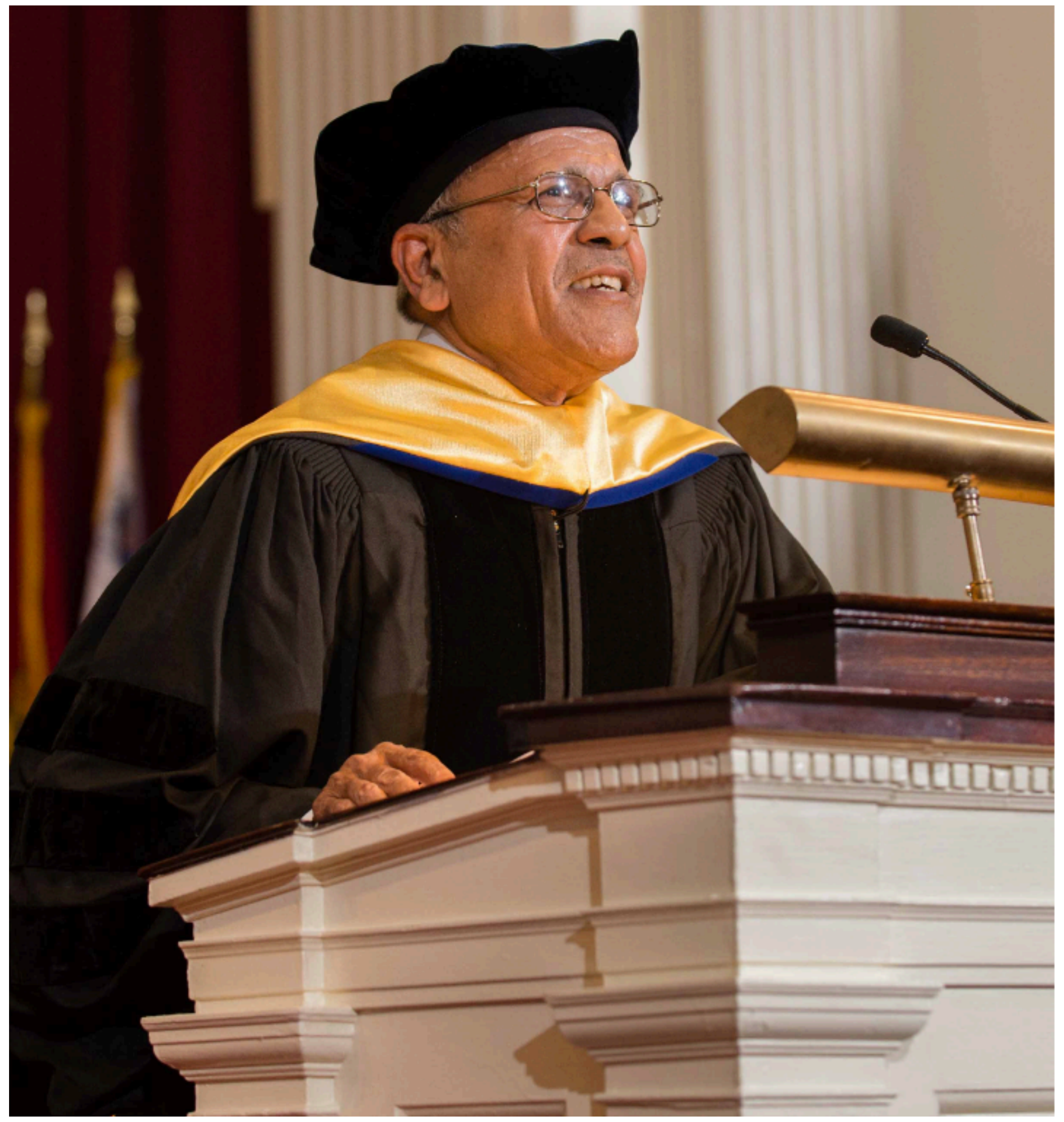
My friendship with Rabi

(And a view on a corner of BSM)

R. Barbieri (SNS, Pisa)



Rabi Fest 2022

Maryland University, College Park, Oct 20-21, 2022

My contacts with Rabi

1973 - College Park

1981 - CERN

1982 - City College

Composite W,Z,q,l
GUT axions
Breaking of B-number

1988 - College Park

Neutrinos, see next page

Both Rabi and myself very much oriented on BSM

I regret for not having insisted after that

About the neutrino magnetic moment

1986-1987

A putative correlation of the solar ν's (Davis) with the 11-year sun-spot cycle of $B_\odot$

Okun, Voloshin, Visotski
B, Fiorentini

$\mu_\nu \approx 10^{-10}\mu_B$ by $\nu_L e \to \nu_R e$

1988

B, Mohapatra

Not to rapidly cool the hot neutron star SN 1987a
$\mu_\nu \lesssim (0.3 \div 1)10^{-10}\mu_B$ with $T_{core} = 30 \div 70\ MeV$

1990 -2013

Raffelt et al

Stellar cooling of Helium stars, globular clusters
$\mu_\nu \lesssim (3 \div 5)10^{-12}\mu_B$

2010

Gemma

$\bar{\nu}_e$ flux from reactors $\mu_\nu \lesssim 3 \cdot 10^{-12}\mu_B$

2022

XENONnT

From solar neutrinos $\mu_\nu \lesssim 2 \cdot 10^{-11}\mu_B$

To
Riccardo,
With best Complements,

Rabi

Rabindra N. Mohapatra

Unification and Supersymmetry

The Frontiers of Quark–Lepton Physics

1986

Contents

1986: Remarkable!

Contents

BSM (chapters 4–16)

1986: Remarkable ... and still today!

Where could some light come from?

1.A theory breakthrough
→ 1a BSM
→ 1b Foundations (FT, QM)

1a Or the experimental sign of some of the great ideas (GUT, Susy, …)

2.Astrophysics, Cosmology
→ 2a DM
→ 2b B-asymmetry
→ 2c Gravity
→ 2d Inflation

3.An experimental deviation from the SM
→ 3a New particles
→ 3b Precision

Where could some light come from?

1.A theory breakthrough → 1a BSM; 1b Foundations (FT, QM)

1a Or the experimental sign of some of the great ideas (GUT, Susy, …)

2.Astrophysics, Cosmology → 2a DM; 2b B-asymmetry; 2c Gravity; 2d Inflation

3.An experimental deviation from the SM → 3a New particles; 3b Precision

Here, and with a view on the next decade or so,
focus on 3b, assuming (which requires) new physics in the MultiTeV

A difference in the two sectors of the SM?

$$\mathcal{L}_{SM} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\Psi}\not{D}\Psi$$

The "gauge sector"

$$+|D_\mu\phi|^2 + M^2|\phi|^2 - \lambda|\phi|^4 + \Lambda + \lambda_{ij}\phi\bar{\Psi}_i\Psi_j$$

The "Higgs sector"
(where the Fermi scale originates)

the hierarchy problem | the CC problem | the flavour problem

In EFT they look much the same

No particle mass calculable (15=17-2)

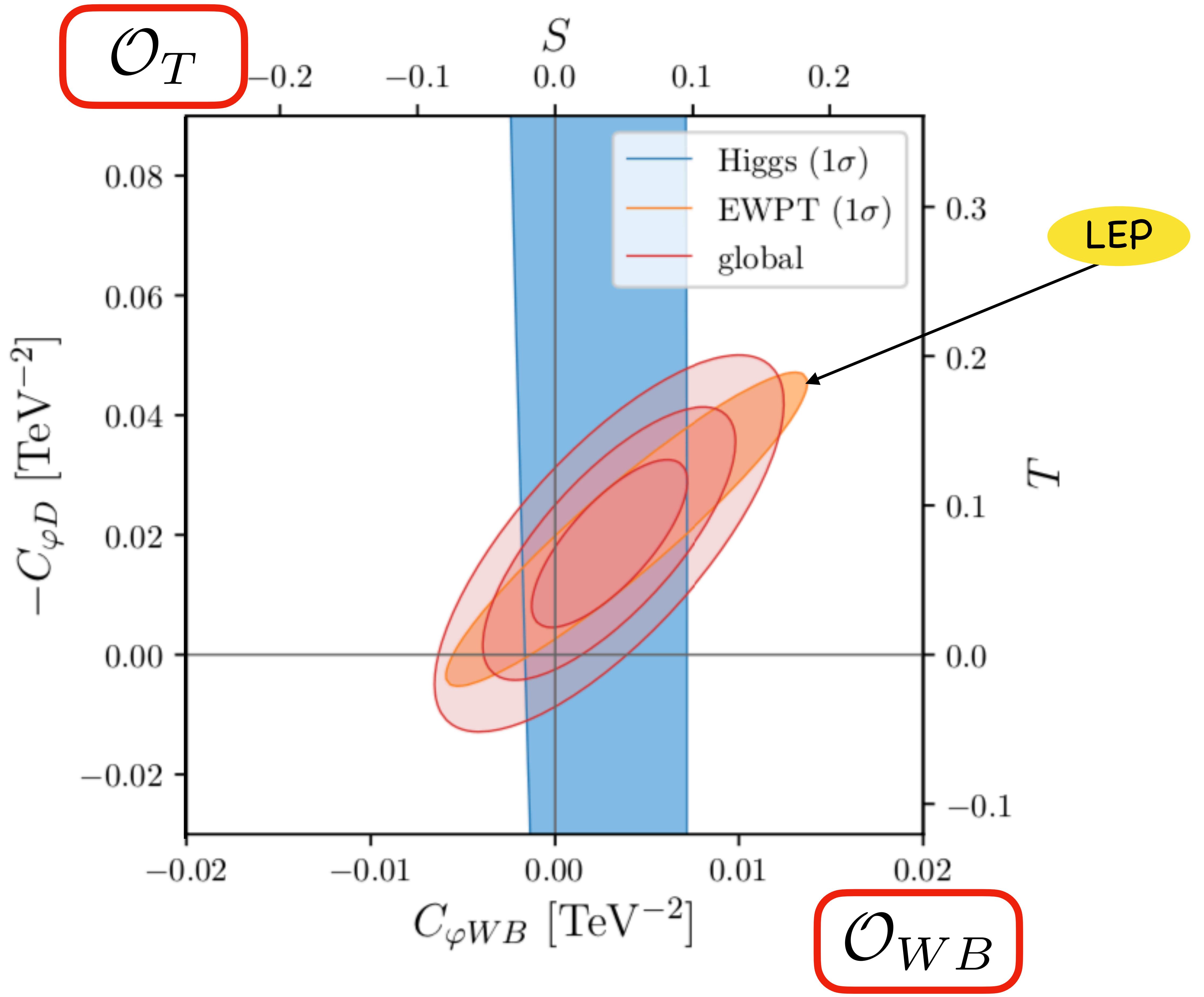
To me: the relatively best motivation for BSM in the MultiTeV

Three examples for the "best LEP" EFT coefficients

1. On shell measurements S, T

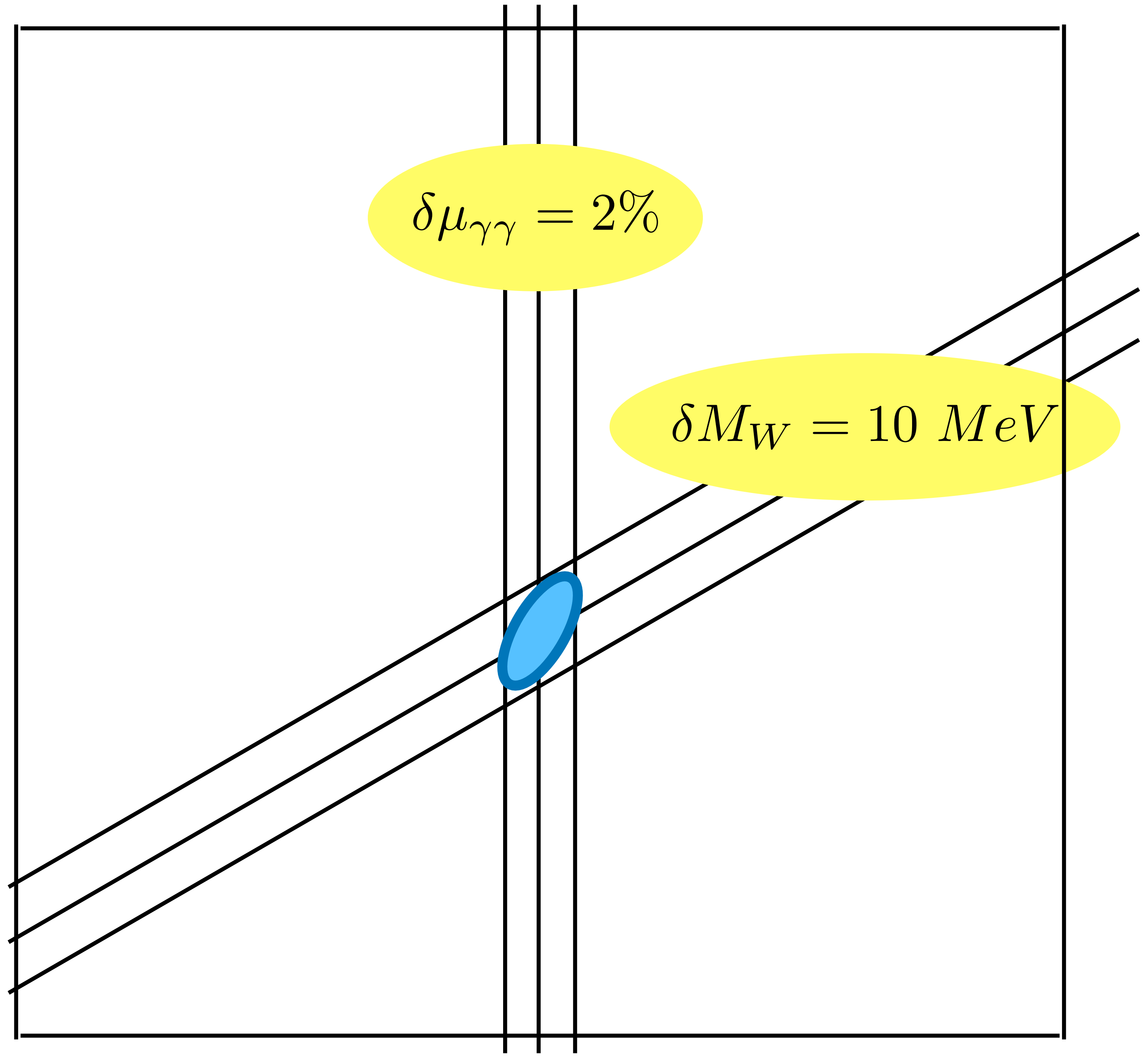
$\mathcal{O}_{WB} = g g' H^+ \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$ $\quad \mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$

$H \to \gamma\gamma$



Falkowski, Straub 2019

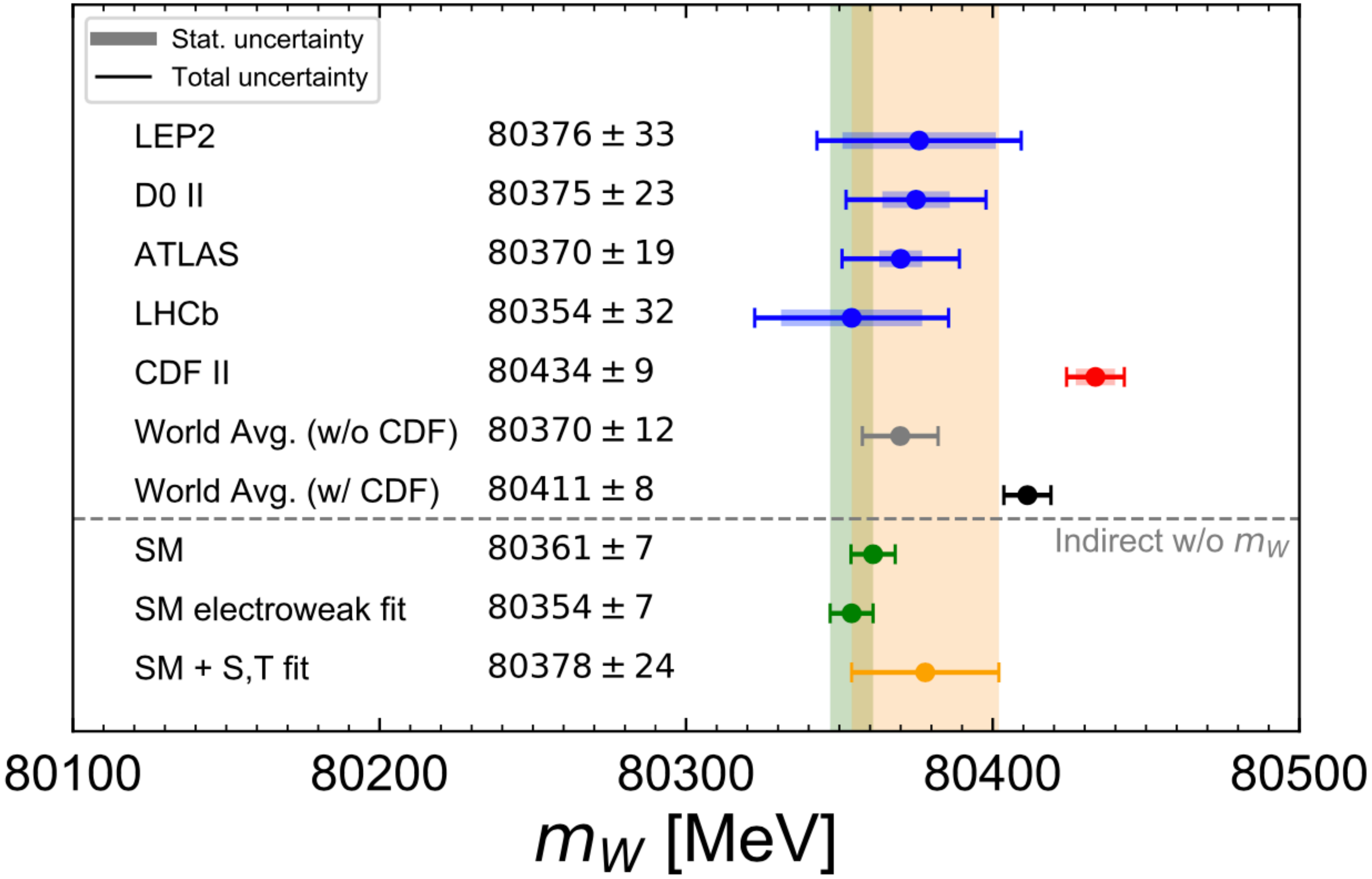
Projection with 2 observables only



(On the same scale as the plot on the left)

Example 1

M_W



Bagnaschi et al, 2022

$$\frac{\delta M_W}{M_W} = 0.7\hat{T} - 0.4\hat{S}$$

(2 more op.s in universal theories)

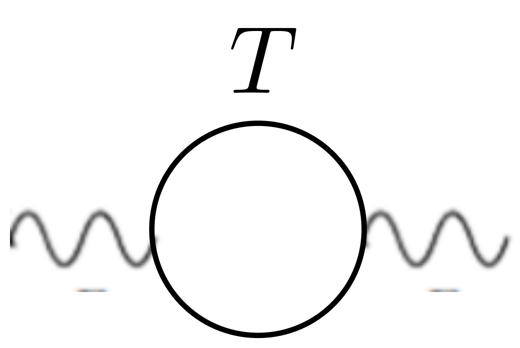
$$\left(\frac{\delta \sin^2_{eff}\theta}{\sin^2_{eff}\theta} = -1.4\hat{T}\right)$$

$$\frac{\delta \sin^2_{eff}\theta}{\sin^2_{eff}\theta}\Big|_{exp} = 10^{-3}$$

$$\frac{\delta M_W}{M_W}\Big|_{exp} = \frac{20\ MeV}{80\ GeV} = 2.5\cdot 10^{-4}$$

VectorLike Heavy top partners T

Ubiquitous in Composite Higgs

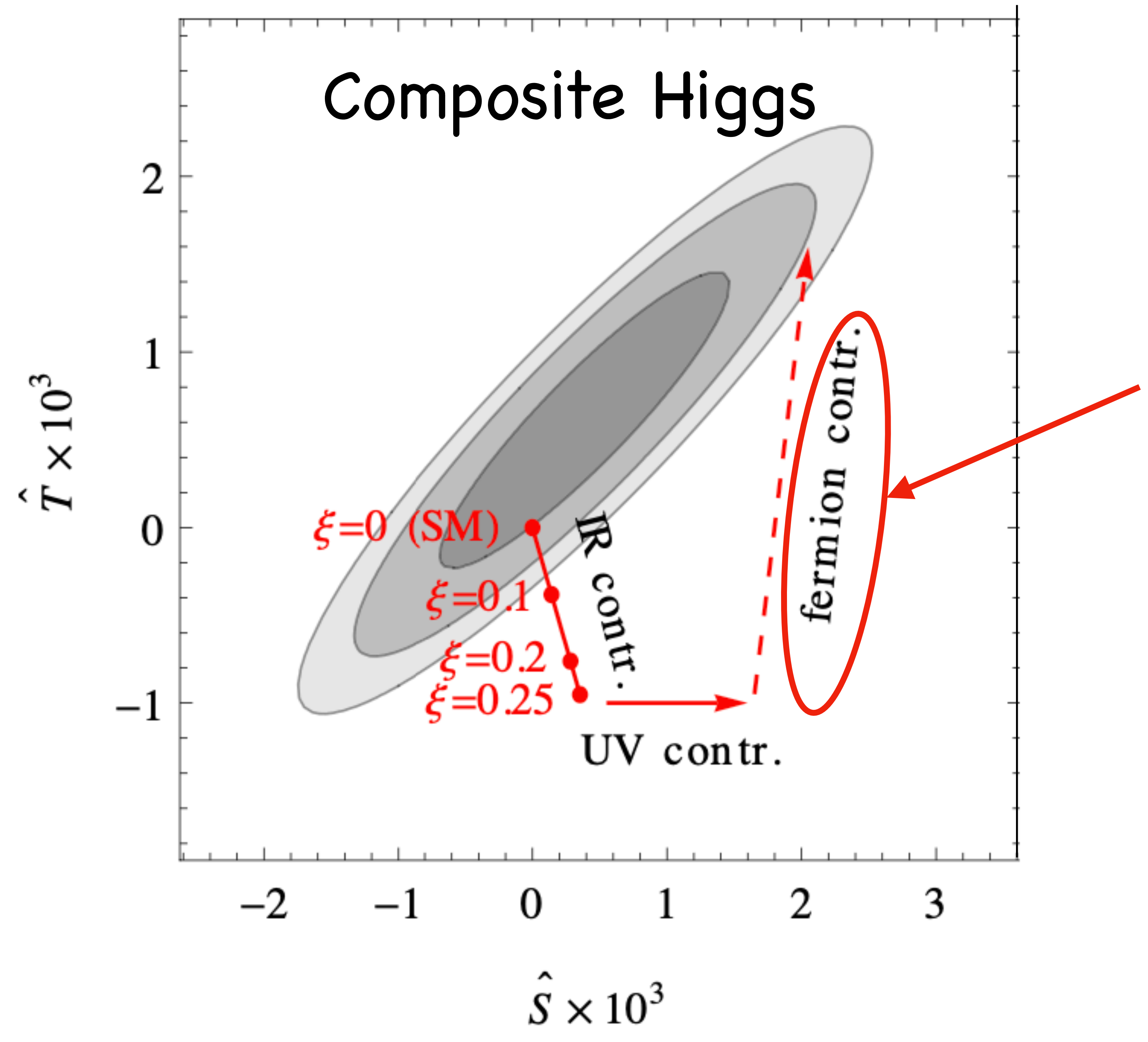


$$Y_T H \bar{q}_L T_R \longrightarrow \hat{T}(T) \approx \frac{3Y_T^2}{16\pi^2}\frac{m_t^2}{M_T^2}\lg\frac{M_T^2}{m_t^2}$$

$$Y_t H \bar{Q}_L t_R, \quad Q = \begin{pmatrix} T \\ B \end{pmatrix} \longrightarrow \hat{T}(T) \approx \frac{3Y_t^2}{8\pi^2}\frac{m_t^2}{M_T^2}\lg\frac{M_T^2}{m_t^2}$$

($\hat{S}, \delta g_b$ smaller)

	If CDF II	If $\delta M_W \lesssim 10\ MeV$
Singlet	$\frac{M_T}{Y_T} \approx (1.8 \div 2.2)\ TeV$	$\frac{M_T}{Y_T} \gtrsim (2.8 \div 3.5)\ TeV$
Doublet	$\frac{M_T}{Y_t} \approx (2.5 \div 3)\ TeV$	$\frac{M_T}{Y_t} \gtrsim (4 \div 5)\ TeV$

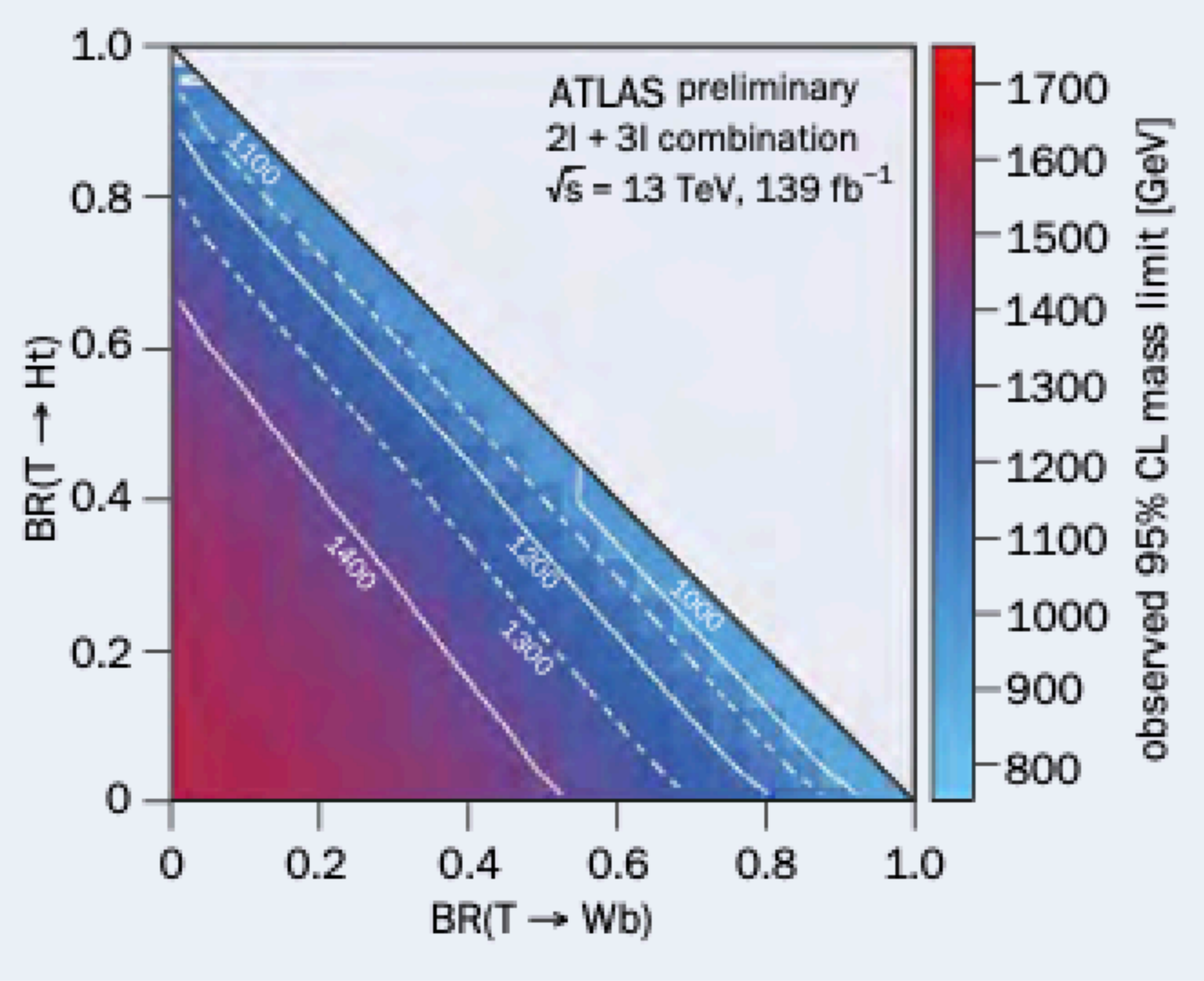


B,Bellazzini et al, 2007

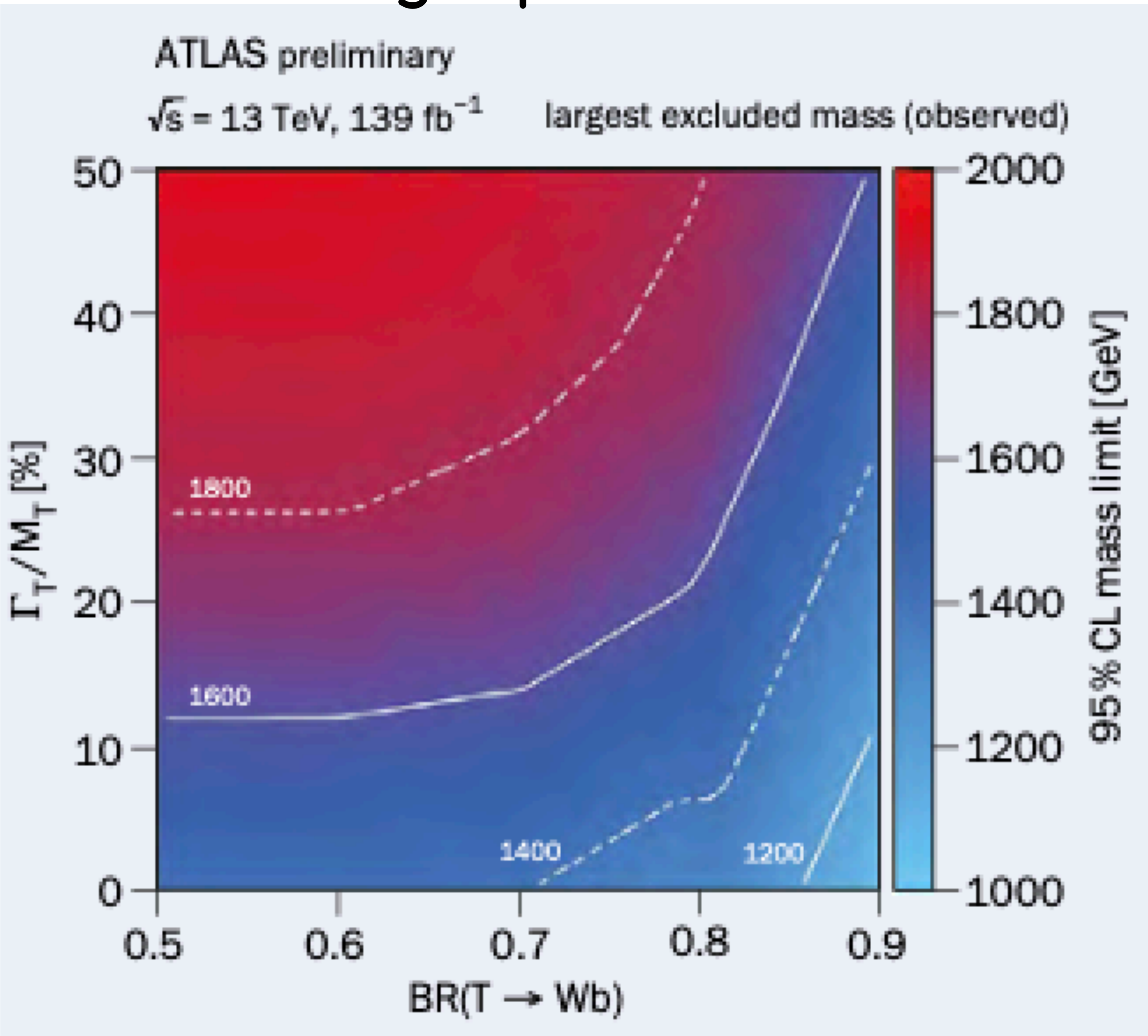
LHC searches of heavy T

$$T \to Ht, Wb$$

Pair production



Single production



Precision in the “near” future of BSM

Two definite goals:

Is there one Higgs boson only?

What is the scale of Higgs compositeness, if any?

What is the radius of Higgs compositeness, if any? $l_H = 1/m_*$

A two-parameter "theory"

———	$m_* = g_* f$
———	f
———	m_H

H = pNGB

f = scale of symmetry breaking

m_* = scale of Higgs compositeness

- Higgs couplings — $c_H \sim g_*^2/m_*^2$ — $\mathcal{O}_H = \frac{1}{2}(\partial_\mu |H|^2)^2$

- Universal ElectroWeak observables

Pole observables: $m_W, sin\theta^l_{eff}$

DiBoson production: Wh, Zh, WZ, WW

Drell-Yan $l^+l^-, l\nu$ at high m_{ll}, m^T_{ll}

$c_W \sim 1/m_*^2$

$c_W \sim 1/m_*^2$

$c_{2W} \sim 1/g_*^2 m_*^2$

$\mathcal{O}_W = \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) D^\nu W^a_{\mu\nu}$

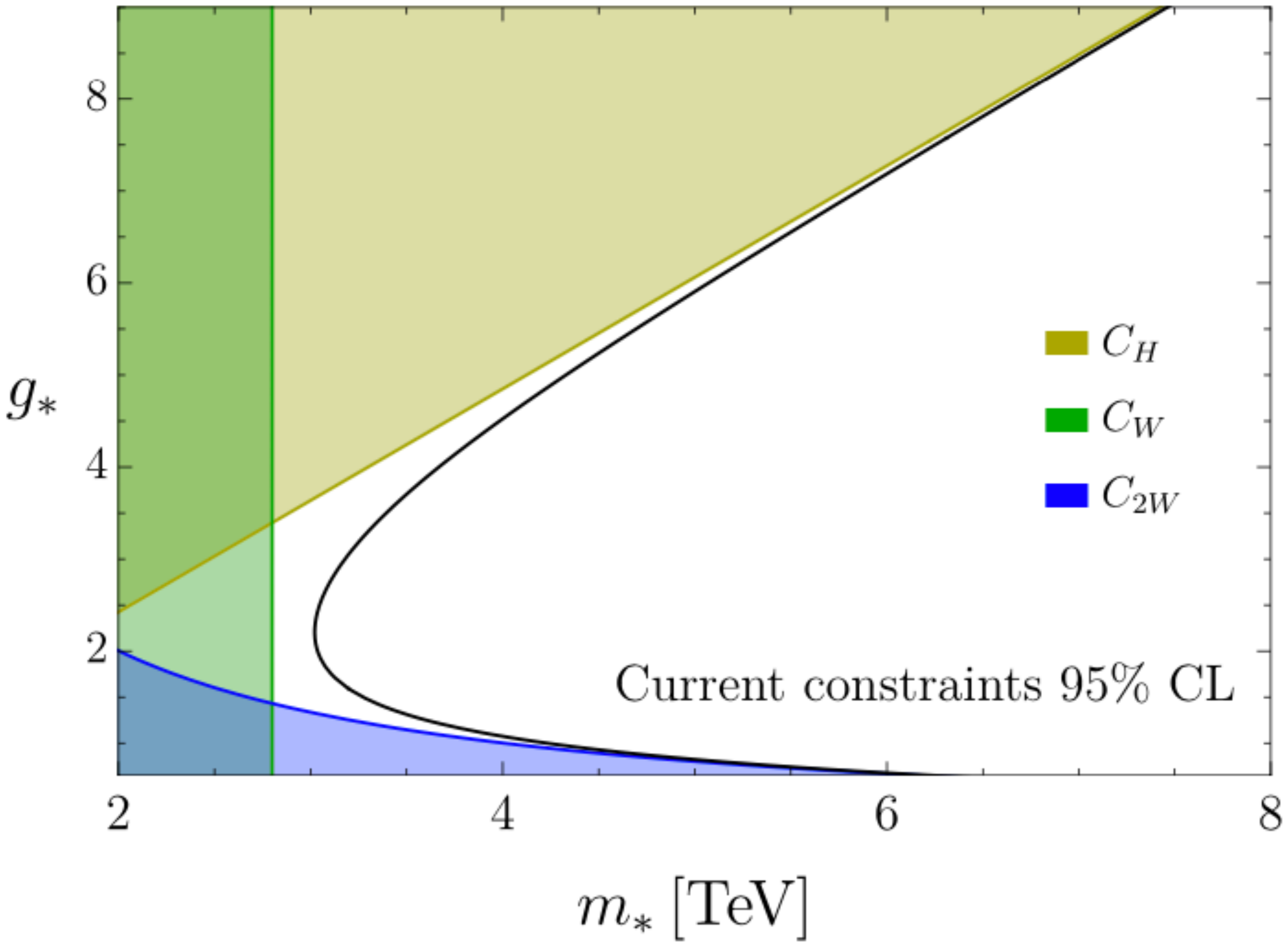
$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$

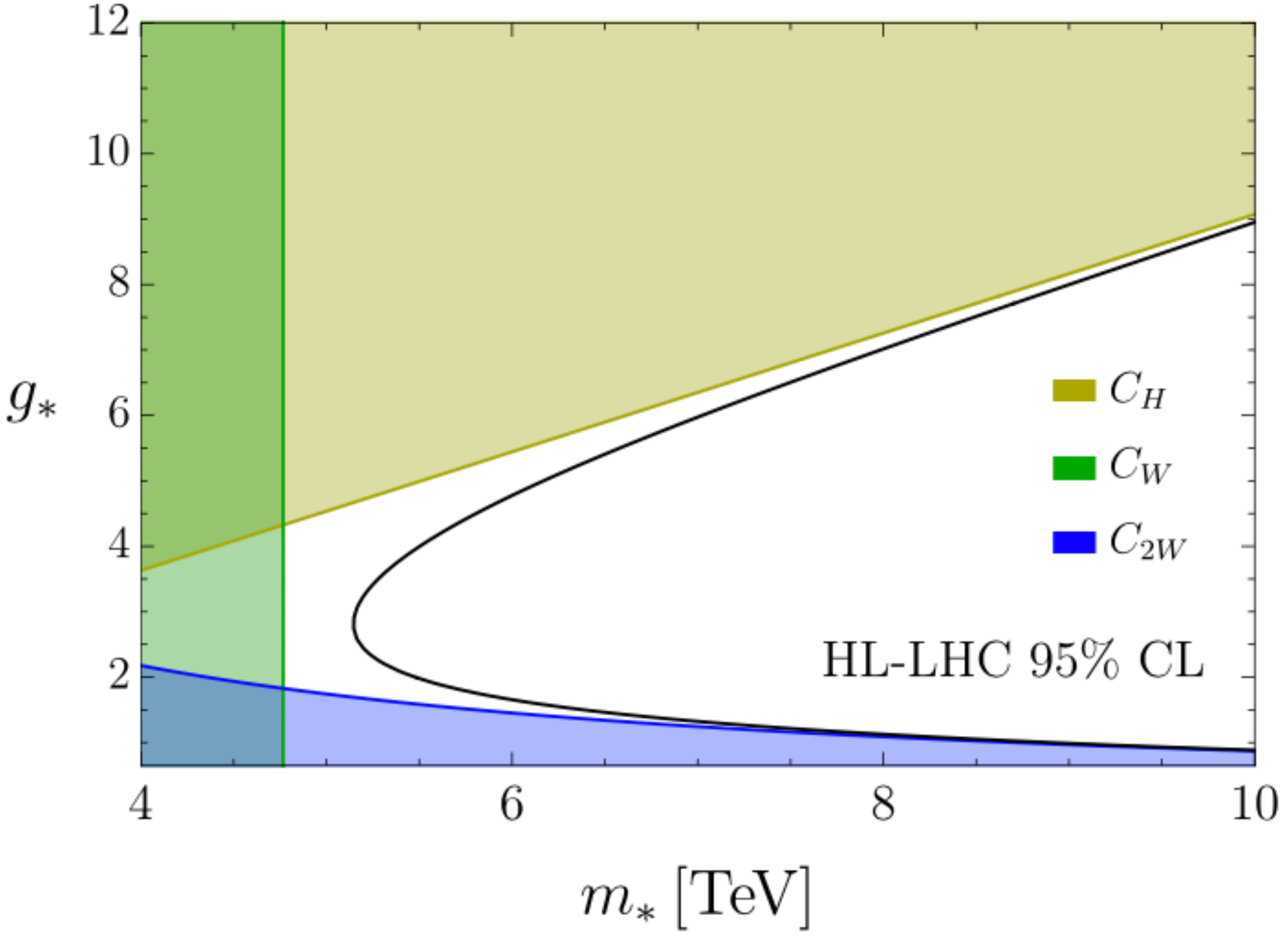
- flavour observables — $g_*^2/m_*^2, g_*/m_*^2, 1/m_*^2$

Universal observables in composite Higgs

$$\mathcal{L}_{\mathrm{EFT}} = \frac{m_*^4}{g_*^2}\hat{\mathcal{L}}\left[\frac{\partial}{m_*}, \frac{g_* H}{m_*}, \frac{g_*\sigma}{m_*}, \frac{g_*\Psi}{m_*^{3/2}}, \frac{gA}{m_*}, \frac{\lambda\psi}{m_*^{3/2}}\right]$$

SILH, 2007





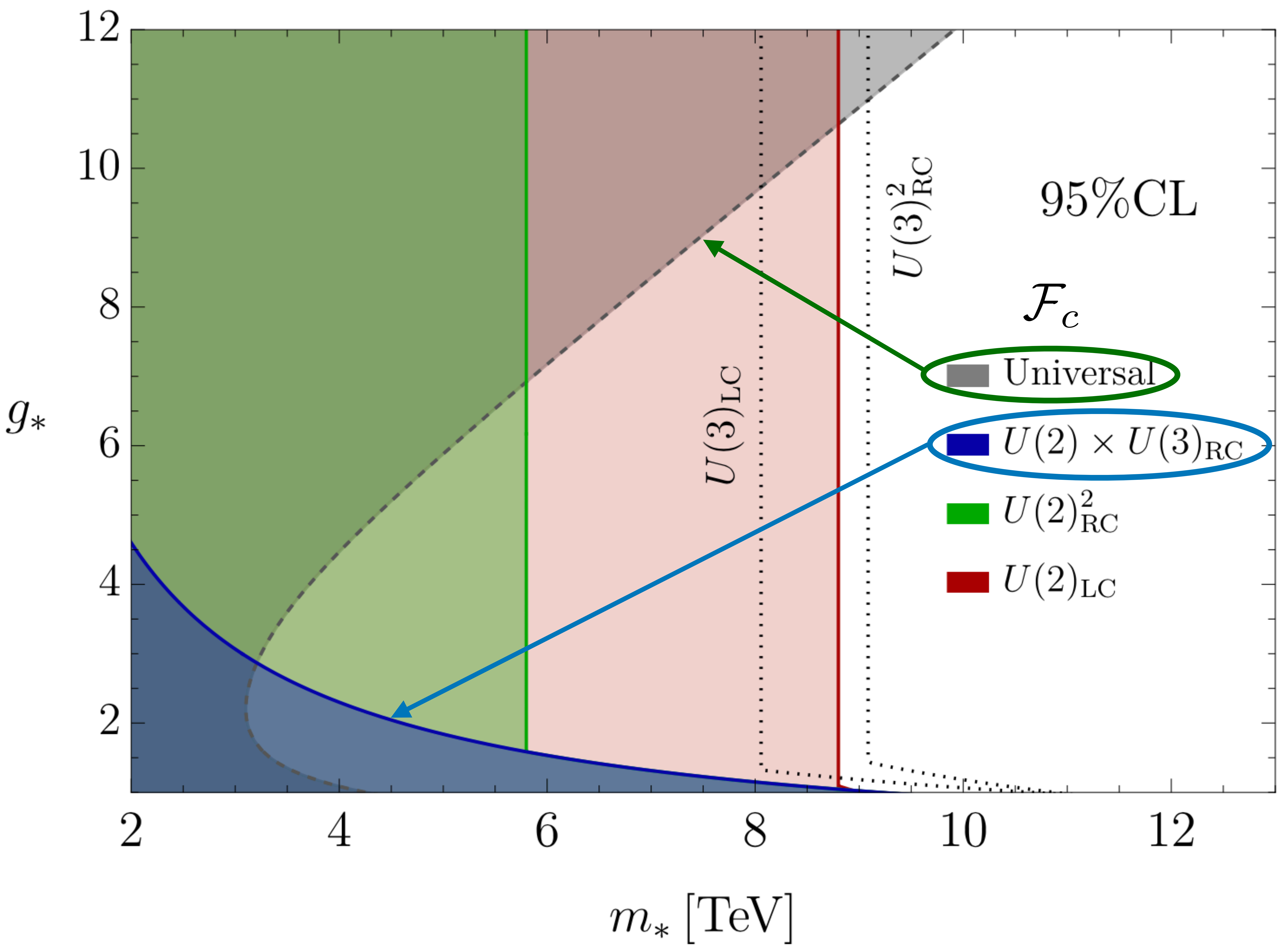
Glioti et al, 2022

Flavour in composite Higgs

Different flavour symmetries $\mathcal{F}_c$ of the strong sector

$$U(3)_q \times U(3)_u \times U(3)_d \times \mathcal{F}_c$$

(but no LFU violations)



Current constraints

Glioti et al, 2022

A projection of the future sensitivity on some key observables

	Observable	Current best	Belle II 50 ab^{-1}	Belle II 250 ab^{-1}	LHCb 50 fb^{-1}	LHCb 300 fb^{-1}
	Lepton-flavor-universality tests					
$b \to s\, ll$	$R_K(1 < q^2 < 6\ GeV^2)$	0.044 [40]	0.036	0.016	0.017	0.007
	$R_{K^*}(1 < q^2 < 6\ GeV^2)$	0.12 [41]	0.032	0.014	0.022	0.009
$b \to cl\nu$	$R(D)$	0.037 [42]	0.008	< 0.003	na	na
	$R(D^*)$	0.018 [42]	0.0045	< 0.003	0.005	0.002

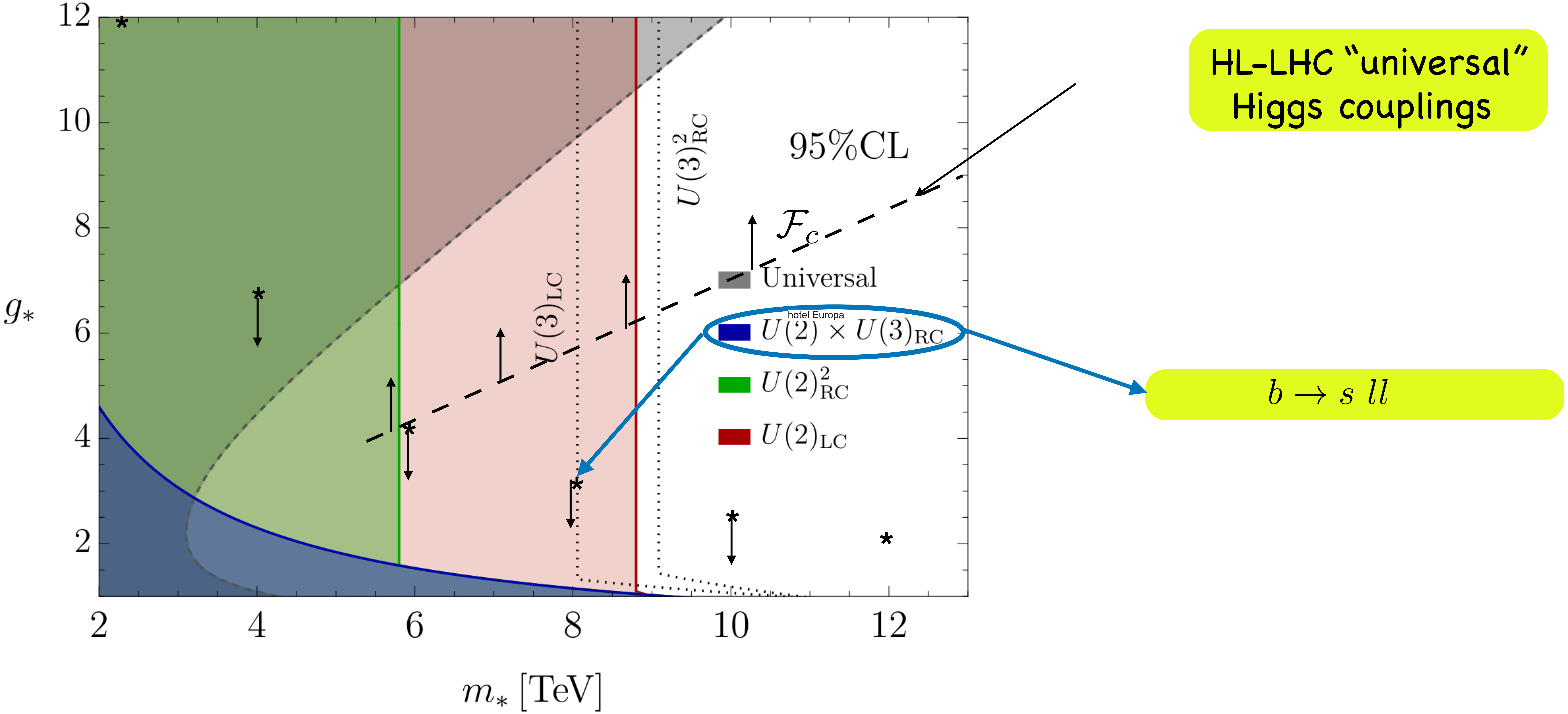
Artuso et al, 2022

Flavour in composite Higgs (prospects)

Different flavour symmetries $\mathcal{F}_c$ of the strong sector

$$U(3)_q \times U(3)_u \times U(3)_d \times \mathcal{F}_c$$

(but no LFU violations)



m_* explorable well inside the MultiTeV

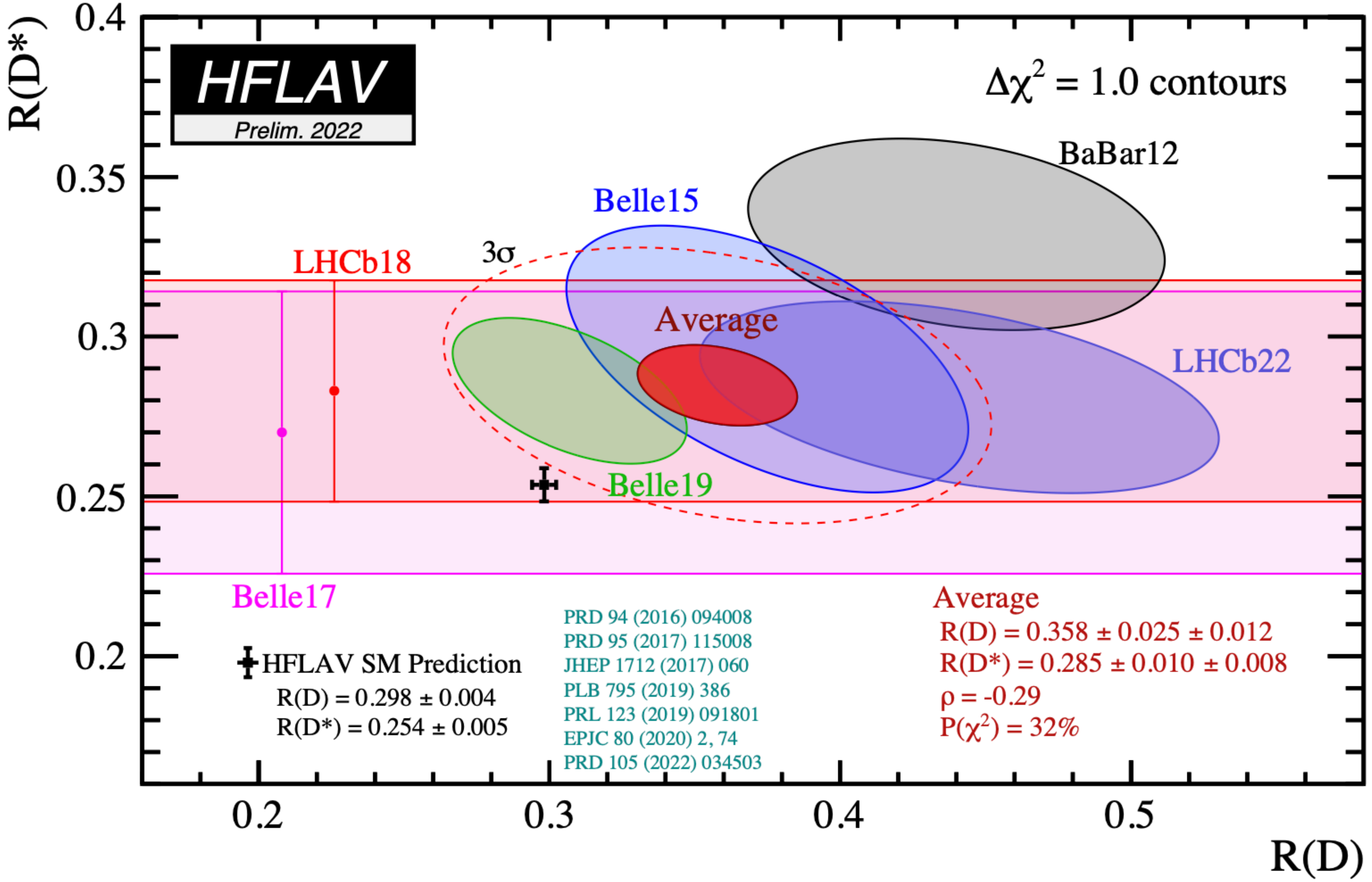
From the last page of Rabi's book

"I thought that my voyage had come to its end at the last limit of my power—that, the path before me was closed, that provisions were exhausted and the time come to take shelter in a silent obscurity.

But I find that thy will knows no end in me. And when old words die out on the tongue, new melodies break forth from the heart; and where the old tracks are lost, new country is revealed with its wonders."

GITANJALI, RABINDRA NATH TAGORE

Cheers to Rabi ... and to the BSM



LHCb seminar, CERN October 18, 2022

Flavour in composite Higgs

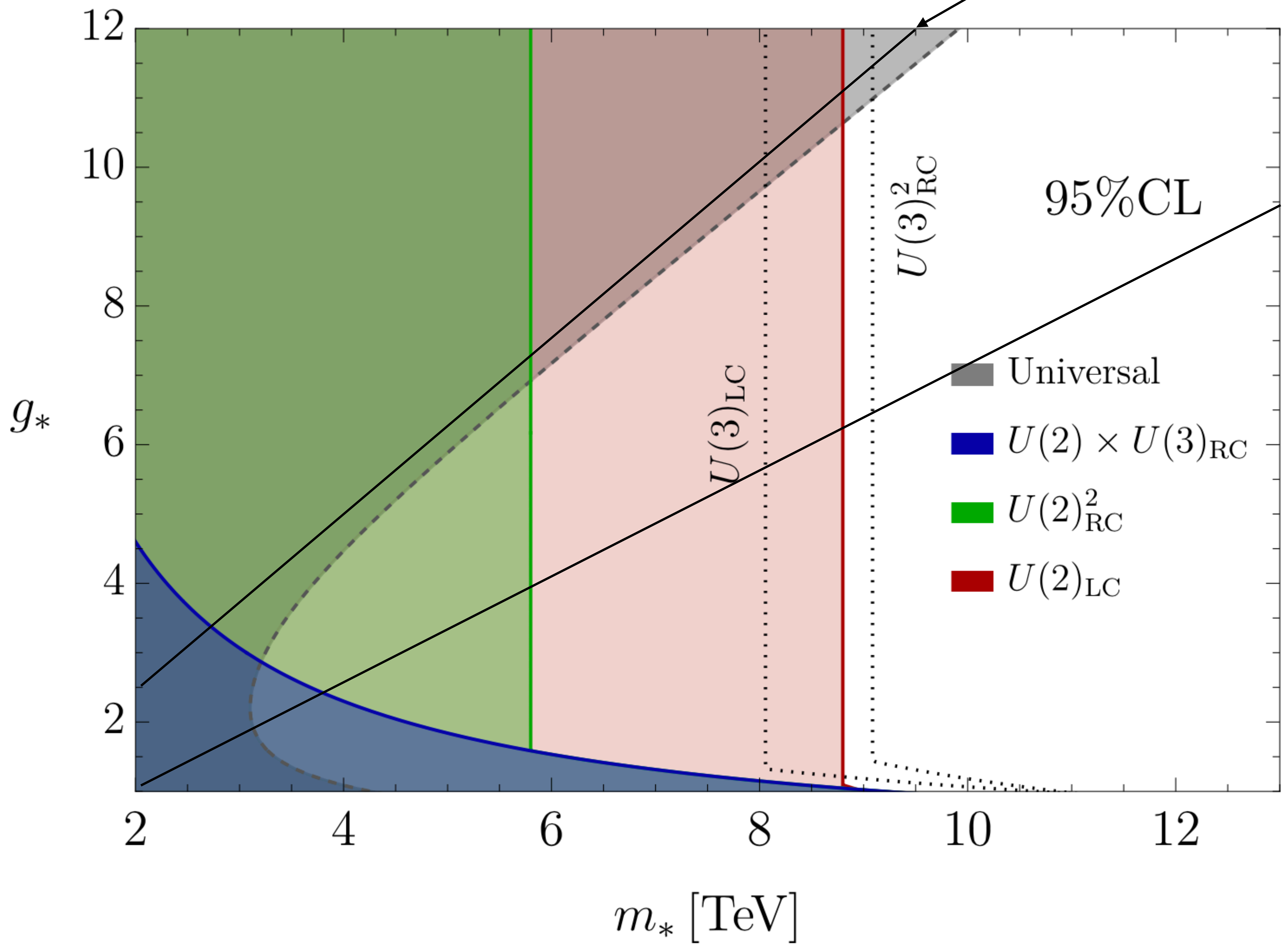
(but no LFU violations)

If $g_U \to g_*$ and $m_U \to m_*$

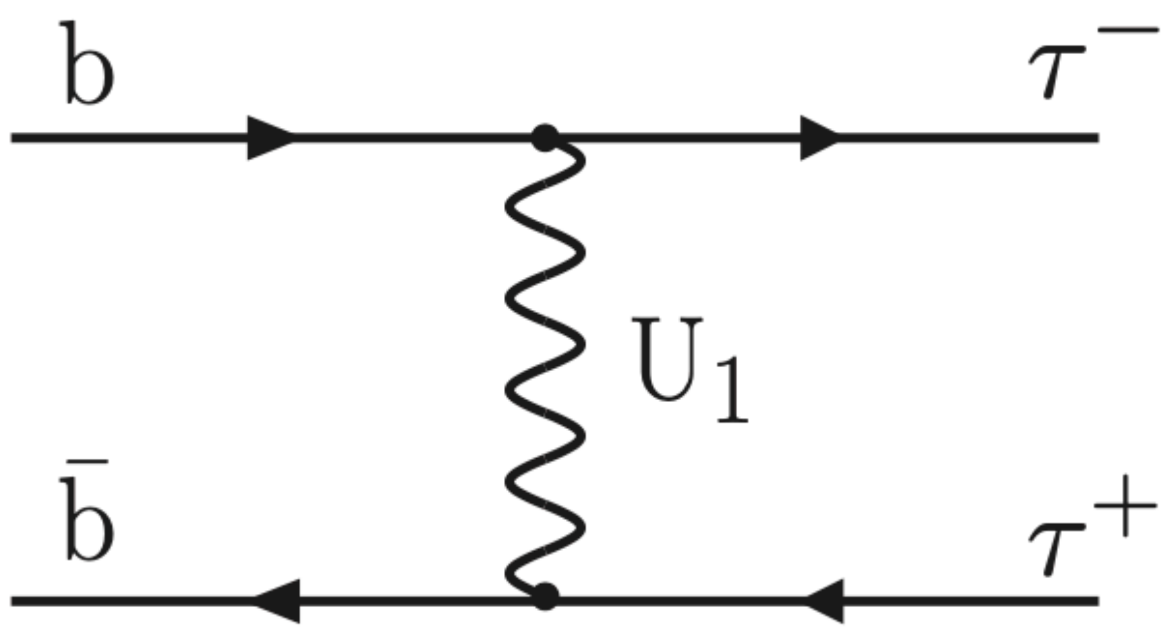
$m_{eff} = 0.8\ TeV$

$m_{eff} = \frac{M_U}{g_U}$

$m_{eff} = 1.5\ TeV$

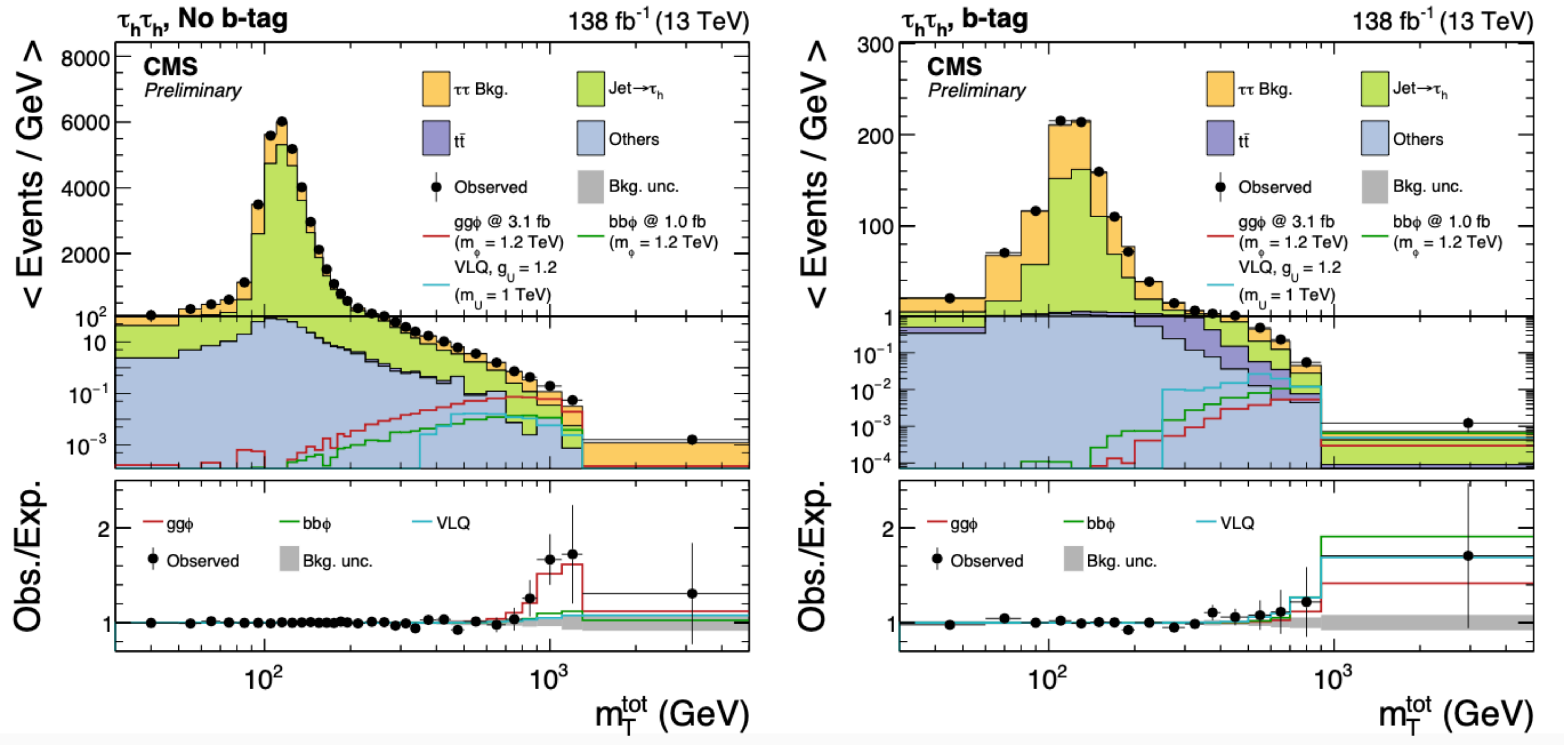


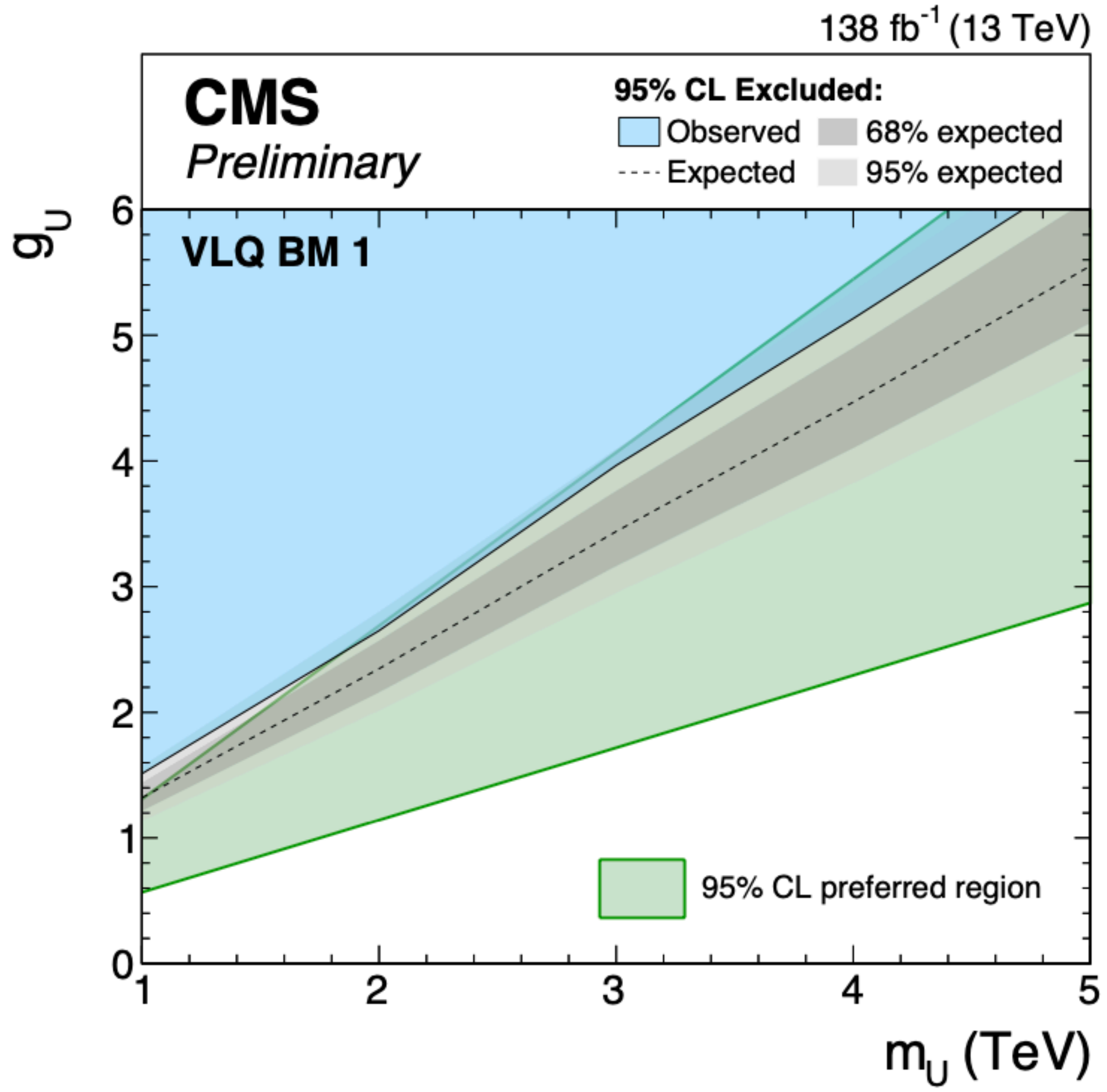
t-channel vector lepto-quark exchange



$$A \propto \left(\frac{g_U}{\sqrt{2}}\right)^2 \frac{1}{M_U^2}$$

($pp \to \tau\mu, \mu\mu$ weaker)





$$m_{eff} \equiv \frac{m_U(TeV)}{g_U} \approx 0.8 \div 1.5$$

Observational

Problems of (questions for) the SM

Structural

0. Which rationale for matter quantum numbers?

$$|Q_p + Q_e - Q_n| < 10^{-21} e$$

1. Phenomena unaccounted for

neutrino masses
Dark matter
matter-antimatter asymmetry
inflation?

2. Why $\theta \lesssim 10^{-10}$?

$$\theta G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Axions? A discrete space-time symmetry?

3. $\mathcal{O}_i : d(\mathcal{O}_i) \leq 4$ only?

neutrino masses
gravity?
Are the protons forever?

4. Lack of calculability

the hierarchy problem
the flavour problem

Three examples for the "best LEP" EFT coefficients

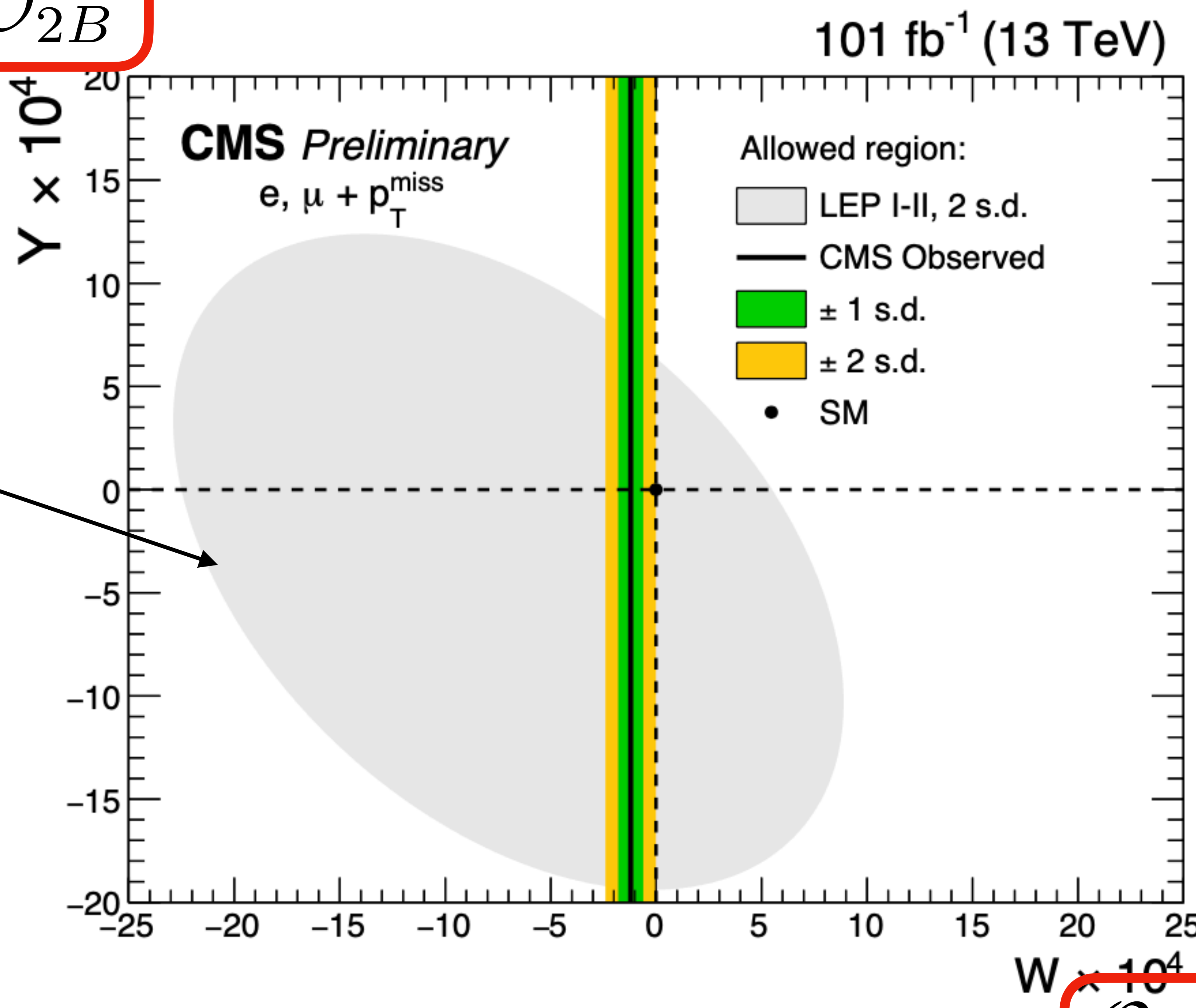
2. Off shell measurements W, Y

$\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$ $\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$

$pp \to l\nu, ll$

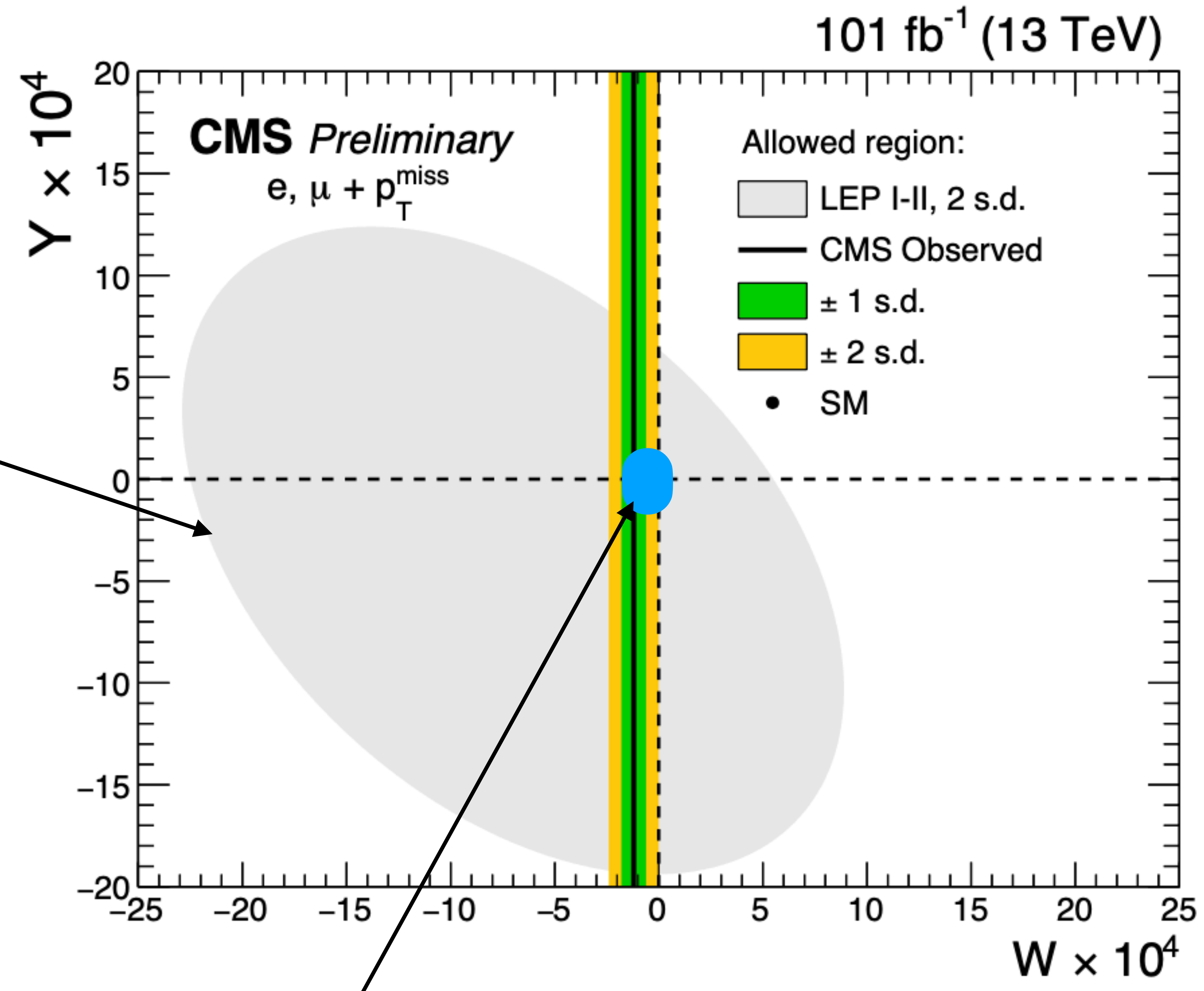
$\mathcal{O}_{2B}$

LEP



$\mathcal{O}_{2W}$

LEP



HL-LHC $W \to 4 \cdot 10^{-5}$ $Y \to 8 \cdot 10^{-5}$

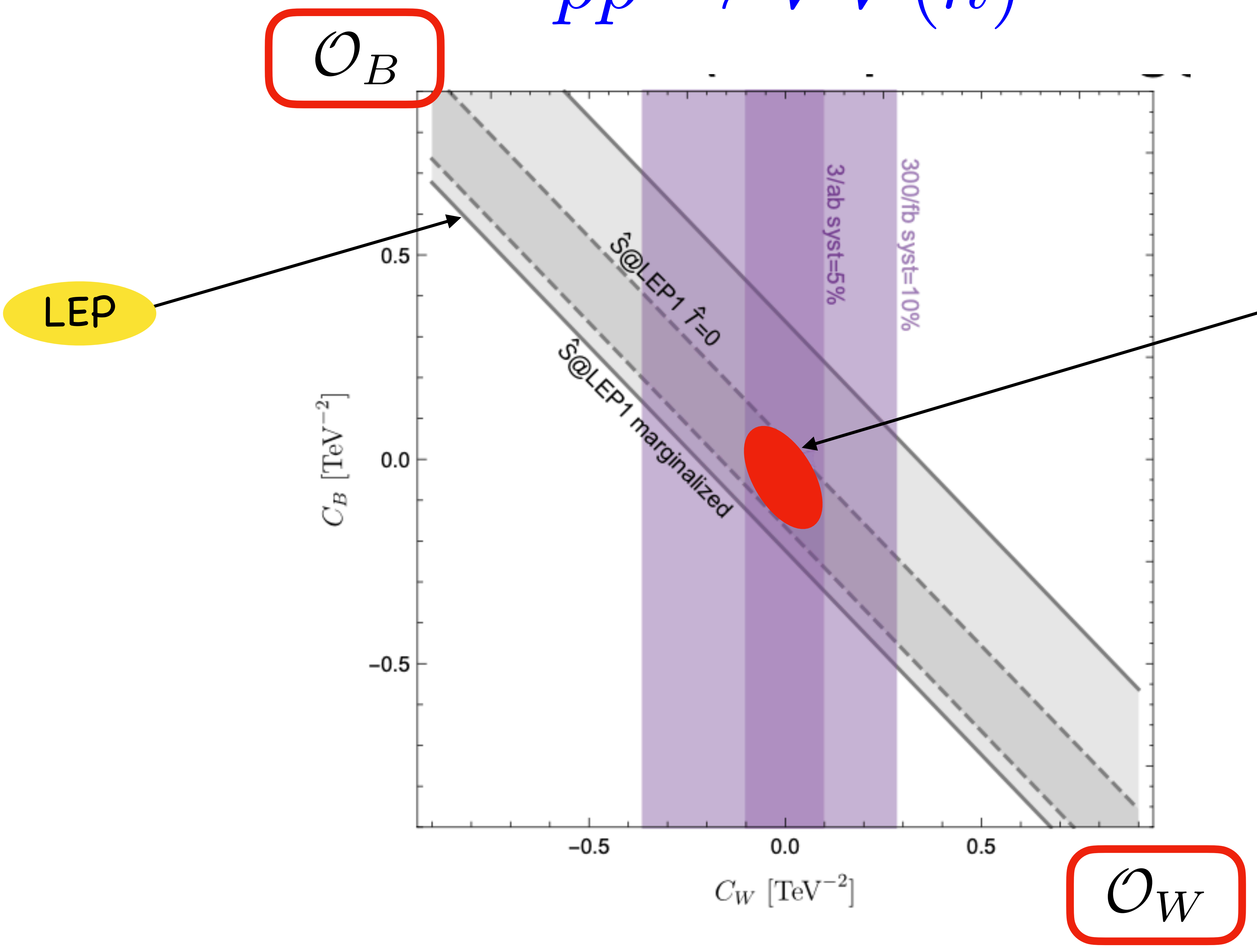
Panico et al, 2021

Three examples for the "best LEP" EFT coefficients

2. Off shell measurements

$$\mathcal{O}_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial^\nu B_{\mu\nu} \qquad \mathcal{O}_W = \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H)D^\nu W^a_{\mu\nu}$$

$pp \to VV(h)$



Franceschini et al, 2018