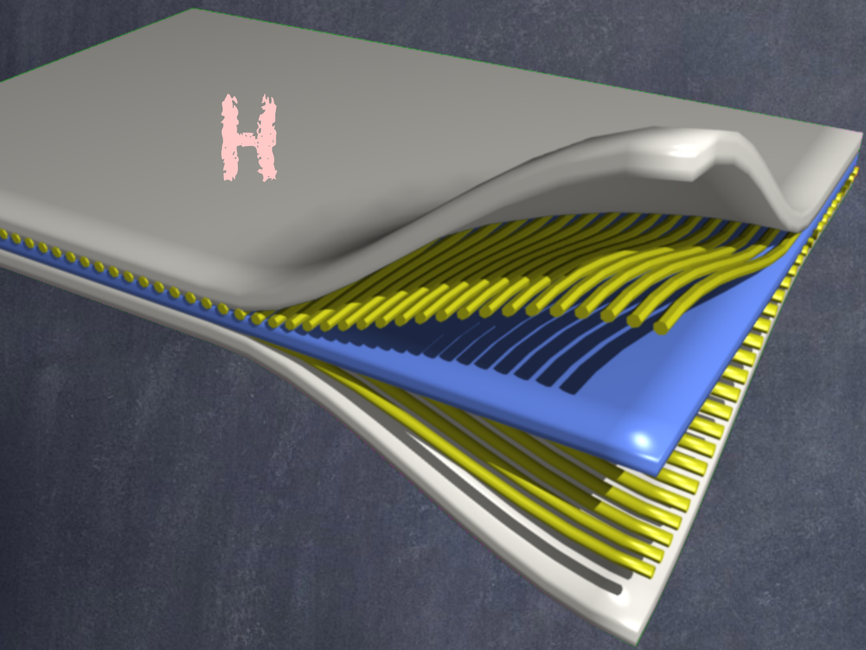
On naturalness of muon anomalies in strongly coupled theories

Giacomo Cacciapaglia
IP2I Lyon, France
(w. F.Sannino and C.Cot)

Portorož 2021

September 23, 2021

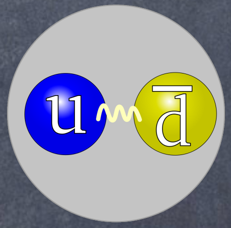
Why compositeness?



- A scalar field may be made of more fundamental fields
- We have seen this in Nature: low-energy QCD!
- Symmetries can be broken dynamically without generating hierarchies of scales!
- Very simple models can be built. (With caveats...)

Composite Higgs models 101

- Symmetry broken by a condensate (of TC-fermions)
- Higgs and longitudinal Z/W emerge as mesons (pions)



Scales:

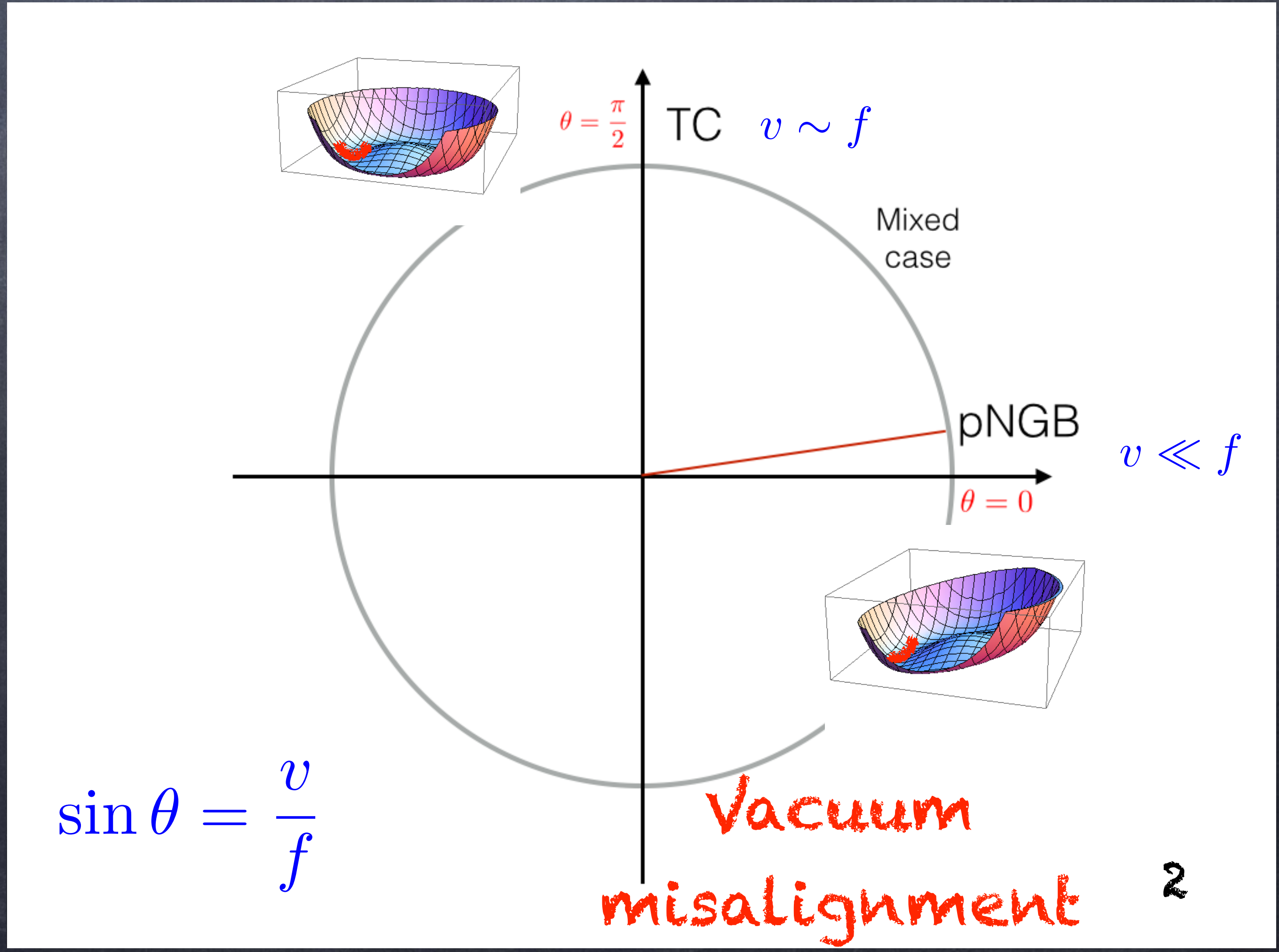
f : Higgs decay constant

v : EW scale

$m_\rho \sim 4\pi f$

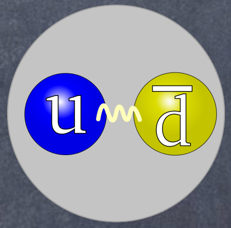
EWPTs + Higgs coupl. limit:

$$f \gtrsim 4v \sim 1\ \mathrm{TeV}$$



Composite Higgs models 101

- Symmetry broken by a condensate (of TC-fermions)
- Higgs and longitudinal Z/W emerge as mesons (pions)

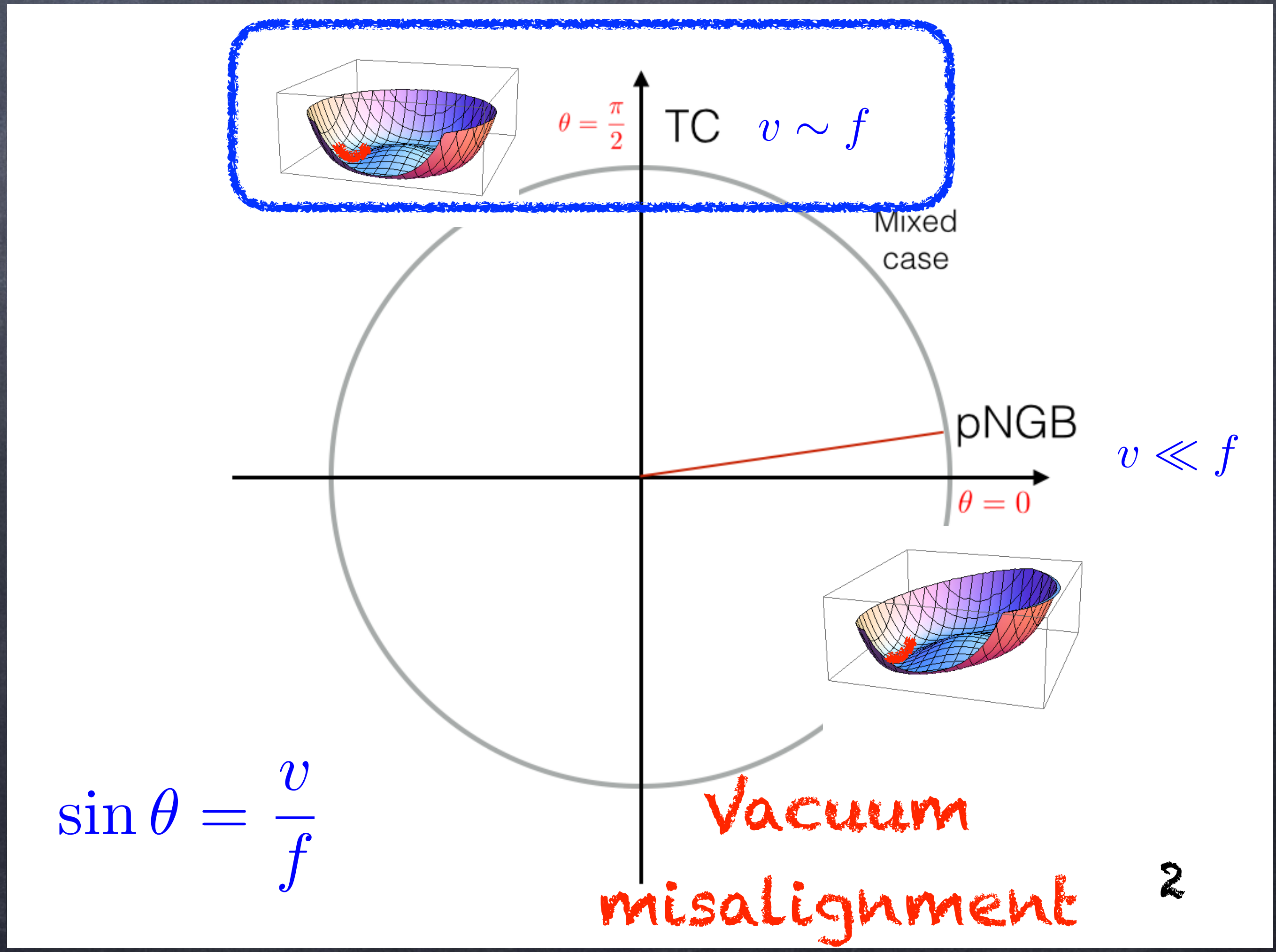


In the TC limit:

$$f = v$$

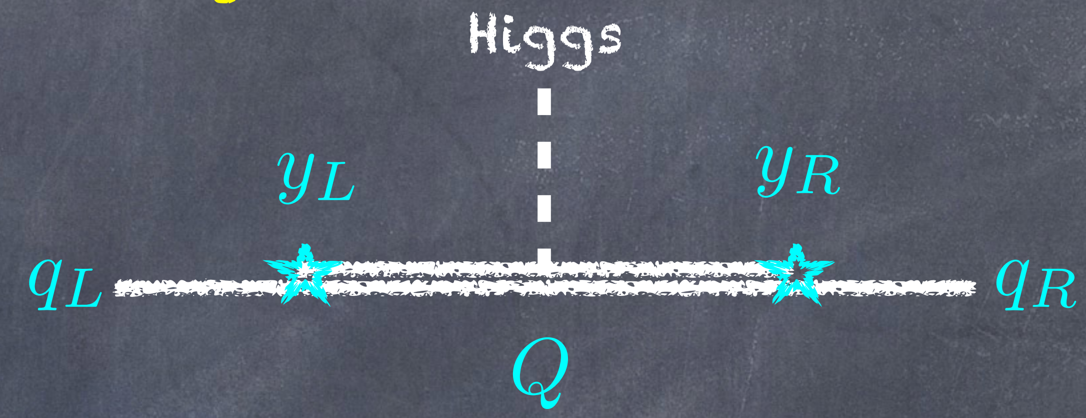
The Higgs is a light scalar resonance (dilaton?)

$$m_\rho \sim 4\pi f \sim 2 \text{ TeV}$$



The fermion partial compositeness paradigm

$$f(y_L\, q_L Q_L + y_R\, q_R Q_R)$$



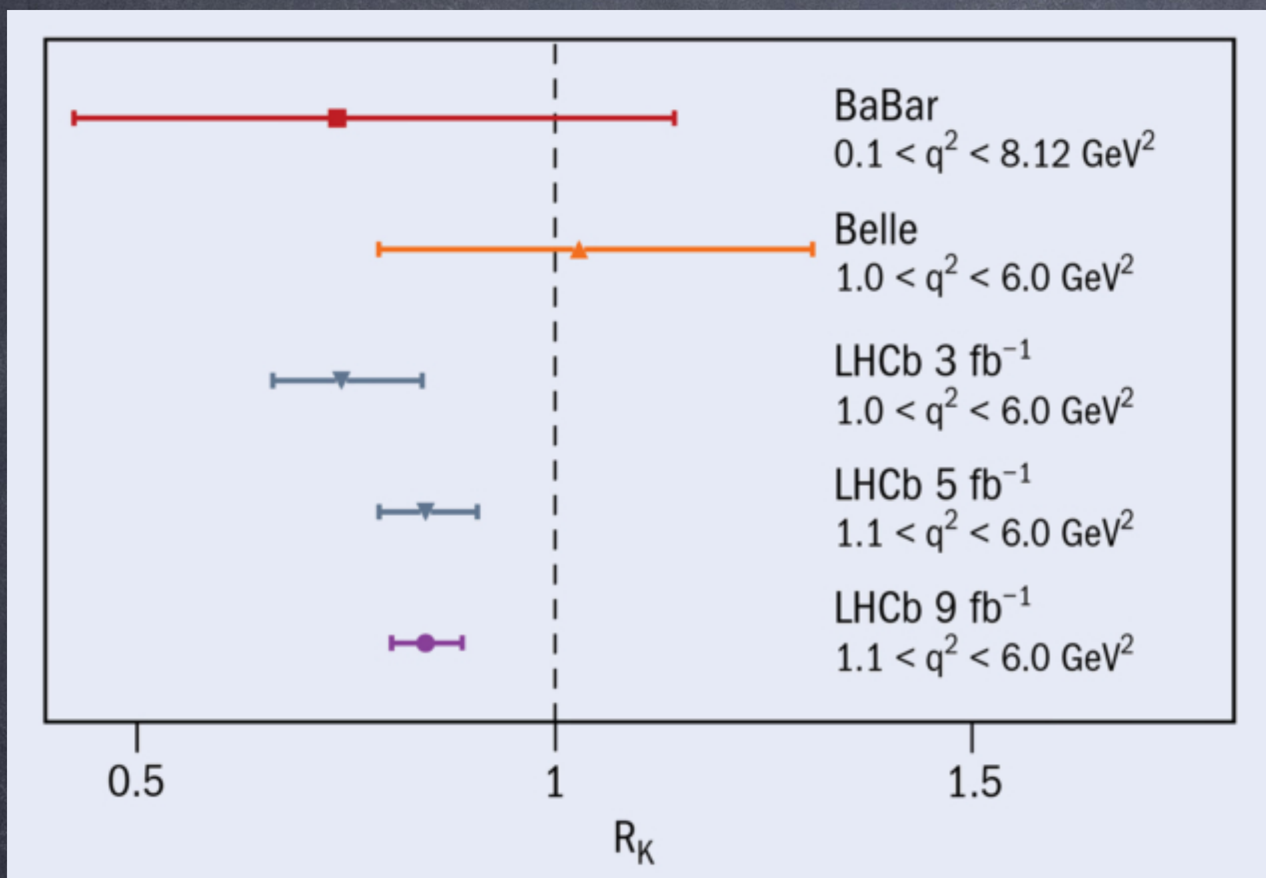
$$m_q \sim \frac{y_L y_R f^2}{M_Q^2} f \sin\theta$$

$$M_Q \sim f \Rightarrow y_L, y_R \sim 1$$

Top can cancel top loop, PUVC

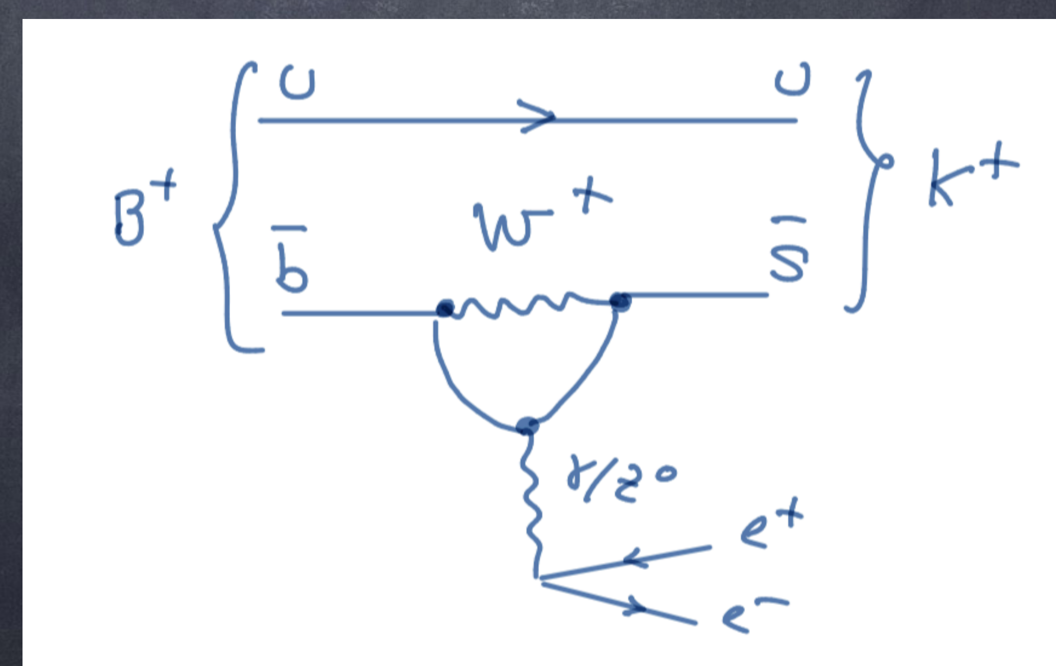
$$M_Q \sim 4\pi f \Rightarrow y_L, y_R \sim 4\pi$$

R_K (and R_{K*})



$$R_K = \frac{\mathrm{BR}\,(B^+ \to K^+\mu^+\mu^-)}{\mathrm{BR}\,(B^+ \to K^+e^+e^-)} = 0.846^{+0.044}_{-0.041}$$

$$R_K \simeq 1 + 2\,\frac{\mathrm{Re}\, C^{BSM}_{b_{L+R}\,(\mu-e)_L}}{C^{SM}_{b_L \mu_L}}$$



This deviation signals violation of lepton universality!

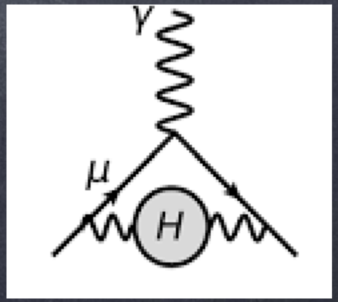
Muon g-2 anomaly

$$\Delta a_\mu = \frac{g_\mu - 2}{2} = \Delta a_\mu|_{QED} + \Delta a_\mu|_{EW} + \Delta a_\mu|_{QCD} + \Delta a_\mu|_{BSM}$$

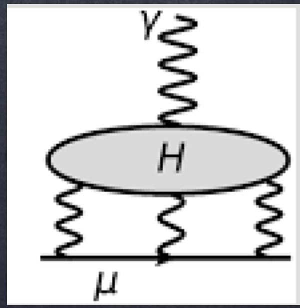
$116584718.9(1) \times 10^{-11}$ 0.001 ppm

$153.6(1.0) \times 10^{-11}$ 0.01 ppm

$6845(40) \times 10^{-11}$ 0.37 ppm

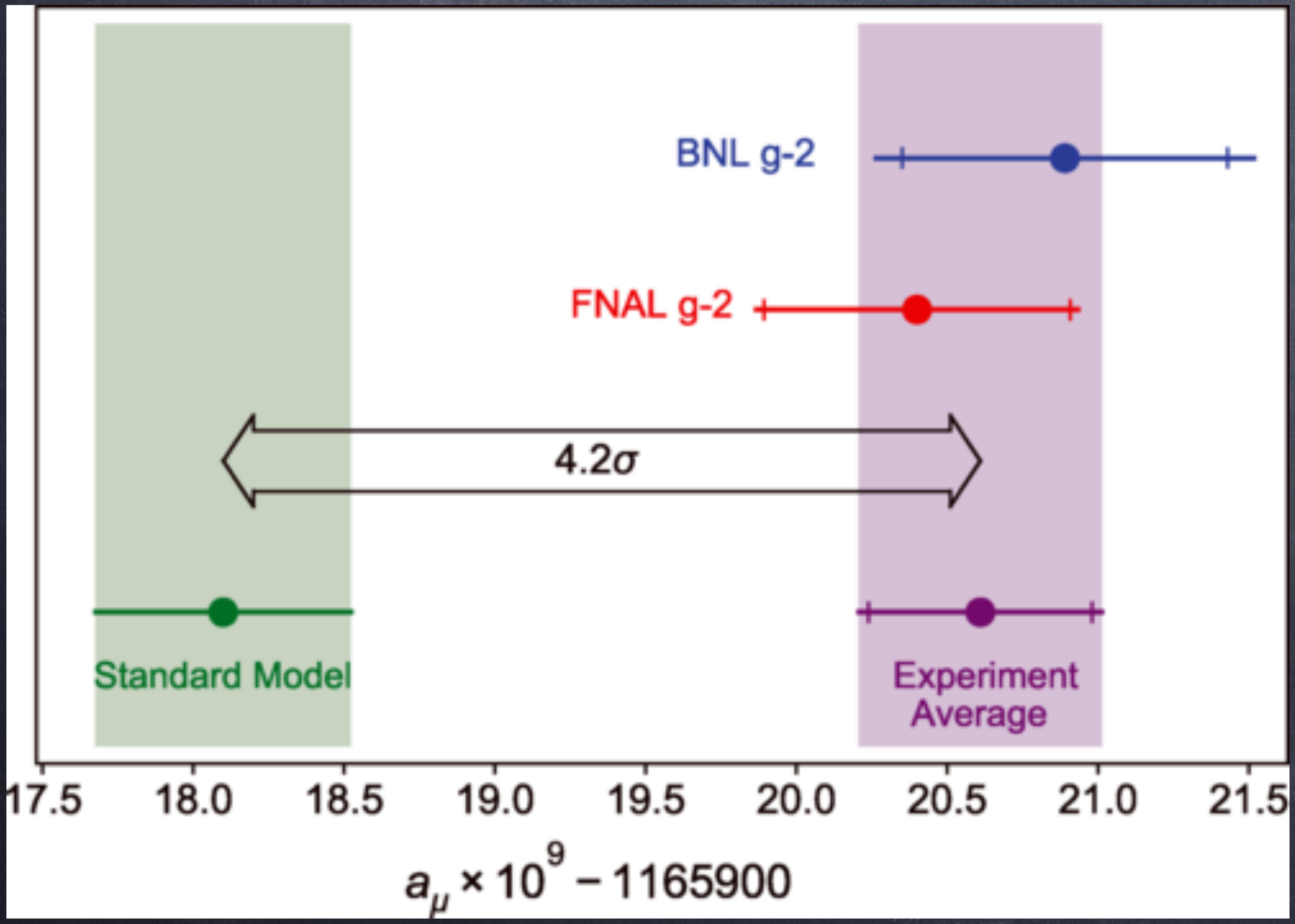


$92(18) \times 10^{-11}$ 0.15 ppm



Muon g-2 anomaly

$$\Delta a_\mu = \frac{g_\mu - 2}{2} = \Delta a_\mu|_{QED} + \Delta a_\mu|_{EW} + \Delta a_\mu|_{QCD} + \Delta a_\mu|_{BSM}$$



$$\Delta a_\mu|_{BSM} = 251(59) \times 10^{-11}$$

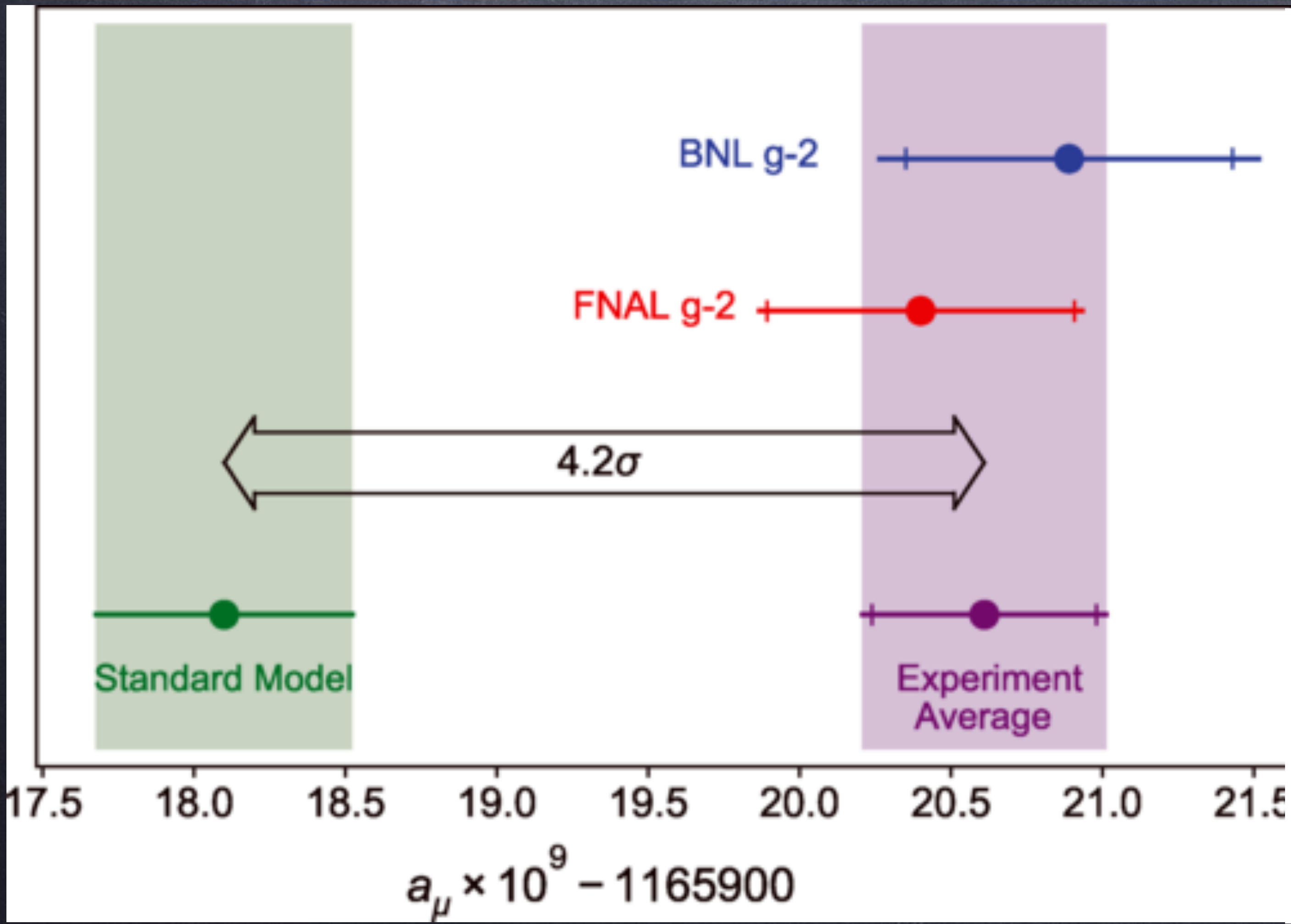
$$\Delta a_\mu|_{BSM} \approx \frac{m_\mu^2}{\Lambda^2}$$

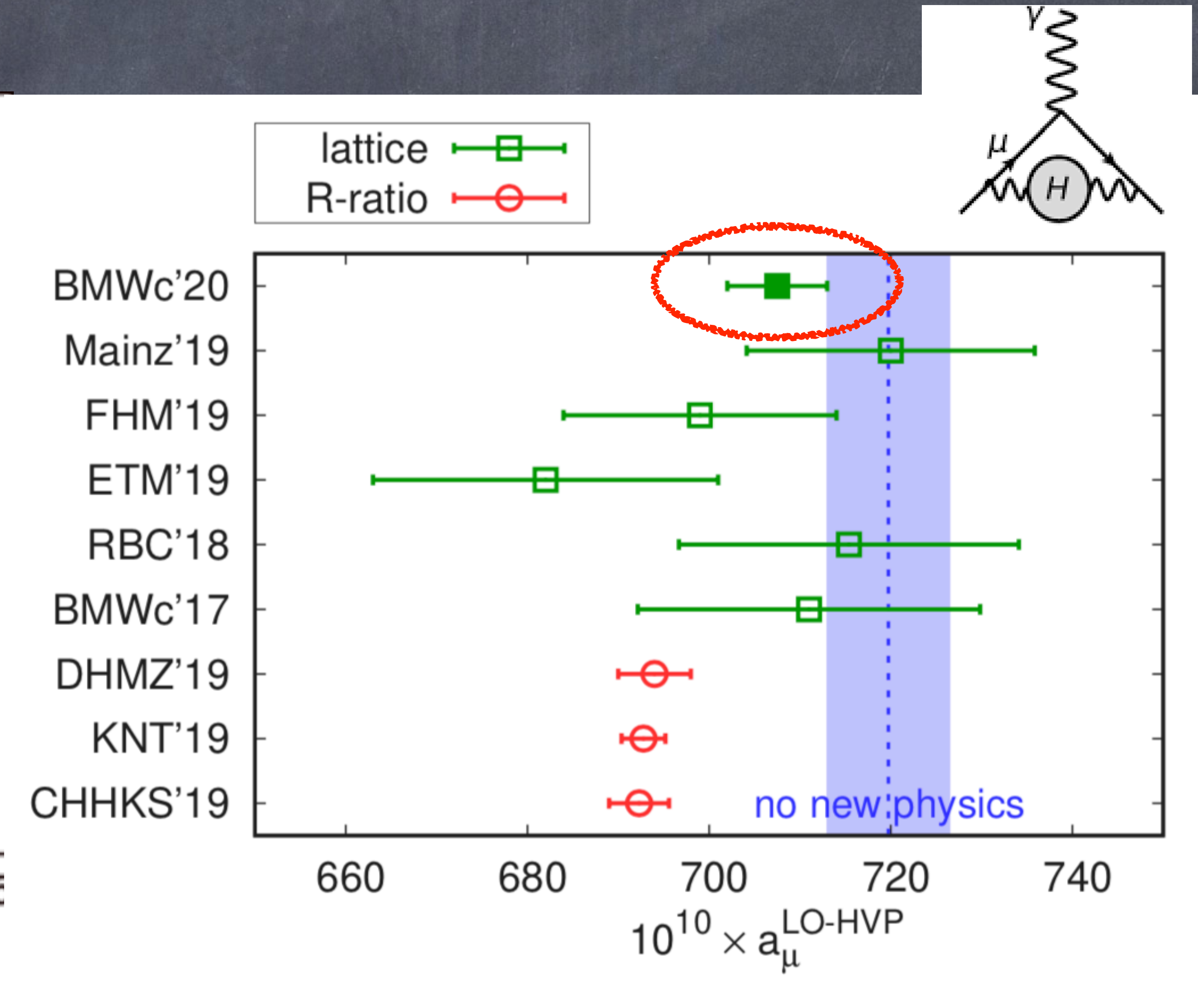
$$\Lambda \approx 2 \text{ TeV} \approx 4\pi v$$

Anomaly point to the most natural scale of Technicolor! (compositeness at the EW scale)

Muon g-2 anomaly

$$\Delta a_\mu = \frac{g_\mu - 2}{2} = \Delta a_\mu|_{QED} + \Delta a_\mu|_{EW} + \Delta a_\mu|_{QCD} + \Delta a_\mu|_{BSM}$$





New lattice results reduce tension: stay tuned!

How to compare different regimes?

G.C., C.Cot, F.Sannino 2104.08818

- We want to compare composite models to perturbative ones.
- To compare pears with pears, we define a template model, interpolating the two regimes.
- Partial compositeness <=> Yukawa model

An effective model

$$-\mathcal{L}_{\rm NP} = y_L^{ij}\, L^i \mathcal{F}_L (\mathcal{S}_E^j)^* + y_E^{ij}\, (E^i)^c \mathcal{F}_N^c \mathcal{S}_E^j + y_Q^{ij}\, Q^i \mathcal{F}_L (\mathcal{S}_D^j)^* + y_U^{ij}\, (U^i)^c \mathcal{F}_E^c \mathcal{S}_D^j + y_D^{ij}\, (D^i)^c \mathcal{F}_N^c \mathcal{S}_D^j + \sqrt{2}\kappa (\mathcal{F}_L \mathcal{F}_N^c + \mathcal{F}_E \mathcal{F}_L^c)\phi_H + \text{h.c.}$$

	$\mathcal{G}_{\rm TC}$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
$\mathcal{F}_L$	$\mathbf{F}$	1	2	Y
$\mathcal{F}_N^c$	$\bar{\mathbf{F}}$	1	1	$-Y-1/2$
$\mathcal{F}_E^c$	$\bar{\mathbf{F}}$	1	1	$-Y+1/2$
$\mathcal{S}_E^j$	$\mathbf{F}$	1	1	$Y-1/2$
$\mathcal{S}_D^j$	$\mathbf{F}$	3	1	$Y+1/6$

Table 1. *Quantum numbers of the new fermions $\mathcal{F}$ and scalars $\mathcal{S}$ in the model. $\mathcal{G}_{\rm TC}$ can be considered either gauged, as in composite scenarios, or global in a renormalisable model of flavour.*

The hypercharge Y can be tuned to reproduce various models.

Weyl spinors in the table!

An effective model

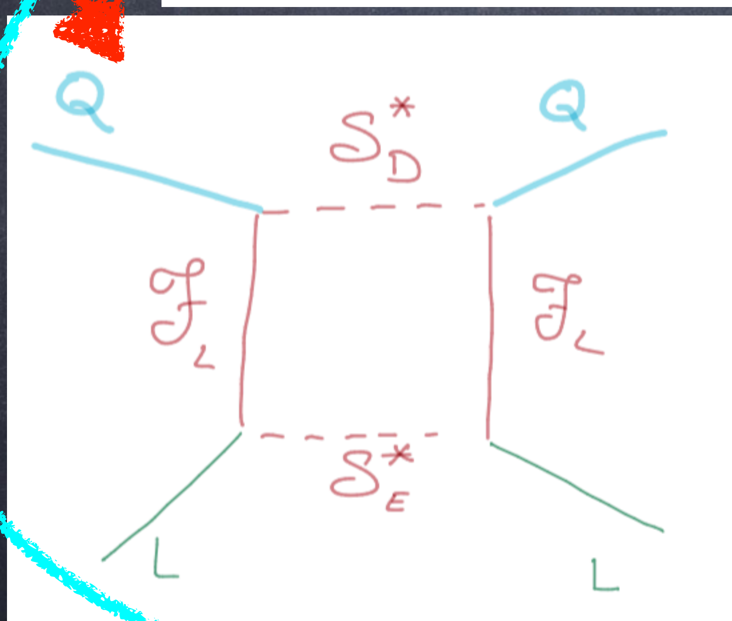
$$-\mathcal{L}_{\rm NP} = y_L^{ij}\, L^i \mathcal{F}_L (\mathcal{S}_E^j)^* + y_E^{ij}\, (E^i)^c \mathcal{F}_N^c \mathcal{S}_E^j + y_Q^{ij}\, Q^i \mathcal{F}_L (\mathcal{S}_D^j)^* + y_U^{ij}\, (U^i)^c \mathcal{F}_E^c \mathcal{S}_D^j + y_D^{ij}\, (D^i)^c \mathcal{F}_N^c \mathcal{S}_D^j + \sqrt{2}\kappa (\mathcal{F}_L \mathcal{F}_N^c + \mathcal{F}_E \mathcal{F}_L^c)\phi_H + \text{h.c.}$$

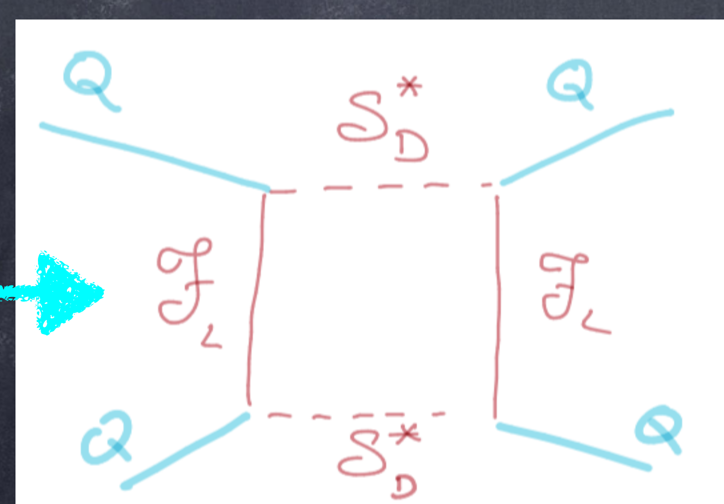
- Elementary weakly coupled fermions and scalars.
- The Higgs is composite, while the scalars S are not (fundamental partial compositeness)
- The Higgs is composite while S are composite operators (fermionic partial compositeness)

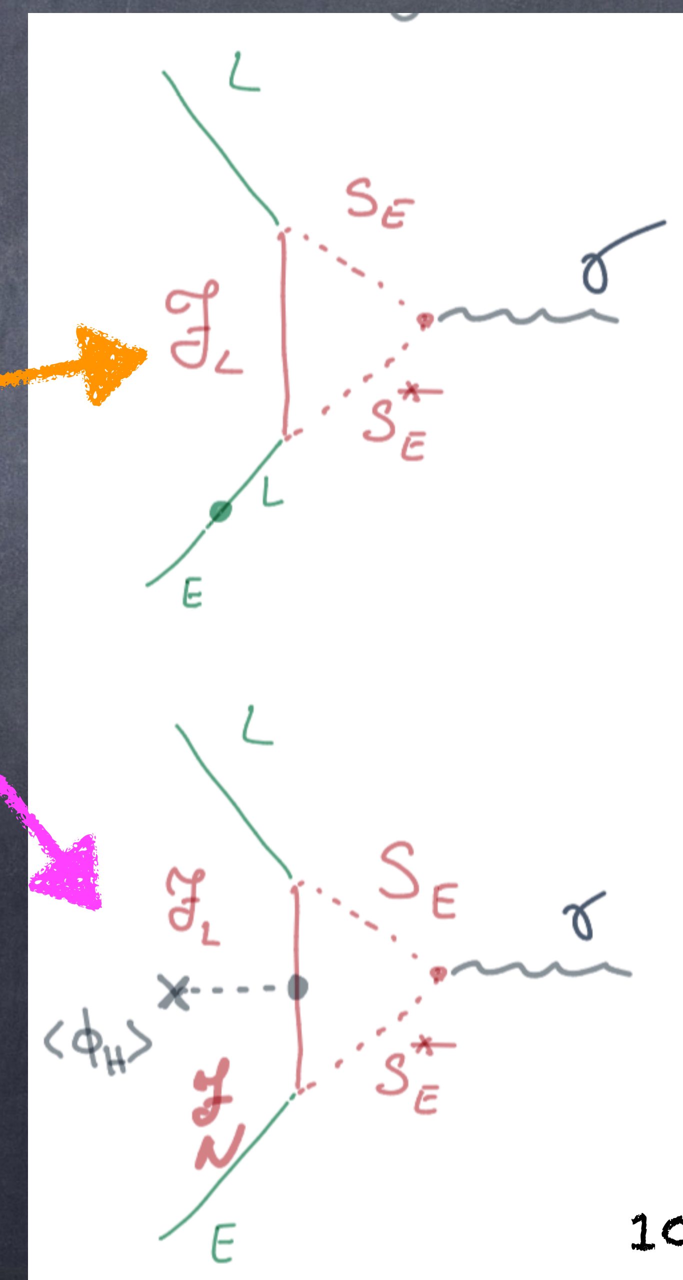
An effective model

Coefficient	Perturbative one-loop result	Non-perturbative NDA
$c_{b_L\mu_L}$	$N_{\rm TC}\frac{(y_L y_L^\dagger)_{\mu\mu}(y_Q y_Q^\dagger)_{bs}}{(4\pi)^2 M_{\mathcal{F}}^2}\frac{1}{4}F(x,y)$	$\frac{(y_L y_L^\dagger)_{\mu\mu}(y_Q y_Q^\dagger)_{bs}}{g_{\rm TC}^2\Lambda_{\rm TC}^2}$
$C_{B\bar{B}}$	$N_{\rm TC}\frac{(y_Q y_Q^\dagger)_{bs}^2}{(4\pi)^2 M_{\mathcal{F}}^2}\frac{1}{8}F(x,x)$	$\frac{(y_Q y_Q^\dagger)_{bs}^2}{g_{\rm TC}^2\Lambda_{\rm TC}^2}$
Δa_μ	$N_{\rm TC}\frac{m_\mu (y_L y_E^\dagger)_{\mu\mu}\kappa v_{\rm SM}}{(4\pi)^2 M_{\mathcal{F}}^2}\left[2q_{S_E}F_{LR}(y)+2q_{\mathcal{F}}G_{LR}(y)\right]+$ $N_{\rm TC}\frac{m_\mu^2 (y_L y_L^\dagger)_{\mu\mu}}{(4\pi)^2 M_{\mathcal{F}}^2}\left[2q_{S_E}F_7(y)+2q_{\mathcal{F}}\tilde{F}_7(y)\right]$	$\frac{m_\mu^2}{\Lambda_{\rm TC}^2}\left(1+\frac{(y_L y_L^\dagger)_{\mu\mu}}{g_{\rm TC}^2}\right)$

$$g_{\rm TC} = \frac{4\pi}{\sqrt{N_{\rm TC}}}$$



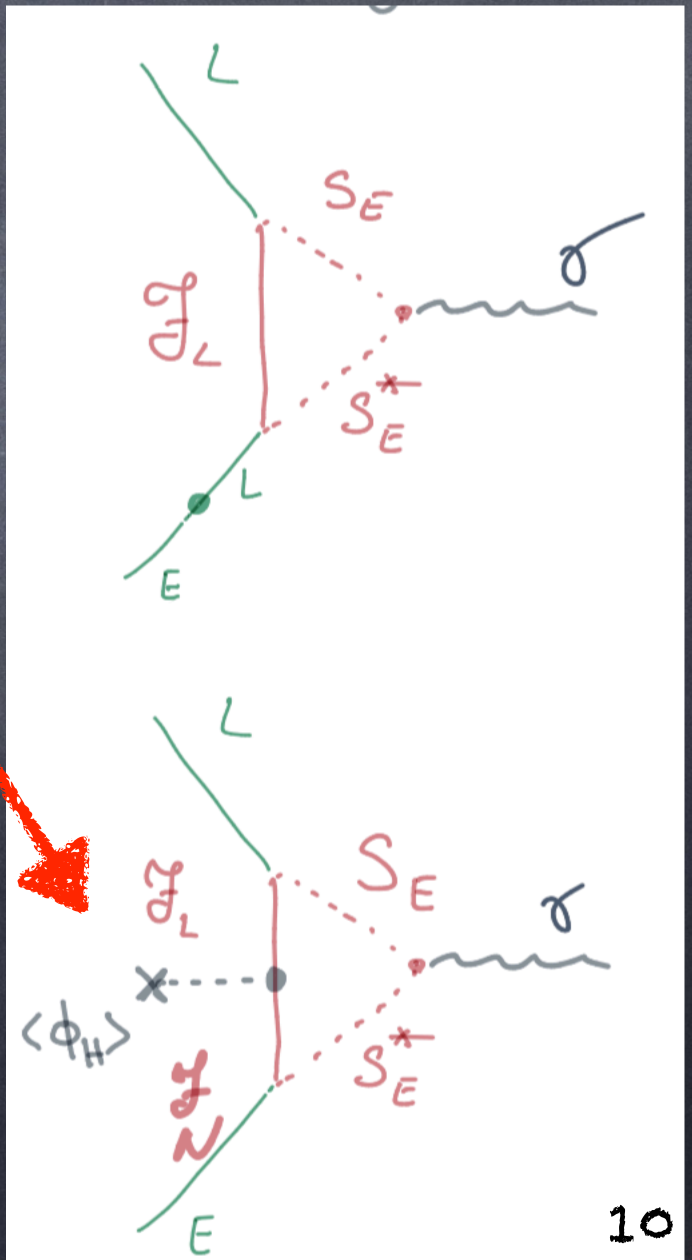




An effective model

Coefficient	Perturbative one-loop result	Non-perturbative NDA
$c_{b_L\mu_L}$	$N_{\rm TC}\dfrac{(y_L y_L^\dagger)_{\mu\mu}(y_Q y_Q^\dagger)_{bs}}{(4\pi)^2 M_{\mathcal{F}}^2}\dfrac{1}{4}F(x,y)$	$\dfrac{(y_L y_L^\dagger)_{\mu\mu}(y_Q y_Q^\dagger)_{bs}}{g_{\rm TC}^2\Lambda_{\rm TC}^2}$
$C_{B\bar{B}}$	$N_{\rm TC}\dfrac{(y_Q y_Q^\dagger)_{bs}^2}{(4\pi)^2 M_{\mathcal{F}}^2}\dfrac{1}{8}F(x,x)$	$\dfrac{(y_Q y_Q^\dagger)_{bs}^2}{g_{\rm TC}^2\Lambda_{\rm TC}^2}$
Δa_μ	$N_{\rm TC}\dfrac{m_\mu(y_L y_E^\dagger)_{\mu\mu}\kappa v_{\rm SM}}{(4\pi)^2 M_{\mathcal{F}}^2}\left[2q_{S_E}F_{LR}(y)+2q_{\mathcal{F}}G_{LR}(y)\right]+$ $N_{\rm TC}\dfrac{m_\mu^2(y_L y_L^\dagger)_{\mu\mu}}{(4\pi)^2 M_{\mathcal{F}}^2}\left[2q_{S_E}F_7(y)+2q_{\mathcal{F}}\tilde{F}_7(y)\right]$	$\dfrac{m_\mu^2}{\Lambda_{\rm TC}^2}\left(1+\dfrac{(y_L y_L^\dagger)_{\mu\mu}}{g_{\rm TC}^2}\right)$

$$g_{\rm TC}=\frac{4\pi}{\sqrt{N_{\rm TC}}}$$



It's the mass insertion diagram that generated the leading contribution to g-2

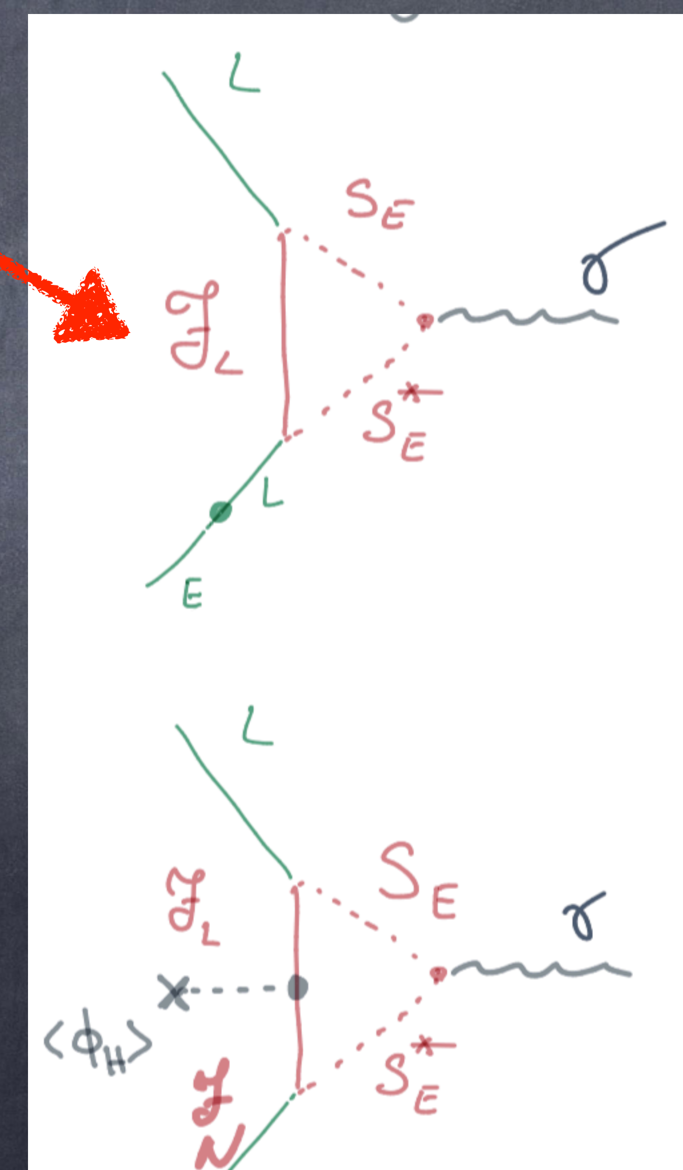
$$m_\mu \sim N_{\rm TC}\frac{(y_L y_E^\dagger)_{\mu\mu}\kappa v_{\rm SM}}{(4\pi)^2}$$

To maximise the effect, we assume that the muon mass is generated by the corresponding loop.

An effective model

Coefficient	Perturbative one-loop result	Non-perturbative NDA
$c_{b_L \mu_L}$	$N_{\rm TC}\frac{(y_L y_L^\dagger)_{\mu\mu}(y_Q y_Q^\dagger)_{bs}}{(4\pi)^2 M_{\mathcal{F}}^2}\frac{1}{4}F(x,y)$	$\frac{(y_L y_L^\dagger)_{\mu\mu}(y_Q y_Q^\dagger)_{bs}}{g_{\rm TC}^2 \Lambda_{\rm TC}^2}$
$C_{B\bar{B}}$	$N_{\rm TC}\frac{(y_Q y_Q^\dagger)_{bs}^2}{(4\pi)^2 M_{\mathcal{F}}^2}\frac{1}{8}F(x,x)$	$\frac{(y_Q y_Q^\dagger)_{bs}^2}{g_{\rm TC}^2 \Lambda_{\rm TC}^2}$
Δa_μ	$N_{\rm TC}\frac{m_\mu (y_L y_E^\dagger)_{\mu\mu}\kappa v_{\rm SM}}{(4\pi)^2 M_{\mathcal{F}}^2}\left[2q_{S_E}F_{LR}(y)+2q_{\mathcal{F}}G_{LR}(y)\right]+$ $N_{\rm TC}\frac{m_\mu^2 (y_L y_L^\dagger)_{\mu\mu}}{(4\pi)^2 M_{\mathcal{F}}^2}\left[2q_{S_E}F_7(y)+2q_{\mathcal{F}}\tilde{F}_7(y)\right]$	$\frac{m_\mu^2}{\Lambda_{\rm TC}^2}\left(1+\frac{(y_L y_L^\dagger)_{\mu\mu}}{g_{\rm TC}^2}\right)$

$$g_{\rm TC} = \frac{4\pi}{\sqrt{N_{\rm TC}}}$$



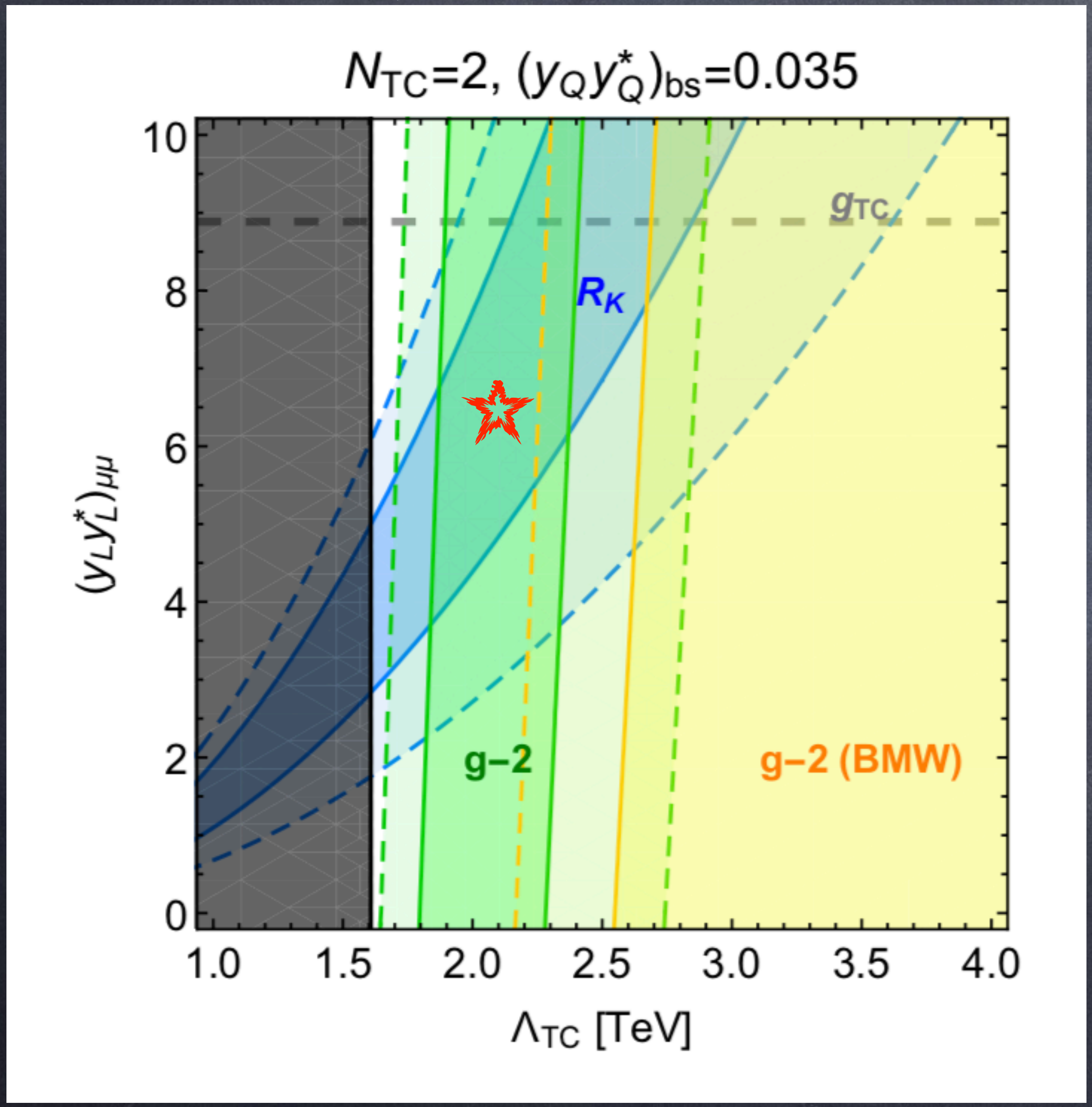
It's the mass insertion diagram that generated the leading contribution to g-2

$$m_\mu \sim N_{\rm TC}\frac{(y_L y_E^\dagger)_{\mu\mu}\kappa v_{\rm SM}}{(4\pi)^2}$$

To maximise the effect, we assume that the muon mass is generated by the corresponding loop.

There's something about Muons

Composite limit:



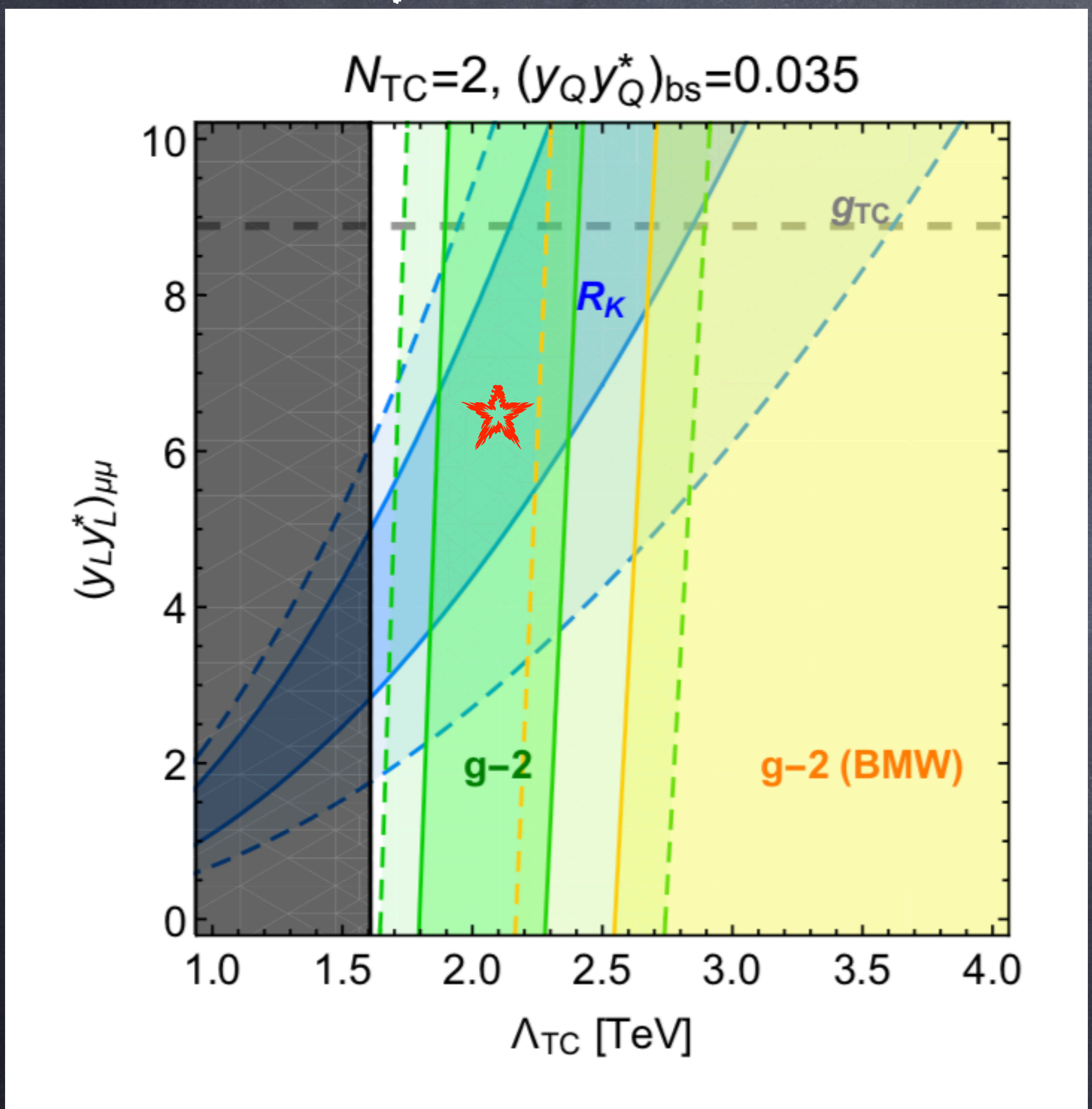
$$R_K = \frac{\mathrm{BR}\left(B^+ \to K^+\mu^+\mu^-\right)}{\mathrm{BR}\left(B^+ \to K^+e^+e^-\right)} = 0.846^{+0.044}_{-0.041}$$

- g-2 fixes the scale of new physics
- natural values for TC-like theories!
- RK requires large muon couplings (attainable in strong dynamics)

These anomalies will be further probed in the near future!

There's something about Muons

Composite limit:



$$R_K = \frac{\text{BR}(B^+ \to K^+\mu^+\mu^-)}{\text{BR}(B^+ \to K^+e^+e^-)} = 0.846^{+0.044}_{-0.041}$$

- Composite Goldstone Higgs models are disfavoured:

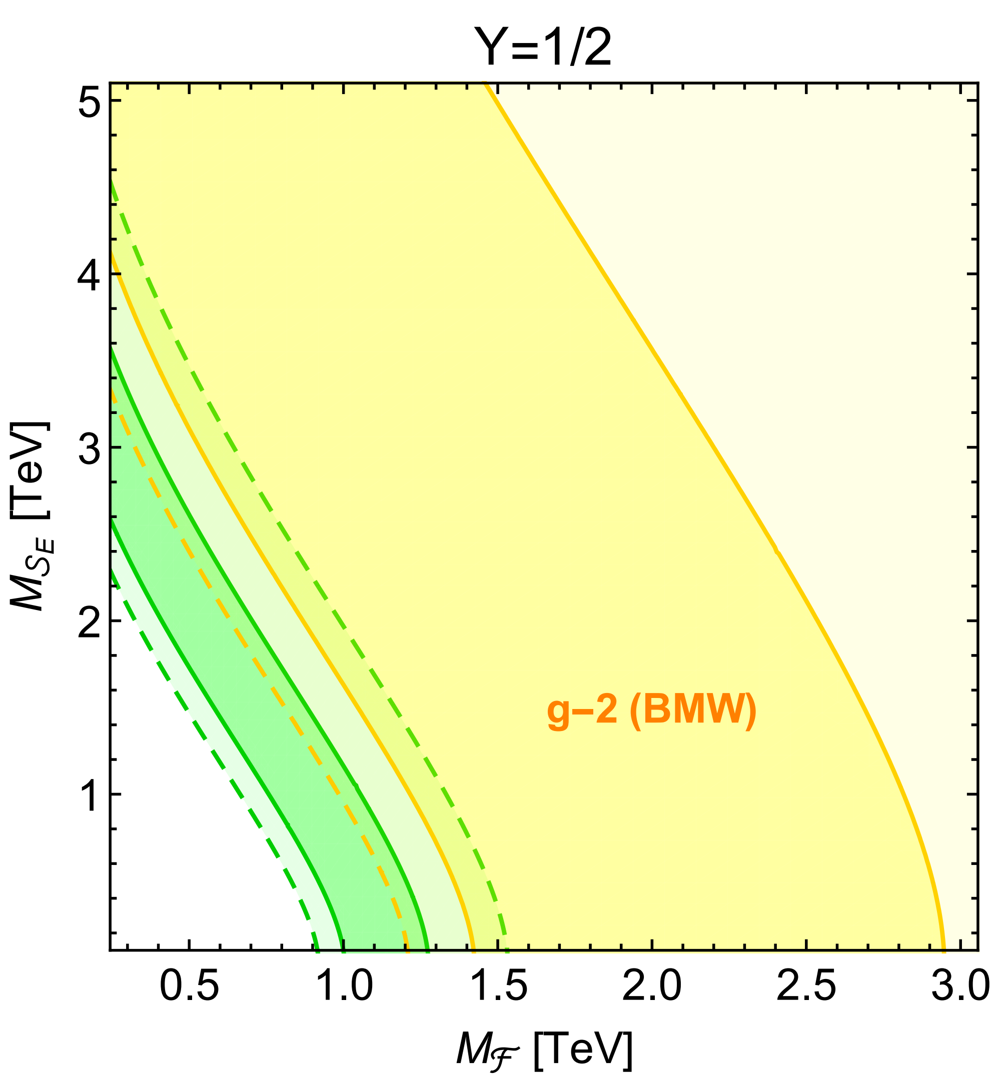
$$\Delta a_\mu(\text{CGH}) \approx \frac{g_*^2}{(4\pi)^2}\frac{m_\mu^2}{m_*^2} = \frac{v_{\text{SM}}^2}{f_{\text{CGH}}^2}\frac{m_\mu^2}{\Lambda_{\text{TC}}^2}$$

Further suppression by 1/10, typically.

There's something about Muons

Perturbative interpretation:

g-2 only depends on masses of F and S_E



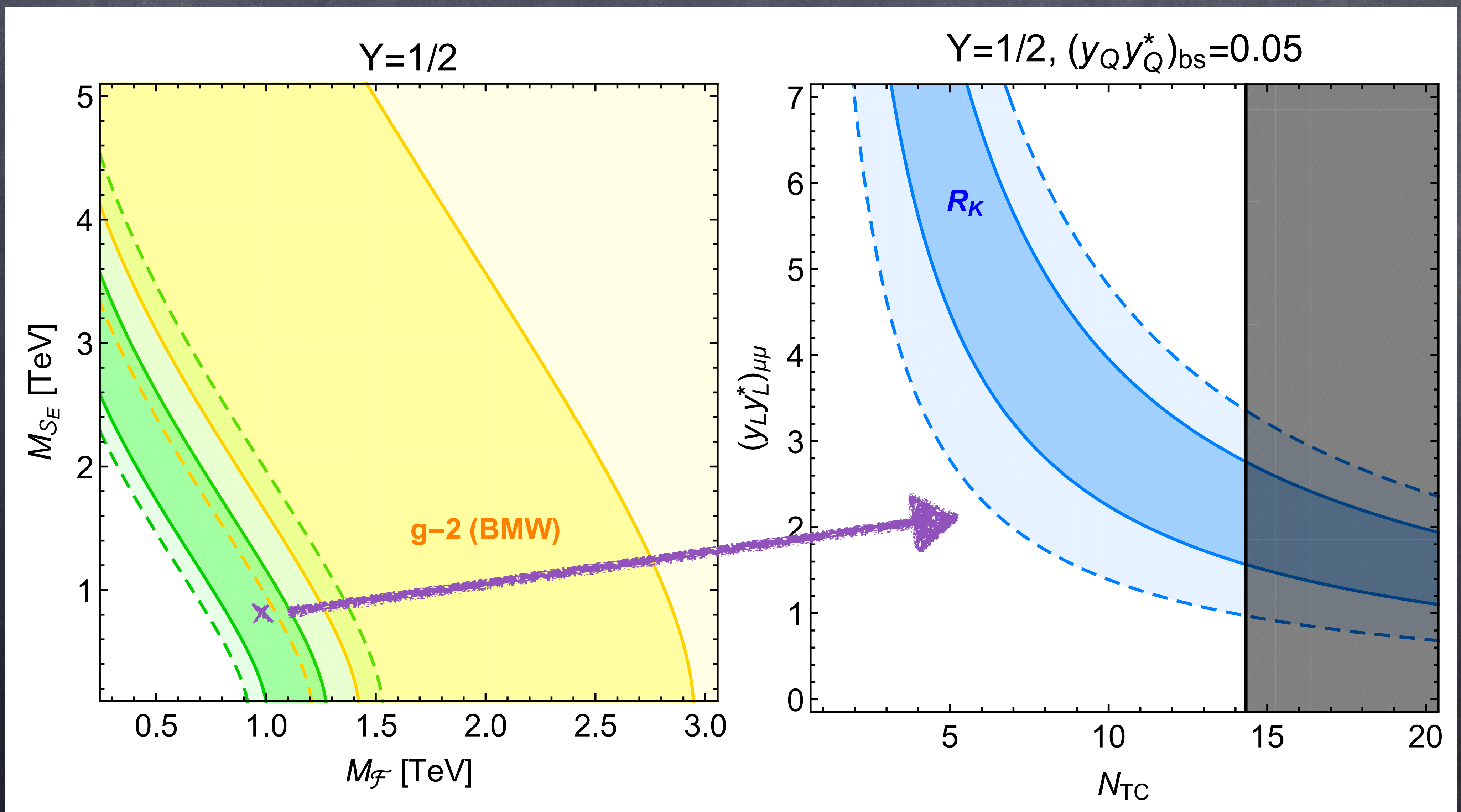
Y=1/2, $(y_Q y_Q^*)_{bs}$=0.05

Coefficient	Perturbative one-loop result
$c_{b_L \mu_L}$	$N_{\rm TC} \frac{(y_L y_L^\dagger)_{\mu\mu}(y_Q y_Q^\dagger)_{bs}}{(4\pi)^2 M_{\mathcal{F}}^2} \frac{1}{4} F(x,y)$
$C_{B\bar{B}}$	$N_{\rm TC} \frac{(y_Q y_Q^\dagger)_{bs}^2}{(4\pi)^2 M_{\mathcal{F}}^2} \frac{1}{8} F(x,x)$
Δa_μ	$N_{\rm TC} \frac{m_\mu (y_L y_E^\dagger)_{\mu\mu} \kappa v_{\rm SM}}{(4\pi)^2 M_{\mathcal{F}}^2} \left[2 q_{S_E} F_{LR}(y) + 2 q_{\mathcal{F}} G_{LR}(y)\right] +$
	$N_{\rm TC} \frac{m_\mu^2 (y_L y_L^\dagger)_{\mu\mu}}{(4\pi)^2 M_{\mathcal{F}}^2} \left[2 q_{S_E} F_7(y) + 2 q_{\mathcal{F}} \tilde{F}_7(y)\right]$

There's something about Muons

However,

RK requires large Yukawas and/or multiplicities



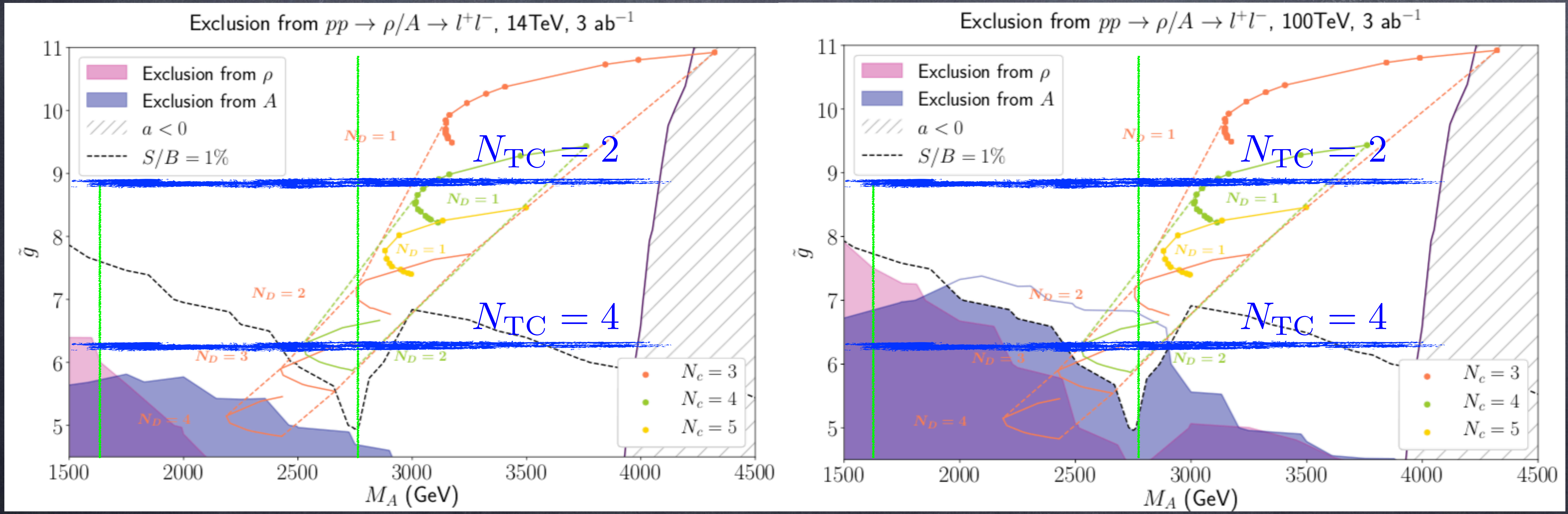
$M_{\mathcal{F}} = 1$ TeV, $M_{\mathcal{S}_E} = 0.9$ TeV and $M_{\mathcal{S}_D} = 1.5$ TeV

Conclusion

- Muon anomalies can be naturally explained by a technicolor-like theory.
- A complete scenario motivated by the muon anomalies can be constructed.
- The Higgs must be a light dilaton-like composite resonance.
- Low scale => testable at the LHC and future colliders.
- BSM lattice studied can point towards the correct underlying theory (model building)

Techni-rho bounds

A.Belyaev et al, 1910.10928



HL-LHC

FCC-hh