Simultaneous explanation of K & B anomalies in vectorlike compositeness

EISA
European Institute for Sciences and Their Applications
Corfu Summer Institute

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KIAS KOREA INSTITUTE FOR ADVANCED STUDY → RB

On 12-13 Sept. 2018

Seoul, Korea — *Zagreb, Croatia*

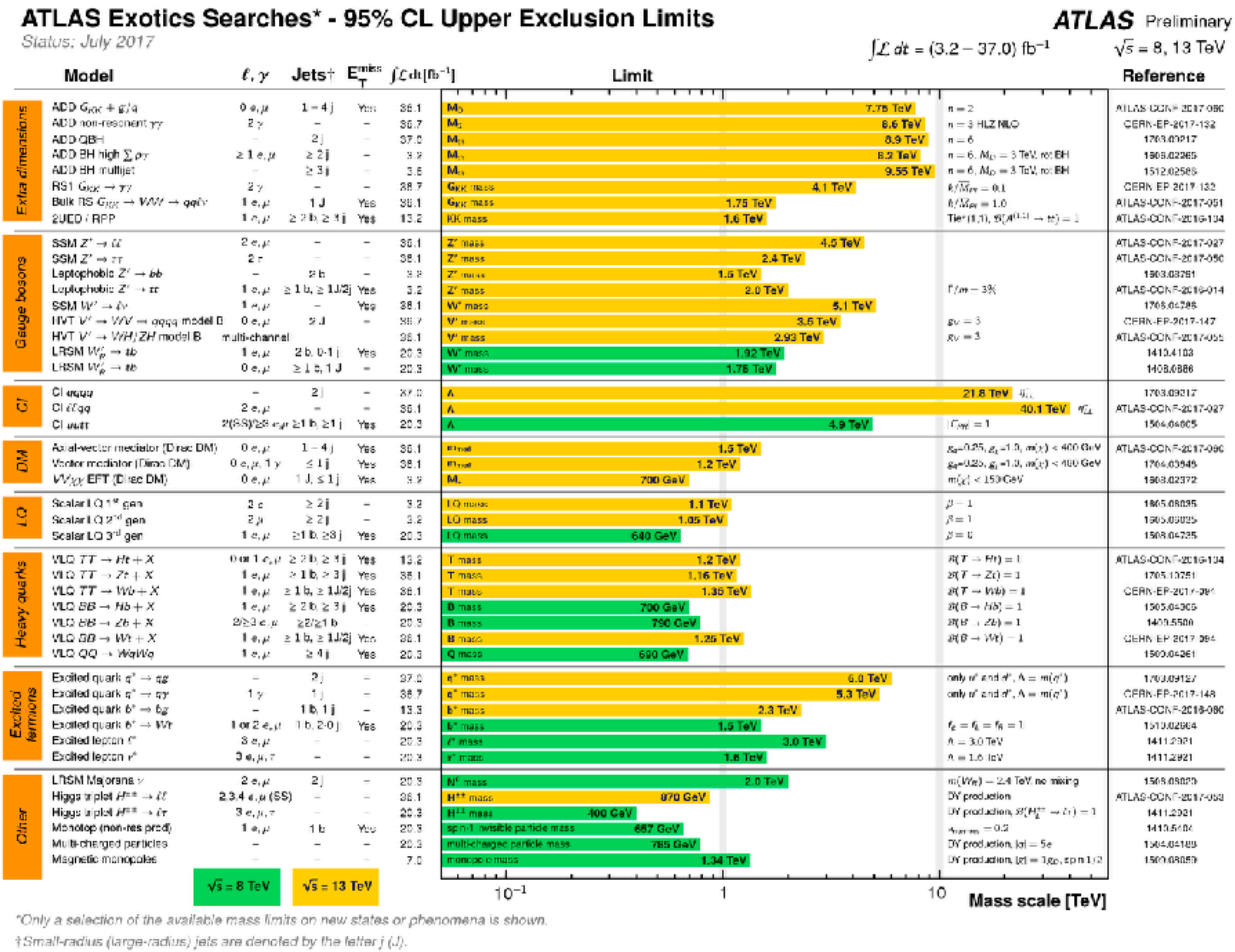
based on collaborations with

Shinya Matsuzaki (Jilin Univ., China),
Kei Yamamoto (Univ. of Zurich)
[arXiv:1806.02312, submitted to JHEP]

talk @ Corfu Summer Institute: Workshop on the Standard Model and beyond (31th Aug. to 9th Sept. 2018),
Mon Repos Estate, Corfu, Greece; 3rd September 2018

Current Status of LHC (cont'd)

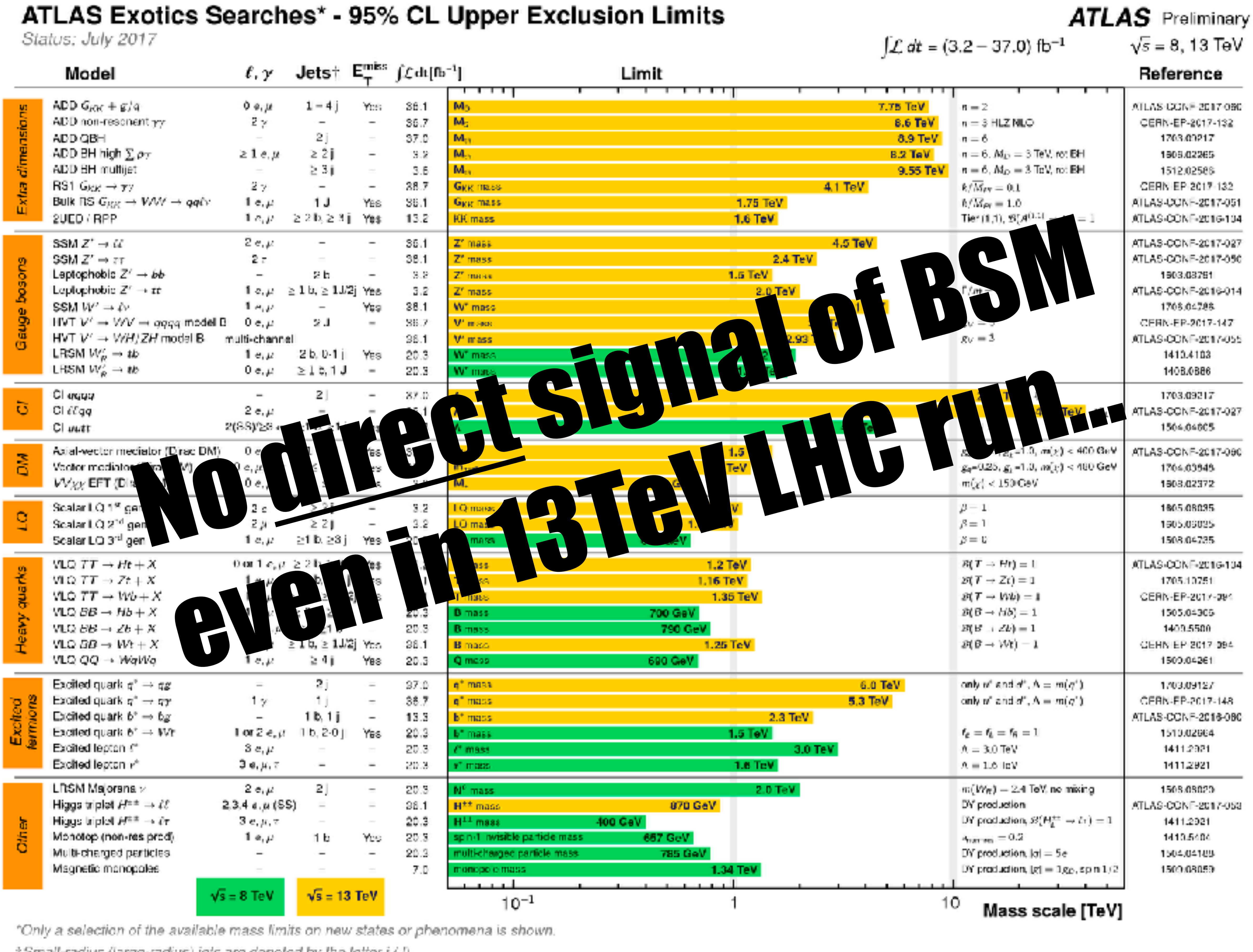
[ATLAS wiki]



Current Status of LHC (cont'd)

Intro: 1/10

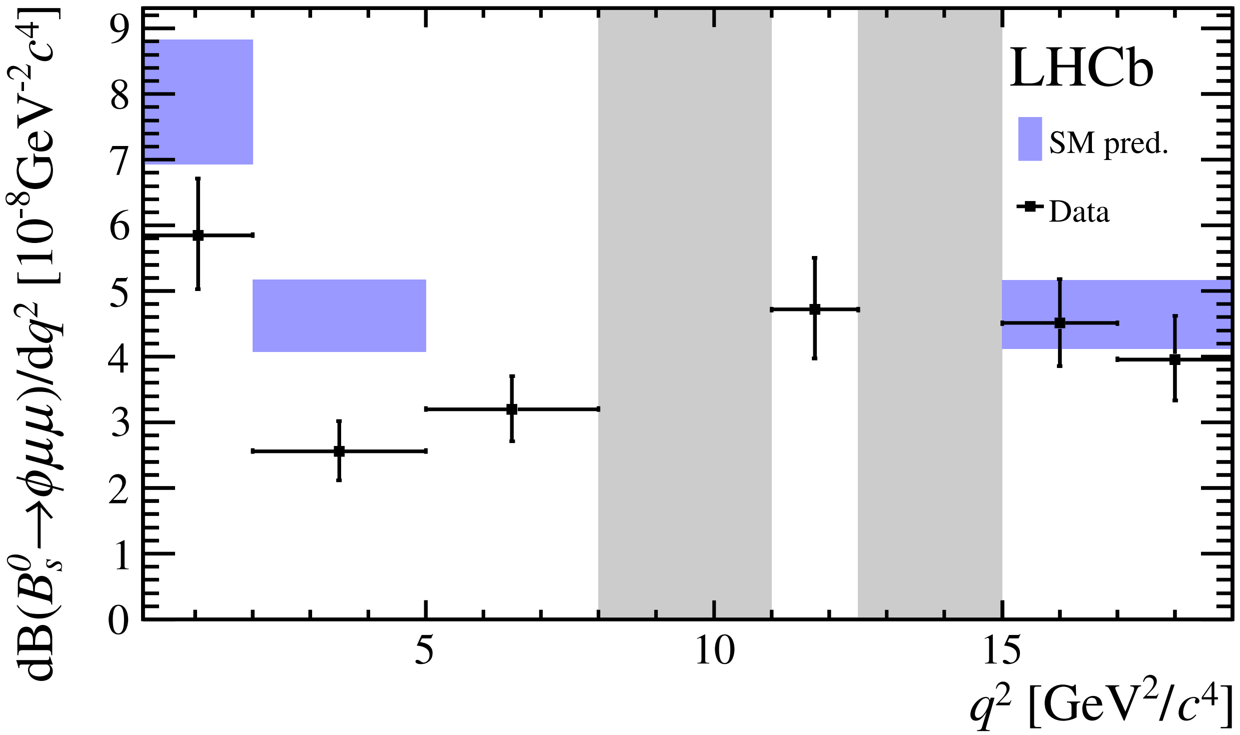
[ATLAS wiki]



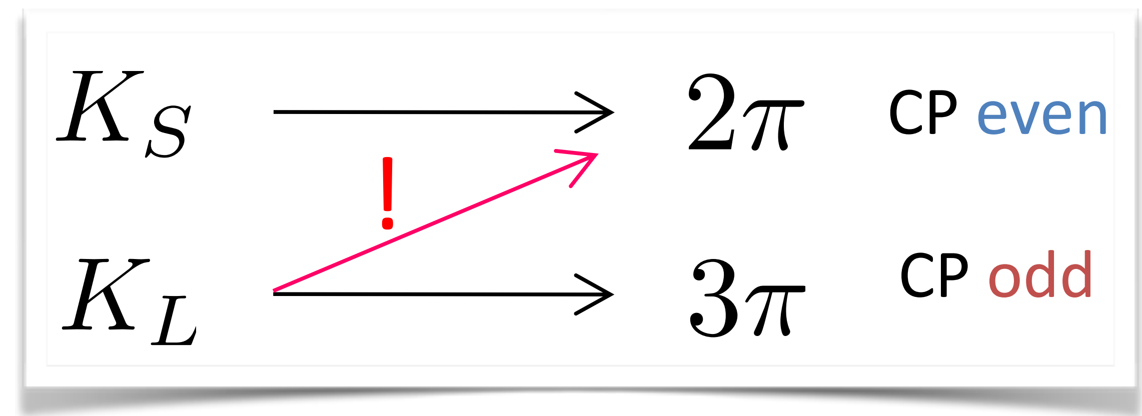
No direct signal of BSM even in 13TeV LHC run...

Anomalies in Flavor Observables have been reported!

[LHCb, arXiv:1506.08777]

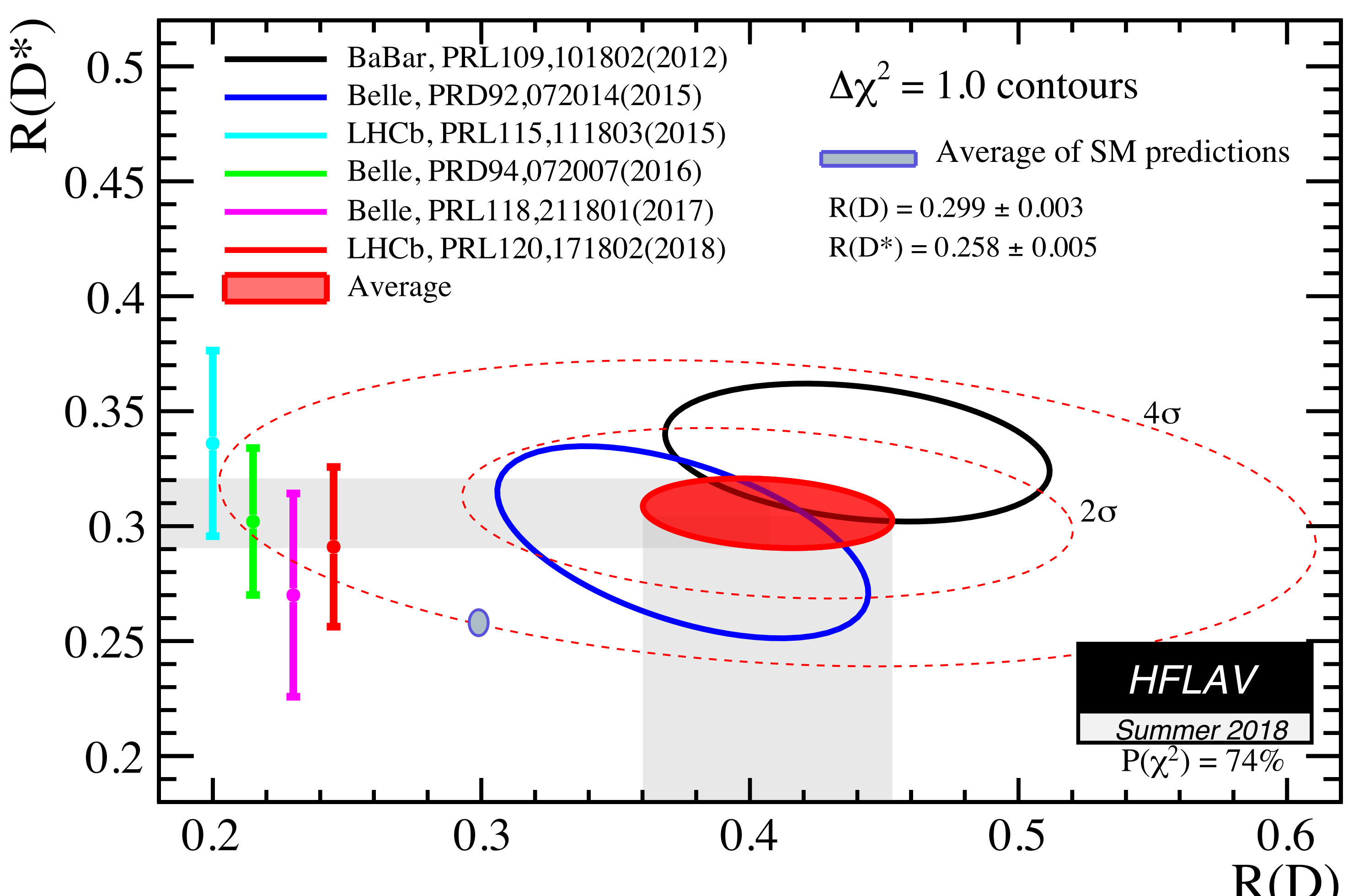


[courtesy of K.Yamamoto]



A discrepancy in the CP-violation of the Kaon.

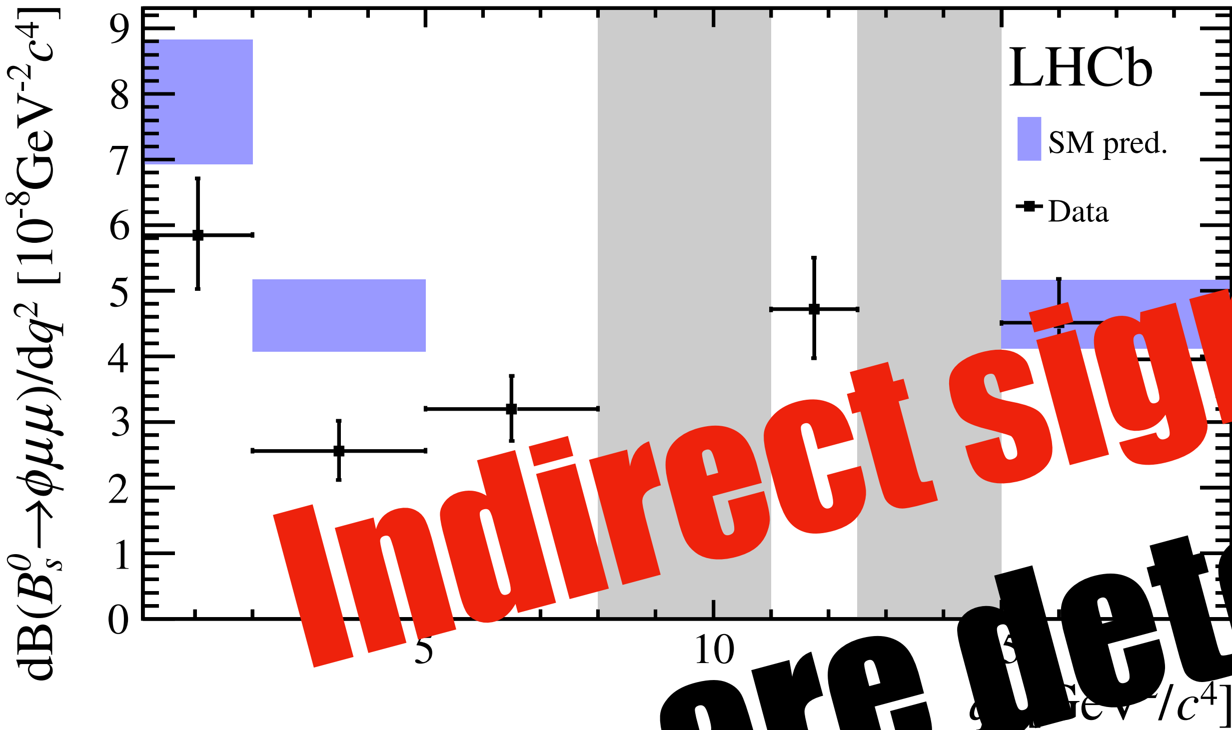
[HFAG summary for Summer 2018]



Anomalies in Flavor Observables have been reported!

Intro: 2/10

[LHCb, arXiv:1506.08777]



[courtesy of K.Yamamoto]

$K_S \longrightarrow 2\pi$ CP even

$K_L \longrightarrow 3\pi$ CP odd

Discrepancy in the CP-violation of the Kaon.

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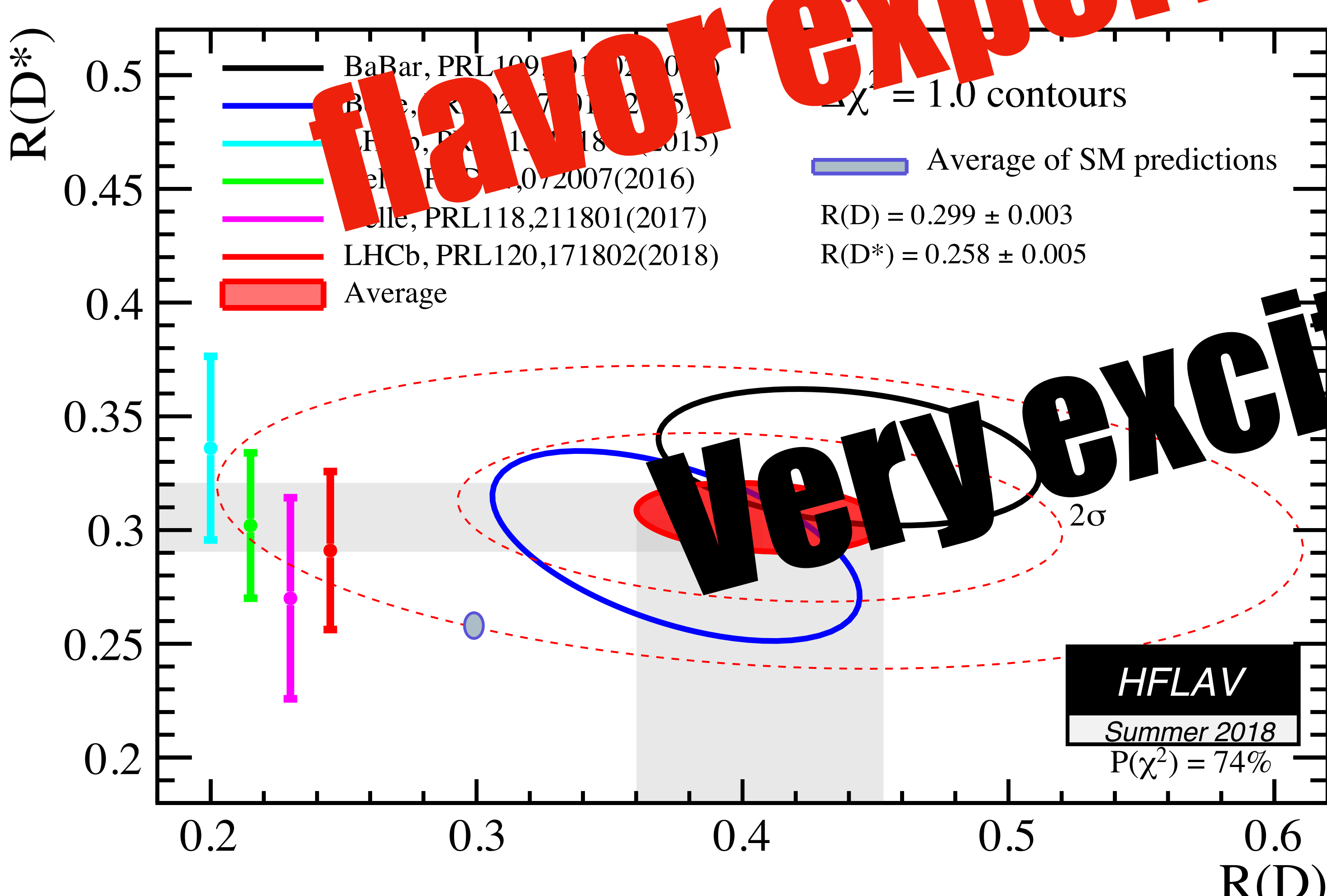
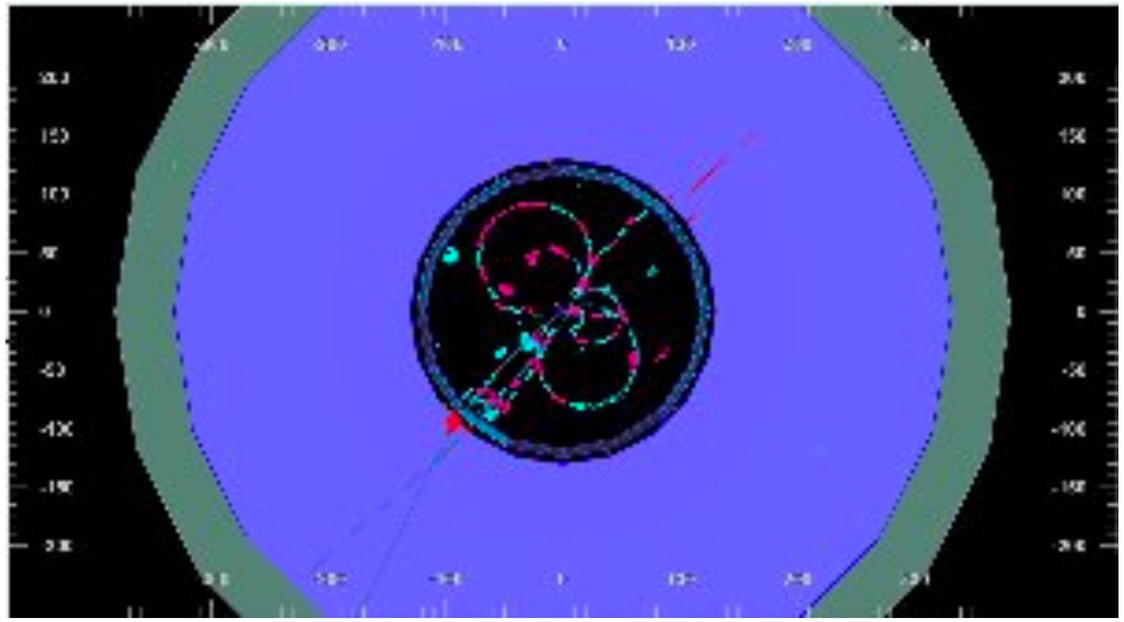


Indirect signals of BSM are detected in flavor experiments!!

Very exciting!

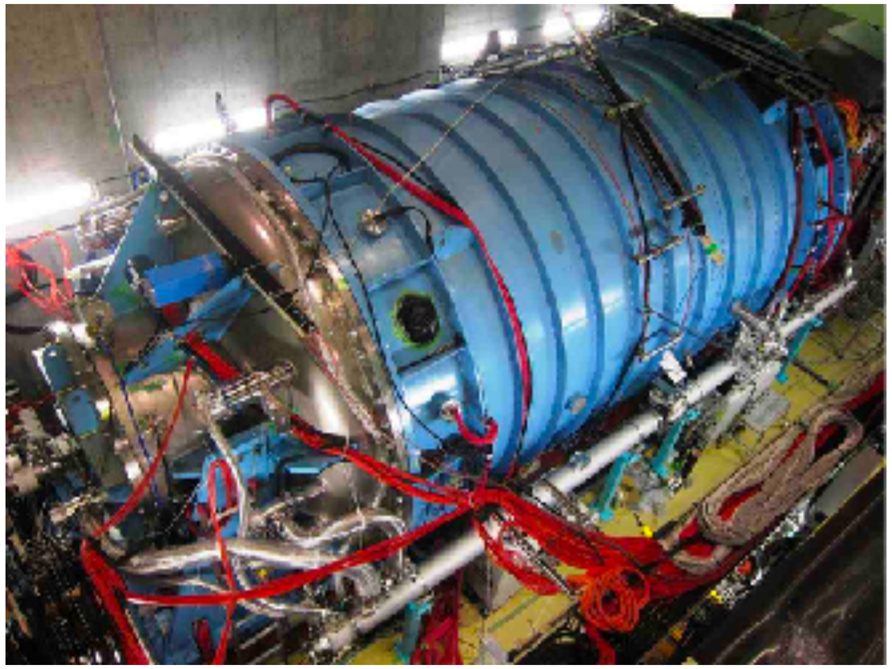
Various (new) experiments are ongoing (planned)!

[picture from the web]



the first collision of the SuperKEKB (Belle II) @ KEK on 26th April 2018

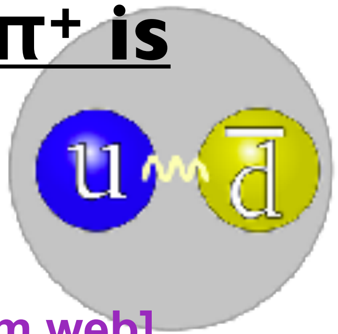
NA62 exp. @ CERN



KOTO exp. @ J-PARC

Three anomalies: $R_{K^{(*)}}$[+associates], $R_{D^{(*)}}$, ε'/ε

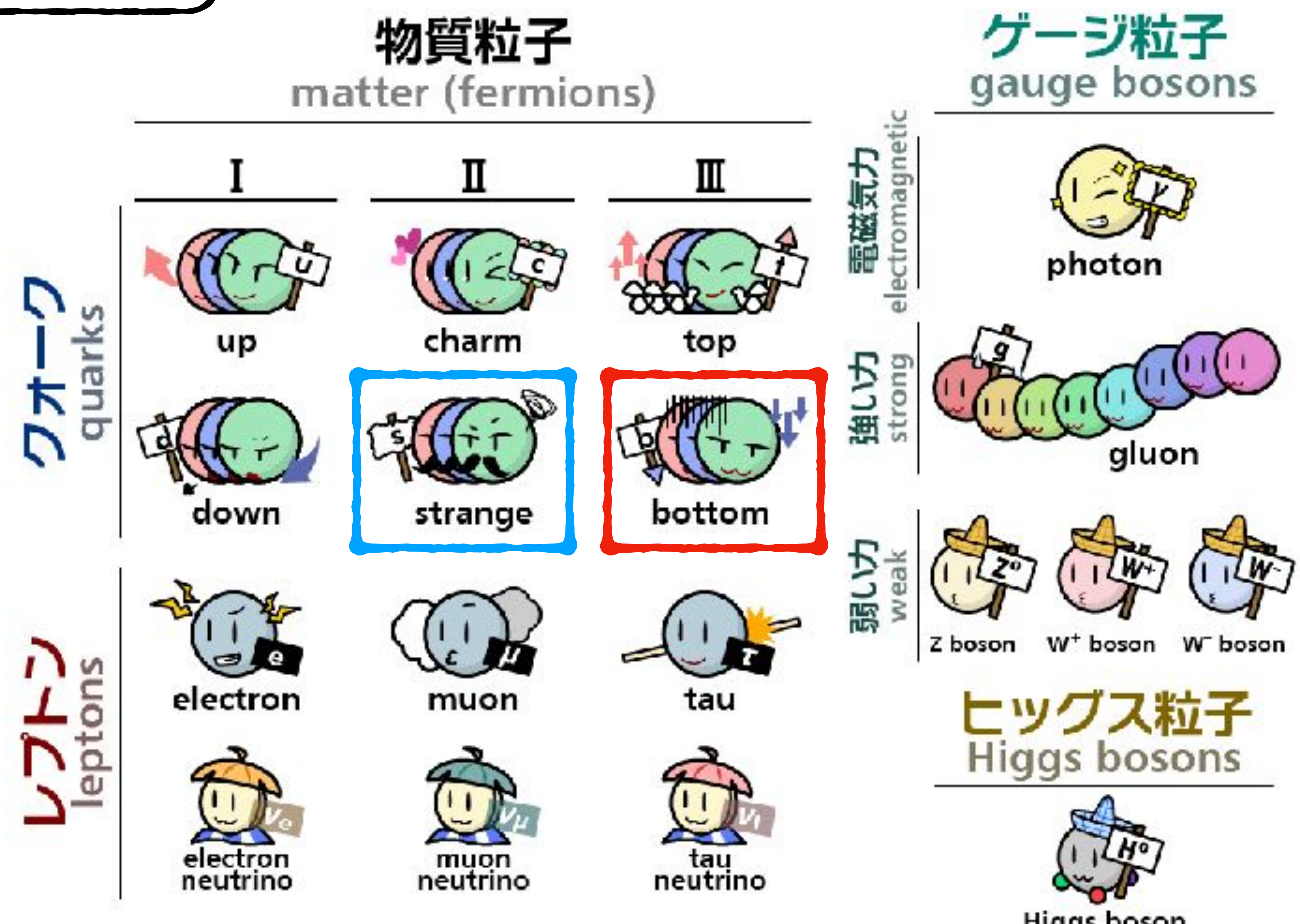
e.g., π^+ is



[picture from web]

in B meson
(including bottom quark)

in K meson
(including strange quark)



Three anomalies: $R_{K^{(*)}}$[+associates], $R_{D^{(*)}}$, ε'/ε

[LHCb, arXiv:1406.6482]

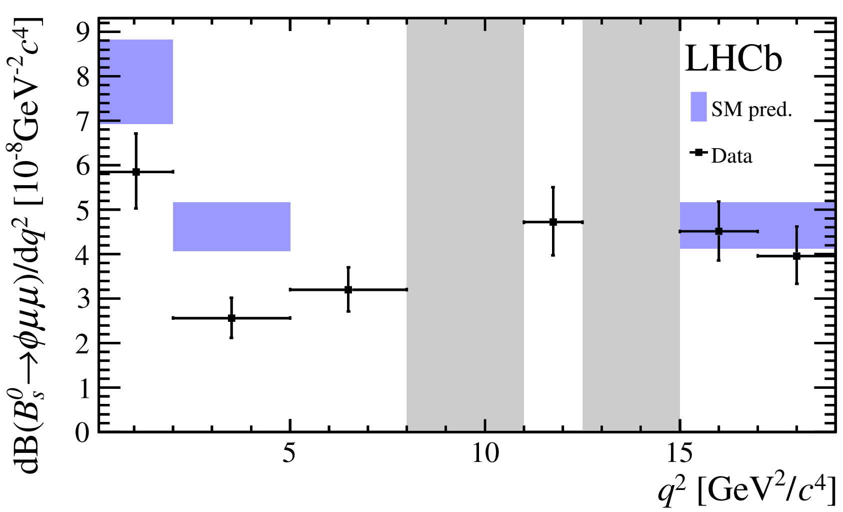
$$R_K \equiv \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036 \qquad \text{for } 1\,\text{GeV}^2 < q^2 < 6\,\text{GeV}^2$$

[LHCb (seminar in CERN on 18th April), arXiv:1705.05802]

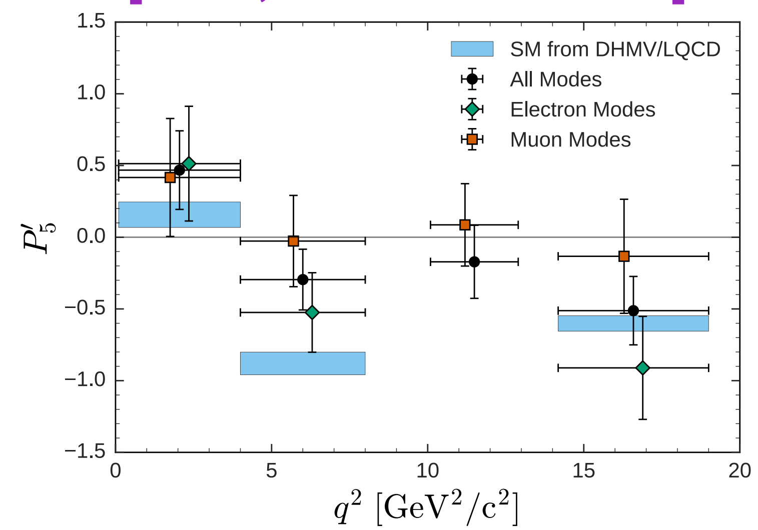
$$R_{K^*} \equiv \frac{\mathcal{B}(B \to K^*\mu^+\mu^-)}{\mathcal{B}(B \to K^*e^+e^-)} = \begin{cases} 0.660^{+0.110}_{-0.070} \pm 0.024 & \text{for } (2m_\mu)^2 < q^2 < 1.1\,\text{GeV}^2 \\ 0.685^{+0.113}_{-0.069} \pm 0.047 & \text{for } 1.1\,\text{GeV}^2 < q^2 < 6\,\text{GeV}^2 \end{cases}$$

suggesting lepton flavor violation (2.2-2.6σ) [=1 in SM]

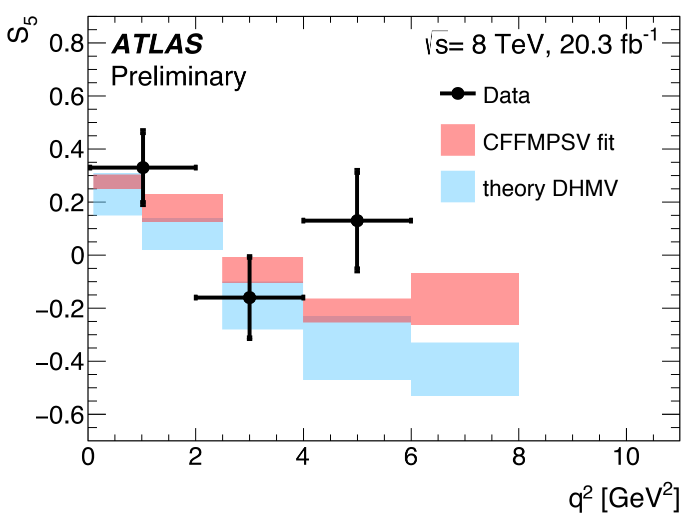
[LHCb, arXiv:1506.08777]



[Belle, arXiv:1612.05014]



[ATLAS, ATLAS-CONF-2017-023]

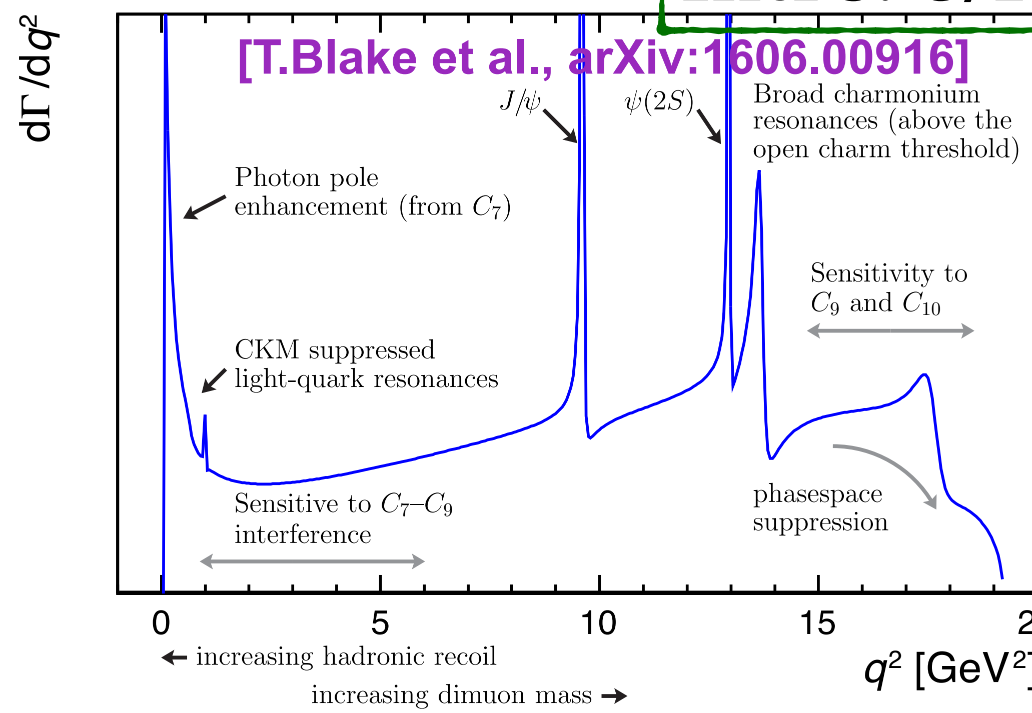


deviations being observed in associated variables

Three anomalies: $R_{K^{(*)}}$[+associates], $R_{D^{(*)}}$, ε'/ε

$$\mathcal{H}_{\rm eff}^{\rm NP} = -\frac{4\,G_F}{\sqrt{2}} V_{tb}V_{ts}^{*}\frac{e^2}{16\pi^2}\sum_{i,\ell}(C_i^{\ell}O_i^{\ell} + C_i'^{\,\ell}O_i'^{\,\ell}) + \text{h.c.}$$

$$O_9^{\ell} = (\bar{s}\gamma_{\mu}P_L b)(\bar{\ell}\gamma^{\mu}\ell), \qquad O_9'^{\,\ell} = (\bar{s}\gamma_{\mu}P_R b)(\bar{\ell}\gamma^{\mu}\ell),$$
$$O_{10}^{\ell} = (\bar{s}\gamma_{\mu}P_L b)(\bar{\ell}\gamma^{\mu}\gamma_5\ell)\,, O_{10}'^{\,\ell} = (\bar{s}\gamma_{\mu}P_R b)(\bar{\ell}\gamma^{\mu}\gamma_5\ell)\,,$$

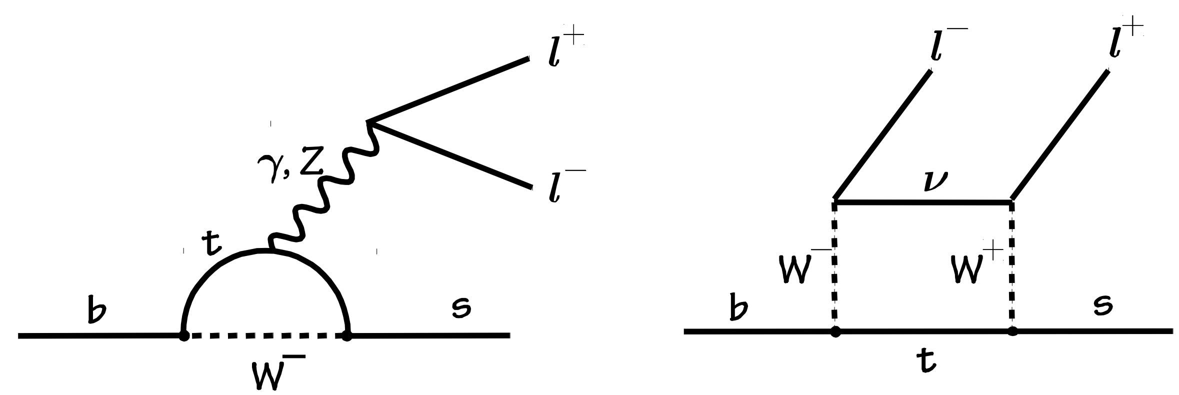


[global fit result for new physics]

[W.Altmannshofer et al., arXiv:1704.05435]

Coeff.	best fit	1σ	2σ	pull
C_9^{μ}	-1.59	$[-2.15,\ -1.13]$	$[-2.90,\ -0.73]$	4.2σ
C_{10}^{μ}	$+1.23$	$[+0.90,\ +1.60]$	$[+0.60,\ +2.04]$	4.3σ
C_9^{e}	$+1.58$	$[+1.17,\ +2.03]$	$[+0.79,\ +2.53]$	4.4σ
C_{10}^{e}	-1.30	$[-1.68,\ -0.95]$	$[-2.12,\ -0.64]$	4.4σ
$C_9^{\mu} = -C_{10}^{\mu}$	-0.64	$[-0.81,\ -0.48]$	$[-1.00,\ -0.32]$	4.2σ
$C_9^{e} = -C_{10}^{e}$	$+0.78$	$[+0.56,\ +1.02]$	$[+0.37,\ +1.31]$	4.3σ
$C_9'^{\,\mu}$	-0.00	$[-0.26,\ +0.25]$	$[-0.52,\ +0.51]$	0.0σ
$C_{10}'^{\,\mu}$	$+0.02$	$[-0.22,\ +0.26]$	$[-0.45,\ +0.49]$	0.1σ
$C_9'^{\,e}$	$+0.01$	$[-0.27,\ +0.31]$	$[-0.55,\ +0.62]$	0.0σ
$C_{10}'^{\,e}$	-0.03	$[-0.28,\ +0.22]$	$[-0.55,\ +0.46]$	0.1σ

[in the SM]



[pictures from Web]

($C_9^{SM} = -C_{10}^{SM} \sim 4$)

[see also e.g., arXiv:1704. 15340,1704.05435,1704.05438,1704.05444, 1704.05446,1704.05447, 1704.05672, 1704.7347, 1704.07397, 1704.08168]

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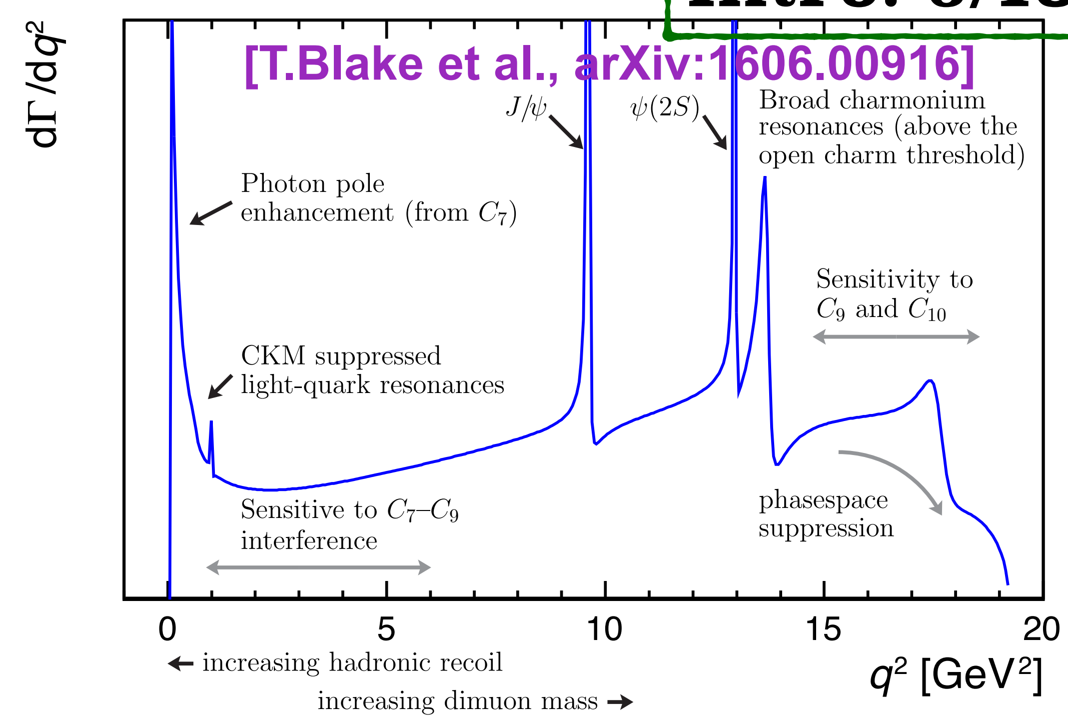

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- ☑ **(effective) vector interaction**
- ☑ **s and b should be left-handed (right-handed is irrelevant).**
- ☑ **Lepton part is ambiguous (vector-like, left-handed,...).**

($C_9^{SM} = -C_{10}^{SM} \sim 4$)

[see also e.g., arXiv:1704. 15340,1704.05435,1704.05438,1704.05444, 1704.05446,1704.05447, 1704.05672, 1704.7347, 1704.07397, 1704.08168]

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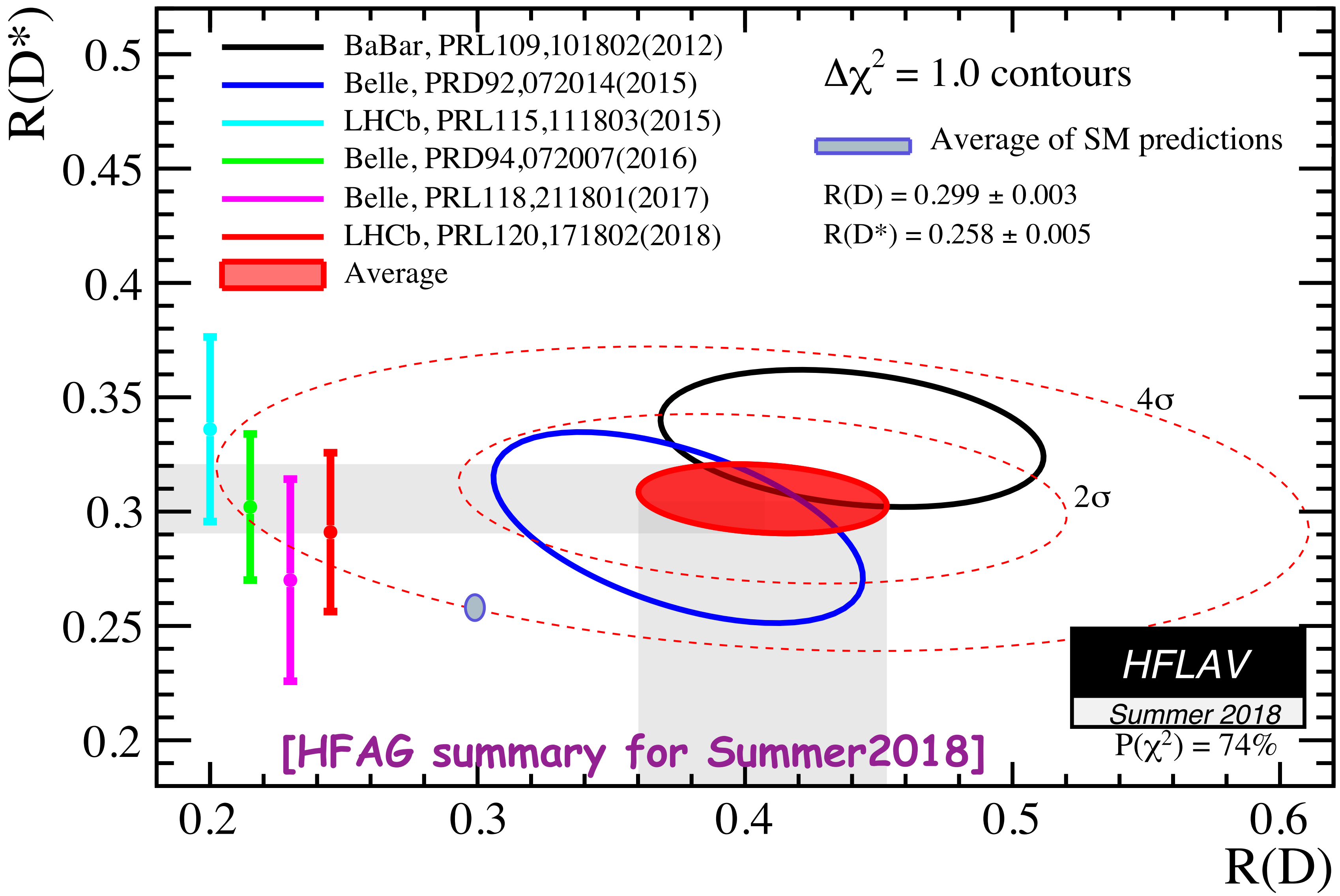
$$R(D) = \frac{\mathcal{B}(\bar{B} \to D\tau^-\bar{\nu}_{(\tau)})}{\mathcal{B}(\bar{B} \to D\ell^-\bar{\nu}_{(\ell)})}, \quad R(D^*) = \frac{\mathcal{B}(\bar{B} \to D^*\tau^-\bar{\nu}_{(\tau)})}{\mathcal{B}(\bar{B} \to D^*\ell^-\bar{\nu}_{(\ell)})}$$

- $\ell = e$ or μ **(taking averages)**
- **$\overline{B}$(D) = $\overline{B}^0$(D^+) or B^-(D^0) (taking averages)**



- **R(D)$_{SM}$ = 0.299 ± 0.003**
- **R(D*)$_{SM}$ = 0.258 ± 0.005**
- **~4σ deviation from the SM**

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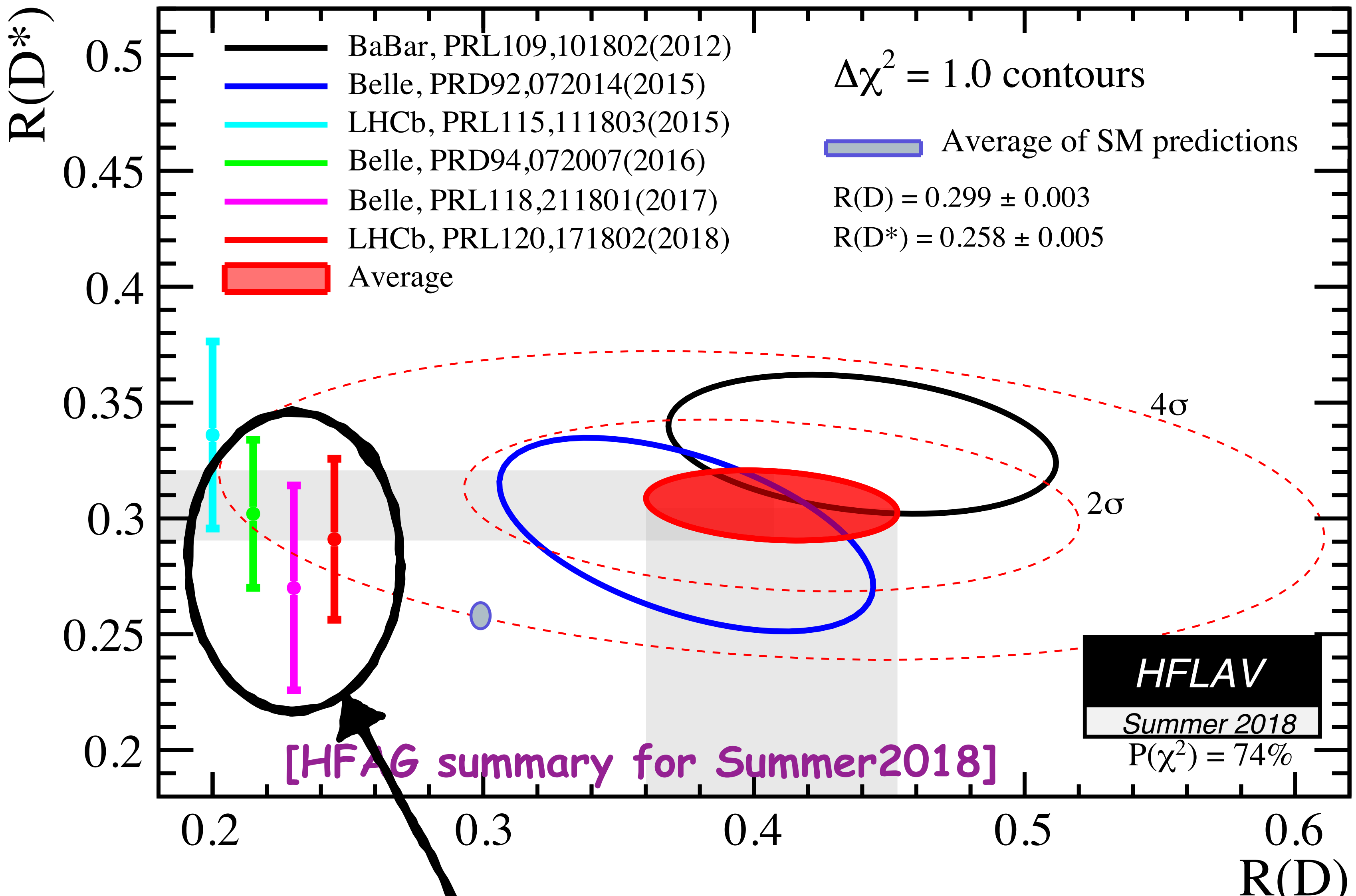


- **$R(D)_{SM}$ = 0.299 ± 0.003**
- **$R(D^*)_{SM}$ = 0.258 ± 0.005**
- **~4σ deviation from the SM**

Latest Belle/LHCb results for R_{D^*} look close to SM.

Three anomalies: $R_{K^{(*)}}$[+associates], $R_{D^{(*)}}$, ε'/ε

- **Recently, the direct CP violation of the $K^0 \to 2\pi$ decays have been reevaluated based on the latest lattice calculations of the hadron matrix elements, where the theoretical uncertainty are significantly reduced.**

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

arXiv:1505.07863
arXiv:1507.06345
arXiv:1607.06727

2.8-2.9σ discrepancy

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

arXiv:hep-ex/0208009, 0208007,1011.0127,PDG

- $K^0(\bar{s}\gamma_5 d)$, $\overline{K^0}(\bar{d}\gamma_5 s)$: **$J^P=0^-$, ≠ (mass, CP eigenstate)**
  - **CP eigenstate:** $|K_{\frac{1}{2}}\rangle = \frac{1}{2}\left[|K^0\rangle \pm |\overline{K^0}\rangle\right] \left(\text{c.f. } CP|K^0\rangle = |\overline{K^0}\rangle\right)$

    CP even CP odd

    CPV parameter (εbar~10^{-3})
  - **mass eigenstate:** $|K_S\rangle \sim \overset{\text{CP-even}}{|K_1\rangle} + \bar{\epsilon}\,\overset{\text{CP-odd}}{|K_2\rangle}, \quad |K_L\rangle \sim \overset{\text{CP-odd}}{|K_2\rangle} + \bar{\epsilon}\,\overset{\text{CP-even}}{|K_1\rangle}$

    shorter lifetime longer lifetime

Three anomalies: $R_{K^{(*)}}$[+associates], $R_{D^{(*)}}$, ε'/ε

- $CP|K^{\pm}\rangle = \pm|K^{\pm}\rangle,\ CP|\pi^0\pi^0\rangle = +|\pi^0\pi^0\rangle,\ CP|\pi^0\pi^0\pi^0\rangle = -|\pi^0\pi^0\pi^0\rangle$

$K_L \to \pi\pi$ is prohibited if CP is an exact symmetry:

$$|K_L\rangle \sim \overbrace{|K_2\rangle}^{\text{CP-odd}} + \bar{\epsilon}\,\overbrace{|K_1\rangle}^{\text{CP-even}}$$

indirect CPV

CPV during oscillation

$|K_1\rangle \to \overbrace{|\pi\pi\rangle}^{\text{CP-even}}$

direct CPV

CPV at decay

$|K_2\rangle \to \overbrace{|\pi\pi\rangle}^{\text{CP-even}}$

- **Two CVP decay modes: $K_L \to \pi^+\pi^-$, $K_L \to \pi^0\pi^0$**

- The ratios of amplitudes works as order parameters:

Indirect CPVs are universal.

- $$\eta_{00} = \frac{\mathcal{A}(K_L \to \pi^0\pi^0)}{\mathcal{A}(K_S \to \pi^0\pi^0)} = \epsilon_{(K)} - 2\epsilon'_{(K)}$$
- $$\eta_{+-} = \frac{\mathcal{A}(K_L \to \pi^+\pi^-)}{\mathcal{A}(K_S \to \pi^+\pi^-)} = \epsilon_{(K)} + \epsilon'_{(K)}$$

Direct CPVs appear differently.

Three anomalies: $R_{K^{(*)}}$[+associates], $R_{D^{(*)}}$, ε'/ε

☑ **What kind of new physics is required (at tree level)?**

→ **Straightforward candidates are new gauge bosons.**

Three anomalies: $R_{K^{(*)}}$[+associates], $R_{D^{(*)}}$, ε'/ε

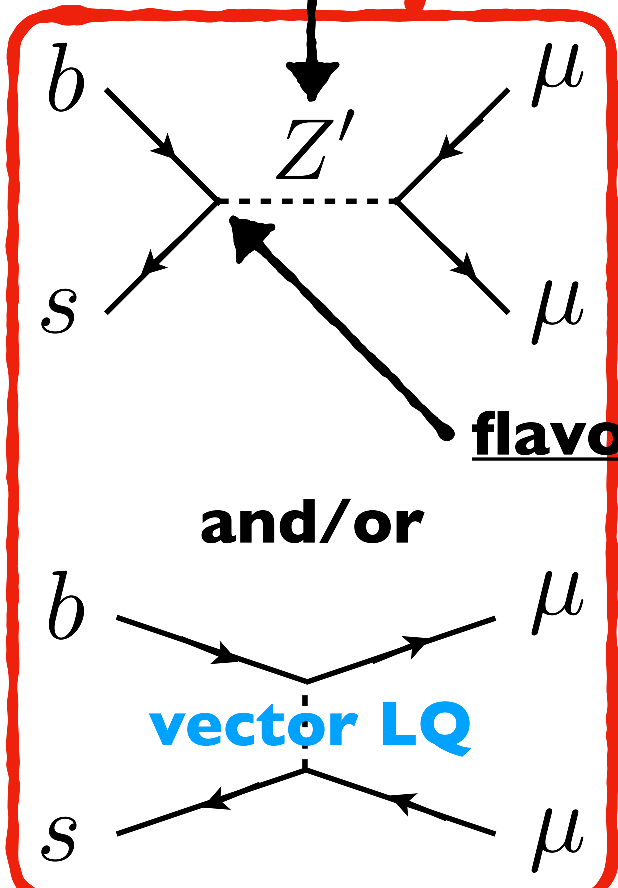
☑ **What kind of new physics is required (at tree level)?**

→ **Straightforward candidates are new gauge bosons.**

W', vector LQ (charged current, semi-leptonic)

W', Z', massive gluon (pure hadronic)

(a) new vector boson



Such a flavorful Z' (and/or vector leptoquark) is a straightforward solution.

Three anomalies: $R_{K^{(*)}}$[+associates], ~~$R_{D^{(*)}}$~~, ε'/ε

☑ **What kind of new physics is required (at tree level)?**

➜ **Straightforward candidates are new gauge bosons.**

see e.g., arXiv:1206.3760, 1210.8443,1303.5877,1306.6493, 1309.0301, plus many others

see e.g., arXiv:1507.06316, 1512.02869, 1603.07960, 1604.07400,1608.01444, plus others

(a) new vector boson

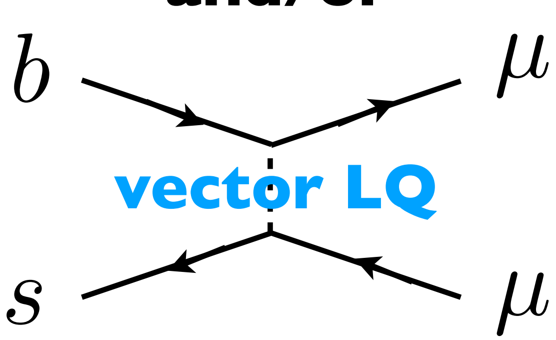
see e.g., arXiv:1303.5794,1307.5683,1308.1501, 1408.1627,1411.3161,1412.1791, plus many others

ark)

ution.

flavor-changing

and/or



Trying to address them simultaneously

- Chiral couplings are requested.
- No enough contribution for $R_{D^{(*)}}$ is achievable.

SU(8) (composite) vector scenario provides all of them!

Three messages

0. Introduction (10 pages)

1. Hidden "QCD" $\Rightarrow$ providing vectors for anomalies (4 pages)

2. Various virtues exist in vector-like compositeness (2 pages)

3. Simultaneous addressing for B & K anomalies,
   which can be surveyed in the very near future (4 pages)

- Summary & Discussions

Three messages

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Summary & Discussions

QCD as Composite scenario

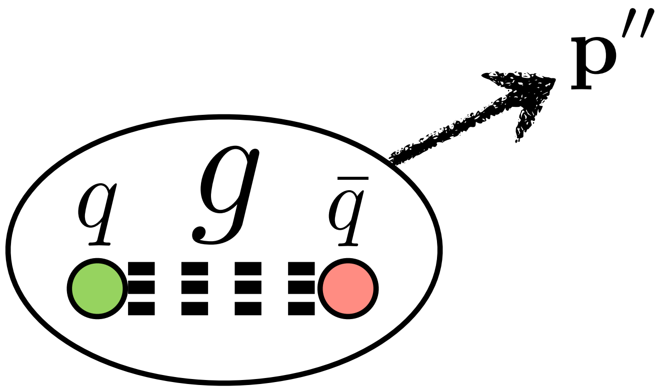
When a coupling becomes strong, composite particles appear.

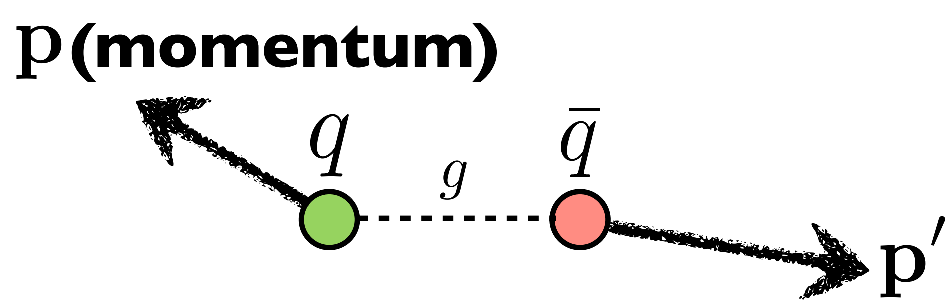
☑ $\langle \bar{q}^A q^B \rangle \sim \Lambda^3_{\rm QCD} \delta^{AB}$ (confinement)

Spontaneous breakdown:
SU(3)$_L$×SU(3)$_R$ → SU(3)$_V$

☑ $q_{L/R} = \begin{pmatrix} u \\ d \\ s \\ \vdots \end{pmatrix}_{L/R}$

SU(3)$_L$×SU(3)$_R$ (approximated) chiral symmetry





strongly coupled (theory of composite particles)

weekly coupled (UV-fundamental) particles

$\Lambda_{\rm QCD}$

Energy

It provides us a well-established way for describing (vector) mesons.

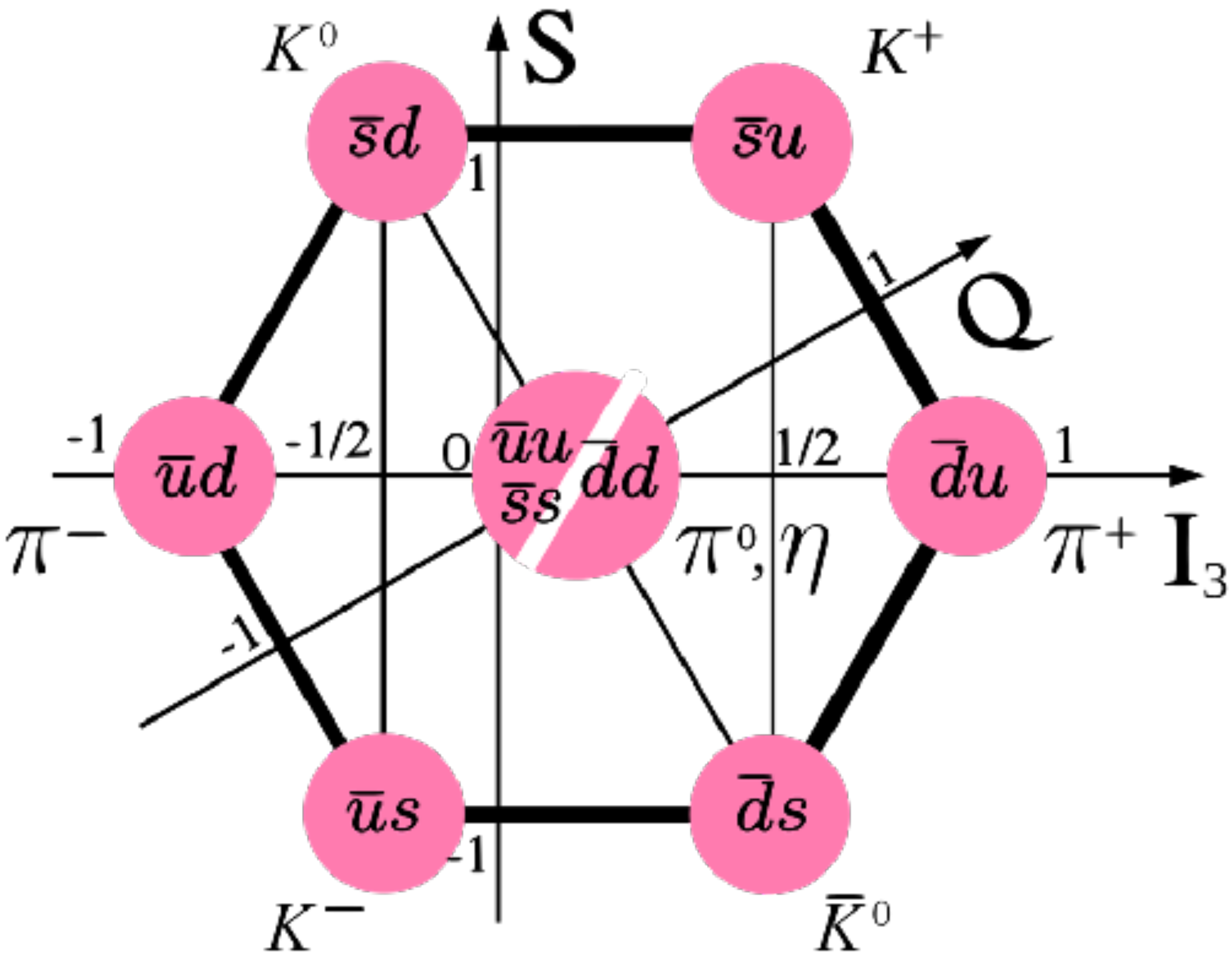
QCD ⟶ Hidden QCD

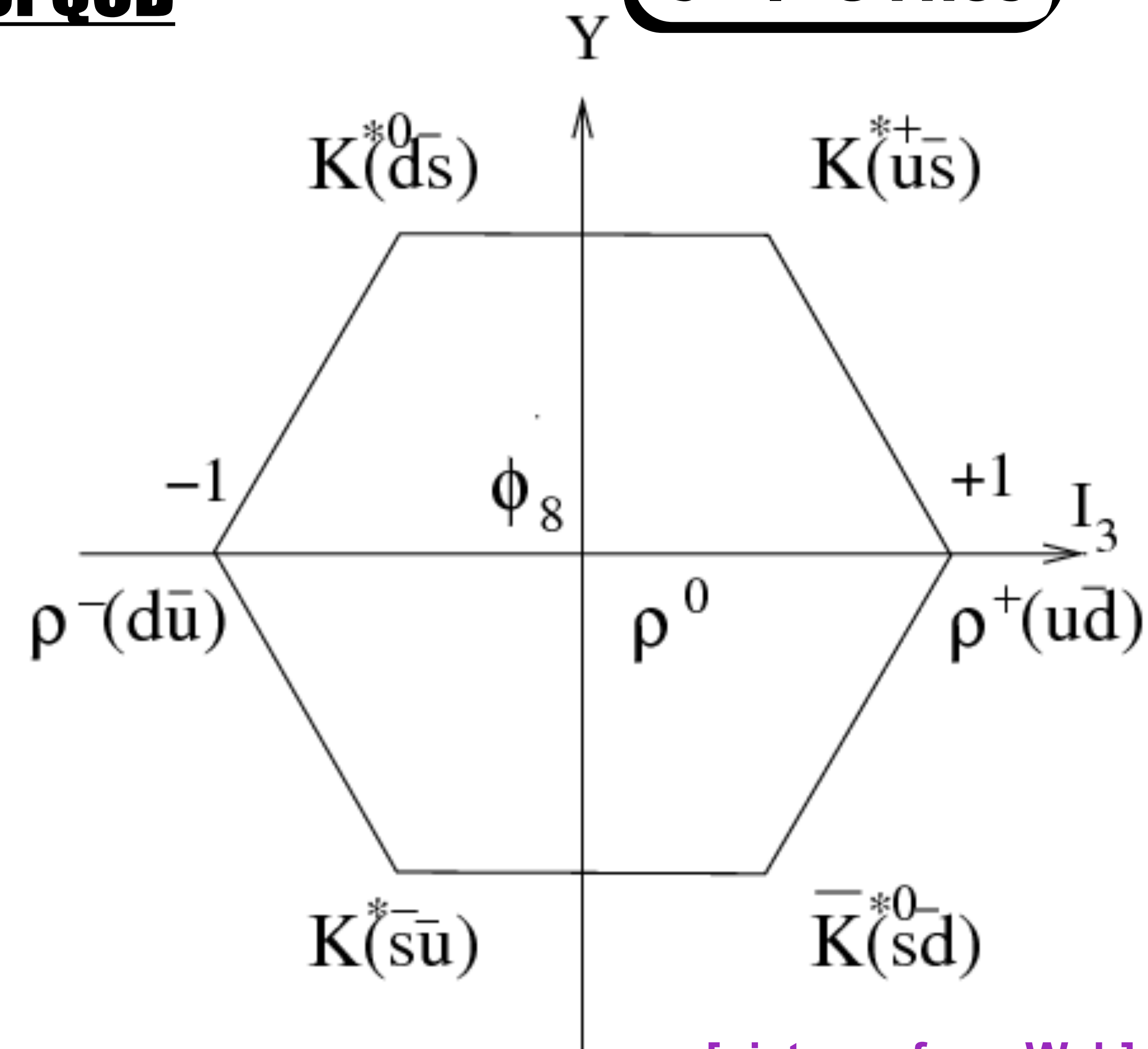
Global symmetry → Meson patterns

3^2-1=8 pions

In case of QCD

3^2-1=8 rhos





[pictures from Web]

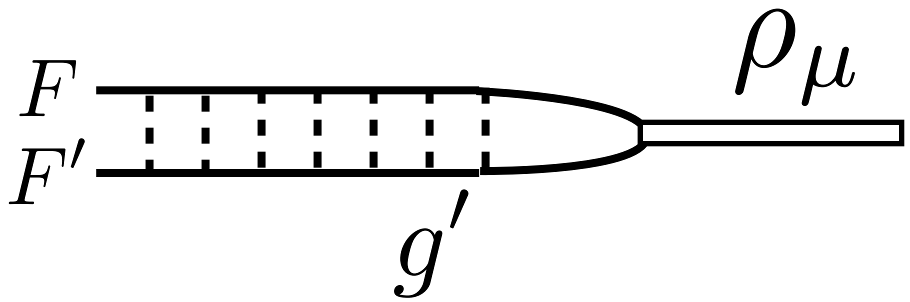
Chiral symmetry governs low-energy composite (meson) spectrum.

- ☑ **pseudo-scalars (pions) as pseudo NG bosons**
- ☑ **vector mesons (rhos) as gauge bosons of hidden local symmetry ($SU(3)_{V,\ gauged}$)**

[Bando,Kugo,Uehara,Yamawaki, Phys.Rev.Lett.,54(1985)1215]
[Bando,Kugo,Yamawaki, Nucl.Phys.,B259(1985)493]
[reviewed by e.g., Harada,Yamawaki, arXiv:hep-ph/0302103]

Vector-like **hidden** “QCD” (hypercolor[**HC**])

We consider an SU(N_{HC}) confining gauge theory (fermion: F, gauge boson: g’)



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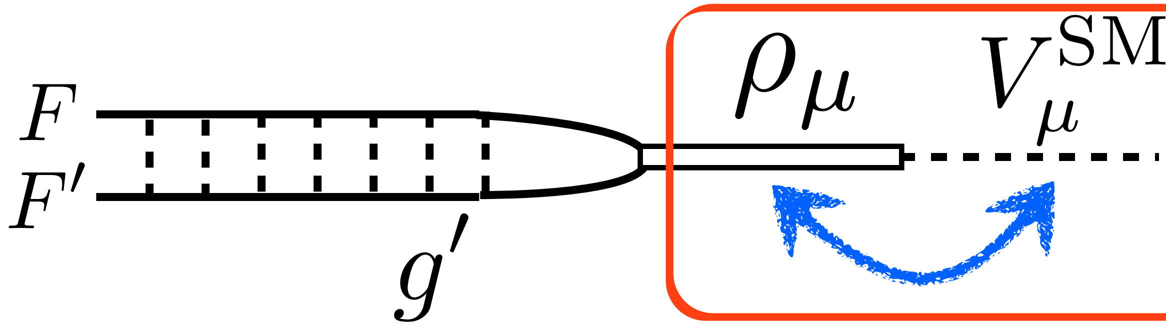
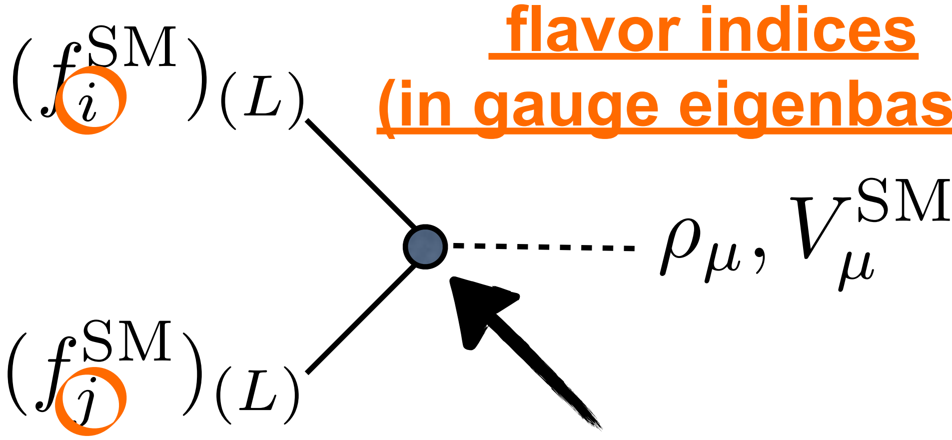


holding the Same (SM) quantum #

flavor indices (in gauge eigenbasis)



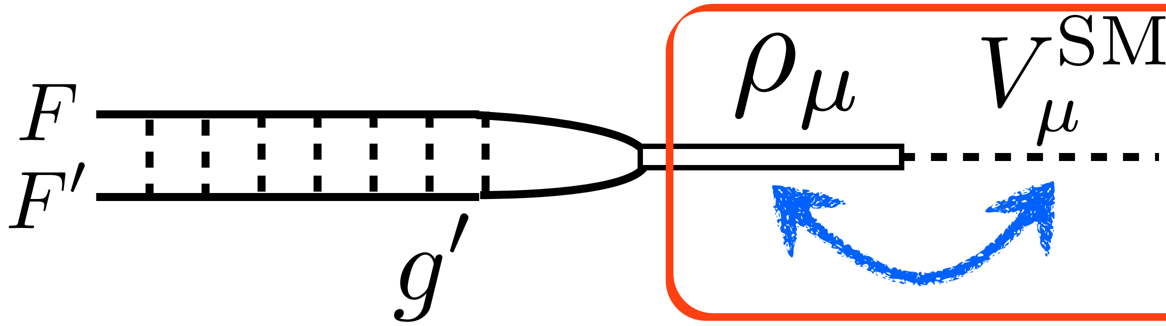
undesignated/assumed physics with flavor-changing

In a situation that ρ_μ "mix with" the SM gauge boson, ρ_μ may couple with the SM fermions in an effective way!

Gauge-invariant (effective) operator including it can be written down in terms of hidden local symmetry (with nonlinear basis)

Vector-like **hidden** "QCD" (hypercolor[**HC**])

- **We consider an SU(N_{HC}) confining gauge theory (fermion: F, gauge boson: g')**



holding the Same (SM) quantum #

In a situation that ρ_μ "mix with" the SM gauge boson, ρ_μ may couple with the SM fermions in an effective way!

- **Configuration:**

anomaly-free — **confined** — **external gauge interactions**

	$SU(N_{\mathrm{HC}})$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
new (HC) quarks $Q_{L/R} = \begin{pmatrix} U \\ D \end{pmatrix}_{L/R}$	N_{HC}	**3**	**2**	$1/6$
new (HC) leptons $L_{L/R} = \begin{pmatrix} N \\ E \end{pmatrix}_{L/R}$	N_{HC}	**1**	**2**	$-1/2$

SU(8)$_L$×SU(8)$_R$ chiral symmetries

$F_{L/R} = \begin{pmatrix} Q \\ L \end{pmatrix}_{L/R}$

(one-family model)

Effectively, formed mesons can couple to SM doublet fermions (left-handed)
← favored by the flavor results

Vector-like **hidden** "QCD" (hypercolor[**HC**])

QCD (quarks)

$$q_{L/R} = \begin{pmatrix} u \\ d \\ s \\ \vdots \end{pmatrix}_{L/R}$$

[N_f=3: 3^2-1= 8 d.o.f.s]

Hidden "QCD" (new fermions)

$$F_{L/R} = \begin{pmatrix} U_R \\ U_G \\ U_B \\ D_R \\ D_G \\ D_B \\ N \\ E \end{pmatrix}_{L/R}$$

[N_f=8: 8^2-1= 63 d.o.f.s]

Configuration:

SU(8)$_L$×SU(8)$_R$ chiral symmetries

$$F_{L/R} = \begin{pmatrix} Q \\ L \end{pmatrix}_{L/R}$$

(one-family model)

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Vector-like **hidden** "QCD" [**HC**] (cont'd)

[vector meson spectrum] NOT ONLY Z' candidates!

composite vector	constituent	color	isospin
$\rho^{\alpha}_{(8)a}$	$\frac{1}{\sqrt{2}}\bar{Q}\gamma_\mu\lambda^a\tau^\alpha Q$	octet	triplet
$\rho^{0}_{(8)a}$	$\frac{1}{2\sqrt{2}}\bar{Q}\gamma_\mu\lambda^a Q$	octet	singlet
$\rho^{\alpha}_{(3)c}\ \left(\bar{\rho}^{\alpha}_{(3)c}\right)$	$\frac{1}{\sqrt{2}}\bar{Q}_c\gamma_\mu\tau^\alpha L$ (h.c.)	triplet	triplet
$\rho^{0}_{(3)c}\ \left(\bar{\rho}^{0}_{(3)c}\right)$	$\frac{1}{2\sqrt{2}}\bar{Q}_c\gamma_\mu L$ (h.c.)	triplet	singlet
$\rho^{\alpha}_{(1)'}$	$\frac{1}{2\sqrt{3}}(\bar{Q}\gamma_\mu\tau^\alpha Q - 3\bar{L}\gamma_\mu\tau^\alpha L)$	singlet	triplet
$\rho^{0}_{(1)'}$	$\frac{1}{4\sqrt{3}}(\bar{Q}\gamma_\mu Q - 3\bar{L}\gamma_\mu L)$	singlet	singlet
$\rho^{\alpha}_{(1)}$	$\frac{1}{2}(\bar{Q}\gamma_\mu\tau^\alpha Q + \bar{L}\gamma_\mu\tau^\alpha L)$	singlet	triplet

19 in total

massive gluons

vector leptoquarks

Z' (and W') included

Vector-like **hidden** "QCD" [**HC**] (cont'd)

[vector meson spectrum] NOT ONLY Z' candidates!

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[gauge structure]

SU(8)$_{V,\ \text{gauged}}$ (ρ_μ)

for SU(2)$_W$-doublet SM quarks

$$\left[\mathcal{L}^f_\mu\right]_{8\times 8} = \left(\begin{array}{c|c} \boxed{\mathbf{1}_{2\times 2}\otimes g_s G^a_\mu \frac{\lambda^a}{2} + \left(g_W W_\mu \tau^\alpha + \frac{1}{6}g_Y B_\mu\right)\otimes \mathbf{1}_{3\times 3}} & \mathbf{0}_{6\times 2} \\ \hline \mathbf{0}_{2\times 6} & \boxed{g_W W^\alpha_\mu \tau^\alpha - \frac{1}{2}g_Y B_\mu \cdot \mathbf{1}_{2\times 2}} \end{array}\right)$$

for SU(2)$_W$-doublet SM leptons

SM gauge boson structure of (q,l)$_L$ in SU(8)$_V$ form

$$\boxed{\rho = \begin{pmatrix} (\rho_{QQ})_{6\times 6} & (\rho_{QL})_{6\times 2} \\ (\rho_{LQ})_{2\times 6} & (\rho_{LL})_{2\times 2} \end{pmatrix}}$$

Vector-like **hidden** “QCD” [**HC**] (cont’d)

[vector meson spectrum] NOT ONLY Z’ candidates!

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mixed with gluon

with B

with W

19 in total

massive gluons

vector leptoquarks

Z’ (and W’) included

V_{SM}-ρ mixing
(if the partner exists)

The following flavor-changing interaction can be added gauge-invariantly.

$$\boxed{g_L^{ij}} \times \left(\bar{q}_i^{\mathrm{SM}} \quad \bar{l}_i^{\mathrm{SM}}\right)_L \gamma^\mu \left(g^{\mathrm{SM}} V_\mu^{\mathrm{SM}} - g_\rho \rho_\mu + \cdots\right) \begin{pmatrix} q_j^{\mathrm{SM}} \\ l_j^{\mathrm{SM}} \end{pmatrix}_L$$

undetermined coefficients

flavor indices (in gauge eigenbasis)

Three messages

0. Introduction (10 pages)

1. Hidden "QCD" ⇒ providing vectors for anomalies (4 pages)

2. Various virtues exist in vector-like compositeness (2 pages)

3. Simultaneous addressing for B & K anomalies,
which can be surveyed in the very near future (4 pages)

Summary & Discussions

Important points for current pheno.

[B.Bhattacharya et al., arXiv:1609.09078]

We adopted the flavor texture:

(SM-fermion) mass eigenbases

$$g_L^{ij} = \begin{pmatrix} 0 & ig_L^{12} & 0 \\ (ig_L^{12})^* & 0 & 0 \\ 0 & 0 & g_L^{33} \end{pmatrix}^{ij} \quad (u_L)^i = U^{iI}(u'_L)^I, \quad (d_L)^i = D^{iI}(d'_L)^I, \quad (e_L)^i = L^{iI}(e'_L)^I, \quad (\nu_L)^i = L^{iI}(\nu'_L)^I,$$

automatically determined (with CKM matrix)

$$D = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_D & \sin\theta_D \\ 0 & -\sin\theta_D & \cos\theta_D \end{pmatrix}, \qquad L = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_L & \sin\theta_L \\ 0 & -\sin\theta_L & \cos\theta_L \end{pmatrix}$$

assuming 2⇔3 matter generation mixings

for B anomaly (in gauge eigenbasis)

[Our phenomenological scheme on flavor changing]

[Endo et al., arXiv:1612.08839]

pure imaginary (1,2) for K anomaly

⇒ very small for $\varepsilon_{(K)}$, $K^0_L \to \mu^+\mu^-$

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assuming 2⇔3 matter generation mixings

$$\begin{aligned} \mathcal{L}^{\text{direct}}_{Vf_Lf_L} = & \; g_L^{ij} \cdot \bar{q}_L^i \gamma_\mu \left[g_s G_a^\mu \left(\mathbf{1}_{2\times2} \otimes \frac{\lambda_a}{2} \right) + \left(g_W W^{\alpha\,\mu} \frac{\sigma^\alpha}{2} + \frac{g_Y}{6} B^\mu \, \mathbf{1}_{2\times2} \right) \otimes \mathbf{1}_{3\times3} - g_\rho \rho^\mu_{QQ} \right] q_L^j \\ & + g_L^{ij} \cdot \bar{l}_L^i \gamma_\mu \left[g_W W^{\alpha\,\mu} \frac{\sigma^\alpha}{2} - \frac{g_Y}{2} B^\mu \, \mathbf{1}_{2\times2} - g_\rho \rho^\mu_{LL} \right] l_L^j \\ & - g_L^{ij} g_\rho \cdot \left[\bar{q}_L^i \gamma_\mu \, \rho^\mu_{QL} \, l_L^j + \text{h.c.} \right], \end{aligned}$$

overall factor

correction to f-f-V_{SM} interaction

f-f-ρ interaction

g_ρ >> g_{SM} is required via EW precisions.
(an example: g_ρ = 6 [vector dominance in QCD])

[flavor-changing effective interaction]

The mixing effect play a significant role in addressing the anomaly in ε'/ε.

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assuming 2⇔3 matter generation mixings

for B anomaly (in gauge eigenbasis)

$$\mathcal{L}^{\rm direct}_{V f_L f_L} = g_L^{ij} \cdot \bar{q}_L^i \gamma_\mu \left[g_s G_a^\mu \left(\mathbf{1}_{2\times 2} \otimes \frac{\lambda_a}{2} \right) + \left(g_W W^{\alpha\,\mu} \frac{\sigma^\alpha}{2} + \frac{g_Y}{6} B^\mu \, \mathbf{1}_{2\times 2} \right) \otimes \mathbf{1}_{3\times 3} - g_\rho \rho^\mu_{QQ} \right] q_L^j$$
$$+ g_L^{ij} \cdot \bar{l}_L^i \gamma_\mu \left[g_W W^{\alpha\,\mu} \frac{\sigma^\alpha}{2} - \frac{g_Y}{2} B^\mu \, \mathbf{1}_{2\times 2} - g_\rho \rho^\mu_{LL} \right] l_L^j$$
$$- g_L^{ij} g_\rho \cdot \left[\bar{q}_L^i \gamma_\mu \, \rho^\mu_{QL} \, l_L^j + \text{h.c.} \right],$$

overall factor

correction to f-f-V_{SM} interaction

f-f-ρ interaction

g_ρ >> g_{SM} is required via EW precisions.
(an example: g_ρ = 6 [vector dominance in QCD])

(HC rho meson mass)^2 ~ $(m_\rho)^2$ * (1 + $[g_{SM}/g_\rho]^2$)

vector-meson spectrum being compressed

Important points for current pheno. (cont'd)

vector-like HC rho mesons ⇒ harmless (tree-level) oblique corrections

Important points for current pheno. (cont'd)

- **vector-like HC rho mesons ⇒ harmless (tree-level) oblique corrections**

- **6 couplings are relevant for (pure) HC vector-ρ phenomena:**

  m_ρ, $(g_L)^{33}$, $(g_L)^{12}$, θ_D, θ_L, g_ρ

Important points for current pheno. (cont'd)

- **vector-like HC rho mesons ⇒ harmless (tree-level) oblique corrections**

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$$m_\rho,\ (g_L)^{33},\ (g_L)^{12},\ \theta_D,\ \theta_L,\ g_\rho$$

- **No dynamical EWSB (vector-like) ⇒ the fundamental Higgs doublet should be introduced (like the SM).**

  ☑ **The 125GeV Higgs signal strengths are good.**

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- **No dynamical EWSB (vector-like) ⇒ the fundamental Higgs doublet should be introduced (like the SM).**

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- **Fascinating aspects:**

  ☑ **The C_9 = -C_{10} texture (for b→sll) is naturally realized.**

  ☑ **Apparently gauge-anomaly free.**

  ☑ **Due to SU(8) symmetry, contribution to $R_{D(*)}$ is minuscule.**
  (⇒ It may be OK due to the 'vanishing' trend in latest exp. results.)

  ☑ **Proton decay via dim-5 operators are banned by hidden local sym.**

  [N.Assad et al., arXiv:1708.06350]

$$\frac{1}{\Lambda}(\overline{q_L^c}H^\dagger)\gamma^\mu d_R\rho^0_{(3)\mu}, \quad \frac{1}{\Lambda}(\overline{q_L^c}\tau^\alpha H^\dagger)\gamma^\mu d_R\rho^\alpha_{(3)\mu}$$

← **prohibited diquark operators**

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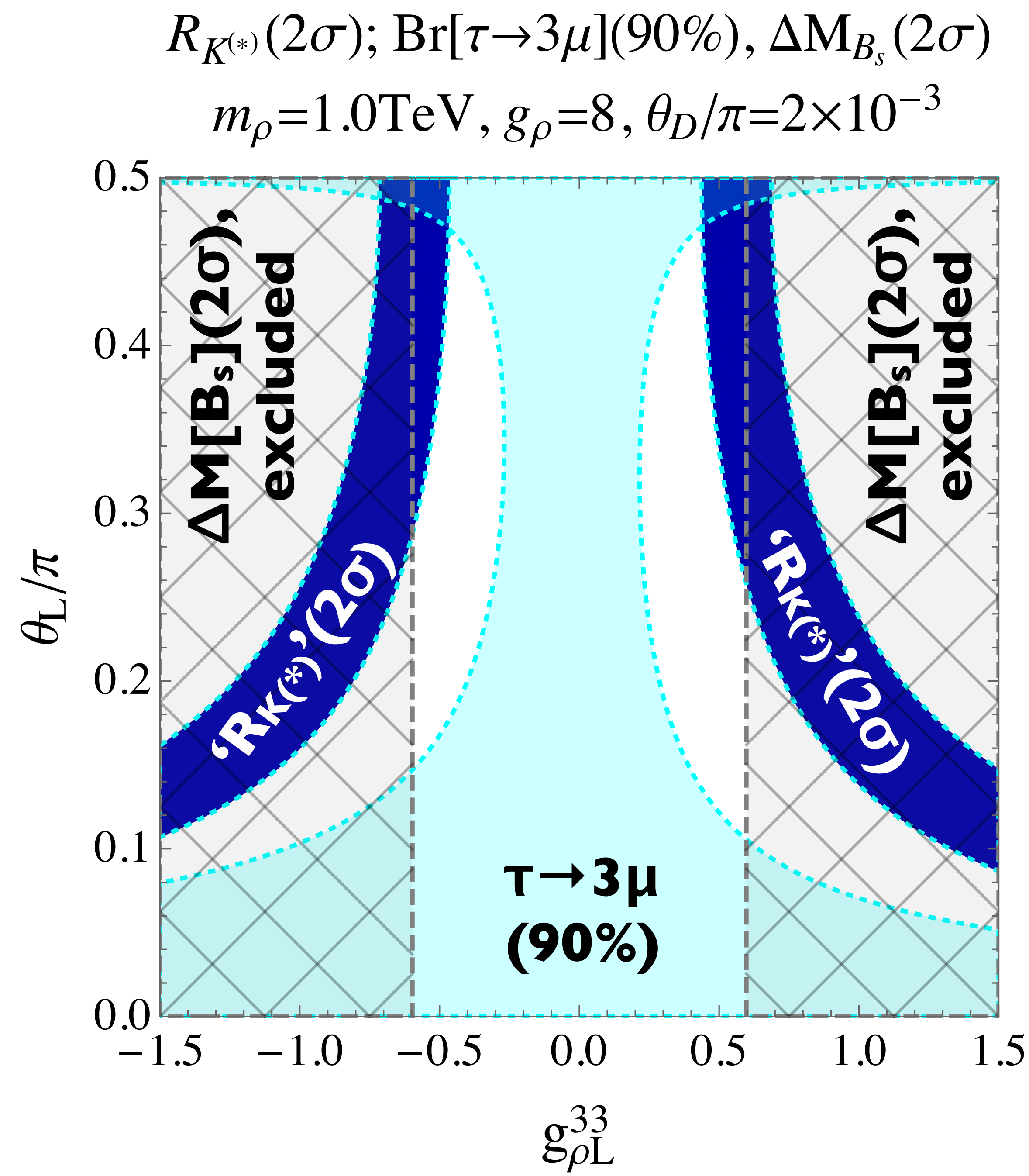
Summary & Discussions

$R_{K^{(*)}}$[+associates] result

$g_{\rho L}^{33} \equiv g_\rho \times g_L^{33}$

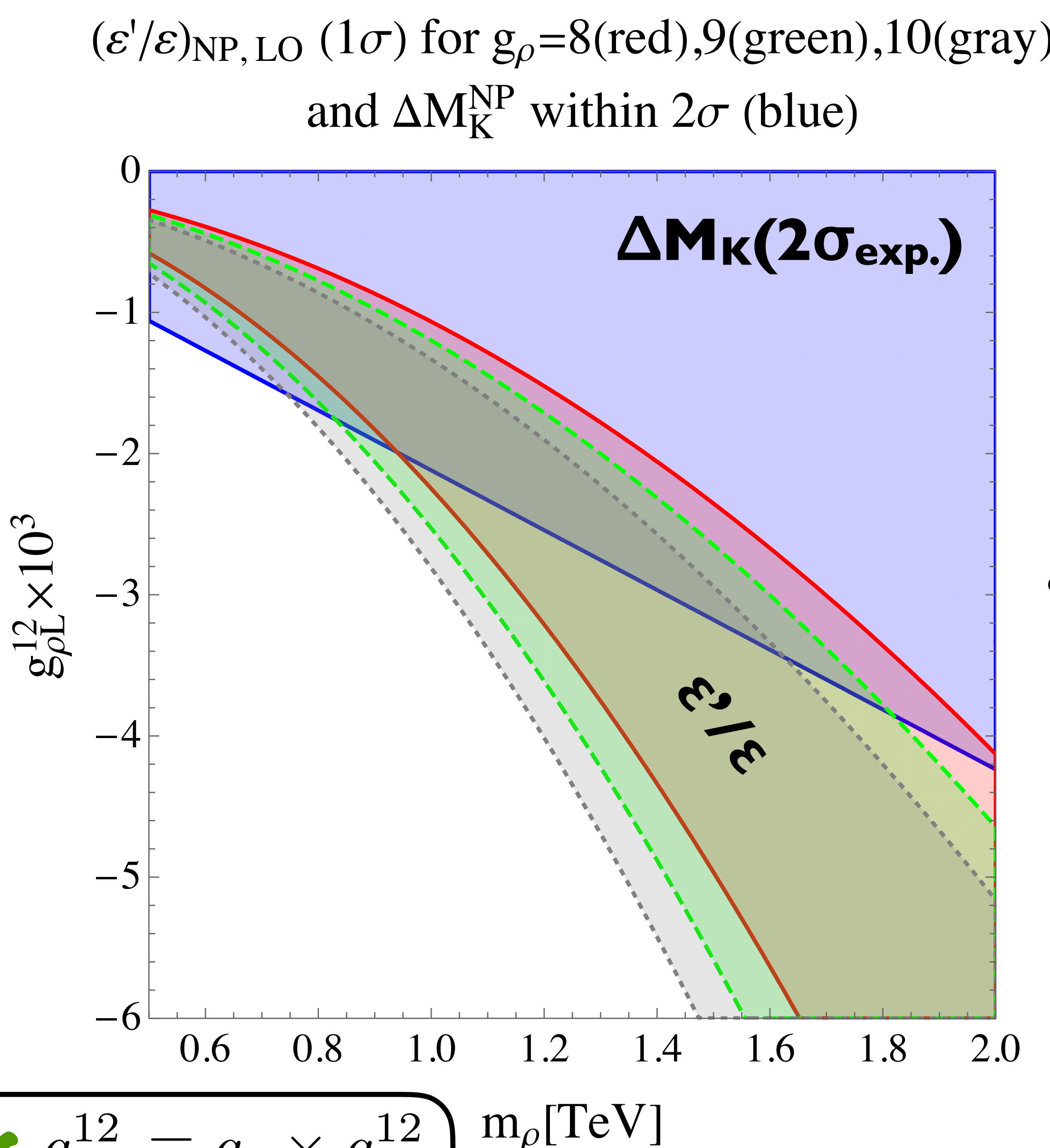


- b→sννbar, τ→φμ are OK in the whole of the shown region.
- The mixing angles should be tuned as $\theta_D \sim 5*10^{-3}$, $\theta_L \sim \pi/2$.
- NLO QCD operator running is taken into account. [D.Becirevie et al., hep-ph/0112303]
- Due to the update of the input, evading M[B_s] became (much) more nontrivial. [L.D.Luzio et al., arXiv:1712.06572]

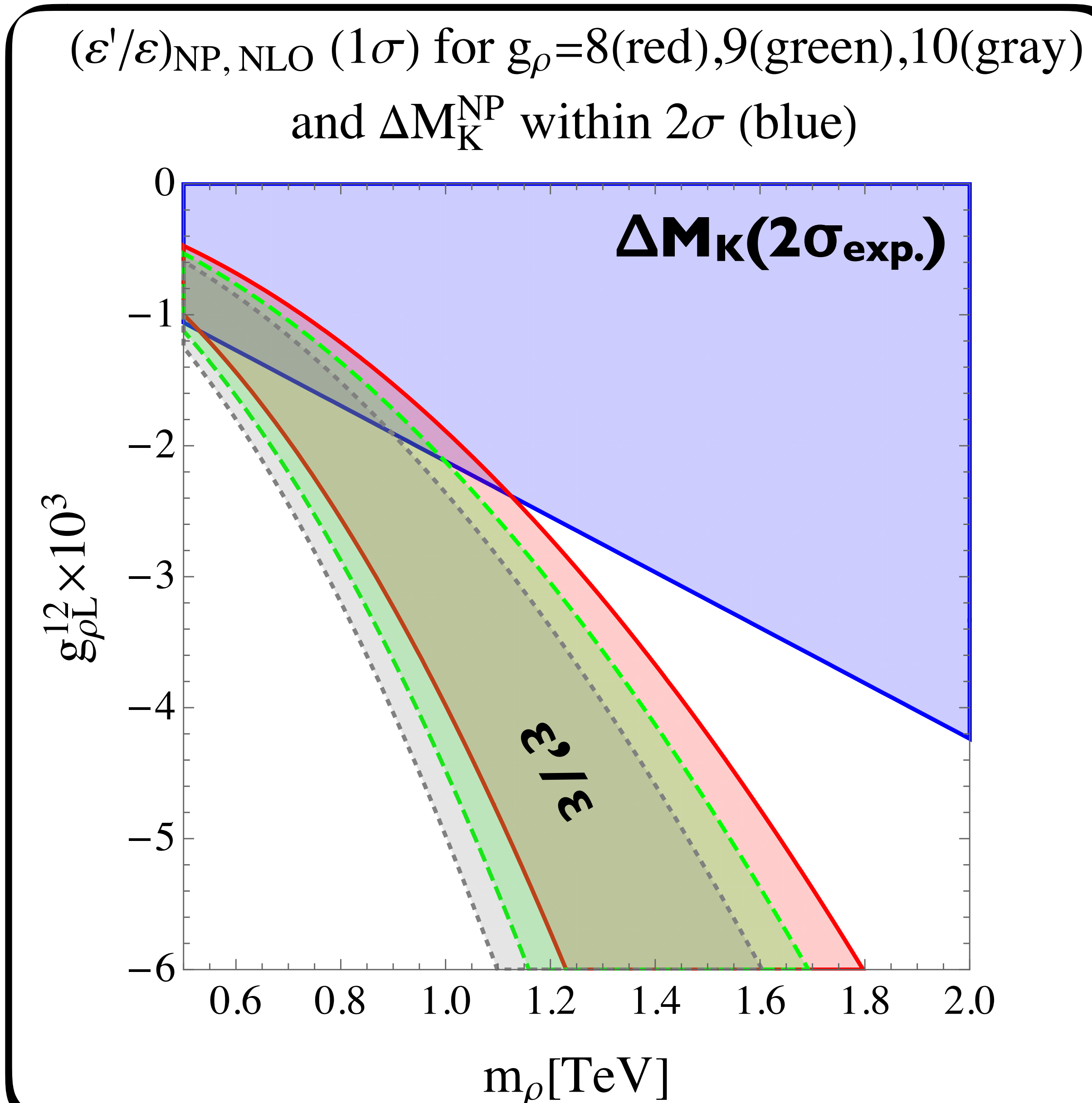
$$\left(f_{B_s}\sqrt{\hat{B}_{B_s}} = (266 \pm 18)\,\text{MeV [FLAG13]} \to (274 \pm 8)\,\text{MeV [FLAG17]} \right)$$

ε'/ε result

[LO QCD operator run]



[NLO QCD operator run]



* $g^{12}_{\rho L} \equiv g_\rho \times g^{12}_L$

$$\longrightarrow \mathcal{H}_{\rm eff} \supset C_6 Q_6 \left(\text{QCD Penguin},\ Q_6 = (\bar{s}^b d^a)_{V-A} \sum_q (\bar{q}^a q^b)_{V+A} \right)$$

Wilson coefficient

1⇄2 mixing (flavorful)

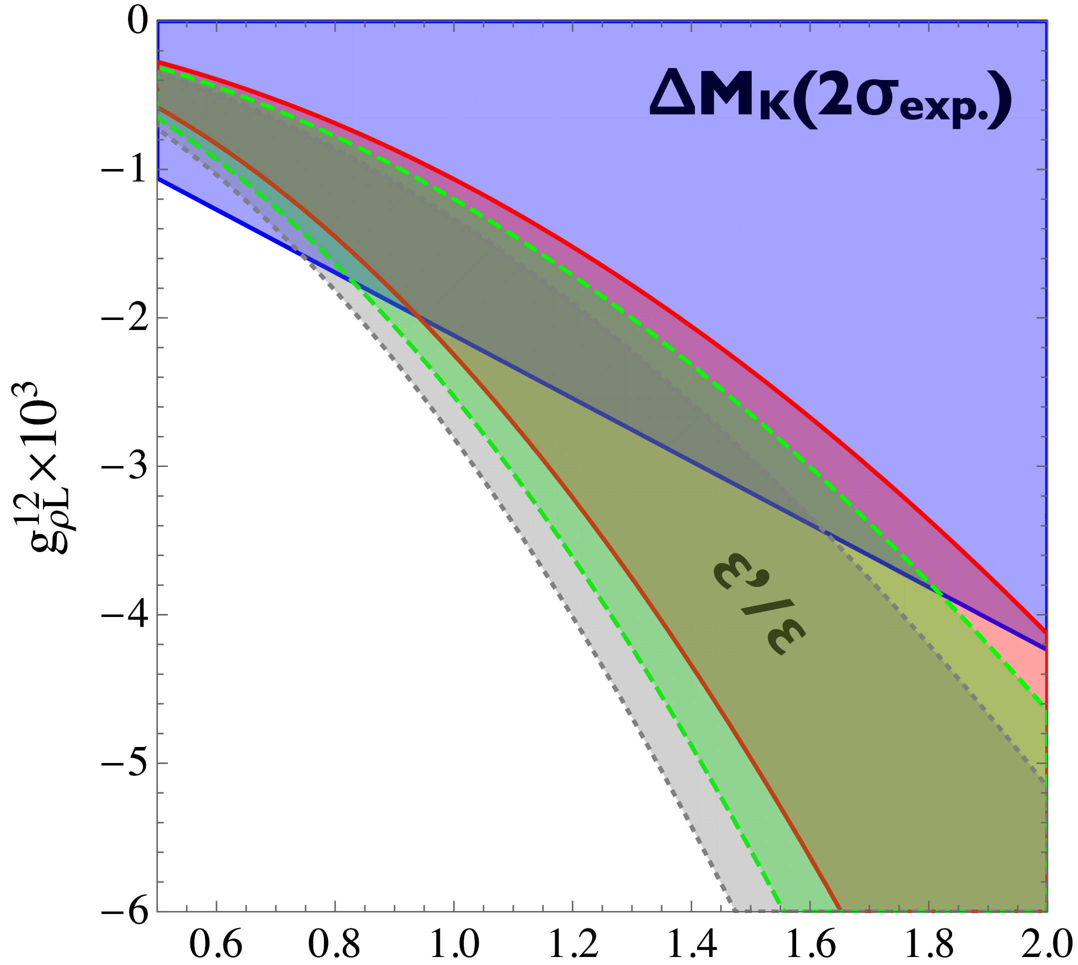
V_{SM}-ρ mixing (universal), required gauge invariance

Electroweak-Penguin, charged-current types also appear.

ε'/ε result

[LO QCD operator run]

$(\varepsilon'/\varepsilon)_{\rm NP,\,LO}$ (1σ) for g_ρ=8(red),9(green),10(gray) and $\Delta M_K^{\rm NP}$ within 2σ (blue)



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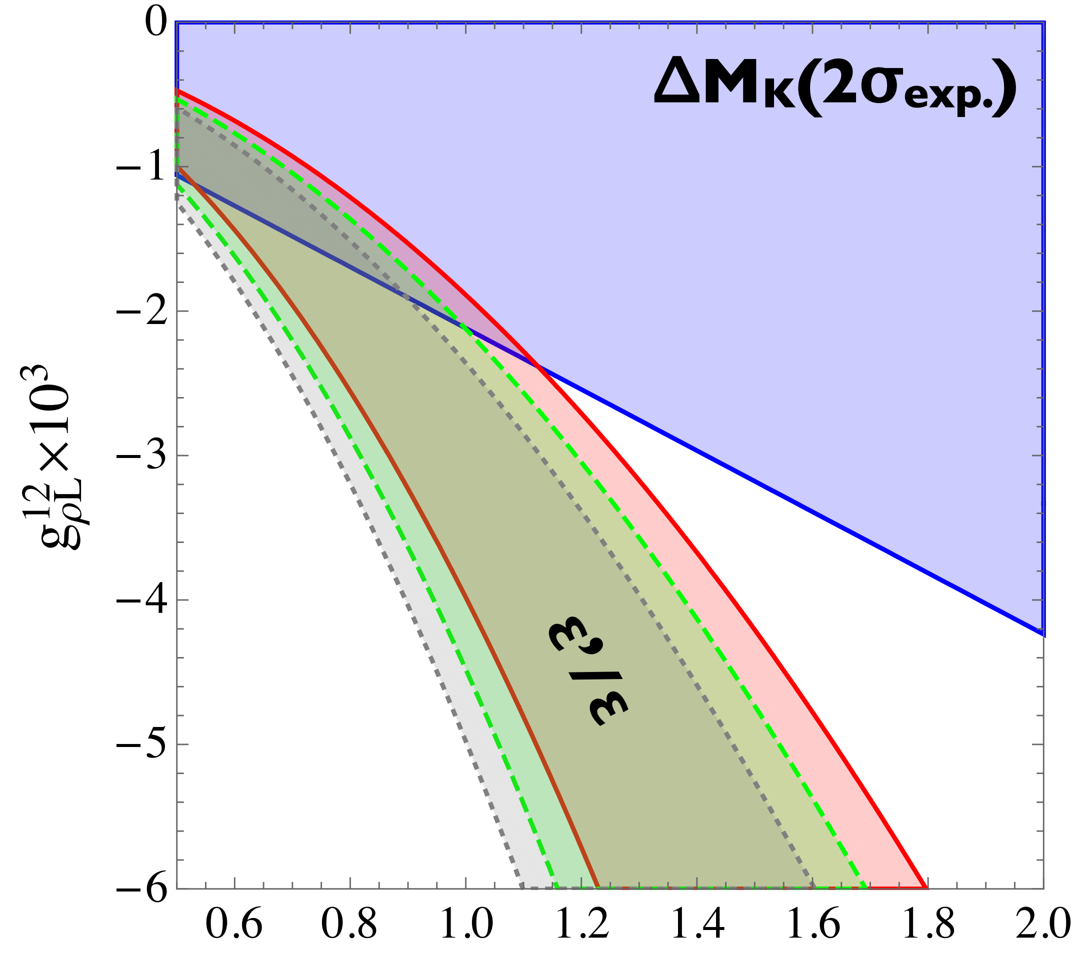
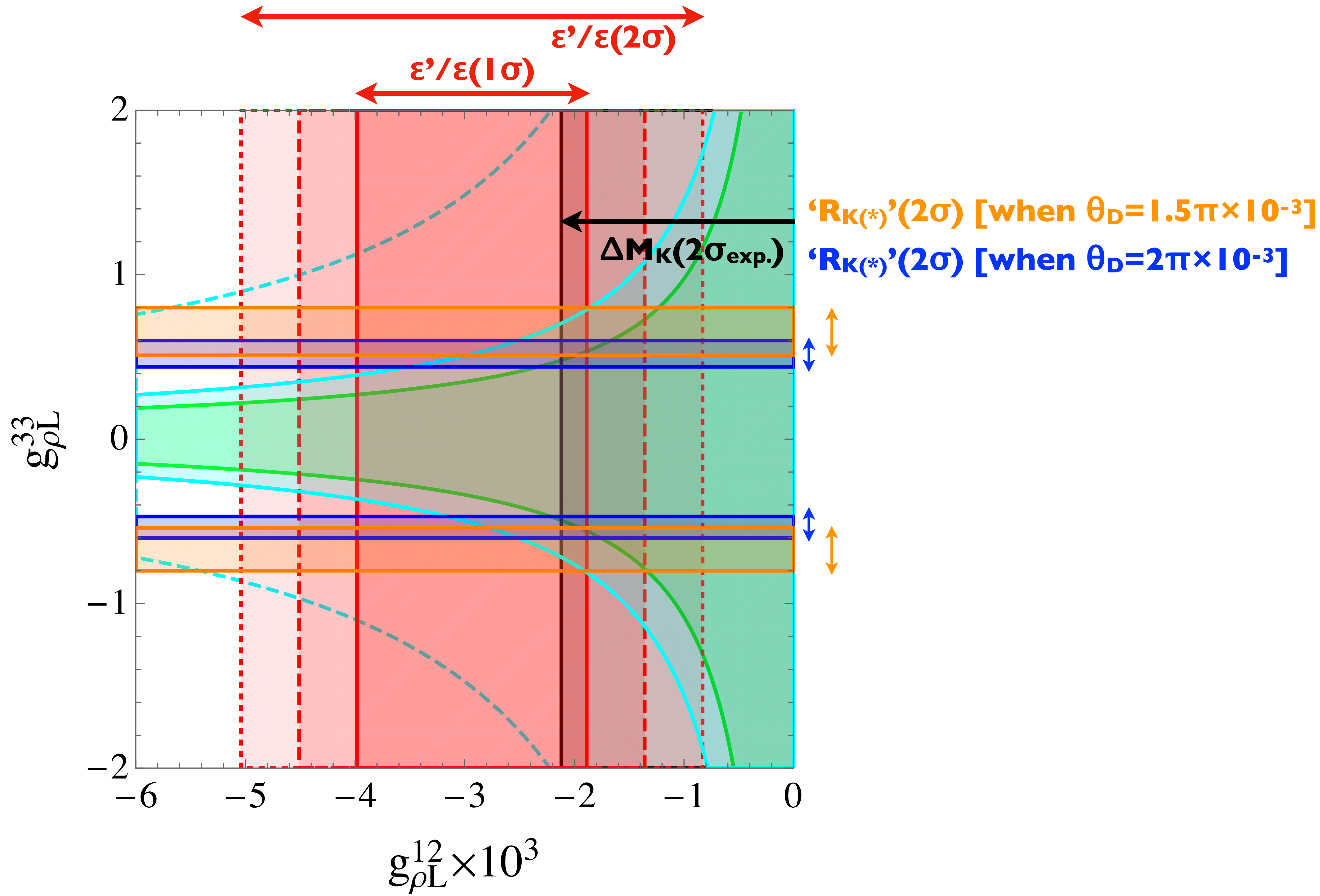


[T.Kitahara et al., arXiv:1607.06727; also hep-ph/9211321,9303284,9212203]
(also arXiv:1807.02520,1808.00466)

- **For ε'/ε, not only QCD, but also EW corrections are significant (due to partial cancellation between QCD & EW Penguins).**
- **m_ρ should be around 1TeV; heavier ones lead to insufficient contrib. to ε'/ε**

(Invisible) ν connects B and K physics

On the benchmark (m_ρ=1TeV, g_ρ=8, θ_L=π/2):



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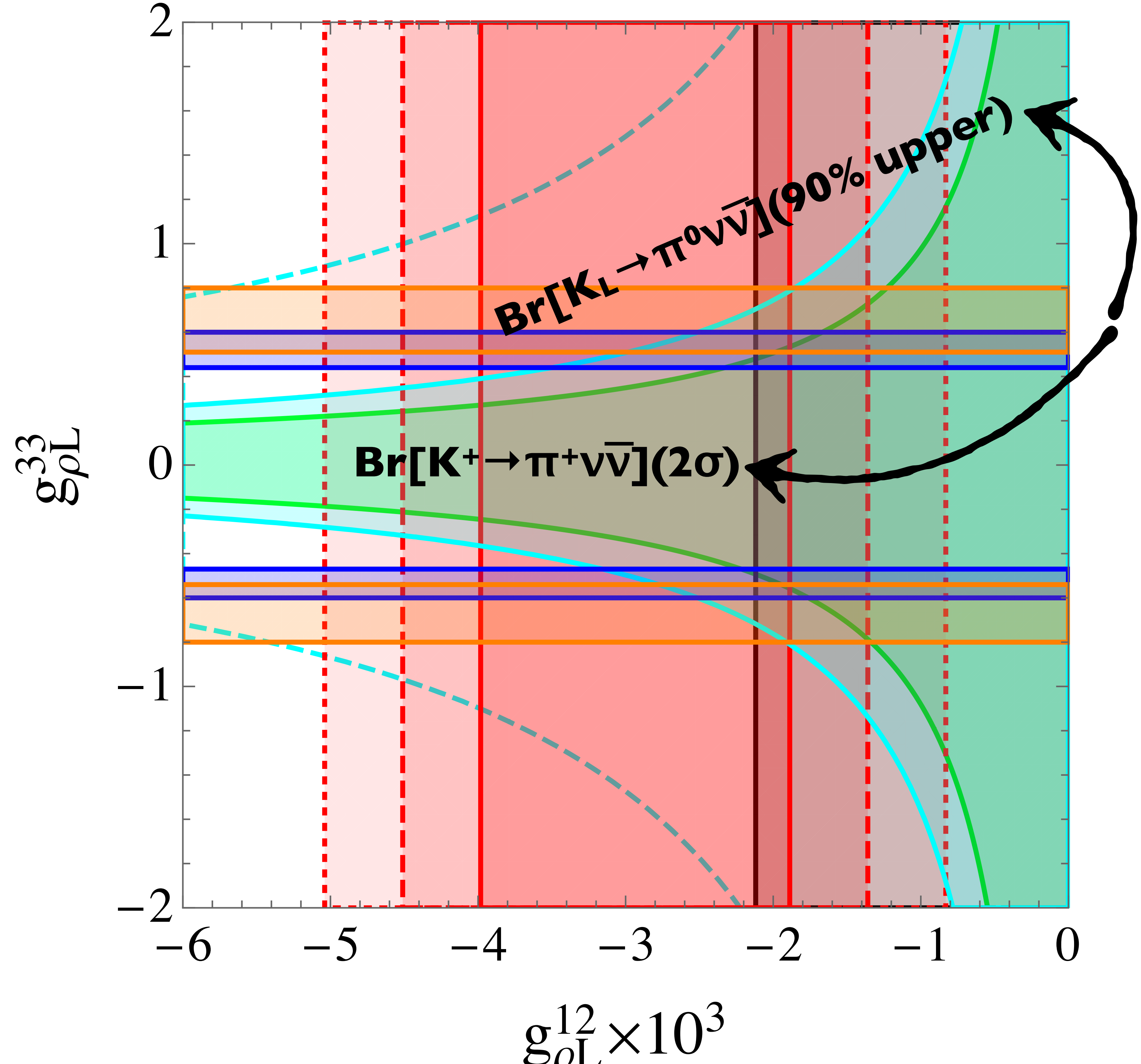

These inclusive-ν channels give us co-related bounds between B & K physics.

(Invisible) ν connects B and K physics

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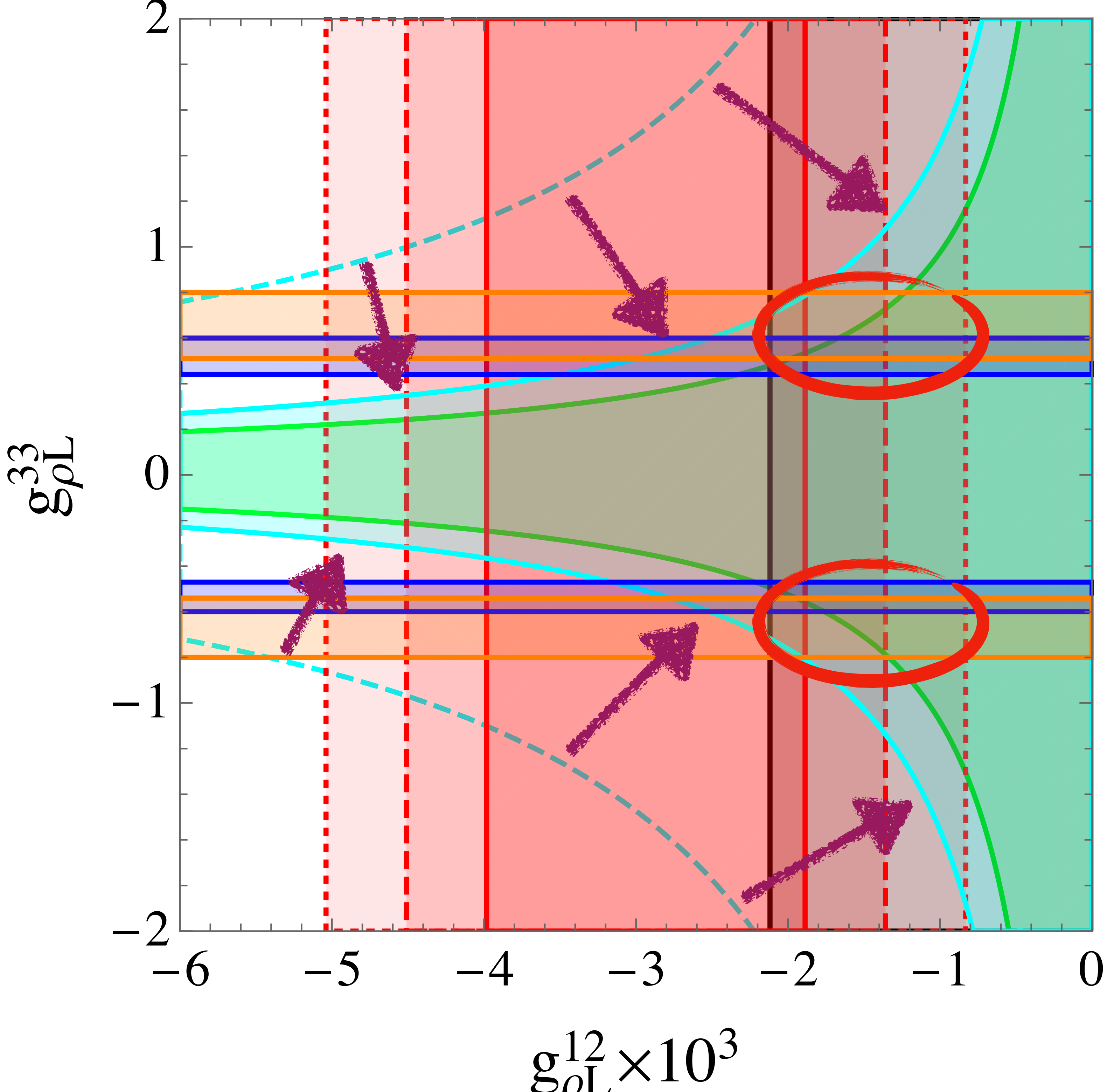
Just updated/announced at ICHEP2018 (by KOTO)!



Interestingly, the valid parameter space will be explored completely by the experiments of NA62(K^+) and KOTO (K^0) in the near future!

(Invisible) ν connects B and K physics

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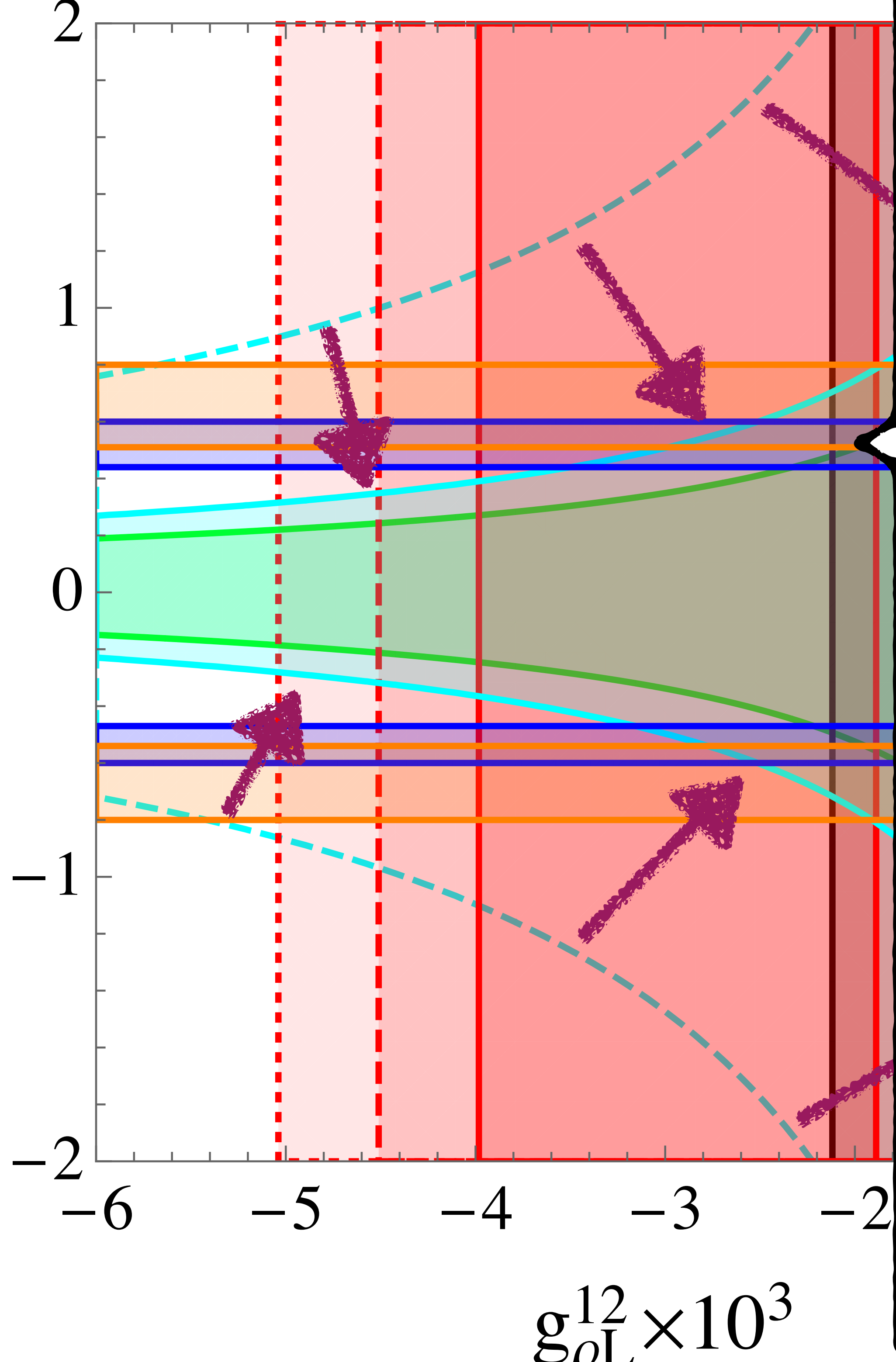

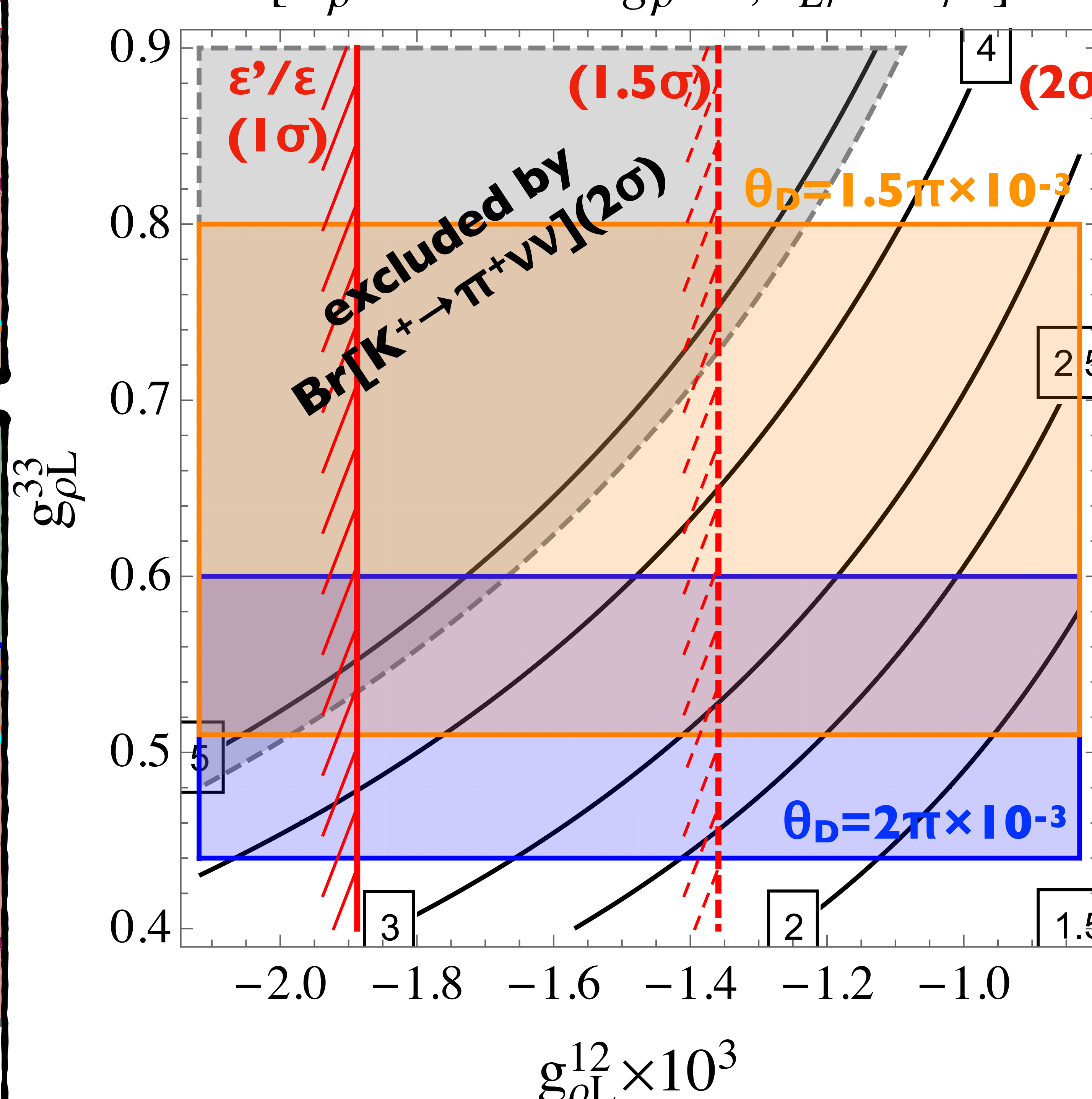

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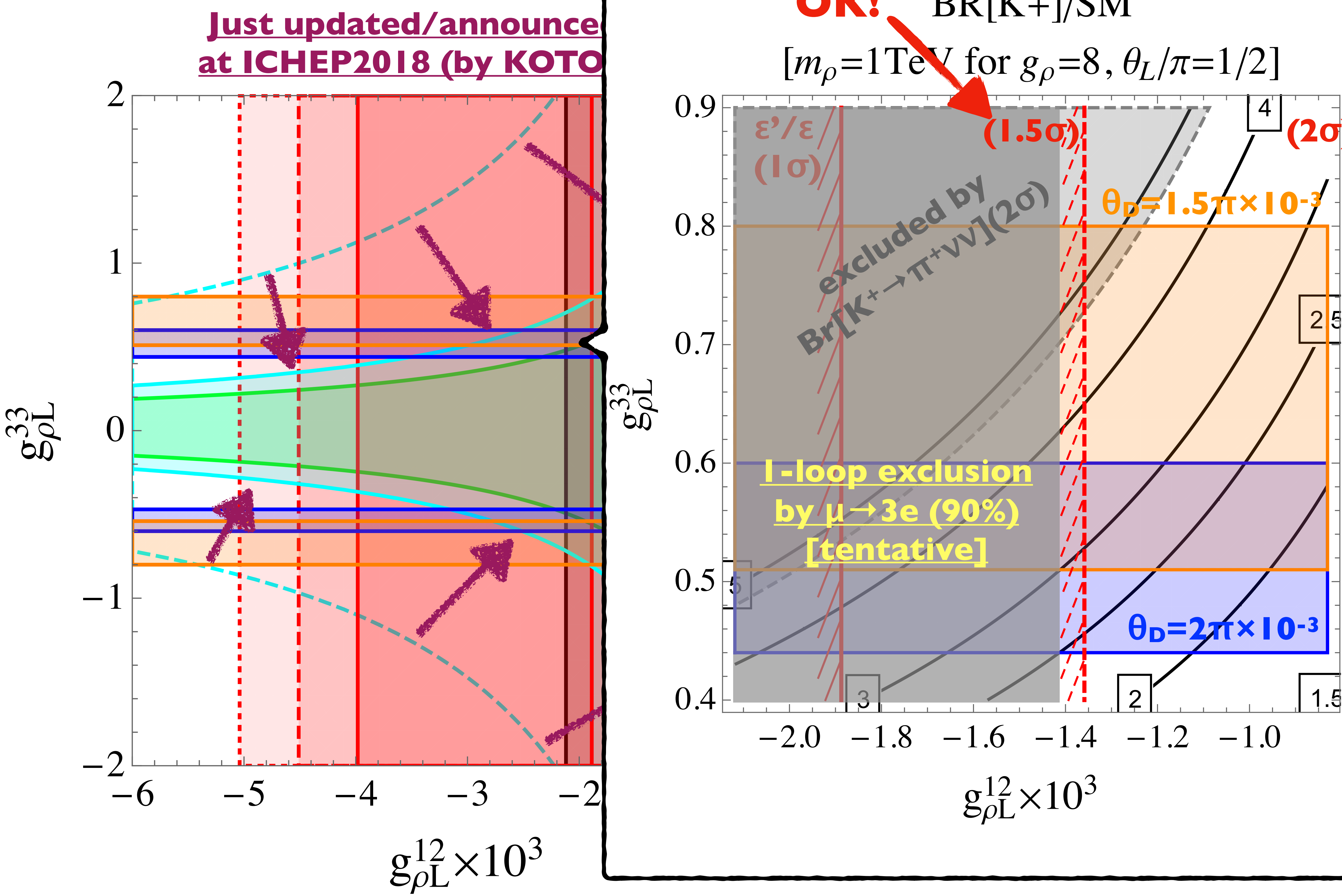
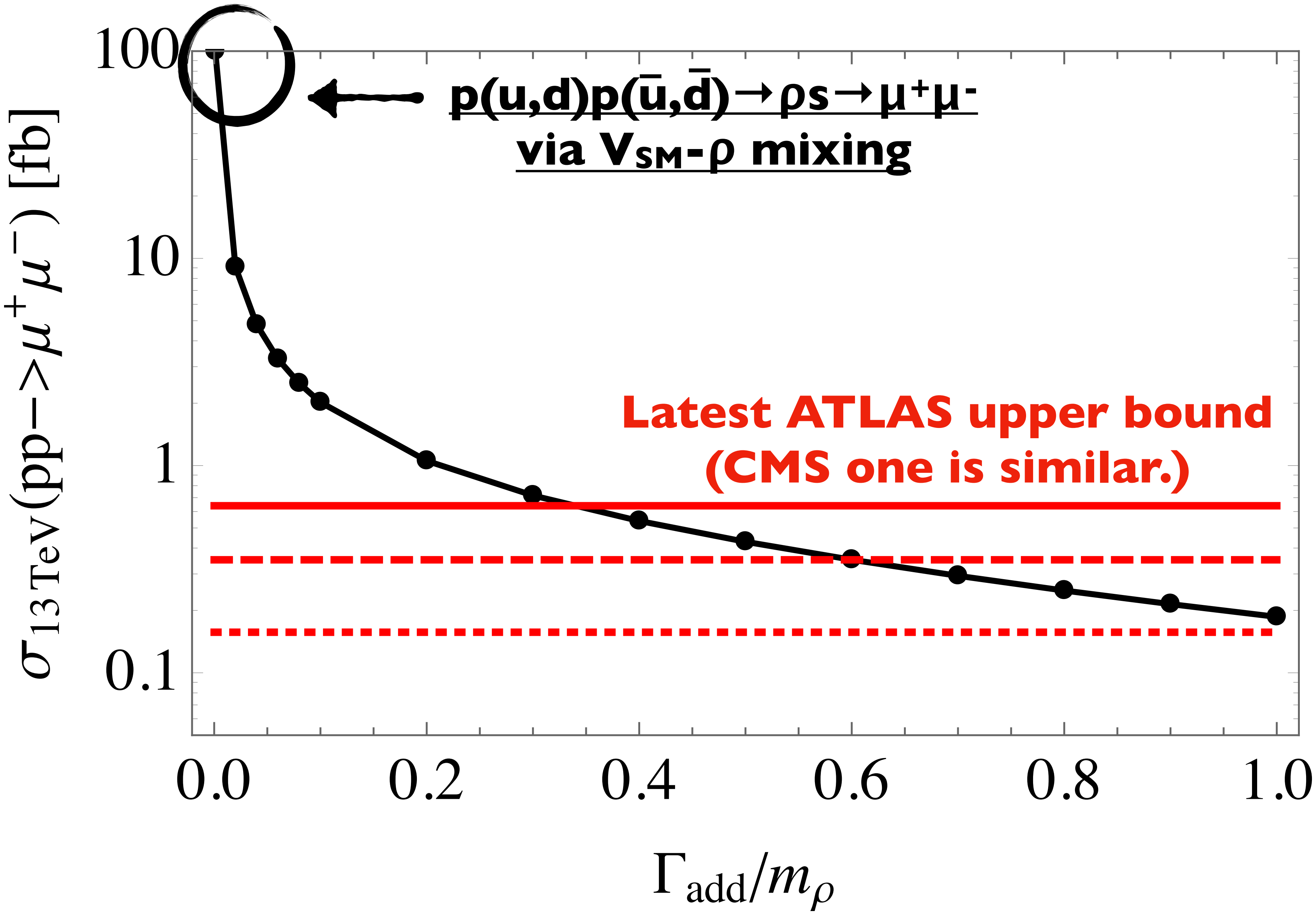


Limit on mρ via LHC di-muon resonance search

Sec. 3: 4/4

g_ρ=8, $(g_{\rho L})^{33}$=0.5, m_ρ=1.0TeV (θ_D~0, θ_L/π=1/2);

solid:36.1/fb, dashed:120/fb, dotted:600/fb



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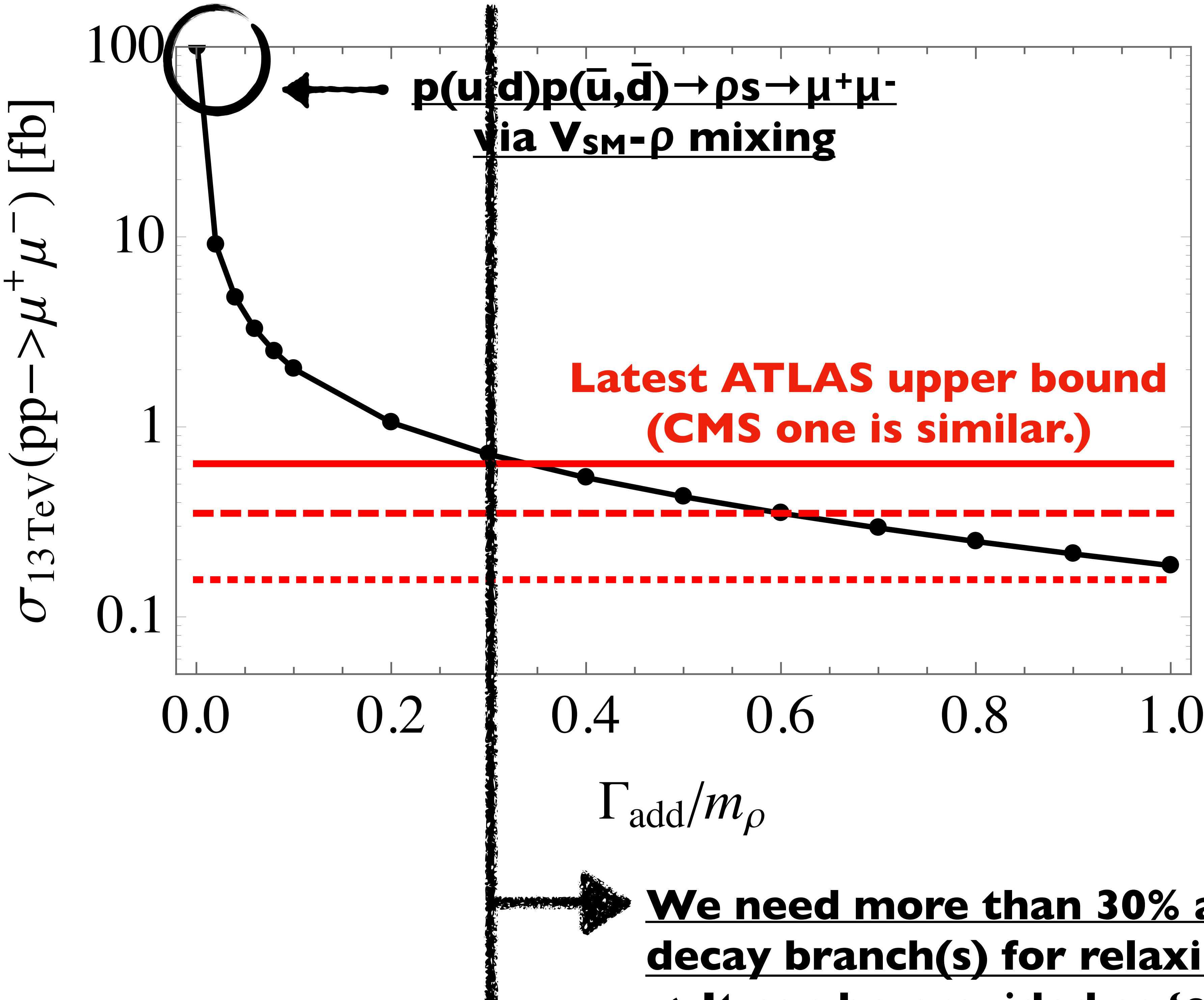

We need more than 30% additional decay branch(s) for relaxing the $\sigma_{13\mathrm{TeV}}$.
⇒ It can be provided as 'ρ→ππ'.

Summary & Discussions

- **Virtues of (vector-like) composite model are (e.g.,)**

  - ☑ **The $C_9 = -C_{10}$ texture (for $b \to sll$) is naturally realized (for '$R_{K(*)}$').**
  - ☑ **Apparently gauge-anomaly free.**
  - ☑ **Due to SU(8) symmetry, contribution to $R_{D(*)}$ is minuscule.**
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  - ☑ **Proton decay via dim-5 operators are banned by hidden local sym.**

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  The region for both of $R_{K(*)}$ & ε'/ε is surveyed in NA62, KOTO; also LHC.

  (probably taking account of opening $\rho \to 2\pi$)

- **Discovering lots of new particles is expected at the LHC, distinguishable from other scenarios.**

Summary & Discussions

- **Virtues of (vector-like) composite model are (e.g.,)**

  - ☑ **The $C_9 = -C_{10}$ texture (for $b \to sll$) is naturally realized (for '$R_{K(*)}$').**
  - ☑ **Apparently gauge-anomaly free.**
  - ☑ **Due to SU(8) symmetry, contribution to $R_{D(*)}$ is minuscule. (⇒ It may be OK due to the 'vanishing' trend in latest exp. results.)**
  - ☑ **Proton decay via dim-5 operators are banned by hidden local sym.**

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BACKUPS

Misc on pions (skippable)

typical spectrum (Λ_{HC}~1TeV, Λ_{UV}~10^{16}GeV)

$$M_{\pi^0_{(1)'}} \sim \mathcal{O}(f_\pi) = \mathcal{O}(100)\,\mathrm{GeV}\,,$$

$$M_{\pi^{\pm,3}_{(1)'}} \sim 2\,\mathrm{TeV}\,,$$

$$M_{\pi^{\pm,3}_{(1)}} \sim 2\,\mathrm{TeV}\,,$$

$$M_{\pi^{\pm,3,0}_{(3)}} \sim 3\,\mathrm{TeV}\,,$$

$$M_{\pi^{\pm,3,0}_{(8)}} \sim 4\,\mathrm{TeV}\,,$$

[Matsuzaki & Yamawaki, arXiv:1508.07688]

large mass correction via near-conformal (walking) gauge theory

$$\boxed{M^2_{\pi_{(3),(8)}} \sim C_2 \alpha_s(M_\pi)\Lambda^2_{\mathrm{HC}} \ln\frac{\Lambda^2_{\mathrm{UV}}}{\Lambda^2_{\mathrm{HC}}}, \text{ with } C_2 = \tfrac{4}{3}\,(3) \text{ for color-triplet (octet)}}$$

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- **(ρ, π)-interactions** $a \equiv m_\rho^2/(g_\rho^2 f_\pi^2)$ **← ~2 in vector dominance**

$$\mathcal{L}_{\rho\text{-}\pi\text{-}\pi} = a g_\rho i\,\mathrm{tr}\,[[\partial_\mu \pi, \pi]\rho^\mu]\,,$$ **← decay channel of ρ**

$$\mathcal{L}_{\mathcal{V}\text{-}\pi\text{-}\pi} = 2i\left(1 - \frac{a}{2}\right)\,\mathrm{tr}\,[[\partial_\mu \pi, \pi]\mathcal{V}^\mu]\,,$$ **← ~0**

$$\mathcal{L}_{\mathcal{V}\text{-}\mathcal{V}\text{-}\pi\text{-}\pi} = -\mathrm{tr}\,\{[\mathcal{V}_\mu, \pi]\,[\mathcal{V}^\mu, \pi]\}\,,$$ **← 'gg→ππ' pair production (evaded)**

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typical pionic decays

- $\rho^0_{(3)} \to \bar{\pi}^0_{(3)}\pi^0_{(1)'}:\ m_{\pi\pi} \sim (3+\mathcal{O}(0.1))\,\mathrm{TeV},$
- $\rho^\alpha_{(3)} \to \bar{\pi}^\alpha_{(3)}\pi^0_{(1)'}:\ m_{\pi\pi} \sim (3+\mathcal{O}(0.1))\,\mathrm{TeV},$
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For m_ρ <~3TeV, ρ decay width is narrow.

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\end{aligned}
$$

If this factor is less than a few, no problem.

typical cross section of resonant π production (through WZW anomaly term)

$$
\sigma(GG \to \pi^0_{(1)'} \to \gamma\gamma) \qquad \sim 0.1\,\mathrm{fb} \times \left[\frac{N_{\mathrm{HC}}}{3}\right]^2 \left[\frac{\alpha_s}{0.1}\right]^2 \left[\frac{\mathcal{B}(\pi^0_{(1)'} \to \gamma\gamma)}{10^{-3}}\right] \boxed{\left(\frac{M_{\pi^0_{(1)'}}}{f_\pi}\right)^2}
$$

Composite scenario: QCD as showing example

- **If a gauge theory is strongly-coupled, composite mesons (and other types) are observed (like QCD below ~1GeV).**

[QCD Lagrangian]

$$\mathcal{L}_{\rm QCD} = \mathcal{L}^0_{\rm QCD} + \underbrace{\overline{q}_L \gamma^\mu \mathcal{L}_\mu q_L + \overline{q}_R \gamma^\mu \mathcal{R}_\mu q_R}_{\text{couplings to external gauge fields } (W^\pm, Z, \gamma)} + \underbrace{\overline{q}_L \left[\mathcal{S} + i\mathcal{P}\right] q_R + \overline{q}_R \left[\mathcal{S} - i\mathcal{P}\right] q_L}_{\text{current mass terms}} \ ,$$

above Λ_{QCD}

couplings to external gauge fields ($W^\pm$,Z,γ)

current mass terms (via the Higgs mechanism)

[explicit breaking: $SU(N_f)_L \times SU(N_f)_R \to SU(N_f)_V$]

$$\mathcal{L}^0_{\rm QCD} = \bar{q} i \not{D} q - \frac{1}{2} {\rm tr}\left[G_{\mu\nu} G^{\mu\nu}\right]$$ ← **pure QCD part**

$$q_{L/R} = \begin{pmatrix} u \\ d \\ s \\ \vdots \end{pmatrix}_{L/R}$$

$SU(N_f)_L \times SU(N_f)_R$ global flavor (chiral) symmetry, realized

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couplings to external gauge fields ($W^\pm$,Z,γ)

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[explicit breaking: $SU(N_f)_L \times SU(N_f)_R \to SU(N_f)_V$]

Confined around below $\Lambda_{\rm QCD}$

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- $\langle \bar{q}^A q^B \rangle \sim \Lambda^3_{\rm QCD} \delta^{AB} ({\rm confinement}) \to$ **$SU(N_f)_L \times SU(N_f)_R \to SU(N_f)_V$ spontaneously**
  → $(N_f)^2-1$ #s of (pseudo) NG bosons emerge.

[reviewed by e.g., M.Harada & K.Yamawaki, arXiv:hep-ph/0302103]

[Chiral perturbation theory ⇒ effective description]

- **Spin-one vector mesons can be described by hidden local symmetry (HLS).**

$SU(N_f)_L \times SU(N_f)_R \Rightarrow [SU(N_f)_L \times SU(N_f)_R]_{\rm global} \times [SU(N_f)_V]_{\rm gauged}$

→ $(N_f)^2-1$ #s of vector mesons are introduced.

Form of effective Lagrangian

Basic ingredients of chiral perturbation theory (with HLS):

- $\xi_{\substack{R\\L}} = \boxed{e^{i\mathcal{P}/f_{\mathcal{P}}}} \cdot \boxed{e^{\pm i\pi/f_\pi}}$ **(non-linear basis of chiral symmetries)**

  would-be NGs for rho mesons (longitudinal d.o.f.s)

  pions (NG bosons)

- $\rho_\mu = \rho_\mu^a T^a \;\; (T^a : SU(8) \text{ generators})$ **(HC rho meson fields)**

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Materials for constructing effective Lagrangian:

$$\rho_{\mu\nu} = \partial_\mu \rho_\nu - \partial_\nu \rho_\mu - i g_\rho [\rho_\mu, \rho_\nu] \,,$$ **[HC rho's field strength]**

$$\hat{\alpha}_{\perp\mu} = \frac{D_\mu \xi_R \cdot \xi_R^\dagger - D_\mu \xi_L \cdot \xi_L^\dagger}{2i} \,, \qquad \hat{\alpha}_{||\mu} = \frac{D_\mu \xi_R \cdot \xi_R^\dagger + D_\mu \xi_L \cdot \xi_L^\dagger}{2i} \,,$$

ρ's gauge coupling

$$D_\mu \xi_{R(L)} = \partial_\mu \xi_{R(L)} - i g_\rho \rho_\mu \xi_{R(L)} + i \xi_{R(L)} \mathcal{R}_\mu (\mathcal{L}_\mu) \,,$$

(external) SM gauge bosons

[(covariantized) Maurer-Cartan one-forms]

[gauge transformations]

$$\xi_L \to h(x) \cdot \xi_L \cdot g_L^\dagger(x) \,, \qquad \xi_R \to h(x) \cdot \xi_R \cdot g_R^\dagger(x) \,,$$

$$\rho_\mu \to h(x) \cdot \rho_\mu \cdot h^\dagger(x) + \frac{i}{g_\rho} h(x) \cdot \partial_\mu h^\dagger(x) \,, \qquad \rho_{\mu\nu} \to h(x) \cdot \rho_{\mu\nu} \cdot h^\dagger(x) \,,$$

$$\hat{\alpha}_{\perp\mu} \to h(x) \cdot \hat{\alpha}_{\perp\mu} \cdot h^\dagger(x) \,, \qquad \hat{\alpha}_{||\mu} \to h(x) \cdot \hat{\alpha}_{||\mu} \cdot h^\dagger(x) \,,$$

Form of effective Lagrangian (cont'd)

Effective Lagrangian (lowest terms):

HC pion decay constant **(typical) HC rho-meson mass scale**

$$\mathcal{L} = -\frac{1}{2}\mathrm{tr}[\rho_{\mu\nu}^2] + f_\pi^2 \mathrm{tr}[\hat{\alpha}_{\perp\mu}^2] + \frac{m_\rho^2}{g_\rho^2}\mathrm{tr}[\hat{\alpha}_{||\mu}^2] + \cdots$$

rhos ('kinetic') pions ('kinetic') rhos ('mass')

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for SU(2)$_W$-doublet quarks

$$\left[\mathcal{L}_\mu^f\right]_{8\times 8} = \left(\begin{array}{c|c} \mathbf{1}_{2\times 2} \otimes g_s G_\mu^a \frac{\lambda^a}{2} + \left(g_W W_\mu \tau^\alpha + \frac{1}{6} g_Y B_\mu\right) \otimes \mathbf{1}_{3\times 3} & \mathbf{0}_{6\times 2} \\ \hline \mathbf{0}_{2\times 6} & g_W W_\mu^\alpha \tau^\alpha - \frac{1}{2} g_Y B_\mu \cdot \mathbf{1}_{2\times 2} \end{array}\right)$$

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Effective couplings of f_L-f_L-ρ (being gauge-invariant):

$$g_L^{ij} \equiv (g_{1L} + 2g_{2L} + g_{3L})^{ij}$$

$$\mathcal{L}_{\rho ff} = g_{1L}^{ij}\left(\bar{\Psi}_L^i \gamma^\mu \hat{\alpha}_{||\mu} \Psi_L^j\right) + g_{2L}^{ij}\left(\bar{\Psi}_L^i \gamma^\mu \hat{\alpha}_{||\mu} \psi_L^j + \mathrm{h.c.}\right) + g_{3L}^{ij}\left(\bar{\psi}_L^i \gamma^\mu \hat{\alpha}_{||\mu} \psi_L^j\right)$$

(undetermined) 3×3 matrices

(No additional fermion/scalar is required.)

Dynamical EWSB Scenarios

type	125GeV scalar	Good Points	Problems(?)
Technicolor (chiral condensation)	dilaton (in walking case)	☑ simplest ☑ UV theory is known.	☑ Another complicated dynamics is required for SM fermion masses. ☑ disfavored by S,T parameters, and Higgs signal strengths

(+ others)

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(+ others)

e.g., [T.Hur & P.Ko, arXiv:1103.2571]

hidden vector fermion   singlet scalar   Higgs doublet

$$V = y_\varphi\, \varphi(\bar{F}F) + \frac{\lambda_\varphi}{4}\varphi^4 + \lambda_H (H^\dagger H)^2 + \kappa_\varphi\, \varphi^2 (H^\dagger H)$$

When this part condensates, a tadpole term emerges ⇒ dynamical EWSB!

Review: Kaon state

- $K^0(\bar{s}\gamma_5 d),\ \overline{K^0}(\bar{d}\gamma_5 s)$: **J^P=0$^-$, ≠ (mass, CP eigenstate)**
  - **CP eigenstate:** $|K_{\frac{1}{2}}\rangle = \frac{1}{2}\left[|K^0\rangle \pm |\overline{K^0}\rangle\right] \left(\text{c.f. } CP|K^0\rangle = |\overline{K^0}\rangle\right)$

    CP even CP odd

    CPV parameter (εbar~10^{-3})
  - **mass eigenstate:** $|K_S\rangle \sim |K_1\rangle + \bar{\epsilon}\,|K_2\rangle,\ |K_L\rangle \sim |K_2\rangle + \bar{\epsilon}\,|K_1\rangle$

    shorter lifetime longer lifetime

[Data]

- **$(M_L + M_S)/2 \sim 500$ MeV**
- **$(M_L - M_S)/2 \sim 10^{-12}$ MeV**

almost mass-degenerated

- **$\Gamma_S \sim 10^{-12}$ MeV**
- **$\Gamma_L \sim 10^{-14}$ MeV**

significant difference due to
CP-conserved primaly decay patterns
($K_S \rightarrow 2\pi$, $K_L \rightarrow 3\pi$)

"CP-even" "CP-odd"

Review: Kaon system

- $|\phi(t)\rangle = a_K(t)|K^0\rangle + a_{\bar{K}}(t)|\overline{K^0}\rangle$
- $i\frac{d}{dt}\begin{pmatrix} a_K(t) \\ a_{\bar{K}}(t) \end{pmatrix} = \mathbf{H}\begin{pmatrix} a_K(t) \\ a_{\bar{K}}(t) \end{pmatrix}, \quad \mathbf{H} = \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{21} - \frac{i}{2}\Gamma_{21} & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix}$
    - **CPT: $M_{11} = M_{22}$, $\Gamma_{11} = \Gamma_{22}$**
    - **Hermiticity: $M_{21} = (M_{12})^*$, $\Gamma_{21} = (\Gamma_{12})^*$**

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  - **Hermiticity: $M_{21} = (M_{12})^*$, $\Gamma_{21} = (\Gamma_{12})^*$**
- $CP|K^{\pm}\rangle = \pm|K^{\pm}\rangle,\ CP|\pi^0\pi^0\rangle = +|\pi^0\pi^0\rangle,\ CP|\pi^0\pi^0\pi^0\rangle = -|\pi^0\pi^0\pi^0\rangle$

☑ **$K_L \to \pi\pi$ is prohibited if CP is an exact symmetry:**

$$|K_L\rangle \sim \overset{\text{CP-odd}}{|K_2\rangle} + \bar{\epsilon}\,\overset{\text{CP-even}}{|K_1\rangle}$$

$|K_1\rangle$ → CP-even $|\pi\pi\rangle$: **indirect CPV** — **CPV during oscillation**

$|K_2\rangle$ → CP-even $|\pi\pi\rangle$: **direct CPV** — **CPV at decay**

Review: CPV in K → 2π

- **Two CVP decay modes: $K_L \rightarrow \pi^+\pi^-$, $K_L \rightarrow \pi^0\pi^0$**

  - The ratios of amplitudes works as order parameters:

Indirect CPVs are universal.

$$\eta_{00} = \frac{\mathcal{A}(K_L \to \pi^0\pi^0)}{\mathcal{A}(K_S \to \pi^0\pi^0)} = \epsilon_{(K)} - 2\epsilon'_{(K)}$$

$$\eta_{+-} = \frac{\mathcal{A}(K_L \to \pi^+\pi^-)}{\mathcal{A}(K_S \to \pi^+\pi^-)} = \epsilon_{(K)} + \epsilon'_{(K)}$$

Direct CPVs appear differently.

Review: ε(K) & ε'(K)

- **Decay amplitudes in gauge-isospin basis:** (including) weak CP phases   strong CP phases

  - $\mathcal{A}(K^0 \to (\pi\pi)_{I=0}) = \mathcal{A}_0 e^{i\delta_0}, \quad \mathcal{A}(\overline{K^0} \to (\pi\pi)_{I=0}) = \mathcal{A}_0^* e^{i\delta_0}$
  - $\mathcal{A}(K^0 \to (\pi\pi)_{I=2}) = \mathcal{A}_2 e^{i\delta_2}, \quad \mathcal{A}(\overline{K^0} \to (\pi\pi)_{I=2}) = \mathcal{A}_2^* e^{i\delta_2}$

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- **Decomposing the final states by isospin:**
  - $|\pi^0\pi^0\rangle = \sqrt{\frac{1}{3}}|(\pi\pi)_{I=0}\rangle - \sqrt{\frac{2}{3}}|(\pi\pi)_{I=2}\rangle$
  - $|\pi^+\pi^-\rangle = \sqrt{\frac{2}{3}}|(\pi\pi)_{I=0}\rangle + \sqrt{\frac{1}{3}}|(\pi\pi)_{I=2}\rangle$

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$$\epsilon_{(K)} = \frac{\mathcal{A}_{0,L}}{\mathcal{A}_{0,S}} \simeq \underset{+\bar{\epsilon}}{i} \frac{\mathrm{Im}(\mathcal{A}_0)}{\mathrm{Re}(\mathcal{A}_0)} \simeq \frac{1}{\sqrt{2}} e^{i\pi/4} \frac{\mathrm{Im}(M_{12})}{\Delta M_K}$$

$\simeq e^{i\pi/4}$ **(⊿I = 1/2 rule)**

$$\omega \equiv \frac{\mathrm{Re}(\mathcal{A}_2)}{\mathrm{Re}(\mathcal{A}_0)} \simeq \frac{1}{22}$$

$$\epsilon'_{(K)} = \frac{1}{\sqrt{2}}\left[\frac{\mathcal{A}_{2,L}}{\mathcal{A}_{0,L}} - \frac{\mathcal{A}_{2,S}}{\mathcal{A}_{0,S}}\right] \simeq \frac{1}{\sqrt{2}} e^{i(\frac{\pi}{2}+\delta_2-\delta_0)} \omega \left[\frac{\mathrm{Im}(\mathcal{A}_2)}{\mathrm{Re}(\mathcal{A}_2)} - \frac{\mathrm{Im}(\mathcal{A}_0)}{\mathrm{Re}(\mathcal{A}_0)}\right]$$

Review: properties of ε'$_{(K)}$/ε$_{(K)}$

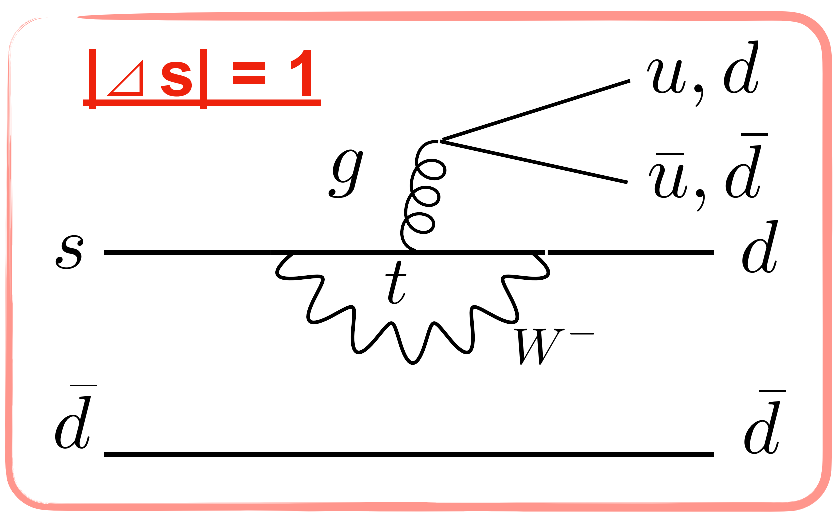
$\simeq 22$ **(enhancement factor)**

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

QCD Penguin operator(s)

EW Penguin operator(s)

[SM contrib.]



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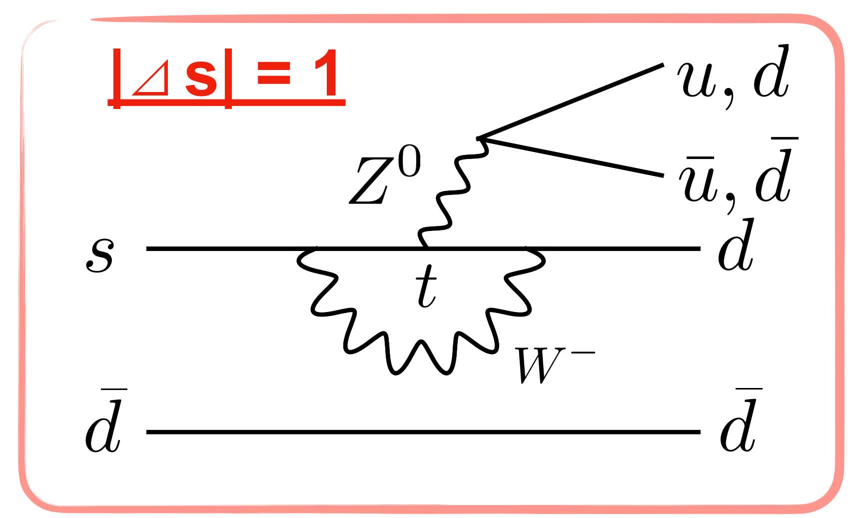

- **EW Penguin(s) are comparable to QCD one(s) due to "1/ω".**
- **(Accidental) almost cancelation happens between $A_0|_{SM}$ & $A_2|_{SM}$. [$|\varepsilon_{SM}| \sim 10^{-3}$, $|\varepsilon'_{SM}| \sim 10^{-7}$]**

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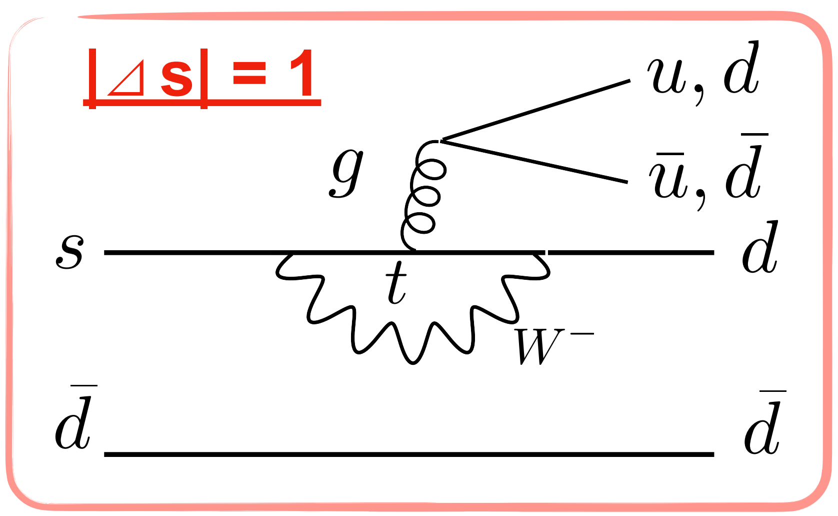
QCD Penguin operator(s) and/or **EW Penguin operator(s)**

[SM contrib.]



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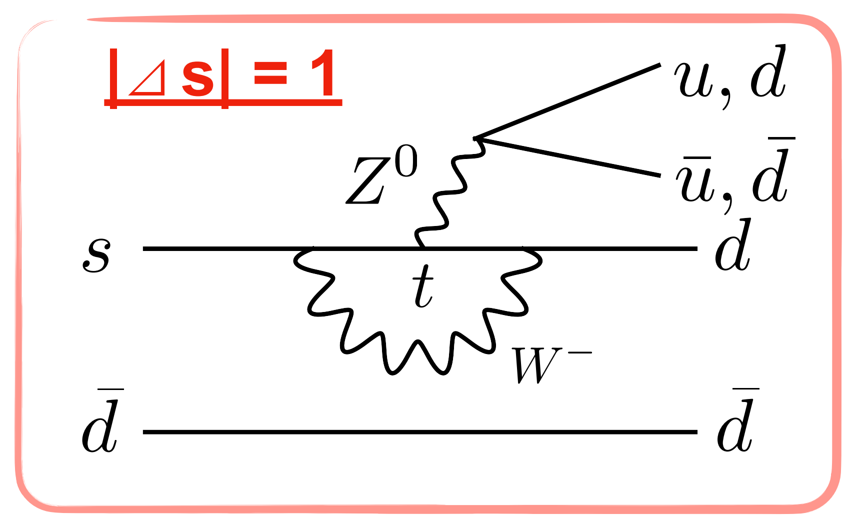

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- **(Accidental) almost cancelation happens between $A_0|_{SM}$ & $A_2|_{SM}$. [$|\varepsilon_{SM}| \sim 10^{-3}$, $|\varepsilon'_{SM}| \sim 10^{-7}$]**
- **If less-canceled, sizable contrib.'s of NP are expected.**

- **operators for ε'/ε:** [A.J.Buras et al., arXiv:1507.06345,1601.00005]

$$\mathcal{H}_{\text{eff}} = \sum_{j=1\text{-}10} C_j \cdot Q_j \,,$$

$$Q_1 = (\bar{s}^{b\prime} u^{a\prime})_{V-A} (\bar{u}^{a\prime} d^{b\prime})_{V-A} \,, \qquad Q_2 = (\bar{s}' u')_{V-A} (\bar{u}' d')_{V-A} \,,$$

$$Q_3 = (\bar{s}' d')_{V-A} \sum_{q'} (\bar{q}' q')_{V-A} \,, \qquad Q_4 = (\bar{s}^{b\prime} d^{a\prime})_{V-A} \sum_{q'} (\bar{q}^{a\prime} q^{b\prime})_{V-A} \,,$$

$$Q_5 = (\bar{s}' d')_{V-A} \sum_{q'} (\bar{q}' q')_{V+A} \,, \qquad Q_6 = (\bar{s}^{b\prime} d^{a\prime})_{V-A} \sum_{q'} (\bar{q}^{a\prime} q^{b\prime})_{V+A} \,,$$

$$Q_7 = \frac{3}{2} (\bar{s}' d')_{V-A} \sum_{q'} Q^q_{em} (\bar{q}' q')_{V+A} \,, \qquad Q_8 = \frac{3}{2} (\bar{s}^{b\prime} d^{a\prime})_{V-A} \sum_{q'} Q^q_{em} (\bar{q}^{a\prime} q^{b\prime})_{V+A} \,,$$

$$Q_9 = \frac{3}{2} (\bar{s}' d')_{V-A} \sum_{q'} Q^q_{em} (\bar{q}' q')_{V-A} \,, \qquad Q_{10} = \frac{3}{2} (\bar{s}^{b\prime}_L d^{a\prime}_L)_{V-A} \sum_{q'} Q^q_{em} (\bar{q}^{a\prime} q^{b\prime})_{V-A} \,,$$

- **Wilson coefficients in our scenario:**

$$C_1(m_\rho) = 0 \,, \qquad C_2(m_\rho) = -i \cdot \frac{1}{8} \frac{g_W^2 g_{\rho L}^{12}}{m_\rho^2 g_\rho} \,,$$

$$C_3(m_\rho) = i \cdot \frac{1}{24} \frac{g_s^2 g_{\rho L}^{12}}{m_\rho^2 g_\rho} + i \cdot \frac{1}{8} \frac{g_W^2 g_{\rho L}^{12} (-Y_q)}{m_\rho^2 g_\rho} - i \cdot \frac{1}{144} \frac{g_Y^2 g_{\rho L}^{12}}{m_\rho^2 g_\rho} \,, \qquad C_4(m_\rho) = -i \cdot \frac{1}{8} \frac{g_s^2 g_{\rho L}^{12}}{m_\rho^2 g_\rho} \,,$$

$$C_5(m_\rho) = i \cdot \frac{1}{24} \frac{g_s^2 g_{\rho L}^{12}}{m_\rho^2 g_\rho} \,, \qquad C_6(m_\rho) = -i \cdot \frac{1}{8} \frac{g_s^2 g_{\rho L}^{12}}{m_\rho^2 g_\rho} \,,$$

$$C_7(m_\rho) = -i \cdot \frac{1}{36} \frac{g_Y^2 g_{\rho L}^{12}}{m_\rho^2 g_\rho} \,, \qquad C_8(m_\rho) = 0 \,,$$

$$C_9(m_\rho) = i \cdot \frac{1}{12} \frac{g_W^2 g_{\rho L}^{12}}{m_\rho^2 g_\rho} \,, \qquad C_{10}(m_\rho) = 0 \,,$$

NLO formula for ε'/ε:

[T.Kitahara et al., arXiv:1607.06727]

$\omega_+|_{\mathrm{SM}} \equiv a\,\mathrm{Re}A_2|_{\mathrm{SM}}/\mathrm{Re}A_0|_{\mathrm{SM}} = 4.53 \times 10^{-2}$

$$\left(\frac{\epsilon'}{\epsilon}\right)^{\mathrm{CFVs}} = \frac{\omega_+}{\sqrt{2}\,|\epsilon_K^{\mathrm{exp}}|\,\mathrm{Re}A_0^{\mathrm{exp}}} \langle \vec{Q}_{\epsilon'}(\mu)^T\rangle \hat{U}\,(\mu, m_\rho)\,\mathrm{Im}\left[\vec{C}(m_\rho)\right]$$

$2.228(11) \times 10^{-3}$ $3.3201(18) \times 10^{-7}\,\mathrm{GeV}$

'Hadronic factor' **evolution matrix** **Wilson coefficients (vector form)**

- $\langle \vec{Q}_{\epsilon'}(\mu)^T\rangle \equiv \frac{1}{\omega_+}\langle \vec{Q}(\mu)^T\rangle_2 - \langle \vec{Q}(\mu)^T\rangle_0 (1 - \hat{\Omega}_{\mathrm{eff}})$

  isospin breaking correction

$$(1-\hat{\Omega}_{\mathrm{eff}})_{ij} = \begin{cases} 0.852 & (i=j=1-6), \\ 0.983 & (i=j=7-10), \\ 0 & (i \neq j). \end{cases}$$

- $$\langle \vec{Q}_{\epsilon'}(1.3\,\mathrm{GeV})^T\rangle = \big(0.345112, 0.132542, 0.0340124, -0.178558, 0.152483, 0.288073, 2.65313, 17.3046, 0.526475, 0.281154\big)(\mathrm{GeV})^3,$$

- $$\hat{U}(1.3\,\mathrm{GeV}, \mu_{\mathrm{NP}}) \simeq \hat{U}_{0,1,fit} + \hat{U}_{0,2,fit} \ln\frac{\mu_{\mathrm{NP}}[\mathrm{GeV}]}{1000\,\mathrm{GeV}}.$$