New results on theoretically clean observables in rare B-meson decays from LHCb

$(B^0_{(s)} \to \mu^+\mu^-$ and $R_K)$

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6 April 2021

Most slides from
M. Santimaria, K. Petridis,
CERN seminar, 23/3/21

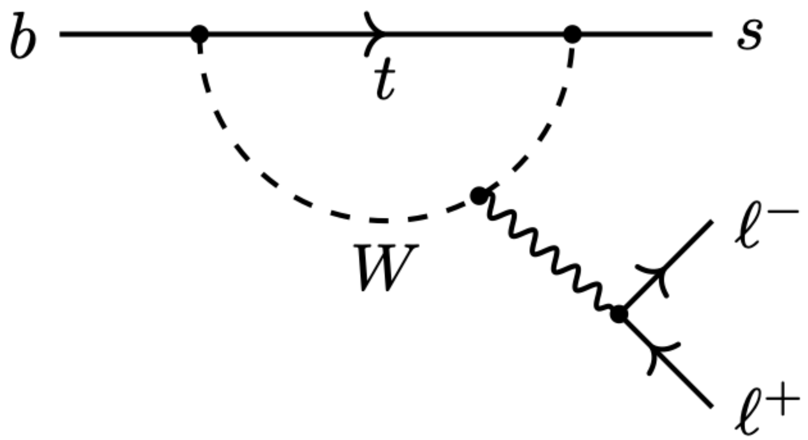
The power of indirect searches

- Precision measurements are a powerful tool to unveil new particles indirectly :
- 1970: charm presence invoked from the suppression of $K^0 \to \mu^+\mu^-$ before the J/ψ discovery
- 1973: 3X3 CKM matrix is needed to explain the CP violation observed in kaons
- 1987: top mass limit from loop contribution in $B^0 - \overline{B}^0$ mixing: $m_t > 50\text{GeV}$

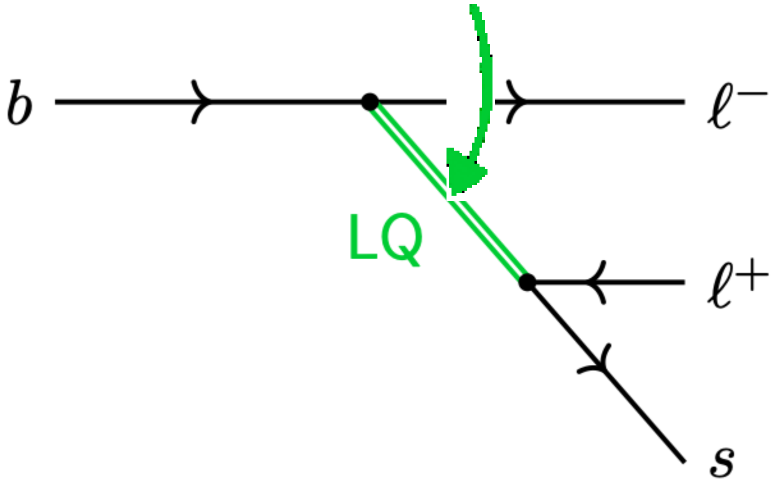
[PRD 2 (1970) 1285] [PTP 49 (1973) 652-657] [PLB 192 (1987) 245-252]

- Because of the large b mass, rare B decays offer a rich phenomenology for indirect searches of New Physics (NP)

$b \to s\ell^+\ell^-$ are FCNC processes that can only occur via loop in the SM

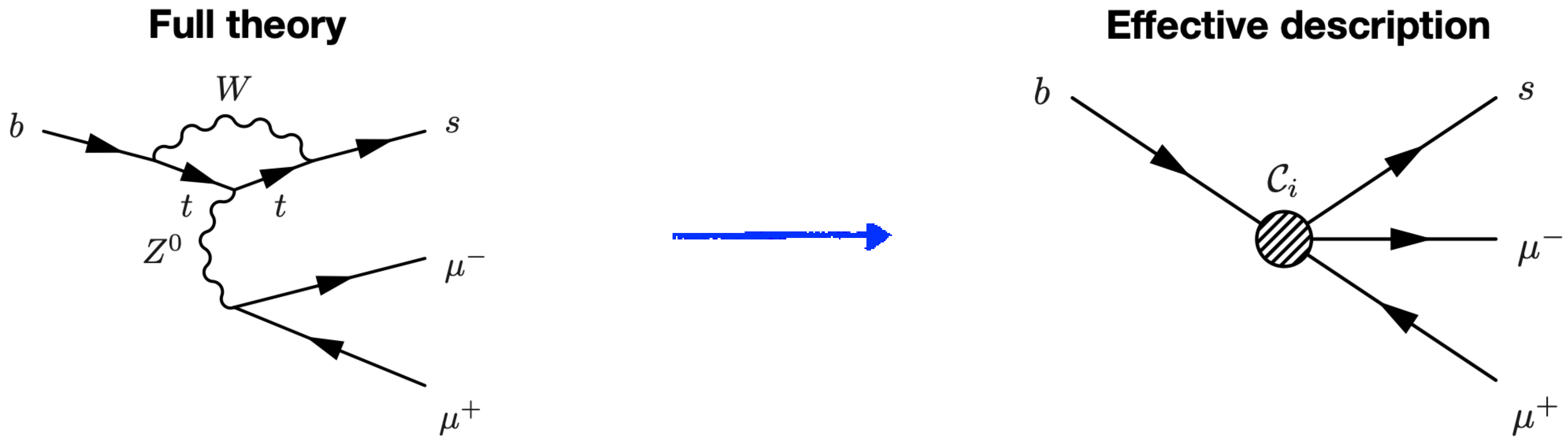


observables are altered by new (virtual) particles



Effective theory for rare B decays

- $b \to s\ell^+\ell^-$ can be described with an "Effective Hamiltonian", where high- and low-energy contributions are factorised ($M_b \ll M_W$)



- "point-like interaction" as in the Fermi description of the neutron decay

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\lambda) \mathcal{O}_i(\lambda)$$

- Wilson coefficients (short-distance): evaluated in perturbation theory
- Local operators (long-distance): the corresponding form factor is computed with, e.g., lattice QCD

Probing new physics with rare B decays

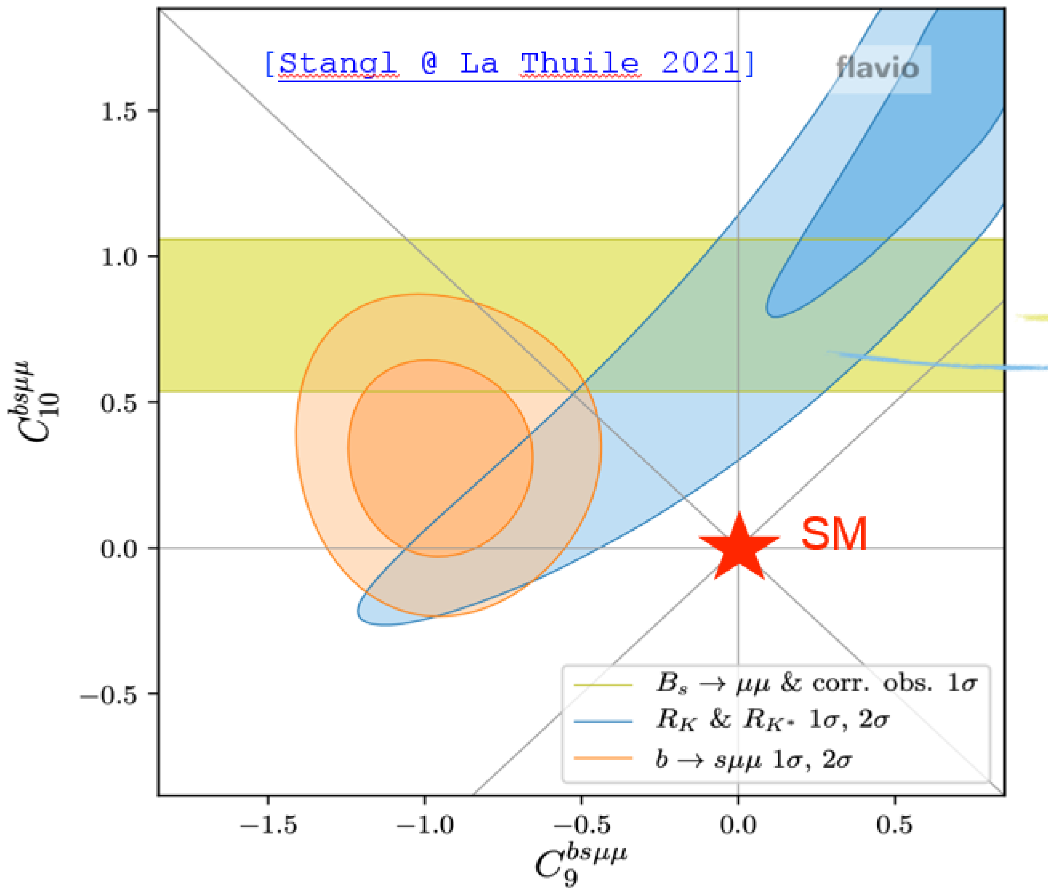
- SM operators for $b \to s\ell^+\ell^-$:

$$\mathcal{O}_9^{(\prime)} = (\bar{s}P_{\mathrm{L(R)}}b)\,(\bar{\ell}\gamma^\mu\ell)$$
$$\mathcal{O}_{10}^{(\prime)} = (\bar{s}P_{\mathrm{L(R)}}b)\,(\bar{\ell}\gamma^\mu\gamma^5\ell)$$

- NP can alter $C_i^{(\prime)}$ but also introduce new operators

$$\Delta\mathcal{H}_{\mathrm{NP}} = \frac{c_i}{\Lambda_{\mathrm{NP}}^2}\mathcal{O}_i$$

Precision measurements go well beyond collision energies



- The latest global fit prefer NP contributions to C_9 and C_{10}
- Input from $B_s^0 \to \mu^+\mu^-$ (here from the latest ATLAS+CMS+LHCb combination)
- And input from R_K and R_{K^*}

Both $B \to \mu\mu$ and R_K SM predictions have robust and very small theory uncertainty

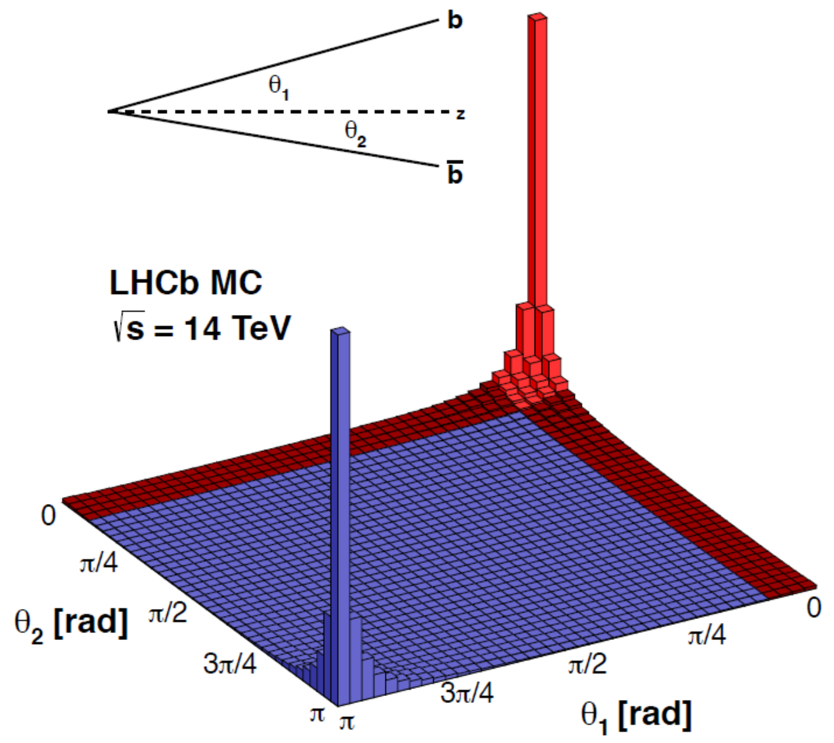
The LHCb data taking

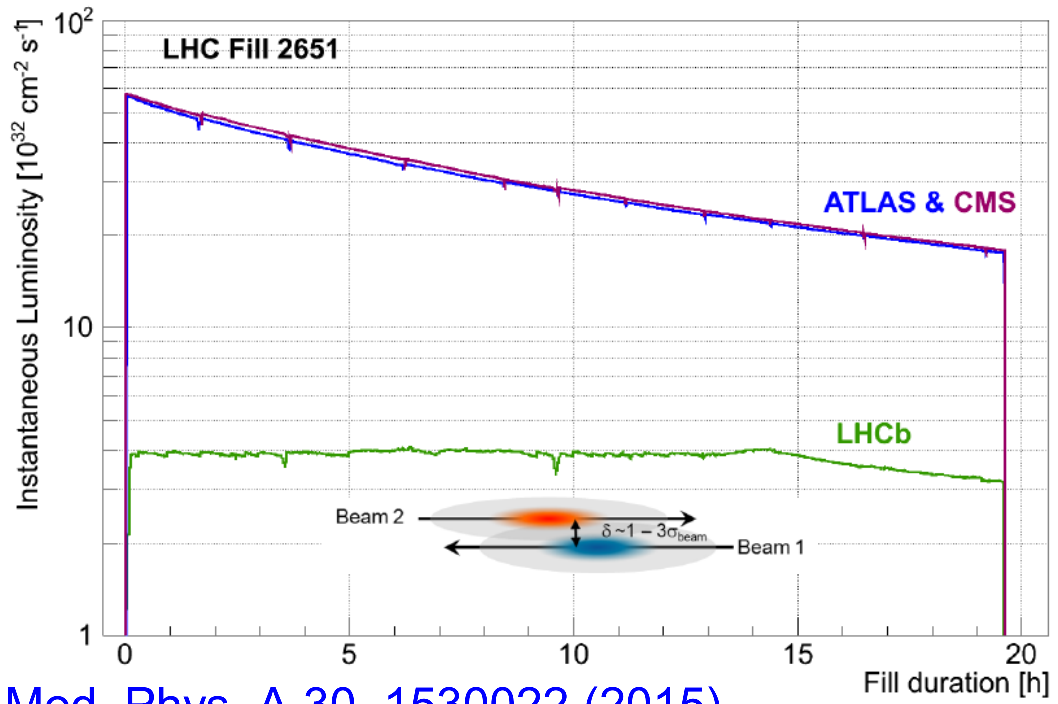
- LHCb exploits the large $pp \to b\bar{b}X$ production cross section in forward direction ($2 < \eta < 5$)

  $\sigma(pp \to b\bar{b}) = 144\ \mu b$ at $\sqrt{s} = 13$ TeV [PRL 118 (2017) 052002]

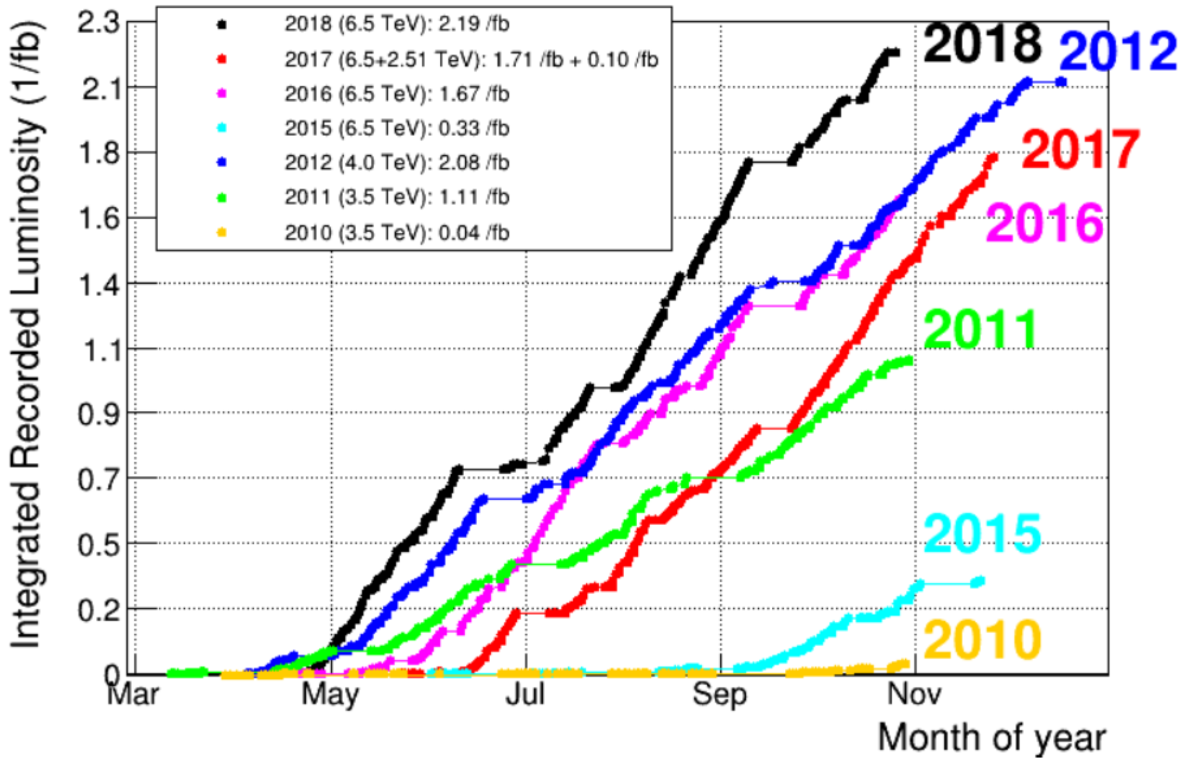
- Run 2 luminosity levelled to $4.4 \times 10^{32}\ cm^{-2}s^{-1}$ (>x2 design value)

- LHCb dataset: $3\ fb^{-1}$ ($\sqrt{s_{Run1}} = 7, 8$ TeV) + $6\ fb^{-1}$ ($\sqrt{s_{Run2}} =$ 13 TeV)

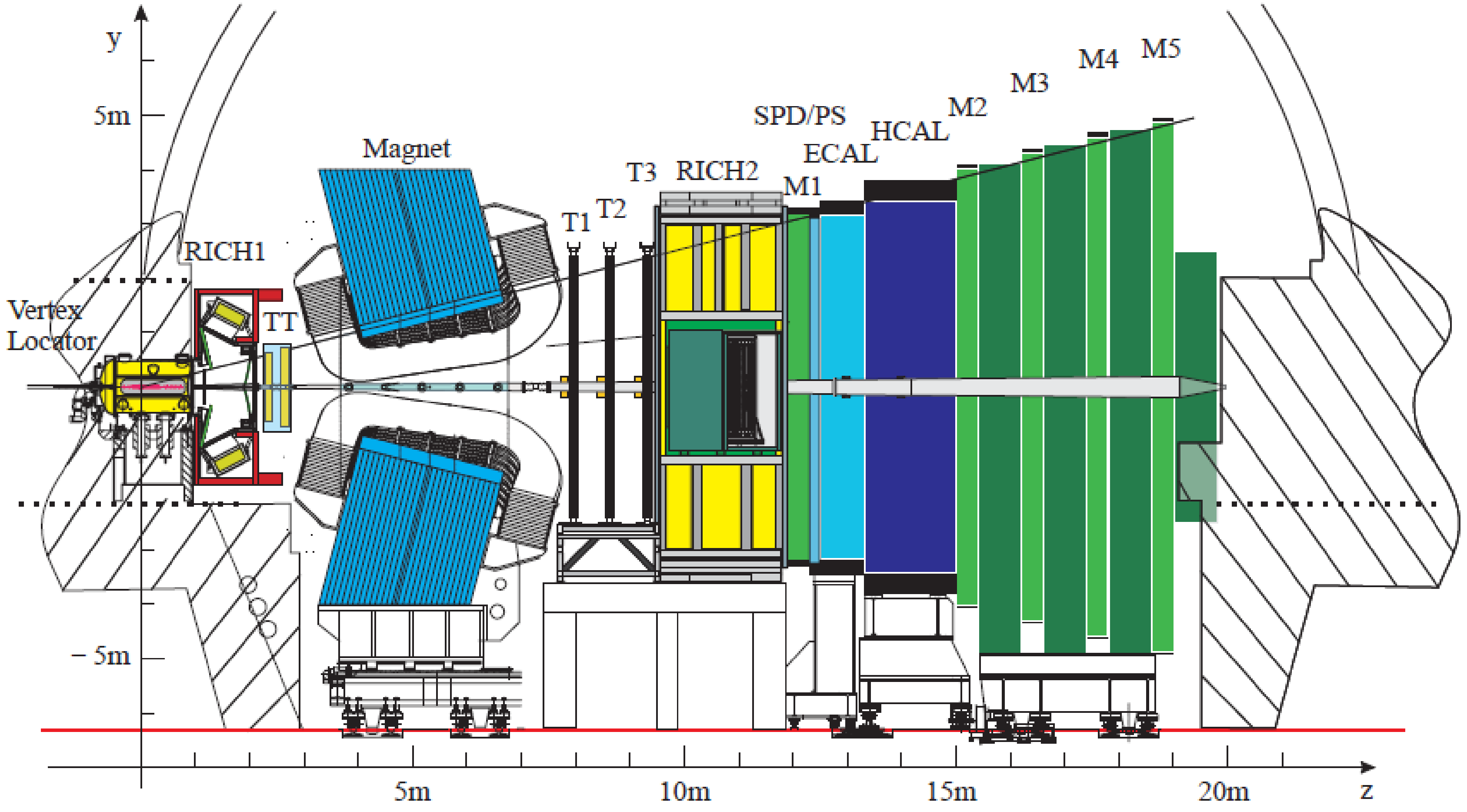




[Int. J. Mod. Phys. A 30, 1530022 (2015)]



The LHCb detector



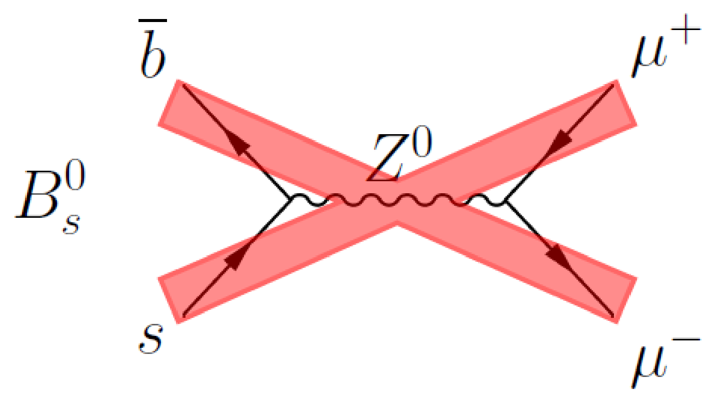
[JINST 3 (2008) S08005](#)

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

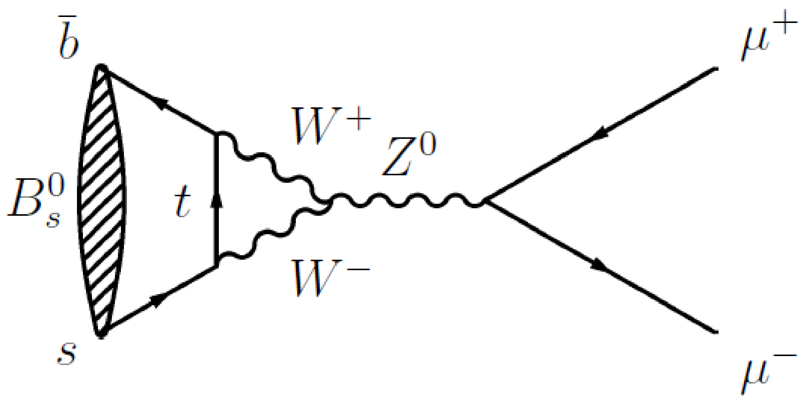
- High vertex resolution (VELO)
  $\sigma_{IP} = 15 + 29/p_T\ \mu m$
- Low momentum muon trigger
  $p_T(\mu) > 1.75\ GeV\ (2018)$
- Good particle identification capabilities (RICH+CALO+MUON)
  $\epsilon_\mu \sim 98\%$ with $\epsilon_{\pi\to\mu} < 1\%$
- Excellent momentum resolution
  $\frac{\sigma p}{p} = 0.5 - 1.0\ \%$ for $p\ in\ [2{,}200] GeV$
  → narrow mass peak

$B \to \mu\mu$ decays in the Standard Model

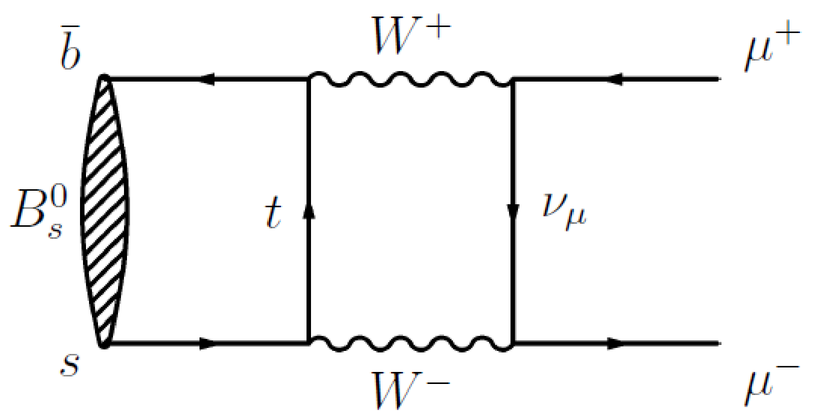
- In the SM, B^0 and B_s^0 decays to two muons are FCNC and helicity suppressed



(tree)



(penguin)



(box)

$$\mathcal{B}(B_q^0 \to \mu^+\mu^-)_{\rm SM} = \frac{\tau_{B_q} G_F^4 M_W^4 \sin^4\theta_W}{8\pi^5} |C_{10}^{\rm SM} V_{tb} V_{tq}^*|^2 f_{B_q}^2 m_{B_q} m_\mu^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_q}^2}} \frac{1}{1-y_q} \qquad q = d, s$$

single Wilson coefficient and single hadronic decay constant (known at 0.5%)

- Very clean prediction of the SM branching fractions

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

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

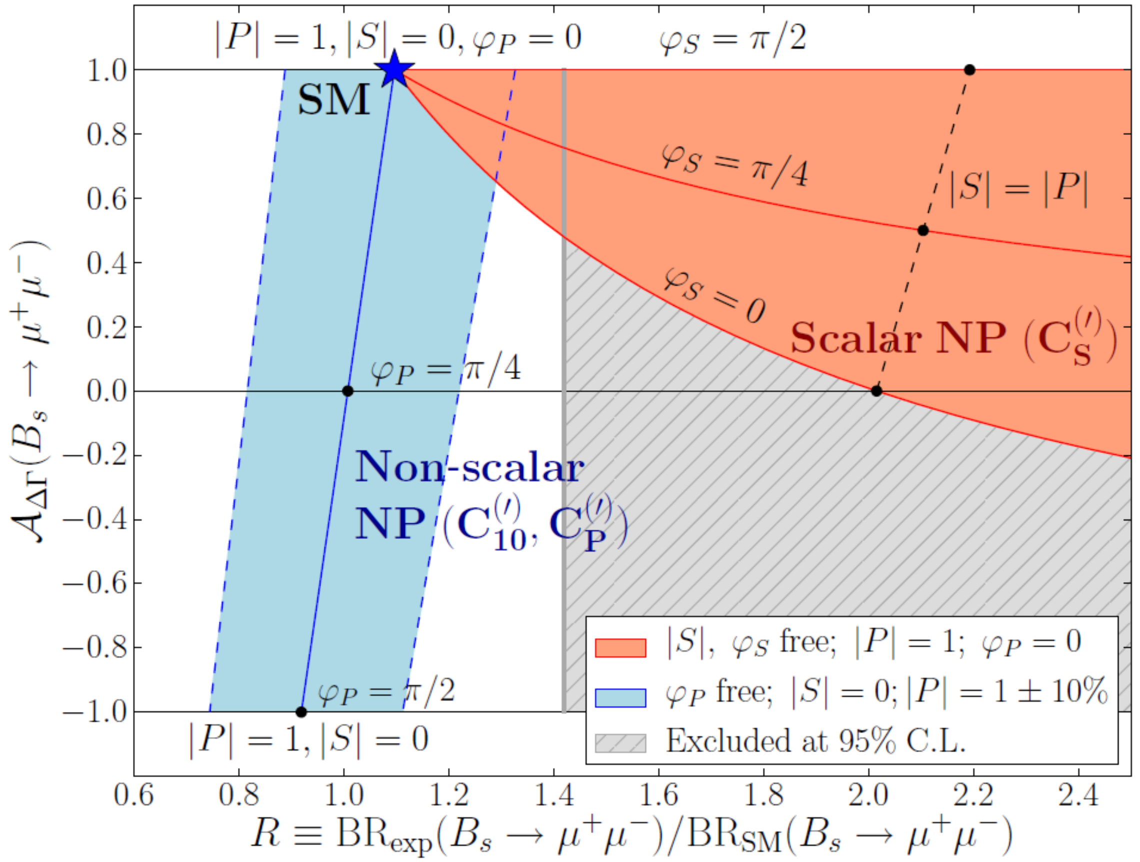
[JHEP 10 (2019) 232]

$B_s^0 \to \mu^+\mu^-$: not only branching fraction

- By measuring the $B_s^0 \to \mu^+\mu^-$ effective lifetime:

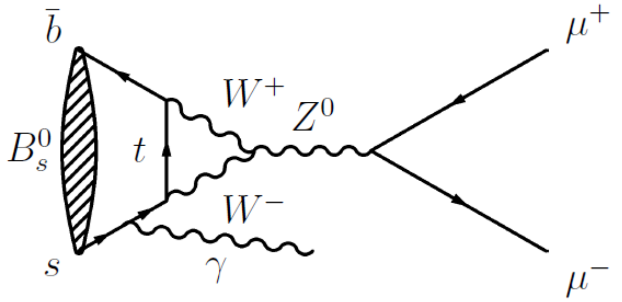
$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s}}{1-y_s^2}\left[\frac{1+2A_{\Delta\Gamma}^{\mu^+\mu^-}y_s+y_s^2}{1+A_{\Delta\Gamma}^{\mu^+\mu^-}y_s}\right] \qquad A_{\Delta\Gamma}^{\mu^+\mu^-} \equiv \frac{R_H^{\mu^+\mu^-}-R_L^{\mu^+\mu^-}}{R_H^{\mu^+\mu^-}+R_L^{\mu^+\mu^-}} \qquad y_s = \frac{\Delta\Gamma_s}{2\Gamma_s}$$

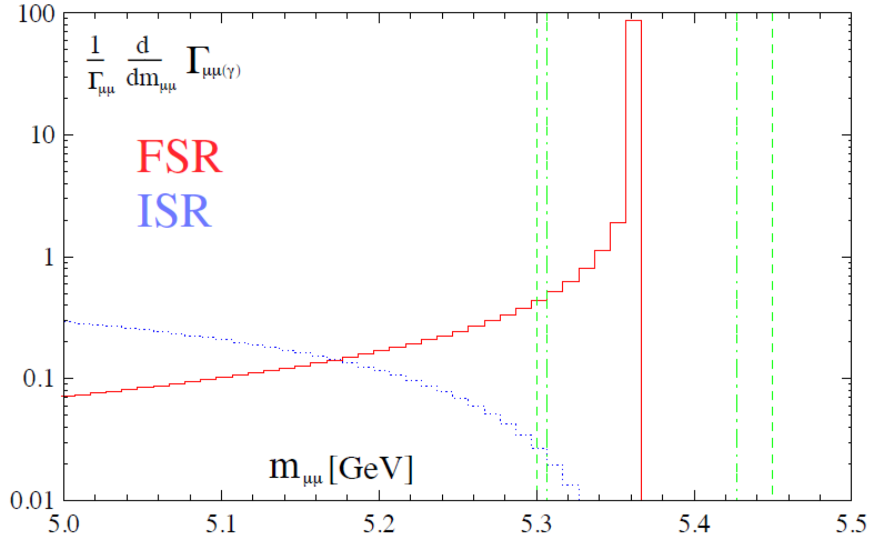
  we can extract the asymmetry $A_{\Delta\Gamma}^{\mu^+\mu^-}$ (=1 in SM)
  Clean observable → additional NP constraint



[PRL 109 (2012) 041801]

- Sensitivity to $B_s^0 \to \mu^+\mu^-\gamma$ (ISR) at high $m_{\mu\mu}$: new observable included in this analysis





[PRL 112 (2014) 101801]

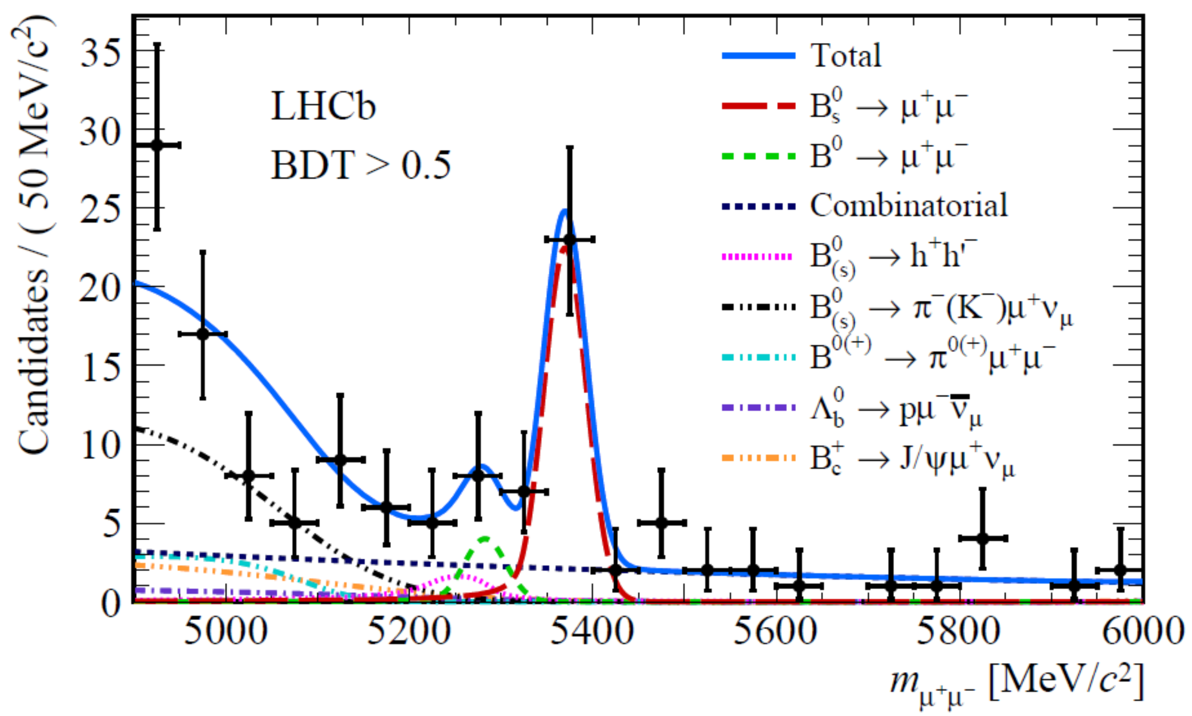
- SM prediction at $O(10^{-10})$ for $m_{\mu\mu} > 4.9\ GeV/c^2$
  [JHEP 11 (2017) 184] [PRD97 (2018) 053007]

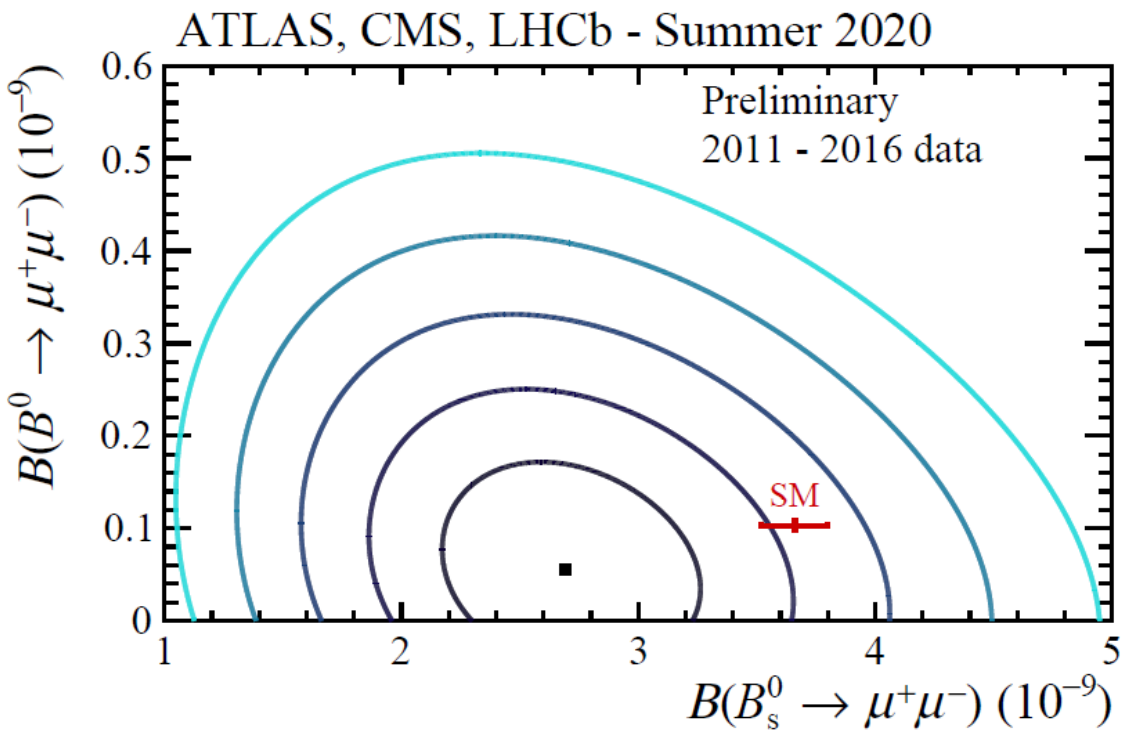
- Bremsstrahlung (FSR) experimentally included in $BF(B_s^0 \to \mu\mu)$ via PHOTOS

Experimental status of $B \to \mu\mu$ measurements

PRL 118 (2017) 191801

- 2015: First observation of Bs->mumu with LHCb and CMS Run 1 data
- 2017: First single-experiment observation by LHCb with Run 1 + 2015/16 data
- 2020: ATLAS+CMS+LHCb combination using Run 1 + 2015+2016 data





- $BF(B_S^0 \to \mu^+\mu^-) = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$
- $\tau(Bs \to \mu^+\mu^-) = 1.91^{+0.37}_{-0.35}\, ps$
- $BF(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-9}$ @ 95% CL

LHCb-CONF-2020-002

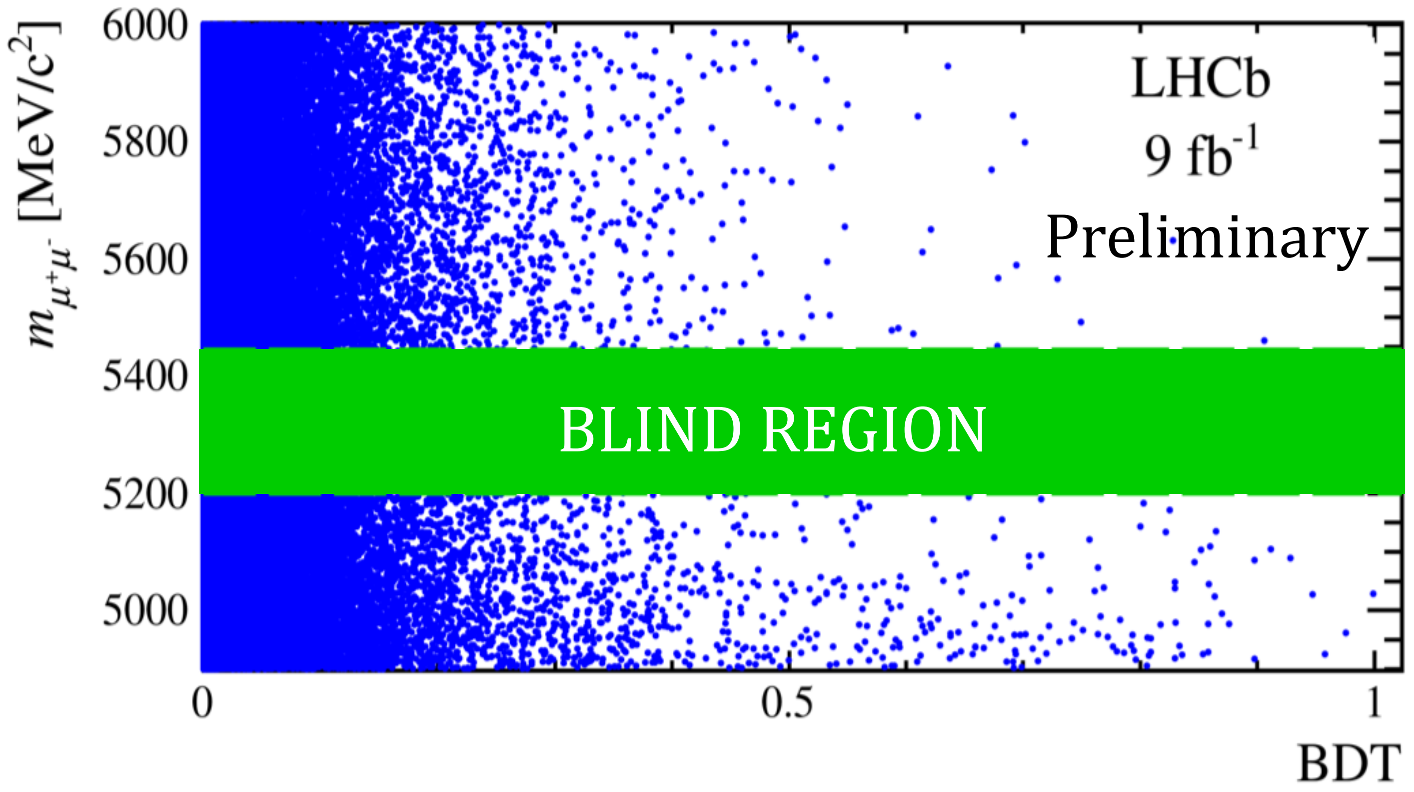
$B \to \mu\mu$ analysis strategy

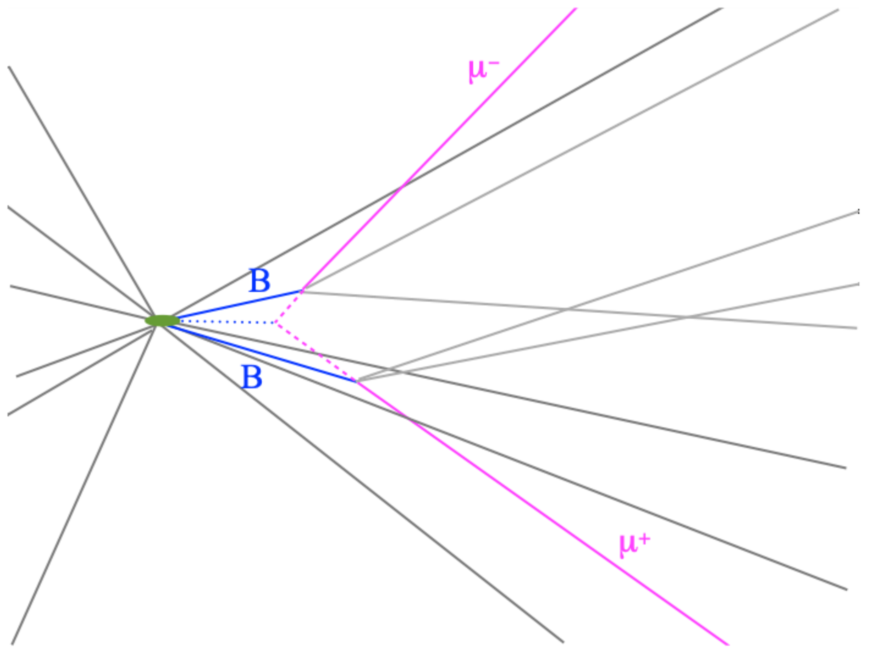
[LHCb-PAPER-2021-007]

- This is the "legacy measurement" of LHCb on the full Run 1 + Run 2 data (9 fb^{-1})
- The strategy is well established since 2017 but introduces several improvements

- Select muon pairs with $m_{\mu^+\mu^-} \in [4900{,}6000]\,MeV$ forming a displaced vertex
- Signal mass region is blinded until the analysis is finalised
- **The BFs are extracted through a fit to $m_{\mu^+\mu^-}$**

- The selected dataset is dominated by combinatorial background
- To reject it we use a multivariate classifier "BDT" (Boosted Decision Tree)
- The algorithm primarily exploits track isolation and vertex properties

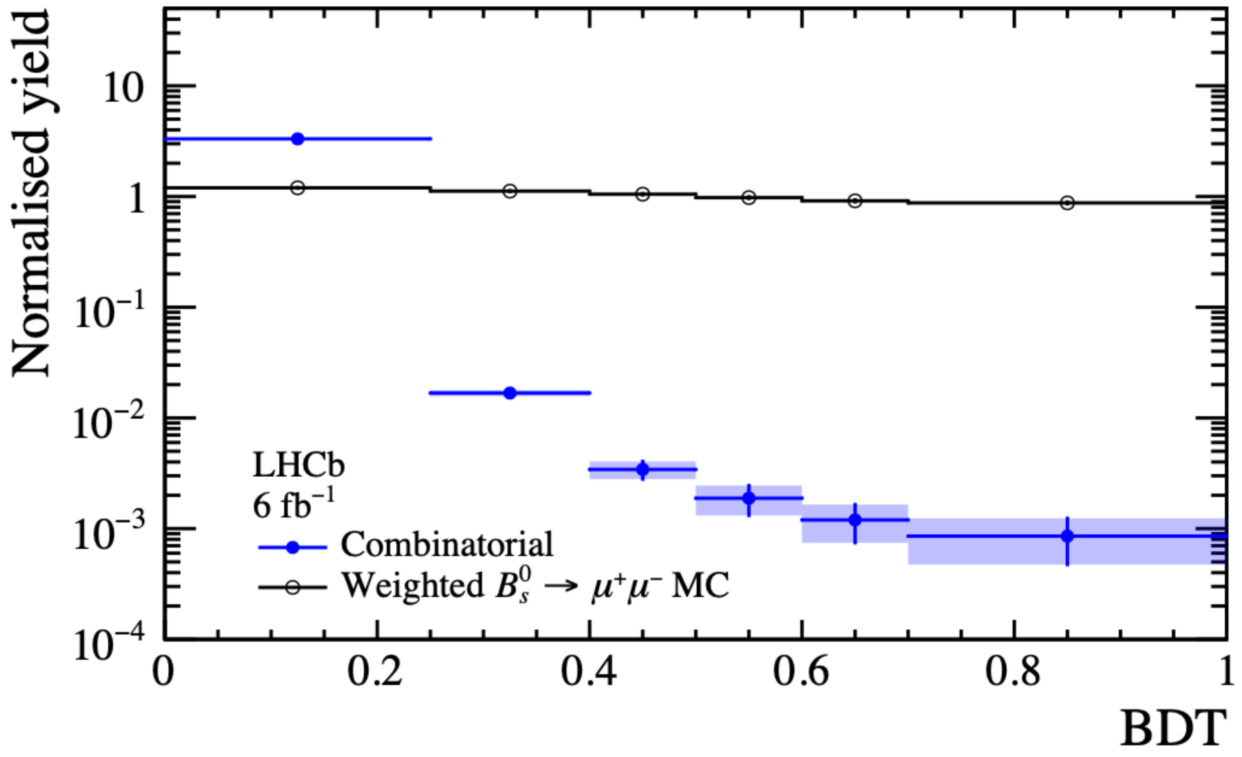




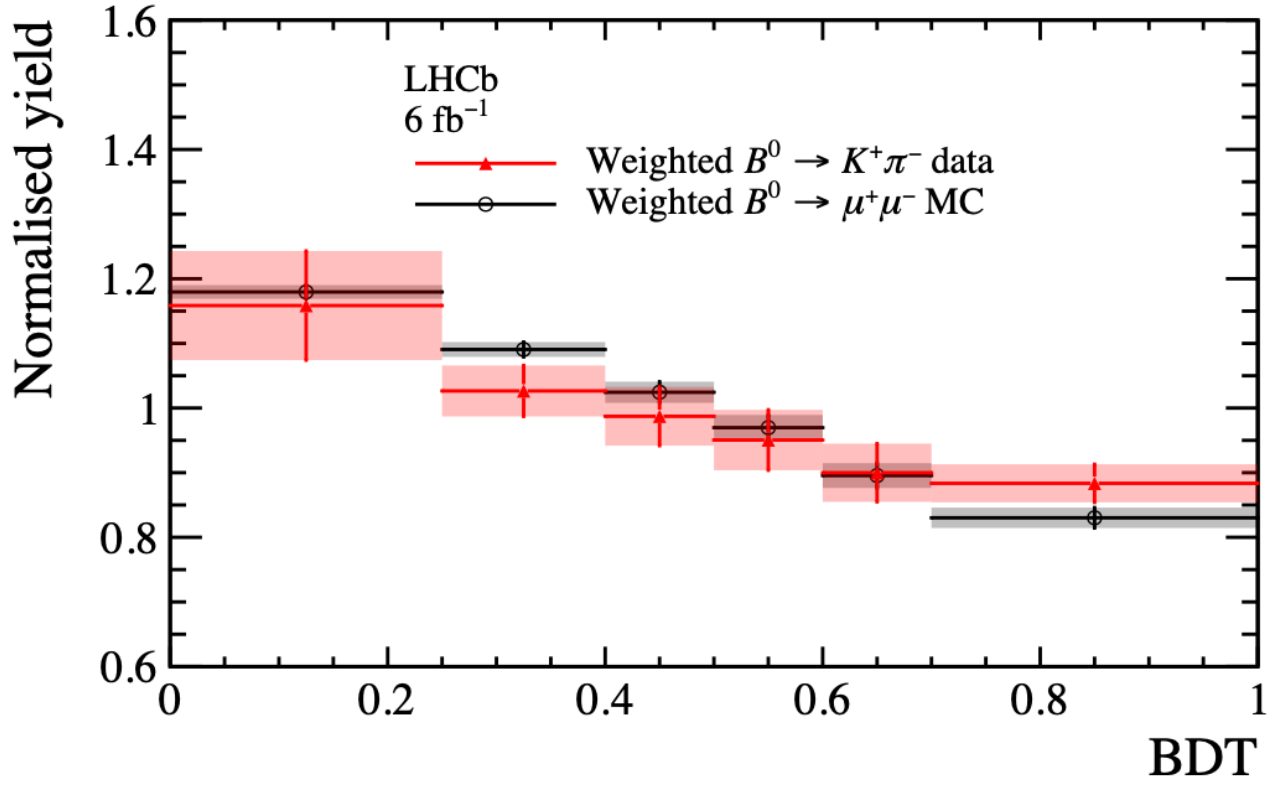
BDT calibration

[LHCb-PAPER-2021-007]

- BDT flat for signal BDT and decreasing for combinatorial bkg. Events are categorised into 6 "BDT bins".
- We measure the branching fractions with a simultaneous mass fit in 10 categories (2 Runs X 5 BDT bins)
- (The first bin [0,0.25] is excluded since it's background-dominated)



- The signal BDT output is calibrated on data-corrected simulation
- Cross-checked on $B^0 \to K^+\pi^-$ data
- Shape corrected for PID and trigger efficiencies
- BDT-lifetime correlations accounted for in the $B_s^0 \to \mu^+\mu^-(\gamma)$ signals

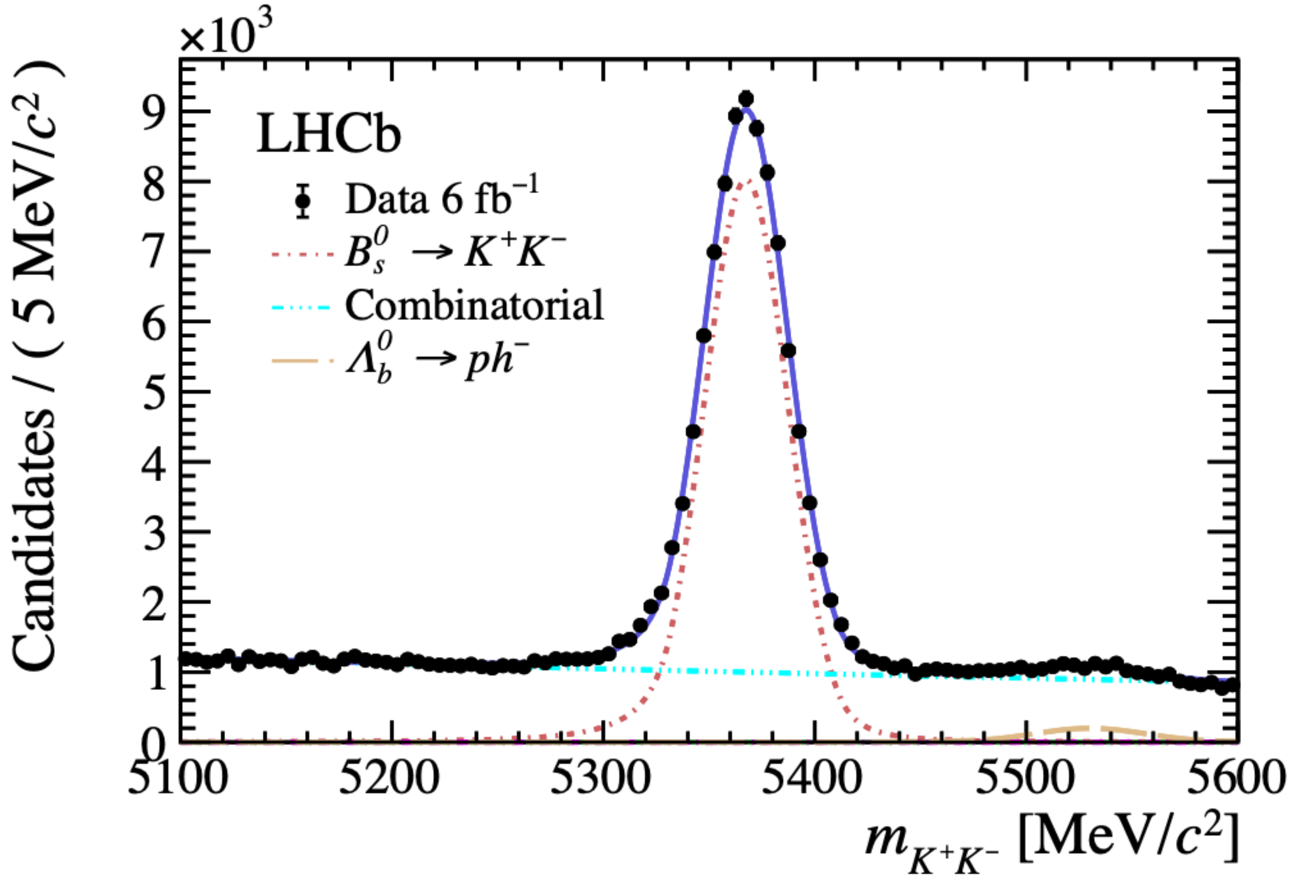


Mass shape calibration

[LHCb-PAPER-2021-007]

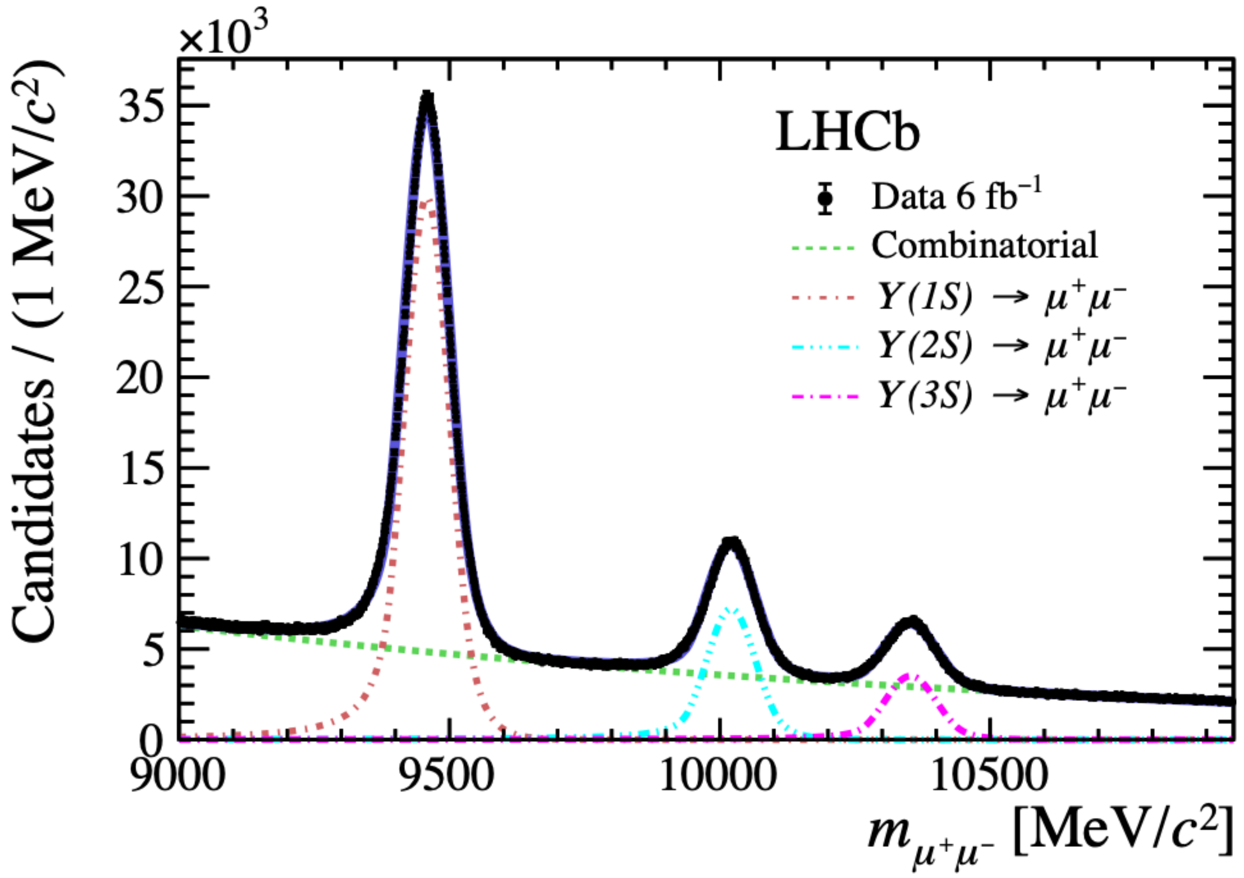
- The $B^0_{(s)} \to \mu^+\mu^-$ mean and resolution values are measured on data

- The mean is obtained from $B^0 \to K^+\pi^-$ and $B^0_s \to K^+K^-$ data for $B^0 \to \mu^+\mu^-$ and $B^0_s \to \mu^+\mu^-$



- The resolution is interpolated from mass fits to $c\bar{c}$ and $b\bar{b}$ resonances:

$$\sigma_{m(\mu^+\mu^-)} = 21.96 \pm 0.63\text{MeV (Run2)}$$



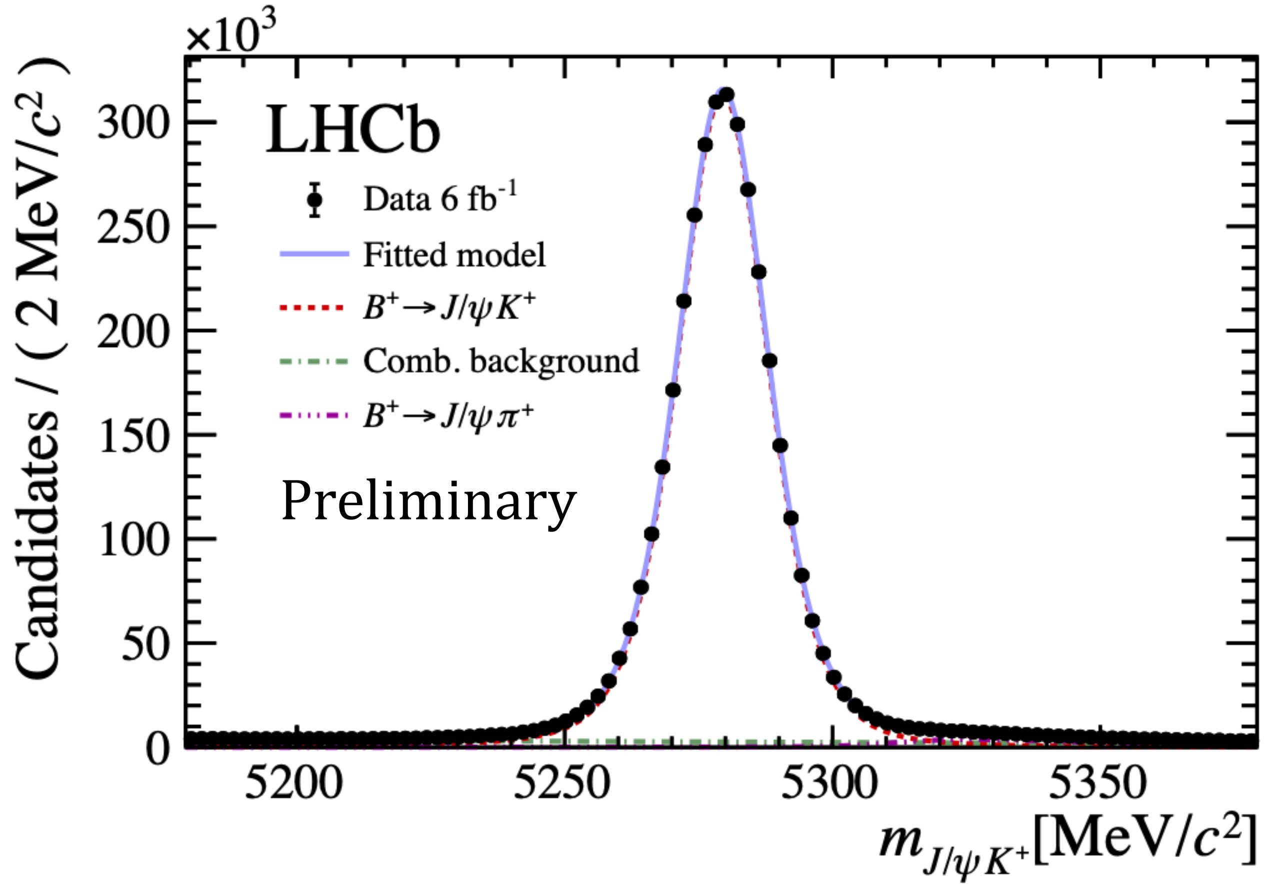
Normalisation of signal yield: mass fit

[LHCb-PAPER-2021-007]

- To measure the branching fraction, luminosity and cross-section uncertainties are avoided by computing the ratio to a well-known channel
- Two normalisation channels are employed: perform mass fits to compute the yields

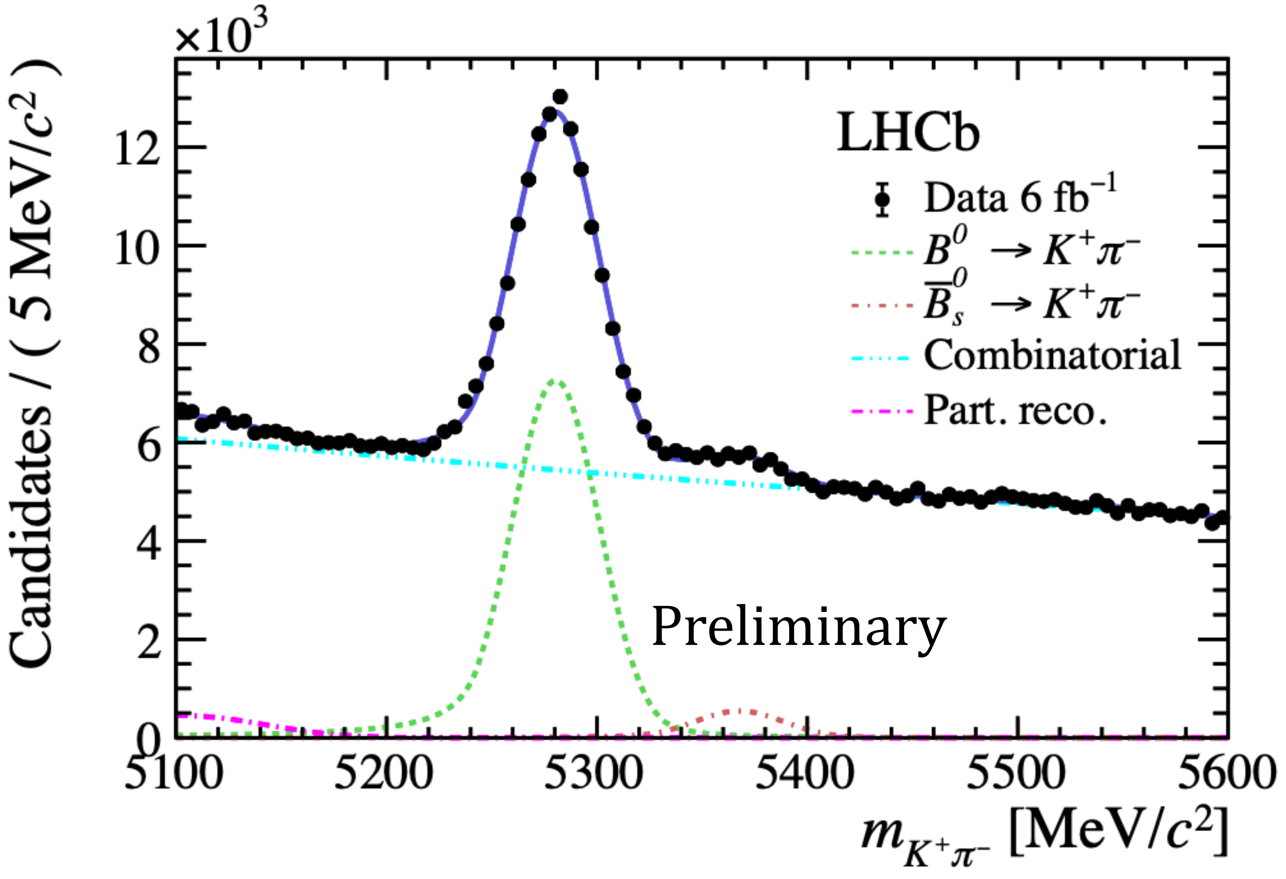
1. $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$

Two muons in the final state → similar trigger and reconstruction



2. $B^0 \to K^+\pi^-$

Two-body B decay → same signal topology



Normalisation of signal yield: results

- The observed signal yield is converted into a BF according to:

$$\mathcal{B}(B^0_{d,s} \to \mu^+\mu^-) = \overbrace{\underbrace{\frac{\mathcal{B}_{norm}}{N_{norm}} \times \frac{\epsilon_{norm}}{\epsilon_{sig}}}_{\alpha_d} \times \frac{f_{norm}}{f_{d,s}}}^{\alpha_s} \times N_{B^0_{d,s}\to\mu^+\mu^-}$$

- BF and yield of the normalisation channel
- Signal/normalisation efficiency ratio
- Ratio of hadronisation fraction (for the B^0_s)

Very recent LHCb combination $f_s/f_d(7\text{TeV}) = 0.239 \pm 0.008$, $f_s/f_d(13\text{TeV}) = 0.254 \pm 0.008$

- Combining the two normalisation channels we obtain the following "single-event sensitivities" :

$$\alpha_{B^0_s\to\mu^+\mu^-} = (2.49 \pm 0.09) \times 10^{-11}$$

$$\alpha_{B^0\to\mu^+\mu^-} = (6.52 \pm 0.11) \times 10^{-12}$$

$$\alpha_{B^0_s\to\mu^+\mu^-\gamma} = (2.98 \pm 0.11) \times 10^{-11}$$

- Assuming SM signals we expect:

$$N(B^0_s \to \mu^+\mu^-)_{SM} = 147 \pm 8$$

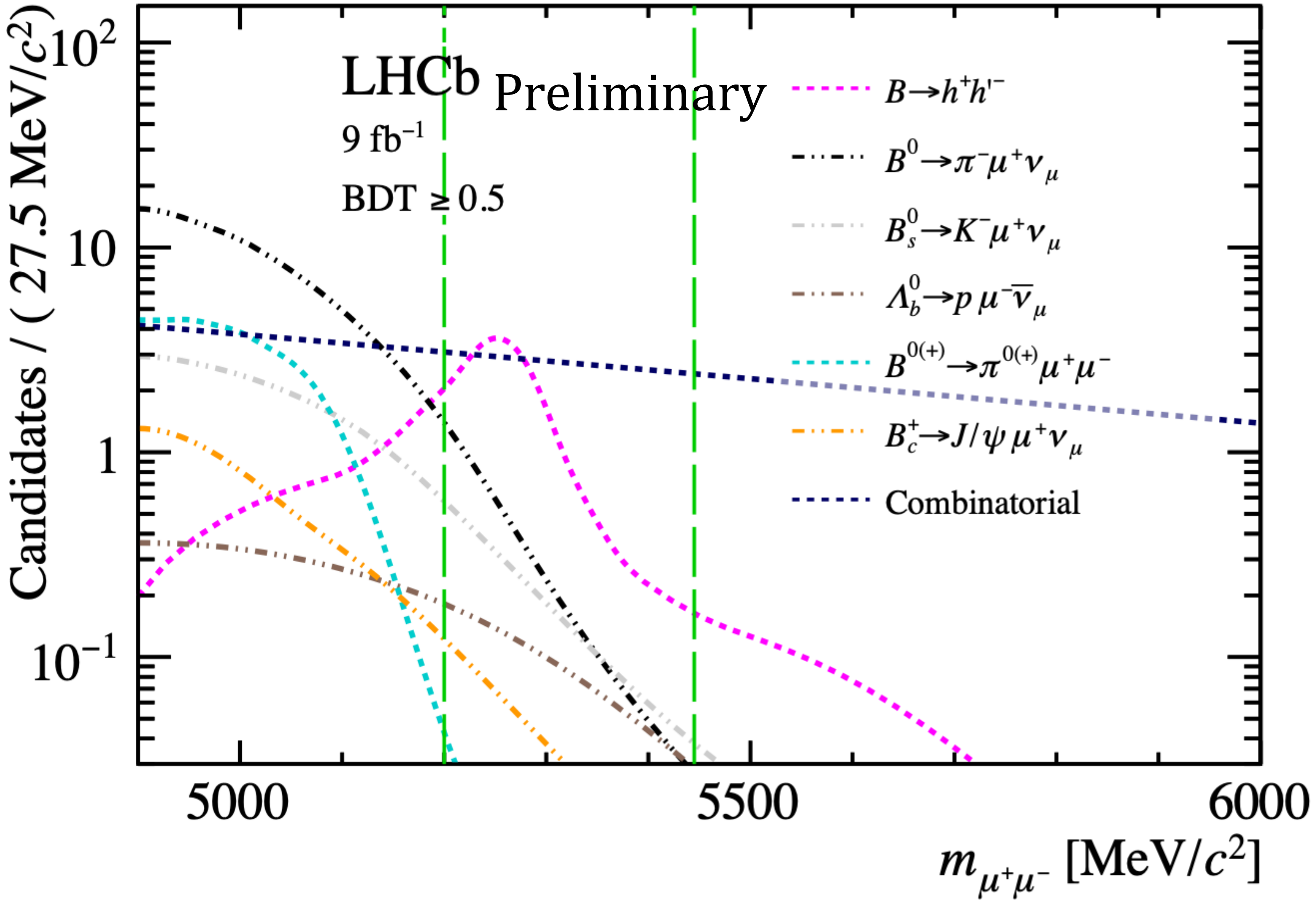
$$N(B^0 \to \mu^+\mu^-)_{SM} = 16 \pm 1$$

$$N(B^0_s \to \mu^+\mu^-\gamma)_{SM} \approx 3$$

Backgrounds

After applying a strong PID cut on both muons, three classes of backgrounds remain:

1. Combinatorial, over the full mass spectrum (floating component)
2. Semileptonic backgrounds (partially reconstructed) populating the left mass sideband
3. $B^0_{(s)} \to h^+ h^{-\prime -} \to \mu^+\mu^-$ doubly misidentified background, peaking in $B^0 \to \mu^+\mu^-$ mass region



Semileptonic backgrounds

- Channels with one misidentified hadron: $B^0 \to \pi^- \mu^+ \nu_\mu$, $B_S^0 \to K^- \mu^+ \nu_\mu$ and $\Lambda_b \to p \mu^- \overline{\nu_\mu}$
- Channels with two muons in the final state: $B^{+(0)} \to \pi^{+(0)} \mu^+ \mu^-$ and $B_c^+ \to J/\psi(\mu^+ \mu^-) \mu^+ \nu_\mu$
- Each source is estimated by normalising to the $B^+ \to J/\psi K^+$ channel:

$$N_x = N_{B+\to J/\psi K+} \frac{f_x}{f_d} \frac{\mathcal{B}_x}{\mathcal{B}_{B+\to J/\psi K+}} \frac{\epsilon_x^{Tot}}{\epsilon_{B+\to J/\psi K+}^{Tot}}$$

- Efficiency- and BF-corrected $B^+ \to J/\psi K^+$ yield
- Branching fraction and hadronisation fraction for background mode X
- Total background efficiency

- Estimated background events in the high BDT region (BDT≥ 0.5):

$B^0 \to \pi^- \mu^+ \nu_\mu$	91 ± 4
$B_s^0 \to K^- \mu^+ \nu_\mu$	23 ± 3
$\Lambda_b^0 \to p \mu^- \overline{\nu}_\mu$	4 ± 2
$B^{+(0)} \to \pi^{+(0)} \mu^+ \mu^-$	26 ± 3
$B_c^+ \to J/\psi(\mu^+ \mu^-) \mu^+ \nu_\mu$	7.2 ± 0.3

Inputs mostly from LHCb:

PDG

PRL 126 (2021) 081804 LHCb

Nature Physics 10 (2015) 1038 LHCb

JHEP 10 (2015) 034 LHCb

PRD 86 (2012) 114025

PRD 100 (2019) 112006 LHCb

$B^0_{(s)} \to h^+ h'^- \to \mu^+\mu^-$ background

- B decays to two hadrons (π, K) form a peaking background when both final-state particles are misidentified as muons
- This contribution is estimated by normalising to $B^0 \to K^-\pi^+$ events:

$$N_{B\to hh\to\mu\mu} = \frac{N_{B^0\to K^+\pi^-}}{\epsilon^{\text{trig}}_{B^0\to K^+\pi^-}} \times \frac{1}{f_{B^0\to K^+\pi^-/B\to hh}} \times \epsilon^{\text{trig}}_{B^0\to\mu^+\mu^-} \times \epsilon_{hh\to\mu\mu}$$

- Efficiency corrected $B^0 \to K^+\pi^-$ yield
- $B^0 \to K^+\pi^-$ contribution within the total $B^0_{(s)} \to h^+h'^-$ PDG
- Trigger efficiency and double misidentification rate (from data)

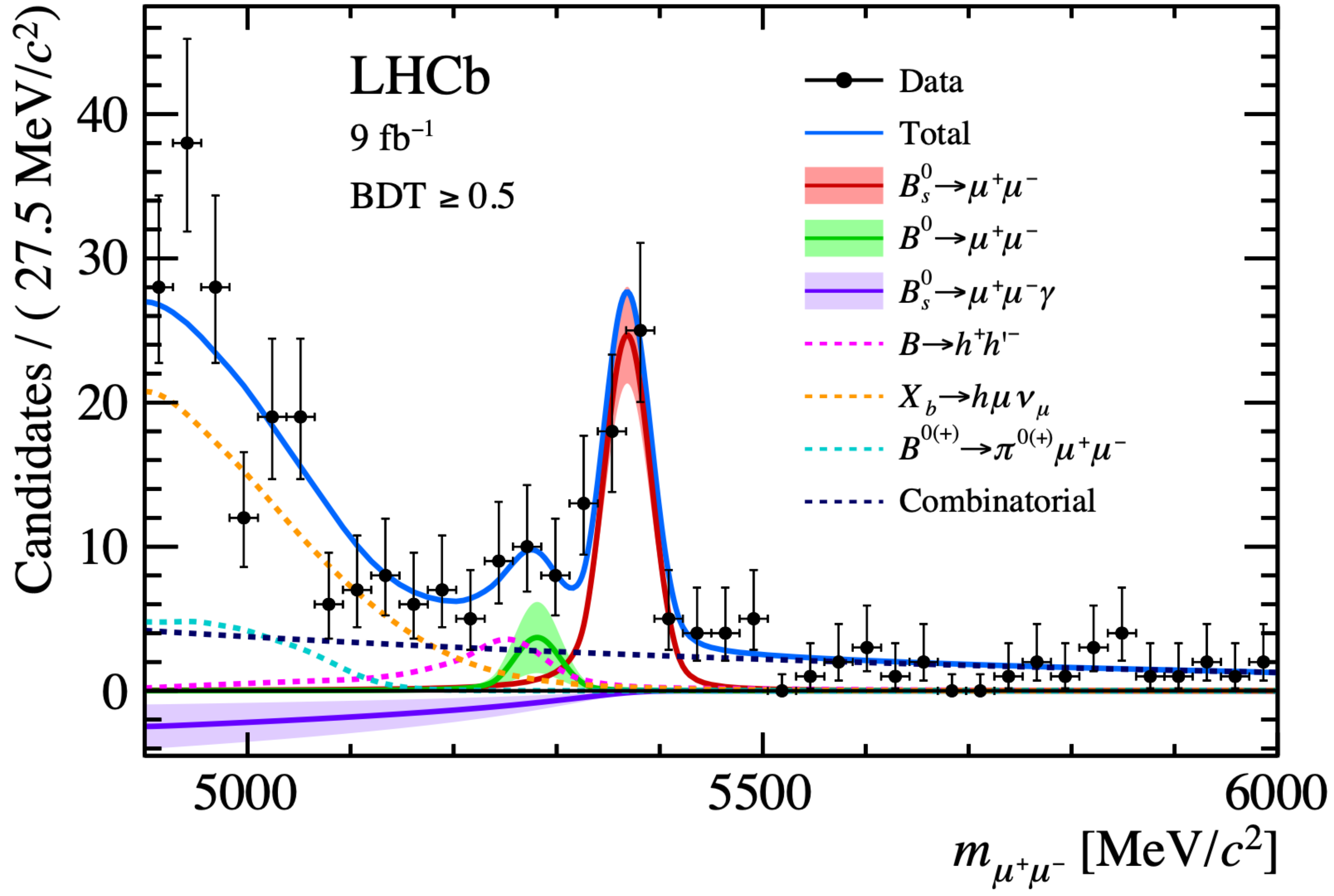
- Each $B \to hh$ channel is weighted according to its expectation to make the total $B^0_{(s)} \to h^+h'^- \to \mu^+\mu^-$
- An alternative estimate is performed on $h\mu$ data (single misidentification) to cross check the result

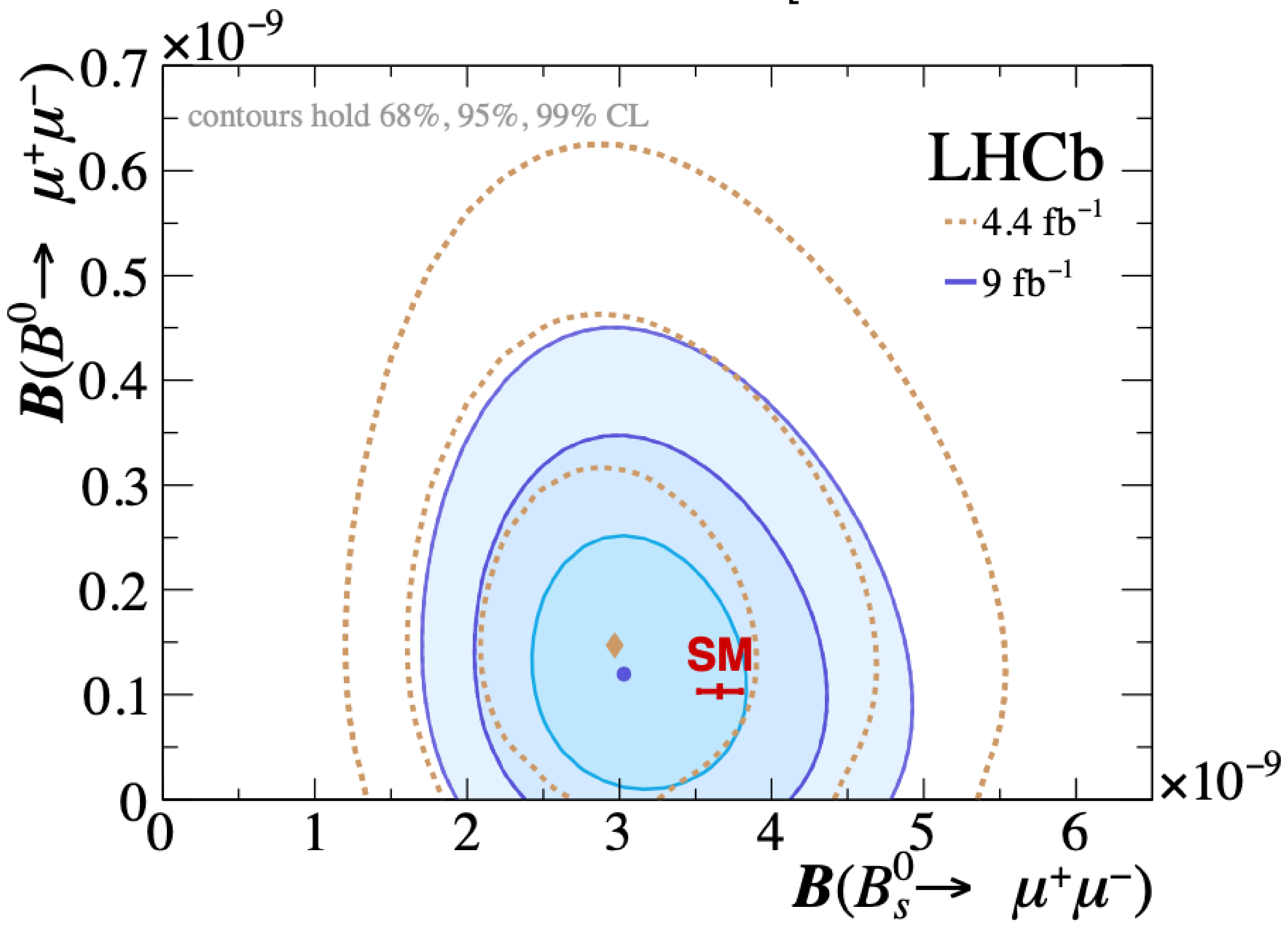
  - Estimated background events in the high BDT region $(\text{BDT} \geq 0.5)$:

$$B^0_{(s)} \to h^+h^{-\prime-} \to \mu^+\mu^-: 22 \pm 1$$

Branching fraction measurements

[LHCb-PAPER-2021-007]





$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.09^{+0.46}_{-0.43}\,(stat)^{+0.15}_{-0.11}\,(sys)\right) \times 10^{-9}\ (10.8\sigma)$$

- $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\gamma$ compatible with 0 signal hypothesis at 1.7σ and 1.5σ

  $\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}$ (95%CL)

  $\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{m_{\mu^+\mu^-}>4.9\text{GeV}} < 2.0 \times 10^{-9}$ (95%CL)

Limits with the CLs method
[J. Phys. G28 (2002) 2693]

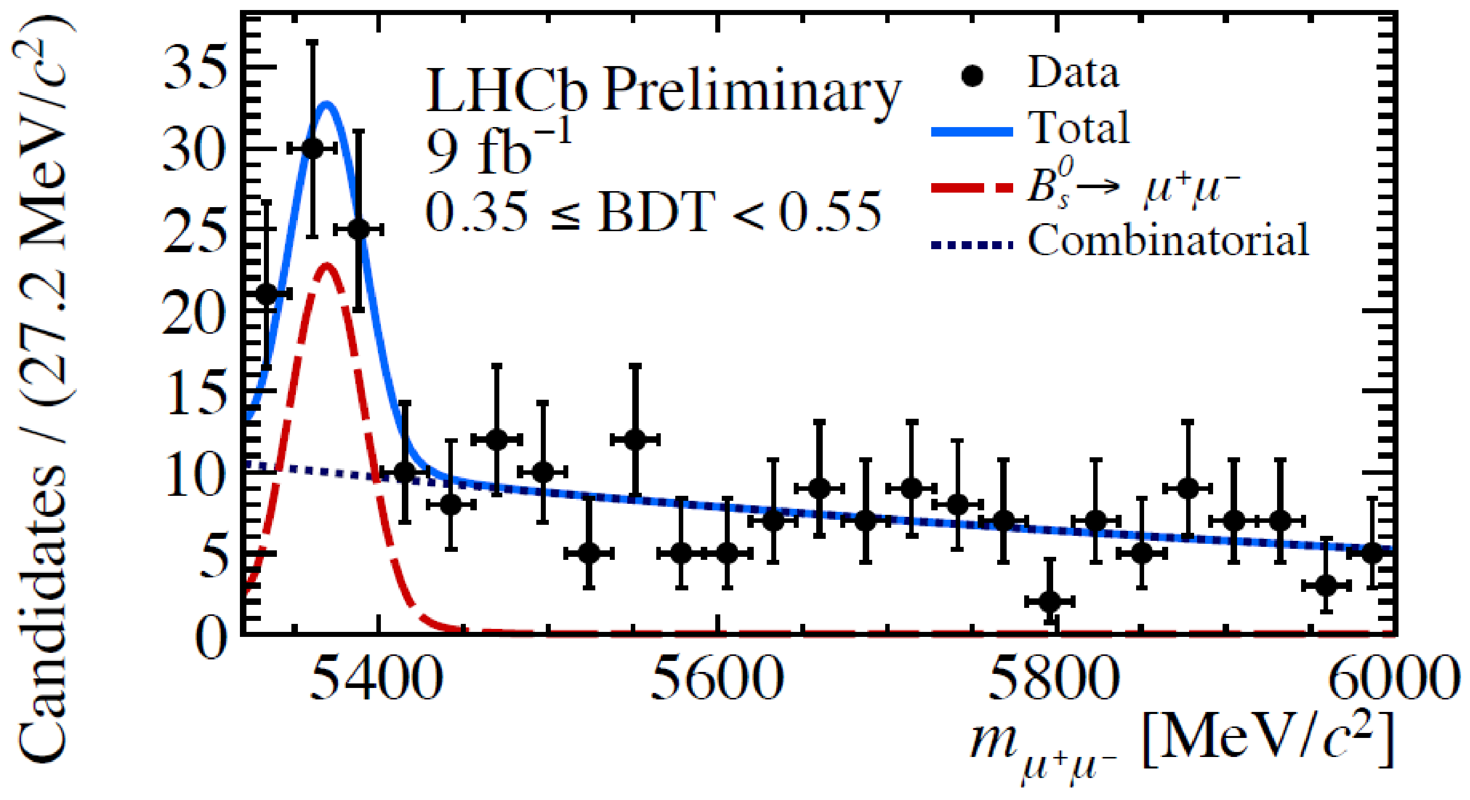
$B_s^0 \to \mu^+\mu^-$ effective lifetime: measurement

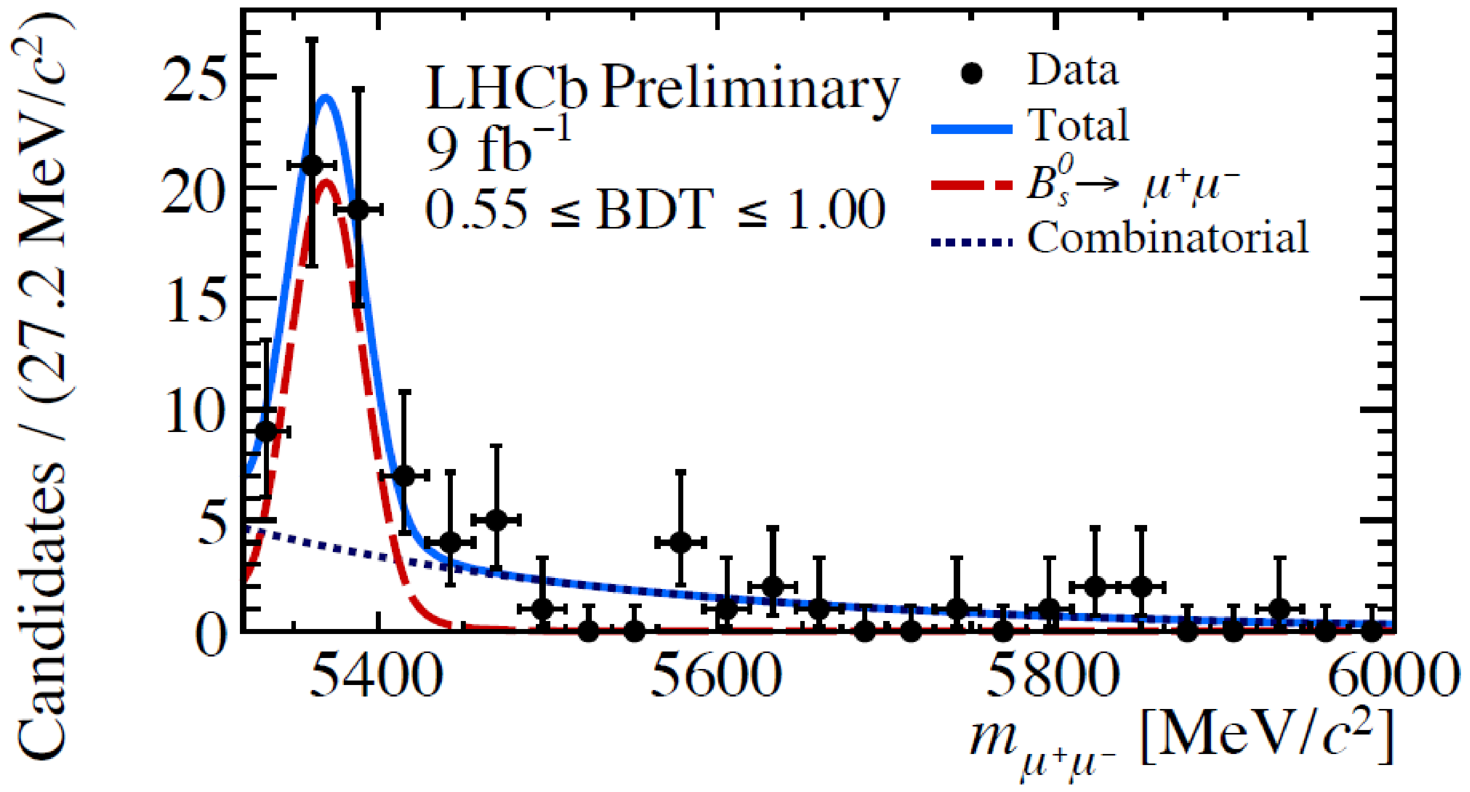
[LHCb-PAPER-2021-007]

Since the expected sensitivity on $A_{\Delta\Gamma}^{\mu^+\mu^-}$ is low, the effective lifetime measurement introduces some simplifications wrt the BF measurement:

- Tighter mass cut, $m_{\mu^+\mu^-} > 5320\text{MeV}$: mass fit model with $B_s^0 \to \mu^+\mu^-$ signal + combinatorial
- Looser PID requirement (no misidentified backgrounds)
- 1. Mass fit on two BDT bins is performed to extract sWeights

[NIM A555 (2005) 356-369]

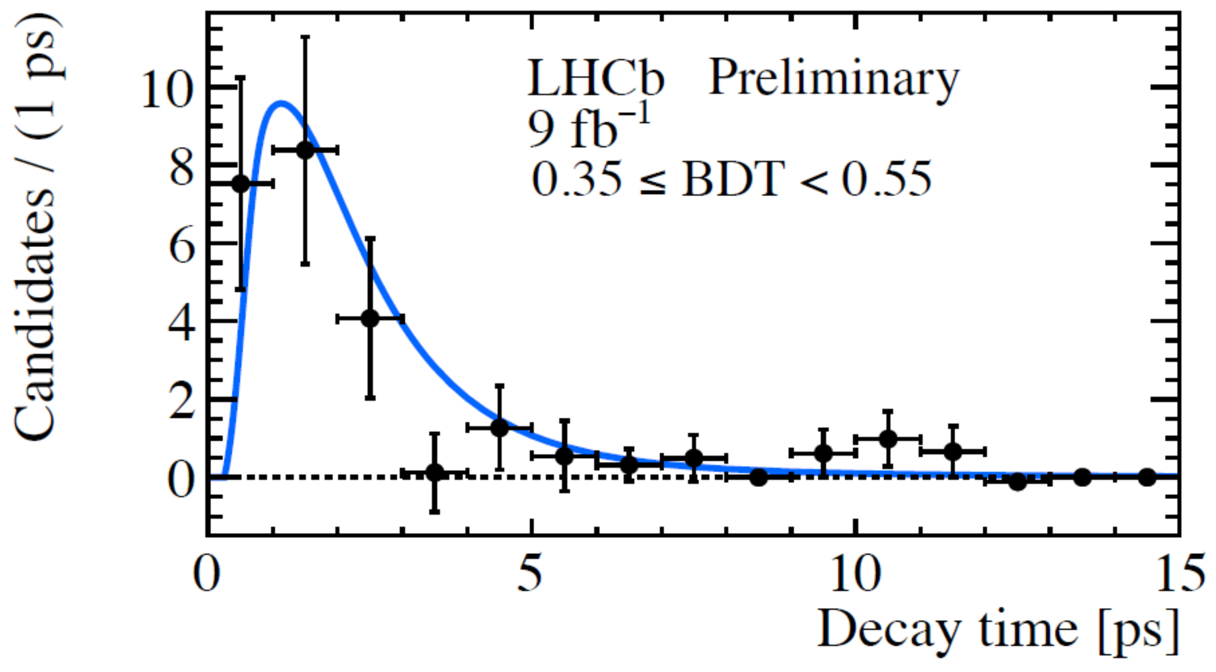


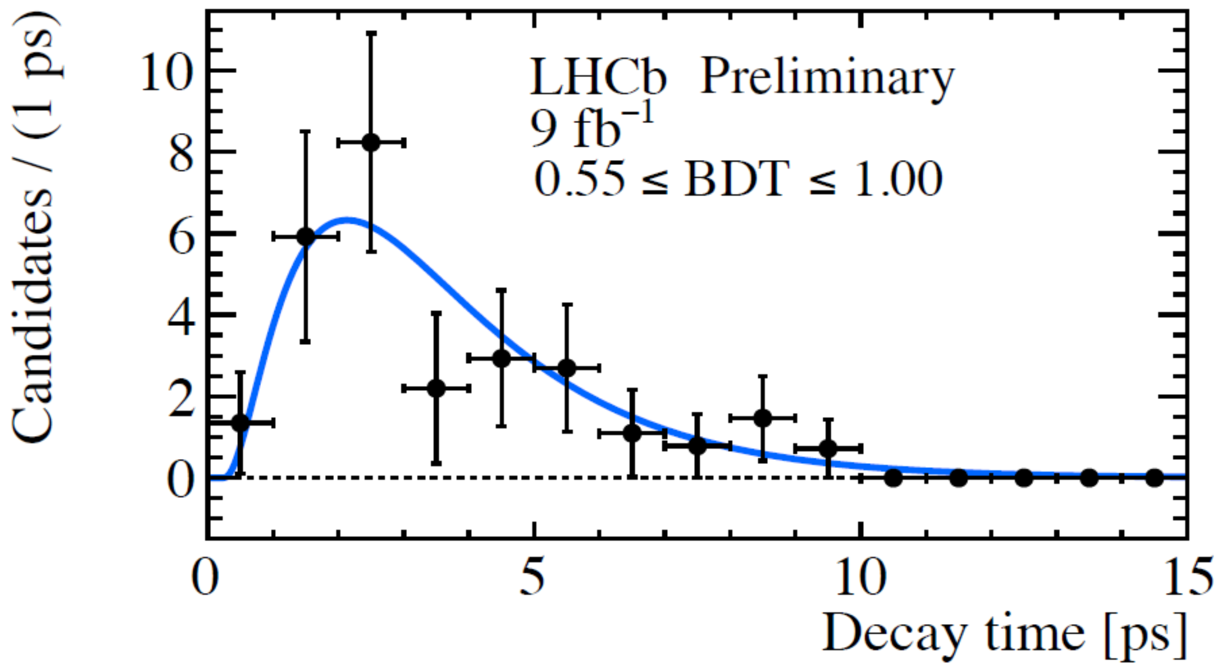


$B_s^0 \to \mu^+\mu^-$ effective lifetime: results

[LHCb-PAPER-2021-007]

- 2. The sWeights are applied to obtain the background-subtracted decay time distribution
- which is then fitted with an exponential × acceptance function





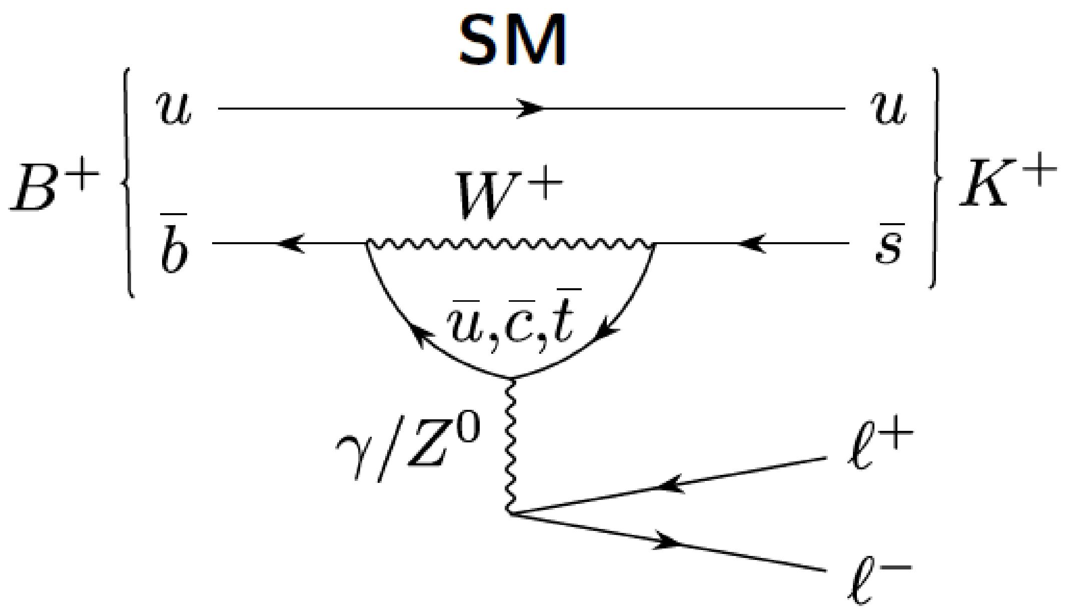
- The acceptance function (efficiency vs decay time) is tested by measuring the known $B^0 \to K^+\pi^-$ and $B_s^0 \to K^+K^-$ effective lifetimes

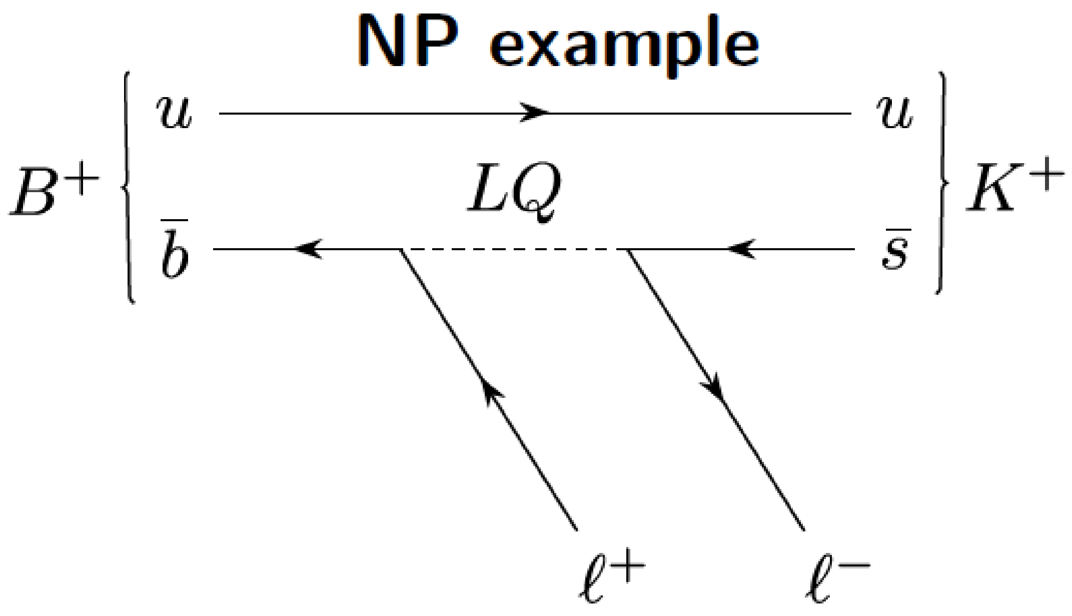
$$\tau_{\mu^+\mu^-} = 2.07 \pm 0.29 \pm 0.03\text{ps}$$

- Result compatible at 1.5σ with $A_{\Delta\Gamma}^{\mu^+\mu^-} = 1$ (SM, $\tau_{\mu\mu} \sim 1.6\, ps$) and at 2.2σ with $A_{\Delta\Gamma}^{\mu^+\mu^-} = -1$ ($\tau_{\mu\mu} \sim 1.4\, ps$)
- Run 3 data are needed to say more

$B^+ \to K^+ l^+ l^-$ and related decays

- They occur through $b \to s l^+ l^-$ transitions but, in contrast to $B_s^0 \to l^+ l^-$ decays, they contain a hadron in the final state





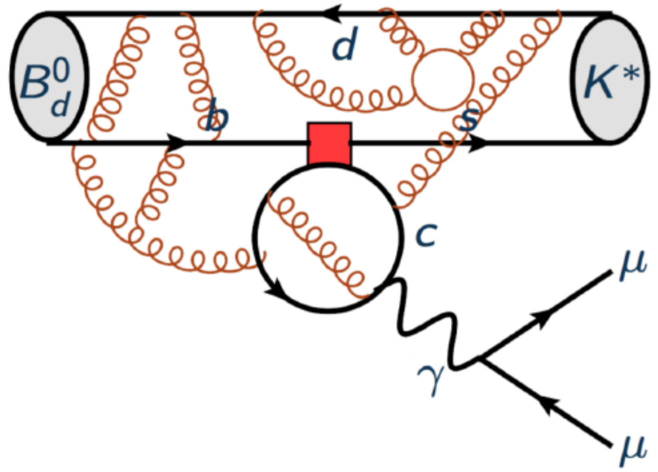
- They offer multitude of observables complementary to $B_{(s)}^0 \to l^+ l^-$ measurements

Flavour anomalies in $b \to s l^+ l^-$ transitions

- Over the past decade we have observed a coherent set of tensions with the SM predictions

- In $b \to s l^+ l^-$ transitions (FCNC)
  - **Branching fractions**
    $B \to K^{(*)}\mu^+\mu^-, B_s \to \phi\mu^+\mu^-, \Lambda_b \to \Lambda\mu^+\mu^-$
  - **Angular analyses**
    $B \to K^{(*)}\mu^+\mu^-$ $\Lambda_b \to \Lambda\mu^+\mu^-$
  - **Lepton flavour universality involving μ/e ratios**
    $B^0 \to K^{(*)0}l^+l^-$ $B^+ \to K^+l^+l^-$

$B \to K^{(*)}l^+l^-$ branching fractions and angular observables potentially suffer from underestimated hadronic uncertainties



LFU observables as $B^0_{(s)} \to \mu^+\mu^-$ decays have very clean theory predictions

Lepton flavour universality test

- In the SM couplings of gauge bosons to leptons are independent of lepton flavour
  → Branching fractions differ only by phase space and helicity-suppressed contributions

- Ratios of the form

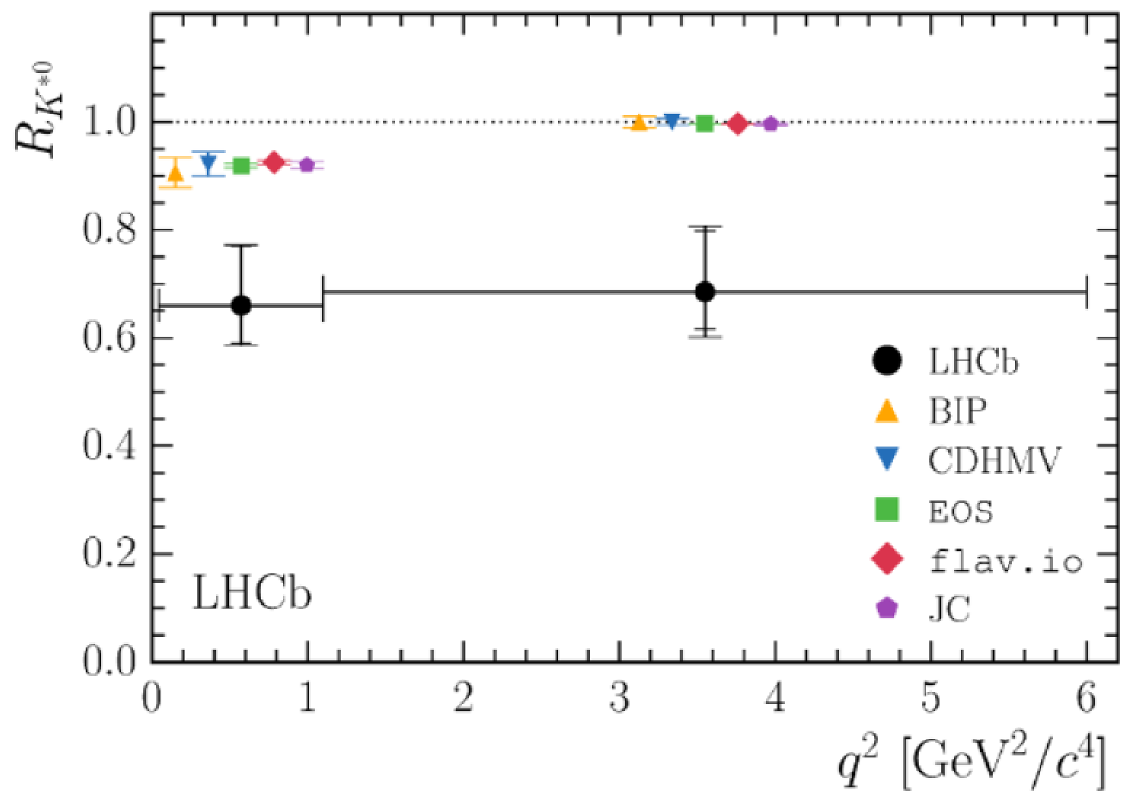
$$R_{K^{(*)}} := \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \overset{\text{SM}}{\cong} 1$$

  in SM are free from QCD uncertainties affecting other observables
  → $O(10^{-4})$ uncertainty [JHEP12 (2007) 040]

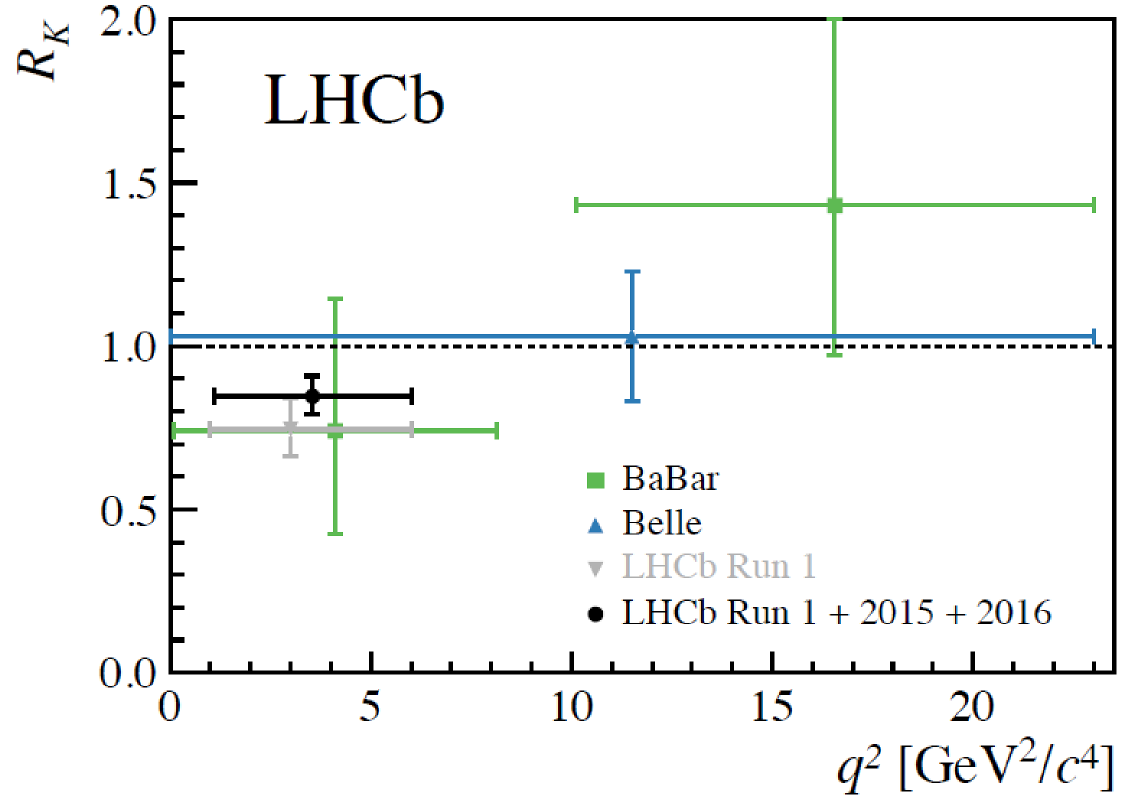
- Up to $O(10^{-2})$ QED corrections [EPJC76, 440 (2016)]

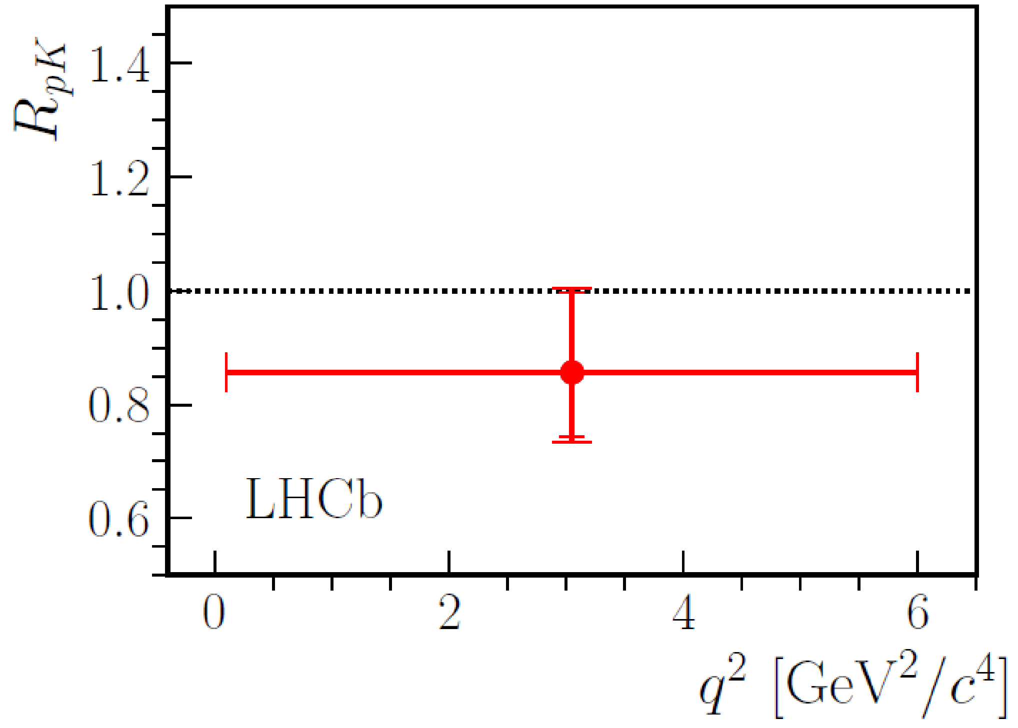
Any significant deviation is sign of New Physics.

Lepton flavour universality test



BaBar:[PRD86(2012)032012],Belle:[PRL103(2009)171801





Top left: $B^0 \rightarrow K^{*0} l^+ l^-$ R_{K^*}, $3fb^{-1}$
[JHEP08 (2017) 055]

Top right : $B^+ \rightarrow K^+ l^+ l^-$ R_K, $5fb^{-1}$
[PRL122 (2019) 191801]

Bottom: $\Lambda_b \rightarrow pK l^+ l^-$ R_{pK}, $4{,}7fb^{-1}$
[JHEP05 (2020) 040]

q^2 = dilepton mass squared

R_K with the full LHCb dataset

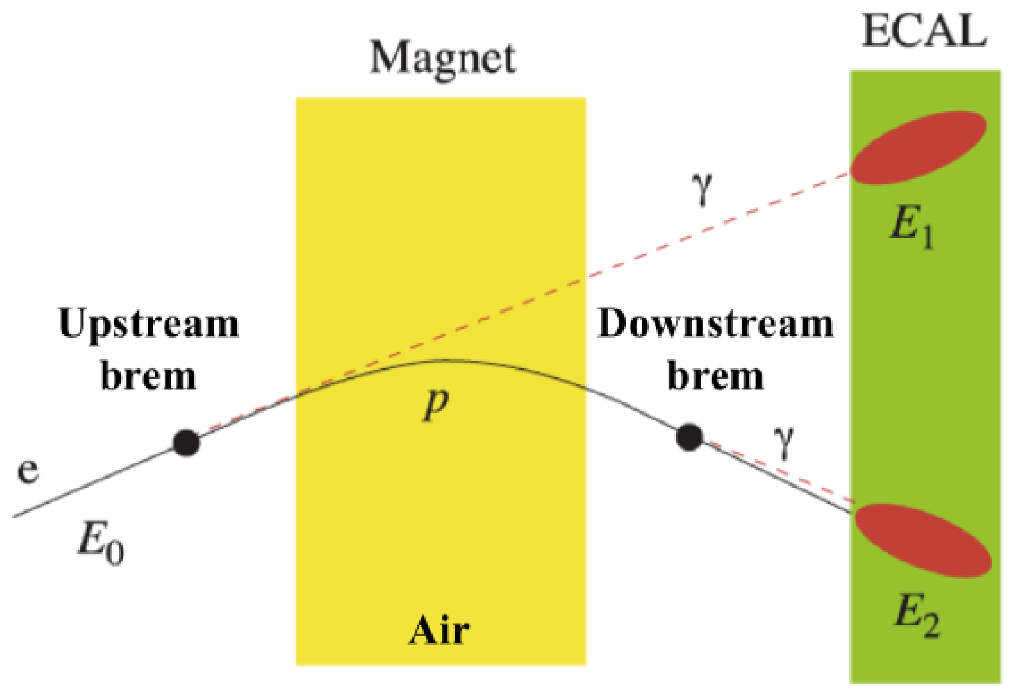
$$R_K = \frac{\int_{1.1\,\mathrm{GeV}^2}^{6.0\,\mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{1.1\,\mathrm{GeV}^2}^{6.0\,\mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+\to K^+e^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2}$$

Measurement performed in $1.1 < q^2 < 6.0\ GeV^2/c^4$

- Previous measurement [PRL122 (2019) 191801] used 5 fb^{-1} of data:
  - 3 fb^{-1} of Run 1 + 2 fb^{-1} of Run 2 (2015+2016)
- This update:
  - Add remaining 4 fb^{-1} of Run 2 (2017+2018)
  - 9 fb^{-1} in total, 2x the number of B mesons as in previous analysis
- The analysis strategy is the same as in the previous measurement
- arxiv:2103.11769, submitted to Nature Physics

Electrons vs muons

- Electrons lose a large fraction of their energy through Bremsstrahlung in detector material

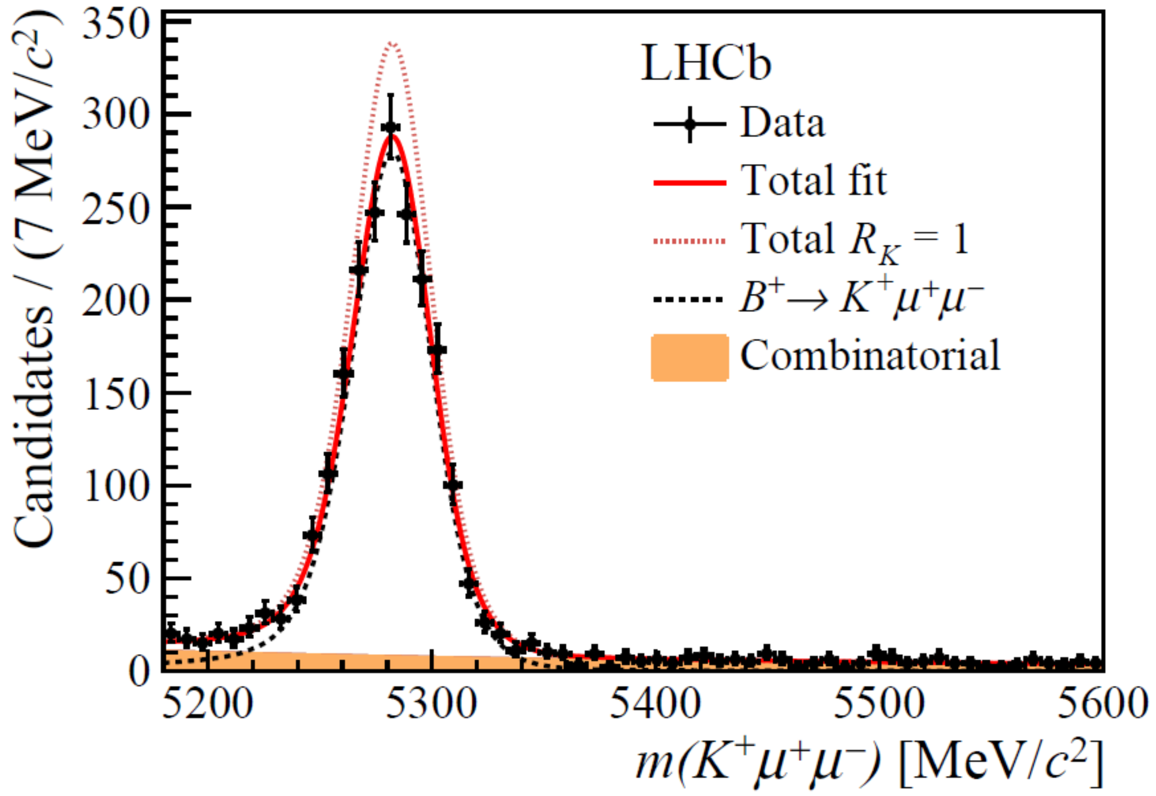


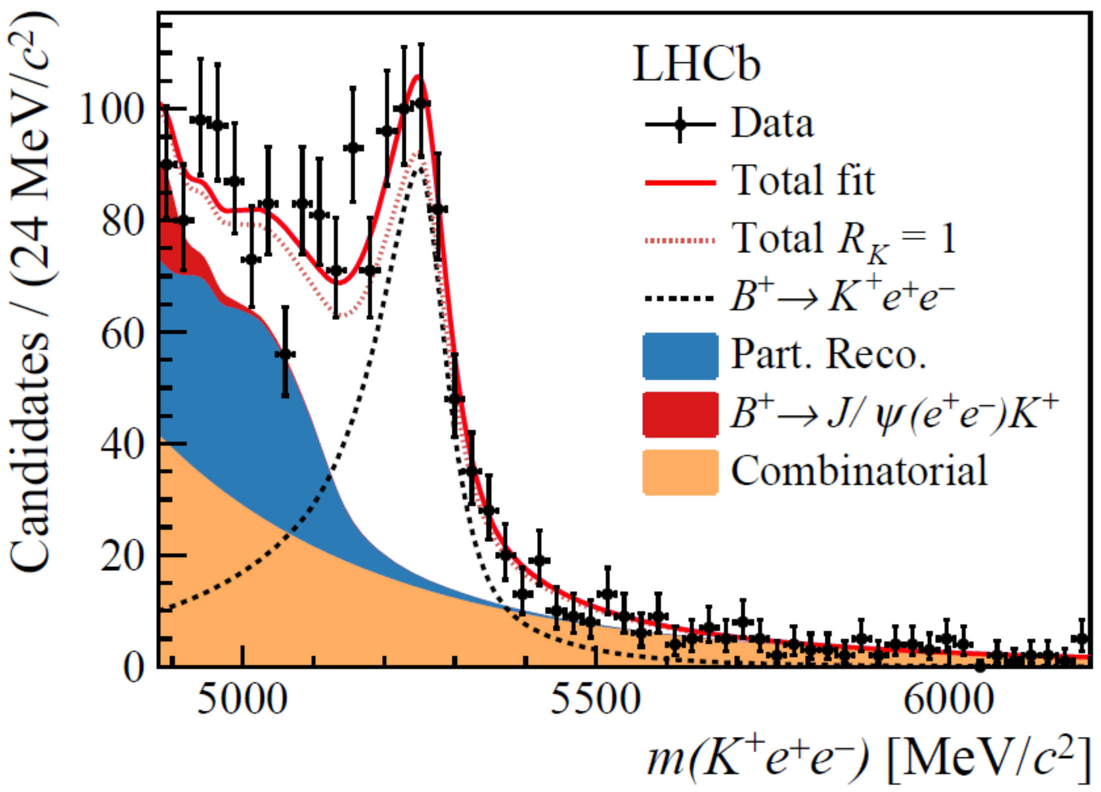
- Most electrons will emit one energetic photon before the magnet.
  → Look for photon clusters in the calorimeter ($E_T > 75\ MeV$) compatible with electron direction before the magnet.
  → Recover brem energy loss by "adding" the cluster energy back to the electron momentum.

Electrons vs muons

- Even after the Bremsstrahlung recovery, electrons still have degraded mass and q^2 resolution

Plots from previous result, LHCb [PRL122(2019)191801]





- L0 calorimeter trigger requires higher thresholds, than L0 muon trigger, due to high occupancy.

  → Use 3 exclusive trigger categories for e^+e^- final states

  1. $e^\pm$ from signal-B; 2. $K^\pm$ from signal-B; 3. rest of event

- Particle ID and tracking efficiency larger for muons than for electrons

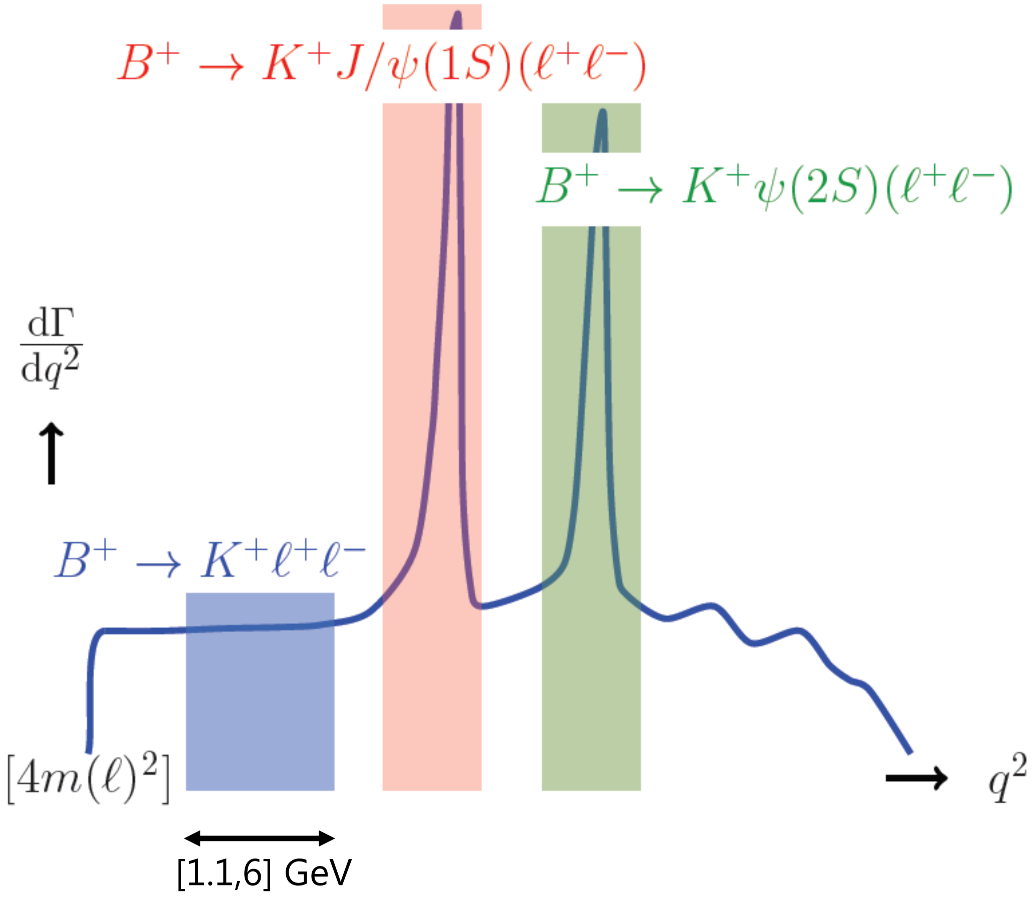
Crucial the control of the difference in efficiency between muons and electrons

Measurement strategy

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))} = \frac{N^{\mathrm{rare}}_{\mu^+\mu^-}\ \varepsilon^{J/\psi}_{\mu^+\mu^-}}{N^{J/\psi}_{\mu^+\mu^-}\ \varepsilon^{\mathrm{rare}}_{\mu^+\mu^-}} \times \frac{N^{J/\psi}_{e^+e^-}\ \varepsilon^{\mathrm{rare}}_{e^+e^-}}{N^{\mathrm{rare}}_{e^+e^-}\ \varepsilon^{J/\psi}_{e^+e^-}}$$

R_K is measured as a double ratio to cancel out most systematics

- Rare and J/ψ modes share identical selections apart from cut on q^2
- Yields determined from a fit to the invariant mass of the final state particles
- Efficiencies computed using simulation that is calibrated with control channels in data

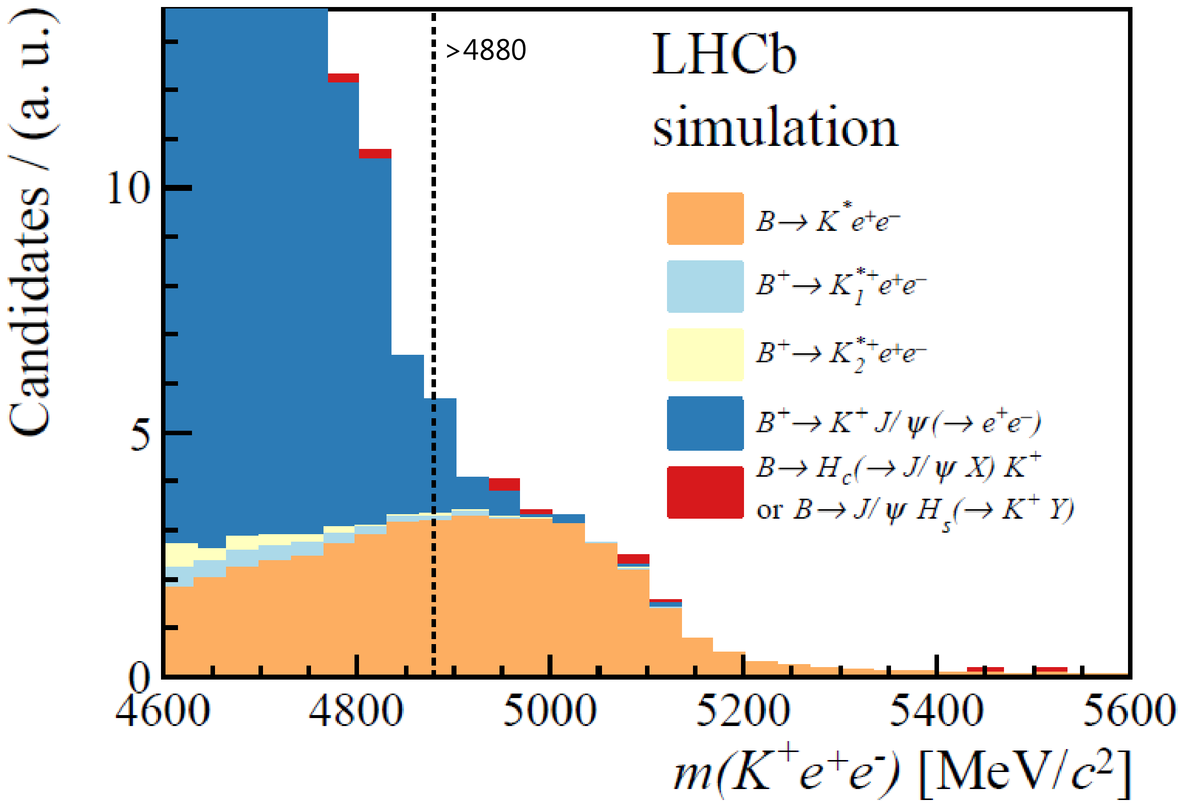


q^2 = dilepton mass squared

Selection and backgrounds

- As in our previous measurement, use particle ID requirements and mass vetoes to suppress peaking backgrounds from exclusive B-decays to negligible levels
  - Backgrounds of e.g $B^+ \to \overline{D^0}(\to K^+e^-\nu)e^+\bar{\nu}$: cut on $m_{K^+e^-} > m_{D^0}$
  - Mis-ID backgrounds, e.g. $B \to K\pi^+_{(\to e^+)}\pi^-_{(\to e^-)}$: cut on electron PID
- Multivariate selection to reduce combinatorial background and improve signal significance (BDT)

arxiv:2103.11769



- Residual backgrounds suppressed by choice of $m(K^+l^+l^-)$ window
  - $B^+ \to K^+ J/\psi\ (e^+e^-)$
  - **Partially reconstructed dominated by $B \to K^+\pi^-e^+e^-$ decays**
  - Model in fit by constraining their fractions between trigger categories and calibrating simulated templates from data.

Cross-check our estimates using control regions in data and changing $m(K^+l^+l^-)$ window in fit

Efficiency calibration

Following identical procedure to our previous measurement, the simulation is calibrated based on control data for the following quantities:

- Trigger efficiency.
- Particle identification efficiency.
- B^+ kinematics.
- Resolutions of q^2 and $m(K^+e^+e^-)$

Verify procedure through numerous cross-checks.

Cross check: measurement of J/psi

- To ensure that the efficiencies are under control, check

$$r_{J/\psi} = \frac{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))} = 1$$

known to be true within 0.4% [PDG].

→ Very stringent check, as it requires direct control of muons vs electrons.

- Result:

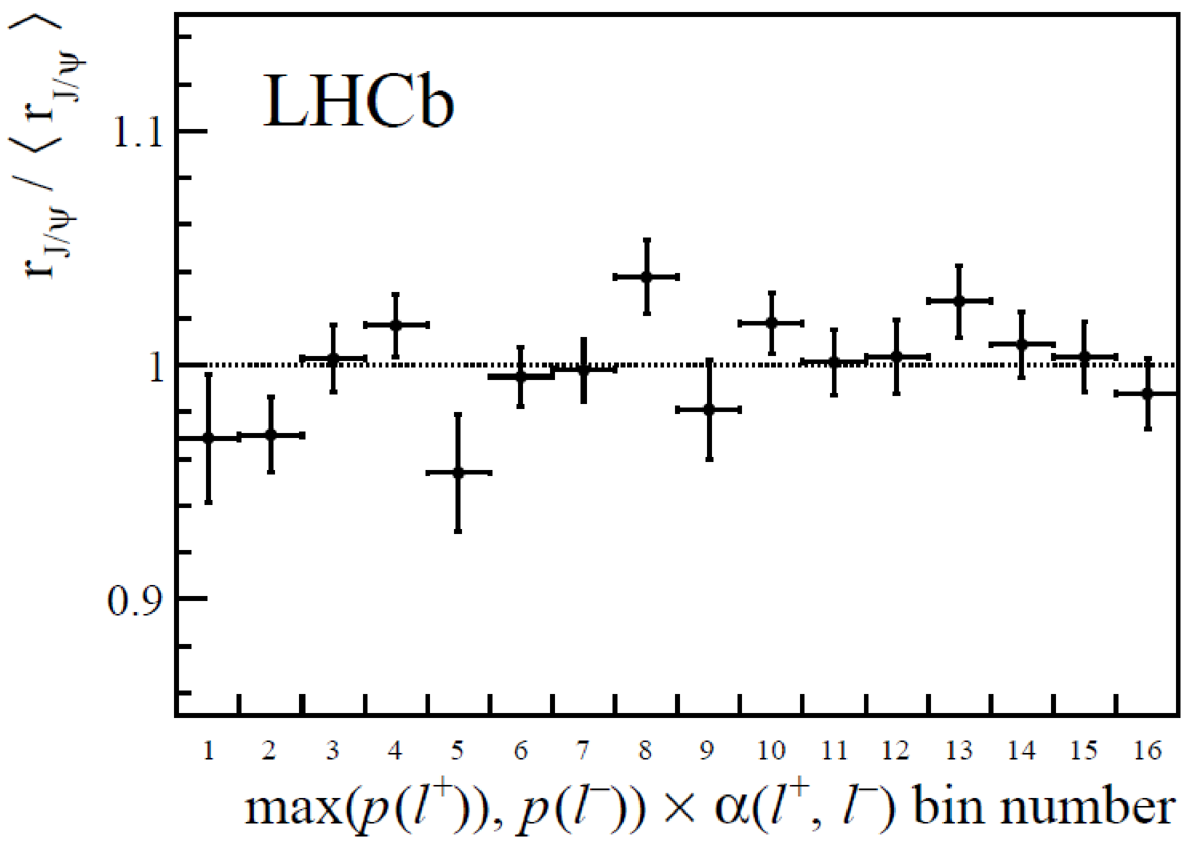
$$r_{J/\psi} = 0.981 \pm 0.020 \text{ (stat+sys)}$$

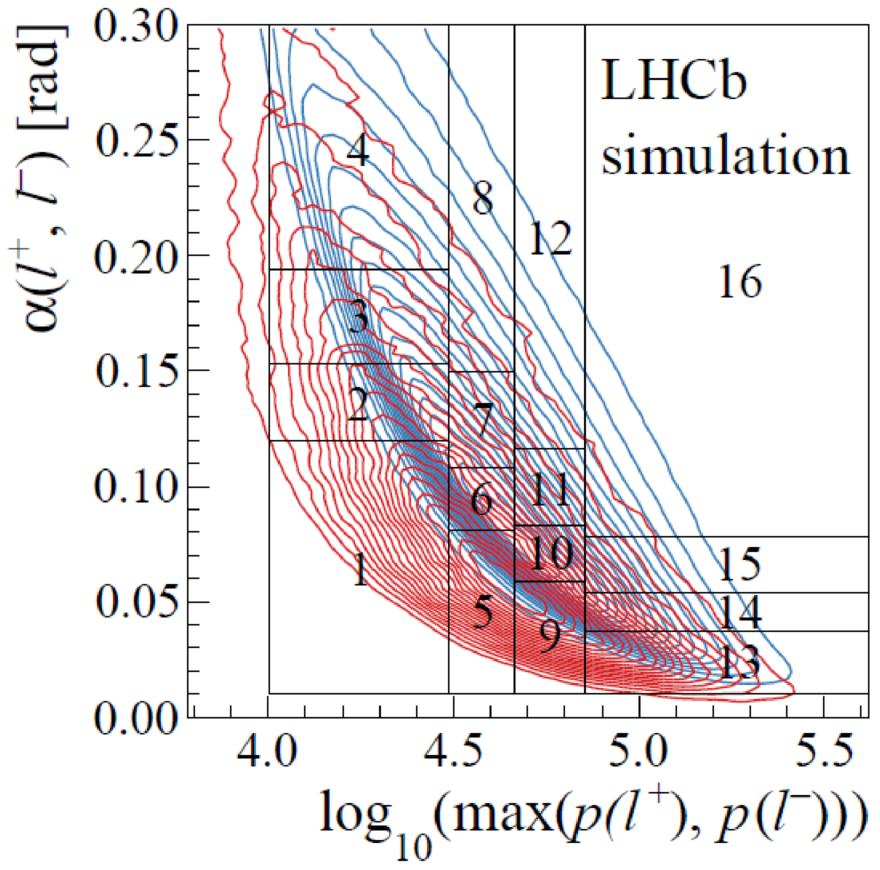
- Checked that the value of $r_{J/\psi}$ is compatible with unity for new and previous datasets and in all trigger samples.

Cross check: $r_{J/\psi}$ vs kinematics

arxiv:2103.11769

- Test efficiencies are understood in all kinematic regions by checking $r_{J/\psi}$ is flat in all variables examined.





- Flatness of $r_{J/\psi}$ 2D plots gives confidence that efficiencies are understood across the entire decay phase space.

→ If take departure from flatness as genuine rather than fluctuations (accounting for rare-mode kinematics), bias expected on R_K is 0.1%

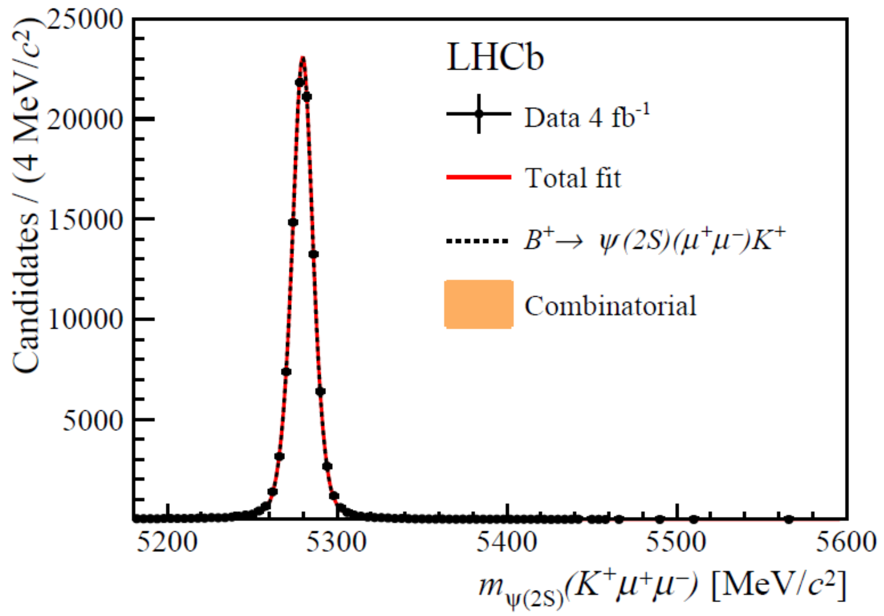
Cross check: Measurement of $R_{\psi(2S)}$

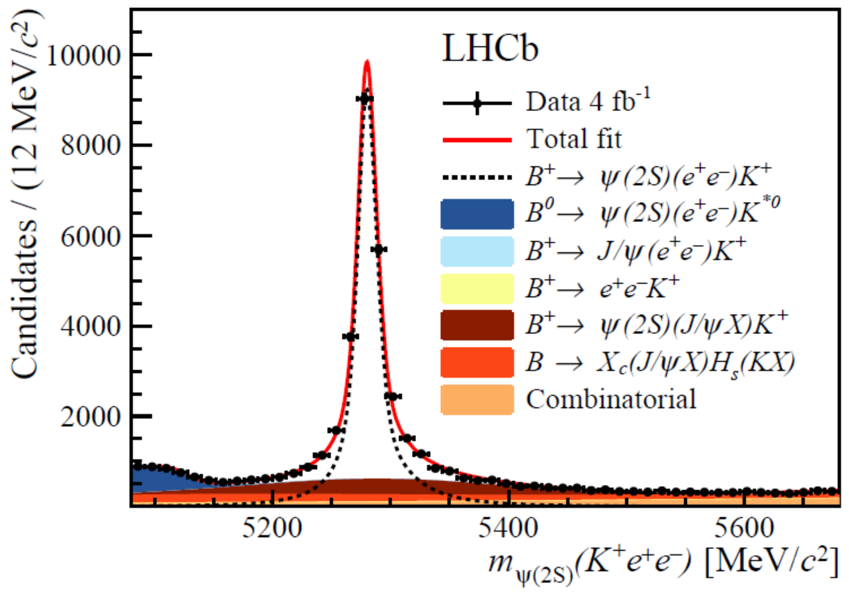
arxiv:2103.11769

Measurement of the double ratio

$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(e^+e^-))}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))}$$

Fit to new $B^+ \to \psi(2S)(l^+l^-)K^+$ data





- Independent validation of double-ratio procedure at q^2 away from J/ψ
- Result well compatible with unity:

$$R_{\psi(2S)} = 0.997 \pm 0.011 \text{ (stat+sys)}$$

→ can be interpreted as world's best LFU test in $\psi(2S) \to l^+l^-$

Systematic uncertainties

Dominant sources: ~1%

- Choice of fit model
  - Associated signal and partially reconstructed background shape
- Statistics of calibration samples
  - Bootstrapping method that takes into account correlations between calibration samples and final measurement

Sub-dominant sources: ~0.1%

- Efficiency calibration

→ Dependence on trigger biases

→ Precision of the q^2 and $m(K^+e^+e^-)$ smearing factors

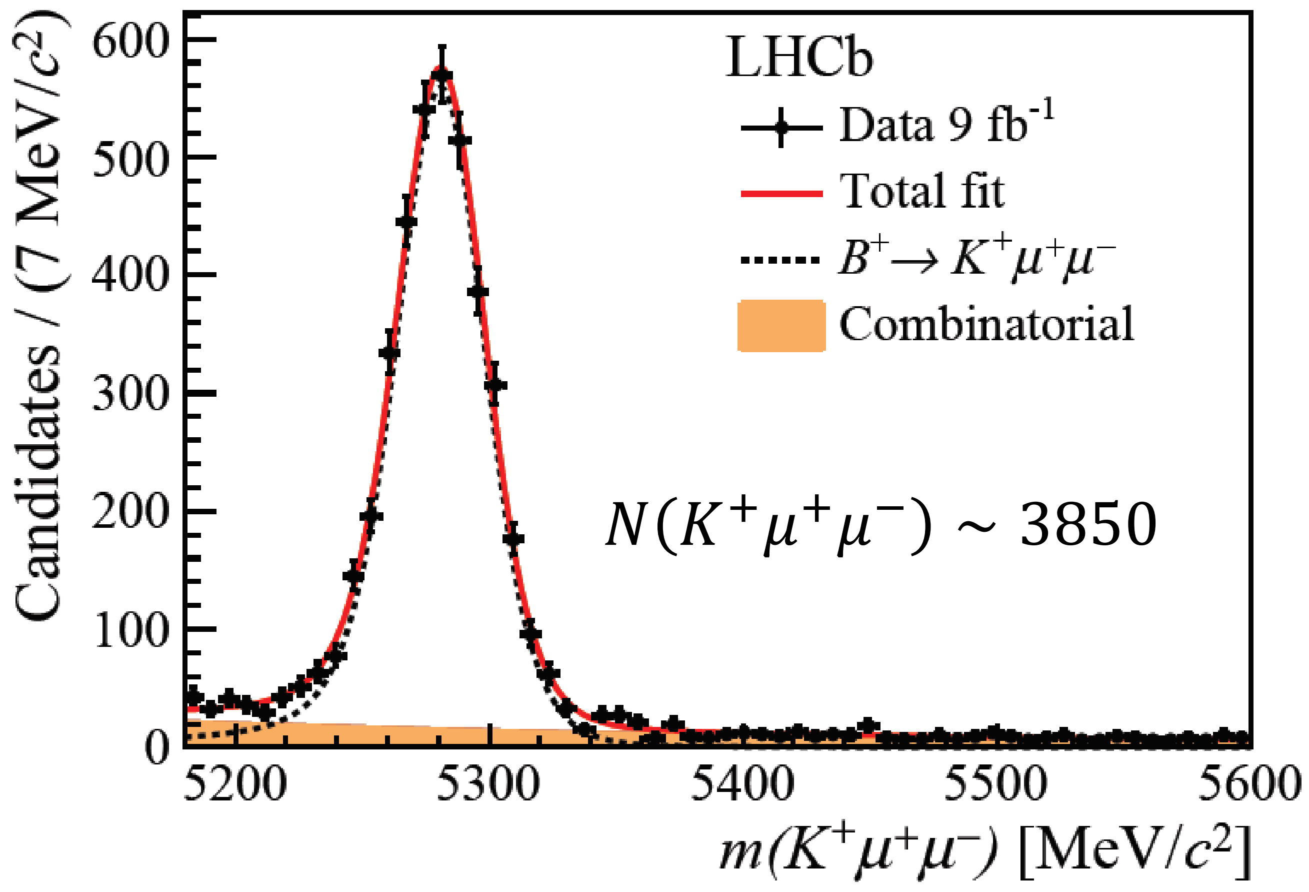
→ Inaccuracies in material description in simulation

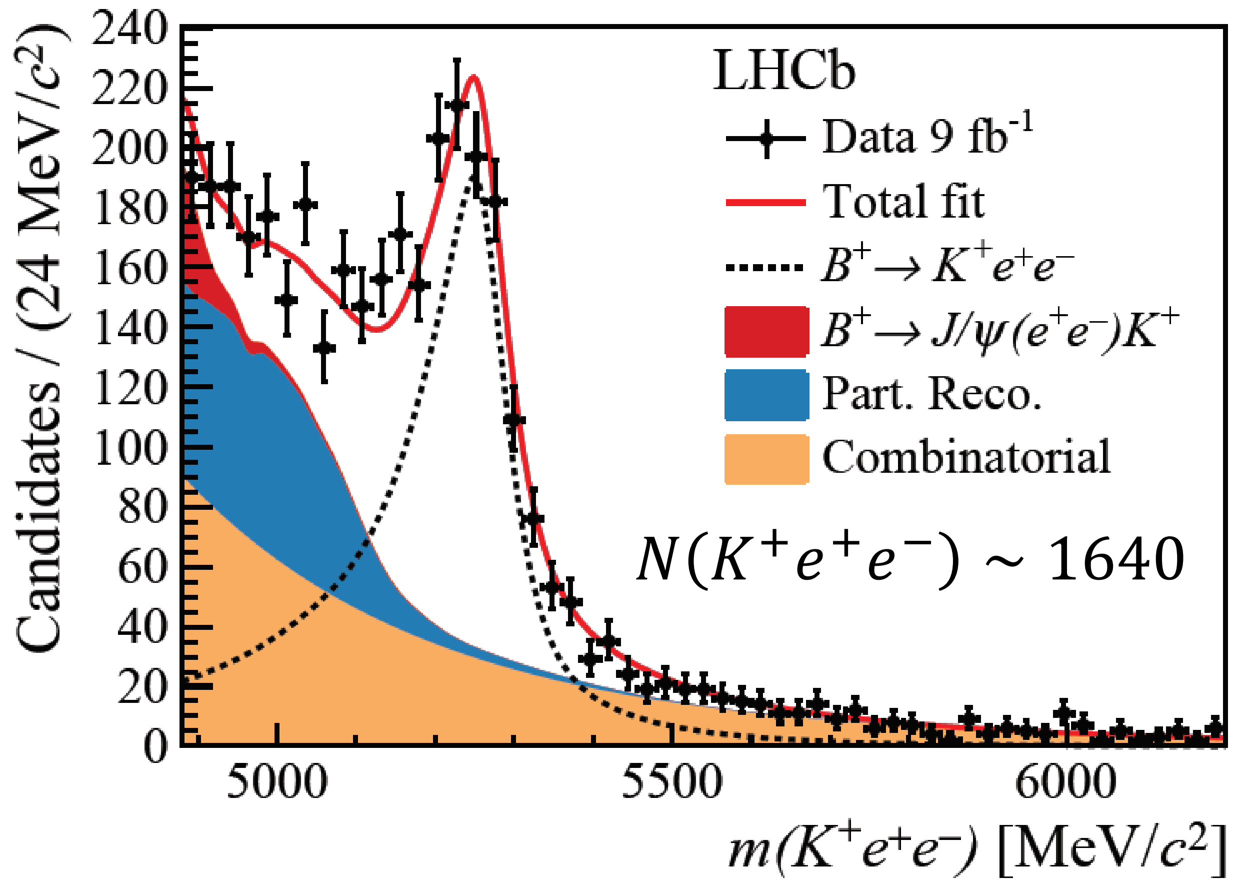
Total relative systematic of 1.5% in the final R_K measurement
→ Expected to be statistically dominated

Measurement of R_K

arxiv:2103.11769

- R_K is extracted as a parameter from an unbinned maximum likelihood fit to $m(K^+\mu^+\mu^-)$ and $m(K^+e^+e^-)$ distributions in $B^+ \rightarrow K^+l^+l^-$ and $B^+ \rightarrow J/\psi(l^+l^-)K^+$ decays



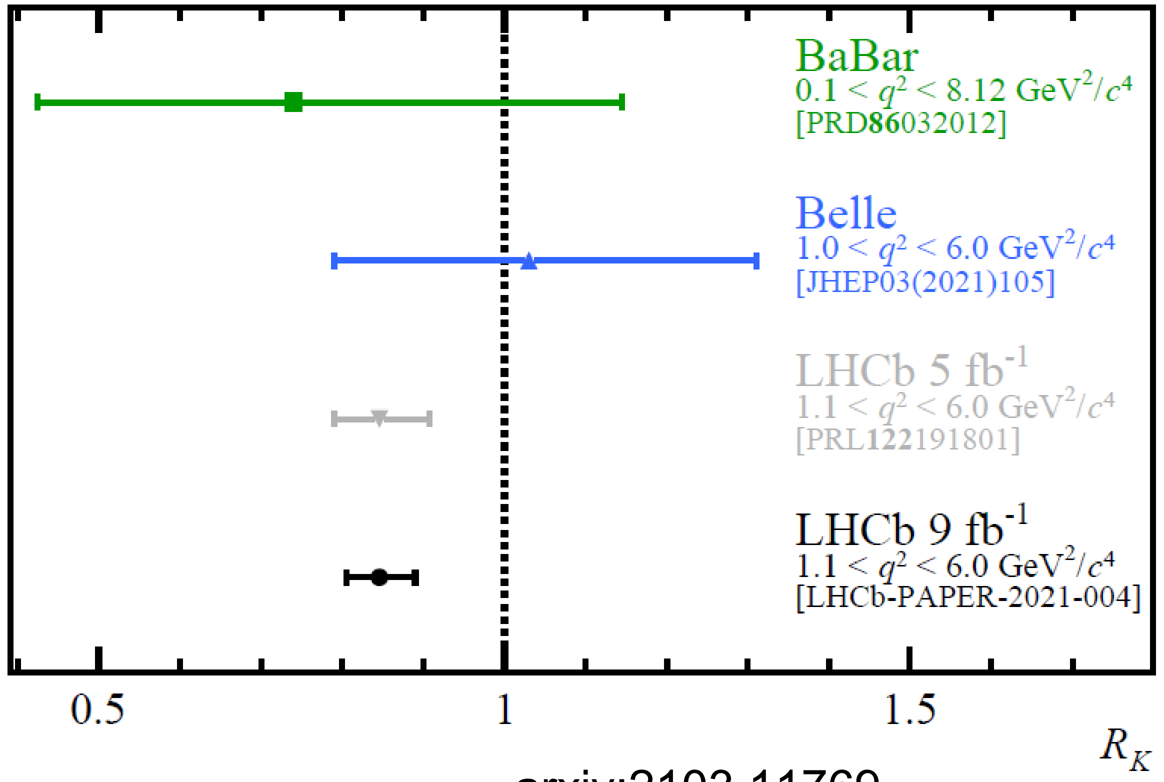


- Correlated uncertainties on efficiency ratios included as multivariate constraint in likelihood

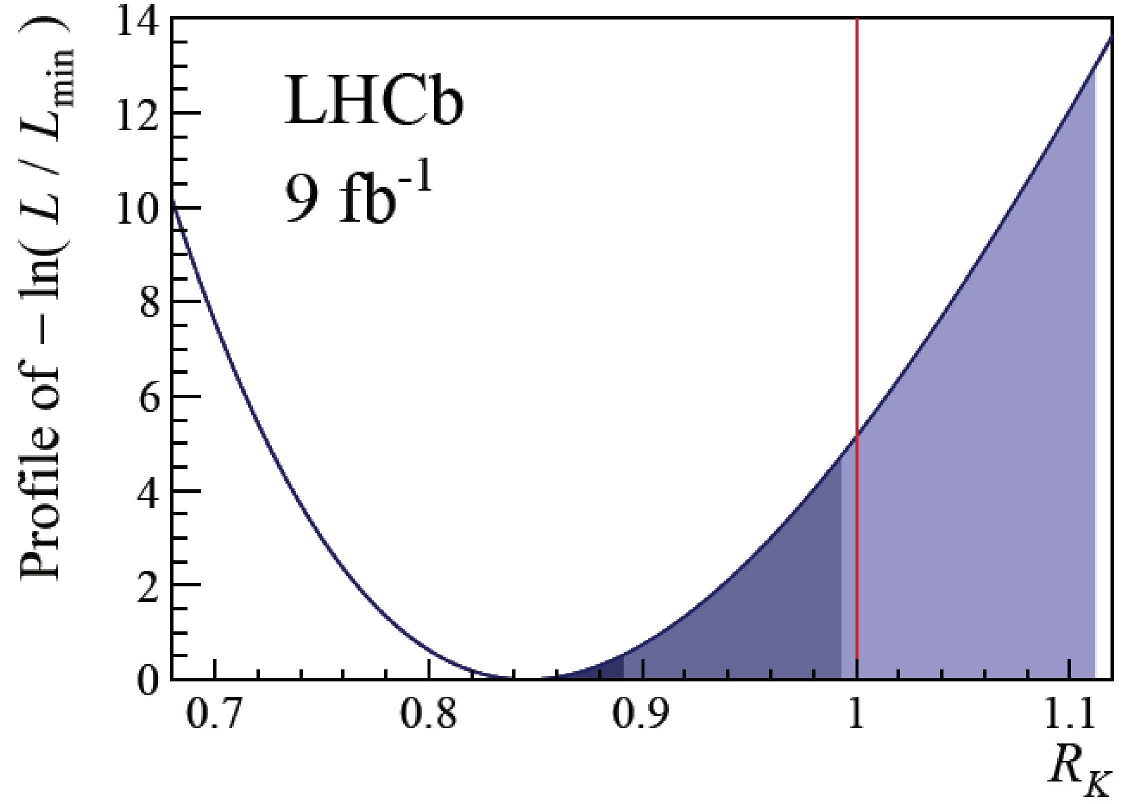
Measurement of R_K with full Run 1 and Run 2 dataset

$$R_K = 0.846^{+0.042}_{-0.039}(stat)^{+0.013}_{-0.012}(sys)$$

- p-value under SM hypothesis: 0.0010
  → evidence of LFU violation at 3.1 σ
- Compatibility with the SM obtained by integrating the profiled likelihood as a function of R_K above 1
  - Taking into account the 1% theory uncertainty on R_K [EPJC76(2016)8,440]



arxiv:2103.11769



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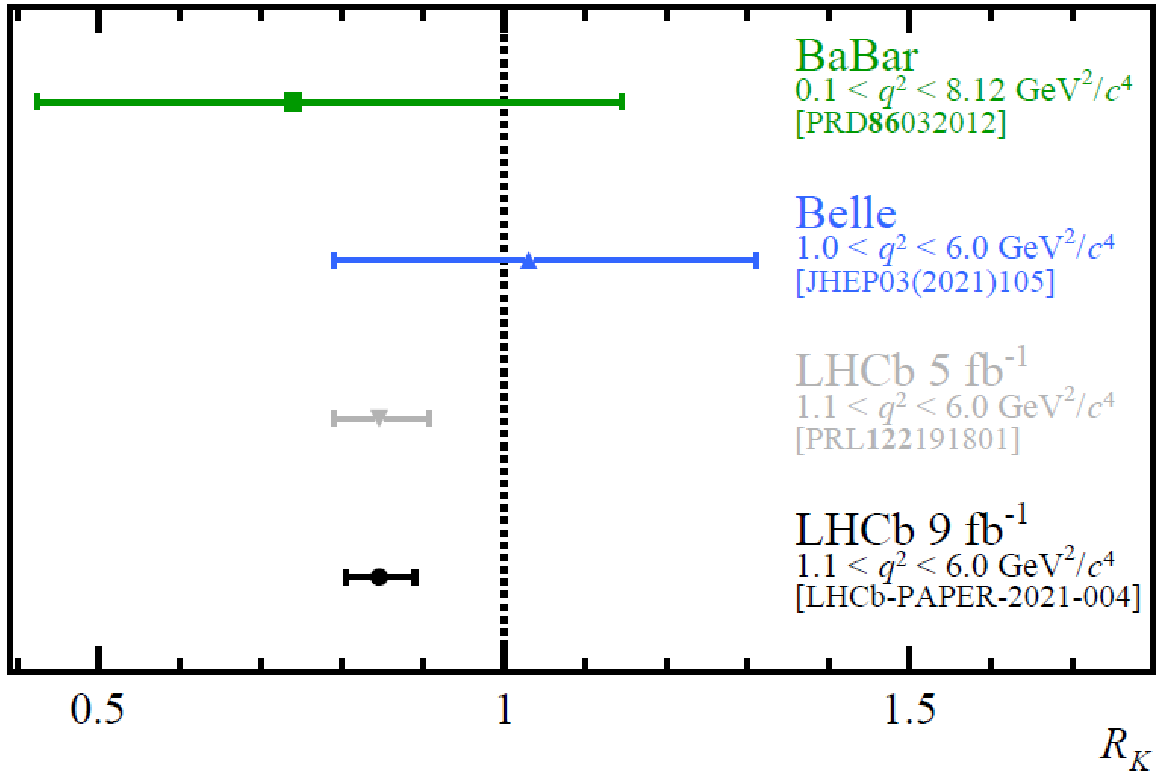
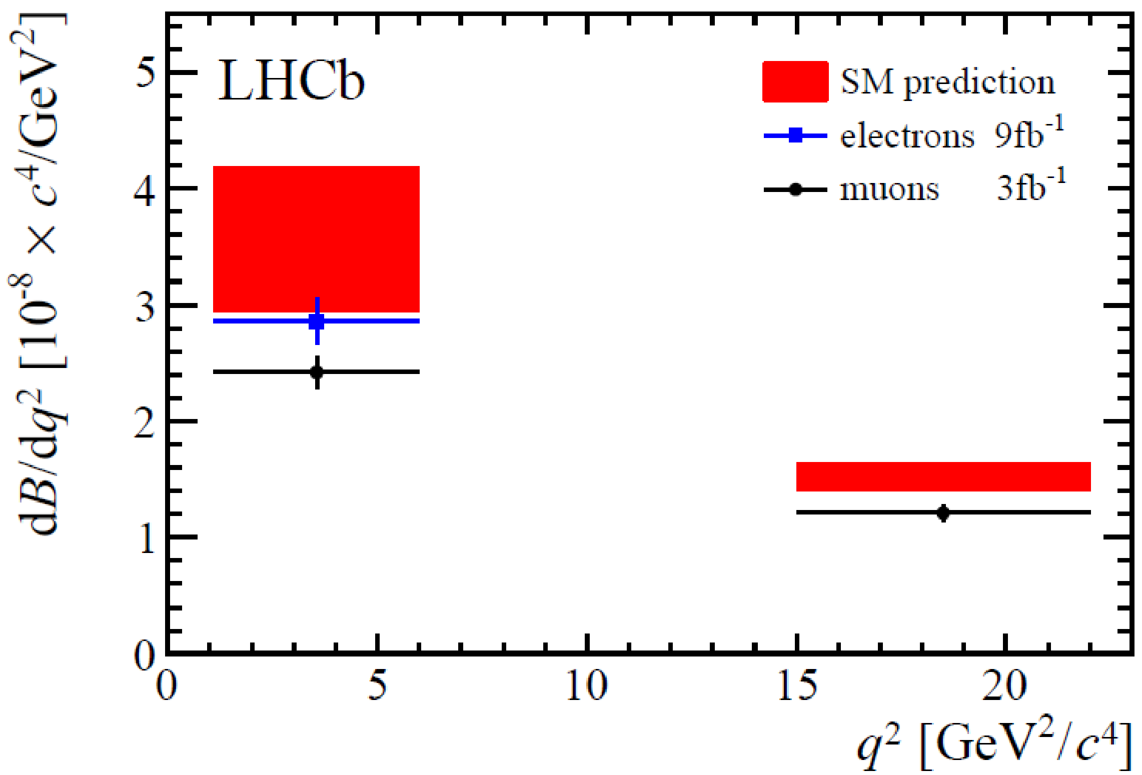
- Compatibility with the SM obtained by integrating the profiled likelihood as a function of R_K above 1
  - Taking into account the 1% theory uncertainty on R_K [EPJC76(2016)8,440]
- Using R_K and previous measurement of $BF(B^+ \to K^+\mu^+\mu^-)$ [JHEP06(2014)133] determine $BF(B^+ \to K^+e^+e^-)$.
- It suggests that electrons are more SM than muons

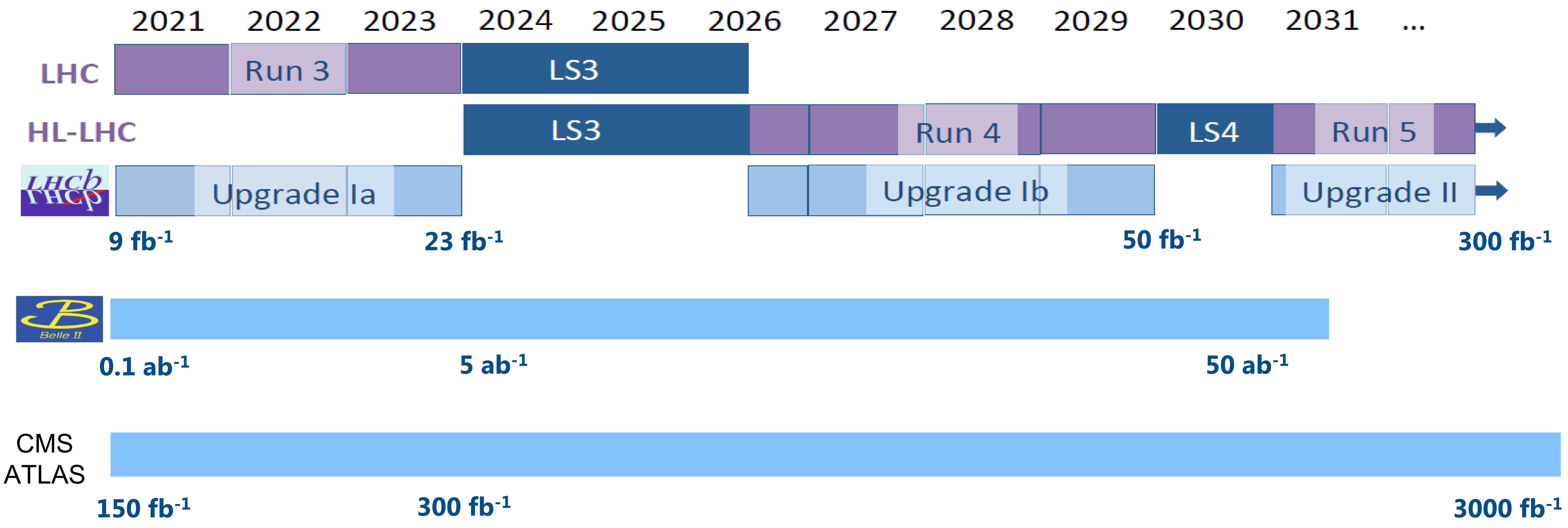
$$\frac{dB(B^+ \to K^+e^+e^-)}{dq^2} = \left(28.6^{+1.5}_{-1.4}(stat) \pm 1.4(sys)\right) \times 10^{-9} c^4/GeV^2$$





Next years: LHCb upgrade-I and upgrade-II phases

LHC Run 3 schedule shifted by +1yr

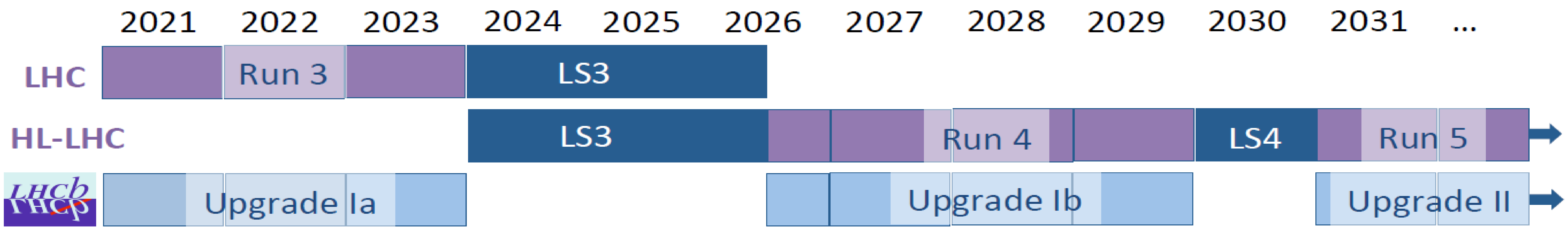


$$L_{LHCb(Run\ 3)} = 4.4 \times 10^{32}\ cm^{-2}s^{-1} \rightarrow 2 \times 10^{33} cm^{-2}s^{-1}$$

$B \to \mu\mu$ uncertainties predictions

[LHCB-PUB-2018-009, ATL-PHYS-PUB-2018-005, CMS PAS FTR-18-013]

LHC Run 3 schedule shifted by +1yr

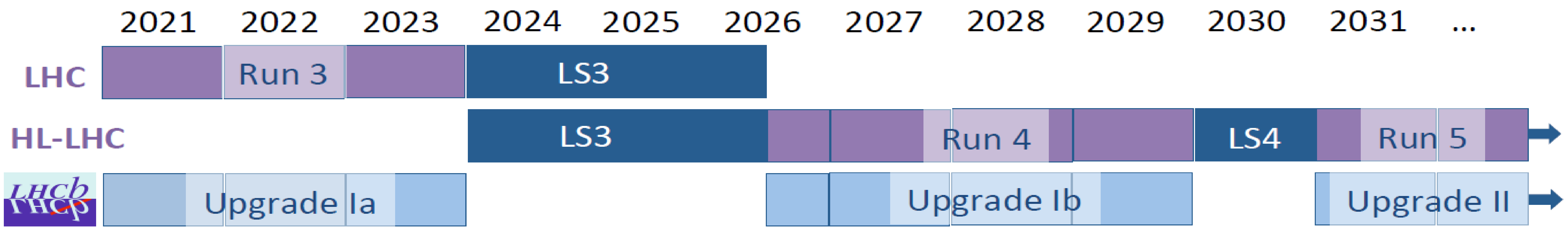


LHCb	**9 fb^{-1} (r1+r2)**	**23 fb^{-1}**	**50 fb^{-1}**	**300 fb^{-1}**
$BF(Bs \to \mu\mu)$	$\pm 0.46 \times 10^{-9}$	$\pm 0.30 \times 10^{-9}$		$\pm 0.16 \times 10^{-9}$
$\tau(Bs \to \mu\mu)$	$\pm 0.29 \pm 0.03$ ps	± 0.16 ps		± 0.04 ps
$\frac{BF(B^0 \to \mu\mu)}{BF(B_s^0 \to \mu\mu)}$	65%	34%		10%
CMS	**61 fb^{-1} (r1+2016)**	**300 fb^{-1}**		**3000 fb^{-1}**
$BF(Bs \to \mu\mu)$	$\pm 0.70 \times 10^{-9}$	$\pm 0.44 \times 10^{-9}$		$\pm 0.26 \times 10^{-9}$
$\tau(Bs \to \mu\mu)$	$\pm 0.51 \pm 0.09$ ps	± 0.15 ps		± 0.05 ps
$\frac{BF(B^0 \to \mu\mu)}{BF(B_s^0 \to \mu\mu)}$	100%	48%		17%
ATLAS	**51 fb^{-1} (r1+2015/16)**			**3000 fb^{-1}**
$BF(Bs \to \mu\mu)$	$\pm 0.75 \times 10^{-9}$			$\pm(0.46 - 0.55) \times 10^{-9}$
$BF(B^0 \to \mu\mu)$	$< 2.1 \times 10^{-10}$			$\pm(0.28 - 0.54) \times 10^{-10}$

$R_{K^{(*)}}$ uncertainties predictions

[LHCB-PUB-2018-009, BELLE2-PAPER-2018-001]

LHC Run 3 schedule shifted by +1yr



LHCb	**9 fb^{-1}**	**23 fb^{-1}**	**50 fb^{-1}**	**300 fb^{-1}**
$\sigma(R_K)$	0.041	0.025	0.017	0.007
$\sigma(R_{K^{*0}})$	0.10 $(Run1)$	0.031	0.020	0.008

Belle II	**5 ab^{-1}**	**50 ab^{-1}**
$\sigma(R_K)$	0.11	0.04
$\sigma(R_{K^{*0}})$	0.09	0.03

NB: The above R_K and $R_{K^{*0}}$ uncertainties refer to $1 < q^2 < 6\ GeV^2/c^4$

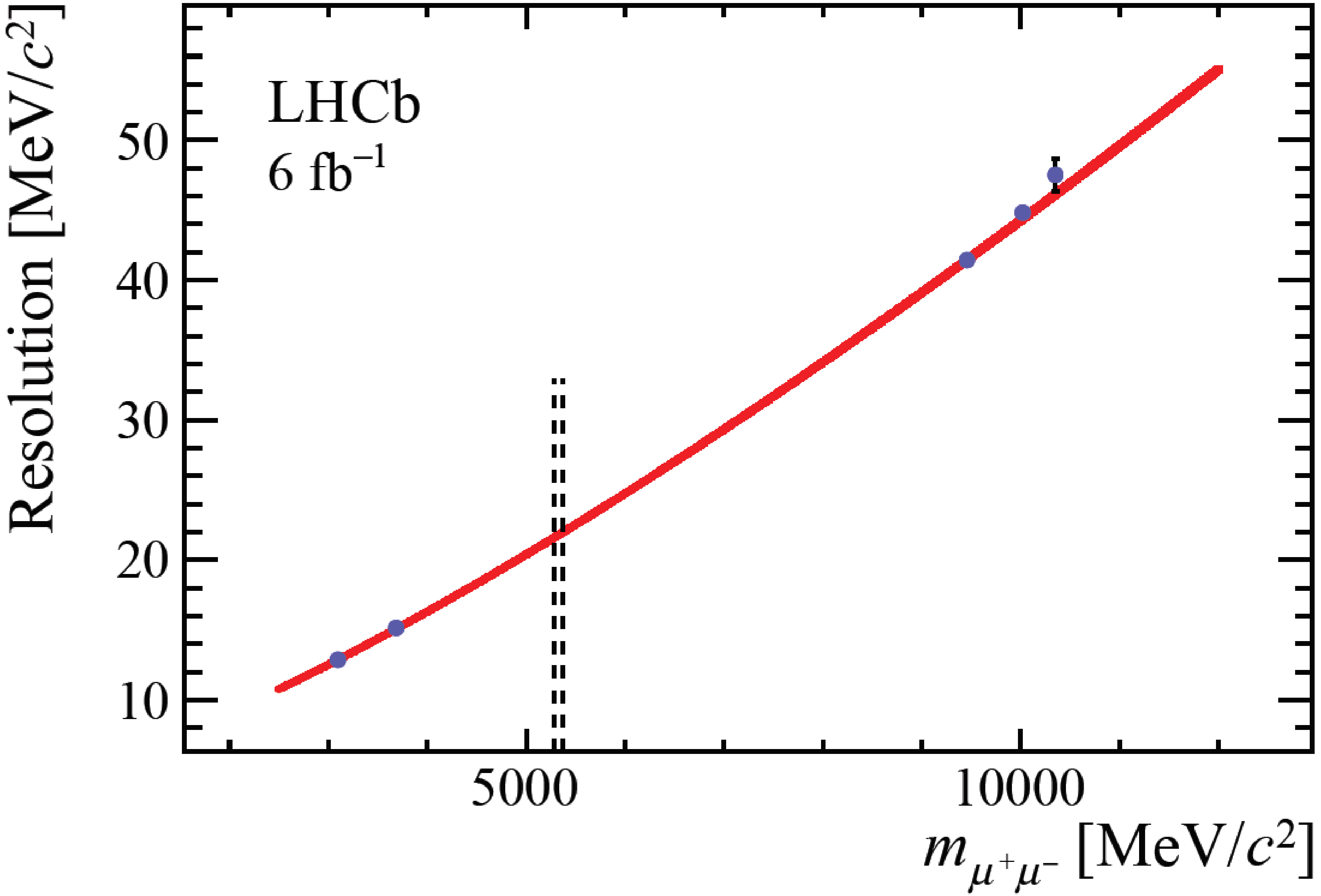
CMS in 2018 has recorded $\sim 1.2 \times 10^{10}$ trigger-unbiased b decays (B parking), which allows to select $B \to K^{(*)}e^+e^-$ decays otherwise not triggerable. ➔ CMS expected to enter the game (future projections N/A to my knowledge)

Conclusions

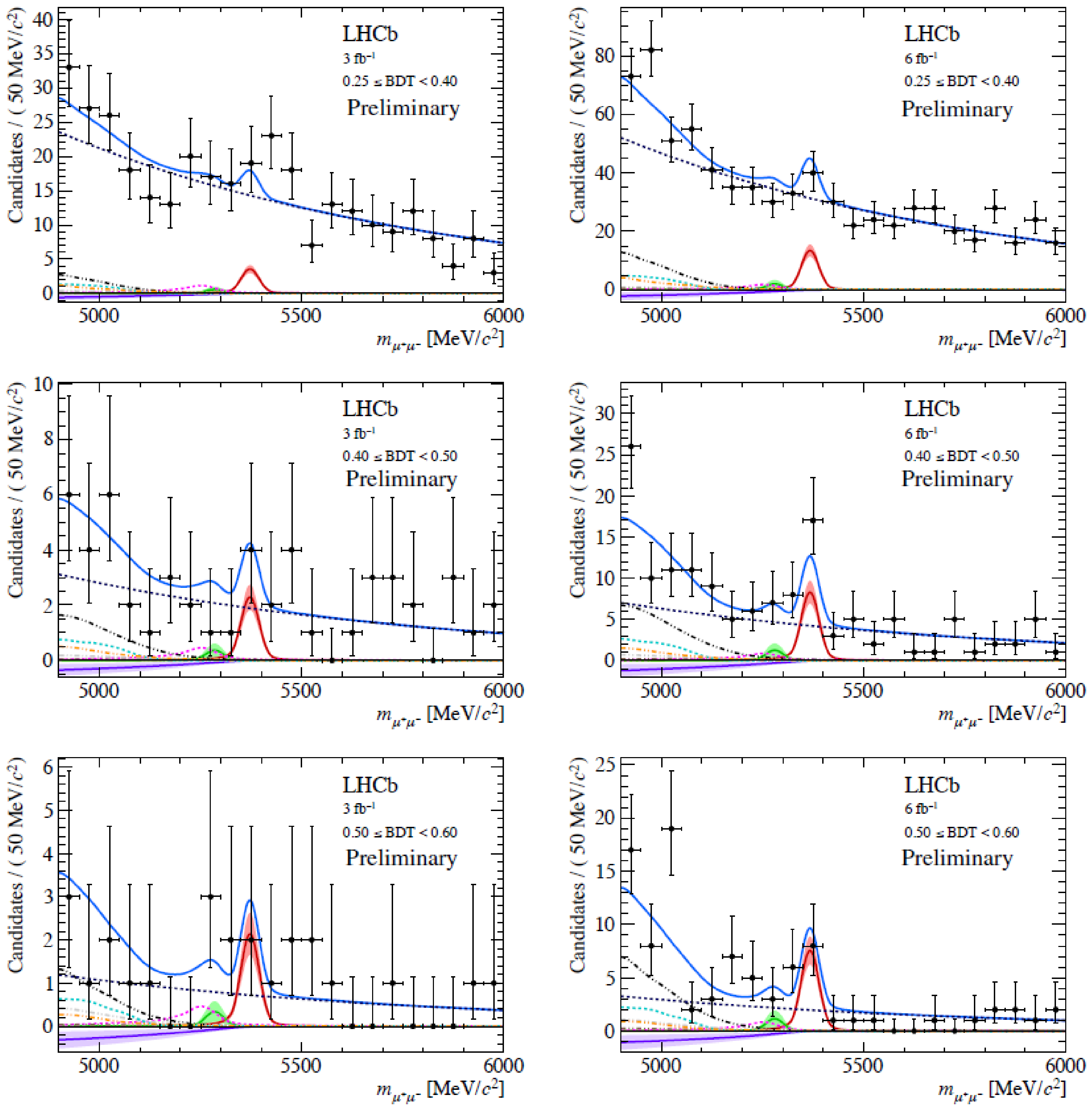
- Updated $B_s^0 \to \mu^+\mu^-$ and R_K measurements with the full Run 1 + Run 2 dataset of LHCb. Both provide theoretically very clean observables that test SM and constrain new physics scenarios.
- Most precise single-experiment measurement of $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ with $\sim 15\%$ error. No evidence of $B^0 \to \mu^+\mu^-$ signal: evidence in Run 3 will rely on hadron misID performance. Most precise measurement of $\tau_{\mu^+\mu^-}$, but still not able to exclude portions of the $A_{\Delta\Gamma}^{\mu^+\mu^-}$ physical region.
- Most precise measurement of R_K confirms and strengthens tension with SM lepton flavour universality hypothesis. Many more $b \to sl^+l^-$ measurements underway with the full LHCb dataset.
- $\times\, 3$ more data in Run 3 starting next year and much more foreseen in Run4&Run5.
- Input from CMS, ATLAS and Belle II will be important

BACKUP

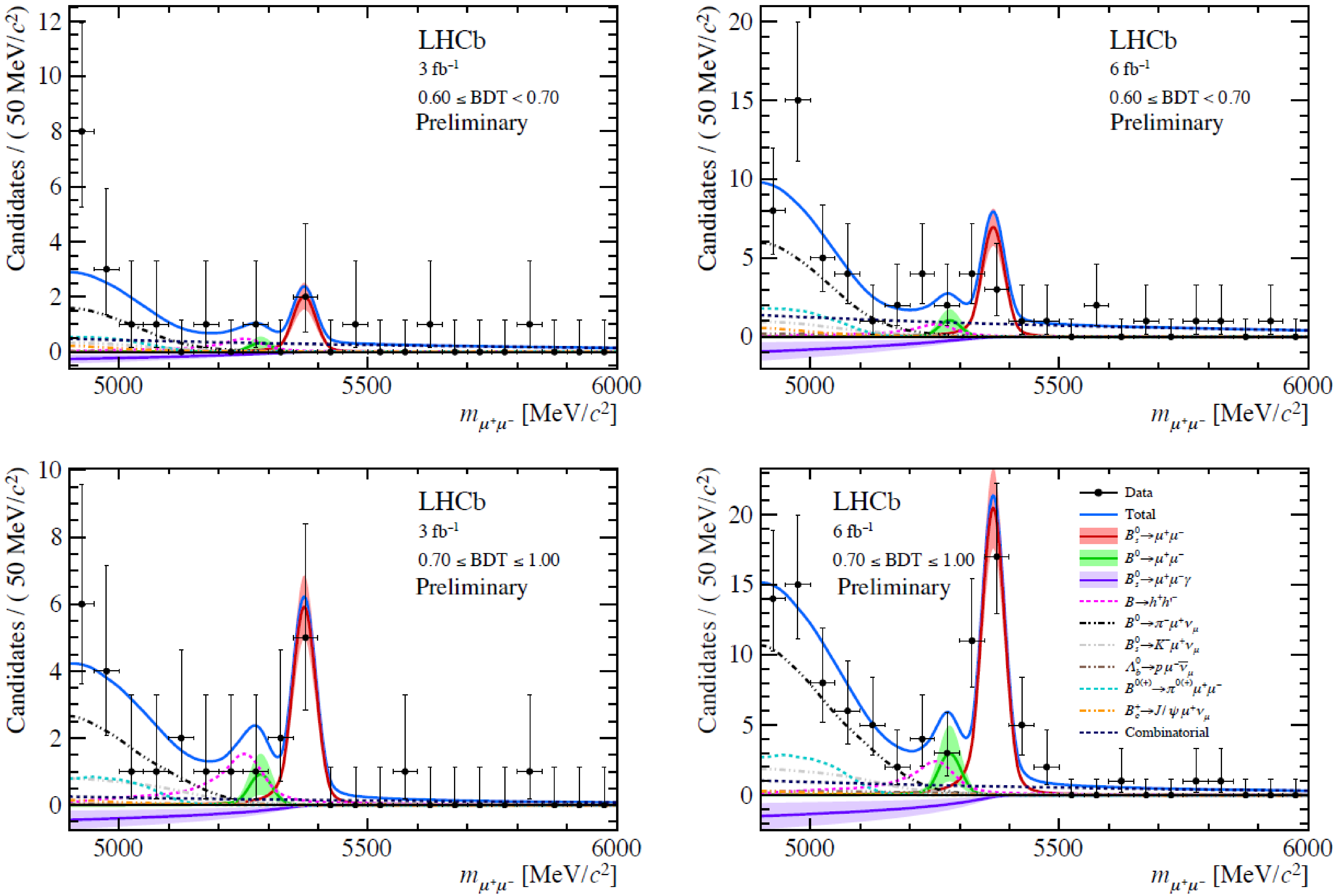
$B \to \mu\mu$ mass resolution calibration



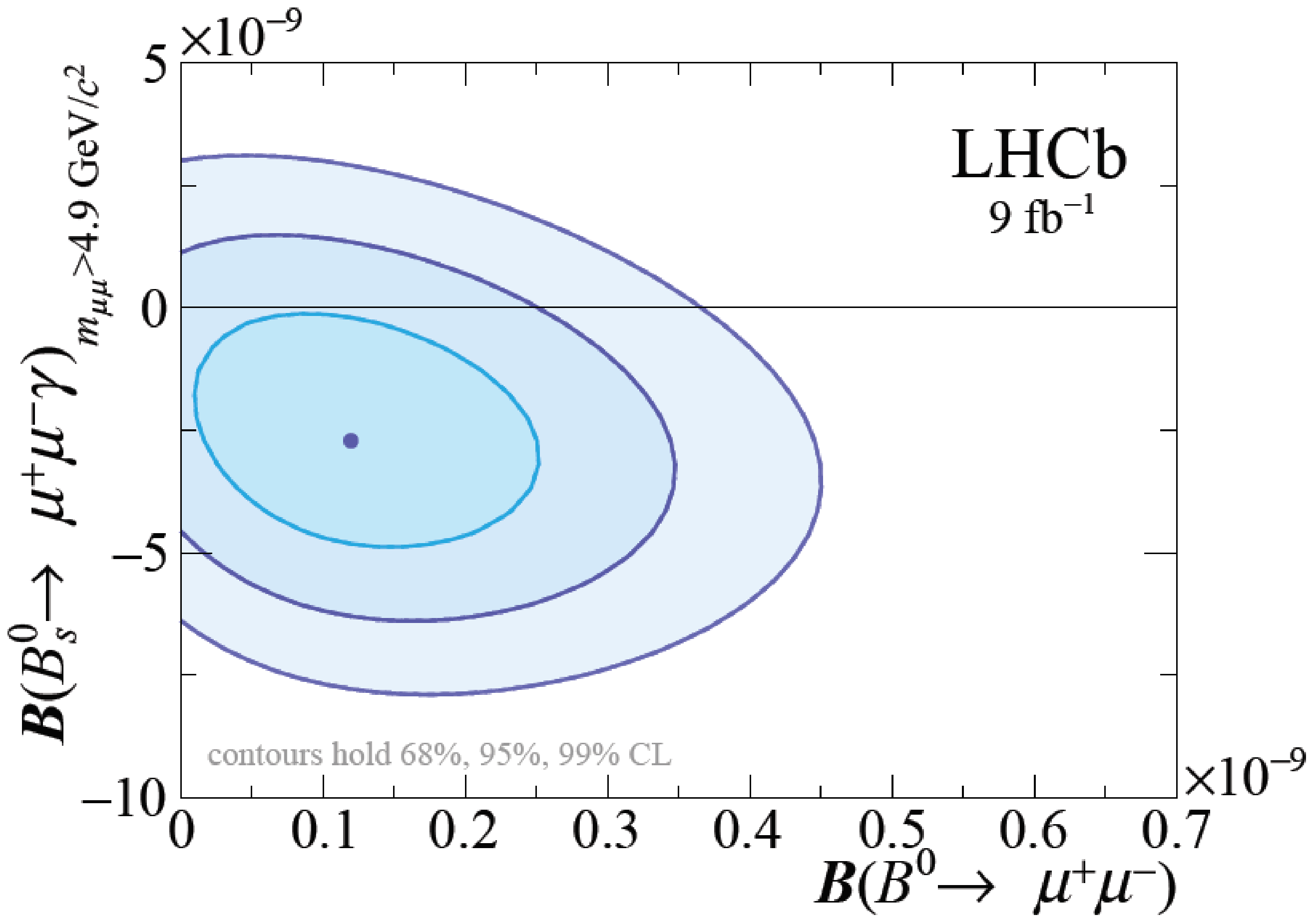
$B \to \mu\mu$ low BDT region

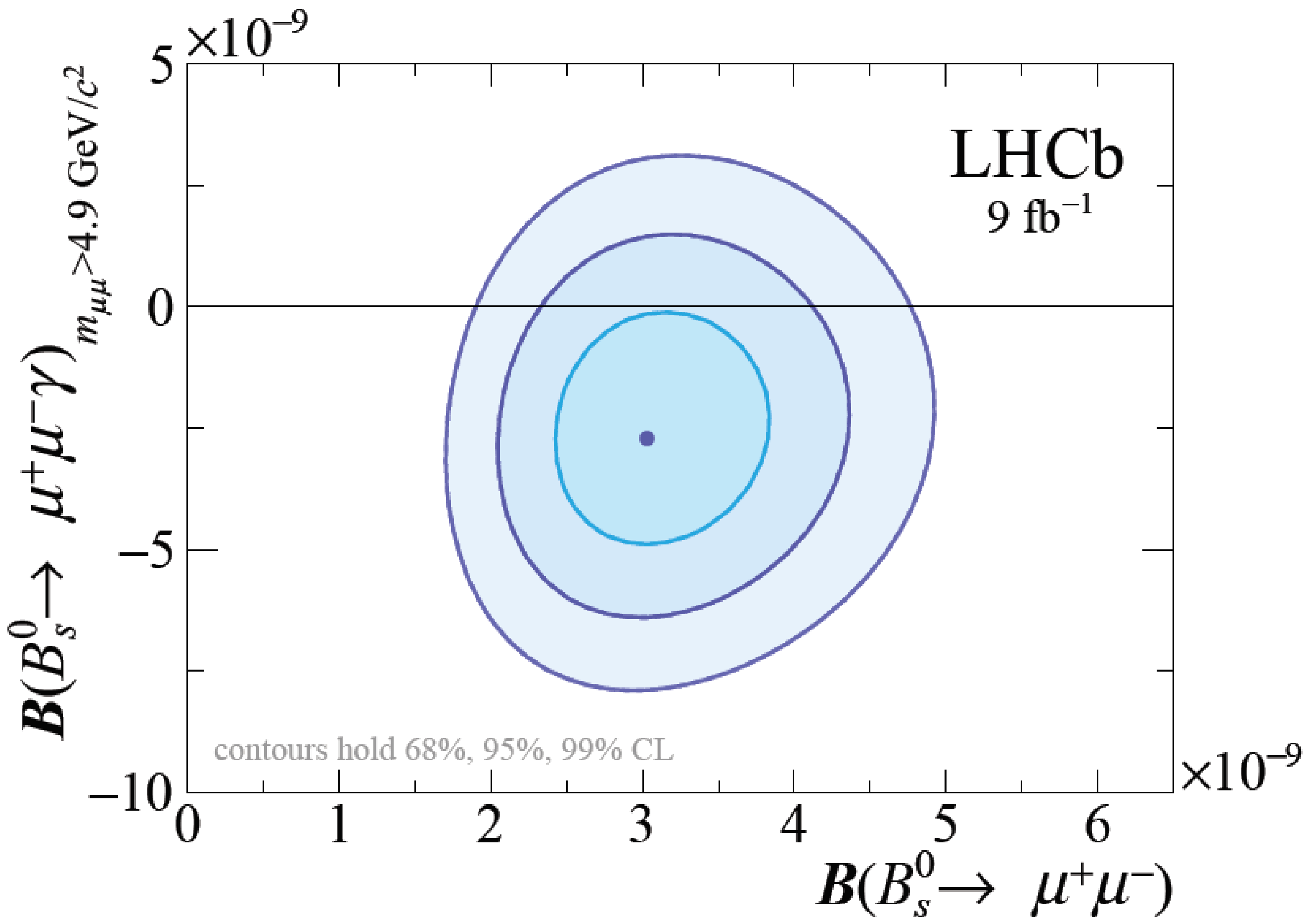


$B \to \mu\mu$ high BDT region

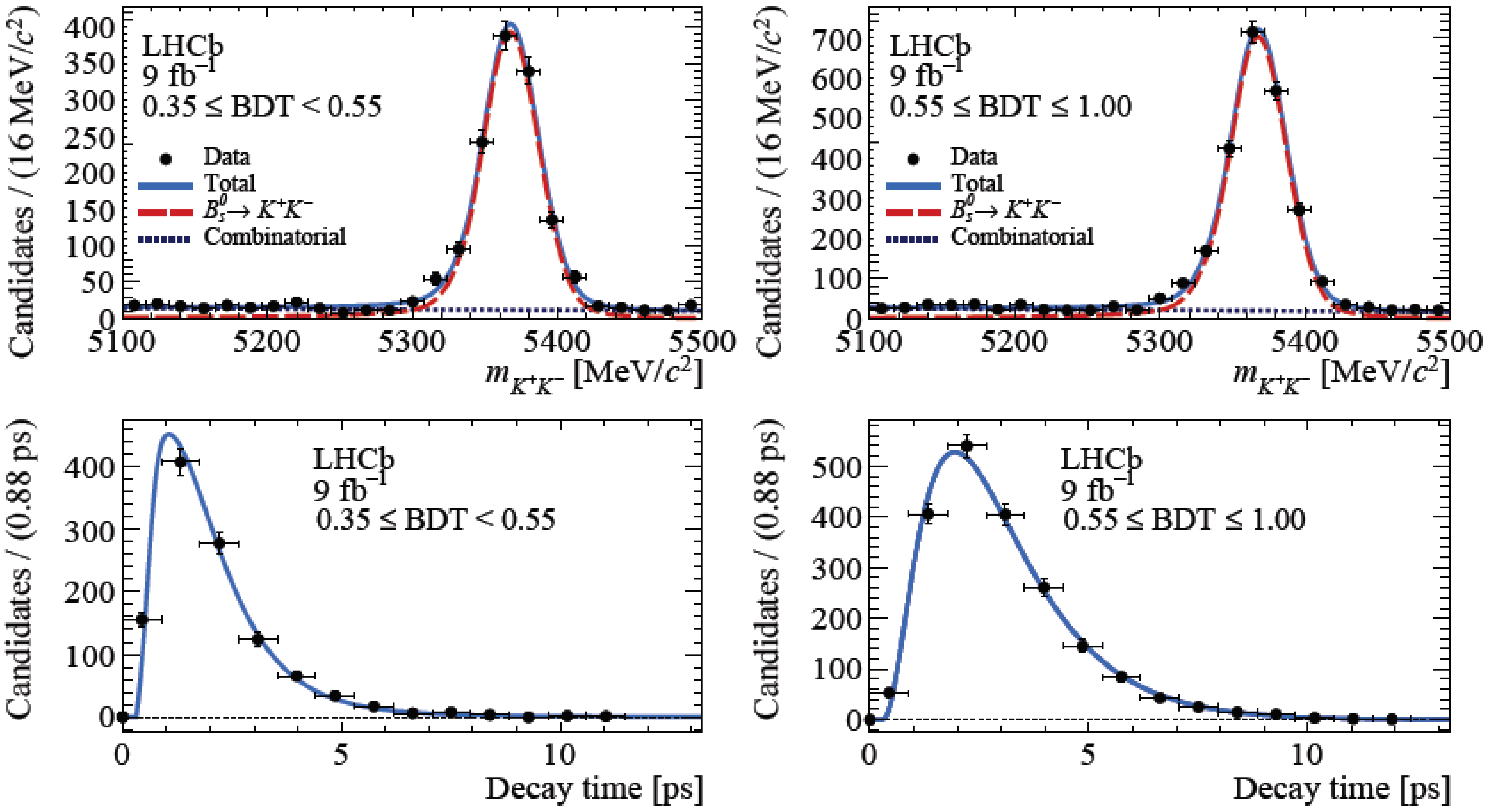


$B \to \mu\mu(\gamma)$ fit results



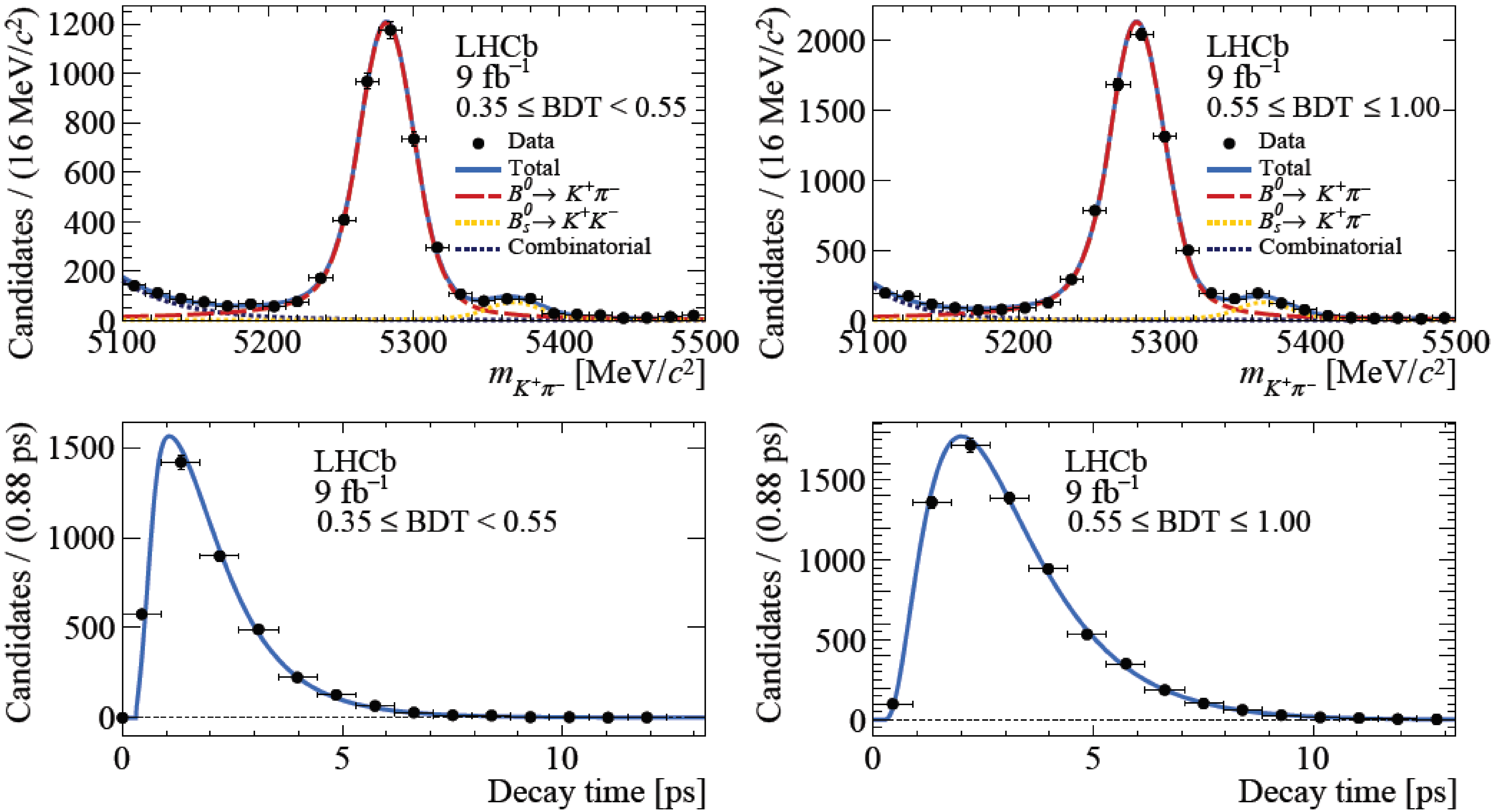


$B_s^0 \to K^+K^-$ lifetime measurement



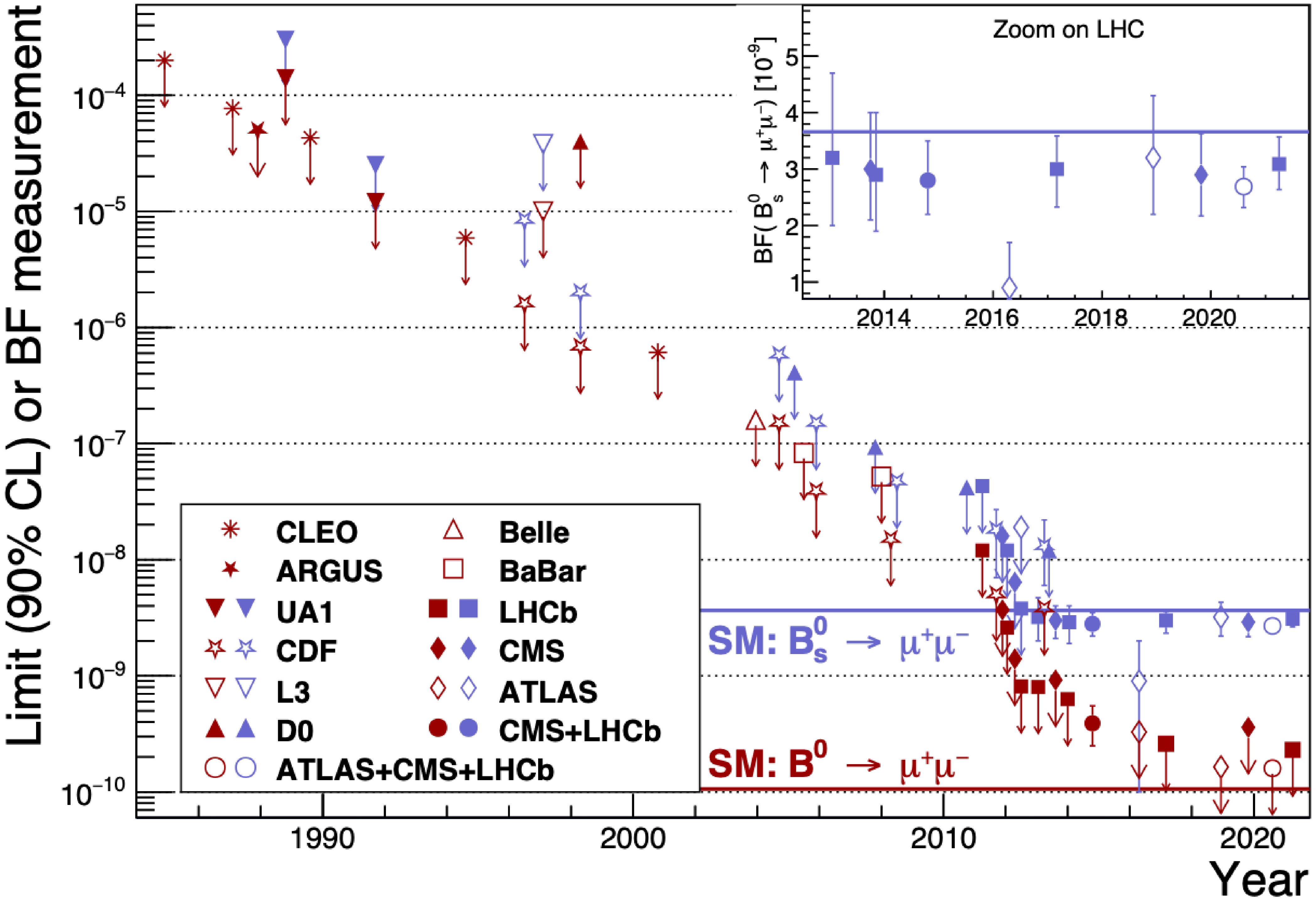
$\tau_{K^+K^-} = 1.433 \pm 0.026\,\text{ps}$ consistent with WA

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



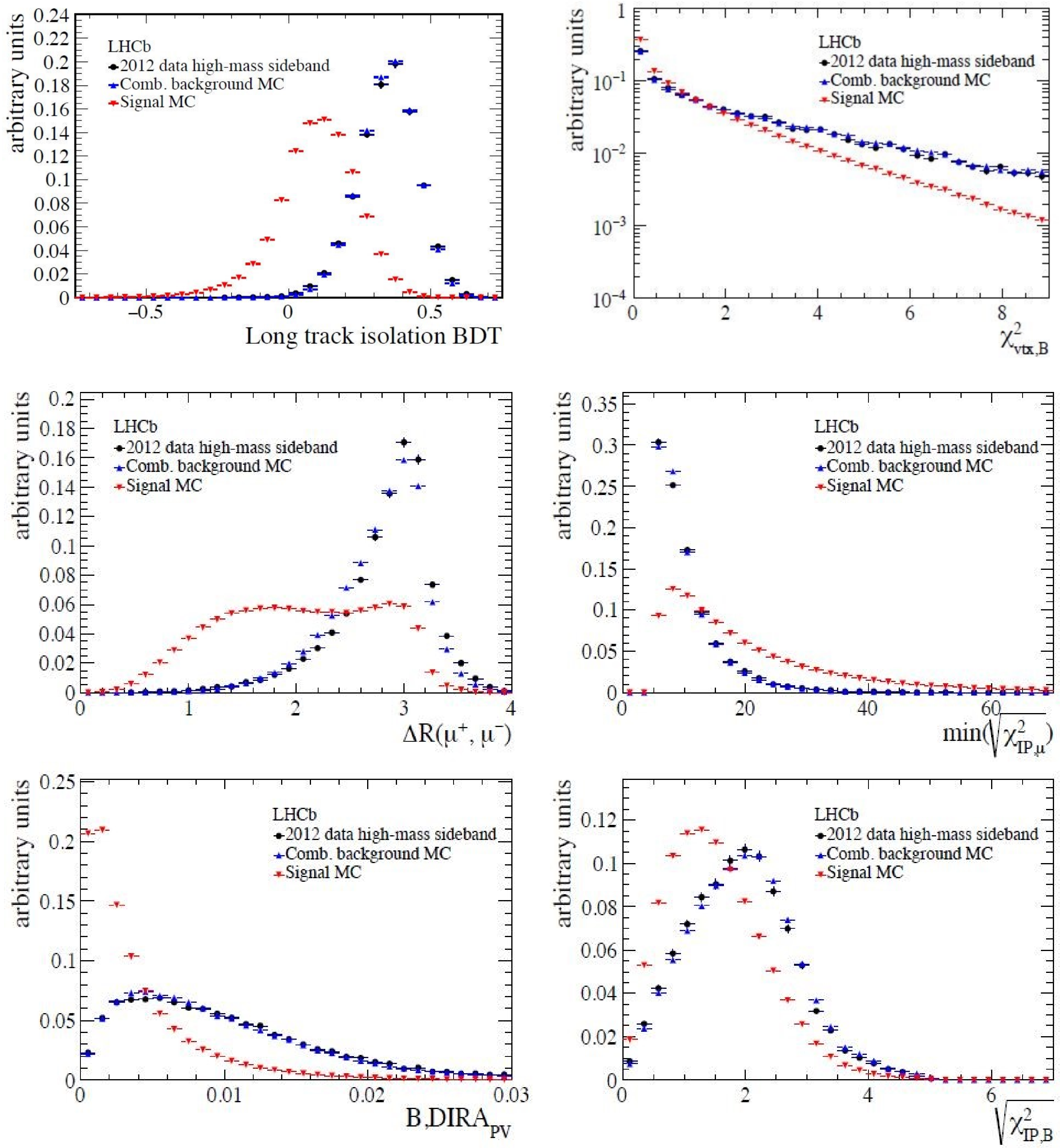
$\tau_{K^+\pi^-} = 1.512 \pm 0.016\,\text{ps}$ consistent with WA

$B \to \mu\mu$ measurement history

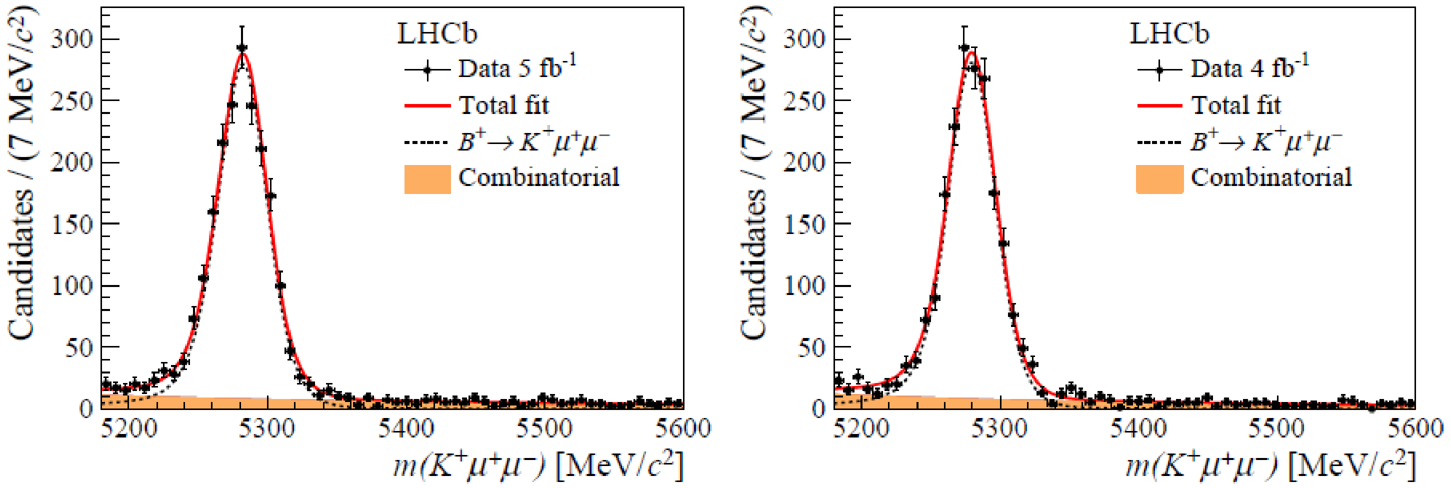


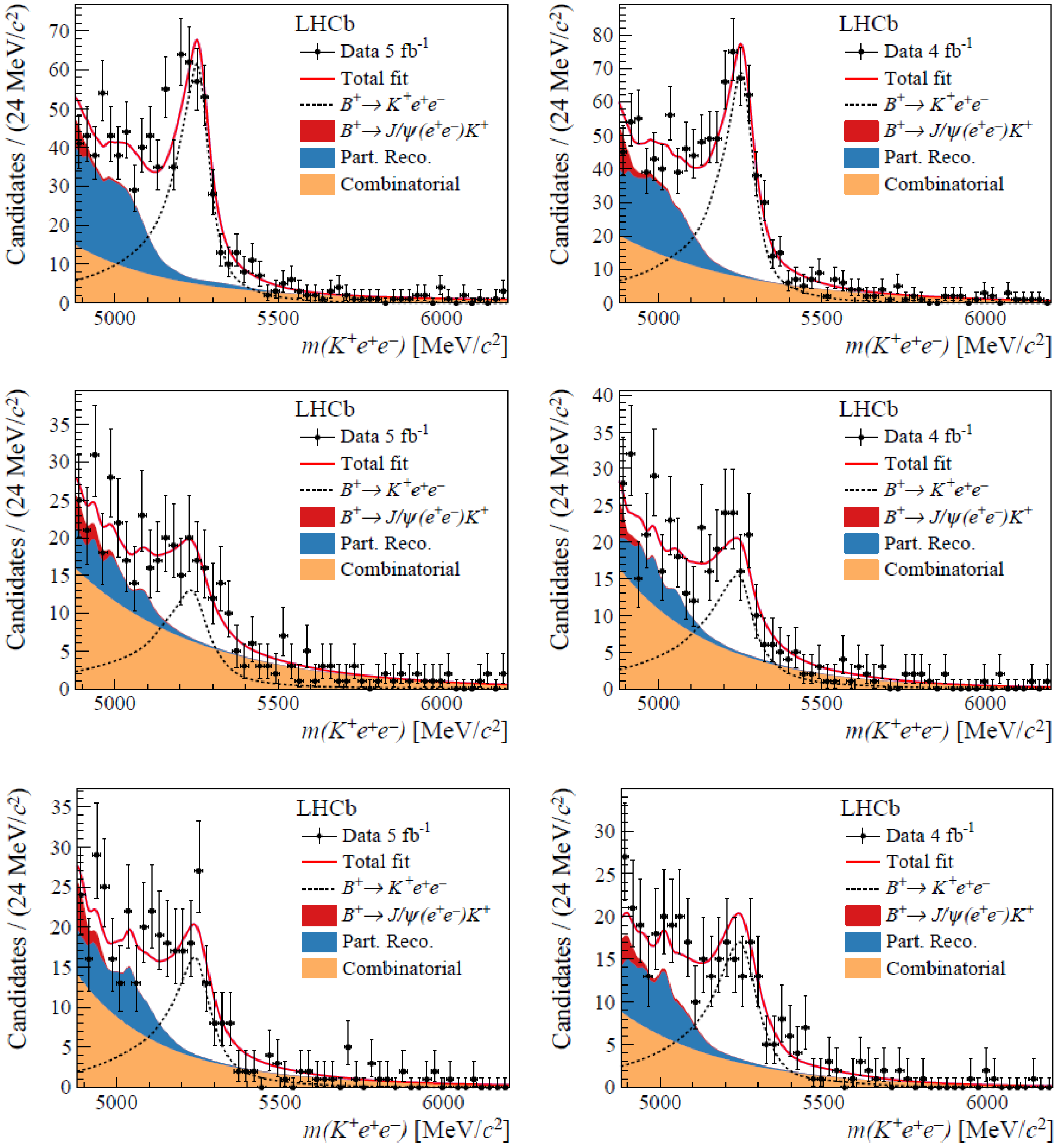
$B \to \mu\mu$ BDT definition

- Long track isolation
- VELO track isolation
- B_ENDVERTEX_CHI2: vertex χ^2 of the B candidate
- B_IPS_OWNPV: impact parameter significance of the B candidate with respect to the primary vertex
- B_ACOSDIRA_OWNPV: angle between the B direction and the vector joining the primary and secondary vertices
- mu_DeltaR: $\sqrt{\Delta\phi^2 + \Delta\eta^2}$, where $\Delta\phi$ and $\Delta\eta$ are the azimuthal angle and pseudo-rapidity differences between the two muons
- mu_MINIPS: smallest value among the muon impact parameter significance of the two muons with respect to the primary vertex associated to the $B^0_{(s)} \to \mu^+\mu^-$ candidate



$B \to K l^+ l^-$ events split by trigger categories





LHCb perspectives

Table 7.2: Estimated yields of $b \to se^+e^-$ and $b \to de^+e^-$ processes and the statistical uncertainty on R_X in the range $1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$ extrapolated from the Run 1 data. A linear dependence of the $b\bar{b}$ production cross section on the pp centre-of-mass energy and unchanged Run 1 detector performance are assumed. Where modes have yet to be observed, a scaled estimate from the corresponding muon mode is used.

Yield	Run 1 result	$9\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
$B^+ \to K^+e^+e^-$	254 ± 29 [274]	1 120	3 300	7 500	46 000
$B^0 \to K^{*0}e^+e^-$	111 ± 14 [275]	490	1 400	3 300	20 000
$B^0_s \to \phi e^+e^-$	–	80	230	530	3 300
$\Lambda^0_b \to pKe^+e^-$	–	120	360	820	5 000
$B^+ \to \pi^+e^+e^-$	–	20	70	150	900
R_X precision	**Run 1 result**	**$9\,\mathrm{fb}^{-1}$**	**$23\,\mathrm{fb}^{-1}$**	**$50\,\mathrm{fb}^{-1}$**	**$300\,\mathrm{fb}^{-1}$**
R_K	$0.745 \pm 0.090 \pm 0.036$ [274]	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$ [275]	0.052	0.031	0.020	0.008
R_ϕ	–	0.130	0.076	0.050	0.020
R_{pK}	–	0.105	0.061	0.041	0.016
R_π	–	0.302	0.176	0.117	0.047

Physics case for an LHCb Upgrade II
arxiv:1808.08865

LHCb perspectives

Table 10.1: Summary of prospects for future measurements of selected flavour observables for LHCb, Belle II and Phase-II ATLAS and CMS. The projected LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. The Belle-II sensitivities are taken from Ref. [608].

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ LUV studies					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Physics case for an LHCb Upgrade II
arxiv:1808.08865

Belle II perspectives

Table 5: Expected errors on several selected observables in radiative and electroweak penguin B decays. Note that 50 ab^{-1} projections for B_s decays are not provided as we do not expect to collect such a large $\Upsilon(5S)$ data set.

The Belle II Physics Book, arxiv:1808.10567

Observables	Belle	Belle II	
	(2017)	5 ab^{-1}	50 ab^{-1}
$\mathcal{B}(B \to K^{*+}\nu\overline{\nu})$	$< 40 \times 10^{-6}$	25%	9%
$\mathcal{B}(B \to K^{+}\nu\overline{\nu})$	$< 19 \times 10^{-6}$	30%	11%
$A_{CP}(B \to X_{s+d}\gamma)$ $[10^{-2}]$	$2.2 \pm 4.0 \pm 0.8$	1.5	0.5
$S(B \to K_S^0\pi^0\gamma)$	$-0.10 \pm 0.31 \pm 0.07$	0.11	0.035
$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$	0.23	0.07
$A_{FB}(B \to X_s\ell^+\ell^-)$ $(1 < q^2 < 3.5$ GeV$^2/c^4)$	26%	10%	3%
$Br(B \to K^+\mu^+\mu^-)/Br(B \to K^+e^+e^-)$ $(1 < q^2 < 6$ GeV$^2/c^4)$	28%	11%	4%
$Br(B \to K^{*+}(892)\mu^+\mu^-)/Br(B \to K^{*+}(892)e^+e^-)$ $(1 < q^2 < 6$ GeV$^2/c^4)$	24%	9%	3%
$\mathcal{B}(B_s \to \gamma\gamma)$	$< 8.7 \times 10^{-6}$	23%	–
$\mathcal{B}(B_s \to \tau\tau)$ $[10^{-3}]$	–	< 0.8	–

$$BF(B^0 \to \mu\mu)_{BABAR} < 5.2 \times 10^{-8} \text{ @ } 320\, fb^{-1} \Rightarrow < 4 \times 10^{-9} \text{ @ } 50\, ab^{-1}$$

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CMS perspectives

CMS-PAS-FTR-18-013

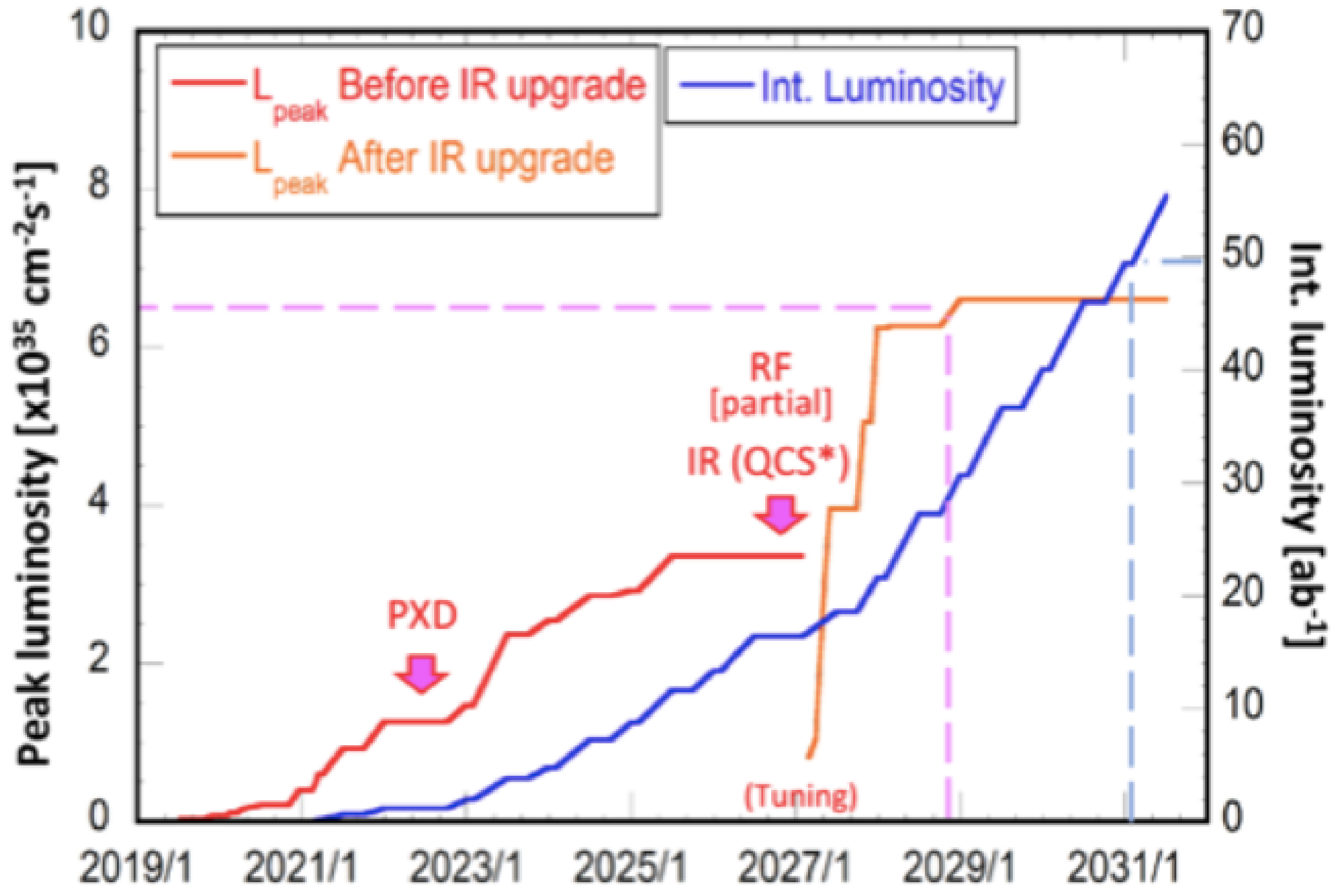
Table 3: Estimated analysis sensitivity for different integrated luminosities. Columns in the table, from left to right: the total integrated luminosity, the median expected number of reconstructed B_s^0 and B^0 mesons, the total uncertainties on the $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ branching fractions, the range of the significance of B^0 observation (the range indicates the $\pm 1\sigma$ of the distribution of significance) and the statistical uncertainty on the $B_s^0 \to \mu^+\mu^-$ effective lifetime.

$\mathcal{L}$ (fb^{-1})	$N(B_s)$	$N(B^0)$	$\delta\mathcal{B}(B_s \to \mu\mu)$	$\delta\mathcal{B}(B^0 \to \mu\mu)$	$\sigma(B^0 \to \mu\mu)$	$\delta[\tau(B_s)]$(stat-only)
300	205	21	12%	46%	$1.4 - 3.5\sigma$	0.15 ps
3000	2048	215	7%	16%	$6.3 - 8.3\sigma$	0.05 ps

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH#Projections

SuperKEKB luminosity projection

- Peak luminosity projections:



From Filippo Dattola, Moriond EW
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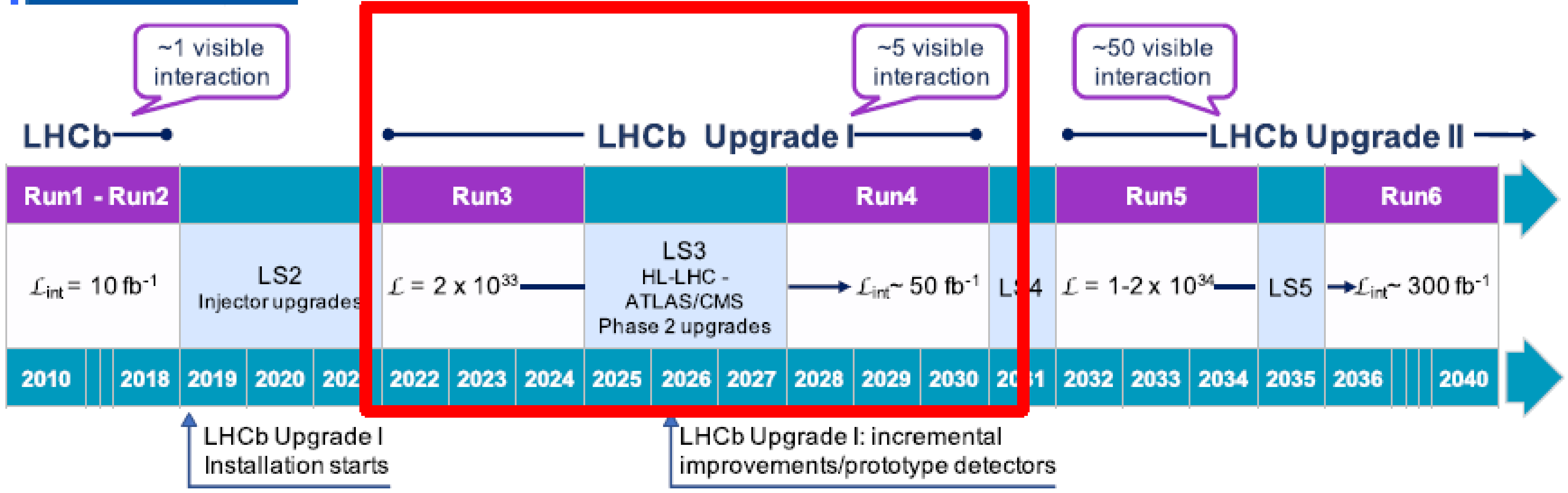
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH#Projections

LHCb upgrade plan

LHCb upgrades plan & strategy



LHCb Phase-I upgrade ongoing now during LS2 for Run3 and Run4

- full software trigger and readout all detectors at 40MHz
- replace tracking detectors + PID + VELO and $\mathscr{L} \sim 2 \times 10^{33}$ sec^{-1} cm^{-2}
- Consolidate PID, tracking and ECAL during LS3

LHCb Phase-II upgrade during LS4 beyond Run4

- Use new detector technologies + timing to increase $\mathscr{L} \sim 1.5 \times 10^{34}$ sec^{-1} cm^{-2}

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