Vector-like compositeness meets B-physics $R_{K^{(*)}}$ anomaly

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based on collaboration with

Shinya Matsuzaki (Nagoya Univ.), Ryoutaro Watanabe (Montréal Univ.)

arXiv:1706.01463, published from JHEP

Talk @ Corfu Summer Institute, Workshop on the Standard Model and Beyond;
Corfu, Greece, 9th September 2017

Introduction

B anomalies [review]

[LHCb, arXiv:1406.6482]

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

[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]**

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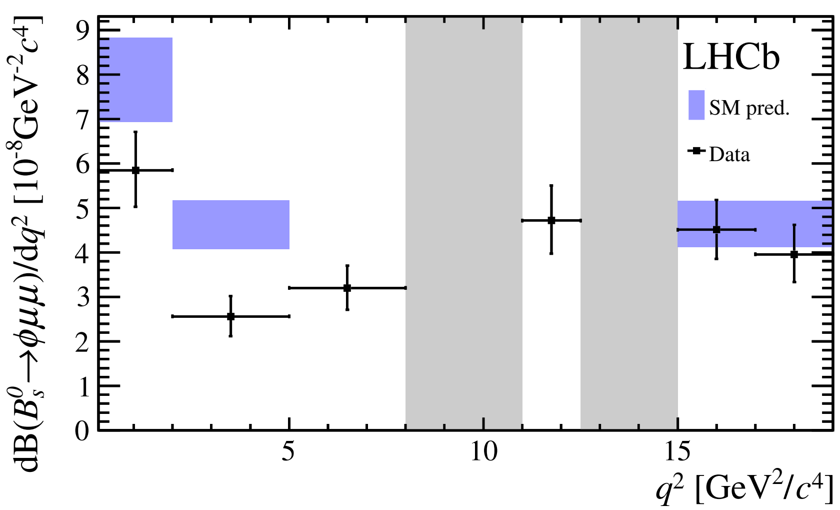
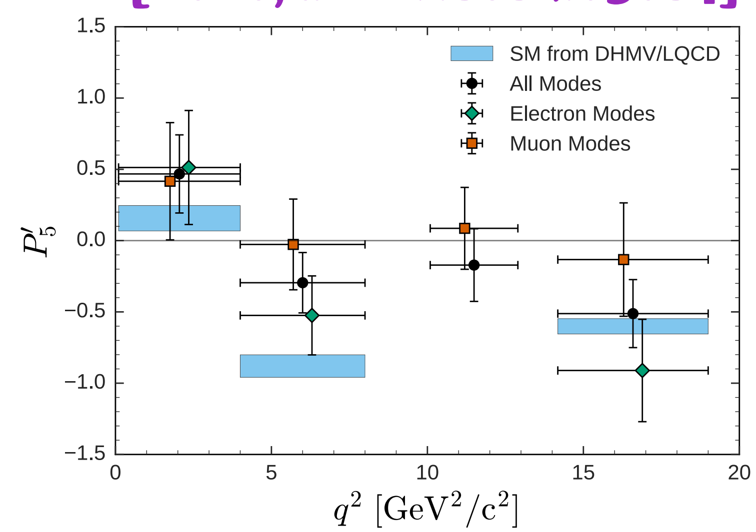
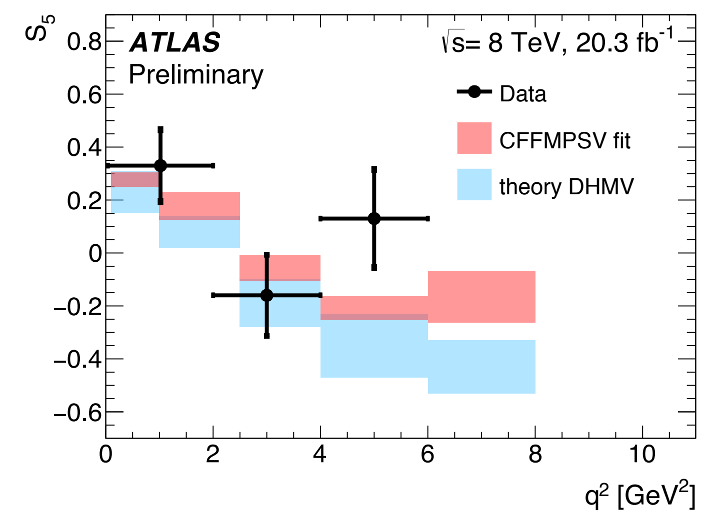


[Belle, arXiv:1612.05014]



[ATLAS, ATLAS-CONF-2017-023]



→ **deviations being observed in associated variables**

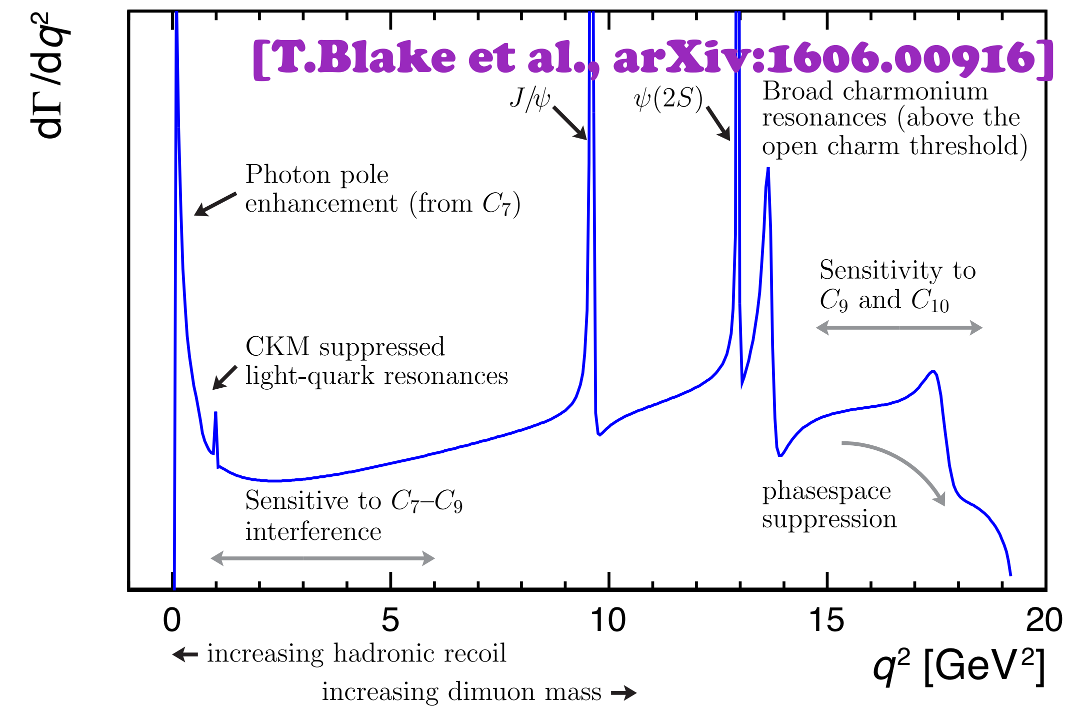
(see the overview talk by Pepe-Altarelli)

Suggestions from global fit(s) [review]

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

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

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



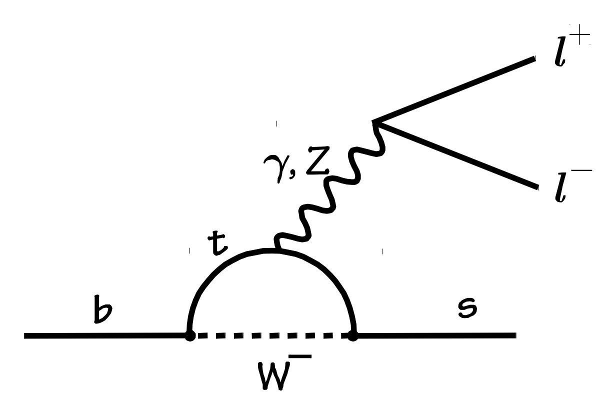
[global fit result for new physics]

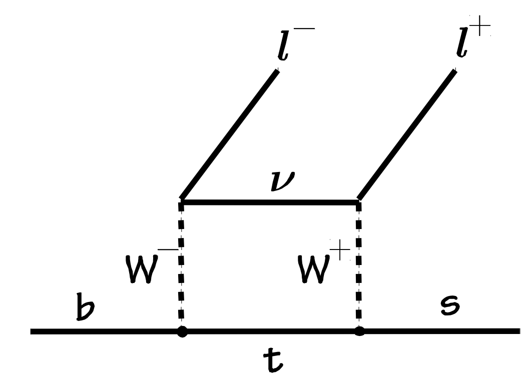
[W.Altmannshofer et al., arXiv:1704.05435]

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

(effective) vector interaction

[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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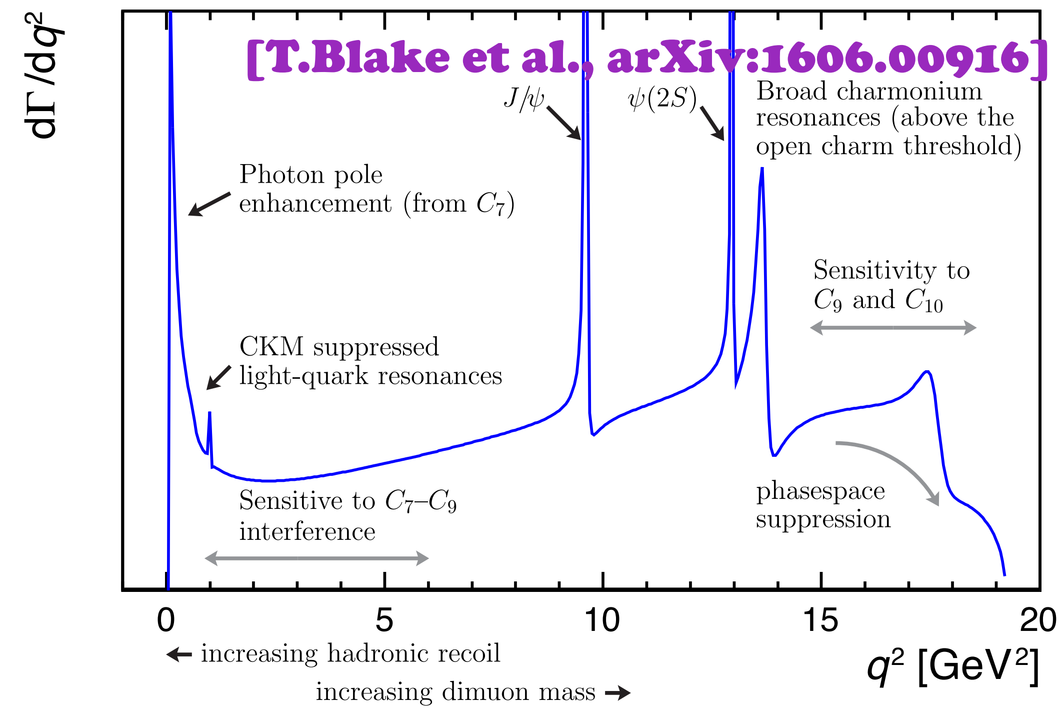

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- ☑ (effective) vector interaction
- ☑ s and b should be left-handed (right-handed is irrelevant).
- ☑ Lepton part is ambiguous (vector-like, left-handed,...).

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

[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]

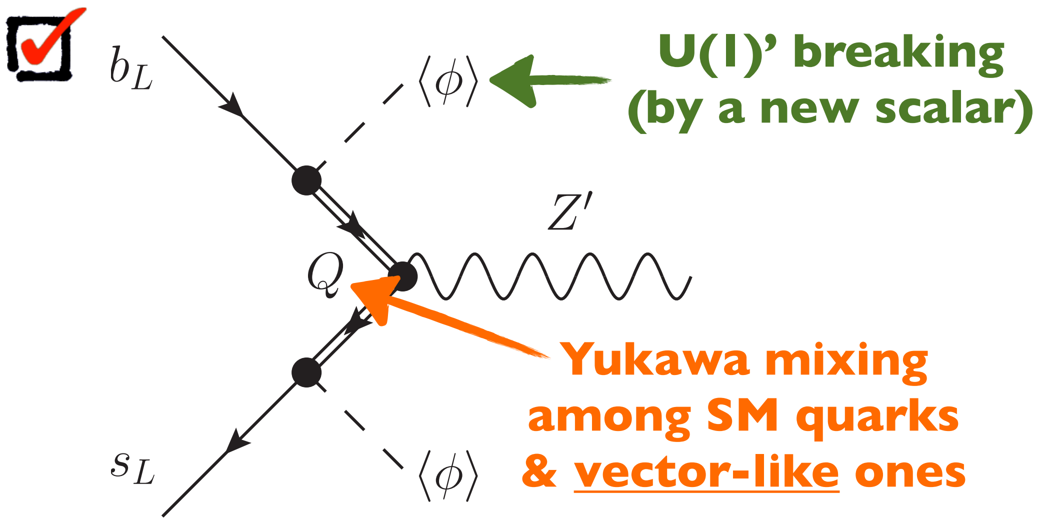
How about Z'? [review]

a straightforward candidate: Z' vector boson → **What is quantum number?**

(or vector leptoquark)

[W.Altmannshofer et al., arXiv:1403.1269]

- **basic pheno. strategy: (e.g.,) $U(1)'_{L\mu-L\tau}$ + vector-like quarks**



- **Fundamental Z' scenarios work [(with additional fermion(s) and scalar(s)].**

(see talks by Mahmoudi, Crivellin, Zwicky, King, Quiros, Leontaris, Ryoutaro ...)

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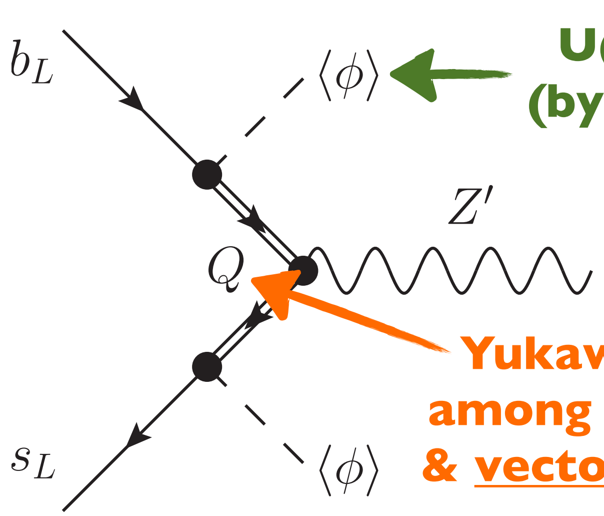

U(1)' breaking (by a new scalar)

Yukawa mixing among SM quarks & vector-like ones

other (anomaly-free) U(1)'

e.g., [L.Bian et al., arXiv:1707.04811]

☑ **U(1; y(L$_\mu$-L$_\tau$) + x(B$_3$-L$_3$))**

(x,y: arbitrary values)

$$\mathcal{L}_Y = -\bar{u}M_u u - \bar{d}M_d d - \bar{l}M_l l - \bar{l}M_D\nu_R - \overline{(\nu_R)^c}M_R\nu_R + \text{h.c.}$$

$$M_u = \begin{pmatrix} y^u_{11}\langle H_1\rangle & y^u_{12}\langle H_1\rangle & 0 \\ y^u_{21}\langle H_1\rangle & y^u_{22}\langle H_1\rangle & 0 \\ h^u_{31}\langle H_2\rangle & h^u_{32}\langle H_2\rangle & y^u_{33}\langle H_1\rangle \end{pmatrix},$$

$$M_d = \begin{pmatrix} y^d_{11}\langle \tilde{H}_1\rangle & y^d_{12}\langle \tilde{H}_1\rangle & h^d_{13}\langle H_2\rangle \\ y^d_{21}\langle \tilde{H}_1\rangle & y^d_{22}\langle \tilde{H}_1\rangle & h^d_{23}\langle H_2\rangle \\ 0 & 0 & y^d_{33}\langle H_1\rangle \end{pmatrix},$$

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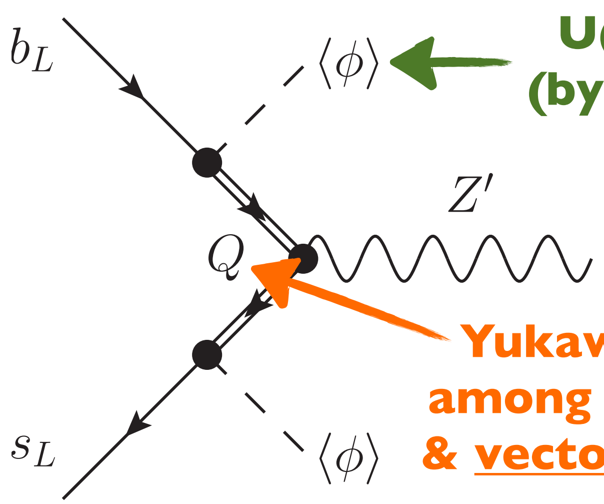

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Q: How about composite case?

Points

0. Introduction (finished)

1. Hidden "QCD" $\Rightarrow$ multiple vector candidates for B anomaly.

2. Various virtues in the vector-like compositeness

3. Large part of parameter space waits for being explored.

- Summary

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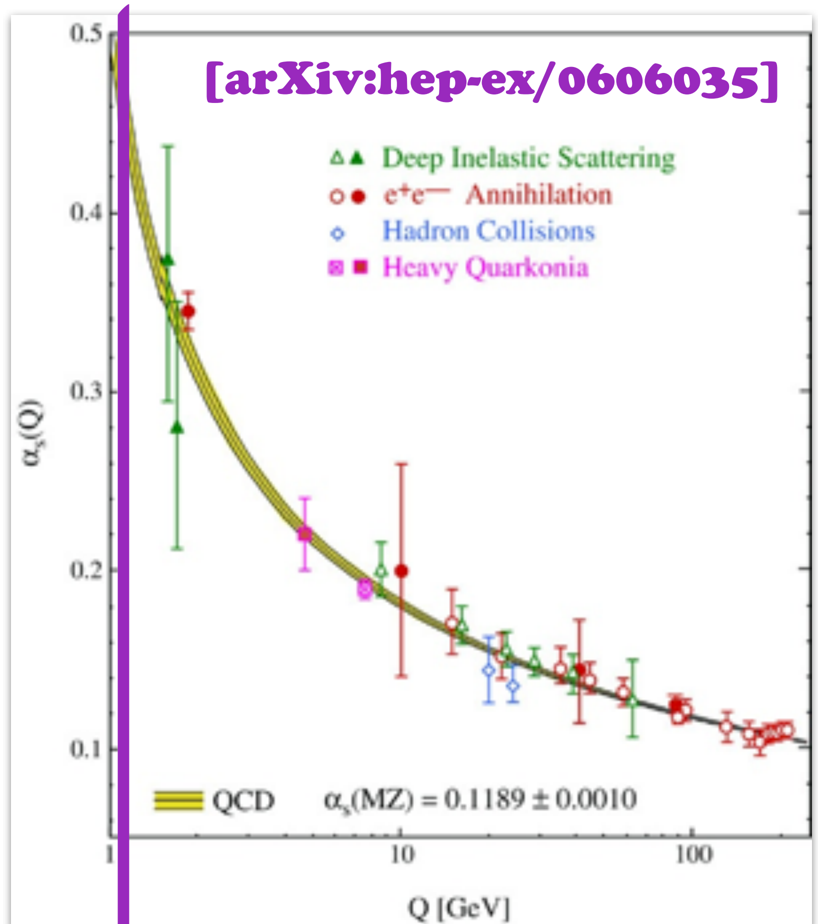
QCD as Composite scenario [Review]

- **When a coupling becomes strong, composite particles appear.**



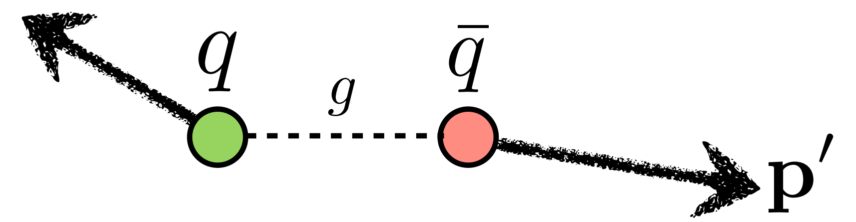
~Λ_{QCD}

weekly coupled (UV-fundamental) particles

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

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

p **(momentum)**

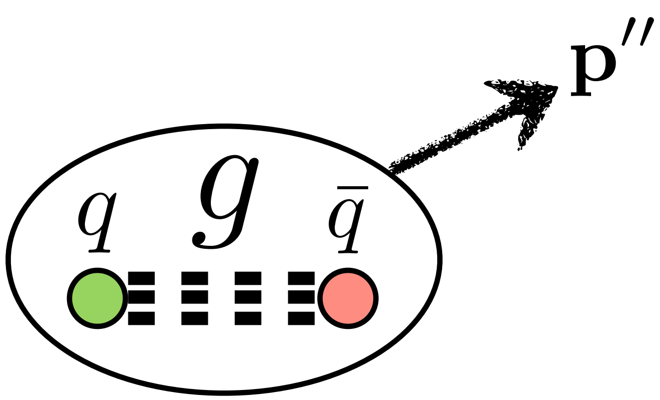


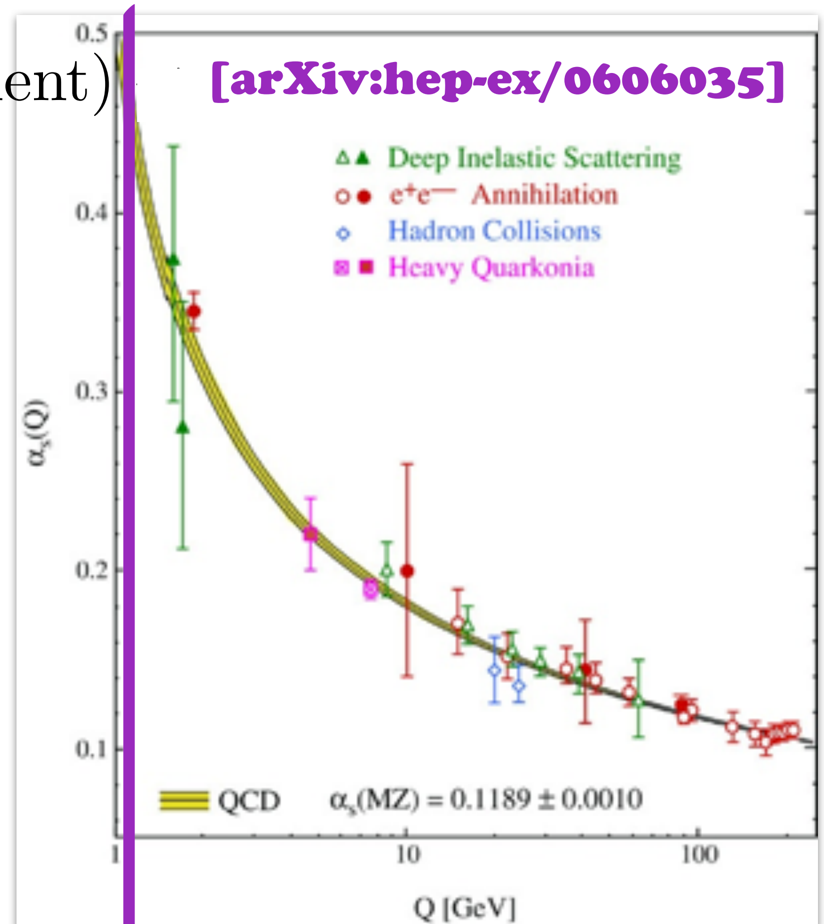
QCD as Composite scenario [Review]

When a coupling becomes strong, composite particles appear.

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

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





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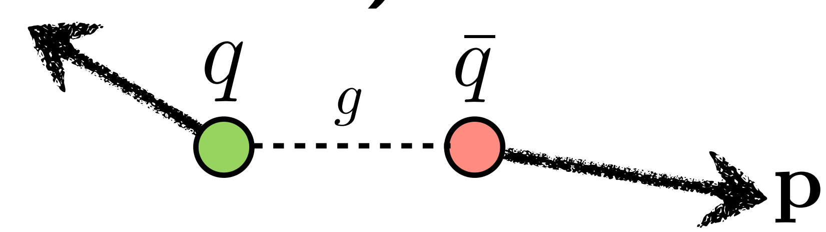
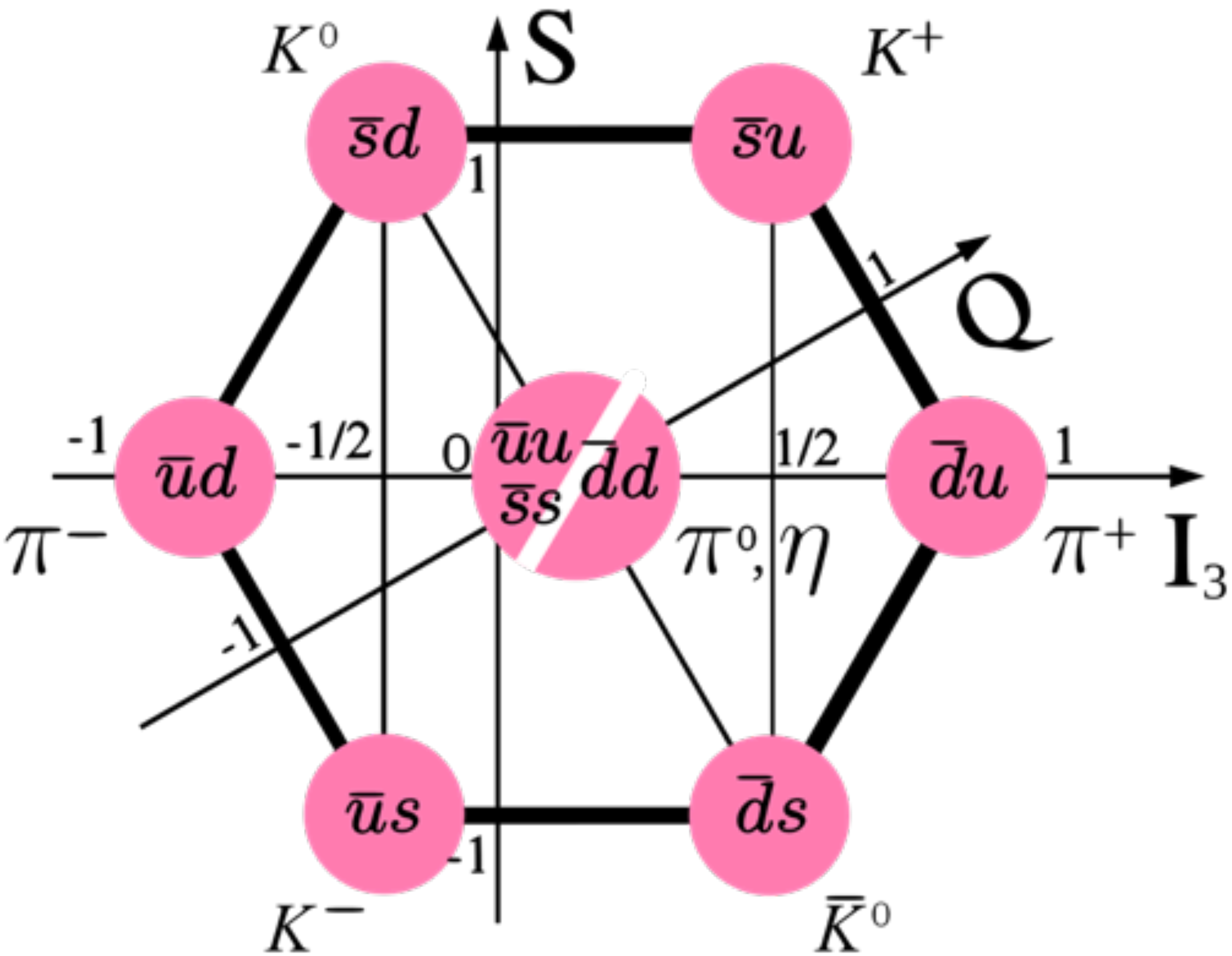
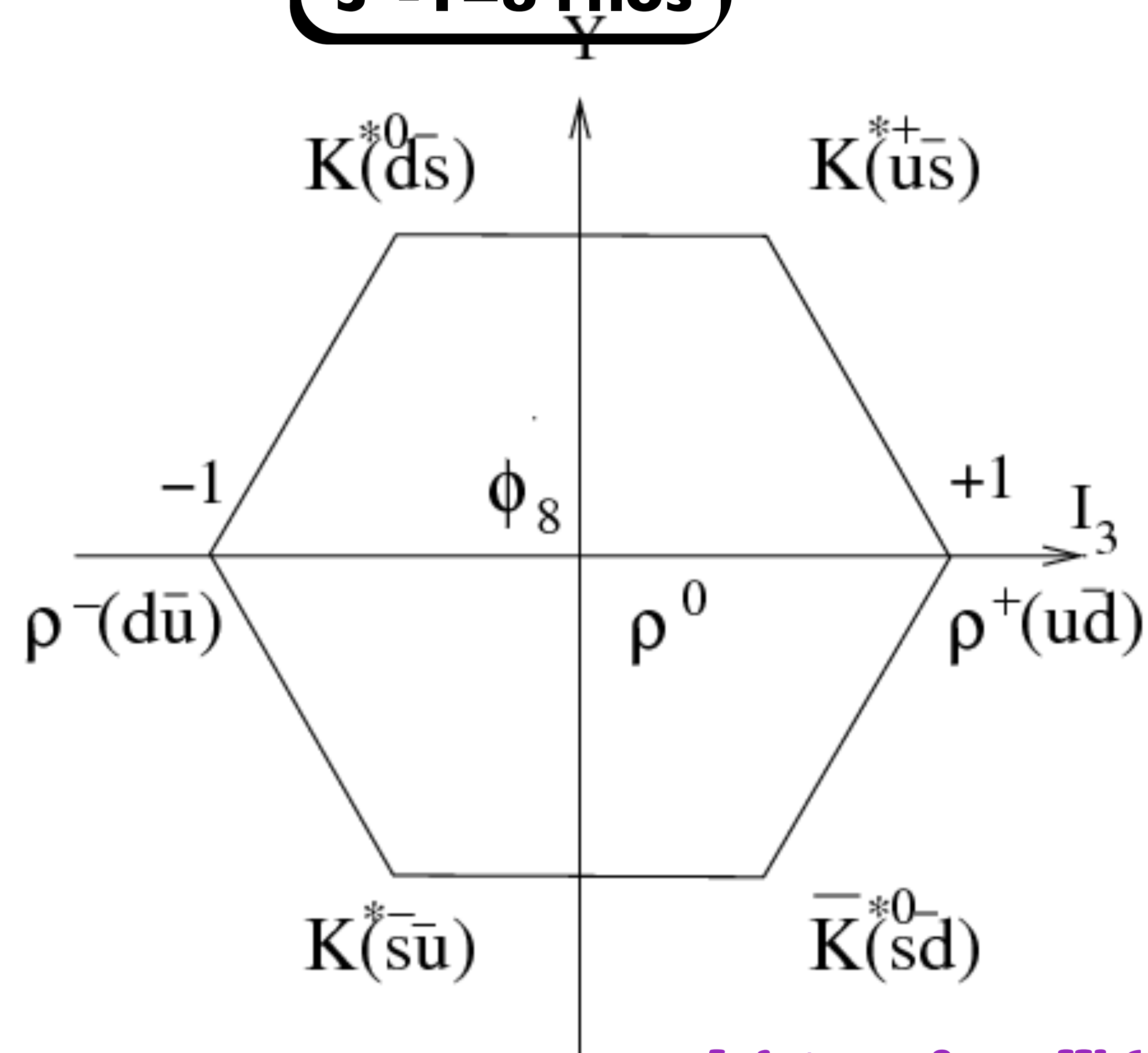


strongly coupled (theory of composite particles) ← ~Λ_{QCD} → **weekly coupled (UV-fundamental) particles**

QCD as Composite scenario [Review]





[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 ($SU(3)_{V,\,\mathrm{gauged}}$)

[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]

QCD as Composite scenario [Review]

Such a confining gauge theory is fascinating since:

- ☑ dynamically-realized symmetry breaking
- ☑ 'predictive' (limited # of parameters)
- ☑ Low-energy meson theory is managed by the chiral symmetry
- ☑ New vector particles are introduced in a consistent way!

▶ **Q: Can we obtain `composite Z'` for $R_{K(*)}$?**

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

- ☑ pseudo-scalars (pions) as pseudo NG bosons
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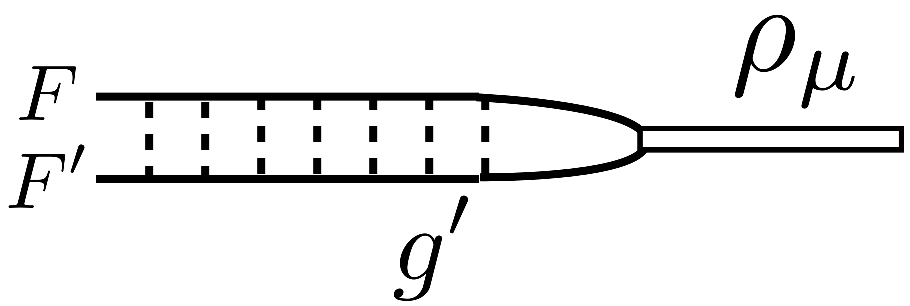
Vector-like hidden "QCD" (hypercolor[**HC**])

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



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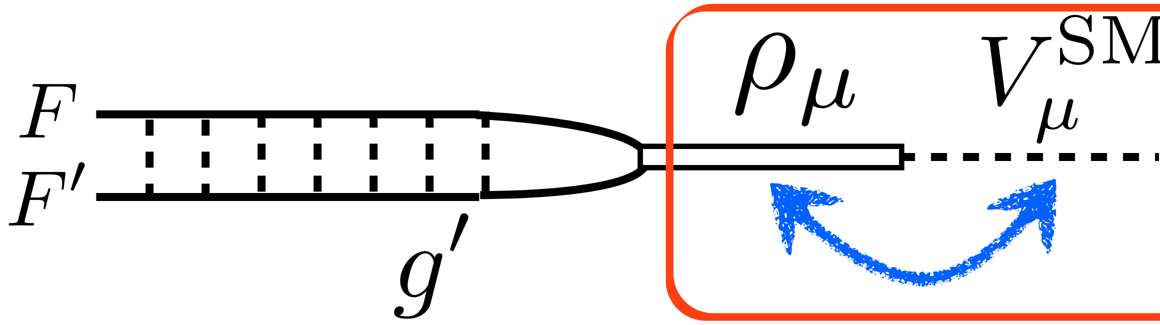
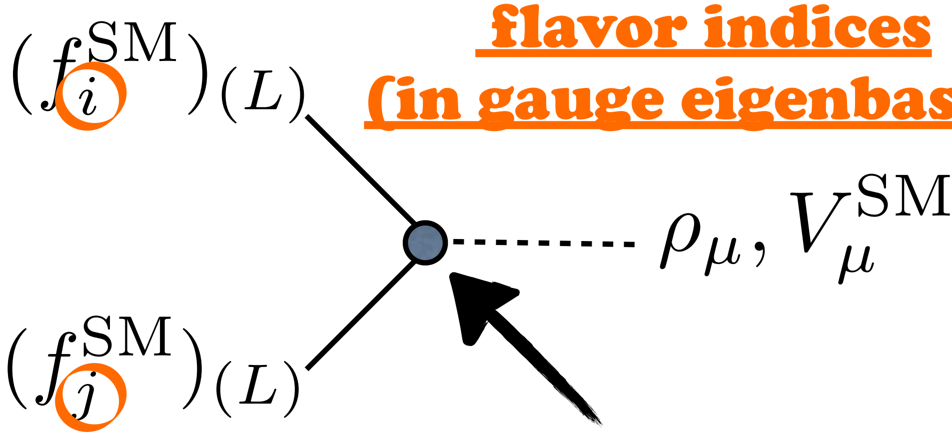


holding the Same (SM) quantum #

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)

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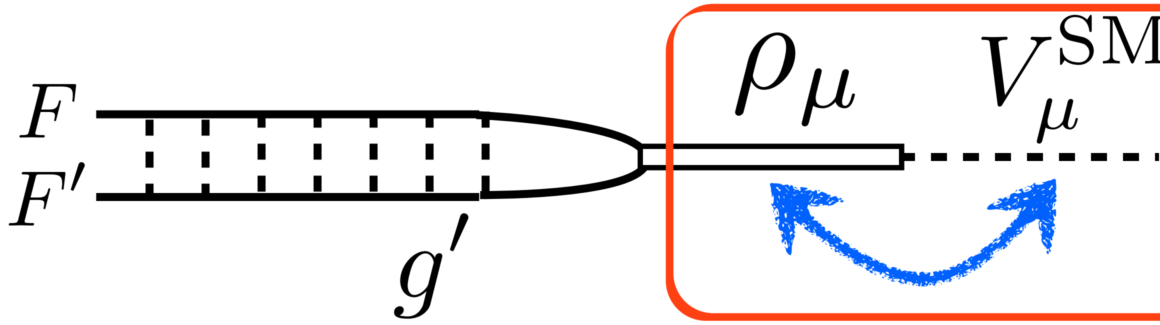

holding the Same (SM) quantum #

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- **Configuration:**

SU(8)$_L$×SU(8)$_R$ chiral symmetries

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

(one-family model)

confined **external gauge interactions**

new (HC) quarks

new (HC) leptons

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

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]

$\longrightarrow$

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]

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

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

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

[vector meson spectrum] NOT ONLY Z' candidates!

15 in total

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

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

$$
\left[\mathcal{L}^f_\mu\right]_{8\times 8} = \left(\begin{array}{c|c} \mathbf{1}_{2\times2}\otimes g_s G^a_\mu \frac{\lambda^a}{2} + \left(g_W W_\mu \tau^\alpha + \frac{1}{6} g_Y B_\mu\right)\otimes \mathbf{1}_{3\times3} & \mathbf{0}_{6\times2} \\ \hline \mathbf{0}_{2\times6} & g_W W^\alpha_\mu \tau^\alpha - \frac{1}{2} g_Y B_\mu \cdot \mathbf{1}_{2\times2} \end{array}\right)
$$

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

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

$$
\rho = \begin{pmatrix} (\rho_{QQ})_{6\times6} & (\rho_{QL})_{6\times2} \\ (\rho_{LQ})_{2\times6} & (\rho_{LL})_{2\times2} \end{pmatrix}
$$

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

[vector meson spectrum] NOT ONLY Z' candidates!

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

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

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

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

undetermined coefficients

flavor indices (in gauge eigenbasis)

Points

0. Introduction (finished)

1. Hidden “QCD” $\Rightarrow$ multiple vector candidates for B anomaly.

2. Various virtues in the vector-like compositeness

3. Large part of parameter space waits for being explored.

- Summary

Important points for current pheno.

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

We adopted the flavor texture:

(SM-fermion) mass eigenbases

$$g_L^{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & g_L^{33} \end{pmatrix}^{ij}$$

assuming (3,3) only in gauge eigenbasis

$$(u_L)^i = U^{iI}(u'_L)^I, \quad (d_L)^i = D^{iI}(d'_L)^I, \quad (e_L)^i = L^{iI}(e'_L)^I, \quad (\nu_L)^i = L^{iI}(\nu'_L)^I,$$

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

[Our phenomenological scheme on flavor changing]

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

overall factor

correction to f-f-V_{SM} interaction

f-f-ρ interaction

g_ρ >> g_{SM} is required via EW precisions.
→ g_ρ = 6 (vector dominance in QCD)

[flavor-changing effective interaction]

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overall factor

correction to f-f-V_{SM} interaction

f-f-ρ interaction

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(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**

- **4 (+1) couplings are relevant for (pure) HC vector-ρ phenomena:**

  m_ρ, $g_{\rho L}$ [= $[g_L]^{33}$ * g_ρ], θ_D, θ_L, (g_ρ)

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- **Fascinating aspects:**
  - ☑ **The candidate of Zs and their mass scale are dynamically generated.**
  - ☑ **The $C_9 = -C_{10}$ texture (for $b \to sll$) is naturally realized.**
  - ☑ **Apparently gauge-anomaly free.**
  - ☑ **Lots of new particles (EW-safe) are 'derived'.**

  (e.g., [T.Hur & P.Ko, arXiv:1103.2571]
  * **Scale-invariant extension (⇒ hierarchy problem)**)

Points

0. Introduction (finished)

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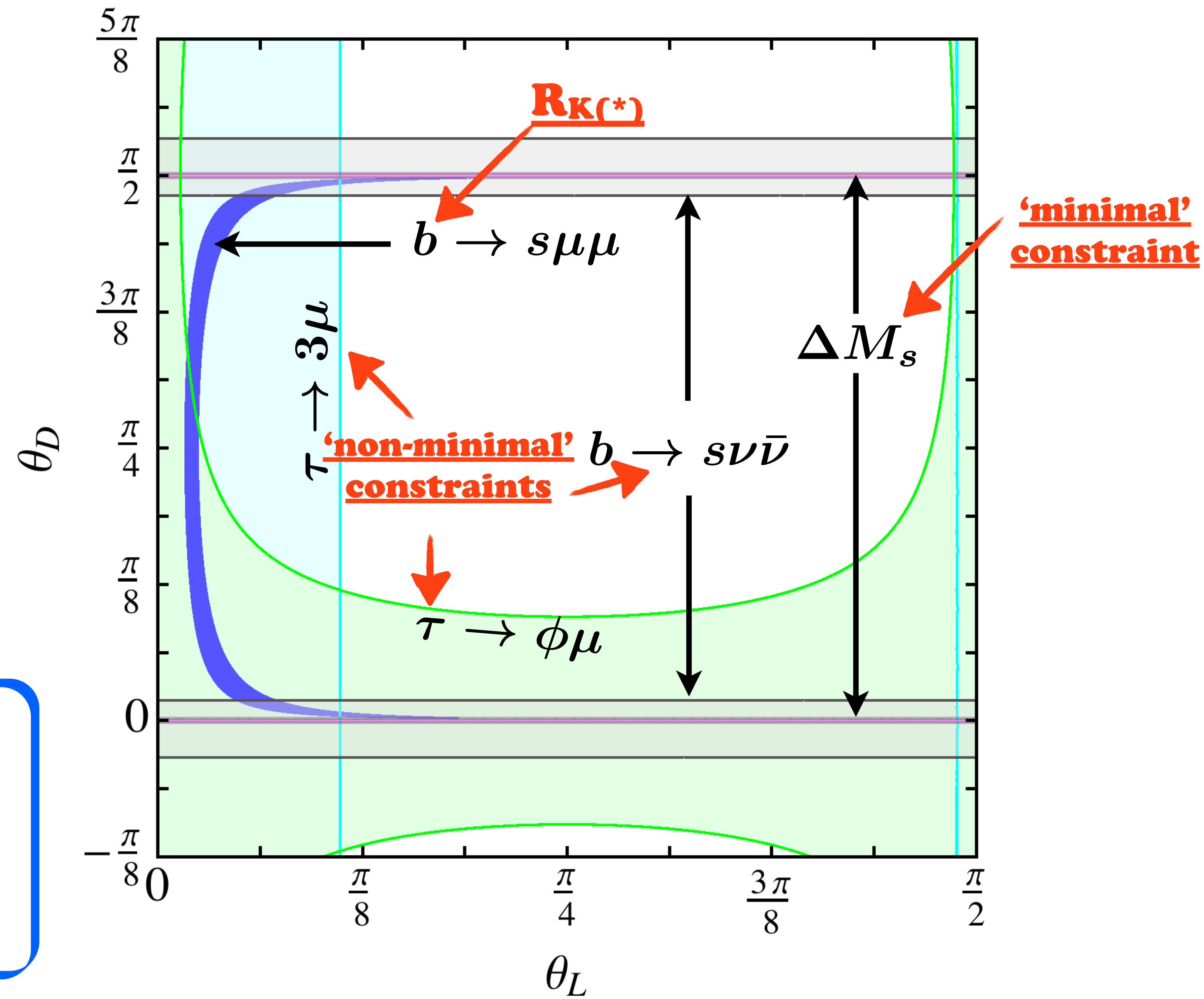
2. Various virtues in the vector-like compositeness

3. Large part of parameter space waits for being explored.

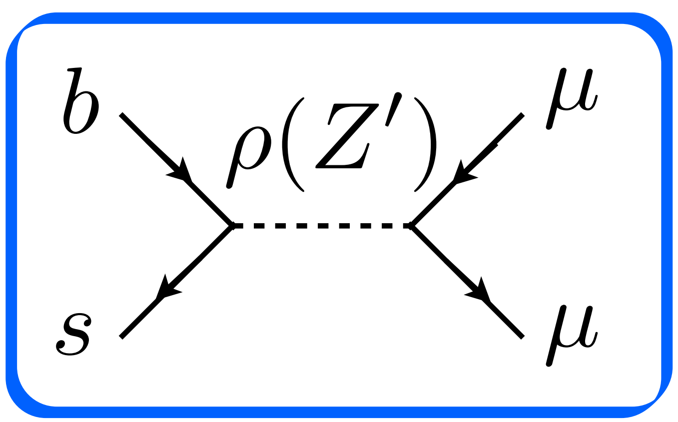
- Summary

Flavor results

HC ρ : $|g_\rho\, g_L^{33}| = 1$, $m_\rho = 1$ TeV



an example of amplitude:



[B.Capdevila et al., arXiv:1704.05340]

- **adopted C_9 (= $-C_{10}$) favored range:** $C_9^{\mu\mu}|_{\rm best} = -0.61$ & $C_9^{\mu\mu}|_{+3\sigma} = -0.23$
- **All of vector ρs (massive gluons, vector LQ, W's, Z's) are taken into account.**

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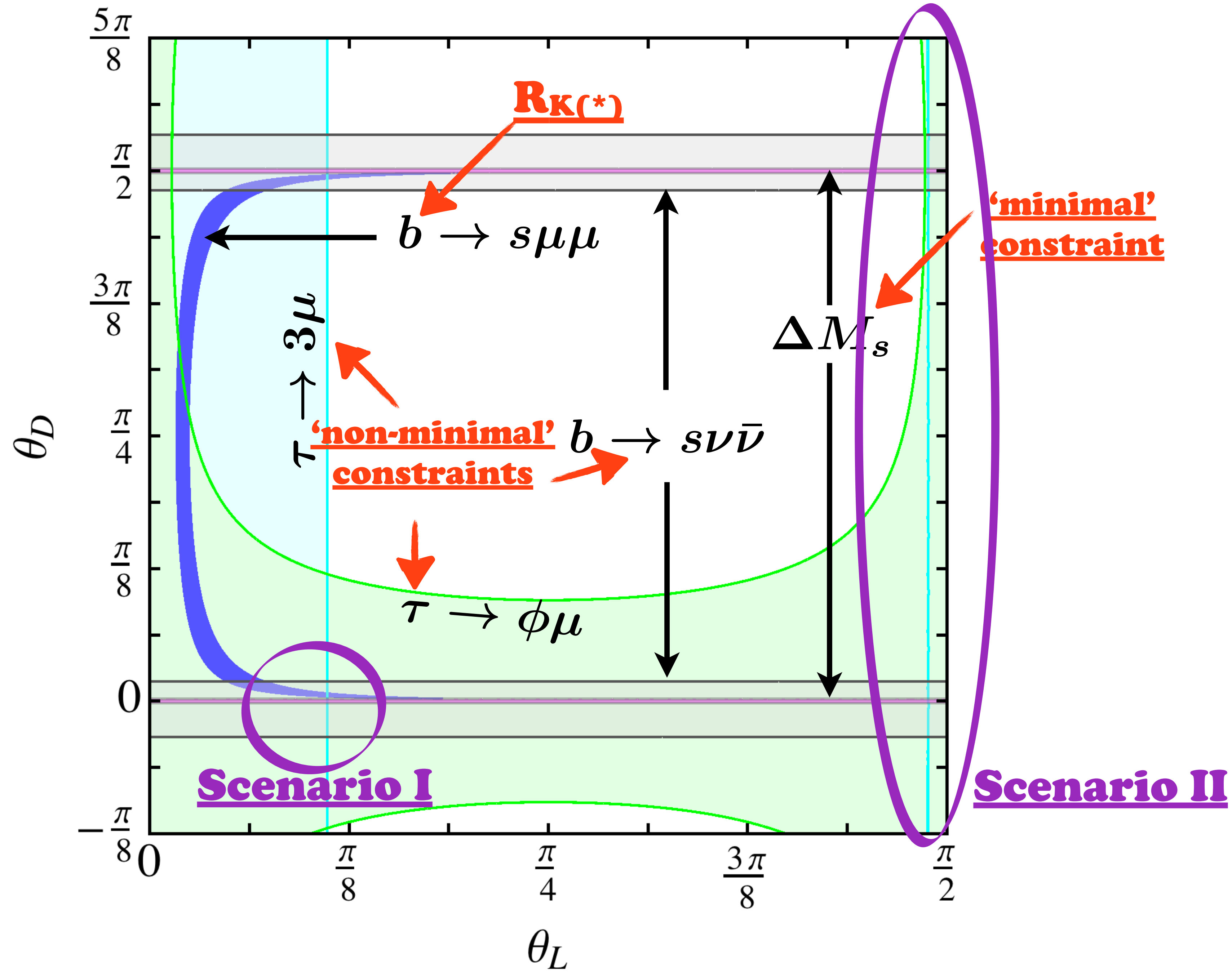

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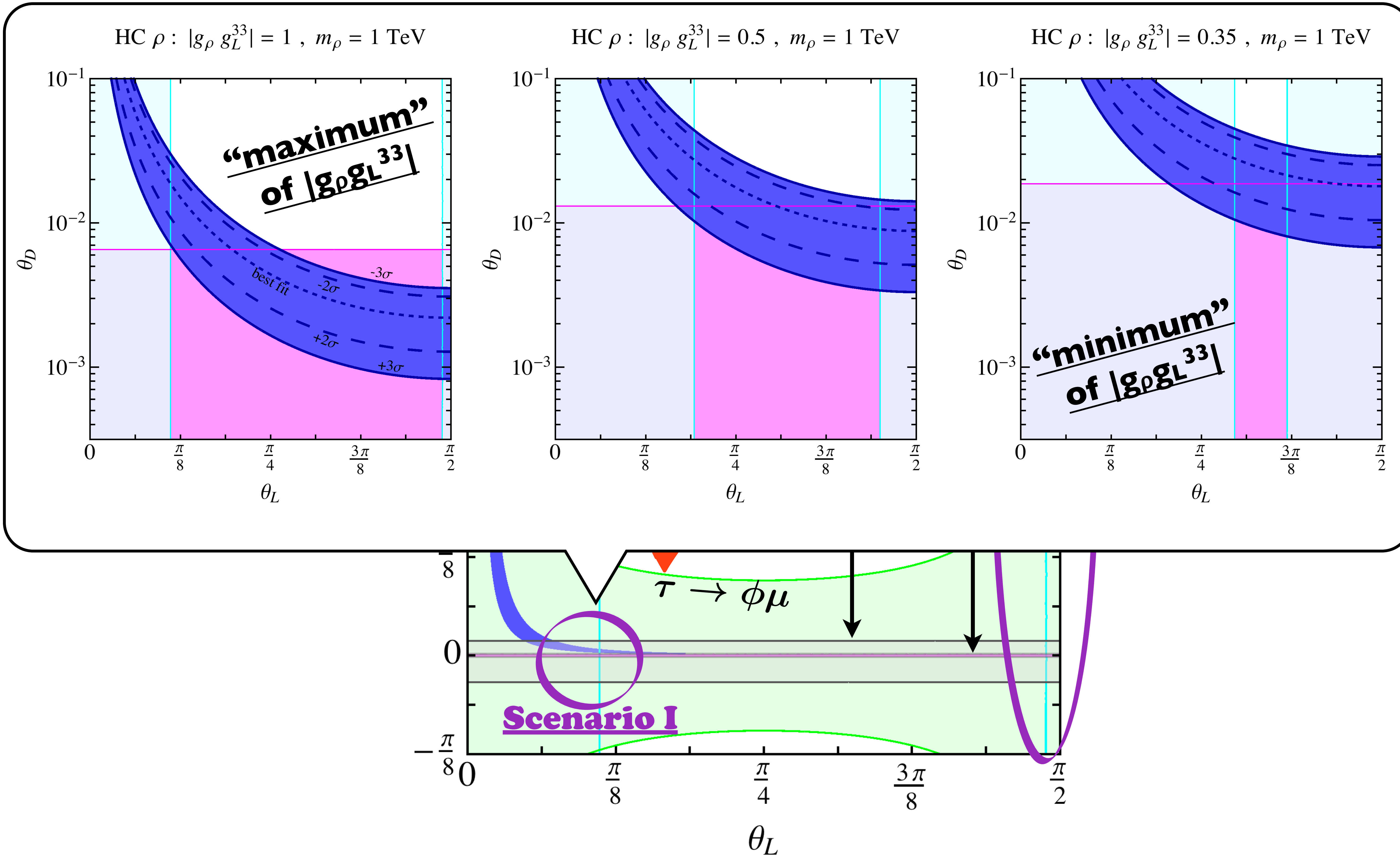

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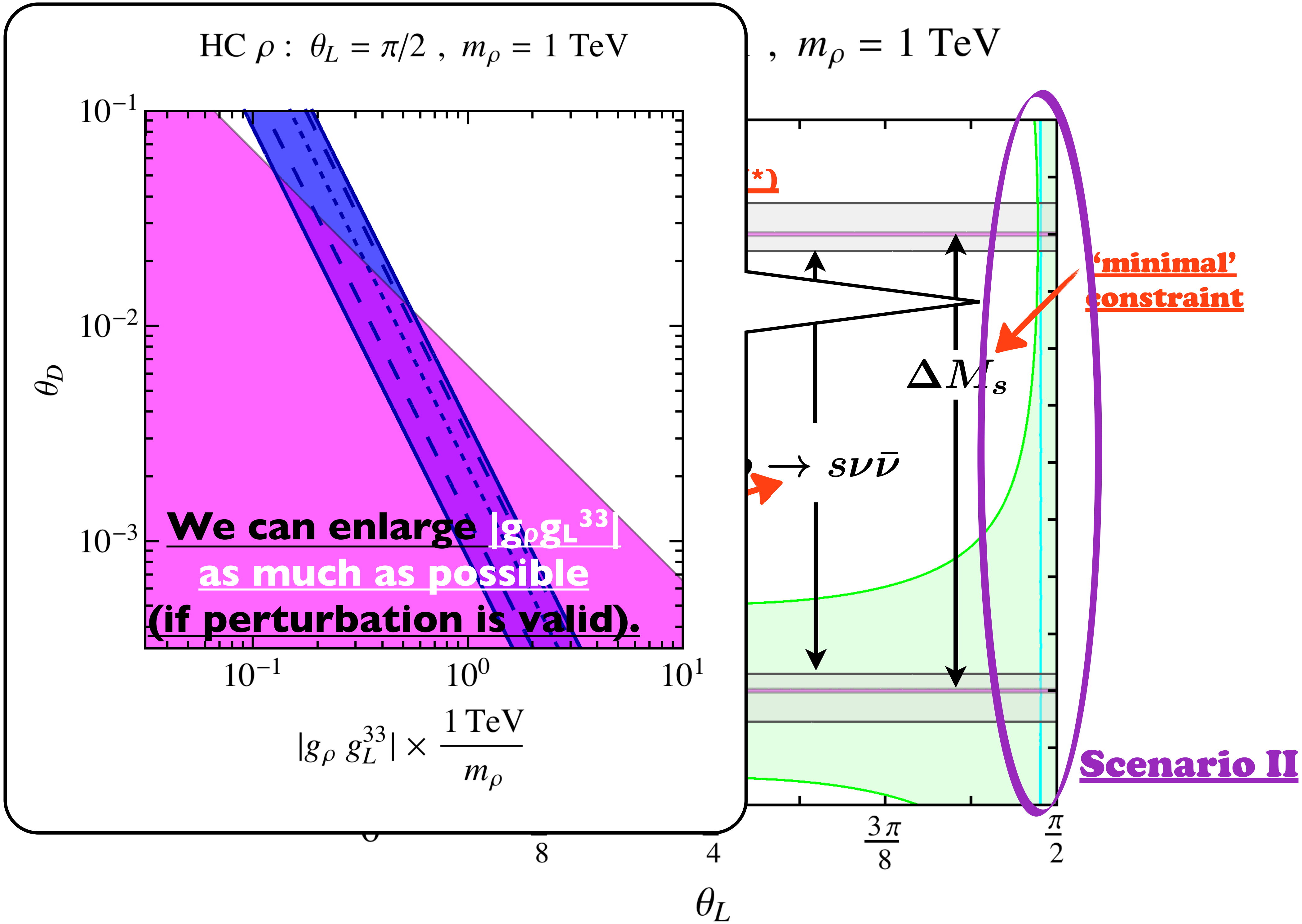

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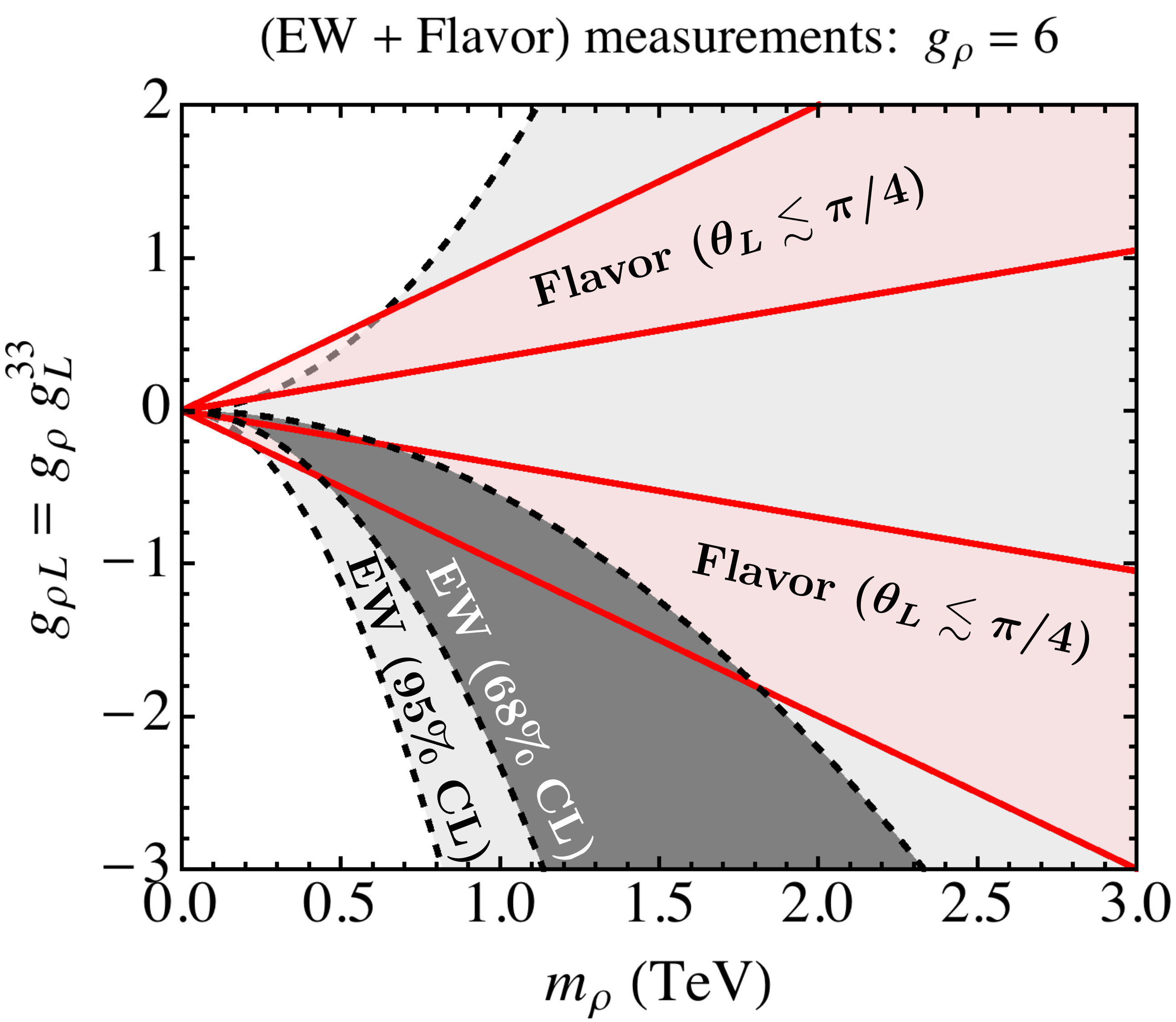
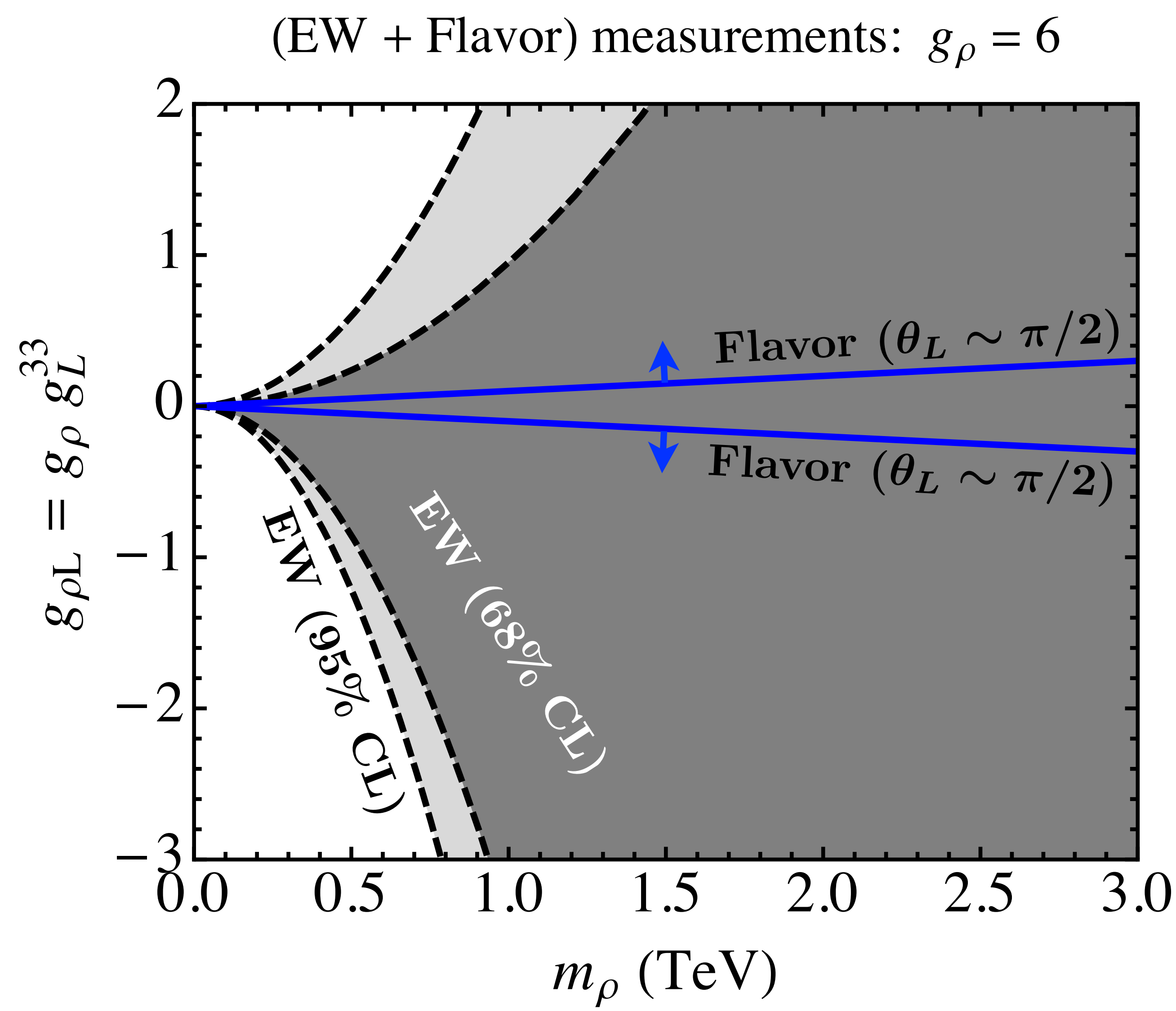
Situation after fixing the mixing angles ($\theta_D \sim 0$)

☑ **in scenario I**



☑ **in scenario II**



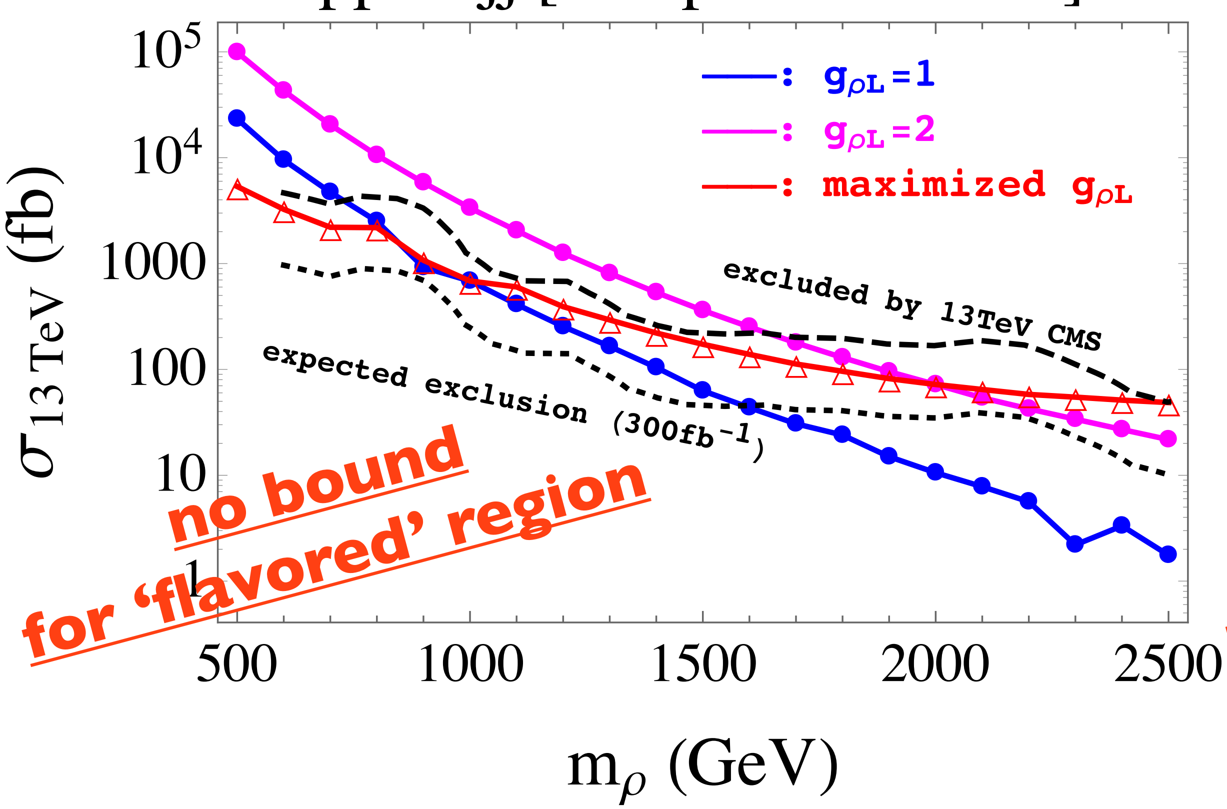
relevant EW constraints: $A_{FB}^{(0,\tau)}$, $A_{FB}^{(0,\mu)}$, R_b

[Flavor-favored region] is inside [EW allowed region (2σ)].

LHC direct search: constraints/prospects

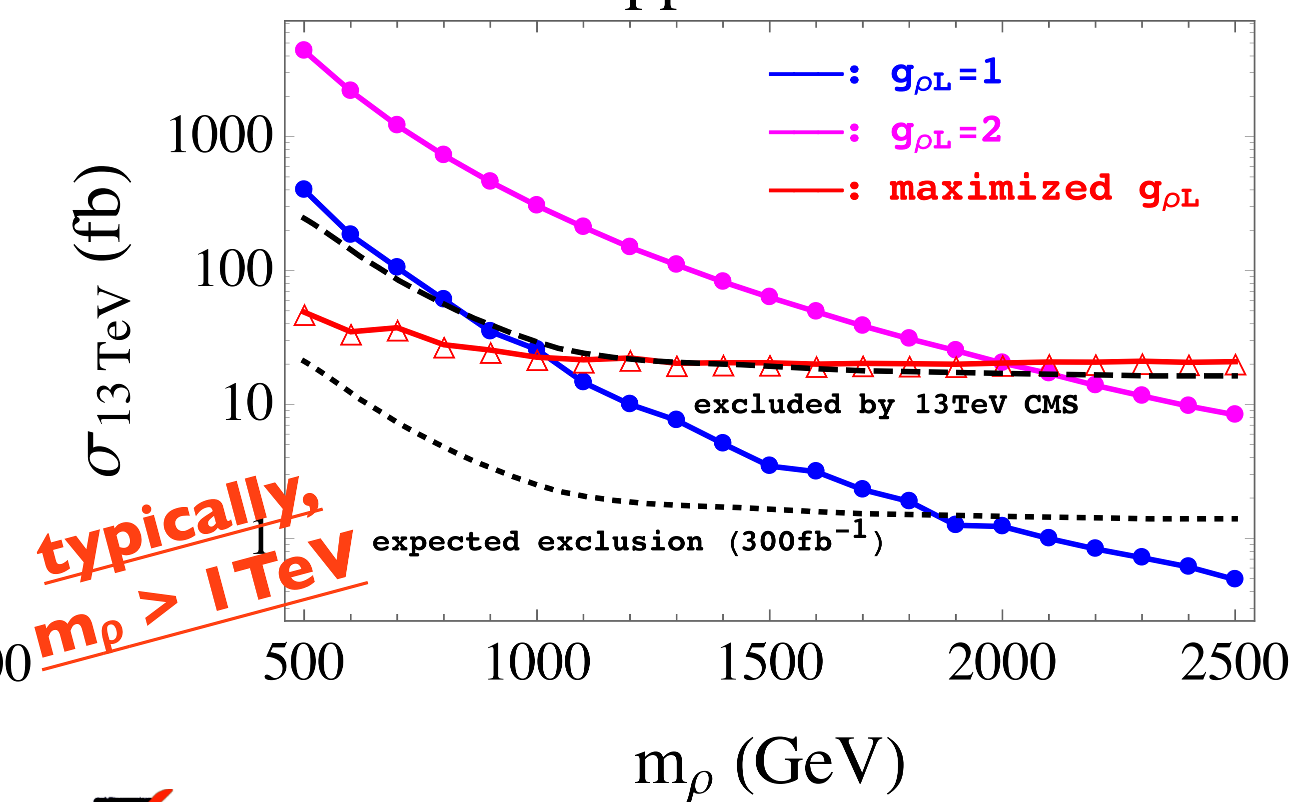
for scenario I & II

pp $\to$ jj [acceptance = 0.69]



for scenario I

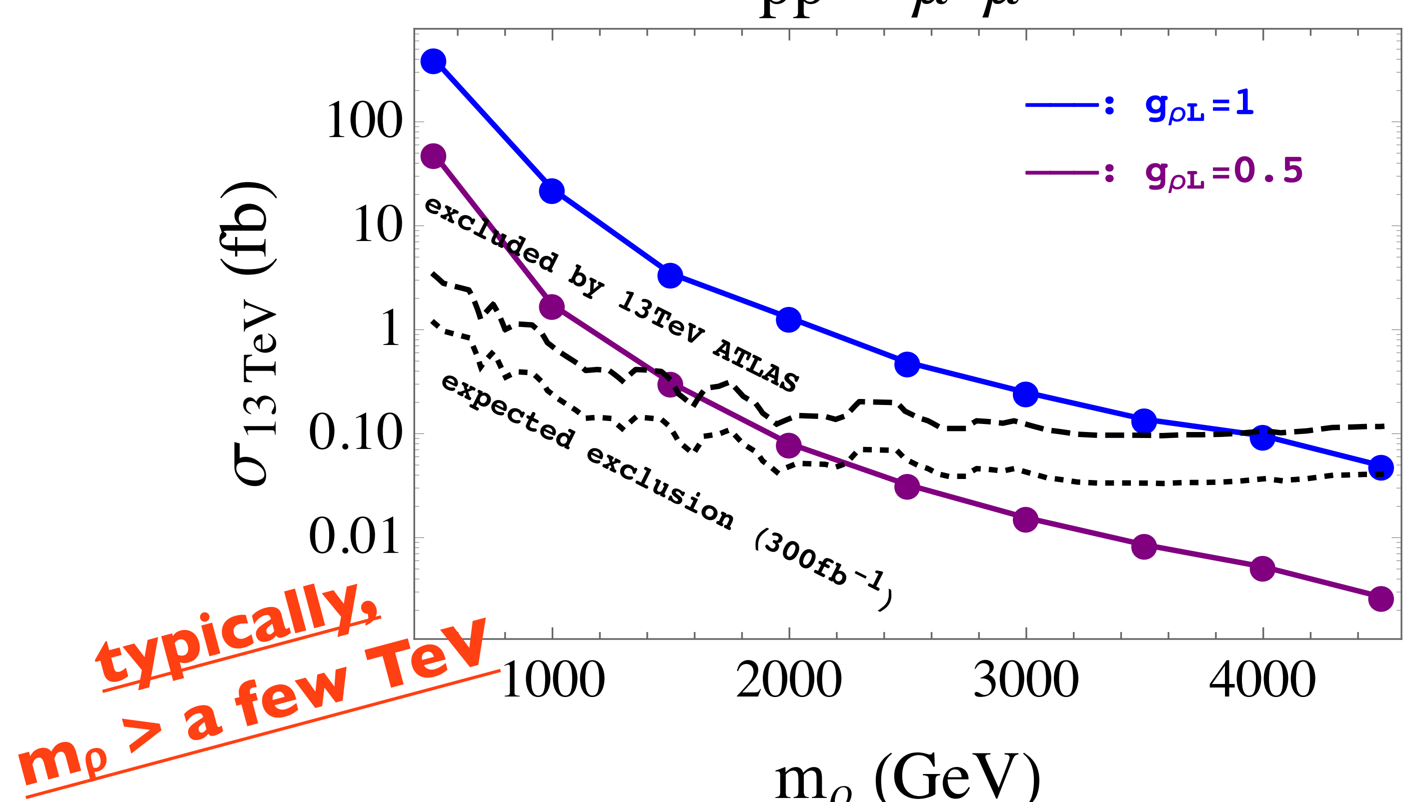
pp $\to \tau^+\tau^-$



(PDF set: CTEQ6L1)

for scenario II

pp $\to \mu^+\mu^-$



Summary

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  - ☑ Well-defined TeV-scale vector leptoquarks
- **The $R_{K(*)}$ anomalies are addressed consistently.**
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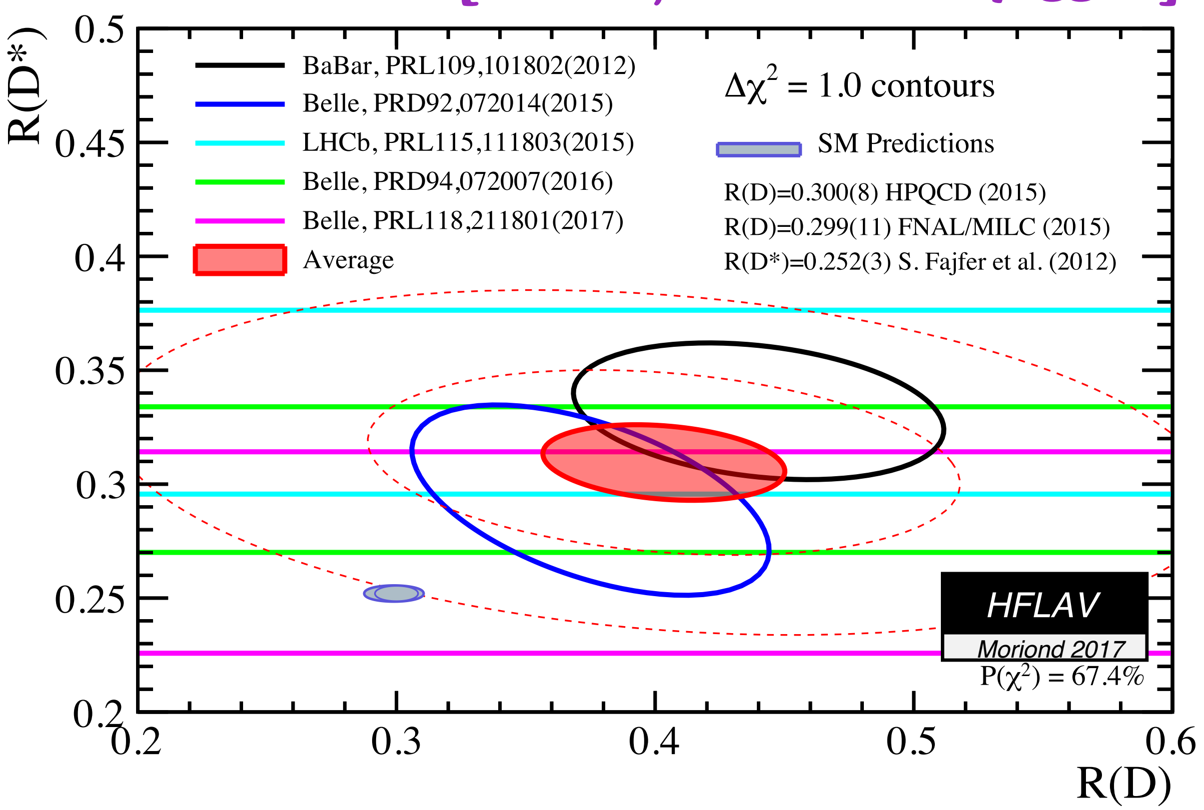
BACKUPS

$R_{D^{(*)}}$ anomaly

[HFLAV, arXiv:1612.07233v2]

- $$R_D = \frac{\mathcal{B}(\bar{B} \to D\tau\bar{\nu})}{\mathcal{B}(\bar{B} \to D\ell\bar{\nu})}\,, \qquad R_{D^*} = \frac{\mathcal{B}(\bar{B} \to D^*\tau\bar{\nu})}{\mathcal{B}(\bar{B} \to D^*\ell\bar{\nu})}$$
  $(\ell = e \text{ or } \mu)$



$R_{D^{(*)}}$ anomaly

[HFLAV, arXiv:1612.07233v2]

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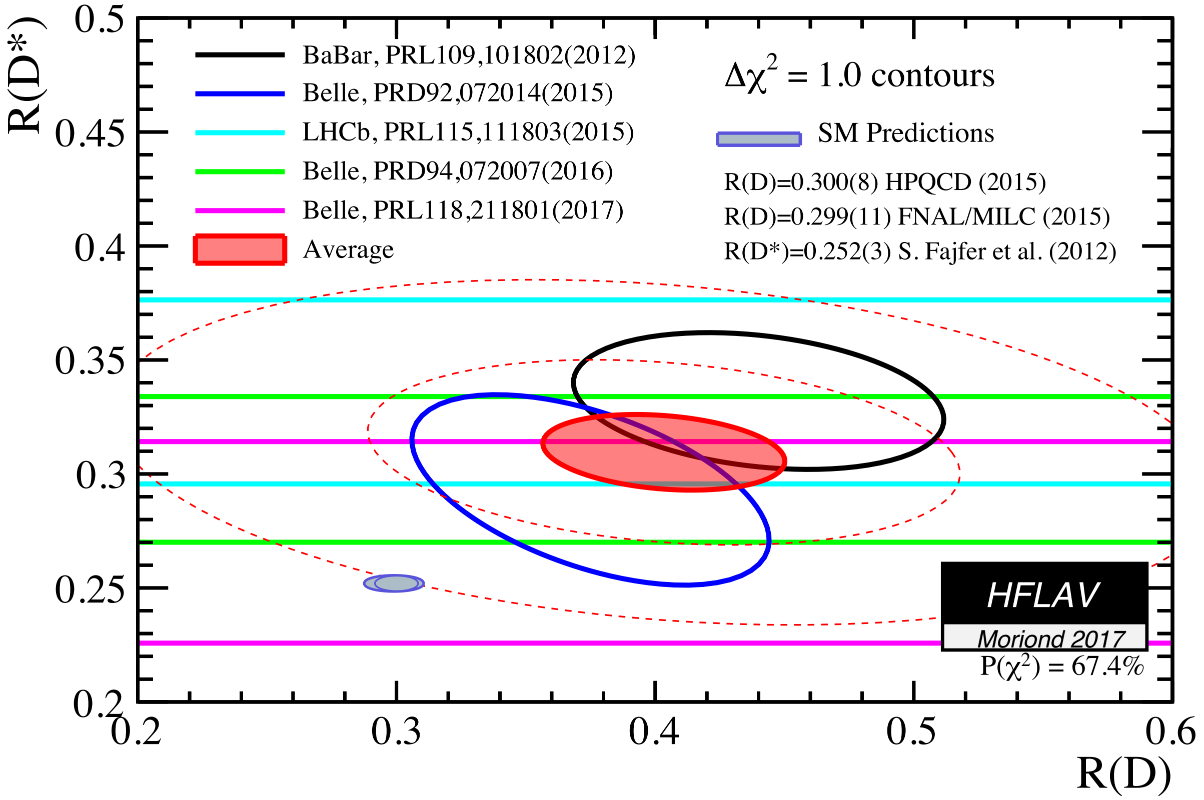
  $(\ell = e \text{ or } \mu)$

- **In our scenario, nonzero contributions to $R_{D^{(*)}}$ are found (via W's and vector LQ).**
  However, they are cancelled out in the degenerated ρ mass limit.
  ⇒ Only negligible effect remains.



$R_{D^{(*)}}$ anomaly

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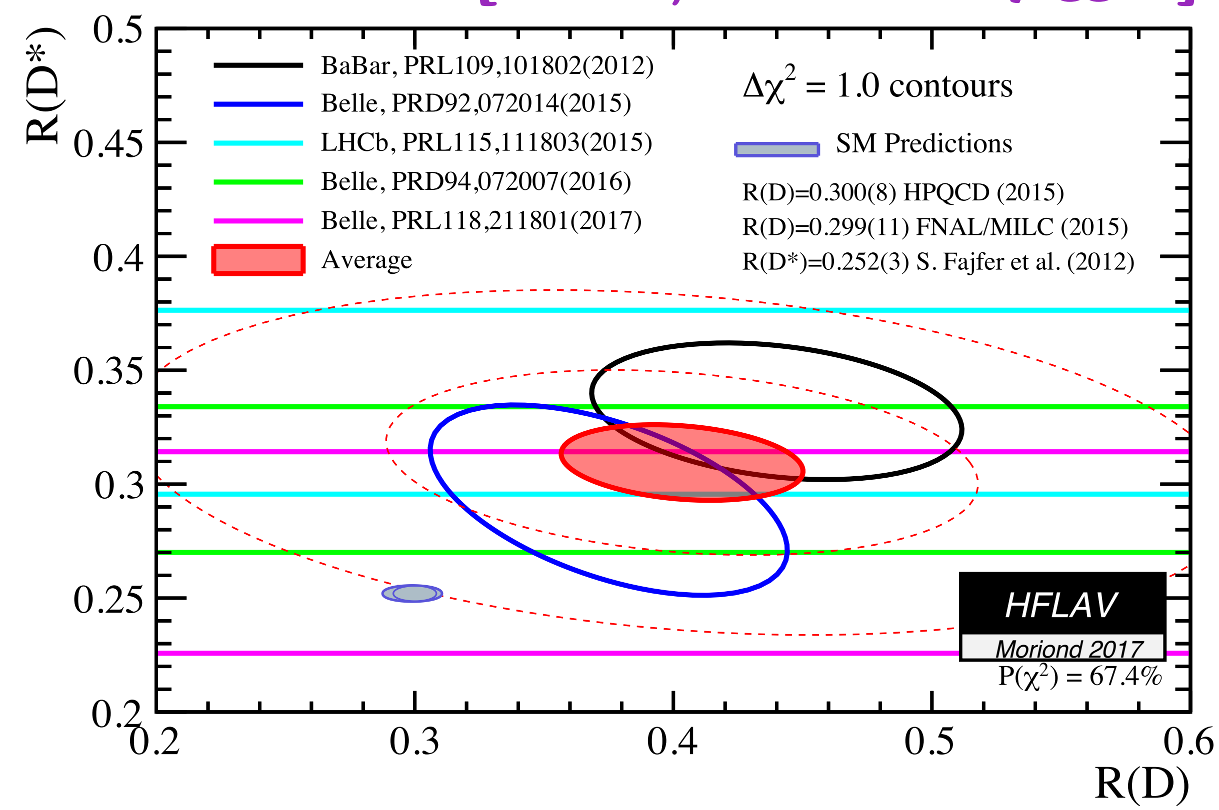
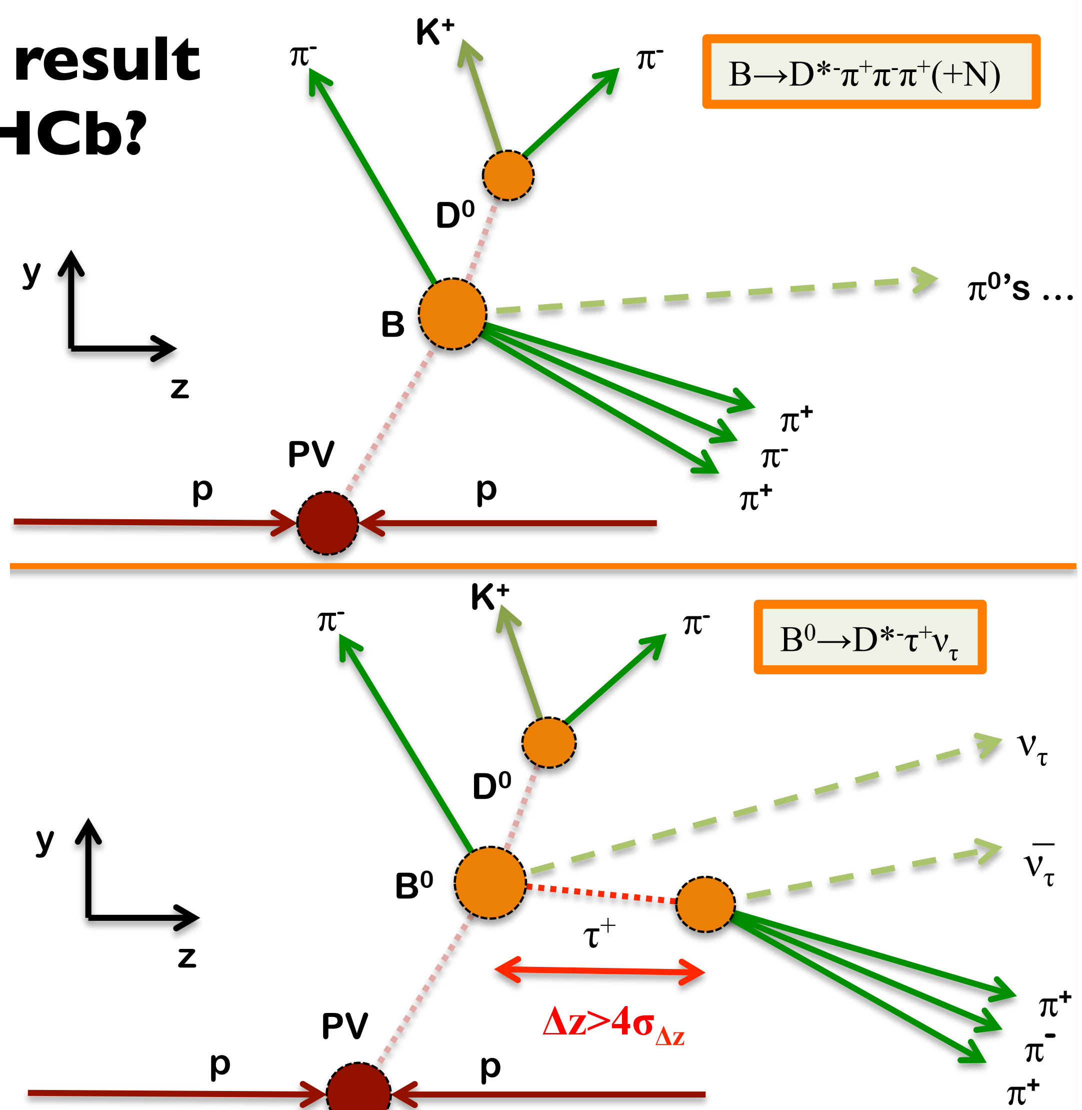
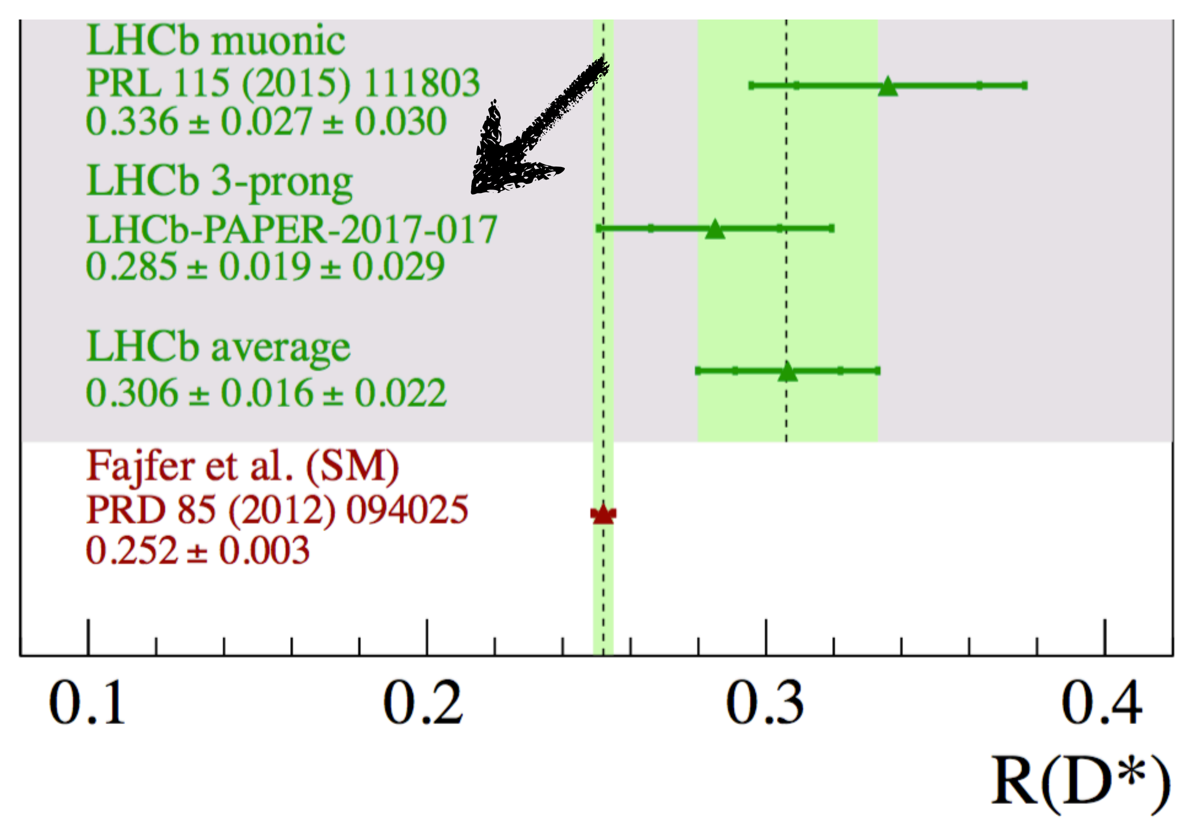


- **A 'null' result from LHCb?**



[CERN LHC seminar, 06/06/2017, A.R.Vidal (LHCb)]



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

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

Misc on pions (skippable)

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

$$
\begin{aligned}
M_{\pi^0_{(1)'}} &\sim \mathcal{O}(f_\pi) = \mathcal{O}(100)\,\mathrm{GeV}\,,\\
M_{\pi^{\pm,3}_{(1)'}} &\sim 2\,\mathrm{TeV}\,,\\
M_{\pi^{\pm,3}_{(1)}} &\sim 2\,\mathrm{TeV}\,,\\
M_{\pi^{\pm,3,0}_{(3)}} &\sim 3\,\mathrm{TeV}\,,\\
M_{\pi^{\pm,3,0}_{(8)}} &\sim 4\,\mathrm{TeV}\,,
\end{aligned}
$$

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

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

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

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

$$\mathcal{L}_{\pi\text{-}\pi\text{-}\pi\text{-}\pi} = -\frac{3}{f_\pi}\mathrm{tr}\left\{(\partial_\mu \pi)\,[\pi, [\pi, \partial^\mu \pi]]\right\}\,,$$

Misc on pions (skippable)

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

$$
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typical pionic decays

- $\rho^0_{(3)} \to \bar\pi^0_{(3)}\pi^0_{(1)'}:\ m_{\pi\pi} \sim (3+\mathcal{O}(0.1))\,\mathrm{TeV},$
- $\rho^\alpha_{(3)} \to \bar\pi^\alpha_{(3)}\pi^0_{(1)'}:\ m_{\pi\pi} \sim (3+\mathcal{O}(0.1))\,\mathrm{TeV},$
- $\rho^0_{(8)} \to \bar\pi^0_{(3)}\pi^0_{(3)}:\ m_{\pi\pi} \sim (3+3)\,\mathrm{TeV} = 6\,\mathrm{TeV},$
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- $\rho^\alpha_{(1)} \to \bar\pi^\beta_{(1)}\pi^\gamma_{(1)}:\ m_{\pi\pi} \sim (1+2)\,\mathrm{TeV} = 3\,\mathrm{TeV}.$

For m_ρ <~3TeV, ρ decay width is narrow.

Misc on pions (skippable)

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

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

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

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

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]

$$\mathcal{L}_{\rm QCD} = \mathcal{L}^0_{\rm QCD} + \overline{q}_L \gamma^\mu \mathcal{L}_\mu q_L + \overline{q}_R \gamma^\mu \mathcal{R}_\mu q_R + \overline{q}_L \left[\mathcal{S} + i\mathcal{P}\right] q_R + \overline{q}_R \left[\mathcal{S} - i\mathcal{P}\right] q_L \ ,$$

above $\Lambda_{\rm QCD}$

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

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

Form of effective Lagrangian (cont'd)

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SM gauge bosons **HC rho mesons**

$$\hat{\alpha}_{||\mu} = \mathcal{V}_\mu - g_\rho \rho_\mu - \frac{i}{2f_\pi^2}[\partial_\mu \pi, \pi] - \frac{i}{f_\pi}[\cancelto{0}{\mathcal{A}_\mu}, \pi] + \cdots$$

$$\hat{\alpha}_{\perp\mu} = \frac{\partial_\mu \pi}{f_\pi} + \cancelto{0}{\mathcal{A}_\mu} - \frac{i}{f_\pi}[\mathcal{V}_\mu, \pi] - \frac{1}{6f_\pi^3}[\pi, [\pi, \partial_\mu \pi]] + \cdots$$

$$\mathcal{V}_\mu = \frac{\mathcal{R}_\mu + \mathcal{L}_\mu}{2} = \mathcal{L}_\mu^f, \qquad \mathcal{A}_\mu = \frac{\mathcal{R}_\mu - \mathcal{L}_\mu}{2} = 0 \qquad f_L = \begin{pmatrix} q \\ l \end{pmatrix}_L, \qquad f_R = \begin{pmatrix} q \\ l \end{pmatrix}_R$$

for SU(2)$_W$-doublet quarks

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

for SU(2)$_W$-doublet leptons

Form of effective Lagrangian (cont'd)

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$$\Psi_L \equiv \xi_L \cdot f_L\,, \qquad \psi_L \equiv \xi_R \cdot f_L$$

$$\Psi_L \xrightarrow[\text{gauge}]{} h(x)\cdot \Psi_L\,, \qquad \psi_L \xrightarrow[\text{gauge}]{} h(x)\cdot \psi_L$$

defining dressed SM fermions

$$\xi_{L/R} = 1 + \cdots$$

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

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

$$\mathcal{L}_{\rho f f} = g_{1L}^{ij}\left(\bar\Psi_L^i \gamma^\mu \hat\alpha_{||\mu}\Psi_L^j\right) + g_{2L}^{ij}\left(\bar\Psi_L^i\gamma^\mu\hat\alpha_{||\mu}\psi_L^j + \text{h.c.}\right) + g_{3L}^{ij}\left(\bar\psi_L^i\gamma^\mu\hat\alpha_{||\mu}\psi_L^j\right)$$

(undetermined) 3×3 matrices

(No additional fermion/scalar is required.)