Recent progress on CP-violating Kaon decay

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What's next after Higgs? — New Physics!

Evidences of physics beyond SM

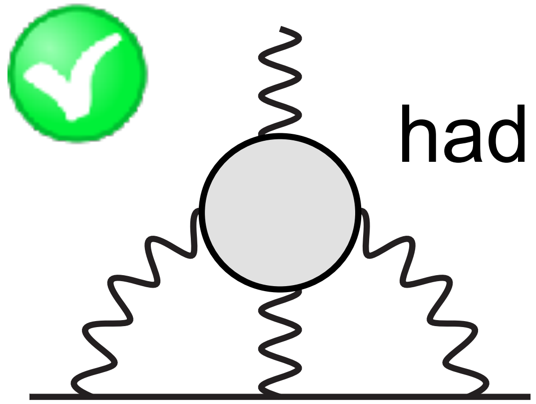
- neutrino oscillations: right-handed neutrinos
- density fluctuations: inflation
- dark matter: new particle, PBH, …
- baryon asymmetry of universe: new CP violations
- dark energy: ???

New physics is not yet revealed

- No signals at LHC $\Rightarrow$ E > 1-2 TeV
- Flavor/CP observables are sensitive to higher scale

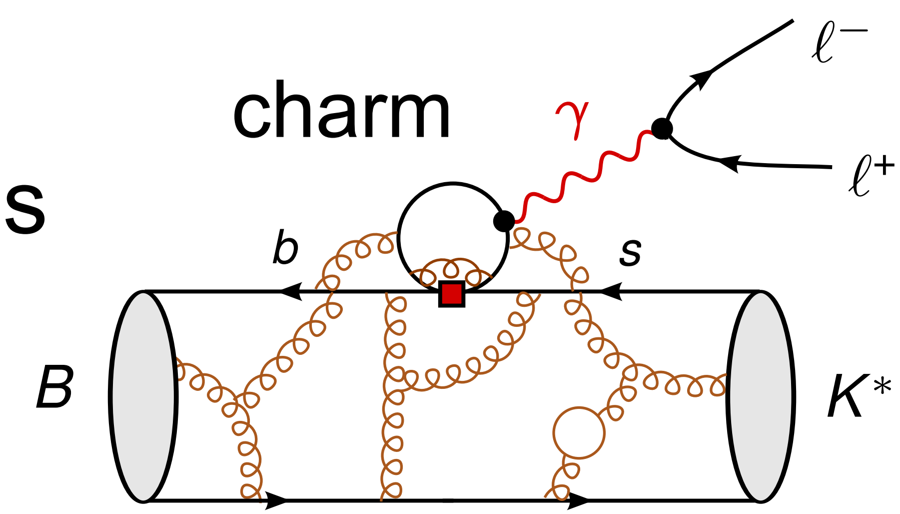
Flavor candidates of NP signal

- **Muon g-2**: >3σ, lattice for light-by-light cont.



- **B→K*ll**: >3σ in P_5' angular distribution
  - may underestimate charm loop

- **$R_{K^{(*)}}=\Gamma(B\to K^{(*)}\mu\mu)/\Gamma(B\to K^{(*)}ee)$**: >2σ
  - LHCb: challenging to identify electrons
  - electron rate looks unclear



- **$R_{D^{(*)}}=\Gamma(B\to D^{(*)}\tau\nu)/\Gamma(B\to D^{(*)}l\nu)$**: >3σ
  - deviation mostly by BaBar ⇒ tau identification?
  - latest LHCb result is consistent with SM

- **CP violation in Kaon decays**

What's new in Kaon?

- **CP violation in Kaon decays**
  - $K_L \to \pi\pi$ proceeds via CP violations
- **First lattice computation of hadron matrix element**

$$(\epsilon'/\epsilon)_{\rm SM} = \begin{cases} (1.38 \pm 6.90) \times 10^{-4} & \text{[lattice; RBC-UKQCD'15]} \\ (1.9 \pm 4.5) \times 10^{-4} & \text{[Buras et.al.'15]} \\ (1.06 \pm 5.07) \times 10^{-4} & \text{[Kitahara et.al.'16]} \end{cases}$$

$$(\epsilon'/\epsilon)_{\rm exp} = (16.6 \pm 2.3) \times 10^{-4} \quad \text{[NA48,KTeV'90-99]}$$

New 2.8–2.9σ discrepancy

Outline

- **Introduction**
  - What is ε'/ε?
  - Status: 2.8–2.9σ anomaly
- **New physics interpretation**
  - Overview of recent approaches

  SUSY scenarios
  - Gluino box contribution [Kitahara,Nierste,Tremper'16]
  - Z-penguin contribution
    [ME,Kitahara,Mishima,Yamamoto'16,ME,Mishima,Ueda,Yamamoto'16]
- **Summary**

CP violations in Kaon: introduction

- $K^0(\bar{s}\gamma_5 d),\ \bar{K}^0(\bar{d}\gamma_5 s)$: $J^P=0^-$, not mass-, not CP eigenstate

- CP eigenstate: $|K_\pm\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle \pm |\bar{K}^0\rangle\right]$

  CP: $|K_+\rangle$: even, $|K_-\rangle$: odd $\quad (\text{cf. } CP|K^0\rangle = |\bar{K}^0\rangle)$

  not mass eigenstate because of CP violation

- Mass eigenstate: $|K_S^0\rangle \sim |K_+\rangle + \bar{\epsilon}|K_-\rangle$

  $|K_L^0\rangle \sim |K_-\rangle + \bar{\epsilon}|K_+\rangle$

$\bar{\epsilon}$: CPV parameter ($\sim 10^{-3}$)

CP violations in Kaon: oscillation

- $K^0 \leftrightarrow \bar{K}^0 \;:\; |\psi(t)\rangle = a(t)|K^0\rangle + b(t)|\bar{K}^0\rangle$

$$\begin{matrix} & K^0 & \bar{K}^0 \\ \mathcal{H} = & \begin{pmatrix} M - \frac{i}{2}\Gamma & \Delta_{12} \\ \Delta_{21} & M - \frac{i}{2}\Gamma \end{pmatrix} \end{matrix}$$

(Δ_{12}: $K^0 \leftrightarrow \bar{K}^0$)

- $|K_\pm\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle \pm |\bar{K}^0\rangle\right]$: 45° rotation

$$\mathcal{H}' = \begin{pmatrix} H'_{11} & \frac{1}{2}(\Delta_{12} - \Delta_{21}) \\ -\frac{1}{2}(\Delta_{12} - \Delta_{21}) & H'_{22} \end{pmatrix}$$

where $\Delta_{12} \sim \langle K^0|H|\bar{K}^0\rangle, \;\; \Delta_{21} \sim \langle \bar{K}^0|H|K^0\rangle$

- Mass eigenstate: $|K^0_S\rangle \sim |K_+\rangle + \bar{\epsilon}|K_-\rangle$

$$|K^0_L\rangle \sim |K_-\rangle + \bar{\epsilon}|K_+\rangle$$

mixing ($\bar{\epsilon}$) ~ CP violation: $\mathrm{Im}\,\langle K^0|H|\bar{K}^0\rangle$

CP-violating K→ππ decay

- CP selection: $K_L \to \pi\pi$ is forbidden if CP is exact
- CP property: $CP|K_\pm\rangle = \pm|K_\pm\rangle \quad CP|\pi\pi\rangle = |\pi\pi\rangle$

$$|K_L\rangle \sim |K_-\rangle + \bar{\epsilon}|K_+\rangle$$

indirect CPV → $|\pi\pi\rangle$

CPV during oscillation

direct CP violation → $|\pi\pi\rangle$

CPV at decay

Direct CP violation: experiment

- Two decay modes: $K_L \to \pi^+\pi^- \quad K_L \to \pi^0\pi^0$

$$\eta_{00} = \frac{\mathcal{A}(K_L \to \pi^0\pi^0)}{\mathcal{A}(K_S \to \pi^0\pi^0)} = \epsilon_K + \overbrace{\text{(CPV at decay)}}^{\boldsymbol{\varepsilon'}}$$

$$\eta_{+-} = \frac{\mathcal{A}(K_L \to \pi^+\pi^-)}{\mathcal{A}(K_S \to \pi^+\pi^-)} = \epsilon_K + \text{(CPV at decay)'}$$

- CP violation in oscillation (ε_K) contributes **equally**
- CP violation at decay generates **difference**

cf. $\epsilon_K \sim \bar{\epsilon}$, exact in Wu-Yang convention

Direct CP violation: experiment

- **Result** **[NA48,KTeV]**

$$\frac{\epsilon'_K}{\epsilon_K} \simeq \frac{1}{6}\left[1 - \frac{|\eta_{00}|^2}{|\eta_{+-}|^2}\right] = (16.6 \pm 2.3) \times 10^{-4}$$

where $\eta_{00} = \frac{\mathcal{A}(K_L \to \pi^0\pi^0)}{\mathcal{A}(K_S \to \pi^0\pi^0)}, \;\; \eta_{+-} = \frac{\mathcal{A}(K_L \to \pi^+\pi^-)}{\mathcal{A}(K_S \to \pi^+\pi^-)}$

cf. $\epsilon_K = (2.228 \pm 0.011) \times 10^{-3} \cdot e^{i(0.97 \pm 0.02)\pi/4}$

Direct CP violation: theory

- Final states characterized by isospin [Note: isovector (π^+,π^0,π^-)]

$$|\pi^0\pi^0\rangle = \sqrt{\tfrac{1}{3}}\,|(\pi\pi)_{I=0}\rangle - \sqrt{\tfrac{2}{3}}\,|(\pi\pi)_{I=2}\rangle$$
$$|\pi^+\pi^-\rangle = \sqrt{\tfrac{2}{3}}\,|(\pi\pi)_{I=0}\rangle + \sqrt{\tfrac{1}{3}}\,|(\pi\pi)_{I=2}\rangle$$

- Decay amplitudes in isospin basis

$$\mathcal{A}(K_L \to (\pi\pi)_{I=0}) = \mathcal{A}_0 e^{i\delta_0},\ \mathcal{A}(K_L \to (\pi\pi)_{I=2}) = \mathcal{A}_2 e^{i\delta_2}$$

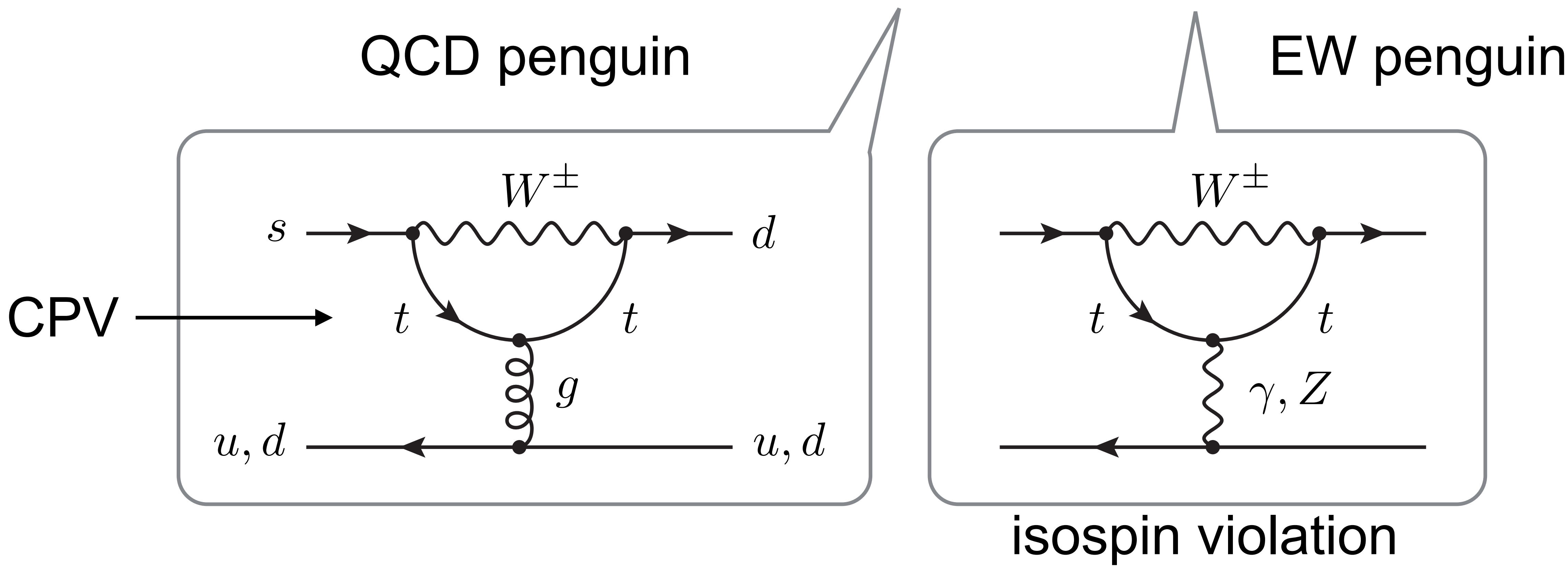
$\delta_{I=0,2}$: strong phase

$$\frac{\epsilon'}{\epsilon} \sim \frac{\omega}{\sqrt{2}\epsilon_K}\left[\frac{\mathrm{Im}\,\mathcal{A}_2}{\mathrm{Re}\,\mathcal{A}_2} - \frac{\mathrm{Im}\,\mathcal{A}_0}{\mathrm{Re}\,\mathcal{A}_0}\right]$$

Note: ΔI=1/2 rule, $\omega = \frac{\mathrm{Re}\,A_2}{\mathrm{Re}\,A_0} \simeq 1/22$

Standard Model

$$\frac{\epsilon'}{\epsilon} \propto \left[\frac{\mathrm{Im}\,\mathcal{A}_2}{\mathrm{Re}\,\mathcal{A}_2} - \frac{\mathrm{Im}\,\mathcal{A}_0}{\mathrm{Re}\,\mathcal{A}_0}\right] \sim \frac{-1}{\mathrm{Re}\,\mathcal{A}_0}\left[\mathrm{Im}\,\mathcal{A}_0 - \frac{1}{\omega}\mathrm{Im}\,\mathcal{A}_2\right]$$



- **EW penguin is comparable to QCD due to 1/ω~22 (ΔI=1/2)**
- **Almost cancel out between A_0 and A_2**

Status

- **SM prediction**

$$(\epsilon'/\epsilon)_{\rm SM} = \begin{cases} (1.38 \pm 6.90) \times 10^{-4} & \text{[lattice; RBC-UKQCD'15]} \\ (1.9 \pm 4.5) \times 10^{-4} & \text{[Buras et.al.'15]} \\ (1.06 \pm 5.07) \times 10^{-4} & \text{[Kitahara et.al.'16]} \end{cases}$$

- **Experimental result**

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

Recent progress on SM prediction

A_I = (Wilson coefficient) $\otimes$ (hadron matrix element)

- First lattice computation of $K \to \pi\pi$ matrix element
  [RBC-UKQCD'15]
  - physical mass, physical kinematics
  - need more studies
- Reduce uncertainty (Re A_0 and Re A_2) by experimental data
  [Buras,Gorbahn,Jager,Jamin'15]
- Sub-leading contributions (Q_3,Q_5,Q_7) + … [calc up to NLO]
  [Kitahara,Nierste,Tremper'16]
- NNLO QCD in progress [Cerda-Sevilla,Gorbahn,Jager,Kokulu]

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New 2.8–2.9σ discrepancy

Exp. result is ~10 larger than SM

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    - Gluino box contribution [Kitahara,Nierste,Tremper'16]
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- **Summary**

New physics interpretation

- Status: $(\varepsilon'/\varepsilon)_{exp} \sim 10\ (\varepsilon'/\varepsilon)_{SM} \Rightarrow$ **$(\varepsilon'/\varepsilon)_{exp} \sim (\varepsilon'/\varepsilon)_{NP}$**
- Naive NP estimation: $(\varepsilon'/\varepsilon)_{NP} \sim 1/m_{NP}^2$

  $(\varepsilon'/\varepsilon)_{NP}/(\varepsilon'/\varepsilon)_{SM} \sim m_{EW}^2/m_{NP}^2 \Rightarrow$ **$m_{NP} < m_{EW}$? — NO**
- Cancellation in SM amplitudes: $(\varepsilon'/\varepsilon)_{SM} \sim c_{SM}/m_{EW}^2$

$$\frac{\epsilon'}{\epsilon} \propto \left[\frac{\mathrm{Im}\,\mathcal{A}_2}{\mathrm{Re}\,\mathcal{A}_2} - \frac{\mathrm{Im}\,\mathcal{A}_0}{\mathrm{Re}\,\mathcal{A}_0}\right] \sim \frac{-1}{\mathrm{Re}\,\mathcal{A}_0}\left[\mathrm{Im}\,\mathcal{A}_0 - \frac{1}{\omega}\mathrm{Im}\,\mathcal{A}_2\right]$$

$(\varepsilon'/\varepsilon)_{NP}/(\varepsilon'/\varepsilon)_{SM} \sim$ **$(1/c_{SM})$** m_{EW}^2/m_{NP}^2 w/ **$c_{SM} \ll 1$**

$\Rightarrow$ **m_{NP} can be larger than m_{EW}**

Recent approach

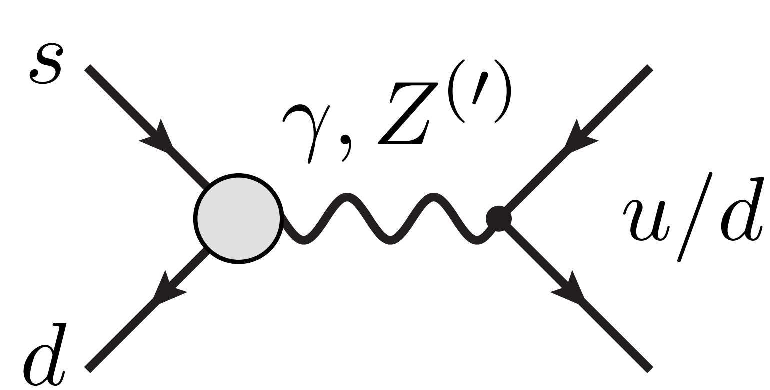
$$\frac{\epsilon'}{\epsilon} \propto \left[\frac{\mathrm{Im}\,\mathcal{A}_2}{\mathrm{Re}\,\mathcal{A}_2} - \frac{\mathrm{Im}\,\mathcal{A}_0}{\mathrm{Re}\,\mathcal{A}_0}\right] \sim \frac{-1}{\mathrm{Re}\,\mathcal{A}_0}\left[\mathrm{Im}\,\mathcal{A}_0 - \frac{1}{\omega}\mathrm{Im}\,\mathcal{A}_2\right]$$

QCD penguin

EW penguin

- NP contributions to ImA_0 or ImA_2 w/o cancellation
- Severe constraint by indirect CP violation, ε_K (⇒ later)
- Recent approach: **NP contributions to EW penguin**

  ⇒ enhanced by $1/\omega \sim 22$



New physics models

$$\frac{\epsilon'}{\epsilon} \propto \left[\frac{\mathrm{Im}\,\mathcal{A}_2}{\mathrm{Re}\,\mathcal{A}_2} - \frac{\mathrm{Im}\,\mathcal{A}_0}{\mathrm{Re}\,\mathcal{A}_0}\right] \sim \frac{-1}{\mathrm{Re}\,\mathcal{A}_0}\left[\mathrm{Im}\,\mathcal{A}_0 - \frac{1}{\omega}\mathrm{Im}\,\mathcal{A}_2\right]$$

QCD penguin

EW penguin

- Enhance flavor-changing *Z* coupling or Z' contributions, …

  [Buras et.al'15-16; VLQ, 331 model, Little Higgs][Cirigliano et.al.'17; RH]

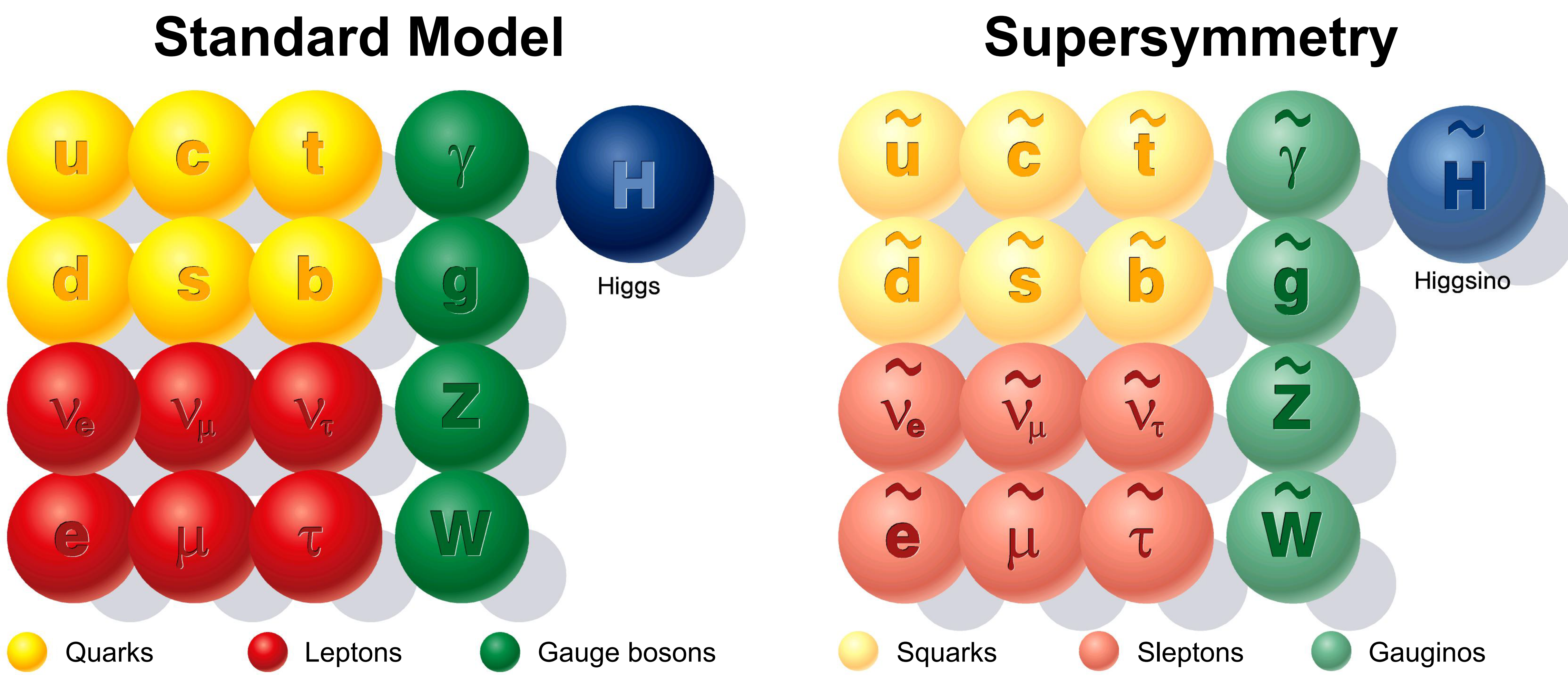
- **SUSY scenarios**
  - Gluino box with large isospin breaking

    [Kitahara,Nierste,Tremper'16]

  - Z penguin contribution

    [Tanimoto,Yamamoto'16;ME,Mishima,Ueda,Yamamoto'16]

SUSY is a well-motivated NP candidate



symmetry between fermion and boson

Motivations

Hints of new physics

SUSY

- neutrino oscillation
- early universe (e.g. DM) → LSP, scalars
- hierarchy problem → good
- GUT → unification
- many flavor and CP sources → flavor, CP signals e.g., in Kaon

New physics models

$$\frac{\epsilon'}{\epsilon} \propto \left[\frac{\mathrm{Im}\,\mathcal{A}_2}{\mathrm{Re}\,\mathcal{A}_2} - \frac{\mathrm{Im}\,\mathcal{A}_0}{\mathrm{Re}\,\mathcal{A}_0}\right] \sim \frac{-1}{\mathrm{Re}\,\mathcal{A}_0}\left[\mathrm{Im}\,\mathcal{A}_0 - \frac{1}{\omega}\mathrm{Im}\,\mathcal{A}_2\right]$$

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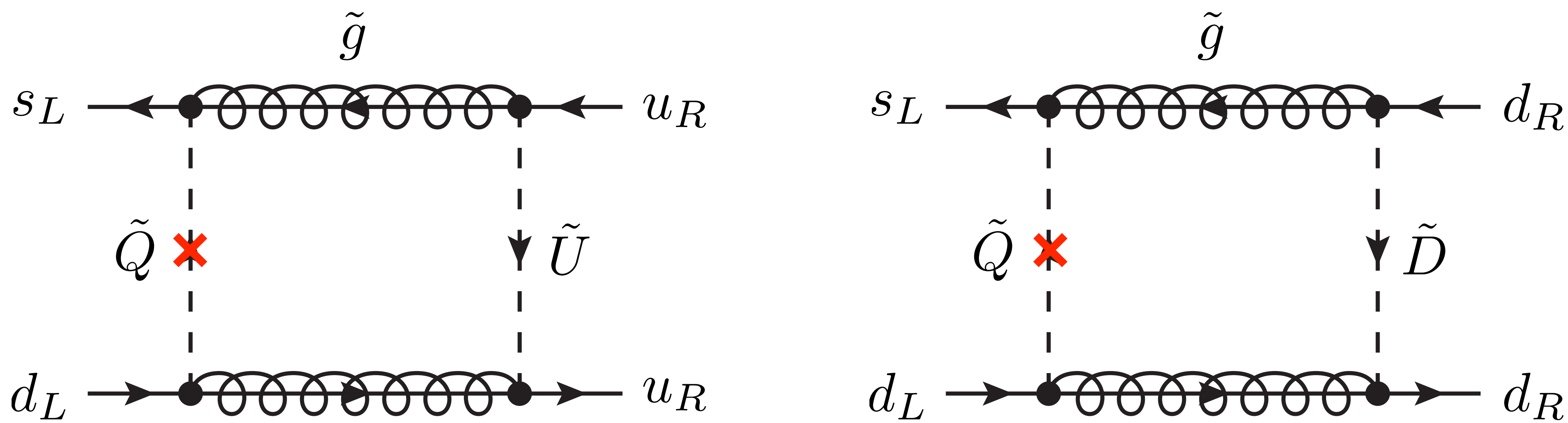
Gluino-box contribution [Kitahara,Nierste,Tremper'16]

ε': direct CP violation in K→ππ



- Flavor and CP violation in left-handed squark

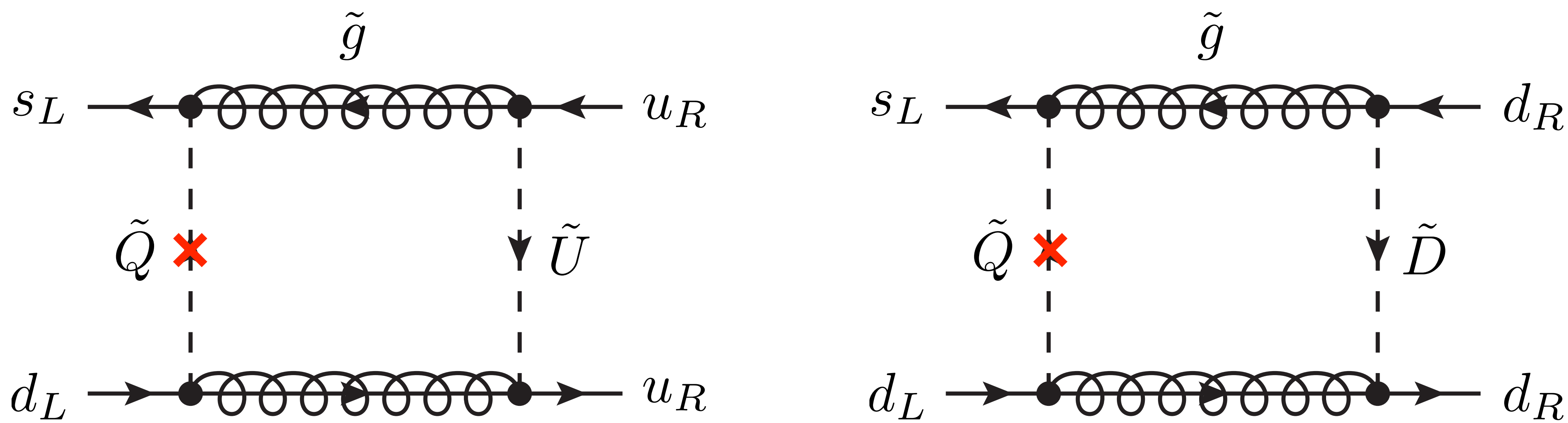
$$\mathcal{M}^2_{\tilde{d}} = \mathrm{diag}(m^2_{\tilde{q}}) + m^2_{\tilde{q}} \begin{pmatrix} \delta_{LL} & \delta_{LR} \\ \delta_{RL} & \delta_{RR} \end{pmatrix}_{ij}$$

- QCD interaction
- Naively excluded by ε_K ⇒ need something ingenious

Gluino-box contribution

[Kitahara,Nierste,Tremper'16]

ε': direct CP violation in K→ππ



sum

difference

Im A_0

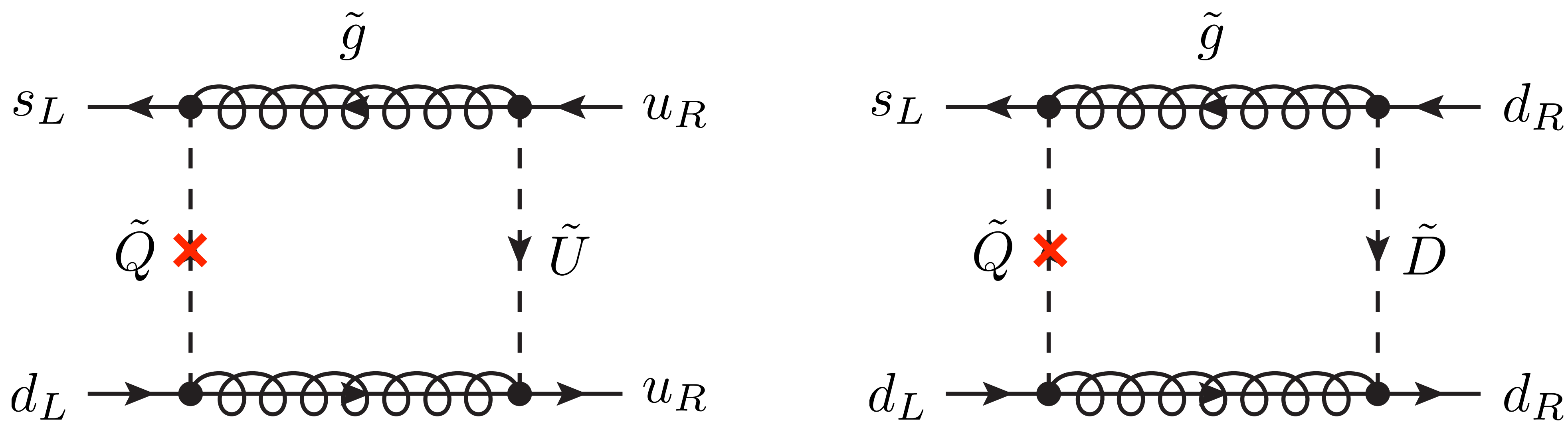
Isospin breaking ⇒ Im A_2

cf. QCD penguin

behave as EW penguin
("trojan" penguin)

Gluino-box contribution [Kitahara,Nierste,Tremper'16]

ε': direct CP violation in K→ππ



- **Isospin violation:** $m_{\tilde{U}} \neq m_{\tilde{D}}$
- **Enhancement**
  - QCD interaction & 1/ω~22
  - Chiral enhancement: ini=L, fin=R

  } relax ε_K bound
- Still constrained by ε_K

Severe ε_K constraint

$$|K_L\rangle \sim |K_-\rangle + \epsilon_K |K_+\rangle$$

$\rightarrow |\pi\pi\rangle$ CPV in $K^0 \leftrightarrow \bar{K}^0$

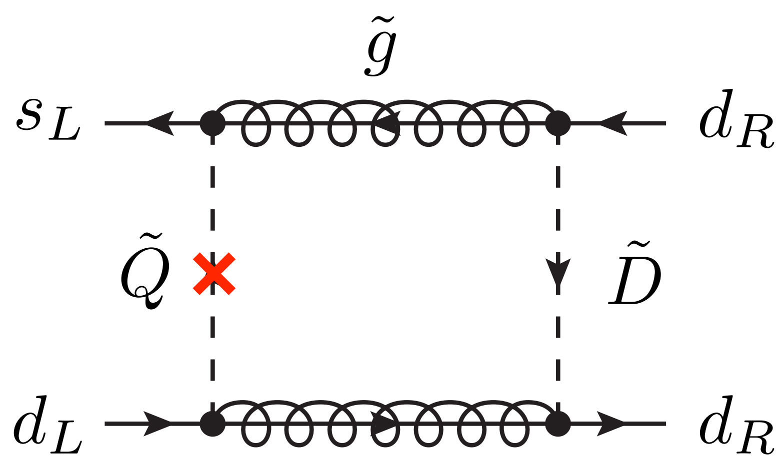
$\rightarrow |\pi\pi\rangle$ CPV at decay ⇒ ε'/ε

- CPV during oscillation mixing: $\epsilon_K \simeq \dfrac{\kappa_\epsilon \, \mathrm{Im}\langle K^0|H|\bar{K}^0\rangle}{\sqrt{2}\Delta m_K}$

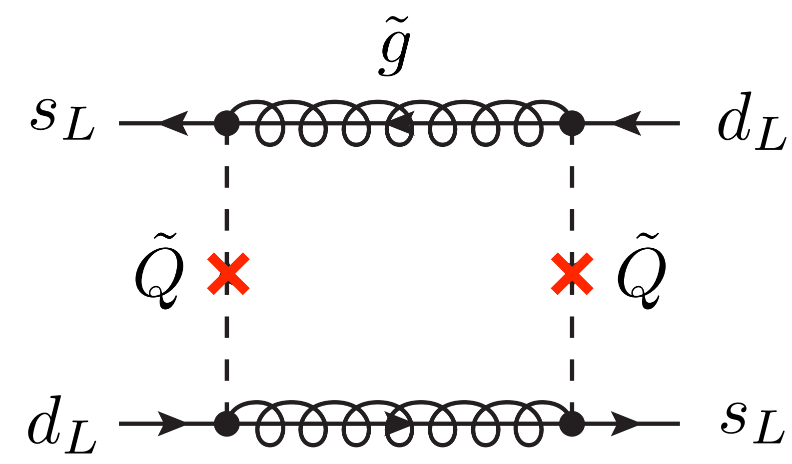
- Experiment: $\epsilon_K^{(\mathrm{exp})} = (2.228 \pm 0.011) \times 10^{-3}$
- SM: $\epsilon_K^{(\mathrm{SM})} = (2.24 \pm 0.19) \times 10^{-3}$

} **very severe constraint**

Gluino-box contribution



ε': K$_L$→ππ

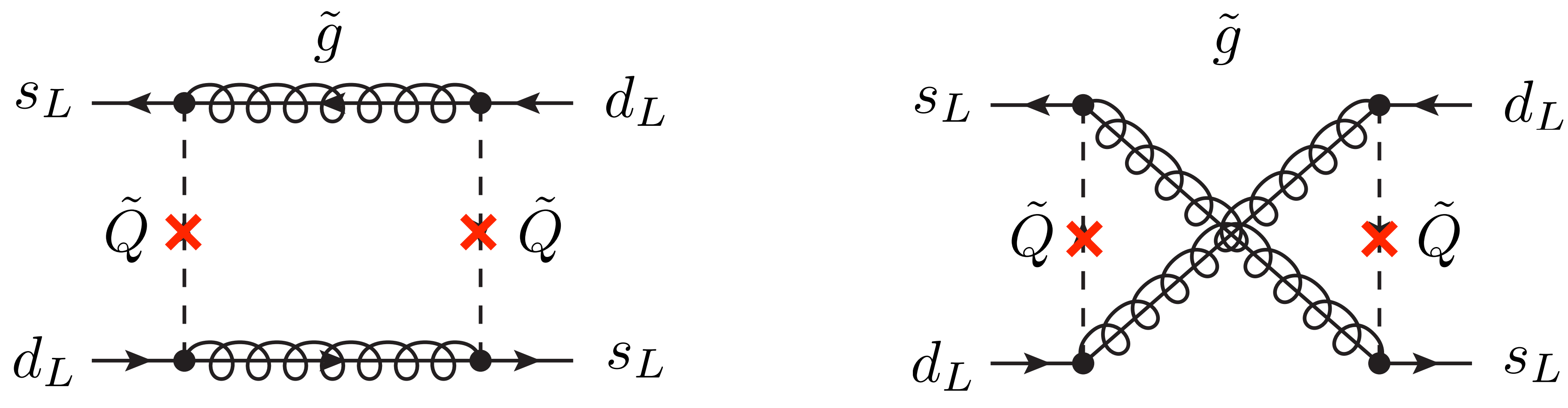


ε$_K$: $K^0 \leftrightarrow \bar{K}^0$

$$\epsilon_K \simeq \epsilon_K^{(\mathrm{SM})} + \frac{\kappa_\epsilon \, \mathrm{Im}\langle K^0 | H | \bar{K}^0 \rangle|_{\mathrm{NP}}}{\sqrt{2}\Delta m_K}$$

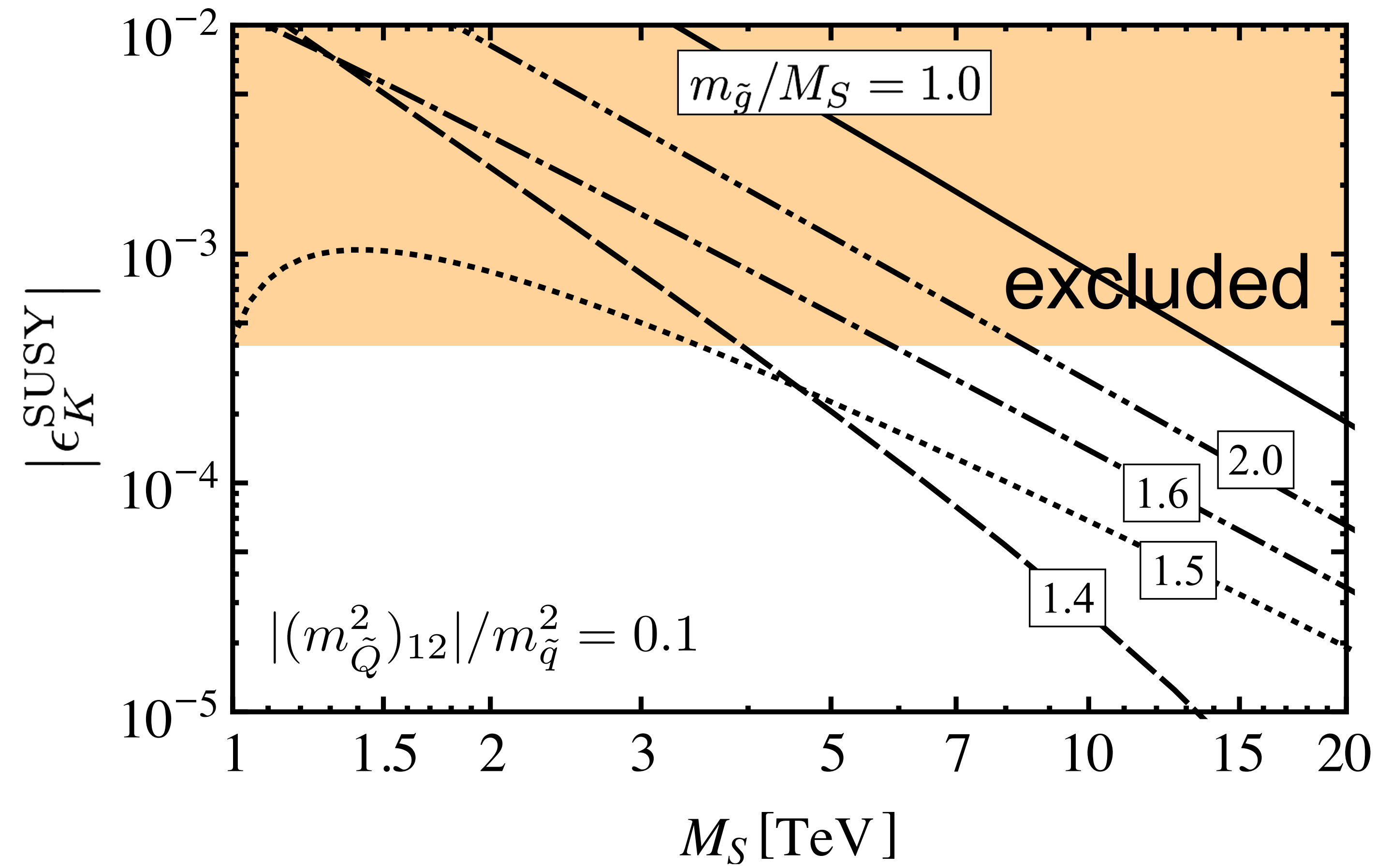
Model is naively excluded

Cancellation



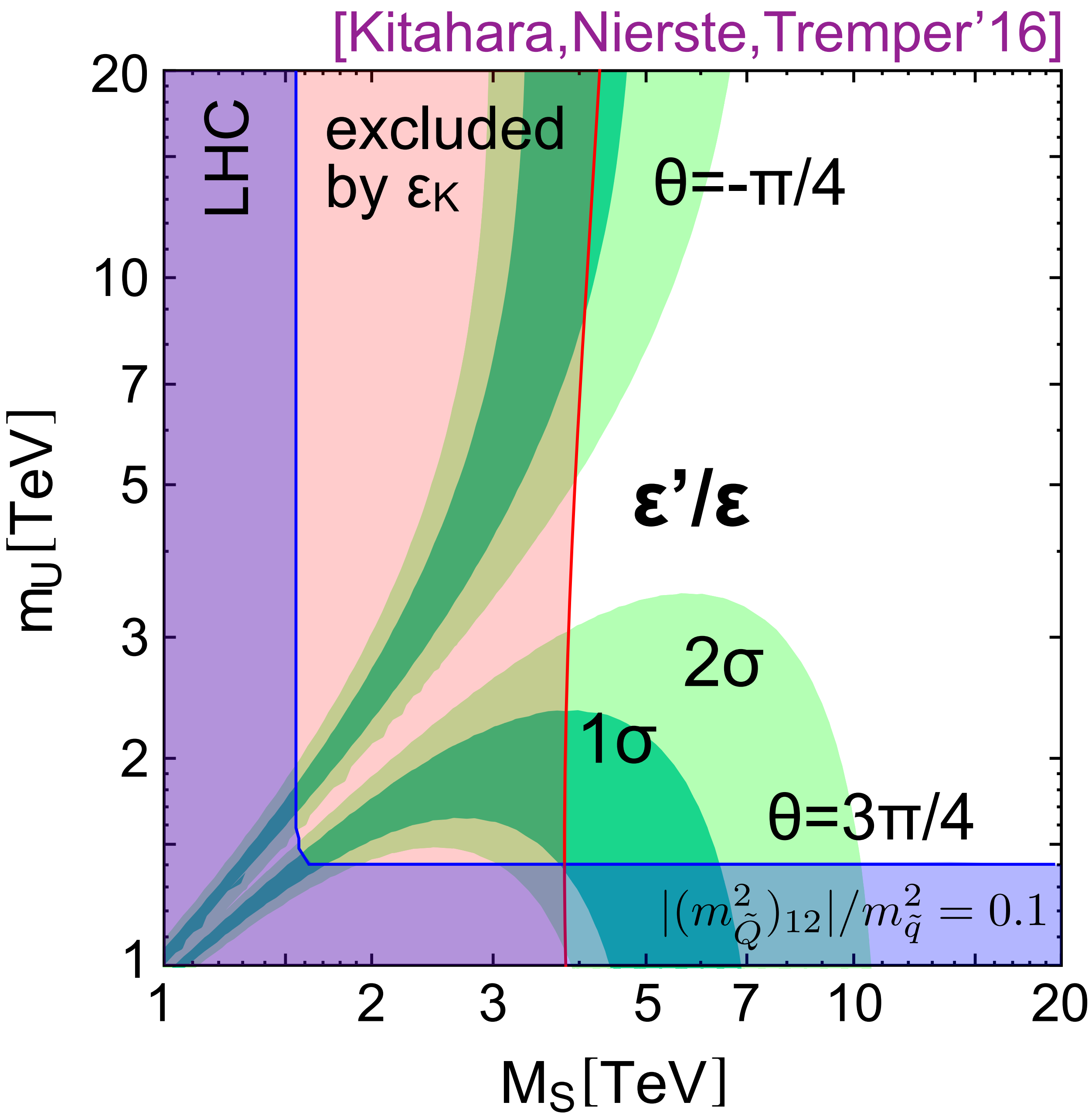
crossed

- crossed diagram because gluino is Majorana
- relatively destructive
- cancellation for $m_{\tilde{g}} \sim 1.5 m_{\tilde{q}}$
- ε_K satisfied for $m_{\tilde{g}} \gtrsim 3\text{–}4\,\mathrm{TeV}$



Result

- Gluino-box with large isospin breaking
- suppress ε_K by $m_{\tilde{g}}/m_{\tilde{Q}} = 1.5$
- ε'/ε discrepancy is explained for $m_{\tilde{Q}} \lesssim 6$TeV



New physics models

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QCD penguin

EW penguin

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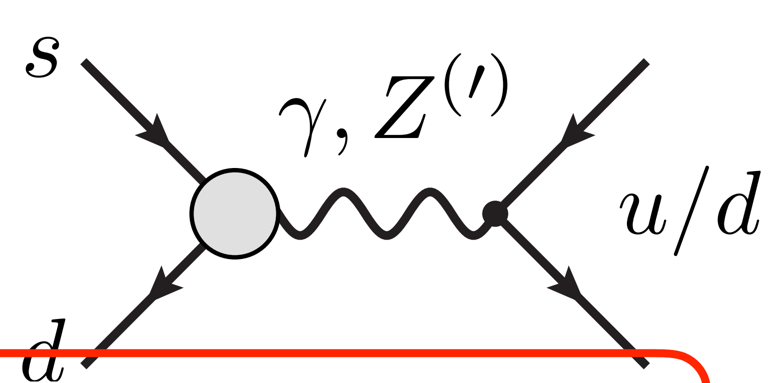
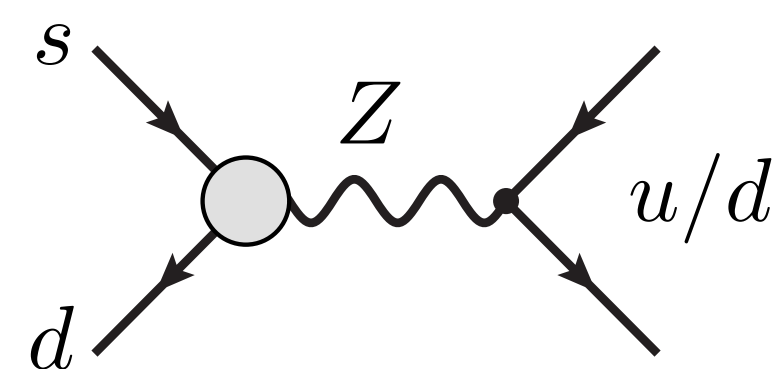


Z-penguin contribution

- (Naive) effective Lagrangian



$$\mathcal{L} = \Delta_L(\bar{s}\gamma^\mu P_L d)Z_\mu + \Delta_R(\bar{s}\gamma^\mu P_R d)Z_\mu$$

$\Rightarrow$ NOT gauge invariant

- Effective Lagrangian in SMEFT [=SU(2)xU(1) inv.]

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \textstyle\sum_i \mathcal{C}_i \mathcal{O}_i^{d\geq 5}$$

EWSB

$$\mathcal{O}_i^{d=6} = (H^\dagger i \overleftrightarrow{D_\mu} H)(\overline{q}_i\gamma^\mu q_j),$$
$$(H^\dagger i\tau^a \overleftrightarrow{D_\mu} H)(\overline{q}_i\tau^a\gamma^\mu q_j),$$

$\Rightarrow$ **Δ_L**

$$(H^\dagger i \overleftrightarrow{D_\mu} H)(\overline{d}_i\gamma^\mu d_j)$$

$\Rightarrow$ **Δ_R**

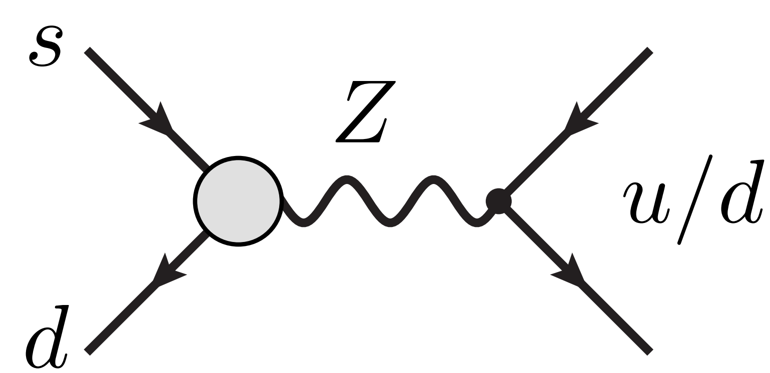
$$\Rightarrow \quad \mathcal{L} = \Delta_L(\bar{s}\gamma^\mu P_L d)Z_\mu + \Delta_R(\bar{s}\gamma^\mu P_R d)Z_\mu + (G_i, W^\pm\text{–terms})$$

Observables

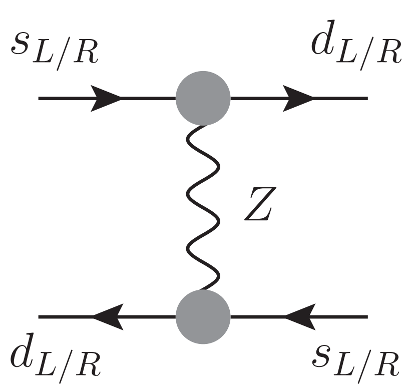
- **ε'/ε**

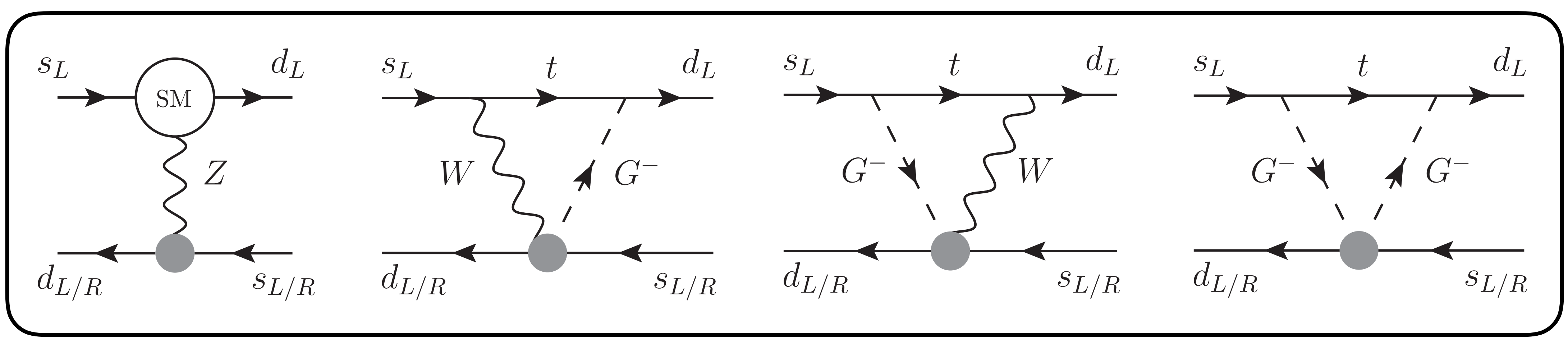
$$(\epsilon'/\epsilon)_{\mathrm{NP}} \propto -\left(\mathrm{Im}\,\Delta_L + \frac{c_W^2}{s_W^2}\mathrm{Im}\,\Delta_R\right)$$

~3.3



- **ε$_K$**

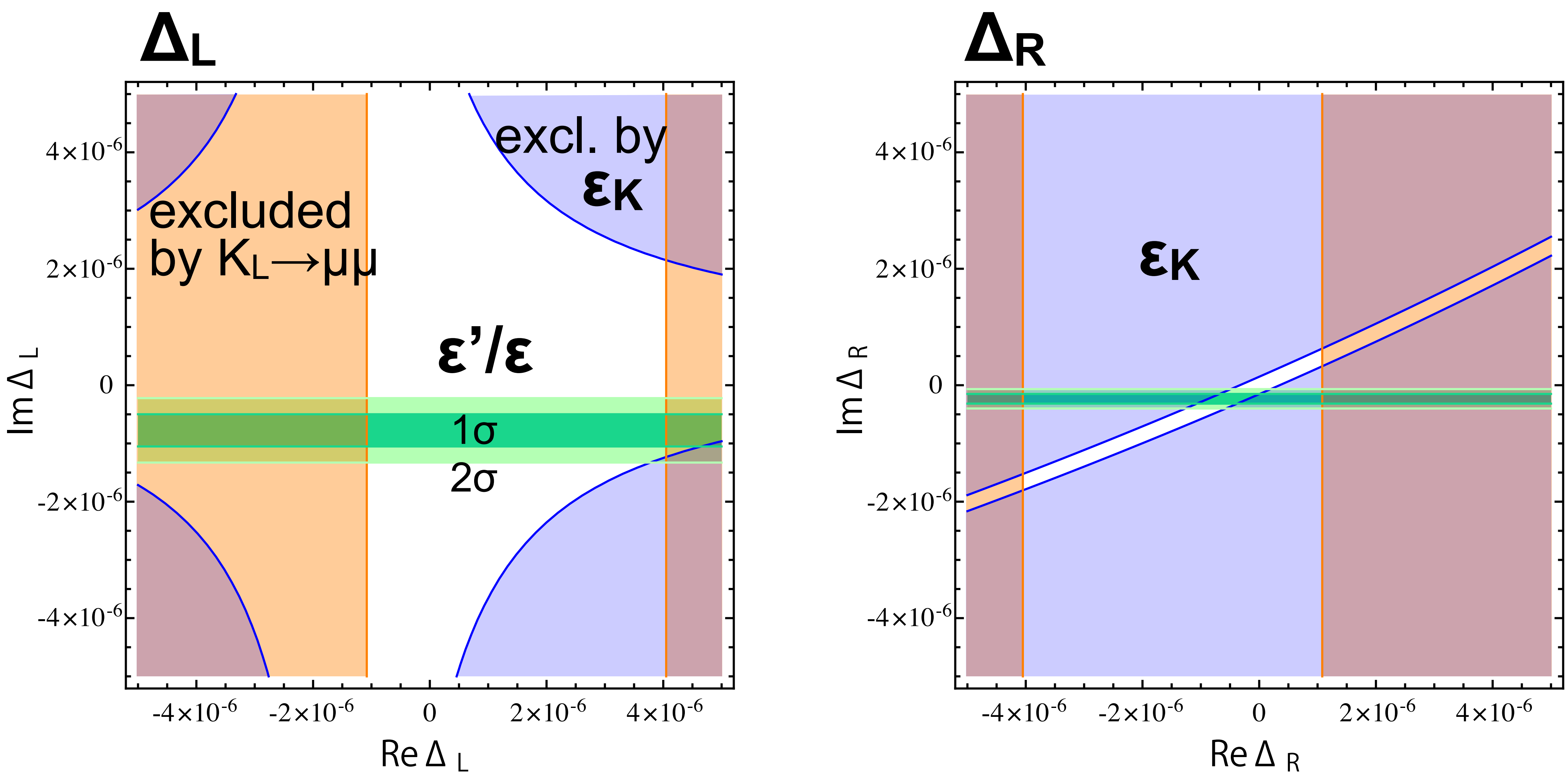




overlooked in literature

[ME,Kitahara,Mishima,Yamamoto'16;Buras et.al.'16]

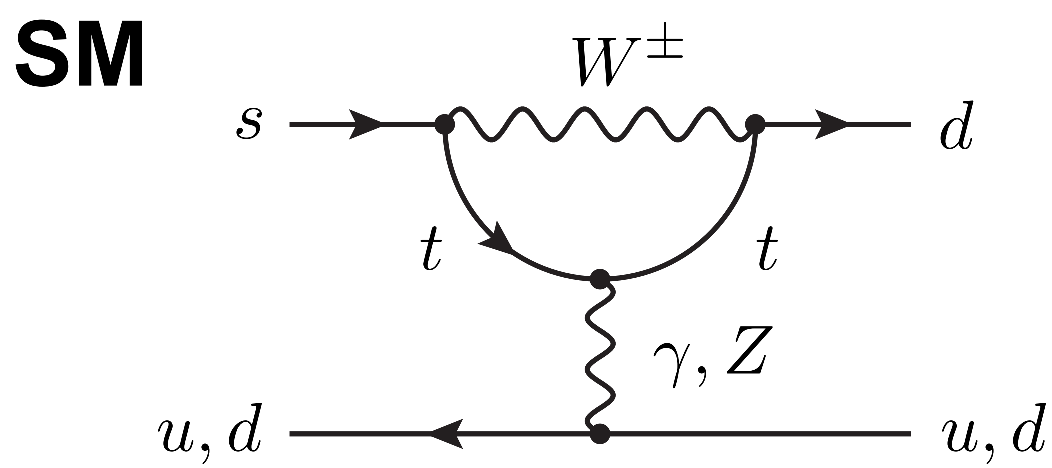
Constraint on general Z scenario

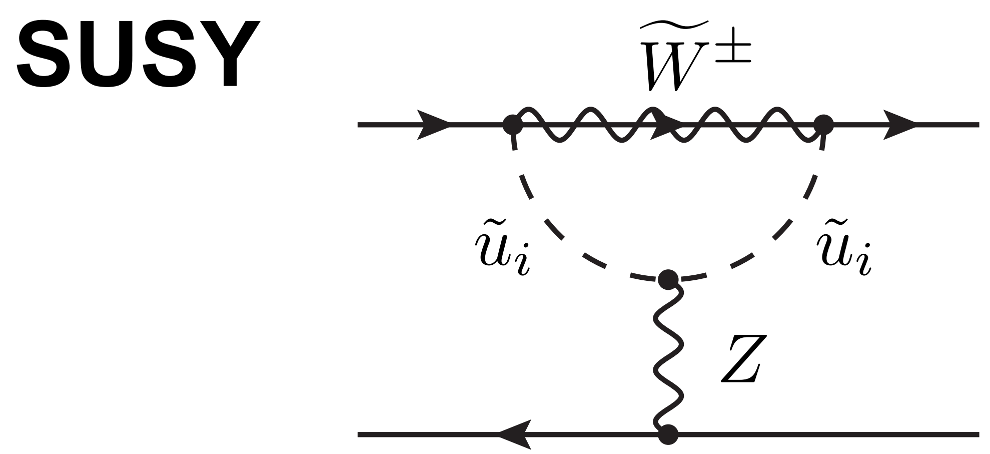


- Severe bound on Δ_R due to chiral enhancement
- **Wide parameter region in Δ_L ⇒ Wino (chargino)**

Chargino Z penguin

[ME,Mishima,Ueda,Yamamoto'16]





Chargino Z penguin

- Flavor and CP violation in LR mixing of squarks

$$\mathcal{M}^2_{\tilde{d}} = \mathrm{diag}(m^2_{\tilde{q}}) + m^2_{\tilde{q}} \begin{pmatrix} \delta_{LL} & \delta_{LR} \\ \delta_{RL} & \delta_{RR} \end{pmatrix}_{ij} \qquad (\delta^u_{LR})_{ij} = \frac{\frac{v_2}{\sqrt{2}}(T_U)^*_{ij}}{m^2_{\tilde{q}}}$$

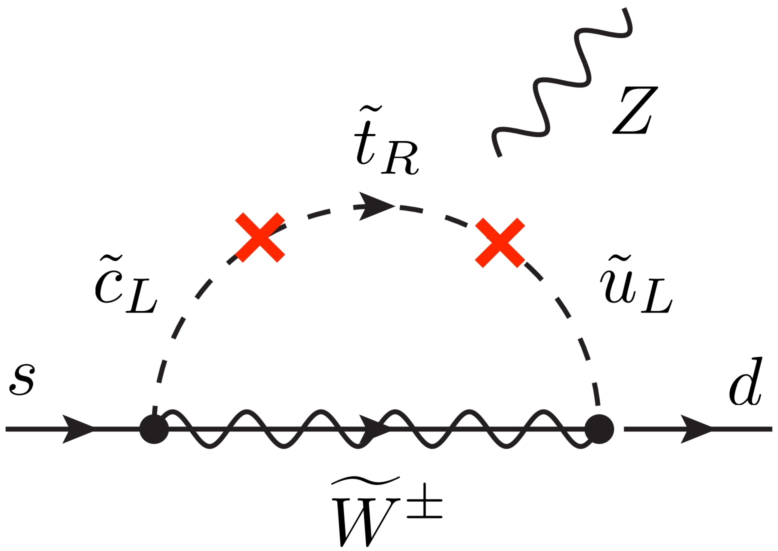
$$\left.\begin{array}{l} (H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{q}_i \gamma^\mu q_j) \\ (H^\dagger i\tau^a \overleftrightarrow{D}_\mu H)(\overline{q}_i \tau^a \gamma^\mu q_j) \end{array}\right\} \; V = (T_U)_{i3} H_u \tilde{u}_{iL} \tilde{t}^*_R$$

Chargino Z penguin

[ME,Mishima,Ueda,Yamamoto'16]

$$\Delta_L \simeq (\delta^u_{LR})^*_{13}(\delta^u_{LR})_{23} H_0(x_{\tilde{q}\tilde{W}})$$

$H_0(x)$: loop function w/ $x_{\tilde{q}\tilde{W}} = m^2_{\tilde{q}}/m^2_{\tilde{W}}$



- Flavor and CP violations in δ_{LR}, δ_{RL}
- Not suppressed by m_{EW}/m_{SUSY} if $\delta_{LR}\delta_{RL}$ is fixed
- ε'/ε can be explained if $\delta_{LR}\delta_{RL}$ is large

$$(\epsilon'/\epsilon)_{\rm NP} \propto -\left(\mathrm{Im}\,\Delta_L + \frac{c_W^2}{s_W^2}\mathrm{Im}\,\Delta_R\right)$$

How large can $\delta_{LR}\delta_{RL}$ (i.e. ε'/ε) be?

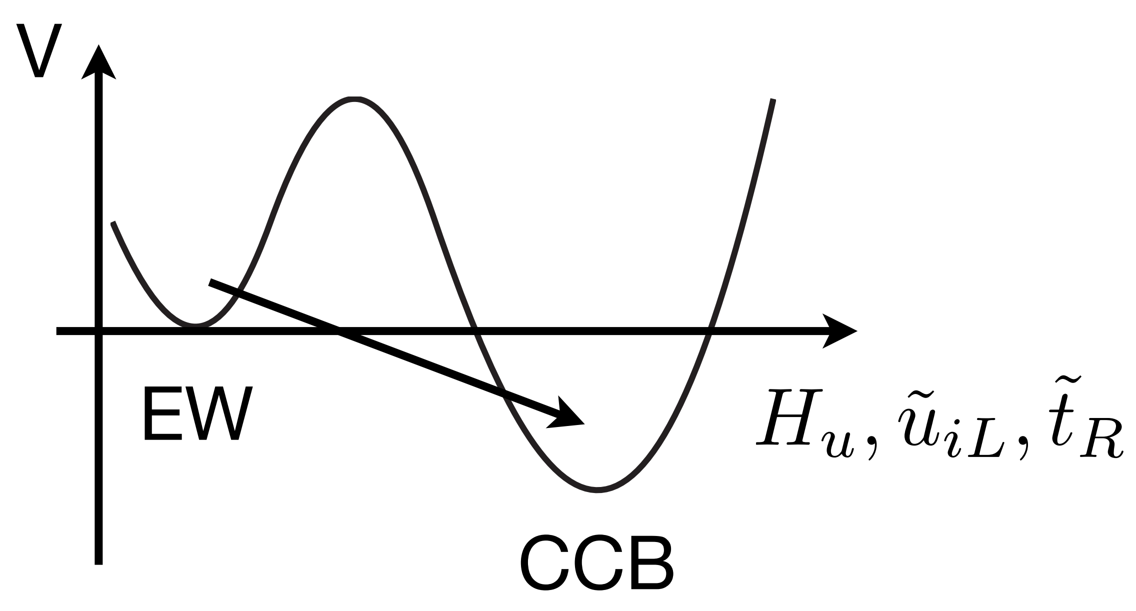
Stability of EW vacuum

- $\delta_{LR,RL}$ are constrained by vacuum stability condition

$$(\delta^u_{LR})_{ij} = \frac{\frac{v_2}{\sqrt{2}}(T_U)^*_{ij}}{m^2_{\tilde{q}}} \Rightarrow V = (T_U)_{i3} H_u \tilde{u}_{iL} \tilde{t}^*_R$$

- large trilinear coupling spoils stability of EW vacuum

  ⇒ ‘tunneling’ to dangerous (charge/color breaking) vacuum



Vacuum decay rate

- decay rate per unit volume [Coleman'77]

$$\Gamma/V = Ae^{-B/\hbar}[1+\mathcal{O}(\hbar)]$$

- bounce action (cf. WKB calculation of tunneling rate)

$$(B =)\ S_E = \int d^4x \left[\frac{1}{2}(\partial\phi_B)^2 + V(\phi_B)\right]$$

Φ_B: solution of $\partial^2\phi_B^2 - V'(\phi_B) = 0$ w/ b.c.

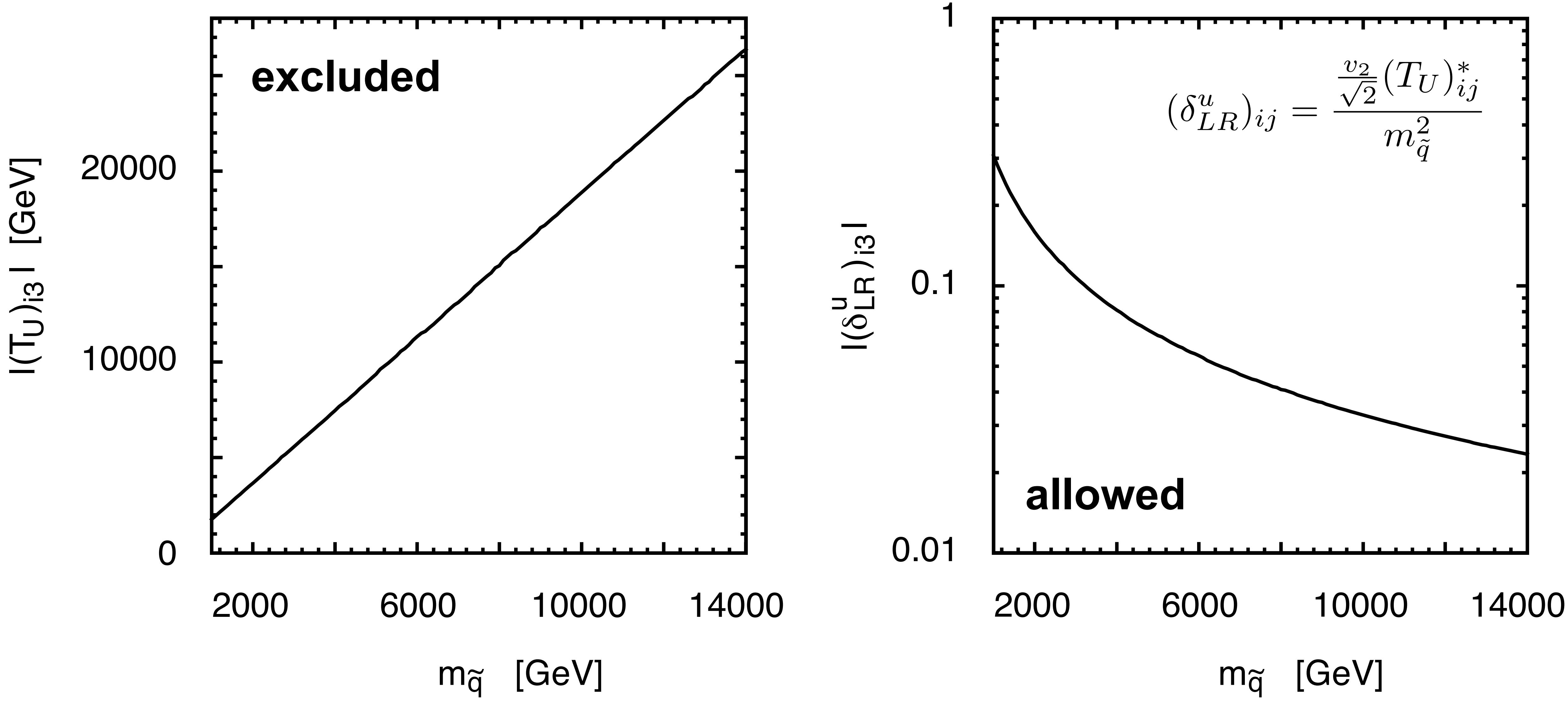
- lifetime must be larger than present age of universe

A~(1TeV)^4 ⇒ $B \gtrsim 400$

⇒ upper bound on trilinear coupling

Upper bound on δ_{LR}

Require vac lifetime to be longer than age of universe

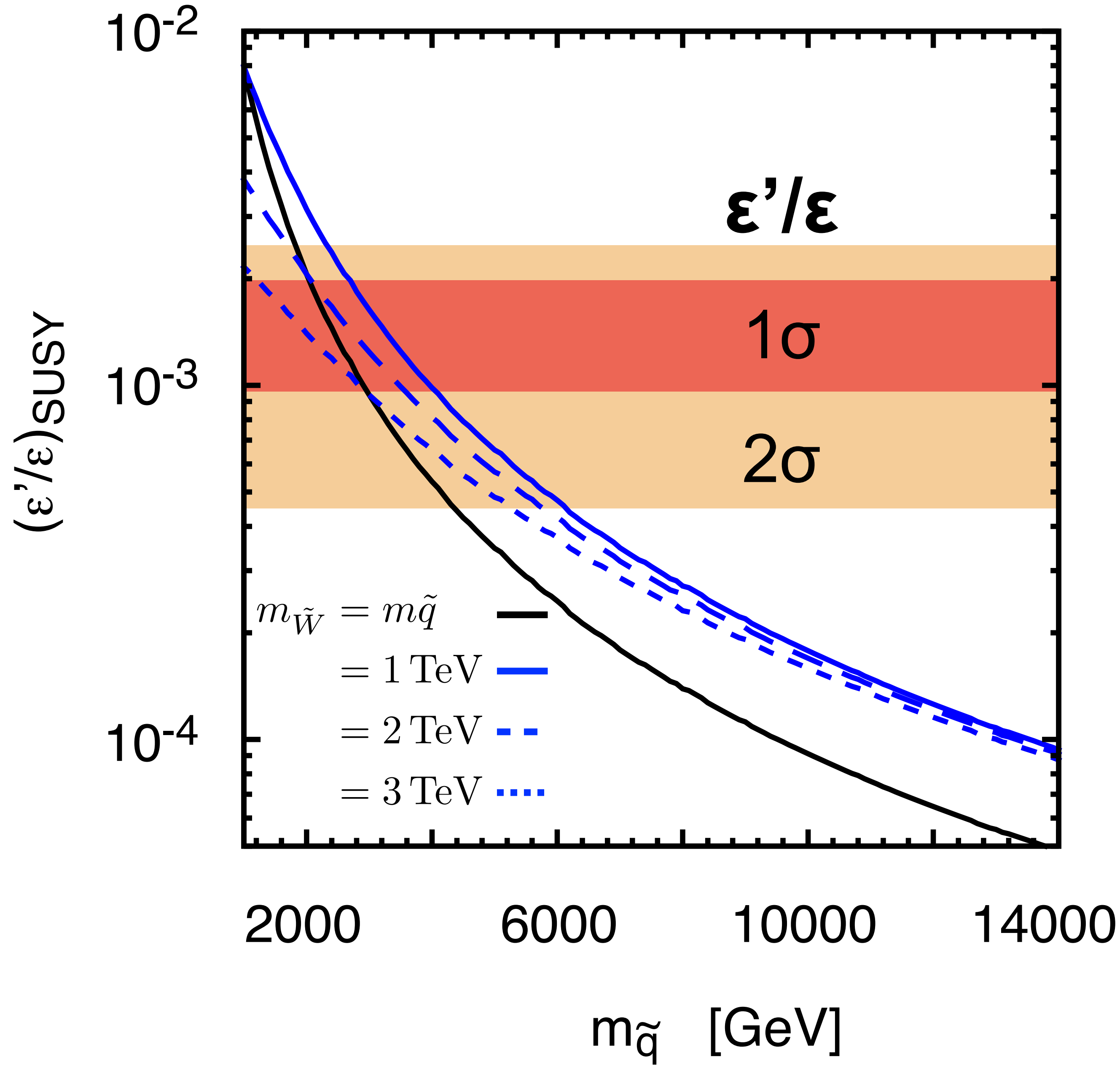


Severer in heavy SUSY

How large can SUSY scale be?

[ME,Mishima,Ueda,Yamamoto'16]

Maximum SUSY contribution to ε'/ε

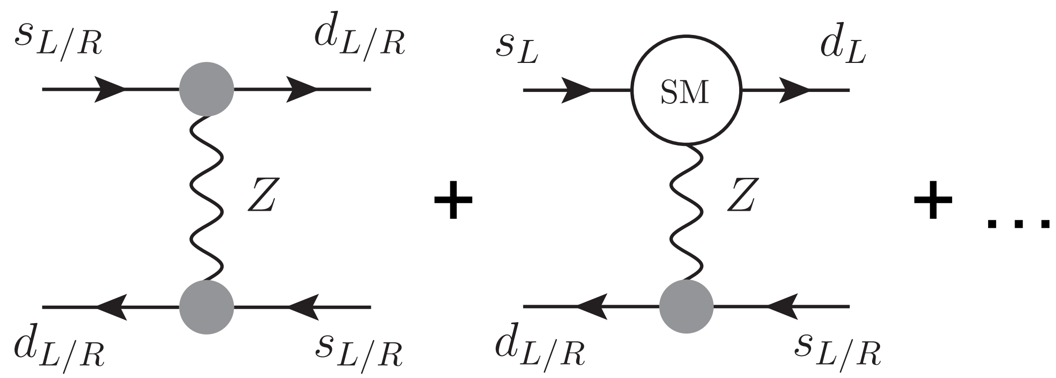


ε'/ε limited by vac stability

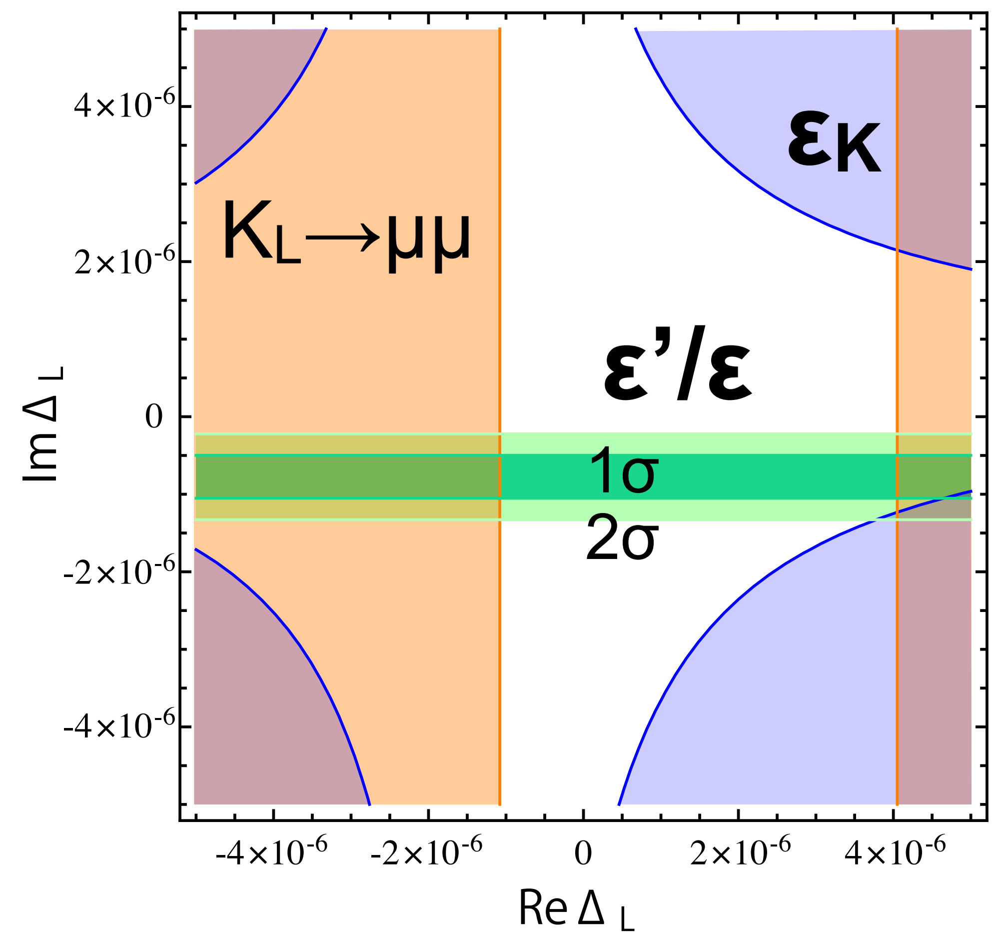
ε'/ε discrepancy is explained for $m_{\tilde{q}} \lesssim 4\text{–}6\,\mathrm{TeV}$

Other constraints: ε_K

- General Z contribution



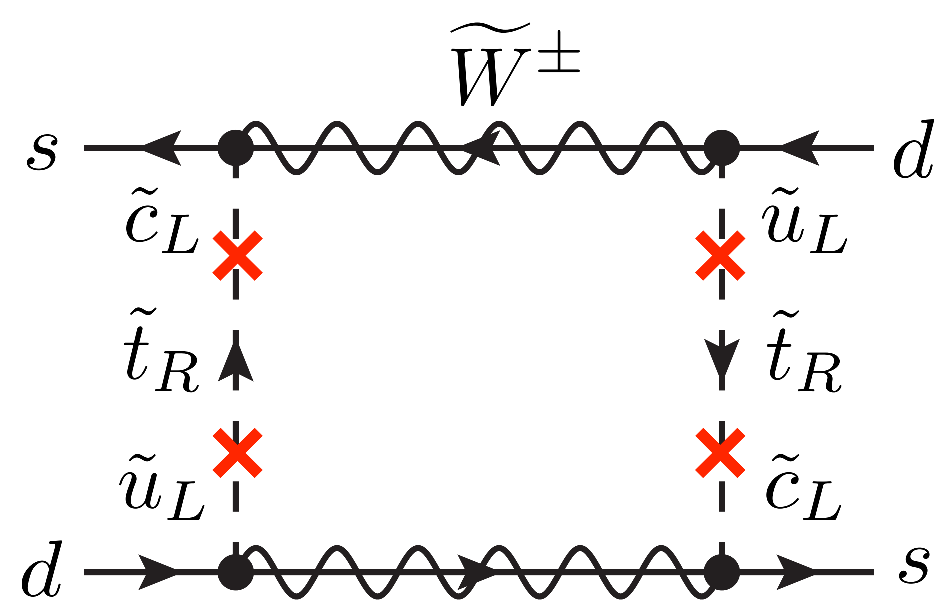
$\Rightarrow$ loosely constrained



- chargino box

$\Rightarrow$ decouple $\sim\delta^4/m_{soft}^2$

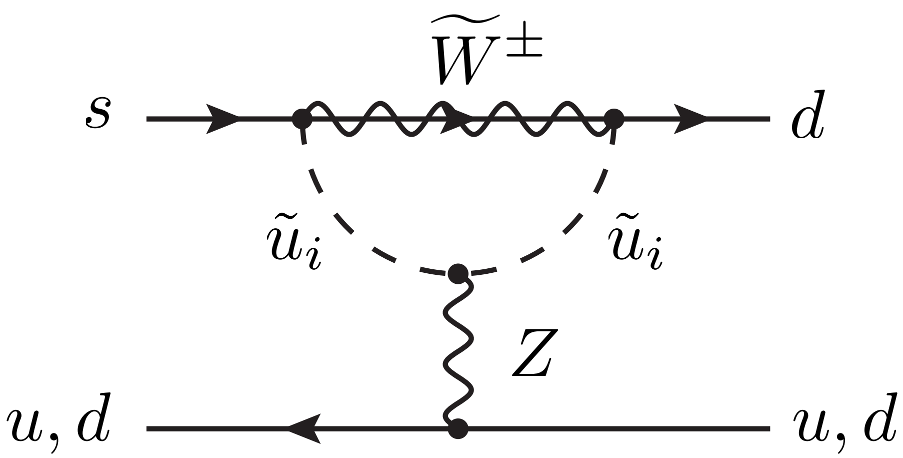
(cf. $\Leftrightarrow$ $\varepsilon'/\varepsilon \sim \delta^2$)



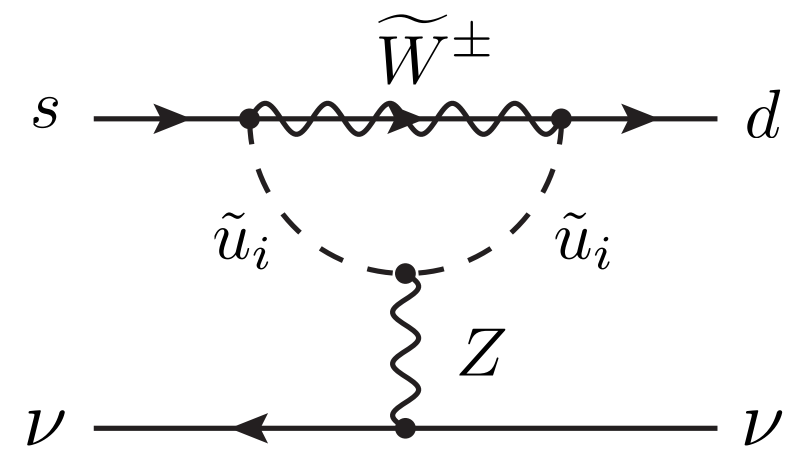
cf. B^0–$\bar{B}^0$, EDM, … satisfied

How to test the scenario?

- direct production: future collider, e.g., 100TeV?
- CP-violating *Zds* coupling induces $K_L \to \pi^0 \nu\bar{\nu}$



ε'/ε



$K_L \to \pi^0 \nu\bar{\nu}$

- $K_L \to \pi^0 \nu\bar{\nu}$ is sensitive to CP violation

cf. $\mathrm{CP}|\pi^0\rangle = -|\pi^0\rangle,\ \mathrm{CP}|\nu\bar{\nu}\rangle = -|\nu\bar{\nu}\rangle$

Negative correlation between ε'/ε & $K_L \to \pi^0 \nu\nu$

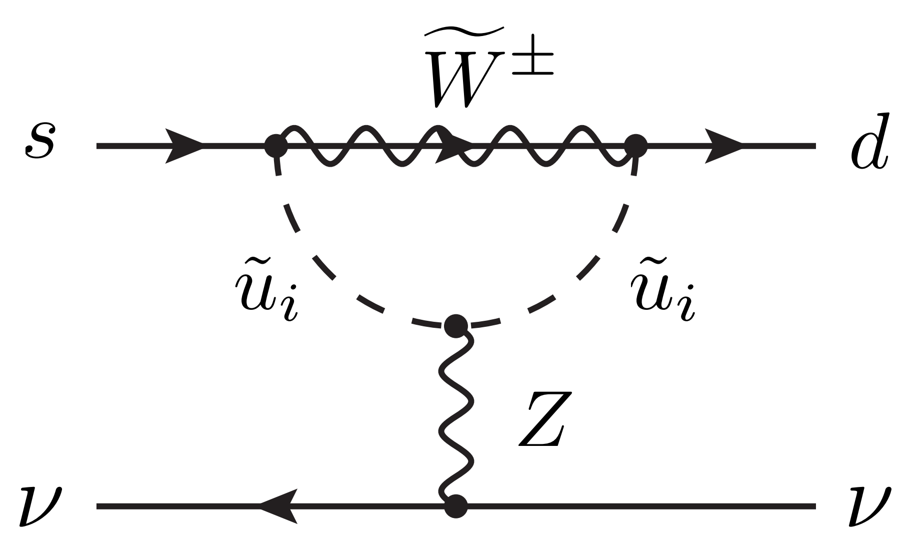
- Observables

$$(\epsilon'/\epsilon)_{\rm NP} \propto -\left(\operatorname{Im}\Delta_L + \frac{c_W^2}{s_W^2}\operatorname{Im}\Delta_R\right)$$

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) \propto \left[\operatorname{Im}(\mathrm{SM} + \Delta_L + \Delta_R)\right]^2$$

- Correlation is negative if either Δ_L or Δ_R dominates

⇒ (Wino-like) chargino contributes only to Δ_L



$K_L \to \pi^0 \nu\nu$

- Branching ratio

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) \propto [\mathrm{Im}(\mathrm{SM} + \Delta_L)]^2$$

- SM prediction

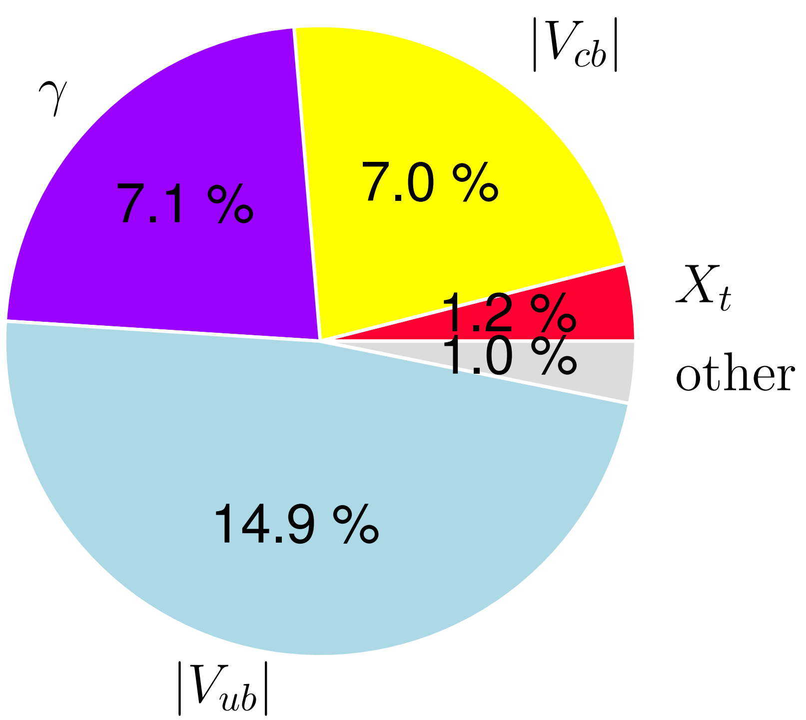
$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{\mathrm{SM}} = (3.0 \pm 0.2) \times 10^{-11}$$

- KOTO experiment @ J-PARC

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{\mathrm{exp}} < 5.1 \times 10^{-8}$$

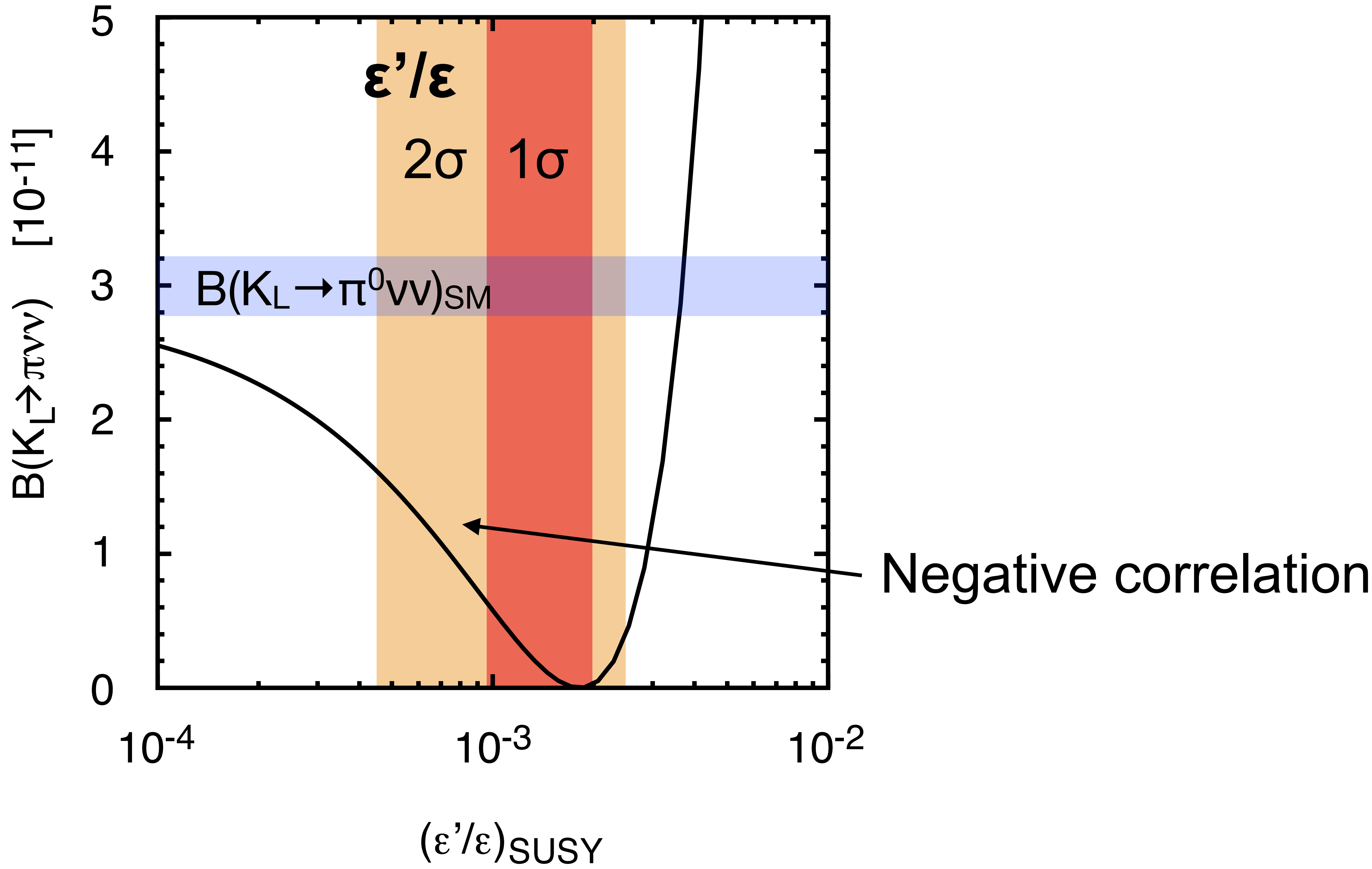
  - collect O(100) events (SM)
  - target: ~10% uncertainty of SM

    ⇒ **Probe deviations > ~10%**



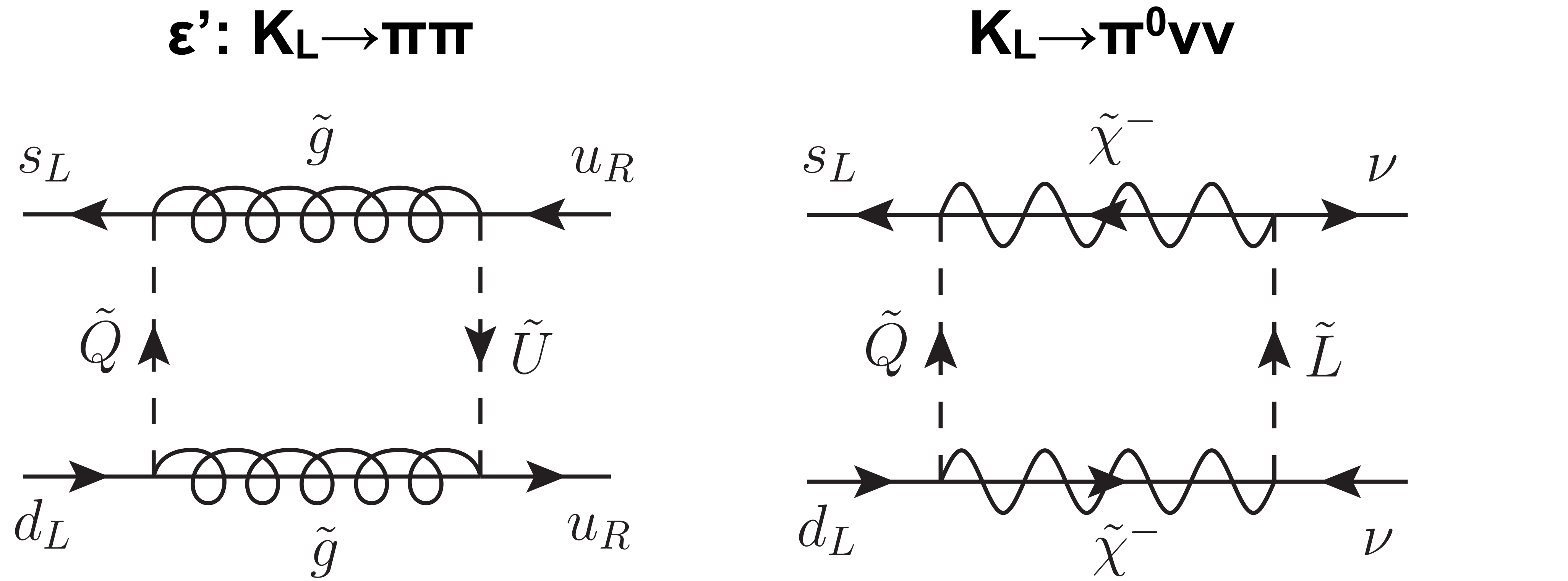
Correlation between ε'/ε & $K_L \to \pi^0 \nu\nu$

[ME,Mishima,Ueda,Yamamoto'16]



Br($K_L \to \pi^0 \nu\nu$) is less than ~60% of SM ⇒ future KOTO

Compared w/ gluino-box scenario: K→πνν



- positive deviation achieved when $m_U > m_D$ (⇔ chargino)

$$\mathrm{sgn}\left[\mathcal{B}(K_L \to \pi^0 \nu\overline{\nu}) - \mathcal{B}^{\mathrm{SM}}(K_L \to \pi^0 \nu\overline{\nu})\right] = \mathrm{sgn}\,(m_{\bar{U}} - m_{\bar{D}})$$

- sizable (>10%) deviation if SUSY particles are light

  e.g., slepton ~300GeV, Wino~1.5TeV, squark ~ 3TeV; ε_K tuned

  ⇒ LHC direct search

[Crivellin,D’Ambrosio,Kitahara,Nierste,’17]

Summary

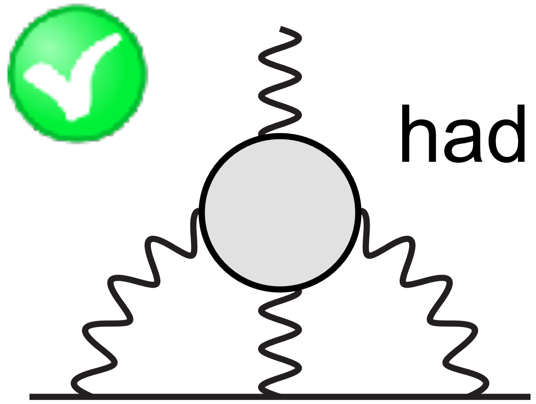
- New 2.8–2.9σ discrepancy in ε'/ε
- Revisit SUSY contributions
- Gluino-box contribution with large isospin violation can explain anomaly for squarks are lighter than ~6TeV
- Chargino contributions to Z penguin can explain anomaly if SUSY scale is lower than 4-6TeV
- Then, $K_L \to \pi^0 \nu\nu$ is predicted to be lower than ~60% of SM

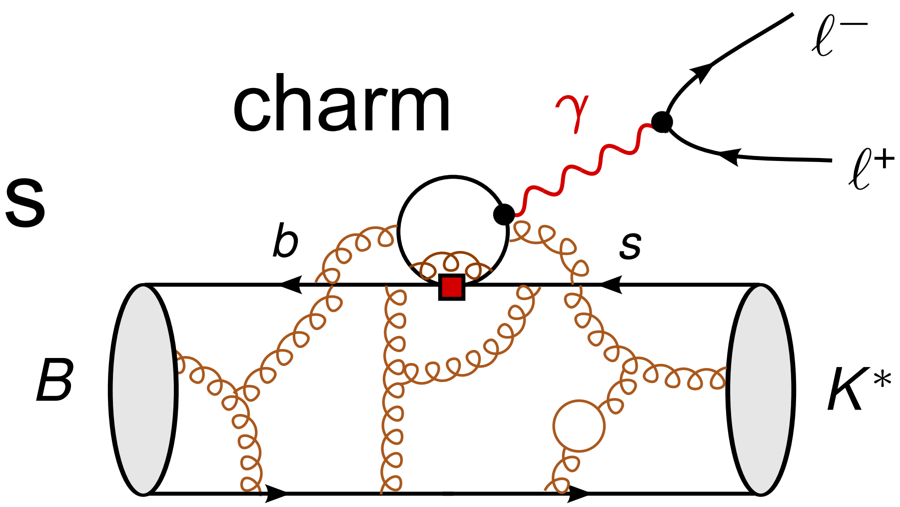
Flavor candidates of NP signal

- **Muon g-2**: >3σ, lattice for light-by-light cont.
- **B→K*ll**: >3σ in P_5' angular distribution
  - may underestimate charm loop
- **$R_{K^{(*)}}$=Γ(B→$K^{(*)}$μμ)/Γ(B→$K^{(*)}$ee)**: >2σ
  - LHCb: challenging to identify electrons
  - electron rate looks unclear
- **$R_{D^{(*)}}$=Γ(B→$D^{(*)}$τν)/Γ(B→$D^{(*)}$lν)**: >3σ
  - deviation mostly by BaBar ⇒ tau identification?
  - latest LHCb result is consistent with SM

Not explained

- **CP violation in Kaon decays**

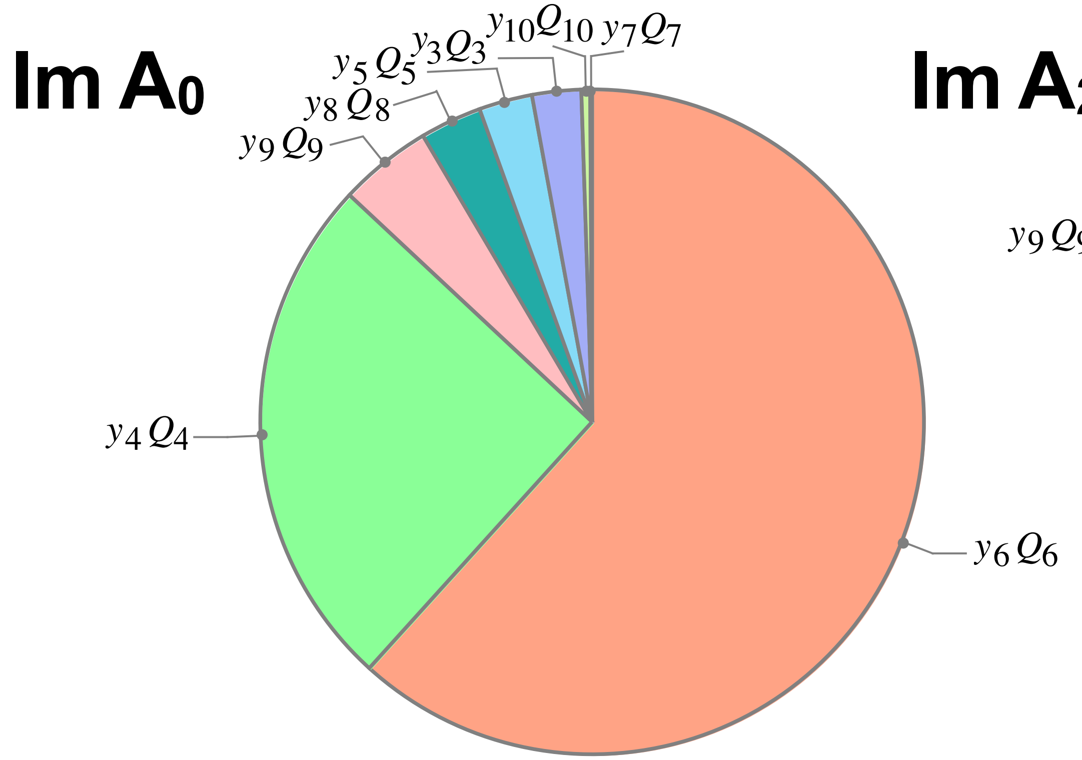


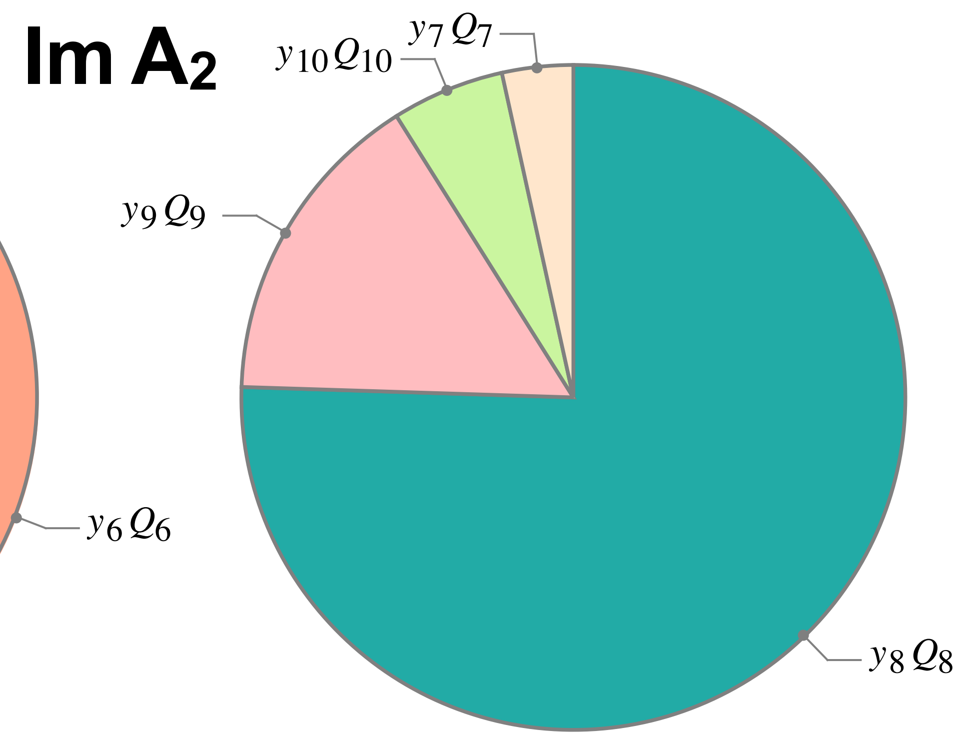


Backup slide

What's new in Kaon? — History of CP violation

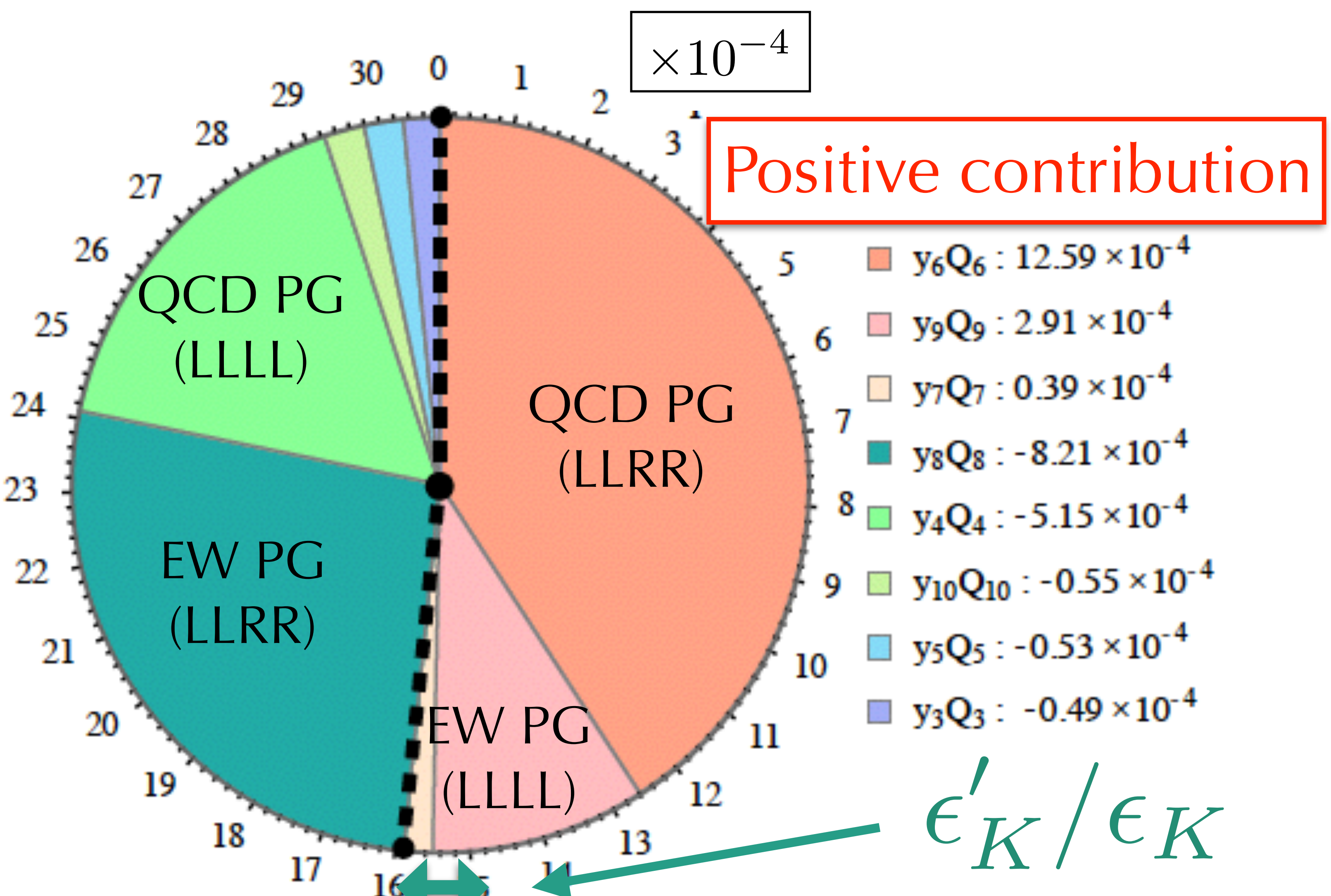
- First discovery of CP violation was made in $K_L \to \pi\pi$ decay
  [Christenson,Cronin,Fitch,Turlay'64]
  - CP violation in oscillation: "indirect CP violation"
  - Nobel prize in 1980 (Cronin and Fitch)
- CPV explained by postulating a third family of quarks
  [Kobayashi,Maskawa'73]
  - Nobel prize in 2008 by discovery of CPV in B system
- Direct CP violation discovered in $K_L \to \pi\pi$ decay
  [NA31,KTeV,NA48,'90-99]
- Many progresses in perturbative and lattice calculations
  - first lattice computation of ε' [RBC-UKQCD'15]





Composition of ϵ'_K/ϵ_K with respect to the operator basis

Negative contribution



[TK, Nierste, Tremper 16′]

Status of standard model prediction

$$\frac{\epsilon'_K}{\epsilon_K} = (1.06 \pm 4.66_{\rm Lattice} \pm 1.91_{\rm NNLO} \pm 0.59_{\rm IV} \pm 0.23_{m_t}) \times 10^{-4}$$

matrix element	strong isospin violation

Enhance ε'/ε and $K_L \to \pi^0 \nu\nu$

Why is correlation negative?

- Observables

$$(\epsilon'/\epsilon)_{\rm NP} \propto -\left(\mathrm{Im}\,\Delta_L + \frac{c_W^2}{s_W^2}\mathrm{Im}\,\Delta_R\right)$$

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) \propto \left[\mathrm{Im}(\mathrm{SM} + \Delta_L + \Delta_R)\right]^2$$

- Correlation is negative if either Δ_L or Δ_R dominates

  ⇒ (Wino-like) chargino contributes only to Δ_L

- $\Delta_L \sim \Delta_R$ to enhance ε'/ε and $B(K_L \to \pi^0 \nu\nu)$ [Buras et.al.'15-16]

  ⇒ Gluino can generate both Δ_L and Δ_R, but constrained by ε_K