Combination of measurements to constrain new physics

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02/12/2016
Introduction

In general, we search for NP indirectly in processes where SM contributions are suppressed, and so, small NP effects can become visible (or even dominant).

Phenomenologically, we can classify potential NP contributions as

- $\Delta F = 2$ (neutral $B$ mixing)
  - 2nd order weak transition in SM, can be enhanced by NP

- $\Delta F = 1$ (B decays)
  - Loop suppression (NP can enter through trees, e.g. FCNC)
  - Helicity suppression (Vector-mediated SM transitions are small compared (pseudo) scalar-mediated NP)

Use few examples (popular global fits) and reflect on the measurements used and how they will evolve

[not mentioning about NP in tree-level decays, see for example M.Tanaka and R.Watanabe, arXiv:1608.05207 and coming B2TiP report

$R_{D^{(*)}}, \ R_\pi = \frac{B(B \to \pi \tau \nu)}{B(B \to \pi l \nu)}, \ R_{ps} = \frac{B(B \to \tau \nu)}{B(B \to \pi l \nu)}, \ R_{pl} = \frac{B(B \to \tau \nu)}{B(B \to \mu \nu)} ...$]
Sensitivity to new physics in $B_d$, $B_s$ and $K$ mixings

Ref: Z. Ligeti, M. Pappuci, CKMfitter
arXiv:1309.2293, arXiv:1501.05013

but also similar studies:
M. Ciuchini et al, hep-ph/0012308
M. Bona et al, hep-ph/051199  [See M.Bona's talk]
J. Laiho et al, arXiv:0910.2928
G. Eigen et al, arXiv:1503.02289

[See A.Perez's talk]
$\Delta F = 2$: New Physics

Evolution of $B^0_{(s)}$ system is described by $H = M - i \Gamma/2$

- $M_{12}$ dominated by (virtual) top boxes
  [affected by NP, e.g. if heavy new particles in the box]
- $\Gamma_{12}$ dominated by tree decays into (real) charm states
  [affected by NP if changes in (constrained) tree-level decays]
- Tree level (4 diff flavours) processes not affected by NP

**Model-independent** parametrisation under the assumption only changes modulus and phase of $M_{12}^d$ and $M_{12}^s$

\[
M_{12}^q = (M_{12}^q)_{SM} \times \Delta_q \quad \Delta_q = |\Delta_q| e^{i \varphi_q^\Delta} = (1 + h_q e^{2i \sigma_q})
\]

affects $\Delta m_q$ ($\leftrightarrow |\Delta_q|$), $a_{SL}^q$ ($\leftrightarrow \Delta_q$), $\Delta \Gamma_q$ and $\varphi_{B_q}$ ($\leftrightarrow \varphi_q^\Delta$)

$\Delta m_d$, $\Delta m_s$, $\beta$, $\varphi_s$, $a_{SL}^d$, $a_{SL}^s$, $\Delta \Gamma_s$ to constrain $\Delta_d$ and $\Delta_s$
$\Delta F = 2$: CKM projections

[CKMfitter, arXiv:1501.05013]

Observables not affected by NP, used to fix CKM:
$|V_{ud}|$, $|V_{us}|$, $|V_{ub}|$, $|V_{cb}|$, $\gamma$ and $\gamma(\alpha) \equiv \pi - \alpha - \beta$ ($\varphi_{B_d}$ cancels)

|                      | 2013                  | Stage I      | Stage II     |
|----------------------|-----------------------|--------------|--------------|
| $|V_{ud}|$            | $0.97425 \pm 0 \pm 0.00022$ | id           | id           |
| $|V_{us}|$ ($K_{\ell 3}$) | $0.2258 \pm 0.0008 \pm 0.0012$ | $0.22494 \pm 0.0006$ | id           |
| $|\epsilon_K|$       | $(2.228 \pm 0.011) \times 10^{-3}$ | id           | id           |
| $\Delta m_d$ [ps$^{-1}$] | $0.507 \pm 0.004$ | id           | id           |
| $\Delta m_s$ [ps$^{-1}$] | $17.768 \pm 0.024$ | id           | id           |
| $|V_{cb}| \times 10^3$ ($b \to c \ell \bar{\nu}$) | $41.15 \pm 0.33 \pm 0.59$ | $42.3 \pm 0.4$ | $42.3 \pm 0.3$ |
| $|V_{ub}| \times 10^3$ ($b \to u \ell \bar{\nu}$) | $3.75 \pm 0.14 \pm 0.26$ | $3.56 \pm 0.10$ | $3.56 \pm 0.08$ |
| $\sin 2\beta$        | $0.679 \pm 0.020$ | $0.679 \pm 0.016$ | $0.679 \pm 0.008$ |
| $\alpha$ (mod $\pi$) | $(85.4^{+4.0}_{-8.5})^\circ$ | $(91.5 \pm 2)^\circ$ | $(91.5 \pm 1)^\circ$ |
| $\gamma$ (mod $\pi$) | $(68.0^{+8.0}_{-8.5})^\circ$ | $(67.1 \pm 4)^\circ$ | $(67.1 \pm 1)^\circ$ |
| $\beta_s$            | $0.0065^{+0.0450}_{-0.0415}$ | $0.0178 \pm 0.012$ | $0.0178 \pm 0.004$ |
| $B(B \to \tau \nu) \times 10^4$ | $1.15 \pm 0.23$ | $0.83 \pm 0.10$ | $0.83 \pm 0.05$ |
| $B(B \to \mu \nu) \times 10^7$ | $3.7 \pm 0.9$ | $3.7 \pm 0.2$ | $3.7 \pm 0.2$ |
| $A_{SL}^d \times 10^4$ | $23 \pm 26$ | $-7 \pm 15$ | $-7 \pm 10$ |
| $A_{SL}^s \times 10^4$ | $-22 \pm 52$ | $0.3 \pm 6.0$ | $0.3 \pm 2.0$ |
Unlimited $\gamma$

Full Frequentist treatment on MC basis

$\sigma_\gamma \sim 6^\circ$

much more modes/ideas ⇒ see WG5's summary

(too) conservative estimate ⇒

[See D.Cervenkov's talk]

plethora

noun [S] • UK /'pleθ.ə.ə/ US

C2 a very large amount of something, especially a larger amount than you need, want, or can deal with:

There's a plethora of books about the royal family.
The plethora of regulations is both contradictory and confusing.

[Belle II Projection (July 2015)]
Toy MC studies based on Belle II MC, LQCD forecasts estimated at 5 years (5, 10 ab$^{-1}$) and 10 years (50 ab$^{-1}$)

$|V_{ub}|$ from $B \rightarrow \pi l \nu$ at Belle II

[B2TiP, to be published]

$|V_{ub}| \pi \ell \nu$ from simultaneous fit for $\mathcal{L} = 5$ ab$^{-1}$, including lattice forecasts and error scaling.

$\delta|V_{ub}| \pi \ell \nu$ estimates for 5, 10 and 50 ab$^{-1}$:
- Tagged: 3.2, 2.7 and 1.7 %
- Untagged: 2.1, 1.9 and 1.3 %

LQCD forecasts: [A. Kronfeld, T. Kaneko, S. Simula]
$\Delta F = 2$: CKM projections

Observables not affected by NP, used to fix CKM:

$|V_{ud}|, |V_{us}|, |V_{ub}|, |V_{cb}|, \gamma$ and $\gamma(\alpha) \equiv \pi - \alpha - \beta$ ($\phi_{B_d}$ cancels)

**Stage I**

7 fb$^{-1}$ LHCb + 5 ab$^{-1}$ Belle II

**Stage II**

50 fb$^{-1}$ LHCb + 50 ab$^{-1}$ Belle II
### ΔF = 2: NP fit

\[ \Delta m_d, \Delta m_s, \beta, \varphi_s, a_{SL}^d, a_{SL}^s, \Delta \Gamma_s \] to constrain \( \Delta_d \) and \( \Delta_s \)

| | 2013 | Stage I | Stage II |
|---|---|---|---|
| | | LHCb | + 5 ab\(^{-1}\) Belle II | LHCb | + 50 ab\(^{-1}\) Belle II |
| \(|V_{ud}|\) | 0.97425 ± 0 ± 0.00022 | id | id |
| \(|V_{us}| (K\ell_3)\) | 0.2258 ± 0.0008 ± 0.0012 | 0.22494 ± 0.0006 | id | id |
| \(|\epsilon_K|\) | (2.228 ± 0.011) \times 10^{-3} | id | id |
| \(\Delta m_d [\text{ps}^{-1}]\) | 0.507 ± 0.004 | id | id |
| \(\Delta m_s [\text{ps}^{-1}]\) | 17.768 ± 0.024 | id | id |
| \(|V_{cb}| \times 10^3 (b \rightarrow c\ell\bar{\nu})\) | 41.15 ± 0.33 ± 0.59 | 42.3 ± 0.4 | 42.3 ± 0.3 | [17] |
| \(|V_{ub}| \times 10^3 (b \rightarrow u\ell\bar{\nu})\) | 3.75 ± 0.14 ± 0.26 | 3.56 ± 0.10 | 3.56 ± 0.08 | [17] |
| tan 2\(\beta\) | 0.679 ± 0.020 | 0.679 ± 0.016 | 0.679 ± 0.008 | [17] |
| \(\alpha \text{ (mod } \pi)\) | (85.4^{+10.0}_{-8.8})^\circ | (91.5 ± 2)^\circ | (91.5 ± 1)^\circ | [17] |
| \(\gamma \text{ (mod } \pi)\) | (68.0^{+8.0}_{-8.5})^\circ | (67.1 ± 4)^\circ | (67.1 ± 1)^\circ | [17, 18] |
| \(\beta_s\) | 0.0065^{+0.0450}_{-0.0415} | 0.0178 ± 0.012 | 0.0178 ± 0.004 | [18] |
| \(B(B \rightarrow \tau\nu) \times 10^4\) | 1.15 ± 0.23 | 0.83 ± 0.10 | 0.83 ± 0.05 | [17] |
| \(B(B \rightarrow \mu\nu) \times 10^7\) | — | 3.7 ± 0.9 | 3.7 ± 0.2 | [17] |
| \(A_{SL}^d \times 10^4\) | 23 ± 26 | –7 ± 15 | –7 ± 10 | [17] |
| \(A_{SL}^s \times 10^4\) | –22 ± 52 | 0.3 ± 6.0 | 0.3 ± 2.0 | [18] |
mostly single analysis with 152MBB
mostly single analysis with 3 fb$^{-1}$

end of the road?
Mixing-induced CP violation in $B \to J/\psi K^0$

$A(t) = \frac{\Gamma(B) - \Gamma(\bar{B})}{\Gamma(B) + \Gamma(\bar{B})}$

$S = \sin 2\beta$

$C = 0$

$A(t) = S \sin (\Delta m_d t) - C \cos (\Delta m_d t)$

$S = 0.731 \pm 0.035 \pm 0.020$

$C = -0.038 \pm 0.032 \pm 0.005$

Belle: $0.67 \pm 0.02 \pm 0.01$

BaBar: $0.69 \pm 0.03 \pm 0.01$

$\sin(2\beta) \equiv \sin(2\phi_1)$

$\beta = (21.9 \pm 0.7)^\circ$ WA 2015
Mixing-induced CP violation in $B_s \rightarrow J/\psi KK$

CP violating phase

$\varphi_s = -0.058 \pm 0.049 \pm 0.006$

CP violating in mixing or direct decay (no CPV: $|\lambda| = 1$)

$|\lambda| = 0.964 \pm 0.019 \pm 0.007$

Decay width difference

$\Delta \Gamma_s = (\Gamma_L - \Gamma_H) = 0.0805 \pm 0.0091 \pm 0.0032 \text{ ps}^{-1}$

$\Delta \Gamma_s^{(SM)} = 0.087 \pm 0.021 \text{ ps}^{-1}$

$\varphi_s^{(SM)} = -0.0363^{+0.0012}_{-0.0014} \text{ rad}$

$\varphi_s = -0.010 \pm 0.039 \text{ rad}$

[combined with $J/\psi \pi \pi$]

[See G.Cowan's talk]
[3 fb$^{-1}$, arXiv:1411.3104]
Semileptonic asymmetries

use semileptonic $B^{0}_{(s)}$ decays

$A_{CP} \equiv a_{SL} = \frac{\Gamma(B \rightarrow B \rightarrow f) - \Gamma(B \rightarrow \bar{B} \rightarrow \bar{f})}{\Gamma(B \rightarrow B \rightarrow f) + \Gamma(B \rightarrow \bar{B} \rightarrow \bar{f})}$

$A_{\text{meas}}(t) = \frac{a_{SL}}{2} \left(1 - \frac{\cos(\Delta m t)}{\cosh(\Delta \Gamma t/2)}\right)$

Standard Model predictions

[A.Lenz, arXiv:1205.1444]

$a_{SL}^d = (-4.1 \pm 0.6) \times 10^{-4}$

$a_{SL}^s = (+1.9 \pm 0.3) \times 10^{-5}$

- **No tagging needed.** Time-dependent ($B^0$) or time-independent ($B^0_s$) SL asymmetry measurement
- 3σ tension coming from D0 dimuon asymmetry measurement

$\frac{\text{a}_{SL}^s}{\%} = (0.39 \pm 0.26 \text{ (stat)} \pm 0.20 \text{ (syst)})\%$

[Phys.Rev.Lett.117(2016)061803]
**ΔF = 2: Current constraints**

\[ M_{12} = M_{12} \Delta, \, \Delta = |\Delta| e^{i\varphi^\Delta} \]

\[ \Delta_d = 0.88^{+0.22}_{-0.10} + i \left( -0.11^{+0.07}_{-0.05} \right) \]

\[ \Delta_s = 1.01^{+0.17}_{-0.09} + i \left( +0.02 \pm 0.04 \right) \]

Bounds/prospects for New Physics at:

- Stage I: 7 fb\(^{-1}\) LHCb + 5 ab\(^{-1}\) Belle II
- Stage II: 50 fb\(^{-1}\) LHCb + 50 ab\(^{-1}\) Belle II
### ΔF = 2: Inputs

**NB:** No D0 A_{SL} input

|                     | 2003                     | 2013                     | Stage I | Stage II |
|---------------------|--------------------------|--------------------------|---------|----------|
| |V_{ud}|               | 0.9738 ± 0.0004          | 0.97425 ± 0 ± 0.00022 | id      | id       |
| |V_{us}| (K_{L3})         | 0.2228 ± 0.0039 ± 0.0018 | 0.2258 ± 0.0008 ± 0.0012 | 0.22494 ± 0.0006 | id      | id       |
| |ε_{K}|                | (2.282 ± 0.017) × 10^{-3} | (2.282 ± 0.011) × 10^{-3} | id      | id       |
| |Δm_{d}| ps^{-1}          | 0.502 ± 0.006            | 0.507 ± 0.004            | id      | id       |
| |Δm_{s}| ps^{-1}          | > 14.5 [95% CL]          | 17.768 ± 0.024           | id      | id       |
| |V_{cb}| × 10^{3} (b → cℓν) | 41.6 ± 0.58 ± 0.8        | 41.15 ± 0.33 ± 0.59      | 42.3 ± 0.4 | 17 | 42.3 ± 0.3 | 17 |
| |V_{ub}| × 10^{3} (b → uℓν) | 3.90 ± 0.08 ± 0.68       | 3.75 ± 0.14 ± 0.26       | 3.56 ± 0.10 | 17 | 3.56 ± 0.08 | 17 |
| sin2β               | 0.726 ± 0.037          | 0.679 ± 0.020            | 0.679 ± 0.016            | 17 | 0.679 ± 0.008 | 17 |
| α (mod π)           | —                       | (85.4^{+4.0}_{-3.8})°    | (91.5 ± 2)°              | 17 | (91.5 ± 1)° | 17 |
| γ (mod π)           | —                       | (68.0^{+8.0}_{-8.5})°    | (67.1 ± 4)°              | 17, 18 | (67.1 ± 1)° | 17, 18 |
| β_{s}               | —                       | 0.0065^{+0.0450}_{-0.0415} | 0.0178 ± 0.012           | 18 | 0.0178 ± 0.004 | 18 |
| B(B → τν) × 10^{4}  | —                       | 1.15 ± 0.23              | 0.83 ± 0.10              | 17 | 0.83 ± 0.05 | 17 |
| B(B → μν) × 10^{7}  | —                       | —                        | 3.7 ± 0.9                | 17 | 3.7 ± 0.2 | 17 |
| A_{SL} × 10^{4}     | 10 ± 140                | 23 ± 26                  | −7 ± 15                  | 17 | −7 ± 10 | 17 |
| A_{SL} × 10^{4}     | —                       | −22 ± 52                 | 0.3 ± 6.0                | 18 | 0.3 ± 2.0 | 18 |
| m_c                  | 1.2 ± 0 ± 0.2           | 1.286 ± 0.013 ± 0.040    | 1.286 ± 0.020            | 1.286 ± 0.010 |
| m_t                  | 167.0 ± 5.0             | 165.8 ± 0.54 ± 0.72      | id                      | id       |
| α_s(m_Z)            | 0.1172 ± 0 ± 0.0020     | 0.1184 ± 0 ± 0.0007      | id                      | id       |
| B_K                  | 0.86 ± 0.06 ± 0.14      | 0.7615 ± 0.0026 ± 0.0137 | 0.774 ± 0.007           | 19, 20 | 0.774 ± 0.004 | 19, 20 |
| f_{B_s} [GeV]       | 0.217 ± 0.012 ± 0.011   | 0.2256 ± 0.0012 ± 0.0054 | 0.232 ± 0.002           | 19, 20 | 0.232 ± 0.001 | 19, 20 |
| B_{B_s}              | 1.37 ± 0.14             | 1.326 ± 0.016 ± 0.040    | 1.214 ± 0.060           | 19, 20 | 1.214 ± 0.010 | 19, 20 |
| f_{B_s}/f_{B_d}      | 1.21 ± 0.05 ± 0.01      | 1.198 ± 0.008 ± 0.025    | 1.205 ± 0.010           | 19, 20 | 1.205 ± 0.005 | 19, 20 |
| B_{B_s}/B_{B_d}      | 1.00 ± 0.02             | 1.036 ± 0.013 ± 0.023    | 1.055 ± 0.010           | 19, 20 | 1.055 ± 0.005 | 19, 20 |
| B_{B_s}/B_{B_d}      | —                       | 1.01 ± 0 ± 0.03          | 1.03 ± 0.02             | id       |
| B_{B_s}              | —                       | 0.91 ± 0.03 ± 0.12       | 0.87 ± 0.06             | id       |

[CKMfitter, arXiv:1501.05013]
$\Delta F = 2: \text{NP}!! \text{ ideal scenario...}$

Hypothetical Stage II fits for NP, assuming that all future experimental results correspond to the current best-fit values of $\bar{\rho}$, $\bar{\eta}$, $h_{d,s}$, $\sigma_{d,s}$

- $\sigma_d$ vs $h_d$
- $\sigma_s$ vs $h_s$

2013 vs Stage II
$\Delta F = 2$: bounds for $B_{d,s}$ mixings

2013  Stage I  Stage II
\[ \Delta F = 2: \text{bounds on energy scale} \]

**Stage I**

NP contribution to the mixing from

\[ \frac{C_{ij}^2}{\Lambda^2} \left( b_L \gamma^\mu q_{j, L} \right)^2 \]

\[ h \approx 1.5 \frac{|C_{ij}|^2 }{ |V_{ti} V_{tj}|^2 G_F \Lambda^2} \simeq \frac{|C_{ij}|^2}{|V_{ti} V_{tj}|^2} \left( \frac{4.5 \text{ TeV}}{\Lambda} \right)^2 \]

probe new particles with CKM-like couplings with masses, M, in the 10-20 TeV range if contribute at tree level \( (\Lambda \sim M) \), in 1-2 TeV range if enter with a loop suppression \( (\Lambda \sim 4\pi M) \)

**Stage II**

| Couplings  | NP loop order | Scales (in TeV) probed by 
|------------|---------------|----------------------|
| \( |C_{ij}| = |V_{ti} V_{tj}^*| \) | one loop | \( B_d \) mixing | \( B_s \) mixing |
| (CKM-like) |               | 1.4 | 1.5 |
| \( |C_{ij}| = 1 \) | one loop | \( 2 \times 10^3 \) | \( 5 \times 10^2 \) |
| (no hierarchy) | one loop | \( 2 \times 10^2 \) | 40 |
NP in K mixing, $\Delta F = 2$: $\epsilon_K$

- $K$, $B_d$ and $B_s$ mixings in general not related
- $\epsilon_K$ not enough to bound NP in K mixing, even if NP only in tt box
- but in the case of MFV, possible to exploit all neutral mesons
  \[ h = h_d e^{2i\sigma_d} = h_s e^{2i\sigma_s} = h_K e^{2i\sigma_K} \text{ with } \sigma_i = 0 \pmod{\pi/2} \]

Arbitrary NP in tt K boxes - Stage II

MFV case
Sensitivity to new physics in rare B decays

References:
M. Ciuchini et al, arXiv:1512.07157
T. Hurth et al, arXiv:1603.00865
S. Descotes-Genon et al, arXiv:1510.04239
...
### Effective field theory

- Model-independent description in effective field theory:
  \[ \mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i \mathcal{O}_i + C_i' \mathcal{O}'_i \]

  Left-handed \quad Right-handed, \quad \frac{m_s}{m_b} \quad \text{suppressed}

- Wilson coefficients $C_i^{(r)}$ encode short-distance physics, $\mathcal{O}_i^{(r)}$ corr. operators

  - $\mathcal{O}_7^{(r)}$ photon penguin
  - $\mathcal{O}_9^{(r)}$ vector coupling
  - $\mathcal{O}_{10}^{(r)}$ axialvector coupling
  - $\mathcal{O}_{S,P}^{(r)}$ (pseudo)scalar penguin

  \[
  \begin{align*}
  b &\to s\gamma \quad B \to \mu\mu \quad b \to s\ell\ell
  \end{align*}
  \]

  \[
  \checkmark \quad \checkmark \quad \checkmark \quad \checkmark \quad \checkmark
  \]

NP changes short-distance $C_i$ and/or add new long-distance ops $O'_i$
## Constraints on NP from radiative $B$ decays

A. Paul, D. Straub, arXiv:1608.02556

| Observable                                                                 | SM prediction | Measurement |
|---------------------------------------------------------------------------|---------------|-------------|
| $10^4 \times \text{BR}(B \rightarrow X_s \gamma)_{E_\gamma > 1.6 \text{GeV}}$ | $3.36 \pm 0.23$ | $3.43 \pm 0.22$ |
| $10^5 \times \text{BR}(B^+ \rightarrow K^* \gamma)$                        | $3.43 \pm 0.84$ | $4.21 \pm 0.18$ |
| $10^5 \times \text{BR}(B^0 \rightarrow K^* \gamma)$                       | $3.48 \pm 0.81$ | $4.33 \pm 0.15$ |
| $10^5 \times \overline{\text{BR}}(B_s \rightarrow \phi \gamma)$           | $4.31 \pm 0.86$ | $3.5 \pm 0.4$   |
| $S(B^0 \rightarrow K^* \gamma)$                                          | $-0.023 \pm 0.015$ | $-0.16 \pm 0.22$ |
| $A_{CP}(B^0 \rightarrow K^* \gamma)$                                      | $0.003 \pm 0.001$ | $-0.002 \pm 0.015$ |
| $A_{\Delta \Gamma}(B_s \rightarrow \phi \gamma)$                          | $0.031 \pm 0.021$ | $-1.0 \pm 0.5$   |
| $\langle P_1 \rangle(B^0 \rightarrow K^* e^+ e^-)_{[0.002,1.12]}$        | $0.04 \pm 0.02$   | $-0.23 \pm 0.24$   |
| $\langle A_{T\text{Im}} \rangle(B^0 \rightarrow K^* e^+ e^-)_{[0.002,1.12]}$ | $0.0003 \pm 0.0002$ | $0.14 \pm 0.23$ |

![Plot of $C_7^{NP}$ vs. BRs](image.png)
At Belle II, significant improvement in the determination of $A_{CP}(t)$ in $K_S^0\pi^0\gamma$ expected.

- Belle II vertex larger than Belle ($6 \rightarrow 11.5cm$)
- 30% more $K_S$ with vertex hits available
- Effective tagging eff. 13% better
**Constraints on NP from radiative B decays**

A. Paul, D. Straub, arXiv:1608.02556

[See talk of A. Oyanguren] [arXiv:1609.02032]

○ Fit untagged decay-time rate

\[
\Gamma_{B_s \to \gamma}(t) \propto [\cosh(\Delta \Gamma_s t/2) - A^\Delta \sinh(\Delta \Gamma_s t/2)]
\]

\[A^\Delta \simeq \sin 2 \psi \cos \varphi_s \quad \tan \psi \equiv \frac{A(B_s^0 \to \varphi \gamma_R)}{A(B_s^0 \to \varphi \gamma_L)}\]

○ Control acceptance by using \(B^0 \to K^{*0} \gamma\) decays

\[A^\Delta = (-0.98^{+0.46}_{-0.52} +0.23^{-0.20}_{-0.20})\]

to be compared with

\[A^\Delta_{SM} = 0.047^{+0.029}_{-0.025}\]
Constraints on NP from radiative B decays

A.Paul, D.Straub, arXiv:1608.02556

| Observable               | SM prediction | Measurement |
|--------------------------|---------------|-------------|
| $10^4 \times \text{BR}(B \rightarrow X_s \gamma)_{E_V > 1.6 \text{GeV}}$ | 3.36 ± 0.23   | 3.43 ± 0.22 |
| $10^5 \times \text{BR}(B^+ \rightarrow K^* \gamma)$ | 3.43 ± 0.84   | 4.21 ± 0.18 |
| $10^4 \times \text{BR}(B^0 \rightarrow K* \gamma)$ | 3.48 ± 0.81   | 4.33 ± 0.15 |
| $10^5 \times \text{BR}(B_s \rightarrow \phi \gamma)$ | 4.31 ± 0.86   | 3.5 ± 0.4   |
| $S(B^0 \rightarrow K* \gamma)$ | -0.023 ± 0.015 | -0.16 ± 0.22 |
| $A_{CP}(B^0 \rightarrow K* \gamma)$ | 0.003 ± 0.001 | -0.002 ± 0.015 |
| $A_{NP}(B_s \rightarrow \phi \gamma)$ | 0.031 ± 0.021 | -1.0 ± 0.5 |

$\langle P_1 \rangle(B^0 \rightarrow K^* e^+ e^-)_{[0.002, 1.12]} = 0.04 \pm 0.02$ | $-0.23 \pm 0.24$ |

$LHCb$, arXiv:1501.03038

see F.Polci's talk

Angular analysis of $B_d^0 \rightarrow K^* e^+ e^-$ at very low $q^2 (\in [0.002, 1.120] \text{GeV}^2)$

LHCb

Data

Model

$B^0 \rightarrow K^0 e^+ e^-$

$B \rightarrow (K^0 X)e^+ e^-$

Combinatorial

| Observable | Measurement | SM prediction$^+$ |
|------------|-------------|-------------------|
| $F_L$      | $+0.16 \pm 0.06 \pm 0.03$ | $+0.10^{+0.11}_{-0.05}$ |
| $A_T^{(2)}$ | $-0.23 \pm 0.23 \pm 0.05$ | $0.03^{+0.05}_{-0.04}$ |
| $A_T^{Re}$  | $+0.10 \pm 0.18 \pm 0.05$ | $-0.15^{+0.04}_{-0.03}$ |
| $A_T^{Im}$  | $+0.14 \pm 0.22 \pm 0.05$ | $(-0.2^{+1.2}_{-1.2}) \times 10^{-4}$ |

S.Jager, J.M.Camalich [arXiv:1412.3283]
Constraints on NP from radiative B decays

A.Paul, D.Straub, arXiv:1608.02556

- inclusive and exclusive branching ratios strongly constrain NP contributions to the real part of $C_7$
- more precise measurement of time-dependent CP asymmetry in $B \rightarrow K^* \gamma$
- improved measurements of the $B \rightarrow K^* e^+ e^-$ angular analysis at very low $q^2$
- measurements of radiative baryonic decays $\Lambda_b \rightarrow \Lambda^{(*)} \gamma$
Global fits including also $b \rightarrow s l^+ l^-$

(many more observables)
Global fits of the observables by minimization of

$$
\chi^2 = (\vec{O}^{\text{th}} - \vec{O}^{\text{exp}}). (\Sigma_{\text{th}} + \Sigma_{\text{exp}})^{-1}. (\vec{O}^{\text{th}} - \vec{O}^{\text{exp}})
$$

$$(\Sigma_{\text{th}} + \Sigma_{\text{exp}})^{-1}$$ is the inverse covariance matrix

More than 100 observables relevant for leptonic and semileptonic decays:

- $\text{BR}(B \to X_s \gamma)$
- $\text{BR}(B \to X_d \gamma)$
- $\Delta_0(B \to K^* \gamma)$
- $\text{BR}^{\text{low}}(B \to X_s \mu^+ \mu^-)$
- $\text{BR}^{\text{high}}(B \to X_s \mu^+ \mu^-)$
- $\text{BR}^{\text{low}}(B \to X_s e^+ e^-)$
- $\text{BR}^{\text{high}}(B \to X_s e^+ e^-)$
- $\text{BR}(B_s \to \mu^+ \mu^-)$
- $\text{BR}(B_d \to \mu^+ \mu^-)$
- $\text{BR}(B \to K^{*+} \mu^+ \mu^-)$
- $\text{BR}(B \to K^0 \mu^+ \mu^-)$
- $\text{BR}(B \to K^+ \mu^+ \mu^-)$
- $\text{BR}(B \to K^* e^+ e^-)$
- $R_K$
- $B \to K^{*0} \mu^+ \mu^-$: BR, $F_L$, $A_{FB}$, $S_3$, $S_4$, $S_5$, $S_7$, $S_8$, $S_9$
  in 8 low $q^2$ and 4 high $q^2$ bins
- $B_s \to \phi \mu^+ \mu^-$: BR, $F_L$, $S_3$, $S_4$, $S_7$
  in 3 low $q^2$ and 2 high $q^2$ bins

calculations done using SuperIso program
Global fits

NP manifests itself in the shifts of the individual coefficients with respect to the SM values: \( C_i(\mu) = C_i^{SM}(\mu) + \delta C_i \)

Assuming NP to appear in two operators:

- **global fit results using full FF approach**
- **global fit results using soft FF approach**
Global fits

"Latest Belle measurement of branching ratio is based on less than 30% of the total luminosity"  Belle hep-ex/0503044

$\Rightarrow B(X_s \mu \mu)_{\text{high } q^2}, B(X_s \mu \mu)_{\text{low } q^2},$

$B(X_{ee})_{\text{high } q^2}, B(X_{ee})_{\text{low } q^2}$

[Belle, sum-of-exclusive, full stat]  [PRD 93 (2016) 032008]

$\circ B(B \rightarrow X_s ll)$ w/full Belle data sample soon?

$\circ B \rightarrow X_s ll$ at LHCb?
If NP then the effect of $C_9$ and $C_{9}'$ are large enough to be checked at Belle II with theoretically clean modes [see J.Virto's talk]
Global analysis of $b \rightarrow sll$ anomalies  

Global analysis needed
- deviations for same quark transition but different hadrons
- eff Hamiltonian adapted for a global model-independent analysis
- further tests of the computations by looking for inconsistencies

96 observables in total (LHCb for exclusive, no CP-violating obs)
- $B \rightarrow K^* \mu \mu$ ($P_{1,2}, P'_{4,5,6,8}, F_L$ in 5 large-recoil bins + 1 low-recoil bin)
- $B_s \rightarrow \phi \mu \mu$ ($P_1, P'_{4,6}, F_L$ in 3 large-recoil bins + 1 low-recoil bin)
- $B^+ \rightarrow K^+ \mu \mu$, $B^0 \rightarrow K^0 \mu \mu$ (BR)
- $B \rightarrow X_s \gamma$, $B \rightarrow X_s \mu \mu$, $B_s \rightarrow \mu \mu$
  (updated for the central values [Misiak et al., Huber et al., Bobeth et al.])
- $B \rightarrow K^* \gamma$ ($A_l$ and $S_{K^* \gamma}$)

Version 2 of the analysis, essentially unchanged conclusions but
- including final results from LHCb on $B \rightarrow K^* \ell \ell$
- correcting the dictionary between LHCb and our kinematics
  (change only for angular observables sensitive to NP phases)

[Grantrex, Hopfer, Zwicky; Becirevic, Sumensari, Zukanovic-Funchal]
Global analysis of $b \to s l l$ anomalies

[S.Descotes-Genon, Q.Matias, J.Virto]

In global fits of the WC to the data, scenarios with a large negative $C_9^{NP}$ are preferred over the SM by typically more than 4σ.
Consistency of different fits

- Good consistency between BRs and Angular observables
- Good consistency between different modes
- Good consistency between different $q^2$ regions
**NP or hadronic effect?**

Possible explanations for shift in $C_9$:
- A potential new physics contribution $C_9^{\text{NP}}$ enters amplitudes always with a charm-loop contribution $C_9^{c\bar{c}i}(q^2)$
  - Spoiling an unambiguous interpretation of the fit result in terms of NP

**New physics**

**NP e.g. $Z'$, leptoquarks**

**hadronic charm loop contributions**
**NP or hadronic effect?**

Bin-by-bin fit of the one-parameter scenario with a single coefficient $C_9^{NP}$

[W. Altmannshofer et al, arXiv:1503.06199]

[S. Descotes-Genon et al, arXiv:1510.04239]

$C_9^{NP}$ doesn't depend on $q^2$, $C_9^{car{c}i}(q^2)$ expected to exhibit a non-trivial $q^2$ dependence

$\Rightarrow$ definitely need more stat.
Lepton-flavour universality violation

QCD effect could not explain the tension in $R_K$ !!

Hurt, Mahmoudi, Neshatpour
arXiv:1603.00865

S.Descotes-Genon et al,
arXiv:1510.04239

W.Altmannshofer et al,
arXiv:1411.3161

Fit prefers an electron-phobic scenario with NP coupling to $\mu^+\mu^-$
We find new particles at the LHC
- Modelling their flavor structure should explain anomalies + new predictions!

We do not find new particles but we confirm LUV
- Reading the shape with more sophisticated (angular) observables
  - Take LUV ratios between angular observables in $B \rightarrow K^* \ell \ell$
- Bottom-up model-building: Path for discovery at LHC or beyond!

No new particles + No LUV
- More data needed to confirm or rule out $q^2$-dependence of the effect
- Tackling theoretical errors systematically will require a theoretical breakthrough
- New ideas: e.g. $B_S^+ \rightarrow \ell \ell$ (Grinstein & JMC, Phys.Rev.Lett. 116 (2016) no.14, 141801)

Only 2.6$\sigma$ deviation for $R_K$... Need more information: $R_{K^*}$, $R_{\varphi}$...

Sensitive probes of LUV and allow to distinguish between different NP scenarios:
- $\text{ratio } e/\mu$ of $A_{FB}(B^0 \rightarrow K^* l^+ l^-)_{[4, 6]}$ GeV$^2$ [W.Altmannshofer and D.Straub]
- $\langle A_{FB}(B^0 \rightarrow K^* \mu^+ \mu^-) \rangle / \langle A_{FB}(B^0 \rightarrow K^* e^+ e^-) \rangle$ at $q^2 \in [4, 6]$ GeV$^2$, $[15, 19]$ GeV$^2$ [F.Mahmoudi et al]
- $\langle Q_i \rangle = \langle P_i^\mu \rangle - \langle P_i^e \rangle$ ... [Q.Matias et al]
Conclusion

- New Physics may manifest itself in B physics in many ways
- Number of exciting tensions !!
- Expect much more data, improved analyses
- Look for new observables: CP-violation, time-dependence, involving $\tau$, LFV observables...