B physics : status and prospects

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Outline

- Why B physics?
- Recent advances
- Future prospects

Why B physics? : Theory motivation

- Low energy gateway to new physics
- Several decay channels
  - Hadronic decays ($B \to \pi\pi, KK, \rho\rho, K + \mathrm{charmonium}$)
  - Semileptonic decays ($B \to K\ell^+\ell^-, B \to D\tau\nu_\tau$)
  - Meson Mixing ($B^0 - \bar{B}^0$, $B^0_s - \bar{B}^0_s$)
- Measure CKM elements : CP violating phases

The CKM framework : Theory

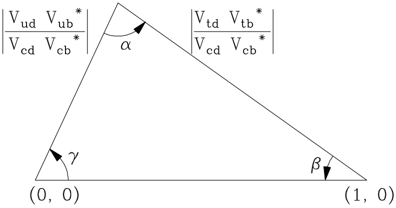
- Flavor changing interactions in the SM : CKM Matrix

$$V_{\rm CKM} = \begin{matrix} & d & s & b \\ u & 1-\lambda^2/2 & \lambda & A(\rho-i\eta)\lambda^3 \\ c & -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ t & A(1-\rho-i\eta)\lambda^3 & -A\lambda^2 & 1 \end{matrix} + \mathcal{O}(\lambda^4)$$

Wolfenstein parametrization

- Powerful $\rightarrow$ predicts a range of phenomena
  $\rightarrow$ only 4 independent parameters
- Unitarity provides consistency checks : $\sum_q^{u,c,t} V^*_{qd} V_{qb} = 0$

CKM unitarity triangle



$\rightarrow \alpha(\phi_2)$: $B \rightarrow \pi\pi,\ \rho\pi,\ \rho\rho$
$b \rightarrow u\bar{u}d$ (loop sensitive)

$\rightarrow \beta(\phi_1)$: $B \rightarrow K\ +$ charmonium
$b \rightarrow c\bar{c}d$ (loop sensitive)

Sensitive to BSM physics

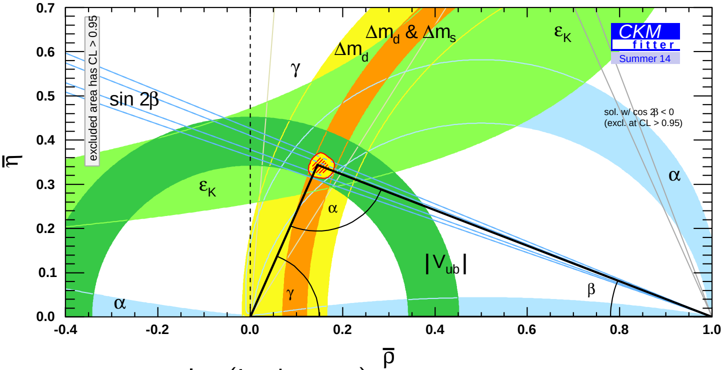
$\rightarrow \gamma(\phi_3)$: GL, GW, ADS, GGSZ methods

Study interference between $B \rightarrow DK(b \rightarrow c\bar{u}s)$ and $B \rightarrow \bar{D}K(b \rightarrow u\bar{c}s)$

TREE level diagrams $\rightarrow$ Theoretically clean!
$\rightarrow$ possibly free from new physics effects
$\rightarrow$ statistics limited

CKM unitarity triangle : experiment

Plot from CKM Fitter collaboration (see also UTFit collaboration)



Direct measurement results (in degrees):

$$\alpha(\phi_2) = 85.4^{+4.0}_{-3.9}\ , \qquad \beta(\phi_2) = 21.5^{+0.75}_{-0.74}\ , \qquad \gamma(\phi_3) = 70.0^{+7.7}_{-9.0}\ .$$

Direct determination of γ_{tree}

- Gronau-London-Wyler method (4 unknowns):
  - $\rightarrow \quad A(B^- \rightarrow D^0 K^-) = |A| \,, \quad A(B^- \rightarrow \overline{D}^0 K^-) = r_B \; |A| \; e^{i\delta} \; e^{-i\gamma}$
  - $\rightarrow$ 4 observables : 2 branching ratios and 2 direct-CP asymmetries
- Extensions : study multi body D decays
  - $\rightarrow$ GGSZ method : Giri et al., hep-ph/0303187
  - $\rightarrow$ additional unknowns + observables from the D decay
- $N_B N_D$ observables with $N_B + N_D$ unknown parameters
  - $\rightarrow$ Use a combination of all available channels
- Limitation : direct-CP asymmetries $\propto r_B$
  - $\rightarrow$ In $B^\pm$ decays $r_B \; = \; f|V^*_{cs}V_{ub}|/|V^*_{us}V_{cb}| \; \sim \; 0.1$ (require high statistics)

Theory uncertainty in $\gamma_{\rm tree}$

- CP violation in charm : methods assume no CPV in charm
  - $\rightarrow$ $D^0 - \overline{D}^0$ mixing : small effects $\leftarrow$ precise measurement of x_D, y_D

    Bondar et al., 1004.2350; Rama, 1307.4384 : $<\sim 1^\circ$ shift
  - $\rightarrow$ direct CPV in D^0 decays : effect $\propto 1/r_B$ (few % shift for $r_B \sim 0.1$)

    Wang, 1211.4531; Martone, Zupan, 1212.0165;

    BB, Gronau, Rosner, 1301.5631
- $K - \overline{K}$, $B_{(s)} - \overline{B}_{(s)}$ mixings : combined effect $<$ few degrees
  - $\rightarrow$ Gronau et al., hep-ph/0702011
- Higher-order EW corrections : fractional shift $\sim \mathcal{O}(10^{-7})$
  - $\rightarrow$ Brod, Zupan, 1308.5663

"γ from loop"

- Alternative strategy : $\rightarrow$ use $b \rightarrow u\bar{u}d$ & $b \rightarrow u\bar{u}s$
  $\rightarrow$ exploit U-spin symmetry ($d \leftrightarrow s$)
- Two-body : $B_d^0 \rightarrow \pi^+\pi^-$ & $B_s^0 \rightarrow K^+K^-$ Fleischer, hep-ph/9903456
  $\rightarrow$ $A_d = |V_{ub}^* V_{ud}|\, e^{i\gamma}\, a_d^u - |V_{cb}^* V_{cd}|\, a_d^c$ U-spin limit : (4 unknowns)
  $\rightarrow$ $A_s = |V_{ub}^* V_{us}|\, e^{i\gamma}\, a_s^u + |V_{cb}^* V_{cs}|\, a_s^c$ $a_d^{u(c)} = a_s^{u(c)}$
  $\rightarrow$ 4 observables (2 branching ratios and 2 direct-CP asymmetries)
  1 relation : $A_s^{CP} B_s = -A_d^{CP} B_d$
- Include (+2) indirect CP asymmetries as observables
  $\rightarrow$ Mixing phase $2\beta_d$ $\leftarrow$ independent measurement ($B^0 \rightarrow J/\psi K_S$)
  $\rightarrow$ Use method to measure γ (and also mixing phase $2\beta_s$)
- LHCb finds : $\gamma = \left(63.5^{+7.2}_{-6.7}\right)^\circ$ Aaij et al., 1408.4368

More on "γ from loop"

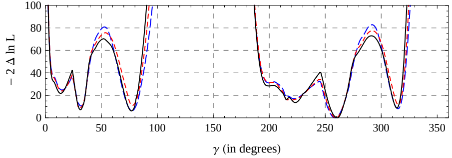
- U-spin breaking can be large : source of theory error!
- Extension to three-body decays : BB, London, 1503.00737
  - $\rightarrow$ Example U-spin pair : $B_s^0 \rightarrow K_S \pi^+ \pi^-$ & $B_d^0 \rightarrow K_S K^+ K^-$
  - $\rightarrow$ Requires time-dependent Dalitz analyses
  - $\rightarrow$ Same principal & $a_q^{u(c)} \equiv a_d^{u(c)}(p_1, p_2, p_3)$ (momentum dependent)
- Test for degree of U-spin breaking : $A_s^{CP} B_s = -A_d^{CP} B_d$
  - $\rightarrow$ U-spin relationship : satisfied locally & integrated over Dalitz plot
  - $\rightarrow$ Reduction of U-spin breaking possible in global analysis

"$B \to \pi K$ puzzle" and γ

- Flavor SU(3) relates: $B^+ \to \pi^+ K^0,\ \pi^0 K^+\ ;\ \ B_d^0 \to \pi^- K^+,\ \pi^0 K^0$
- 9 measurements : 4 branching ratios + 4 direct CP asymmetries
  + 1 indirect CP asymmetry
- 9 unknowns : 4 magnitudes + 3 relative strong phases + β + γ
- SM can explain data but still room for NP
  - → Best fit value for $\gamma = (35.9 \pm 7.7)^\circ$: large deviation from $\gamma_{\rm tree}$
  - → Baek, Chiang, London, 0903.3086
- Problematic in SUSY/SUSY can't explain puzzle
  - → Imbeault, Baek, London, 0802.1175
  - → Endo, Yoshinaga, 1206.0067

"$B \to K\pi\pi, K\overline{K}K$ puzzle?"

- 3-body final state under SU(3) : $B \to K\pi\pi, K\overline{K}K$
  - $\to$ 6 final state symmetries : permutations of 3 particles
- Group theory analysis : I-spin, U-spin, SU(3) relations
  - $\to$ BB, Gronau, Imbeault, London, Rosner, 1402.2909
- Fully-symmetric state (Rey-Le Lorier, London, 1109.0881)
  - $\to$ More observables than unknowns $\Rightarrow$ γ can be extracted
  - $\to$ BB, Imbeault, London, 1303.0846



$\to$ SM-like : $(77 \pm 2)^\circ$

$\to$ 32°, 259°, 315°

$K\pi\pi - K\overline{K}K$ puzzle ?

Future analyses on other symmetry states planned

Why bother about γ?

- Very small theory error in $\gamma_{\rm tree}$: theoretically clean
- LHCb upgrade promise : precision $\sim$ few degrees with 5 fb^{-1};
  (also BELLE II) $<\sim 1^\circ$ very long term
- Precise determination of $\gamma \Rightarrow$ NP weak phases
  - $\rightarrow$ Brod et al., 1412.1446
- Long term hope : γ measurements $\Rightarrow$ New Physics
  - $\rightarrow$ Possible disagreements between multiple γ measurements
- Disagreement between γ from tree and loop:
  - $\rightarrow$ small : study hadronic parameters, flavor symmetry violation
  - $\rightarrow$ large : Indications of NP in the loop

Another weak phase! β_s

- $B_s - \overline{B}_s$ mixing phase : $2\beta_s = -2\,\arg(V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$
- SM result obtained by CKM Fitter : $2\beta_s = 0.03634^{+0.00136}_{-0.00120}$
- Direct measurement : golden mode $B_s \to J/\psi\phi$
  - $\to$ Indirect CP asymmetry contains mixing phase information
  - $\to$ Time-dependent angular analysis required
- Possible theoretical error due to "penguin pollution"
  - $\to$ Theory input from $B_s^0 \to J/\psi\overline{K}^{*0}$: Faller et al., 0810.4248
  - $\to$ Modify angular analysis (higher stat) : BB, Datta, London, 1209.1413
- LHCb measurement : -0.010 $\pm$ 0.039 Aaij et al. 1411.3104
- Consistent with SM : still plenty of room for NP!

Rare decays : route to NP

- Tree-level processes : $B \to DK, K\pi, J/\psi\phi$
  - $\rightarrow$ Large branching ratios : typically SM contributions dominate
  - $\rightarrow$ NP may be present but quite difficult to separate
- No tree-level contributions : $B_s \to \phi\phi, K^*\overline{K}^*$
  - $\rightarrow$ SM contribution is (loop-)suppressed : Rare decay!
  - $\rightarrow$ NP can potentially be as large as SM : easier to separate
- Rare decays are experimentally challenging to observe

  Future colliders will play important role (including LHC and Belle II)
- See $B \to K^*\mu^+\mu^-$ talks in this session

Recent developments in $B \to K\ell^+\ell^-$

- $B \to K\ell^+\ell^-$ transition in SM : $b \to s$ transition $\leftarrow$ FCNC
  - $\rightarrow$ EW penguin and box diagrams $\Rightarrow$ loop suppressed
  - $\rightarrow$ $B^+ \to K^+e^+e^-$ measurement : $\mathcal{B} \sim \mathcal{O}(10^{-7})$ ($\sim$ 10% error)
- Lot of theory work: Data agrees with SM
  - $\rightarrow$ Altmannshofer et al., 1111.1257; Bobeth et al., 1111.2558; ...
  - $\rightarrow$ Deviations in individual channels $\leftarrow$ Large hadronic uncertainties
- SM result is lepton-flavor universal for light leptons
  - $\rightarrow$ Uncertainties cancel in the ratio of μ channel to e channel
- LHCb measured : $R_K = \mathcal{B}(B^+ \to K^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+e^+e^-)$

  $\rightarrow$ $1 < q^2_{\ell^+\ell^-} < 6$ GeV^2 $R_K = 0.745^{+0.097}_{-0.082}$ Aaij et al., 1406.6482

R_K measurement a big deal?

- Theory prediction : $R_K = 1.0003 \pm 0.0001$ (measured 0.75 ± 0.10)
  - $\rightarrow$ includes α_s and $1/m_b$ corrections : Bobeth et al., 0709.4174
- LHCb result : 2.6 σ away from 1 $\Rightarrow$ potential NP signal
- A lot of theory papers discuss NP sources
  - $\rightarrow$ Alonso, Grinstein, Martin Camalich, 1406.6681
  - $\rightarrow$ Hiller, Schmaltz, 1408.1627
  - $\rightarrow$ Ghosh, Nardecchia, Renner, 1408.4097
  - $\rightarrow$ Biswas, Chowdhury, Han, Lee, 1409.0882
  - $\rightarrow$ Glashow, Guadagnoli, Lane, 1411.0565
  - $\rightarrow$ BB, Datta, London, Shivashankara, 1412.7164
  - $\rightarrow$ many more ...

Highlights of a few theory works

- Hiller & Schmaltz, 1411.4773 : Double ratios are sensitive NP probes
  - $\rightarrow$ Generic $R_H(= H\mu\mu/Hee) = 1 \pm \mathcal{O}(m_\mu^2/m_b^2)$ $(H = K, K^*, X_s, \cdots)$
  - $\rightarrow$ $R_{X_s} \sim 1/2$ (about 3σ away from 1) : Precision measurement required
  - $\rightarrow$ R_H/R_K depends only on lepton non-universality in right-handed currents
- Alonso et al., 1406.6681 : High-scale NP must respect $\mathrm{SU}(2)_W$ gauge
  - $\rightarrow$ Constraints on dim-6 NP effective operators (no tensor operators)
  - $\rightarrow$ Effects observable in $B \rightarrow K^{(*)}\ell^+\ell^-$, $B_q \rightarrow \ell^+\ell^-$
- Glashow et al., 1411.0565 : NP in third generation

  $(\overline{b}_L\gamma^\mu b_L)(\overline{\tau}_L\gamma_\mu\tau_L)$ in EW basis $\Rightarrow$ New Lepton non-universal couplings for μ

  $\rightarrow$ Violates Lepton-flavor : Look for $B \rightarrow K\mu(e,\tau)$, $B_s \rightarrow \mu(e,\tau)$

  $\rightarrow$ Predicts $B_s \rightarrow \mu^+\mu^-$ smaller than in SM by ~ 0.75

  (agrees with LHCb + CMS, 1411.4413 result, at current level of precision)

Relating R_K and $R(D^{(*)})$

- BB, Datta, London, Shivashankara 1412.7164
  - $\rightarrow$ NP in third generation with down type quarks above electro-weak scale
  - $\Rightarrow$ Electro-weak symmetry must be respected by the Lagrangian
- Two NP operators in weak basis: (1) $(\overline{Q}_L \gamma^\mu Q_L)(\overline{L}_L \gamma_\mu L_L)$
  (2) $(\overline{Q}_L \gamma^\mu \sigma^I Q_L)(\overline{L}_L \gamma_\mu \sigma^I L_L)$
- (1) contributes to neutral current; (2) also contributes to charged current
  - $\rightarrow$ Up-sector lepton non-universality from (2) in $b \rightarrow c\tau\nu / b \rightarrow c\ell\nu$
- $R(D^{(*)}) = \mathcal{B}(\overline{B} \rightarrow D^{(*)}\tau\overline{\nu}) / \mathcal{B}(\overline{B} \rightarrow D^{(*)}\ell\overline{\nu})$: BaBar finds $2-3\sigma$ deviation
  - $\rightarrow$ Large mixing element involving τ vs μ, e
- Prediction : $R(D)/R(D^*)$ unaffected (true for generic LH couplings)
  - $\rightarrow$ Precise measurement of double ratio can distinguish SM from RH NP

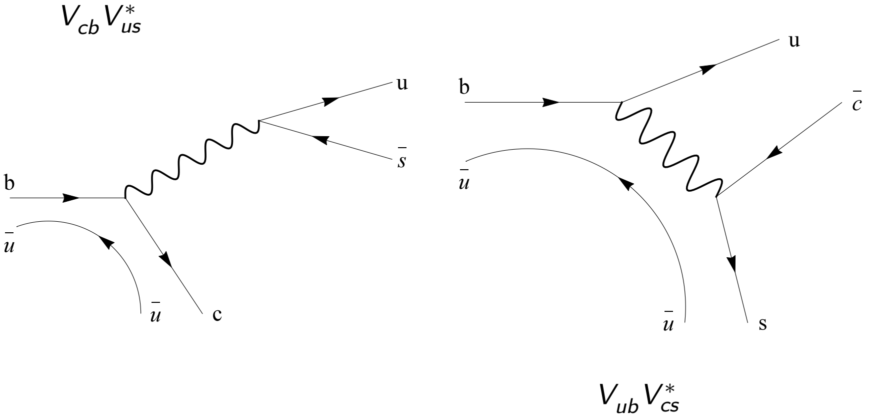
Miscellaneous applications

- Flavored fermionic dark matter models : fDM-quark-scalar Yukawas
  - $\rightarrow$ See for example Agrawal et al., 1404.1373
  - $\rightarrow$ GC Photon Excess through annihilation to $q - \overline{q}$ pairs
- FCNC measurements restrict couplings : generic models ruled out
  - $\rightarrow$ Symmetry arguments restore flavor safety through restricted couplings
- MFV : Flavor violation only through SM Yukawas & CKM elements
  - $\rightarrow$ Indirect evidence of DM through precision measurements
- DM searches (direct, indirect, collider) + precision flavor observables
  - $\rightarrow$ Restriction of parameter space/rule out models

Summary

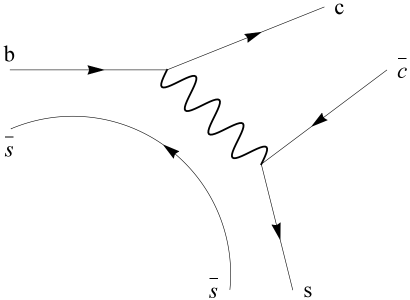
- B factories have set CKM framework on firm footing
- Heavy-flavor physics still low-energy gateway to NP
- Further precision in flavor measurements not far away!
- Key measurement channels :
  - $\rightarrow$ $B \rightarrow DK + D \rightarrow 2, 3, \ldots$ for $\gamma_{\rm tree}$
  - $\rightarrow$ 2 & 3 body B decays for $\gamma_{\rm loop}$
  - $\rightarrow$ $B_s \rightarrow J/\psi\phi, \phi\phi, \ldots$ for β_s
  - $\rightarrow$ $b \rightarrow s$ and other rare decays for NP in FCNC's
- LHCb + Belle II measurements will shape the future

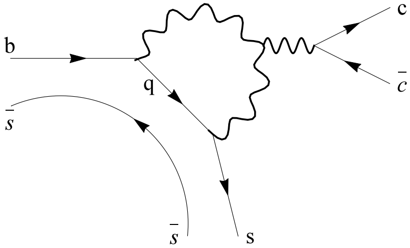
Diagrams : $B \to DK$



Diagrams : $B_s \to J/\psi\phi$

$V_{cb} V_{cs}^*$





$V_{qb} V_{qs}^*$

Note : $\sum_q V_{qb} V_{qs}^* = 0$

References

- Belle $b \to s$ results : Iijima talk, Lepton Photon '09

  $\to$ $B \to X_s \mu\mu$: $(1.9 \pm 1.0) \times 10^{-6}$

  $\to$ $B \to X_s ee$: $(4.6 \pm 1.2) \times 10^{-6}$ (Updates?)

- BaBar results for $B_s \to X_s \ell^+ \ell^-$: Lees et al., 1312.5364

- BaBar results for $b \to c$: Lees et al., 1205.5442

  Lees et al., 1303.0571

  $R(D) = 0.440 \pm 0.058 \pm 0.042$ $R(D^*) = 0.332 \pm 0.024 \pm 0.018$

- SM expectations for $b \to c$:

  $R(D)_{\mathrm{SM}} = 0.297 \pm 0.017$ $R(D^*)_{\mathrm{SM}} = 0.252 \pm 0.003$