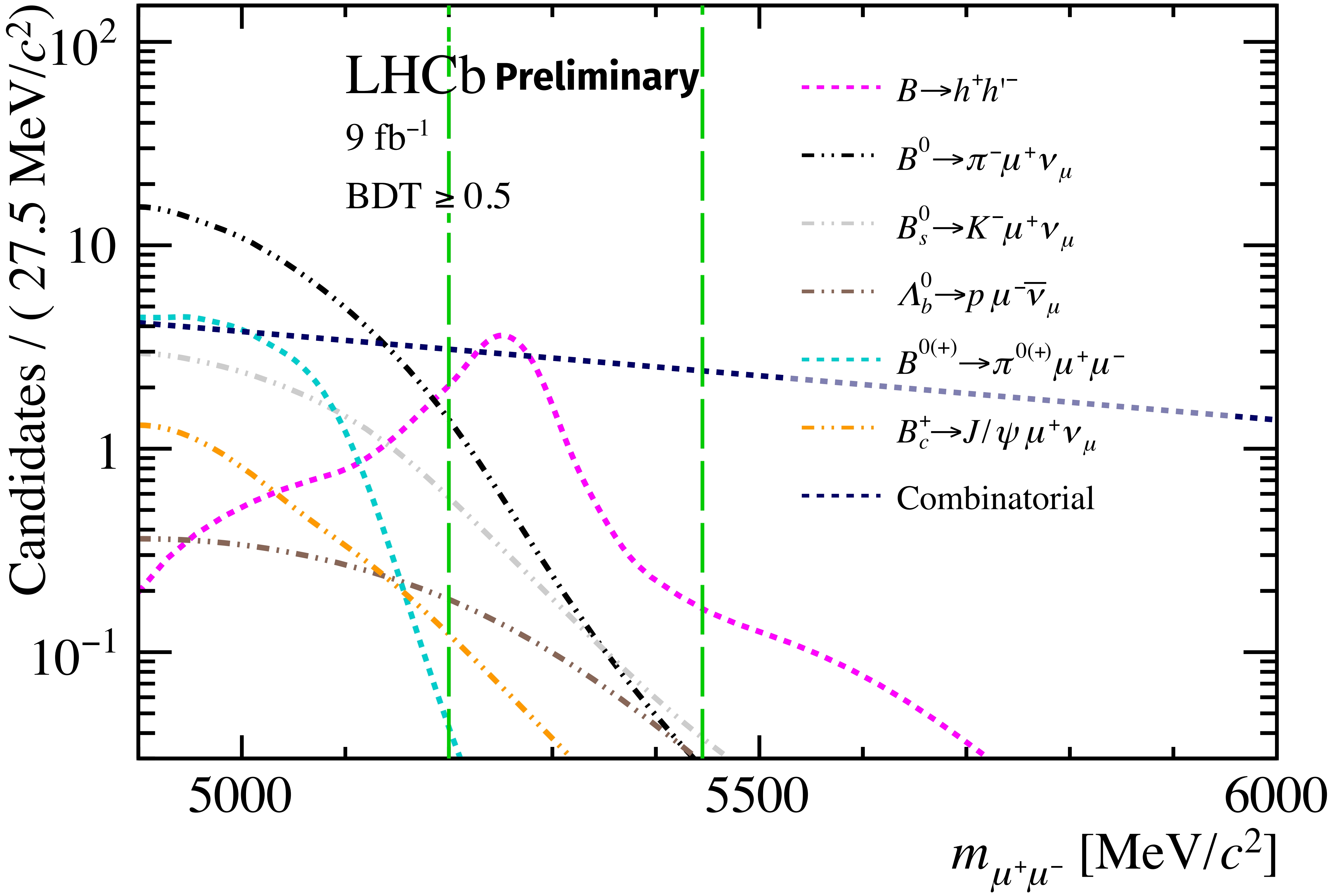
Background description

- Combinatorial background (exponential shape)
- Exclusive backgrounds (shape from simulation)
  - MisID: $B \to hh'$, $X_b \to h\mu\nu$
  - Partially reconstructed: $B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$, $B_c^+ \to J/\psi(\mu^+\mu^-)\mu^+\nu$
- Efficiencies from simulation calibrated on control channel data
- **Improved:** MisID efficiency obtained from calibration data

  → Cross check $B \to hh'$ on $h\mu$ data (single misID)



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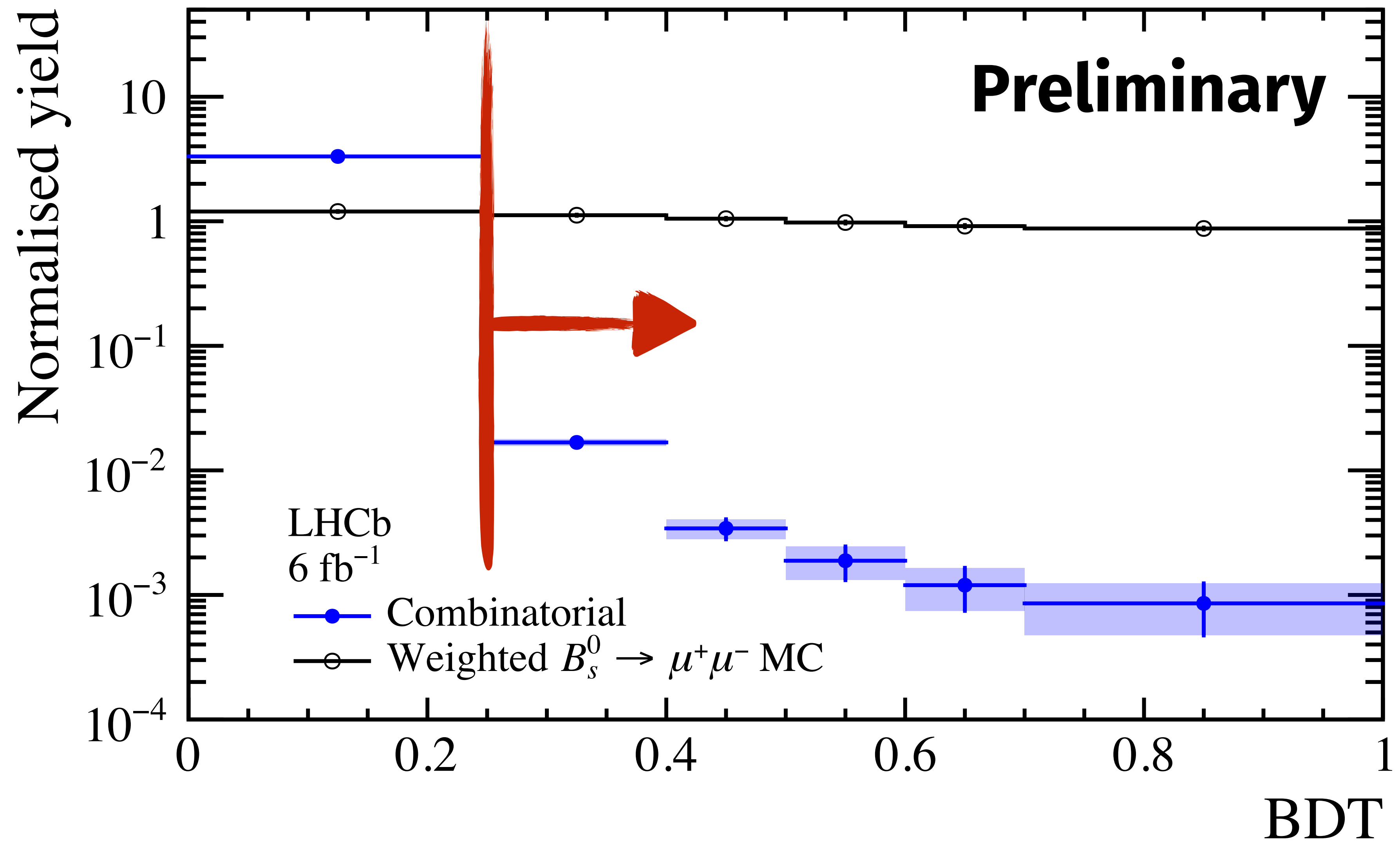
Fit for branching fractions

- Simultaneous unbinned maximum likelihood fit in 10 categories:
  - 5 BDT bins for each Run 1 and Run 2, exclude low BDT region (dominated by combinatorial)
- Fit setup:
  - Signal branching fractions and combinatorial yield free parameters
  - Signal BDT fractions and exclusive background yields constrained to expectations



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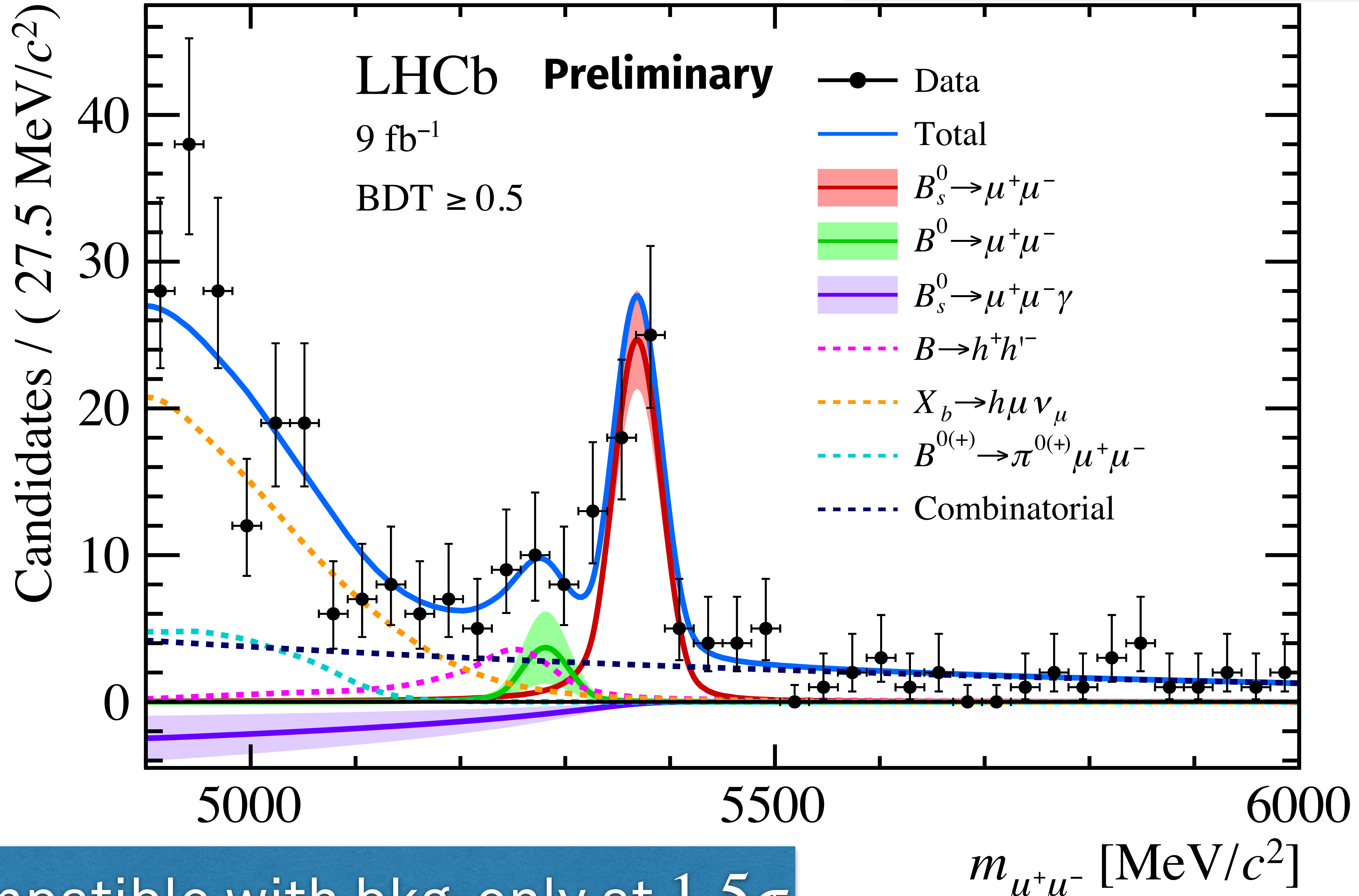
Fit for branching fractions

Find $B_s^0 \to \mu^+\mu^- > 10\sigma$,
No evidence for $B^0 \to \mu^+\mu^-$ ($< 2\sigma$)

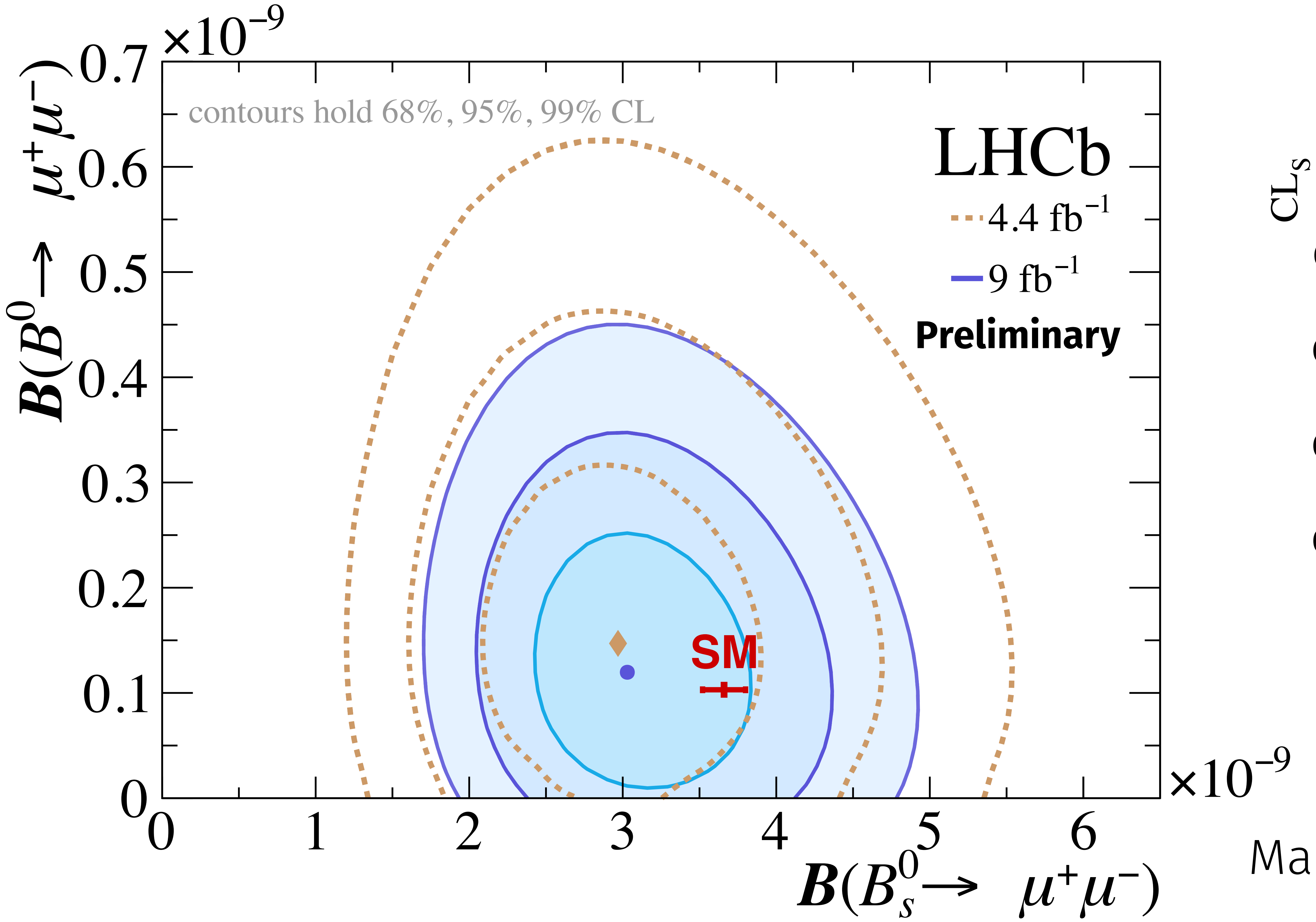


$B_s^0 \to \mu^+\mu^-\gamma$ compatible with bkg-only at 1.5σ

Numerical results

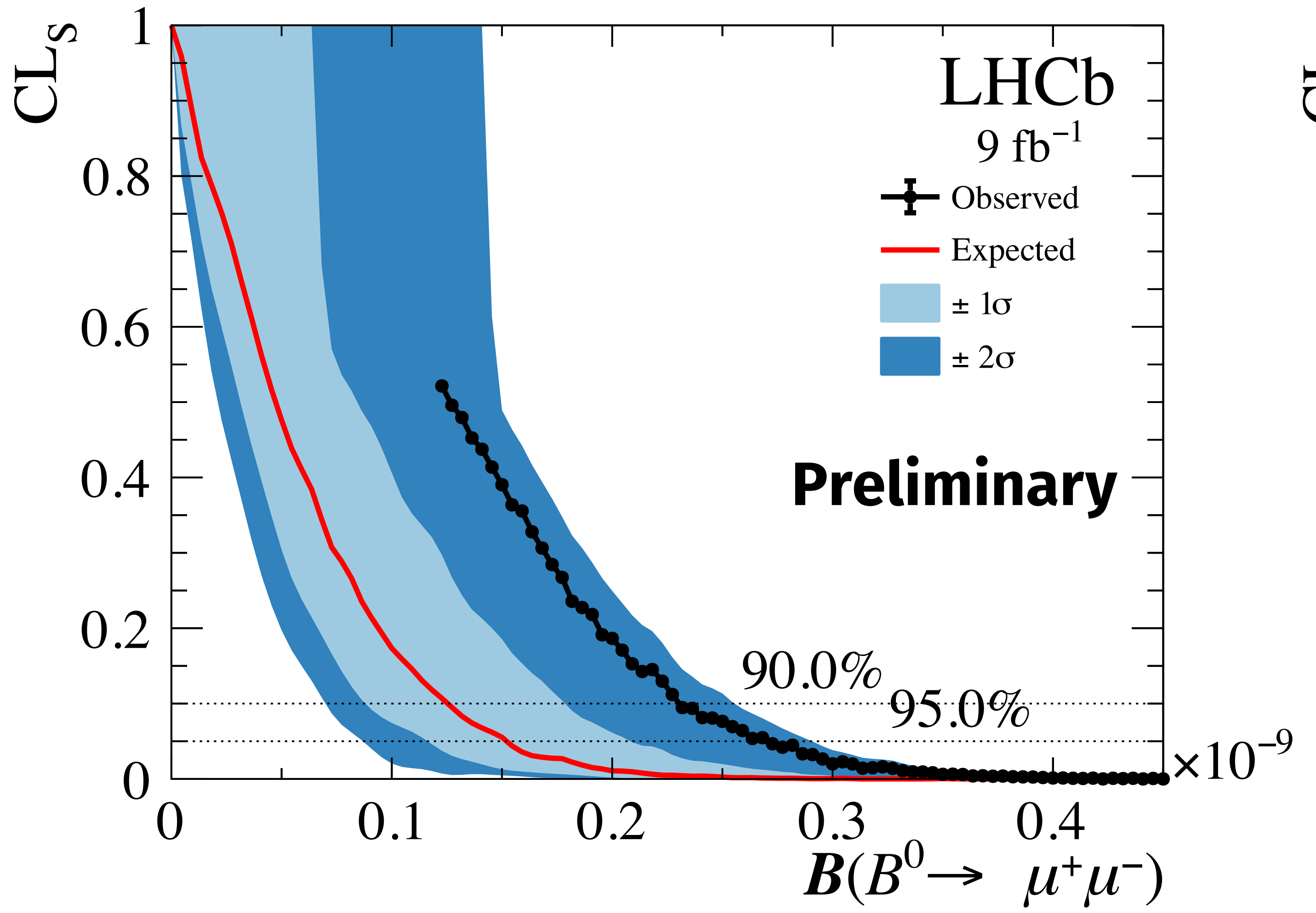
$$\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46}_{-0.43}{}^{+0.15}_{-0.11}) \times 10^{-9}$$

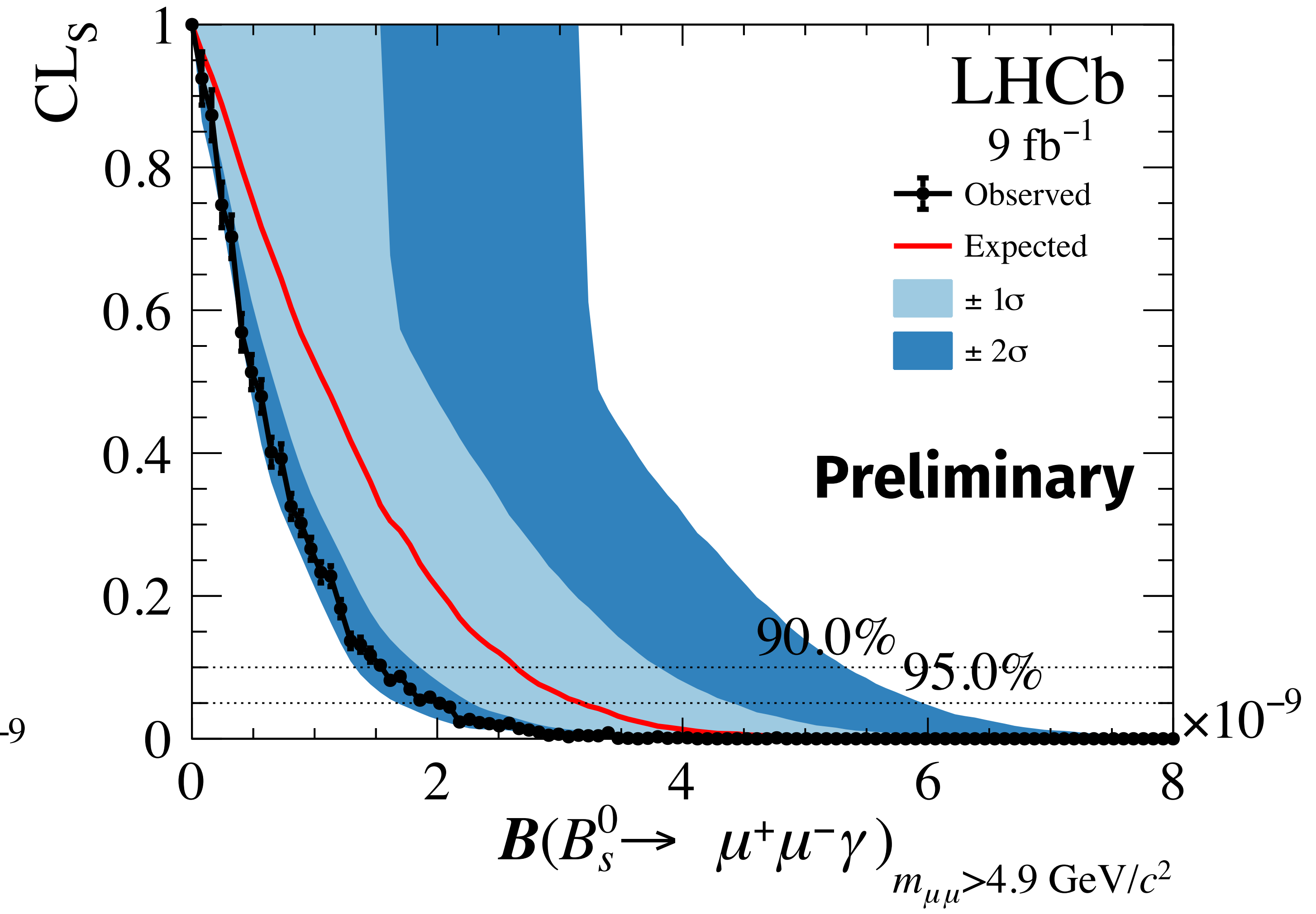
Most precise single experiment measurement!



Use CLs method to obtain upper limits:

- $\mathscr{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}$ @ 95 % CL
- $\mathscr{B}(B_s^0 \to \mu^+\mu^-\gamma)_{m_{\mu^+\mu^-}>4.9\,\mathrm{GeV}/c^2} < 2.0 \times 10^{-9}$ @ 95 % CL





Main systematics from f_s/f_d (3%), normalisation $\mathscr{B}$ (3%), bkg description

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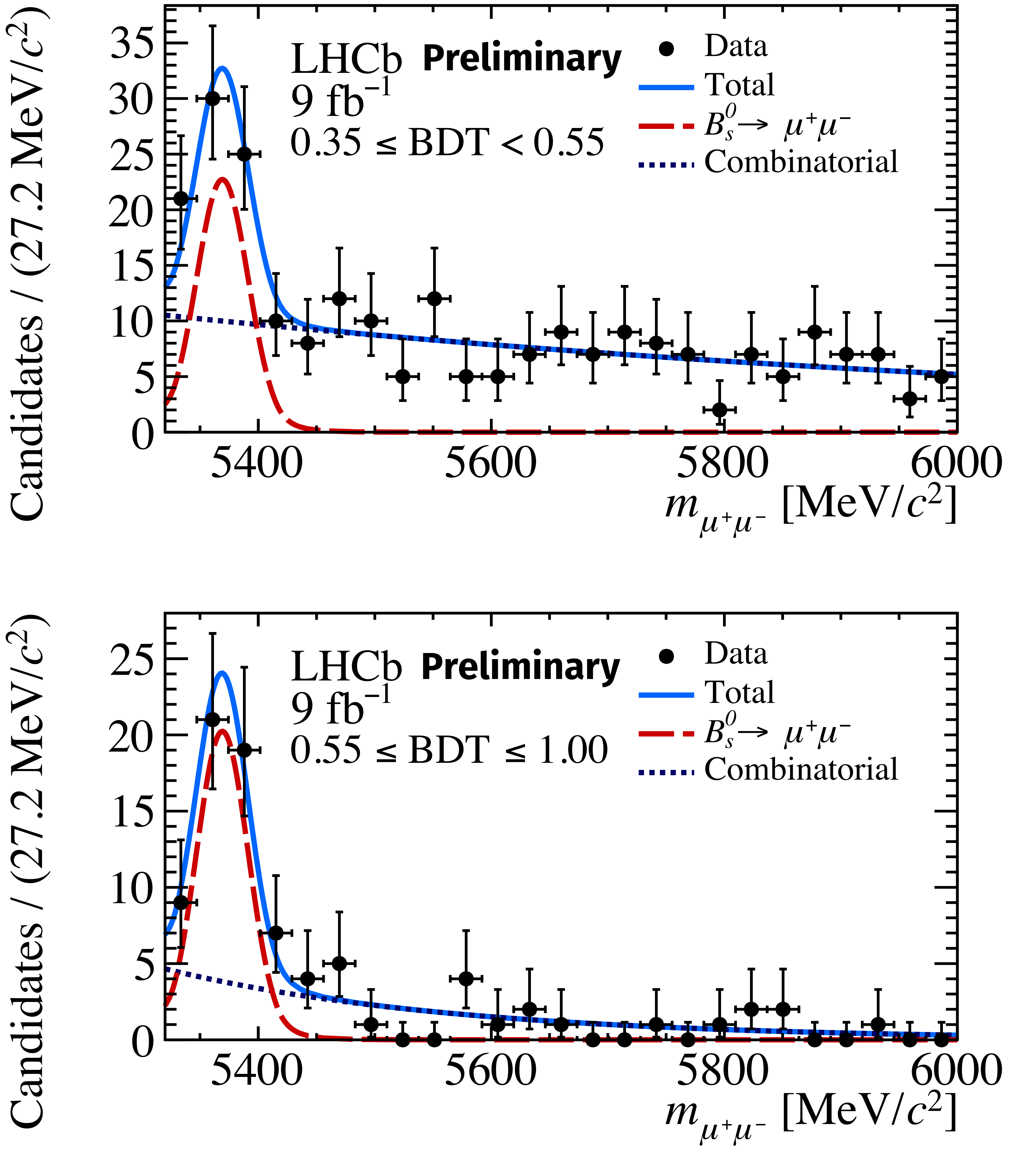
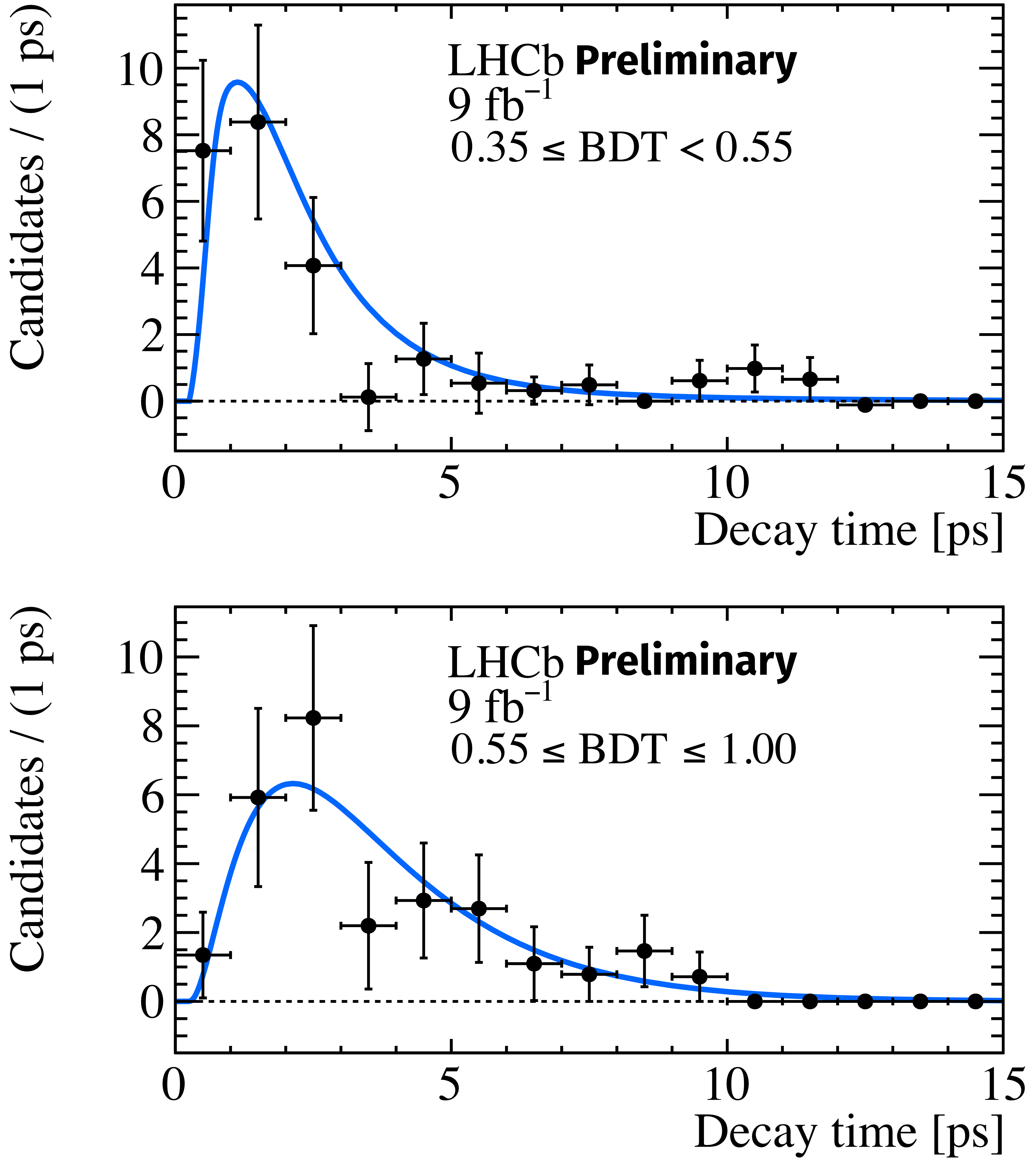
Lifetime measurement: strategy

- Loosen PID requirements wrt branching fraction measurement
- Consider 2 BDT regions
- 2-staged fit:
  - Mass fit with $m_{\mu^+\mu^-} > 5320$ MeV/c^2: background-subtraction with sPlot method [NIM A555 (2005) 356-369]
    $\rightarrow$ mass region removes exclusive backgrounds
  - Fit background-subtracted decay time distribution, acceptance modelled from $B_s^0 \rightarrow \mu^+\mu^-$ simulation
- Test procedure with $B^0 \rightarrow K^+\pi^-$ and $B_s^0 \rightarrow K^+K^-$, good agreement to previous LHCb analysis!



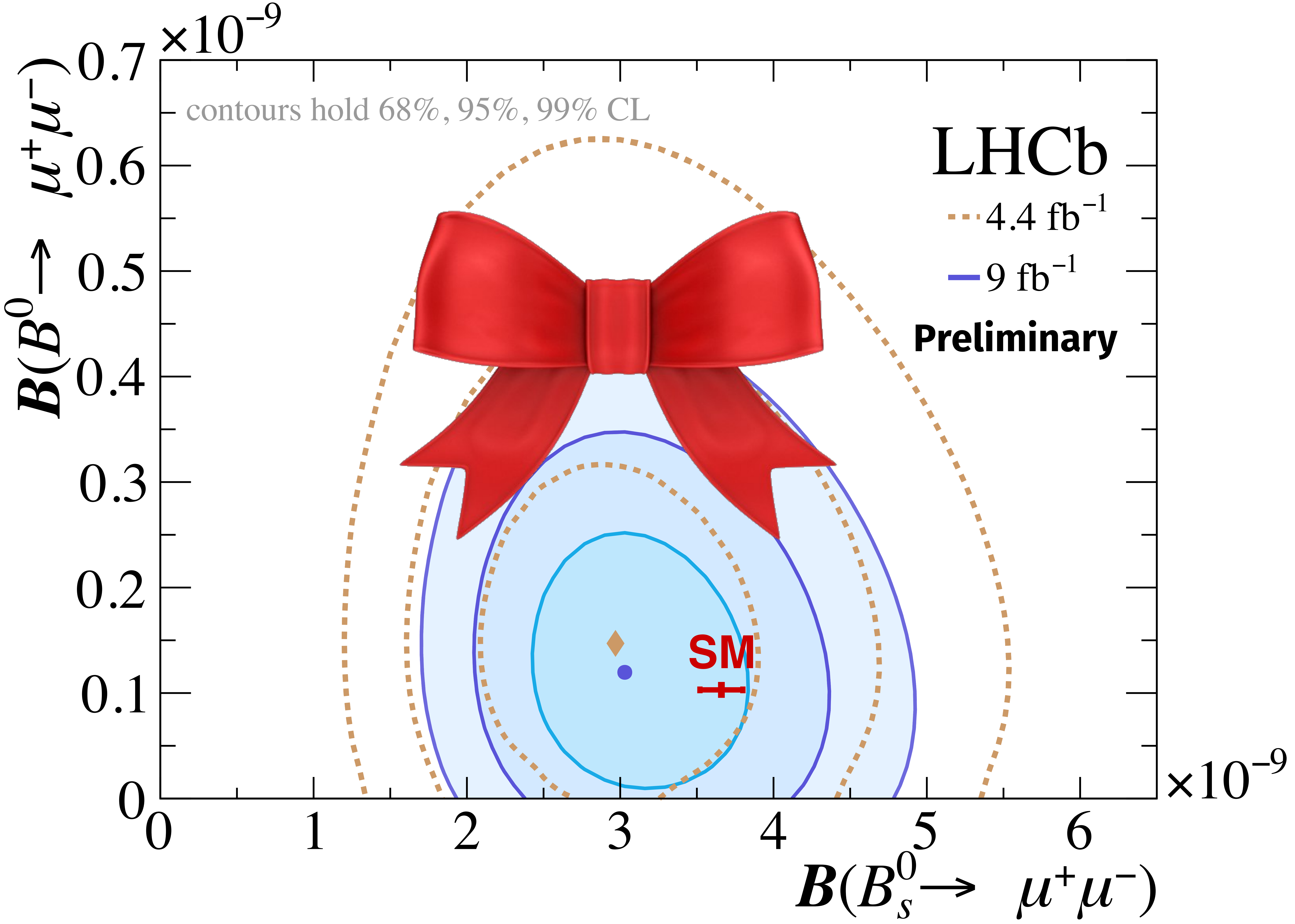
Lifetime measurement: result

- $\tau_{\mu\mu} = (2.07 \pm 0.29 \pm 0.03)$ ps
- Compatible at 1σ (2σ) with CP-odd/SM (CP-even) B_s^0 eigenstate
- Systematic uncertainties negligible:
  - Decay time acceptance description
  - Background contamination ($B \to hh', \Lambda_b \to p\mu^-\nu$)
  - Fit bias



Conclusion

- $B^0_{(s)} \to \mu^+\mu^-$ provides a clean and growing lab to test the SM
  $\to$ Complementary to Lepton Flavour Universality tests
- Strong constraints on allowed NP space from improved analysis with full Run 1+2 LHCb data set
  - $\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.09^{+0.46}_{-0.43}{}^{+0.15}_{-0.11}) \times 10^{-9}$ most precise single experiment measurement!
  - Significant improvement on effective lifetime measurement
  - First ever search for $B^0_s \to \mu^+\mu^-\gamma_{\mathrm{ISR}}$ at high $m_{\mu\mu}$



Happy Easter!

LHCb Detector

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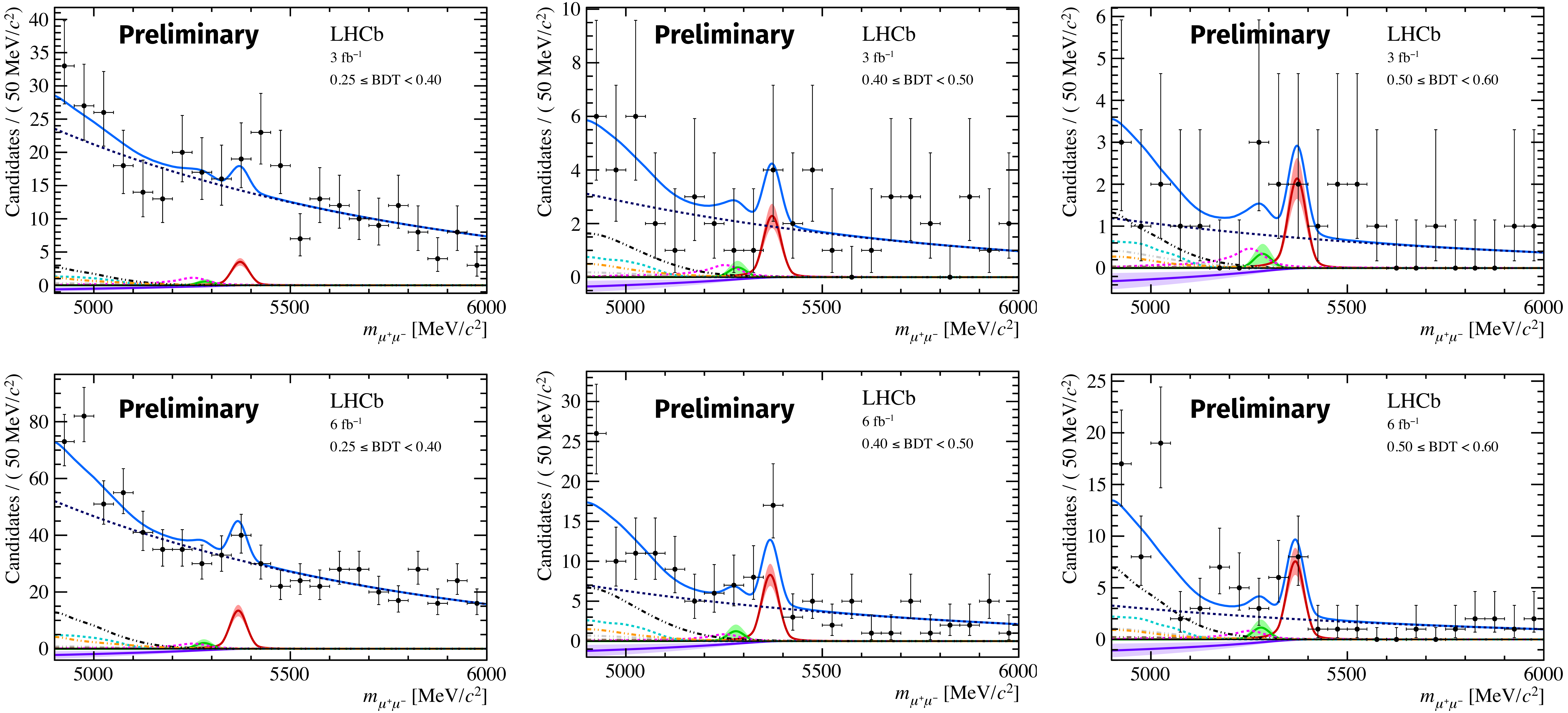
Mass fit low BDT regions

Run 1

Run 2



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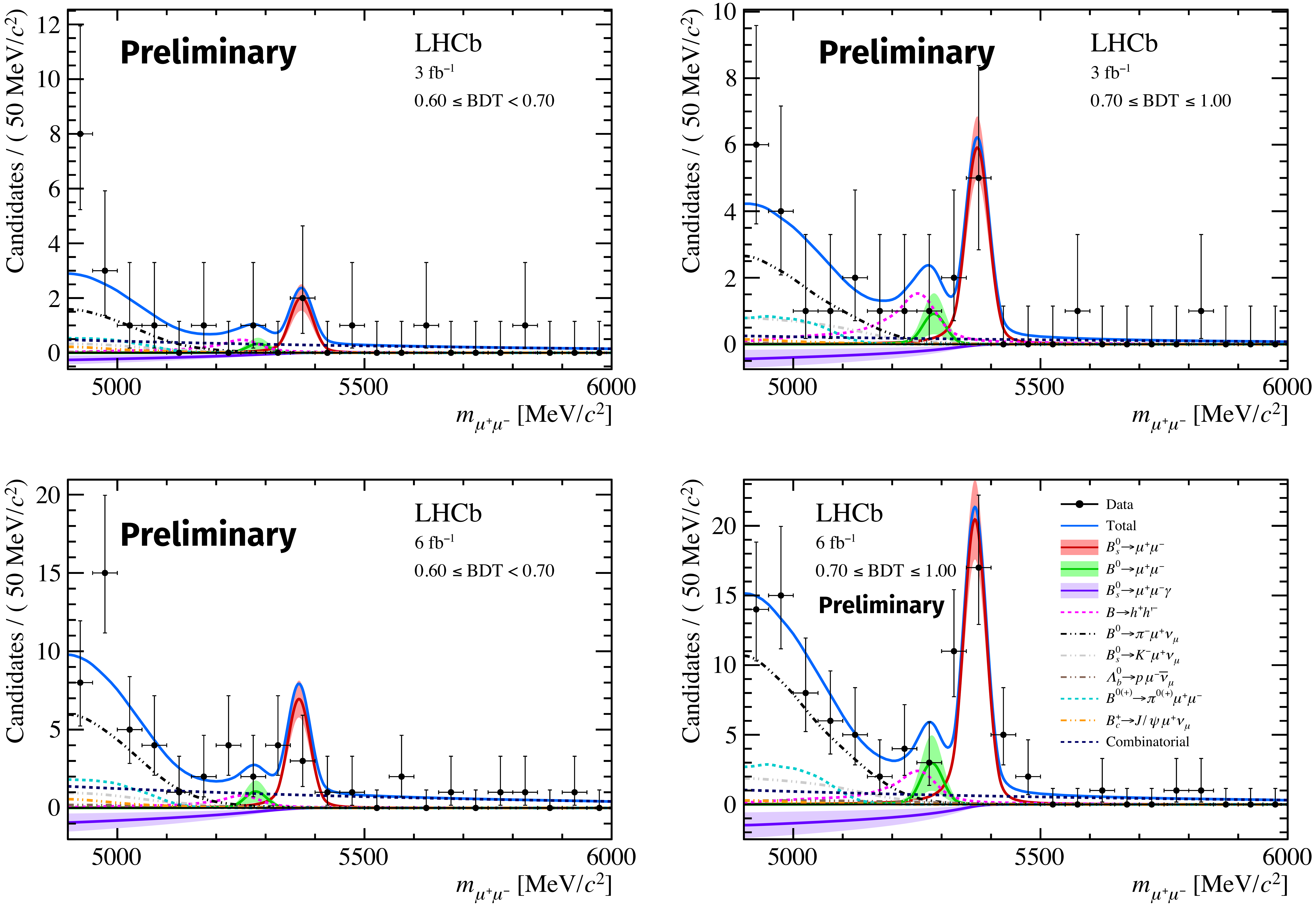
Mass fit high BDT regions

Run 1

Run 2



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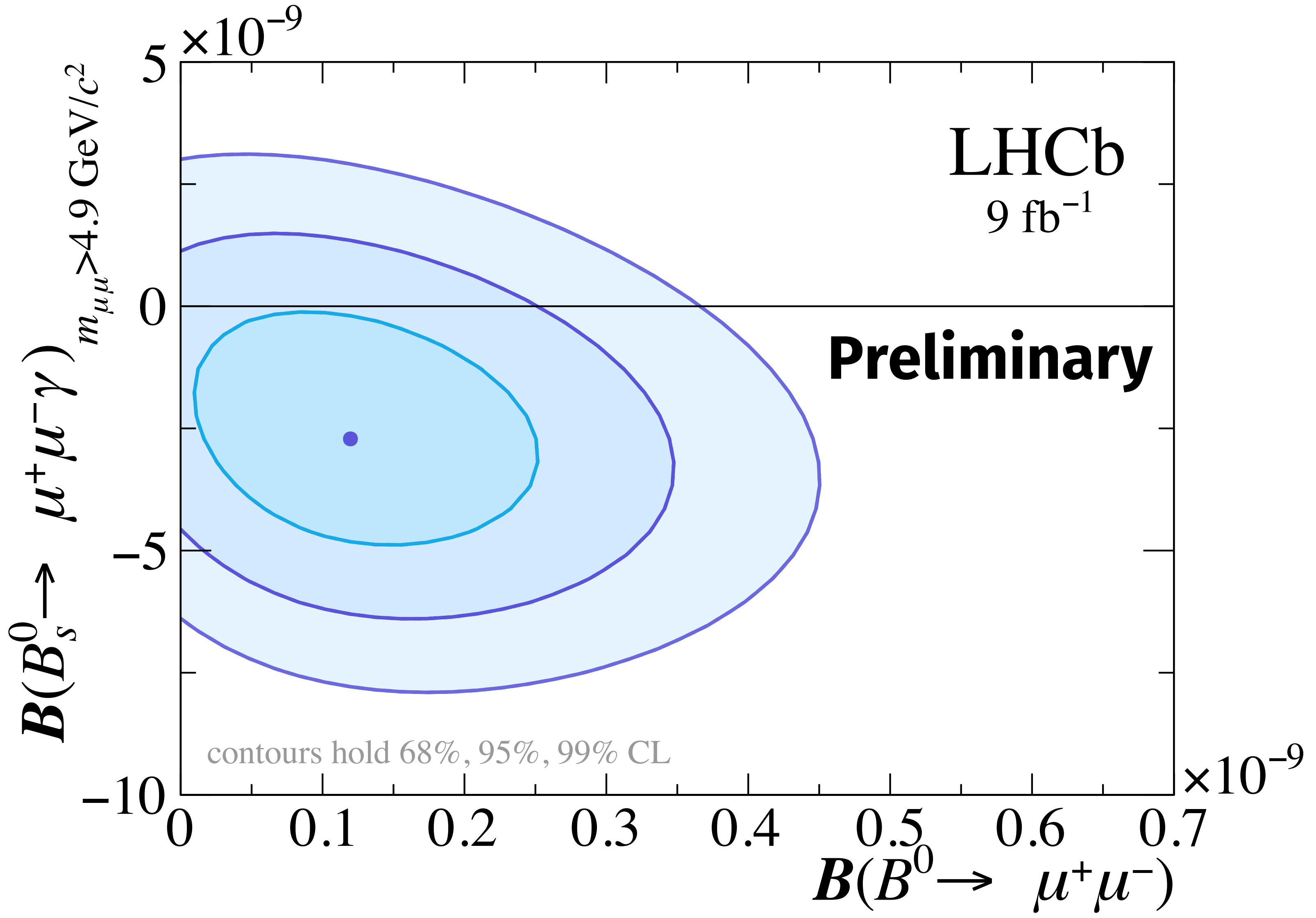
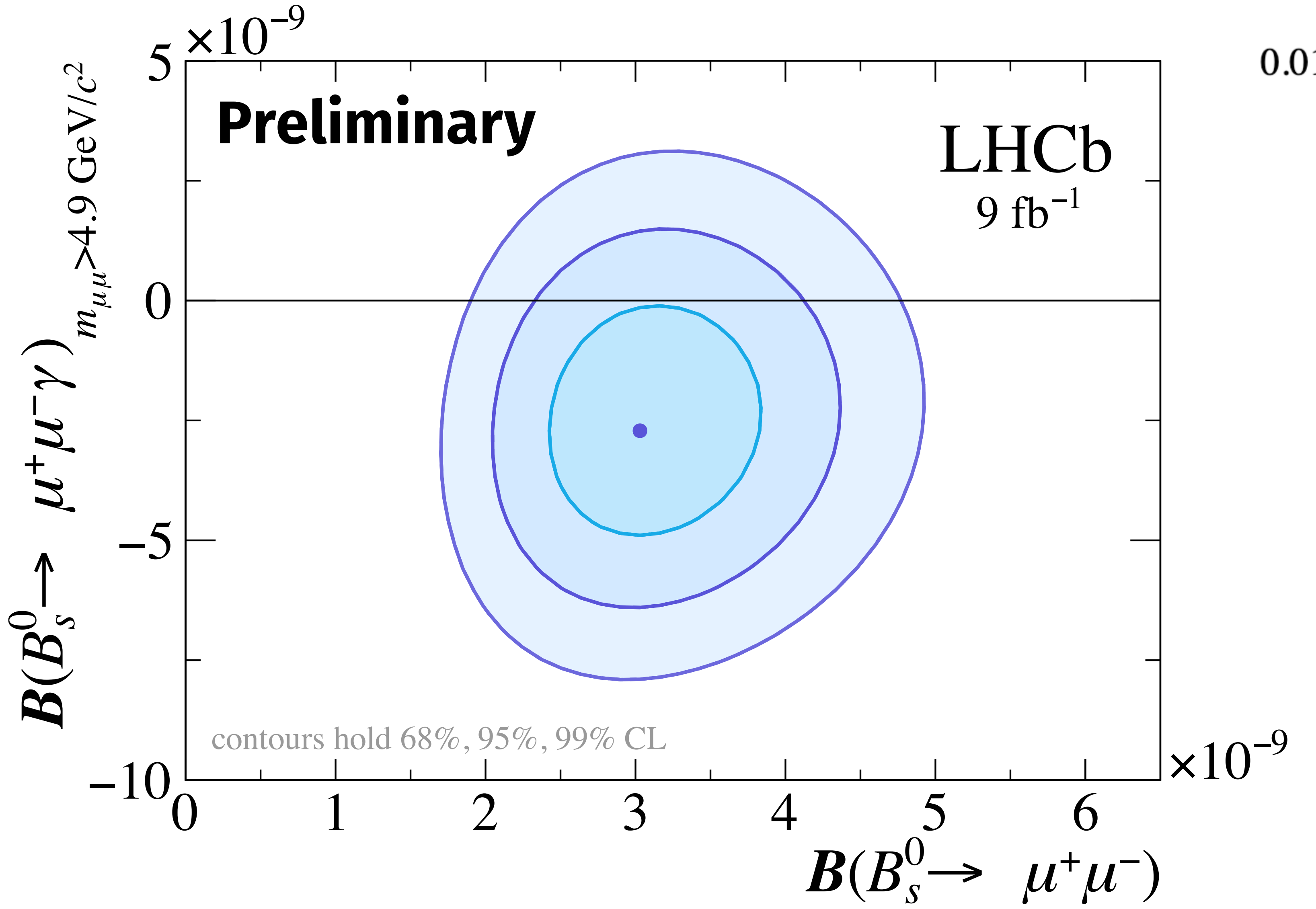
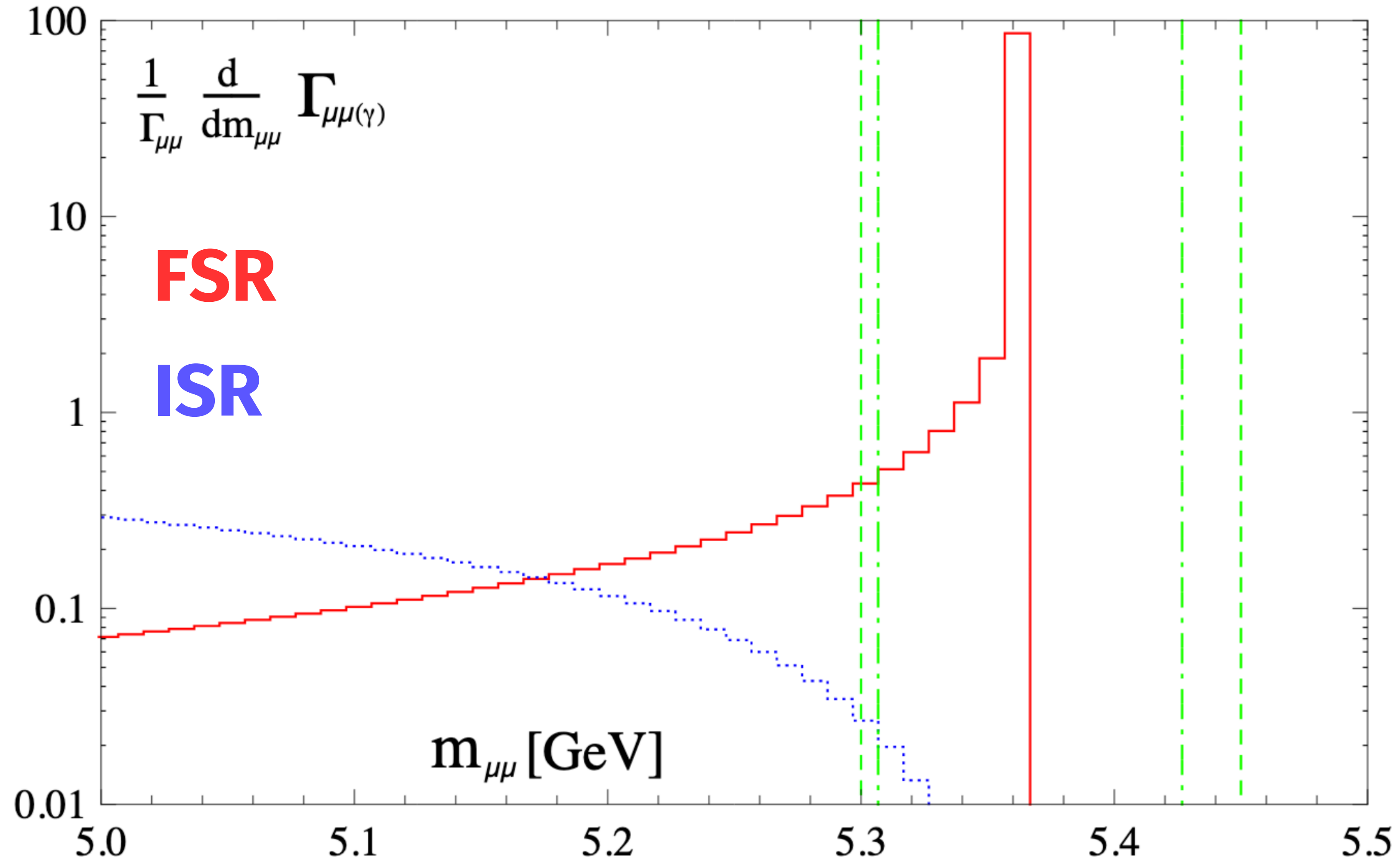
The measurement of $B_s^0 \to \mu^+\mu^-\gamma_{\text{ISR}}$

- FSR experimentally included in $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ via PHOTOS
- Experimental correlation to the other signals:





[Bobeth et al., PRL 112 (2014) 101801]



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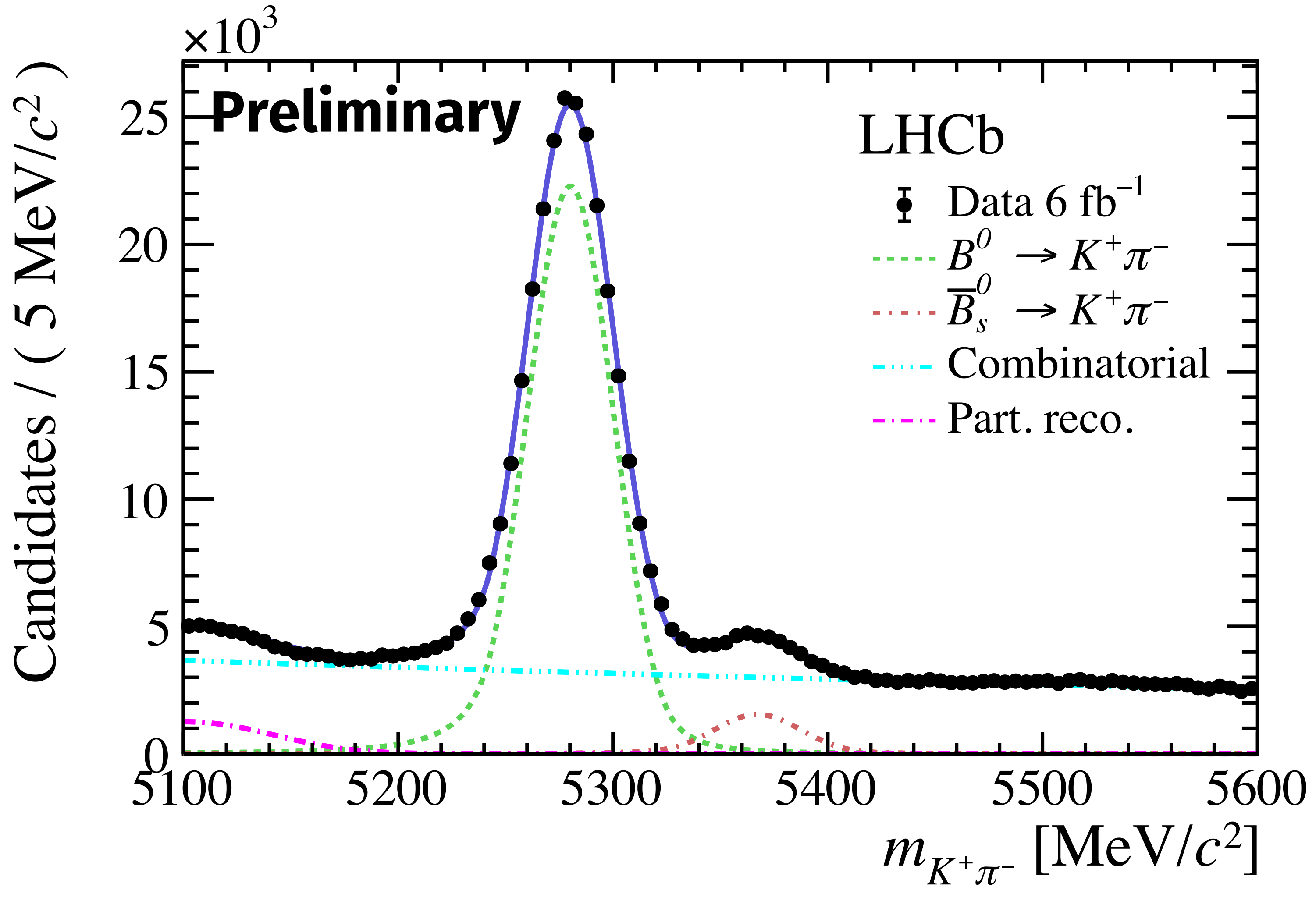
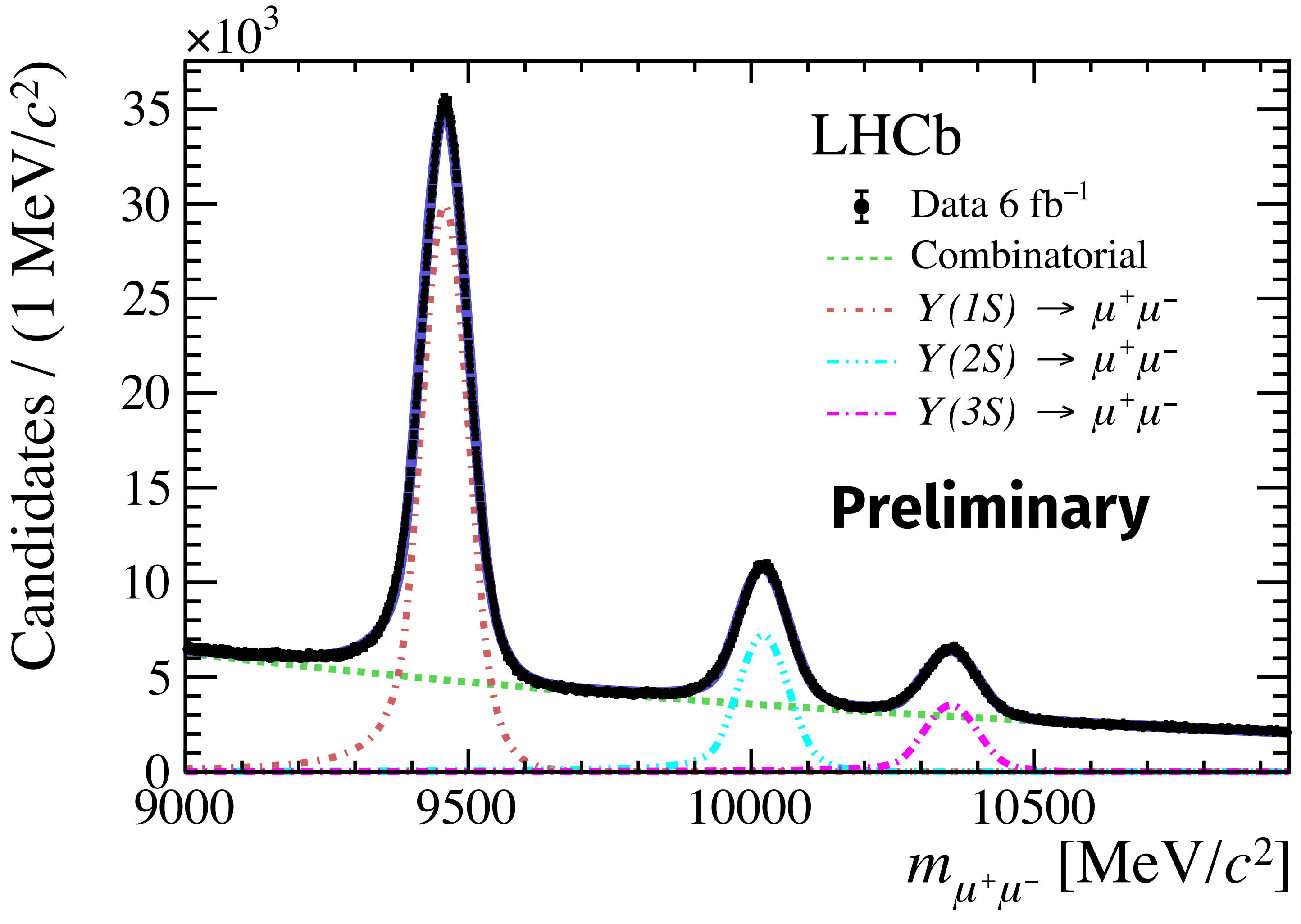
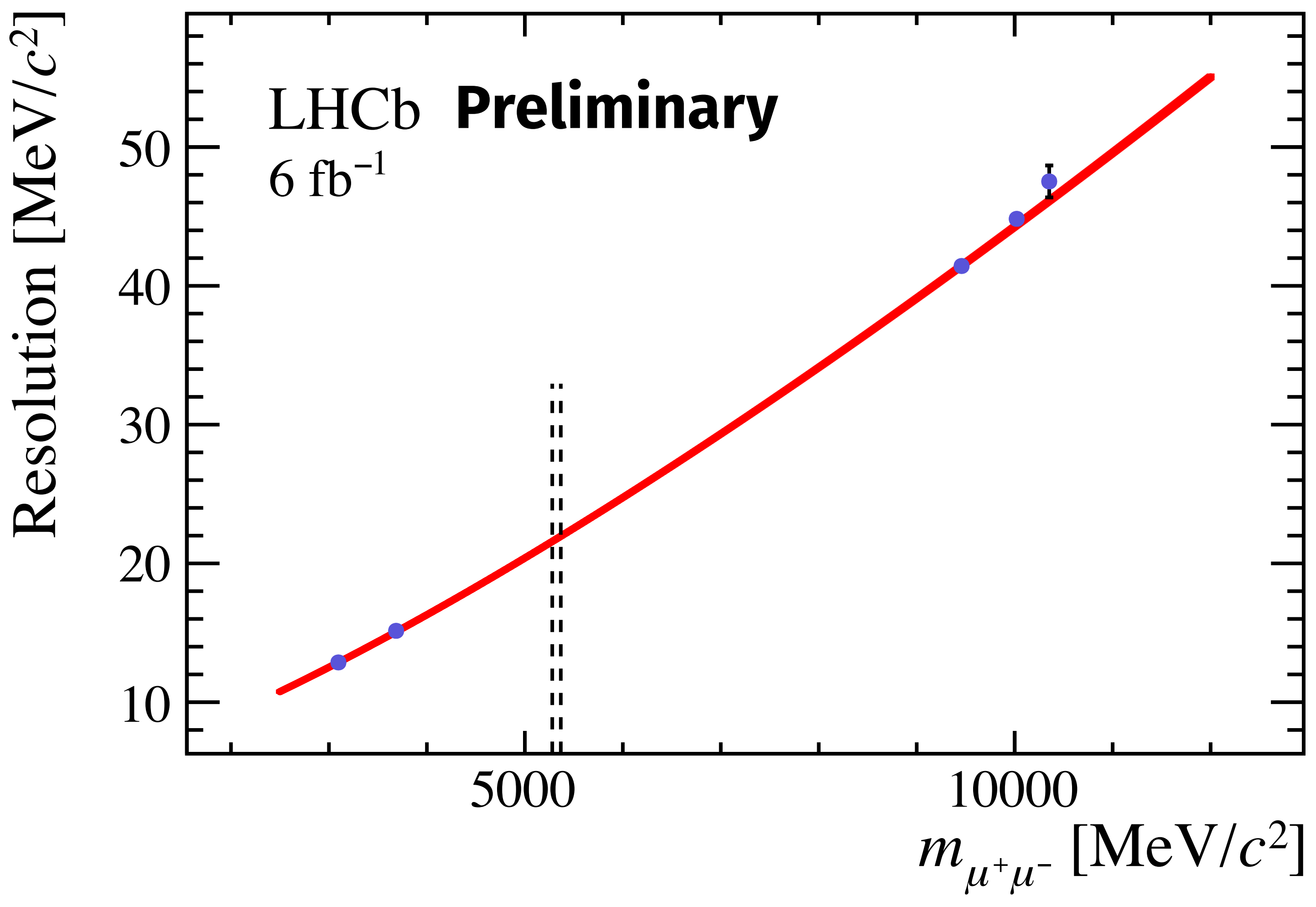
Mass calibration on data control modes

- Use $B^0 \to K^+\pi^-$ and $B_s^0 \to K^+K^-$ to determine mass peak position
- Mass resolution ≈ 22 MeV/c^2 from power law interpolation between dimuon resonances

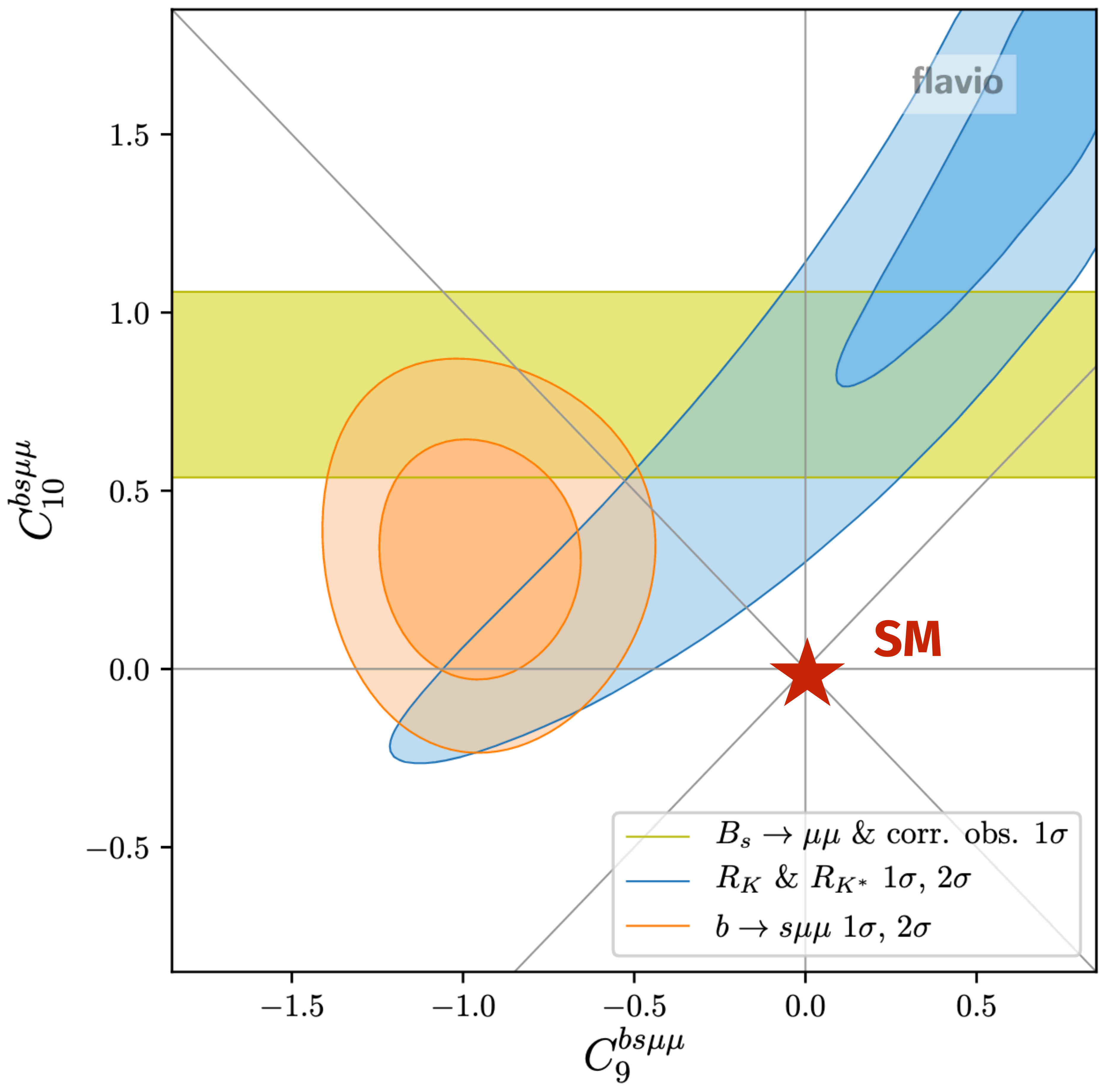






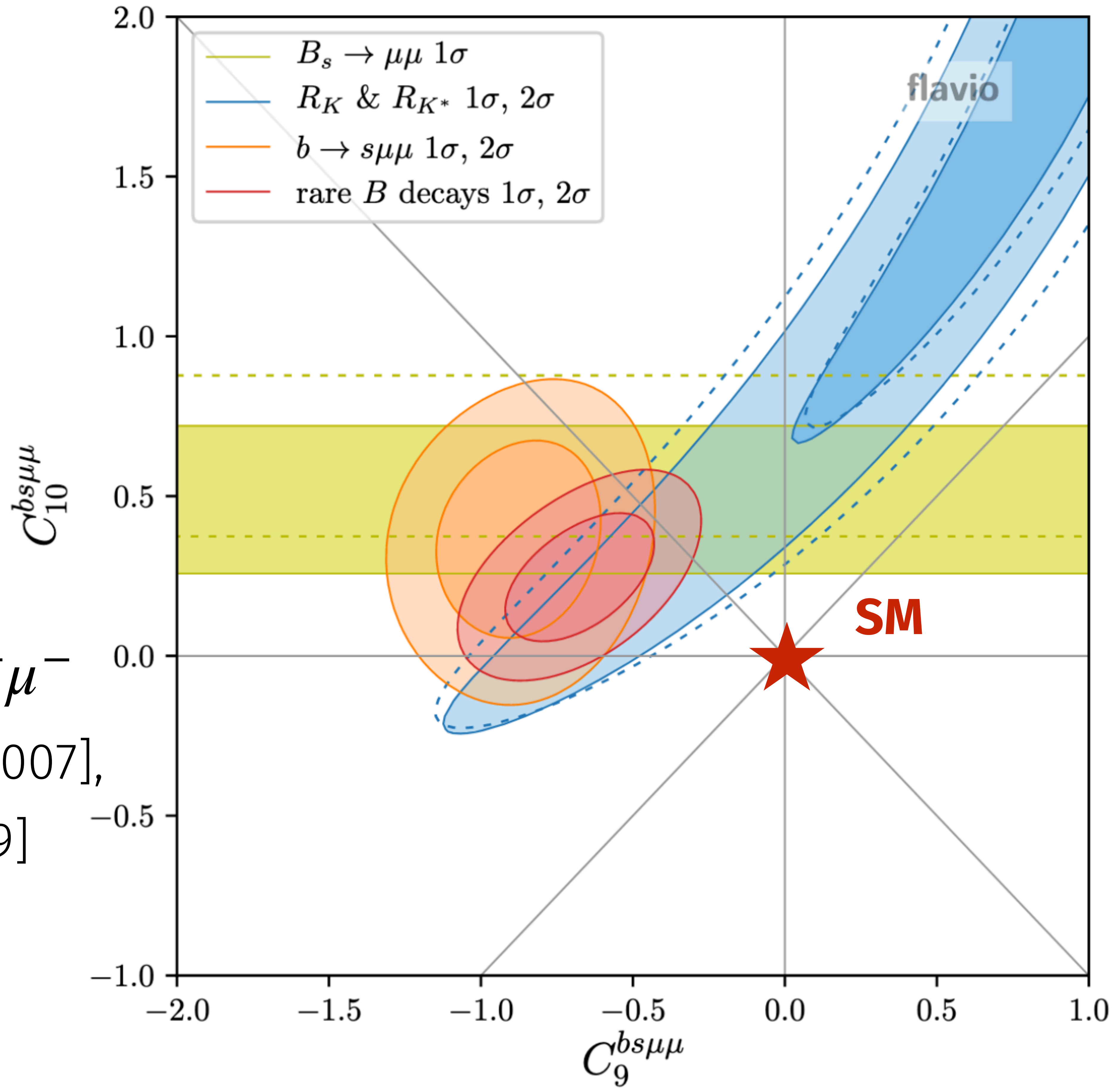
Global fits before and after latest measurements

[P. Stangl, La Thuile 2021]



Including new R_K and $B_s^0 \to \mu^+\mu^-$ [LHCb-PAPER-2021-007], [arXiv: 2103.11769]

[Altmannshofer/Stangl, arXiv:2103.13370]



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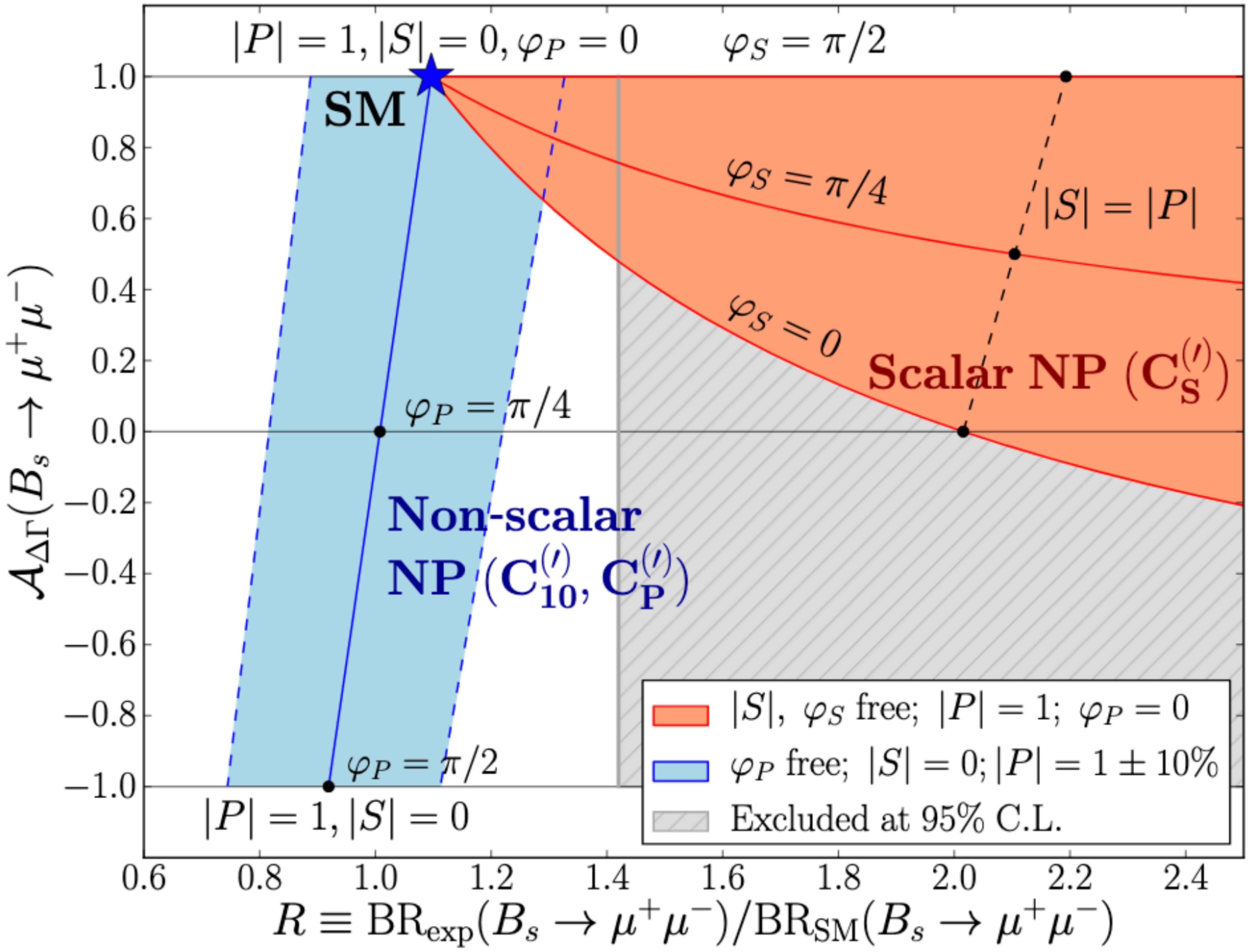
Effective lifetime

$A_{\Delta\Gamma}^{\mu\mu}$ can reveal new (pseudo-)scalar contributions even if $\mathscr{B}(B_s^0 \to \mu^+\mu^-)$ is SM-like

$$A_{\Delta\Gamma}^{\mu\mu} = \frac{\Gamma_\mathrm{H} - \Gamma_\mathrm{L}}{\Gamma_\mathrm{H} + \Gamma_\mathrm{L}} \overset{\mathrm{SM}}{=} +1$$

$$\tau_{\mu\mu} = \frac{\tau_{B_s^0}}{1 - y_s^2}\left[\frac{1 + 2A_{\Delta\Gamma}y_s + y_s^2}{1 + A_{\Delta\Gamma}y_s}\right]$$

$$y_s = \tau_{B_s^0}\Delta\Gamma/2 = 0.062 \pm 0.006$$



[De Bruyn et al., PRL 109 (2012) 041801]

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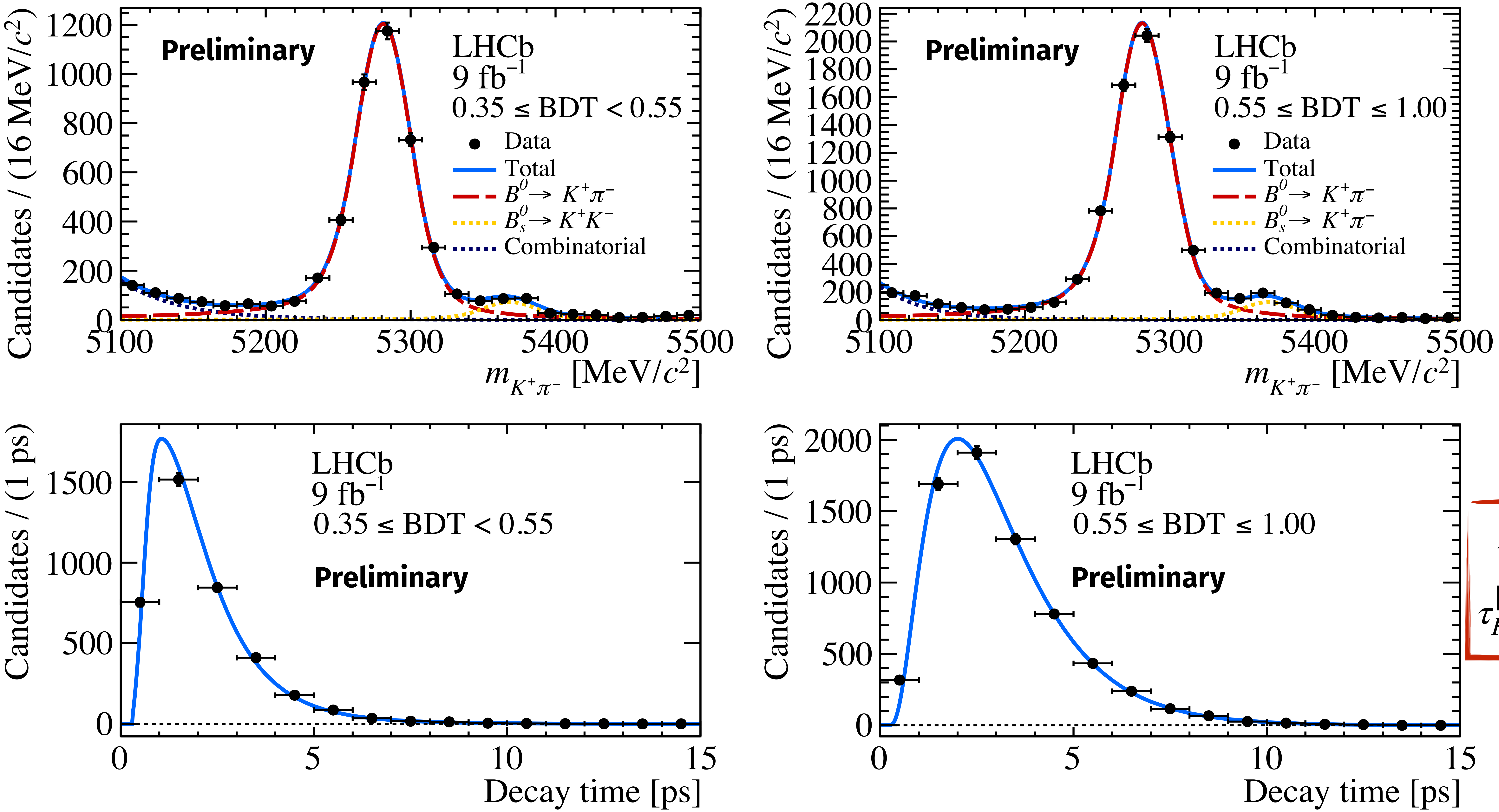
Effective lifetime measurement of $B^0 \to K^+\pi^-$



$\tau_{K\pi}^{\text{Test}} = (1.512 \pm 0.016)$ ps

$\tau_{K\pi}^{\text{LHCb}} = (1.524 \pm 0.011)$ ps

[PLB 736 (2014) 446]

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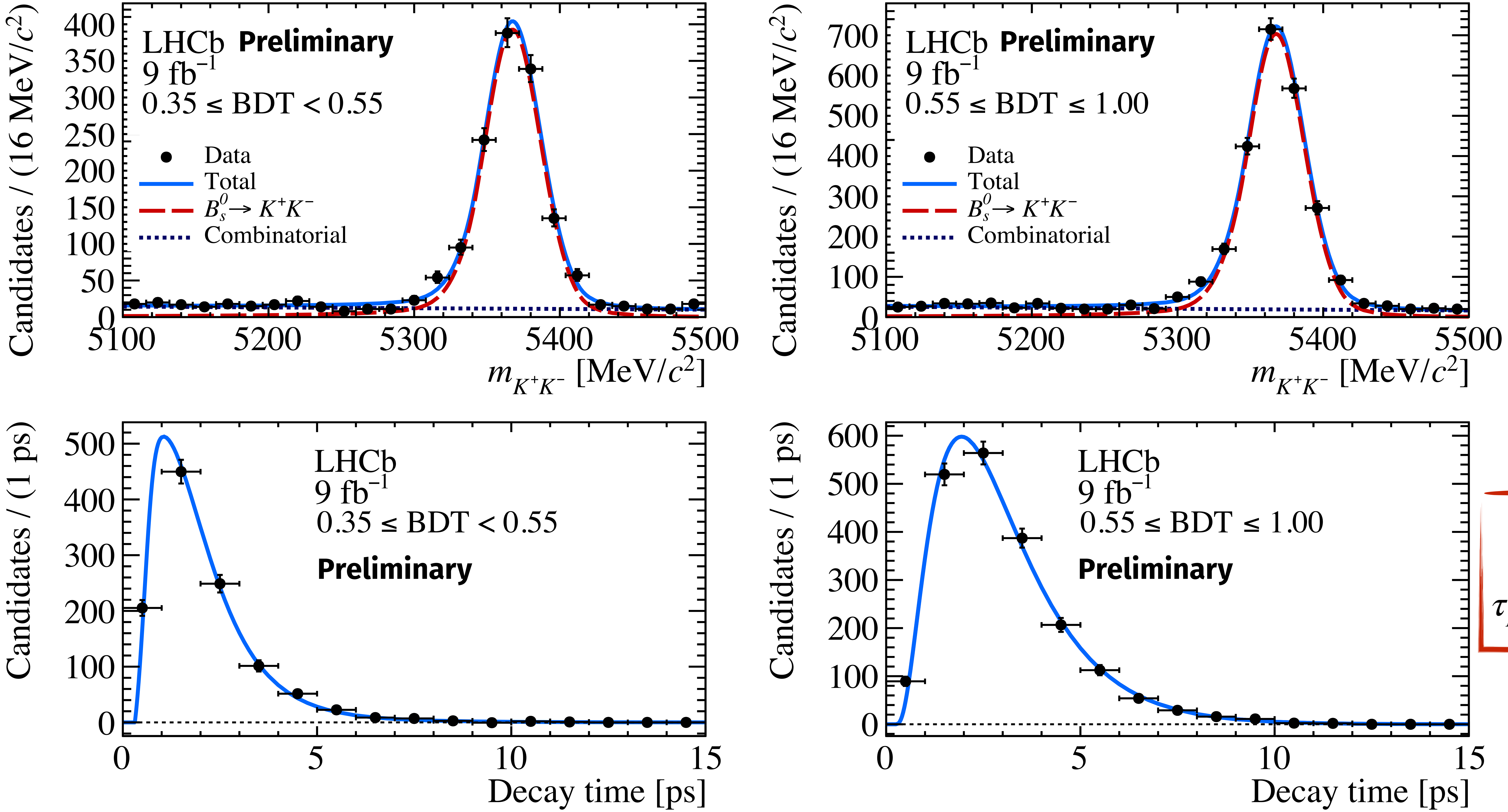
Effective lifetime measurement of $B_s^0 \to K^+K^-$



$\tau_{KK}^{\text{Test}} = (1.433 \pm 0.026)$ ps

$\tau_{KK}^{\text{LHCb}} = (1.407 \pm 0.016)$ ps

[PLB 736 (2014) 446]