Rare decays, exotica and CP Violation
16. July 2019
Johannes Albrecht, TU Dortmund
on behalf of LHCb, with material from ATLAS & CMS
Introduction

• Historically, most new particles were found after indirect evidence
  – Electroweak precision observables
    → a lot to learn in Higgs couplings, consistency of the SM
  – Flavour

• This talk focuses on flavour physics:
  Search for new heavy particles in measurements of quantum effects

• Flavour measurements test very high scales: $O(10^3 \text{ TeV})$

arXiv:1812.07638
Introduction

• Intense flavour programme at the LHC
  – LHCb: Dedicated flavour physics experiment
  – CMS has exploited parked data to record $10^{10}$ trigger unbiased B decays
    [M. Pierini, HL-LHC workshop 10/18]
  – ATLAS impressive progress in flavour tagging

• Very successful data taking in Run 2
  – Very large production cross section for b-quarks,
    e.g. ~2.5 million $b\bar{b}$-pairs per second in ATLAS/CMS acceptance
  – Significant challenge: Online event selection
    ATLAS & CMS can record a few 100 $b\bar{b}$-pairs per second
  – LHCb runs at lower luminosity, but specialized detector and trigger

• Belle 2 is currently starting up: hope for sporty competition

• This presentation: Review of current flavour data from the LHC
  – CP violation
  – Rare decays
• CP violation in charm
  – Direct CP violation discovered by LHCb earlier this year
  – Search for indirect CPV ongoing
  → CPV in charm not covered here, see talk by K. Müller

• CP violation in beauty
  – Determination of the CKM angle $\gamma$
  – Charmless (amplitude) analyses for CPV
    – $B_s$ decays to charmonium
  → Very broad field, focus here on last aspect with most recent measurements
CP violating phase $\phi_s$

- Time dependent CP violation essentially measures the phase of $V_{ts}$
- Standard Model prediction:
  $\phi_s = -2 \beta_s = -0.04 \pm 0.01$
  
  A. Lenz, arXiv:0705.3802

- Measure CP violating phase in $B_s \to J/\psi K^+ K^-$ and $B_s \to J/\psi \pi^+ \pi^-$ decays
  - $\phi_s$ accessible by a flavour tagged, time dependent angular analysis
ATLAS: $B_S \rightarrow J/\psi KK$ decay to measure CPV

Tagging performance:

$\varepsilon = 14.74\pm0.02\%$

$D = 33.4\pm0.1\%$

$\varepsilon D^2 = 1.65\pm0.01\%$

O. Igonkina, MEW2019
ATLAS: $B_s \rightarrow J/\psi KK$ decay to measure CPV

$B_s \rightarrow J/\psi K^+K^-$
477k signal candidates
$\varepsilon D^2 \sim 1.65\%$

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$\varepsilon = 14.74\pm0.02 \%$
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O. Igonkina, MEW2019
LHCb: CPV in $B_s$ decays: $J/\psi KK$ and $J/\psi \pi\pi$

$B_s \rightarrow J/\psi K^+K^-$

117k signal candidates
$\varepsilon D^2 \sim 5\%$

`arXiv:1906.08356`

$B_s \rightarrow J/\psi \pi^+\pi^-$

34k signal candidates
$\varepsilon D^2 \sim 5\%$

`arXiv:1903.05530`
LHCb: CPV in $B_s$ decays: $J/\psi KK$ and $J/\psi\pi\pi$

$B_s \rightarrow J/\psi K^+K^-$

Vector-vector final state:
3 angular momenta allowed

$L=0, 2$ CP-even
$L=1$ CP-odd
S-wave CP-odd

Disentangle with amplitude analysis

$B_s \rightarrow J/\psi\pi^+\pi^-$

Dominantly $J/\psi f_0(980)$ final state
→ CP-odd, but rich hadronic structure

Disentangle with amplitude analysis

arXiv:1906.08356

arXiv:1903.05530
New results on $\phi_s$

- This March: several updates on $\phi_s$
New results on $\phi_s$

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- ATLAS: impressive $B_s \to J/\psi \phi$ analysis with $\sim 20+80 \text{ fb}^{-1}$
  \[
  \phi_s = -0.076 \pm 0.039 \\
  \Delta \Gamma_S = 0.068 \pm 0.005 \\
  \text{ATLAS-CONF-2019-009}
  \]

- LHCb measures with $\sim 3+2 \text{ fb}^{-1}$ combining $B_s \to J/\psi K^+K^-$ and $B_s \to J/\psi \pi^+\pi^-$
  \[
  \phi_s = -0.041 \pm 0.025 \\
  \Delta \Gamma_S = 0.082 \pm 0.005 \\
  \text{arXiv:1906.08356&1903.05530}
  \]

- Both results and their average very consistent with SM
  \( \to \) both published $\sim \frac{1}{2}$ of their data
Rare decays: Testing $b \rightarrow s \ell^+\ell^-$ transitions

$b \rightarrow s \mu^+\mu^-$ base diagram

- **Purely leptonic**
  - “add nothing”

- **Semileptonic**
  - add d quark as spectator
    $\Rightarrow B^0 \rightarrow K^{*0} \mu^+\mu^-$
  - add s quark as spectator
    $\Rightarrow B_s \rightarrow \phi \mu^+\mu^-$
  - add u quark as spectator
    $\Rightarrow B^+ \rightarrow K^+ \mu^+\mu^-$

- **Lepton Universality**
  - Compare muons to electrons
**BS → µ⁺µ⁻ and B⁰ → µ⁺µ⁻**

**JHEP 04 (2019) 098**

- 25+36fb⁻¹ of Run 1 + 2
  - Most stringent limit on $B_d → $µ⁺µ⁻

**PRL 111 (2013) 101804**

- 25fb⁻¹ of Run 1 data
  - Sensitivity on comparable dataset very similar to LHCb

**PRL 118 (2017) 191801**

- Update: 3+1.4fb⁻¹
  - First single experiment observation

- Effective $B_s$ lifetime also measured

---

**BR($B_s → µ⁺µ⁻$) = $(3.0^{+1.0}_{-0.9}) × 10^{-9}$**

**BR($B^0 → µ⁺µ⁻$) = $(3.5^{+2.1}_{-1.8}) × 10^{-10}$**

$BR(B^0 → µ⁺µ⁻) < 11 × 10^{-10} @ 95\%CL$

**BR($B^0 → µ⁺µ⁻$) < 3.4 × 10^{-10} @ 95\%CL**

---

**Run 1 + Run 2 combined:**

$BR(B_s → µ⁺µ⁻) = (2.8^{+0.8}_{-0.7}) × 10^{-9}$

$BR(B^0 → µ⁺µ⁻) < 2.1 × 10^{-10} @ 95\%CL$

**BS Significance: 4.6σ**

**BS Significance: 4.3σ**

**BS Significance: 7.8σ**

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16. July 2019

Johannes Albrecht

11/25
$B \rightarrow \mu^+ \mu^- :$ Combination from LHC

- Combination of ATLAS, CMS & LHCb

Combining all three LHC experiments

\[
BR(B_s \rightarrow \mu^+ \mu^-) = (2.71 \pm 0.4) \times 10^{-9}
\]

→ agrees within $2\sigma$

ATLAS: JHEP 04 (2019) 098
CMS: PRL111(2013)101804
LHCb: PRL118(2017)191801

SM: Buras, Isidori et al
EPJC72(2012) 2172
$BR(B_s \rightarrow \mu^+ \mu^-) = 3.5 \pm 0.3 \times 10^{-9}$

D. Straub, Moriond EW 2019 & 1903.10434
Rare menu

\[ b \rightarrow s \, \mu^+ \mu^- \text{ base diagram} \]

- **Purely leptonic**
  - “add nothing”

- **Semileptonic**
  - add d quark as spectator
    \[ B^0 \rightarrow K^0 \, \mu^+ \mu^- \]
  - add s quark as spectator
    \[ B_s \rightarrow \phi \, \mu^+ \mu^- \]
  - add u quark as spectator
    \[ B^+ \rightarrow K^+ \, \mu^+ \mu^- \]
  - …

- **Lepton Universality**
  - Compare muons to electrons
Branching fractions of $b \to s \mu^+\mu^-$

- Analysis of large class of $b \to s \mu^+\mu^-$ decays
  - Tendency measure lower BR than SM prediction
    $\Rightarrow$ intriguing hint or theoretical issue in prediction?
- SM predictions suffer from sizeable uncertainties
Angular observables in $b \rightarrow s \mu^+\mu^-$

- Hadronic effects are smaller in angular observables
- Golden decay: $B^0 \rightarrow K^{*0} \mu^+\mu^-$
  - Dynamics can be described by three angles and di-μ mass
  - LHCb has performed the first full angular analysis (Run 1 data, 3fb$^{-1}$)
    → Generally good agreement with SM prediction

[JHEP 02 (2016) 104]
Angular observables in $b \to s \mu^+\mu^-$

• Hadronic effects are smaller in angular observables
• Golden decay: $B^0 \to K^{*0} \mu^+\mu^-$
  – Dynamics can be described by three angles and di-\(\mu\) mass
  – LHCb has performed the first full angular analysis
  → Generally good agreement with SM prediction
  – ATLAS and CMS see consistent picture

[PLB 753 (2016) 424] [JHEP 10 (2018) 047]
Puzzling deviations: $B^0 \rightarrow K^{*0} \mu^+\mu^-$

- Ratios of observables show reduced dependence on form factors. Let's construct observables like:

$$P_5' = \frac{S_5}{\sqrt{F_L(1 - F_L)}}$$

Form factor free at leading order.

- LHCb sees puzzling deviation in observable $P_5'$

![Graph showing $P_5'$ vs $q^2$]
Puzzling deviations: $B^0 \to K^{*0} \mu^+\mu^-$

- Ratios of observables show reduced dependence on form factors.
  - construct observables like

\[
P_5' = \frac{S_5}{\sqrt{F_L(1 - F_L)}}
\]

Form factor free at leading order

- LHCb sees puzzling deviation in observable $P_5'$
- Adding ATLAS, CMS, Belle data does not make picture conclusive

LHCb: JHEP 02 (2016) 104
BELLE: PRL 118 (2017)
ATLAS ATLAS-CONF-2017-023
CMS PLB 781 (2018) 517541
Puzzling deviations: $B^0 \to K^{*0} \mu^+ \mu^-$

- Ratios of observables show reduced dependence on form factors
  → construct observables like

$$P_5' = \frac{S_5}{\sqrt{F_L (1 - F_L)}}$$

  Form factor free at leading order

- LHCb sees puzzling deviation in observable $P_5'$
- Adding ATLAS, CMS, Belle data does not make picture conclusive

- Consistent picture in BF and angular data, best fit:
  - Shifted vector coupling [$C_9$]
  - Or vector and axial-vector [$C_9$ & $C_{10}$]

- Need more $b \to s \mu^+ \mu^-$ data to establish anomalies

LHCb: JHEP 02 (2016) 104
BELLE: PRL 118 (2017)
ATLAS ATLAS-CONF-2017-023
CMS PLB 781 (2018) 517541
Lepton universality

• In the SM, leptons couple universally to $W^\pm$ and $Z^0$ → test this in ratios of semileptonic decays

$$R_K = \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)}$$

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

• Experimentally best accessible:

• Ratios differ from unity only by phase space
LHCb saw low values in LFU tests of $R_K$ and $R_{K^*}$

$$R_{K^*}^{SM} = 1.00 \pm O(10^{-2}) \pm O(10^{-4})$$

Very low hadronic uncertainties, electroweak corrections $O(1\%)$

Any significant deviation from 1.0 would be a clear sign for New Physics

Observed anomalies make a “natural pattern” with $b \to s e^+e^-$ anomalies
- From $b \to s \mu^+\mu^-$ angular and BF data one can expect $R_K^{(*)}$ reduced by $\sim 25\%$
- Electron modes compatible with SM
New result on $R_K$

- LHCb published an update to $R_K$ @ MEW19
  - Analysis of Run 1 + ½ Run 2 data (3+1.6 fb$^{-1}$)
    \begin{equation}
    R_K = 0.846^{+0.060}_{-0.054} \text{(stat)}^{+0.016}_{-0.014} \text{(syst)}
    \end{equation}
  - Consistent with SM at 2.5σ
  - Dominant systematic uncertainties:
    fit shape, trigger calibration, $B^+$ kinematics

![Graph showing $R_K$ vs $q^2$]
**New result on $R_K$**

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    fit shape, trigger calibration, $B^+$ kinematics

- **Compatibility tests, if Run 1 and Run 2 are fitted separately:**
  - Previous Run 1 result PRL113(2014)151601 vs. this Run 1 result: <1σ (updated reconstruction & selection)
  - Run 1 vs. Run 2 result: 1.9σ

\[
\begin{align*}
\text{Run 1: } R_{K}^{\text{new}} & = 0.717^{+0.083}_{-0.071}(\text{stat})^{+0.017}_{-0.016}(\text{syst}) \\
\text{Run 2: } R_{K}^{\text{new}} & = 0.928^{+0.089}_{-0.076}(\text{stat})^{+0.020}_{-0.017}(\text{syst}) \\
\text{Run 1: } R_{K}^{\text{old}} & = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})
\end{align*}
\]
New result on $R_K$

- LHCb published an update to $R_K$ @ MEW19
  - Analysis of Run 1 + $\frac{1}{2}$ Run 2 data (3+1.6 fb$^{-1}$)
    
    $$ R_K = 0.846^{+0.060}_{-0.054} \text{(stat)}^{+0.016}_{-0.014} \text{(syst)} $$

    - Consistent with SM at 2.5$\sigma$
    - Dominant systematic uncertainties:
      - fit shape, trigger calibration, $B^+$ kinematics

- Observed pattern still fits naturally with other $b \to s \ell^+\ell^-$ data, but picture is not conclusive
  - Significant individual measurements needed

- Updates on LFU expected soon
  - LHCb has more data on tape (factor 2 for $R_K$ and 4 for $R_{K^*}$)
  - Wait with interest for CMS’ parked data
  - Mid term: Belle 2 will also provide input
Some New Physics models that explain the flavour anomalies predict sizeable branching fractions in **lepton flavour violating decays**


Natural candidate: $B^+ \rightarrow K^+ e^+ \mu^-$

LHCb recently published a search using the Run 1 dataset

- No signal seen, determine limits @90% CL

$$BR(B^+ \rightarrow K^+ \mu^- e^+) \leq 7.0 \times 10^{-9}$$
$$BR(B^+ \rightarrow K^+ \mu^+ e^-) \leq 7.1 \times 10^{-9}$$

- Limits improved by more than 1 order of magnitude
LFV: $B \rightarrow \tau^+\mu^-$

- $B \rightarrow \tau^+\mu^-$ is a strong constraint for many BSM models
- Experimental status before spring 2019
  - $\text{BR}(B^0 \rightarrow \tau^+\mu^-) < 2.2 \times 10^{-5}$ [BaBar PRD77(2008)091104]
  - $B_s \rightarrow \tau^+\mu^-$: no limit yet

- LHCb published a Run 1 analysis using $\tau \rightarrow 3\pi\nu$ decays

- No signal seen, limits are set at 90% CL

\[
\text{BR}(B^0 \rightarrow \tau^+\mu^+) \leq 1.2 \times 10^{-5} \\
\text{BR}(B_s \rightarrow \tau^+\mu^+) \leq 3.4 \times 10^{-5}
\]

  - First measurement for $B_s$
  - $B^0$ result improved by $\sim$factor 2

\[\text{arXiv:1905.06614}\]
LFV: $\tau^- \rightarrow \mu^-\mu^+\mu^-$

- New result from CMS on $\tau^- \rightarrow \mu^-\mu^+\mu^-$:
  - Using 33fb$^{-1}$ from Run 2
  - Sample from B and D meson decays

- Observed (expected) limits at 90% of CL:

$$BR(\tau^- \rightarrow \tau^-\tau^-\tau^+) \leq 8.8(9.9) \times 10^{-8}$$

- Compare to previous limits:
  - Belle $< 2.1 \times 10^{-8}$ [PLB687(2010)139143]
  - Babar $< 3.3 \times 10^{-8}$ [PRD81(2010)111101]
  - LHCb $< 4.6 \times 10^{-8}$ [JHEP02(2015)121]
  - ATLAS $< 3.8 \times 10^{-7}$ [EPJC76(2016)232]
First Measurement of the $\text{BR}(B^+ \rightarrow K^+ X(3872))$ and of $\text{BR}(X(3872) \rightarrow J/\psi \pi \pi)$ by the BABAR collaboration

Evidence of $B^+ \rightarrow K^+ X(3872)$ at $3\sigma$ level

\[
\text{BR} (B^+ \rightarrow K^+ X(3872)) = (2.1 \pm 0.6 \pm 0.3 \pm 0.1) \times 10^{-4}
\]
\[
\text{BR}(X(3872) \rightarrow J/\psi \pi \pi) = (4.1 \pm 1.3)\%
\]

Results tend to support a molecular component of $X(3872)$
Summary

• Interesting pattern of *flavour anomalies* seen, but no conclusive individual measurements (yet)
  – Intense experimental program ongoing to verify anomalies

• Healthy competition between LHC experiments
  – And Belle 2 is starting up

• Bright future for flavour physics

LHC timeline: lhccommissioning/schedule/HL-LHC-plots.htm, Belle2 timeline: G. Mohanty, Moriond EW 2019
Recent LFU results from Belle

**Update on $R_K$ presented on July 12, S. Choudhury:**

<table>
<thead>
<tr>
<th>Bin</th>
<th>$R_{K^+}$</th>
<th>$R_{K^0}$</th>
<th>$R_K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.1 &lt; q^2 &lt; 4$</td>
<td>$0.92^{+0.27}_{-0.24} \pm 0.05$</td>
<td>$1.5^{+1.2}_{-1.0} \pm 0.1$</td>
<td>$0.95^{+0.27}_{-0.24} \pm 0.06$</td>
</tr>
<tr>
<td>$4 &lt; q^2 &lt; 8.12$</td>
<td>$1.22^{+0.42}_{-0.37} \pm 0.07$</td>
<td>$0.50^{+0.39}_{-0.30} \pm 0.03$</td>
<td>$0.81^{+0.28}_{-0.23} \pm 0.05$</td>
</tr>
<tr>
<td>$1 &lt; q^2 &lt; 6$</td>
<td>$1.31^{+0.34}_{-0.31} \pm 0.07$</td>
<td>$0.53^{+0.44}_{-0.33} \pm 0.03$</td>
<td>$0.98^{+0.27}_{-0.23} \pm 0.06$</td>
</tr>
<tr>
<td>$q^2 &gt; 14.18$</td>
<td>$1.08^{+0.30}_{-0.27} \pm 0.06$</td>
<td>$1.52^{+1.23}_{-0.97} \pm 0.10$</td>
<td>$1.11^{+0.29}_{-0.26} \pm 0.07$</td>
</tr>
<tr>
<td>whole $q^2$</td>
<td>$1.04^{+0.16}_{-0.15} \pm 0.06$</td>
<td>$1.25^{+0.50}_{-0.44} \pm 0.08$</td>
<td>$1.06^{+0.15}_{-0.14} \pm 0.07$</td>
</tr>
</tbody>
</table>

**Update on $R_{K^*}$ presented at Moriond EW 19:**

<table>
<thead>
<tr>
<th>$q^2$ in GeV$^2$/c$^4$</th>
<th>All modes</th>
<th>$B^0$ modes</th>
<th>$B^+$ modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0.045, 1.1]</td>
<td>$0.52^{+0.36}_{-0.26} \pm 0.05$</td>
<td>$0.46^{+0.55}_{-0.27} \pm 0.07$</td>
<td>$0.62^{+0.60}_{-0.36} \pm 0.10$</td>
</tr>
<tr>
<td>[1.1, 6]</td>
<td>$0.96^{+0.45}_{-0.29} \pm 0.11$</td>
<td>$1.06^{+0.63}_{-0.38} \pm 0.13$</td>
<td>$0.72^{+0.72}_{-0.44} \pm 0.18$</td>
</tr>
<tr>
<td>[0.1, 8]</td>
<td>$0.90^{+0.52}_{-0.21} \pm 0.10$</td>
<td>$0.86^{+0.33}_{-0.24} \pm 0.08$</td>
<td>$0.96^{+0.56}_{-0.35} \pm 0.14$</td>
</tr>
<tr>
<td>[15, 19]</td>
<td>$1.18^{+0.32}_{-0.10} \pm 0.10$</td>
<td>$1.12^{+0.61}_{-0.36} \pm 0.10$</td>
<td>$1.40^{+1.99}_{-0.68} \pm 0.11$</td>
</tr>
<tr>
<td>[0.045, ]</td>
<td>$0.94^{+0.17}_{-0.14} \pm 0.08$</td>
<td>$1.12^{+0.27}_{-0.21} \pm 0.09$</td>
<td>$0.70^{+0.24}_{-0.19} \pm 0.07$</td>
</tr>
</tbody>
</table>
A new player coming up: Belle 2

- Physics run of Belle 2 started
  - First results envisaged for LP2019
  - Significant luminosity ~2022
Complementarity LHCb – Belle II

- Time dependent $B_s$ physics
  - CPV in $B_s \rightarrow J/\psi \phi$, $B_s \rightarrow \phi \phi$
- $B_s \rightarrow \mu^+\mu^-$
- CKM angle $\gamma$
- CPV in $B_d$
- $B \rightarrow X_s \ell^+\ell^-$ (exclusive) $\rightarrow$ LFU
- $B \rightarrow X_s \gamma$ (exclusive)
- Charm physics
- Semileptonic $B$ decays
- $B \rightarrow D \tau^- \nu$, $B \rightarrow D^* \tau^- \nu$
- Dark matter
- $\tau$ – physics: LFV
  - $B \rightarrow \tau^- \nu$, $B \rightarrow \mu^- \nu$
  - $B \rightarrow K^* \nu\nu$, $B \rightarrow \nu\nu$
  - $B \rightarrow X_s \ell^+\ell^-$ (inclusive)
  - $B \rightarrow X_s \gamma$ (inclusive)

“$B_s$ & charged tracks”

Important overlap: sporty competition!

“inclusive & neutrals ”
Details on $R_K$ results

If instead the Run 1 and Run 2 were fitted separately:

$$R_{K, \text{Run 1}}^{\text{new}} = 0.717^{+0.083+0.017}_{-0.071-0.016}, \quad R_K \text{ Run 2} = 0.928^{+0.089+0.020}_{-0.076-0.017},$$

$$R_{K, \text{Run 1}}^{\text{old}} = 0.745^{+0.090}_{-0.074} \pm 0.036 \text{ (PRL113(2014)151601)},$$

Compatibility taking correlations into account:

- Previous Run 1 result vs. this Run 1 result (new reconstruction selection): $< 1 \sigma$;
- Run 1 result vs. Run 2 result: $1.9 \sigma$.

$B^+ \to K^+ \mu^+ \mu^-$ branching fraction:

- Compatible with previous result (JHEP06(2014)133) at $< 1 \sigma$;
- Run 1 and Run 2 results compatible at $< 1 \sigma$.

$B^+ \to K^+ e^+ e^-$ branching fraction:

$$\frac{d\mathcal{B}(B^+ \to K^+ e^+ e^-)}{dq^2} \mid_{(1.1 < q^2 < 6.0 \text{ GeV}^2)} = (28.6^{+2.0}_{-1.7} \pm 1.4) \times 10^{-9} \text{ GeV}^{-2}$$
Cross check 1 for RK: $R_{J\psi}$ in 1D

To check efficiencies are correct, check:

$$r_{J/\psi} = \frac{\mathcal{B}(B \to K^+ J/\psi(\mu\mu))}{\mathcal{B}(B \to K^+ J/\psi(ee))} = 1.0,$$

Result:

$$r_{J/\psi} = 1.014 \pm 0.035 \text{ (stat. + syst.)}$$

- Check that efficiencies are understood as a function of any variable:
  - differential $r_{J/\psi}$ demonstrates it is the case: $r_{J/\psi}$ is flat for all variables examined.

Given expected $\min(p_T(\ell^+), p_T(\ell^-))$ spectra, bias expected on RK if deviations are genuine rather than fluctuations is 0.1%.
Cross check 2 for $R_K^\psi$: $r_{J/\psi}$ in 2D

- Repeat the exercise in 2D, to check against correlated effects.
- Choose $q^2$-dependent variables relevant for the detector response.
- Select $B^+ \to K^+ J/\psi(\ell^+\ell^-)$ events in bins of this 2D space and compute $r_{J/\psi}$ in each of them.

\[ \rightarrow \text{Flatness of } R_{J/\psi}^{2D} \text{ plots gives confidence that efficiencies are understood over all phase-space} \]
Expected sensitivity: LFU in $b \rightarrow s$

Effective Hamiltonian:

$$H = \sum_i \left( C_i^{SM} + C_i^{NP} \right) O_i$$

- $i = 7$  Photon penguin
- $i = 9,10$  Electroweak penguin
- $i = S$  Higgs (scalar) penguin
- $i = P$  Pseudoscalar penguin

- Global fit to $b \rightarrow s$ data: Current data well consistent with $C_9 - 25\%$

- If current tensions persist, they will will be established with $>5\sigma$ by LHCb (Run 2), and then also by Belle2

[Arxiv: 1709.10308]