Flavour Physics: Outlook

David M. Straub  Universe Cluster/TUM, Munich
Disclaimer

- Not a summary of the workshop
- Not a fair representation of all interesting topics
Some lessons learned
Even beloved anomalies can go away

No signal in direct searches: underlines importance of indirect searches (but is depressing nevertheless!)

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NP could show up in unexpected places

In lack of a clear hint of new physics, crucial to keep an open mind!
LHCb always good for a surprise

Keep suprising us!
Exploiting the apparent mass gap

If new physics is heavy, can use SM gauge symmetry to restrict form of NP, e.g.

- Relation between scalar & pseudoscalar operators in $b \to s$ transitions Alonso et al. 1407.7044
- Right-handed $W$ coupling does not violate LFU Talk by J. Martin Camalich
- Indirect electroweak precision tests using flavour Brod et al. 1408.0792, Bobeth and Haisch 1503.04829
- Charged lepton flavour violation (without hadrons) from LFU violation Feruglio et al. 1606.00524
- ...
Is it worth going for 300 fb$^{-1}$?
Yes
Why?

- No signal in direct searches → leave no stone unturned
- $O(1)$ effects in many modes excluded → precision, precision, precision
- Plethora of (quasi-) null tests or clean observables
  - $\gamma_{\text{CKM}}$ Talk by D. Johnson
  - $B_{s,d}$ mixing phases
  - $T$-odd CP asymmetries in $B \rightarrow V\mu^+\mu^-$ Talk by K. Petridis
  - Rare $D$ decays Talk by S. de Boer
  - ...

- Impressive progress from LQCD Talk by M. Hansen, R. Van de Water
- Complementarity to Belle-II ($\Lambda_b$, $B_s$, …)
- ...

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Status of $b \rightarrow s \mu^+ \mu^-$ anomalies
Current tensions in $b \rightarrow s\mu^+\mu^-$ transitions

<table>
<thead>
<tr>
<th>Mode</th>
<th>Observable</th>
<th>Bin</th>
<th>Pull</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow K^*\mu^+\mu^-$</td>
<td>$P'_5$</td>
<td>4–6</td>
<td>$-2.6\sigma$</td>
</tr>
<tr>
<td>$B_s \rightarrow \phi\mu^+\mu^-$</td>
<td>BR</td>
<td>1–6</td>
<td>$-3.3\sigma$</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+\mu^+\mu^-$</td>
<td>BR</td>
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<td>$-2.0\sigma$</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+\mu^+\mu^-$</td>
<td>BR</td>
<td>15–22</td>
<td>$-2.6\sigma$</td>
</tr>
</tbody>
</table>

Suspects: New physics? Form factors? Charm loop?

(flavio v0.13.1 using combined LCSR+LQCD FFs for $B \rightarrow V$ FFs Bharucha et al. 1503.05534 and FNAL/MILC $B \rightarrow K$ FFs Bailey 1509.06235; hadronic unc. estimated as in Altmannshofer and Straub 1411.3161)
Global constraints on $C_9$ & $C_{10}$

Altmannshofer and Straub 1411.3161, Descotes-Genon et al. 1510.04239
see also Hurth et al. 1603.00865
Update 2016

- including 3 fb$^{-1}$ LHCb measurements of $\text{BR}(B^0 \rightarrow K^* \mu^+ \mu^-)$ (2016) and $B_s \rightarrow \varphi \mu^+ \mu^-$ (2015)
- Updated $B \rightarrow V$ FFs from v2 of Bharucha et al. 1503.05534
- Best fit point: **4.5σ pull** from SM

What does it mean?
Update 2016

Reproduce this plot with flavio

- including 3 fb$^{-1}$ LHCb measurements of $\text{BR}(B^0 \rightarrow K^* \mu^+ \mu^-)$ (2016) and $B_s \rightarrow \phi \mu^+ \mu^-$ (2015)
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What does it mean?
A closer look

Pulls for individual modes:

- $B \to K^* \mu^+ \mu^- : 2.7\sigma$
  - famous $P'_5$ anomaly
- $B_s \to \phi \mu^+ \mu^- : 3.4\sigma$
  - BR @ low & high $q^2$
    - cf. Bharucha et al. 1503.05534,
    - Ronald R. Horgan et al. 1310.3887
- $B \to K \mu^+ \mu^- : 2.6\sigma$
  - BR @ low $q^2 \to R_K$
  - First pointed out in:
    - Khodjamirian et al. 1211.0234
Facts

1. Clearly, a significant tension between measurements and (these) predictions
2. All tensions solved simultaneously by a minimal new physics (EFT) assumption
$B \rightarrow K^*$: form factors?

- Complementary LCSR & LQCD results show good agreement
  Bharucha et al. 1503.05534, R. R. Horgan et al. 1501.00367

- Agreement of full FFs vs. heavy quark limit “soft” FFs using “optimised” observables Descotes-Genon et al. 1510.04239
  - Eventually, some arbitrariness in how to quantify power corrections without using info from LCSR or LQCD
  cf. Sebastian Jäger and Jorge Martin Camalich 1412.3183
  vs. Descotes-Genon et al. 1407.8526
B → K*: form factors?

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  - Comment 1: when contemplating large corrections to low-$q^2$ form factors use high $q^2$ info (data, LQCD) to check consistency
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- Comment 1: when contemplating large corrections to low-$q^2$ form factors use high $q^2$ info (data, LQCD) to check consistency
- Comment 2: several open source codes now at disposal to compare different approaches on a common basis
But,

- Branching ratios more problematic than angular observables
- Significance in angular observables does depend on form factors
- $B \to K^*$ and $B_s \to \phi$ more difficult than $B \to K$

Future:

- LCSR systematically limited
- Crucial to treat the unstable $K^*$ on the lattice
  
  Agadjanov et al. 1605.03386,
  
  Talk by M. Hansen
Charm loops in $B \rightarrow K^* \mu^+ \mu^-$

- Culprit: matrix element of $O_{1,2}$

$$\langle \bar{K}^* | T\{i^{\mu}_{\text{em}}(x)C_{1,2}O_{1,2}(0)\} | \bar{B} \rangle$$

- Since $O_9 \propto \bar{\ell} \gamma^\mu \ell$, $h_\lambda$ could mimic a new physics effect in $C_9$

- can be parametrised as complex-valued (CP-even) functions of $q^2$: $h_{+, -, 0}(q^2)$ for the 3 helicity amplitudes

How can we disentangle $h_\lambda$ from $C_9$?

$$O_2 = (\bar{s}_L \gamma_{\mu} c_L)(\bar{c}_L \gamma^\mu b_L)$$
Anatomy of $h_\lambda$

- Without loss of generality, absorb $h_\lambda$ in a $q^2$ and helicity dependent shift of $C_9$:
  \[ C_9^{\text{SM}} + \Delta C_9^{+,,-,0}(q^2) \]

- $h_-$ is expected to be helicity-suppressed
  
  S. Jäger and J. Martin Camalich 1212.2263

  - This can be tested by looking at $S_3$, $P_2$ → ignore for now

- Imaginary parts hardly relevent → ignore for now

What is the $q^2$ and helicity dependence of the apparent shift in $C_9$?
$q^2$ dependence of $\Delta C^\lambda_9$

DS @ Moriond EW 2015; Altmannshofer and Straub 1503.06199
(1σ boxes)
$q^2$ dependence of $\Delta C^9_{\lambda}$

Descotes-Genon et al. 1510.04239
$q^2$ dependence of $\Delta C_9^\lambda$

Ciuchini et al. 1512.07157

- Bayesian fit assuming a polynomial form for $h_\lambda$
- roughly: $\tilde{g}_1 \propto \Delta C_9^-$, $\tilde{g}_3 \propto \Delta C_9^0$
$q^2$ dependence of $\Delta C_9^\lambda$

Bayesian fit assuming a polynomial form for $h_\lambda$
- roughly: $\tilde{g}_1 \propto \Delta C_9^-, \tilde{g}_3 \propto \Delta C_9^0$
- assuming small $\Delta C_9^\lambda$ for small $q^2$ (expected for SM, but not NP!)
$q^2$ dependence of $\Delta C^\lambda_9$

- Bin-by-bin fit of $\Delta C^0_9$ vs. $\Delta C^-_9$
- New physics: expect $\Delta C^0_9 = \Delta C^-_9$ equal for all bins

Current data **not precise enough** to exclude new physics hypothesis!

Plot based on discussion with C. Bobeth.
Current situation

1. Data shows significant preference for sizable effect around 4–6 GeV$^2$
2. $q^2$ dependence is compatible both with new physics and with charm hypothesis  

Talk by N. Mahmoudi
We can do better!

- Charm contribution obeys a dispersion relation
  Khodjamirian et al. 1006.4945 Talk by T. Mannel

Schematically:

\[ h_-(q^2) = h_-(0) + q^2 h'_-(0) + q^4 \left[ BW_{J/\psi} + BW_{\psi(2S)} + h^{\text{higher}}_-(q^2) \right] \]

- Measured from $B \rightarrow \psi K^*$ up to overall phase
- Small impact below $m_{J/\psi}^2$ (?)

- Need to fulfill this constraint in fits to data!
Charmonium interference

The $q^2$ dependence of the differential rate between the $J/\psi$ and $\psi(2S)$ resonances can be used to infer the sign of the interference

Khodjamirian et al. 1006.4945

* this is only a cartoon – not actual numerics

Would be extremely helpful if LHCb could measure this Talk by K. Petridis
Homework: $b \rightarrow s\mu^+\mu^-$ anomalies

THEORY

- Improved lattice form factors
  - $B \rightarrow K, B \rightarrow K^*$ (finite lifetime!), $B_s \rightarrow \phi, \Lambda_b \rightarrow \Lambda$
- Exploit dispersion relation to get better handle on charm
- Non-factorisable corrections to baryon decays

EXPERIMENT

- Measure charm resonances, including relative phases between short-distance and charmonium
- finer $q^2$ binning
- More precise measurements of related modes: $\Lambda_b \rightarrow \Lambda\mu^+\mu^-$, ...
A comment on fits & codes

Open source codes allow to make flavour pheno results accessible to experimentalists & model builders
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BUT please keep in mind that theories (both new physics and hadronic uncertainties) can change. Make sure data is published as independently of that as possible.
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(i.e., Wilson coefficient fits fine “in addition”, but not “instead”.)
Violation of LFU: status of new physics explanations
Violation of lepton flavour universality?

\[ B^+ \rightarrow K^+ ee \text{ vs. } B^+ \rightarrow K^+ \mu\mu \]

- 2.6\(\sigma\)
- seen in single experiment
- theoretically very clean \textit{Talk by M. Bordone}

\[ B \rightarrow D^{(*)}\tau\nu \text{ vs. } B \rightarrow D^{(*)}(e, \mu)\nu \]

- 4.0\(\sigma\) combined
- 3 experiments
- dependent on form factors (\(D: \text{LQCD}, D^*: \text{HQET}\)
## Unified new physics explanations

Models with a single (heavy*) new particle/multiplet:

<table>
<thead>
<tr>
<th>Spin</th>
<th>$SU(3)_C$</th>
<th>$SU(2)_L$</th>
<th>Name</th>
<th>Suggested</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>3</td>
<td>$W', Z'$</td>
<td>Greljo et al. 1506.01705</td>
</tr>
<tr>
<td>0</td>
<td>3</td>
<td>1</td>
<td>$S_1$</td>
<td>Bauer and Neubert 1511.01900</td>
</tr>
<tr>
<td>0</td>
<td>3</td>
<td>3</td>
<td>$S_3$</td>
<td>Medeiros Varzielas and Hiller 1503.01084</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>1</td>
<td>$U_1$</td>
<td>Barbieri et al. 1512.01560</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>3</td>
<td>$U_3$</td>
<td>Fajfer and Košnik 1511.06024</td>
</tr>
</tbody>
</table>

... and many more studies in the last 2 years [Talk by A. Crivellin](#)

* See [Bečirević et al. 1608.08501](#) for a LQ model with RH neutrinos
Indirect constraints

- $U_3, S_3$: strong constraint from $B \rightarrow K\tau\bar{\nu}_\mu$ cf. Buras et al. 1409.4557
- $S_1$:
  - $b \rightarrow s\mu^+\mu^-$ generated at 1-loop level Bauer and Neubert 1511.01900
  - Once all constraints (including $K$ and $D$ decays) taken into account, no simultaneous solution of anomalies Bečirević et al. 1608.07583

- All models generate $B \rightarrow K\tau\mu$ and $B_s \rightarrow \tau\mu$, but too small to be observed at Belle-II or LHCb Bhattacharya et al. 1609.09078
- RG effects lead to purely leptonic LFV Feruglio et al. 1606.00524
Direct constraints

- Strong constraints from $b\bar{b} \rightarrow \tau^+\tau^-$ searches at ATLAS/CMS
  Greljo et al. 1506.01705, Faroughy et al. 1609.07138
  - both $Z'$ (s-channel) and LQ (t-channel)

- $U_1$ LQ on the verge of being excluded
- $W'/Z'$ only allowed if light ($M < 500$ GeV) or broad ($\Gamma/M > 30\%$)
Summary of new physics explanations

Single-particle explanations of all $B$ decay anomalies are increasingly challenged by a fruitful interplay between

- model building
- $B$ factory constraints ($B \rightarrow K\nu\bar{\nu}$)
- LHCb constraints
- Charged lepton flavour violation
- Direct constraints from ATLAS/CMS

... of course, more elaborate constructions possible!
The crucial role of $B_s \rightarrow \mu^+ \mu^-$

- All single-particle explanations of all anomalies predict $C_9^{\text{NP}} = -C_{10}^{\text{NP}}$

- $C_{10}$ affects $B_s \rightarrow \mu^+ \mu^-$ – free from photon-mediated effects!
Future constraints on $C_{10}$ from $B_s \rightarrow \mu^+\mu^-$

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Homework: violation of LFU

EXPERIMENT

- $R_{K^*}, R_\varphi$, and all that  
  Talk by B. Capdevila

- $\Lambda_b \to \Lambda_c \tau \nu$ etc.  
  Talk by G. Ciezarek
Homework: violation of LFU

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THEORY

- be patient
Looking ahead
(a few examples)
Status: new physics in $B^0$ mixing

- Using CKM from tree and matrix element from FNAL/MILC
- best fit $1.5\sigma$ from SM
- Currently probing SM at 10% level in CP conserving, few-% level in CP violating observable
Status: new physics in $B_s$ mixing

- Using CKM from tree and matrix element from FNAL/MILC
- best fit again $1.5\sigma$ from SM
\( \Delta M_s \) error budget

\[
\Delta M_s \propto f_{B_s}^2 \hat{B}_{B_s} | V_{tb} V_{ts}^* |^2 = f_{B_s}^2 \hat{B}_{B_s} \left[ V_{cb}^2 (1 + O(\lambda^2)) \right]
\]

Relative uncertainty:

- Theory: 9%
- Experiment: 0.1%

Clearly, need lattice & CKM from tree to make progress!

(Using FNAL/MILC bag parameters and neglecting the correlation between \( f_{B_s} \) and \( B_1^{(s)} \))
$$\Delta M_d \text{ error budget}$$

$$\Delta M_s \propto f_{B_d}^2 \hat{B}_{B_d} |V_{tb} V_{td}^\ast|^2 \approx f_{B_d}^2 \hat{B}_{B_d} \left( V_{ub}^2 + V_{cb}^2 V_{us}^2 - 2 V_{ub} V_{cb} V_{us} \cos \gamma \right)$$

Relative uncertainty:

- **Theory:** 15%
- **Experiment:** 0.4%

(Using FNAL/MILC bag parameters and neglecting the correlation between $f_{B^0}$ and $B_1^{(d)}$)
Tree vs. loop

Crucial to test UT from tree vs. loop processes: importance of $\gamma$

Talk by D. Johnson
Future constraints from $B^0$ mixing

Dream scenario:

- current central values
- $f_{B^0}$ to 0.5%
- $\hat{B}_{B^0}$ to 0.5%
- $V_{ub}$ and $V_{cb}$ to 1%
- $\gamma$ to 0.5°
Future constraints from $B_s$ mixing

Dream scenario:

- current central values
- $f_{B_s}$ to 0.5%
- $\hat{B}_{B_s}$ to 0.5%
- $V_{ub}$ and $V_{cb}$ to 1%
- $\gamma$ to 0.5°
Determining the chirality of $b \rightarrow s\gamma$

- Wilson coefficient $C'_7$ strongly suppressed in the SM
- Need exclusive decays to determine chirality
- recent LHCb measurements of $B \rightarrow K^* e^+ e^-$ angular observables and $B_s \rightarrow \phi\gamma$ time-dependent decay rate

Paul and Straub 1608.02556
Future exclusive constraints on $b \rightarrow s\gamma$

Even more info on chirality and CP phases from

- Amplitude analysis of $B \rightarrow K\pi\pi\gamma$
- $\Lambda_b \rightarrow \Lambda\gamma$
New FCNC frontiers

- $b \to s$ transitions
  - $\Lambda_b \to \Lambda$ decays
  - $b \to s\tau^+\tau^-$ transitions

- $b \to d$ transitions
  - LCHb: 1st measurements of $B \to \pi\mu^+\mu^-$, $B \to \rho(\to \pi\pi)\mu^+\mu^-$, slight excess in $B_d \to \mu^+\mu^-$. Only the beginning!
  - Theory: better understanding of $O(V_{ub}V_{ud}^*)$ effects in semi-leptonic decays? see e.g. Hambrock et al. 1506.07760

- $c \to u$ transitions
  - Rare charm decays Talk by S. de Boer & V. Chobanova
  - Charm mixing Talk by A. Davis & A. Petrov
Conclusion

- Indirect searches crucial to find new physics → $300 \text{ fb}^{-1}$
  extremely well motivated

- Significant tensions in $b \rightarrow s\mu^+\mu^-$ transitions could be new physics, but SM explanations possible with current data

- Simultaneous new physics explanations of all $b \rightarrow s\mu^+\mu^-$ and $b \rightarrow c\tau\nu$ anomalies increasingly challenged by interplay of direct & indirect constraints

- Many exciting physics opportunities at LHCb run 2-3-4-5 (and Belle-II) that I didn’t mention

- Time for new data!