B→K*ee, JHEP 05 (2013) 159, [arXiv:1304.3035]
Kᵈ→μμ, JHEP 01 (2013) 090, [arXiv:1209.4029]

(1fb⁻¹) (1fb⁻¹) (3fb⁻¹) (3fb⁻¹) (1fb⁻¹) (1fb⁻¹) (0.9fb⁻¹) (1fb⁻¹) (1fb⁻¹) (1fb⁻¹) (1fb⁻¹) (1fb⁻¹) (1fb⁻¹) (1fb⁻¹) (1fb⁻¹) (1fb⁻¹) (1fb⁻¹) (1fb⁻¹) (1fb⁻¹)
Outline

- Rare B decays
- The LHCb experiment
- Leptonic decays: $B_{s/d} \rightarrow \mu^+ \mu^-$
- Lepton Flavour Violation: $B_{s/d} \rightarrow e^+ \mu^-$
- Semi(di)leptonic decays: $B_d \rightarrow K^*0 \mu^+ \mu^-$
- Radiative decays: $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$
- Conclusions
Rare B decays

- $b \rightarrow s$ transitions are **Flavor Changing Neutral Currents (FCNCs)**, forbidden in the Standard Model (SM) at tree level → they go through loops (*penguin and box diagrams*)

- **Leptonic**, **semileptonic** and **radiative** $b \rightarrow s$ decays are of particular interest since the SM rates (and other observables) can be calculated with high precision using effective theories (in terms of the Wilson coefficients)

- Rare (and very rare) processes: $\text{BR}_{\text{SM}} \sim 10^{-5} – 10^{-10}$, but experimentally accessible by flavour experiments (*B- factories & LHCb*) → Experimental signature: high $P_T$ leptons/photons

- Excellent probe for physics beyond the SM → sensitivity to **new heavy particles** in the loops
The LHCb experiment
The LHCb experiment

- LHC: Large $b\bar{b}$ cross section in pp collisions (gluon fusion) ($\sim 250 \, \mu\text{b} - 500 \, \mu\text{b} @ \sqrt{s}=7 - 14 \text{ TeV}$):
- LHCb: single-arm forward spectrometer ($2 < \eta < 5$): 
  $\sim 4\%$ of the solid angle, $\sim 30\%$ of the $b$ hadron production
- Very good performance: $3 \, \text{fb}^{-1}$ accumulated in Run1

LHCb Integrated Luminosity

LHCb beams are adjusted to level luminosity $\mathcal{L}_\text{inst.} \sim 4 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$
The LHCb experiment
Precise tracking
Good mass and Impact Parameter (IP) resolution
Good vertex resolution
The LHCb experiment

Excellent particle identification
π/K separation over 2-100 GeV
Powerful μ identification

Calorimeter system
Trigger
Photon reconstruction
Leptonic decays: $B_{s/d} \rightarrow \mu^+ \mu^-$

- FCNC + helicity suppressed $\rightarrow$ Very Rare decay:

Standard Model prediction:

\[
\mathcal{B}(B_{s}^{0} \rightarrow \mu^+ \mu^-) = (3.35 \pm 0.28) \times 10^{-9},
\]
\[
\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (1.07 \pm 0.10) \times 10^{-10}.
\]

- First evidence by LHCb in 2012 [LHCb, PRL110 (2013)021801] (2fb$^{-1}$)

$\rightarrow$ Now updated with 3fb$^{-1}$

FIRST EVIDENCE (3.5σ)
Leptonic decays: $B_s/d \rightarrow \mu^+\mu^-$

[**LHCb, PRL 111 (2013) 101805**] (3fb⁻¹)

- Reconstruct opposite charged muons making a good vertex and separated from the PV, with $m_{\mu\mu}$ in the range [4.9-6] GeV/c²
- Data control channels and normalization using the $B^+ \rightarrow J/\Psi K^+$ ($J/\Psi \rightarrow \mu^+\mu^-$) and $B_d \rightarrow K\pi$ ($\pi\pi, KK$) decays with similar selection
- Signal and background discrimination based on the invariant mass and Boosted Decision Tree (BDT), using kinematic and topological properties (trained with MC signal and $bb \rightarrow \mu\mu X$ background)

- Blind analysis: don’t look the data in $m(B_{d/s}) \pm 60$ MeV/c² until the end of the analysis
**Leptonic decays:** $B_{s/d} \rightarrow \mu^+ \mu^-$

- Signal shape derived from $B_{d/s} \rightarrow K\pi$ data and dimuon resonances (same topology as the signal):

- Background from dimuon mass sidebands:

$\Rightarrow$ BDT output (defined to be flat for signal and peaked at 0 for background):
Leptonic decays: $B_s/d \rightarrow \mu^+\mu^-$

- Two different normalization channels used:
  
  $$B^+ \rightarrow J/\psi K^+$$

  - Similar trigger, one additional track

  $$B_d \rightarrow K\pi$$

  - Same topology, different trigger

  - $\approx 1.1$M events

  - $\approx 38k$ events

\[
\mathcal{B}(B^0_{(s)} \rightarrow \mu^+\mu^-) = \frac{\mathcal{B}_{\text{norm}} \varepsilon_{\text{norm}} f_{\text{norm}}}{N_{\text{norm}} \varepsilon_{\text{sig}} f_d(s)} \times N_{B^0_{(s)} \rightarrow \mu^+\mu^-}
\]

$\varepsilon_{\text{sig}}$ and $\varepsilon_{\text{norm}} = \varepsilon_{\text{trigger}} \times \varepsilon_{\text{selection}} \times \varepsilon_{\text{reconstruction}}$

$f_{\text{norm}}$ and $f_d(s) =$ production fractions @ LHCb  \[LHCb-CONF-2013-011\]

→ The 2 normalization channels give compatible results
Leptonic decays: $\text{B}_s/d \rightarrow \mu^+\mu^-$

- Results:

\[
\begin{align*}
\text{BR}(\text{B}_s^0 \rightarrow \mu^+\mu^-) &= (2.9^{+1.1}_{-1.0} \text{ (stat)}^{+0.3}_{-0.1} \text{ (syst)}) \times 10^{-9} \\
\text{BR}(\text{B}^0 \rightarrow \mu^+\mu^-) &= (3.7^{+2.4}_{-2.1} \text{ (stat)}^{+0.6}_{-0.4} \text{ (syst)}) \times 10^{-10}
\end{align*}
\]

Significance: 4.0 $\sigma$

Significance: 2.0 $\sigma$

@ 95% C.L:
Leptonic decays: $B_{s/d} \rightarrow \mu^+\mu^-$

- Combination with CMS: [CMS PAS BPH-13-007]

- New Physics constraints:

[D.M. Straub, arXiv:1205.6094]
Lepton Flavour Violation: $B_{s/d} \rightarrow e^+\mu^-$

- Forbidden in the Standard Model
- Constrain New Physics models: Pati-Salam -LeptoQuarks (LQ)- model, 2HDM (Type III) ...

\[ \begin{array}{c}
\text{b} & \text{e(\mu)} \\
B_s & \text{LQ} \\
\bar{s} & \text{\mu(e)} \\
\end{array} \]

- Similar analysis method to $B_{s/d} \rightarrow \mu^+\mu^-$: normalization and control channels $B_{s/d} \rightarrow K\pi$ (KK, $\pi\pi$)

[**LHCb, PRL 111 (2013) 141801**] (1fb$^{-1}$)
Lepton Flavour Violation: $B_{s/d} \rightarrow e^+\mu^-$

- Results:

\[ \mathcal{B}(B_{s}^{0} \rightarrow e^\pm \mu^\mp) < 1.1 (1.4) \times 10^{-8} \]

\[ \mathcal{B}(B^{0} \rightarrow e^\pm \mu^\mp) < 2.8 (3.7) \times 10^{-9} \]

→ Largely improves (~ /20) CDF limits [PRL102(2009)201801]
Lepton Flavour Violation: $B_{s/d} \rightarrow e^+\mu^-$

- New Physics constraints: Pati-Salam Model (coupling different generations)

$$M_{LQ}(B_{s}^0 \rightarrow e^{\pm}\mu^{\mp}) > 107\ (101)\ \text{TeV}/c^2$$
$$M_{LQ}(B^0 \rightarrow e^{\pm}\mu^{\mp}) > 135\ (126)\ \text{TeV}/c^2$$

[Pati and A. Salam PRD10(1974)275].

- Direct searches at LEP/TeVatron/DESY/LHC (first generation) [PDG'13]
  (not directly comparable)
Semi(di)leptonic Decays: $B_d \rightarrow K^* \mu^+ \mu^-$

- New Physics amplitudes can modify branching fractions, angular observables, CP and isospin asymmetries ...

- The differential decay width depends on three angles $\theta_\ell$, $\theta_K$, $\phi$ and $q^2=m_{\mu\mu}^2$

\[
\frac{1}{d\Gamma/dq^2} = \frac{d^4 \Gamma}{d \cos \theta_K \, d \phi \, dq^2} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K - F_L \cos^2 \theta_K \cos 2\theta \\
+ \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi \\
+ S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + S_6 \sin^2 \theta_K \cos \theta_\ell \\
+ S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]
\]

- $F_L$ and $S_i$ are observables which are functions of the Wilson coefficients (sensitive to NP) and form factors (long distance effects, non-perturbative methods)

- A new set of observables, $P'_{i=4,5,6,8} = S_{i=4,5,7,8}/\sqrt{F_L(1-F_L)}$ can be defined, being less sensitive to the hadronic form-factors uncertainties

[S. Descotes-Genon, T. Hurth, J. Matias, J. Virto, JHEP 05 (2013) 137]
Semi(di)leptonic Decays: \( B_d \rightarrow K^* \mu^+ \mu^- \)

- Select at least one high \( P_T \) muon (> 1.5GeV/c) and one hadron displaced from PV

- Candidates are retained in the \( K^*(\rightarrow K^+ \pi^-) \) invariant mass range

- Signal selected with a BDT using kinematic, topological and PID info; trained with resonant \( B \rightarrow J/\psi K^* \) data (signal) and data from sidebands (background), and keeping flat the angular acceptance

- \( B \rightarrow J/\psi K^* \) data as control channel for Data/MC efficiencies

- \( \Psi(2S) \) and \( J/\Psi \) resonance regions vetoed

- Analysis performed in six bins of \( q^2 \) and in the region 1<\( q^2 <6 \) GeV\(^2\)
Semi(di)leptonic Decays: $B_d \rightarrow K^* \mu^+ \mu^-$

peaking backgrounds reduced to a negligible level
Semi(di)leptonic Decays: $B_d \rightarrow K^* \mu^+ \mu^-$

In the SM, $A_{FB}$ changes sign as function of $q^2$. The zero crossing-point is free of hadronic uncertainties:

→ First measurement of the zero-crossing point in $A_{FB}$: $q_0^2 = 4.9 \pm 0.9$ GeV$^2$/c$^4$
Semi(di)leptonic Decays: $B_d \rightarrow K^* \mu^+ \mu^-$

- In terms of the new observables $P'_i$:

  ![Graphs showing SM Predictions and Data for $P'_4$, $P'_5$, $P'_8$ with local discrepancy and Wilson coefficient $C_9$.]

  - Agreement with the SM for $P'_4$, $P'_6$, $P'_8$
  - Local discrepancy of $3.7\sigma$ is observed in the interval $4.30 < q^2 < 8.68$ GeV$^2$/c$^4$ for $P'_5$
  - Integrating over the region $1.0 < q^2 < 6.0$ GeV$^2$/c$^4$, the observed discrepancy is $2.5\sigma$

  $\rightarrow C_9$ Wilson coefficient?  (update with 3fb$^{-1}$ in progress)

Comparison with other experiments:

\[ B_d \rightarrow K^* \mu^+ \mu^- \]

[ATLAS-CONF-2013-038]
[CMS PAS BPH-11-009]
Semi(di)leptonic Decays: $B_d \rightarrow K^* \mu^+ \mu^-$

- Other (non angular) observables:

**CP asymmetry:**

$$A_{CP} = \frac{\Gamma(B^0 \rightarrow K^{*0} \mu^+ \mu^-) - \Gamma(B^0 \rightarrow K^{*0} \mu^- \mu^+)}{\Gamma(B^0 \rightarrow K^{*0} \mu^+ \mu^-) + \Gamma(B^0 \rightarrow K^{*0} \mu^- \mu^+)}$$

Corrected for production/detection asymmetry using $B \rightarrow J/\psi K^*$ data →

$$A_{CP} (B^0 \rightarrow K^{*0} \mu^+ \mu^-) = -0.072 \pm 0.040 \pm 0.005$$
Radiative Decays: $B^+ \to K^+ \pi^- \pi^+ \gamma$

- Radiative $b \to s$ decays are also FCNC, with a photon in the final state.
- Branching fractions and CP asymmetries can be largely affected by New Physics contributions.
- In the SM, the photon from $b$ decays is predominantly left handed, with small corrections of order $m_s/m_b \sim 2\%$

$\to$ The photon polarization is then sensitive to the spin structure of the New Physics.
$\to$ It is largely affected in New Physics Models (particularly in Left-Right Symmetric Models).

The photon polarization parameter $\lambda_\gamma$

$$
\lambda_\gamma \equiv \frac{|C_R|^2 - |C_L|^2}{|C_R|^2 + |C_L|^2}
$$

expected to be $-1$ ($\bar{B}$) or $+1$ ($B$) with corrections of $(m_s/m_b)^2$

($C_R$, $C_L$ right and left amplitudes)

Can be extracted by studying the three body decay of a $K_j (J^P)$ resonant state in

$B \to K_{\text{res}} \gamma$ radiative decays

Radiative Decays: $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$

- For a radiative $B \rightarrow K_{\text{res}} \gamma$, with the $K_{\text{res}}$ a three body decay $K_{\text{res}} \rightarrow P_1 P_2 P_3$

$$\frac{d\Gamma(\overline{B} \rightarrow \overline{K}_{\text{res}} \gamma \rightarrow P_1 P_2 P_3 \gamma)}{ds \, ds_{13} \, ds_{23} \, d\cos \theta}$$

with $s_{ij} = (p_i + p_j)^2$; $s = (p_1 + p_2 + p_3)^2$

is the sum of the helicity amplitudes

The **Up-down asymmetry** $A_{\text{UD}}$

$$A_{\text{up-down}} = \frac{\int_0^1 d\cos \theta \frac{d\Gamma}{d\cos \theta} - \int_{-1}^0 d\cos \theta \frac{d\Gamma}{d\cos \theta}}{\int_{-1}^1 d\cos \theta \frac{d\Gamma}{d\cos \theta}} \propto \lambda_\gamma$$

Allows to extract the photon polarization information

→ Need to count the number of events with photon emitted above/below the $\vec{p}_1 \vec{p}_2$-plane and subtract them.

- There are two known $K_1(1^+)$ states, decaying into $K\pi\pi$ final state via $K^*\pi$ and $\rho K$ modes: the $K_1(1270)$ and $K_1(1400)$ resonances, from where the $\lambda_\gamma$ can be measured.
Radiative Decays: $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$

[LHCb-CONF -2013-009] (2fb$^{-1}$)

- Use the full mass range to measure $A_{CP}$

$$A_{CP} = \frac{N(K^-\pi^+\pi^-\gamma) - N(K^+\pi^-\pi^+\gamma)}{N(K^-\pi^+\pi^-\gamma) + N(K^+\pi^-\pi^+\gamma)}$$

- Avoid the interference mass regions to measure $A_{UD}$

$$A_{UD} = \frac{N(K\pi\pi\gamma)_{\cos\theta > 0} - (K\pi\pi\gamma)_{\cos\theta < 0}}{N(K\pi\pi\gamma)_{\cos\theta > 0} + (K\pi\pi\gamma)_{\cos\theta < 0}}$$

(see figure)

- Background substracted $K\pi\pi$ spectrum showing the expected resonant contributions

Individual resonances cannot be resolved without angular analysis, then:

- Reconstruct a kaon resonance from three charged tracks: two pions of opposite sign and a kaon, plus a high $E_T$ photon.
Radiative Decays: $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$

Corrections to raw $A_{CP}$:

$A_{D}$ and $A_{P}$: $0.013 \pm 0.008$

$\Delta A_{CP}^{raw}$: $0.002 \pm 0.001$

Fit model: $0.000 \pm 0.002$

$A_{CP} = -0.007 \pm 0.015 \text{ (stat)} \pm 0.008 \text{ (syst)}$
Radiative Decays: $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$

Contributions to the $A_{ud}$ uncertainties very small ($\sim 1\text{-}3\%$)

$$A_{ud}^+ = -0.084 \pm 0.026 \text{ (stat)} \pm 0.003 \text{ (syst)}$$

$$A_{ud}^- = -0.086 \pm 0.025 \text{ (stat)} \pm 0.002 \text{ (syst)}$$

$A_{ud} = -0.085 \pm 0.019 \text{ (stat)} \pm 0.003 \text{ (syst)}$

Proportional to photon polarization (first evidence at $4.6\sigma$)
Conclusions:

● LHCb has performed very well in Run1: $3\text{fb}^{-1}$
● Rare B decays are probes for Physics Beyond SM
● Many new measurements on Rare Decays at LHCb:
  → $\text{B}$, charm, tau sectors
  → Leptonic, Semi(di)leptonic, Radiative decays

Only a few have been covered here!

● Few discrepancy with SM predictions to be followed
● Completing the analyses with the full statistics
Thank you!