

Flavour & New Physics

Flavour & New Physics

- How much can NP still contribute to flavour observables?

- Example:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.0021(12)$$

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

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 $B \rightarrow DK$ decays
- \Rightarrow allows to predict SM contributions also to loop suppressed observables!

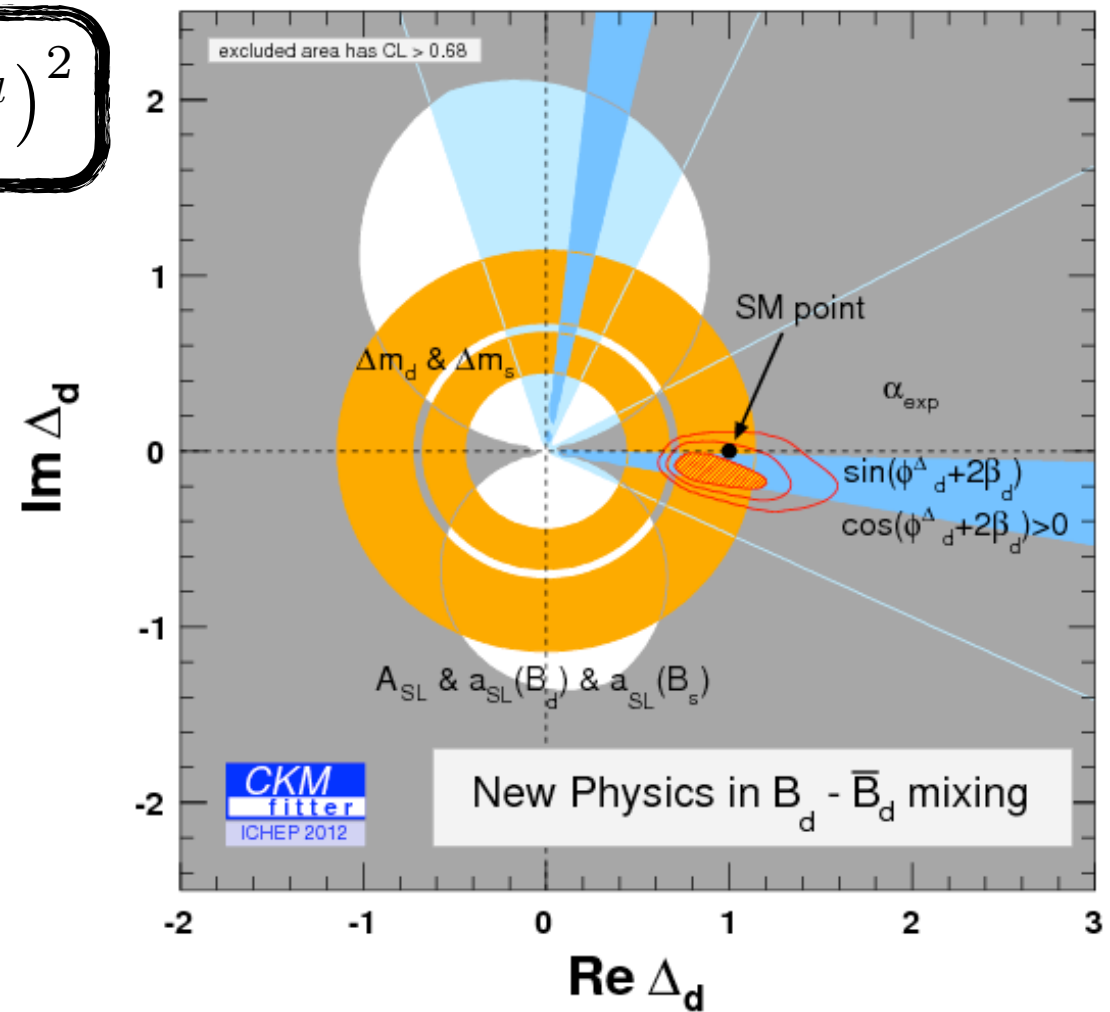
NP in B mixing

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

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

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

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



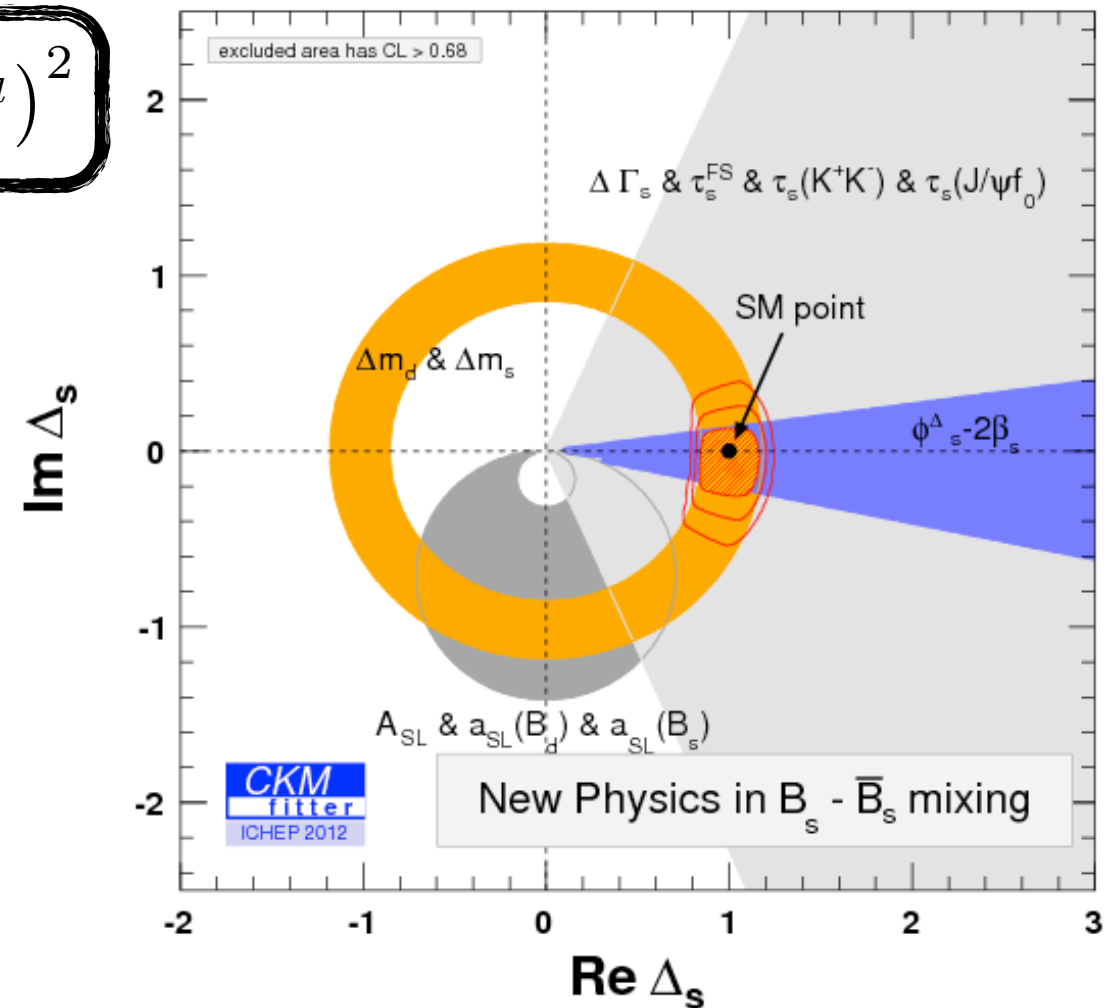
NP in B mixing

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

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

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

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



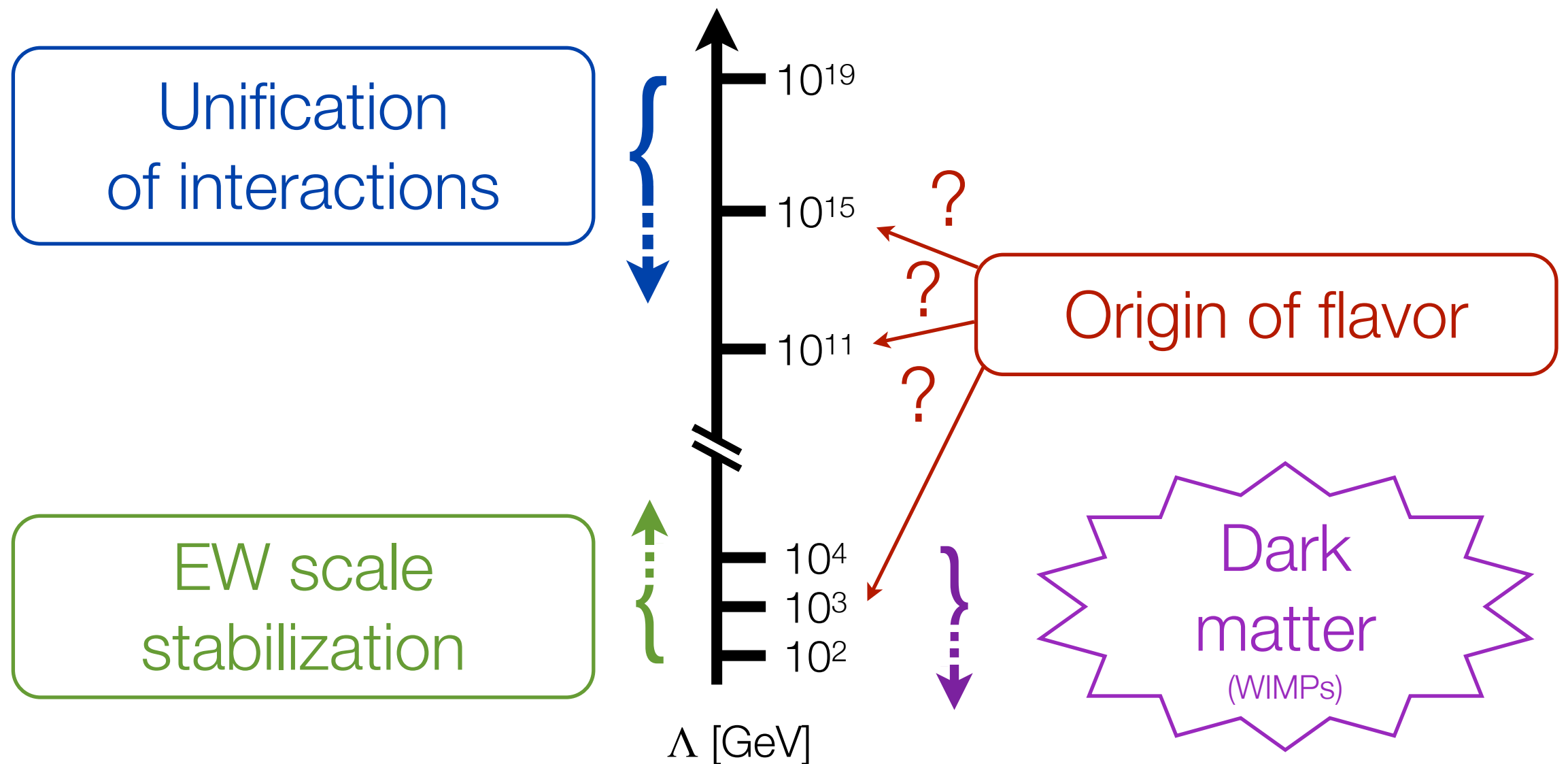
The NP flavour puzzle

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

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

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

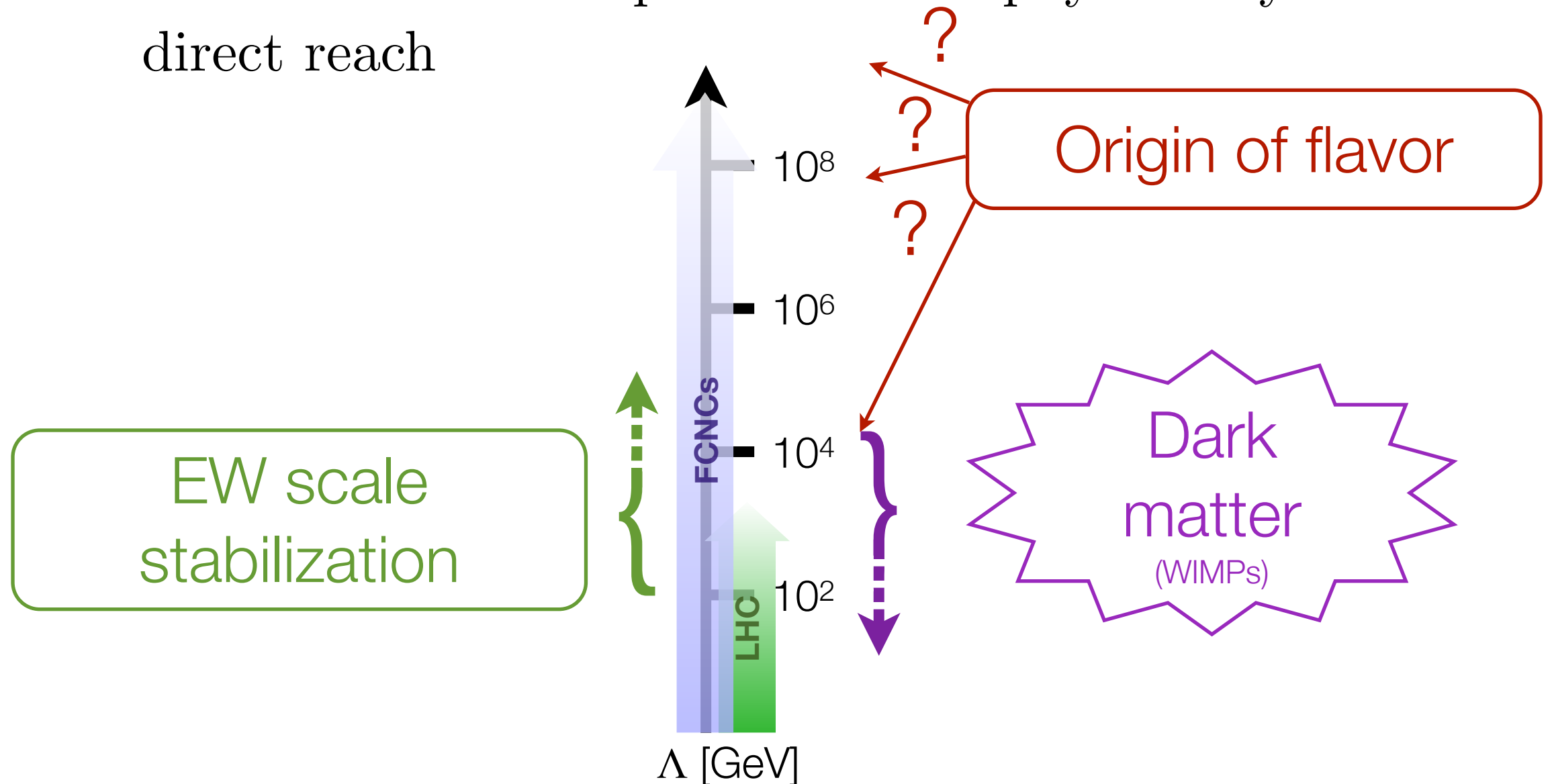
- NP flavour puzzle:

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

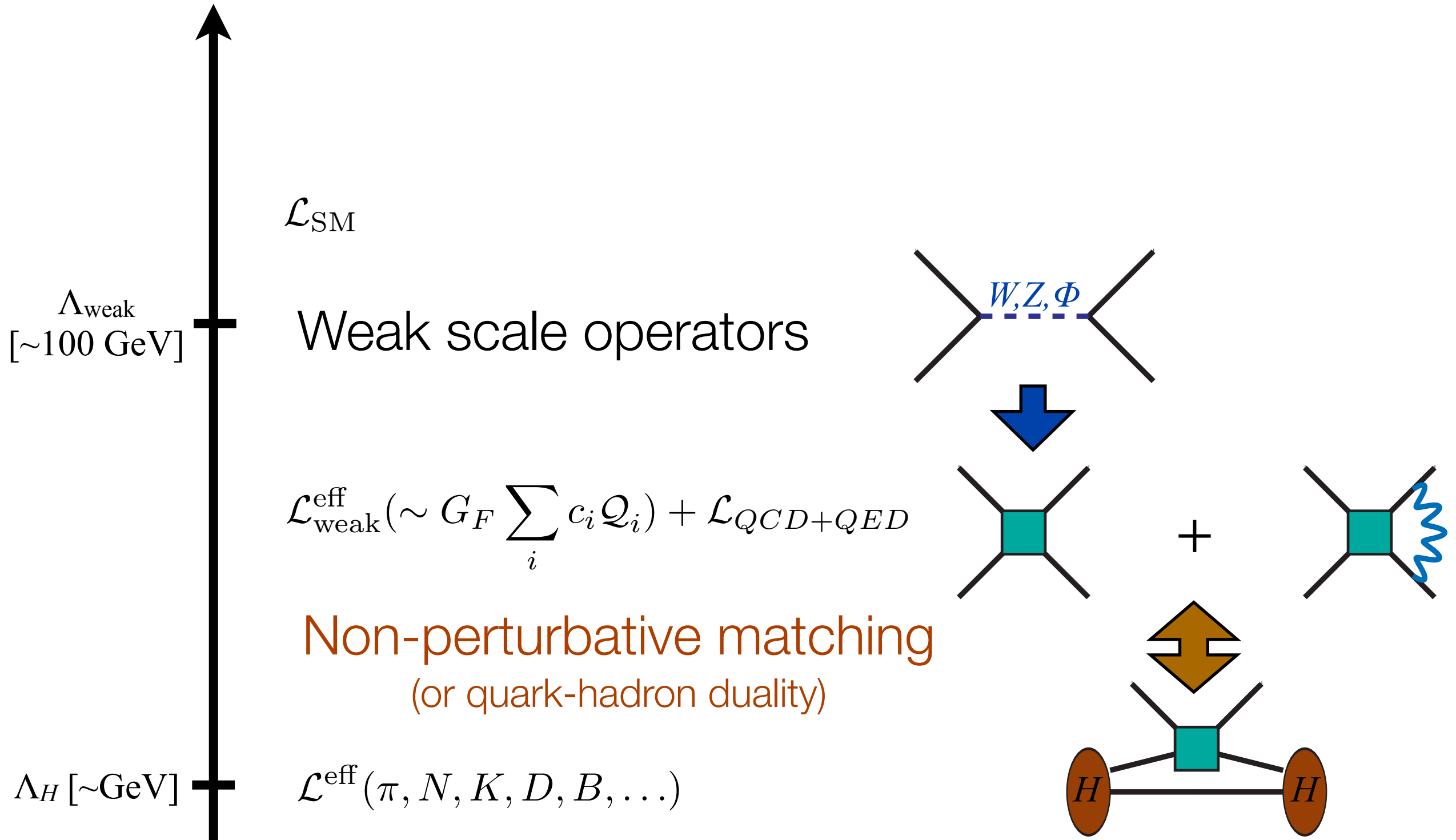
The NP flavour puzzle

SM as effective field theory

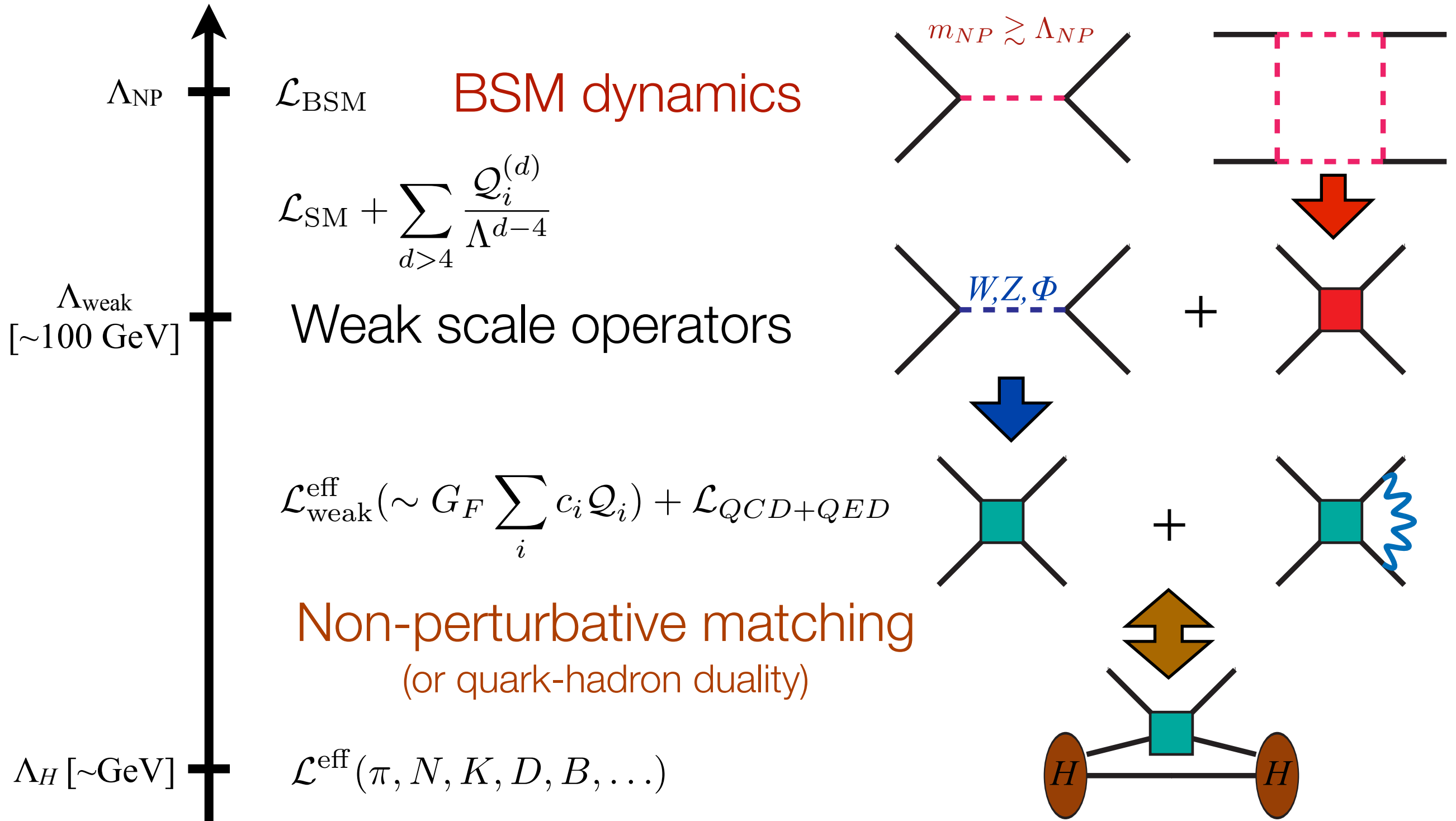
- Flavour as indirect probe of BSM physics beyond direct reach



(Over)constraining the SM flavor sector



(Over)constraining the SM flavor sector & NP



NP in $\Delta F=2$

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

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

$$\underbrace{\frac{(Y_u Y_u^*)_{ij}^2}{128\pi^2 m_t^2}}_{\text{}} \quad F(x) \sim \mathcal{O}(1)$$

$$F(\infty) = 1$$

NP in $\Delta F=2$

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

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$$\underbrace{\frac{(Y_u Y_u^*)_{ij}^2}{128\pi^2 m_t^2}}_{\text{}} \quad \begin{aligned} F(x) &\sim \mathcal{O}(1) \\ F(\infty) &= 1 \end{aligned}$$

- 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 $\Delta F=2$

$$\mathcal{L}_{\Delta F=2} = \frac{z_{sd}}{\Lambda_{\text{NP}}^2} (\bar{d}_L \gamma_\mu s_L)^2 + \frac{z_{cu}}{\Lambda_{\text{NP}}^2} (\bar{c}_L \gamma_\mu u_L)^2 + \frac{z_{bd}}{\Lambda_{\text{NP}}^2} (\bar{d}_L \gamma_\mu b_L)^2 + \frac{z_{bs}}{\Lambda_{\text{NP}}^2} (\bar{s}_L \gamma_\mu b_L)^2.$$

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CPC NP

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

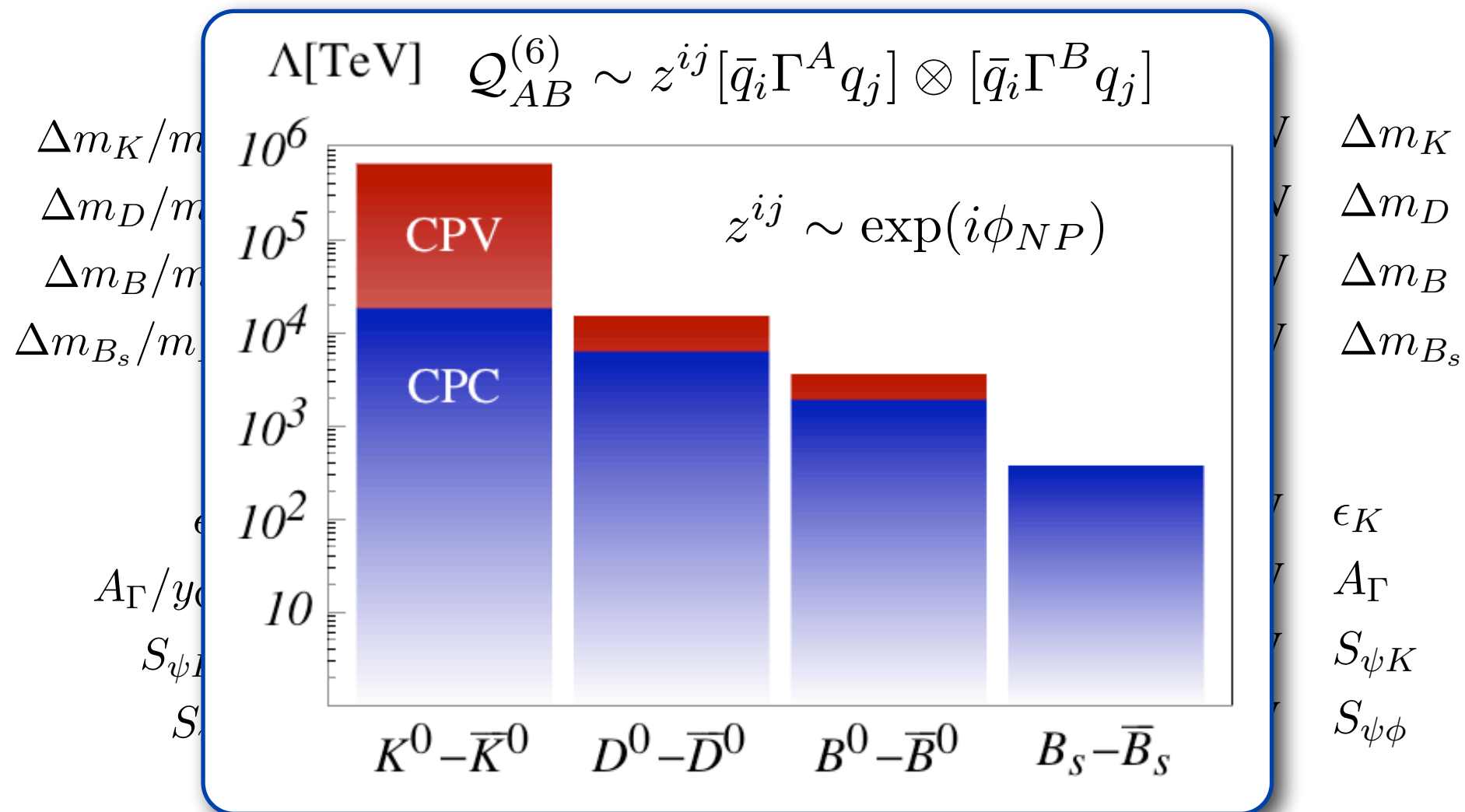
CPV NP

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

NP with a generic flavour structure is irrelevant for EW hierarchy

NP in $\Delta F=2$

$$\mathcal{L}_{\Delta F=2} = \frac{z_{sd}}{\Lambda_{\text{NP}}^2} (\bar{d}_L \gamma_\mu s_L)^2 + \frac{z_{cu}}{\Lambda_{\text{NP}}^2} (\bar{c}_L \gamma_\mu u_L)^2 + \frac{z_{bd}}{\Lambda_{\text{NP}}^2} (\bar{d}_L \gamma_\mu b_L)^2 + \frac{z_{bs}}{\Lambda_{\text{NP}}^2} (\bar{s}_L \gamma_\mu b_L)^2.$$



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CPC NP

$$\begin{array}{ll} \Delta m_K/m_K \sim 7.0 \times 10^{-15}, & z_{sd} \lesssim 8 \times 10^{-7} (\Lambda_{\text{NP}}/\text{TeV})^2, \\ \Delta m_D/m_D \sim 8.7 \times 10^{-15}, & z_{cu} \lesssim 5 \times 10^{-7} (\Lambda_{\text{NP}}/\text{TeV})^2, \\ \Delta m_B/m_B \sim 6.3 \times 10^{-14}, & z_{bd} \lesssim 5 \times 10^{-6} (\Lambda_{\text{NP}}/\text{TeV})^2, \\ \Delta m_{B_s}/m_{B_s} \sim 2.1 \times 10^{-12}, & z_{bs} \lesssim 2 \times 10^{-4} (\Lambda_{\text{NP}}/\text{TeV})^2, \end{array} \Rightarrow$$

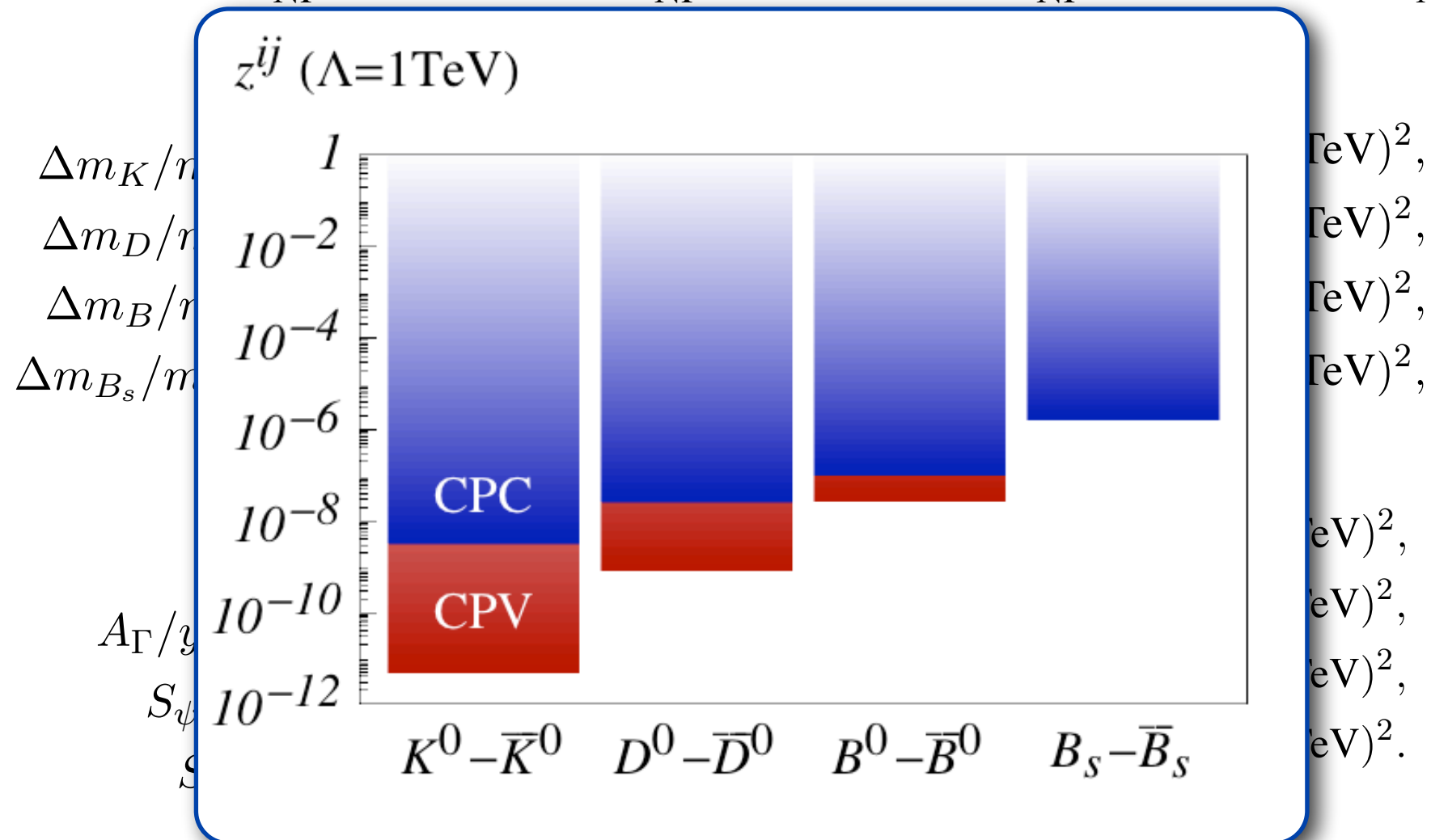
CPV NP

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

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

NP in $\Delta F=2$

$$\mathcal{L}_{\Delta F=2} = \frac{z_{sd}}{\Lambda_{\text{NP}}^2} (\bar{d}_L \gamma_\mu s_L)^2 + \frac{z_{cu}}{\Lambda_{\text{NP}}^2} (\bar{c}_L \gamma_\mu u_L)^2 + \frac{z_{bd}}{\Lambda_{\text{NP}}^2} (\bar{d}_L \gamma_\mu b_L)^2 + \frac{z_{bs}}{\Lambda_{\text{NP}}^2} (\bar{s}_L \gamma_\mu b_L)^2.$$



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$$\mathcal{L}_{\Delta F=2} = \frac{z_{sd}}{\Lambda_{\text{NP}}^2} (\bar{d}_L \gamma_\mu s_L)^2 + \frac{z_{cu}}{\Lambda_{\text{NP}}^2} (\bar{c}_L \gamma_\mu u_L)^2 + \frac{z_{bd}}{\Lambda_{\text{NP}}^2} (\bar{d}_L \gamma_\mu b_L)^2 + \frac{z_{bs}}{\Lambda_{\text{NP}}^2} (\bar{s}_L \gamma_\mu b_L)^2.$$

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

$$\begin{aligned} \Im(z_{sd}^{\text{SM}}) &\sim \frac{\lambda_t^2}{64\pi^2} |V_{td} V_{ts}^*|^2 \sim 10^{-10} \\ \Re(z_{sd}^{\text{SM}}) &\sim \frac{\lambda_c^2}{64\pi^2} |V_{cd} V_{cs}^*|^2 \sim 5 \times 10^{-9} \\ |z_{bd}^{\text{SM}}| &\sim \frac{\lambda_t^2}{64\pi^2} |V_{td} V_{tb}^*|^2 \sim 9 \times 10^{-8} \\ |z_{bs}^{\text{SM}}| &\sim \frac{\lambda_t^2}{64\pi^2} |V_{ts} V_{tb}^*|^2 \sim 3 \times 10^{-6} \end{aligned}$$

$$\begin{aligned} z_{sd} &\lesssim 8 \times 10^{-7} (\Lambda_{\text{NP}}/\text{TeV})^2, \\ z_{cu} &\lesssim 5 \times 10^{-7} (\Lambda_{\text{NP}}/\text{TeV})^2, \\ z_{bd} &\lesssim 5 \times 10^{-6} (\Lambda_{\text{NP}}/\text{TeV})^2, \\ z_{bs} &\lesssim 2 \times 10^{-4} (\Lambda_{\text{NP}}/\text{TeV})^2, \\ z_{sd}^I &\lesssim 6 \times 10^{-9} (\Lambda_{\text{NP}}/\text{TeV})^2, \\ z_{cu}^I &\lesssim 1 \times 10^{-7} (\Lambda_{\text{NP}}/\text{TeV})^2, \\ z_{bd}^I &\lesssim 1 \times 10^{-6} (\Lambda_{\text{NP}}/\text{TeV})^2, \\ z_{bs}^I &\lesssim 2 \times 10^{-4} (\Lambda_{\text{NP}}/\text{TeV})^2. \end{aligned}$$

NP in $\Delta F=1$

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

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

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

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

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

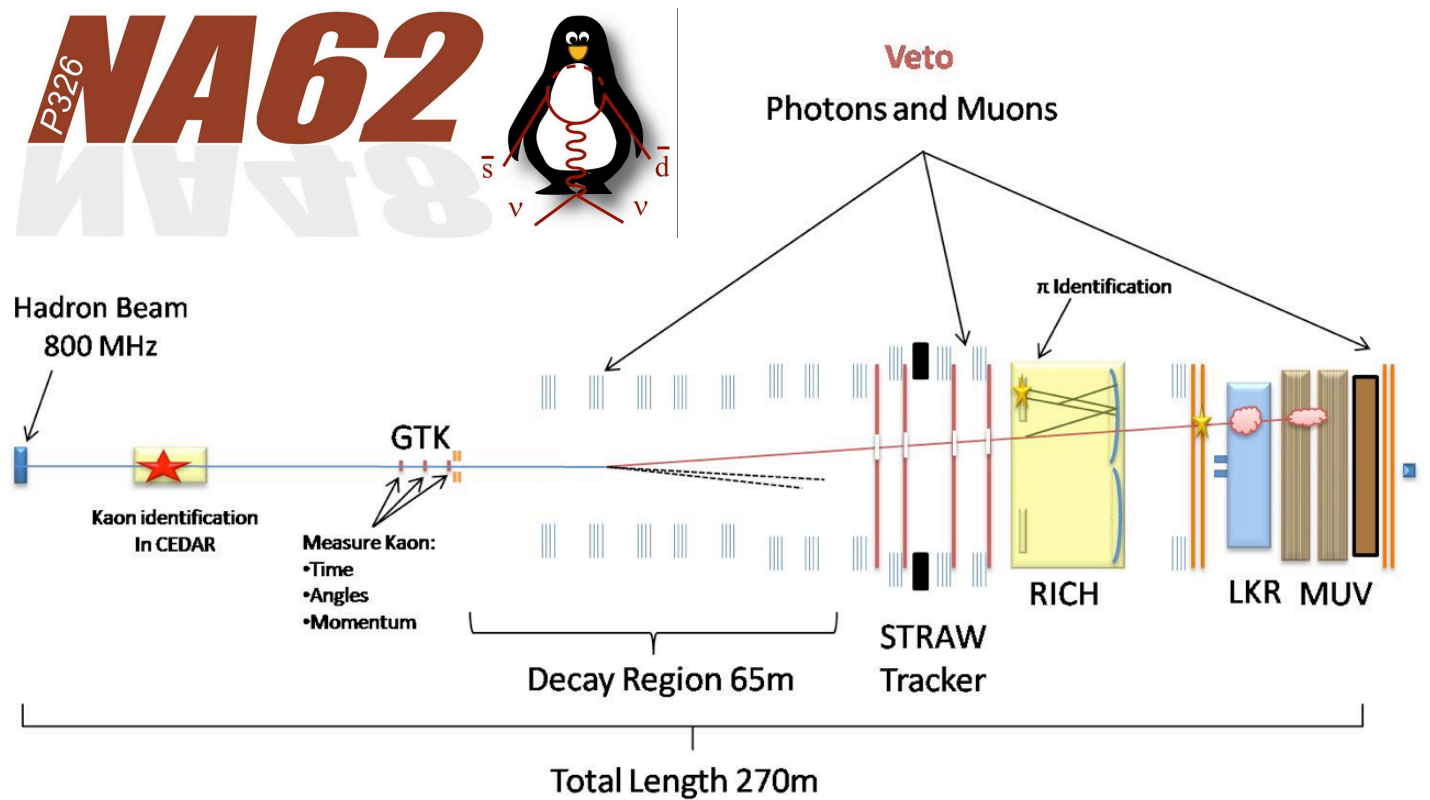
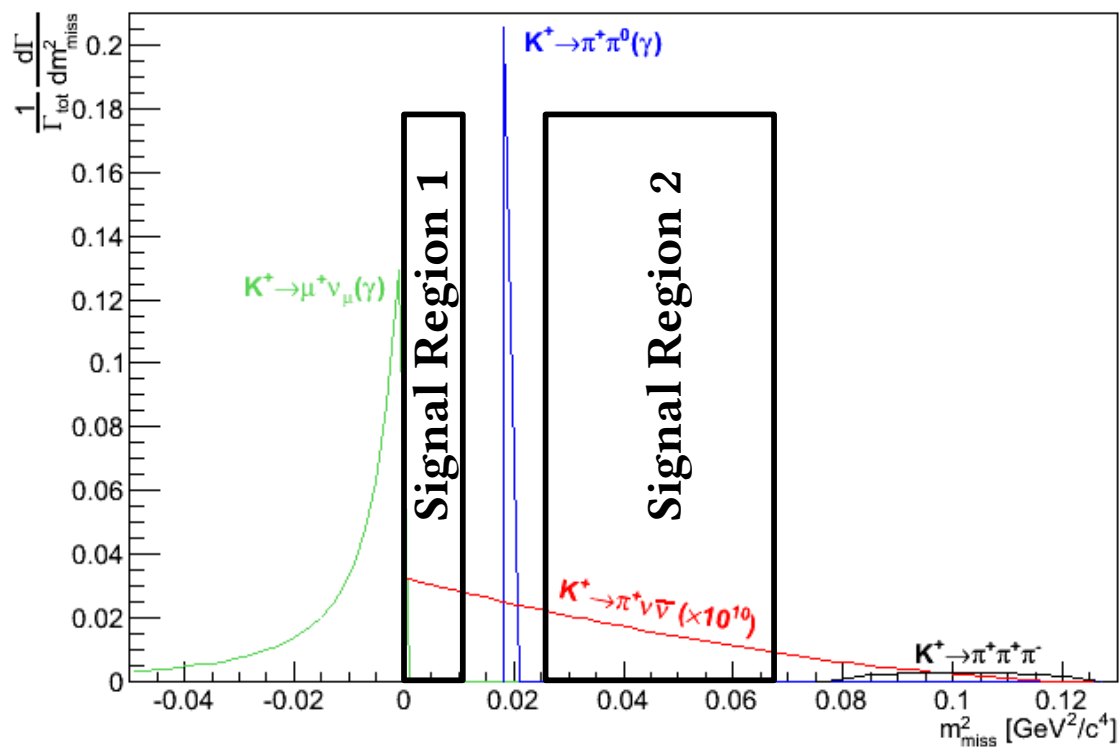
$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \sim 8 \times 10^{-11},$$

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

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

NP in $\Delta F=1$

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



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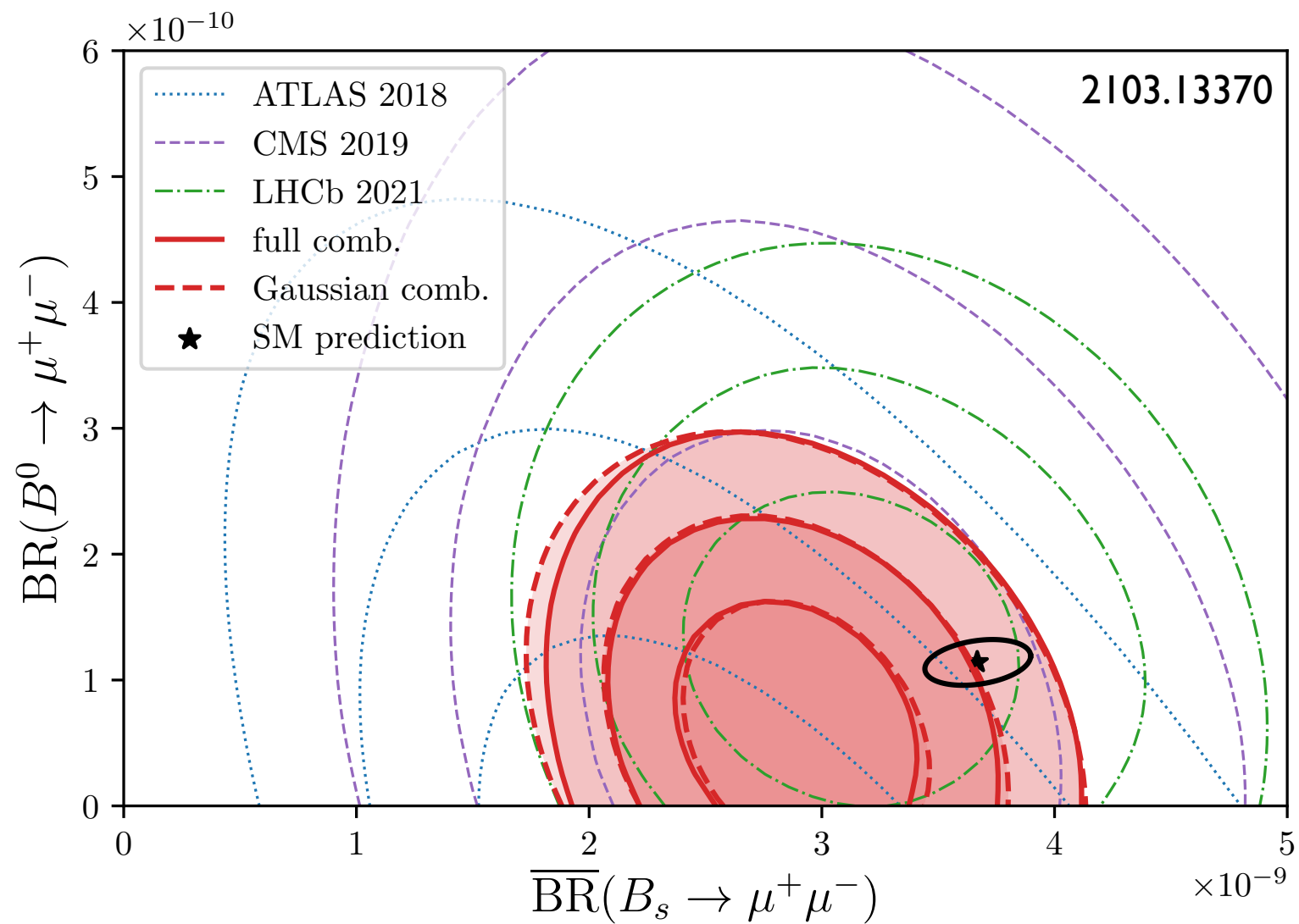
Na62 Physics Handbook Workshop

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$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{Exp}} = 11.0_{-3.5}^{+4.0} \times 10^{-11} \Rightarrow \Lambda_{NP} \gtrsim \sqrt{y_{sd}} 2 \times 10^2 \text{ TeV}$$

NP in $\Delta F=1$

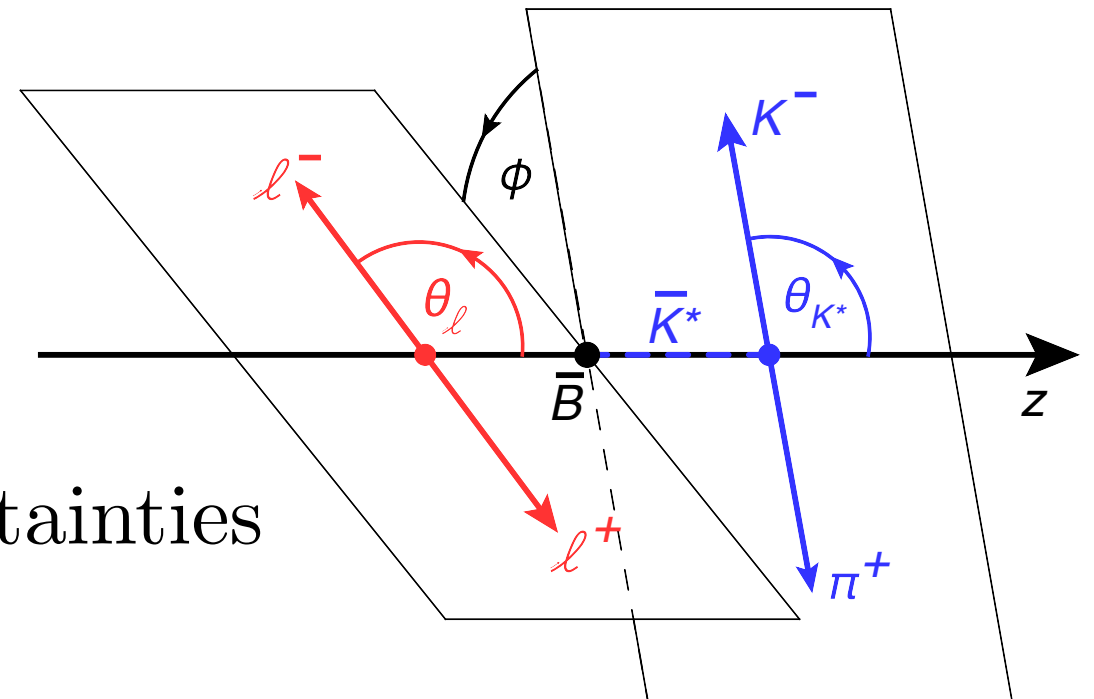
$$\mathcal{L}_{\Delta F=1} = y_{sd} \frac{v^2}{\Lambda_{NP}^2} \frac{g}{c_W} \bar{d}_L \not{Z} s_L + y_{cu} \frac{v^2}{\Lambda_{NP}^2} \frac{g}{c_W} \bar{u}_L \not{Z} c_L + \boxed{y_{bd} \frac{v^2}{\Lambda_{NP}^2} \frac{g}{c_W} \bar{d}_L \not{Z} b_L + y_{bs} \frac{v^2}{\Lambda_{NP}^2} \frac{g}{c_W} \bar{s}_L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



NP in $\Delta F=1$

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

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

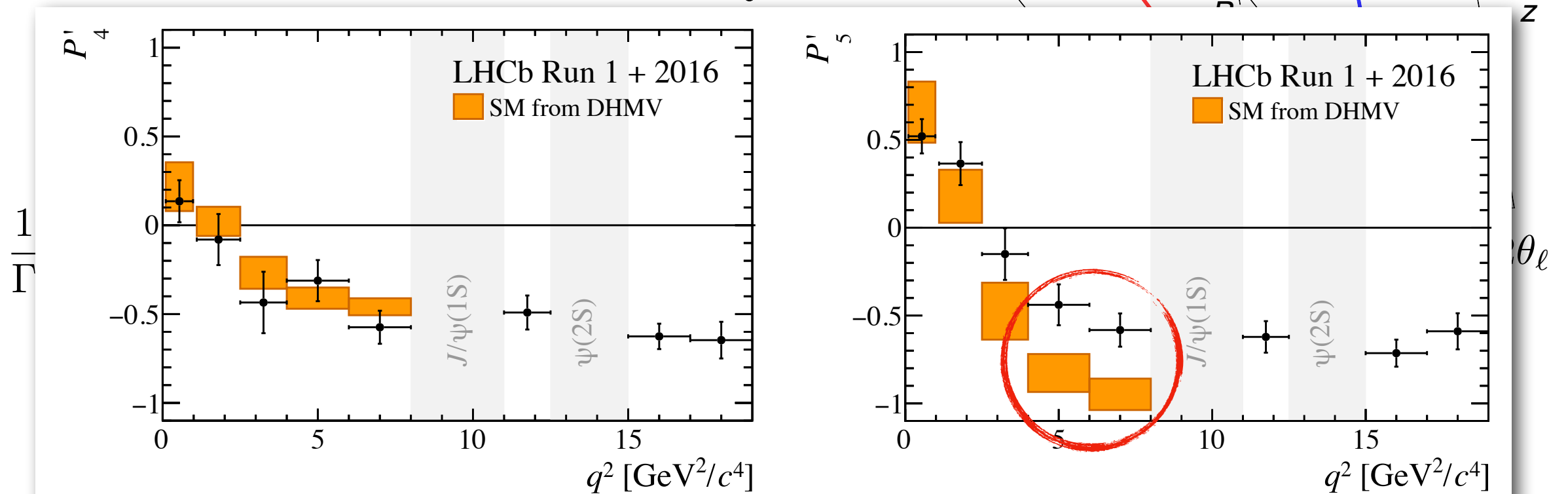
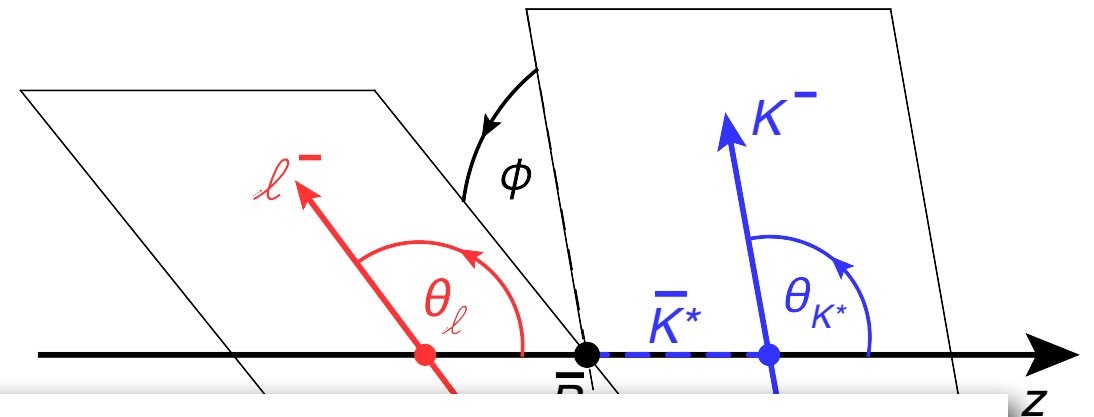


$$\begin{aligned} \frac{1}{\Gamma} \frac{d^3(\Gamma + \Gamma)}{d \cos \theta_\ell d \cos \theta_K d \Phi} &= \frac{9}{32\pi} \left[\frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell \right. \\ &\quad - F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\Phi \\ &\quad + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \Phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \Phi \\ &\quad + \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \Phi \\ &\quad \left. + S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \Phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\Phi \right] \end{aligned}$$

NP in $\Delta F=1$

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

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



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

2003.04831

NP in $\Delta F=1$

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

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

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

NP in $\Delta F=1$

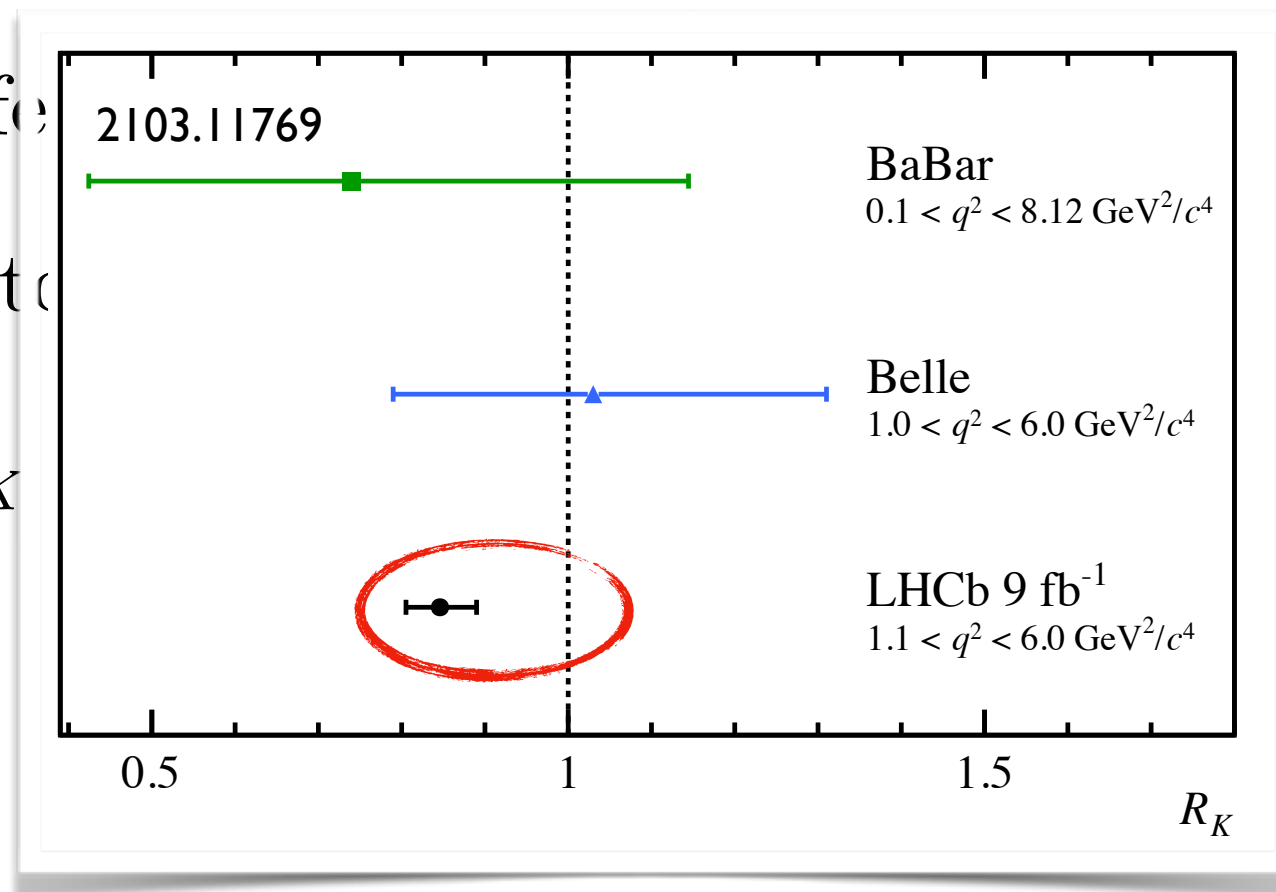
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- $B_0 \rightarrow K^{*0} [\rightarrow K^+ \pi^-] \mu^+ \mu^-$, $B^+ \rightarrow K^+ \mu^+ \mu^- / e^+ e^-$

- difference

- leptonic

\mathcal{R}_K



in the SM

Conclusions

- Absence of significant deviations from SM in quark flavour physics is key constraint on any extension of SM
- 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