Standard Model and New physics for ϵ'_K/ϵ_K

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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],
Phys.Rev.D96, 015023 (2017) [arXiv:1703.05786],
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Flavour Changing and Conserving Processes (FCCP) 2017,
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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 :

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

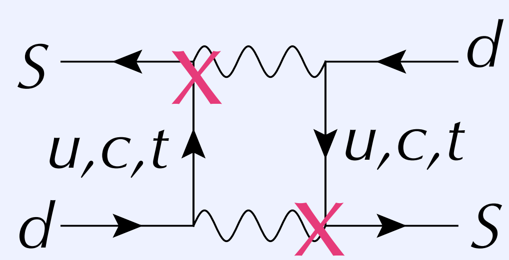
[Christenson, Cronin, Fitch, Turlay, '64 with Nobel prize]

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

[NA48/CERN and KTeV/FNAL '99]

ΔS=2
Indirect CP violation
[Kaon mixing]
W box

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

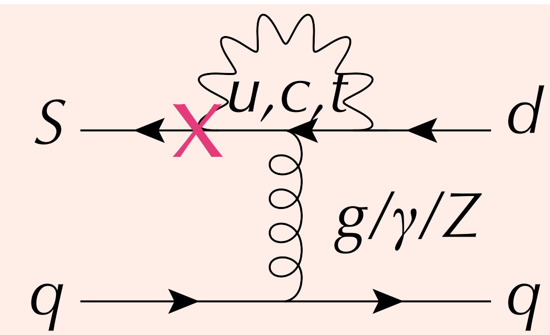


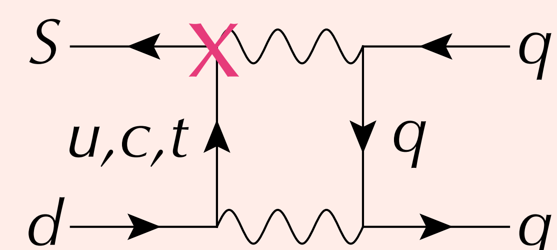
$K^0 \longleftrightarrow \overline{K}^0$

ΔS=1
Direct CP violation

W-box and penguin

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



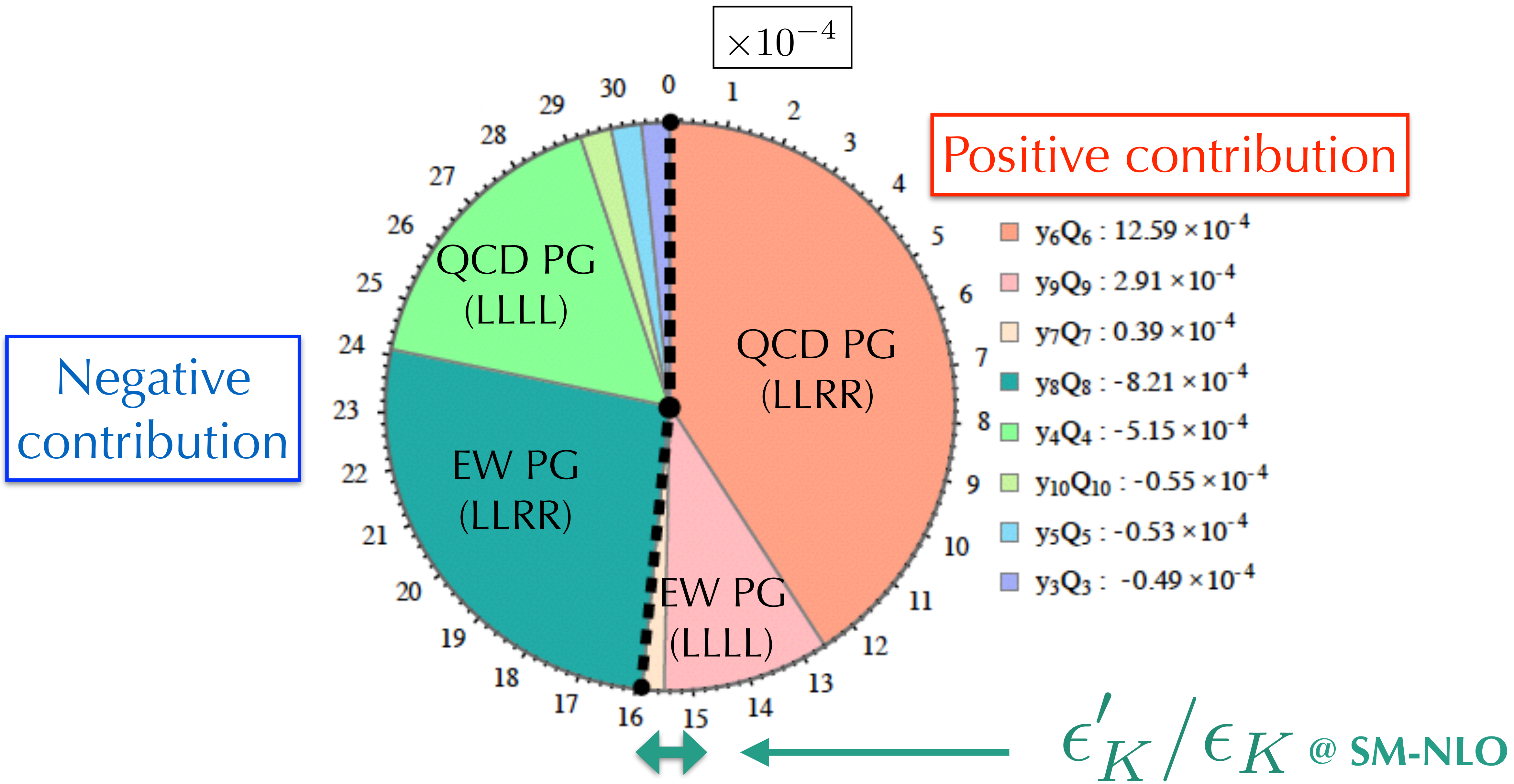


- **The strong suppression** of ϵ'_K comes from the smallness of the ΔIsospin-3/2 amplitude (ΔI = 1/2 rule) and an accidental cancellation between the SM contributions

Accidental cancellation

[TK, Nierste, Tremper, JHEP '16]

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



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 of QCD,QED, and their mixture

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

[TK, Nierste, Tremper, JHEP '16]

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

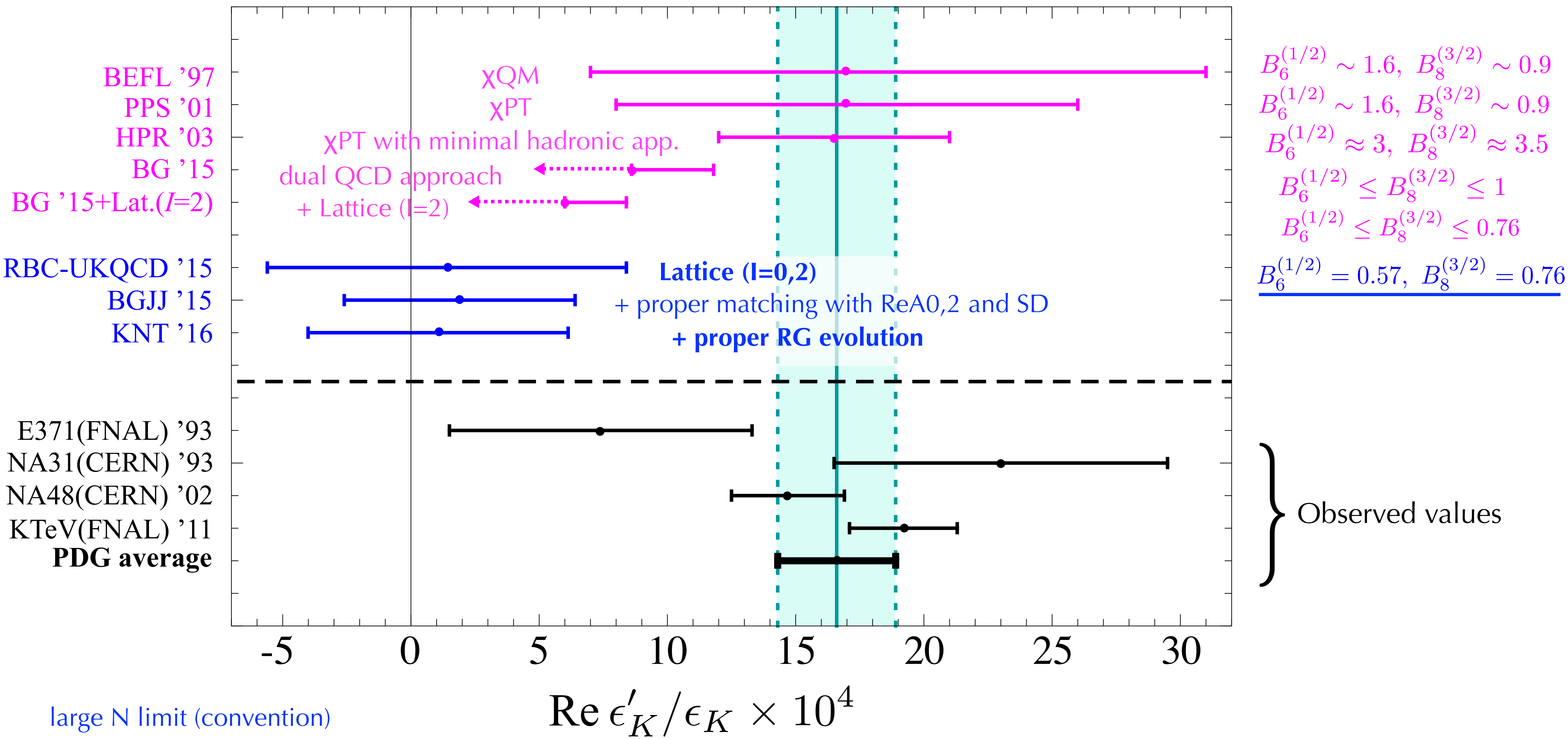
- World average of experimental results $\mathrm{Re}\left(\frac{\epsilon'_K}{\epsilon_K}\right)_{\text{exp}} = (16.6 \pm 2.3) \times 10^{-4}$ [NA62, KTeV, PDG]

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

Buras et al. obtained 2.9σ discrepancy. NNLO QCD in progress [Cerdà-Sevilla, Gorbahn, Jäger, Kokulu]

Current situation of ϵ'_K/ϵ_K

$$\propto \underbrace{\mathrm{Im}A_0}_{\propto B_6^{(1/2)}} - \left(\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2}\right) \underbrace{\mathrm{Im}A_2}_{\propto B_8^{(3/2)}}$$



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/ϵ_K vs **new physics**

Preliminary for NP

- 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 ϵ'_K/ϵ_K discrepancy; Little Higgs Model with T-parity (LHT), 331 model, vector-like quarks (VLQ), 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, Bobeth, Buras, Celis, Jung '17]

Other rare kaon decays

- **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 with each other

ϵ'_K discrepancy $(K_L \to \pi\pi)$ → deviations of the other rare kaon decays

$K \to \pi\nu\bar{\nu}$ **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 $K_S \to \pi^0\ell^+\ell^-$ → **LHCb**
direct detection of $K_L \to \pi^0\ell^+\ell^-$ is necessary

$K_S \to \mu^+\mu^-$: CPC + CPV, Br is amplified by $\tan^3\beta/M_A^2$
Good : Direct CP asymmetry could be probed
→ **LHCb** talked by **Martinez Santos**

Slide from Kei Yamamoto (FPCP2017)

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

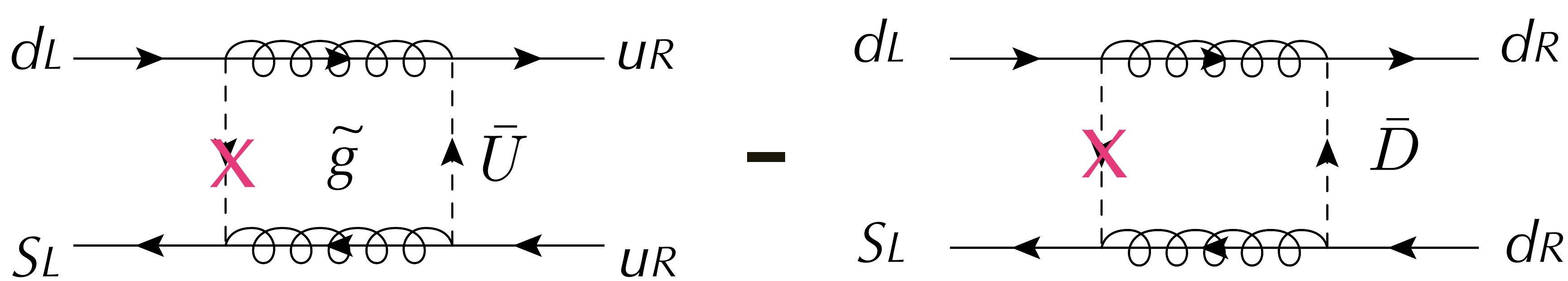
Simultaneous consideration of various flavor observables ($K \to \pi\nu\nu$, P5', $B_s \to \mu\mu$, EDM,,,) may allow to distinguish among these models.

ϵ'_K/ϵ_K vs **gluino box**

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

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

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 $\Delta S = 1$ parameter $\boldsymbol{\delta}$ and is mediated by heavy particles of mass M, one finds

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

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

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

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

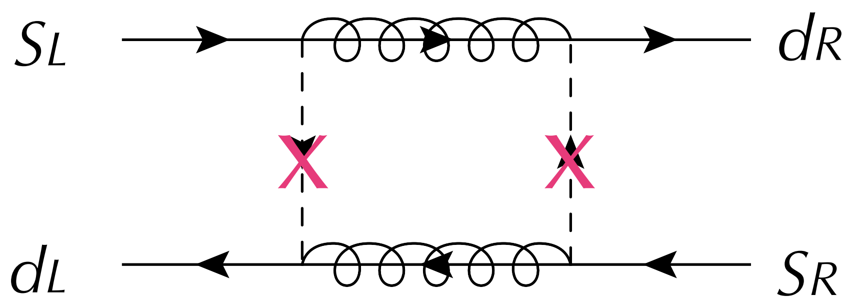
when loop factor $1/(4\pi)$ is the same as the SM

- With $M > 1$ TeV, NP effects can only be basically relevant for **$|\delta| >> |\tau|$**, 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.

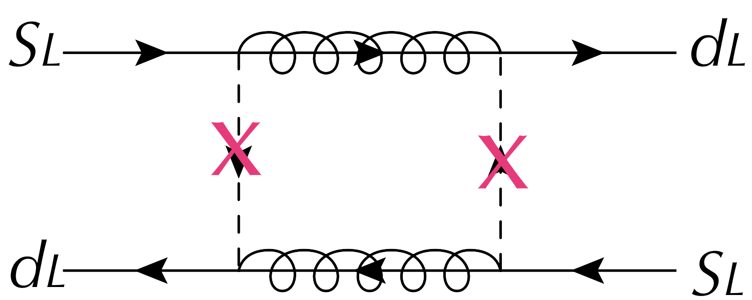
- The leading contribution is given by $\overline{d_L} s_L \overline{d_R} s_R$

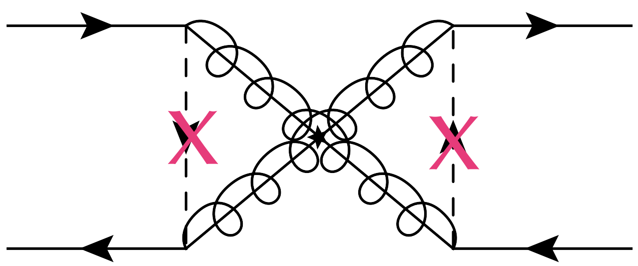


$$\propto \left(\frac{m_K}{m_s + m_d} \right)^2$$

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

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





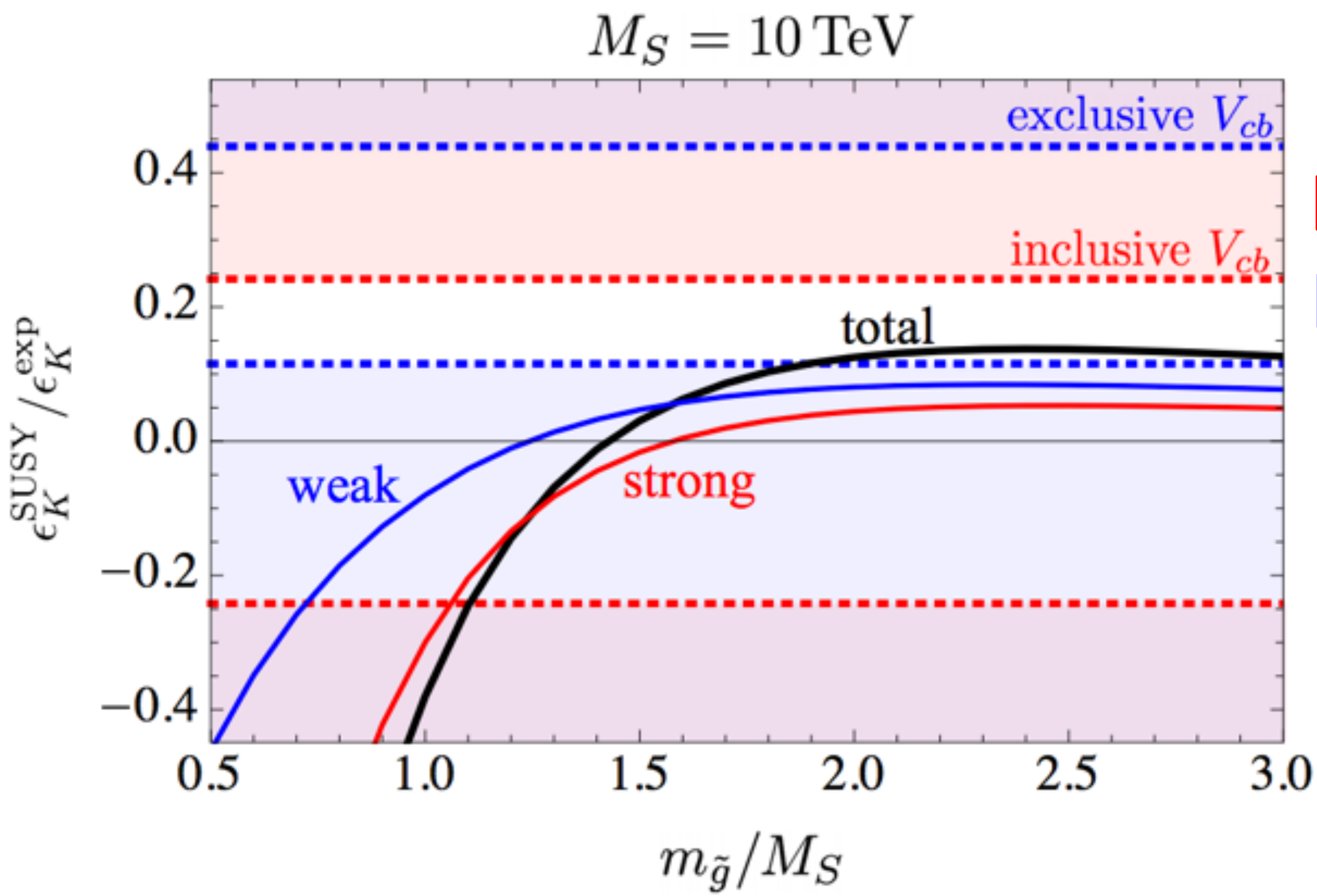
Crossed diagram gives relatively negative contributions

$m_{\tilde{g}} \simeq 1.5 m_{\tilde{q}}$: **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

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

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

Heavier gluino (than squark) is preferred

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

$|V_{cb}|_{\mathrm{incl.}}$, measured in inclusive $b \to c l \nu$ decays….. ε_K is consistent with exp. value

$|V_{cb}|_{\mathrm{incl.}}$, measured in exclusive $B \to D^{(*)} l \nu$ decays….. ε_K is 3σ below the exp. value

SUSY contributions to ϵ'_K/ϵ_K

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

- We take universal SUSY mass (M_S) **without gaugino masses (M_3) and right-handed up-type squark mass ($m_{\overline{U}}$)**

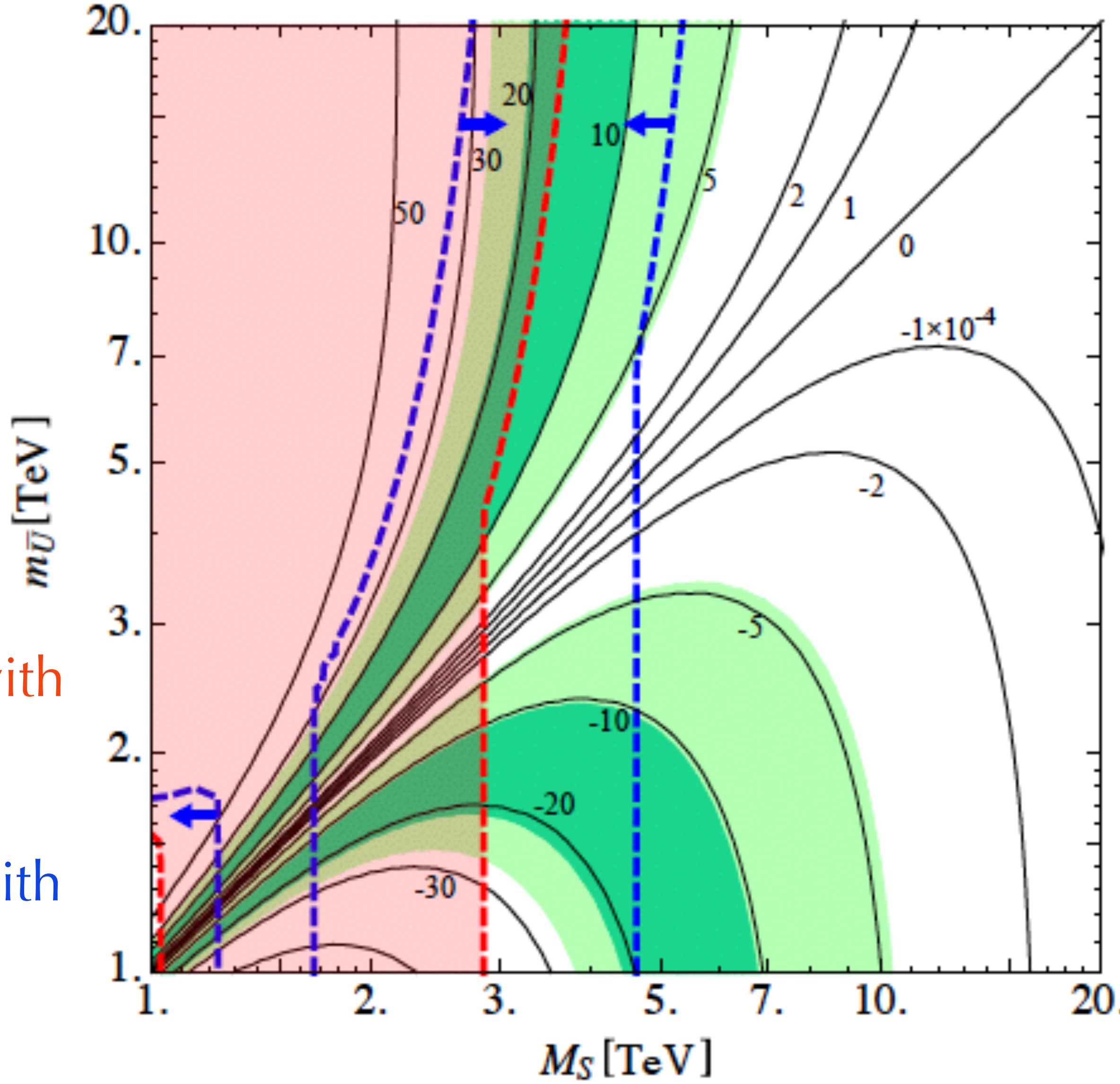
ϵ'_K/ϵ_K discrepancy can be solved at

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

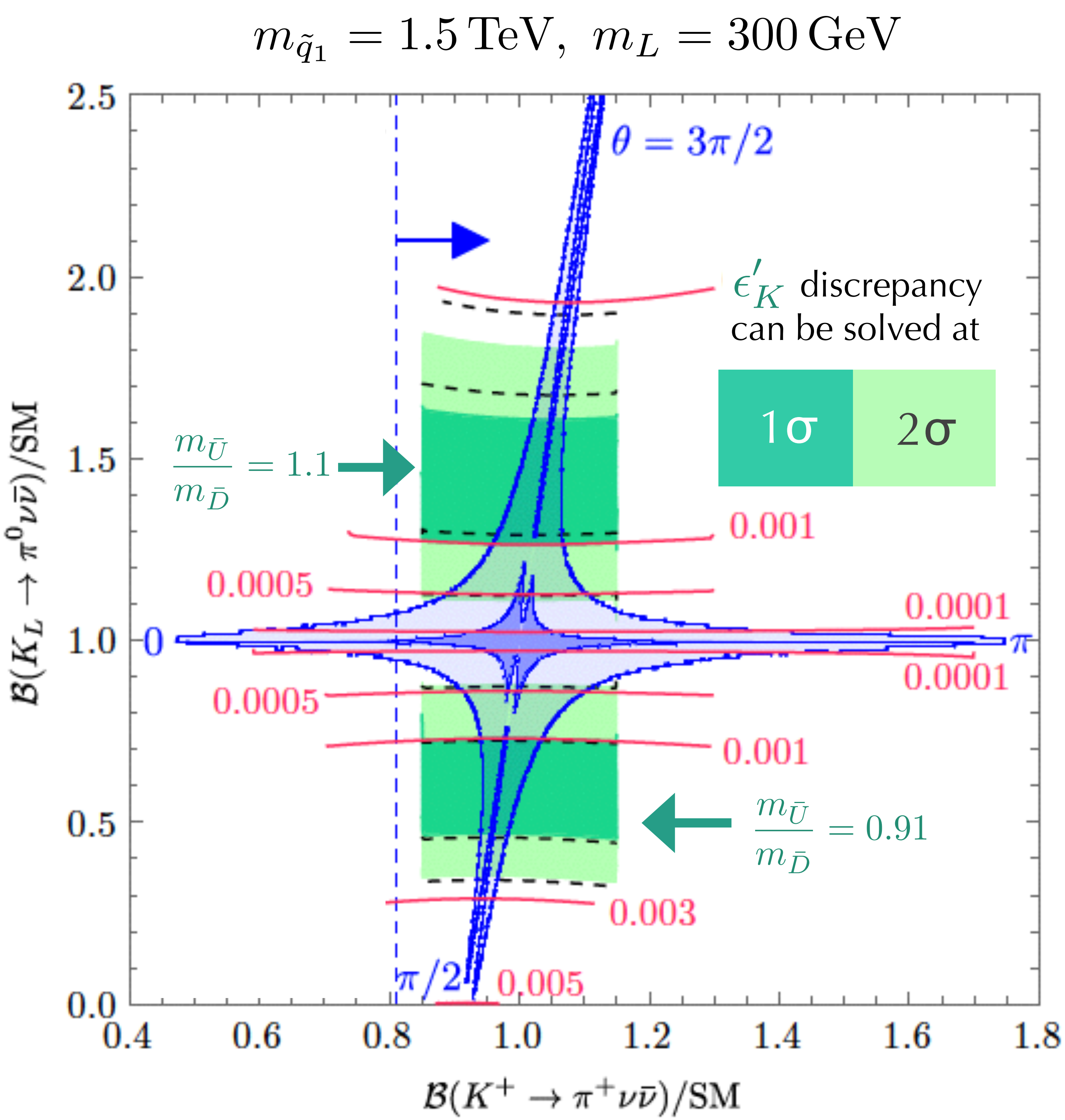
when $i\pi/4 \to i\pi/2$

amplifies ϵ'_K/ϵ_K

suppresses ϵ_K

B($K \to \pi\nu\nu$)

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



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 vs **modified Z coupling**

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]

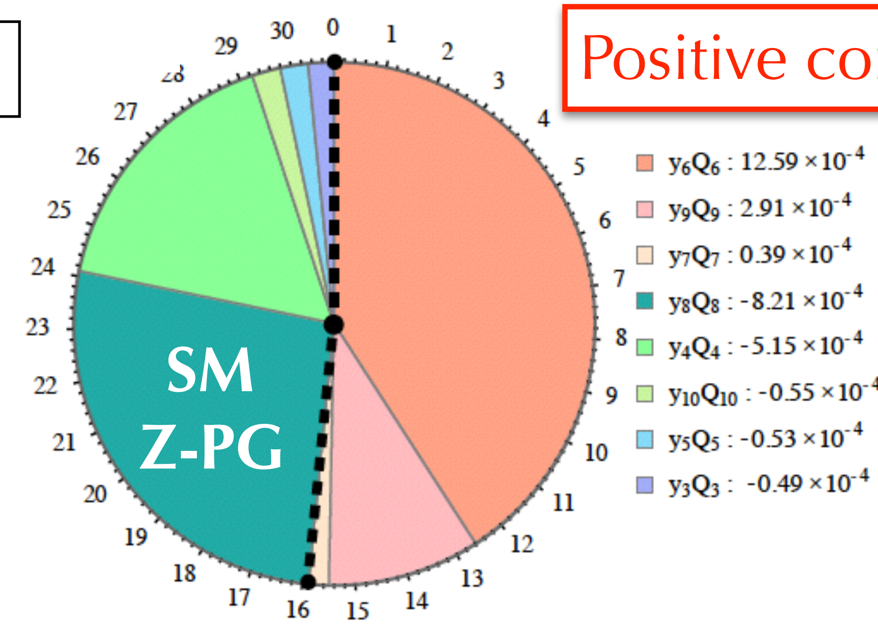
- NP contributions to *sdZ* coupling which has the same magnitude as the SM Z-penguin can explain ϵ'_K discrepancy

ϵ'_K/ϵ_K $\boxed{\times 10^{-4}}$

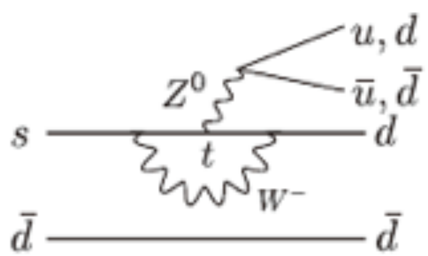
Negative contribution

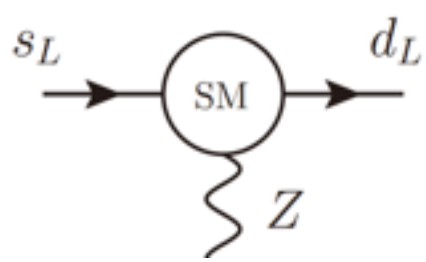
SM Z-penguin gives the biggest negative contribution

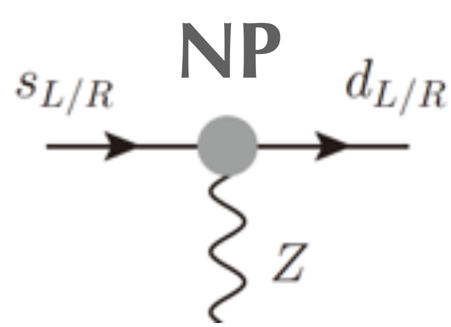
Positive contribution



$\leftrightarrow$ 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: Although Z′ FCNC scenario can also explain ϵ'_K , a correlation to $\mathcal{B}(K \to \pi\nu\bar{\nu})$ is model-dependent

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]

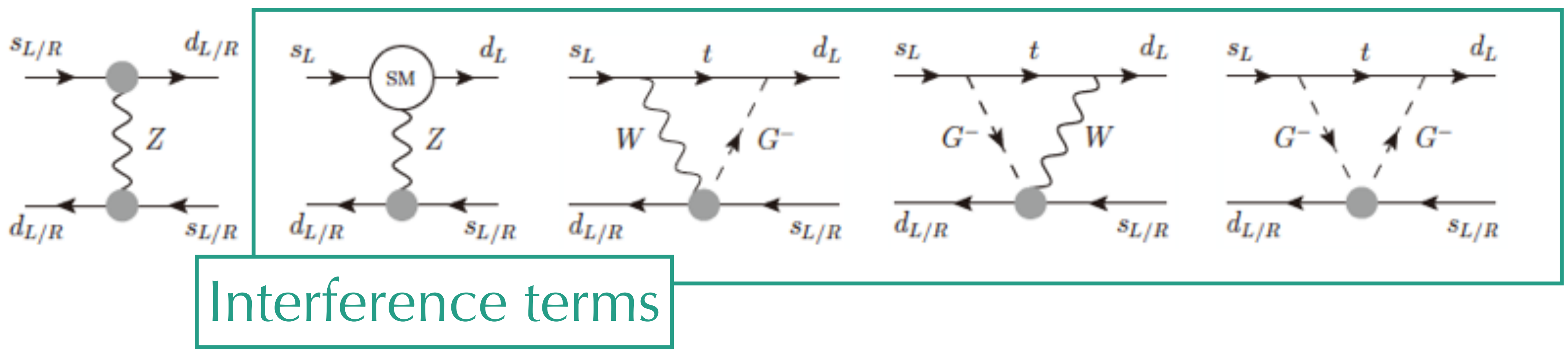
- SM + dim-6 eff. (SMEFT) operators include

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

→ modified Z-couplings (FCNC) emerge

- Constraint comes from ΔS=2 process : ϵ_K (Assumption: NP ΔS=2 $(sd)^2$ operators are suppressed)

$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{s}_R \gamma^\mu d_R)$ @high scale $\xrightarrow{\text{Yukawa RG}}$ $(\overline{s}_L \gamma_\mu d_L)(\overline{s}_R \gamma^\mu d_R)$ @low scale



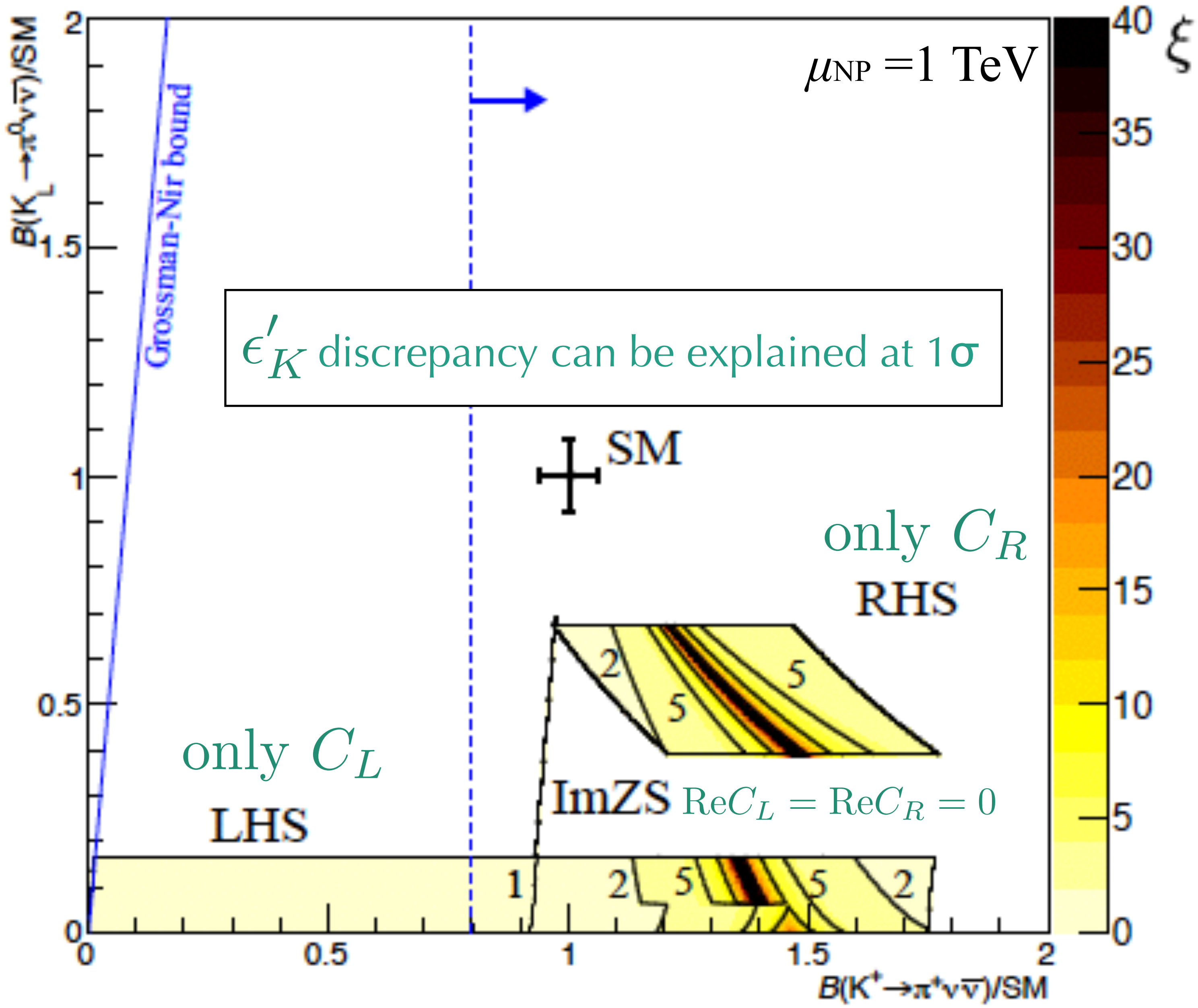
[Endo, TK, Mishima, Yamamoto, '16] [Bobeth, Buras, Celis, Jung,'17]

B($K \to \pi\nu\nu$)

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

Result of simplified case

constraint comes from $\epsilon_K,\ \Delta M_K,\ \mathcal{B}(K_L \to \mu^+\mu^-)$



- 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

Direct CP asymmetry in $K_S \to \mu\mu$

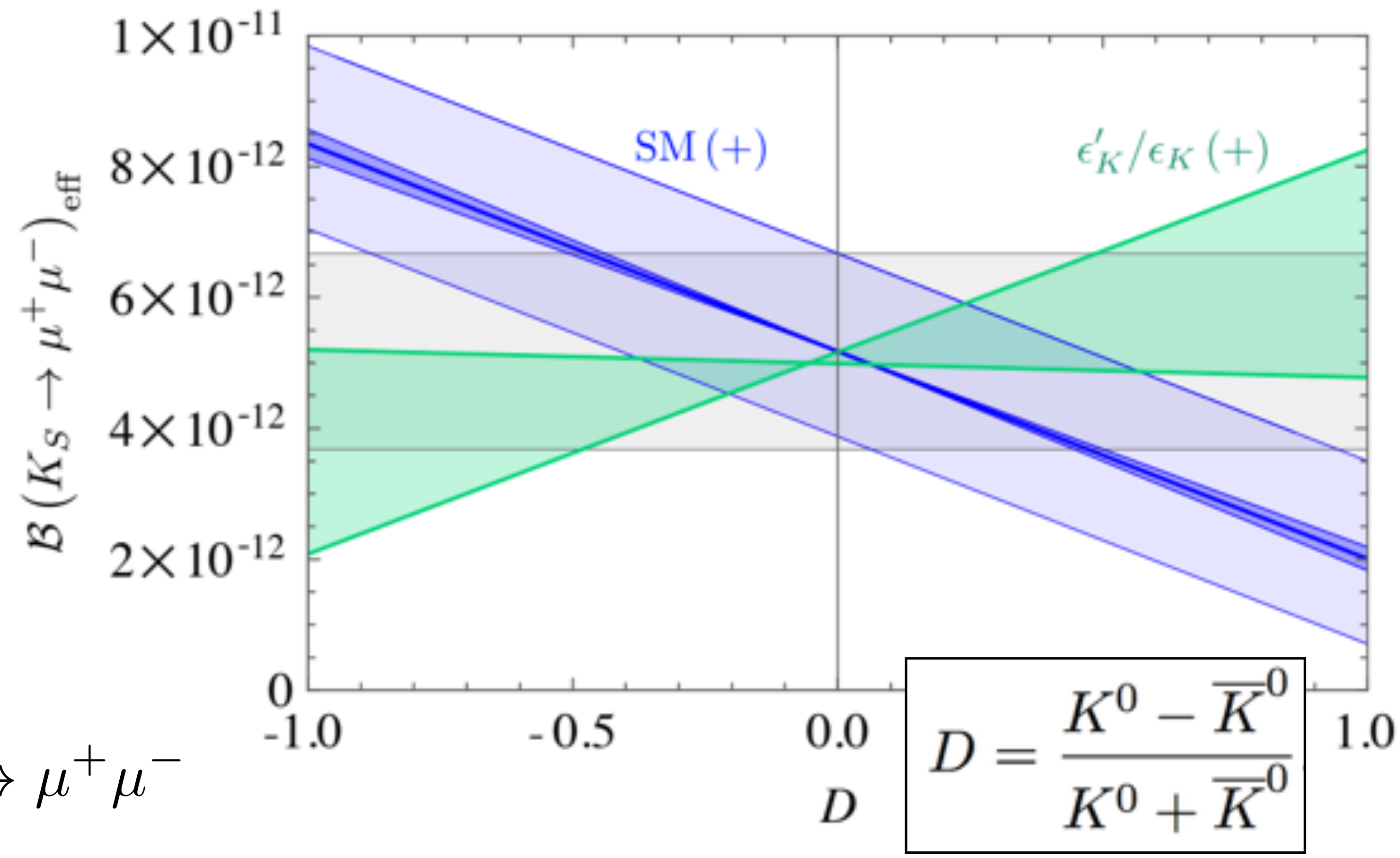
[TK, D'Ambrosio, arXiv:1707.06999]

- $K_S \to \mu\mu$ (almost CPC) can be detected by an upgrade of the LHCb experiment. $K_L \to \mu\mu$ (CPC) has been observed precisely by BNL E871 [BNL E871, PRL '00] (talked by **Martinez Santos).**
- An interference contribution between K_L and K_S emerges from **a genuine direct CP violation**
- Interference contribution is comparable size to CPC thanks to the large LD contribution to $K_L \to \mu\mu$
- Nonzero dilution factor (D) could be obtained by an accompanying charged kaon tagging and a charged pion tagging

$$pp \to K^0 K^- X$$

$$pp \to K^{*+} X \to K^0 \pi^+ X$$

with $K^0 \to \{K_S, K_L\} \to \mu^+\mu^-$



Summary

- RBC-UKQCD lattice group and perturbative calculations of ϵ'_K/ϵ_K have revealed that the SM expected value deviates significantly from exp. data (**2.8σ**)
- Correlations with the other rare decays are crucial
- In the SUSY, gluino box diagram with mass splitting of the right-handed squarks can contribute to ϵ'_K/ϵ_K significantly
  - $\mathcal{B}(K \to \pi\nu\bar{\nu})$ 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 $@\mu = 1.3\ \mathrm{GeV}$ $\quad C_i(\mu) \equiv z_i(\mu) - \frac{V_{ts}^* V_{td}}{V_{us}^* V_{ud}} y_i(\mu)$ 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 $@\mu = 1.3\ \mathrm{GeV}$

i	$\langle Q_i(\mu)\rangle_0^{\overline{\mathrm{MS}}\text{–NDR}}(\mathrm{GeV})^3$
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	$\langle Q_i(\mu)\rangle_2^{\overline{\mathrm{MS}}\text{–NDR}}(\mathrm{GeV})^3$
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

Lattice simulations (by RBC-UKQCD) are calculated 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 $\qquad L_\mu = -iU^\dagger D_\mu U \qquad U = \exp\left(i \frac{\sqrt{2}\Phi}{f} \right)$

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

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

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

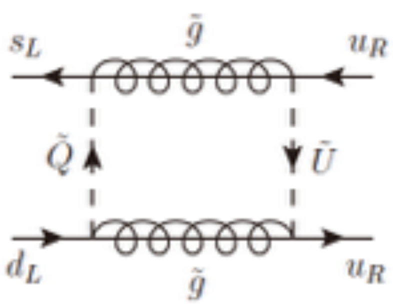
$$\mathcal{L} = \mathcal{L}_{QCD} - M\left(\bar{q}_R U q_L + \bar{q}_L U^\dagger q_R\right)$$

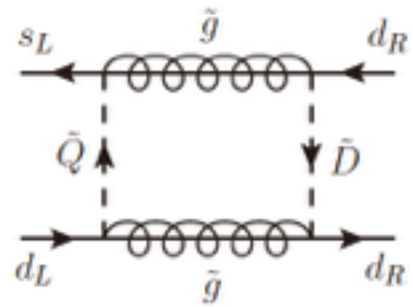
Overview in our SUSY scenario

- 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

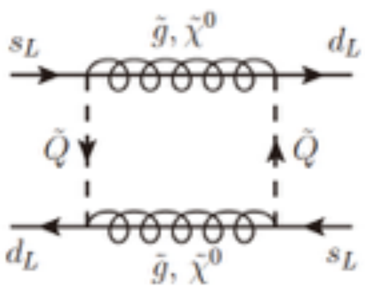


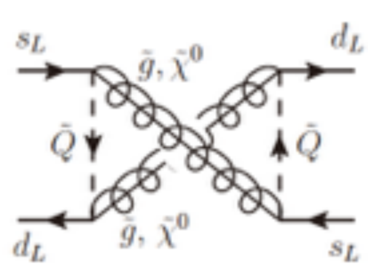


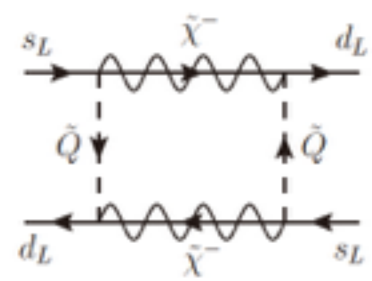
can explain ϵ'_K discrepancy

[TK, Nierste, Tremper, '16]

ΔS=2



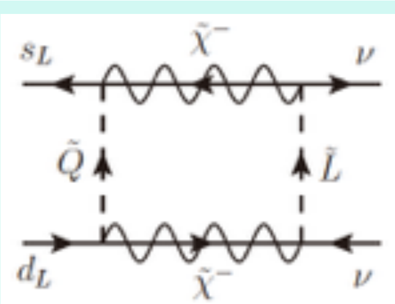




can **suppress** ΔS=2 process

[Crivellin, Davidkov, '10]

ΔS=1



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

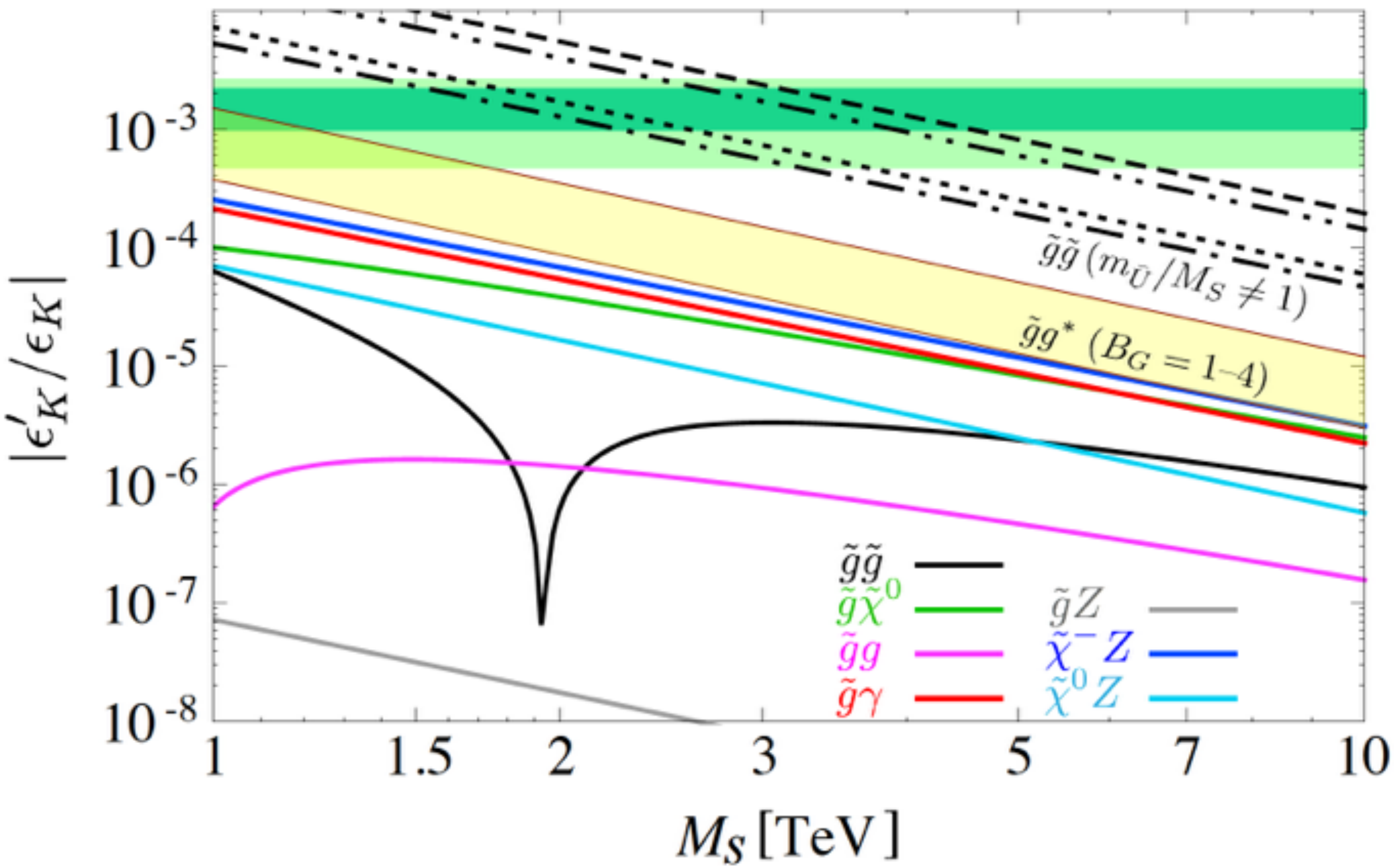
[Crivellin, D'Ambrosio, TK, Nierste, '17]

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

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

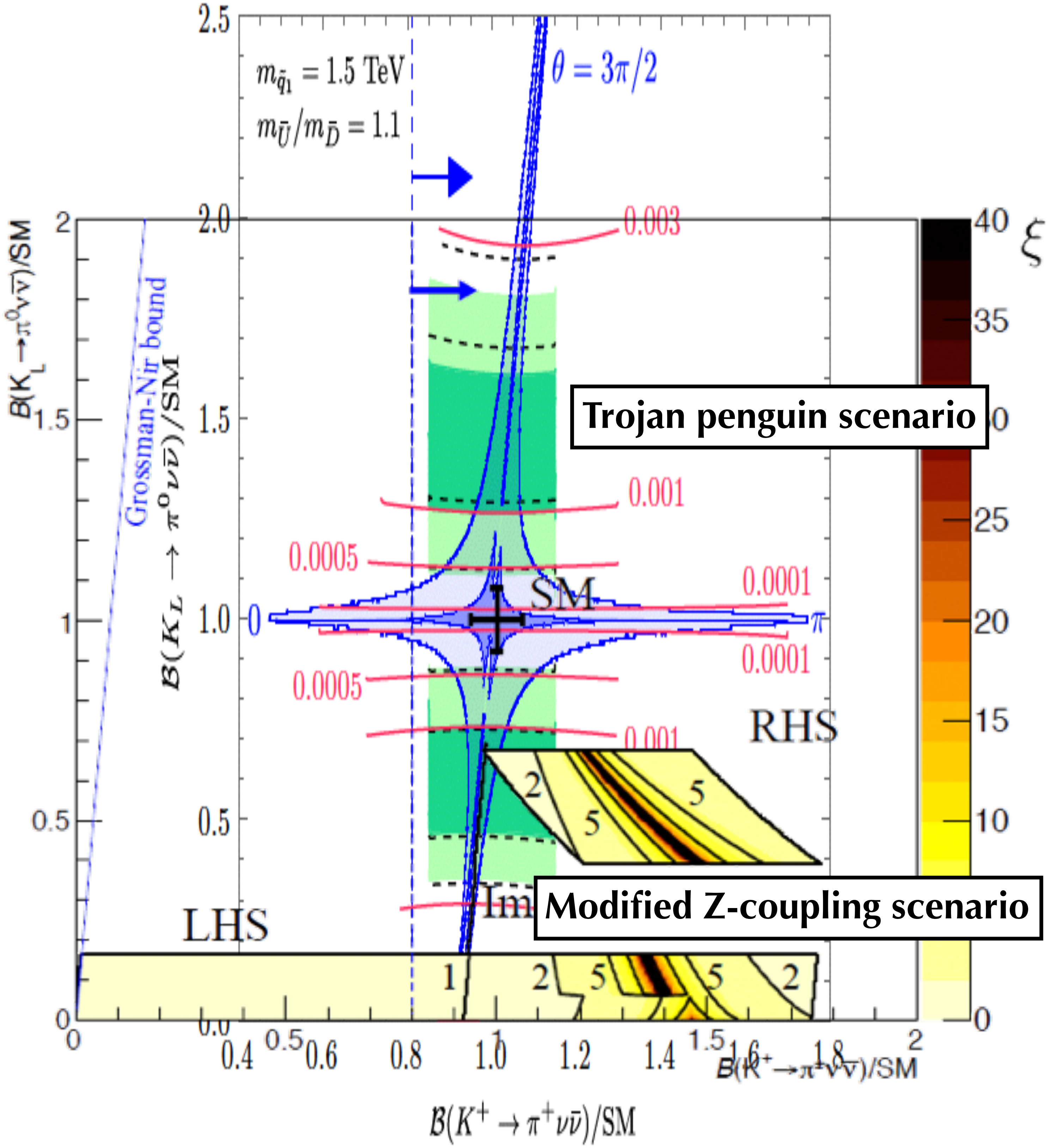
$\Delta_{Q,12,13,23} = 0.1 \exp(-i\pi/4)$

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