FLAVOR PHYSICS BEYOND THE STANDARD MODEL

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Standard Model of Particle Physics

renormalizable quantum field theory + local symmetry

$$SU(3) \times SU(2) \times U(1) \rightarrow SU(3) \times U(1)$$

$$\mathcal{L} = -\frac{1}{4}F^2 + \bar{\psi} i \not{D} \psi + \frac{1}{2}(D\Phi)^2 + \bar{\psi} Y \psi \Phi + \mu^2 \Phi^2 - \lambda \Phi^4$$

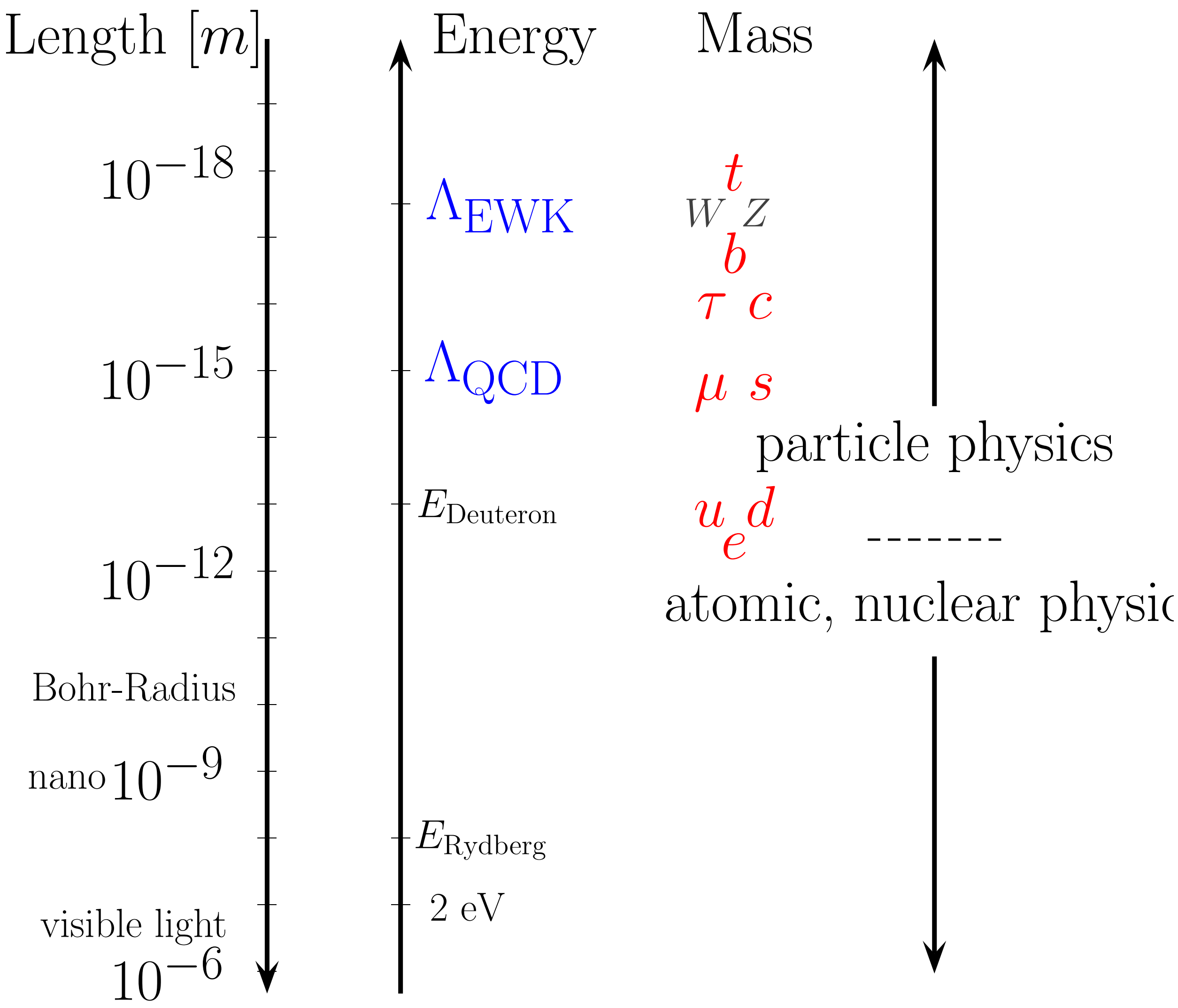
F: carriers of strong, weak and electromagnetic force

Φ: Higgs particle

ψ: fundamental matter: quarks + leptons

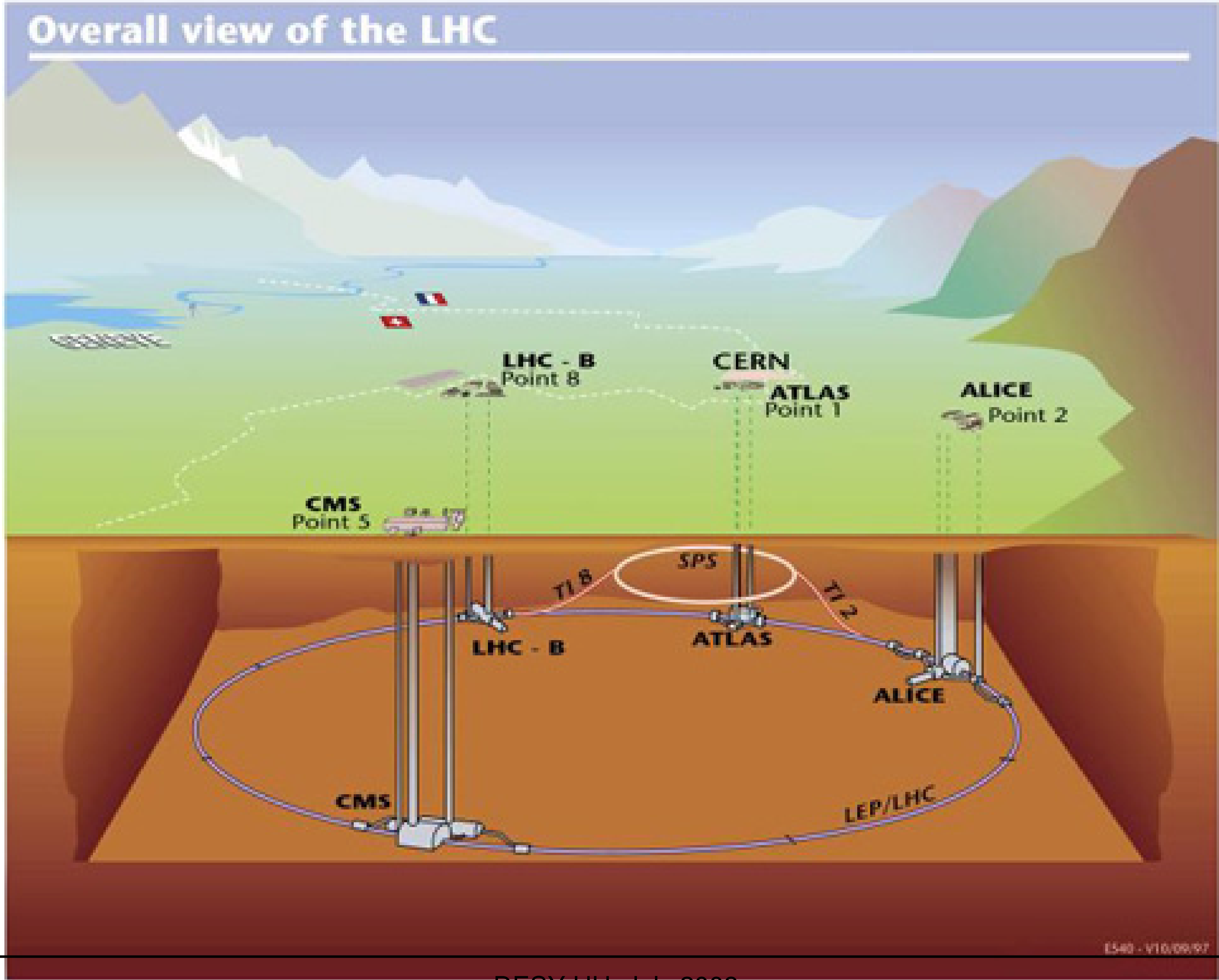
$$\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix} \qquad \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

Shortest Distance=Highest Energies



Physics at the LHC (2008 – this Year !)

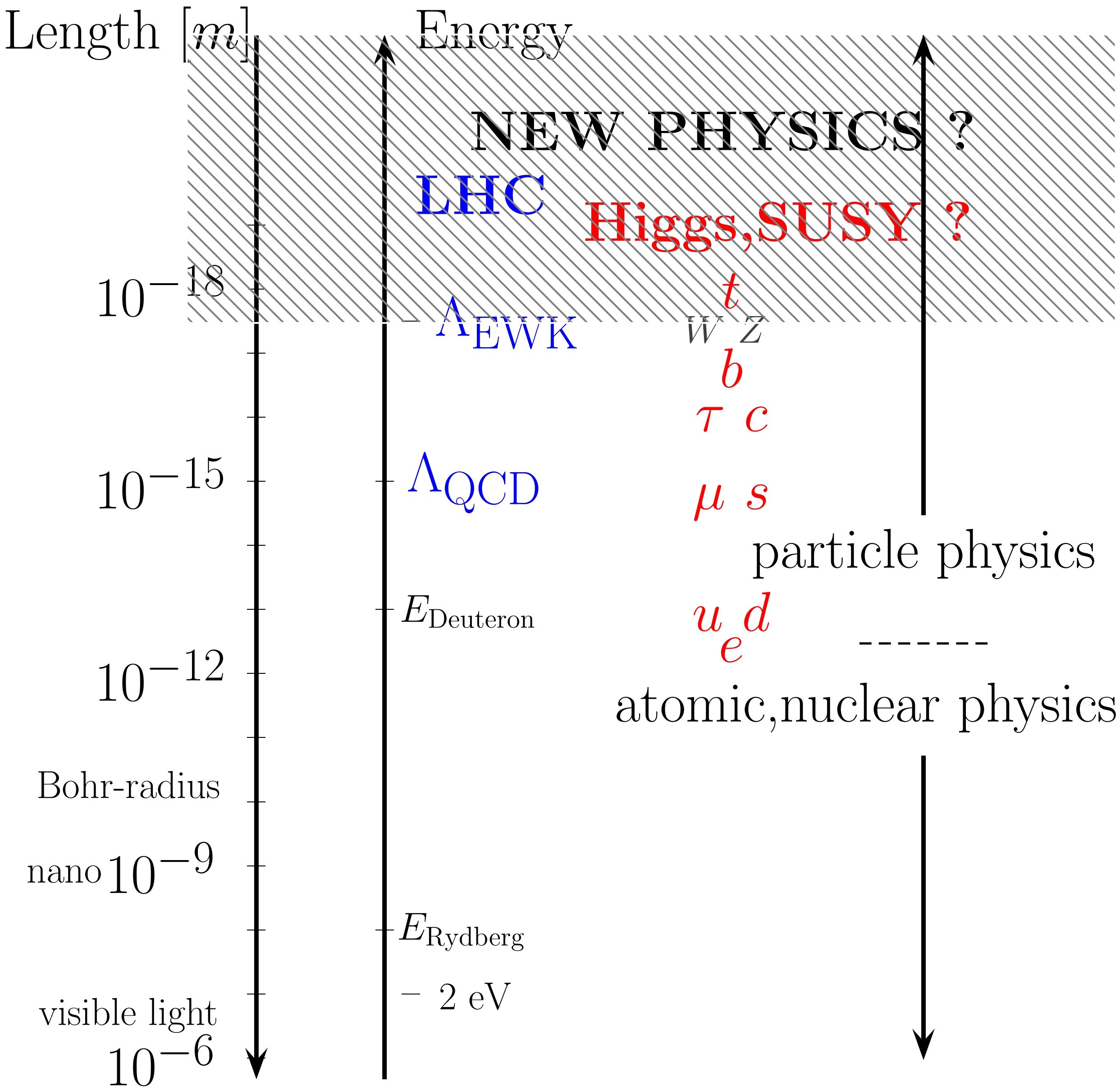
pp-collisions with 7 TeV on 7 TeV $\qquad$ 1 TeV = 1000 m_{proton}



Beyond the Standard Model (SM)

- dark matter $\Omega_{DM} \simeq 22\%$
- antimatter-matter asymmetry in the universe $(n - \bar{n})/s \simeq 10^{-10}$
- neutrino masses
- unification of forces
- flavor: $m_u/m_t \simeq 10^{-5}$, mixing
- strong CP problem: why is $\bar{\Theta} \lesssim 10^{-10}$ and $\delta_{CKM} = \mathcal{O}(1)$?
- Higgs mass $m_h^2 \ll \Lambda^2$
- gravity, dark energy

SM is an effective theory up to $\mathcal{O}(100)$ GeV


Length [m]
Energy
NEW PHYSICS ?
LHC
Higgs,SUSY ?
10^{-18}
t
Λ_{EWK}
W Z
b
τ c
10^{-15}
Λ_{QCD}
μ s
particle physics
E_{Deuteron}
u d
e

10^{-12}
atomic,nuclear physics
Bohr-radius
nano 10^{-9}
E_{Rydberg}
2 eV
visible light
10^{-6}

Flavor and CP violation within the Standard Model

$$\mathcal{L} \supset \bar{Q} i \not{D} Q - \bar{Q} Y_u \langle h^C \rangle U - \bar{Q} Y_d \langle h \rangle D \qquad \langle h \rangle \simeq 174 \text{ GeV}$$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix} ; \quad \lambda \simeq 0.22$$

3 generations $=$ 10 parameters in flavor $\&$ CP sector: 6 masses, 3 angles and 1 phase in CKM-matrix unitary, complex, hierarchical, known

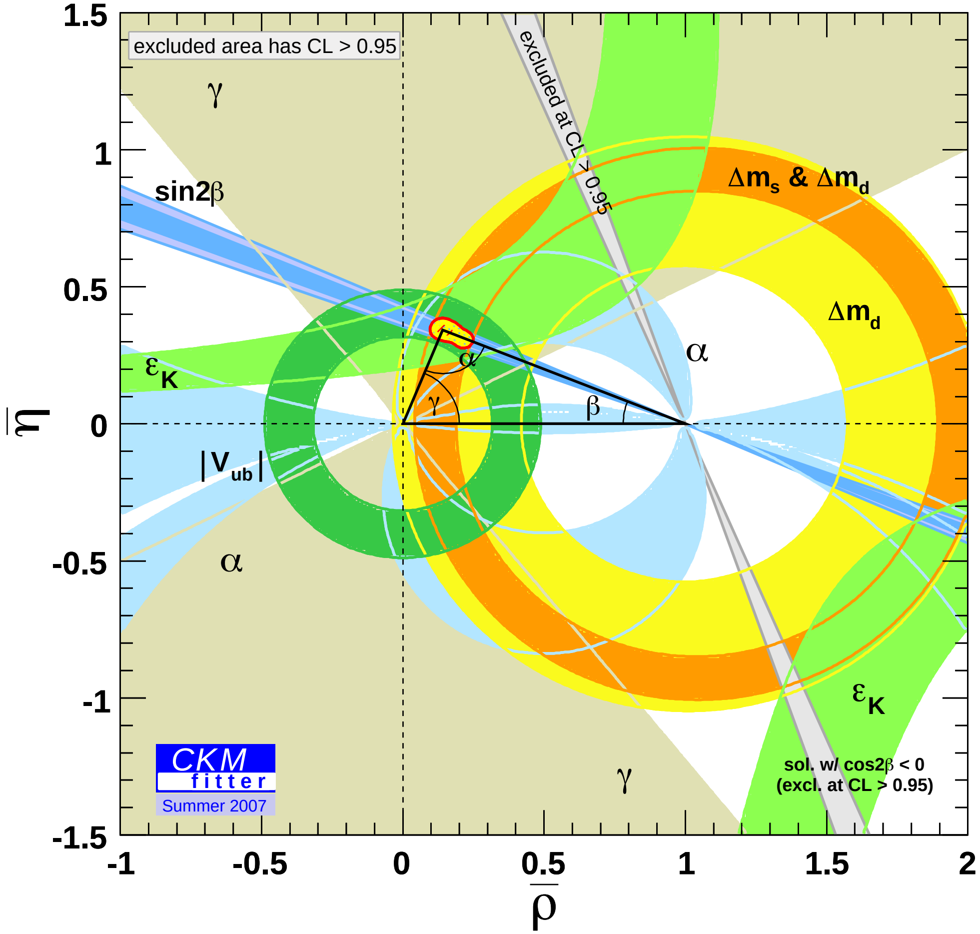
$|V_{us}| = 0.2257(21), \quad |V_{cb}| = 41.6 \pm 0.6 \cdot 10^{-3}, \quad |V_{ub}| = 4.31 \pm 0.3 \cdot 10^{-3}$

β(measured) $= (21.23^{+1.03}_{-0.99})^\circ$

-third generation is decoupled from the first two

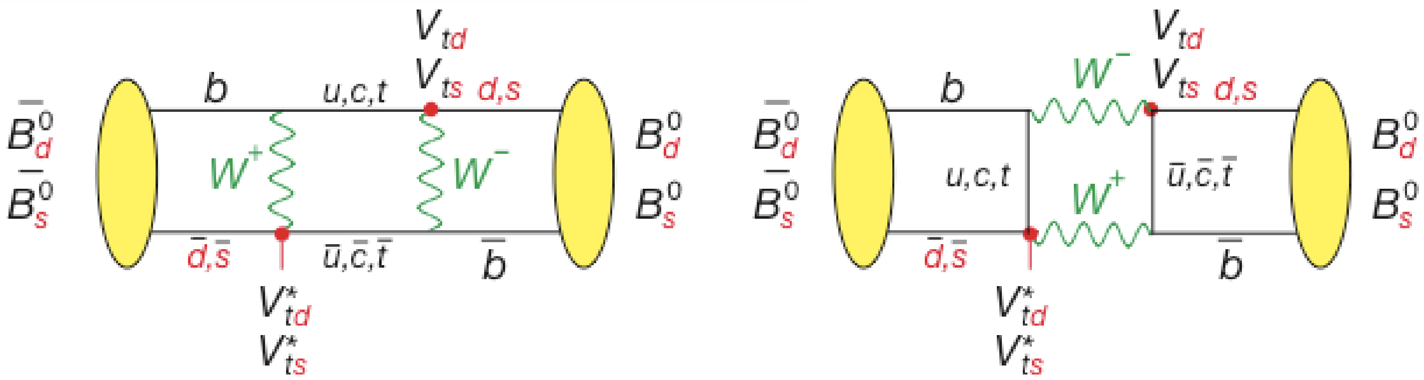
-CP phase is order one

the unitarity triangle $V_{ub}V_{ud}^* + V_{cb}V_{cd}^* + V_{tb}V_{td}^* = 0$



-fit consistent; contains tree and loop processes of B,K-mesons

New Physics in rare Processes, Where is it ?



$$\Delta m_s^{\rm SM} \sim \quad (V_{tb}^* V_{ts})^2 \times \frac{g^4}{16\pi^2} \quad \times \frac{(\bar{b}\Gamma s)(\bar{b}\Gamma' s)}{m_W^2}$$

$$\Delta m_s^{\rm NP} \sim \quad \text{flavor} \quad \times \text{loop/tree} \times \frac{(\bar{b}\Gamma s)(\bar{b}\Gamma' s)}{\Lambda^2}$$

Λ: scale of New Physics; $\quad m_W = 80.4$ GeV

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	New Physics from loops	tree level New Physics
$B_s - \bar B_s$	$\Lambda \gtrsim m_W/\lvert V_{ts}\rvert \sim O(2-3)$ TeV	$\Lambda \gtrsim 4\pi m_W/\lvert V_{ts}\rvert \sim O(30)$ TeV
$B_d - \bar B_d$	$\Lambda \gtrsim m_W/\lvert V_{td}\rvert \sim O(10-15)$ TeV	$\Lambda \gtrsim 4\pi m_W/\lvert V_{td}\rvert \sim O(100)$ TeV
“SM” flavor	$\Lambda \gtrsim m_W \sim O(100)$ GeV	$\Lambda \gtrsim 4\pi m_W \sim O(1)$ TeV

With generic flavor: $\Lambda \gg \sqrt{s_{LHC}} \sim \Lambda_{EWKSB}$

flavor and CP in SM: $-\mathcal{L}_Y = \bar{Q} Y_U h^C U + \bar{Q} Y_D h D + \bar{L} Y_E h E + h.c.$

flavor symmetry: $U(3)^5 \stackrel{Y}{\rightarrow} U(1)_B \times U(1)_L \times U(1)_Y$

non-abelian quark part: $G_F \equiv SU(3)_Q \times SU(3)_D \times SU(3)_U$

Yukawas are spurions of G_F: $Y_D(3, \bar{3}, 1)$, $Y_U(3, 1, \bar{3})$

Minimal Flavor Violation (MFV)= Y_D, Y_U are the only spurions of flavor G_F breaking Chivukula, Georgi '87; d'Ambrosio et al '02

MFV is property of the Standard Model.

MFV: potential organizing principle for New Physics.

non-symmetry based definitions: Ali,London '99; Buras^2 '00

What does MFV imply for SUSY? Simplification !

superpotential ($N = 1$, unbroken R-parity):

$$W_{MSSM} = QY_u H_u U + QY_d H_d D + LY_e H_d E + \mu H_d H_u$$

MFV !

SUSY-breaking constrained by MFV:

$$\tilde{Q}^\dagger \tilde{m}_Q^2 \tilde{Q} + \tilde{U}^\dagger \tilde{m}_U^2 \tilde{U} + \tilde{D}^\dagger \tilde{m}_D^2 \tilde{D} + (A_u \tilde{Q} H_u \tilde{U}^* + A_d \tilde{Q} H_d \tilde{D}^* + h.c.)$$

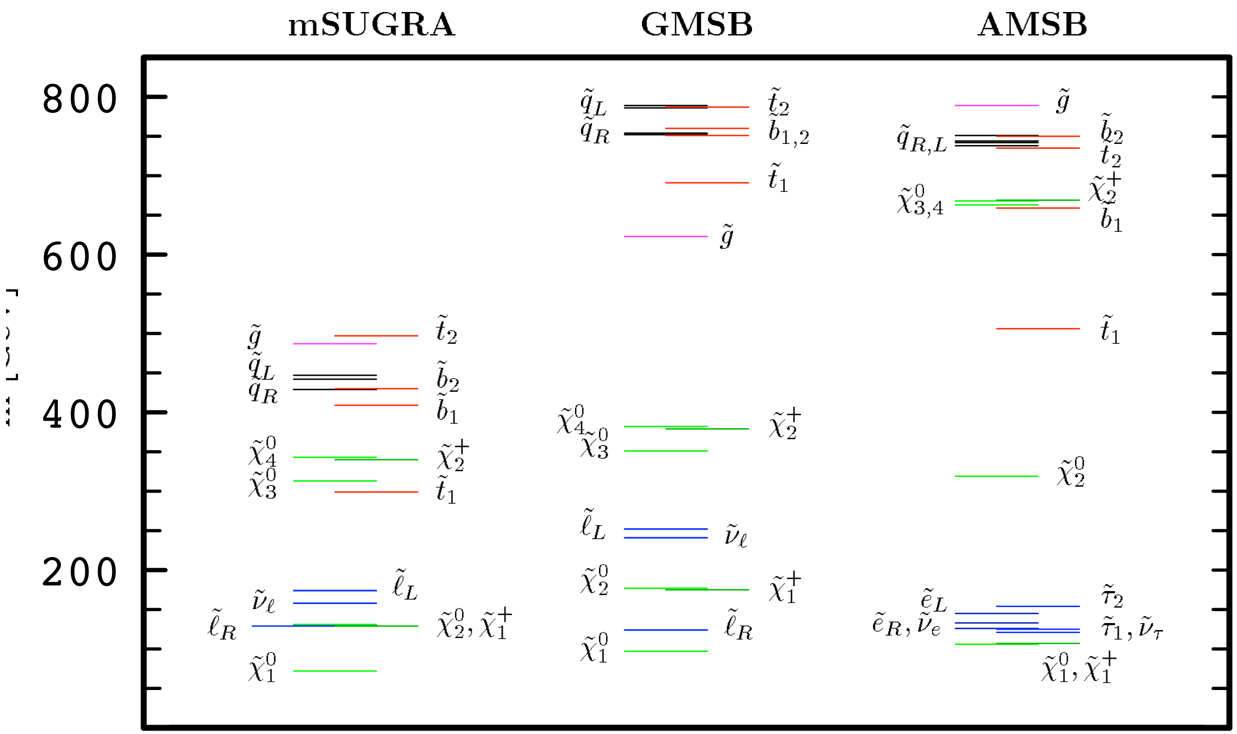
$$\begin{aligned}
\tilde{m}_Q^2 &= \tilde{m}^2 (a_1 \mathbf{1} + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger) \\
\tilde{m}_U^2 &= \tilde{m}^2 (a_2 \mathbf{1} + b_5 Y_u^\dagger Y_u) \\
\tilde{m}_D^2 &= \tilde{m}^2 (a_3 \mathbf{1} + b_6 Y_d^\dagger Y_d) \\
A_u &= A(a_4 \mathbf{1} + b_7 Y_d Y_d^\dagger) Y_u \\
A_d &= A(a_5 \mathbf{1} + b_8 Y_u Y_u^\dagger) Y_d
\end{aligned}$$

D'Ambrosio et al '02

- 3rd generation decoupled (via V_{CKM})
- highly degenerate squarks of 1st and 2nd generation:

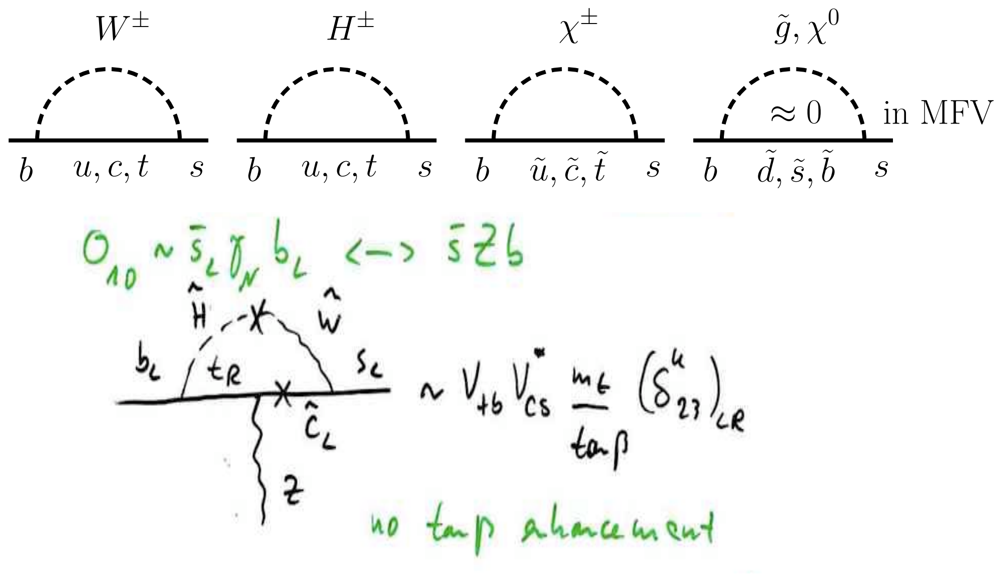
$\Delta m/m_0 \sim \lambda_c^2/2$; $\Delta m < 1$ GeV GH,Schmaltz '01

-squark spectrum is approx. 10+2 (8+4 for large $\tan\beta$)



TESLA TDR Part III '01

FCNC quantum loops:

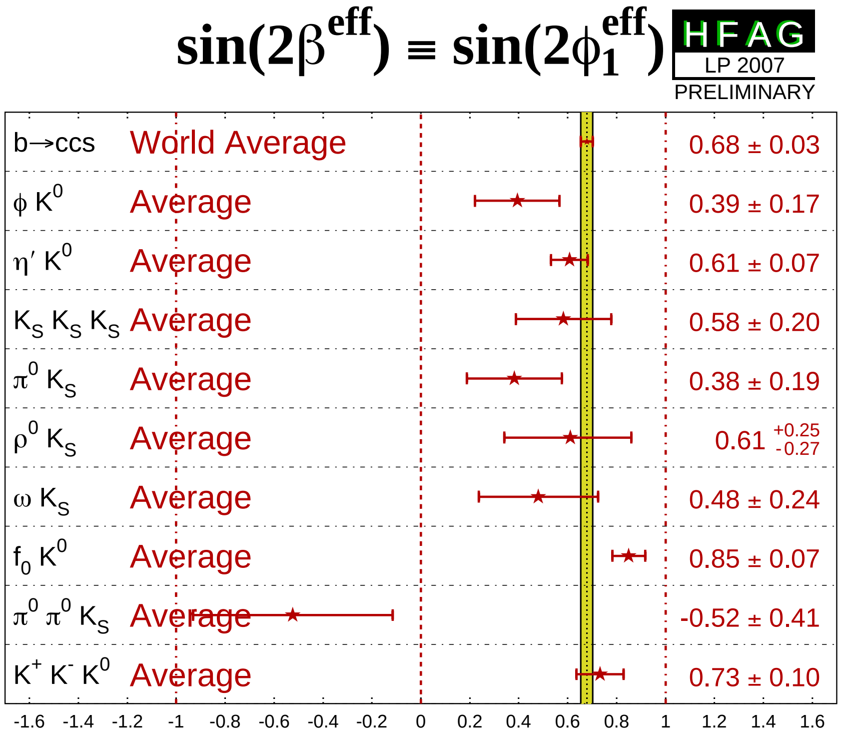


constraints from K,D,B-physics "penguins", meson-mixing

potentially huge effects if flavor is not minimally broken.

ongoing tests at B-factories and Tevatron; extended searches at LHC

Challenges for Minimal Flavor Violation



$$\eta_{CP} \sin 2\beta(\underbrace{(\bar{s}s)K_S}_{FCNC}) = \sin 2\beta(\underbrace{(\bar{c}c)K_S}_{tree}) + |\underbrace{\frac{V_{ub}V_{us}^*}{V_{tb}V_{ts}^*}}_{0.02}| \cdot \#(hadronic)$$

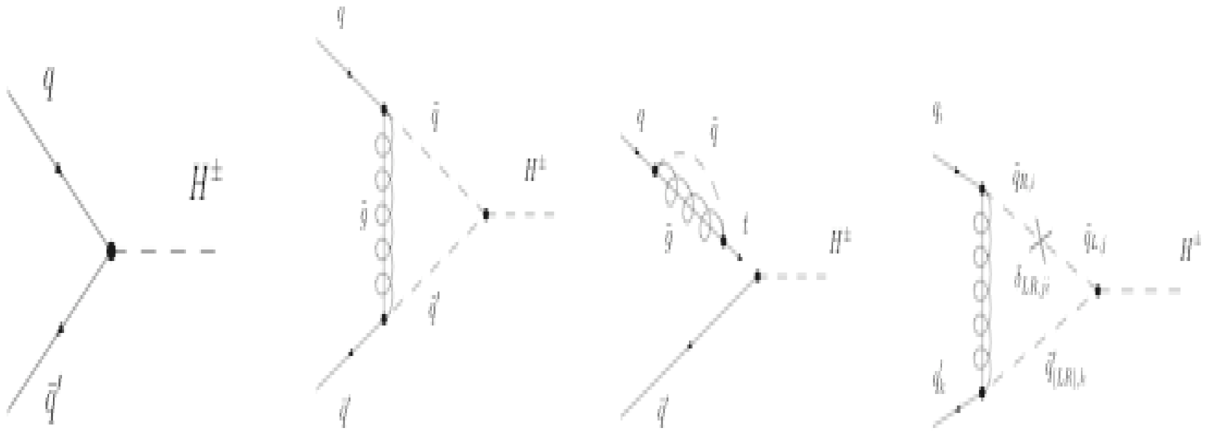
non-CKM CP-phases, right-handed currents, CKM-links broken, e.g., $\mathcal{B}(B_d \to \mu\mu)/\mathcal{B}(B_s \to \mu\mu) \neq |f_{B_d} V_{td}|^2 / |f_{B_s} V_{ts}|^2$

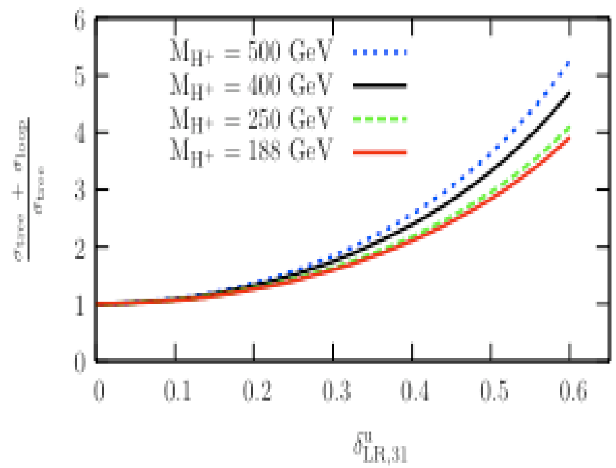
Testing MFV: 2. Production of Heavy Particles

potentially huge effects if flavor is not minimally broken.

MFV-null test: if we see signal in particular reaction, MFV (or MSSM) must be broken:

Charged-Higgs-production with or without flavor $pp \to H^+X$, $pp \to H^+ + jet + X$ Diaz-Cruz,He,Yuan; Dittmaier,GH,Plehn,Spannowsky '07





sensitive to flavor mixing essentially unconstrained by K,D,B-physics

Measuring MFV Mixing at the LHC

In MFV, mixing between third and other generations is suppressed:

$$\tilde{m}_Q^2 = \tilde{m}^2(a_1\mathbf{1} + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger) \qquad (\tilde{m}_Q^2)_{23} = \tilde{m}^2 b_2 \lambda_b^2 V_{cb} V_{tb}^*$$

There is an opportunity to measure the mixing because it is so small: measure lifetime instead of branching ratio GH,Nir '08

This is a counterexample to the lore that colliders determine only masses, and mixings are measured in low energy experiments

requirement: $\tilde{t} \to c\chi^0$ dominant decay & sufficiently suppressed rate

stop lifetime $\tau_{\tilde{t}} \sim \text{ ps} \left(\frac{m_{\tilde{t}}}{100\text{ GeV}}\right)\left(\frac{0.03}{\Delta m/m_{\tilde{t}}}\right)^2\left(\frac{10^{-5}}{Y}\right)^2$ is long

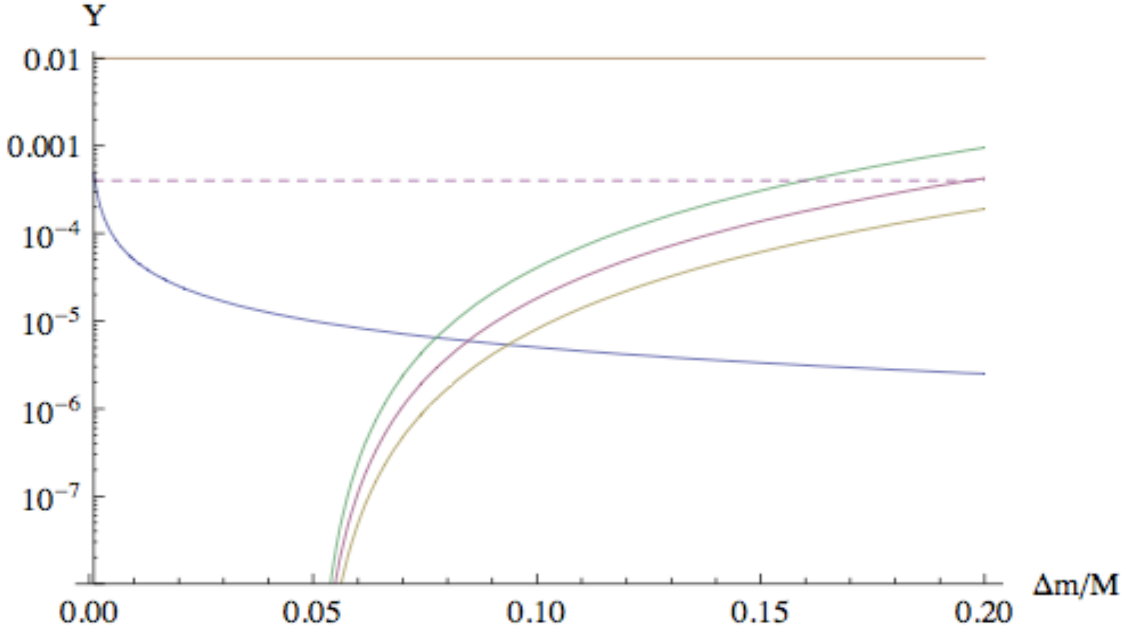
$\Delta m = m_{\tilde{t}} - m_{\chi^0}$; macroscopic decay length (small $Y \sim \lambda_b^2 V_{cb}$)

unique to MFV

$\Delta m > m_b$ opens up tree level 4-body decays $\tilde{t} \to b\chi^0 l\nu$.

$$\frac{\Gamma(\tilde{t}\to b\chi^0 l\nu)}{\Gamma(\tilde{t}\to c\chi^0)} \approx \frac{g^6|V_{tb}|^2}{2}\frac{(\Delta m - m_b)^7}{[Y(\Delta m/M)]^2 M m_W^4 m_{\chi^+}^2}$$

solid curve: $\beta\gamma\tau_{\tilde{t}} > 0.1mm$; dashed: Y_{min} alignement; horizontal solid line $Y \simeq \lambda_c$ anarchy +extended R-symm.GH,Nir '08



light stop ingredient of EWK baryogenesis; supports coannihilation of relic density; stop NLSP in hypercharged anomaly mediation

Dermisek et al'07

Summary

- Flavor has been intimately linked to the Making of the SM.
- The LHC will explore for the first time the scale of electroweak symmetry breaking. What are the flavor quantum numbers of new particles/SM partners ?
- Already strong constraints from flavor physics: Either TeV-BSM is accidentally small in measured K, D, B-observables, or there is a symmetry behind such as “Minimal Flavor Violation “; implications for collider physics.
- If MFV is confirmed, the origin of flavor is most likely unrelated to the TeV-scale.