Rare decays and anomalies at LHCb: a potential violation of lepton flavor universality

Reunión Anual de la División de Partículas y Campos,
Sociedad Mexicana de Física (en línea)
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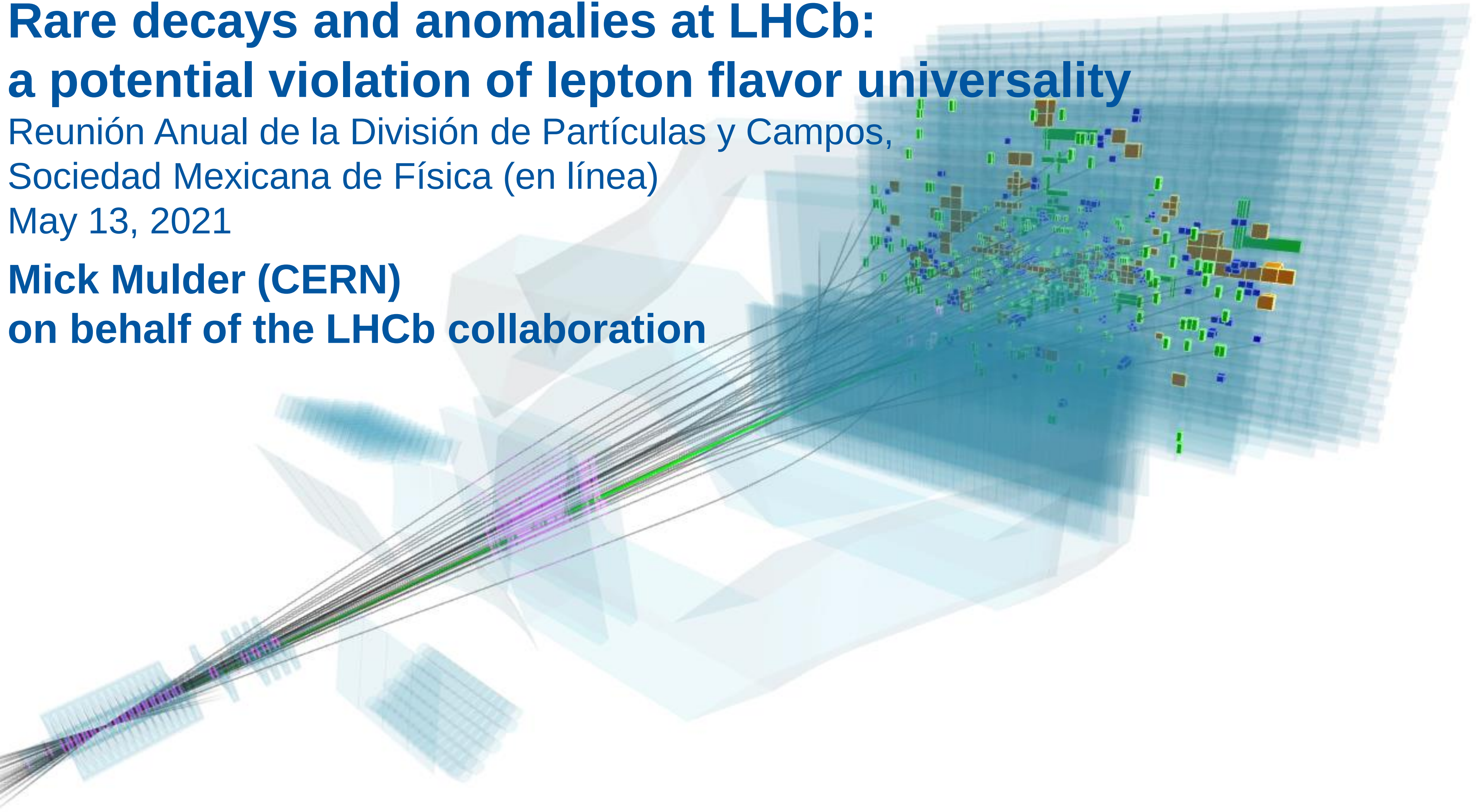
Mick Mulder (CERN)
on behalf of the LHCb collaboration



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...

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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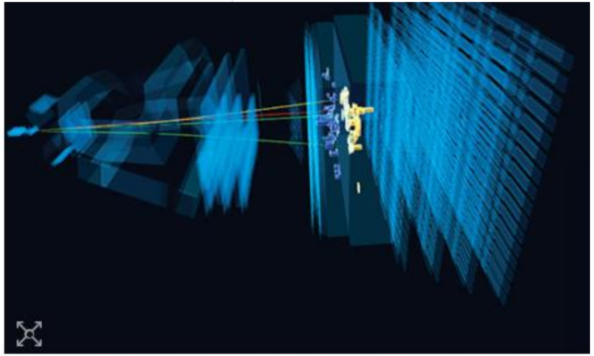
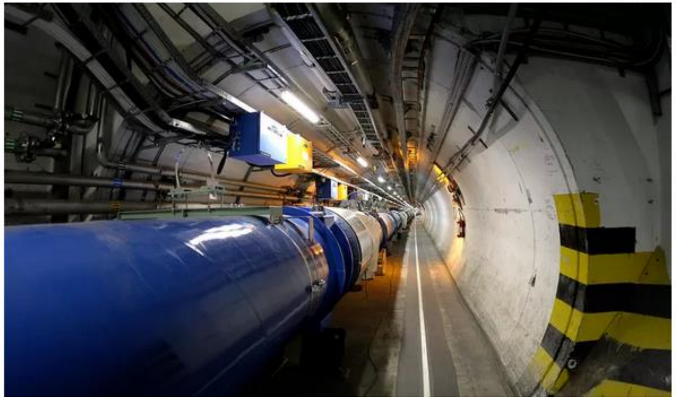
...allenges leading theory

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

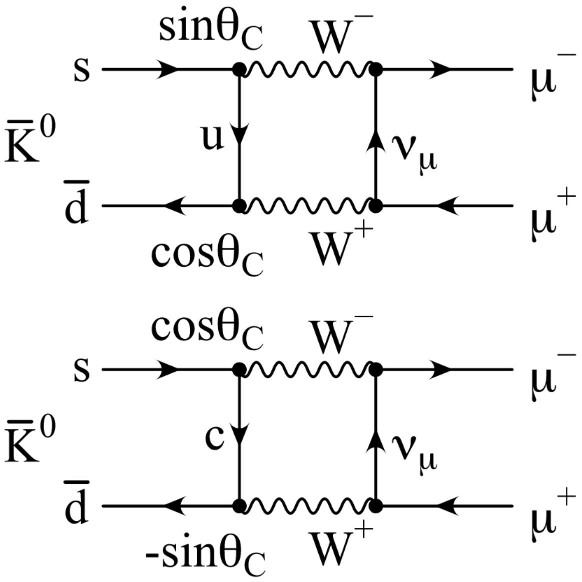


Fleeting glance: decay of a beauty quark involving an electron and positron as o... CERN)



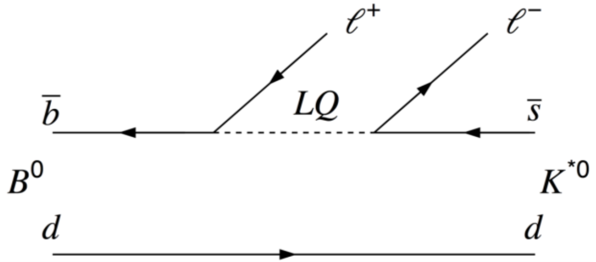
Rare decays

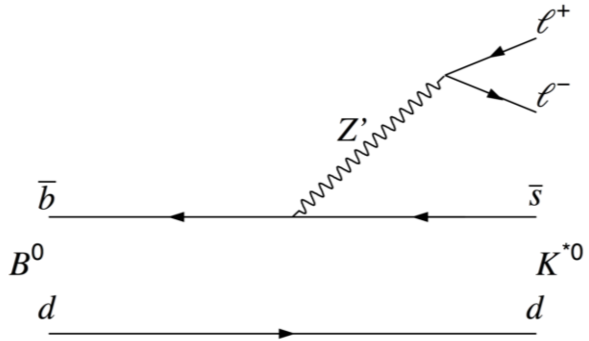
- **Loop-level decays mediated by weak interaction** (Flavour Changing Neutral Currents)
- **Transition strongly suppressed**: loops, CKM elements, sometimes GIM mechanism
- **Perfect for indirect discovery**: even small contributions have large effects on rare decays!
- Previous discoveries:
  - charm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

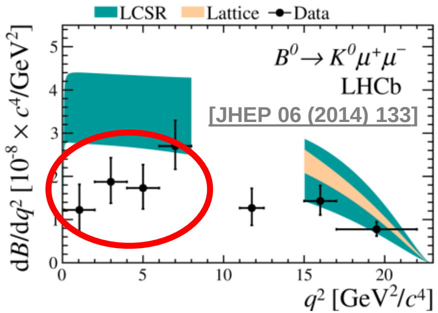
- **Precise tests of SM with third generation of matter**
- Mediated by “box” or “penguin” diagrams in SM
- Branching fractions $\leq O(10^{-6})$
- New Physics (Z’ / leptoquark) can be tree-level, contribute strongly!

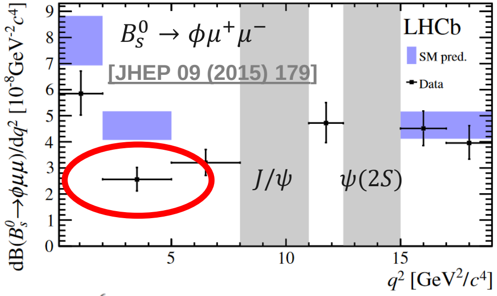


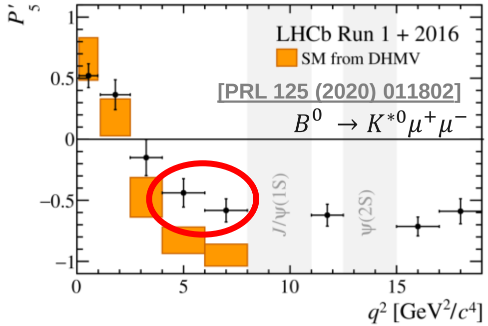


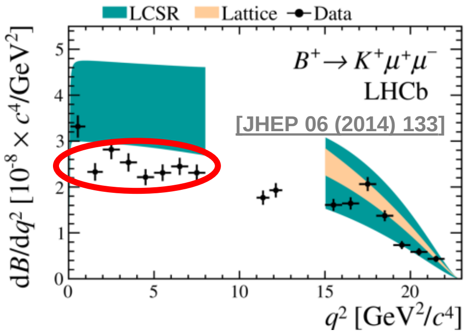
Anomalies

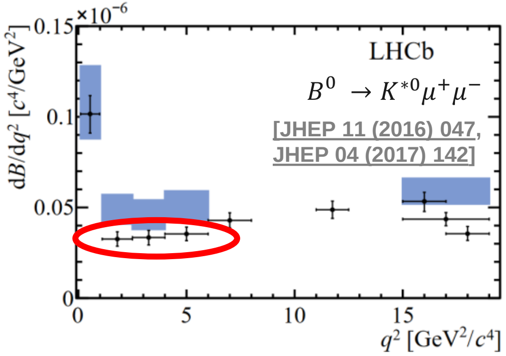
Results in rare B decays deviate from predictions in LHCb data…. (not only there)

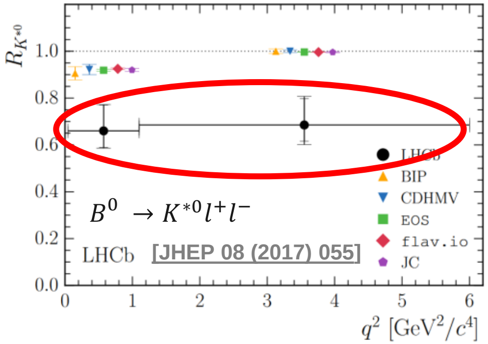






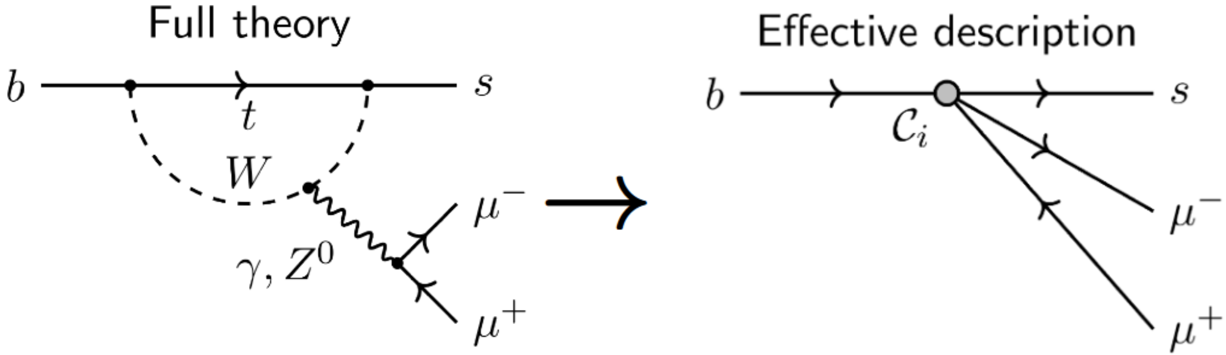






Effective field theory

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

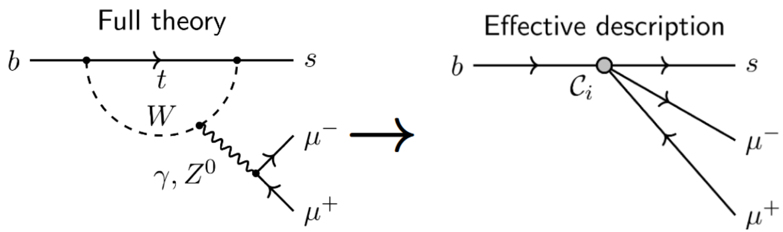


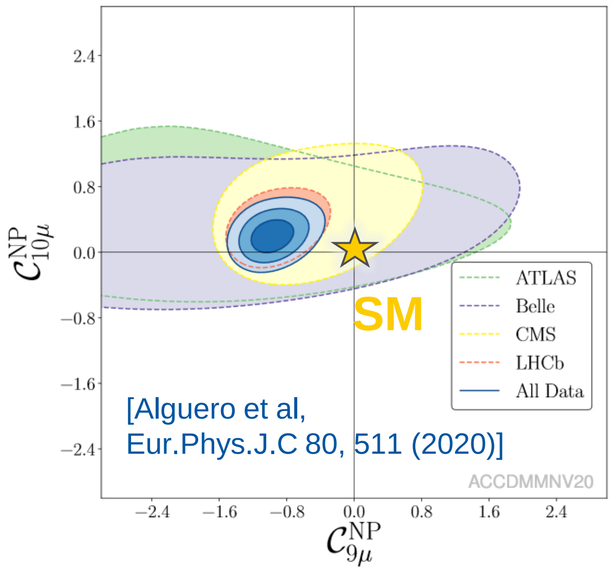
Effective field theory

- 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)
- **Global fits indicate consistent deviation: reduction of C_9 for muons** (perhaps also in $\boldsymbol{C_{10}}$)?



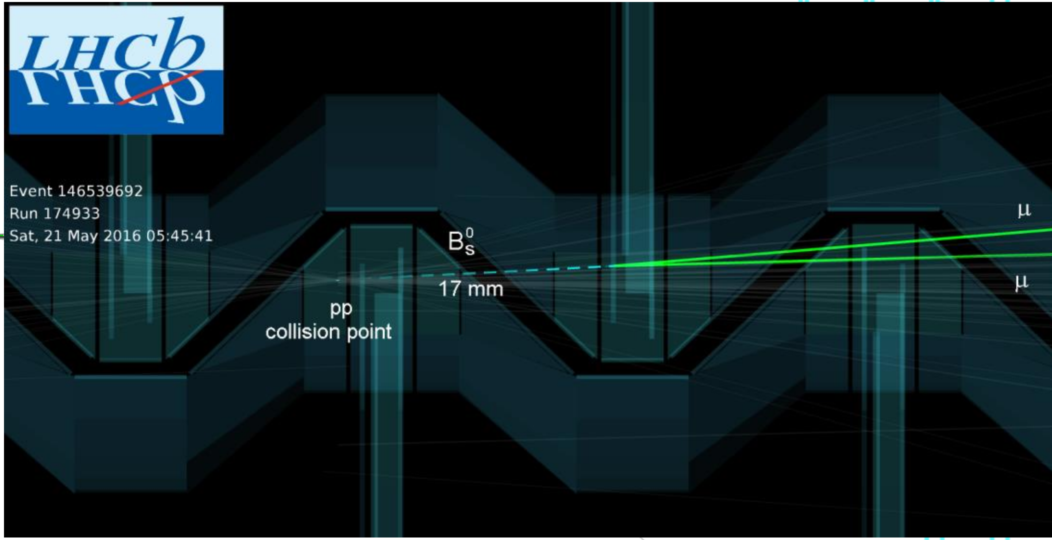


[Alguero et al, Eur.Phys.J.C 80, 511 (2020)]

LHCb detector

- Designed to study B hadrons with high precision: forward direction spectrometer [JINST 3 S08005]
- **Around 10^{12} B hadrons produced from 2011 to 2012 (Run 1) + 2015 to 2018(Run 2)!**

- Very good momentum resolution
  ($\Delta p/p = 0.5 - 1.0\%$)
  → **Sufficient to separate B_s^0, B^0 decays**
- Excellent charged particle identification:
  μ ID ~ 97 % w. 1-3% $\pi \rightarrow \mu$ mis-id
  e ID ~ 90 % w. ~ 5% $e \rightarrow h$ mis-id
  → **required to reject hadronic B decays**
- Clear separation of
  B hadron decay vertex, pp collision:
  45 fs decay time resolution ≅3% of B lifetime
  → **essential to reduce backgrounds**



f_s/f_d combination: introduction

[arXiv:2103:06810]

- At LHCb, produce many types of b-hadrons: B^0 , B^+ , B_s^0, Λ_b^0, $\Xi_b^{0/-}$, B_c^+, …
- **Essential rare decay measurements include branching fractions of B_s^0 mesons,** such as $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$, $\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)$
- **Determine B_s^0 branching fractions relative to B^0 or B^+ mode with known branching fraction** (with efficiency-corrected yield n_{corr} from experiment):

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

- **Need to know B_s^0/B_d^0 production ratio = f_s/f_d!**
- f_s/f_d is interesting as well as probe of hadronisation, previously found to depend on p_T (not on η)

- **Measure f_s/f_d using modes with prediction of branching fraction ratio**
- Five previous LHCb measurements (2011 to 2020)**:**
  today, show combination to determine single value with higher precision

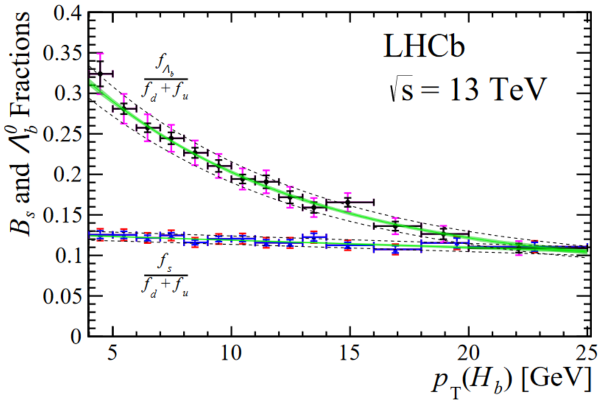
f_s/f_d combination: input measurements

- Measurements at main energies (7, 8, 13 TeV), full LHCb acceptance ($p_T \in [0.5, 40]$ GeV, $\eta \in [2, 6.4]$)

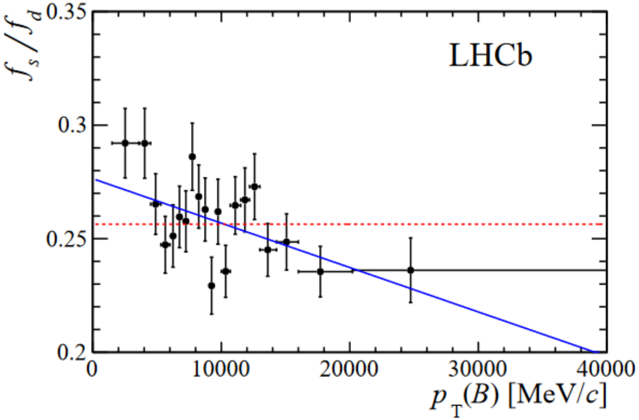
- Three decay modes: $B \to D\mu X, B \to Dh,$ (both with predictions), $B \to J/\psi X$ (no prediction → dependence)
- **Update external inputs for predictions (e.g. D branching fraction, B lifetimes): significant improvement in sensitivity!**

[arXiv:2103:06810]

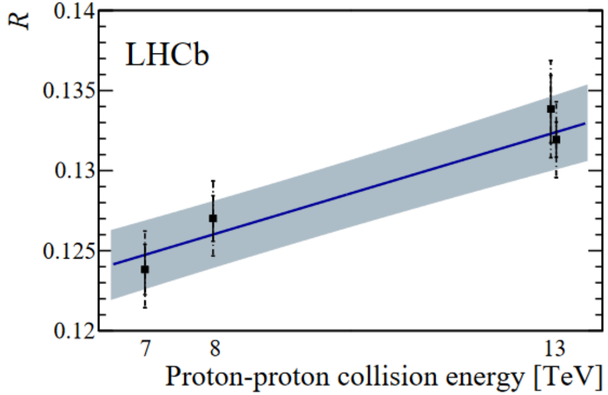
$B \to D\mu X$, 13 TeV



$B \to Dh$, 7 TeV



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

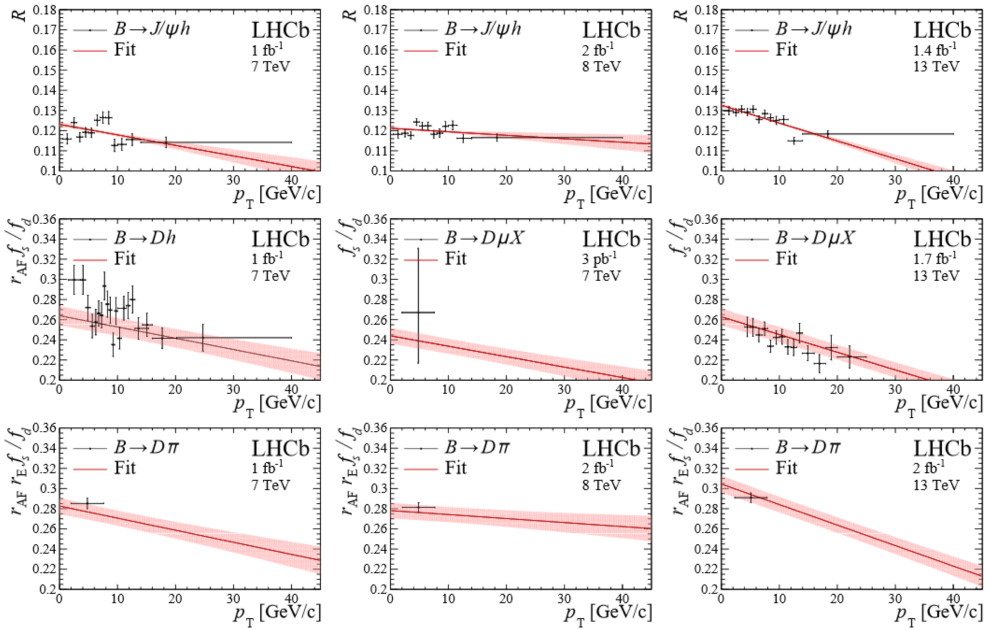


f_s/f_d combination: results

[arXiv:2103:06810]

- Integrated value (13 TeV) in LHCb acceptance: $\frac{f_s}{f_d} = 0.2539 \pm 0.0079$
- **Uncertainty reduced by ~factor 2 to 3.1%**
- **Measure $\boldsymbol{B(B_s^0 \to J/\psi\phi), B(B_s^0 \to D_s^-\pi^+)}$ with similar precision**
- **Essential improvement for $\boldsymbol{B(B_s^0 \to \mu^+\mu^-), B(B_s^0 \to \phi\mu^+\mu^-)}$!**

- First observation of $\sqrt{s}$ dependence, hint of p_T dependence variation vs $\sqrt{s}$
- Future predictions of $\sqrt{s}$ and p_T dependence would be very useful

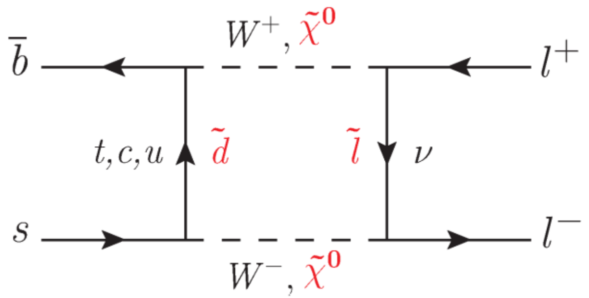


On the menu today: **all new, Run 1 + Run 2!**

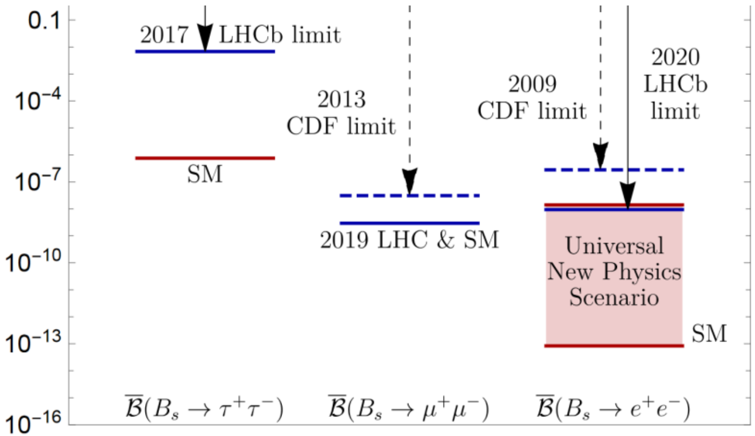
- Improved measurement of $B^0_{(s)} \to \mu^+\mu^-$ decay observables
- $R_K = \frac{B(B^+ \to K^+\mu^+\mu^-)}{B(B^+ \to K^+e^+e^-)}$:evidence for lepton universality violation
- $B(B^0_s \to \phi\mu^+\mu^-)$ measurement
- Angular analysis of $B^+ \to K^{*+}\mu^+\mu^-$
- Interpretation and conclusions

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

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

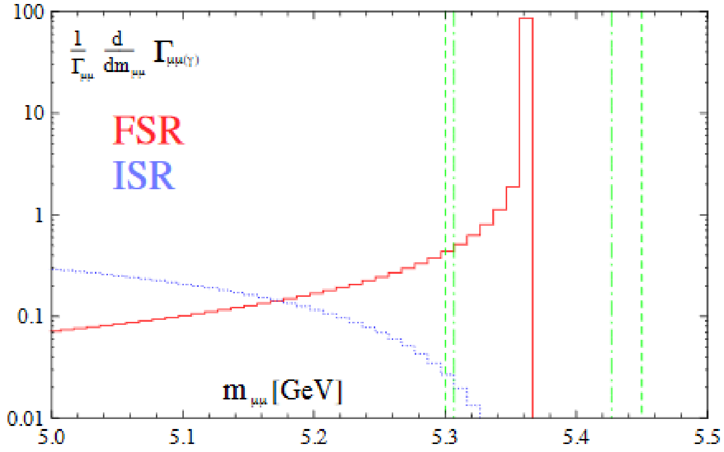


Fleischer et al., JHEP 05 (2017) 156



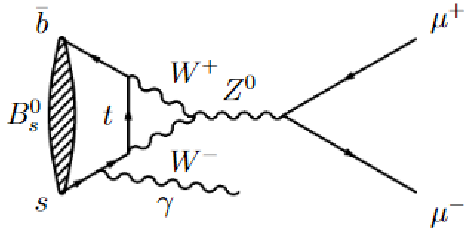
$B^0_{(s)} \to \mu^+\mu^-$ and photon radiation

- Initial State Radiation: photon emitted from quarks, **sensitive to C_9 and C_{10},** here referred to as $B^0_{(s)} \to \mu^+\mu^-\gamma$
- **New observable in this analysis,** without reconstructing photon for $m_{\mu^+\mu^-} > 4.9$ GeV
- SM prediction $O(10^{-10})$ [JHEP 11 (2017) 184, PRD 97 (2018) 053007]
- Final State Radiation: soft photons emitted from muons, sensitive to C_{10} only, included in $B^0_s \to \mu^+\mu^-$ via PHOTOS

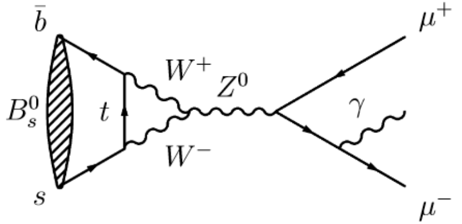


[PRL 112 (2014) 101801]

Initial State Radiation

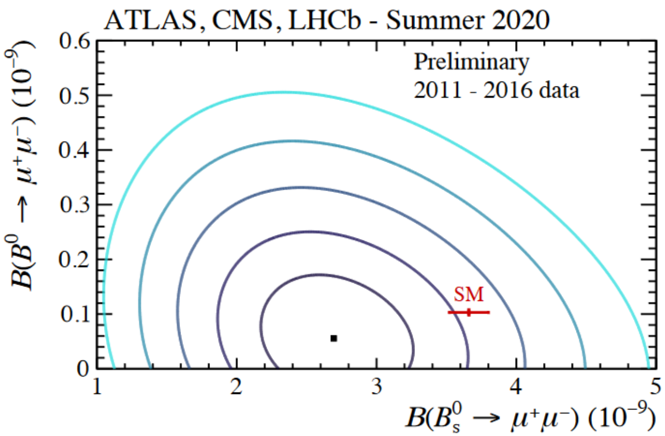


Final State Radiation



Previous results

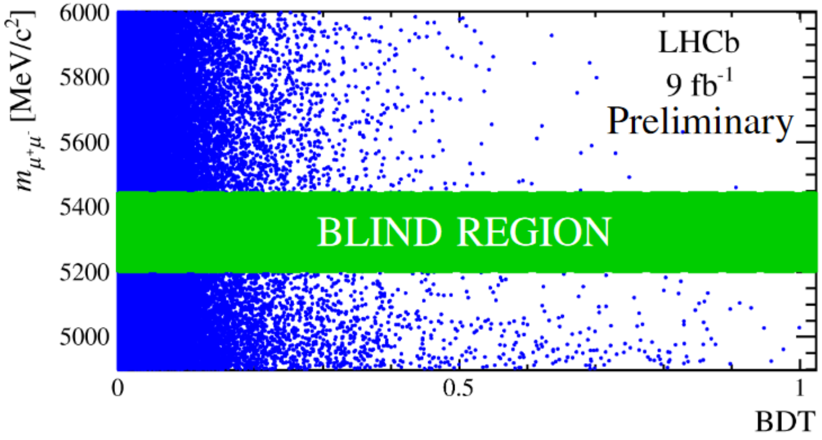
- Recent combination of ATLAS, CMS, LHCb results with data up to 2016: **[LHCb-CONF-2020-002]**
  - $B(B_s^0 \to \mu^+\mu^-) = \left(2.69^{+0.37}_{-0.35}\right) \times 10^{-9}$
  - $B\left(B^0 \to \mu^+\mu^-\right) < 1.9 \times 10^{-10}$ at 95% CL
- **Mild tension with SM (2.1σ),** compatible with new physics in $\boldsymbol{C_9 - C_{10}}$
- **No search yet for $\boldsymbol{B_s^0 \to \mu^+\mu^-\gamma}$**
  - $B(B^0 \to \mu^+\mu^-\gamma) < 1.5 \times 10^{-7}$ at 90% CL **[BaBar: PRD 77 (2008) 011104]**

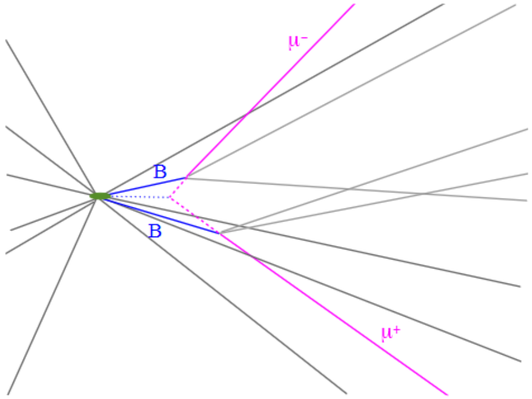


Analysis strategy

- **Similar strategy to previous analysis, strongly improved calibration**
- Use full Run 1 + Run 2 data
- 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 $\mathbf{m_{\mu\mu}}$ and BDT**

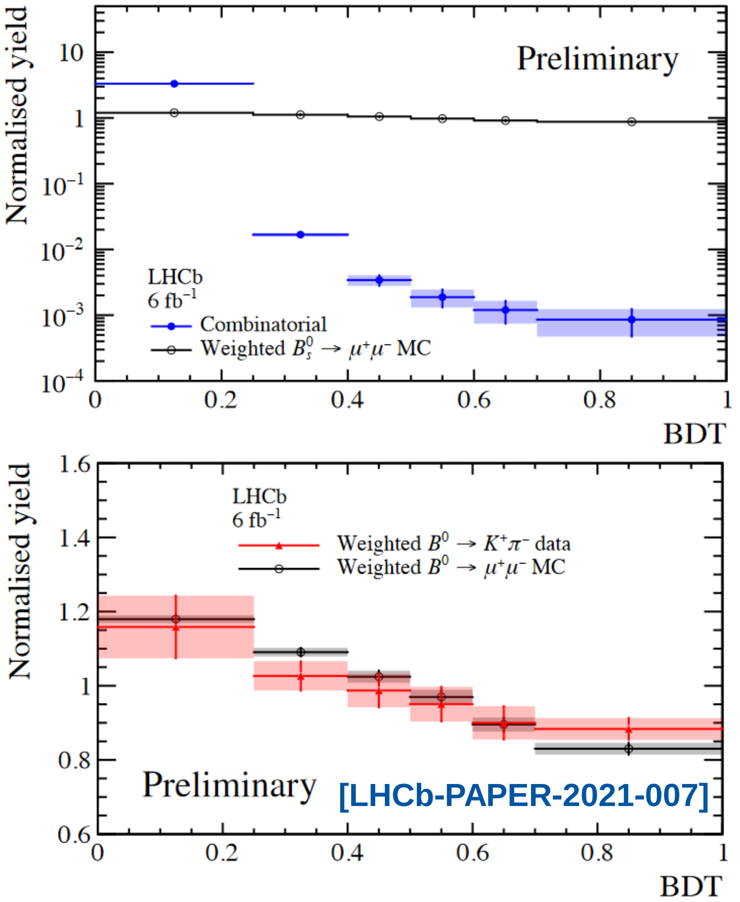




BDT calibration

- 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**

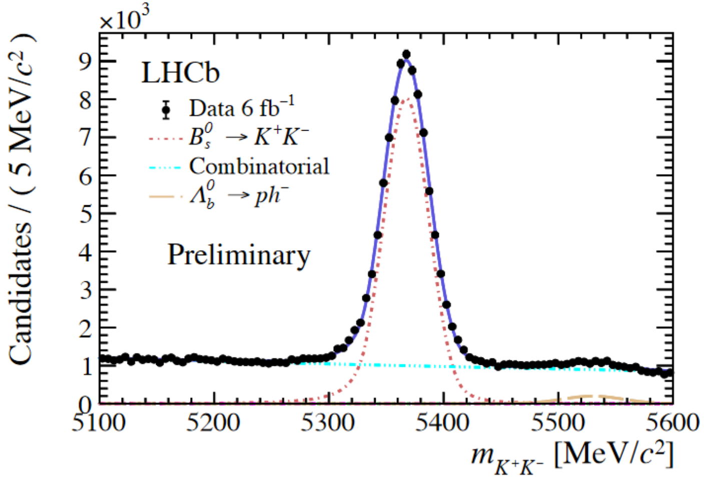


[LHCb-PAPER-2021-007]

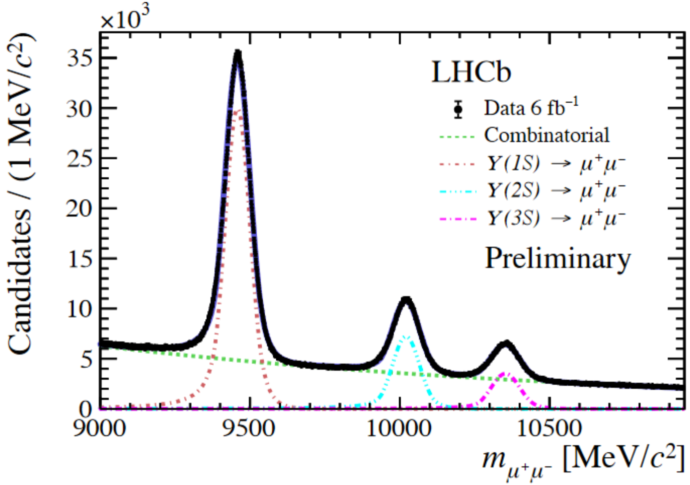
Mass calibration

[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



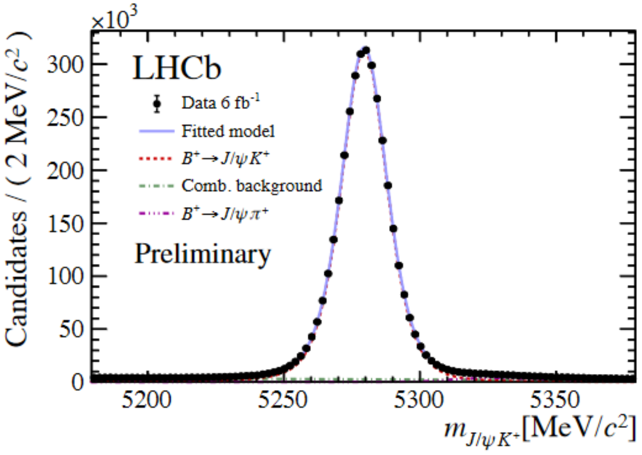
Tail parameters (for FSR) calibrated on smeared simulation
Include correlation of mass shape with BDT

Normalisation: strategy

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

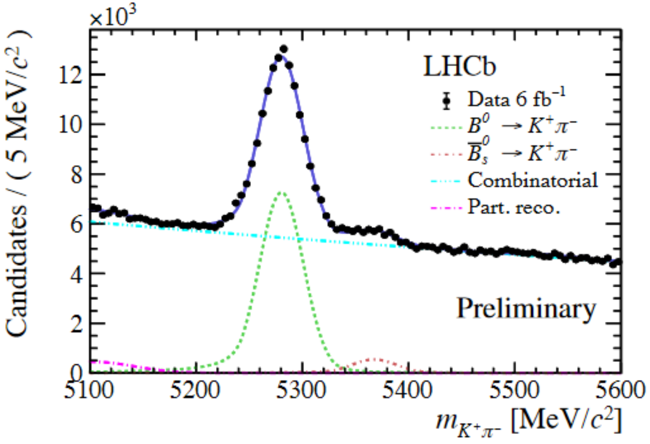
$B^+ \to J/\psi(\to \mu^+\mu^-)K^+$

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

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

- 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**
- **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):

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

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

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

Backgrounds

[LHCb-PAPER-2021-007]

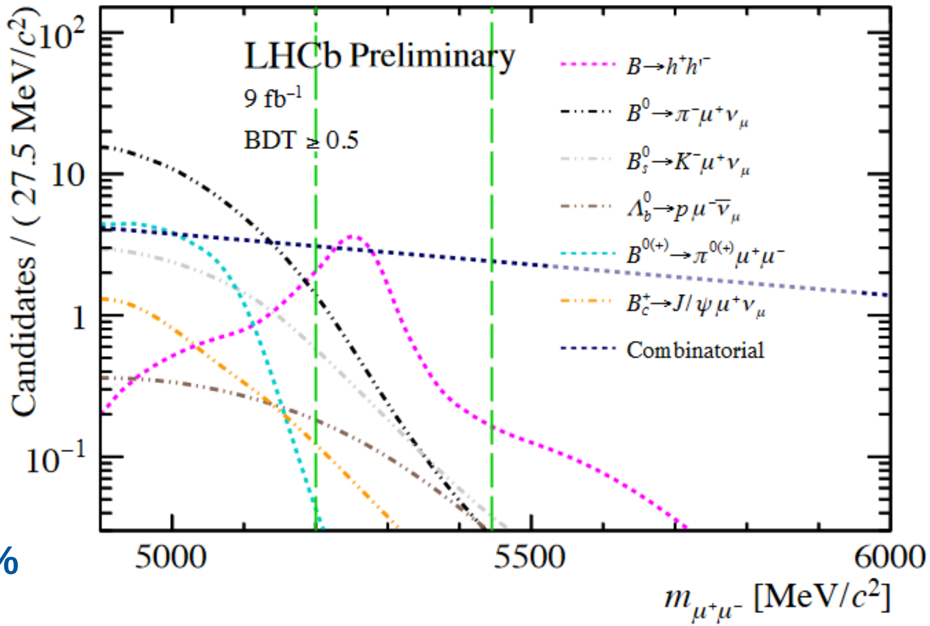
Three types of backgrounds in fit:

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!

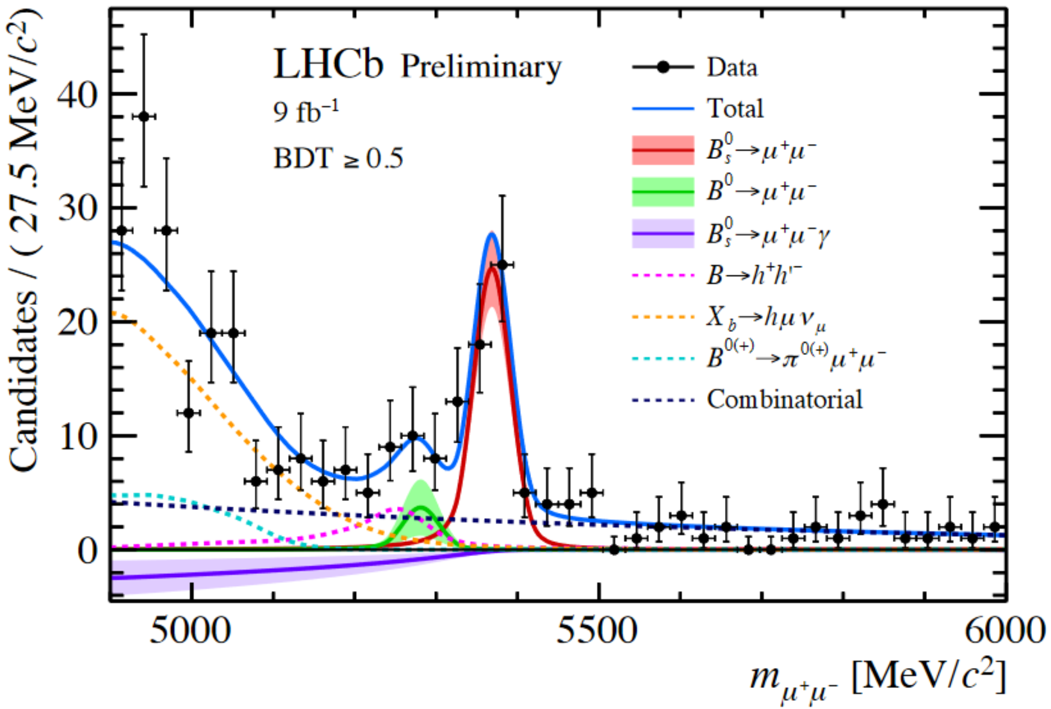


Results: branching fraction

[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**
- **Similar uncertainty to previous LHC combination**

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

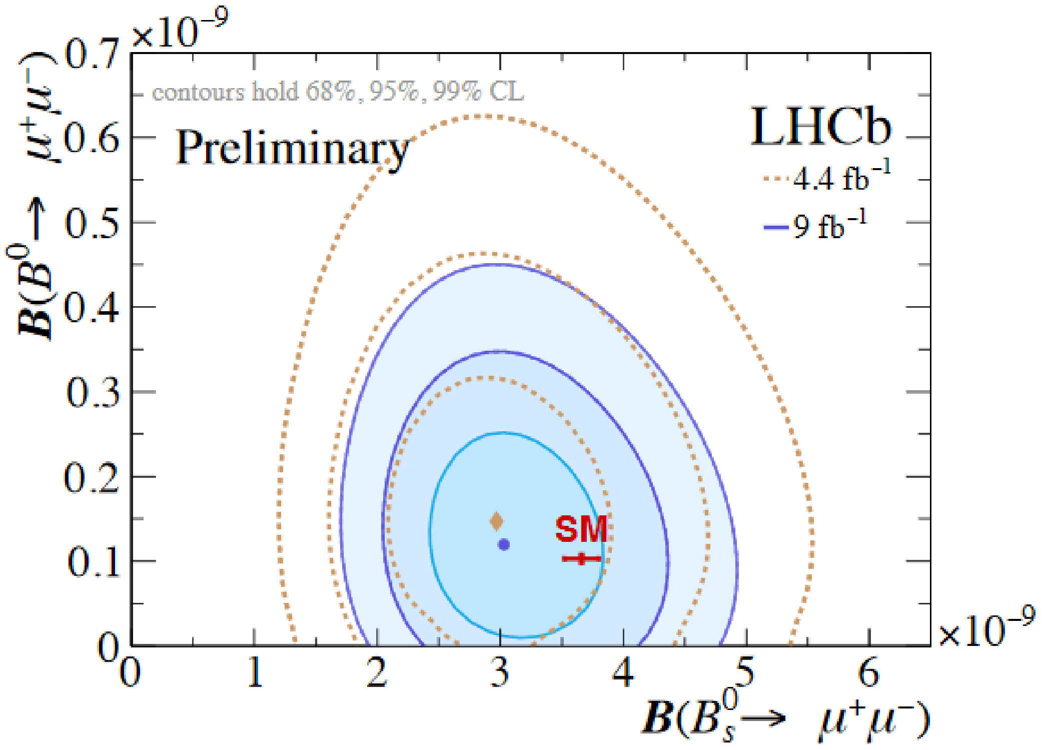


Results: compatibility with SM

[LHCb-PAPER-2021-007]

- 2D likelihood contour of $B(B_s^0 \rightarrow \mu^+\mu^-)$ vs. $B\left(B^0 \rightarrow \mu^+\mu^-\right)$: **result compatible with SM (<1σ) and previous LHCb result**

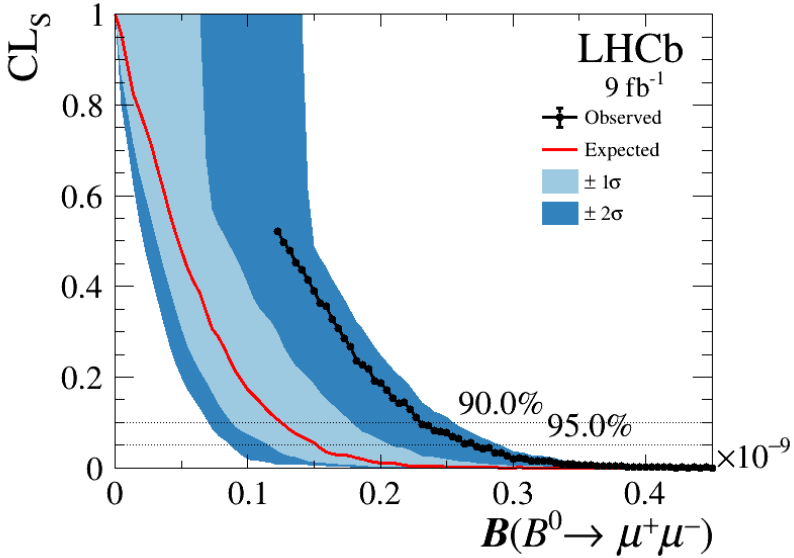
- Correlation is small (-7%)



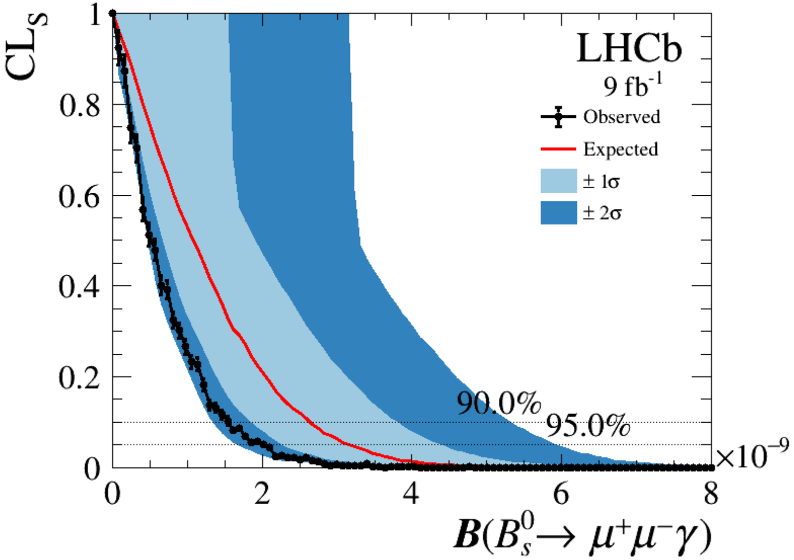
Results: limits (CLs method)

[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

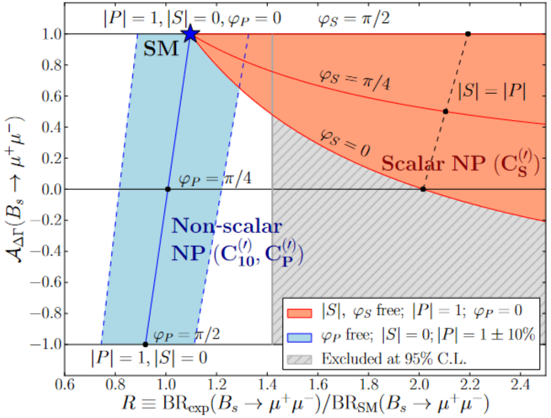


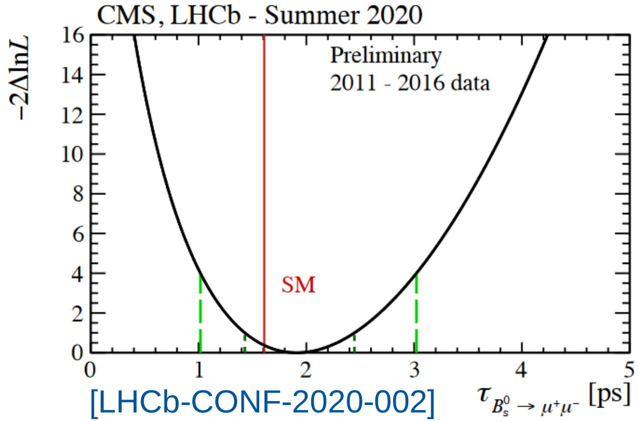
Effective lifetime of $B_s^0 \to \mu^+\mu^-$

- Neutral $B^0_{(s)}$ mesons undergo mixing, propagate as CP-odd and CP-even eigenstates
- 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_s^0 mass(~CP) eigenstates characterised by sizeable difference in decay width, $\Delta\Gamma_s/\Gamma_s = 0.124 \pm 0.008$
- **Measure effective lifetime τ_{eff} to test for CP-even contribution, scalar NP (C_s, C_P)!**

- Combination of first LHCb, CMS measurements: $\tau_{\text{eff}}(B_s^0 \to \mu^+\mu^-) = \left(1.91^{+0.37}_{-0.35}\right)$ ps (dominated by statistics)

[PRL 109 (2012) 041801]

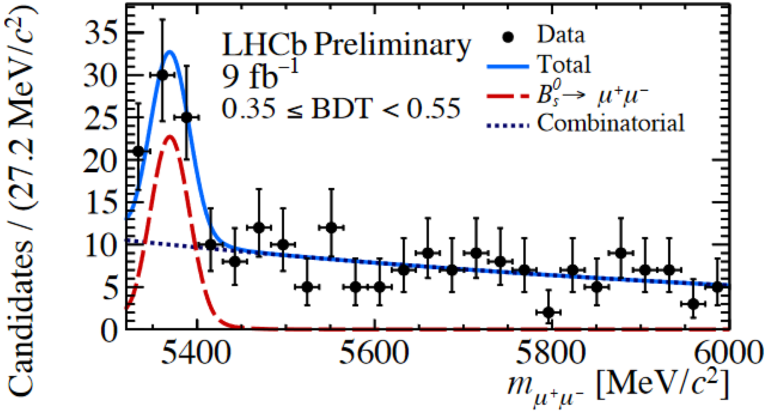




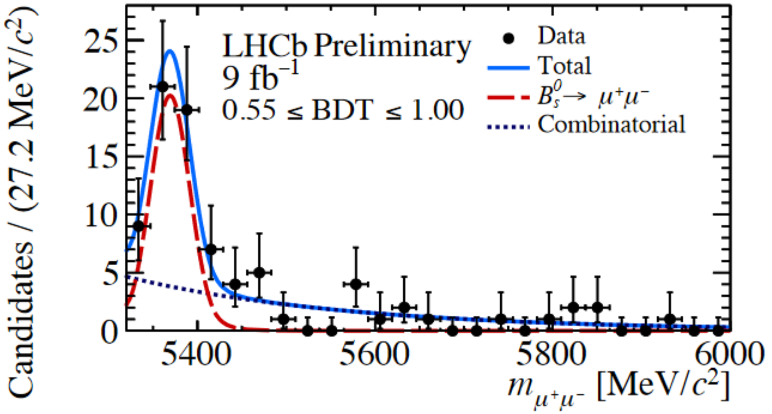
[LHCb-CONF-2020-002]

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. 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

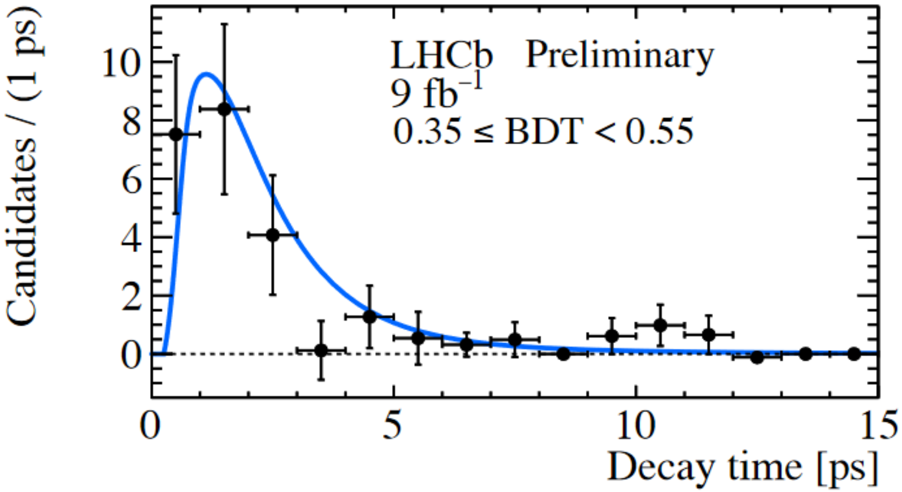


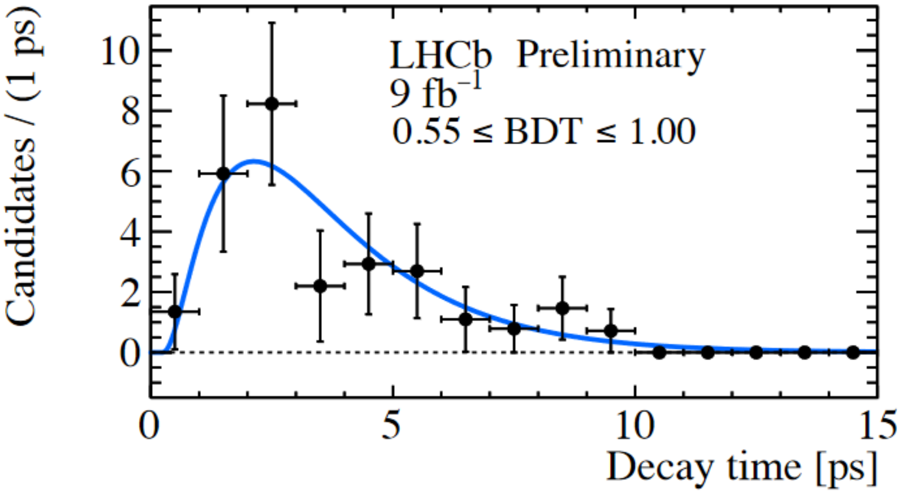
[LHCb-PAPER-2021-007]



Results: effective lifetime fit

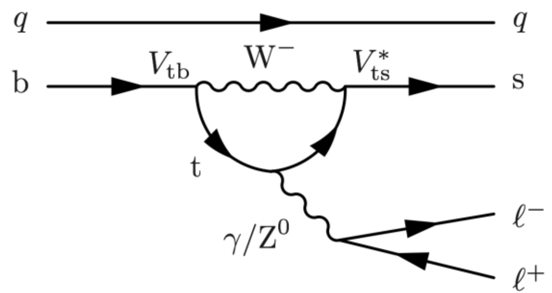
[LHCb-PAPER-2021-007]



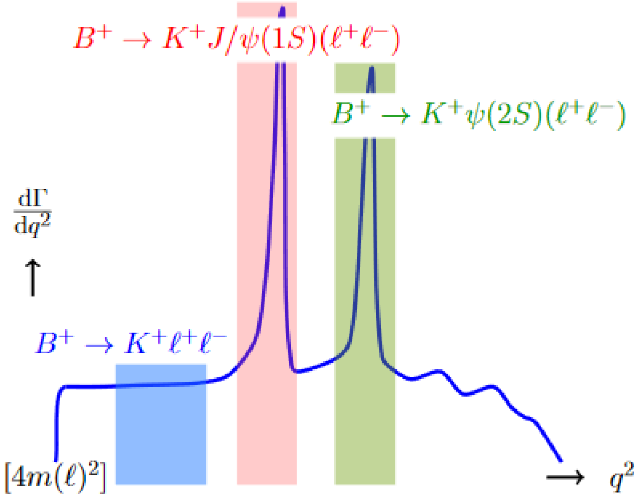


- $\boldsymbol{\tau(B_s^0 \to \mu^+\mu^-) = 2.07 \pm 0.29 \pm 0.03}$ **ps** (previously $2.04 \pm 0.44 \pm 0.05$ ps)
- 1.5 sigma from SM (i.e. $A^{\mu\mu}_{\Delta\Gamma_s} = 1$), 2.2 sigma from extreme non-SM (i.e. $A^{\mu\mu}_{\Delta\Gamma_s} = -1$)
- **Run 3 data needed to start providing significant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

Semileptonic rare B decays



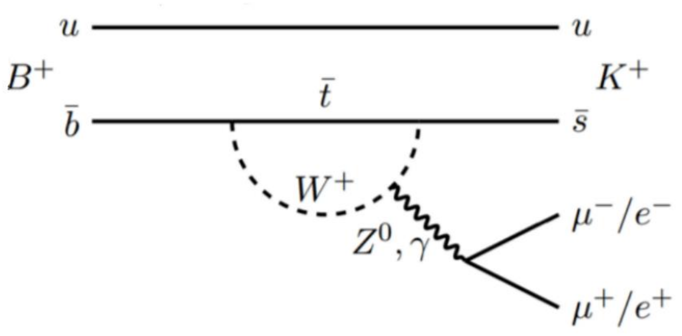
- "Regular" rare B decay
  - Includes spectator quark
  - At least 3-body final state
- Physics depends on dilepton invariant mass: q^2
- Additional observables:
  - Branching fraction (difficult to predict)
  - Angular observables (better, still tricky)
  - Lepton universality (clean tests of SM)
  - 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**
- Today: update with full Run 1 + Run 2 data!

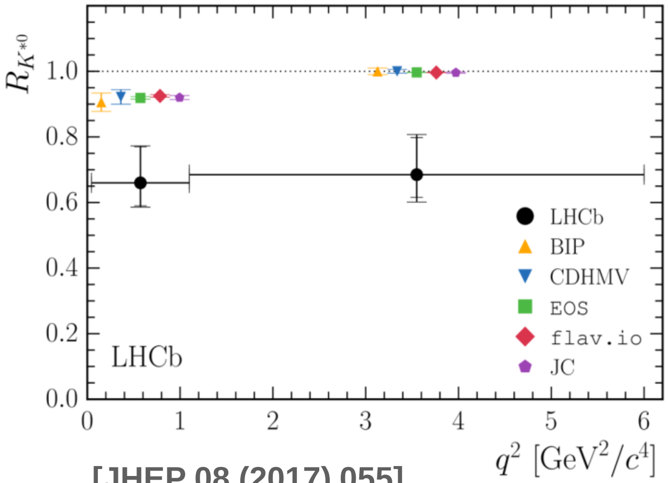


Previous measurements

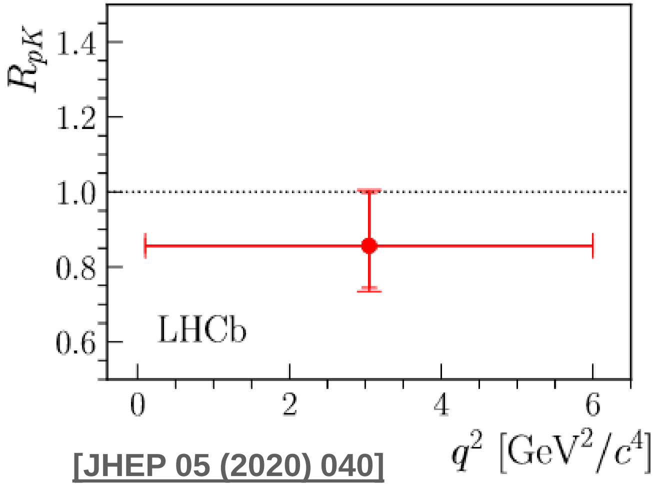
Other tests of lepton universality at LHCb:

$R_{K^{*0}} = \frac{B(B^0 \to K^{*0}\mu\mu)}{B(B^0 \to K^{*0}ee)} \neq 1$ ($\sim 2.5\sigma$ per bin)

$R_{pK} = \frac{B(\Lambda_b^0 \to pK\mu\mu)}{B(\Lambda_b^0 \to pKee)} \neq 1$ (1σ)



[JHEP 08 (2017) 055]

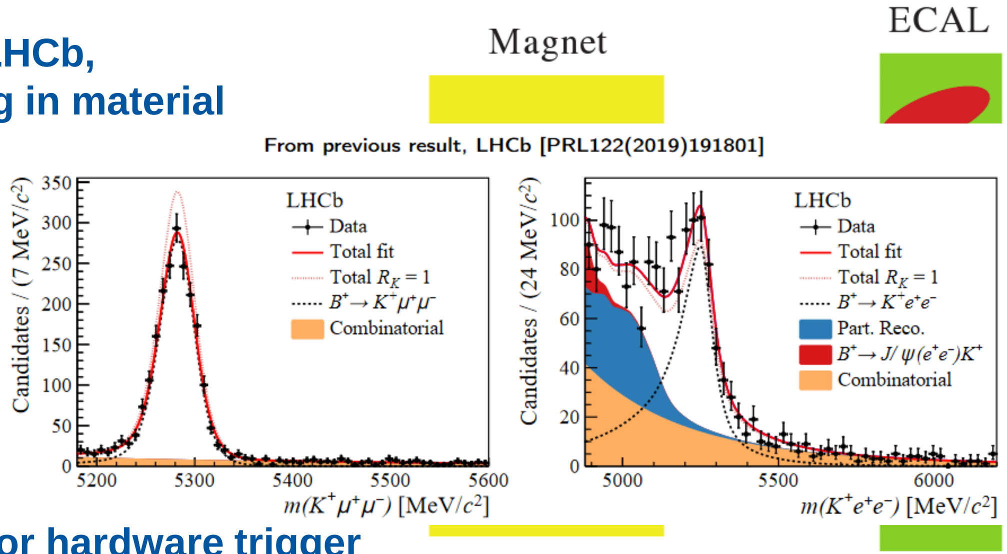


[JHEP 05 (2020) 040]

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**



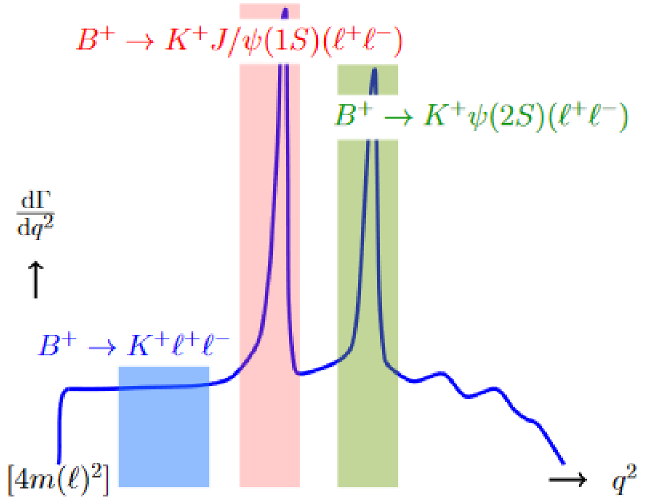
- **Additionally, electrons more difficult for hardware trigger (than muons)**
- Electron sample divided based on hardware trigger category: electron, rest-of-event, or hadron trigger

Strategy

[arXiv:2103.11769]

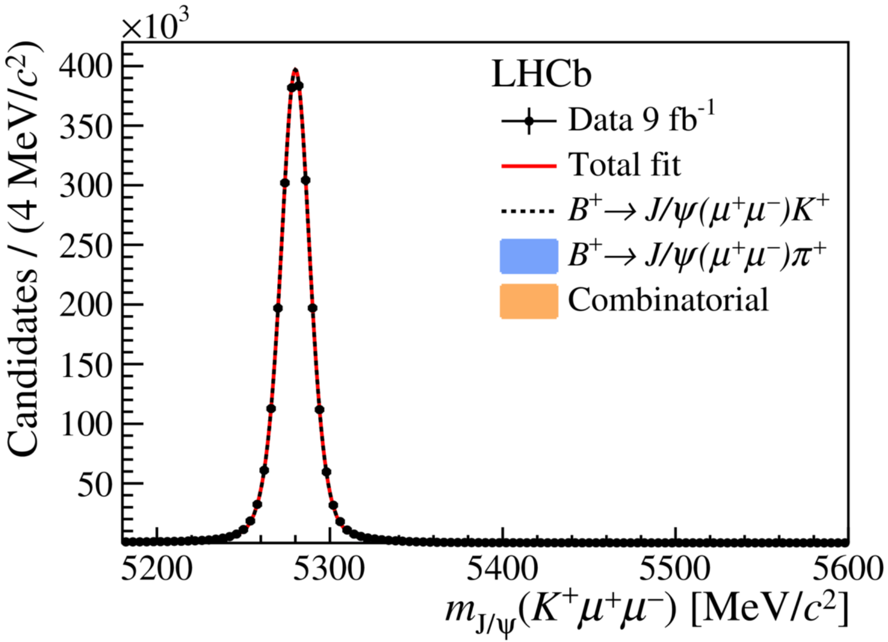
$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))} = \frac{N^{\mathrm{rare}}_{\mu^+\mu^-}\ \varepsilon^{J/\psi}_{\mu^+\mu^-}}{N^{J/\psi}_{\mu^+\mu^-}\ \varepsilon^{\mathrm{rare}}_{\mu^+\mu^-}}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

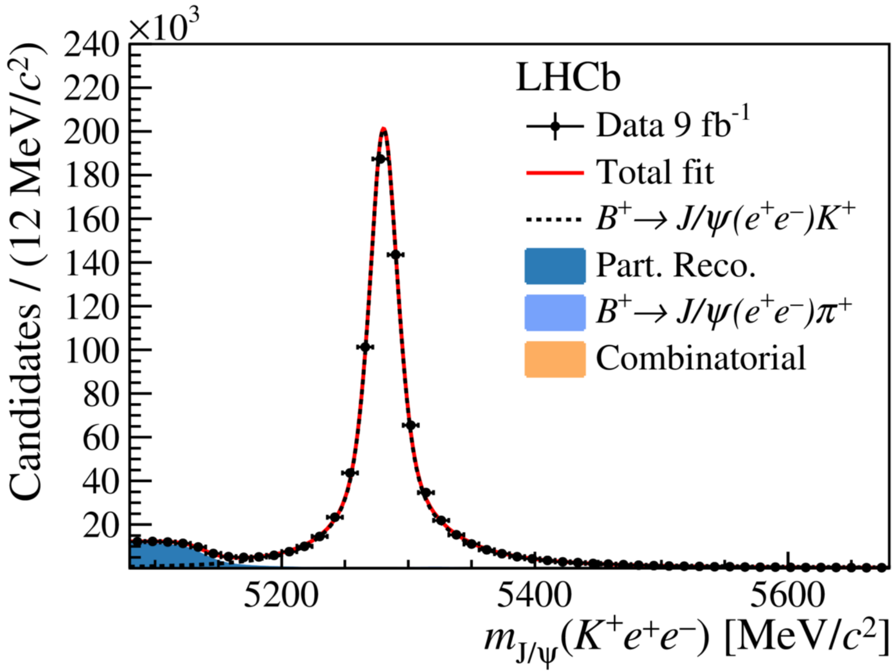
- **Measure R_K as double ratio (relative to $B^+ \to K^+ J/\psi$)**
- Selection with BDT to reduce combinatorial, PID cuts and mass vetoes to reduce exclusive backgrounds
- Rare and J/ψ modes share identical selections but for q^2
- Yields determined from mass fits
- Efficiencies computed from simulation 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%

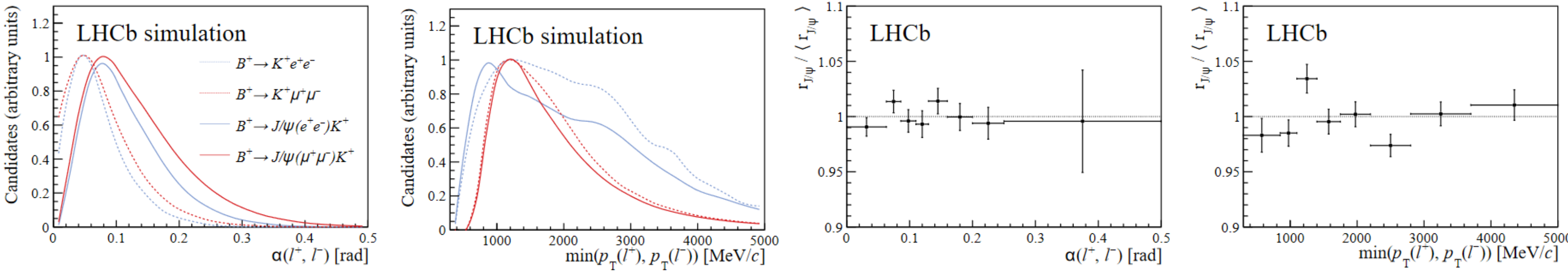
- **Requires direct control of muons versus electrons**
- Result:

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

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]

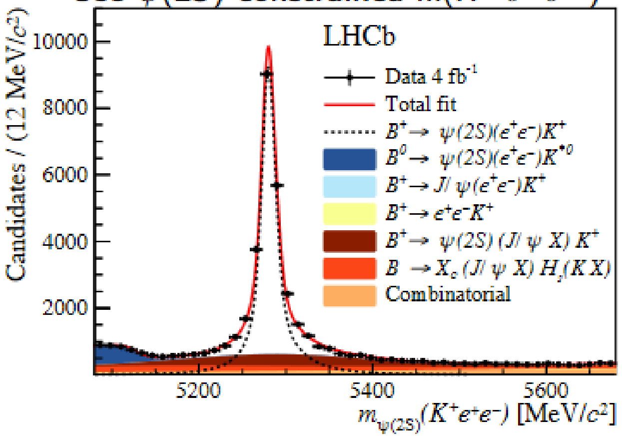
- Measurement of double ratio

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

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

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

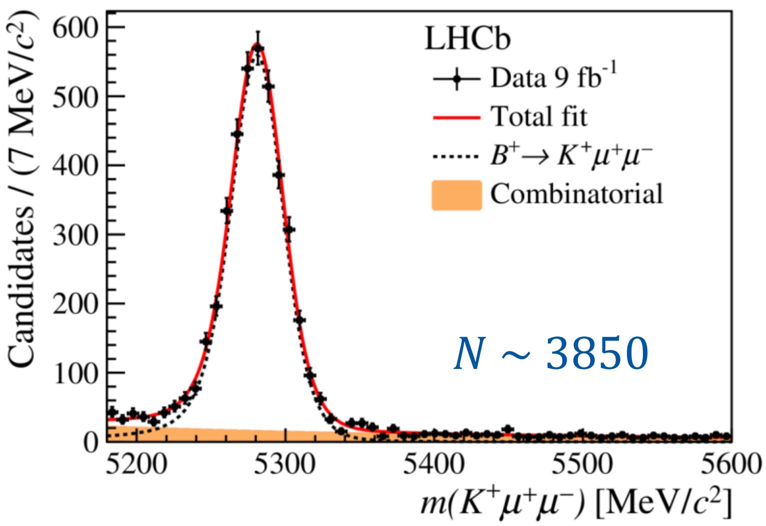
Use $\psi(2S)$ constrained $m(K^+\ell^+\ell^-)$

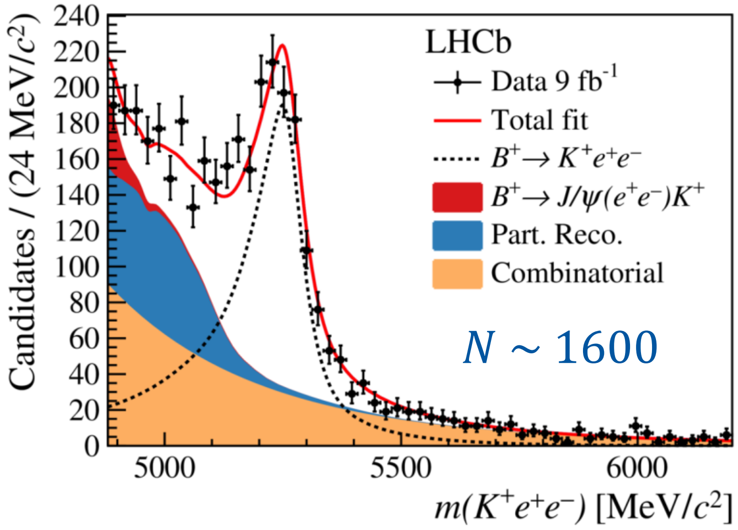


Determining R_K

[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





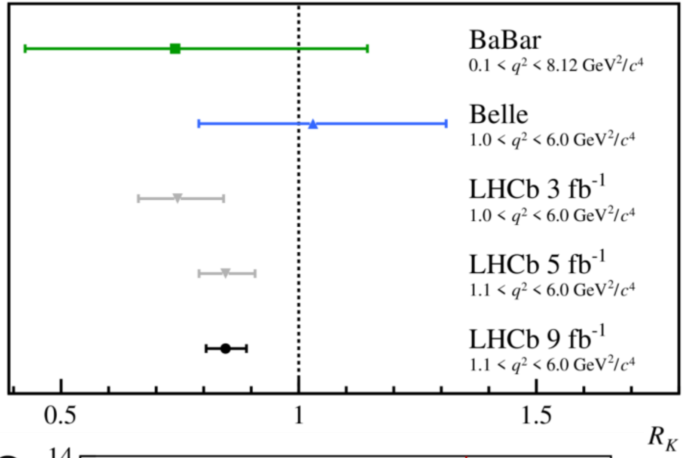
Results: R_K

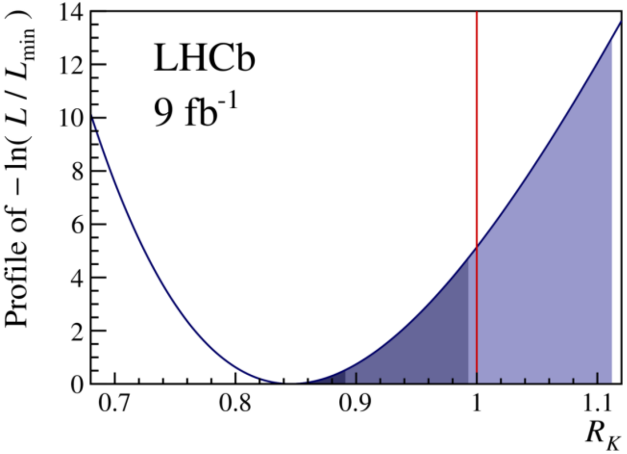
[arXiv:2103.11769]

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

- Exact same central value as before
- 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%)
- SM hypothesis p-value: 0.0010,
  evidence of lepton universality violation at 3.1σ





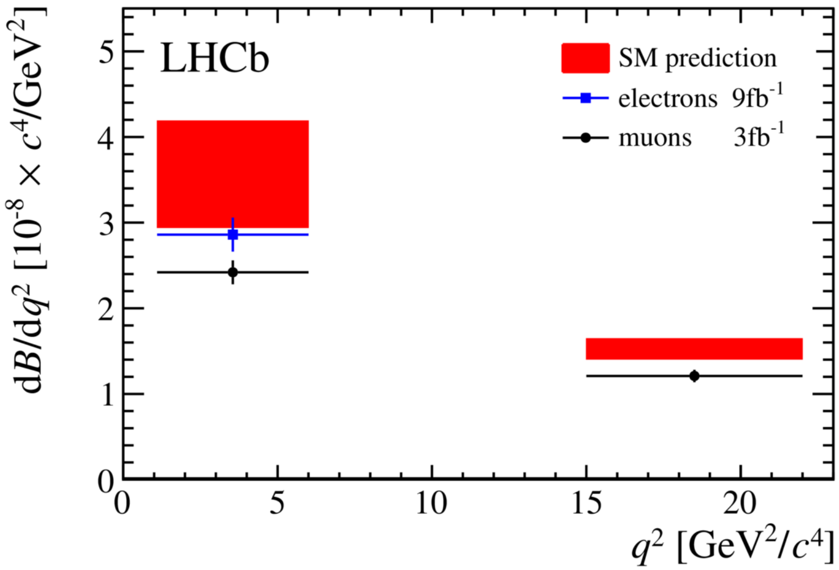
Results: $B(B^+ \to K^+e^+e^-)$

- 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]

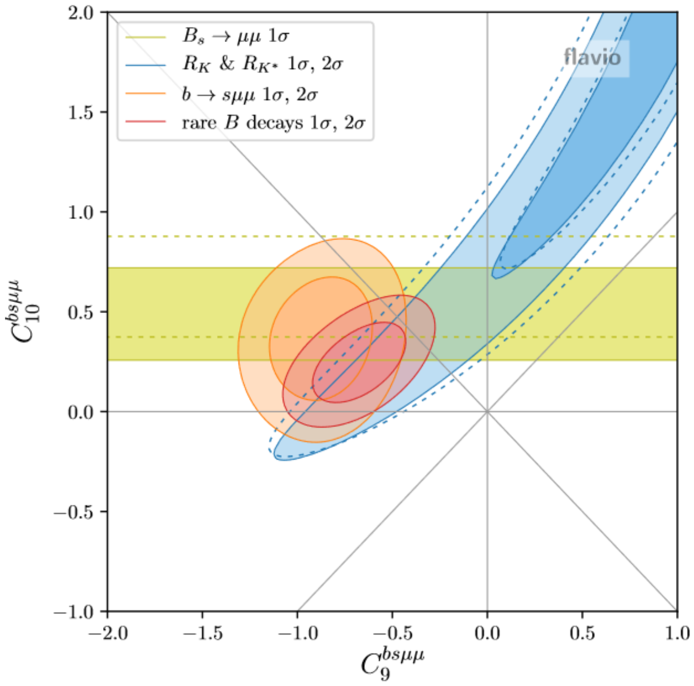
First consider new physics in $b \to s\mu\mu$ only,
including new $R_K, B(B_s^0 \to \mu^+\mu^-)$ results:

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 $C_9 - C_{10}$

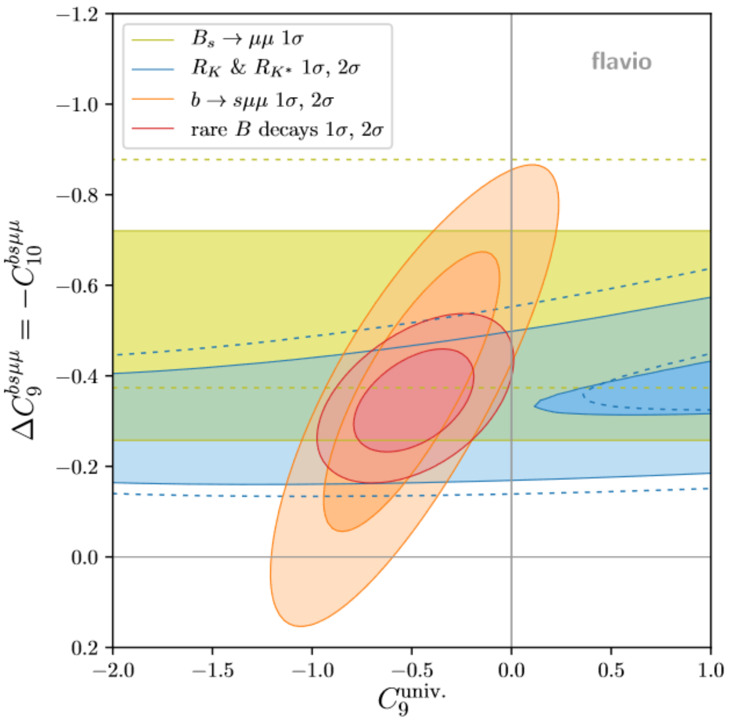
Different scenarios indicate new (axial)-vector contributions to **$b \to s\mu\mu$ transition**
Any other options?



Current EFT fit

[arXiv:2103.13370]

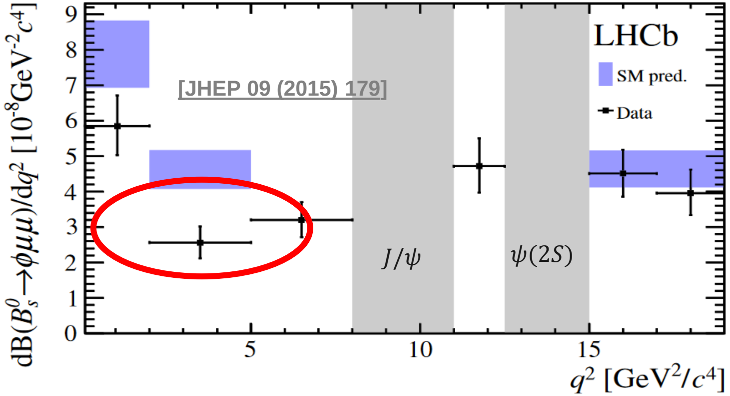
- **Interesting option (personal opinion):**
  - Universal contribution to $\boldsymbol{C_9}$ (vector) ($b \to see, b \to s\mu\mu$ and $b \to s\tau\tau$)
  - $b \to s\mu\mu$ only contribution to $\boldsymbol{C_9} - \boldsymbol{C_{10}}$ (vector – axial vector)
- Slightly favoured by data over NP in $b \to s\mu\mu$-only (pull of 6.4 sigma)
- **Interesting scenario: can be linked to anomalies in $b \to c\tau\nu$ transition through SM EFT (see backup)**
- **How about other recent results?**

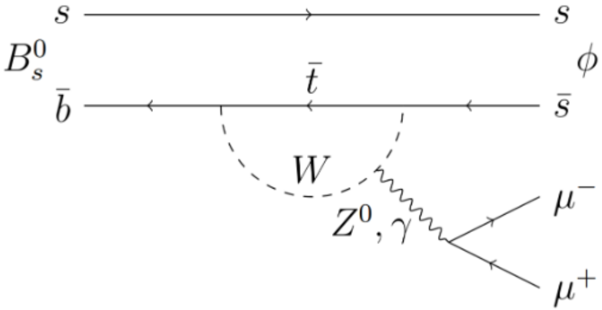


$\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)$: first shown two weeks ago!

- Semileptonic rare B decay with s spectator quark
- Run 1 result at 3σ tension with SM

- Update with full Run 1 + Run 2 data
- Similar strategy to R_K analysis (but with single ratio)
- Normalise to $B_s^0 \to J/\psi\phi$ decay (same final state) with improved uncertainty from f_s/f_d combination

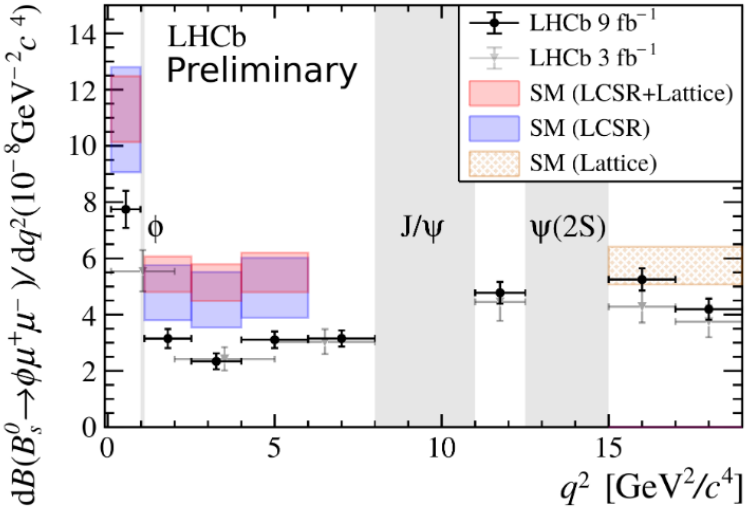




$\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)$: results

- New results: **similar central values, uncertainty reduced by factor 2**
- Main systematic uncertainty: physics model (incl. $\Delta\Gamma_s$)

- Tension with SM at 1.8, 3.6σ, resp. for Light Cone Sum Rules(LCSR)-only or LCSR+Lattice predictions
$\rightarrow$ **better understanding required**
- Looking forward to inclusion in global fits



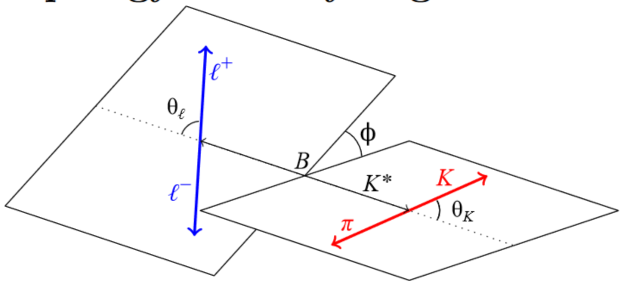
[JHEP 08 (2016) 098, EPJC 75 (2015382), arXiv:1810.08132, PRL 112 (2014) 212003, PoSLATTICE2014 (2015) 372]

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

[arXiv:2012.13241]

- **First full angular analysis of $B^+ \to K^{*+}\mu^+\mu^-$ mode**
- Around 740 candidates from mass fit
- Fitting strategy:
    1. Fit to B^+, K^{*+} candidate mass (2D) to constrain non-resonant $B^+ \to K_S^0\pi^+\mu^+\mu^-$ contribution
    2. Fit to mass, 3 helicity angles (4D) to determine 8 angular observables
- 5 different foldings of angles to determine observables without bias or loss of sensitivity
- Angular acceptance determined from corrected simulation samples

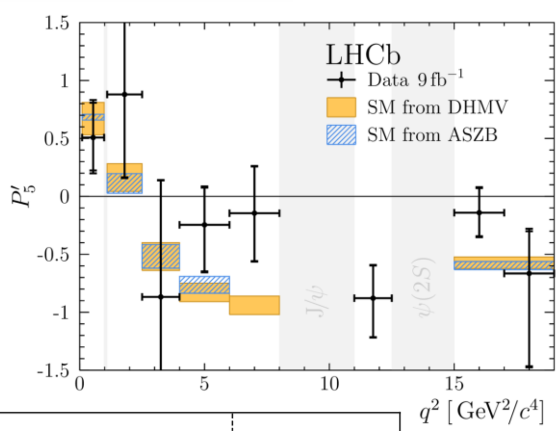
topology of decay angles:



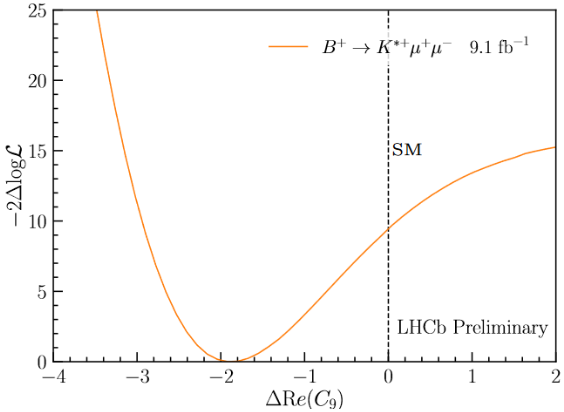
leptonic and hadronic decay part

[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 with global fit using Flavio package
- **Results inconsistent with SM at 3σ level, favour reduction in C_9**
- **Including this result and March '20 update of $B^0 \to K^{*0}\mu^+\mu^-$ mode in global fits improves consistency (see e.g. arXiv:2104.08921)**
- **Take-home message: current $b \to sll$ measurements paint consistent picture!**



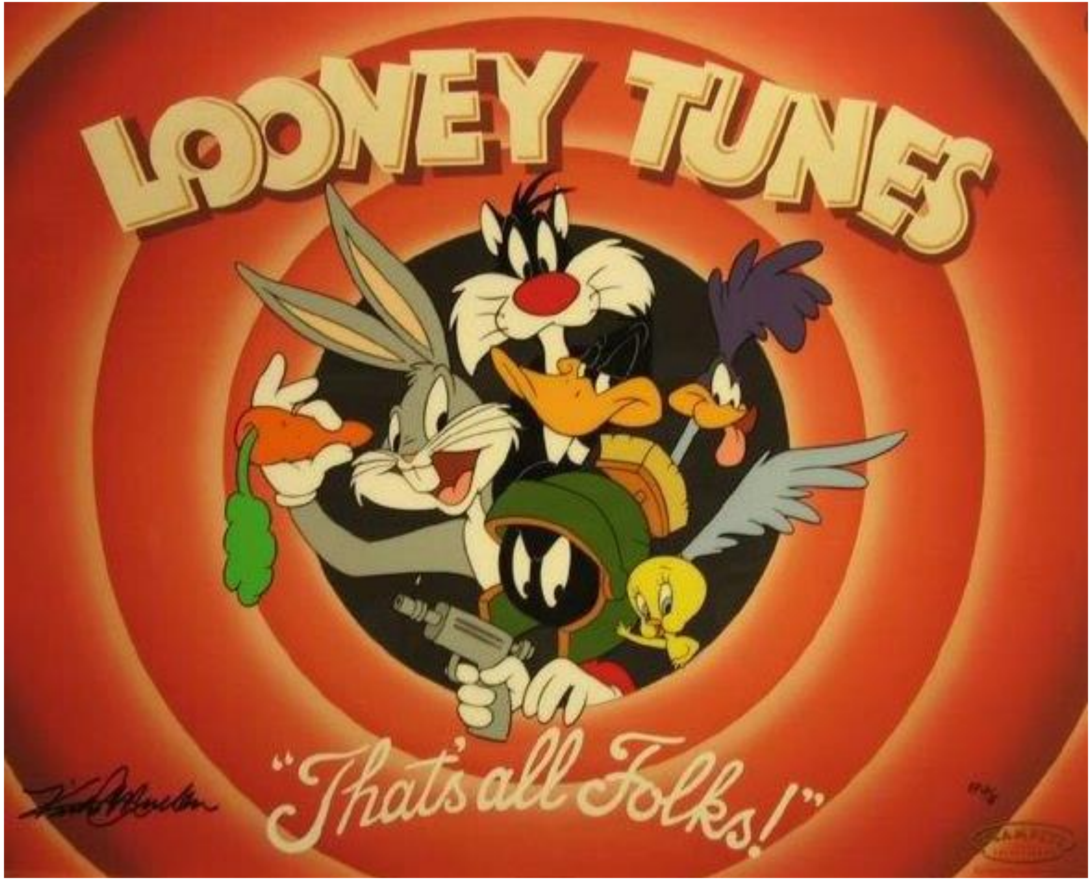
Plots generated with flavio: [arXiv:1810.08132]

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…**

- $B(B_s^0 \to \mu^+\mu^-)$ and $B(B_s^0 \to \phi\mu^+\mu^-)$ reaching new level of precision, aided by new measurement of f_s/f_d
- **Evidence found of lepton universality violation in $\boldsymbol{R_K}$**
- Angular measurements provide additional and consistent constraints

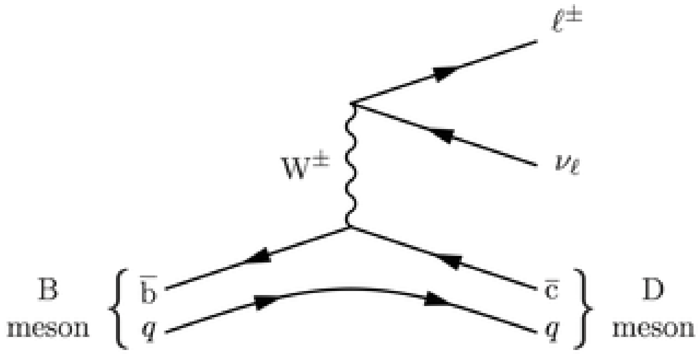
- Many measurements underway ($R_{K^{*(0,+)}}, R_\phi, R_{K_S^0}, R_\Lambda$, angular analyses, LFV with τ)
- LHCb upgrade ongoing: increase luminosity by factor 5, remove hardware trigger!
- **Many more results still to come!**

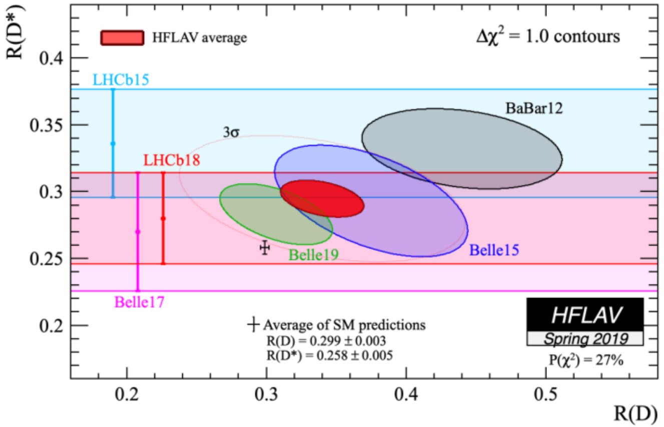

LOONEY TUNES
"That's all Folks!"

Backup

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!**

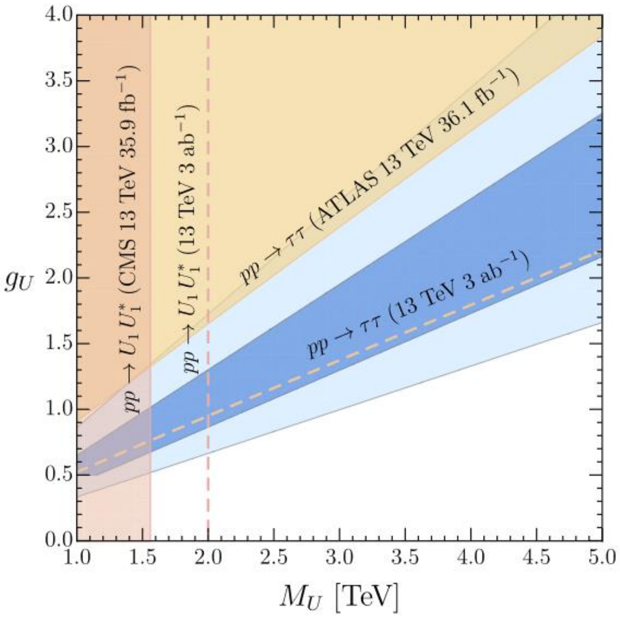




Link with R(D*): combined fit

[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?**

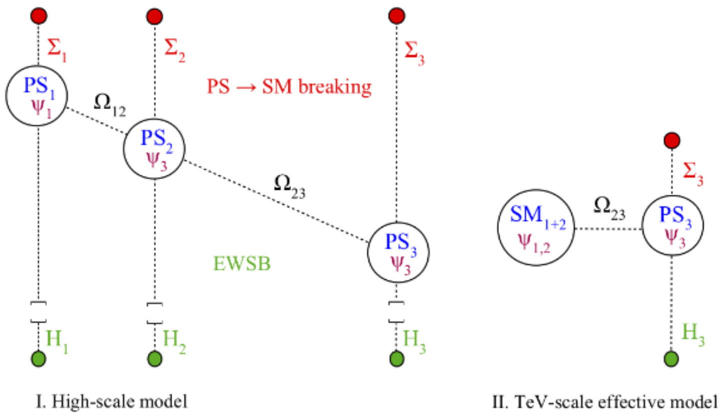


Solving the flavour puzzle?

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

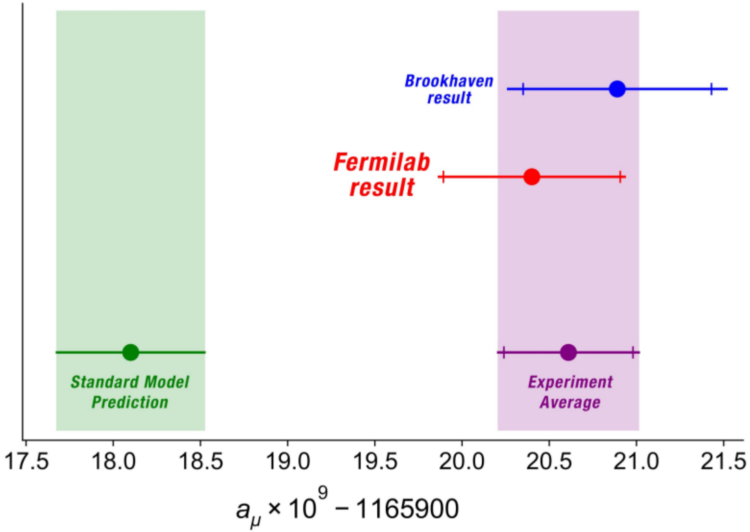
The three-site Pati-Salam model [18] originates from the ambitious attempt to i) unify and quantize the $U(1)$ charges of quark and leptons, ii) obtain a natural description of all the SM Yukawa couplings in terms of $\mathcal{O}(1)$ parameters and fundamental scale ratios, and iii) address the recent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



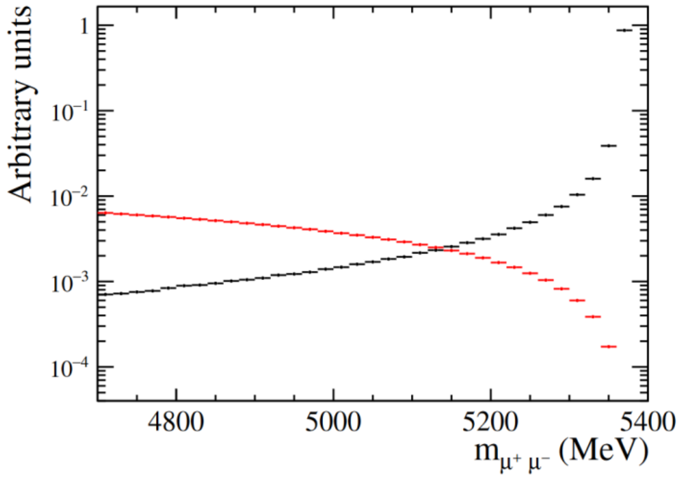
Link with $(g-2)_\mu$?

- Muon magnetic moment, $(g-2)_\mu$:
  - Lower energy observable, **many possible contributions**
- **A month 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**

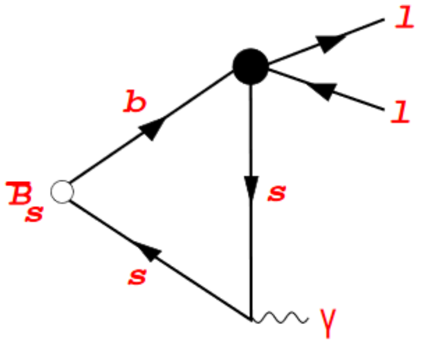


$B_s^0 \to \mu^+\mu^-\gamma$: ISR/FSR

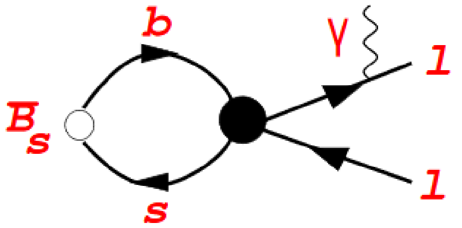


- ISR: photon from b, s quarks, effectively three-body semileptonic B decay (vs q^2): **partially reconstructed background for $B_s^0 \to \mu^+\mu^-$ reconstruction**
- FSR: soft photons from muons, same Wilson coefficients: **additional tail for $B_s^0 \to \mu^+\mu^-$, modelled with PHOTOS**

Initial State Radiation



Final State Radiation

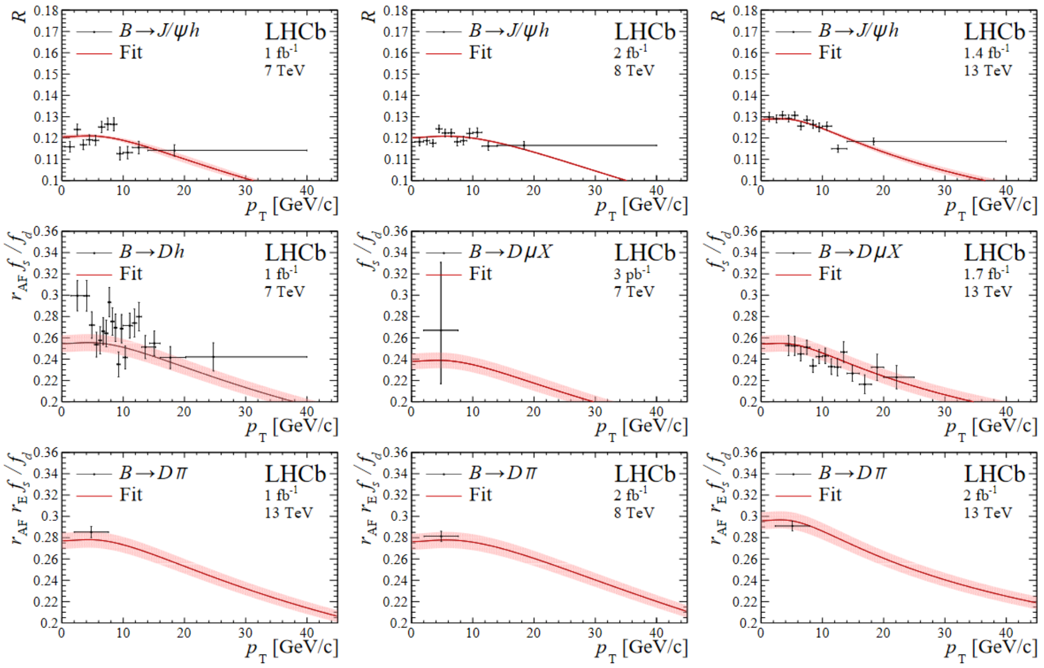


Combination of f_s/f_d: technicalities

[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
- No clear theoretical prediction for p_T dependence;
  linear function chosen for simplicity
  (other functions tried with similar or worse fit quality)

Fit with Tsallis function



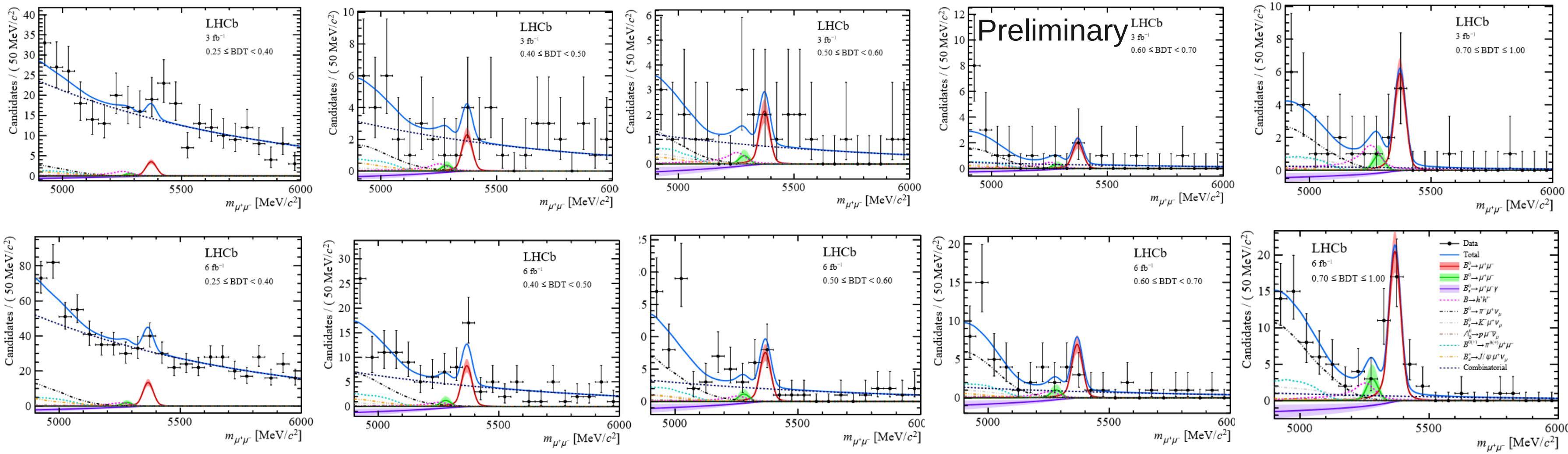
Results: mass fit in all BDT bins

[LHCb-PAPER-2021-007]

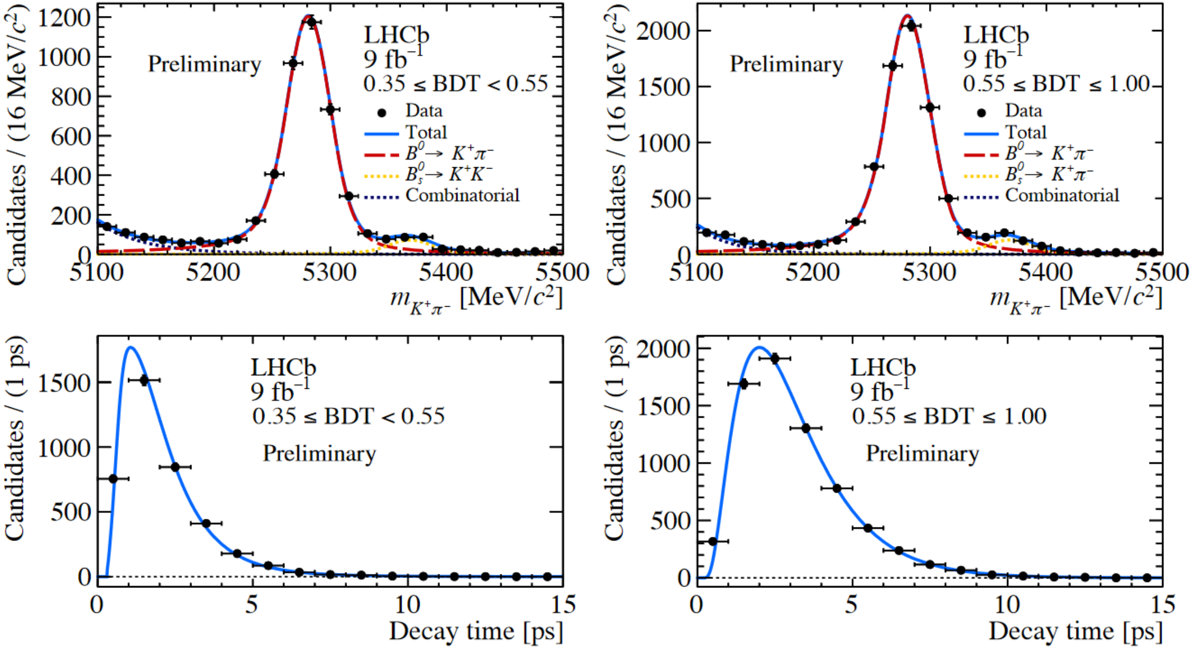
BDT [0.25,0.4] BDT [0.4,0.5] BDT [0.5,0.6] BDT [0.6,0.7] BDT [0.7,1.0]

Run 1

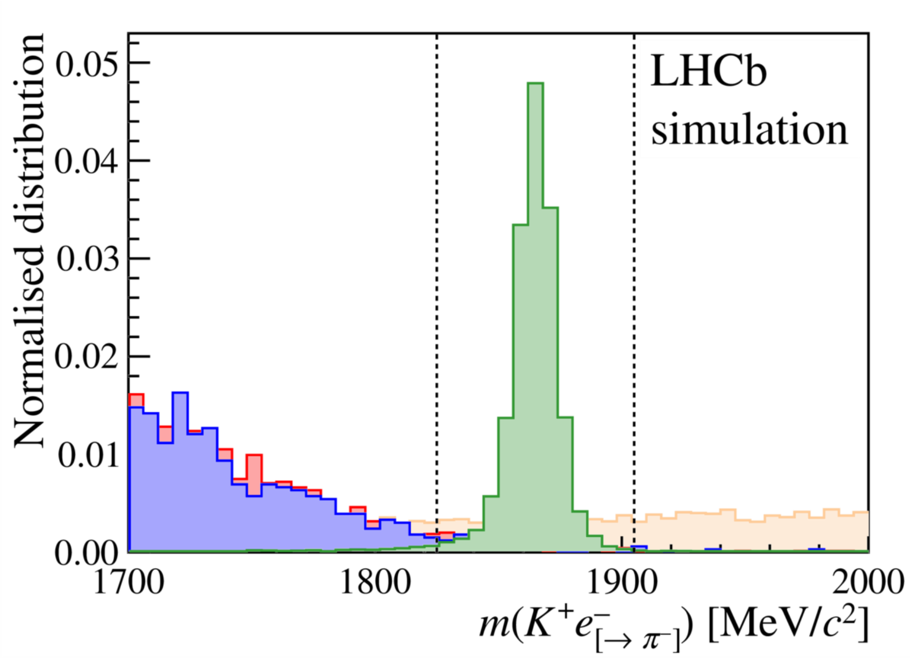
Run 2

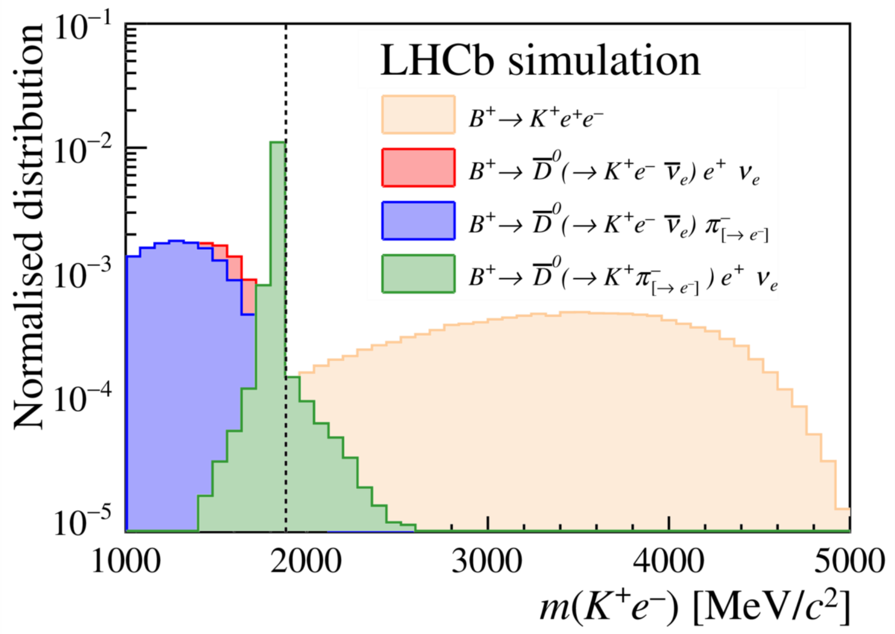


Effective lifetime: acceptance validation

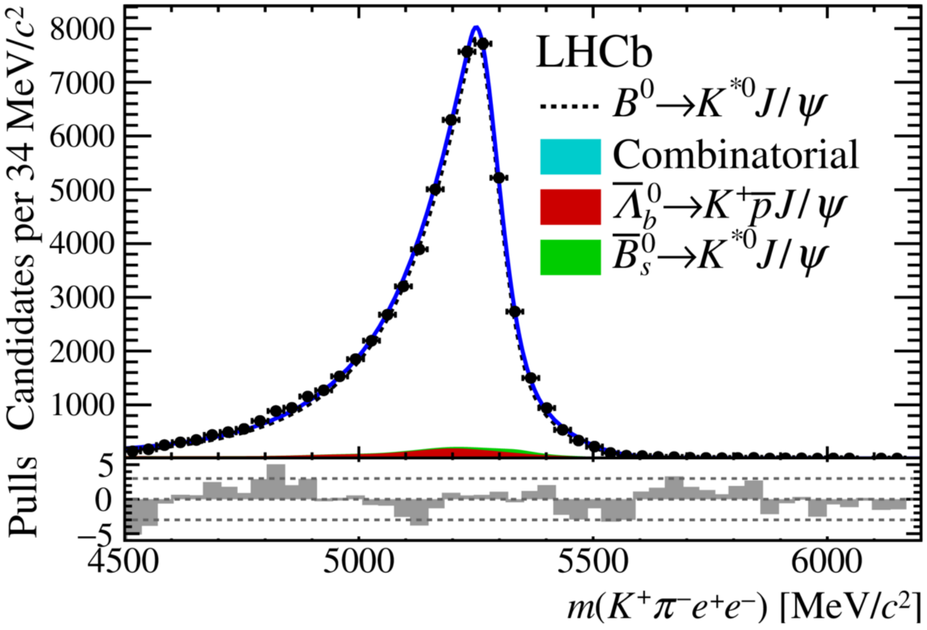


RK: semileptonic backgrounds



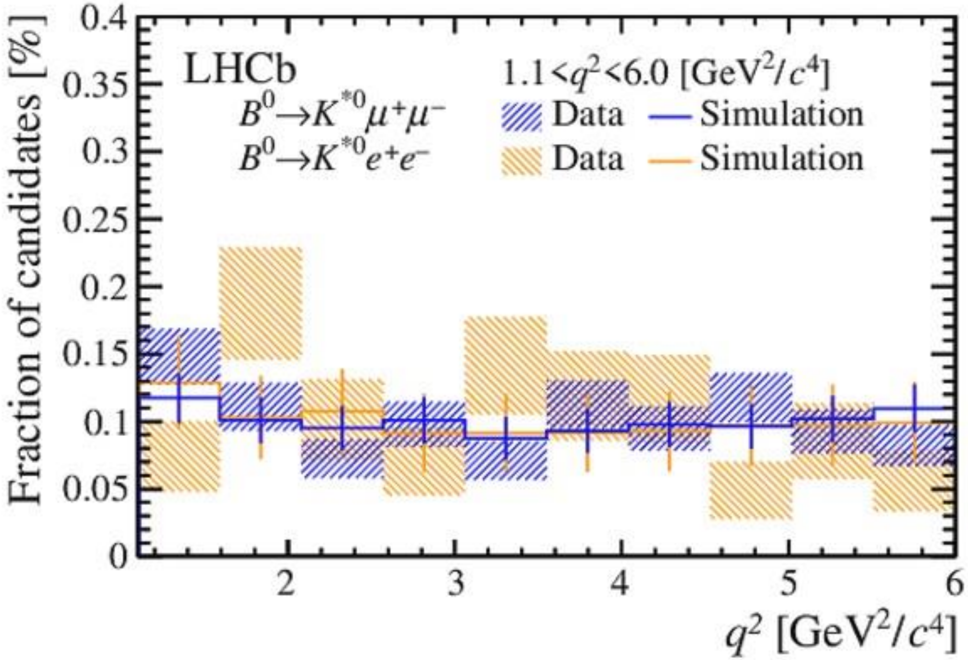


R_{K^*}: example fit without J/ψ mass constraint



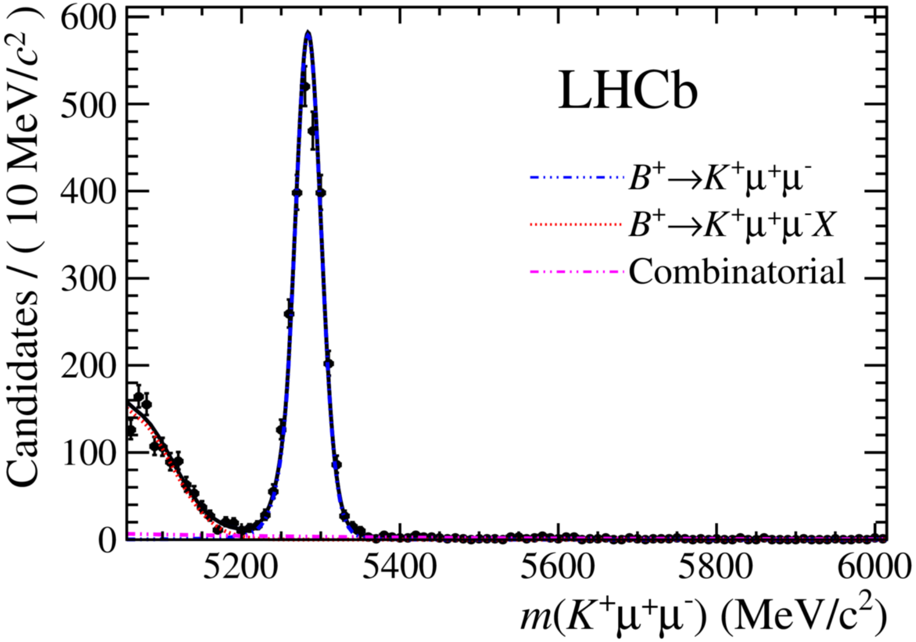
[JHEP 08 (2017) 055]

R_{K^*}: q^2 dependence in main bin



[JHEP 08 (2017) 055]

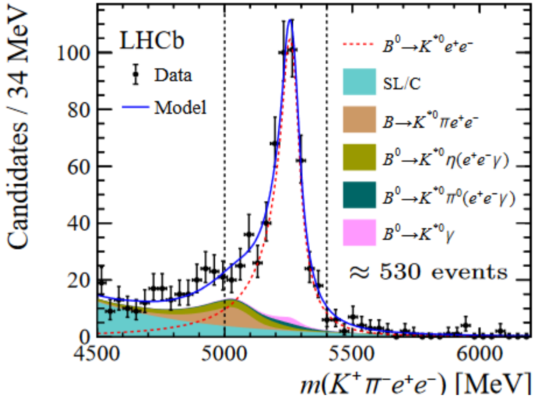
RK: Dimuon fit w. partially reconstructed bkg



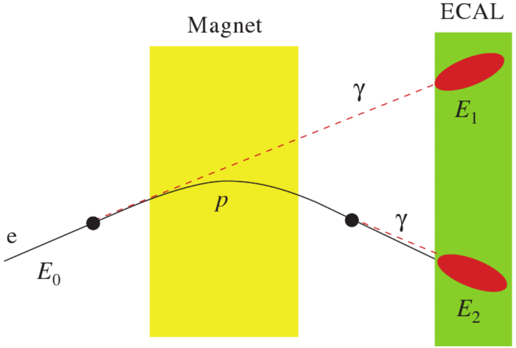
[JHEP 10 (2015) 034]

Photon polarisation with $B^+ \to K^{*0} e^+ e^-$

- **Angular analysis with electrons close to photon resonance, sensitive to right-handed currents in $b \to s\gamma$ transition**
- Uses very low q^2 : $[0.0008, 0.257]\mathrm{GeV}^2$
- Update of Run 1 analysis with full Run 1 + Run 2 data
  - Increased signal purity
  - Lower reach in q^2
- Folding $\tilde{\phi} = \phi + \pi$ if $\phi < 0$
  (sensitive to all relevant observables)
- Fit to mass and 3 helicity angles to extract angular observables
- **Electrons provide extra challenge:**
  - Bremsstrahlung leads to energy losses, worse mass shape
  - More difficult to trigger

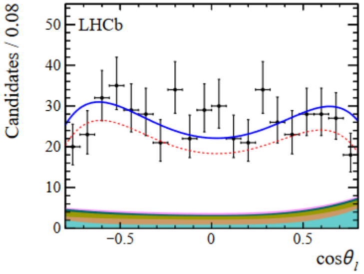


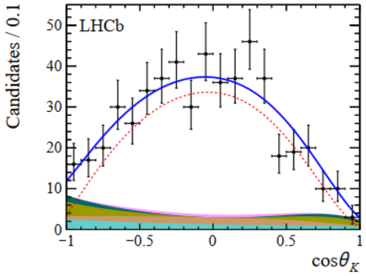
[JHEP 12 (2020) 081]



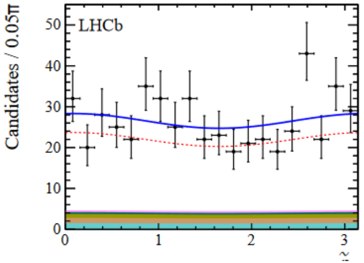
Photon polarisation with $B^{+} \to K^{*0} e^{+} e^{-}$

- Angular projections and results shown below left
- **Results consistent with SM, strongest constraints on C_7' (right-handed $b \to s\gamma$)**



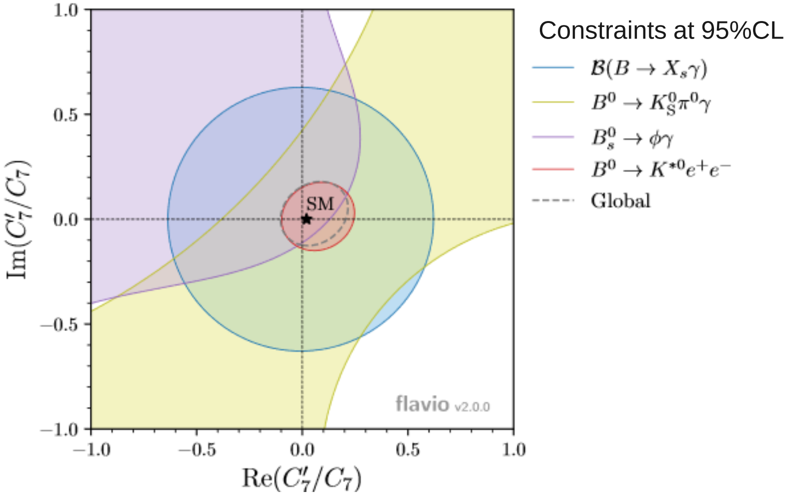


[JHEP 12 (2020) 081]



Angular observables:

$$F_L = 0.044 \pm 0.026 \pm 0.014$$
$$A_T^{Re} = -0.06 \pm 0.08 \pm 0.02$$
$$A_T^{(2)} = +0.11 \pm 0.10 \pm 0.02$$
$$A_T^{Im} = +0.02 \pm 0.10 \pm 0.01$$



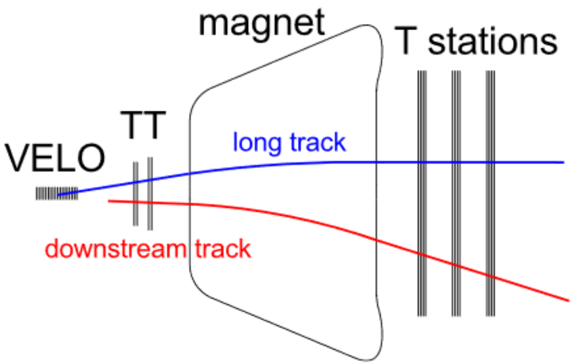
Plots generated with flavio: [arXiv:1810.08132]

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

[arXiv:2012.13241]

- **First full angular analysis of $B^+ \to K^{*+}\mu^+\mu^-$ mode**
- Reconstruct $K^{*+} \to K_S^0\pi^+$ decay;
  K_S^0 candidates decay inside (outside) VELO, resulting in long (downstream) pions
- Analyse in four samples: Run 1+2 and LL/DD
- Around 740 candidates from mass fit

LHCb tracking detectors:



modified from

J.Phys.:Conf.Ser.**664**(2015)072047

Historical footnote: muon discovery

In 1936, muon was discovered

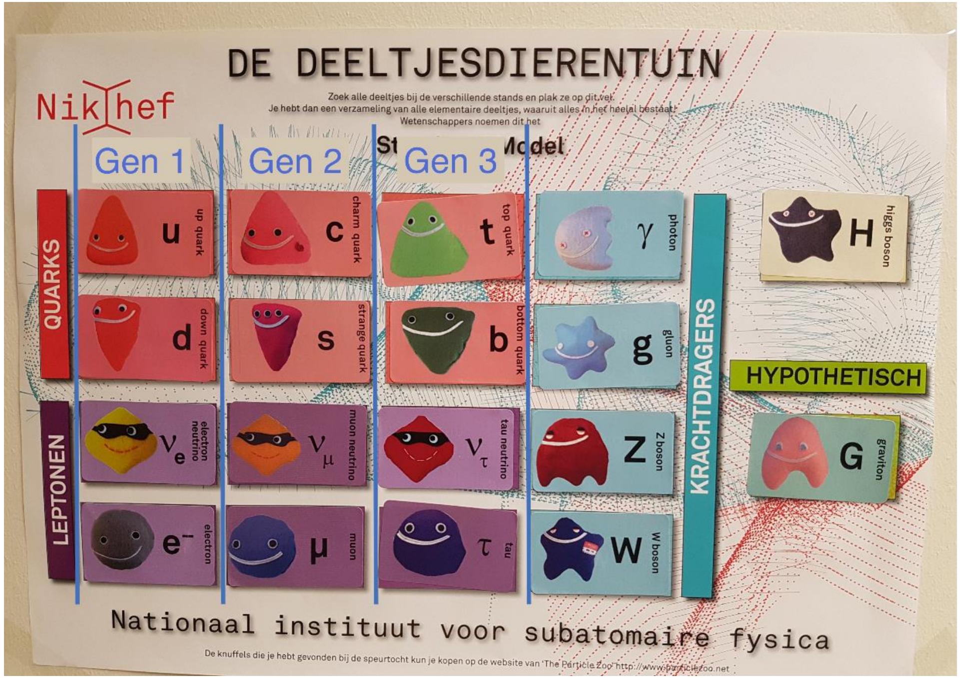
First 2nd generation particle, not expected at all!

Led Isidor Rabi to say: "Who ordered that?"

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

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

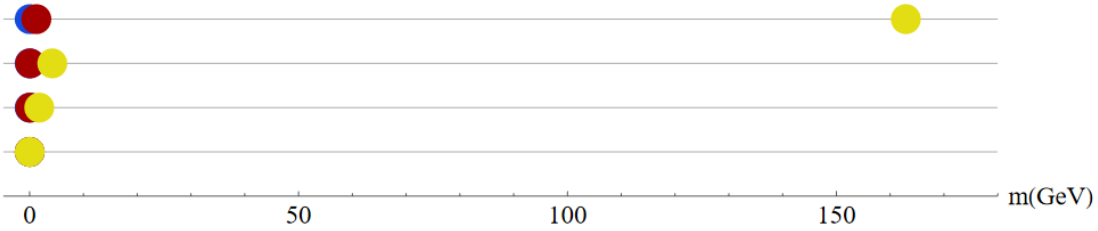
[Thesis Reinier Adelhart]

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

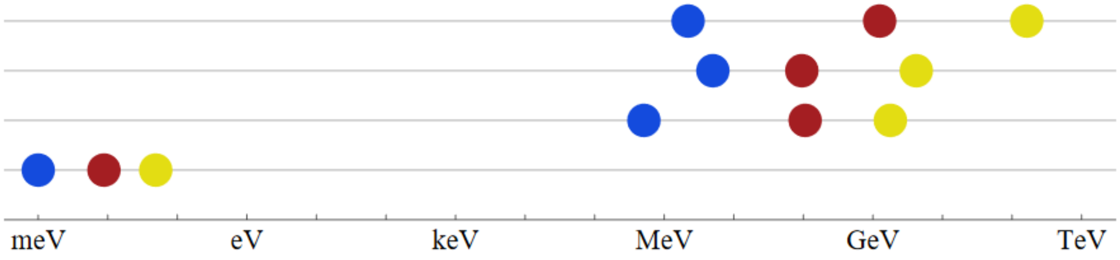
Why are masses so hierarchical for quarks + charged leptons?

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

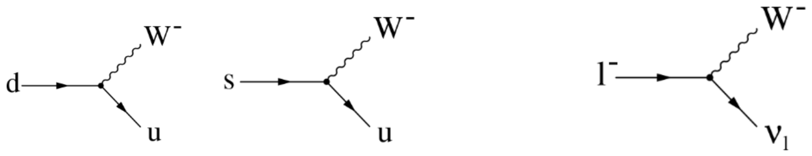


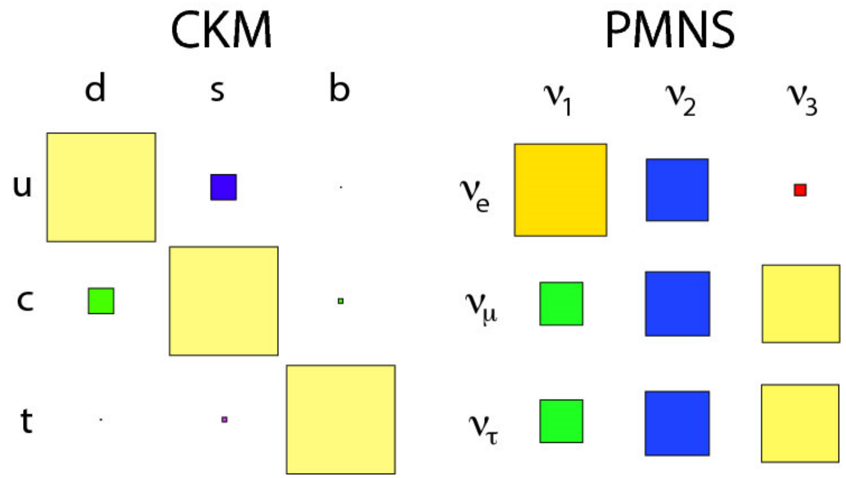
Flavour puzzle: fermion mixing

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





Impression of mass hierarchy