Flavour Physics (& CP Violation)

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Main references:

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Y. Grossman, CERN Yellow Report CERN-2010-002, 111-144 [arXiv:1006.3534 [hep-ph]];
Y. Nir, CERN Yellow Report CERN-2010-001, 279-314 [arXiv:1010.2666 [hep-ph]];
G. Isidori, arXiv:1302.0661 [hep-ph].

19-20/01/2015, Grindelwald

What is flavour?

- In SM: fermionic fields (spin 1/2)
- *matter flavours*: several copies of the same gauge representation

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- In SM: fermionic fields (spin 1/2)
- *matter flavours*: several copies of the same gauge representation
- unbroken SM gauge group $\mathrm{SU}(3)_\mathrm{c} \times \mathrm{U}(1)_\mathrm{EM}$
  - up-type quarks: $(3)_{2/3} : u,\ c,\ t,$
  - down-type quarks: $(3)_{-1/3} : d,\ s,\ b,$
  - chrged leptons: $(1)_{-1} : e,\ \mu,\ \tau,$
  - neutrinos: $(1)_0 : \nu_1,\ \nu_2,\ \nu_3,$

$$\leftrightarrow$$

differ only in mass

What is flavour?

- Ordinary matter essentially first generation:
  - u and d quarks bound within protons & neutrons,
  - electrons form atoms;
  - "electron neutrinos", (admixture of $\nu_{1,2,3}$) are produced in reactions inside stars.
- 2nd and 3rd generation families decay via weak interactions into first generation particles.

Why there are thee almost identical replicas of quarks and leptons and which is the origin of their different masses?

What is flavour?

- *Flavour physics*
  - Within SM: weak and Yukawa interactions.
- *Flavour parameters*
  - Within SM: 9 masses of charged fermions & 4 mixing parameters (3 angles + 1 phase)
- *Flavour universal* (*flavour blind*)
  - Within SM: QCD & QED
- *Flavour diagonal*
  - Within SM: Yukawa interaction

What is flavour?

- *Flavour changing processes*
  - *Flavour changing charged currents:*

    $\mu^- \to e^-\nu_i\bar{\nu}_j \quad K^- \to \mu^-\bar{\nu}_i \ (s\bar{u} \to \mu^-\bar{\nu}_i)$

    - Within SM: single W exchange at tree-level ($\mathcal{A} \propto G_F$)
  - *Flavour changing neutral currents:*

    $\mu^- \to e^-\gamma \quad K_L \to \mu^+\mu^- \ (s\bar{d} \to \mu^+\mu^-)$

    - Within SM: higher orders in weak expansion (loops) - often highly suppressed

Why is flavour interesting?

- $\dfrac{\Gamma(K_L \to \mu^+\mu^-)}{\Gamma(K^- \to \mu^-\bar{\nu}_i)} \Rightarrow$ prediction of charm quark
- $\Delta m_K \equiv m_{K_L} - m_{K_S} \Rightarrow$ prediction of charm mass
- $K_L \to \pi^+\pi^-$ $(\varepsilon_K) \Rightarrow$ prediction of 3rd generation
- *CP Violation*
    - Within SM: single CP violating parameter

Why is flavour interesting?

- Electroweak (EW) hierarchy problem
  - requires NP $\leq$ 1 TeV
  - if generic flavour structure $\Rightarrow$ FCNCs
  - flavour probes NP scales $\leq 10^5$ TeV

NP flavour puzzle

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NP flavour puzzle

- SM flavour parameters
  - hierarchical: $m_u << m_c << m_t$
  - most are small: $m_{f \neq t} << m_{W,Z}$

SM flavour puzzle

Flavour in SM

Flavour in SM

$$\mathcal{L} = ?$$

i) Symmetries & their spontaneous breaking

ii) Representations of fermions & scalars

Flavour in SM

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i) Symmetries & their spontaneous breaking

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i) $\mathcal{G}^{\rm SM}_{\rm local} = SU(3)_c \times SU(2)_L \times U(1)_Y$

$\mathcal{G}^{\rm SM}_{\rm local} \to SU(3)_c \times U(1)_{\rm EM}$

ii) $Q^i_L \sim (3,2)_{1/6}\,,\ U^i_R \sim (3,1)_{2/3}\,,$

$D^i_R \sim (3,1)_{-1/3}\,,\ L^i_L \sim (1,2)_{-1/2}\,,$

$\phi \sim (1,2)_{1/2}\,,\ \langle \phi^0 \rangle \equiv \frac{v}{\sqrt{2}} \simeq 174\text{GeV}\,,$

Flavour in SM

$$\mathcal{L}_{\text{SM}} = \mathcal{L}^{\text{SM}}_{\text{kinetic}} + \mathcal{L}^{\text{SM}}_{\text{EWSB}} + \mathcal{L}^{\text{SM}}_{\text{Yukawa}}$$

- simple and symmetric (g, g', g_s)
- EWSB, 2 params
- SM flavour dynamics, flavour parameters

Interaction basis

$$\mathcal{L}_{\rm kinetic}^{\rm SM} = (D_\mu\phi)^\dagger(D^\mu\phi) + \sum_{i,j=1,2,3}\sum_{\psi=Q_L,\dots,E_R}\bar{\psi}^i i\not{D}\delta^{ij}\psi^j$$
$$-\frac{1}{4}\sum_{a=1,\dots,8}G^a_{\mu\nu}G^{a,\mu\nu} - \frac{1}{4}\sum_{a=1,2,3}W^a_{\mu\nu}W^{a,\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

- $D_\mu = \partial_\mu + ig_s G^a_\mu L^a + igW^b_\mu T^b + ig' B_\mu Y$

$$\mathcal{L}_{\rm EWSB}^{\rm SM} = \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2$$

Interaction basis

$$\mathcal{G}_{\text{flavour}}^{\text{SM}} = U(3)^5 = SU(3)_q^3 \times SU(3)_\ell^2 \times U(1)^5 \,,$$
$$SU(3)_q^3 = SU(3)_Q \times SU(3)_U \times SU(3)_D \,,$$
$$SU(3)_\ell^2 = SU(3)_L \times SU(3)_E \,,$$
$$U(1)^5 = U(1)_B \times U(1)_L \times U(1)_Y \times U(1)_{\text{PQ}} \times U(1)_E \,.$$

- Exercise: compute embedding of $U(1)^5$ into $U(3)^5$

Interaction basis

$$-\mathcal{L}^{\rm SM}_{\rm Yukawa} = Y_d^{ij}\bar{Q}_L^i\phi D_R^j + Y_u^{ij}\bar{Q}_L^i\tilde{\phi}U_R^j + Y_e^{ij}\bar{L}^i\phi E_R^j + {\rm h.c.}\,,$$

$$\tilde{\phi} = i\sigma_2\phi,$$

- in general flavour dependent (unless $Y_F \propto I_{ij}$) & CPV

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– $SU(3)_Q \times SU(3)_U \to U(1)_u \times U(1)_c \times U(1)_t$ is due to $Y_u \not\propto {\rm I}\,,$

– $SU(3)_Q \times SU(3)_D \to U(1)_d \times U(1)_s \times U(1)_b$ is due to $Y_d \not\propto {\rm I}\,,$

(Y_U & Y_D together break remaining $U(1)$ factors to $U(1)_B$)

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- in general flavour dependent (unless $Y_F \propto I_{ij}$) & CPV

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(Y_U & Y_D together break remaining $U(1)$ factors to $U(1)_B$)

– finally, $SU(3)_L \times SU(3)_E \to U(1)_e \times U(1)_\mu \times U(1)_\tau$ due to $Y_e \not\propto \mathrm{I}$

$$\mathcal{G}^{\rm SM}_{\rm global}(Y_f \neq 0) = U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$$

Interaction basis

- *Flavour physics*: interactions which break $SU(3)^3_q \times SU(3)^2_\ell$ are *flavour violating*
- Spurion analysis:

  $Y_u \sim (3, \bar{3}, 1)_{SU(3)^3_q}\ ,\ Y_d \sim (3, 1, \bar{3})_{SU(3)^3_q}\ ,\ Y_e \sim (3, \bar{3})_{SU(3)^2_\ell}\ .$

  - parameter counting
  - identification of suppression factors
  - idea of Minimal Flavour Violation

Counting SM quark flavour parameters

- global symmetry group G_f with $N_{\rm total}$ generators
- $G_f \to H_f$ with $N_{\rm total} - N_{\rm broken}$ generators
- $N_{\rm physical} = N_{\rm general} - N_{\rm broken}$

Counting SM quark flavour parameters

- global symmetry group G_f with N_{total} generators
- $G_f \to H_f$ with $N_{\text{total}} - N_{\text{broken}}$ generators
- $N_{\text{physical}} = N_{\text{general}} - N_{\text{broken}}$
- Within SM: $U(3)_Q \times U(3)_U \times U(3)_D \to U(1)_B$

$$N_{\text{total}} = 3\times(3+6i), \quad N_{\text{broken}} = N_{\text{total}} - 1i = 9+17i,$$
$$N_{\text{general}} = 2\times(9+9i) \ (Y_U, \ Y_D)$$
$$N_{\text{physical}} = N_{\text{general}} - N_{\text{broken}} = 9 + 1i$$

Discrete SM symmetries

- Any local Lorentz invariant QFT conserves CPT
  $\Rightarrow$ CP violation = T violation

- In SM: C & P violation maximally
  - C & P change chirality
  - Left- & right-handed fields in different gauge reps.

independent of SM parameters

Discrete SM symmetries

- Any local Lorentz invariant QFT conserves CPT
  $\Rightarrow$ CP violation = T violation

- In SM: CP violation depends on parameters

$$Y_{ij}\bar{\psi}^i_L\phi\psi^j_R + Y^*_{ij}\bar{\psi}^j_R\phi^\dagger\psi^i_L \stackrel{\text{CP}}{\to} Y_{ij}\bar{\psi}^j_R\phi^\dagger\psi^i_L + Y^*_{ij}\bar{\psi}^i_L\phi\psi^j_R\,.$$

  - CP symmetric if $Y_{ij} = Y^*_{ij}$.

  - Jarlskog invariant

$$J \equiv \text{Im}[\det(Y_d Y_d^\dagger, Y_u Y_u^\dagger)] = 0\,.$$

Discrete SM symmetries

- Any local Lorentz invariant QFT conserves CPT
  $\Rightarrow$ CP violation $=$ T violation

- Experimental discovery of CPV in kaon decays

Cronin 1980 **Fitch**

Mass basis

- $\mathrm{Re}(\phi^0) \to (v+h)/\sqrt{2}$, ⇒ $M_q = \frac{v}{\sqrt{2}} Y_q \,.$
  - mass basis corresponds to diagonal M_q
- $Q_L \to V_Q Q_L\,,\; U_R \to V_U U_R\,,\; D_R \to V_D D_R$
  - $Y_u \to V_Q Y_u V_U^\dagger\,,\; Y_d \to V_Q Y_d V_D^\dagger$
- $V_Q^u M_u V_U^\dagger = M_u^{\mathrm{diag}} = \frac{v}{\sqrt{2}} \lambda_u\,; \quad \lambda_u = \mathrm{diag}(y_u, y_c, y_t)\,,$

  $V_Q^d M_d V_D^\dagger = M_d^{\mathrm{diag}} = \frac{v}{\sqrt{2}} \lambda_d\,; \quad \lambda_d = \mathrm{diag}(y_d, y_s, y_b)\,.$

Mass basis

- $V_{U,}\ V_D$ unphysical
- since $[M_u, M_d] \neq 0, \quad V_Q^u V_Q^{d\dagger} \equiv V_{\rm CKM} \neq 1$

Cabibbo, Kobayashi & Maskawa

2008

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- SM flavour Lagrangian

$$\mathcal{L}_m^F = \left(\bar{q}_i \not{D} q^j \delta_{ij}\right)_{\rm NC} + \frac{g}{\sqrt{2}} \bar{u}_L^i \not{W}^+ V_{\rm CKM}^{ij} d_L^j$$
$$+ \bar{u}_L^i \lambda_u^{ij} u_R^j \left(\frac{v+h}{\sqrt{2}}\right) + \bar{d}_L^i \lambda_d^{ij} d_R^j \left(\frac{v+h}{\sqrt{2}}\right) + \text{h.c.}\,,$$

$\text{NC} = \text{neutral currents } (g, \gamma, Z)$ $\qquad (u_L^i, d_L^i) \equiv Q_L^T$

Mass basis

- Exercise: Show that NC's are diagonal

- Exercise:Show that in absence of neutrino masses there is no mixing in the leptonic sector

Testing the CKM

- Flavour conversion in SM:
  - fully parametrized by 3 CKM angles
  - mediated by charged current weak interactions
  - these involve left-handed fields only

CKM Parametrization

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

(mass-ordered)

CKM Parametrization

PDG parametrization

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -s_{23}c_{12} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$|V_{ud}| \sim |V_{cs}| \sim |V_{tb}| \sim 1$$

$$|V_{us}| \sim |V_{cd}| \sim 0.22$$

$$|V_{cb}| \sim |V_{ts}| \sim 0.04$$

$$|V_{ub}| \sim |V_{td}| \sim 0.005$$

hierarchical

CKM Parametrization

Wolfenstein parametrization

$$V = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\varrho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\varrho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\lambda \doteq s_{12}\ , \qquad A\lambda^2 \doteq s_{23}\ , \qquad A\lambda^3(\varrho - i\eta) \doteq s_{13}e^{-i\delta}\ .$$

CKM Parametrization

Wolfenstein parametrization

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda+\mathcal{O}(\lambda^7) & A\lambda^3(\varrho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\varrho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2+\mathcal{O}(\lambda^8) \\ A\lambda^3(1-\bar{\varrho}-i\bar{\eta}) & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\varrho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

$$\bar{\varrho} = \varrho(1-\frac{\lambda^2}{2})+\mathcal{O}(\lambda^4)\,, \qquad \bar{\eta} = \eta(1-\frac{\lambda^2}{2})+\mathcal{O}(\lambda^4)\,.$$

Unitarity of CKM

$$\sum_k V_{ik}^* V_{jk} = \delta_{ij} \, , \quad \sum_k V_{ki}^* V_{kj} = \delta_{ij} \, .$$

- most interesting for i=1, j=3

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0 \, ,$$

- all three terms on LHS of same order in λ

$$\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} + \frac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*} + 1 = 0 \, ,$$

$$[\bar\rho + i\bar\eta] + [(1 - \bar\rho) - i\bar\eta] + 1 = 0 \, ,$$

Unitarity of CKM

$|V_{us}|(\lambda)$ from $K \to \pi\ell\nu$

$|V_{cb}|$ (A) from $B \to X_c\ell\nu$

$$\lambda = 0.2253(9)$$
$$A = 0.822(12)$$

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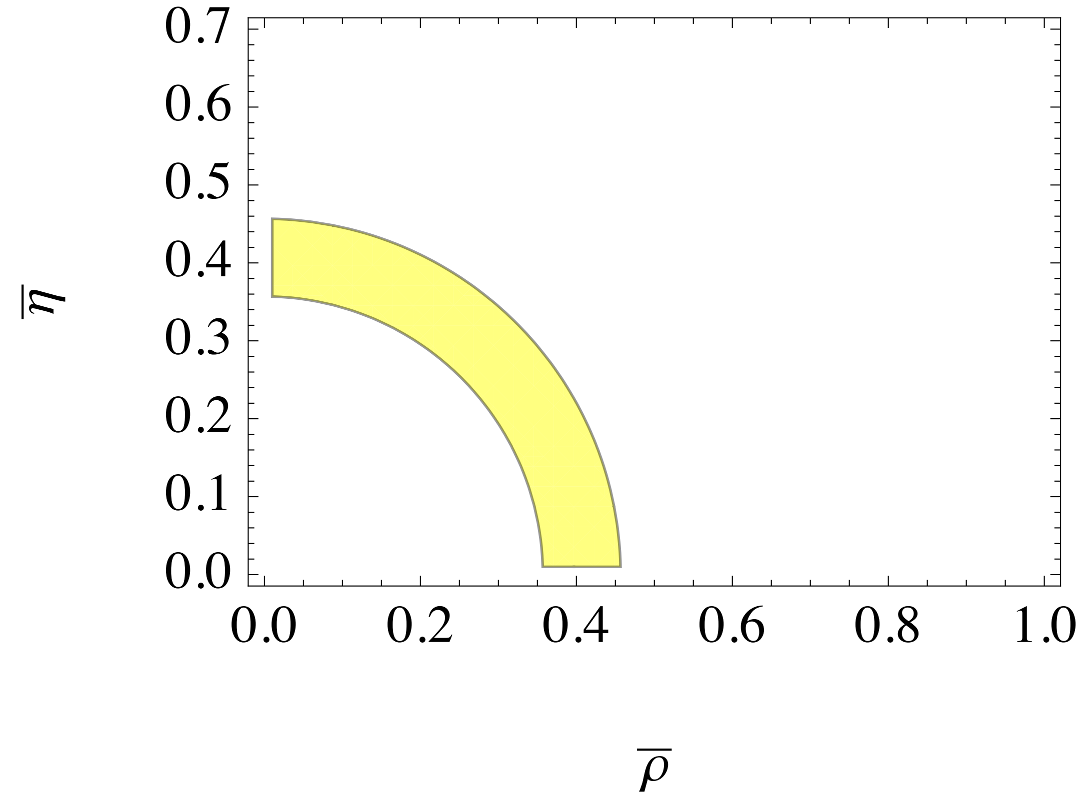

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$$S_{\psi K_S} = \sin 2\beta = \frac{2\bar{\eta}(1-\bar{\rho})}{(1-\bar{\rho})^2 + \bar{\eta}^2}$$

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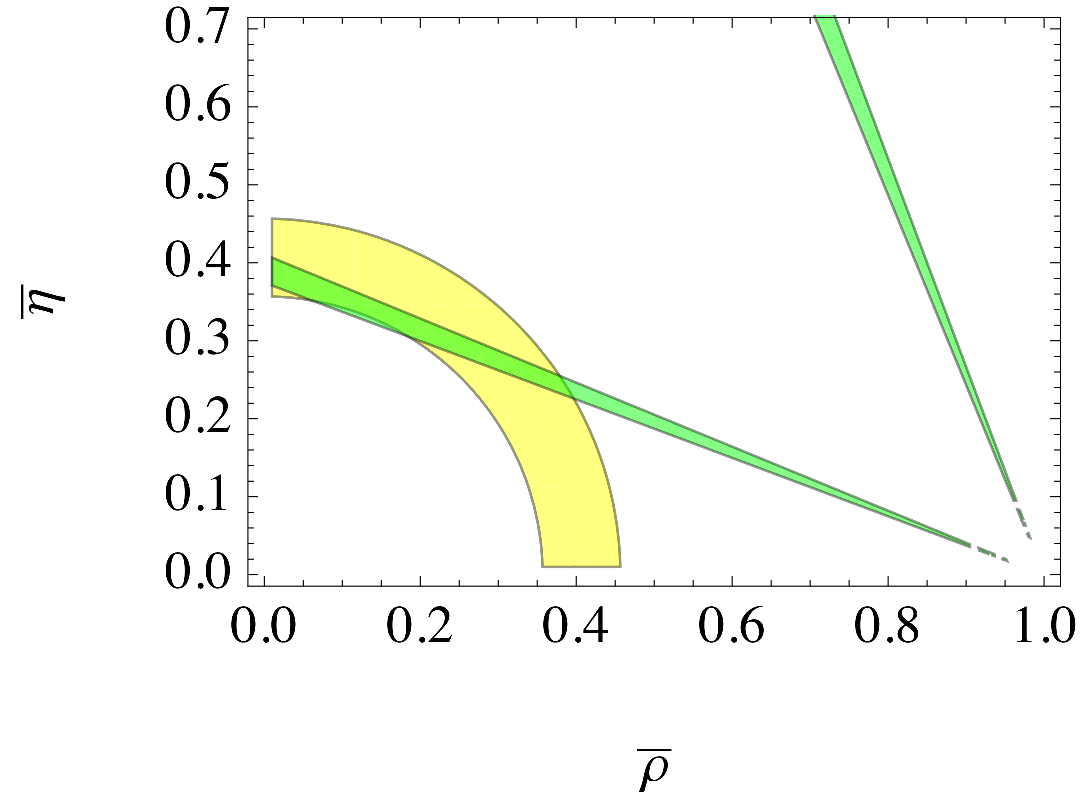

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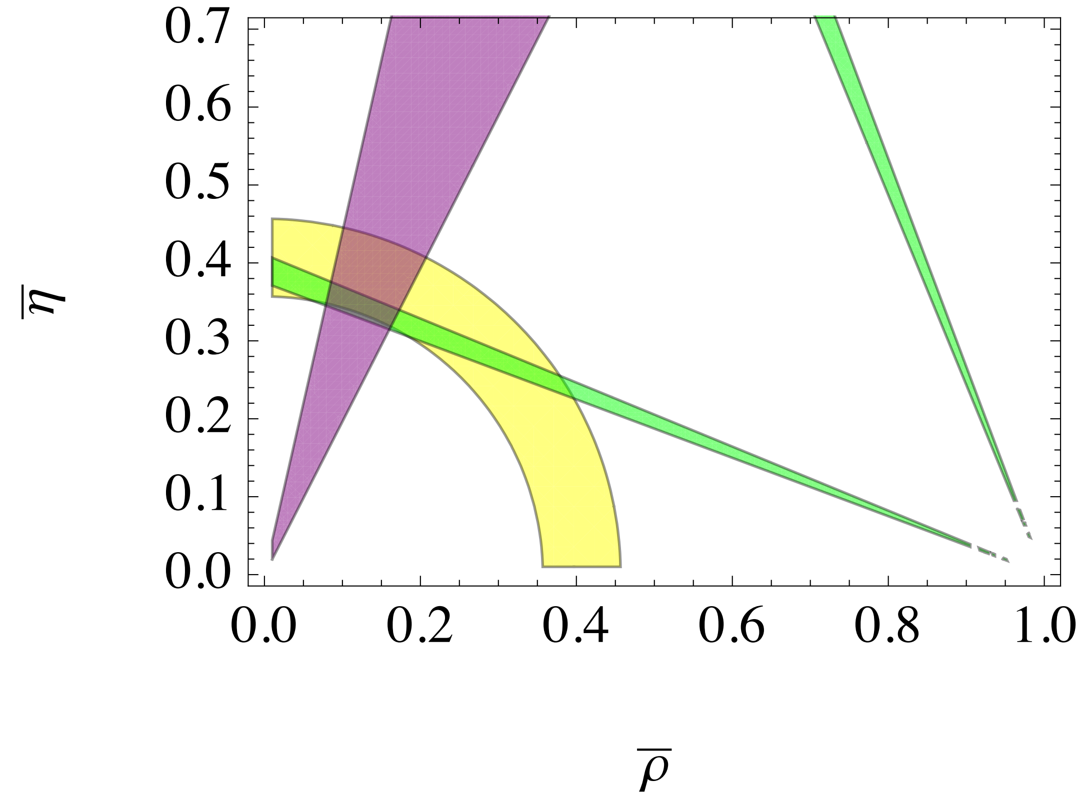

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$\alpha = \pi - \beta - \gamma$ ($B \to \pi\pi, \varrho\pi, \varrho\varrho$ rates)

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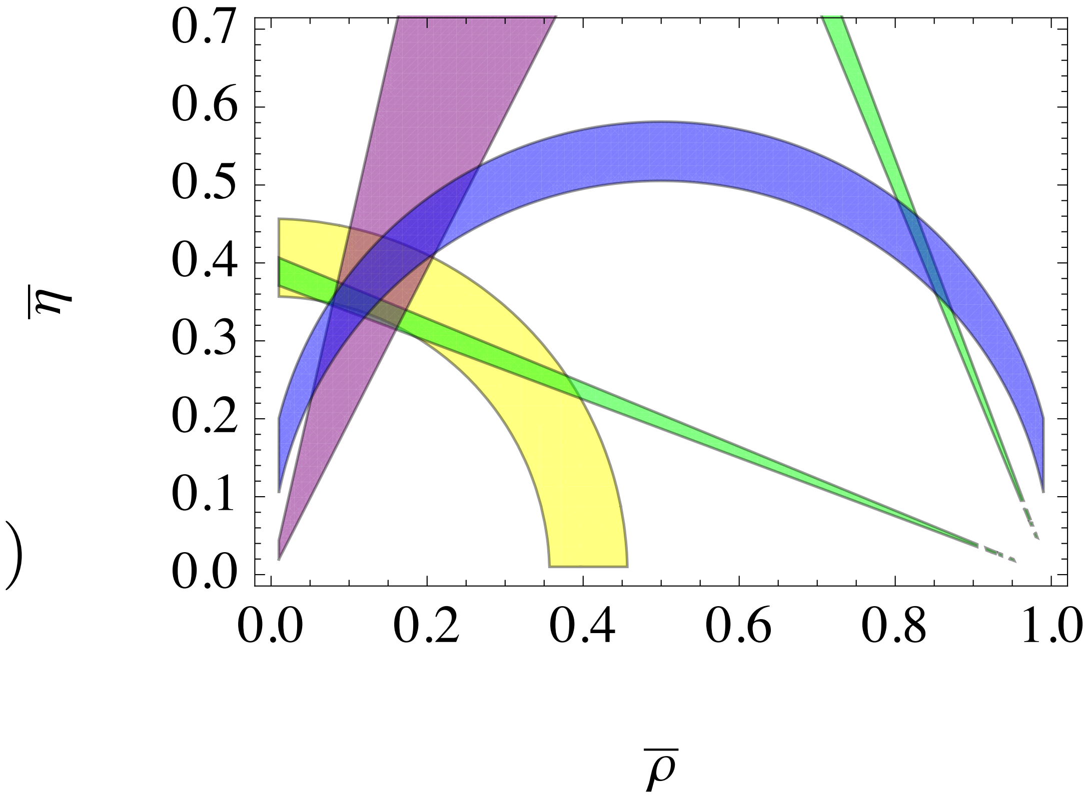

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$$\frac{\Delta m_d}{\Delta m_s} \propto \left|\frac{V_{td}}{V_{ts}}\right|^2 = \lambda^2[(1-\bar{\rho})^2 + \bar{\eta}^2]$$

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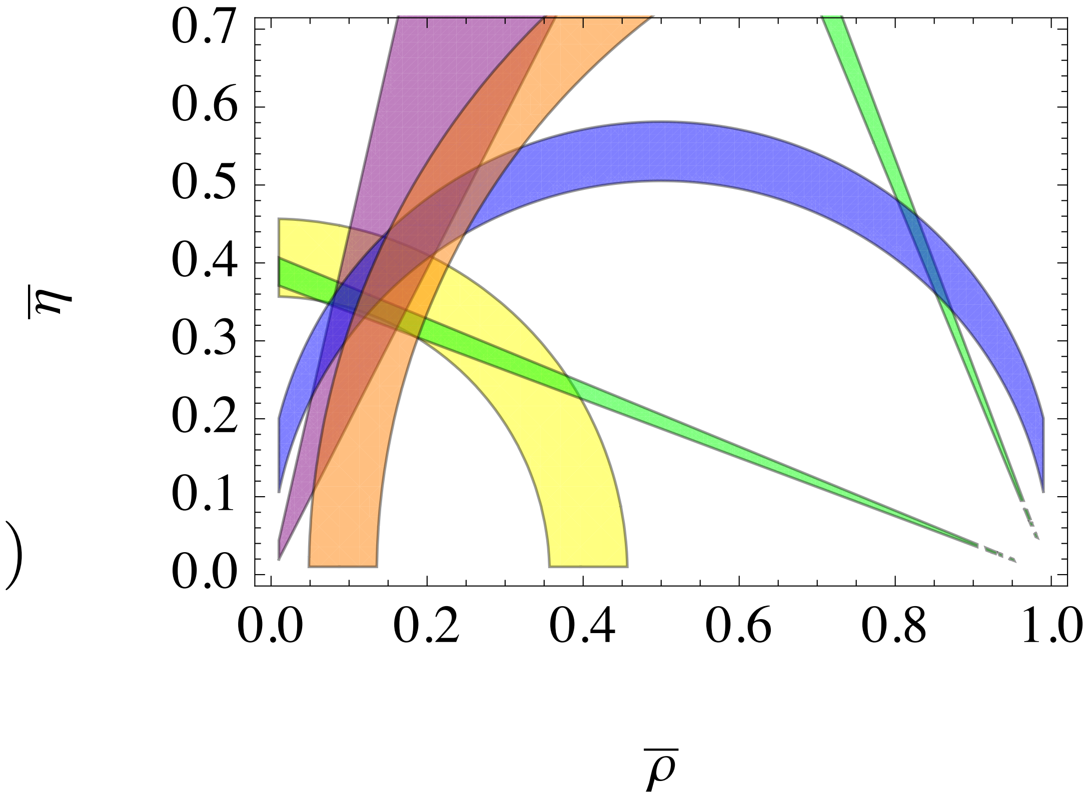

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ϵ_K (CPV in $K \to \pi\pi$)

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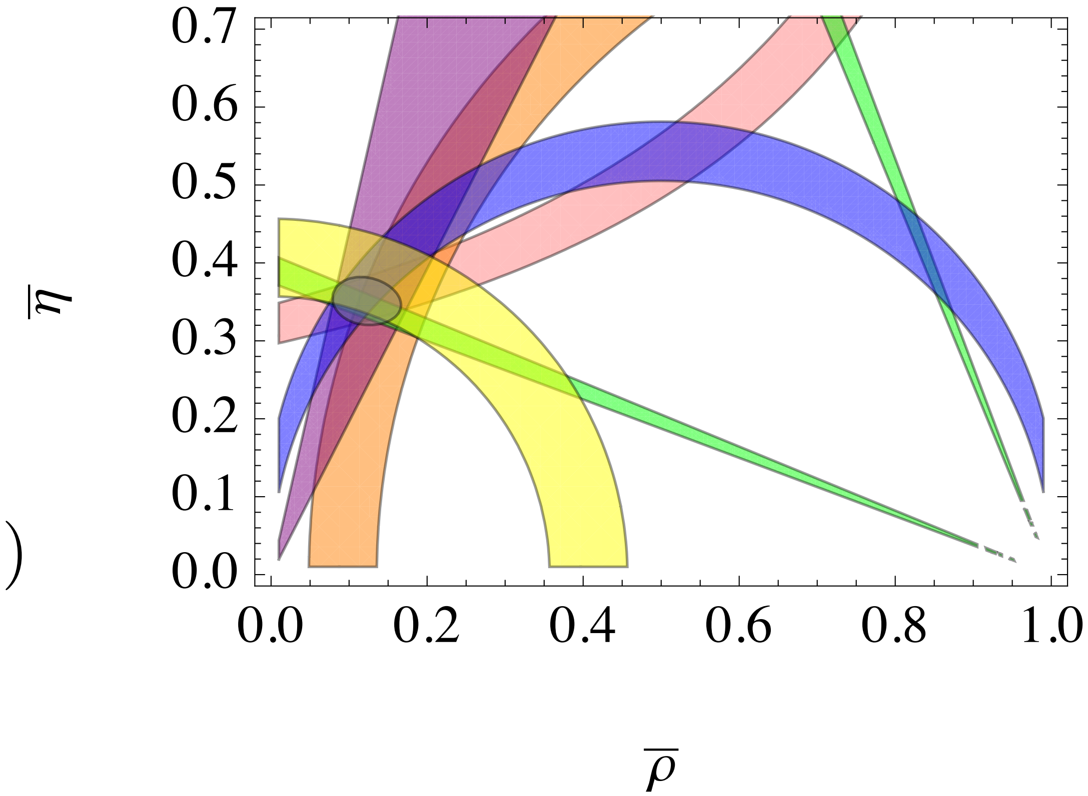
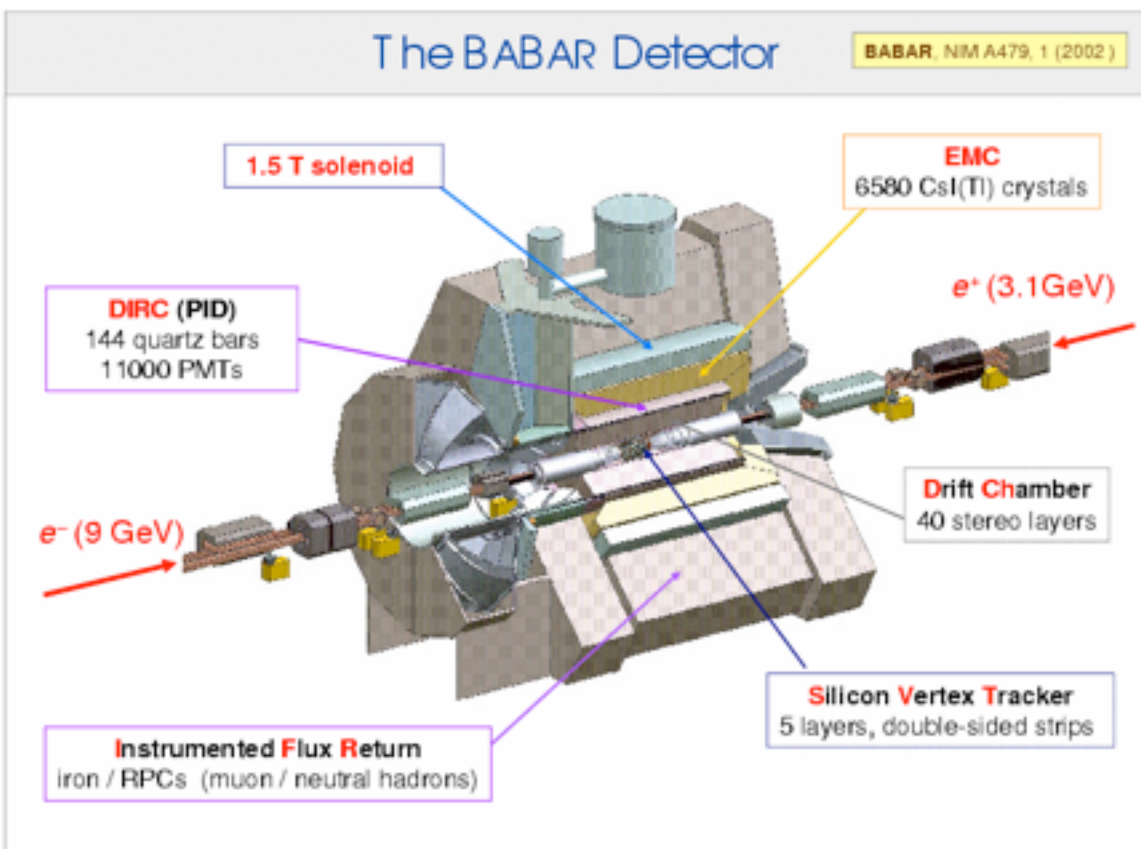
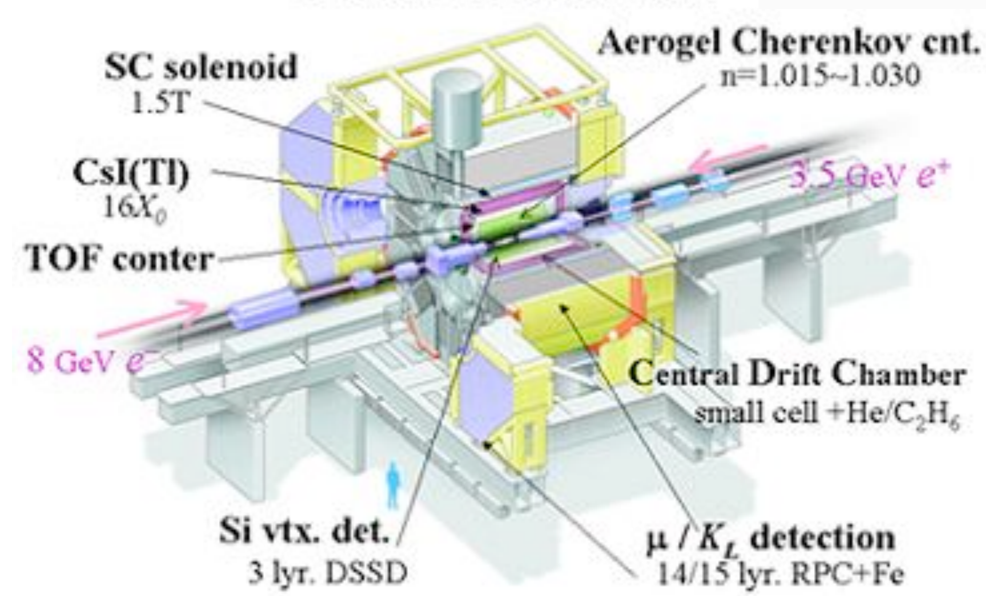


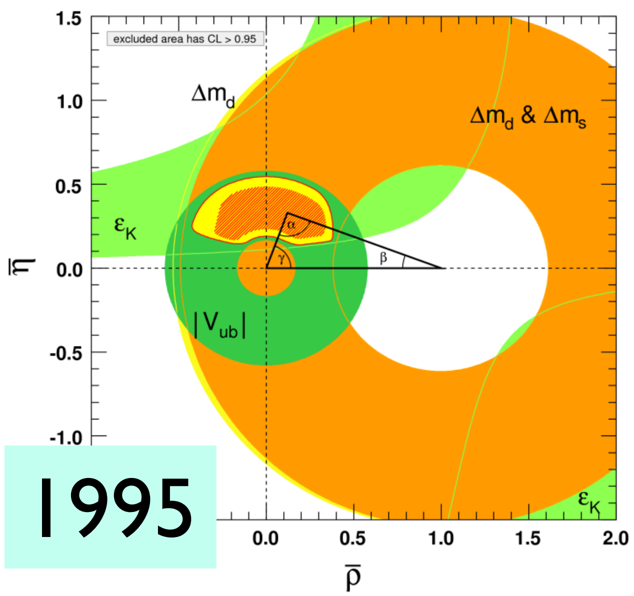
$$\bar{\rho} = 0.130 \pm 0.024$$
$$\bar{\eta} = 0.362 \pm 0.014$$

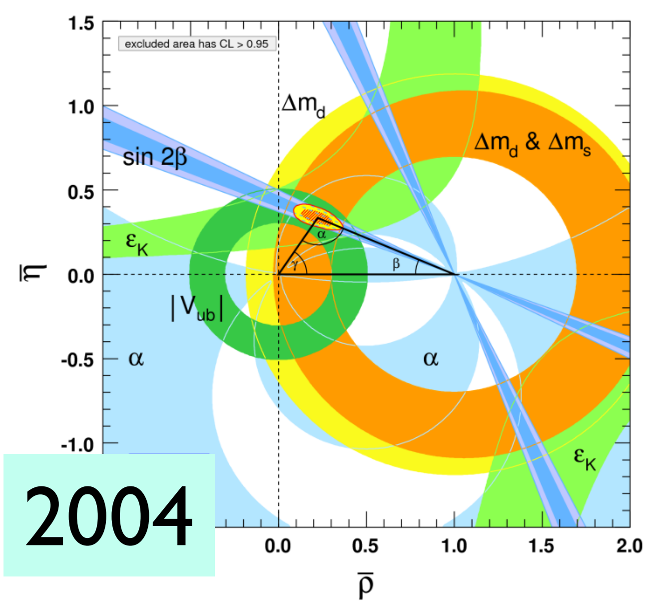
Legacy of B-factories

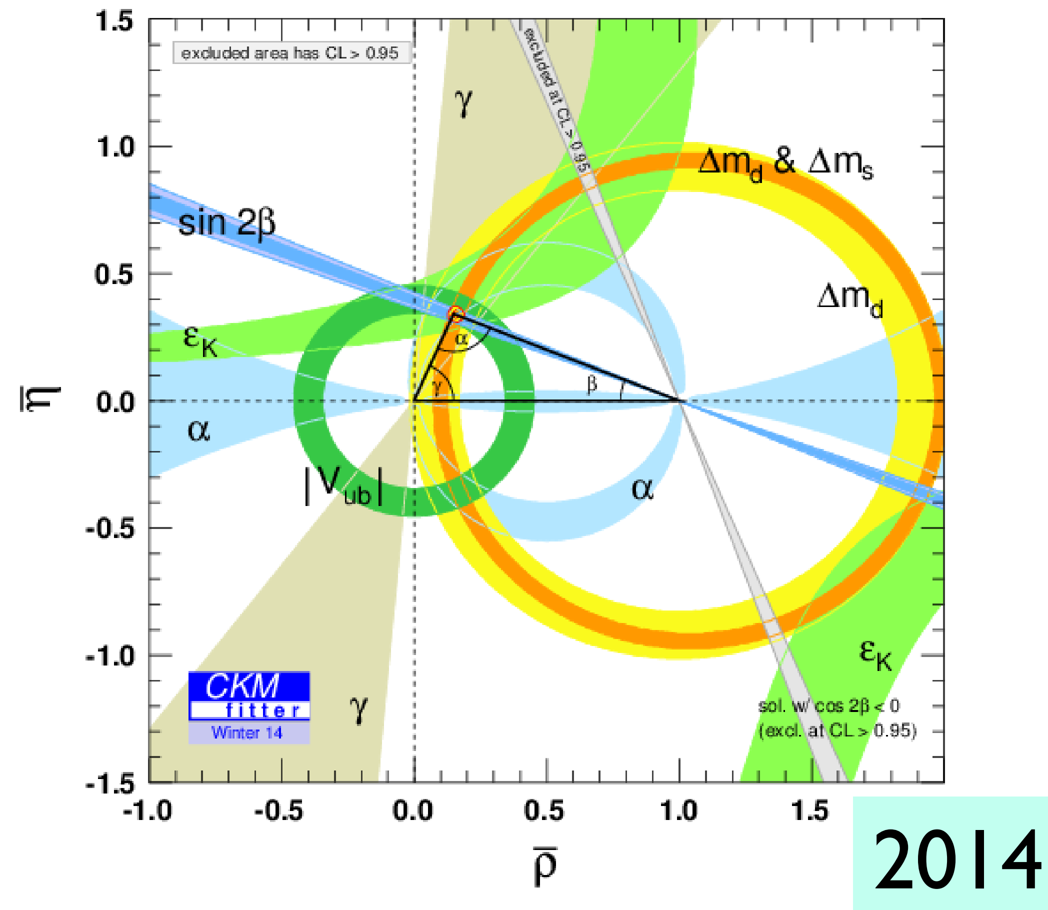




Legacy of B-factories







Unitarity of CKM

- Very likely, CPV in flavour changing processes is dominated by CKM phase & Kobayashi-Maskawa mechanism of CPV is at work

Unitarity of CKM

- Very likely, CPV in flavour changing processes is dominated by CKM phase & Kobayashi-Maskawa mechanism of CPV is at work

- Reparametrisation invariant measure of CPV

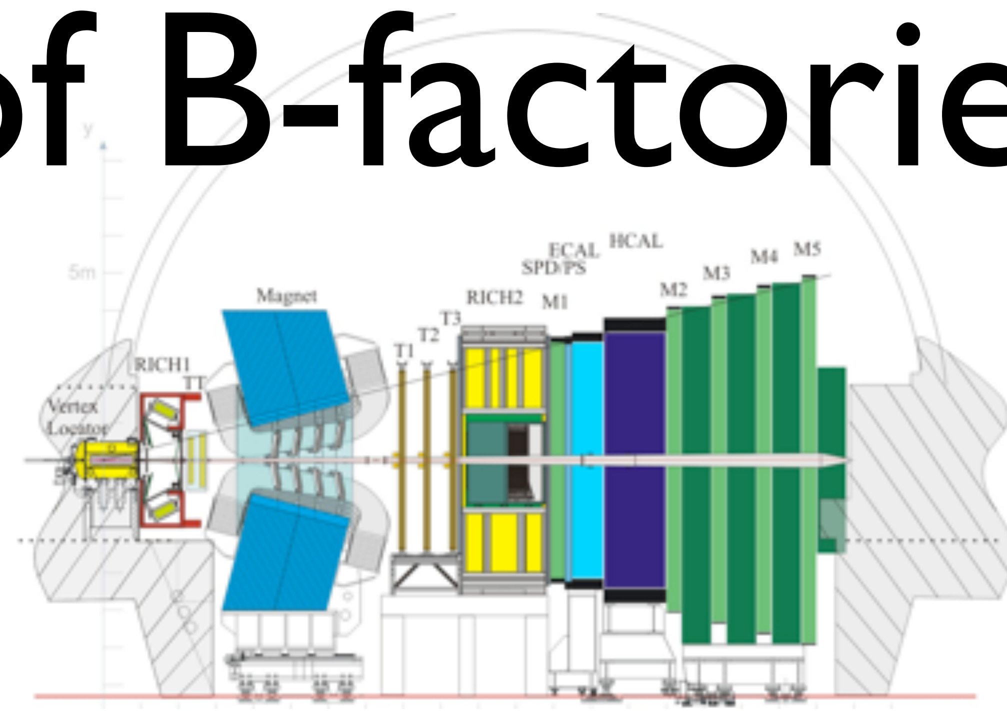
$$\mathrm{Im}[V_{ij}V_{kj}^*V_{kl}V_{il}^*] = J_{KM}\sum \epsilon_{ikm}\epsilon_{jln}\,,$$

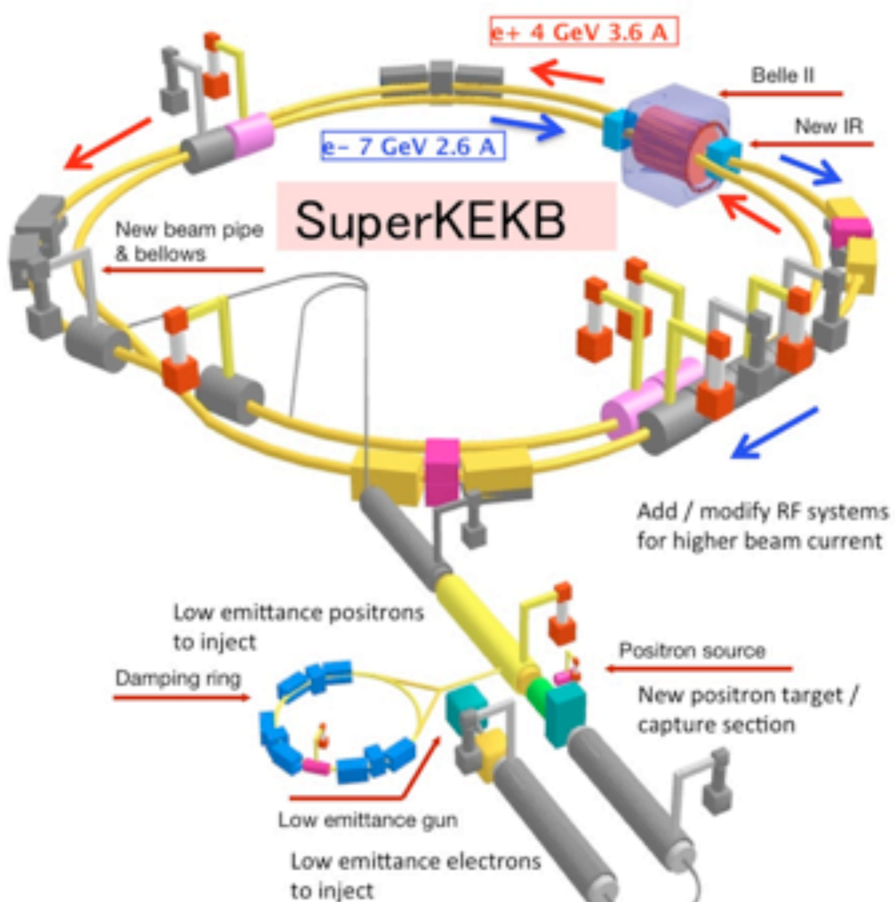
- $J_{KM} = \lambda^6 A^2 \eta = \mathcal{O}(10^{-5})$

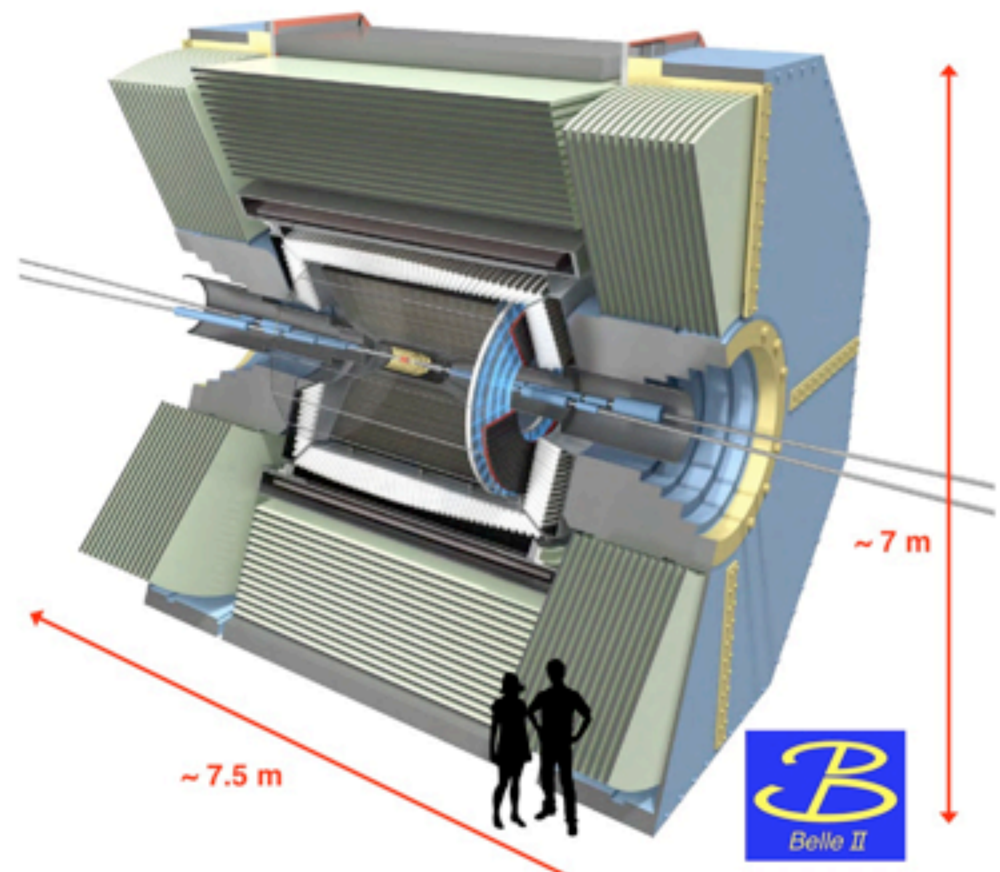
- Jarlskog determinant in SM

$$J = J_{KM}\prod_{i>j}\frac{m_i^2 - m_j^2}{v^2} = \mathcal{O}(10^{-22})\,.$$

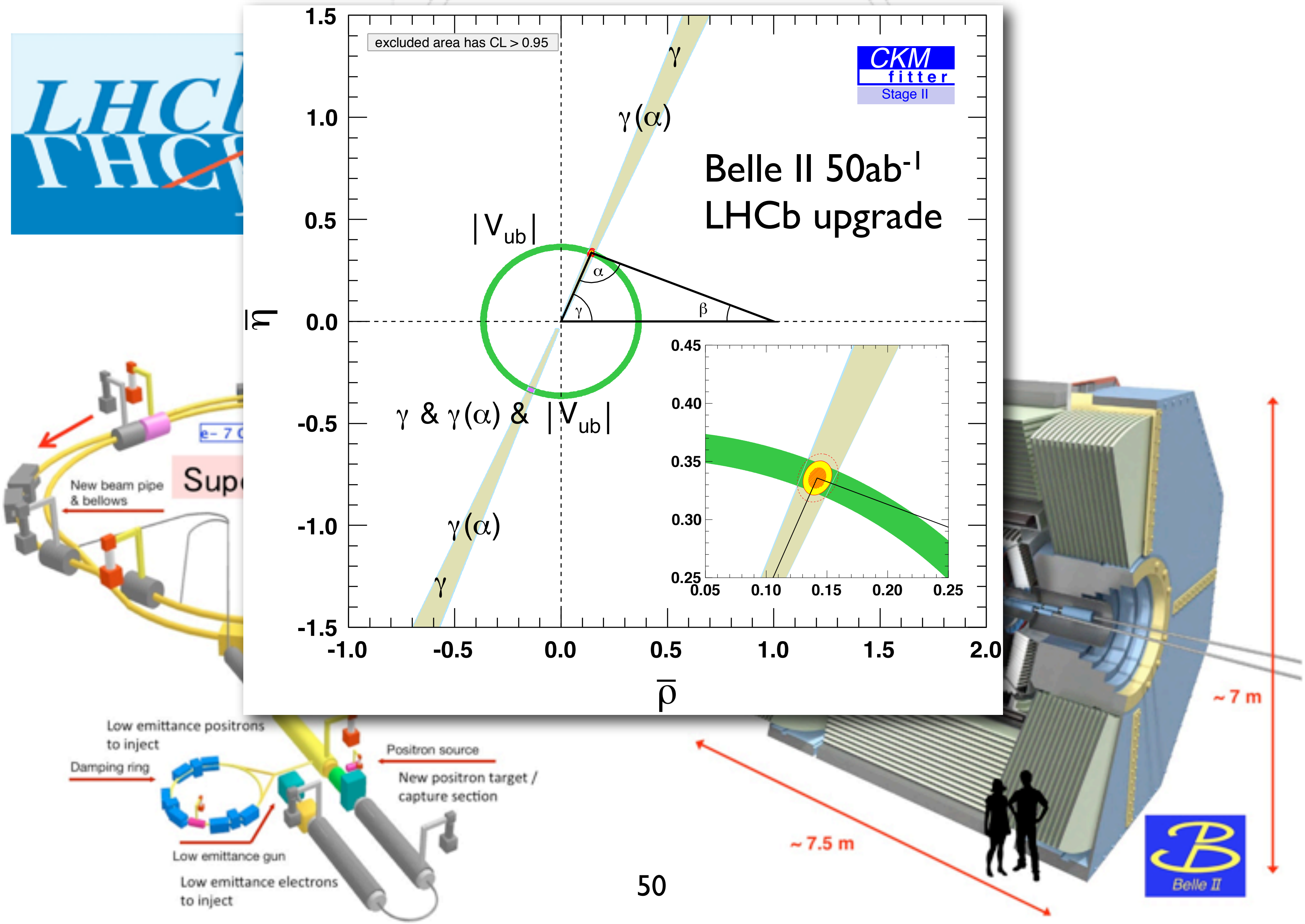
Continuing the Legacy of B-factories







Continuing the Legacy of B-factories



CPV in neutral meson mixing and decays

CPV in neutral meson mixing and decays

- Focus on the neutral B meson system: flavour states

$$B^0 \sim \bar{b}d \qquad\qquad \bar{B}^0 \sim b\bar{d}.$$

$$CP|B^0\rangle = e^{i\xi_B}|\bar{B}^0\rangle\,,$$
$$CP|\bar{B}^0\rangle = e^{-i\xi_B}|B^0\rangle\,.$$

- Time evolution

$$|\psi(0)\rangle = a(0)|B^0\rangle + b(0)|\bar{B}^0\rangle$$
$$|\psi(t)\rangle = a(t)|B^0\rangle + b(t)|\bar{B}^0\rangle + c_1(t)|f_1\rangle + c_2(t)|f_2\rangle + \ldots\,,$$

B decay products

CPV in neutral meson mixing and decays

- If only interested $a(t)$, $b(t)$:

$$i\frac{d}{dt}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = H \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}, \qquad \mathcal{H} = M + i\frac{\Gamma}{2}$$

- M & Γ: time-independent, Hermitian 2×2 matrices,

- M-oscillations (dispersive); Γ-decays (absorptive)

CPV in neutral meson mixing and decays

- H eigenvectors

$$|B_{L,H}\rangle = p_{L,H}|B^0\rangle \pm q_{L,H}|\bar{B}^0\rangle$$

$$|p_{L,H}|^2 + |q_{L,H}|^2 = 1$$

CPV in neutral meson mixing and decays

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$$|p_{L,H}|^2 + |q_{L,H}|^2 = 1$$

- If CPT: $M_{11} = M_{22}$, $\Gamma_{11} = \Gamma_{22}$,

  $\Rightarrow p_L = p_H \equiv p,\ q_L = q_H \equiv q$

CPV in neutral meson mixing and decays

- H eigenvectors

$$|B_{L,H}\rangle = p_{L,H}|B^0\rangle \pm q_{L,H}|\bar{B}^0\rangle$$

$$|p_{L,H}|^2 + |q_{L,H}|^2 = 1$$

- If CPT: $M_{11} = M_{22}$, $\Gamma_{11} = \Gamma_{22}$,
  ⇒ $p_L = p_H \equiv p$, $q_L = q_H \equiv q$

- If CP: $\mathrm{Arg}(M_{12}) = \mathrm{Arg}(\Gamma_{12})$
  ⇒ $|q/p| = 1$

- Exercise: Check!

CPV in neutral meson mixing and decays

- CP conserving oscillation parameters:

$$m \equiv \frac{M_L + M_H}{2}\,, \qquad \Gamma \equiv \frac{\Gamma_L + \Gamma_H}{2}\,,$$

$$\Delta m \equiv M_H - M_L\,, \qquad \Delta\Gamma \equiv \Gamma_H - \Gamma_L\,,$$

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

- Time evolution:

  - at $t = 0$: $|B^0(t)\rangle \ \Rightarrow\ |B^0\rangle$

    $|\bar{B}^0(t)\rangle \ \Rightarrow\ |\bar{B}^0\rangle$

CPV in neutral meson mixing and decays

- Time evolution:

$$|B^0(t)\rangle = g_+(t)|B^0\rangle - \frac{q}{p} g_-(t)|\bar{B}^0\rangle \,,$$

$$|\bar{B}^0(t)\rangle = g_+(t)|\bar{B}^0\rangle - \frac{q}{p} g_-(t)|B^0\rangle \,,$$

$$g_\pm \equiv \frac{1}{2}\left(e^{-m_H t - \Gamma_H t/2} \pm e^{-m_L t - \Gamma_L t/2}\right)$$

- Decay to final state after time t:

$$\langle f|\mathcal{H}|B^0\rangle \equiv A_f \,,$$

$$\langle \bar{f}|\mathcal{H}|B^0\rangle \equiv A_{\bar{f}} \,.$$

CPV in neutral meson mixing and decays

- Decay to final state after time t:

$$\frac{d\Gamma(|B^0(0)\rangle) \to |f(t)\rangle}{dt} = \mathcal{N}_0 e^{-\Gamma t}|A_f|^2 \times \left\{ \frac{1+|\lambda_f|^2}{2}\cosh\frac{\Delta\Gamma\, t}{2} + \frac{1-|\lambda_f|^2}{2}\cos\Delta m\, t \right.$$
$$\left. + \mathrm{Re}\lambda_f \sinh\frac{\Delta\Gamma\, t}{2} - \mathrm{Im}\lambda_f \sin\Delta m\, t \right\},$$
$$\frac{d\Gamma(|\bar{B}^0(0)\rangle) \to |f(t)\rangle}{dt} = \mathcal{N}_0 e^{-\Gamma t}|\bar{A}_f|^2 \times \left\{ \frac{1+|\bar{\lambda}_f|^2}{2}\cosh\frac{\Delta\Gamma\, t}{2} + \frac{1-|\bar{\lambda}_f|^2}{2}\cos\Delta m\, t \right.$$
$$\left. + \mathrm{Re}\bar{\lambda}_f \sinh\frac{\Delta\Gamma\, t}{2} - \mathrm{Im}\bar{\lambda}_f \sin\Delta m\, t \right\},$$

- N_0 - flux norm., $\lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}, \ \bar{\lambda}_f \equiv \frac{p}{q}\frac{A_f}{\bar{A}_f} = \frac{1}{\lambda_f},$

CPV in neutral meson mixing and decays

- Terms proportional to $|A_f|^2, |\bar{A}_f|^2$ describe a decay without net oscillation.
- Terms proportional to $|\lambda_f|^2, |\bar{\lambda}_f|^2$ describe a decays following net oscillations.
- Terms proportional to $\sin(\Delta m t)$, $\sinh(\Delta\Gamma t/2)$ describe interference between the above two cases.
- CP violation in interference is possible only if $\mathrm{Im}(\lambda_f) \neq 0$.

CPV in neutral meson mixing and decays

- CP violation in neutral B meson decays to CP eigenstates

$$A_{f_{CP}}(t) \equiv \frac{\frac{d\Gamma}{dt}\left[\bar{B}^0(0) \to f_{CP}(t)\right] - \frac{d\Gamma}{dt}\left[B^0(0) \to f_{CP}(t)\right]}{\frac{d\Gamma}{dt}\left[\bar{B}^0(0) \to f_{CP}(t)\right] + \frac{d\Gamma}{dt}\left[B^0(0) \to f_{CP}(t)\right]}$$

- In the B (& B_s) system experimentally $\Delta\Gamma << \Delta$m $\Rightarrow |q/p| \approx 1$:

$$A_f(t) = S_f \sin(\Delta m\, t) - C_f \cos(\Delta m\, t)\,,$$

$$S_f \equiv \frac{2\,\mathrm{Im}(\lambda_f)}{1+|\lambda_f|^2}\,, \quad C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\,.$$

Phases in decay amplitudes

- $B \to f$: amplitude A_f

  $\Updownarrow$ CP conjugation $\Updownarrow$

- $\overline{B} \to \overline{f}$: amplitude $\overline{A}_{\overline{f}}$.

- complex parameters in L appear complex conjugated after CP $\Rightarrow$ opposite signs

  - CP odd *weak phases*

- on-shell intermediate states (even for real L) $\Rightarrow$ same signs (CP even) - *strong phases*

Phases in decay amplitudes

$$A_f = |a_1|e^{i(\delta_1+\phi_1)} + |a_2|e^{i(\delta_2+\phi_2)} + \dots ,$$
$$\bar{A}_{\bar{f}} = |a_1|e^{i(\delta_1-\phi_1)} + |a_2|e^{i(\delta_2-\phi_2)} + \dots ,$$

- $a_{1,2}$,... contributions to amplitude with different phases
- $\delta_{1,2}$... strong phases
- $\varphi_{1,2}$... weak phases

CPV in $B \to \psi K_S$

$$A_f = |a_f| e^{i(\delta_f + \phi_f)} \,, \qquad \lambda_f = \eta_f (q/p) \exp(-2i\phi_f)$$
$$\bar{A}_f = |a_f| e^{i(\delta_f - \phi_f)} \eta_f \,,$$

- In B_d system $|\Gamma_{12}| << |M_{12}|$, due to O($G_F^2$) long distance effects, suppressed by small CKM elements

$$\left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}} \simeq e^{2i\xi_B} \,,$$

$$\lambda_f \simeq \eta_f \exp[i(\xi_B - 2\phi_f)]$$

$$S_{f_{CP}} \simeq \eta_f \sin(\xi_B - 2\phi_f)$$

CPV in $B \to \psi K_S$

- In SM:

$$\xi_B = -\mathrm{Arg}(M_{12}) \simeq -\mathrm{Arg}[(V_{tb}^* V_{td})^2] = -\mathrm{Arg}\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)$$

$$-e^{-2i\phi_f} = \frac{\bar{A}^{(B)}_{\psi K_S}}{A^{(B)}_{\psi K_S}} = -\frac{V_{cb} V_{cs}^* \, a_T + \dots}{V_{cb}^* V_{cs} \, a_T + \dots} e^{i\xi_K} \simeq -\frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}} \frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*}$$

↑ $K - K$ oscillations forming K_S

CPV in $B \to \psi K_S$

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$$-e^{-2i\phi_f} = \frac{\bar{A}_{\psi K_S}^{(B)}}{A_{\psi K_S}^{(B)}} = -\frac{V_{cb} V_{cs}^* \, a_T + \ldots}{V_{cb}^* V_{cs} \, a_T + \ldots} e^{i\xi_K} \simeq -\frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}} \frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*}$$

↑ $K - K$ oscillations forming K_S

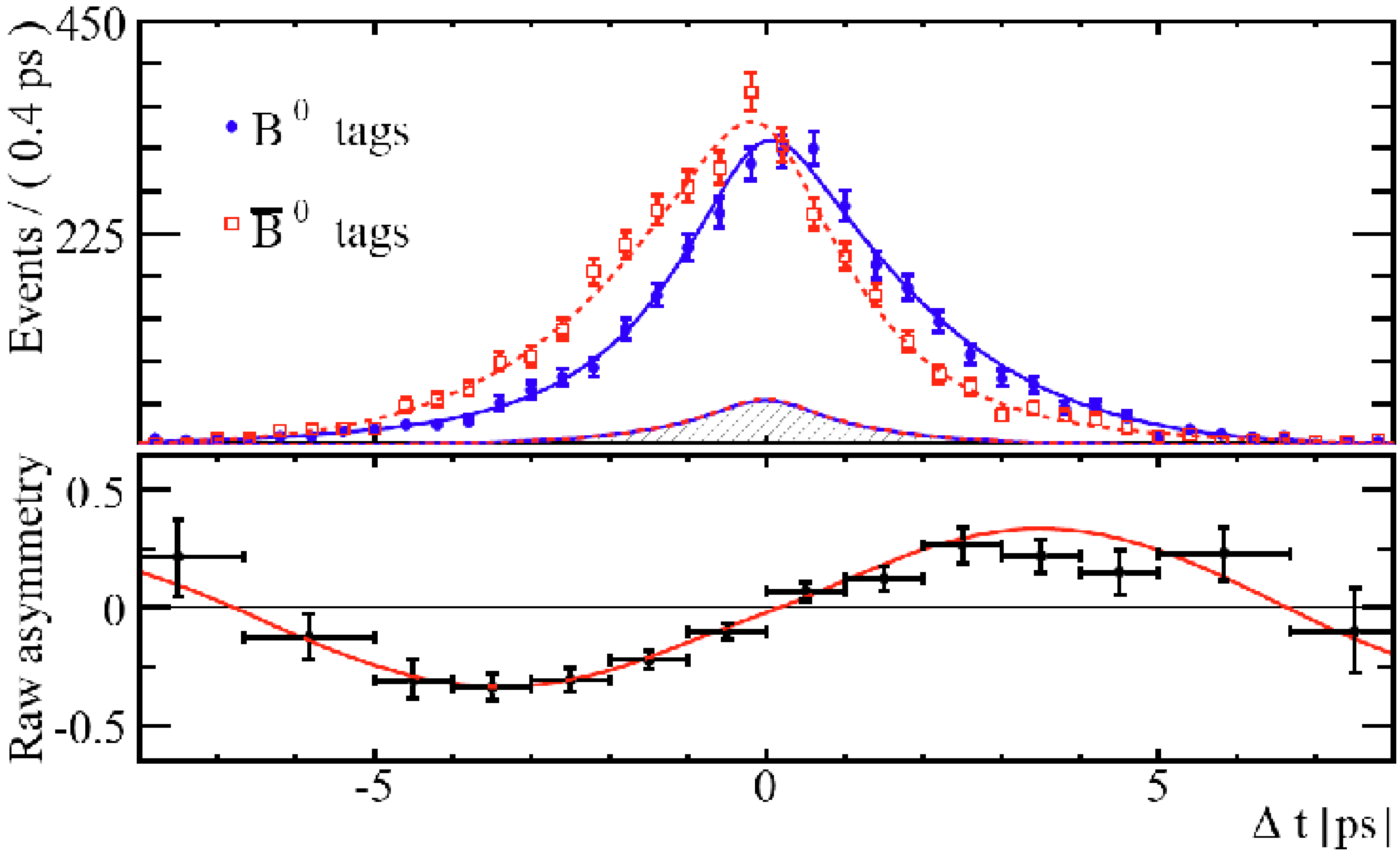
$$\lambda_{\psi K_S}^{(B)} \simeq \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \frac{V_{cb} V_{cd}^*}{V_{cb}^* V_{cd}} = -e^{-2i\beta}$$

CPV in interference

$$S_{\psi K_S}^{(B)} \simeq \sin 2\beta \text{ (note that } C_{\psi K_S}^{(B)} \simeq 0)$$

Experimentally measured to an accuracy of ~ 1%

CPV in $B \to \psi K_S$



Experimentally measured to an accuracy of ~ 1%

CPV in B_s mixing

- Golden channel: $B_s \to \psi\varphi$
  - angular analysis required
  - B_s oscillations much faster than those of B_d

$$\frac{\Delta m_s}{\Delta m_d} \sim \frac{|M_{12}^s|}{|M_{12}^d|} \propto \left|\frac{V_{ts}}{V_{td}}\right|^2 \sim 30\,.$$

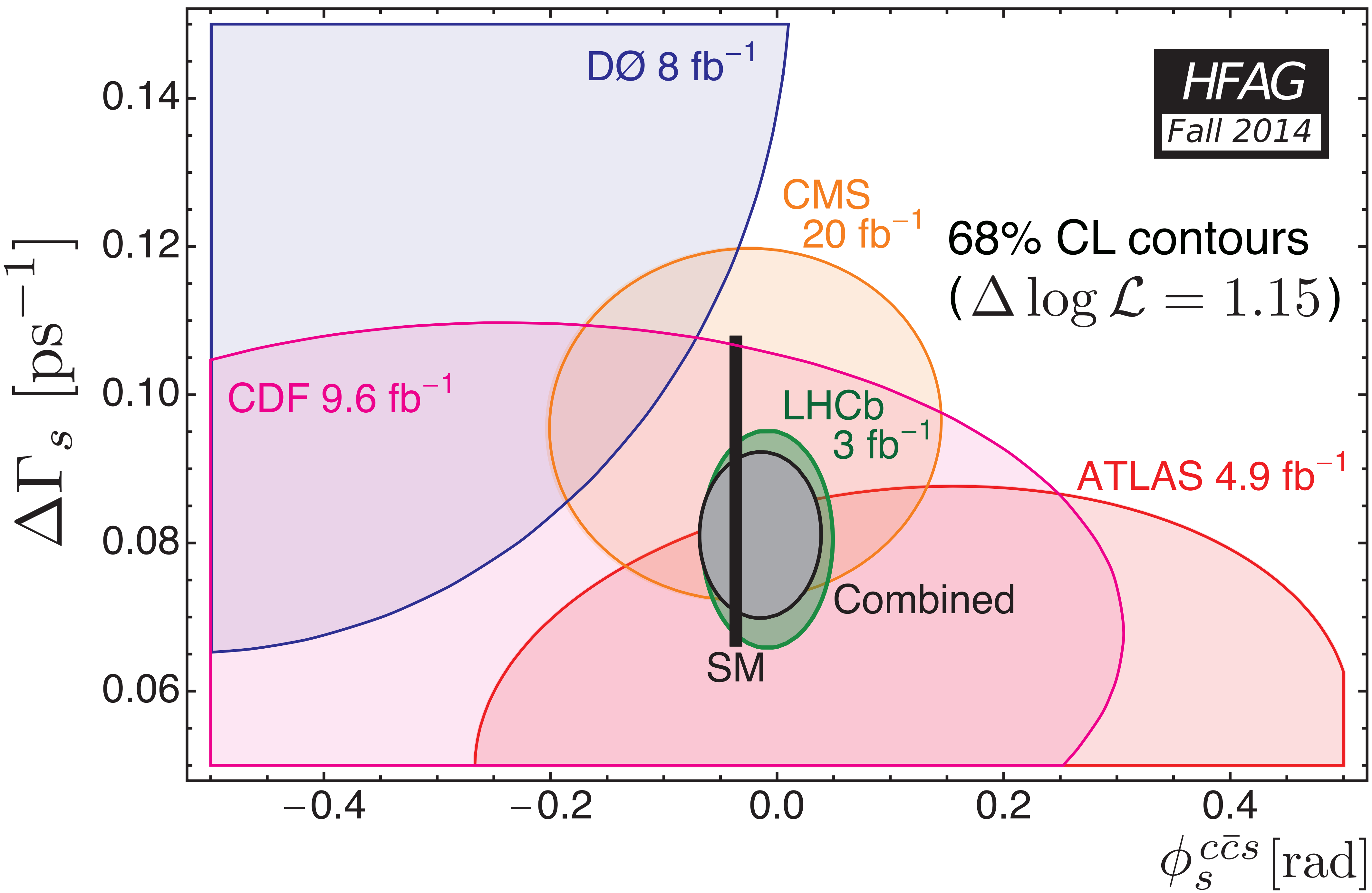
  - $\Delta\Gamma_s$ effects cannot be neglected

CPV in B_s mixing

- In SM: $\lambda_{\psi\phi}^{(B_s)} = -\exp[i(\xi_{B_s} - 2\phi_{\psi\phi})]$

$$\left[S_{\psi\phi}^{(B_s)}\right]_{\rm SM} = 2{\rm Arg}\frac{V_{tb}^* V_{ts}}{V_{cb}^* V_{cs}} = 0.036(1)\,,$$

CPV in B_s mixing



CPV in B_s mixing

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$$\left[S_{\psi\phi}^{(B_s)}\right]_{\rm SM} = 2{\rm Arg}\frac{V_{tb}^* V_{ts}}{V_{cb}^* V_{cs}} = 0.036(1)\,,$$

- Experimentally: $S_{\psi\phi}^{(B_s)} = 0.02(4)$

- Exercise: Show that if B $\to$ ππ is dominated by a single (tree) amplitude, then $S_{\pi\pi} = \sin(2\alpha)$

CP violation in *B* decays to CP conjugate states

- If $B_0 \to \overline{f}$ and $\overline{B}_0 \to f$ forbidden:

$$|A_f| = |\bar{A}_{\bar{f}}| \text{ and } |A_{\bar{f}}| = |\bar{A}_f| = 0$$

$$\frac{\frac{d\Gamma}{dt}\left[\bar{B}^0(0) \to f(t)\right] - \frac{d\Gamma}{dt}\left[B^0(0) \to \bar{f}(t)\right]}{\frac{d\Gamma}{dt}\left[\bar{B}^0(0) \to f(t)\right] + \frac{d\Gamma}{dt}\left[B^0(0) \to \bar{f}(t)\right]} = \frac{\left|\frac{p}{q}\right|^2 - \left|\frac{q}{p}\right|^2}{\left|\frac{p}{q}\right|^2 + \left|\frac{q}{p}\right|^2} \simeq \mathrm{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right) + \mathcal{O}\left(\left|\frac{\Gamma_{12}}{M_{12}}\right|^2\right)$$

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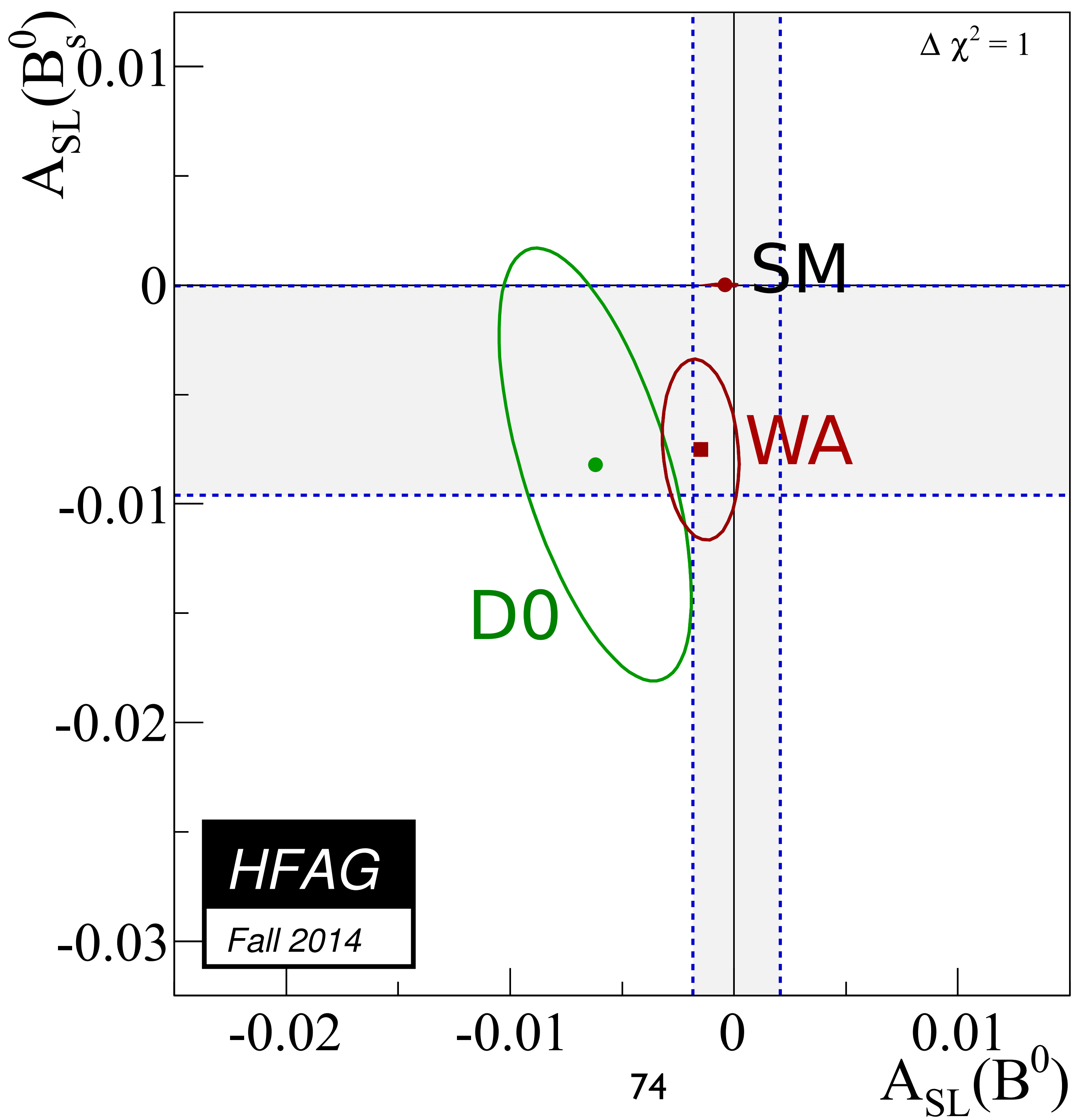
- Time-independent measurement
- *CP violation in mixing*, (*indirect CP violation*)
- Example: $a_{SL}^{(d)} = \dfrac{\Gamma(\bar{B}^0 \to X\ell^+\nu) - \Gamma(B^0 \to X\ell^-\bar{\nu})}{\Gamma(\bar{B}^0 \to X\ell^+\nu) + \Gamma(B^0 \to X\ell^-\bar{\nu})}$
  - In SM: $a_{SL}^{(d)} = -8(2) \times 10^{-4}$

CP violation in *B* decays to CP conjugate states



CP violation in charged *B* decays

- Interesting example: $B^{\pm} \to DK^{\pm}$

$$B^- \to D^0 K^- : \; b \to c\bar{u}s \,,$$
$$B^- \to \bar{D}^0 K^- : \; b \to \bar{c}us \,.$$

- Particularly transparent in D decays to CP eigenstates

$$D^0 \to f_{CP} : \; c \to d\bar{d}u \,, s\bar{s}u \,,$$
$$\bar{D}^0 \to f_{CP} : \; \bar{c} \to d\bar{d}\bar{u} \,, s\bar{s}\bar{u} \,.$$

CP violation in charged *B* decays

- In SM:

$$\frac{A^B_{(D\to f)K}}{A^B_{(\bar{D}\to f)K}} = \frac{V^*_{cb}V_{us}a^B_{DK}}{V^*_{ub}V_{cs}a^B_{\bar{D}K}} e^{i(\delta^B_{DK}-\delta^B_{\bar{D}K})}\eta_f \frac{V_{cd}V^*_{ud}}{V^*_{cd}V_{ud}}\frac{a^D_f}{a^{\bar{D}}_f} e^{i(\delta^D_f-\delta^{\bar{D}}_f)} \simeq \eta_f r_B e^{i(\delta_B-\gamma)}$$

  - $\gamma \equiv \mathrm{Arg}(-V_{ud}V^*_{ub}/V_{cd}V^*_{cb}) \simeq 70^\circ$

- Several decay rates: *CPV in decay (direct CPV)*

$$A(B^- \to f_+K^-) = A_0\left[1 + r_B e^{i(\delta_B-\gamma)}\right] ,$$

$$A(B^- \to f_-K^-) = A_0\left[1 - r_B e^{i(\delta_B-\gamma)}\right] ,$$

$$A(B^+ \to f_+K^+) = A_0\left[1 + r_B e^{i(\delta_B+\gamma)}\right] ,$$

$$A(B^+ \to f_-K^+) = A_0\left[1 - r_B e^{i(\delta_B+\gamma)}\right] .$$

Flavour & New Physics

Flavour & New Physics

- How much can NP still contribute to flavour observables?
- <u>Example</u>:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.0008(7)\,.$$

  - $|V_{ud}|$ extracted from $0^+ \to 0^+ e\nu$ super-allowed nuclear β decays
  - $|V_{us}|$ from semileptonic kaon decays $K^+ \to \pi^+ l\nu$
  - $|V_{ub}|$ measured using charmless semileptonic B decays $B \to X_u l\nu$

Flavour & New Physics

- Consider NP contributions to observables which are (loop, CKM) suppressed in SM
- Can use CKM determination from tree-level observables:
  - $|V_{ud}|$, $|V_{us}|$, $|V_{cb}|$ and $|V_{ub}|$ as well as γ from $B \to DK$ decays

⇒ allows to predict SM contributions also to loop suppressed observables!

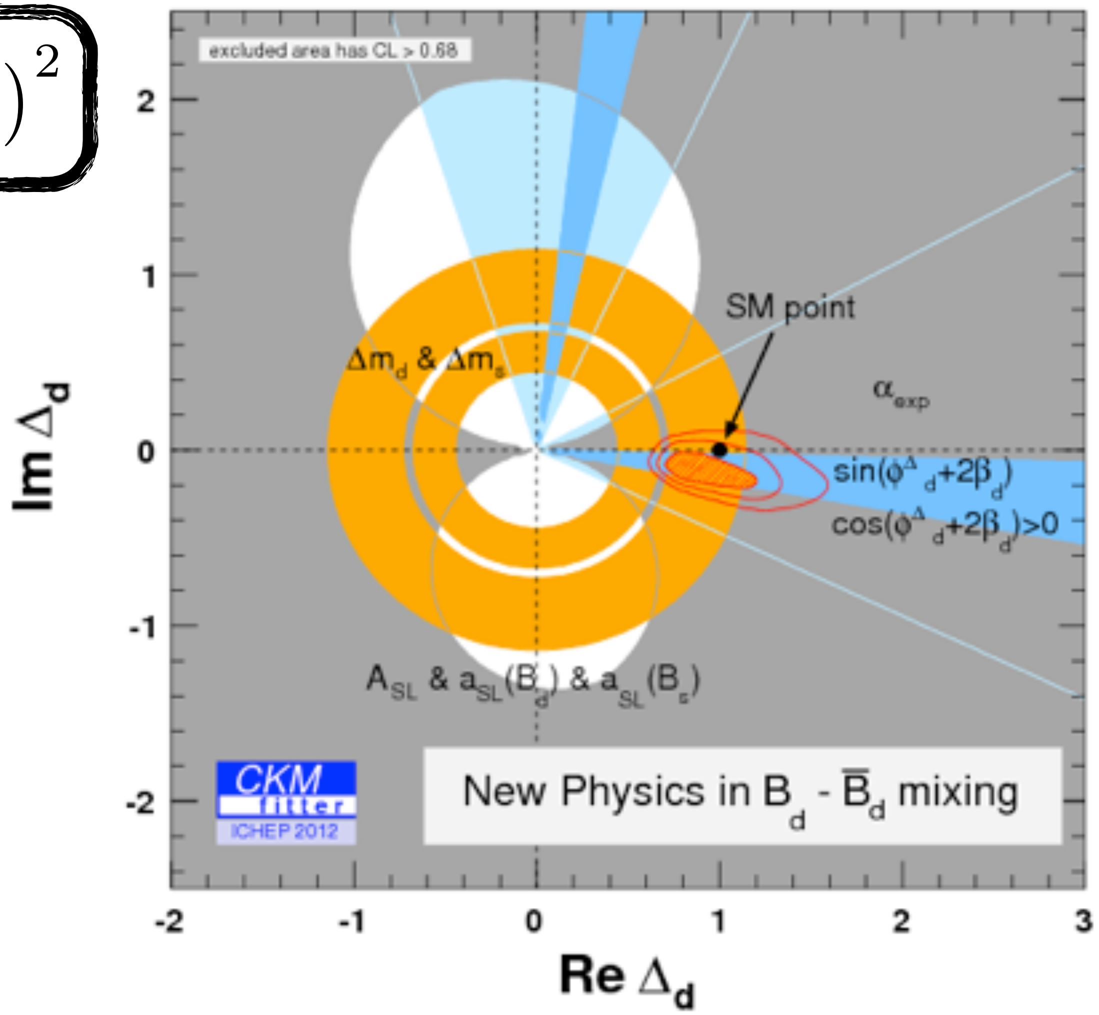
NP in B mixing

$$M_{12} = M_{12}^{\rm SM}\Delta_d\,, \quad \Delta_d = \left(r_d e^{i\theta_d}\right)^2$$

$$\Delta m_d = r_d^2 (\Delta m_d)^{\rm SM}$$

$$S_{\psi K_S}^{(B)} = \sin(2\beta + 2\theta_d)$$

$$a_{SL}^{(d)} = \Re\left(\frac{\Gamma_{12}}{M_{12}}\right)^{\rm SM} \frac{\sin\theta_d}{r_d^2} + \Im\left(\frac{\Gamma_{12}}{M_{12}}\right)^{\rm SM} \frac{\cos 2\theta_d}{r_d^2}$$



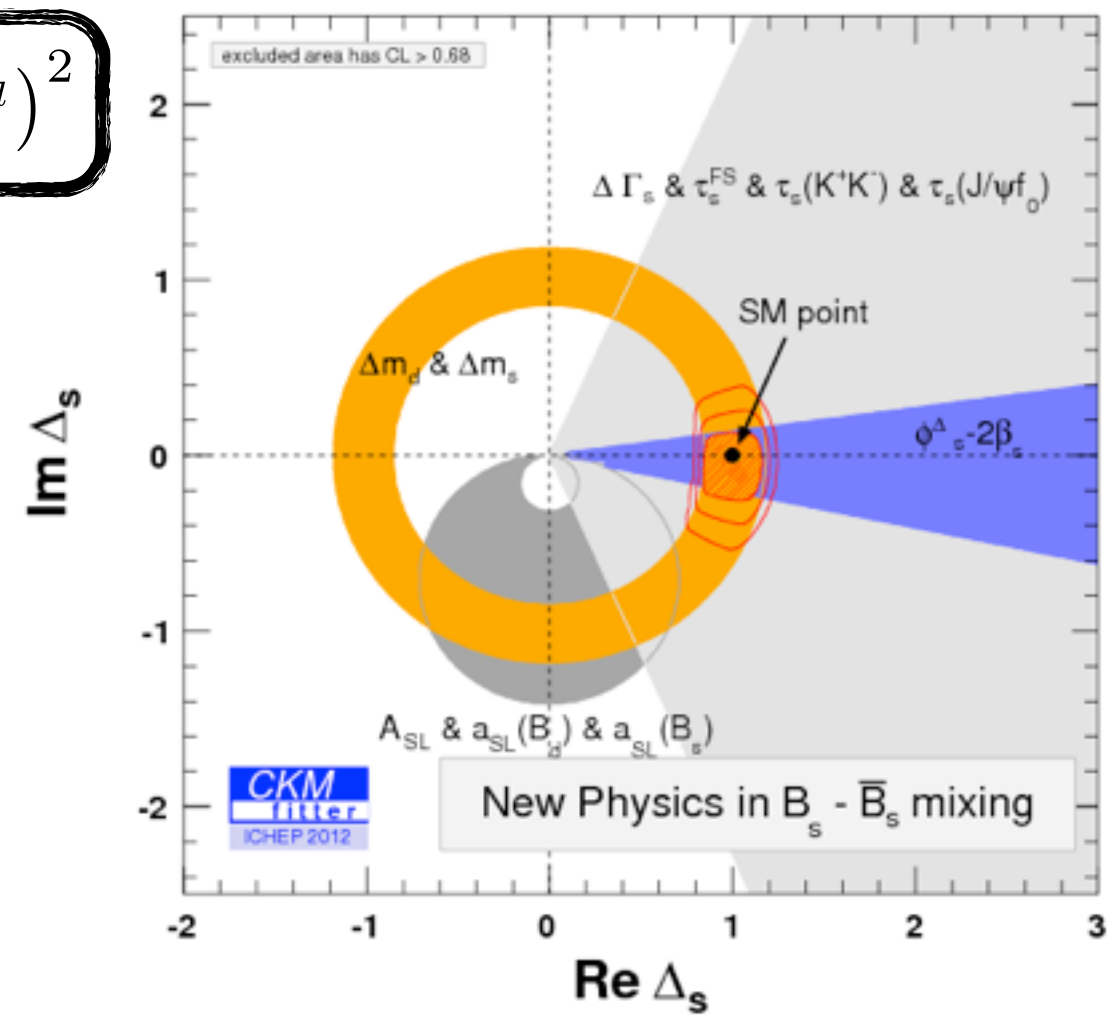
NP in B mixing

$$M_{12} = M_{12}^{\rm SM}\Delta_d\,, \quad \Delta_d = \left(r_d e^{i\theta_d}\right)^2$$

$$\Delta m_s = r_s^2 (\Delta m_s)^{\rm SM}$$

$$S_{\psi\phi}^{(B_s)} = \sin(2\beta_s + 2\theta_s)$$

$$a_{SL}^{(s)} = \Re\left(\frac{\Gamma_{12}}{M_{12}}\right)^{\rm SM}\frac{\sin\theta_s}{r_s^2} + \Im\left(\frac{\Gamma_{12}}{M_{12}}\right)^{\rm SM}\frac{\cos 2\theta_s}{r_s^2}$$



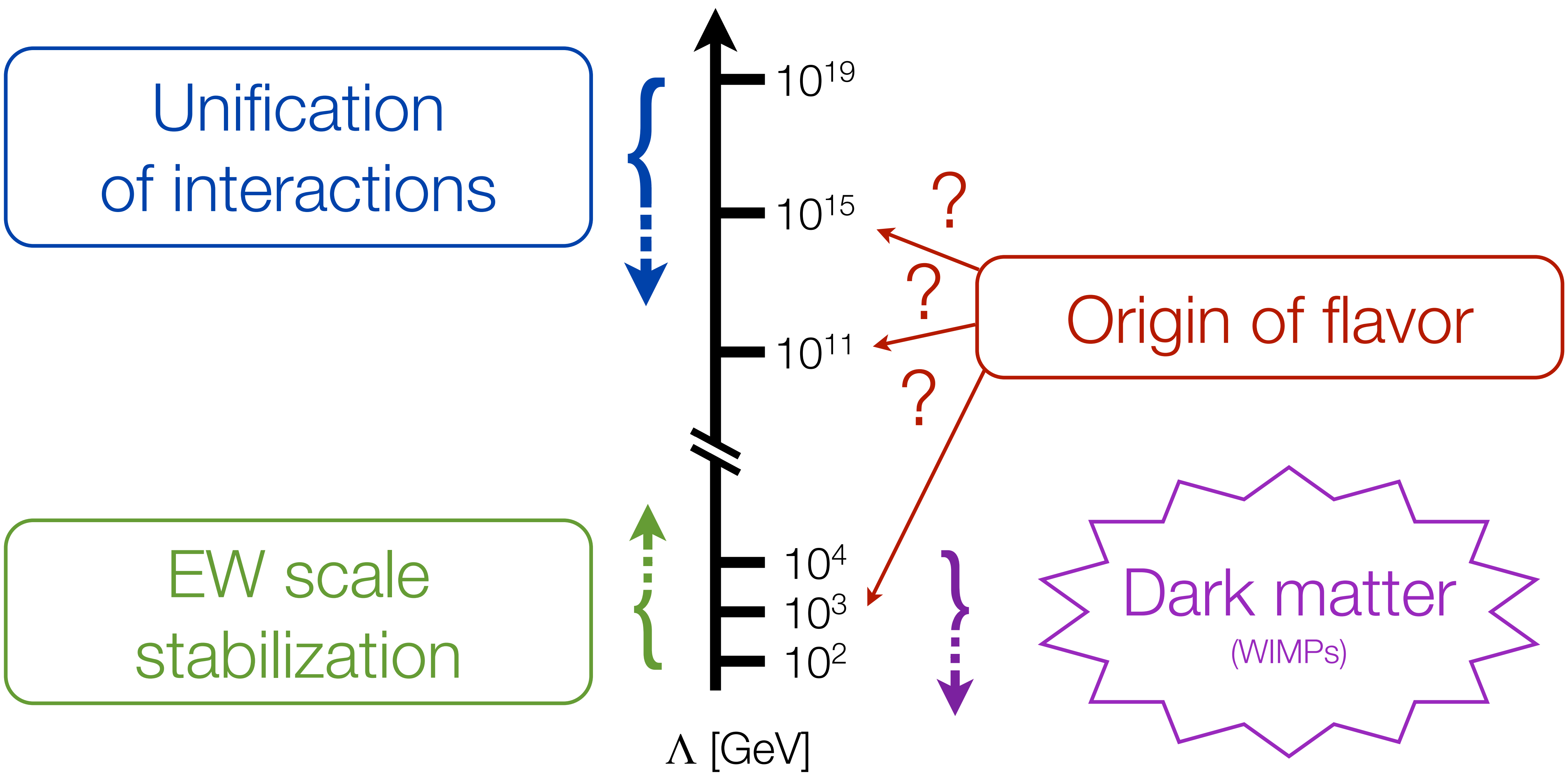
The NP flavour puzzle

SM is not a complete theory of Nature

- (quantum) description of gravity $< 10^{19}$ GeV
- neutrino masses $< 10^{15}$ GeV
- EW fine-tuning suggests NP @ $4\pi v \sim 1$ TeV

The NP flavour puzzle

SM is not a complete theory of Nature



The NP flavour puzzle

SM as effective field theory

- valid below cut-off scale Λ

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_{d>4} \sum_n \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}_n^{(d)} \,.$$

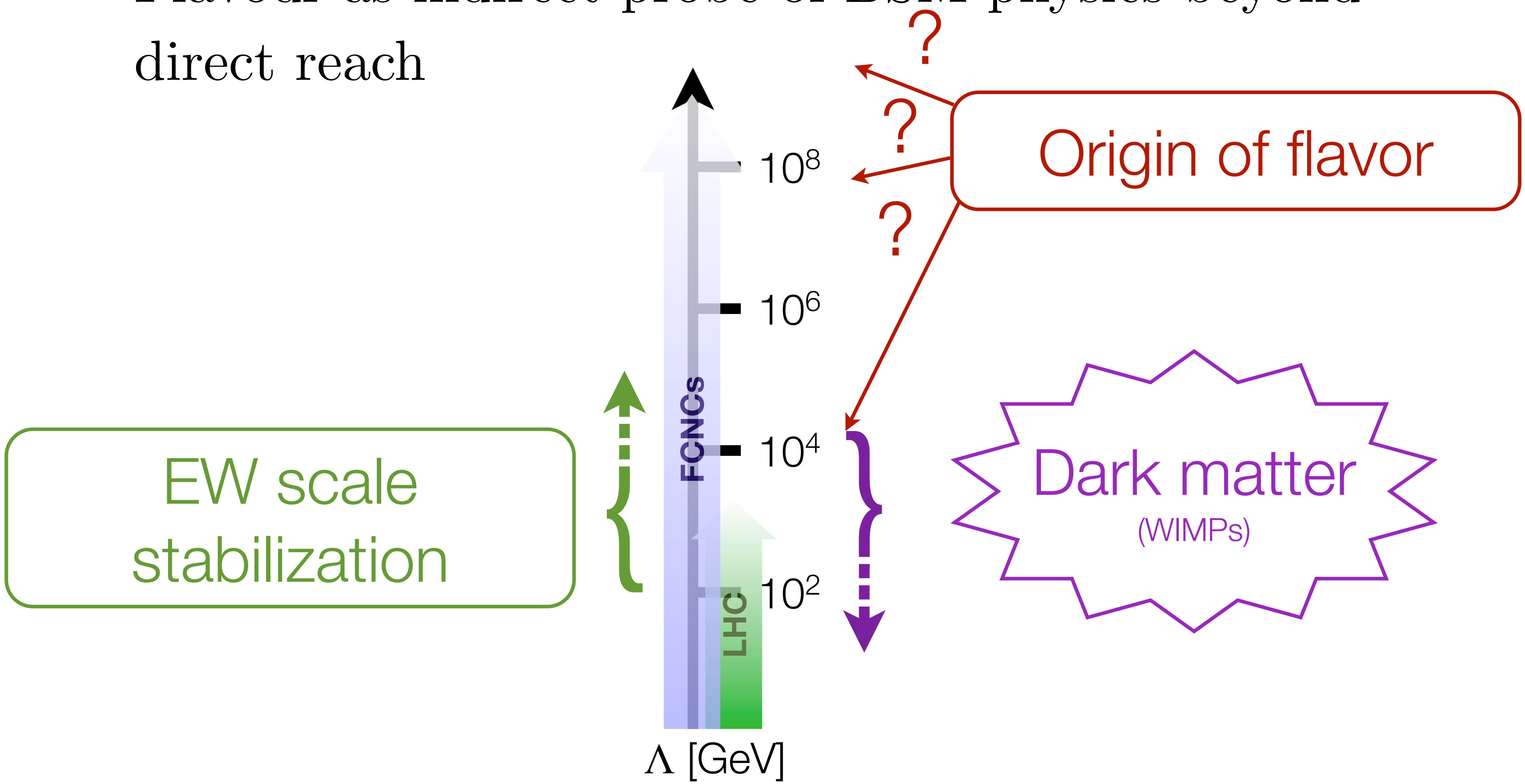
- for natural theory: $c_n^{(d)} \sim \mathcal{O}(1)$

- NP flavour puzzle:
  If there is NP at the TeV scale, why haven't we seen its effects in flavour observables?

The NP flavour puzzle

SM as effective field theory

- Flavour as indirect probe of BSM physics beyond direct reach



(Over)constraining the SM flavor sector

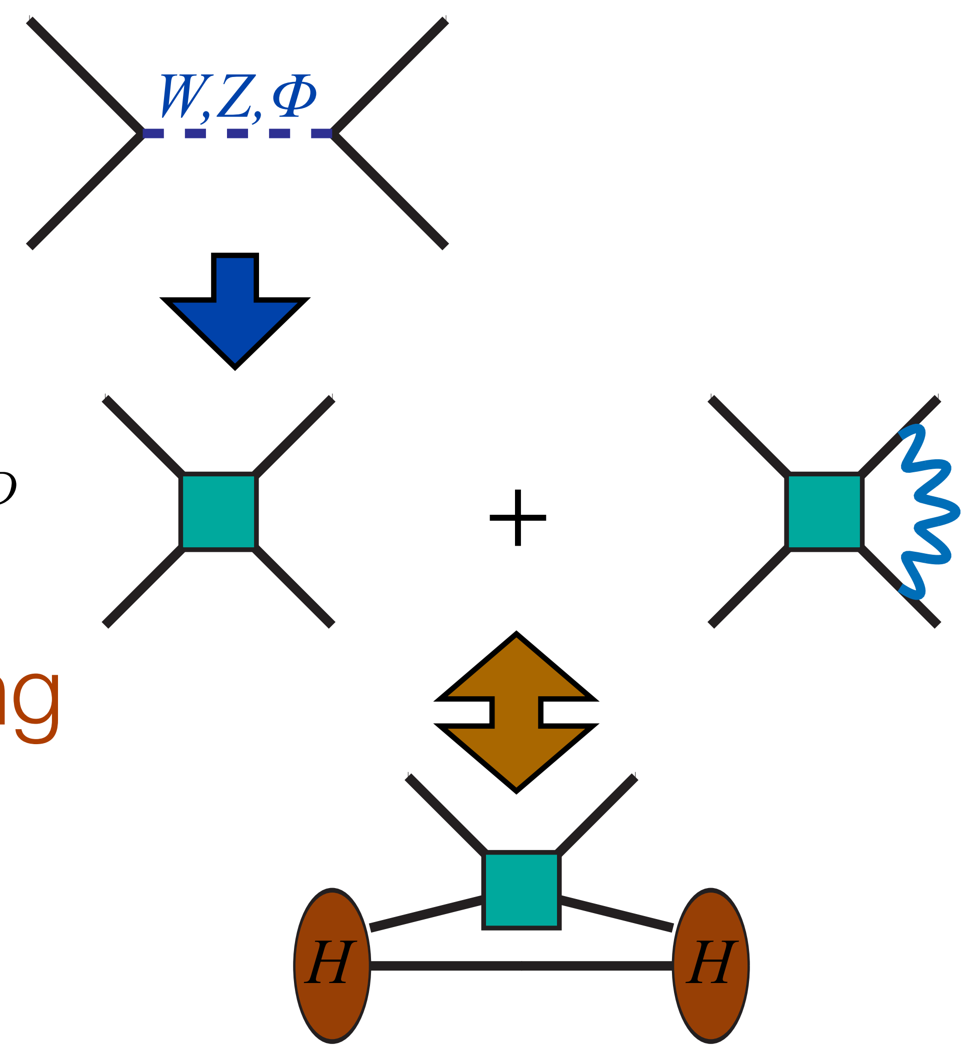
$\mathcal{L}_{\rm SM}$

$\Lambda_{\rm weak}$ [~100 GeV] — Weak scale operators

$\mathcal{L}^{\rm eff}_{\rm weak}(\sim G_F \sum_i c_i \mathcal{Q}_i) + \mathcal{L}_{QCD+QED}$

Non-perturbative matching
(or quark-hadron duality)

Λ_H [~GeV] — $\mathcal{L}^{\rm eff}(\pi, N, K, D, B, \ldots)$



(Over)constraining the SM flavor sector & NP

$\Lambda_{\rm NP}$ — $\mathcal{L}_{\rm BSM}$ — BSM dynamics

$$\mathcal{L}_{\rm SM} + \sum_{d>4} \frac{\mathcal{Q}_i^{(d)}}{\Lambda^{d-4}}$$

$\Lambda_{\rm weak}$ [~100 GeV] — Weak scale operators

$$\mathcal{L}^{\rm eff}_{\rm weak}(\sim G_F \sum_i c_i \mathcal{Q}_i) + \mathcal{L}_{QCD+QED}$$

Non-perturbative matching

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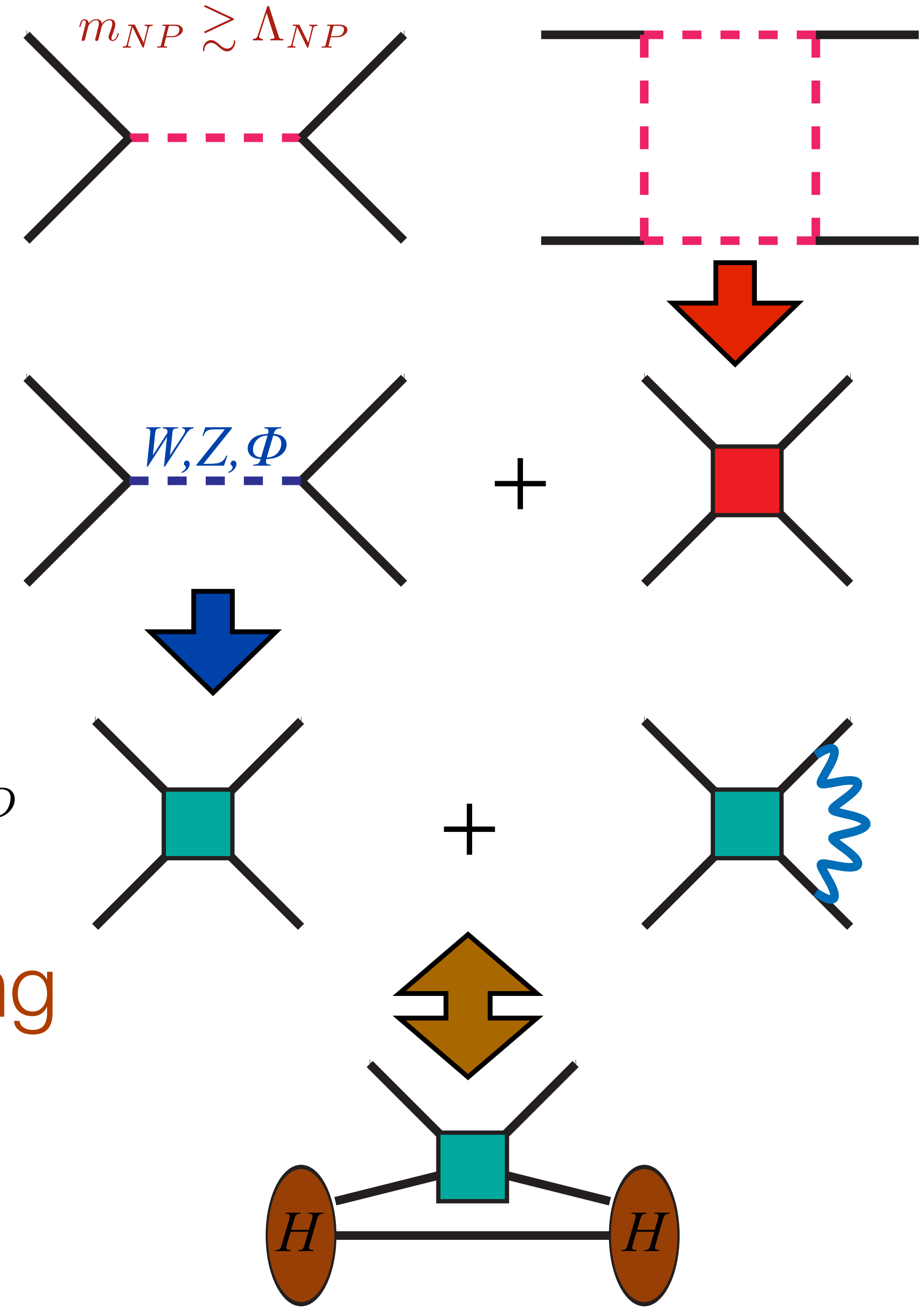


NP in ΔF=2

- In SM:($M = K^0,\ B^0,\ B_s$)

$$M_{12}^{\mathrm{SM}} = \underbrace{\frac{G_F^2 m_t^2}{16\pi^2}\,(V_{ti}^* V_{tj})^2}_{\frac{(Y_u Y_u^*)_{ij}^2}{128\pi^2 m_t^2}}\,\langle \bar{M}|(\bar{d}_L^i \gamma_\mu d_L^j)^2|M\rangle F\left(\frac{m_t^2}{m_W^2}\right) + \ldots\,,$$

$$F(x) \sim \mathcal{O}(1)$$

$$F(\infty) = 1$$

NP in Δ*F*=2

- In SM:$(M = K^0,\ B^0,\ B_s\ )$

$$M_{12}^{\rm SM} = \underbrace{\frac{G_F^2 m_t^2}{16\pi^2}\,(V_{ti}^* V_{tj})^2}_{\frac{(Y_u Y_u^*)_{ij}^2}{128\pi^2 m_t^2}} \langle \bar{M}|(\bar{d}_L^i \gamma_\mu d_L^j)^2|M\rangle F\left(\frac{m_t^2}{m_W^2}\right) + \dots\,,$$

$$F(x) \sim \mathcal{O}(1)$$
$$F(\infty) = 1$$

- Hadronic matrix elements:

$$\langle \bar{M}|(\bar{d}_L^i \gamma_\mu d_L^j)(\bar{d}_L^i \gamma^\mu d_L^j)|M\rangle = \frac{2}{3} f_M^2 m_M^2 \hat{B}_M \quad \hat{B}_M \sim \mathcal{O}(1)$$

$$\langle 0|d^i \gamma_\mu \gamma_5 d^j|M(p)\rangle \equiv i p_\mu f_M$$

- tremendous progress in past 30 yrs - Lattice QCD

NP in ΔF=2

$$\mathcal{L}_{\Delta F=2} = \frac{z_{sd}}{\Lambda_{\text{NP}}^2}(\overline{d_L}\gamma_\mu s_L)^2 + \frac{z_{cu}}{\Lambda_{\text{NP}}^2}(\overline{c_L}\gamma_\mu u_L)^2 + \frac{z_{bd}}{\Lambda_{\text{NP}}^2}(\overline{d_L}\gamma_\mu b_L)^2 + \frac{z_{bs}}{\Lambda_{\text{NP}}^2}(\overline{s_L}\gamma_\mu b_L)^2.$$

NP in Δ*F*=2

$$\mathcal{L}_{\Delta F=2} = \frac{z_{sd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu s_L)^2 + \frac{z_{cu}}{\Lambda_{\rm NP}^2}(\overline{c_L}\gamma_\mu u_L)^2 + \frac{z_{bd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu b_L)^2 + \frac{z_{bs}}{\Lambda_{\rm NP}^2}(\overline{s_L}\gamma_\mu b_L)^2.$$

CPC NP

$$\begin{aligned} \Delta m_K/m_K &\sim 7.0\times10^{-15}, \\ \Delta m_D/m_D &\sim 8.7\times10^{-15}, \\ \Delta m_B/m_B &\sim 6.3\times10^{-14}, \\ \Delta m_{B_s}/m_{B_s} &\sim 2.1\times10^{-12}, \end{aligned} \quad \Rightarrow \Lambda_{\rm NP} \gtrsim \begin{cases} \sqrt{z_{sd}}\ 1\times10^3\ \text{TeV} & \Delta m_K \\ \sqrt{z_{cu}}\ 1\times10^3\ \text{TeV} & \Delta m_D \\ \sqrt{z_{bd}}\ 4\times10^2\ \text{TeV} & \Delta m_B \\ \sqrt{z_{bs}}\ 7\times10^1\ \text{TeV} & \Delta m_{B_s} \end{cases}$$

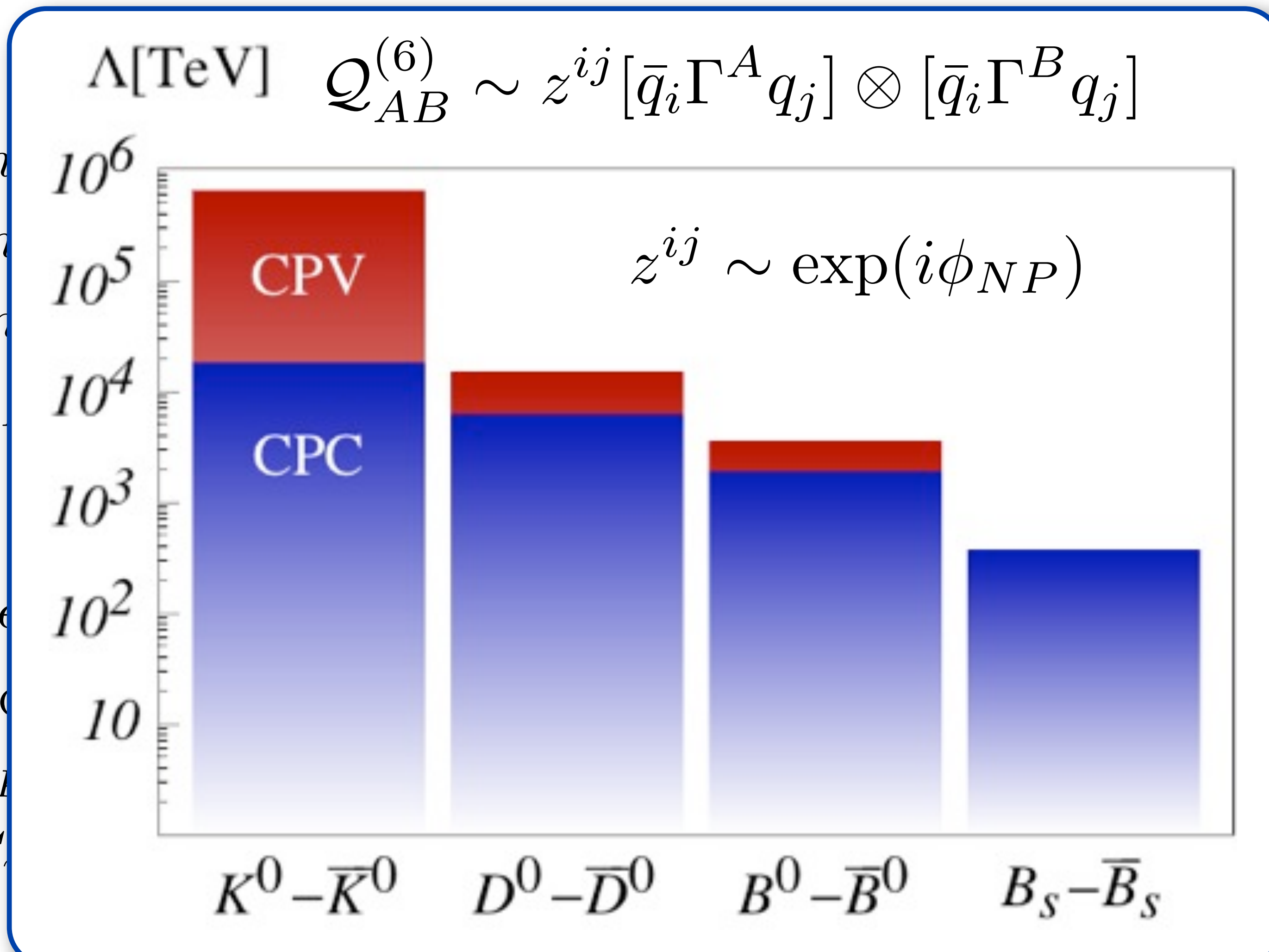
CPV NP

$$\begin{aligned} \epsilon_K &\sim 2.3\times10^{-3}, \\ A_\Gamma/y_{\rm CP} &\lesssim 0.2, \\ S_{\psi K_S} &= 0.67\pm0.02, \\ S_{\psi\phi} &\lesssim 1. \end{aligned} \quad \Rightarrow \Lambda_{\rm NP} \gtrsim \begin{cases} \sqrt{z_{sd}}\ 2\times10^4\ \text{TeV} & \epsilon_K \\ \sqrt{z_{cu}}\ 3\times10^3\ \text{TeV} & A_\Gamma \\ \sqrt{z_{bd}}\ 8\times10^2\ \text{TeV} & S_{\psi K} \\ \sqrt{z_{bs}}\ 7\times10^1\ \text{TeV} & S_{\psi\phi} \end{cases}$$

NP with a generic flavour structure is irrelevant for EW hierarchy

NP in ΔF=2

$$\mathcal{L}_{\Delta F=2} = \frac{z_{sd}}{\Lambda^2_{\rm NP}}(\overline{d_L}\gamma_\mu s_L)^2 + \frac{z_{cu}}{\Lambda^2_{\rm NP}}(\overline{c_L}\gamma_\mu u_L)^2 + \frac{z_{bd}}{\Lambda^2_{\rm NP}}(\overline{d_L}\gamma_\mu b_L)^2 + \frac{z_{bs}}{\Lambda^2_{\rm NP}}(\overline{s_L}\gamma_\mu b_L)^2.$$



$\Delta m_K/m$ ... Δm_K

$\Delta m_D/m$ ... Δm_D

$\Delta m_B/m$ ... Δm_B

$\Delta m_{B_s}/m$ ... Δm_{B_s}

... ϵ_K

A_Γ/y ... A_Γ

S_{ψ} ... $S_{\psi K}$

S ... $S_{\psi\phi}$

NP with a generic flavour structure is irrelevant for EW hierarchy

NP in ΔF=2

$$\mathcal{L}_{\Delta F=2} = \frac{z_{sd}}{\Lambda^2_{\rm NP}}(\overline{d_L}\gamma_\mu s_L)^2 + \frac{z_{cu}}{\Lambda^2_{\rm NP}}(\overline{c_L}\gamma_\mu u_L)^2 + \frac{z_{bd}}{\Lambda^2_{\rm NP}}(\overline{d_L}\gamma_\mu b_L)^2 + \frac{z_{bs}}{\Lambda^2_{\rm NP}}(\overline{s_L}\gamma_\mu b_L)^2.$$

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CPV NP

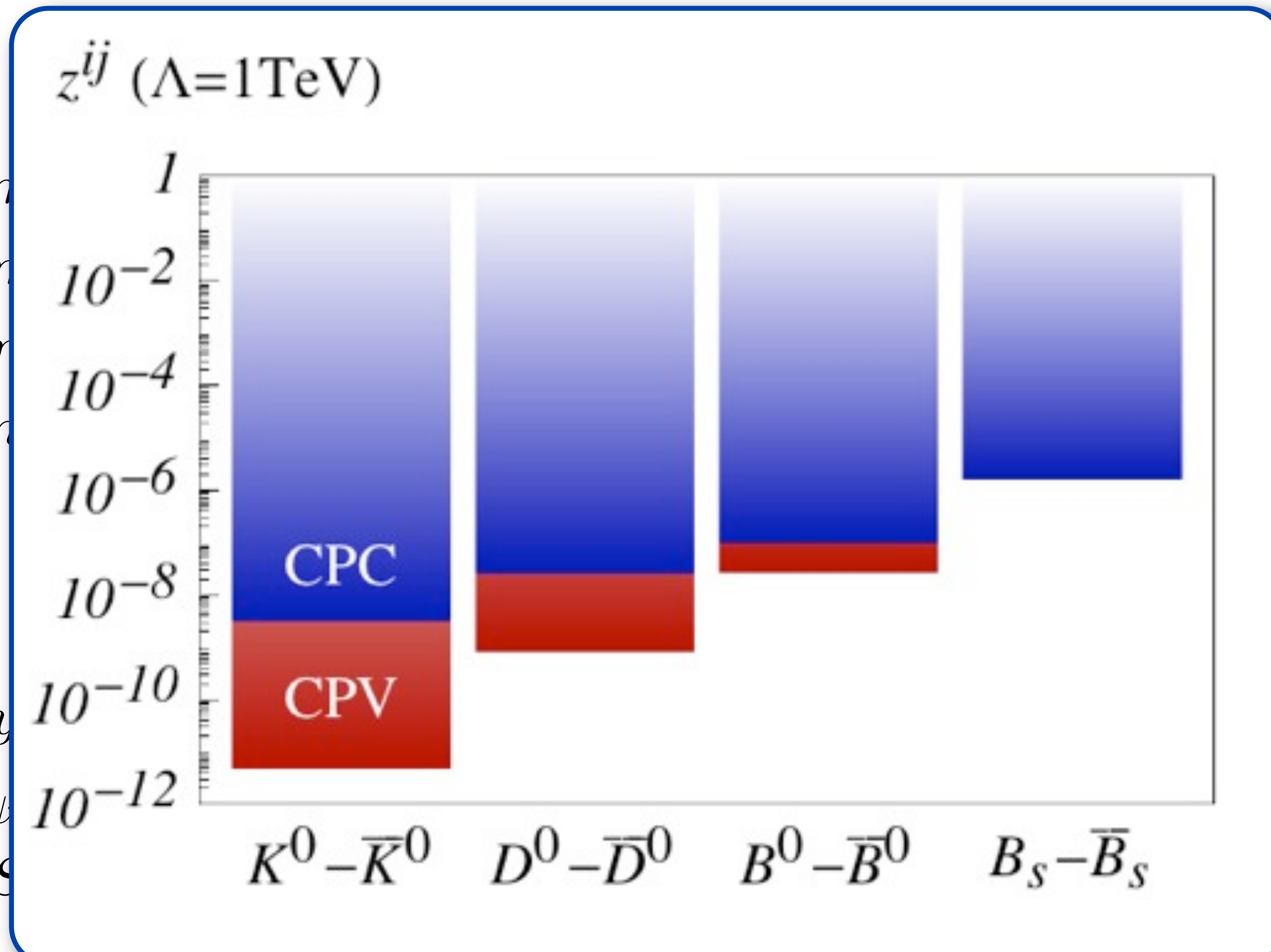
$$\begin{aligned} \epsilon_K &\sim 2.3\times 10^{-3}, \\ A_\Gamma/y_{\rm CP} &\lesssim 0.2, \\ S_{\psi K_S} &= 0.67\pm 0.02, \\ S_{\psi\phi} &\lesssim 1. \end{aligned} \quad \Rightarrow \quad \begin{aligned} z^I_{sd} &\lesssim 6\times 10^{-9}\,(\Lambda_{\rm NP}/{\rm TeV})^2, \\ z^I_{cu} &\lesssim 1\times 10^{-7}\,(\Lambda_{\rm NP}/{\rm TeV})^2, \\ z^I_{bd} &\lesssim 1\times 10^{-6}\,(\Lambda_{\rm NP}/{\rm TeV})^2, \\ z^I_{bs} &\lesssim 2\times 10^{-4}\,(\Lambda_{\rm NP}/{\rm TeV})^2. \end{aligned}$$

in case of TeV NP, flavour structure needs to be far from generic

NP in Δ*F*=2

$$\mathcal{L}_{\Delta F=2} = \frac{z_{sd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu s_L)^2 + \frac{z_{cu}}{\Lambda_{\rm NP}^2}(\overline{c_L}\gamma_\mu u_L)^2 + \frac{z_{bd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu b_L)^2 + \frac{z_{bs}}{\Lambda_{\rm NP}^2}(\overline{s_L}\gamma_\mu b_L)^2.$$

$\Delta m_K/m$ … TeV$)^2$,
$\Delta m_D/m$ … TeV$)^2$,
$\Delta m_B/m$ … TeV$)^2$,
$\Delta m_{B_s}/m$ … TeV$)^2$,
… eV$)^2$,
A_Γ/y … eV$)^2$,
S_ψ … eV$)^2$,
S … eV$)^2$.



in case of TeV NP, flavour structure needs to be far from generic

NP in ΔF=2

$$\mathcal{L}_{\Delta F=2} = \frac{z_{sd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu s_L)^2 + \frac{z_{cu}}{\Lambda_{\rm NP}^2}(\overline{c_L}\gamma_\mu u_L)^2 + \frac{z_{bd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu b_L)^2 + \frac{z_{bs}}{\Lambda_{\rm NP}^2}(\overline{s_L}\gamma_\mu b_L)^2.$$

SM ($\Lambda_{\rm SM}\approx v$)

$$\Im(z_{sd}^{\rm SM}) \sim \frac{\lambda_t^2}{64\pi^2}|V_{td}V_{ts}^*|^2 \sim 10^{-10}$$

$$\Re(z_{sd}^{\rm SM}) \sim \frac{\lambda_c^2}{64\pi^2}|V_{cd}V_{cs}^*|^2 \sim 5\times 10^{-9}$$

$$|z_{bd}^{\rm SM}| \sim \frac{\lambda_t^2}{64\pi^2}|V_{td}V_{tb}^*|^2 \sim 9\times 10^{-8}$$

$$|z_{bs}^{\rm SM}| \sim \frac{\lambda_t^2}{64\pi^2}|V_{ts}V_{tb}^*|^2 \sim 3\times 10^{-6}$$

$$\begin{aligned} z_{sd} &\lesssim 8\times 10^{-7}\,(\Lambda_{\rm NP}/{\rm TeV})^2, \\ z_{cu} &\lesssim 5\times 10^{-7}\,(\Lambda_{\rm NP}/{\rm TeV})^2, \\ z_{bd} &\lesssim 5\times 10^{-6}\,(\Lambda_{\rm NP}/{\rm TeV})^2, \\ z_{bs} &\lesssim 2\times 10^{-4}\,(\Lambda_{\rm NP}/{\rm TeV})^2, \end{aligned}$$

$$\begin{aligned} z_{sd}^I &\lesssim 6\times 10^{-9}\,(\Lambda_{\rm NP}/{\rm TeV})^2, \\ z_{cu}^I &\lesssim 1\times 10^{-7}\,(\Lambda_{\rm NP}/{\rm TeV})^2, \\ z_{bd}^I &\lesssim 1\times 10^{-6}\,(\Lambda_{\rm NP}/{\rm TeV})^2, \\ z_{bs}^I &\lesssim 2\times 10^{-4}\,(\Lambda_{\rm NP}/{\rm TeV})^2. \end{aligned}$$

NP in Δ*F*=1

$$\mathcal{L}_{\Delta F=1} = y_{sd}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{d}_L \not{Z} s_L + y_{cu}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{u}_L \not{Z} c_L + y_{bd}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{d}_L \not{Z} b_L + y_{bs}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{s}_L \not{Z} b_L$$

SM ($\Lambda_{\rm SM} \approx v$)

$$|y_{sd}^{\rm SM}| \sim \frac{\lambda_t^2}{64\pi^2}|V_{td}V_{ts}^*| \sim 5\times 10^{-7}$$

$$|y_{bd}^{\rm SM}| \sim \frac{\lambda_t^2}{64\pi^2}|V_{td}V_{tb}^*| \sim 10^{-5}$$

$$|y_{bs}^{\rm SM}| \sim \frac{\lambda_t^2}{64\pi^2}|V_{ts}V_{tb}^*| \sim 6\times 10^{-5}$$

$$\Rightarrow$$

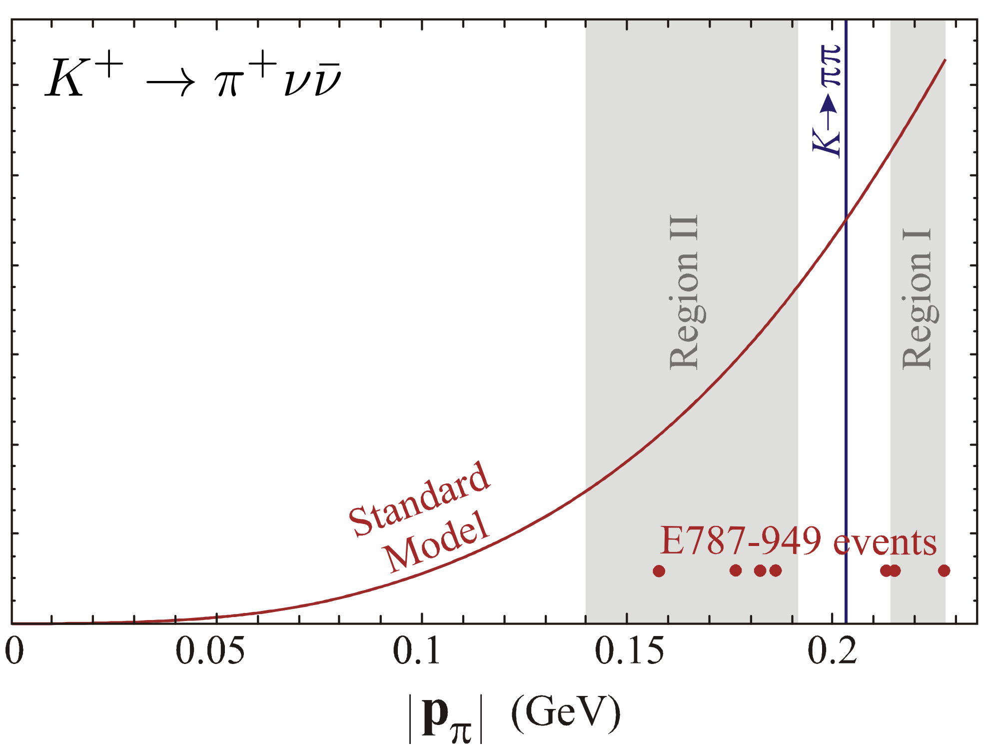
$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) \sim 8\times 10^{-11}\,,$$

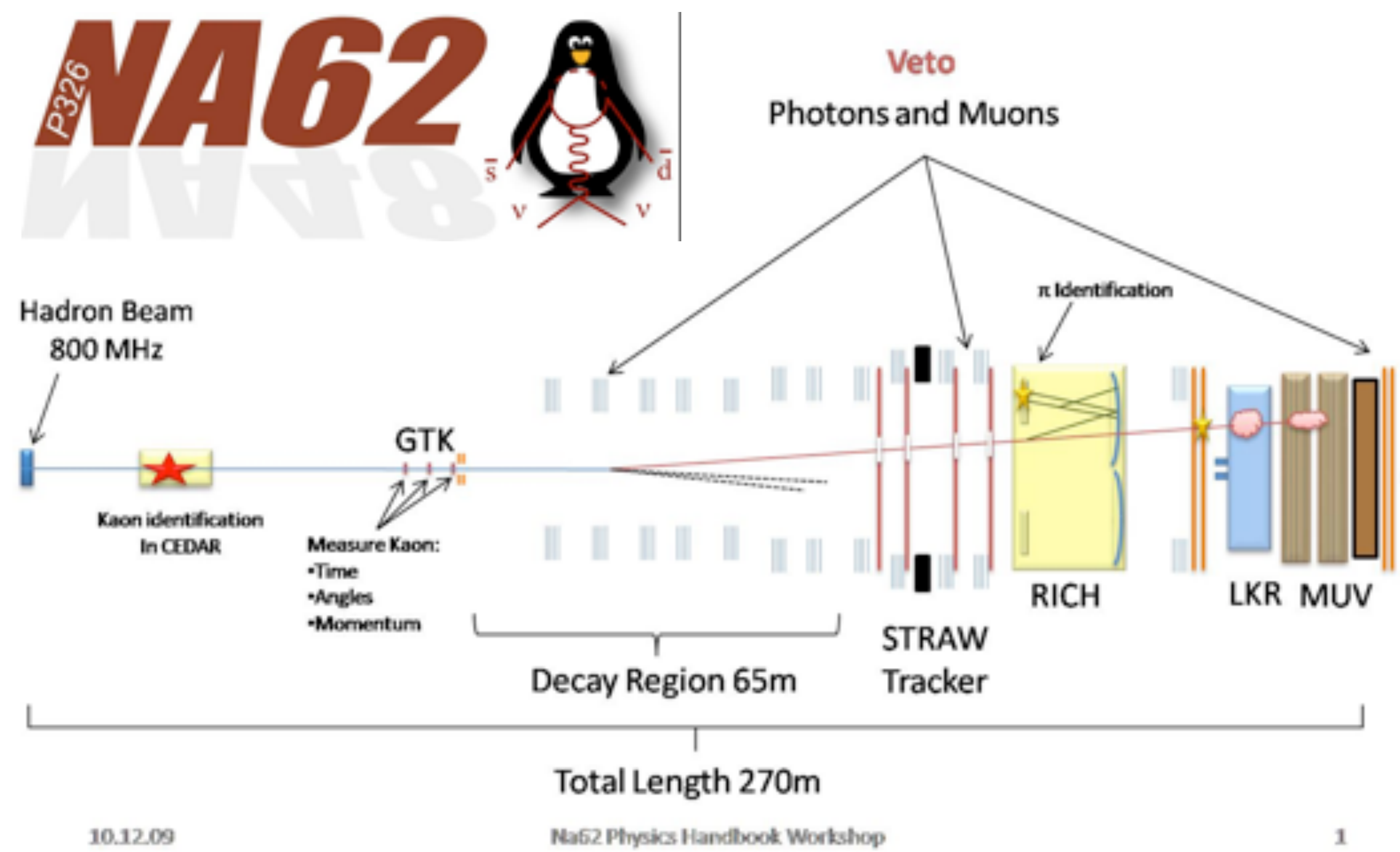
$$\mathcal{B}(B_d \to \mu^+\mu^-) \sim 10^{-10}\,,$$

$$\mathcal{B}(B_s \to \mu^+\mu^-) \sim 4\times 10^{-9}\,.$$

NP in ΔF=1

$$\mathcal{L}_{\Delta F=1} = y_{sd}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{d}_L \not{Z} s_L + y_{cu}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{u}_L \not{Z} c_L + y_{bd}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{d}_L \not{Z} b_L + y_{bs}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{s}_L \not{Z} b_L$$



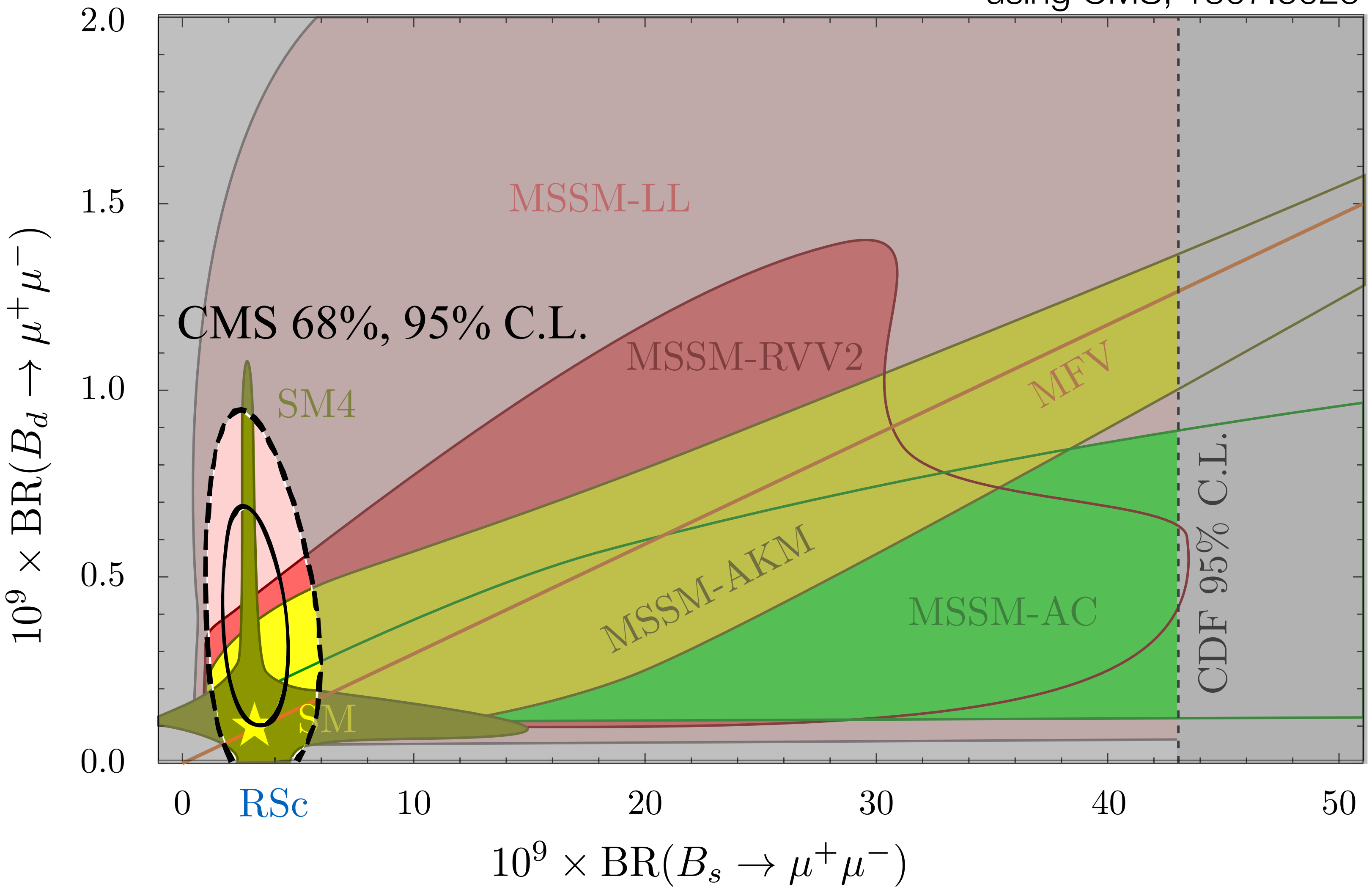


$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\text{Exp}} = 17.3^{+11.5}_{-10.5} \times 10^{-11} \Rightarrow \Lambda_{NP} \gtrsim \sqrt{y_{sd}}\, 2 \times 10^2 \text{ TeV}$$

NP in ΔF=1

$$\mathcal{L}_{\Delta F=1} = y_{sd}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{d}_L \not{Z} s_L + y_{cu}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{u}_L \not{Z} c_L + y_{bd}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{d}_L \not{Z} b_L + y_{bs}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{s}_L \not{Z} b_L$$

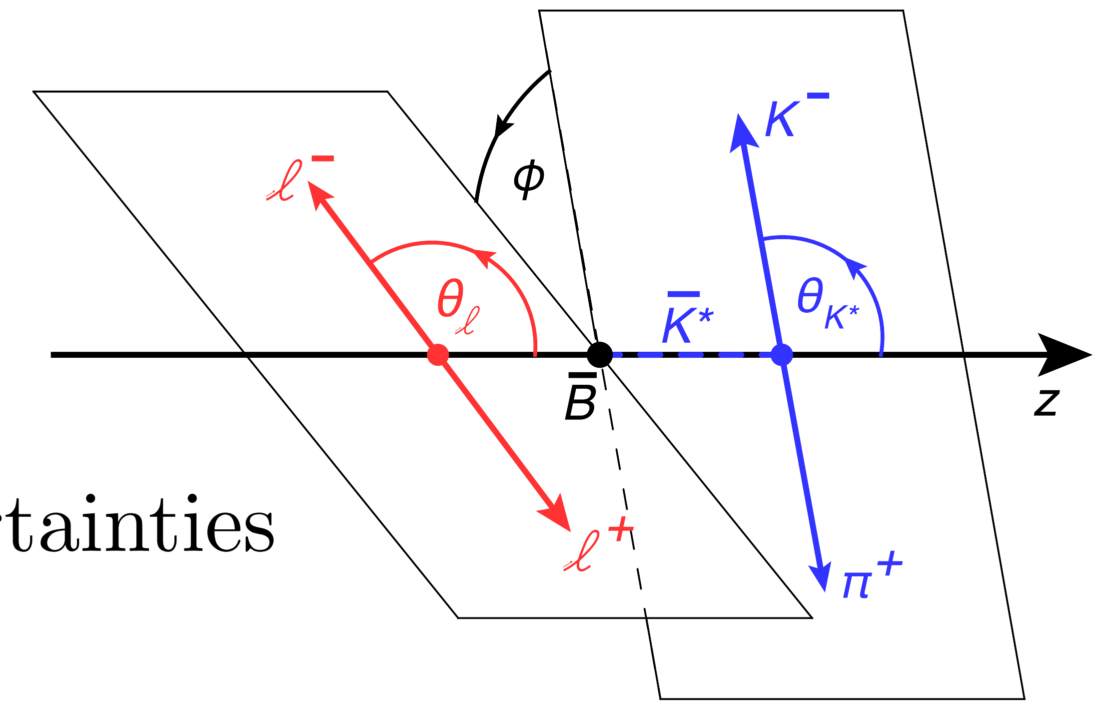
update of Straub, 1012.3893
using CMS, 1307.5025



NP in Δ*F*=1

$$\mathcal{L}_{\Delta F=1} = y_{sd}\frac{v^2}{\Lambda^2_{NP}}\frac{g}{c_W}\bar{d}_L \not{Z} s_L + y_{cu}\frac{v^2}{\Lambda^2_{NP}}\frac{g}{c_W}\bar{u}_L \not{Z} c_L + y_{bd}\frac{v^2}{\Lambda^2_{NP}}\frac{g}{c_W}\bar{d}_L \not{Z} b_L + y_{bs}\frac{v^2}{\Lambda^2_{NP}}\frac{g}{c_W}\bar{s}_L \not{Z} b_L$$

- $B_0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$
  - differential rate analysis
  - challenging theory uncertainties

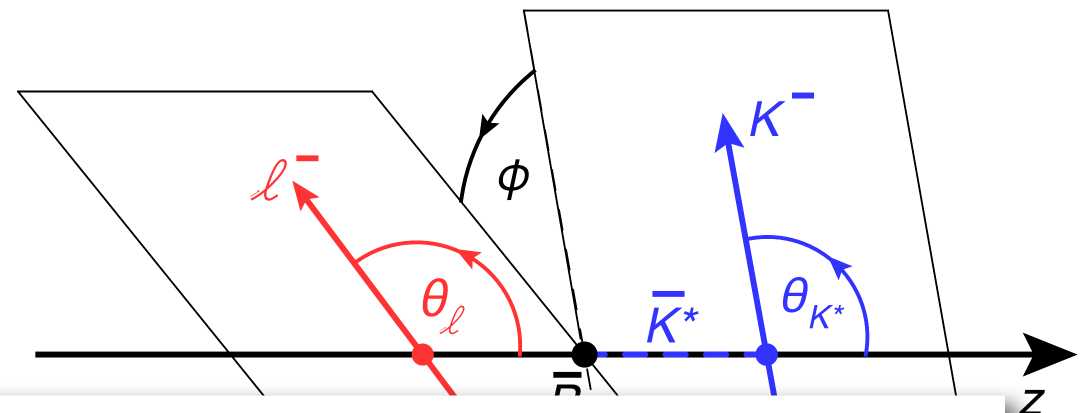


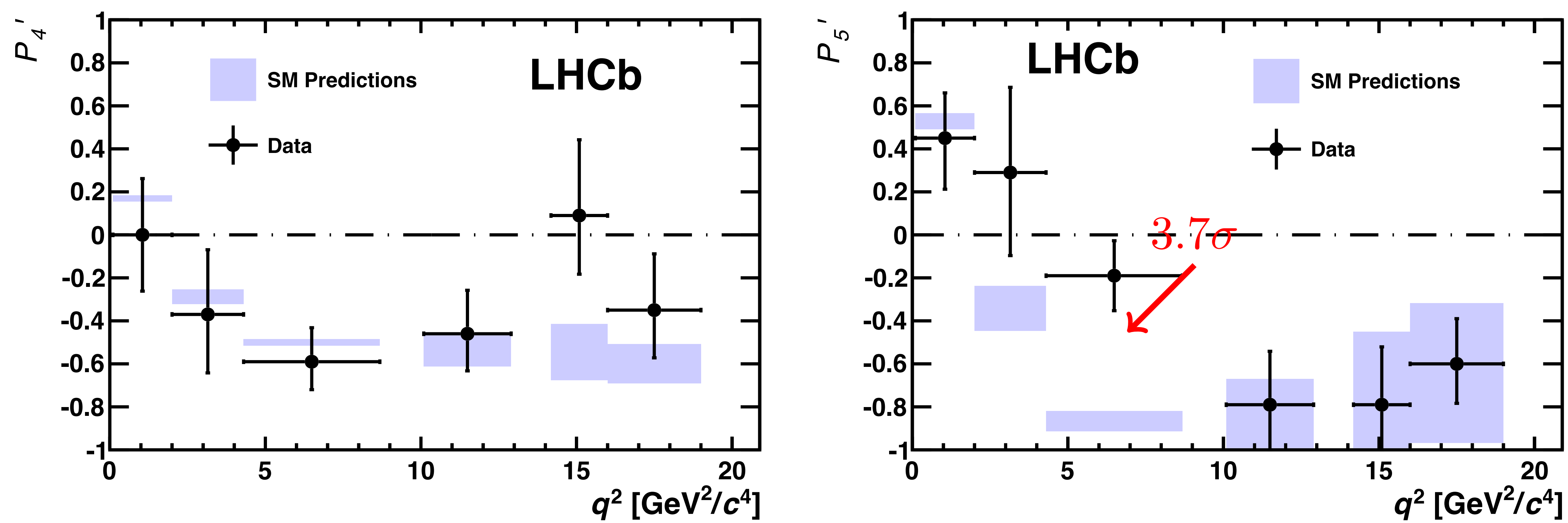
$$\frac{1}{\Gamma}\frac{d^5(\Gamma+\Gamma)}{d\cos\theta_\ell d\cos\theta_K d\Phi} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \tfrac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\Phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\Phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\Phi$$
$$+ \tfrac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\Phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\Phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\Phi\Big]$$

NP in Δ*F*=1

$$\mathcal{L}_{\Delta F=1} = y_{sd}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{d}_L \not{Z} s_L + y_{cu}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{u}_L \not{Z} c_L + y_{bd}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{d}_L \not{Z} b_L + y_{bs}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{s}_L \not{Z} b_L$$

- $B_0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$
  - differential rate analysis





$$P'_{4,5} = S_{4,5}/\sqrt{F_L(1-F_L)}$$

[PRL 111, 191801 (2013)]

NP in ΔF=1

$$\mathcal{L}_{\Delta F=1} = y_{sd}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{d}_L \not{Z} s_L + y_{cu}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{u}_L \not{Z} c_L + y_{bd}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{d}_L \not{Z} b_L + \boxed{y_{bs}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{s}_L \not{Z} b_L}$$

- $B_0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-,\ B^+ \to K^+\mu^+\mu^-/e^+e^-$
  - differential rate analysis
  - lepton flavour universality tests

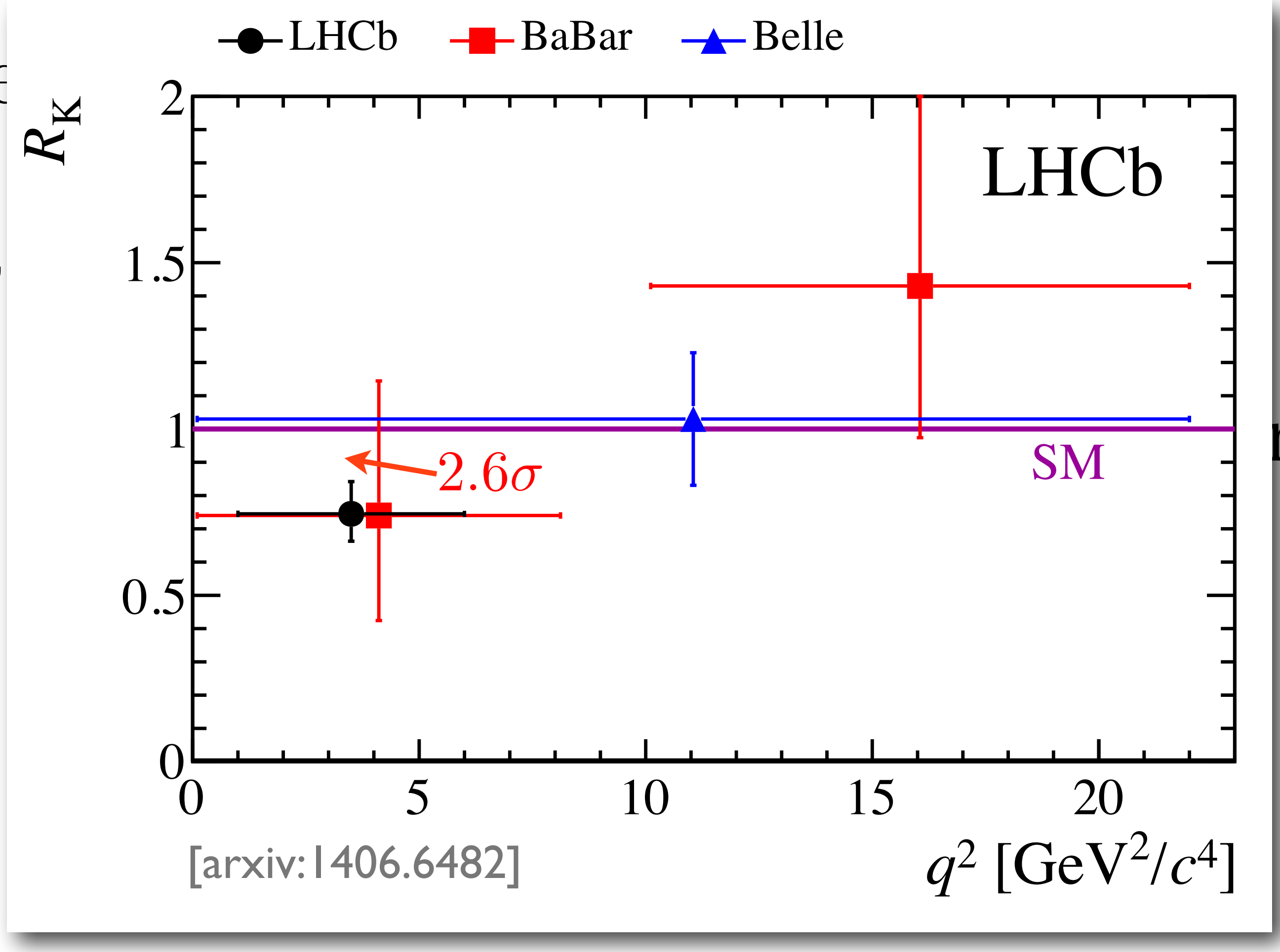
$$\mathcal{R}_K = \frac{\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathcal{B}(B^+\to K^+e^+e^-)} = 1 \pm \mathcal{O}(10^{-3}) \ \text{ in the SM}$$

NP in ΔF=1

$$\mathcal{L}_{\Delta F=1} = y_{sd}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{d}_L \not{Z} s_L + y_{cu}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{u}_L \not{Z} c_L + y_{bd}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{d}_L \not{Z} b_L + y_{bs}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{s}_L \not{Z} b_L$$

- $B_0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-,\ B^+ \to K^+\mu^+\mu^-/e^+e^-$
  - diffe
  - lept

$\mathcal{R}_K$ ... n the SM



NP in Flavour

Example: Supersymmetry

- SUSY models in general provide new sources of flavor violation
  - supersymmetry breaking soft mass terms for squarks and sleptons
  - trilinear couplings of a Higgs field with a squark-antisquark or slepton-antislepton pairs

$$\tilde{q}^*_{Mi}(M^2_{\tilde{q}})^{MN}_{ij}\tilde{q}_{Nj} = (\tilde{q}^*_{Li}\ \tilde{q}^*_{Rk}) \begin{pmatrix} (M^2_{\tilde{q}})_{Lij} & A^q_{il}v_q \\ A^q_{jk}v_q & (M^2_{\tilde{q}})_{Rkl} \end{pmatrix} \begin{pmatrix} \tilde{q}_{Lj} \\ \tilde{q}_{Rl} \end{pmatrix}$$

NP in Flavour

Example: Supersymmetry

- MSSM contributions to neutral meson mixing

$$M_{12}^{D} = \frac{\alpha_s^2 m_D f_D^2 B_D \eta_{\rm QCD}}{108 m_{\tilde{u}}^2}[11\tilde{f}_6(x_u) + 4x_u f_6(x_u)]\frac{(\Delta m_{\tilde{u}}^2)^2}{m_{\tilde{u}}^4}(K_{21}^u K_{11}^{u*})^2,$$

$$M_{12}^{K} = \frac{\alpha_s^2 m_K f_K^2 B_K \eta_{\rm QCD}}{108 m_{\tilde{d}}^2}[11\tilde{f}_6(x_d) + 4x_d f_6(x_d)]\frac{(\Delta \tilde{m}_{\tilde{d}}^2)^2}{\tilde{m}_d^4}(K_{21}^{d*} K_{11}^{d})^2.$$

NP in Flavour

Example: Supersymmetry

- MSSM contributions to neutral meson mixing

$$M_{12}^{D} = \frac{\alpha_s^2 m_D f_D^2 B_D \eta_{\rm QCD}}{108 m_{\tilde{u}}^2}[11\tilde{f}_6(x_u) + 4x_u f_6(x_u)]\frac{(\Delta m_{\tilde{u}}^2)^2}{m_{\tilde{u}}^4}(K_{21}^u K_{11}^{u*})^2,$$

$$M_{12}^{K} = \frac{\alpha_s^2 m_K f_K^2 B_K \eta_{\rm QCD}}{108 m_{\tilde{d}}^2}[11\tilde{f}_6(x_d) + 4x_d f_6(x_d)]\frac{(\Delta \tilde{m}_{\tilde{d}}^2)^2}{\tilde{m}_d^4}(K_{21}^{d*} K_{11}^{d})^2.$$

- Experimental bounds on

$$(\delta_{ij}^q)_{MM} = \frac{\Delta\tilde{m}^2_{q_j q_i}}{\tilde{m}_q^2}(K_M^q)_{ij}(K_M^q)^*_{jj}\,,$$

for m_q =1TeV, x_i=1

q	ij	$(\delta_{ij}^q)_{MM}$
d	12	0.03
d	13	0.2
d	23	0.6
u	12	0.1

NP in Flavour

Example: Supersymmetry

- MSSM contributions to neutral meson mixing

$$M_{12}^D = \frac{\alpha_s^2 m_D f_D^2 B_D \eta_{\rm QCD}}{108 m_{\tilde{u}}^2}[11\tilde{f}_6(x_u) + 4x_u f_6(x_u)]\frac{(\Delta m_{\tilde{u}}^2)^2}{m_{\tilde{u}}^4}(K_{21}^u K_{11}^{u*})^2,$$

$$M_{12}^K = \frac{\alpha_s^2 m_K f_K^2 B_K \eta_{\rm QCD}}{108 m_{\tilde{d}}^2}[11\tilde{f}_6(x_d) + 4x_d f_6(x_d)]\frac{(\Delta \tilde{m}_{\tilde{d}}^2)^2}{\tilde{m}_d^4}(K_{21}^{d*} K_{11}^d)^2.$$

- Ways to avoid stringent exp. bounds on 1↔2 mixing
  - Heaviness: $m_q \gg 1$ TeV.
  - Degeneracy: $\Delta m_{\tilde{q}}^2 \ll m_{\tilde{q}}^2$.
  - Alignment: $K_{21}^{d,u} \ll 1$.

NP in Flavour

Minimal Flavour Hypothesis

- flavour-violating interactions are linked to known Yukawa couplings also beyond SM

  (i) flavour symmetry: $\mathrm{SU}(3)^3$

  (ii) set of symmetry-breaking terms:

$$Y_u \sim (3, \bar{3}, 1) \,, \qquad Y_d \sim (3, 1, \bar{3}) \,.$$

- tractable due to peculiar structure of SM flavour

$$\left[Y_u (Y_u)^\dagger \right]^n_{i \neq j} \; \approx \; y_t^n V_{it}^* V_{tj} \,.$$

NP in Flavour

Minimal Flavour Hypothesis

- leading $\Delta F = 2$ and $\Delta F = 1$ FCNC amplitudes

$$\mathcal{A}(d^i \to d^j)_{\rm MFV} = (V_{ti}^* V_{tj})\ \mathcal{A}_{\rm SM}^{(\Delta F=1)} \left[1 + a_1 \frac{16\pi^2 M_W^2}{\Lambda^2}\right] ,$$

$$\mathcal{A}(M_{ij} - \bar{M}_{ij})_{\rm MFV} = (V_{ti}^* V_{tj})^2 \mathcal{A}_{\rm SM}^{(\Delta F=2)} \left[1 + a_2 \frac{16\pi^2 M_W^2}{\Lambda^2}\right] .$$

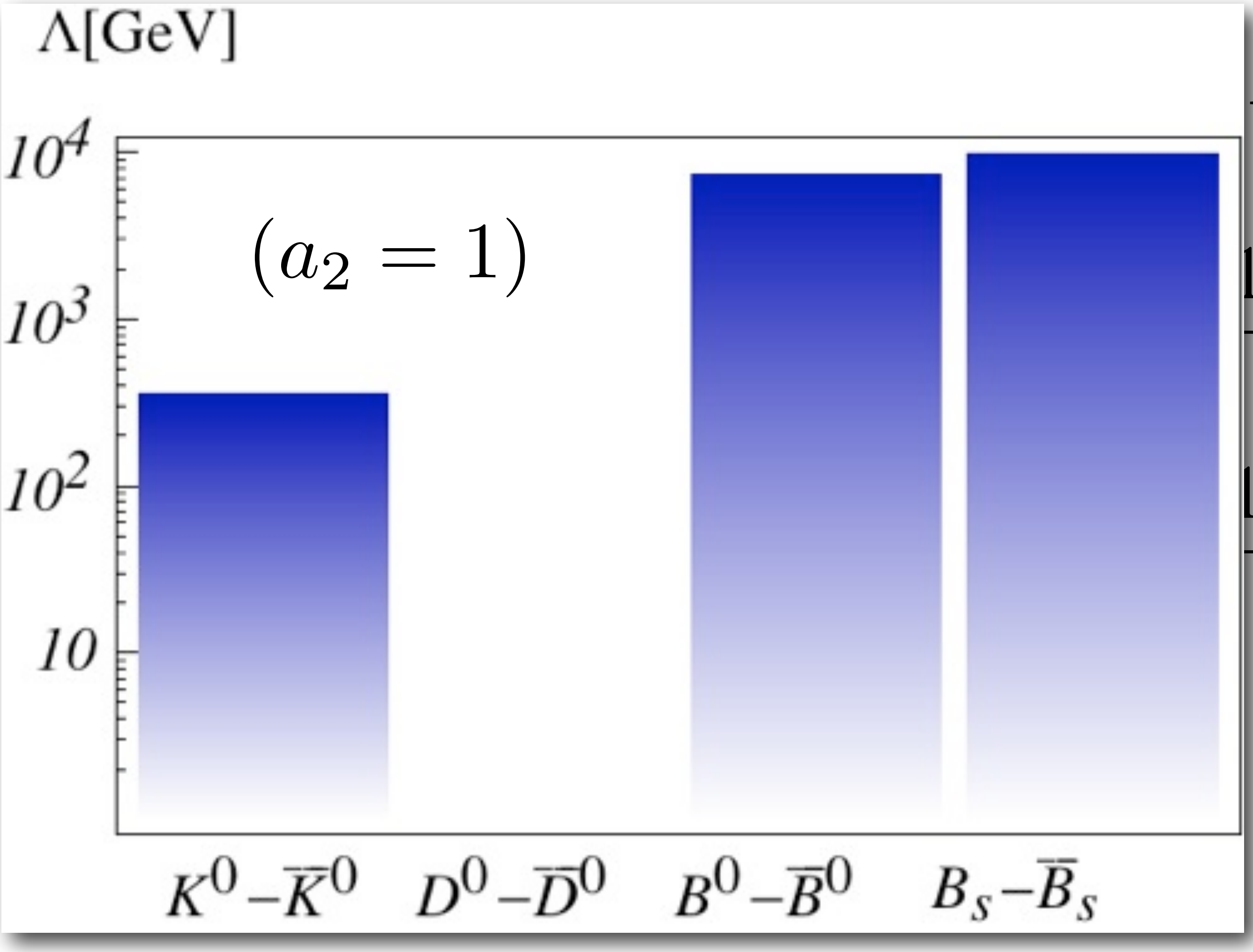
NP in Flavour

Minimal Flavour Hypothesis

- leading ... udes

$$\mathcal{A}(d^i \to d^j ... \frac{16\pi^2 M_W^2}{\Lambda^2}\Bigg] ,$$

$$\mathcal{A}(M_{ij} - \bar{M}_{ij} ... \frac{16\pi^2 M_W^2}{\Lambda^2}\Bigg] .$$



NP in Flavour

Minimal Flavour Hypothesis

- Example: Supersymmetry

$$\begin{aligned}
\tilde{m}^2_{Q_L} &= \tilde{m}^2 \left(a_1 1\!\!1 + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger + b_3 Y_d Y_d^\dagger Y_u Y_u^\dagger + \ldots \right) , \\
\tilde{m}^2_{U_R} &= \tilde{m}^2 \left(a_2 1\!\!1 + b_5 Y_u^\dagger Y_u + \ldots \right) , \\
A_U &= A \left(a_3 1\!\!1 + b_6 Y_d Y_d^\dagger + \ldots \right) Y_d , \\
&\ldots
\end{aligned}$$

- combination of degeneracy & alignment

Conclusions

- Absence of significant deviations from SM in quark flavour physics is key constraint on any extension of SM (example: Supersymmetry)

- Various open questions regarding flavour structure of SM itself; can be possibly addressed only using flavour measurements

- Set of flavour observables to be measured with higher precision in search for NP is limited, but not necessarily small (examples: CPV in B_s and D)

- NP effects could still lurk in rare K, D and B decays