Rare decays at LHC
LHCb, CMS and ATLAS results

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Interplay between Particle & Astroparticle physics
2014
Motivation

The Standard Model (SM) is an exhaustive theory able to explain the particles interactions and make many predictions with a very high precision ...

... still suffers of a series of theoretical and cosmological problems

hierarchy problem: how to get from Planck scale ($10^{19}$ GeV) to EW scale (100 GeV) without “fine tuning” quantum corrections?

flavor puzzle: unexplained hierarchical structure of the Yukawa coupling

matter-antimatter asymmetry: from current measurements baryogenesis can only generate $10^{-20}$, but $10^{-10}$ is needed

no good candidate for dark matter

neutrino oscillations, .... gravity

Standard Model (SM) is likely to be the low-energy limit of a more fundamental theory, with new degrees of freedom. Expect New Physics (NP).
Motivation (2)

What is a “rare decay”

A decay that is forbidden by a symmetry of the Standard Model (SM) or highly suppressed to such an extent that it cannot be observed in any plausible experiment (e.g. charged lepton flavor violation, Baryon number violation)

A decay that occurs in the Standard Model only at loop level (FCNC forbidden at tree level, e.g. penguin or box diagrams) and for which the BF and/or differential distributions of final state particles may be sensitive to new physics

Rare decays is a rich soil to look at if we want to test the standard model and/or find new physics beyond it

Two complementary ways to look for NP:

direct searches [ATLAS and CMS]: NP particles decays
indirect searches [ATLAS, CMS, and LHCb]: discrepancies from the SM predictions due to NP contribution (we “already observe” NP, but difficult to distinguish from SM)
Outline

Search for SM forbidden decay

- Search for heavy Majorana neutrinos in B mesons decays

Study of SM-allowed rare decays

- $B_s \rightarrow \mu^+\mu^-$ and $B_d \rightarrow \mu^+\mu^-$
- $B^0 \rightarrow K^{*0} \mu^+\mu^-$ decay: BF and angular analysis
- Photon polarization in $b \rightarrow s\gamma$ transition
The tools

ATLAS and CMS largely in central region (|η|<2.4), LHCb forward region (2<η<5)

Measured $\sigma(pp\to bbX)$ cross-section (at 7 TeV):
\begin{align*}
\text{ATLAS} & \quad (32.7 \pm 0.8^{+5.8}_{-5.6}) \, \mu b \quad \text{(pT(B) > 9 GeV and |η| < 2.5)} \\
\text{CMS} & \quad (28.1 \pm 2.4 \pm 2.0 \pm 3.1) \, \mu b \quad \text{(pT(B) > 5 GeV and |η| < 2.4)} \\
\text{LHCb} & \quad (75.3 \pm 5.4 \pm 13.0) \, \mu b \quad \text{(2<η<6)}
\end{align*}

Each experiment: $O(10^{10})$/fb bb pairs on tape

Compare to combined BaBar and Belle data sample of $\sim10^9 B^0\bar{B}^0$ pairs. For any channel where the (trigger, reconstruction, stripping, offline) efficiency is not too small, LHC have the \textbf{world's largest data sample}... the right place to look for very rare B decays.
Search for Majorana neutrinos in $B^- \to \pi^+\mu^-\mu^-$

- Forbidden LNV decay, probes Majorana neutrino **masses** between **250 MeV** and **5000 MeV**
- Search valid for neutrino **lifetimes** between **1 ps** and **1000 ps**
- Measurement with all the **3 fb^{-1} LHCb** data
- **Normalised** to $B^- \to J/\psi K^-$
- Combinatorial background from sidebands fit, peaking background from simulation

PRL 112, 131802 (2014)
Search for Majorana neutrinos in $B^- \rightarrow \pi^+\mu^+\mu^-$

- No signal observed $\rightarrow$ **limit as a function of $m_{\nu}$ and $\tau_{\nu}$ using $CL_S$ method**
- $BF(B^- \rightarrow \pi^+\mu^+\mu^-) < 4.0\cdot10^{-9}$ at 95% CL
- From BF limit it is possible to extract a limit on the fourth generation coupling $|V_{\mu 4}|^2$, as a function of neutrino mass (A. Atre et al., JHEP 05(2009)030)
Search for Majorana neutrinos in $B^- \rightarrow \pi^+ \mu^- \mu^-$

In the $B^- \rightarrow \pi^+ \mu^- \mu^-$ and $B^- \rightarrow K^+ \mu^- \mu^-$ decays, LHCb lower in a sizable way the previous BABAR limits.
\[ B_{d,s} \rightarrow \mu^+ \mu^- \]
$B_{s(d)} \to \mu^+\mu^-$

$B^0$ and $B_s \to \mu^+\mu^-$ decays are both **GIM (loop) and helicity suppressed**

Sensitive to contributions from (pseudo)scalar sector. Interesting **probe to NP models** with extended Higgs sectors (e.g. MSSM, 2HDM, . . . )

Very **precise prediction** in the SM

<table>
<thead>
<tr>
<th>$B_s \to \mu^+\mu^-$</th>
<th>$(3.65 \pm 0.23) \times 10^{-9}$</th>
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<tbody>
<tr>
<td>$B^0 \to \mu^+\mu^-$</td>
<td>$(1.06 \pm 0.09) \times 10^{-10}$</td>
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In the Minimal SUSY Model

$$B(\mathcal{B}(\mathcal{B}_s \to \mu^+\mu^-)_{\text{MSSM}} \propto \frac{m_b^2 m_{\mu}^2 \tan^6 \beta}{m_A^4}$$

Very sensitive to the $\beta$ and $m_A$ parameters


Theory error budget

Bobeth et al. PRL 112 101801 (2014)
$B_s(d) \rightarrow \mu^+\mu^-$ at CMS

Normalise to $B^+ \rightarrow J/\Psi K^+$

Use multivariate classifier (BDT) and tight particle identification requirements

Selection cuts differentiated for barrel and endcap region (all other pairs).

BDT stable versus event multiplicity

In the figure events are weighted with $S/\sqrt{S+B}$

$\mathcal{B}(B_s \rightarrow \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$

$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 1.1 \times 10^{-9}$

$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10}$

ATLAS: $\mathcal{B}(B_s \rightarrow \mu^+\mu^-) < 1.5 \times 10^{-8}$

[ATLAS-CONF-2013-076]

25 fb$^{-1}$: 4.3σ / 95% CL

20 August 2014 IPA workshop, 18-22 August, London
$B_s(d) \rightarrow \mu^+\mu^- \text{ at LHCb}$

A typical $B_s \rightarrow \mu\mu$ decay candidate event
$B_s(d) \rightarrow \mu^+\mu^-$ at LHCb

- **Normalise** to $B_s \rightarrow J/\Psi \Phi$, $B^+ \rightarrow J/\Psi K^+$, $B^0 \rightarrow K\pi$

- **Background rejection** key for rare decay searches → use **multivariate classifiers (BDTs)** and tight particle identification requirements

- BDT calibrated on $B \rightarrow hh$ and the $\mu^+\mu^-$ mass. All points in mass window are used in result, but only BDT > 0.7 shown below

- Search in a two dimensional plane of invariant mass and BDT (blind analysis)

- Unbinned maximum likelihood (UML) fit in case of signal, CLs method for the limits

\[ B(B^0 \rightarrow \mu^+\mu^-) = 2.9^{+1.1}_{-1.0} (\text{stat})^{+0.3}_{-0.1} (\text{syst}) \times 10^{-9} \]

\[ B(B^0 \rightarrow \mu^+\mu^-) = 3.7^{+2.4}_{-2.1} (\text{stat})^{+0.6}_{-0.4} (\text{syst}) \times 10^{-10} \]

3 fb$^{-1}$, 4σ / 2σ significance
**$B_s \to \mu^+ \mu^-$: CMS+LHCb average**

Naive combination (central value, no significance assessment)

\[
\mathcal{B}(B_s^0 \to \mu^+ \mu^-) = 2.9 \pm 0.7 \times 10^{-9} \\
\mathcal{B}(B^0 \to \mu^+ \mu^-) = 3.6^{+1.6}_{-1.4} \times 10^{-10}
\]

Work is ongoing to do a full combination of LHCb and CMS measurements: combined fit to the two datasets, sharing of all PDFs etc.

$B_s \to \mu^+ \mu^-$ in excellent agreement with SM prediction, $B_d \to \mu^+ \mu^-$ shows small excess (still < 2σ)

20 August 2014
IPA workshop, 18-22 August, London
$B_s \rightarrow \mu^+\mu^-$: closing up on NP

$10^9 \times \text{BR}(B_s \rightarrow \mu^+\mu^-)$

- MSSM-LL
- MSSM-RVV2
- MFV
- MSSM-AKM
- MSSM-AC
- SM
- SM4
- CDF 95% C.L.

July 2011

D.Straub arXiv:1205.6094
$B_s \rightarrow \mu^+\mu^-$: closing up on NP

D. Straub arXiv:1205.6094

March 2012
\(B_s \rightarrow \mu^+\mu^-\): closing up on NP

“The value of a negative result […] Arguably, this year’s most significant result from CERN was a negative one. […] This kind of result doesn’t generate the same media attention that comes with a discovery, but by focusing theoretical attention in the right place it can be very positive for the evolution of the field” Rolf Heuer
\[ B \rightarrow s l^+ l^- \]
$B \rightarrow s \mu^+\mu^-$ Introduction

$b \rightarrow s/d \, l^+l^-\, \text{FCNC processes represent a very rich environment.}$

The three/four particles final states are special as:

- They allow for a wealth of angular observables, rates and asymmetries sensitive to NP
- Experimentally clean signatures
- Theoretically well predicted

Sensitive to magnetic, vector, and axial semileptonic penguin operators: O7, O9, O10
B → K* μ⁺μ⁻ at LHCb

Decay described in three angles (θ_l, θ_K, φ) and dimuon mass q²

Fit to θ_l, θ_K, φ and q² to extract the interesting parameters

\[ \frac{1}{\Gamma} \frac{d^4\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi dq^2} = \frac{9}{16\pi} \left[ F_L \cos^2\theta_K + \frac{3}{4}(1 - F_L)(1 - \cos^2\theta_K) + \right. \\ \left. F_L \cos^2\theta_K (2 \cos^2\theta_\ell - 1) + \right. \\ \frac{1}{4}(1 - F_L)(1 - \cos^2\theta_K)(2 \cos^2\theta_\ell - 1) + \right. \\ S_3(1 - \cos^2\theta_K)(1 - \cos^2\theta_\ell) \cos 2\phi + \right. \\ \frac{4}{3} A_{FB} (1 - \cos^2\theta_K) \cos \theta_\ell + \right. \\ S_9(1 - \cos^2\theta_K)(1 - \cos^2\theta_\ell) \sin 2\phi \right] \]

- Forward-backward asymmetry \( S_6 = \frac{4}{3} A_{FB} \)
- Transverse asymmetry \( S_3 = (1-F_L)A_T^2 \)
- Fraction of longitudinal K* polarization \( F_L \)
- CP asymmetry \( S_9 \)
B $\rightarrow$ K* $\mu^+\mu^-$ at LHCb

Select B $\rightarrow$ K* $\mu^+\mu^-$ using BDT selection

Cut on J/$\Psi$ and $\Psi(2S)$: these events are used to study systematic effects

Normalize to B$^0 \rightarrow$ J/$\Psi$ K*

Observe 883 ± 34 events in 1 fb$^{-1}$

Bin in $q^2 = m(\mu^+\mu^-)^2$ in order to measure all the quantities as a function of $q^2$

SM: [Bobeth et al., JHEP 1107:067, 2011]
B → K* μ+μ- at ATLAS and CMS

Integrating over two of three angles

\[ \frac{1}{\Gamma} \frac{d\Gamma}{d\phi} = \frac{1}{2\pi} \left( 1 + S_3 \cos 2\phi + A_9 \sin 2\phi \right), \]

\[ \frac{1}{\Gamma} \frac{d\Gamma}{d\cos \theta_K} = \frac{3}{2} F_L \cos^2 \theta_K + \frac{3}{4} (1 - F_L) (1 - \cos^2 \theta_K), \]

\[ \frac{1}{\Gamma} \frac{d\Gamma}{d\cos \theta_\ell} = \frac{3}{4} F_L (1 - \cos^2 \theta_\ell) + \frac{3}{8} (1 - F_L) (1 + \cos^2 \theta_\ell) + A_{FB} \cos \theta_\ell. \]

Cut out J/ψ and ψ(2S)

**CMS** observe 415±30 events in 5.2 fb⁻¹ (2011)

**ATLAS** 466±34 in 4.9 fb⁻¹
**B → K* μ+μ- branching fractions**

Comparison of all the BF measurements
No evident discrepancy with SM

CDF [CONF Note 10894]
Belle [PRL 103 (2009) 171801]
BaBar [PRD 86 (2012) 032012]
ATLAS [CONF-2013-038]
Theory (SM) [JHEP 1107 (2011) 067]
B → K* μ⁺μ⁻ angular distribution

ATLAS (prelim.) [ATLAS-CONF-2013-038], CMS 5.2 fb⁻¹ [PLB 727 (2013) 77], LHCb 1 fb⁻¹ [JHEP 08 (2013) 131]

Theory prediction from Bobeth et al. [JHEP 07 (2011)] and references therein.
**P'$_5$ anomaly**

LHCb also measured

\[ P'_{4,5} = \frac{S_{4,5}}{\sqrt{F_L(1 - F_L)}} \]

which are quite free from form-factor uncertainties [Decotes-Genon et al. JHEP 05 (2013) 137]

Local discrepancy in P'$_5$ at 3.7σ (probability that at least one bin varies by this much is 0.5%)

![Graphs showing data and predictions for P'$_4$ and P'$_5$](image)
$P'_5$ anomaly

Many theoretical papers to understand data

Altmannshofer & Straub perform a global analysis and find discrepancies at the level of 3σ. Data best described by modified $C_9$, by introducing a flavour-changing Z' boson at O(1TeV or higher). [EPJC 73 2646 (2013), Gaul, Goertz & Haisch, JHEP 01 (2014) 069]

Data could be also explained by floating form-factor uncertainties. In this way the discrepancy can be reduced to $\approx 2\sigma$. [Jaeger & Camalich, JHEP 05 (2013) 043]

Lattice QCD predictions + measurements in related channels can help clarify the situation
Differential BFs of $B \to K^{(*)} \mu^+\mu^-$

Reconstruct $B^+ \to K^+\mu^+\mu^-$

$B^+ \to K^+J/\psi$ is taken as normalisation mode.

Removing the charmonia, one gets the mass plot

... and the differential branching fraction versus $q^2 = m^2(\mu^+\mu^-)$

Standard Model prediction from
JHEP 07 (2011) 067, [JHEP 01 (2012) 107]

Lattice input from
[PRL 111 (2013) 162002], [arXiv:1310.3887]
Differential BFs of $B \to K(\ast) \mu^+\mu^-$

Reconstruct $B^0 \to K^0 \mu^+\mu^-$ ($K^0$ from $K_S \to \pi^+\pi^-$)

$B^0 \to K_S J/\psi$ is taken as normalisation mode.

Much lower statistics due to high $K_S$ lifetime.

The theoretical expectation of $dB/dq^2$ is the same up to $\tau_{B^0} = \tau_{B^+}$

The BFs are compatible with the SM expectation, but on the low side

[arXiv:1403.8044]
B $\rightarrow$ K(*) $\mu^+\mu^-$ isospin asymmetry

$$A_I = \frac{B(B^0 \rightarrow K(*)^0 \mu^+\mu^-) - \frac{\tau_0}{\tau_+} B(B^+ \rightarrow K(*)^+ \mu^+\mu^-)}{B(B^0 \rightarrow K(*)^0 \mu^+\mu^-) + \frac{\tau_0}{\tau_+} B(B^+ \rightarrow K(*)^+ \mu^+\mu^-)}$$

SM prediction is close to zero
The isospin asymmetry is compatible with zero at the 1.5$\sigma$ level
**B^+ → K^+ μ^+μ^- vs B^+ → K^+ e^+e^-**

Measurements of *different dilepton* final states in \( b \rightarrow s l^+l^- \) can test the lepton and flavor couplings simultaneously.

Consider the *ratio of decay rates* for \( B^+ \rightarrow K^+μ^+μ^- \) and \( B^+ \rightarrow K^+e^+e^- \)

\[
R \equiv \frac{\int_{4m_{μ}^2}^{q_{max}^2} dq^2 \frac{dΓ(B^+→K^+μ^+μ^-)}{dq^2}}{\int_{4m_{e}^2}^{q_{max}^2} dq^2 \frac{dΓ(B^+→K^+e^+e^-)}{dq^2}}
\]

Enable *more precise* predictions than the O(30%) theoretical error in the single BR!

**Standard model:**

\[
R_{SM}^H = 1 + O(m_{μ}^2/m_b^2)
\]

Equality of coupling is concept of *lepton universality*.

Enhancement for either muon or electron modes can come from anything which breaks lepton universality, for example *R-parity violating models*. 

Hiller, Kruger: 0310219

LHCb: arXiv:1406.6482
$B^+ \rightarrow K^+ \mu^+\mu^-$ vs $B^+ \rightarrow K^+ e^+e^-$ at LHCb

$R_K = 0.745^{+0.090}_{-0.074} (stat) \pm 0.036 (syst)$

(2.6 $\sigma$ from 1)

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BABAR arXiv: 1204.3933
Belle, arXiv: 0904.0770
LHCb: arXiv:1406.6482

LHCb: arXiv:1406.6482
$b \rightarrow s\gamma$
No tree diagram → suppressed

First penguin ever observed (92) by CLEO Experiment (WA): $\text{BF} = (3.40 \pm 0.21) \cdot 10^{-4}$

SM: $\text{BF} = (3.15 \pm 0.23) \cdot 10^{-4}$

[Misiak et al., hep-ph/0609232]

Strong **constraint** on New Physics
Photon polarization in $b \rightarrow s\gamma$ transition

Polarisation so far unobserved.

The SM predicts the photon in $b \rightarrow s$ is left-handed (charged current interaction). Naively

$$r = \frac{C_{\gamma\gamma}'}{C_{\gamma\gamma}}, \quad r_{SM} \sim \frac{m_s}{m_b}$$

Gluons contribute a few percent [Ball & Zwicky PLB642:478,2006]

Right-handed operators could contribute

Photon polarization can be measured studying $B^+ \rightarrow K^{**}(K^+\pi^+\pi^-)\gamma$ [Gronau & Pirjol, PRD 66 (2002) 054008]

Can infer the photon polarisation from the up-down asymmetry of the photon direction in the $K^+\pi^+\pi^-$ rest-frame. Unpolarised photons would have no asymmetry

$$A_{ud} \equiv \frac{\int_0^1 d\cos \theta \frac{d\Gamma}{d\cos \theta} - \int_{-1}^0 d\cos \theta \frac{d\Gamma}{d\cos \theta}}{\int_{-1}^1 d\cos \theta \frac{d\Gamma}{d\cos \theta}}$$
At LHCb we look at $B^+ \rightarrow K^{+}\pi^{+}\pi^{-}\gamma$ decays using calorimeter photons.

Observe 13000 signal candidates in 3 fb$^{-1}$

There are a large number of overlapping resonances in the $m(K^{+}\pi^{+}\pi^{-})$ mass spectra. No attempt is made to separate these in the analysis, we simply bin in 4 bins of $m(K^{+}\pi^{+}\pi^{-})$. 

[Figures showing mass spectra and signal candidates]
Combining the 4 bins, the photon is observed to be polarised at $5.2\sigma$.

Unfortunately you need to understand the hadronic system to know if the polarisation is left-handed, as expected in the SM.

**First observation** of photon polarisation in $b \to s$ decays

**Best Fit,** $\text{Fit with } (C'7 - C7)/(C'7 + C7) = 0$
Conclusions

Rare decays are **powerful way to search for new physics** beyond the Standard Model.

$B_s \rightarrow \mu^+\mu^-$ and $b \rightarrow s$ transitions **do not highlight large SUSY effects**. Severe constraints to NP models.

Interesting **deviation** from the SM in $B \rightarrow K^*\mu\mu$.

Many analyses are still to be updated with the full Run I dataset. Many new results to come.

**Thank you for the attention!**
Spares
Search for Majorana neutrinos in $D^+_{(s)} \rightarrow \pi^-\mu^+\mu^+$

$D^+_{(s)} \rightarrow \pi^-\mu^+\mu^+$ decay can occur via leptonic mixing via a Majorana neutrino exchange.

**Previous limits** was from BaBar $2 \times 10^{-6}$ and $1.4 \times 10^{-5}$ for $D^+ \rightarrow \pi^-\mu^+\mu^+$ and $D^+_s \rightarrow \pi^-\mu^+\mu^+$ respectively.

Normalise to $D^+ \rightarrow \pi^-\mu^+\mu^+$

Event selection with PID cut and multivariate analysis (BDT) using geometric and kinematic variables

Peaking background from $D^+ \rightarrow \pi^-\pi^+\pi^+$ (gray) with shape extracted from data.

Fit in bins of $m(\pi^-\mu^+)$ to improve statistical significance.

Limits are $2.2 \times 10^{-8}$ and $1.2 \times 10^{-7}$ for $D^+ \rightarrow \pi^-\mu^+\mu^+$ and $D^+_s \rightarrow \pi^-\mu^+\mu^+$ respectively.
Something new

Branching Fraction measurements at high $q^2$ in tension with SM predictions from the Lattice, and consistent with best fit point for NP from low $q^2$

→ NP or unaccounted QCD effects?
Something new? or something new to understand?

Lattice QCD predictions + measurements in related channels (e.g $b \rightarrow d \mu^+ \mu^-$) (to reveal information on MFV nature of NP) can help clarify the situation at high $q^2$