LHCb results on lepton flavour universality ratios and very rare *B*-meson decays

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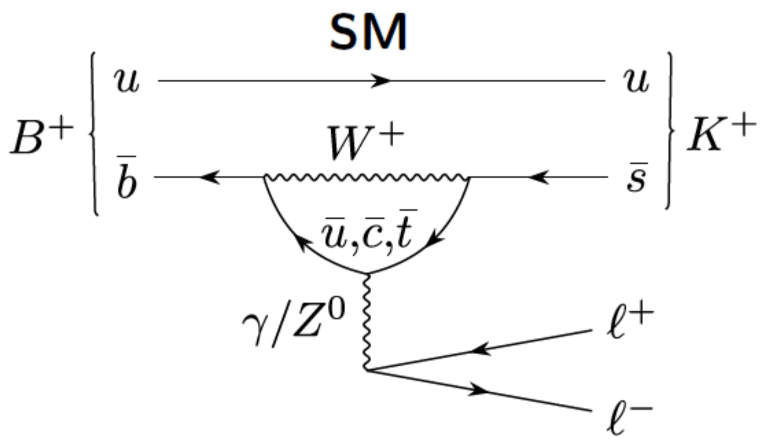
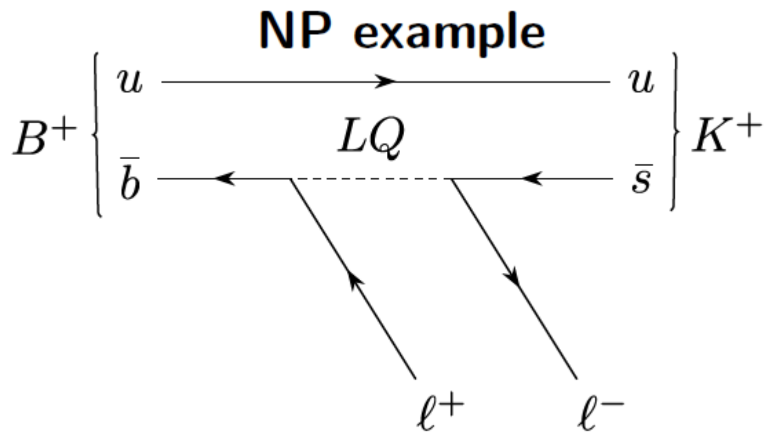
Flavour anomalies in $b \to sl^+l^-$ transitions

- Processes mediated by $b \to sl^+l^-$ FCNC transitions can be sensitive probes of NP
- Coherent set of tensions with SM predictions observed over the past decade

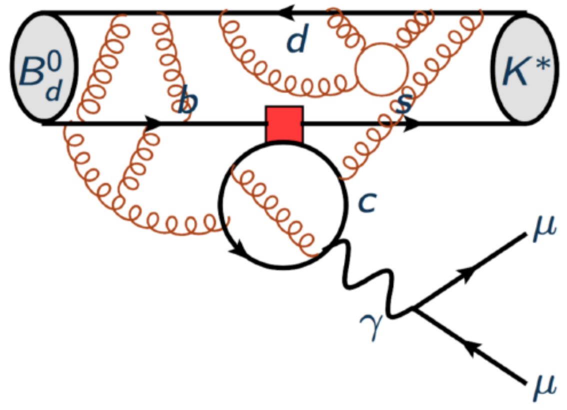


- Three main categories of observables:
  - **Branching fractions**
    $B \to K^{(*)}\mu^+\mu^-, B_s \to \phi\mu^+\mu^-, \Lambda_b \to \Lambda\mu^+\mu^-, \ldots$
  - **Angular analyses**
    $B \to K^{(*)}\mu^+\mu^-, B_s \to \phi\mu^+\mu^-, \Lambda_b \to \Lambda\mu^+\mu^-, \ldots$
  - **Lepton flavour universality involving μ/e ratios**
    $B^0 \to K^{(*)0}l^+l^-, B^+ \to K^{(*)+}l^+l^-, \Lambda_b \to pK^-l^+l^- \ldots$

} Michal Kreps' talk tomorrow



BFs and angular observables more affected by hadronic uncertainties



LFU observable have very clean theory predictions

Searches for LFV decays: Elena Dell'Occo yesterday
LFU tests in $b \to cl\nu$: Mark Smith this morning

Lepton flavour universality test

- Couplings of gauge bosons to leptons are independent on lepton flavour in SM (*flavour universality*)
- Ratios of the form

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

are free of hadronic uncertainties and predicted by SM with $O(10^{-2})$ precision (from QED corrections)

[Bordone et al, EPJC76, 440 (2016)]

Any significant deviation from SM prediction would be unambiguous sign of New Physics

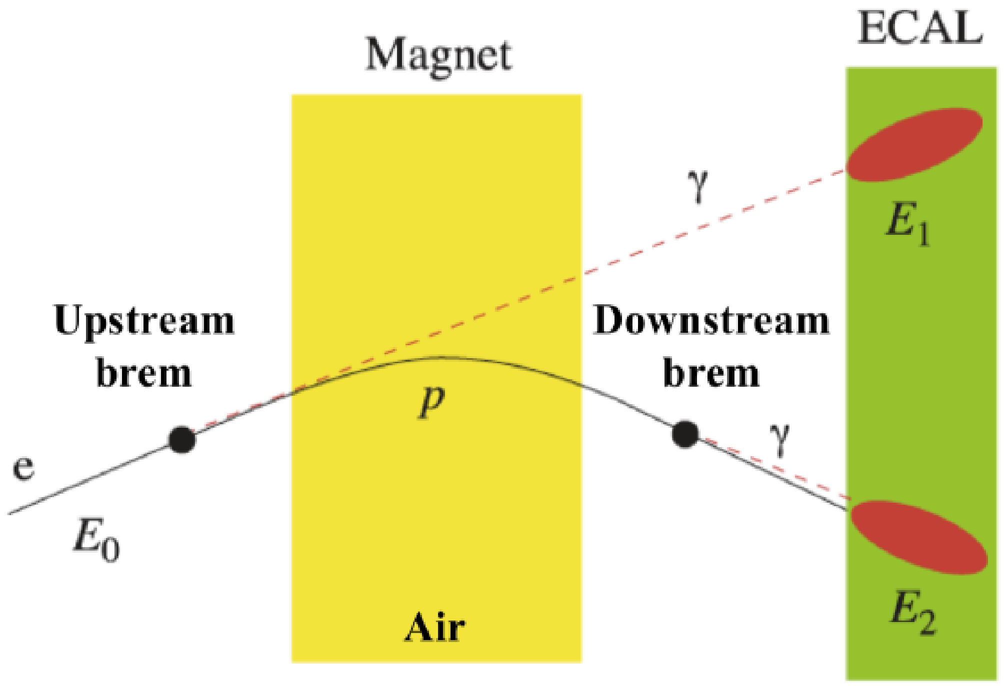
- LHCb has updated the measurement of

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

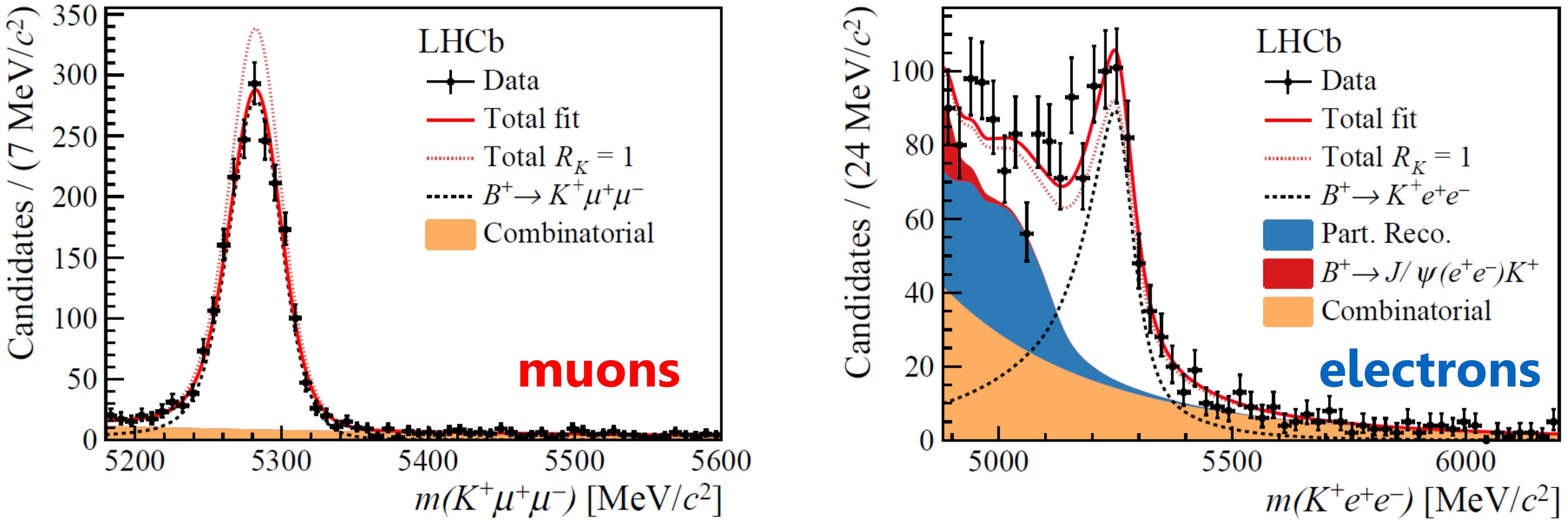
Full Run 1 + Run 2 dataset, 2x the number of B mesons used in previous measurement, where a 2.5σ tension with SM was observed (PRL122 (2019) 191801)

Electrons vs muons

- Most electrons will emit one bremsstrahlung energetic photon before the magnet
  → Recover brem. energy loss by "adding" the cluster energy back to the electron momentum



Plots from previous result, <u>PRL 122 (2019) 191801</u>



- Hardware calorimeter trigger requires higher thresholds than muon trigger, due to high occupancy in ECAL
  → 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
- $e^\pm$ have lower PID and tracking efficiency and worse p resolution than muons

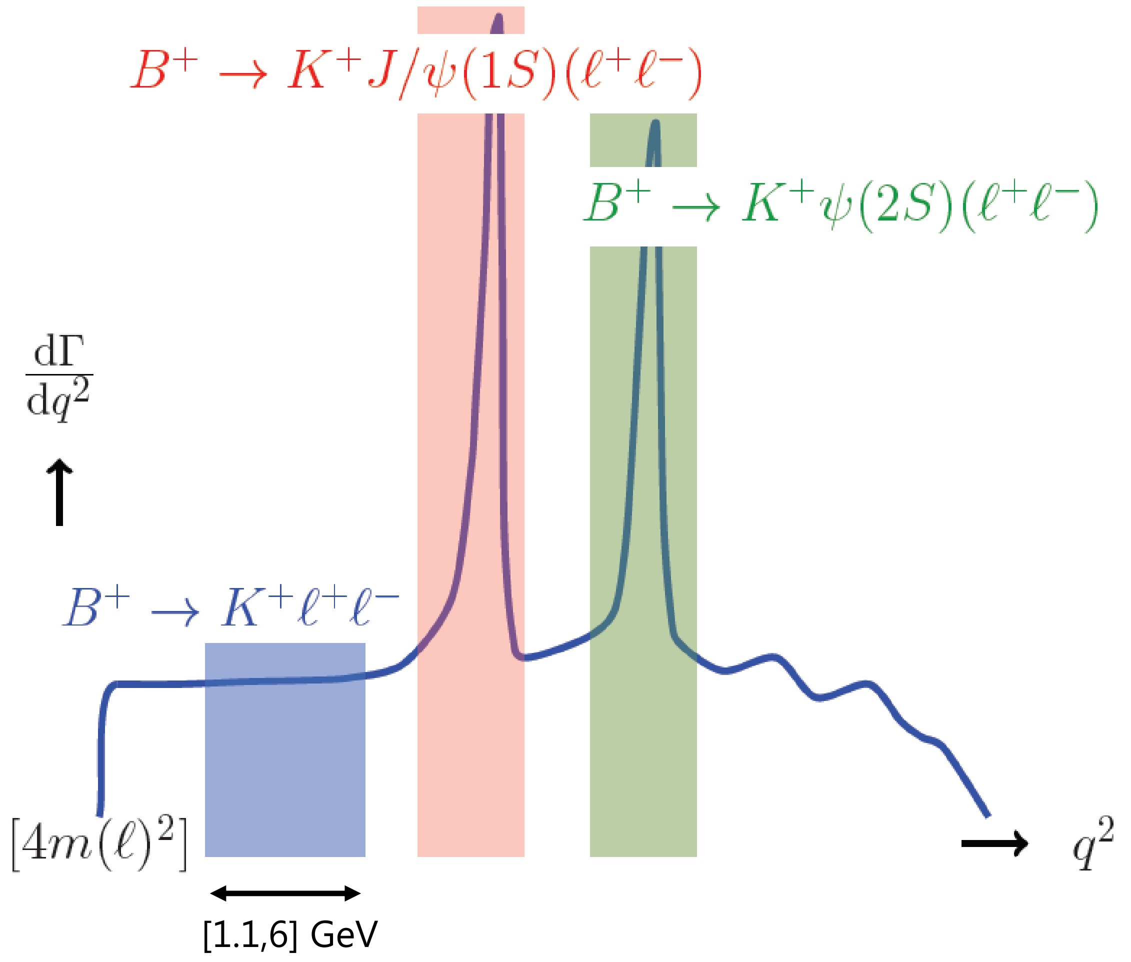
Crucial the control of the difference in efficiency between muons and electrons

R_K measurement strategy

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

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

- LFU in $B^+ \to J/\psi[l^+l^-]K^+$ decays experimentally proved at 0.4% precision
- 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
- Efficiencies computed using simulation that is calibrated with control channels in data



q^2 = dilepton mass squared

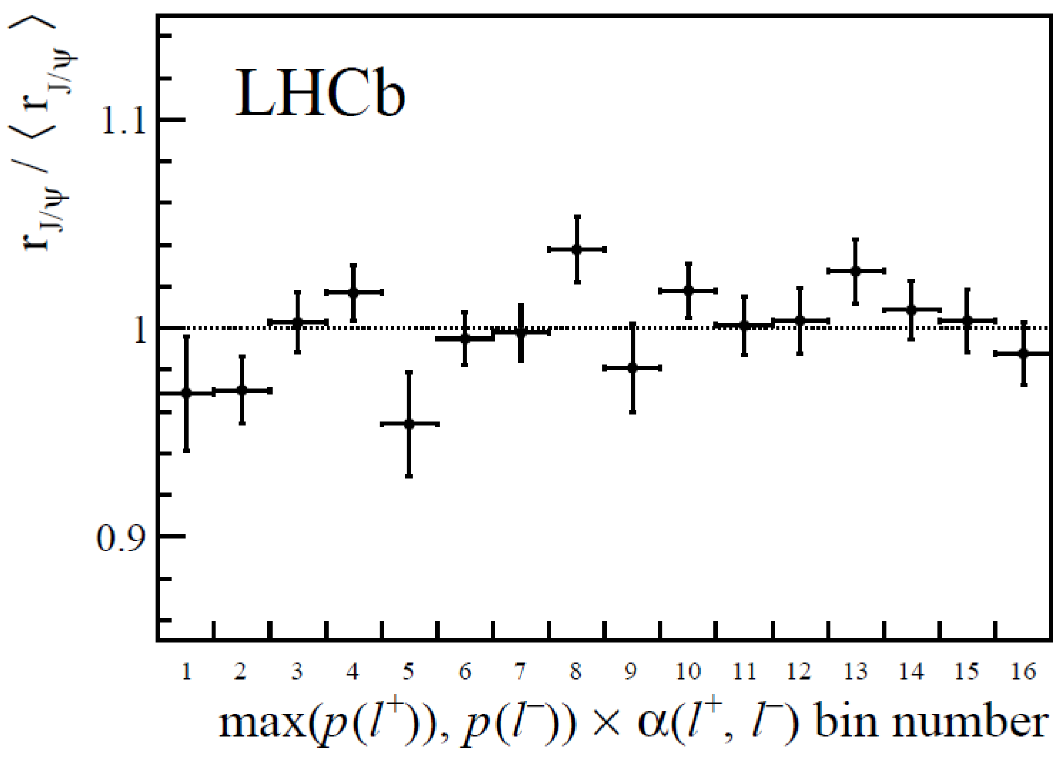
Cross check: $r_{J/\psi}$ vs kinematics

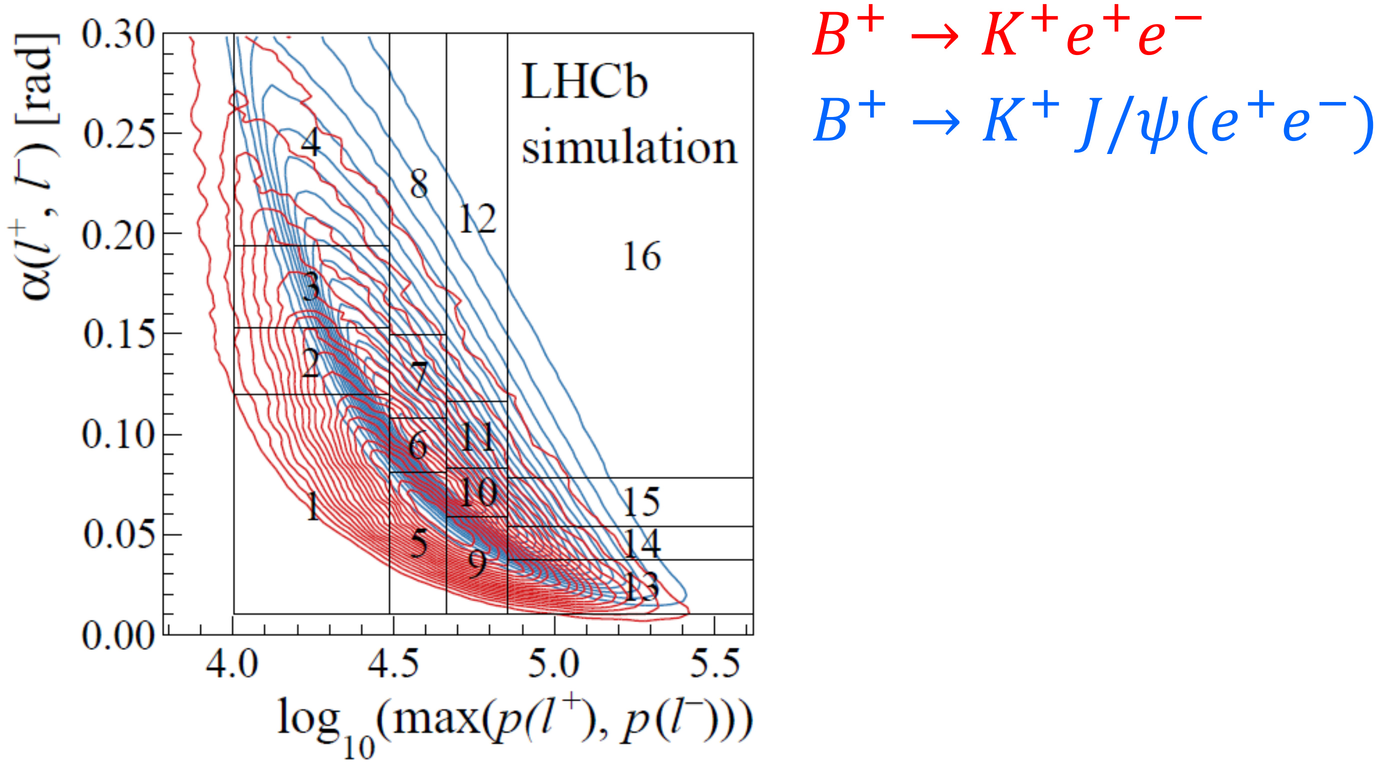
arxiv:2103.11769

- To ensure that the efficiencies are under control, check: $r_{J/\psi} = \frac{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))} = 1$ (within 0.4%, PDG)

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

- Test of efficiencies vs 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.

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

arxiv:2103.11769

Measurement of the double ratio

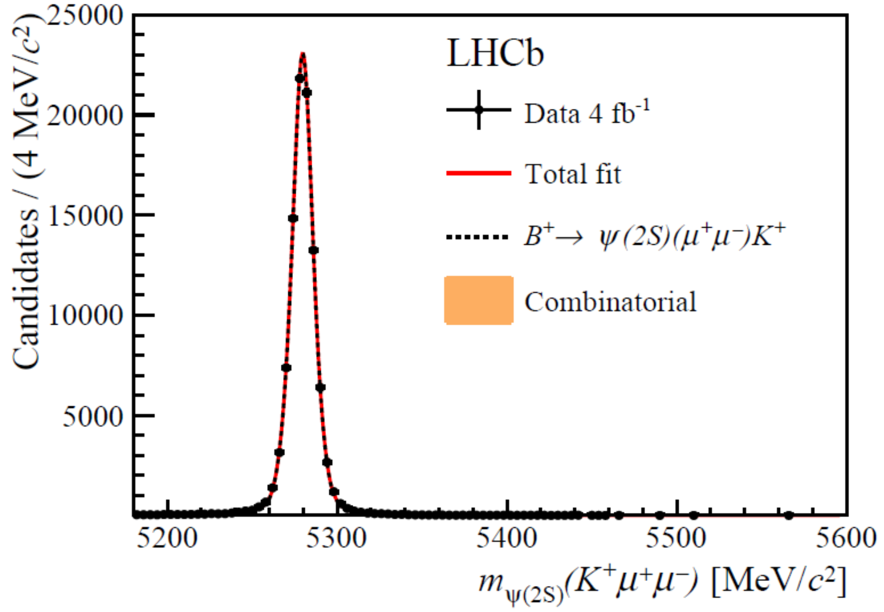
$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(e^+e^-))}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))}$$

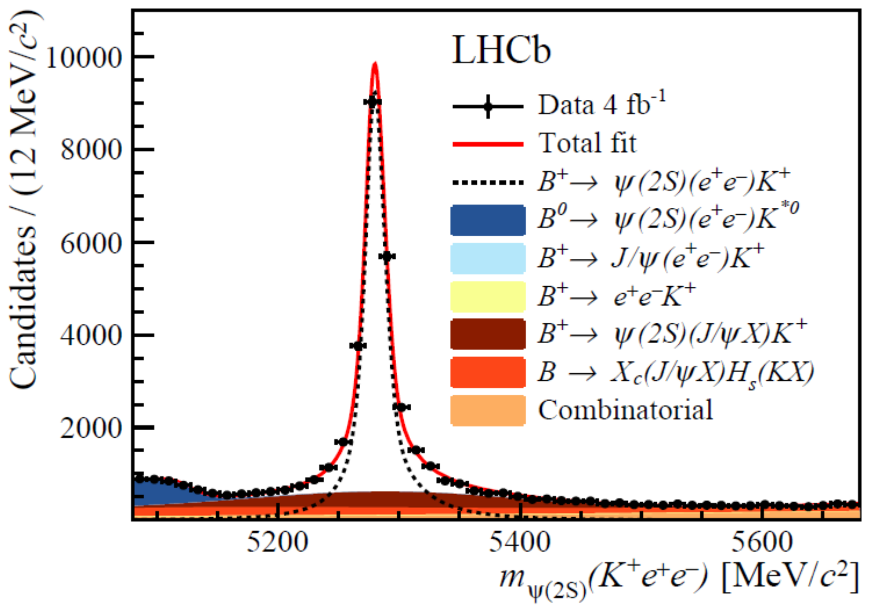
- Independent validation of double-ratio procedure at q^2 away from J/ψ
- Result well compatible with unity:

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

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

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

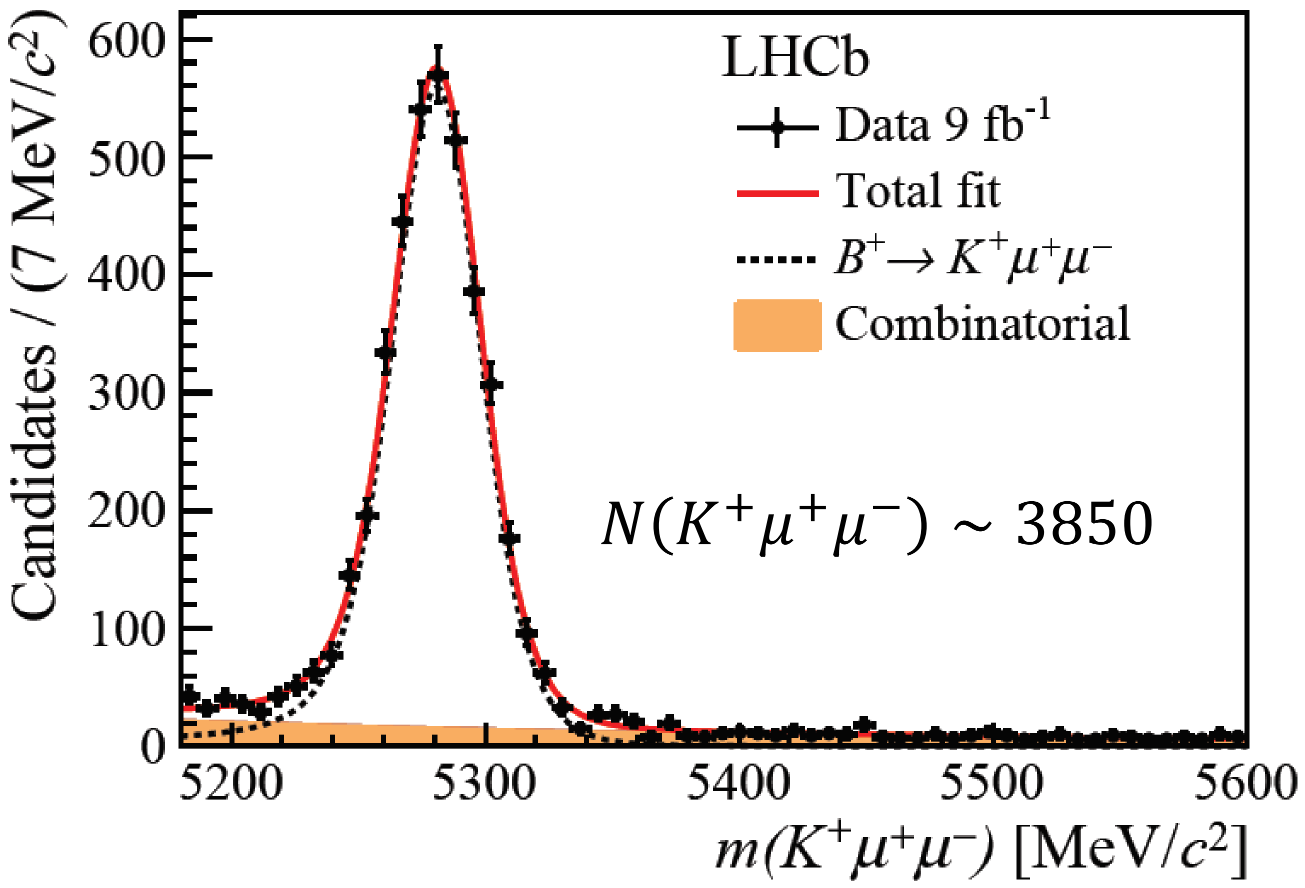


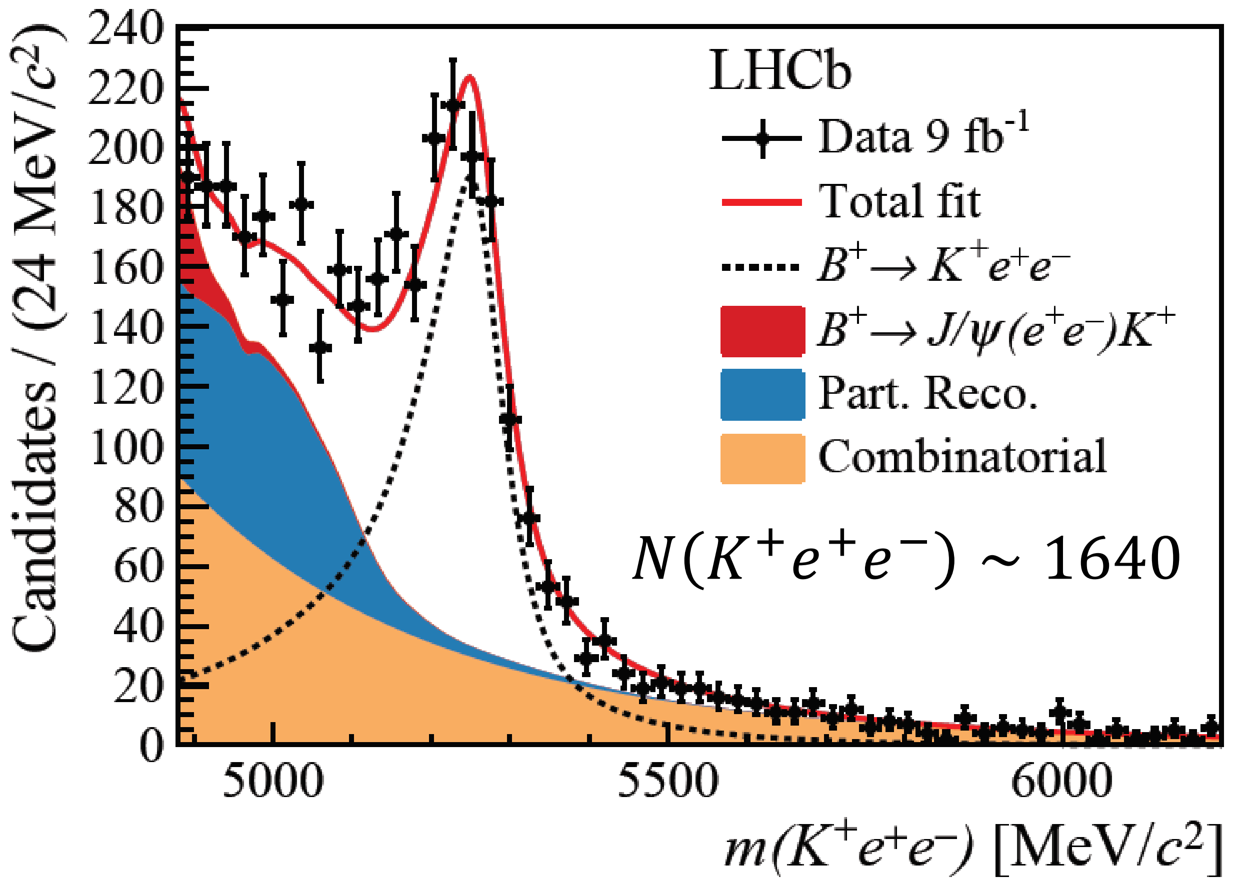


Measurement of R_K

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 $B^+ \to K^+l^+l^-$ and $B^+ \to J/\psi(l^+l^-)K^+$ decays





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

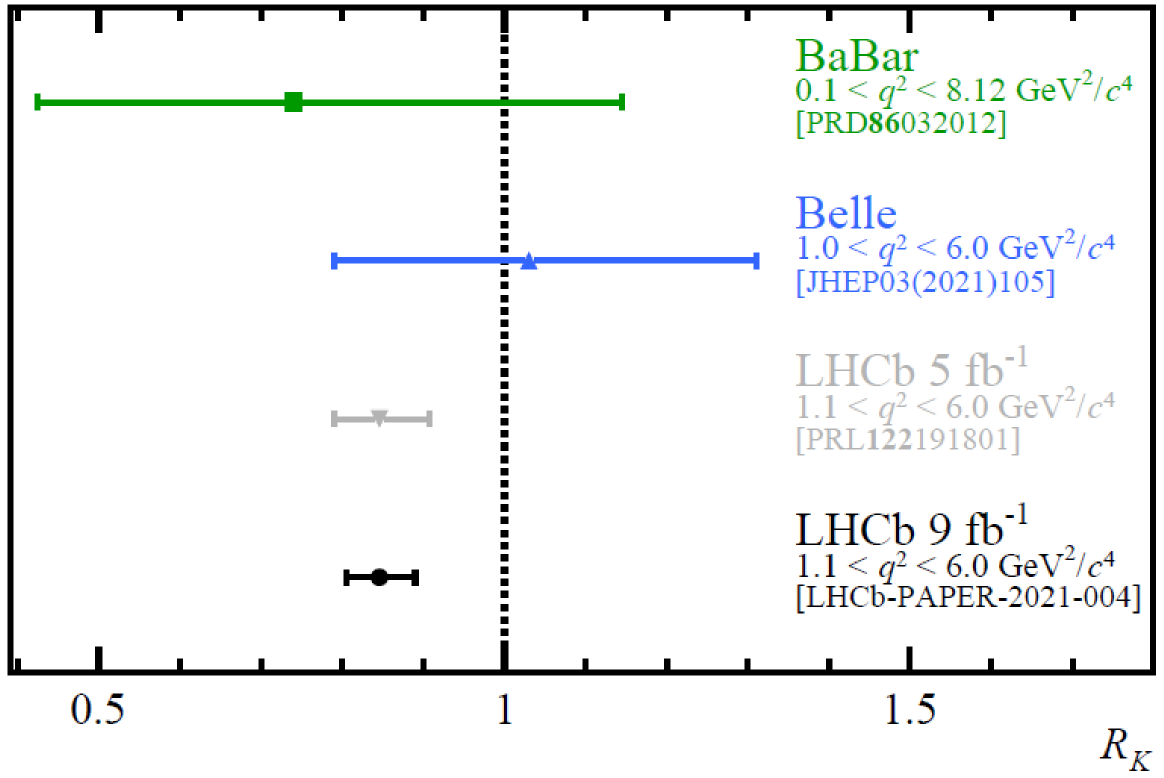
Measurement of R_K

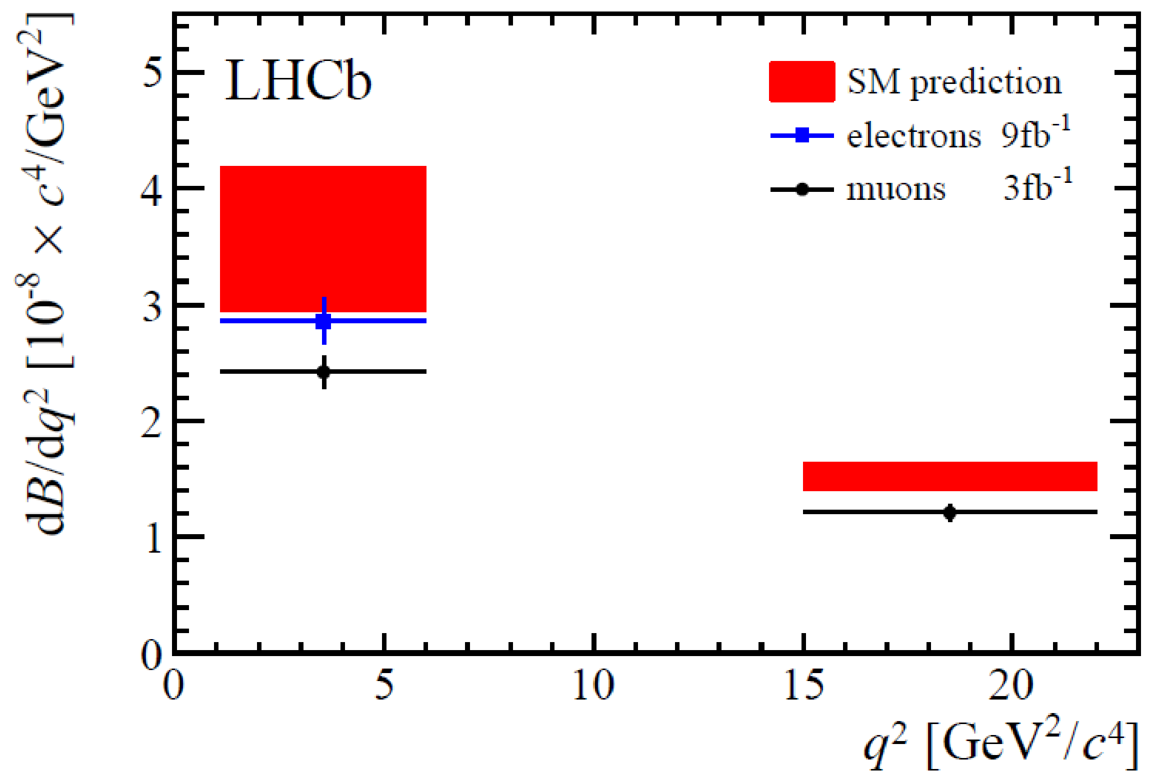
arxiv:2103.11769

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

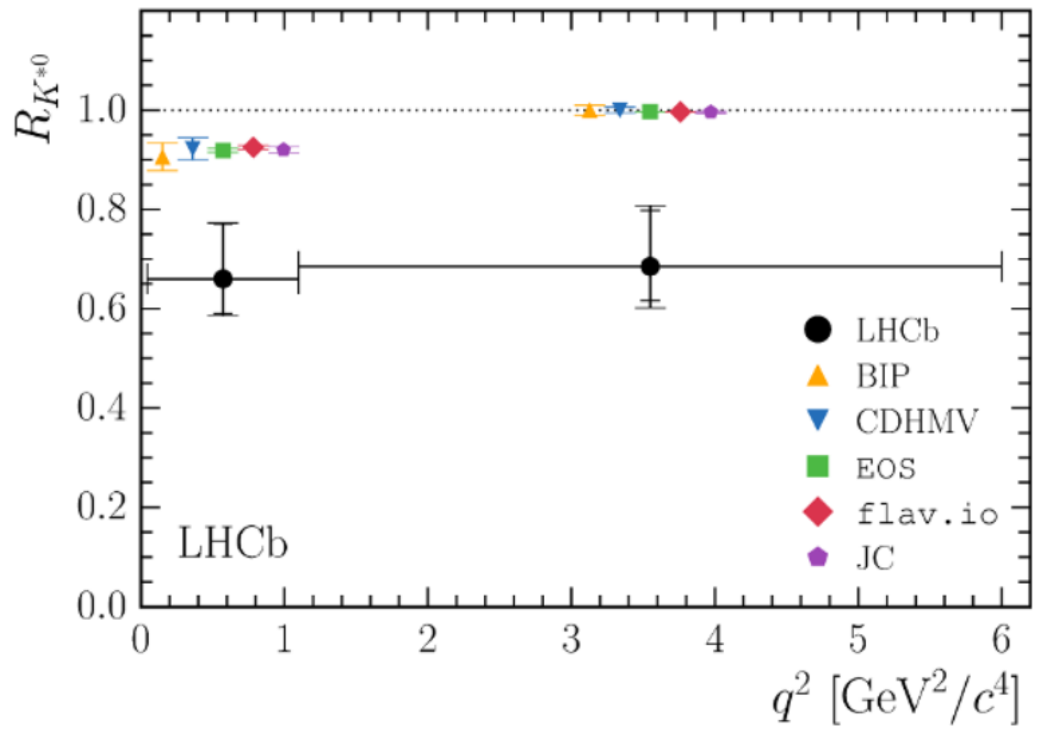
- p-value under SM hypothesis: 0.0010
  → evidence of LFU violation at 3.1 σ
- Compatibility with the SM obtained by integrating the profiled likelihood as a function of R_K above 1
  - Taking into account the 1% theory uncertainty on R_K
- Using R_K and previous measurement of $BF(B^+ \to K^+\mu^+\mu^-)$ [JHEP06(2014)133] determine $BF(B^+ \to K^+e^+e^-)$.
- It suggests that electrons are more SM than muons

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

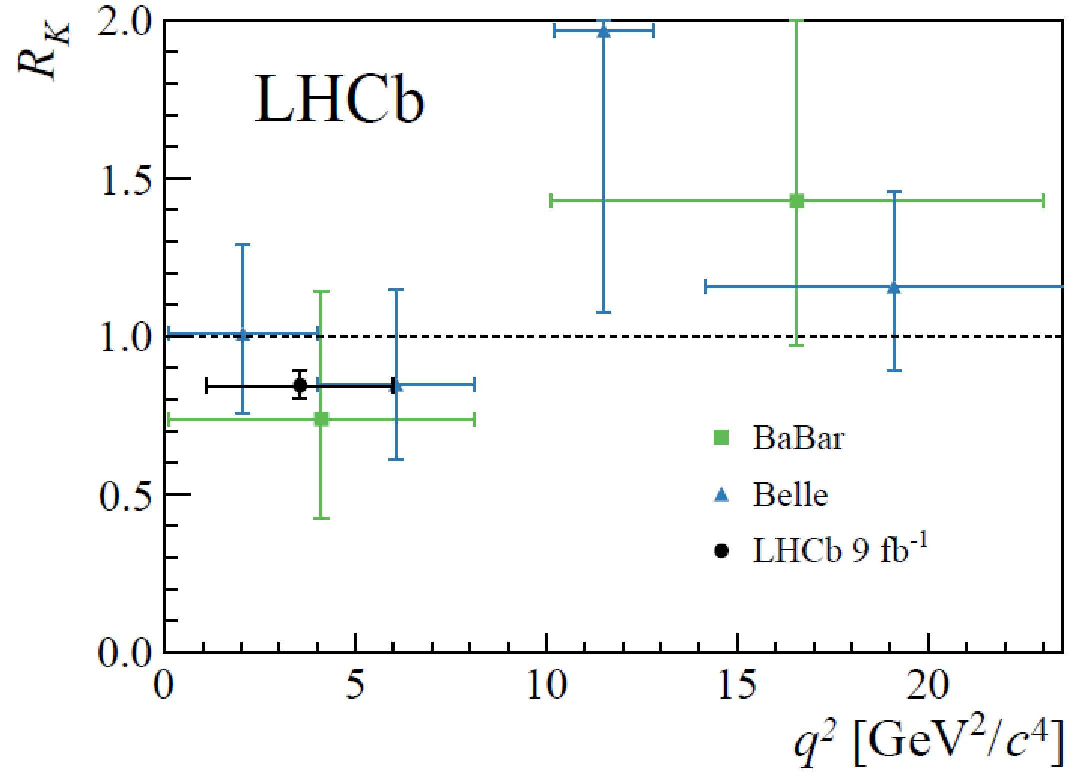


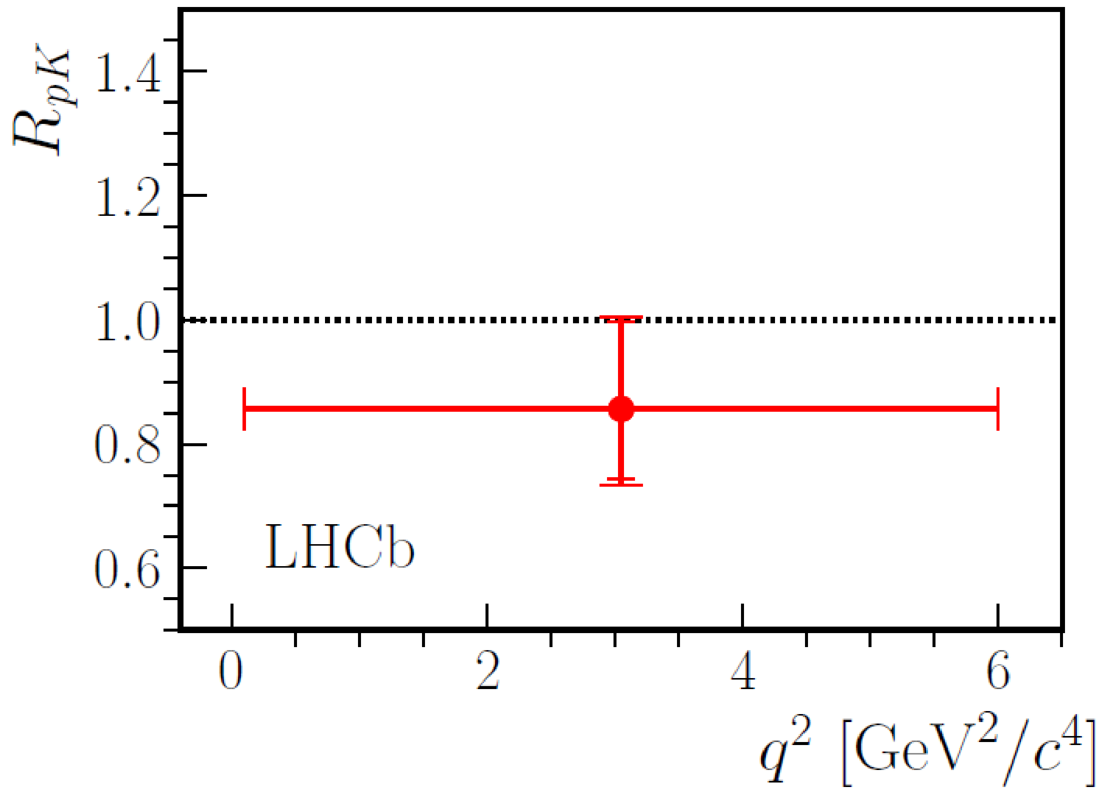


Lepton flavour universality tests



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





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

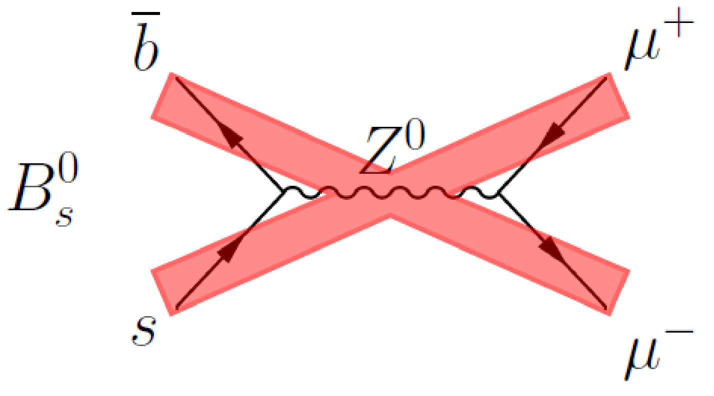
Top right : $B^+ \to K^+ l^+ l^-$ R_K, $9 fb^{-1}$
[arxiv:2103.11769]

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

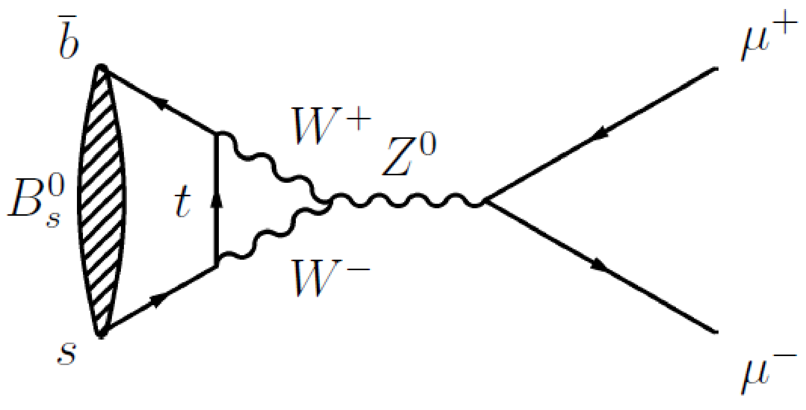
Work in progress to analyse more data and more decay channels. Exciting times ahead.

$B \to l^+ l^-$ decays in the Standard Model

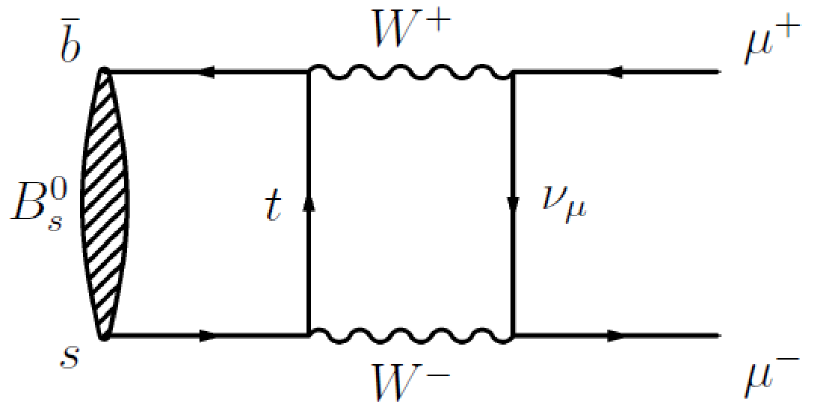
- In the SM, B^0 and B_s^0 decays to two leptons are FCNC and helicity suppressed



(tree)



(penguin)



(box)

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

single Wilson coefficient and single hadronic decay constant

helicity suppression of BF:
$e : \mu : \tau = 2.3\ 10^{-5} : 1 : 210$

- Very clean prediction of the SM branching fractions

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

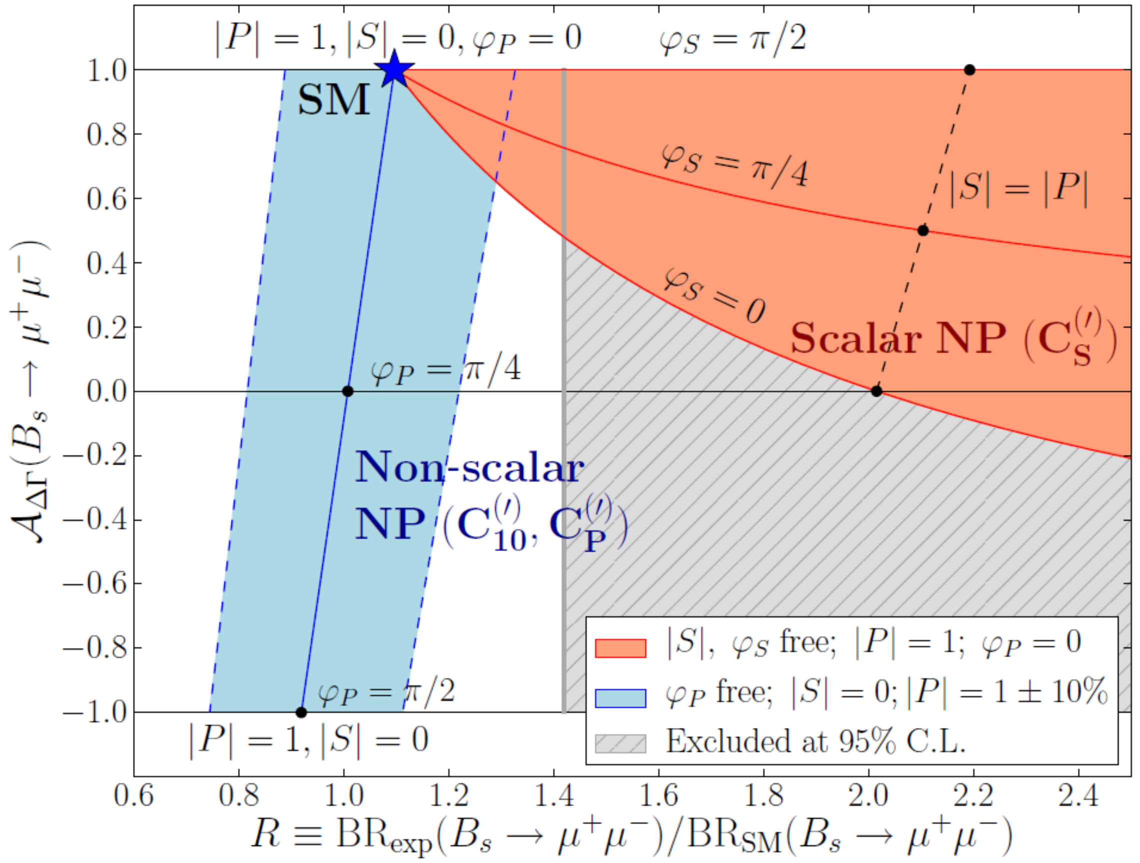
[Beneke et al, JHEP 10 (2019) 232]

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

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

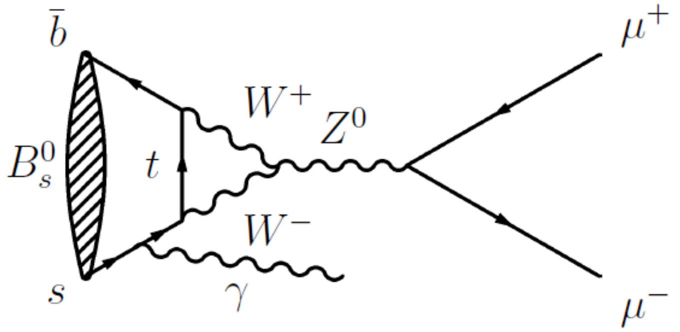
$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s}}{1-y_s^2}\left[\frac{1+2A_{\Delta\Gamma}^{\mu^+\mu^-}y_s+y_s^2}{1+A_{\Delta\Gamma}^{\mu^+\mu^-}y_s}\right] \qquad A_{\Delta\Gamma}^{\mu^+\mu^-} \equiv \frac{R_H^{\mu^+\mu^-}-R_L^{\mu^+\mu^-}}{R_H^{\mu^+\mu^-}+R_L^{\mu^+\mu^-}} \qquad y_s = \frac{\Delta\Gamma_s}{2\Gamma_s}$$

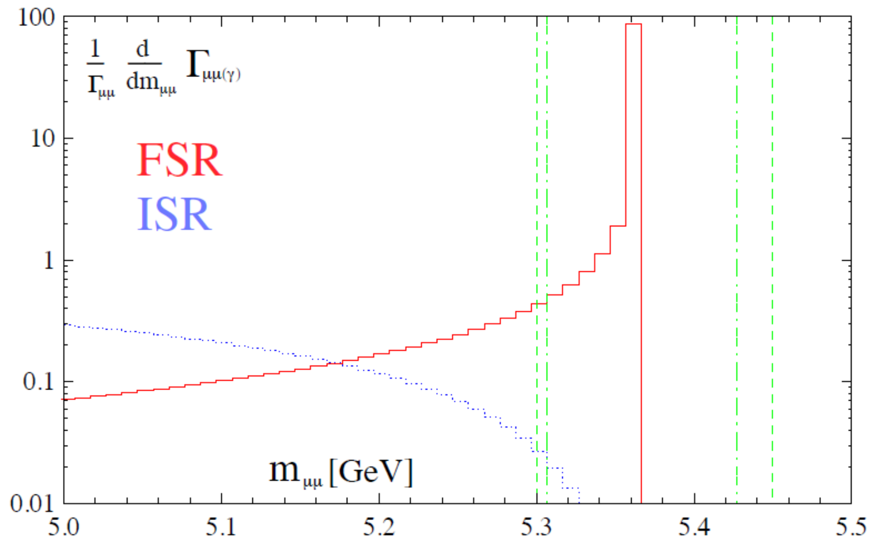
we can extract the asymmetry $A_{\Delta\Gamma}^{\mu^+\mu^-}$ (=1 in SM)
Clean observable → additional NP constraint



[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]

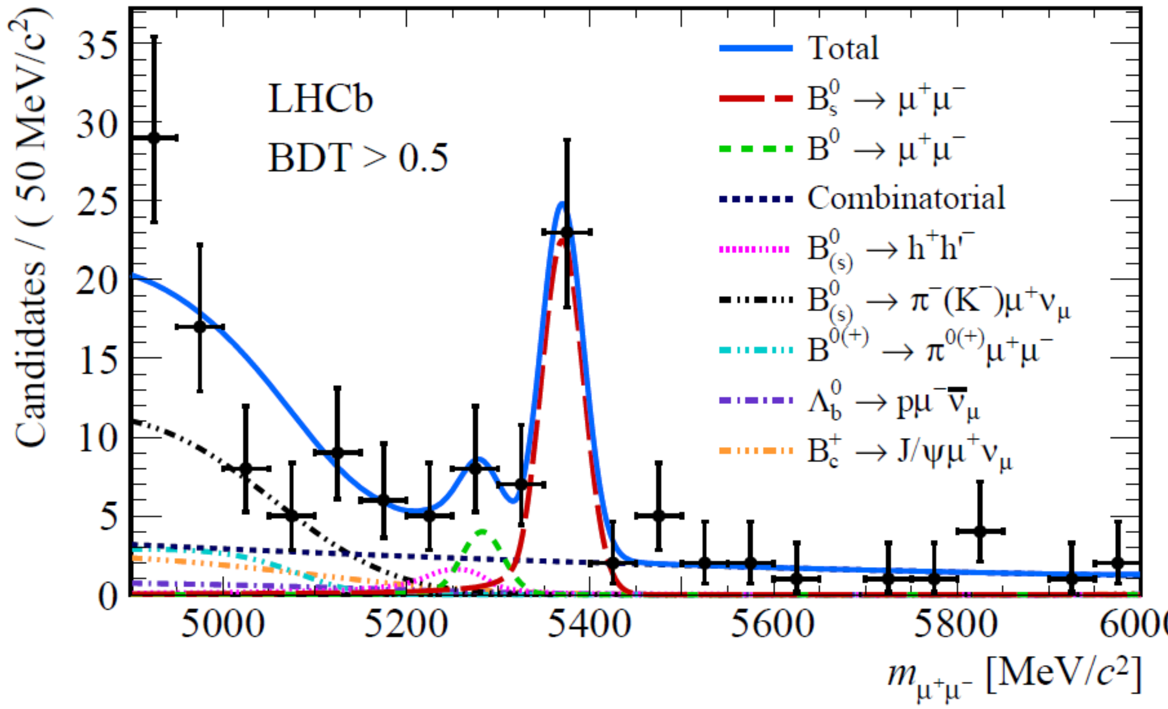
- SM prediction at $O(10^{-10})$ for $m_{\mu\mu} > 4.9\ GeV/c^2$
  [JHEP 11 (2017) 184] [PRD97 (2018) 053007]

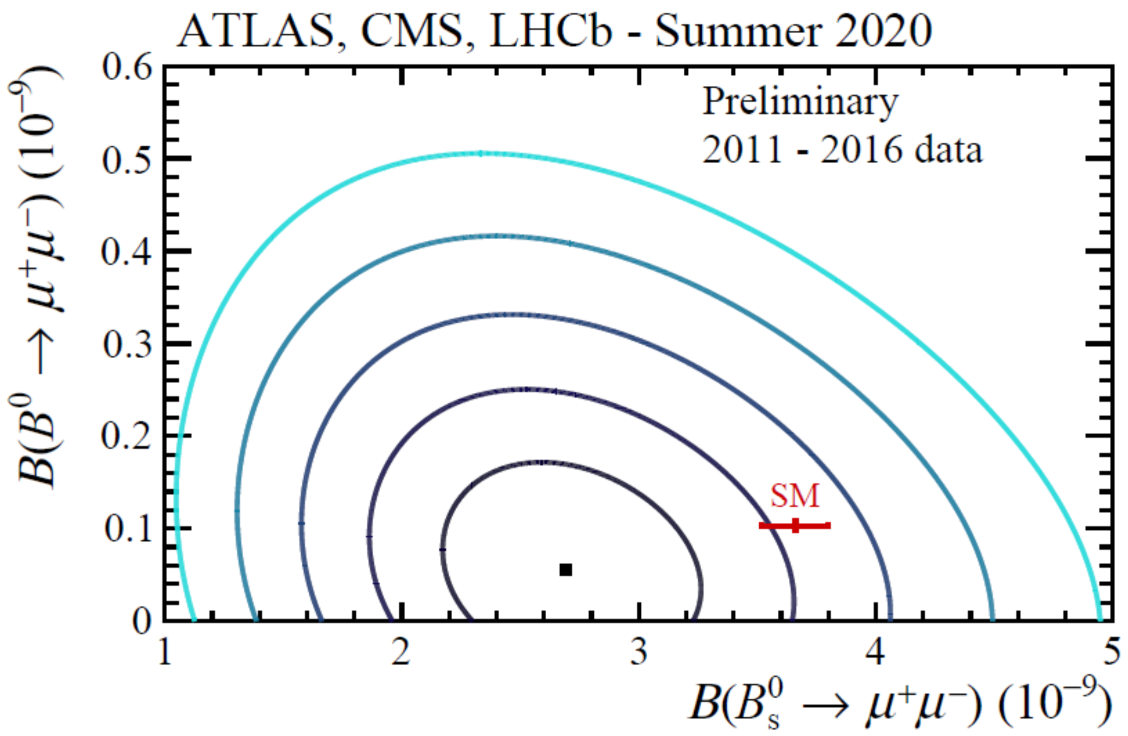
- Bremsstrahlung (FSR) experimentally included in $BF(B_s^0 \to \mu\mu)$ via PHOTOS

Experimental status of $B \to \mu\mu$ measurements till 2020

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





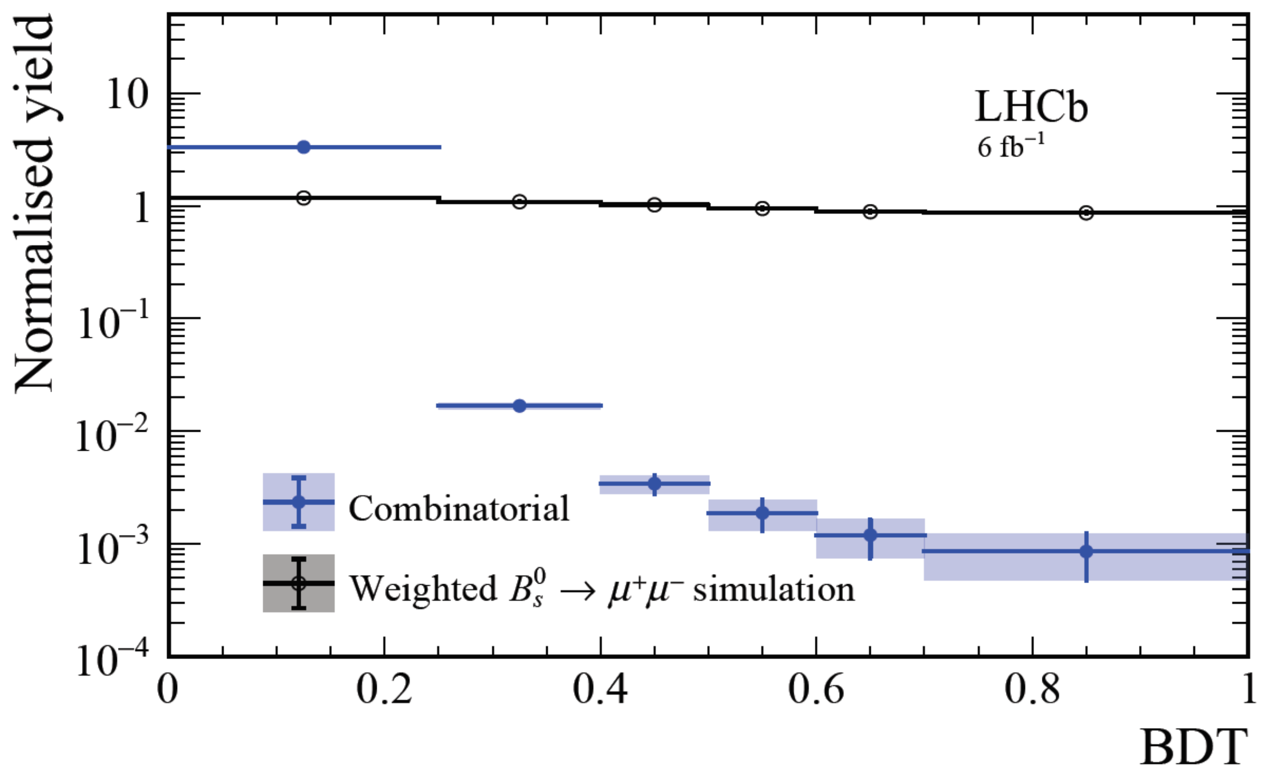
- $BF\left(B_S^0 \to \mu^+\mu^-\right) = \left(2.69^{+0.37}_{-0.35}\right) \times 10^{-9}$
- $\tau(Bs \to \mu^+\mu^-) = 1.91^{+0.37}_{-0.35}\, ps$
- $BF(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-9}$ @ 95% CL

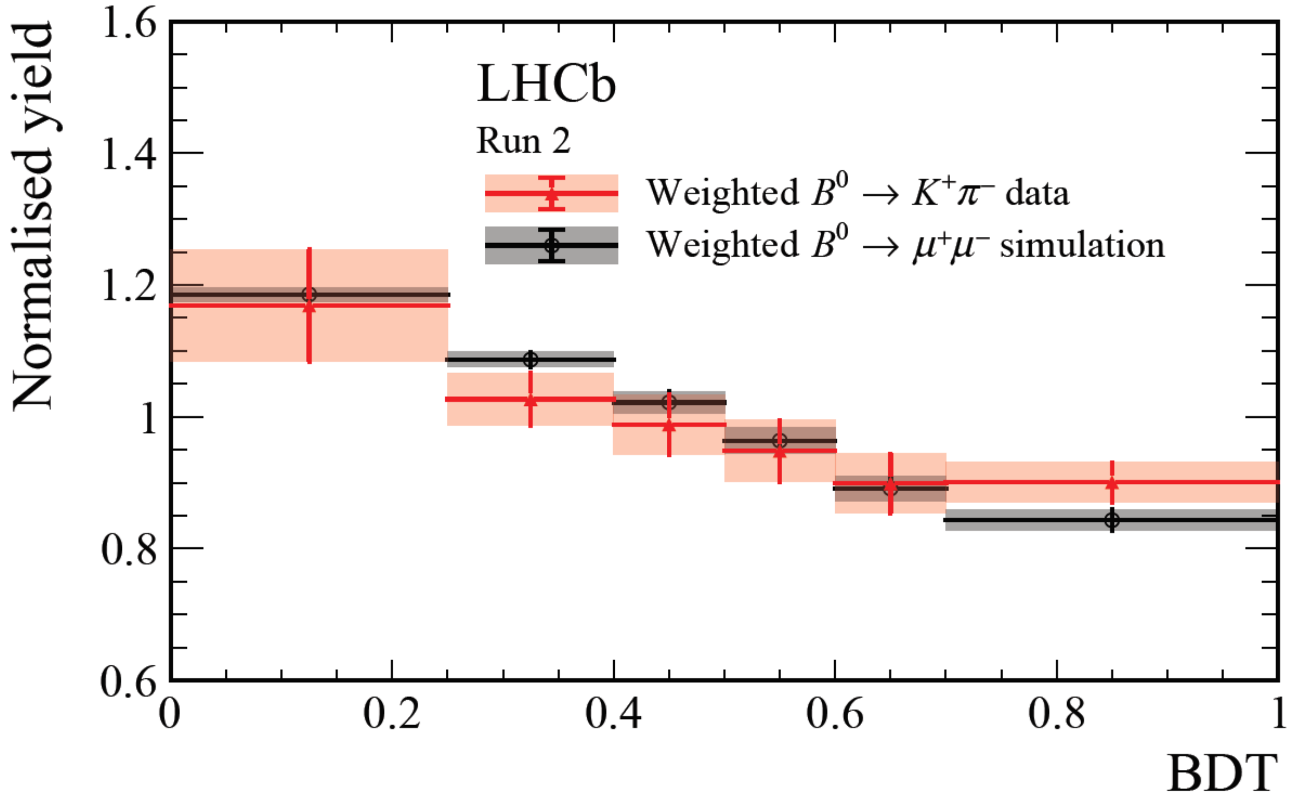
LHCb-CONF-2020-002

BDT calibration

arxiv:2108.09283
arxiv:2108.09284

- Multivariate classifier (“BDT”) to reject combinatorial background
- BDT flat for signal **BDT and decreasing for combinatorial bkg. Events are categorized 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

Normalisation of signal yield: mass fit

arxiv:2108.09283
arxiv:2108.09284

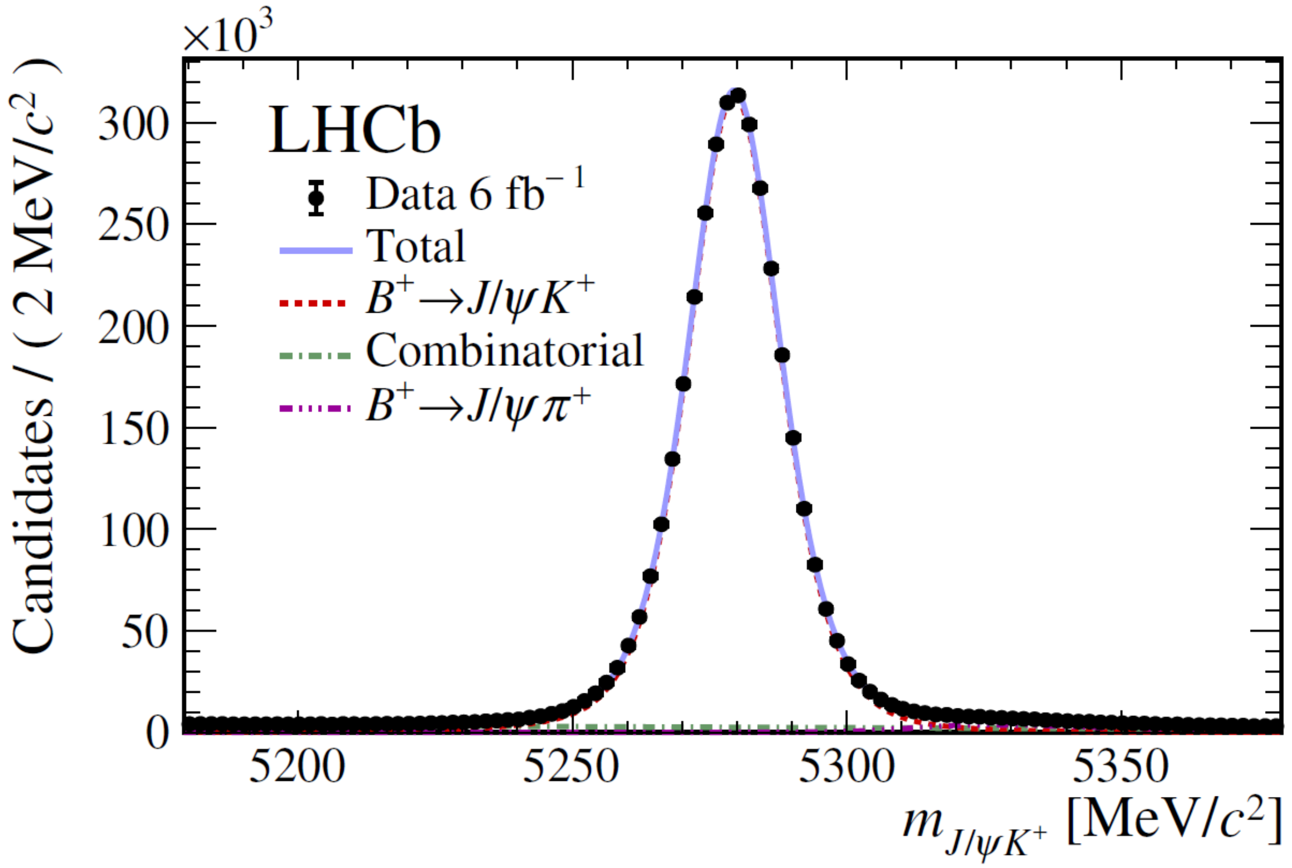
- To measure the branching fraction, int. luminosity and cross-section uncertainties are avoided by computing the ratio to well-known channels

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

New LHCb measurement of f_s/f_d reduces the main syst uncertainty of $B(B^0_s \to \mu\mu)$ from 6% to 3%

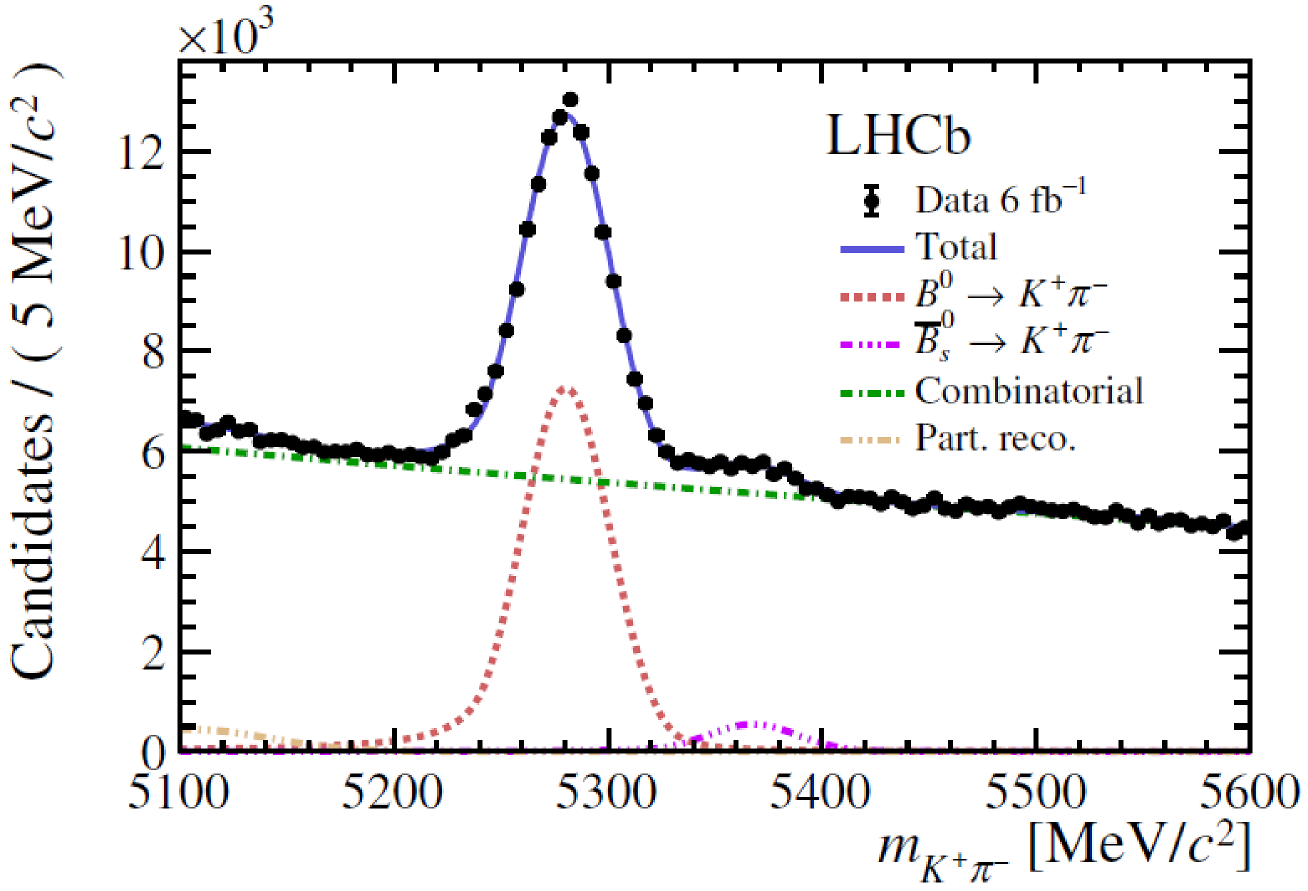
1. $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$

Two muons in the final state → similar trigger and reconstruction



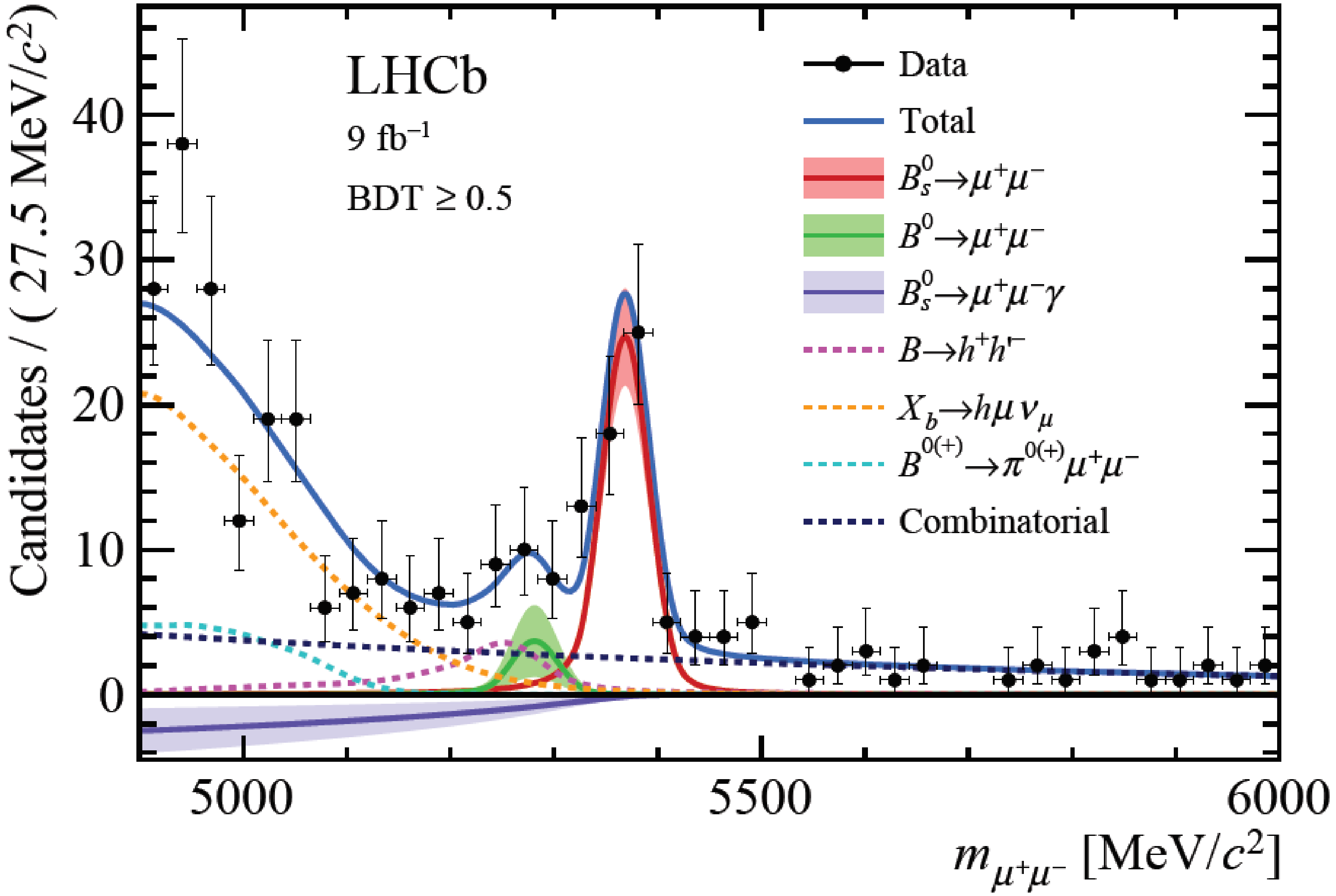
2. $B^0 \to K^+\pi^-$

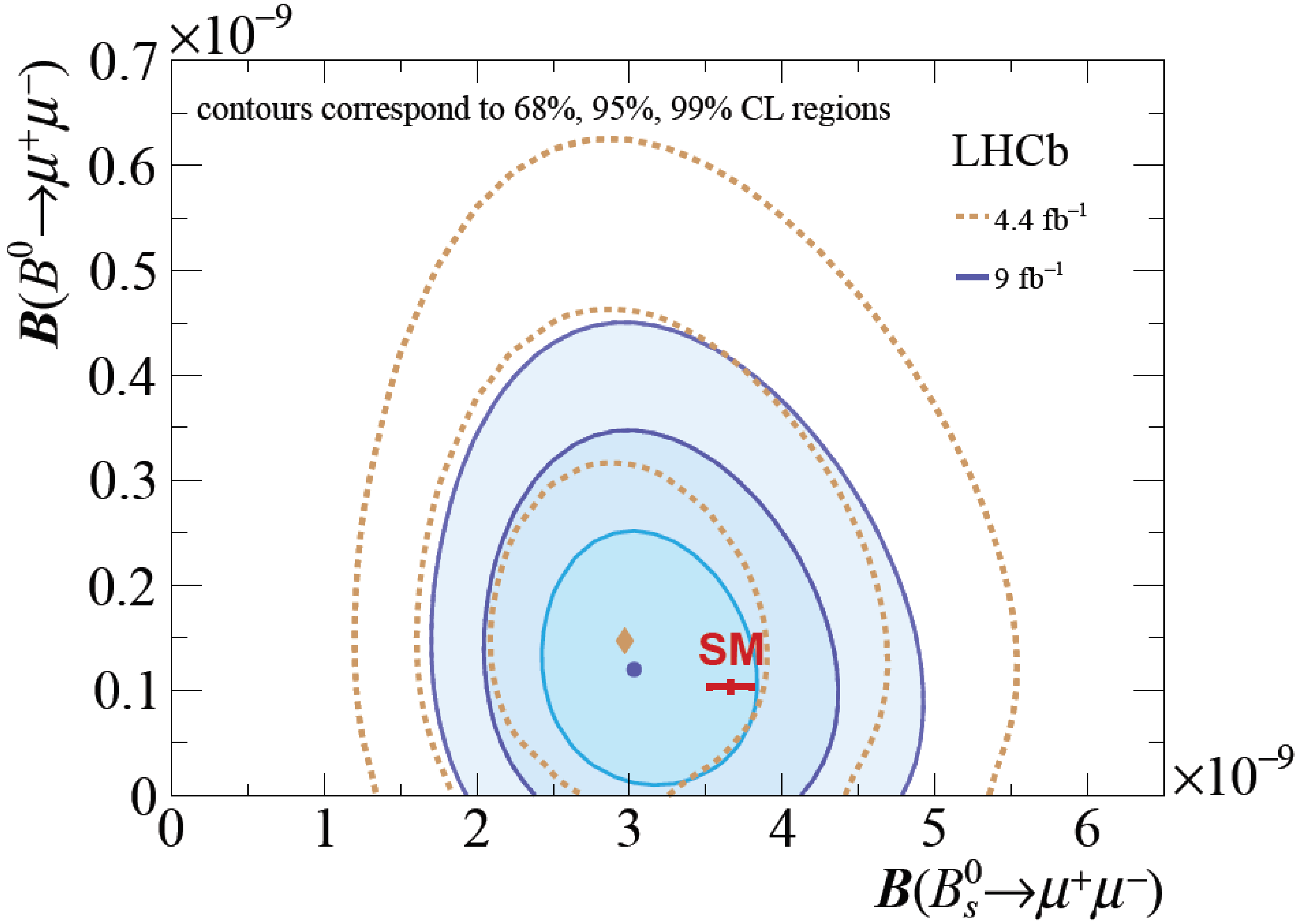
Two-body B decay → same signal topology



Branching fraction measurements

arxiv:2108.09283
arxiv:2108.09284





$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.09^{+0.46}_{-0.43}\,(stat)^{+0.15}_{-0.11}\,(sys)\right) \times 10^{-9}\ (10.3\sigma)$$

- $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\gamma$ compatible with 0 signal hypothesis at 1.7σ and 1.6σ

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

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

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

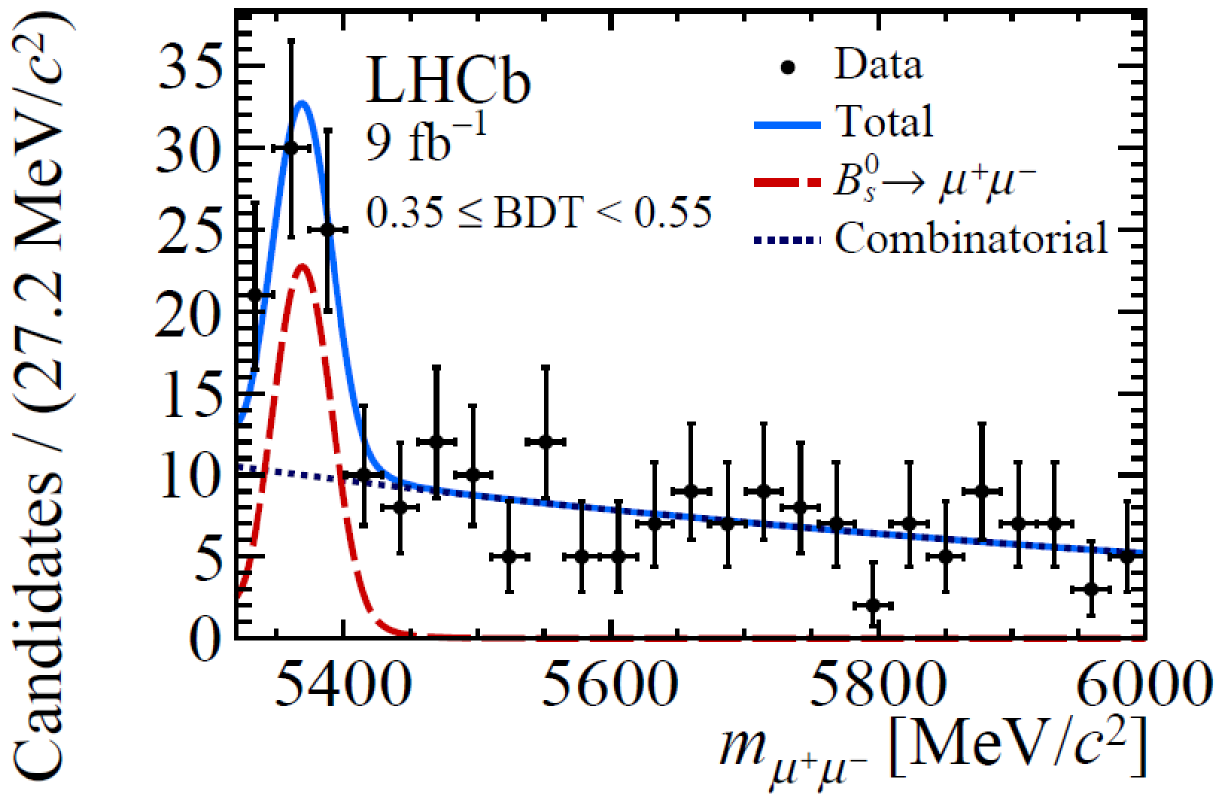
$B_s^0 \to \mu^+\mu^-$ effective lifetime: measurement

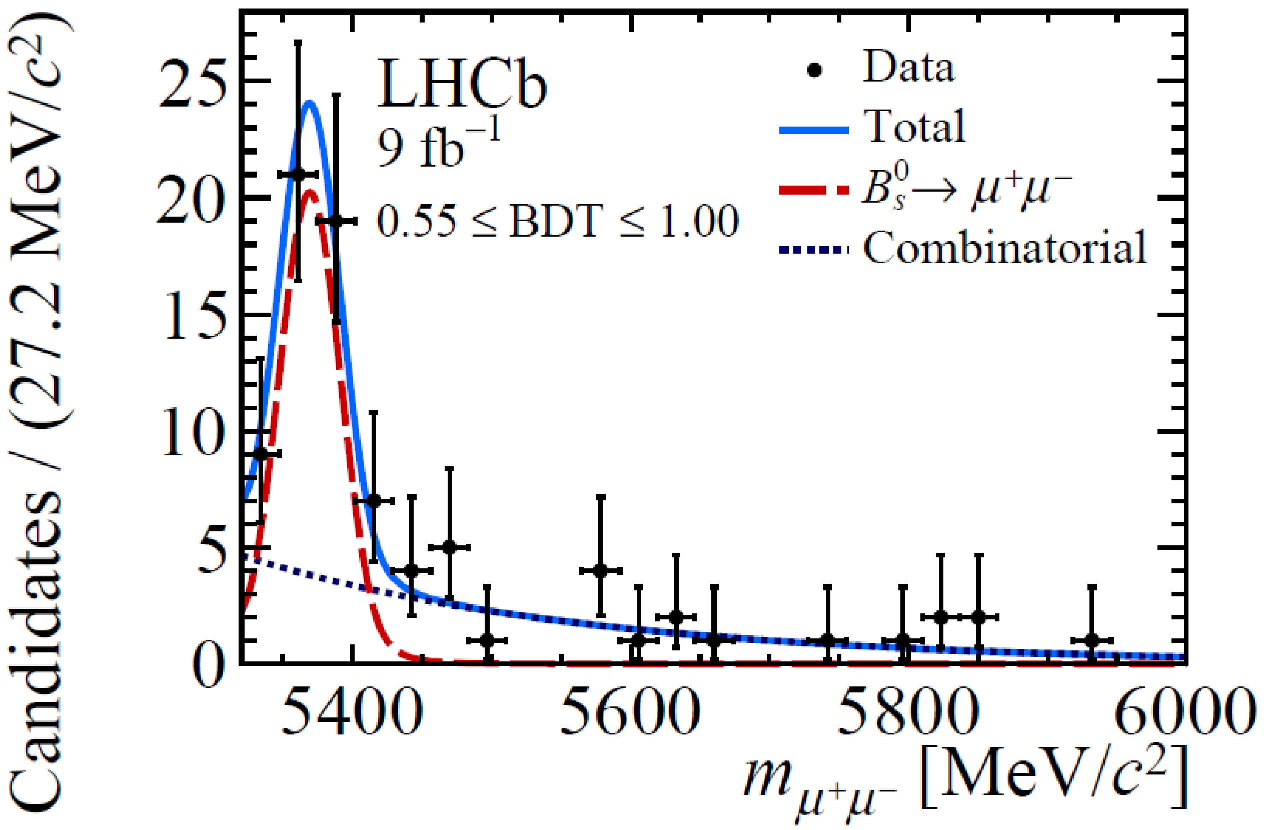
arxiv:2108.09283
arxiv:2108.09284

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]

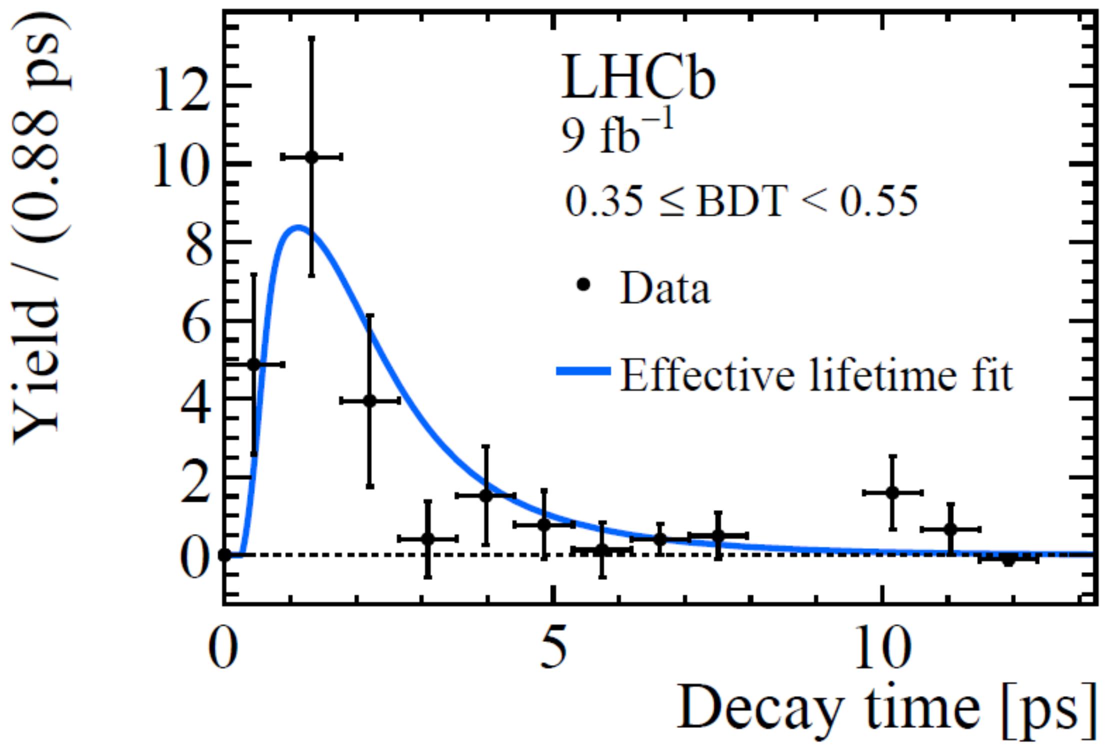


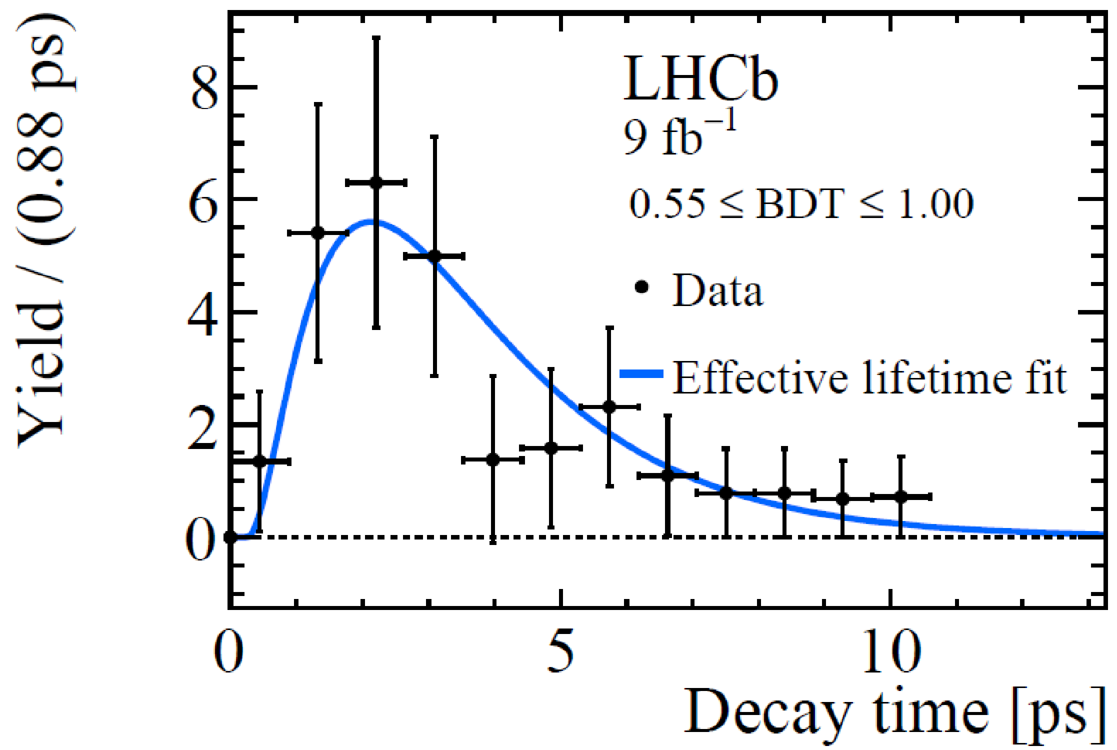


$B_s^0 \to \mu^+\mu^-$ effective lifetime: results

arxiv:2108.09283
arxiv:2108.09284

- 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 needed to say more

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

PRL 124 (2020) 211802

- FCNC processes analogous to $B^0_{(s)} \to \mu^+\mu^-$ but much more helicity-suppressed due to the m_e^2/m_μ^2 scaling

  $BF(B^0_s \to e^+e^-) = (8.60 \pm 0.36) \times 10^{-14}$
  $BF(B^0 \to e^+e^-) = (2.41 \pm 0.13) \times 10^{-15}$ Beneke et al, JHEP 10 (2019), 232

  SM signal out of experimental reach, but BFs up to 10^{-8} in some NP scenarios (see eg Fleischer et al, JHEP 05 (2017))

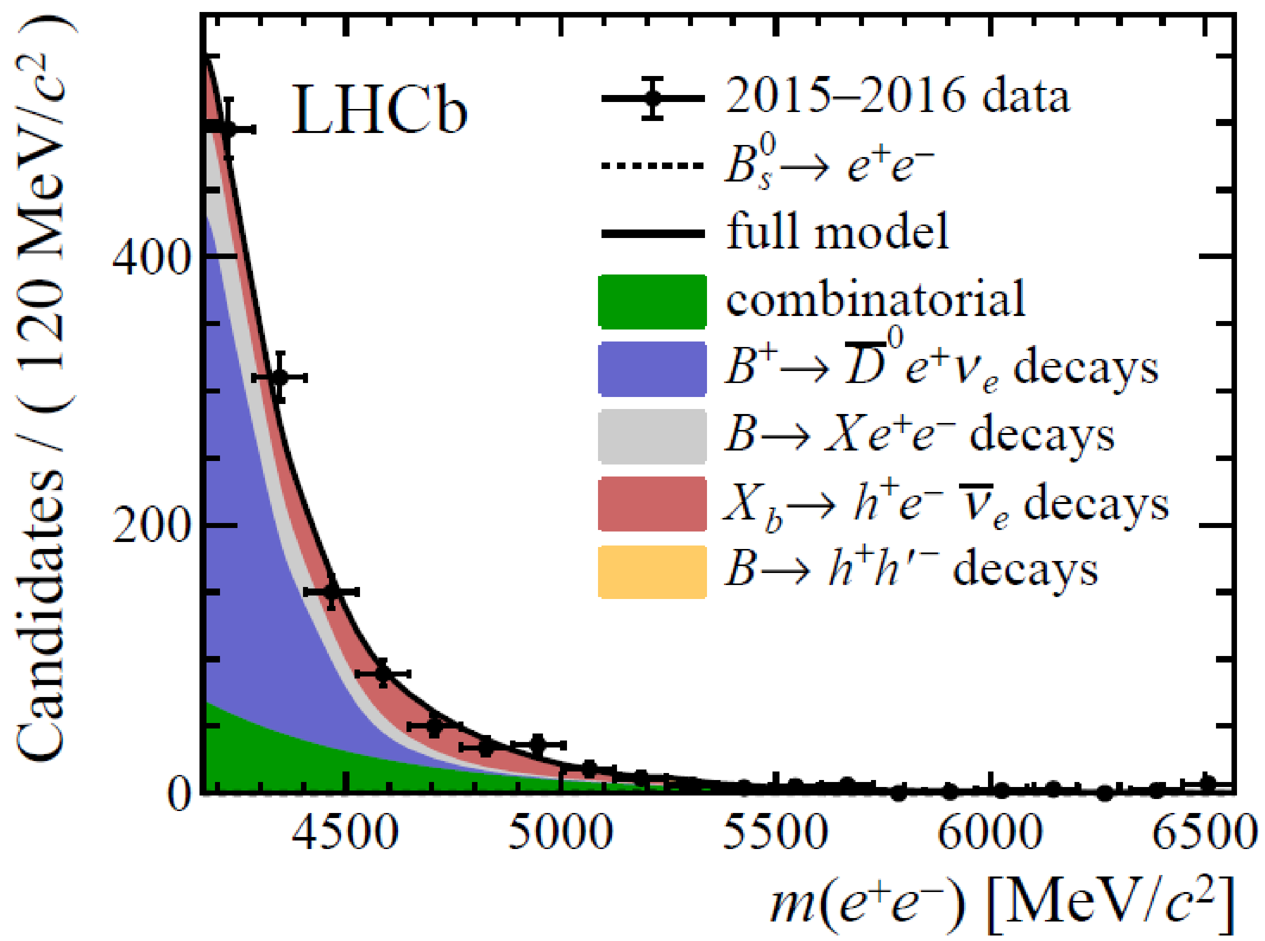
- Run 1 + 2015/16 data, analysis procedure similar to $B \to \mu\mu$

- Signal $B^0_{(s)} \to e^+e^-$ reconstructed in 3 brems. categories (0, 1, 2 $e^\pm$ with γ recovery)

$BF(B^0_s \to e^+e^-) < 11.2 \times 10^{-9}$ @ 95% CL
$BF(B^0 \to e^+e^-) < 3.0 \times 10^{-9}$ @ 95% CL

x 30 improvement wrt previous limits by CDF

2015/16 data, $B^0 \to \mu^+\mu^-$ fixed to 0



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

PRL 118 (2017) 251802

- FCNC processes analogous to $B^0_{(s)} \to \mu^+\mu^-$ but much less helicity-suppressed

$$\frac{\mathcal{B}(B^0_{(s)} \to \tau^+\tau^-)}{\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-)} = \frac{m_\tau^2}{m_\mu^2} \times \sqrt{\frac{m_B^2 - 4m_\tau^2}{m_B^2 - 4m_\mu^2}} \sim 210$$

$$BF(B_s^0 \to \tau^+\tau^-) = (7.73 \pm 0.49) \times 10^{-7}$$
$$BF(B^0 \to \tau^+\tau^-) = (2.22 \pm 0.19) \times 10^{-8}$$

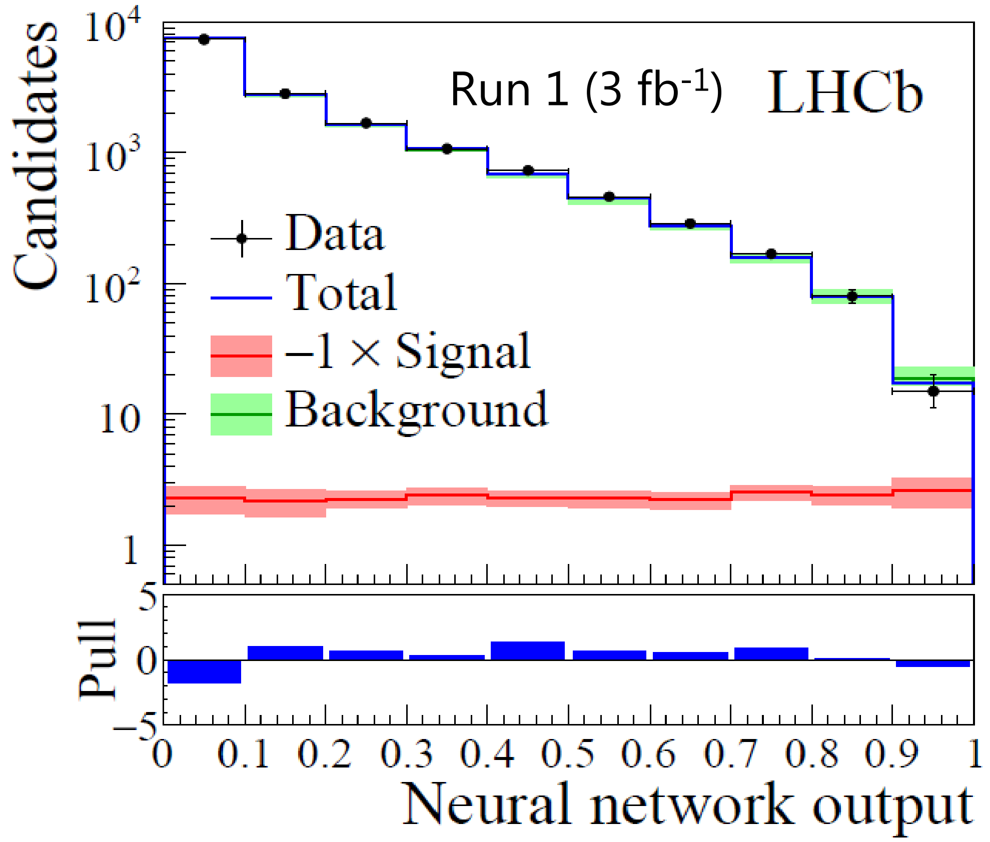
Bobeth et al, PRL 112 (2014) 101801

- NP models explaining observed SM tensions in $b \to sl^+l^-$ and $b \to cl^-\overline{\nu}_l$ transitions allow possible increase of BF by orders of magnitude

- $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_l$. Decay model of τ tuned on BaBar data. Approximate reconstruction of $B \to \tau^+\tau^-$ using geo. and mass constraints

- Neural Network built with geometric, kinematic and isolation variables to separate signal and background

- Signal extracted from fit to NN in signal region
  - Yield→BF using $B^0 \to D^+[K^-\pi^+\pi^+]D_s^-[K^+K^-\pi^-]$



$$BF(B_s^0 \to \tau^+\tau^-) < 6.8 \times 10^{-3} \ @\ 95\%\ CL$$ first limit

$$BF(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3} \ @\ 95\%\ CL$$ x 2.6 improvement wrt BaBar limit

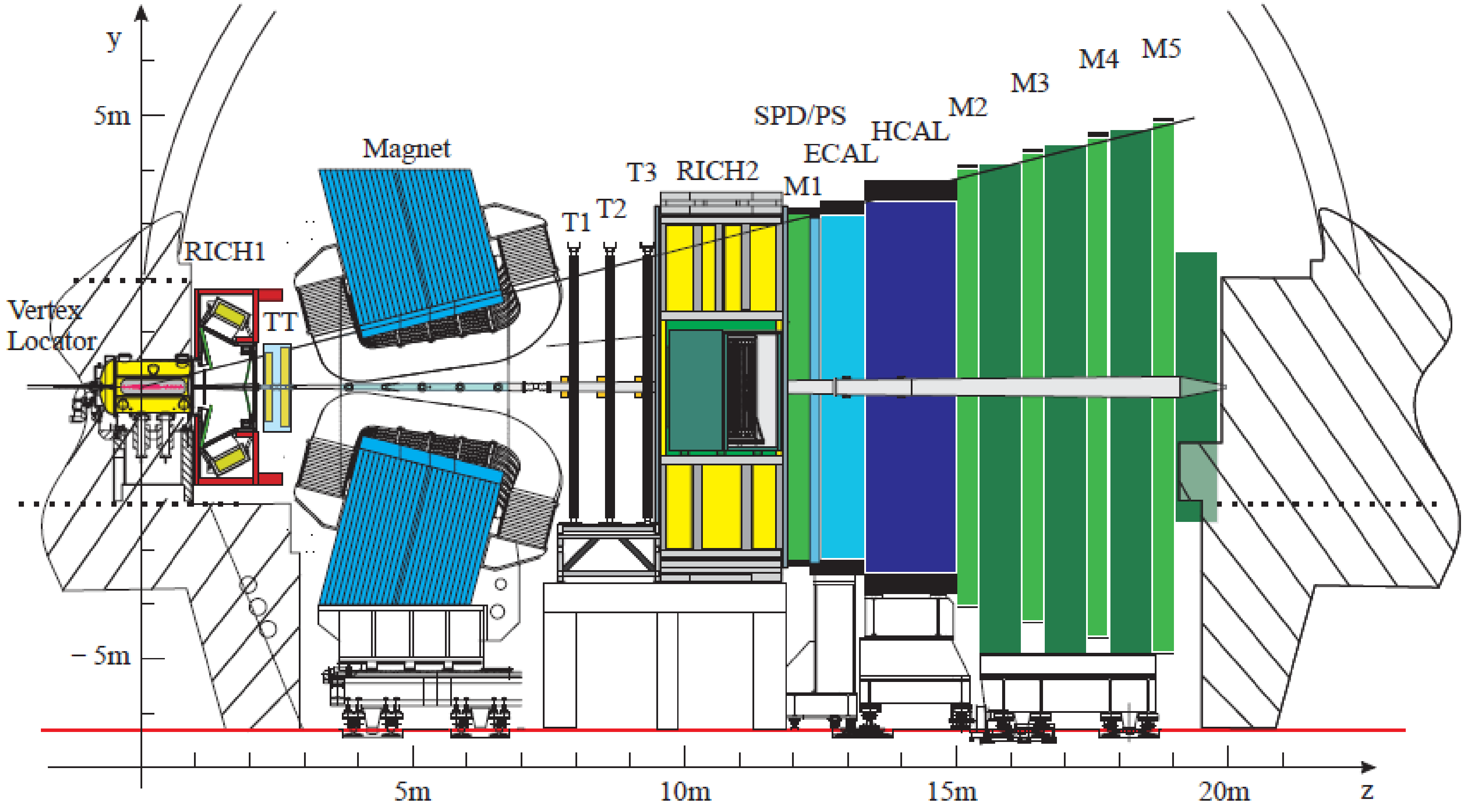
Conclusions

- The direct observation of phenomena incompatible with the SM of particle physics is one of the main goals of research in Physics.
- Precise measurements of flavour observables are powerful probes for NP, complementary to the direct search of new fundamental particles.
- Test of lepton flavour universality in $b \to s l^+ l^-$ transitions and measurement of $B \to l^+ l^-$ decays are among the theoretically cleanest probes in this search.
- Flavour anomalies in $b \to s l^+ l^-$ transitions seem to persist as new data are analysed. No statistically conclusive answers yet. However:
  - Current LHCb measurements are already putting strong constraints on NP
  - A number of LHCb measurements still have to fully exploit the collected Run 1 + Run 2 dataset
  - Run 3 with the new LHCb detector is about to start, expected to give ~3 × more data in 3 years
  - More input expected from other experiments, such as Belle 2, CMS, ATLAS…

These are exciting times for flavour physics

Backup

The LHCb detector



JINST 3 (2008) S08005

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

- High vertex resolution (VELO)
  $\sigma_{IP} = 15 + 29/p_T \ \mu m$

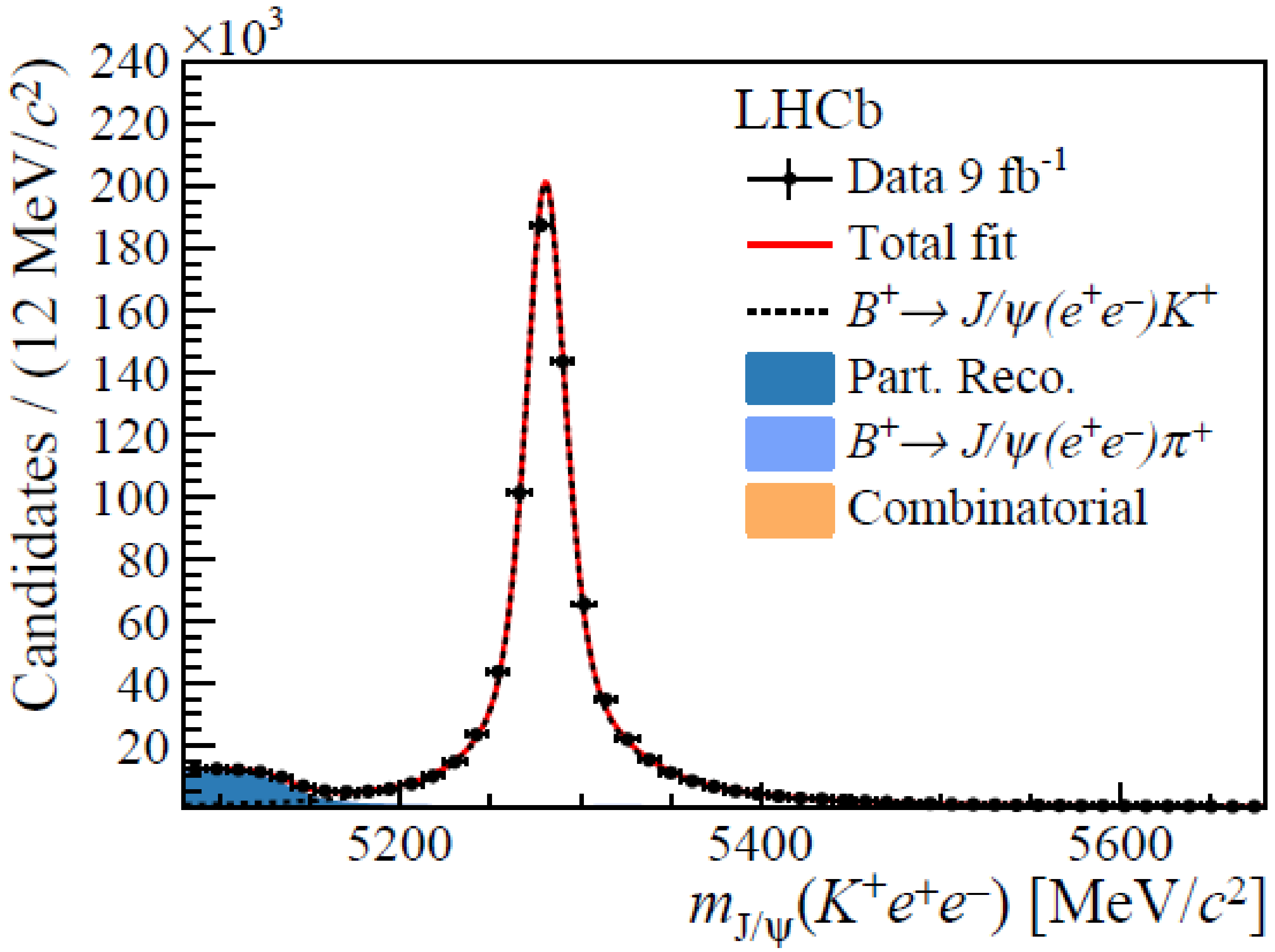
- Low momentum muon trigger
  $p_T(\mu) > 1.75 \ GeV \ (2018)$

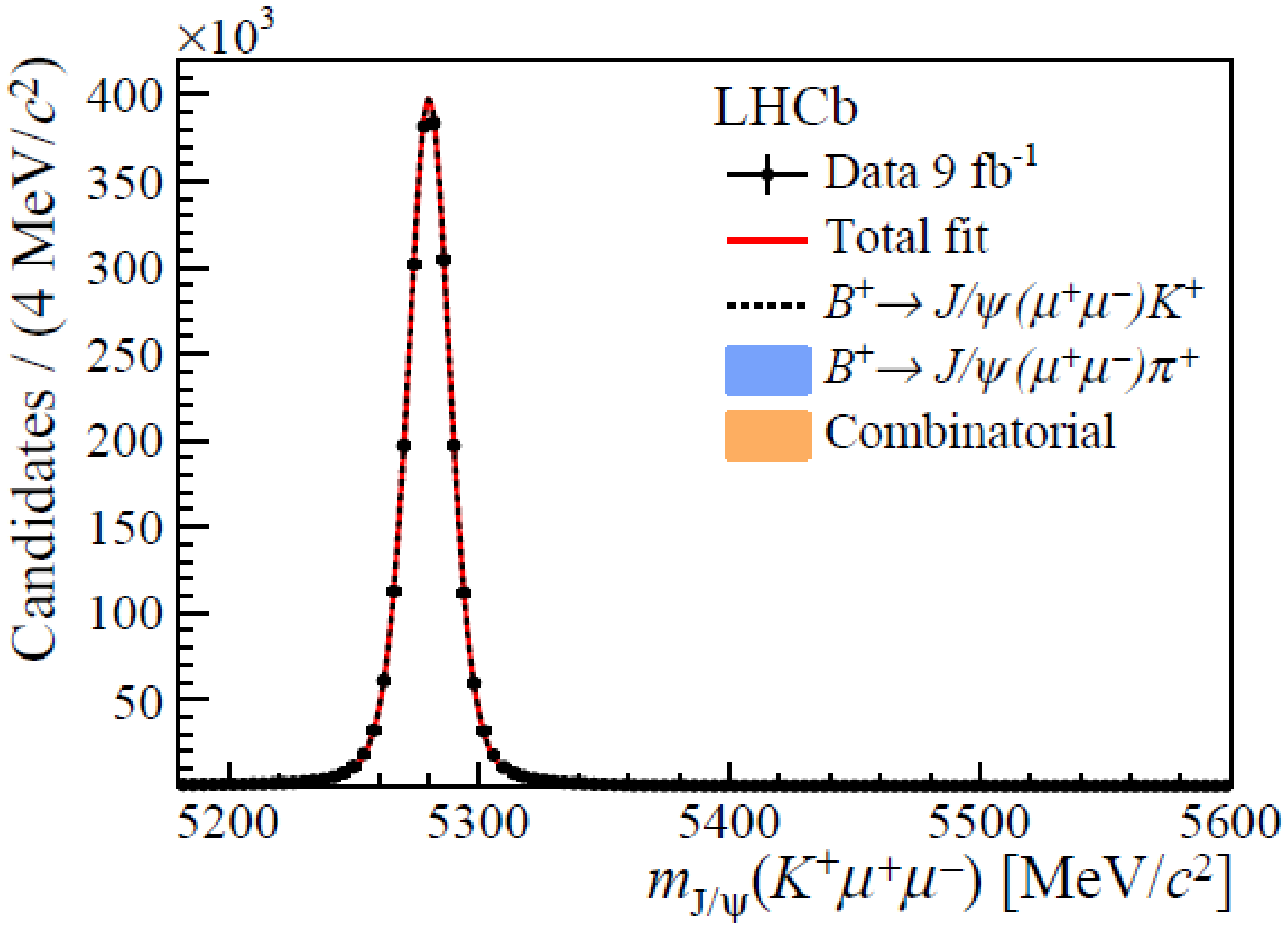
- Good particle identification capabilities (RICH+CALO+MUON)
  $\epsilon_\mu \sim 98\%$ with $\epsilon_{\pi\to\mu} < 1\%$

- Excellent momentum resolution
  $\frac{\sigma p}{p} = 0.5 - 1.0 \ \%$ for $p \ in \ [2{,}200] GeV$

  → narrow mass peak

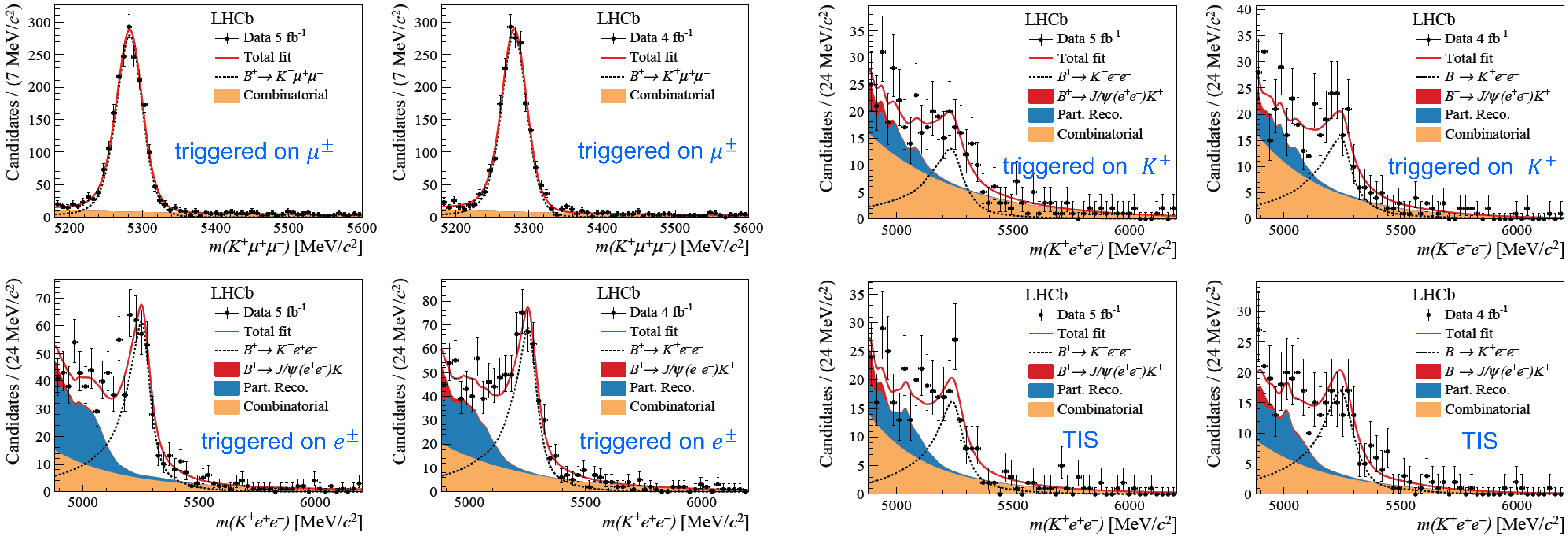
Calibration channels for R_K





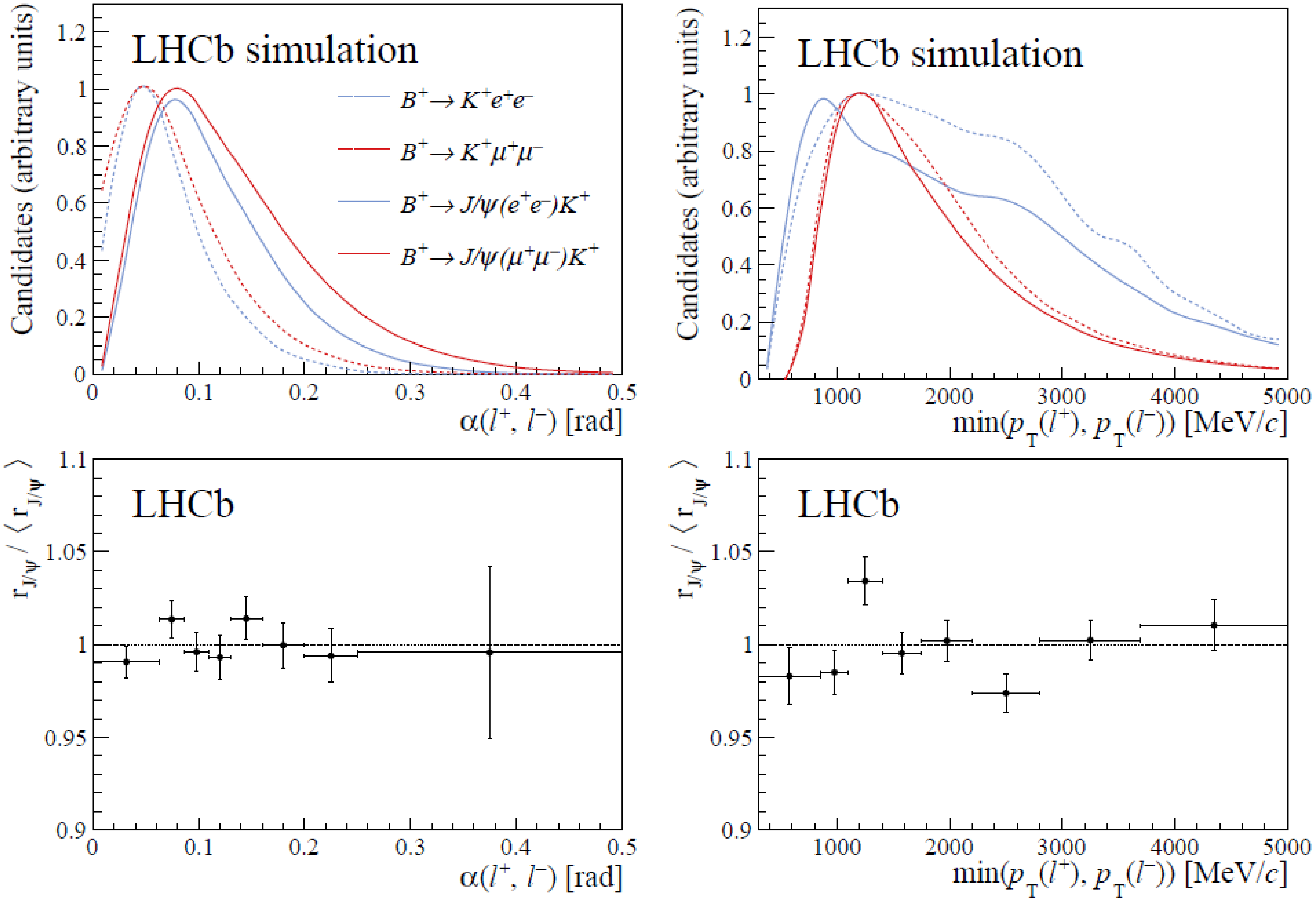
Decay mode	Yield
$B^+ \to K^+e^+e^-$	$1\,640 \pm 70$
$B^+ \to K^+\mu^+\mu^-$	$3\,850 \pm 70$
$B^+ \to J/\psi\,(\to e^+e^-)K^+$	$743\,300 \pm 900$
$B^+ \to J/\psi\,(\to \mu^+\mu^-)K^+$	$2\,288\,500 \pm 1\,500$

Signal vs trigger category in R_K measurement



TIS=Triggered independent of signal

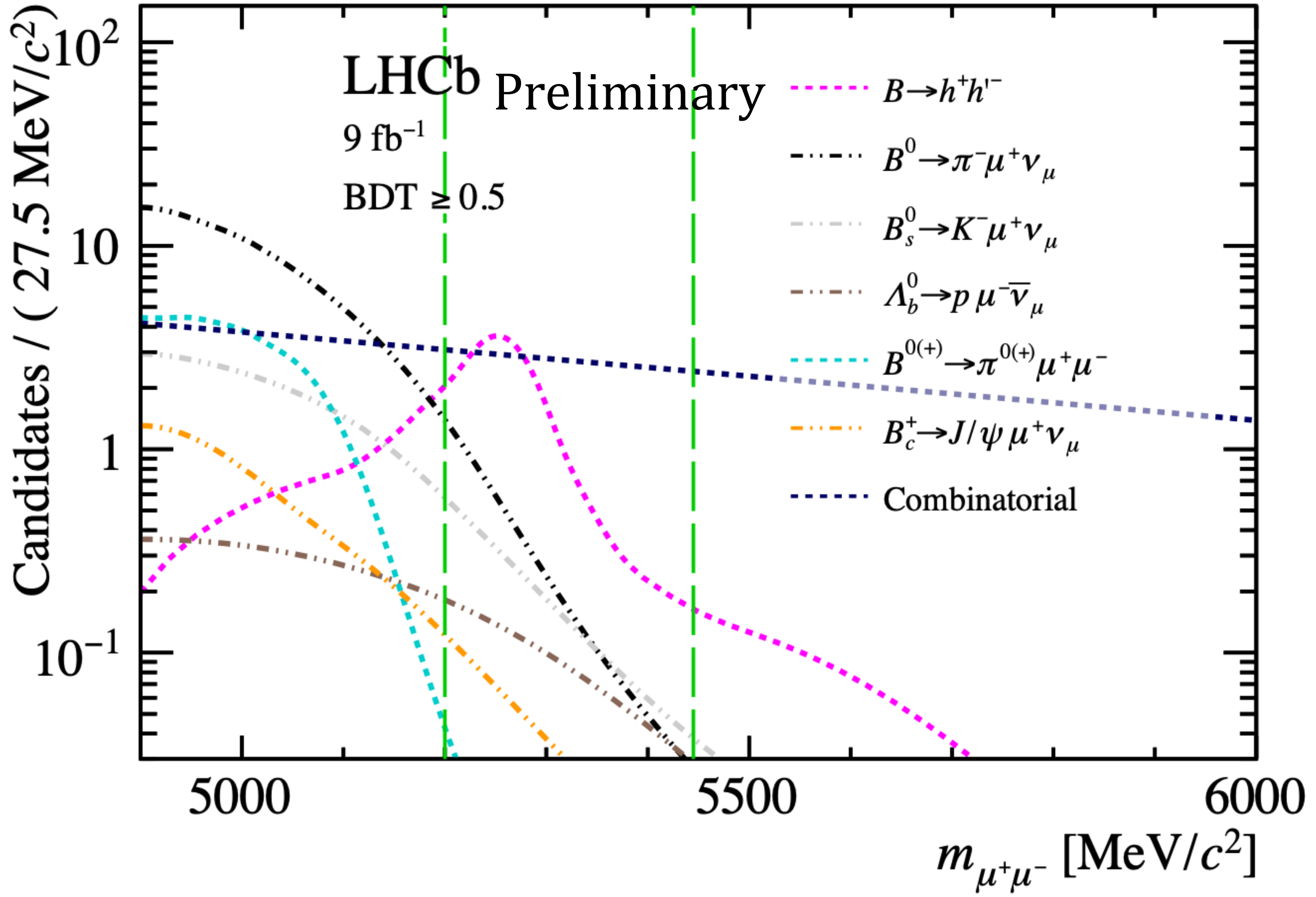
$r_{J/\psi}$ check for R_K



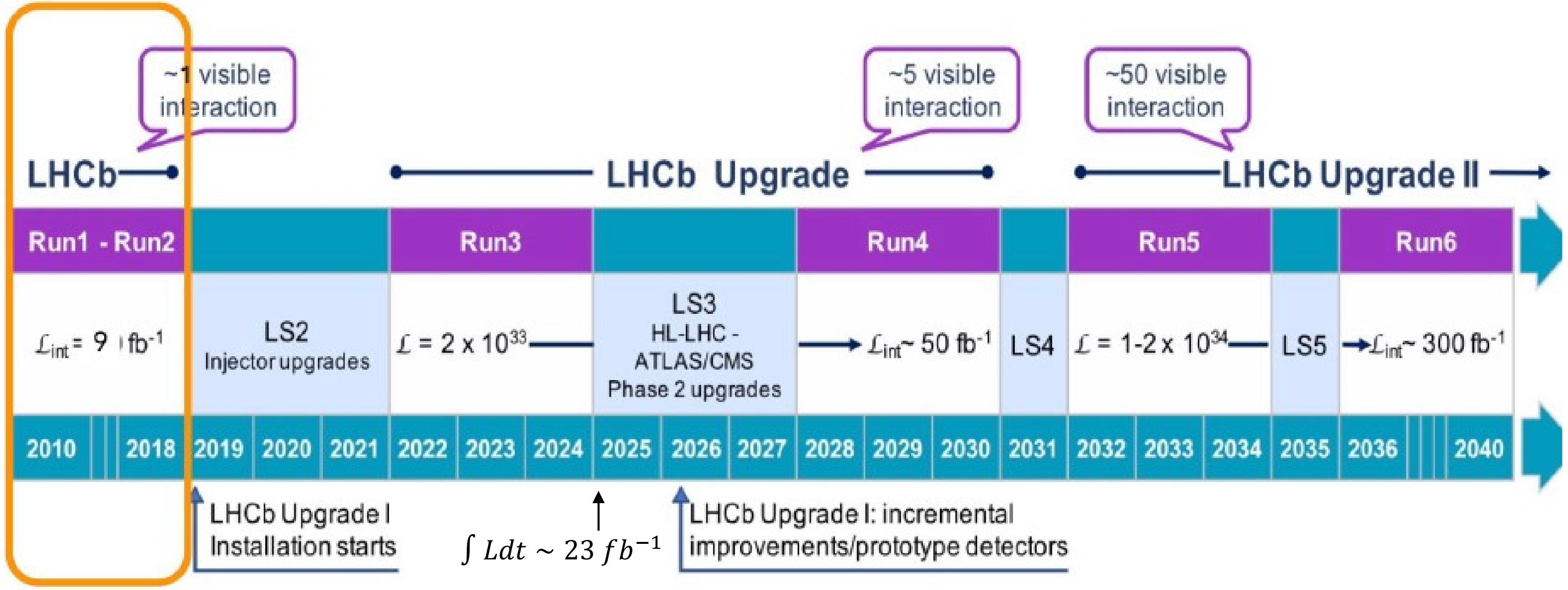
Backgrounds in $B^0_{(s)} \to \mu^+\mu^-$ selection

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



Prospects for $B \to l^+ l^-$ at LHCb



Pic from Monica Pepe Altarelli @ Corfu Summer Institute 2021

	now	$\int Ldt = 23$ fb^{-1}	$\int Ldt = 300$ fb^{-1}
err $BF(B_s^0 \to \mu^\pm\mu^\mp)$	0.46×10^{-9}	0.30×10^{-9} [1]	0.13×10^{-9} [1]
rel err $BF_{B^0\to\mu\mu}/BF_{B_s^0\to\mu\mu}$	65%	34% [1]	10% [1]
rel err $\tau_{B_s^0\to\mu\mu}$	14%	8% [1]	2% [1]
err $S_{B_s^0\to\mu\mu}$	–	–	0.2 [1]
UL @95%CL $BF(B_s^0 \to e^+ e^-)$	11.2×10^{-9}	4.7×10^{-9} [2]	1.2×10^{-9} [2]
UL @95%CL $BF(B_s^0 \to \tau^+ \tau^-)$	6.8×10^{-3}	1.9×10^{-3} [2]	5×10^{-4} [1]

[1] CERN-LHCb-PUB-2018-009
[2] From current limit assuming $1/\sqrt{\int Ldt}$ scaling