Istituto Nazionale di Fisica Nucleare
Sezione di Napoli

QCD@Work - International Workshop on QCD Theory and Experiment
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Flavour anomalies

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Collaboration with Andreas Crivellin and Julian Heeck

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Phys.Rev. D91 (2015) 7, 075006

Collaboration with Crivellin, A Hoferichter, M and Tunstall, L

Phys.Rev. D 2016

Collaboration with Coluccio-Leskow, E. Greynat,D. and Nath,A.
Phys.Rev. D 2016

Outline

- QCD at work in flavor
- Flavor physics
- $(g-2)_\mu$

QCD at work: Short Distance expansion for weak interaction

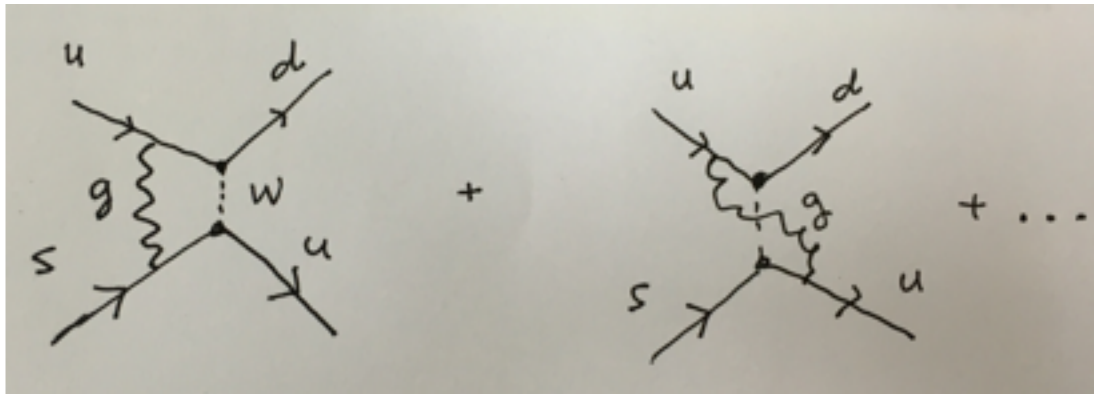
- Fermi lagrangian: description of the ΔS=1 weak lagrangian, in particular the explanation of ΔI =1/2 rule

$$\frac{A(K^+ \to \pi^+\pi^0)}{A(K_S \to \pi^+\pi^-)} \sim \frac{1}{22}$$

- Wilson suggestion (Feynman) , short distance expansion

$$-\frac{G_F}{\sqrt{2}} V_{ud} V_{us}^* C_- (\overline{s}_L \gamma^\mu u_L)(\overline{u}_L \gamma_\mu d_L)$$

- Gaillard Lee, Altarelli Maiani: right direction but not fully understood (Long distance?)



QCD at work, theoretical tools

- analytic calculation 't Hooft, large Nc (it explains basic phenomenological facts of QCD, i.e. Zweig's rule) many implications: Skyrme model, VMD, Maldacena
- G. Parisi, `80s lattice: can we predict from QCD the proton mass at 10% level?
- Precise calculation of low energy QCD?

Chiral Perturbation theory

χPT effective field theory approach based on two assumptions

- π's Golstone bosons of $SU(3)_L \times SU(3)_R \rightarrow SU(3)_V$

$SU(3)_L \times SU(3)_R$ symm. $\mathcal{L}_{QCD}$ $m_q = 0$

- (chiral) power counting There is a small expansion parameter $p^2/\Lambda^2_{\chi SB}$

$\Lambda_{\chi SB} \simeq 4\pi F_\pi \sim 1.2$ GeV

$$U = e^{\frac{i\sqrt{2}\ \pi}{F_\pi}} \qquad U \xrightarrow{SU(3)_L \times SU(3)_R} g_L\, U\, g_R^\dagger$$

π non-lin. real U lin. transf.

Chiral sym. breaking through dim. parameter

F_π, χ related to $\langle 0|J_{5\mu}|\pi\rangle$, $\langle 0|\bar{q}_L q_R|0\rangle$

$F_\pi \approx 93$ MeV

$m_\pi^2 \sim \langle 0|\bar{q}_L q_R|0\rangle m_q$
GOR rel.

$$\mathcal{L}_{\Delta S=0} = \mathcal{L}^2_{\Delta S=0} + \mathcal{L}^4_{\Delta S=0} + \cdots = \frac{F_\pi^{\ 2}}{4} \overbrace{\langle D_\mu U D^\mu U^\dagger + \chi U^\dagger + U\chi^\dagger \rangle}^{\pi\to l\nu,\ \pi\pi\to\pi\pi,\ K\to\pi..} + \overbrace{\sum_i L_i O_i}^{K\to\pi..} + \cdots$$

Fantastic chiral prediction

$A_{\pi\pi} \sim (s - m_\pi^2)/F_\pi^2$

L_i Gasser Leutwyler coeff determined from expts.
O_i p^4 operator

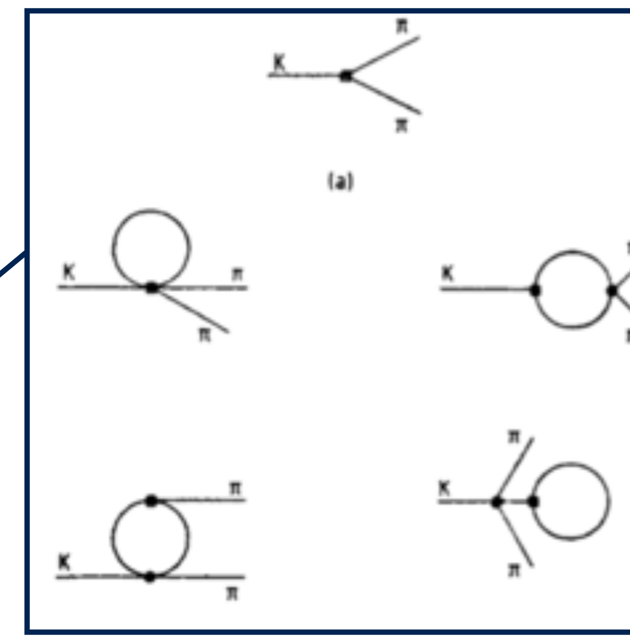
Bardeen Buras Gerard approach to K->ππ

Also evaluated ΔS=2 transitions, epsilon′ (Buras) and $\pi^+ - \pi^0$ mass diff.

Main idea: phys. amplitudes scale independent

Match SD with LD with a precise prescription for CT

CHPT+Large Nc



$$H_{\text{eff}} = \sum_i C_i(\mu)\, Q_i(\mu)$$

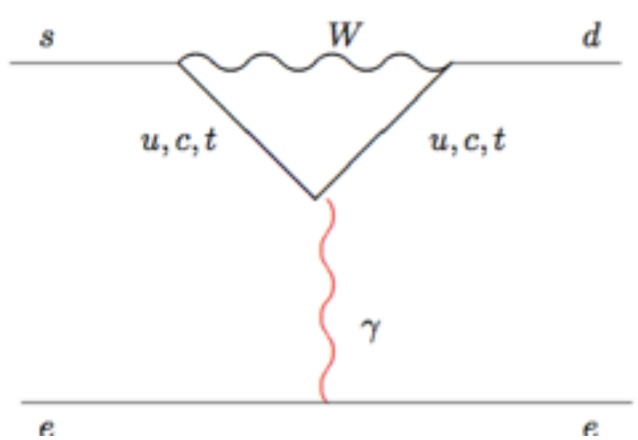
SD

Can we test somewhereelse the Bardeen Buras Gerard (BBG) approach?

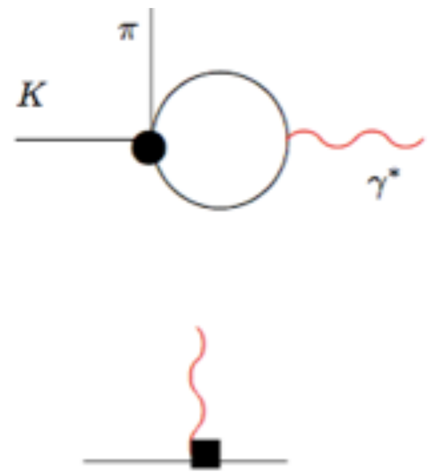
Coluccio-Leskow, Estefania, GD, Greynat,David and Nath,Atanu

$K^+ \to \pi^+ e^+ e^-$ $\quad$ $K_S \to \pi^0 e^+ e^-$

SD



CHPT



CHPT

$$W^i = G_F m_K^2 (a_i + b_i z) + W^i_{\pi\pi}(z)$$

$$i = \pm, S$$

$$a_i, b_i \sim O(1), \qquad z = \frac{q^2}{m_K^2}$$

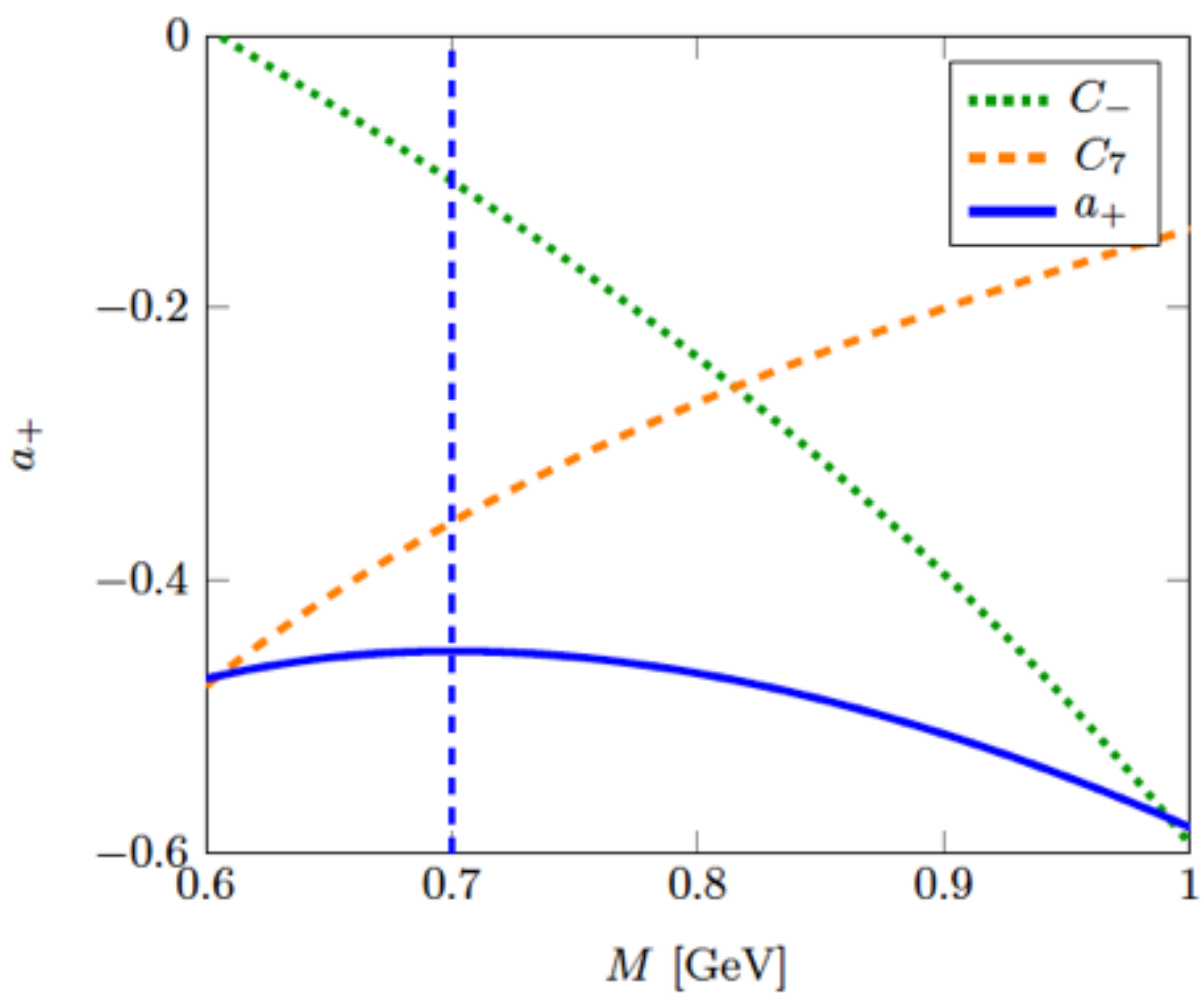
- Observables $\Gamma(K^+ \to \pi^+ e^+ e^-)$, $\Gamma(K^+ \to \pi^+ \mu\bar{\mu})$, slopes
- $a_i \quad O(p^4) \qquad a_+ \sim N_{14} - N_{15}, \qquad a_S \sim 2N_{14} + N_{15}$ Ecker, Pich, de Rafae
- $b_i \quad O(p^6)$ G.D., Ecker, Isidori, Portole
- $a_+,\ b_+$ in general not related to $a_S,\ b_S$

averaging flavour

$$a_+^{\text{exp.}} = -0.578 \pm 0.016$$
$$b_+^{\text{exp.}} = -0.779 \pm 0.066$$

Matching a la BBG for $K^+ \to \pi^+ e^+ e^-$

Coluccio-Leskow,E. G.D ,Greynat, D and Nath, A



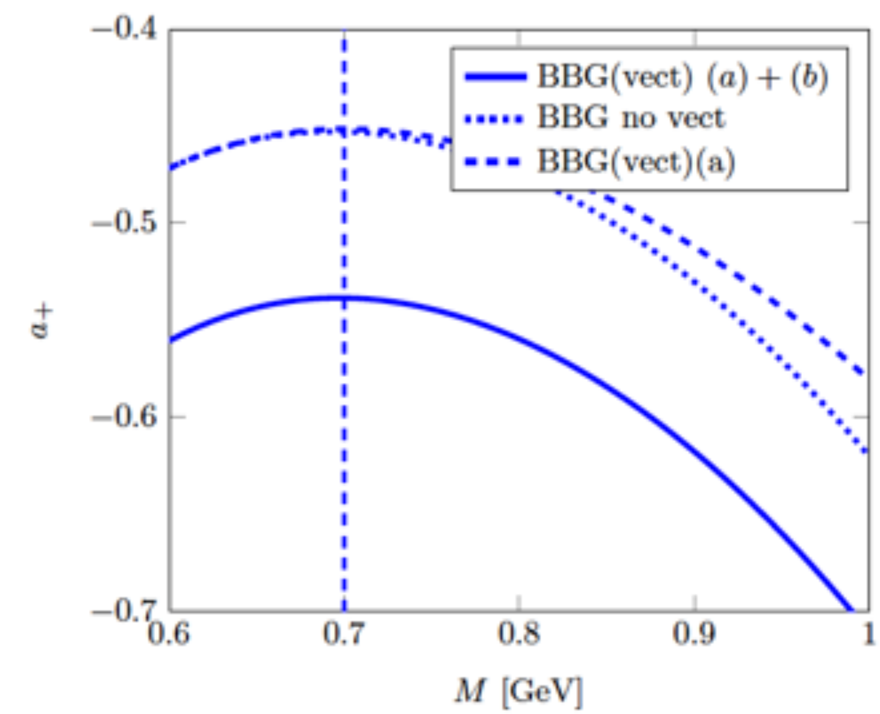


FIG. 5. a_+ as a function of M in the three different frameworks:'BBG no vect.' where vectors are not included, 'BBG(vect)(a)' represents the contribution coming only from diagrams (a) in Fig. 4 and 'BBG(vect) $(a) + (b)$' is the case where both (a) and (b) diagrams were included. The vertical line indicates the value $M = 0.7$ GeV.

The flavor problem

- In the SM the Higgs generates EWSB **and** the fermion masses through the Yukawas. In the flavor sector this is well tested

$$\mathcal{L}_{SM}^{Y} = \bar{Q} Y_D D H + \bar{Q} Y_U U H_c + \bar{L} Y_E E H$$

$$\mathcal{H}_{\Delta F=2}^{SM} \sim \frac{G_F^2 M_W^2}{16\pi^2} \left[\frac{(V_{td}^* m_t^2 V_{tb})^2}{v^4} (\bar{d}_L \gamma^\mu b_L)^2 + \frac{(V_{td}^* m_t^2 V_{ts})^2}{v^4} (\bar{d}_L \gamma^\mu s_L)^2 \right] + \text{charm}$$

Generic Flavor structures strongly constrained

Operator	Bounds on Λ in TeV ($c_{NP}=1$) Re	Im	Bounds on c_{NP} ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert_D$, ϕ_D
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $\sin(2\beta)$ from $B_d\to\psi K$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $\sin(\phi_s)$ from $B_s\to\psi\phi$
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	

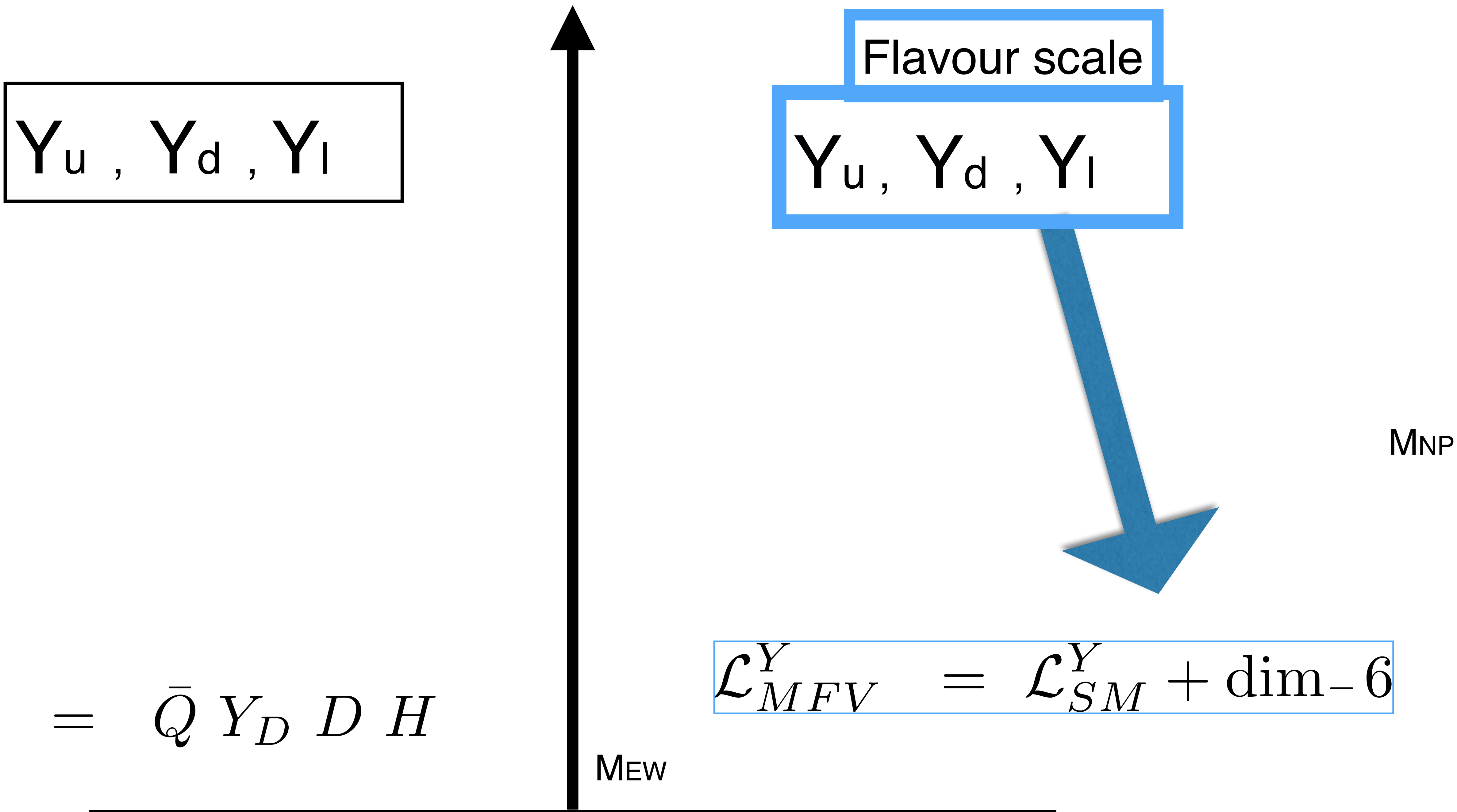
Isidori Nir Perez 10

Problem already known since ’86 technicolour (Chivukula Georgi) susy (Hall Randall) extra dimensions (Rattazzi Zafferoni)

Maybe there is an energy gap between the theory of flavor and the EW scale , ameliorating also a clash from the scale of the bounds in the table above and the requirement of solving the hierarchy problem

SM

MFV



$$\mathcal{L}_{SM}^{Y} = \bar{Q}\, Y_D\, D\, H$$

$$\mathcal{L}_{MFV}^{Y} = \mathcal{L}_{SM}^{Y} + \text{dim-}6$$

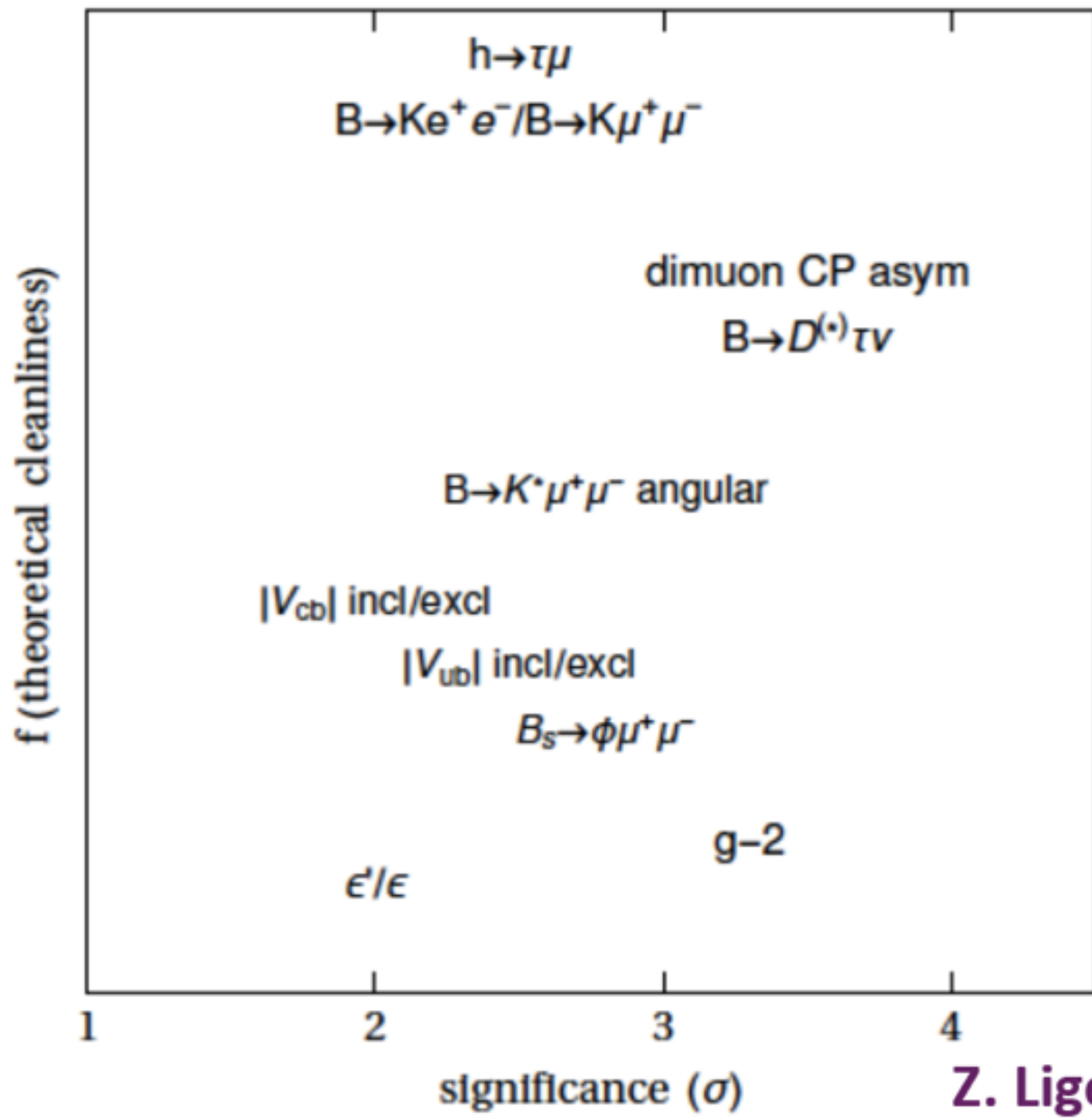
$$G_F = \overbrace{\mathrm{U}(3)_Q \otimes \mathrm{U}(3)_U \otimes \mathrm{U}(3)_D \otimes \mathrm{U}(3)_L \otimes \mathrm{U}(3)_E}^{\text{global symmetry}} + \overbrace{Y_{U,D,E}}^{\text{spurions}}$$

Bounds ameliorated

Minimally flavour violating dimension six operator	main observables	Λ [TeV] −	+	
$\mathcal{O}_0 = \frac{1}{2}(\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)^2$	$\epsilon_K, \quad \Delta m_{B_d}$	6.4	5.0	
$\mathcal{O}_{F1} = H^\dagger \left(\bar{D}_R \lambda_d \lambda_{\rm FC} \sigma_{\mu\nu} Q_L \right) F_{\mu\nu}$	$B \to X_s \gamma$	8.3	13.4	
$\mathcal{O}_{G1} = H^\dagger \left(\bar{D}_R \lambda_d \lambda_{\rm FC} \sigma_{\mu\nu} T^a Q_L \right) G^a_{\mu\nu}$	$B \to X_s \gamma$	2.3	3.8	
$\mathcal{O}_{\ell 1} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(\bar{L}_L \gamma_\mu L_L)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.1	2.7	*
$\mathcal{O}_{\ell 2} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu \tau^a Q_L)(\bar{L}_L \gamma_\mu \tau^a L_L)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.4	3.0	*
$\mathcal{O}_{H1} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(H^\dagger i D_\mu H)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	1.6	1.6	*
$\mathcal{O}_{q5} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(\bar{D}_R \gamma_\mu D_R)$	$B \to K\pi, \quad \epsilon'/\epsilon, \ldots$	~ 1		

GD,Giudice,Isidori,Strumia
Buras et al

Deviations from the SM expectations: significance of such deviations vs. their theoretical cleanliness



Z. Ligeti, LP 2015

(Incomplete) List of Anomalies in Flavor Physics

$\sim 3.5\sigma$	$(g-2)_\mu$ anomaly
$\sim 3.5\sigma$	non-standard like-sign dimuon charge asymmetry
$\sim 3.5\sigma$	enhanced $B \to D^{(*)}\tau\nu$ rates
$\sim 3.5\sigma$	suppressed branching ratio of $B_s \to \phi\mu^+\mu^-$
$\sim 3\sigma$	tension between inclusive and exclusive determination of $\lvert V_{ub}\rvert$
$\sim 3\sigma$	tension between inclusive and exclusive determination of $\lvert V_{cb}\rvert$
$2-3\sigma$	anomaly in $B \to K^*\mu^+\mu^-$ angular distributions
$2-3\sigma$	SM prediction for ϵ'/ϵ below experimental result
$\sim 2.5\sigma$	lepton flavor non-universality in $B \to K\mu^+\mu^-$ vs. $B \to Ke^+e^-$
$\sim 2.5\sigma$	non-zero $h \to \tau\mu$

More refs

- see Wolfgang Altmannshofer Aspen Winter Conference"Particle Physics on the Verge of Another Discovery?" Aspen, January 11 - 16, 2016

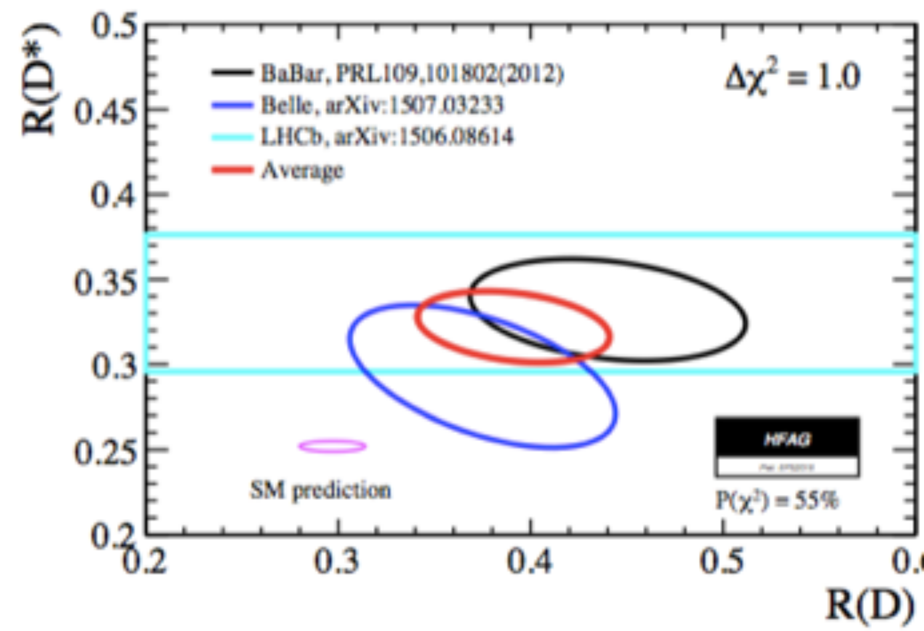
- Lewis Tunstall and Andreas Buras at MITP Workshop "NA62 Kaon Physics Handbook", Mainz, 11-22 Jan, 2016

From Ligeti's talk

The highest σ deviation from the SM

- Belle & LHCb results on the anomaly seen by BaBar in $R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X(e/\mu)\bar{\nu})}$

	$R(D)$	$R(D^*)$
BaBar	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$
Belle	$0.375 \pm 0.064 \pm 0.026$	$0.293 \pm 0.038 \pm 0.015$
LHCb		$0.336 \pm 0.027 \pm 0.030$
Average	0.391 ± 0.050	0.322 ± 0.022
my SM expectation	0.300 ± 0.010	0.252 ± 0.005
Belle II, 50/ab	± 0.010	± 0.005

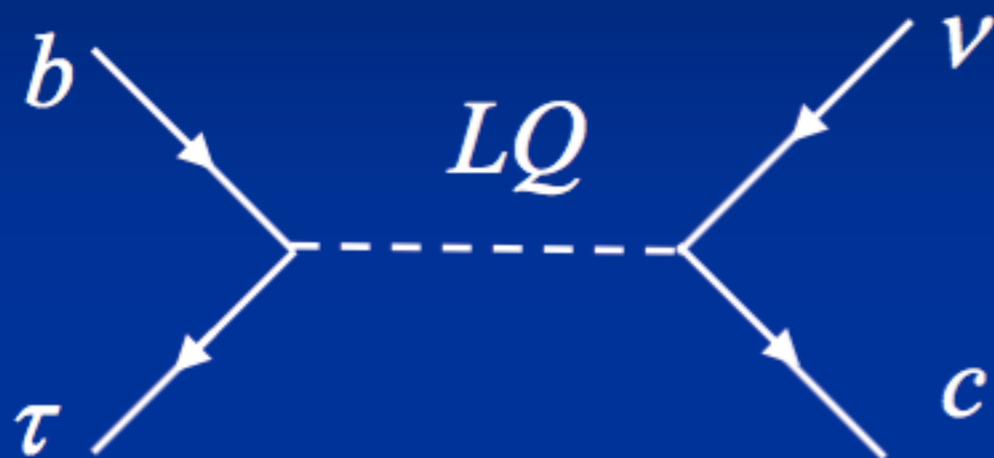


New last week: Belle semileptonic tag, $R(D^*) = 0.302 \pm 0.030 \pm 0.011$ [1603.06711, today]

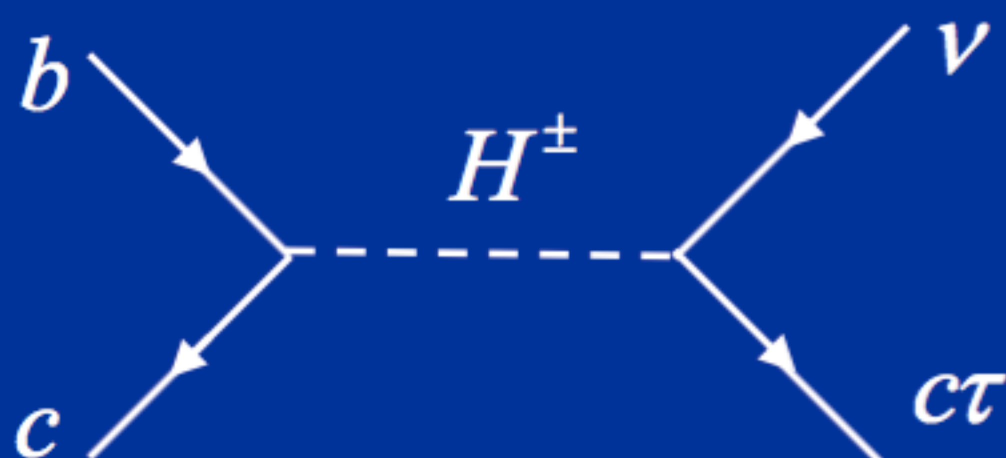
Slightly reduce WA, higher significance (no HFAG update yet, correlations)

R(D) Explanations

- Leptoquark (scalar or vector)



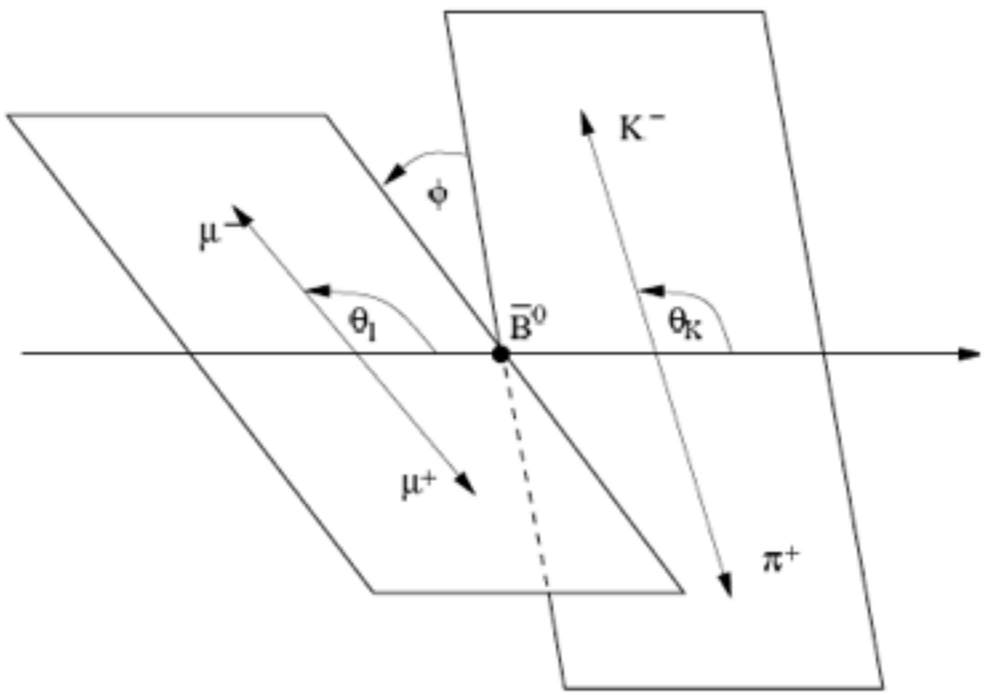
- Charged Higgs ➡ different differential distribution

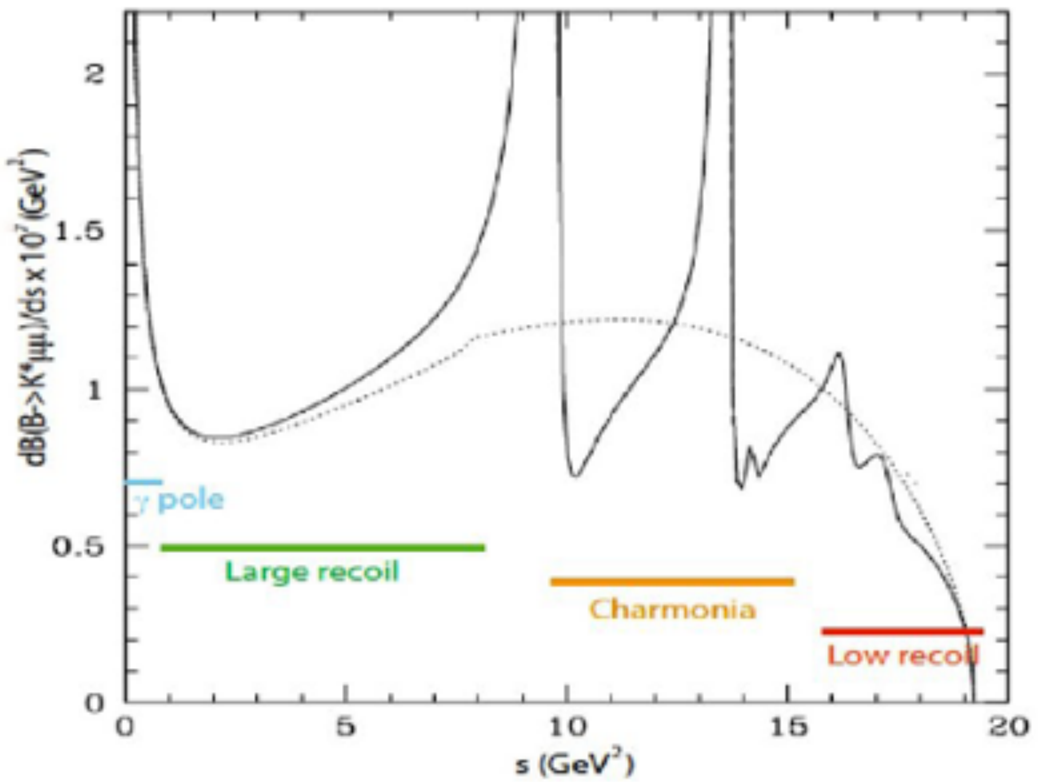


- W’ ???

$B \to K^* \mu^+ \mu^-$

4-body decay $\bar{B}_d \to \bar{K}^{*0}(\to K^- \pi^+) l^+ l^-$ with on-shell K^{*0}





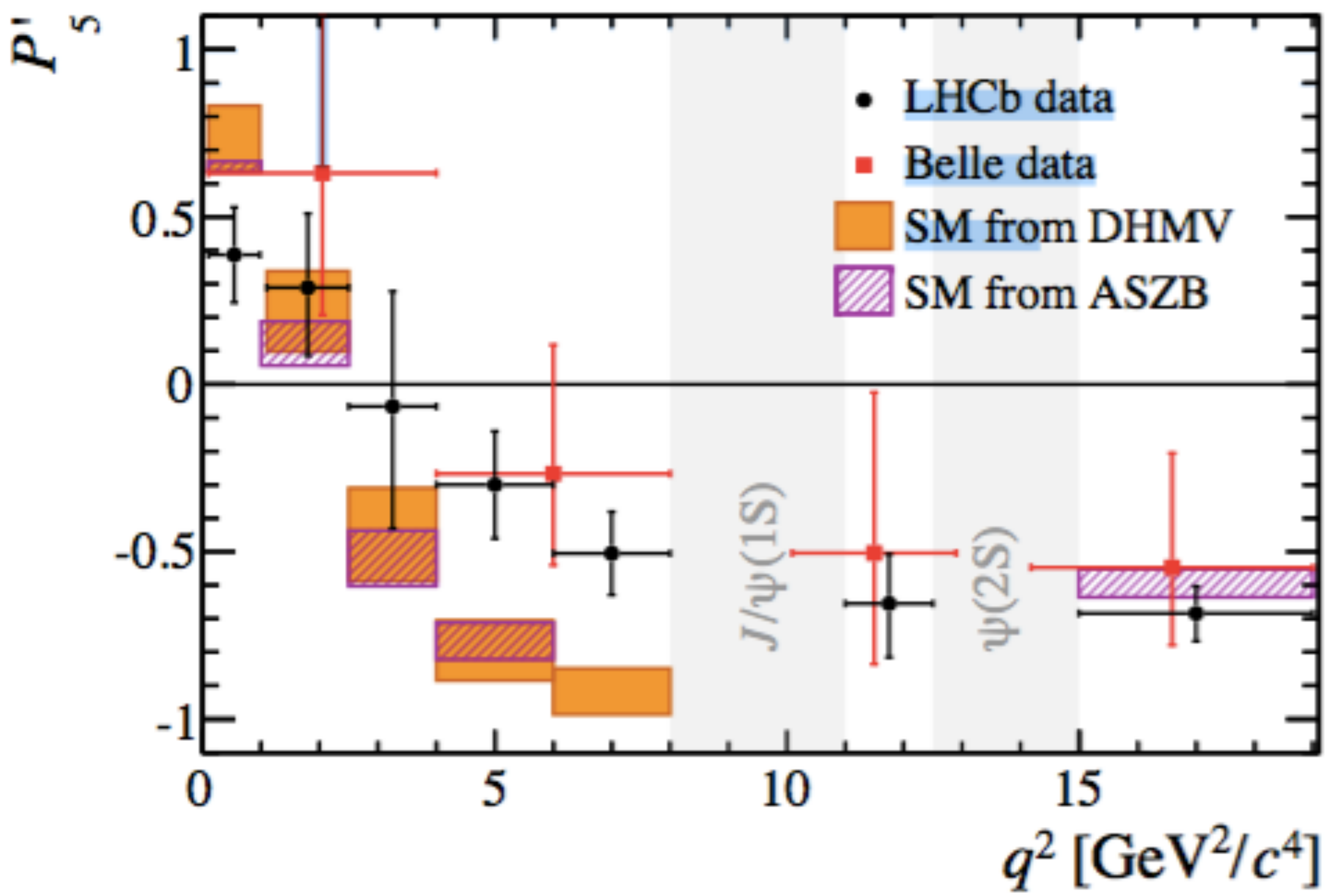
$$\frac{d^4\Gamma(\bar{B}_d)}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi} \sum_i J_i(q^2) f_i(\theta_\ell, \theta_K, \phi)$$

invariant mass of lepton-pair q^2

angles $\theta_\ell, \theta_K, \phi$

- observables $S_i, P_i^{(\prime)}$ as ratios of J_i
- most interesting region: small $q^2 \lesssim 8\,\mathrm{GeV}$

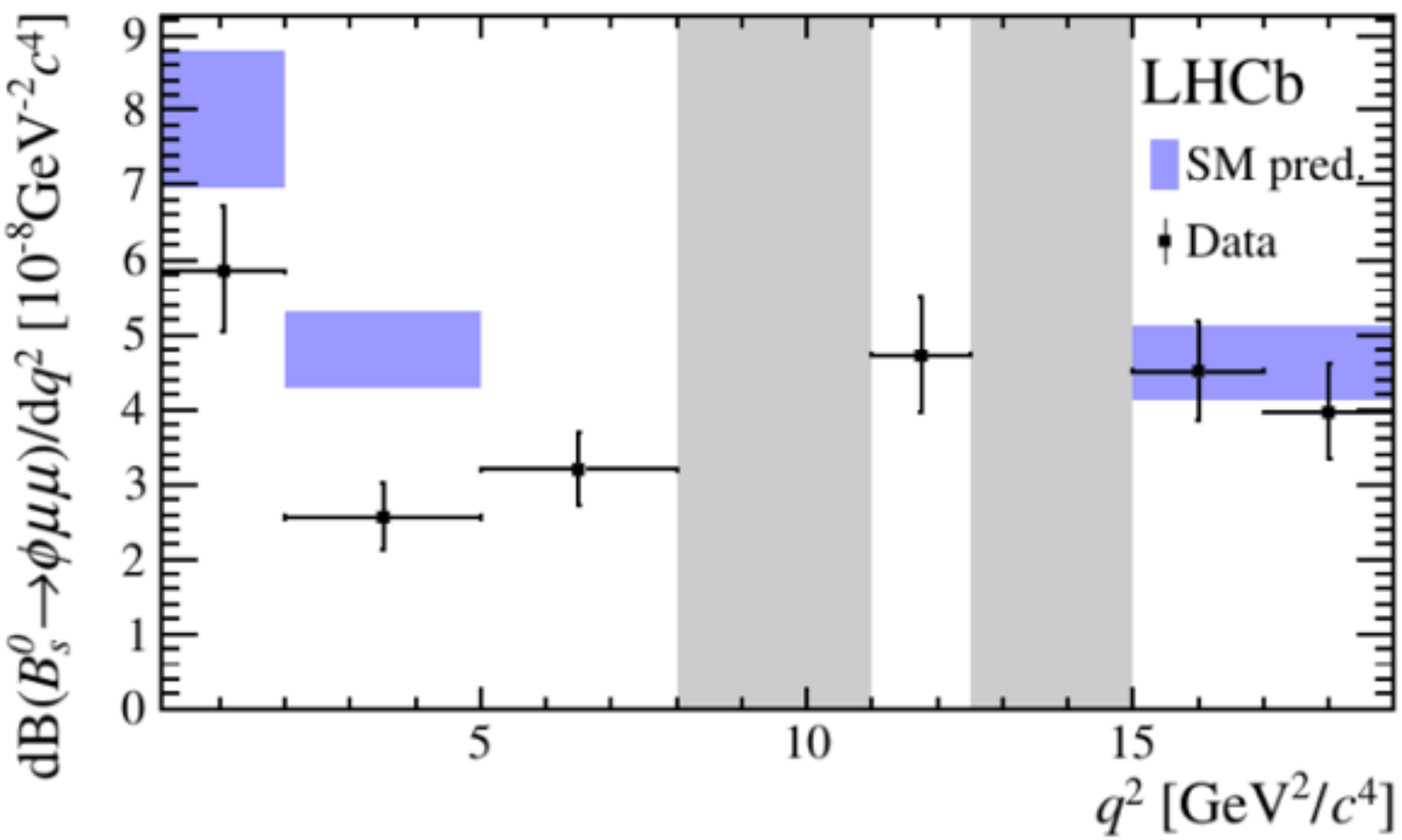
$B \to K^{*}\mu^{+}\mu^{-}$ anomaly



It is 3 sigma away from SM

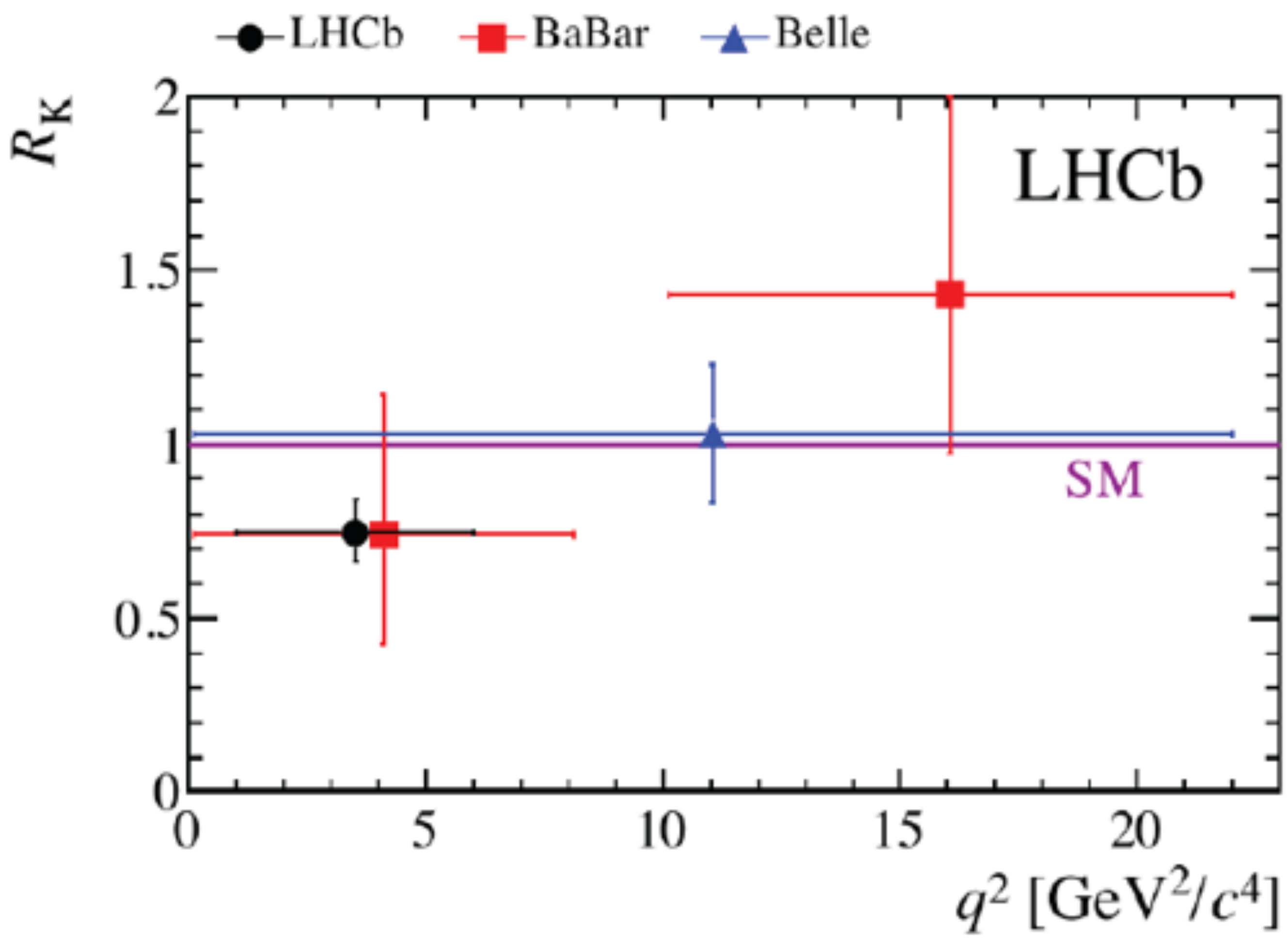
“The $B_s \to \phi\mu^+\mu^-$ Anomaly”

LHCb 1506.08777



branching ratio is 3.5σ below SM prediction for $1\,\text{GeV}^2 < q^2 < 6\,\text{GeV}^2$

LHCb 1406.6482



2.6σ hint for violation of lepton flavor universality (LFU)

$$R_K = \frac{\text{BR}(B \to K\mu^+\mu^-)_{[1,6]}}{\text{BR}(B \to Ke^+e^-)_{[1,6]}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

Global Fits of $b \to s$ Data

many processes and many observables are modified simultaneously

$\Rightarrow$ global fits are required

WA, Straub, Paradisi ’11; Bobeth, Hiller, van Dyk, Wacker ’11; WA, Straub ’12 - ’15;

Beaujean, Bobeth, van Dyk, Wacker; ’12; Descotes-Genon, Matias, Virto ’13, ’14;

Beaujean, Bobeth, van Dyk ’13; Hurth, Mahmoudi ’13; Ghosh, Nardecchia, Renner ’14;

Hurth, Mahmoudi, Neshatpour ’14; Jäger, Martin Camalich ’14;

Beaujean, Bobeth, Jahn ’15; Descotes-Genon, Hofer, Matias, Virto ’15;

Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli ’15; ...

A Hint for Flavorful New Physics

favored new physics parameter space

(WA, Straub '11 - '15)

$O_9 \propto (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$

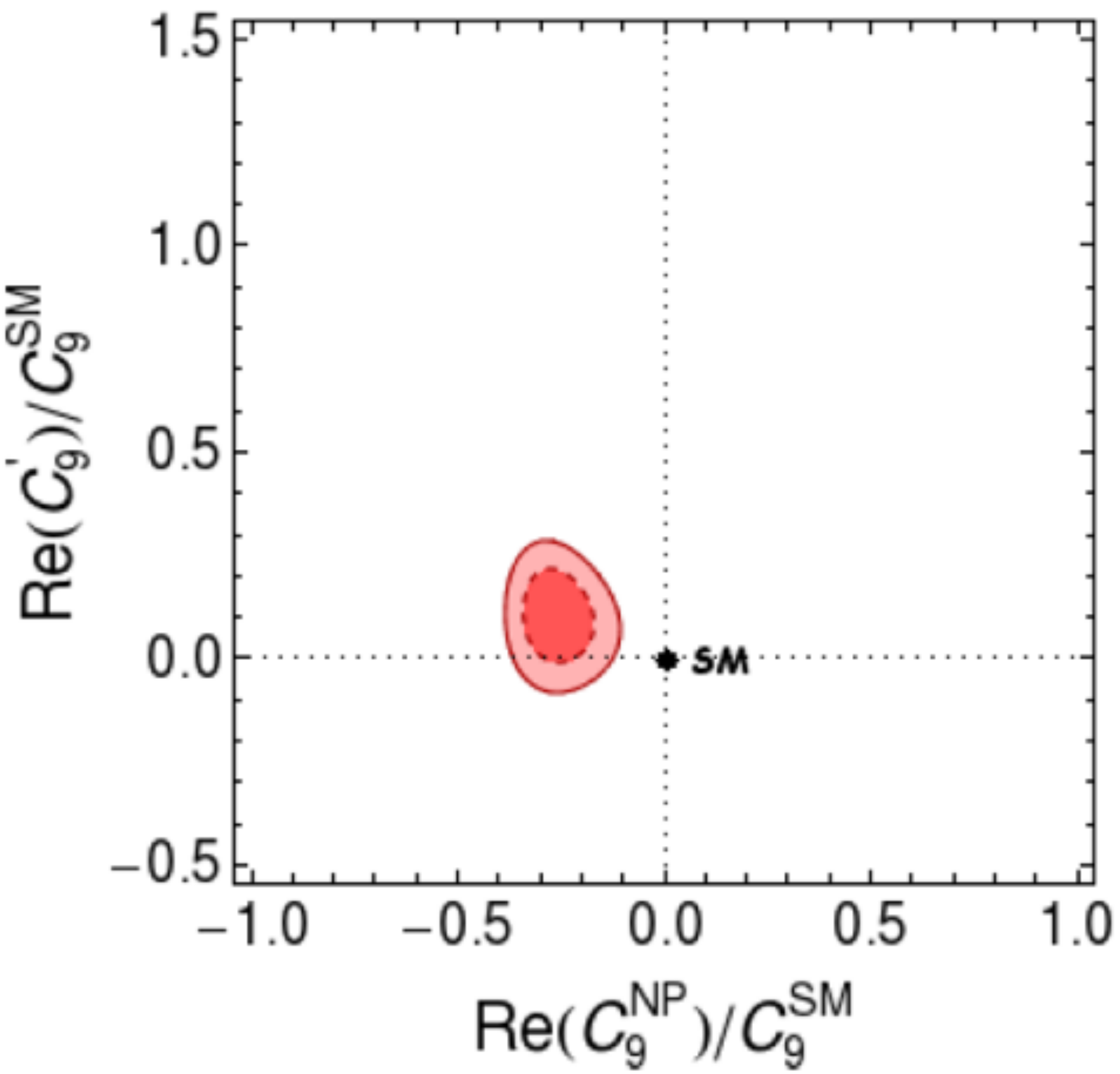
$O_9' \propto (\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu \mu)$

muonic vector current

- $\Delta\chi^2 = 15.2$
- p-value: 12.4% (2.1% in the SM)

(only $b \to s\mu^+\mu^-$ data)

2015



Altmannshofer, Gori, Pospelov, Yari

$$\mathcal{H}_{\text{eff}} = C_9(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu) + C_9'(\bar{s}\gamma_\alpha P_R b)(\bar{\mu}\gamma^\alpha \mu)$$

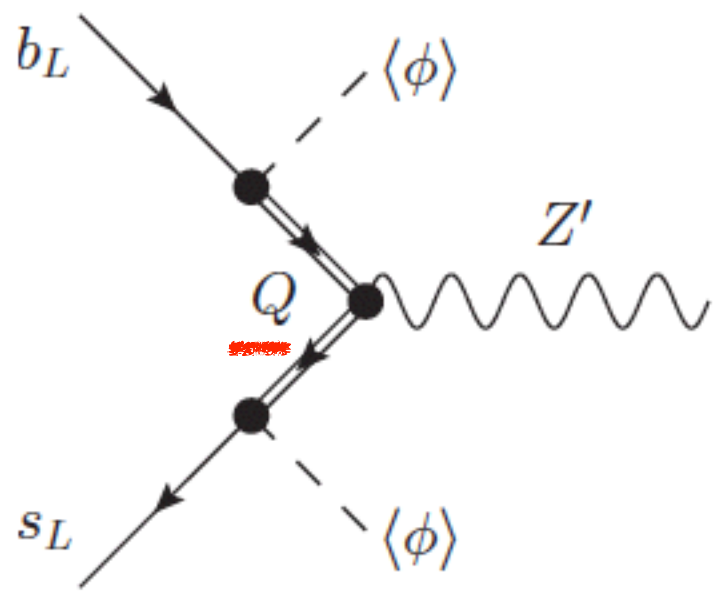
- Good fit with vectorial leptonic coupling
- UV complete model, Z' coupled to vector leptonic current, anomaly free
- Gauged Lmu -Ltau: naturally implemented

- Good zeroth order approximation to neutrino mixing with quasi-degenerate masses ($m_{1,2,3} \simeq 1\,\mathrm{eV}$ and $\beta = \pi/2$):

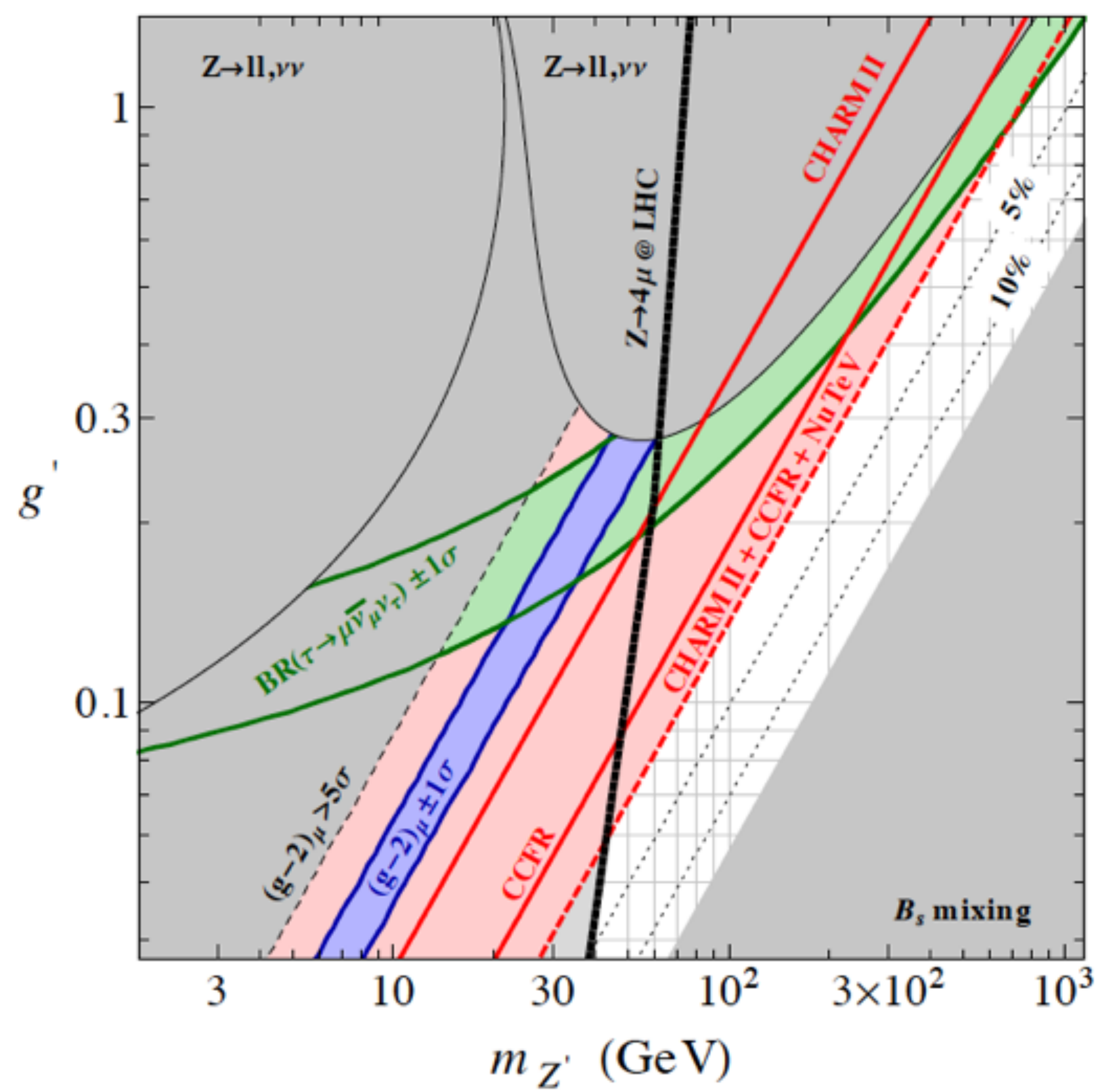
$$\begin{aligned}\mathcal{M}_\nu &= U_{\mathrm{PMNS}}\,\mathrm{diag}(m_1, m_2, m_3) U_{\mathrm{PMNS}}^T \\ &\simeq \begin{pmatrix} 0.96 & -0.20 & -0.22 \\ \cdot & 0.11 & -0.97 \\ \cdot & \cdot & -0.07 \end{pmatrix} \mathrm{eV} \sim \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix} \leftarrow L_\mu - L_\tau\end{aligned}$$

- $L_\mu - L_\tau$ gives $\theta_{23} = \pi/4$ and $\theta_{13} = 0$.[8]

Altmannshofer, Gori, Pospelov, Yari



Quark part is built with vector like states (Q)



Integrating out Q

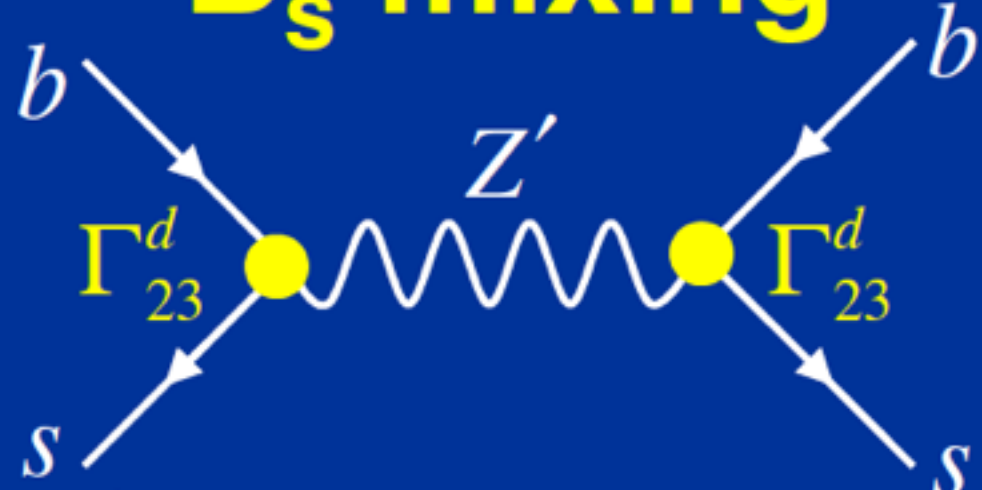
Γ_{ij}^{dR}

B→K*μμ, R(K)

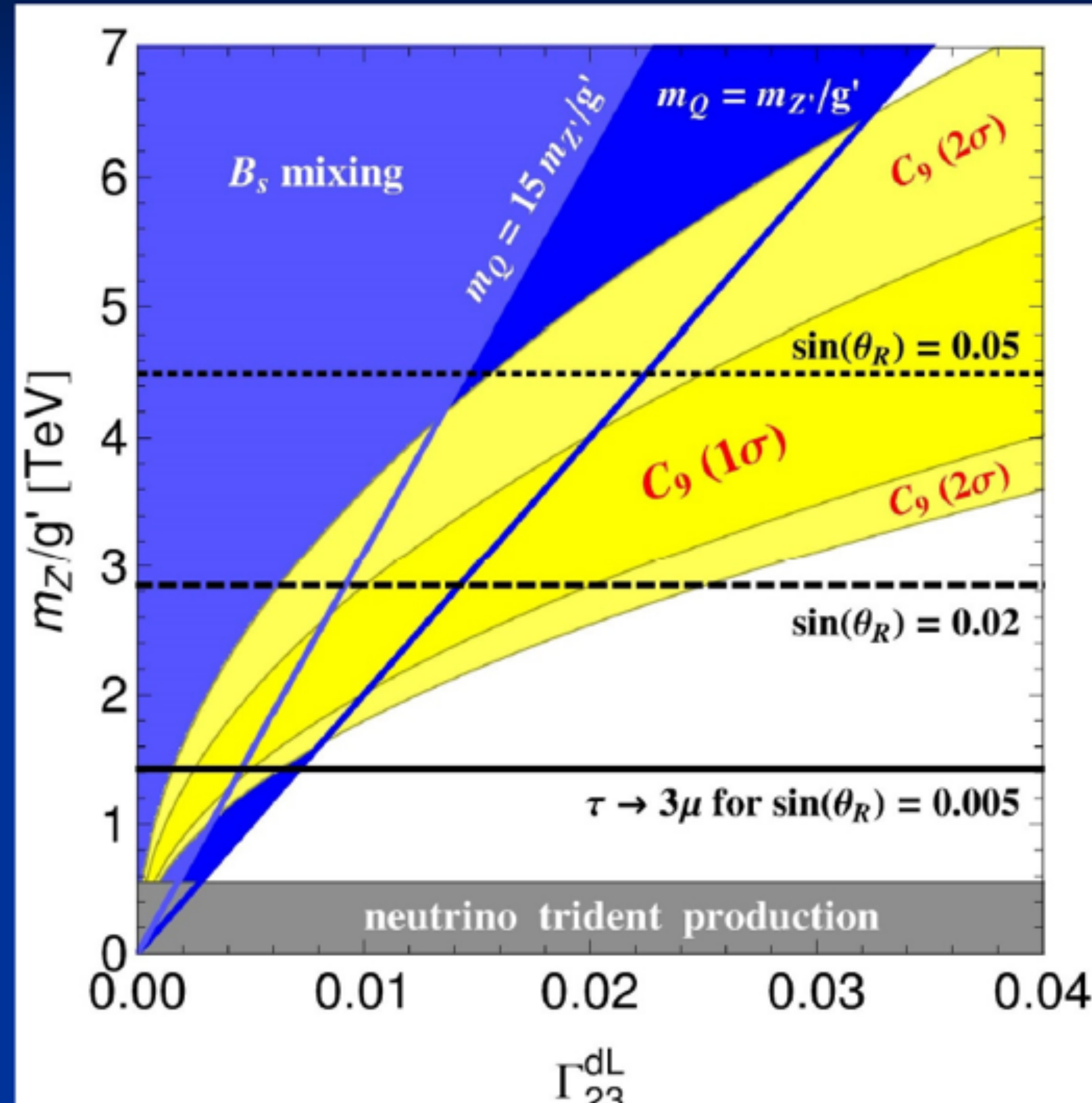
$$m_D^2 \to \infty$$

$$C_9^{\mu\mu} \propto \Gamma_{23}^{dL}\, g'^2 / m_{Z'}^2$$

B_s mixing



$$\frac{\Delta M_{12}}{M_{12}^{SM}} \propto \left(\Gamma_{23}^{dL}\right)^2 g'^2 / m_{Z'}^2$$



allowed regions

2^{nd} Doublet breaks $L_\mu - L_\tau$

J. Heeck, M. Holthausen, W. Rodejohann and Y. Shimizu, 1412.3671

- Two Higgs doublets

$$Q_{L_\mu - L_\tau}(\Psi_2) = 0 \qquad Q_{L_\mu - L_\tau}(\Psi_1) = 2$$

- Yukawa couplings

$$\mathcal{L}_Y \supset -\overline{\ell}_f Y_i^\ell \delta_{fi} \Psi_2 e_i - \xi_{\tau\mu} \overline{\ell}_3 \Psi_1 e_2 - \overline{Q}_f Y_{fi}^u \tilde{\Psi}_2 u_i - \overline{Q}_f Y_{fi}^d \Psi_2 d_i + \text{h.c.}.$$

- Flavour changing SM-like Higgs coupling

$$\Gamma_{\tau\mu}^h \overline{\tau} P_R \mu h^0 \approx \frac{m_\tau}{v} \frac{\cos(\alpha - \beta)}{\cos(\beta)\sin(\beta)} \theta_R \overline{\tau} P_R \mu h^0$$

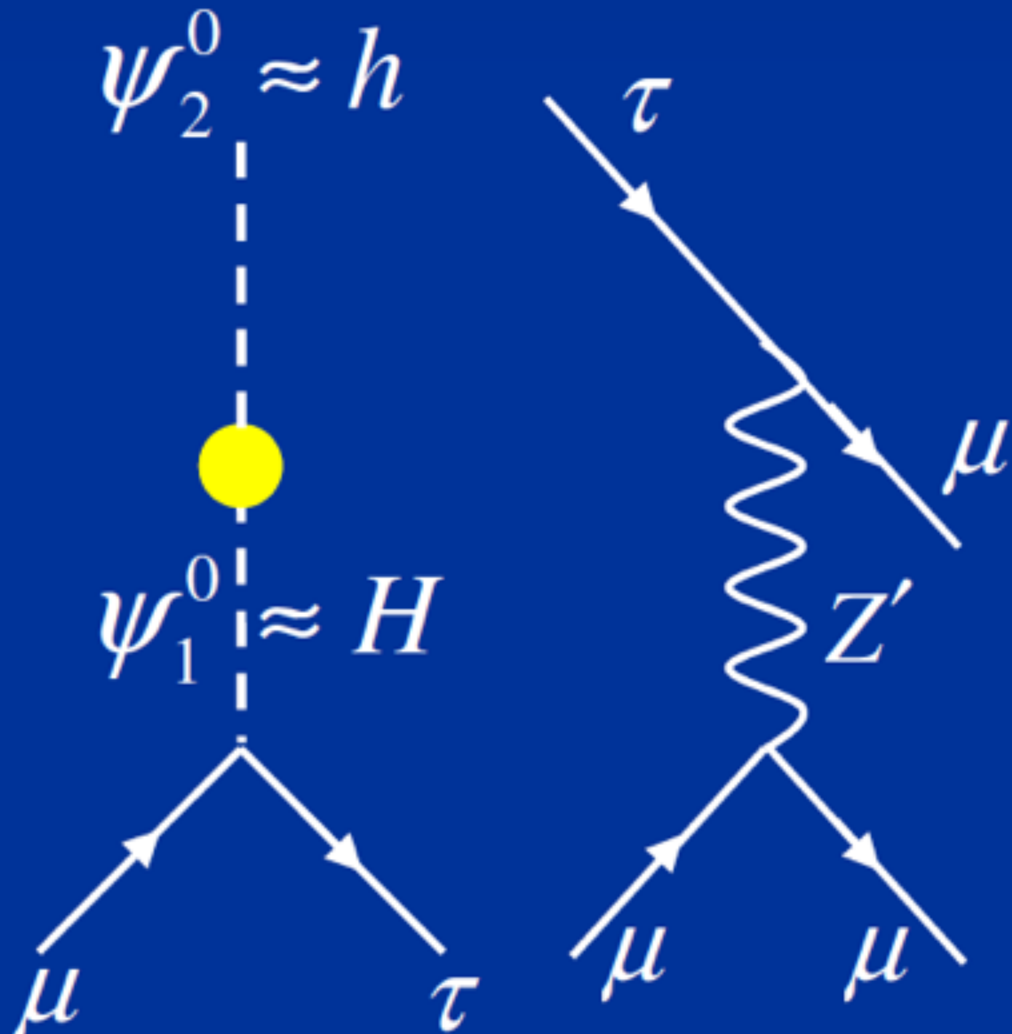
$$\sin\theta_R \simeq \frac{v}{\sqrt{2} m_\tau} \xi_{\tau\mu} \cos\beta$$

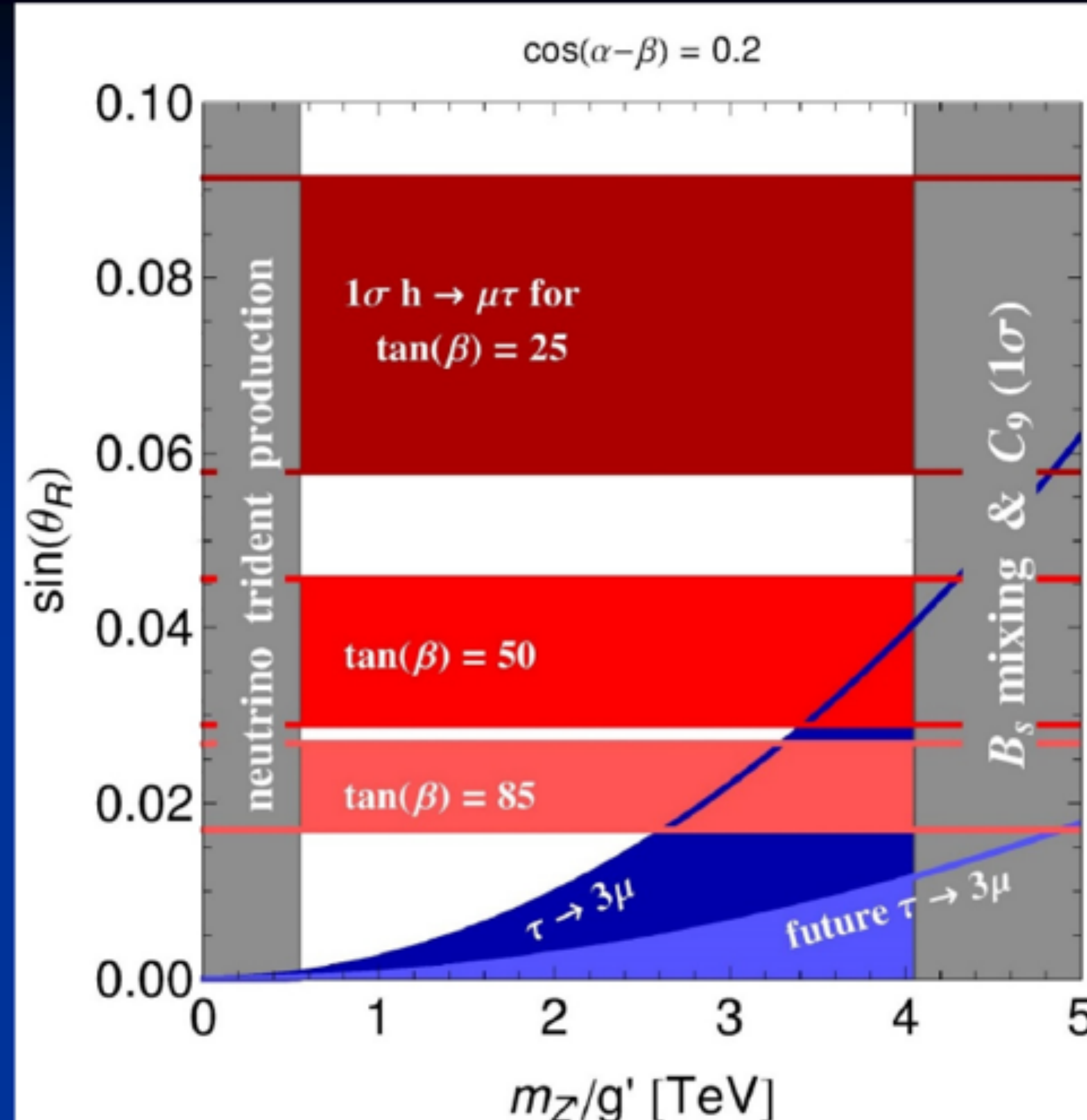
$$\sin\theta_L \simeq 0$$

- Lepton flavour violating Z' couplings

$$g' Z' (\overline{\mu}, \overline{\tau}) \begin{pmatrix} \cos 2\theta_R & \sin 2\theta_R \\ \sin 2\theta_R & -\cos 2\theta_R \end{pmatrix} \gamma^\nu P_R \begin{pmatrix} \mu \\ \tau \end{pmatrix}$$

$\tau \to \mu\mu\mu$
$h \to \mu\tau$





excluded

allowed by $h \to \tau\mu$

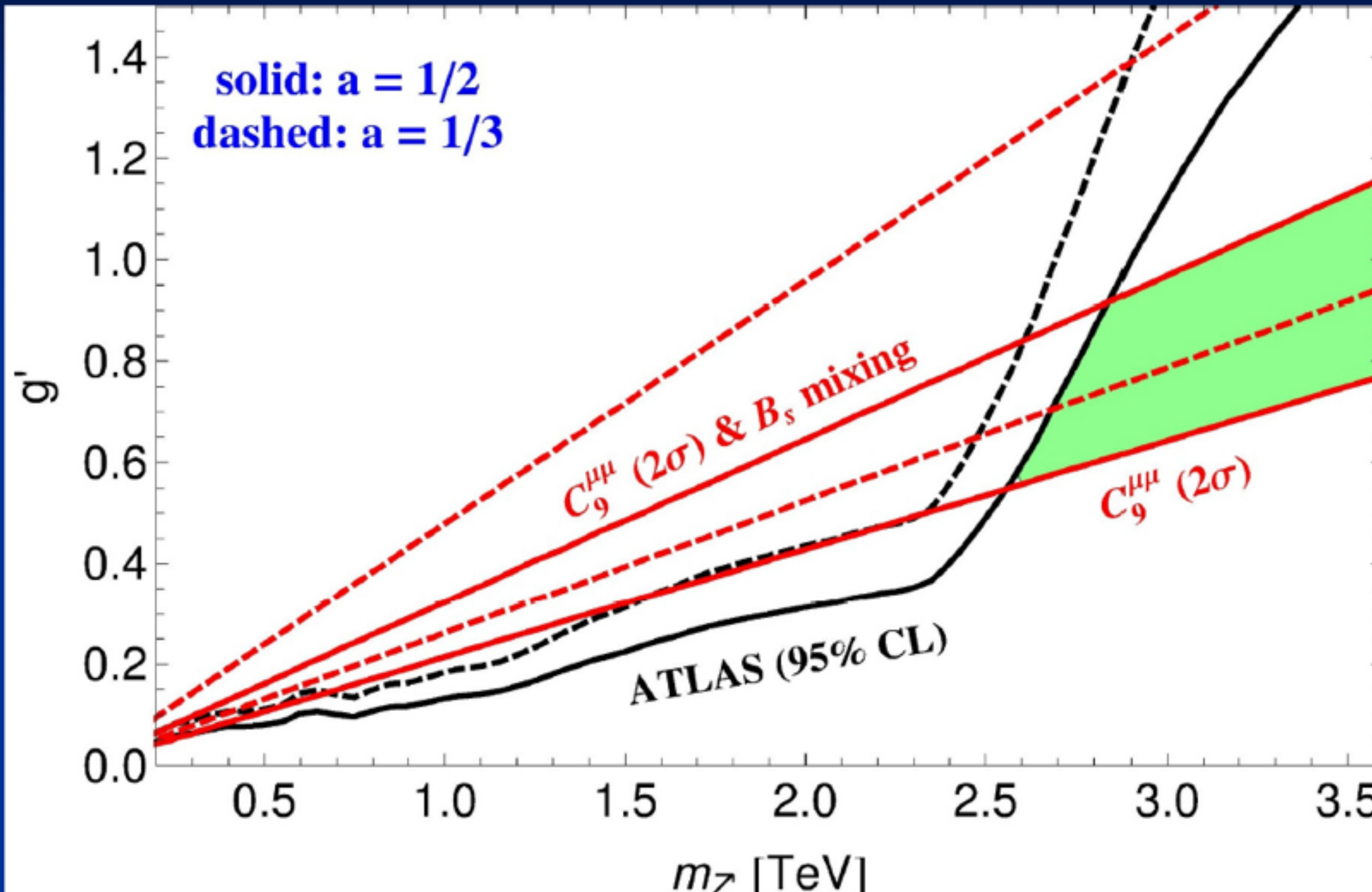
allowed by $\tau \to \mu\mu\mu$

Horizontal gauge symmetries

Crivellin, G.D., Heeck

- Avoiding vector like quarks by charging baryons
  $Q(B)=(-a,-a, 2a)$

LHC limits



ATLAS $C_9^{\mu\mu}$ & $B_s - \overline{B}_s$ a = 1 / 2 allowed

1 | Constraining LFUV and LFV at NA62?

Consider analogous processes to those relevant for B-anomalies:

- Key mode for **LFUV**: $K^{\pm} \to \pi^{\pm}\ell^{+}\ell^{-}\,, \qquad \ell = \mu \text{ or } e$
- Spectrum measured, but PDG average of $\mu^{+}\mu^{-}$ mode dominated by E787 measurement (scale factor = 2.6):

$$\mathrm{Br}[K^{+} \to \pi^{+}e^{+}e^{-}] = (3.00 \pm 0.09) \times 10^{-7}$$
$$\mathrm{Br}[K^{+} \to \pi^{+}\mu^{+}\mu^{-}] = (9.4 \pm 0.6) \times 10^{-8}$$

- Also have neutral decays: $K_{L,S} \to \pi^{0}\ell^{+}\ell^{-}$

$$\mathrm{Br}[K_S \to \pi^{0}e^{+}e^{-}] = 3.0^{+1.5}_{-1.2} \times 10^{-9}$$
$$\mathrm{Br}[K_S \to \pi^{0}\mu^{+}\mu^{-}] = 2.9^{+1.5}_{-1.2} \times 10^{-9}$$

} No spectrum, prospects for LHCb?

$$\mathrm{Br}[K_L \to \pi^{0}e^{+}e^{-}] < 2.8 \times 10^{-10}$$
$$\mathrm{Br}[K_L \to \pi^{0}\mu^{+}\mu^{-}] < 3.8 \times 10^{-10}$$

} Future measurement at KOTO or NA**XX**?

3 | LFUV and $K^\pm \to \pi^\pm \ell^+ \ell^-$

- Observe: in SM $a_+^{\ell\ell}$ same in both modes, so difference (if any) must be due to NP

Crivellin, A GD, Hoferichter, M and Tunstall, L

$$C_{7V}^{\mu\mu} - C_{7V}^{ee} = \alpha \frac{a_+^{\mu\mu} - a_+^{ee}}{2\pi\sqrt{2}V_{ud}V_{us}^*}$$

- Fits to E865 and NA48/2 spectra

$$a_+^{ee} = -0.584 \pm 0.008 \qquad a_+^{\mu\mu} = -0.575 \pm 0.039$$

- Can correlate with B-sector coefficients via **M**inimal **F**lavour **V**iolation (MFV) hypothesis:

$$C_9^{B,\mu\mu} - C_9^{B,ee} = -\frac{a_+^{\mu\mu} - a_+^{ee}}{\sqrt{2}V_{td}V_{ts}^*} \approx -19 \pm 79 \quad \Longleftrightarrow \quad C_9^{B,\mathrm{NP}} = O(1)$$

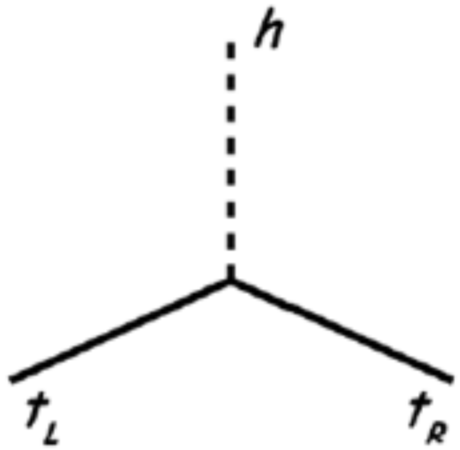
- Determination of $a_+^{ee} - a_+^{\mu\mu}$ requires improvement of $O(50-100)$

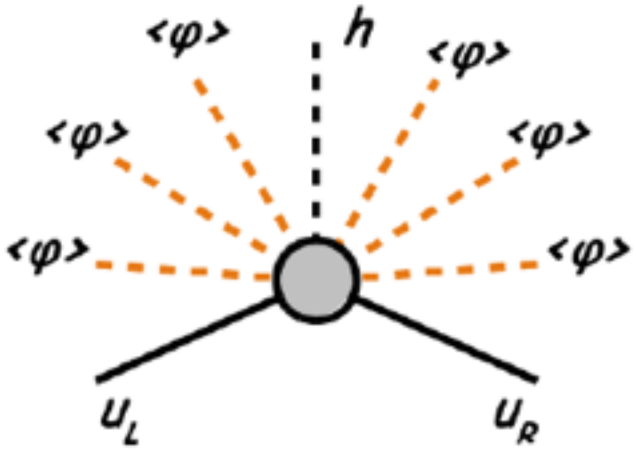
If we are convinced of flavor anomalies we should find some good theory

Hierarchy from Symmetry

(Froggatt, Nielsen '79; ...)

fermion masses are forbidden by flavor symmetries
and arise only after spontaneous breaking of the symmetry





Simple U(1) model:

Q(t_L)=Q(t_R)=0
Q(u_L)=-Q(u_R)=3
Q(h)=0
Q(φ)=-1

$h\bar{t}_R t_L$

$\frac{\varphi^6}{M^6} h\bar{u}_R u_L$

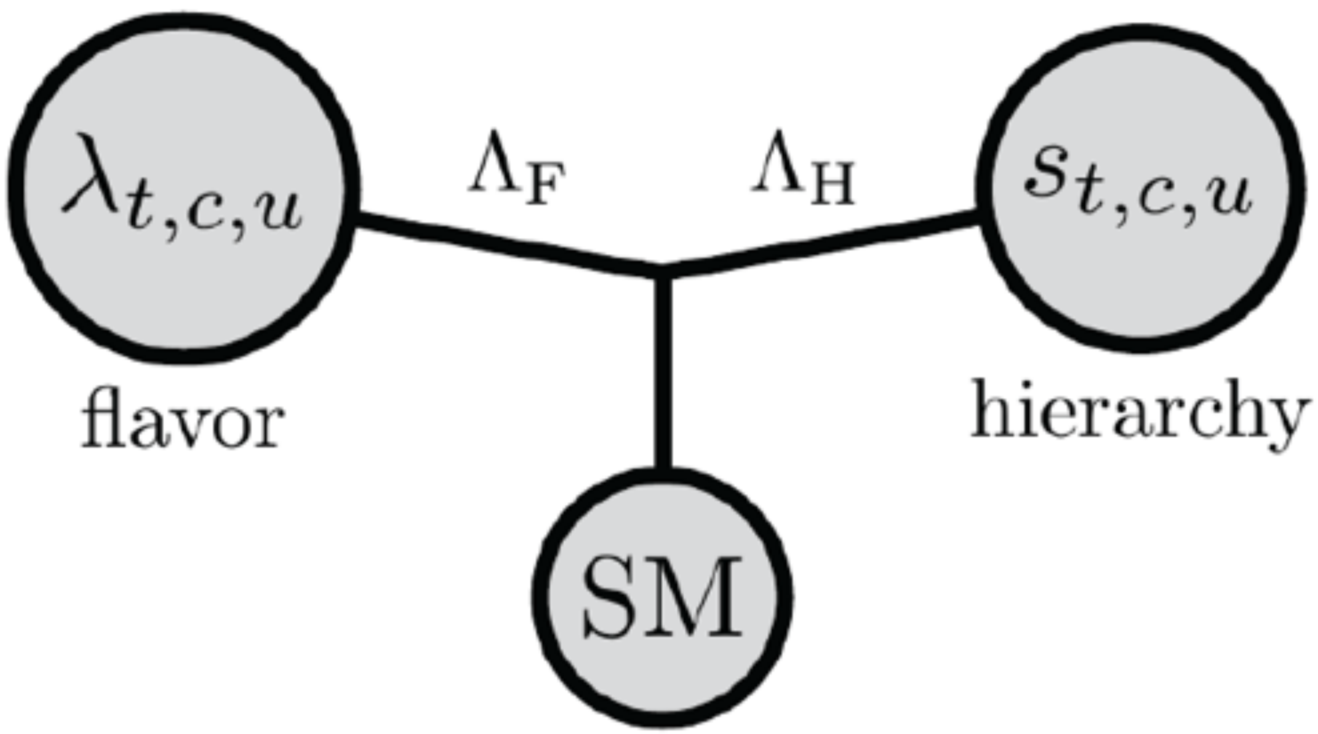
mass and mixing hierarchies given by powers of the spurion $\langle\varphi\rangle/M$

$$\frac{m_u}{m_t} \sim \left(\frac{\langle\varphi\rangle}{M}\right)^n$$

(see recent work by Bauer, Carena, Gemmler '15)

Disentangeling Mass and Mixing Hierarchies

Knapen, Robinson '15



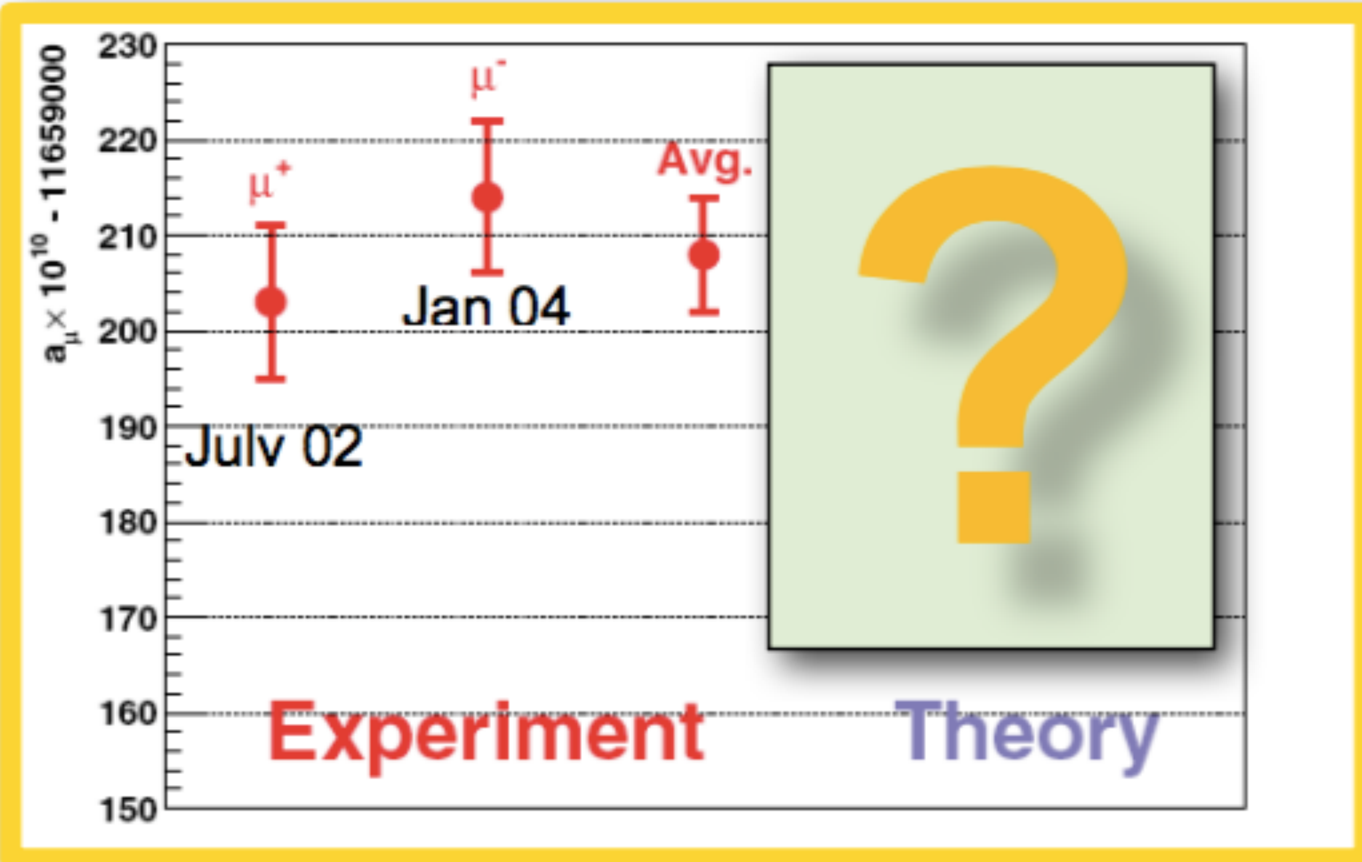
one sector with scale Λ_F responsible for flavor mixing

Λ_F is strongly constrained by low energy flavor observables (in some cases at the level of 1000s or 100,000s of TeV)

separate sector with scale Λ_H responsible for mass hierarchies

Λ_H could be much lower, close to the electroweak scale and in reach of the LHC

The muon g-2: experimental status



- **Today:** $a_\mu^{EXP} = (116592089 \pm 54_{stat} \pm 33_{sys}) \times 10^{-11}$ [0.5ppm].
- **Future:** new muon g-2 experiments at:
  - Fermilab E989: aiming at $\pm 16 \times 10^{-11}$, ie 0.14ppm. Beam expected in 2017. First result expected in 2018 with a precision comparable to that of BNL E821.
  - J-PARC proposal: aiming at 2019 Phase 1 start with 0.4ppm.
- Are theorists ready for this (amazing) precision? Not yet

Muon g-2 @FNAL
(>13 FTE)

- **Sept 2014 – May 2015**

– Reassembly of the storage ring with cryogenic system; fully operational

- **June 2015**

– Start of cooling

- **July-August 2015**

– **CD2/3 received**

- **September 2015**

– Magnet cooled, ON (5300 A, 1.45T)

– 8 months needed for shimming

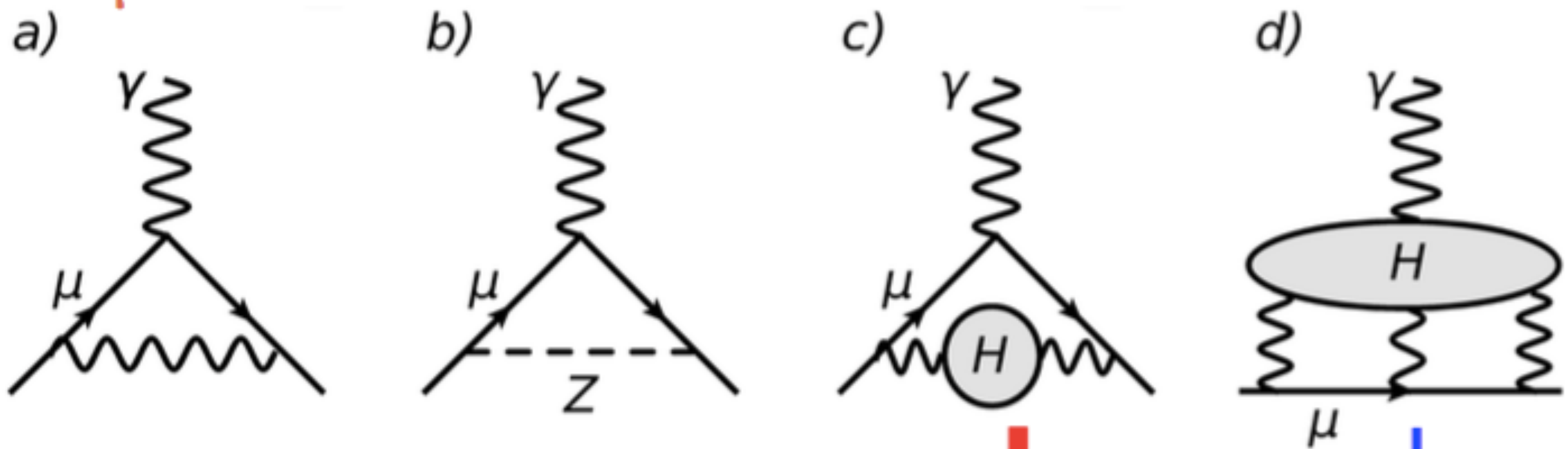
READY FOR BEAM APRIL 2017

INFN contribution:

Laser monitoring system for calorimeter calibration
Gain stability 10^{-4} per hour

RISE EU-grant MUSE with Mu2e starting Jan 2016

a_μ(SM): There are really 2 numbers in play here



	Value ($\times 10^{-11}$) units
QED ($\gamma + \ell$)	$116\,584\,718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077_\alpha$
HVP(lo)	$6\,923 \pm 42$
HVP(lo)	$6\,949 \pm 43$
HVP(ho	-98.4 ± 0.7
HLbL	105 ± 26
EW	154 ± 1
Total SM	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$
Total SM	$116\,591\,828 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 50_{\text{tot}})$

Conclusions

- Indirect and direct searches vs theory prejudice
- Atlas and CMS, LHCb and BelleII , FNAL, NA62 and KOTO will definitely shed light

electron g-2

$a_e^{exp} = 1159652180.73\ (28) \times 10^{-12}$ Hanneke et al, PRL100 (2008) 120801

- in agreement SM , QED calculation at fourth order , EW smaller

see refs in Giudice Paradisi Passera arXiv:1208.6583

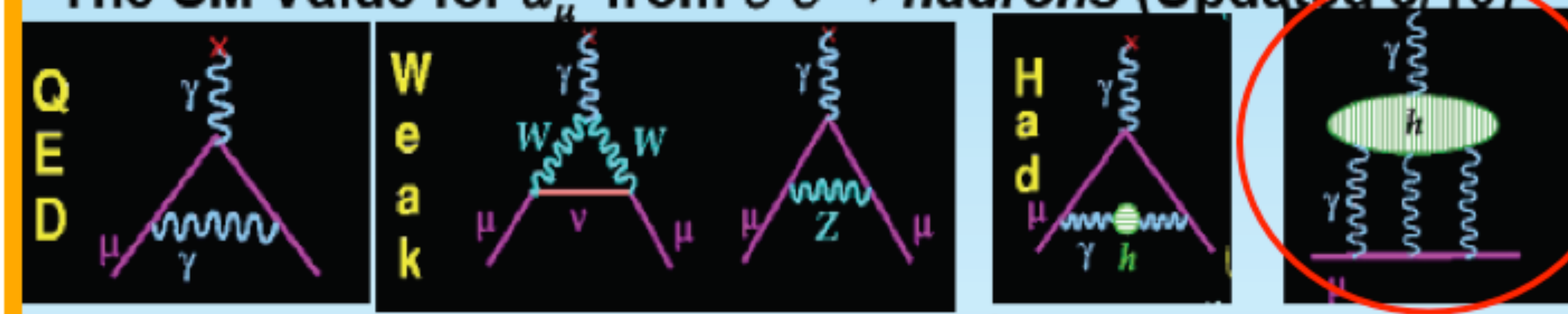
LHCb & upgrade sensitivities

Table 28: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming $5\,\text{fb}^{-1}$ recorded during Run 2) and for the LHCb Upgrade ($50\,\text{fb}^{-1}$). An estimate of the theoretical uncertainty is also given – this and the potential sources of systematic uncertainty are discussed in the text.

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.050	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\text{sl}}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\text{eff}}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.023**	0.02
	$\phi_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm CP violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

SM contribution to g-2 muon

The SM Value for a_μ from $e^+e^- \to hadrons$ (Updated 9/10)



well known

significant work ongoing

Pion exchange diagram dominates HLbL

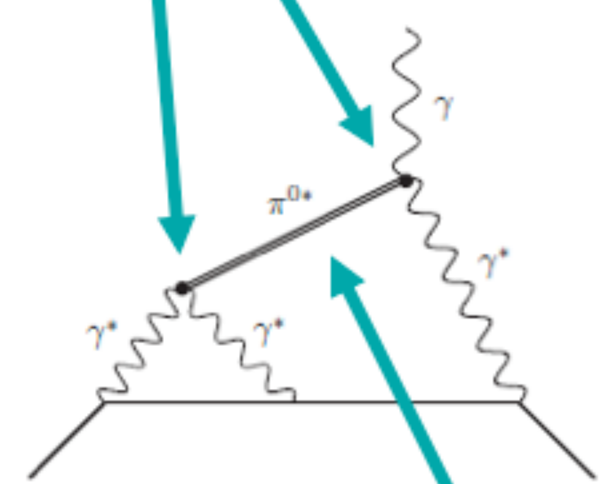
CONTRIBUTION	RESULT ($\times 10^{-11}$) UNITS
QED (leptons)	$116\,584\,718.09 \pm 0.14 \pm 0.04_\alpha$
HVP(lo)	$6\,914 \pm 42_{\rm exp} \pm 14_{\rm rad} \pm 7_{\rm pQCD}$
HVP(ho)	$-98 \pm 1_{\rm exp} \pm 0.3_{\rm rad}$
HLxL	105 ± 26
EW	$152 \pm 2 \pm 1$
Total SM	$116\,591\,793 \pm 51$

A. Höcker Tau 2010, U. Manchester September 2010 **116 592 089 +- 63**

EXP

Pion Form Factor

$$F_{\pi^0\gamma^*\gamma^*}(Q_1^2, Q_2^2)$$



Off-Shell Pion

Pseudoscalar exchanges

Our result

Model for $\mathcal{F}_{P^{(*)}\gamma^*\gamma^*}$	$a_\mu(\pi^0) \times 10^{11}$	$a_\mu(\pi^0,\eta,\eta') \times 10^{11}$
modified ENJL (off-shell) [BPP]	59(9)	85(13)
VMD / HLS (off-shell) [HKS,HK]	57(4)	83(6)
LMD+V (on-shell, $h_2 = 0$) [KN]	58(10)	83(12)
LMD+V (on-shell, $h_2 = -10$ GeV^2) [KN]	63(10)	88(12)
LMD+V (on-shell, constant FF at ext. vertex) [MV]	77(7)	114(10)
nonlocal χQM (off-shell) [DB]	65(2)	—
LMD+V (off-shell) [N]	72(12)	99(16)
AdS/QCD (off-shell ?) [HoK]	69	107
AdS/QCD/DIP (off-shell) [CCD]	65.4(2.5)	—
DSE (off-shell) [FGW]	58(7)	84(13)
[PdRV]	—	114(13)
[JN]	72(12)	99(16)

BPP = Bijnens, Pallante, Prades '95, '96, '02 (ENJL = Extended Nambu-Jona-Lasinio model); HK(S) = Hayakawa, Kinoshita, Sanda '95, '96; Hayakawa, Kinoshita '98, '02 (HLS = Hidden Local Symmetry model); KN = Knecht, Nyffeler '02; MV = Melnikov, Vainshtein '04; DB = Dorokhov, Broniowski '08 (χQM = Chiral Quark Model); N = Nyffeler '09; HoK = Hong, Kim '09; CCD = Cappiello, Catà, D'Ambrosio '10 (used AdS/QCD to fix parameters in DIP (D'Ambrosio, Isidori, Portolés) ansatz); FGW = Fischer, Goecke, Williams '10, '11 (Dyson-Schwinger equation)

Reviews on LbyL: PdRV = Prades, de Rafael, Vainshtein '09; JN = Jegerlehner, Nyffeler '09

A. Nyffeler Seattle 2011

There are many competing models:
ENJL (Chiral quark model)
Lowest Meson Dominance
Hidden Symmetry
Non-Local ChQM
Bethe-Salpeter
Holographic QCD
Lattice QCD

A theoretical effort should be done to make them talk to each other

Uncertainty can increase of 10-15 % due to poor knowledge of the parameter χ_0 which we used to encode the pion off-shellness by the high-Q^2 constraint

$$\lim_{Q^2\to\infty} F_{\pi^{0*}\gamma^*\gamma^*}(Q^2,Q^2,0) = -\frac{f_\pi}{3}\chi_0 + \cdots$$

Notice that the low-Q^2 predictions for PFF of the holographic models could be tested at KLOE-2

$$\lim_{Q_1^2,Q_2^2\to 0} F_{\pi^0\gamma^*\gamma^*}(Q_1^2,Q_2^2) \simeq -\frac{N_C}{12\pi^2 f_\pi}\times \left[1+\hat{\alpha}\,(Q_1^2+Q_2^2)+\hat{\beta}\,Q_1^2Q_2^2+\hat{\gamma}\,(Q_1^4+Q_2^4)\right]$$

Exp.

$$\hat{\alpha} = -1.76(22)\ \mathrm{GeV}^{-2}$$

$$\hat{\beta} = 3.33(32)\ \mathrm{GeV}^{-4},\quad \hat{\gamma} = 2.84(21)\ \mathrm{GeV}^{-4}.$$

The Flavor of the Higgs

$$\mathcal{L}_{\text{Yukawa}} = Y_{ij}\,\bar{\Psi}_i \Psi_j\,H + \frac{\tilde{Y}_{ij}}{\Lambda^2}\,\bar{\Psi}_i \Psi_j\,H^3$$

In the Standard Model the Yukawa couplings are
the only sources of flavor and CP violation

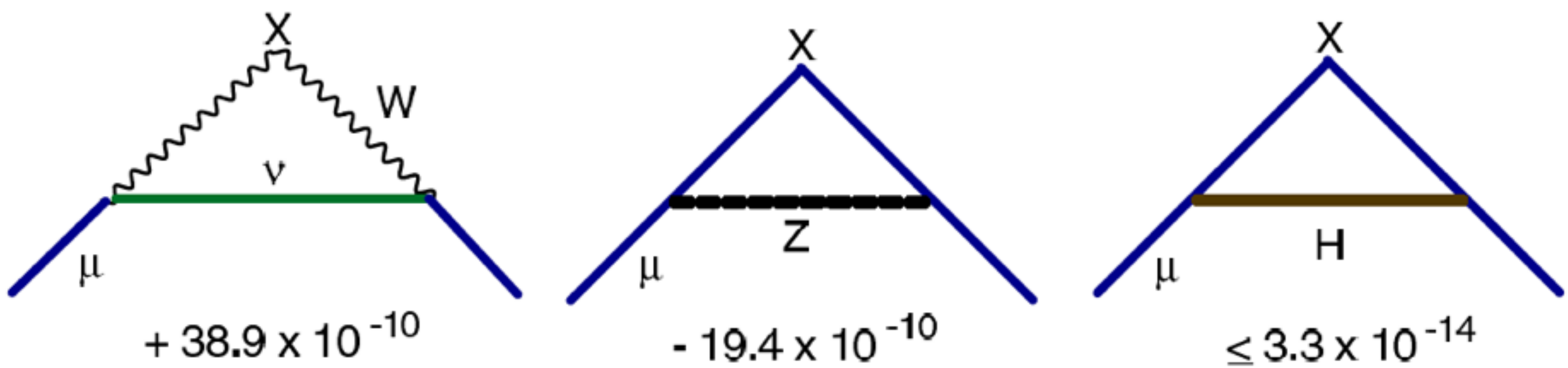
→ the couplings of the Higgs to fermion mass eigenstates are
flavor diagonal and CP conserving

$$\frac{1}{v}\begin{pmatrix} m_{u,d,e} & 0 & 0 \\ 0 & m_{c,s,\mu} & 0 \\ 0 & 0 & m_{t,b,\tau} \end{pmatrix} + \frac{v^2}{\Lambda^2}\begin{pmatrix} \star & \star & \star \\ \star & \star & \star \\ \star & \star & \star \end{pmatrix}$$

1) New Physics can modify the flavor diagonal Higgs couplings
2) New Physics can lead to flavor and CP violating Higgs couplings

EW contribution to g-2 muon

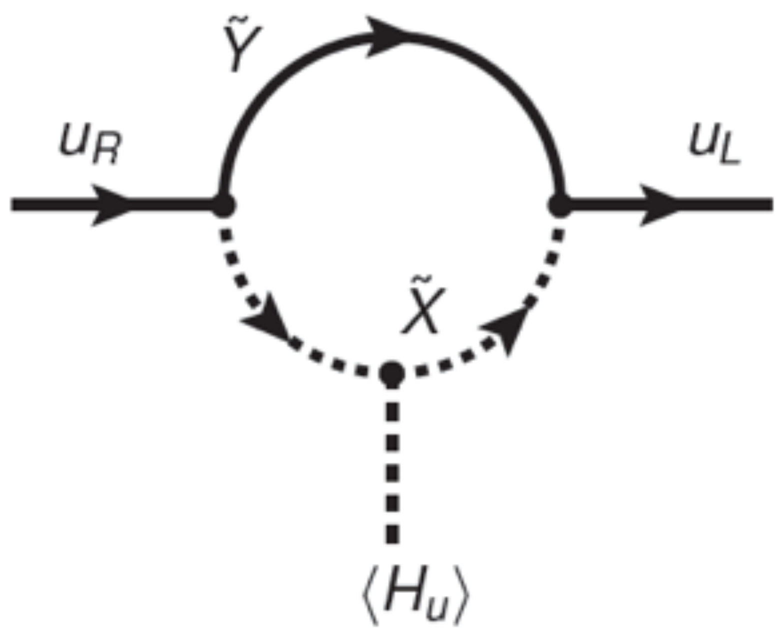
from Eduardo de Rafael



$$a_\mu^{(\mathrm{W})} = \frac{G_F}{\sqrt{2}} \frac{m_\mu^2}{8\pi^2} \left[\frac{5}{3} + \frac{1}{3}(1 - 4\sin^2\theta_W) + \mathcal{O}\left(\frac{m_\mu^2}{M_Z^2} \log \frac{M_Z^2}{m_\mu^2} \right) + \frac{m_\mu^2}{M_H^2} \int_0^1 dx \frac{2x^2(2-x)}{1 - x + \frac{m_\mu^2}{M_H^2} x^2} \right] = 19.48 \times 10^{-10}$$

(Weinberg '72; ...)

light fermion masses arise only from quantum effects



light fermions do not couple to the higgs directly

couplings are loop-induced by flavor violating new particles

mass and mixing hierarchies from loop factors

$$\frac{m_u}{m_t} \sim \left(\frac{1}{16\pi^2} \right)^n$$

(various studies in recent years:

Arkani-Hamed et al. '12; Baumgart, Stolarski, Zorawski '14; WA, Frugiuele, Harnik '14;

Ibarra, Solaguren-Beascoa '14; Joaquim, Penedo '14; ...)