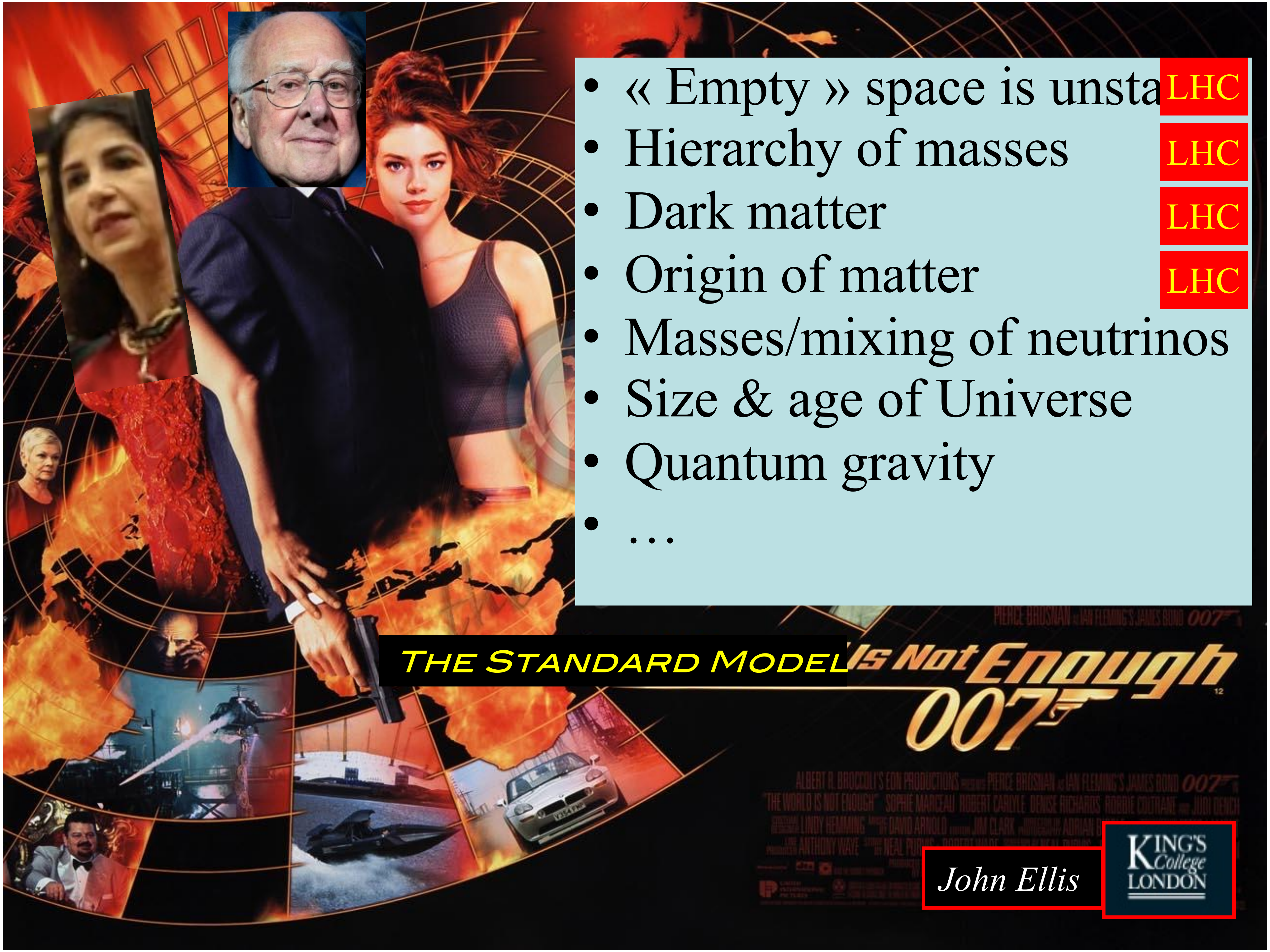
John Ellis

KING'S College LONDON



- « Empty » space is unsta LHC
- Hierarchy of masses LHC
- Dark matter LHC
- Origin of matter LHC
- Masses/mixing of neutrinos
- Size & age of Universe
- Quantum gravity
- …

THE STANDARD MODEL

John Ellis

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Everything about Higgs is Puzzling

$$\boxed{\mathcal{L} = yH\psi\overline{\psi} + \mu^2|H|^2 - \lambda|H|^4 - V_0} \boxed{+ \ldots}$$

- Pattern of Yukawa couplings y:
  - **Flavour problem**
- Magnitude of mass term μ:
  - **Naturalness/hierarchy problem**
- Magnitude of quartic coupling λ:
  - **Stability of electroweak vacuum**
- Cosmological constant term V_0:
  - **Dark energy**

Higher-dimensional interactions?

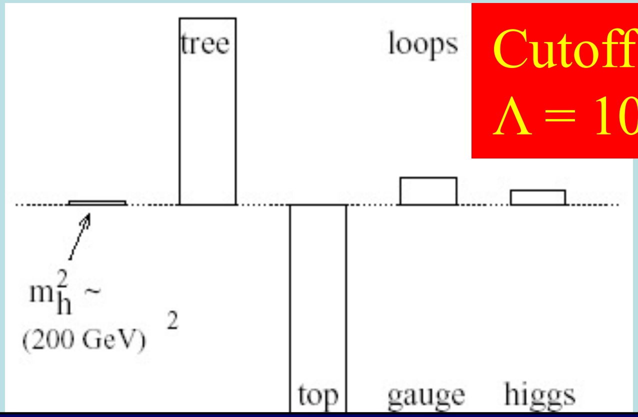
Theoretical worries about the Higgs boson

Elementary Higgs or Composite?

- Higgs field:

$$v = \langle 0|H|0\rangle \neq 0$$

- Quantum loop problems
- M_h, v, other masses have quadratic divergences



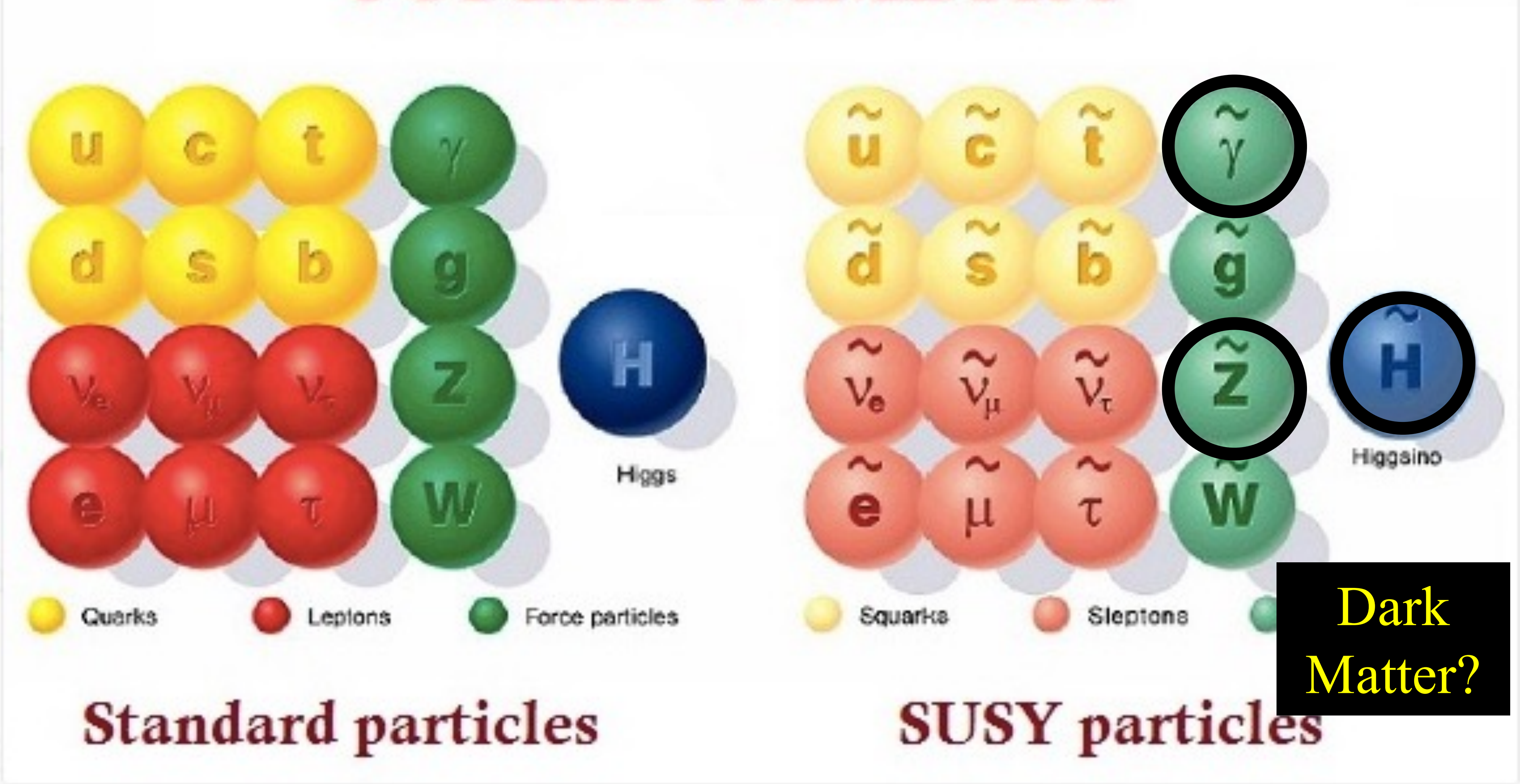
Cutoff
$\Lambda = 10$ TeV

Cut-off $\Lambda \sim 1$ TeV with
Supersymmetry?

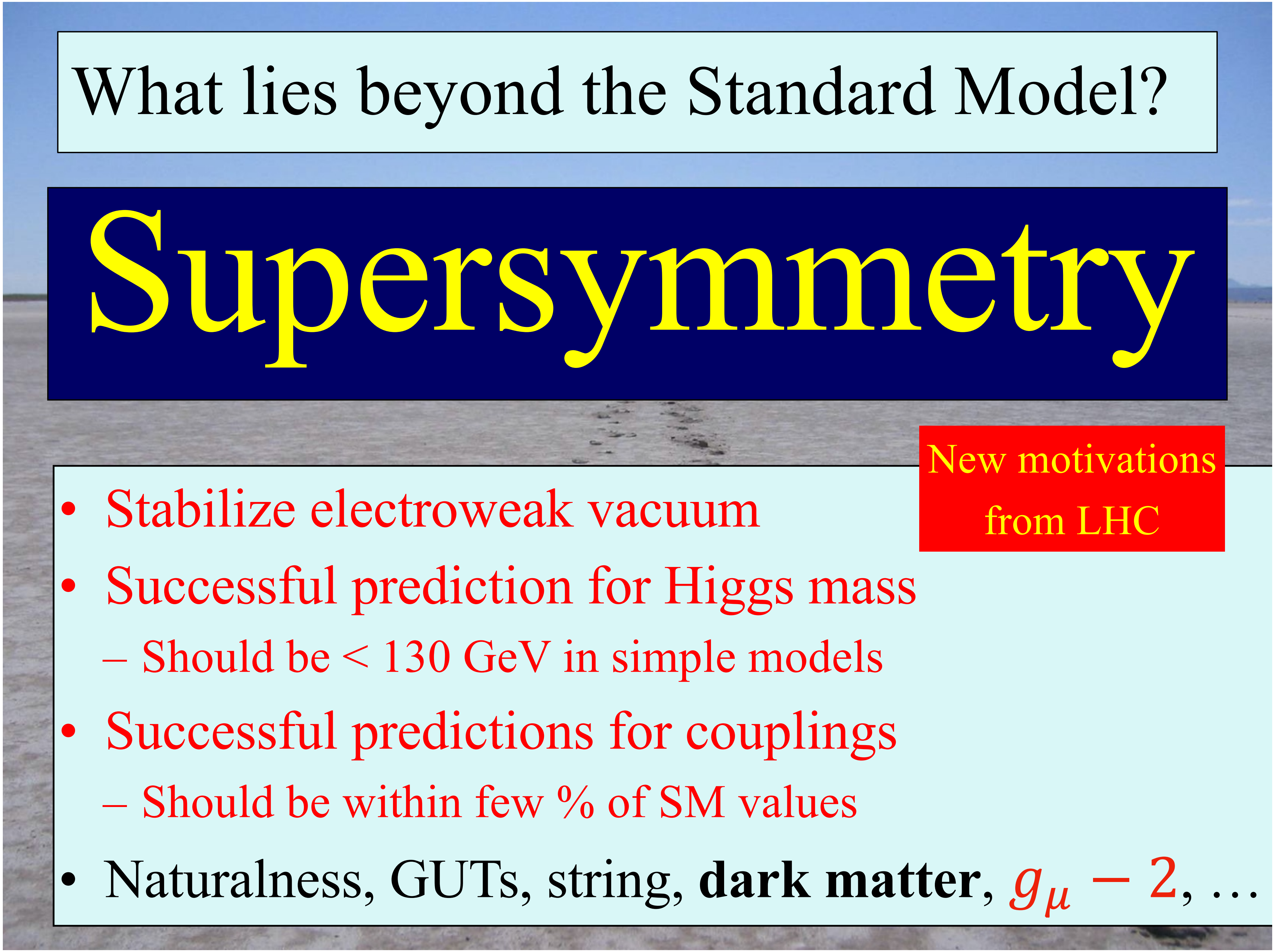
- Fermion-antifermion condensate?
- Just like π in QCD, Cooper pairs in BCS superconductivity
- Need new ‘technicolour’ force

- Heavy scalar resonance?
- (Problems with precision electroweak data)
- Pseudo-Nambu-Goldstone boson?

Minimal Supersymmetric Extension of the Standard Model



Dark Matter?



What lies beyond the Standard Model?

Supersymmetry

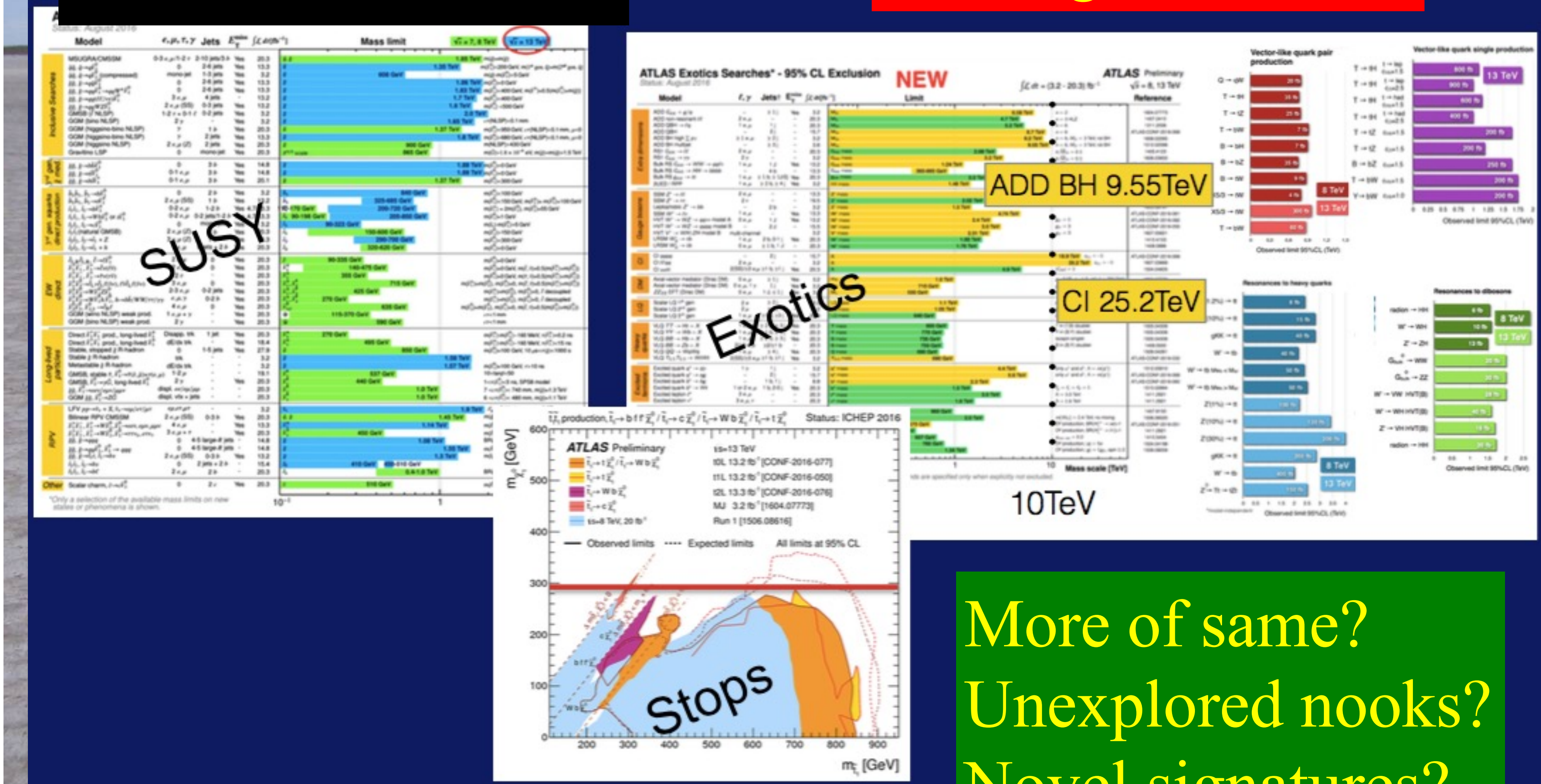
New motivations from LHC

- Stabilize electroweak vacuum
- Successful prediction for Higgs mass
  - Should be < 130 GeV in simple models
- Successful predictions for couplings
  - Should be within few % of SM values
- Naturalness, GUTs, string, **dark matter**, $g_\mu - 2$, …

Nothing (yet) at the LHC

No supersymmetry

Nothing else, either



More of same?
Unexplored nooks?
Novel signatures?

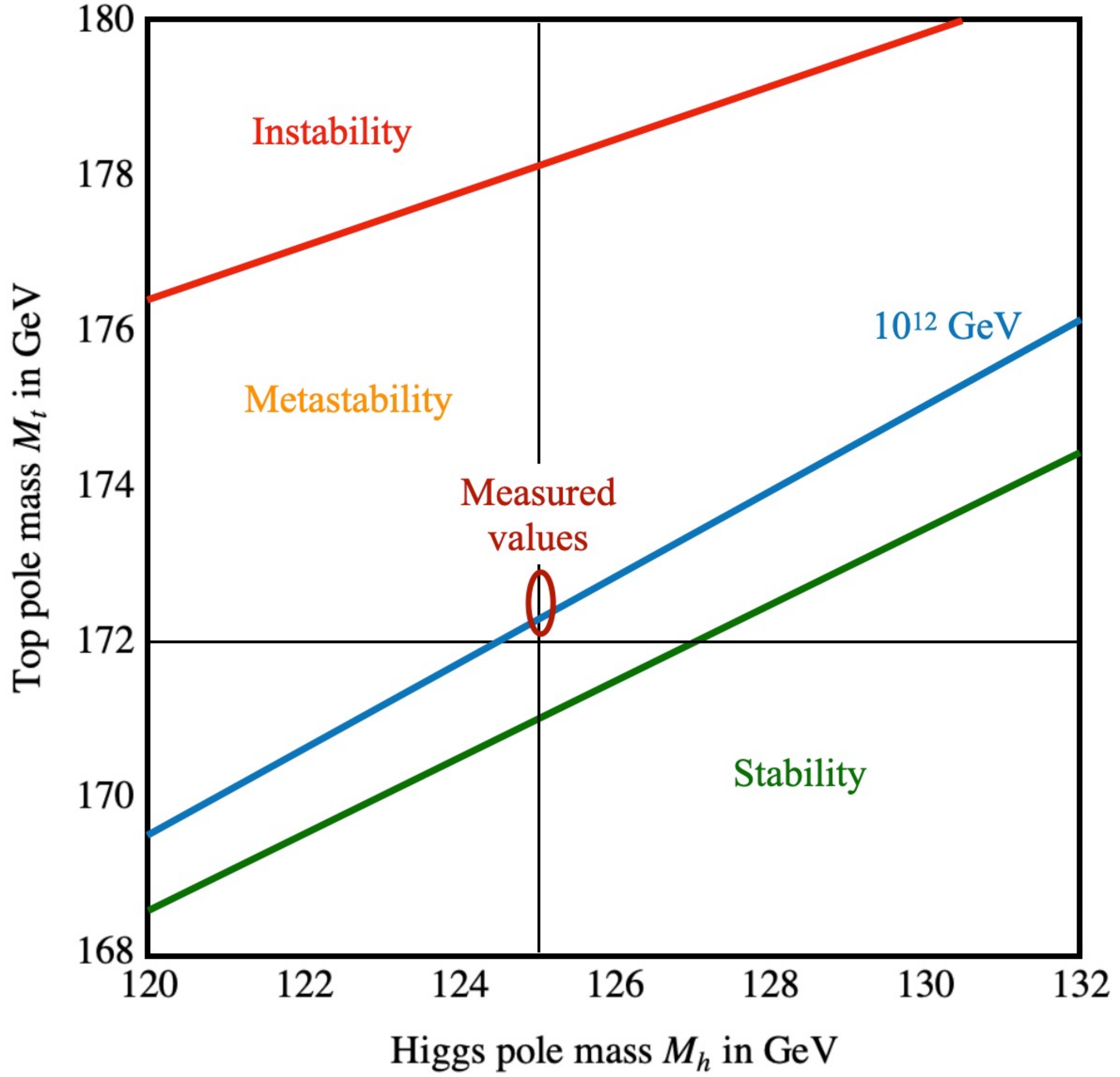
Is “Empty Space” Unstable?

Politzer & Wolfram,
Hung,
Cabibbo, Maiani, Parisi & Petronzio;

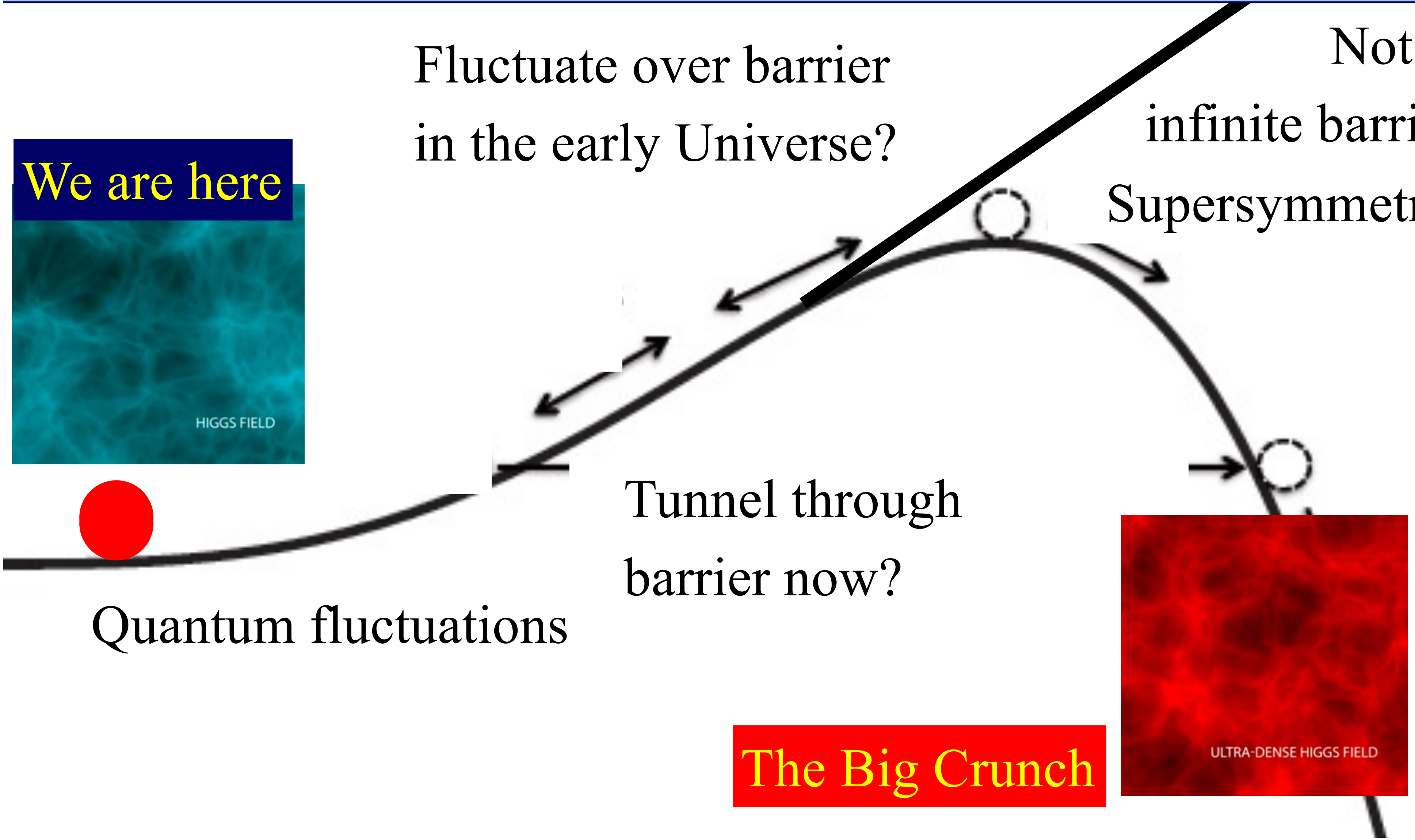
Depends on masses of Higgs boson and top quark, strong coupling

Instability scale
~ 10^{12} GeV

Buttazzo et al, arXiv:1307.3536;
Franceschini et al, 2203.17197



Will the Universe Collapse?
Should it have Collapsed already?



Fluctuate over barrier
in the early Universe?

Not if
infinite barrier:
Supersymmetry?

We are here

Tunnel through
barrier now?

Quantum fluctuations

The Big Crunch

Is “Empty Space” Unstable?

- Dependence of instability scale on masses of Higgs boson and top quark, and strong coupling:

$$\mathrm{Log}_{10}\frac{\Lambda}{\mathrm{GeV}} = 10.5 - 1.3\left(\frac{m_t}{\mathrm{GeV}} - 172.6\right) + 1.1\left(\frac{m_H}{\mathrm{GeV}} - 125.1\right) + 0.6\left(\frac{\alpha_s(m_Z) - 0.1179}{0.0009}\right)$$

Buttazzo et al, arXiv:1307.3536;
Franceschini et al, 2203.17197

- New CMS value of m_t:

$$m_t = 171.77 \pm 0.38\mathrm{GeV}$$

CMS Collaboration, April 2022

- Particle Data Group values:

$$m_H = 125.25 \pm 0.17\mathrm{GeV}, \alpha_s(m_Z) = 0.1179 \pm 0.0009$$

- Instability scale:

$$\mathrm{Log}_{10}\frac{\Lambda}{\mathrm{GeV}} = 11.7 \pm 0.8$$

- Dominant uncertainties those in α_s and m_t

Comments on Dark Energy

- Many orders of magnitude smaller than expected contributions from ‘known’ physics:

today: 10^{-48} GeV^4

QCD: $\Lambda_{QCD}{}^4 \sim 10^{-4}$ GeV^4

Higgs: $m_W{}^4 \sim 10^8$ GeV^4

Broken susy: $m_{susy}{}^4 \sim 10^{12}$ GeV^4

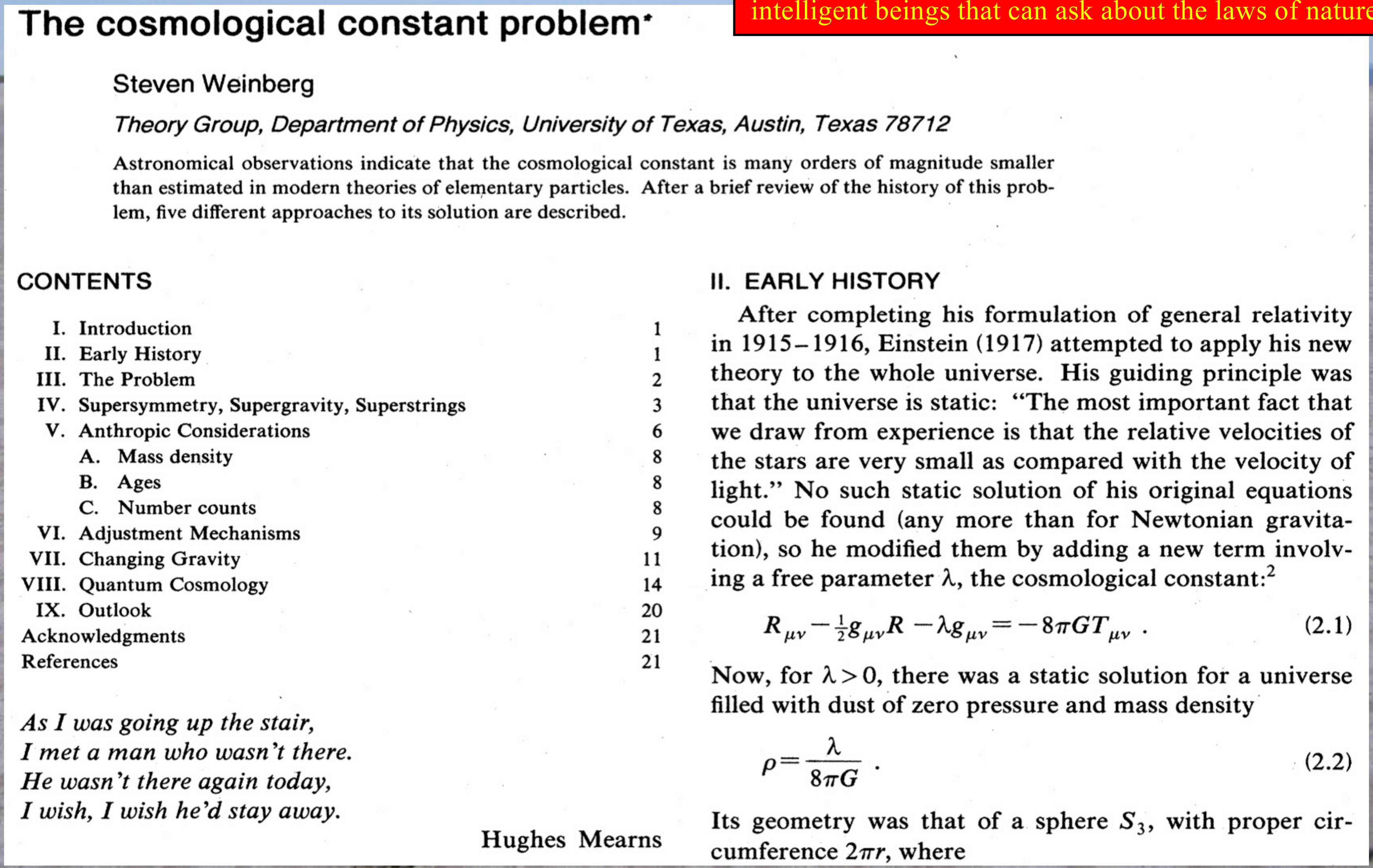
GUT: $m_{GUT}{}^4 \sim 10^{64}$ GeV^4

Quantum Gravity: $m_P{}^4 \sim 10^{76}$ GeV^4

- Need new physics!
- A great challenge for string theory

Weinberg: Anthropic Estimate of the Cosmological Constant

"… the laws of nature should allow the existence of intelligent beings that can ask about the laws of nature …"



The cosmological constant problem*

Steven Weinberg

Theory Group, Department of Physics, University of Texas, Austin, Texas 78712

Astronomical observations indicate that the cosmological constant is many orders of magnitude smaller than estimated in modern theories of elementary particles. After a brief review of the history of this problem, five different approaches to its solution are described.

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As I was going up the stair,
I met a man who wasn't there.
He wasn't there again today,
I wish, I wish he'd stay away.

Hughes Mearns

II. EARLY HISTORY

After completing his formulation of general relativity in 1915–1916, Einstein (1917) attempted to apply his new theory to the whole universe. His guiding principle was that the universe is static: "The most important fact that we draw from experience is that the relative velocities of the stars are very small as compared with the velocity of light." No such static solution of his original equations could be found (any more than for Newtonian gravitation), so he modified them by adding a new term involving a free parameter λ, the cosmological constant:[2]

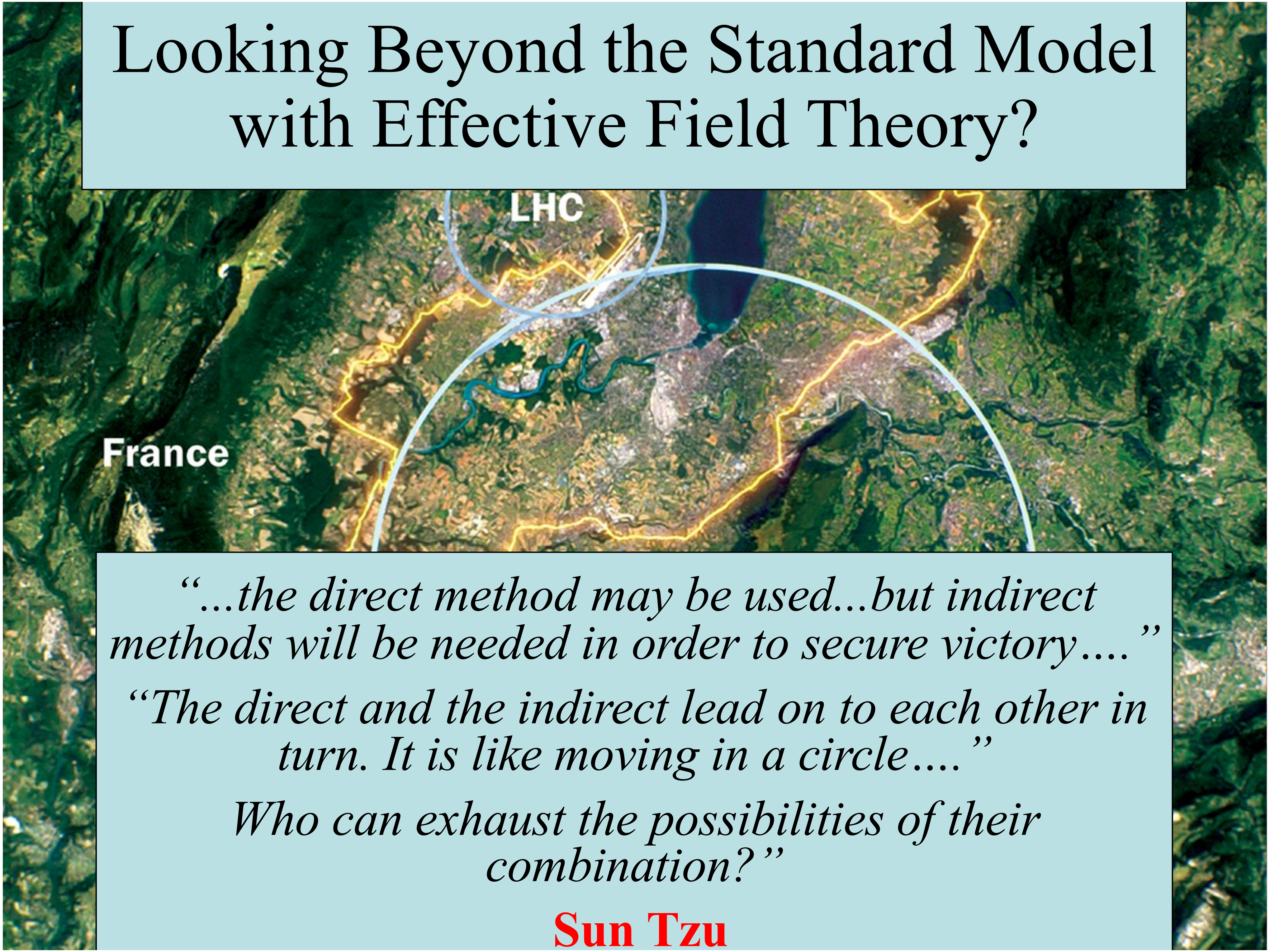
$$R_{\mu\nu}-\tfrac{1}{2}g_{\mu\nu}R-\lambda g_{\mu\nu}=-8\pi G T_{\mu\nu}\ . \qquad (2.1)$$

Now, for $\lambda>0$, there was a static solution for a universe filled with dust of zero pressure and mass density

$$\rho=\frac{\lambda}{8\pi G}\ . \qquad (2.2)$$

Its geometry was that of a sphere S_3, with proper circumference $2\pi r$, where

Looking Beyond the Standard Model with Effective Field Theory?



"...the direct method may be used...but indirect methods will be needed in order to secure victory...."

"The direct and the indirect lead on to each other in turn. It is like moving in a circle....

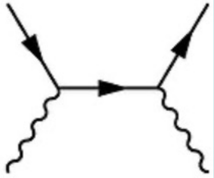
Who can exhaust the possibilities of their combination?"

Sun Tzu

Effective Field Theories (EFTs)

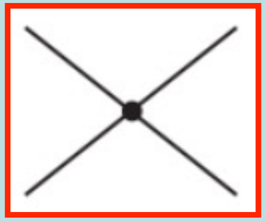
a long and glorious History

- 1930's: "Standard Model" of QED had

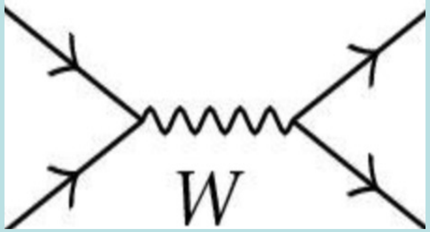


- **Fermi's four-fermion theory of the weak force**

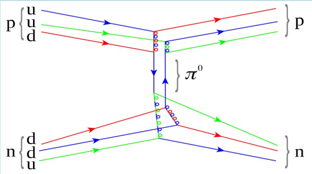
- Dimension-6 operators: form = S, P, V, A, T?
  - Due to exchanges of massive particles?



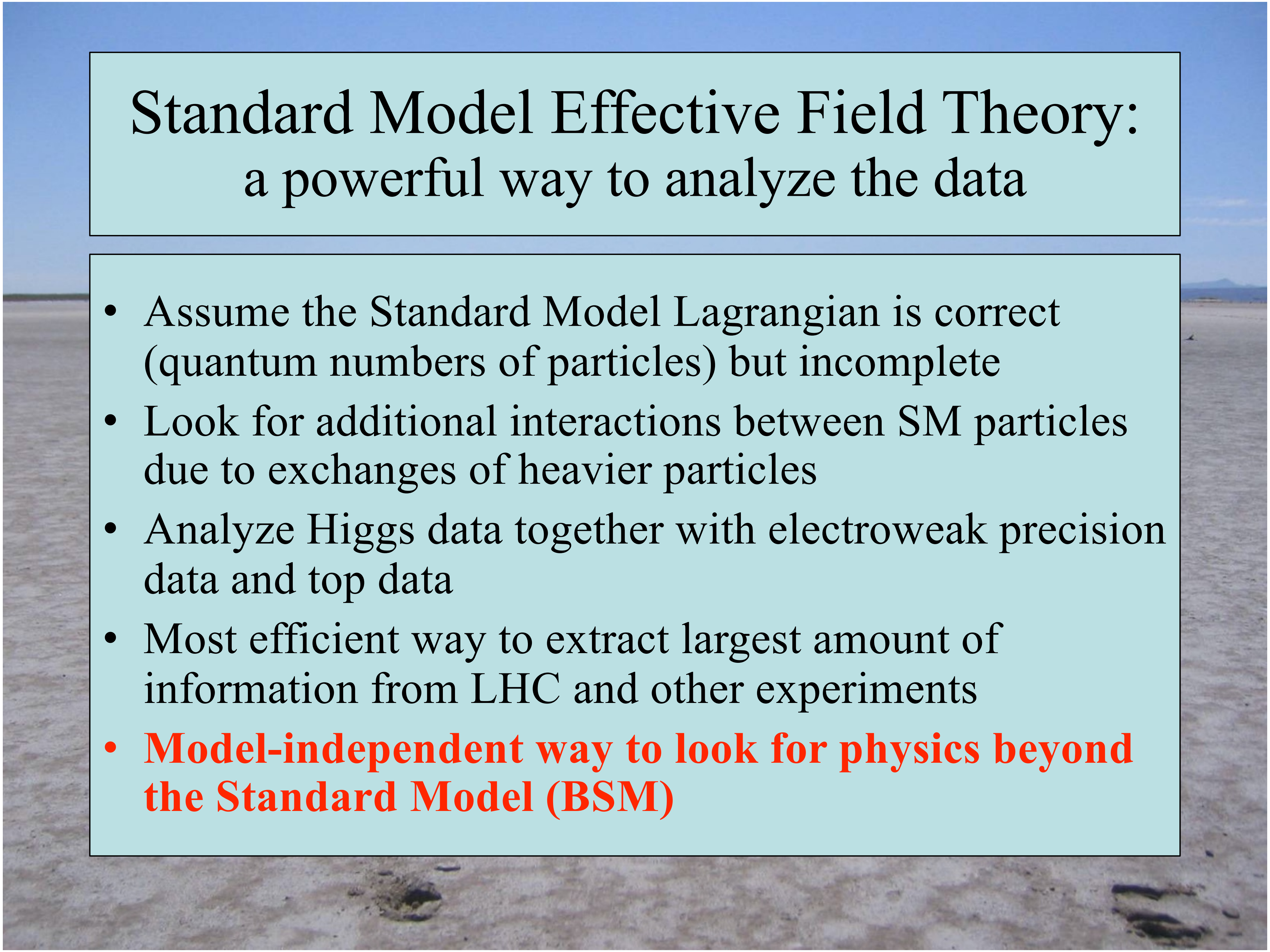
- V-A ➔ massive vector bosons ➔ gauge



- Yukawa's meson theory of the strong N-N force
  - Due to exchanges of mesons? ➔ pions



- Chiral dynamics of pions: $(\partial\pi\partial\pi)\pi\pi$ clue ➔ QCD



Standard Model Effective Field Theory: a powerful way to analyze the data

- Assume the Standard Model Lagrangian is correct (quantum numbers of particles) but incomplete
- Look for additional interactions between SM particles due to exchanges of heavier particles
- Analyze Higgs data together with electroweak precision data and top data
- Most efficient way to extract largest amount of information from LHC and other experiments
- **Model-independent way to look for physics beyond the Standard Model (BSM)**

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Summarize Analysis Framework

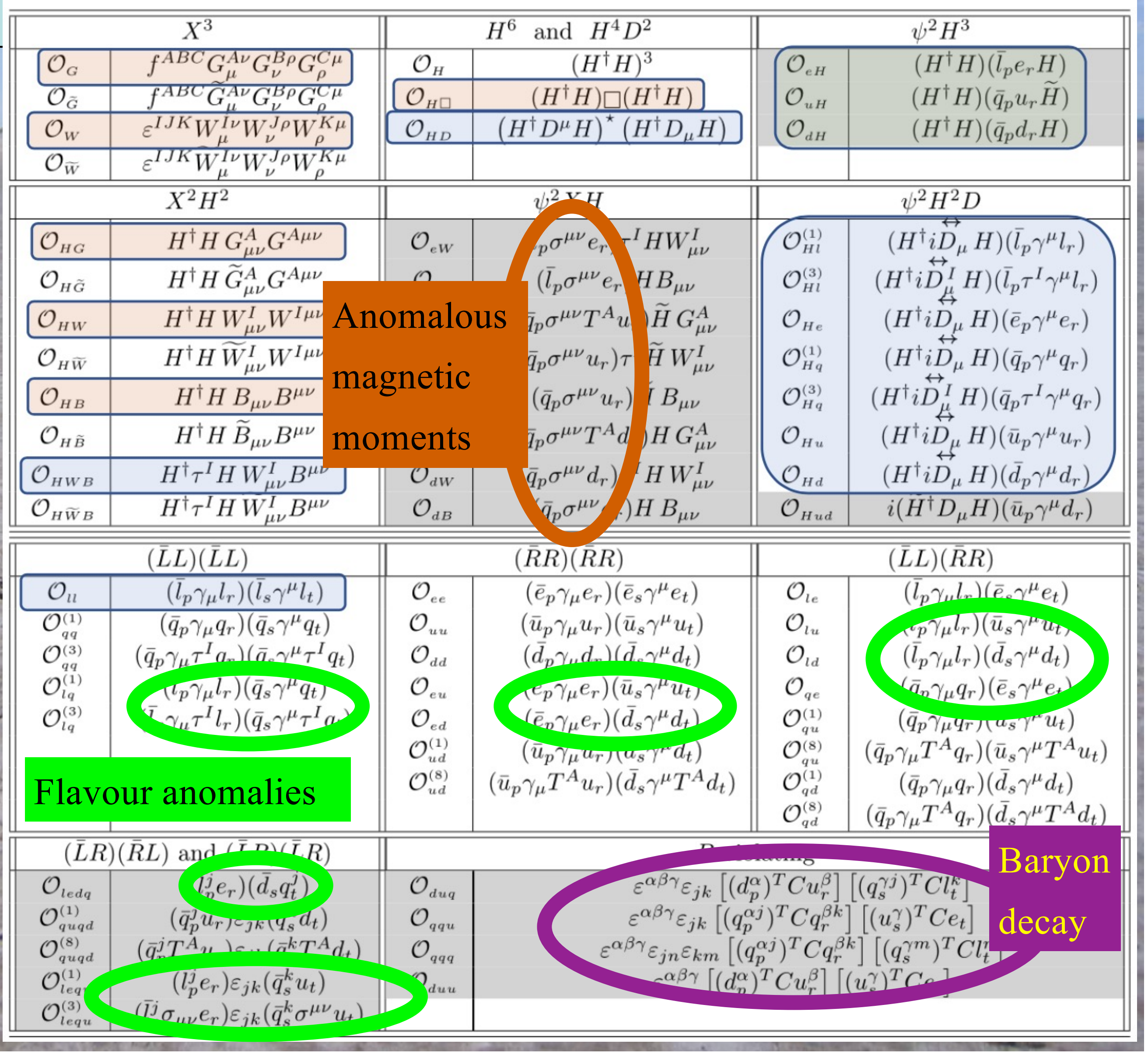
- Include all leading dimension-6 operators?

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i=1}^{2499} \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

- Simplify by assuming flavour $SU(3)^5$ or $SU(2)^2 \times SU(3)^3$ symmetry for fermions
- Work to linear order in operator coefficients, i.e. $\mathcal{O}(1/\Lambda^2)$
- Use G_F, M_Z, α as input parameters

Dimension-6 SMEFT Operators

- Including bosonic, 2- and 4-fermion operators
- Different colours for different data sectors
- Grey cells violate SU(3)^5 symmetry
- Important when including top observables



X^3		H^6 and H^4D^2		ψ^2H^3	
$\mathcal{O}_G$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar{l}_p e_r H)$
$\mathcal{O}_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
$\mathcal{O}_W$	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\star(H^\dagger D_\mu H)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar{q}_p d_r H)$
$\mathcal{O}_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

X^2H^2		ψ^2XH		ψ^2H^2D	
$\mathcal{O}_{HG}$	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I H W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$
$\mathcal{O}_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$	[illegible]	$(\bar{l}_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$\mathcal{O}^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$\mathcal{O}_{HW}$	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$	[illegible]	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$
$\mathcal{O}_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$	[illegible]	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\, W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$
$\mathcal{O}_{HB}$	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	[illegible]	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\, B_{\mu\nu}$	$\mathcal{O}^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$\mathcal{O}_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	[illegible]	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)H\, G^A_{\mu\nu}$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$
$\mathcal{O}_{HWB}$	$H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I H\, W^I_{\mu\nu}$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$
$\mathcal{O}_{H\widetilde{W}B}$	$H^\dagger\tau^I H\, \widetilde{W}^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}^{(1)}_{qq}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$\mathcal{O}^{(3)}_{qq}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}^{(1)}_{lq}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}^{(3)}_{lq}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}^{(1)}_{qu}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$\mathcal{O}^{(1)}_{ud}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}^{(8)}_{qu}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$\mathcal{O}^{(8)}_{ud}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$\mathcal{O}^{(1)}_{qd}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$\mathcal{O}^{(8)}_{qd}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
$\mathcal{O}_{ledq}$	$(\bar{l}^j_p e_r)(\bar{d}_s q^j_t)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$
$\mathcal{O}^{(1)}_{quqd}$	$(\bar{q}^j_p u_r)\varepsilon_{jk}(\bar{q}^k_s d_t)$	$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(u^\gamma_s)^T C e_t\right]$
$\mathcal{O}^{(8)}_{quqd}$	$(\bar{q}^j_p T^A u_r)\varepsilon_{jk}(\bar{q}^k_s T^A d_t)$	$\mathcal{O}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$
$\mathcal{O}^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\varepsilon_{jk}(\bar{q}^k_s u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(u^\gamma_s)^T C e_t\right]$
$\mathcal{O}^{(3)}_{lequ}$	$(\bar{l}^j_p\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}^k_s\sigma^{\mu\nu}u_t)$		

Anomalous magnetic moments

Flavour anomalies

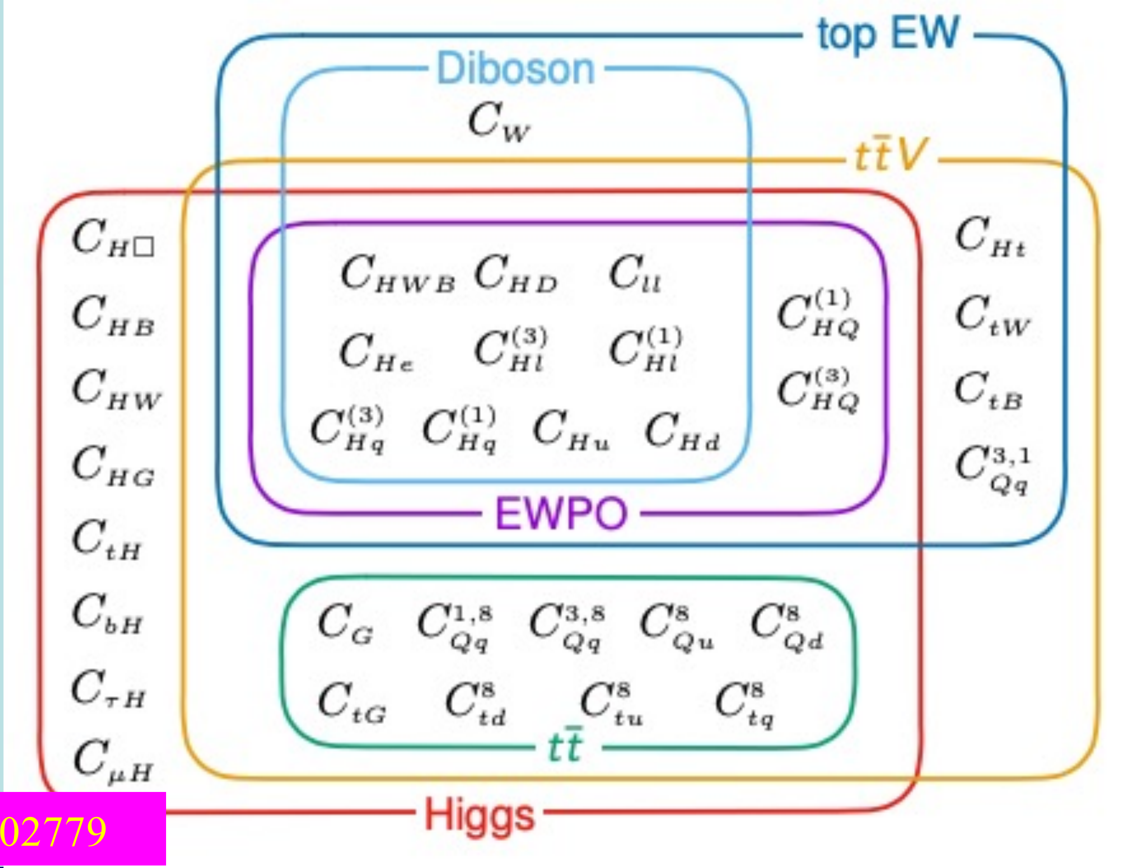
Baryon decay

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Global SMEFT Fit

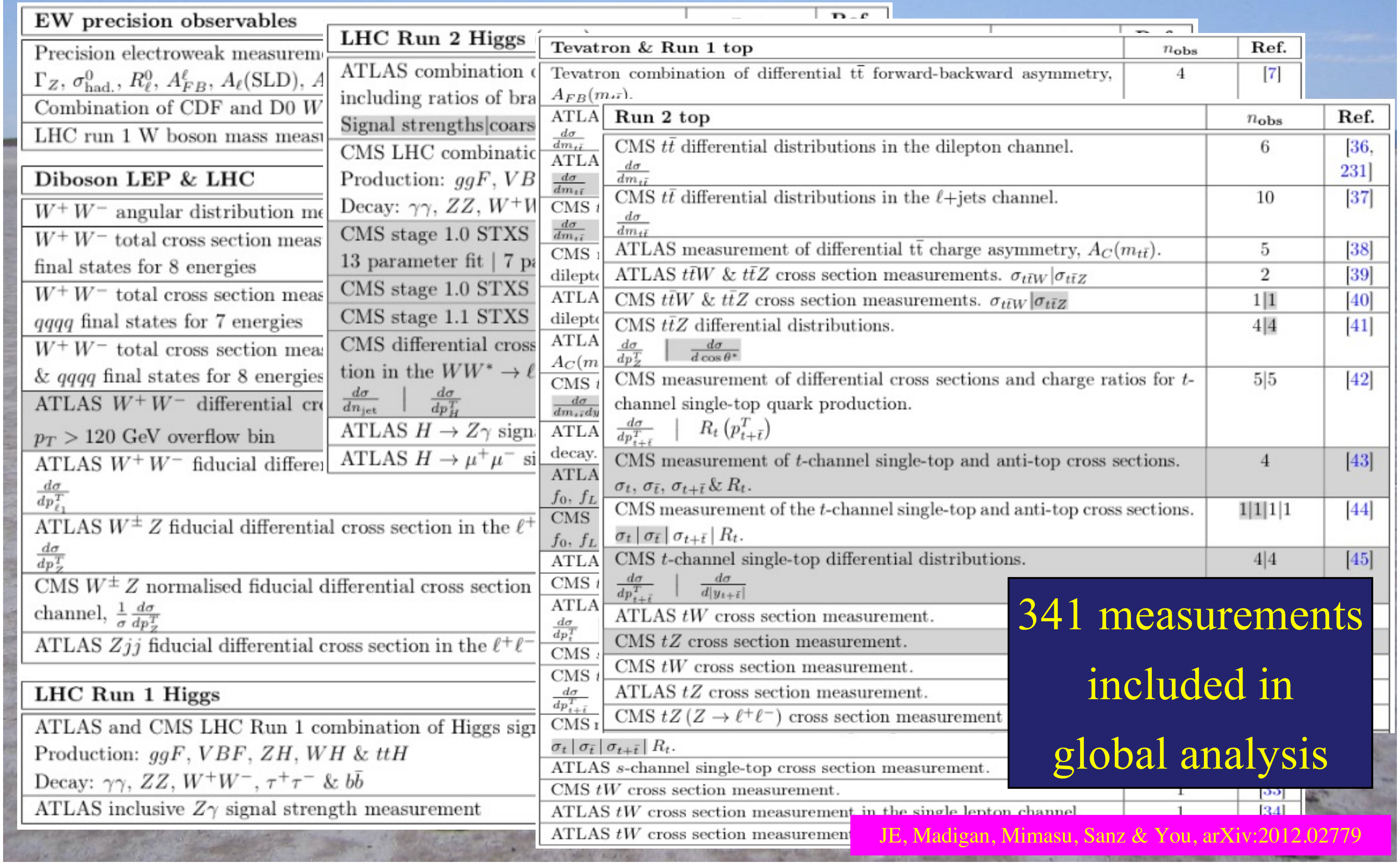
to Top, Higgs, Diboson, Electroweak Data

- Global fit to dimension-6 operators using precision electroweak data, W^+W^- at LEP, top, Higgs and diboson data from LHC Runs 1, 2
- Search for BSM
- Constraints on BSM
  - At tree level
  - At loop level



JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Data included in Global Fit



EW precision observables

Precision electroweak measurem
Γ_Z, $\sigma^0_{\text{had.}}$, R^0_ℓ, A^ℓ_{FB}, A_ℓ(SLD), A
Combination of CDF and D0 W
LHC run 1 W boson mass meas

Diboson LEP & LHC

W^+W^- angular distribution me
W^+W^- total cross section meas final states for 8 energies
W^+W^- total cross section meas $qqqq$ final states for 7 energies
W^+W^- total cross section meas & $qqqq$ final states for 8 energies
ATLAS W^+W^- differential cr $p_T > 120$ GeV overflow bin
ATLAS W^+W^- fiducial differe $\frac{d\sigma}{dp^T_{\ell_1}}$
ATLAS $W^\pm Z$ fiducial differential cross section in the ℓ^+ $\frac{d\sigma}{dp^T_Z}$
CMS $W^\pm Z$ normalised fiducial differential cross section channel, $\frac{1}{\sigma}\frac{d\sigma}{dp^T_Z}$
ATLAS Zjj fiducial differential cross section in the $\ell^+\ell^-$

LHC Run 1 Higgs

ATLAS and CMS LHC Run 1 combination of Higgs sig
Production: ggF, VBF, ZH, WH & ttH
Decay: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$ & $b\bar{b}$
ATLAS inclusive $Z\gamma$ signal strength measurement

LHC Run 2 Higgs

ATLAS combination including ratios of bra
Signal strengths|coars
CMS LHC combinatio
Production: ggF, VB
Decay: $\gamma\gamma$, ZZ, W^+W
CMS stage 1.0 STXS
13 parameter fit | 7 p
CMS stage 1.0 STXS
CMS stage 1.1 STXS
CMS differential cross tion in the $WW^* \to \ell$ $\frac{d\sigma}{dn_{\text{jet}}}$ | $\frac{d\sigma}{dp^T_H}$
ATLAS $H \to Z\gamma$ sign
ATLAS $H \to \mu^+\mu^-$ si

Tevatron & Run 1 top	n_{obs}	**Ref.**
Tevatron combination of differential $t\bar{t}$ forward-backward asymmetry, $A_{FB}(m_{t\bar{t}})$.	4	[7]
ATLA $\frac{d\sigma}{dm_{t\bar{t}}}$		
ATLA $\frac{d\sigma}{dm_{t\bar{t}}}$		
CMS $\frac{d\sigma}{dm_{t\bar{t}}}$		
CMS dilept		
ATLA dilept		
ATLA $A_C(m$		
CMS $\frac{d\sigma}{dm_{t\bar{t}}dy}$		
ATLA decay.		
ATLA f_0, f_L		
CMS f_0, f_L		
ATLA		
CMS		
ATLA $\frac{d\sigma}{dp^T_t}$		
CMS		
CMS $\frac{d\sigma}{dp^T_{t+\bar{t}}}$		
CMS $\sigma_t \mid \sigma_{\bar{t}} \mid \sigma_{t+\bar{t}} \mid R_t$.		
ATLAS s-channel single-top cross section measurement.		
CMS tW cross section measurement.	1	
ATLAS tW cross section measurement in the single lepton channel	1	[34]
ATLAS tW cross section measuremen		

Run 2 top	n_{obs}	**Ref.**
CMS $t\bar{t}$ differential distributions in the dilepton channel. $\frac{d\sigma}{dm_{t\bar{t}}}$	6	[36, 231]
CMS $t\bar{t}$ differential distributions in the ℓ+jets channel. $\frac{d\sigma}{dm_{t\bar{t}}}$	10	[37]
ATLAS measurement of differential $t\bar{t}$ charge asymmetry, $A_C(m_{t\bar{t}})$.	5	[38]
ATLAS $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W} \mid \sigma_{t\bar{t}Z}$	2	[39]
CMS $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W} \mid \sigma_{t\bar{t}Z}$	1|1	[40]
CMS $t\bar{t}Z$ differential distributions. $\frac{d\sigma}{dp^T_Z}$ | $\frac{d\sigma}{d\cos\theta^*}$	4|4	[41]
CMS measurement of differential cross sections and charge ratios for t-channel single-top quark production. $\frac{d\sigma}{dp^T_{t+\bar{t}}}$ | $R_t\,(p^T_{t+\bar{t}})$	5|5	[42]
CMS measurement of t-channel single-top and anti-top cross sections. σ_t, $\sigma_{\bar{t}}$, $\sigma_{t+\bar{t}}$ & R_t.	4	[43]
CMS measurement of the t-channel single-top and anti-top cross sections. $\sigma_t \mid \sigma_{\bar{t}} \mid \sigma_{t+\bar{t}} \mid R_t$.	1|1|1|1	[44]
CMS t-channel single-top differential distributions. $\frac{d\sigma}{dp^T_{t+\bar{t}}}$ | $\frac{d\sigma}{d\lvert y_{t+\bar{t}}\rvert}$	4|4	[45]
ATLAS tW cross section measurement.		
CMS tZ cross section measurement.		
CMS tW cross section measurement.		
ATLAS tZ cross section measurement.		
CMS $tZ\,(Z \to \ell^+\ell^-)$ cross section measurement		

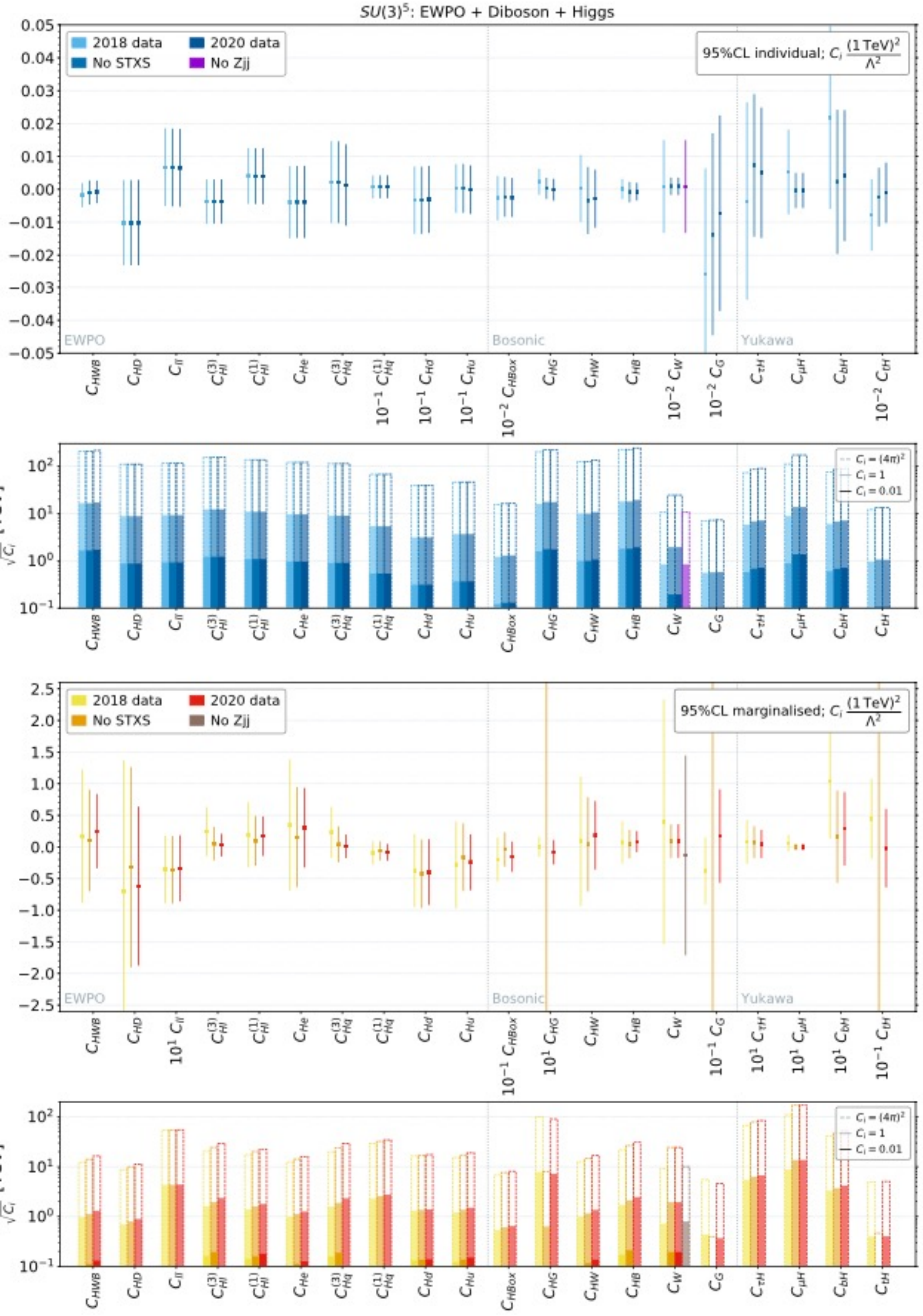
341 measurements included in global analysis

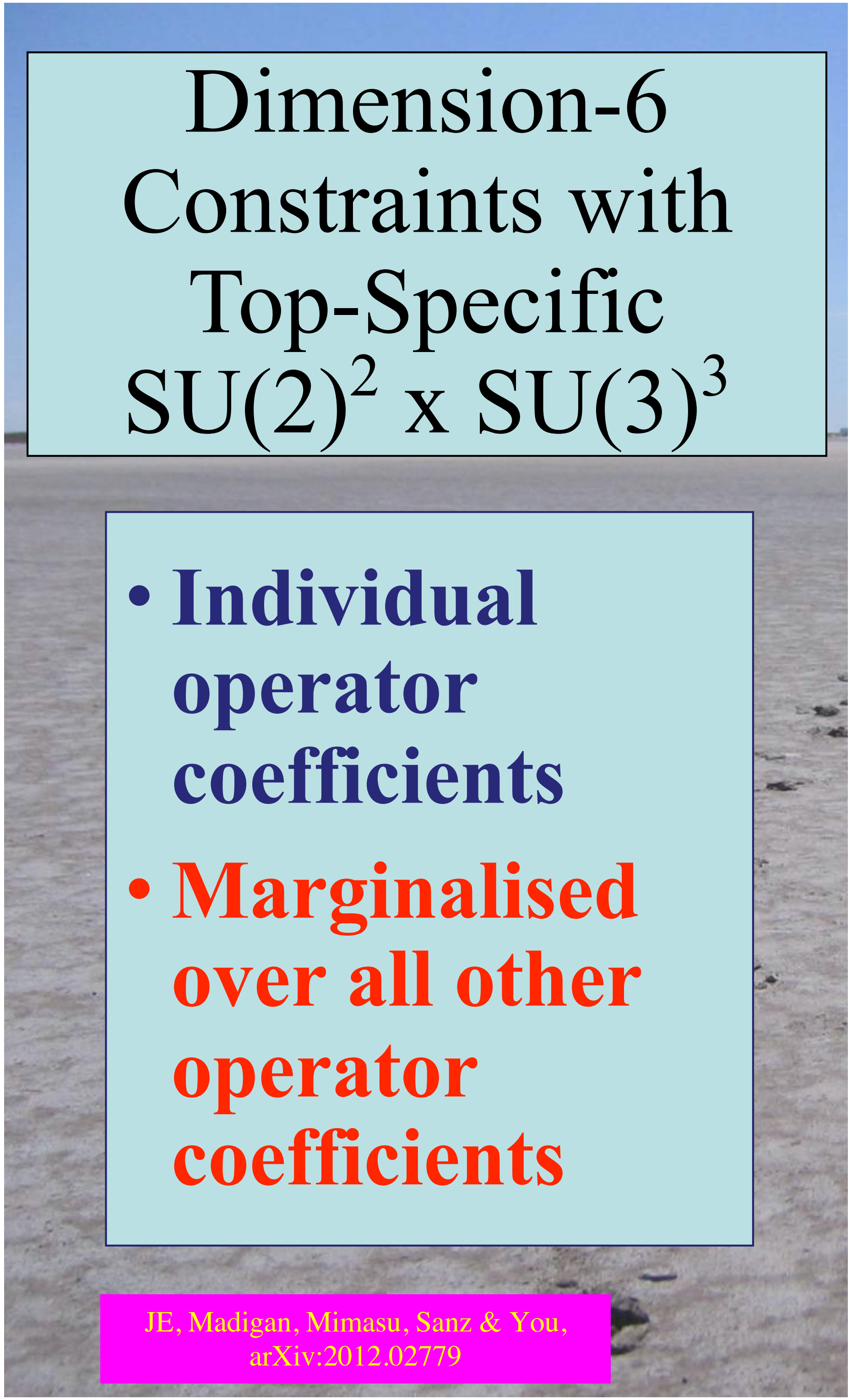
JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Dimension-6 Constraints with Flavour-Universal SU(3)^5 Symmetry

- **Individual operator coefficients**
- **Marginalised over all other operator coefficients**

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

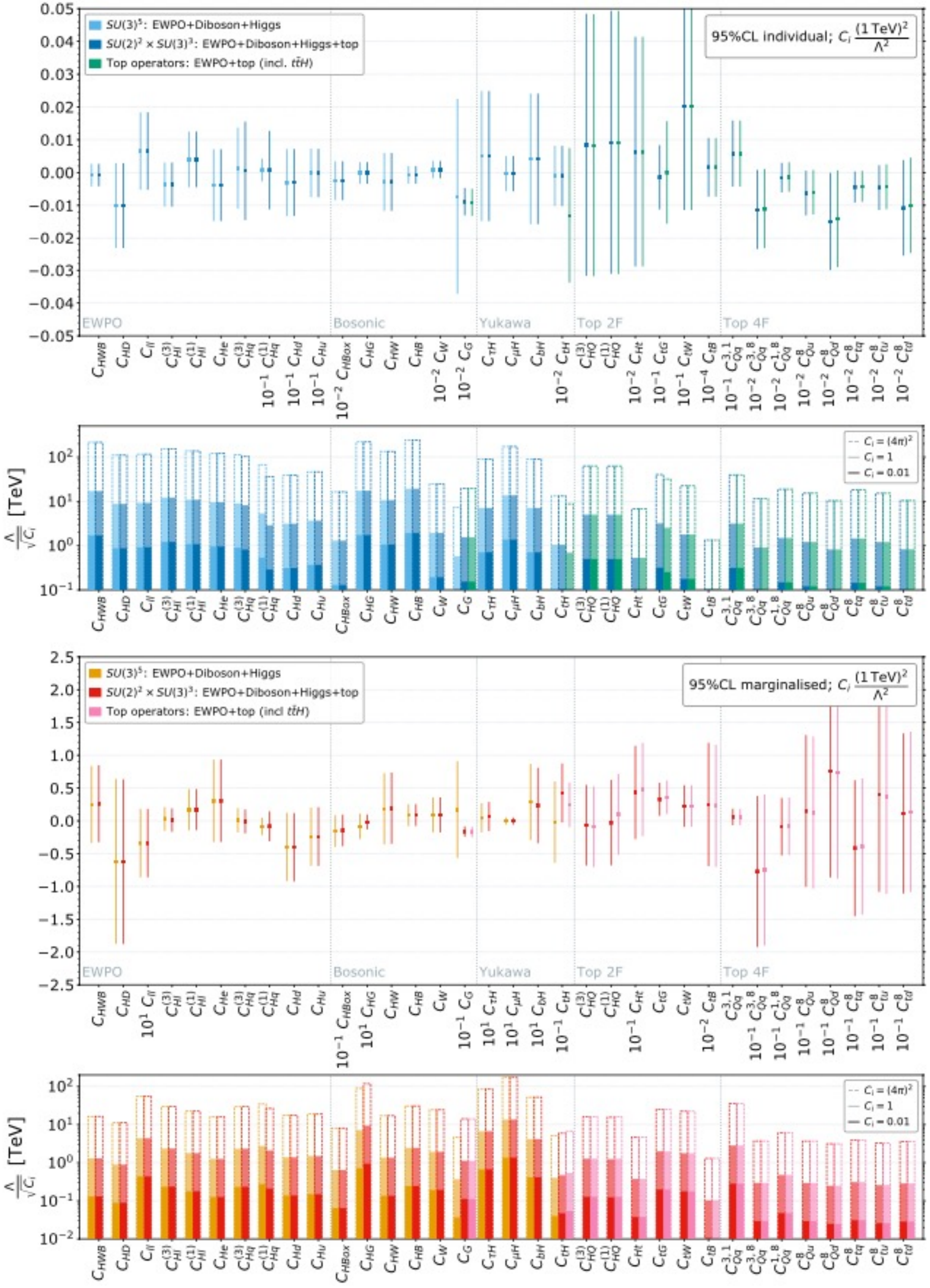




Dimension-6 Constraints with Top-Specific SU(2)^2 x SU(3)^3

- **Individual operator coefficients**
- **Marginalised over all other operator coefficients**

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779



CDF Collaboration, Science 376 (2022) p170

PARTICLE PHYSICS

High-precision measurement of the *W* boson mass with the CDF II detector

CDF Collaboration[†,‡], T. Aaltonen[1,2], S. Amerio[3,4], D. Amidei[5], A. Anastassov[6], A. Annovi[7], J. Antos[8,9], G. Apollinari[6], J. A. Appel[6], T. Arisawa[10], A. Artikov[11], J. Asaadi[12], W. Ashmanskas[6], B. Auerbach[13], A. Aurisano[12], F. Azfar[14], W. Badgett[6], T. Bae[15,16,17,18,19,20,21], A. Barbaro-Galtieri[22], V. E. Barnes[23], B. A. Barnett[24], P. Barria[25,26], P. Bartos[8,9], M. Bauce[3,4], F. Bedeschi[25], S. Behari[6], G. Bellettini[25,27], J. Bellinger[28], D. Benjamin[29], A. Beretvas[6], A. Bhatti[30], K. R. Bland[31], B. Blumenfeld[24], A. Bocci[29], A. Bodek[32], D. Bortoletto[23], J. Boudreau[33], A. Boveia[34], L. Brigliadori[35,36], C. Bromberg[37], E. Brucken[1,2], J. Budagov[11,§], H. S. Budd[32], K. Burkett[6], G. Busetto[3,4], P. Bussey[38], P. Butti[25,27], A. Buzatu[38], A. Calamba[39], S. Camarda[40], M. Campanelli[41], B. Carls[42], D. Carlsmith[28], R. Carosi[25], S. Carrillo[43,§], B. Casal[44], M. Casarsa[45], A. Castro[35,36], P. Catastini[46], D. Cauz[45,47,48], V. Cavaliere[42], A. Cerri[22], L. Cerrito[41], Y. C. Chen[49], M. Chertok[50], G. Chiarelli[25], G. Chlachidze[6], K. Cho[15,16,17,18,19,20,21], D. Chokheli[11], A. Clark[51], C. Clarke[52], M. E. Convery[6], J. Conway[50], M. Corbo[6], M. Cordelli[7], C. A. Cox[50], D. J. Cox[50], M. Cremonesi[25], D. Cruz[12], J. Cuevas[44], R. Culbertson[6], N. d'Ascenzo[6], M. Datta[6], P. de Barbaro[32], L. Demortier[30], M. Deninno[35,§], M. D'Errico[3,4], F. Devoto[1,2], A. Di Canto[25,27], B. Di Ruzza[6], J. R. Dittmann[31], S. Donati[25,27], M. D'Onofrio[53], M. Dorigo[45,54], A. Driutti[45,47,48], K. Ebina[10], R. Edgar[5], A. Elagin[34], R. Erbacher[50], S. Errede[42], B. Esham[42], S. Farrington[14], J. P. Fernández Ramos[55], R. Field[43], G. Flanagan[6], R. Forrest[50], M. Franklin[46], J. C. Freeman[6], H. Frisch[34], Y. Funakoshi[10], C. Galloni[25,27], A. F. Garfinkel[23], P. Garosi[25,26], H. Gerberich[42], E. Gerchtein[6], S. Giagu[56], V. 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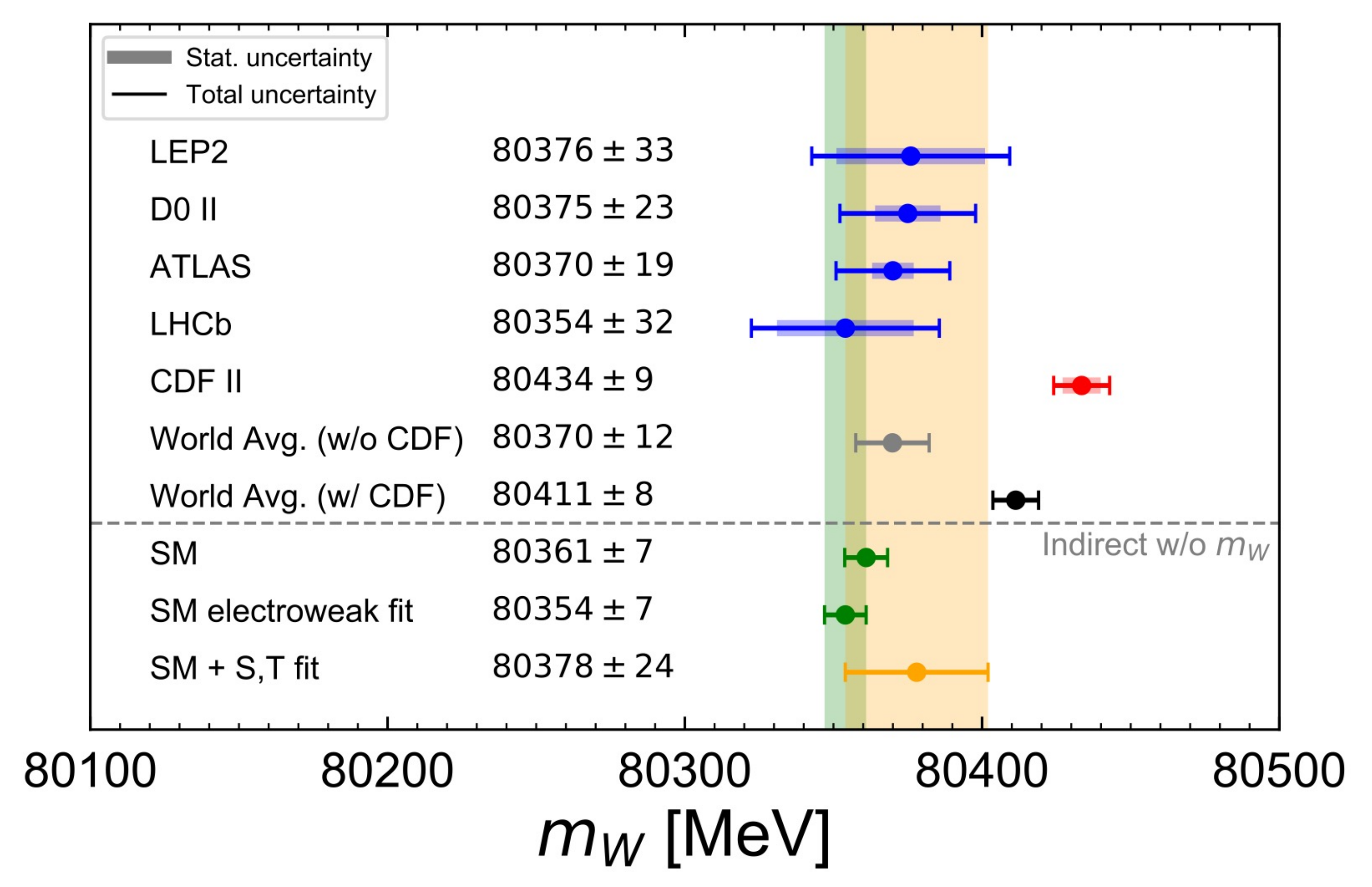
CDF Measurement of m_W

compared with previous measurements

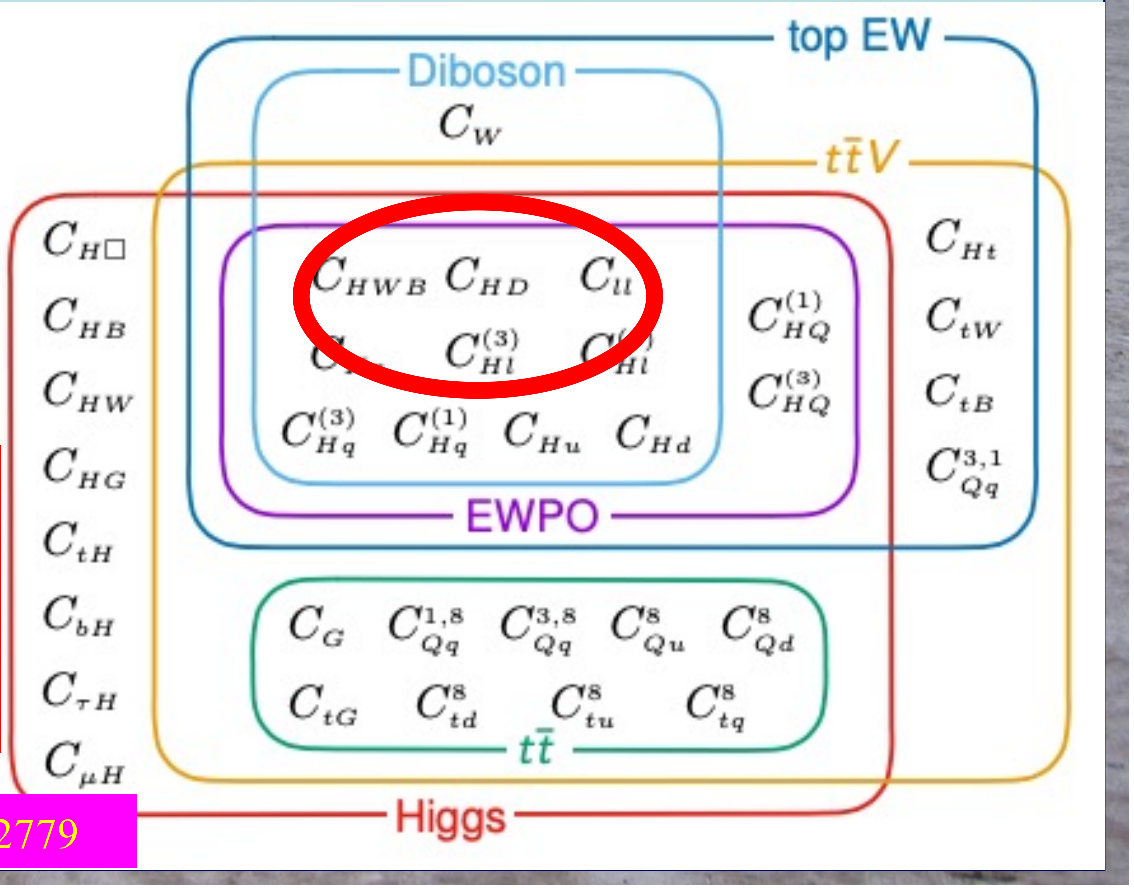


- Tension: 7-σ discrepancy with Standard Model?

Global SMEFT Fit

to m_W, Top, Higgs, Diboson, Electroweak Data

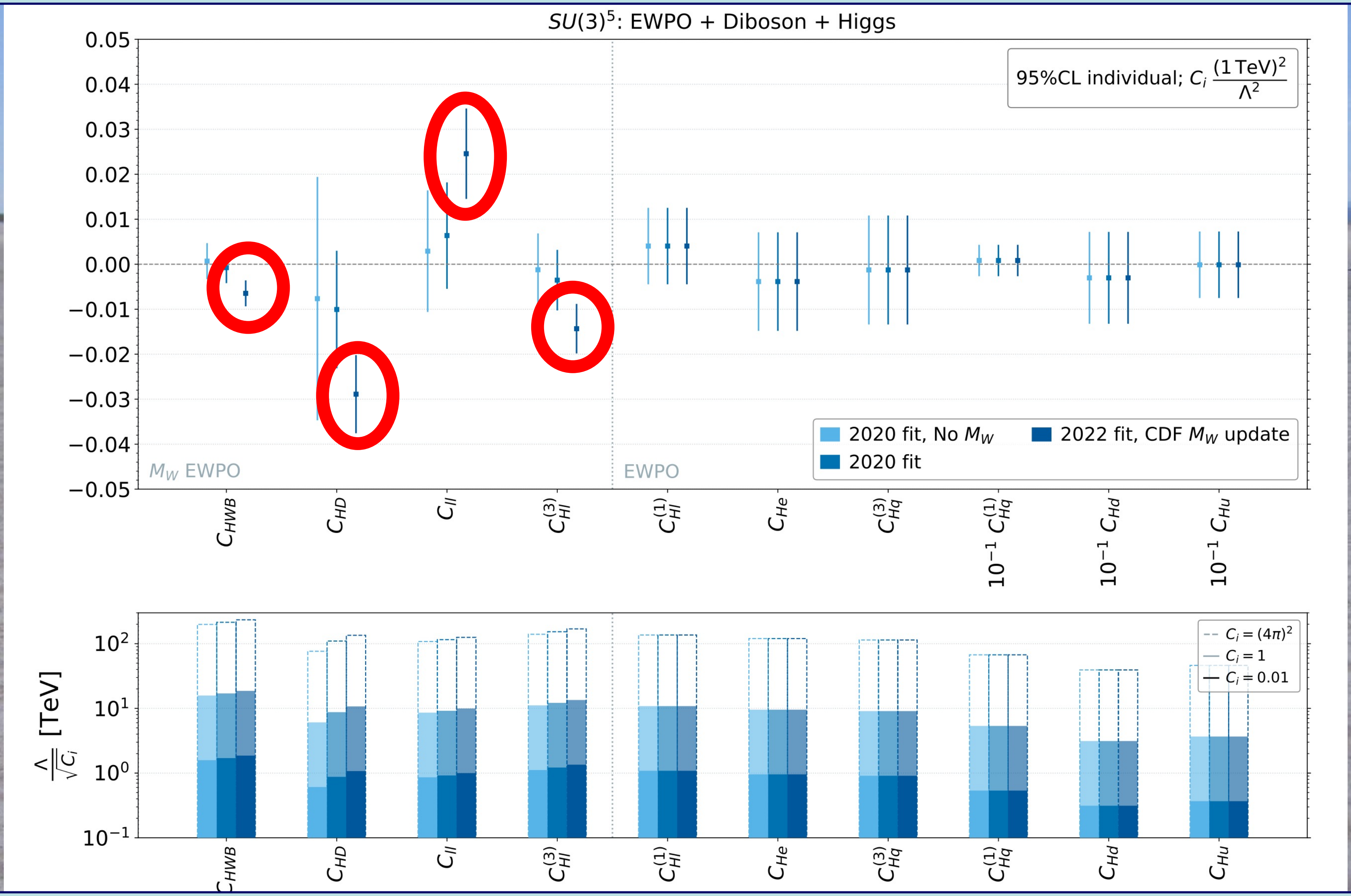
- Global fit to dimension-6 operators using precision electroweak data, W^+W^- at LEP, top, Higgs and diboson data from LHC Runs 1, 2
- Search for BSM
- Constraints on BSM
  - At tree level
  - At loop level



Positive contributions to mw

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

SMEFT Fit with the Mass of the W Boson



- Non-zero coefficients for any of four operators can fit W mass

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Single-Field Extensions of the Standard Model

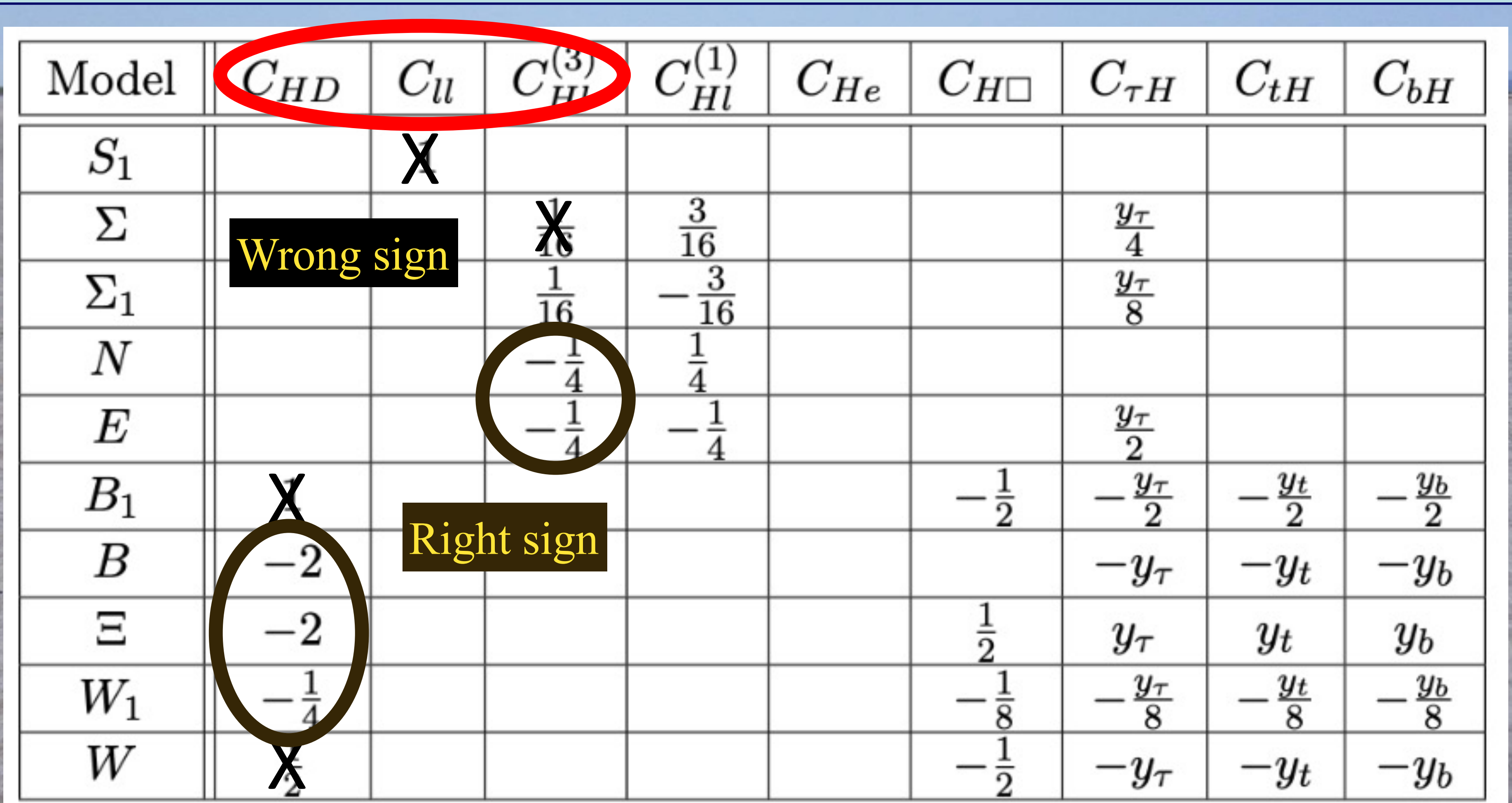
Name	Spin	SU(3)	SU(2)	U(1)	Name	Spin	SU(3)	SU(2)	U(1)
S	0	1	1	0	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
S_1	0	1	1	1	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
φ	0	[illegible]	2	$\frac{1}{2}$	Σ	$\frac{1}{2}$	1	3	0
Ξ	0	1	3	0	Σ_1	$\frac{1}{2}$	1	3	-1
Ξ_1	0	1	3	1	U	$\frac{1}{2}$	3	1	$\frac{2}{3}$
B	1	1	1	0	D	$\frac{1}{2}$	3	1	$-\frac{1}{3}$
B_1	1	1	1	1	Q_1	$\frac{1}{2}$	3	2	$\frac{1}{6}$
W	1	1	3	0	Q_5	$\frac{1}{2}$	3	2	$-\frac{5}{6}$
W_1	1	1	3	1	Q_7	$\frac{1}{2}$	3	2	$\frac{7}{6}$
N	$\frac{1}{2}$	1	1	0	T_1	$\frac{1}{2}$	3	3	$-\frac{1}{3}$
E	$\frac{1}{2}$	1	1	-1	T_2	$\frac{1}{2}$	3	3	$\frac{2}{3}$
T	$\frac{1}{2}$	3	1	$\frac{2}{3}$	TB	$\frac{1}{2}$	3	2	$\frac{1}{6}$

Spin zero

Vector

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Single-Field Models that can Contribute to W Mass



Model	C_{HD}	C_{ll}	$C_{Hl}^{(3)}$	$C_{Hl}^{(1)}$	C_{He}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
S_1		~~1~~							
Σ			~~$\frac{1}{16}$~~	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			$\frac{1}{16}$	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
B_1	~~1~~					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
B	-2						$-y_\tau$	$-y_t$	$-y_b$
Ξ	-2					$\frac{1}{2}$	y_τ	y_t	y_b
W_1	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
W	~~$\frac{1}{2}$~~					$-\frac{1}{2}$	$-y_\tau$	$-y_t$	$-y_b$

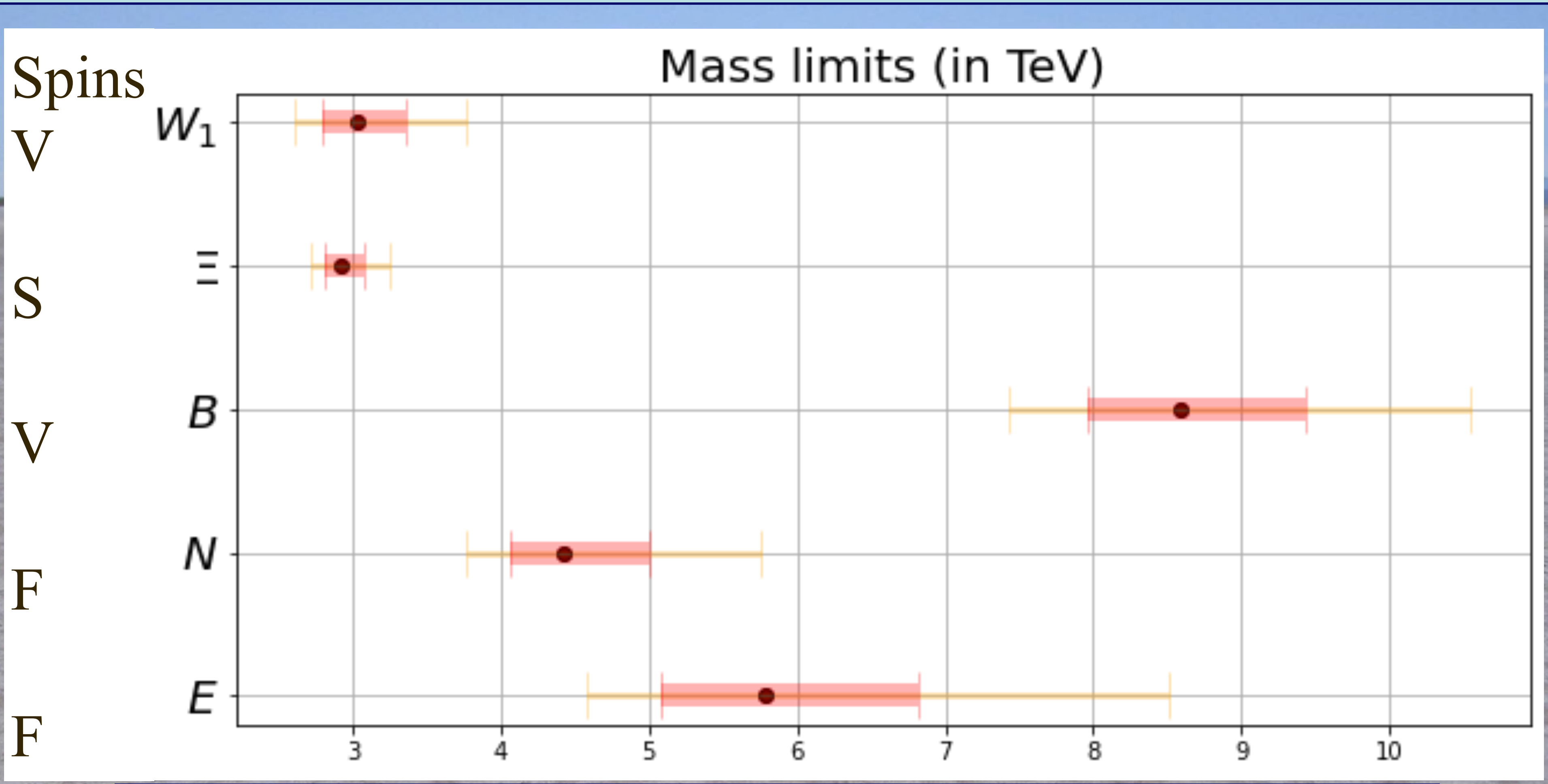
Wrong sign

Right sign

Operators contributing to mw

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Models Fitting the Mass of the W Boson



- 68 and 95% CL ranges of masses assuming unit coupling
- Masses proportional to couplings
- Large masses consistent with SMEFT approximation

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Models Fitting W Mass

Spins	Model	Pull	Best-fit mass (TeV)	1-σ mass range (TeV)	2-σ mass range (TeV)	1-σ coupling^2 range
V	W_1	6.4	3.0	[2.8, 3.6]	[2.6, 3.8]	[0.09, 0.13]
S	B	6.4	8.6	[8.0, 9.4]	[7.4, 10.6]	[0.011, 0.016]
V	Ξ	6.4	2.9	[2.8, 3.1]	[2.7, 3.2]	[0.011, 0.016]
F	N	5.1	4.4	[4.1, 5.0]	[3.8, 5.8]	[0.040, 0.060]
F	E	3.5	5.8	[5.1, 6.8]	[4.6, 8.5]	[0.022, 0.039]

Best-fit, 68 and 95% CL ranges
of masses assuming
unit couplings

68% CL ranges
of couplings for
1 TeV

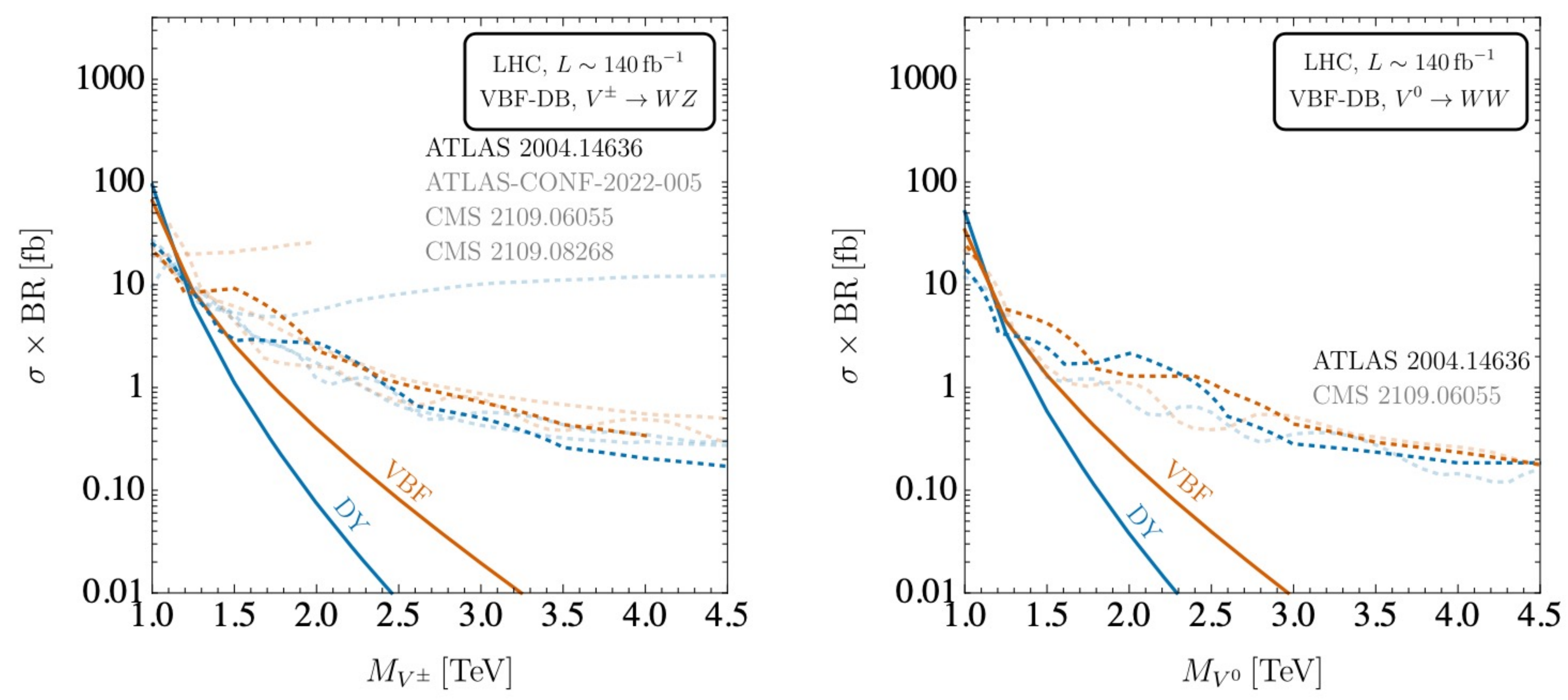
Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Searching for Models Fitting the Mass of the W Boson

- W: Isotriplet vector boson, mass ~ 3 TeV x coupling, electroweak production, accessible at LHC?
- B: Singlet vector boson, mass ~ 8 TeV x coupling, phenomenology depends on fermion couplings, too heavy for LHC?
- Ξ: Isotriplet scalar boson, mass ~ 3 TeV x coupling, detectable in LHC searches for heavy Higgs bosons?
- N: Isosinglet neutral fermion, mass ~ 4 TeV x coupling, similar to (right-handed) singlet neutrino
- E: Isosinglet charged fermion, mass ~ 6 TeV x coupling, similar to (right-handed) singlet electron

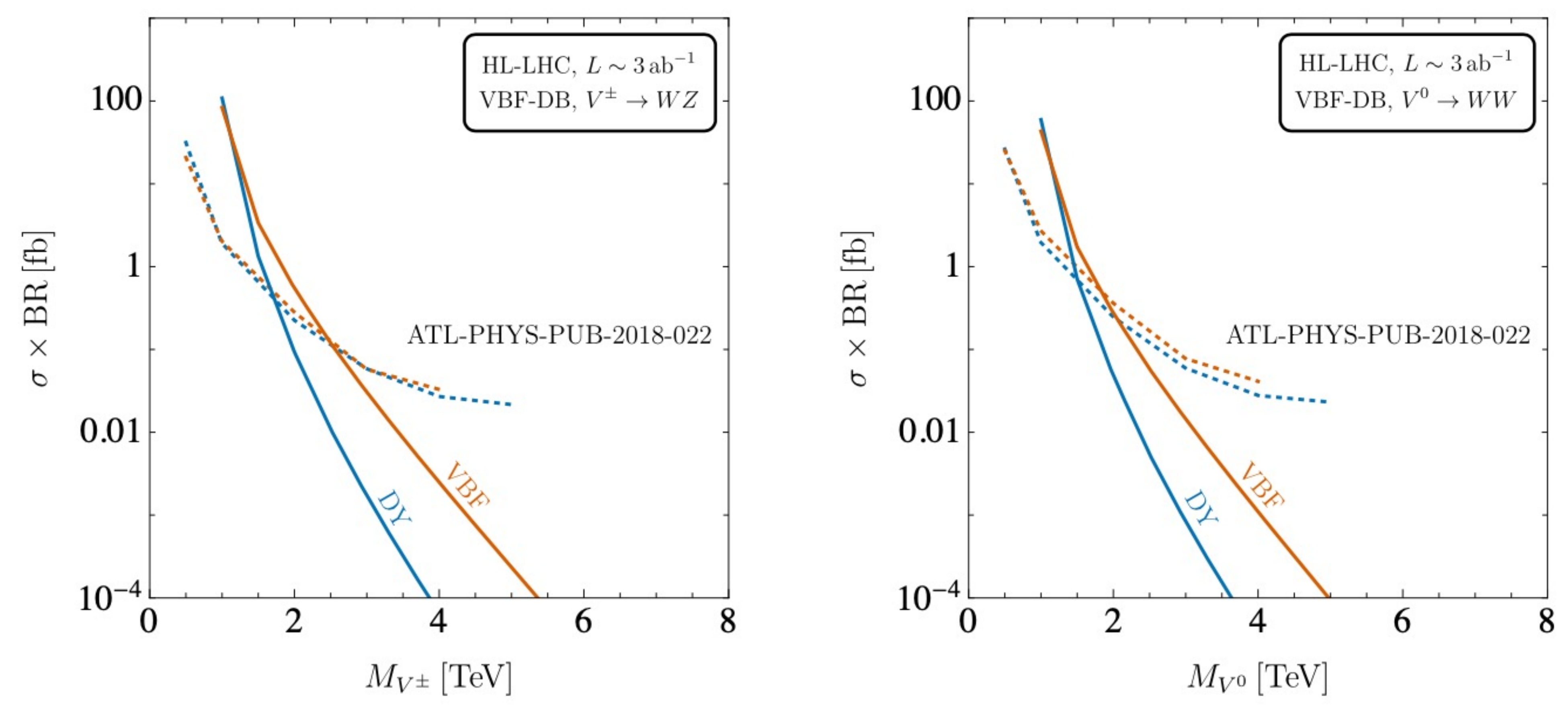
Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

LHC Searches for Triplet Vector Boson



Baker, Martonhelyi, Thamm & Torre, arXiv:2207.05091

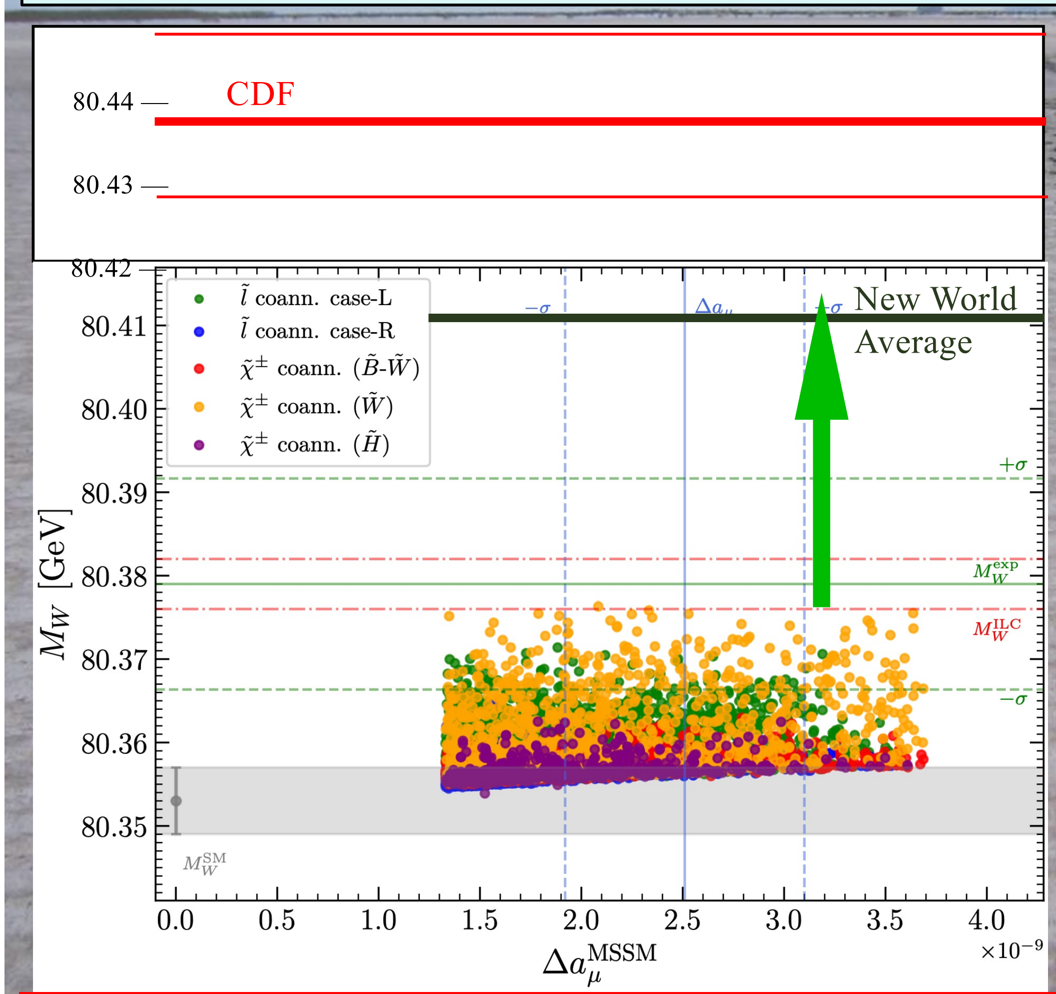
LHC Searches for Triplet Vector Boson

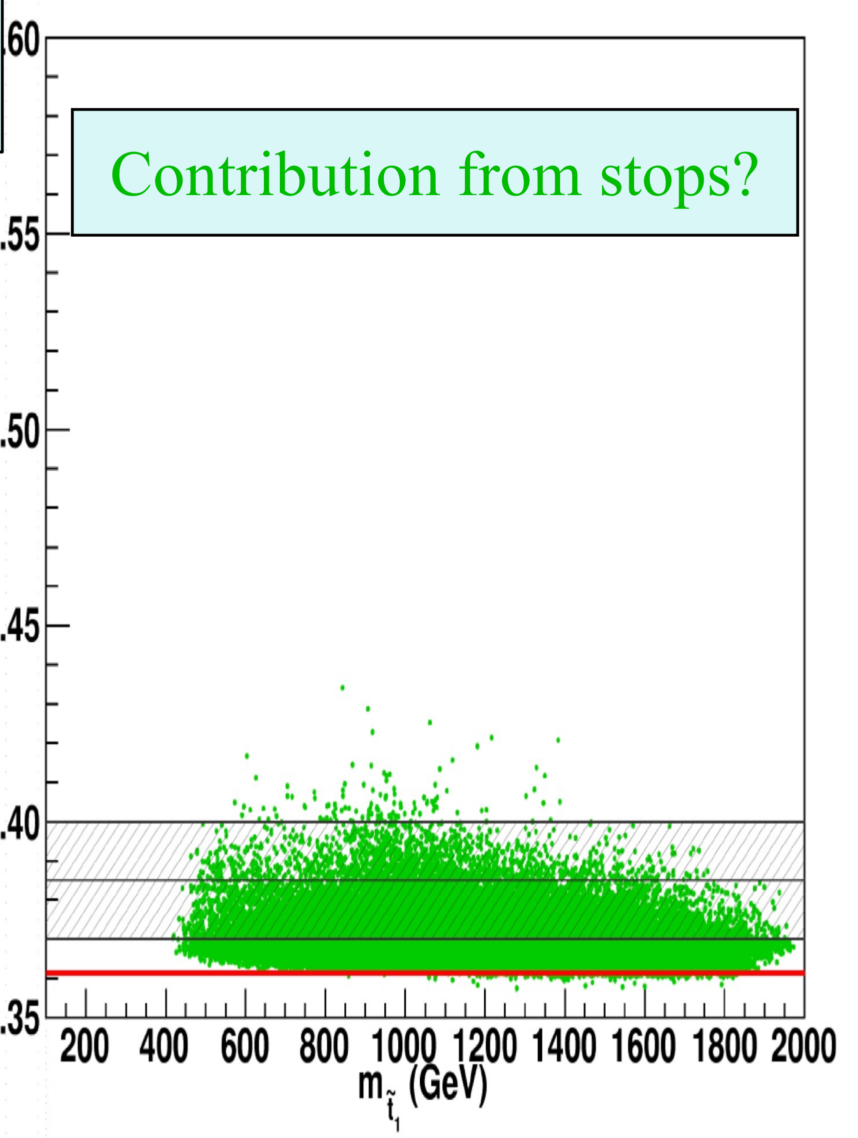


Baker, Martonhelyi, Thamm & Torre, arXiv:2207.05091

W Mass in Supersymmetry?

Assuming supersymmetric dark matter:
electroweak sparticles reach old world average, but not CDF or new world average




Contribution from stops?

Bagnaschi, Chakraborti, Heinemeyer, Saha & Weiglein, arXiv:2203.15710

Heinemeyer, Weiglein & Zeune, 2013

Known knowns (= SM)

Known unknowns (e.g., DM)

Unknown unknowns

$g_\mu - 2$?

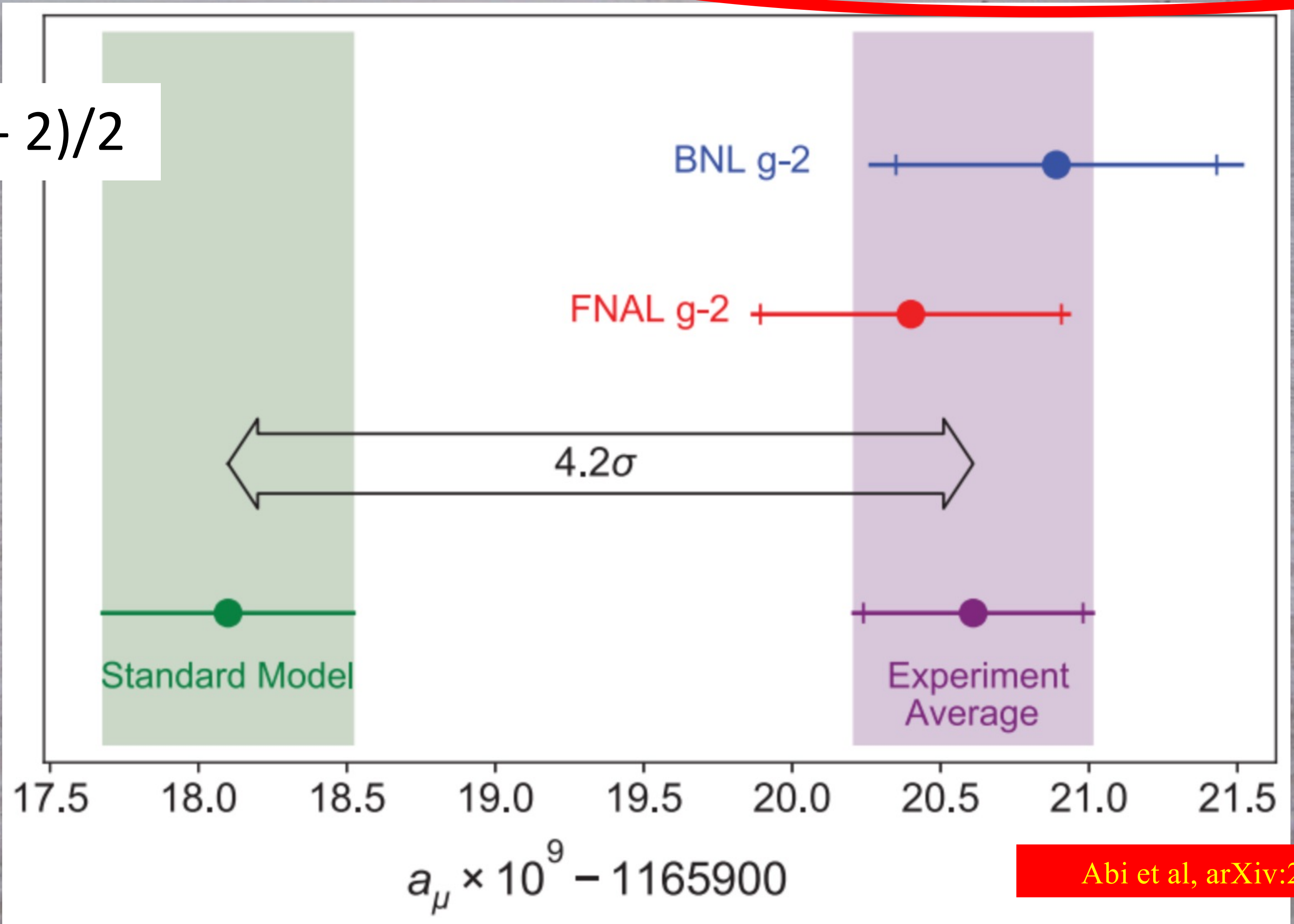
Fermilab Measurement of $g_\mu - 2$

FNAL result $a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm})$

Combined result: $a_\mu(\mathrm{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35\,\mathrm{ppm})$

Difference from Standard Model: $a_\mu(\mathrm{Exp}) - a_\mu(\mathrm{SM}) = (251 \pm 59) \times 10^{-11}$

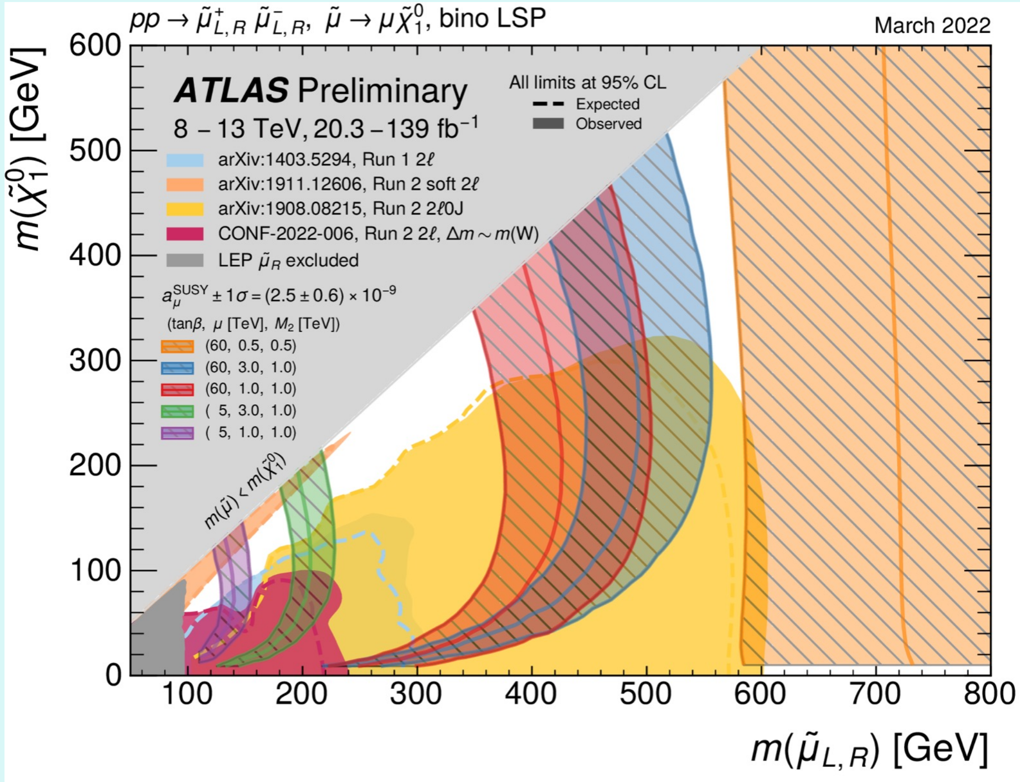
$a_\mu = (g_\mu - 2)/2$

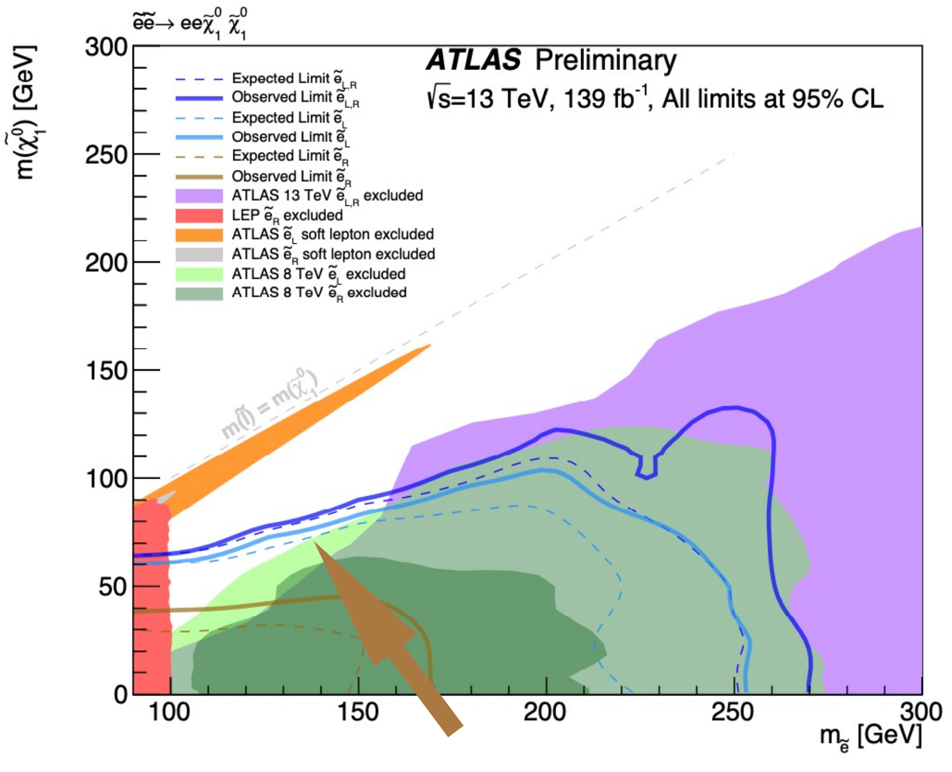


Abi et al, arXiv:2104.03281

LHC vs Supersymmetry

- LHC favours squarks & gluinos > 2 TeV (but loopholes)
- Does not exclude lighter electroweakly-interacting particles, e.g., sleptons

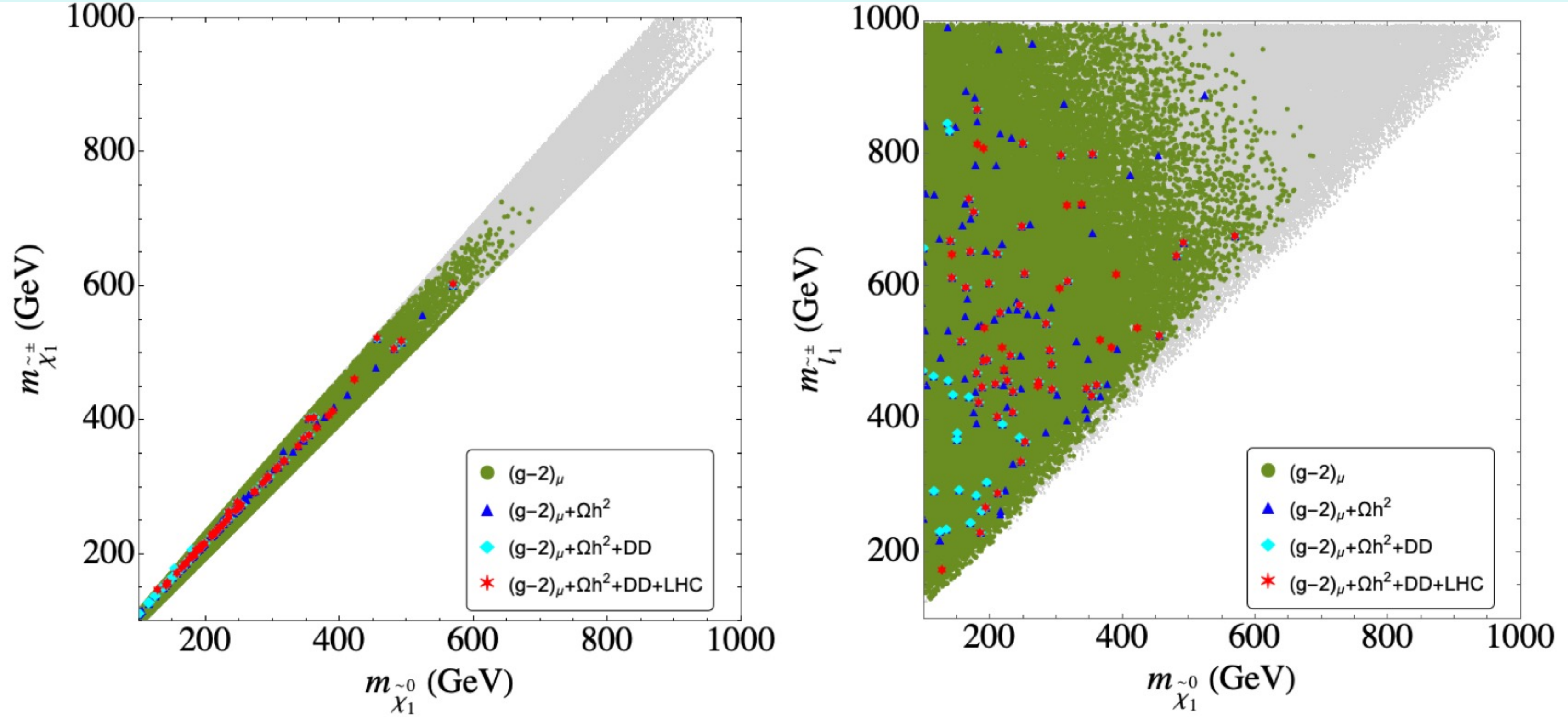




- Most models have $m_{\tilde\mu_L} > m_{\tilde\mu_R}$ but $m_{\tilde\mu_R} \simeq m_{\tilde e_R}$: **relevant constraint**

Supersymmetry

- $g_\mu - 2$-friendly scenario with light neutralino, chargino & slepton

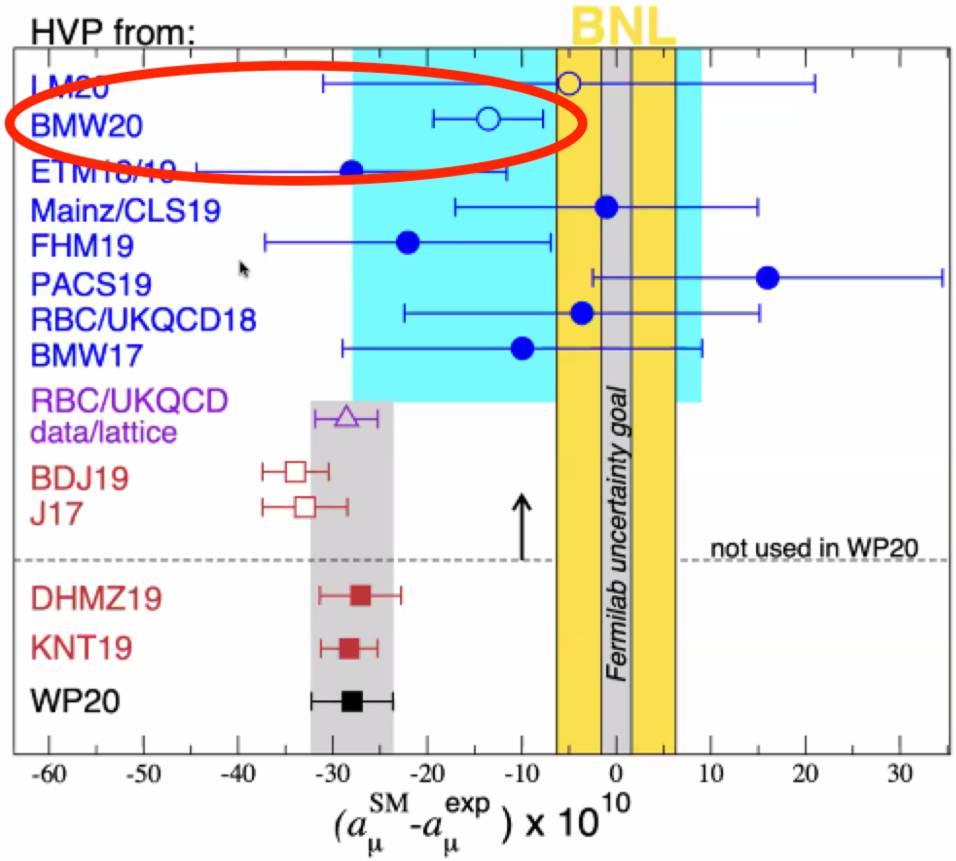


- Red star points include all relevant LHC, dark matter density and direct scattering constraints

Chakraborti, Heinemeyer & Saha, arXiv:2104.03287

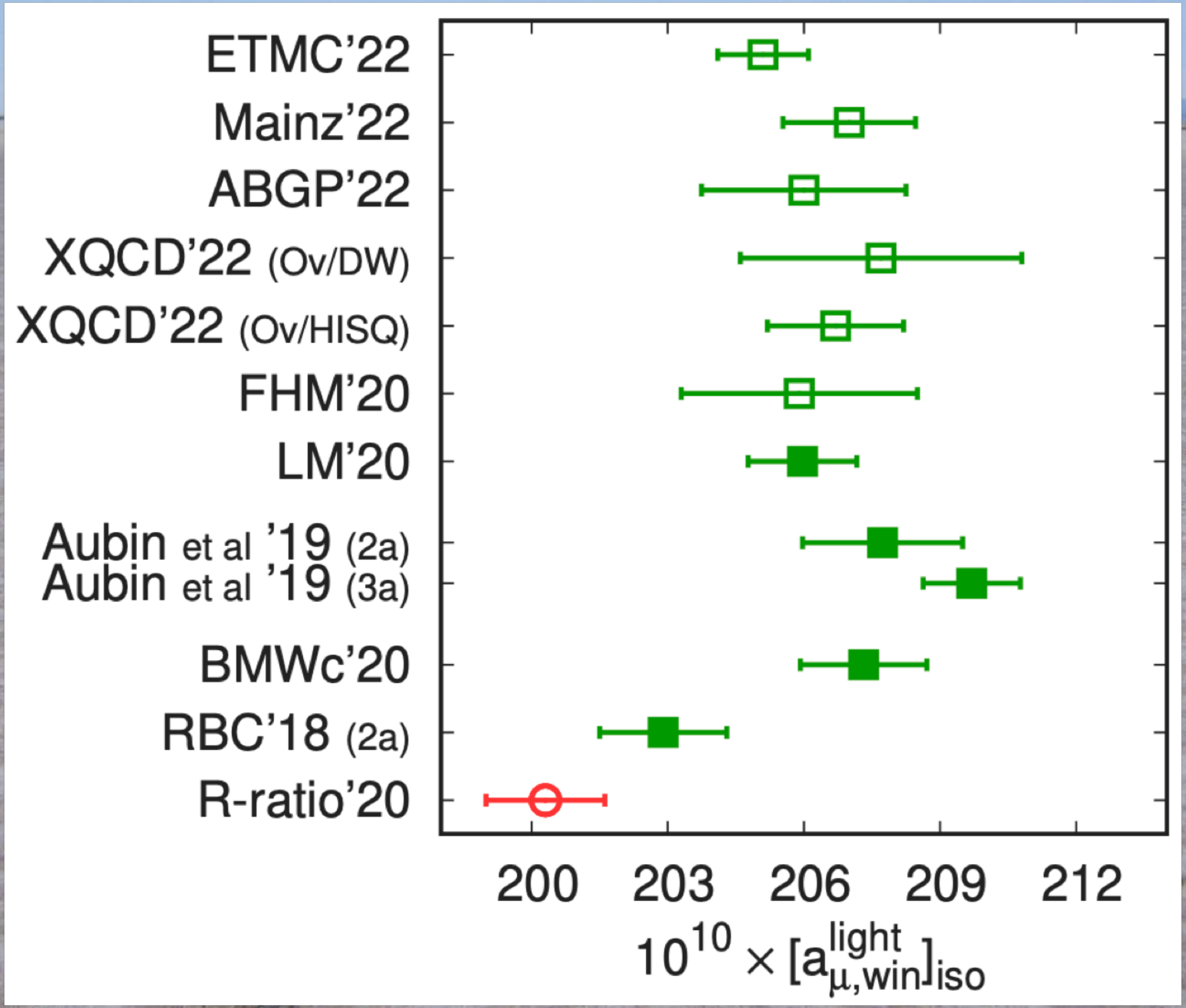
Comparison with Lattice Calculations of Hadronic Vacuum Polarization

$$\boxed{a_\mu^{\mathrm{HVP}} + \left[a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{Weak}} + a_\mu^{\mathrm{HLbL}}\right]} \rightarrow a_\mu^{\mathrm{SM}}$$



Aoyama et al, arXiv:2006.04822

Update on Lattice Calculations



General Interest in Antimatter Physics

Physicists cannot make enough for
Star Trek or Dan Brown!

How do Matter and Antimatter Differ?

Dirac predicted the existence of antimatter:
- same mass
- opposite internal properties:
  - electric charge, …

Discovered in cosmic rays
Studied using accelerators
Used in PET scanners

Matter and antimatter not quite equal and opposite: WHY?

Why does the Universe mainly contain matter, not antimatter?

Experiments at LHC and elsewhere looking for answers

How to Create the Matter in the Universe?

Sakharov

- Need a difference between matter and antimatter

  observed in the laboratory

- Need interactions able to create matter

  predicted by theories

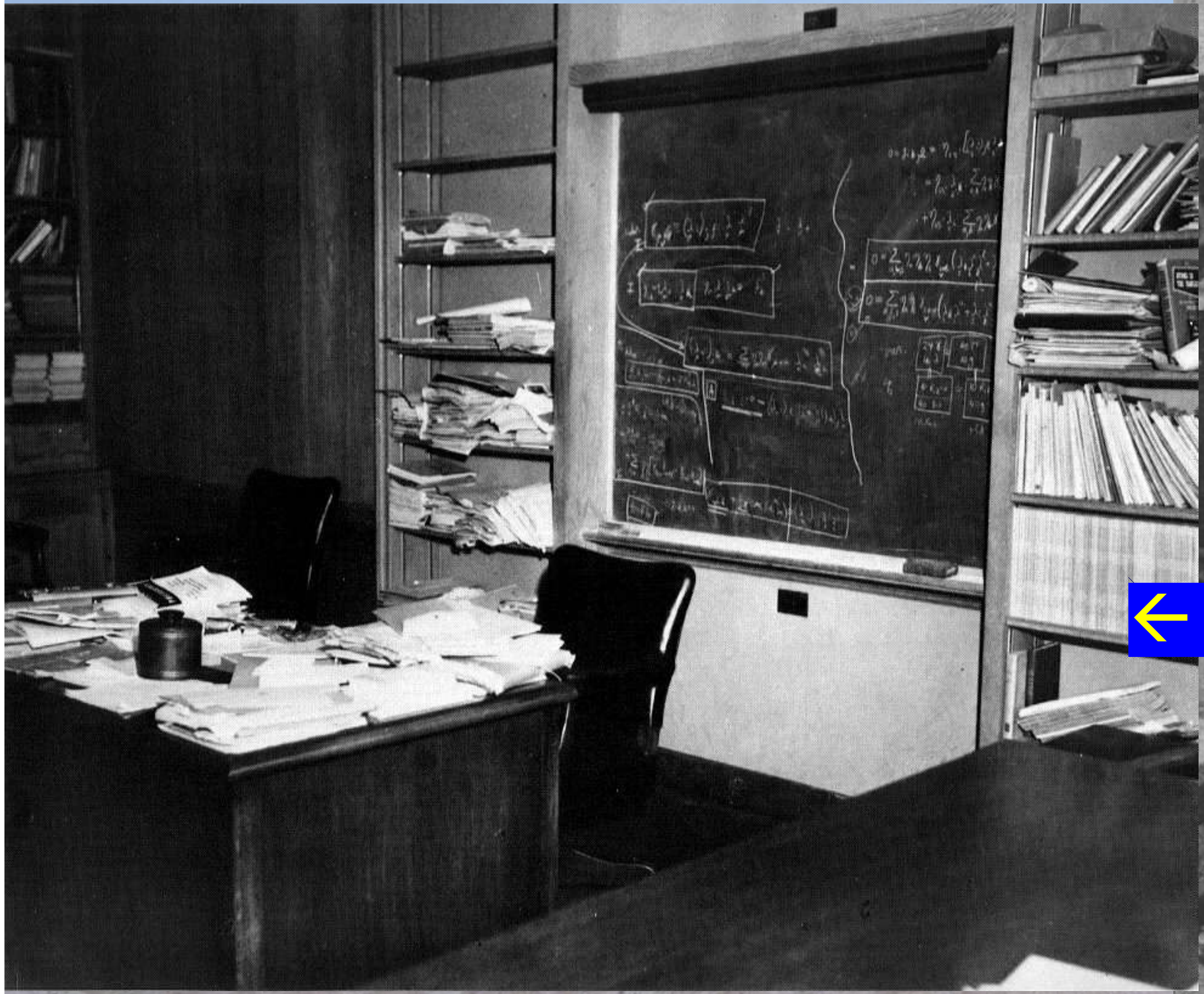
  not yet seen by experiment

- Need the expansion of the Universe

  a role for the Higgs boson?

Will we be able to calculate using laboratory data?

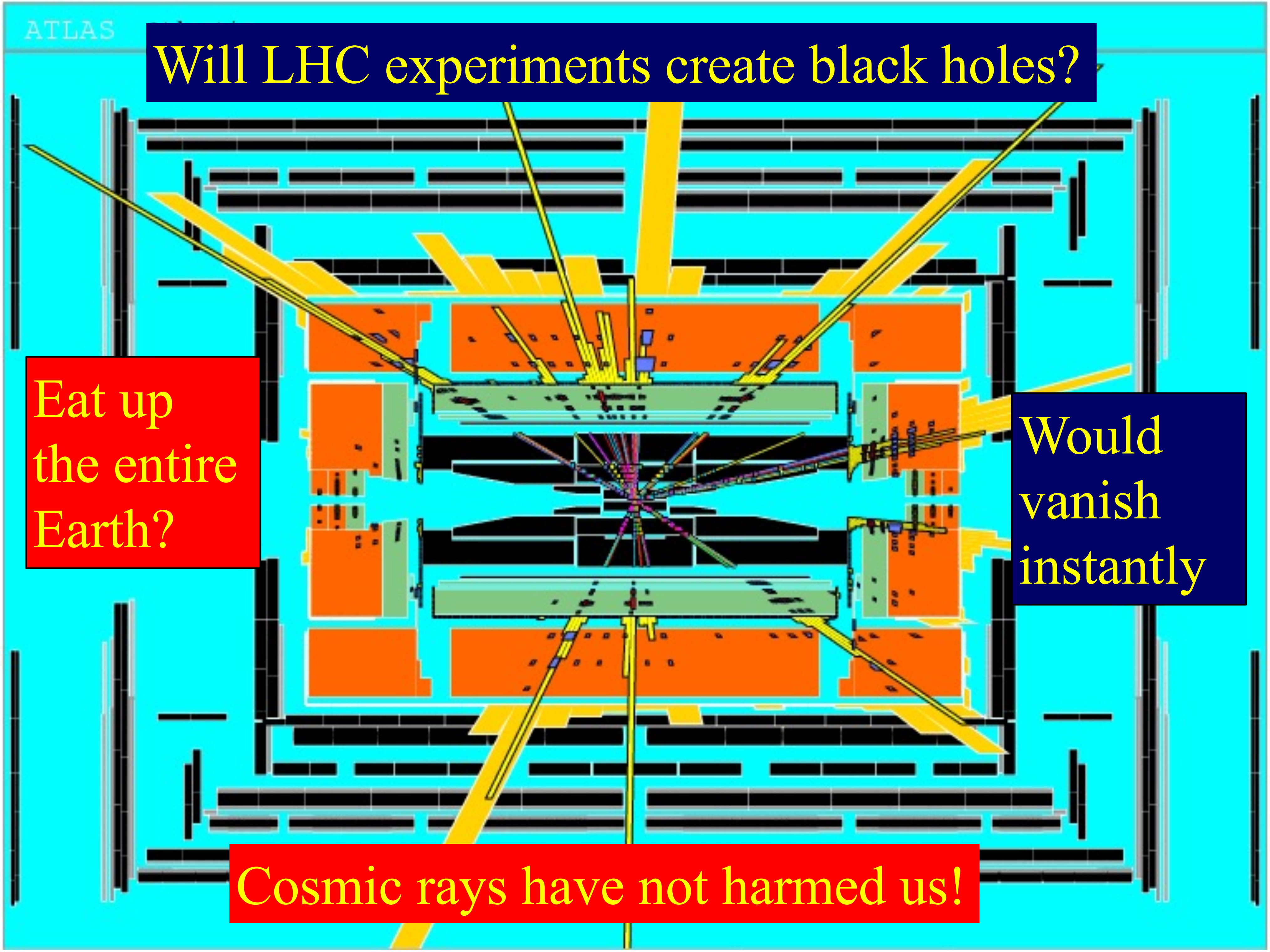
Unify the Fundamental Interactions: Einstein's Dream …



← … but he never succeeded

Unification via extra dimensions of space?

Will LHC experiments create black holes?

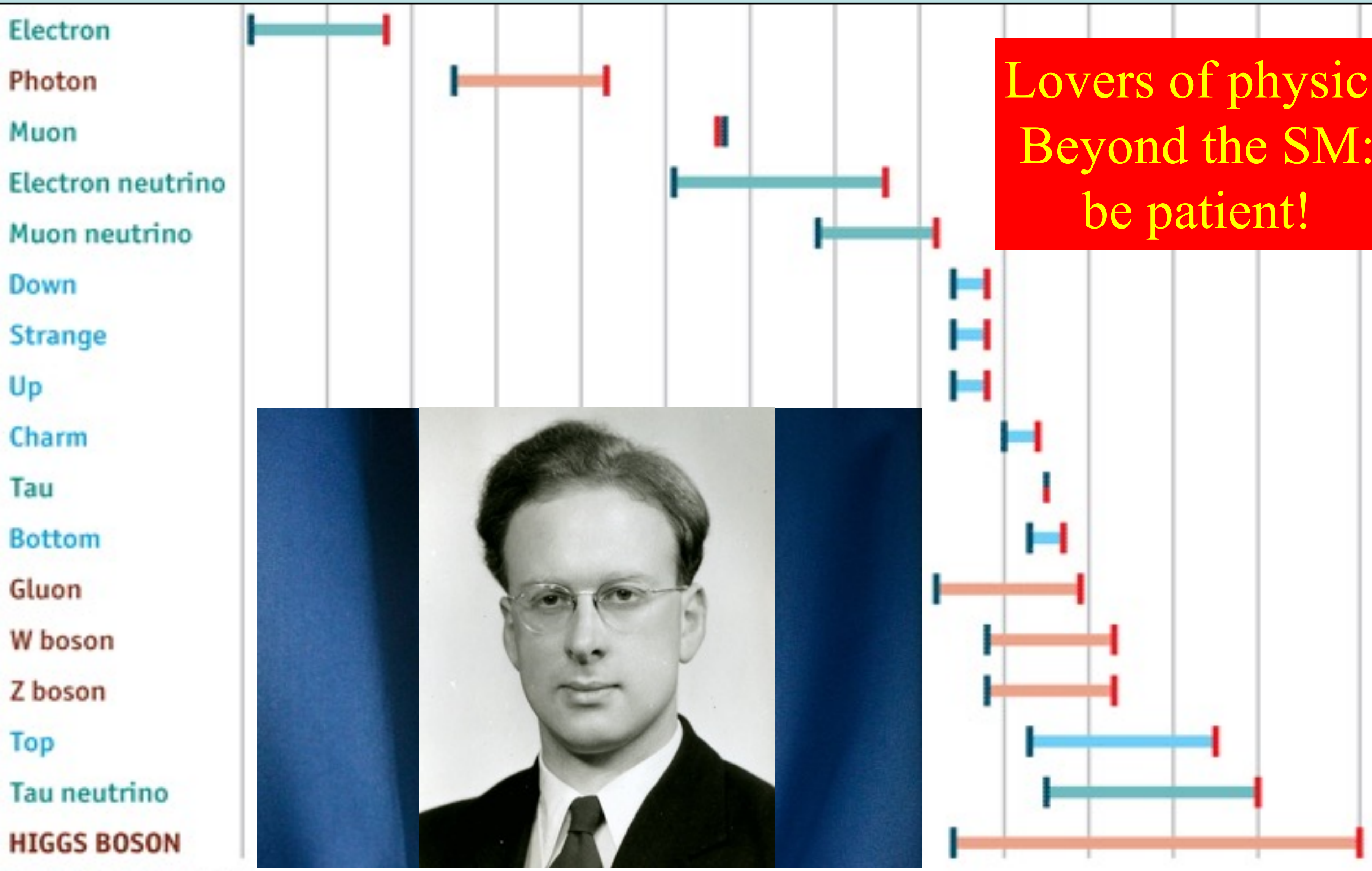


Eat up
the entire
Earth?

Would
vanish
instantly

Cosmic rays have not harmed us!

Standard Model Particles:
Years from Proposal to Discovery



Source: *The Economist*

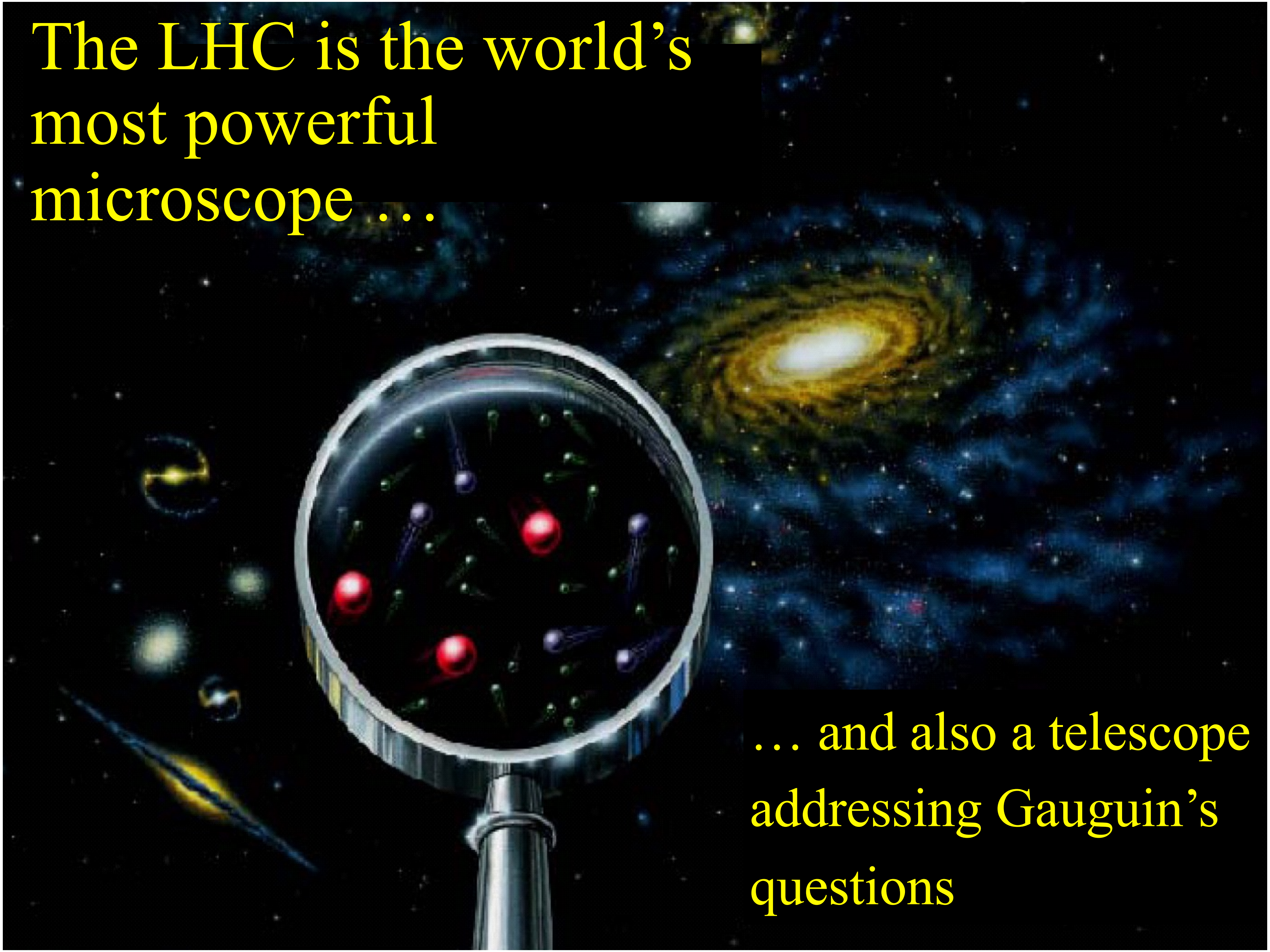
Lovers of physics
Beyond the SM:
be patient!

Higgstorical Summary

- Speculation
- Hypothesis
- Theory
- Search
- Discovery
- Building-block

} Repeat?

The LHC is the world’s most powerful microscope …



… and also a telescope addressing Gauguin’s questions