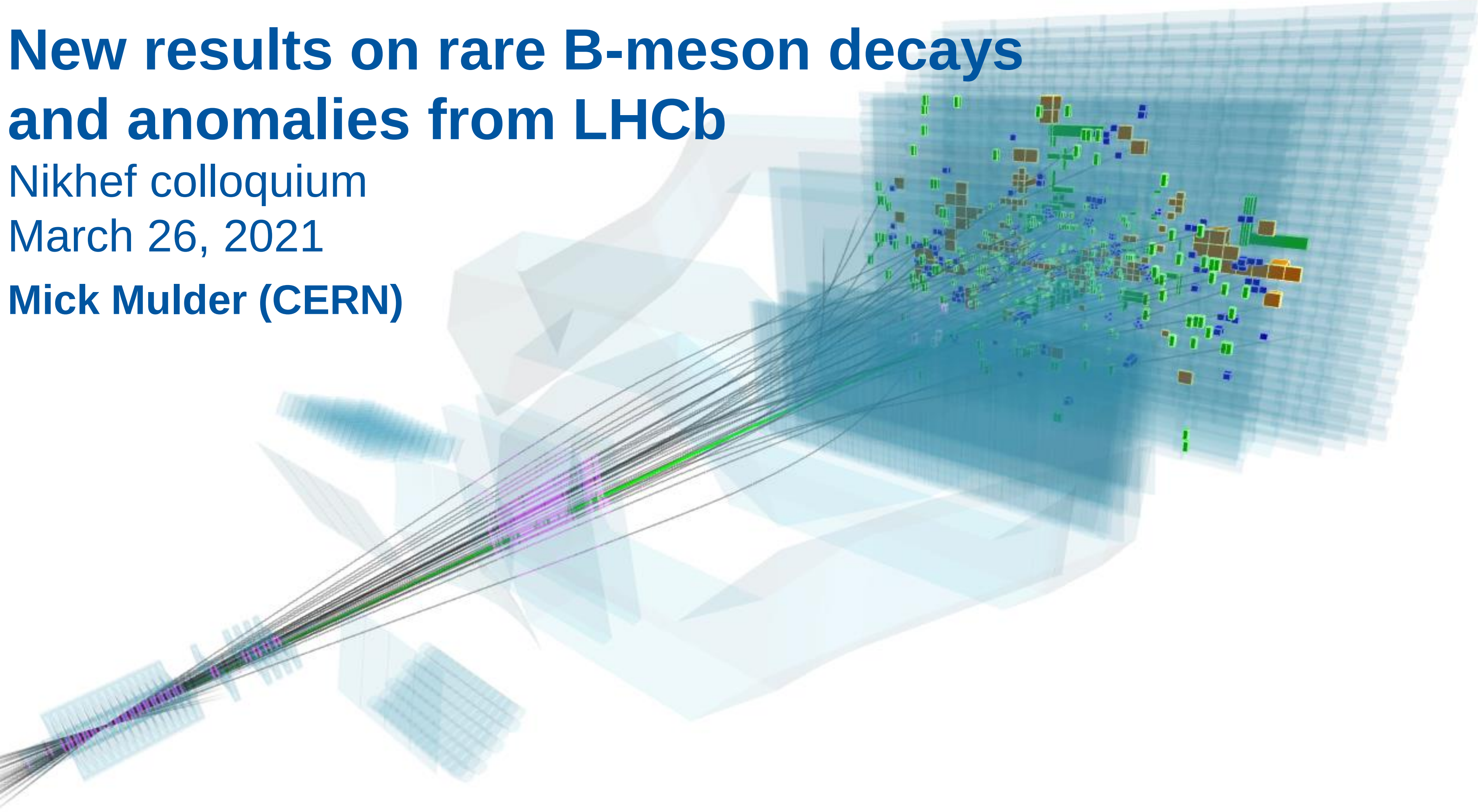
New results on rare B-meson decays and anomalies from LHCb

Nikhef colloquium

March 26, 2021

Mick Mulder (CERN)



Large Hadron Collider

Cern experiment hints nature

Experts reveal 'cautious excitement' over u fail to decay as standard model suggests

Ian Sample *Science editor*

@iansample

Tue 23 Mar 2021 08.05 GMT

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Sci
signal in their data that may be the first hin

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NIEUWS

Natuurkundigen van Cern vinden aanwijzing die ons begrip van de werkelijkheid op zijn kop kan zetten

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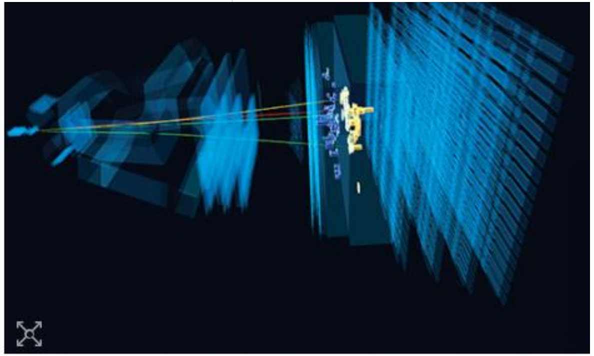
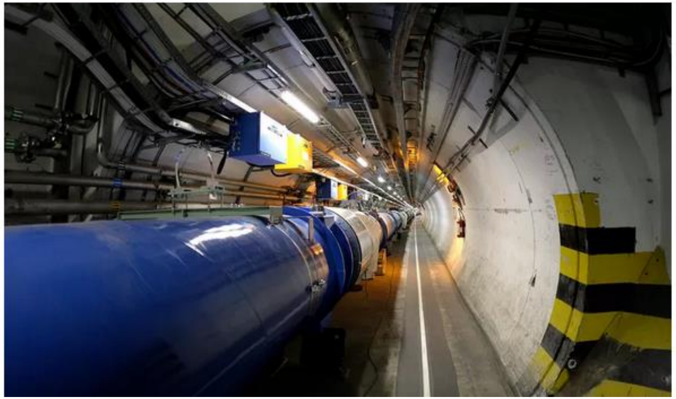
allenges leading theory

What is all the news about?
Why are we #CautiouslyExcited?

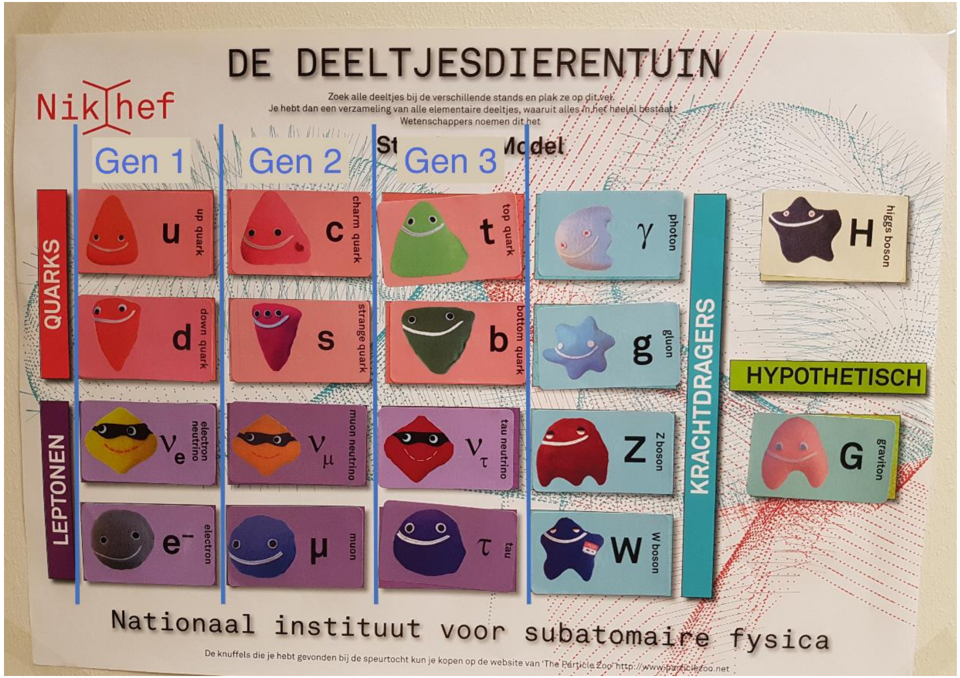


Fleeting glance: decay of a beauty quark involving an electron and positron as o CERN)



Flavour puzzle: generations

There are three generations of matter:
Why exactly three?
Perhaps because at least three are needed for CP violation,
i.e. matter-antimatter differences?



Flavour puzzle: masses

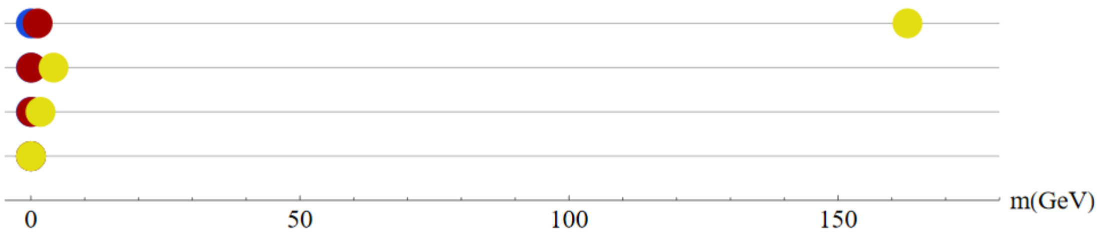
[Thesis Reinier Adelhart]

20 out of 26 Standard Model parameters associated with Higgs particle
12 masses, one per fermion

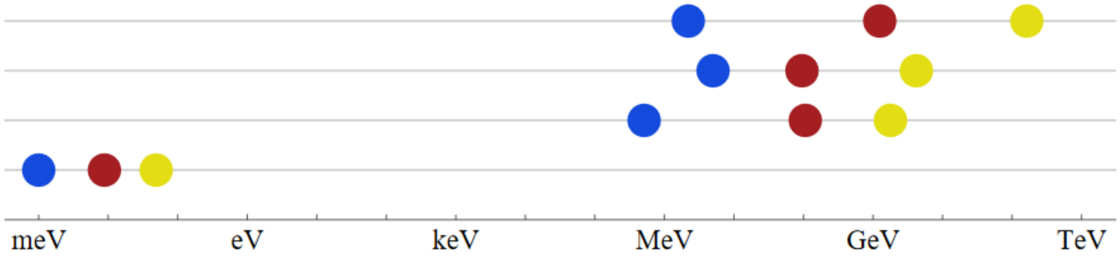
Why are masses so hierarchical for quarks + charged leptons?

Why are neutrino masses so much smaller?

Masses on linear scale for **first**, **second**, **third** gen



Masses on log scale for **first**, **second**, **third** gen

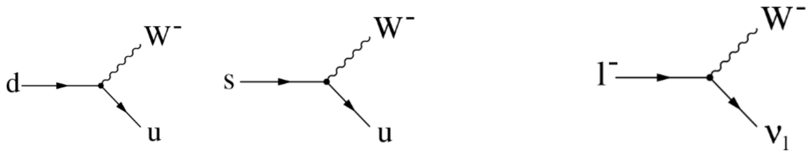


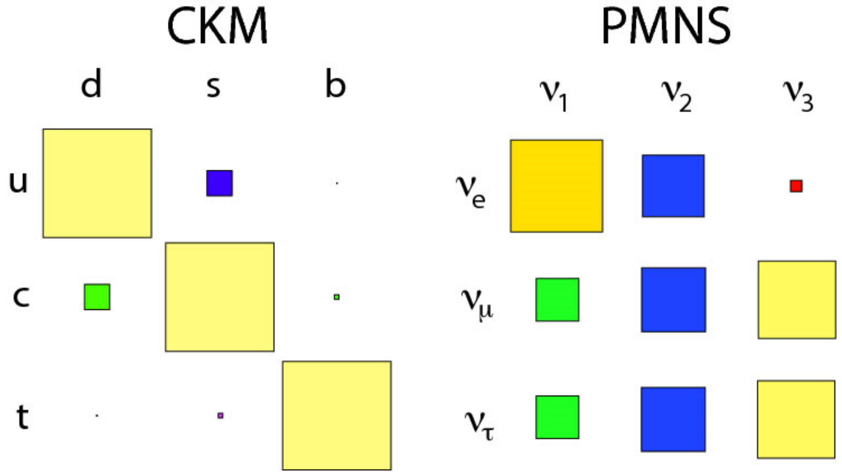
Flavour puzzle: fermion mixing

Quark mixing caused by separate eigenstates for Higgs, weak interaction → 4 parameters for quarks, 4 parameters for leptons

Why do mixing parameters for quarks look hierarchical and anarchical for neutrinos?

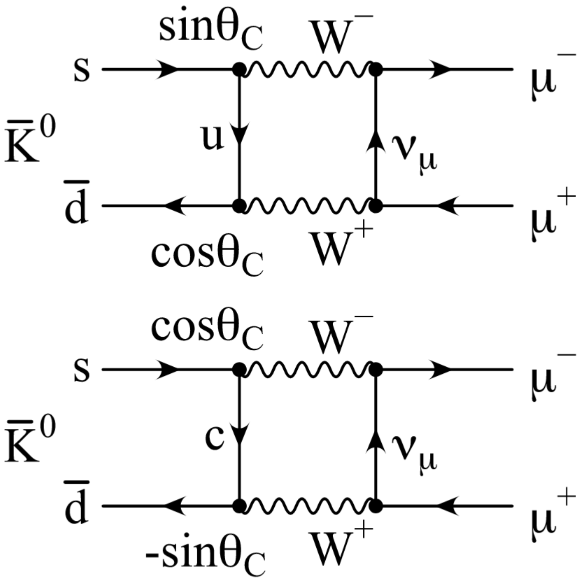
To solve flavour puzzle: study third generation → rare decays of beauty quarks





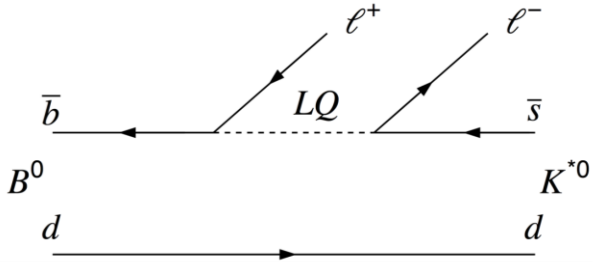
Rare decays

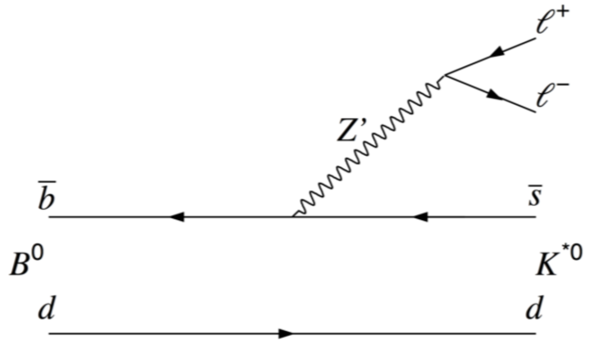
- **Loop-level decays mediated by weak interaction** (Flavour Changing Neutral Currents)
- **Transition strongly suppressed**: loops, CKM elements, sometimes GIM mechanism
- **Perfect for indirect discovery**: even small contributions have large effects on rare decays!
- Previous discoveries:
  - charm quark based on (lack of) $K_L^0 \to \mu^+\mu^-$
  - mass of top quark > 50 GeV with $B^0 - \bar{B}^0$ mixing
- **Recently, some anomalies have shown up in rare B decays**…



Rare B decays: $b \to s(d)ll$

- **Precise tests of SM with third generation of matter**
- Mediated by “penguin” or “box” diagrams in SM
- Branching fractions $\leq O(10^{-6})$
- New Physics (Z’ / leptoquark) can be tree-level, contribute strongly!

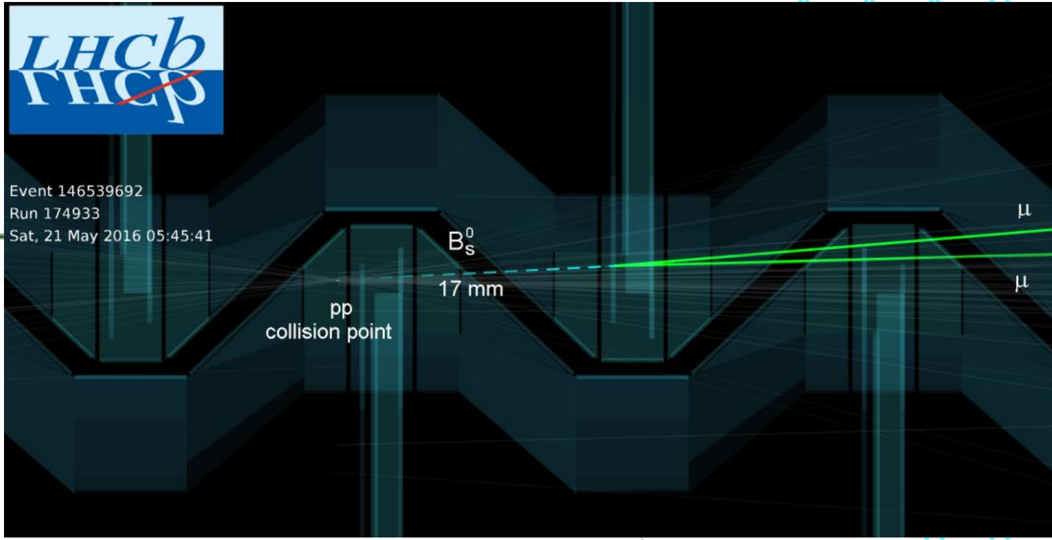




LHCb detector

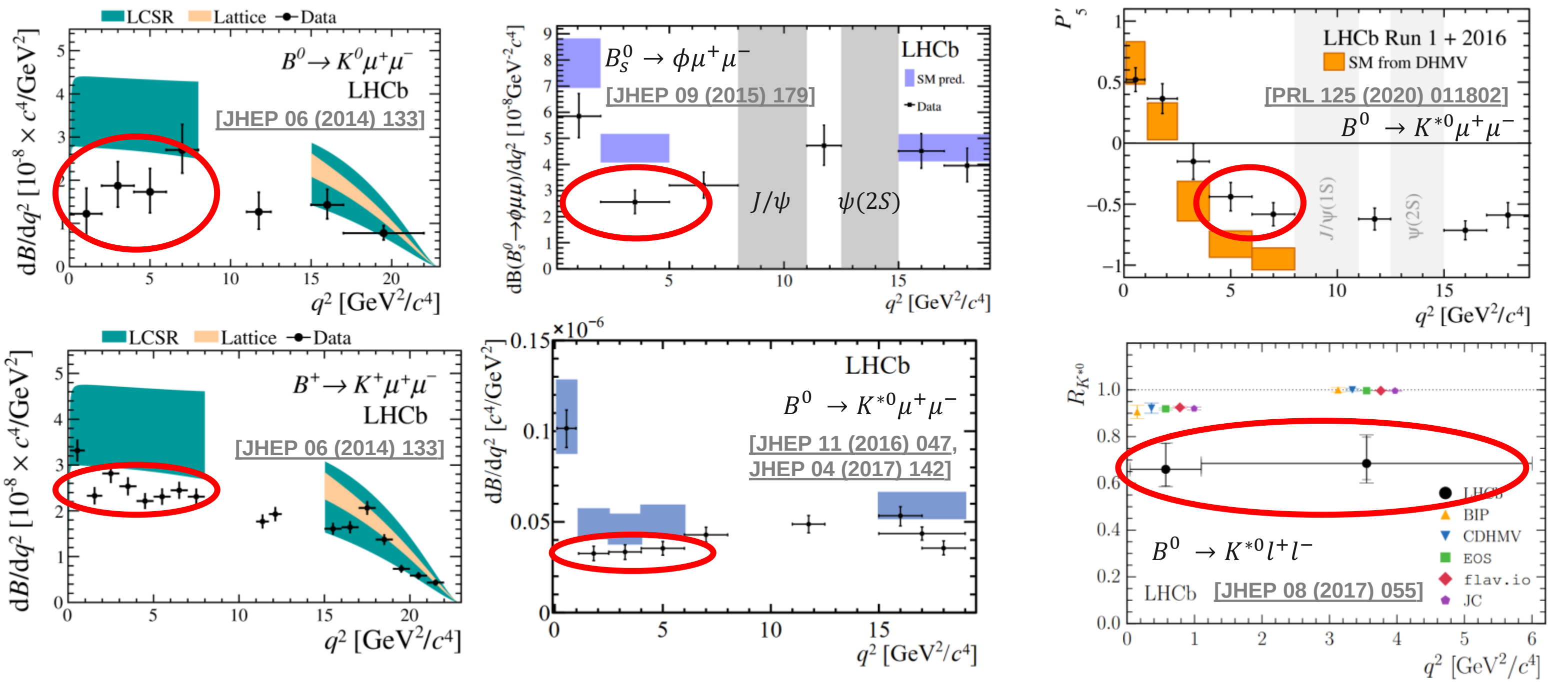
- Designed to study B hadrons with high precision: forward direction spectrometer
- **Around 10^{12} B hadrons produced!**

- Very good momentum resolution (0.5% of momentum)
  → **Sufficient to separate B_s^0, B^0 decays**
- Excellent charged particle identification, especially for muons, electrons
  → **required to suppress B decay backgrounds**
- Good vertex resolution: clear separation of B hadron decay vertex from pp collision
  → **essential to reduce backgrounds**



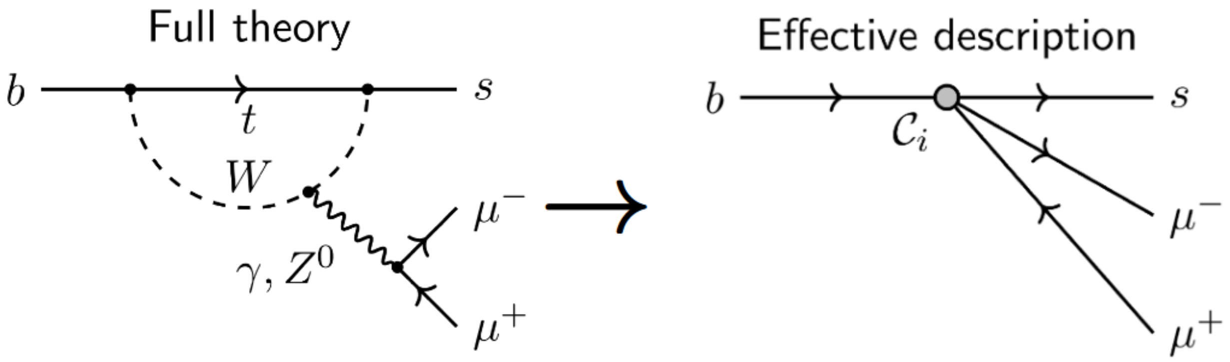
Anomalies

Results in rare B decays deviate from predictions in LHCb data…. (not only there)



Effective field theory

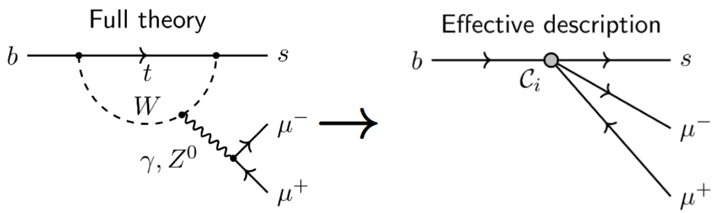
- Are anomalies consistent with each other?
- **Use effective field theory at B-hadron scale, just like beta decay four-point interaction!**



Effective field theory

- An EFT probes different couplings:

$$\mathcal{H}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} V_{\text{CKM}} \sum_i \mathcal{C}_i \mathcal{O}_i$$

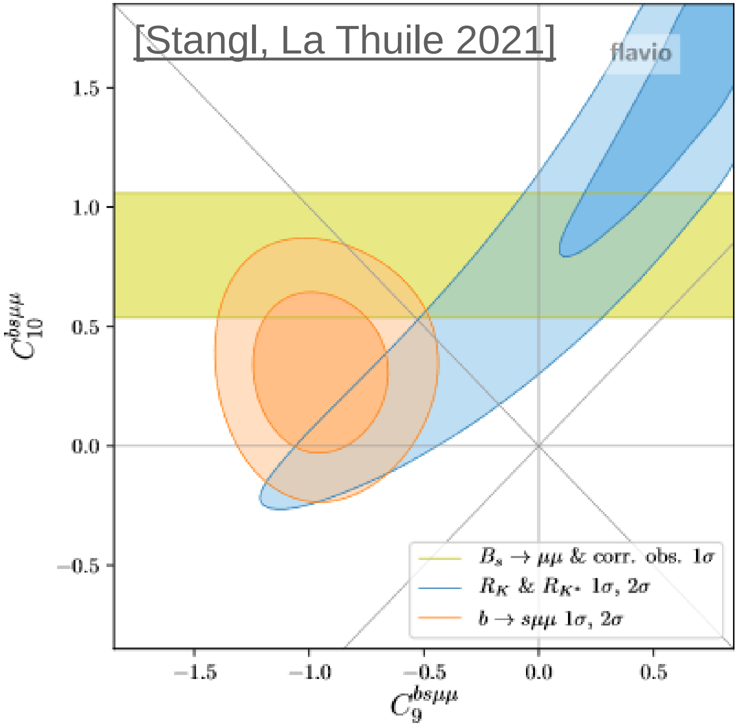


- Fermion operators O_i, Wilson coefficients C_i
- Grouped by leptonic current: (SM,NP)
  - C_7 photon penguin
  - $(C_{10})C_9$ (axial) vector
  - $(C_P)C_S$ (pseudo) scalar
- Note: operators, coefficients with opposite quark current handedness from SM marked with O_i', C_i' (negligible in SM and not relevant today)

Effective field theory: fit results

- Global fits combine measurements of $B_s^0 \to \mu\mu$, $R_{K^{(*)}}$, other $b \to s\mu\mu$ results
- **Global fits indicate consistent deviation: reduction of C_9 for muons** (perhaps also in C_{10})?
- **Could this solve flavour puzzle?**

Time to discuss the new results…



On the menu today: all new!

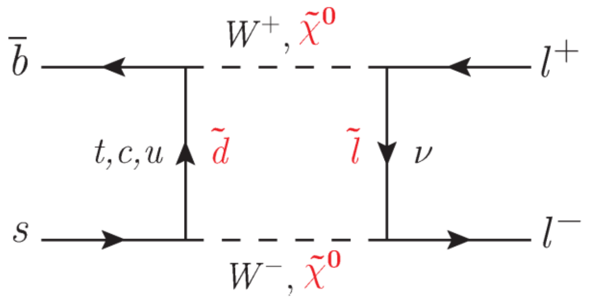
- Improved measurement of $B^0_{(s)} \to \mu^+\mu^-$ decay observables
(+ B^0_s/B^0 production fraction at LHCb (f_s/f_d))

- $R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$ and evidence for lepton universality violation

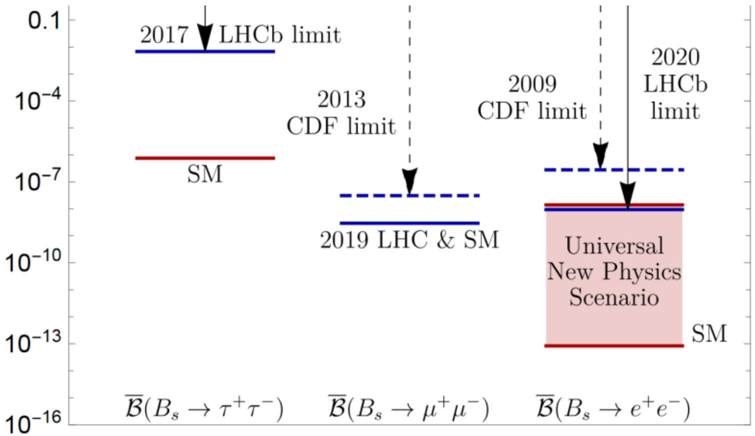
- Interpretation and conclusions

Leptonic decays: $B^0_{(s)} \to l^+ l^-$

- Excellent decays to study $b \to s(d)ll$ transition
  - Helicity suppression: **very rare in SM, sensitive to C_{10}**
  - **Scalar contributions (C_S, C_P) not helicity suppressed → enhanced!**
  - **Precise theory predictions**, even for branching fraction
- Only $B^0_{(s)} \to \mu^+\mu^-$ in current experimental reach
- Predictions
  - $B(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$
  - $B(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$
  - $\frac{B(B^0 \to \mu^+\mu^-)}{B(B^0_s \to \mu^+\mu^-)} = 0.0281 \pm 0.0006$ (extra clean test)

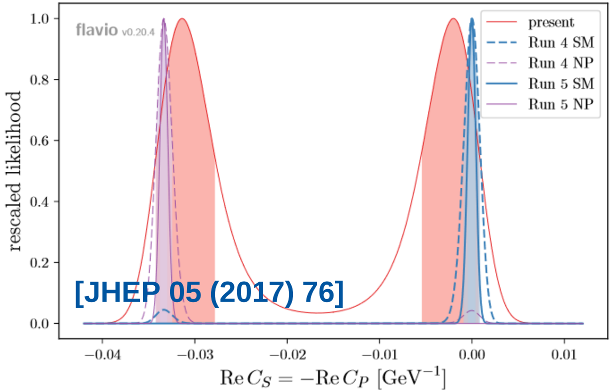


Fleischer et al., JHEP 05 (2017) 156



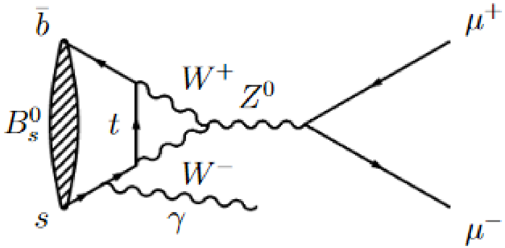
$B^0_{(s)} \to \mu^+\mu^-$: extra observables

τ_{eff} finds solution: C_S/C_P **or not**?

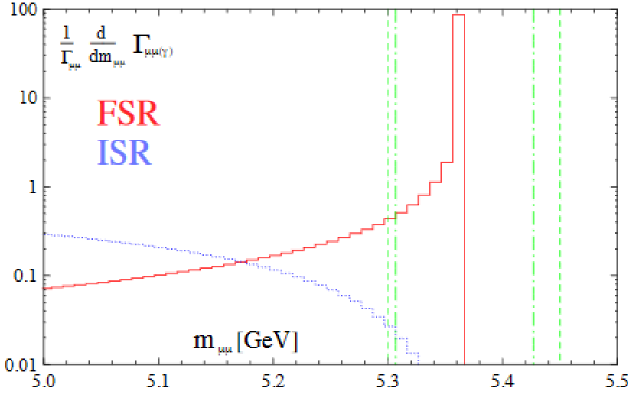


- Only CP-odd state contributes to $B^0_{(s)} \to \mu^+\mu^-$ in SM: CP amplitude asymmetry $A^{\mu\mu}_{\Delta\Gamma_s} = +1$
- Neutral B^0_s mass(~CP) eigenstates characterised by sizeable difference in decay width, $\Delta\Gamma_s = 0.085 \pm 0.006\ \text{ps}^{-1}$
- **Measure effective lifetime τ_{eff} to test for CP-even contribution, scalar NP (C_S, C_P)!** ($A^{\mu\mu}_{\Delta\Gamma_s} \in [-1, +1]$)

- $B^0_{(s)} \to \mu^+\mu^-\gamma$: Initial State Radiation for $m_{\mu^+\mu^-} > 4.9\ \text{GeV}$
- **New observable in this analysis, sensitive to C_9, C_{10} together**
- SM prediction $O(10^{-10})$ [JHEP 11 (2017) 184, PRD 97 (2018) 053007]
- Final State Radiation included in $B^0_s \to \mu^+\mu^-$ via PHOTOS



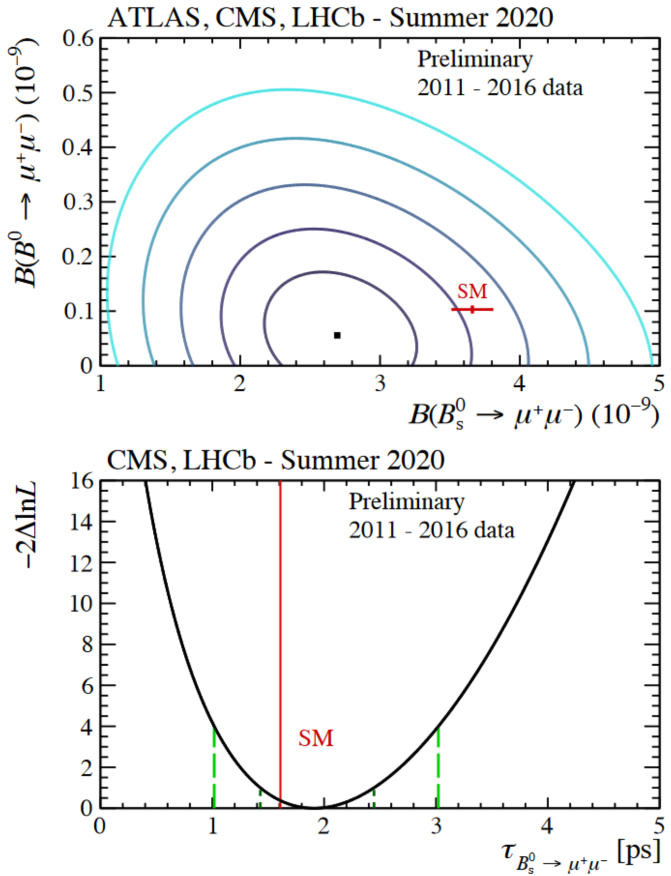
[PRL 112 (2014) 101801]



Previous results

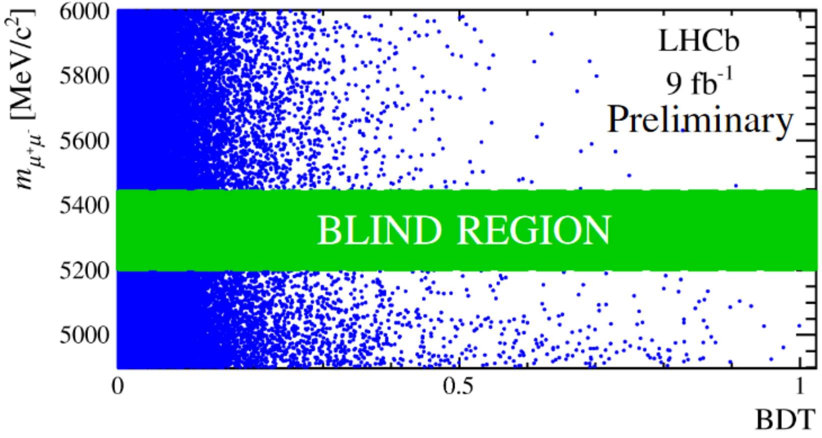
- Recent combination of ATLAS, CMS, LHCb results with data up to 2016: **[LHCb-CONF-2020-002]**
  - $B(B_s^0 \to \mu^+\mu^-) = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$
  - $B(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10}$ at 95% CL
  - $\tau_{\text{eff}}(B_s^0 \to \mu^+\mu^-) = (1.91^{+0.37}_{-0.35})$ ps
- **Mild tension with SM, compatible with anomalies**

- **No search yet for $B_s^0 \to \mu^+\mu^-\gamma$**
  - $B(B^0 \to \mu^+\mu^-\gamma) < 1.5 \times 10^{-7}$ at 90% CL **[BaBar: PRD 77 (2008) 011104]**



Analysis strategy

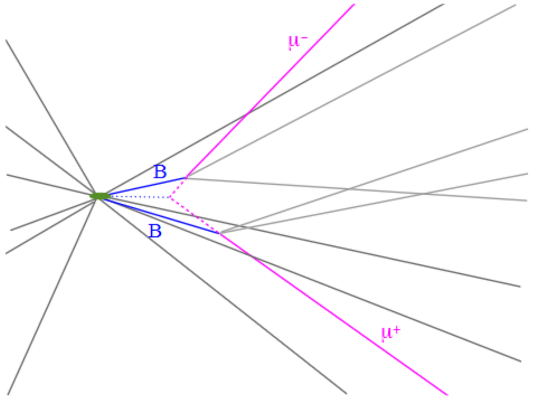
[LHCb-PAPER-2021-007]



- **Similar strategy to previous analysis, strongly improved calibration**

- Muon pairs with $m_{\mu^+\mu^-} \in [4.9, 6.0]$ GeV with good displaced vertex
- Signal region blind until analysis is finalised
- Suppress misID with tight PID cut

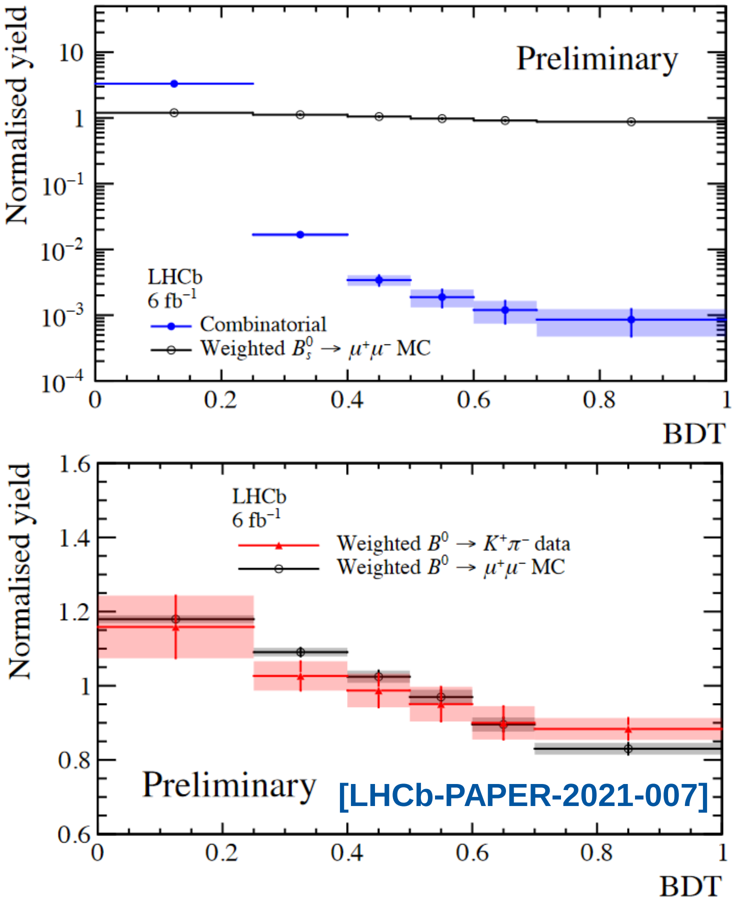
- Main background: combinatorial
- Rejected with multivariate classifier, namely Boosted Decision Tree (BDT)
- **Determine signal from fit to mass and BDT**



BDT calibration

- BDT usage: divide fit sample in 6 BDT bins, exclude first bin (too much background)
- Flat for signal before PID, trigger selection, strongly falling for combinatorial background
- Require determination of signal shape

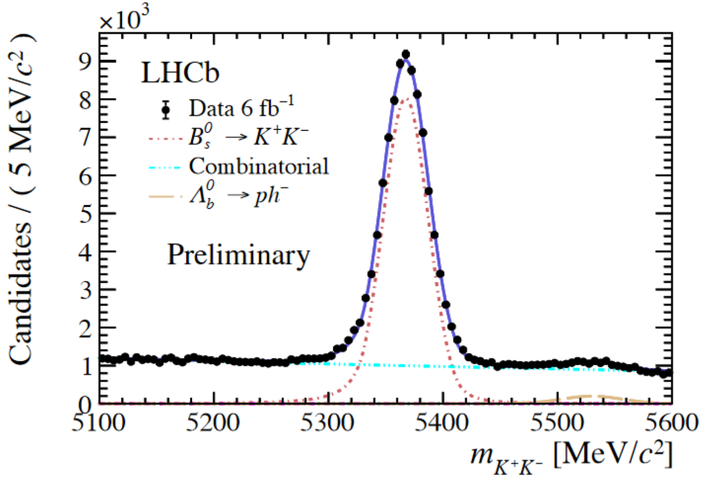
- **New procedure**: simulation samples corrected using data control channels (kinematics, occupancy, PID, trigger)
- Essential: cross-check with $B \to hh$ data!
- **Uncertainty reduced significantly with new procedure, thanks to Silvia!**



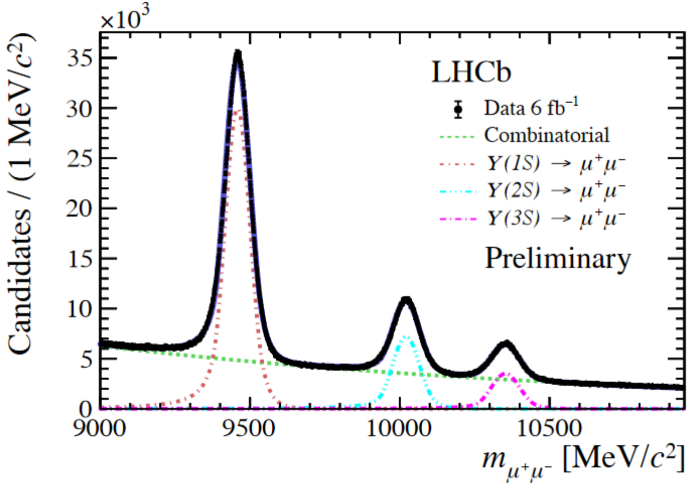
Mass calibration

[LHCb-PAPER-2021-007]

Mean calibrated from fits to $B^0 \to K^+\pi^-, B_s^0 \to K^+K^-$ data



Resolution calibrated with fits to $J/\psi, \psi(2S), \Upsilon(1S), \Upsilon(2S), \Upsilon(3S) \to \mu^+\mu^-$ data



Tail parameters calibrated on smeared simulation

Include correlation of mass shape with BDT

Thanks to Jacco!

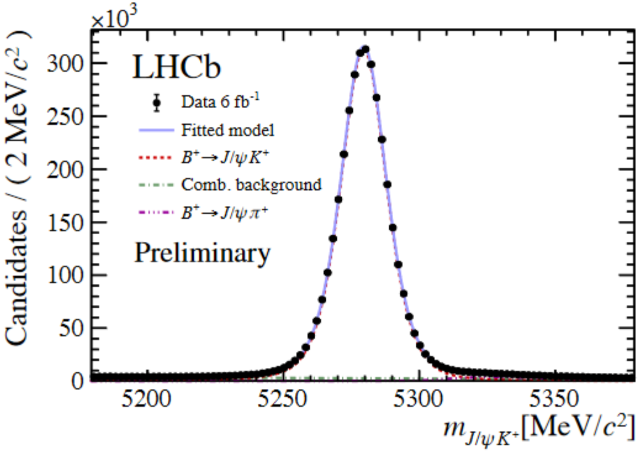
Normalisation: strategy

[LHCb-PAPER-2021-007]

- Normalise branching fraction to well-known channels
- Use two modes, yields determined from mass fits

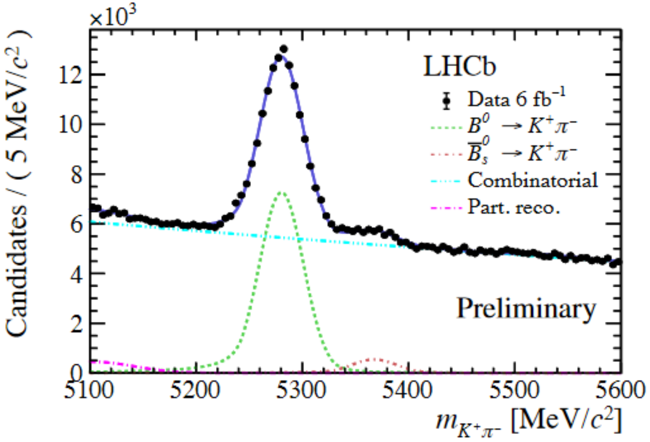
$B^+ \to J/\psi(\to \mu^+\mu^-)K^+$

Muons in final state: similar trigger, PID



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

Two-body B decay: similar decay topology



Normalisation: results

[LHCb-PAPER-2021-007]

- Normalisation used to convert yield into BF using

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

- Normalisation yield and BF
- Signal/normalisation efficiency ratio evaluated from simulation, control channels
- Ratio of hadronisation fractions (for B_s^0): **f_s/f_d from new combination → see next slides ☺**
- **Signal yields consistent with expected improvement**
- Cross-check: $B(B^0 \to K^+\pi^-)/B(B^+ \to J/\psi K^+)$ consistent w. PDG

Estimated total signal yields (before BDT):

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

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

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

f_s/f_d: introduction

[arXiv:2103:06810]

- f_s/f_d = B_s^0/B_d^0 production ratio
  - **Required to measure B_s^0 branching fractions such as $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$**
  - Interesting per se as probe of hadronisation and fragmentation
  - Previously found to depend on p_T (not on η)
  - Assume equal production of B_d^0, B^+
- **f_s/f_d measured at LHCb with ratio of B_s^0/B_d^0 (or B^+) efficiency-corrected yields n_{corr} using prediction for branching fraction ratio:**

$$\frac{n_{\text{corr}}(B_s^0 \to X)}{n_{\text{corr}}(B^{0(+)} \to Y)} = \frac{\mathcal{B}(B_s^0 \to X)}{\mathcal{B}(B^{0(+)} \to Y)} \frac{f_s}{f_{d(u)}}$$

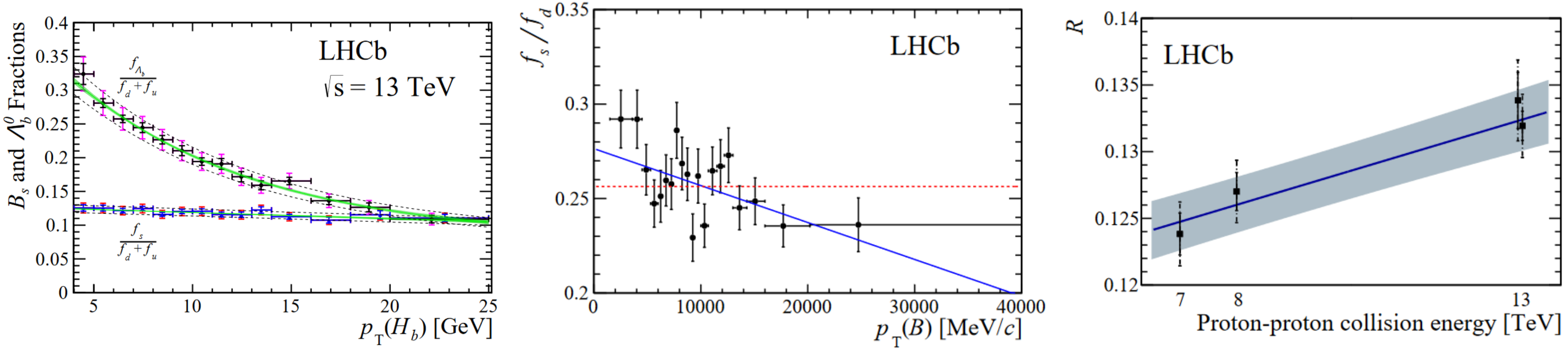
- Five previous measurements (2011 to 2020)**:**
  combination to determine single value with higher precision

Combination of f_s/f_d measurements: inputs

- Previous LHCb measurements performed at 7, 8, 13 TeV, $p_T \in [0.5,40]$ GeV, $\eta \in [2,6.4]$
- Three decay modes: $B \to D\mu X, B \to Dh, B \to J/\psi X$ (no prediction)
- **Update external inputs for $B \to D\mu X, B \to Dh$ (e.g. D branching fraction, B lifetimes): significant improvement in sensitivity!**

[arXiv:2103:06810]

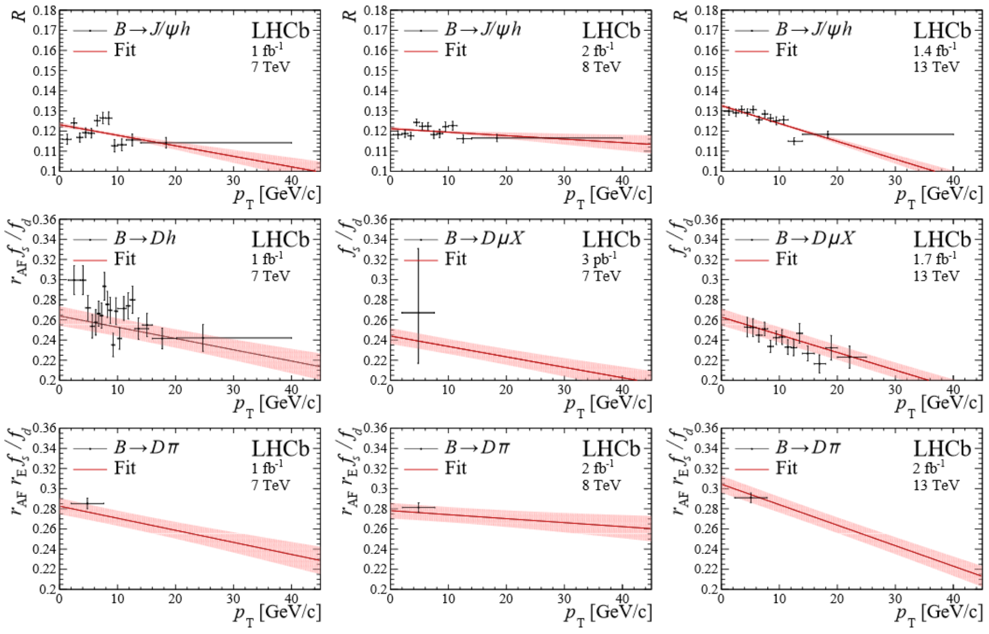
$B \to D\mu X$, 13 TeV | $B \to Dh$, 7 TeV | $B \to J/\psi X$, various $\sqrt{s}$



Combination of f_s/f_d measurements: results

[arXiv:2103:06810]

- First observation of $\sqrt{s}$ dependence, hint of p_T dependence variation vs $\sqrt{s}$
- Integrated value (13 TeV) in LHCb acceptance: $\frac{f_s}{f_d} = 0.2539 \pm 0.0079$
- **Uncertainty reduced by ~factor 2 to ~3%**
- **Also measure $\boldsymbol{B(B_s^0 \to J/\psi\phi)}$, $\boldsymbol{B(B_s^0 \to D_s^- \pi^+)}$ with similar precision**
- Update previous B_s^0 branching fraction measurements
- **Essential improvement for this measurement of $\boldsymbol{B(B_s^0 \to \mu^+\mu^-)}$!**



Backgrounds

[LHCb-PAPER-2021-007]

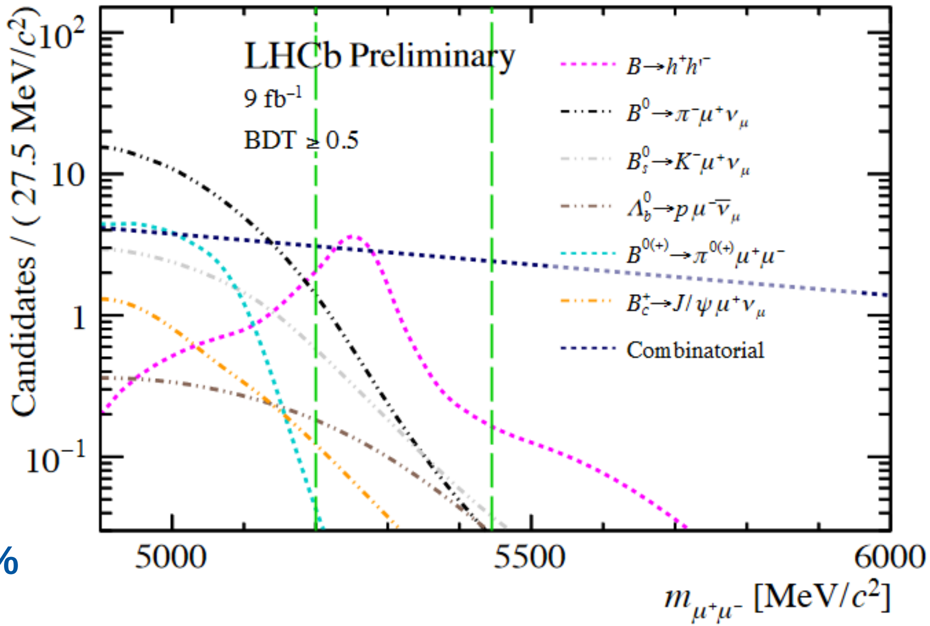
Three types of backgrounds in fit:

1. Combinatorial, over full mass spectrum (free in fit)
2. Mis-identified backgrounds:
   $B^0 \to \pi^- \mu^+ \nu_\mu$, $B_s^0 \to K^- \mu^+ \nu_\mu$,
   $B^0_{(s)} \to h^+ h'^-$, $\Lambda_b^0 \to p \mu^- \overline{\nu_\mu}$
3. Real muons:
   $B^{0/+} \to \pi^{0/+} \mu^+ \mu^-$, $B_c^+ \to J/\psi \mu^+ \nu_\mu$

Calibrate on corrected simulation samples

Cross-check with fit to $B^0_{(s)} \to h^+ h'^-$ data with one hadron mis-identified, consistent within 10%

Everything calibrated, time to fit!

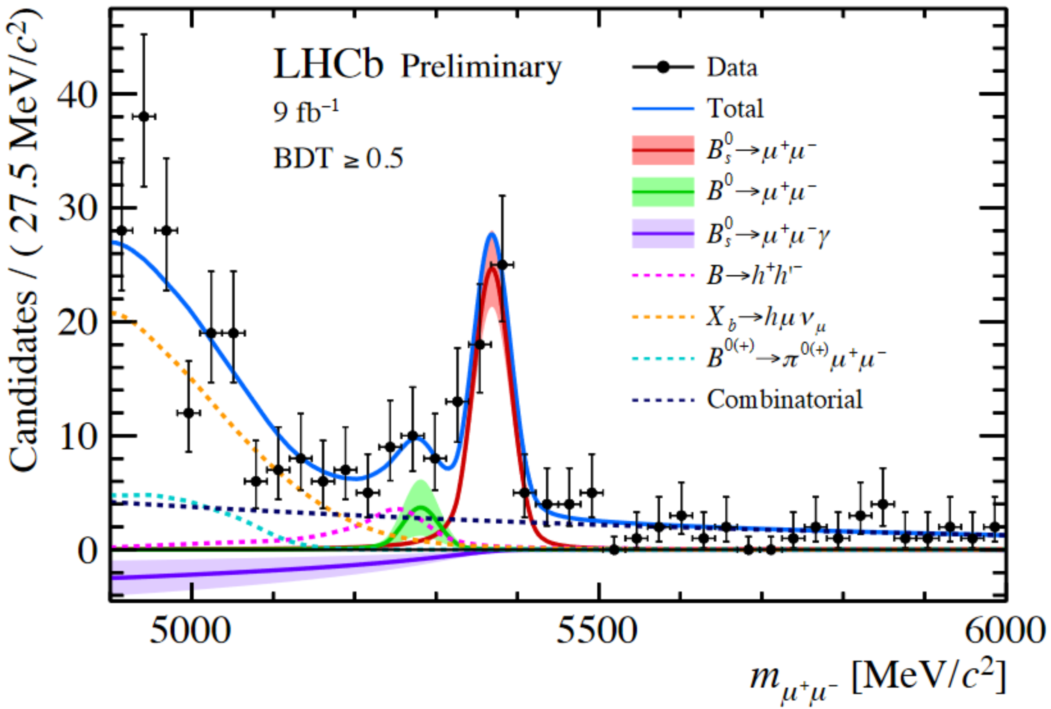


Results: branching fraction

[LHCb-PAPER-2021-007]

- $\boldsymbol{B(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}}$ **with significance > 10$\boldsymbol{\sigma}$**

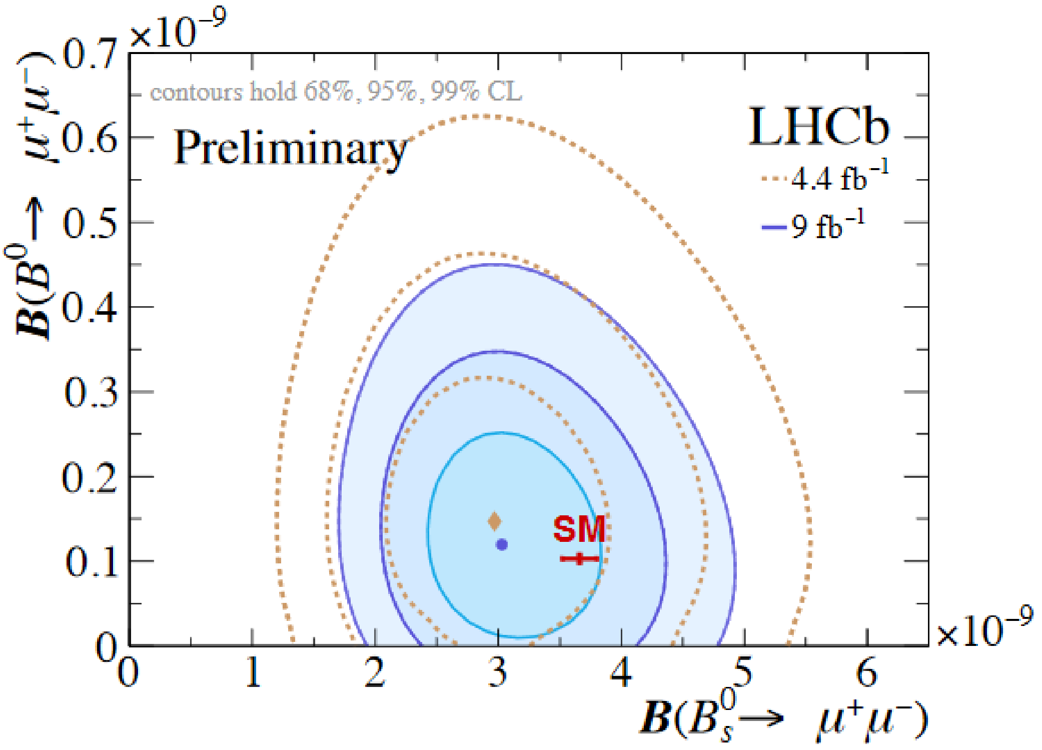
- $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\gamma$ compatible with background-only at 1.7σ, 1.5σ



Results: compatibility with SM

[LHCb-PAPER-2021-007]

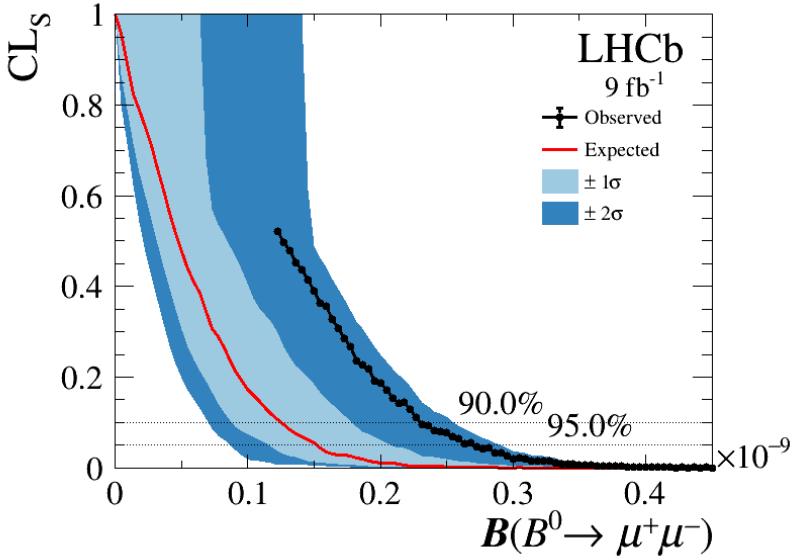
- 2D likelihood contour of $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ vs. $\mathcal{B}(B^0 \to \mu^+\mu^-)$: **result well compatible with SM and previous LHCb result**
- Correlation is small (-7%)



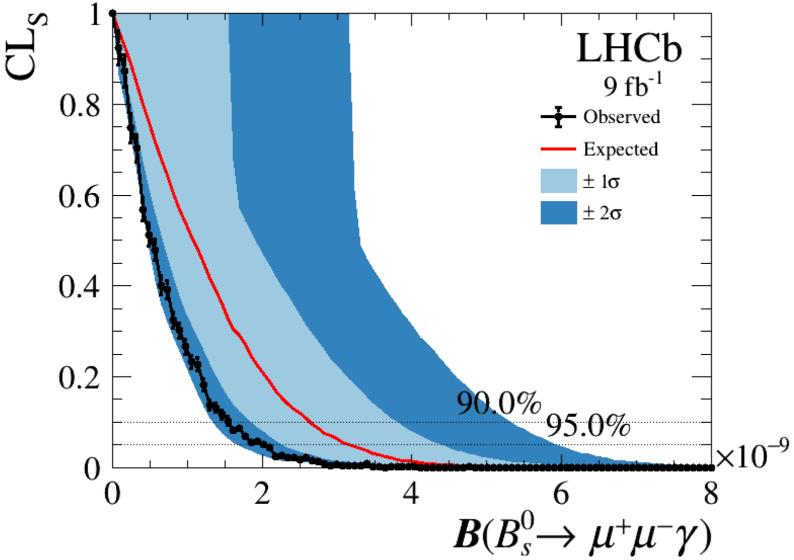
Results: limits (CLs method)

[LHCb-PAPER-2021-007]

$B(B^0 \to \mu^+\mu^-) < 2.3(2.6) \times 10^{-10}$ at 90(95)% CL

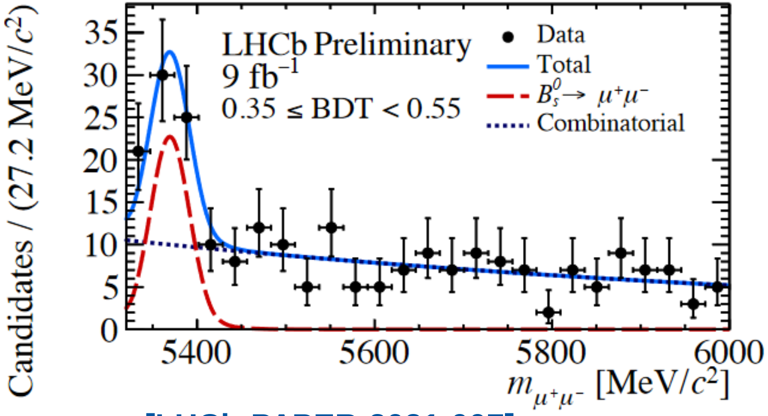


$B(B_s^0 \to \mu^+\mu^-\gamma) < 1.5(2.0) \times 10^{-9}$
for $m_{\mu^+\mu^-} > 4.9$ GeV at 90(95)% CL

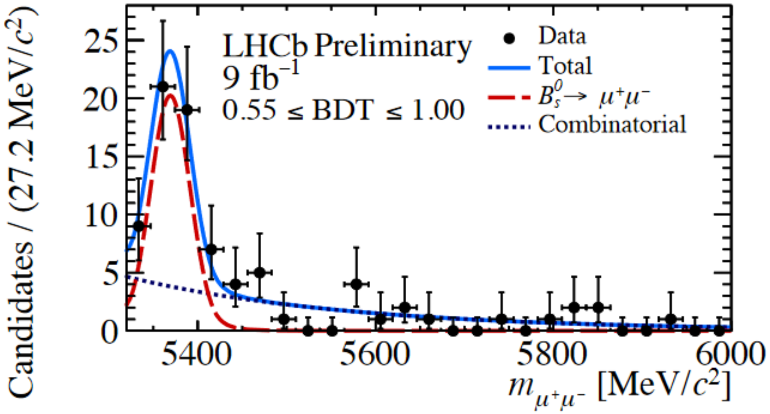


Effective lifetime

- $B_s^0 \to \mu^+\mu^-$ **measurement only: separate optimisation**
  - Smaller mass window (>5.32 GeV): contains only B_s^0, combinatorial
  - Looser PID requirements
- Procedure:
  1. Perform mass fit in two BDT bins to subtract background (with sWeights) [NIM A555 (2005) 356–369]
  2. Calibrate lifetime acceptance on simulation, test with $B^0 \to K^+\pi^-, B_s^0 \to K^+K^-$ decays
  3. Fit lifetime distribution including acceptance to determine effective lifetime

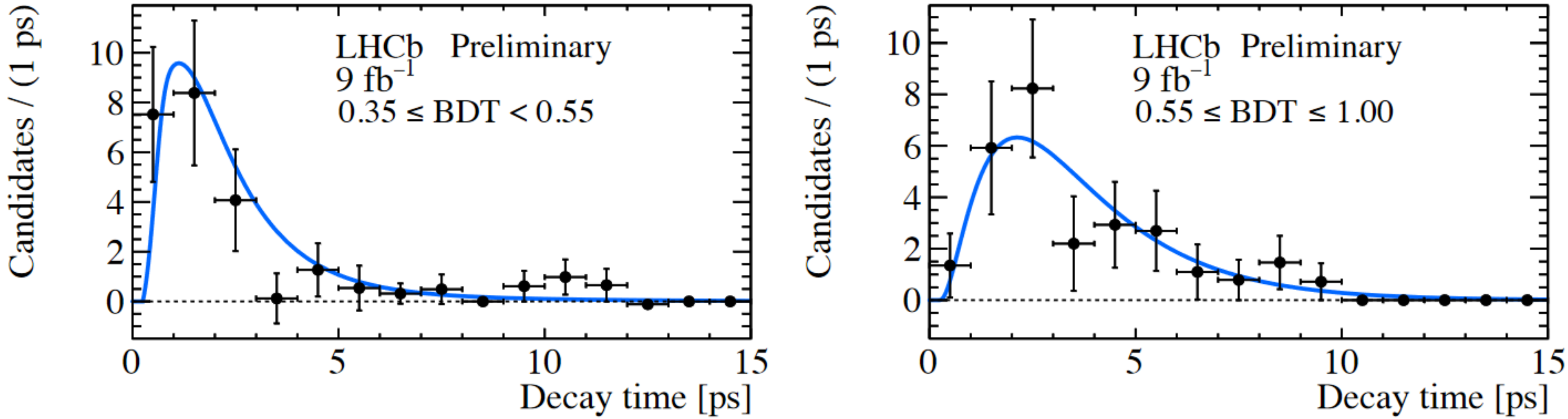


[LHCb-PAPER-2021-007]



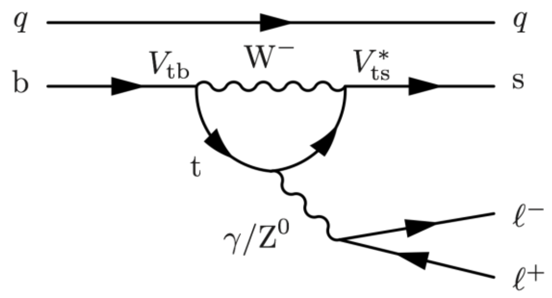
Results: effective lifetime fit

[LHCb-PAPER-2021-007]

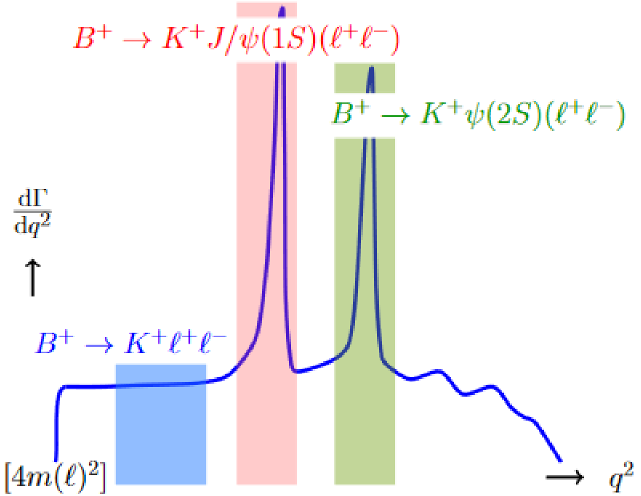


- $\boldsymbol{\tau(B_s^0 \to \mu^+\mu^-) = 2.07 \pm 0.29 \pm 0.03}$ **ps** (previously $2.04 \pm 0.44 \pm 0.05$ ps)
- 1.5 sigma from SM (i.e. $A_{\Delta\Gamma_s}^{\mu\mu} = 1$), 2.2 sigma from extreme non-SM (i.e. $A_{\Delta\Gamma_s}^{\mu\mu} = -1$)
- **Run 3 data needed to start providing significant constraints**

Semileptonic rare B decays



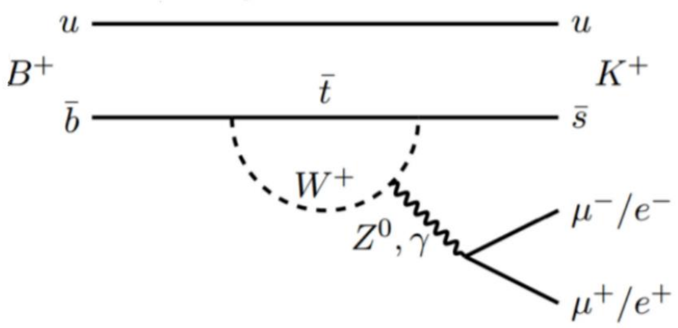
- "Regular" rare B decay
  - Includes spectator quark
  - At least 3-body final state
- Physics depends on dilepton invariant mass: q^2
- Additional observables:
  - Branching fraction (difficult to predict)
  - Angular observables (better, still tricky)
  - Lepton universality (clean tests of SM)
  - Note: not testing CP violation in these observables (yet)



Lepton universality: R_K

[arXiv:2103.11769]

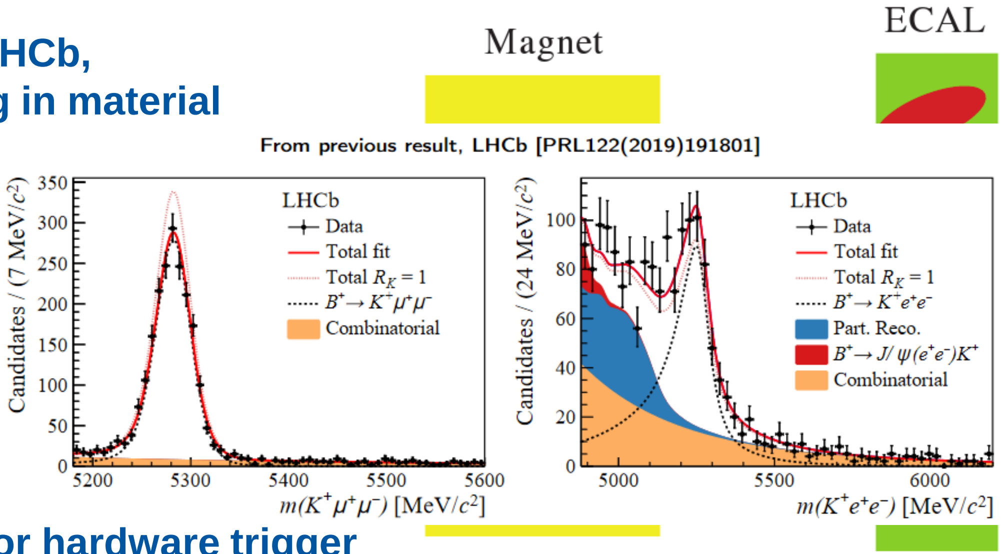
- **Lepton universality: only difference between muons, electrons is mass**
- Strong test of lepton universality with $R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e)} \cong 1$ (in SM) for $q^2 > 0.1\ \mathrm{GeV}$
- Uncertainty of $O(1\%)$ in SM (from QED)
- Sensitive to $\boldsymbol{C_9, C_{10}}$ **in muons versus electrons**
- **Any significant deviation in $\boldsymbol{R_K}$ is clear sign of New Physics**



Measurements with electrons at LHCb

[arXiv:2103.11769]

- **Electrons provide extra challenge in LHCb, because of significant bremsstrahlung in material**
- If bremsstrahlung is emitted before magr momentum is underestimated
- Recover bremsstrahlung by searching for photon clusters in calorime
- If found, correct electron momentum
- **Still, mass shape worse for electron m**



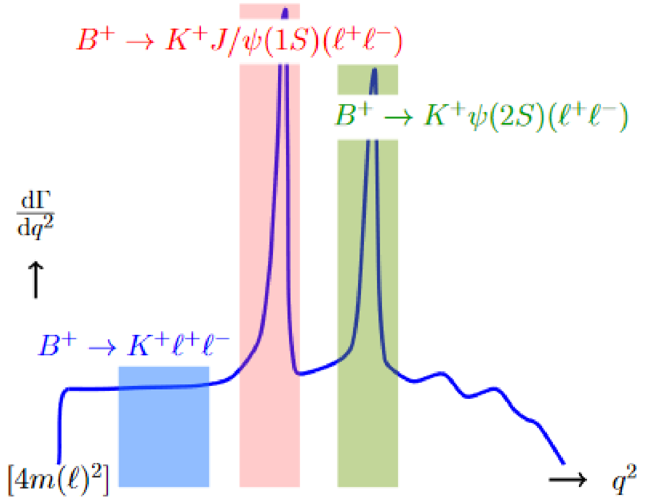
- **Additionally, electrons more difficult for hardware trigger (than muons)**
- Electron sample divided based on hardware trigger category: electron, rest-of-event, or hadron trigger

Strategy

[arXiv:2103.11769]

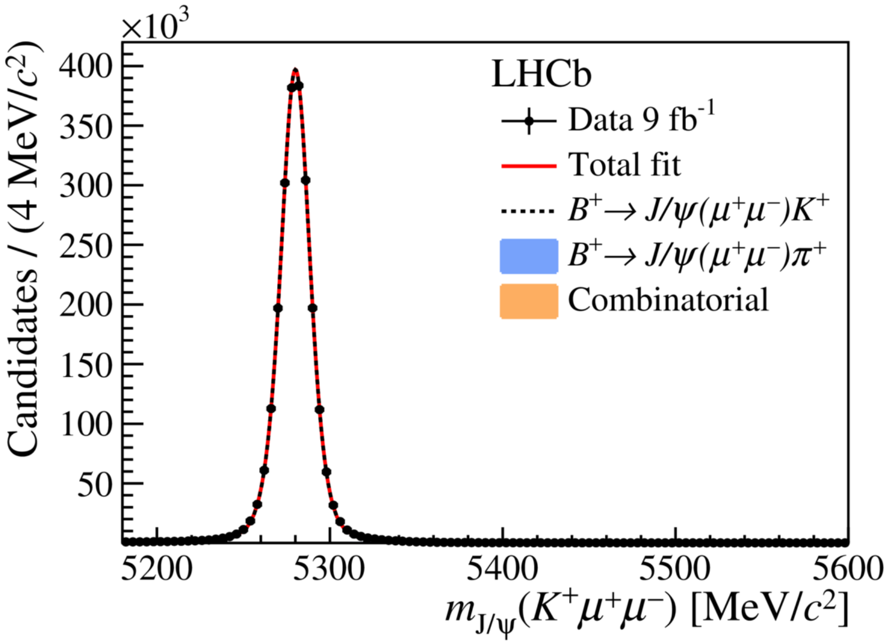
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))} = \frac{N^{\rm rare}_{\mu^+\mu^-}\ \varepsilon^{J/\psi}_{\mu^+\mu^-}}{N^{J/\psi}_{\mu^+\mu^-}\ \varepsilon^{\rm rare}_{\mu^+\mu^-}}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

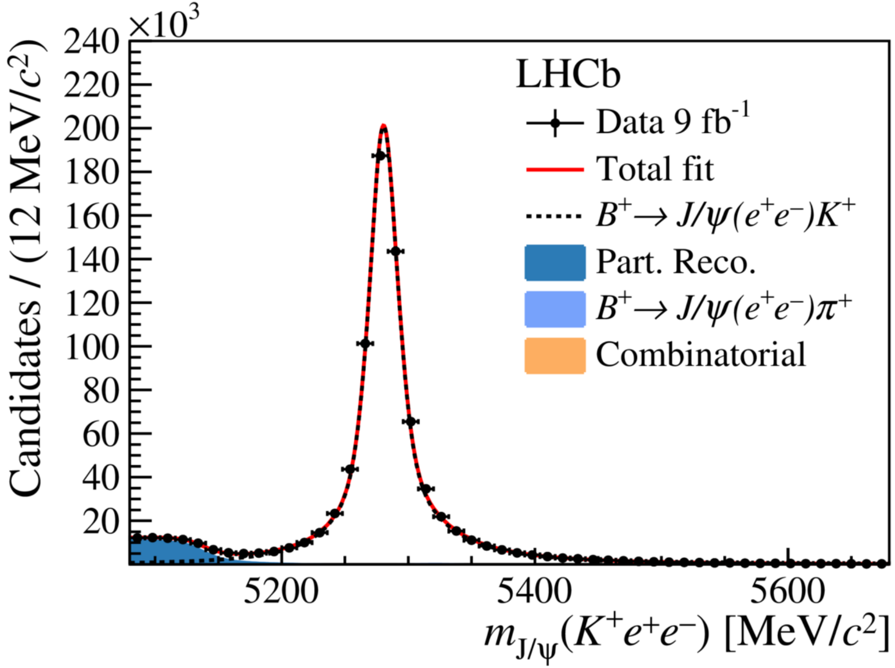
- **Measure R_K as double ratio (relative to $B^+ \to K^+ J/\psi$)**
- Selection with BDT to reduce combinatorial,
  PID cuts and mass vetoes to reduce exclusive backgrounds
- Rare and J/ψ modes share identical selections but for q^2
- Yields determined from mass fits
- Efficiencies computed from simulation calibrated
  with control channels from data:
  - Trigger, particle identification efficiency
  - B-meson kinematics
  - Resolution of q^2, mass
- **Essential to validate with cross-checks!**



Mass fits for calibration modes

[arXiv:2103.11769]





Cross-checks: $r_{J/\psi}$

[arXiv:2103.11769]

- **To ensure efficiencies are well calibrated, determine single ratio:**

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

known to hold within 0.4%

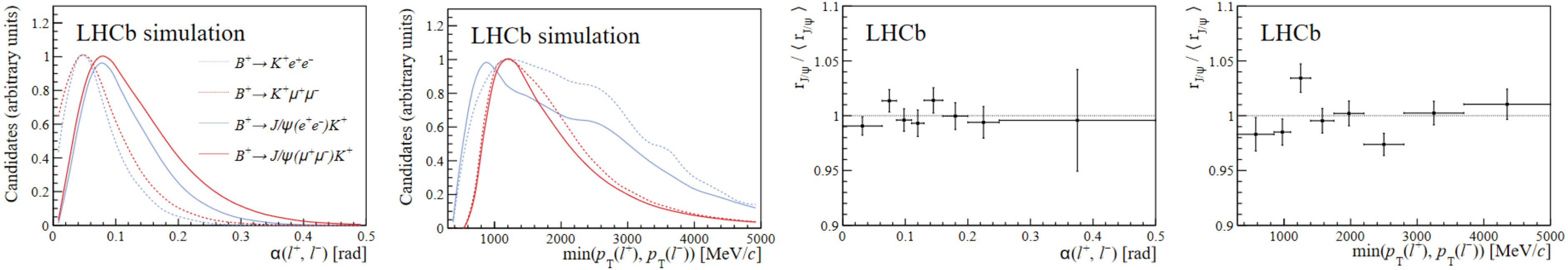
- **Requires direct control of muons versus electrons**
- Result:

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

compatible with expectation per subsample, including per trigger category

Cross-checks: differential $r_{J/\psi}$ [arXiv:2103.11769]

- **Validate $r_{J/\psi}$ is flat to ensure efficiency transfers to rare mode in various variables (e.g. kinematics, lepton opening angle)**



- Taking largest observed departure from flatness as genuine effect, bias on R_K is 0.1%

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

[arXiv:2103.11769]

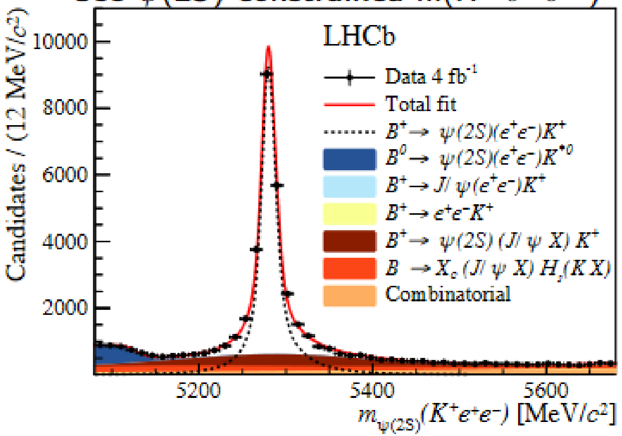
- Measurement of double ratio

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

- **Independent validation of double-ratio procedure**
- **Result well compatible with unity:**

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

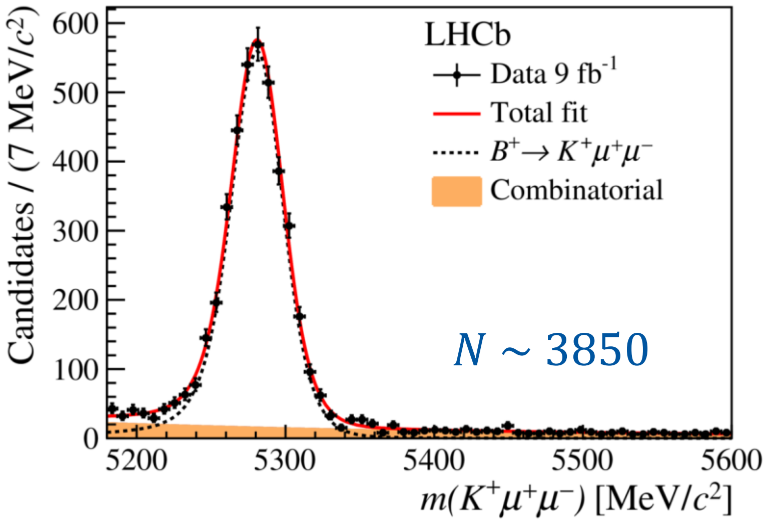
Use $\psi(2S)$ constrained $m(K^+\ell^+\ell^-)$

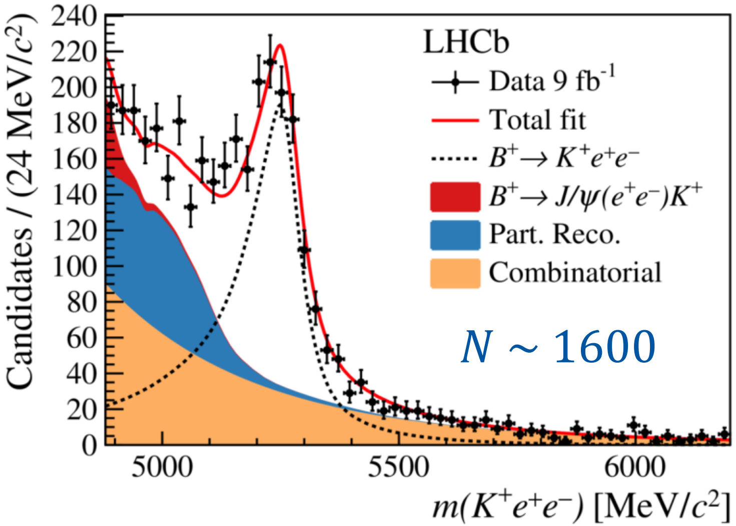


Determining R_K

[arXiv:2103.11769]

- R_K is measured as parameter in simultaneous fit to $m(K^+\mu^+\mu^-)$ and $m(K^+e^+e^-)$ for signal and J/ψ modes
- Uncertainties on efficiency ratios propagated as multivariate constraint on likelihood





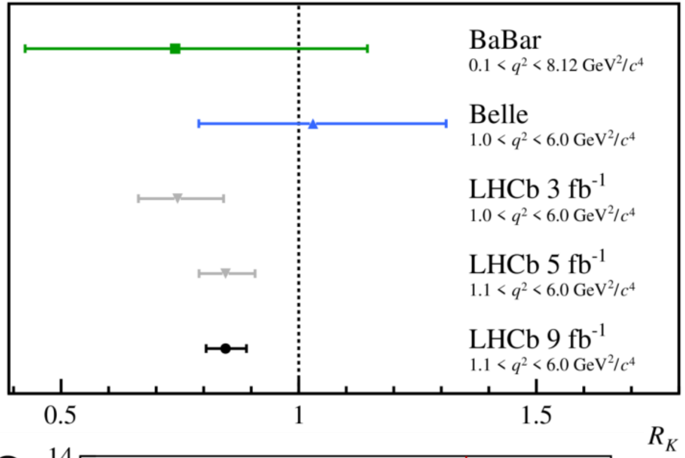
Results: R_K

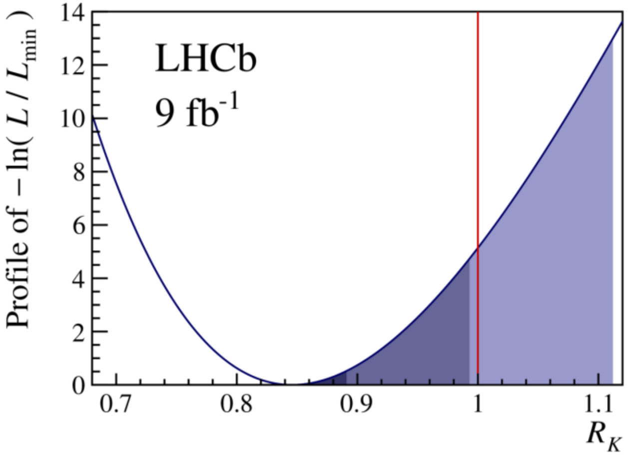
[arXiv:2103.11769]

$$R_K = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

- Exact same central value as before
- SM hypothesis p-value: 0.0010,
  evidence of lepton universality violation at 3.1σ
- Main systematic uncertainties (~1%)
  from fit model, statistics of calibration samples

- Compatibility with SM determined from integration of profile likelihood
  (including uncertainty on SM prediction of 1%)





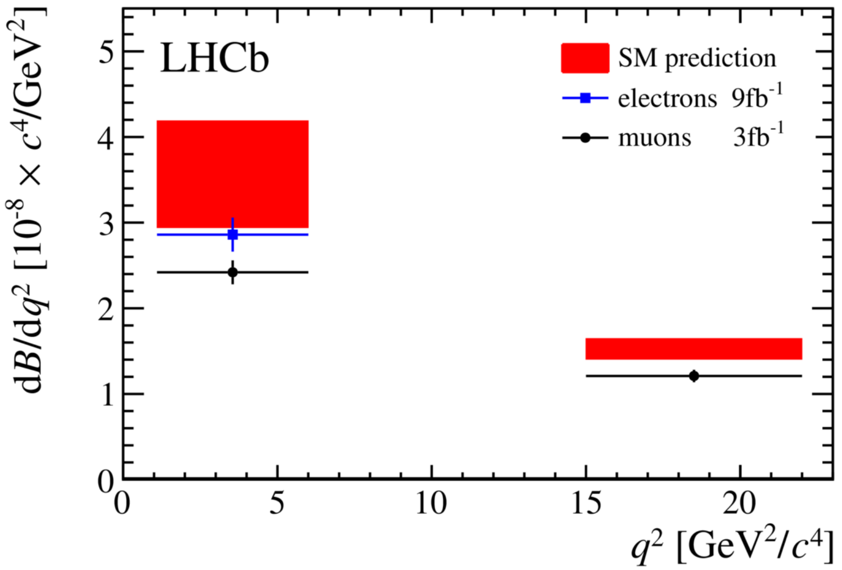
Results: $B(B^+ \to K^+e^+e^-)$

- Using R_K, previous measurement of $B(B^+ \to K^+\mu^+\mu^-)$, determine

$$\boldsymbol{B(B^+ \to K^+e^+e^-) = (28.6 \pm 1.5 \pm 1.4) \times 10^{-9}}$$

- **Suggests that electrons are more SM-like than muons**

- **Time to have a look at the EFT ☺**



Current EFT fit

[arXiv:2103.13370]

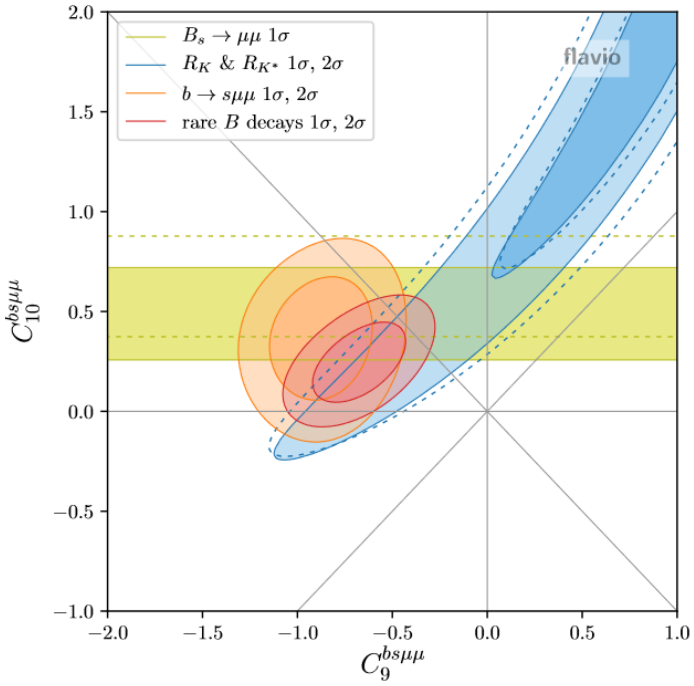
First consider new physics in $b \to s\mu\mu$ only,
including new $R_K, B(B_s^0 \to \mu^+\mu^-)$ results:

Clean observables ($R_{K^{(*)}}, B(B_s^0 \to \mu^+\mu^-)$)
pull of 4.7 sigma in C_{10} or $C_9 - C_{10}$

Other $b \to s\mu\mu$ observables:
pull of 4.9 sigma in C_9 or $C_9 - C_{10}$

All rare B decays:
pull of 6.2 sigma in C_9 or $C_9 - C_{10}$

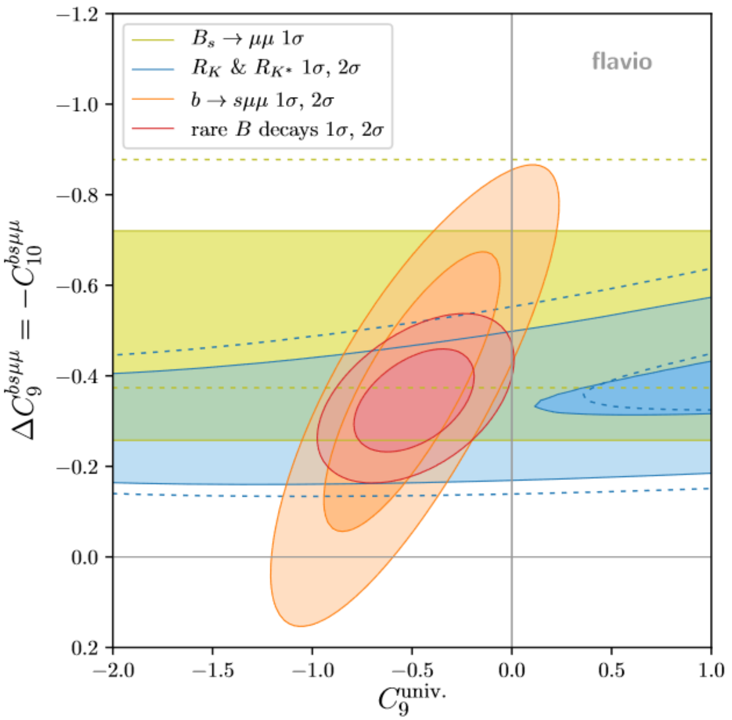
Any other options?



Current EFT fit

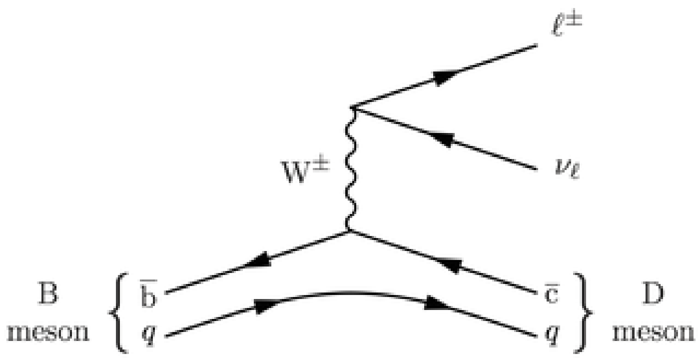
[arXiv:2103.13370]

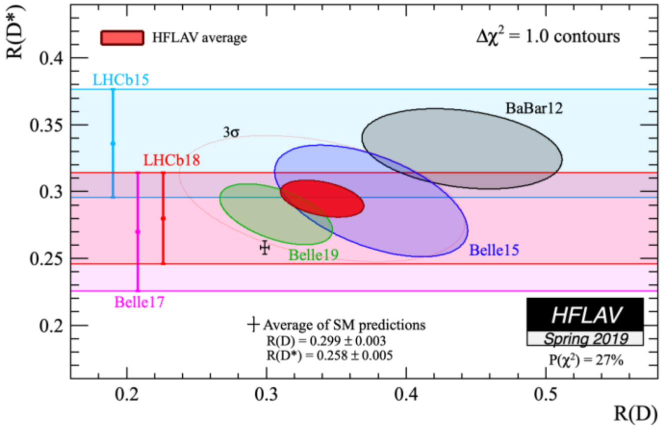
- **Interesting option (personal opinion):**
  - Universal contribution to $\boldsymbol{C_9}$ ($b \to see, b \to s\mu\mu$ and $b \to s\tau\tau$)
  - $b \to s\mu\mu$ only contribution to $\boldsymbol{C_9 - C_{10}}$
- Slightly favoured by data over NP in $b \to s\mu\mu$-only (pull of 6.4 sigma)
- **Any reason to favour this scenario?**



Link with R(D*)

- Another test of lepton universality that shows tension with SM: $b \to c\tau\nu$ transition!
- $R(D^{(*)}) = \frac{B(B\to D^{(*)}\tau\nu)}{B(B\to D^{(*)}\mu\nu)}$, ~15% more $B \to D^{(*)}\tau\nu$ seen than expected, **measured by B-factories + LHCb**
- But $b \to c\tau\nu$ is tree-level process, with branching fractions of O(5%)? How can they be connected to $b \to sll$?
- **Through generation-dependent couplings!**

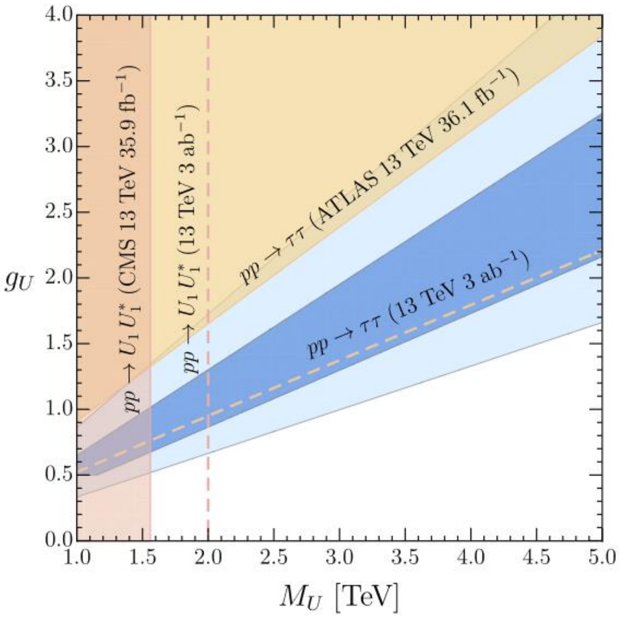




Link with R(D*): combined fit

[arXiv:1903.10434, arXiv:1901.10480]

- Can combine $b \to sll$ results with $R(D^{(*)})$ through EFT at electroweak scale: SMEFT, finding:
  - Large contribution to $b \to c\tau\nu$ type-operator (3233)
  - Smaller contribution to $b \to s\mu\mu$ type-operator (2223)
  - $b \to sll$ universal contribution to $\boldsymbol{C_9}$ from (3233) operator
- **Consistent solution possible passing constraints from EW, other flavour measurements!**
- **If single mediator, implies vector leptoquark $\boldsymbol{U_1}$** at TeV scale, with important constraints:
  - Indirect: $B \to K\tau\mu$, leptonic τ decay, $B \to X_s\gamma, B_s^0 \to \tau\tau$
  - Direct: $pp \to \tau\tau, \tau\nu$, but not easy to constrain yet
- **What could UV-complete theory for leptoquark be?**



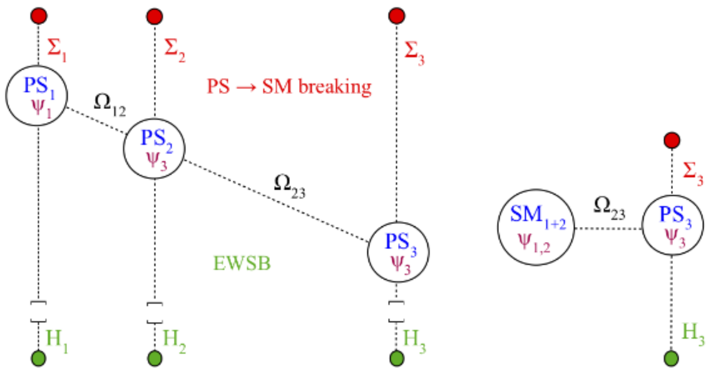
Solving the flavour puzzle?

[arXiv:1712.01368, arXiv:2012.10492]

- UV completion of vector leptoquark U_1 suggests Pati-Salam unification
- **Interesting model: PS_3**, for which
  - **Quarks and leptons are unified**
  - **Natural structure of Yukawa couplings**
  - **Leptoquark U_1 couples mainly to third generation**
  - **Thereby addressing B-anomalies**
- Seems to be possible to address neutrino masses with same model

- **Possible solution of flavour puzzle!?**

The three-site Pati-Salam model [18] originates from the ambitious attempt to i) unify and quantize the $U(1)$ charges of quark and leptons, ii) obtain a natural description of all the SM Yukawa couplings in terms of $\mathcal{O}(1)$ parameters and fundamental scale ratios, and iii) address the recent hints of lepton-flavor non-universality violations in semileptonic B decays.



I. High-scale model

II. TeV-scale effective model

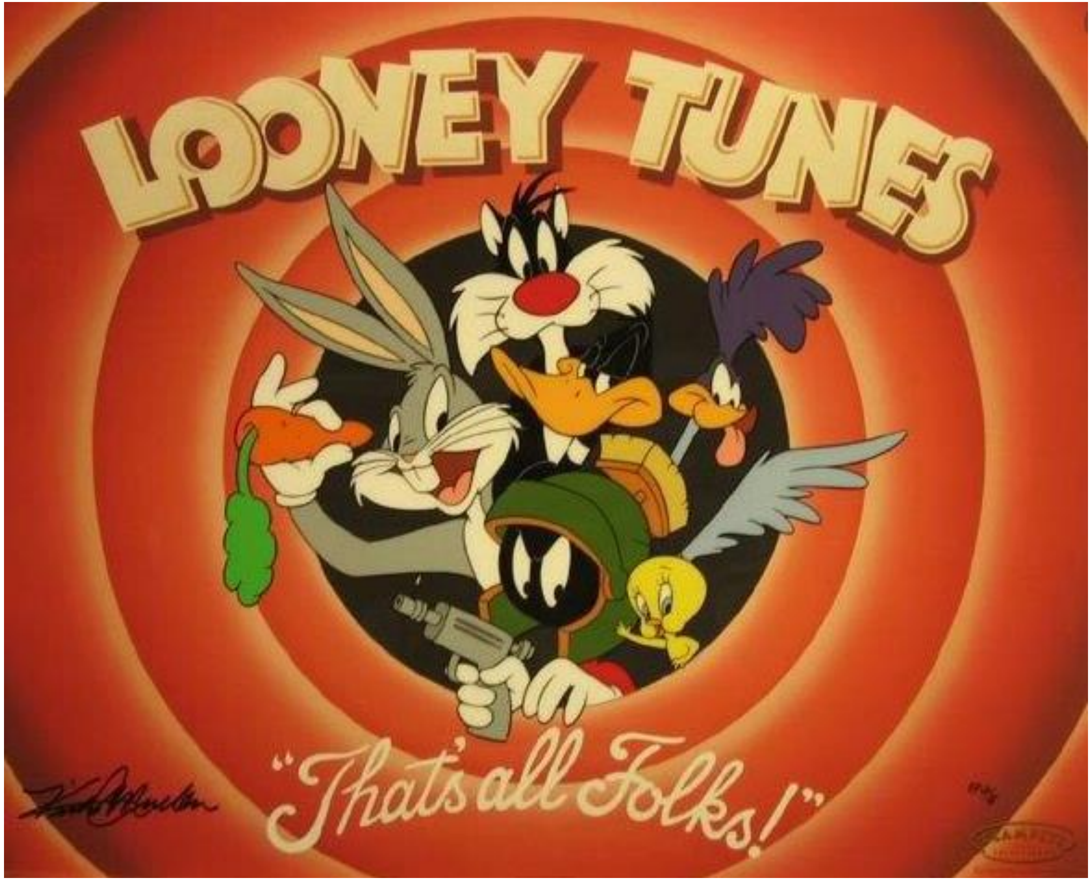
Summary

- Rare $b \to sll$ decays are sensitive probe of new physics
- Many observables combined through global fit to Wilson coefficients
- **Global fits suggest a consistent set of anomalies…**

- $B(B_s^0 \to \mu^+\mu^-)$ reaching new level of precision aided by new measurement of f_s/f_d
- **Evidence found of lepton universality violation in $\boldsymbol{R_K}$**

- Possible to link with deviations in $b \to c\tau\nu$ transition consistently
- **Could these measurements solve the flavour puzzle?**

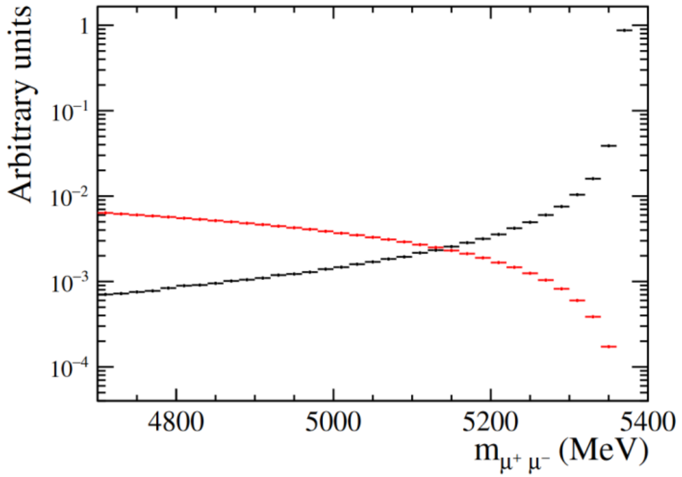
- Many measurements underway ($R_{K^*}, R_\phi, R_{K_S^0}, R_{K^{*+}}$, angular analyses, LFV with τ)
- LHCb upgrade ongoing: increase luminosity by factor 5, remove hardware trigger!


LOONEY TUNES
"That's all Folks!"

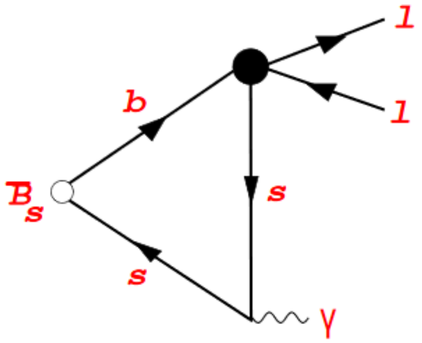
Backup

$B_s^0 \to \mu^+\mu^-\gamma$: ISR/FSR

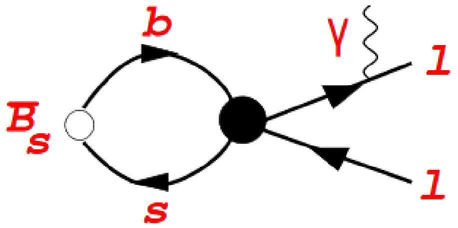
- ISR: photon from b, s quarks, effectively three-body semileptonic B decay (vs q^2): **partially reconstructed background for $B_s^0 \to \mu^+\mu^-$ reconstruction**
- FSR: soft photons from muons, same Wilson coefficients: **additional tail for $B_s^0 \to \mu^+\mu^-$, modelled with PHOTOS**



Initial State Radiation



Final State Radiation



Combination of f_s/f_d: technicalities

[LHCb-PAPER-2020-046]

- Combination through χ^2 minimization
- External inputs included as Gaussian constraints with appropriate correlations (e.g. $B \to D\mu X, B \to Dh$ 100% correlated with $\tau_{B_s^0}/\tau_{B_d^0}$)
- Fit procedure validated with pseudoexperiments, found to be unbiased and with proper coverage
- Some $B \to Dh$ theoretical inputs deviate from expectation, included on y-scale to appropriately show fit result

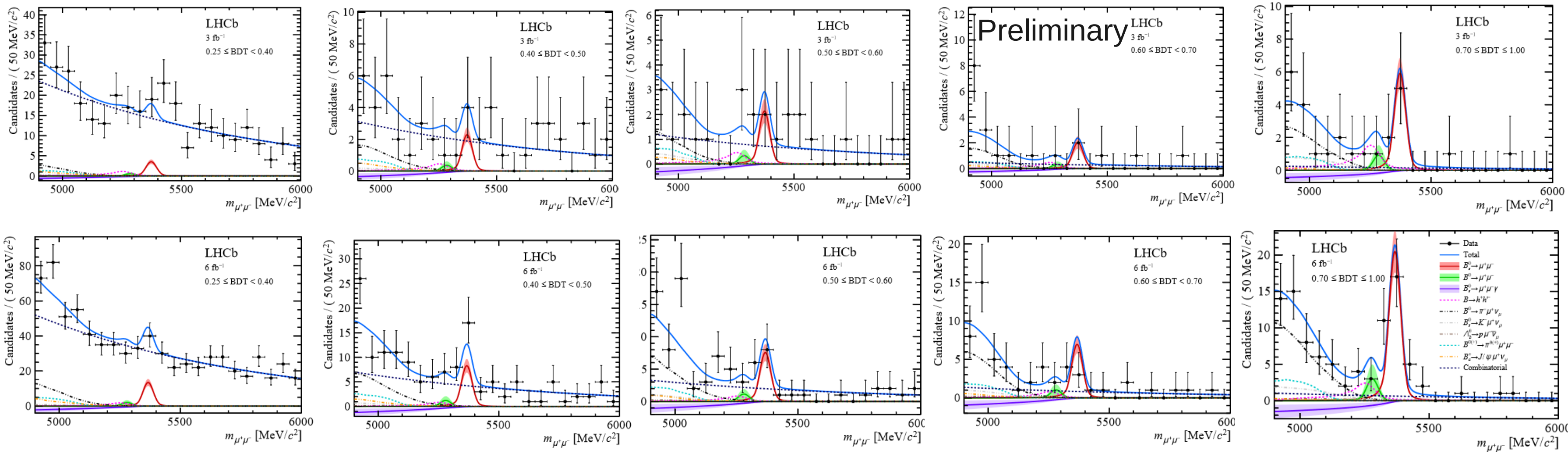
Results: mass fit in all BDT bins

[LHCb-PAPER-2021-007]

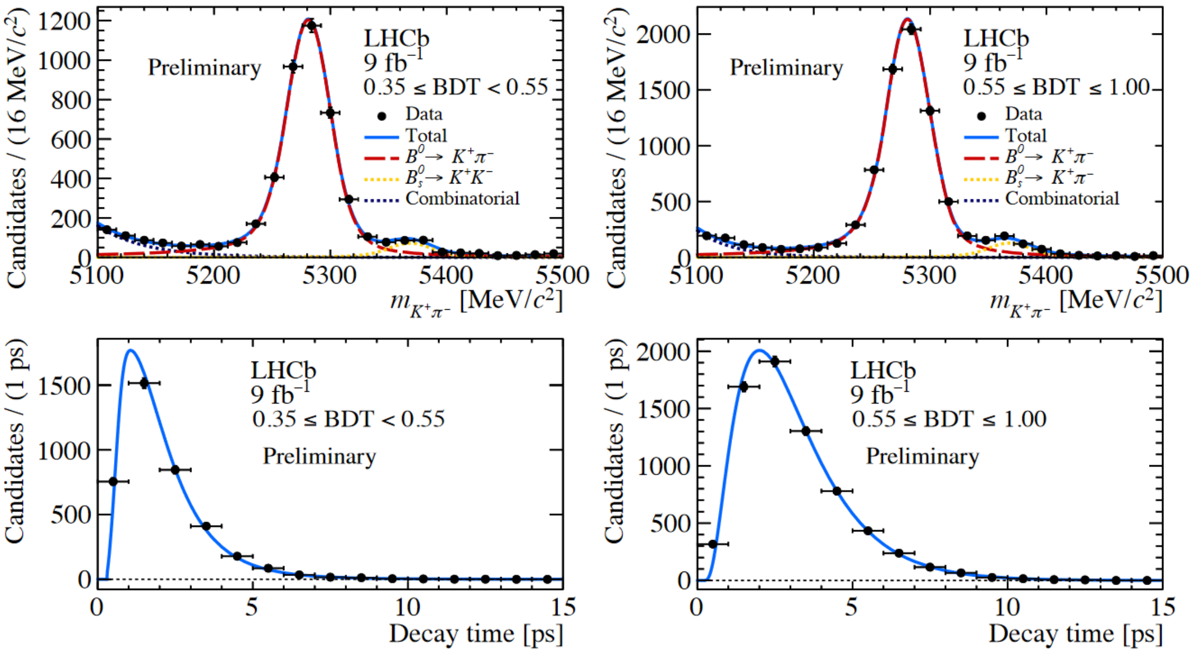
BDT [0.25,0.4] BDT [0.4,0.5] BDT [0.5,0.6] BDT [0.6,0.7] BDT [0.7,1.0]

Run 1

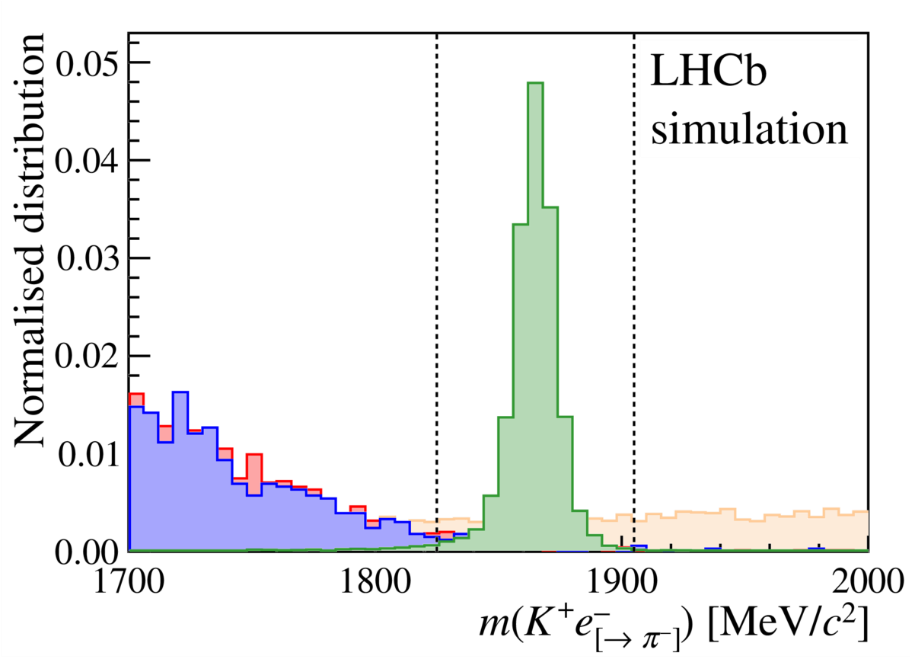
Run 2

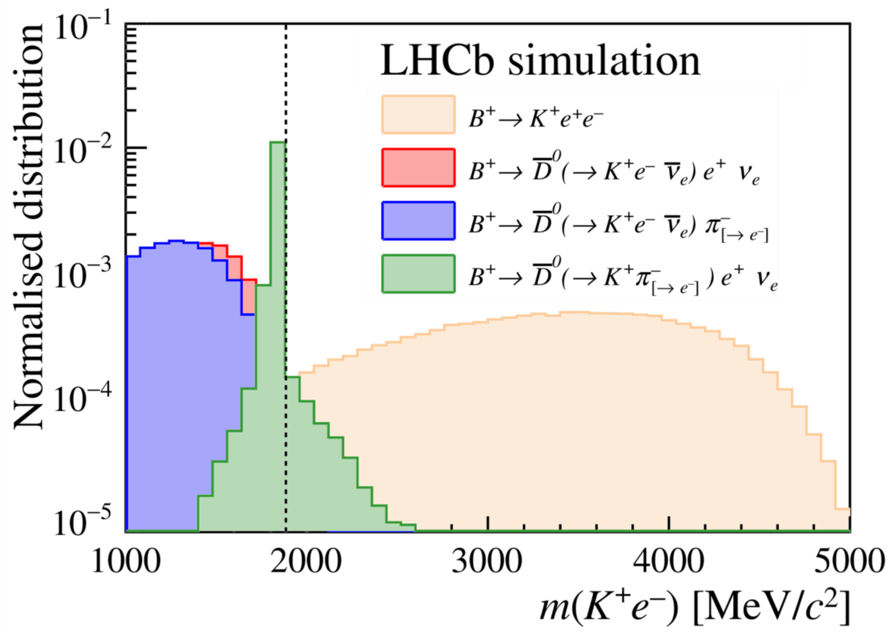


Effective lifetime: acceptance validation

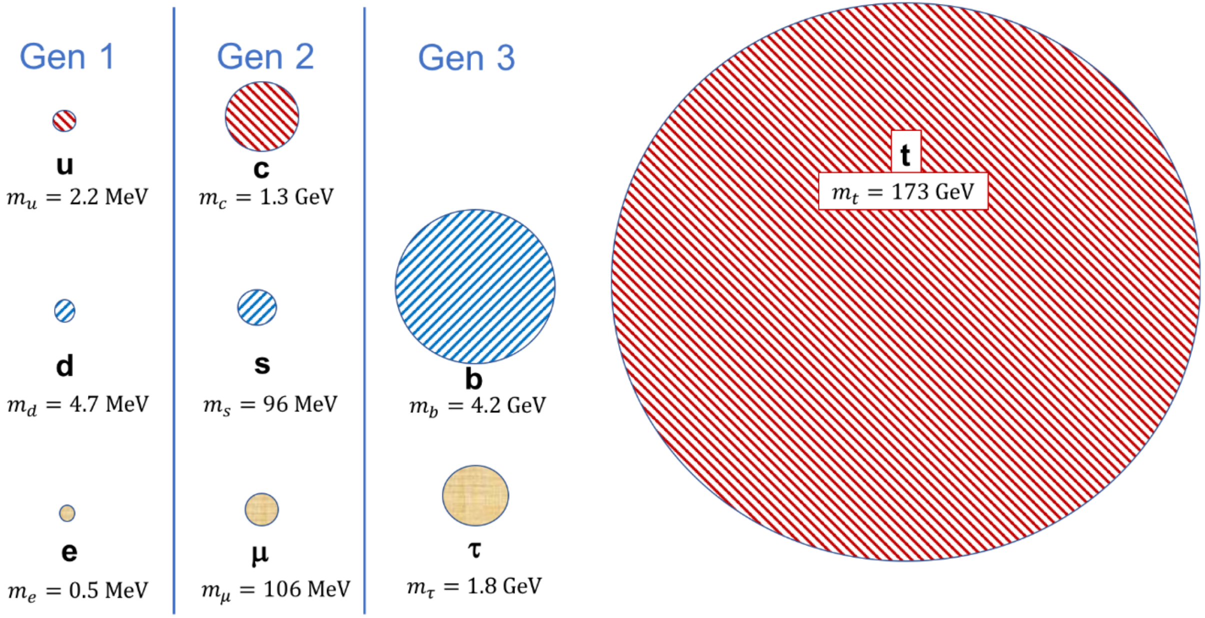


RK: semileptonic backgrounds



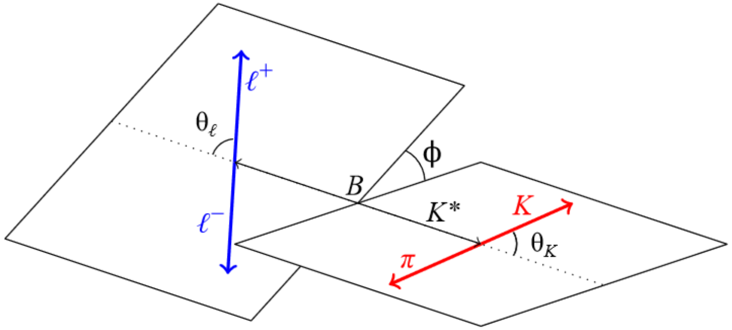


Impression of mass hierarchy



Angular decay rate ($B^{+/0} \to K^{(*)(+/0)} \ell^+ \ell^-$)

topology of decay angles:



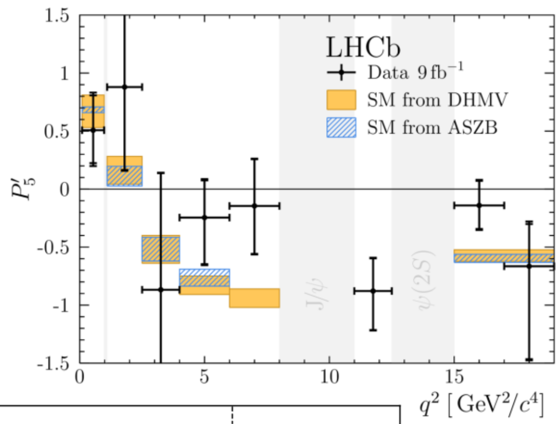
leptonic and hadronic decay part

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2} \frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\Big|_{\mathrm{P}} =$$

$$\frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+S_{6s}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

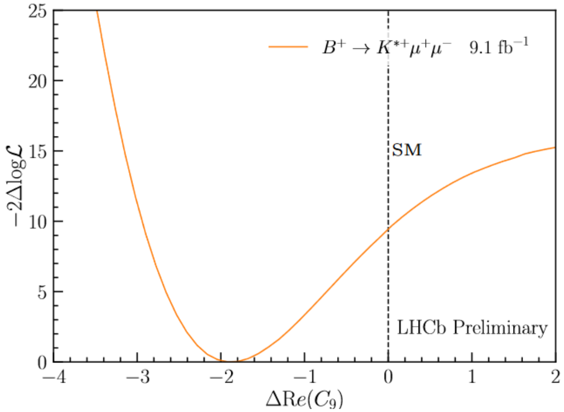
[arXiv:2012.13241]

Angular analysis of $B^+ \to K^{*+}\mu^+\mu^-$



- Determine results of all 8 angular observables, including P_5' (plot)
- Evaluate consistency with SM of results in S_i basis with global fit using Flavio
- **Results inconsistent with SM at 3σ level, favour reduction in C_9**

- **Similar tension with SM in $B^0 \to K^{*0}\mu^+\mu^-$**



Plots generated with flavio: [arXiv:1810.08132]