Flavour Physics at the IPPP

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Outline

- Motivation for Flavour Physics
  - Search for the Origin of Matter in the Universe
  - Identify New Physics (NP) Effects
  - Constrain Models for New Physics
- Status Quo
  - The SM rules
  - Test of our theoretical Tools
  - Still Space for sizable New Physics Effects
  - Several interesting Deviations are still there
- Some Roads to follow
  - Higher Precision necessary
  - New Observables in the Search for New Physics
- FP@IPPP

Flavour Physics

There are (at least) six kinds (=**flavours**) of quarks

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix} \quad \begin{pmatrix} q = +2/3 \\ q = -1/3 \end{pmatrix}$$

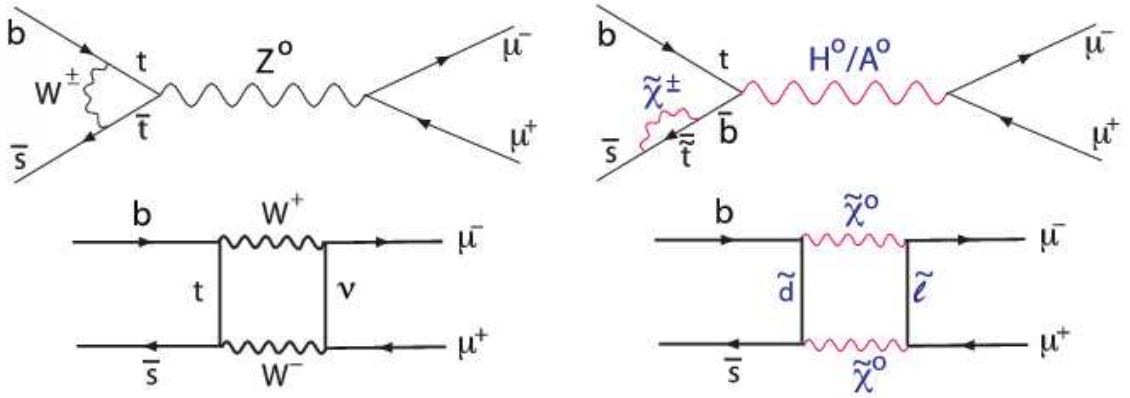
- Proton p = $|uud\rangle$
- **(Heavy) Flavour Physics** describes hadrons with a charm- or a bottom-quark

	$D^0 = (\bar{u}c)$	$D^+ = (\bar{d}c)$	$D_s^+ = (\bar{s}c)$	$\Lambda_c = (udc)$
Mass (GeV)	1.86486	1.86962	1.96850	2.28646
Lifetime (ps)	0.4101	1.040	0.500	0.200

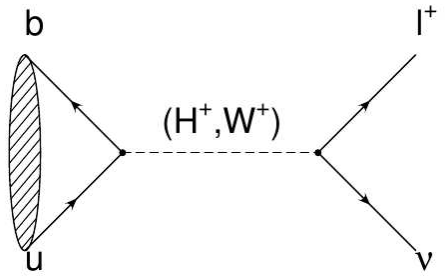
	$B_d = (\bar{b}d)$	$B^+ = (\bar{b}u)$	$B_s = (\bar{b}s)$	$B_c^+ = (\bar{b}c)$	$\Lambda_b = (udb)$
Mass (GeV)	5.27958	5.27926	5.3667	6.2745	5.6194
Lifetime(ps)	1.519	1.638	1.512	0.500	1.451

Why Flavour Physics?

- **CP violation** till now only found in quark flavour physics
- **Theoretically clean:** $\alpha_s(m_b) \approx 0.2 \approx \Lambda/m_b$
- many processes strongly suppressed in the SM due to quantum corrections:
  - $B_s \to \mu\mu$ or $b \to s\gamma$: **F**lavour **C**hanging **N**eutral **C**urrents



  - But also: $B \to \tau\nu$,...



Strong constraints on many NP models

- **Many experiments**, e.g. **LHCb, ATLAS, CMS; Super-Belle, Panda, LINAC, TLEP,...**

Status Quo: The SM rules

- Huge # of flavour observables are **SM-like**, e.g. lifetimes, hadronic decays,...
- Unitarity triangle is SM like **HFAG, CKMfitter (at CKM 2014), UTfit**

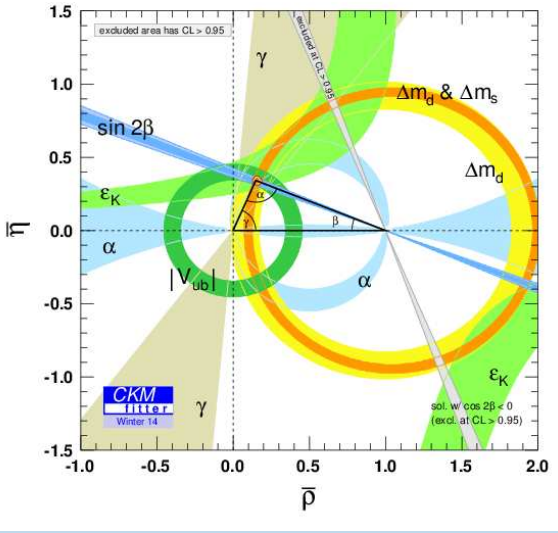
$$\sin 2\beta^{direct} = 0.679 \pm 0.020 \qquad \gamma^{direct} = \left(73.2^{+6.3}_{-7.0}\right)^\circ$$

$$\sin 2\beta^{indirect} = 0.774^{+0.017}_{-0.036} \qquad \gamma^{indirect} = \left(66.4^{+1.3}_{-2.5}\right)^\circ$$

There is still space for sizable NP effects

- **Even very rare processes are SM-like, e.g.**
  - $B_s \to \mu\mu$
  - $b \to s\gamma$
  - **B-mixing:** ΔM_q, $\Delta\Gamma_s$, a^q_{sl}
  - **...**

  There is still space for sizable NP effects



Status Quo: Deviations

1. Huge # of flavour observables are **SM-like**
2. **Still some sizable space for NP effects**
3. **There are several interesting deviations in the present data**

- **Tree-level observables**
  - V_{ub} and V_{cb} - about 3 σ
  - $B \to \tau\nu$ - about 2 σ
  - Lepton universality: $R(D^{(*)})$ - 3.4 σ
  - direct/indirect determination of the CKM angle γ
- **Loop-induced observables**
  - direct/indirect determination of the CKM angle β; about 2 σ
  - The dimuon asymmetry - about 3 σ
  - $B \to K^{(*)}ll$ - Br, P_5' up to 4 σ
  - $B_s \to \phi ll$ - Br
  - Lepton universality: $Br(B^+ \to K^+\mu\mu)/Br(B^+ \to K^+ee)$ deviates by 2.6 σ
  - $Br(B_d \to \mu\mu)/Br(B_s \to \mu\mu)$ deviates by 2.3 σ **1411.4413**
- **Observables in the Charm-sector**
  - CPV in D-decays?

Roads to follow

1. Huge # of flavour observables are **SM-like**
2. **Still some sizable space for NP effects**
3. **There are several interesting deviations in the present data**

Prepare for detecting smaller (i.e. not huge) deviations from the SM

1. Higher precision in theory and experiment - **NNLO-QCD, Lattice**
2. Challenge some text-book wisdom, e.g.
   - **Penguins are negligible**
   - **NP effects in tree-level decays are negligible**
3. Investigate quantities that are difficult to measure, e.g.: $B_q \to \tau\tau$, inclusive non-leptonic decays, $\Delta\Gamma_d$, ...
4. Look at the charm sector
5. Find NP in flavour observables

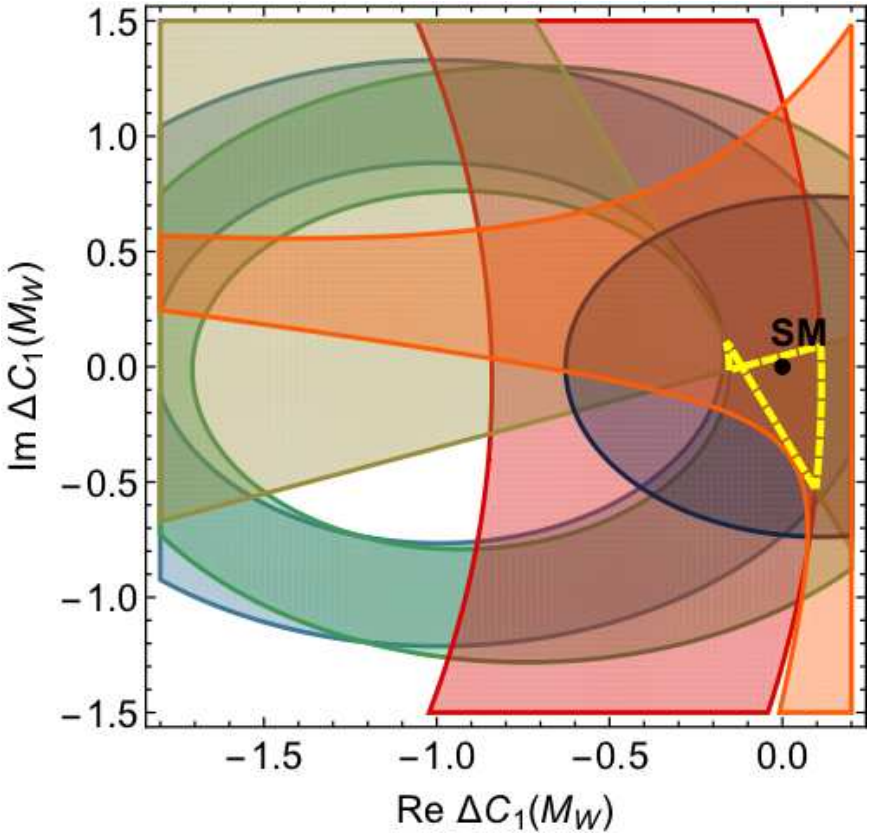
Roads to follow - NP in tree-level decays

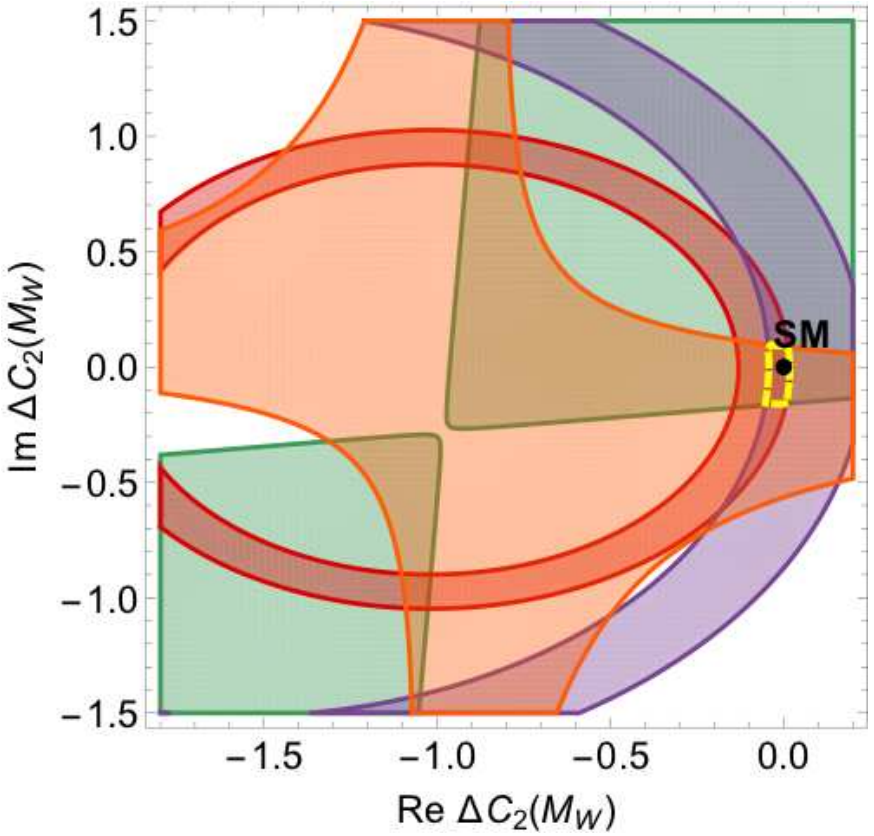
- NP effects in penguins are quite well studied - many fits for C_7, C_9, C_{10},...
- *No NP effects in tree-level decays*, i.e. C_1 and C_2
  was a reasonable approximation some years ago,
  but should be challenged in view of the current experimental precision
- First systematic studies of NP effects in C_1 and C_2 in 2014:
  - Effects on $\Delta\Gamma_d$: **Bobeth, Haisch, AL, Pecjak, Tetlalmatzi-Xolocotzi, 1404.2531**
  - $B \to K\pi$-puzzle: **Bobeth, Gorbahn, Vickers, 1409.3252**
  - Effects on CKM-angle γ: **Brod, AL, Tetlalmatzi-Xolocotzi, Wiebusch, 1412.1446**
- Look at observables that
  - depend strongly on C_1 and C_2
  - can be reliably predicted
  - are precisely measured

  $\Rightarrow$ take bounds from
  $B \to D\pi$, $b \to s\gamma$, $b \to d\gamma$, lifetimes, $\sin\beta$, $B \to \pi\pi$, $\Delta\Gamma_s$ and $a_{sl}^{d,s}$

Roads to follow - NP in tree-level decays

Bounds on C_1 and C_2





Bobeth, Haisch, AL, Pecjak, Tetlalmatzi-Xolocotzi, 1404.2531

Is Im $\Delta C_1 = \pm 0.1$ large or small?

Roads to follow - NP in tree-level decays

Effects on the determination of the CKM angle γ: **aim** $< 1^\circ$**!**

NP effects in C_1 and C_2 induce a shift $\delta\gamma$ in the determination of γ

$$\delta\gamma = (r_A - r_{A'}) \frac{\mathrm{Im}\Delta C_1}{C_2}$$

with the ratios of hadronic matrix elements (**different topologies!**)

$$r_{A'} = \frac{\langle \bar{D}^0 K^- | Q_1^{\bar{u}cs} | B^- \rangle}{\langle \bar{D}^0 K^- | Q_2^{\bar{u}cs} | B^- \rangle} \qquad r_A = \frac{\langle D^0 K^- | Q_1^{\bar{c}us} | B^- \rangle}{\langle D^0 K^- | Q_2^{\bar{c}us} | B^- \rangle}$$

with naive estimates for r_A and $r_{A'}$ we obtain

$$\mathrm{Im}\Delta C_1 = \pm 0.1 \Rightarrow \delta\gamma = \pm 4^\circ$$

This is huge!

Roads to follow - NP in tree-level decays

How to improve the bounds on C_1 and C_2?

- Include more observables
- NNLO-QCD to lifetimes and $\Delta\Gamma_s$
- smaller experimental error of $a_{sl}^{q,d}$
- Do a real fit - till now only scan
- Investigate more effects of NP in C_1 and C_2, e.g. $\Delta\Gamma_d$
- Identify NP models with effects in C_1 and C_2
- Include NP effects in penguin coefficients

How to improve the bounds on γ?

- Improved estimates on $r_A$and $r_{A'}$

work in progress

FP@IPPP I: Staff

- ’01 - ’10 **Patricia Ball** - **Heavy Flavour** (now retired)
- ’11 **Thorsten Feldmann** - **Heavy Flavour** (now University of Siegen)

- since ’05 **Silvia Pascoli** - **Lepton Flavour - not covered here**
- since 1.10.’12 **Ben Pecjak** - **representing top physics**
- since 1.10.’12 **Alexander Lenz** - **representing beauty and charm**
- since ’01 **Valery Khoze** - **Part-time Flavour: exclusive physics**

FP@IPPP II: People doing the real work

- Post-Docs
  - Since 10/13 **Martin Wiebusch**
  - Since 10/14 **Rhorry Gauld**

- PhD-students
  - Since 10/12 **Gilberto Tetlalmatzi-Xolocotzi**
  - Since 10/13 **Darren Scott**
  - Since 10/14 **Matthew Kirk**

FP@IPPP III: Recent Projects

1412.1446 Brod, AL, Gilberto, Martin NP in tree-level
1409.6963 AL CKM conference
1408.0222 AL + l2/l3 students Testing QM with B-mixing
1405.3601 AL HQE and lifetimes - book contribution
1404.6197 AL Selected topics in HF physics - award
1404.2531 Bobeth, Haisch, AL, Gilberto, Ben NP in $\Delta\Gamma_d$
1311.6447 AL Charm conference
1308.6176 AL... TLEP
1305.5390 Krinner, AL, Rauh NLO-QCD to $b \to c\bar{c}s$
1305.3588 AL, Rauh τ_D in HQE
AHEP 2013 AL SM4 review
1209.1101 Eberhardt, Herbert, Lacker, AL, Nierste, Martin - Kill SM4
1503.00859 Frings, Nierste, Martin Penguin pollution
1412.6102 Martin HEP Math
1411.2029 Ghosh, Martin Dim 6 triple gluon operator
1403.1264 Baglio, Eberhardt, Nierste, Martin Higgs pair production in 2HDM
1501.01938 Gilberto Conference - Freudenstadt

FP@IPPP IV: Recent Projects

1409.5294 Broggio, Ferroglia, Ben, Zhang NNLO

1409.3989 Ferroglia,Marzani, Ben, Yang Conference - top pair in SCET

1404.2531 Bobeth, Haisch, AL, Gilberto, Ben NP in $\Delta\Gamma_d$

1310.3836 Ferroglia, Marzani, Ben, Yang Boosted top

1306.1537 Ferroglia, Ben, Yang Top quark pair production, NNLO

1212.5859 Ahrens, Ferroglia, Neubert, Ben, Yang Conference - FB and A_{charge}

1409.4785 Harland-Lang, Valery, Ryskin Exclusive double J/ψ

1405.0018 Harland-Lang, Valery, Ryskin, Stirling Durham model

1312.4553 Harland-Lang, Valery, Ryskin Exclusive meson pair

1304.4262 Harland-Lang, Valery, Ryskin, Stirling Perturbative ...

1302.2004 Harland-Lang, Valery, Ryskin, Stirling Exclusive production vs $\eta(')$

1204.4803 Harland-Lang, Valery, Ryskin, Stirling Phenomenology ...

1204.4803 Harland-Lang, Valery, Ryskin, Stirling Phenomenology ...

CMS note Installation forward shower counter, also LHCb, ALICE

FP@IPPP V: Workshops

- Organisation
  - **UK Flavour Physics** in Durham 2013
  - **LHCb Associateship-workshop** in the Lake District 2013
  - **Kick-off workshop** for Senior Experimental Fellowship in Durham 2014
  - **YETI Flavour** in Durham 2014
  - **LHCb-UK meeting** in Durham 2014
  - $B \to Kll$ **workshop** in London 2014
  - **D0/ATLAS Associateship-workshop** in the Lancaster 2014
- Co-organisation with financial contributions
  - **CHARM 2013** in Manchester
  - **UK HEP Forum 2013** *Quarks and Leptons* in Abingdon
  - **BEAUTY 2014** in Edinburgh
  - **BEACH 2014** in Birmingham
- Many co-organisation without financial contributions, e.g.
  - **LHCb-UK meeting** 2014 in Bristol
  - ...

FP@IPPP VI: Associates, Fellows,...

- IPPP Associateship
  - 2012/2013: Chris Parkes, Marco Gersabeck, Silvia Borghi (LHCb - Manchester)
  - 2013/2014: Guennadi Borissov (D0, ATLAS - Lancaster)
- Senior experimental fellowships
  - 2013/14: Ulrik Egede et al. (LHCb - Imperial London) International Workshop at Imperial with 32 participants

FP@IPPP VII: Flavour seminars in the UK

- Manchester 2012
- Lancaster 2013
- Edinburgh 2013
- Cambridge, Cavendish 2013
- Cambridge, DAMTP 2013
- Southampton 2013
- Birmingham 2013
- Warwick 2013
- *Trinity College, Dublin 2014*
- Plymouth 2014
- Bristol 2014
- Glasgow 2015

- Liverpool 2014
- Southampton 2013
- Lancaster 2014
- Edinburgh 2015
- Liverpool 2015
- Sussex 2015
- Cambridge, Cavendish 2013
- Imperial, London 2014

FP@IPPP: What's next?

Charm, Beauty and Top within the IPPP - current cooperations:

- **Celine Boehm**: DM vs Flavour constraints
- **Valya Khoze**: 2HDM vs flavour
- **Frank Krauss**: MC studies of inclusive decays and update of Monte Carlo Input
- **Michael Spannowsky**: Higgs/EW vs flavour

Conferences:

- Contribution to **Lattice 2016**, Southampton
- Programme Advisory Committee **CKM 2016**, India
- Contribution to **KAON 2016**, Birmingham
- **Heavy Flavour 20xx** on Islay
- Application for **FPCP 2017** in Durham