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

$\Rightarrow$ allows to predict SM contributions also to loop suppressed observables!

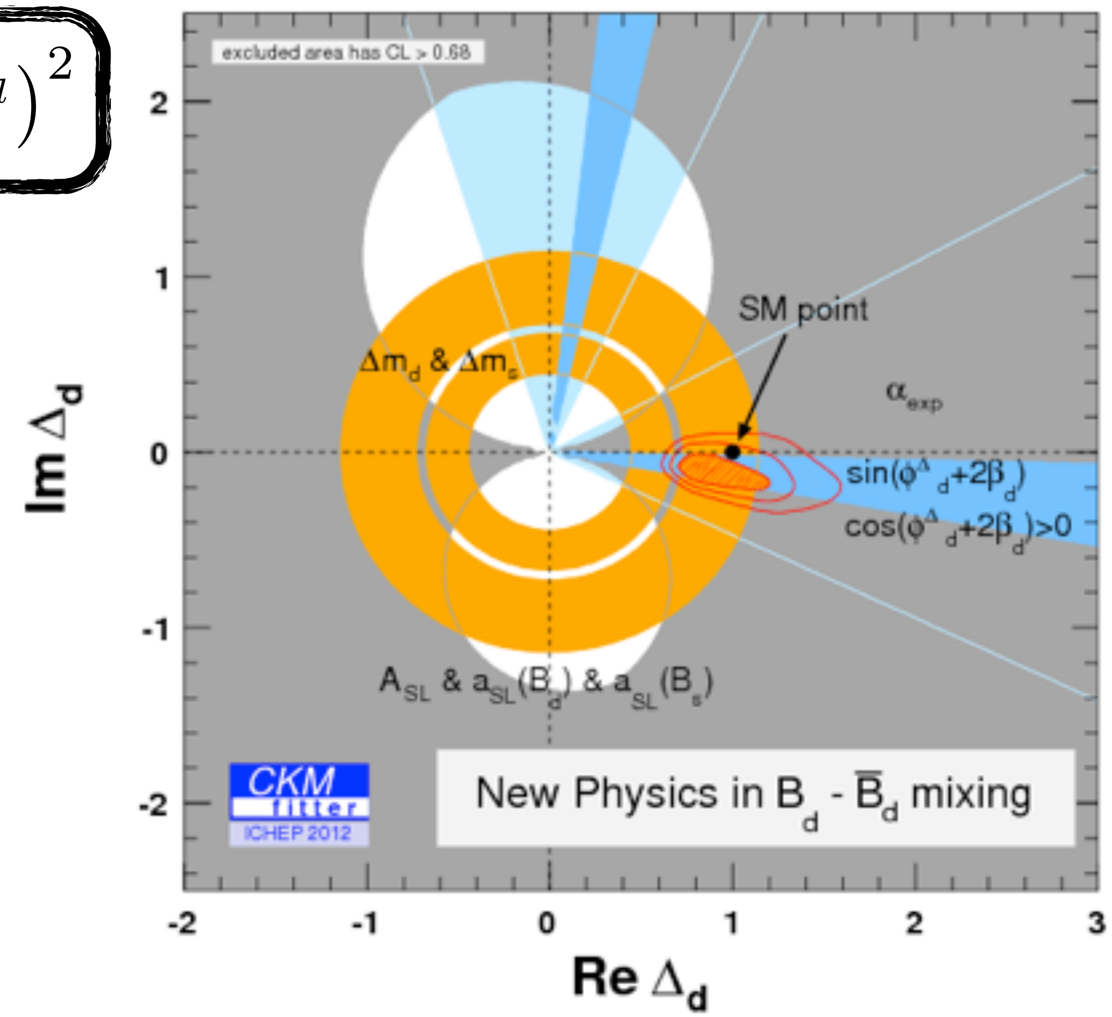
NP in B mixing

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

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

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

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



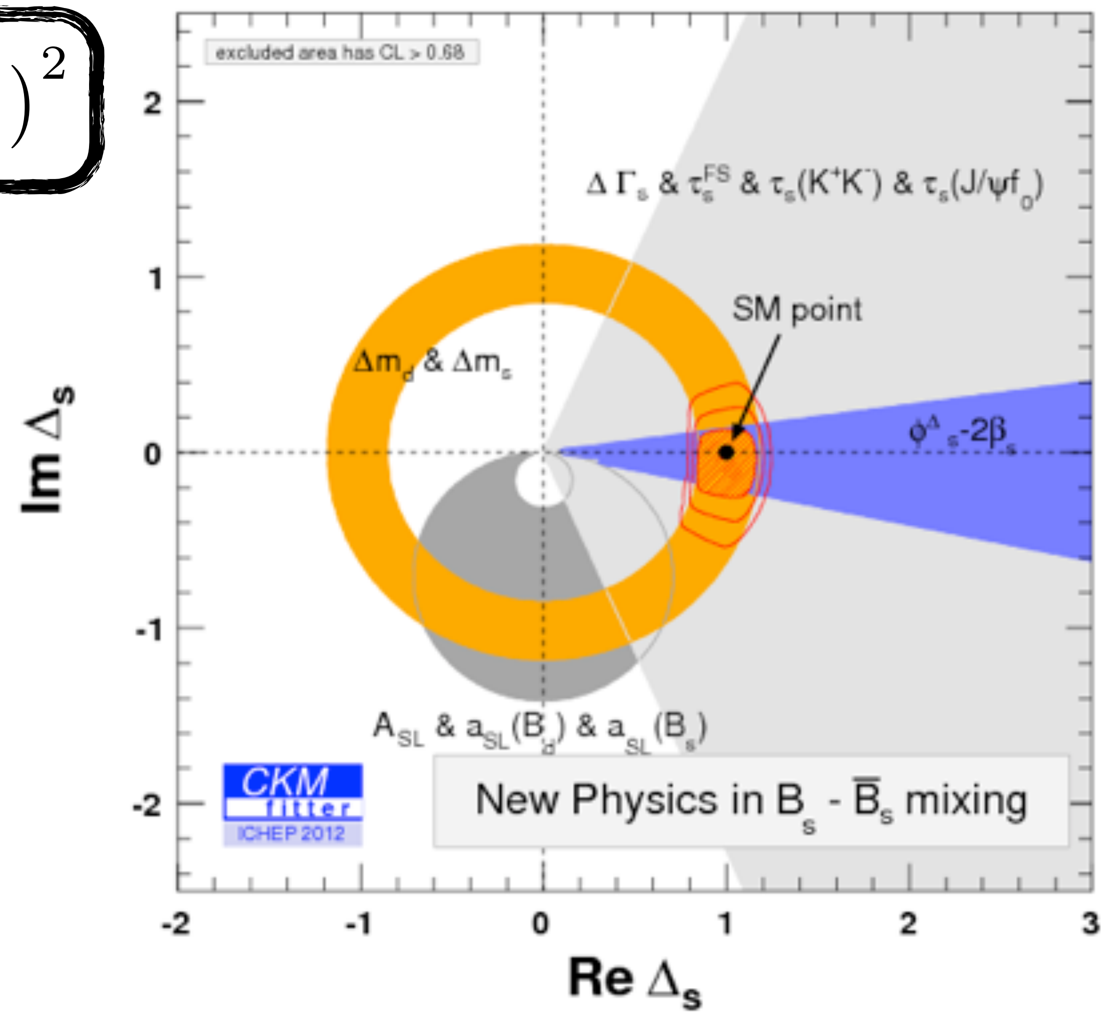
NP in B mixing

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

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

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

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



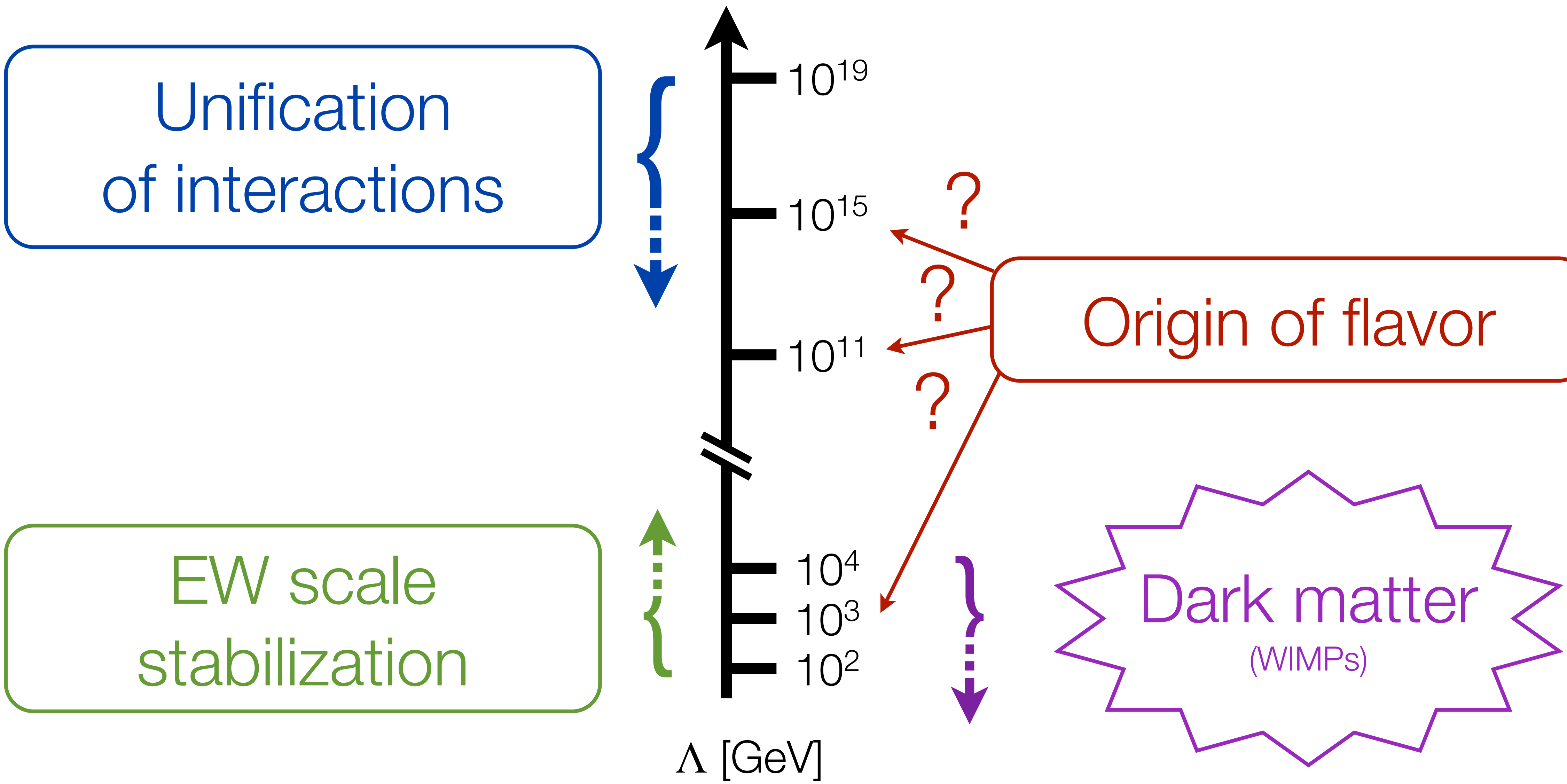
The NP flavour puzzle

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

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

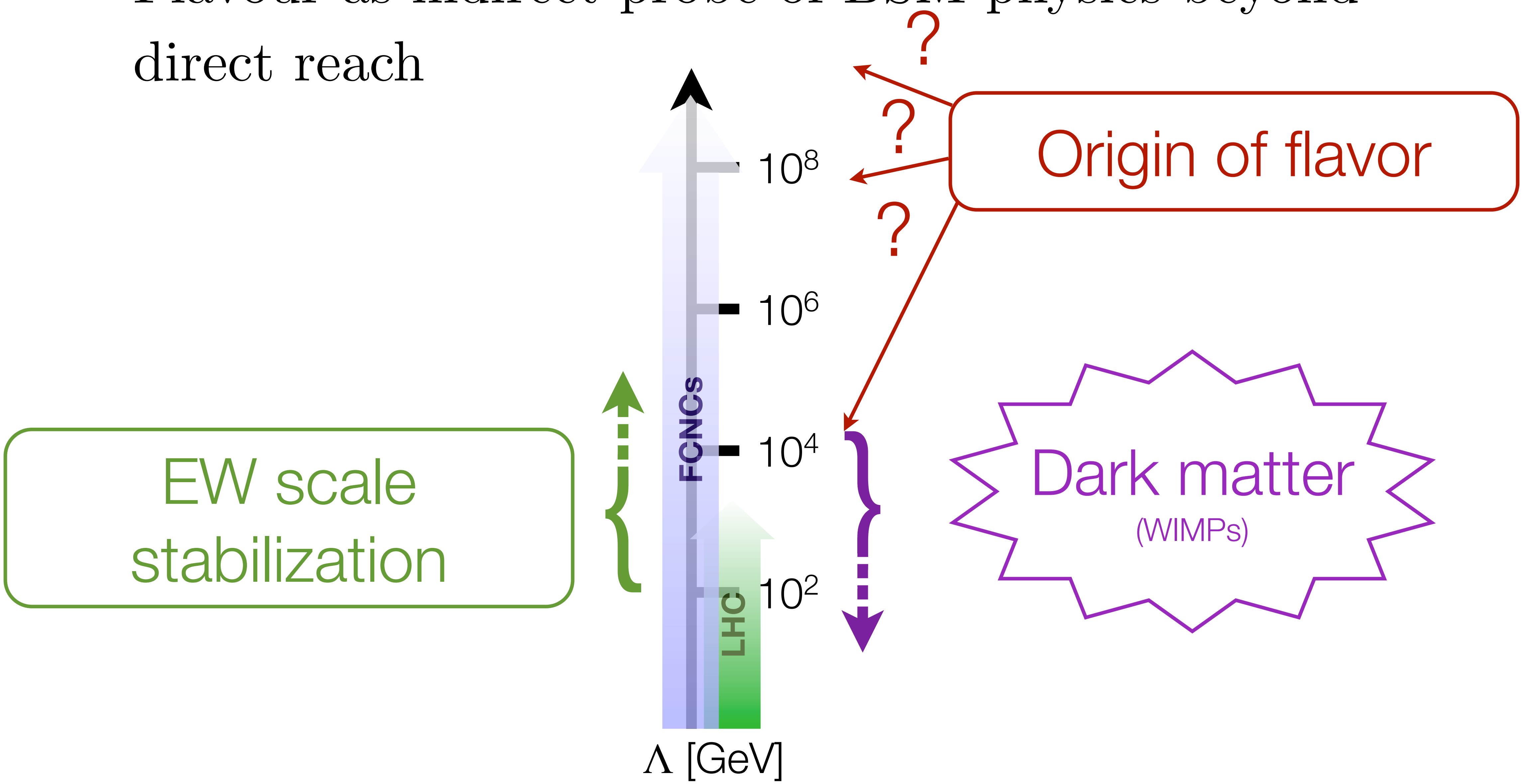
- for natural theory: $c_n^{(d)} \sim \mathcal{O}(1)$

- 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

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

Λ_{weak} [~100 GeV]

Weak scale operators

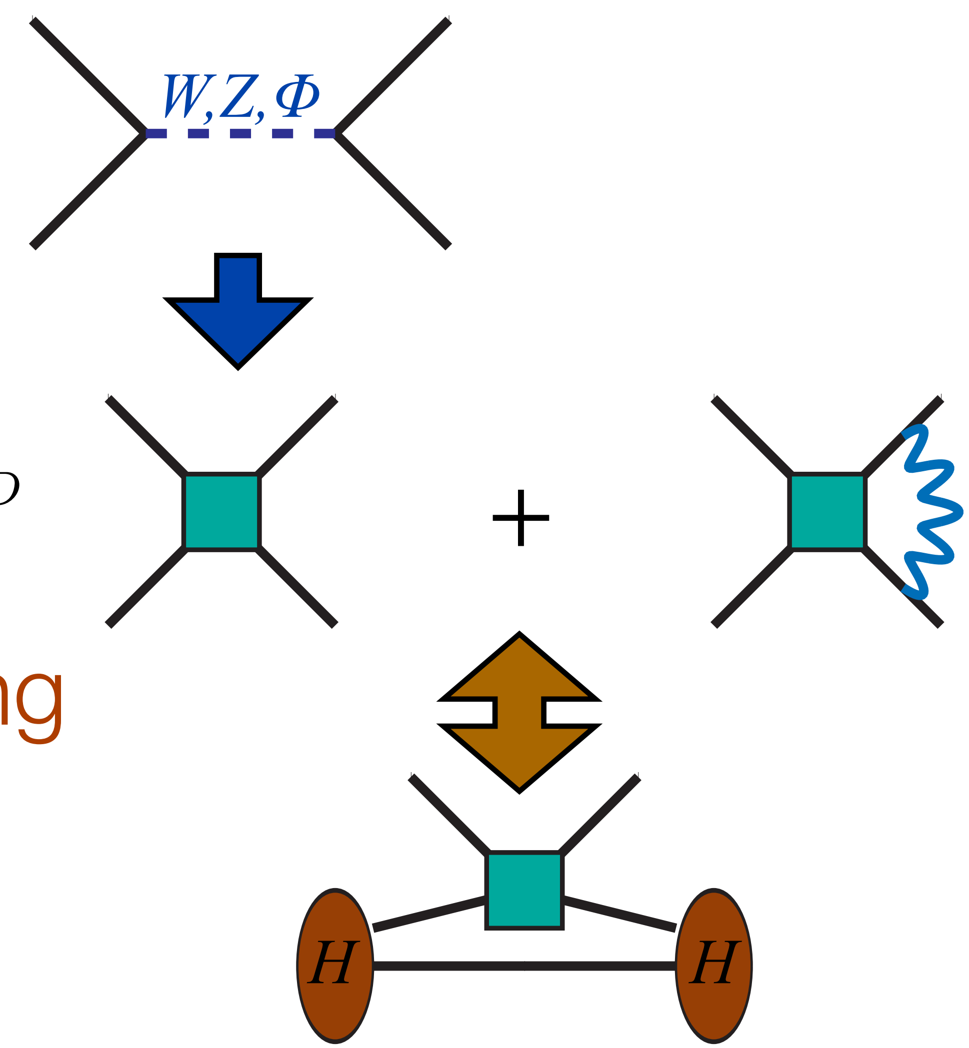
$\mathcal{L}^{\mathrm{eff}}_{\mathrm{weak}}(\sim G_F \sum_i c_i \mathcal{Q}_i) + \mathcal{L}_{QCD+QED}$

Non-perturbative matching

(or quark-hadron duality)

Λ_H [~GeV]

$\mathcal{L}^{\mathrm{eff}}(\pi, N, K, D, B, \ldots)$



(Over)constraining the SM flavor sector & NP

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

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

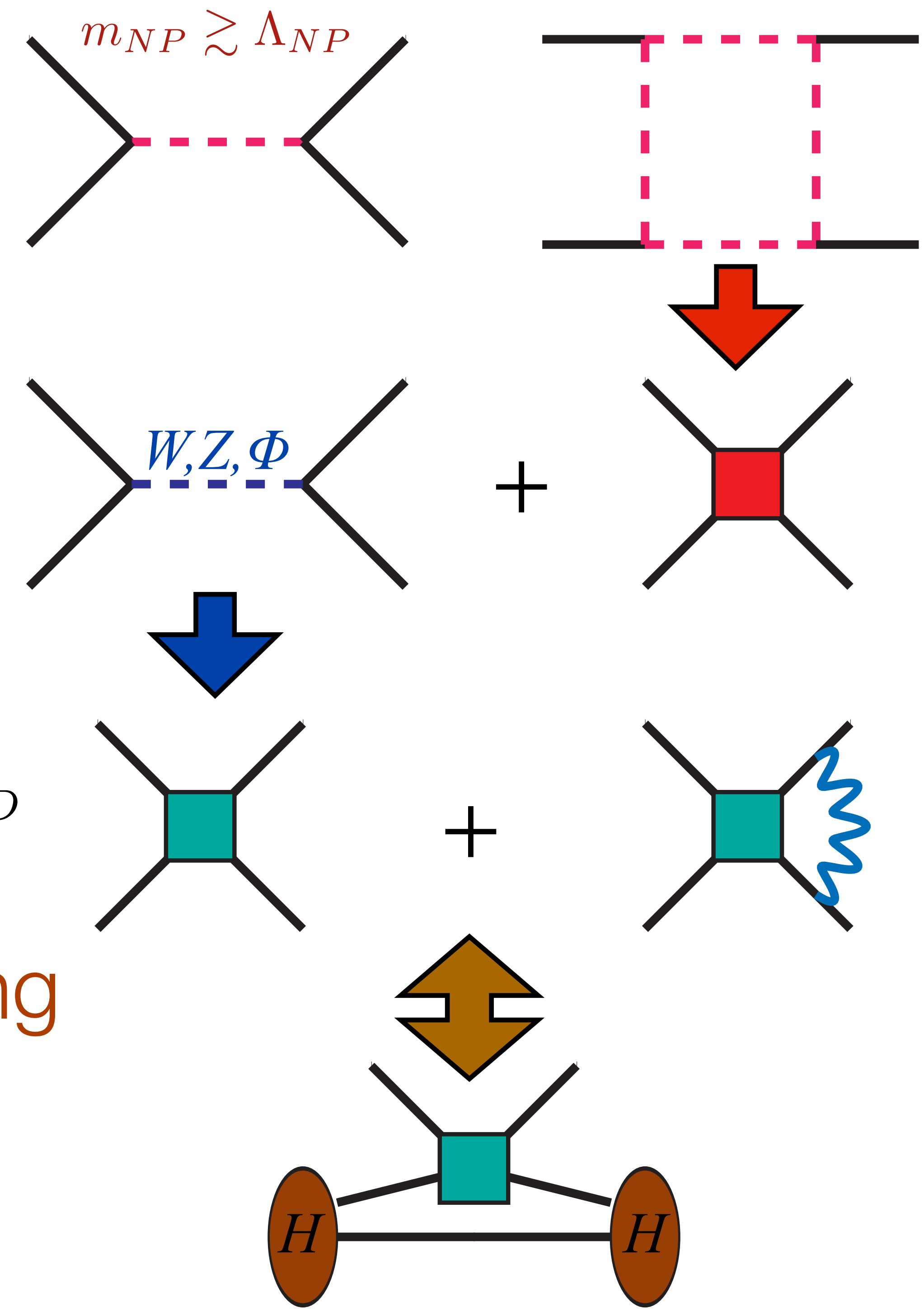
$\Lambda_{\rm weak}$ [~100 GeV] — Weak scale operators

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

Non-perturbative matching

(or quark-hadron duality)

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



NP in Δ*F*=2

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

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

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

NP in Δ*F*=2

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

- 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

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

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CPC NP

$$\begin{aligned} \Delta m_K/m_K &\sim 7.0\times 10^{-15}, \\ \Delta m_D/m_D &\sim 8.7\times 10^{-15}, \\ \Delta m_B/m_B &\sim 6.3\times 10^{-14}, \\ \Delta m_{B_s}/m_{B_s} &\sim 2.1\times 10^{-12}, \end{aligned} \quad \Rightarrow \Lambda_{\rm NP} \gtrsim \begin{cases} \sqrt{z_{sd}}\; 1\times 10^3 \text{ TeV} & \Delta m_K \\ \sqrt{z_{cu}}\; 1\times 10^3 \text{ TeV} & \Delta m_D \\ \sqrt{z_{bd}}\; 4\times 10^2 \text{ TeV} & \Delta m_B \\ \sqrt{z_{bs}}\; 7\times 10^1 \text{ TeV} & \Delta m_{B_s} \end{cases}$$

CPV NP

$$\begin{aligned} \epsilon_K &\sim 2.3\times 10^{-3}, \\ A_\Gamma/y_{\rm CP} &\lesssim 0.2, \\ S_{\psi K_S} &= 0.67\pm 0.02, \\ S_{\psi\phi} &\lesssim 1. \end{aligned} \quad \Rightarrow \Lambda_{\rm NP} \gtrsim \begin{cases} \sqrt{z_{sd}}\; 2\times 10^4 \text{ TeV} & \epsilon_K \\ \sqrt{z_{cu}}\; 3\times 10^3 \text{ TeV} & A_\Gamma \\ \sqrt{z_{bd}}\; 8\times 10^2 \text{ TeV} & S_{\psi K} \\ \sqrt{z_{bs}}\; 7\times 10^1 \text{ TeV} & S_{\psi\phi} \end{cases}$$

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

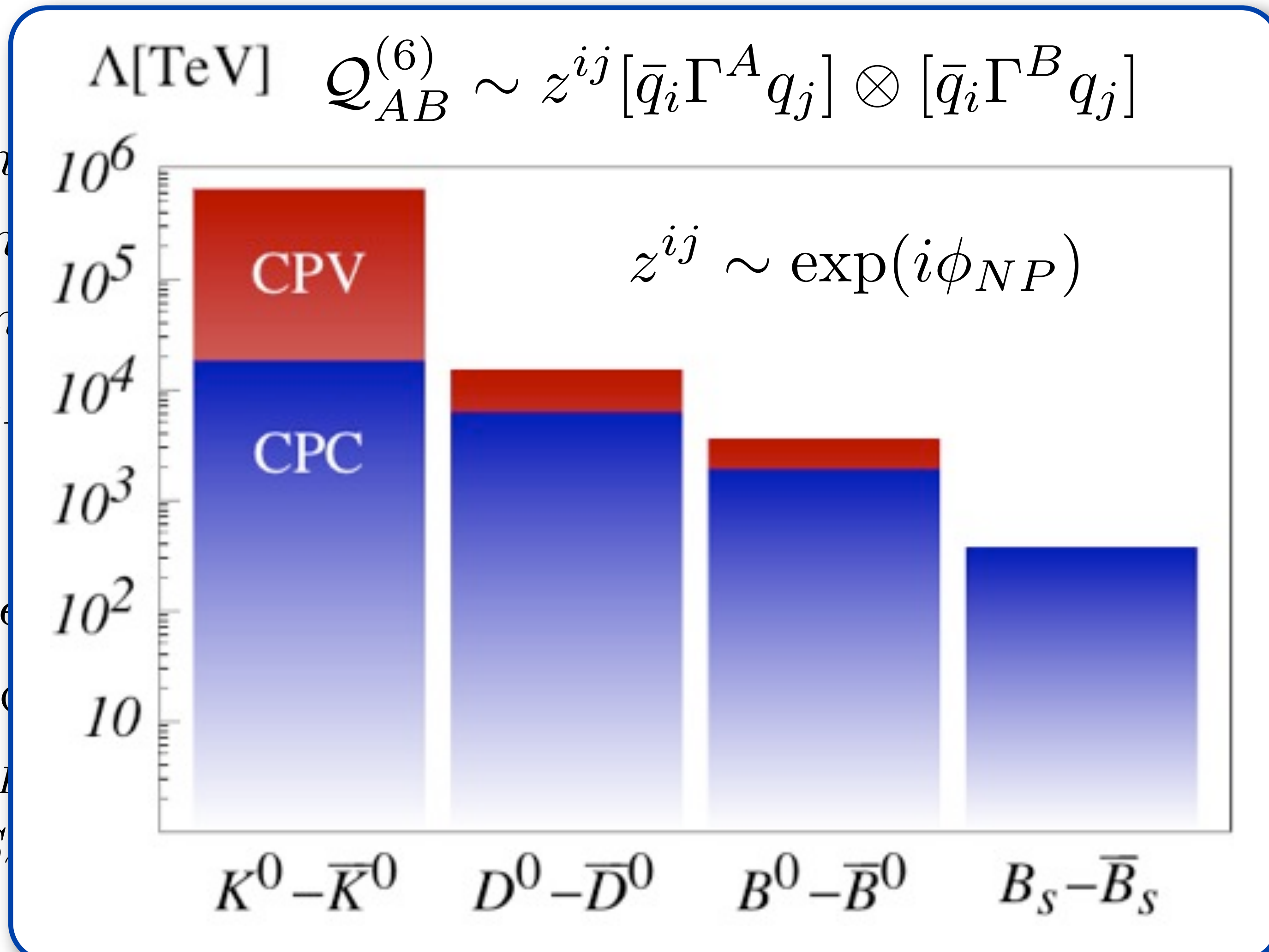
$\Delta m_{B_s}/m$ Δm_{B_s}

ϵ_K

A_Γ/y A_Γ

$S_{\psi K}$

$S_{\psi\phi}$



NP with a generic flavour structure is irrelevant for EW hierarchy

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CPV NP

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

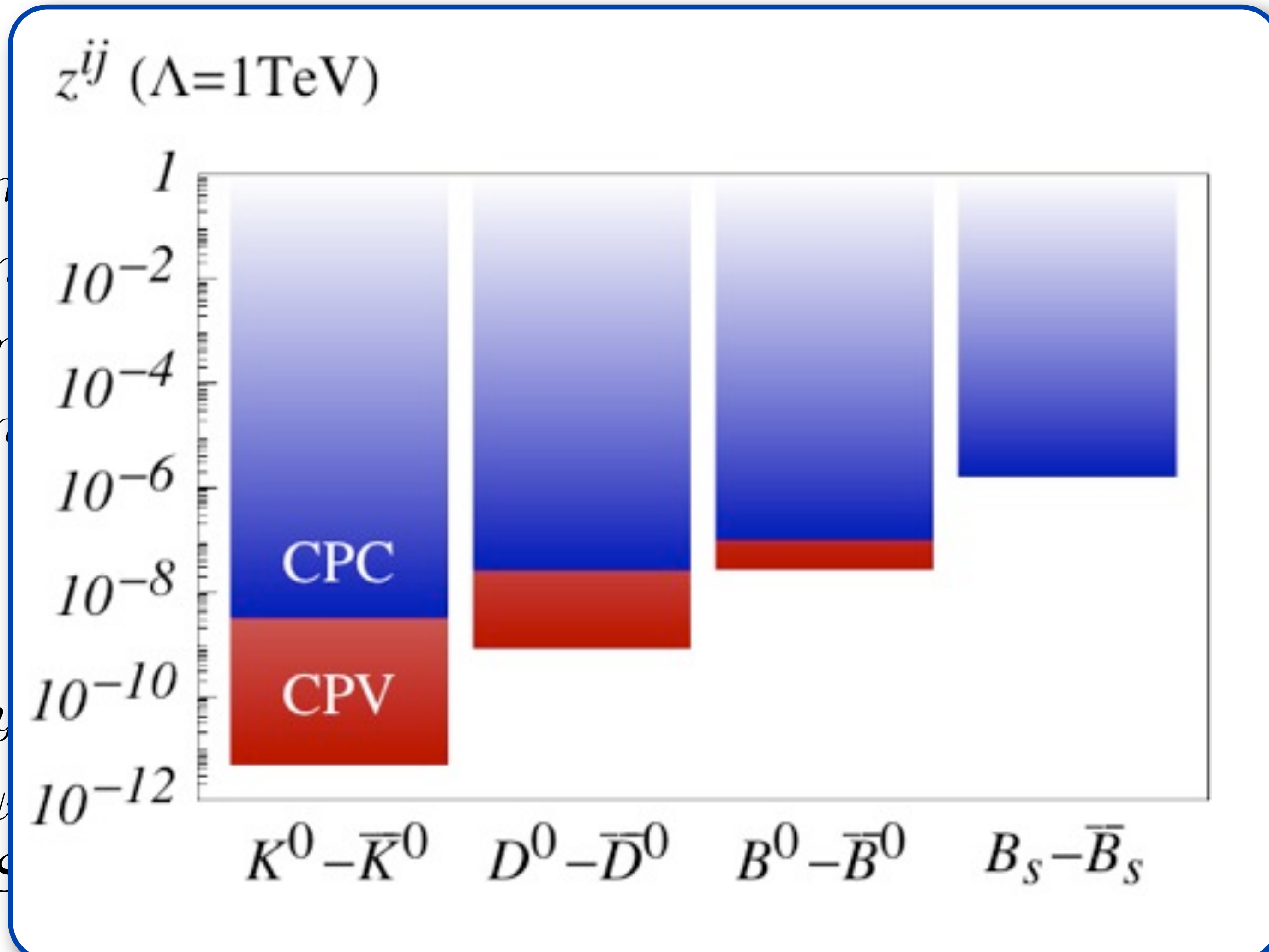
in case of TeV NP, flavour structure needs to be far from generic

NP in ΔF=2

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

$\Delta m_K/m$ … 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$)^2$.



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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 ΔF=1

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

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

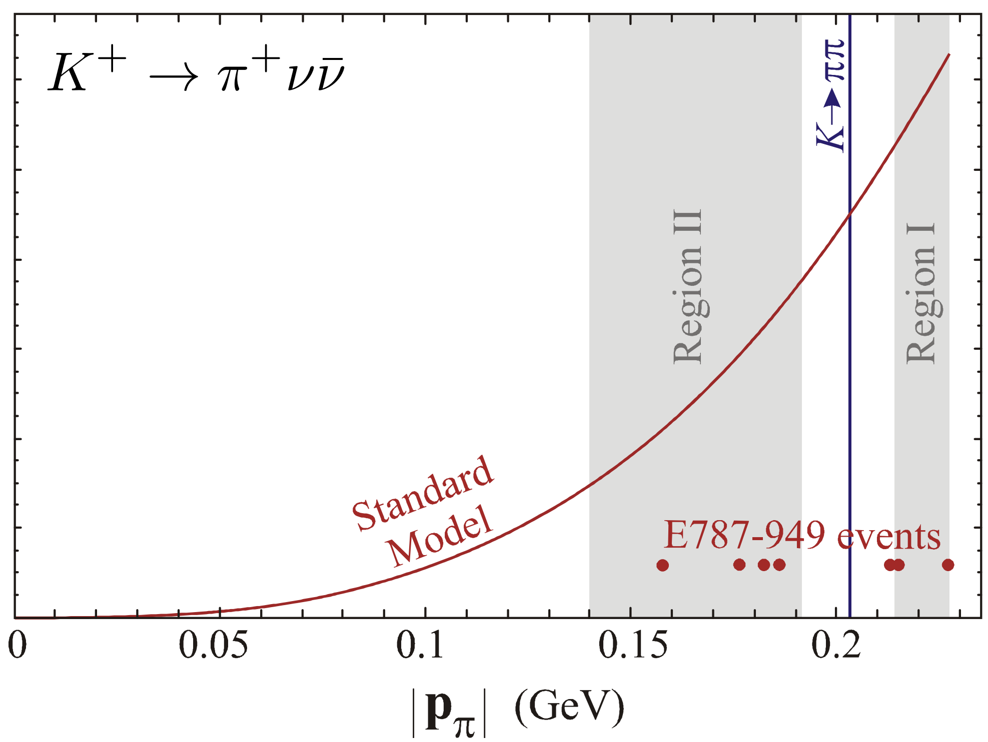
$$|y_{sd}^{\rm SM}| \sim \frac{\lambda_t^2}{64\pi^2}|V_{td}V_{ts}^*| \sim 5\times 10^{-7}$$
$$|y_{bd}^{\rm SM}| \sim \frac{\lambda_t^2}{64\pi^2}|V_{td}V_{tb}^*| \sim 10^{-5}$$
$$|y_{bs}^{\rm SM}| \sim \frac{\lambda_t^2}{64\pi^2}|V_{ts}V_{tb}^*| \sim 6\times 10^{-5}$$

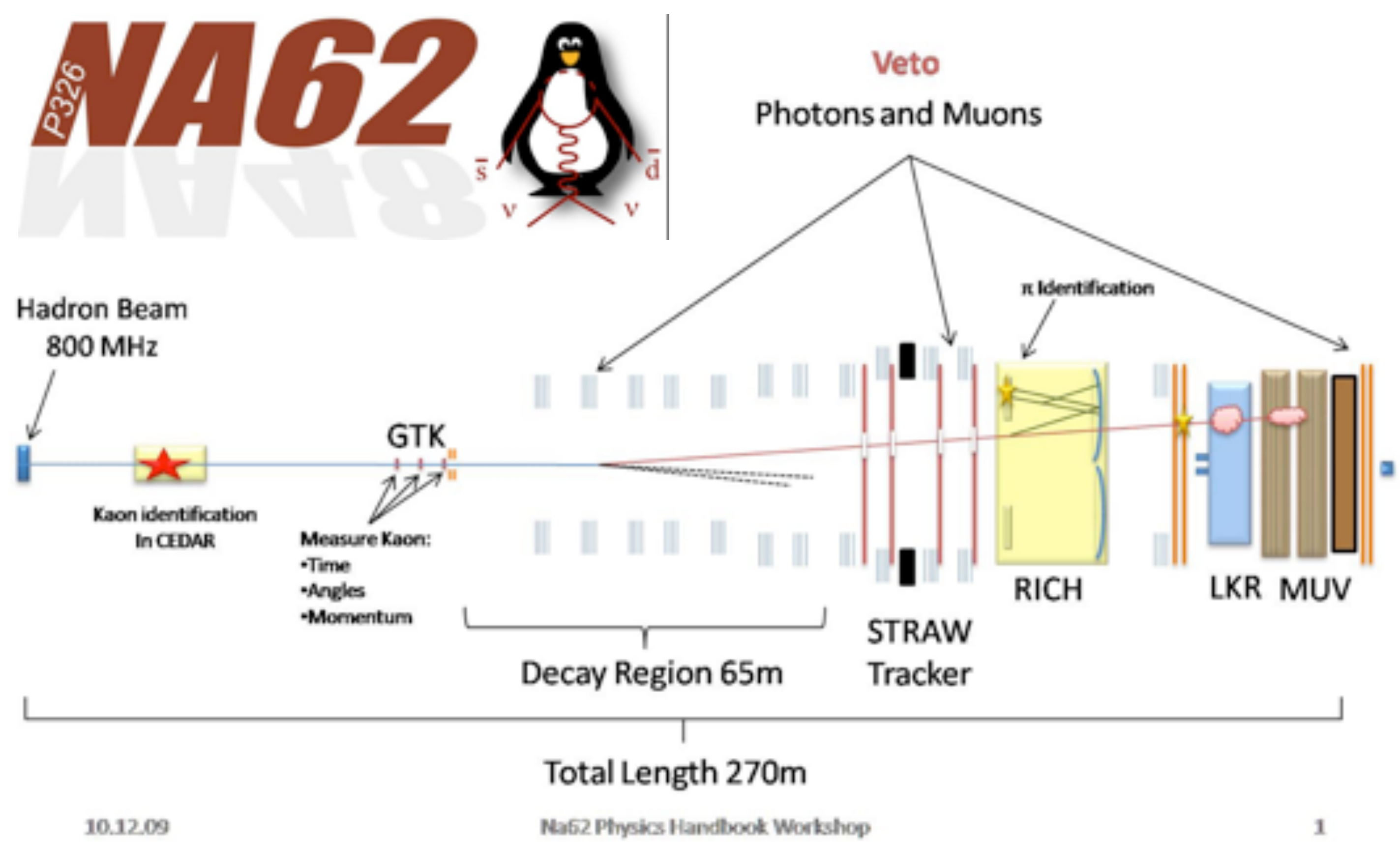
$\Rightarrow$

$$\mathcal{B}(K^+\to\pi^+\nu\bar{\nu}) \sim 8\times 10^{-11}\,,$$
$$\mathcal{B}(B_d\to\mu^+\mu^-) \sim 10^{-10}\,,$$
$$\mathcal{B}(B_s\to\mu^+\mu^-) \sim 4\times 10^{-9}\,.$$

NP in ΔF=1

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



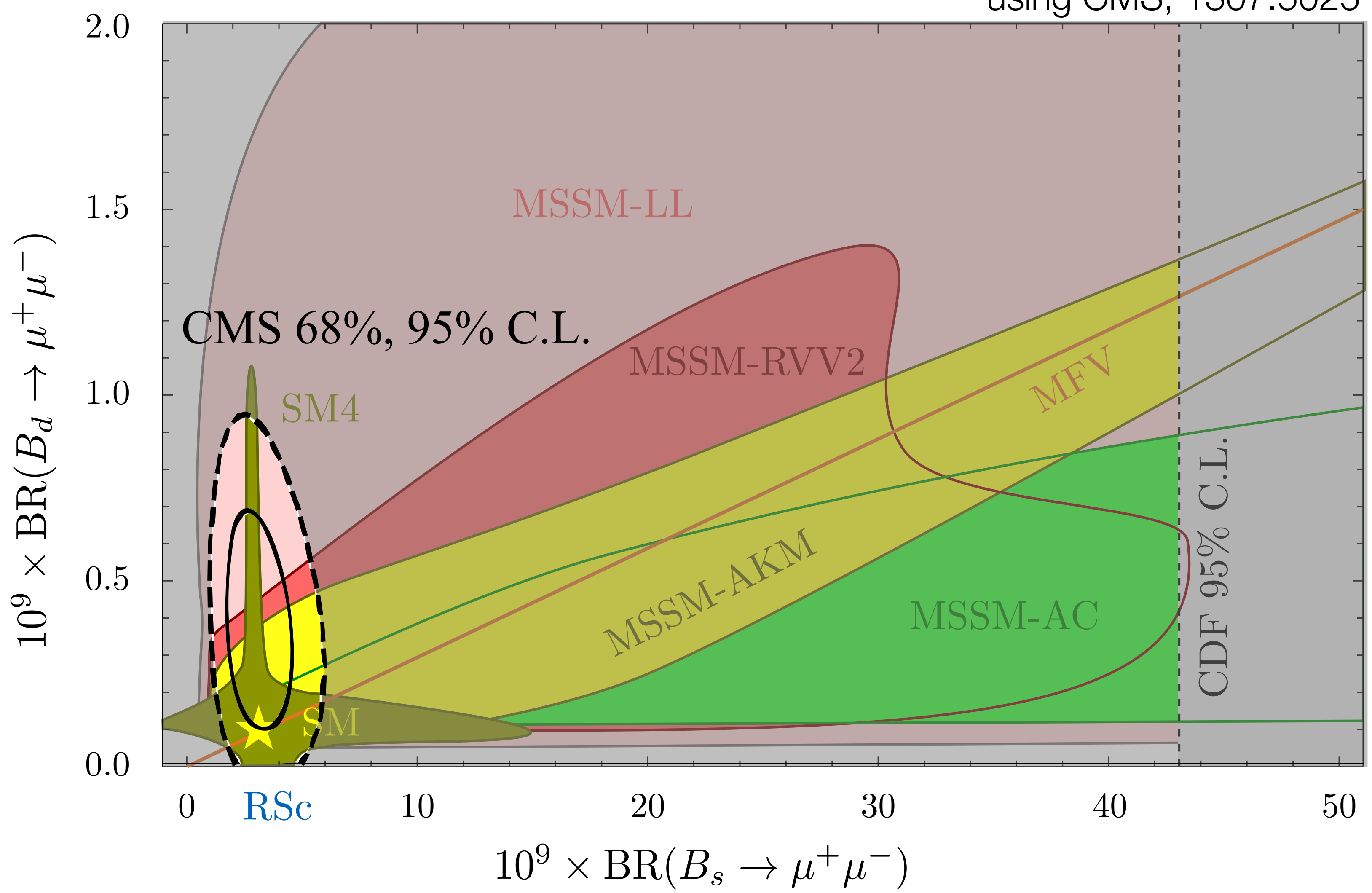


$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\rm Exp} = 17.3^{+11.5}_{-10.5} \times 10^{-11} \Rightarrow \Lambda_{NP} \gtrsim \sqrt{y_{sd}}\, 2 \times 10^2 \text{ TeV}$$

NP in ΔF=1

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

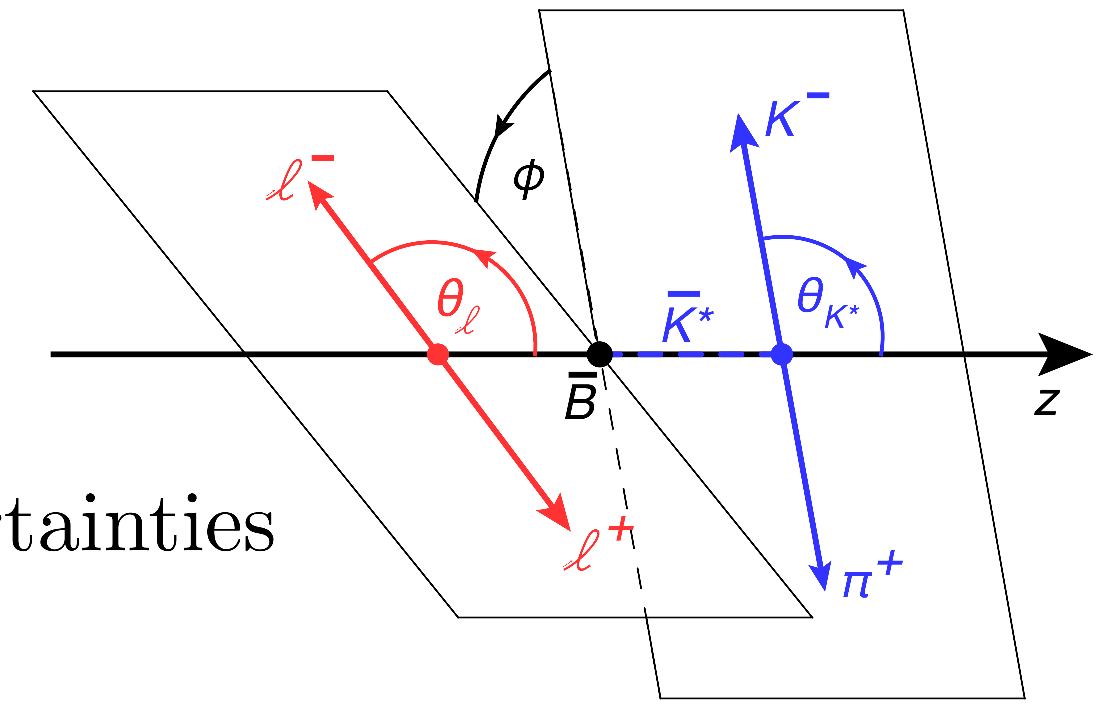
update of Straub, 1012.3893
using CMS, 1307.5025



NP in Δ*F*=1

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

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

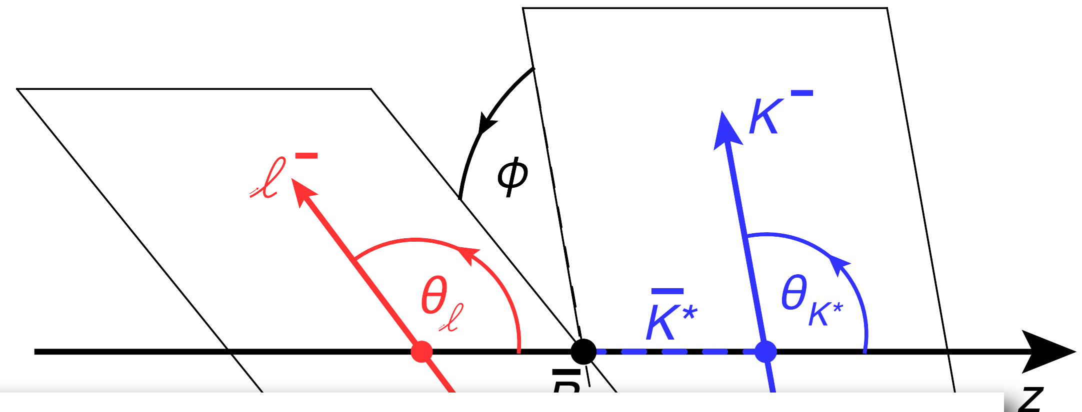


$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\Gamma)}{\mathrm{d}\cos\theta_\ell \mathrm{d}\cos\theta_K \mathrm{d}\Phi} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos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

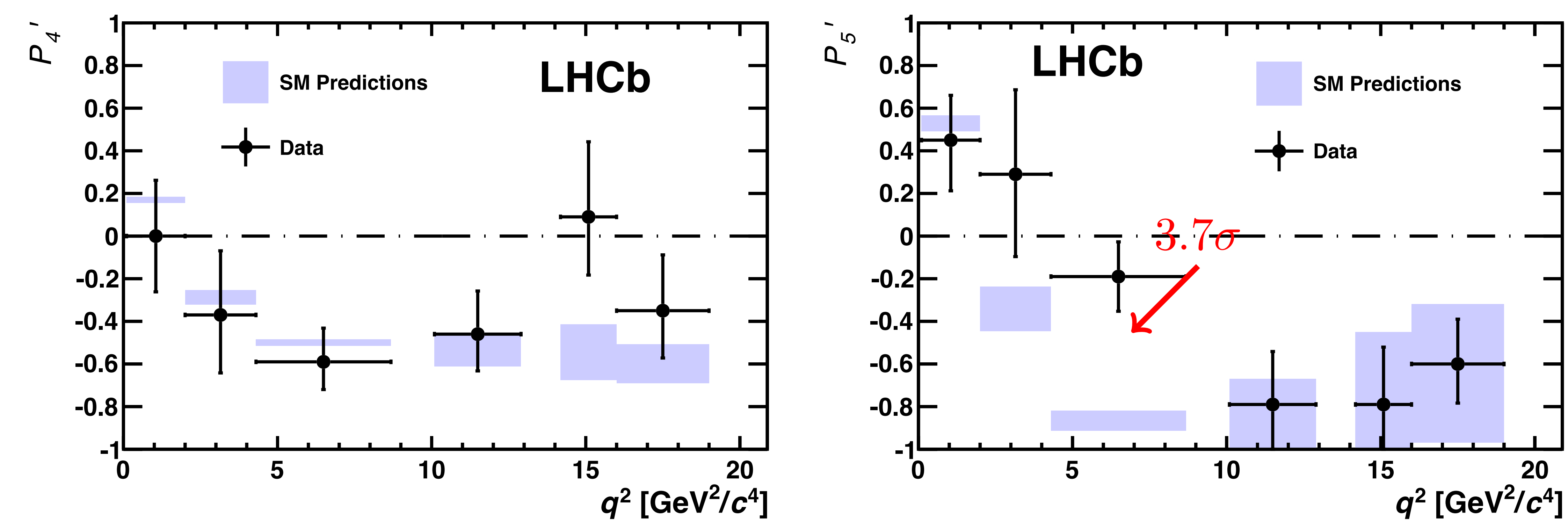
NP in ΔF=1

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

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



  - differential rate analysis



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

[PRL 111, 191801 (2013)]

NP in ΔF=1

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

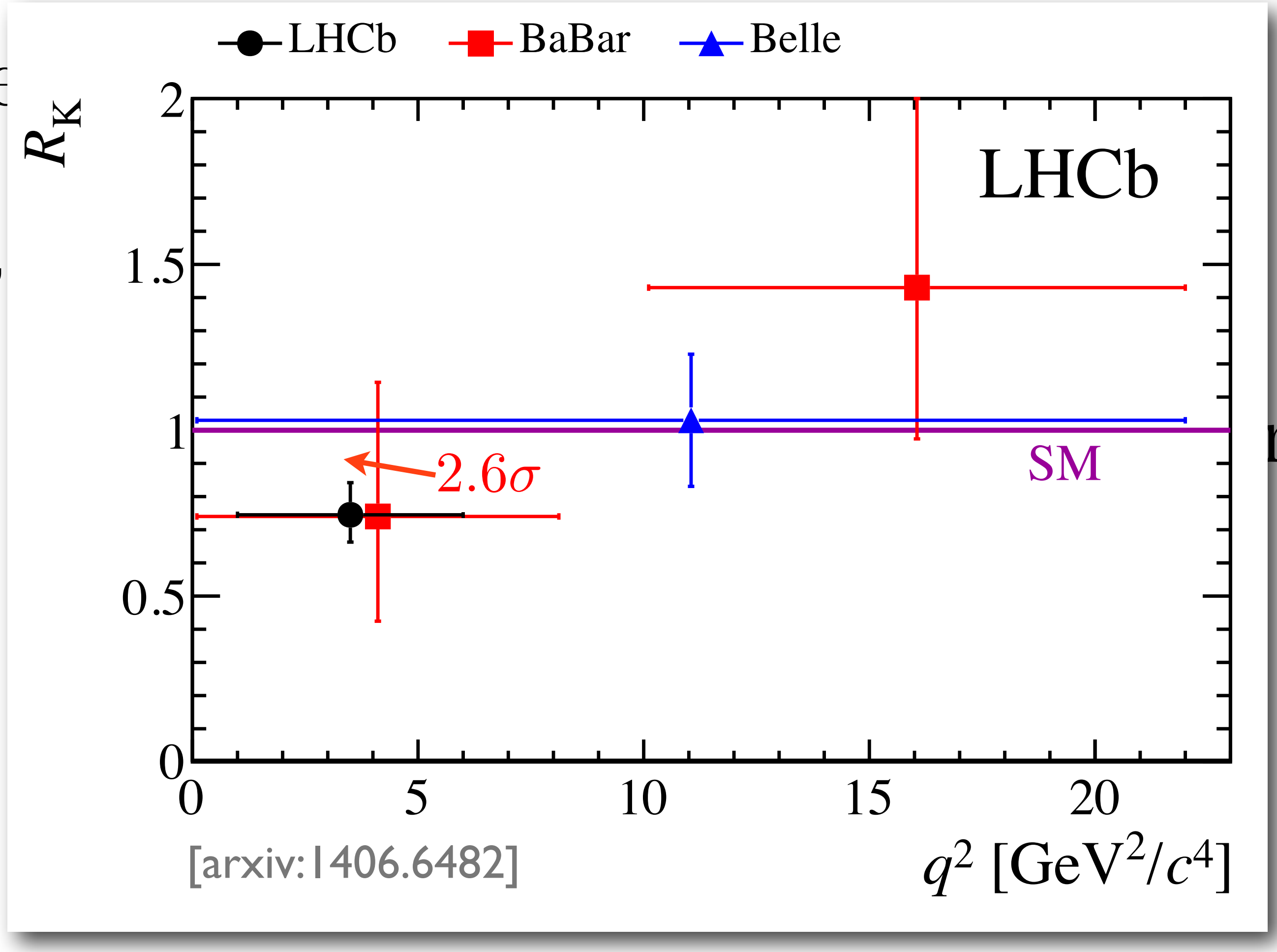
$$\mathcal{R}_K = \frac{\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathcal{B}(B^+\to K^+e^+e^-)} = 1 \pm \mathcal{O}(10^{-3}) \text{ in the SM}$$

NP in ΔF=1

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

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

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

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- Experimental bounds on

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

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

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

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- 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

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

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

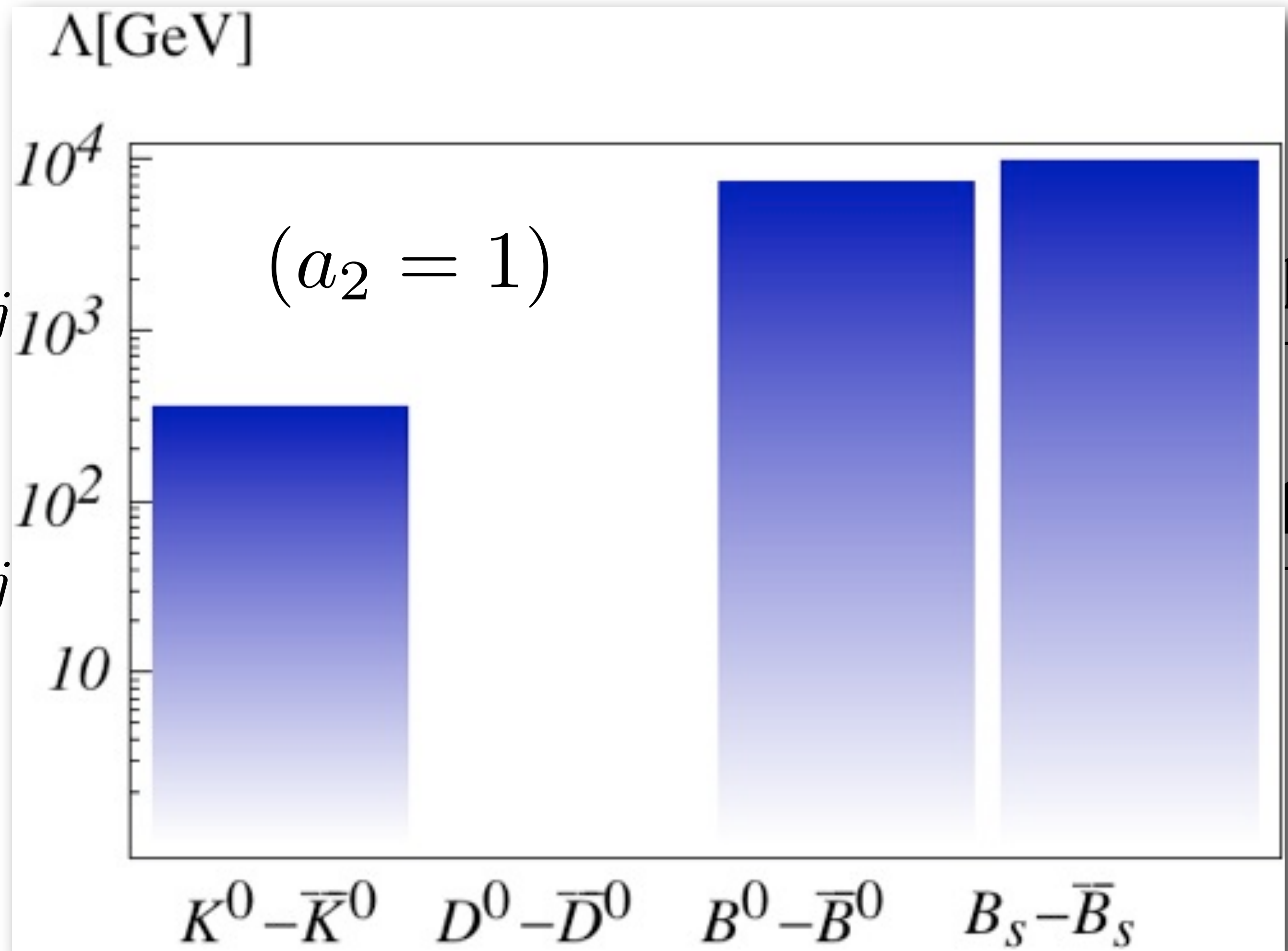
NP in Flavour

Minimal Flavour Hypothesis

- leading … udes

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

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



NP in Flavour

Minimal Flavour Hypothesis

- Example: Supersymmetry

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

- 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