Standard Model Predictions for Rare b Decays

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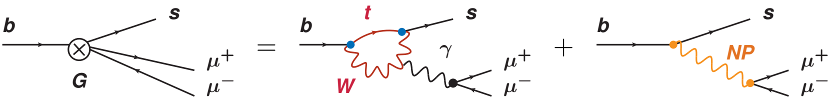
New Physics in Rare b Decays



$$G \sim \frac{1}{16\pi^2} \frac{g^4}{m_W^2} \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{NP}}{\Lambda_{NP}^2}$$

measure precisely

calculate precisely the SM contribution

get information on NP coupling and scale

High Sensitivity to Flavorful New Physics

For new physics couplings of O(1) we can estimate the sensitivity to the new physics scale

$$\Lambda_{\rm NP} \sim \frac{4\pi v}{\sqrt{|V_{tb} V_{ts}^*|}} \sim O(10\ \text{TeV})$$

O(1) anomalies in rare $b \to s$ decays could establish a new scale in particle physics within reach of future colliders

(Incomplete) List of Rare b Decays

	inclusive	exclusive
radiative		
leptonic		
semi-leptonic		

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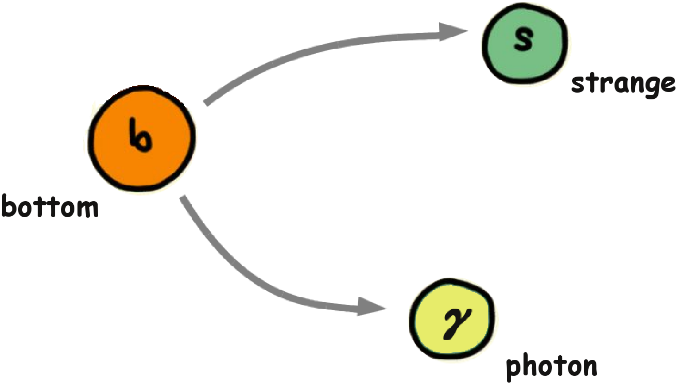
semi-leptonic	$B \to X_s \ell^+ \ell^-$ $B \to X_d \ell^+ \ell^-$	$B \to K^{(*)} \ell^+ \ell^-$, $B \to \pi \ell^+ \ell^-$ $B_s \to \phi \ell^+ \ell^-$, $\Lambda_b \to \Lambda \ell^+ \ell^-$

The $B \to X_s\gamma$ Decay



Refined Standard Model Prediction

Misiak et al., Phys. Rev. Lett. **114**, no. 22, 221801 (2015)

SM prediction

$$\text{BR}(B \to X_s\gamma)_{\text{SM}} = (3.36 \pm 0.23) \times 10^{-4} \quad \text{for } E_0 = 1.6 \text{ GeV}$$

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error budget

- non-perturbative effects (dominant uncertainty): $\sim 5\%$
- higher order perturbative contributions: $\sim 3\%$
- interpolation (charm mass): $\sim 3\%$
- parametric (mainly from normalization to BR($b \to c\ell\nu$)): $\sim 2\%$

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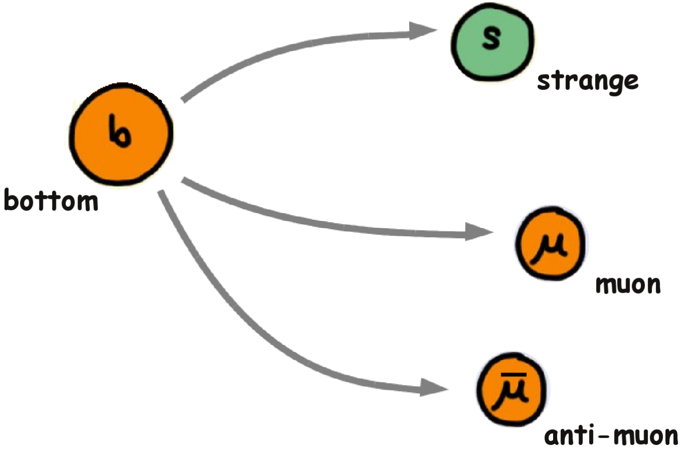
constraints on charged Higgs bosons: $M_{H^\pm} > 480$ GeV

The $B \to X_s \ell^+ \ell^-$ Decay



Differential Decay Rate

Lee, Ligeti, Stewart, Tackmann, Phys. Rev. D75 (2007) 034016

$$\frac{d\Gamma}{dq^2 d\cos\theta} = \frac{3}{8}\Big(H_T(q^2)(1+\cos^2\theta) + 2H_L(q^2)\sin^2\theta + 2H_A(q^2)\cos\theta \Big)$$

- total decay rate $\sim H_T + H_L$
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at low q^2 good control over hadronic effects

at high q^2 large uncertainties from $1/m_b^2$ and $1/m_b^3$ power corrections can be reduced by normalizing to inclusive $B \to X_u \ell \nu$ rate

(Ligeti, Tackmann, Phys. Lett. B 653 (2007) 404)

Refined Standard Model Prediction

Huber, Hurth, Lunghi, JHEP 1506 (2015) 176

include NNLO QCD and NLO QED corrections
+ detailed treatment of collinear photons

$$\text{low } q^2 : \quad \text{BR}(B \to X_s \mu^+ \mu^-)_{[1,6]} = (1.62 \pm 0.09) \times 10^{-6}$$

- main uncertainty is renormalization scale variation
- non-perturbative effects are estimated to be $\sim 5\%$ (not included in above uncertainty)

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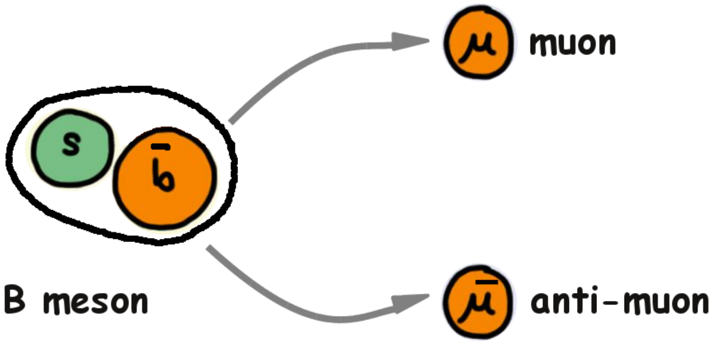
high q^2 : $R = \dfrac{\text{BR}(B \to X_s \mu^+ \mu^-)_{>14.4}}{\text{BR}(B \to X_u \mu \nu)_{>14.4}} = (2.62 \pm 0.30) \times 10^{-3}$

- main uncertainty is from CKM element V_{ub}

(Similar uncertainties for SM predictions of other observables)

The $B_s \to \mu^+\mu^-$ Decay



The SM Predictions

Bobeth et al., Phys. Rev. Lett. **112**, 101801 (2014)

include NNLO QCD corrections and NLO electroweak corrections
+ effects due to the non-zero width difference in the B_s system

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.65 \pm 0.23) \times 10^{-9}$$

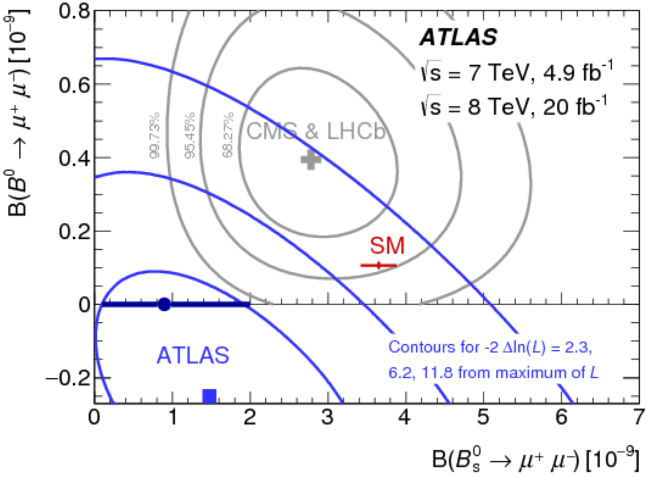
$$\mathrm{BR}(B_d \to \mu^+\mu^-)_{\mathrm{SM}} = (1.06 \pm 0.09) \times 10^{-10}$$

error budget

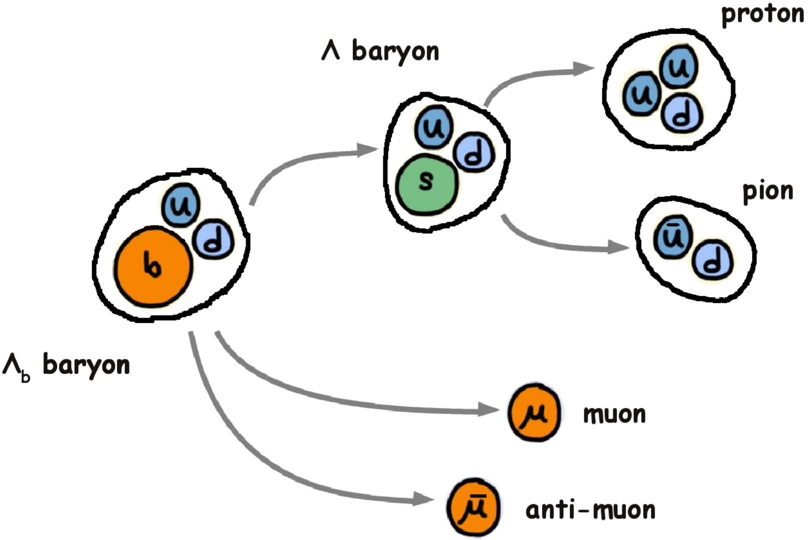
- CKM elements $\sim$ 4% for B_s; $\sim$ 7% for B_d
- B meson decay constants $\sim$ 4 %
- top mass $\sim$ 1.6%
- "non parametric" uncertainties $\sim$ 1.5 %

Experimental Result for the Branching Ratio

LHCb + CMS Nature **522**, 68-72 + ATLAS arXiv:1604.04263 [hep-ex]



The $\Lambda_b \to \Lambda\mu^+\mu^-$ Decay



SM Predictions for Rare Baryon Decays

$$\Lambda_b \to \Lambda(\to p\pi)\ell^+\ell^-$$

four body final state $\to$ plethora of observables

(Böer et al. 1410.2115; van Dyk, Meinel 1603.02974)

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- QCD factorization for baryons not yet fully developed

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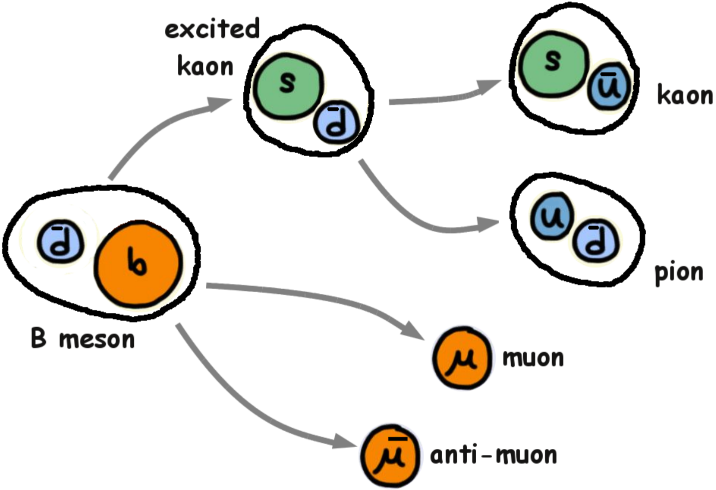
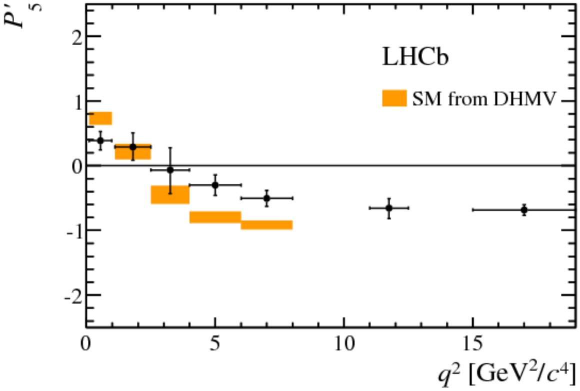
theory effort required to fully exploit the
large number of rare baryon decays at LHCb


excited
kaon
s
d
s
u
kaon
u
d
pion
d
b
B meson
μ
muon
μ
anti-muon

LHCb Collaboration JHEP 1602 (2016) 104



2.8σ in [4,6] GeV^2 bin (+3.0σ in [6,8] GeV^2 bin)

(also supported by recent Belle result arXiv:1604.04042 [hep-ex])

Underestimated Hadronic Contributions? ...

generic structure of the relevant amplitudes (slightly oversimplified)

$$\text{amplitudes} \sim \text{Wilson coefficients} \times \text{form factors} \\ + \text{non-local terms}$$

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form factors

at high q^2 from the lattice

Horgan et al. 1310.3722

Bouchard et al. 1306.0434

Bailey et al. 1509.06235

at low q^2 from LCSR

Ball, Zwicky hep-ph/0412079

Bharucha, Straub, Zwicky 1503.05534

up to 10%-15% differences
with heavy quark limit

Jäger, Martin Camalich 1412.3183

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non-local terms

known at NLO in α_s in heavy quark limit

beyond heavy quark limit, e.g. soft gluon correction to charm loop

Khodjamirian et al. 1006.4945

...

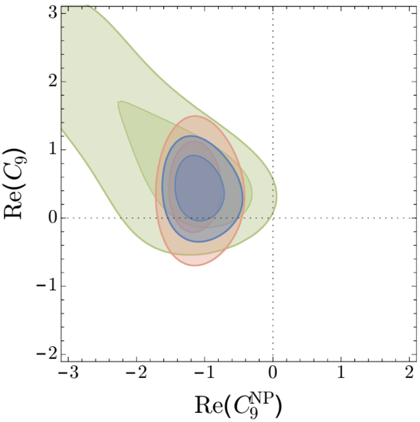
uncertainties of O(10%) ?

should one try to fit the hadronic corrections?

Ciuchini et al. 1512.07157

WA, Straub Eur. Phys. J. C75 (2015) no.8, 382
(update in 1503.06199)

Perform global fits of all relevant rare decay data



$$O_9 \propto (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$$

$$O_9' \propto (\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu \mu)$$

muonic vector current

$$\sqrt{\Delta\chi^2} = 3.9$$

(see also Beaujean et al.; Descotes-Genon et al.; Hurth et al.; ...)

Implications for the New Physics Scale

generic tree	$\frac{1}{\Lambda_{\rm NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 35$ TeV
MFV tree	$\frac{1}{\Lambda_{\rm NP}^2}\, V_{tb}V_{ts}^*\, (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 7$ TeV
generic loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 3$ TeV
MFV loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}\, V_{tb}V_{ts}^*\, (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 0.6$ TeV

Distinguishing New Physics from Hadronic Effects

	LFU violation
hadronic effects?	✗
New Physics?	✓

Distinguishing New Physics from Hadronic Effects

	LFU violation	RH currents
hadronic effects?	✗	✗
New Physics?	✓	✓

Distinguishing New Physics from Hadronic Effects

	LFU violation	RH currents	CP violation
hadronic effects?	✗	✗	✗
New Physics?	✓	✓	✓

Distinguishing New Physics from Hadronic Effects

	LFU violation	RH currents	CP violation	non-trivial q^2 dependence
hadronic effects?	✗	✗	✗	✓
(heavy) New Physics?	✓	✓	✓	✗

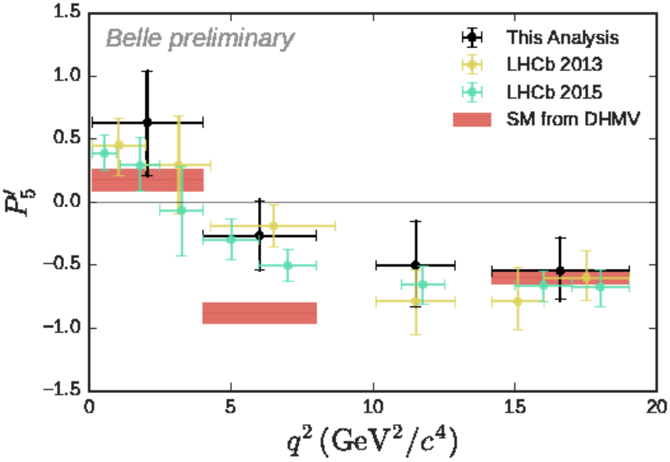
Summary

- Rare b decays are highly sensitive to new physics up to tens of TeV
- SM predictions have in many cases reached uncertainties of less than 10%
- Some experimental results show discrepancies with SM expectations
- Statistical fluctuations? Hadronic effects? New physics?
- Looking forward to an exciting future with new data from LHC(b) and Belle II

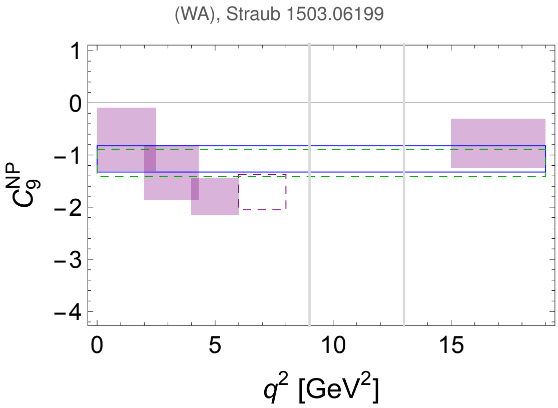
Back Up

The $B \to K^* \mu^+ \mu^-$ Anomaly at Belle

Belle Collaboration arXiv:1604.04042 [hep-ex]



q^2 Dependence of the Anomaly



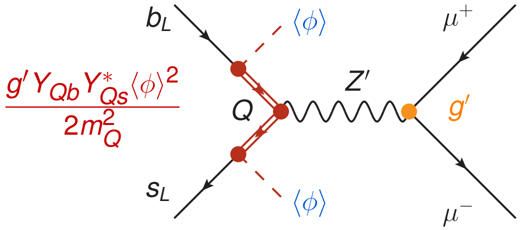
compatible with a q^2 independent short distance contribution from new physics

preferred value for C_9 seems to increase closer to the J/ψ
$\rightarrow$ indication for a charm loop effect?

My Favorite Model for the Anomaly

Z' based on gauging $L_\mu - L_\tau$
with effective flavor violating couplings to quarks

WA, Gori, Pospelov, Yavin 1403.1269



$$C_9 = \frac{Y_{Qb} Y^*_{Qs}}{2m_Q^2}$$

Q: heavy vector-like fermions with mass $\sim 1 - 10$ TeV
ϕ: scalar that breaks $L_\mu - L_\tau$

Probing the Z' Parameter Space

WA, Gori, Pospelov, Yavin, 1406.2332