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The Branco Weiss Fellowship Society in Science

KING'S College LONDON

LHC BSM physics opportunities and theoretical challenges

Tevong You

Outline

- Context
- BSM theory challenges
- BSM physics opportunities
- Beyond the LHC
- Conclusion

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- **Context**
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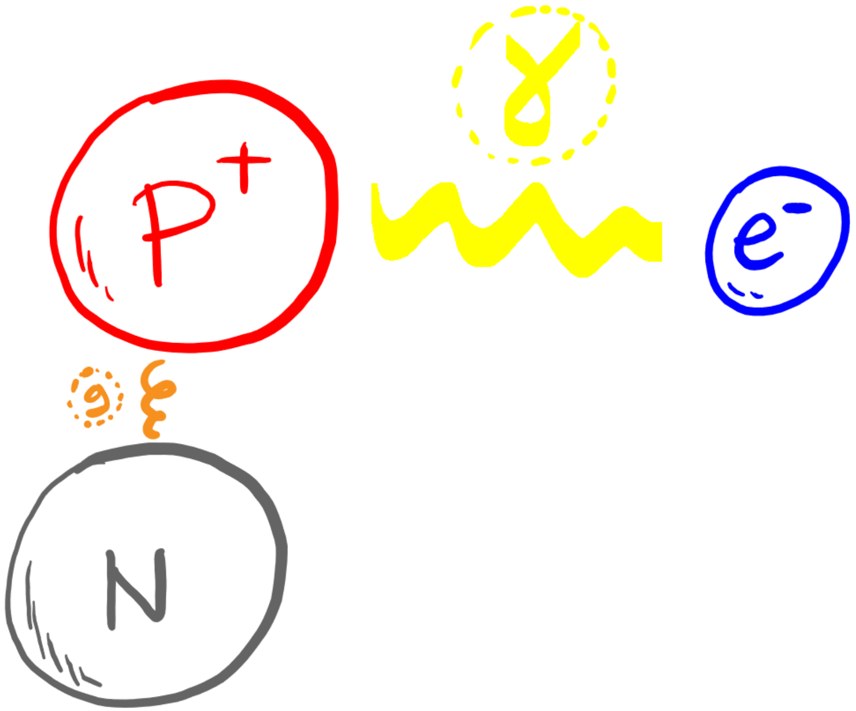
Context

- **3 lessons** from history

Context

- *1930s*: *everything* is made of **protons**, **neutrons**, and **electrons**

Minimal, economical theory!
However…



- Held together by **electromagnetism** and the **strong force**

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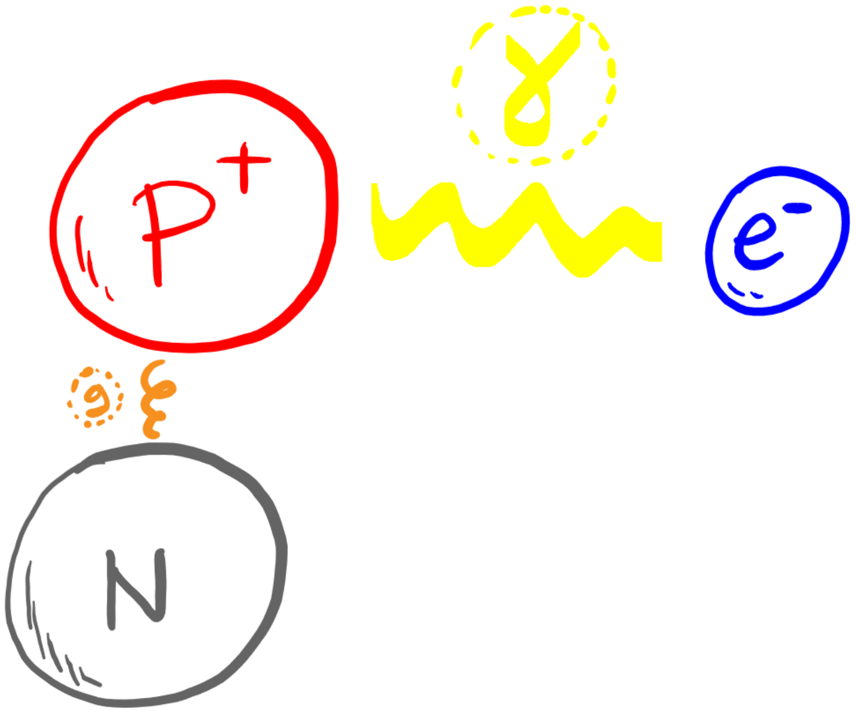


"If we consider protons and neutrons as elementary particles, we would have three kinds of elementary particles [p,n,e].... This number may seem large but, from that point of view, two is already a large number."

Paul Dirac 1933 Solvay Conference

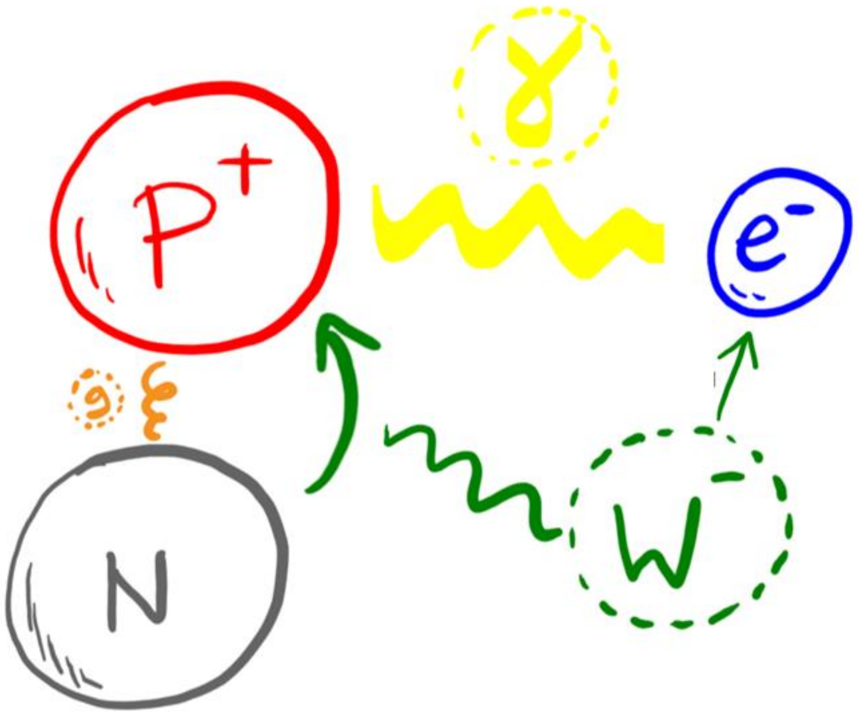
From D. Tong slide

Lesson 1: Beauty in fundamental physics is not an economy of particle multiplicities, it's an *economy of theoretical principles*

- Held together by **electromagnetism** and the **strong force**

Context

- **Weak force** explains *radioactivity*



- **Neutron** can change into **proton**, emitting **electron**

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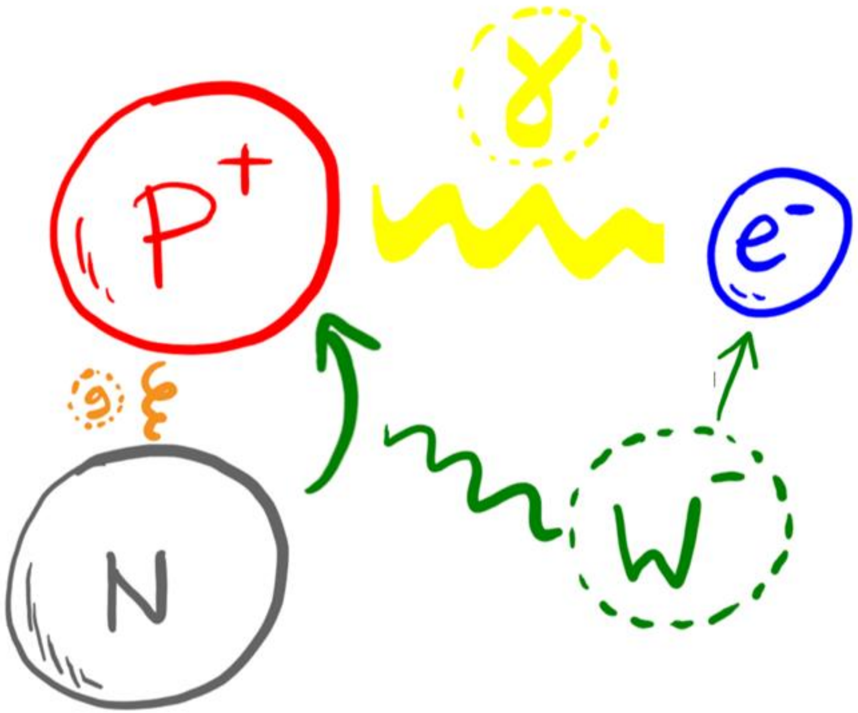

Missing energy? Pauli postulates *"a desperate remedy"*

(Bohr suggests fundamental violation of energy conservation principle)

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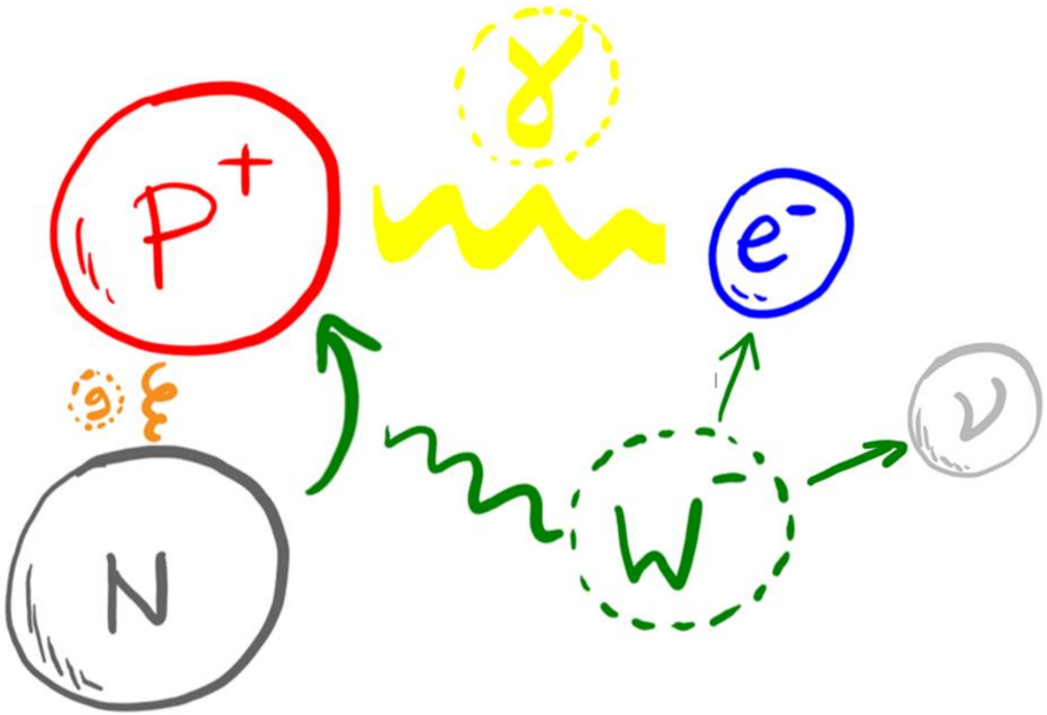

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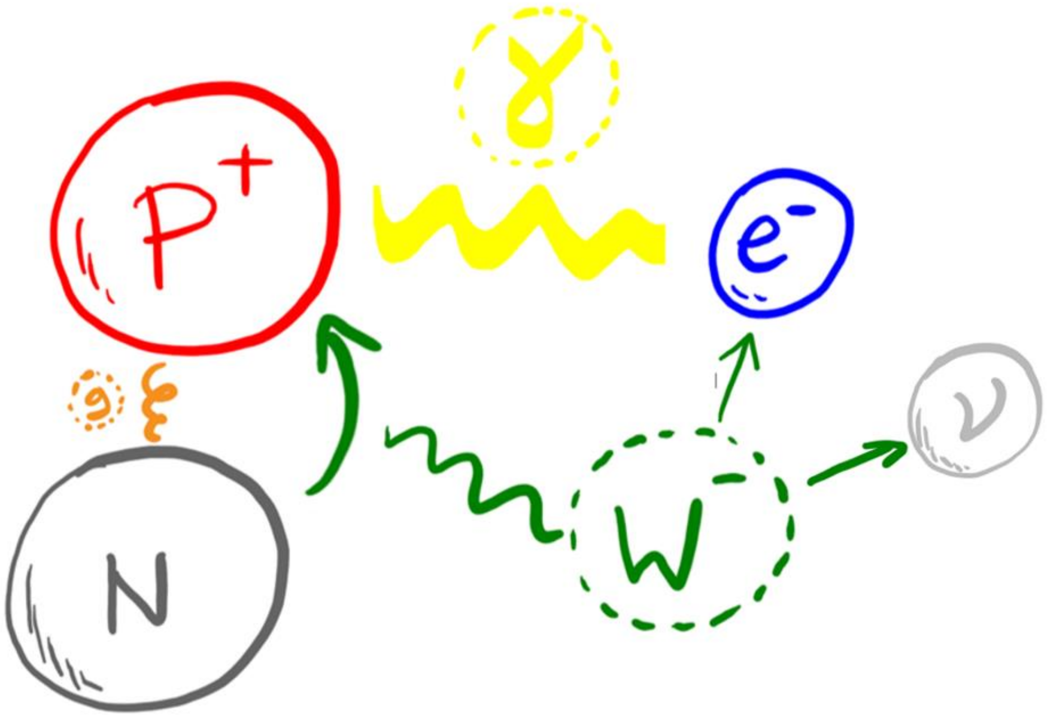

Missing energy? Pauli postulates *"a desperate remedy"*

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Lesson 2: *perceived* prospects of experimental confirmation is *not a useful scientific criteria* for establishing **what nature actually does**

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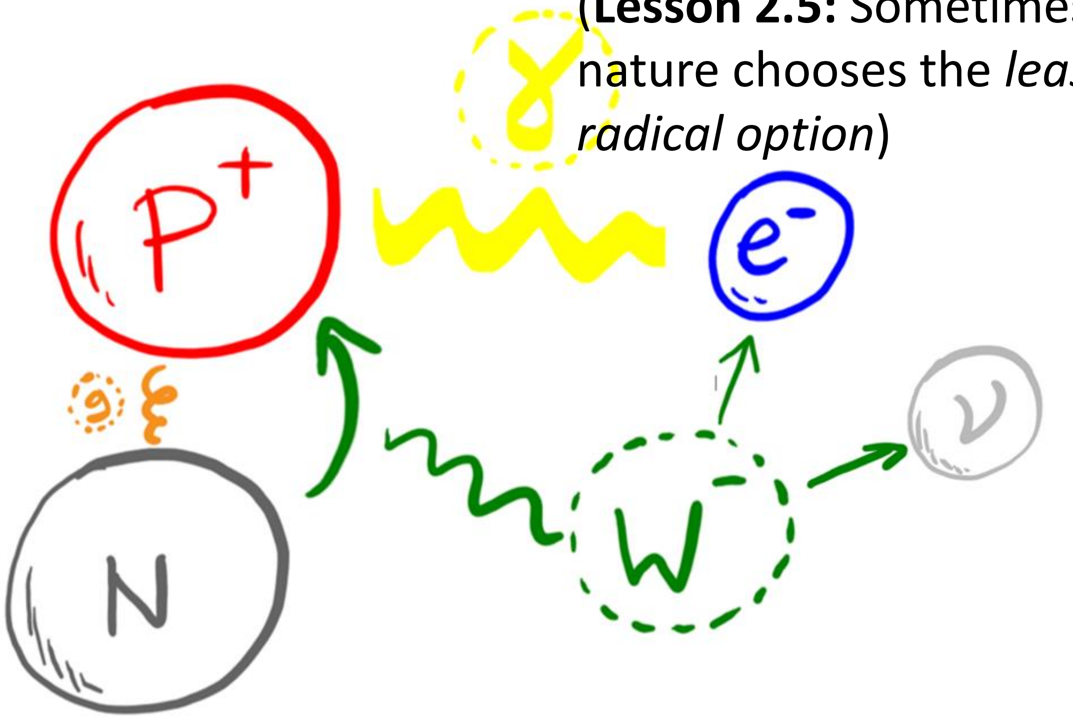

(**Lesson 2.5:** Sometimes nature chooses the *least radical option*)

Missing energy? Pauli postulates *"a desperate remedy"*

(Bohr suggests fundamental violation of energy conservation principle)

Lesson 2: *perceived* prospects of experimental confirmation is *not a useful scientific criteria* for establishing **what nature actually does**

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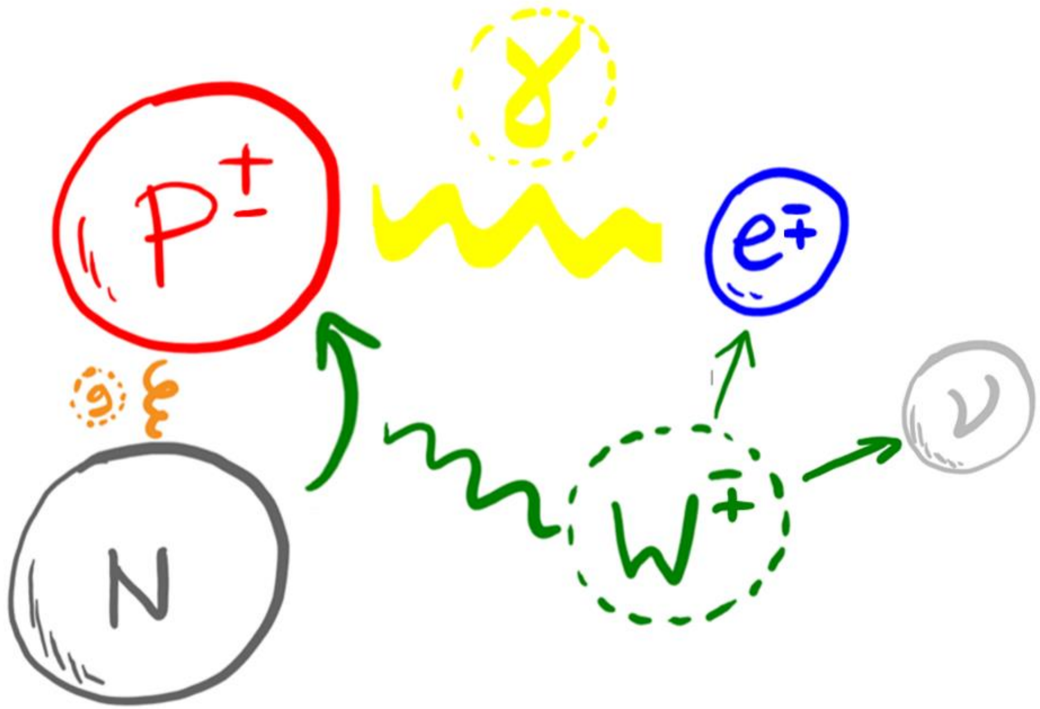
Context

- Dirac: Einstein's **relativity** + **quantum mechanics** = **antiparticles**



- *Every particle has an oppositely charged antiparticle partner*

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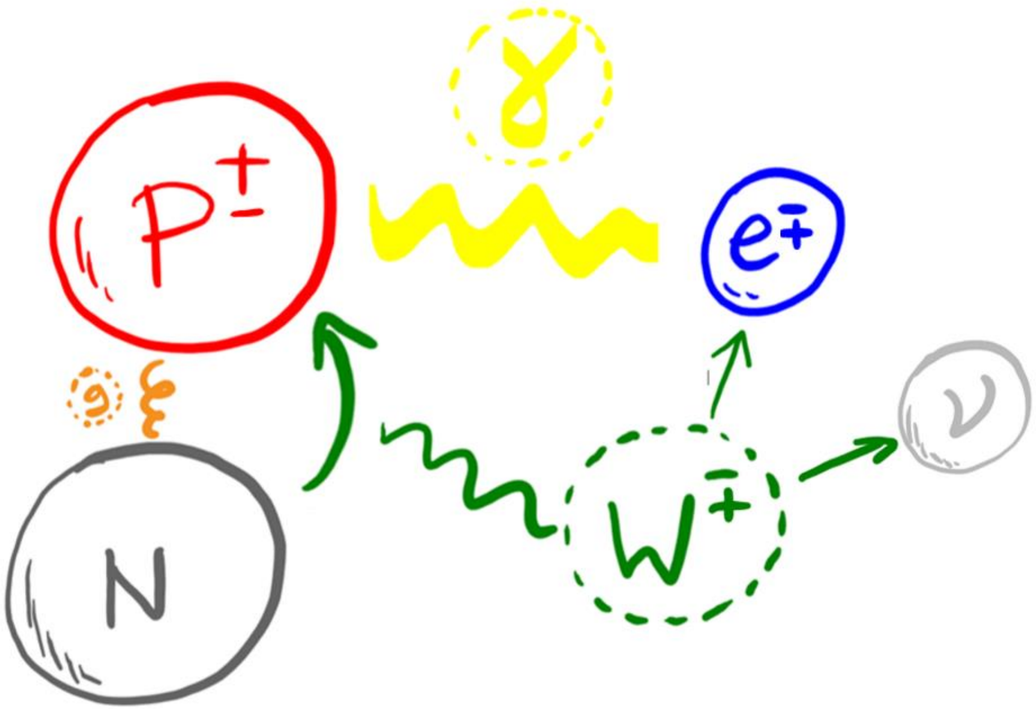
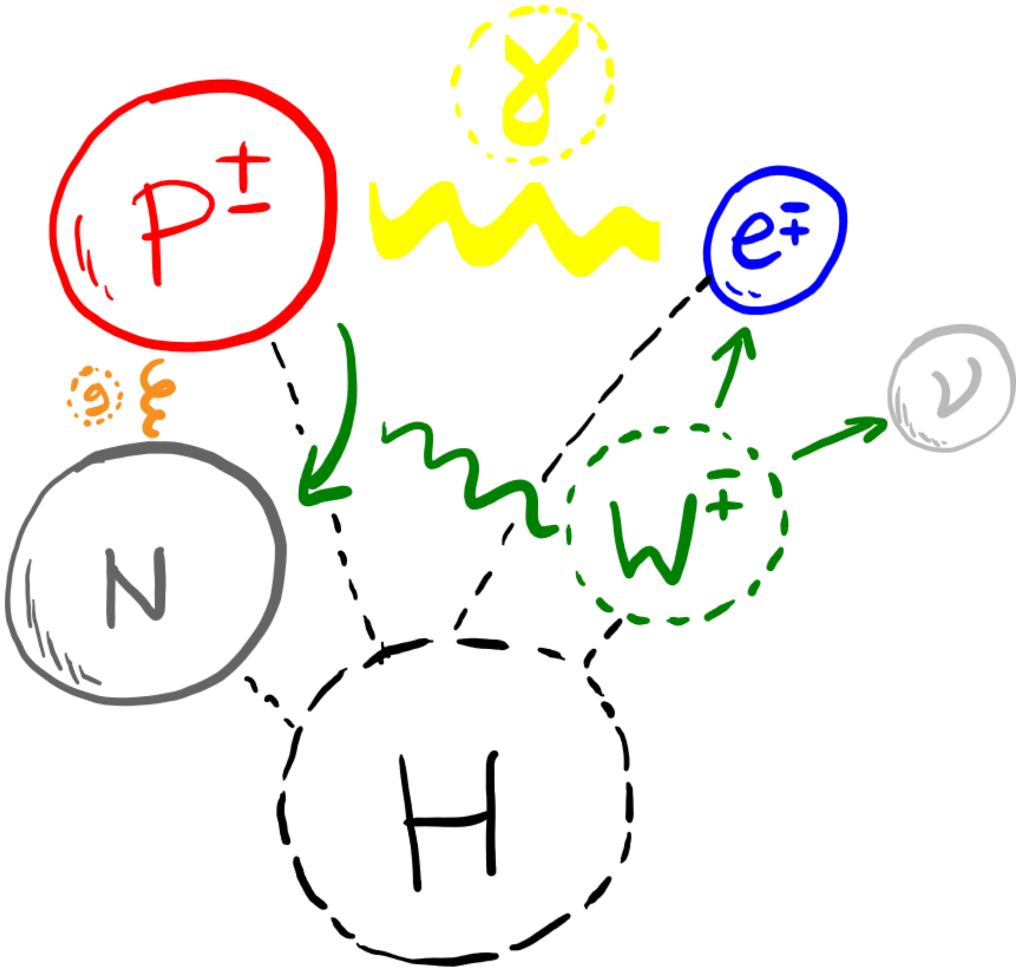


c.f. **Lesson 1**: antiparticles *double the particle spectrum*. Nevertheless, the theory is **much tighter**, **less arbitrary**, and **more elegant**

- *Every particle has an oppositely charged antiparticle partner*

Context

- *Higgs(+Brout+Englert):* **particle masses** require a new **scalar boson H**



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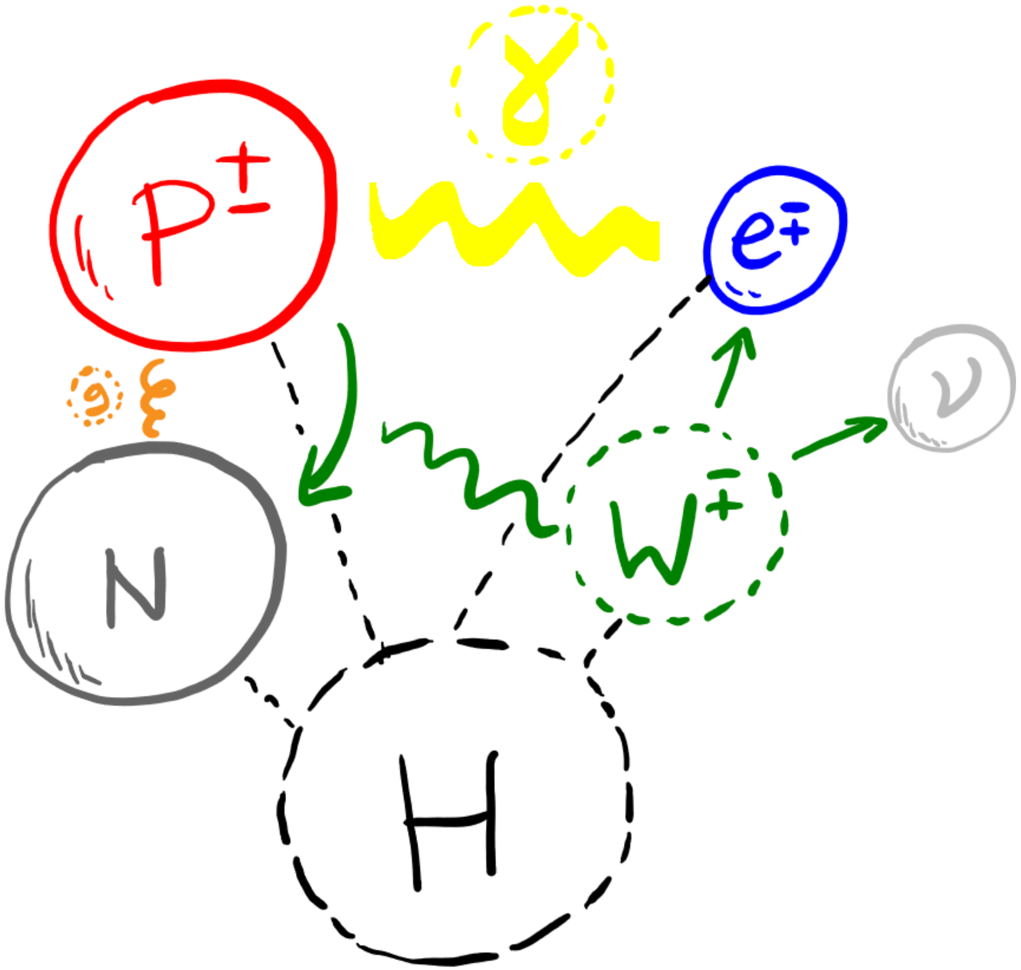
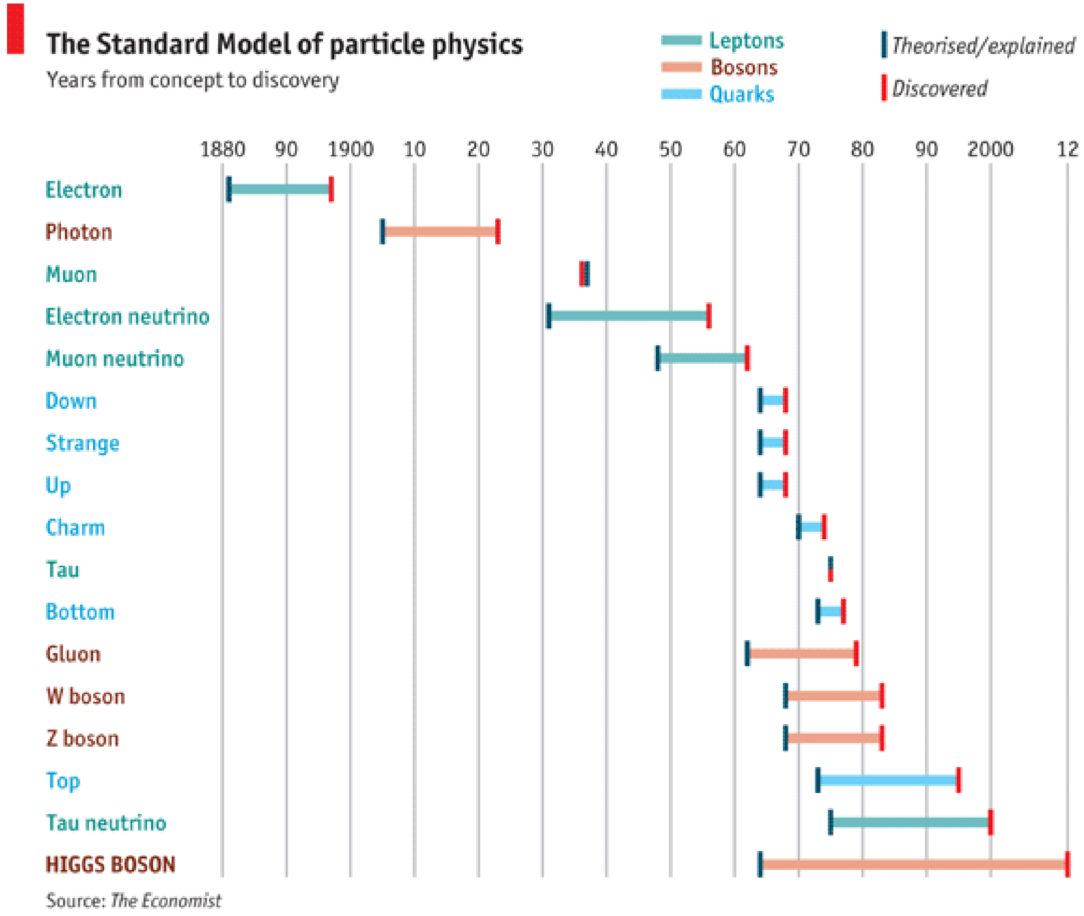


Lesson 3: Ideas initially dismissed as **unrealistic** (*e.g.* non-abelian gauge theories and spontaneous symmetry breaking because they predicted **unobserved massless** gauge bosons and goldstones) can *click together suddenly and make sense*

Context

- The Higgs boson discovery caps a **remarkable century** of particle physics



- *What next?*

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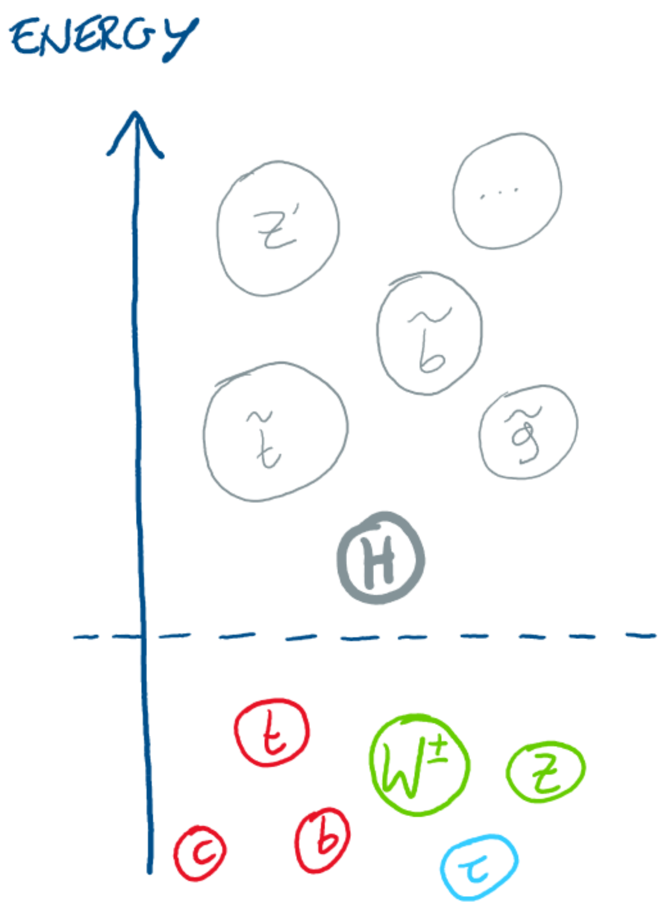
BSM theory challenges

- Until now, there had been a **clear roadmap**



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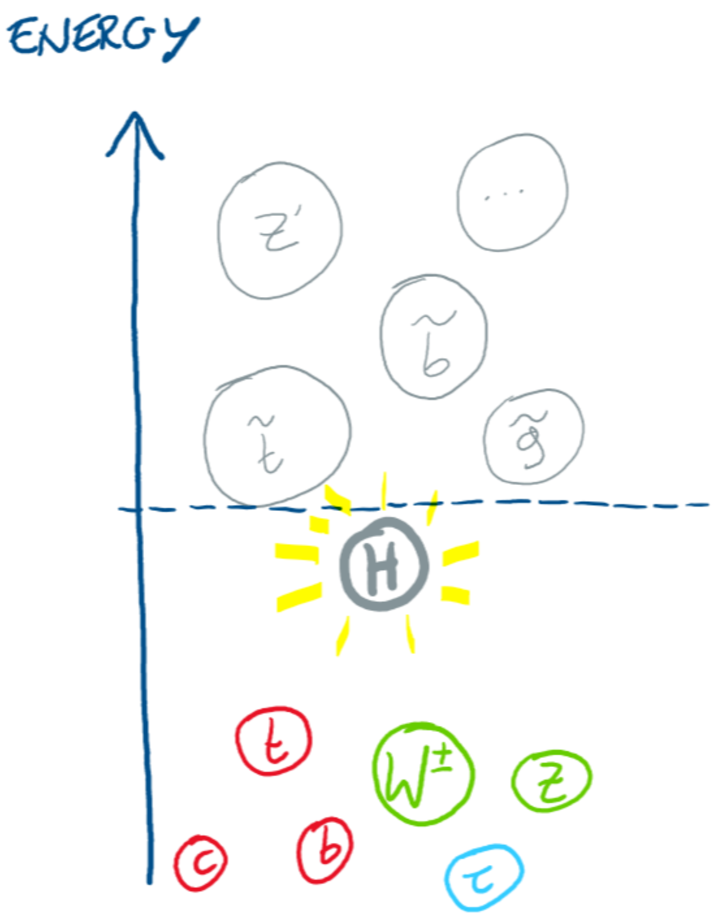

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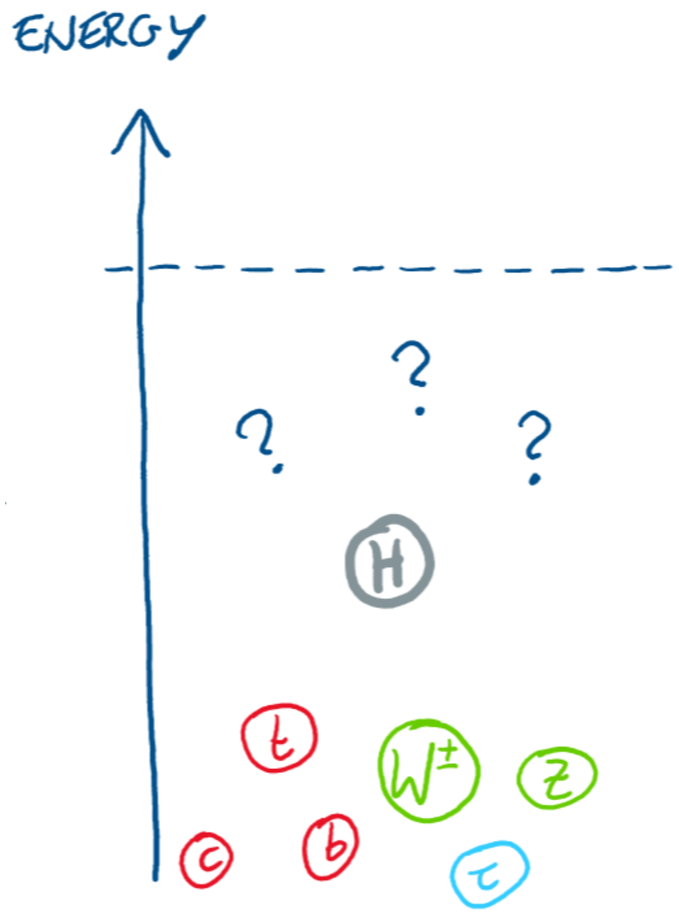

Conventional **symmetry-based** solutions *have not shown up*!

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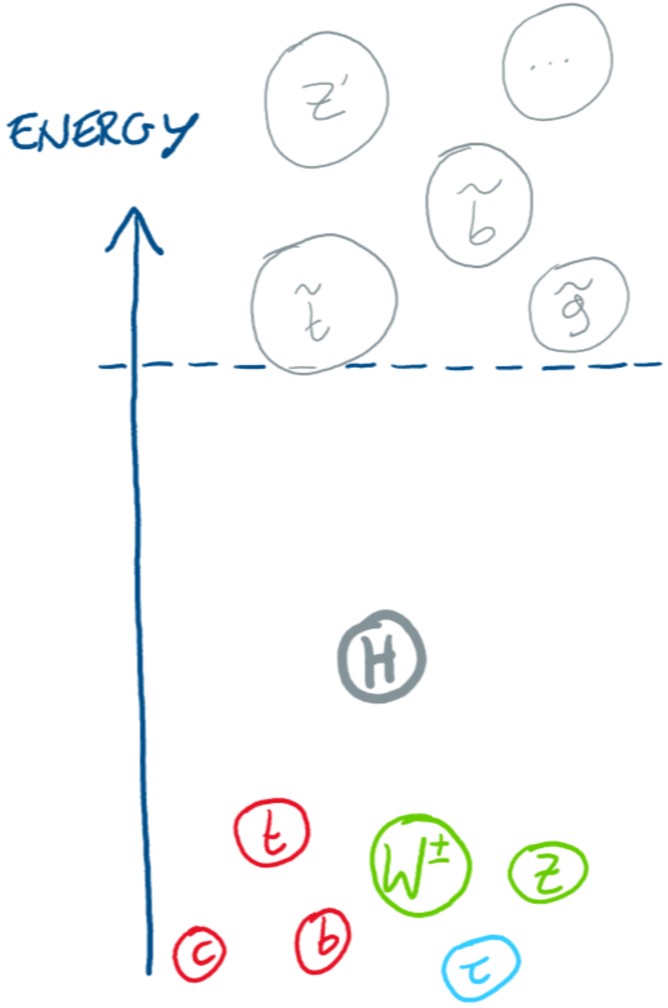

Maybe **just around the corner**…

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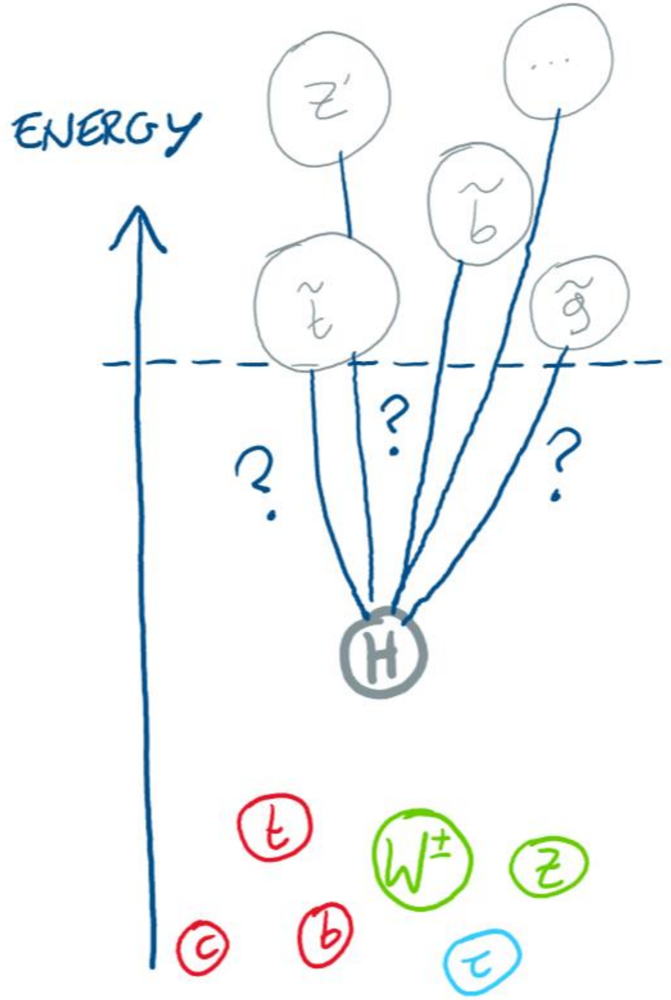

…but the larger the separation of scales, the more **fine-tuned** the underlying theory is

The Higgs is **more mysterious** than ever!

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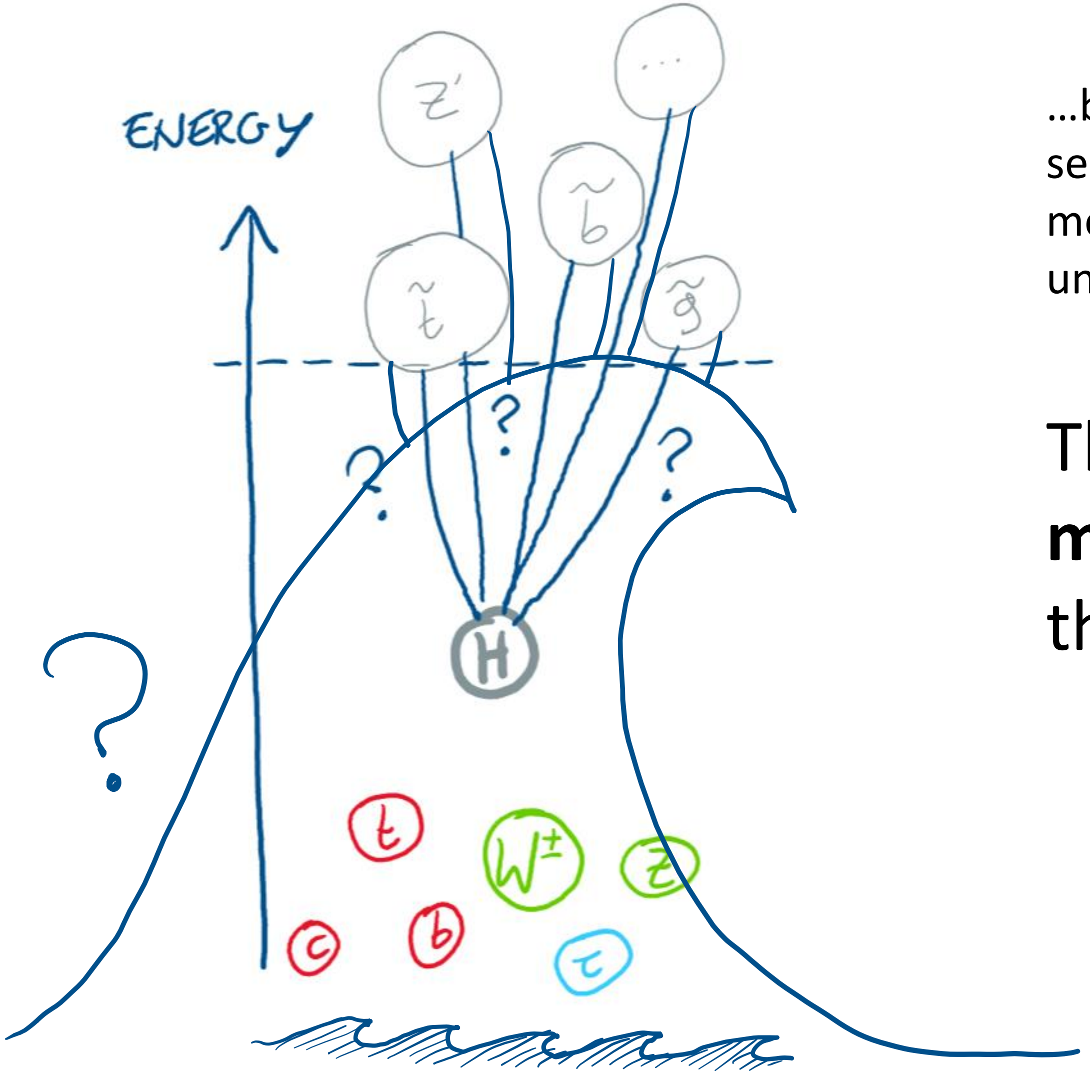


…but the larger the separation of scales, the more **fine-tuned** the underlying theory is

The Higgs is **more mysterious** than ever!

Vacuum energy is also *peculiarly tiny*

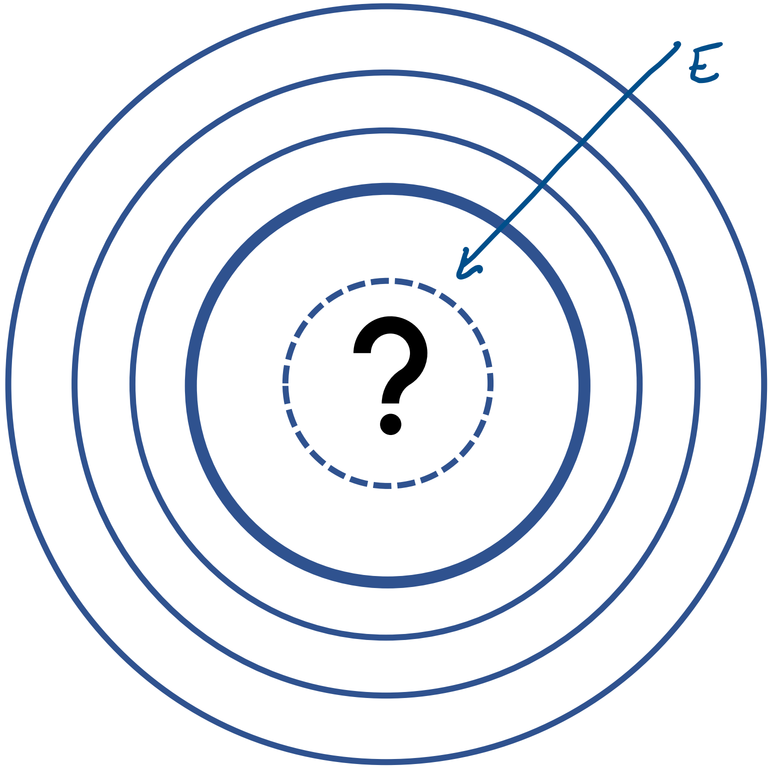
BSM theory challenges

- *Why is fine-tuning such a big deal?*

BSM theory challenges

- *Why is fine-tuning such a big deal?*
- Delicate **UV-IR cancellations** indicate *an unprecedented breakdown of the effective theory* organisational structure of nature

Effective theory at each scale is **predictive** as a **self-contained** theory at that scale



Un-natural Higgs means the next layer *is no longer predictive* without including contributions from much smaller scales

The Hierarchy Problem

- Hierarchy problem *is still a problem*: $(m_h)^2_{tree} + (m_h)^2_{radiative} = (m_h)^2_v$

[If Higgs mass is *calculable* in underlying UV theory]

$$\delta m_\phi^2 \propto m_{\rm heavy}^2, \quad \delta m_\psi \propto m_\psi \log\left(\frac{m_{\rm heavy}}{\mu}\right)$$

Historical precedent

- Take aesthetic issues seriously
- Earliest example of an unnatural, **arbitrary** feature of a fundamental theory:

$$m_{inertial} = q_{gravity}$$

- Classical electromagnetism fine-tuning:

$$(m_e c^2)_{\rm obs} = (m_e c^2)_{\rm bare} + \Delta E_{\rm coulomb}, \qquad \Delta E_{\rm coulomb} = \frac{e^2}{4\pi\epsilon_0 r_e}$$

- Pions, GIM mechanism, etc.

- Higgs? Expect new physics close to weak scale

Understanding the origin of EWSB

- The SM has many *arbitrary* features put in by hand which hint at **underlying structure**

  - *Pattern of Yukawa couplings, CKM*
  - *QCD Theta term*
  - *Neutrino mass*
  - *Higgs potential*
  - *…*

- Maybe it just is what it is ¯_(ツ)_/¯

- but we would like a **deeper understanding** i.e. an *explanation* for why things are the way they are

  - *e.g. PQ axion for Theta term, see-saw for neutrino mass, Froggat-Nielsen for Yukawas…*

- In SM, **no understanding** of Higgs sector: Higgs potential and couplings *put in by hand and unexplained*

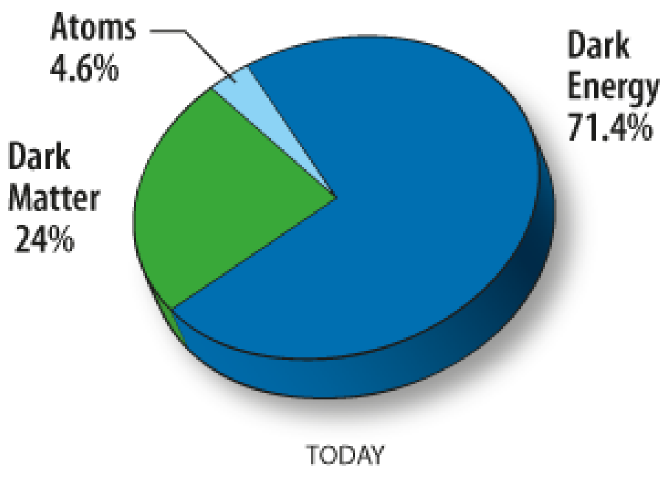
- We feel there must be some underlying system that **explains the origin of EWSB**

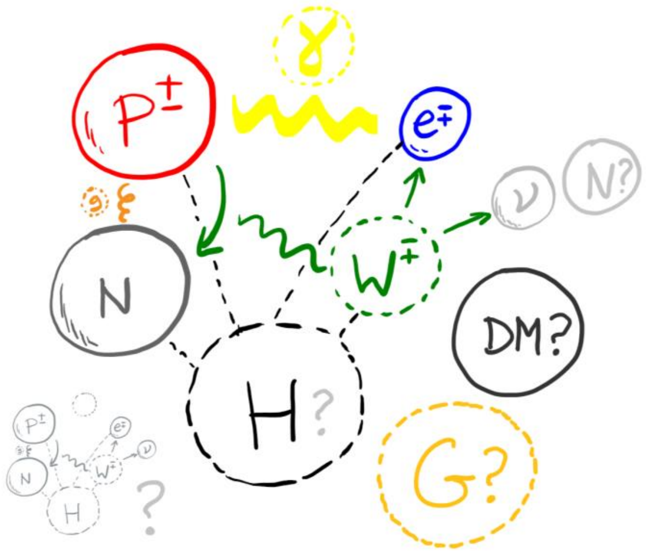
- In any such theory *in which the Higgs potential is calculable*, there is a **UV sensitivity** to the Higgs mass (*that is no longer a free parameter*) which requires fine-tuned cancellations

- Unlike solutions to other arbitrary features, this one points to **weak-scale new physics** or **a breakdown of EFT**

BSM theory challenges

- What is the **origin of the Higgs**?
- What is the **origin of matter**?
- What is the **origin of flavour**?
- What is the **origin of dark matter** and **dark energy**?
- What is the **origin of neutrino mass**?
- What is the **origin of the Standard Model**?





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BSM physics opportunities

- **LHC Run 3**: *improved detector performance* and *double the data*
- Establish *Higgs coupling to second generation*
- **SND/FASERnu**: *Neutrinos from colliders* to be detected for the first time
- **Anomalies** and **excesses** will be *confirmed* or *refuted*
- New types of searches / **new types of theories**
- **SM EFT** analyses will further *probe indirectly* the scale of new physics

SM to SMEFT framework

- New physics appear to be decoupled at higher energies
- Given particle content, write down *all* terms allowed by symmetries…

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
Q_L	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$
q_R^u	$\mathbf{3}$	$\mathbf{1}$	$\frac{2}{3}$
q_R^d	$\mathbf{3}$	$\mathbf{1}$	$-\frac{1}{3}$
L_L	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$
l_R	$\mathbf{1}$	$\mathbf{1}$	-1
ϕ	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$

$$\mathcal{L}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y \quad ,$$

$$\mathcal{L}_m = \bar{Q}_L i\gamma^\mu D_\mu^L Q_L + \bar{q}_R i\gamma^\mu D_\mu^R q_R + \bar{L}_L i\gamma^\mu D_\mu^L L_L + \bar{l}_R i\gamma^\mu D_\mu^R l_R$$

$$\mathcal{L}_G = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W_{\mu\nu}^a W^{a\mu\nu}$$

$$\mathcal{L}_H = (D_\mu^L \phi)^\dagger (D^{L\mu}\phi) - V(\phi)$$

$$\mathcal{L}_Y = y_d \bar{Q}_L \phi q_R^d + y_u \bar{Q}_L \phi^c q_R^u + y_L \bar{L}_L \phi l_R + \text{h.c.} \quad ,$$

- …Including **higher-dimensional** operators!

$$+ \quad \mathcal{L}_{\text{SM}}^{\text{dim-6}} = \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

- Generated by new physics at scale $\Lambda \gg v$

We’ve always been doing EFT (even before we knew about EFT)

- **QED EFT = QED + Euler-Heisenberg + Fermi theory**

$$\mathcal{L}^{EFT}_{QED} = \bar{\Psi} i \gamma^\mu D_\mu \Psi - m \bar{\Psi}\Psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

Fermi theory (1933)

$$+ \sum_i \frac{c_6^{(i)}}{\Lambda^2} (\bar{\Psi} \Gamma \Psi)(\bar{\Psi} \Gamma \Psi) \qquad \Gamma = \{\mathbb{1}, \gamma_5, \gamma_\mu, \gamma_\mu \gamma_5, \sigma_{\mu\nu}\}$$

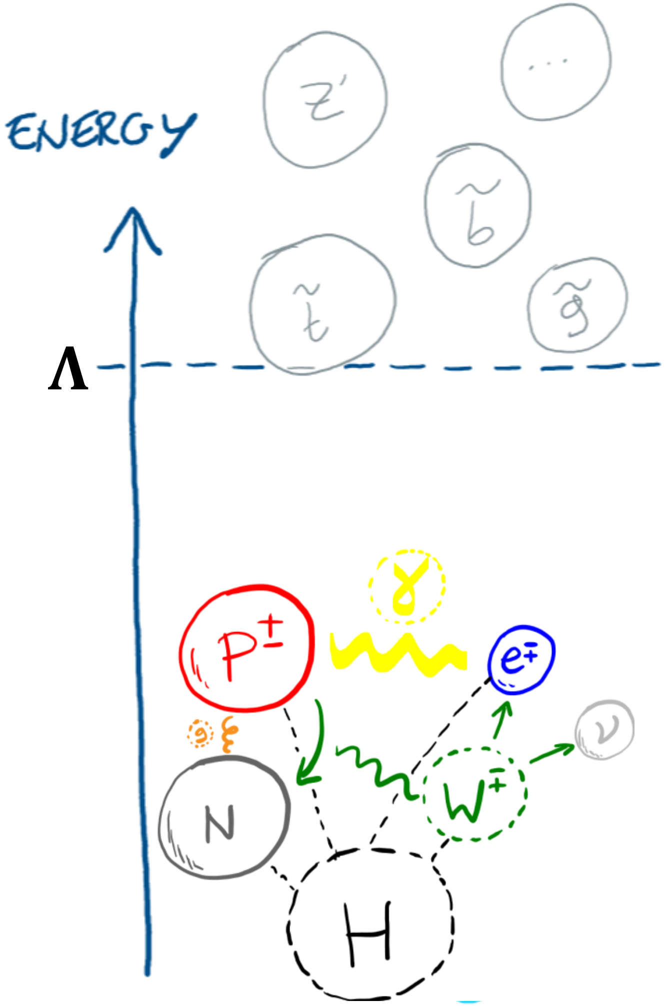
Euler-Heisenberg (1936)

$$+ \frac{c_8^{(1)}}{\Lambda^4} (F_{\mu\nu} F^{\mu\nu})^2 + \frac{c_8^{(2)}}{\Lambda^4} F_{\mu\nu} F^{\nu\rho} F_{\rho\lambda} F^{\lambda\mu} + \ldots$$

- **EFT fits** to experimental data **established V-A** structure

SMEFT: phenomenology in the 21st century

- **Standard Model Effective Field Theory** (SMEFT) framework



$$\mathcal{L}_{UV} = ?$$

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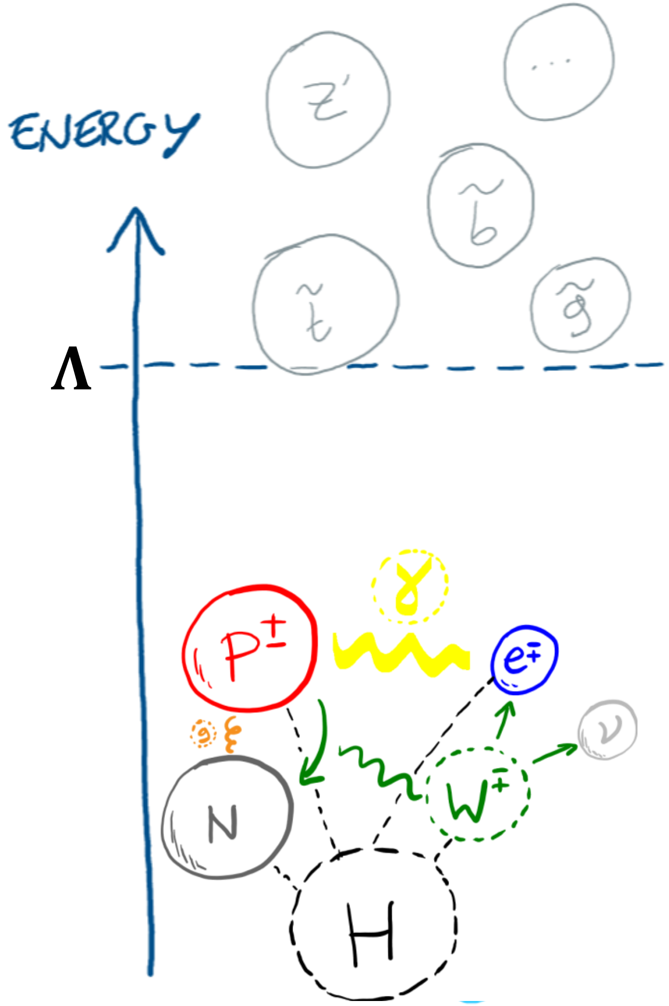

- Characterises *heavy* new ultra-violet (**UV**) physics
- Parametrised by coefficients $\boldsymbol{c_i}$ and heavy energy scale $\boldsymbol{\Lambda}$

$\mathcal{L}_{UV} = ?$

$$\mathcal{L}_{SM}^{\text{EFT}} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y + \frac{c_5}{\Lambda}\mathcal{O}^{(5)} + \frac{c_6}{\Lambda^2}\mathcal{O}^{(6)} + \frac{c_7}{\Lambda^3}\mathcal{O}^{(7)} + \frac{c_8}{\Lambda^4}\mathcal{O}^{(8)} + \ldots$$

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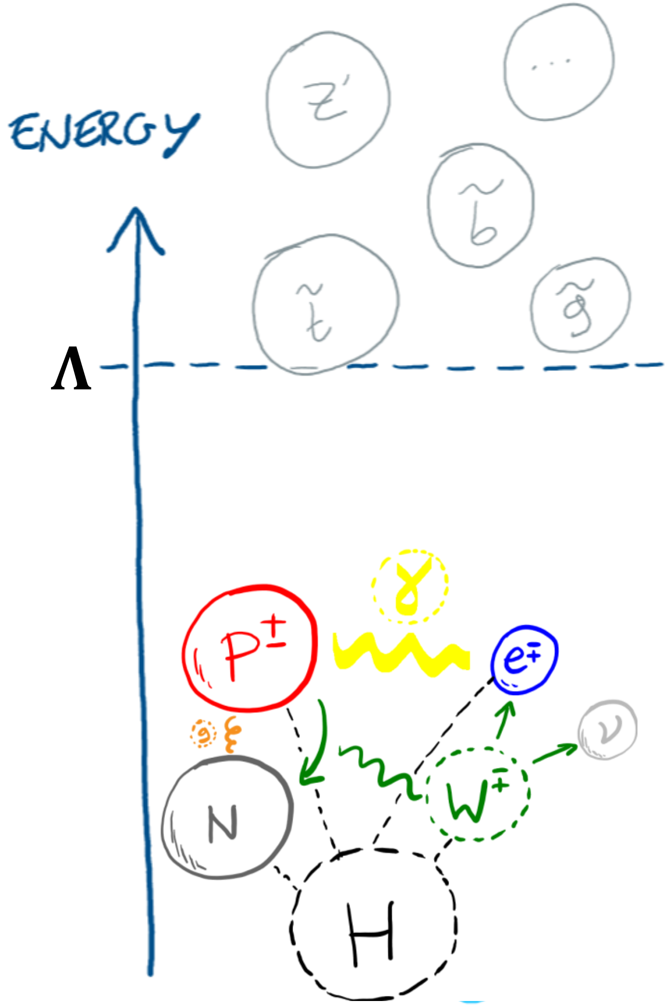

- What are the experimental constraints on the **energy scale** of new physics, $\boldsymbol{\Lambda}$?
- What are the experimental constraints on their **interaction strengths**, $\boldsymbol{c_i}$?

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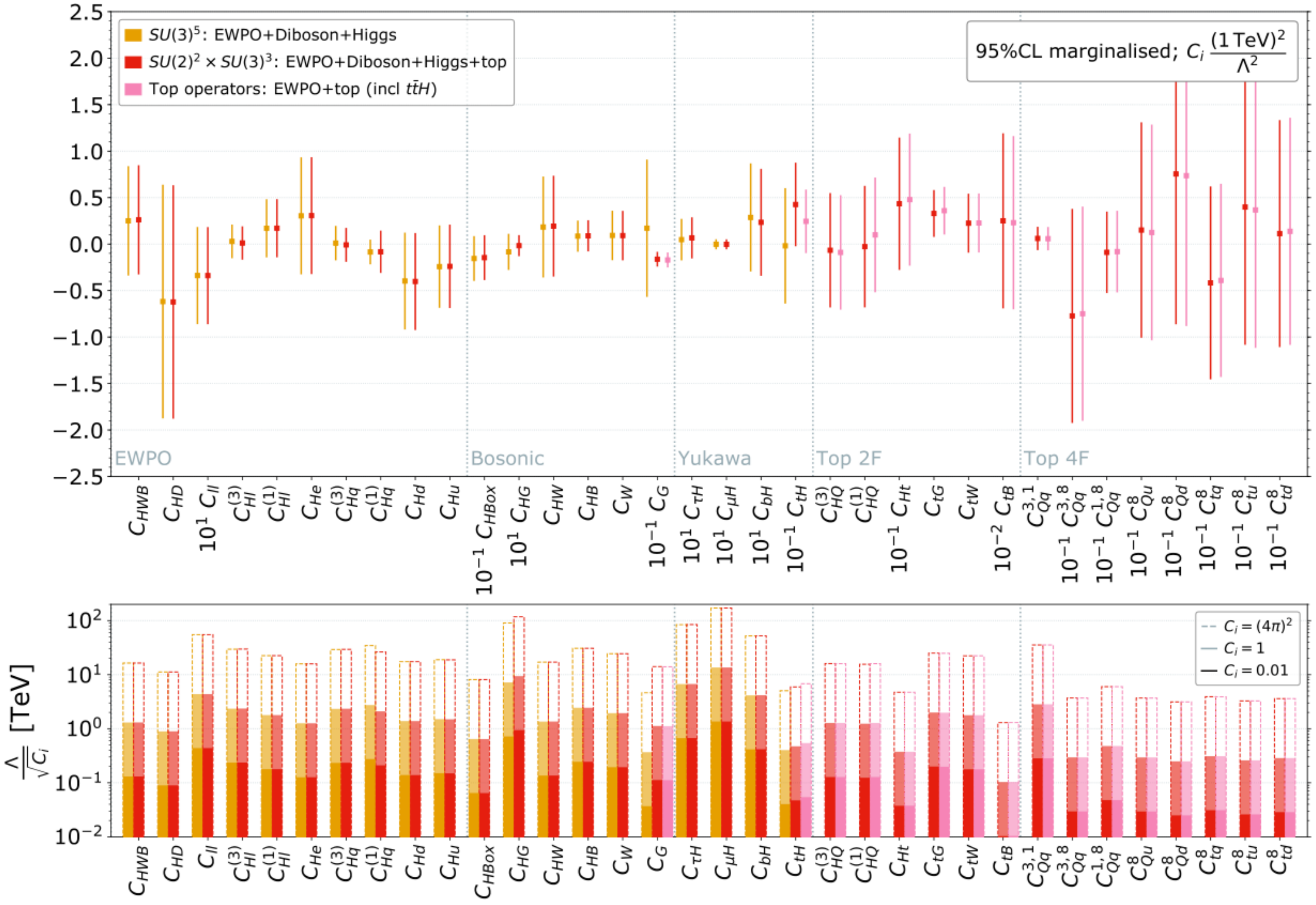

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J. Ellis, Madigan, Mimasu, Sanz, TY [2012.02779]

- *e.g.* Combined global fit to **Top**, **Higgs**, **diboson**, and **electroweak** experimental data

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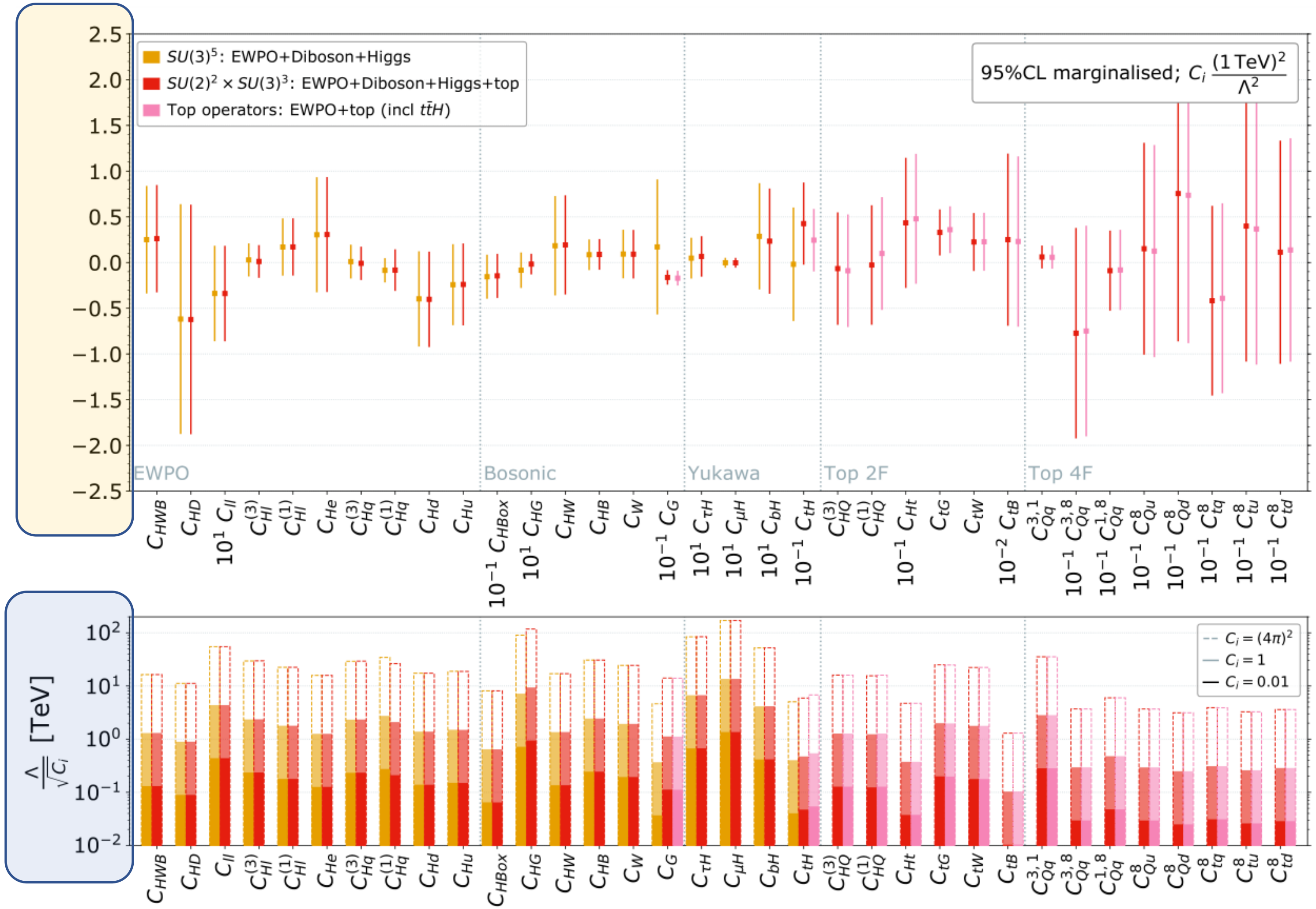

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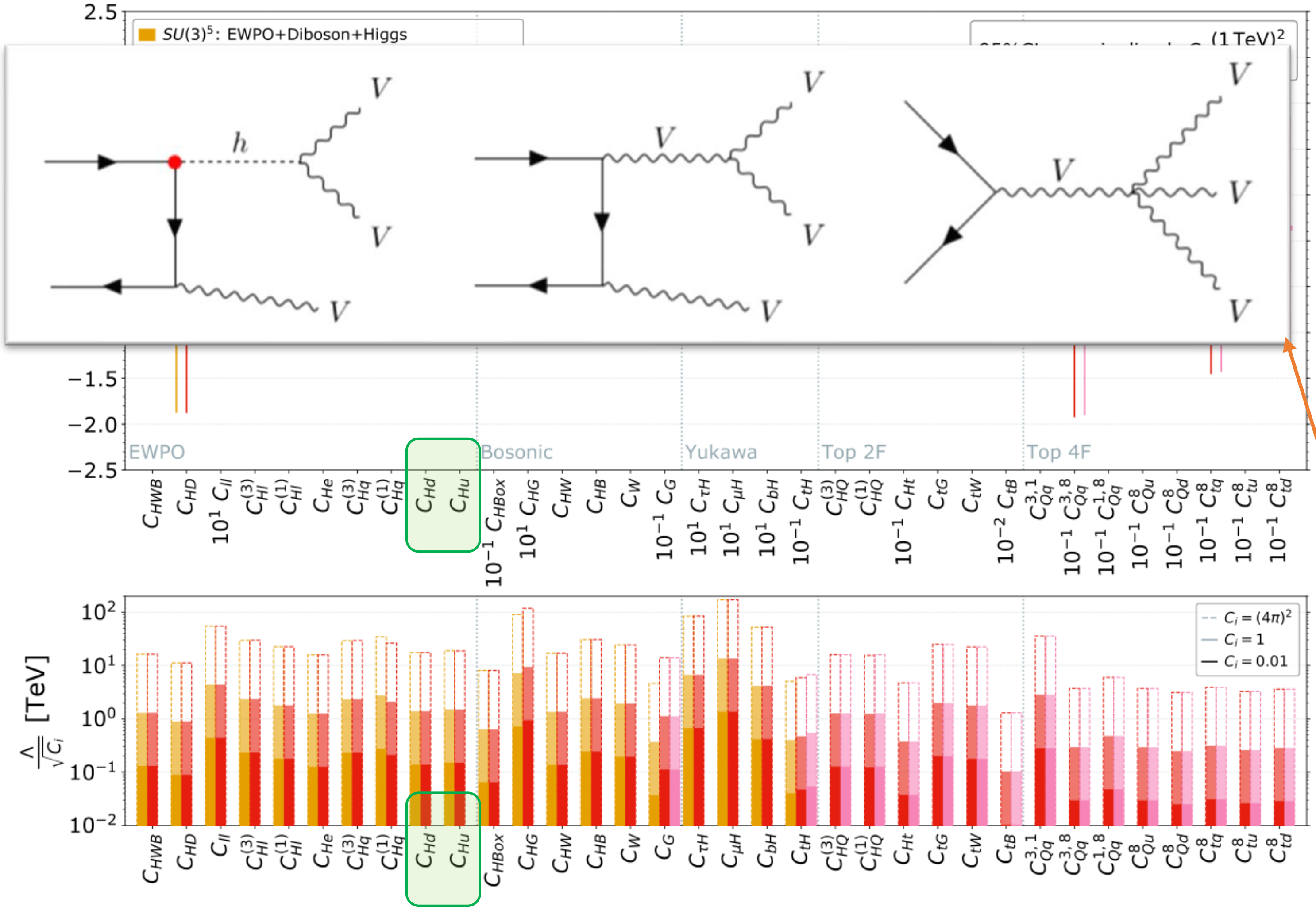

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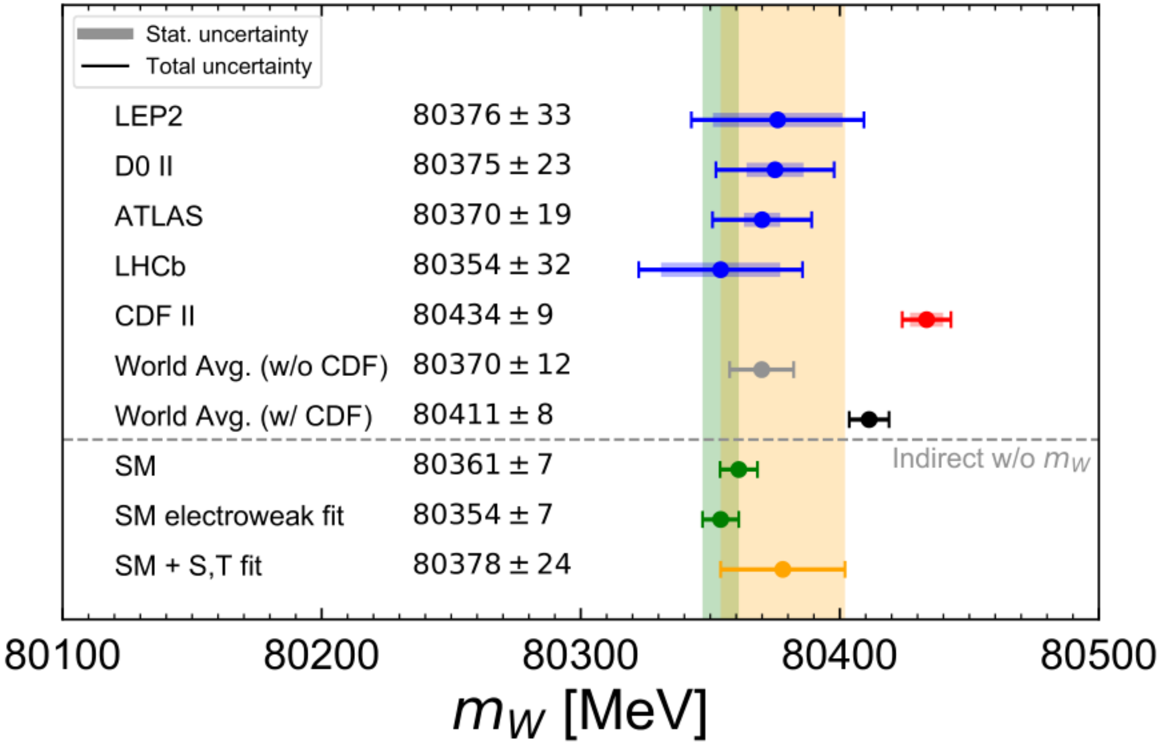
- Can now include also **triboson**

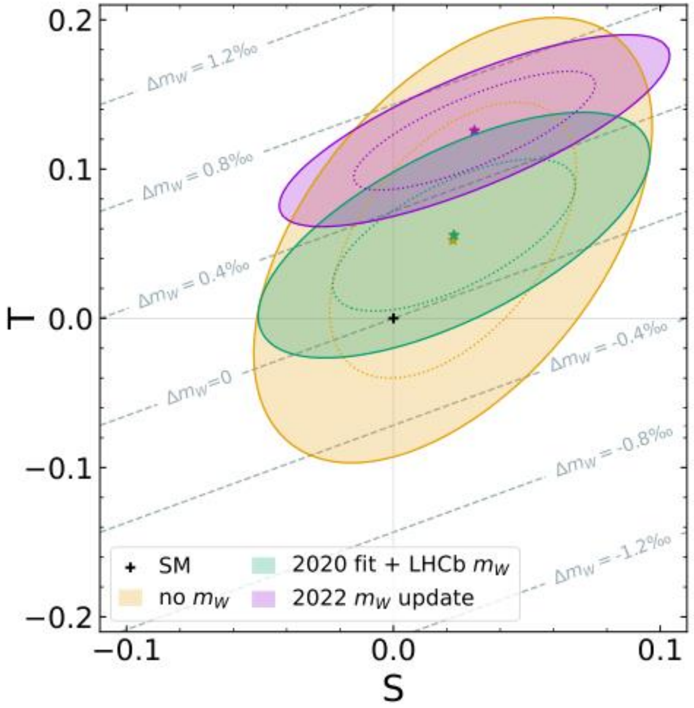
A. Falkowski, S. Ganguly, P. Gras, J. No, K. Tobioka, N. Vignaroli, TY [2011.09551]

SMEFT Analysis of m_W

Bagnaschi, Ellis, Madigan, Mimasu, Sanz, and You [2204.05260]

- S+T fit **excluding m_W**: *other data* compatible (~1.5σ) with **measurements avg.** *including* **CDF**





$$\frac{v^2}{\Lambda^2} C_{HWB} = \frac{g_1 g_2}{16\pi} S \quad , \quad \frac{v^2}{\Lambda^2} C_{HD} = -\frac{g_1 g_2}{2\pi(g_1^2 + g_2^2)} T$$

- True in SMEFT **more generally**? $\frac{\delta m_W^2}{m_W^2} = -\frac{\sin 2\theta_w}{\cos 2\theta_w} \frac{v^2}{4\Lambda^2} \left(\frac{\cos\theta_w}{\sin\theta_w} C_{HD} + \frac{\sin\theta_w}{\cos\theta_w} \left(4C_{Hl}^{(3)} - 2C_{ll} \right) + 4C_{HWB} \right)$

Note: *sign* of shift

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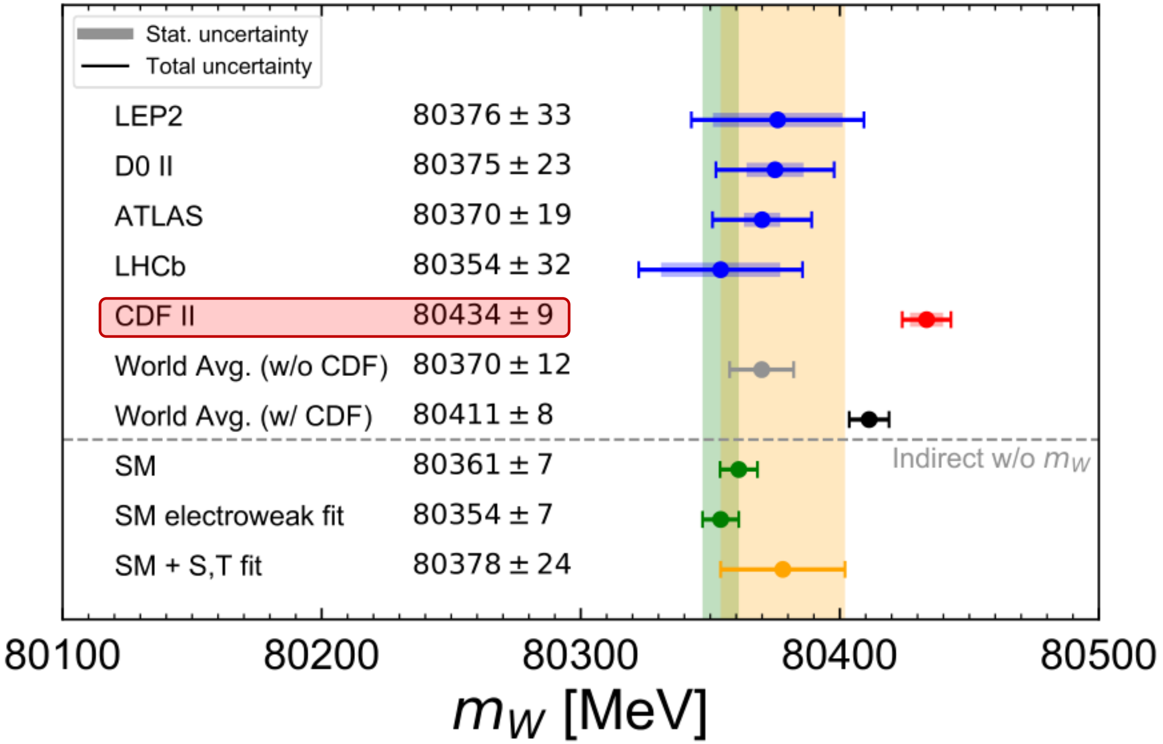

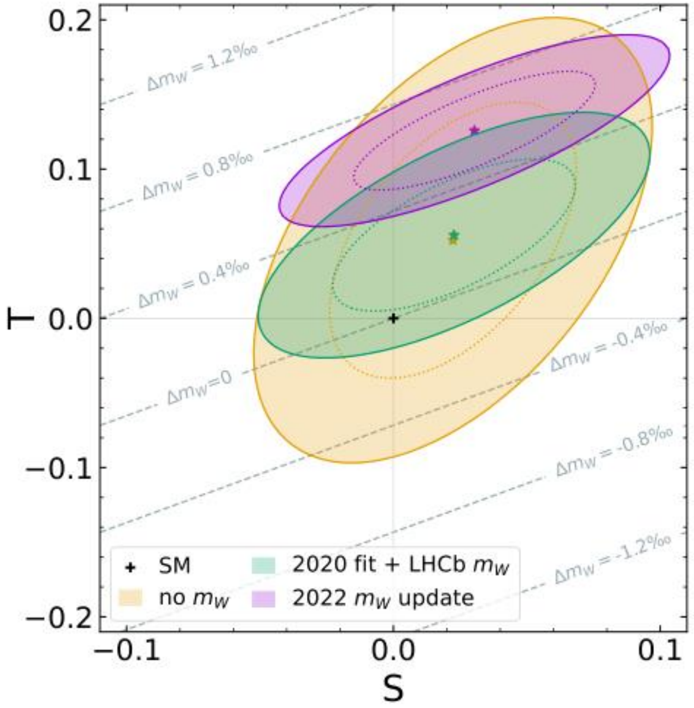

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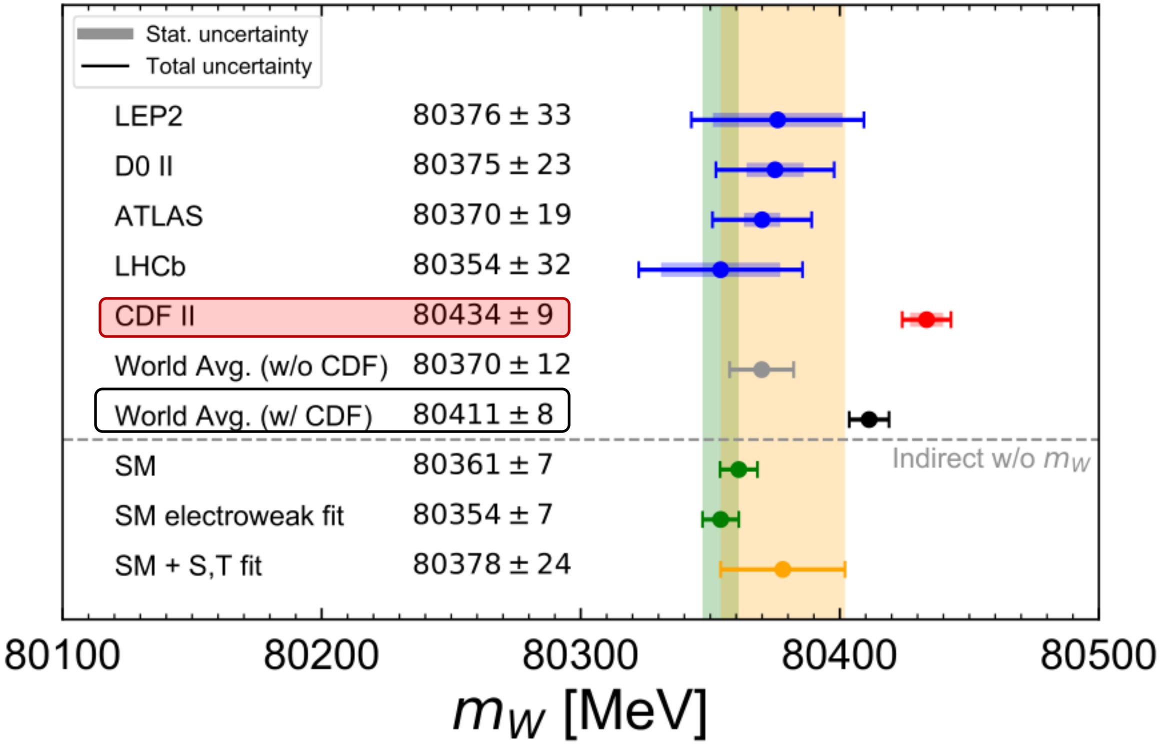

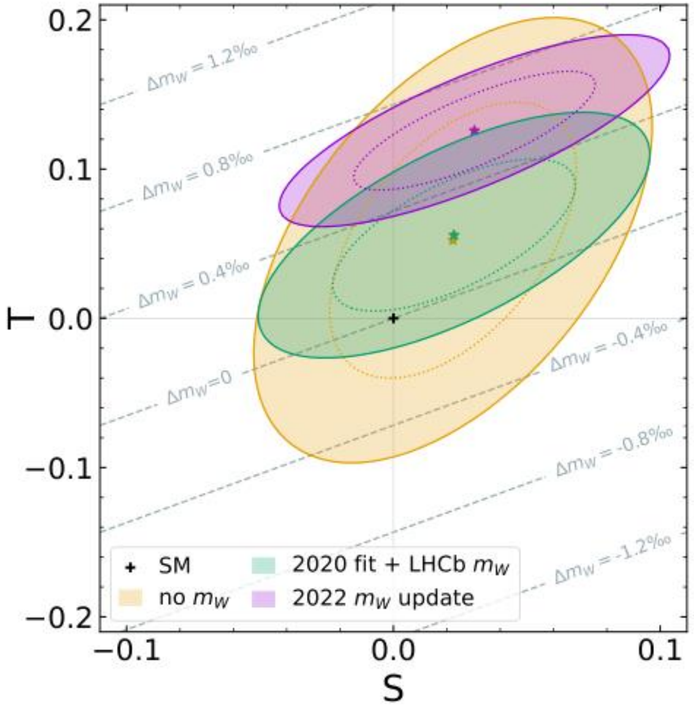

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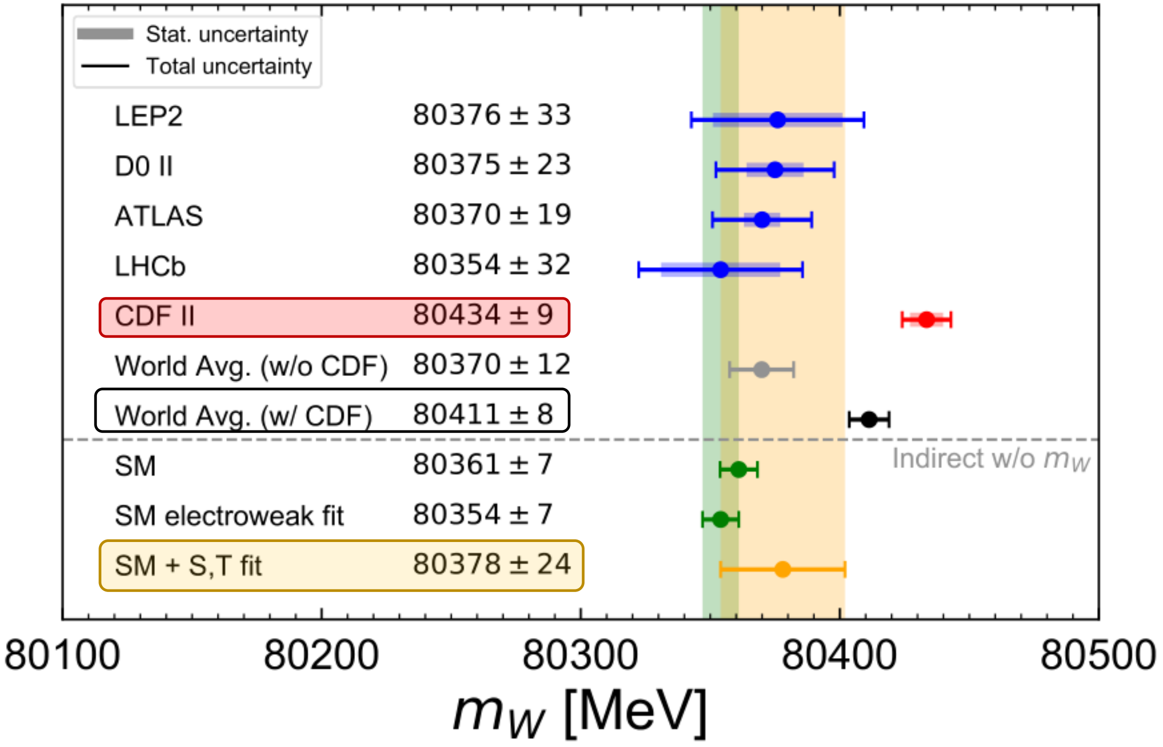

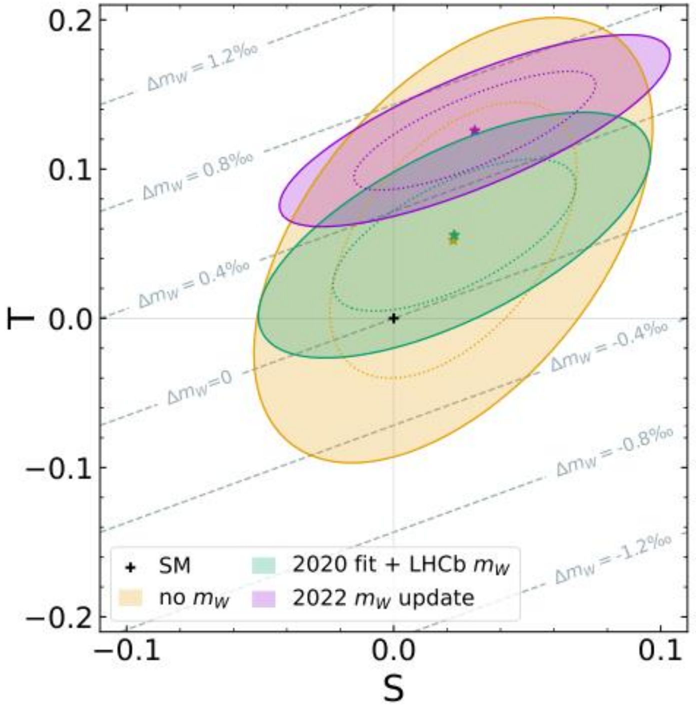

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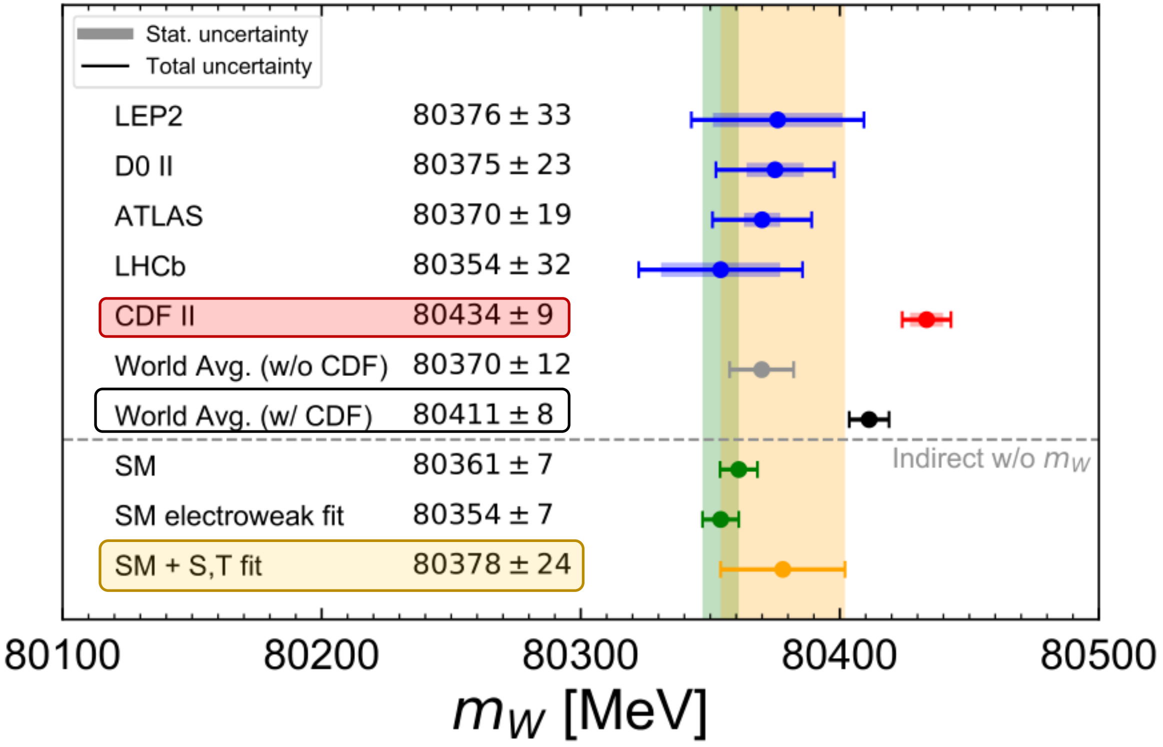

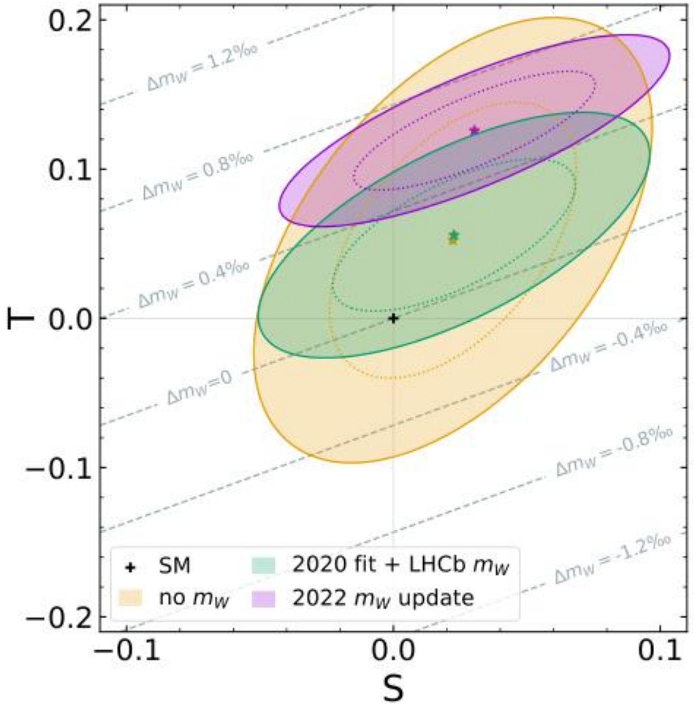

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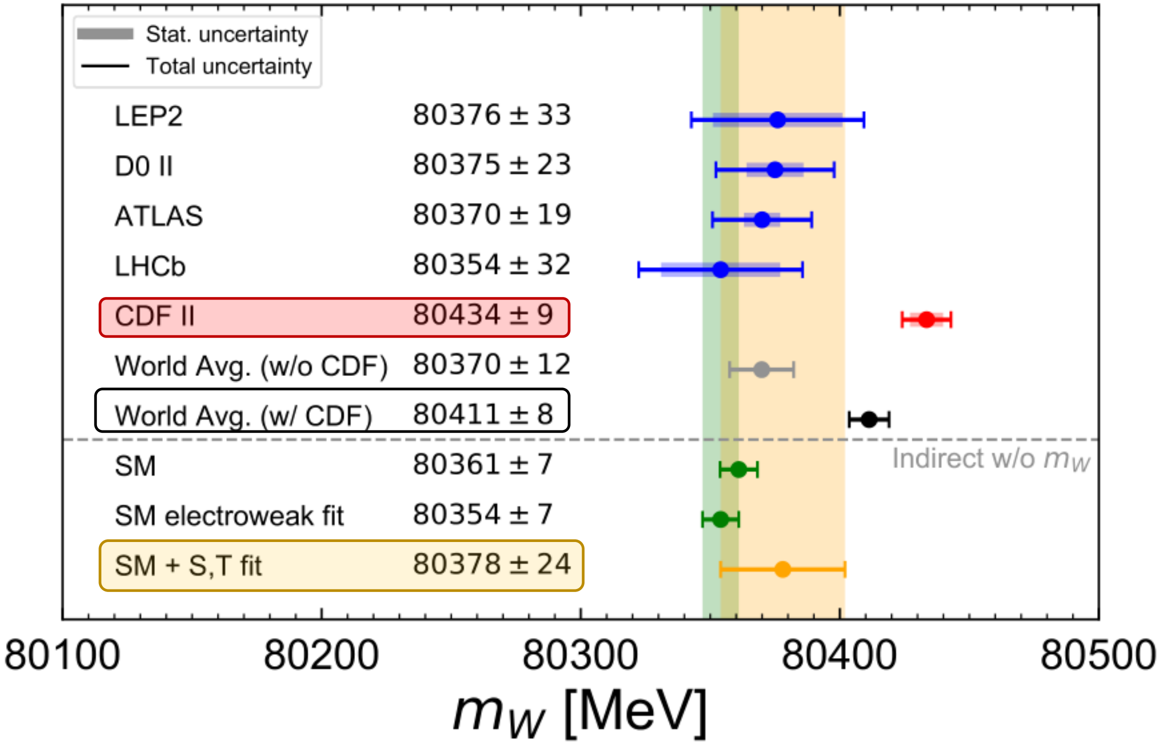

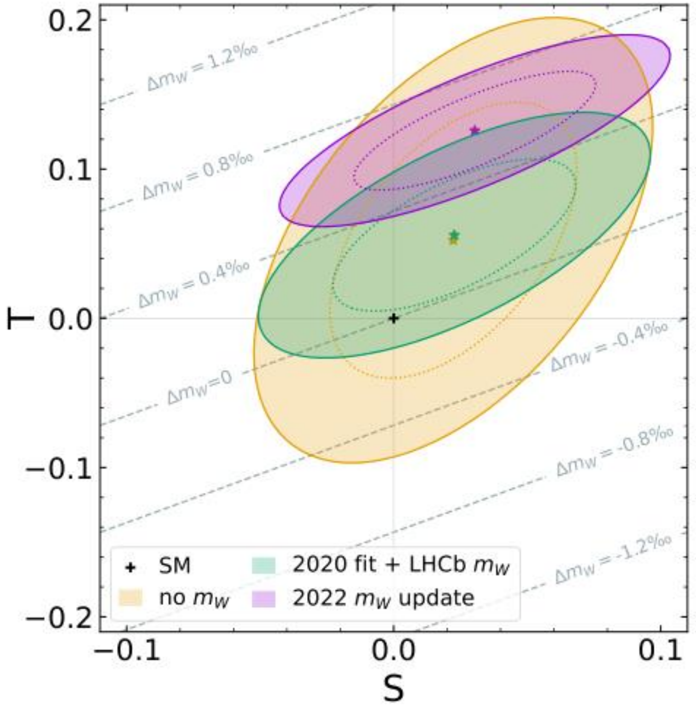

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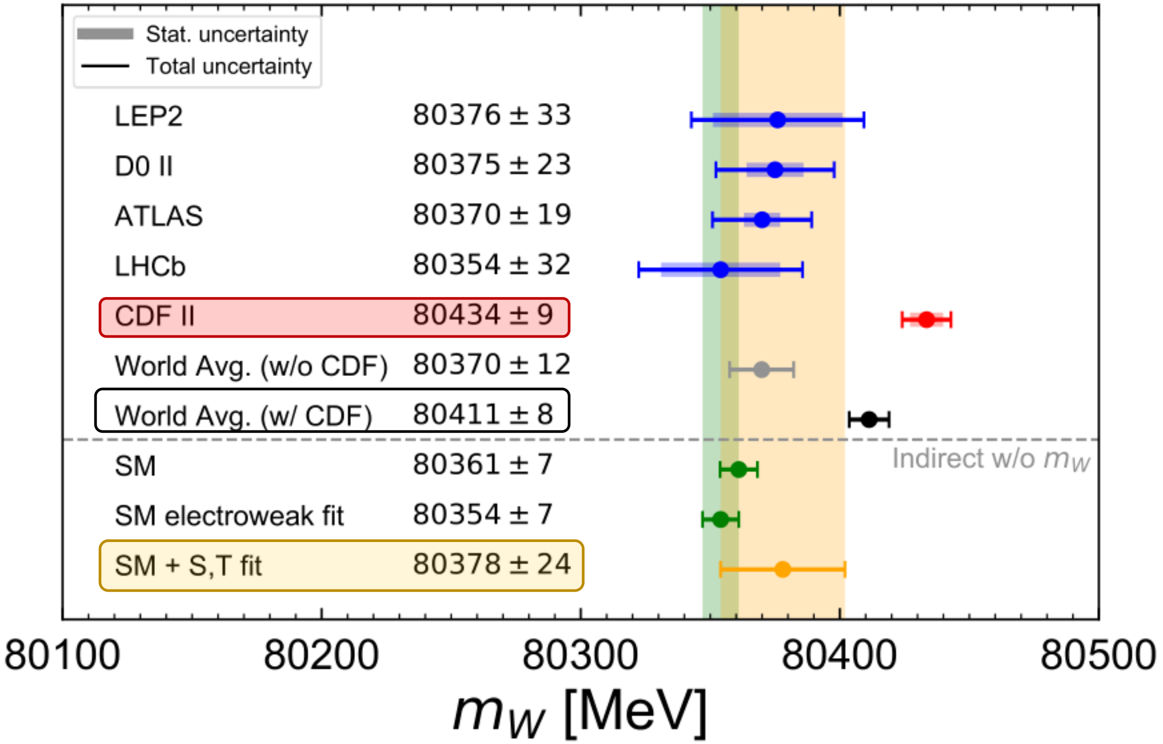

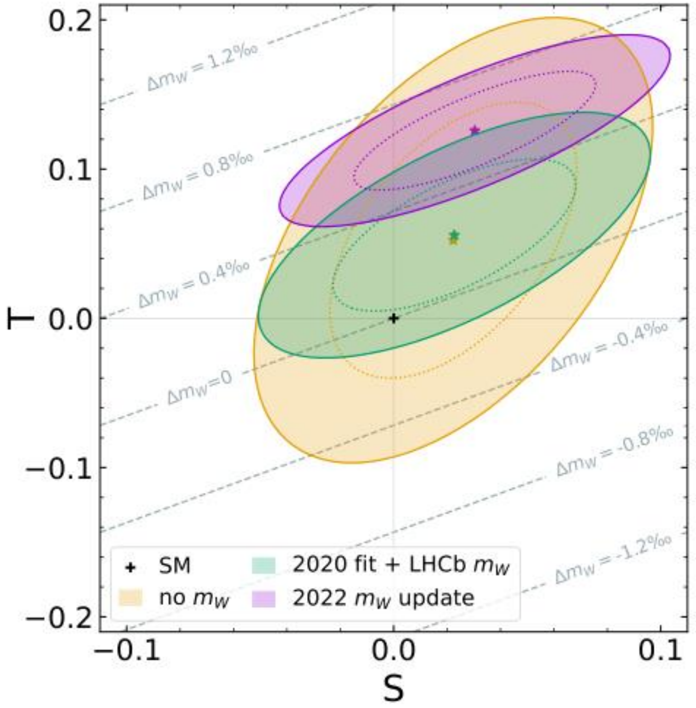

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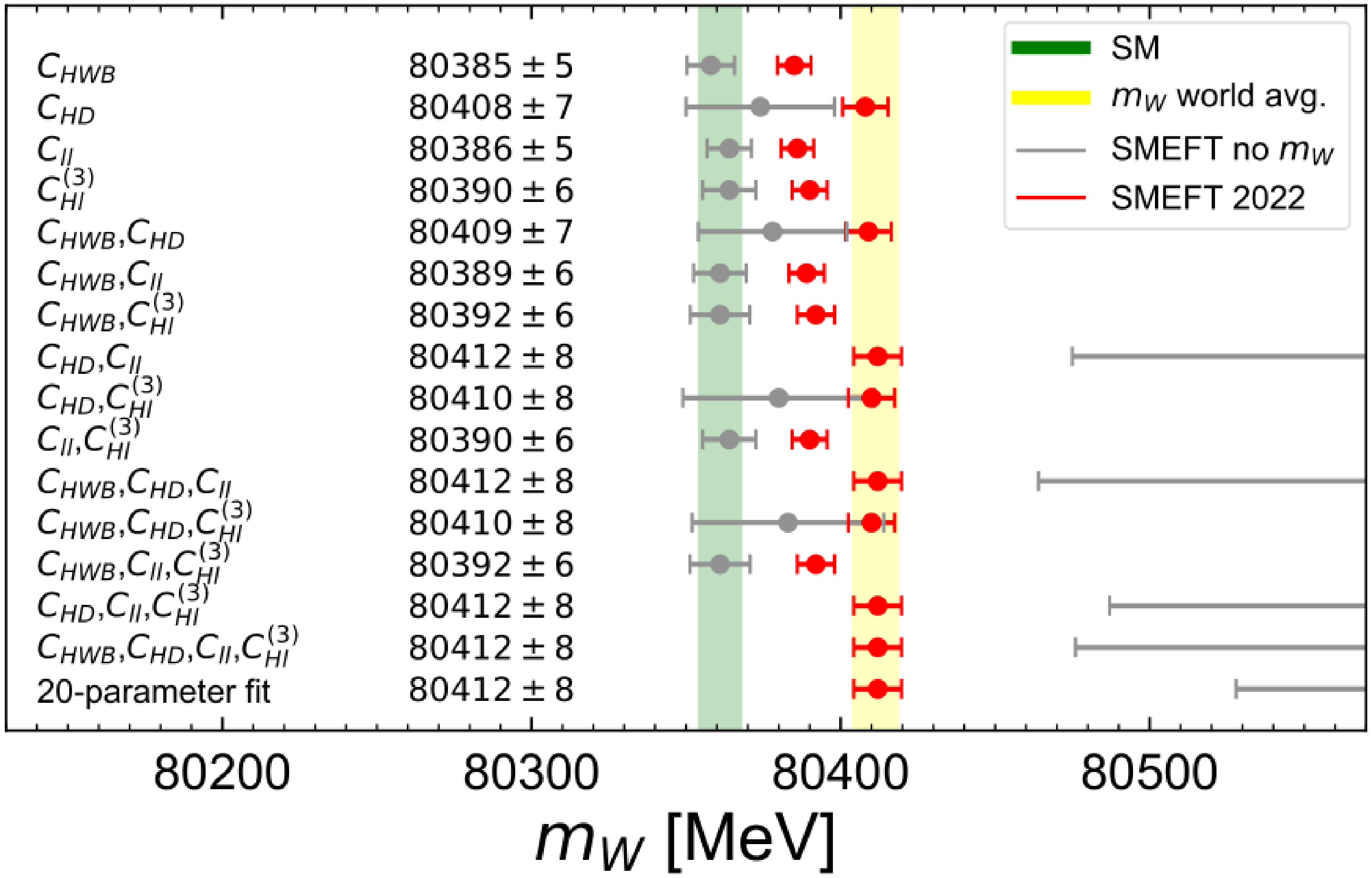

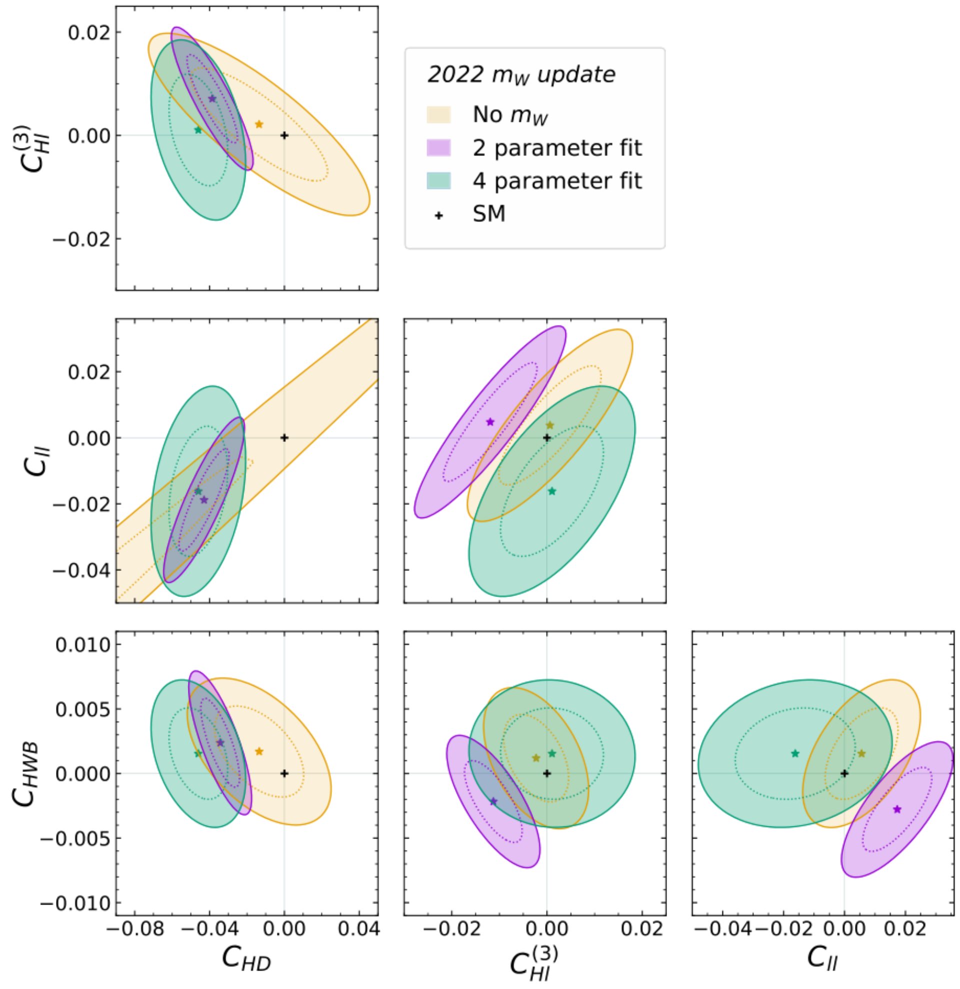

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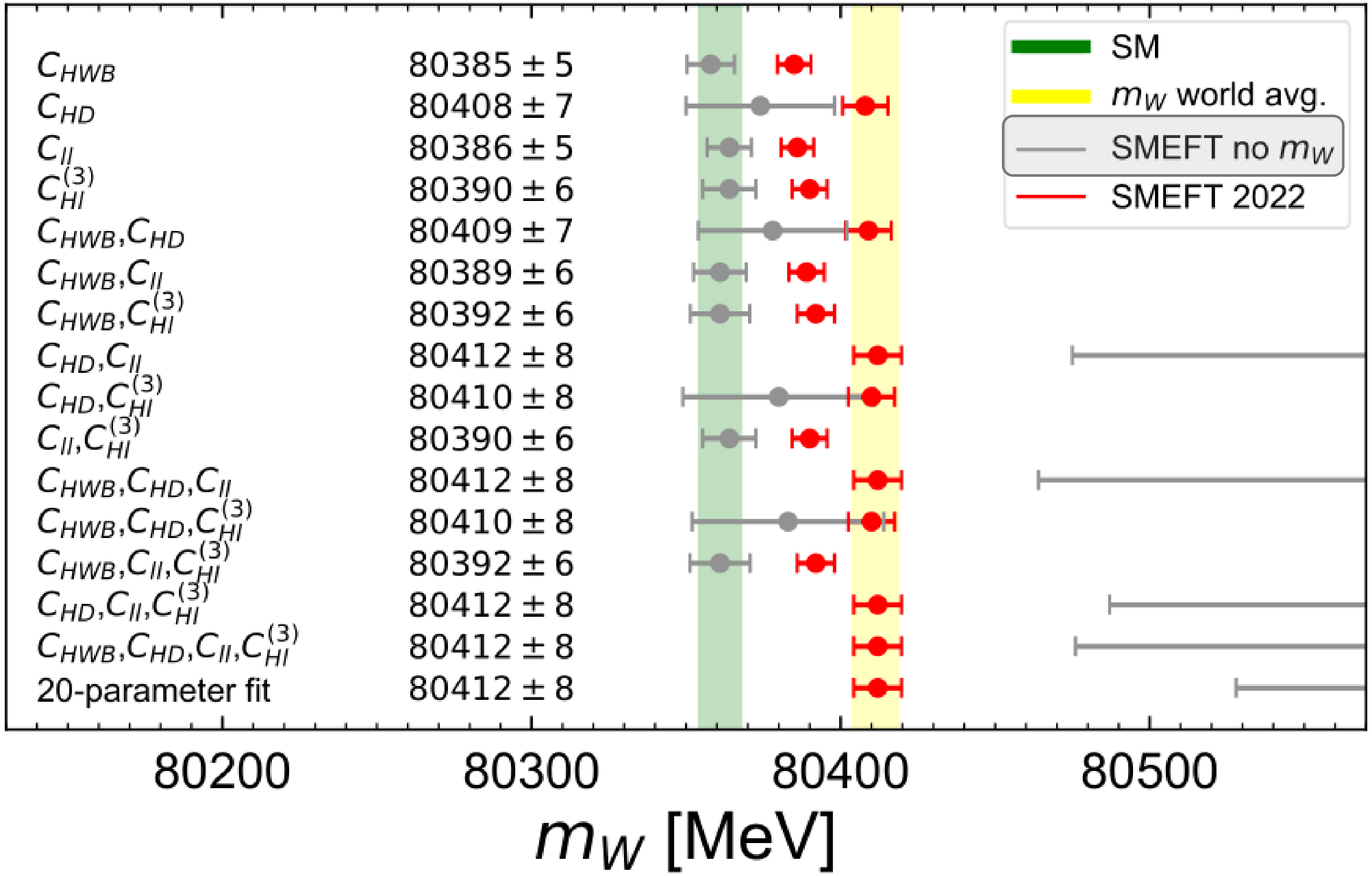

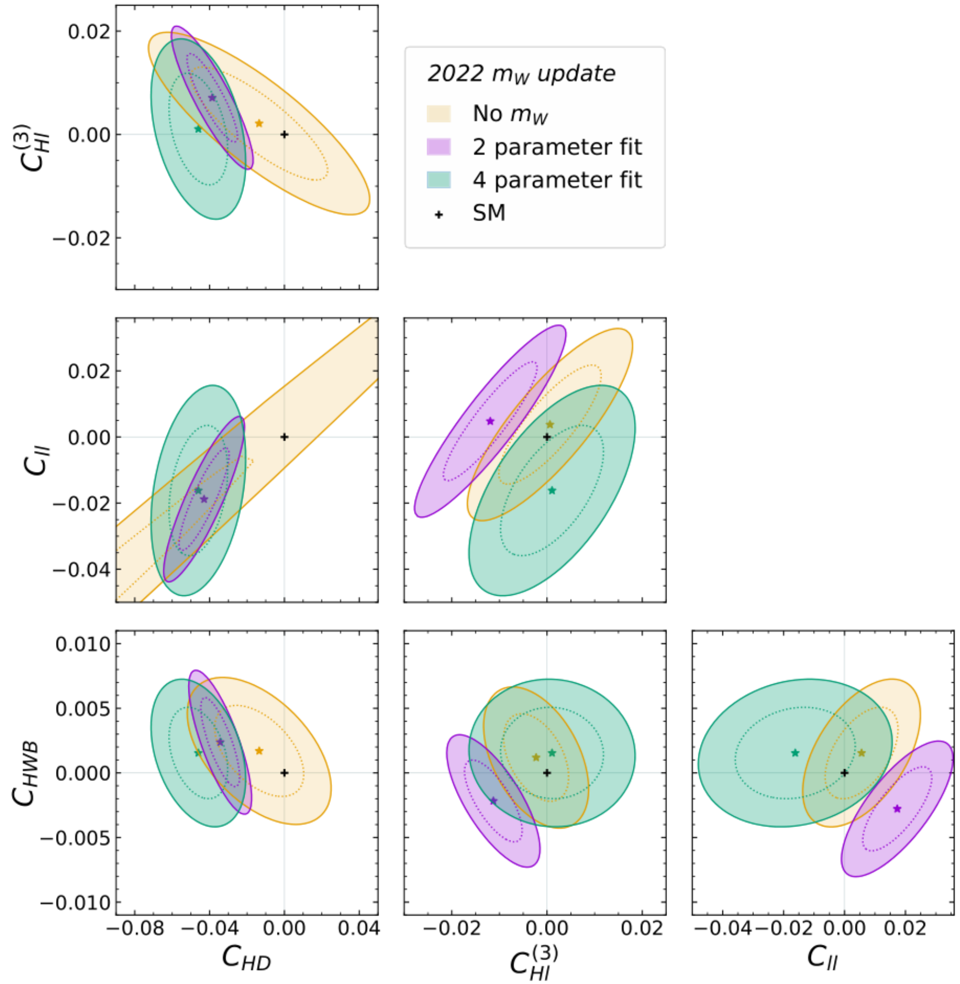

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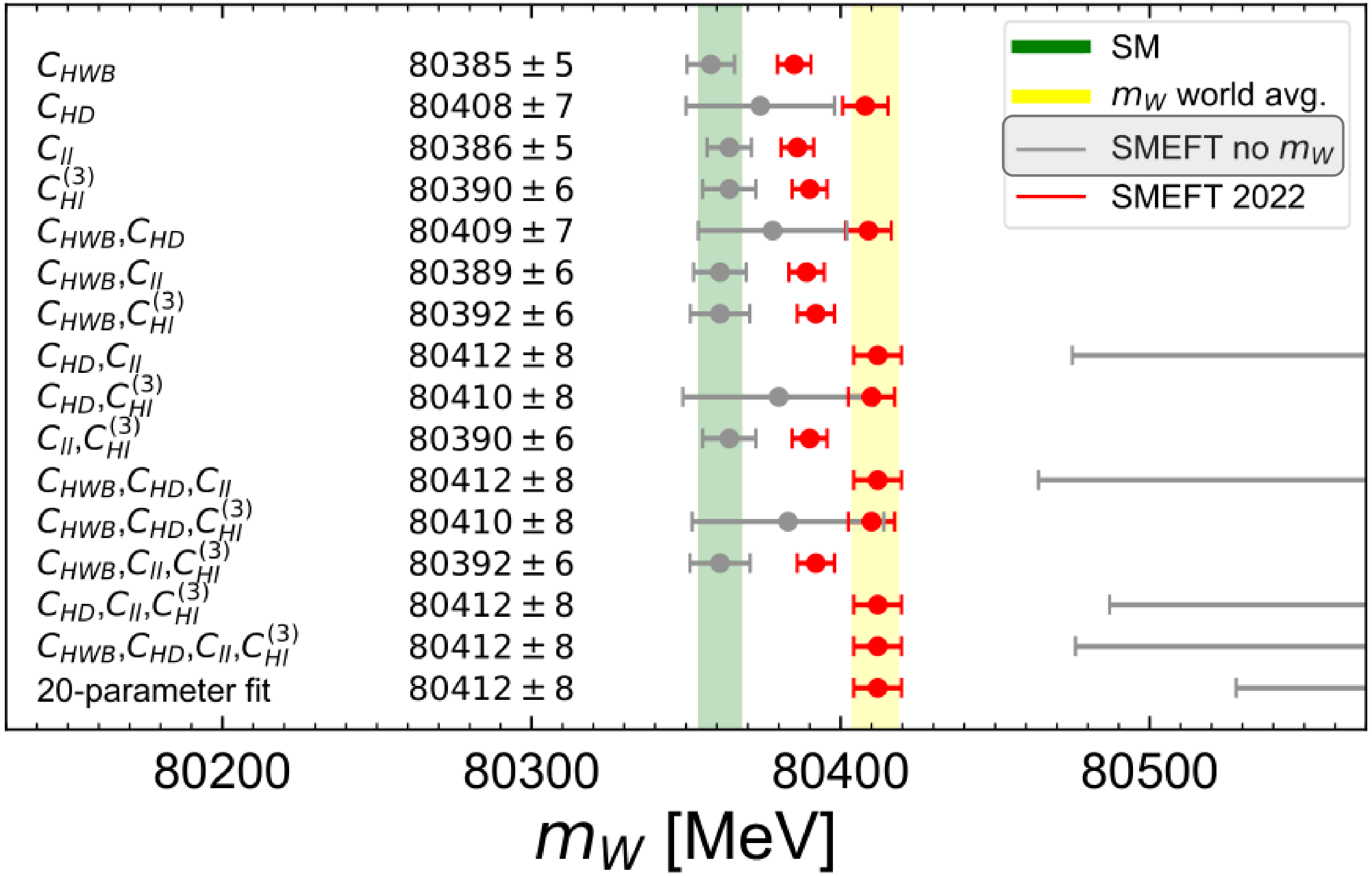

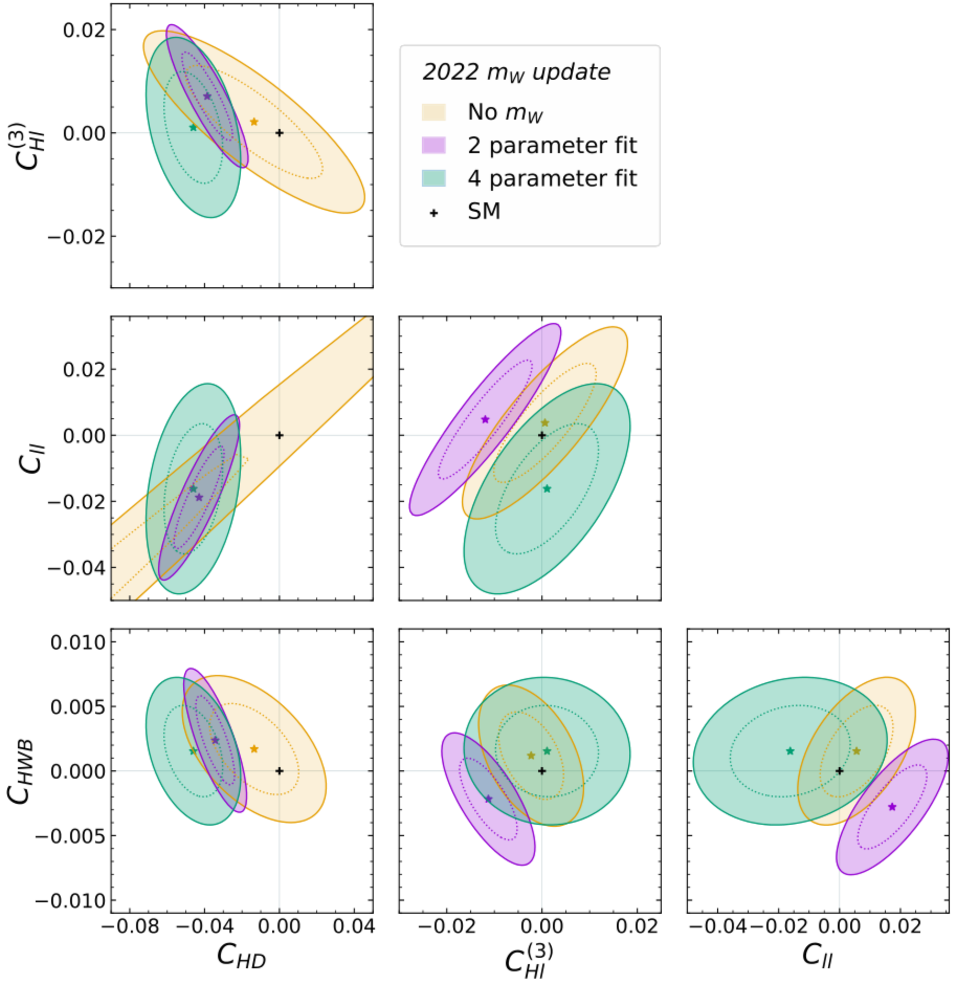

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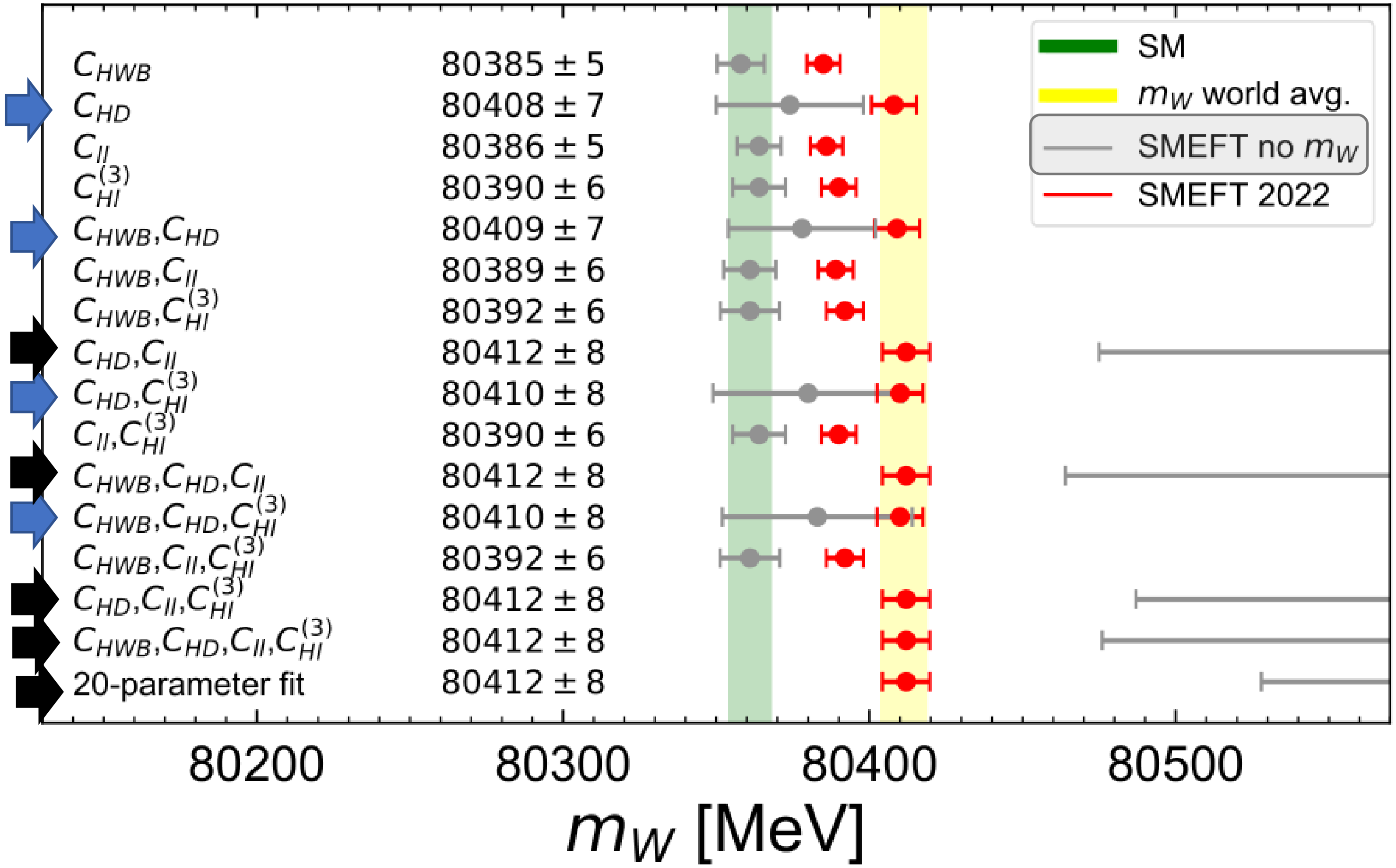

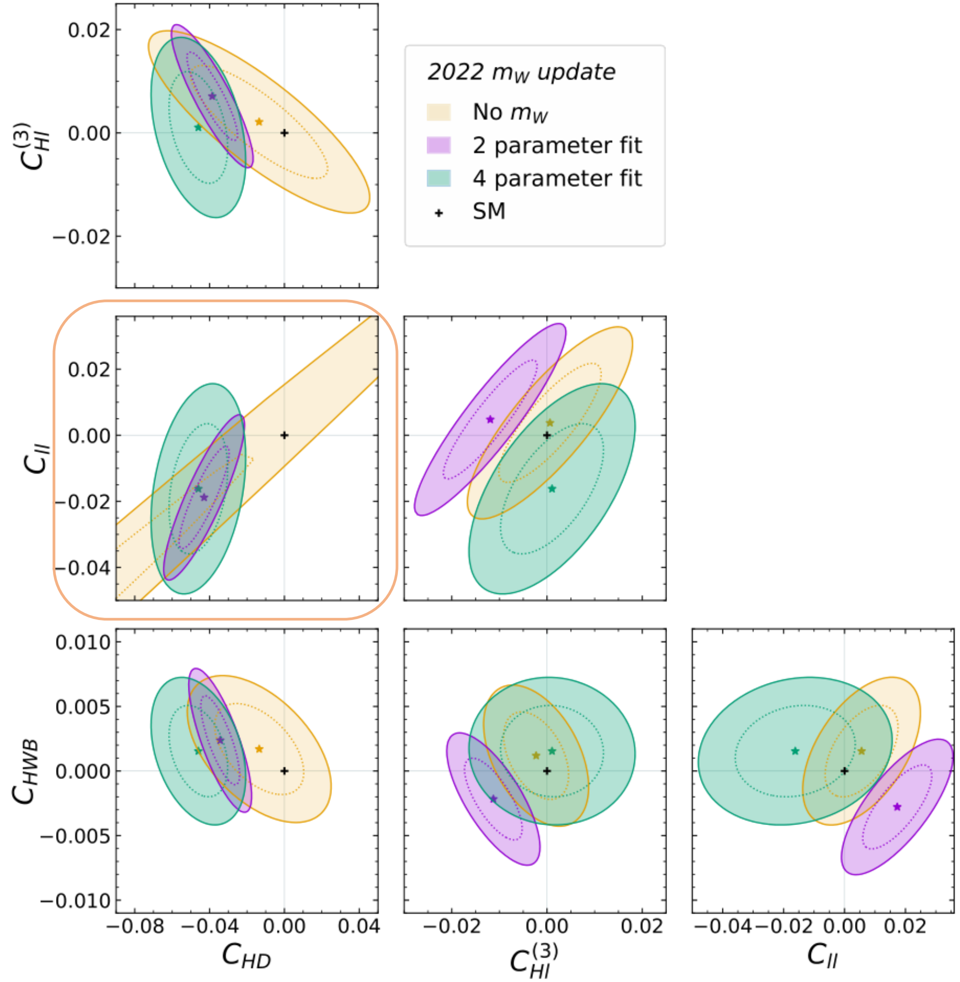

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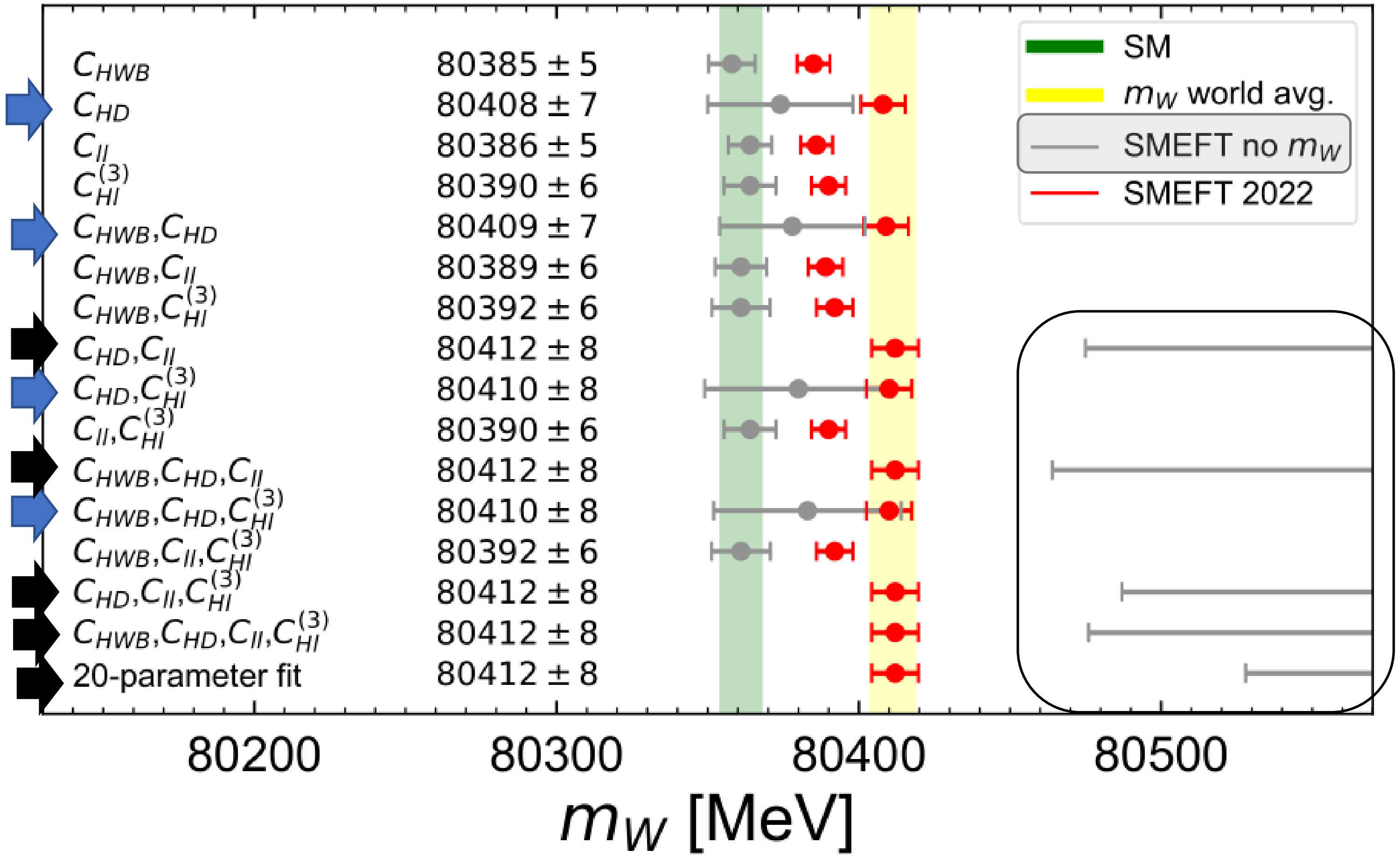

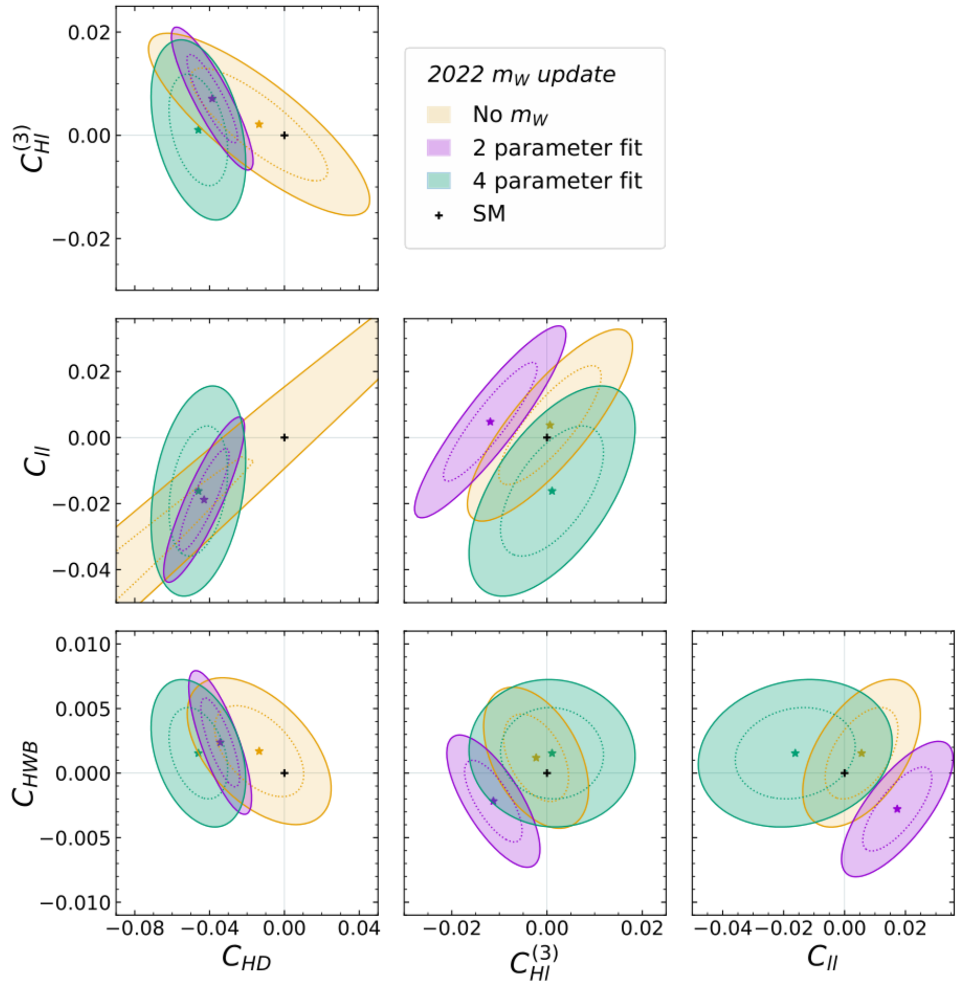

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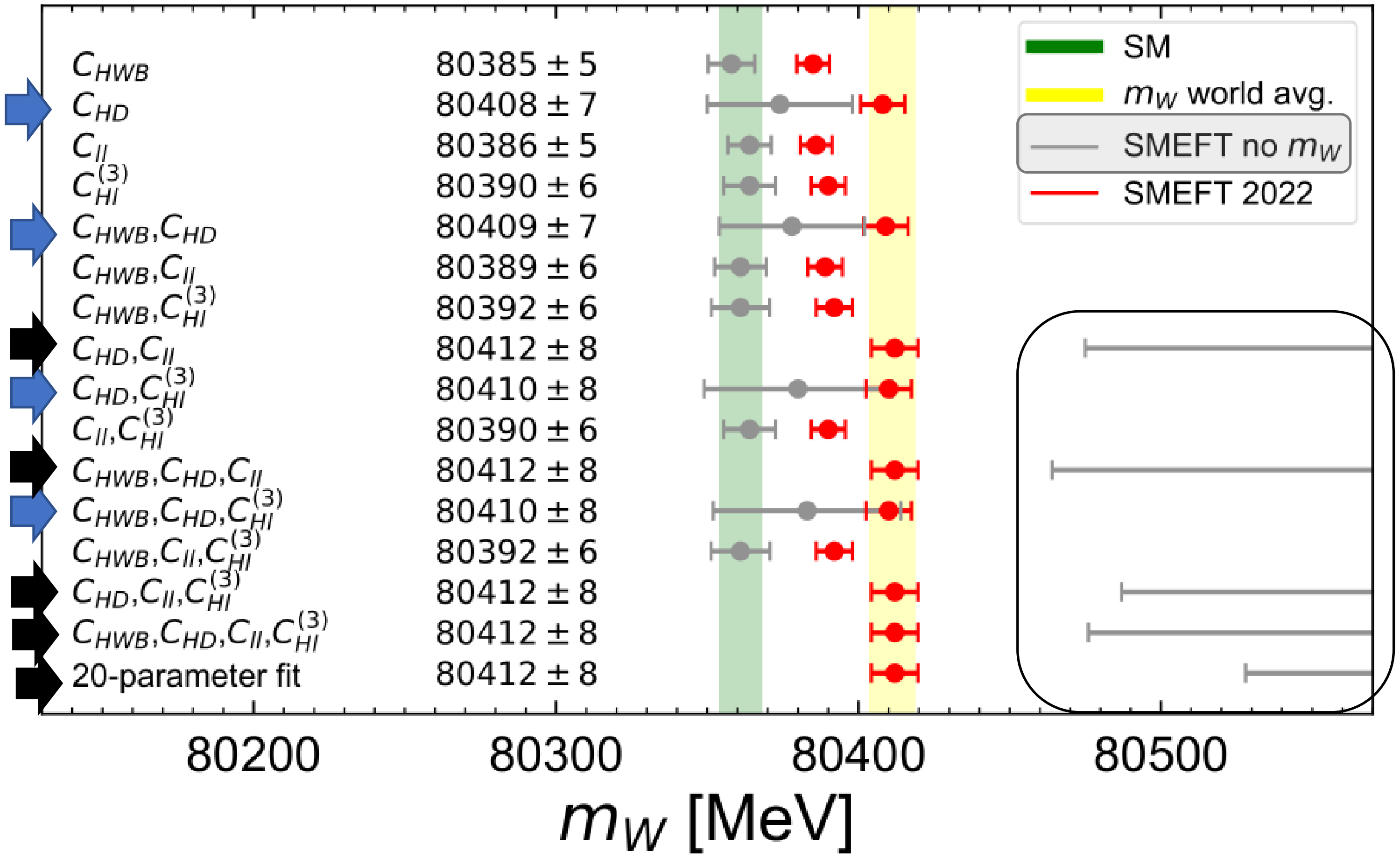

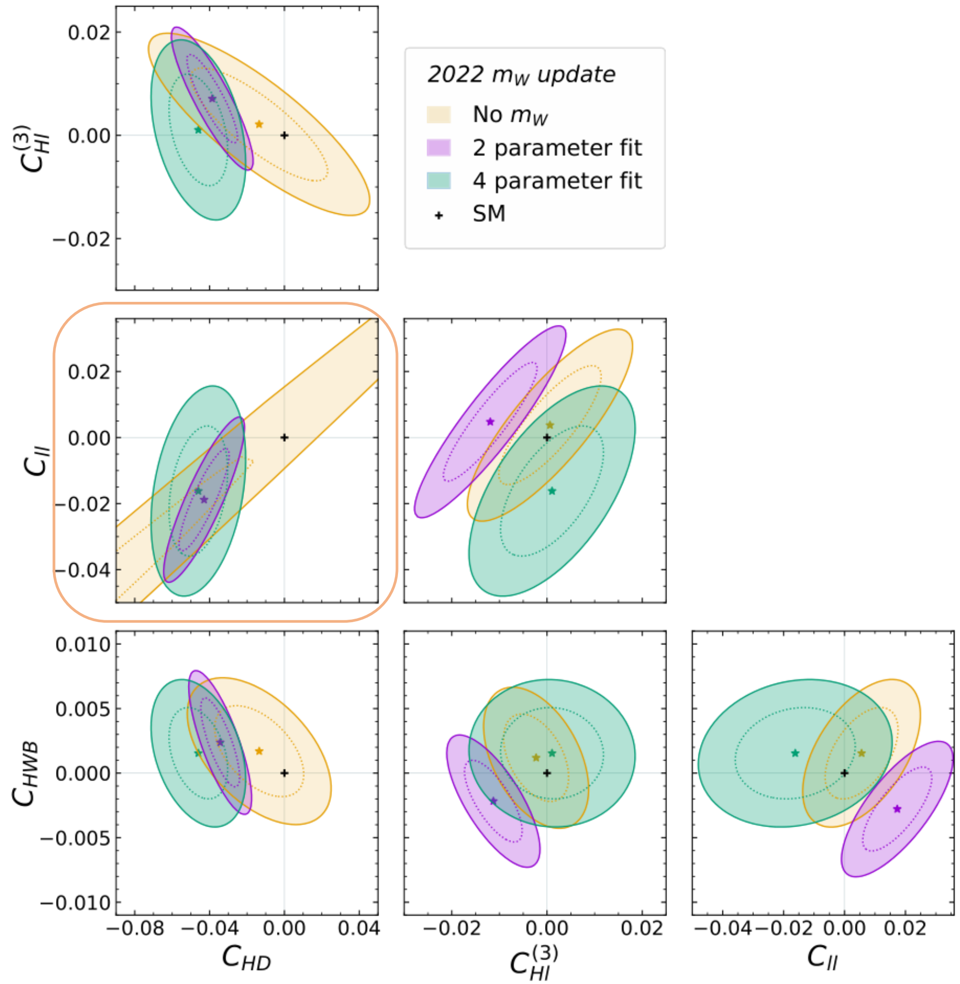

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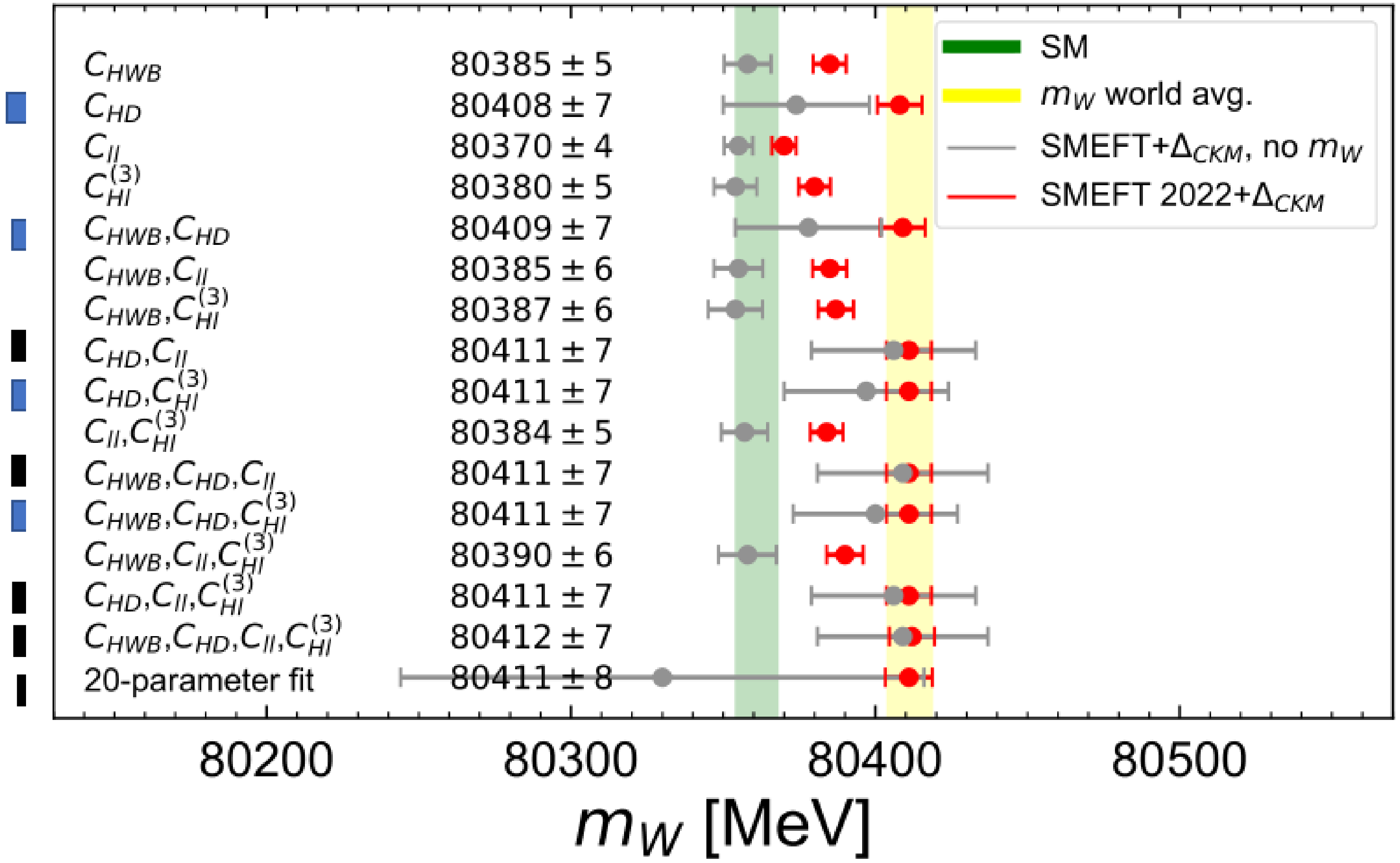

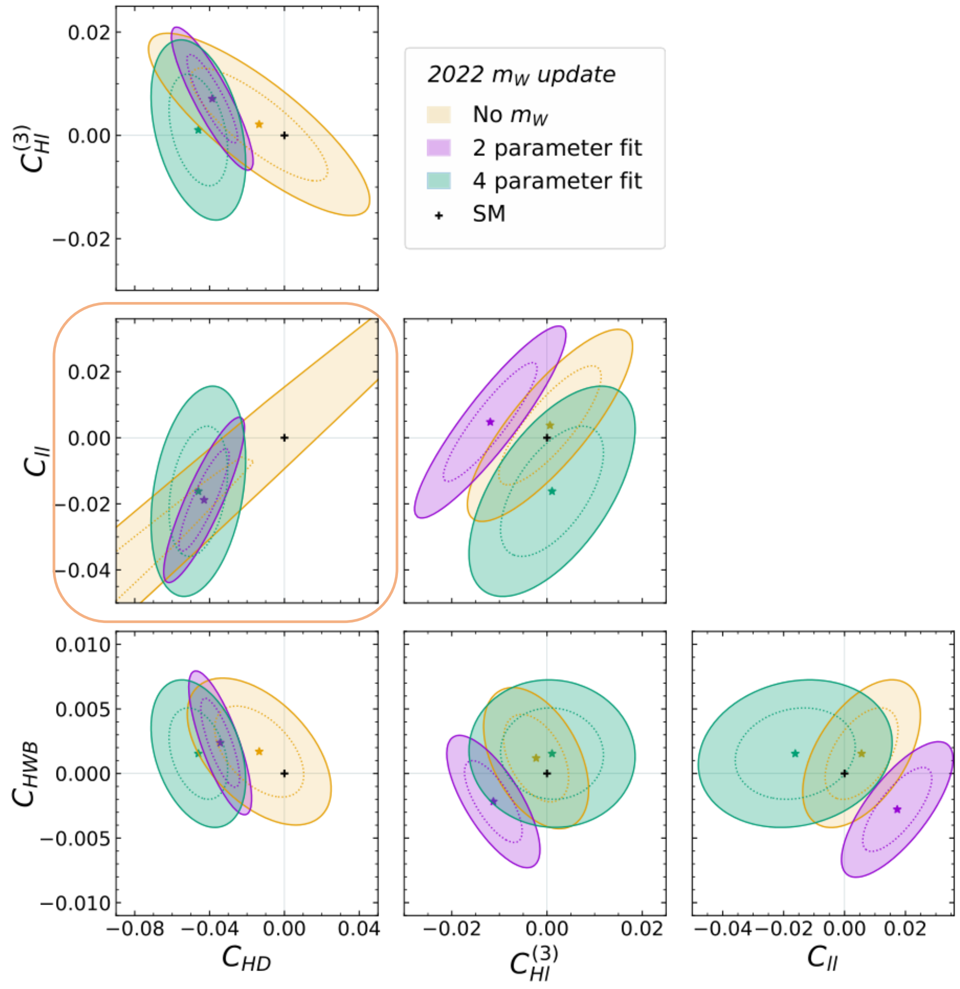

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- SMEFT enables **more systematic** phenomenological survey of UV completions *and their pulls*
- e.g. Tree-level single-field extensions with simplified couplings assumption:

De Blas, Criado, Perez-Victoria, Santiago [1711.10391]

	Model		C_{HD}	C_{ll}	$C_{Hl}^{(3)}$	$C_{Hl}^{(1)}$	C_{He}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
$0^{(1,1,1)}$	S_1	✗		-1							
$1/2^{(1,3,1)}$	Σ	✗			$\frac{1}{16}$	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
$1/2^{(1,3,-1)}$	Σ_1	✗			$\frac{1}{16}$	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
$1/2^{(1,1,0)}$	N	✓			$-\frac{1}{4}$	$\frac{1}{4}$					
$1/2^{(1,1,-1)}$	E	✓			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
$1^{(1,1,1)}$	B_1	✗	1					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
$1^{(1,1,0)}$	B	✓	-2						$-y_\tau$	$-y_t$	$-y_b$
$0^{(1,3,0)}$	Ξ	✓	$-2\left(\frac{1}{M_\Xi}\right)^2$					$\frac{1}{2}\left(\frac{1}{M_\Xi}\right)^2$	$y_\tau\left(\frac{1}{M_\Xi}\right)^2$	$y_t\left(\frac{1}{M_\Xi}\right)^2$	$y_b\left(\frac{1}{M_\Xi}\right)^2$
$1^{(1,3,1)}$	W_1	✓	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
$1^{(1,3,0)}$	W	✗	$\frac{1}{2}$					$-\frac{1}{2}$	$-y_\tau$	$-y_t$	$-y_b$

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

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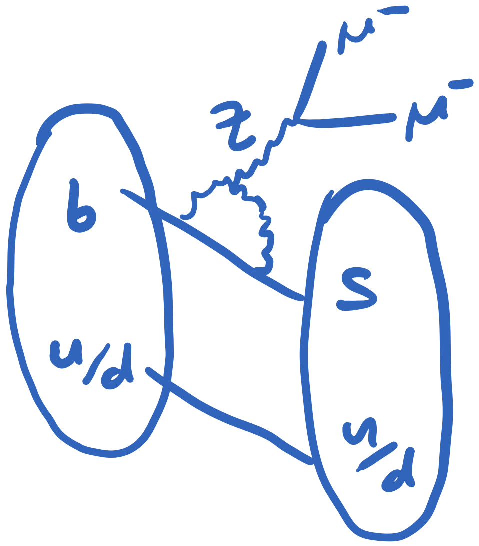
- New physics **beyond the Standard Model** in processes involving $\mathrm{b} \to s\,\mu^+\mu^-$ transitions?



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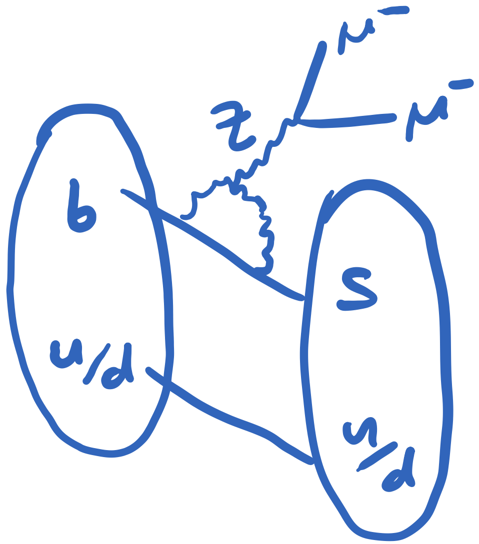

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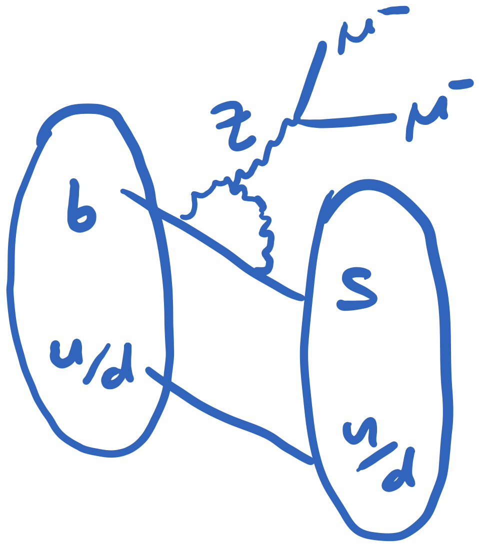

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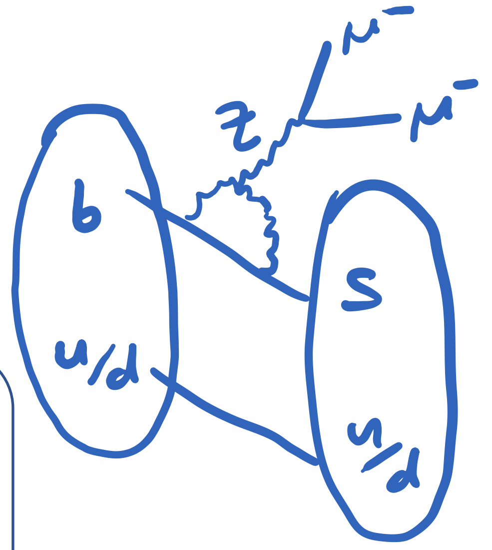

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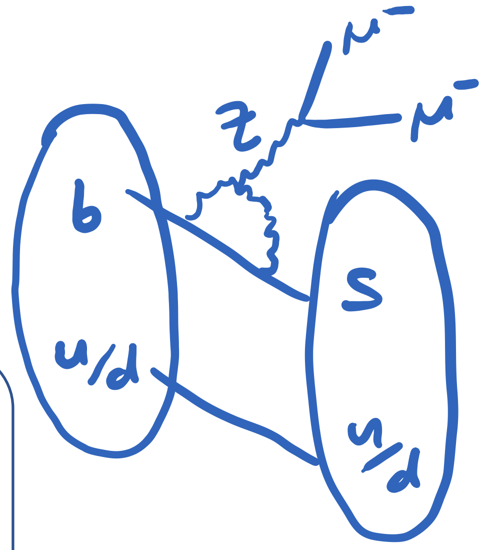

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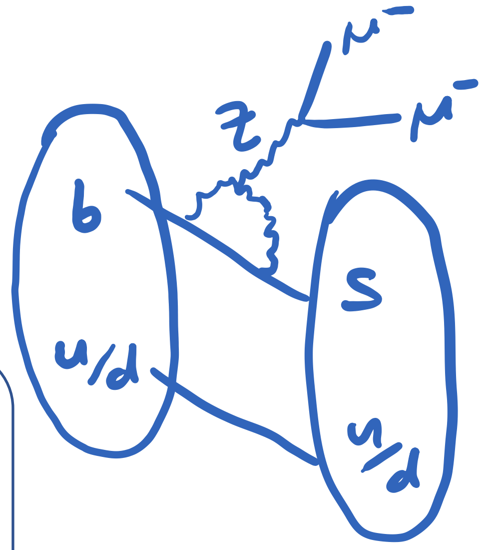

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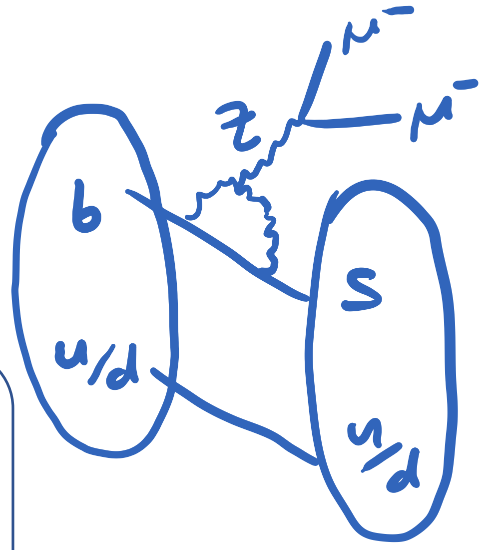

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(19/10/2021): **1.4 σ** in $R_{K_S^0}$, **1.5 σ** in $R_{K^{*+}}$

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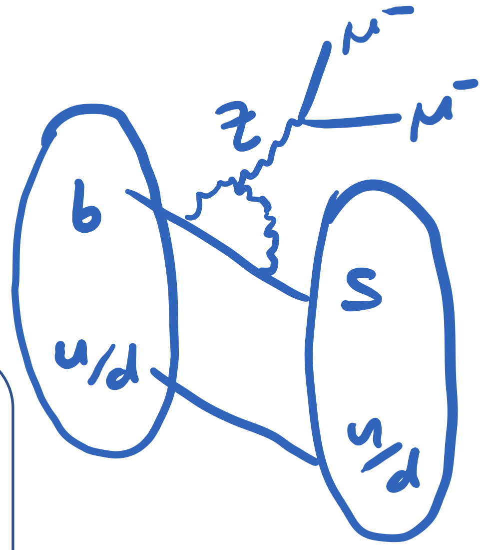

- LHCb **3.4 σ** in **P5' angular distribution** of $\mathrm{B} \to K^*\,\mu^+\mu^-$ **(2 σ** for Belle)
- Various **other kinematic observables** in $\mathrm{b} \to s\,\mu^+\mu^-$
- **3.2 σ** in $B_s \to \varphi\,\mu^+\mu^-$
- ⇒**~4 σ** non-zero Wilson coefficient in **global fit** to these *"messy"* observables

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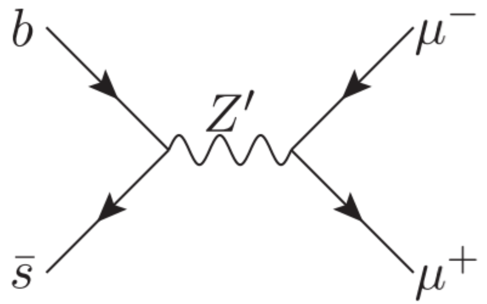

- *Consistency* of all these various anomalies is **extremely non-trivial**
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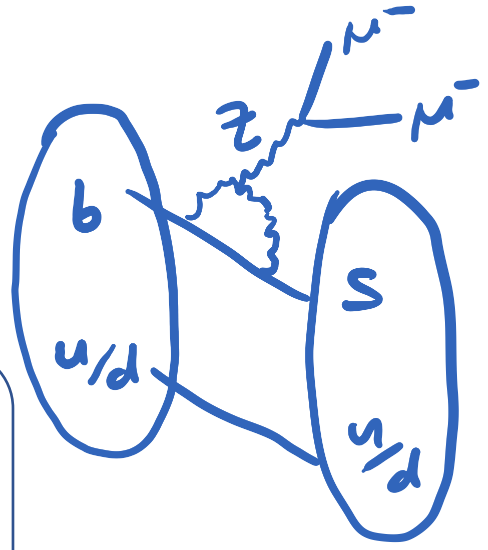
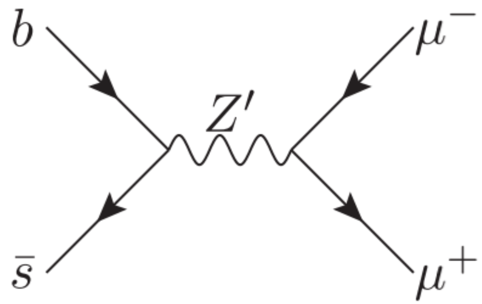
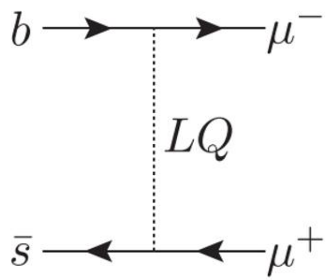






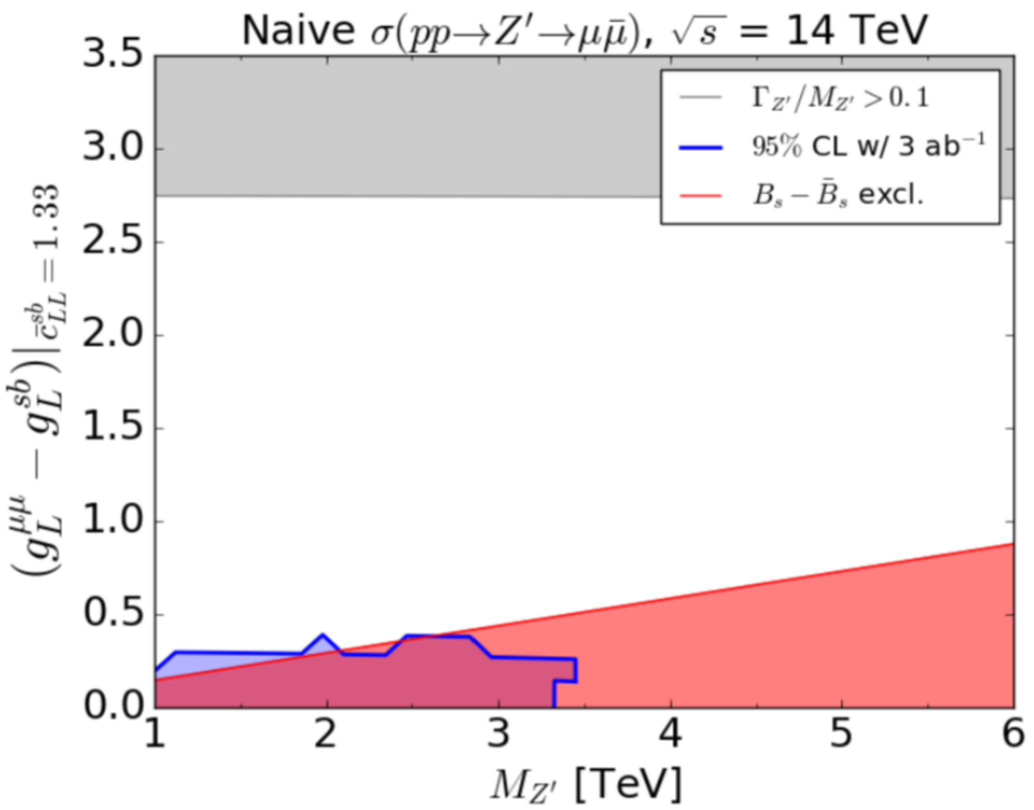
Flavour anomalies in B physics

- If confirmed, *can we guarantee a discovery at FCC-hh*?

80 TeV unitarity limit = **no general no-lose theorem** at FCC-hh [Di Luzio, Nardecchia, 1706.01868]

- Project **Z'** sensitivity in **most pessimistic scenario** assuming only couplings required for $b \to s\mu^+\mu^-$

LHC



Allanach, Gripaios, TY [1710.06363]

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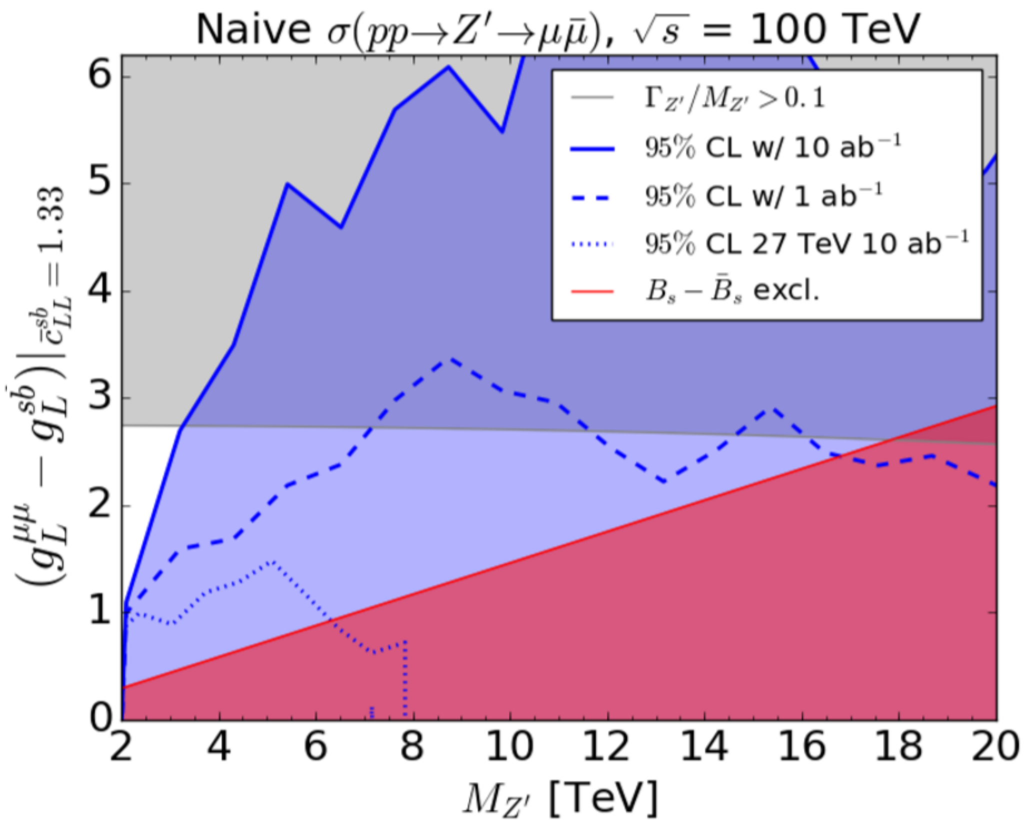

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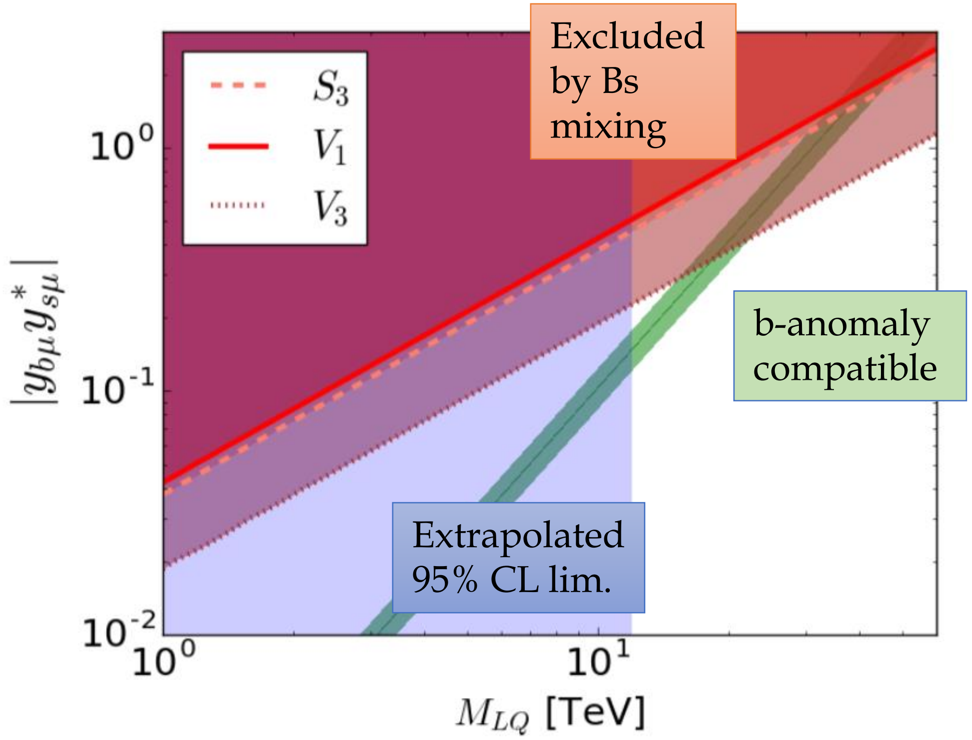

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Max $M_{LQ} = 37, 41, 18$ TeV for S_3, V_1, V_3

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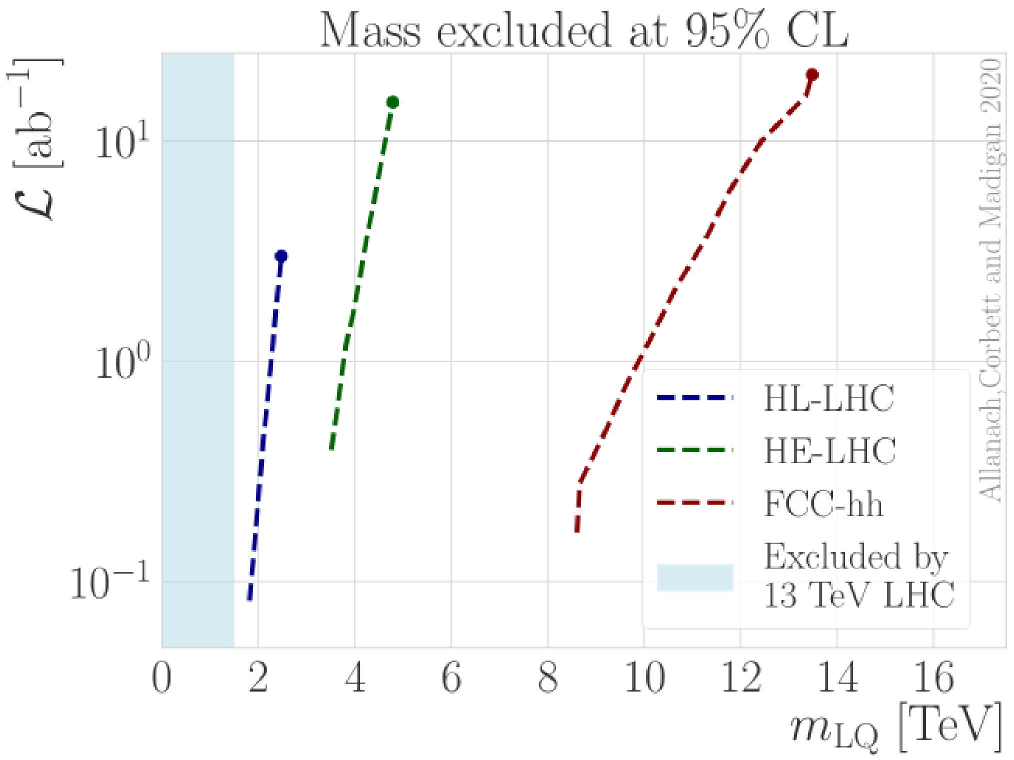
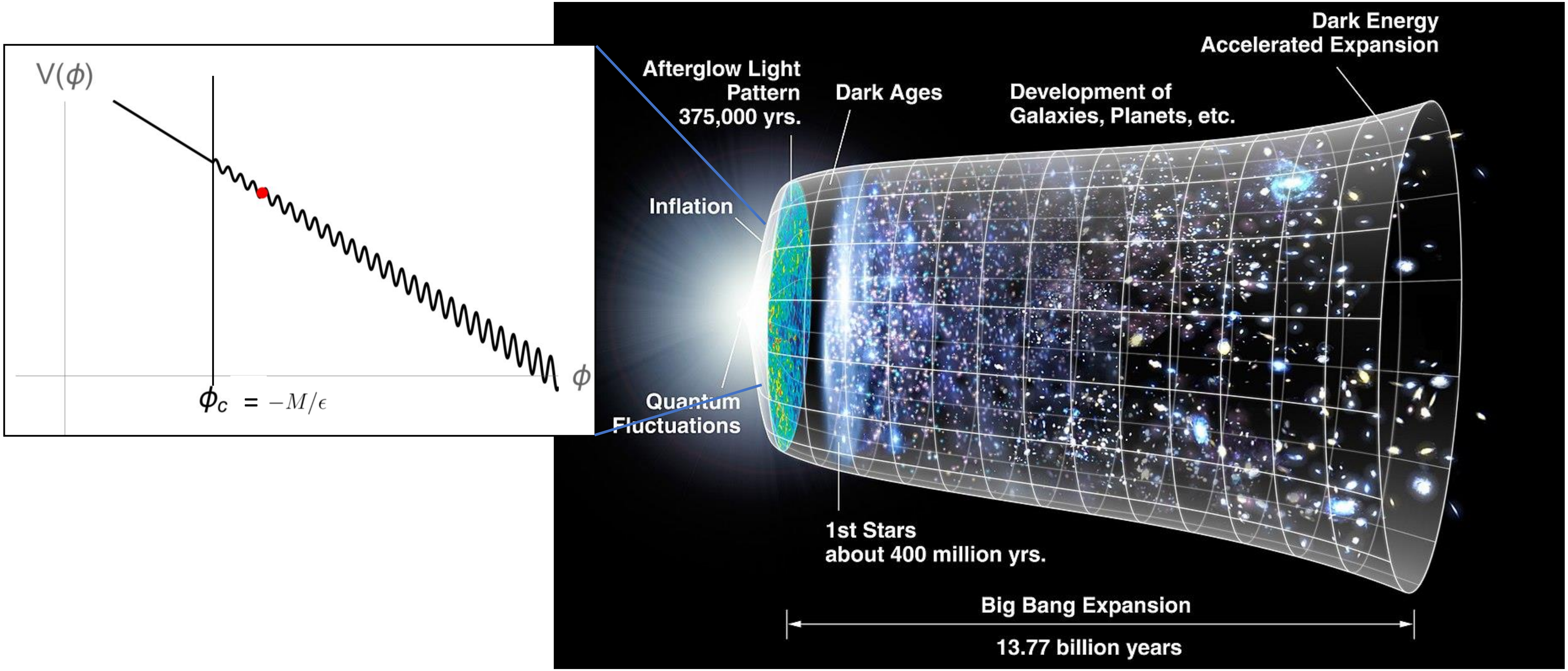


Allanach, Corbett, Madigan [1911.04455]

Theory opportunities: missing a new principle?

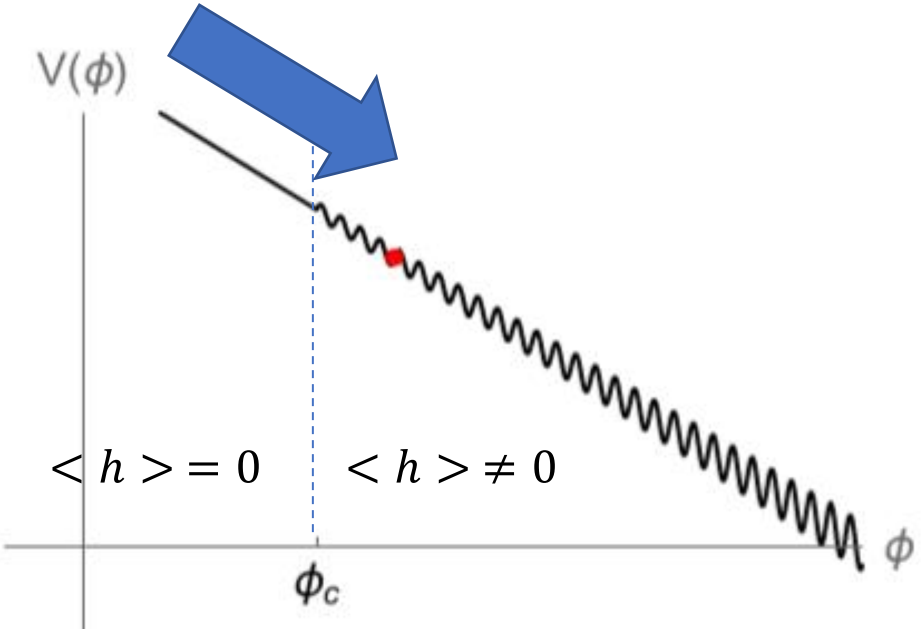
- **Cosmological evolution** could play a role



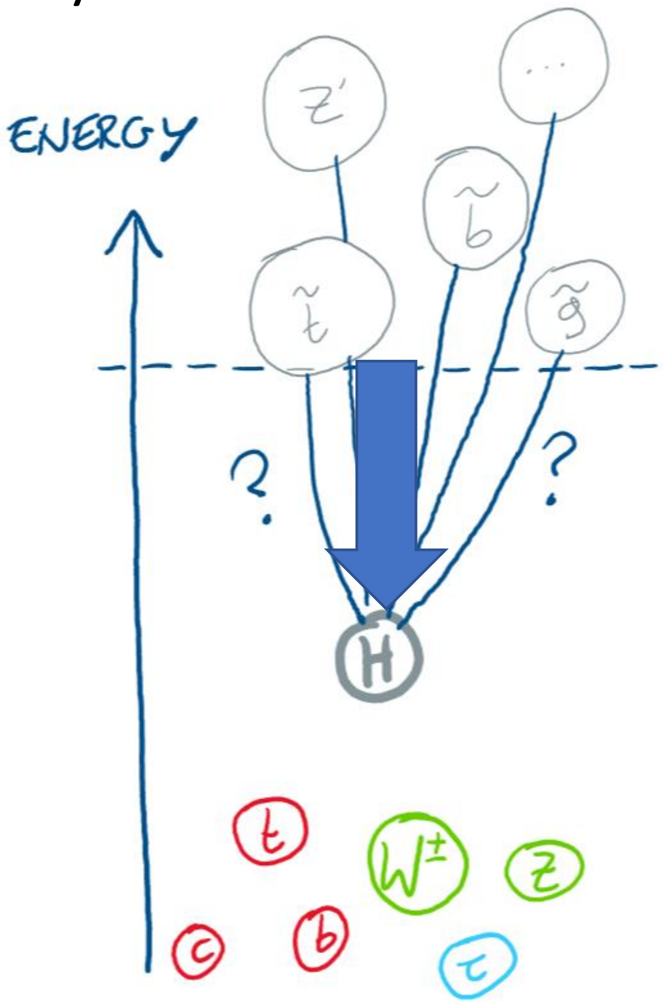
Cosmological relaxation of the weak scale

- **Axions** could solve a variety of fundamental problems
- **Relaxion** *scanning the Higgs mass* in the early universe

A *dynamical* solution to the hierarchy problem



Graham, Kaplan, Rajendran '15



Cosmological Self-Organised Criticality

(See also J. Khoury et al 1907.07693, 1912.06706, 2003.12594)

- **Self-Organised Localisation** (SOL) Giudice, McCullough, TY (2105.08617)
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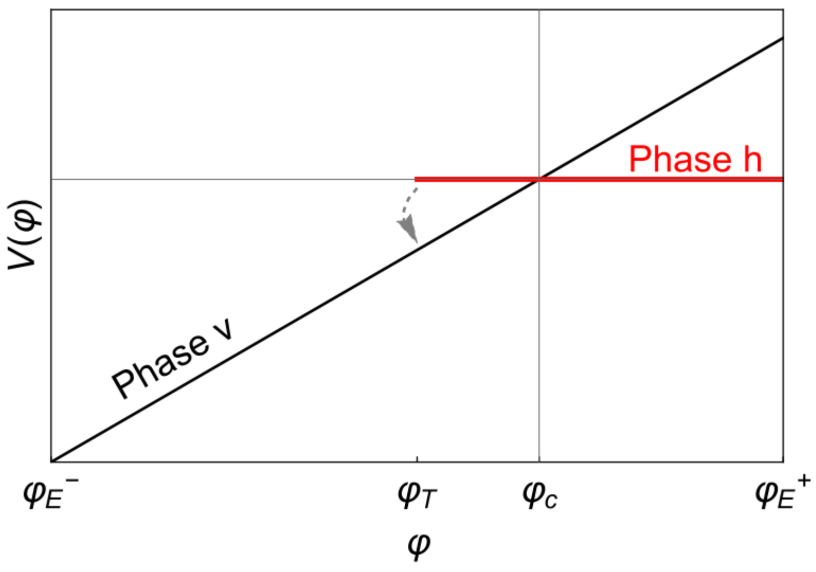

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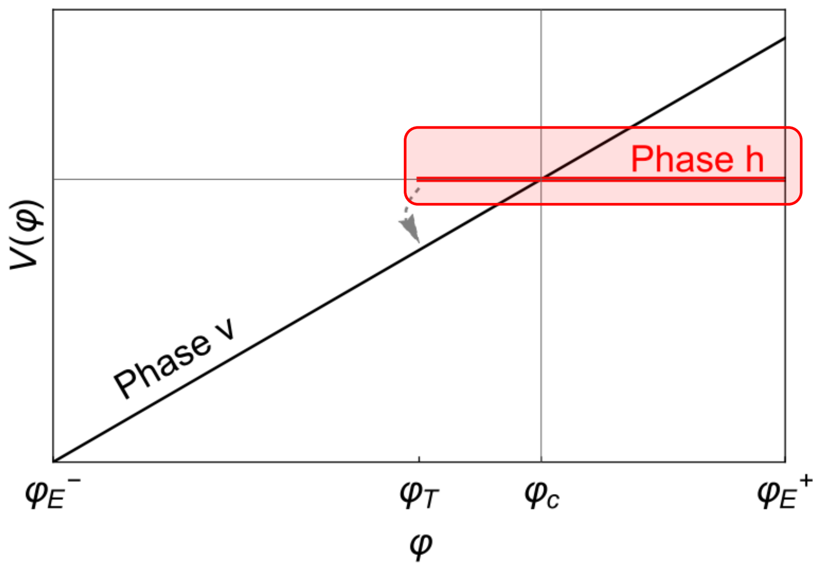

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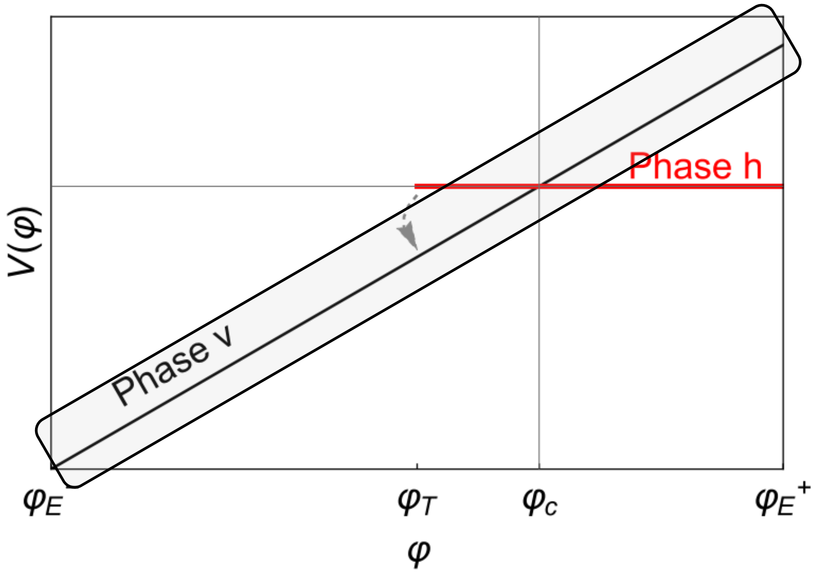

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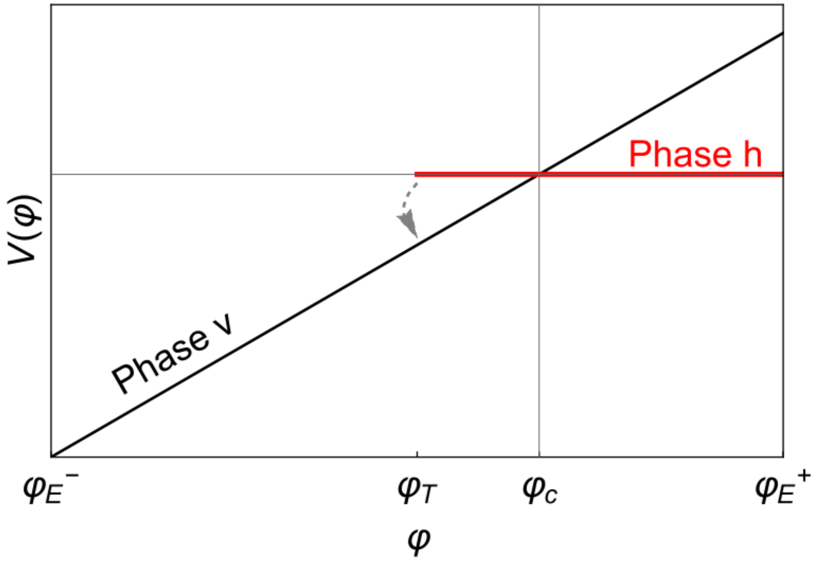

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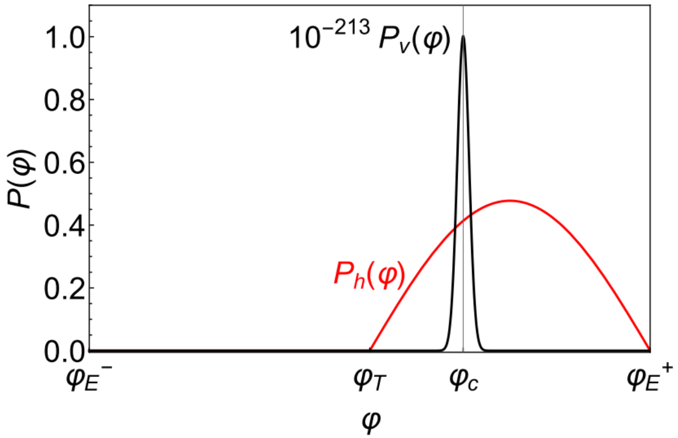

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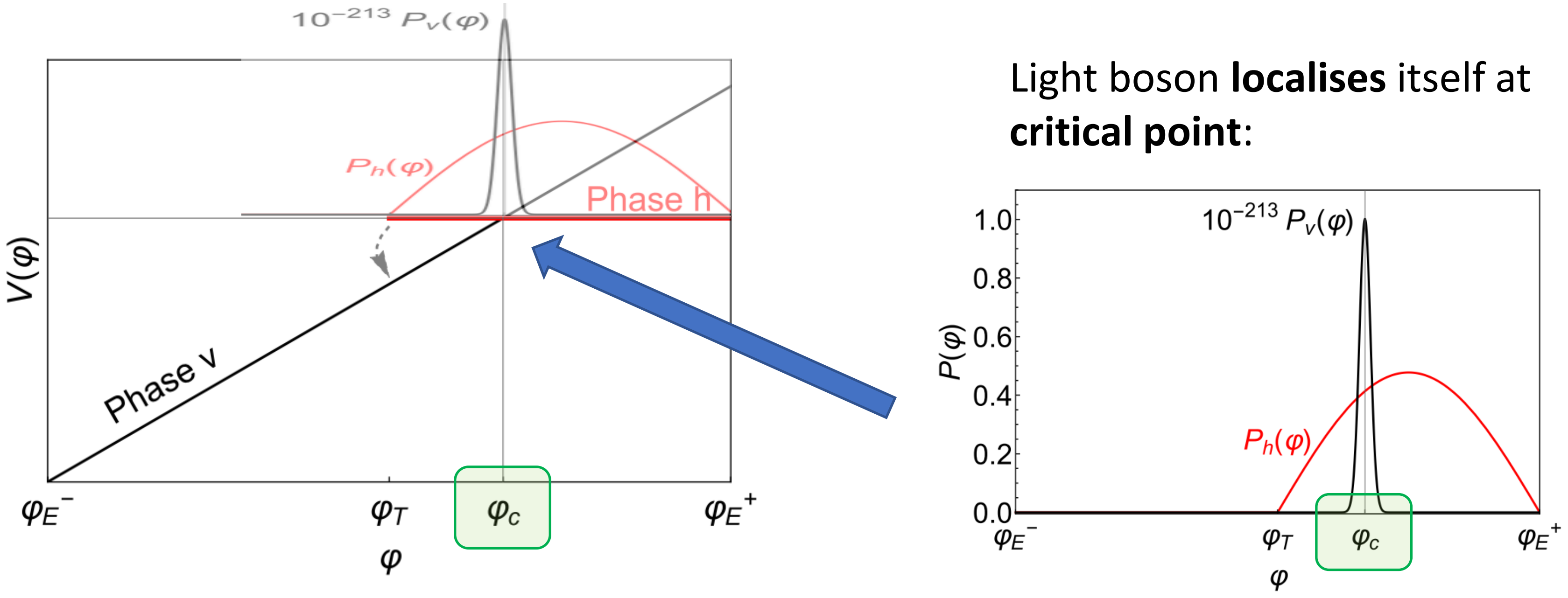

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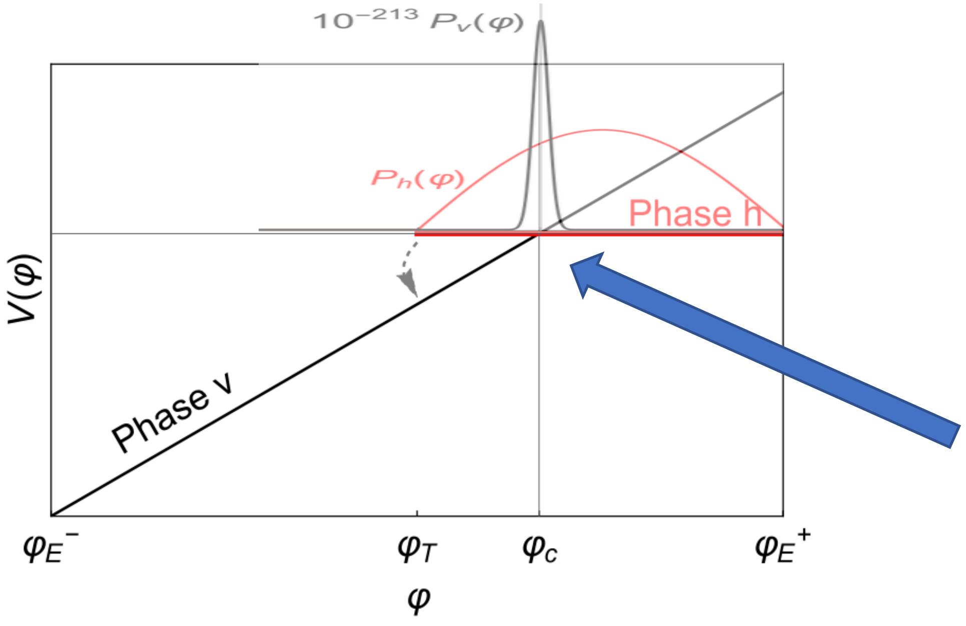

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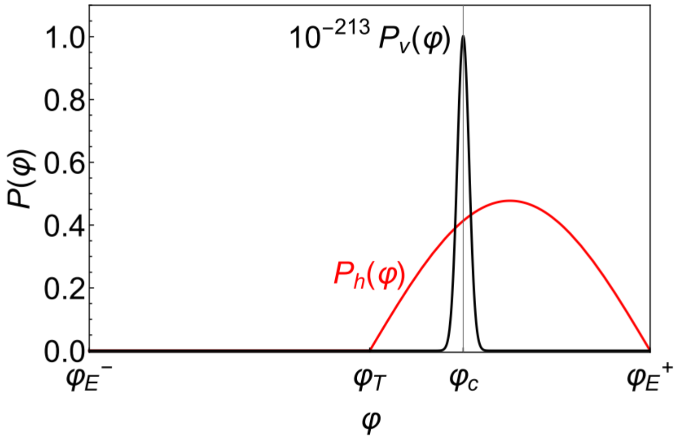

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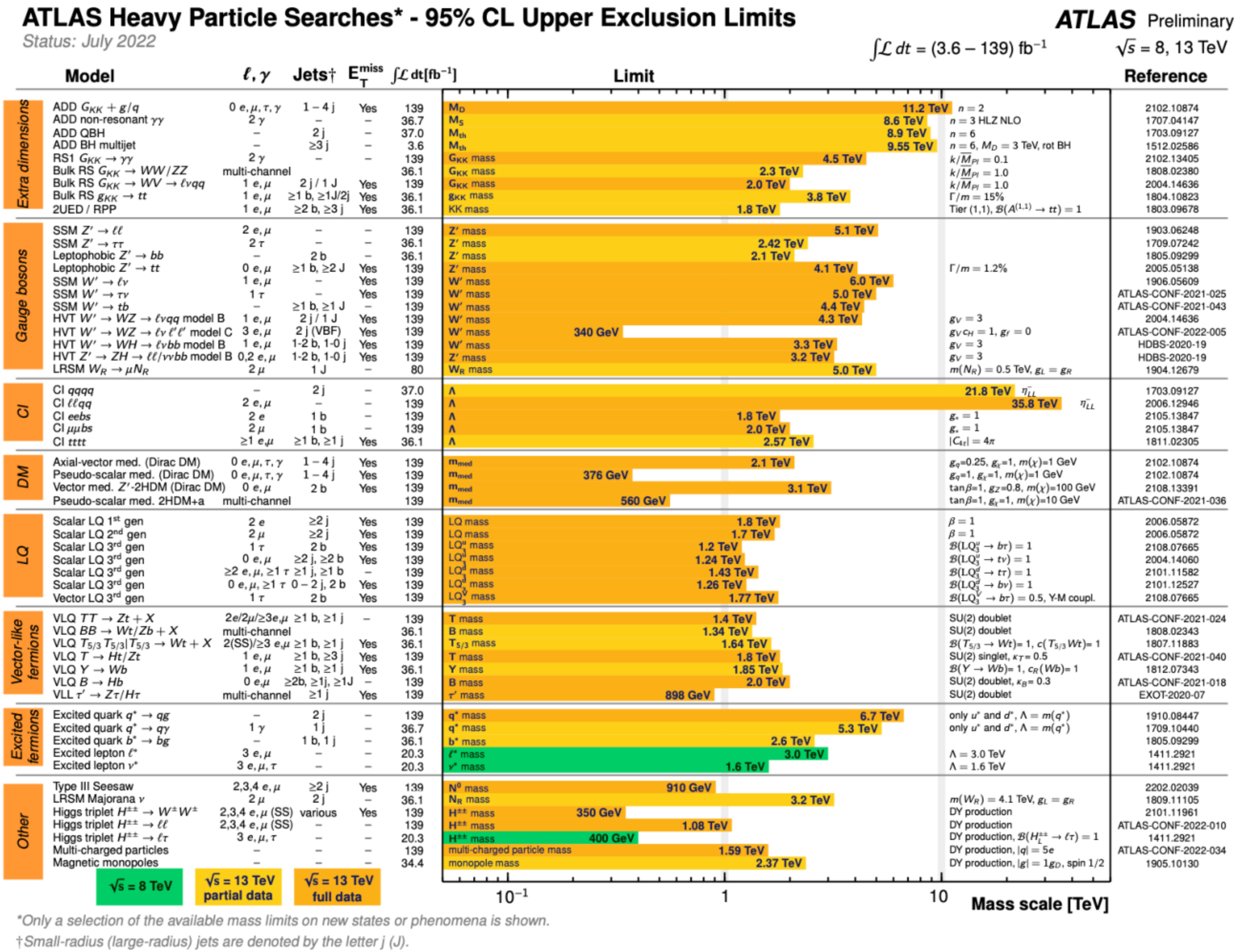

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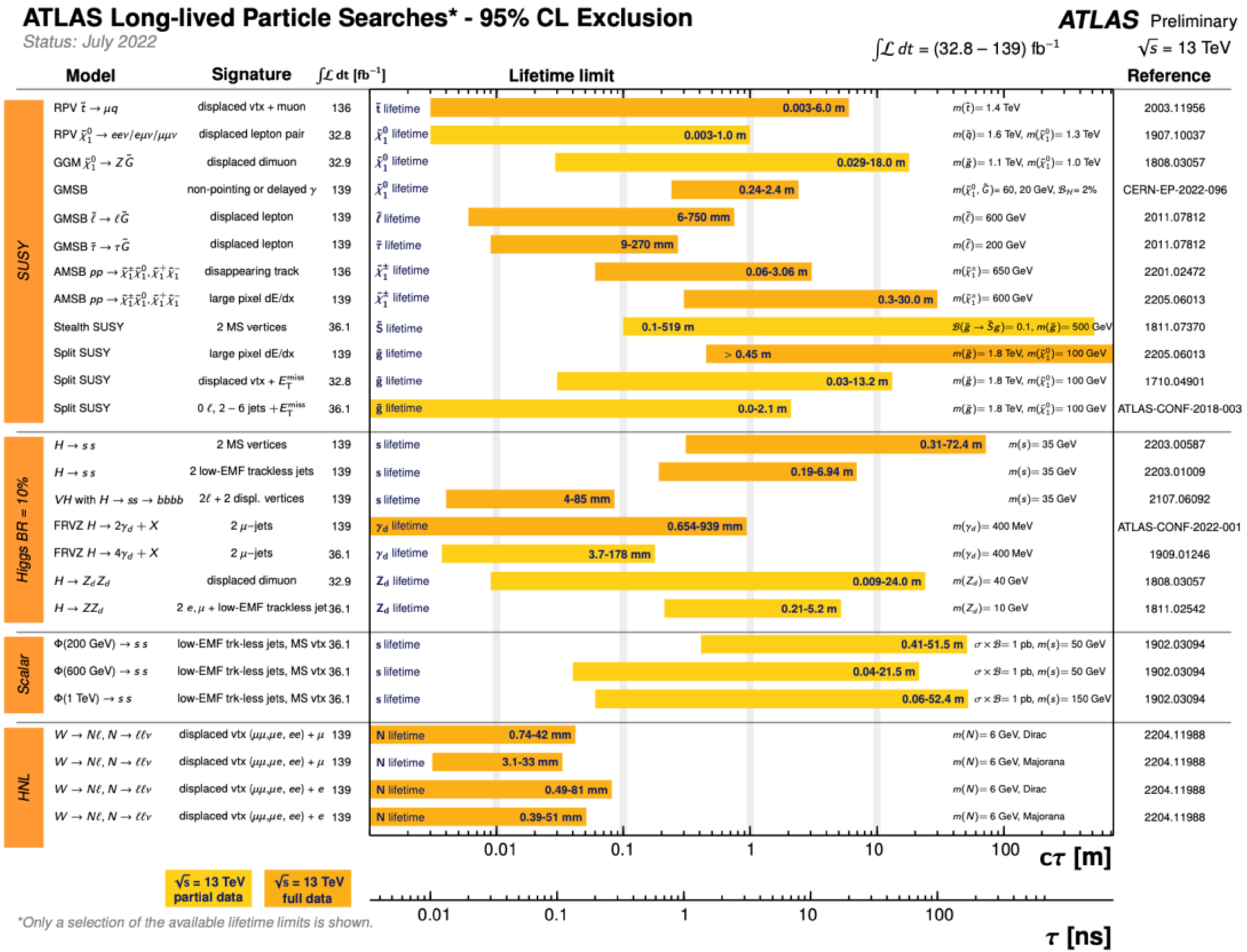

BSM physics opportunities

Search for heavy, long-lived, charged particles with large ionisation energy loss in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS experiment and the full Run 2 dataset

The ATLAS Collaboration (2205.06013)

Observed yields and distributions agree with the SM background expectations, with the exception of an accumulation of events in the high-dE/dx and high-mass range. The local (global) significance of this excess is 3.6σ (3.3σ) in a sub-range of the signal region optimised for a target mass hypothesis of 1.4 TeV.

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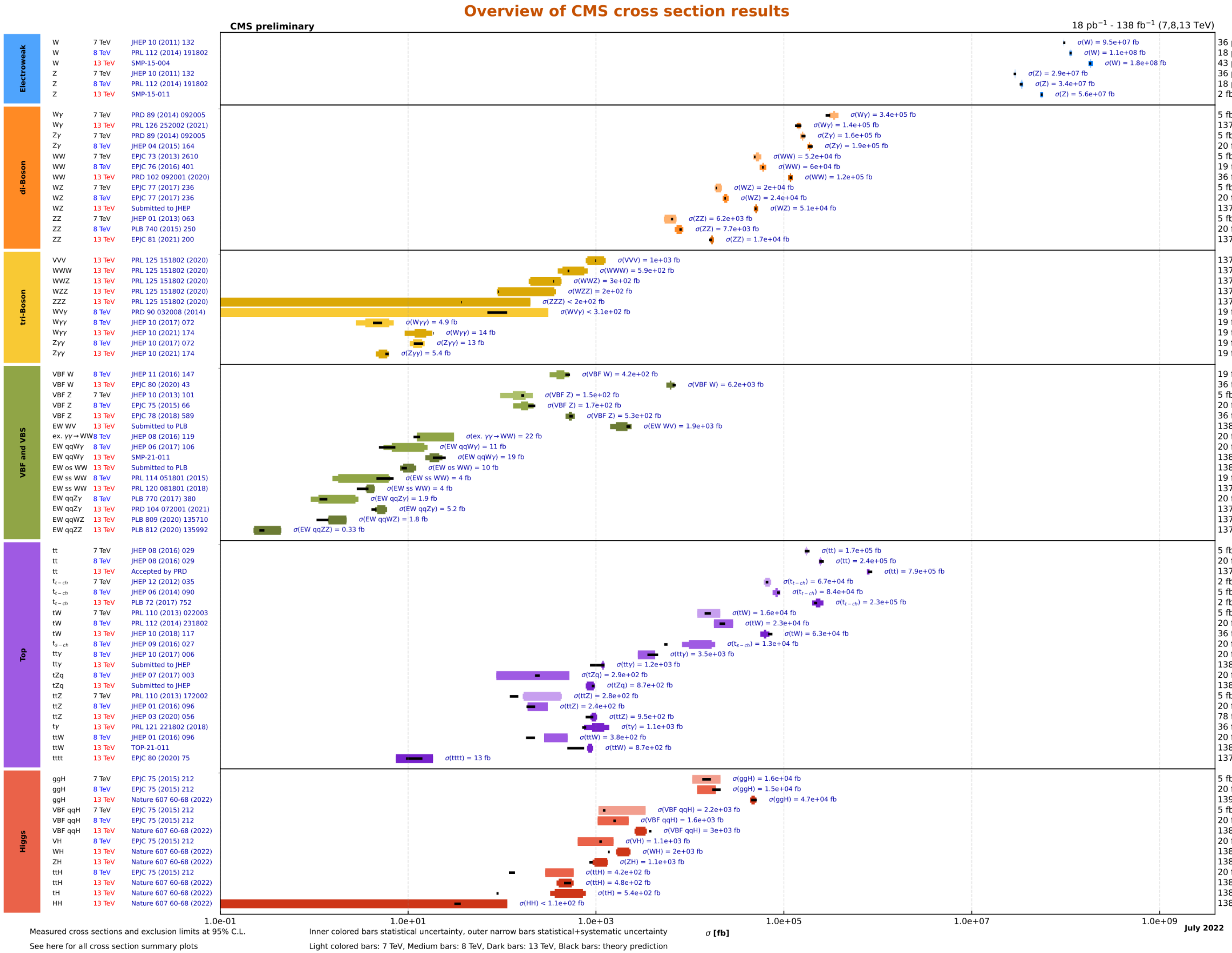
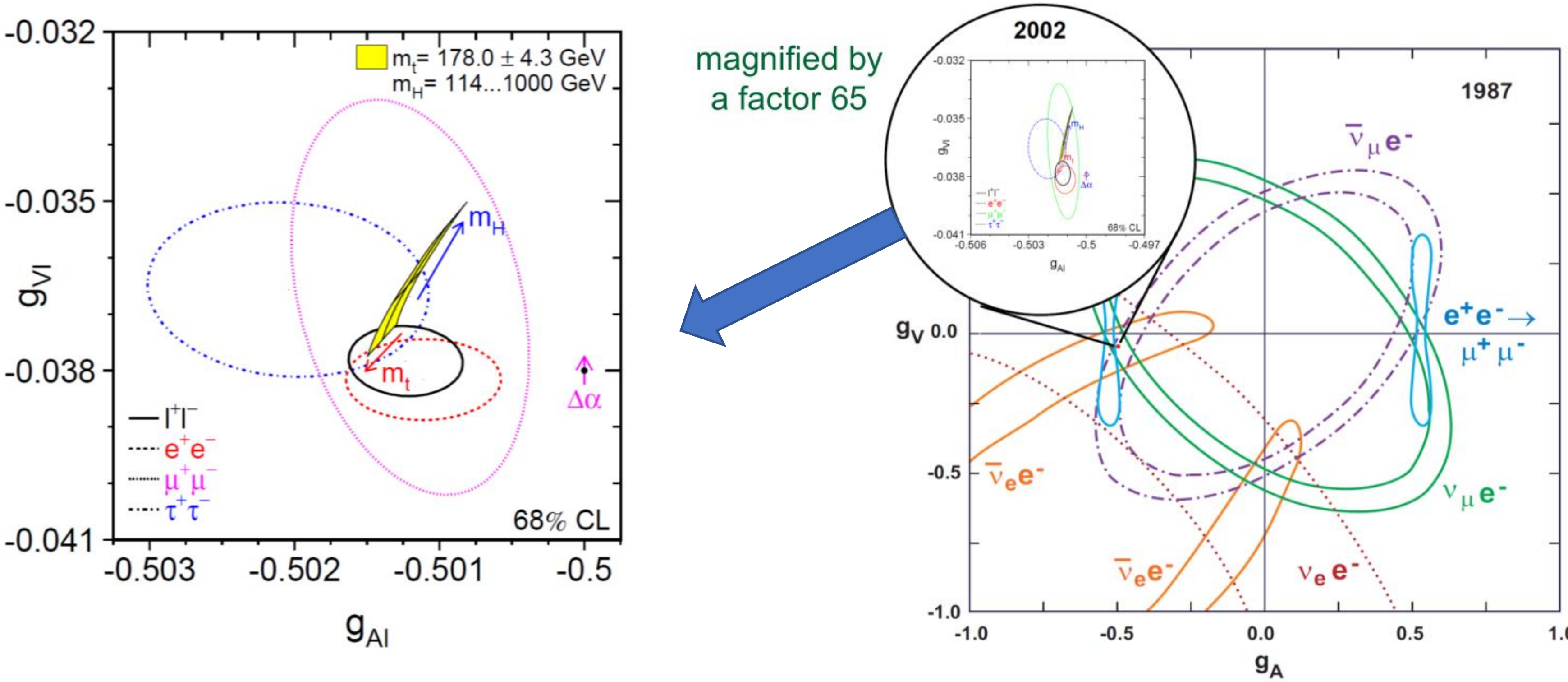


Outline

- Context
- BSM theory challenges
- BSM physics opportunities
- **Beyond the LHC**
- Conclusion

No BSM or new discoveries at LEP

- 1980-1990s: LEP physics programme **a resounding success**
- Improved our fundamental picture of nature *by orders of magnitude*

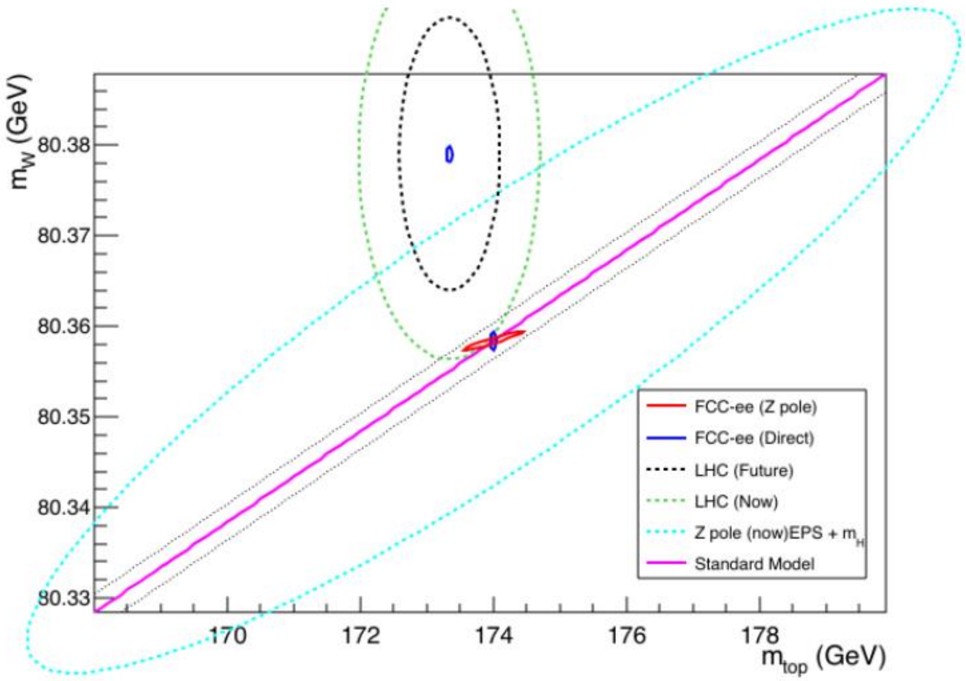


Guy Wilkinson slide

- *Indirect precision probe* of physics at **higher energies**

No guarantee of new discoveries at FCC

- Further **zooming in** on our fundamental picture of nature



- **Rich physics programme** covering Higgs, top, electroweak, multi-bosons, flavour, rare decays, neutrinos, QCD, heavy ions *and more*.

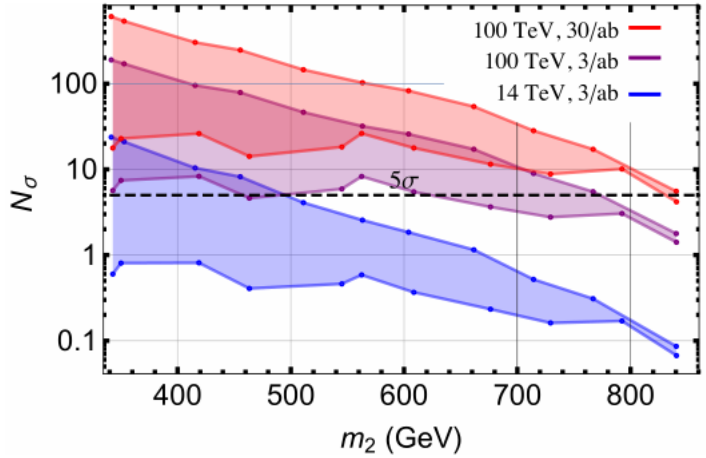
No guarantee of new discoveries at FCC

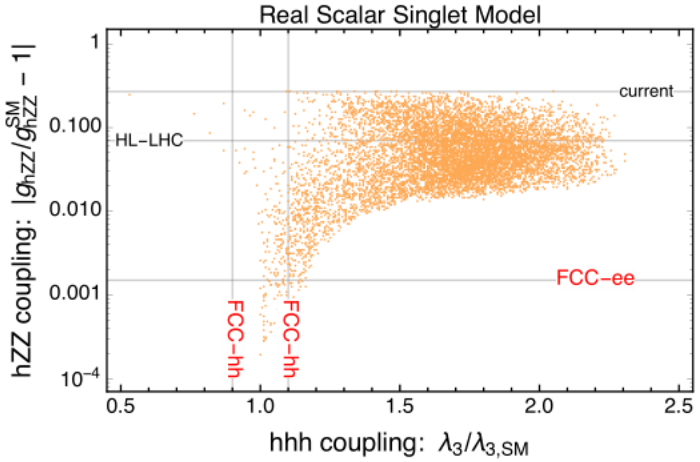
- **No guarantee of discovery** at Tevatron either. Hadron collisions thought by some *to be too messy to do physics*.
- **Value in pushing frontiers**: we learn something *regardless of outcome*
- **Definite questions** are answered, *even if in the negative*
- Science is about *continually refining existing knowledge* and *exploring the unknown*
- **A new generation** of data management, analysis techniques, improved measurements, theoretical calculational tools, hardware development, cutting-edge engineering, large international collaboration, popular culture inspiration, and spirit of fundamental exploration**, can only benefit humanity** regardless of our own short-sighted disappointment at lack of BSM. *Doing good science is its own reward.*

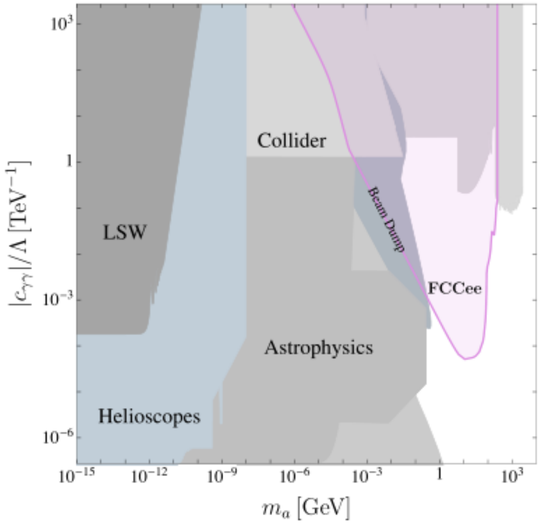
Potential BSM discoveries at FCC

- First order electroweak phase transition
- CP violation
- Dark matter
- Light dark sectors
- Axion-like particles
- Sterile neutrinos
- Higgs portal
- BSM Higgs couplings
- Additional Higgs doublets
- Supersymmetric partners
- Top partners
- Leptoquarks
- New forces
- …
- Implications for naturalness?

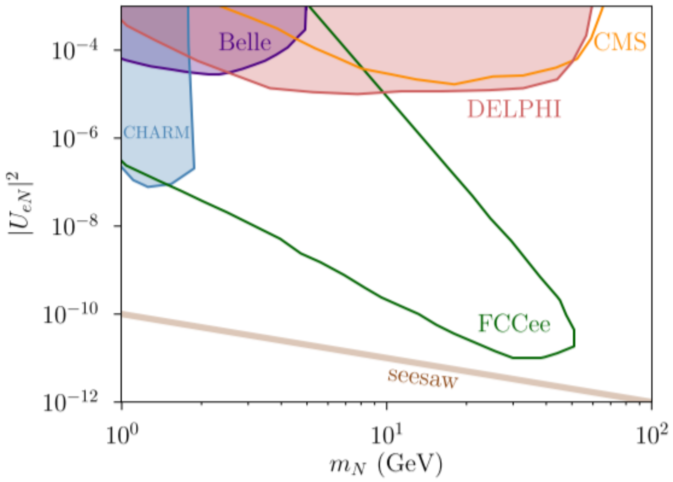
FCC CDR Vol. 1







Bauer et al 1808.10323



Knapen, Thamm 2108.08949

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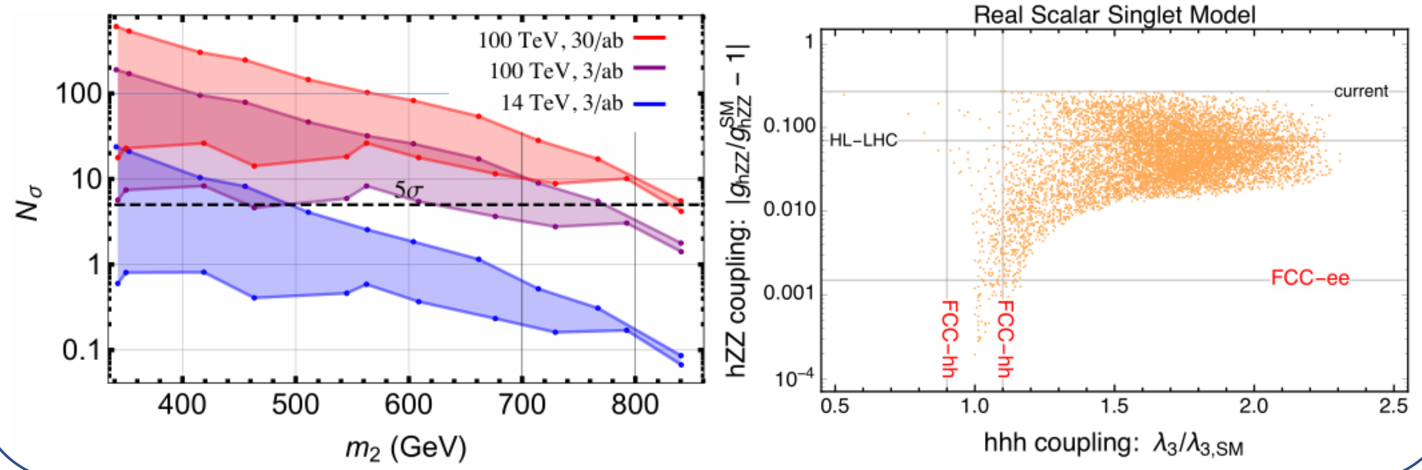

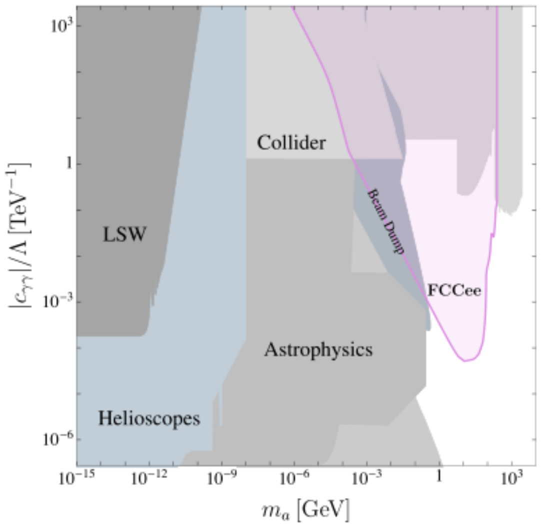

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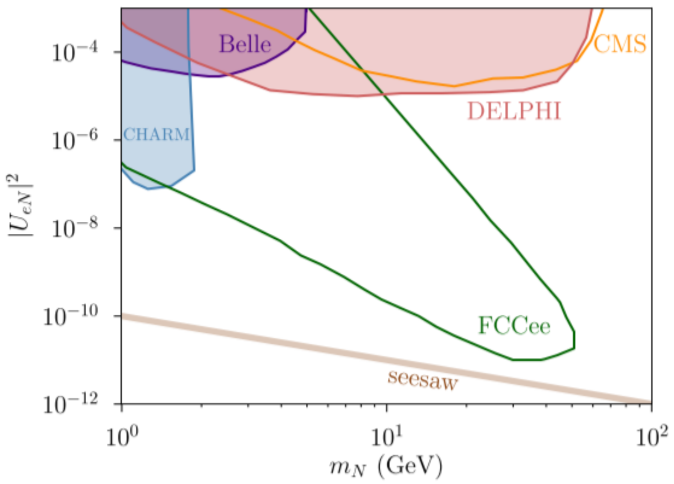

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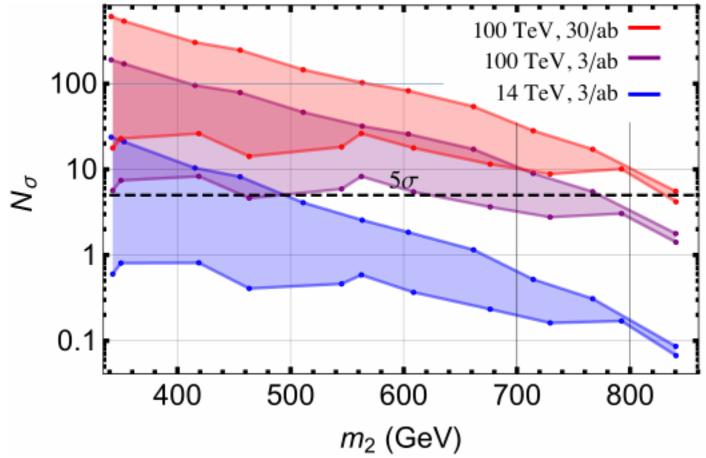

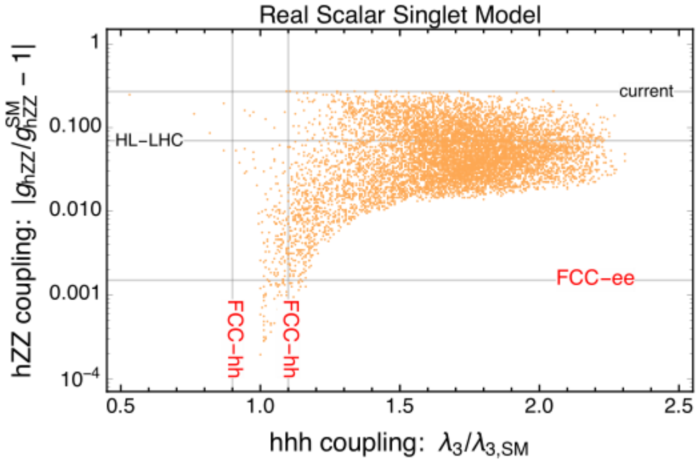

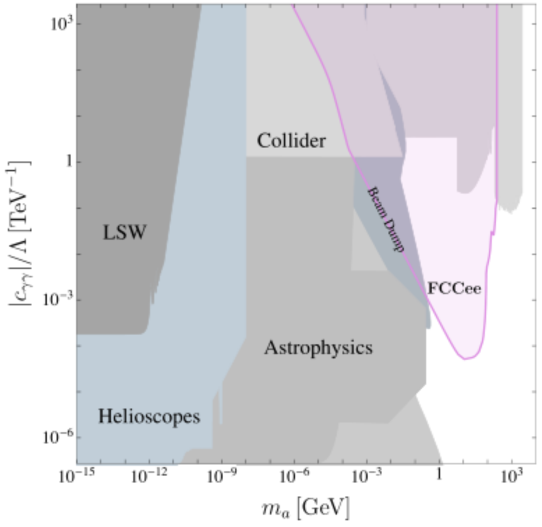

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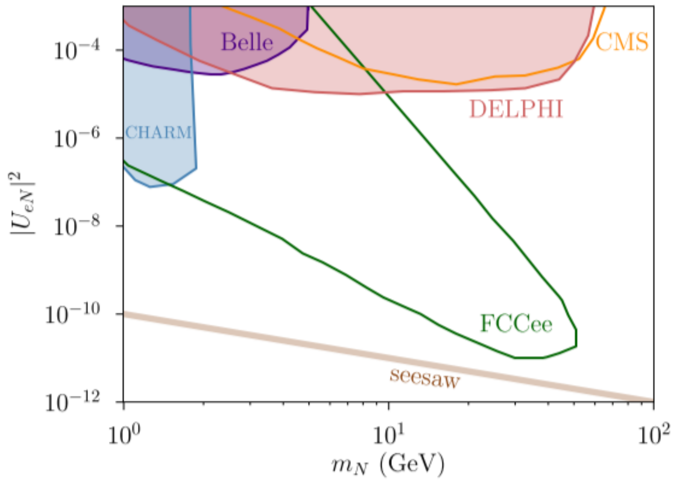

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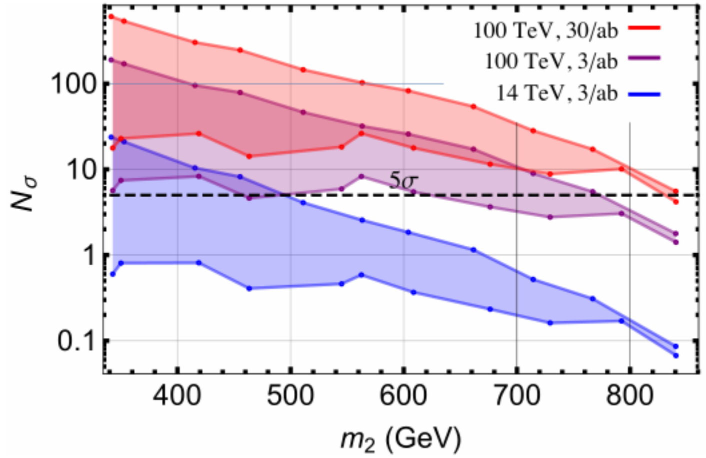

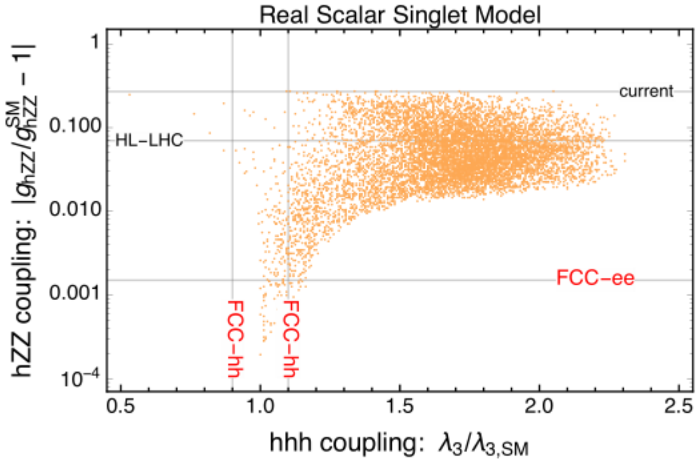

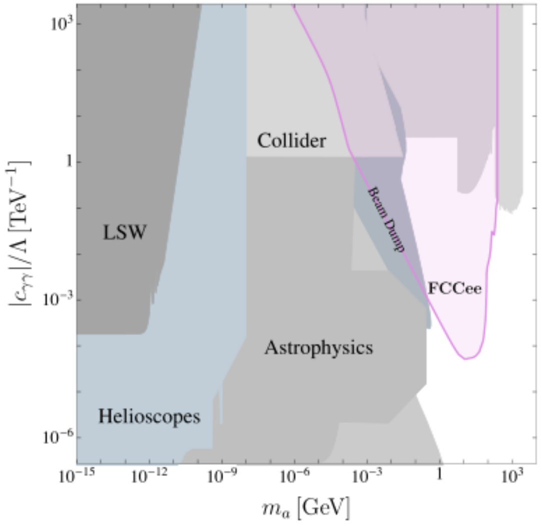

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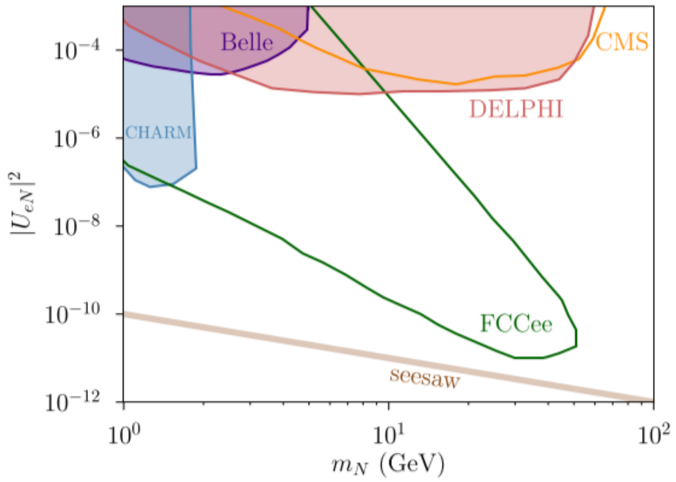

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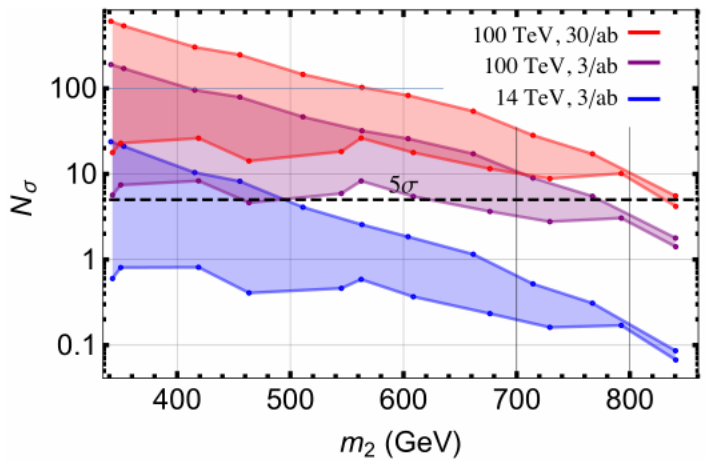

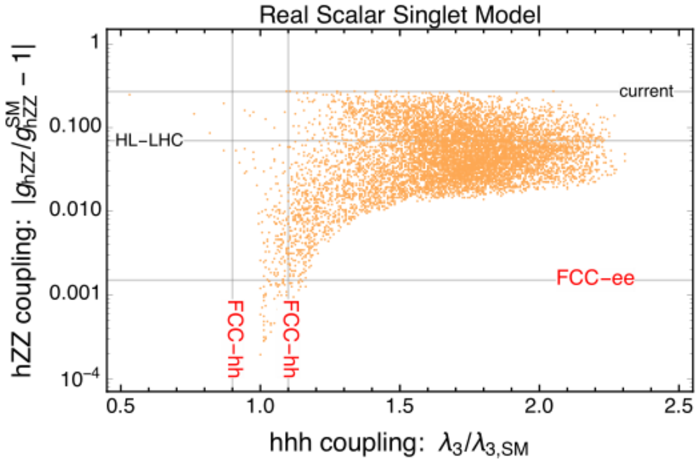

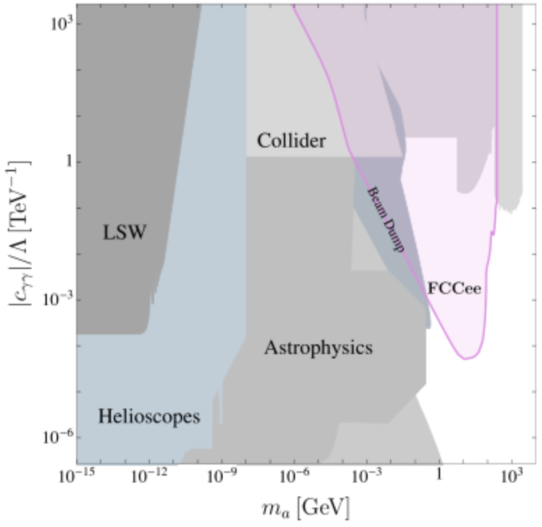

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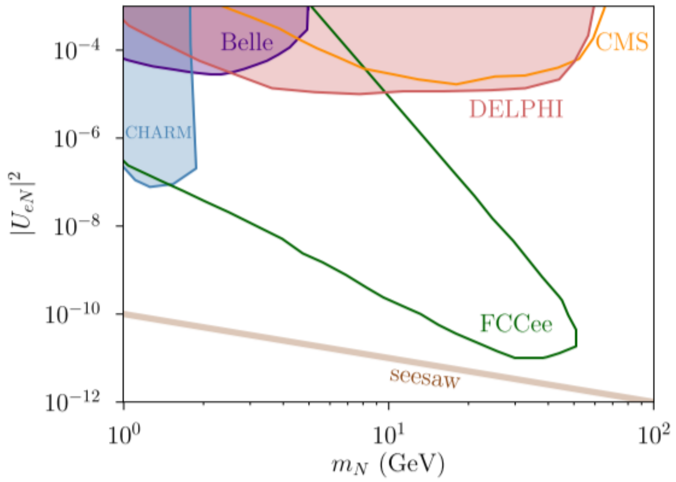

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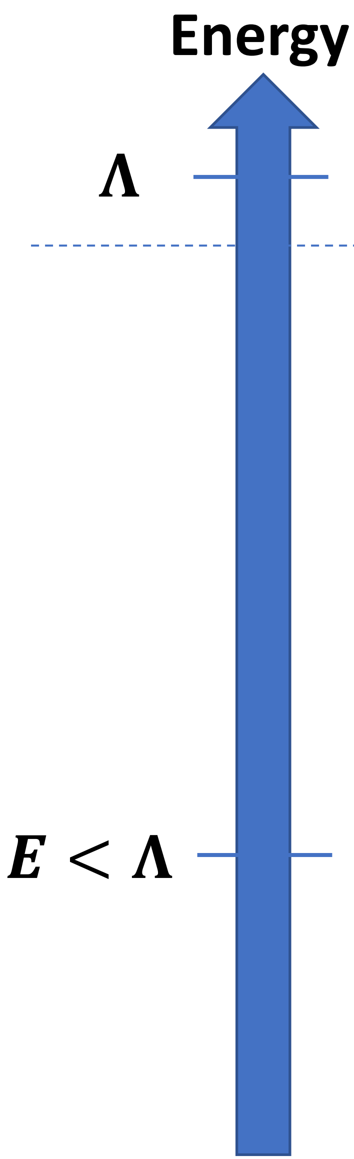
Potential BSM outcomes for naturalness

- **Radically conservative**: naturalness restored just around the corner
  - Natural supersymmetry
  - Composite Higgs/extra dimensions
- **Creatively conservative**
  - Twin Higgs
  - Stealth supersymmetry
- **Post-naturalness** BSM
  - Split supersymmetry
  - Vector-like fermions only
  - Lowered vacuum instability scale
  - Weak-scale new physics for cosmological dynamics
- **Radically new?**
  - Breakdown of QFT/EFT above the TeV scale a real possibility
  - Hard to imagine what form this might take, by definition
  - How might this show up?

Potential BSM outcomes for naturalness

- **Radically conservative**: naturalness restored just around the corner
  - Natural supersymmetry
  - Composite Higgs/extra dimensions
- **Creatively conservative**
  - Twin Higgs
  - Stealth supersymmetry
- **Post-naturalness** BSM
  - Split supersymmetry
  - Vector-like fermions only
  - Lowered vacuum instability scale
  - Weak-scale new physics for cosmological dynamics
- **Radically new?**
  - Breakdown of QFT/EFT above the TeV scale *a real possibility*
  - Hard to imagine what form this might take, by definition
  - How might this show up?

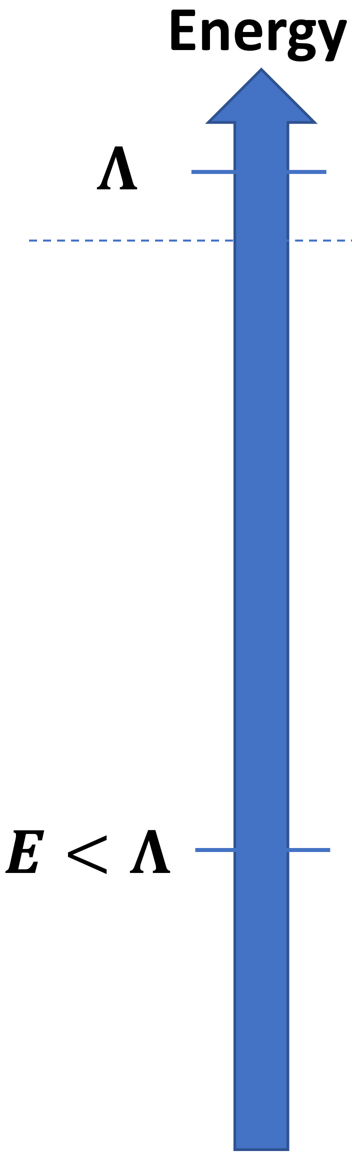
Radically new BSM?



$$\mathcal{L}_{UV} = ?$$

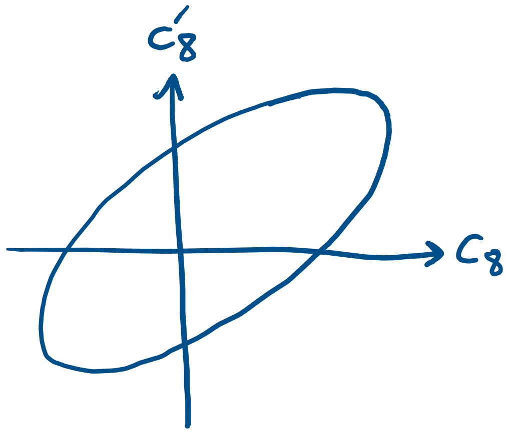
$$\mathcal{L}_{IR} = \Lambda^4 + \Lambda^2\mathcal{O}^{(2)} + m\mathcal{O}^{(3)} + \mathcal{O}^{(4)} + \frac{c_5}{\Lambda}\mathcal{O}^{(5)} + \frac{c_6}{\Lambda^2}\mathcal{O}^{(6)} + \frac{c_7}{\Lambda^3}\mathcal{O}^{(7)} + \frac{c_8}{\Lambda^4}\mathcal{O}^{(8)} + \ldots$$

Radically new BSM?



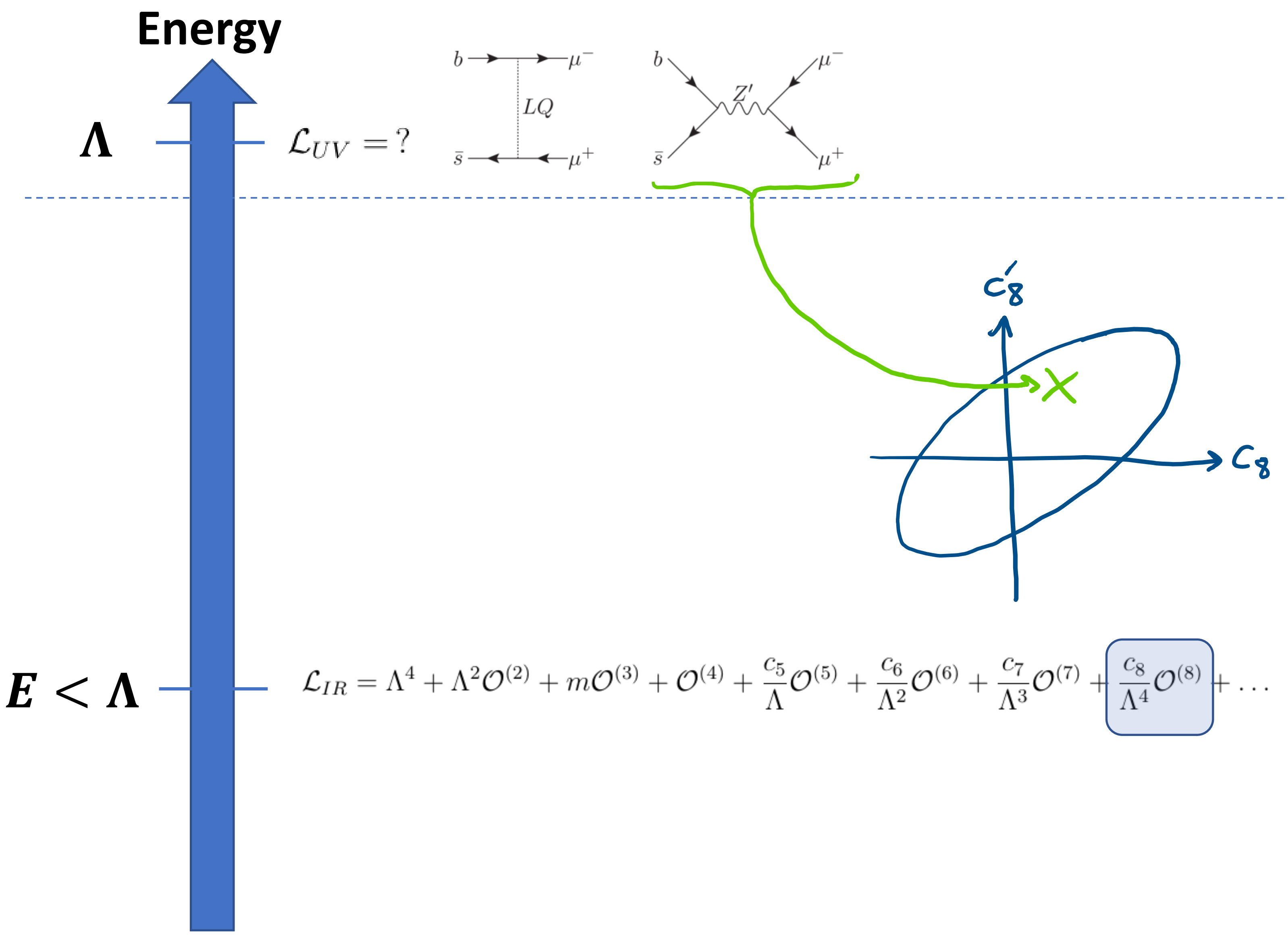
$\mathcal{L}_{UV} = ?$

$$\mathcal{L}_{IR} = \Lambda^4 + \Lambda^2 \mathcal{O}^{(2)} + m\mathcal{O}^{(3)} + \mathcal{O}^{(4)} + \frac{c_5}{\Lambda}\mathcal{O}^{(5)} + \frac{c_6}{\Lambda^2}\mathcal{O}^{(6)} + \frac{c_7}{\Lambda^3}\mathcal{O}^{(7)} + \boxed{\frac{c_8}{\Lambda^4}\mathcal{O}^{(8)}} + \dots$$



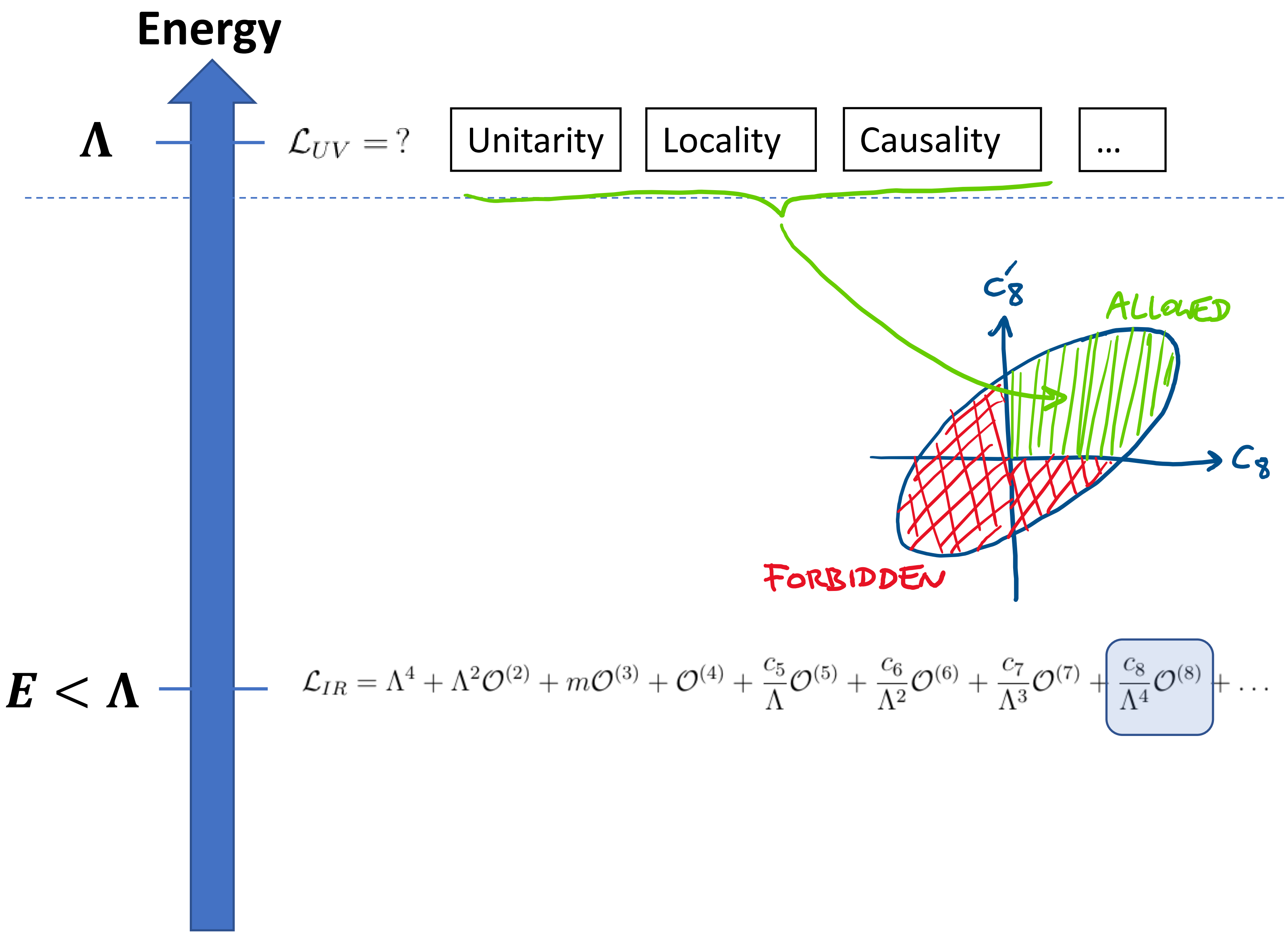
e.g. Consider indirect sensitivity to UV theory

Radically new BSM?



Matching explicit UV models populates a **subspace** of SMEFT coefficient space

Radically new BSM?



Positivity bounds forbid **negative signs** of SMEFT coefficients *assuming only general fundamental principles* in the UV

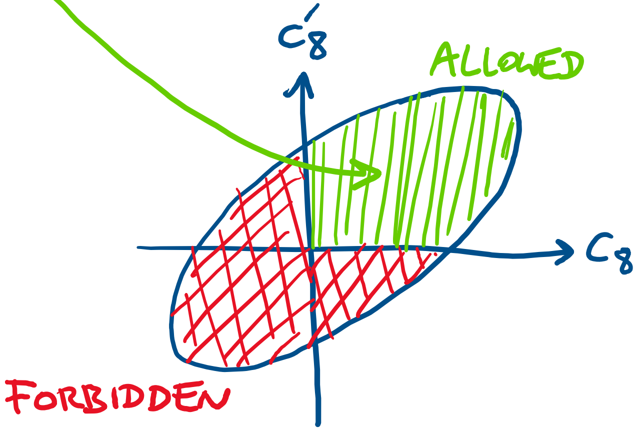
Measuring the *"wrong" sign* experimentally would have **truly revolutionary** consequences for the underlying theory!

Radically new BSM?

Energy

May not even have a Lagrangian description

Λ $\mathcal{L}_{UV} = ?$ | Unitarity | Locality | Causality | ...



Positivity bounds forbid **negative signs** of SMEFT coefficients *assuming only general fundamental principles* in the UV

$\boldsymbol{E < \Lambda}$

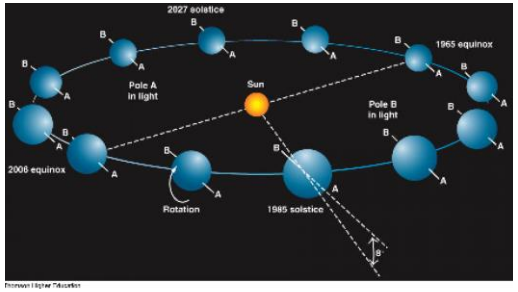
$$\mathcal{L}_{IR} = \Lambda^4 + \Lambda^2\mathcal{O}^{(2)} + m\mathcal{O}^{(3)} + \mathcal{O}^{(4)} + \frac{c_5}{\Lambda}\mathcal{O}^{(5)} + \frac{c_6}{\Lambda^2}\mathcal{O}^{(6)} + \frac{c_7}{\Lambda^3}\mathcal{O}^{(7)} + \frac{c_8}{\Lambda^4}\mathcal{O}^{(8)} + \dots$$

Measuring the *"wrong" sign* experimentally would have **truly revolutionary** consequences for the underlying theory!

Radically new BSM?

- Sometimes an anomaly in **indirect precision** measurement = *something missing*

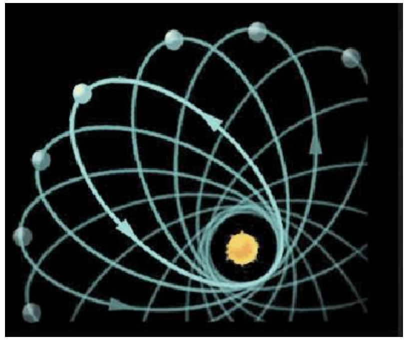
Anomaly in orbit of Uranus

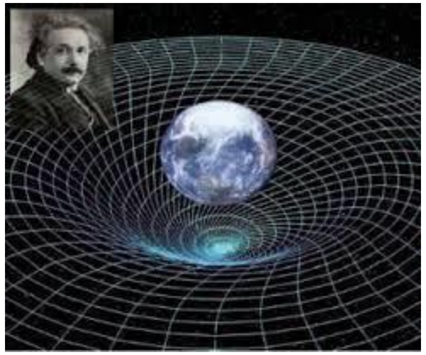


Discovery of Neptune

- Sometimes its implications are *far more radical*

Anomaly in orbit of Mercury



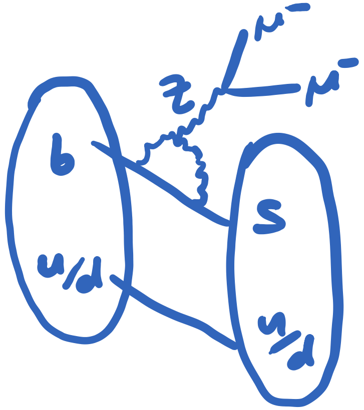


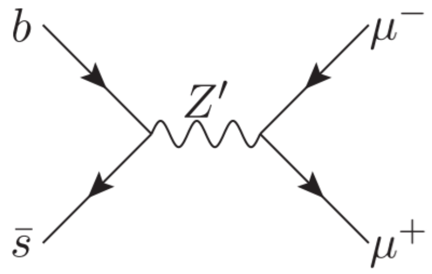
Explained by General Relativity

Radically new BSM?

- Sometimes an anomaly in **indirect precision** measurement = *something missing*

Anomaly in Flavour physics

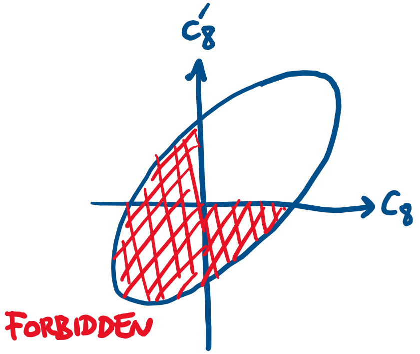




Discovery of Z'?

- Sometimes its implications are *far more radical*

Anomaly in positivity bounds?



$$\mathcal{L}_{UV} = ?$$

Explained by ???

Outline

- Context
- BSM theory challenges
- BSM physics opportunities
- Beyond the LHC
- **Conclusion**

Conclusion

- Lack of new physics accompanying the Higgs is **a major theoretical challenge**

- It is also **an opportunity** to rethink BSM possibilities **with an open mind**

- **Exploiting the full potential of the LHC** and **fully exploring the multi-TeV scale at FCC** is crucial

Conclusion

- 1900: Almost all data agree spectacularly with the fundamental framework of the time, *no reason to doubt its universal applicability or completeness*.

- 1920s: A combination of **precision measurements** (Mercury), **aesthetic arguments** (relativity) supported by **null experimental results** (Michelson-Morley), and **theoretical inconsistencies** (Rayleigh-Jeans UV catastrophe) lead to an overhaul of the fundamental picture at **smaller scales** and **higher energies** after *pushing the frontiers of technology and theory into new regimes.*

Conclusion

- 2020: Almost all data agree spectacularly with the fundamental framework of the time, *no reason to doubt its universal applicability or completeness*.

- 2050s: A combination of **precision measurements** (B mesons, Hubble), **aesthetic arguments** (naturalness) supported by **null experimental results** (LHC), and **theoretical inconsistencies** (black hole information paradox) lead to an overhaul of the fundamental picture at **smaller scales** and **higher energies** after *pushing the frontiers of technology and theory into new regimes*.