Status and prospects of LFV at LHCb

WIFAI 2023
Workshop Italiano sulla Fisica ad Alta Intensità
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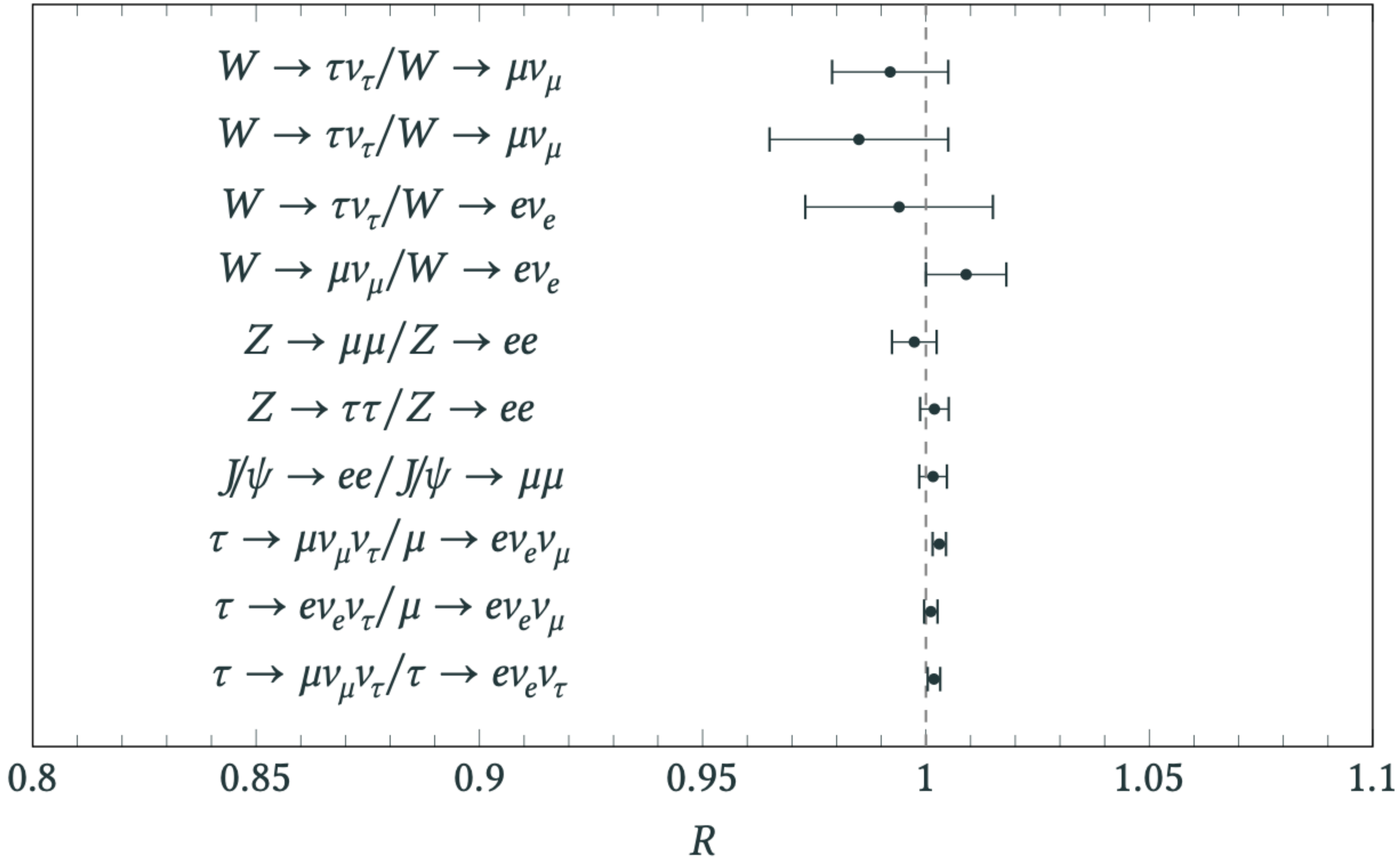
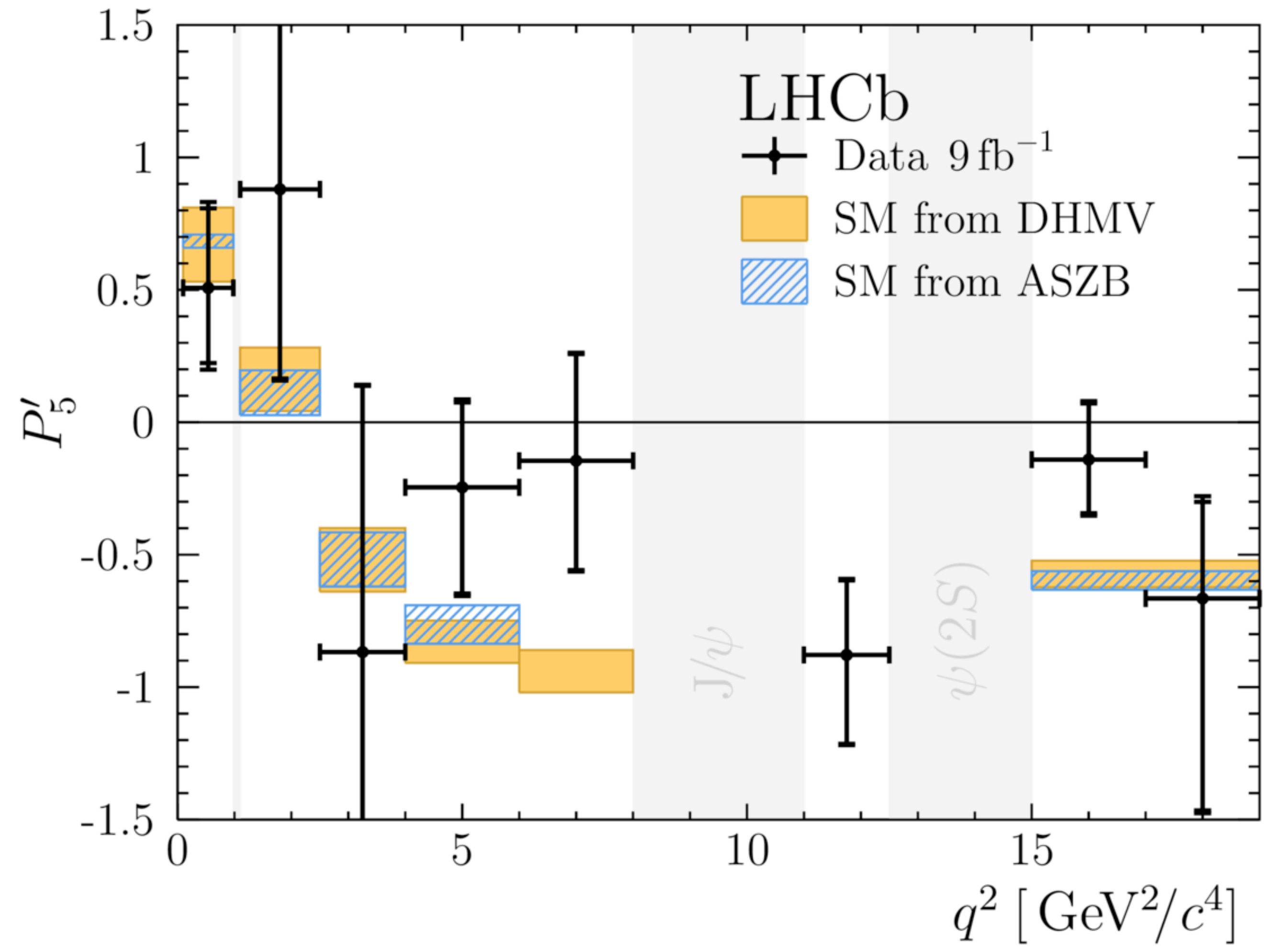
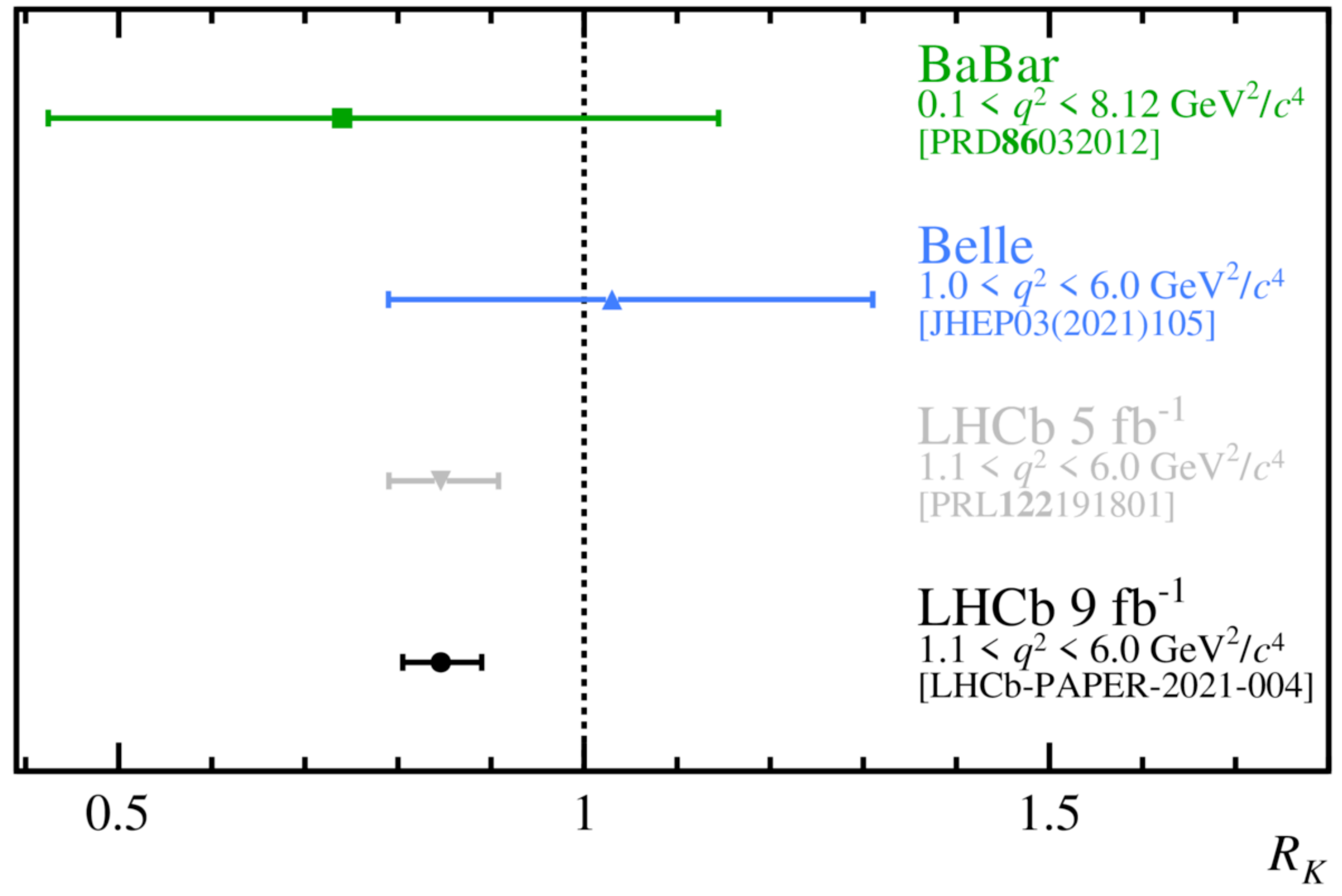
Flavio Archilli - 10/11/2023

Introduction

- Standard Model (SM) predicts same electroweak coupling for all three lepton flavours: Lepton Flavour Universality
- Experimentally established with W/Z boson, $c\bar{c}$, and lepton decays.
- Recent anomalies in $b \to s\ell\ell$ may suggest a violation of LFU
- LFU violation generally implies Lepton Flavour Violation (LFV)







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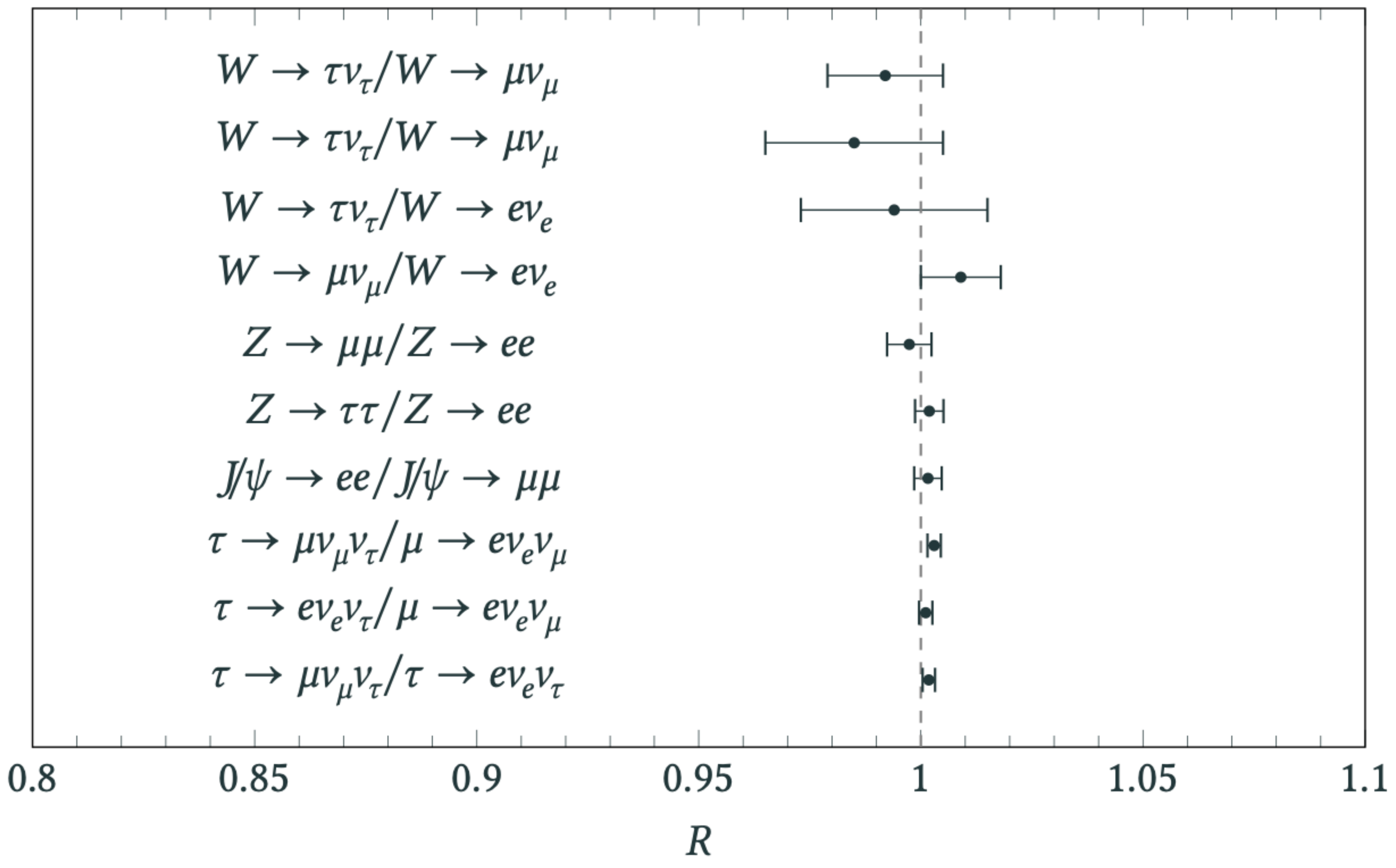
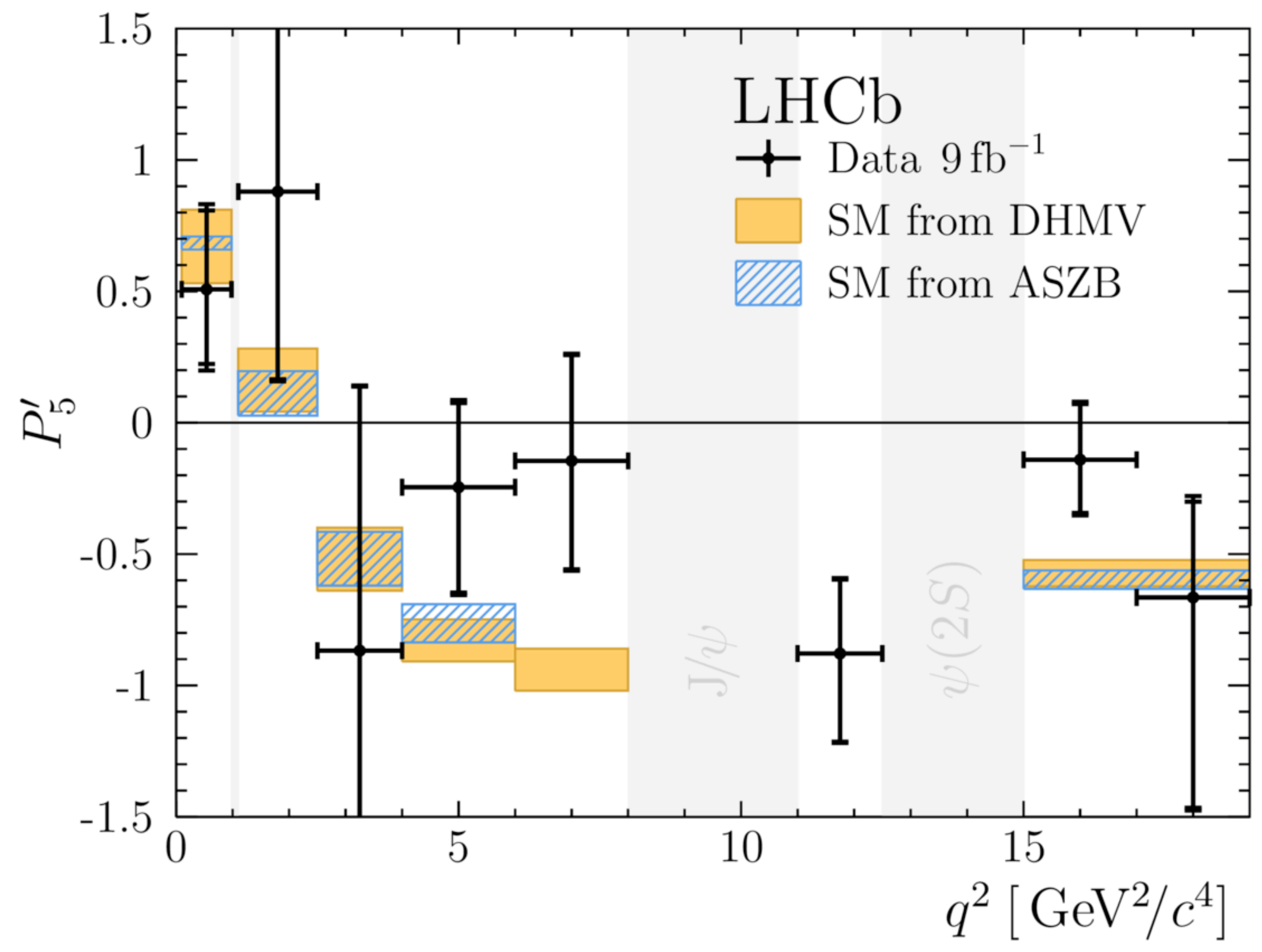
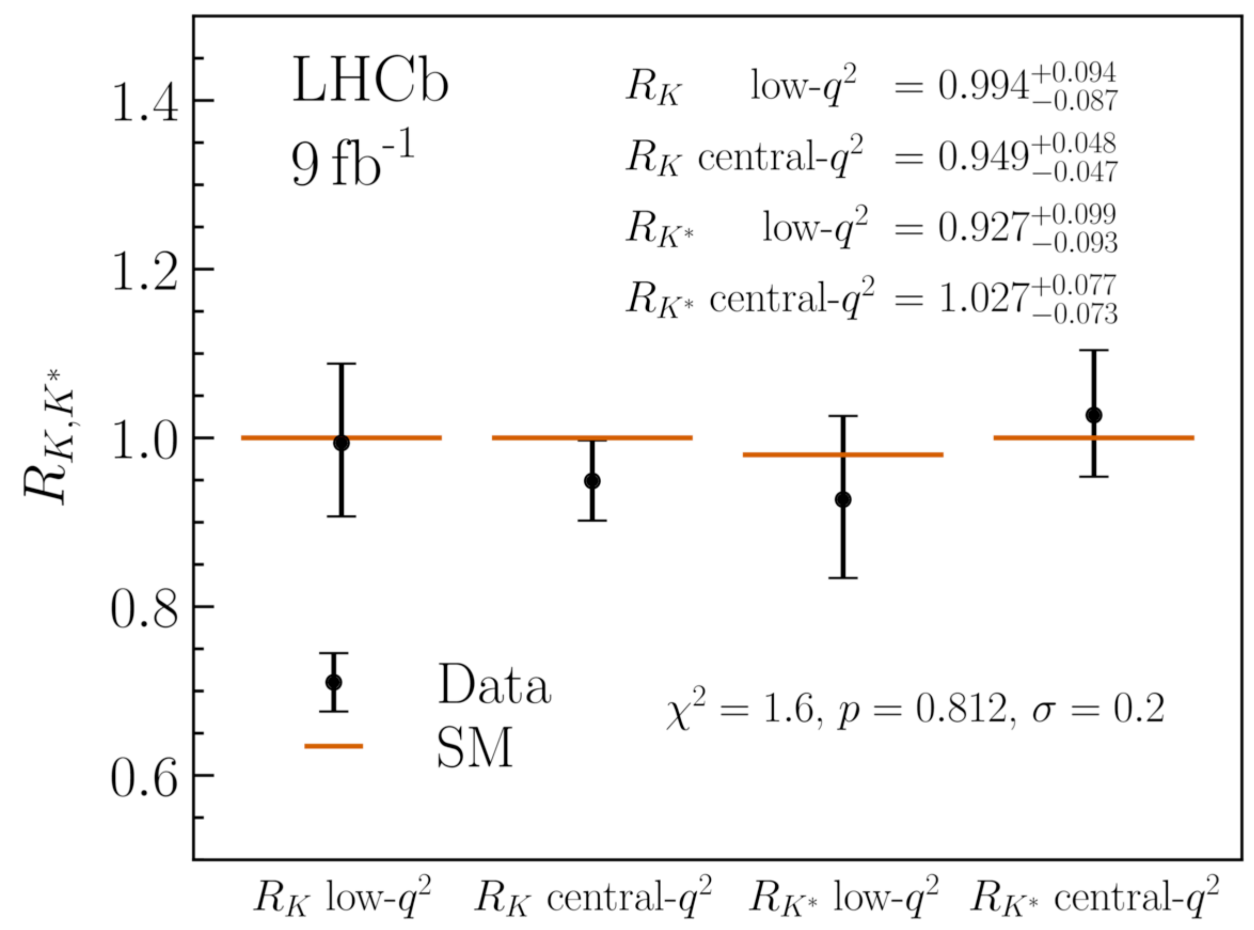
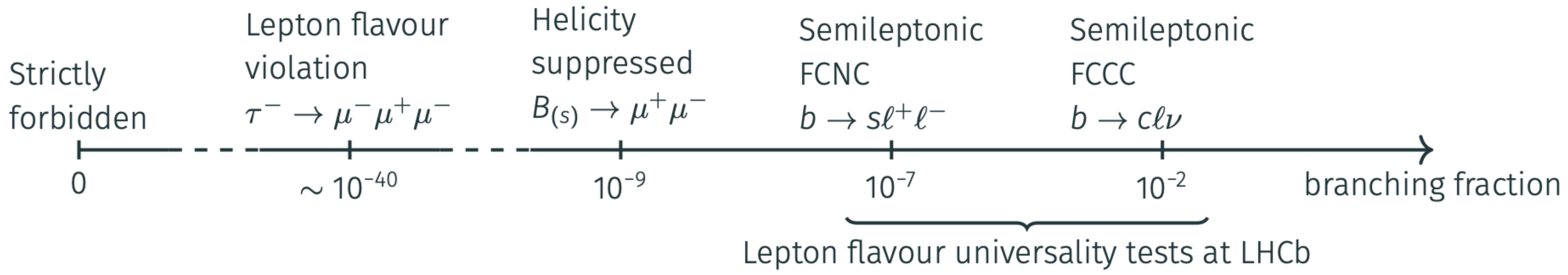


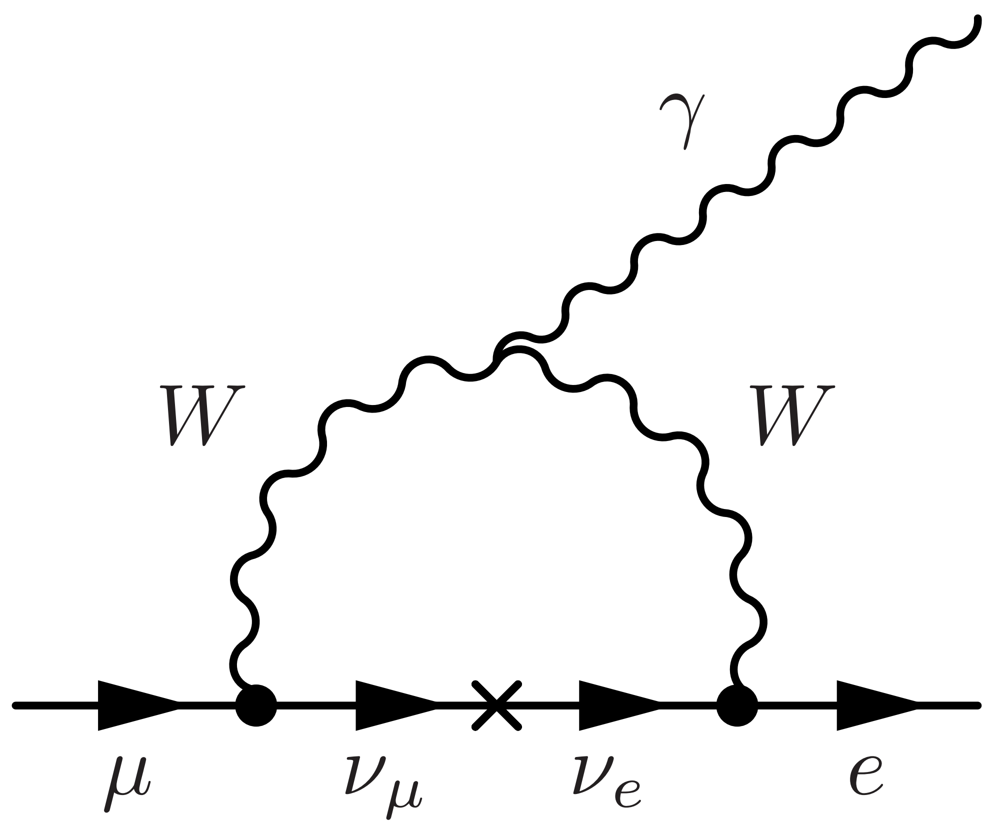




Search for LFV decays

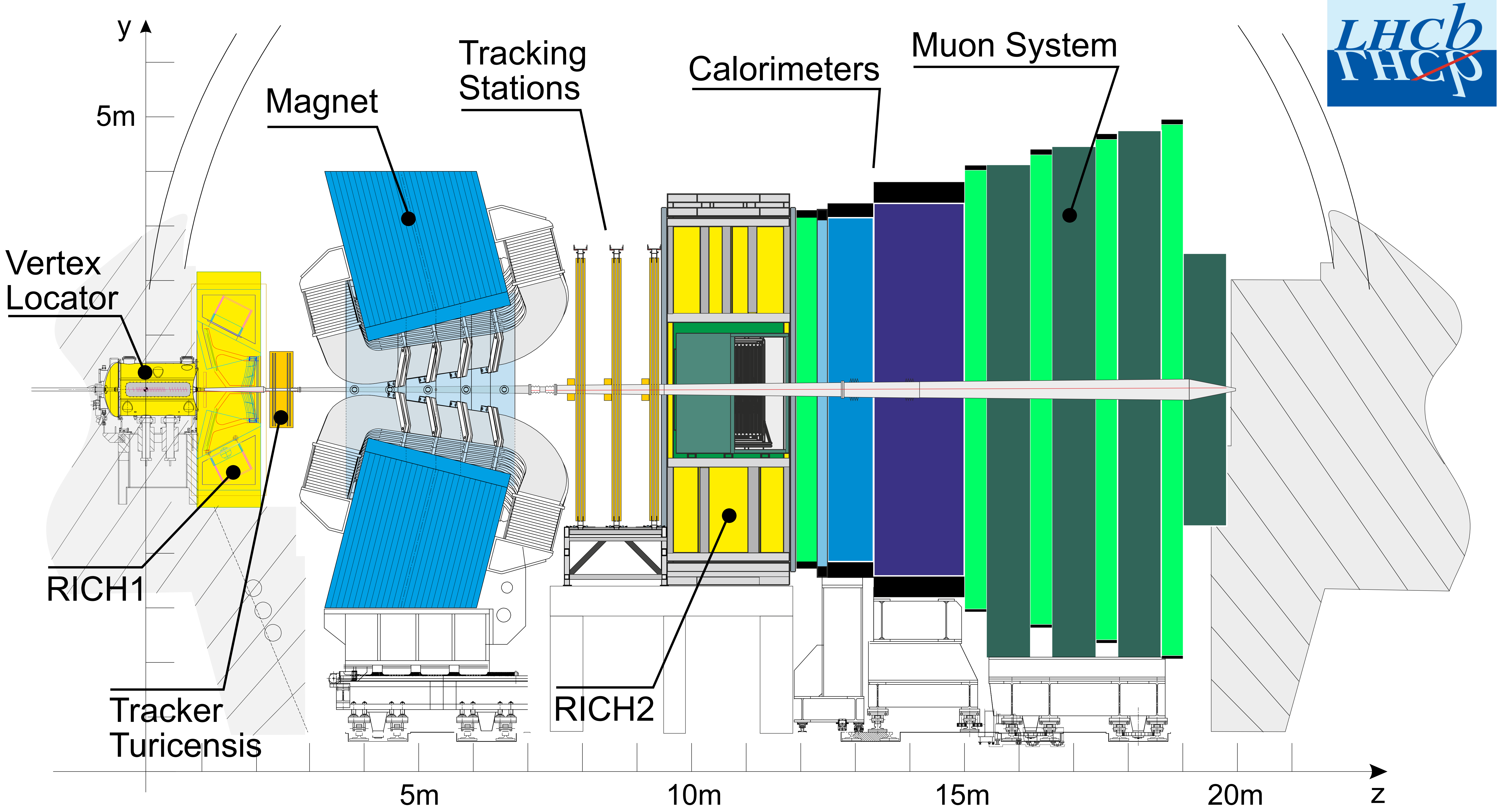
- Lepton Flavour Violation forbidden in the SM
- Observation of neutrino oscillation → evidence of LFV in the neutral sector. However no observation of LFV in the charged sector so far





LHCb

- Large $pp \to b\bar{b}X$ cross section
- $b\bar{b}$ produced at low angle → forward spectrometer
- b-hadrons produced with large boost → excellent vertex resolution for background reduction



- Excellent muon identification (ε_μ = 98%) and low misID $\varepsilon_{h\to\mu}$ ~ 0.5%
- High trigger efficiency on B decays with muons (ε_μ~90%)

- Boosted b-hadrons: most electrons emit hard bremsstrahlung photon
- momentum resolution heavily affected.

Run1: $\int \mathscr{L} = 3\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 7-8$ TeV

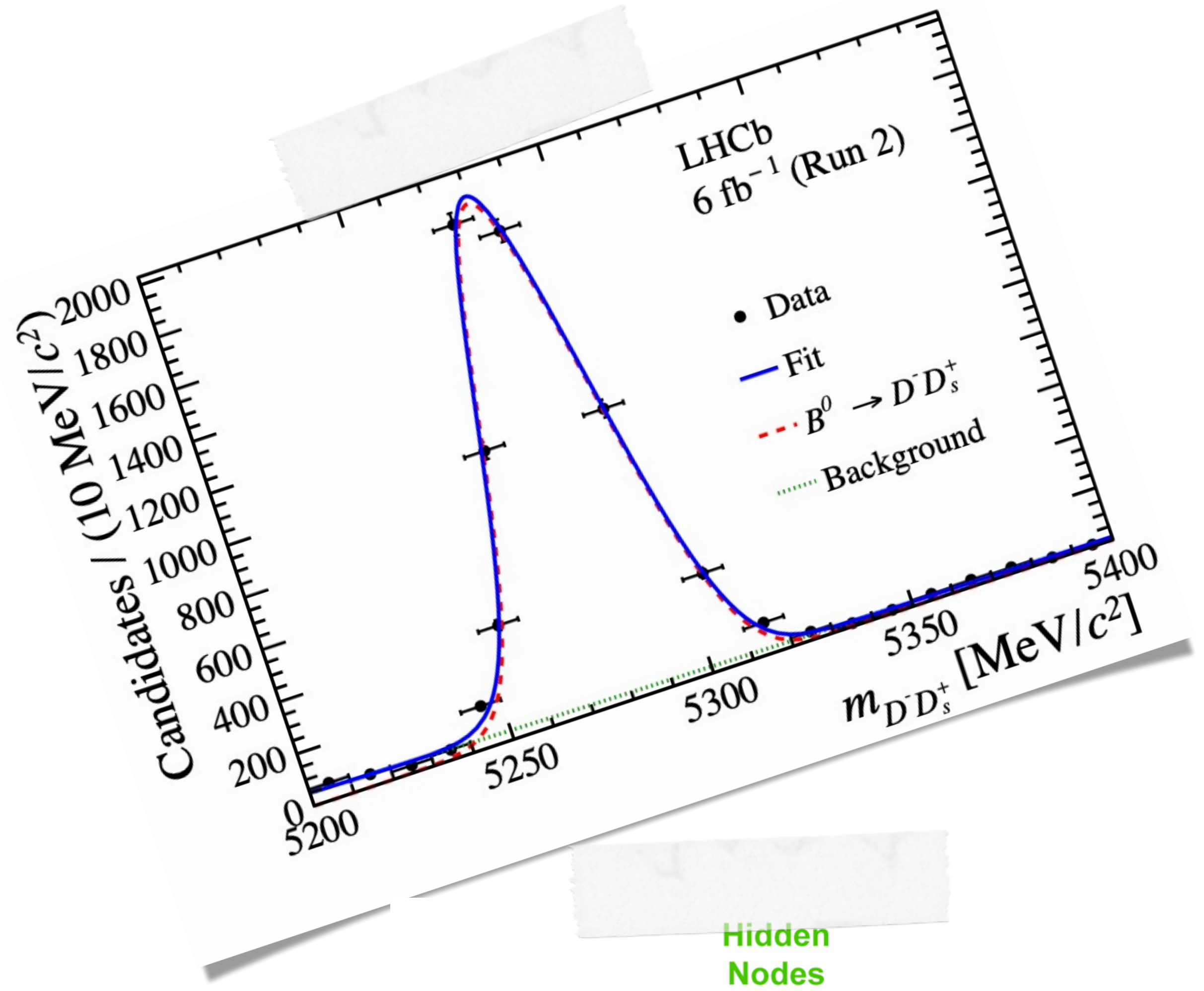
Run2: $\int \mathscr{L} = 6\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 13$ TeV

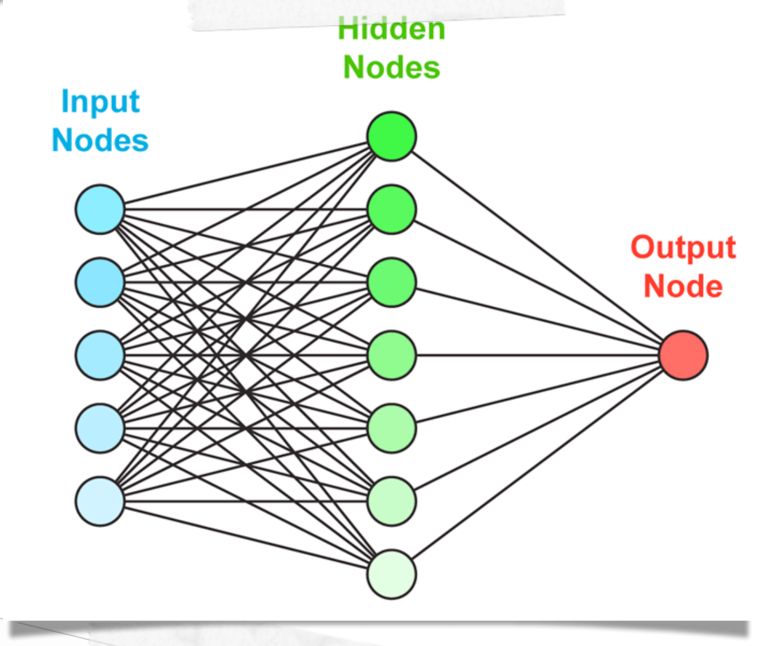
On the menu today

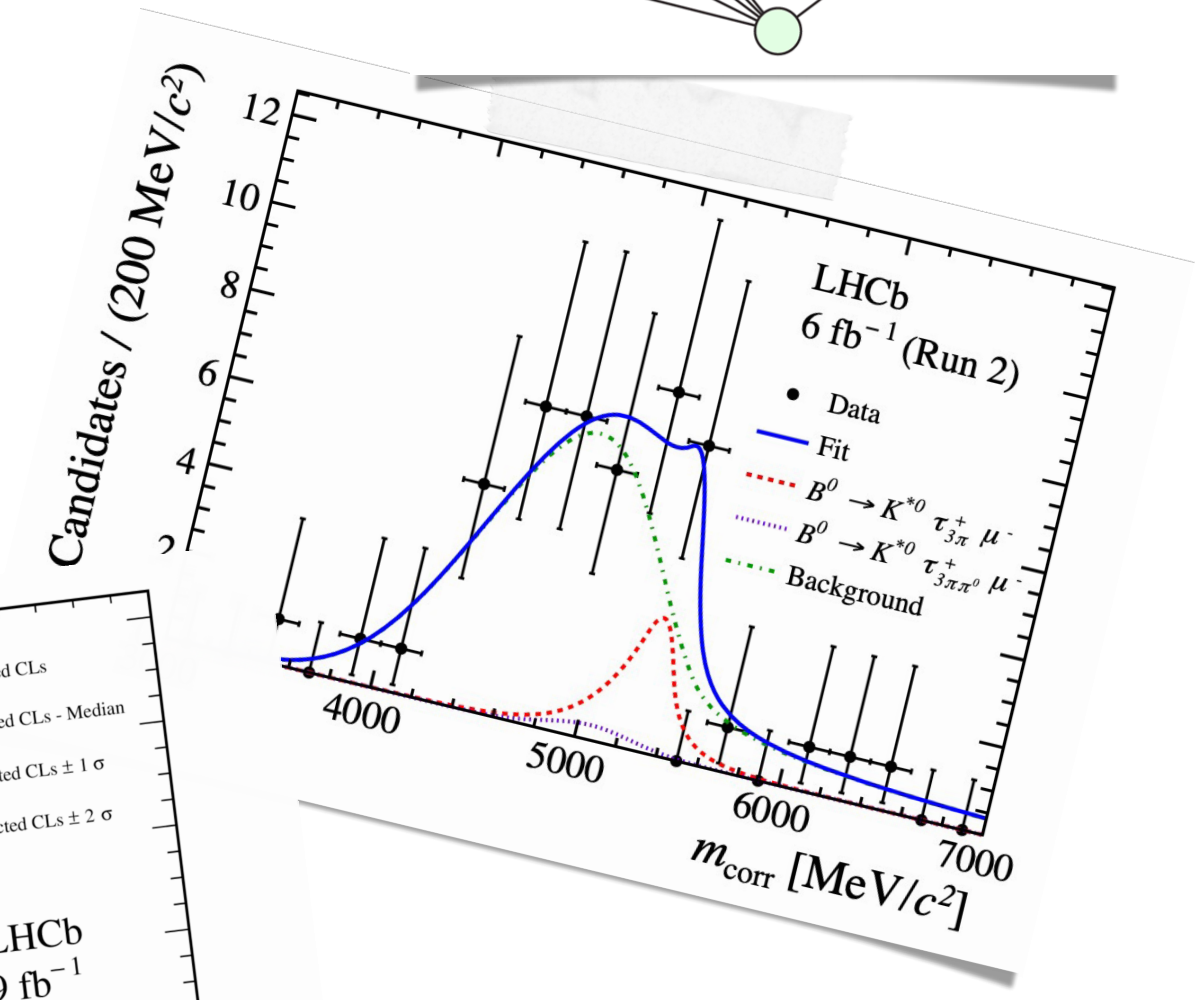
- $B^+ \to K^+\mu^\pm e^\mp$
- $B^+ \to K^+\mu^-\tau^-$
- $B^0 \to K^{*0}\mu^\pm e^\mp$ and $B^0 \to K^{*0}\mu^\pm e^\mp$
- $B^0 \to K^{*0}\tau^\pm\mu^\mp$
- $B^0_{(s)} \to \tau^\pm\mu^\mp$
- $\tau \to \mu\mu\mu$
- LFV charm decays

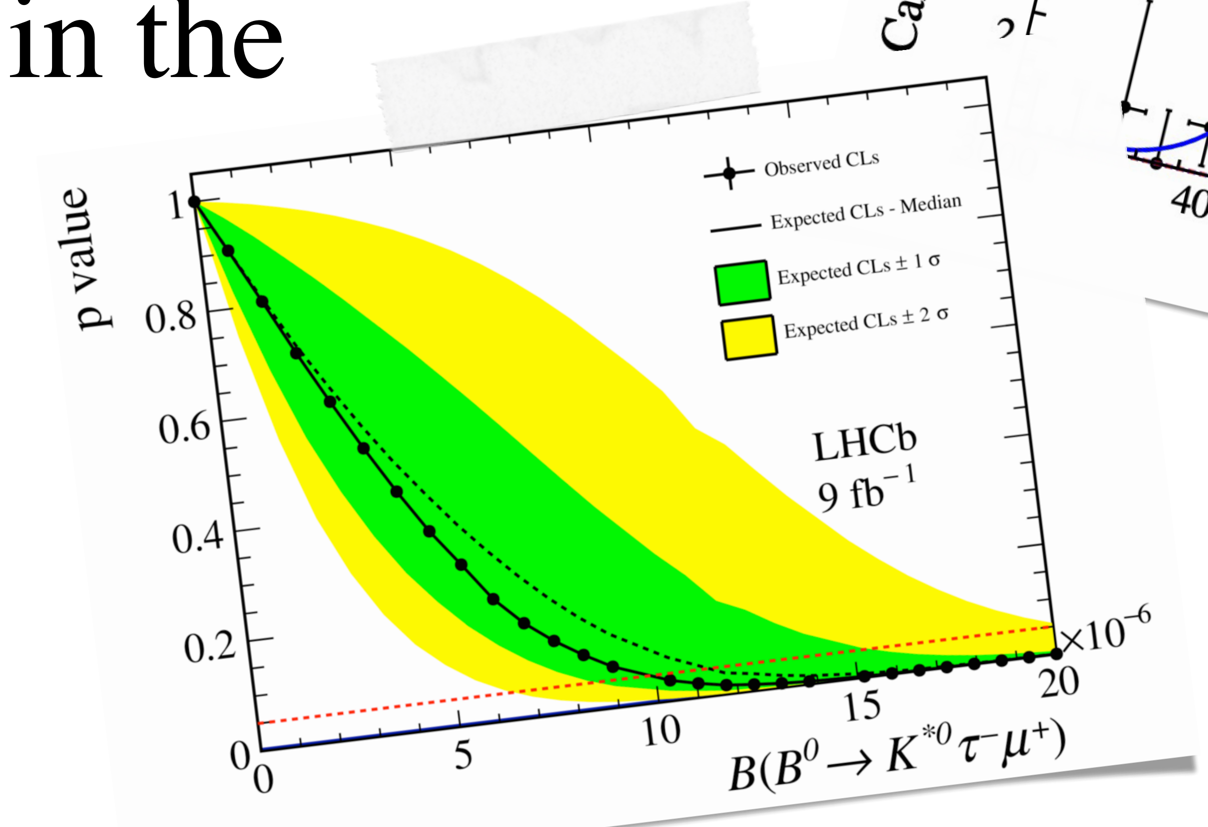
Analysis strategy with LFV decays at LHCb

- All the measurements shown today are normalised to channel that usually share the same topology with the searched decay
- To reduce the large background contamination multivariate classifier are used, trained on MC and data "sidebands"
- MC calibrated on reference channel in order to reproduce the correct experimental resolution
    - Important for the final fit on the decay observable
    - Usually not easy due to the particle composition in the final state
- Upper limit usually set with CL_s method





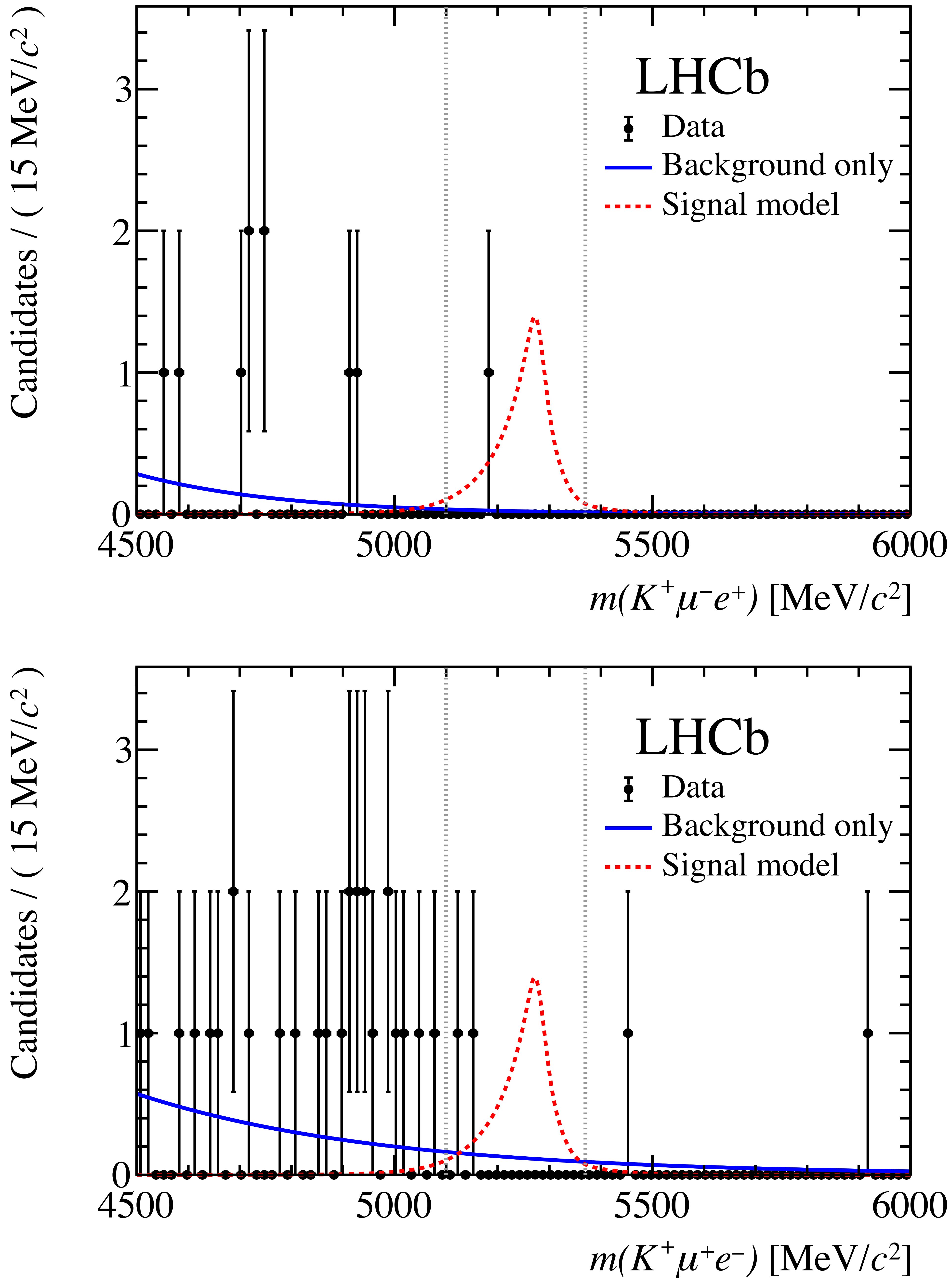




Phys. Rev. Lett.123 (2019) 241802

$B^+ \to K^+\mu^\pm e^\mp$

- Leptoquark/Z' scenario: $\mathscr{B} \sim \mathcal{O}(10^{-9} - 10^{-8})$
  - Leptoquarks: [PRD 97 (2018) 015019, JHEP 06 (2015) 072, JHEP 12 (2016) 027]
  - Z': [PRD 92 (2015) 054013]
- Search for $B^+ \to K^+\mu^\pm e^\mp$ performed with Run1 (3fb^{-1})
- Use high statistics modes $B^+ \to K^+J/\psi(\mu^+\mu^-)$ as control and normalisation modes
- Exploit tight particle identification and two multivariate classifiers based on B kinematics and topology.
  - Main bkg sources: combinatorial and partially reconstructed $B \to D\ell\nu$
- Observed upper limits
  - $\mathscr{B}(B^+ \to K^+\mu^+e^-) < 8.8 \times 10^{-9}$ @95 % CL
  - $\mathscr{B}(B^+ \to K^+\mu^-e^+) < 9.5 \times 10^{-9}$ @95 % CL
- Update on full Run1+Run2 in progress



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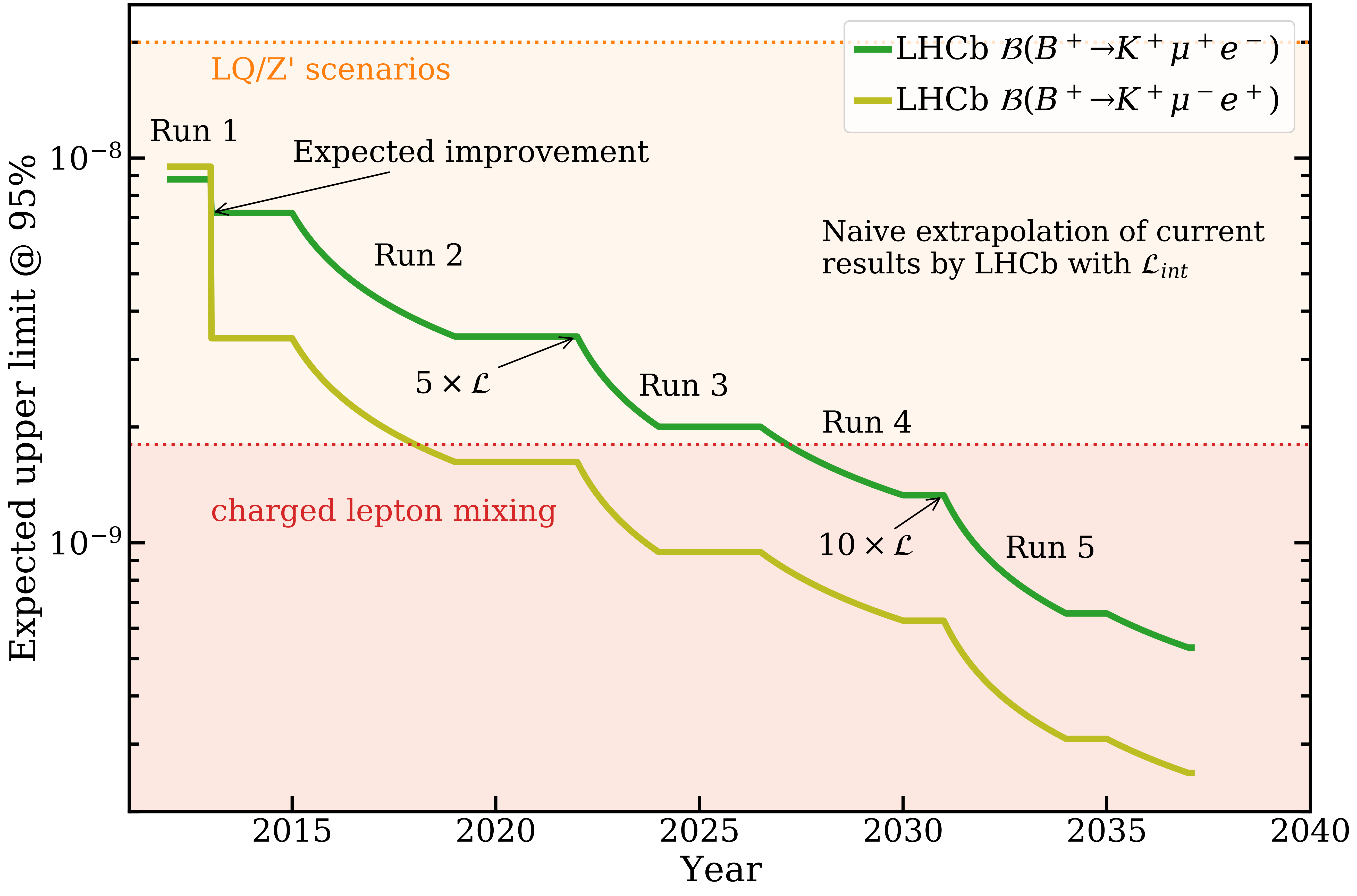
Projections

- Expected upper limit scales with $\sqrt{\mathscr{L}}$
- Selection improvement gains quite a bit
- Strongly constraining New Physics predictions
- Potential backgrounds like $B^+ \to K^+\pi^+\pi^-$ might become relevant with larger statistics

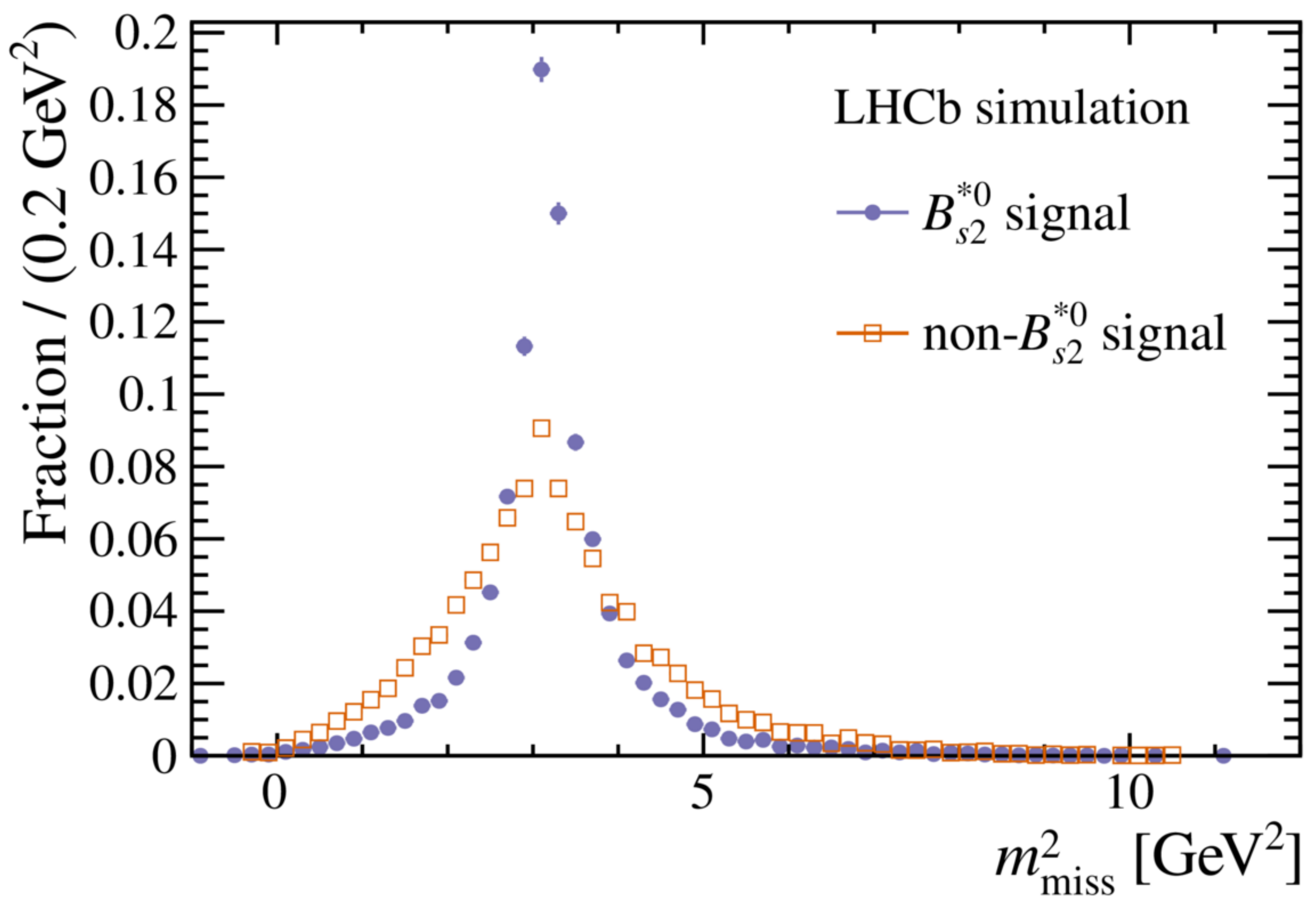
LQ: PRD 97 (2018) 015019, JHEP 06 (2015) 072, JHEP 12 (2016) 027]
Z': PRD 92 (2015) 054013
CPV: PLB 750 (2015) 367

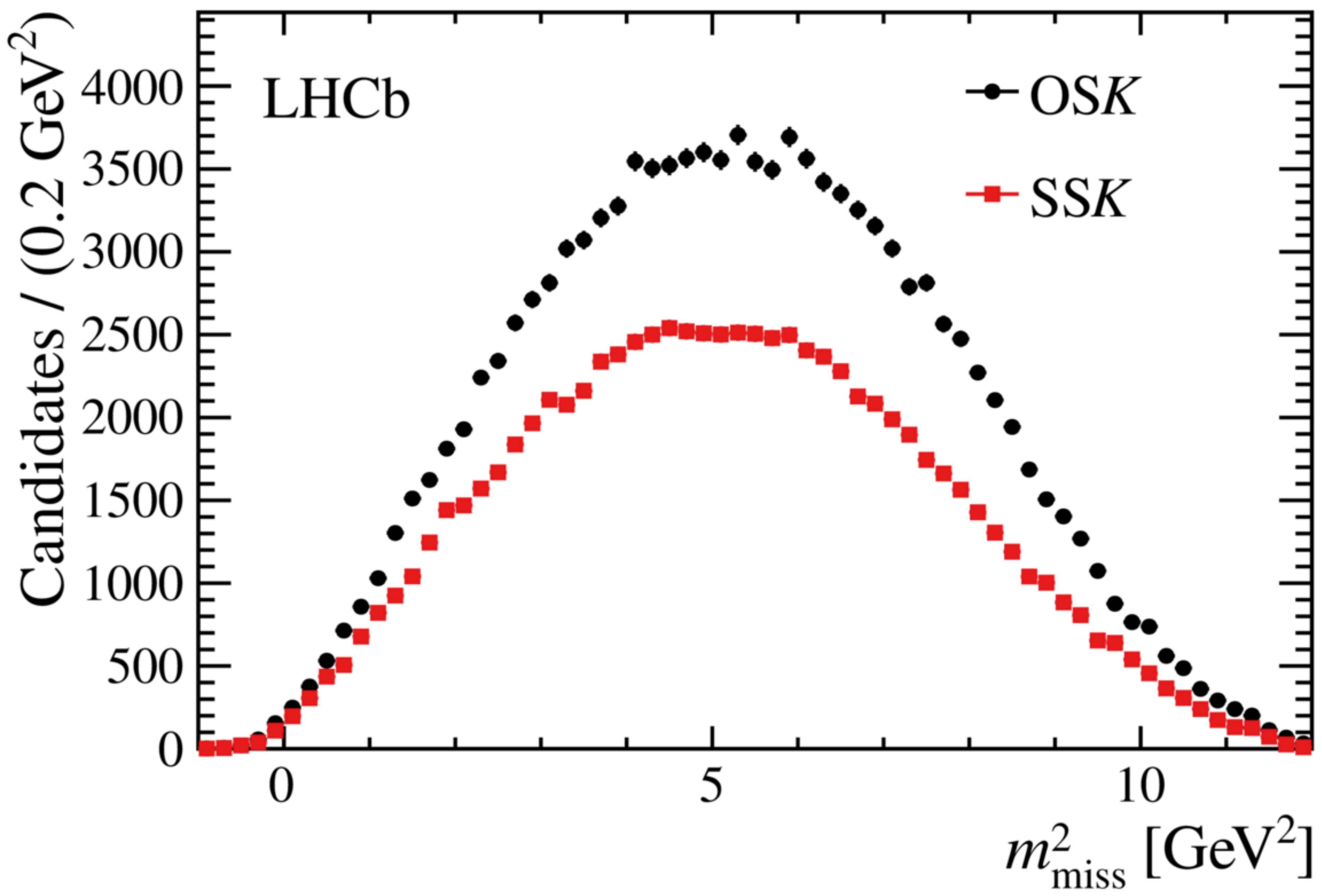


JHEP 06 (2020) 129

$B^+ \to K^+\mu^\pm\tau^\mp$

- BSM models predict to have large enhancement:
  - PS[3] model predicts BF ~ 10^{-5}
- Best experimental limit from BaBar
  - $\mathcal{B}(B^+ \to K^+\mu^-\tau^+) < 2.8 \times 10^{-5}$ @ 90 % CL
- Analysis performed on Run1 and Run2 data
- τ four-momentum fully reconstructed using $B_{s2}^{*0} \to B^+K^-$ decays (~1% of B+ production)
  - kinematic constraint to reconstruct missing mass m_τ





$B^+ \to K^+\mu^\pm\tau^\mp$

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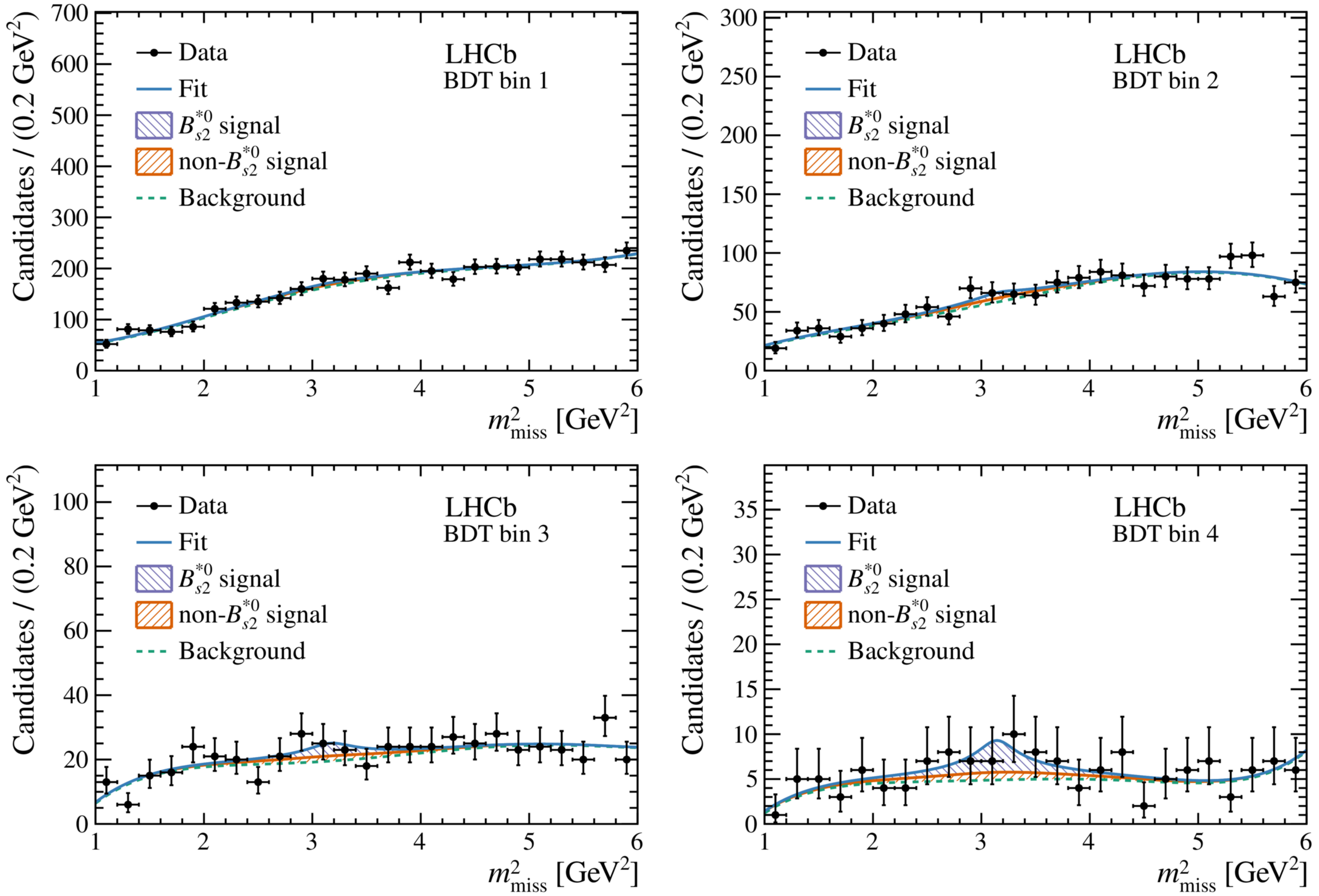
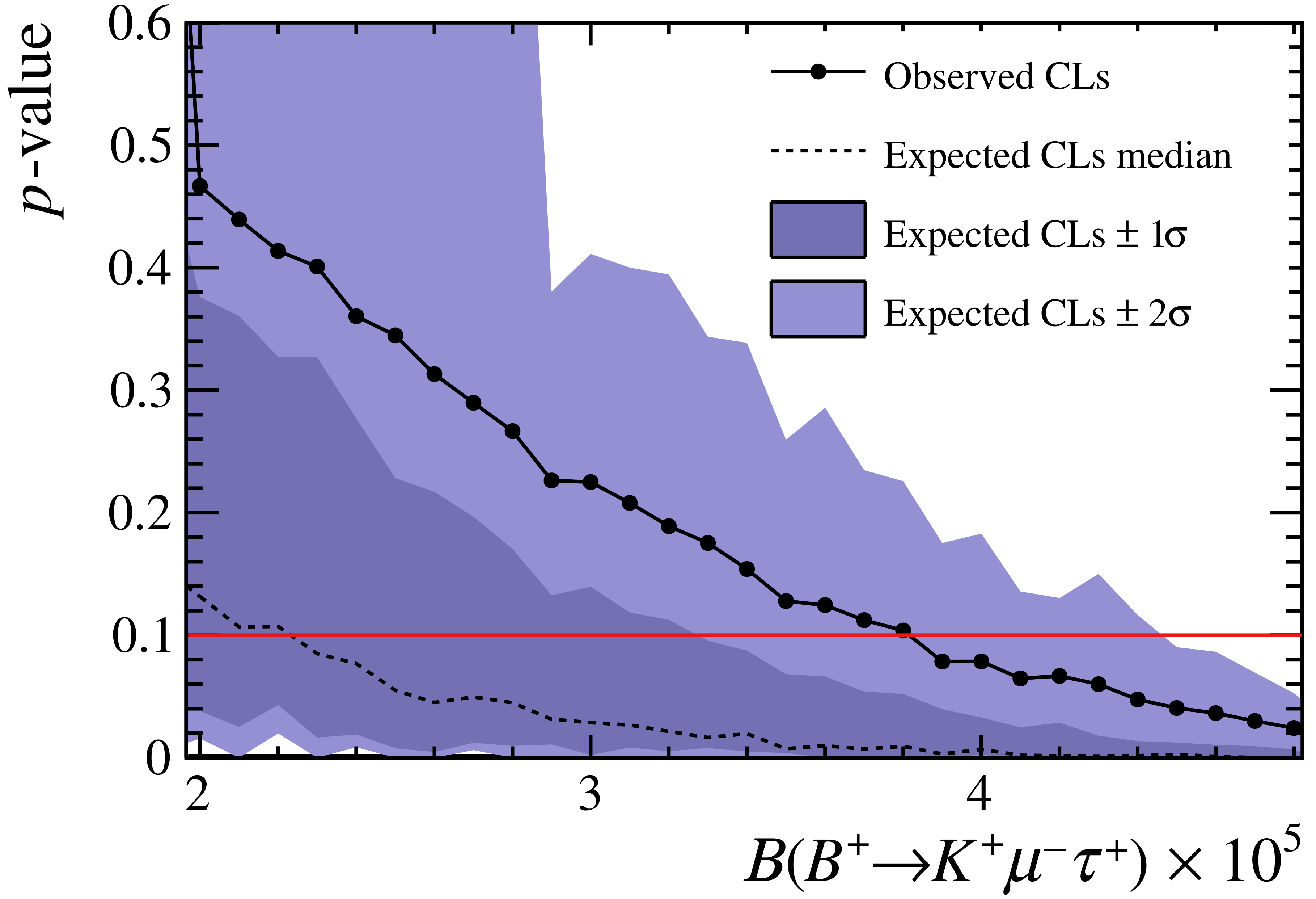
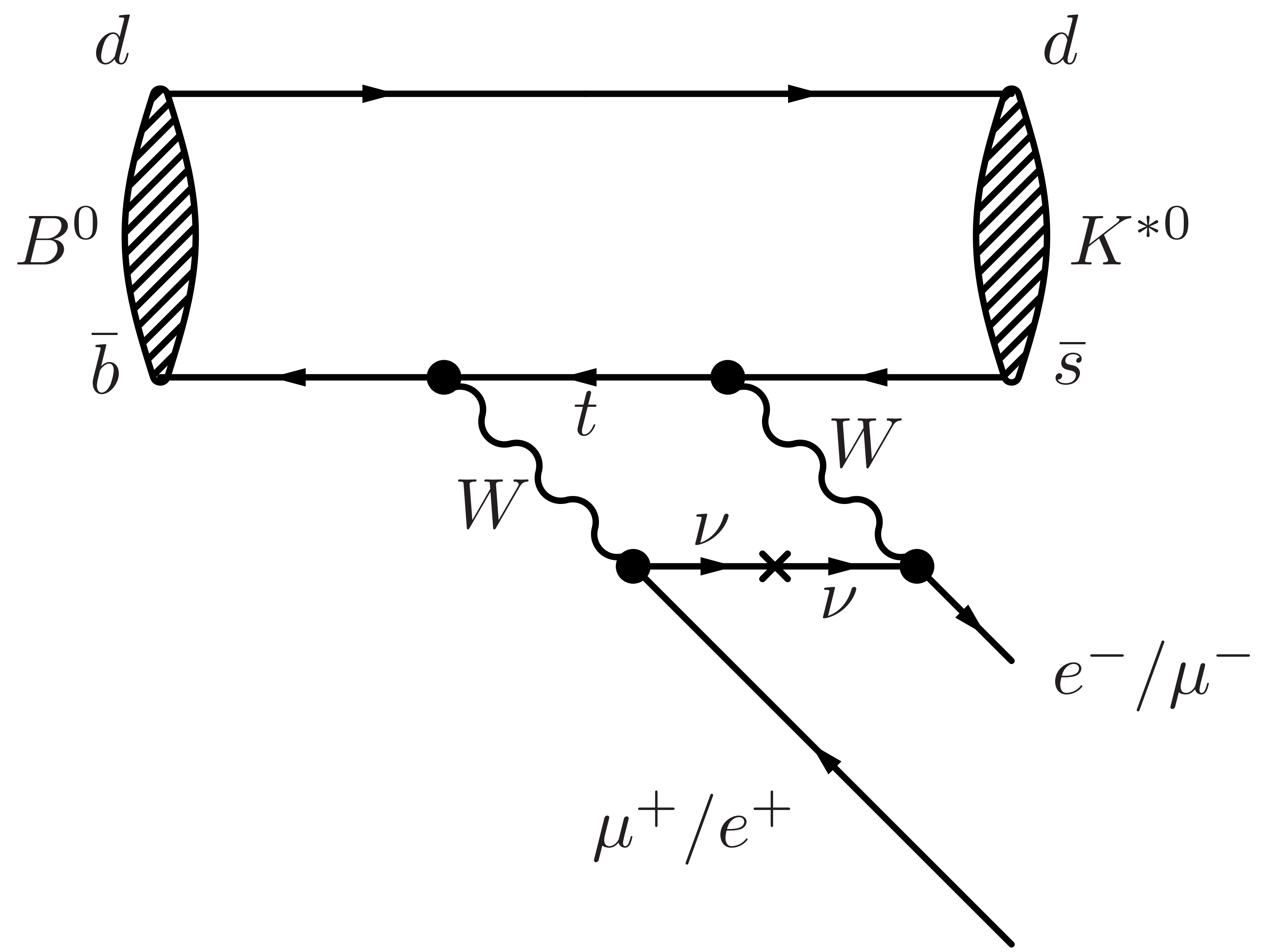
- Simultaneous fit in four bins of BDT:
  - background shape from same-sign kaon sample
  - No excess of events observed
  - CL_s method used to set the limit:
  - $\mathscr{B}(B^+ \to K^+\mu^-\tau^+) < 3.9(4.5) \times 10^{-5}$ @ 90 % (95%) CL
- Promising analysis using three-prong τ decays
- Experiments at e^+e^- collider set more stringent limits [PRL 130, 261802 (2023)]

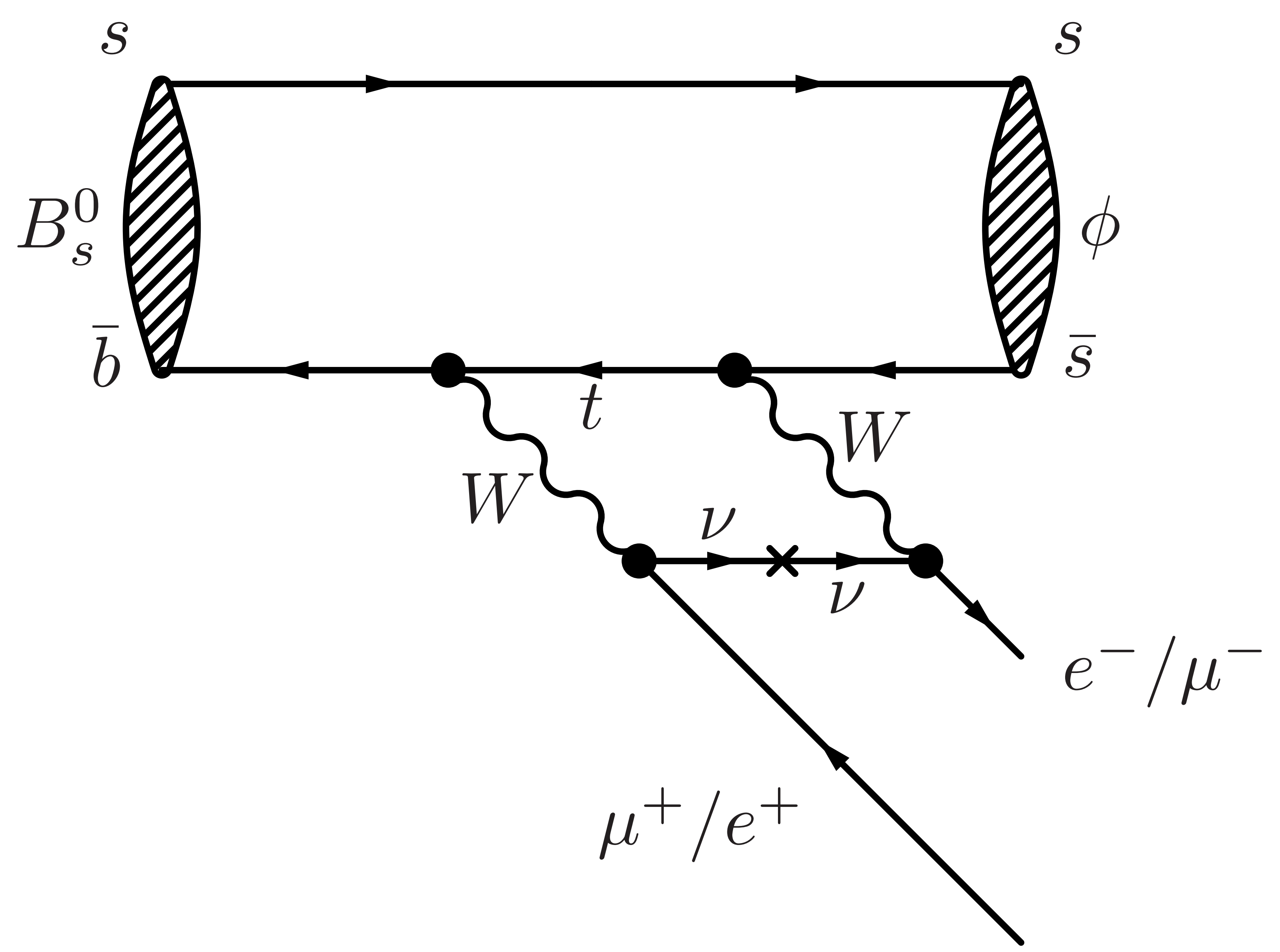




$B^0 \to K^{*0}\mu^\pm e^\mp$ and $B_s^0 \to \phi\mu^\pm e^\mp$

- NP predictions can reach 10^{-7} [Phys. Rev. D 92, 054013]
- Analysis performed using Run1+Run2 LHCb data
- $B^0 \to K^{*0}\mu^\pm e^\mp$ treated separately depending on charge configuration of $K\mu$
  - NP and backgrounds differ between charge configurations
- $K^+\pi^-$ (K^+K^-) required to be close to $K^{*0}(\phi)$ mass





$B^0 \to K^{*0}\mu^{\pm}e^{\mp}$ and $B_s^0 \to \phi\mu^{\pm}e^{\mp}$

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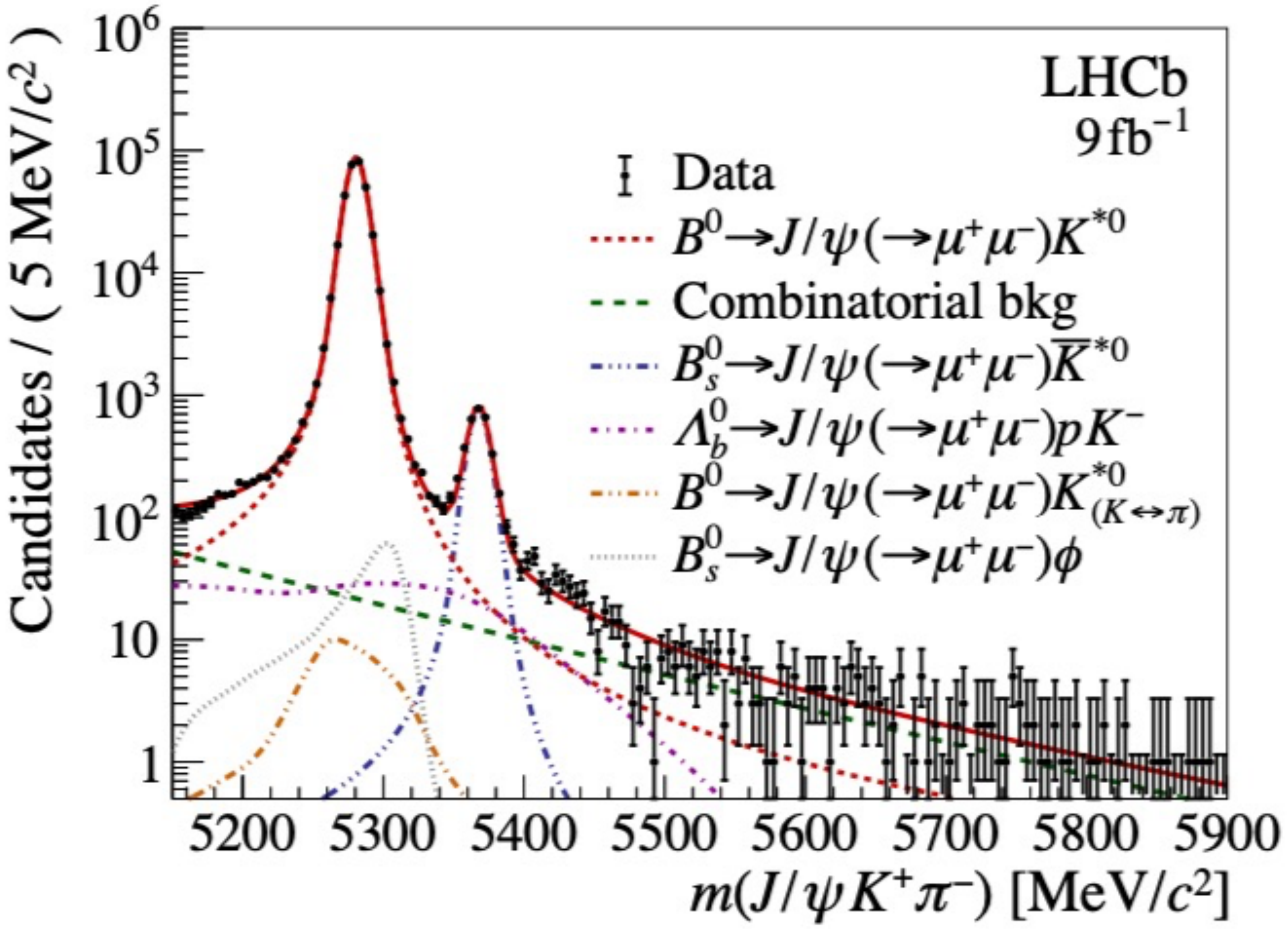
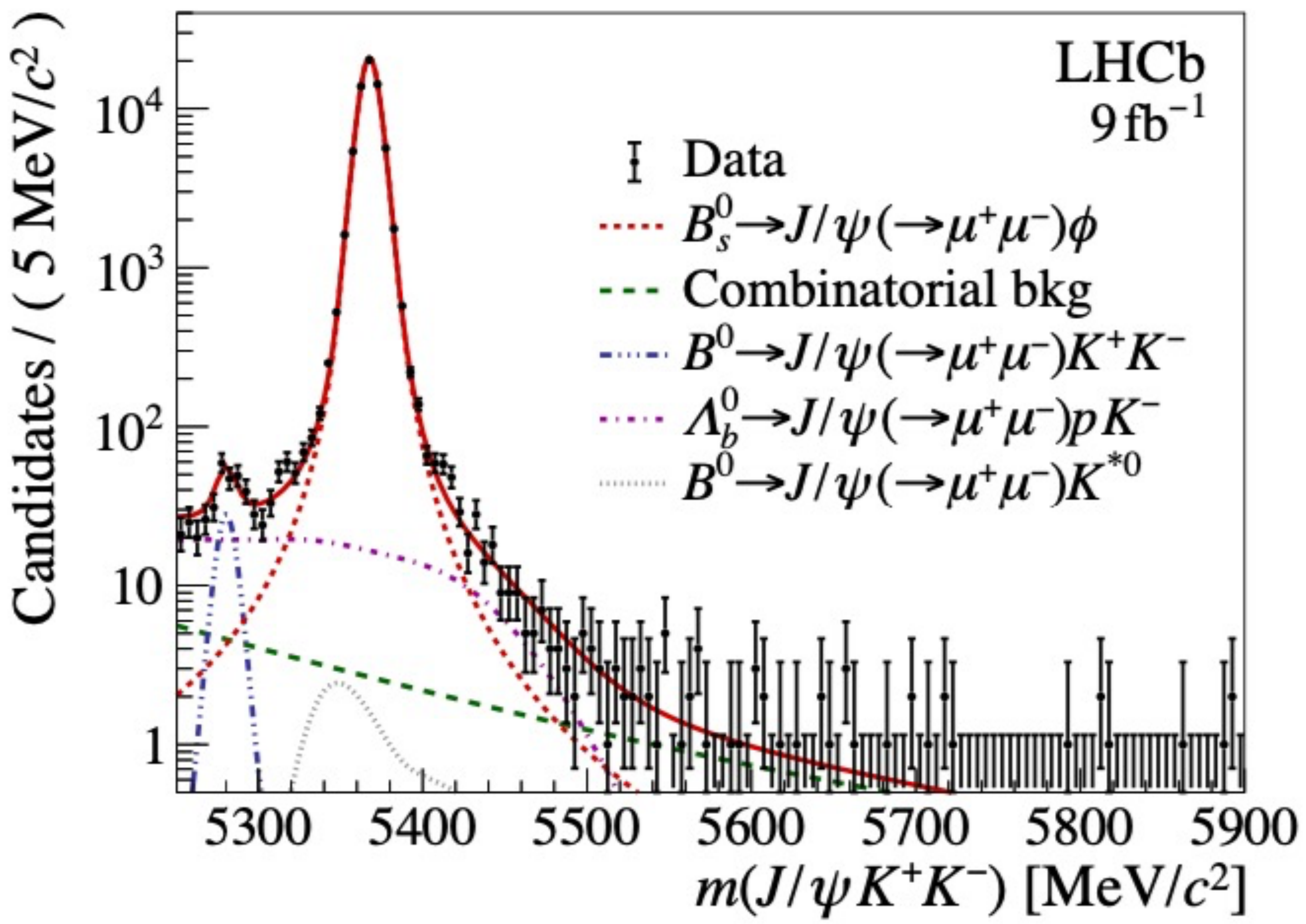
- Combinatorial background removed using BDT
- Separate BDT for the K^{*0} and ϕ channels
- Backgrounds from double misidentification ($B \to (K^{*0}/\phi)\pi^+\pi^-$) reduced with requirements on particle identification
- $B^0 \to K^{*0}J/\psi(\mu^+\mu^-)$ and $B_s^0 \to \phi J/\psi(\mu^+\mu^-)$ used as control and normalisation channels



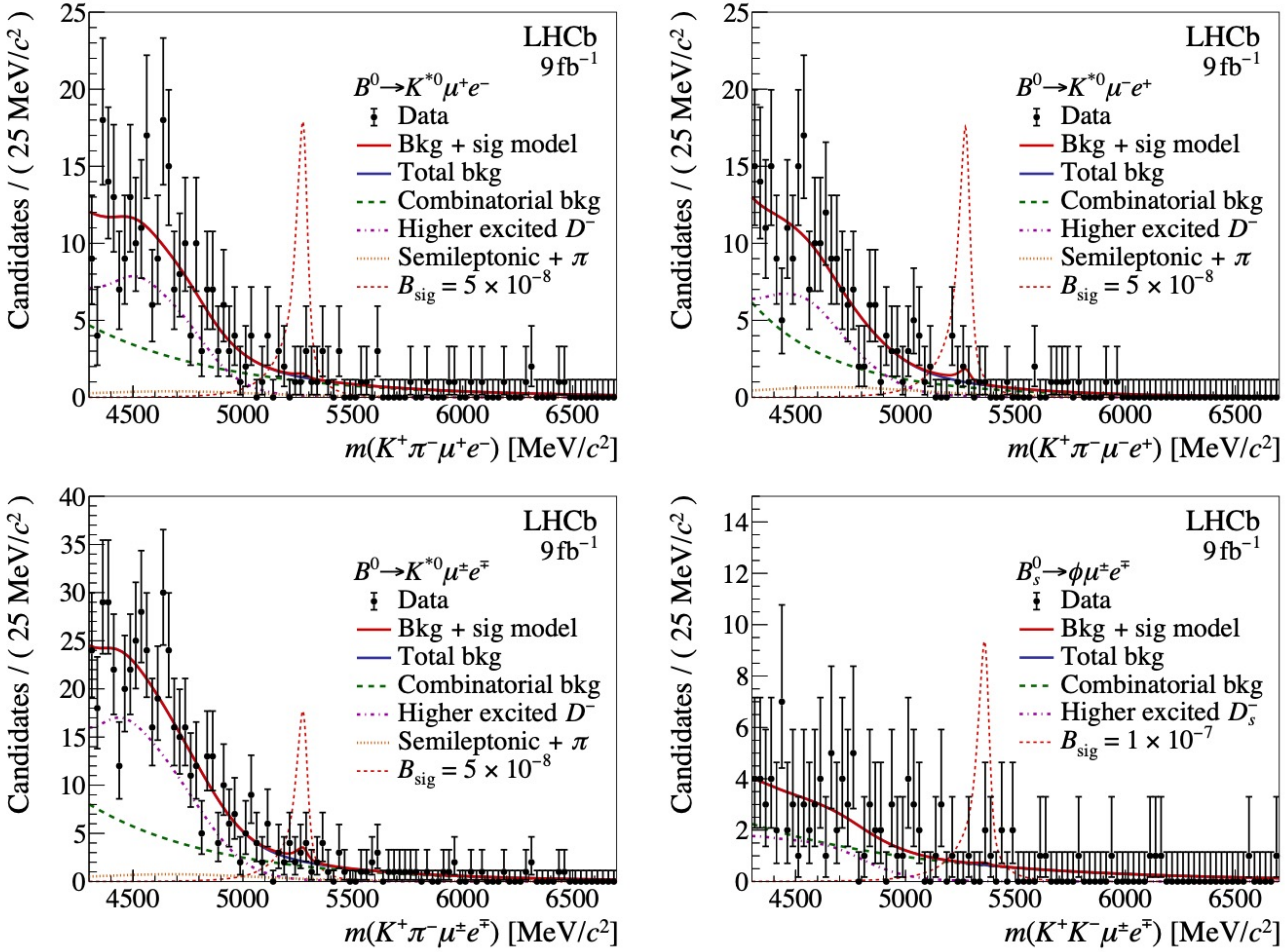


JHEP 06 (2023) 073

$B^0 \to K^{*0}\mu^\pm e^\mp$ and $B_s^0 \to \phi\mu^\pm e^\mp$

JHEP 06 (2023) 073

- Upper limits at 90(95)% CL determined as:
  - $\mathscr{B}(B^0 \to K^{*0}\mu^+ e^-) < 5.7(6.9) \times 10^{-9}$
  - $\mathscr{B}(B^0 \to K^{*0}\mu^- e^+) < 6.8(7.9) \times 10^{-9}$
  - $\mathscr{B}(B^0 \to K^{*0}\mu^\pm e^\mp) < 10.1(11.7) \times 10^{-9}$
- wrt Belle's result $\mathcal{O}(10^{-7})$ [PRD 98, 071101(R) (2018)]
  - $\mathscr{B}(B_s^0 \to \phi\mu^\pm e^\mp) < 16.0(19.8) \times 10^{-9}$
- Limits on BFs assuming uniform phase-space decay model
- (Re-)interpretation in terms of scalar and left-handed LF violating NP models also provided



$B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$

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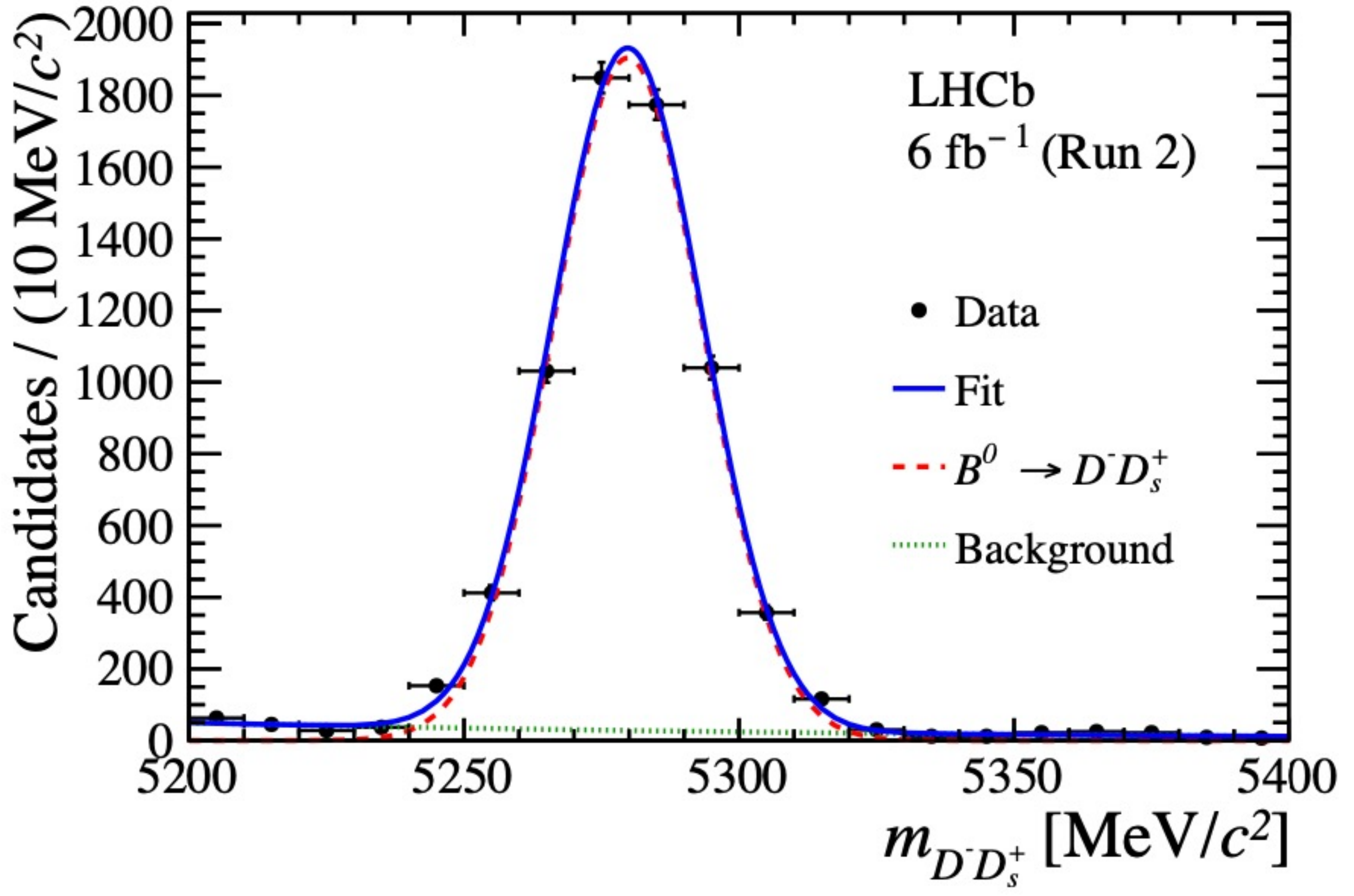
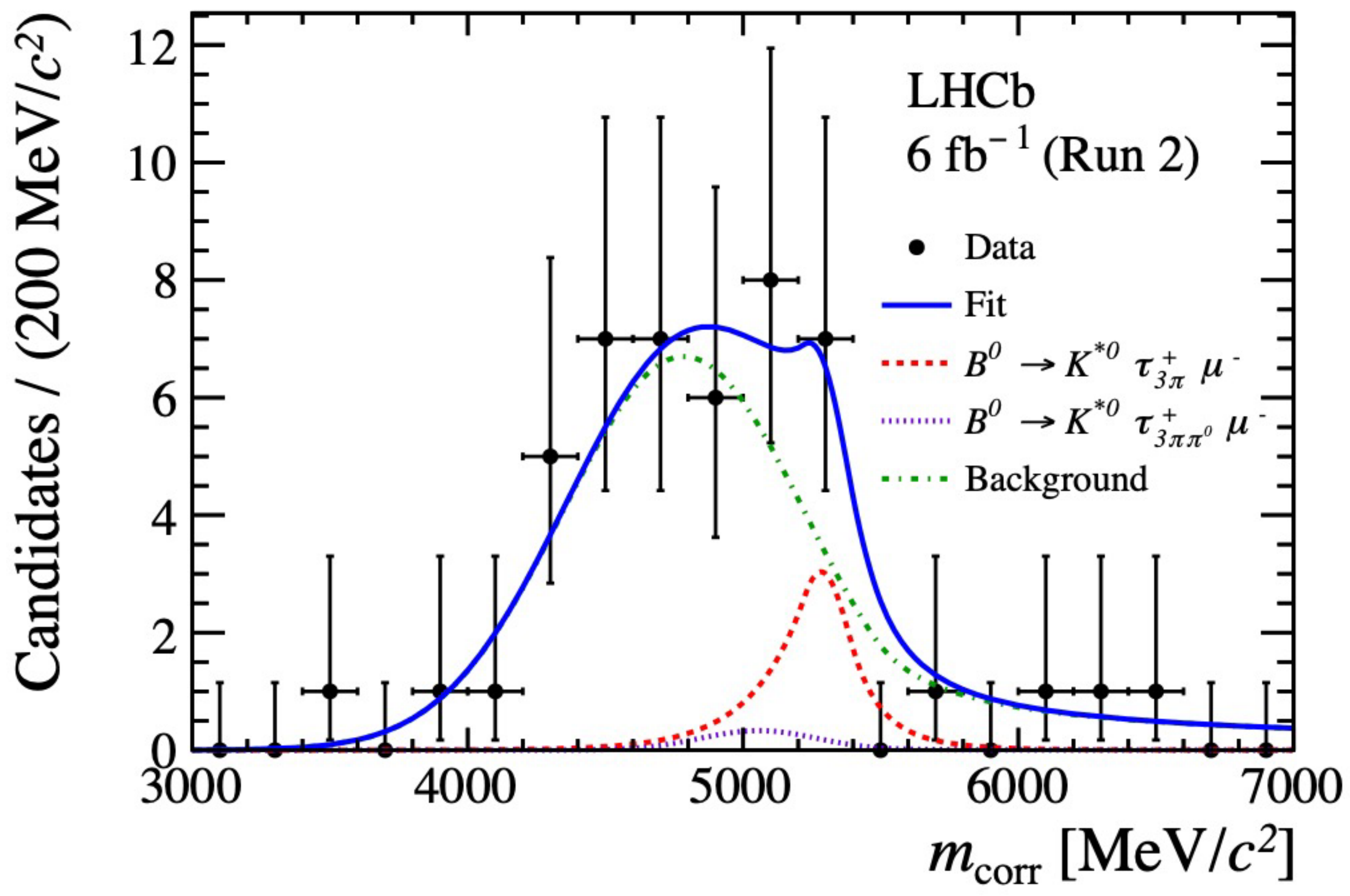
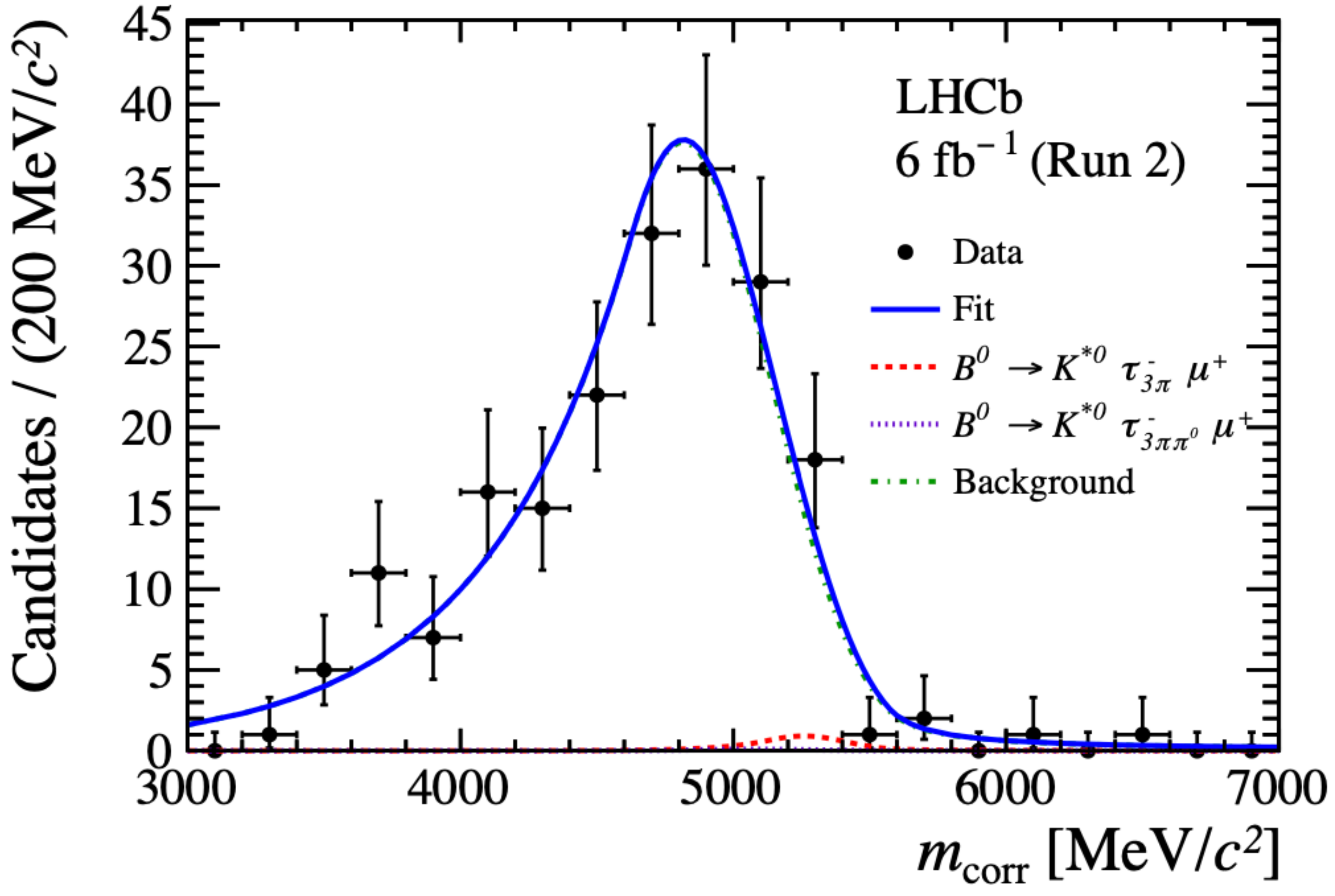
- First search for the $B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$ decay on Run 1 + Run 2 data
- K^{*0} reconstructed through $K^{*0} \to K^+\pi^-$
- τ reconstructed through $\tau \to 3\pi(\pi^0)\nu_\tau$
- Normalisation relative to $B^0 \to D^-(K^+\pi^-\pi^-)D_s^+(K^+K^-\pi^+)$
- Independent analysis on $\tau\mu$ charge configuration:
  - Affected by different backgrounds
  - Different theoretical interpretation
- Two stage multivariate selection based on BDTs trained against combinatorial and mis-ID background
- Requirements on particle identification to remove mis-id



$B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$

- Due to the large energy loss, use corrected mass $m_{corr} = \sqrt{p_{\perp}^2 + m_{K^*\tau\mu}^2} + p_{\perp}$
- No significant excess is observed
- Most stringent limits on $b \to s\tau\mu$ transitions set at 90%(95%) CL
- $\mathscr{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0(1.2) \times 10^{-5}$
- $\mathscr{B}(B^0 \to K^{*0}\tau^-\mu^+) < 8.9(9.8) \times 10^{-6}$

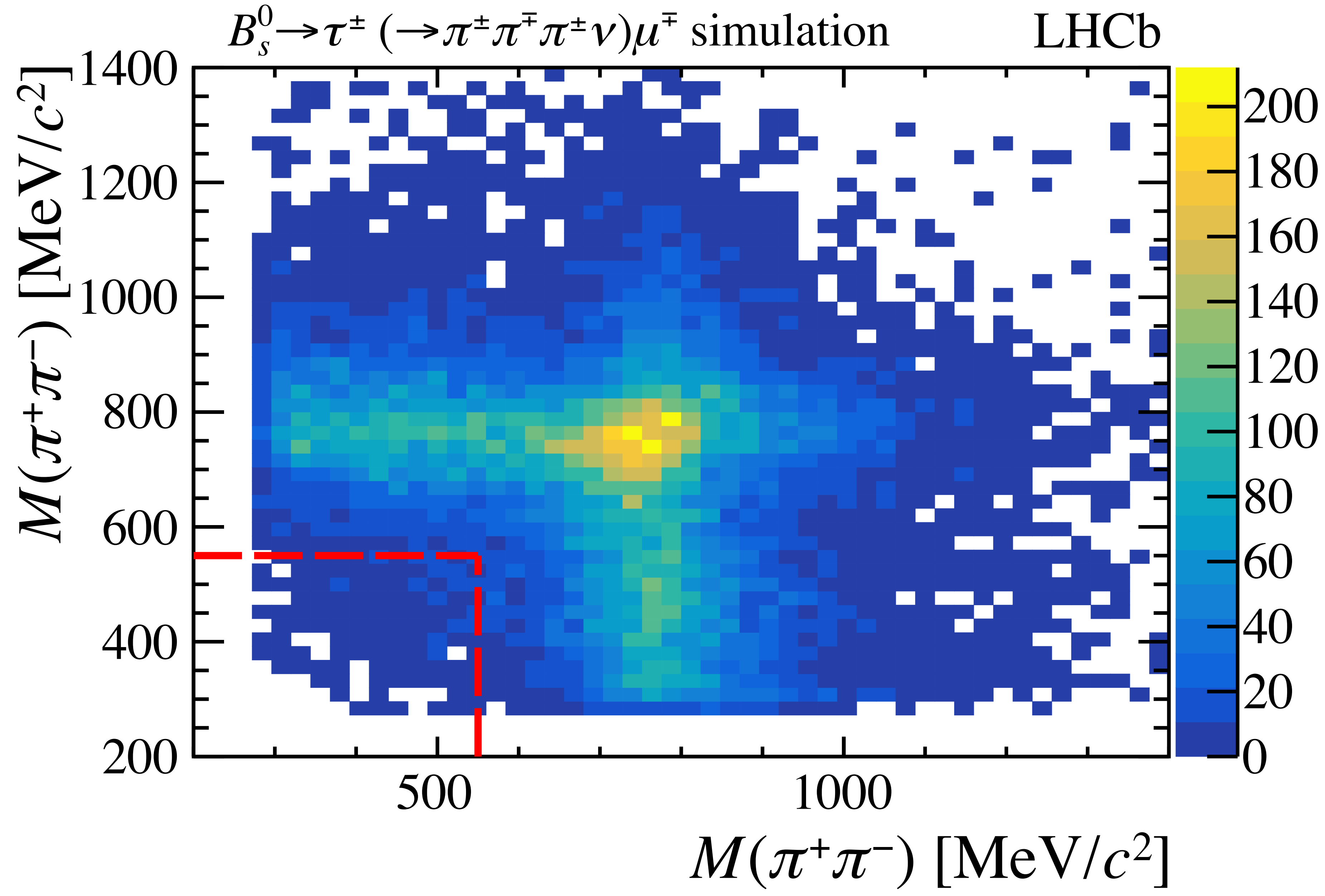


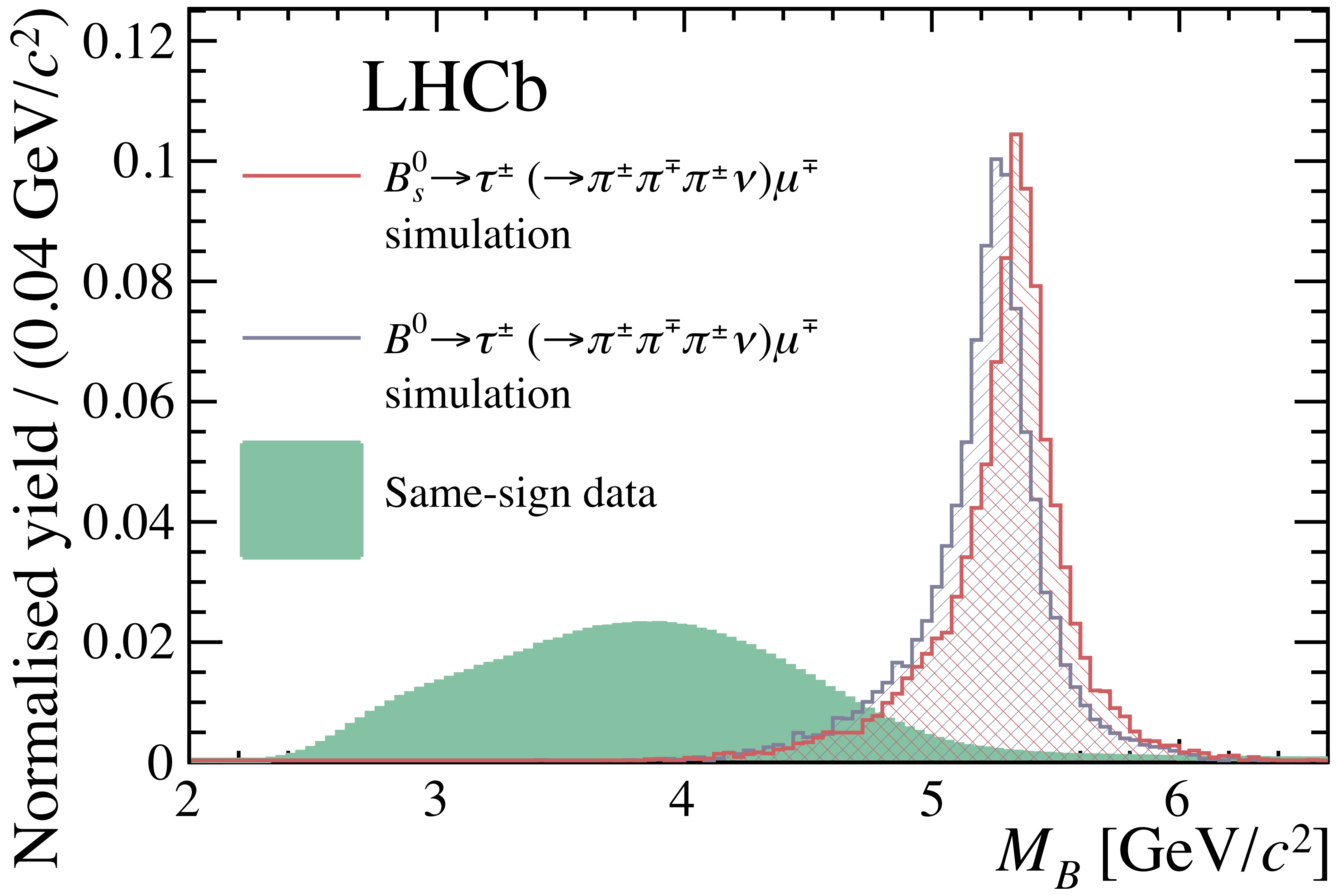


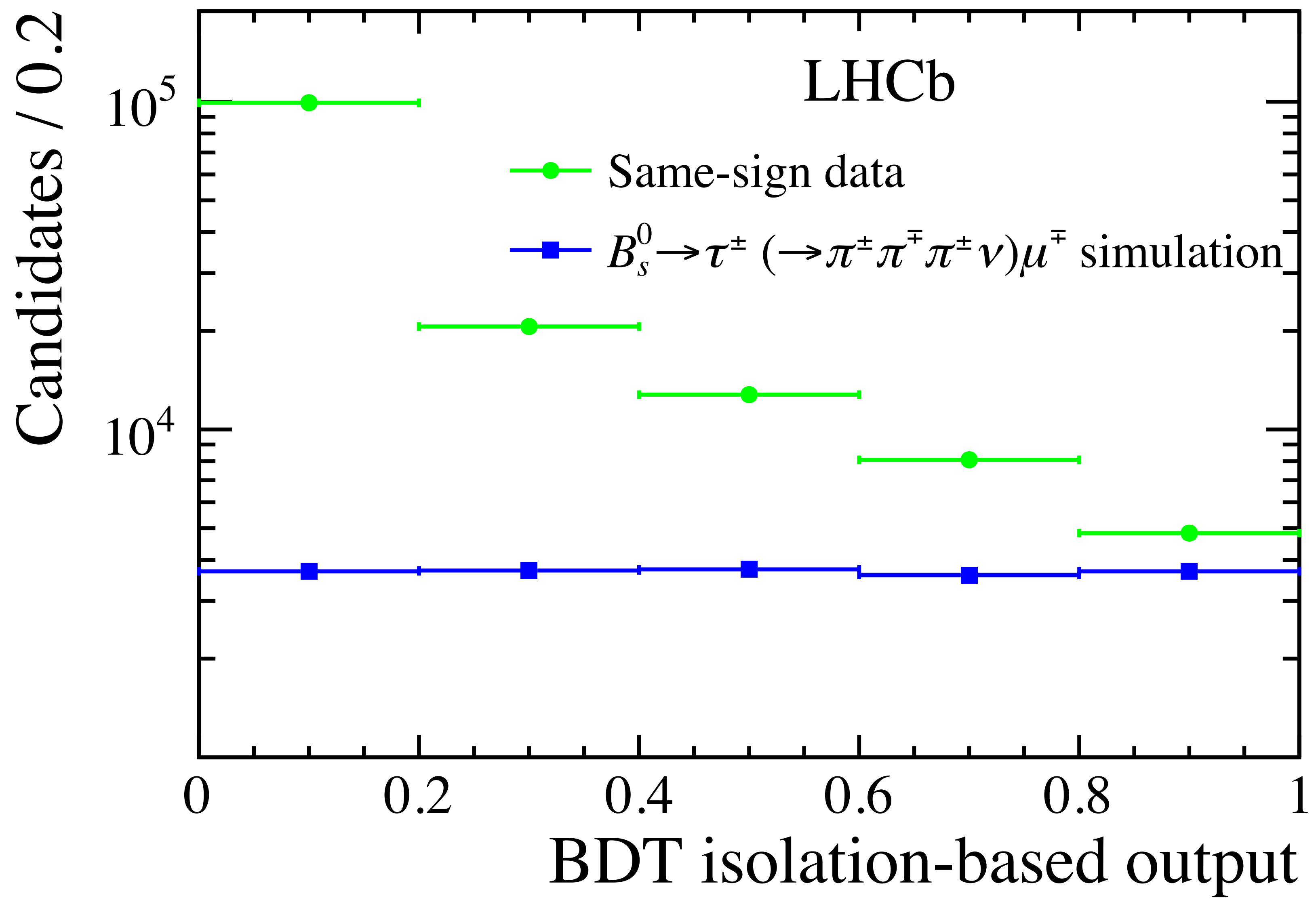
Phys. Rev. Lett. 123 (2019) 211801

$B^0_{(s)} \to \tau^{\pm}\mu^{\mp}$

- BF can be $\sim \mathcal{O}(10^{-5})$ in some models with Z′/ leptoquarks [JHEP 11 (2016) 035]
- LHCb analysis with Run1 data ($3\,fb^{-1}$)
- Reconstruct $B^0_{(s)} \to \tau^{\pm}\mu^{\mp}$ candidates using the 3-prong τ decay
- Events classified with multivariate operator and invariant mass (kinematically constrained)







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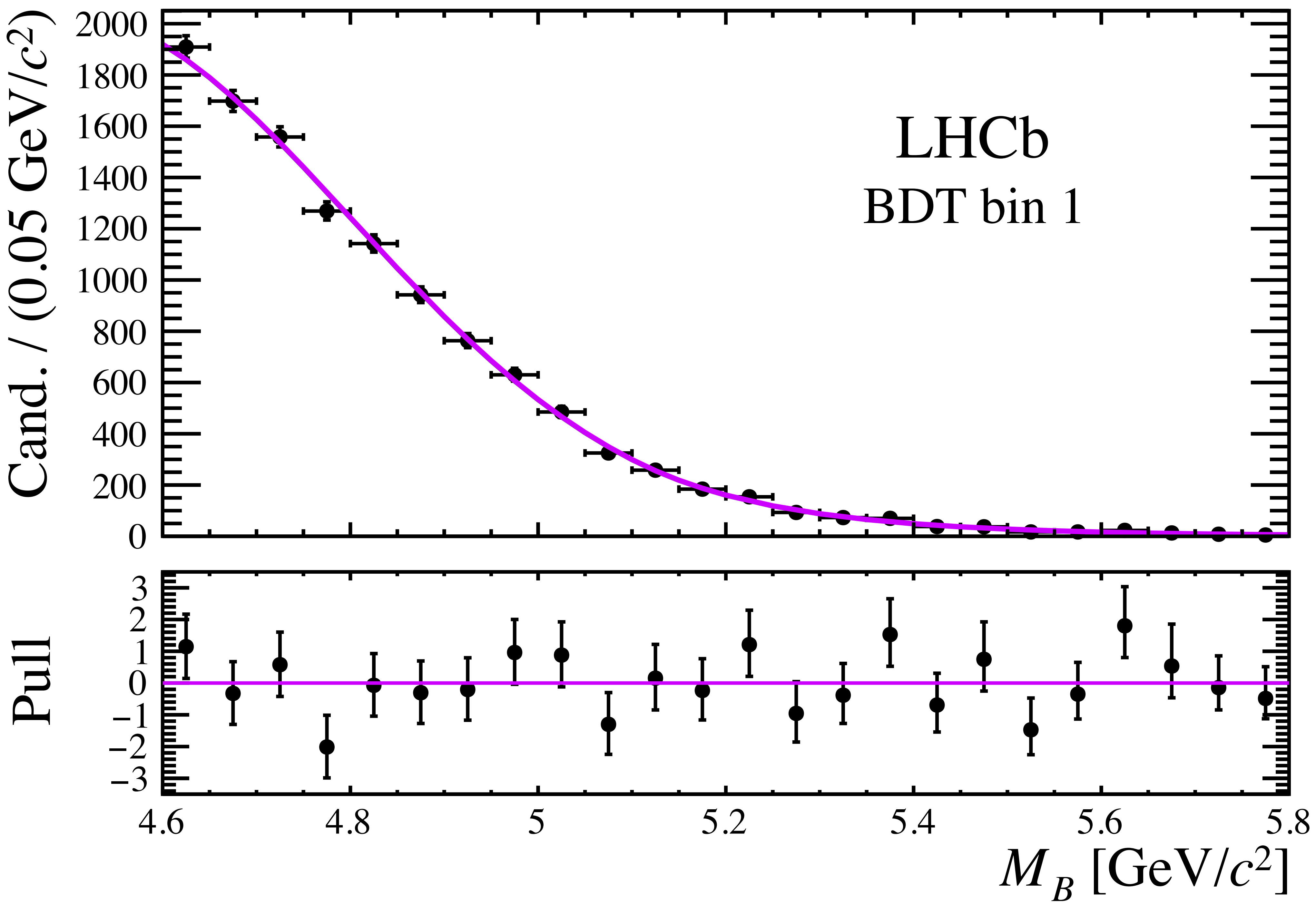
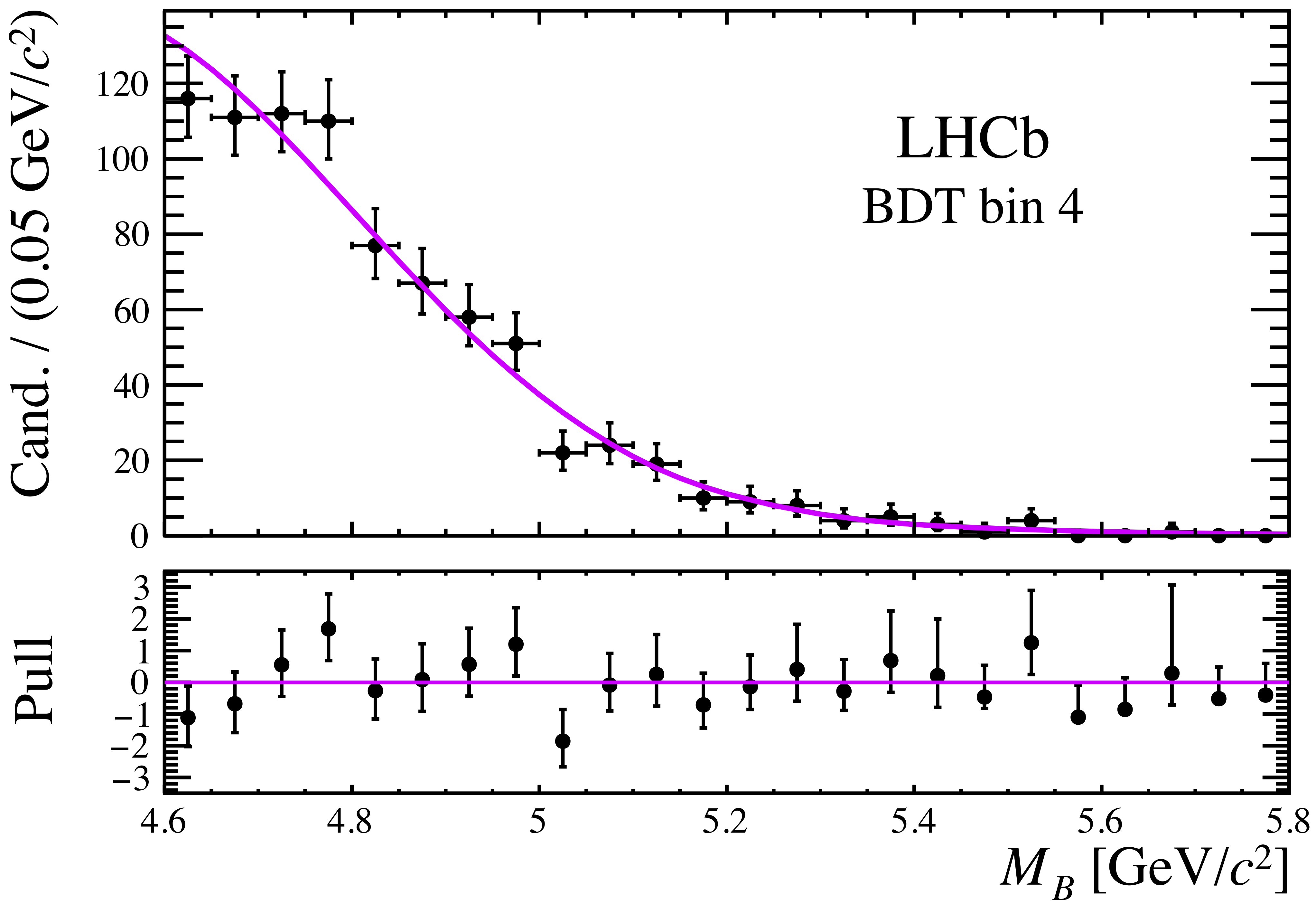
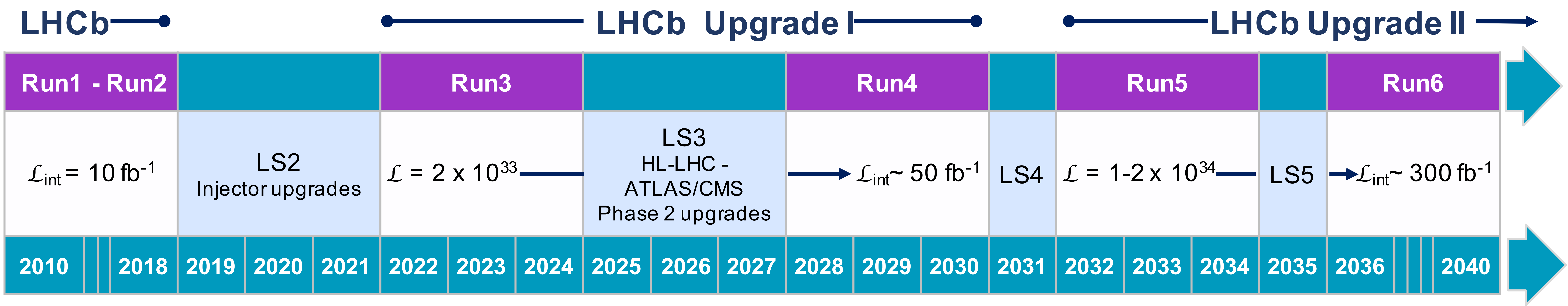
Phys. Rev. Lett. 123 (2019) 211801





Mode	Limit	90% CL	95% CL
$B^0_s \to \tau^{\pm}\mu^{\mp}$	Observed	3.4×10^{-5}	4.2×10^{-5}
	Expected	3.9×10^{-5}	4.7×10^{-5}
$B^0 \to \tau^{\pm}\mu^{\mp}$	Observed	1.2×10^{-5}	1.4×10^{-5}
	Expected	1.6×10^{-5}	1.9×10^{-5}

Projections with two body

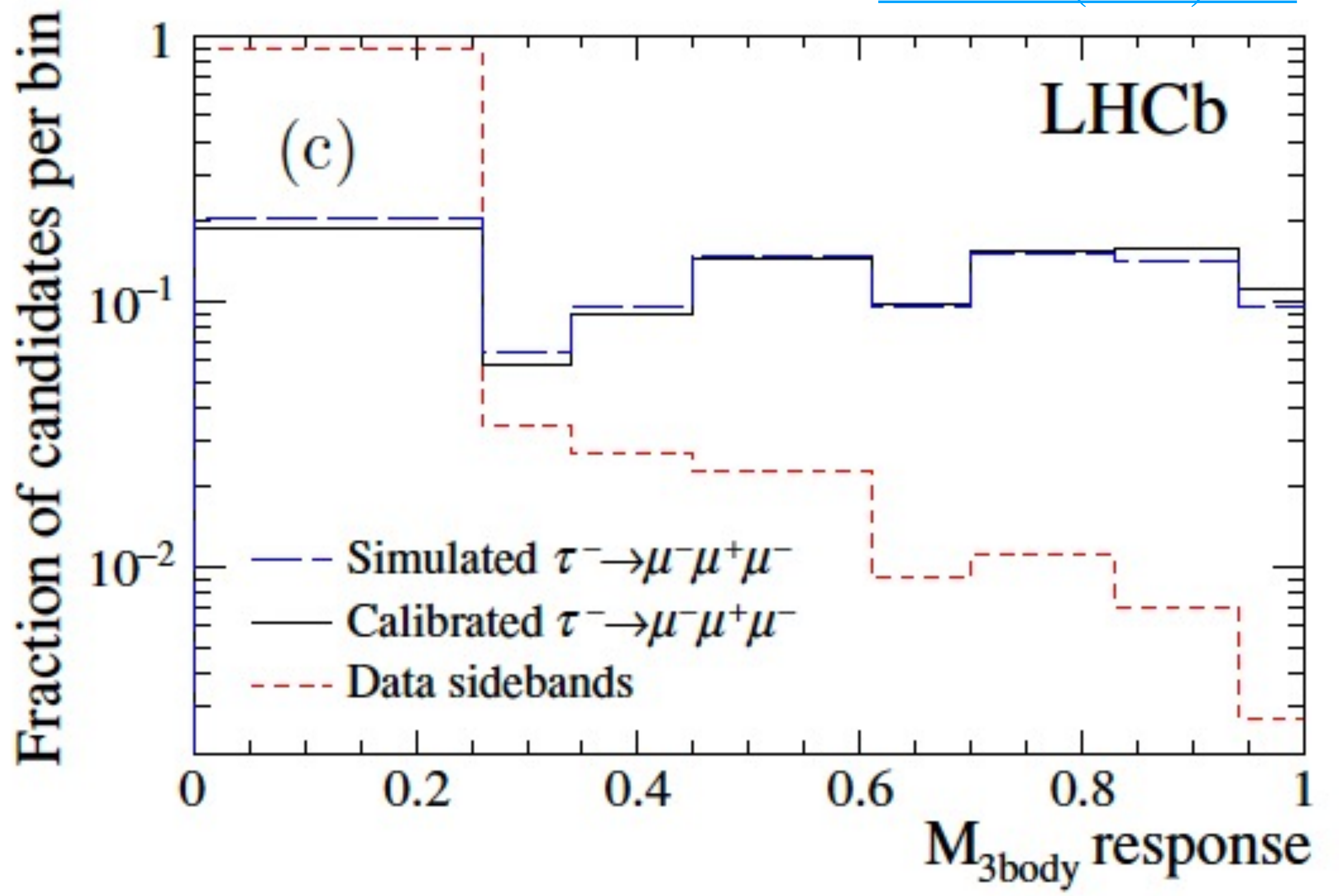


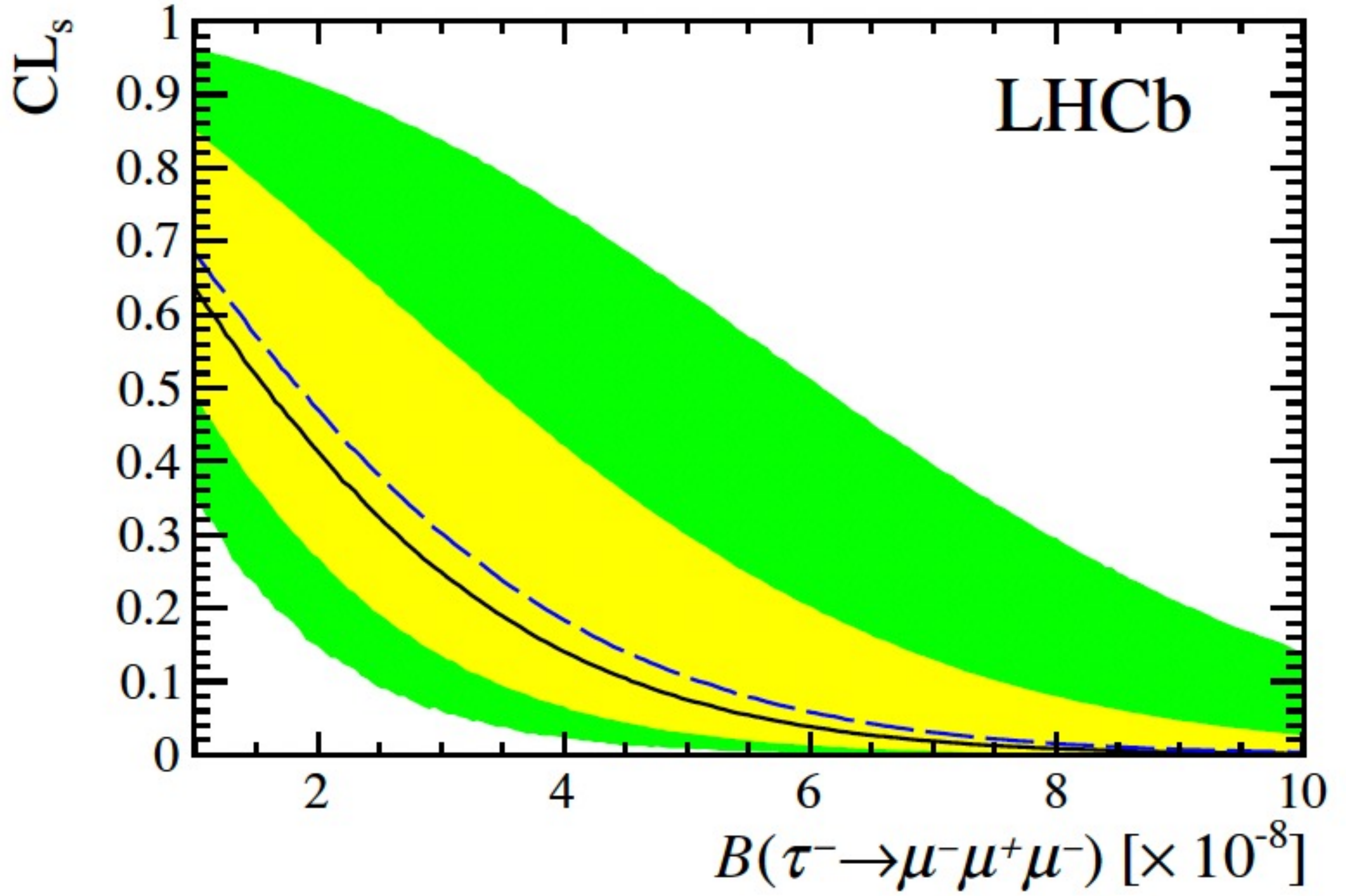
JHEP 03 (2018) 078	LHCb Run1	Upgrade I	Upgrade II
$\mathscr{B}(B^0 \to e^\pm \mu^\mp)$	$< 1.3 \times 10^{-9}$	$< 2 \times 10^{-10}$	$< 9 \times 10^{-11}$
$\mathscr{B}(B_s^0 \to e^\pm \mu^\mp)$	$< 6.3 \times 10^{-9}$	$< 8 \times 10^{-10}$	$< 3 \times 10^{-10}$
$\mathscr{B}(B^0 \to \tau^\pm \mu^\mp)$	$< 1.4 \times 10^{-5}$	–	$< 3 \times 10^{-6}$

JHEP 02 (2015) 121

$\tau \to \mu\mu\mu$

- Current best experimental limit from Belle [PLB 2010 03 037]:
  - $\mathscr{B}(\tau \to \mu\mu\mu) < 2.1 \times 10^{-8}$ at 90 % CL
- LHCb analysis on Run 1 data
  - $D_s^+ \to \phi(\mu^+\mu^-)\pi^+$ used as normalisation
  - Main challenge due to background sources:
    - Combinatorial and mis-ID background ($D_{(s)}^+ \to 3\pi, D^+ \to K^-\pi^+\pi^+$)
  - Background suppression achieved by means of multivariate classifiers
  - Upper limit: $\mathscr{B}(\tau \to \mu\mu\mu) < 4.6(5.6) \times 10^{-8}$ at 90 % (95%) CL
- Ongoing analysis with Run 2 data (coming out soon!)
- Extrapolated limit from Run 1 to Run 1 + Run 2 (higher luminosity and cross section): $\mathscr{B}(\tau \to \mu\mu\mu) < 2.5(3.1) \times 10^{-8}$ at 90 % (95%) CL

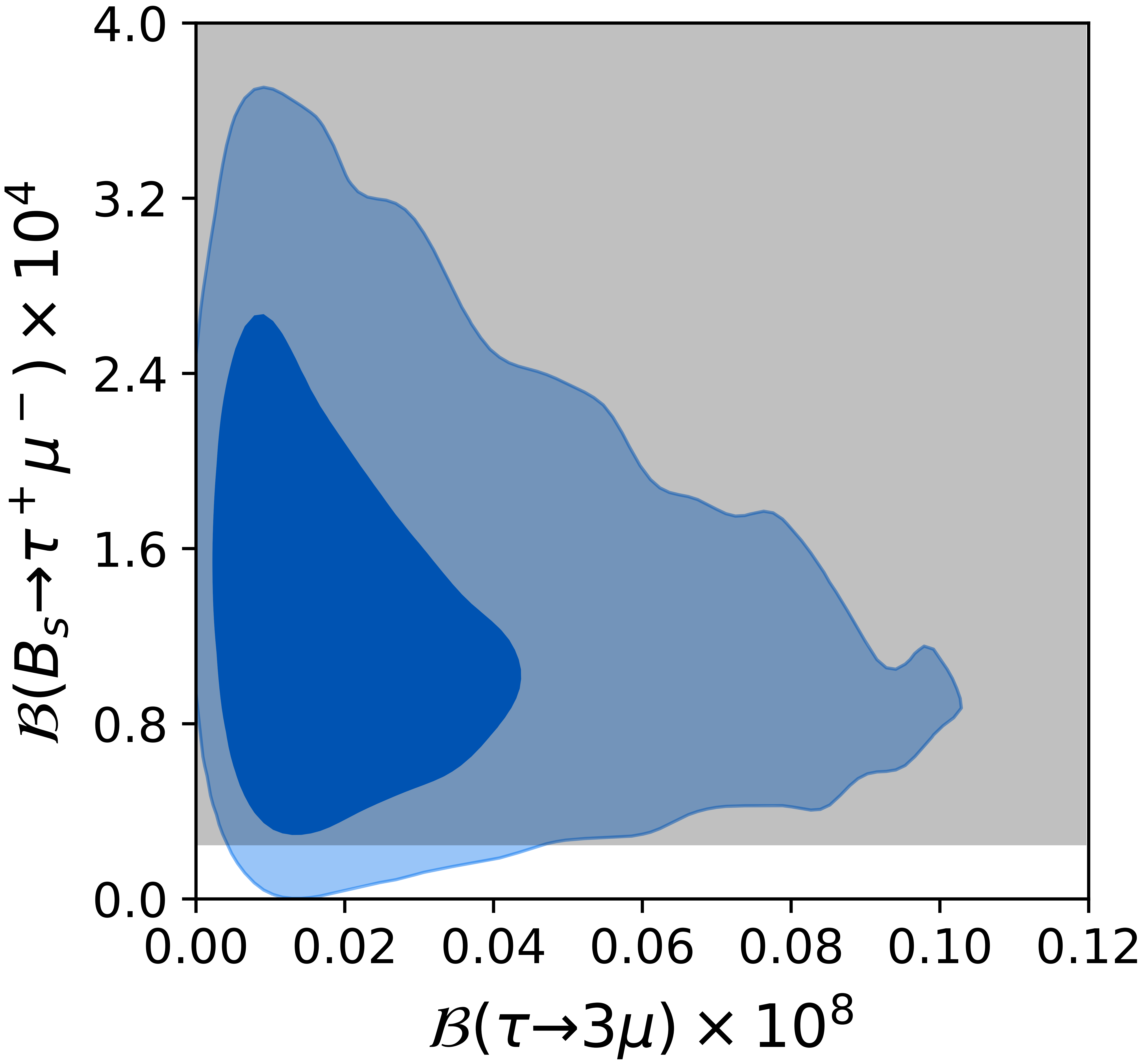




Complementarity

- Already very effective in constraining BSM models such Pati-Salam extensions
- Complementary to cLFV searches with τ

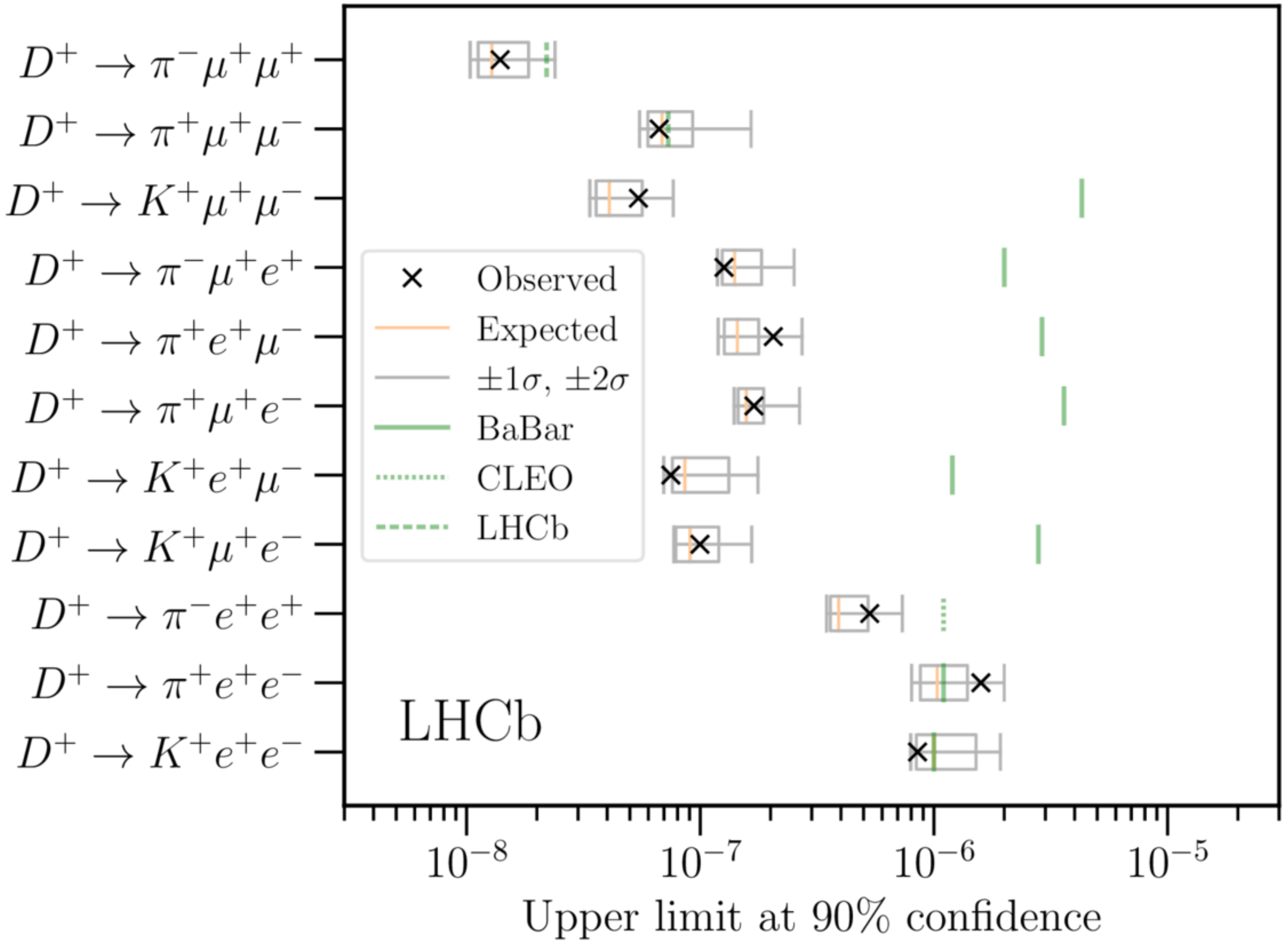
Bordone et al. JHEP10(2018)148 2018

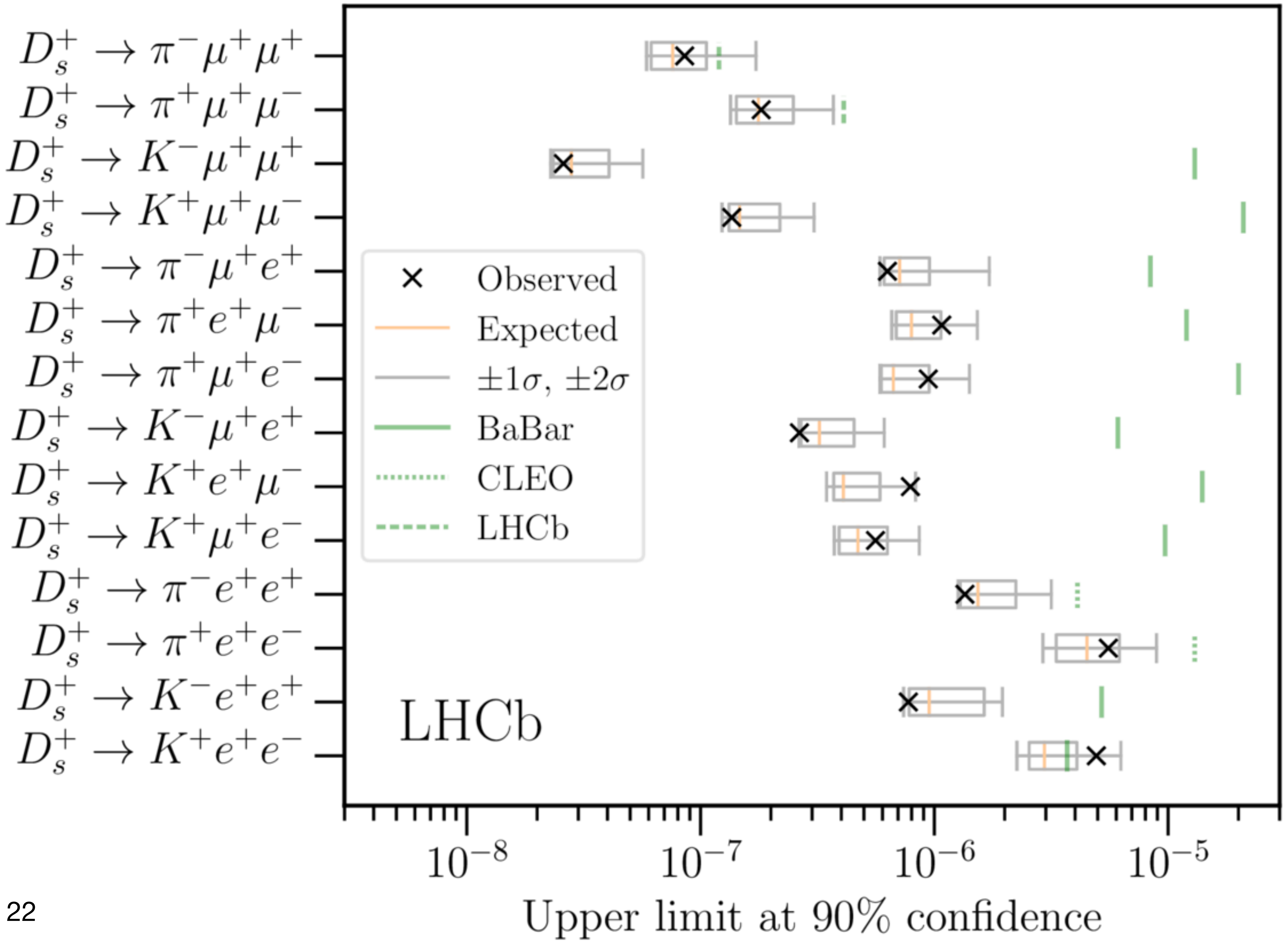


LFV in charm sector

- Searches for 25 new charm rare/LFV/LNV with 2016 data ($1.6\,\mathrm{fb}^{-1}$)
- Results compatible with bkg-only hypothesis
- Most precise result for all studied LFV modes!

JHEP 06 (2021) 044





Summary

- LFV is an active field at LHCb, stringent constraints on many models.
- LHCb started taking data again and commissioning is ongoing:
    - Completely new detector!
    - Fully exploiting the new trigger model, exclusive trigger lines can give large statistics boost!
    - Improved electron efficiency (was limited by hardware trigger).
    - Strongly boost soft and displaced signatures (D, τ decays), in principle can go down to $p_T \sim 50$ MeV!
    - Enable new searches: LFV in strange decays such as $K_S \to e\mu$.

Backuppa

$B^0 \to K^{*0}\mu^\pm e^\mp$ and $B_s^0 \to \phi\mu^\pm e^\mp$

- NP predictions can reach 10^{-7} [Phys. Rev. D 92, 054013]
- Analysis performed using Run1+Run2 LHCb data
- $B^0 \to K^{*0}\mu^\pm e^\mp$ treated separately depending on charge configuration of $K\mu$
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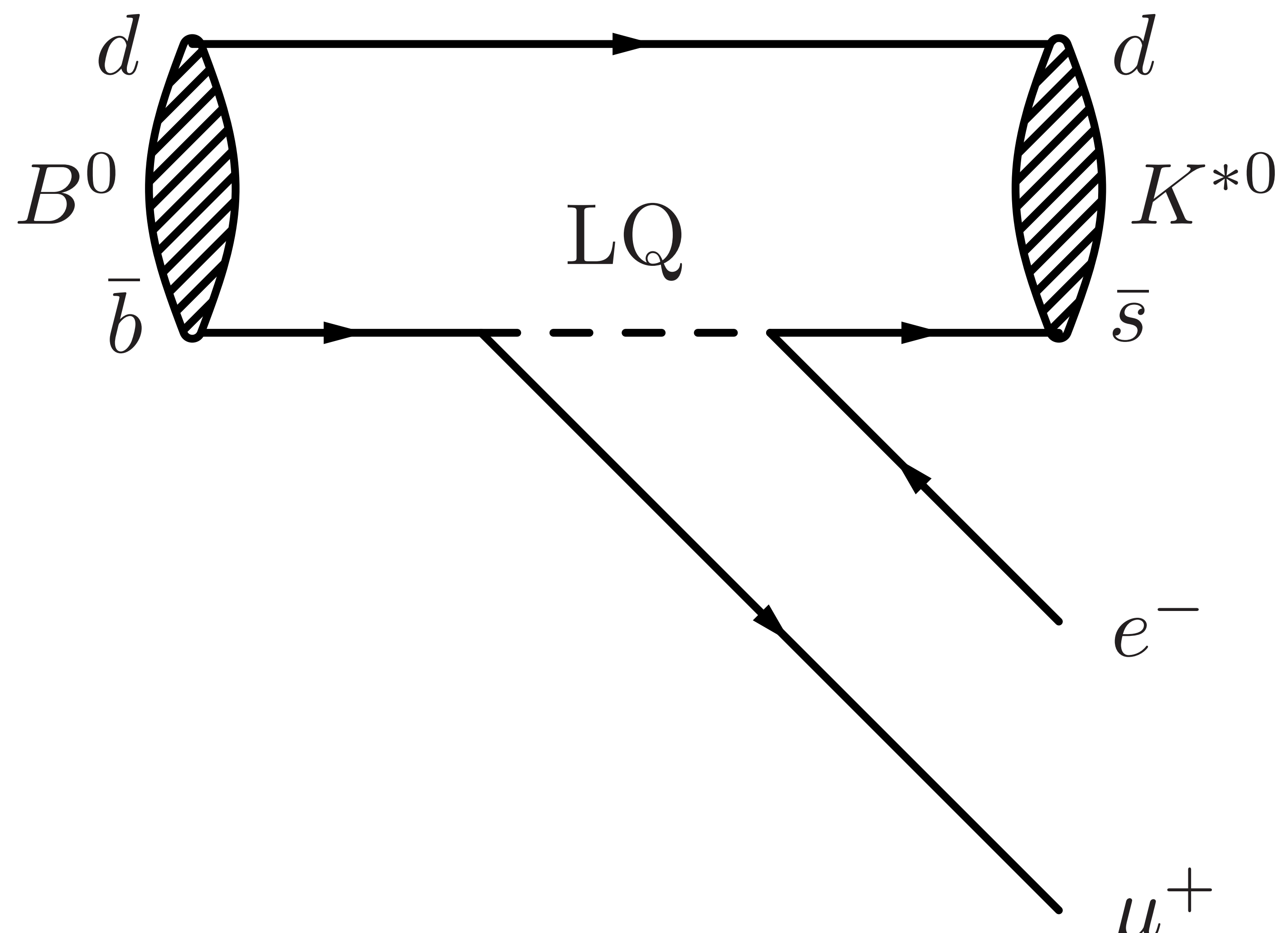

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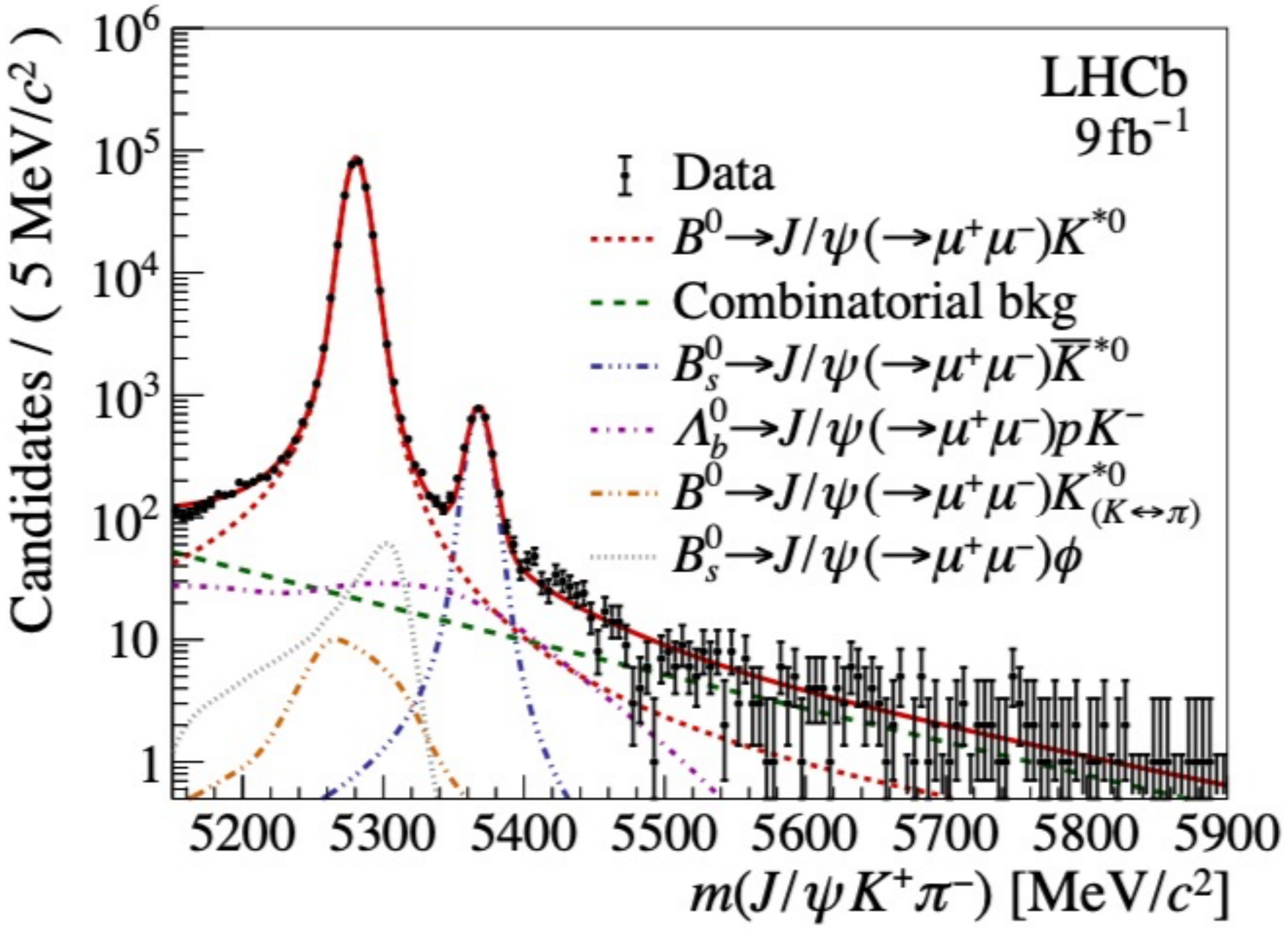
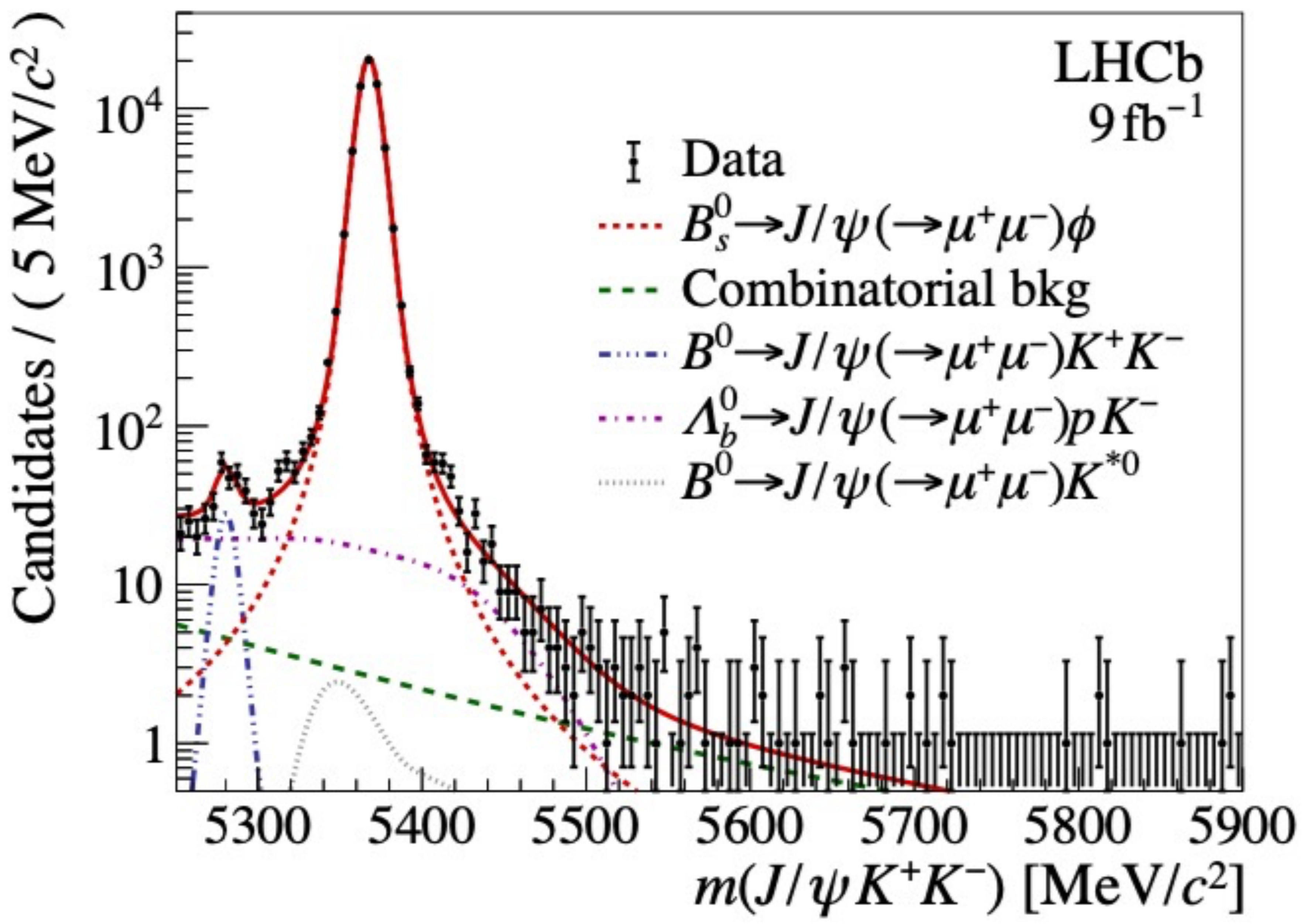
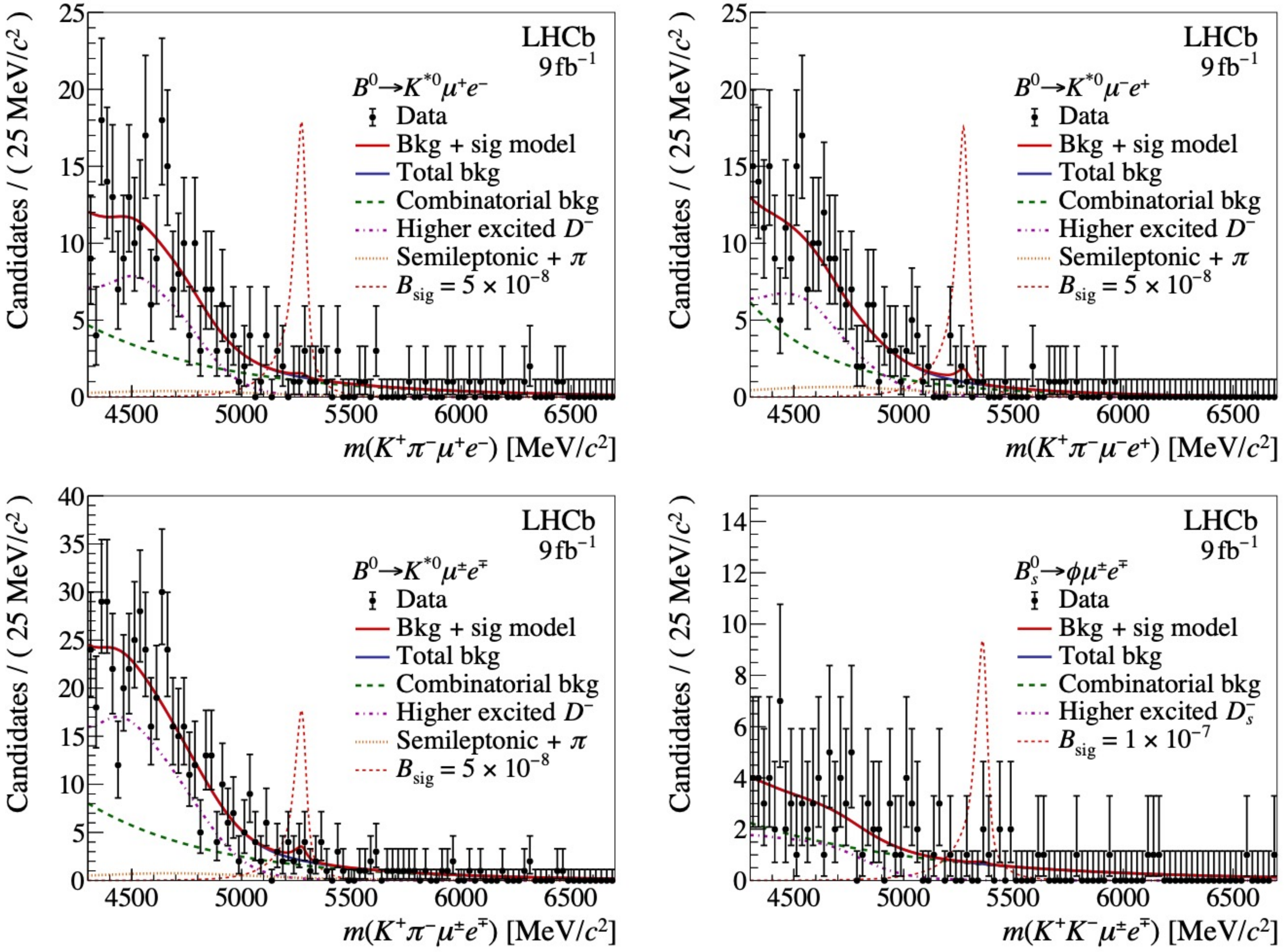




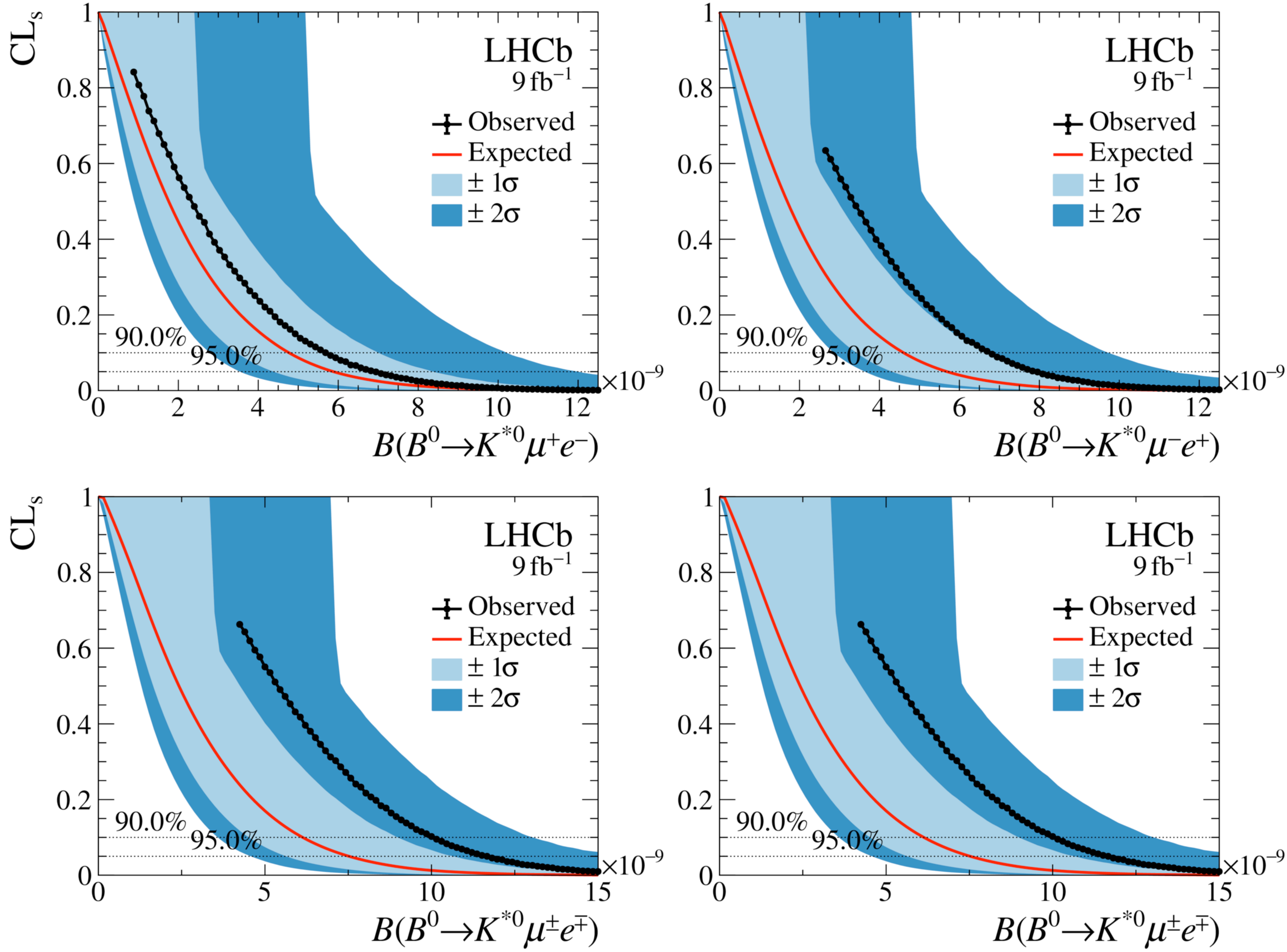
$B^0 \to K^{*0}\mu^{\pm}e^{\mp}$ and $B_s^0 \to \phi\mu^{\pm}e^{\mp}$

- Remaining backgrounds in the sidebands studied in detail
- Higher excited D resonances can pass the veto requirements
  - Multiple possible modes studied and described in the fit



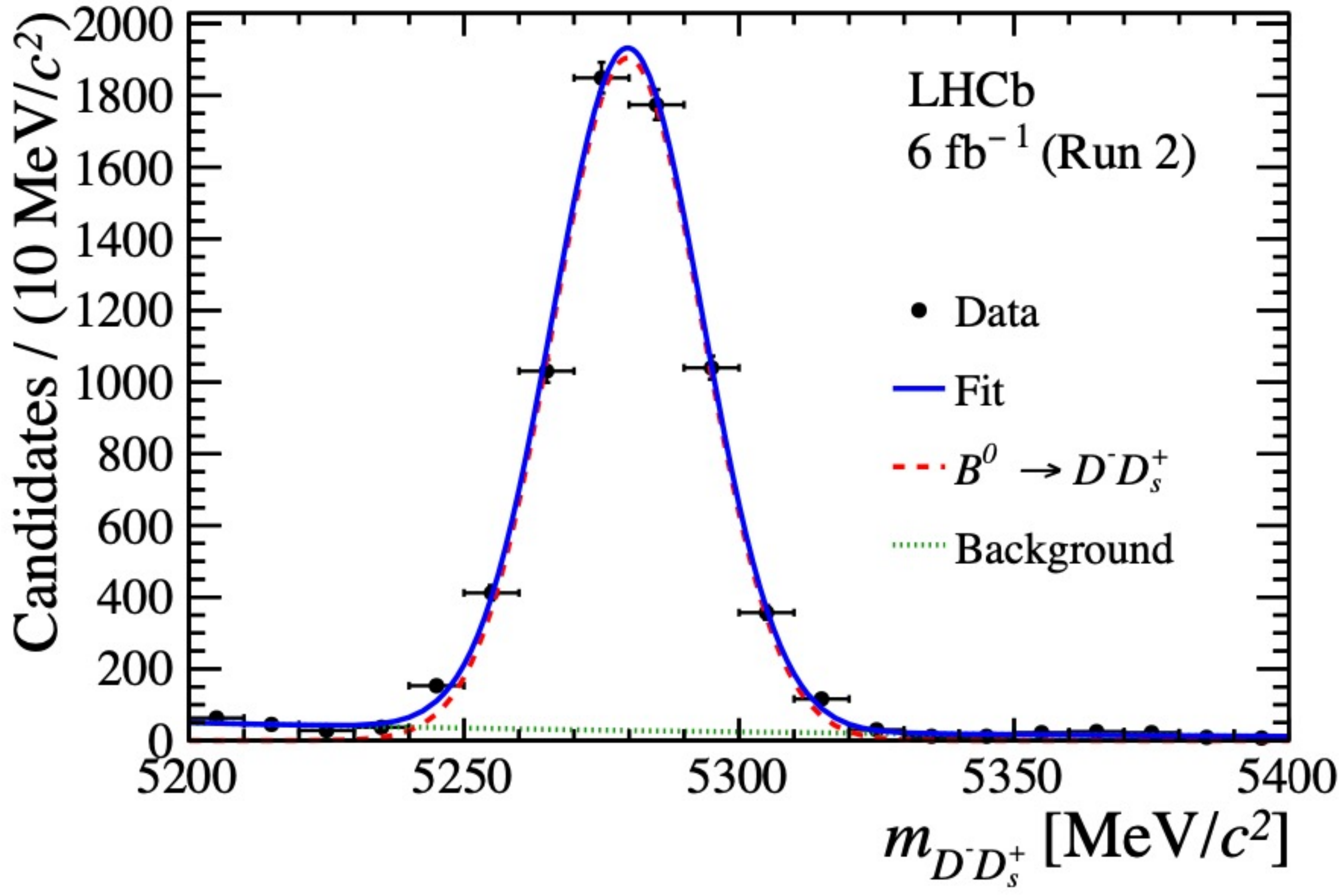
$B^0 \to K^{*0}\mu^\pm e^\mp$ and $B_s^0 \to \phi\mu^\pm e^\mp$

- No significant signal observed
- Upper limits at 90(95)% CL determined as:
  - $\mathcal{B}(B^0 \to K^{*0}\mu^+e^-) < 5.7(6.9) \times 10^{-9}$
  - $\mathcal{B}(B^0 \to K^{*0}\mu^-e^+) < 6.8(7.9) \times 10^{-9}$
  - $\mathcal{B}(B^0 \to K^{*0}\mu^\pm e^\mp) < 10.1(11.7) \times 10^{-9}$
- wrt Belle's result $\mathcal{O}(10^{-7})$ [PRD 98, 071101(R) (2018)]
  - $\mathcal{B}(B^0 \to K^{*0}\mu^\pm e^\mp) < 16.0(19.8) \times 10^{-9}$
- Limits on BFs assuming uniform phase-space decay model
- (Re-)interpretation in terms of scalar and left-handed LF violating NP models also provided



$B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$

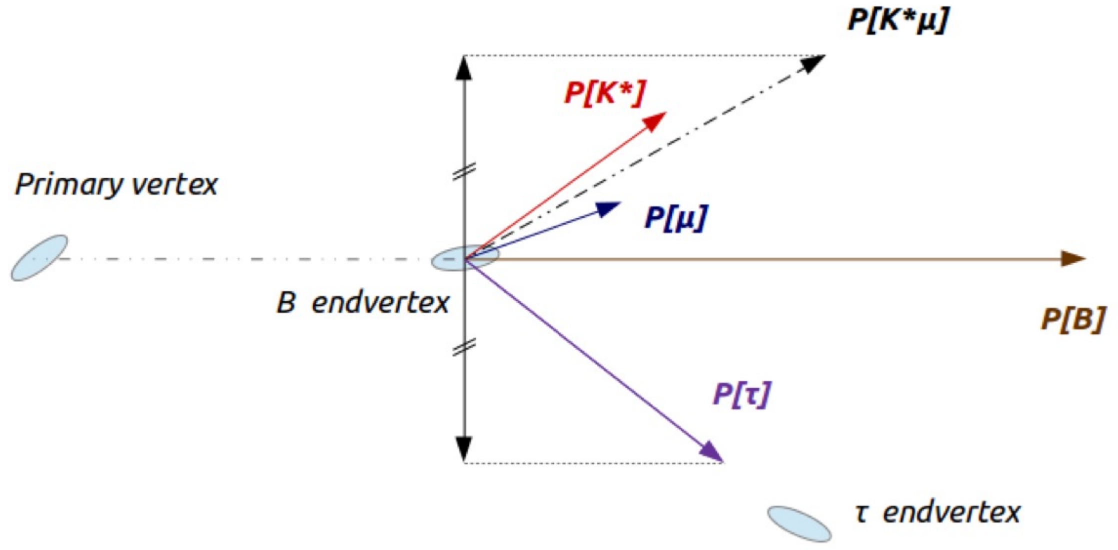
- First search for the $B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$ decay on Run 1 + Run 2 data
- K^{*0} reconstructed through $K^{*0} \to K^+\pi^-$
- τ reconstructed through $\tau \to \pi^+\pi^-\pi^+(\pi^0)\nu_\tau$
- Normalisation relative to $B^0 \to D^-(K^+\pi^-\pi^-)D_s^+(K^+K^-\pi^+)$
- Independent analysis on $\tau\mu$ charge configuration:
    - Affected by different backgrounds
    - Different theoretical interpretation



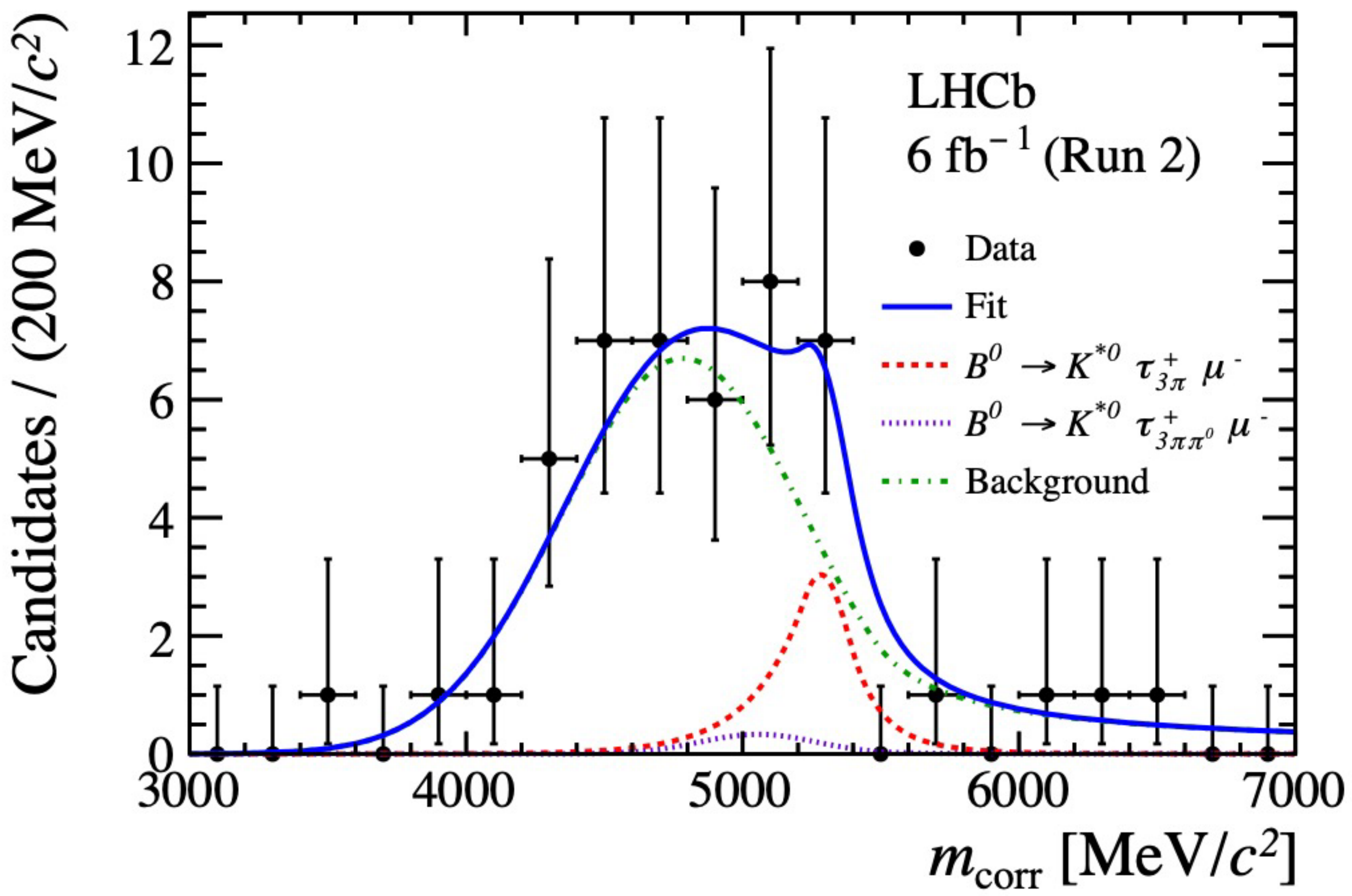
- Two stage multivariate selection based on BDTs trained against combinatorial and mis-ID background
- Requirements on particle identification to remove mis-id

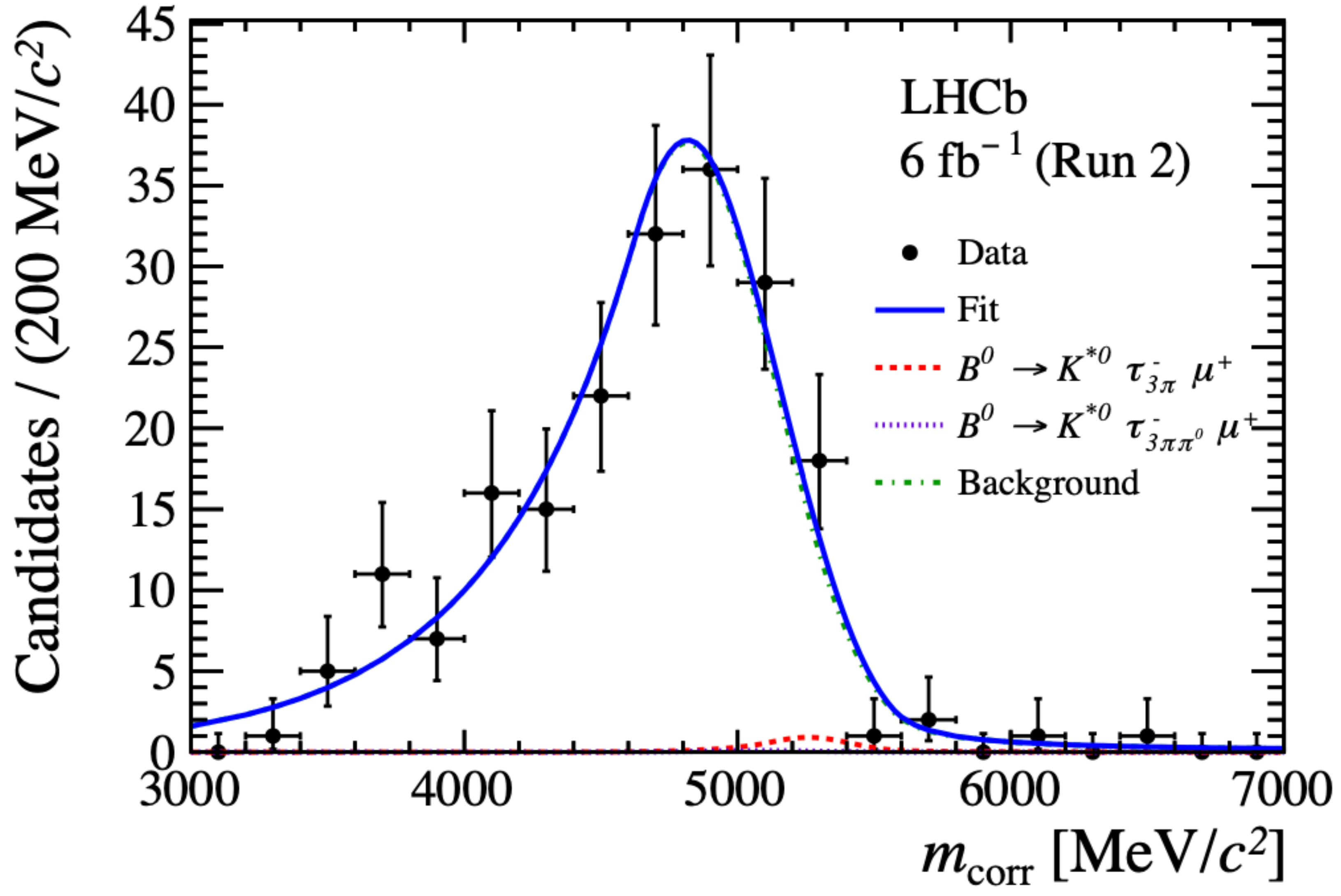
$B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$

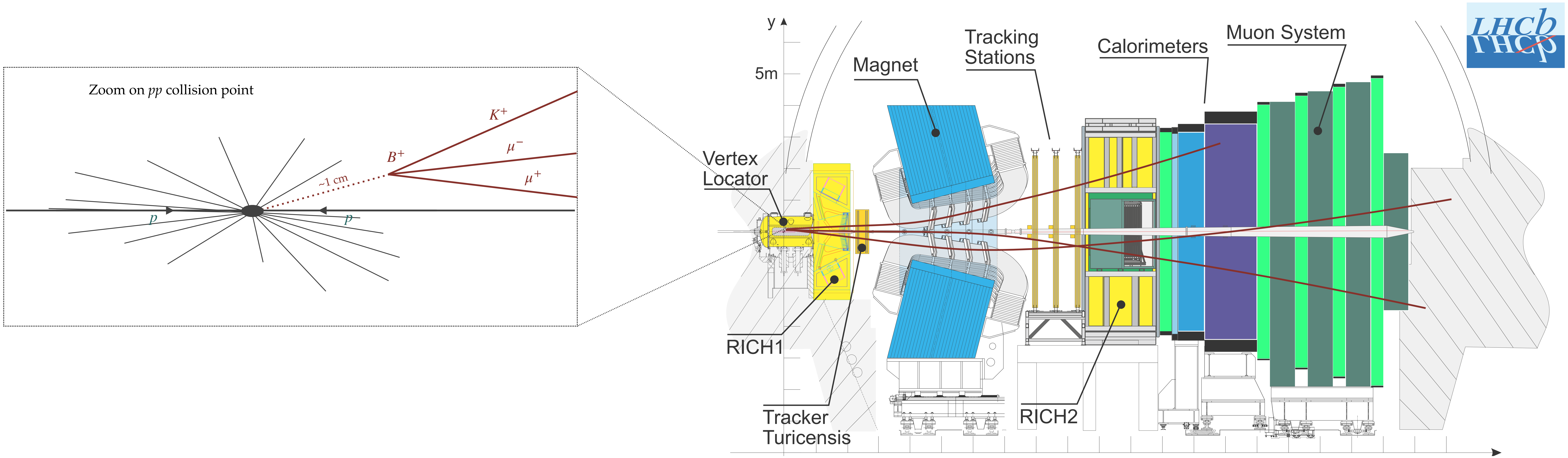
- Due to the large energy loss, use corrected mass
  $m_{corr} = \sqrt{p_\perp^2 + m_{K^*\tau\mu}^2} + p_\perp$



- No significant excess is observed
- Most stringent limits on $b \to s\tau\mu$ transitions set at 90%(95%) CL
- $\mathscr{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0(1.2) \times 10^{-5}$
- $\mathscr{B}(B^0 \to K^{*0}\tau^-\mu^+) < 8.9(9.8) \times 10^{-6}$

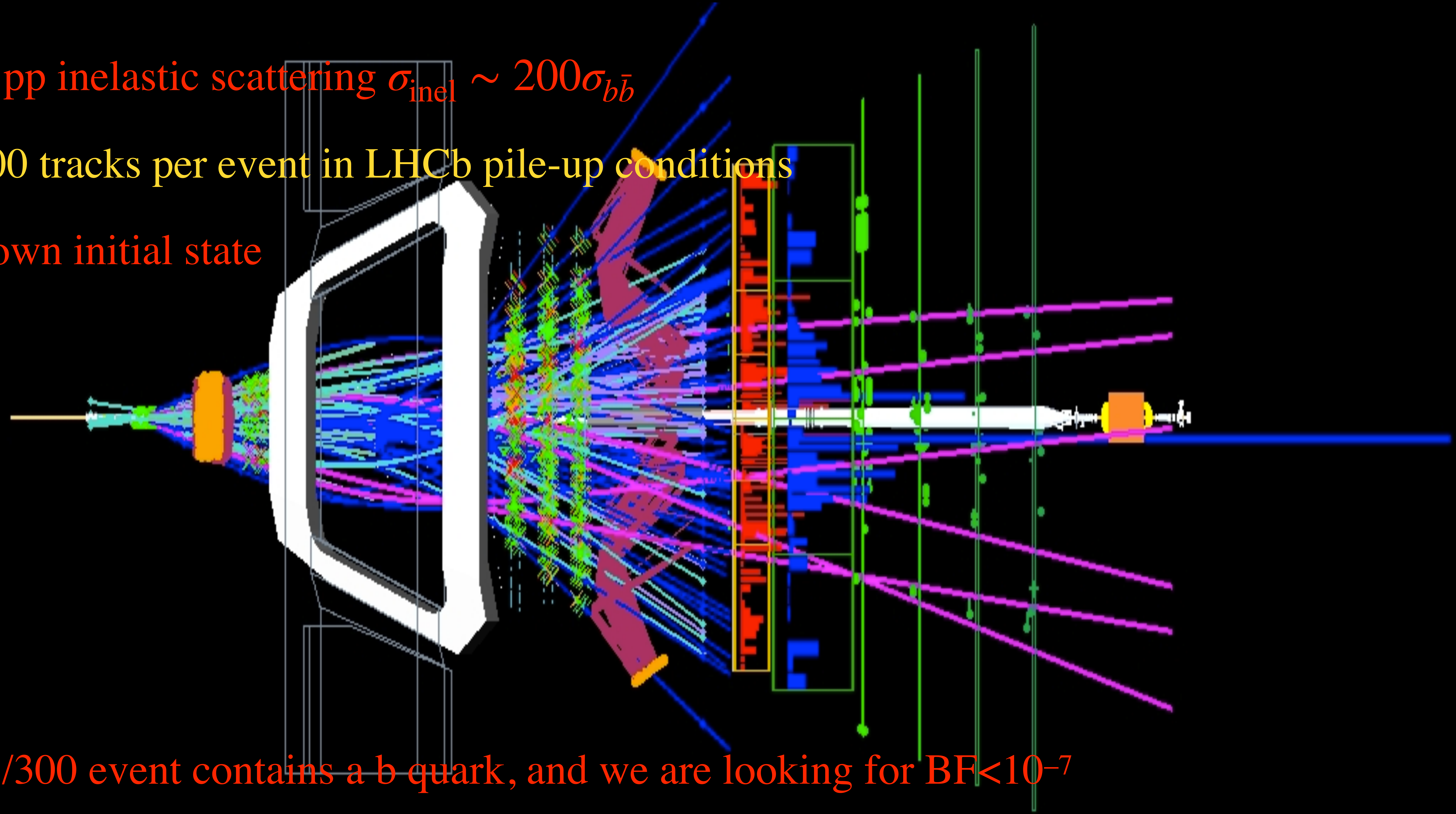






Zoom on pp collision point
K+
μ−
B+
μ+
~1 cm
p
p
y
5m
Magnet
Tracking
Stations
Calorimeters
Muon System
Vertex
Locator
RICH1
Tracker
Turicensis
RICH2

- Large pp inelastic scattering $\sigma_{\text{inel}} \sim 200\sigma_{b\bar{b}}$
  - ~100 tracks per event in LHCb pile-up conditions
- Unknown initial state



- only 1/300 event contains a b quark, and we are looking for BF<10^{-7}

Detector upgrade I

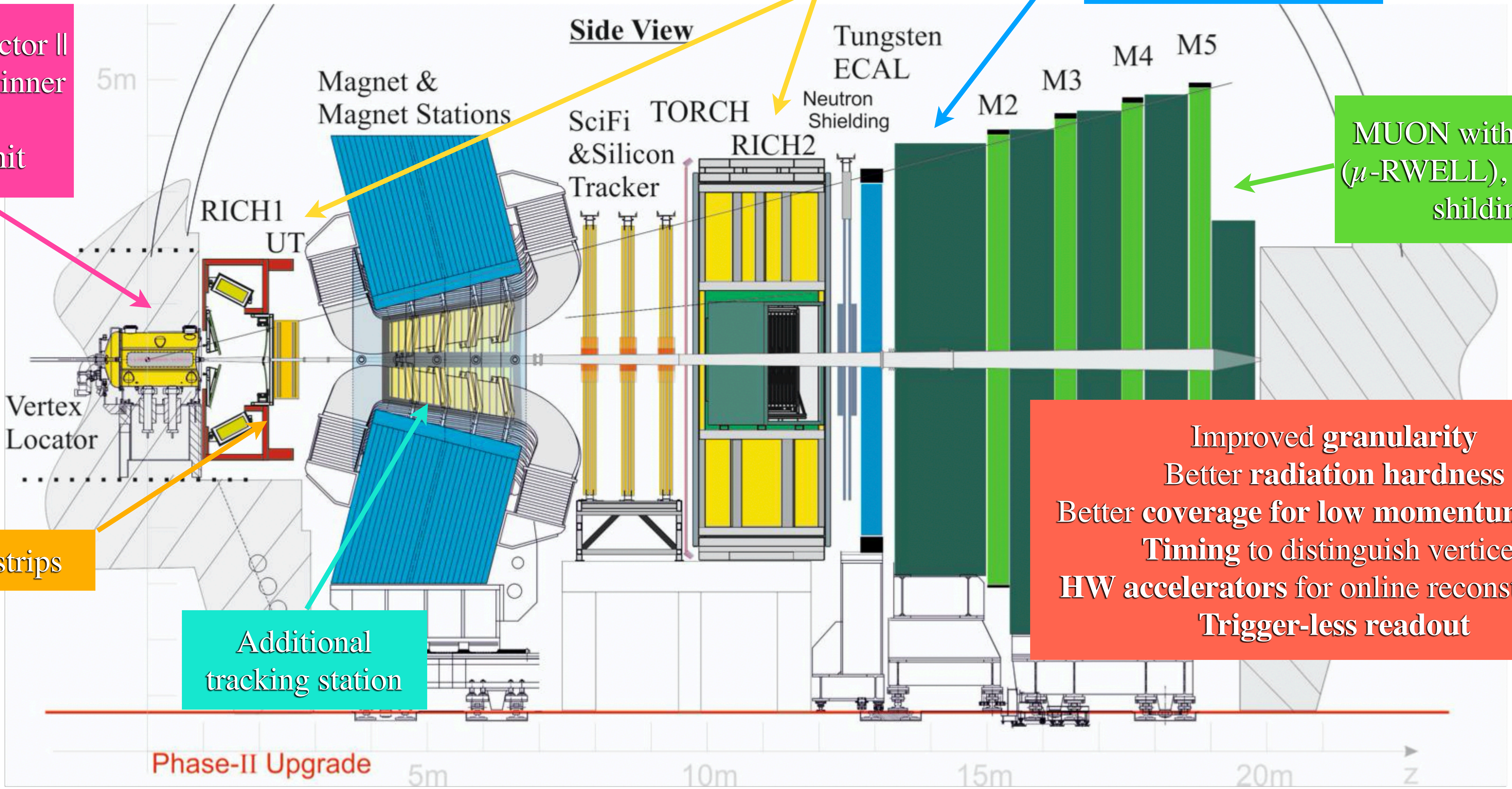
Detector upgrade II

RICH with new photon detectos $\sigma_t < 100$ ps/photon, TORCH detector

ECAL with finer segmentation and timing with $\sigma_t \sim 20 - 50$ ps

New Vertex Detector II smaller pixels, thinner sensors, $\sigma_t < 200$ ps/hit

MUON with MPGD (μ-RWELL), modified shilding



Si-strips

Additional tracking station

Improved **granularity**
Better **radiation hardness**
Better **coverage for low momentum** tracks
Timing to distinguish vertices
HW accelerators for online reconstruction
Trigger-less readout

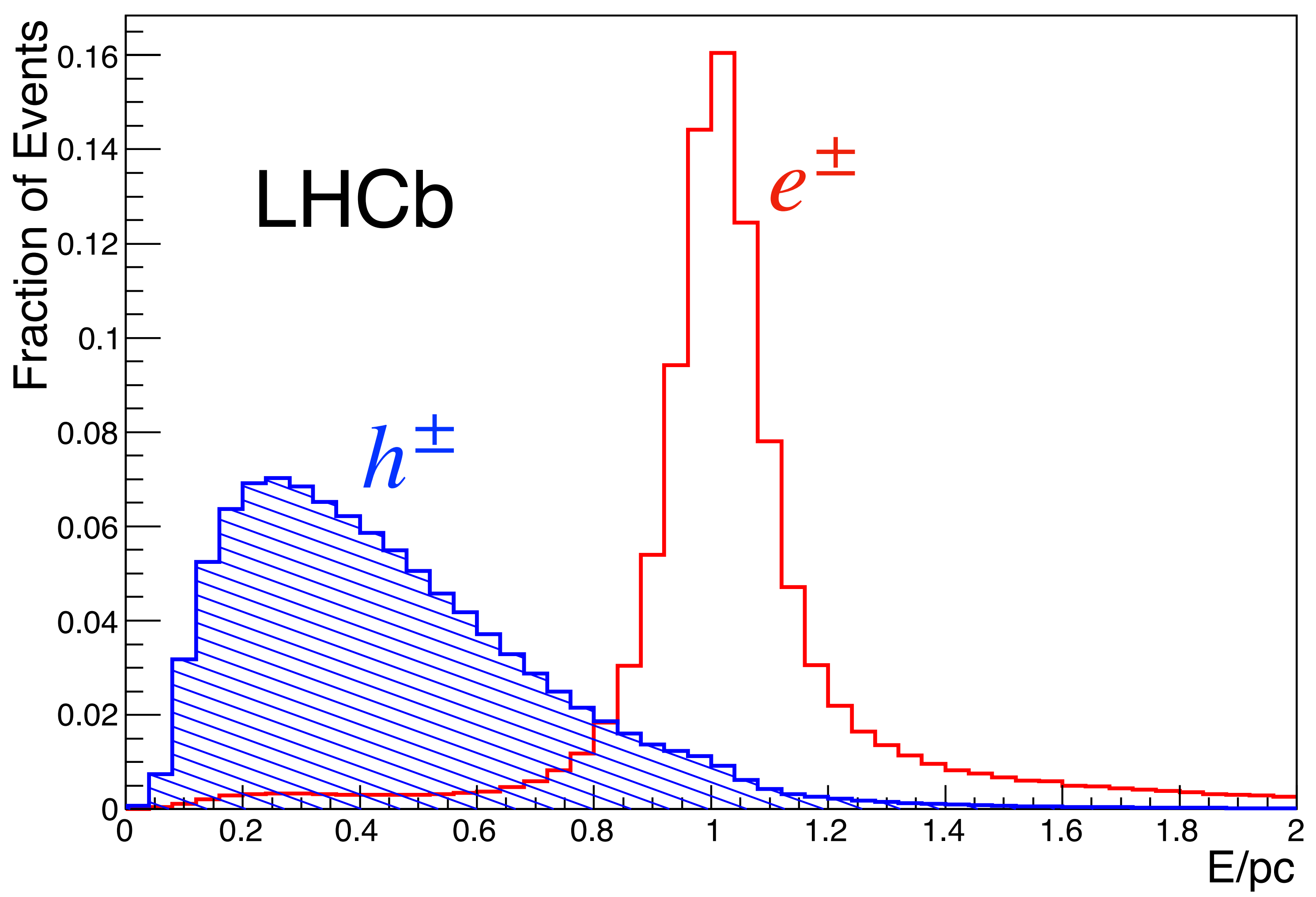
Disclaimer

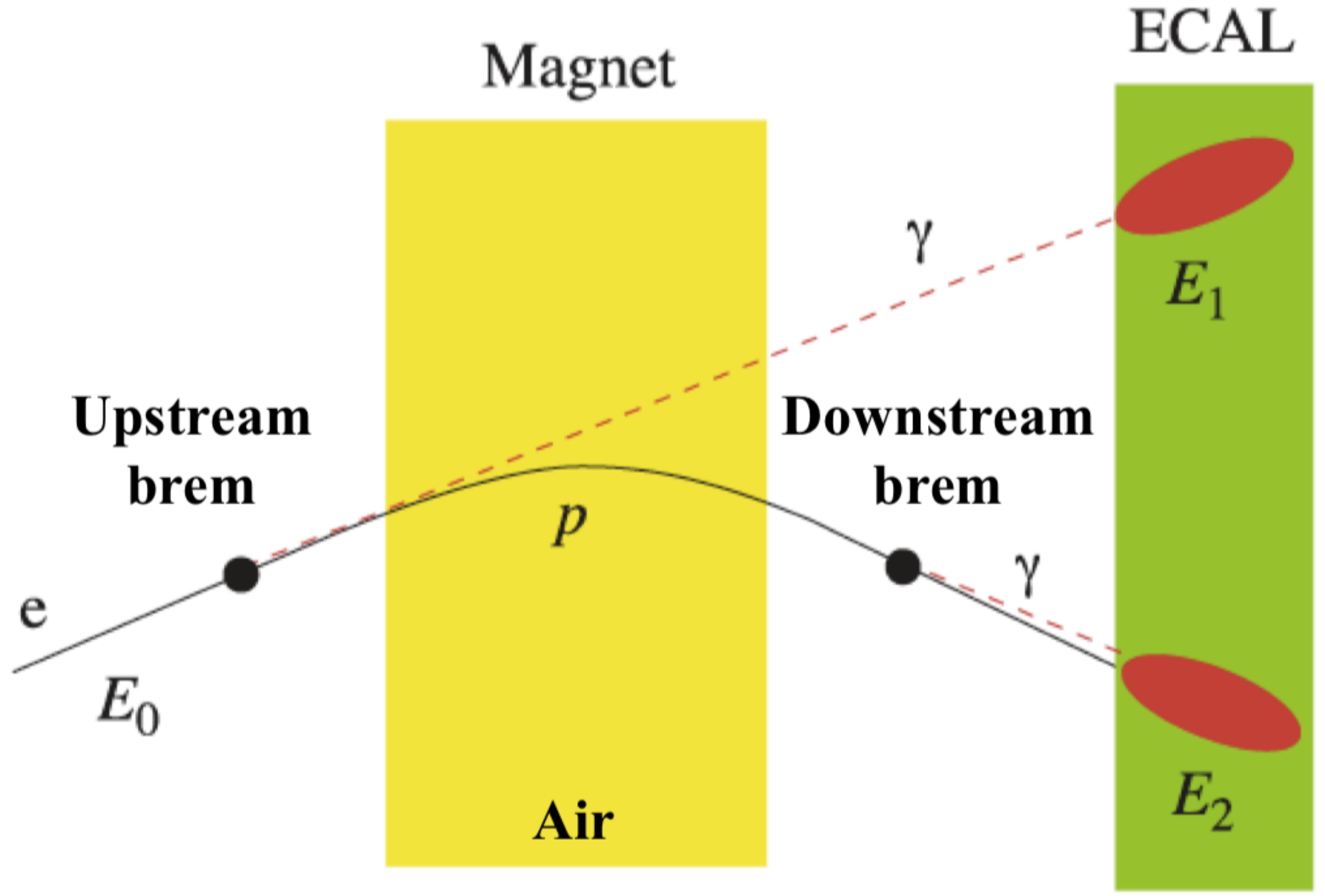
Most of the theoretical prediction with model driven by LFU anomalies may result in optimistic goals

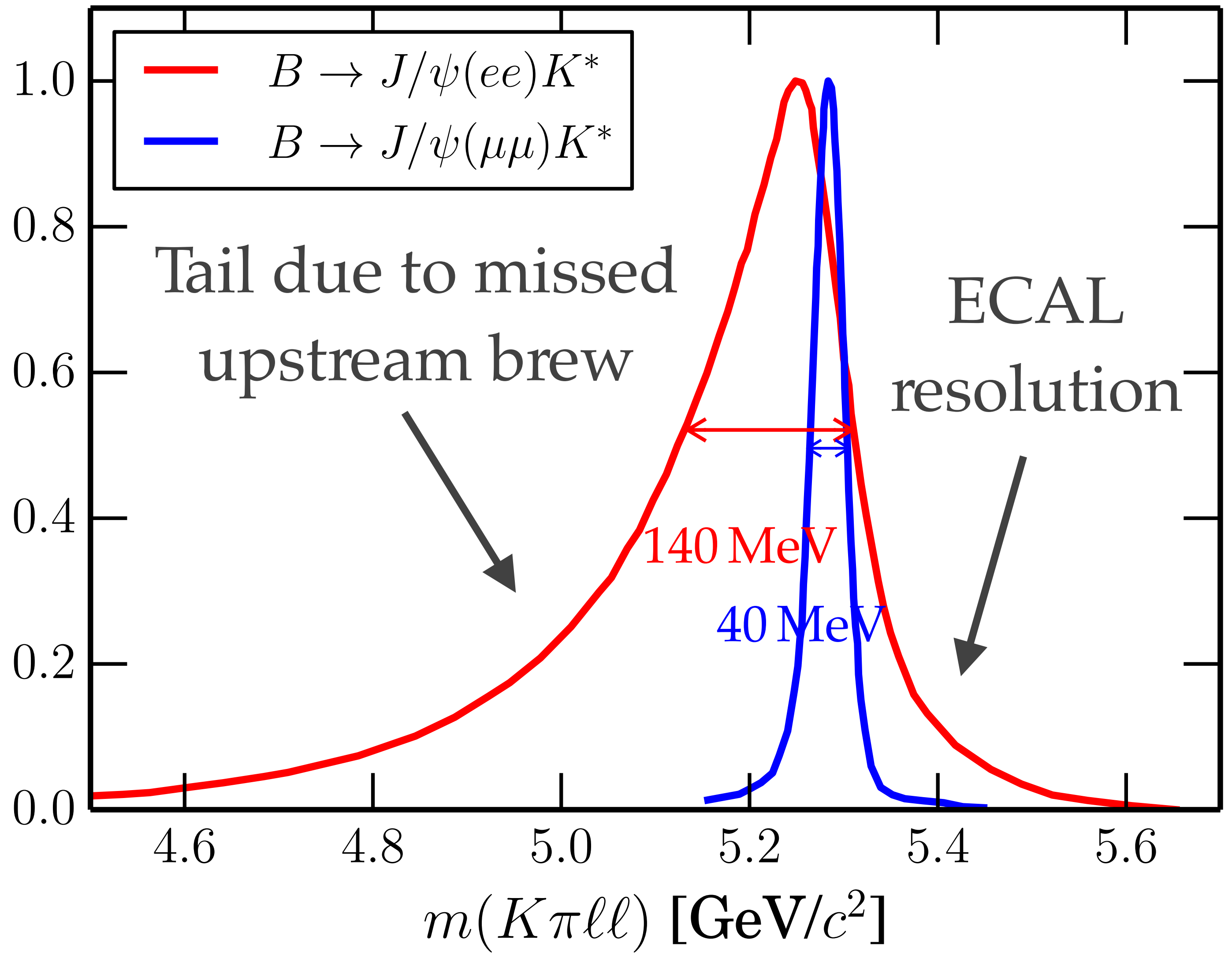
Electrons

- Triggered on large energy deposit on calorimeter
- Electron ID based on calorimetric information
- Selection is a factor ~3 less efficient than muons
- Boosted b-hadrons from LHC collision: most electron emit hard bremsstrahlung photon
  - momentum resolution heavily affected.

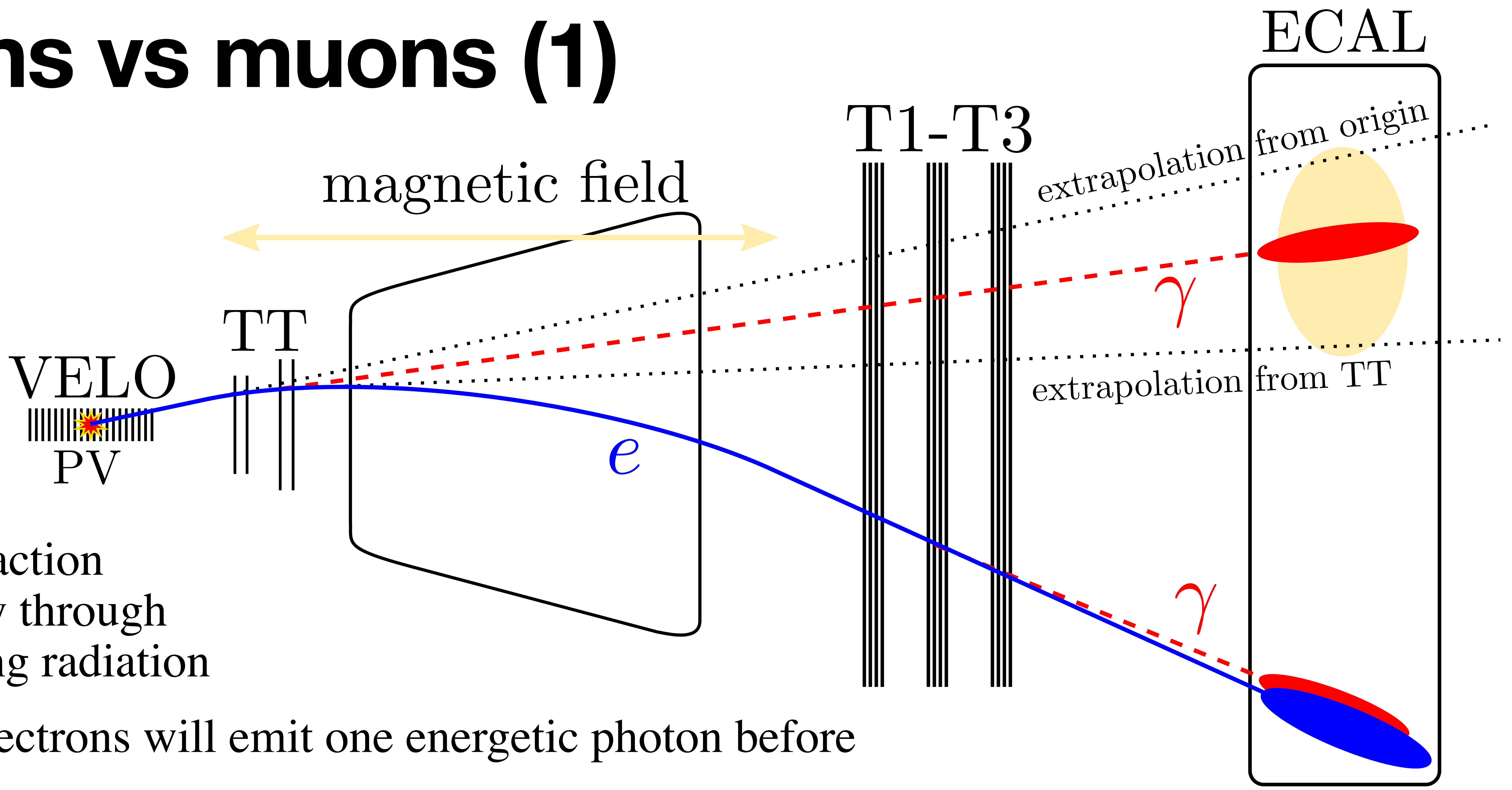
Int.J.Mod.Phys. A 30, 1530022 (2015)







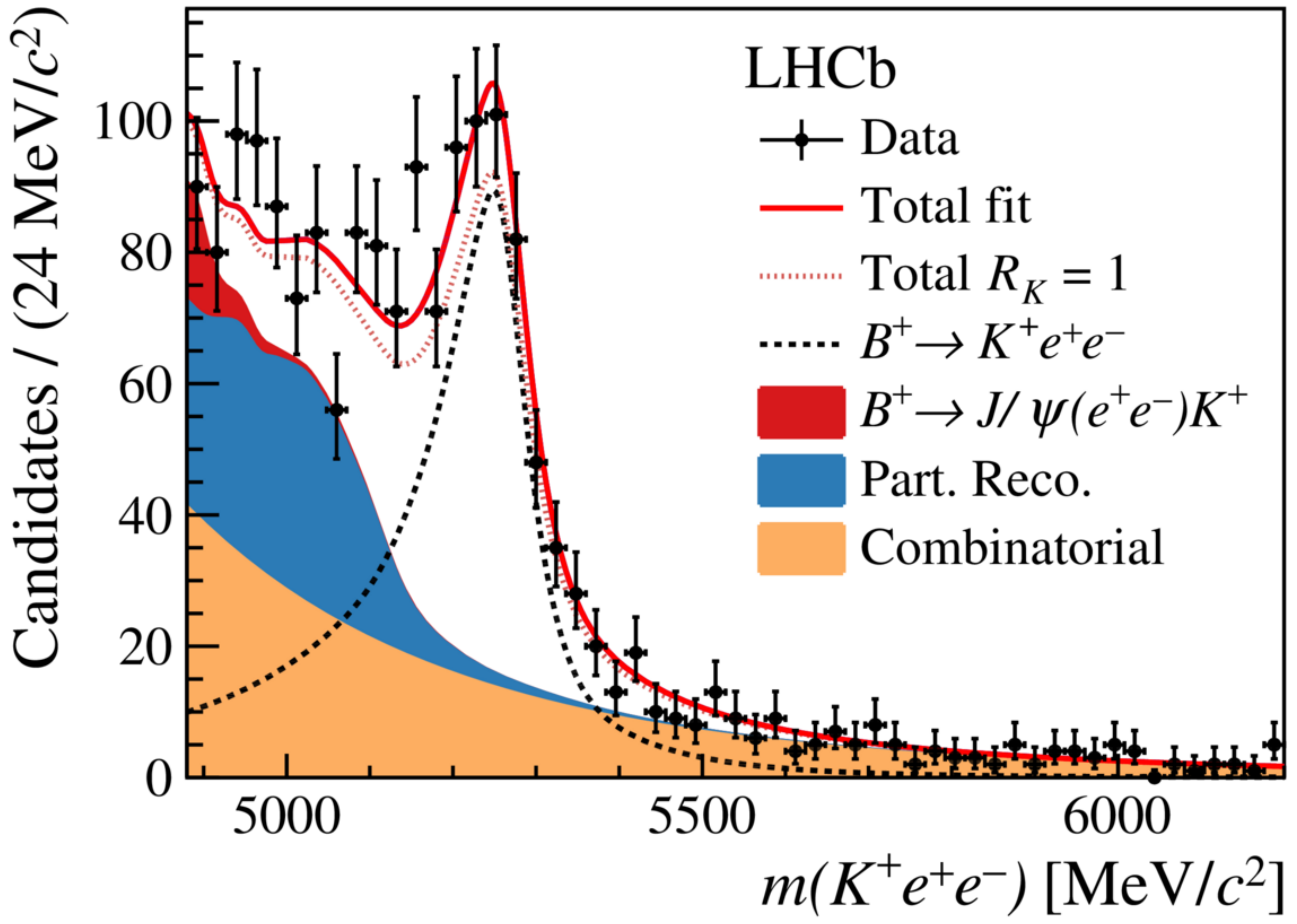
Electrons vs muons (1)

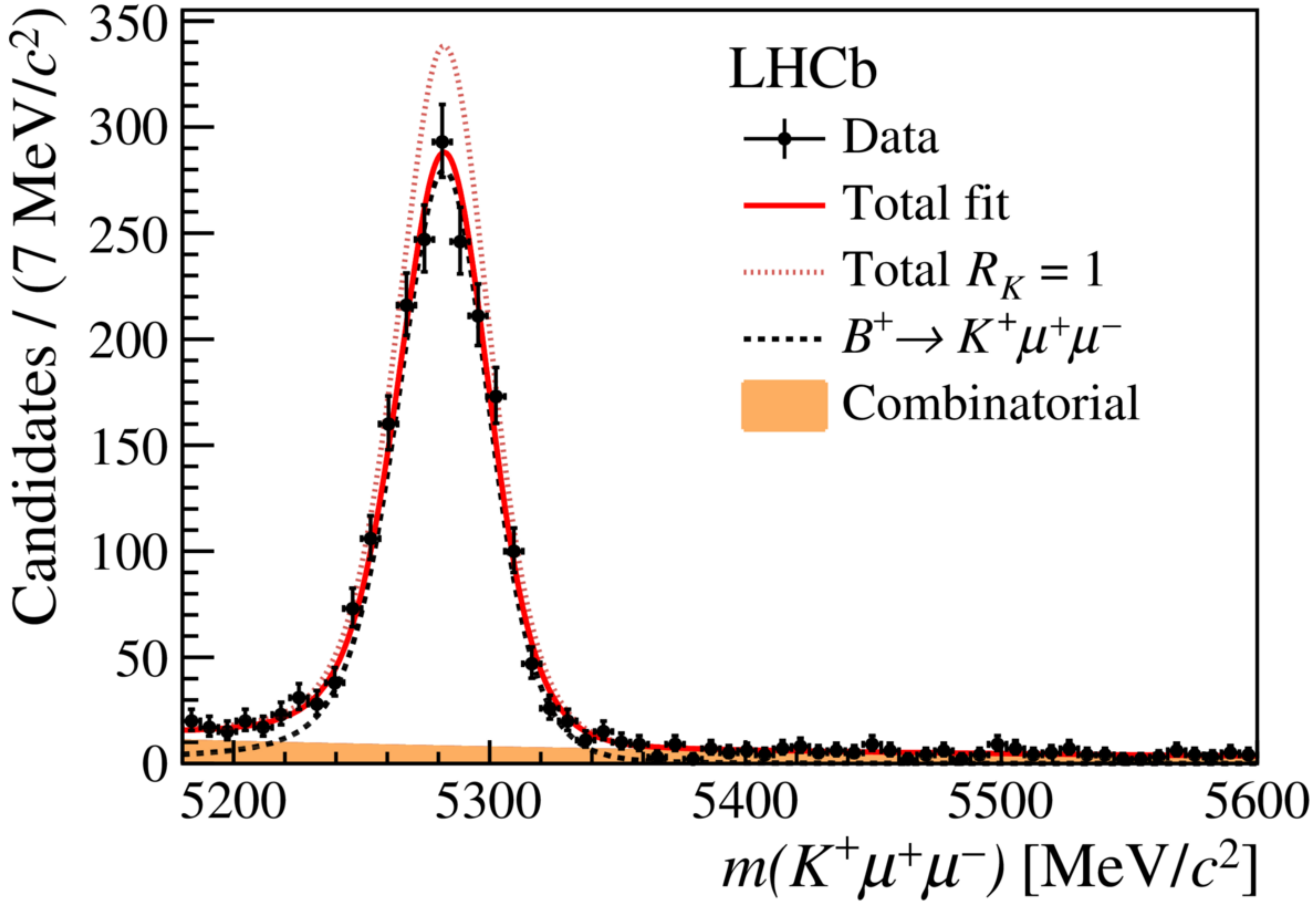


- Electrons lose a large fraction of their energy through Bremsstrahlung radiation
- Most of the electrons will emit one energetic photon before magnet
  - Look for photon clusters compatible with the direction of the electron before the magnet
  - Recover the energy loss by adding the cluster energy back to the electron momentum

Electrons vs muons (2)

From previous result, LHCb [PRL122(2019)191801]





- Bremsstrahlung recovery not sufficient, worse mass resolution!
- Lower trigger rate in case of electrons due to ECAL occupancy (higher thresholds)
  - Use of 3 exclusive trigger categories for e^+e^- final states
- Tracking and Particle ID efficiencies larger for muons

Purely leptonic rare decays

LHCb PRL 118, 191801 (2017)

- Loop and helicity suppressed precisely predicted in the SM:
  - $\mathscr{B}_{SM}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$
  - $\mathscr{B}_{SM}(B^0 \to \mu^+\mu^-) = (1.09 \pm 0.09) \times 10^{-10}$
  - $\tau_{\mu\mu} = 1.609 \pm 0.010$ ps
- LHCb results @ Run1+1.4fb^{-1}:
  - $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$
  - $\mathscr{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$ @ 95 % CL
- Main systematics from f_s/f_d and BF of normalisation mode
- At 300fb^{-1} (with conservative assumption on sys ~4%):
  - $\Delta\mathscr{B}(B_s^0 \to \mu\mu) \sim 0.16 \times 10^{-9}$
  - $\sigma(\mathscr{B}(B^0 \to \mu\mu)/\mathscr{B}(B_s^0 \to \mu\mu)) \sim 10\,\%$