New Physics implications from ε'/ε

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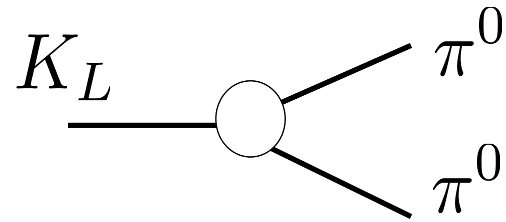
FPCP2017 - Flavor Physics & CP Violation @ Prague
8th. June 2017

Direct CP violation (K->ππ decay) : ε'/ε

$$K_L \to \pi^+\pi^- \;\&\; K_L \to \pi^0\pi^0$$



$$\eta_{00} = \frac{A(K_\mathrm{L} \to \pi^0\pi^0)}{A(K_\mathrm{S} \to \pi^0\pi^0)}$$

$$\eta_{+-} = \frac{A(K_\mathrm{L} \to \pi^+\pi^-)}{A(K_\mathrm{S} \to \pi^+\pi^-)}$$

$$\left|\frac{\eta_{00}}{\eta_{+-}}\right|^2 \simeq 1 - 6\,\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)$$

$$\left(\frac{\epsilon'}{\epsilon}\right)_{\mathrm{exp}} = (16.6 \pm 2.3) \times 10^{-4}$$ [NA48, KTeV]

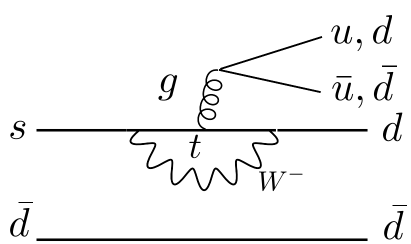
ε'/ε

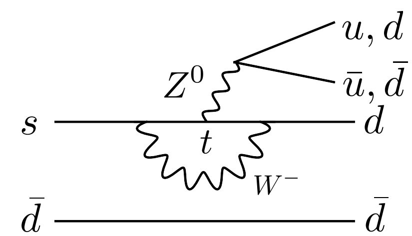
$$A_{0,2} = A(K^0 \to (\pi\pi)_{I=0,2})$$

$$\frac{\epsilon'_K}{\epsilon_K} = -\frac{\omega}{\sqrt{2}\,|\epsilon_K|_{\exp}\,\mathrm{Re}A_0}\left(\mathrm{Im}A_0 - \frac{1}{\omega}\,\mathrm{Im}A_2\right)$$

QCD penguin

EW penguin



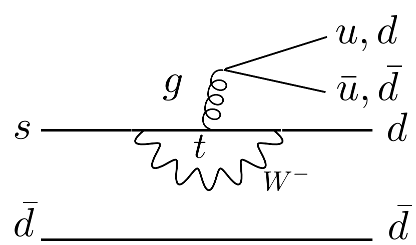


ε’/ε

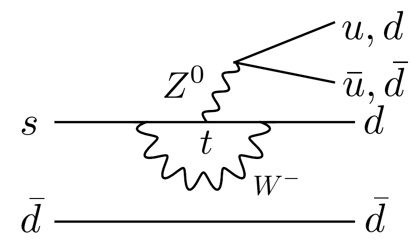
$$A_{0,2} = A(K^0 \to (\pi\pi)_{I=0,2})$$

$$\frac{\epsilon'_K}{\epsilon_K} = -\frac{\omega}{\sqrt{2}\,|\epsilon_K|_{\rm exp}\ {\rm Re}A_0}\left({\rm Im}A_0 - \boxed{\frac{1}{\omega}}\,{\rm Im}A_2\right)$$

QCD penguin



EW penguin



ΔI=1/2 rule

$$\frac{{\rm Re}A_0}{{\rm Re}A_2} \equiv \frac{1}{\omega} = 22.46$$

In SM, there is accidental cancellation between $\mathrm{Im}A_0$ and $\mathrm{Im}A_2$ due to the enhancement factor 1/ω

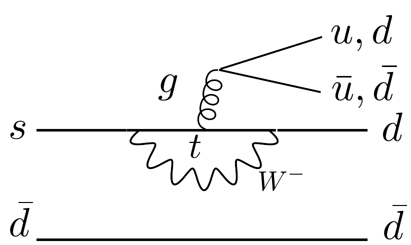
ε'/ε

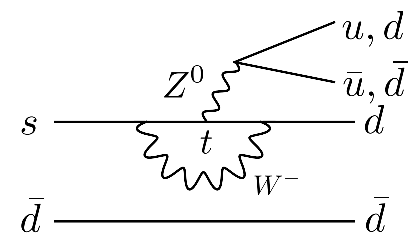
$$A_{0,2} = A(K^0 \to (\pi\pi)_{I=0,2})$$

$$\frac{\epsilon'_K}{\epsilon_K} = -\frac{\omega}{\sqrt{2}\,|\epsilon_K|_{\exp}\ \mathrm{Re}A_0}\left(\mathrm{Im}A_0 - \frac{1}{\omega}\,\mathrm{Im}A_2\right)$$

QCD penguin

EW penguin





$$O_6 = (\bar{s}_\alpha d_\beta)_{V-A} \sum_q (\bar{q}_\beta q_\alpha)_{V+A}$$

$$O_8 = \frac{3}{2}(\bar{s}_\alpha d_\beta)_{V-A} \sum_q e_q (\bar{q}_\beta q_\alpha)_{V+A}$$

- <O6> and <O8> have chiral enhancement factor

$$\langle Q_6(\mu)\rangle_0 = -4\left[\frac{m_K^2}{m_s(\mu)+m_d(\mu)}\right]^2 (F_K - F_\pi)\, \boxed{B_6^{(1/2)}}$$

$$\langle Q_8(\mu)\rangle_2 = \sqrt{2}\left[\frac{m_K^2}{m_s(\mu)+m_d(\mu)}\right]^2 F_\pi\, \boxed{B_8^{(3/2)}}.$$

First Lattice results in 2015 !

See C. Sachrajda Talk

ε'/ε anomaly

Using the first lattice result, ε'/ ε has been calculated in the SM as

SM

$$\left(\frac{\epsilon'}{\epsilon}\right)_{\rm SM} = \begin{cases} (1.38 \pm 6.90) \times 10^{-4}, & \text{[RBC-UKQCD]} \\ (1.9 \pm 4.5) \times 10^{-4}, & \text{[Buras et al.]} \\ (1.06 \pm 5.07) \times 10^{-4}. & \text{[Kitahara et al.]} \end{cases}$$

※ NNLO QCD in progress *[M.Cerda-Sevilla, M.Gorbahn, S.Jager, A.Kokulu]*

Exp

$$\left(\frac{\epsilon'}{\epsilon}\right)_{\rm exp} = (16.6 \pm 2.3) \times 10^{-4}$$ [NA48, KTeV]

2.9σ difference

New physics in ε'/ε ?

ε'/ε beyond SM

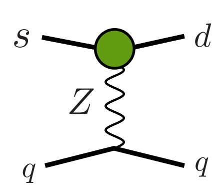
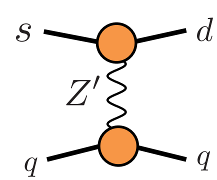
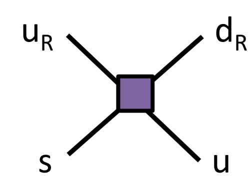
- Recall :

$$\frac{\epsilon'_K}{\epsilon_K} = -\frac{\omega}{\sqrt{2}\,|\epsilon_K|_{\rm exp}\,{\rm Re}A_0}\left({\rm Im}A_0 - \frac{1}{\omega}\,{\rm Im}A_2\right)$$

NP in ImA_2 (O_8) is favored because of ΔI=1/2 enhancement factor : 1/ω ～22

- The type of $(\mathrm{Im}A_2)_{NP}$:

$$(\mathrm{Im}A_2)_{NP} :$$

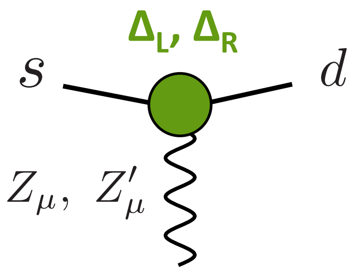
Z scenario	Z' scenario	Others
		
Chargino Z penguin gluino Z penguin VLQ LHT	VLQ 331	RH scenario Gluino box

Let us discuss the model-independent features firstly, and then model-dependent ones.

Kaon observables in Z & Z' scenario

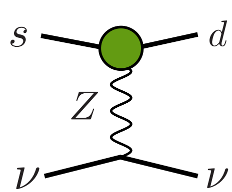
Correlations between Kaon observables

[A.J.Buras, D.Buttazzo and R.Knegjens, JHEP1511(2015)166
A.J.Buras, JHEP1604(2016)071
C.Bobeth, A.J.Buras, A.Celis and M.Jung, 1703.04753]



	ε'/ε	ε_K	$K_L \to \pi^0 \nu\bar{\nu}$	$K^+ \to \pi^+ \nu\bar{\nu}$	$K_L \to \mu^+\mu^-$	ΔM_K
ImΔ	*	*	*	*		*
ReΔ		*		*	*	*

$K_L \to \pi^0\nu\nu$: Direct CPV and depends on only Im part $\Rightarrow$ Strong correlation with ε'/ ε



Only RH (or LH) scenario $\Rightarrow$ $K_L \to \pi^0\nu\nu$ is suppressed
RH + LH scenario $\Rightarrow$ $K_L \to \pi^0\nu\nu$ can be enhanced

$$BR(K_L \to \pi^0 \nu\bar{\nu})_{\rm exp} < 2.6 \times 10^{-8} \ (90\%\text{C.L.})$$

← KOTO @ J-PARC

$K^+ \to \pi^+\nu\nu$: depends on Im & Re parts $\Rightarrow$ no strong correlation with ε'/ ε

can be enhanced by up to a factor of 2 (LH) and 5.7 (RH)

$$BR(K^+ \to \pi^+ \nu\bar{\nu})_{\rm exp} = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

← NA62 @ CERN

See R. Marchevski Talk

Notes on Z scenario

SMEFT

- Recently, the Z scenarios have been studied in the framework of SMEFT ($\mu_{EW} < \mu < \mu_{NP}$)

[C.Bobeth, A.J.Buras, A.Celis and M.Jung, JHEP 1704 (2017) 079 & 1703.04753]
[M.Endo, T.Kitahara, S.Mishima and KY, PLB771(2017)37]

- RH Z NP scenario gets strong constraint from KKbar mixing (ΔF=2) through RG effects

[C.Bobeth, A.J.Buras, A.Celis and M.Jung, 1703.04753]

$$\left(H^\dagger i \overleftrightarrow{D}_\mu H\right)(\bar{s}_R\gamma^\mu d_R)$$

RG evolution

$$(\bar{s}_R\gamma^\mu d_R)Z_\mu$$

new

ΔF=2 operator

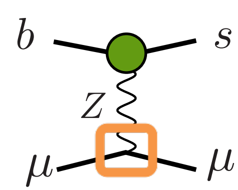
$$(\bar{s}_L\gamma_\mu d_L)(\bar{s}_R\gamma^\mu d_R)$$

Anomaly in B sector

- Z model is not favored by anomalies in b → s transitions (P_5', R(K), R(K*),,,), which suggest negative C_9^{NP}

$$C_9^{NP} < 0 \qquad O_9 = (\bar{s}_L\gamma_\mu b_L)(\bar{\mu}\gamma^\mu\mu)$$

In Z model, it is hard to produce large C_9^{NP} due to smallness of the vector coupling to charged lepton



$(1 - 4\, s_w^2)$

Models solving ε'/ε anomaly

- Several new physics models have been studied to explain ε'/ε anomaly

MSSM	-- chargino Z penguin	*[M. Endo, S. Mishima, D. Ueda and KY, PLB762(2016)493]*
	-- gluino Z penguin	*[M. Tanimoto and KY, PTEP(2016)no.12,123B02]*
	-- gluino box	*[T.Kitahara, U.Nierste and P.Tremper, PRL117(2016)no.9, 091802 A.Crivellin, G.D'Ambrosio, T.Kitahara and U.Nierste, 1703.05786]*
Vector-like quarks		*[C.Bobeth, A.J.Buras, A.Celis and M.Jung, JHEP1704(2017)079]*
Little Higgs Model with T-parity		*[M.Blanke, A.J.Buras and S.Recksiegel, EPJ.C76 (2016)no.4,182]*
331 model		*[A.J.Buras and F.De Fazio, JHEP1603(2016)010 & JHEP1608 (2016) 115]*
Right handed current		*[V.Cirigliano, W.Dekens, J.de Vries and E.Mereghetti, PLB 767 (2017) 1 S.Alioli, V.Cirigliano, W.Dekens, J.de Vries and E.Mereghetti, JHEP1705 (2017)086]*

- Different implications (correlations & predictions) for other observables appear depending on models $\Rightarrow$ Possibility of model discriminations

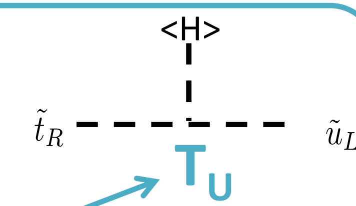
MSSM

Model

- Flavor violating effects come from off diagonal elements of squark mass matrix

$$\mathcal{M}^2_{\tilde{u}} = \mathrm{diag}(m^2_{\tilde{q}}) + m^2_{\tilde{q}} \begin{pmatrix} \delta^u_{LL} & \delta^u_{LR} \\ \delta^u_{RL} & \delta^u_{RR} \end{pmatrix}$$

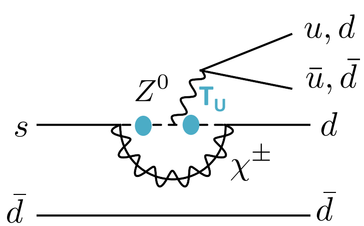
$$(\delta^u_{LR})_{ij} = \frac{\frac{v_2}{\sqrt{2}}(T_U)^*_{ij}}{m^2_{\tilde{q}}}$$



$(\varepsilon'/\varepsilon)_{NP}$ in MSSM

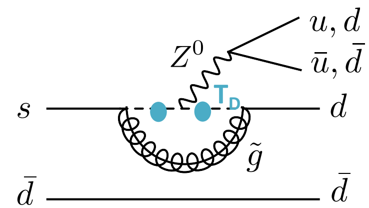
- Large trilinear coupling (A-term) bring enhancement of $(\varepsilon'/\varepsilon)$

Chargino Z penguin *[Endo, Mishima, Ueda and KY '16]*



Z model (LH)

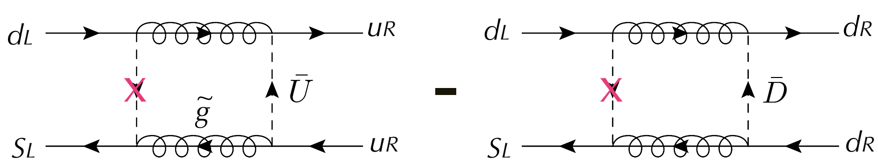
Gluino Z penguin *[Tanimoto and KY, '16]*



Z model (RH + LH)

- Gluino box with large isospin breaking ($m_{\tilde{U}} \neq m_{\tilde{D}}$) gives effect on ImA2

[Kitahara, Nierste and Tremper,'17]

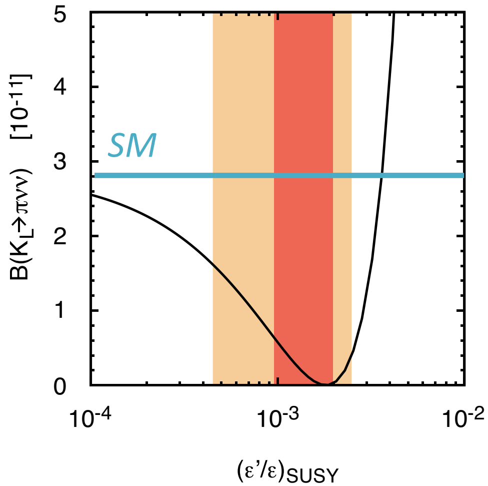


Implications of $(\varepsilon'/\varepsilon)_{NP}$ in MSSM

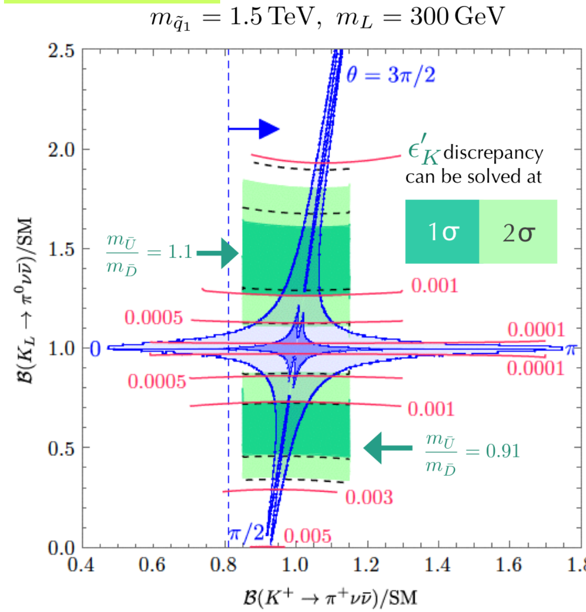
- SUSY scale is O(TeV)
- Different correlations between $(\varepsilon'/\varepsilon)$ and **$K \to \pi\nu\nu$** appear depending on scenarios

Chargino Z penguin

LH Z scenario ⇒ negative correlation



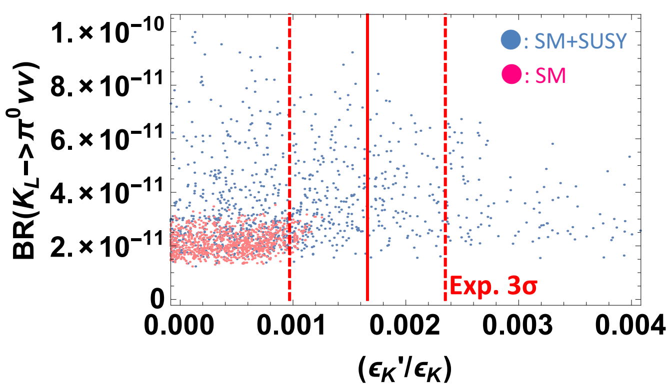
Gluino box   Chargino box -> $K \to \pi\nu\nu$



Gluino Z penguin

※ need more study including vacuum stability & RG effect

LH & RH Z scenario ⇒ positive correlation



	$B(K_L \to \pi^0\nu\nu)$	$B(K^+ \to \pi^+\nu\nu)$
Chargino Z penguin	< 0.6 SM	O(10~100%) effect
Gluino Z penguin	< 3 SM ?	O(10~100%) effect?
Gluino box	< 2 SM	< 1.4 SM

[C.Bobeth, A.J.Buras, A.Celis and M.Jung '17]

Vector-Like Quarks (VLQ)

Model

$$\mathrm{G_{SM}} \equiv \mathrm{SU(3)_c} \otimes \mathrm{SU(2)_L} \otimes \mathrm{U(1)_Y},$$

$$\mathrm{G'_{SM}} \equiv \mathrm{G_{SM}} \otimes \mathrm{U(1)_{L_\mu - L_\tau}}.$$

↓

new gauge : Z'

$G'_{\mathrm{SM}}(S)$ (S : $SU(2)_L$ singlet)

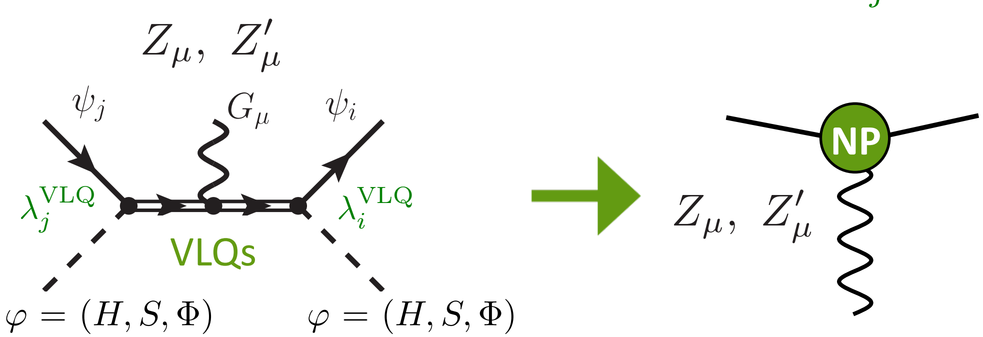
$G'_{\mathrm{SM}}(\Phi)$ (Φ : $SU(2)_L$ doublet)

- 11 VLQ models under single-VLQ scenario

G_{SM}	(D, Td, Tu, QV, Qd)	3LH, 2RH
$G'_{\mathrm{SM}}(S)$	(D, QV)	1LH, 1RH
$G'_{\mathrm{SM}}(\Phi)$	(D, Td, Tu, Qd)	3LH, 1RH

singlets :	$D(1,-1/3,-X)$,	
doublets :	$Q_V(2,+1/6,+X)$,	$Q_d(2,-5/6,-X)$,
triplets :	$T_d(3,-1/3,-X)$,	$T_u(3,+2/3,+X)$,

- FCNC is occurred through yukawa couplings λ_j^{VLQ}



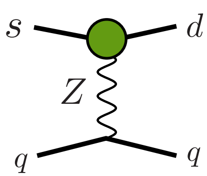
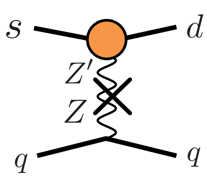
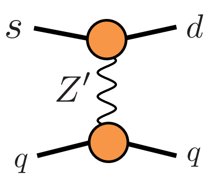
G_{SM} Z model

$G'_{\mathrm{SM}}(S)$ Z' model

(No Z contribution because $(\bar\psi_i \gamma_\mu \psi_j)(S^\dagger D^\mu S)$ is absent)

$G'_{\mathrm{SM}}(\Phi)$ Z & Z' model

$(\varepsilon'/\varepsilon)_{NP}$ in VLQs

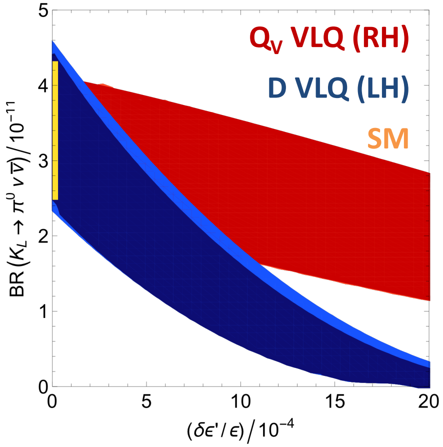
		O_8 & O'_8	$O_8 = \frac{3}{2}(\bar{s}_\alpha d_\beta)_{V-A}\sum_q e_q(\bar{q}_\beta q_\alpha)_{V+A}$	$(\varepsilon'/\varepsilon)_{NP}$
	((G_{SM} ,$G'_{SM}(\Phi)$))	✓		OK
	(($G'_{SM}(\Phi)$))	✓	But Z-Z' mixing is constrained by EW precision test	NO
	(($G'_{SM}(S)$, $G'_{SM}(\Phi)$))	Can not produce (Z'sd coupling has L or R, only)		NO

$\Rightarrow$ $(\varepsilon'/\varepsilon)_{NP}$ can be realized in G_{SM} : Z (LH, RH) model
and $G'_{SM}(\Phi)$: Z (LH, RH) model

Implications of $(\varepsilon'/\varepsilon)_{NP}$ in VLQs

$(\varepsilon'/\varepsilon)_{NP}$ vs. $K_L \to \pi^0\nu\nu$

G_{SM} M_{VLQ} = 10TeV(Dark) 1TeV(Light)



In G_{SM} scenario, $K_L \to \pi^0\nu\nu$ is suppressed.
This suppression is significantly weaker for QV and Qd models (RH) than for D, Td and Tu (LH).

$G'_{SM}(\Phi)$ Similar to G_{SM}

$K^+ \to \pi^+\nu\nu$

G_{SM} $Br(K^+ \to \pi^+\nu\nu)$ < 1.5 SM (RH)
< SM (LH)

$G'_{SM}(\Phi)$ $Br(K^+ \to \pi^+\nu\nu)$ < 5 SM (RH)
< 2 SM (LH)

Little Higgs Model with T-parity (LHT)

Model

- Idea : Higgs as a pseudo-Goldstone boson of a spontaneously broken global symmetry
- New heavy gauge bosons $W_{H\pm}$, Z_H, A_H & heavy scalar triplet Φ are introduced
- Consider T-parity to avoid the constraint from EW precision test

T-even SM sector :

SM quarks (L,R) + T+

Cancelle quadratic divergence

$\Rightarrow$ CKM

T-odd mirror sector :

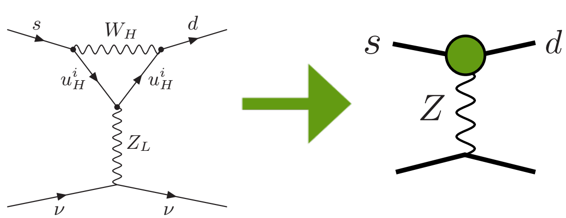
$$\begin{pmatrix} u_H^1 \\ d_H^1 \end{pmatrix}, \quad \begin{pmatrix} u_H^2 \\ d_H^2 \end{pmatrix}, \quad \begin{pmatrix} u_H^3 \\ d_H^3 \end{pmatrix}. \quad T_-$$

$\Rightarrow$ new CKM-like mixing matrices V_{Hu}, V_{Hd}

- FCNC structure : New sources of flavor & CP violation are introduced in T-odd sector

Operators are same as SM

Z penguin :



$\propto V_{Hd}^{*is} V_{Hd}^{id}$

Z' penguin does not appear due to T-parity

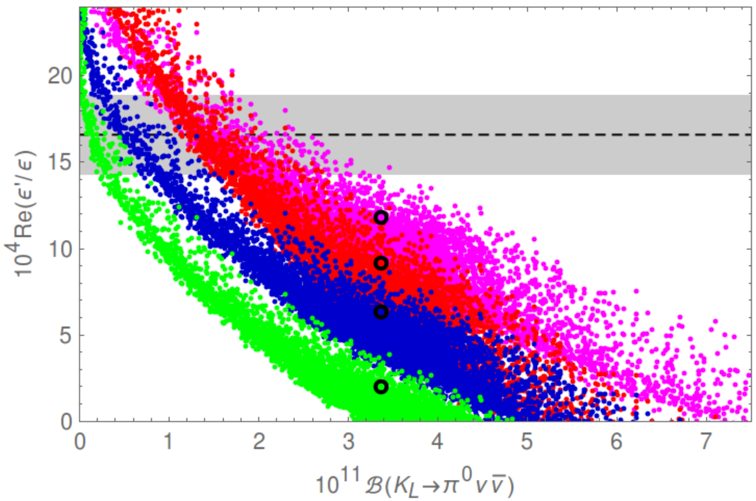
$(\varepsilon'/\varepsilon)_{NP}$ in LHT

- Z model with LH scenario

[M.Blanke, A.J.Buras and S.Recksiegel,’16]

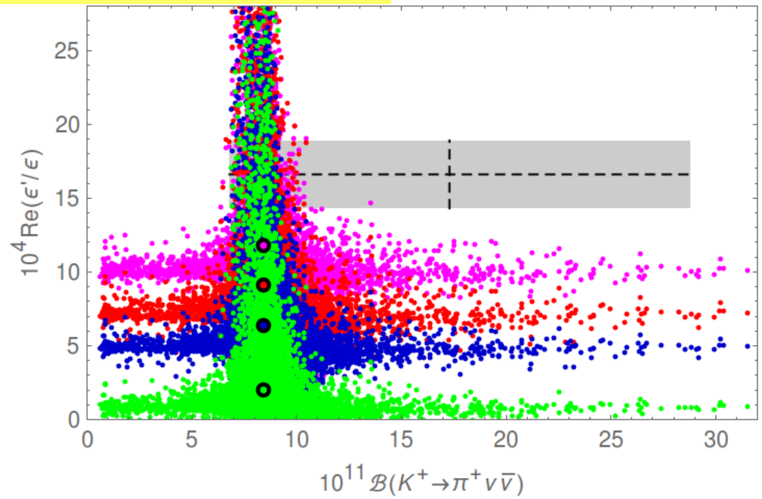
Implications of $(\varepsilon'/\varepsilon)_{NP}$ in LHT

$(\varepsilon'/\varepsilon)_{NP}$ vs. $K_L \rightarrow \pi^0\nu\nu$



$K_L \rightarrow \pi^0\nu\nu$ is suppressed

$(\varepsilon'/\varepsilon)_{NP}$ vs. $K^+ \rightarrow \pi^+\nu\nu$



$K^+ \rightarrow \pi^+\nu\nu$ has small modification

[A.J.Buras and F.De Fazio '16]

331 model

Model

$$SU(3)_C \times SU(3)_L \times U(1)_X \Rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{em}$$

- Requirement of anomaly cancelation + asymptotic freedom of QCD implies number of generations = number of colors

- 24 models characterized by different β, tanβbar and fermion representations

  24 → 7 (by EWPT) $\mathrm{M9}, \quad \mathrm{M8}, \quad \mathrm{M6}, \quad \mathrm{M11}, \quad \mathrm{M3}, \quad \mathrm{M16}, \quad \mathrm{M14}$

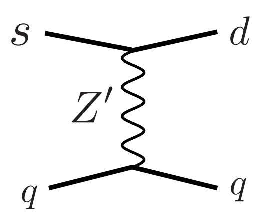
- FCNC structure

The different treatment of the 3rd generation LH quarks generates FCNCs at tree level through Z'

$$\boxed{\begin{pmatrix} u \\ d \\ D \end{pmatrix}_L \qquad \begin{pmatrix} c \\ s \\ S \end{pmatrix}_L} \qquad \boxed{\begin{pmatrix} b \\ -t \\ T \end{pmatrix}_L}$$

New heavy quark

SU(3)L triplet **SU(3)L antitriplet**



$\propto \quad \tilde{s}_{13}\tilde{s}_{23}$

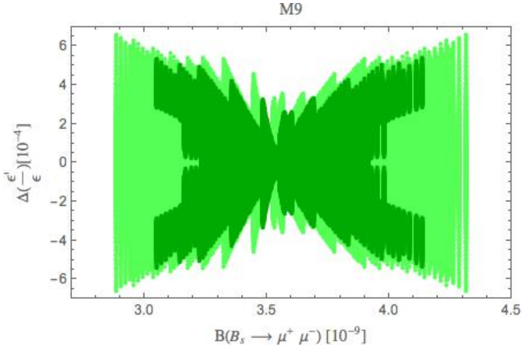
[A.J.Buras and F.De Fazio '16]

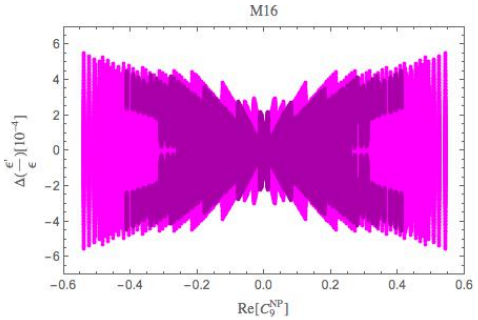
$(\varepsilon'/\varepsilon)_{NP}$ in 331 model

- Z' model with LH scenario
- Three models M8, M9, M16 can explain $(\varepsilon'/\varepsilon)$

Implications of $(\varepsilon'/\varepsilon)_{NP}$ in 331 model

	$K_L \to \pi^0 \nu\nu$ & $K^+ \to \pi^+ \nu\nu$	$B_s \to \mu\mu$	C_9 (P5' anomaly)
M8	Very small effect	Can be up to 20%	no impact
M9	Very small effect	Can be up to 20%	no impact
M16	Small effect	no impact	$\delta C9 < 0$ can realize





※ $M_{Z'}$ = 3TeV

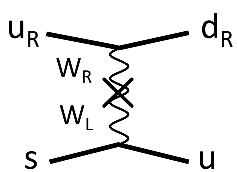
[S.Alioli, V.Cirigliano, W.Dekens, J.de Vries and E.Mereghetti,’17]

Right handed model

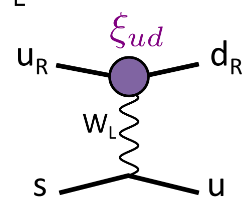
Model

- Consider new right-handed dim.6 operator

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{2}{v^2} i\tilde{\varphi}^\dagger D_\mu \varphi\, \bar{u}^i_R \gamma^\mu\, \xi_{ij} d^j_R + \text{h.c.}, \rightarrow \mathcal{L}_{\rm SM} + \frac{g}{\sqrt{2}} \left[\xi_{ij}\, \bar{u}^i_R \gamma^\mu d^j_R\, W^+_\mu \right] \left(1 + \frac{h}{v}\right)^2 + \text{h.c.}$$



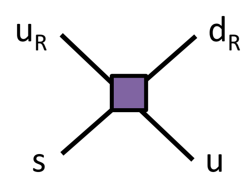
$\Rightarrow$



$\Downarrow$

- New Left-Right operator become O8 & O6

$$\mathcal{O}^{ij\,lm}_{1\,LR} = \bar{d}^m \gamma^\mu P_L u^l\, \bar{u}^i \gamma_\mu P_R d^j$$
$$\mathcal{O}^{ij\,lm}_{2\,LR} = \bar{d}^m_\alpha \gamma^\mu P_L u^l_\beta\, \bar{u}^i_\beta \gamma_\mu P_R d^j_\alpha$$



$\Rightarrow \quad O_6 \;\&\; O_8$

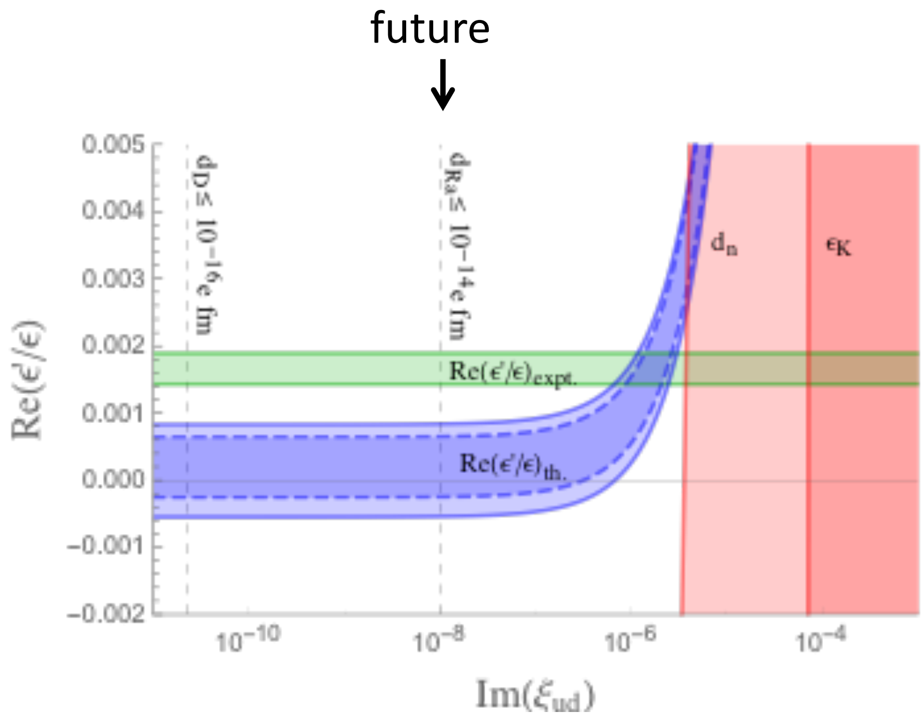
($\varepsilon'/\varepsilon)_{NP}$ in RH model

(ε'/ε) anomaly $\Rightarrow \quad \text{Im}\,\xi_{ud} \in [0.7,\,3]\cdot 10^{-6}\,, \qquad \text{Im}\,\xi_{us} \in [1,\,7]\cdot 10^{-7}$

Correspond to m_{WR} ~ [100, 300] TeV for O(1) phase $\quad \text{Im}\,\xi_{ud,us} \sim (v^2/\Lambda^2)\sin\phi_{ud,us}$

Implications of $(\varepsilon'/\varepsilon)_{NP}$ in RH model

- Right handed currents are constrained by EDMs



- Other constraints are weaker

Collider search > 1 TeV

Beta decay > 1~10 TeV

Model discrimination

		$K_L \to \pi^0 \nu\nu$	$K^+ \to \pi^+ \nu\nu$	Others
MSSM chargino Z pen.	Z (LH)	negative	O(10~100%) effect	C_9^{NP} NO
MSSM gluino Z pen.	Z (LH + RH)	positive (< 3 SM) ? negative	O(10~100%) effect?	C_9^{NP} NO
MSSM gluino box	box	positive (< 2 SM) negative	< 1.4 SM	
VLQ G_{SM}	Z (LH or RH)	negative	< 1.5 SM (RH) < SM (LH)	C_9^{NP} NO
VLQ $G'_{SM}(\Phi)$	Z (LH or RH)	negative	< 5 SM (RH) < 2 SM (LH)	C_9^{NP} by Z' (only partly solved)
LHT	Z' (LH)	negative	< 10% effect	$B(B_s \to \mu\mu) > SM$, C_9^{NP} NO
331 model M8	Z' (LH)	< O(1%) effect	< O(1%) effect	$\delta B(B_s \to \mu\mu) < 0.2$ SM, C_9^{NP} [-0.2, 0.2]
331 model M9	Z' (LH)	< O(1%) effect	< O(1%) effect	$\delta B(B_s \to \mu\mu) < 0.2$ SM, C_9^{NP} [-0.2, 0.2]
331 model M16	Z' (LH)	< 20% effect	< 5% effect	$\delta B(B_s \to \mu\mu) < 0.07$ SM, C_9^{NP} [-0.6, -0.6]
Right handed model	W_R	no effect	no effect	EDM

Simultaneous consideration of various flavor observables ($K \to \pi\nu\nu$, P5', $B_s \to \mu\mu$, EDM,,,) may allow to distinguish between these models.

Summary

- New 2.9 σ anomaly in ε'/ε.
- The ε'/ε anomaly has been explained in several NP models (MSSM, VLQs, LHT, 331, RH current).
- In most of the models, NP contributions to ε'/ε are dominated by Z or Z' exchanges.
- $K_L \to \pi^0 \nu\nu$ has strong correlation with ε'/ε.
- The measurements of $K^+ \to \pi^+ \nu\nu$ & $K_L \to \pi^0 \nu\nu$ will be important test of these models.
- Moreover, simultaneous consideration of various flavor observables ($K \to \pi\nu\nu$, P5', $B_s \to \mu\mu$, EDM,,,) will allow further to discriminate among the models.