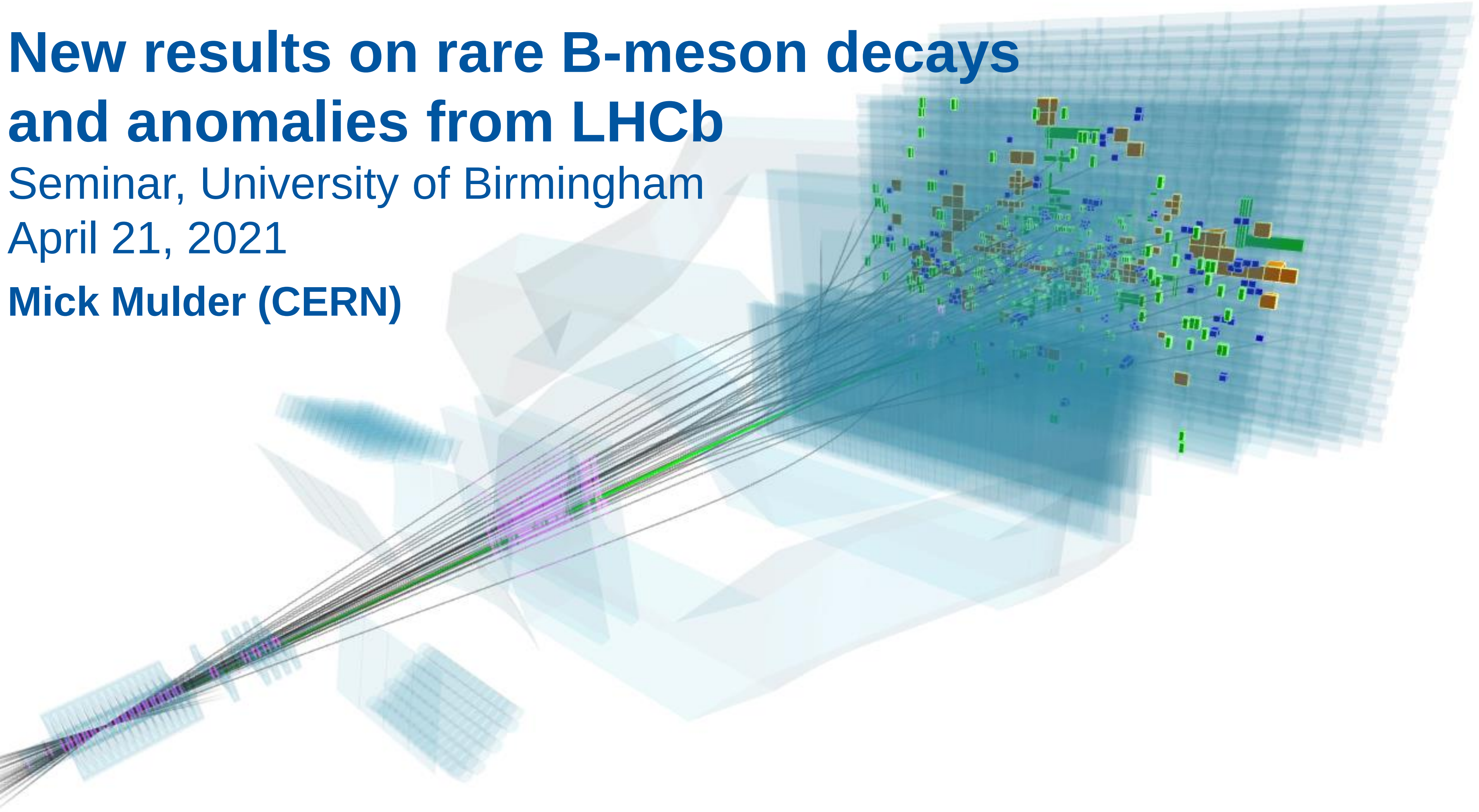
New results on rare B-meson decays and anomalies from LHCb

Seminar, University of Birmingham

April 21, 2021

Mick Mulder (CERN)



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

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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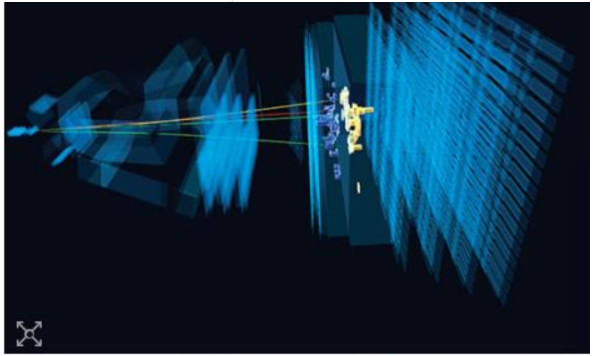
Sci…
signal in their data that may be the first hin…



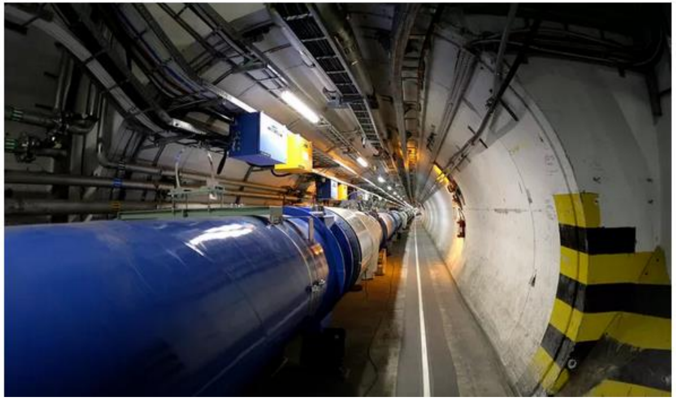
Fleeting glance: decay of a beauty quark involving an electron and positron as o… CERN)

deVolkskrant

Columns & Opinie | Uitgelicht | Wetenschap | Mensen | Beter Leven | Cultuur &…

NIEUWS

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



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…allenges leading theory

Discovery of muon: “Who ordered that?”

In 1936, muon was discovered

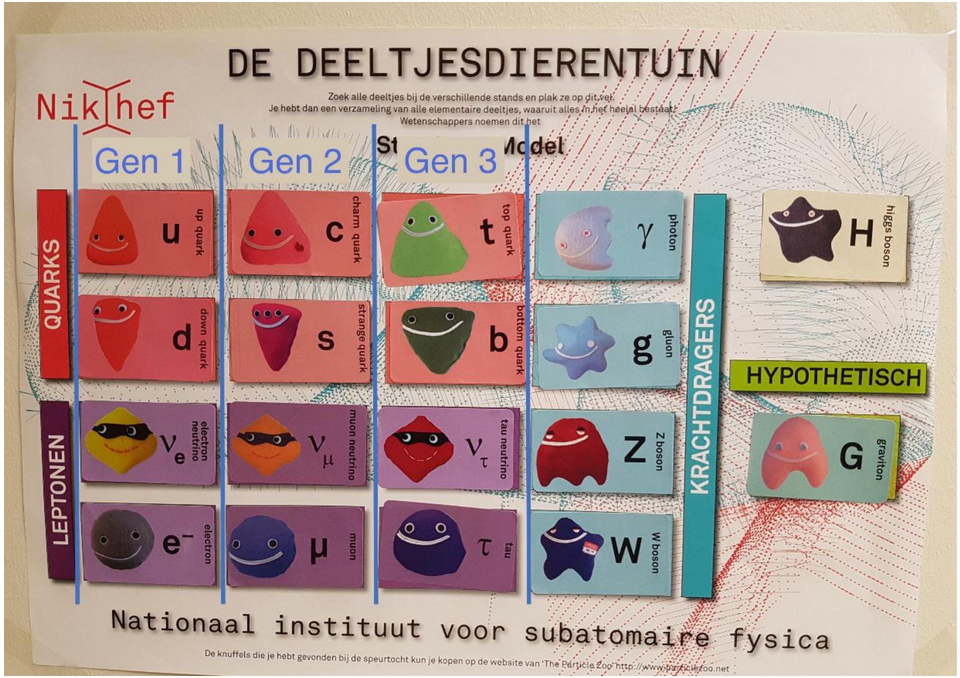
Turned out to behave exactly like electron,
but with 200 times its mass

First 2nd generation particle, not expected at all!

Led Isidor Rabi to say: “Who ordered that?”

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

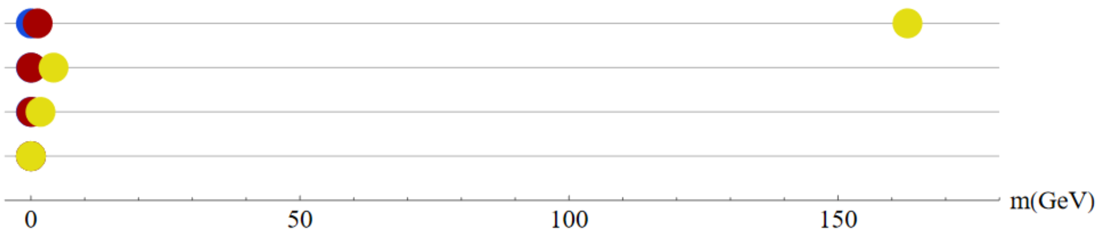
[Thesis Reinier Adelhart]

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

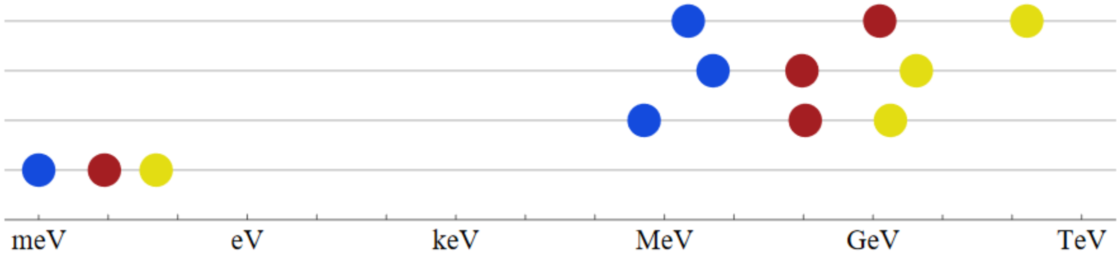
Why are masses so hierarchical for quarks + charged leptons?

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

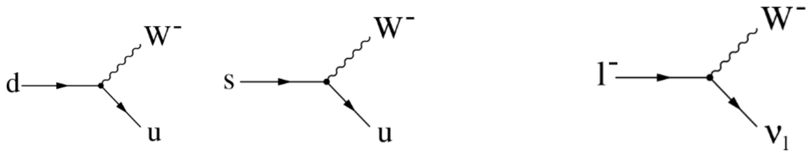


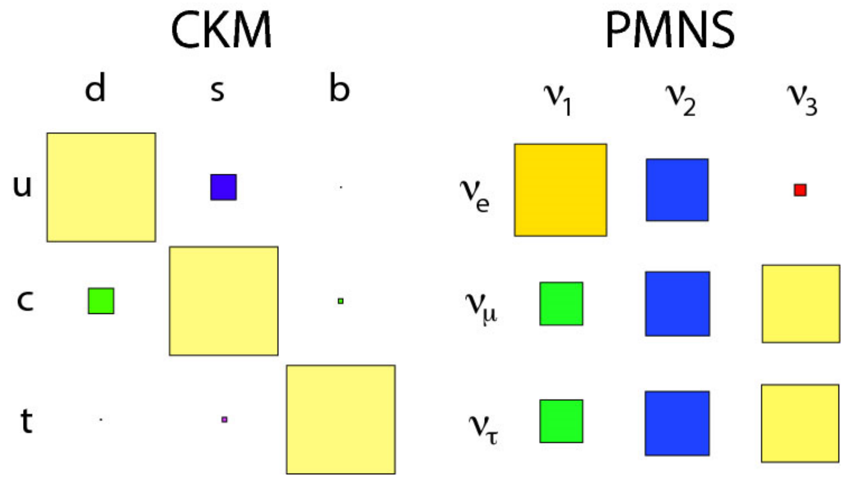
Flavour puzzle: fermion mixing

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?

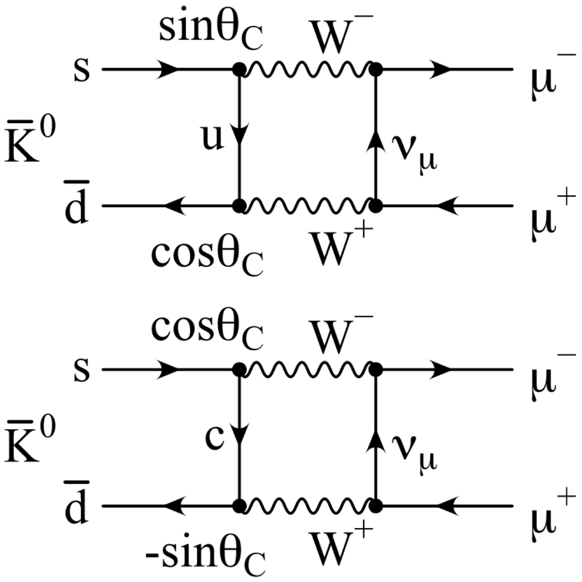
To solve flavour puzzle: study third generation
→ rare decays of beauty quarks





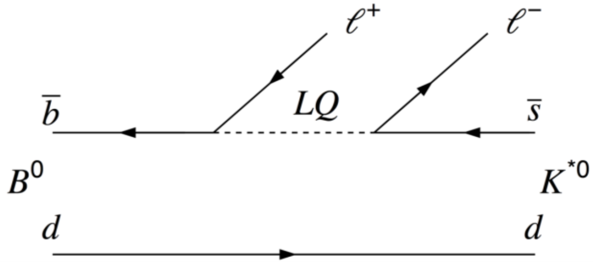
Rare decays

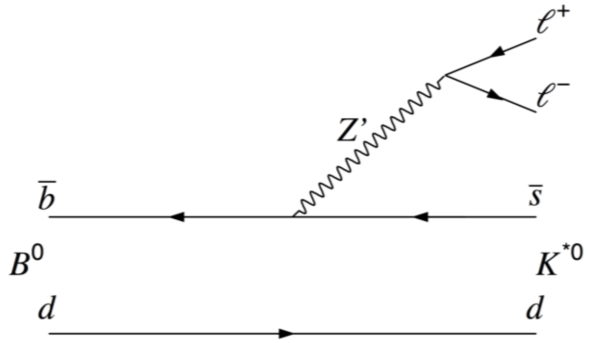
- **Loop-level decays mediated by weak interaction** (Flavour Changing Neutral Currents)
- **Transition strongly suppressed**: loops, CKM elements, sometimes GIM mechanism
- **Perfect for indirect discovery**: even small contributions have large effects on rare decays!
- Previous discoveries:
  - charm 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!

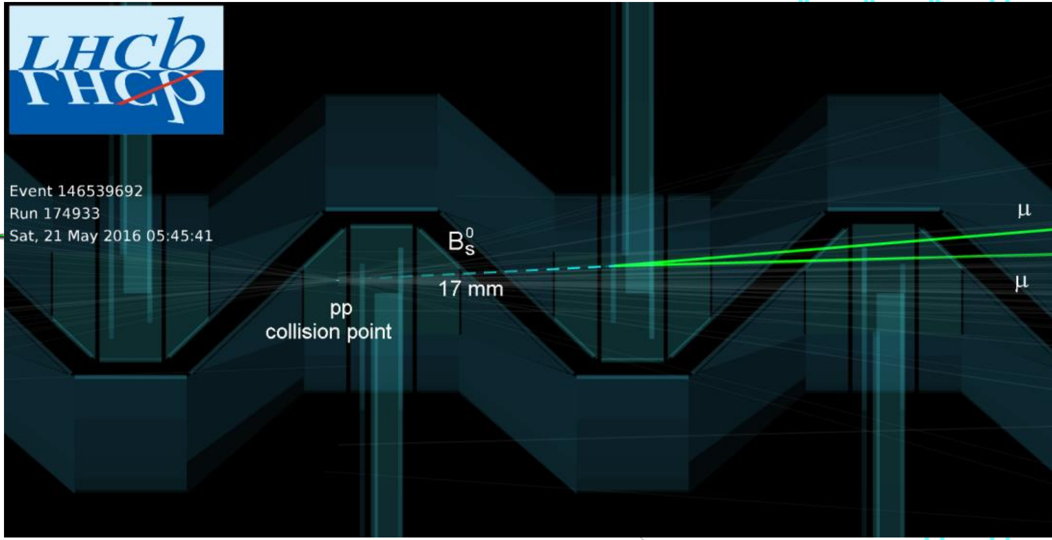




LHCb detector

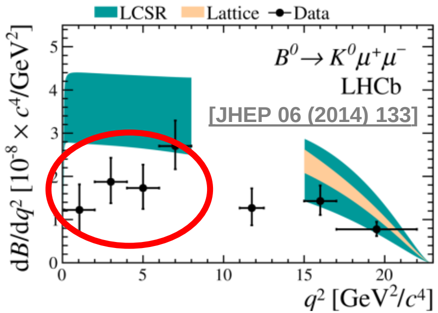
- Designed to study B hadrons with high precision: forward direction spectrometer
- **Around 10^{12} B hadrons produced!**

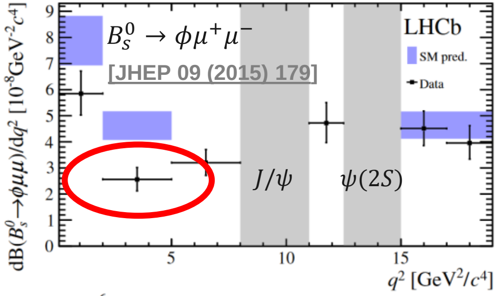
- Very good momentum resolution (0.5% of momentum)
  → **Sufficient to separate B_s^0, B^0 decays**
- Excellent charged particle identification, especially for muons, electrons
  → **required to suppress B decay backgrounds**
- Good vertex resolution: clear separation of B hadron decay vertex from pp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

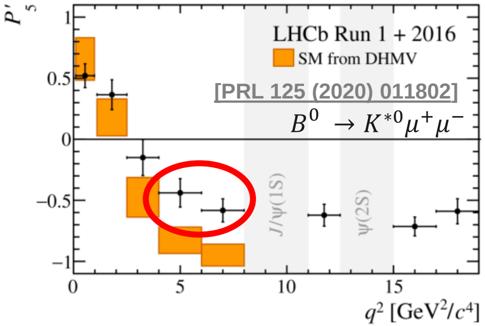


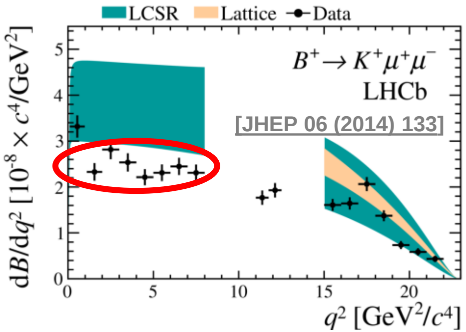
Anomalies

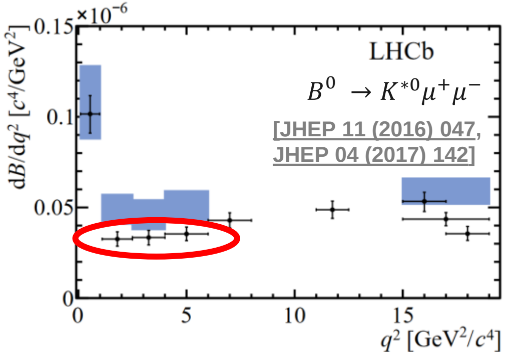
Results in rare B decays deviate from predictions in LHCb data…. (not only there)

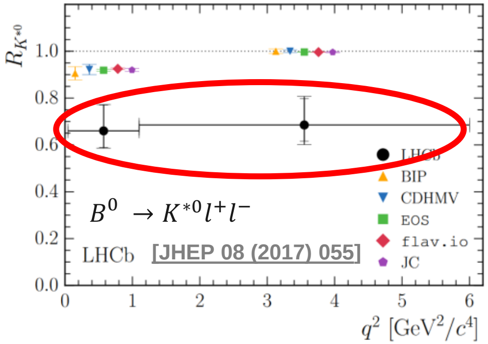






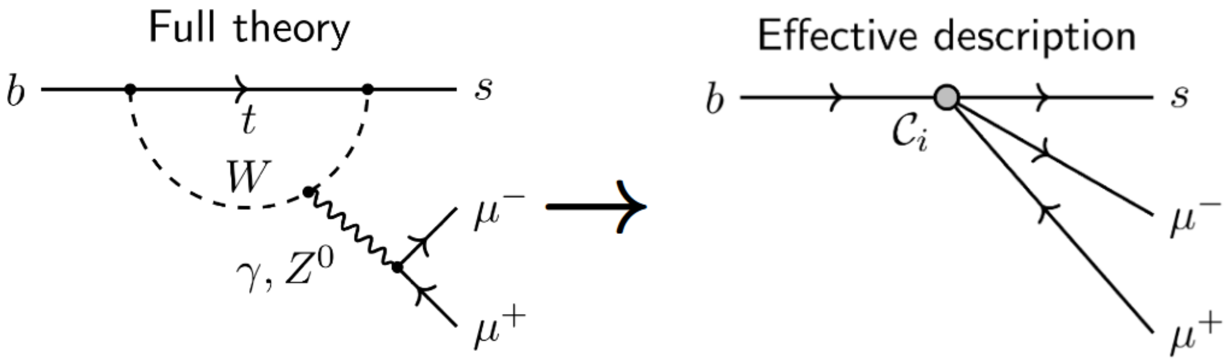






Effective field theory

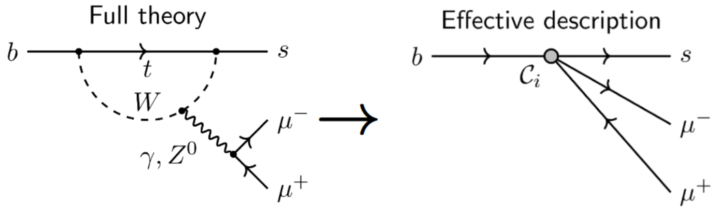
- Are anomalies consistent with each other?
- **Use effective field theory at B-hadron scale, just like beta decay four-point interaction!**



Effective field theory

- An EFT probes different couplings:

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

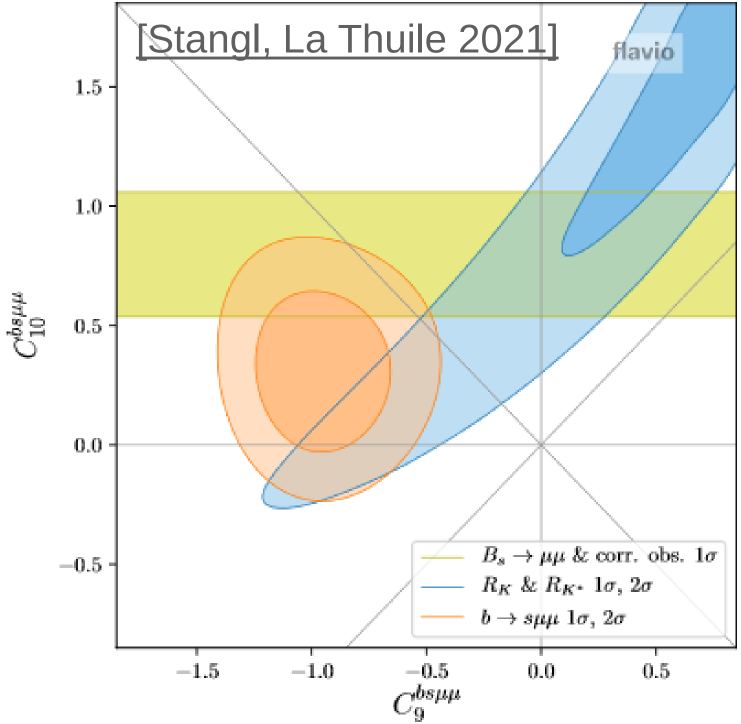


- Fermion operators O_i, Wilson coefficients C_i
- Grouped by leptonic current: (SM,NP)
  - C_7 photon penguin
  - $(C_{10})C_9$ (axial) vector
  - $(C_P)C_S$ (pseudo) scalar
- Note: operators, coefficients with opposite quark current handedness from SM marked with O_i', C_i'
  (negligible in SM and 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!

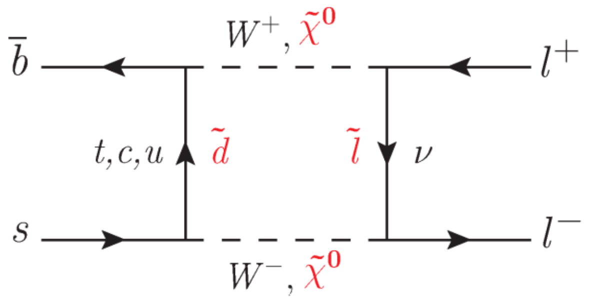
- Improved measurement of $B^0_{(s)} \to \mu^+\mu^-$ decay observables (+ B^0_s/B^0 production fraction at LHCb (f_s/f_d))

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

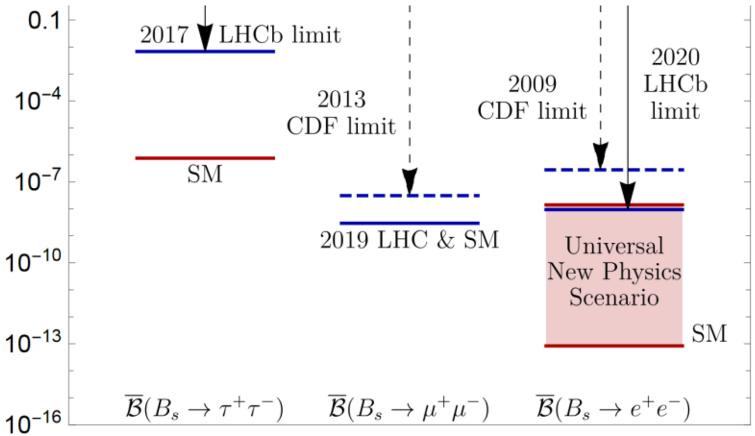
- Interpretation and conclusions

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)



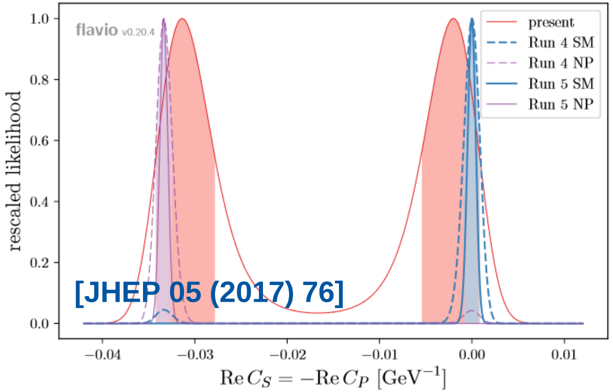
Fleischer et al., JHEP 05 (2017) 156



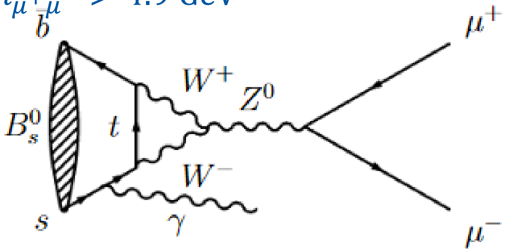
$B^0_{(s)} \to \mu^+\mu^-$: extra observables

- 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, $\Delta\Gamma_s = 0.085 \pm 0.006\ \mathrm{ps}^{-1}$
- **Measure effective lifetime τ_{eff} to test for CP-even contribution, scalar NP (C_S, C_P)!** ($A^{\mu\mu}_{\Delta\Gamma_s} \in [-1, +1]$) (first suggested by Fleischer et al., [PRL 109, 041801 (2012)])

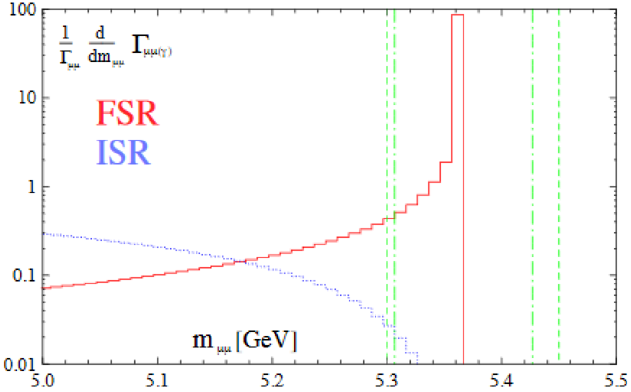
τ_{eff} finds solution: C_S/C_P or not?



- $B^0_{(s)} \to \mu^+\mu^-\gamma$: Initial State Radiation for $m_{\mu^+\mu^-} > 4.9$ 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

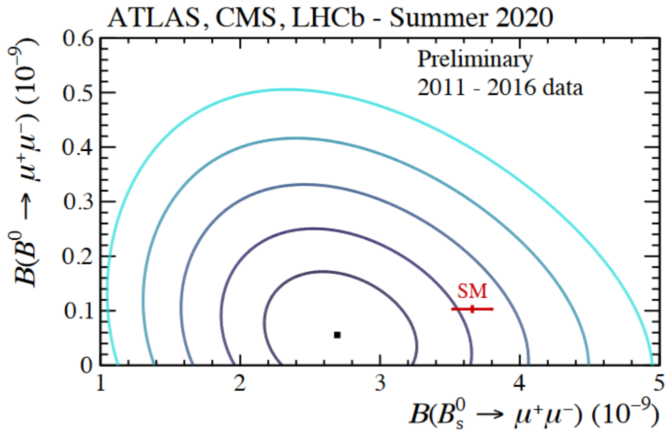


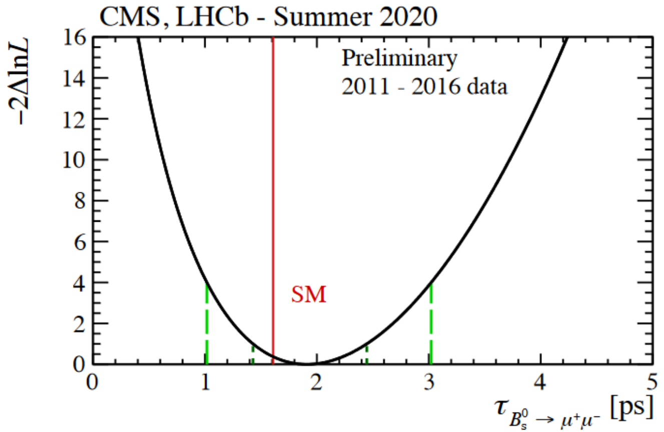
[PRL 112 (2014) 101801]



Previous results

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





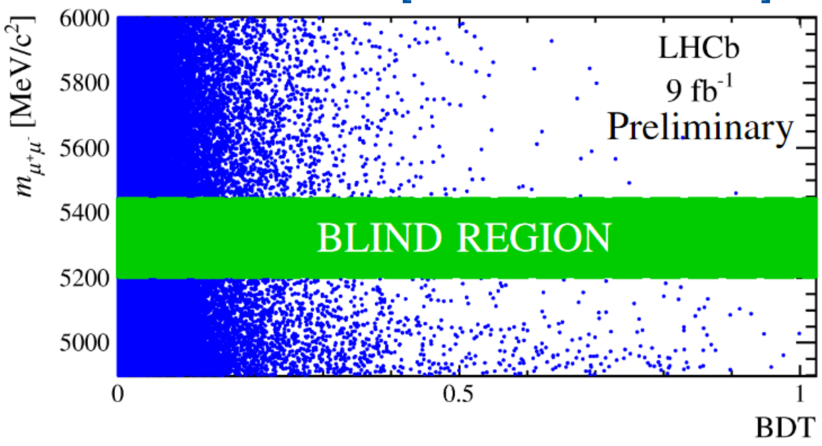
[LHCb-PAPER-2021-007]

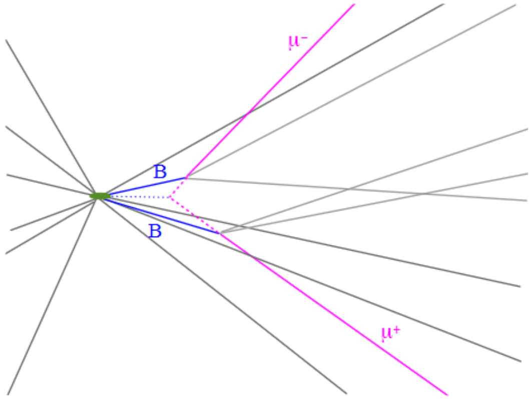
Analysis strategy

- **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**

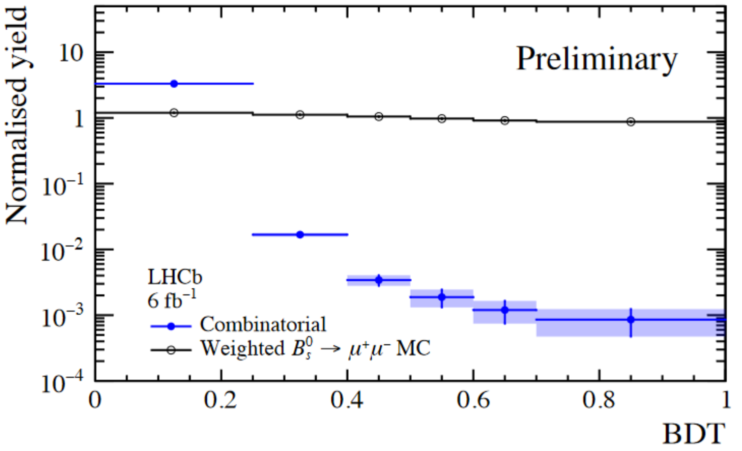


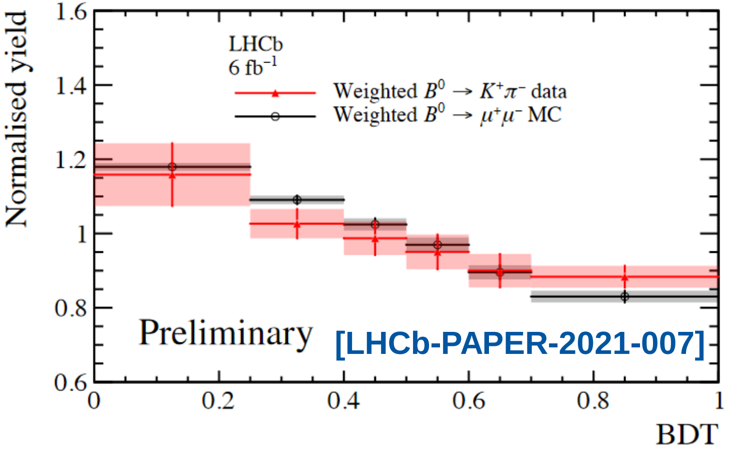


BDT calibration

- 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!**



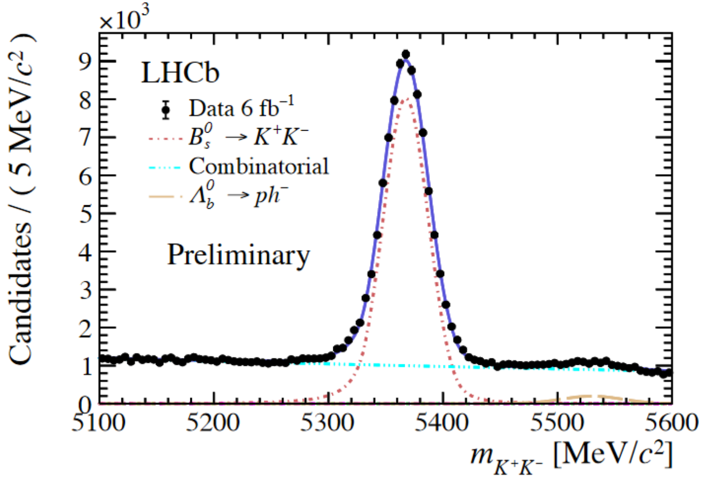


[LHCb-PAPER-2021-007]

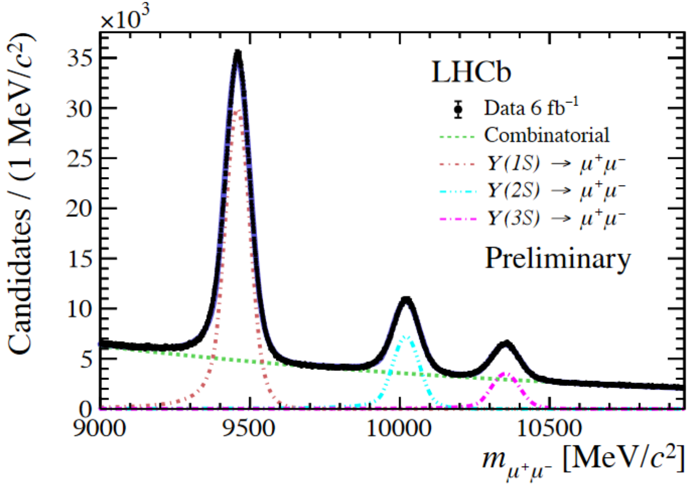
Mass calibration

[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!

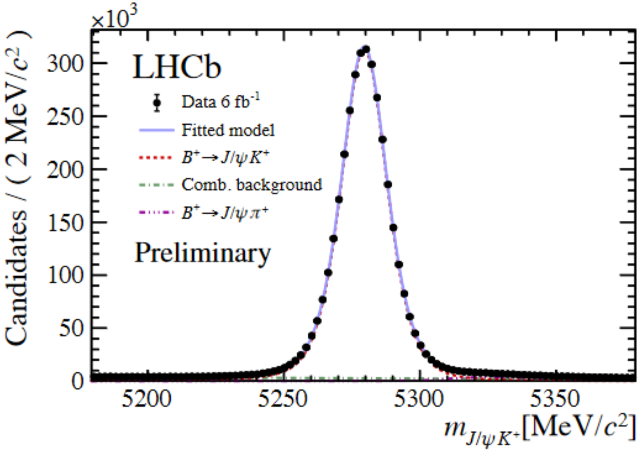
Normalisation: strategy

[LHCb-PAPER-2021-007]

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

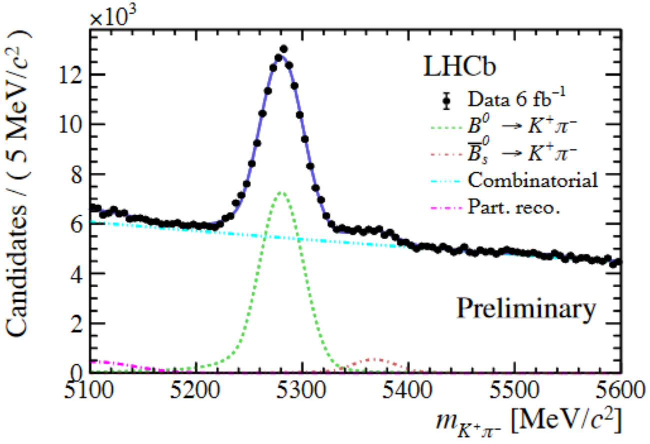
$B^+ \to J/\psi(\to \mu^+\mu^-)K^+$

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

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

- Normalisation yield and BF
- Signal/normalisation efficiency ratio evaluated from simulation, control channels
- Ratio of hadronisation fractions (for B^0_s): **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):

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

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

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

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:**

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

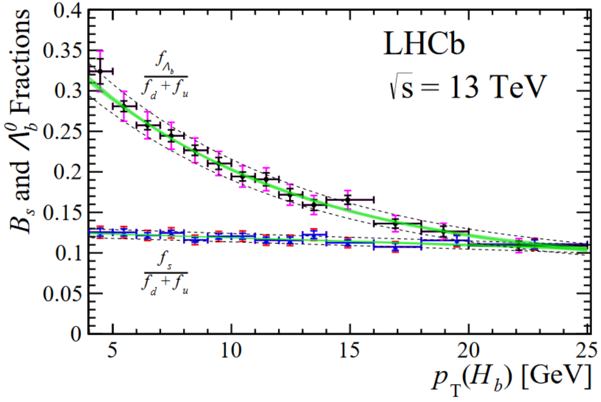
- Five previous measurements (2011 to 2020)**:**
  combination to determine single value with higher precision

Combination of f_s/f_d measurements: inputs

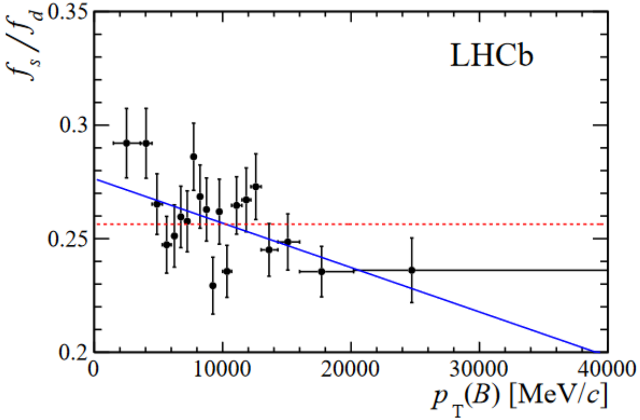
- Previous LHCb measurements performed at 7, 8, 13 TeV, $p_T \in [0.5{,}40]$ GeV, $\eta \in [2{,}6.4]$
- Three decay modes: $B \to D\mu X, B \to Dh, B \to J/\psi X$ (no prediction)
- **Update external inputs for $B \to D\mu X, B \to Dh$ (e.g. D branching fraction, B lifetimes): significant improvement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

[arXiv:2103:06810]

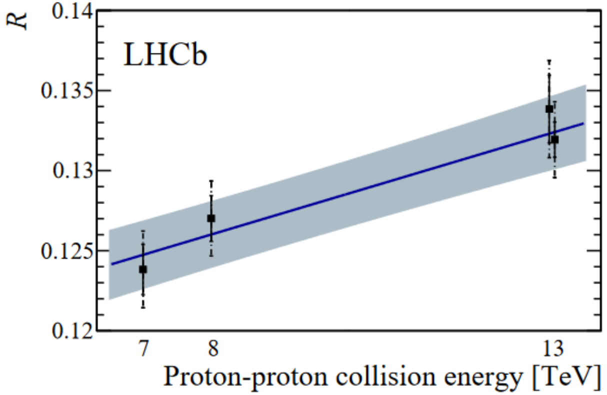
$B \to D\mu X$, 13 TeV



$B \to Dh$, 7 TeV



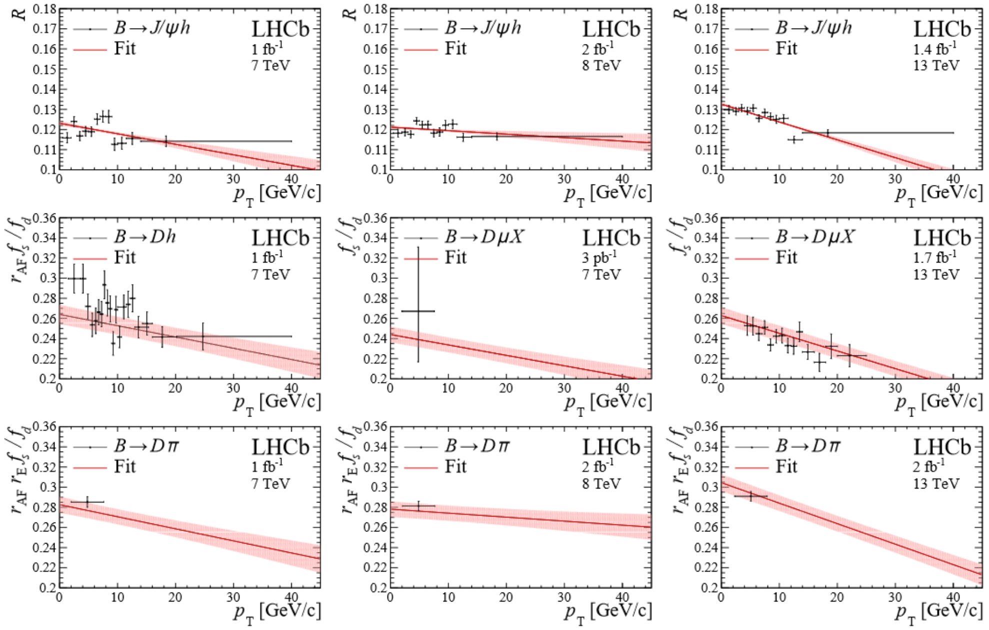
$B \to J/\psi X$, various $\sqrt{s}$



Combination of f_s/f_d measurements: results

- 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 $\boldsymbol{B(B_s^0 \to \mu^+\mu^-)}$!**

[arXiv:2103:06810]



Backgrounds

[LHCb-PAPER-2021-007]

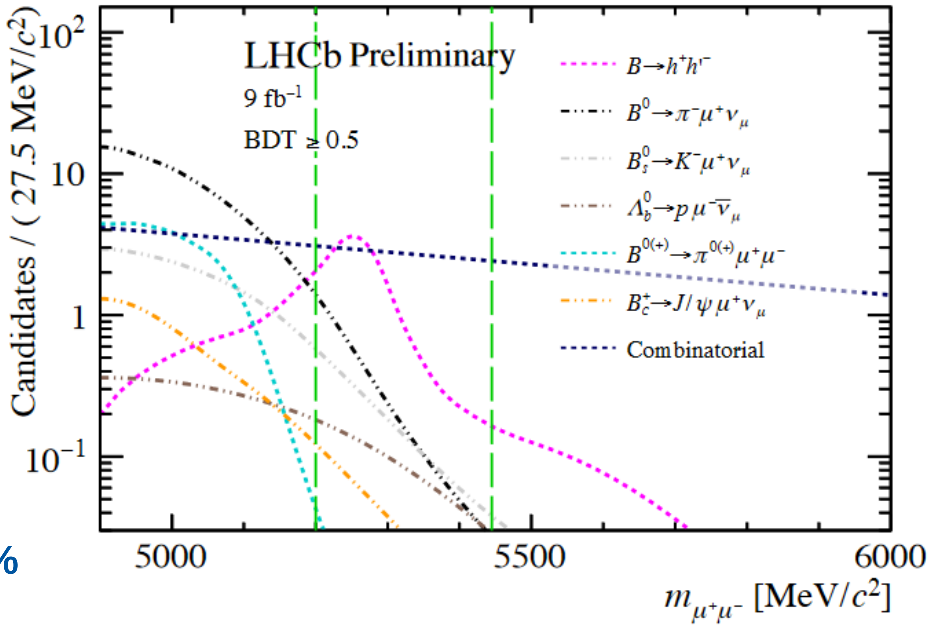
Three types of backgrounds in fit:

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%

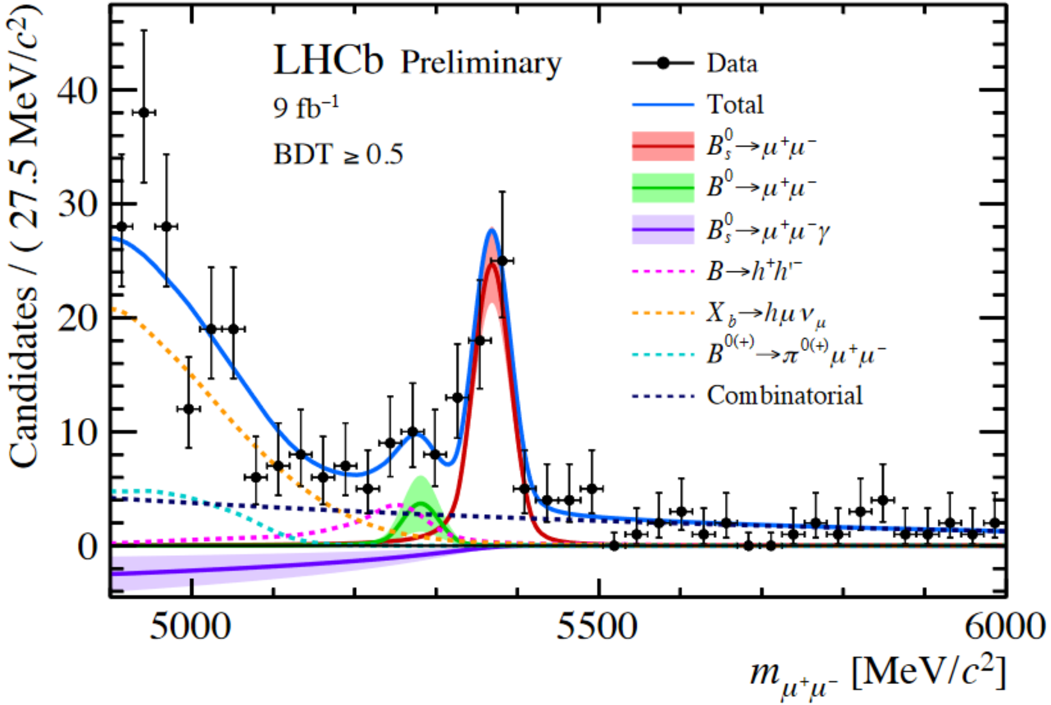
Everything calibrated, time to fit!



Results: branching fraction

[LHCb-PAPER-2021-007]

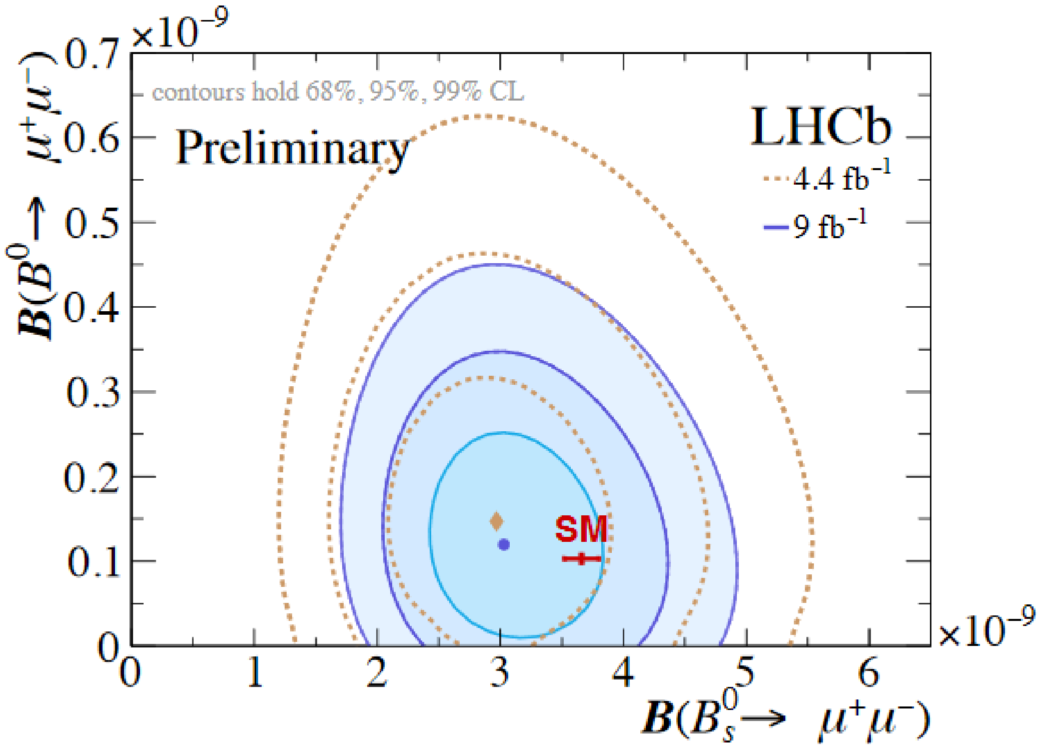
- $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$ **with significance > 10σ**
- $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\gamma$ compatible with background-only at 1.7σ, 1.5σ



Results: compatibility with SM

[LHCb-PAPER-2021-007]

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

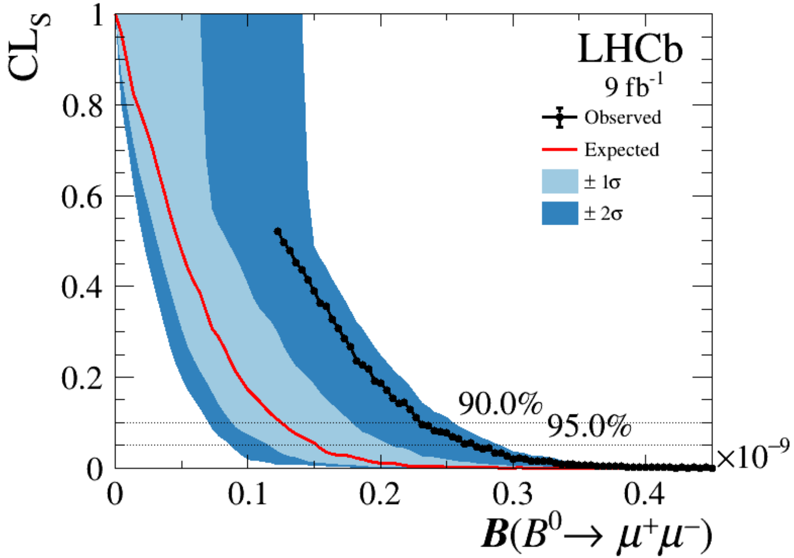


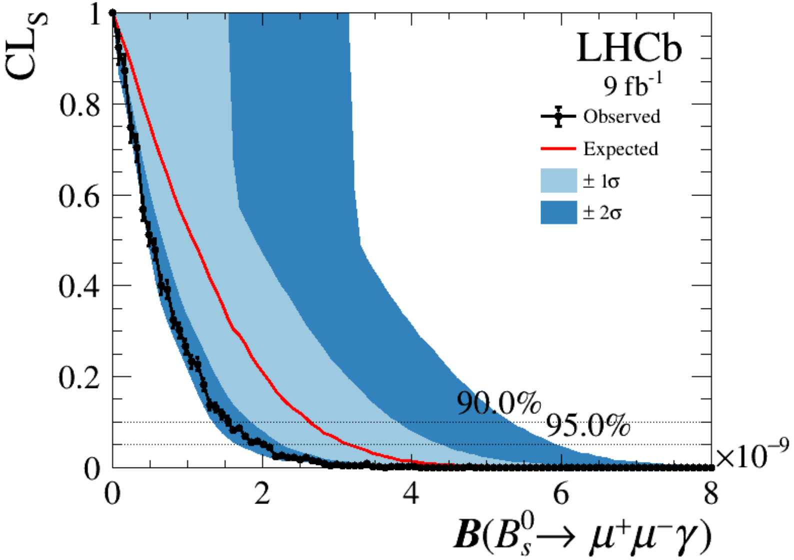
Results: limits (CLs method)

[LHCb-PAPER-2021-007]

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

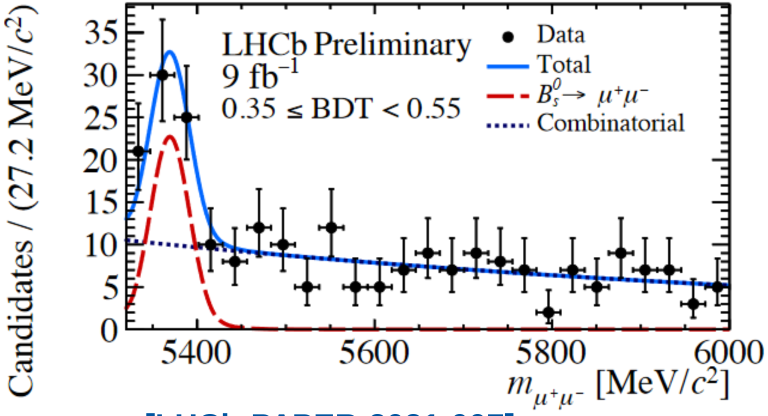
$B(B_s^0 \to \mu^+\mu^-\gamma) < 1.5(2.0) \times 10^{-9}$
for $m_{\mu^+\mu^-} > 4.9$ GeV at 90(95)% CL



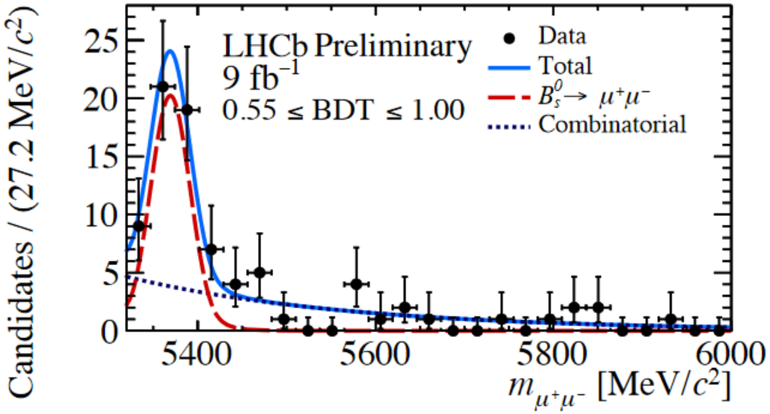


Effective lifetime

- **$B_s^0 \to \mu^+\mu^-$ 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

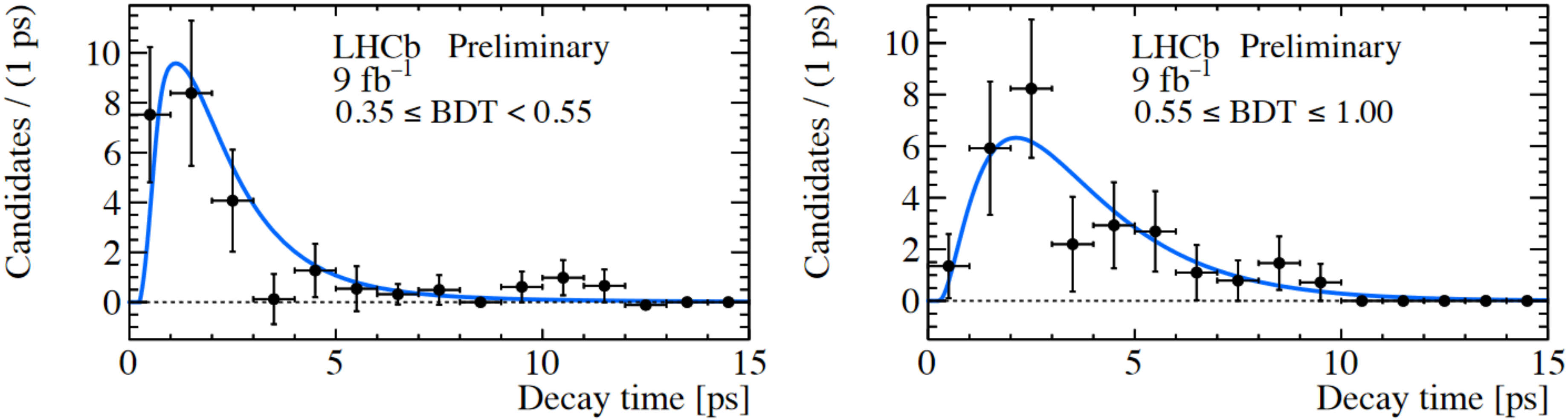


[LHCb-PAPER-2021-007]



Results: effective lifetime fit

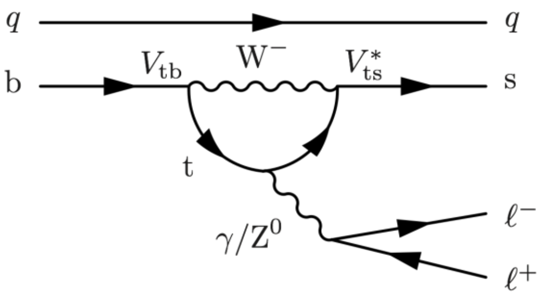
[LHCb-PAPER-2021-007]

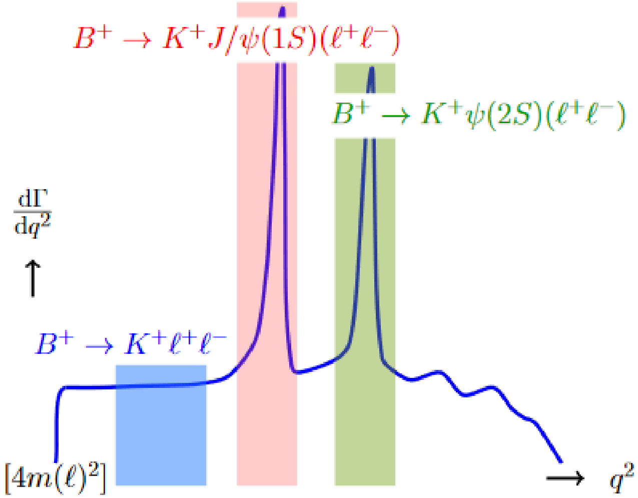


- $\boldsymbol{\tau(B_s^0 \to \mu^+\mu^-) = 2.07 \pm 0.29 \pm 0.03}$ **ps** (previously $2.04 \pm 0.44 \pm 0.05$ ps)
- 1.5 sigma from SM (i.e. $A_{\Delta\Gamma_s}^{\mu\mu} = 1$), 2.2 sigma from extreme non-SM (i.e. $A_{\Delta\Gamma_s}^{\mu\mu} = -1$)
- **Run 3 data needed to start providing significant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

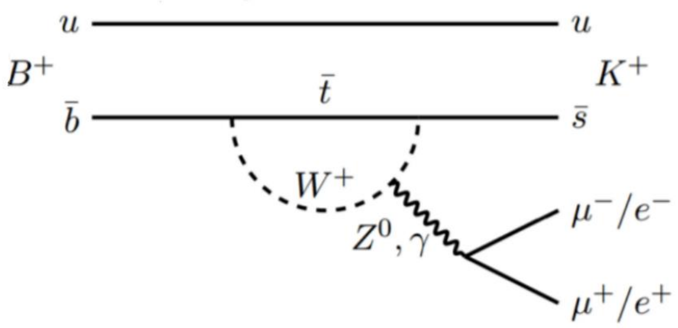




Lepton universality: R_K

[arXiv:2103.11769]

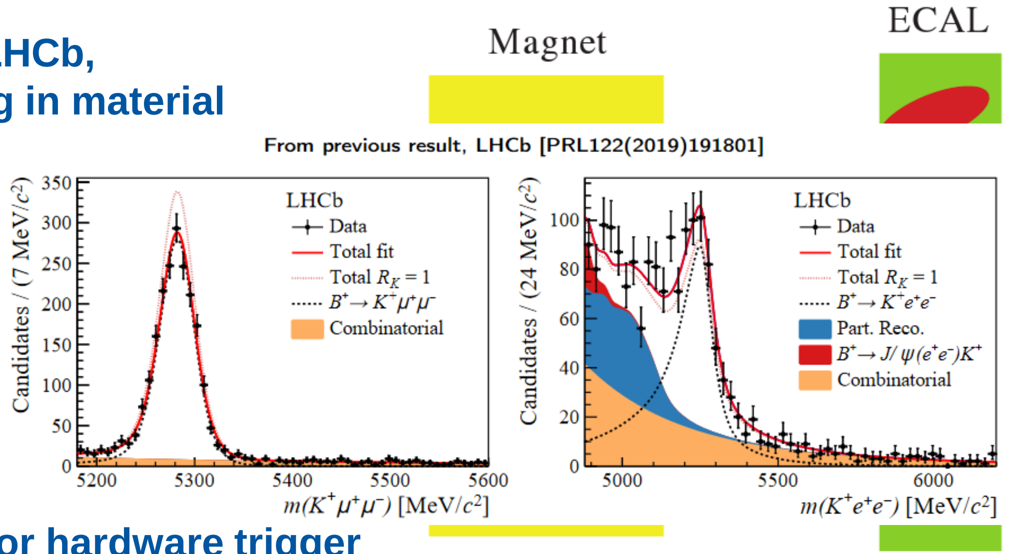
- **Lepton universality: only difference between muons, electrons is mass**
- Strong test of lepton universality with $R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e)} \cong 1$ (in SM) for $q^2 > 0.1\ \mathrm{GeV}$
- Uncertainty of $O(1\%)$ in SM (from QED)
- Sensitive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



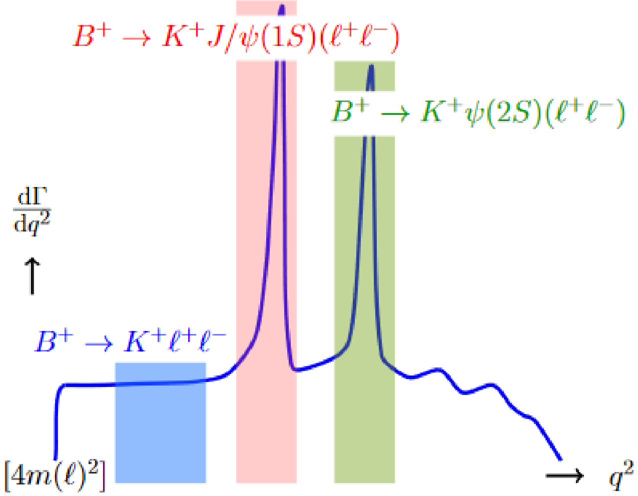
- **Additionally, electrons more difficult for hardware trigger (than muons)**
- Electron sample divided based on hardware trigger category: electron, rest-of-event, or hadron trigger

Strategy

[arXiv:2103.11769]

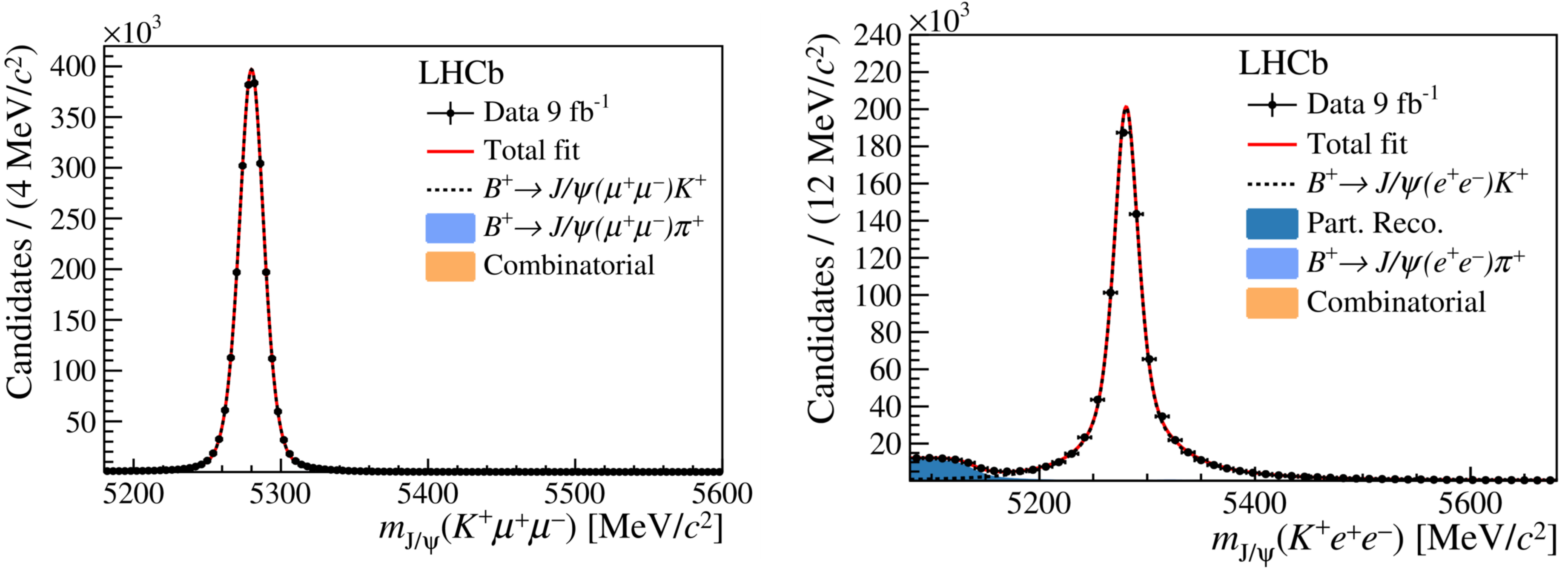
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))} = \frac{N^{\mathrm{rare}}_{\mu^+\mu^-}\ \varepsilon^{J/\psi}_{\mu^+\mu^-}}{N^{J/\psi}_{\mu^+\mu^-}\ \varepsilon^{\mathrm{rare}}_{\mu^+\mu^-}}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

- **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%

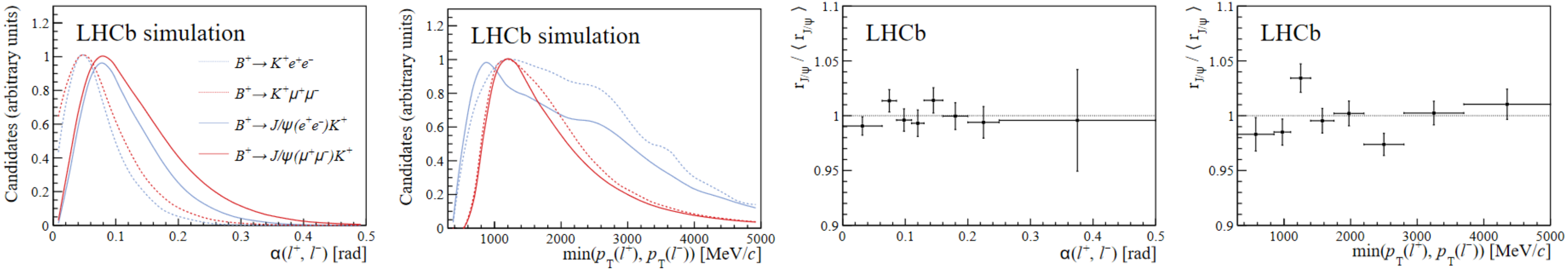
- **Requires direct control of muons versus electrons**
- Result:

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

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]

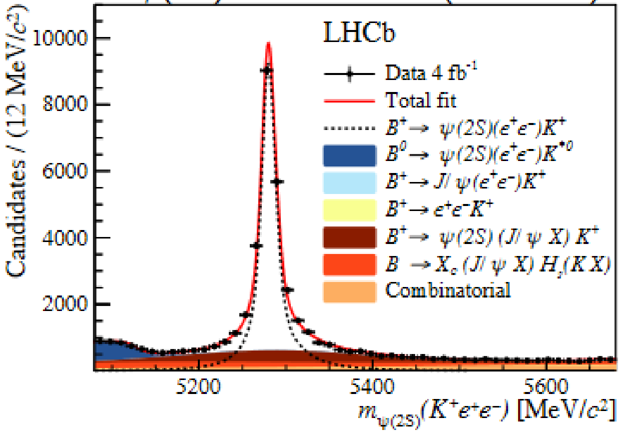
- Measurement of double ratio

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

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

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

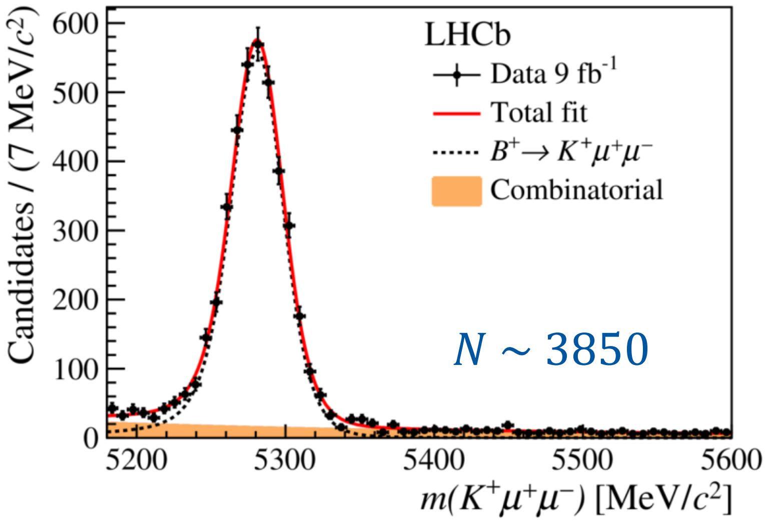
Use $\psi(2S)$ constrained $m(K^+\ell^+\ell^-)$

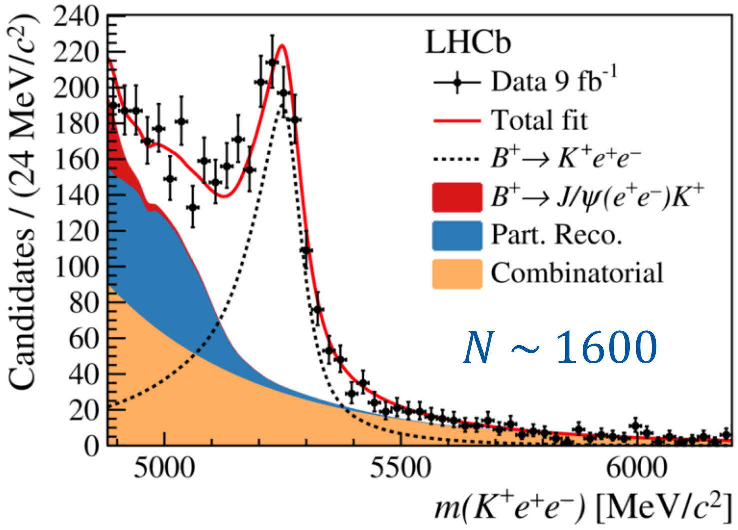


Determining R_K

[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





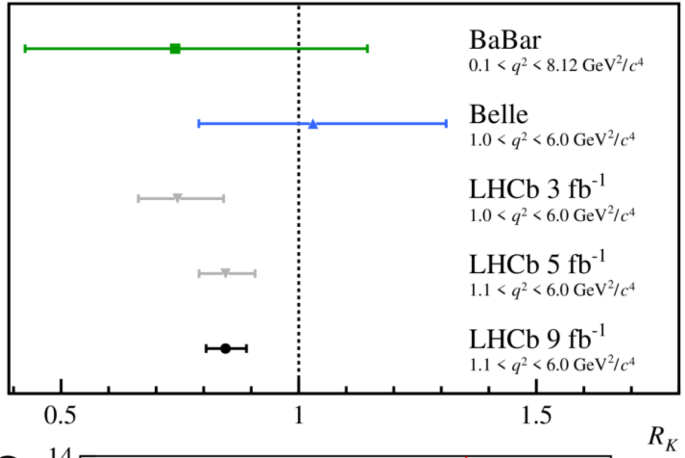
Results: R_K

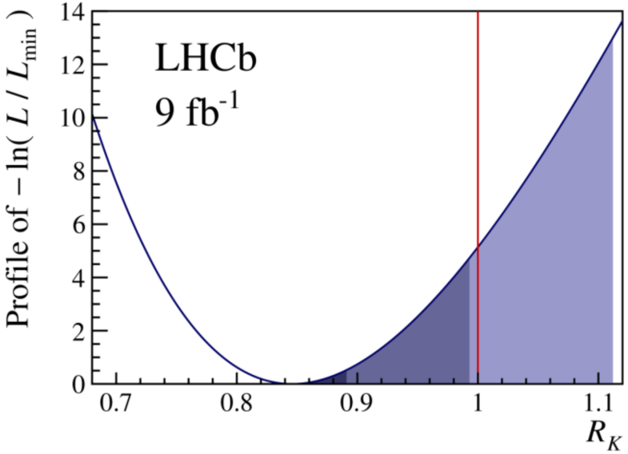
[arXiv:2103.11769]

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

- 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%)





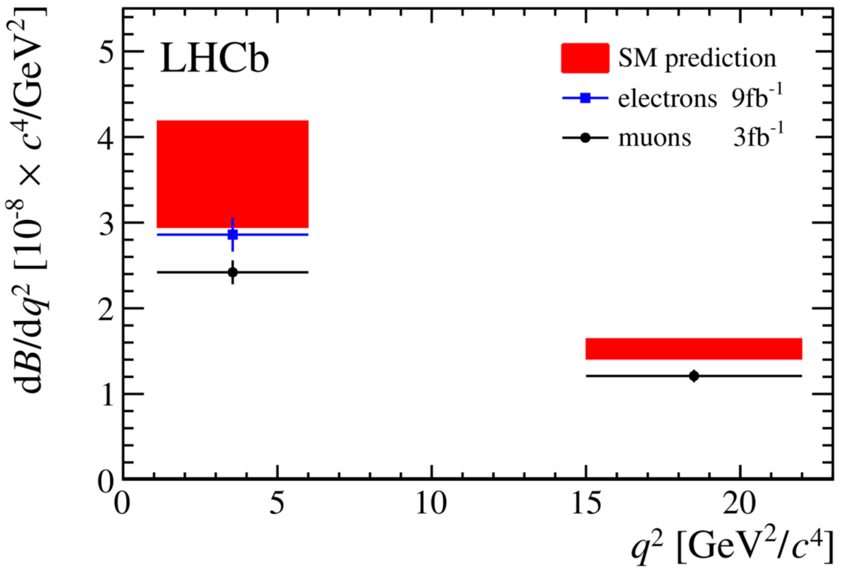
Results: $B(B^+ \to K^+ e^+ e^-)$

- 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]

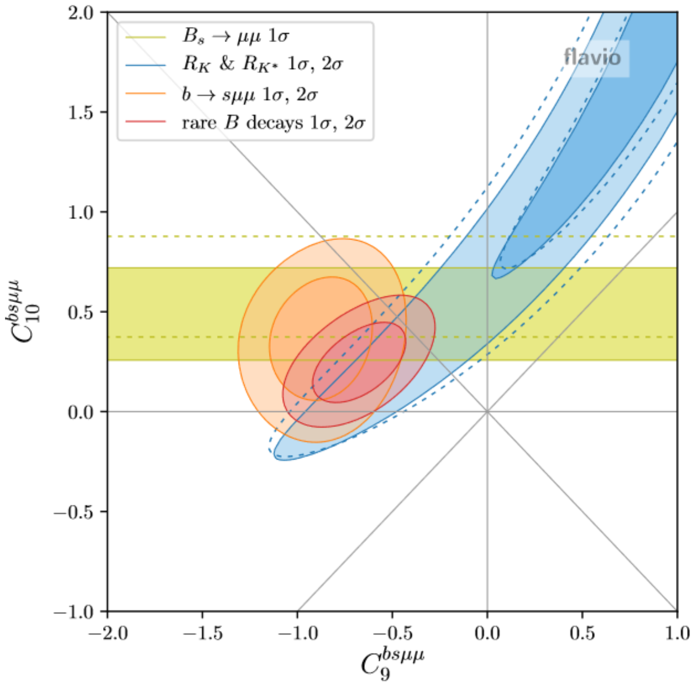
First consider new physics in $b \to s\mu\mu$ only,
including new R_K, $B(B_s^0 \to \mu^+\mu^-)$ results:

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 $C_9 - C_{10}$

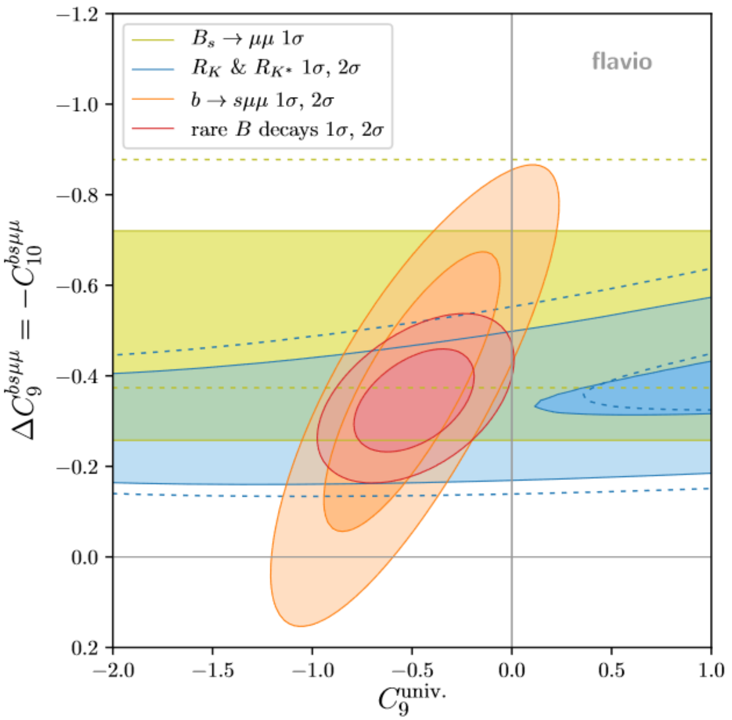
Any other options?



Current EFT fit

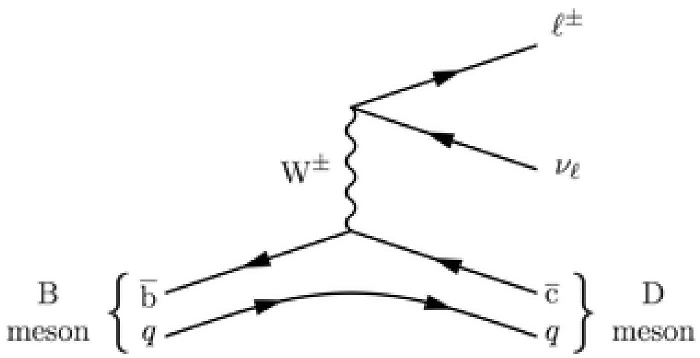
[arXiv:2103.13370]

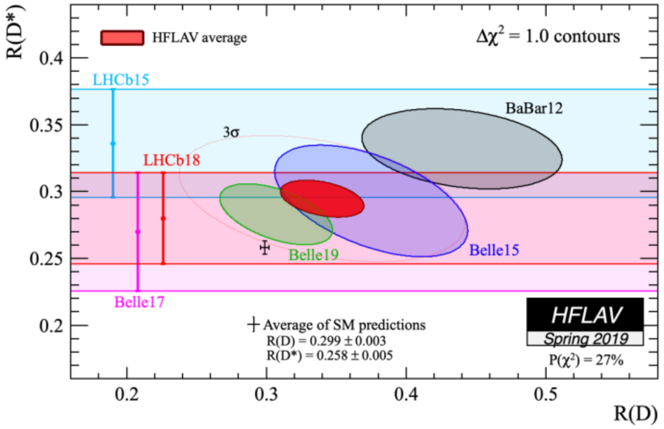
- **Interesting option (personal opinion):**
  - Universal contribution to $\boldsymbol{C_9}$ ($b \to see, b \to s\mu\mu$ and $b \to s\tau\tau$)
  - $b \to s\mu\mu$ only contribution to $\boldsymbol{C_9 - C_{10}}$
- Slightly favoured by data over NP in $b \to s\mu\mu$-only (pull of 6.4 sigma)
- **Any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

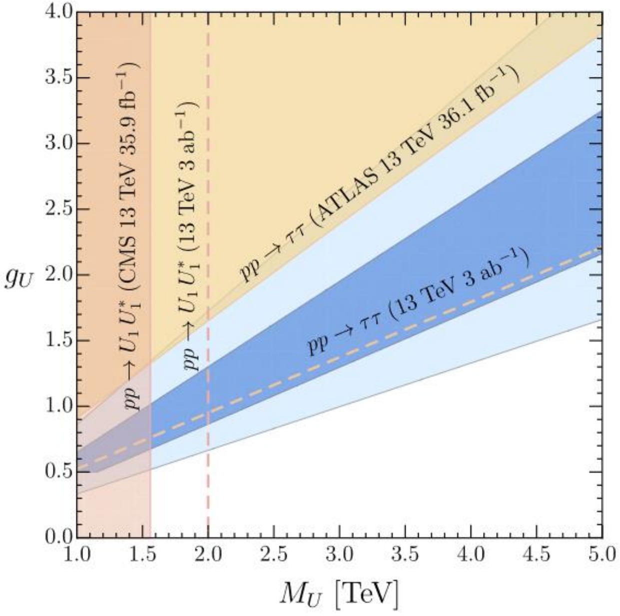




Link with R(D*): combined fit

[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 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?**



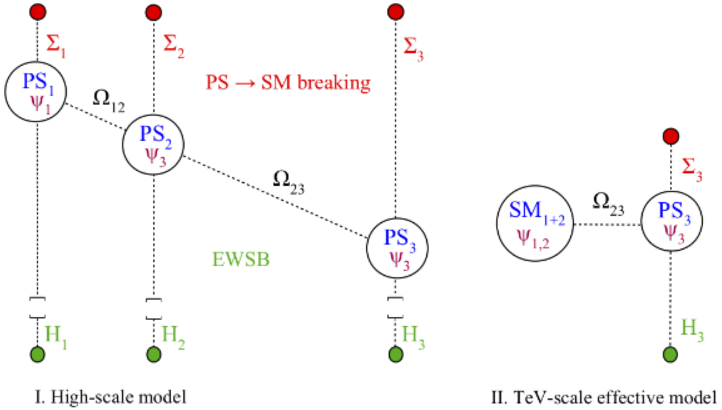
Solving the flavour puzzle?

[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!?**
  i.e. could explain "who ordered that?"

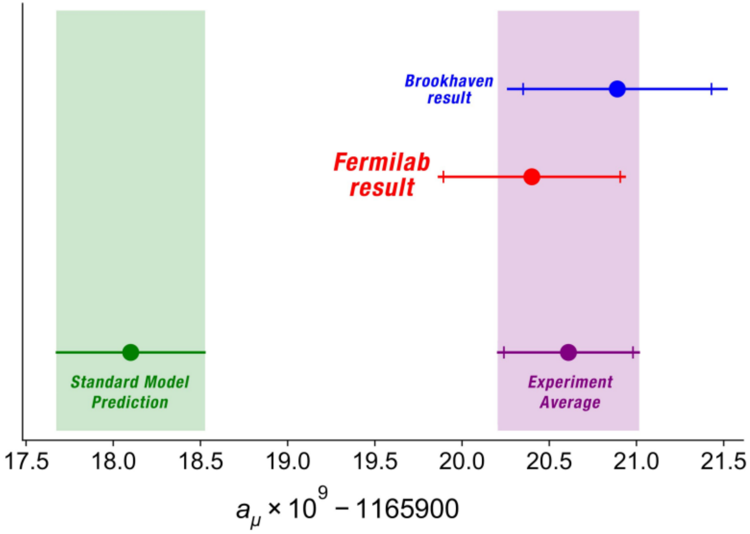
The three-site Pati-Salam model [18] originates from the ambitious attempt to i) unify and quantize the $U(1)$ charges of quark and leptons, ii) obtain a natural description of all the SM Yukawa couplings in terms of $\mathcal{O}(1)$ parameters and fundamental scale ratios, and iii) address the recent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



Link with $(g-2)_\mu$?

- Muon magnetic moment, $(g-2)_\mu$:
  - Lower energy observable, **many possible contributions**
- **Two weeks ago: $(g-2)_\mu$ deviation confirmed by Fermilab, currently at 4.2 sigma from SM**
- **Experimental uncertainty will reduce by ~3 w. full data**
- **Reduction of theory uncertainty essential to confirm deviation**

- General interest in $(g-2)_\mu$, many different models:
  - Adding one or two particles 'ad hoc' (leptoquark or Z')
  - Supersymmetry models
  - Flavour-specific gauge interactions
- **Can be explained together with B anomalies with single vector leptoquark or scalar leptoquark + charged scalar**
- **Not required to solve flavour puzzle, but could be related**



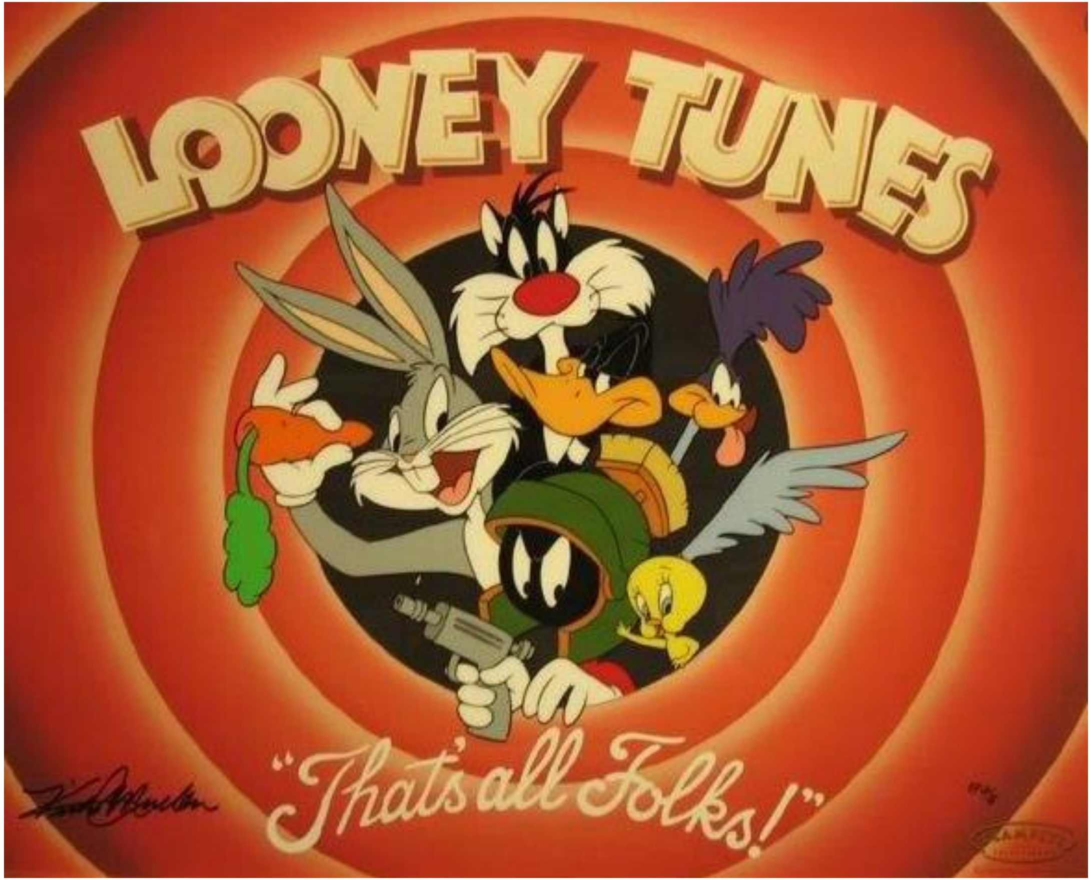
Summary

- 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?**

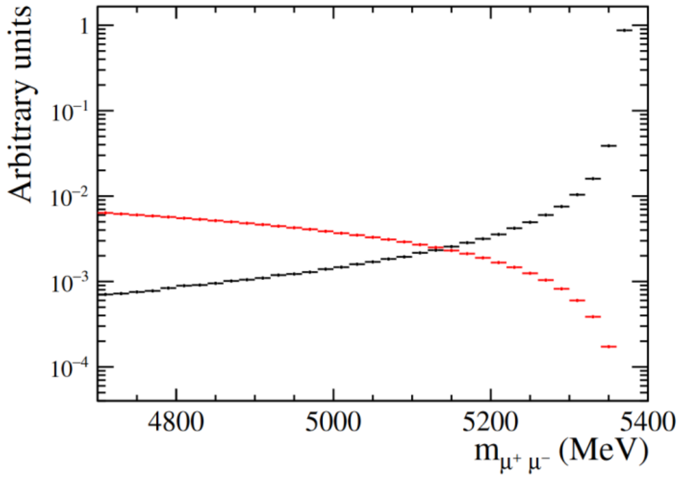
- Many measurements underway ($R_{K^*}, R_\phi, R_{K_S^0}, R_{K^{*+}}$, angular analyses, LFV with τ)
- LHCb upgrade ongoing: increase luminosity by factor 5, remove hardware trigger!


LOONEY TUNES
"That's all Folks!"

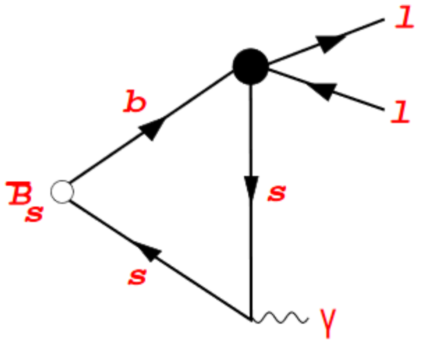
Backup

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

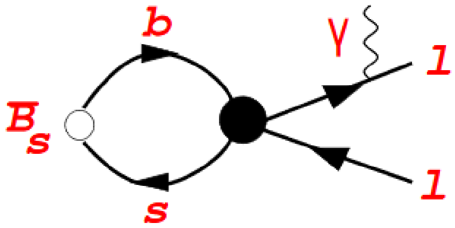
- ISR: photon from b, s quarks, effectively three-body semileptonic B decay (vs q^2): **partially reconstructed background for $B_s^0 \to \mu^+\mu^-$ reconstruction**
- FSR: soft photons from muons, same Wilson coefficients: **additional tail for $B_s^0 \to \mu^+\mu^-$, modelled with PHOTOS**



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

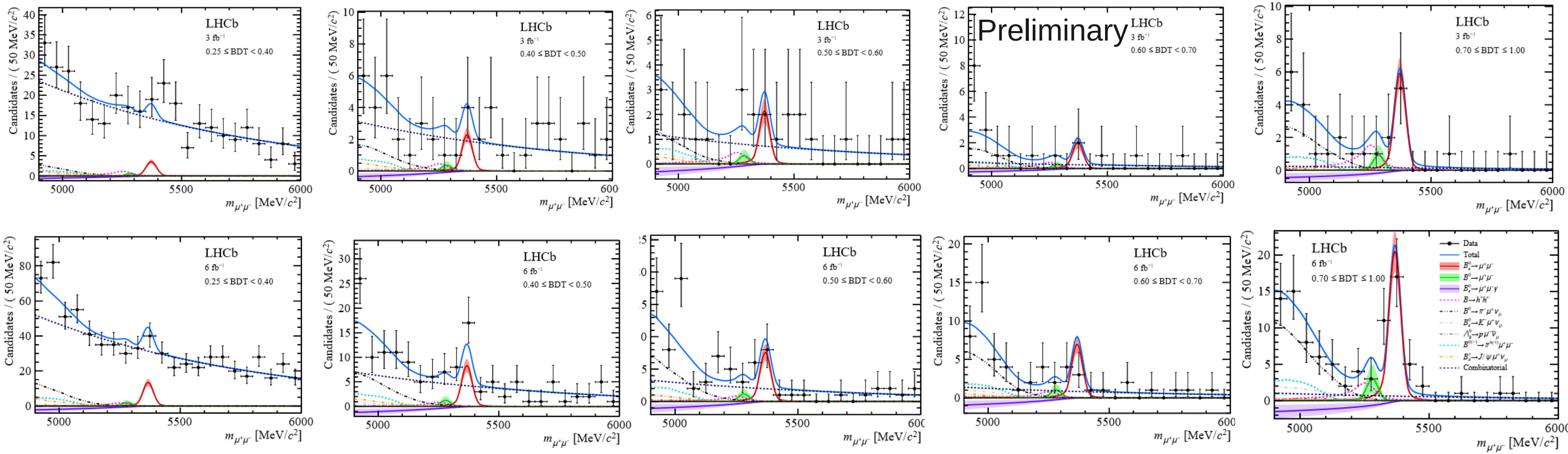
Results: mass fit in all BDT bins

[LHCb-PAPER-2021-007]

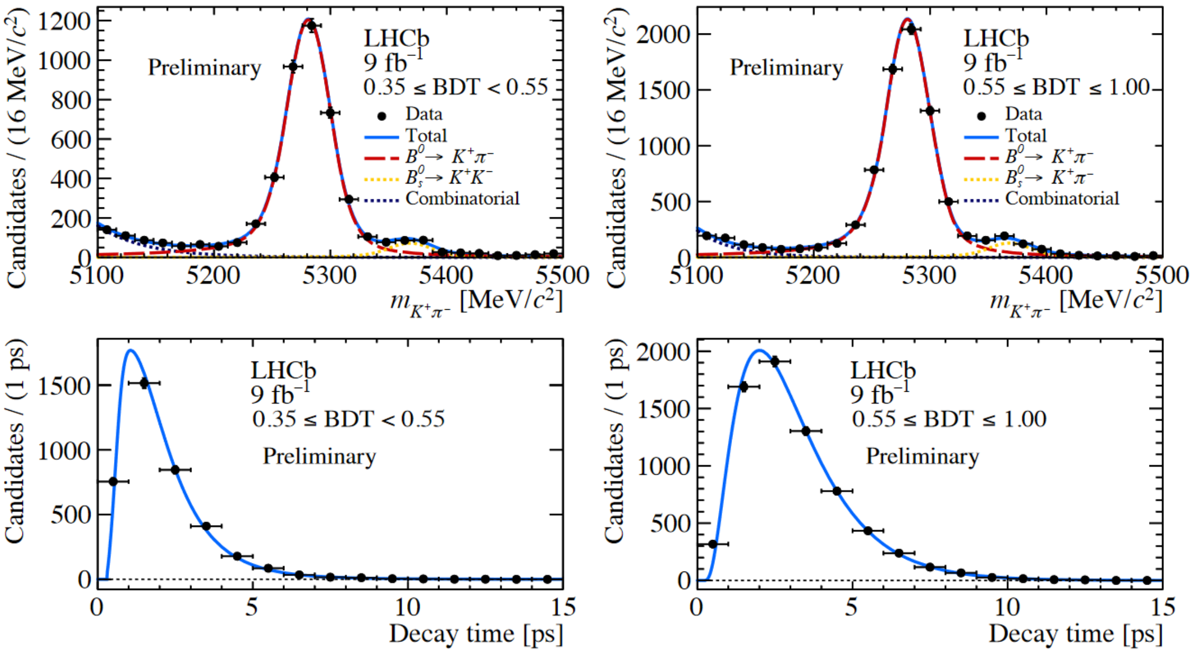
BDT [0.25,0.4] BDT [0.4,0.5] BDT [0.5,0.6] BDT [0.6,0.7] BDT [0.7,1.0]

Run 1

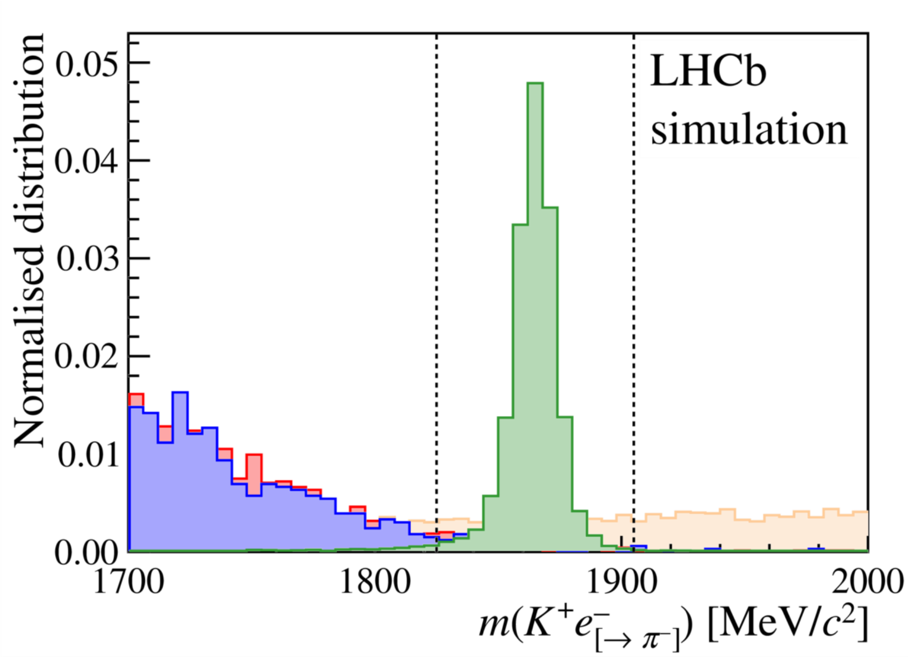
Run 2

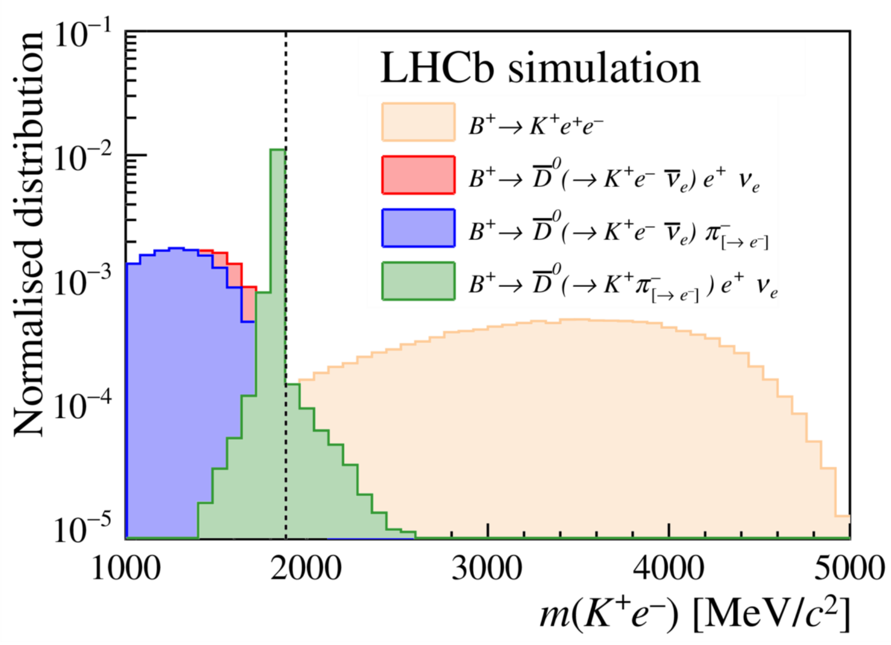


Effective lifetime: acceptance validation

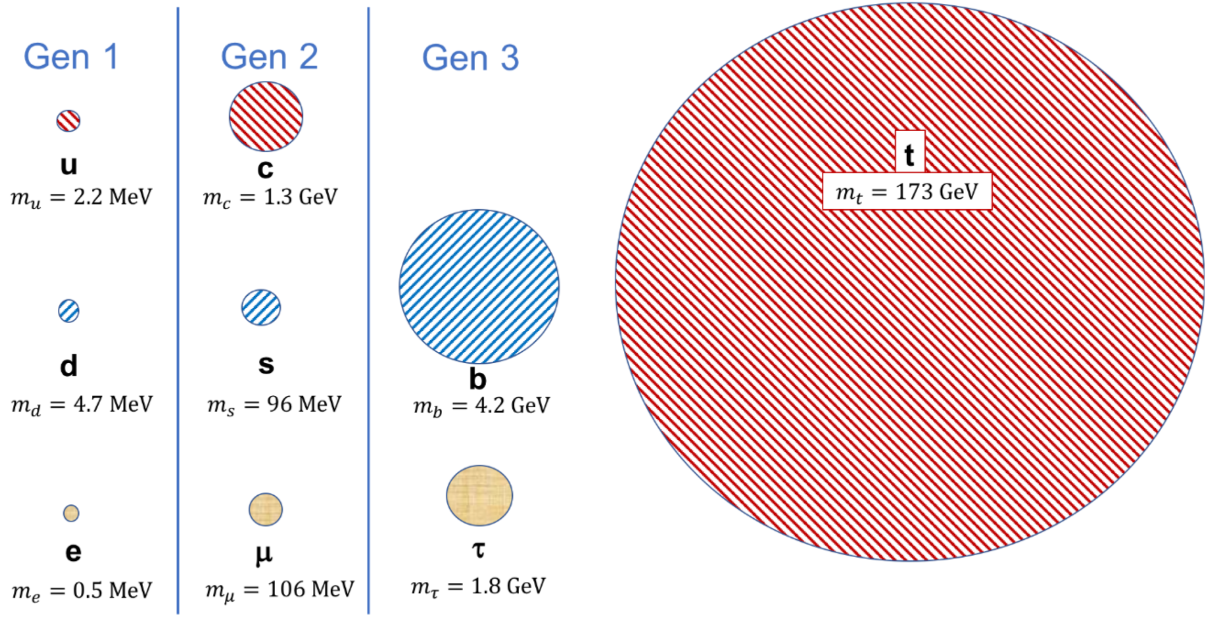


RK: semileptonic backgrounds



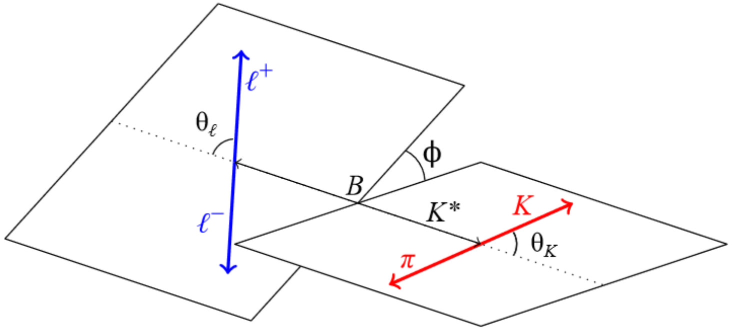


Impression of mass hierarchy



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

topology of decay angles:



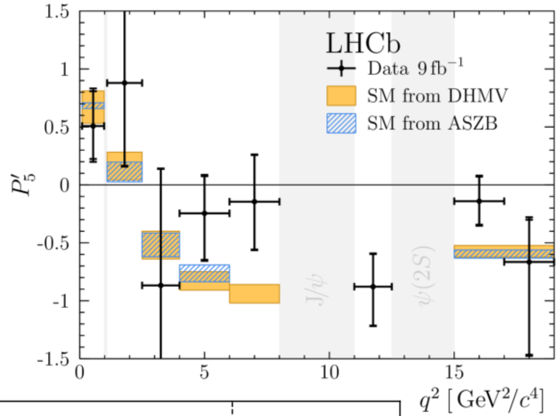
leptonic and hadronic decay part

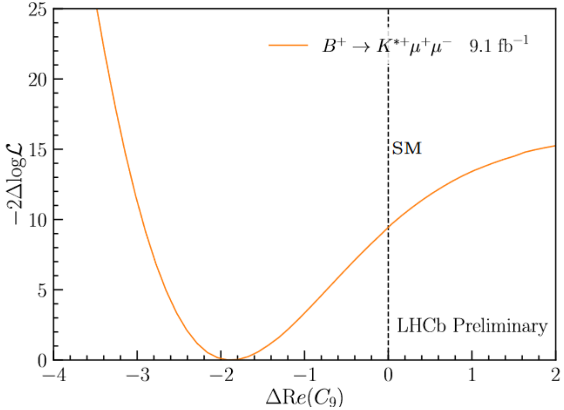
$$
\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\Bigg|_{\mathrm{P}} =
\frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K
+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell
-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi
+S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi
+S_{6s}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi
+S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]
$$

[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]