InterNational Conference on Flavour, composite models and dark matter

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Explaining the LHC flavour anomalies

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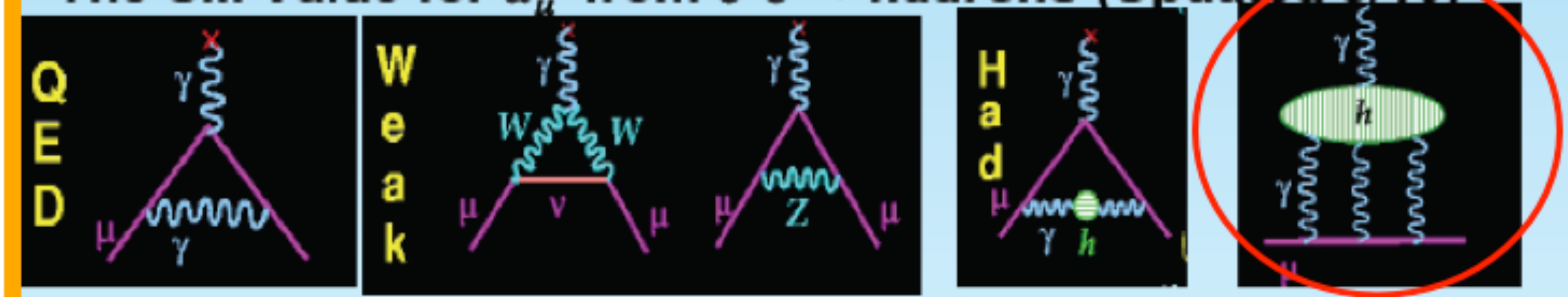
Outline

- g-2 muon/electron (NP?)
- Lepton flavour symmetries, why Lmu -Ltau ?
- Higgs Yukawa couplings, bounds on BSM
- Explaining flavour anomalies with vector like quarks (with vector like quarks)
- Our model I , two Higgs doublets addressing flavour anomalies and H-> mu tau, (with vector like quarks)
- Our model II , three Higgs doublets addressing flavour anomalies and H-> mu tau : B- L gauge theory

SM contribution to g-2 muon

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



well known

significant work ongoing

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

BOSTON UNIVERSITY

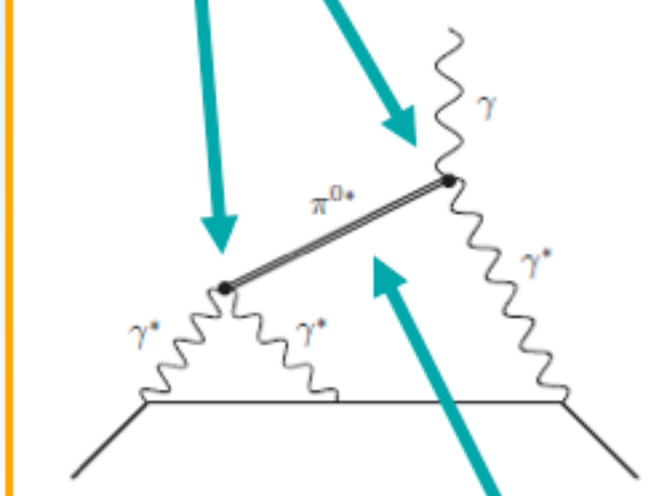
Lee Roberts - INT Workshop on HLBL 28 February 2011

- p. 21/30

Pion exchange diagram dominates HLbL

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, $h_2 = -10\ \mathrm{GeV}^2$) [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

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

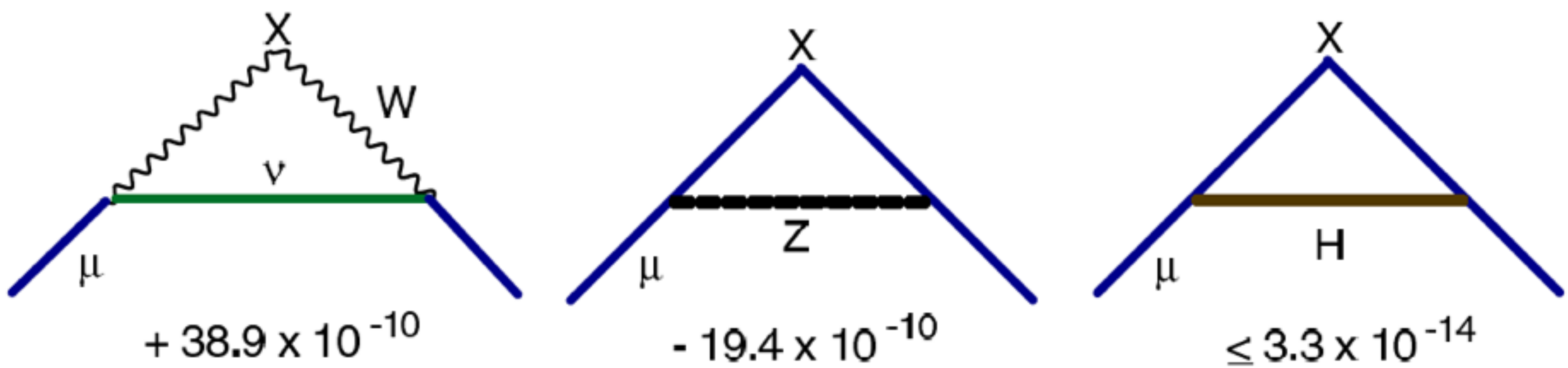
Exp.

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

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

EW contribution to g-2 muon

from Eduardo de Rafael



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

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

Neutrinos:two interesting features

- see-saw mechanism

- Leptogenesis scenario explains matter antimatter asymmetry in the universe

But

- no expt determination yet

Lepton flavour SM symmetries

- Lepton numbers are accidental symmetries of the SM
- SU(2) x U(1) violates B at the quantum level (B+L violated, B-L conserved)
- Gauging for instance Lmu -Ltau explains large mixing angle in PMNS matrix

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

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

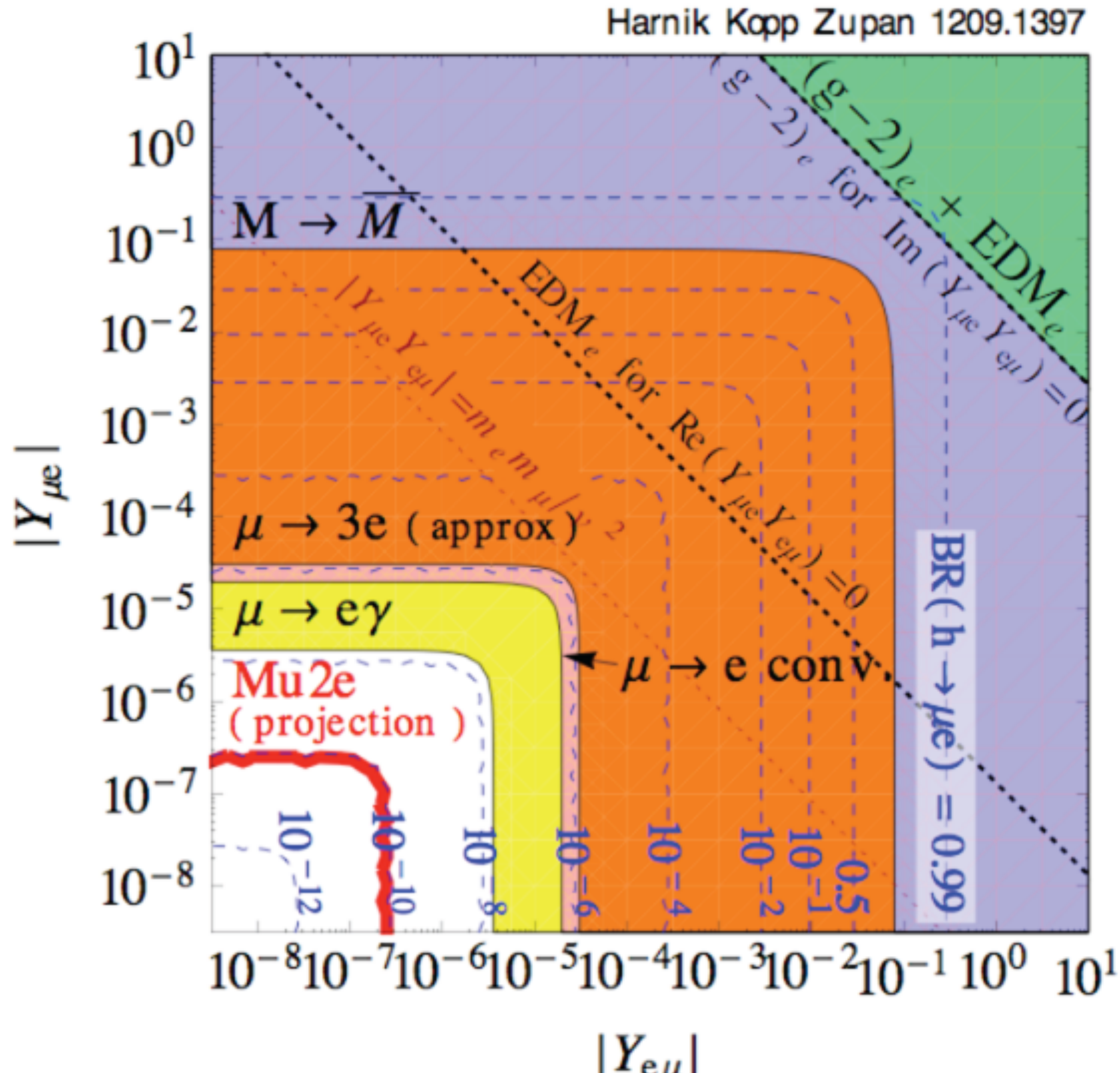
- $L_\mu - L_\tau$ gives $\theta_{23} = \pi/4$ and $\theta_{13} = 0$.[8]

Higgs couplings to leptons

- In the SM Yukawa couplings are diagonal and real
- NP through higher dimensional Higgs couplings, for instance, generates off-diagonal couplings and CP violation
- several groups worked on this interesting topic

Blankenburg, Ellis, Isidori 1202.5704
Harnik, Kopp Zupan 1209.1397
Brod, Haisch, Zupan 1310.1385

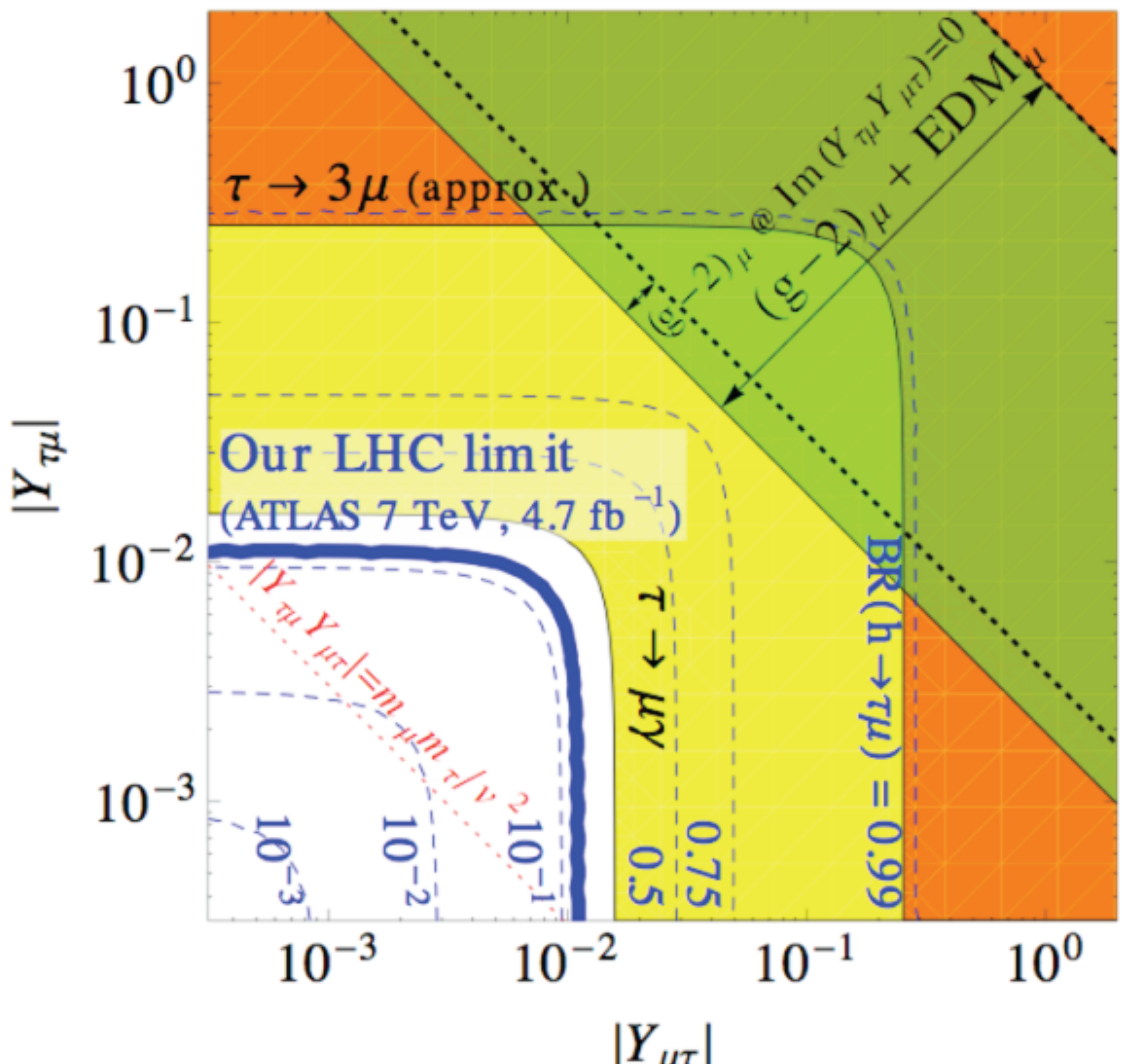
Higgs couplings to μe



Outside of LHC reach.

Probing "natural" models.

Higgs couplings to $\tau\mu$



LHC $h \to \tau\mu$ gives dominant bound.

(currently just a theorist's re-interpretation)

"natural models" are within reach.

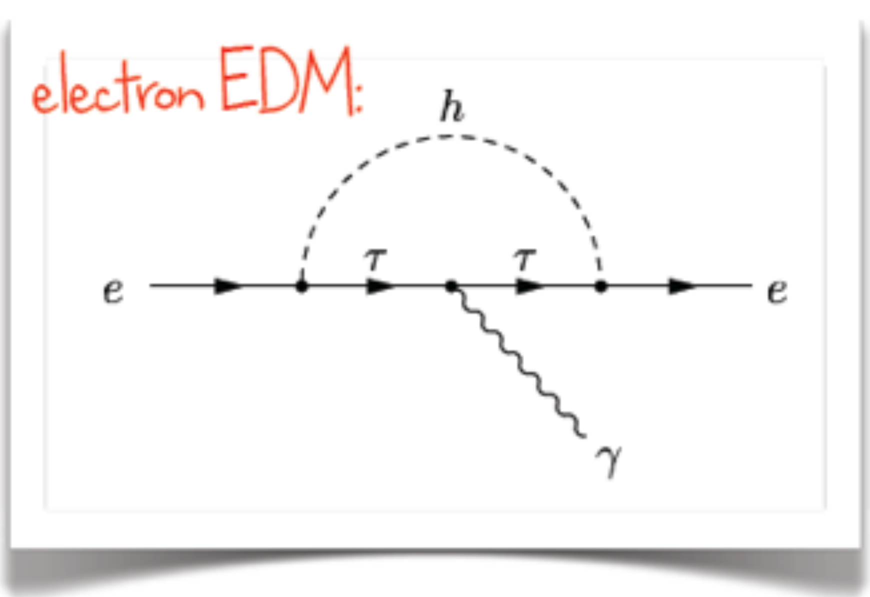
RH, Kopp, Zupan 1209.1397

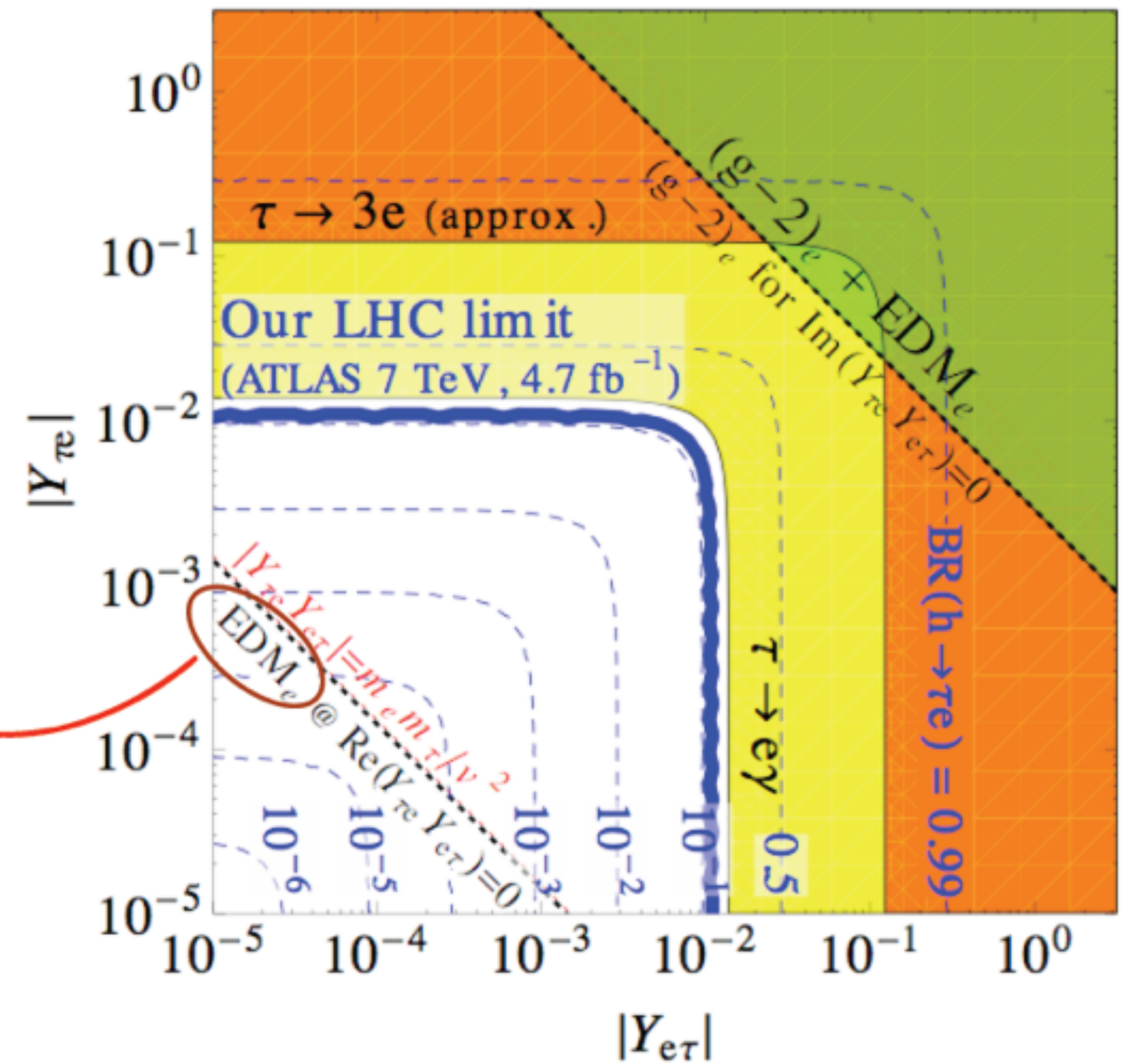
Higgs couplings to τe

* τe is similar to $\tau\mu$.... but:

Harnik, Kopp Zupan 1209.1397

Electron EDM is interesting here!





In the meanwhile Flavour anomalies

Babar,Belle,LHCb

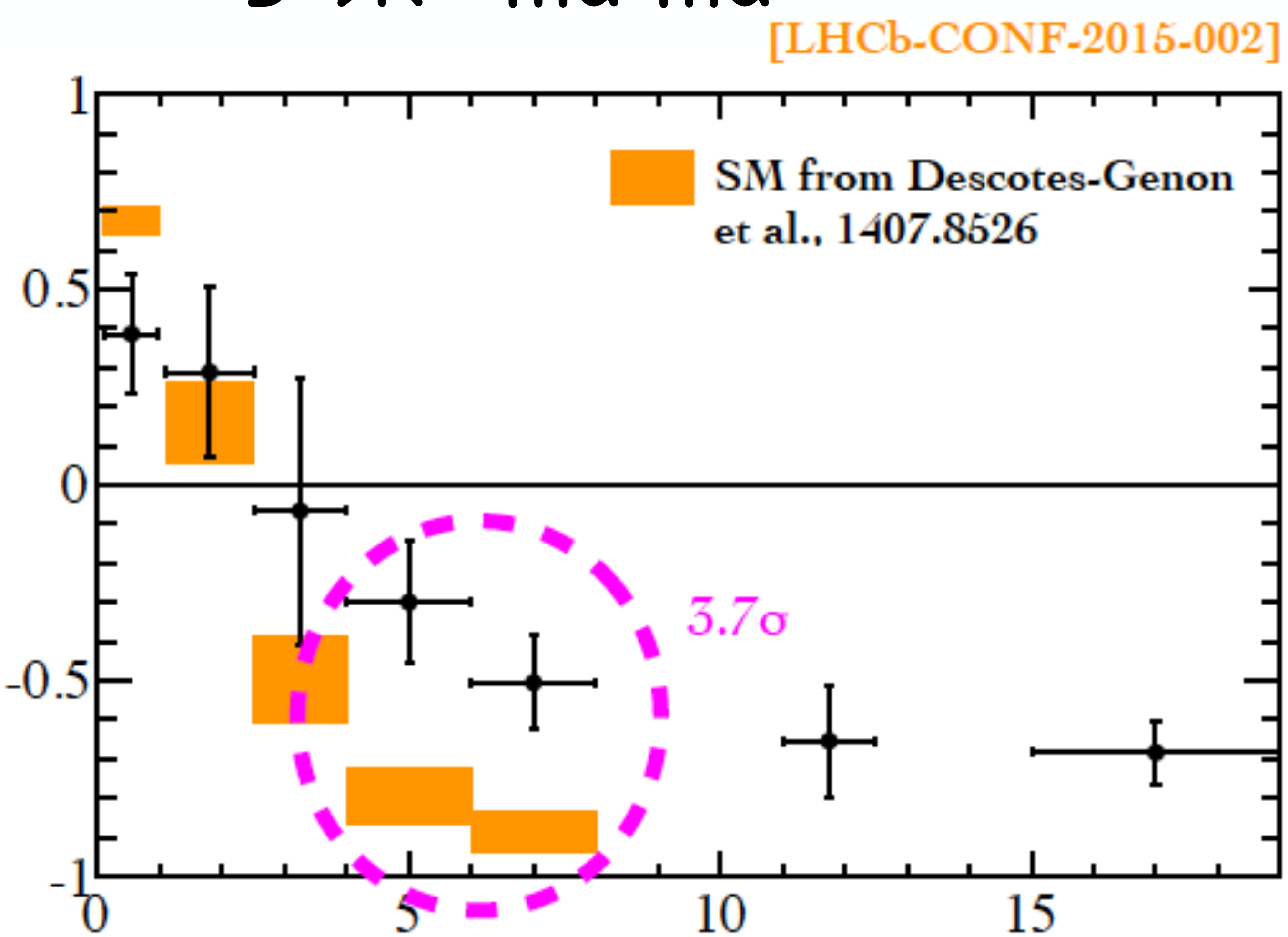
$$R(K) = \frac{B \to K\mu^+\mu^-}{B \to Ke^+e^-} = 0.745^{+0.090}_{-0.074} \pm 0.036\,,$$

VS

$$\bar{R}_K^{SM} = 1.0003 \pm 0.0001$$

Bobeth et al

P′5 B->K* mu mu



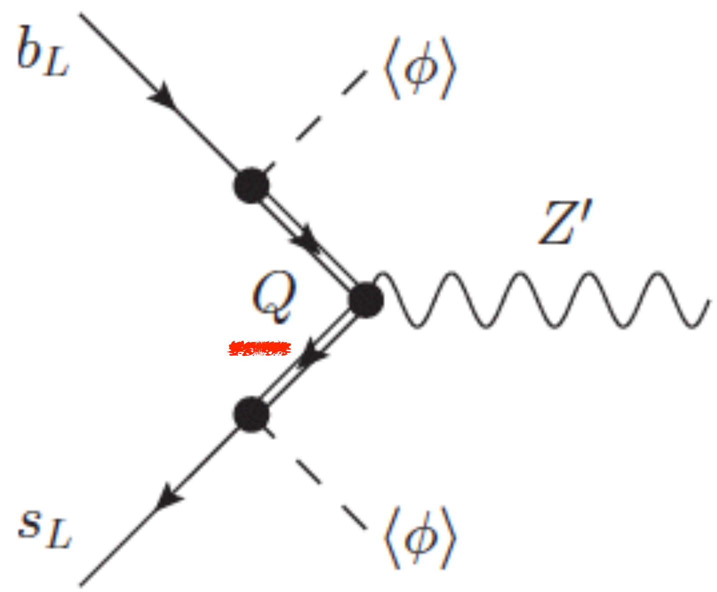
see DETTORI ,BHARUCHA,NESHATPOUR,

Altmannshofer, Gori, Pospelov, Yari

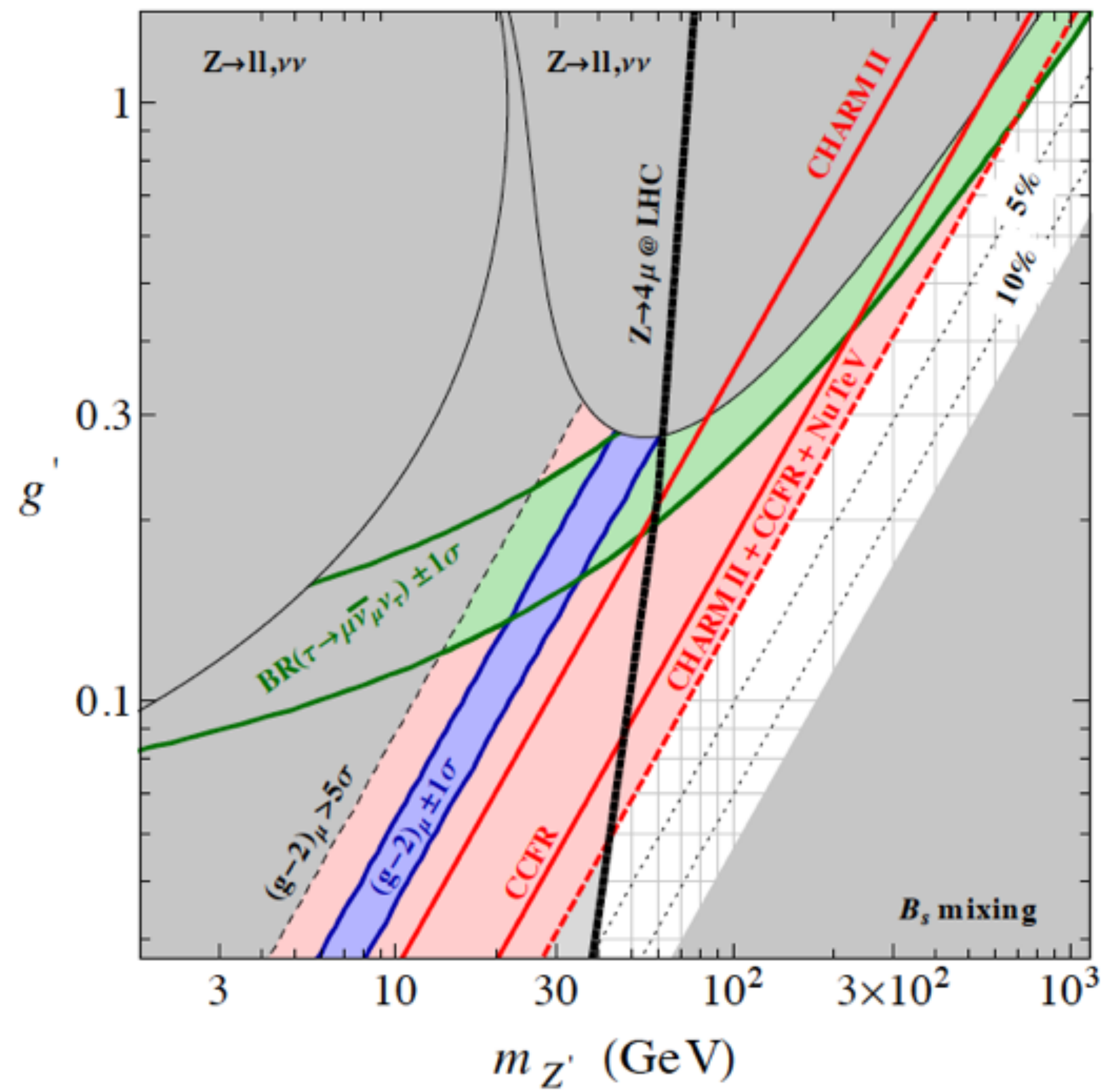
$$\mathcal{H}_{\text{eff}} = C_9(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu) + C_9'(\bar{s}\gamma_\alpha P_R b)(\bar{\mu}\gamma^\alpha \mu)$$

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

Altmannshofer, Gori, Pospelov, Yari



Quark part is built with vector like states (Q)



Integrating out Q

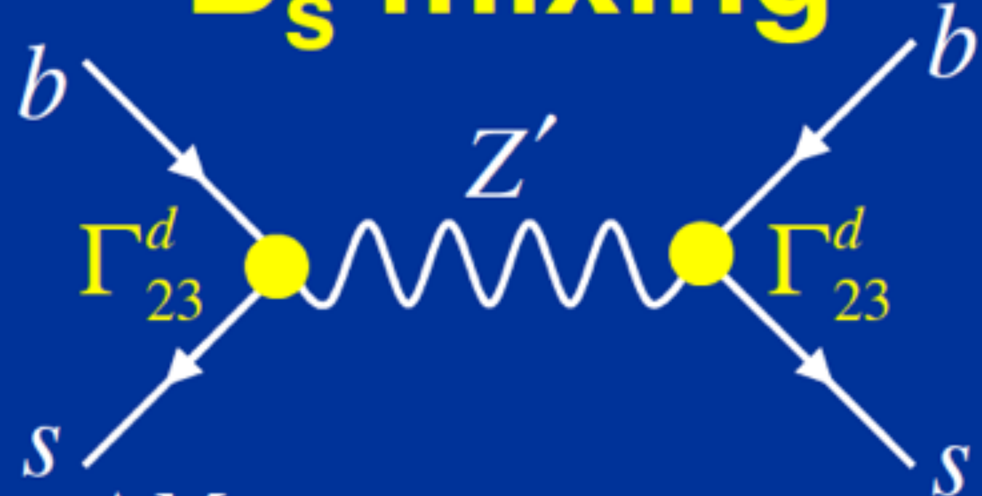
Γ^{dR}_{ij}

$B \to K^* \mu\mu$, R(K)

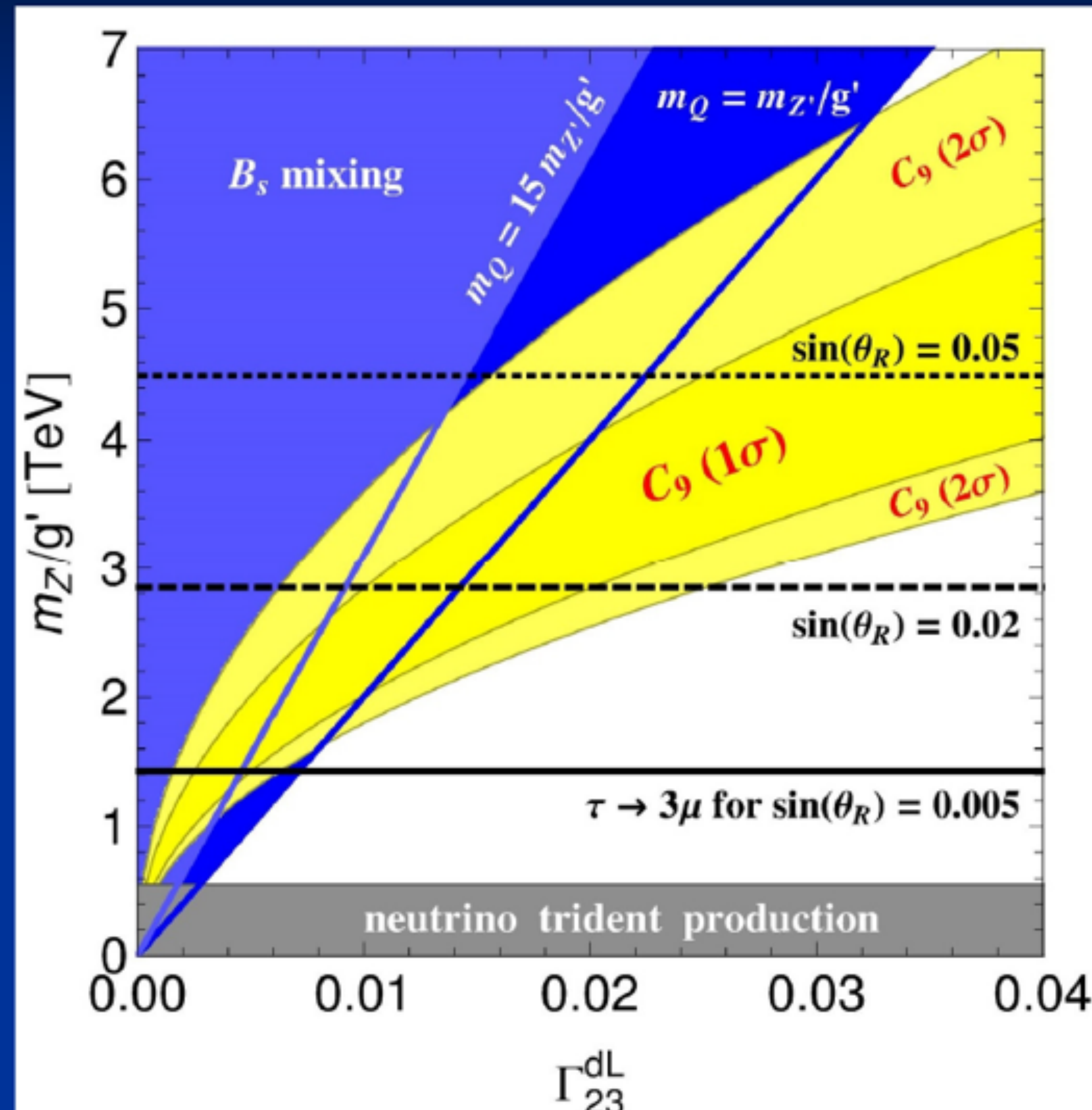
$m_D^2 \to \infty$

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

B_s mixing



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



allowed regions

Muon pair-production by neutrinos

Pospelov

VOLUME 66, NUMBER 24 PHYSICAL REVIEW LETTERS 17 JUNE 1991

Neutrino Tridents and *W*-*Z* Interference

S. R. Mishra,[a] S. A. Rabinowitz, C. Arroyo, K. T. Bachmann,[b] R. E. Blair,[c] C. Foudas,[d] B. J. King,

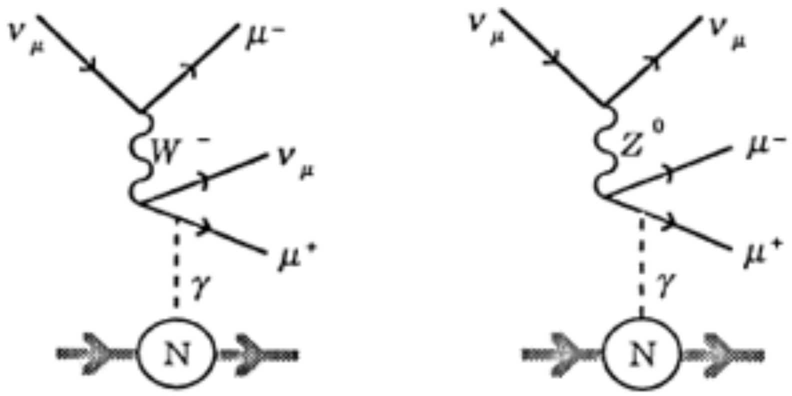


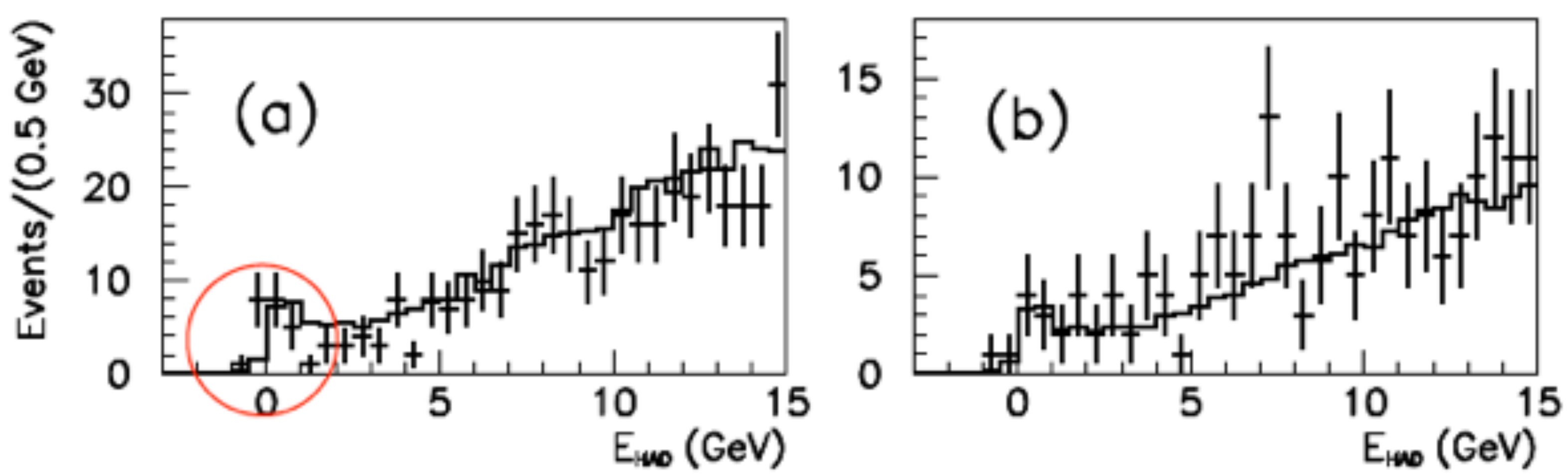
FIG. 1. Feynman diagram showing the neutrino trident production in ν_μ-A scattering via the W and the Z channels.

$$\sigma_{\nu N}(\mathrm{CC}) = (0.680 \pm 0.015) E_\nu \times 10^{-38}\ \mathrm{cm}^2/\mathrm{GeV},$$

$$\sigma(\nu\ \mathrm{trident}) = (4.7 \pm 1.6) E_\nu \times 10^{-42}\ \frac{\mathrm{cm}^2}{\mathrm{Fe\ nucleus}}$$

$$\text{at } \langle E_\nu \rangle = 160\ \mathrm{GeV}.$$

- NuTeV results:



Trident production was seeing with O(20) events, and is fully consistent with the SM destructive W-Z interference.

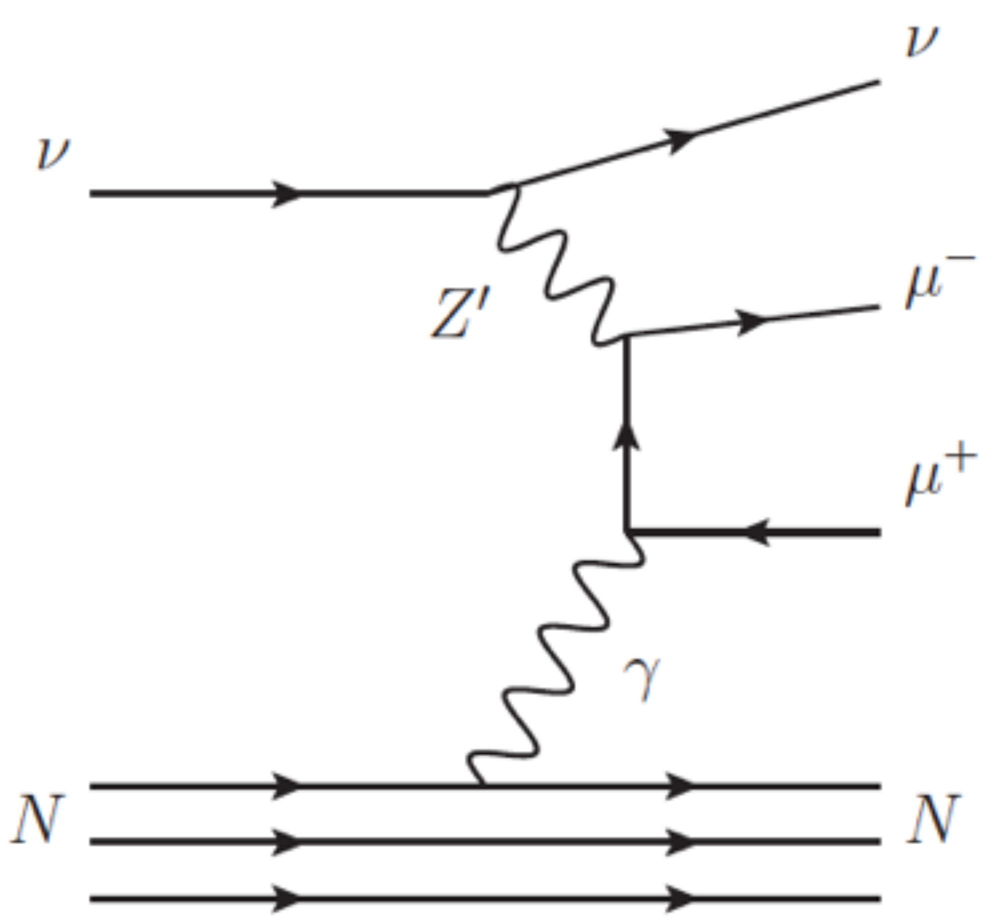
Additional contribution from Z' of $L_\mu - L_\tau$

Pospelov

Experimental results

$$\sigma_{\rm CHARM-II}/\sigma_{\rm SM} = 1.58 \pm 0.57\ ,$$
$$\sigma_{\rm CCFR}/\sigma_{\rm SM} = 0.82 \pm 0.28\ ,$$
$$\sigma_{\rm NuTeV}/\sigma_{\rm SM} = 0.67 \pm 0.27\ .$$

Hypothetical Z' (any Z' coupled to L_μ) contributes constructively to cross section.



In the heavy Z' limit the effect simply renormalizes SM answer:

$$\frac{\sigma}{\sigma_{\rm SM}} \simeq \frac{1 + \left(1 + 4s_W^2 + 2v^2/v_\phi^2\right)^2}{1 + (1 + 4s_W^2)^2}$$

LHC anomalies: H-> mu tau

$$\mathrm{Br}[h \to \mu\tau] = (0.89^{+0.40}_{-0.37})\,\%$$

CMS

- Actually 2HDM Lmu - Ltau symmetry was discussed by Heeck and collaborators to discuss Higgs and LHC physics

2nd 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

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

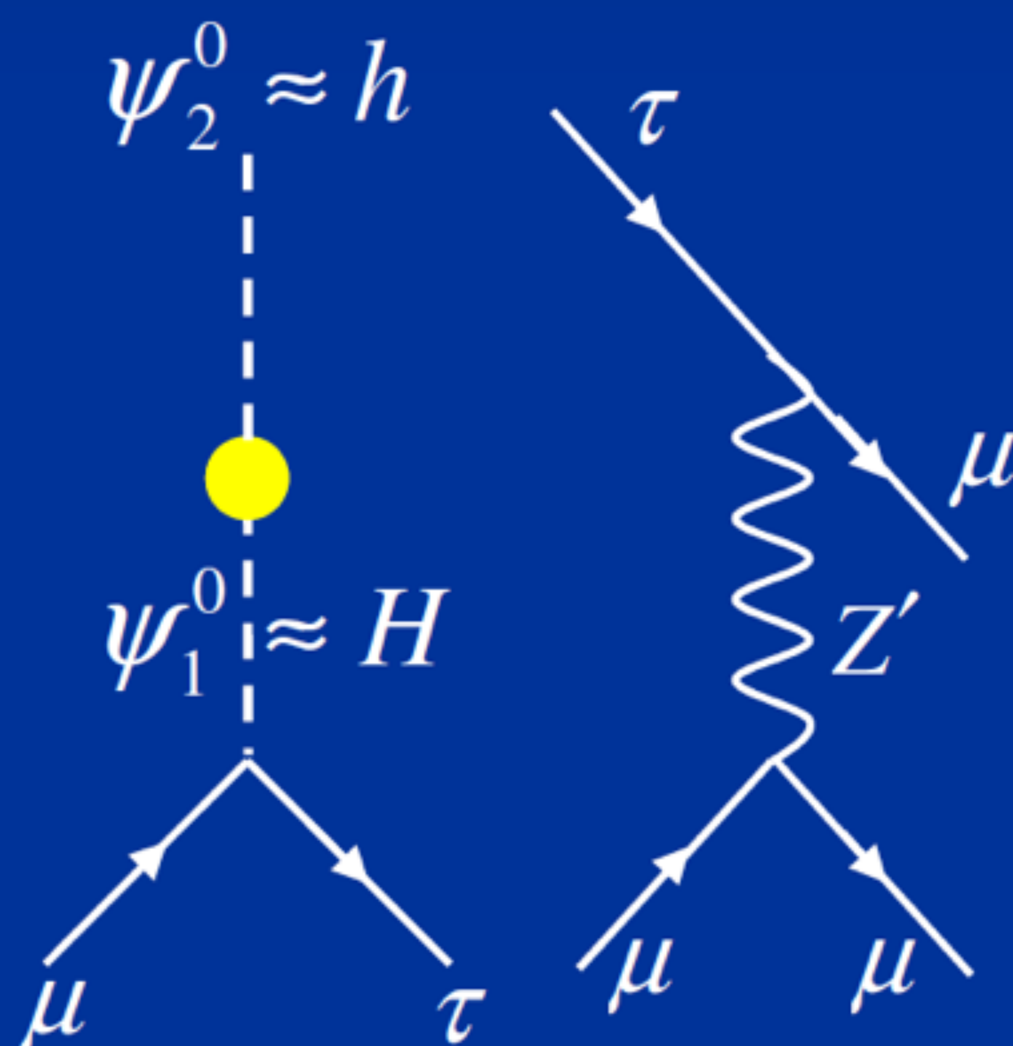
$$\sin\theta_R \simeq \frac{v}{\sqrt{2} m_\tau} \xi_{\tau\mu} \cos\beta$$

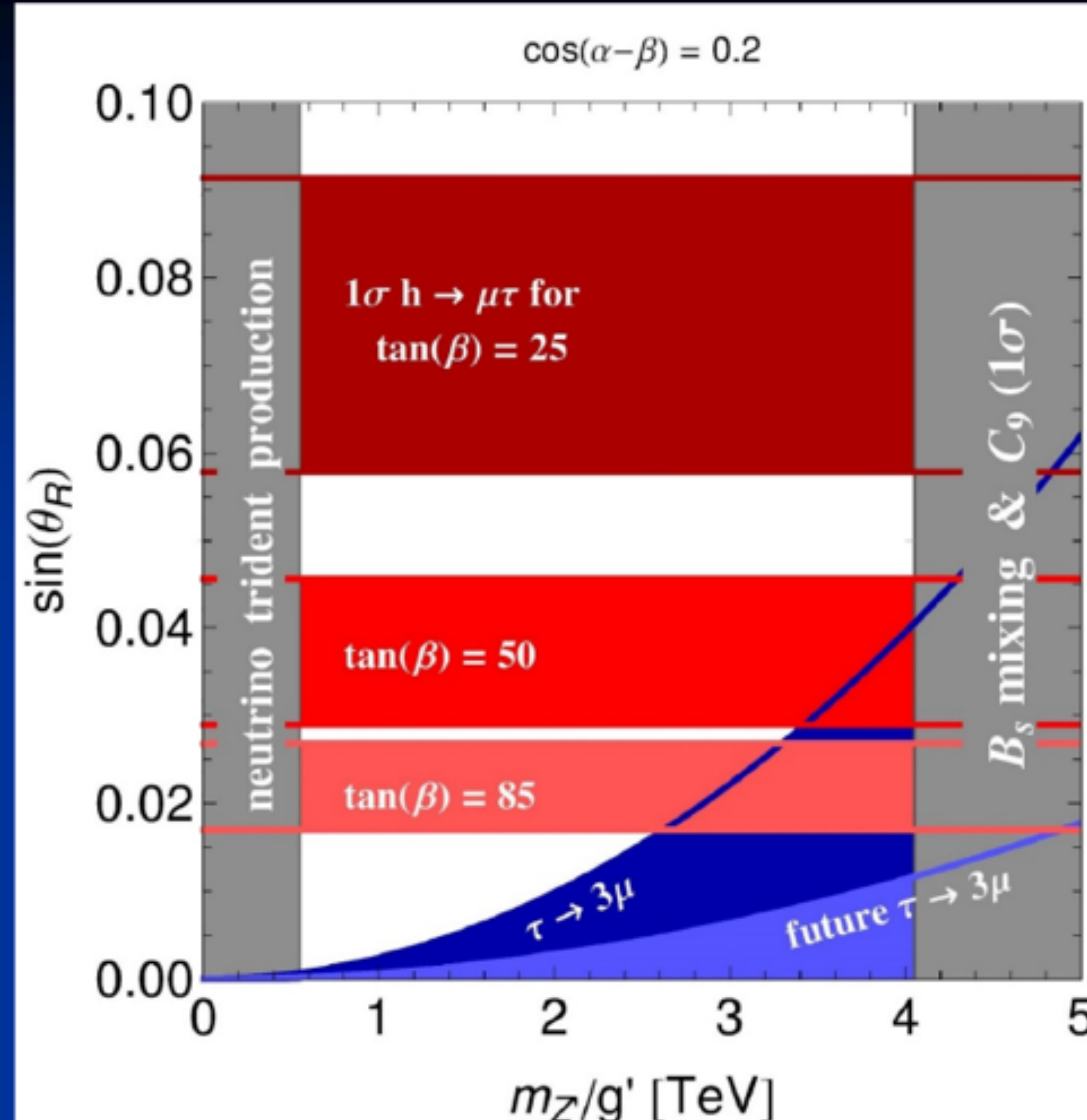
$$\sin\theta_L \simeq 0$$

- 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

Charge assignment

- Avoid vector-like quarks by assigning charges to baryons as well

➡ same mechanism in the quark and lepton sector

- Use $L_\mu - L_\tau$ in the lepton sector

➡ good symmetry for the PMNS matrix
effect in $C_9^{\mu\mu}$ but not C_9^{ee}

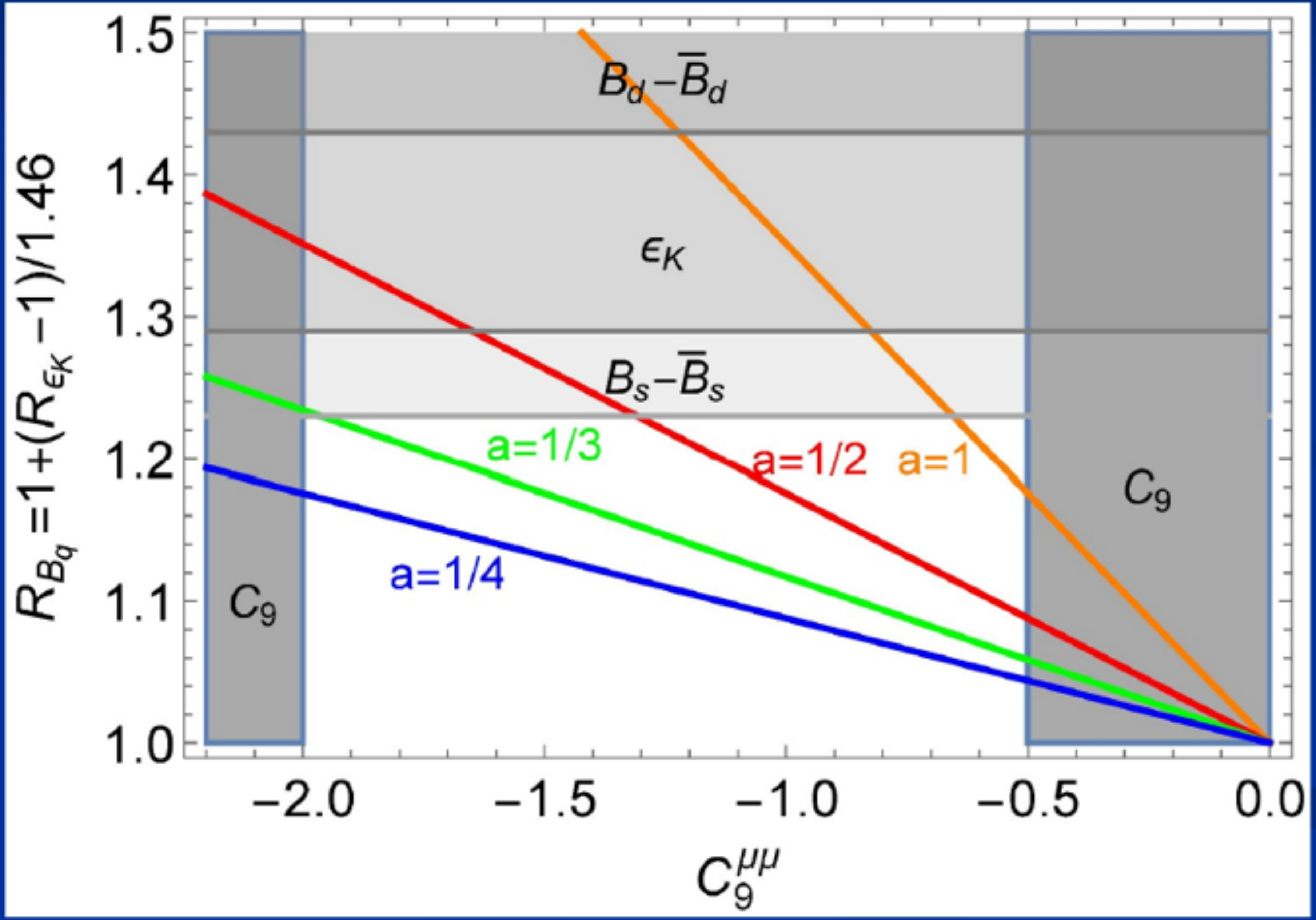
- First two quark generations must have the same charges because the large Cabibbo angle would lead to huge effect in Kaon mixing
- Anomaly free

➡ $Q(B) = (-a, \quad -a, \quad 2a)$

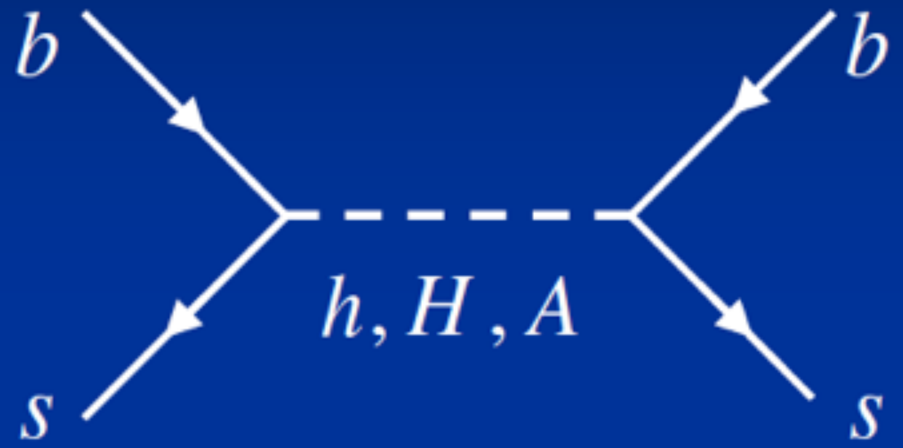
ΔF=2: Z' contribution

$$R_{B_q} = \frac{\Delta m_{B_q}}{\Delta m_{B_q}^{SM}}$$

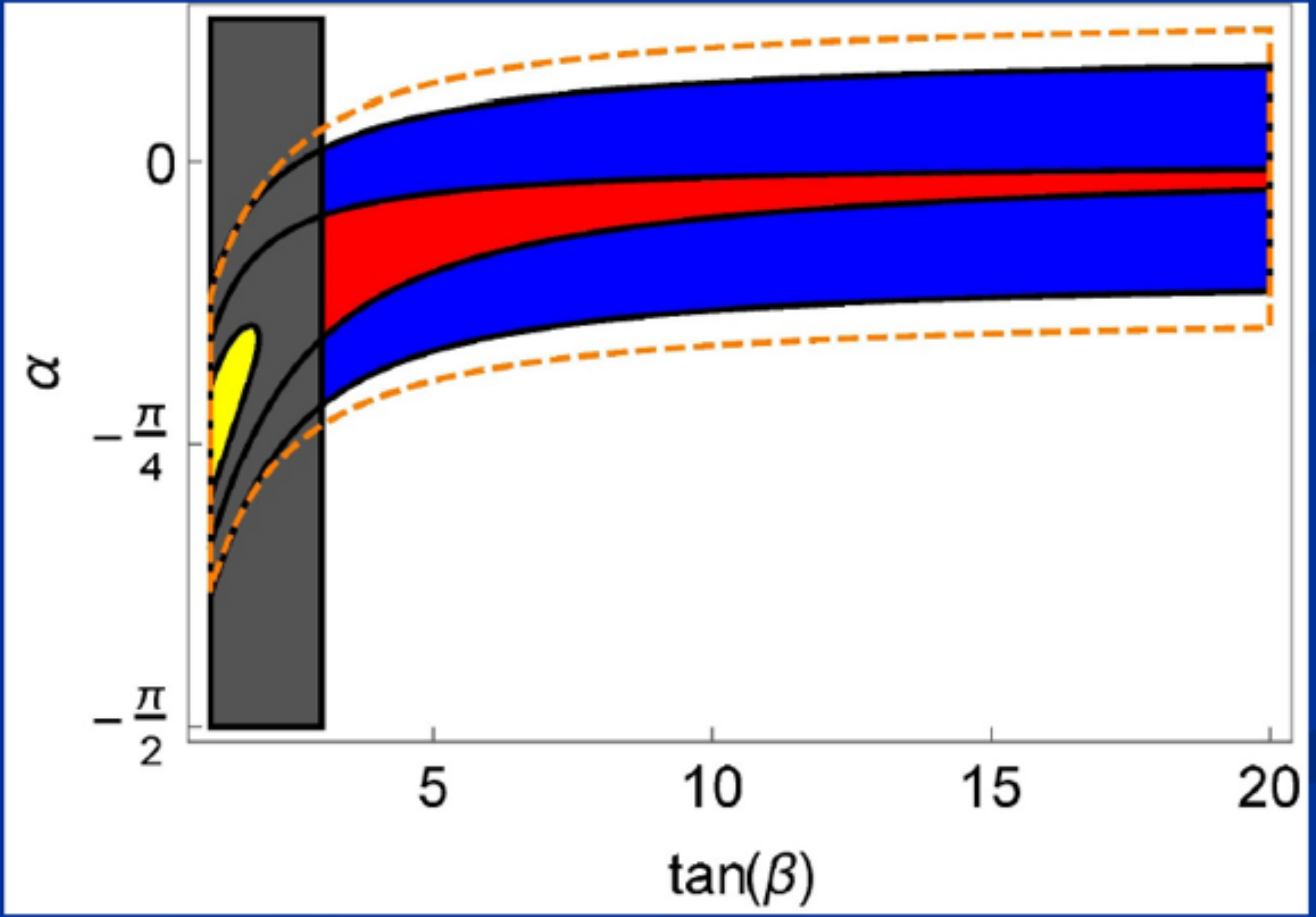
$$R_{\epsilon_K} = \frac{\epsilon_K}{\epsilon_K^{SM}}$$



ΔF=2: Higgs contributions



$m_H = 300\ \mathrm{GeV}, \quad C_9^{\mu\mu} = -1.3$

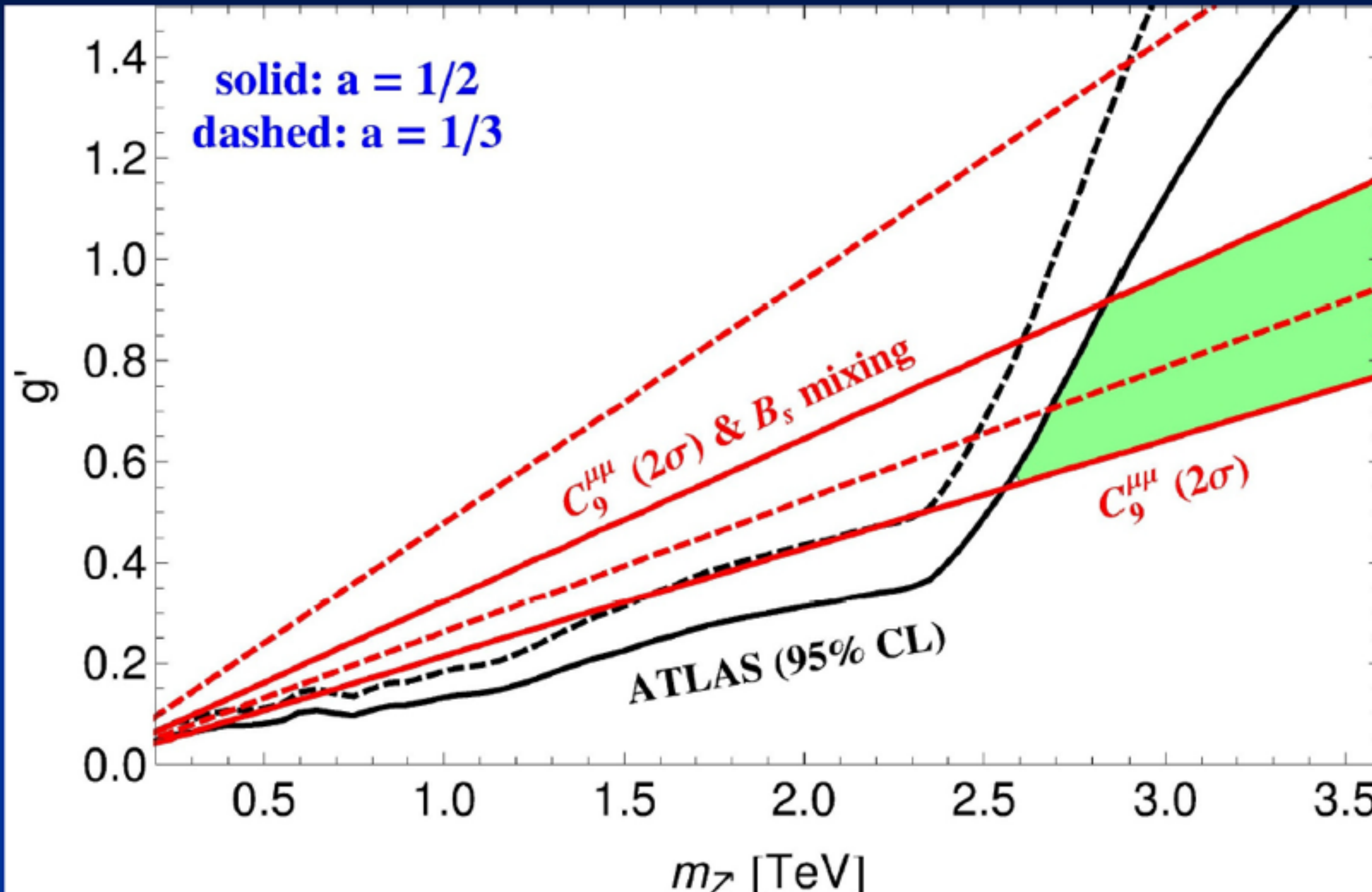


$m_A = 350\ \mathrm{GeV}$

$m_A = 300\ \mathrm{GeV}$

$m_A = 250\ \mathrm{GeV}$

LHC limits



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

3HDM

- Same effect in

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

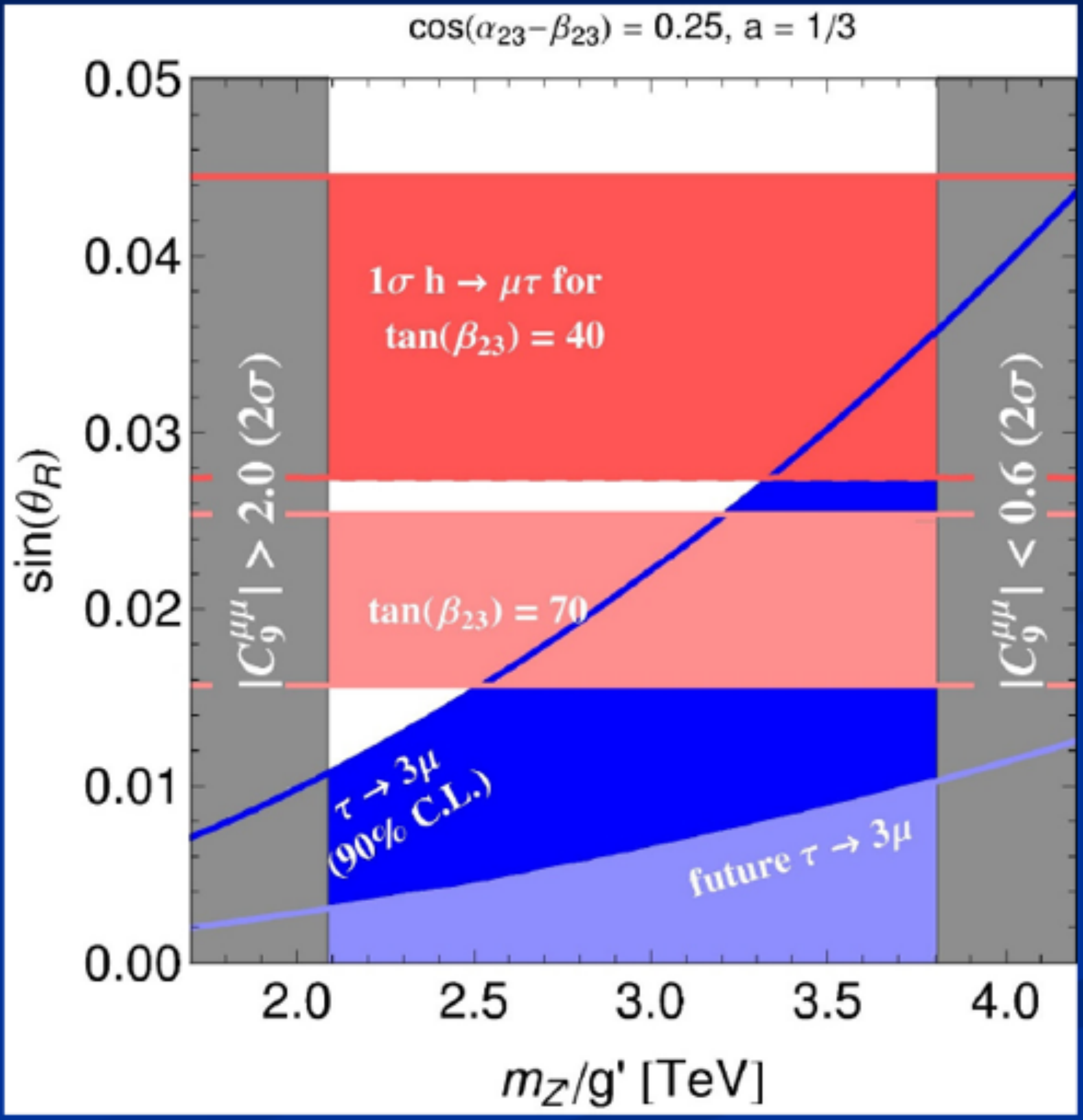
$h \to \mu\tau$

provided that the mixing among the doublets is small

excluded

allowed by $h \to \tau\mu$

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



Conclusions

- Flavour and LHC anomalies (?) useful to discuss some possible interesting NP scenario