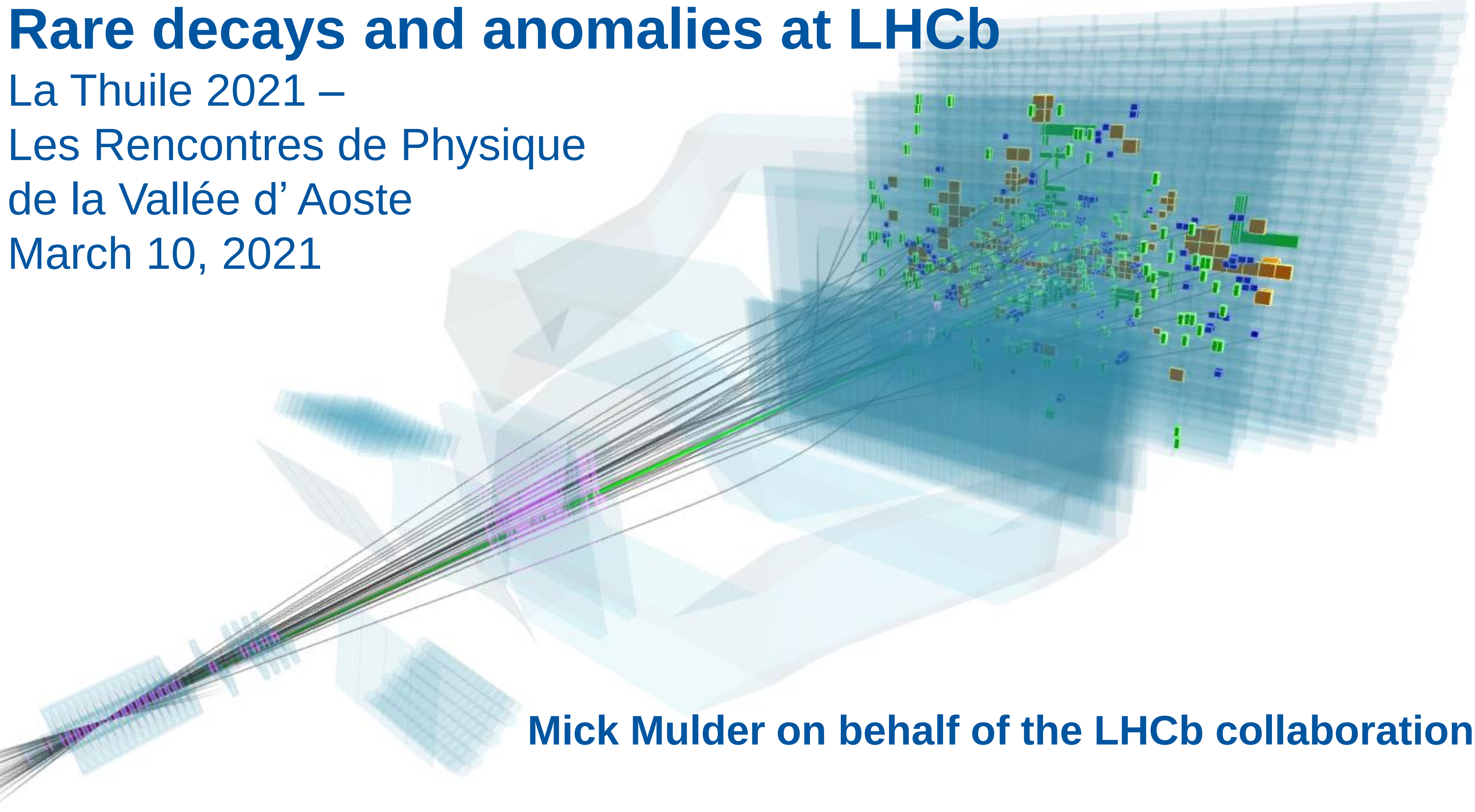
Rare decays and anomalies at LHCb

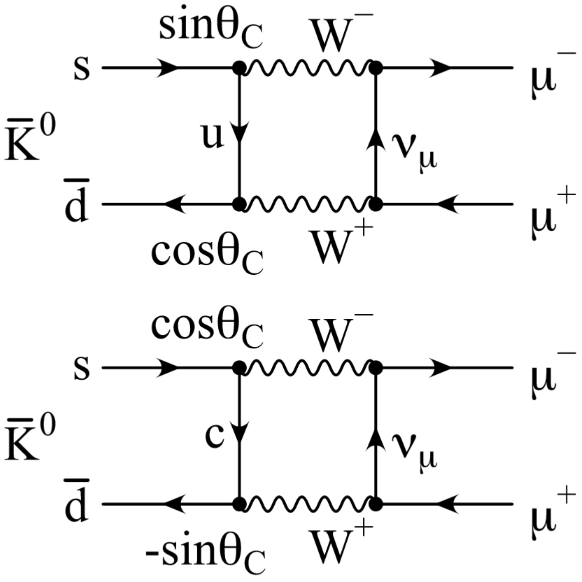
La Thuile 2021 –
Les Rencontres de Physique
de la Vallée d’ Aoste
March 10, 2021



Mick Mulder on behalf of the LHCb collaboration

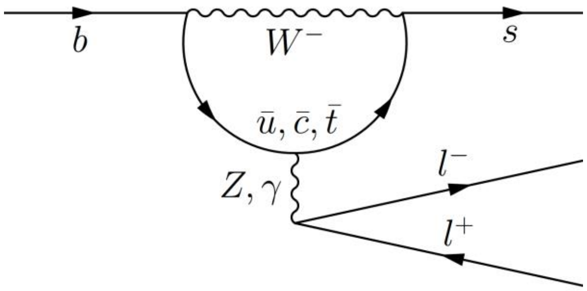
Rare Decays

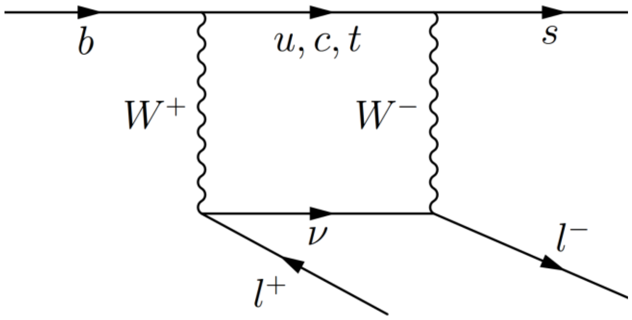
- **Loop-level decays mediated by weak interaction** (Flavour Changing Neutral Currents)
- **Transition strongly suppressed**: loops, CKM elements, sometimes GIM mechanism
- **Perfect for indirect discovery**: even small contributions have large effects on rare decays!
- Previous discoveries:
  - charm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

- **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!





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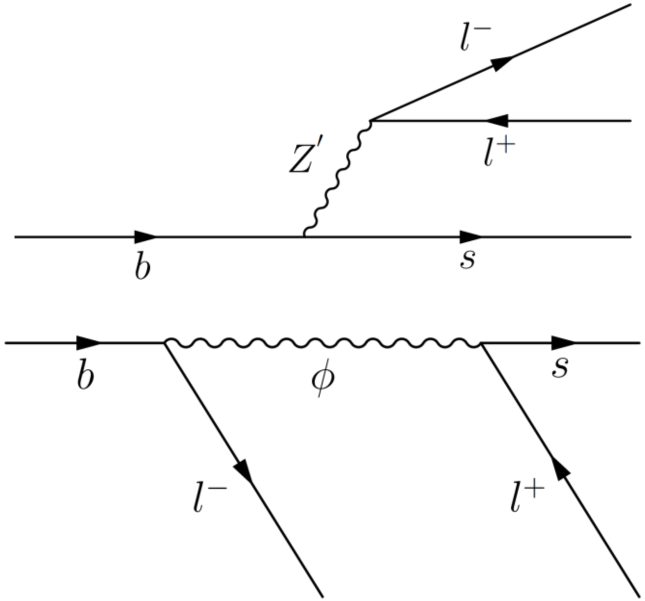
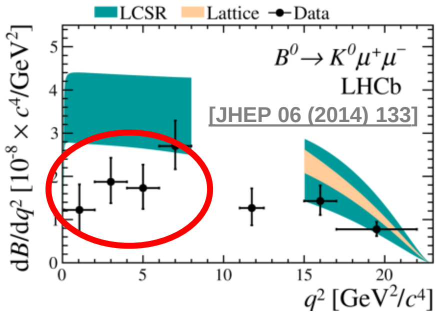
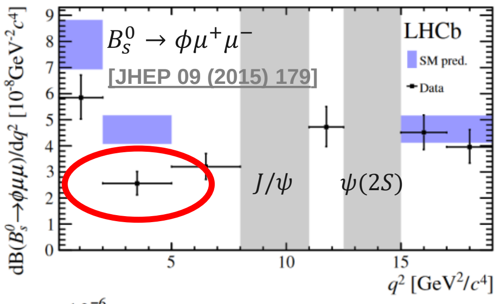
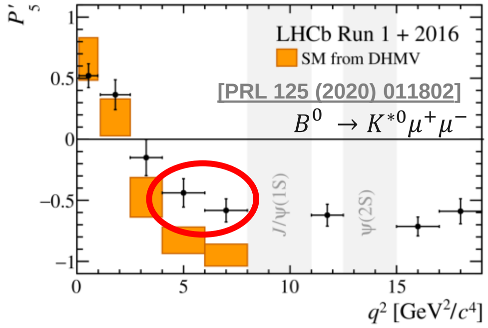


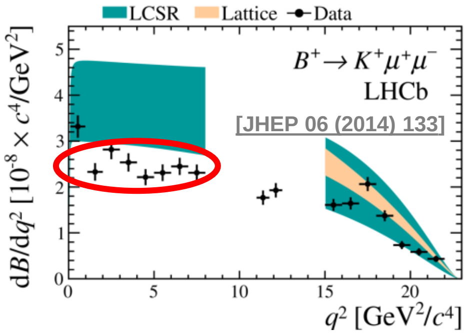
Anomalies

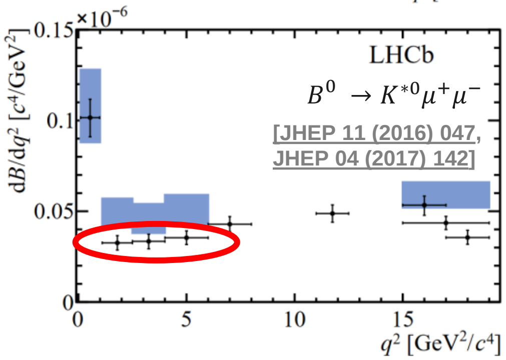
Results in rare B decays deviate from predictions in Run 1 LHCb data…. (not only there)

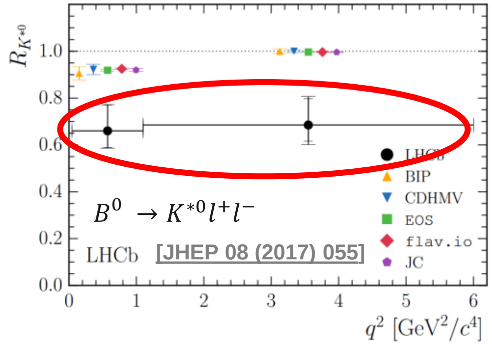




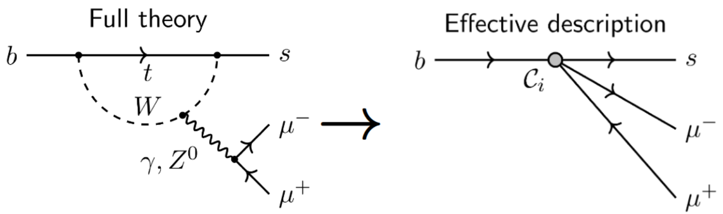








Effective field theory

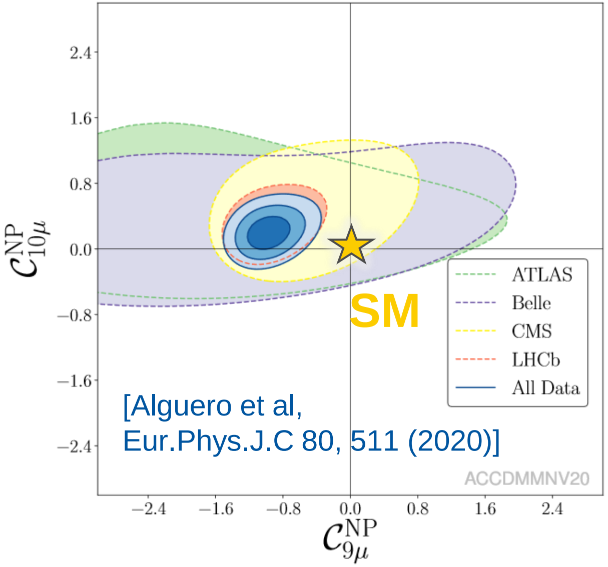


- Are anomalies consistent with each other?
- Use effective field theory at B-hadron scale, just like beta decay four-point interaction!

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

- Fermion operators $O_i^{(\prime)}$, Wilson coefficients $C_i^{(\prime)}$
- Leptonic current types (SM, New Physics):
  - $C_7^{(\prime)}$ photon penguin
  - $(C_{10}^{(\prime)})C_9^{(\prime)}$(axial) vector
  - $(C_P^{(\prime)})C_S^{(\prime)}$ (pseudo) scalar
- **Model-independent comparison through global fits indicate consistent deviation!**
  reduction of C_9 for muons (perhaps also in C_{10})?

Example of global fit to C_9, C_{10}



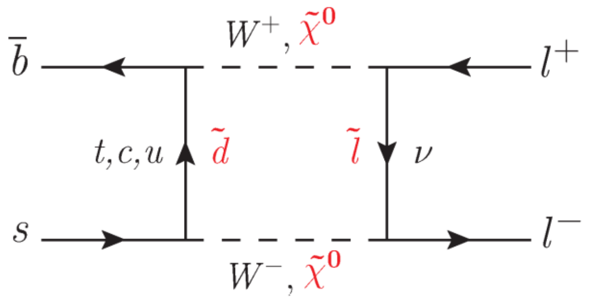
[Alguero et al, Eur.Phys.J.C 80, 511 (2020)]

On the menu today (new)

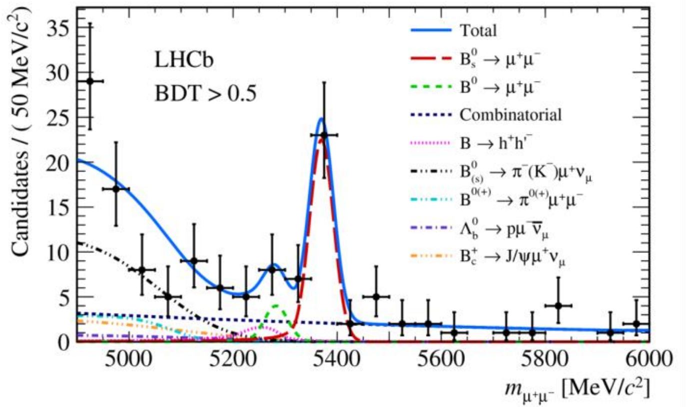
- $B^0_{(s)} \to \mu^+\mu^-$ + B^0_s/B^0 production fraction at LHCb (f_s/f_d)
- Angular analyses: $B^+ \to K^{*+}\mu^+\mu^-$, $B^0 \to K^{*0}e^+e^-$ (photon polarisation)
- Lepton universality: $R_K = \mathcal{B}(B^+ \to K^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+e^+e^-)$

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

- Leptonic $b \to s(d)ll$ decay
  - Helicity suppression: **very rare in SM, sensitive to C_{10}**
  - **Scalar contributions (C_S, C_P) enhanced** (not helicity suppressed!)
  - **Precise theory predictions**, even for branching fraction
- Predictions
  - $B(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$
  - $B(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$
  - $\frac{B(B^0 \to \mu^+\mu^-)}{B(B^0_s \to \mu^+\mu^-)} = 0.0281 \pm 0.0006$
- Today: combination of recent measurements (ATLAS, CMS, LHCb) with data up to 2016;



Last LHCb result



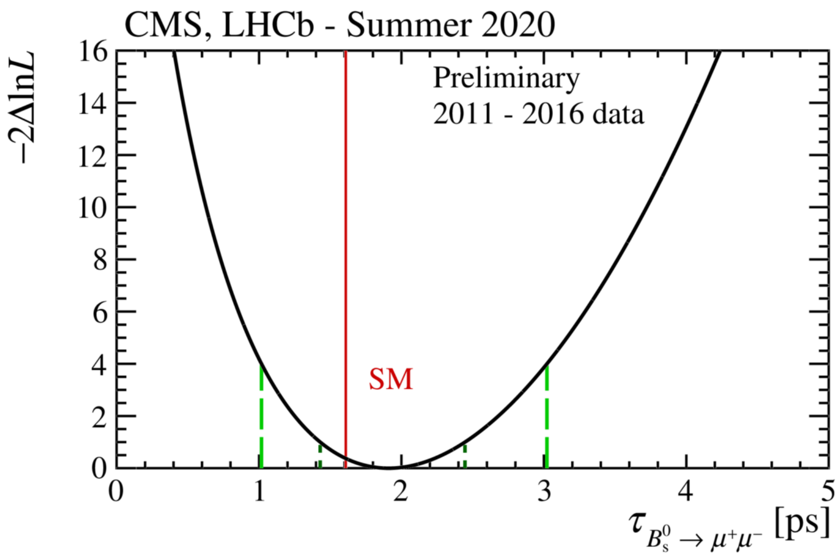
[PRL 118 (2017) 191801]

$B^0_{(s)} \to \mu^+\mu^-$: effective lifetime [NEW!]

[LHCb-CONF-2020-002]

- Neutral $B^0_{(s)}$ mesons mix with their anti-particle, forming two mass/CP eigenstates
- Heavy/CP-odd B^0_s eigenstate is longer-lived, only one that decays to $\mu^+\mu^-$ in SM
- **Test which B^0_s eigenstates contribute by measuring $B^0_s \to \mu^+\mu^-$ effective lifetime!**

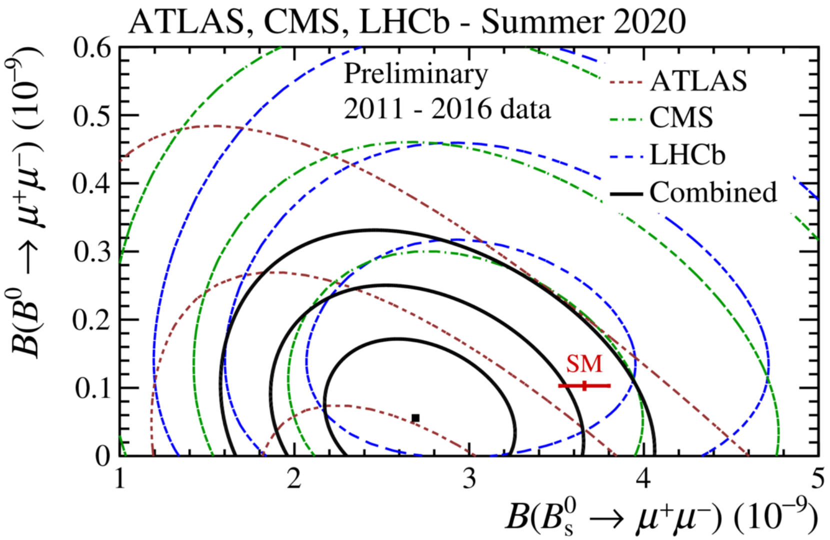
- Result from CMS, LHCb combination:
$$\tau_{\mathrm{eff}} = 1.91^{+0.37}_{-0.35}\ \mathrm{ps}$$
- **More statistics needed to distinguish between B^0_s eigenstates**



$B^0_{(s)} \to \mu^+\mu^-$: branching fraction [NEW!]

[LHCb-CONF-2020-002]

- Combination of 2D likelihoods measured by experiments
- Results:
  - $B(B^0_s \to \mu^+\mu^-) = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$
  - $B\left(B^0 \to \mu^+\mu^-\right) = (0.6 \pm 0.7) \times 10^{-10}$
- **Consistent with SM, between experiments**
- Correlated, **dominant systematic uncertainty** on $B(B^0_s \to \mu^+\mu^-)$: B^0_s/B^0_d production ratio, $\boldsymbol{f_s/f_d}$ = **~6%, about 50% of stat. unc.**
- Experiments working on Run 2 updates



f_s/f_d: introduction [NEW!] [LHCb-PAPER-2020-046]

- $f_s/f_d = B_s^0/B_d^0$ production ratio
  - **Required to measure B_s^0 branching fractions such as $B\left(B_s^0 \to \mu^+\mu^-\right)$**
  - 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 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

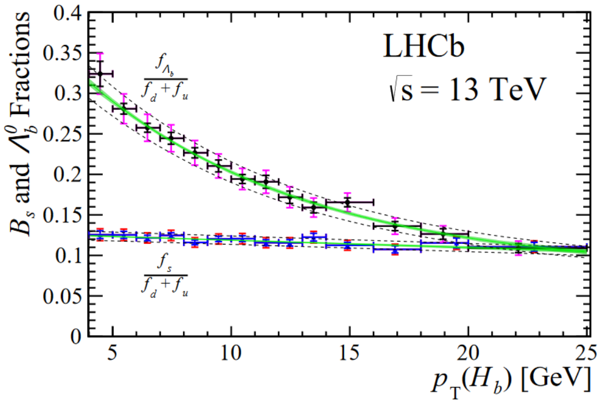
Combination of f_s/f_d measurements: inputs

[NEW!]

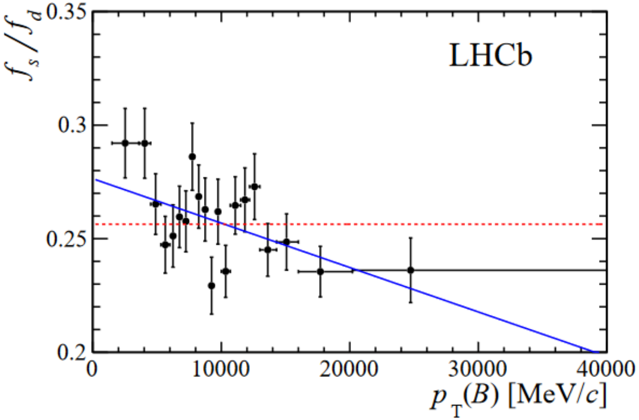
- Previous LHCb measurements performed at 7, 8, 13 TeV, $p_T \in [0.5, 40]$ GeV, $\eta \in [2, 6.4]$
- Three decay modes: $B \to D\mu X, B \to Dh, B \to J/\psi X$(no prediction)
- **Update external inputs for $B \to D\mu X, B \to Dh$ (e.g. D branching fraction, B lifetimes): significant improvement in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

[LHCb-PAPER-2020-046]

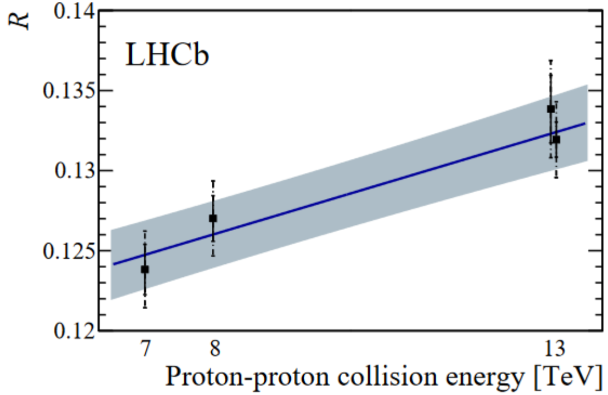
$B \to D\mu X$, 13 TeV



$B \to Dh$, 7 TeV



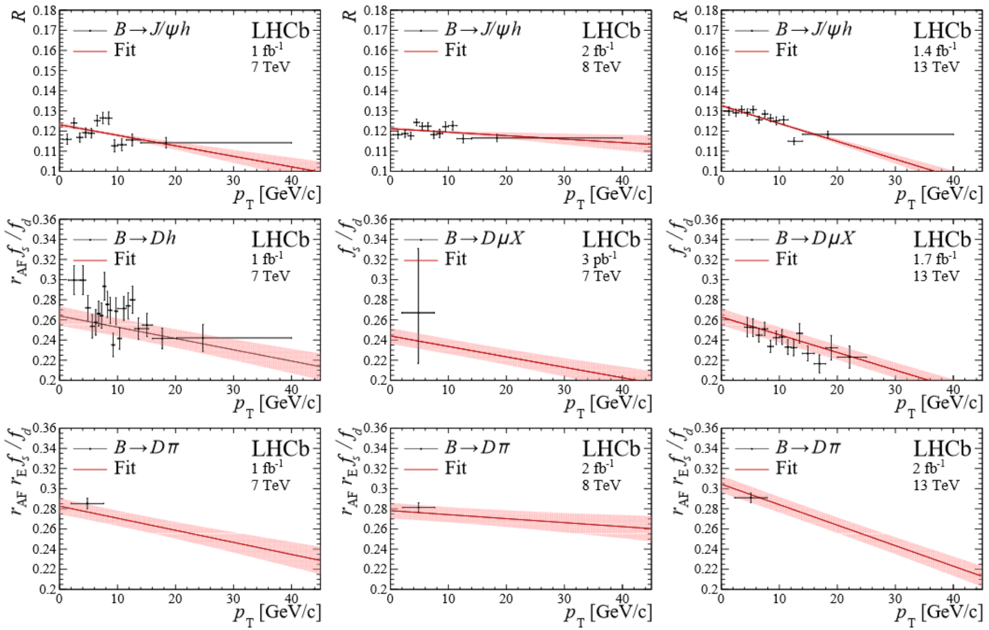
$B \to J/\psi X$, various $\sqrt{s}$



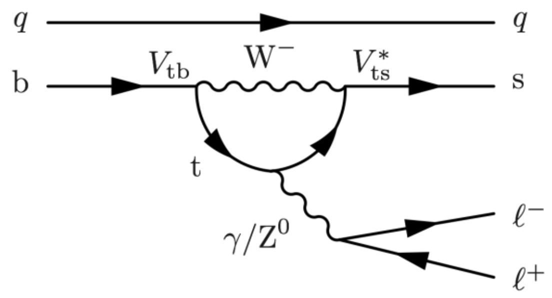
Combination of f_s/f_d measurements: results [NEW!]

[LHCb-PAPER-2020-046]

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

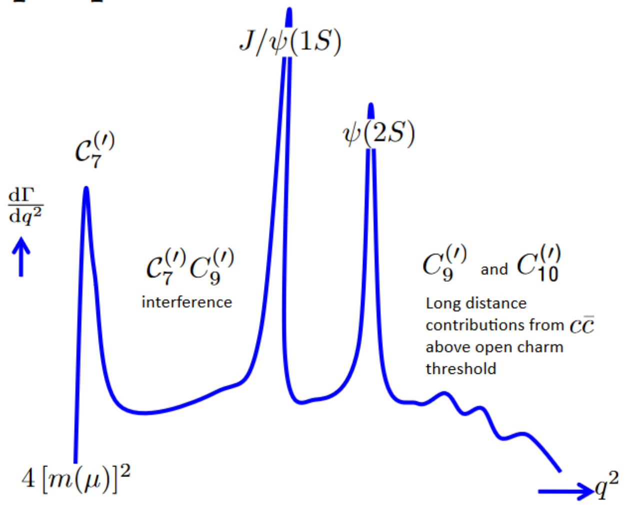


Semileptonic rare B decays



- "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)

q^2 spectrum:

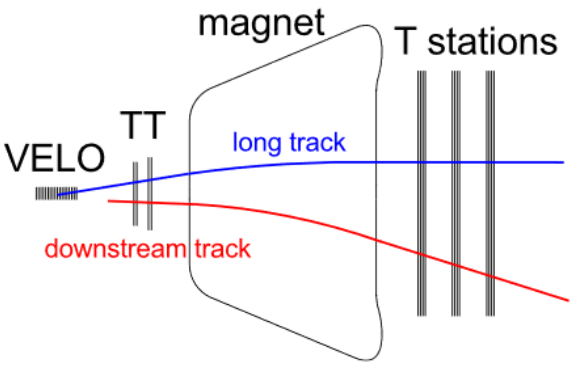


Angular analysis of $B^+ \to K^{*+}\mu^+\mu^-$ [NEW!]

[arXiv:2012.13241]

- **First full angular analysis of $B^+ \to K^{*+}\mu^+\mu^-$ mode**
- Reconstruct $K^{*+} \to K^0_S\pi^+$ decay;
  K^0_S 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

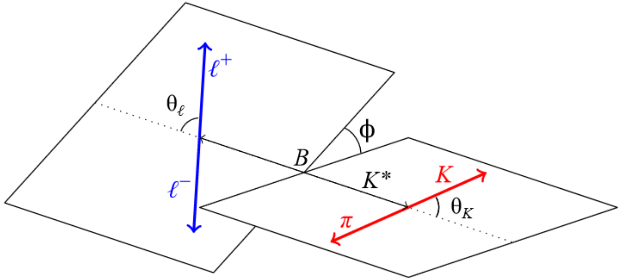
J.Phys.:Conf.Ser.**664**(2015)072047

Angular analysis of $B^+ \to K^{*+}\mu^+\mu^-$ [NEW!]

[arXiv:2012.13241]

- 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
- Two angular bases (S_i, P_i) available
- 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:

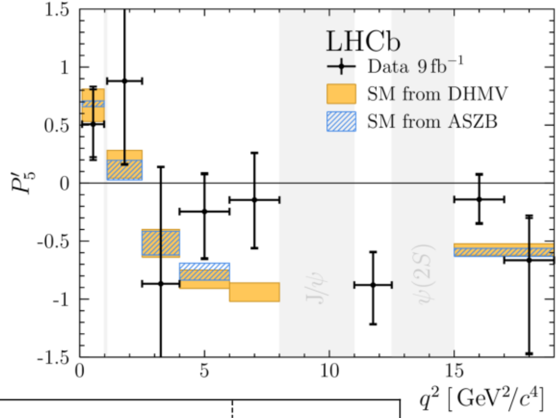


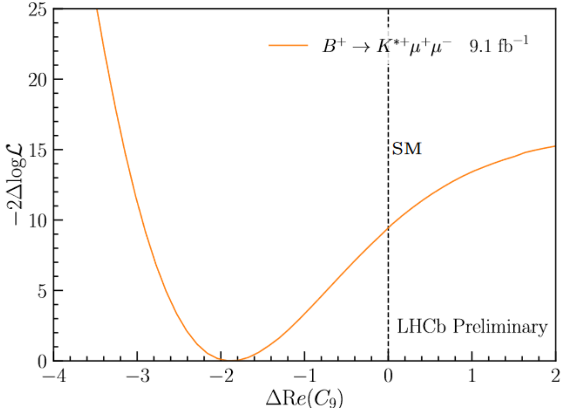
leptonic and hadronic decay part

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

[NEW!] [arXiv:2012.13241]

- 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**

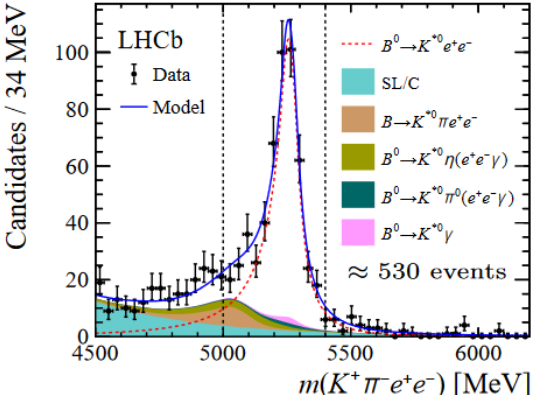




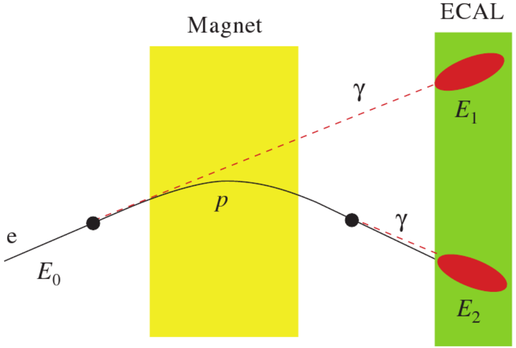
Plots generated with flavio: [arXiv:1810.08132]

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

- **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

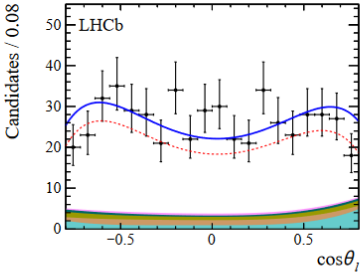


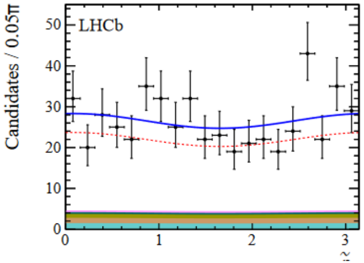
[JHEP 12 (2020) 081]

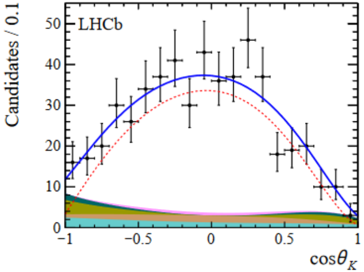


Photon polarisation with $B^+ \to K^{*0} e^+ e^-$ [NEW!]

- 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]

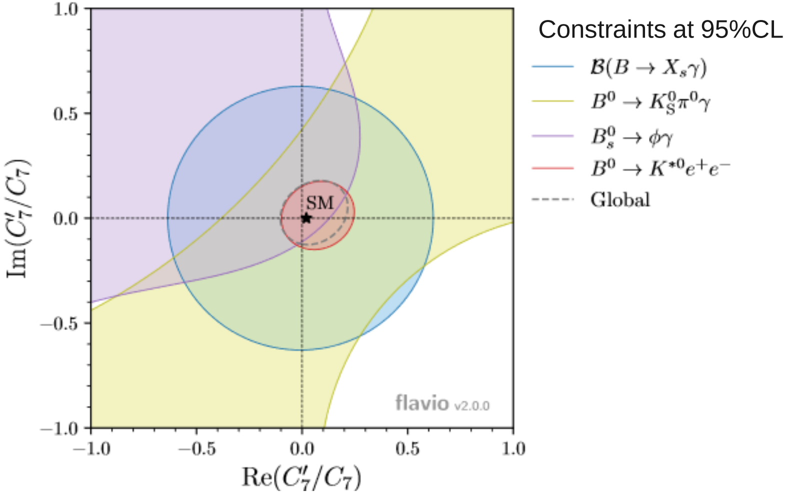
Angular observables:

$$F_L = 0.044 \pm 0.026 \pm 0.014$$

$$A_T^{Re} = -0.06 \pm 0.08 \pm 0.02$$

$$A_T^{(2)} = +0.11 \pm 0.10 \pm 0.02$$

$$A_T^{Im} = +0.02 \pm 0.10 \pm 0.01$$

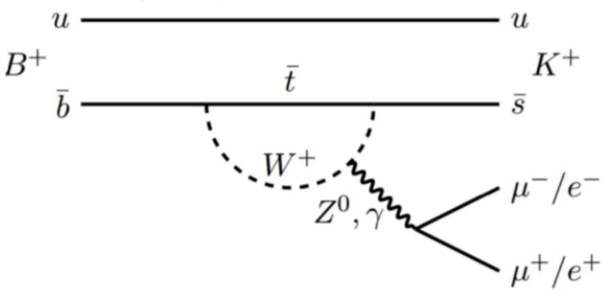


Plots generated with flavio: [arXiv:1810.08132]

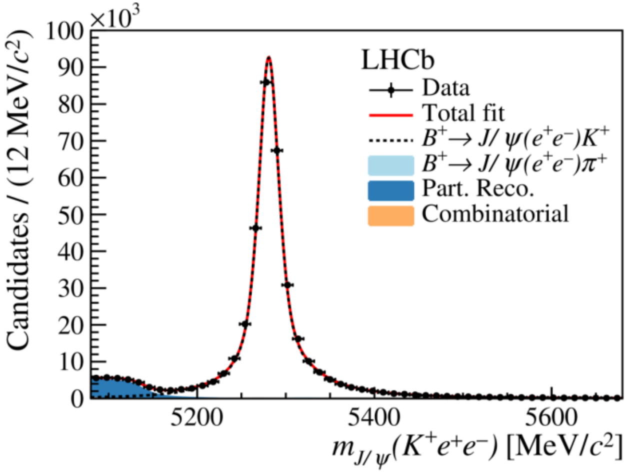
Lepton universality: R_K

[PRL122 (2019) 191801]

- Lepton universality: only difference between muons, electrons is mass
- Strong test with $R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e)}$
- Prediction: $R_K = 1 \pm O(1\%)$ (for $q^2 > 0.1\ \mathrm{GeV}^2$)
- Normalise experimental measurement with double ratio relative to $B^+ \to K^+ J/\psi(\to \mu^+ \mu^- / e^+ e^-)$

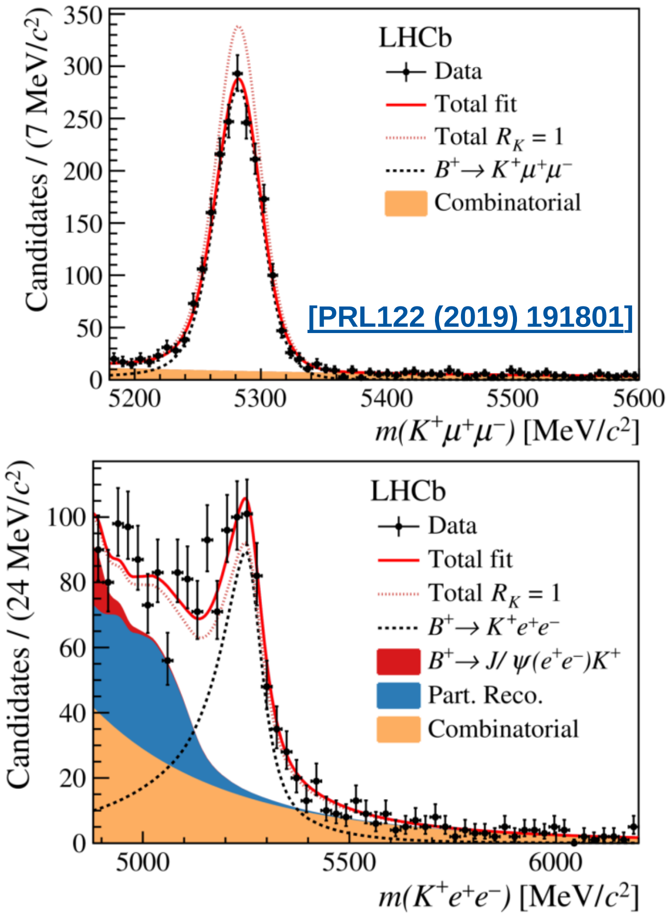


Mass fit to $B^+ \to K^+ J/\psi(\to e^+ e^-)$



Lepton universality: R_K

- $R_K = 0.846^{+0.060+0.016}_{+0.054-0.014}$ (stat,syst)
- Compatible with Standard Model at **2.5σ**
- Fewer muons than expected,
  similar amount of electrons
- Ongoing updates with full Run 1 + Run 2 data

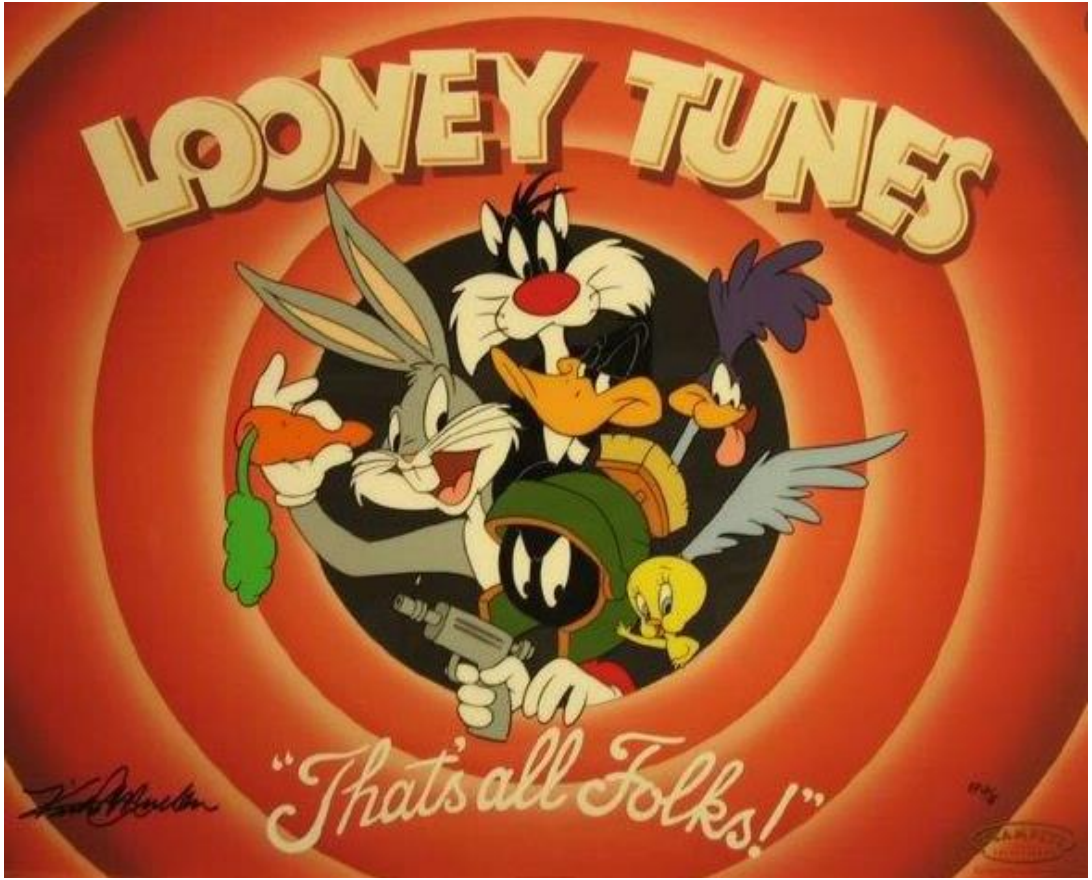


[PRL122 (2019) 191801]

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
- New f_s/f_d measurement significantly reduces dominant systematic uncertainty on $B(B_s^0 \to \mu^+\mu^-)$, $B(B_s^0 \to \phi\mu^+\mu^-)$
- Angular measurements provide complementary constraints
- More measurements coming soon!


LOONEY TUNES
"That's all Folks!"

Backup

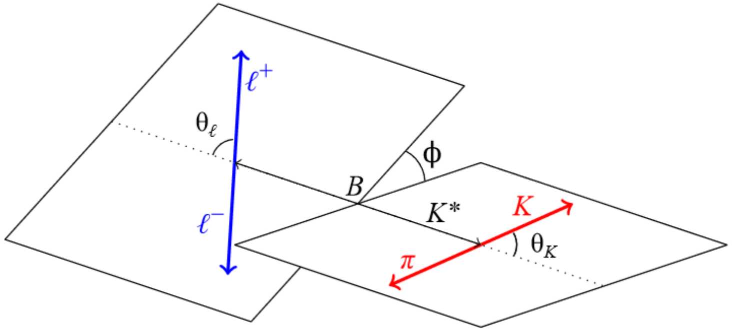
Combination of f_s/f_d: technicalities

[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

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

topology of decay angles:



leptonic and hadronic decay part

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

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