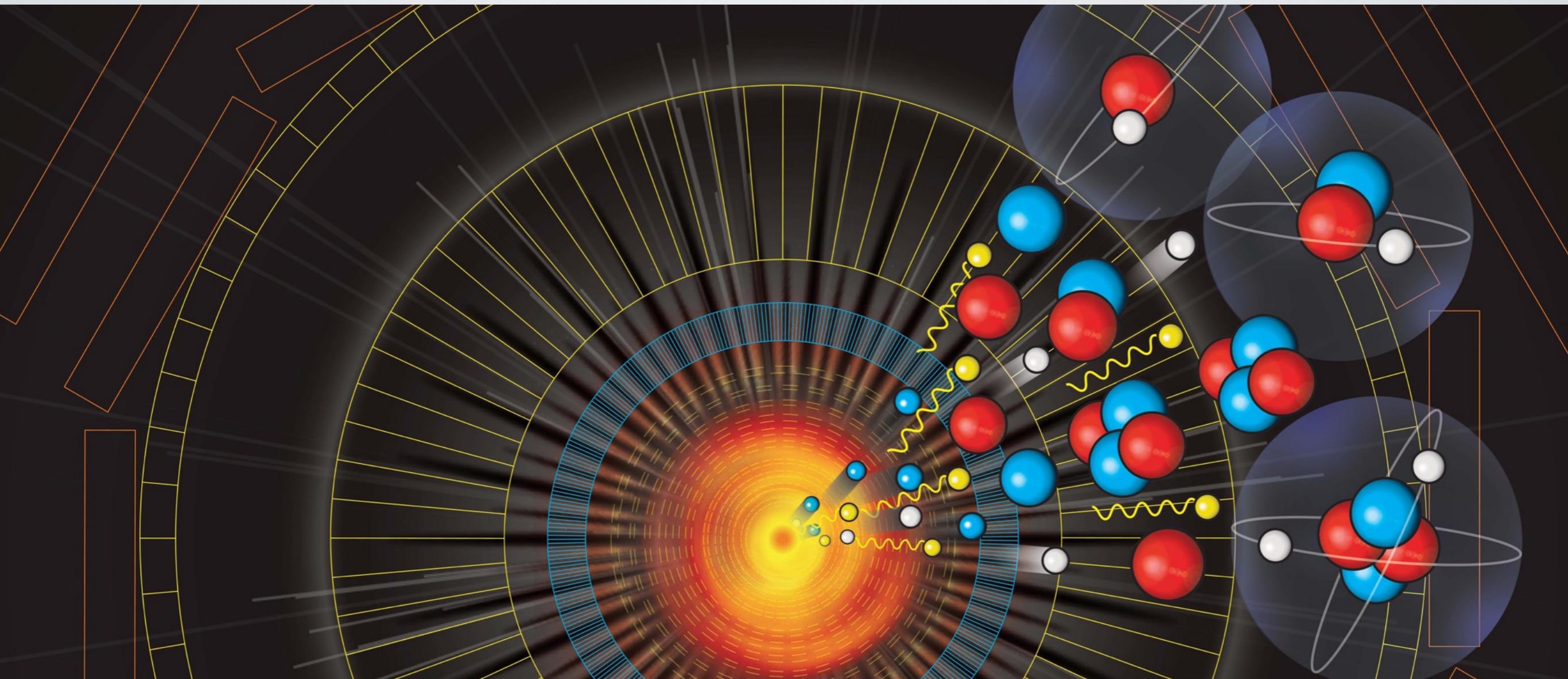


(Non) Standard Model Higgs

Francesco Sannino

2023



D-IAS

SDU

SSM
Scuola Superiore Meridionale



CP³ Origins

Standard model ~ 2023

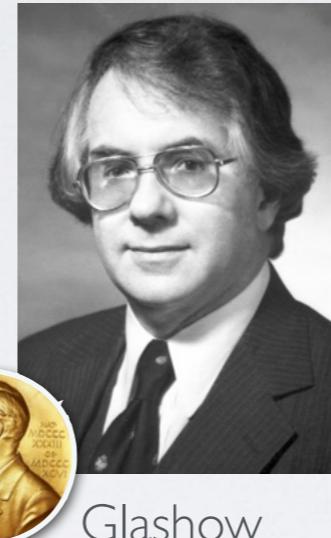
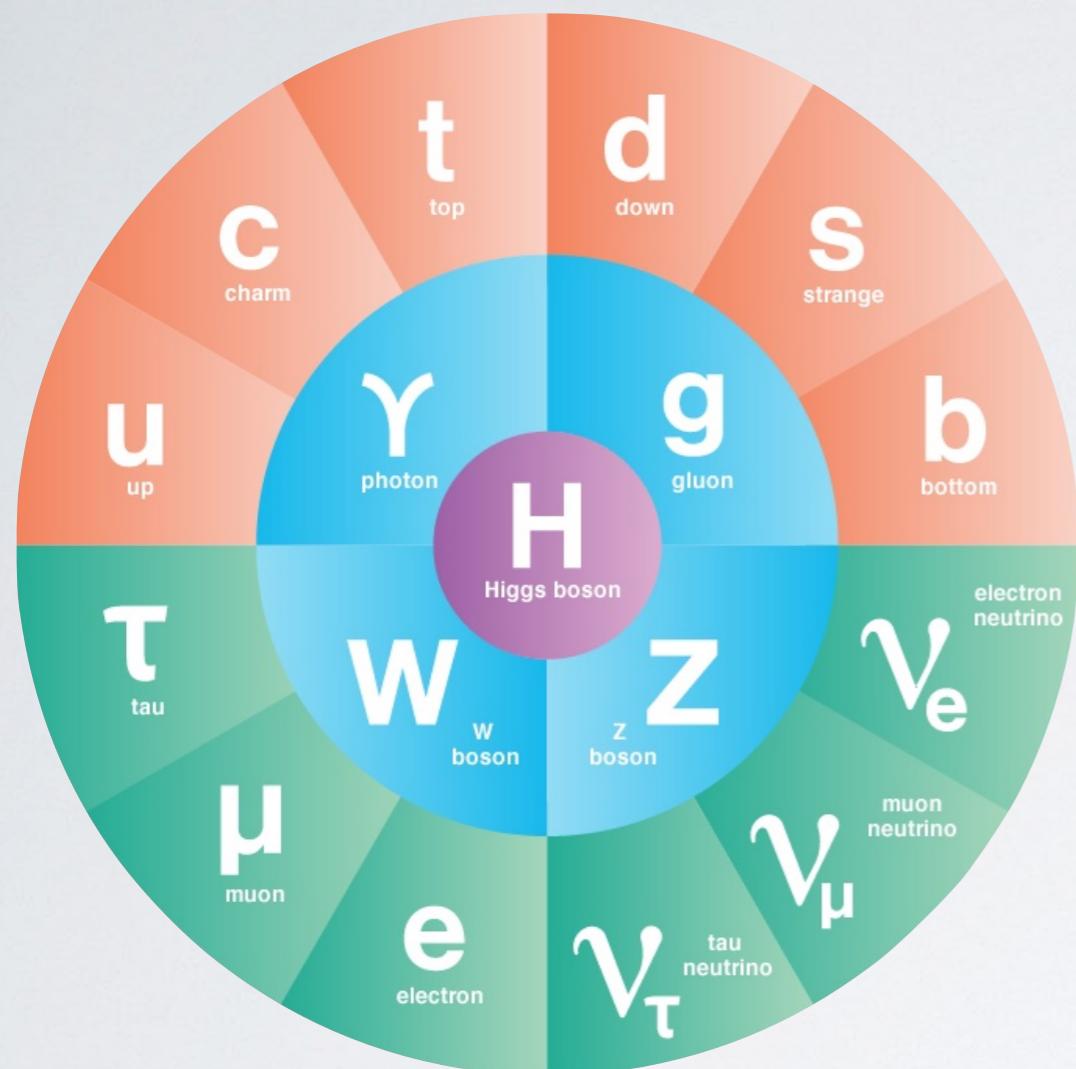
$$L = -\frac{1}{2}F^2 + i\bar{Q}\gamma_\mu D^\mu Q + y(\bar{Q}_L H Q_R + \text{h.c.}) \quad \text{Yukawa}$$

Gauge $\text{Tr} [D H^\dagger D H] - \lambda_u \text{Tr} [(H^\dagger H)^2] - \lambda_v \text{Tr} [(H^\dagger H)]^2$

Scalar selfinteractions

- Gauge structure established
- Yukawa structure to be determined
- Higgs (nature) self-coupling to be determined

Standard model, 1979, 2004, 2013



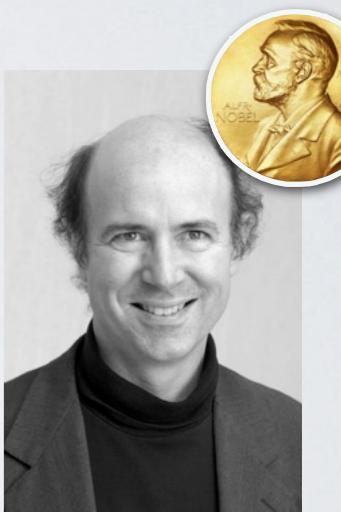
Glashow



Salam



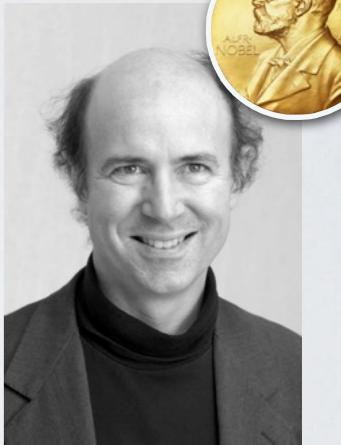
Weinberg



Gross



Politzer



Wilczek



Higgs



Englert



What's left of the anomalies

D'Alise, De Nardo, Di Luca, Fabiano, Frattulillo, Gaudino, Iacobacci, Sannino, Santorelli, Vignaroli, JHEP 08 (2022) 125, 2204.03686

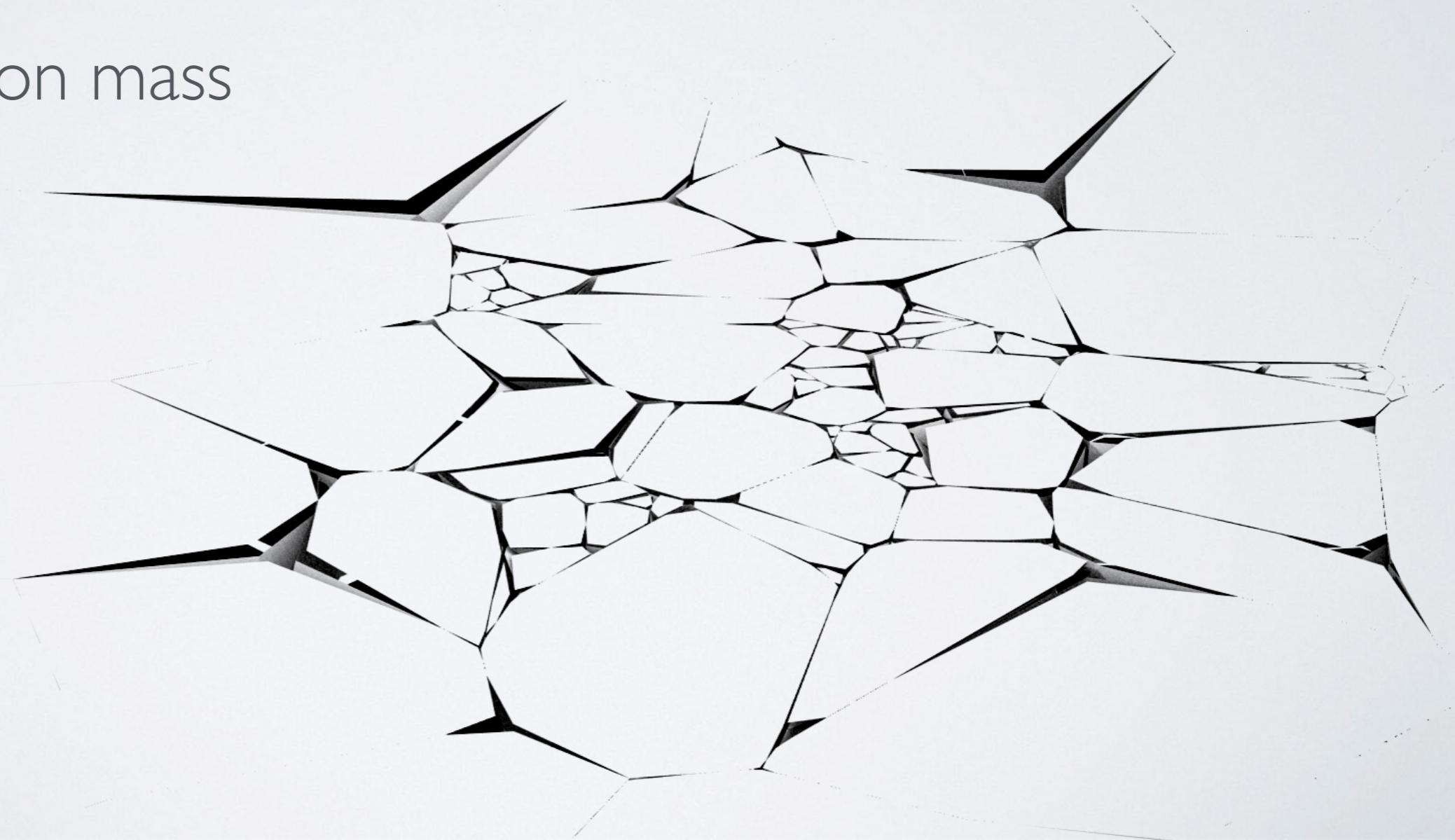
Calabrese, De Iorio, Cacciapaglia, Morisi, Sannino et al. PRD 107 (2023), 2210.0731

Cacciapaglia, Sannino PLB 832 (2022), 2204.04514

Cacciapaglia, Cot, Sannino, Phys. Lett. B 825 (2022) 2104.08818

2022 ~ Cracks

- ◆ Lepton flavour (non) universality
- ◆ g-2 of the muon
- ◆ W boson mass



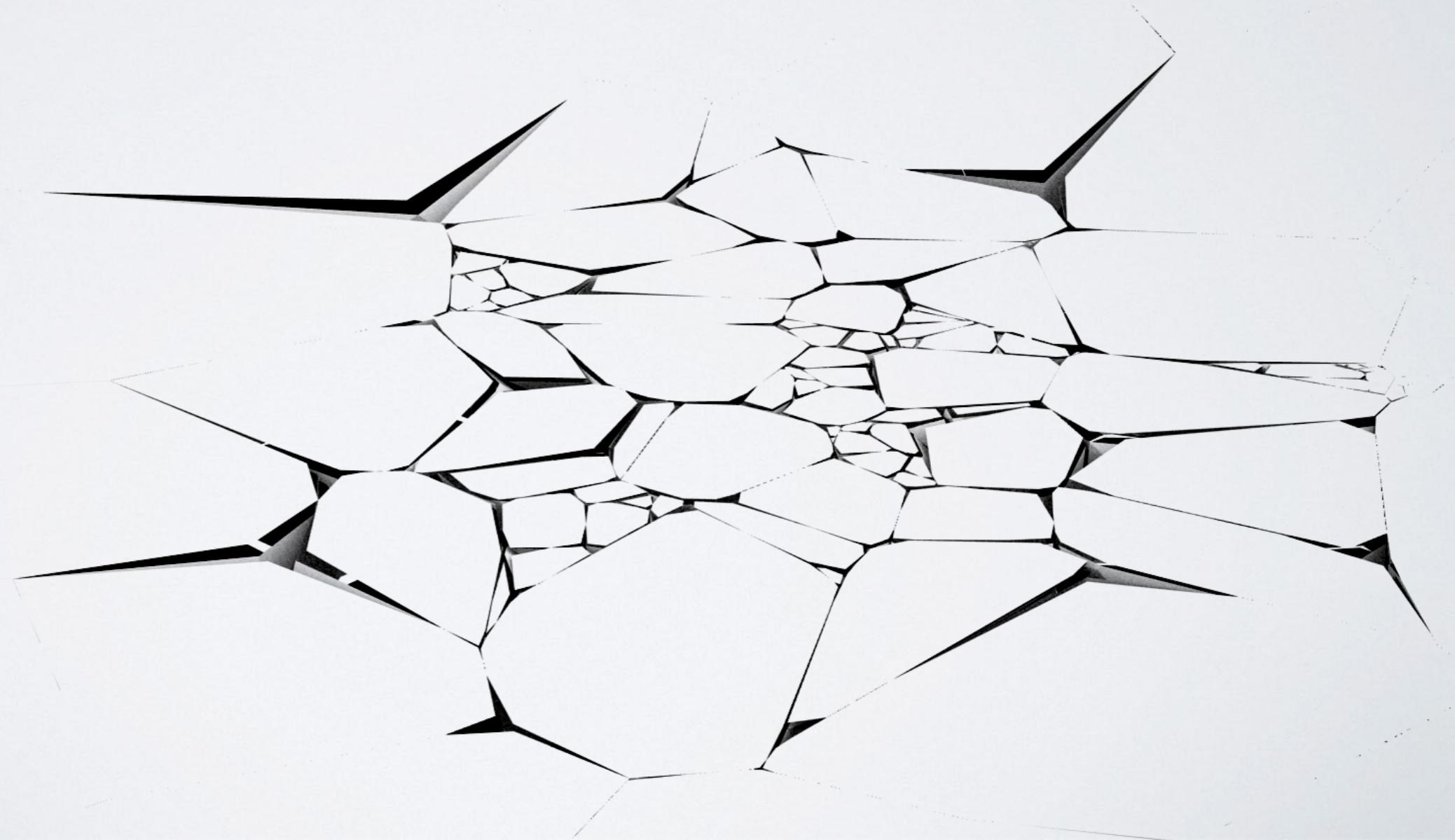
December 2022

- ◆ Lepton flavour (non) universality



2023/24 (on the way out?)

- ◆ W boson mass
- ◆ And perhaps also g-2 of the muon



Muon g-2

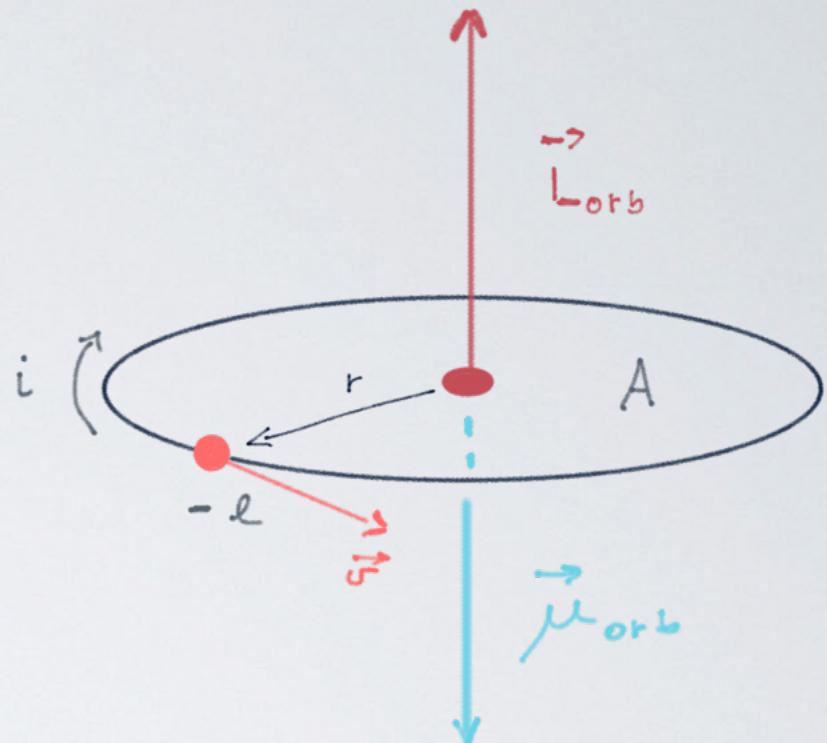
Orbital magnetic moment

$$\vec{\mu}_{\text{orb}} = i \vec{A} = -\frac{e}{2\pi r} v \pi r^2 \hat{A} = -\frac{e}{2m} \vec{L}_{\text{orb}}$$

$$\vec{L}_{\text{orb}} = \vec{r} \wedge m \vec{v}$$

Intrinsic angular momentum

$$\vec{\mu} = g \frac{q}{2m} \vec{S}$$



$g = 2$ Dirac equation

PHYSICAL REVIEW

VOLUME 72, NUMBER 3

AUGUST 1, 1947

Fine Structure of the Hydrogen Atom by a Microwave Method* **

WILLIS E. LAMB, JR. AND ROBERT C. RETHERFORD

Columbia Radiation Laboratory, Department of Physics, Columbia University, New York, New York

(Received June 18, 1947)

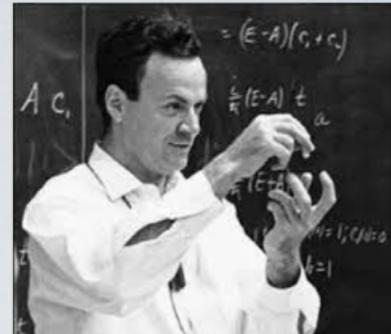


$g > 2$

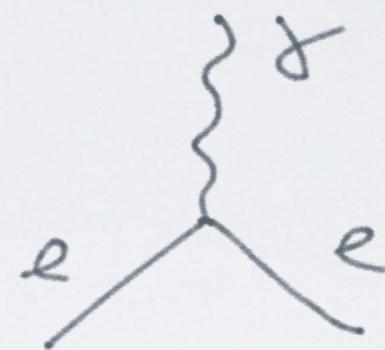
1955

QED

Schwinger, Tomonaga Feynman



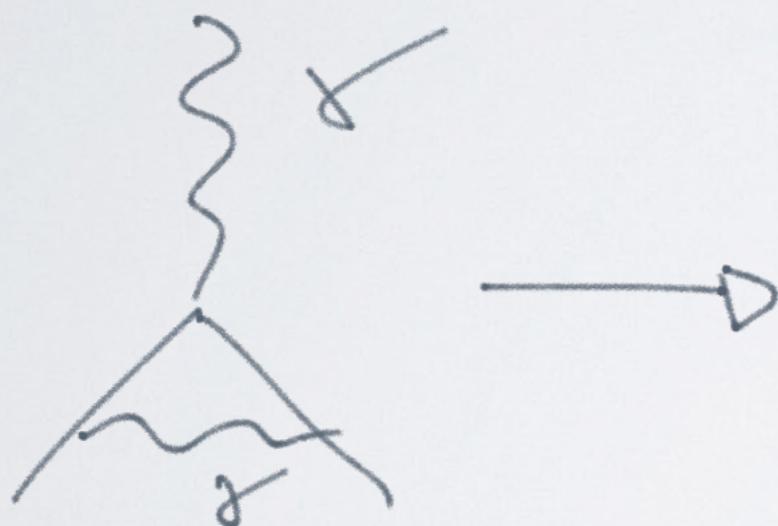
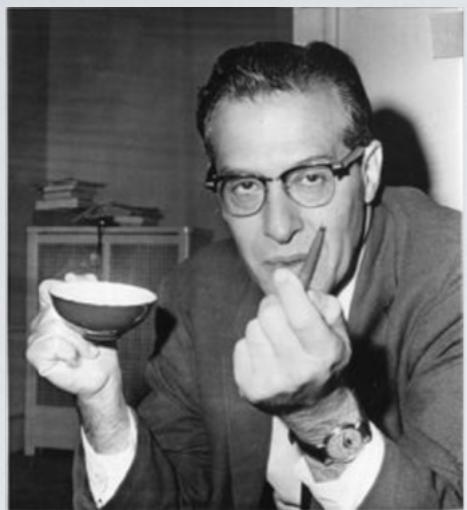
Elementary process



Schwinger's One loop computation



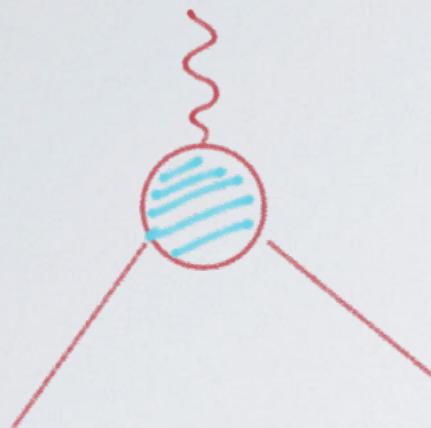
↳ Dirac's limit



$$\frac{g_e - 2}{2} = \varrho_e = \frac{\alpha}{2\pi} + \mathcal{O}(\alpha^2)$$

1948

Muon g-2



g-2 anomaly

$$\alpha_{\text{lepton}} = \frac{g_l - 2}{2} = \underbrace{\alpha_e^{\text{QED}} + \alpha_e^{\text{weak}} + \alpha_e^{\text{hadronic}}}_{\text{SM}} + \underbrace{\alpha_e^{\text{NP}}}_{\text{BSM}}$$

Standard Model Corrections

Representative contributions



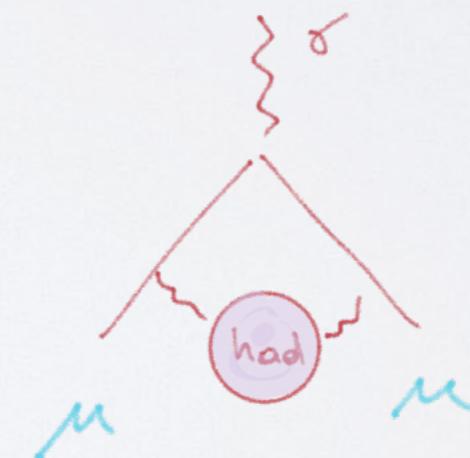
QED



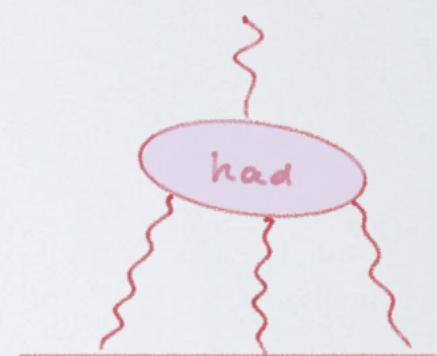
Weak



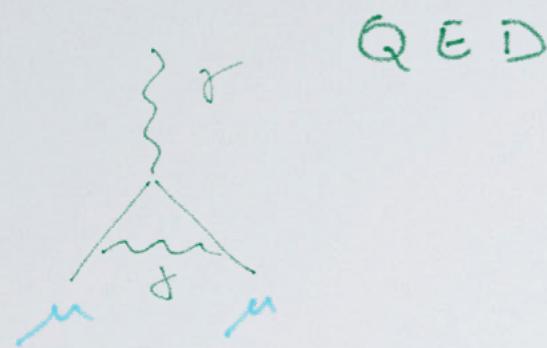
hadronic
vacuum
polarization



QCD/hadronic



hadronic
light by light



Q E D

α^5 5th-order

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

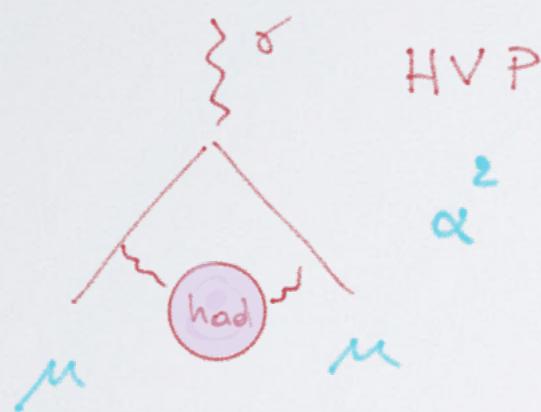


Weak

α^3

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

0.01 ppm

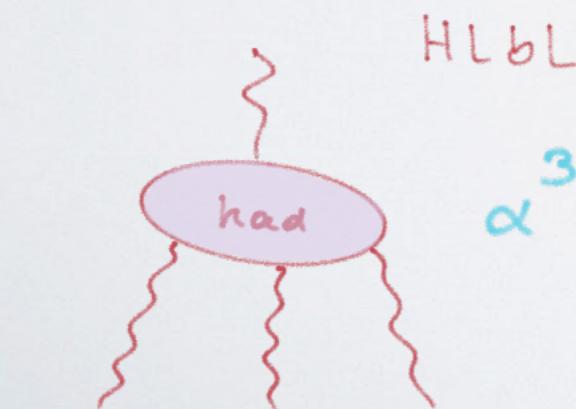


H V P

α^2

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

0.37 ppm



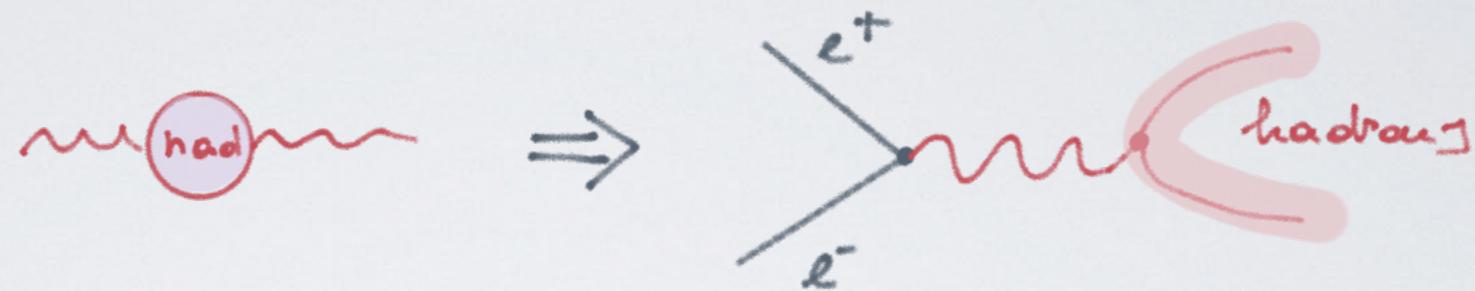
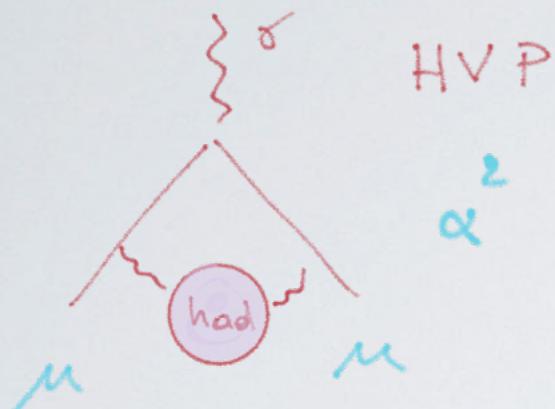
H L B L

α^3

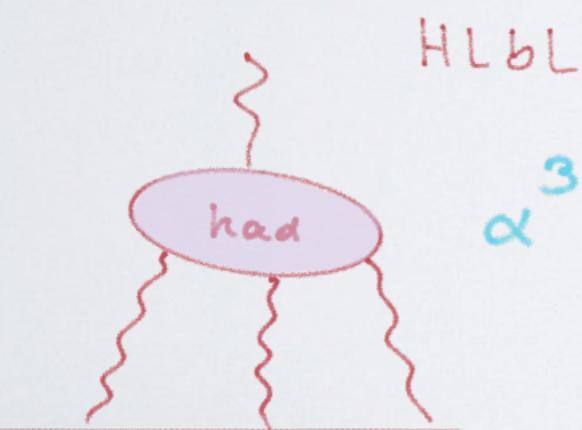
$$92(18) \times 10^{-11}$$

0.15 ppm

Dispersive approach

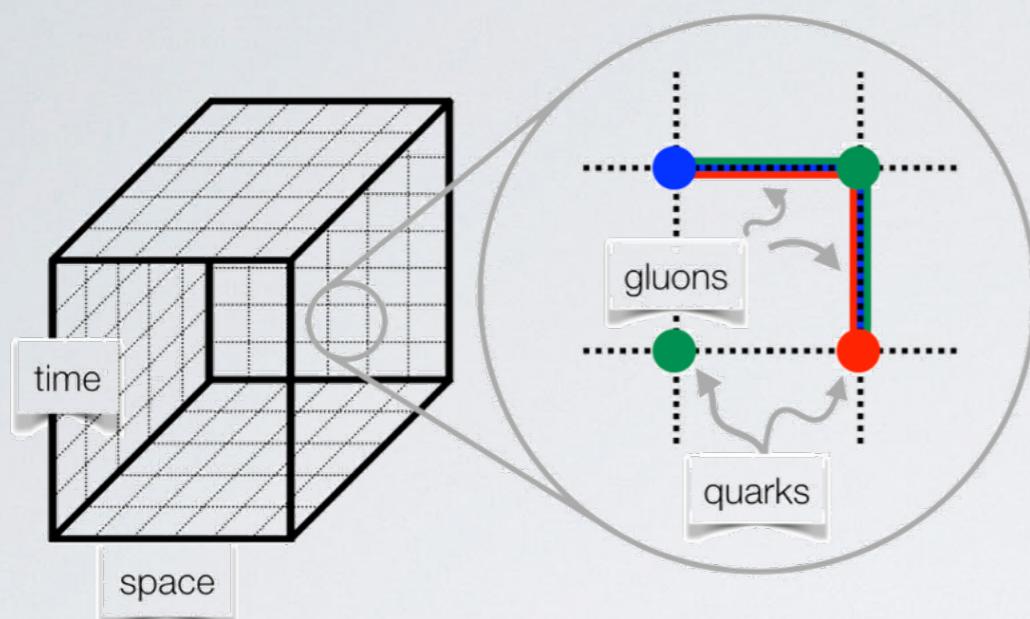


Experimental data + dispersion theory
 \Rightarrow HVP with $\sim 0.6\%$ error



Allow data-driven evaluation
with 20% error.
(HLBL subleading)

Data driven



Lattice QCD

Discrete space-time
Finite spatial volume
Finite time extent

Expensive

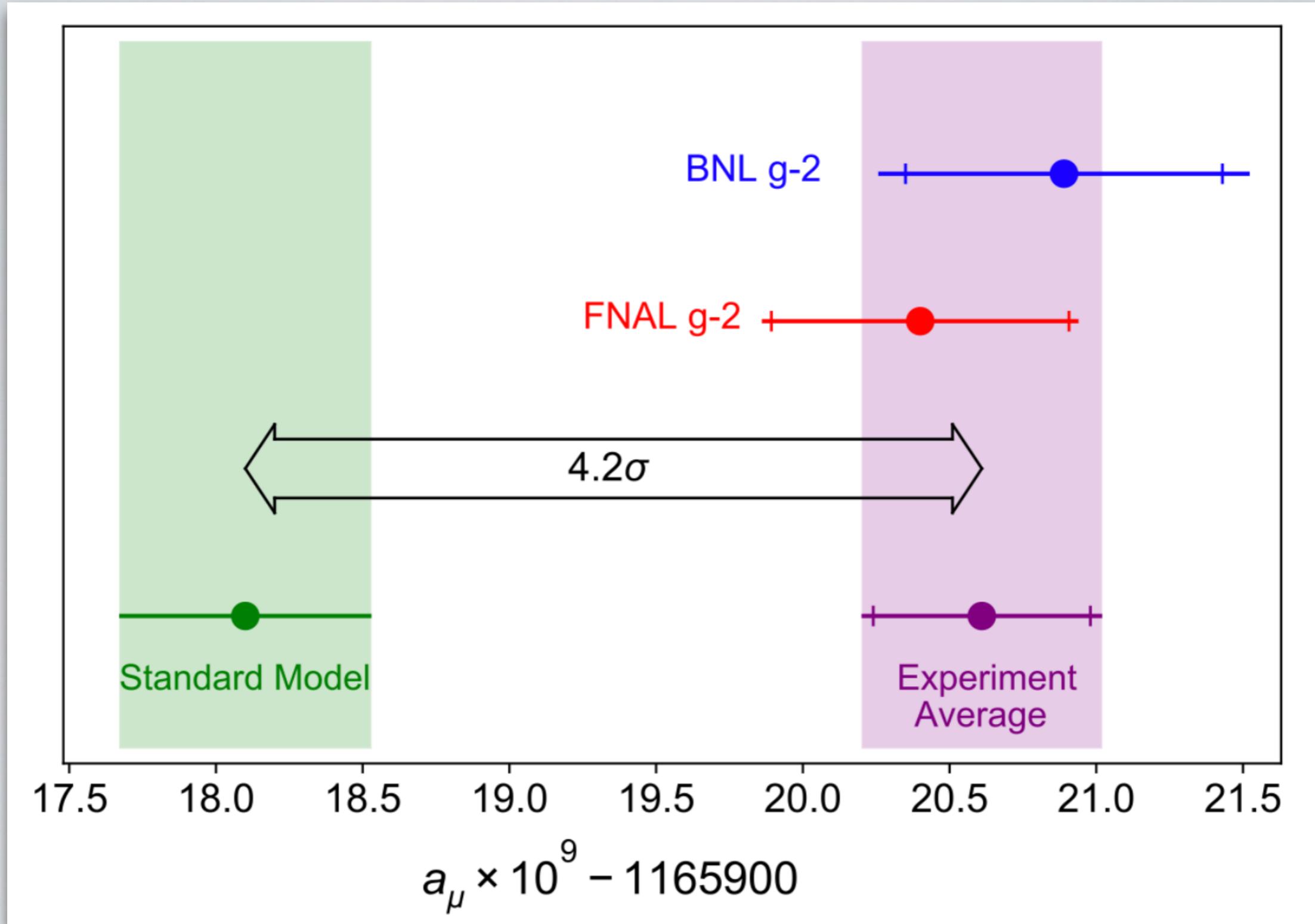
Ab-initio QCD

SM-based evaluations

HVP : $\sim 2\%$ error vs 0.2% dispersive*

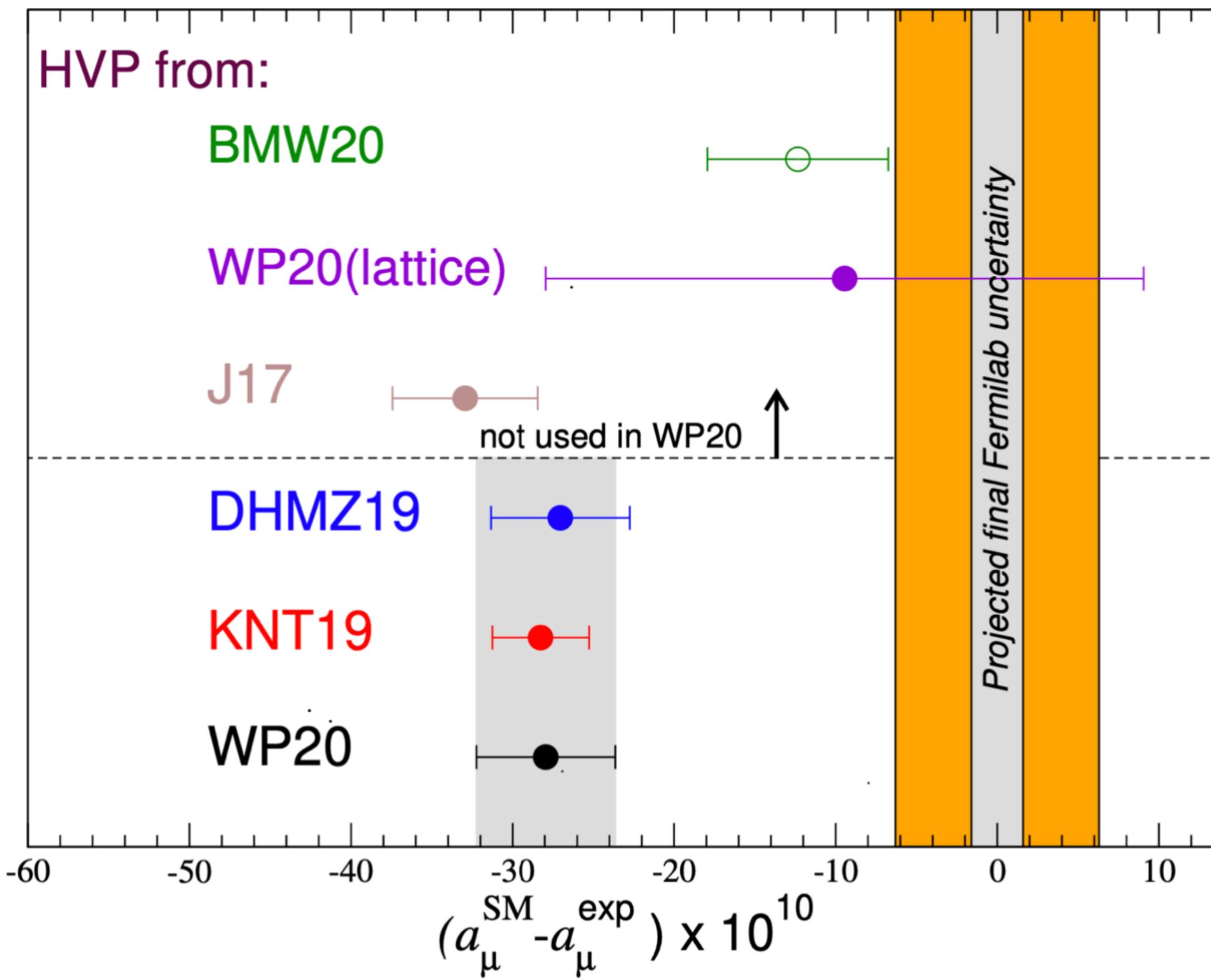
HLbL : $\sim 45\%$ error vs 20% dispersive

BHW20*



$$\Delta a_\mu = a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}$$

BNL-E821



Fundamental Composite Physics

Sannino, Acta Phys. Polon. B 40 (2009) 3533-3743, 0911.0931

Sannino, Strumia, Tesi, Vigiani, JHEP 11 (2016) 029, 1607.01659

Cacciapaglia, Pica, Sannino, Phys. Rept. 877 (2020) 1-70, 2002.04914

Skeleton Lagrangian

$$\begin{aligned}
 -\mathcal{L}_{NP} = & g_L^{ij} \bar{\phi}_L S_E^j + g_E E^c \bar{\phi}_N^c S_E + g_Q Q \bar{\phi}_L S_D^* + g_U U^c \bar{\phi}_E^c S_D + g_D D^c \bar{\phi}_N^c S_D \\
 & + \sqrt{2} \kappa (\bar{\phi}_L \bar{\phi}_N^c + \bar{\phi}_E \bar{\phi}_L^c) \phi_H + h.c.
 \end{aligned}$$

Template for

- (Walking) TC
- Composite Goldstone Higgs
- Non standard Higgs
- Radiative models

	g_{TC}	$SU(3)_c$	$SU(2)$	$U_Y(1)$
$\bar{\phi}_L$	0	1	0	γ
$\bar{\phi}_N^c$	0	1	1	$-\gamma - \gamma_2$
$\bar{\phi}_E^c$	0	1	1	$-\gamma + \gamma_2$
S_E^j	0	1	1	$\gamma - \gamma_2$
S_D^j	0	0	1	$\gamma + 1/6$

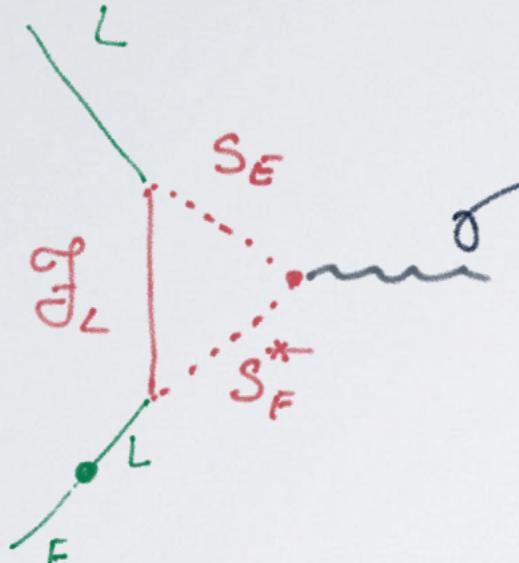
Radiative models

If new scalars are composite \Rightarrow natural

Cabibbi, Ziegler, Zupan, 1804.00009
 Arnan, Hofer, Mescia, Crivellin, 1608.07832,
 with DM Arcadi, Cabibbi, Fedele, Mescia, 2104.03228

Skeleton diagrams/estimates

$g-2$

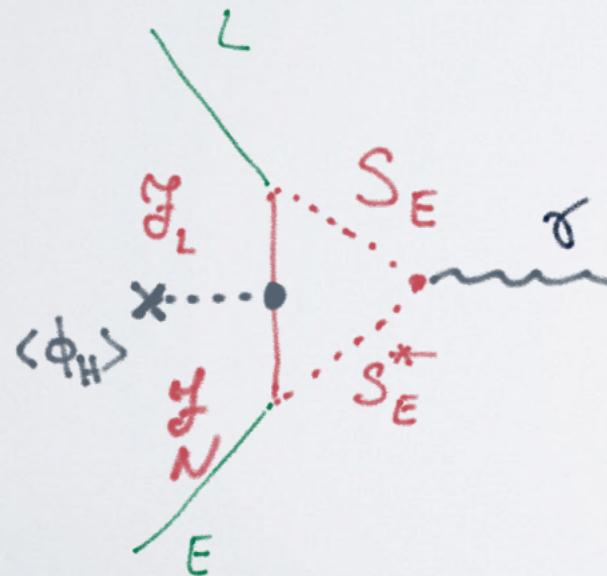


Exp. value for TC scale $\Lambda \approx 2$ TeV

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

Cacciapaglia, Cot, Sannino, Phys. Lett. B 825 (2022) 2104.08818

Composite Goldstone Higgs



$$\Delta a_\mu(CH) \approx \frac{v^2}{f_{CH}^2} \frac{m_\mu^2}{\Lambda^2}$$

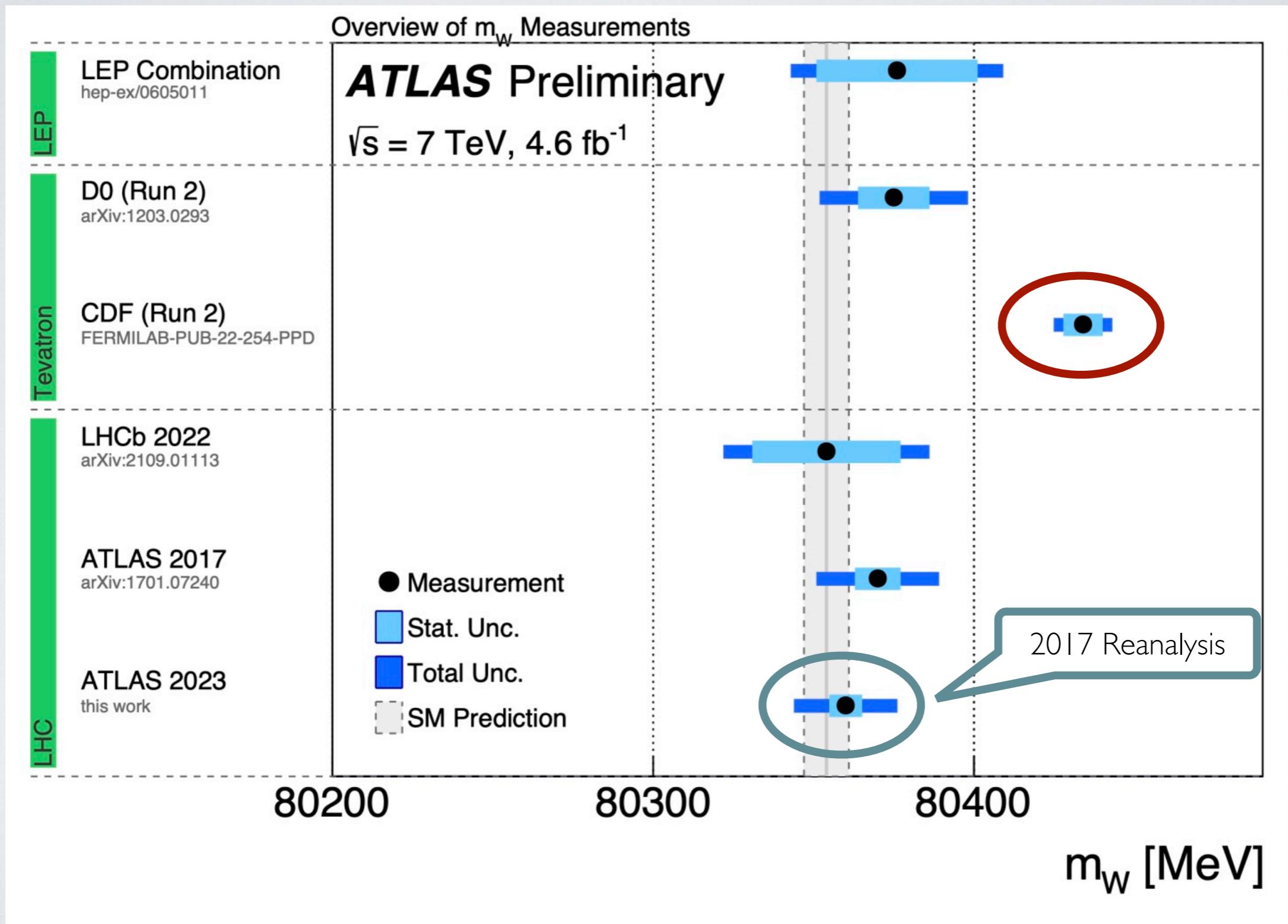
$$\Lambda \approx 4\pi v \approx 2 \text{ TeV}$$

$$f_{CH} \approx (4 - 5) \text{ TeV} \Rightarrow \text{too small } \Delta a_\mu$$

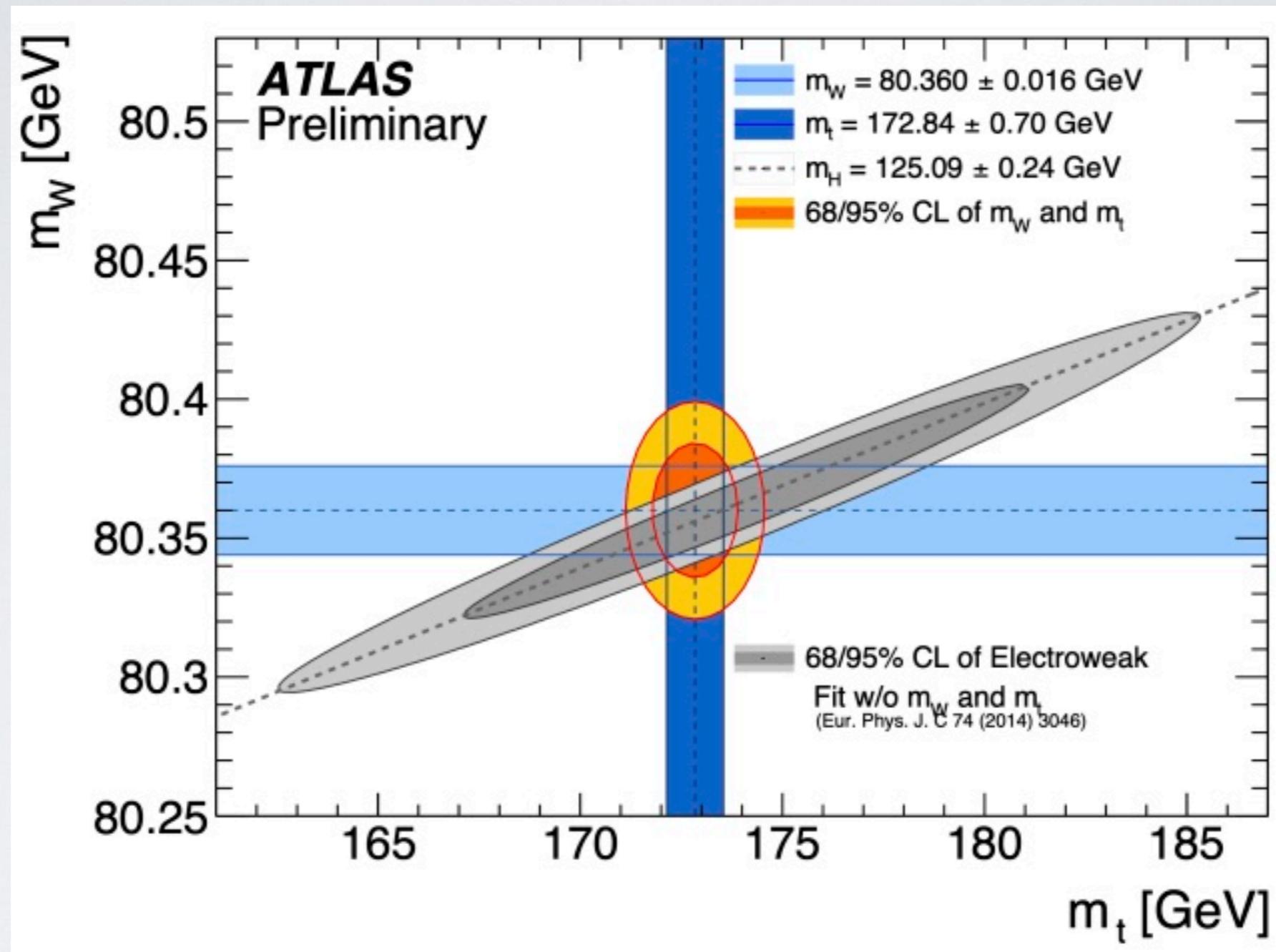
General observations

- ◆ Theory uncertainty for g - 2
- ◆ No $R_K^{(*)}$ anomalies \Rightarrow back to lepton flavour universality
- ◆ (Natural) composite model works for g-2
- ◆ Non-standard Higgs as pseudo-dilaton (near conformal)

W - mass/mess



Should one bet against the SM?



68% & 95% CL contours for W and top-mass from
Global Electroweak Fit vs Atlas direct measurements

To good to be true ?

What can we say?

CDF result claim increase statistics/better understanding of PDFs and detector
(PDFs alone reduce uncertainty from 10 to 3.9 MeV)

CDF is in Tension with ATLAS measurement and SM!

Study correlations w.r.t. to PDFs, higher order QCD and QED effects.

What the numbers say?

$$M_W \Big|_{\text{SM}} = 80,357 \pm 4_{\text{inputs}} \pm 4_{\text{theory}} \text{ MeV}$$

$$M_W \Big|_{\text{CDF}} = 80,433.5 \pm 6.4_{\text{stat}} \pm 6.9_{\text{syst}} = 80,433.5 \pm 9.4 \text{ MeV} ,$$

$$M_W \Big|_{\text{LEP}} = 80,385 \pm 15 \text{ MeV}$$

$$M_W \Big|_{\text{LHCb}} = 80,354 \pm 32 \text{ MeV}$$

$$M_W \Big|_{\text{ATLAS/23}} = 80,360 \pm 16 \text{ MeV}$$

Weighted average for incompatible measures

$$M_W \Big|_{\text{AVG}} = 80,408 \pm 19 \text{ MeV}$$

Only 2.4σ discrepancy with SM

Uncertainty increased by $\sqrt{\chi^2/\text{ndr}}$

Precision electroweak

$$\Delta M_W \approx 300 \text{ MeV} \times (1.43 T - 0.86 S)$$

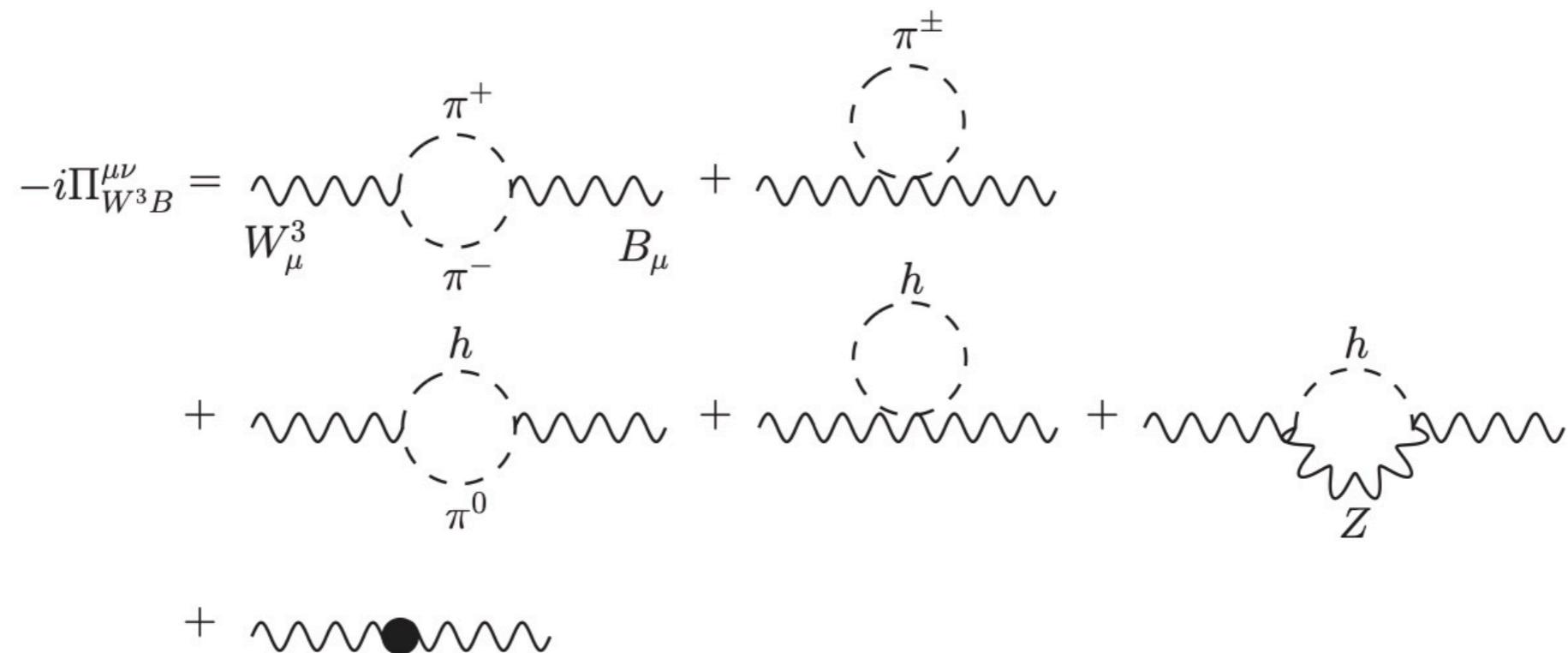
Altarelli, Barbieri, Caravaglios PLB 349, 145 (1995)

Sannino, Phys. Rev. D 93 (2016), 1508.07413

Cacciapaglia, Sannino 2204.04514

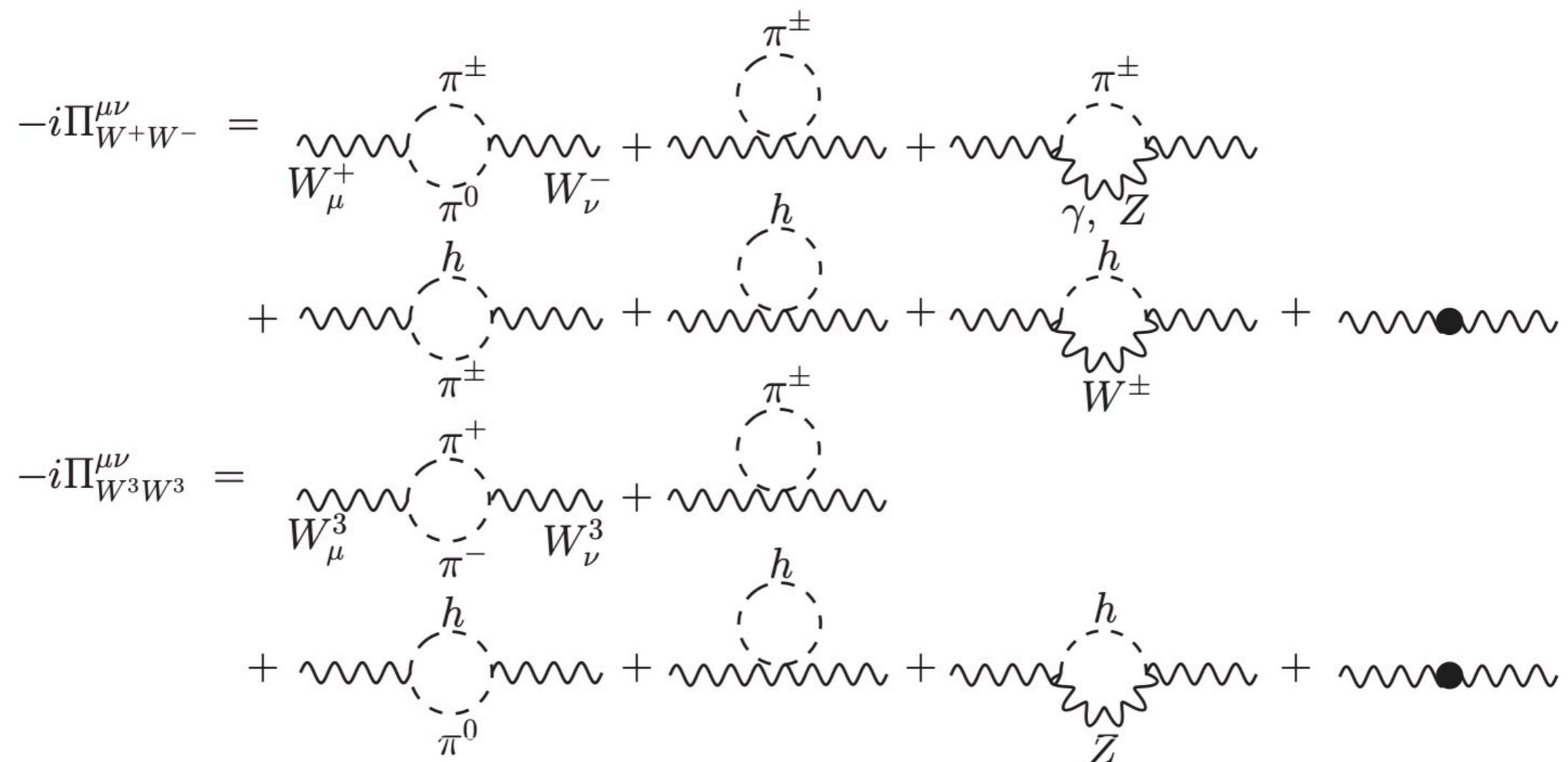
Electroweak parameters

$$S = -16\pi \frac{\Pi_{3Y}(M_Z^2) - \Pi_{3Y}(0)}{M_z^2}$$



Precision electroweak

$$T = 4\pi \frac{\Pi_{11}(0) - \Pi_{33}(0)}{s_W^2 c_W^2 M_z^2}$$



Precision electroweak

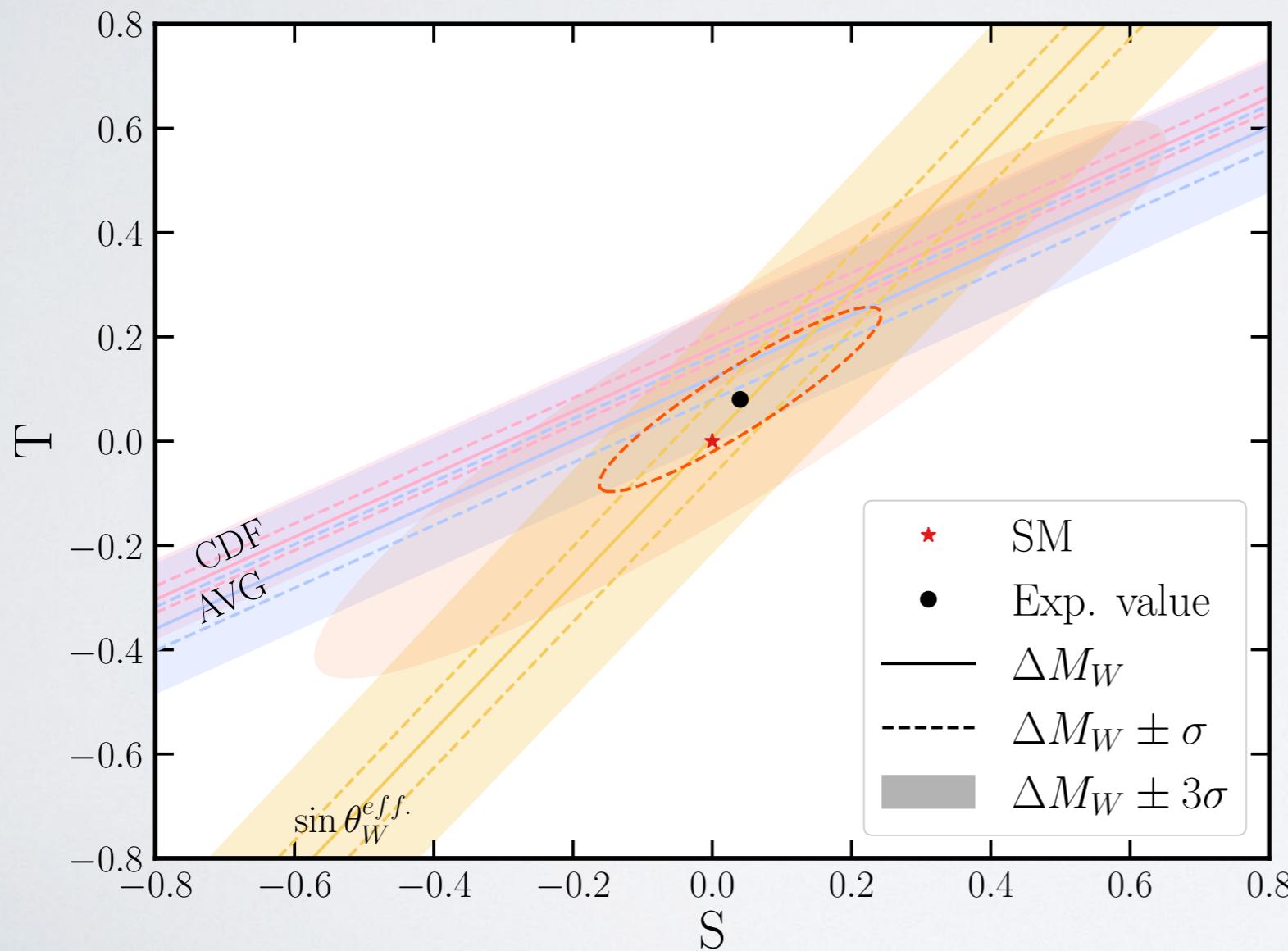
$$\Delta M_W \approx 300 \text{ MeV} \times (1.43 T - 0.86 S)$$

Altarelli, Barbieri, Caravaglios PLB 349, 145 (1995)

Sannino, Phys. Rev. D. 93 (2016), 1508.07413

Cacciapaglia, Sannino PLB 832 (2022), 2204.04514

Calabrese, De Iorio, et al. PRD 107 (2023), 2210.0731



Yellow band = bound on direct s_W^2

Black dot - Mean value of S and T

Orange ellipses 3σ S & T region

Non Standard Higgs

Glueball Higgs

$$\begin{aligned}
 \mathcal{L}_{\text{Glueball-Higgs}} = & \mathcal{L}_{\overline{\text{SM}}} + \left(1 + \frac{2r_\pi}{N\Lambda_H} h + \frac{s_\pi}{N^2\Lambda_H^2} h^2 \right) \frac{v^2}{4} \text{Tr } D_\mu U^\dagger D^\mu U \\
 & + \frac{1}{2} \partial_\mu h \partial^\mu h - \frac{m_h^2}{2} h^2 \left[1 + \frac{V_{0,1}}{N} \frac{h}{\Lambda_H} + \frac{V_{0,2}}{N^2} \frac{h^2}{\Lambda_H^2} \right] \\
 & - m_t \left(1 + \frac{r_t}{N\Lambda_H} h \right) \left[\bar{q}_L U \left(\frac{1}{2} + T^3 \right) q_R + \text{h.c.} \right] \\
 & - m_b \left(1 + \frac{r_b}{N\Lambda_H} h \right) \left[\bar{q}_L U \left(\frac{1}{2} - T^3 \right) q_R + \text{h.c.} \right] + \dots \\
 & + O\left(\frac{1}{4\pi v}, \frac{\partial^2}{\Lambda_H^2}\right)
 \end{aligned}$$

$$V_{a,b} \sim \mathcal{O}(1)$$

$V_{0,b}$ Non-derivative series in h

$$h \sim G_{\mu\nu} G^{\mu\nu}$$

Lightest SU(N) glueball

$$\Lambda_H \neq v \quad v = 246 \text{ GeV}$$

N-independent String Tension

$$U = \exp(i2\pi^a T^a/v)$$

$$D_\mu U = \partial_\mu U - ig W_\mu^a T^a U + ig' U B_\mu T^3$$

SM for

$$r_\pi = r_t = r_b = N \frac{\Lambda_H}{v} \quad s_\pi = N^2 \frac{\Lambda_H^2}{v^2}$$

Technicolor Higgs

$$\begin{aligned}\mathcal{L}_{TC}(N) = & \mathcal{L}_{\overline{\text{SM}}} + \left(1 + \cancel{g} \frac{2r_\pi}{2m_W} h + \cancel{g^2} \frac{s_\pi}{4m_W^2} h^2\right) \frac{m_W^2}{g^2} \text{Tr } D_\mu U^\dagger D^\mu U \\ & + \frac{1}{2} \partial_\mu h \partial^\mu h - \frac{m_h^2}{2} h^2 \left[1 + g V_{0,1} \frac{h}{2m_W} + g^2 V_{0,2} \frac{h^2}{4m_W^2}\right] \\ & - m_t \left(1 + g \frac{r_t}{2m_W} h\right) \left[\bar{q}_L U \left(\frac{1}{2} + T^3\right) q_R + \text{h.c.}\right] \\ & - m_b \left(1 + g \frac{r_b}{2m_W} h\right) \left[\bar{q}_L U \left(\frac{1}{2} - T^3\right) q_R + \text{h.c.}\right] + \dots\end{aligned}$$

Pions \sim Higgs dynamics governed by N (via F_Π)

$$\begin{aligned}h &\sim \frac{\mathcal{F} \mathcal{F}}{F_\Pi^2} & F_\Pi^2 &= N \Lambda_{TC}^2 \\ v &= F_\Pi & m_q &= y_q v \frac{N}{2\bar{N}} \\ m_W^2 &= g^2 v^2 \frac{N}{4\bar{N}} & \sqrt{\frac{N}{\bar{N}}} v &= 2 \frac{m_W}{\cancel{g}}\end{aligned}$$

g monitors $1/\sqrt{N}$ cost of extra h

SM recovered for (up to Higgs potential)

$$r_\pi = r_t = r_b = \frac{2m_W}{v g}$$

$$s_\pi = \frac{4m_W^2}{v^2 g^2}$$

Pseudo Dilaton Higgs

$$\begin{aligned}\mathcal{L}_{\text{Dilaton}}(N) = & \mathcal{L}_{\overline{\text{SM}}} + \left(1 + \frac{2h}{N\Lambda_H} + \frac{h^2}{N^2\Lambda_H^2}\right) \frac{v^2}{4} \text{Tr } D_\mu U^\dagger D^\mu U \\ & + \frac{1}{2} \partial_\mu h \partial^\mu h - \frac{m_h^2}{2} h^2 \left[1 + \frac{V_{0,1}}{N} \frac{h}{\Lambda_H} + \frac{V_{0,2}}{N^2} \frac{h^2}{\Lambda_H^2} \right] \\ & - m_t \left(1 + \frac{h}{N\Lambda_H}\right) \left[\bar{q}_L U \left(\frac{1}{2} + T^3\right) q_R + \text{h.c.} \right] \\ & - m_b \left(1 + \frac{h}{N\Lambda_H}\right) \left[\bar{q}_L U \left(\frac{1}{2} - T^3\right) q_R + \text{h.c.} \right] + \dots\end{aligned}$$

Higgs via near conformal dynamics

$f_d = N\Lambda_H$ (Large N dynamics)

Coefficients dictated by conformality

Higgs potential coefficients $V_{0,i}$ depend on conformal dynamic breaking

SM recovered for

$$f_d = v$$

General Non-Standard Higgs Lagrangian

$$\begin{aligned} \mathcal{L} = & \mathcal{L}_{\overline{\text{SM}}} + \xi_V \left(1 + 2\kappa_V \frac{h}{v} + \kappa_{2V} \frac{h^2}{v^2} \right) \frac{v^2}{4} \text{Tr } D_\mu U^\dagger D^\mu U + \frac{1}{2} \partial_\mu h \partial^\mu h - \frac{\tilde{m}_h^2}{2} h^2 \left(1 + V_{0,1} \lambda_{3h} \frac{h}{v} \right) \\ & - \frac{\tilde{y}_t v}{\sqrt{2}} \xi_t \left(1 + \kappa_t \frac{h}{v} \right) \left[\bar{q}_L U \left(\frac{1}{2} + T^3 \right) q_R + \text{h.c.} \right] - \frac{\tilde{y}_b v}{\sqrt{2}} \xi_b \left(1 + \kappa_b \frac{h}{v} \right) \left[\bar{q}_L U \left(\frac{1}{2} - T^3 \right) q_R + \text{h.c.} \right] + \dots \end{aligned}$$

$$U = \exp(i2\pi^a T^a/v) \quad v = 246 \text{ GeV}$$

Sannino, Phys. Rev. D. 93 (2016), 1508.07413

Non-standard Higgs coupling to WW/ZZ

Cacciapaglia, Sannino PLB 832 (2022), 2204.04514

$$\kappa_V^2 = \frac{\sigma_{\text{VBF}}}{\sigma_{\text{VBF}}^{\text{SM}}} \equiv \frac{\Gamma_{h \rightarrow WW/ZZ}}{\Gamma_{h \rightarrow WW/ZZ}^{\text{SM}}}$$

	ξ_V	κ_V	κ_{2V}	λ_{3h}	ξ_f	κ_f	higher orders
Glueball	1	$\frac{r_\pi v}{N \Lambda_H}$	$\frac{s_\pi v^2}{N^2 \Lambda_H^2}$	$\frac{v}{N \Lambda_H}$	1	$\frac{r_f v}{N \Lambda_H}$	$\frac{1}{4\pi v}, \frac{\partial^2}{\Lambda_H^2}$
Technicolor-like	$\frac{N}{\overline{N}}$	$r_\pi \sqrt{\frac{N}{\overline{N}}}$	$s_\pi \frac{\overline{N}}{N}$	$\sqrt{\frac{\overline{N}}{N}}$	$\sqrt{\frac{N}{\overline{N}}}$	$r_f \sqrt{\frac{N}{\overline{N}}}$	$\frac{1}{4\pi v}, \frac{\partial^2}{v^2}$
pseudo-dilaton	1	$\frac{v}{N \Lambda_H}$	$\frac{v^2}{N^2 \Lambda_H^2}$	$\frac{v}{N \Lambda_H}$	1	$\frac{v}{N \Lambda_H}$	
Goldstone/Holographic	1	c_θ	$c_{2\theta}$	c_θ	1	c_θ	$\frac{1}{4\pi f}, \frac{\partial^2}{f^2}$

Non-standard (composite) Higgs

Glueball:

Lightest glueball with string tension $\Lambda_H \neq v$

Technicolor:

TC fermion bound state assume reference $SU(\bar{N})$ (Fund. Rep.)

Dilaton:

Couplings related and single scale $N\Lambda_H$

Goldstone/Holo:

EW vev misalignment $v = f \sin \theta \equiv f s_\theta$ with $s_\theta \ll 1$

Non-standard S & T

$$S = \frac{1}{12\pi} (1 - \kappa_V^2) \ln \frac{\Lambda^2}{m_h^2} + \Delta S_{\text{UV}}$$

ΔS_{UV} = unknown UV contributions

Assuming UV custodial

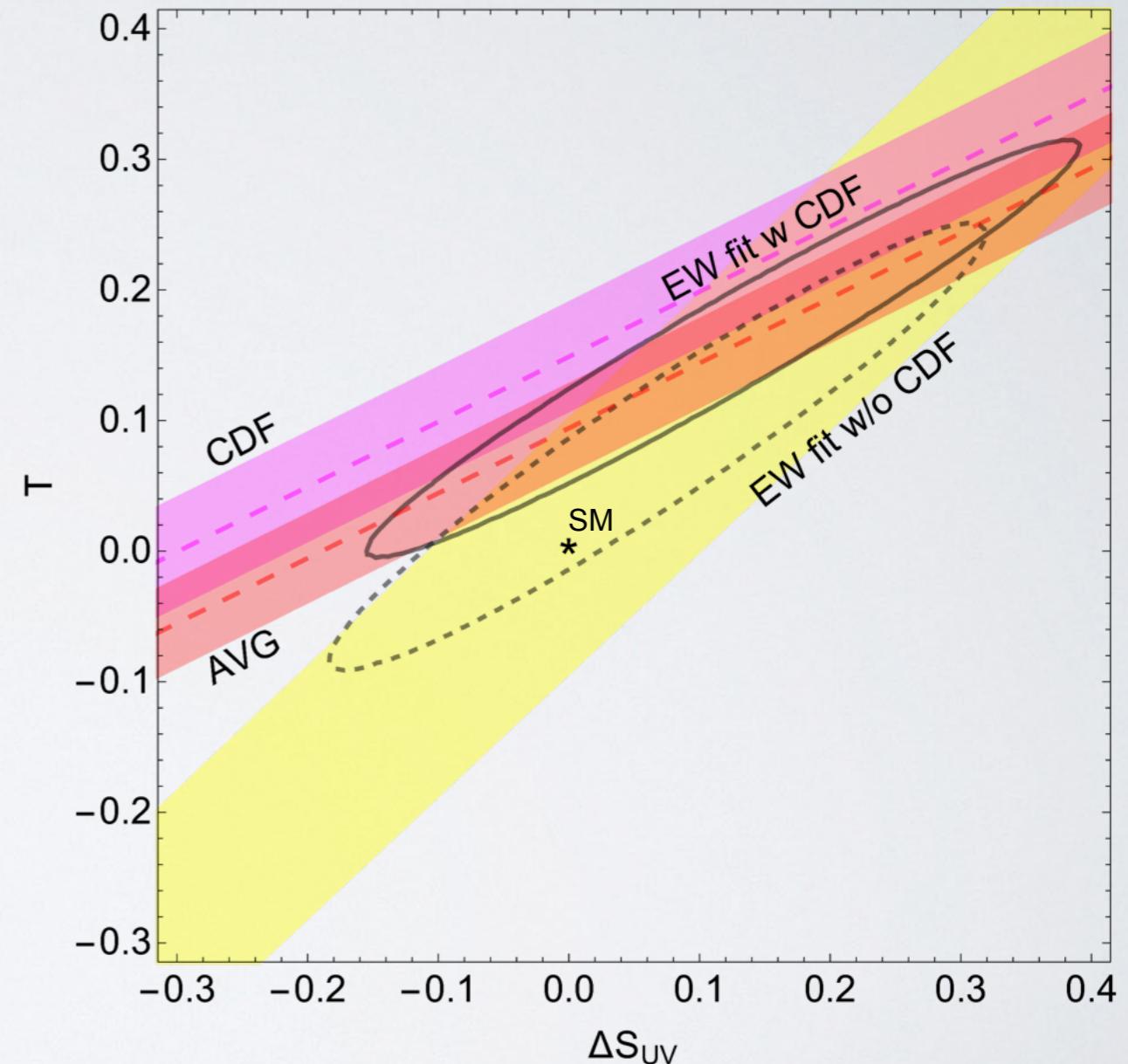
$$T = -\frac{3}{16\pi c_W^2} (1 - \kappa_V^2) \ln \frac{\Lambda^2}{m_h^2},$$

$$S = -\frac{4}{9} c_W^2 T + \Delta S_{\text{UV}}$$

$$\Delta S_{\text{UV}} = \frac{n_d}{6\pi}$$

Reference UV model

n_d = # weak doublets

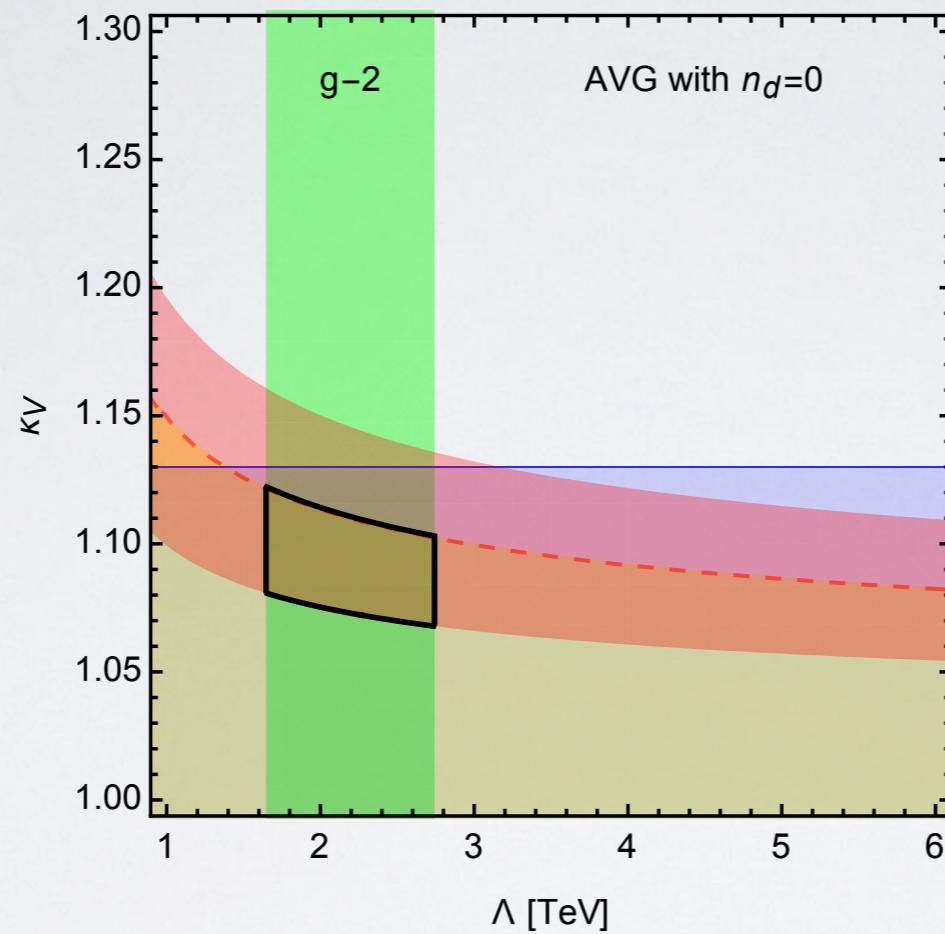


CDF - W (magenta) and s_W^2 (yellow) \Rightarrow small positive ΔS_{UV} & positive T

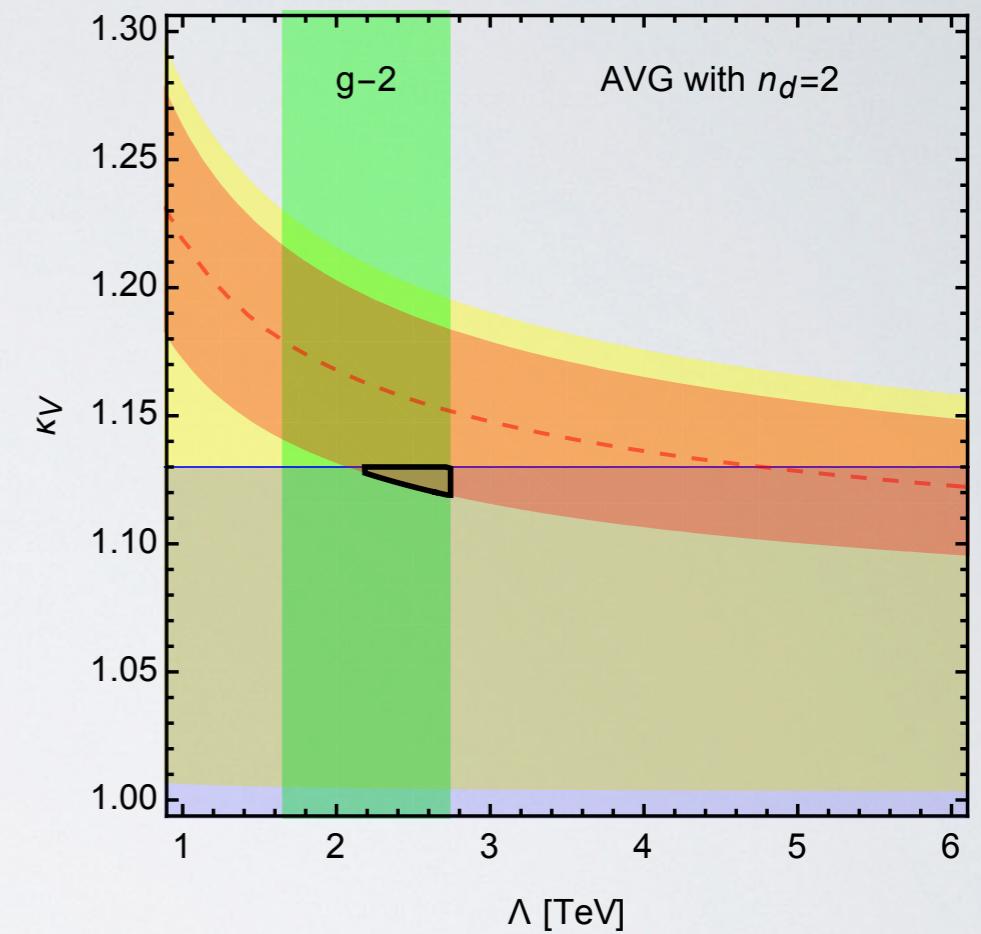
What works

$$\Delta S_{\text{UV}} = \frac{n_d}{6\pi}$$

$$\Delta a_\mu = \frac{m_\mu^2}{\Lambda^2}$$



Positive enhancement of around 5% for κ_V



Yellow band = bound on s_W^2

Blue region allowed by ATLAS

Orange is fit to Mw average to 2σ

General results

Goldstone/Holo $\Rightarrow \kappa_V = c_\theta \leq 1$

Dilaton, TC and Glueball Higgs $\Rightarrow \kappa_V \geq 1$ for $\Lambda < v$ and/or $r_\pi > 1$

Dilaton, TC & Glueball Higgs work but small coupling for Goldstone/Holo Higgs

Natural composite dynamics can address W and g-2 anomalies

Final considerations

Landscape of strongly interacting theories is vastly unknown

Hard to tackle, especially in strongly coupled regimes (see g-2 and $R_{D^{(*)}}$)

Phase diagram of strongly interacting theories needed for model building

New promising analytic and numeric methodologies underway

To be continued...

“Our imagination is stretched to the utmost, not, as in fiction, to imagine things which are not really there, but just to comprehend those things which 'are' there.”

Richard Feynman