The ϵ'_K/ϵ_K tension and supersymmetric interpretation

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Phys.Rev.Lett.117, 091802 (2016) [arXiv:1604.07400],
JHEP 1612, 078 (2016) [arXiv:1607.06727],
Phys.Lett.B771, 37-44 (2017) [arXiv:1612.08839],
and arXiv:1703.05786

XIIth Meeting on B Physics. Tensions in Flavour measurements: a path toward Physics beyond the Standard Model

Napoli, Italy, May 23, 2017

Karlsruhe Institute of Technology
Institute for Theoretical Particle Physics

$K \to \pi\,\pi$ system

- Precise measurements for Kaon decay into two pions have discovered the **two type of CP violations**: indirect CPV ϵ_K & direct CPV ϵ'_K :

$$\mathcal{A}\left(K_L \to \pi^+\pi^-\right) \propto \varepsilon_K + \varepsilon'_K \quad \text{with } \varepsilon_K = \mathcal{O}(10^{-3}) \neq 0$$

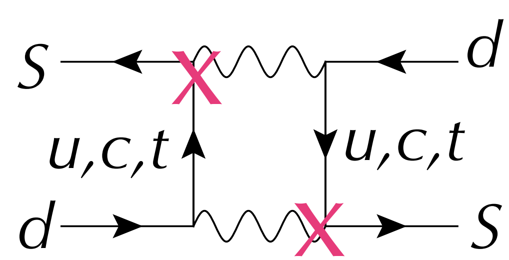
[Christenson, Cronin, Fitch, Turlay, '64 with Nobel prize]

$$\mathcal{A}\left(K_L \to \pi^0\pi^0\right) \propto \varepsilon_K - 2\varepsilon'_K \qquad \varepsilon'_K = \mathcal{O}(10^{-6}) \neq 0$$

[NA48/CERN and KTeV/FNAL '99]

ΔS=2
Indirect CP violation
Kaon oscillation
W box

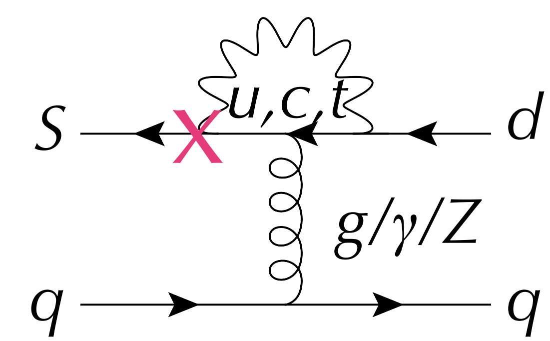
$\varepsilon_K \propto \mathrm{Im}[(\mathrm{CKM})^2]$

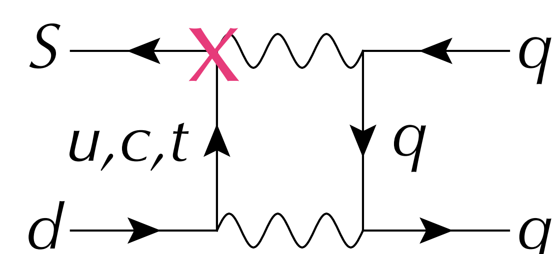


$K^0 \longleftrightarrow \overline{K}^0$

ΔS=1
Direct CP violation
W-box and penguin

$\varepsilon'_K \propto \mathrm{Im}[\mathrm{CKM}]$



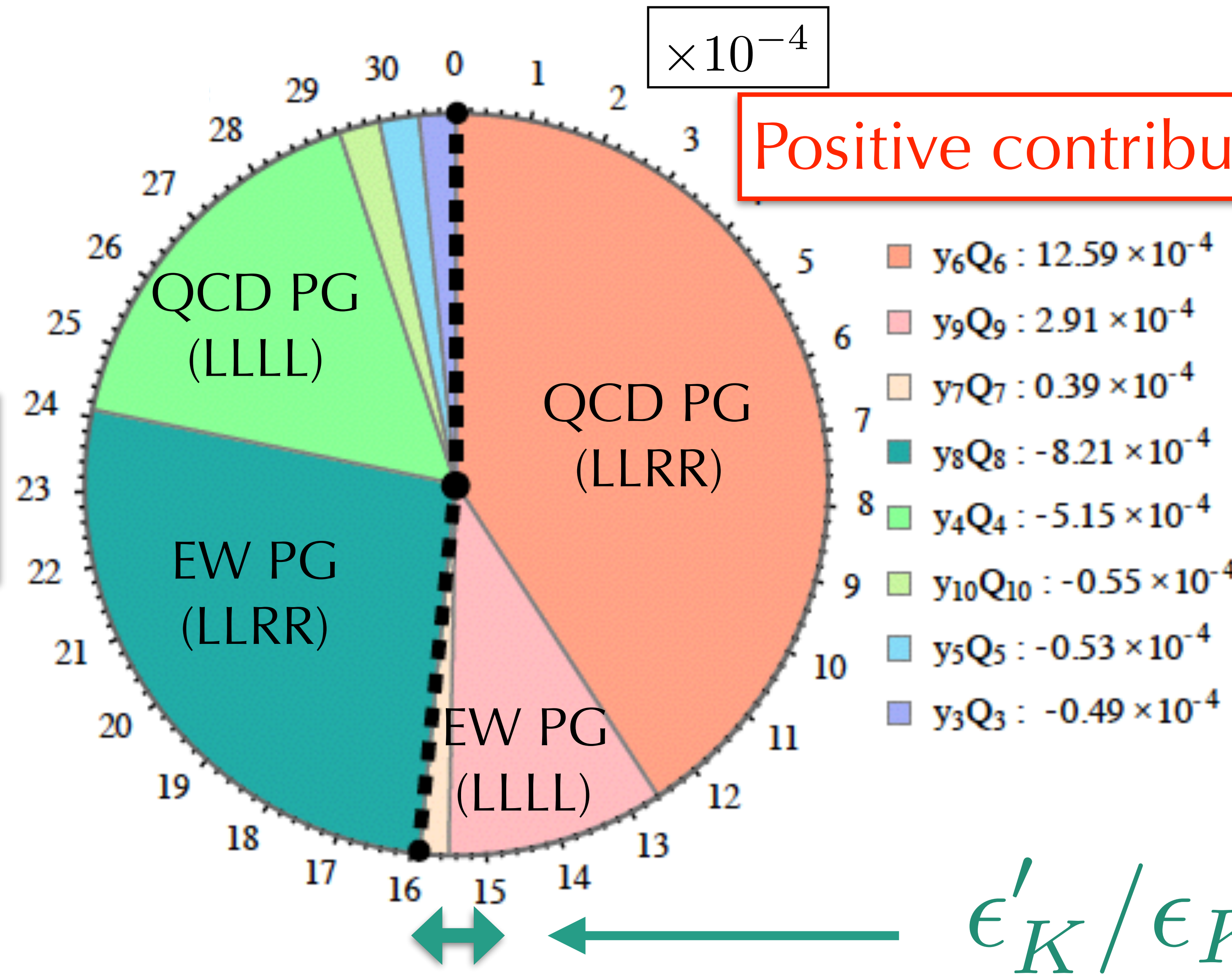


- **The strong suppression** of ϵ'_K comes from the smallness of the isospin-3/2 amplitude ($\Delta I = 1/2$ rule) and an accidental cancellation of the SM contribution

Accidental cancellation

[**TK**, Nierste, Tremper, JHEP '16]

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



Positive contribution

Negative contribution

ϵ'_K/ϵ_K @ **SM-NLO**

ϵ'_K/ϵ_K discrepancy

- A determination of all hadronic matrix elements for ϵ'_K/ϵ_K by **RBC-UKQCD group** has been obtained **with controlled errors** (**first lattice result),** so that one becomes able to estimate ϵ'_K/ϵ_K without using the effective theories, e.g. chiPT, dual QCD model, NJL model, … [RBC-UKQCD, PRL '15]

- SM expectation value at NLO [**TK**, Nierste, Tremper, JHEP '16]

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

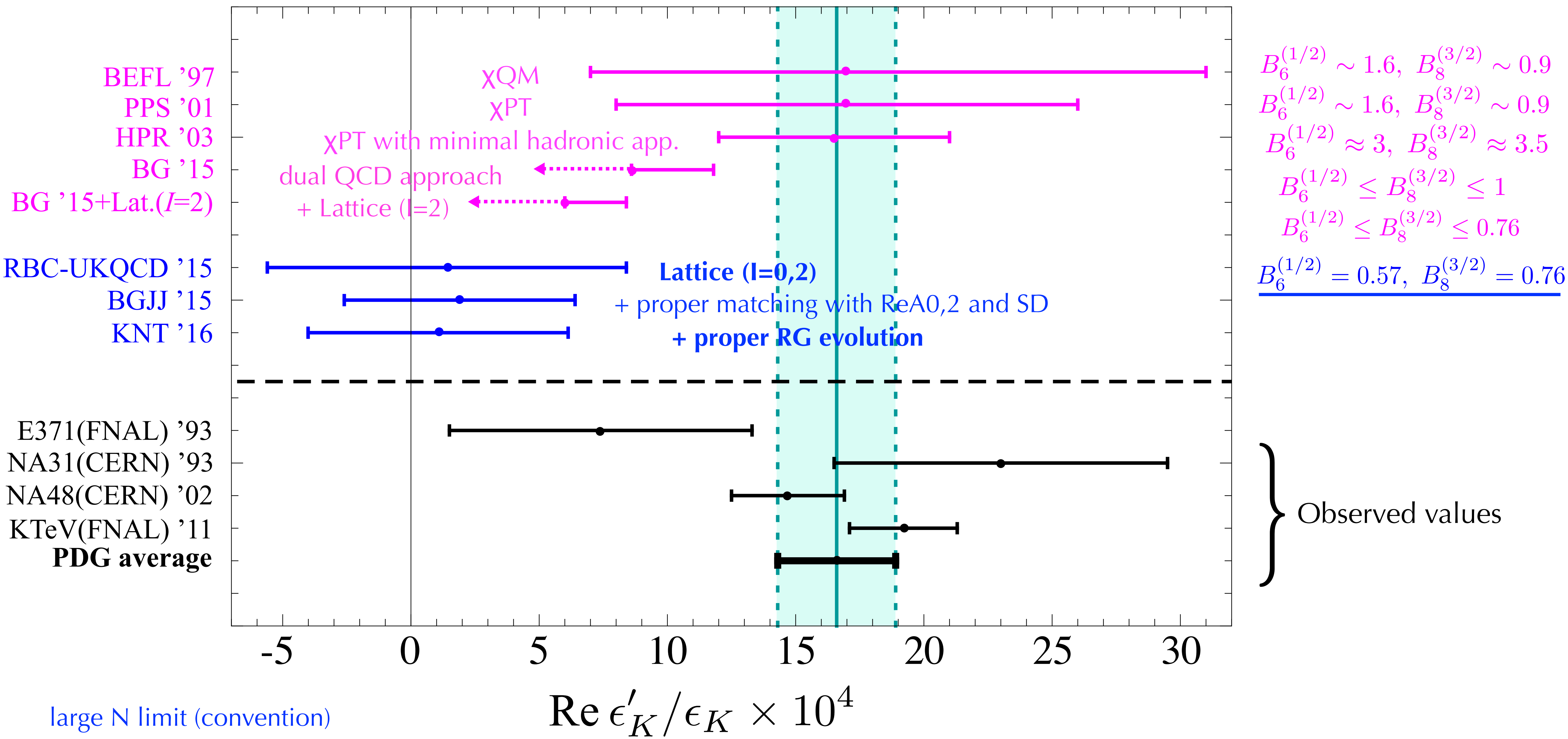
Our prediction uses the methodology of Buras et al. (JHEP 1511 (2015) 202) (taking ReA0,2 from data) and a **new formula** for the NLO RG evolution

- World average of experimental results $\text{Re}\left(\frac{\epsilon'_K}{\epsilon_K}\right)_{\text{exp}} = (16.6 \pm 2.3) \times 10^{-4}$ [NA62, KTeV, PDG]

- **Discrepancy with a significance of 2.8σ**

Buras et al. (JHEP 1511 (2015) 202) obtained 2.9σ discrepancy

Current situation of $\epsilon'_K/\epsilon_K \propto \mathrm{Im}A_0 - \left(\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2}\right)\mathrm{Im}A_2$



large N limit (convention)

$$B_6^{(1/2)} = B_8^{(3/2)} = 1$$

dual QCD prediction

$$B_6^{(1/2)} \leq B_8^{(3/2)} < 1,\ B_8^{(3/2)} = 0.8$$

	Exp.	χPT	dual QCD	**Lattice (I=0,2)**
$\left(\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2}\right)$	22.45 ± 0.05	~ 14	16.0 ± 1.5	31.0 ± 11.1

ϵ_K and ϵ'_K

in the supersymmetric model

Preliminary for NP part

- The SM prediction of ϵ'_K/ϵ_K is **2.8 sigma below** the experimental values, which give strong motivation for searching for NP contributions

- ϵ'_K/ϵ_K is highly sensitive to CP violation of NP

SM loop suppression × GIM suppression × accidental cancelation

vs.

NP (loop suppression) × (large coupling) × NP scale suppression

- Some models can explain this discrepancy, e.g. Littlest Higgs model, 331 model, generic Z′ models, modified Z-coupling model, RH coupling of quarks to W, and **supersymmetric (SUSY) models**

  [Buras,Fazio,Girrbach '14, Buras,Buttazzo,Knegjens '15, Buras '15, Buras, Fazio '15, '16, Goertz,Kamenik,Katz,Nardecchia '15, Blanke,Buras,Recksiegel '16, Cirigliano,Dekens, Vries, Mereghetti '16, **TK**,Nierste,Tremper '16, Tanimoto, Yamamoto '16, Endo,Mishima,Ueda,Yamamoto '16]

Main Constraint: ϵ_K (ΔS=2, ID-CPV)

- Although ϵ'_K/ϵ_K (ΔS=1, D-CPV) is sensitive to NP, once ϵ_K (ΔS=2, ID-CPV) constraint is taken into account, NP effects in ΔS=1 is highly suppressed

If the NP CPV contribution comes with the ΔS = 1 parameter ***δ*** and is mediated by heavy particles of mass *M*, one finds

$$\epsilon_K^{\rm NP} \propto \frac{{\rm Im}(\delta^2)}{M^2} \qquad \epsilon_K'^{\rm NP} \propto \frac{{\rm Im}\delta}{M^2}$$

$$\boxed{\frac{\epsilon_K'^{\rm NP}}{\epsilon_K'^{\rm SM}} \leq \frac{\frac{\epsilon_K'^{\rm NP}}{\epsilon_K^{\rm NP}}}{\frac{\epsilon_K'^{\rm SM}}{\epsilon_K^{\rm SM}}} = \mathcal{O}\left(\frac{{\rm Re}\tau}{{\rm Re}\delta}\right)}$$

$\epsilon_K^{\rm NP} \leq \epsilon_K^{\rm SM}$: ID-CPV constraint

$$\tau = -\frac{V_{td}V_{ts}^*}{V_{ud}V_{us}^*} \sim (1.5 - i0.6)\cdot 10^{-3}$$

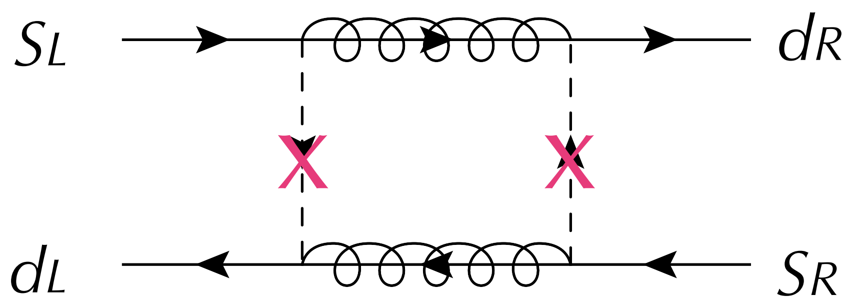
when loop factor 1/(4π) is the same as the SM

- With M > 1 TeV, NP effects can only be basically relevant for **|δ| >> |τ|**, so that this equation seemingly forbids detectable NP contributions to ϵ'_K/ϵ_K

There is a loophole in the SUSY model (next slide)

Main Constraint: ϵ_K (ΔS=2, ID-CPV) cont.

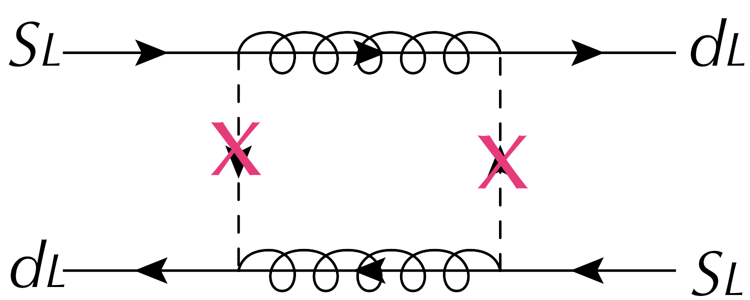
- The leading contribution is given by $\overline{d_L} s_L \overline{d_R} s_R$

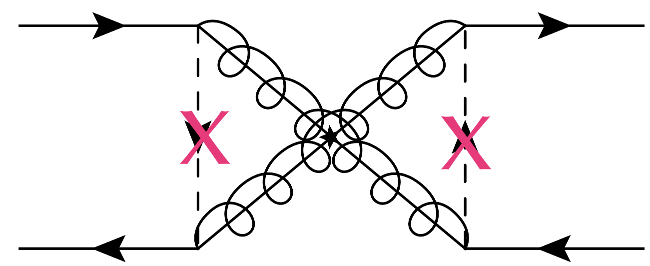


$$\propto \left(\frac{m_K}{m_s + m_d}\right)^2$$

this contribution is suppressed when $\Delta_{\bar{D},12} \simeq 0$

- The next contribution is given by $\overline{d_L} s_L \overline{d_L} s_L$





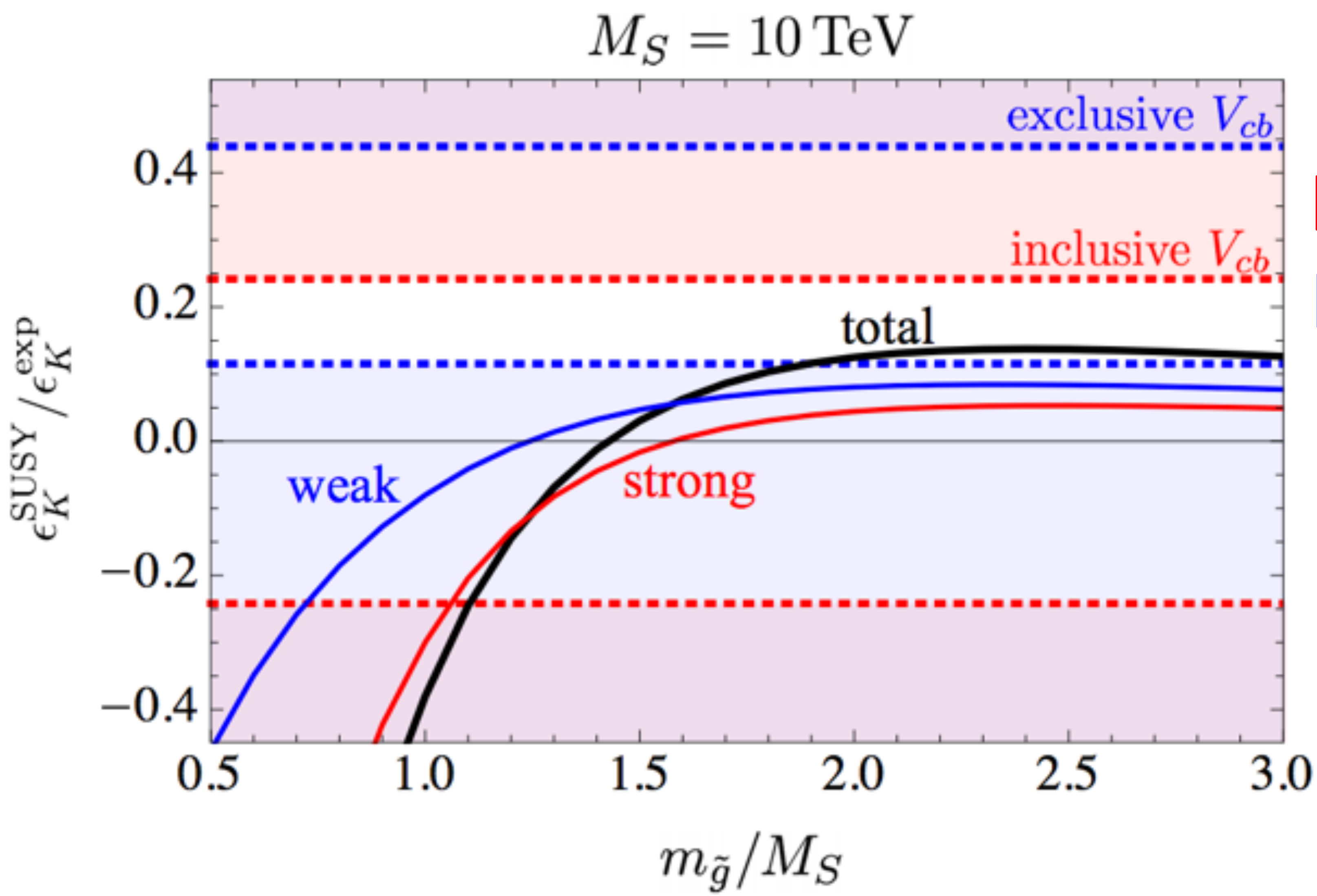
Crossed diagram gives **relatively negative** contributions

$m_{\tilde{g}} \simeq 1.5 m_{\tilde{q}}$: these contributions almost cancel out [Crivellin, Davidkov '10]

$m_{\tilde{g}} \gtrsim 1.5\ m_{\tilde{q}}$: suppressed by heavy gluing mass

Constraint from ϵ_K

[**TK**, Nierste, Tremper, PRL '16]



values in our plot

$|V_{cb}|_{\mathrm{inc.}} = 42.21(78) \times 10^{-3}$

$|V_{cb}|_{\mathrm{exc.}} = 39.04(74) \times 10^{-3}$

value from Silvestrini's slide

$|V_{cb}|_{\mathrm{UTfit\ \ predictions2017}}$

$= 42.1(6) \times 10^{-3}$

- Actually, there are several expected values of ε_K depending on the input CKM parameters

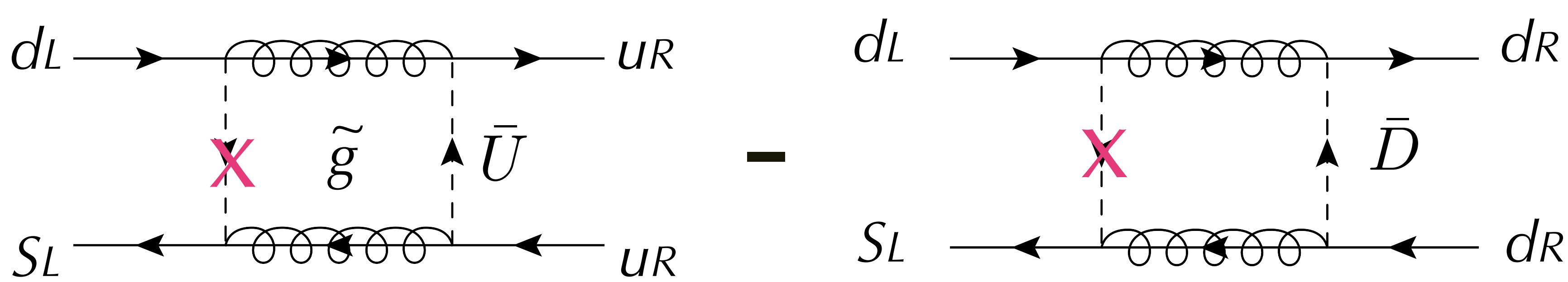
|Vcb|incl., measured in inclusive b → clν decays….. ε_K is consistent with exp. value

|Vcb|incl., measured in exclusive B → D(*)lν decays….. ε_K is 3σ below the exp. value

Gluino contribution to ϵ'_K/ϵ_K

[Kagan, Neubert, PRL '99, Grossman, Kagan, Neubert, JHEP '99]

- The main contribution to ϵ'_K/ϵ_K comes from gluino box loop
- In spite of QCD correction, gluino box diagrams **can** break isospin symmetry through mass difference between right-handed up and down squark masses, and they can contribute **ImA2**, which is enhanced by small **ReA2,exp** value



$m_{\bar{U}} \neq m_{\bar{D}} \xrightarrow{\text{RGE}}$ EW penguin operators are generated at the low energy scale

$\xrightarrow{\text{with HMEs}}$ contribute to **ImA2**

$$\frac{\epsilon'_K}{\epsilon_K} = \frac{1}{\sqrt{2}|\epsilon_K|_{\rm exp}} \frac{\omega_{\rm exp}}{({\rm Re}A_0)_{\rm exp}} \left(-{\rm Im}A_0 + \frac{1}{\omega_{\rm exp}} {\rm Im}A_2 \right) \quad \text{where} \quad \frac{1}{\omega} \equiv \frac{{\rm Re}A_0}{{\rm Re}A_2} = 22.46 \ (\text{exp.})$$

SUSY contributions to ϵ'_K/ϵ_K

[**TK**, Nierste, Tremper, PRL, '16]

- We take universal SUSY mass (***MS***) **without gaugino masses (*M*3) and right-handed up-type squark mass (*m*$\overline{U}$)**

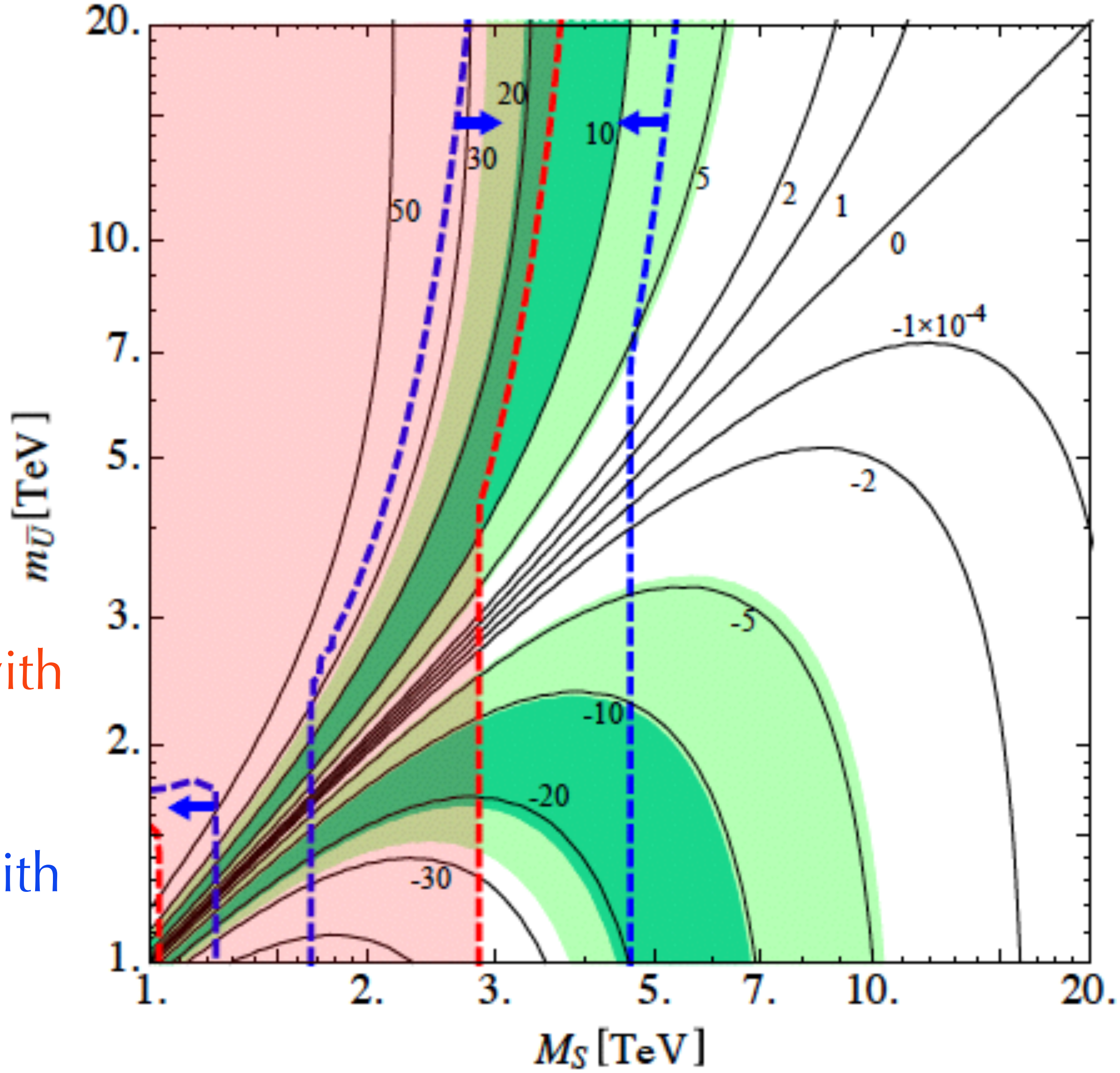
ϵ'_K/ϵ_K discrepancy can be solved at

1σ	2σ

excluded by ε_K with inclusive |Vcb|

preferred by ε_K with exclusive|Vcb|

contour of $\varepsilon_K^{\prime\,\mathrm{SUSY}}/\varepsilon_K$



$M_3 = 1.5 M_S$

for suppressed ϵ_K

$m^2_{Q,ij} = \Delta_{Q,ij} M_S^2$

$\Delta_{Q,12,13,23} = 0.1 \exp(-i\pi/4)$

maximum CPV phase for ϵ_K

when $i\pi/4 \to i\pi/2$

amplifies ϵ'_K/ϵ_K

suppresses ϵ_K

ϵ_K, ϵ'_K, and $\mathcal{B}(K \to \pi\nu\overline{\nu})$ in the supersymmetric model

Other rare kaon decay

- **CP violation + FCNC decays of kaon** $K \to \pi\pi,\ K \to \pi\nu\bar{\nu},\ K \to \pi\ell\bar{\ell}$ are **extremely sensitive to NP** and can probe virtual effects of particles with masses far above the reach of LHC

- They are correlated to each other

ϵ'_K discrepancy $\longrightarrow$ deviations of the other rare kaon decay

$(K_L \to \pi\pi)$

$K \to \pi\nu\bar{\nu}$ **Good** The experiments are on-going!

NA62 experiment at CERN $K^+ \to \pi^+\nu\bar{\nu}$, target : **10% precision compared with SM** (2018)

KOTO experiment at J-PARC $K_L \to \pi^0\nu\bar{\nu}$, target :**100%** (step1), **10%** (step2)

$K_L \to \pi^0\ell^+\ell^-$: CPV, the theoretical uncertainty can be reduced by precise measurement of $K_S \to \pi^0\ell^+\ell^-$ $\longrightarrow$ LHCb

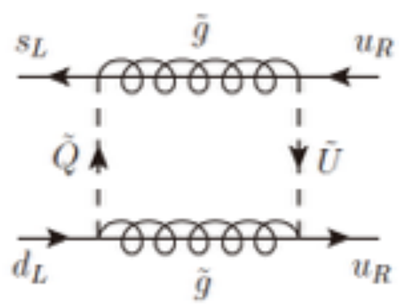
direct detection of $K_L \to \pi^0\ell^+\ell^-$ is also important

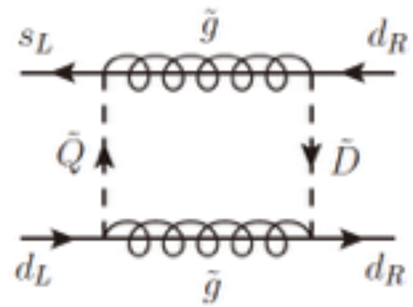
Overview in our SUSY scenario

- In the supersymmetric model (MSSM), the following parameter region is interesting for ϵ'_K discrepancy:

$$M_3 \gtrsim 1.5 M_S,\ m^2_{Q,12} \neq 0,\ \text{and}\ m_{\bar{U}}/m_{\bar{D}} \neq 1$$

ΔS=1

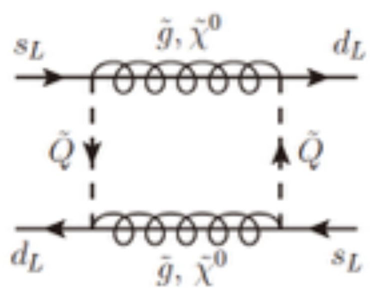


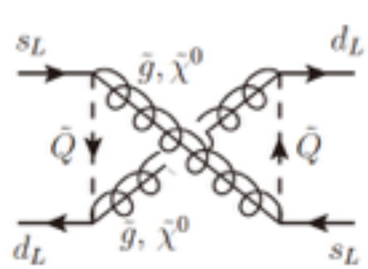


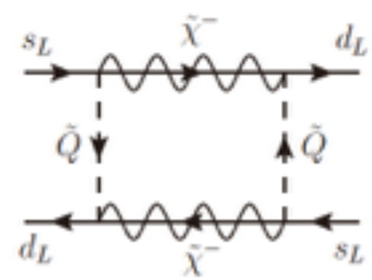
can explain ϵ'_K discrepancy

[**TK**, Nierste, Tremper, '16]

ΔS=2



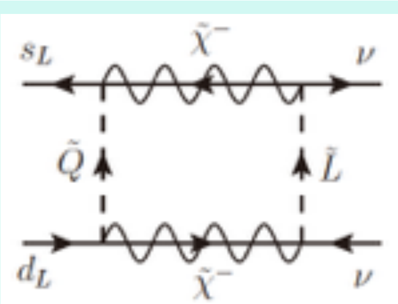




can **suppress** ΔS=2 process

[Crivellin, Davidkov, '10]

ΔS=1



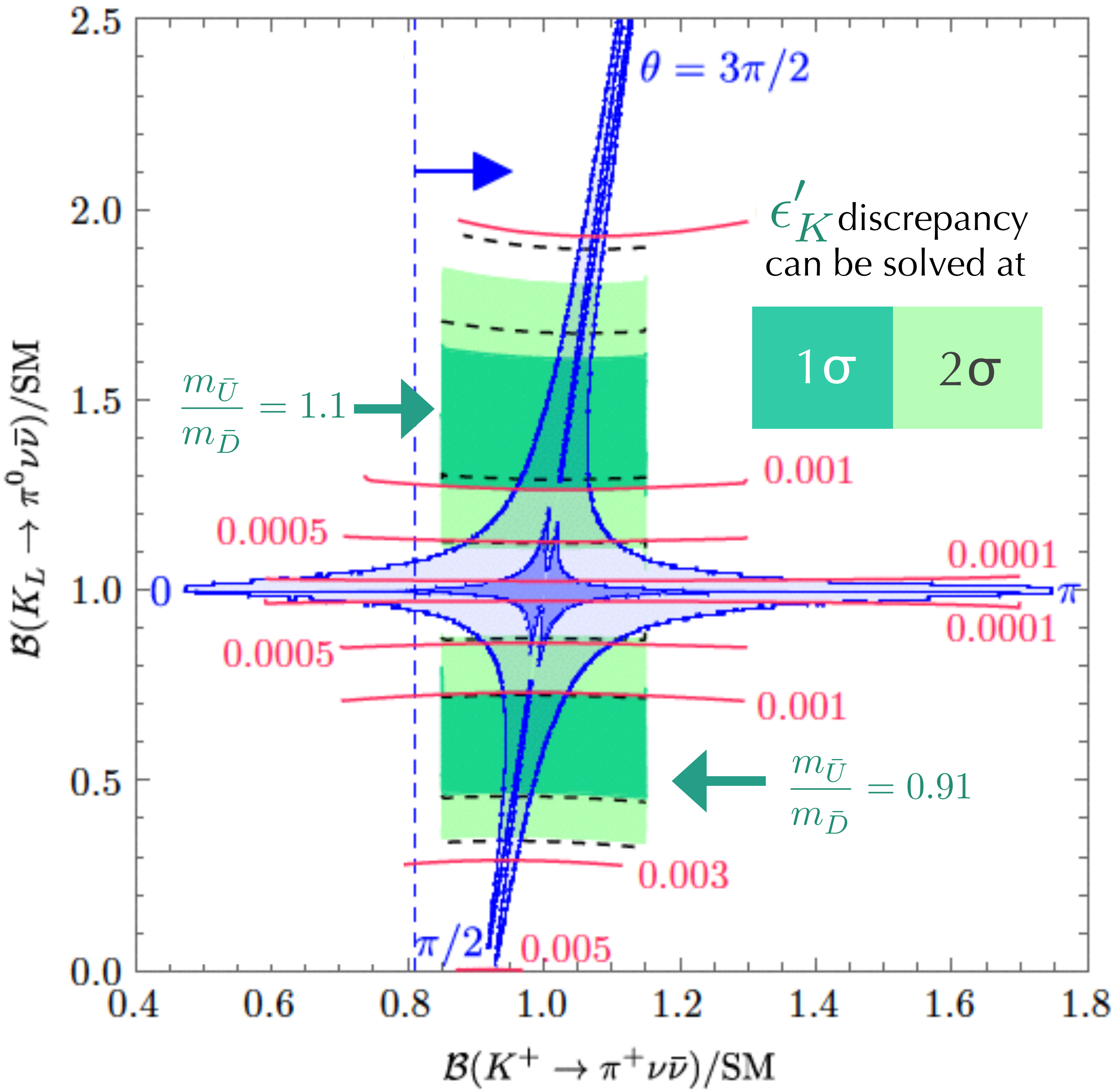
can contribute to $K \to \pi\nu\bar{\nu}$ **correlating with** above two physics

[Crivellin, D'Ambrosio, **TK**, Nierste, '17]

B(K→πνν)

[Crivellin, D'Ambrosio, **TK**, Nierste, '17]

$m_{\tilde{q}_1} = 1.5\,\mathrm{TeV},\ m_L = 300\,\mathrm{GeV}$



more than 10% mass shift of the gluino mass from $M_3 \simeq 1.45 M_S$ is possible in light of the constraint from ϵ_K

1-10 % mass shift of the gluino mass is possible

$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})/\mathrm{SM} \lesssim 2\,(1.2)$

$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})/\mathrm{SM} \lesssim 1.4\,(1.1)$

for a fine-tuning at the 1(10)% level

- $m_{\bar{U}}/m_{\bar{D}}$ determines a position of the green band
- Positive ϵ'_K predicts a strict correlation

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

$$\mathrm{sgn}\left[m_{\bar{U}} - m_{\bar{D}}\right] \xrightarrow[\epsilon'_K]{} \arg\left[m^2_{Q12}\right]$$

$$\downarrow$$

$$\mathrm{sgn}\left[\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) - \mathcal{B}^{\mathrm{SM}}(K_L \to \pi^0\nu\bar{\nu})\right]$$

ϵ_K, ϵ'_K, and $\mathcal{B}(K \to \pi\nu\overline{\nu})$

in modified Z-coupling scenario

(SUSY/non-SUSY)

Modified Z-coupling scenario

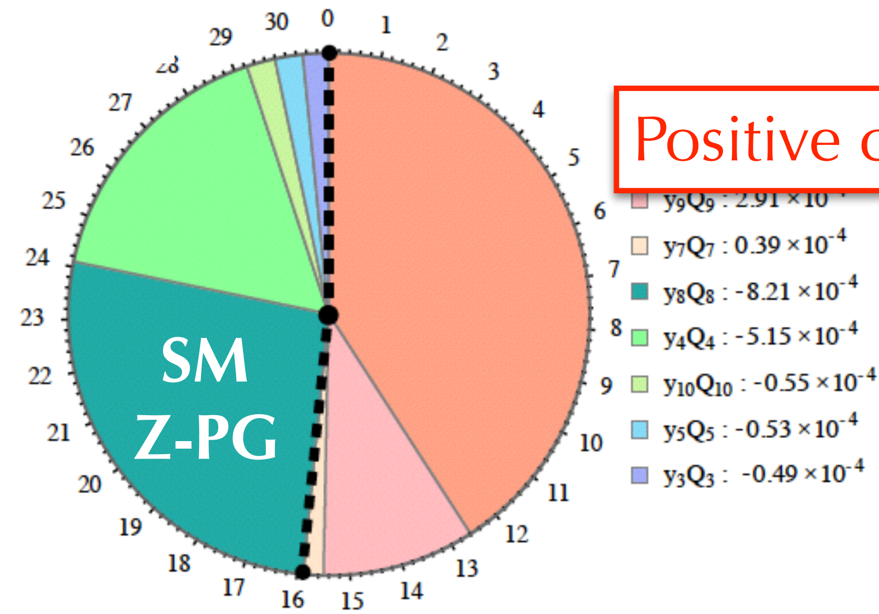
[Buras, De Fazio, Girrbach, '13, '14]
[Buras, Buttazzo, Knegjens, '15]
[Buras, '16]
[Endo, **TK**, Mishima, Yamamoto, '16]
[Bobeth, Buras, Celis, Jung,'17]

- NP contributions to *sdZ* coupling which has the same magnitude as the SM Z-penguin can explain ϵ'_K discrepancy

ϵ'_K/ϵ_K $\boxed{\times 10^{-4}}$

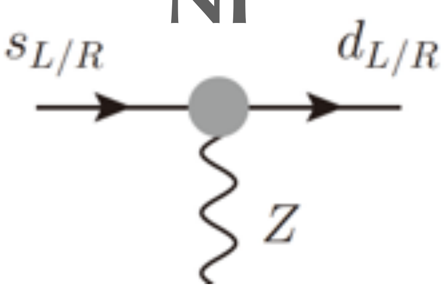
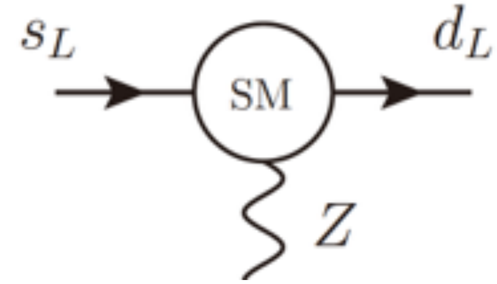
Negative contribution

SM *Z*-penguin gives the biggest negative contribution



Positive contribution

$\leftrightarrow$ ϵ'_K/ϵ_K

Im  $\simeq -$ Im 

$\longrightarrow$ ϵ'_K **can be solved**

O(1) contribution to $\mathcal{B}(K \to \pi\nu\bar{\nu})$

Note: SM is suppressed by the GIM mechanism, so that it is a numerically small coupling

Modified Z-coupling scenario cont.

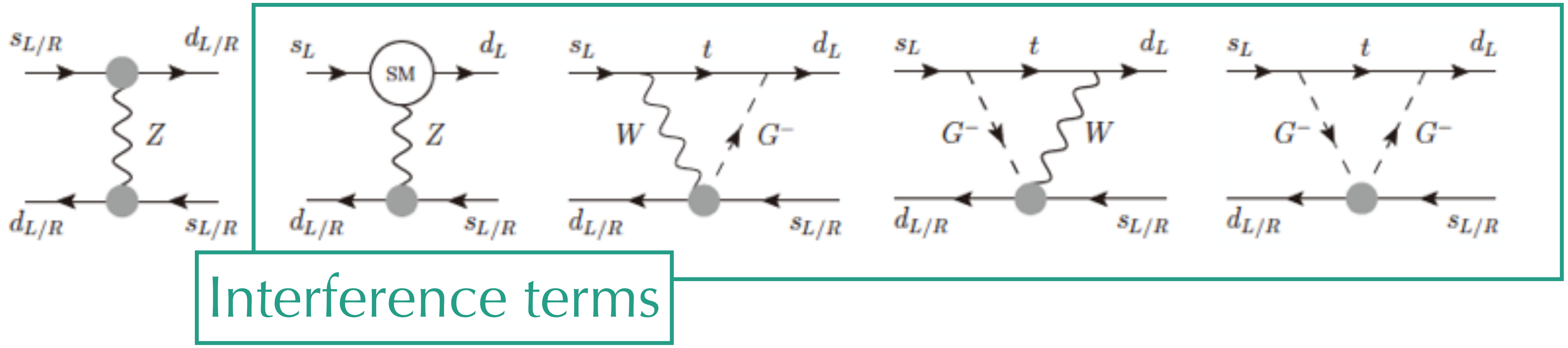
[Buras, De Fazio, Girrbach, '13, '14]
[Buras, Buttazzo, Knegjens, '15]
[Buras, '16]
[Endo, **TK**, Mishima, Yamamoto, '16]
[Bobeth, Buras, Celis, Jung,'17]

- SM + dim-6 eff. operators

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{c_L}{\Lambda^2} i(H^\dagger \overleftrightarrow{D_\mu} H)(\overline{Q}_L \gamma^\mu Q'_L) + \frac{c_R}{\Lambda^2} i(H^\dagger \overleftrightarrow{D_\mu} H)(\overline{d}_R \gamma^\mu d'_R),$$
$$= \mathcal{L}_{\rm SM} - \frac{\sqrt{2} v M_Z}{\Lambda^2} (c_L \overline{s} \gamma^\mu Z_\mu P_L d + c_R \overline{s} \gamma^\mu Z_\mu P_R d) + \dots$$

→ modified Z-couplings (FCNC) emerge

- Constraint comes from ΔS=2 process : ϵ_K (Assumption: NP ΔS=2 (sd)^2 operator is suppressed)



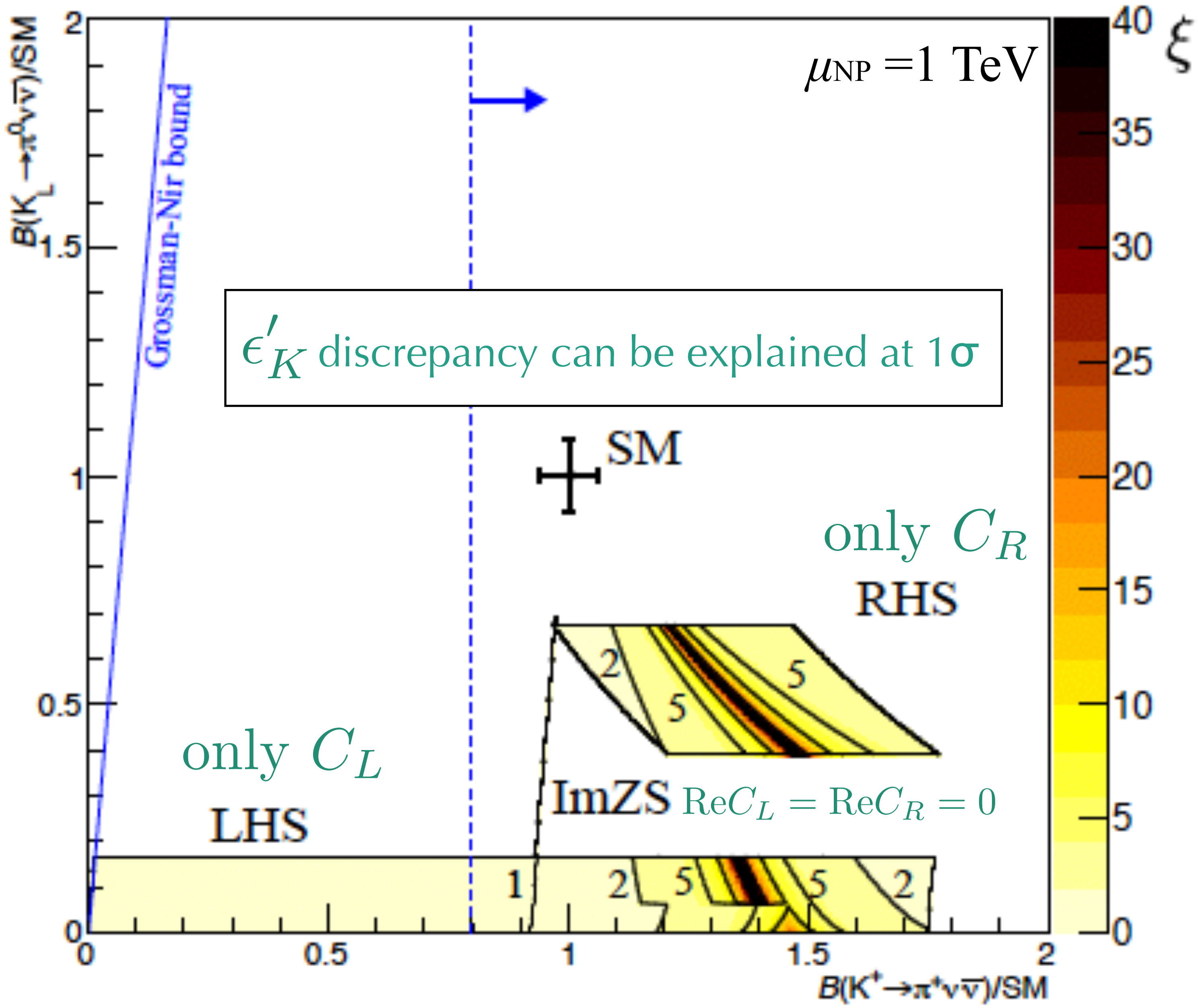
we included these contributions: **Novel point**

B(K→πνν)

[Endo, **TK**, Mishima, Yamamoto, '16]

Result of simplified case

constraint comes from ϵ_K, ΔM_K, $\mathcal{B}(K_L \to \mu^+\mu^-)$



- The interference contributions are crucial, especially in right-handed scenario (RHS)
- $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ is smaller than the SM prediction

....

- $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ can be enhanced by **overshooting** ϵ'_K from C_R + **destructive** ϵ'_K from C_L case
  - parameter tuning is required
  - UV complete model would be implausible in light of the assumption
    : NP ΔS=2 $(sd)^2$ is negligible

Summary

- RBC-UKQCD lattice group and the SM calculations of ϵ'_K/ϵ_K have revealed that the SM expected value deviates significantly from exp. data (**2.8σ**)
- In the SUSY, gluino box diagram with mass splitting of the right-handed squarks can contribute to ϵ'_K/ϵ_K significantly
  - Heavy gluino ($M_3 > 1.5 M_S$) can relax the constraint from ϵ_K
  - $\mathcal{B}(K \to \pi\nu\bar{\nu})$ data will test our scenario. $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ can determine whether the right-handed up or down squark is the heavier one
- The modified Z-coupling scenario can also explain ϵ'_K/ϵ_K discrepancy with $O(1)$ contribution to $\mathcal{B}(K \to \pi\nu\bar{\nu})$
  - NA62 experiment $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ with **10% precision** (2018) could probe whether modified Z-coupling scenario is realized or not
  - KOTO experiment $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ with **10% precision** can probe both SUSY and modified-Z coupling scenarios


BACKUP
made by
Philipp Frings

Numerical results

- Wilson coefficients $@\mu = 1.3$ GeV $C_i(\mu) \equiv z_i(\mu) - \frac{V_{ts}^* V_{td}}{V_{us}^* V_{ud}} y_i(\mu)$ new results

i	$z_i(\mu)$	$y_i(\mu)$	$\mathcal{O}(1)$	$\mathcal{O}(\alpha_{EM}/\alpha_s)$	$\mathcal{O}(\alpha_s)$	$\mathcal{O}(\alpha_{EM})$	$\mathcal{O}(\alpha_{EM}^2/\alpha_s^2)$
1	-0.3903	0	0	0	0	0	0
2	1.200	0	0	0	0	0	0
3	0.0044	0.0275	0.0254	0.0001	0.0007	0.0012	0
4	-0.0131	-0.0566	-0.0485	-0.0002	-0.0069	-0.0009	0
5	0.0039	0.0068	0.0124	0.0001	-0.0059	0.0001	0
6	-0.0128	-0.0847	-0.0736	-0.0003	-0.0099	-0.0008	0
$7/\alpha_{EM}$	0.0040	-0.0321	0	-0.1116	0	0.0760	0.0035
$8/\alpha_{EM}$	0.0019	0.1148	0	-0.0227	0	0.1366	0.0009
$9/\alpha_{EM}$	0.0051	-1.3815	0	-0.1267	0	-1.2581	0.0034
$10/\alpha_{EM}$	-0.0013	0.4883	0	0.0217	0	0.4672	-0.0006

- Hadronic matrix elements $@\mu = 1.3$ GeV

i	$\langle Q_i(\mu)\rangle_0^{\overline{\rm MS}-{\rm NDR}}({\rm GeV})^3$
1	-0.144 ± 0.046
2	0.105 ± 0.015
3	-0.040 ± 0.068
4	0.210 ± 0.069
5	-0.179 ± 0.068
6	-0.338 ± 0.121
7	0.154 ± 0.065
8	1.540 ± 0.372
9	-0.197 ± 0.070
10	0.053 ± 0.038

i	$\langle Q_i(\mu)\rangle_2^{\overline{\rm MS}-{\rm NDR}}({\rm GeV})^3$
1	0.01006 ± 0.00002
2	0.01006 ± 0.00002
3	—
4	—
5	—
6	—
7	0.127 ± 0.012
8	0.852 ± 0.052
9	0.01509 ± 0.00003
10	0.01509 ± 0.00003

RBC-UKQCD lattice simulation calculated them at μ=1.5GeV(I=0) and μ=3.0GeV(I=2) with 2+1F

We exploit CP-conserving data (with z_i) to reduce hadronic uncertainties

[**TK**, Nierste, Tremper, JHEP '16]

Overview of effective models

- Chiral perturbation theory
  - Effective theory of the QCD Goldstone bosons: $\Phi = \begin{pmatrix} \sqrt{\frac{1}{2}}\pi^0 + \sqrt{\frac{1}{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\sqrt{\frac{1}{2}}\pi^0 + \sqrt{\frac{1}{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}$

$$\mathcal{L} = -\frac{G_F}{\sqrt{2}} V_{ud} V_{us}^* \left(g_8 f^4 \mathrm{tr}\left(\lambda L_\mu L^\mu\right) + g_{27} f^4 \left(L_{\mu 23} L_{11}^\mu + \frac{2}{3} L_{\mu 21} L_{13}^\mu \right) + \mathcal{O}(g_E W) \right)$$

with $\qquad L_\mu = -i U^\dagger D_\mu U \qquad U = \exp\left(i \frac{\sqrt{2}\Phi}{f} \right)$

- dual QCD method [Bardeen, Buras, Gerard, '87, '14]
  - Effective theory of the truncated pseudo-scalar and vector mesons:

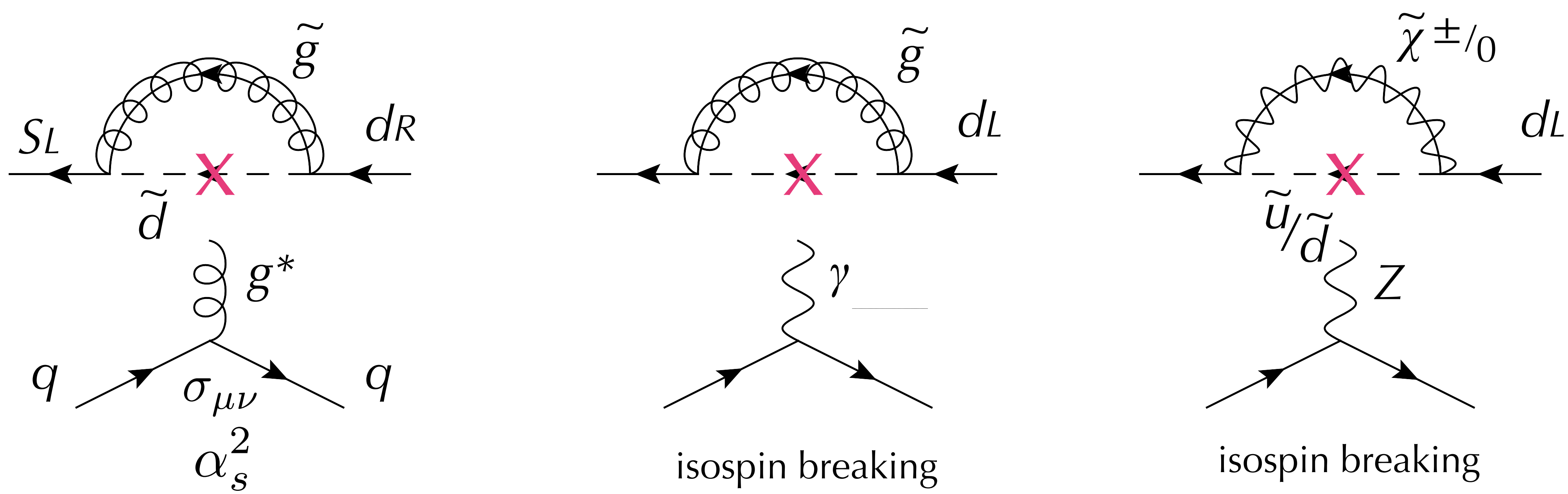
$$\mathcal{L} = \frac{f^2}{4} \mathrm{tr}\left(\partial_\mu U \partial^\mu U^\dagger\right) - \frac{1}{4} \mathrm{tr}\left(V_{\mu\nu} V^{\mu\nu}\right) - \frac{f^2}{2} \mathrm{tr}\left(\partial_\mu \xi^\dagger \xi + \partial_\mu \xi \xi^\dagger - 2 i g V_\mu\right)^2 \quad \text{with} \quad U = \xi\xi$$

- Chiral quark model
  - Mean-field approximation of the full extended NJL model

$$\mathcal{L} = \mathcal{L}_{QCD} - M \left(\bar{q}_R U q_L + \bar{q}_L U^\dagger q_R \right)$$

Sub leading contributions

- Gluino chromomagnetic penguin operator can give subleading contribution, but there is no reliable results for hadronic matrix element
  [Buras,Colangero,Ishidori,Romanino,Silvestrini, '00]
- Gluino photon-penguin breaks isospin sym. explicitly, but is suppressed by $\alpha/\alpha s$
  [Langacker,Sathiapalan, '84,Grossman,Worah, '97,Abel,Cottingham,Whittingham, '98]
- Z-penguin contribution needs to break the EW sym. like $\mathcal{L}_{\rm eff} = \frac{\lambda_{ij}}{M^2}|H|^2 \bar{d}_i \not{D} d_j$, Hence, chargino Z-penguin contribution is always larger than gluino Z-penguin
  [Colangelo,Isidori, '98@$K\to\pi\nu\nu$]

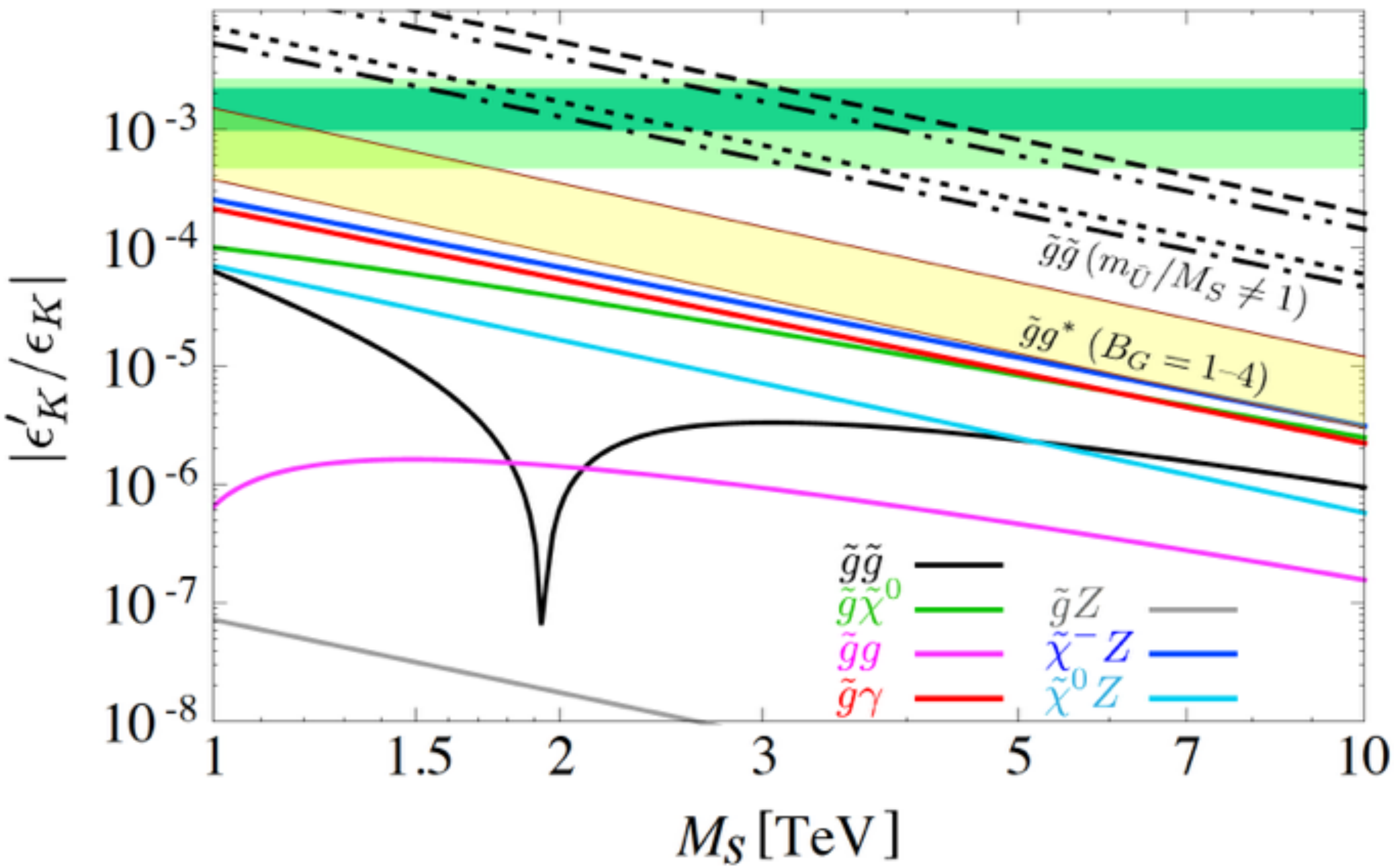


SUSY contributions to ϵ'_K/ϵ_K

ϵ'_K/ϵ_K discrepancy can be solved at

1σ	2σ

[**TK**, Nierste, Tremper, PRL, '16]



$M_3 = 1.5 M_S$

for suppressed ϵ_K

$m^2_{Q,ij} = \Delta_{Q,ij} M_S^2$

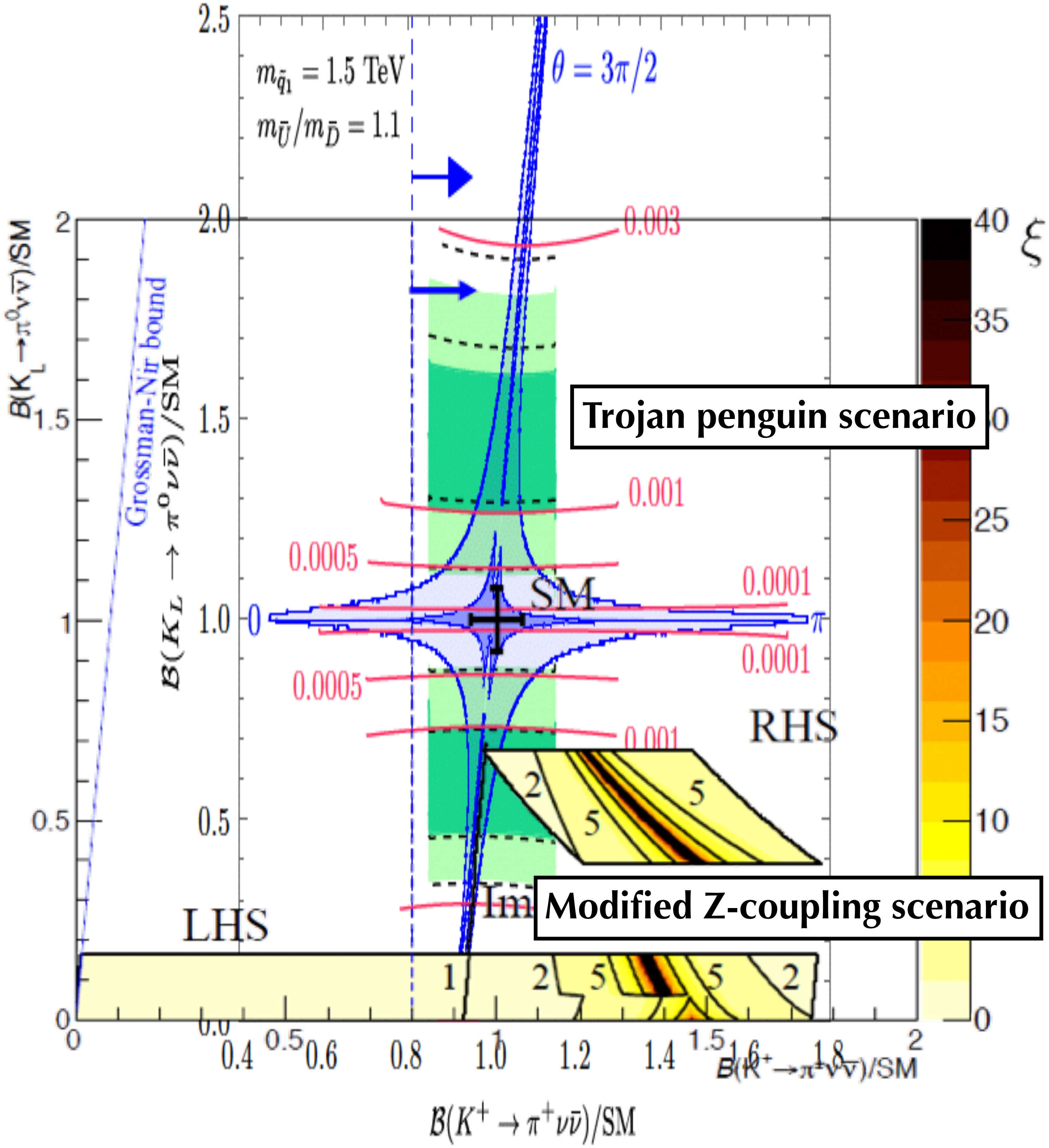
$\Delta_{Q,12,13,23} = 0.1 \exp(-i\pi/4)$

maximum CPV phase for ϵ_K

when $i\pi/4 \to i\pi/2$

amplifies ϵ'_K/ϵ_K

suppresses ϵ_K



- NA62 experiment $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ with **10% precision** (2018) could probe whether modified Z-coupling scenario is realized or not

- KOTO experiment $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$ with **10% precision** can probe both Trojan penguin and modified-Z coupling scenario