THEORETICAL STATUS OF B MESON PHYSICS

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OVERVIEW

- WHY B PHYSICS ?
  - CP violation
  - manifestations of CP violation
- UNITARY TRIANGLE (UT) FROM B PHYSICS
  - leptonic B decays
  - semileptonic B decays
  - nonleptonic B decays
- EXPLORATION OF UT AND NEW PHYSICS IN B SECTOR
  - benchmark decays
- OUTLOOK

CP VIOLATION:

- in kaon decays known from 1964
- 2001 experimentally confirmed in B – decays

origin in SM : Yukawa couplings in SCALAR sector of SM

$$\mathcal{L}_Y = -\lambda_d^{ij} \bar{Q}_L^i \cdot \Phi d_R^j - (\lambda_d^{ij})^* \bar{d}_R^j \Phi^\dagger \cdot Q_L^i + \dots$$

λ_d : general, not necessary symmetric or hermitian matrices, not constrained by gauge symmetry

CP: $\lambda_d \leftrightarrow \lambda_d^*$ $\Longrightarrow$ explicit CP violation if λ_d complex

this happens in SM with 3 generations of quarks

- diagonalization of Yukawa matrices -> quark mass eigenstates
- mass eigenstates mix under weak interations
- weak eigenstates and mass eigenstates are connected through the unitary transformation -> CKM MATRIX

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

THREE angles and ONE PHASE :

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\,\lambda^3\,(\rho - i\,\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\,\lambda^2 \\ A\,\lambda^3\,(1 - \rho - i\eta) & -A\,\lambda^2 & 1 \end{pmatrix}$$

$\lambda = |V_{us}| \approx 0.22$ $(A \approx 0.8,\ \rho \approx 0.2,\ \eta \approx 0.3)$

Further requirements for CP violation in SM:

$$(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2) \times J_{\mathrm{CP}} \neq 0,$$

$$J_{\mathrm{CP}} = |\mathrm{Im}(V_{i\alpha} V_{j\beta} V_{i\beta}^* V_{j\alpha}^*)| \quad (i \neq j,\, \alpha \neq \beta)\,.$$

If two quark would have the same mass -> CP-violating phase could be eliminated !

-> CP –violation is related to the FLAVOUR PROBLEM – understanding of quark mass hierarchy and the number of fermion generations

JARLSKOG PARMETER J_{CP} = measure of the strength of CP violation in SM = $O(10^{-5})$ - small !

What we know about THE SCALAR SECTOR of SM ?

- CP violation is confirmed: size and origin of CP phases are UNKNOWN
- fermion masses and masses of gauge bosons are measured

- NO SCALAR PARTICLE OBSERVED :
  - the Higgs mechanism of $SU(2)_L \times U(1)_Y$ breaking and generation of quark masses IS NOT (YET) VERIFIED

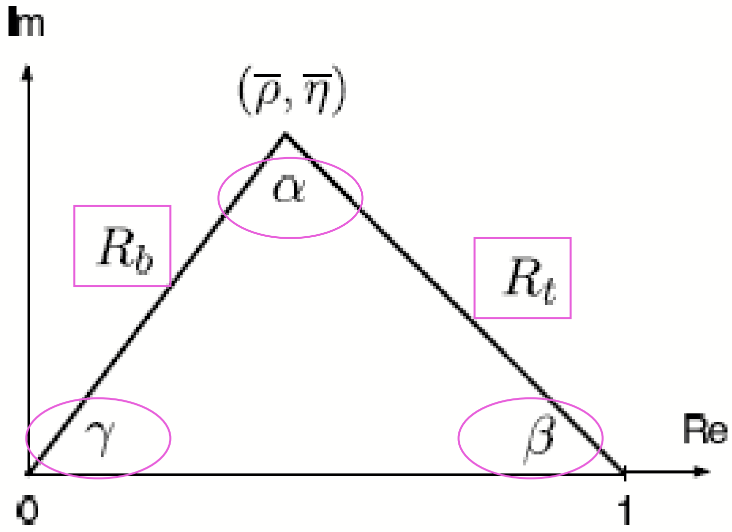
- MECHANISM OF CP-VIOLATION IS NOT IDENTIFIED

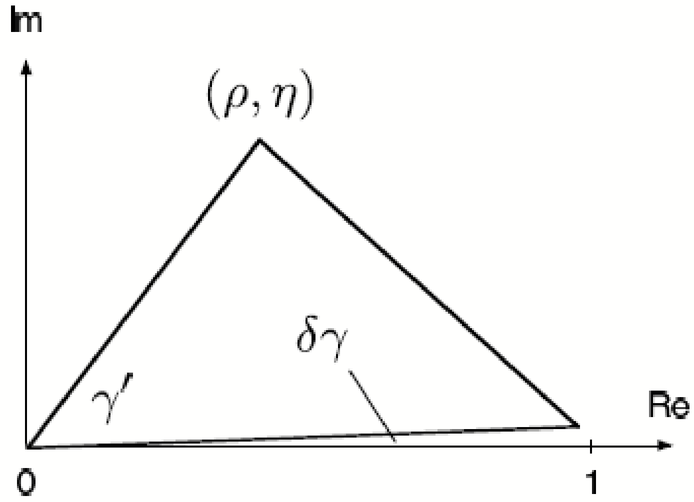
Next generation of accelerators – LHC

- direct Higgs searches
- exploration of B meson physics - CP violation

} complementary tests of scalar sector of SM !

two non-squashed triangles in a complex plane: $\hat{V}^{\dagger}_{\rm CKM} \cdot \hat{V}_{\rm CKM} = \hat{1} = \hat{V}_{\rm CKM} \cdot \hat{V}^{\dagger}_{\rm CKM}$





$$\underbrace{V_{ud}V^*_{ub}}_{(\rho+i\eta)A\lambda^3} + \underbrace{V_{cd}V^*_{cb}}_{-A\lambda^3} + \underbrace{V_{td}V^*_{tb}}_{(1-\rho-i\eta)A\lambda^3} = 0$$

$$\underbrace{V^*_{ud}V_{td}}_{(1-\rho-i\eta)A\lambda^3} + \underbrace{V^*_{us}V_{ts}}_{-A\lambda^3} + \underbrace{V^*_{ub}V_{tb}}_{(\rho+i\eta)A\lambda^3} = 0$$

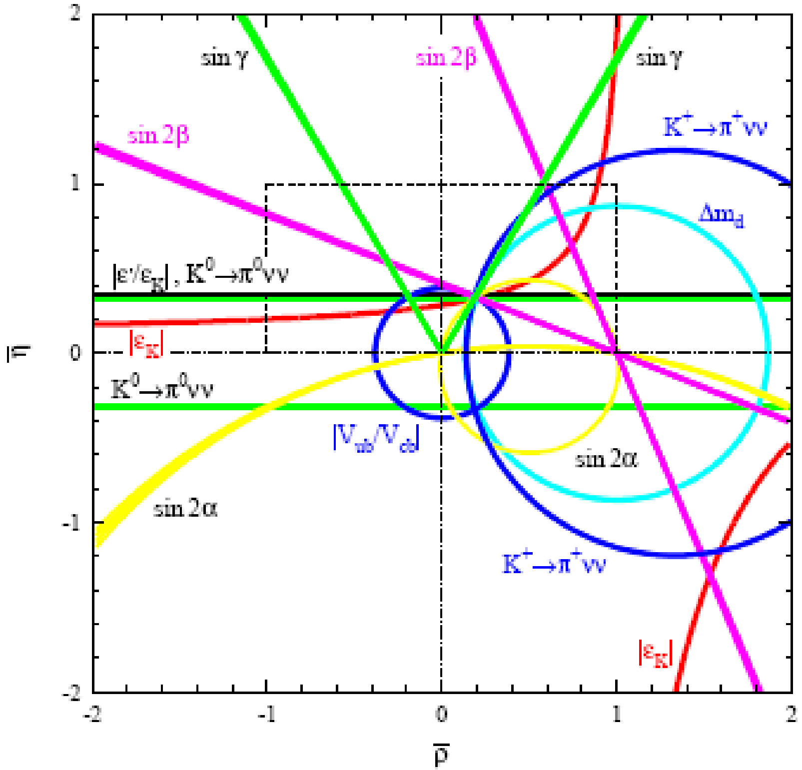
these triangles coincide at the λ^3 level - LHC will reach precision for exploring both triangles at λ^5 level

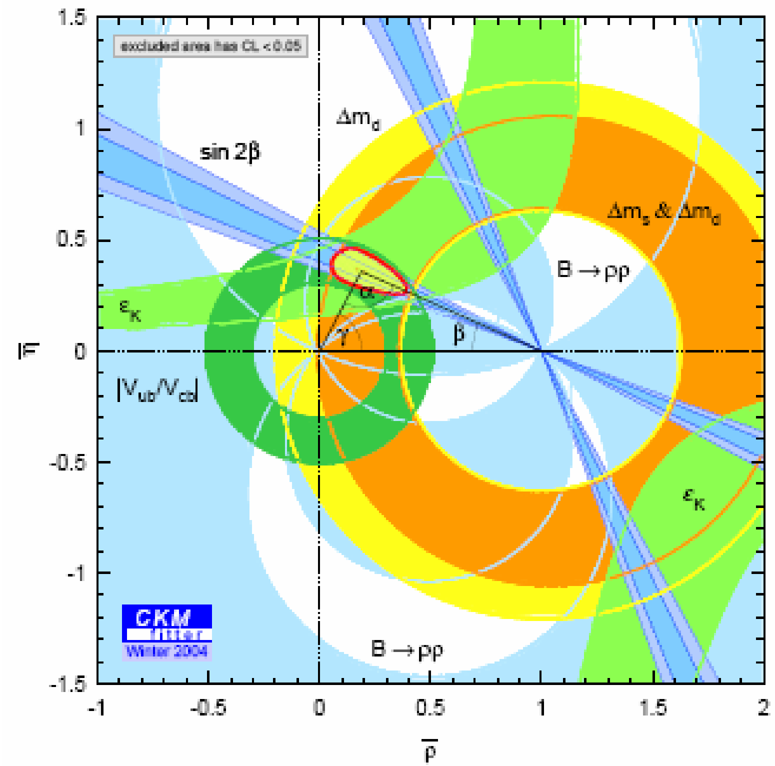
$$s_{12} \equiv \lambda = 0.22, \quad s_{23} \equiv A\lambda^2, \quad s_{13}e^{-i\delta_{13}} \equiv A\lambda^3(\rho - i\eta)$$

$$\bar{\rho} \equiv \rho\left(1 - \frac{1}{2}\lambda^2\right), \quad \bar{\eta} \equiv \eta\left(1 - \frac{1}{2}\lambda^2\right)$$

$R_b = \left|\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}}\right|$

$R_t = \left|\frac{V_{td}V^*_{tb}}{V_{cd}V^*_{cb}}\right|$





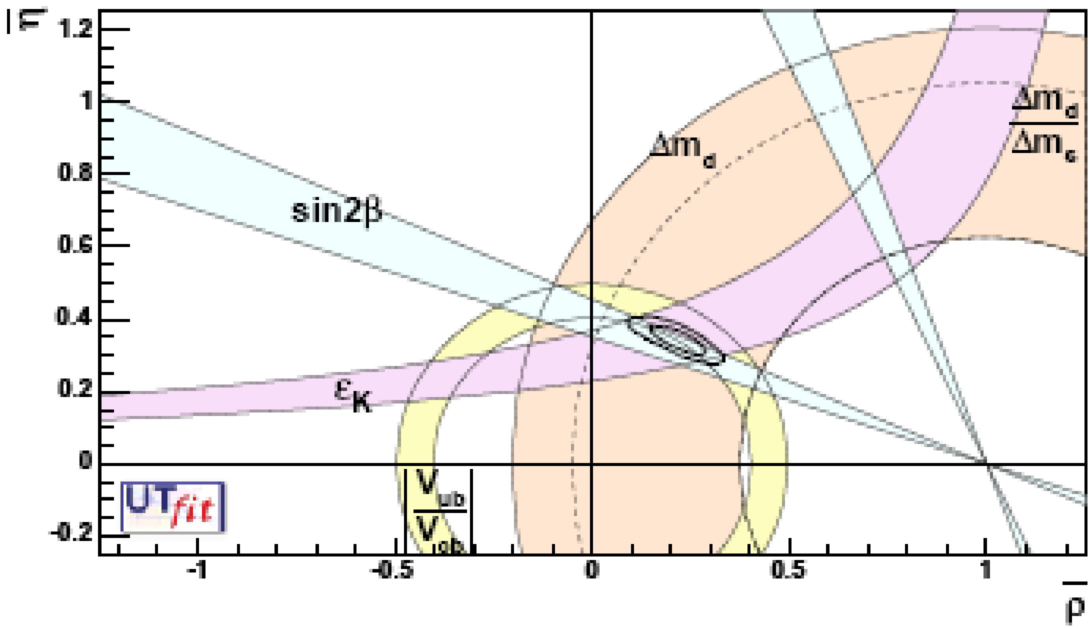
THE IDEAL.....

THE REALITY....

CKM fits – theory is used to convert experimental data into contours in $\bar{\rho}$-$\bar{\eta}$ plane

THE GOAL is to OVERCONSTRAIN CKM matrix as much as possible
-> NEW PHYSICS (NP)

UTfit collaboration:



MANIFESTATIONS OF CP VIOLATION:

- CP violation in the decay (direct CP violation):

$$|\mathcal{A}(B \to F)| \neq |\mathcal{A}(\bar{B} \to \bar{F})|$$

- CP violation in mixing:

$$\text{mass eigenstates} \neq \text{CP eigenstates}$$

- CP violation in the

interference of decays with and without mixing

$$\mathcal{A}(B \to F) \neq \mathcal{A}(\bar{B} \to F)$$

DIRECT CP VIOLATION:

$$
\begin{aligned}
A(\bar{B} \to \bar{f}) &= e^{+i\varphi_1}|A_1|e^{i\delta_1} + e^{+i\varphi_2}|A_2|e^{i\delta_2} \\
A(B \to f) &= e^{i[\phi_{\rm CP}(B)-\phi_{\rm CP}(f)]}\left[e^{-i\varphi_1}|A_1|e^{i\delta_1} + e^{-i\varphi_2}|A_2|e^{i\delta_2}\right]
\end{aligned}
$$

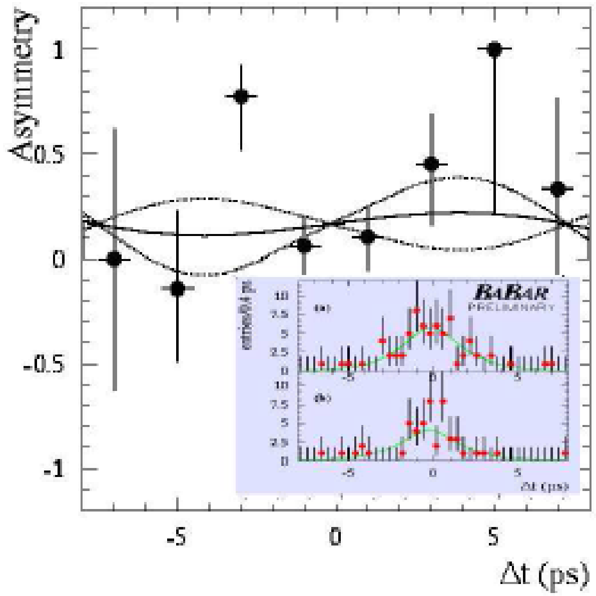
$\varphi_{1,2}$ weak phases (CP violating –CKM)

$$
\mathcal{A}_{\rm CP}^{\rm dir}(B_q \to f) = \frac{|A(B_q^0 \to f)|^2 - |A(\bar{B}_q^0 \to \bar{f})|^2}{|A(B_q^0 \to f)|^2 + |A(\bar{B}_q^0 \to \bar{f})|^2}
$$

$$
= \frac{2|A_1||A_2|\sin(\delta_1-\delta_2)\sin(\varphi_1-\varphi_2)}{|A_1|^2 + 2|A_1||A_2|\cos(\delta_1-\delta_2)\cos(\varphi_1-\varphi_2) + |A_2|^2}
$$

-at least TWO amplitudes with TWO WEAK CP-violating PHASES
and TWO STRONG CP-conserving PHASES

TIME-DEPENDENT ASYMMETRY:



Measure time-dependent CP asymmetry:

$$\frac{\Gamma(B_q^0(t) \to F) - \Gamma(\bar{B}_q^0(t) \to F)}{\Gamma(B_q^0(t) \to F) + \Gamma(\bar{B}_q^0(t) \to F)}$$

$$= \Big\{ \mathcal{A}_{\rm CP}^{\rm dir}(B_q \to F) \cos(\Delta M_q t) + \mathcal{A}_{\rm CP}^{\rm mix}(B_q \to F) \sin(\Delta M_q t) \Big\}$$

$\mathcal{A}_{\rm CP}^{\rm dir}$ and $\mathcal{A}_{\rm CP}^{\rm mix}$ depend on hadronic matrix elements

Exceptional case : ONLY one amplitude is dominant (theoretically clean)

$$\mathcal{A}_{\rm CP}^{\rm mix} = {\rm Im}\left(\mp e^{-i\phi_q}\right)$$

$\longrightarrow$ **"gold-plated" decay** (e.g. $B \to J/\psi K_S$)

$$\mathcal{A}_{\rm CP}^{\rm dir} = 0$$

(CP is governed only by weak phase; no hadronic uncertainties)

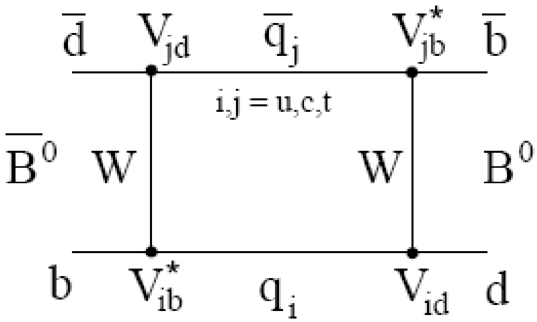
UNITARY TRIANGLE FROM B-PHYSICS:

- ❑ large number of different decay channels, sensitive to different weak phases

- ❑ expected large CP asymmetries due to the non-squashed unitary triangles

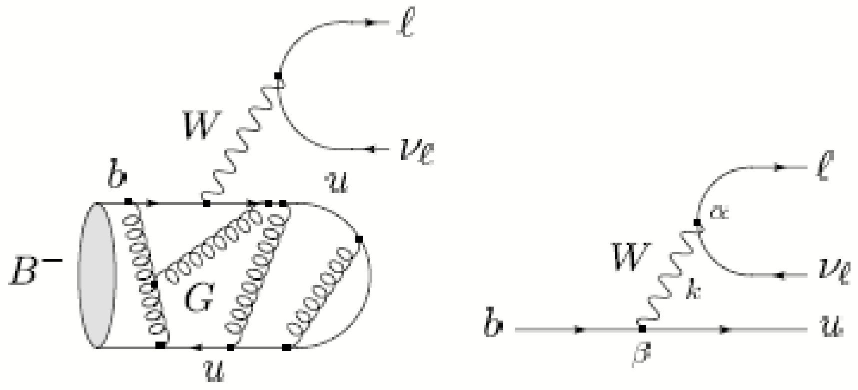
- ❑ GIM suppression largely relaxed due to $m_t \gg m_c, m_u$

  - large and clean effects from B – B mixing:



  - large effects from penguin operators:

LEPTONIC B-DECAYS



$$\Gamma(B^- \to \ell \bar{\nu}_\ell) = \frac{G_F^2}{8\pi} M_B m_\ell^2 \left(1 - \frac{m_\ell^2}{M_B^2}\right)^2 f_B^2 |V_{ub}|^2$$

very small BR due to the small $|V_{ub}| \propto \lambda^3$ and helicity suppression for l = e, μ

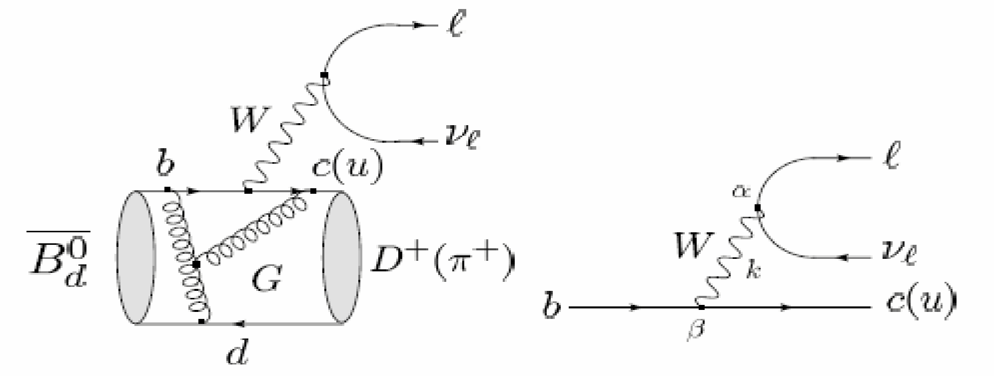
from $\mathrm{BR}(B^- \to \tau^- \bar{\nu}_\tau) = \left[1.06^{+0.34}_{-0.28}\,(\mathrm{stat})\,^{+0.18}_{-0.16}\,(\mathrm{syst})\right] \times 10^{-4}$ (Belle)

$$\boxed{f_B |V_{ub}| = \left[7.73^{+1.24}_{-1.02}\,(\mathrm{stat})\,^{+0.66}_{-0.58}\,(\mathrm{syst})\right] \times 10^{-4}\,\mathrm{GeV}}$$

sum rules, lattice ⟶ $|V_{ub}|$

SEMILEPTONIC B-DECAYS

exclusive:



$$T_{fi} = \frac{G_F}{\sqrt{2}} V_{cb} \left[\bar{u}_\ell \gamma^\alpha (1-\gamma_5) v_\nu\right] \langle D^+ | \bar{c}\gamma_\alpha (1-\gamma_5) b | \bar{B}_d^0 \rangle$$

$$\langle D^+(k) | \bar{c}\gamma_\alpha b | \bar{B}_d^0(p)\rangle = \boxed{F_1(q^2)} \left[(p+k)_\alpha - \left(\frac{M_B^2 - M_D^2}{q^2} \right) q_\alpha \right] + \boxed{F_0(q^2)} \left(\frac{M_B^2 - M_D^2}{q^2} \right) q_\alpha$$

HEAVY QUARK EFFECTIVE THEORY: heavy quark symmetry - for $\Lambda_{QCD}/m_{b,c} \to 0$

$$\frac{1}{\sqrt{M_D M_B}} \langle D(v') | \bar{c}_{v'} \gamma_\alpha b_v | \bar{B}(v) \rangle = \xi(v' \cdot v)(v + v')_\alpha$$

$$\boxed{F_1(q^2)} = \frac{M_D + M_B}{2\sqrt{M_D M_B}} \xi(w)$$

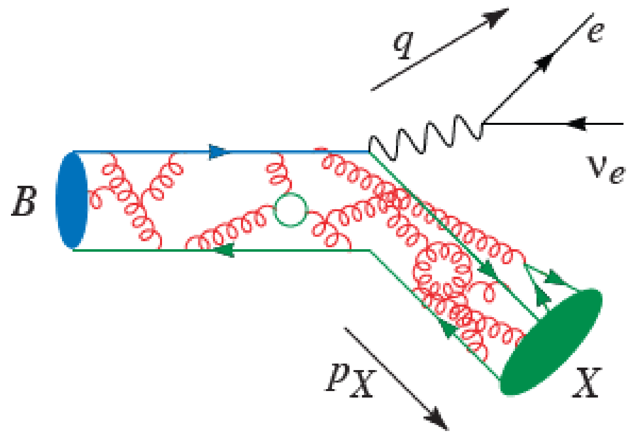
$$\boxed{F_0(q^2)} = \frac{2\sqrt{M_D M_B}}{M_D + M_B} \left[\frac{1+w}{2} \right] \xi(w),$$

only one function
ISGUR-WISE FUNCTION

$$\xi(1) = 1$$

$$w \equiv v_D \cdot v_B = \frac{M_D^2 + M_B^2 - q^2}{2 M_D M_B}.$$

inclusive:



averaged properties of b quark
interactions with light quarks

$$\Gamma(B \to X_u \ell \bar{\nu}_\ell) = \frac{G_F^2 |V_{ub}|^2 m_b^5}{192\pi^3} \left(1 - 2.41\frac{\alpha_s}{\pi} - 21.3\left(\frac{\alpha_s}{\pi}\right)^2 + \frac{\lambda_1 - 9\lambda_2}{2m_b^2} + O\left(\alpha_s^2, \frac{\Lambda_{QCD}^3}{m_b^3}\right)\right)$$

problems with large backgrounds which originate from $b \to c\ell\bar{\nu}$

→ cuts – large th. uncertainties

$$|V_{ub}|_{\rm incl} = (4.4 \pm 0.3) \times 10^{-3}, \quad |V_{ub}|_{\rm excl} = (3.8 \pm 0.6) \times 10^{-3}$$

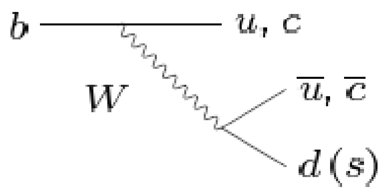
there is a need for better determination of $|V_{ub}|$ to check consistency with sin2β

extraction of $|V_{cb}|$ from $B \to X_c \ell \bar{\nu}$ is more favorable:

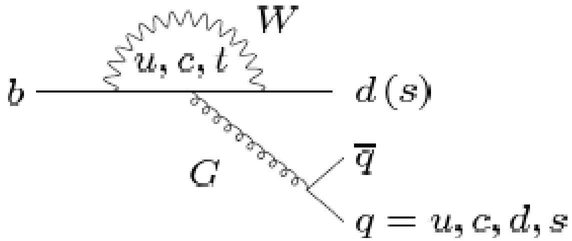
$$|V_{cb}| = (42.0 \pm 0.7) \times 10^{-3}$$

NONLEPTONIC DECAYS

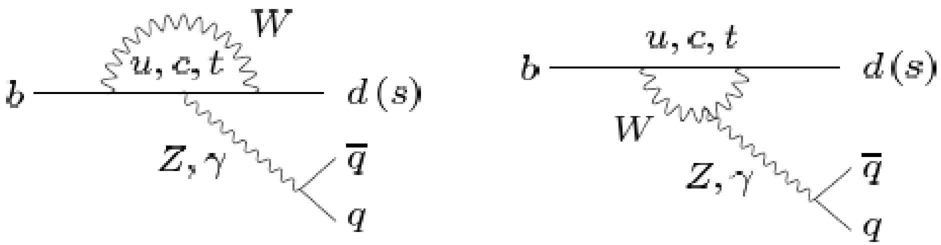
- different topologies:



tree diagrams



QCD penguin diagrams



EW penguin diagrams

$$\mathcal{H}_{weak} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} V_{pb}V^*_{pd} \left\{ C_1(\mu)\mathcal{O}_1^p + C_2(\mu)\mathcal{O}_2^p + \sum_{i=3,...,10} C_i(\mu)\mathcal{O}_i + C_{7\gamma}\mathcal{O}_{7\gamma} + C_{8g}\mathcal{O}_{8g} \right\}$$

C_i =Wilson coeff. - perturbative

O_i =four quark operators

$O_{1,2}$ = tree operators

$O_{3\text{-}6}$ = QCD penguin operators

$O_{7\text{-}10}$ = EW penguin operators

$$|A|e^{i\delta} \sim \langle \overline{f}|\mathcal{H}_{weak}|\overline{B}\rangle = \sum_k \underbrace{C_k(\mu)}_{\text{pert. QCD}} \times \underbrace{\langle \overline{f}|\mathcal{O}_k(\mu)|\overline{B}\rangle}_{\text{non-pert. QCD}}$$

How to calculate matrix elements of $\mathcal{O} = (\overline{q_1}_i \Gamma_\mu q_{2i})(\overline{q_3}_j \Gamma^\mu b_j)$?

$$\begin{aligned} \langle \pi\pi|\mathcal{O}_1|B\rangle &= \underbrace{\langle \pi|\overline{d}\Gamma_\mu u|0\rangle\langle \pi|\overline{u}\Gamma^\mu b|B\rangle}_{'naive'\ factorization}\left[1 + \mathcal{O}(\alpha_s) + \mathcal{O}(\Lambda_{QCD}/m_b)\right] \\ &= i m_b^2 f_\pi F^+_{B\to\pi}(m_\pi^2)\left[1 + \mathcal{O}(\alpha_s) + \mathcal{O}(\Lambda_{QCD}/m_b)\right] \end{aligned}$$

$$\langle\pi\pi|\mathcal{O}_1|B\rangle = \underbrace{\langle\pi|\bar{d}\Gamma_\mu u|0\rangle\langle\pi|\bar{u}\Gamma^\mu b|B\rangle}_{'naive'\ factorization}\left[1+\mathcal{O}(\alpha_s)+\mathcal{O}(\Lambda_{QCD}/m_b)\right]$$

$$= i m_b^2 f_\pi F^+_{B\to\pi}(m_\pi^2)\left[1+\mathcal{O}(\alpha_s)+\mathcal{O}(\Lambda_{QCD}/m_b)\right]$$

Models for calculating matrix elements of four quark operators beyond naive factorization:

- QCD factorization – at the leading order of a Λ_{QCD}/m_b expansion **(Beneke, Buchalla, Neubert, Sachrajda)**
- perturbative QCD approach– the complete matrix element is calculated perturbatively **(Keum, Li, Sanda)**
- SCET (soft-collinear effective theory) – for B -> light particle decays **(Bauer, Fleming, Luke, Stewart)**
- LCSR (light-cone sum rule approach) – $O(\alpha_s)$ and $O(\Lambda_{QCD}/m_b)$ corrections are calculable **(Khodjamirian)**

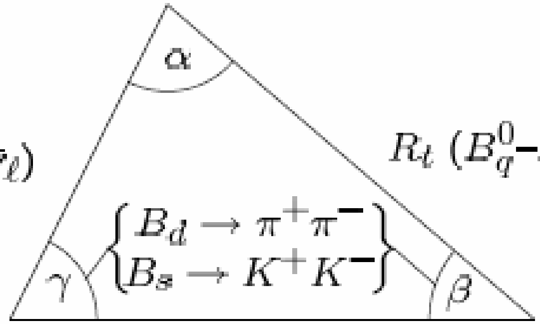
EXPLORATION OF CP VIOLATION IN NONLEPTONIC B DECAYS

R.Fleischer, hep-ph/0608010

$B \to \pi\pi$ (isospin), $B \to \rho\pi$, $B \to \rho\rho$

R_b $(b \to u, c\ell\bar{\nu}_\ell)$

R_t $(B_q^0$–$\bar{B}_q^0$ mixing)



$B \to \pi K$ (penguins)

$B_d \to \psi K_S$ $(B_s \to \psi\phi : \phi_s \approx 0)$

$B_d \to \phi K_S$ (pure penguin)

$$\left.\begin{array}{l} B_u^\pm \to K^\pm D \\ B_d \to K^{*0} D \\ B_c^\pm \to D_s^\pm D \end{array}\right\} \text{only trees}$$

$$\left.\begin{array}{l} B_d \to D^{(*)\pm}\pi^\mp : \ \gamma + 2\beta \\ B_s \to D_s^\pm K^\mp : \ \gamma + \phi_s \end{array}\right\} \text{only trees}$$

How could new physics enter ?

- NP may modify the strength of SM operators through new short-distance effects depending on the masses of new particles
  NP enters at the loop level
  – box diagrams and penguin topologies – and may be integrated out like the W-boson and top quark in SM

$$C_i \rightarrow C_i^{SM} + C_i^{NP}$$

- NP may introduce new operators

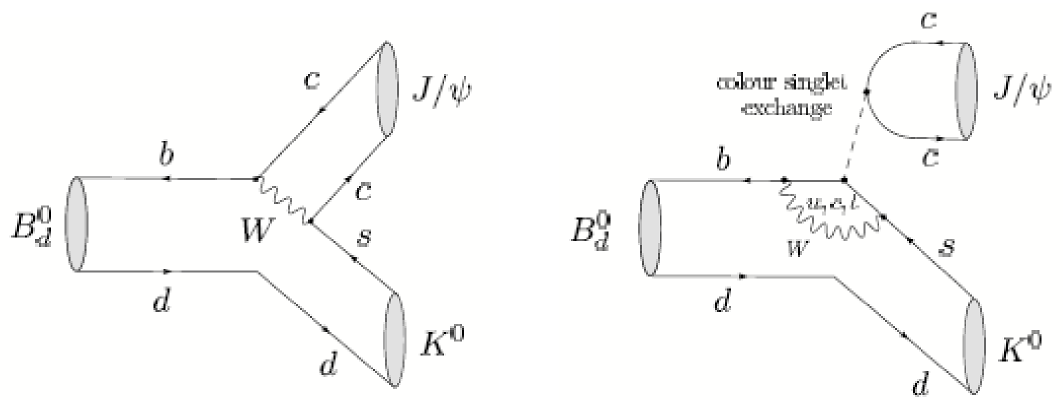
$$\{O_i\} \rightarrow \{O_i^{SM}, O_i^{NP}\}$$

SCENARIOS:

- SUSY
- left-right symmetric models
- extra dimensions
- models with an extra Z'
- 'little' Higgs
- fourth generation

- CRUTIAL PROBLEM – to distinguish NP from hadronic uncertainties in SM !

WHY IS B -> J/Ψ K GOLD PLATED ?



$\bar{b} \to \bar{c}\, c\, \bar{s}$

$$A(B_d^0 \to J/\psi K^0) = \frac{G_F}{\sqrt{2}}\left(1-\frac{\lambda^2}{2}\right)\lambda^2 A\left\{A_c^{(0)} + A_c^{(1)}\right\}\left[1 + \frac{\lambda^2 R_b}{1-\lambda^2/2}\left\{\frac{A_u^{(0)} + A_u^{(1)}}{A_c^{(0)} + A_c^{(1)}}\right\} e^{i\gamma}\right]$$

EW penguins

$$A(B_d^0 \to J/\psi K^0) = \frac{G_F}{\sqrt{2}}\left(1-\frac{\lambda^2}{2}\right)\lambda^2 A\, A_c^{(0)}$$

negigible $\mathcal{O}(\bar{\lambda}^3)$

only one amplitude dominates!

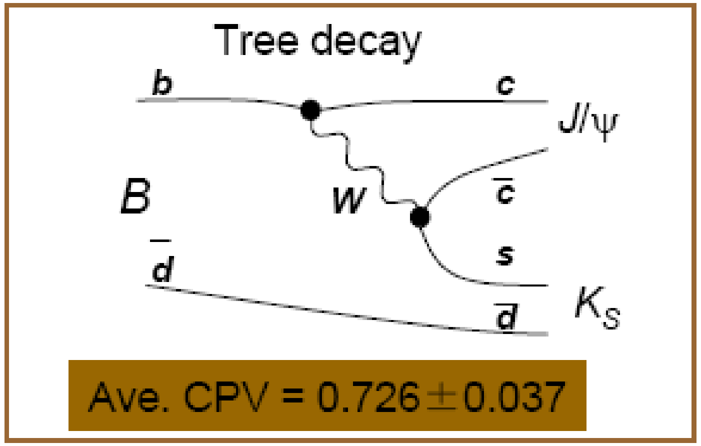
Any measurable deviation from

$a_{CP}(t) = -\sin(2\beta)\sin(\Delta m t)$

is the sign of New Physics

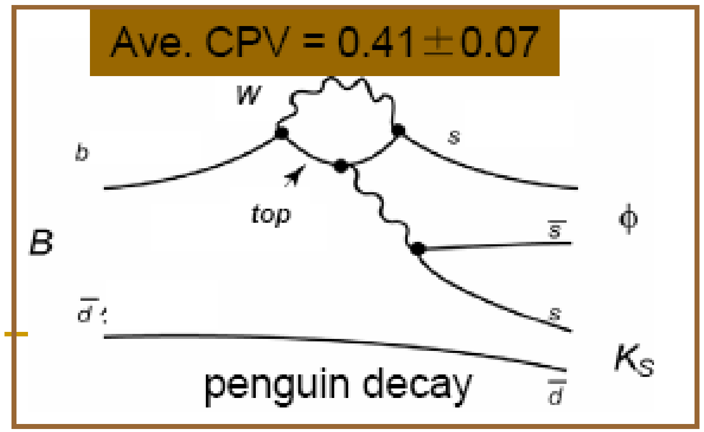
TESTING SM IN $B_d^0 \rightarrow \Phi K_S$ DECAY

also measures sin2β



penguins can be neglected

SM physics: equal asymmetries -> 3.8σ deviations observed !



$$B_d^0 \rightarrow \phi K_S$$

pure penguin process (gluonic and EW penguins)
-> can be affected by NEW PHYSICS

B $\rightarrow \pi\pi$ AND B $\rightarrow \pi$ K DECAYS

- problems to explain neutral B decays

$$A(B_d^0 \rightarrow \pi^+\pi^-) = \mathcal{C}\left[e^{i\gamma} - de^{i\theta}\right]$$

$$de^{i\theta} \equiv \frac{1}{R_b}\left[\frac{A_P^c - A_P^t}{A_T^u + A_P^u - A_P^t}\right]$$

penguin amplitudes does not enter at doubly Cabibbo suppressed level
-> PENGUIN POLLUTION

- if penguins would be negligible -> d = 0 and

$$\begin{aligned} \mathcal{A}_{CP}^{dir}(B_d \rightarrow \pi^+\pi^-) &= 0 \\ \mathcal{A}_{CP}^{mix}(B_d \rightarrow \pi^+\pi^-) &= \sin(\phi_d + 2\gamma) \overset{SM}{=} \sin(\underbrace{2\beta + 2\gamma}_{2\pi - 2\alpha}) = -\sin 2\alpha \end{aligned}$$

-inconsistency between eperiments:

$$\mathcal{A}_{CP}^{dir}(B_d \rightarrow \pi^+\pi^-) = \begin{cases} -0.09 \pm 0.15 \pm 0.04 & \text{Babar} \\ -0.56 \pm 0.12 \pm 0.06 & \text{Belle} \end{cases}$$

$$\mathcal{A}_{CP}^{mix}(B_d \rightarrow \pi^+\pi^-) = \begin{cases} +0.30 \pm 0.17 \pm 0.03 & \text{Babar} \\ +0.67 \pm 0.16 \pm 0.06 & \text{Belle} \end{cases}$$

average:

$$\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^+\pi^-) = -0.37 \pm 0.10$$
$$\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to \pi^+\pi^-) = +0.50 \pm 0.12$$

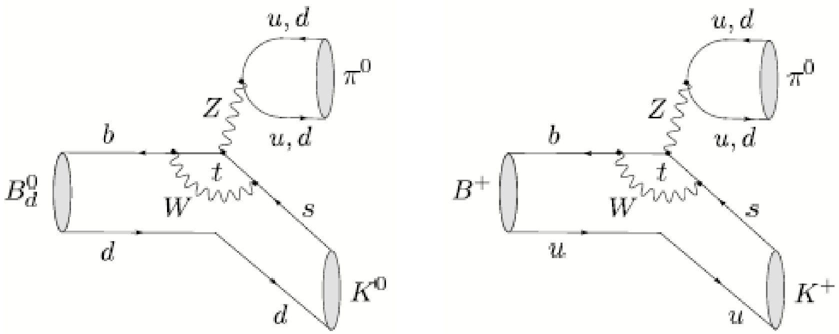
such large $\mathcal{A}_{\rm CP}^{\rm dir}$ indicate large penguin contributions with large CP conserving strong phases !?

Similarly for $\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^\mp K^\pm) = 0.115 \pm 0.018$

- B -> π K puzzle :

$B_d^0 \to \pi^0 K^0$ **and** $B^+ \to \pi^0 K^+$ **decays**

EW penguins are not suppressed -> could have significant impact on the BR?



-> exp. $B_d^0 \to \pi^0 K^0$ is observed with unexpectedly large decay rate

$$R_c \equiv 2\left[\frac{{\rm BR}(B^+ \to \pi^0 K^+) + {\rm BR}(B^- \to \pi^0 K^-)}{{\rm BR}(B^+ \to \pi^+ K^0) + {\rm BR}(B^- \to \pi^- \bar{K}^0)}\right] = 1.01 \pm 0.09$$

$$R_n \equiv \frac{1}{2}\left[\frac{{\rm BR}(B_d^0 \to \pi^- K^+) + {\rm BR}(\bar{B}_d^0 \to \pi^+ K^-)}{{\rm BR}(B_d^0 \to \pi^0 K^0) + {\rm BR}(\bar{B}_d^0 \to \pi^0 \bar{K}^0)}\right] = 0.83 \pm 0.08$$

B -> π K puzzle

$$R_c|_{\rm SM} = 1.15 \pm 0.05, \quad R_n|_{\rm SM} = 1.12 \pm 0.05$$

AMPLITUDE RELATIONS: $B^{\pm} \to K^{\pm} D$ (pure tree decays)

Since there are only tree contributions -> clean way of extracting γ angle:

$$A(B^+ \to K^+ \bar{D}^0) = A(B^- \to K^- D^0)$$
$$A(B^+ \to K^+ D^0) = A(B^- \to K^- \bar{D}^0) \times e^{2i\gamma}$$

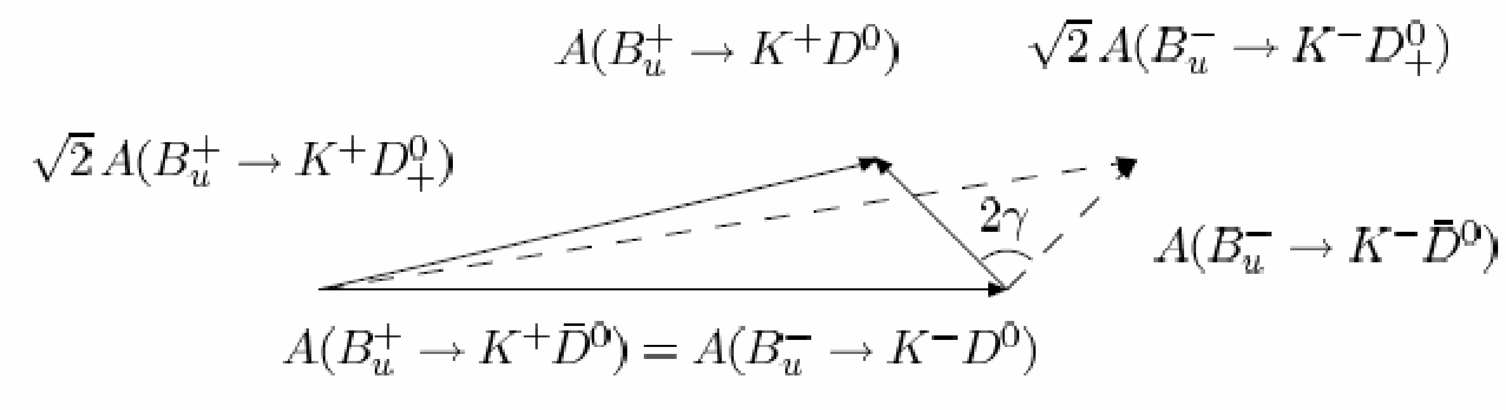
CP = +1 eigenstate:

$$|D^0_+\rangle = \frac{1}{\sqrt{2}}\left[|D^0\rangle + |\bar{D}^0\rangle\right]$$

Isospin analysis:

$$\sqrt{2}A(B^+ \to K^+ D^0_+) = A(B^+ \to K^+ D^0) + A(B^+ \to K^+ \bar{D}^0)$$
$$\sqrt{2}A(B^- \to K^- D^0_+) = A(B^- \to K^- \bar{D}^0) + A(B^- \to K^- D^0)$$

squashed traingles: $B^+ \to K^+ D^0$ is color-suppressed vs $B^+ \to K^+ \bar{D}^0$



$$\gamma|_{D^{(*)}K^{(*)}} = \begin{cases} (62^{+35}_{-25})^\circ \\ (65 \pm 20)^\circ \end{cases}$$

CKMfitter collaboration

UTfit collaboration

Similarly one can use $B_c^{\pm} \to D_s^{\pm} D$ to extract γ -> favourable (non-squashed triangles)

LHCb ?

SU(2) and SU(3) symmetry is used for exploring

$B^0 \to \rho^+ \rho^-$

$B^0 \to \rho^\pm \pi^\mp$

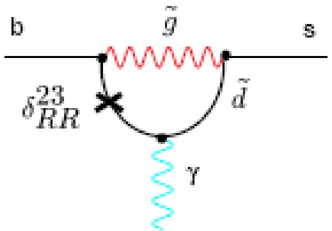
$B^0 \to \pi^+ \pi^-$

BaBar 2004 : $B \to \rho\,\rho \longrightarrow \sin 2\alpha$

RADIATIVE B DECAYS – also $b \to s\,\ell^+\ell^-$ and inclusive modes $\bar{B} \to X_s\gamma$

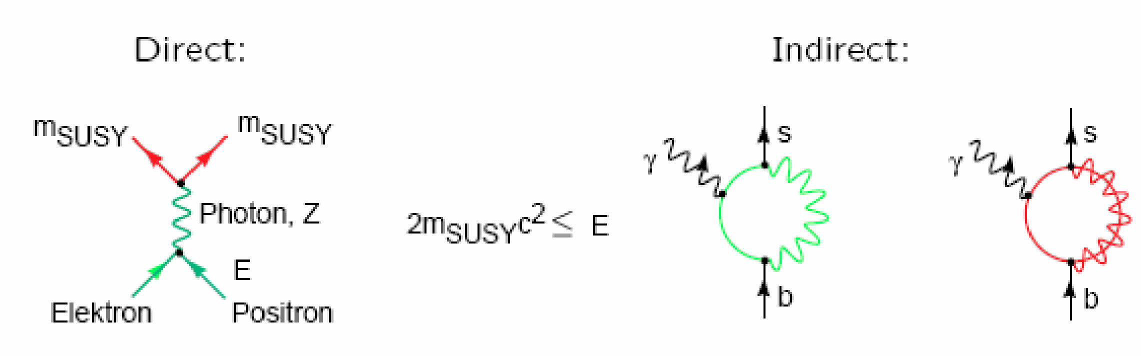
direct probe of SM at one loop level:

b -> s γ loop decay BR(10%) ~ 3 10-4 new physics, $|V_{ts}|$



b -> d γ loop decay BR(10%) ~ 10-6 new physics, $|V_{td}|$
(2005)

NEW PHYSICS (i.e. SUSY):



B→ργ / B→K*γ allow determination of $|V_{td}/ V_{ts}|$ that is independent of form factors

$b \to s\,\ell^+\ell^-$ - forward-backward asymmetry can be measured

NEW ERA – EXPLORING B_s SYSTEM (at Tevatron and LHC)

- $B_s - \overline{B}_s$ MIXING - search for NP

$$\Delta M_q \equiv M_{\rm H}^{(q)} - M_{\rm L}^{(q)}$$

$$\Delta M_s = \left[17.31^{+0.33}_{-0.18}({\rm stat}) \pm 0.07({\rm syst})\right] {\rm ps}^{-1}$$ (CDF) vs $$\Delta M_d = (0.507 \pm 0.004)\,{\rm ps}^{-1}$$

$$\rho_q \equiv \left|\frac{\Delta M_q}{\Delta M_q^{\rm SM}}\right| \longrightarrow$$

$$\rho_s|_{\rm JLQCD} = 1.08^{+0.03}_{-0.01}({\rm exp}) \pm 0.19({\rm th})$$
$$\rho_s|_{\rm (HP+JL)QCD} = 0.74^{+0.02}_{-0.01}({\rm exp}) \pm 0.18({\rm th})$$

f_B and bag parameter are obtained from lattice collaborations

- $B_s^0 \to J/\psi\phi$

  - CP violating effect are tiny in SM for this decay
  - this decay measures $\sin\phi_s$ $\quad \phi_s = -2\delta\gamma = -2\lambda^2\eta \sim -2^\circ$ in SM

- MANY B_s DECAY CHANNELS TO D, π AND K

  - similar analysis as for B_d decays

❑ LEPTONIC B_s DECAYS $B_s^0 \to \mu^+\mu^-$ -very clean rare decay

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = 4.1 \times 10^{-9} \times \left[\frac{f_{B_s}}{0.24\,\mathrm{GeV}}\right]^2 \left[\frac{|V_{ts}|}{0.040}\right]^2 \left[\frac{\tau_{B_s}}{1.5\,\mathrm{ps}}\right] \left[\frac{m_t}{167\,\mathrm{GeV}}\right]^{3.12}$$

$$\mathrm{BR}(B_d \to \mu^+\mu^-) = 1.1 \times 10^{-10} \times \left[\frac{f_{B_d}}{0.20\,\mathrm{GeV}}\right]^2 \left[\frac{|V_{td}|}{0.008}\right]^2 \left[\frac{\tau_{B_d}}{1.5\,\mathrm{ps}}\right] \left[\frac{m_t}{167\,\mathrm{GeV}}\right]^{3.12}$$

using recent experiments would allow for extraction of $\left|\frac{V_{td}}{V_{ts}}\right|^2$ **(UT side Rt) :**

$$\frac{\mathrm{BR}(B_d \to \mu^+\mu^-)}{\mathrm{BR}(B_s \to \mu^+\mu^-)} = \left[\frac{\tau_{B_d}}{\tau_{B_s}}\right] \left[\frac{M_{B_d}}{M_{B_s}}\right] \left[\frac{f_{B_d}}{f_{B_s}}\right]^2 \left|\frac{V_{td}}{V_{ts}}\right|^2$$

another way around:

$$\frac{\mathrm{BR}(B_s \to \mu^+\mu^-)}{\mathrm{BR}(B_d \to \mu^+\mu^-)} = \left[\frac{\tau_{B_s}}{\tau_{B_d}}\right] \left[\frac{\hat{B}_{B_d}}{\hat{B}_{B_s}}\right] \left[\frac{\Delta M_s}{\Delta M_d}\right]$$

from where it follows:

$$\begin{aligned}\mathrm{BR}(B_s \to \mu^+\mu^-) &= (3.35 \pm 0.32) \times \times 10^{-9} \\ \mathrm{BR}(B_d \to \mu^+\mu^-) &= (1.03 \pm 0.09) \times 10^{-10},\end{aligned}$$

which has to be compared with today's data:

$$\mathrm{BR}(B_s \to \mu^+\mu^-) < 1.0 \times 10^{-7}, \quad \mathrm{BR}(B_d \to \mu^+\mu^-) < 3.0 \times 10^{-8}$$ **(CDF)**

- tree decays are not expected to lead to large inconsistency with the SM

- more theor. and exp. efforts go into the determination of the UT from penguin-dominated B decays

- many rare B decays are studied that may reveal specific signs of NP through unexpected CP violation or enhanced BRs

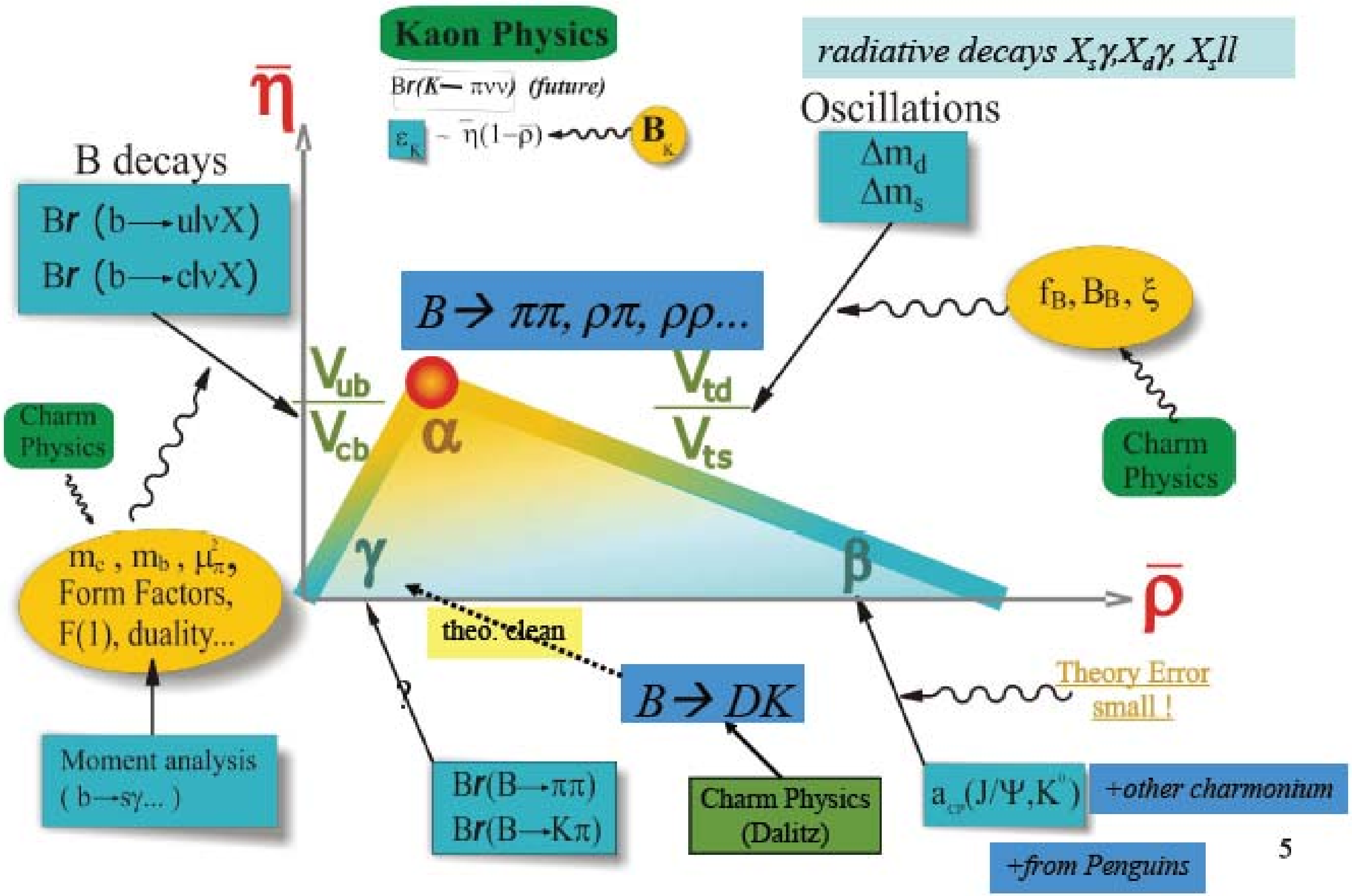
-there are already couple of puzzles from the B-factory data

-> it will be interesting to monitor these data

THERE ARE ALREADY INDICATIONS THAT SM IS INCOMPLETE:

Neutrino oscillations are established

Baryon asymmetry in the universe -> CP violation in the SM is not sufficient to fulfill Saharov's condition

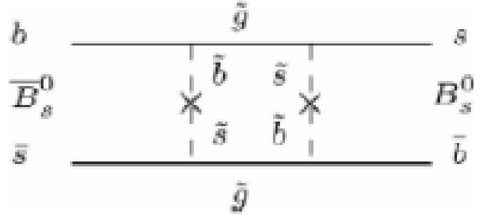


Silvestrini, Beauty 2005

PROSPECTS OF B PHYSICS AT LHC
– CHALLENGE FOR BOTH, EXPERIMENTALISTS AND THEORISTS

- B_s MIXING AND B_s DECAYS

$B_s \to D_s \pi$, …
$B_s \to J/\psi\phi$, $B_s \to J/\psi\eta^{(\prime)}$



- CKM ANGLES - especially γ

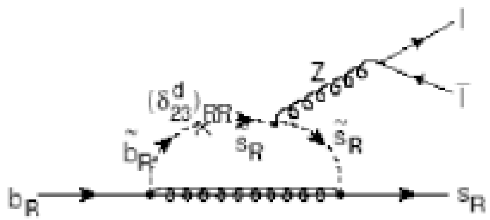
$B_s \to D_s K$, $B^0 \to D^0 K^{*0}$,
$B^0 \to \pi\pi$ & $B_s \to KK$, …

- CP VIOLATION - overconstraining UT

$B^0 \to \phi K_s$, $B_s \to \phi\phi$, ...
$B^0 \to \rho\pi$, $B^0 \to \rho\rho$, …

- SEARCH FOR NEW PHYSICS IN RARE DECAYS

$B^0 \to K^* \gamma$, $B^0 \to K^{*0} l^+ l^-$,
$b \to s l^+ l^-$, $B_s \to \mu^+\mu^-$...



INTRODUCTION:

- b-quark – member of the third generation quark doublet

- decays into quarks of first two generations:

  - mostly b -> c
  - rearly b -> s, d, u

$$\hat{V}_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

[u d'] [c s'] [t b']

relativley LONG lifetime -> testing ground for SM physics
– CP violation and quark-flavour sector of SM

$$\hat{V}_{\mathrm{CKM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$

CP VIOLATION:

-in kaon decays known from 1964
-1999 experimentally confirmed in B - decays

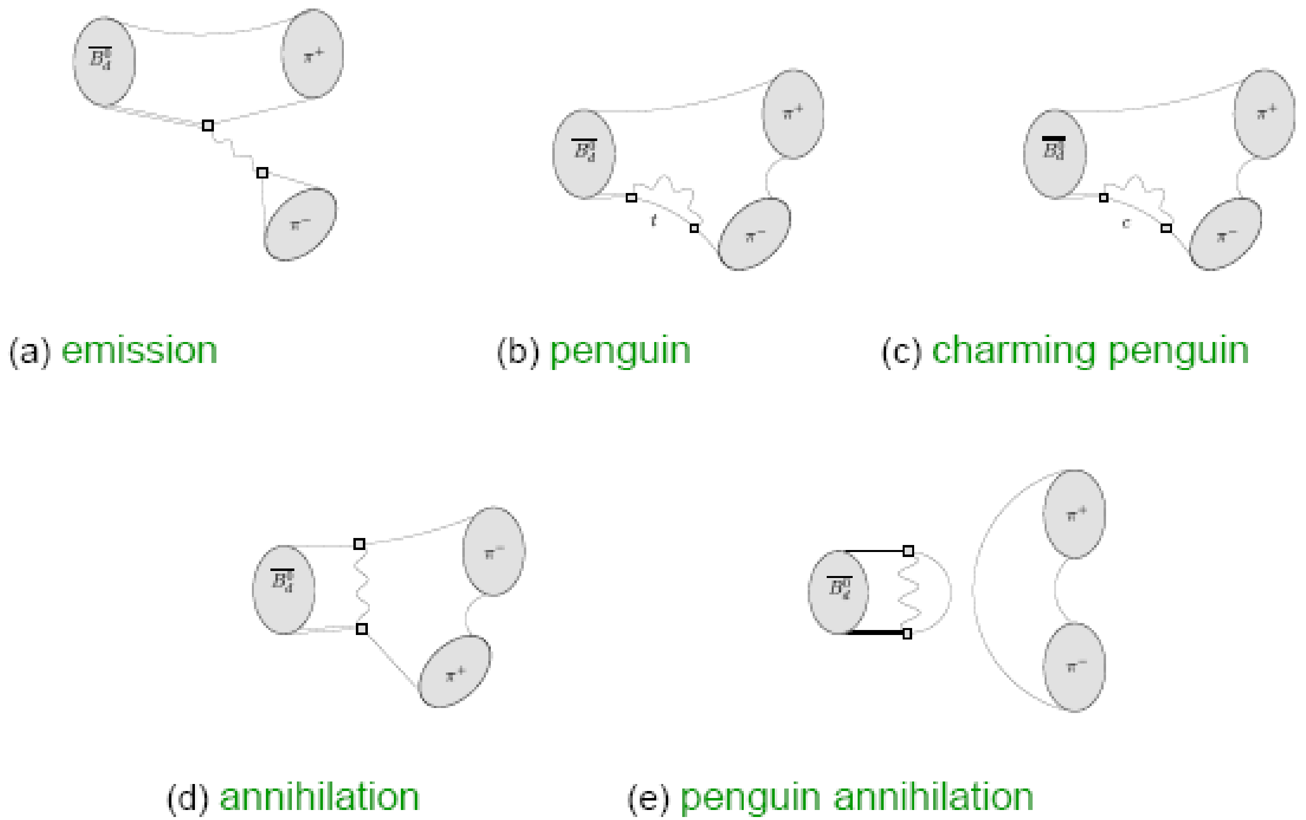
-origin in SM : Yukawa couplings

$$\mathcal{L}_{\rm SM} = \underbrace{\mathcal{L}_G(\psi, W, \phi)}_{\text{kinetic energy + gauge IA}} + \underbrace{\mathcal{L}_H(\phi)}_{\text{Higgs potential} \to \text{spontaneous symmetry breaking}} + \underbrace{\mathcal{L}_Y(\psi, \phi)}_{\text{Yukawa IA} \to \text{fermion masses}}$$

kinetic energy + gauge IA → gauge sector

Higgs potential → spontaneous symmetry breaking; Yukawa IA → fermion masses → scalar sector

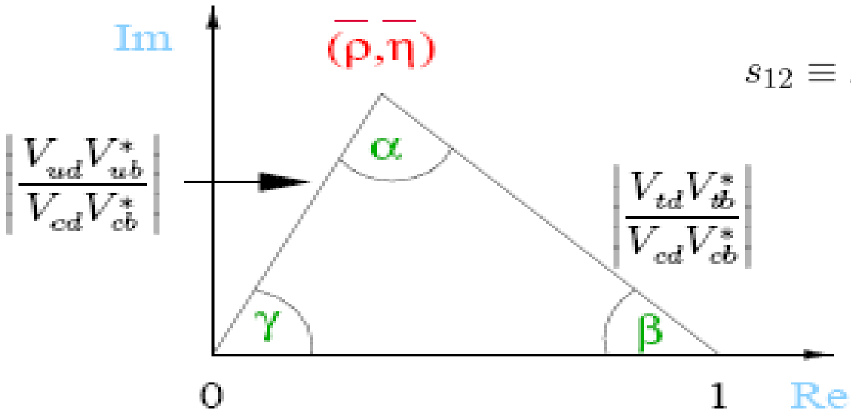
DIFFERENT TOPOLOGIES which can contribute to B decay:



UNITARY TRIANGLES OF CKM MATRIX:

$$\hat{V}_{\text{CKM}}^{\dagger} \cdot \hat{V}_{\text{CKM}} = \hat{1} = \hat{V}_{\text{CKM}} \cdot \hat{V}_{\text{CKM}}^{\dagger}$$

visualisation of the relation: $\sum V_{dj} V_{jb}^{*} = 0$ as a triangle in a complex plane



$$s_{12} \equiv \lambda = 0.22, \quad s_{23} \equiv A\lambda^2, \quad s_{13}e^{-i\delta_{13}} \equiv A\lambda^3(\rho - i\eta)$$

$$\bar{\rho} \equiv \rho\left(1 - \frac{1}{2}\lambda^2\right), \quad \bar{\eta} \equiv \eta\left(1 - \frac{1}{2}\lambda^2\right)$$

e.g.

$$V_{ub} \equiv A\lambda^3(\rho - i\eta)$$

$$V_{td} = A\lambda^3(1 - \bar{\rho} - i\,\bar{\eta})$$

$$V_{us} = \lambda$$

$$V_{cb} = A\lambda^2$$