A Minimal Flavor Violating Z' Boson

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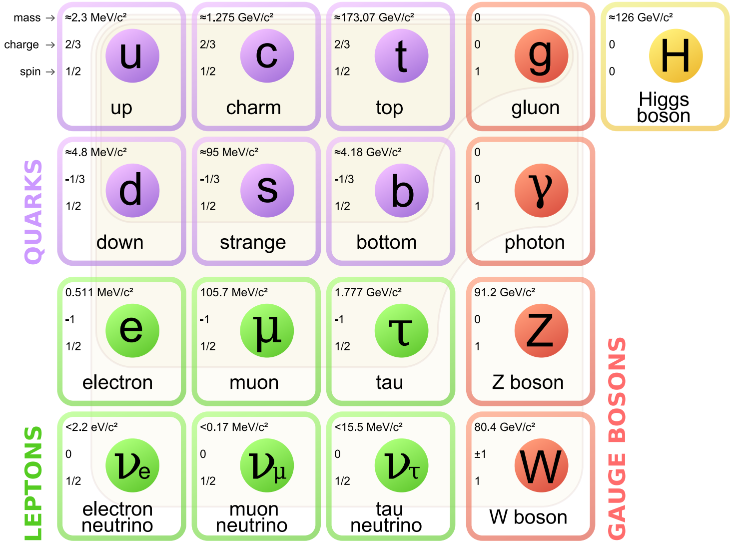
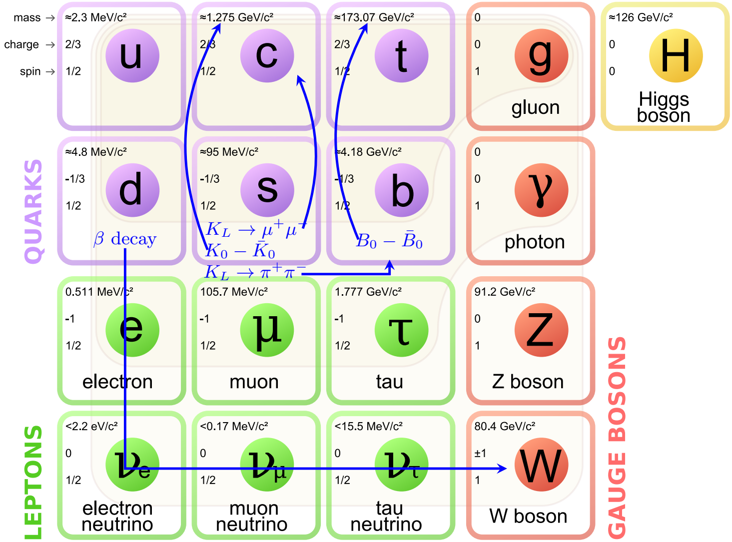
Outline

1. Standard Model and Beyond
2. Energy Scale of New Physics Beyond the SM
3. Minimal Flavor Violation
4. Minimal Flavor Violating Z' boson

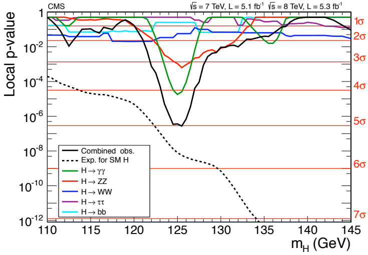
Standard Model

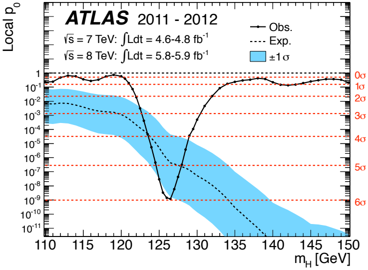


Flavor Physics and Standard Model



Higgs discovery





- mass: $m_h = 126\,\mathrm{GeV}$ ☺
- spin ☺
- party ☺
- Yukawa coupling ☺
- gauge coupling ☺

New Physics Beyond the SM

Experimental argument:

- Neutrino oscillation
- Dark Matter
- Origin of the Baryon Asymmetry
- Dark Energy
- Gravity
- ... ...

Theoretical argument:

- 19 free parameters, particle masses and mixing patterns
- gauge group and particle representation
- origin of EW symmetry breaking, why Higgs mechanism
- ... ...

What we know about New Physics

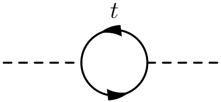
Energy Scale

Outline

1. Standard Model and Beyond
2. Energy Scale of New Physics Beyond the SM
   - ▷ From Naturalness: Higgs boson
   - ▷ From Flavor Physics: meson mixing
3. Minimal Flavor Violation
4. Minimal Flavor Violating Z' boson

NP Scale: from Naturalness

- If SM is an effective theory below NP scale Λ
- Higgs mass receives quadratically divergent radiative corrections

$\delta m_h^2 =$  $+ \ldots = \dfrac{c}{16\pi^2}\,\Lambda^2$

- Unnatural cancellation for large Λ — reg. independent

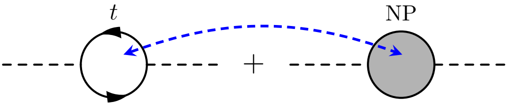
  e.g. $\Lambda_{\mathrm{GUT}} = \mathcal{O}(10^{16})\,\mathrm{GeV}$, $\Lambda_{\mathrm{Planck}} = \mathcal{O}(10^{18})\,\mathrm{GeV}$

fine-tuning

$$m_h^2 = m_{h,0}^2 + \frac{c}{16\pi^2}\,\Lambda^2 = 126\,\mathrm{GeV}^2$$

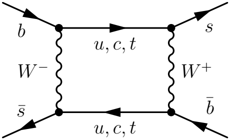
Possible Answer: $\Lambda_{\mathrm{NP}} = \mathcal{O}(1)\,\mathrm{TeV}$.

There must be new degree of freedom that manifest themselves in high energy collisions at the TeV energy scale.

$\delta m_h^2 =$  $+ \ldots$

NP Scale: from Flavor Physics

- Meson mixing: $B_d - \bar{B}_d$, $B_s - \bar{B}_s$, $K_0 - \bar{K}_0$
- Feynman Diagram



- Mass eigenstate

$$|B_s^{\mathrm{H}}\rangle = \frac{|B_s\rangle + \epsilon|\bar{B}_s\rangle}{\sqrt{1+|\epsilon|^2}} \qquad |B_s^{\mathrm{L}}\rangle = \frac{\epsilon|B_s\rangle + |\bar{B}_s\rangle}{\sqrt{1+|\epsilon|^2}}$$

- Time evolution

$$i\frac{d\psi(t)}{dt} = \hat{H}\psi(t) \qquad \psi(t) = \begin{pmatrix} |B_s\rangle \\ |\bar{B}_s\rangle \end{pmatrix}$$

- Hamiltonian

$$\hat{H} = \hat{M} - \frac{i}{2}\hat{\Gamma} = \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{21} - \frac{i}{2}\Gamma_{21} & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix}$$

NP Scale: from Flavor Physics

- Mass difference

$$\Delta M_s \equiv M_{\rm H}^s - M_{\rm L}^s = 2|M_{12}|$$

- Numerics

$$\Delta M_s^{\rm SM} = (17.3 \pm 2.6)\,{\rm ps}^{-1}$$
$$\Delta M_s^{\rm exp} = (17.757 \pm 0.021)\,{\rm ps}^{-1}$$

- NP contribution within EFT: $M_{12} = M_{12}^{\rm SM} + M_{12}^{\rm NP}$

$$M_{12}^{\rm NP} \propto \frac{C^k}{\Lambda_{\rm NP}^2} \langle \bar{B}_s | (\bar{b}\Gamma^k s)^2 | B_s \rangle$$

- NP scale

$$\Lambda_{\rm NP} > \begin{cases} 2\times 10^5\,{\rm TeV} \times |C_{12}^4|^{1/2} & K_0 - \bar{K}_0 \\ 2\times 10^3\,{\rm TeV} \times |C_{13}^4|^{1/2} & B_d - \bar{B}_d \\ 3\times 10^2\,{\rm TeV} \times |C_{23}^4|^{1/2} & B_s - \bar{B}_s \end{cases}$$

NP scale: problem

- From naturalness argument about Higgs mass

$$\Lambda_{\mathrm{NP}} = \mathcal{O}(1)\,\mathrm{TeV}$$

- From flavor physics

$$\Lambda_{\mathrm{NP}} > \begin{cases} 2\times 10^5\,\mathrm{TeV}\times |C^4_{12}|^{1/2} & K_0 - \bar{K}_0 \\ 2\times 10^3\,\mathrm{TeV}\times |C^4_{13}|^{1/2} & B_d - \bar{B}_d \\ 3\times 10^2\,\mathrm{TeV}\times |C^4_{23}|^{1/2} & B_s - \bar{B}_s \end{cases}$$

- Flavor Problem: if we insist on the theoretical prejudice that NP has to emerge in the TeV region, we have to conclude that the new theory possesses a highly nongeneric flavor structure.
  - C_{ij} should be not generic
  - derived from EFT, but appears in SUSY, technicolor, ...
- Solution ?

NP scale: problem and a solution

- From naturalness argument about Higgs mass

$$\Lambda_{\rm NP} = \mathcal{O}(1)\,{\rm TeV}$$

- From flavor physics

$$\Lambda_{\rm NP} > \begin{cases} 2\times 10^5\,{\rm TeV}\times |C^4_{12}|^{1/2} & K_0 - \bar{K}_0 \\ 2\times 10^3\,{\rm TeV}\times |C^4_{13}|^{1/2} & B_d - \bar{B}_d \\ 3\times 10^2\,{\rm TeV}\times |C^4_{23}|^{1/2} & B_s - \bar{B}_s \end{cases}$$

- Flavor Problem: if we insist on the theoretical prejudice that NP has to emerge in the TeV region, we have to conclude that the new theory possesses a highly nongeneric flavor structure.
  - C_{ij} should be not generic
  - derived from EFT, but appears in SUSY, technicolor, ...
- Solution: Minimal Flavor Violation hypothesis

$$C_{ij} = (\lambda_t V^*_{ti} V_{tj})^2 C \implies \Lambda_{\rm NP} > \text{few TeV}$$

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1. Standard Model and Beyond
2. Energy Scale of New Physics Beyond the SM
3. Minimal Flavor Violation
    - ▷ Flavor Puzzle
    - ▷ Natural Flavor Violation
    - ▷ Minimal Flavor Violation
4. Minimal Flavor Violating Z' boson

Flavor Puzzle

- In the SM, the flavor structure comes from the Yukawa couplings

$$\mathcal{L}_{\mathrm{SM}} = \mathcal{L}_{\mathrm{gauge}} + \mathcal{L}_{\mathrm{Higgs}} + \mathcal{L}_{\mathrm{Yukawa}}$$

- It can not account for the matter-antimatter asymmetry of the universe.
- All the flavor data is consistent with the SM prediction.

Flavor Puzzle

- Diagonal Yukawa coupling:
  mass spectrum is strongly hierarchical, e.g. $m_u \ll m_c \ll m_t$

- Non-diagonal flavor mixing matrix

small for quarks

$$V_{\mathrm{CKM}} = \begin{pmatrix} \sim 1 & \lambda & \lambda^3 \\ \lambda & \sim 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \sim 1 \end{pmatrix}$$

$$\lambda \sim 0.22$$

large for leptons

$$U_{\mathrm{PMNS}} = \begin{pmatrix} +0.8 & +0.8 & +0.2 \\ -0.4 & +0.5 & -0.7 \\ -0.4 & +0.5 & +0.7 \end{pmatrix}$$

- Suppression of the Flavor Changing Neutral Current (FCNC) for quarks
  - consistent with all the flavor data
  - small room for New Physics contribution
  - FCNC in NP models should be naturally suppressed

Progress for how to naturally suppress FCNC

1978-1987: Natural Flavor Conservation

- Natural Flavor Conservation hypothesis (NFC)
- S.Glashow and S.Weinberg, PRD, 1977
- Basic idea
  - No tree-level FCNC coupling in NP models
  - Flavor conservation follows from the group structure and representation content of the theory, rather than from the particular values of the parameters.
- Example: NFC Two-Higgs doublet model
  - Quarks receive their mass from one neutral Higgs.
  - Realized by discrete Z_2 symmetry

Progress for how to naturally suppress FCNC

1987-2001: From NFC To MFV

- 1987: B. Chivukula and H. Georgi, PLB
  - $[SU(3) \times U(1)]^5$ flavor symmetry
  - Flavor symmetry breaking and spurion: $\bar{Q}_L Y_D H D_R$

- SUSY with minimal flavor violation

- 1996: G. Branco, W. Grimus and L. Lavoura, PLB
  - A class of 2HDM: FCNC couplings of the neutral Higgs are related in an exact way of the CKM.

- 2001: A.J.Buras, P.Gambino, M.Gorbahn, S.Jager, L.Silvestrini, PLB
  - "*Here we will concentrate on models like the SM, the 2HDM I and II and the MSSM with minimal flavour violation, that do not have any new operators beyond those present in the SM [14] and in which all flavour-changing transitions are governed by the CKM matrix with no new phases beyond the CKM phase.*"

Minimal Flavor Violation

- Minimal Flavor Violation hypothesis (MFV)
- G.D'Ambrosio, G.Giudice, G.Isodori, A.Strumia, NPB, 2002
- MFV: the dynamics of flavor violation is completely determined by the structure of the ordinary Yukawa couplings and all CP violation originates from the CKM phase.
- Effective theory with MFV

MFV: Realization in EFT

- Flavor symmetry

$$SU(3)_q^3 = SU(3)_{Q_L} \otimes SU(3)_{U_R} \otimes SU(3)_{D_R}$$
$$SU(3)_\ell^2 = SU(3)_{L_L} \otimes SU(3)_{E_R}$$

- Flavor symmetry breaking Lagrangian: Yukawa interaction

$$\mathcal{L}_Y = \bar{Q}_L Y_D D_R H + \bar{Q}_L Y_U U_R H_c + \bar{L}_L Y_E E_R H + h.c.$$

- Flavor symmetry recovering
  - formally, assigned transformation property, spurions

$$Y_U \sim (3, \bar{3}, 1)_{SU(3)_q^3} \quad Y_D \sim (3, 1, \bar{3})_{SU(3)_q^3} \quad Y_E \sim (3, \bar{3})_{SU(3)_\ell^2}$$

- Choose basis (field redefinition by flavor symmetry)

$$Y_U = V^\dagger \lambda_u \quad Y_D = \lambda_d \quad Y_L = \lambda_\ell$$

MFV: Realization in EFT

- Spurion representation

$$Y_U \sim (3, \bar{3}, 1)_{SU(3)_q^3} \quad Y_D \sim (3, 1, \bar{3})_{SU(3)_q^3} \quad Y_E \sim (3, \bar{3})_{SU(3)_\ell^2}$$

- Example: effective FCNC operators for down-type quarks

$$\bar{Q}_L Y_U Y_U^\dagger Q_L \quad \bar{D}_R Y_D^\dagger Y_U Y_U^\dagger Q_L \quad \bar{D}_R Y_D^\dagger Y_U Y_U^\dagger Y_D D_R$$

- Basic flavor changing couplings for down-type quarks

$$(\lambda_{\rm FC})_{ij} = \begin{cases} (Y_U Y_U^\dagger)_{ij} \approx \lambda_t^2 V_{3i}^* V_{3j}, & i \neq j \\ 0, & i = j \end{cases}$$

MFV: Lepton Sector

- V.Cirigliano, B.Grinstein, G.Isidori, M.B.Wise, NPB, 2005
- Not straightforward: Quark MFV $\Longrightarrow$ Lepton MFV
- Mechanism for neutrino masses
  - Minimal field content: SM field (L_L^i and e_R^i)
  - Extended field content: SM field + ν_R^i

MFV: Lepton Sector with minimal field content

- Flavor symmetry

$$G_{\rm LF} = SU(3)_L \otimes SU(3)_E$$

- Flavor symmetry breaking Lagrangian

$$\mathcal{L} = -\bar{e}_R \lambda_e H^\dagger L_L - \frac{1}{2\Lambda_{\rm LN}} (\bar{L}_L^c \tau_2 H) g_\nu (H^T \tau_2 L_L) + h.c.$$

$$\to v \bar{e}_R \lambda e_L - \frac{v^2}{2\Lambda_{\rm LN}} \bar{\nu}_L^c g_\nu \nu_L + h.c.$$

  - ▷ $U(1)_{\rm LN}$ breaking is independent from $G_{\rm LF}$ breaking
  - ▷ small ν mass is attributed to the smallness of $v/\Lambda_{\rm LN}$

- Flavor symmetry recovering: spurion representation

$$L_L \to V_L L_L \qquad \lambda_e \to V_R \lambda_e V_L^\dagger$$

$$e_R \to V_R e_R \qquad g_\nu \to V_L^* g_\nu V_L^\dagger$$

- Basic LFV coupling

$$\Delta = g_\nu^\dagger g_\nu = \frac{\Lambda_{\rm LN}^2}{v^4} \hat{U} m_\nu^2 \hat{U}^\dagger$$

MFV: summary

- Why introduce MFV
  - Quark sector: solve flavor problem of Λ_{NP}, naturally suppress FCNC
  - Lepton sector: in fact no reason, just analogy to quark sector
- How to realize MFV
  - EFT: flavor symmetry breaking and its restore with Yukawa spurion
  - Concrete BSM model: easily impose, just as in EFT (MFV 2HDM)
  - Concrete BSM model building: generally speaking, still difficult

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   - ▷ Why Z' boson
   - ▷ Minimal Flavor Violating Z'
   - ▷ Experimental constraints
   - ▷ Predictions

Z' boson

- Z' boson/additional $U(1)'$ gauge symmetry
  - Grand Unified Theoryies, e.g. $E_6 \to SU(5) \times U(1)_\chi \times U(1)_\phi$
  - EWSB scenarios, e.g. little Higgs, extra dimension, ...
  - Models to explain Darker Matter

- Quark sector: Tree-level FCNC Z' couplings appear in some scenarios

- For a particular NP model containing a Z' boson, it is quite good if the FCNC Z' couplings are MFV-pattern.

I don't know how to realize this idea for a particular NP model.
But, ...

Z' boson within MFV

- Z' couplings to quark and lepton generally

$$\mathcal{O}_L^q = \left(\bar{Q}_L \Delta_q \gamma^\mu Q_L\right) Z'_\mu \qquad \text{and} \qquad \mathcal{O}_L^\ell = \left(\bar{L}_L \Delta_\ell \gamma^\mu L_L\right) Z'_\mu$$

- MFV: invariant under flavor symmetry $G_{\rm QF}$ and $G_{\rm LF}$

$$\Delta_q = \kappa_0 \mathbb{1} + \kappa_1 Y_U Y_U^\dagger + \ldots, \quad \Delta_\ell = \lambda_0 \mathbb{1} + \lambda_1 \frac{\Lambda_{\rm LN}^2}{v^4} \hat{U} m_\nu^2 \hat{U}^\dagger + \ldots$$

- some comments: not considered yet but easily added
  - high order Yukawa polynomials: 1. Cayley-Hamilton identity 2. Non-Linear Rep. of flavor symmetry (e.g. CCWZ)
  - right handed operators with u_R, d_R and e_R also possible but FCNC highly suppressed by down-type Yukawa e.g. λ_b, λ_μ.
  - Lepton MFV with seesaw
  - $Z' - Z$ mixing

Z' boson within MFV

- Lagrangian

$$\mathcal{L} = \Gamma^L_{\ell\ell'} \left(\bar{\ell}\gamma^\mu P_L \ell'\right) Z'_\mu + \Gamma^L_{qq'} \left(\bar{q}\gamma^\mu P_L q'\right) Z'_\mu + L \leftrightarrow R$$

- Coupling matrix within MFV

$$\Gamma^L_{\ell\ell'} = \lambda_0 \delta_{\ell\ell'} + \lambda \frac{\Lambda^2_{\rm LN}}{v^4} \sum_{\nu_i} m^2_{\nu_i} U_{\ell\nu_i} U^*_{\ell'\nu_i}, \qquad \Gamma^R_{\ell\ell'} = 0,$$

$$\Gamma^L_{qq'} = \kappa_0 \delta_{qq'} + \kappa \lambda_t^2 V^*_{tq} V_{tq'}, \qquad \Gamma^R_{qq'} = 0.$$

- Numerics: $\Lambda_{\rm LN} = 10^{14}\,\rm GeV$, $m_{\nu_1} = 0.2\,\rm eV$

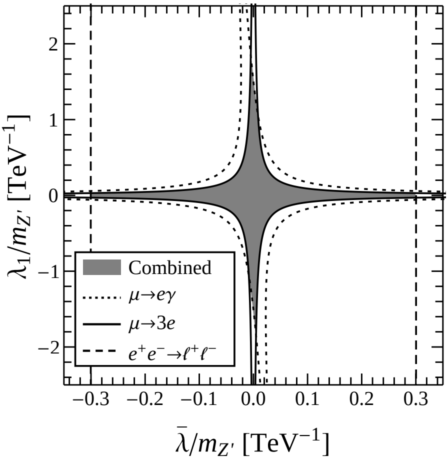
$$\Gamma_{\ell\ell'} = \begin{pmatrix} \bar{\lambda} & 0.0026e^{+1.8i}\lambda_1 & 0.0031e^{+2.0i}\lambda_1 \\ 0.0026e^{-1.8i}\lambda_1 & \bar{\lambda} & 0.0128\lambda_1 \\ 0.0031e^{-2.0i}\lambda_1 & 0.0128\lambda_1 & \bar{\lambda} \end{pmatrix}$$

$$\Gamma_{qq'} = \begin{pmatrix} \kappa_0 + 0.0001\kappa_1 & 0.0003e^{-2.7i}\kappa_1 & 0.0076e^{+0.4i}\kappa_1 \\ 0.0003e^{+2.7i}\kappa_1 & \kappa_0 + 0.0014\kappa_1 & 0.0358e^{+3.1i}\kappa_1 \\ 0.0076e^{-0.4i}\kappa_1 & 0.0358e^{-3.1i}\kappa_1 & \kappa_0 + 0.8869\kappa_1 \end{pmatrix}$$

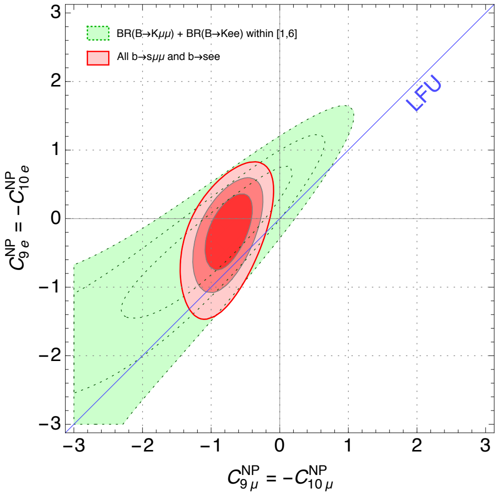
MFV Z' boson: experimental constraints

- lepton $(\bar{\lambda}/m_{Z'}, \lambda_1/m_{Z'})$
  - $\tau \to \mu\nu\bar{\nu}$ (2σ), $\tau \to e\nu\bar{\nu}$, $\mu \to e\nu\bar{\nu}$ (G_F)
  - $\tau \to 3\mu$, $\mu \to 3e$, $\tau^\pm \to e^\pm\mu^+\mu^-$, $\tau^\pm \to e^\mp\mu^\pm\mu^\pm$, $\tau^\pm \to \mu^\pm e^+e^-$, $\tau^\pm \to \mu^\mp e^\pm e^\pm$
  - $\tau \to \mu\gamma$, $\tau \to e\gamma$, $\mu \to e\gamma$
  - a_μ (3σ)
  - LEP: $e^+e^- \to \ell^+\ell^-$
  - NTP: $\nu_\mu N \to \nu N \mu^+\mu^-$
  - $\mu \leftrightarrow e$ conversion: $\mu^-e^+ \to \mu^+e^-$
- quark $(\kappa_0/m_{Z'}, \kappa_1/m_{Z'})$
  - $B_s - \bar{B}_s$, $B_d - \bar{B}_d$, $K^0 - \bar{K}^0$ mixing
- quark and lepton $(\bar{\lambda}/m_{Z'}, \lambda_1/m_{Z'}, \kappa_0/m_{Z'}, \kappa_1/m_{Z'})$
  - LEP: $e^+e^- \to q\bar{q}$
  - $\mu \leftrightarrow e$ conversion: $\mu^-N \to e^-N$
  - $b \to s\ell^+\ell^-$: $B \to K^*\mu^+\mu^-$ $(F_L/2.9\sigma)$, $B_s \to \phi\mu^+\mu^-$ (3.1σ), $R(K) = \mathcal{B}(B \to K\mu^+\mu^-)/\mathcal{B}(B \to Ke^+e^-)$ (2.6σ)
  - B and K LFV decays: e.g. $K_L \to e^\pm\mu^\mp$

MFV Z' boson: lepton process

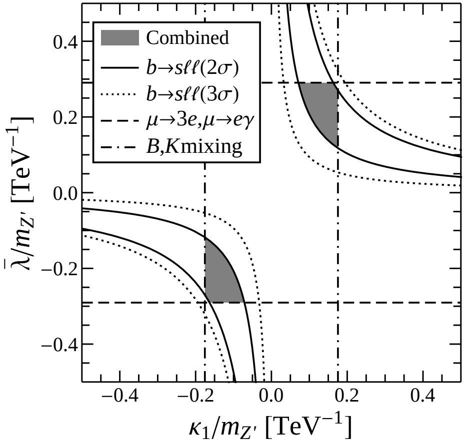


MFV Z' boson: current $b \to s\ell^+\ell^-$ anomaly

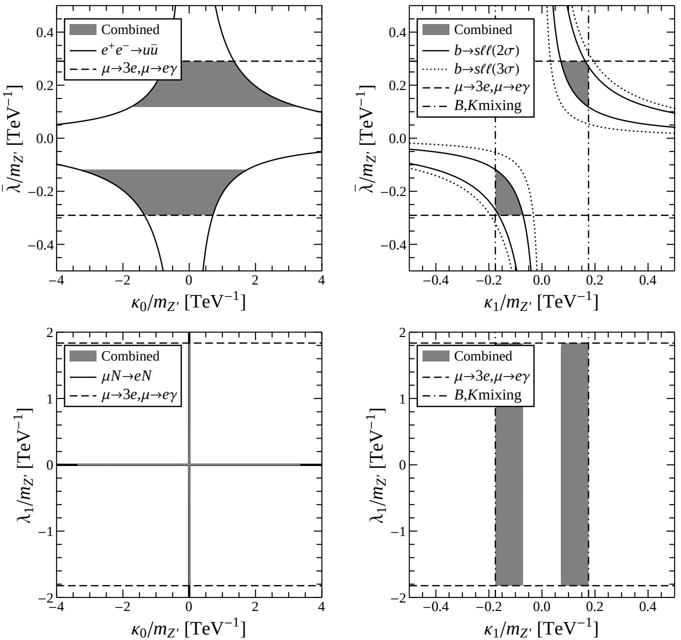


- ($C_{9\mu} = -C_{10\mu}, C_{9e} = -C_{10e}$: model-independent NP contributions to $b \to s\ell^+\ell^-$
- Red region: from all current $b \to se^+e^-$ and $b \to s\mu^+\mu^-$ data.
- MFV Z' allowed within 2σ

MFV Z' boson

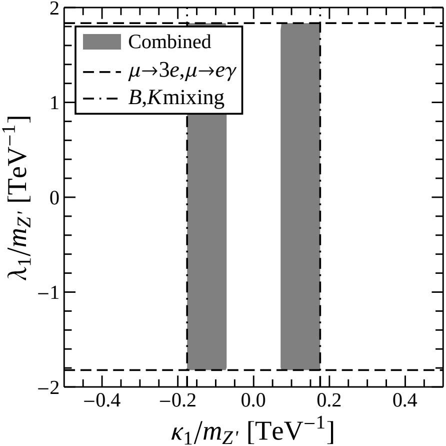


Combined
b→sℓℓ(2σ)
b→sℓℓ(3σ)
μ→3e,μ→eγ
B,Kmixing
0.4
0.2
0.0
−0.2
−0.4
−0.4
−0.2
0.0
0.2
0.4
λ̄/m_Z′ [TeV^−1]
κ_1/m_Z′ [TeV^−1]



Combined
$e^+e^- \to u\bar{u}$
$\mu \to 3e, \mu \to e\gamma$
$\bar{\lambda}/m_{Z'}$ [TeV^{-1}]
$\kappa_0/m_{Z'}$ [TeV^{-1}]
Combined
$b \to s\ell\ell(2\sigma)$
$b \to s\ell\ell(3\sigma)$
$\mu \to 3e, \mu \to e\gamma$
B,Kmixing
$\bar{\lambda}/m_{Z'}$ [TeV^{-1}]
$\kappa_1/m_{Z'}$ [TeV^{-1}]
Combined
$\mu N \to eN$
$\mu \to 3e, \mu \to e\gamma$
$\lambda_1/m_{Z'}$ [TeV^{-1}]
$\kappa_0/m_{Z'}$ [TeV^{-1}]
Combined
$\mu \to 3e, \mu \to e\gamma$
B,Kmixing
$\lambda_1/m_{Z'}$ [TeV^{-1}]
$\kappa_1/m_{Z'}$ [TeV^{-1}]

MFV Z' boson prediction: B and K mixing



$$1.04 < \Delta m_s/\Delta m_s^{\rm SM} < 1.22$$

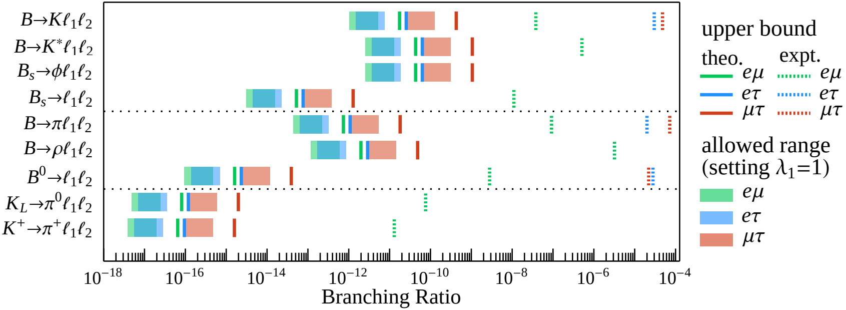
$$1.05 < \Delta m_d/\Delta m_d^{\rm SM} < 1.22$$

$$1.03 < |\varepsilon_K|/|\varepsilon_K^{\rm SM}| < 1.17$$

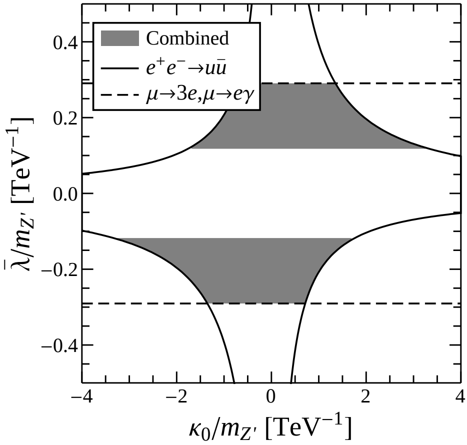
uncertainty dominated by theo

$10\% \to 3 \sim 5\%$ in next few years

MFV Z' boson prediction: B and K LFV decays

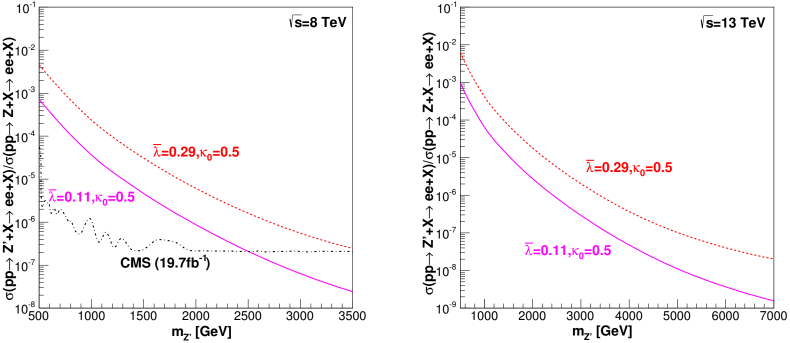


MFV Z' boson prediction: LHC signal



- leptonic Drell-Yan process: $pp \to Z' \to \ell^+\ell^-$

MFV Z' boson prediction: LHC signal



Summary

- a Z' boson couples to quark and lepton within MFV
- many experimental constraints are considered: $\ell_j \to \ell_i \ell_k \bar{\ell}_l$, $\ell_j \to \ell_i \gamma$, $\mu^- N \to e^- N$, $b \to s\ell^+\ell^-$, B and K mixing, $e^+e^- \to f\bar{f}$ at LEP, ...
- MFV Z' boson can explain current $b \to s\ell^+\ell^-$ anomaly
- some predictions
  - ☺ B and K mixing: $\sim 15\%$ enhanced, larger than future total uncertainty
  - ☹ B and K LFV decays: quite small, difficult to reach detectable level
  - ☺ $pp \to Z' \to \ell^+\ell^-$ at Run II LHC
- built in a concrete model ?

Thank You !

Backup

Z' boson: a_μ

- Anomalous magnetic moment: $a_\mu = (g-2)_\mu/2$
- Longstanding discrepancy with the SM:
  $\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (2.9 \pm 0.9) \times 10^{-9}$
- Due to no right-handed Z' coupling, $a_\mu^{\rm NP}$ is always negative within MFV Z'. Therefore, MFV Z' can not explain a_μ problem.