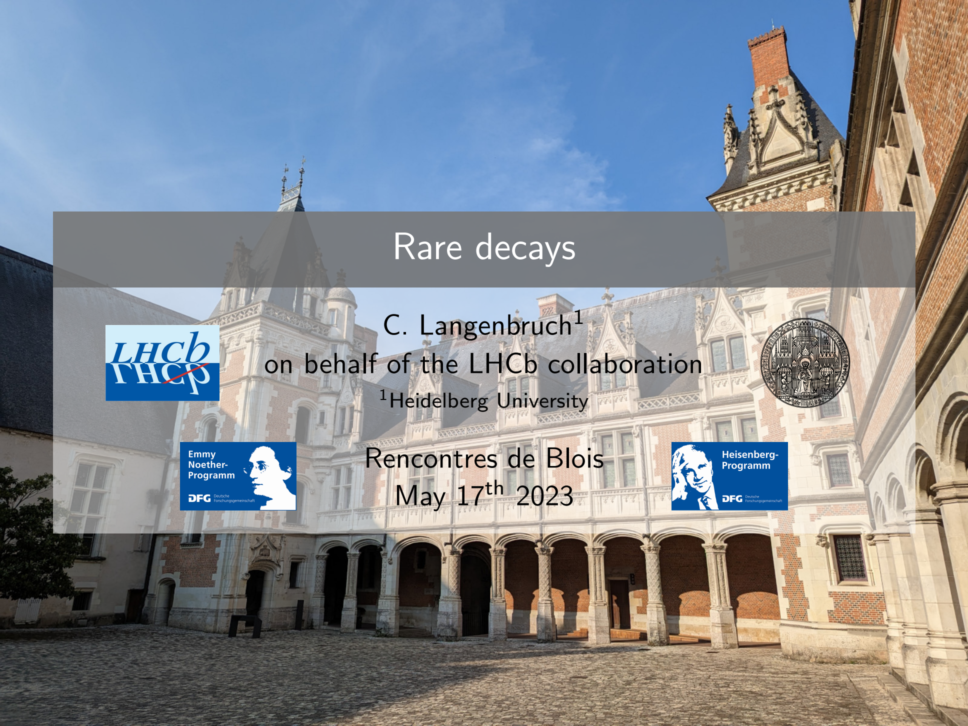

Rare decays

C. Langenbruch[1]
on behalf of the LHCb collaboration
[1]Heidelberg University

Rencontres de Blois
May 17th 2023

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

Heisenberg-Programm
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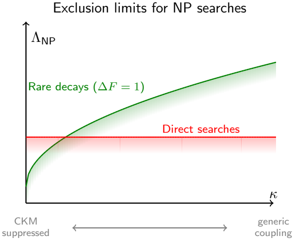
Lepton universality

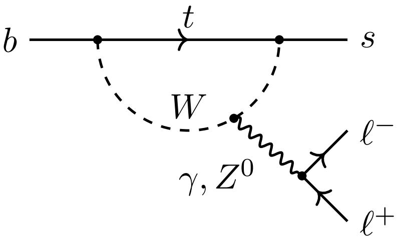
Prospects and Conclusions



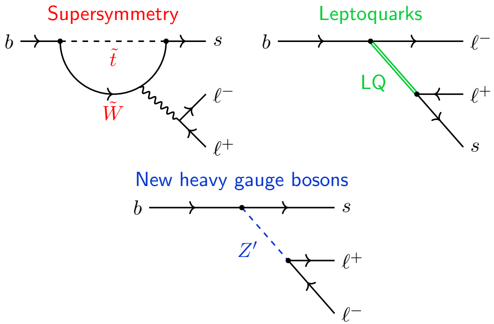
Exclusion limits for NP searches

Rare decays as sensitive probes for New Physics

$b \to s\ell\ell$ decays in the SM

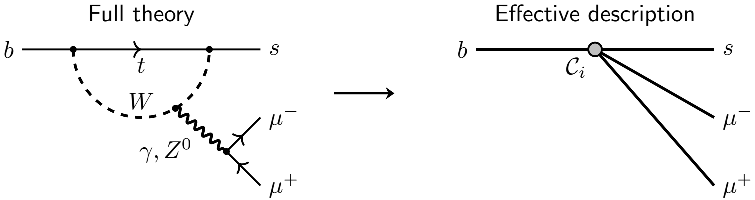


Possible contributions from NP



- Rare decays heavily (loop-)suppressed in the SM
- New heavy particles can significantly contribute and affect decay rates, angular distributions, and rate asymmetries

Rare B decays in effective field theory


Full theory

Effective description

- Model-independent description in effective field theory

Local operator

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{ts}}^* \frac{e^2}{16\pi^2} \sum_i \boxed{\mathcal{C}_i} \boxed{\mathcal{O}_i}$$

Wilson coefficient
("effective coupling")

Flavour-violating coupling

$$\Delta\mathcal{H}_{\text{NP}} = \frac{\boxed{\kappa}}{\boxed{\Lambda_{\text{NP}}^2}} \mathcal{O}_i$$

NP scale

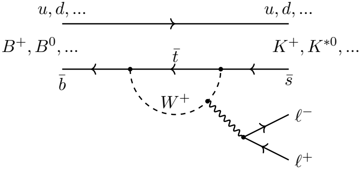
- Rare B decays allow to probe several operators $\mathcal{O}_i^{(\text{NP})}$
- Λ_{NP} up to $\mathcal{O}(100\,\text{TeV})$ reachable [JHEP 11 (2014) 121]

Wilson coefficient		Operator		
γ-penguin[1]	$\mathcal{C}_7^{(\prime)}$	$\frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$	$b \to s\gamma$	$b \to s\ell\ell$
ew. penguin	$\mathcal{C}_9^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu)$		
	$\mathcal{C}_{10}^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$	$B_s^0 \to \mu^+\mu^-$†	
scalar	$\mathcal{C}_S^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\mu)$		
pseudoscalar	$\mathcal{C}_P^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\gamma_5 \mu)$		

† [see backup]

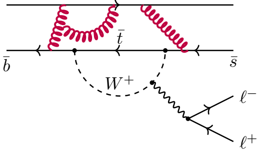
Observables in rare $b \to s\ell\ell$ decays and their cleanliness

Quarks bound in hadrons, *e.g.*

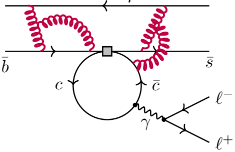


Hadronic uncertainties

Form-factors



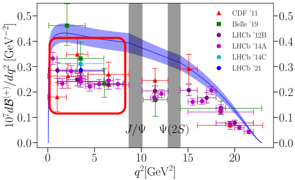
SM $c\bar{c}$-*loop*



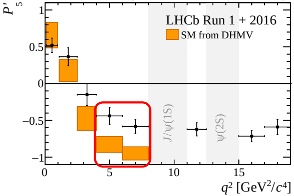
$b \to s\ell\ell$ Observables

Increasing precision of SM prediction

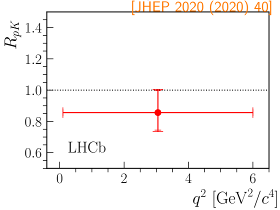
[JHEP 06 (2014) 133] [PRD 107 (2023) 014511]



[PRL 125 (2020) 011802]



[JHEP 2020 (2020) 40]



Branching fractions
affected by form-factors
and $c\bar{c}$-loop

Angular observables
affected by $c\bar{c}$-loop

Lepton Universality Tests
clean

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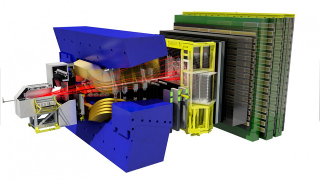
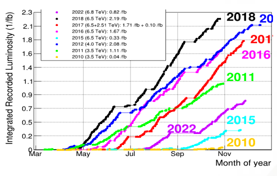
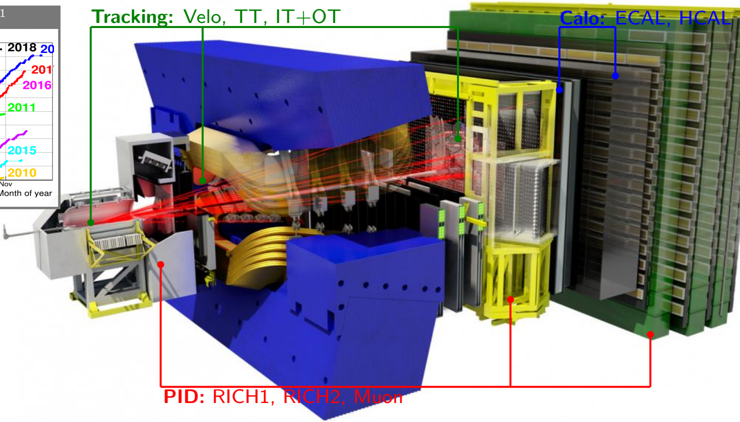


The LHCb experiment: Optimized for heavy flavour

Run 1: $3\,\text{fb}^{-1}$, Run 2: $6\,\text{fb}^{-1}$





Tracking: Velo, TT, IT+OT

Calo: ECAL, HCAL

PID: RICH1, RICH2, Muon

- Large $\sigma_{b\bar{b}}$: $(284 \pm 53)\,\mu\text{b}$ at $7\,\text{TeV}$ and $(495 \pm 52)\,\mu\text{b}$ at $13\,\text{TeV}$ [PLB 694 (2010) 209-216] [JHEP 10 (2015) 172]
- Excellent IP resolution $\sim 20\,\mu\text{m}$ to identify B decay vertices, $\Delta p/p = 0.5 - 1\%$
- Particle identification: $\epsilon_{K\to K} \sim 95\%$, $\epsilon_{\pi\to K} \sim 5\%$ and $\epsilon_{\mu\to\mu} \sim 97\%$, $\epsilon_{\pi\to\mu} \sim 1 - 3\%$
- Low trigger thresholds: $p_{\rm T}(\mu) > 1.8\,\text{GeV}$, $E_{\rm T}(e) > 3.0\,\text{GeV}$

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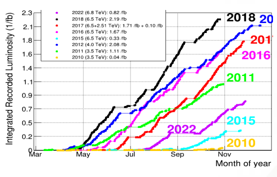
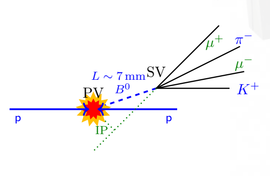
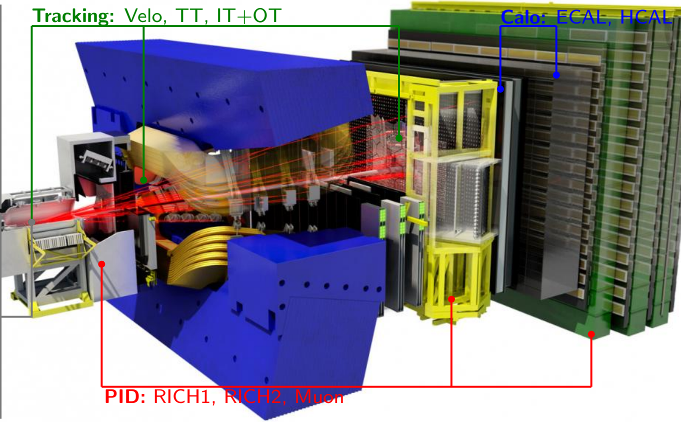


Heavy flavour signature





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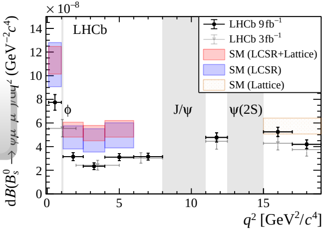
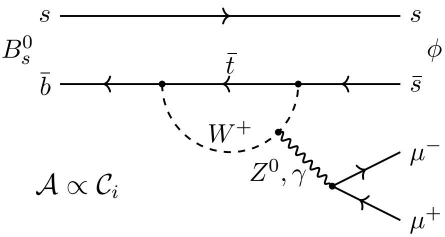
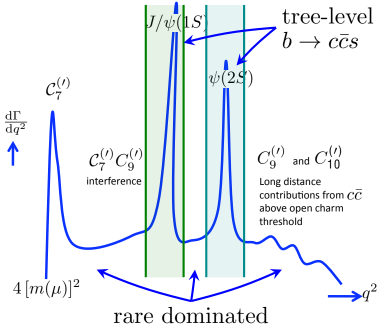


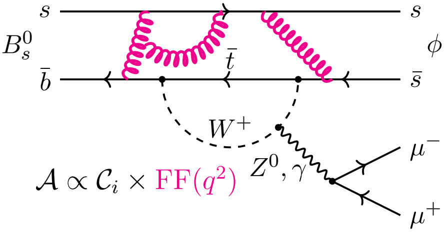
Branching fraction of $B^0_s \to \phi\mu^+\mu^-$



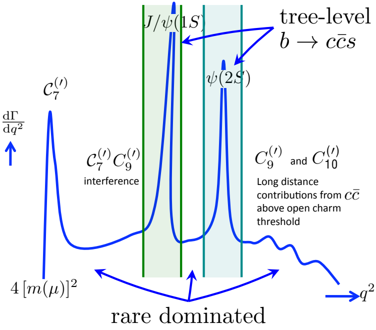


- Branching fraction of semileptonic $b \to s\mu^+\mu^-$ decays can be affected by NP
- Central: $q^2 = m(\ell^+\ell^-)^2$, different operators contribute depending on q^2
- At $q^2 = m^2_{J/\psi}$ important tree-level $b \to c\bar{c}s$ normalisation mode $B^0_s \to J/\psi\,\phi$
- SM predictions directly affected by significant form factor uncertainties
  Low q^2: LCSRs [PRD 71 (2005) 014029] [JHEP 08 (2016) 98] [PRD 75 (2007) 054013] [JHEP 09 (2010) 089] High q^2: Lattice [PRD 89 (2014) 094501] [PRD 88 (2013) 054509]

Branching fraction of $B_s^0 \to \phi\mu^+\mu^-$



$\mathcal{A} \propto \mathcal{C}_i \times \mathrm{FF}(q^2)$



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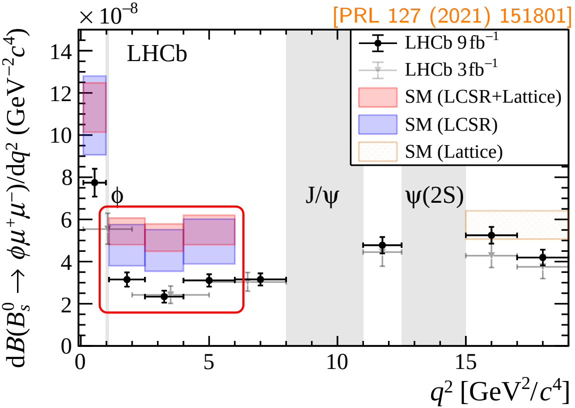
$B_s^0 \to \phi\mu^+\mu^-$ branching fraction

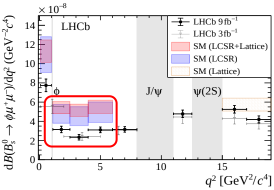


SM LCSR
[JHEP 08 (2016) 098]
[EPJC 75 (2015) 8]
SM LCSR+Lattice
[PRL 112 (2014) 212003]
[PoS Lattice 2014 372]

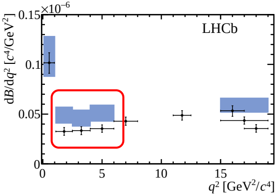
- Recent LHCb measurement using full Run 1+2 sample [PRL 127 (2021) 151801]
- $\mathrm{d}\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-, 1.1 < q^2 < 6\,\mathrm{GeV}^2/c^4) = (2.88 \pm 0.21)^{-8}\,\mathrm{GeV}^2/c^4$
- Tension with SM at $3.6\,\sigma$ (LCSR+Lattice) and $1.8\,\sigma$ (LCSR only)

Low $\mathcal{B}$ also found for other $b\to s\mu^+\mu^-$ decays

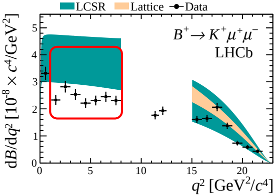
LHCb $B_s^0\to\phi\mu^+\mu^-$ [PRL 127 (2021) 151801]



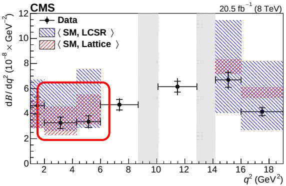
LHCb $B^0\to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]



LHCb $B^+\to K^+\mu^+\mu^-$ [JHEP 06 (2014) 133]



CMS $B^0\to K^{*0}\mu^+\mu^-$ [PLB 753 (2016) 424]



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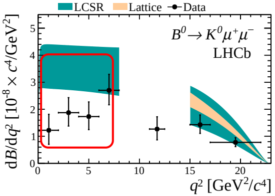
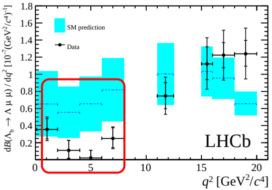
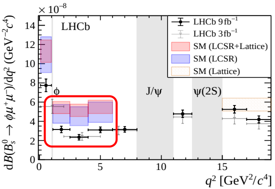


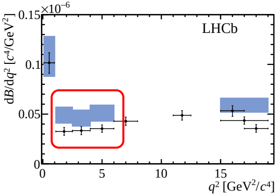
LHCb $\Lambda_b^0\to\Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]



- Data consistently below SM predictions (particularly at low q^2)
- Tensions at 1–3σ level, SM predictions exhibit sizeable had. uncertainties
- Exciting recent developements on non-local corrections [JHEP 09 (2022) 133] and new results from Lattice QCD [HPQCD, PRD 107 (2023) 1]
- Work on updates with full data sample, clean observables like A_I

Low $\mathcal{B}$ also found for other $b \to s\mu^+\mu^-$ decays


LHCb $B_s^0 \to \phi\mu^+\mu^-$ [PRL 127 (2021) 151801]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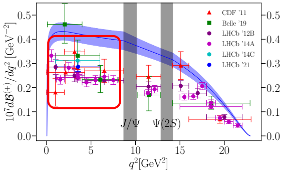
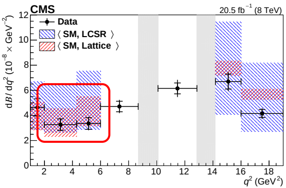

Lattice $B^+ \to K^+\mu^+\mu^-$ [arXiv:2207.13371]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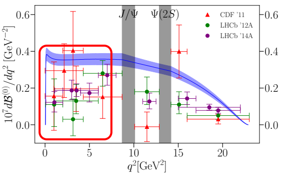
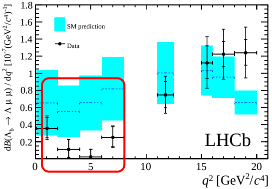

Lattice $B^0 \to K^0\mu^+\mu^-$ [arXiv:2207.13371]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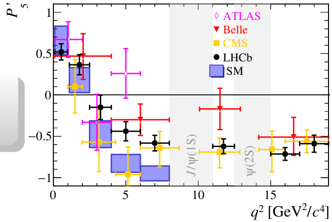
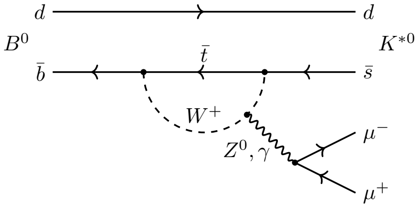
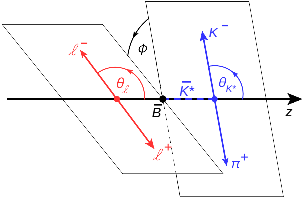


Angular analysis of $B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$





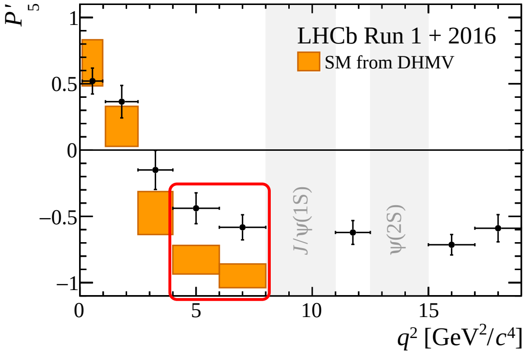
- Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$
- $$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

For completeness

- Angular observables $F_{\mathrm{L}}, A_{\mathrm{FB}}, S_i$ sensitive to NP contributions
- Perform ratios of observables where form factors cancel at leading order
Example: $P_5' = \frac{S_5}{\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}}$ [S. Descotes-Genon *et al.*, JHEP, 05 (2013) 137]

Angular observable P_5' from $B^0 \to K^{*0}\mu^+\mu^-$

[PRL 125 (2020) 011802]



- In q^2 bins $[4.0, 6.0]$ and $[6.0, 8.0]$ GeV^2/c^4 local tensions of $2.5\,\sigma$ and $2.9\,\sigma$
- [LHCb, PRL 125 (2020) 011802] consistent with [Belle, PRL 118 (2017) 111801] [CMS, PLB 781 (2018) 517] [ATLAS, JHEP 10 (2018) 047]
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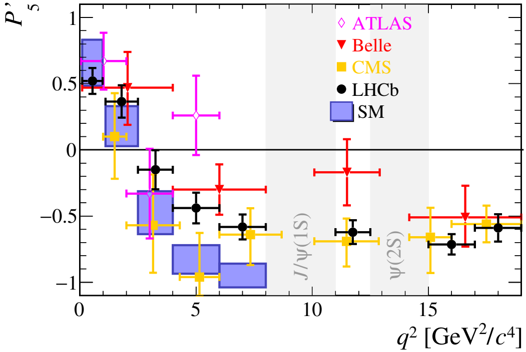
Angular observable P_5' from $B^0 \to K^{*0}\mu^+\mu^-$

[PIPNP 120 (2021) 103885]



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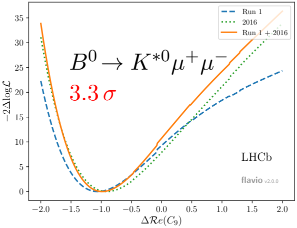
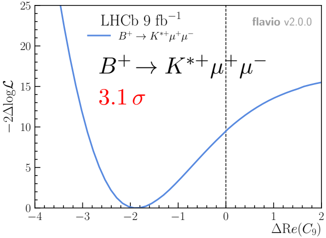
Consistency of $b \to s\mu^+\mu^-$ angular analyses

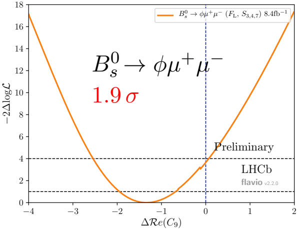
[PRL 125 (2020) 011802]



[PRL 126 (2021) 161802]



[JHEP 11 (2021) 043]



- Use `flavio` [arXiv:1810.08132] to determine tension with SM hypothesis
- Variation of vector coupling $\mathcal{R}e(\mathcal{C}_9)$ results in improved description of data
- Consistent trend for $B^0 \to K^{*0}\mu^+\mu^-$ [PRL 125 (2020) 011802], $B^+ \to K^{*+}\mu^+\mu^-$ [PRL 126 (2021) 161802] and $B_s^0 \to \phi\mu^+\mu^-$ [JHEP 11 (2021) 043] angular observables
- However, interpretation not clear due to significant hadronic uncertainties

Rare decays

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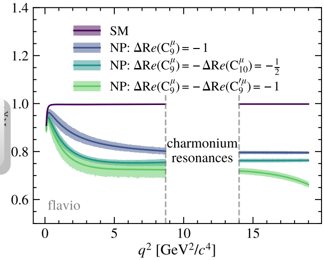
Branching fractions of rare B decays

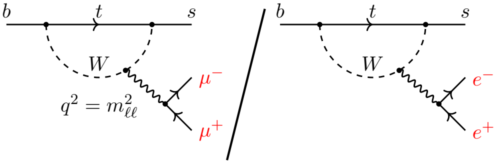
Angular analyses of rare B decays

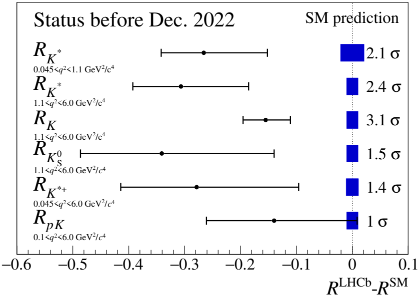
Lepton universality

Prospects and Conclusions



Lepton Flavour Universality tests in $b \to s\ell\ell$ decays



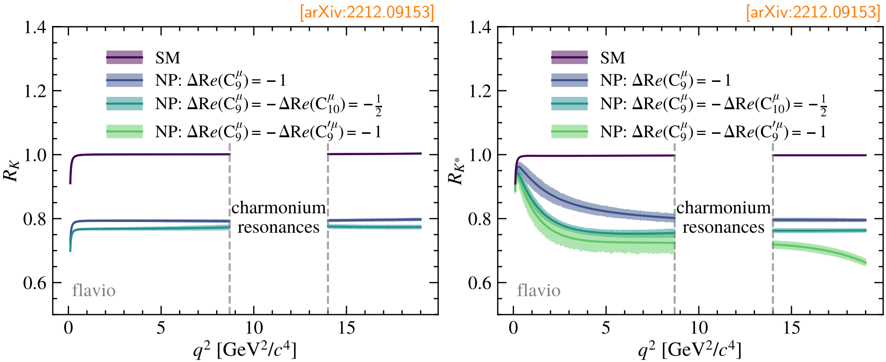


- Lepton flavour universality central property of SM
- Testable using ratios of branching fractions of rare $b \to s\ell^+\ell^-$ decays:

$$R_{K,K^*} = \frac{\mathcal{B}(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\mathcal{B}(B^{(+,0)} \to K^{(+,*0)}e^+e^-)}$$

- Exactly unity in SM, differences only through lepton mass effects
- QED corrections $\mathcal{O}(1\,\%)$ [EPJC 76 (2016) 440]
- Hadronic uncertainties (form-factors and $c\bar{c}$-loop) cancel in the ratio

R_K and R_{K^*} in different NP scenarios



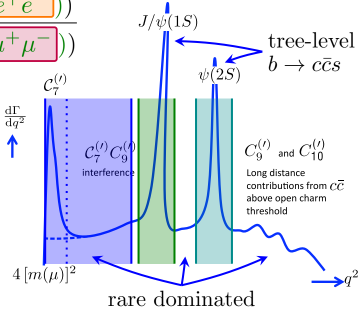
- Example NP models assuming NP only in muons
- Some ability to disentangle different scenarios with R_K and R_{K^*}
- Simultaneous R_K and R_{K^*} determination with $9\,\text{fb}^{-1}$ Run 1+2 data
  - low–q^2: $q^2 \in [0.1, 1.0]\,\text{GeV}^2/c^4$
  - central–q^2: $q^2 \in [1.1, 6.0]\,\text{GeV}^2/c^4$

Analysis strategy: Double ratio (Example: R_K)

- Analysis strategy: Double ratio of rare modes $B^+ \to K^+\ell^+\ell^-$ with resonant decays $B^+ \to K^+ J/\psi(\to \ell^+\ell^-)$:

$$R_K = \frac{\mathcal{B}(B^+\to K^+\boxed{\mu^+\mu^-})}{\mathcal{B}(B^+\to K^+\boxed{e^+e^-})} \times \overbrace{\frac{\mathcal{B}(B^+\to K^+J/\psi(\to\boxed{e^+e^-}))}{\mathcal{B}(B^+\to K^+J/\psi(\to\boxed{\mu^+\mu^-}))}}^{r^{-1}_{J/\psi}=1 \text{ [PRD 88 (2013) 3]}}$$

- **Electron** and **Muon** reconstruction very different at LHCb
- Efficiencies from corrected simulation
- Double ratio cancels most experimental systematic effects in efficiency ratios

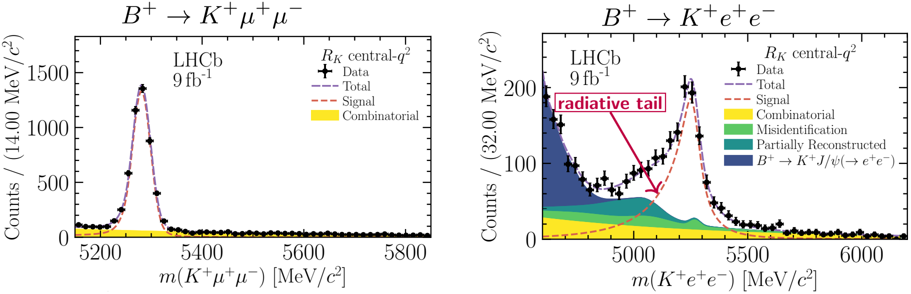


- Important cross-checks: $r_{J/\psi} = \frac{\mathcal{B}(B^+\to K^+J/\psi(\to\boxed{\mu^+\mu^-}))}{\mathcal{B}(B^+\to K^+J/\psi(\to\boxed{e^+e^-}))}$ and

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

- Both $r_{J/\psi}$ and $R_{\psi(2S)}$ compatible with unity at better than $2\,\sigma$ ✓

Experimental challenges for electron modes at LHCb

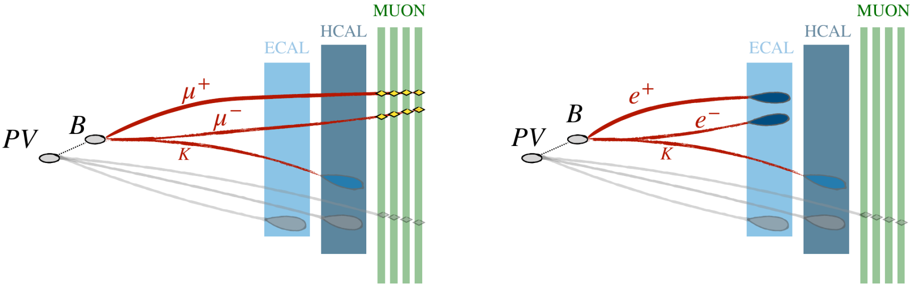


[arXiv:2212.09152] [arXiv:2212.09153]

Experimental Challenges for electron modes:

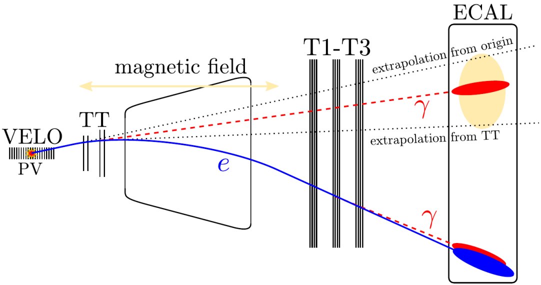
1. Low e trigger efficiencies due to higher thresholds compared to muons
2. Electrons strongly emit Bremsstrahlung traversing material
3. Contribution from several background sources, bkg. modeling critical

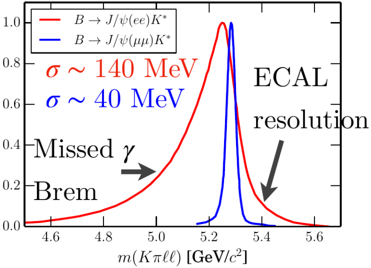
Experimental challenge: 1. Electron trigger



- Trigger signatures for muon and electron modes very different
- $p_{\mathrm{T}}^{\mathrm{L0\ trigger}}(\mu) > 1.5\text{–}1.8\,\mathrm{GeV}$
  $E_{\mathrm{T}}^{\mathrm{L0\ trigger}}(e) > 2.5\text{–}3.0\,\mathrm{GeV}$
- Combine exclusive trigger categories to improve ϵ for electron modes:
  1. Trigger on rest of event (independent of signal)
  2. Trigger on e/μ from signal

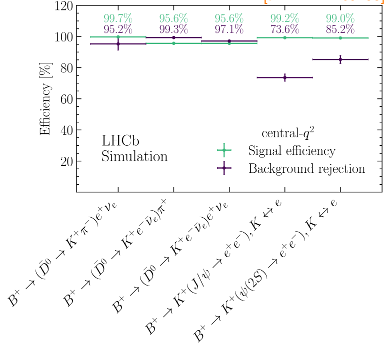
Experimental challenge: 2. Bremsstrahlung



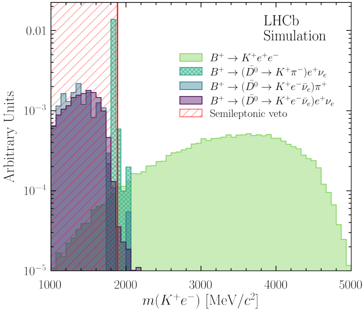


- Correct electron momentum by adding matching photons ($E_{\mathrm{T}} > 75\,\mathrm{MeV}/c^2$) reconstructed in the ECAL
- Bremsstrahlung recovery $\sim 50\%$ efficient, well simulated
- Bremsstrahlung reconstruction impacts momentum resolution
  $\to$ higher background pollution and more sensitive to bkg. modeling

Experimental challenge: 3. Background suppression



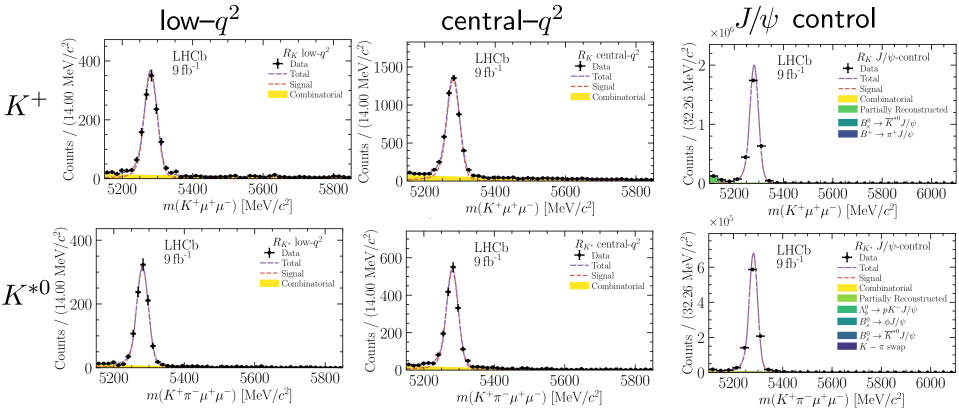
[arXiv:2212.09153]



[arXiv:2212.09153]

- Combinatorial: multivariate classifier using kinematic quantities and vertex quality information
- Partially reconstructed: multivariate classifier in electron mode and corrected mass exploiting PV/SV reconstruction
- Misidentification: Lepton and hadron particle identification
- Residual backgrounds from misidentification explicitly modeled with data-driven approach [see talk by R.-D. Moise] [backup]

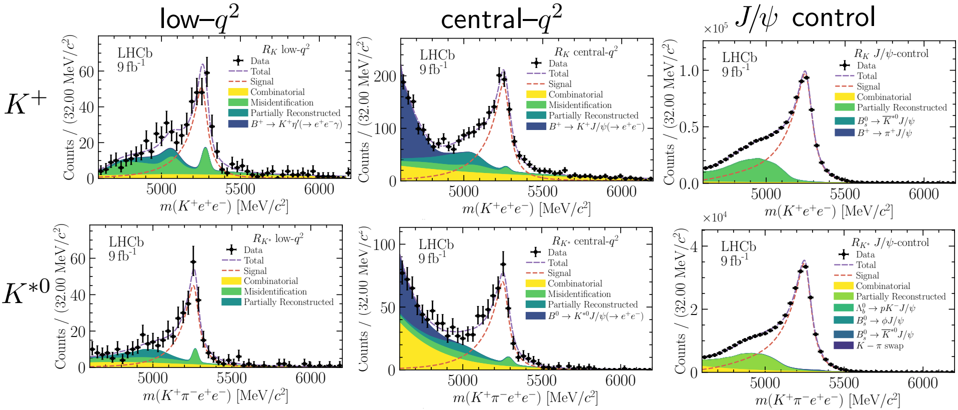
Muon mode fits



[arXiv:2212.09152] [arXiv:2212.09153]

- Muon mode is very clean!
- Muon branching fraction compatible with published results
  [JHEP 06 (2014) 133] [JHEP 11 (2016) 047]

Electron mode fits

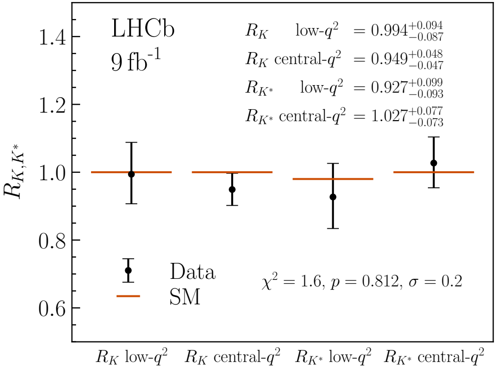


[arXiv:2212.09152] [arXiv:2212.09153]

- Brems. tails from J/ψ entering rare modes constrained in sim. fit
- Partially reconstructed bgk. from $K^{*0}e^+e^-$ constrained in $K^+e^+e^-$

R_K and R_{K^*} results

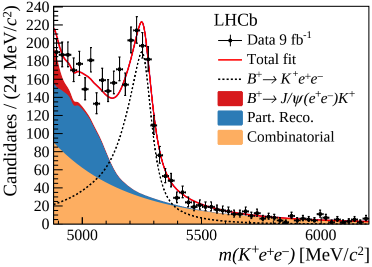
[arXiv:2212.09152] [arXiv:2212.09153]



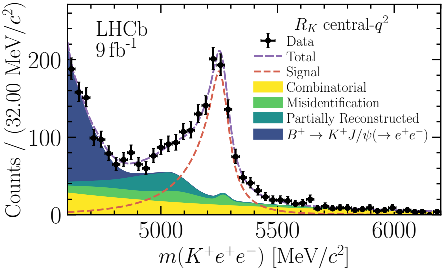
- Most precise test of LFU in $b \to s\ell^+\ell^-$ transitions
- Supersedes previous results
- Compatible with the SM at $0.2\,\sigma$ using simple χ^2 test
- Statistical uncertainty dominates

Difference to previous R_K measurement

[Nature Phys. 18 (2022) 277]



[arXiv:2212.09152] [arXiv:2212.09153]



$$R_K = 0.846^{+0.042}_{-0.039}{}^{+0.013}_{-0.012} \rightarrow R_K = 0.949^{+0.042}_{-0.041}{}^{+0.022}_{-0.022}$$

[Nature Phys. 18 (2022) 277] [arXiv:2212.09152] [arXiv:2212.09153]

- Different selection allows for statistical scatter of ± 0.033
- Shift of ~ 0.1 due to pollution by misidentified backgrounds not appropriately accounted for in [Nature Phys. 18 (2022) 277]
  - Tighter particle identification cuts: Shift of $+0.064$
  - Explicit inclusion of residual misid. backgrounds: Shift of $+0.038$

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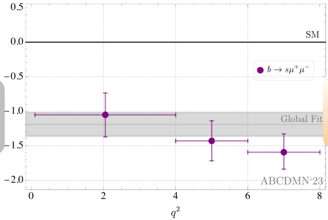
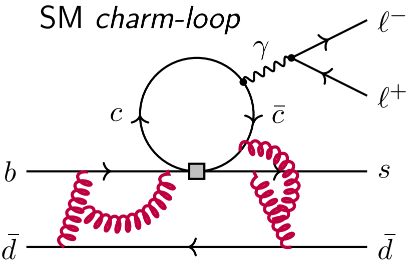
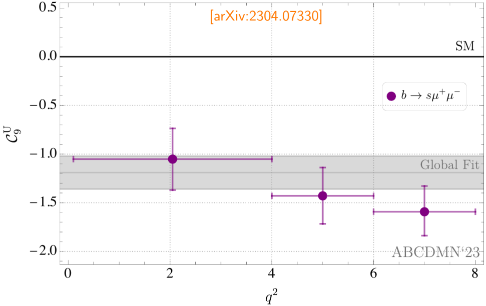


Disentangling hadronic contributions from potential NP





- Disentangling hadr. contributions requires work from theory and experiment
- Progress on theory side:
  - Form-factors are systematically improved on the lattice [PRD 107 (2023) 1]
  - Recent more precise estimation of charm-loop effect [JHEP 09 (2022) 133]
- Exploit q^2-dependence:
  - charm-loop rises towards $c\bar{c}$-resonances
  - NP q^2-independent
- q^2-unbinned approaches to better exloit data [JHEP 11 (2017) 176]
  Different $c\bar{c}$-loop parameterisations pursued [EPJC 78 (2018) 453] [EPJC 80 (2020) 12] [JHEP 10 (2019) 236] [JHEP 09 (2022) 133]

Summary and conclusions

- SM describes large majority of results with excellent precision, but some tensions appeared in the sector of rare decays
- Status of these *flavour anomalies*
  - Branching fractions of $b \to s\mu^+\mu^-$ decays $\sim 1\text{–}3\,\sigma$
  - Angular observables of $b \to s\mu^+\mu^-$ decays $\sim 2\text{–}3\,\sigma$
  - Lepton universality in R_{K,K^*} $\cancel{3\,\sigma} \to 0.2\,\sigma$
- Tensions in $b \to s\mu^+\mu^-$ $\mathcal{B}$ and angular observables not theoretically clean, Progress requires synergistic work between experiment and theory!
- LHC Run 3 just started, will allow for unprecedented reach with flavour observables with brand new LHCb detector
- Belle 2 will provide important additional and complementary information

Backup

cc-by-2.0, Christopher Michel

NP contributions and reach with indirect searches

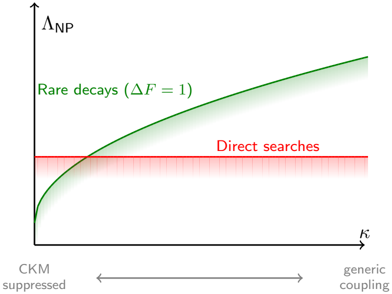
- NP can contribute to different operators $\mathcal{O}_i$ depending on its type

$$\mathcal{H}_{\text{eff}} = -\underbrace{\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{ts}}^{*} \frac{e^2}{16\pi^2}}_{\sim 1/(35\,\text{TeV})^2} \sum_i \mathcal{C}_i \mathcal{O}_i \qquad \Delta\mathcal{H}_{\text{NP}} = \frac{\boxed{\kappa} \xleftarrow{} \boxed{\text{Flavour-viol. coupling}}}{\boxed{\Lambda^2_{\text{NP}}} \xleftarrow{} \boxed{\text{NP scale}}} \mathcal{O}_i$$

$$\Rightarrow \boxed{\Lambda_{\text{NP}} \sim 35\,\text{TeV}\sqrt{\kappa/\Delta\mathcal{C}_i}}$$

- NP reach not limited by $\sqrt{s}$, complementary with direct searches

Exclusion limits for NP searches



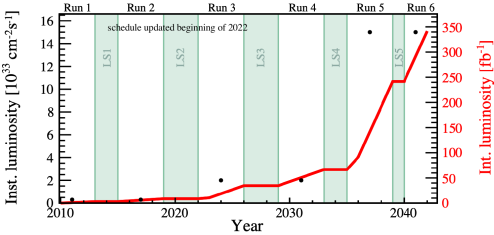
NP Scenario	Coupling κ
Tree-level generic	1
Tree-level CKM suppressed	$V_{\text{tb}}V_{\text{ts}}$
Loop-level generic	$\frac{1}{16\pi^2}$
Loop-level CKM suppressed	$\frac{V_{\text{tb}}V_{\text{ts}}}{16\pi^2}$

Prospects in Run 3 and the Upgrade II

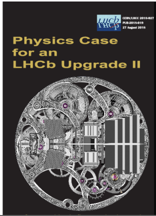
Prospects from [arXiv:1808.08865]

$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis

$\int \mathcal{L}\mathrm{d}t$	$3\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
$\sigma^{\mathrm{stat}}(S_i)$	≤ 0.058	≤ 0.016	≤ 0.004
$\sigma(\mathcal{C}'_{10})$	0.31	0.15	0.06
$\Lambda_{\mathrm{NP}}^{\text{tree generic}}\,[\mathrm{TeV}]$	50	75	115

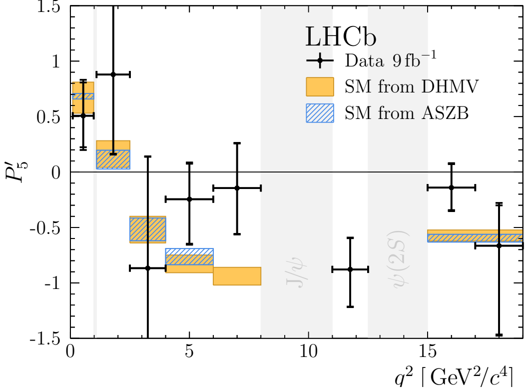


- Run 3 just started, will more than double $\int \mathcal{L}\mathrm{d}t$ from $9\,\mathrm{fb}^{-1}$ (Run 1+2) to around $23\,\mathrm{fb}^{-1}$
- Upgrade 2 will increase $\int \mathcal{L}\mathrm{d}t$ to $300\,\mathrm{fb}^{-1}$ Framework TDR [CERN-LHCC-2021-012], Physics case [CERN-LHCC-2018-027], CERN Yellow report [arxiv:1812.07638]
- NP reach in Upgrade II increases by more than factor 2 wrt. Run 1+2
- Λ_{NP} reach beyond $100\,\mathrm{TeV}$ through precision



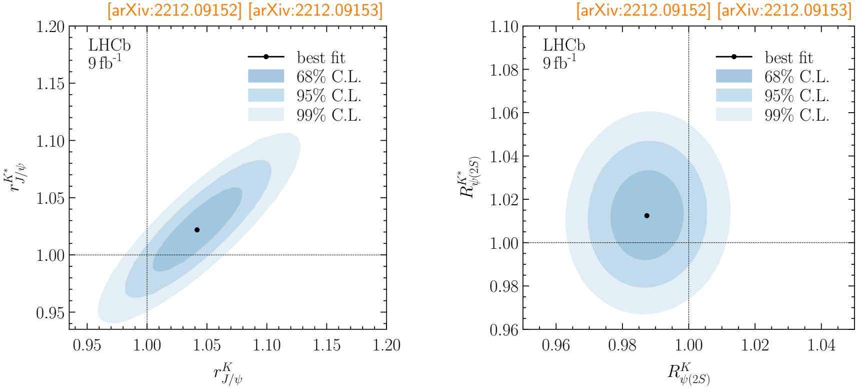
Angular observable P_5' from $B^+ \to K^{*+}(\to K^0_{\mathrm{S}}\pi^+)\mu^+\mu^-$

[PRL 126 (2021) 161802]



- Recent LHCb measurement using Run 1+2 data [PRL 126 (2021) 161802]
- Global tension corresponding to $3.1\,\sigma$, consistent with $B^0 \to K^{*0}\mu^+\mu^-$
- Angular analysis ($F_{\mathrm{L}}+A_{\mathrm{FB}}$) also by CMS [JHEP 04 (2021) 124]

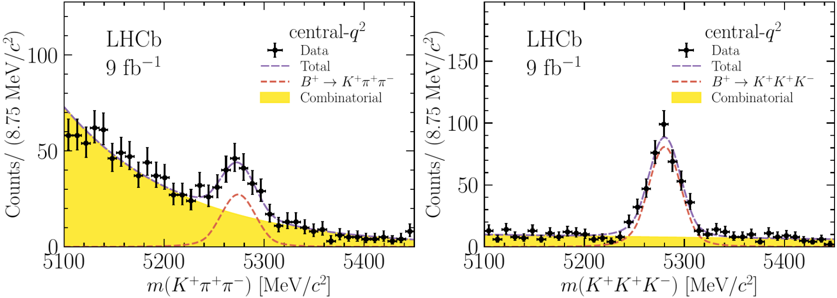
Crosschecks $r_{J/\psi}$ and $R_{\psi(2S)}$



- Both $r_{J/\psi}$ and $R_{\psi(2S)}$ compatible with unity at better than $2\,\sigma$

Residual backgrounds from misidentification

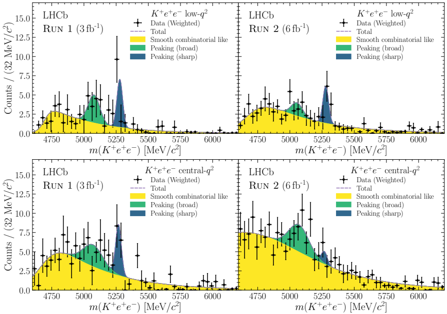
[arXiv:2212.09152] [arXiv:2212.09153]

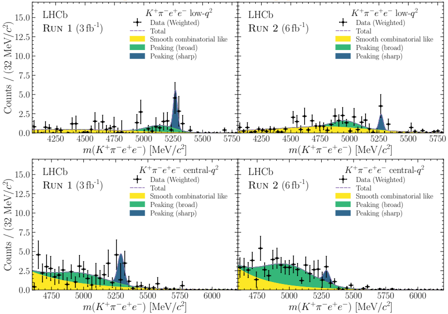


- Misidentified backgrounds can be isolated by inverting particle ID cuts: Examples are (left) $B^+ \to K^+\pi^+\pi^-$ and (right) $B^+ \to K^+K^+K^-$
- Similar backgrounds for $K^{*0}e^+e^-$, however Dalitz structure not well known
- Backgrounds from single misidentification less well known, complex shape
- Developed new inclusive data-driven treatment of misidentified residual backgrounds

Residual backgrounds from misidentification

[arXiv:2212.09152] [arXiv:2212.09153]

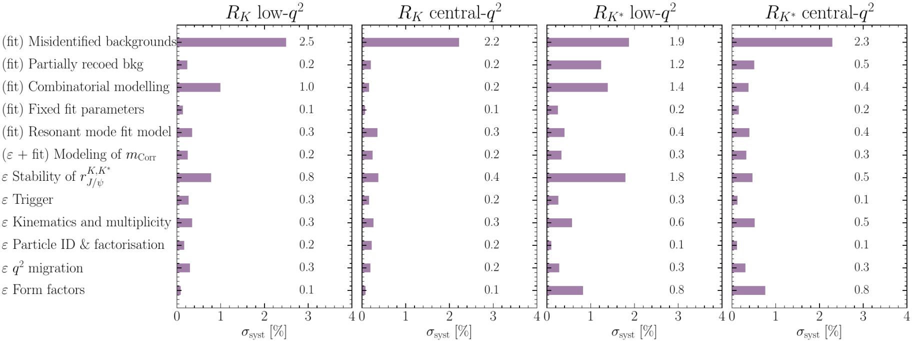




- Invert electron PID selection to obtain control region
- Use control samples from data to weight control region events according to their misidentification probability $w_e = \epsilon_{\text{pass PID}}/\epsilon_{\text{fail PID}}$
- Resulting distribution and expected background yield used in nominal rare electron mode fit

Systematic uncertainties

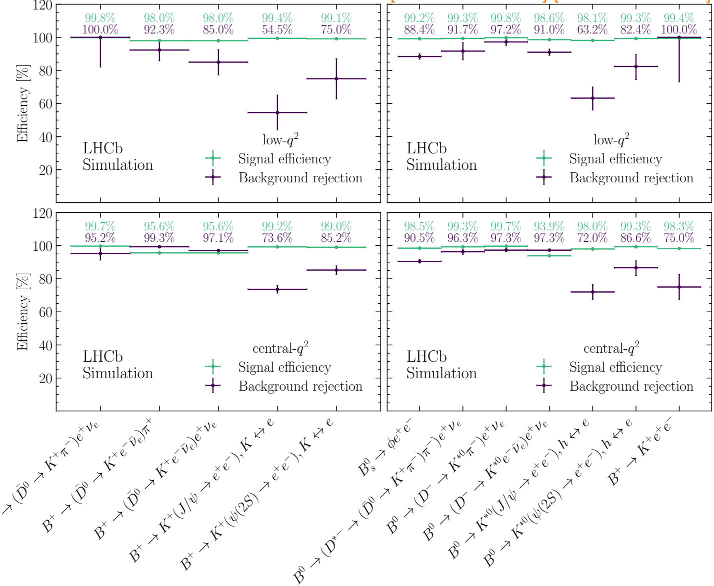
[arXiv:2212.09152] [arXiv:2212.09153]



- Dominant systematic: Modeling of residual misidentified bgks.
- Measurement statistically limited

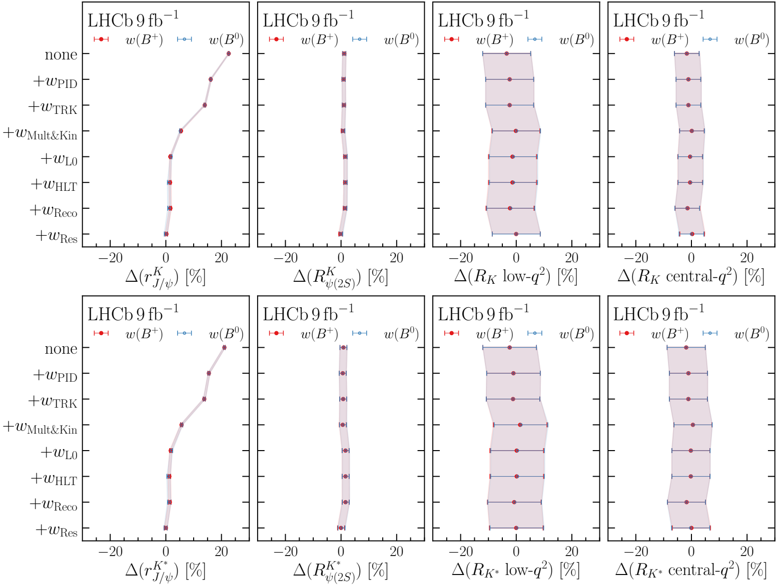
R_{K,K^*} specific background vetos

[arXiv:2212.09152] [arXiv:2212.09153]

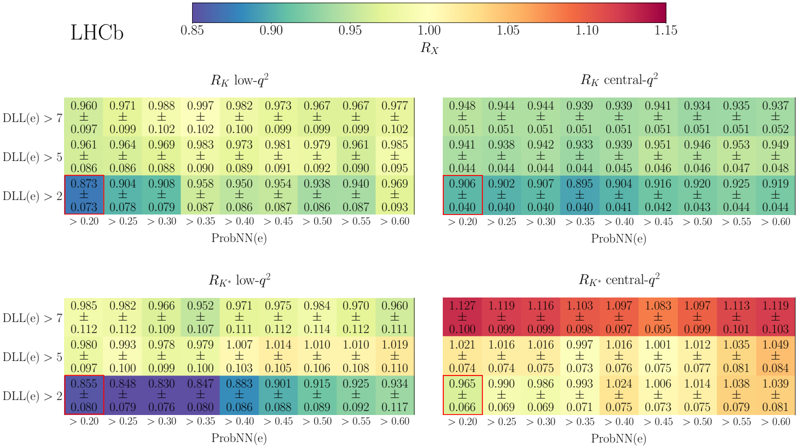


R_{K,K^*} efficiency corrected ratios

[arXiv:2212.09152] [arXiv:2212.09153]



R_{K,K^*} PID dependence



R_K low-q^2

	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60
DLL(e) > 7	0.960 ± 0.097	0.971 ± 0.099	0.988 ± 0.102	0.997 ± 0.102	0.982 ± 0.100	0.973 ± 0.099	0.967 ± 0.099	0.967 ± 0.099	0.977 ± 0.102
DLL(e) > 5	0.961 ± 0.086	0.964 ± 0.086	0.969 ± 0.088	0.983 ± 0.090	0.973 ± 0.089	0.981 ± 0.091	0.979 ± 0.092	0.961 ± 0.090	0.985 ± 0.095
DLL(e) > 2	0.873 ± 0.073	0.904 ± 0.078	0.908 ± 0.079	0.958 ± 0.087	0.950 ± 0.086	0.954 ± 0.087	0.938 ± 0.086	0.940 ± 0.087	0.969 ± 0.093

ProbNN(e)

R_K central-q^2

	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60
DLL(e) > 7	0.948 ± 0.051	0.944 ± 0.051	0.944 ± 0.051	0.939 ± 0.051	0.939 ± 0.051	0.941 ± 0.051	0.934 ± 0.051	0.935 ± 0.051	0.937 ± 0.052
DLL(e) > 5	0.941 ± 0.044	0.938 ± 0.044	0.942 ± 0.044	0.933 ± 0.044	0.939 ± 0.045	0.951 ± 0.046	0.946 ± 0.046	0.953 ± 0.047	0.949 ± 0.048
DLL(e) > 2	0.906 ± 0.040	0.902 ± 0.040	0.907 ± 0.040	0.895 ± 0.040	0.904 ± 0.041	0.916 ± 0.042	0.920 ± 0.043	0.925 ± 0.044	0.919 ± 0.044

ProbNN(e)

R_{K^*} low-q^2

	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60
DLL(e) > 7	0.985 ± 0.112	0.982 ± 0.112	0.966 ± 0.109	0.952 ± 0.107	0.971 ± 0.111	0.975 ± 0.112	0.984 ± 0.114	0.970 ± 0.112	0.960 ± 0.111
DLL(e) > 5	0.980 ± 0.097	0.993 ± 0.100	0.978 ± 0.099	0.979 ± 0.100	1.007 ± 0.103	1.014 ± 0.105	1.010 ± 0.106	1.010 ± 0.108	1.019 ± 0.110
DLL(e) > 2	0.855 ± 0.080	0.848 ± 0.079	0.830 ± 0.076	0.847 ± 0.080	0.883 ± 0.086	0.901 ± 0.088	0.915 ± 0.089	0.925 ± 0.092	0.934 ± 0.117

ProbNN(e)

R_{K^*} central-q^2

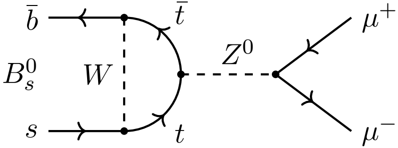
	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60
DLL(e) > 7	1.127 ± 0.100	1.119 ± 0.099	1.116 ± 0.099	1.103 ± 0.098	1.097 ± 0.097	1.083 ± 0.095	1.097 ± 0.099	1.113 ± 0.101	1.119 ± 0.103
DLL(e) > 5	1.021 ± 0.074	1.016 ± 0.074	1.016 ± 0.075	0.997 ± 0.073	1.016 ± 0.076	1.001 ± 0.075	1.012 ± 0.077	1.035 ± 0.081	1.049 ± 0.084
DLL(e) > 2	0.965 ± 0.066	0.990 ± 0.069	0.986 ± 0.069	0.993 ± 0.071	1.024 ± 0.075	1.006 ± 0.073	1.014 ± 0.075	1.038 ± 0.079	1.039 ± 0.081

ProbNN(e)

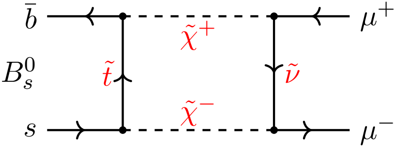
[arXiv:2212.09152] [arXiv:2212.09153]

The very rare decay $B_s^0 \to \mu^+\mu^-$

SM diagram



Possible NP contribution



- Loop-, helicity- and CKM suppressed
- Purely leptonic final state, theoretically and experimentally very clean
- Precise SM prediction[1] [PRL 112 (2014) 101801] [JHEP 10 (2019) 232]

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

- Very sensitive to new scalar sector (*e.g.* extended Higgs sector, SUSY)

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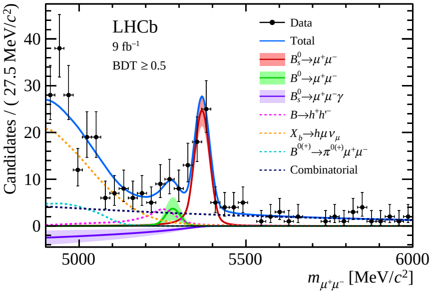
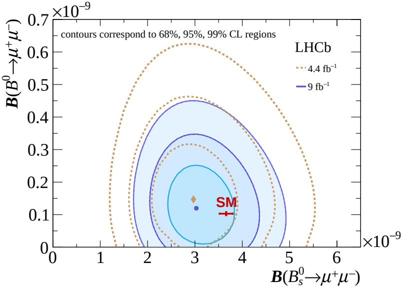
[1] SM prediction without V_{cb} dependence available, in good agreement [APP B 53 (2021) 6]

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

[PRL 128 (2022) 041801] [PRD 105 (2022) 012010]





- Recent LHCb measurement [PRL 128 (2022) 041801] [PRD 105 (2022) 012010]

  $$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$$
  $$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.2^{+0.8}_{-0.7} \pm 0.1) \times 10^{-10} \quad (\mathcal{B} < 2.6 \times 10^{-10} \text{ @ } 95\% \text{ CL})$$

  in good agreement with SM

- New precise CMS measurement [arXiv:2212.10311] moves average further to SM

  $$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.83^{+0.38}_{-0.36}(\text{stat})^{+0.19}_{-0.16}(\text{syst})^{+0.14}_{-0.13}(f_s/f_u)) \times 10^{-9}$$
  $$\mathcal{B}(B^0 \to \mu^+\mu^-) = (0.37^{+0.75+0.08}_{-0.67-0.09}) \times 10^{-10} \quad (\mathcal{B} < 1.9 \times 10^{-10} \text{ @ } 95\% \text{ CL})$$

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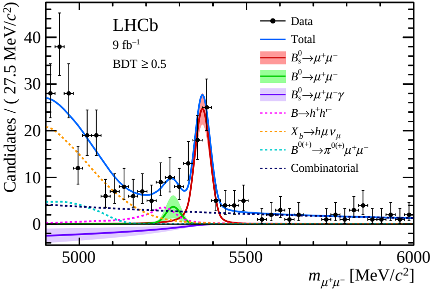
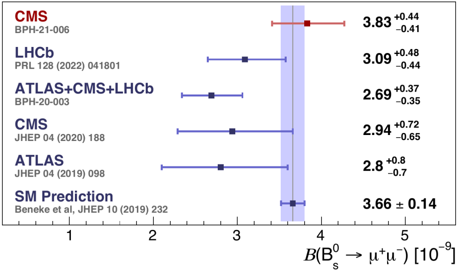
[PRL 128 (2022) 041801] [PRD 105 (2022) 012010]



[arXiv:2212.10311]



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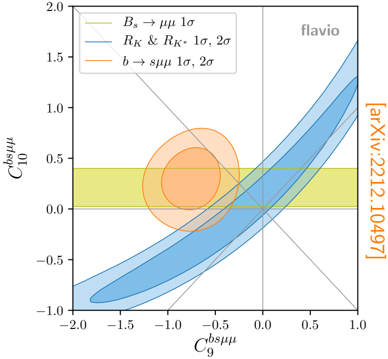
Interpretation in global fits



[arXiv:2212.10497]

- $b \to s\ell^+\ell^-$ data can be interpreted using *global fits* of Wilson coefficients
- Assuming NP only in muon-sector ($\mathcal{R}e(C_9^{bs\mu\mu})$ and $\mathcal{R}e(C_{10}^{bs\mu\mu})$) reveals tension between $b \to s\mu^+\mu^-$ angular and $\mathcal{B}$ measurements and R_{K,K^*}
- Can be resolved in presence of LFU NP which does not affect R_{K,K^*}
- Data prefers negative $C_9^{\text{univ.}}$, tension depends on hadronic uncertainties

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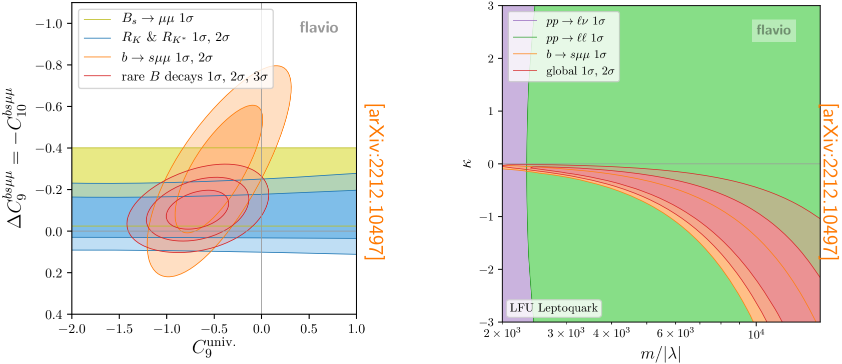

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