Flavor physics: A Theoretical Introduction

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IIT Hyderabad, 19 - 23 Oct 2024

Outline

1. Role of flavor physics in building up the SM
2. The CKM paradigm and its precision tests
3. Some results that have been in the limelight
4. Rare FCNC processes
5. Looking for BSM Physics
   - Specific new physics models
   - Model-independent BSM searches
6. Concluding remarks

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Role of flavor physics in building up the SM

- $\tau - \theta$ puzzle $\Rightarrow$ Parity violation
- Cabibbo angle $\Rightarrow$
  weak coupling universality $\oplus$ quark mixing
- GIM mechanism $\Rightarrow$ no FCNC at tree level, charm
- CKM paradigm $\Rightarrow$ (at least) three quark families
- Large B–$\overline{B}$ mixing $\Rightarrow$ heavy top quark (box)
- Rate of radiative B decay $\Rightarrow$ top quark mass (penguin)

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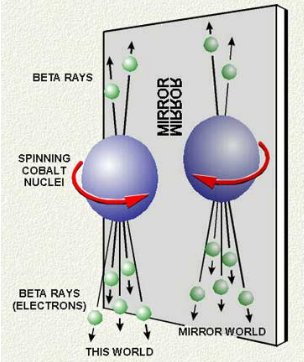
Discovery of parity violation: 1956-57



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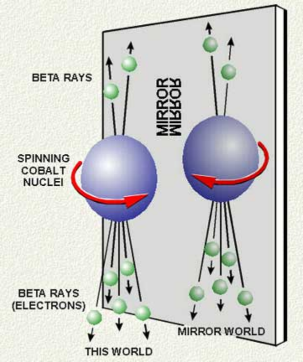

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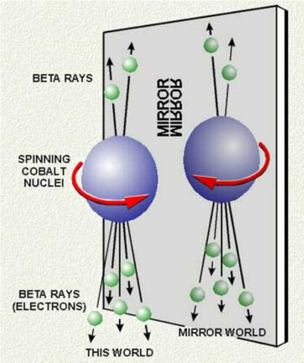

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Universality of weak interactions: Cabibbo angle

Interrelated coupling constants:

- (i) muon decay: $g_{e\mu}$
  $\mu^- \to \nu_\mu e^- \bar{\nu}_e$
- (ii) neutron decay : g_{ud}
  $n \to p e^- \bar{\nu}_e \; (d \to u e^- \bar{\nu}_e)$
- (ii) kaon decay: g_{us}
  $K^- \to \pi^0 e^- \bar{\nu}_e \; (s \to u e^- \bar{\nu}_e)$

$$\boxed{|g_{e\mu}|^2 = |g_{ud}|^2 + |g_{us}|^2}$$

Universality:

- There is only one coupling constant, $g = g_{e\mu}$
- u quark couples to only one combination of d and s:

$$d' \equiv \cos\theta_c \cdot d + \sin\theta_c \cdot s$$

- Cabibbo angle θ_c: the first quark mixing angle

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Suppression of flavor-changing neutral currents

- Cabibbo angle unable to explain why

$$\Gamma(K_L \to \mu^+\mu^-) << \Gamma(K^+ \to \mu^+\nu_\mu)$$

- Possible explanation via another "c" quark: charge $+2/3$, couples to

$$s' \equiv -\sin\theta_c \cdot d + \cos\theta_c \cdot s$$

- The $s \to u \to d$ and $s \to c \to d$ contribution cancel, leading to the suppression of FCNC $s \to d$
- GIM mechanism: existence of the "charmed" quark.

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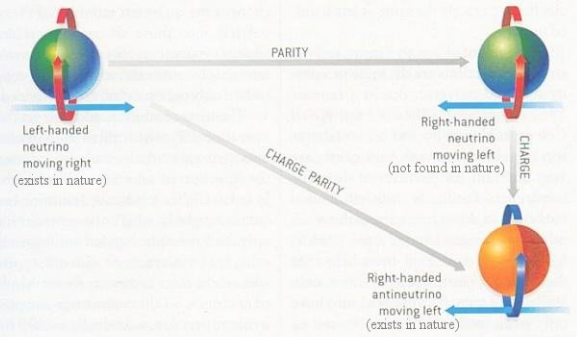
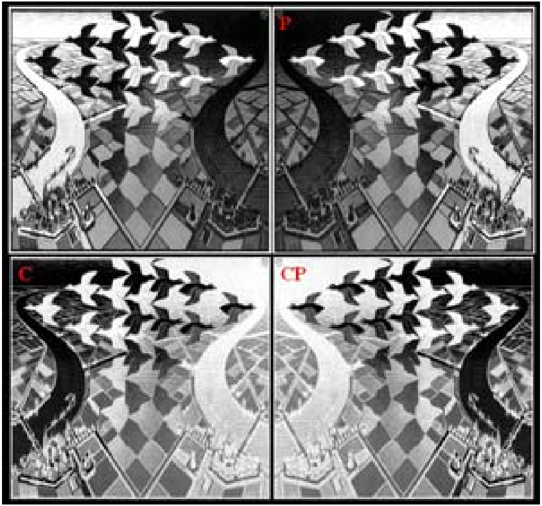
Can Charge $\oplus$ Parity may be conserved ?

Parity: left landed $\leftrightarrow$ right handed



- Neutrinos violate parity: they are only left-handed
- But antineutrinos are right-handed !
- Does that mean C and P violations cancel each other to give CP conservation ?

Charge-parity violated slightly



“Day and Night”, M.C.Escher
(Modifications by Tobias Hurth)

Testing CP violation in K decay

$$K^0 \equiv d\bar{s} \qquad \overline{K^0} \equiv s\bar{d}$$

- CP eigenstates:

$$\begin{aligned} K_1 &\equiv (K^0 + \overline{K})/\sqrt{2} \qquad \text{(CP even)} \\ K_2 &\equiv (K^0 - \overline{K})/\sqrt{2} \qquad \text{(CP odd)} \end{aligned}$$

- CP even decay channel: $\pi\pi$
- CP odd decay channel: $\pi\pi\pi$
- CP conservation $\Rightarrow$

$$\begin{aligned} K_1 &\to \pi\pi \text{ short-lived, } K_{\mathrm{Short}} \\ K_2 &\to \pi\pi\pi \text{ long-lived, } K_{\mathrm{Long}} \end{aligned}$$

- Original $K^0 = (K_{\mathrm{Short}} + K_{\mathrm{Long}})/\sqrt{2}$

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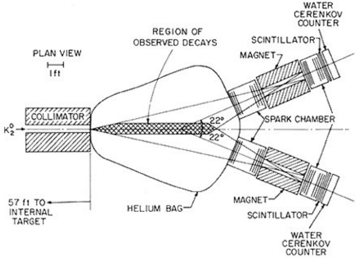
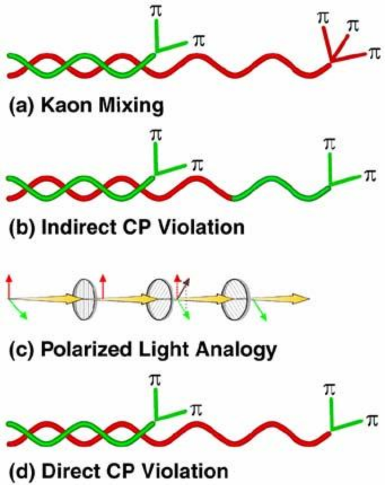
Discovery of CP violation: 1964

Cronin-Fitch experiment



Nobel prize 1980



Questions raised by the discovery of CP violation

- Is it small or large ? Is CP an approximate symmetry ?
- Is the symmetry breaking spontaneous ?
- Where does it come from ? Are there extra interactions ?

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Nobel Prize 2008

Makato Kobayashi

Toshihide Maskawa

... for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature

The Kobayashi-Maskawa paradigm

Flavor basis vs. mass basis:

$$U' \equiv \begin{pmatrix} u \\ c \\ t \end{pmatrix} , \quad D' \equiv \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Charged current in the basis of flavor eigenstates:

$$\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} \overline{U'_L} \gamma^\mu D'_L W^+_\mu + h.c.$$

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V_{UL}, V_{DL}: unitary matrices that change the basis

Cabibbo-Kobayashi-Maskawa (CKM) matrix

Coupling between U_L and D_L: $(g/\sqrt{2}) V_{CKM}$

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Wolfenstein parametrization of the CKM matrix

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\begin{aligned}
V_{CKM} &= \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \\
&= \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)
\end{aligned}
$$

- $\lambda \approx 0.2$: Cabibbo angle
- η: the imaginary component of V_{CKM}
- η/ρ large $\Rightarrow$ CP violation is large, not approximate
- All CP violation in terms of a single number: Jarlskog invariant $J \equiv s_1 s_2 s_3 c_1^2 c_2 c_3 s_\delta = A^2\lambda^6\eta$

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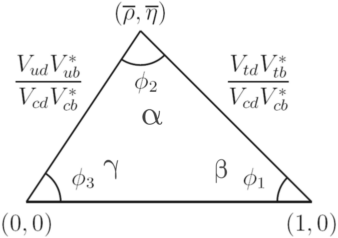
Unitarity relations and triangles

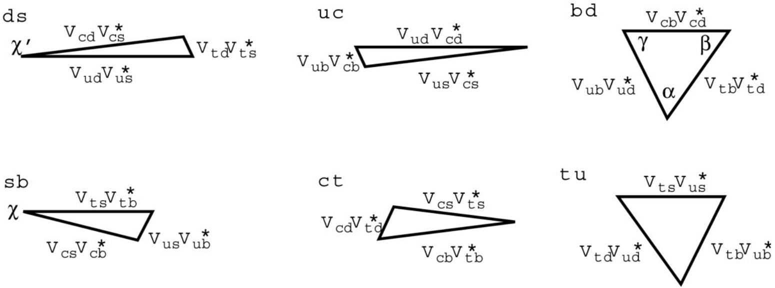
Unitarity relation $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$



$$\alpha \equiv \mathrm{Arg}\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right), \quad \beta \equiv \mathrm{Arg}\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right), \quad \gamma \equiv \mathrm{Arg}\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right),$$

- α, β, γ rephase invariant, so well-defined
- $\alpha + \beta + \gamma = 180°$

More unitarity triangles



- All triangles have the same area, $J/2$
- $\chi \equiv \beta_s \equiv \phi_s \equiv \mathrm{Arg}\left(-\frac{V_{cs}V_{cb}^*}{V_{ts}V_{tb}^*}\right) \sim \lambda^2$,
- $\chi' \equiv \beta_K \equiv \mathrm{Arg}\left(-\frac{V_{ud}V_{us}^*}{V_{cd}V_{cs}^*}\right) \sim \lambda^4$,

How to search for new physics with unitarity triangle ?

- Only one phase controls CPV, only one Jarlskog invariant
- SM predictions are severely restricted !
- A triangle can be constructed in multiple ways
- Measure sides, angles and check consistency

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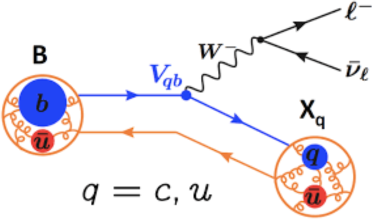
Measurements for determination of CKM elements

$$\begin{pmatrix}
\begin{array}{c} V_{ud} \\ \pi \to \mu\nu \end{array} & \begin{array}{c} V_{us} \\ K \to \pi \ell\nu \\ K \to \mu\nu \end{array} & \begin{array}{c} V_{ub} \\ B \to \pi \ell\nu,\ B_s \to K \ell\nu \\ \Lambda_b \to p \ell\nu \end{array} \\
\begin{array}{c} V_{cd} \\ D \to \pi \ell\nu \\ D \to \ell\nu \end{array} & \begin{array}{c} V_{cs} \\ D \to K \ell\nu \\ D_s \to \ell\nu \end{array} & \begin{array}{c} V_{cb} \\ B_{(s)} \to D_{(s)}, D^*_{(s)} \ell\nu \end{array} \\
\begin{array}{c} V_{td} \\ B^0 - \overline{B^0} \end{array} & \begin{array}{c} V_{ts} \\ B_s^0 - \overline{B_s^0} \end{array} & V_{tb}
\end{pmatrix}$$

Semileptonic decays

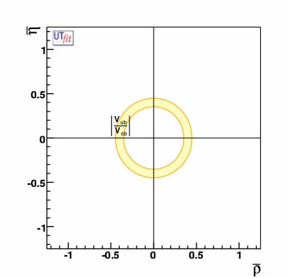
$|V_{ub}|$ and $|V_{cb}|$:



$$\Gamma(b \to c\ell\nu) \approx \frac{G_F^2}{192\pi^2}|V_{cb}|^2 m_b^3 (m_b - m_c)^2$$

$$\Gamma(b \to u\ell\nu) \approx \frac{G_F^2}{192\pi^2}|V_{ub}|^2 m_b^5$$

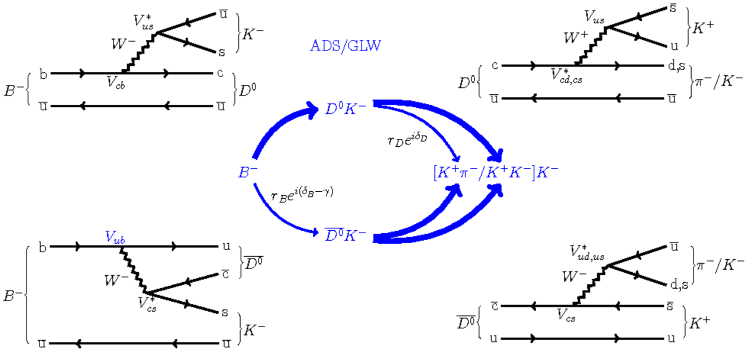
Semileptonic constraints in the UT plane



- Semileptonic decays
  $b \to c\ell\nu, \; b \to u\ell\nu$

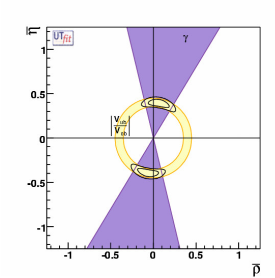
Measurement of angle γ

CPV in decay to charmed mesons:



$$
\begin{aligned}
\mathrm{CPV} &\propto A_1 A_2 \sin(\theta_2-\theta_1)\sin(\delta_2-\delta_1) \\
&\propto \sin(\delta_2-\delta_1)\sin\left[\mathrm{Arg}\left(\frac{V_{ub}^* V_{cs}}{V_{cb}^* V_{us}}\right)\right] \\
&\propto \sin\gamma
\end{aligned}
$$

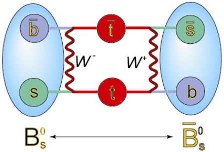
Constraints on γ in the UT plane



- Semileptonic decays
  $b \to c\ell\nu,\ b \to u\ell\nu$
- "Charmed" decays $B \to DK$

Neutral meson mixing and oscillations

B_q–$\overline{B_q}$ mixing: parametrization



- Oscillation and decay of $a|B_q\rangle + b|\overline{B}_q\rangle$:

$$i\frac{d}{dt}\begin{pmatrix} a \\ b \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\Gamma\right)\begin{pmatrix} a \\ b \end{pmatrix}$$

$$\mathbf{M} \equiv \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \quad , \quad \Gamma \equiv \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix}$$

$$\mathcal{CP}|B_q\rangle = e^{i\varphi}|\bar{B}_q\rangle,\ \mathcal{CP}|\bar{B}_q\rangle = e^{-i\varphi}|B_q\rangle$$

- CPT invariance : $M_{11} = M_{22}, \quad \Gamma_{11} = \Gamma_{22}$
- Hermiticity : $M_{21} = M_{12}^*, \quad \Gamma_{21} = \Gamma_{12}^*$

Mass difference and lifetime difference

- Mass eigenstates:
  $|B_{L,H}\rangle = p|B_q\rangle \pm q|\bar{B}_q\rangle \qquad (|q|^2 + |p|^2 = 1)$
- Mass difference $\qquad$ Lifetime difference
  $\Delta m = M_H - M_L \qquad \Delta\Gamma = \Gamma_L - \Gamma_H$
  $(\rightarrow \Delta m > 0, \Delta\Gamma > 0$ in SM)
- Eigenvalue equations:

$$\begin{aligned}(\Delta m)^2 - \frac{1}{4}(\Delta\Gamma)^2 &= (4|M_{12}|^2 - |\Gamma_{12}|^2) \\ \Delta m \Delta\Gamma &= -4\mathrm{Re}(M_{12}^*\Gamma_{12}).\end{aligned}$$

$$\begin{aligned}\Delta m &= 2|M_{12}| + O(m_b^4/m_t^4) \\ \Delta\Gamma &= -\frac{2\mathrm{Re}(M_{12}^*\Gamma_{12})}{|M_{12}|} + O(m_b^4/m_t^4).\end{aligned}$$

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Time evolution of a tagged B_q or $\bar{B}_q$ decay

$$A_f \equiv \langle f|B_q\rangle, \ \overline{A}_f \equiv \langle f|\overline{B}_q\rangle \ , \quad \lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

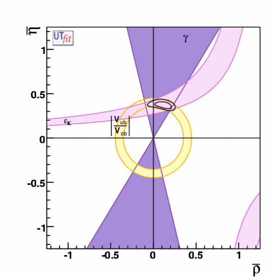
(λ_f independent of the unphysical phase φ)

$$\Gamma(B_q(t) \to f) \;=\; \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t} \times$$
$$\left[\cosh \frac{\Delta\Gamma_q \, t}{2} + \mathcal{A}_{\rm CP}^{\rm dir} \, \cos(\Delta m \, t) \;+\; \mathcal{A}_{\Delta\Gamma} \, \sinh \frac{\Delta\Gamma_q \, t}{2} + \mathcal{A}_{\rm CP}^{\rm mix} \, \sin(\Delta m \, t)\right],$$

$$\Gamma(\overline{B}_q(t) \to f) \;=\; \mathcal{N}_f \, |\bar{A}_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t} \times$$
$$\left[\cosh \frac{\Delta\Gamma_q \, t}{2} - \mathcal{A}_{\rm CP}^{\rm dir} \, \cos(\Delta m \, t) \;+\; \mathcal{A}_{\Delta\Gamma} \, \sinh \frac{\Delta\Gamma_q \, t}{2} - \mathcal{A}_{\rm CP}^{\rm mix} \, \sin(\Delta m \, t)\right].$$

$$\mathcal{A}_{\rm CP}^{\rm dir} = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \qquad \mathcal{A}_{\rm CP}^{\rm mix} = -\frac{2\,{\rm Im}\lambda_f}{1+|\lambda_f|^2} \quad \mathcal{A}_{\Delta\Gamma} = -\frac{2\,{\rm Re}\lambda_f}{1+|\lambda_f|^2},$$

Constraints in the UT plane from ϵ in $K - \bar{K}$ system



- Semileptonic decays
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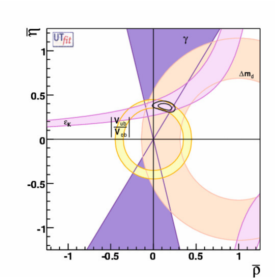
- "Charmed" decays $B \to DK$
- CP violation in K mesons

B_d-$\bar{B}_d$ mixing constraints in the UT plane

$$\Delta M_d = 2|M_d^{12}| \approx (V_{tb}V_{td}^*)^2 \frac{G_F^2}{6\pi^2} M_{B_d} B_{B_d} f_{B_d}^2 M_W^2 S_0(x_t)$$



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B_s-$\bar{B}_s$ mixing constraints in the UT plane

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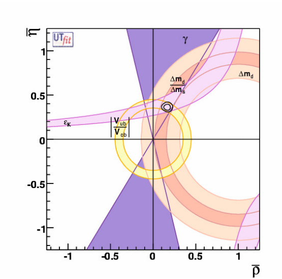

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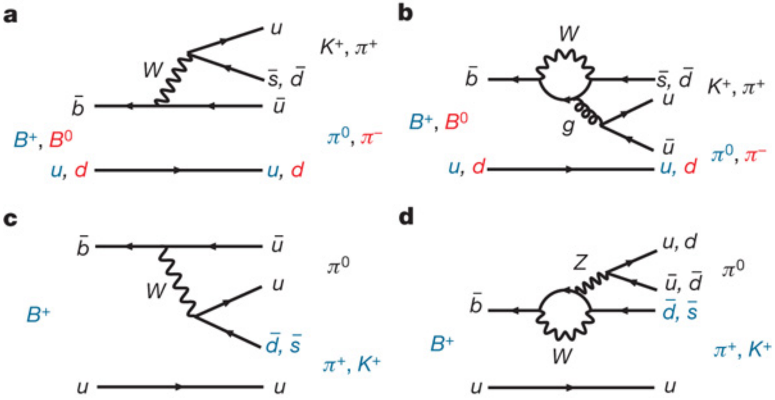
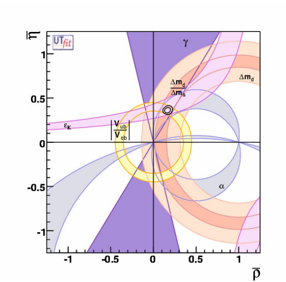
α measurement from decays to π and K



$$\alpha \equiv \mathrm{Arg}\left(-\frac{V_{td}V_{tb}^{*}}{V_{ud}V_{ub}^{*}}\right)$$

α constraints in the UT plane



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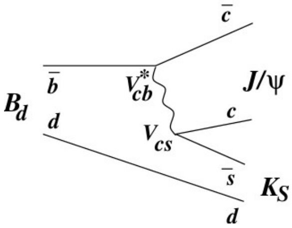
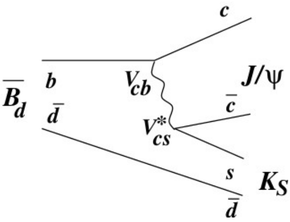
β measurement from CP asymmetry in $B_d \to J/\psi K_S$

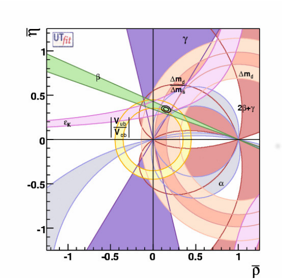




$$\frac{q}{p}\frac{\bar{A}}{A} = e^{2i\beta}$$

$$\begin{aligned}\mathcal{A}_{J/\psi K_S} \quad &\equiv \quad \frac{\frac{d\Gamma}{dt}(\bar{B}_d(t) \to J/\psi K_S) - \frac{d\Gamma}{dt}(B_d(t) \to J/\psi K_S)}{\frac{d\Gamma}{dt}(\bar{B}_d(t) \to J/\psi K_S) + \frac{d\Gamma}{dt}(B_d(t) \to J/\psi K_S)} \\ &\approx \quad \sin 2\beta \sin(\Delta m t)\ .\end{aligned}$$

β constraints in the UT plane



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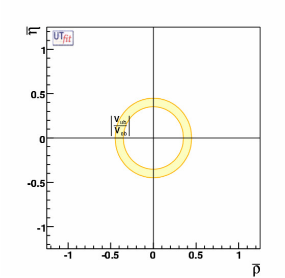
More and more stringent tests of the CKM mechanism



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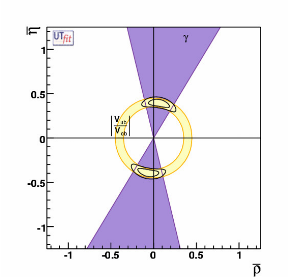

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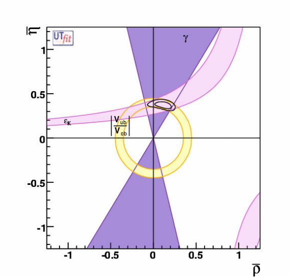

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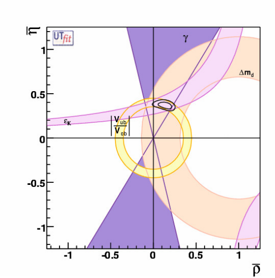

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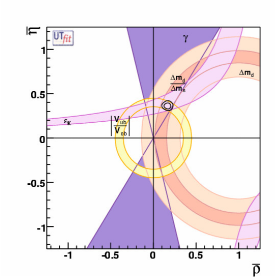

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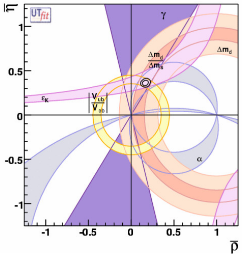

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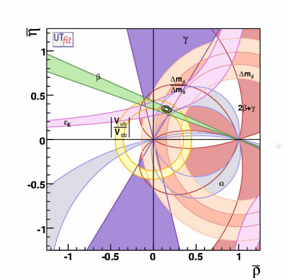

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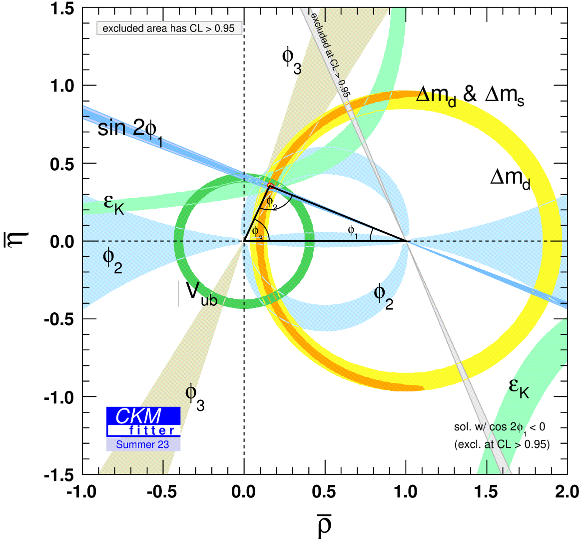
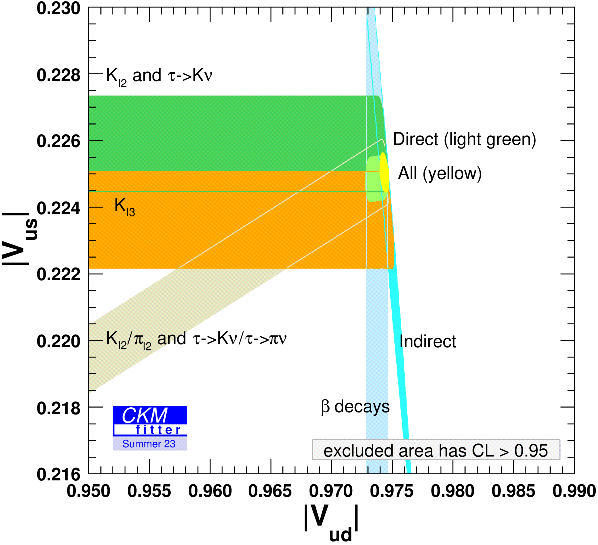
Current status



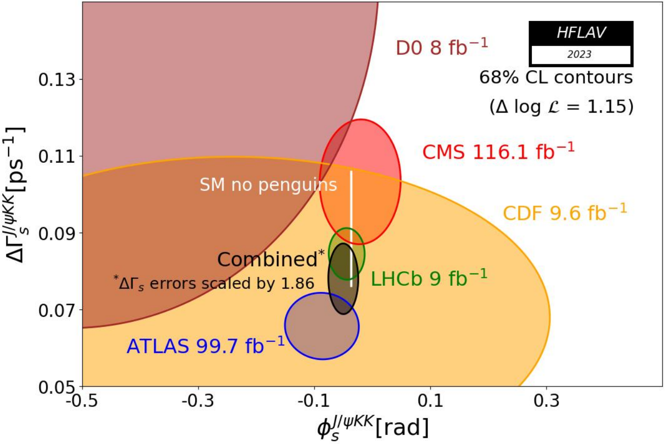
Outline

1. Role of flavor physics in building up the SM
2. The CKM paradigm and its precision tests
3. Some results that have been in the limelight
4. Rare FCNC processes
5. Looking for BSM Physics
    - Specific new physics models
    - Model-independent BSM searches
6. Concluding remarks

$|V_{us}|$: Cabibbo Angle Anomaly (CAA)

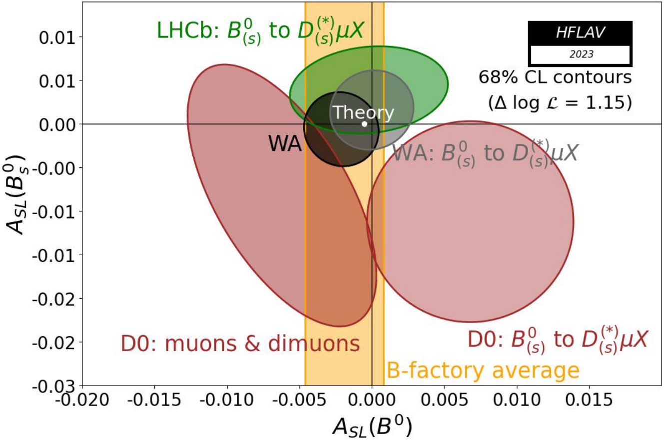


$\phi_s^{J/\psi\phi}$: Angular analysis of $B_s \to J/\psi\phi$

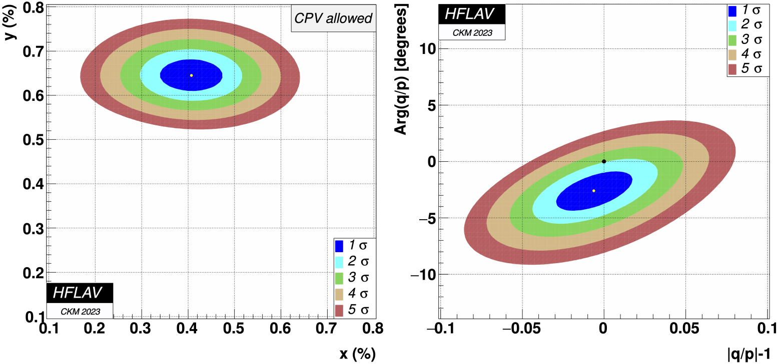


$$\phi_s = -2\beta_s^{J/\psi\phi}$$

β_s^{sl}: Like-sign dimuon CP asymmetry

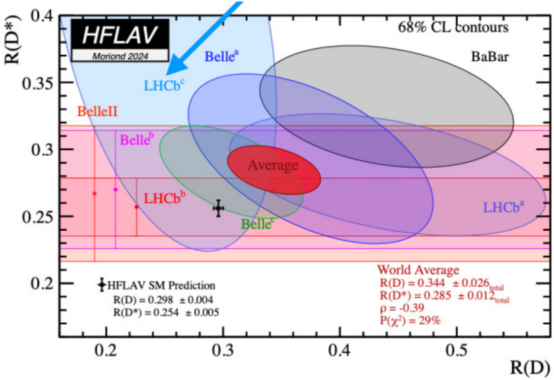


D–$\bar{D}$ mixing



$x \equiv \Delta m/\Gamma$ $y \equiv \Delta\Gamma/(2\Gamma)$

τ vs electrons/muons



$$R_{D^{(*)}} \equiv \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)}$$

- Affect $b \to c\tau\nu$, indicate lepton-universality violation ?

New Physics in leptons ?

- For semileptonic B decays $b \to u\ell\nu$ and $b \to c\ell\nu$, inclusive decay rates are systematically larger than the exclusive ones.
- Lepton non-universality at play in $b \to c\ell\nu$?
- Lepton non-universality is severely constrained in the first two generations, not so much for the third one. Models with H^+/Z' are natural candidates.
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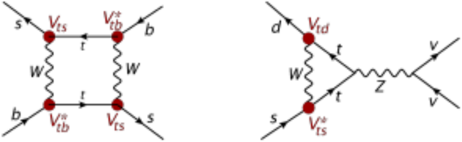
Flavour changing neutral current processes

- Suppressed in the SM due to the loop factor, CKM hierarchy, chiral structure and GIM mechanism.
- Boxes and penguins



CKM hierarchy predicts specific pattern of effects in the SM

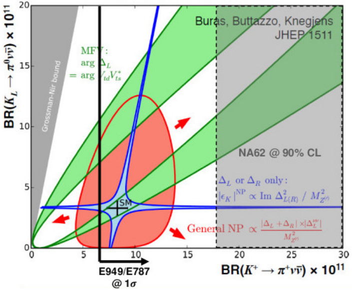
$$\underbrace{V_{ts}^*V_{td}}_{K\text{ system}} \sim 5\cdot 10^{-4} \ll \underbrace{V_{tb}^*V_{td}}_{B_d\text{ system}} \sim 10^{-2} < \underbrace{V_{tb}^*V_{ts}}_{B_s\text{ system}} \sim 4\cdot 10^{-2}$$

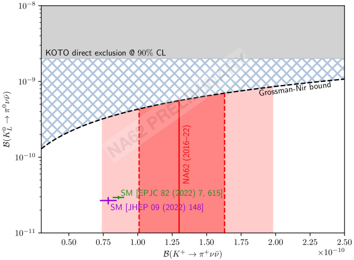
➢ K decays in general most sensitive to BSM physics

(Slide from M. Blanke)

Enhancement of decay rates

Exp-hard but Th-clean decays $K \to \pi\nu\bar{\nu}$:



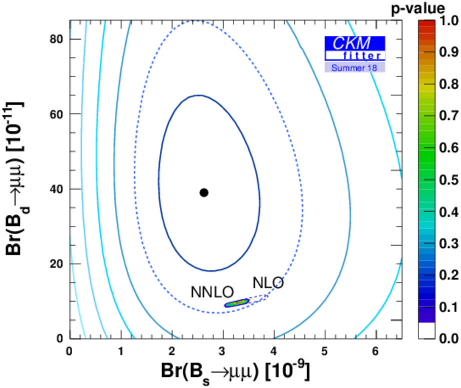


$$\mathscr{B}^{16-22}_{\pi\nu\bar{\nu}} = \left(13.0^{+3.3}_{-2.9}\right) \times 10^{-11}$$

NA62

- Models can change the relative BRs of $K_L \to \pi^0\nu\bar{\nu}$ and $K^+ \to \pi^+\nu\bar{\nu}$ to a large extent

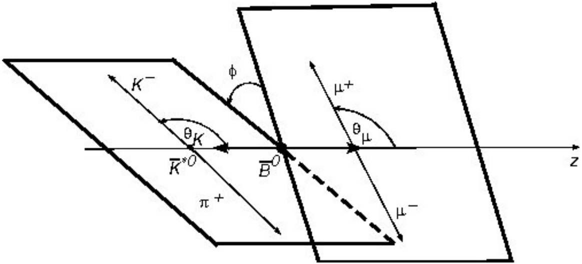
Branching ratios of $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$



- $B(B_s \to \mu\mu) = (3.20^{+0.18}_{-0.12}) \times 10^{-9}$
- $B(B_d \to \mu\mu) = (9.39^{+0.62}_{-0.32}) \times 10^{-11}$

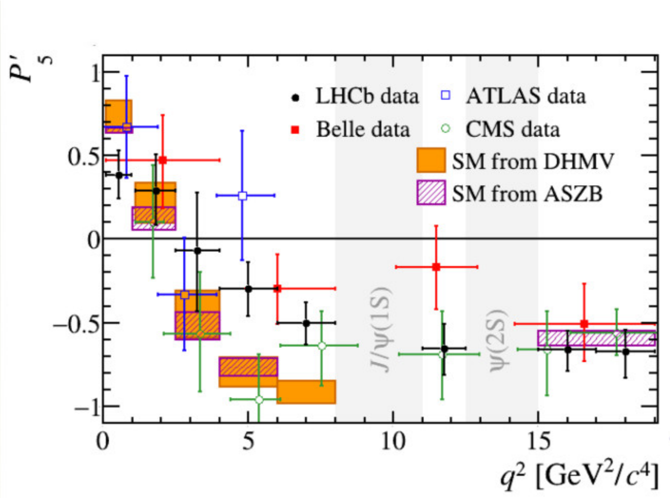
Angular distributions

Angular distribution in $B \to K^* \mu^+ \mu^-$:



$$\begin{aligned}\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} =& \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell \\ & - F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi \\ & + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi \\ & + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi \\ & + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],\end{aligned}$$

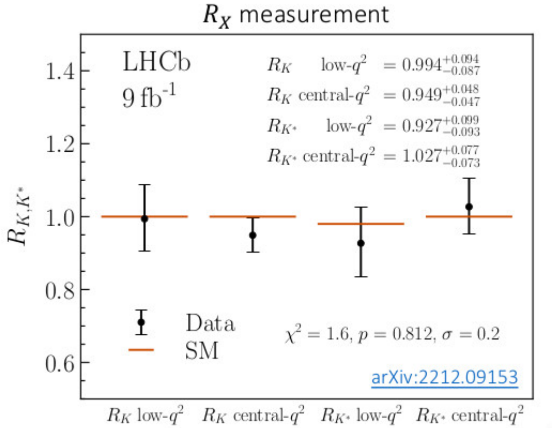
The P_5' anomaly in $B \to K^*\mu\mu$



- $P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$, largely free from formfactor uncertainties
- Local discrepancy of 3.7σ in P_5'.

Lepton flavor non-universality

Muons vs electrons:



- $R_{K^{(*)}}(q^2) \equiv \frac{\Gamma(B^+ \to K^{(*)}\mu^+\mu^-)}{\Gamma(B^+ \to K^{(*)}e^+e^-)}$

Remarks on FCNC processes

- Flavor physics exploration is not linear. There are intricate networks and intertwined patterns
- BSM Physics may be searched using deviations from SM predictions. Needs good understanding of SM predictions
- Identification of theoretically clean and experimentally feasible decay modes / observables necessary
- Indirect hints for BSM physics possible, access to particles that have masses in excess of energies at colliders

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Remarks on FCNC processes

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2. The CKM paradigm and its precision tests
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Possible effects of BSM physics

- Models motivated by broad open questions
- Models motivated by observed anomalies
- Classes of models consistent with current data
- Model-independent parameterizations of BSM physics

Quantifying and constraining BSM physics

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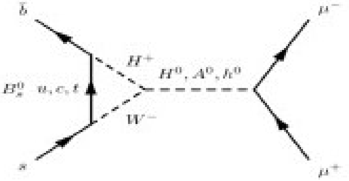
Enhancement of $B(B_{s/d} \to \mu\mu)$

- Sensitive to minimal SUSY model parameters:

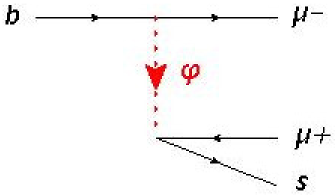


$$B(B_q \to \mu\mu) \propto |V_{tb}^* V_{tq}| \frac{m_b^2 m_\ell^2 \tan^6 \beta}{m_A^4}$$

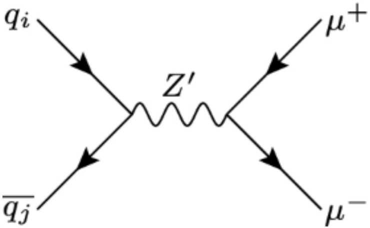
- Severely restricts large $\tan\beta$

Explaining $b \to s\ell\ell$ anomalies

- $R_{K^{(*)}} < 1 \Rightarrow$
  Depletion in $b \to s\mu\mu$ or enhancement in $b \to see$



Leptoquark



New Z’ boson

Multiple things models with Z' and leptoquarks can do

- Enhance $K \to \pi\nu\bar{\nu}$ decay rates

Buras 2014

- Enhance Γ_{12}, and hence $\Delta\Gamma$, in B_d-$\bar{B}_d$ and B_s-$\bar{B}_s$ systems
- Enhance $B(B_s \to \tau\tau)$ by orders of magnitude

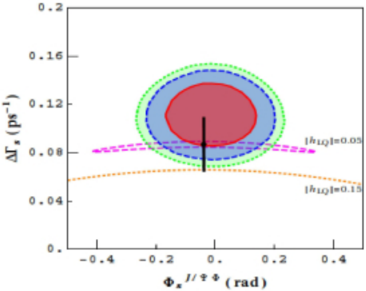
AD, Kundu, Nandi, 2007

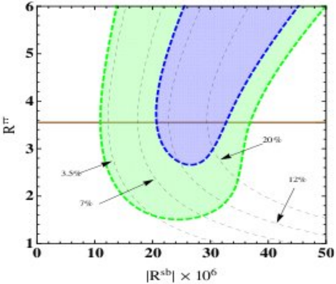
- Account for the dimuon anomaly

AD, A. Kundu, S, Nandi, 2010

- Change the ratio of B_d and B_s lifetimes

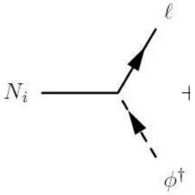
AD, Ghosh, Kundu, Patra, 2011; AD, Ghosh, 2012





Vector-like lepton models

Four minimal models and Cabibbo Angle Anomaly:

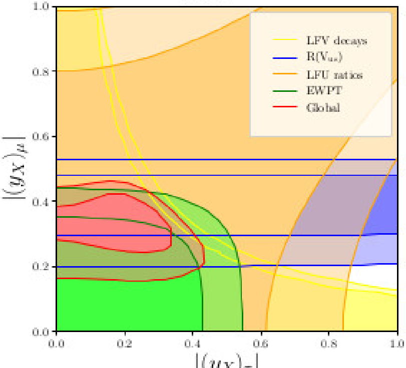


Vector-like leptons	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
N	1	1	0
E	1	1	-1
Σ	1	3	0
X	1	3	-1

$$
\begin{aligned}
\mathcal{L}_N &= (y_N)_i \, \bar{N}_R \, \tilde{\phi}^\dagger \, \ell_{Li} \,, \\
\mathcal{L}_E &= (y_E)_i \, \bar{E}_R \, \phi^\dagger \, \ell_{Li} \,, \\
\mathcal{L}_\Sigma &= \frac{1}{2} (y_\Sigma)_i \, \bar{\Sigma}_R^a \, \tilde{\phi}^\dagger \, \tau^a \, \ell_{Li} \,, \\
\mathcal{L}_X &= \frac{1}{2} (y_X)_i \, \bar{X}_R^a \, \phi^\dagger \, \tau^a \, \ell_{Li} \,.
\end{aligned}
$$

Alok, AD, Kumar, Gangal 2021

$(y_X)_e = 0$



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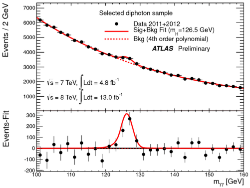
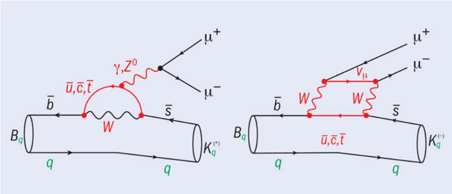
Indirect searches of new physics

- Direct searches: Produce the heavy particle “on shell” and detect them through “peaks”
- Indirect searches: “Off-shell” / Virtual heavy particles contribute to processes (if in loops, give quantum corrections)

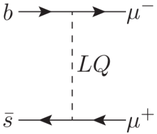


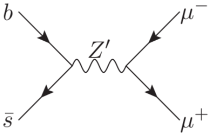


Effective field theories

- What happens inside the loop is not completely known
- Then what exactly is known from measurements ?
- Bottom-up approach: Consider “effective” operators

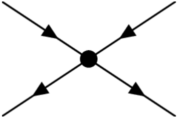
“Actual”:





Masses
couplings

“Effective”:



Lorentz structures
Wilson coefficients

Salient features of EFTs

- Model-independent, can handle multiple models.
- Strictly speaking, if an operator / WC is not forbidden by a symmetry, it must be allowed.
- But it is often convenient to study the effect of each WC separately

- Operators may be required to obey certain gauge symmetries
- Low-energy 0perators must originate in a high scale theory with such a gauge symmetry
- Low-scale WCs must be correlated, depending on the model
- Can we distinguish among high-scale theories by looking at low-energy Wilson coefficients ?

Next two talks by Rukmani Mohanta and Suchismita Sahoo

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- Flavor physics, through loop processes, can access BSM physics at high energy scales, inaccessible for direct particle production. (Indirect searches for new physics)
- Precision measurements, including those related to CKM elements and rare decays, crucial in looking for NP
- Increasing precision on theoretical calculations is also important: lattice calculations for non-perturbative contributions, low-energy effective theories like HQET, SCET, ChPT
- Looking for predictions of well-motivated models can constrain their parameters in complementary ways
- However, since what lies beyond SM is uncertain, model-independent searches using EFT techniques will play a big role in flavor physics in future.

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