Purely Leptonic Rare Decays at LHCb

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40th **I**nternational **C**onference of **H**igh **E**nergy **P**hysics

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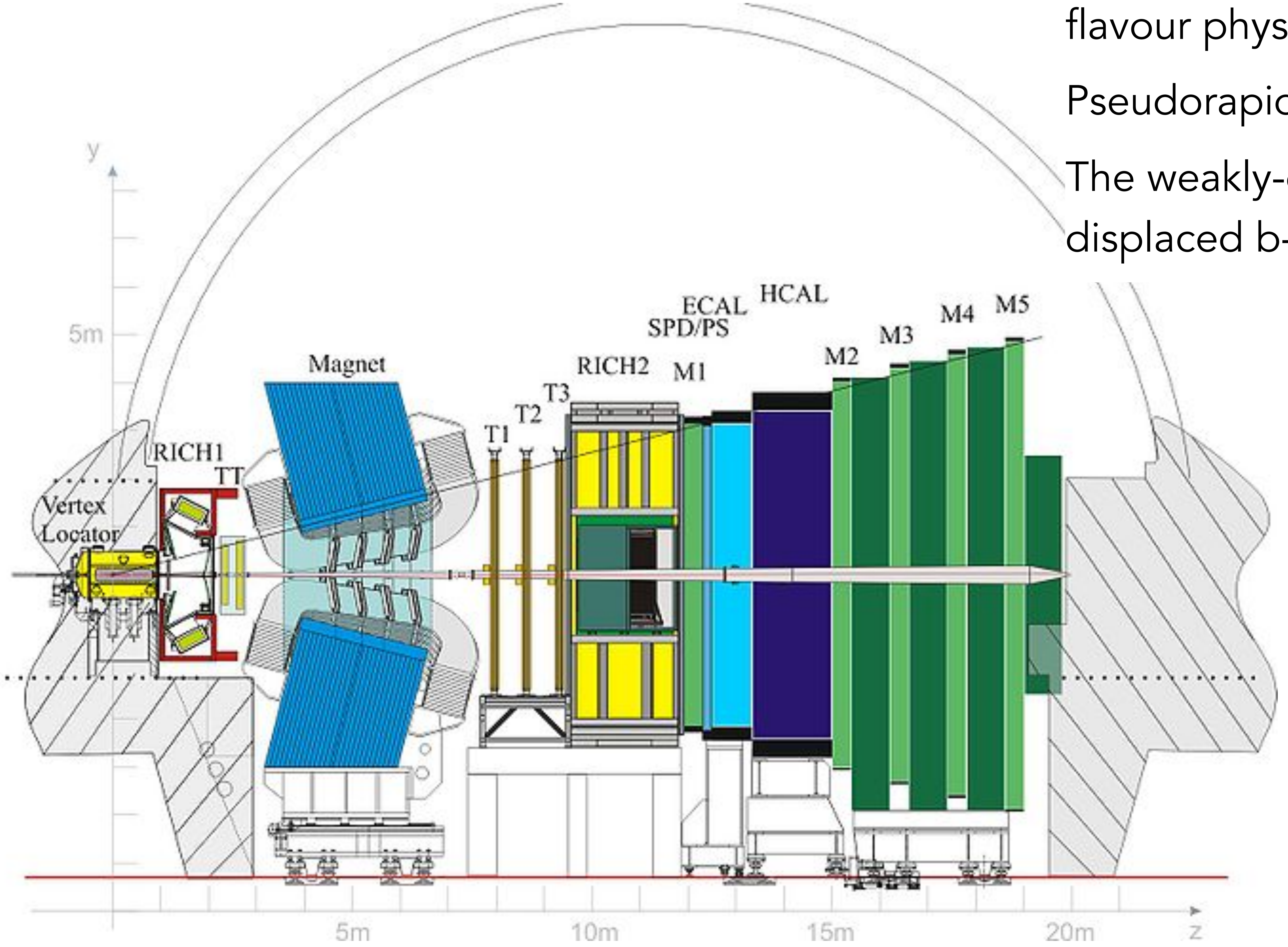
Outline

- **Overview of LHCb**
- **Rare Decays at LHCb**
- **Selection of recent analysis;**
  - $B_s^0 \to e^+e^-$ and $B^0 \to e^+e^-$
  - $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$
  - $B_s^0 \to \tau^+\tau^-$ and $B^0 \to \tau^+\tau^-$
  - $B_s^0 \to \tau^\pm\mu^\mp$ and $B^0 \to \tau^\pm\mu^\mp$
  - $K_S^0 \to \mu^+\mu^-$
- **Summary**

The LHCb detector

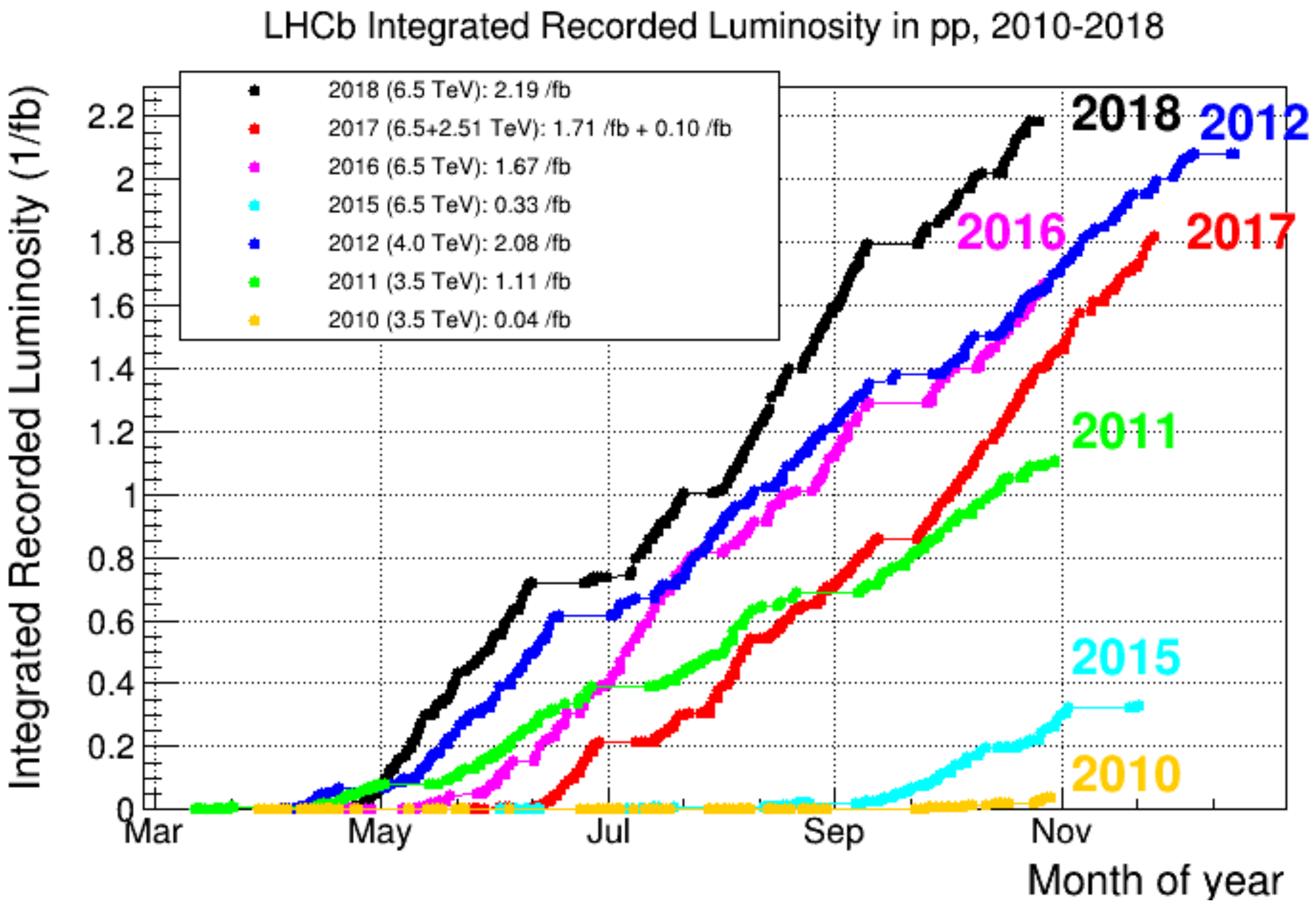
[JINST 3 (2008) S08005]



Forward spectrometer at the LHC designed for the study of heavy flavour physics

Pseudorapidity coverage $2<\eta<5$

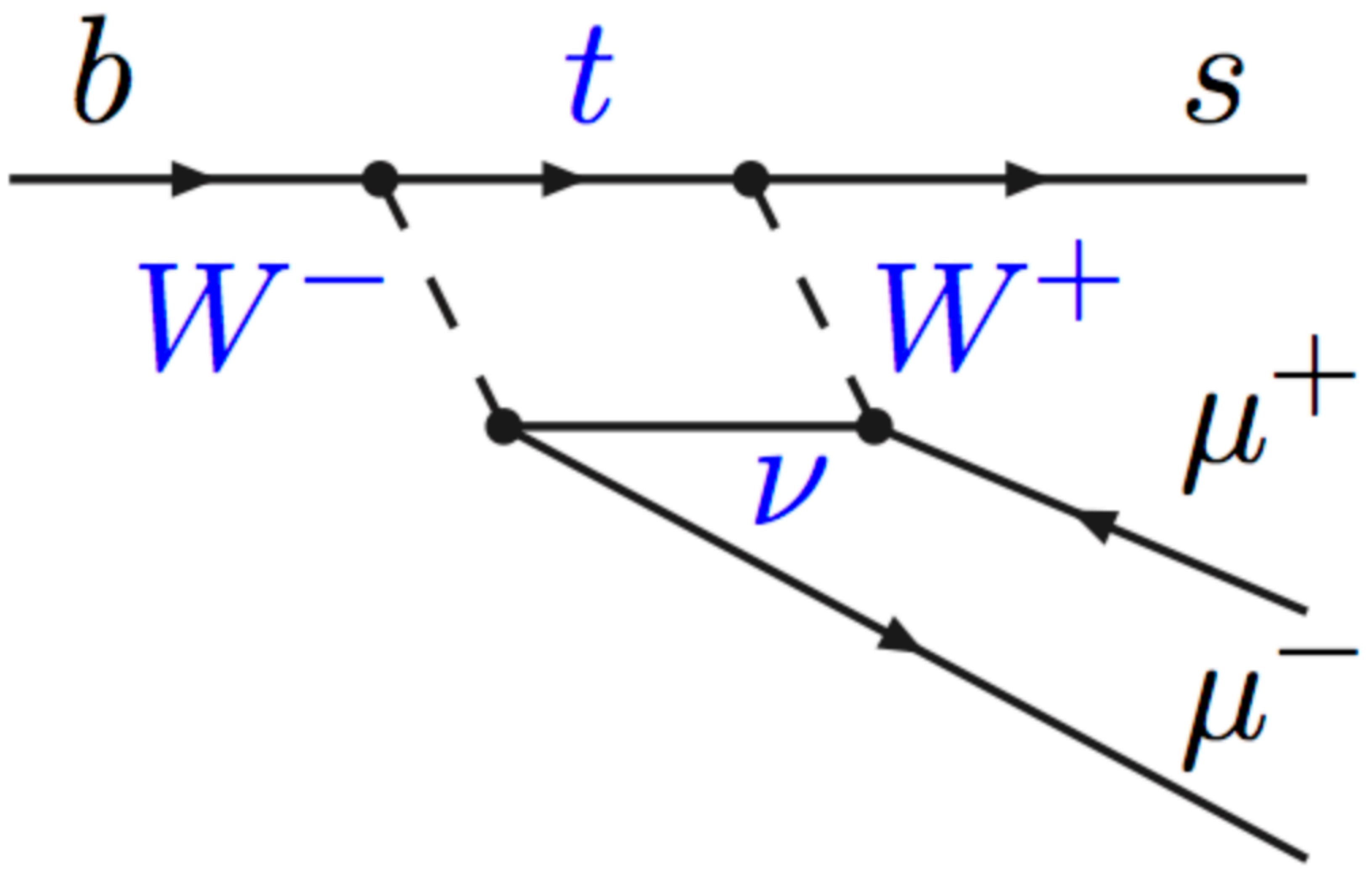
The weakly-decaying (boosted) b-particles fly ~ cm. Locating the displaced b-decay vertex separates signal from background.



> 10 fb^{-1} delivered, > 9fb^{-1} collected

Rare Decays

- Flavour-Changing-Neutral-Currents forbidden at leading-order (making certain decays extremely rare).
- Rare decays are powerful tools for probing NP interactions.
- Pure leptonic decays $B^0_{(s)} \to \ell^+\ell^-$ are even rarer in the SM due to helicity suppression, sensitive to BSM effects.
- Recent measurements of decays involving $b \to s\ell^+\ell^-$ transitions hint at deviations from SM predictions in lepton-flavour universality tests - motivation for measurements of decays to leptons



$B_s^0 \to e^+e^-$ and $B^0 \to e^+e^-$

[Phys. Rev. Lett. 124 (2020) 211802]

SM Predictions:

$\mathscr{B}(B_s^0 \to e^+e^-) = (8.60 \pm 0.36) \times 10^{-14}$

$\mathscr{B}(B^0 \to e^+e^-) = (2.41 \pm 0.13) \times 10^{-15}$

[M. Beneke *et al.* JHEP 10 (2019) 232]

With NP contributions could reach values of $\mathcal{O}(10^{-8})$ for $\mathscr{B}(B_s^0 \to e^+e^-)$ and $\mathcal{O}(10^{-10})$ for $\mathscr{B}(B^0 \to e^+e^-)$

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

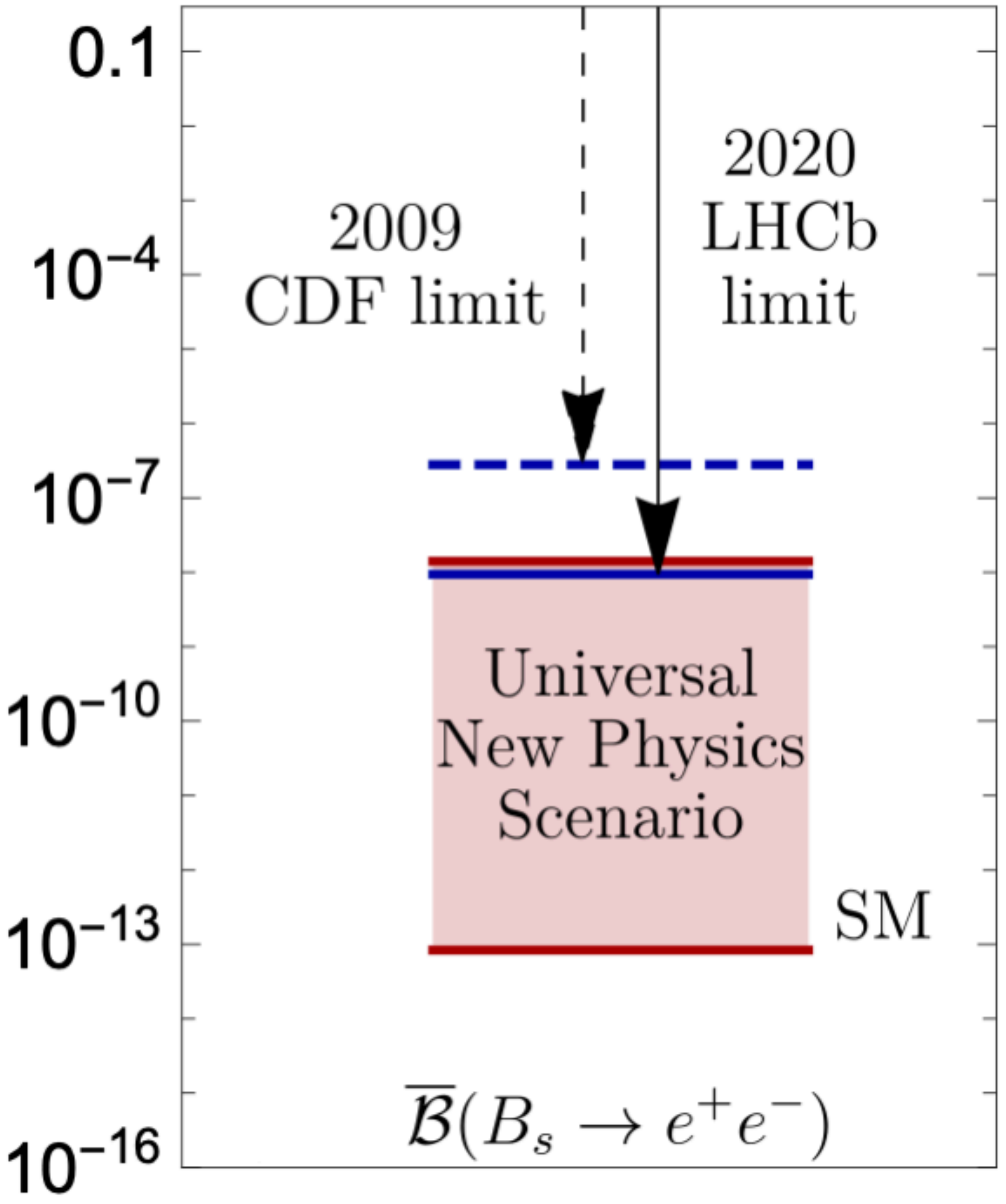
Previous experimental bounds (CDF collaboration):

$\mathscr{B}(B_s^0 \to e^+e^-) < 2.8 \times 10^{-7}$

$\mathscr{B}(B^0 \to e^+e^-) < 8.3 \times 10^{-8}$

at 90 % CL

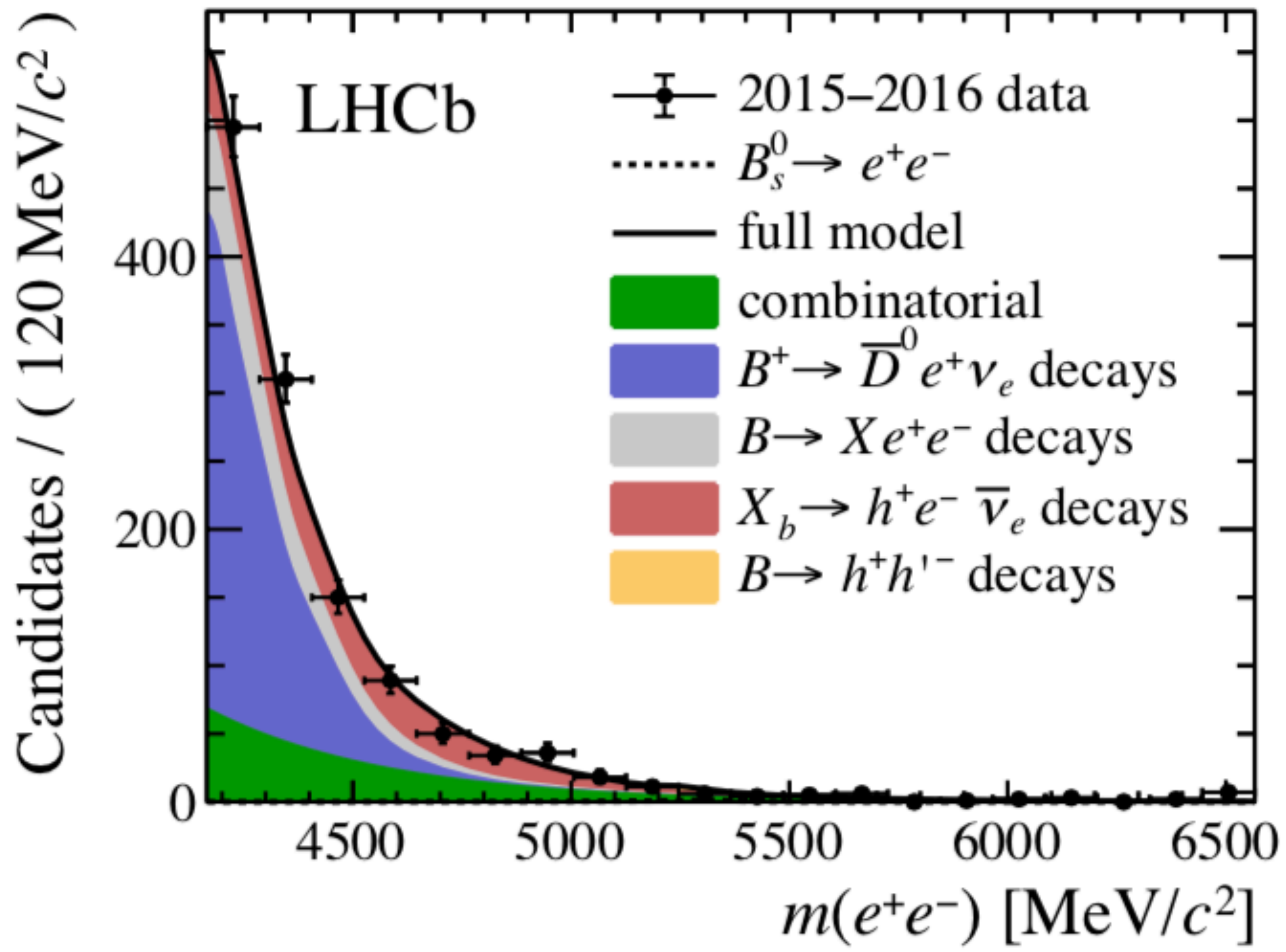
[Phys.Rev.Lett.102:201801,2009]



Normalisation channel:

$B^+ \to (J/\psi \to e^+e^-)K^+$

Year	COM	Lumi
2011	7 TeV	~ 1 fb^{-1}
2012	8 TeV	~ 2 fb^{-1}
2015-16	13 TeV	~ 2 fb^{-1}



- No excess of events is observed over the background.
- Limits: $\mathscr{B}(B_s^0 \to e^+e^-) < 9.4\ (11.2) \times 10^{-9}$ and $\mathscr{B}(B^0 \to e^+e^-) < 2.5\ (3.0) \times 10^{-9}$ at 90 (95) % CL when neglecting the contribution from the other decay.

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

[Phys. Rev. Lett. 118, 191801 (2017)]

SM Predictions:

$\mathscr{B}(B_s^0 \to \mu^+\mu^-)$ = (3.65 ± 0.23) × 10^{-9}

$\mathscr{B}(B^0 \to \mu^+\mu^-)$ = (1.06 ± 0.09) × 10^{-10}

[C. Bobeth *et al.* Phys. Rev. Lett. 112, 101801 (2014)]

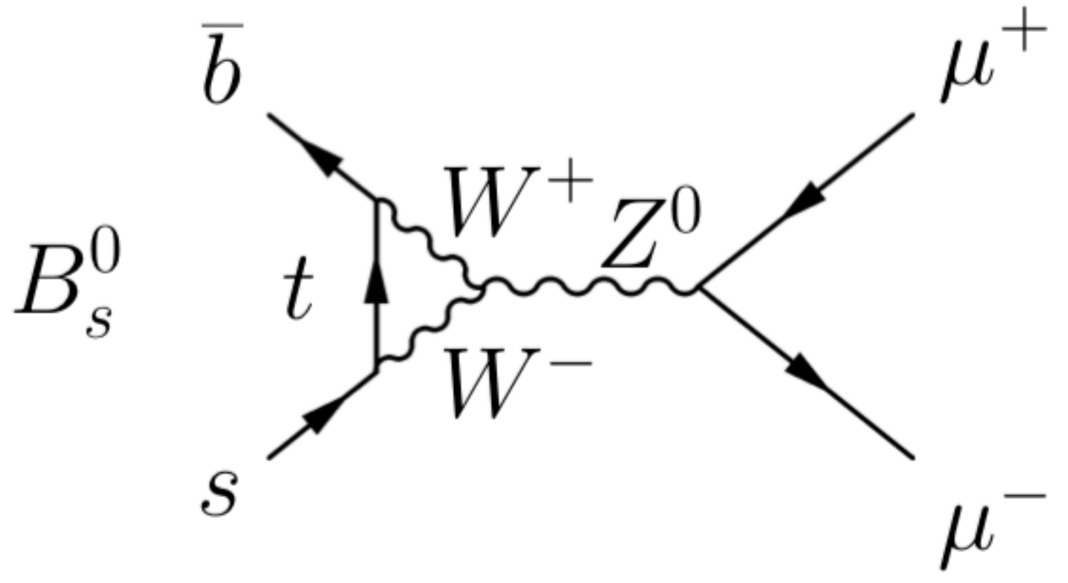
Normalisation channels:

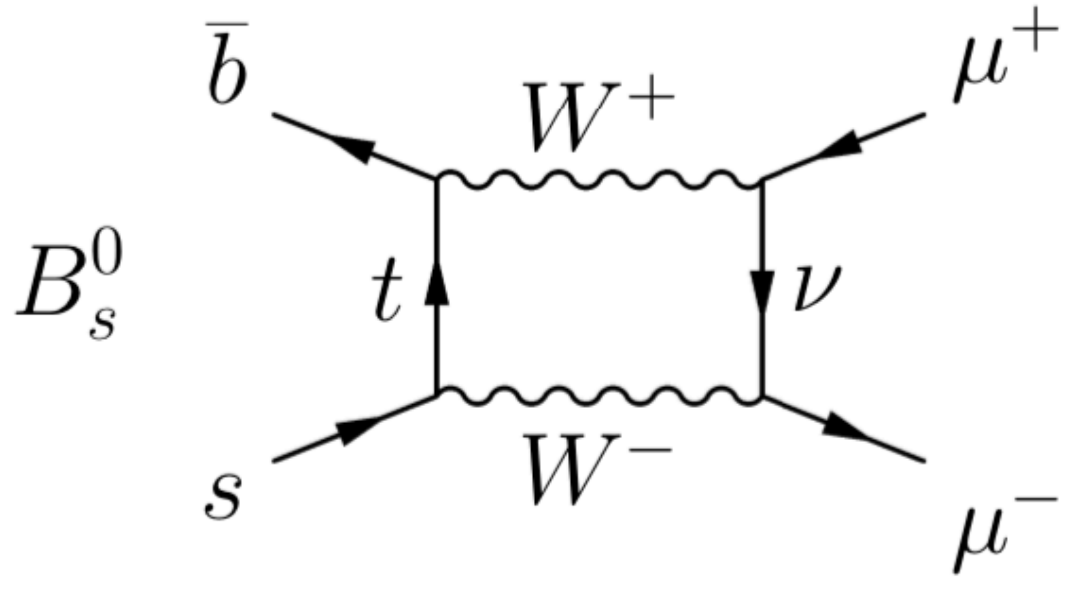
$B^+ \to (J/\psi \to \mu^+\mu^-)K^+$

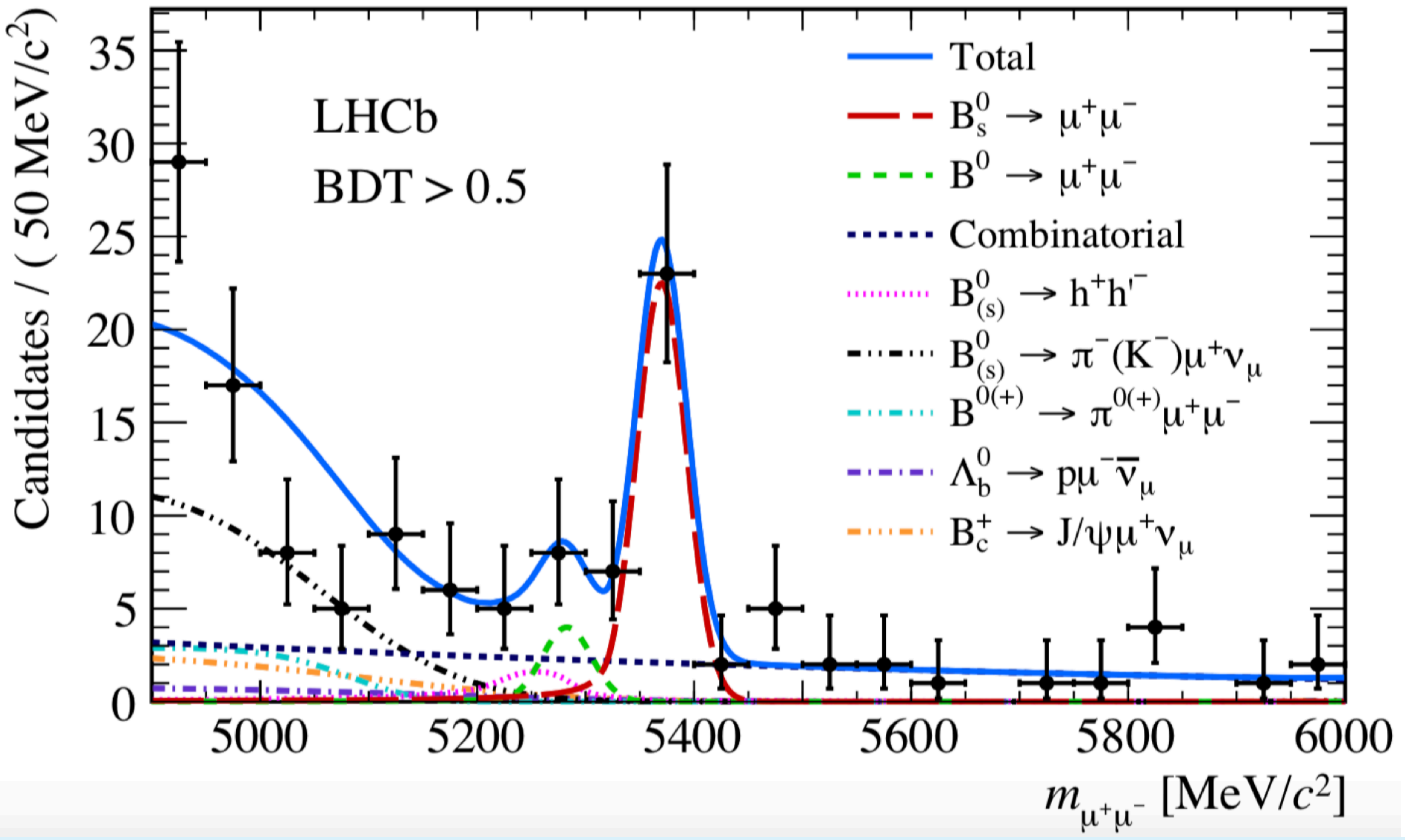
and $B^0 \to K\pi$

Year	COM	Lumi
2011	7 TeV	~ 1 fb^{-1}
2012	8 TeV	~ 2 fb^{-1}
2015-16	13 TeV	~ 1.4 fb^{-1}

- Evidence of $B^0 \to \mu^+\mu^-$ with observed significance of 3.2σ (1.8σ and 2.6σ from LHCb and CMS data, respectively).
- $\mathscr{B}(3.9^{+1.6}_{-1.4}) \times 10^{-10}$ — 2.2σ above the SM prediction
  [Nature (London) 522, 68 (2015)]
- $B_s^0 \to \mu^+\mu^-$ observed with a significance of 7.8σ, BR is in agreement with the SM prediction







$B_s^0 \to \tau^+\tau^-$ and $B^0 \to \tau^+\tau^-$

[Phys. Rev. Lett. 118, 251802 (2017)]

SM Predictions:

$\mathscr{B}(B_s^0 \to \tau^+\tau^-) = (7.73 \pm 0.49) \times 10^{-7}$

$\mathscr{B}(B^0 \to \tau^+\tau^-) = (2.22 \pm 0.19) \times 10^{-8}$

[C. Bobeth *et al.* Phys. Rev. Lett. 112, 101801 (2014)]

Previous experimental bounds (BaBar collaboration):

$\mathscr{B}(B^0 \to \tau^+\tau^-) < 4.10 \times 10^{-3}$

at 90 % confidence level (CL)

[Phys.Rev.Lett.96:241802,2006]

The τ decay proceeds predominantly via the decay chain:

(at least two undetected neutrinos in the B decay)

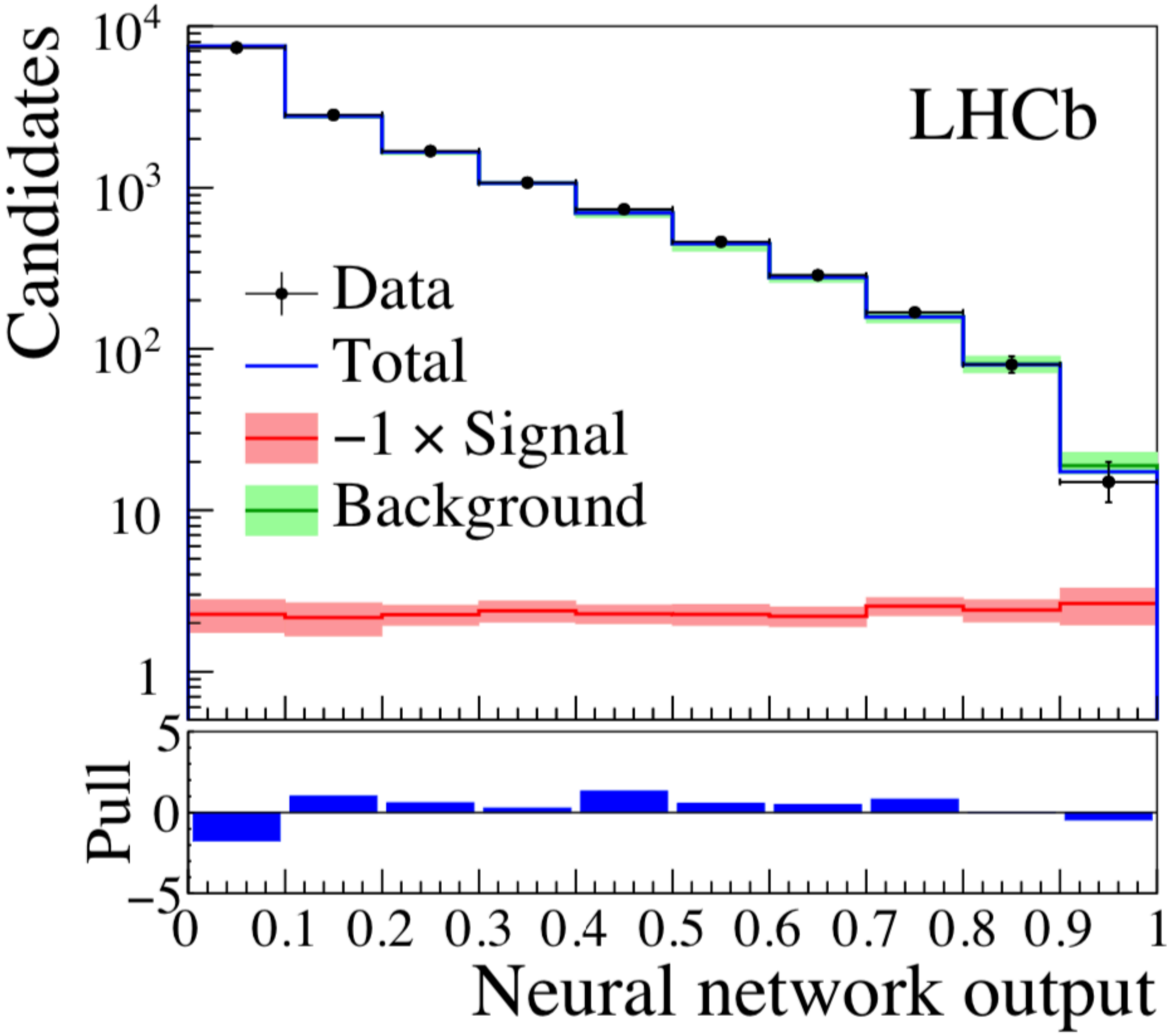
$$\tau^- \to a_1(1260)^-\nu_\tau$$

$$\downarrow$$

$$a_1(1260)^- \to \rho(770)^0\pi^-$$

$$\downarrow$$

$$\rho(770)^0 \to \pi^+\pi^-$$



Year	COM	Lumi
2011	7 TeV	~ 1 fb^{-1}
2012	8 TeV	~ 2 fb^{-1}

Normalisation channel:

$B^0 \to D^-D_s^+$ with:

$D^- \to K^+\pi^-\pi^-$ and

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

- No excess of events is observed over the background.
- Limits - $\mathscr{B}(B_s^0 \to \tau^+\tau^-) < 6.8\times10^{-3}$ and $\mathscr{B}(B^0 \to \tau^+\tau^-) < 2.1\times10^{-3}$ at 95 % confidence level, when neglecting the contribution from the other decay.
- First direct limit on $\mathscr{B}(B_s^0 \to \tau^+\tau^-)$ and world's best limit on $\mathscr{B}(B^0 \to \tau^+\tau^-)$

$B_s^0 \to \tau^\pm\mu^\mp$ and $B^0 \to \tau^\pm\mu^\mp$

[Phys. Rev. Lett. 123, 211801 (2019)]

SM Predictions:

$\mathscr{B}(B^0_{(s)} \to \tau^\pm\mu^\mp)$ = ~ 10^{-54}

[L. Calibbi *et al.* Riv. Nuovo Cimento 41, 71 (2018)]

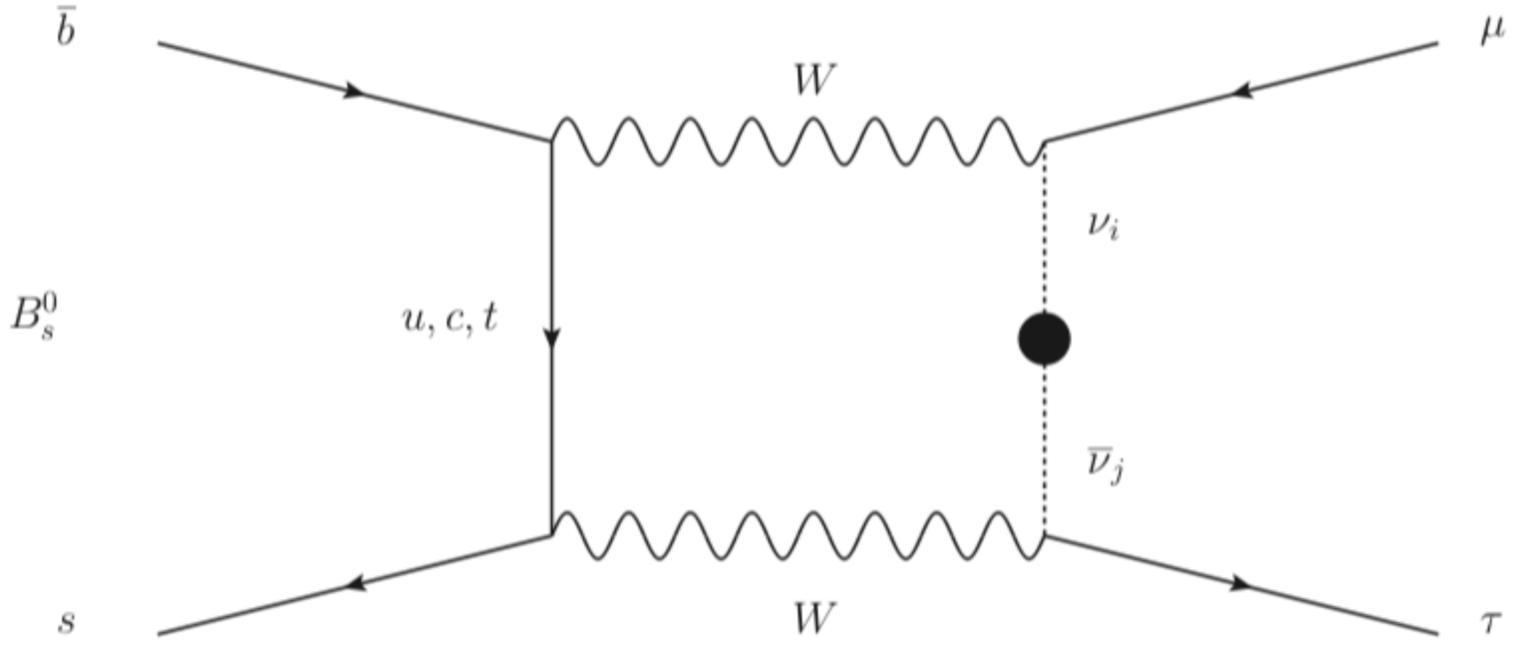
LFV B decays, such as $B^0_{(s)} \to \tau^\pm\mu^\mp$ forbidden in the SM unless neutrino mass oscillations are included

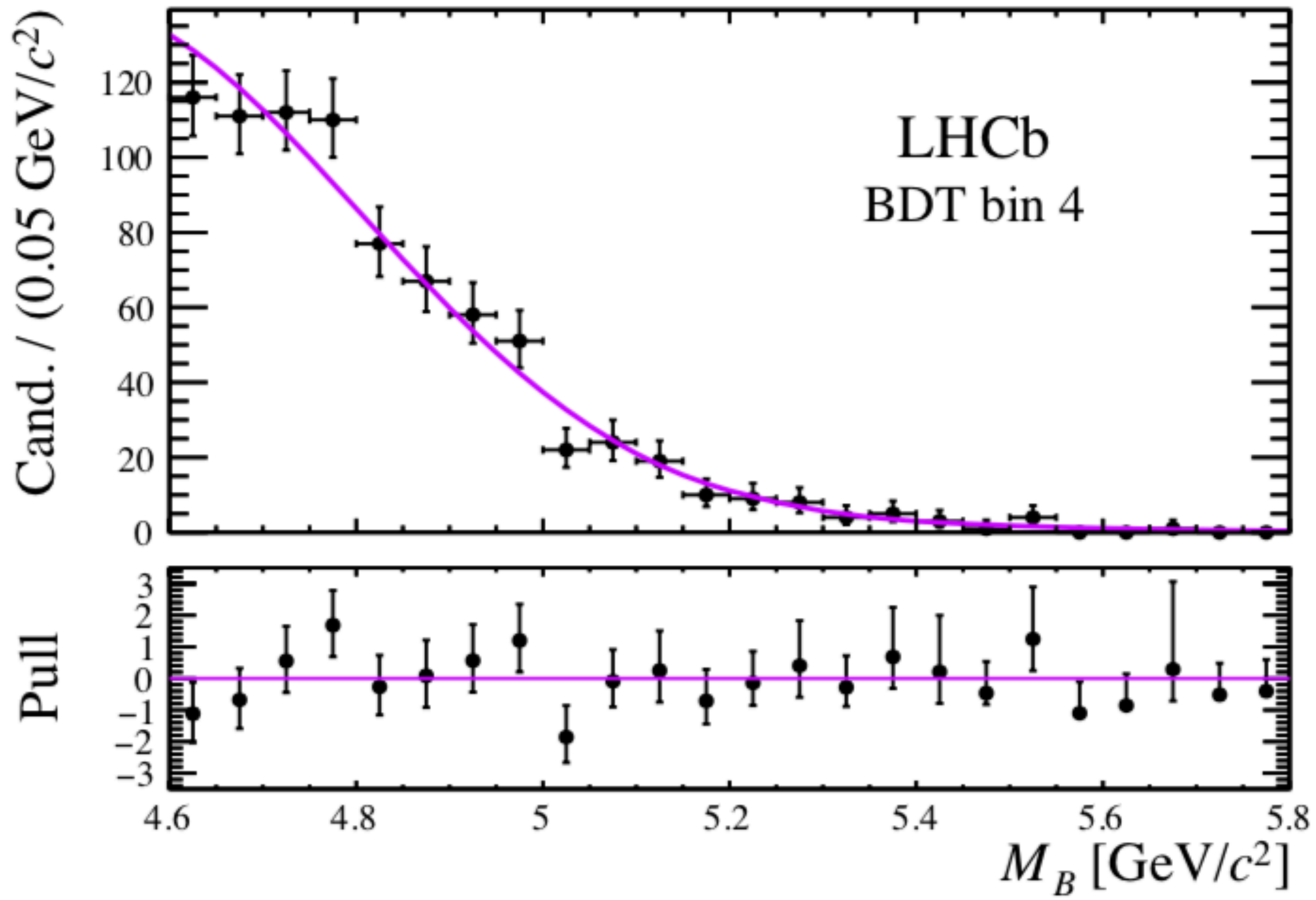
Previous experimental bounds (BaBar collaboration):

$\mathscr{B}(B^0 \to \tau^\pm\,\mu^\mp) < 2.2 \times 10^{-5}$

at 90 % confidence level (CL)

[Phys.Rev.D77:091104,2008]





Year	COM	Lumi
2011	7 TeV	~ 1 fb^{-1}
2012	8 TeV	~ 2 fb^{-1}

Normalisation channel:

$B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+$

$N^{sig}_{B_s^0\to\tau^\pm\mu^\mp} = -16 \pm 38$

$N^{sig}_{B^0\to\tau^\pm\mu^\mp} = -65 \pm 58$

No signal excess

- Limits - $\mathscr{B}(B_s^0 \to \tau^\pm\mu^\mp) < 4.2 \times 10^{-5}$ and $\mathscr{B}(B^0 \to \tau^\pm\mu^\mp) < 1.4 \times 10^{-5}$ at 95% confidence level, when neglecting the contribution from the other decay.
- Results represent first limit on $B_s^0 \to \tau^\pm\mu^\mp$ and most stringent limit on $B^0 \to \tau^\pm\mu^\mp$
- Imposes new limits on vector leptoquark model [C. Cornella *et al.* JHEP 1907 (2019) 168]

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

[arXiv:2001.10354]

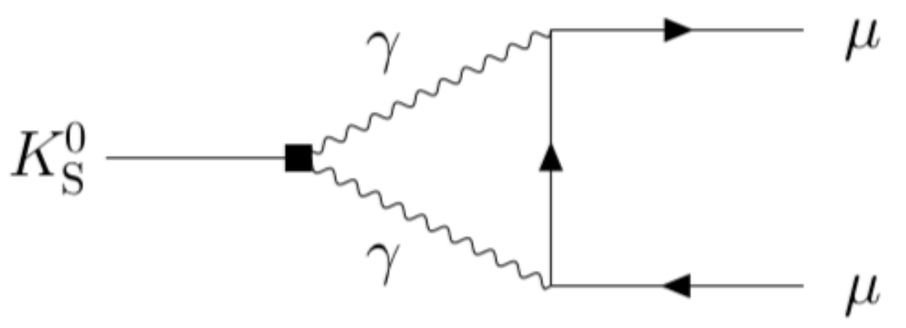
SM Prediction:

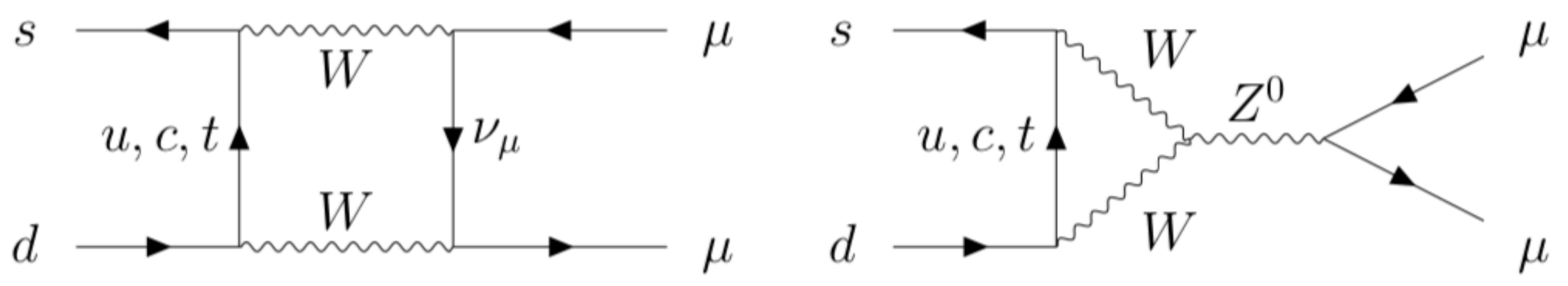
$\mathcal{B}(K_S^0 \to \mu^+\mu^-) = (5.18 \pm 1.5_{\mathrm{LD}} \pm 0.02_{\mathrm{SD}}) \times 10^{-12}$

Where LD and SD signify long and short distance effects.

[G. D'Ambrosio *et al*. Phys. Rev. Lett. 119 (2017) 201802]

Long distance (top) and short distance (bottom) contributions to decay mode



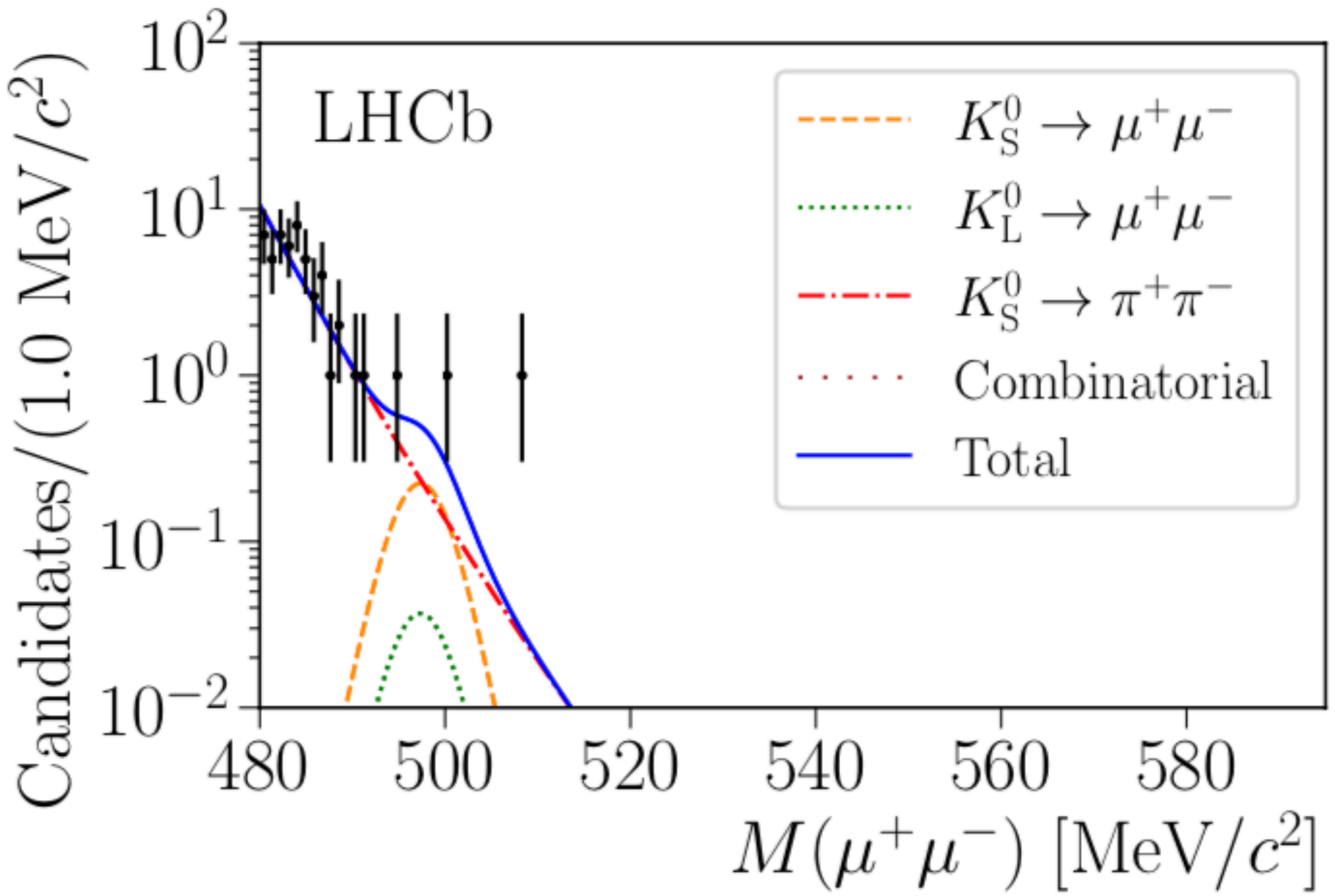


- Run 1 Limit - $\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 9 \times 10^{-9}$ at 90% CL
  [Eur. Phys. J. C77 (2017) 678]
- New and improved trigger strategy for Run2

Year	COM	Lumi
2016-18	13 TeV	~ 5.6 fb^{-1}

Normalisation channel:

$K_S^0 \to \pi^+\pi^-$



- Observed signal yield consistent with zero
- Limits - $\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 2.2 \times 10^{-10}$ reduced to $< 2.1 \times 10^{-10}$ at 90% confidence level when combined with Run1 result

Summary

- Rare decays are sensitive probes of BSM physics
- Rare decays involving leptons allow tests of LFU
- Several interesting purely leptonic decay analyses already completed within LHCb - many more ongoing

Thank you for listening!

BACKUP

Search Strategy

Many analysis presented use normalisation channels in order to cancel large uncertainties in $\sigma_{pp\to b\bar{b}}$ and also potential systematic effects in lepton reconstruction and selection.

$$\mathcal{B}(Signal) = \frac{N_{Signal}}{2 \times \mathcal{L}_{int} \times \sigma_{pp\to b\bar{b}} \times f \times \epsilon_{Signal}}$$

Large uncertainties in these measurements - not ideal for Rare Decays..

Where:

- N is number of events
- $\mathcal{L}_{int}$ is the Integrated Luminosity
- $\sigma_{pp\to b\bar{b}}$ is the bb cross-section
- f is the hadronisation fraction (measured by LHCb)
- ϵ is the total efficiency

So, we normalise against another decay channel in order to elevate these uncertainties

→

$$\mathcal{B}(Signal) = \frac{\mathcal{B}(Norm)}{N_{Norm}} \times \frac{\epsilon_{Norm}}{\epsilon_{Signal}} \times \frac{f_{Norm}}{f_{Signal}} \times N_{Signal}$$

$B_s^0 \to e^+e^-$ and $B^0 \to e^+e^-$

FSR corrections:

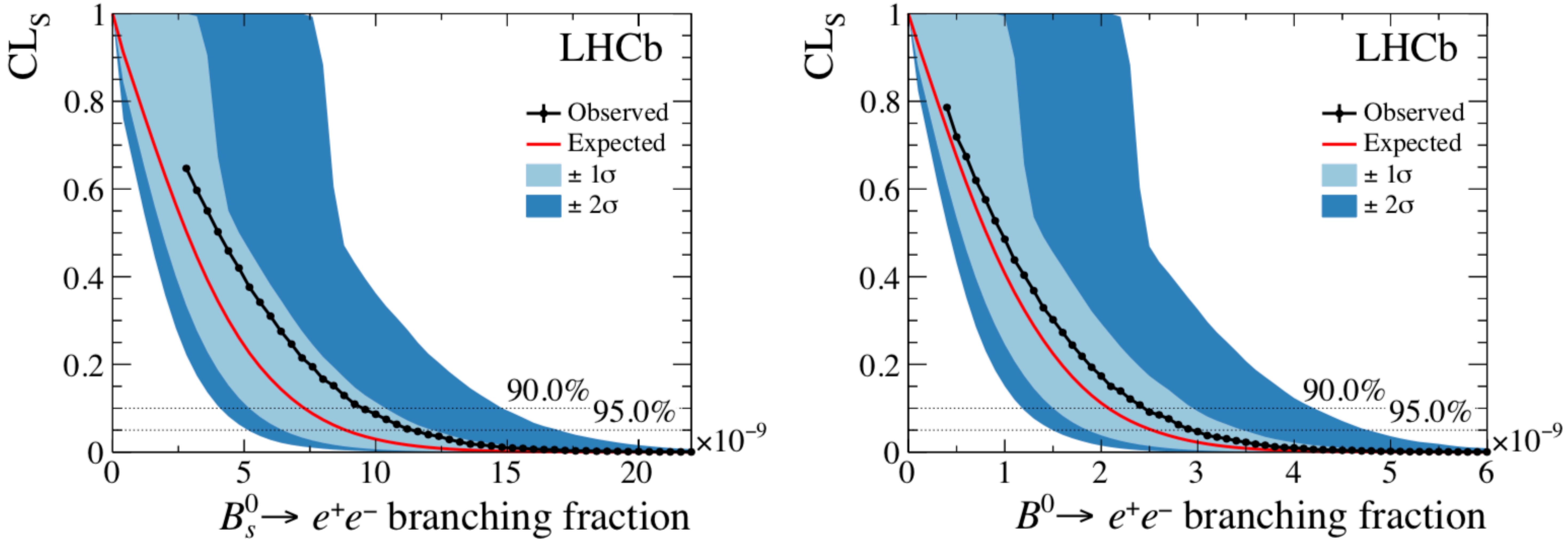
The measured electron momenta are corrected for losses due to bremsstrahlung radiation by adding the momentum of photons consistent with being emitted upstream of the magnet . Candidates in data and simulation are separated into three categories with either zero, one, or both electrons having a bremsstrahlung correction applied.

MAIN SOURCES OF BACKGROUND:

Combinatorial - Use BDT to reject this

Lower mass region - Partially reconstructed backgrounds of the types $B \to Xe^+e^-$ and $B^+ \to D^0(\to Y^+e^-\nu_e)e^+\nu_e$ dominate, where X and Y represent hadronic systems.

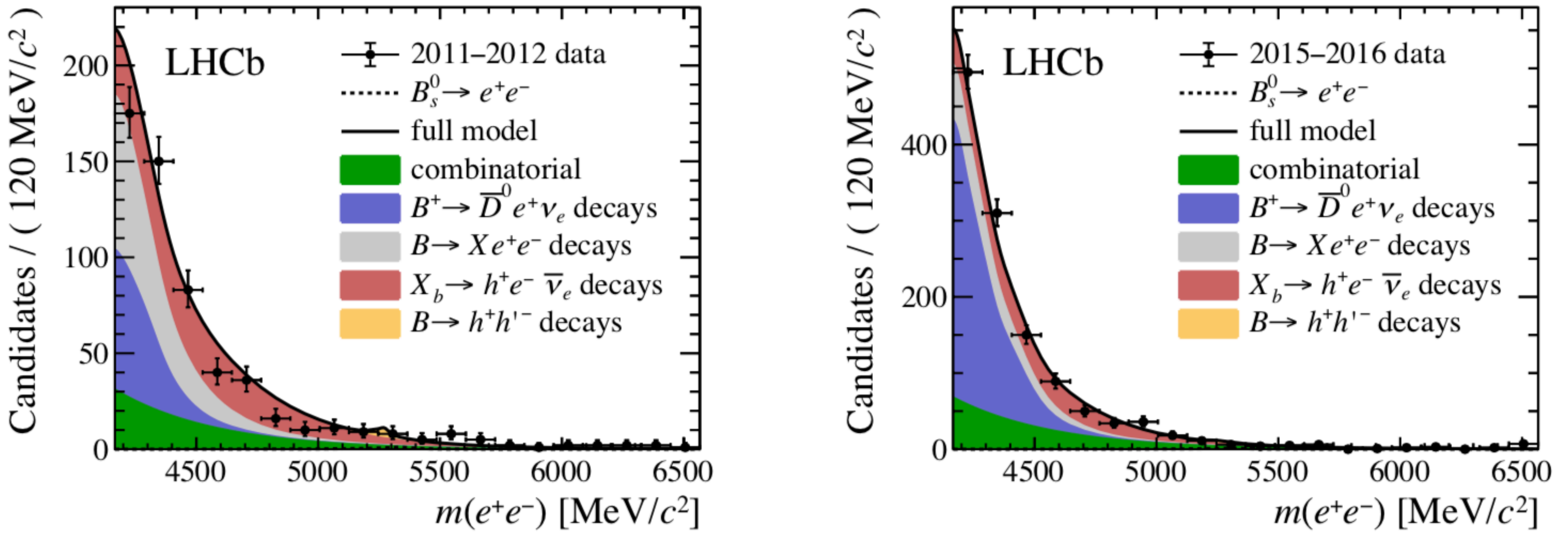
B mass region - misidentified particles in the decays $B^0 \to \pi^-e^+\nu_e$ and $B \to h^+h'^-$, where h and h′ are hadrons



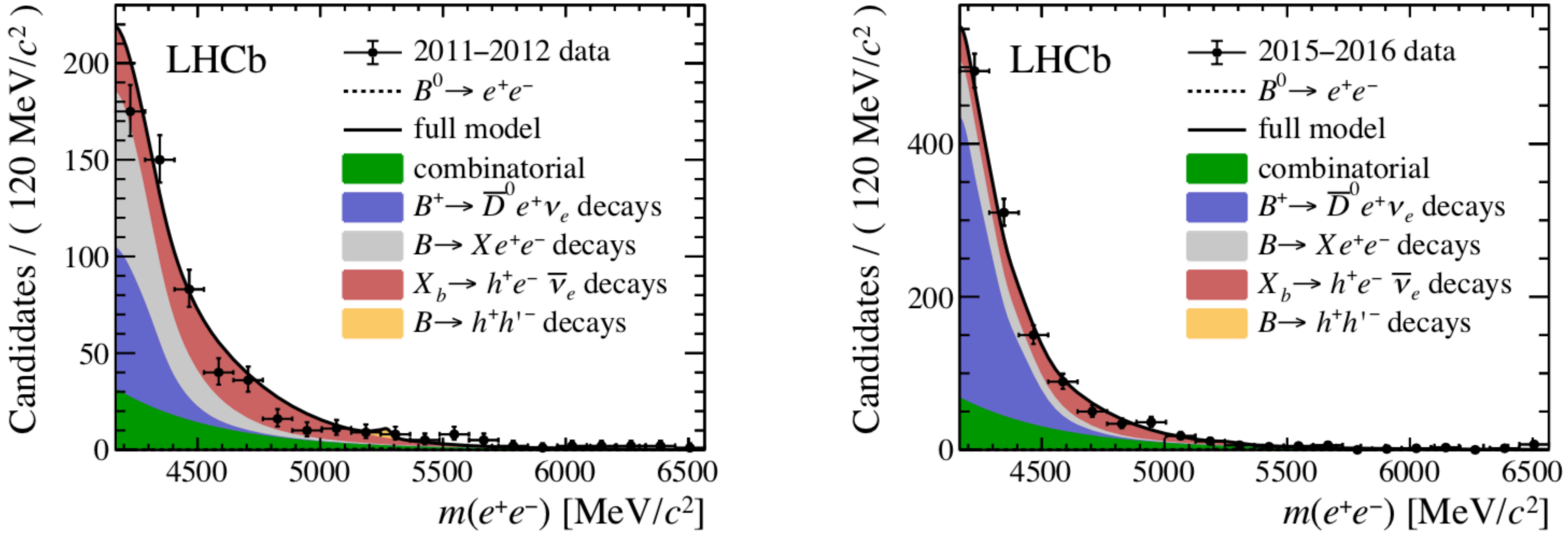
$B_s^0 \to e^+e^-$ and $B^0 \to e^+e^-$

[Phys. Rev. Lett. 124 (2020) 211802]

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



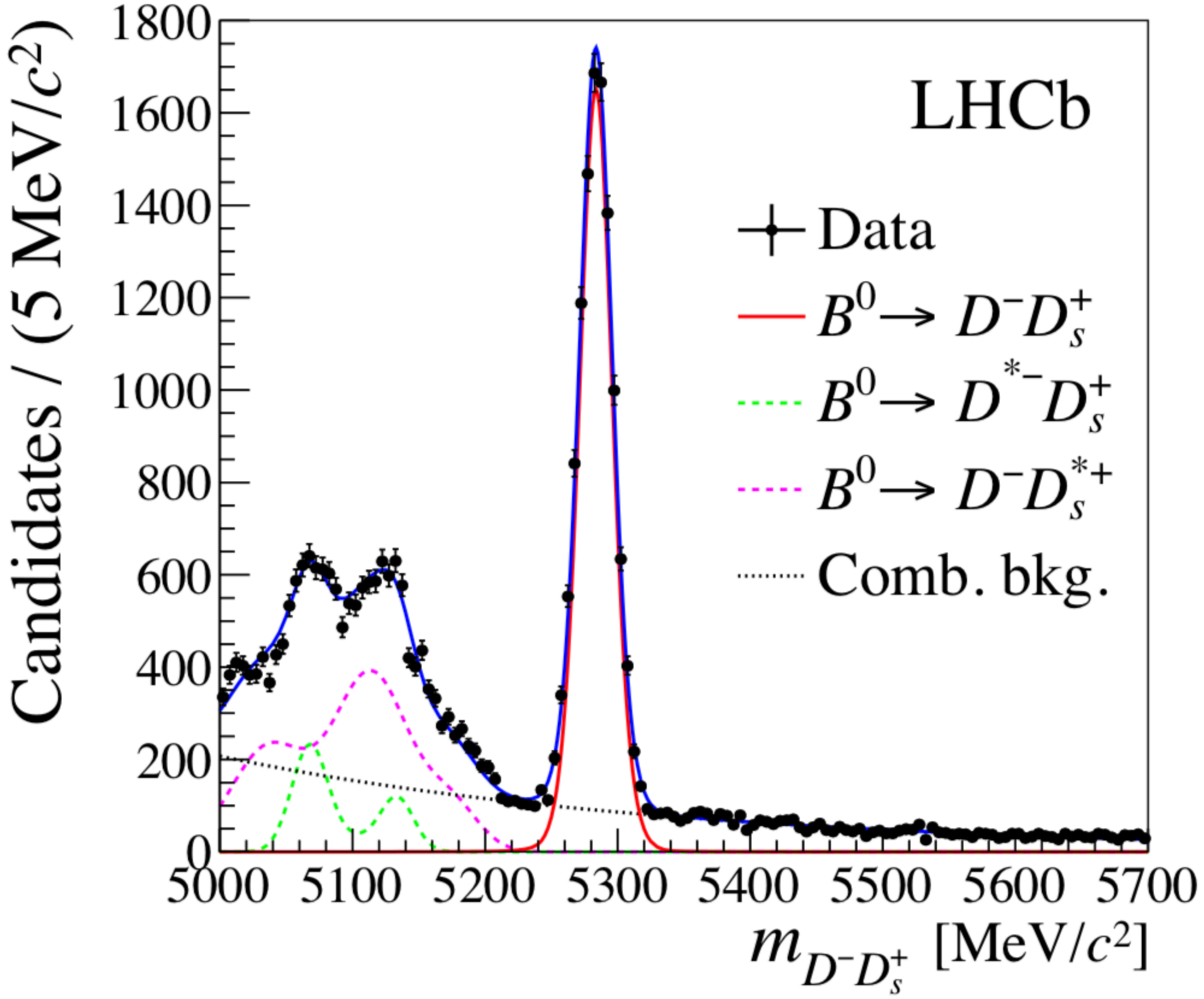
$B^0 \to e^+e^-$



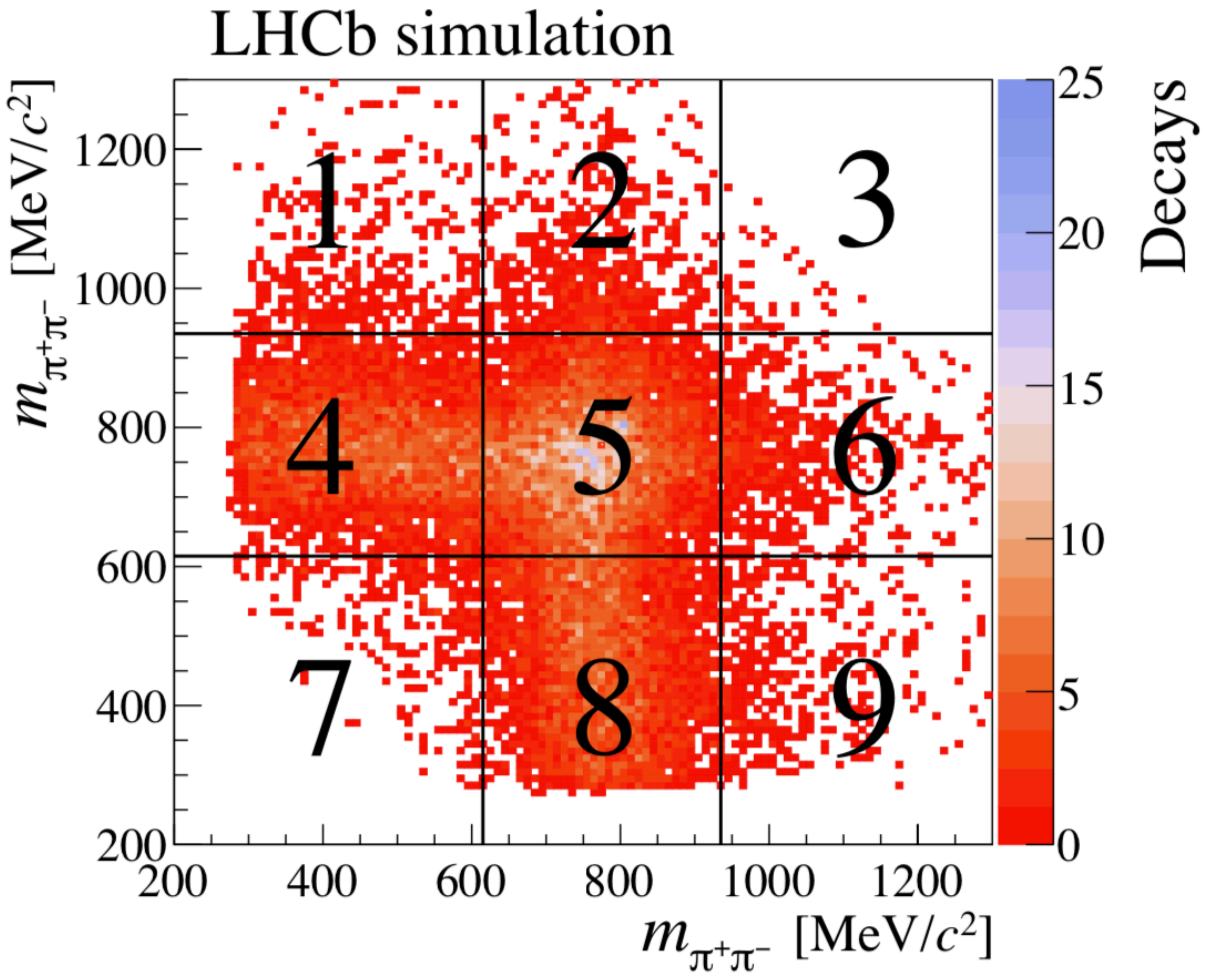
The bremsstrahlung categories are summed over the (left) Run 1 and (right) Run 2 data sets. The relative proportions of background contributions change between Run 1 and Run 2 due to different performances of the particle-identification algorithms and BDT selections.

$B_s^0 \to \tau^+\tau^-$ and $B^0 \to \tau^+\tau^-$

Backgrounds: $B^0 \to D^-\pi^+\pi^-\pi^+$ with $D^- \to K^0\pi^-\pi^+\pi^-$, or $B_s^0 \to D_s^-\pi^+\pi^-\pi^+$ with $D_s^- \to \tau^-\nu_\tau$



Invariant mass distribution of the reconstructed $B^0 \to D^-D_s^+$ candidates in data (black points), together with the total fit result (blue line) used to determine the $B^0 \to D^-D_s^+$ yield.



Two-dimensional distribution of the invariant masses $m_{\pi^+\pi^-}$ of the two oppositely charged two-pion combinations for simulated $B_s^0 \to \tau^+\tau^-$ candidates. The distribution is symmetric by construction. The vertical and horizontal lines illustrate the sector boundaries.

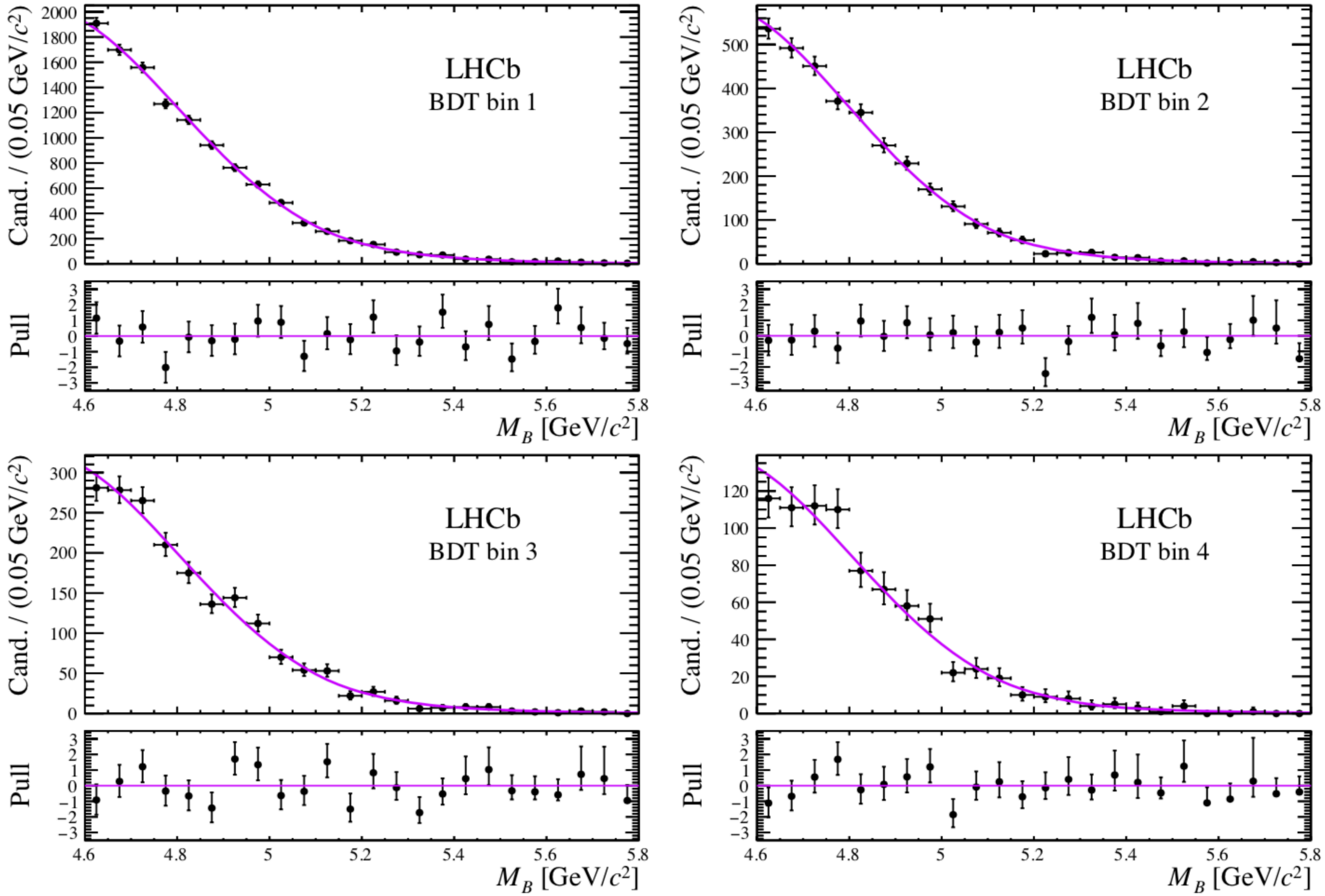
Signal - both τ candidates in sector 5 (used to determine the signal yield.)

Signal-depleted - at least one τ candidate in sectors 1, 3, 7 or 9, (provides a sample used when optimising the selection.)

Control region - one τ candidate in sectors 4, 5 or 8 and the other in sectors 4 or 8 (provides the background model.)

$B_s^0 \to \tau^\pm\mu^\mp$ and $B^0 \to \tau^\pm\mu^\mp$

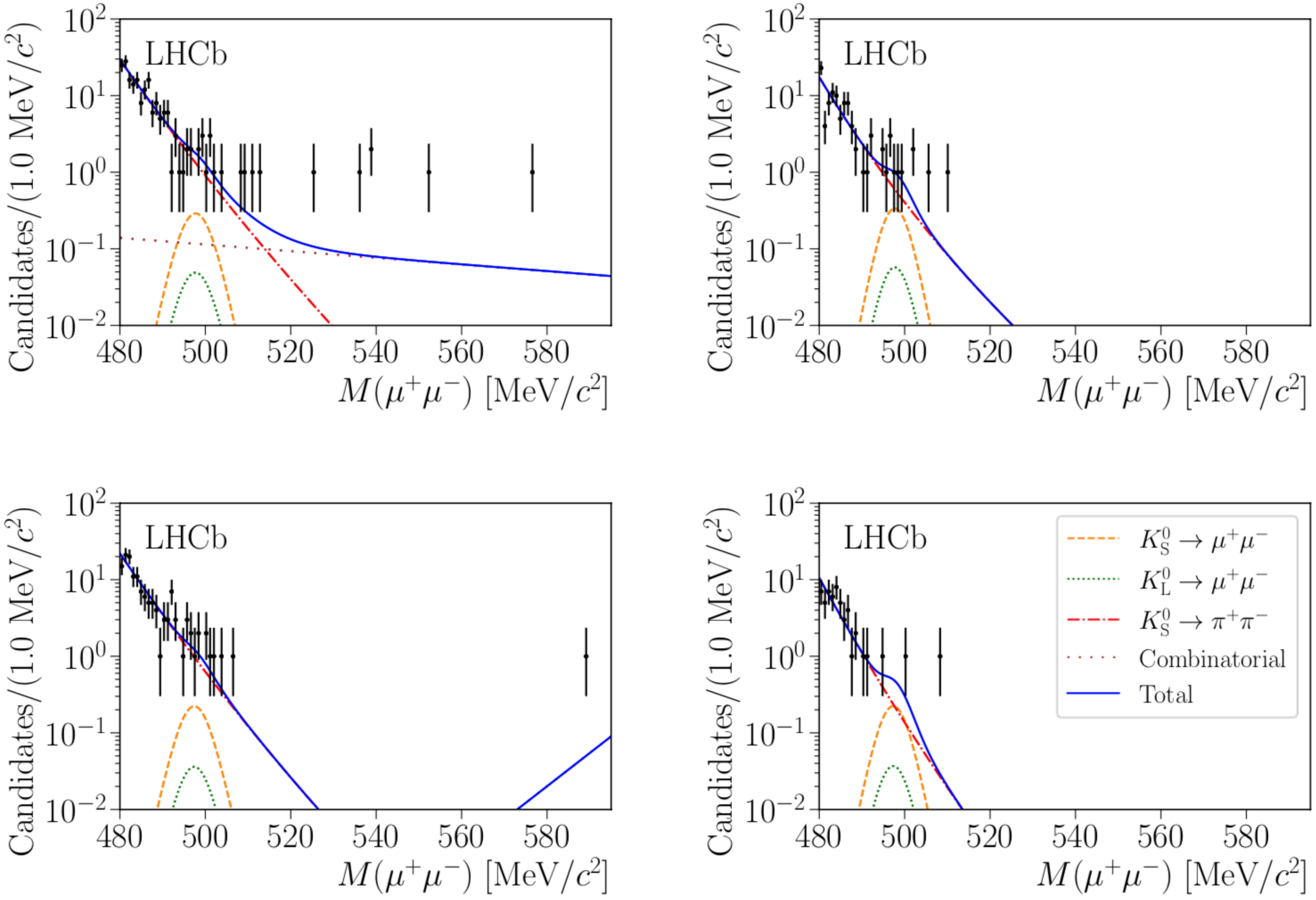
[Phys. Rev. Lett. 123, 211801 (2019)]



Distributions of the reconstructed B invariant-mass in data in the four final BDT bins with the projections of the fit for the B_s^0 signal-only hypothesis overlaid. The lower-part of each figure shows the normalised residuals.

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

[arXiv:2001.10354]



Projection of the fit to the dimuon invariant mass distribution for (top) two TIS and (bottom) two xTOS BDT bins. These bins correspond to the BDT response with the biggest signal-to-background ratio (increasing from left to right).