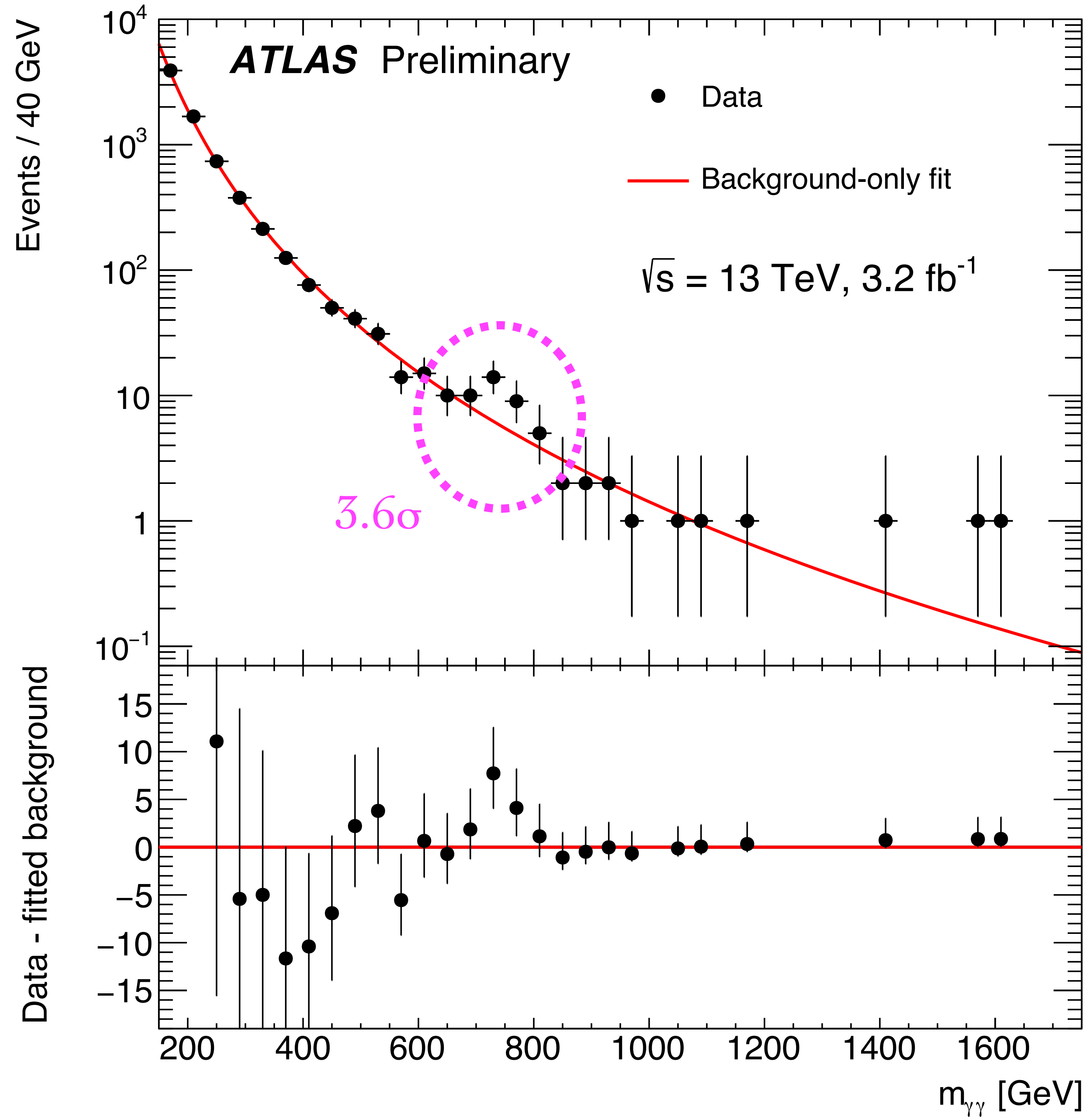
Kaon physics effectively

Uli Haisch,
Oxford University

NA62 Kaon Physics Handbook Workshop,
University of Mainz, 22 January 2016

Who ordered that?

[ATLAS-CONF-2015-081]



Ways to study new physics (NP)

Top-down approach:

- concrete model of new physics
- predict observables & correlations directly
- are smoking gun signals possible?

→ talks by Andrzej, Monika & Sebastian

Bottom-up approach:

- what data can be obtained?
- how is it parametrized efficiently?
- what can be learned about model classes?

→ discussed below, see also Jorge's talk

Bottom-up approach

$\mathcal{L}_{\text{NP}} =$ 

Λ

$$\mathcal{L}_{\text{SMEFT}} = \sum_i \frac{c_i}{\Lambda^2} Q_i + \ldots$$

$Q_i =$ all dimension-6 $SU(2)_L \times U(1)_Y$ invariant operators constructed from SM fields

M_W

$\mathcal{L}_{\text{weak}}$

m_c

2500 – 1 = too many

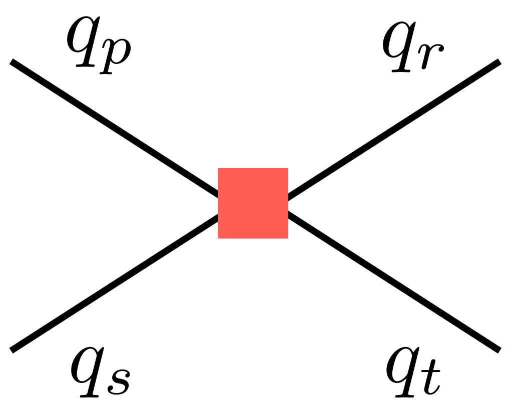
- Considering all possible flavour structures, complete set of dimension-6 SM effective field theory (SMEFT) operators consists of 1350 CP-even & 1149 CP-odd composites

[Buchmüller & Wyler, NPB (1986) 268; Grzadkowski et al., 1008.4884]

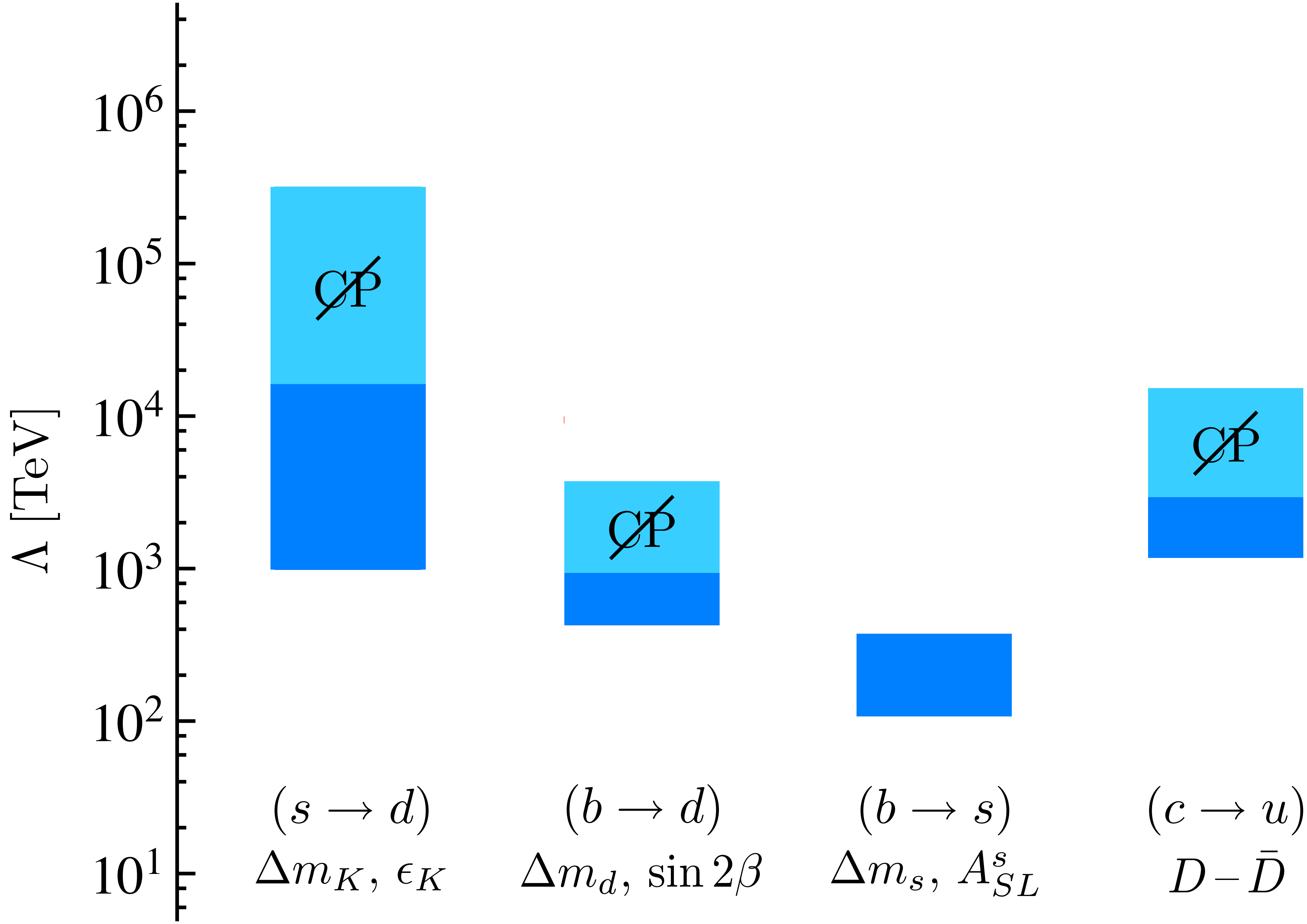
- In this talk I will try to address questions of following type: Which are dimension-6 operators that are most constrained by kaon physics? To which extent are $\Delta S = 1, 2$ channels linked? Does this rule out order of magnitude effects in rare decays? …

Four-quark operators

ψ^4: $Q_{LL}^{(1)} = (\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)\,, \ \ldots$



Bounds on four-quark operators[†]



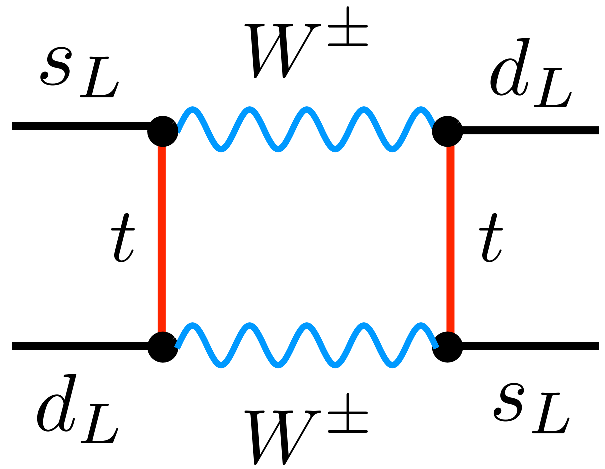
[†]figure assumes Wilson coefficients c_{pr} = 1, i.e. a generic flavour structure

Anatomy of εK

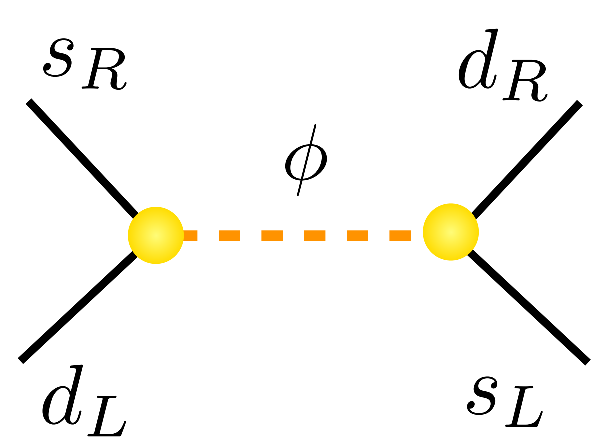
- Most severe flavour constraint in many non-minimal flavour violating (MFV) models due to CP violation in kaon sector:

$$\epsilon_K \propto \boxed{\mathrm{Im}}\left(C^{sd}_{LL} + \boxed{115}\, C^{sd}_{LR}\right)$$

$$Q^{sd}_{LL} = (\bar{s}_L \gamma_\mu d_L)(\bar{s}_L \gamma^\mu d_L)$$

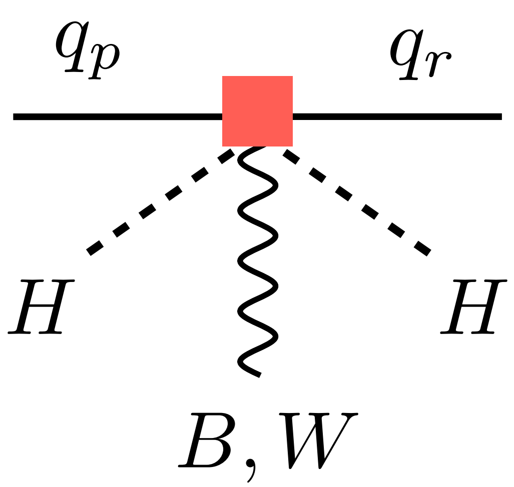


$$Q^{sd}_{LR} = (\bar{s}_R d_L)(\bar{s}_L d_R)$$



Z-penguin operators

$\psi^2 H^2 D$: $\quad Q_{Hq}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)\,, \ldots$

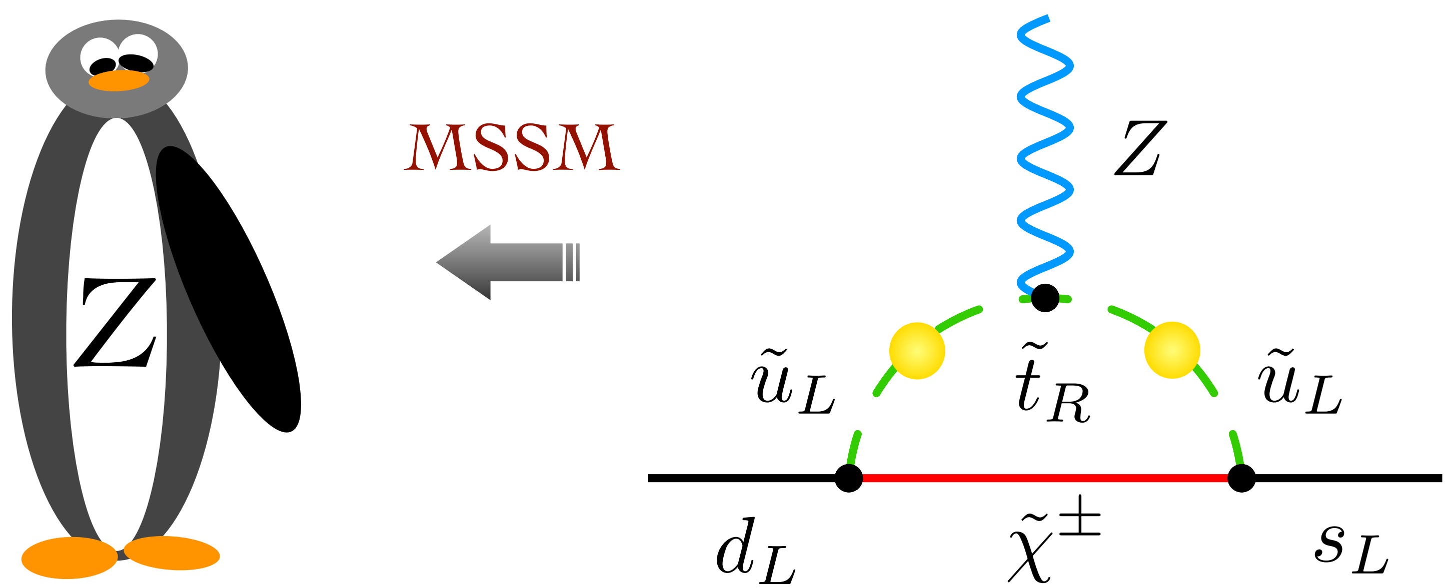


Z-penguin operators

- After electroweak symmetry breaking, one has

$$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r) \quad \Longrightarrow \quad \bar{d}_L \gamma_\mu s_L Z^\mu + \bar{u}_L \gamma_\mu c_L Z^\mu + \ldots$$

which is left-handed (LH) Z penguin known from minimal supersymmetric SM (MSSM), Randall-Sundrum (RS) models, ...



Z-penguin operators

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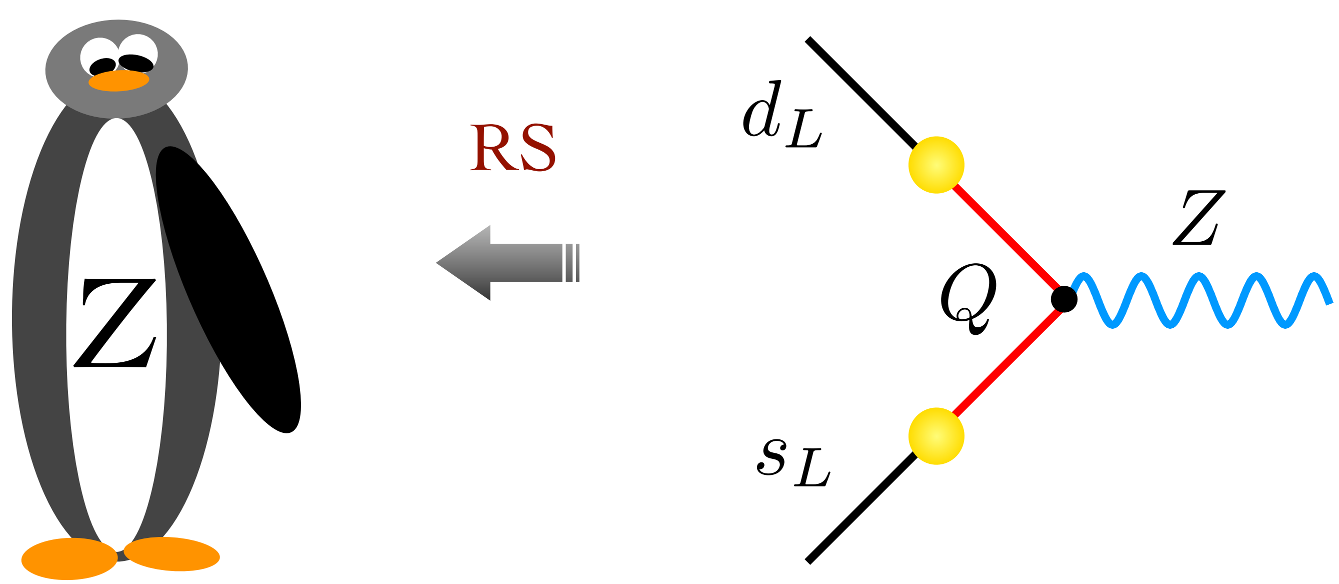


Z-penguin operators

- Similarly, there is right-handed (RH) Z penguin

$$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r) \Rightarrow \bar{d}_R \gamma_\mu s_R Z^\mu + \ldots$$

which has no counterpart in SM

- Parametrize flavour-changing Z-boson vertices by

$$(V_{ts}^* V_{td} \, C_{\rm SM} + C_{\rm NP}) \, \bar{d}_L \gamma_\mu s_L Z^\mu + \widetilde{C}_{\rm NP} \, \bar{d}_R \gamma_\mu s_R Z^\mu$$

where V_{ij} are Cabibbo-Kobayashi-Maskawa (CKM) elements & $C_{SM} \approx 0.8$ is value of Inami-Lim function characterizing LH Z penguin in SM

Anatomy of neutrino modes

- After summation over neutrino flavours, branching ratios of $K \rightarrow \pi\nu\bar{\nu}$ channels can be written as

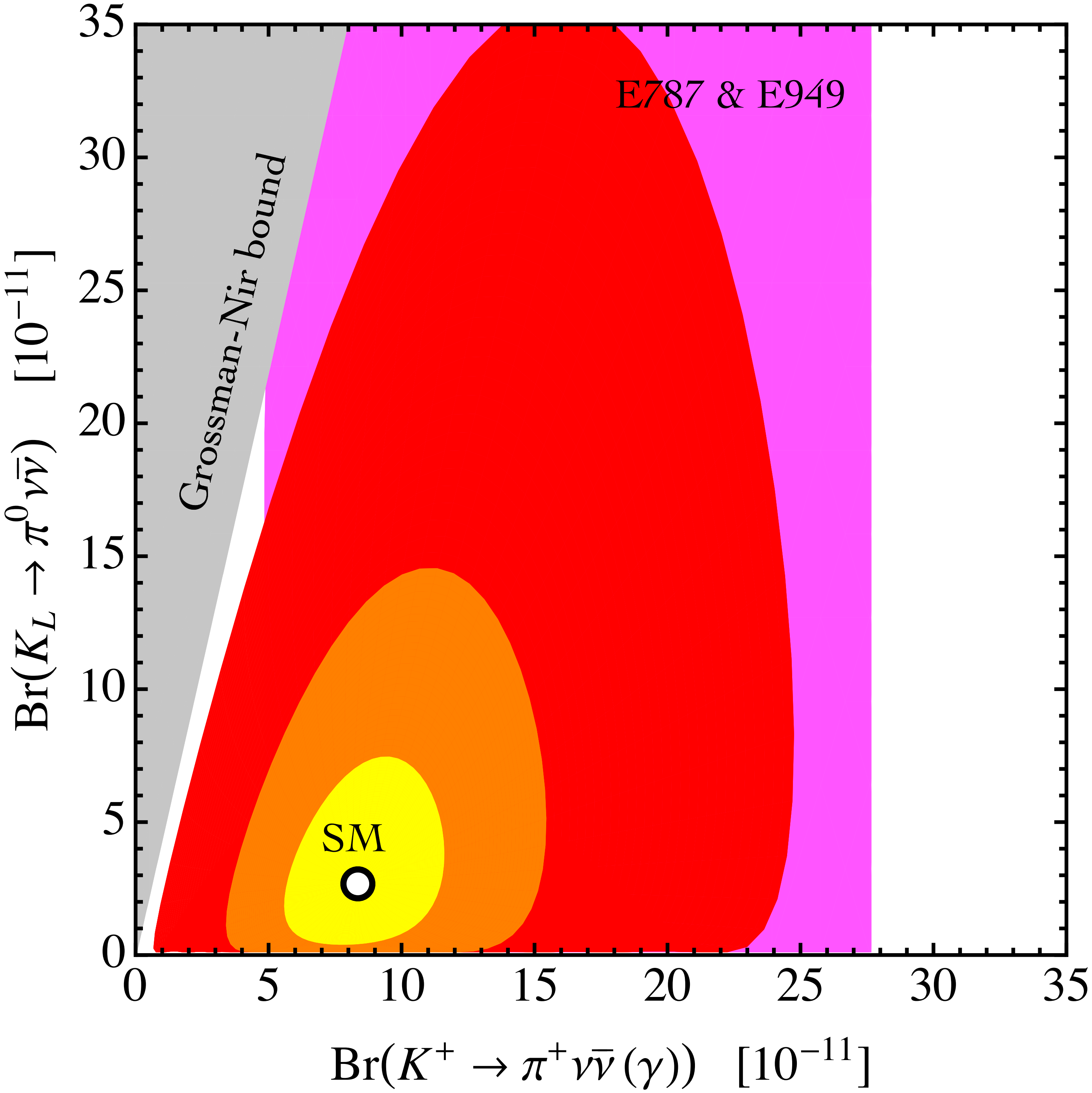
$$\mathrm{Br}(K_L \to \pi^0 \nu\bar{\nu}) \propto (\mathrm{Im}\, X)^2$$

$$\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu}(\gamma)) \propto |X|^2$$

$$X = \frac{\lambda_t}{\lambda^5} X_t + \frac{\mathrm{Re}\lambda_c}{\lambda} X_c + \frac{1}{\lambda^5}\left(C_{\mathrm{NP}} + \widetilde{C}_{\mathrm{NP}}\right)$$

$$\lambda_i = V_{is}^* V_{id}\,, \quad \lambda \approx 0.23\,, \quad X_t \approx 1.5\,, \quad X_c \approx 0.4$$

Z penguins in neutrino modes



$|C_{\rm NP}| \leq 0.5\,|\lambda_t C_{\rm SM}|$

$|C_{\rm NP}| \leq |\lambda_t C_{\rm SM}|$

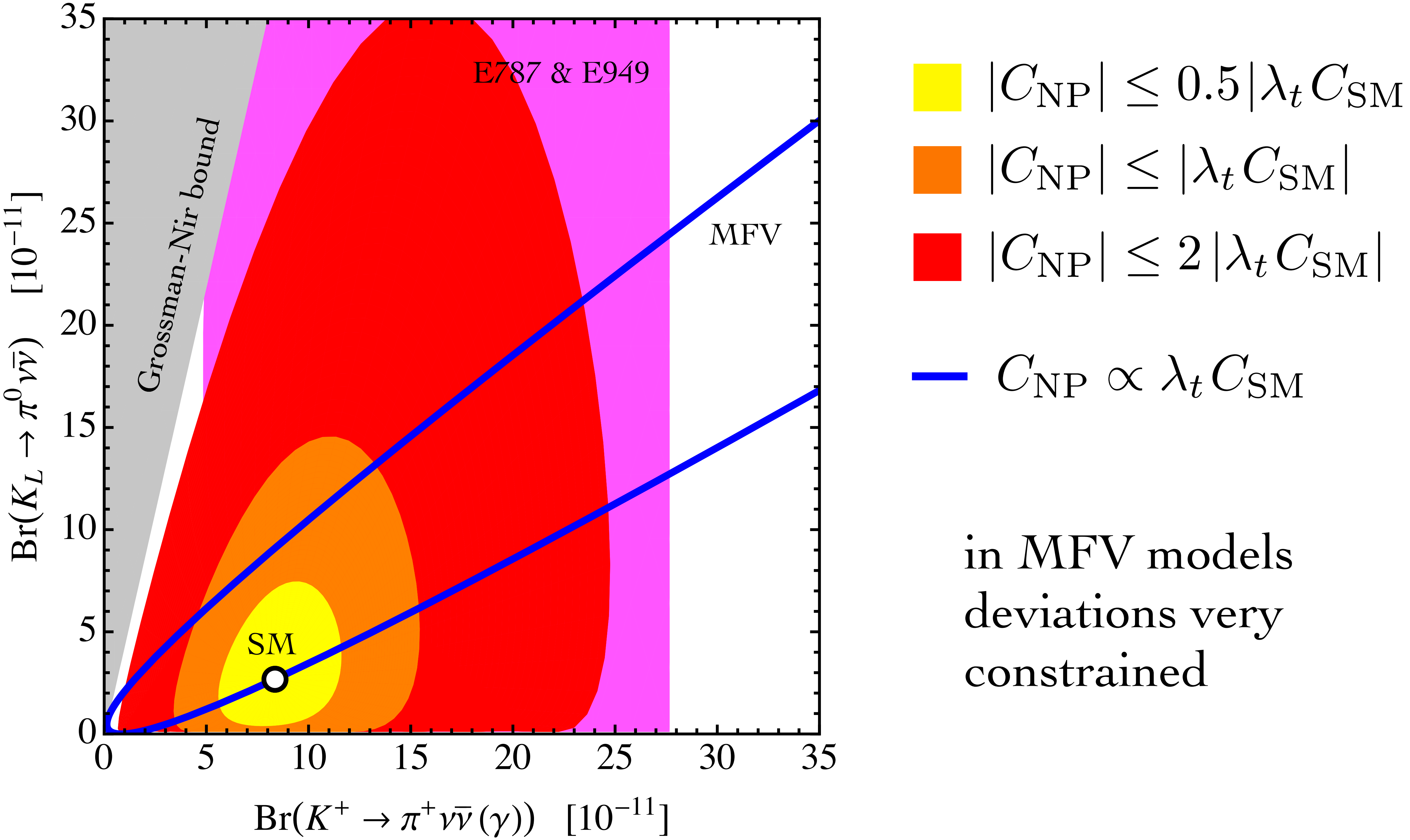
$|C_{\rm NP}| \leq 2\,|\lambda_t C_{\rm SM}|$

$$C_{\rm NP} = |C_{\rm NP}|\, e^{i\phi_C}$$

same results obtained for RH Z penguin

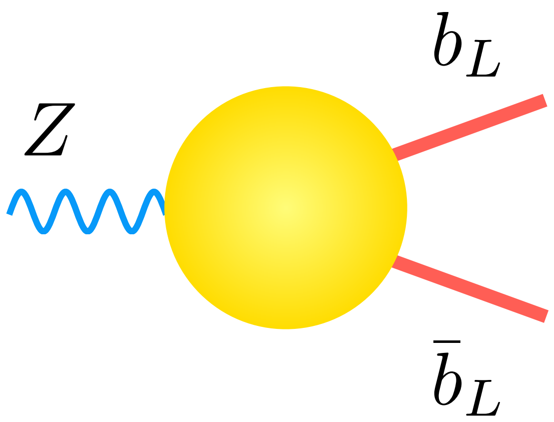
[see for instance Jäger, talk at first NA62 Physics Handbook Workshop]

Z penguins in neutrino modes

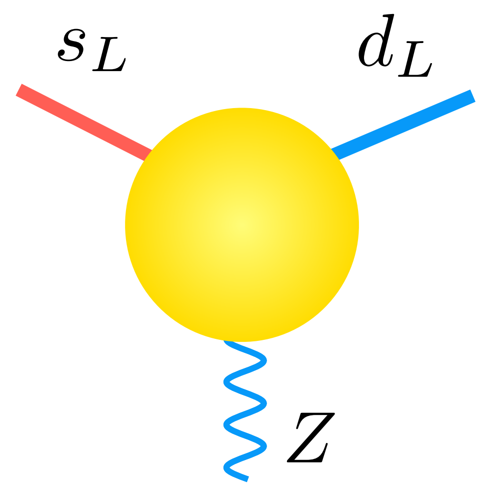


in MFV models deviations very constrained

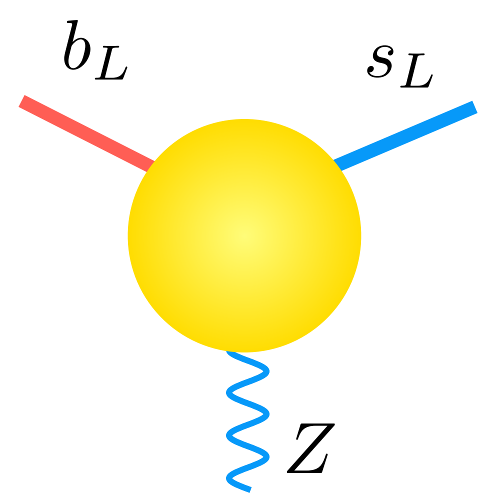
One to rule them all



$$|V_{tb}|^2\, C_{\rm NP}\, \bar{b}_L \not{Z} b_L + \mathcal{O}(M_Z^2)$$



$$V_{ts}^* V_{td}\, C_{\rm NP}\, \bar{d}_L \not{Z} s_L$$

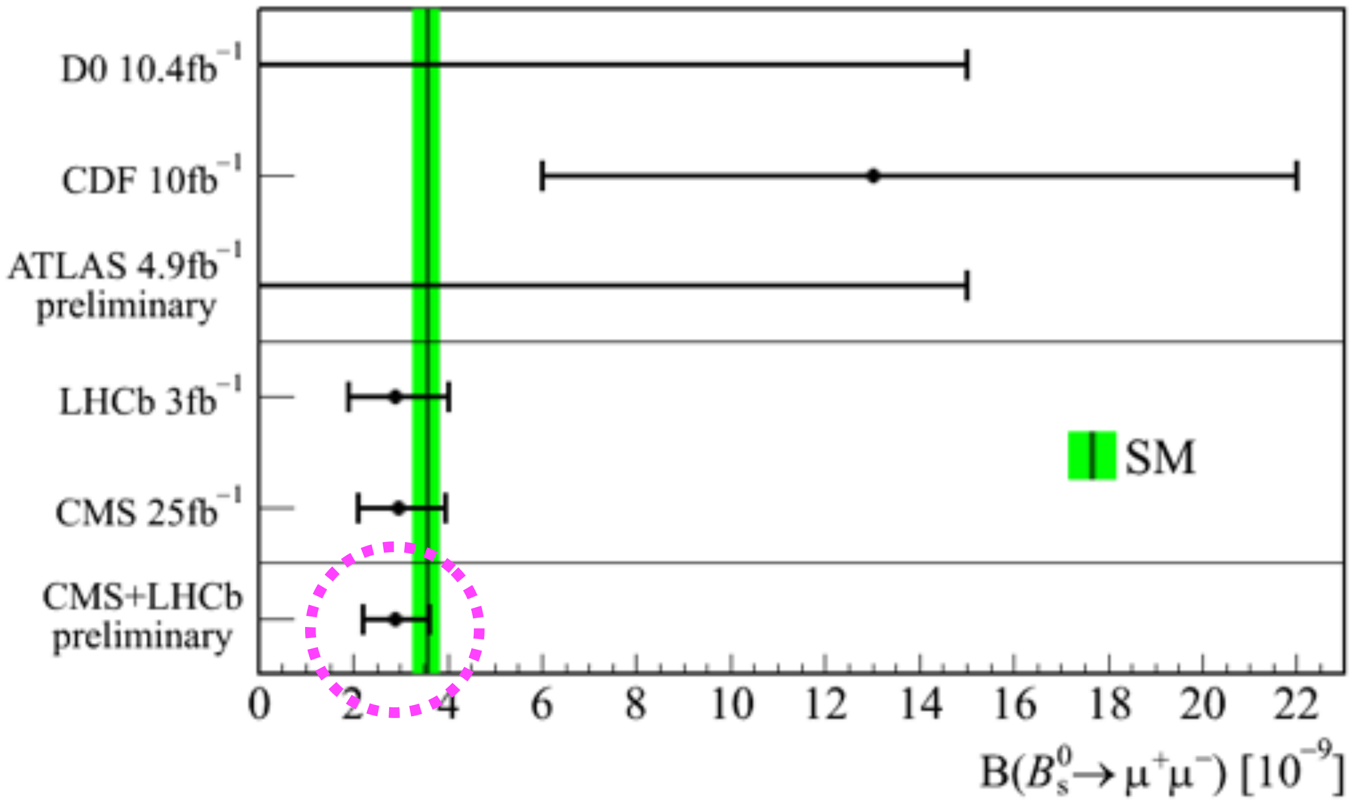


$$V_{tb}^* V_{ts}\, C_{\rm NP}\, \bar{s}_L \not{Z} b_L$$

- In MFV both flavour-diagonal & -changing Z vertices involving down-type quarks are governed by same Inami-Lim function

[see for example UH & Weiler, 0706.2054]

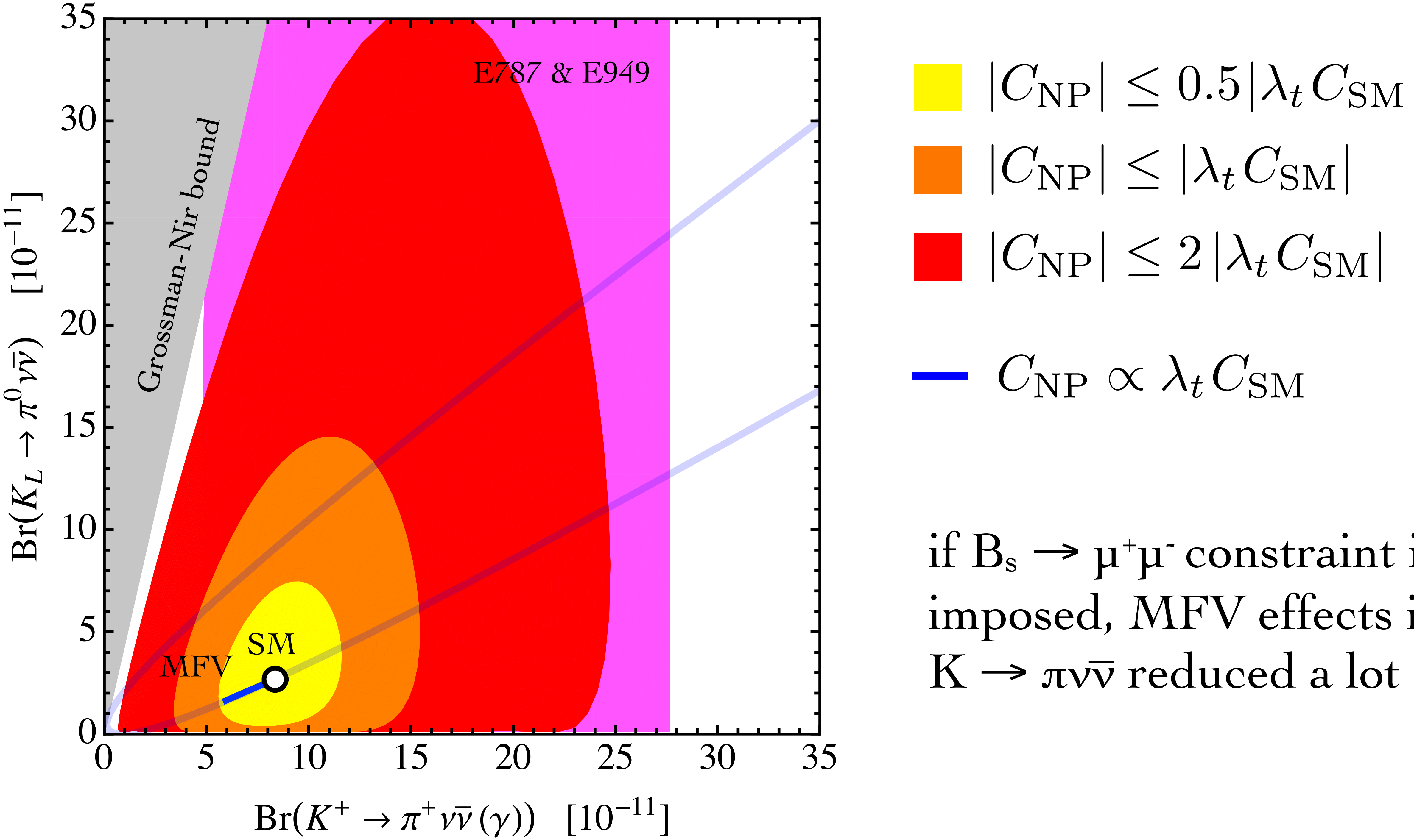
One to rule them all



$$\mu_{B_s \to \mu^+\mu^-} = 0.78 \pm 0.18$$

$$\mu_{B_s \to \mu^+\mu^-} = \frac{\mathrm{Br}(B_s \to \mu^+\mu^-)}{\mathrm{Br}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}} \simeq (1 + C_{\mathrm{NP}})^2$$

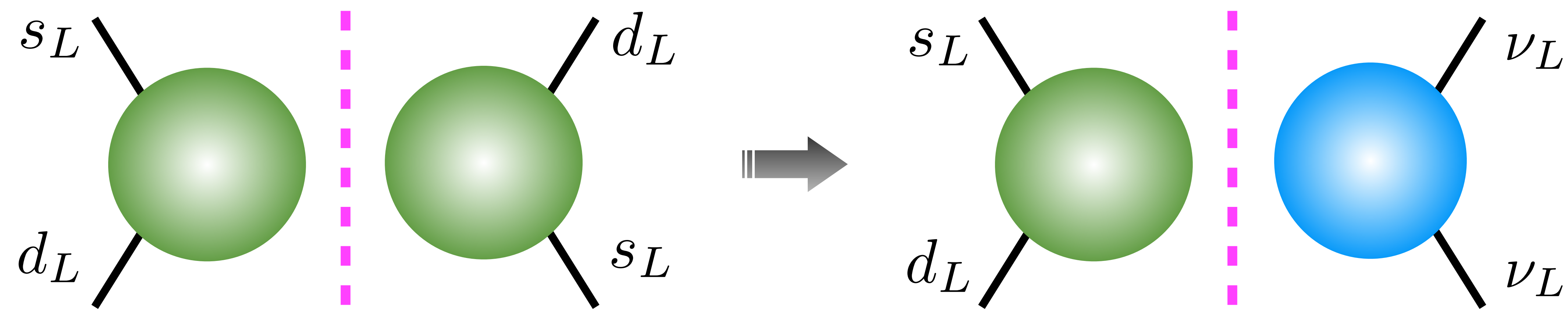
Z penguins in neutrino modes

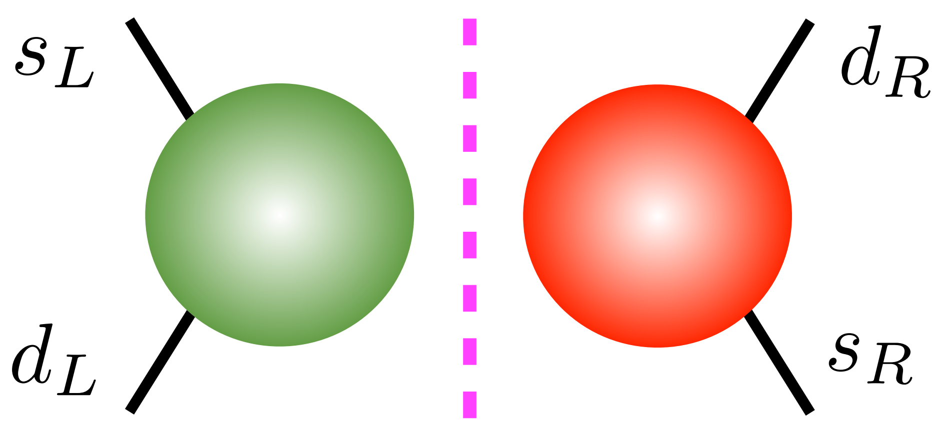


if $B_s \to \mu^+\mu^-$ constraint is imposed, MFV effects in $K \to \pi\nu\bar{\nu}$ reduced a lot

Link between ε_K & $K \to \pi\nu\bar{\nu}$

- SM extensions fall into two classes, those with pure LH structure & those with both LH & RH currents:

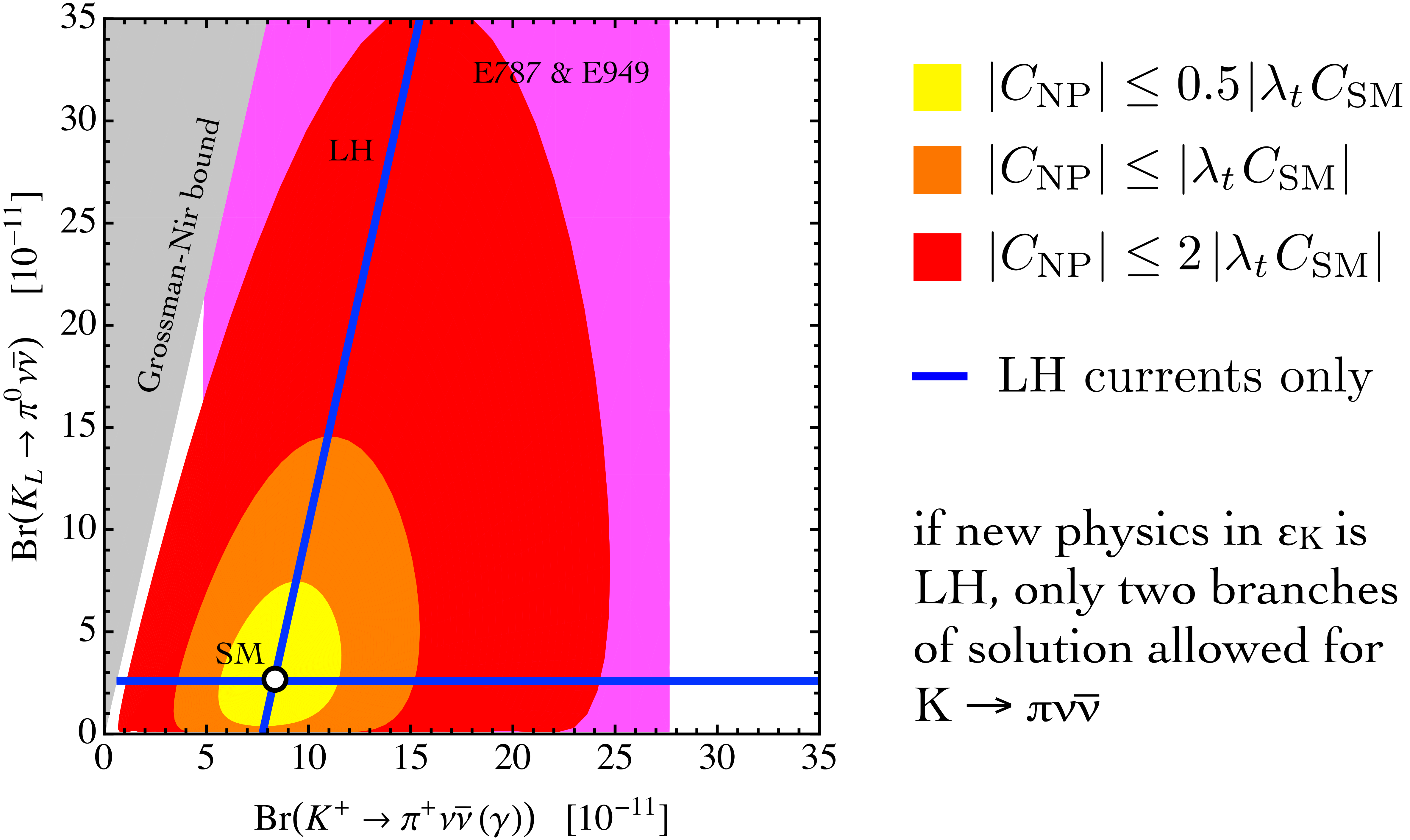




while in LH case, ε_K restricts phase in $s \to d$ transition, connection between $\Delta S = 2,1$ lost, if RH interactions present

[Blanke, 0904.2528]

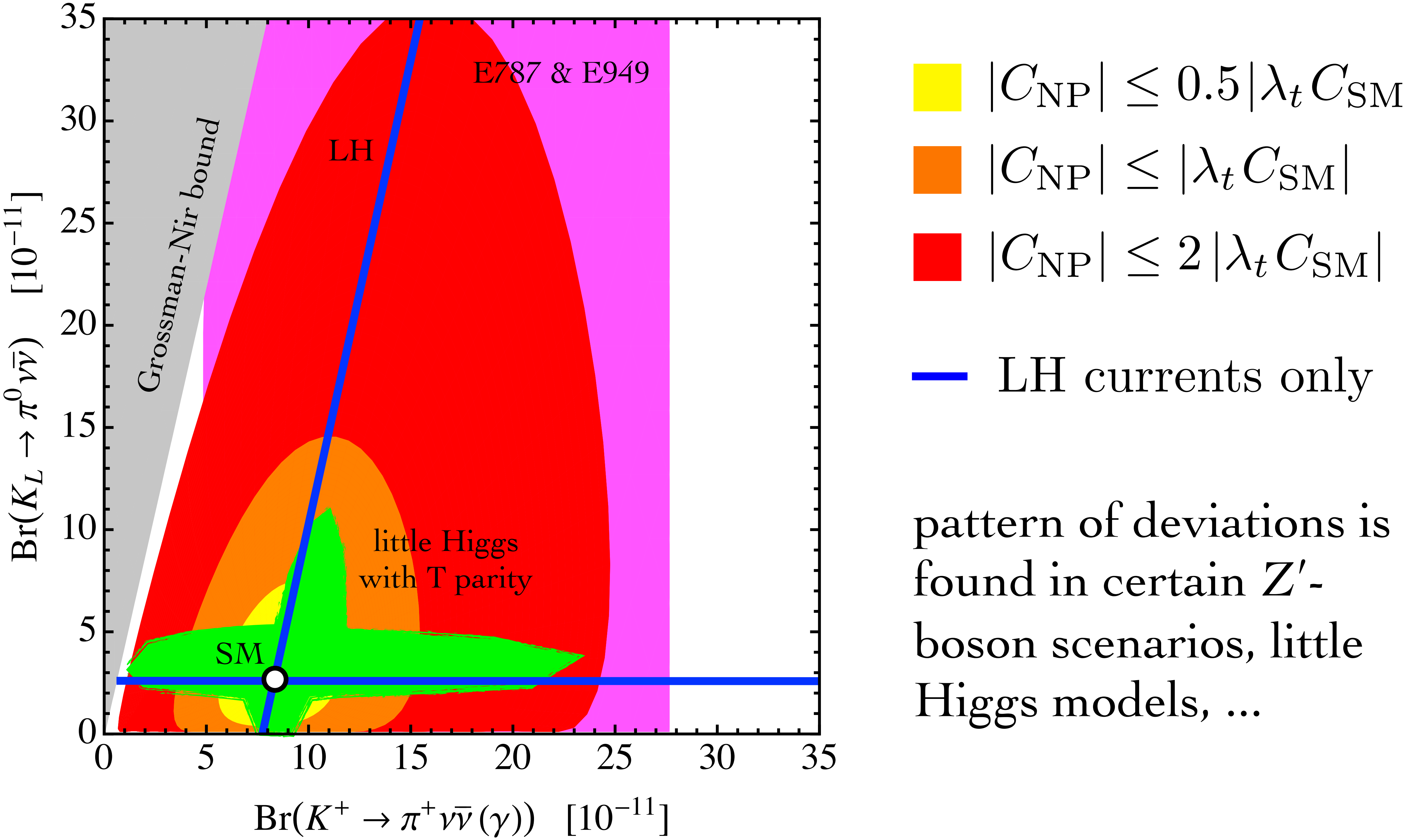
Link between ε_K & $K \to \pi\nu\bar{\nu}$



if new physics in ε_K is LH, only two branches of solution allowed for $K \to \pi\nu\bar{\nu}$

[Blanke, 0904.2528]

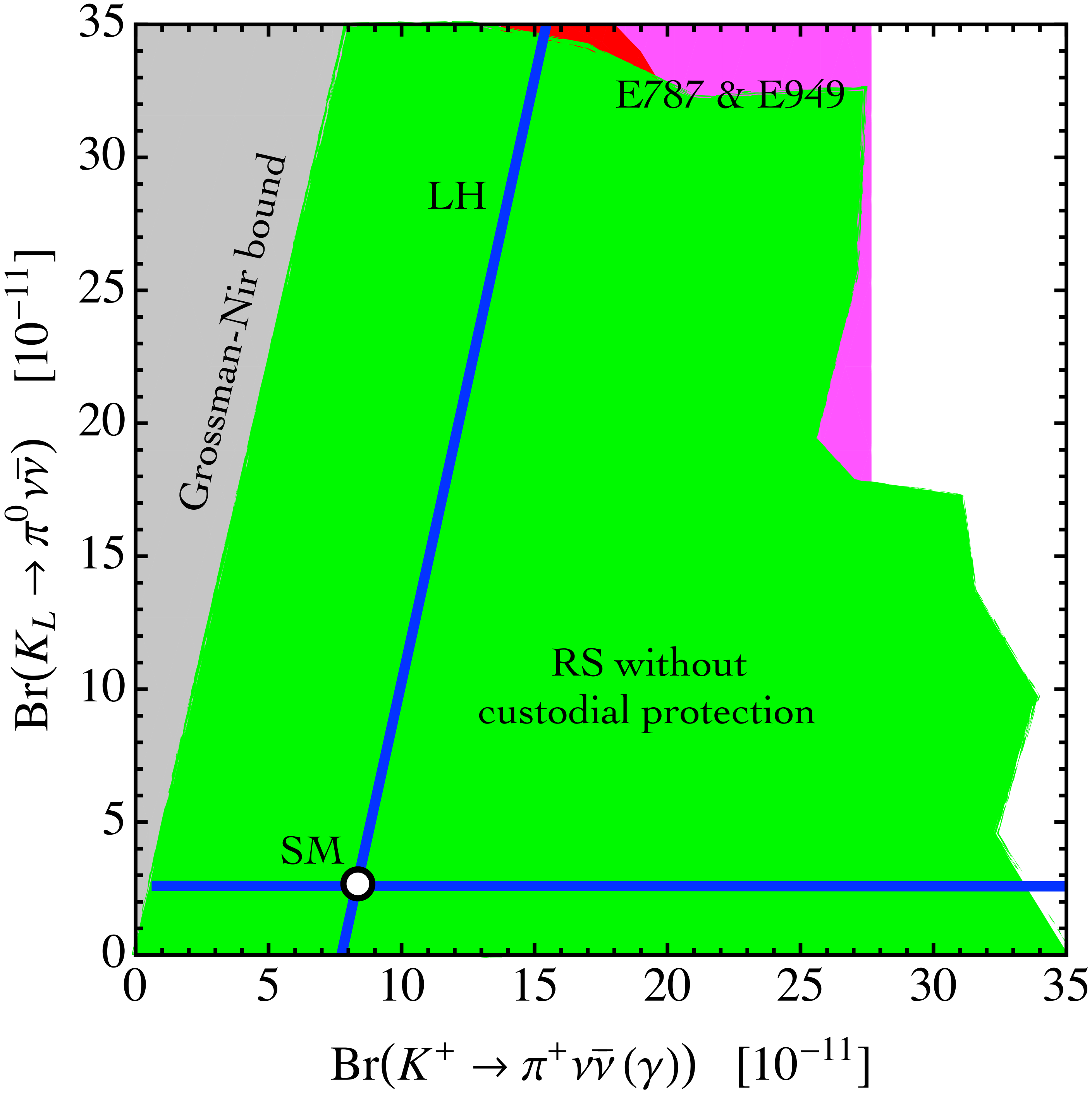
Link between ε_K & $K \to \pi\nu\bar{\nu}$



pattern of deviations is found in certain Z'-boson scenarios, little Higgs models, ...

[see for instance Promberger et al., 0702169; Blanke et al., 0605214; ...]

Link between ε_K & $K \to \pi\nu\bar{\nu}$



$|C_{\mathrm{NP}}| \leq 0.5\,|\lambda_t C_{\mathrm{SM}}|$

$|C_{\mathrm{NP}}| \leq |\lambda_t C_{\mathrm{SM}}|$

$|C_{\mathrm{NP}}| \leq 2\,|\lambda_t C_{\mathrm{SM}}|$

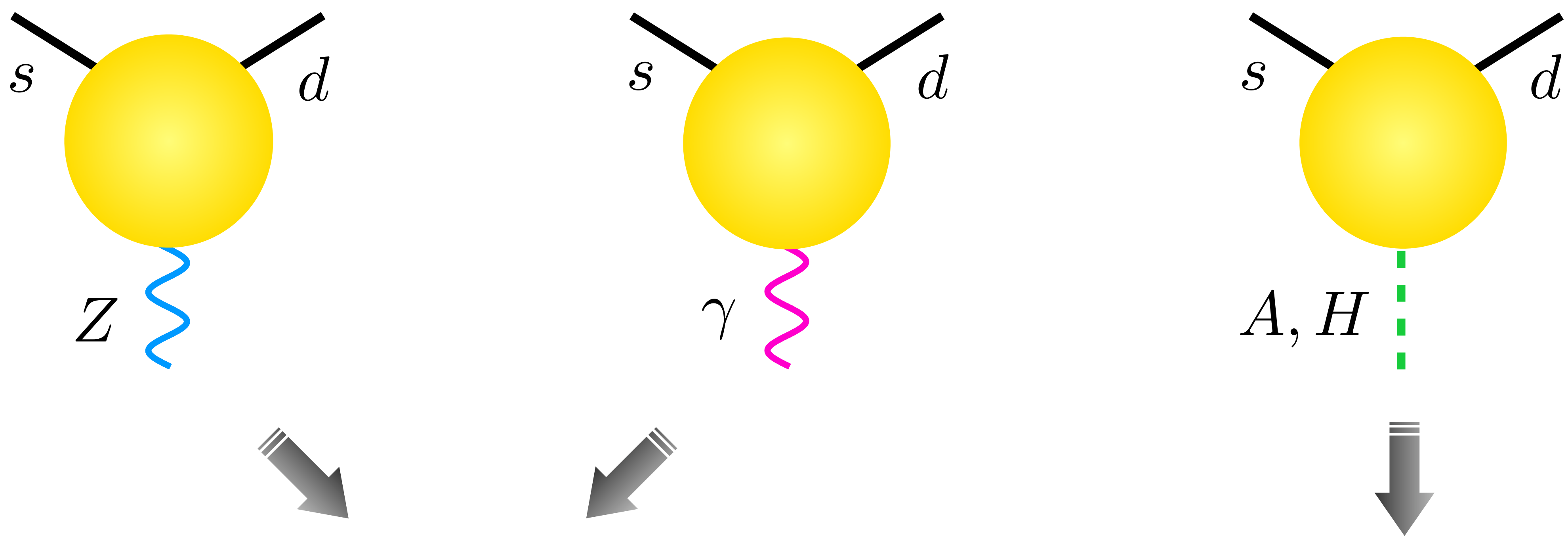
LH currents only

but pattern not generic & absent in MSSM, RS, ..., as $Q_{\mathrm{LR}}^{\mathrm{sd}}$ renders dominant contribution to ε_K

[see for example Buras et al., 0408142; Bauer et al., 0912.1625; ...]

Anatomy of semileptonic modes

- $K_L \to \pi^0 l^+ l^-$ modes receive contributions from (axial-)vector (A, V), (pseudo-)scalar (P, S), ... operators:



$$Q_V = (\bar{d}\gamma_\mu s)(\bar{l}\gamma^\mu l)$$

$$Q_A = (\bar{d}\gamma_\mu s)(\bar{l}\gamma^\mu \gamma_5 l)$$

$$Q_S = (\bar{d}s)(\bar{l}l)$$

$$Q_P = (\bar{d}s)(\bar{l}\gamma_5 l)$$

Anatomy of semileptonic modes

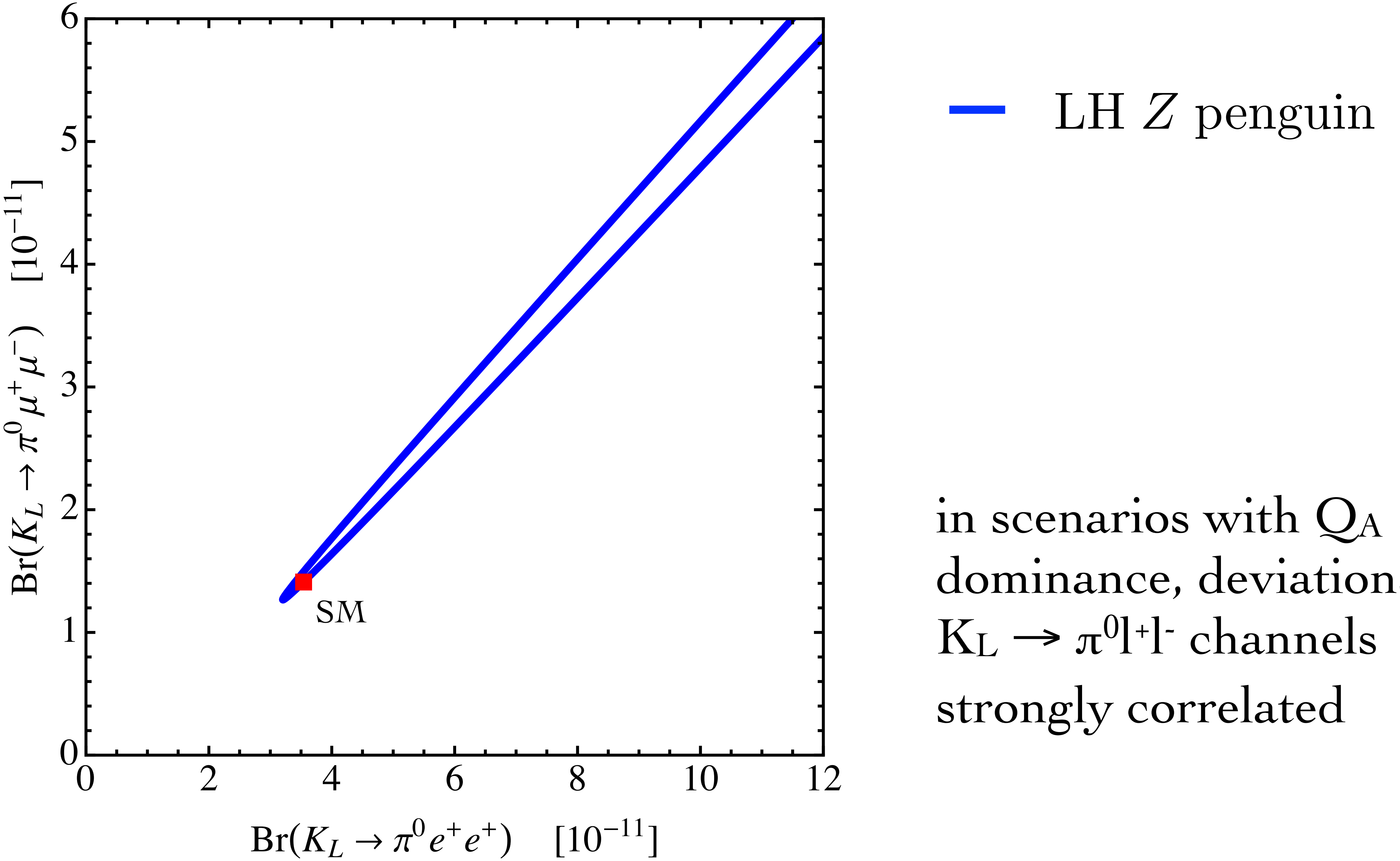
- In many explicit SM extensions such as RS scenarios, little Higgs models, scenarios with extra matter, ..., contribution from Q_A dominates over those of Q_V, Q_S & Q_P:

$$C_V \propto \left(\frac{1}{s_w^2} - 4\right)\left(C_{\rm NP} + \tilde{C}_{\rm NP}\right) \approx 0.4\left(C_{\rm NP} + \tilde{C}_{\rm NP}\right)$$

$$C_A \propto -\frac{1}{s_w^2}\left(C_{\rm NP} - \tilde{C}_{\rm NP}\right) \approx -4.4\left(C_{\rm NP} - \tilde{C}_{\rm NP}\right)$$

$$C_{S,P} \propto m_s m_l$$

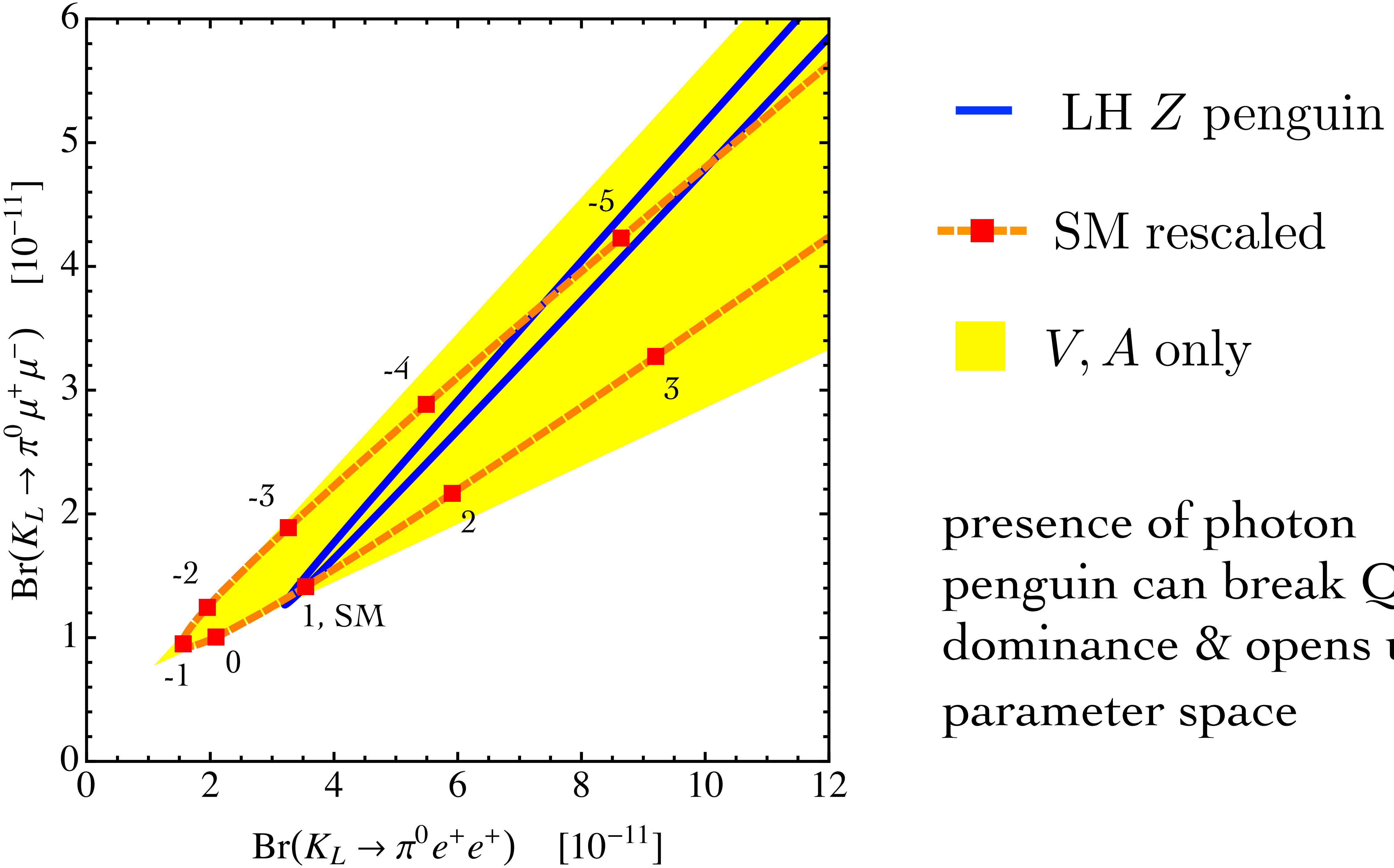
Correlations of semileptonic modes



in scenarios with Q_A dominance, deviations in $K_L \to \pi^0 l^+ l^-$ channels strongly correlated

[Mescia, Smith & Trine, 0606081]

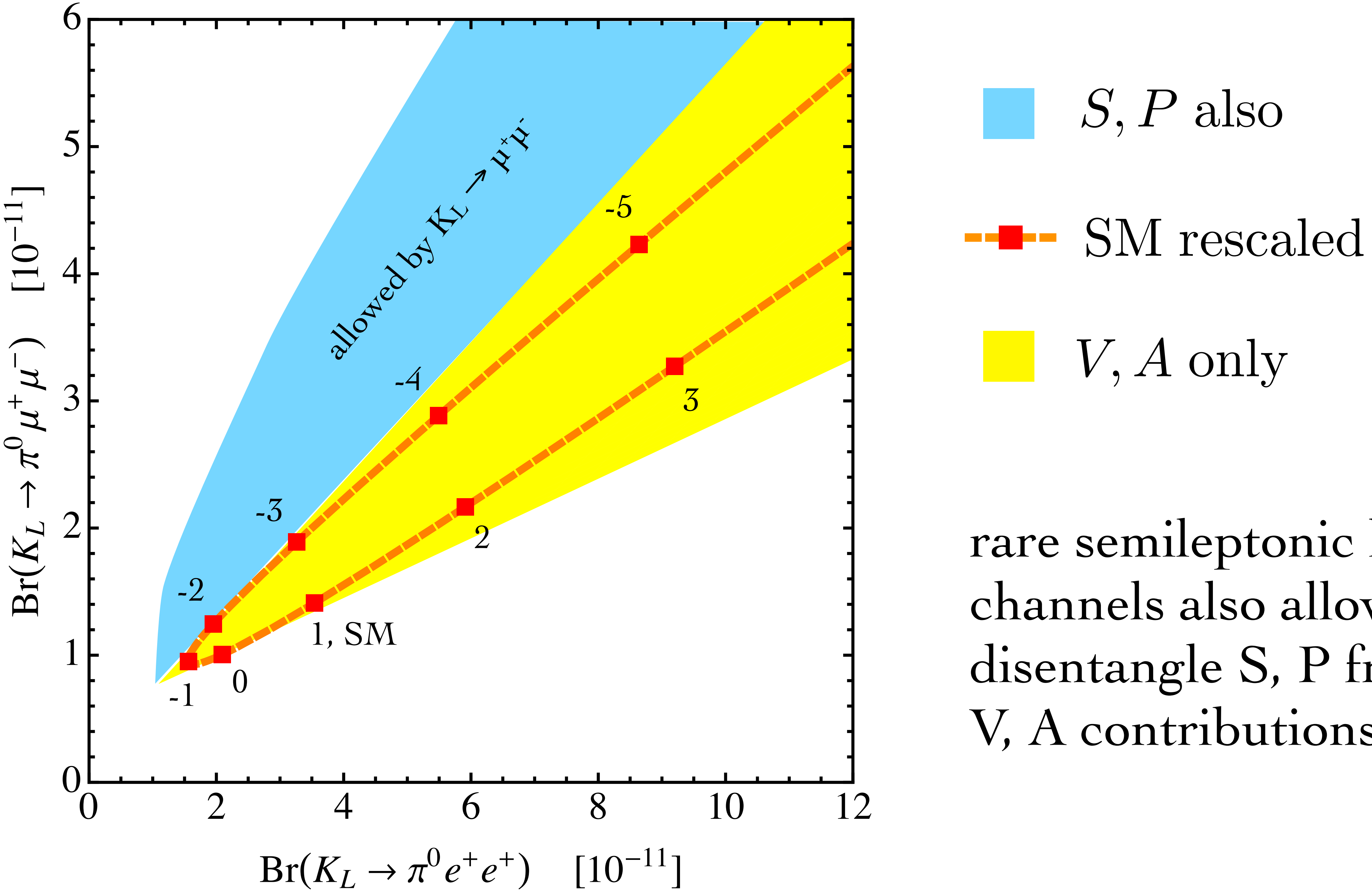
Correlations of semileptonic modes



presence of photon penguin can break Q_A dominance & opens up parameter space

[Mescia, Smith & Trine, 0606081]

Correlations of semileptonic modes



rare semileptonic kaon channels also allow to disentangle S, P from V, A contributions

[Mescia, Smith & Trine, 0606081]

Anatomy of $K_L \to \mu^+\mu^-$

- Short-distance (SD) part of purely leptonic decay takes form

$$\mathrm{Br}(K_L \to \mu^+\mu^-)_{\mathrm{SD}} \propto (\mathrm{Re}\, Y)^2$$

$$Y = \frac{\lambda_t}{\lambda^5}\, Y_t + \frac{\lambda_c}{\lambda}\, Y_c + \frac{1}{\lambda^5}\left(C_{\mathrm{NP}} - \widetilde{C}_{\mathrm{NP}}\right)$$

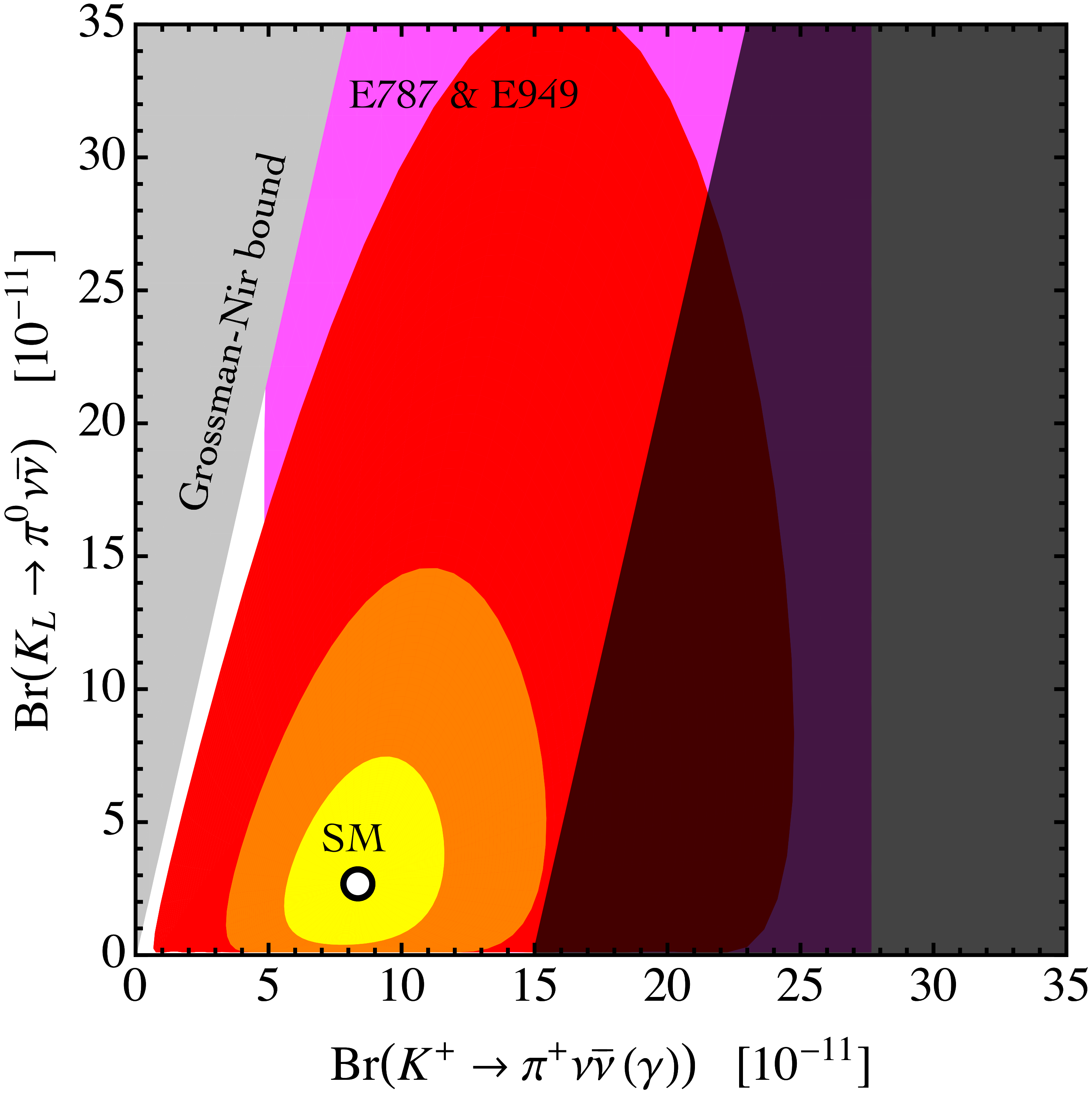
$$Y_t \approx 0.95\,, \quad Y_c \approx 0.12$$

& is bounded

$$\mathrm{Br}(K_L \to \mu^+\mu^-)_{\mathrm{SD}} < 2.5 \cdot 10^{-9} \approx 3\, \mathrm{Br}(K_L \to \mu^+\mu^-)^{\mathrm{SM}}_{\mathrm{SD}}$$

[Isidori & Unterdorfer, 0311084]

Z penguins in neutrino modes



$|C_{\rm NP}| \leq 0.5\,|\lambda_t C_{\rm SM}|$

$|C_{\rm NP}| \leq |\lambda_t C_{\rm SM}|$

$|C_{\rm NP}| \leq 2\,|\lambda_t C_{\rm SM}|$

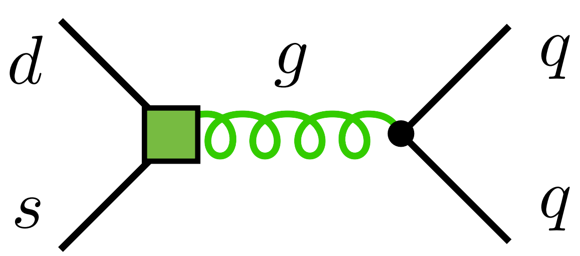
$$C_{\rm NP} = |C_{\rm NP}|\, e^{i\phi_C}$$

disfavoured by $K_L \to \mu^+\mu^-$

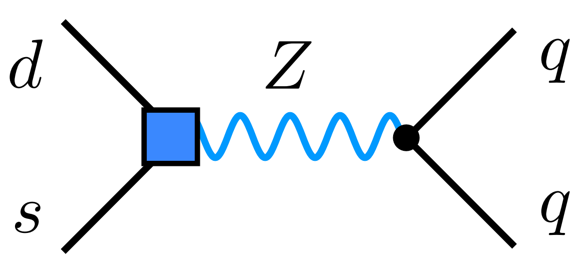
Anatomy of ε′/ε

- Prediction for ε′/ε very sensitive to interplay between QCD (Q_6) & electroweak (Q_8) penguin operators:

$$\frac{\epsilon'}{\epsilon} \propto -\mathrm{Im}\Big[\lambda_t\left(-1.7 + 15.3\,B_6 - 7.5\,B_8\right) + \left(1.5 + 0.1\,B_6 - 13.6\,B_8\right)\left(C_{\mathrm{NP}} - \widetilde{C}_{\mathrm{NP}}\right)\Big]$$



$$B_6 \propto \langle(\pi\pi)_{I=0}|Q_6|K\rangle \approx 0.6$$



$$B_8 \propto \langle(\pi\pi)_{I=2}|Q_8|K\rangle \approx 0.8$$

[Bai et al., 1505.07863; Buras et al., 1507.06345]

Anatomy of ε′/ε

- Let us now assume that $B_{6,(8)}$ parameters from lattice are correct. In such a case one finds, that SM value deviates by almost 3σ from experimental world average by NA48 & KTeV

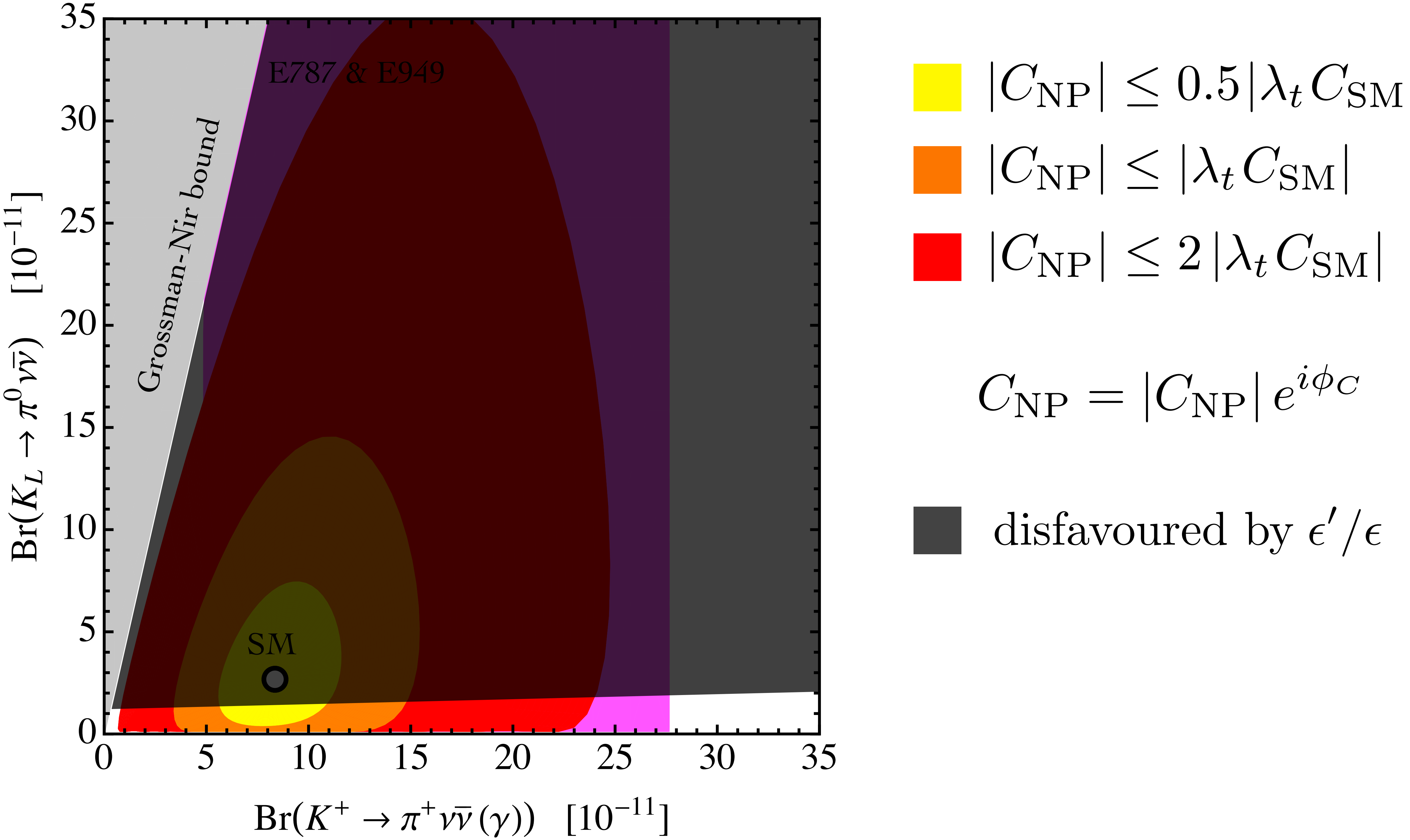
$$\left(\frac{\epsilon'}{\epsilon}\right)_{\rm SM} = (1.9 \pm 5.4) \cdot 10^{-4}$$

$$\left(\frac{\epsilon'}{\epsilon}\right)_{\rm exp} = (16.6 \pm 2.3) \cdot 10^{-4}$$

This disfavours destructive new-physics effects in ε′/ε

[Buras et al., 1507.06345]

Z penguins in neutrino modes



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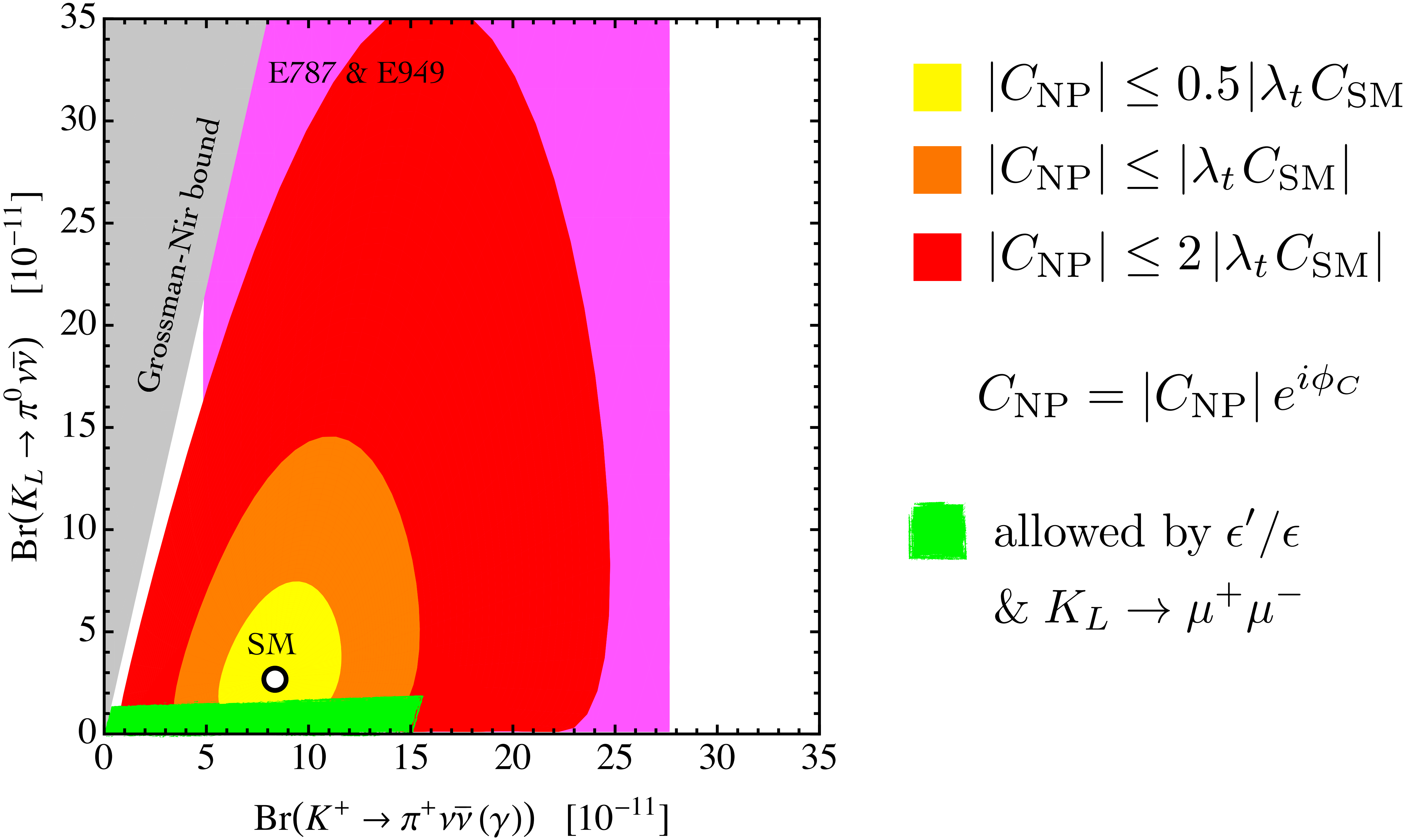
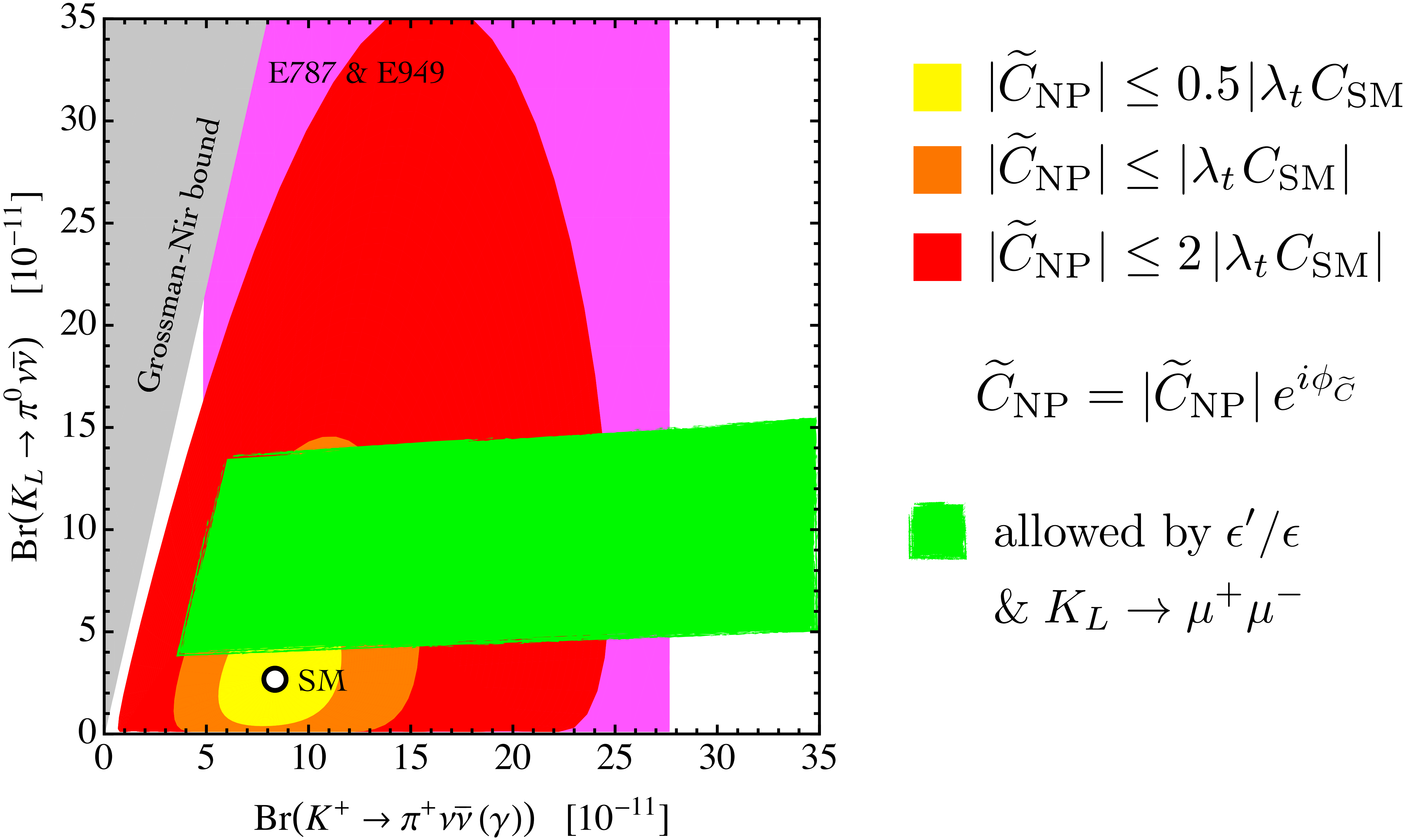
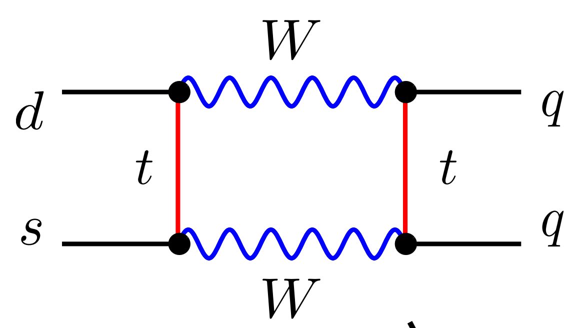
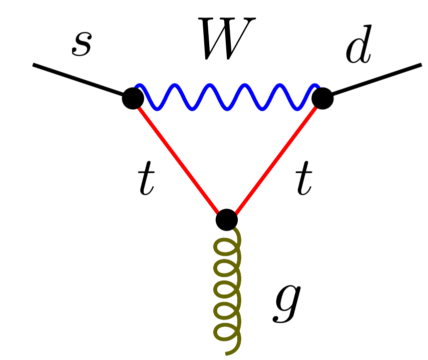


Z penguins in neutrino modes

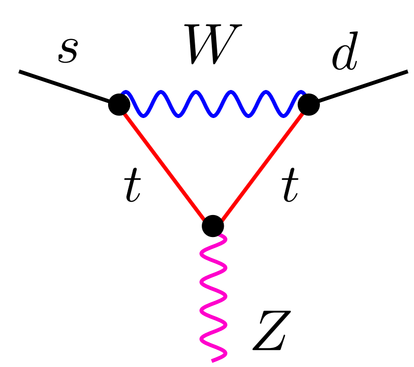


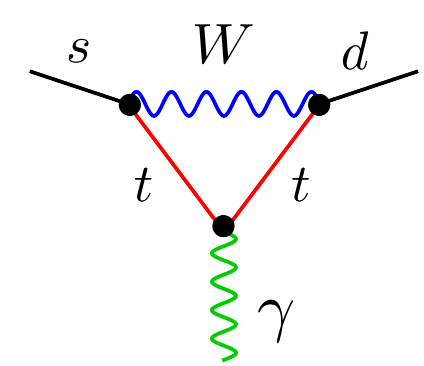
Decoupling $K_L \to \pi^0 \nu\bar{\nu}$ & ε'/ε





$$\left(\frac{\epsilon'}{\epsilon}\right)_{\rm SM} \propto {\rm Im}\Big[\lambda_t\left(0.4\,B_{\rm SM} + C_{\rm SM} + 0.3\,D_{\rm SM} + 0.03\,E_{\rm SM}\right)\Big]$$





- In order to have huge effects in $K_L \to \pi^0 \nu\nu$, one needs to have strong cancellations in ε'/ε, e.g. between Z & gluon penguin. Don't know of a ultraviolet complete model where this happens

Chromomagnetic penguins in ε′/ε

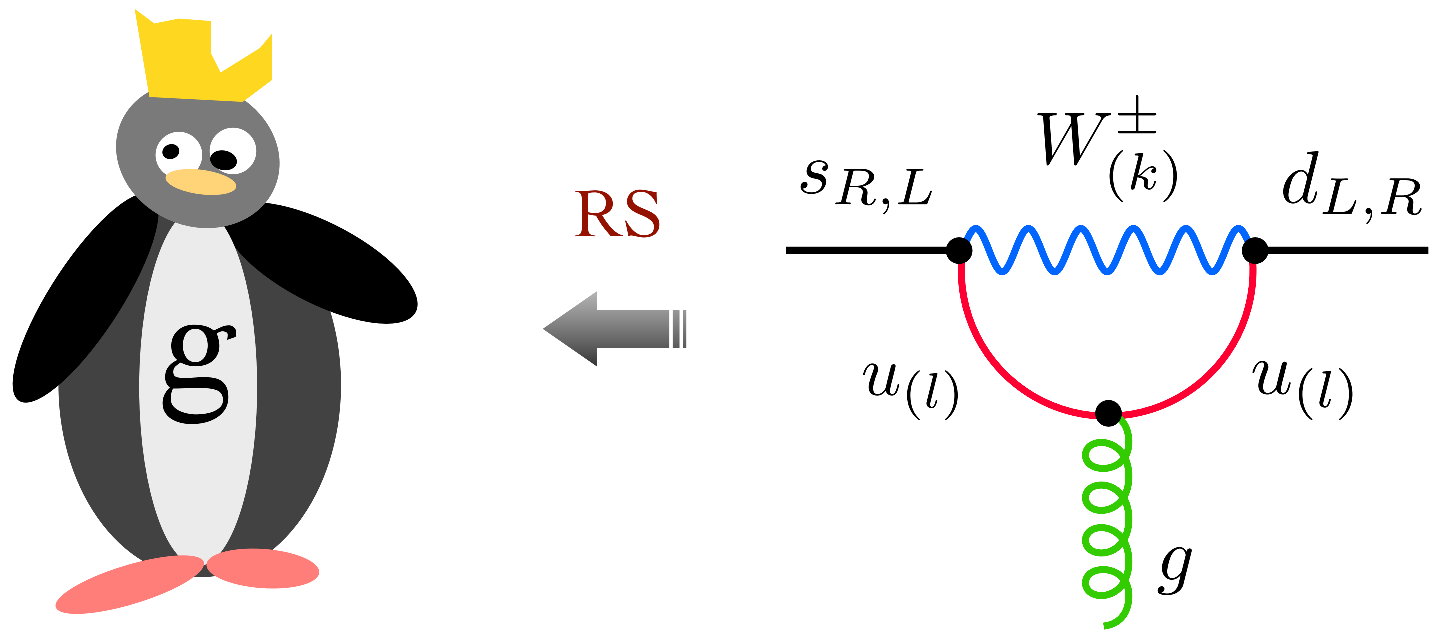
- Chromomagnetic penguins ($Q_{8g}^{(\prime)}$) can also give large correction to ε′/ε of form:

$$\left(\frac{\epsilon'}{\epsilon}\right)_{8g^-} \simeq 3B_{8g^-}\frac{\mathrm{Im}(C_{8g}-C'_{8g})}{G_F m_K} \simeq 520\,B_{8g^-}\ \mathrm{Im}(C_{8g}-C'_{8g})\ \mathrm{TeV}$$

$B_{8g^-} \in [1,4]$ ➡ $B_{8g^-} = 0.29 \pm 0.11$

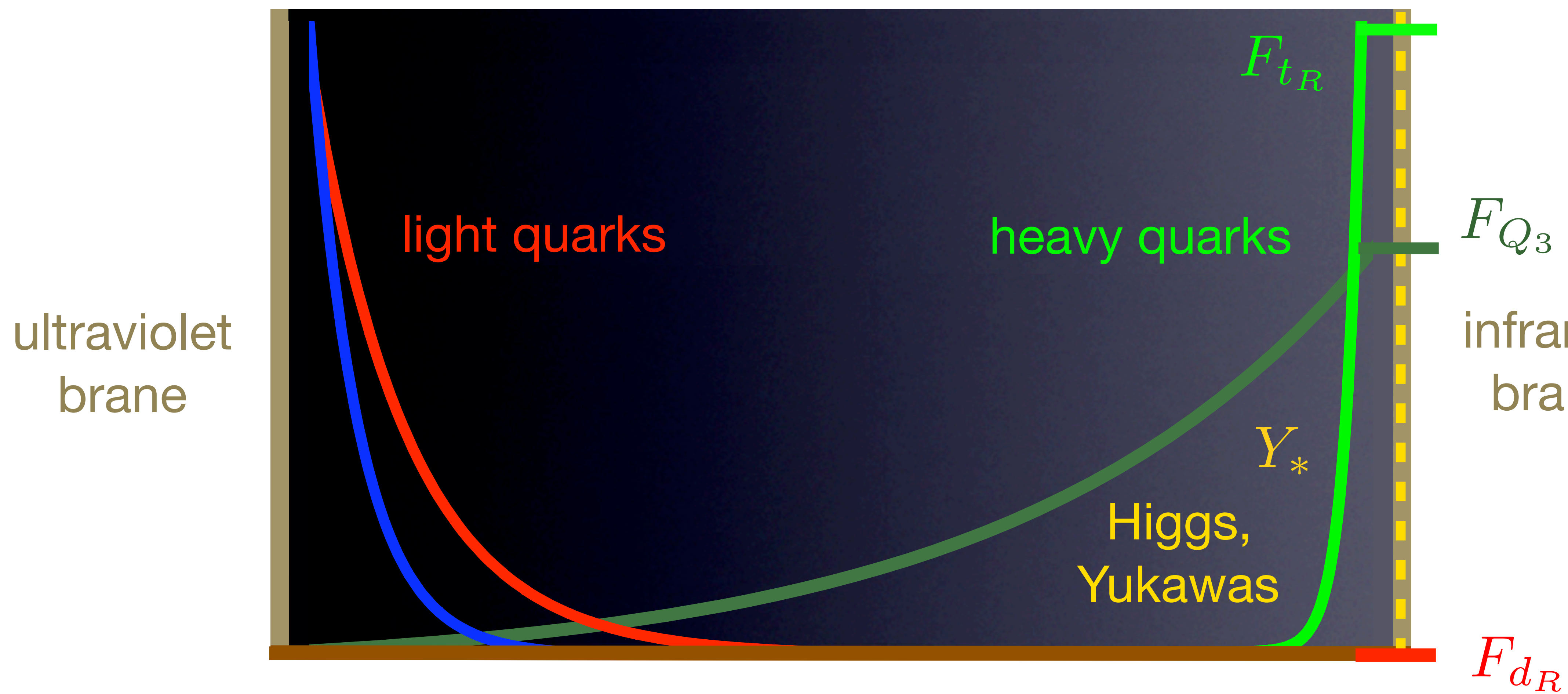
[Buras et al., 9908371] [Constantinou et al., 1412.1351]

Chromomagnetic penguins in ε′/ε



- In explicit models such as MSSM, RS, … there is no strict correlation with Z penguin. Often possible to decouple effects

Chromomagnetic penguins in ε′/ε

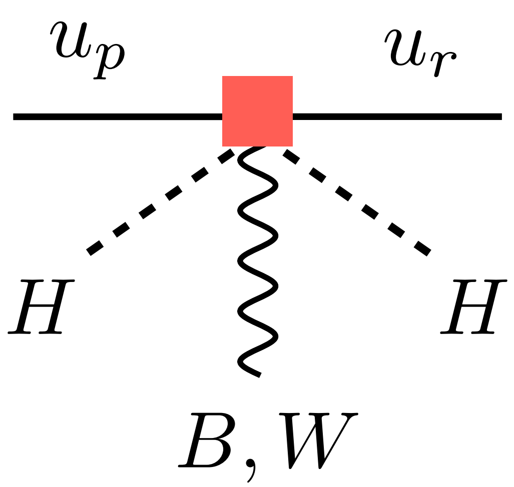


$$C_{\rm NP} \propto \frac{A^2\lambda^5}{Y_*^2 F_{t_R}^2}\,, \quad \widetilde{C}_{\rm NP} \propto \frac{m_d m_s F_{t_R}^2}{A^2\lambda^5 m_t^2}\,, \quad C^{(\prime)}_{8g,\rm NP} \propto \left\{\lambda m_s, \frac{m_s}{\lambda}\right\}\frac{Y_*^2}{m_t}$$

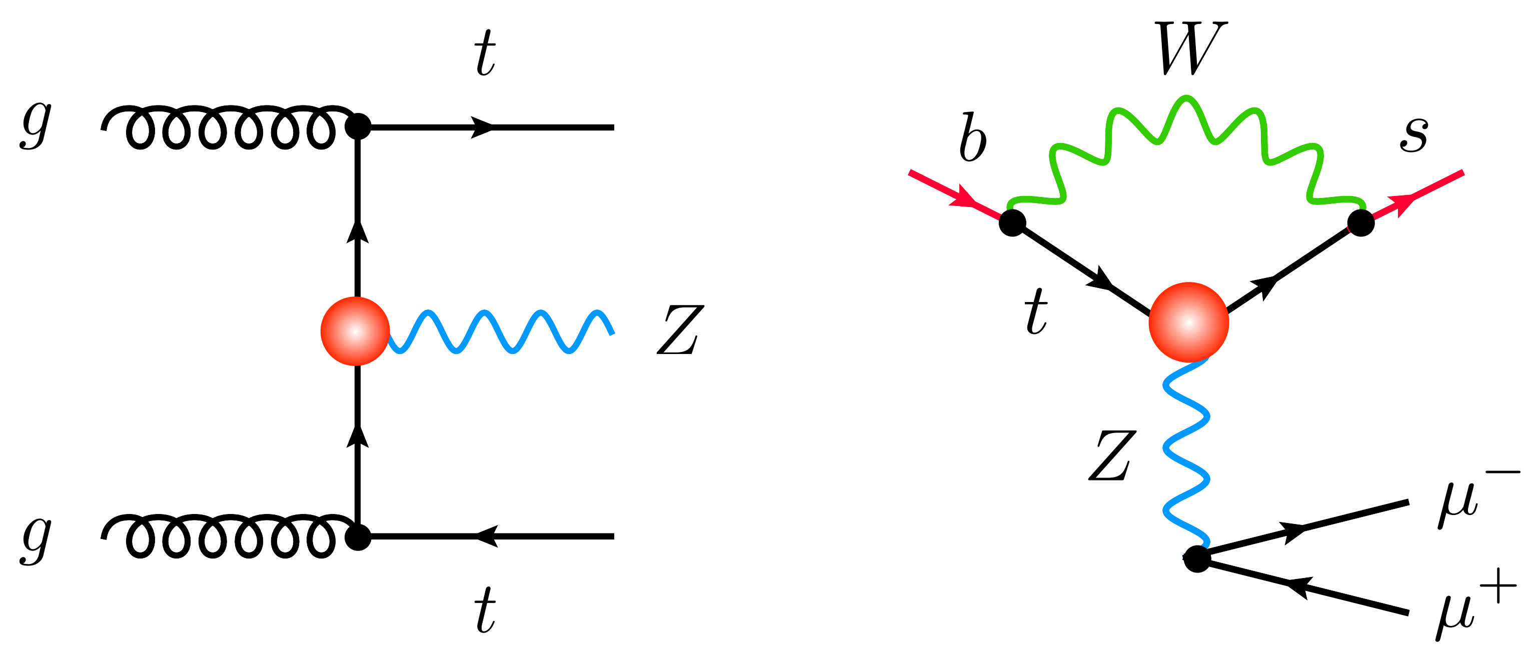
[see for example Bauer et al., 0912.1625]

Up-quark Z-penguin operators

$\psi^2 H^2 D$: $\quad Q_{Hu} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)\,, \;\ldots$

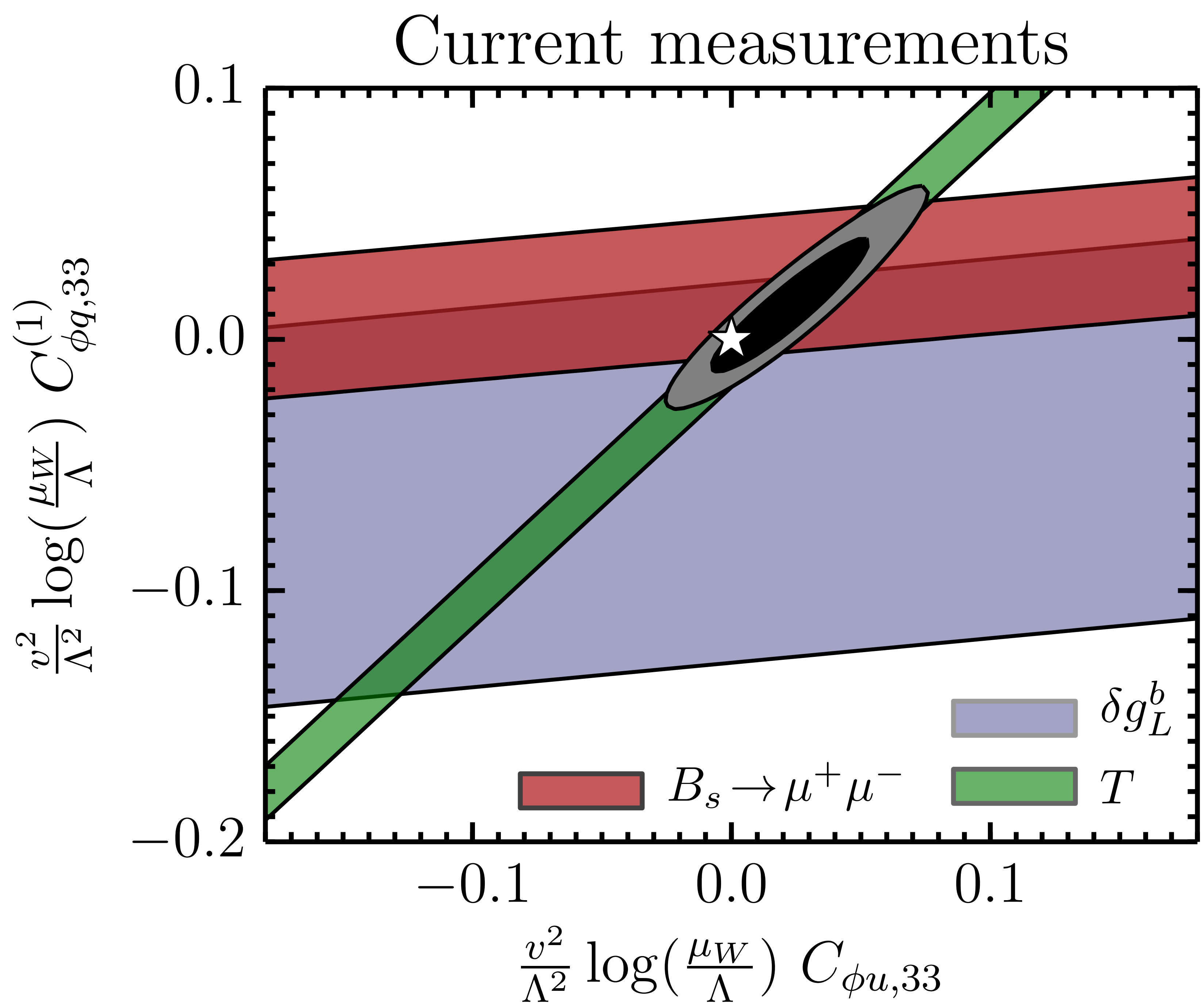


Anomalous $Zt\bar{t}$ couplings



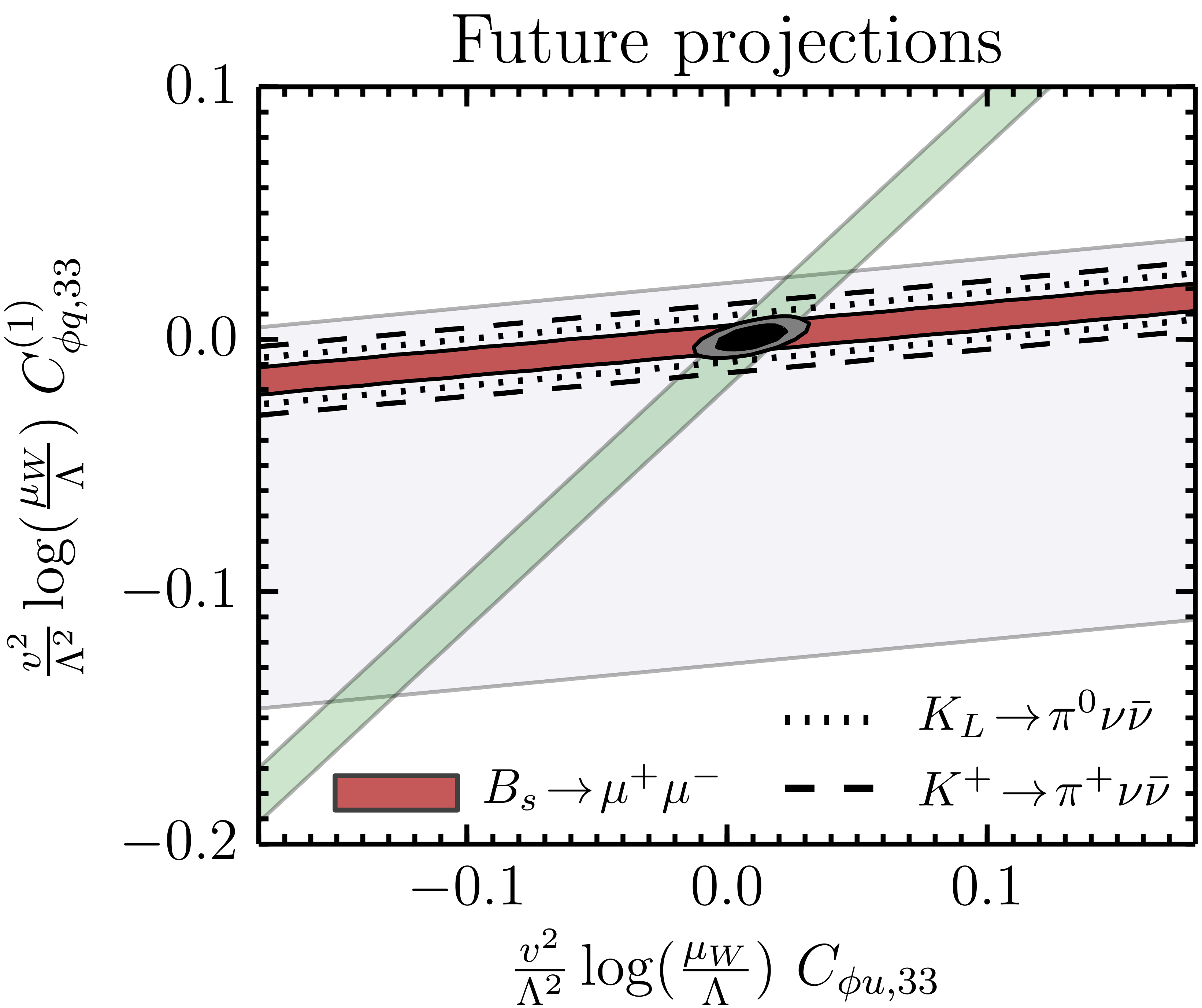
- $\psi^2 H^2 D$ composites with third generation quarks can be constrained directly (single-top production, pp → $Zt\bar{t}$, …), but also contribute to B & K decays, Z → $b\bar{b}$ & T via loops

$Zt\bar{t}$ couplings: indirect tests



[Brod et al., 1408.0792]

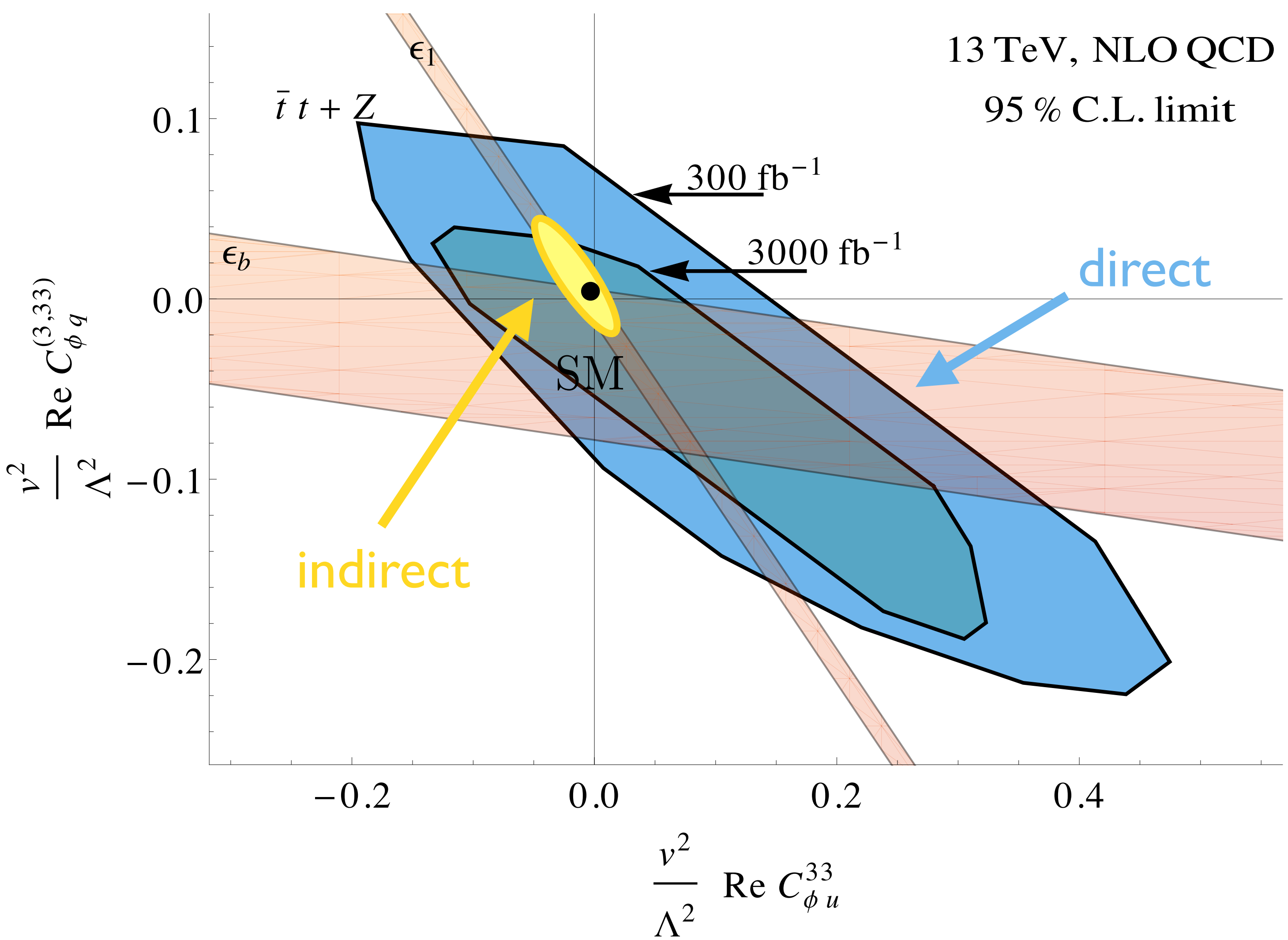
$Zt\bar{t}$ couplings: indirect tests



[Brod et al., 1408.0792]

$Zt\bar{t}$ couplings: comparison

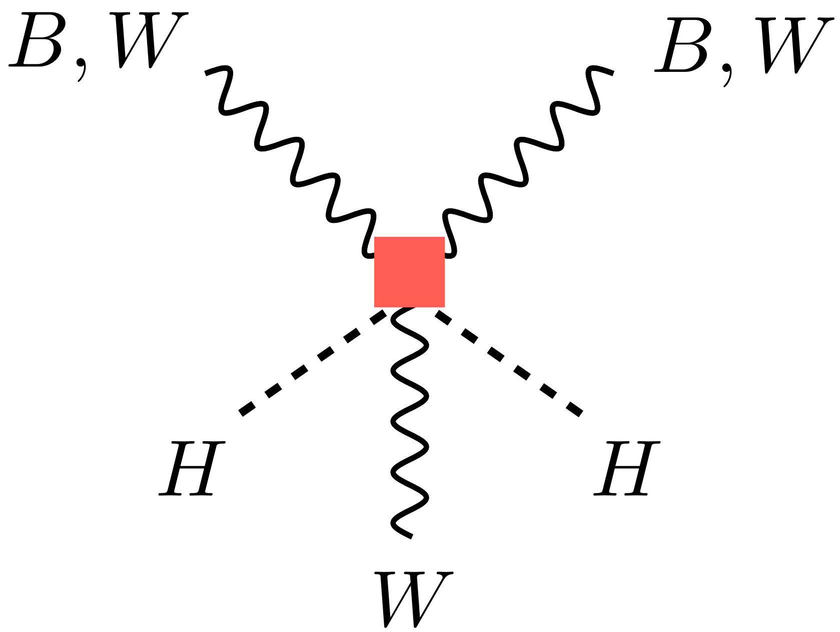
[Röntsch & Schulze, 1404.1005; Brod et al., 1408.0792]



- Indirect bounds stronger than direct limits for $Zt\bar{t}$ couplings. Still worth looking at pp $\rightarrow Zt\bar{t}$, as cancellation in former case possible

Non-fermion operators

$H^2 D^2 X$: $\quad Q_{HW} = (D_\mu H)^\dagger \tau^i (D_\nu H) W^{i,\mu\nu}\,, \ \ldots$

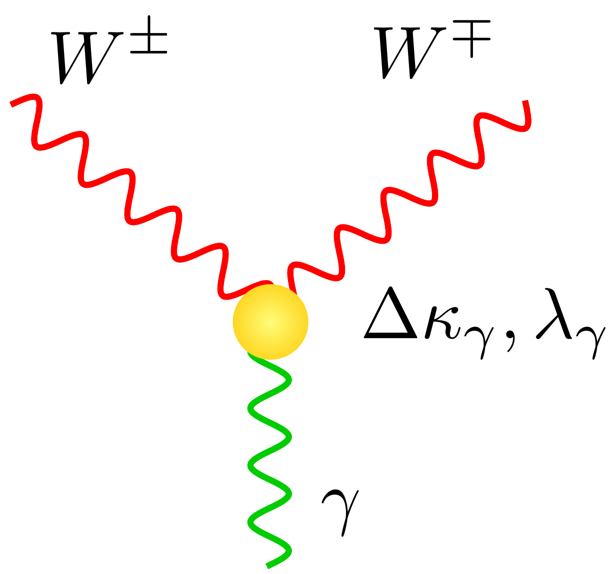


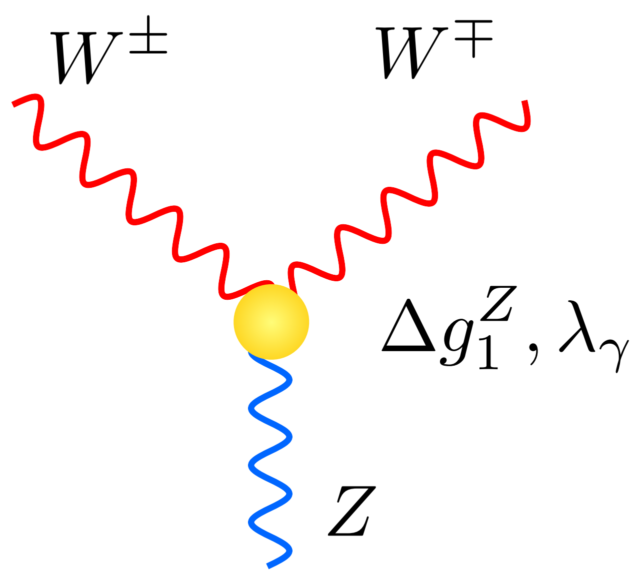
Triple gauge couplings

- $\mathrm{H^2D^2X}$ operators contribute to triple gauge couplings (TGCs):

$$\mathcal{L}_{WWV} = -ig_{WWV}\left[g_1^V\left(W^+_{\mu\nu}W^{-\mu}V^\nu - W^+_\mu V_\nu W^{-\mu\nu}\right)\right.$$

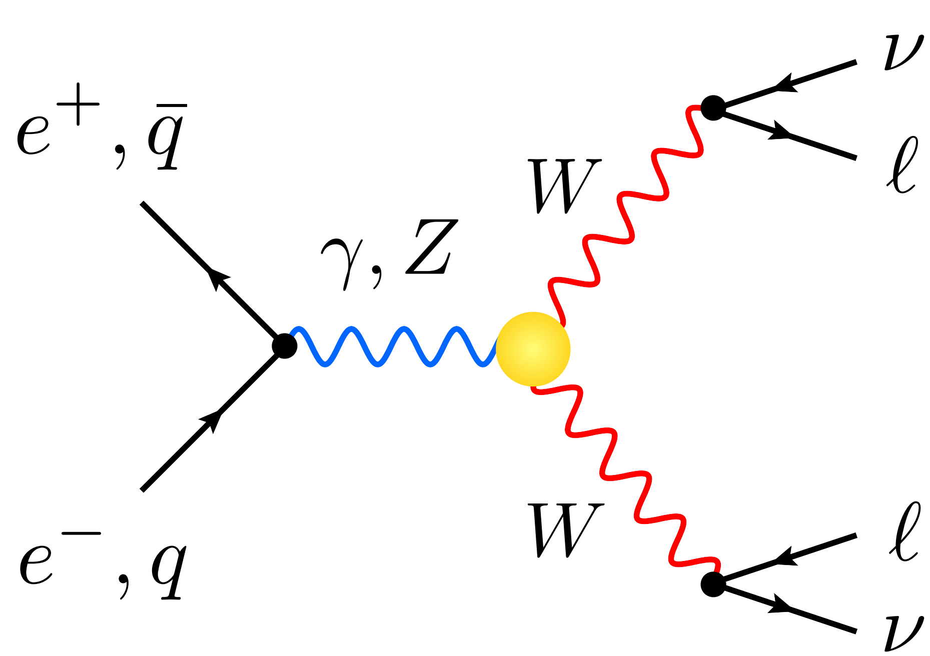
$$\left. + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2} W^+_{\mu\nu} W^{-\nu\rho} V_\rho{}^\mu\right]$$

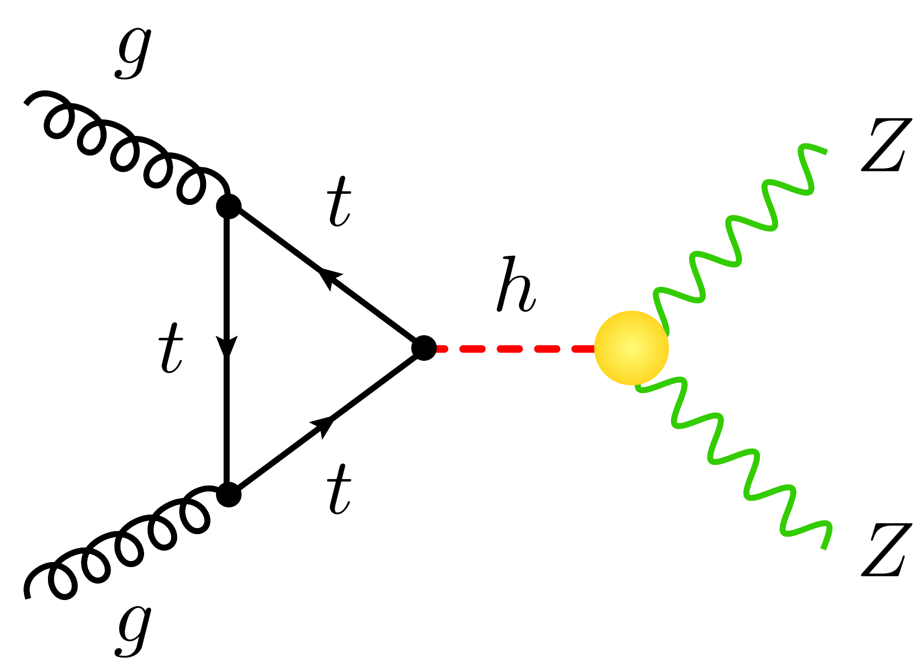




[Hagiwara et al., NPB (1987) 282; PRD (1993) 48]

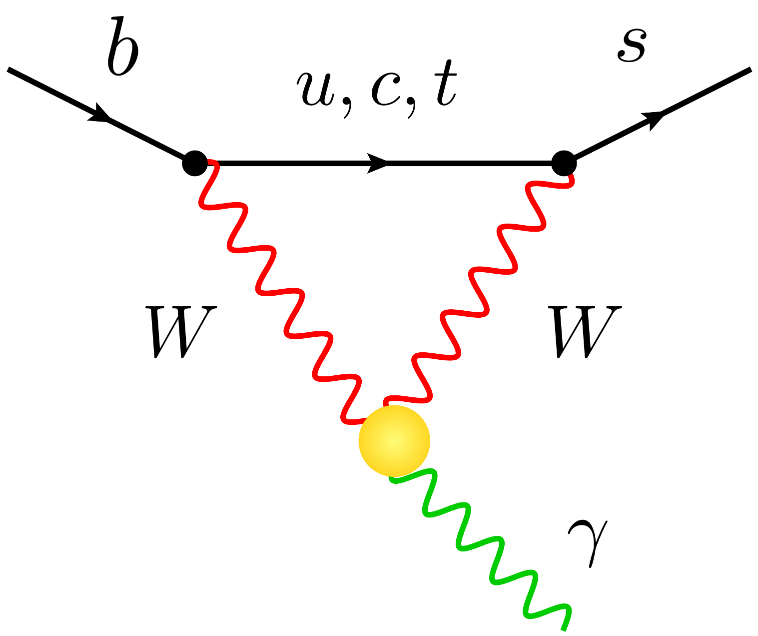
Direct probes of anomalous TGCs

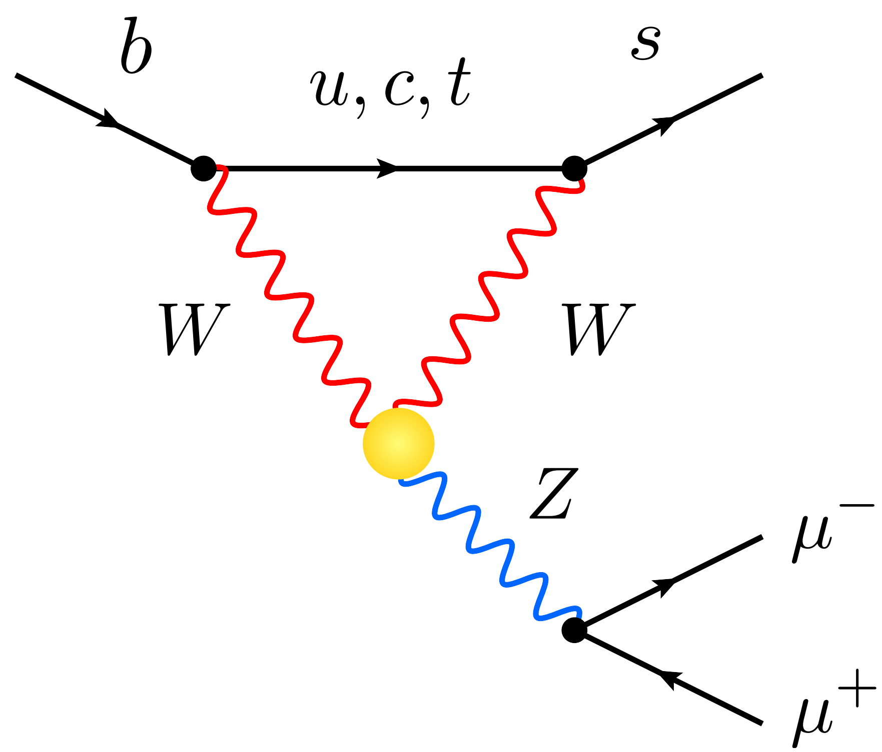




- Searches for anomalous TGCs have been performed at LEP, Tevatron & LHC (WW, WZ, Wγ, Zγ, … production). They can also be probed in Higgs physics (pp → h → ZZ, …)

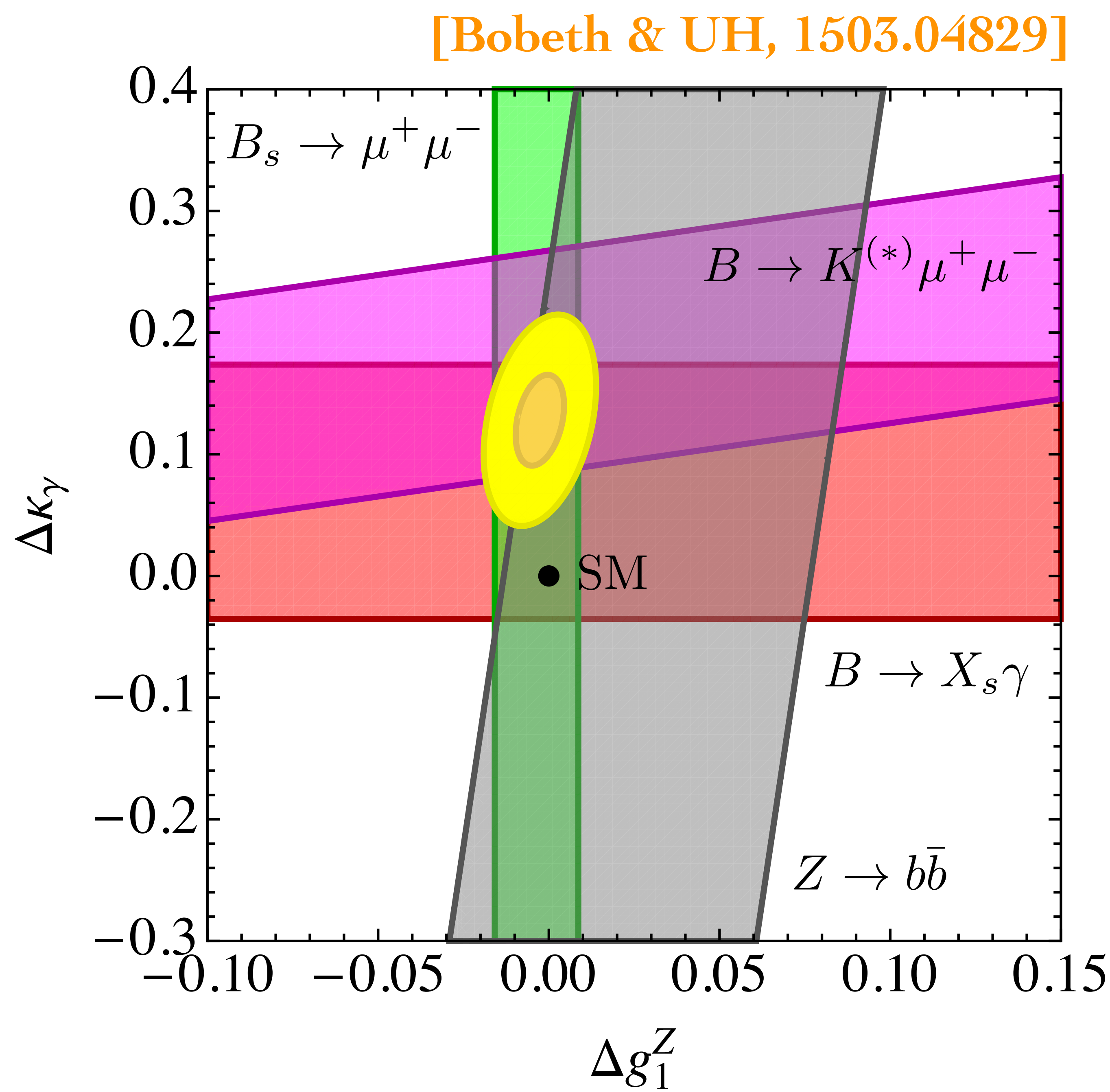
Indirect tests of anomalous TGCs





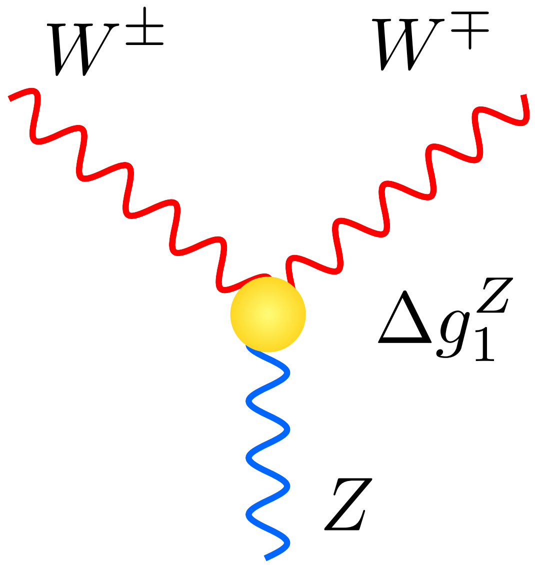
- Anomalous TGCs contribute to observables such as $B \to X_s\gamma$, $B \to K^*\mu^+\mu^-$, $B_s \to \mu^+\mu^-$, $K \to \pi\nu\bar{\nu}$ & ε'/ε as well as $Z \to b\bar{b}$ from one-loop level & beyond

Anomalous TGCs from flavour



- b → sμ⁺μ⁻ anomalies lead to 3σ deviation of best fit from SM

Bounds on H^{2}D^{2}X operators



- Indirect bound on Δg_1^Z from $B_s \to \mu^+\mu^-$ alone slightly better than direct LEP II constraint

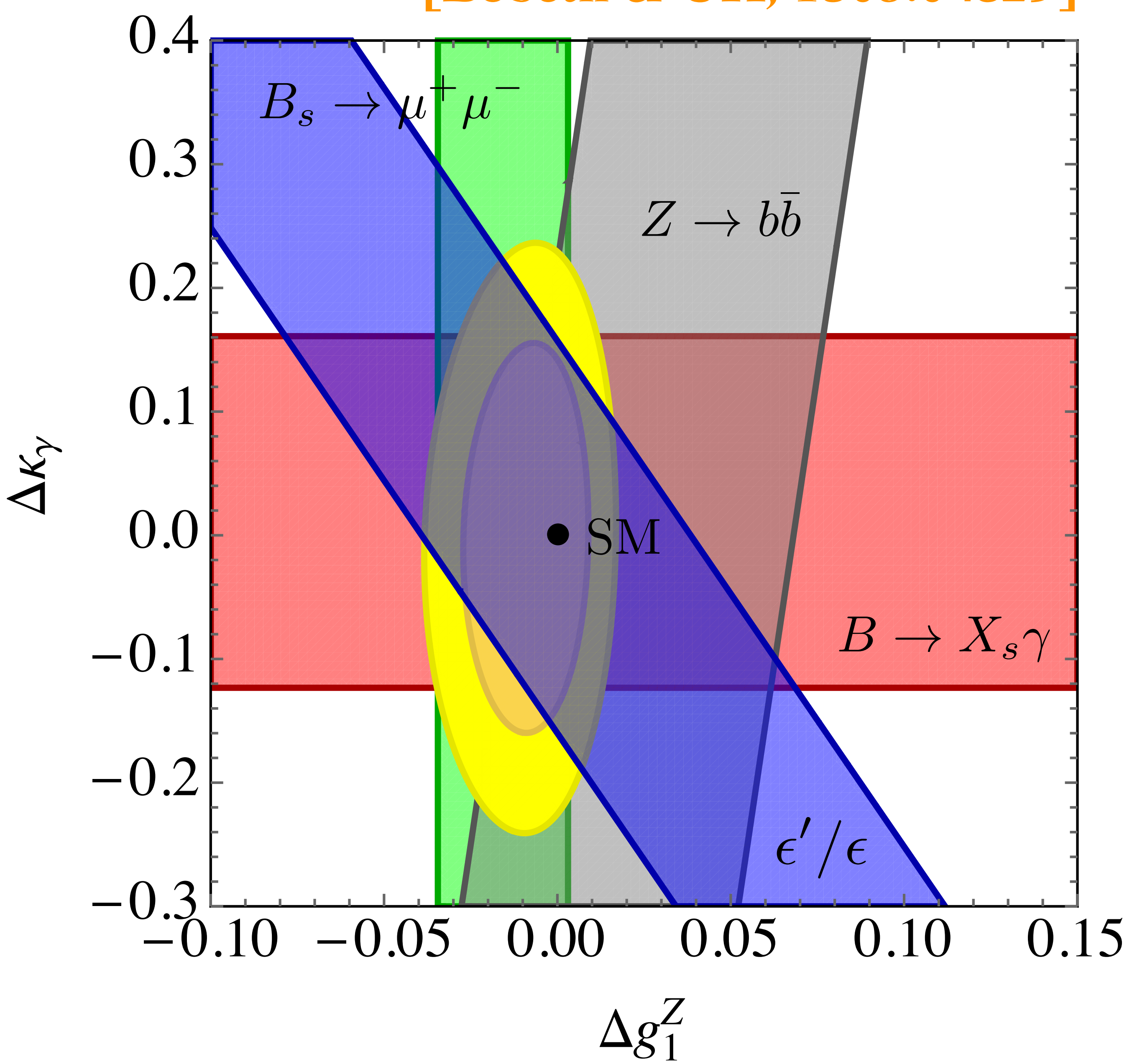
[Falkowski et al., 1508.00581]

$$\Delta g_1^Z = \frac{M_Z^2}{2\Lambda^2}\, c_{HW} = \begin{cases} 0.017 \pm 0.023 & \text{(direct)} \\ -0.009 \pm 0.019 & \text{(indirect)} \end{cases}$$

[Bobeth & UH, 1503.04829]

Anomalous TGCs from ε′/ε

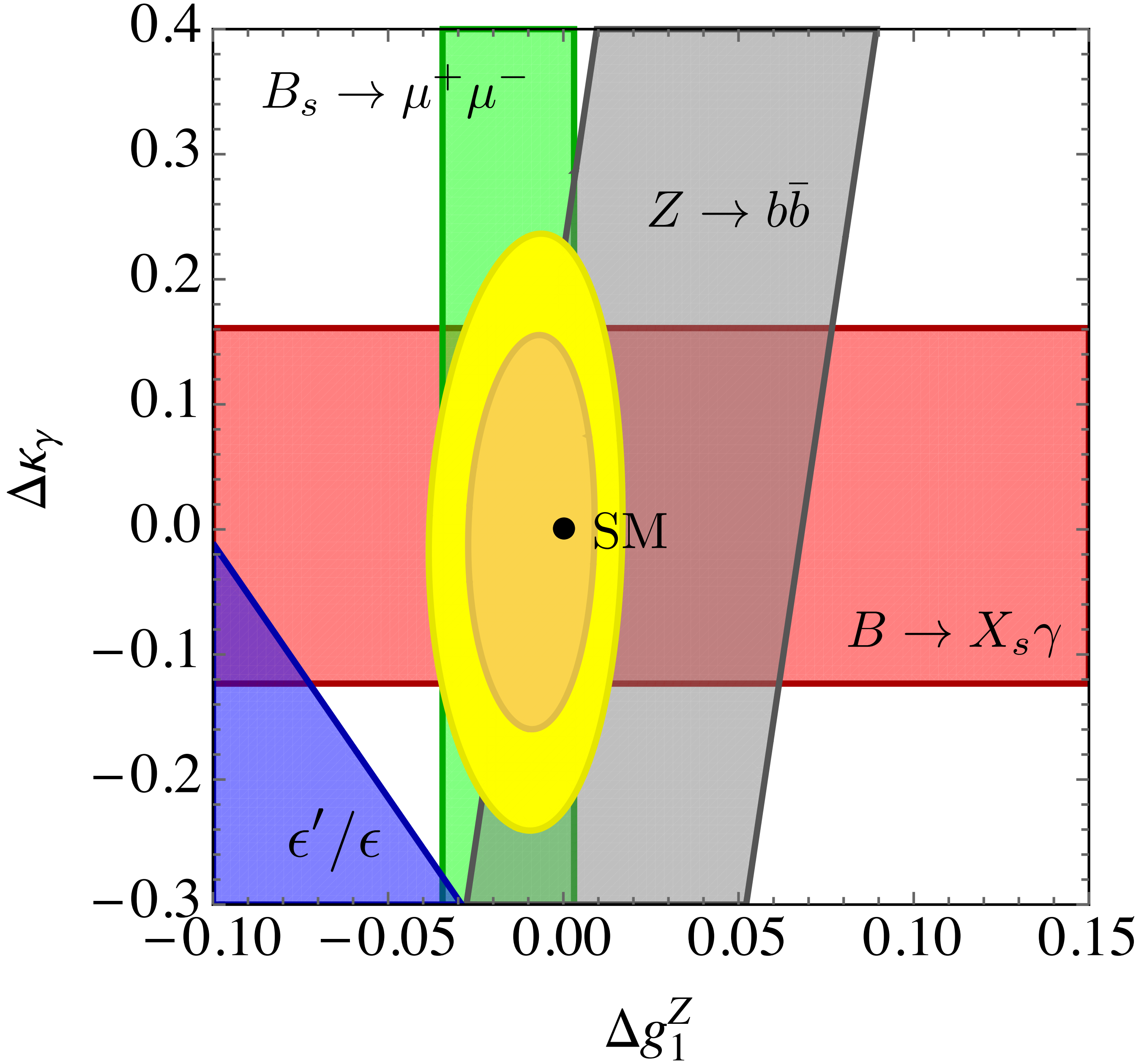
[Bobeth & UH, 1503.04829]



$$\left(\frac{\epsilon'}{\epsilon}\right)_{\rm SM} = (16.5 \pm 2.6) \cdot 10^{-4}$$

- ε′/ε can provide meaningful additional constraints on anomalous TGCs & resolve blind directions

Anomalous TGCs from ε′/ε

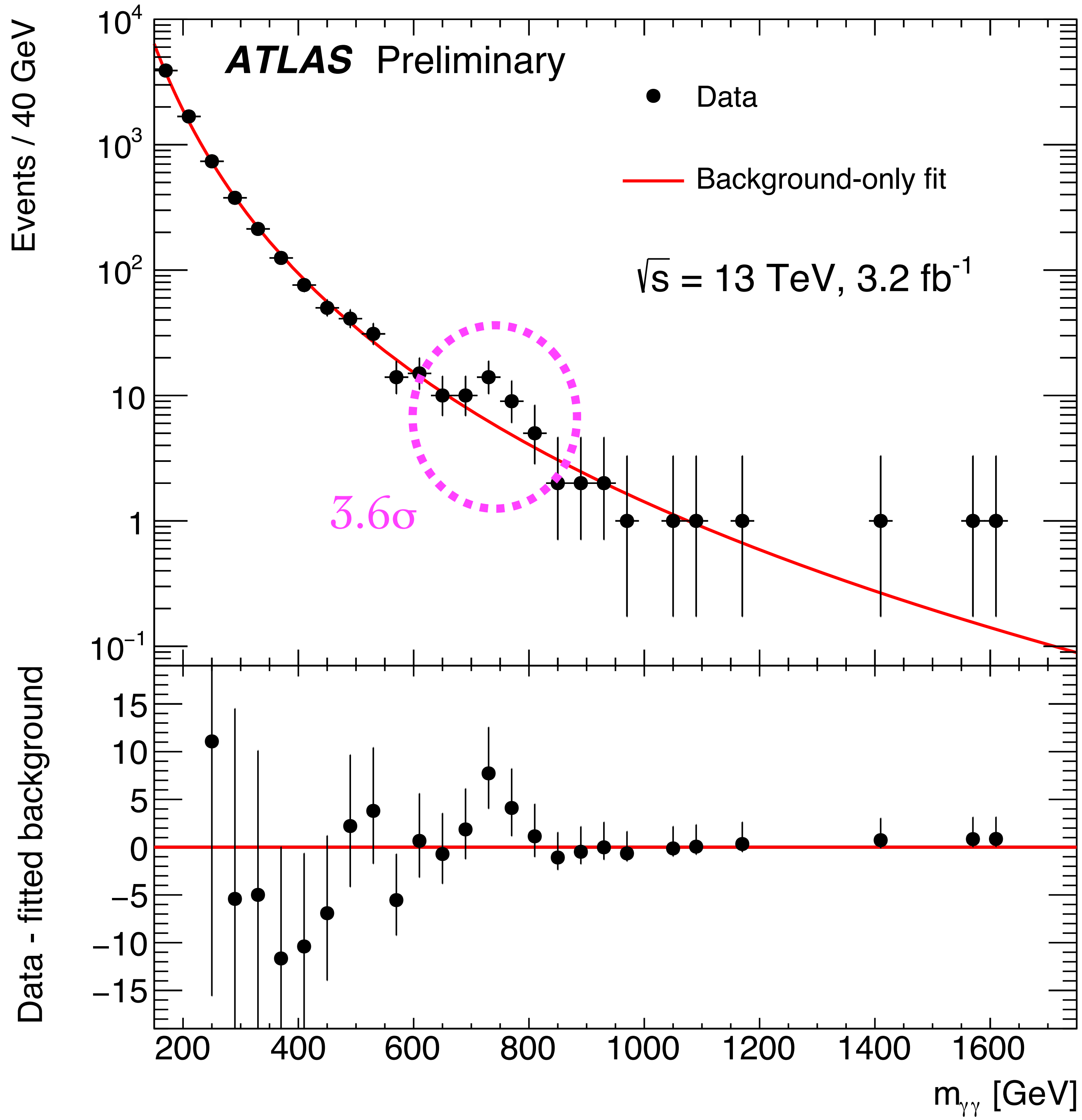


$$\left(\frac{\epsilon'}{\epsilon}\right)_{\rm SM} = (1.9 + 5.4)\cdot 10^{-4}$$

- ε′/ε can provide meaningful additional constraints on anomalous TGCs & resolve blind directions

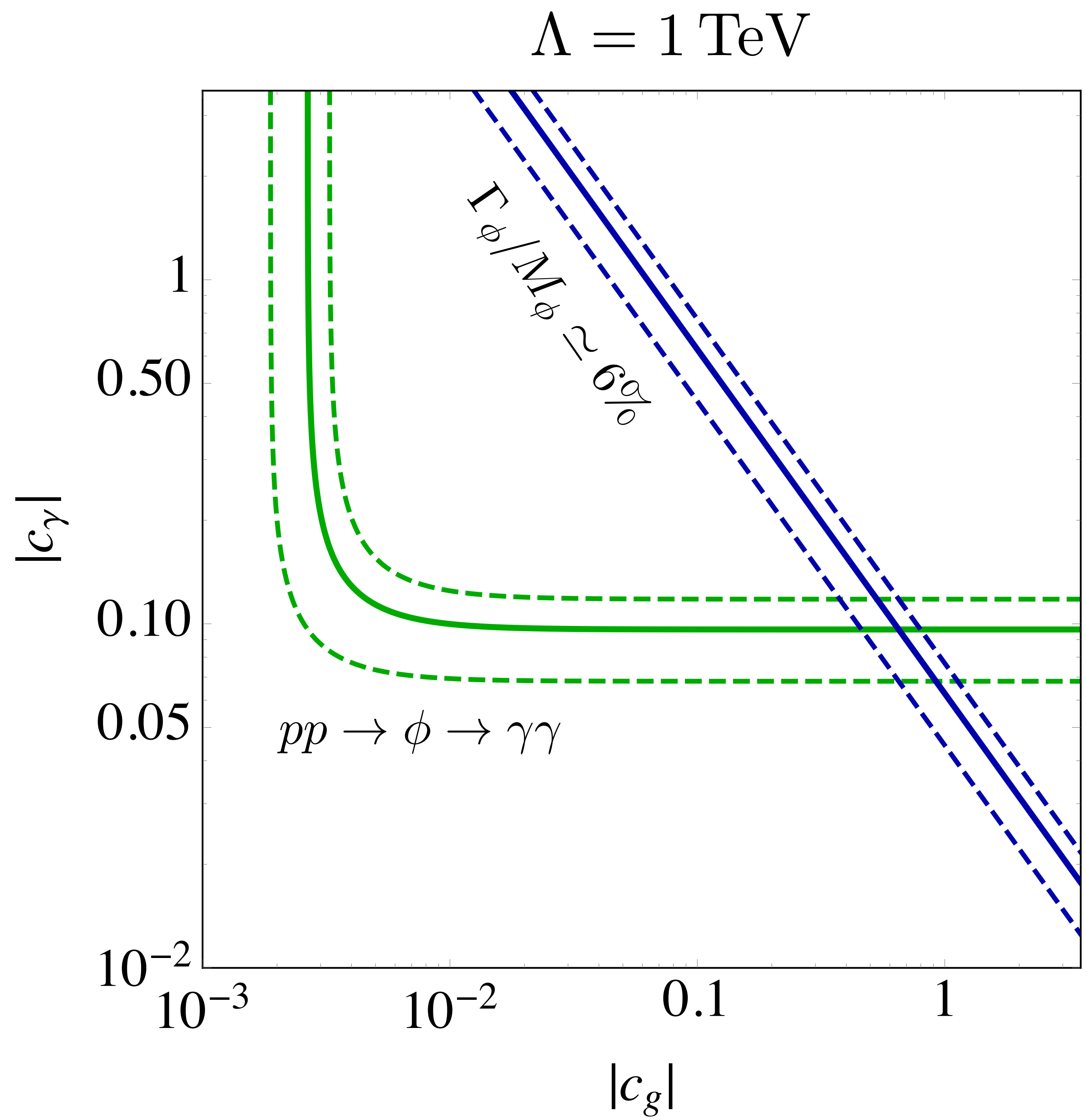
Who ordered that?

[ATLAS-CONF-2015-081]



A toy model for 750 GeV excess

$$\mathcal{L}_{\rm eff} \supset -\frac{e^2 c_\gamma}{2\Lambda}\,\phi F_{\mu\nu}F^{\mu\nu} - \frac{g_s^2 c_g}{2\Lambda}\,\phi\, G^a_{\mu\nu}G^{a,\mu\nu}$$

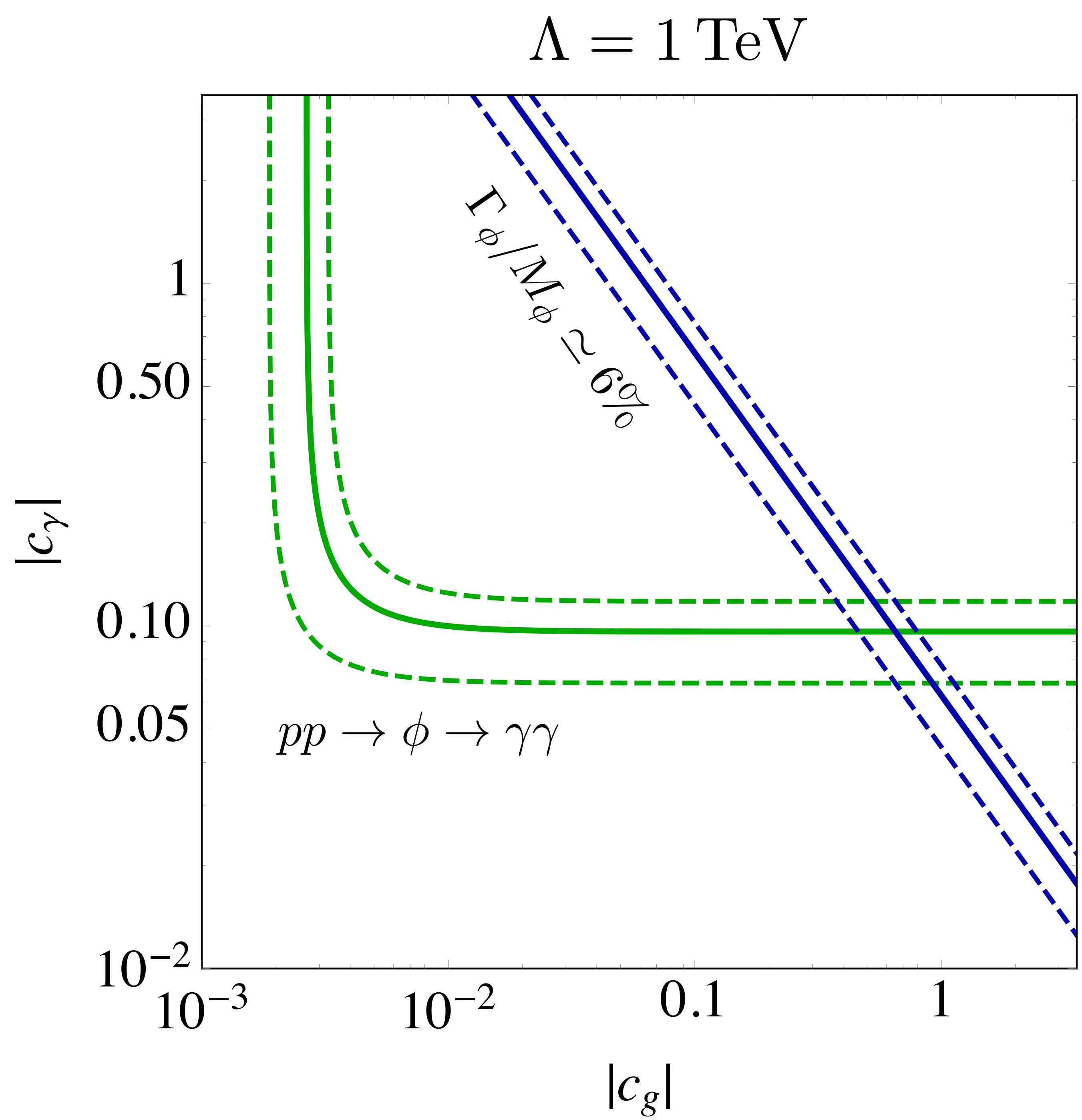


Let's add flavour violation

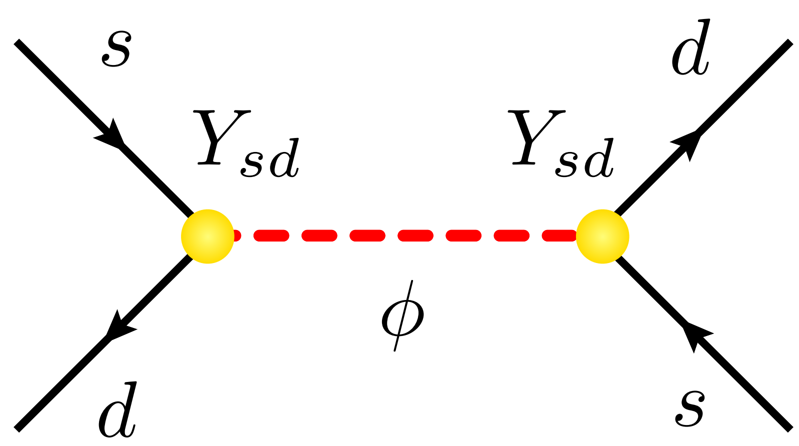
$$\mathcal{L}_{\rm eff} \supset -\frac{e^2 c_\gamma}{2\Lambda}\,\phi F_{\mu\nu}F^{\mu\nu}$$

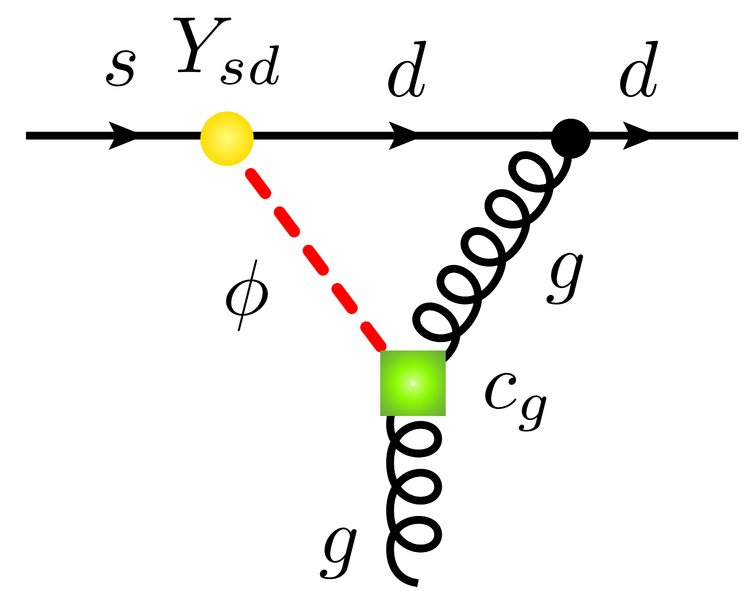
$$-\frac{g_s^2 c_g}{2\Lambda}\,\phi\, G^a_{\mu\nu}G^{a,\mu\nu}$$

$$-Y_{sd}\,\phi\,\bar{s}_L d_R + \text{h.c.}$$



We get contributions to εK & ε′/ε





from εK

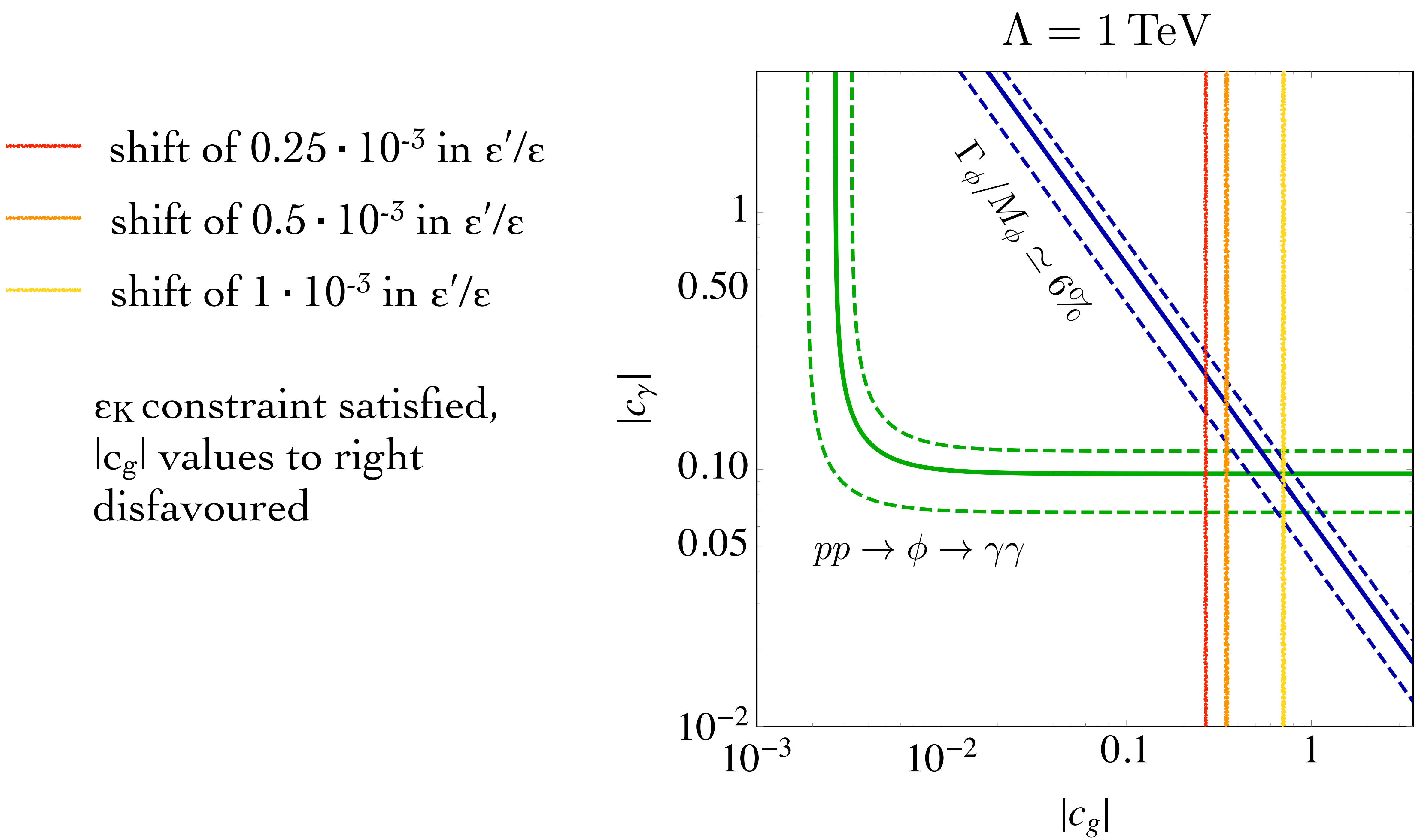
from ε′/ε

$$\sqrt{|\mathrm{Im}\,(Y_{sd}^2)\,|} < 6.4 \cdot 10^{-6}$$

$$|c_g\,\mathrm{Im}\,(Y_{sd})\,| < \{1.1, 2.2, 4.4\} \cdot 10^{-6}\,{}^{\dagger}$$

† numbers assume shifts of {0.25, 0.5, 1} · 10^{-3} in ε′/ε & $B_{8g^-} = 0.3$

We get contributions to ε_K & ε'/ε



ε_K constraint satisfied, $|c_g|$ values to right disfavoured

Backup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email: Info@BaldorFood.com
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Anomalous t$\bar{\text{t}}$Z couplings

$$\mathcal{L}_{\text{eff}} = \boxed{\mathcal{L}_{\text{SM}}} + \sum_{i=\substack{(3)\\ \phi Q},\phi Q,\phi u} \frac{C_i}{\Lambda^2} \boxed{O_i} + \ldots$$

$$\boxed{O_{\phi Q}^{(3)}} = \left(\phi^\dagger i \overleftrightarrow{D}_\mu \sigma^a \phi\right)\left(\bar{Q}_{L,3}\gamma^\mu \sigma^a Q_{L,3}\right) ,$$

$$\boxed{O_{\phi Q}} = \left(\phi^\dagger i \overleftrightarrow{D}_\mu \phi\right)\left(\bar{Q}_{L,3}\gamma^\mu Q_{L,3}\right) ,$$

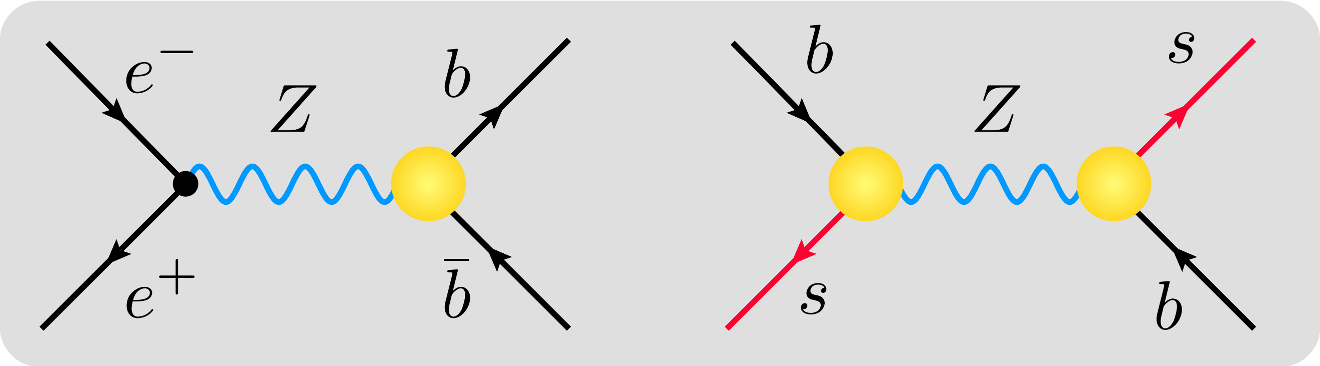
$$\boxed{O_{\phi u}} = \left(\phi^\dagger i \overleftrightarrow{D}_\mu \phi\right)\left(\bar{t}_R\gamma^\mu t_R\right)$$

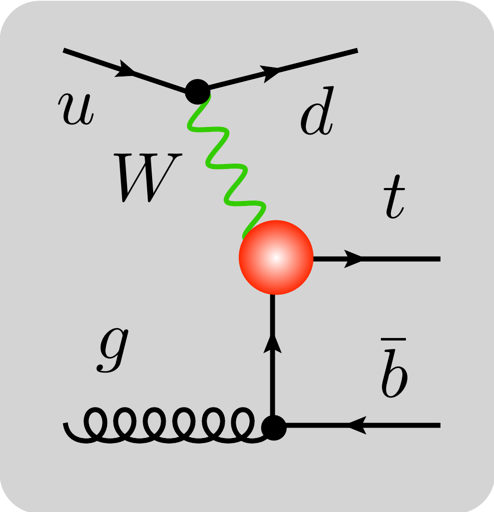
"Closed" tt̄Z couplings

$$\mathcal{L}_{t\bar{t}Z} = g_L\,\bar{t}_L \not{Z} t_L + \boxed{g'_L}\, V^*_{ti} V_{tj} \bar{d}_{L,i} \not{Z} d_{L,j} + g_R \bar{t}_R \not{Z} t_R$$

$$+ \left(\boxed{k_L}\, \bar{t}_L \not{W}^+ b_L + \text{h.c.} \right)$$

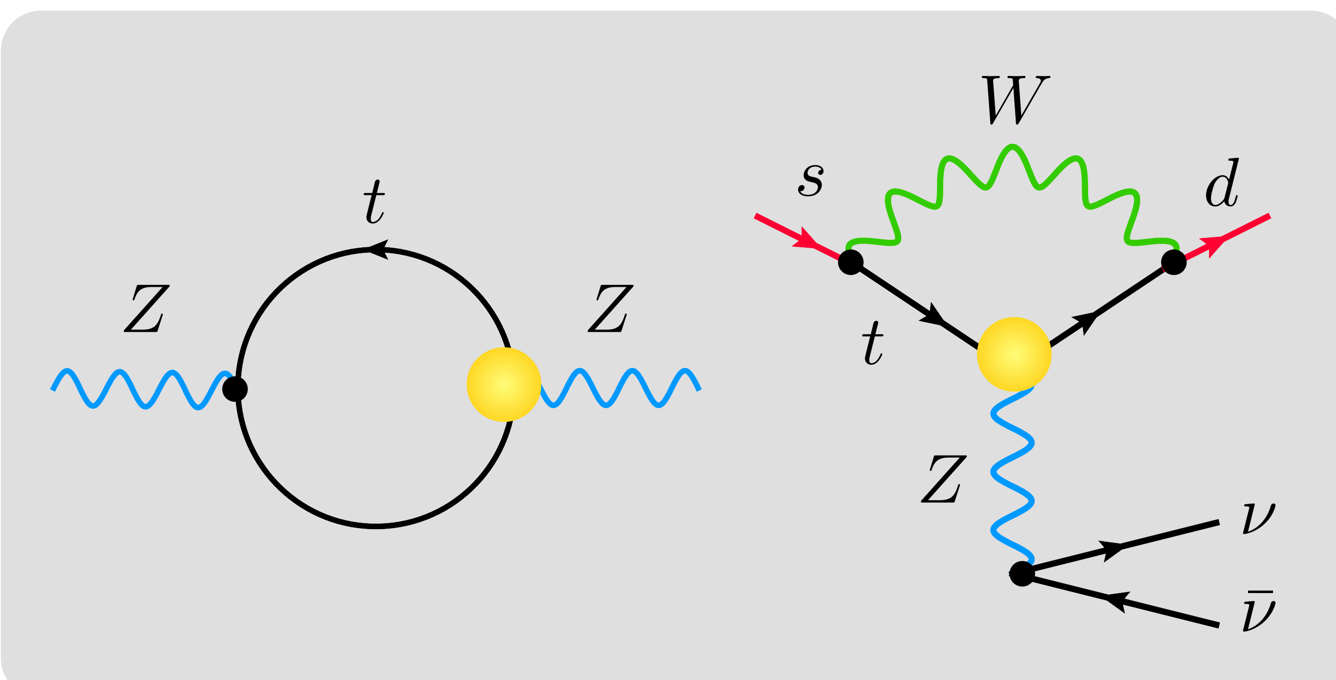
$$\boxed{g'_L} \propto \frac{v^2}{\Lambda^2} \left(C^{(3)}_{\phi Q} + C_{\phi Q} \right) \simeq 0\,, \qquad \boxed{k_L} \propto \frac{v^2}{\Lambda^2}\, C^{(3)}_{\phi Q} = -0.006 \pm 0.038$$

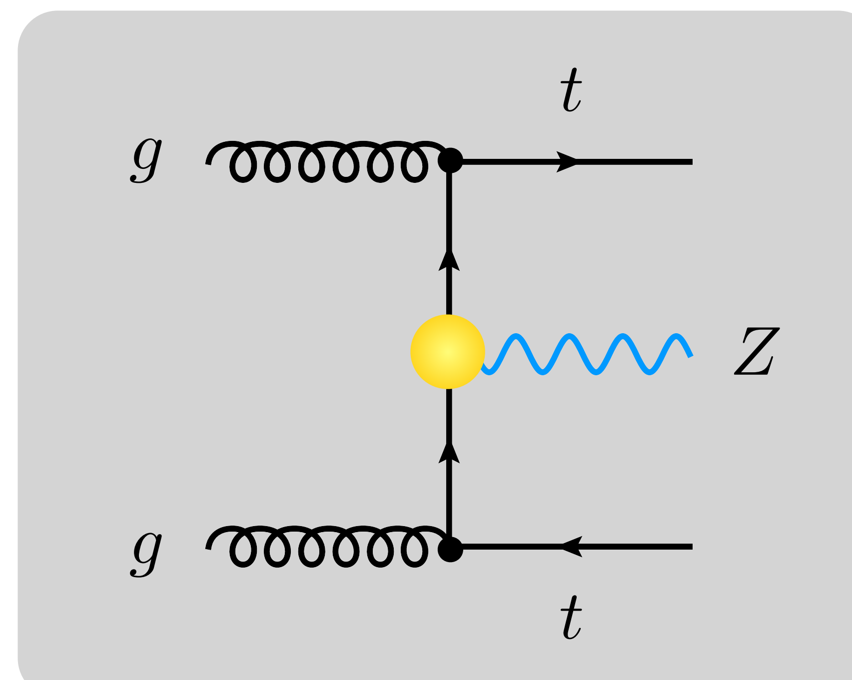




"Open" tt̄Z couplings

$$g_L \propto \frac{v^2}{\Lambda^2}\left(C_{\phi Q}^{(3)} - C_{\phi Q}\right)\,, \qquad g_R \propto \frac{v^2}{\Lambda^2}\, C_{\phi u}$$

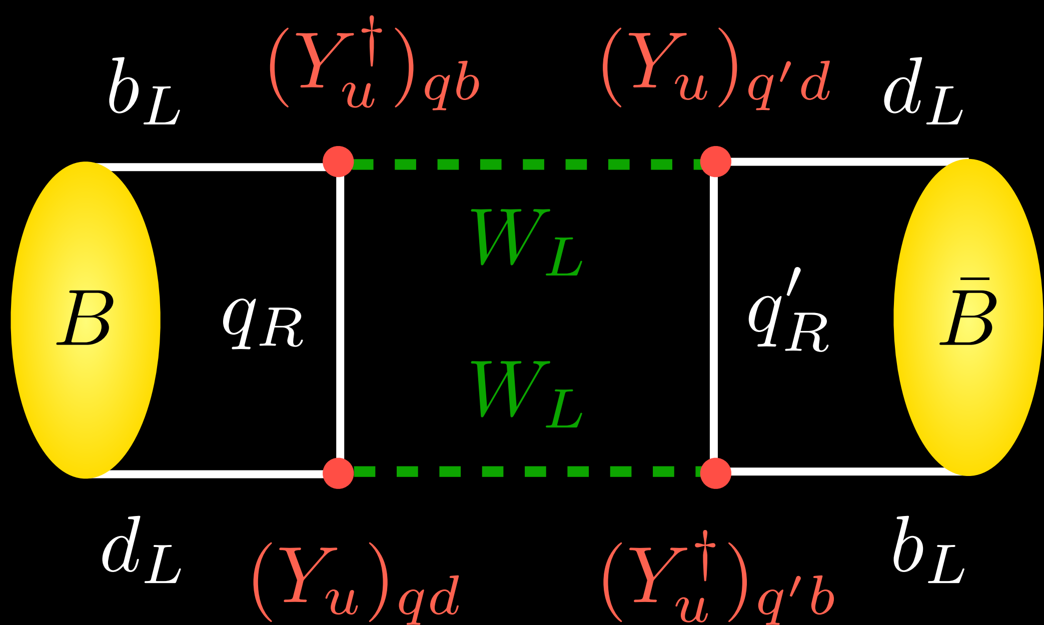




Flavor changing neutral currents

[see e.g. D'Ambrosio et al., hep-ph/0207036]

In fact, neutral meson mixing & other flavor changing processes test structure of Yukawa interactions beyond tree level



$$Y_u = V^\dagger \,\mathrm{diag}\,(y_u, y_c, y_t)$$
$$\approx V^\dagger \,\mathrm{diag}\,(0, 0, y_t)$$

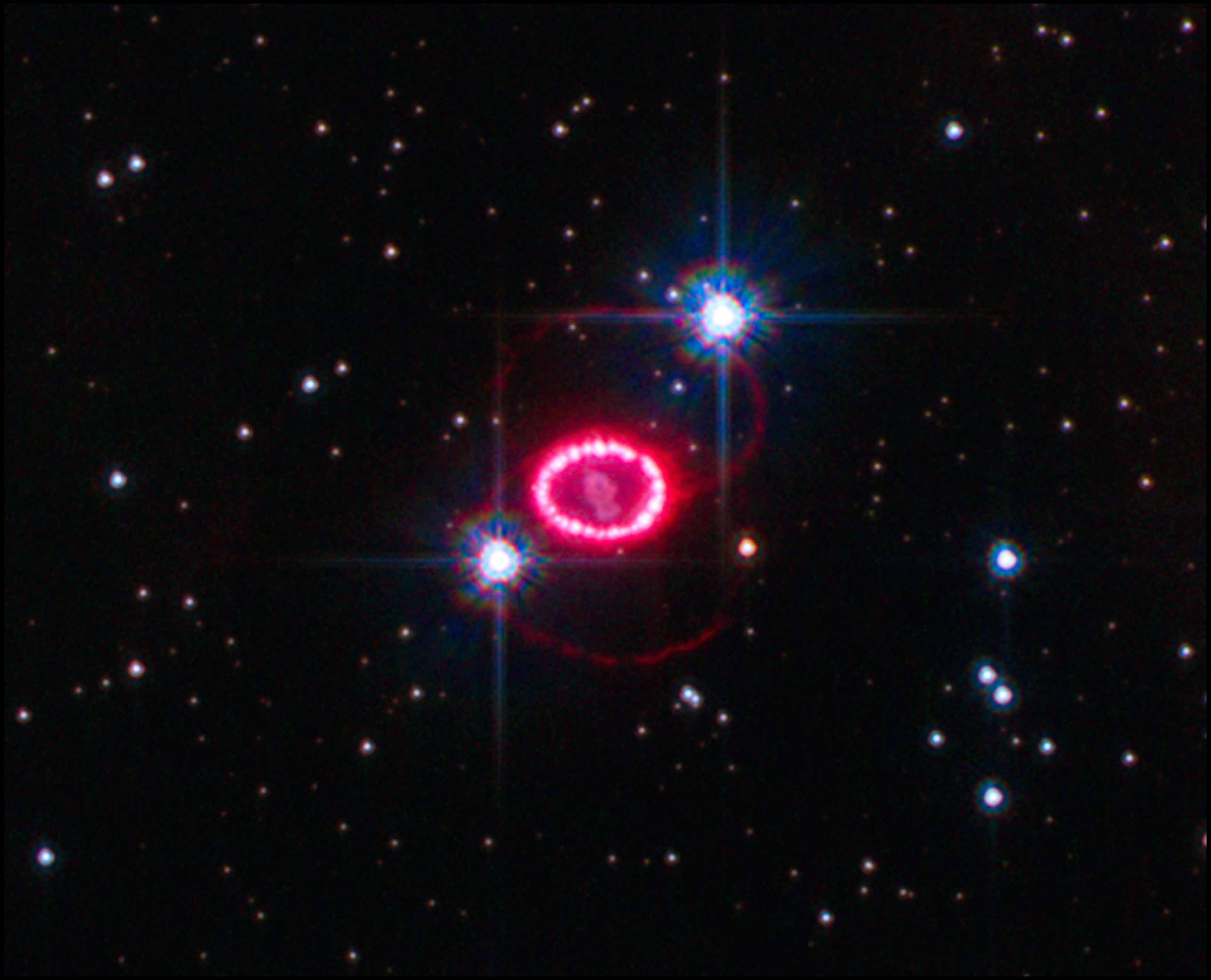
$$\Longrightarrow \quad \frac{m_t^2}{16\pi^2 m_W^4 m_t^4}\, y_t^4 \,(V_{tb}^* V_{td})^2 \;\propto\; \frac{g_2^2}{16\pi^2 m_W^4}\,\boxed{m_t^2}\,(V_{tb}^* V_{td})^2$$

1987

[http://en.wikipedia.org/wiki/1987]

Events:

- …
- February 23 – SN 1987A, the first "naked-eye" supernova since 1604, is observed



1987

[http://en.wikipedia.org/wiki/1987]

Events:

- …
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- …
- March 9 – The Irish rock band U2 releases their studio album "The Joshua Tree"


THE JOSHUA TREE U2

1987

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- …
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1987

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- …
- June 12 – During a visit to Berlin, Germany, U.S. President Ronald Reagan challenges Soviet Premier Mikhail Gorbachev to tear down the Berlin Wall


ALL OF THIS IN THE NAME OF THE
HI MOM
MAUER
BERLIN

1987

[http://en.wikipedia.org/wiki/1987]

Events:

- …
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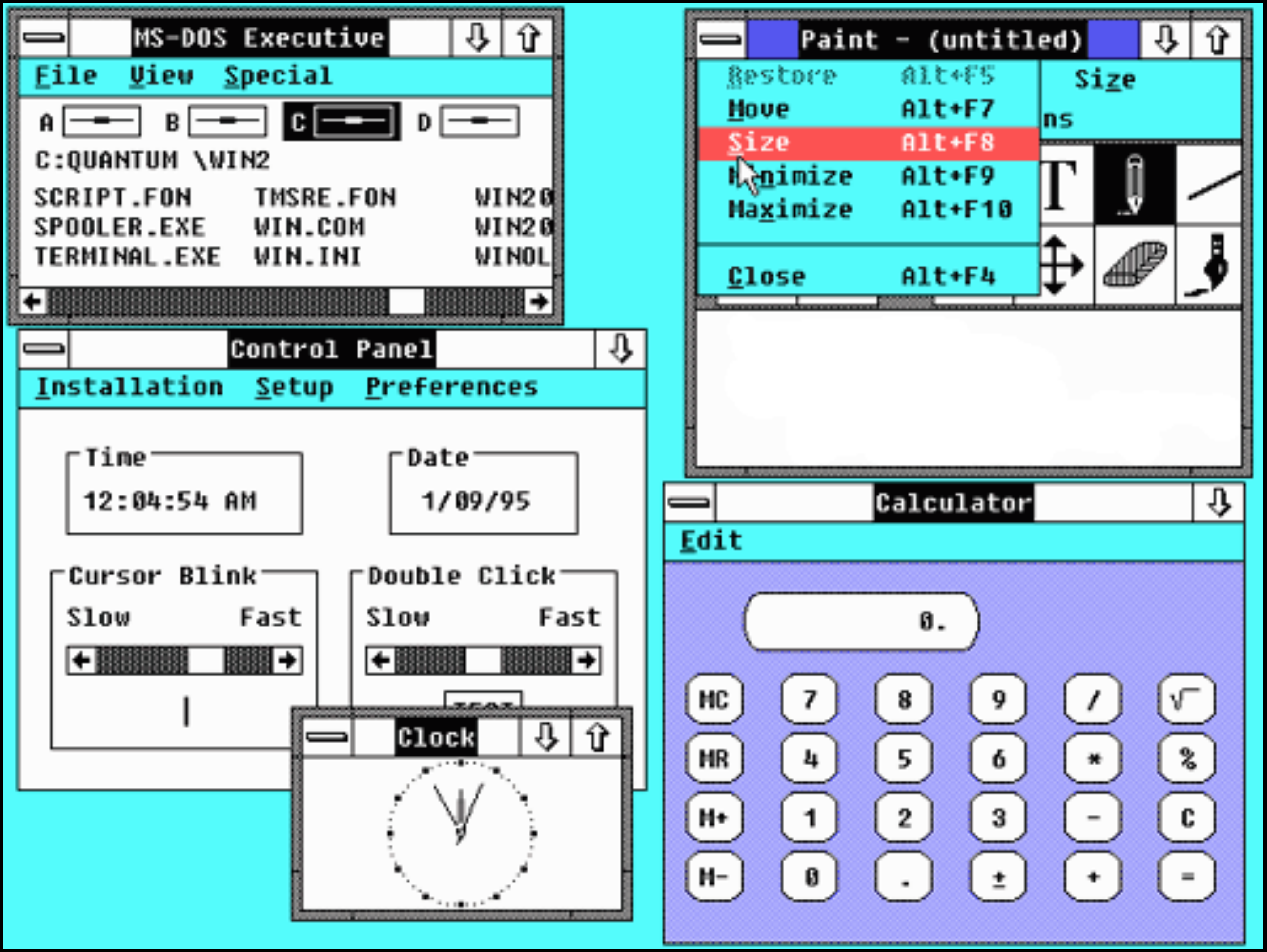
- …
- June 12 – During a visit to Berlin, Germany, U.S. President Ronald Reagan challenges Soviet Premier Mikhail Gorbachev to tear down the Berlin Wall
- …
- December 9 – Microsoft releases Windows 2.0


MS-DOS Executive
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TERMINAL.EXE WIN.INI
Paint - (untitled)
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Minimize Alt+F9
Maximize Alt+F10
Close Alt+F4
Control Panel
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MR 4 5 6 * %
M+ 1 2 3 - C
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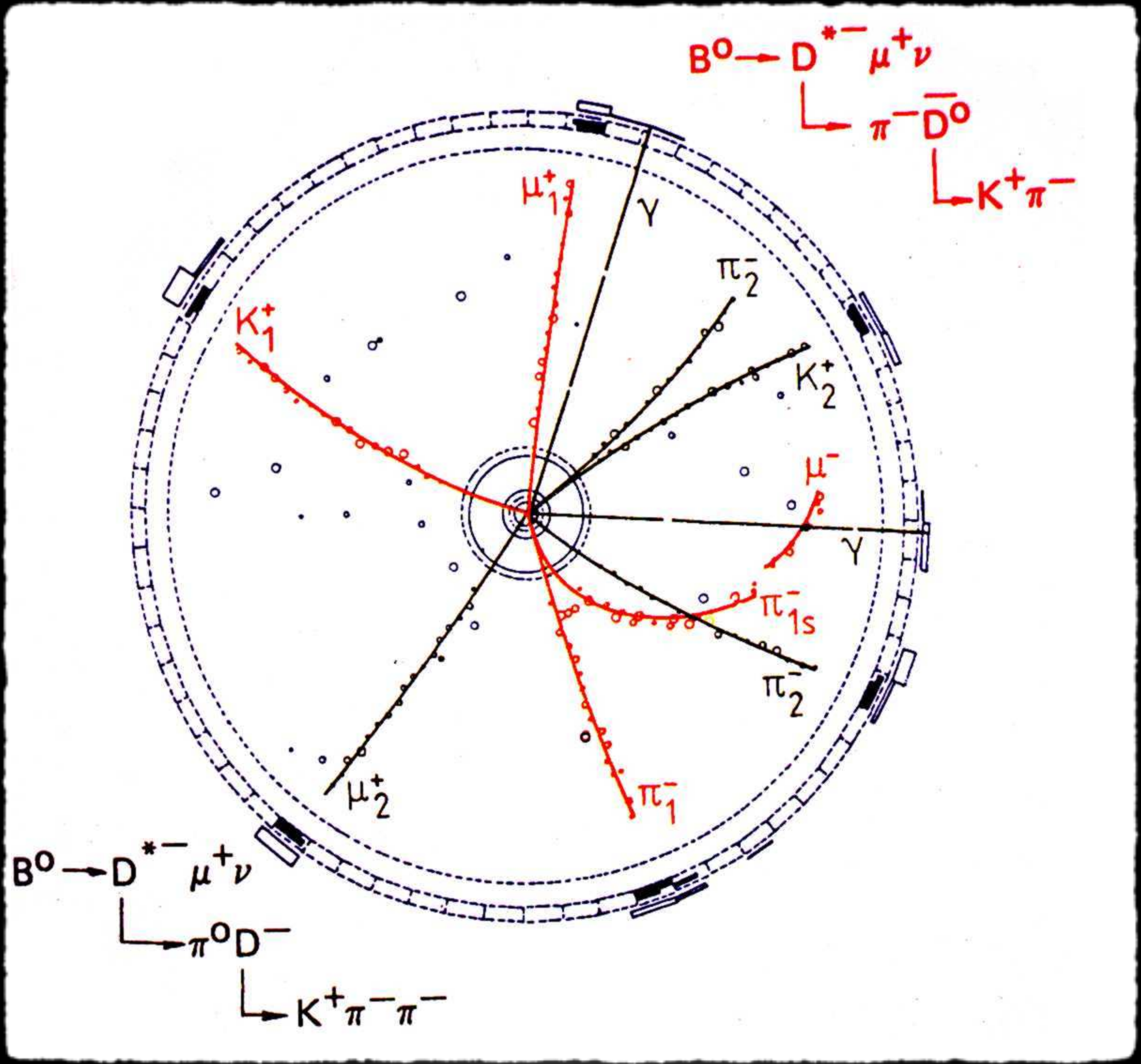
Not on list: $\Upsilon(4S) \to B^0\bar{B}^0 \to B^0B^0$

[ARGUS, Phys. Lett. B192, 245 (1987)]



Implications for top mass

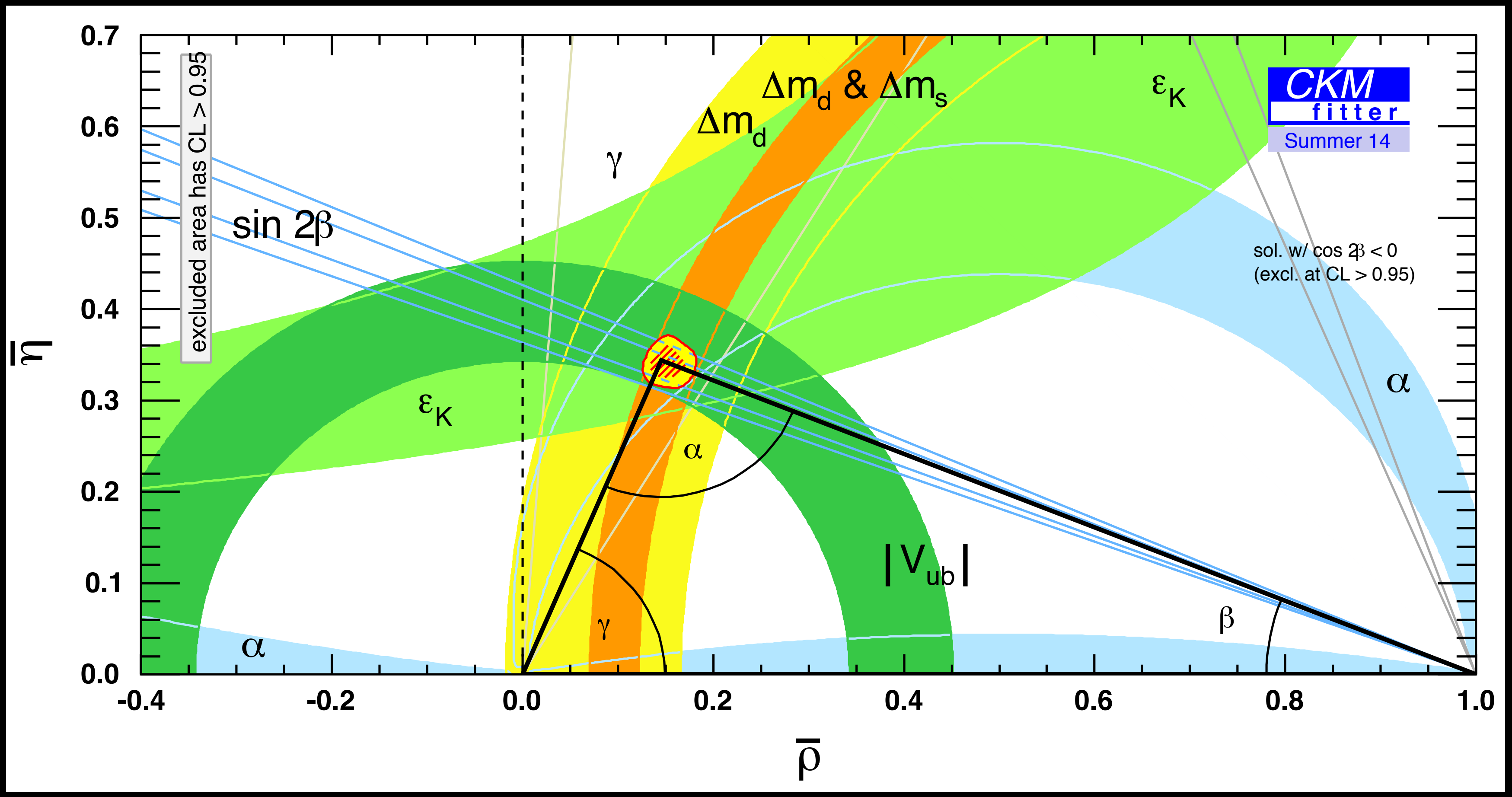
[ARGUS, Phys. Lett. B192, 245 (1987)]

$r > 0.09\,(90\%\mathrm{CL})$	this experiment
$x > 0.44$	this experiment
$B^{1/2} f_{\mathrm{B}} \approx f_{\pi} < 160$ MeV	B meson ($\approx$ pion) decay constant
$m_{\mathrm{b}} < 5\ \mathrm{GeV}/c^2$	b-quark mass
$\tau < 1.4 \times 10^{-12}\mathrm{s}$	B meson lifetime
$\lvert V_{\mathrm{td}} \rvert < 0.018$	Kobayashi–Maskawa matrix element
$\eta_{\mathrm{QCD}} < 0.86$	QCD correction factor
$m_{\mathrm{t}} > 50\ \mathrm{GeV}/c^2$	t quark mass

By 1987 it was general belief that top mass was much smaller than 50 GeV, but ARGUS found that it is (probably significantly) larger

Top mass from unitarity triangle

[CKMfitter, CKM14 results]



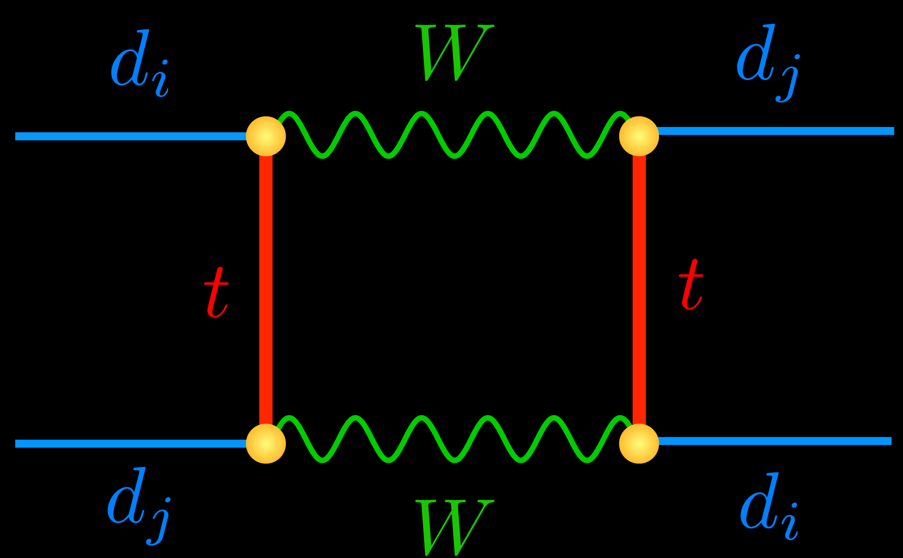
$$\Downarrow$$

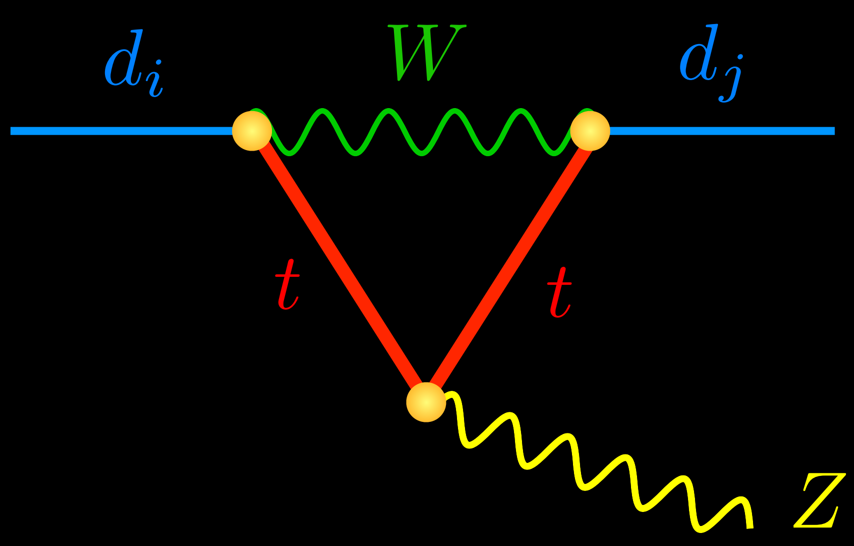
$$\boxed{m_t^{\text{pole}} = (169 \pm 5)\ \text{GeV}}$$

Boxes & Z penguins

[see e.g. Buras, hep-ph/9806471]

Within SM, only two 1-loop topologies lead to a quadratic dependence on top mass





$$\Downarrow$$

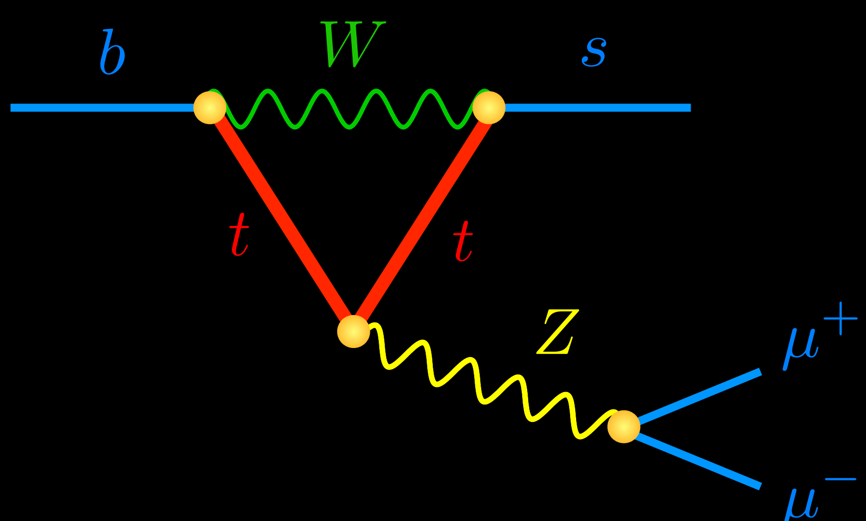
$$\Delta M_K, \Delta M_{B_d}, \Delta M_{B_S}, \epsilon_K$$

$$\Downarrow$$

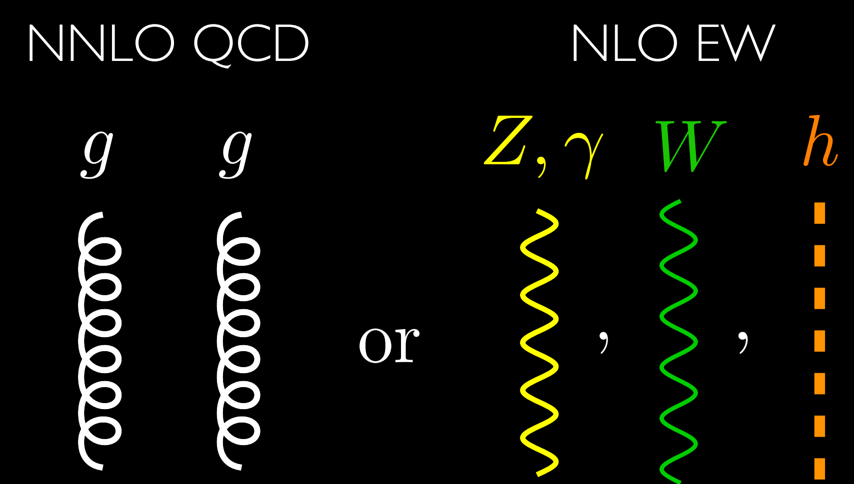
$$B_{d,s} \to \mu^+\mu^-, B \to K^{(*)}, X_s\mu^+\mu^-$$
$$K \to \pi\nu\bar{\nu}, K \to \pi\mu^+\mu^-, \epsilon'/\epsilon, Z \to b\bar{b}$$

Top mass from $B_s \to \mu^+\mu^-$: Present

[Bobeth et al., 1311.0903]



$\times$



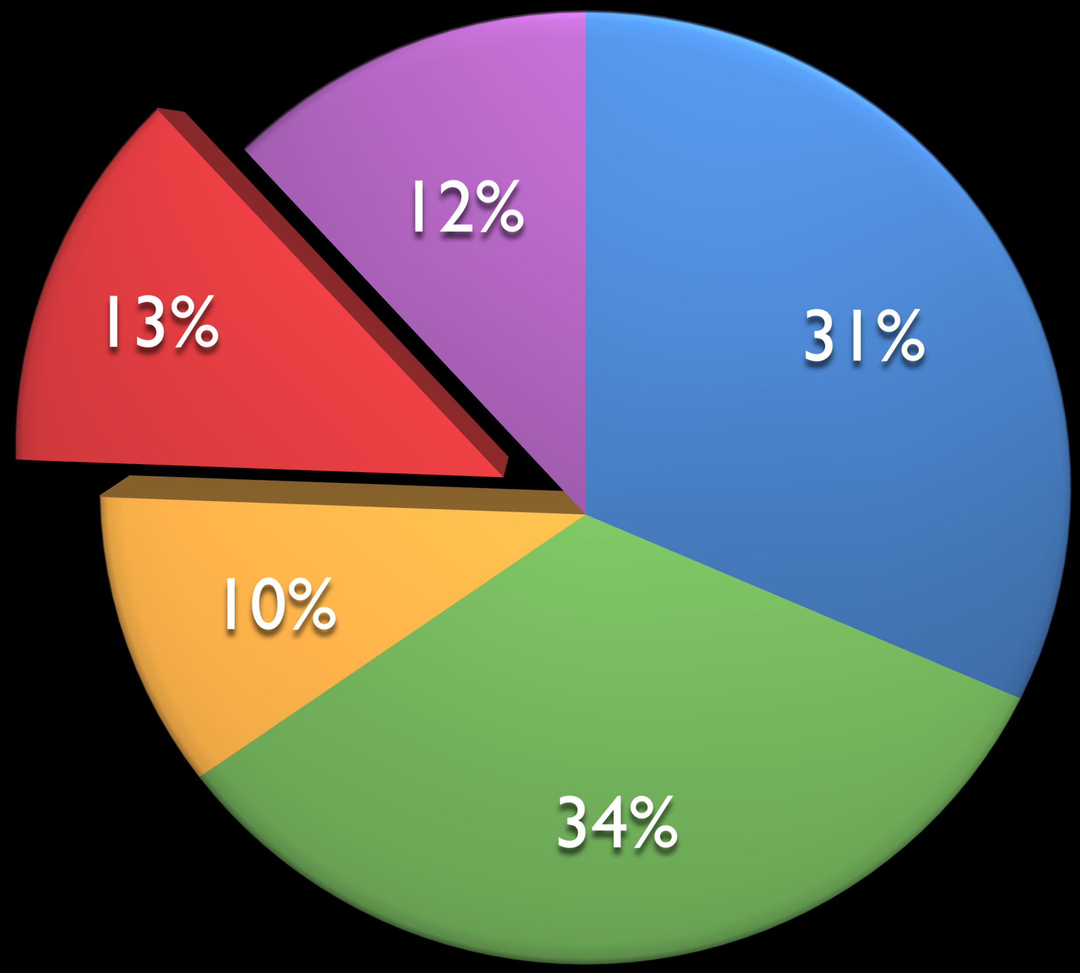
$$\mathrm{Br}\big(B_s \to \mu^+\mu^-\big)_{\mathrm{SM}} = 3.65 \left(\frac{m_t^{\mathrm{pole}}}{173.1\,\mathrm{GeV}}\right)^{3.06} (1 \pm 6.4\%) \cdot 10^{-9}$$

$$\mathrm{Br}\big(B_s \to \mu^+\mu^-\big)_{\mathrm{exp}} = 2.8\left(1^{+25\%}_{-21\%}\right) \cdot 10^{-9}$$ [CMS & LHCb, 1411.4413]

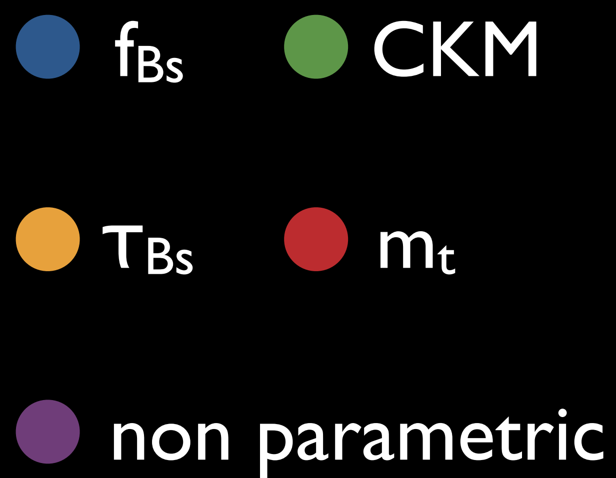
$$\Longrightarrow \boxed{m_t^{\mathrm{pole}} = (158 \pm 13)\ \mathrm{GeV}}$$

$B_s \to \mu^+\mu^-$ relative error budget

[Bobeth et al., 1311.0903]



6.4% total uncertainty



Improvements in lattice QCD calculations may reduce errors due to decay constant f_{Bs} & V_{cb}. Might result in future total uncertainty of 3%

Top mass from $B_s \to \mu^+\mu^-$: Reach

[Bobeth et al., 1311.0903]

$$\mathrm{Br}\big(B_s \to \mu^+\mu^-\big)_{\mathrm{SM}} = 3.65 \left(\frac{m_t^{\mathrm{pole}}}{173.1\,\mathrm{GeV}}\right)^{3.06} (1 \pm 3\%) \cdot 10^{-9}$$

$$\mathrm{Br}\big(B_s \to \mu^+\mu^-\big)_{\mathrm{exp}} = 3.65\,(1 \pm 4\%) \cdot 10^{-9}$$

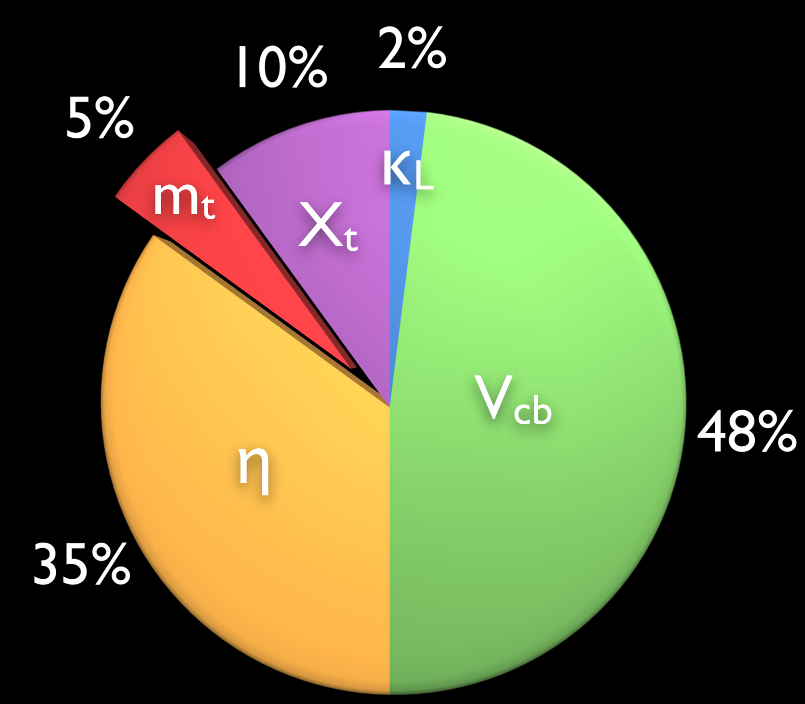
[LHCb, 1208.3355]

$$\Downarrow$$

$$\boxed{m_t^{\mathrm{pole}} = (173.0 \pm 2.8)\ \mathrm{GeV}}$$

Top mass from $K_L \to \pi^0 \nu\bar{\nu}$

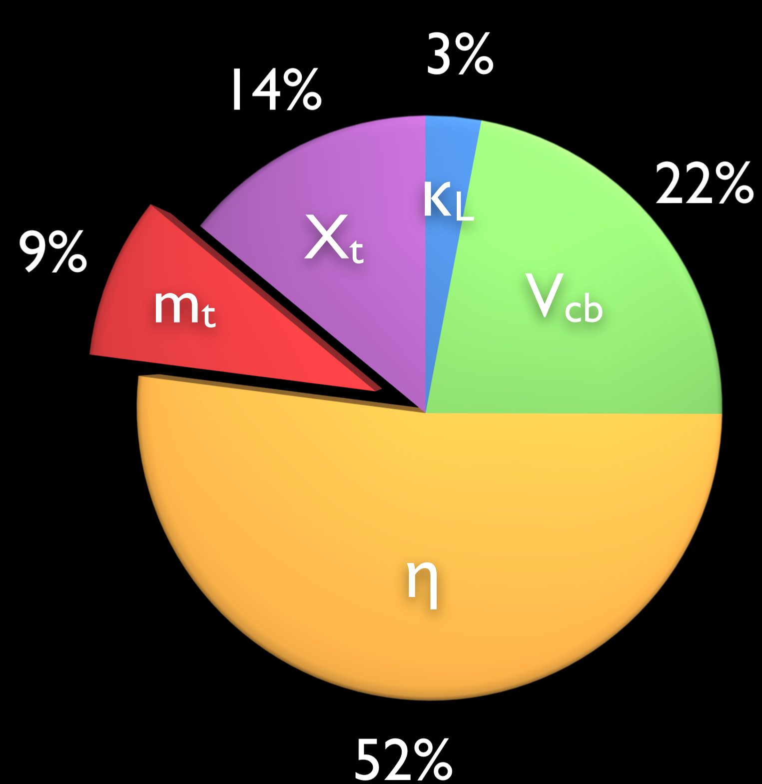
[Brod et al., 1009.0947]



$$\mathrm{Br}\big(K_L \to \pi^0 \nu\bar{\nu}\big)_{\mathrm{SM}} = 2.4\,(1 \pm 15\%)\cdot 10^{-11}$$

$$\underset{10\%\ \text{measurement}}{\Longrightarrow} \qquad \boxed{\delta m_t^{\text{pole}} = 14\ \text{GeV}}$$

$$\Big\Downarrow \quad \text{if } V_{cb} \text{ known to } 1\%$$

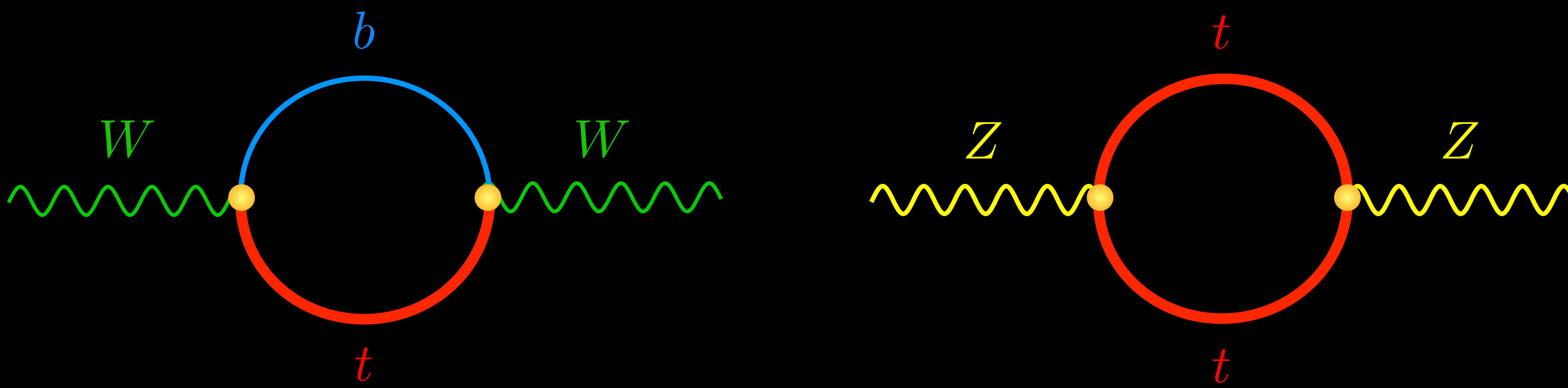


$$\mathrm{Br}\big(K_L \to \pi^0 \nu\bar{\nu}\big)_{\mathrm{SM}} = 2.4\,(1 \pm 10\%)\cdot 10^{-11}$$

$$\underset{10\%\ \text{measurement}}{\Longrightarrow} \qquad \boxed{\delta m_t^{\text{pole}} = 11\ \text{GeV}}$$

1-loop corrections to ρ

[cf. Veltman, Nucl. Phys. B123, 89 (1977)]

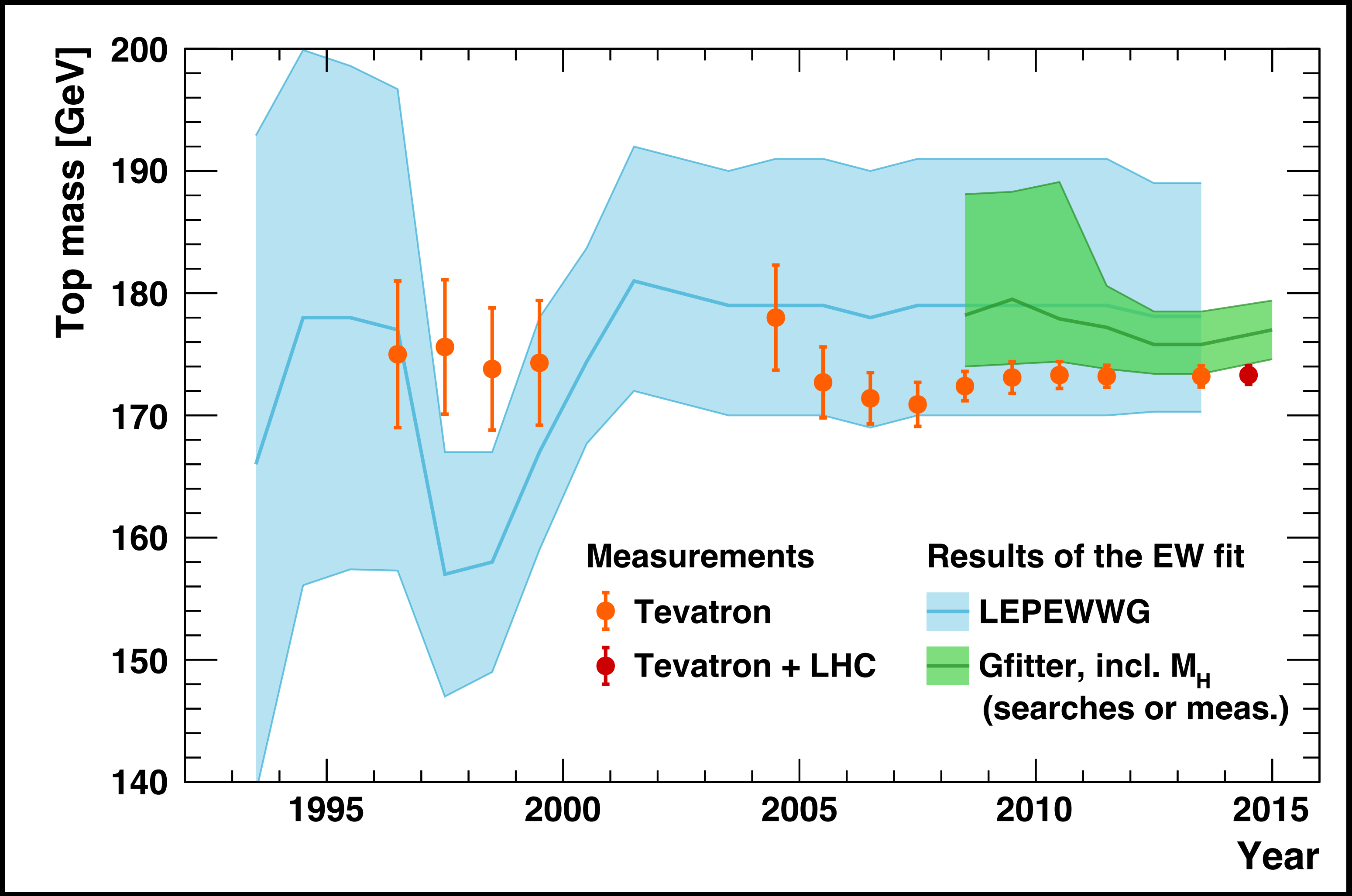


$$\Delta\rho = \alpha\Delta T = \frac{3G_F}{8\sqrt{2}\pi^2}\boxed{m_t^2}\left\{1+\frac{m_b^2}{m_t^2}\left[1+\frac{2\ln\left(\frac{m_b^2}{m_t^2}\right)}{1-\frac{m_b^2}{m_t^2}}\right]\right\}$$

Dominant 1-loop corrections due to top exchange & proportional to y_t^2. In contrast, Higgs contribution scales as $g_1^2 \ln(m_h^2/m_Z^2)$

History of m_t from electroweak fit

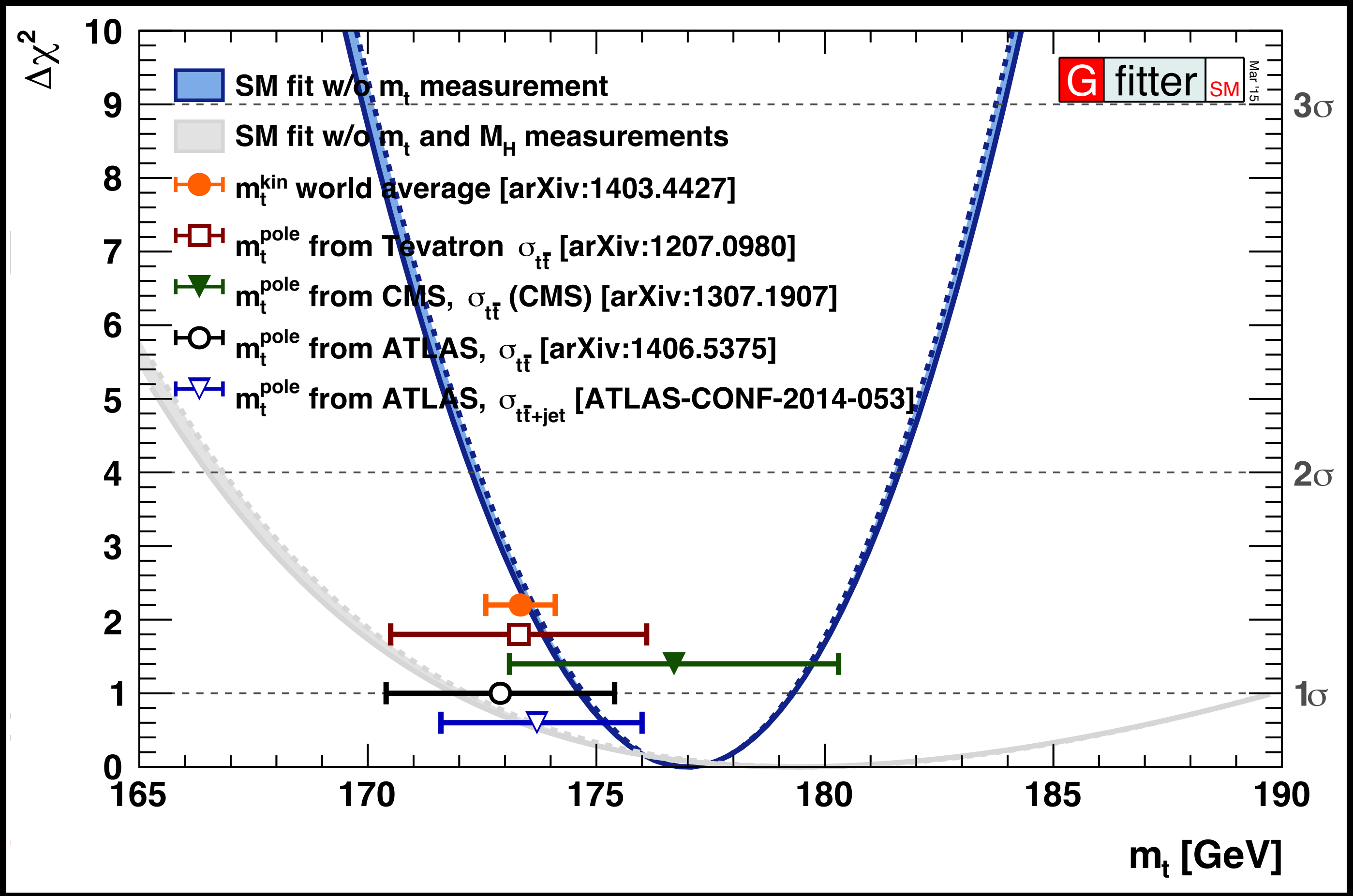
[Gfitter, November 2014]



Even before top discovery at Fermilab in 1995, global electroweak (EW) fits have always been able to predict mass correctly

Top mass from EW fit: Present

[Kogler, Moriond EW 2015]



$$\Downarrow$$

$$\boxed{m_t^{\text{pole}} = \left(177.0 \pm 2.3_{M_W, \sin^2\theta^f_{\text{eff}}} \pm 0.6_{\alpha_s} \pm 0.5_{\Delta\alpha_{\text{had}}} + 0.4_{M_Z}\right) \text{ GeV}}$$