Quo Vadis Particle Physics?

Status of the Standard Model
Exploring Higgs couplings
Motivations for physics beyond the SM
Higgs mysteries
SM Effective Field Theory to scan for new physics
Status of $g_\mu - 2$

John Ellis
KING'S College LONDON

Where are we now?

Summary of the Standard Model

- Particles and SU(3) × SU(2) × U(1) quantum numbers:

L_L E_R	$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L, \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L, \begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}_L$ e_R^-, μ_R^-, τ_R^-	$(\mathbf{1},\mathbf{2},-1)$ $(\mathbf{1},\mathbf{1},-2)$
Q_L U_R D_R	$\begin{pmatrix}u\\ d\end{pmatrix}_L, \begin{pmatrix}c\\ s\end{pmatrix}_L, \begin{pmatrix}t\\ b\end{pmatrix}_L$ u_R, c_R, t_R d_R, s_R, b_R	$(\mathbf{3},\mathbf{2},+1/3)$ $(\mathbf{3},\mathbf{1},+4/3)$ $(\mathbf{3},\mathbf{1},-2/3)$

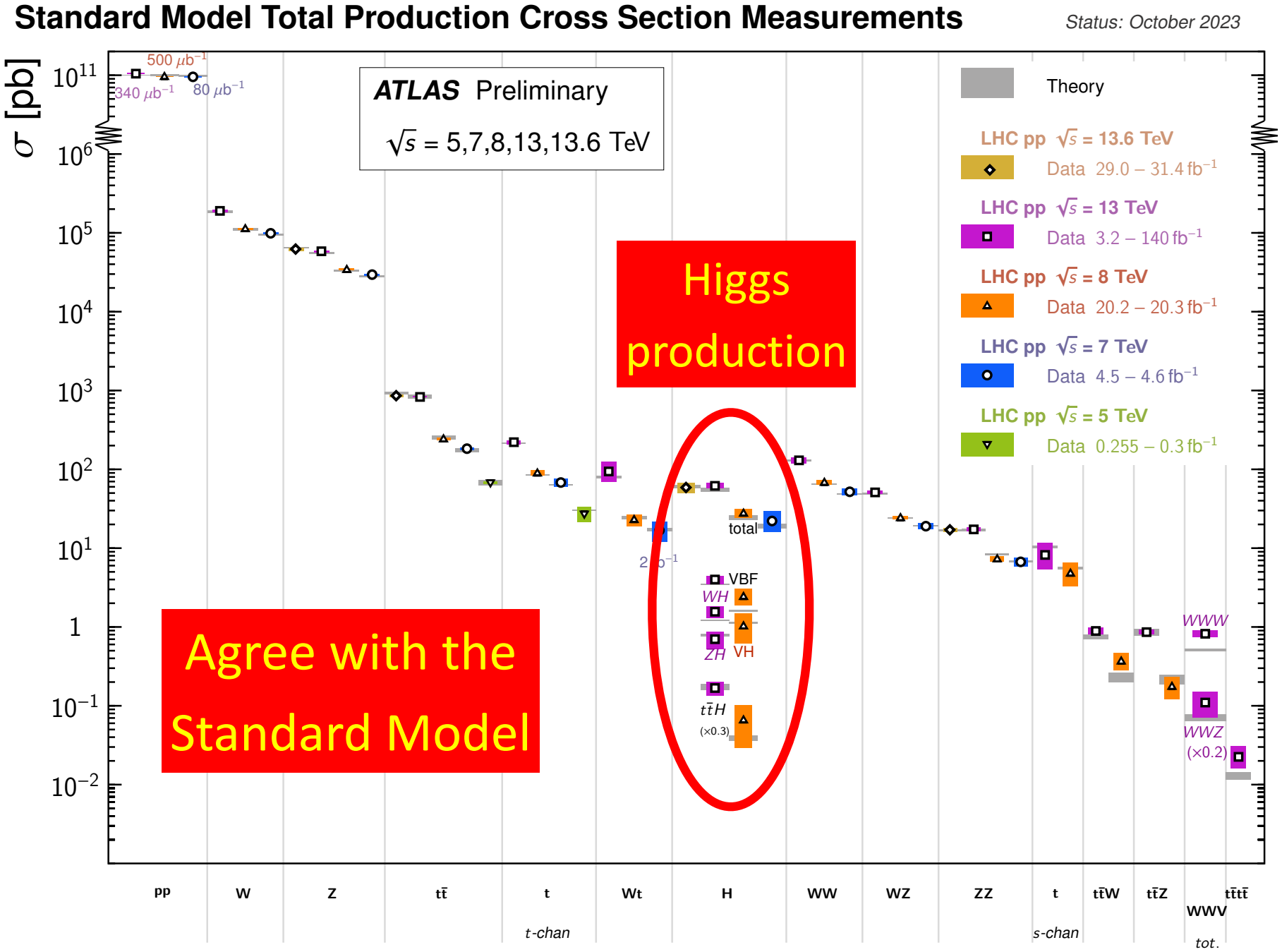
- Lagrangian:

$$\begin{aligned}\mathcal{L} &= -\frac{1}{4}F^a_{\mu\nu}F^{a\,\mu\nu} && \text{gauge interactions}\\ &+ i\bar{\psi}\not{D}\psi + h.c. && \text{matter fermions}\\ &+ \psi_i y_{ij}\psi_j\phi + h.c. && \text{Yukawa interactions}\\ &+ |D_\mu\phi|^2 - V(\phi) && \text{Higgs potential}\end{aligned}$$

Tested < 0.1% before LHC

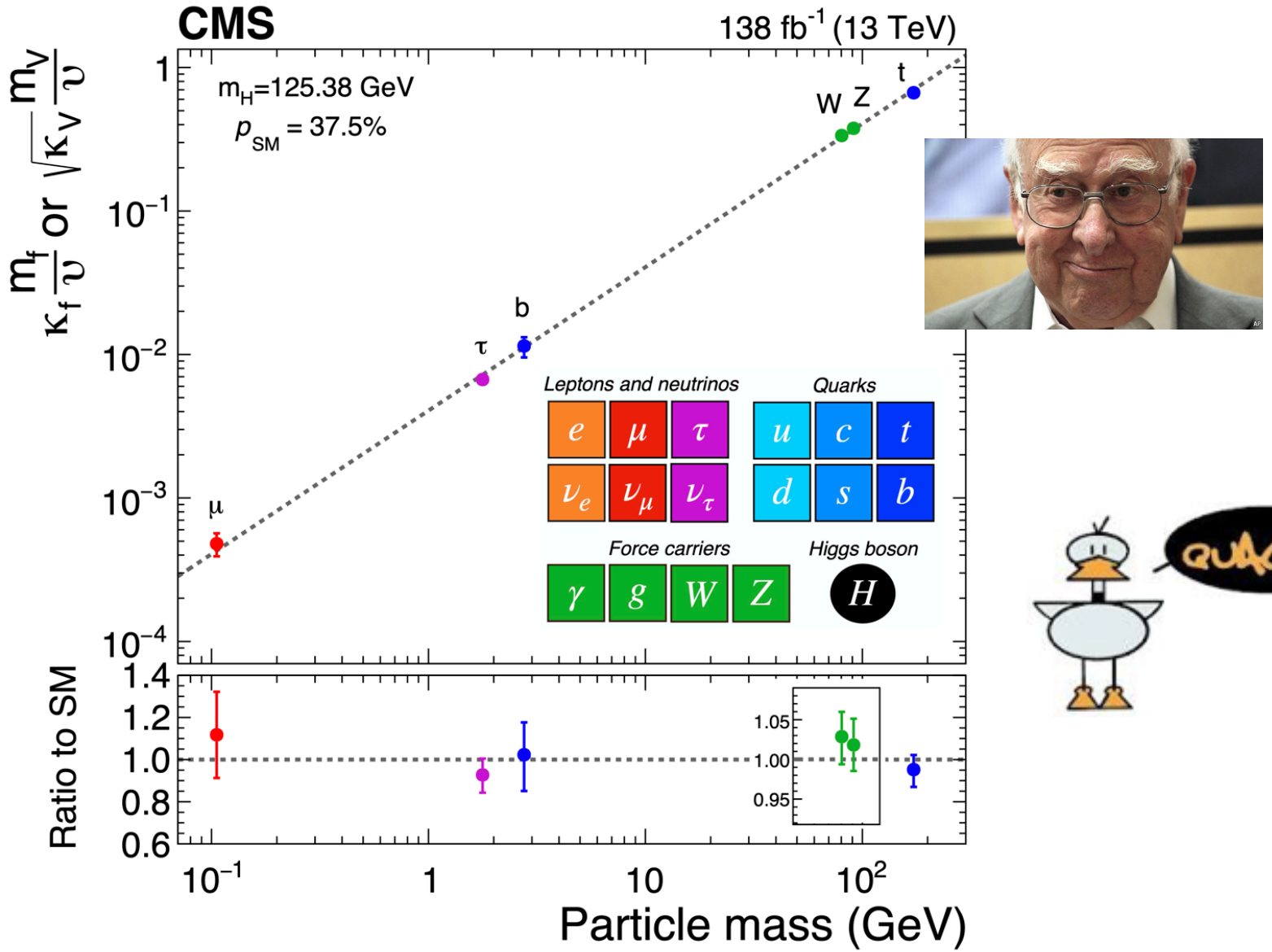
Testing now in progress

LHC Measurements



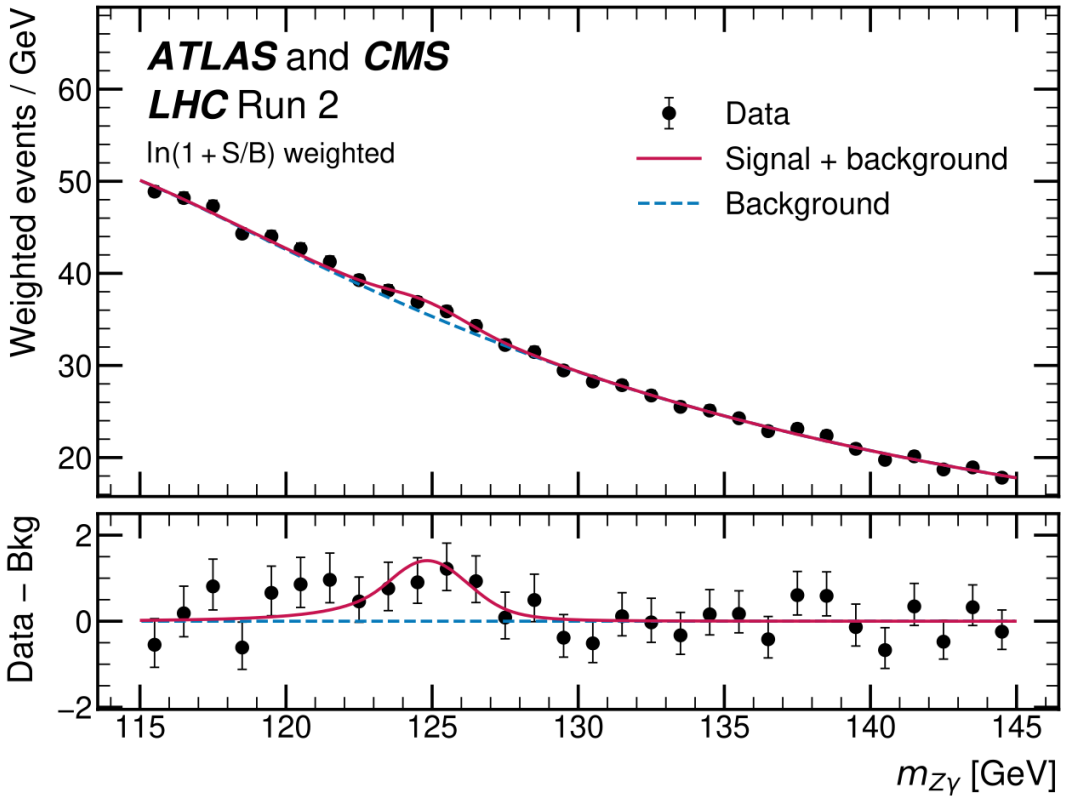
It Walks and Quacks like a Higgs

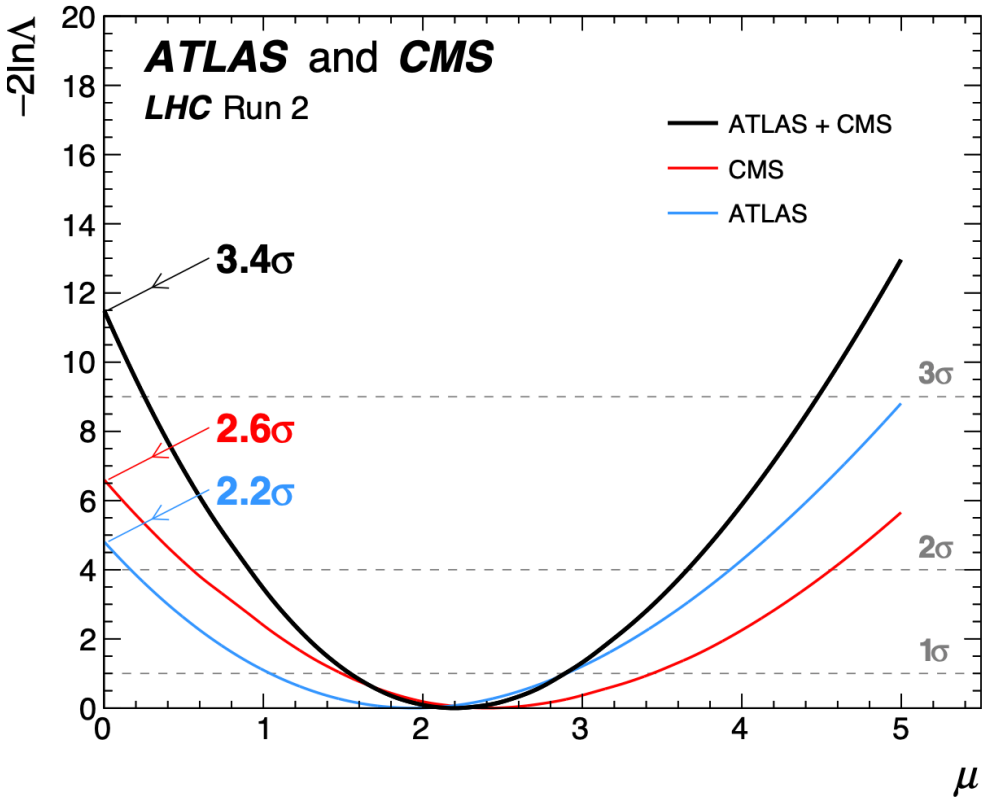
- Couplings scale ~ mass, with scale ~ v



ATLAS & CMS, arXiv:2309.03501

Emerging Decay Mode: $H \to Z\gamma$





Signal strength $\mu = 2.2 \pm 0.7$ times Standard Model value

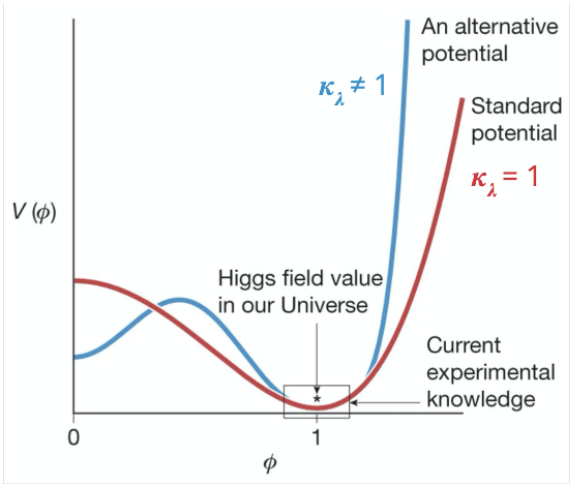
Negligible change in NLO QCD

Buccioni, Devoto, Djouadi, JE, Quevillon, Tancredi, arXiv:2312.12384

Higher-order EW unimportant

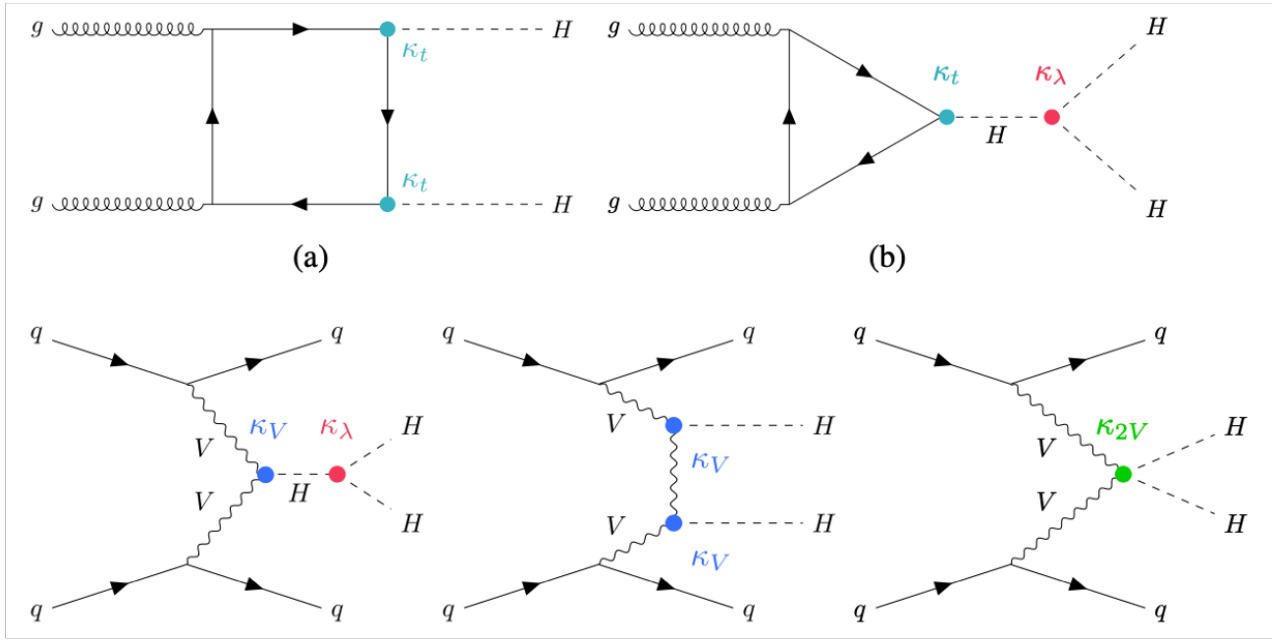
Chen, Chen, Qiao & Zhu, arXiv:2404.114441

Statistics? BSM physics?

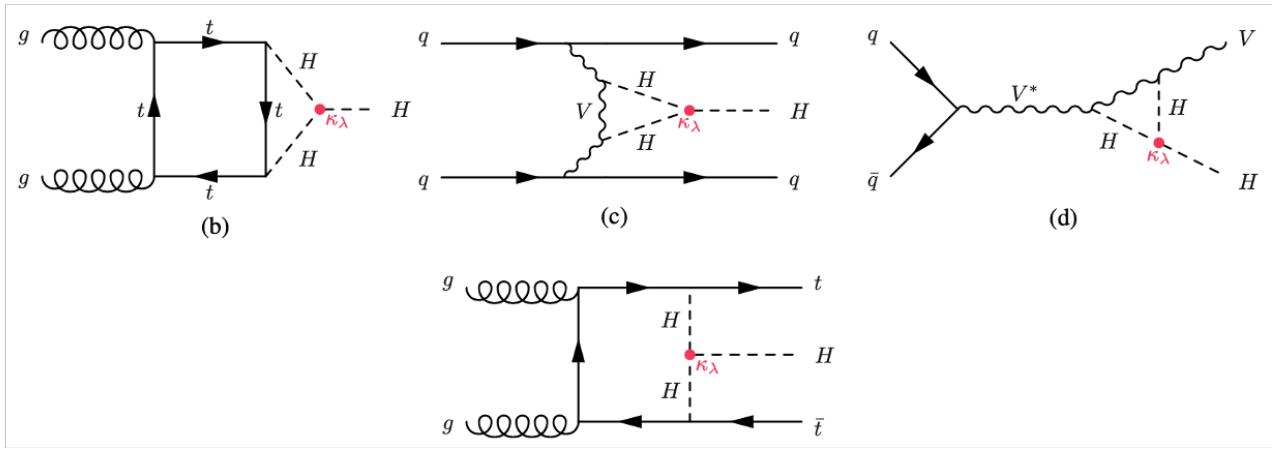


Search for Triple-H Coupling

Diagrams for double-Higgs production



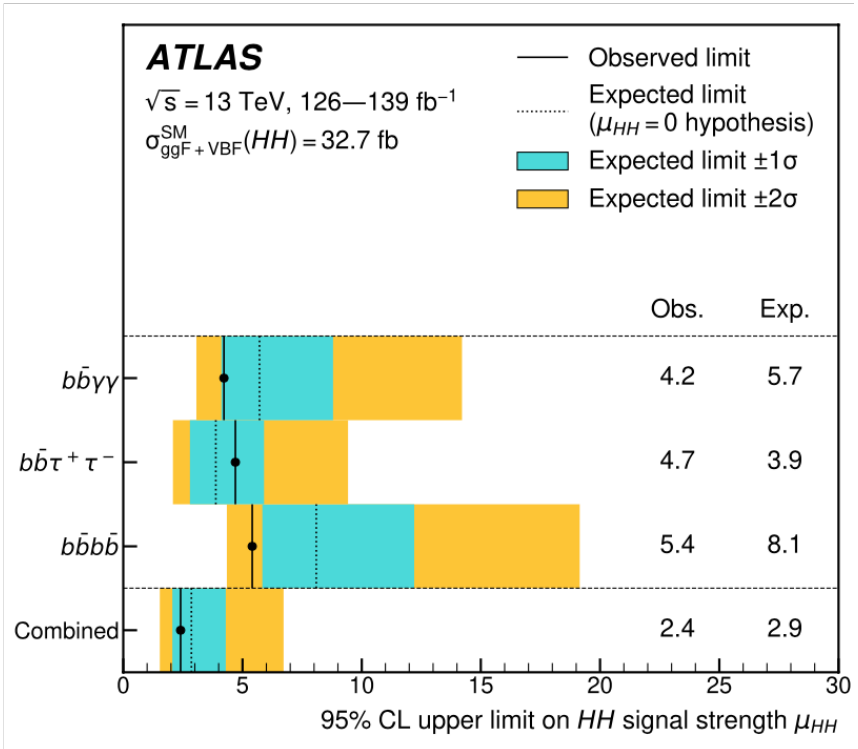
Loop corrections to single Higgs production



ATLAS Collaboration, arXiv: 2211.01216

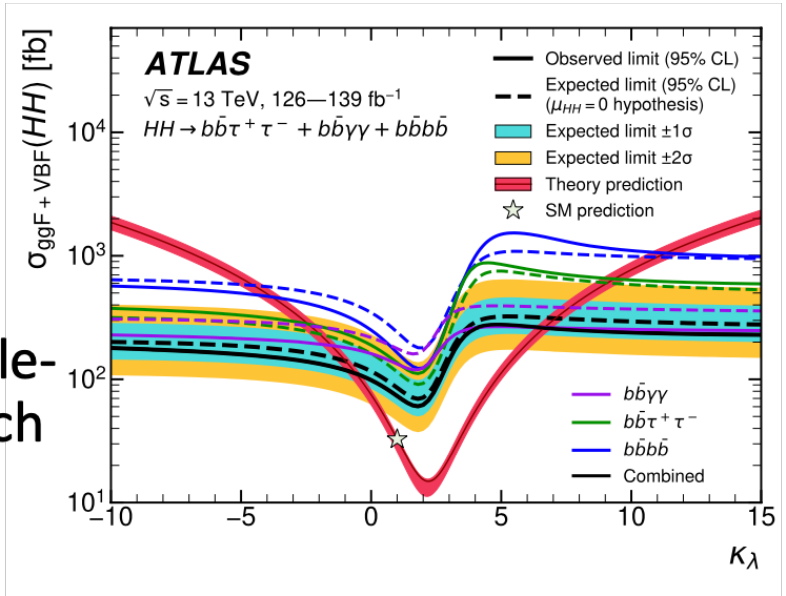
Search for HHH Coupling

Limit on double-Higgs production

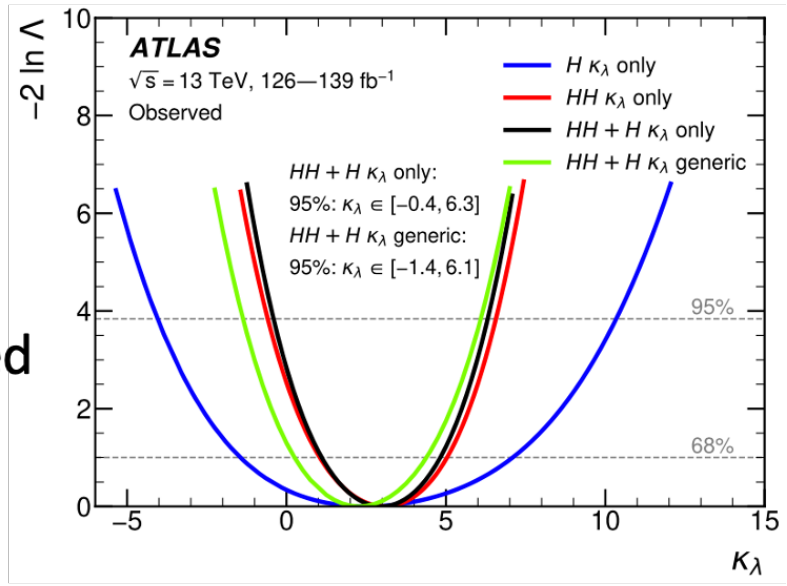


Limits on triple-Higgs coupling

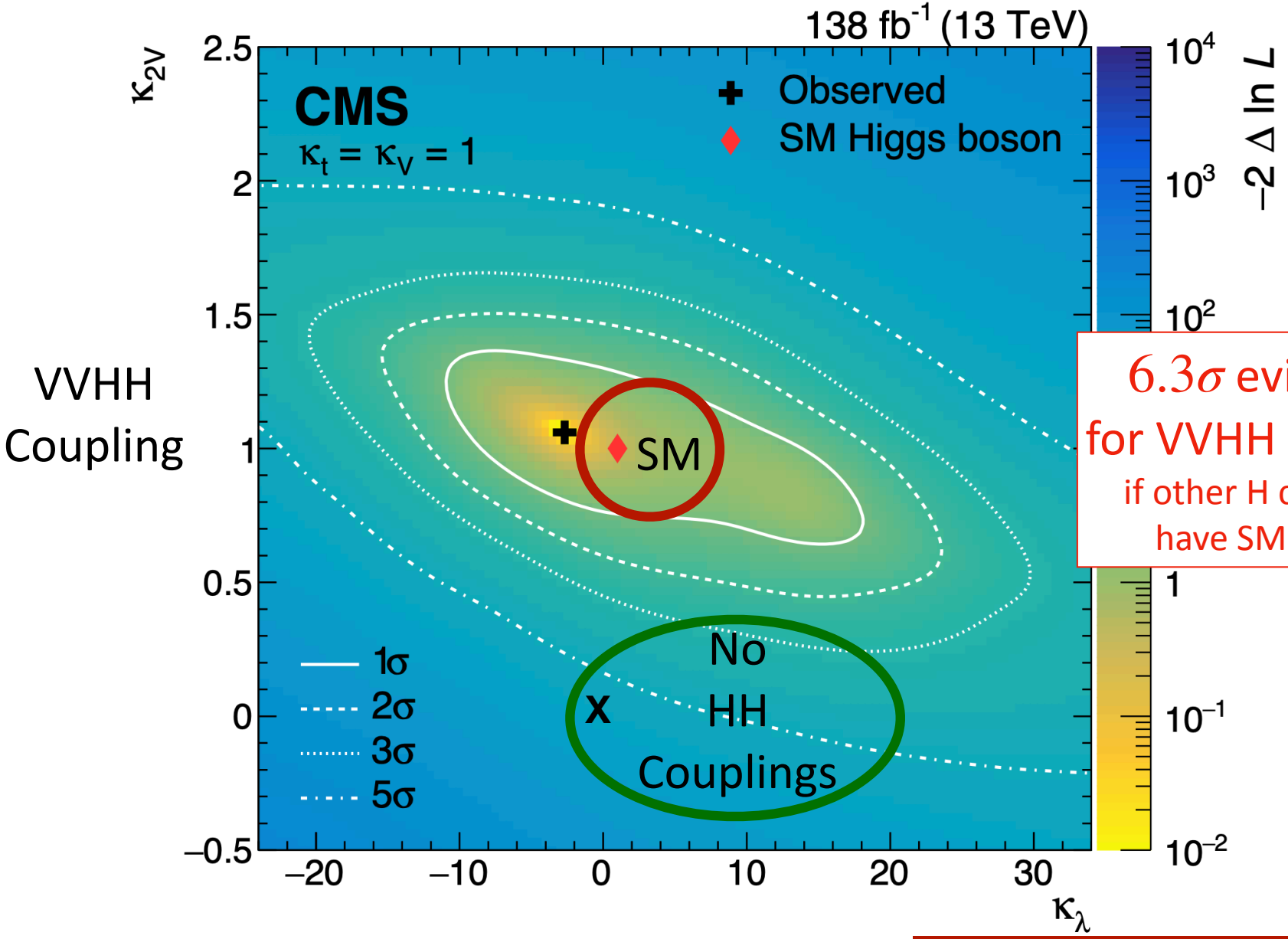
From double-Higgs search



Combined limit



Evidence for VVHH Coupling



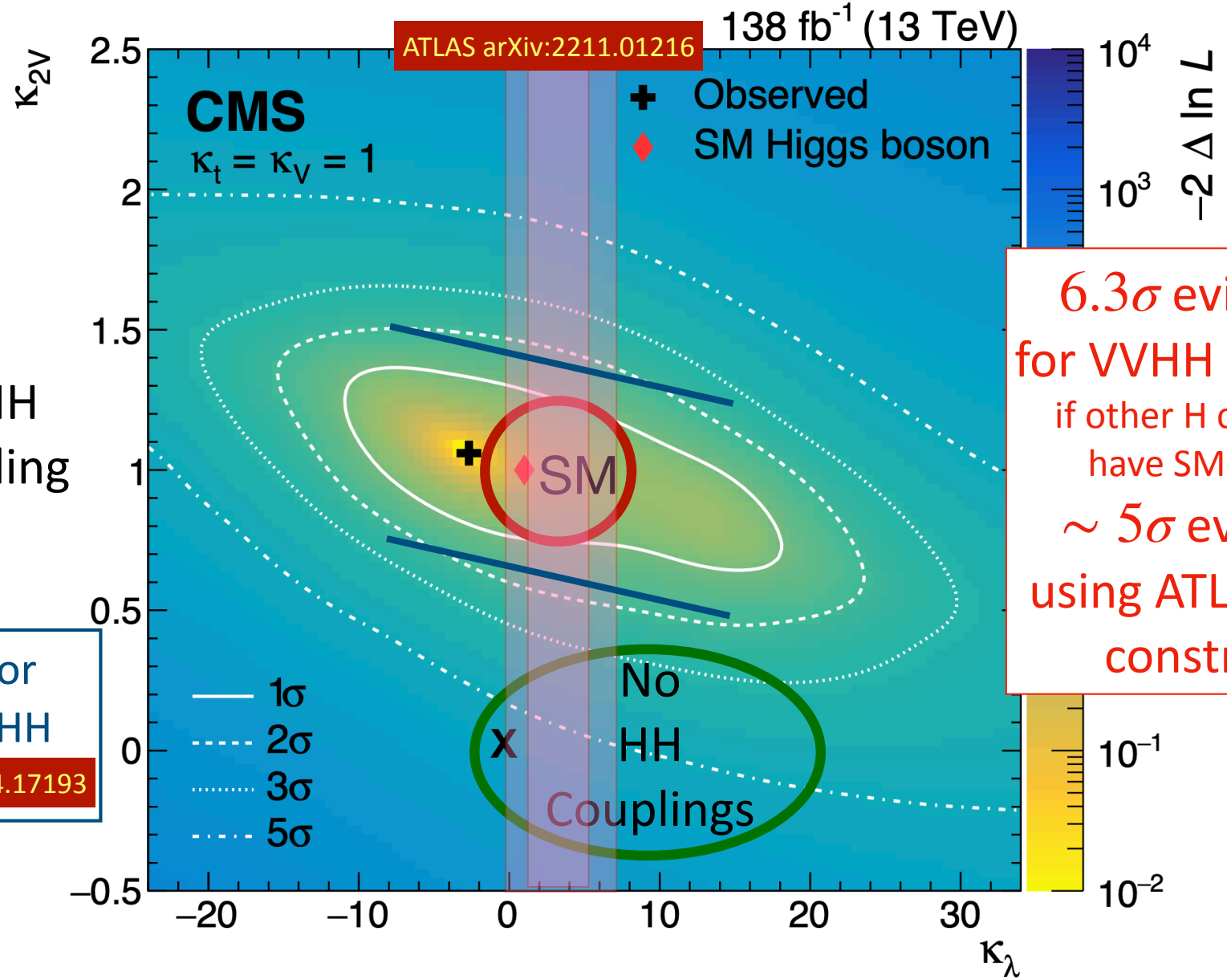
VVHH Coupling

HHH Coupling

6.3σ evidence for VVHH coupling if other H couplings have SM values

CMS collaboration arXiv:2205.06667

Evidence for VVHH Coupling



6.3σ evidence for VVHH coupling if other H couplings have SM values

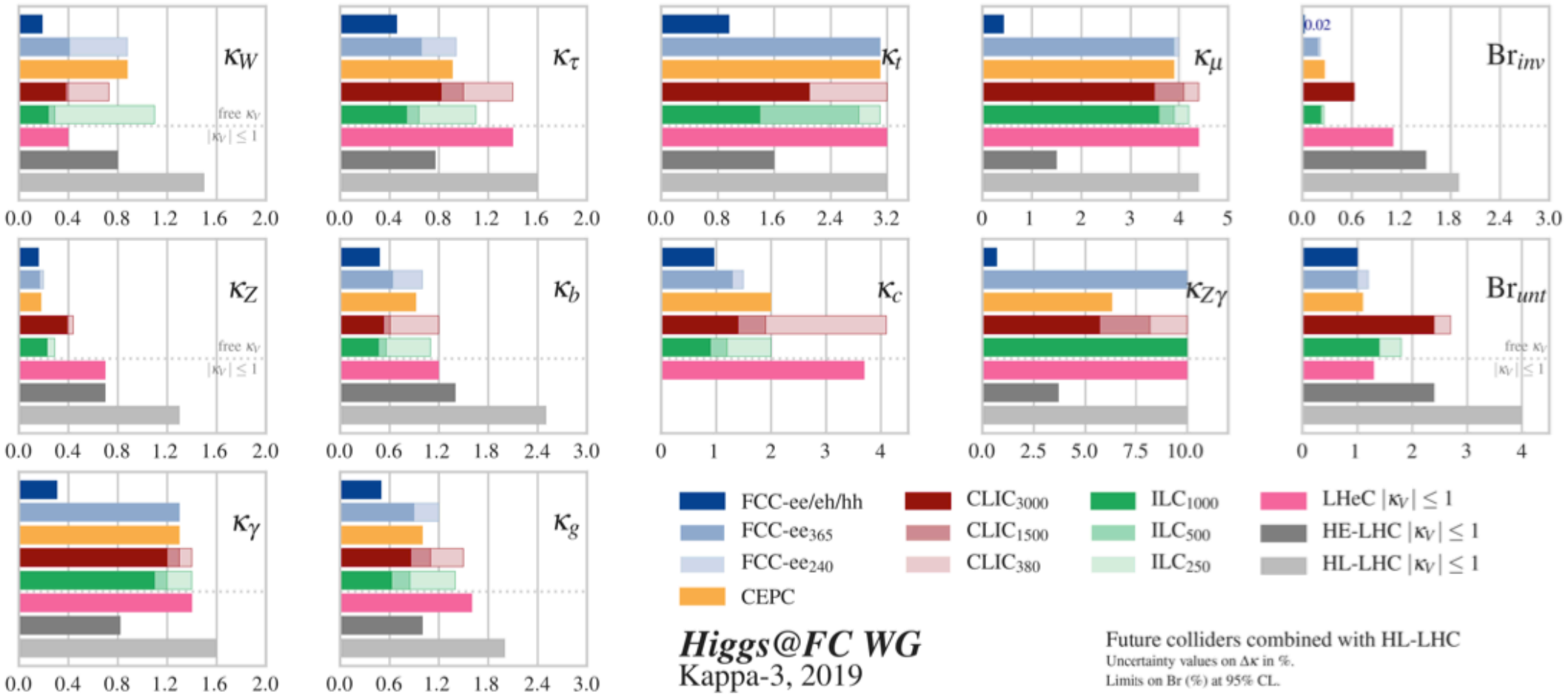
$\sim 5\sigma$ evidence using ATLAS HHH constraint

Search for boosted HH

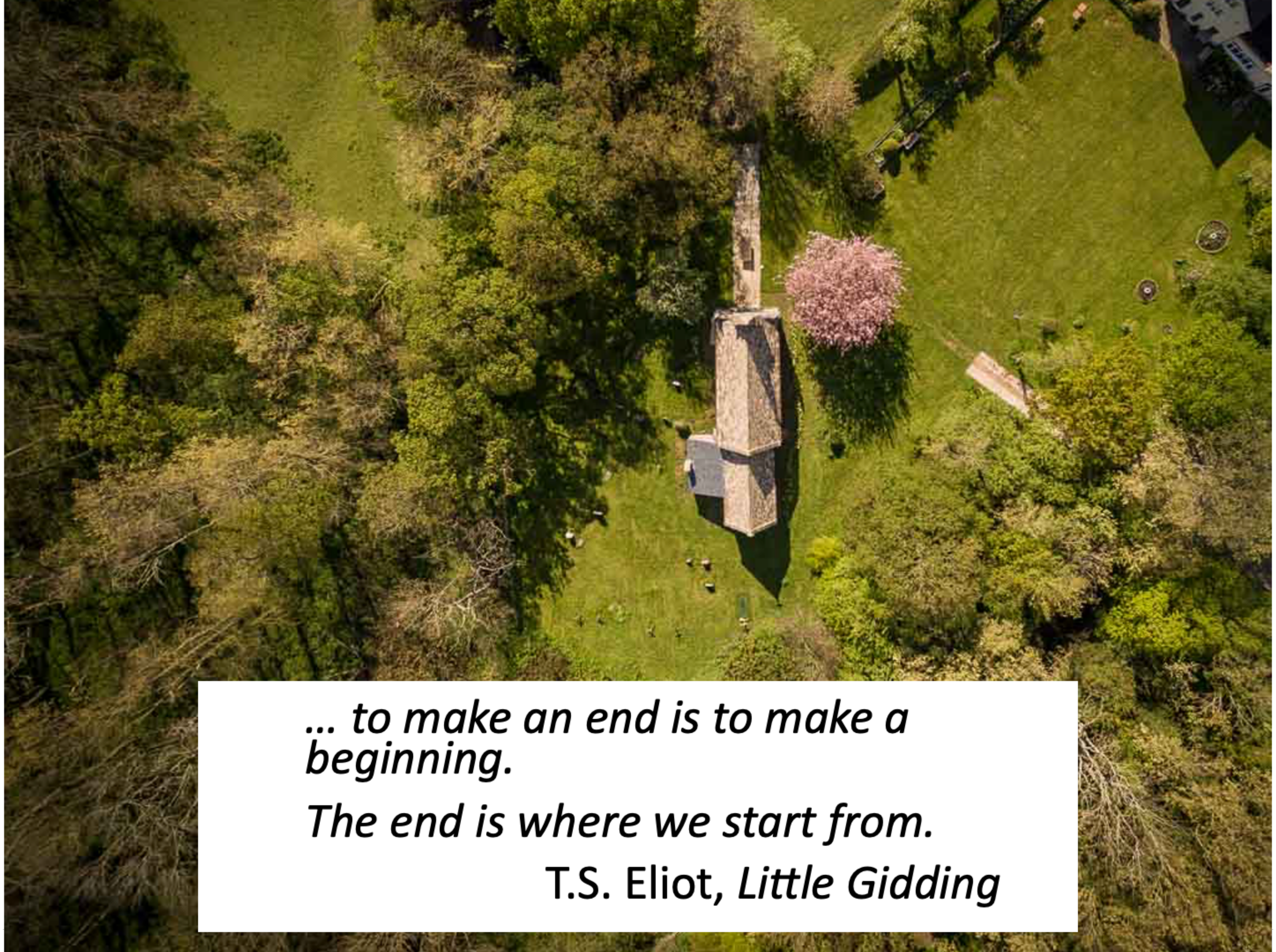
ATLAS arXiv:2404.17193

CMS collaboration arXiv:2205.06667

Future Prospects



R.K. Ellis et al (European Strategy), arXiv:1910.11775



… to make an end is to make a beginning.

The end is where we start from.

T.S. Eliot, *Little Gidding*


ALBERT R. BROCCOLI'S EON PRODUCTIONS
PIERCE BROSNAN
IAN FLEMING'S JAMES BOND 007
The World Is Not Enough
007
12
ALBERT R. BROCCOLI'S EON PRODUCTIONS
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"THE WORLD IS NOT ENOUGH"
SOPHIE MARCEAU
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DENISE RICHARDS
ROBBIE COLTRANE
JUDI DENCH
LINDY HEMMING
DAVID ARNOLD
JIM CLARK
ADRIAN BIDDLE
PETER LAMONT
ANTHONY WAYE
NEAL PURVIS & ROBERT WADE
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BRUCE FEIRSTEIN
MICHAEL G. WILSON
BARBARA BROCCOLI
MICHAEL APTED
NEIL MURRAY
BRUCE FEIRSTEIN


• « Empty » space is unstable
• Dark matter
• Origin of matter
• Sizes of masses
• Masses of neutrinos
• Inflation
• Quantum gravity
• …
LHC
LHC
LHC
LHC
The Standard Model
Is Not Enough
007

Everything about Higgs is Puzzling

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

- 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?

What lies beyond the Standard Model?

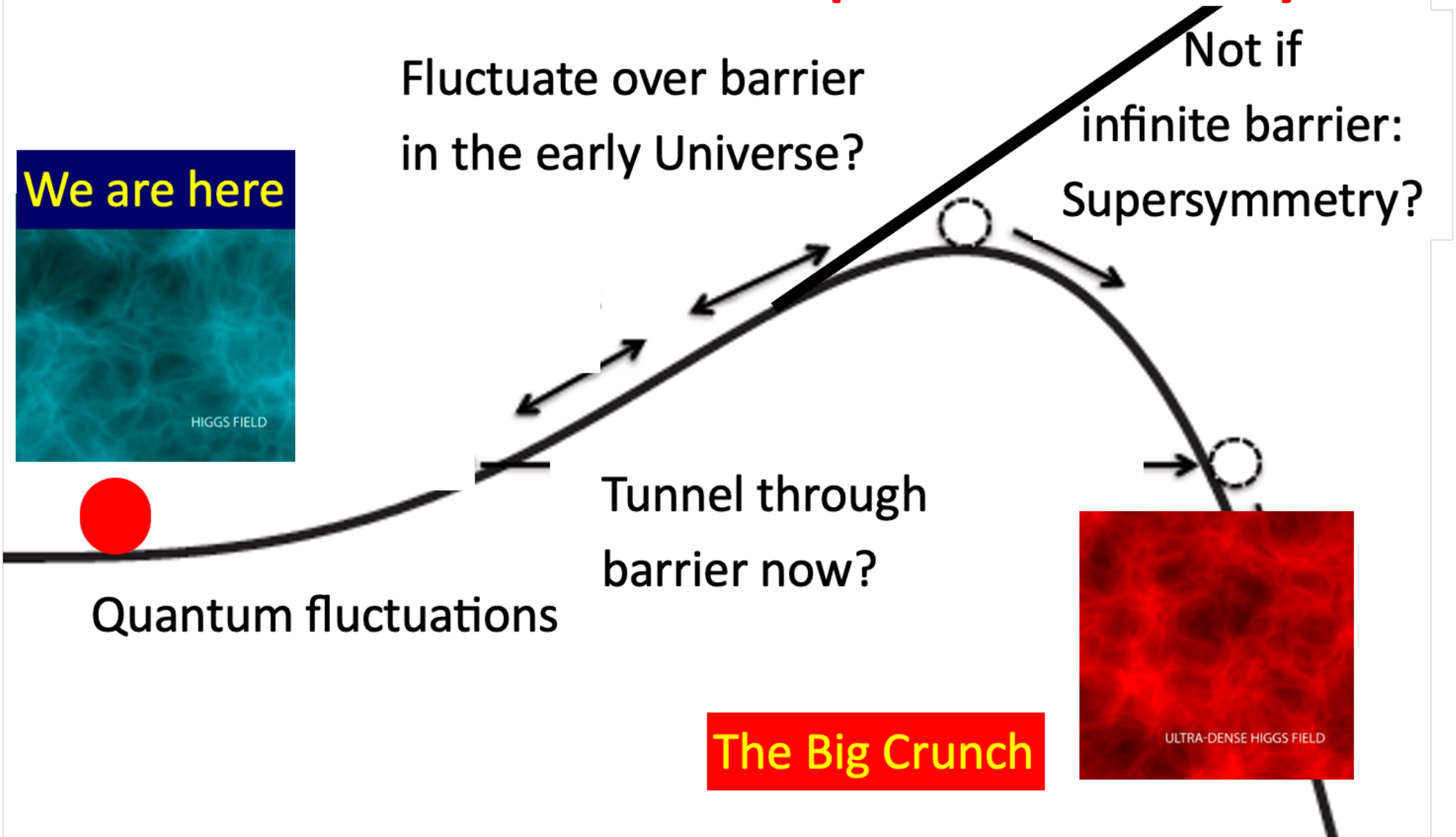
Supersymmetry?

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**, $g_\mu - 2$?... ,

Will the Universe Collapse?

Should it have Collapsed already?



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 LHC value of m_t :

$$m_t = 172.52 \pm 0.33\ \mathrm{GeV}$$

ATLAS & CMS, CERN-LPCC-2023-02

- Latest experimental values:

$$m_H = 125.1 \pm 0.1\ \mathrm{GeV},\ \alpha_s(m_Z) = 0.1183 \pm 0.0009$$

ATLAS & CMS

ATLAS, arXiv:2309.12986

- Instability scale:

$$\log_{10}\frac{\Lambda}{\mathrm{GeV}} = 10.9 \pm 0.8$$

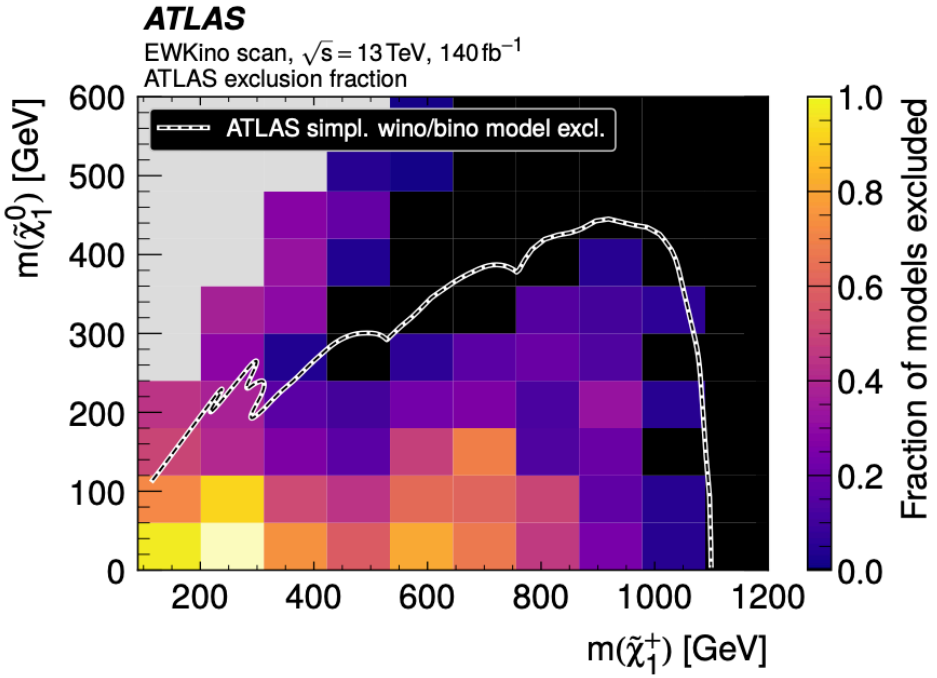
- Dominant uncertainties those in α_s and m_t

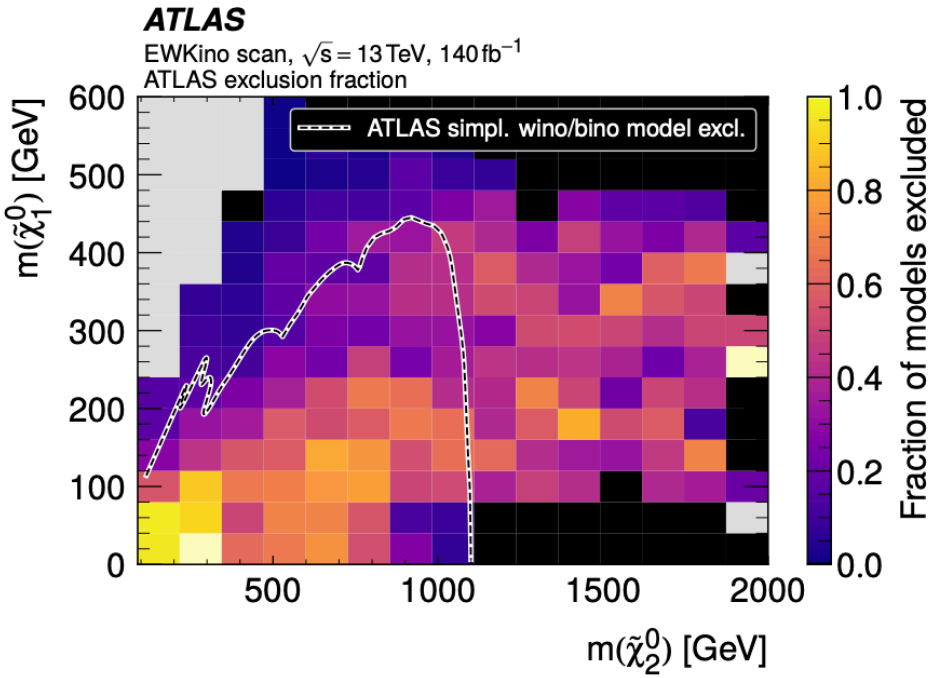
Survey of SUSY searches in pMSSM

Lines = Exclusions in searches with simplifying assumptions on spectrum and decay modes

Black = < 10% of pMSSM models excluded

Cream = > 90% of pMSSM models excluded



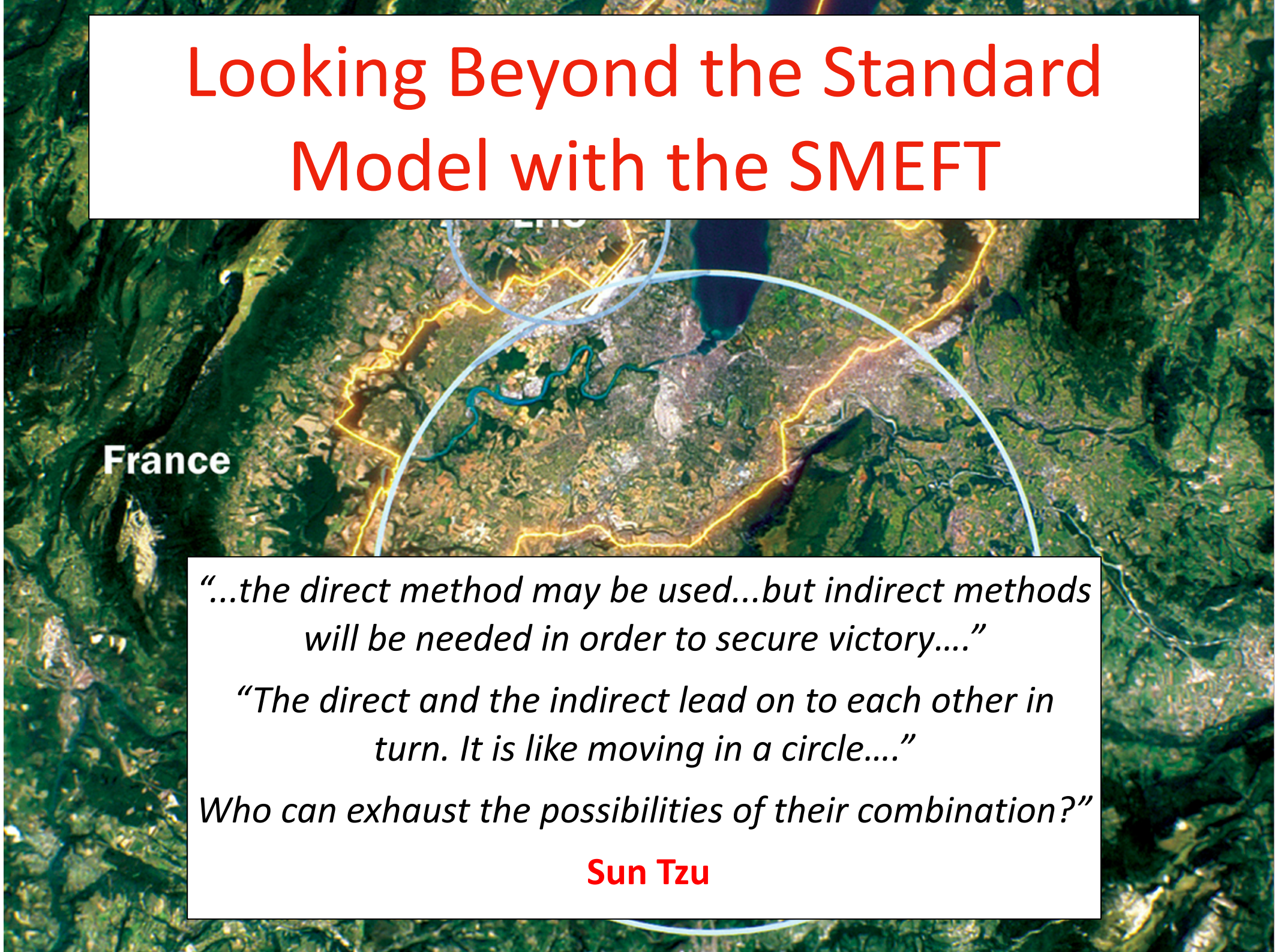


Many low-mass pMSSM models consistent with constraints

Hope springs eternal!

ATLAS Collaboration, arXiv:2402.01392

Looking Beyond the Standard Model with the SMEFT



"...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...."

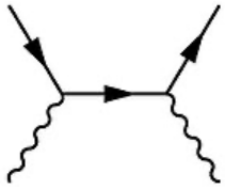
Who can exhaust the possibilities of their combination?"

Sun Tzu

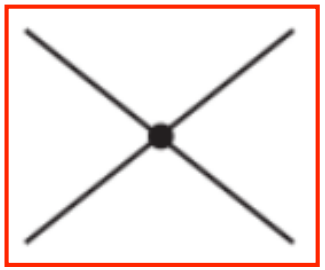
Effective Field Theories (EFTs)

a long and glorious History

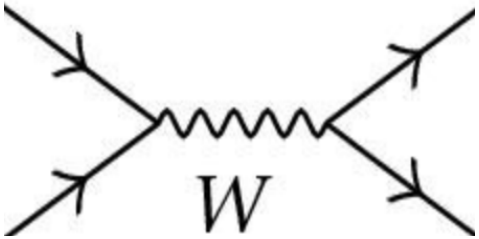
- 1930's: "Standard Model" of QED had d=4



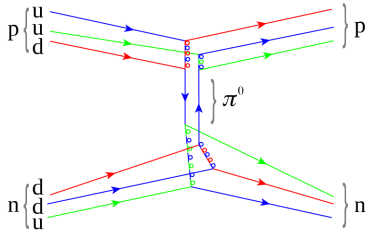
- **Fermi's four-fermion theory of the weak force**



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



- V-A ➔ massive vector bosons ➔ gauge theory
- 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

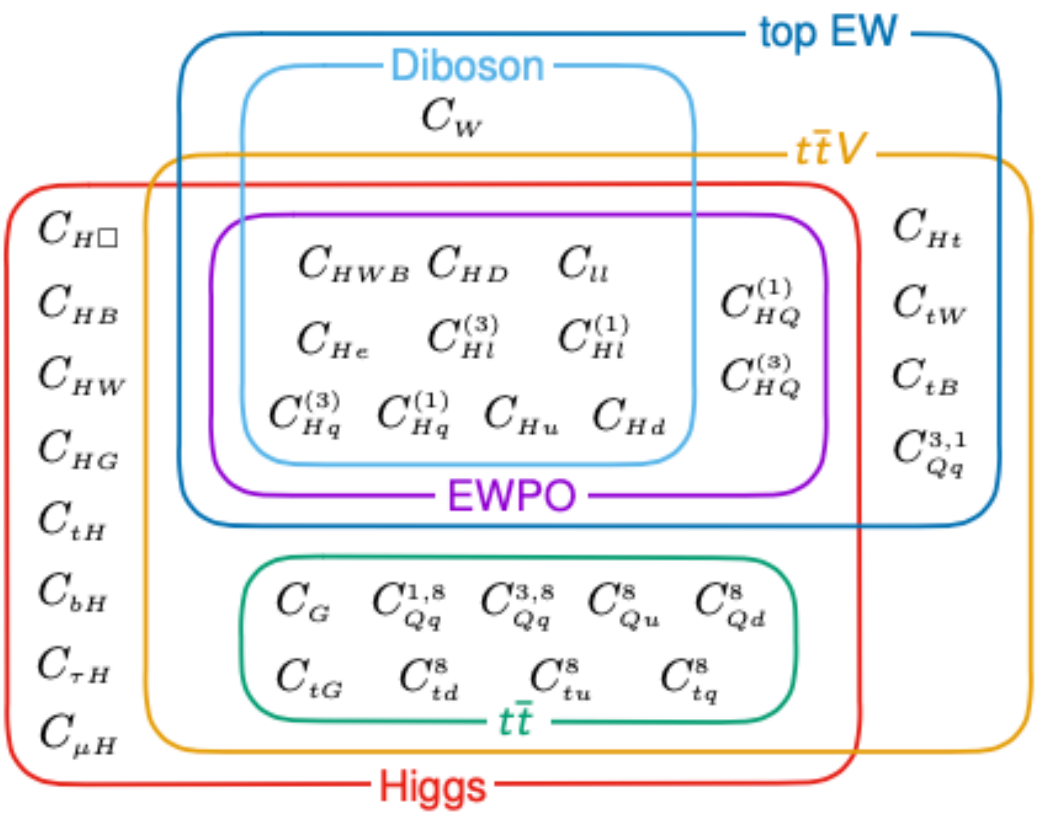
Global SMEFT Fit

to Top, Higgs, Diboson, Electroweak Data

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

- 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

341 measurements included in global analysis

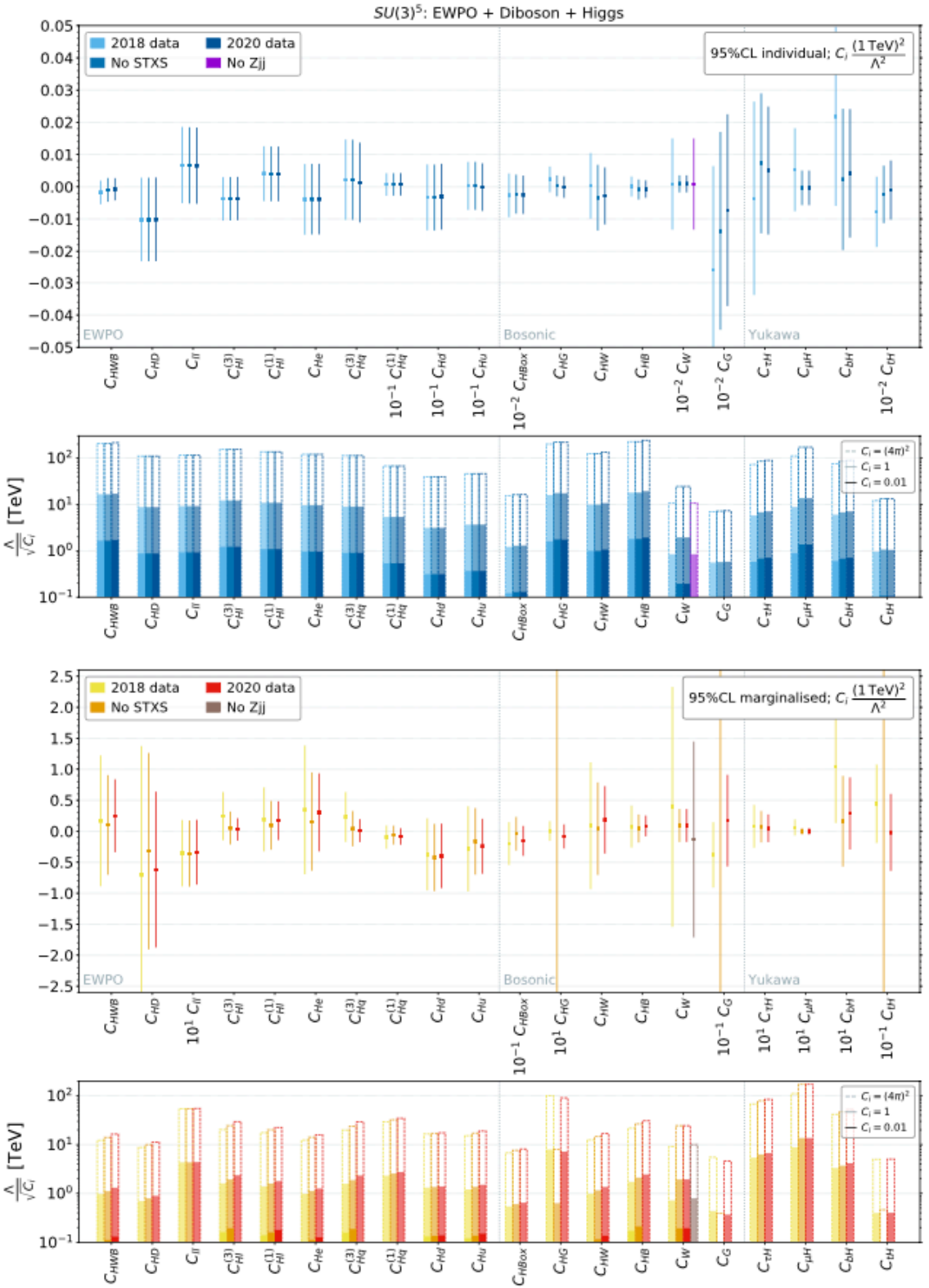


Dimension-6 Constraints with Flavour-Universal $SU(3)^5$ Symmetry

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

No significant deviations from SM

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



Single-Field Extensions of the Standard Model

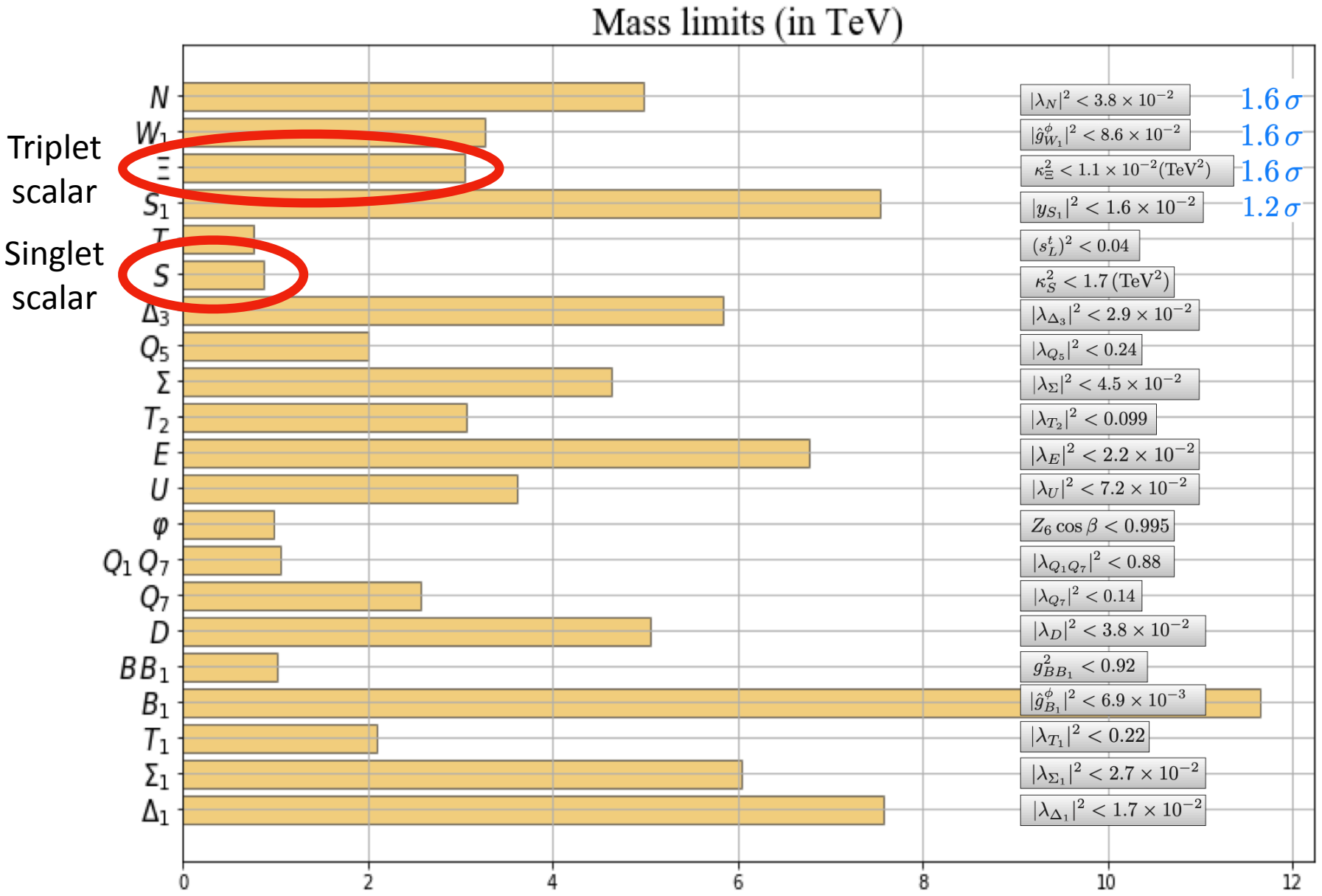
Name	Spin	SU(3)	SU(2)	U(1)	Name	Spin	SU(3)	SU(2)	U(1)
S	0	1	1	0	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
S_1	0	1	1	1	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
φ	0	1	2	$\frac{1}{2}$	Σ	$\frac{1}{2}$	1	3	0
Ξ	0	1	3	0	Σ_1	$\frac{1}{2}$	1	3	-1
Ξ_1	0	1	3	1	U	$\frac{1}{2}$	3	1	$\frac{2}{3}$
B	1	1	1	0	D	$\frac{1}{2}$	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 Extensions of the Standard Model

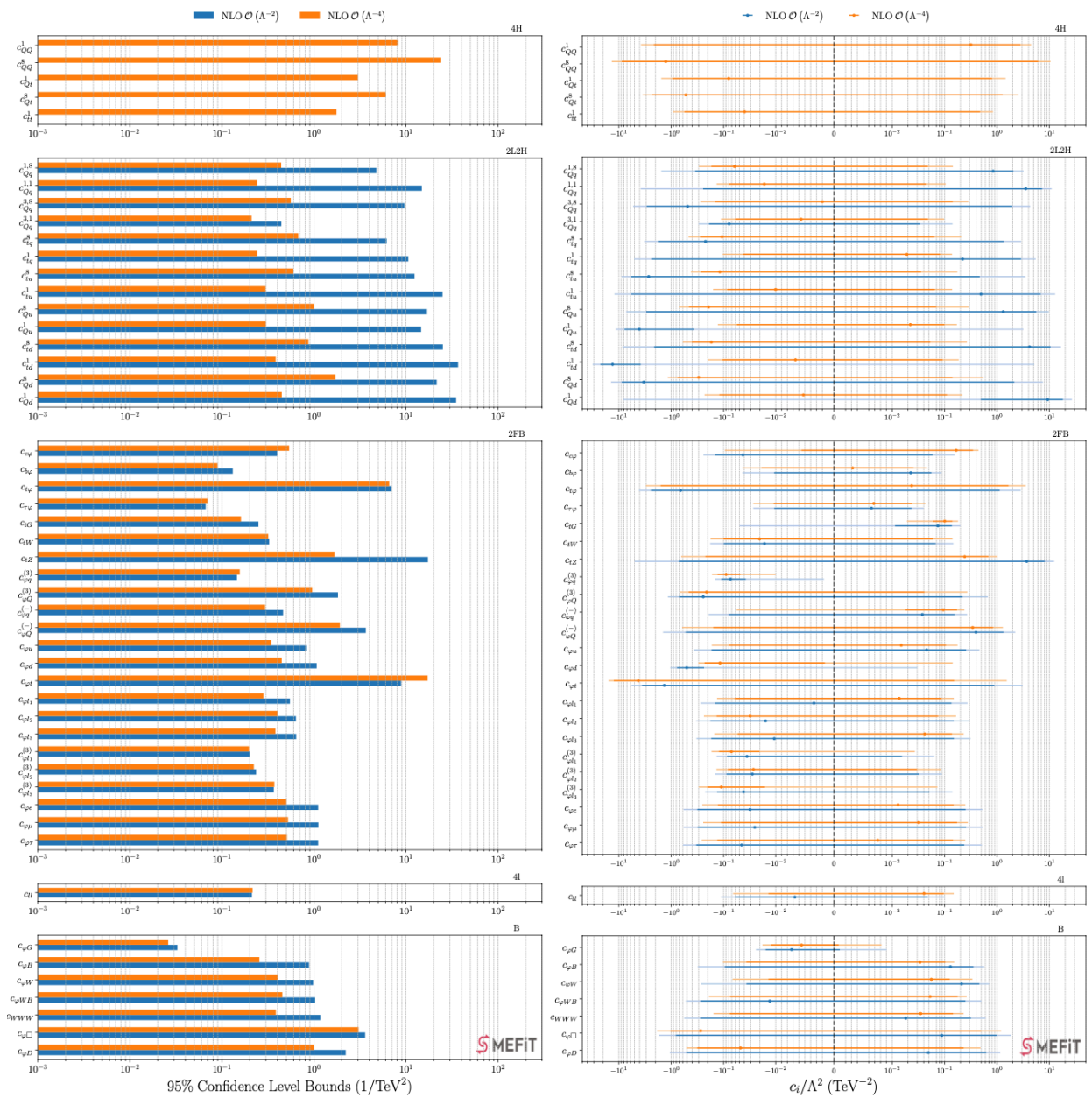


JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Quo Vadis SMEFT?

- Powerful framework for global analyses of LHC and other data
- Systematic way to search for BSM physics
- Can be used in principle to identify “interesting” BSM scenarios
- Dimension-6 operators are a first approximation
- Important to check lesser importance of dimension-8, convergence towards ultraviolet-complete model
- Interesting direct windows on dimension-8 operators

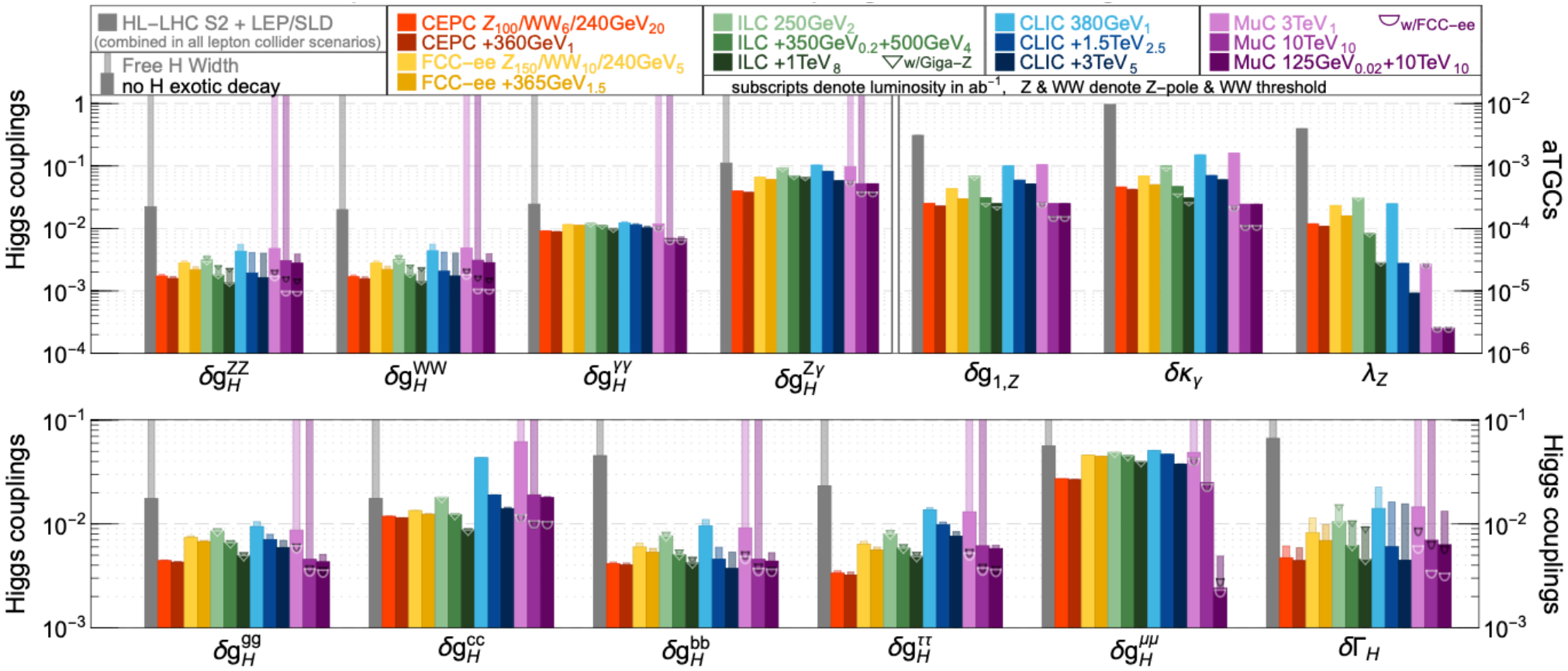
SMEFiT Analysis



- Includes linear dimension-8 as well as quadratic dimension-6
- No significant evidence for non-zero operator coefficients
- Experiments, please enter the game!

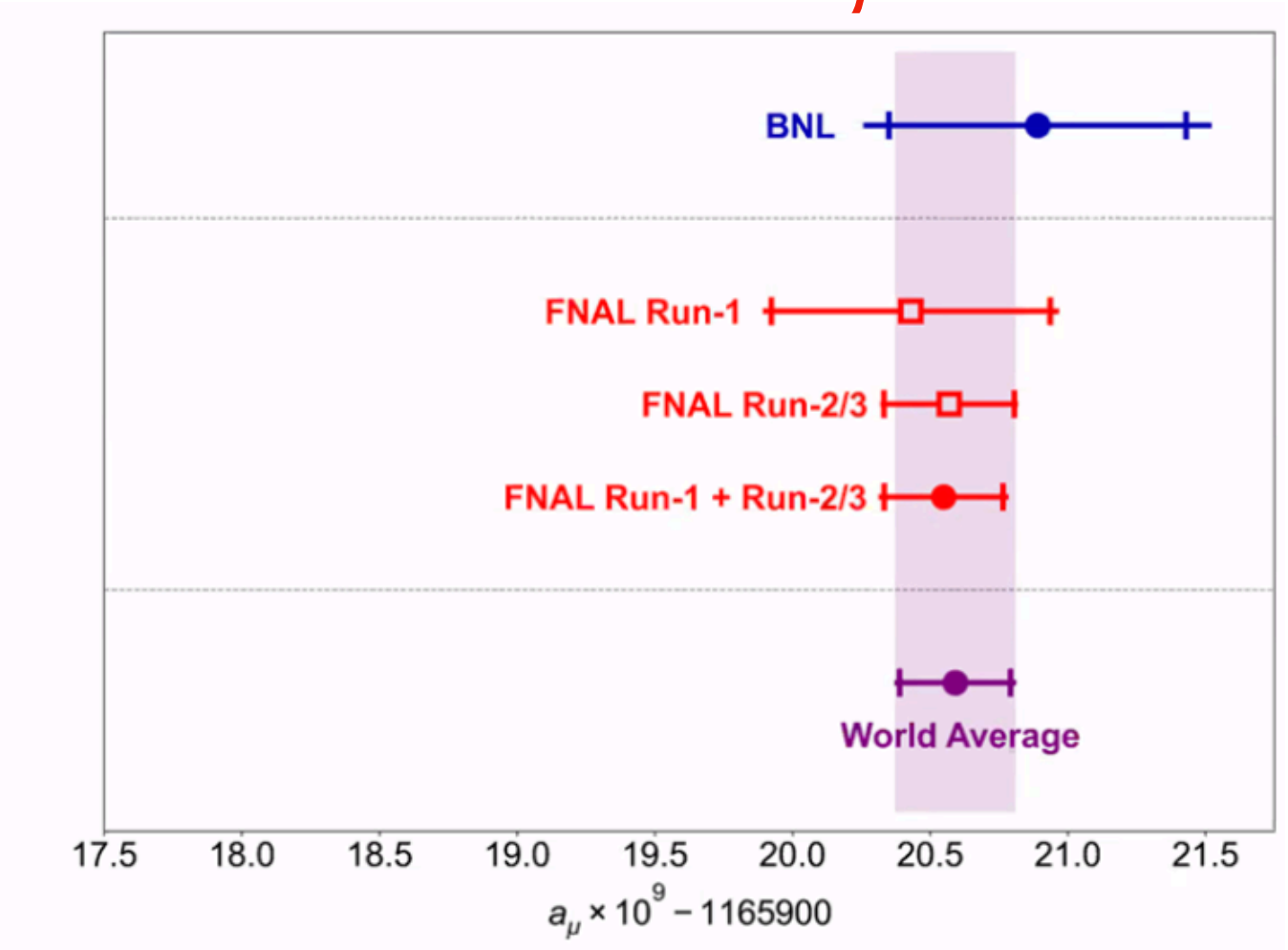
Celada et al, arXiv:2004.12809

Future SMEFT Prospects



de Blas et al (Snowmass), arXiv:2206:08326

Quo Vadis $g_\mu - 2$?



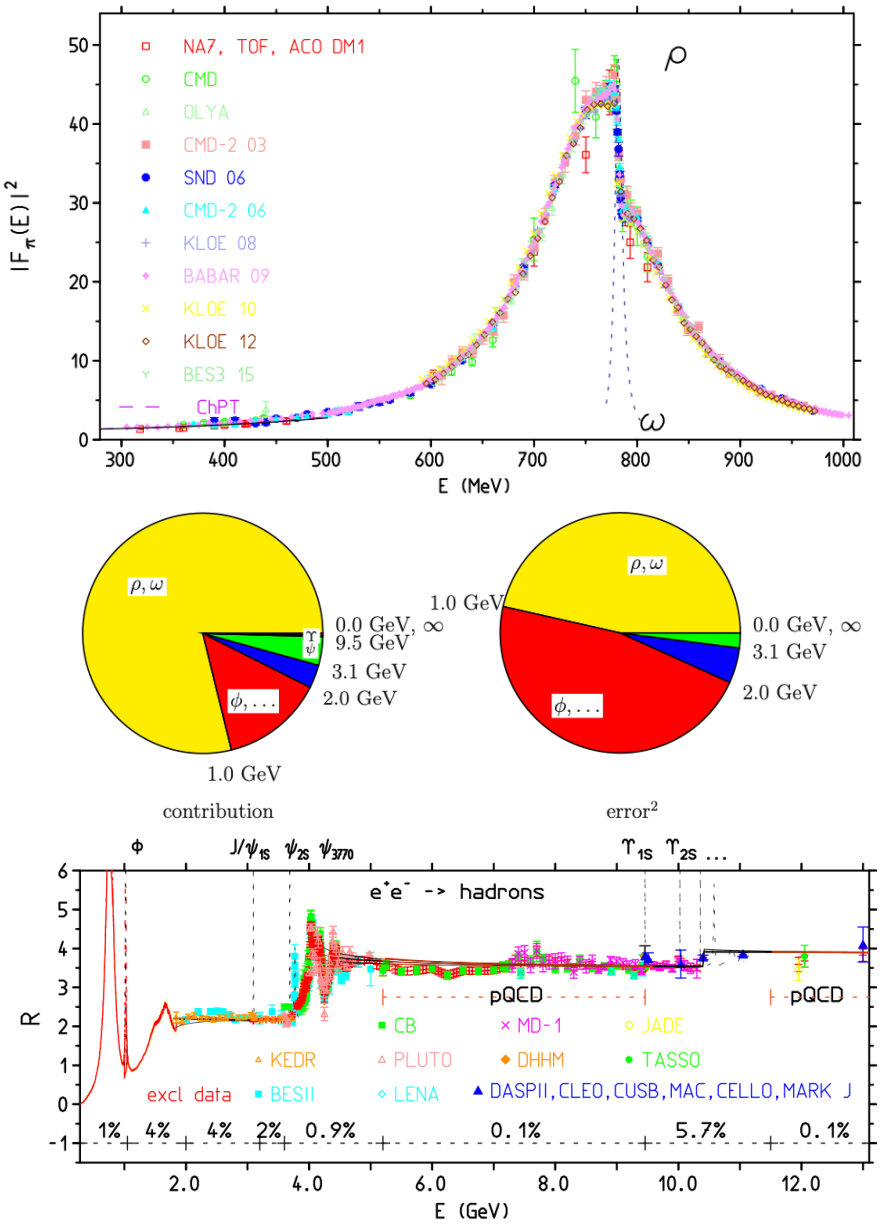
- New Fermilab result confirms previous measurements, uncertainty reduced by factor ~ 2

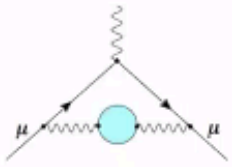
Hadronic Vacuum Polarization

- Most important contribution is from low energies $\lesssim 1$ GeV, dominated by ρ and ω peaks, taking account of interference effects
- Uncertainties dominated by ρ and ω region, and by region between 1 and 2 GeV (ϕ, etc.)
- High energies under good control from perturbative QCD

$$a_\mu^{\mathrm{HVP,\,LO}} = 693.1(2.8)_{\mathrm{exp}}(2.8)_{\mathrm{sys}}(0.7)_{\mathrm{DV+QCD}} \times 10^{-10}$$
$$= 693.1(4.0) \times 10^{-10}\,.$$

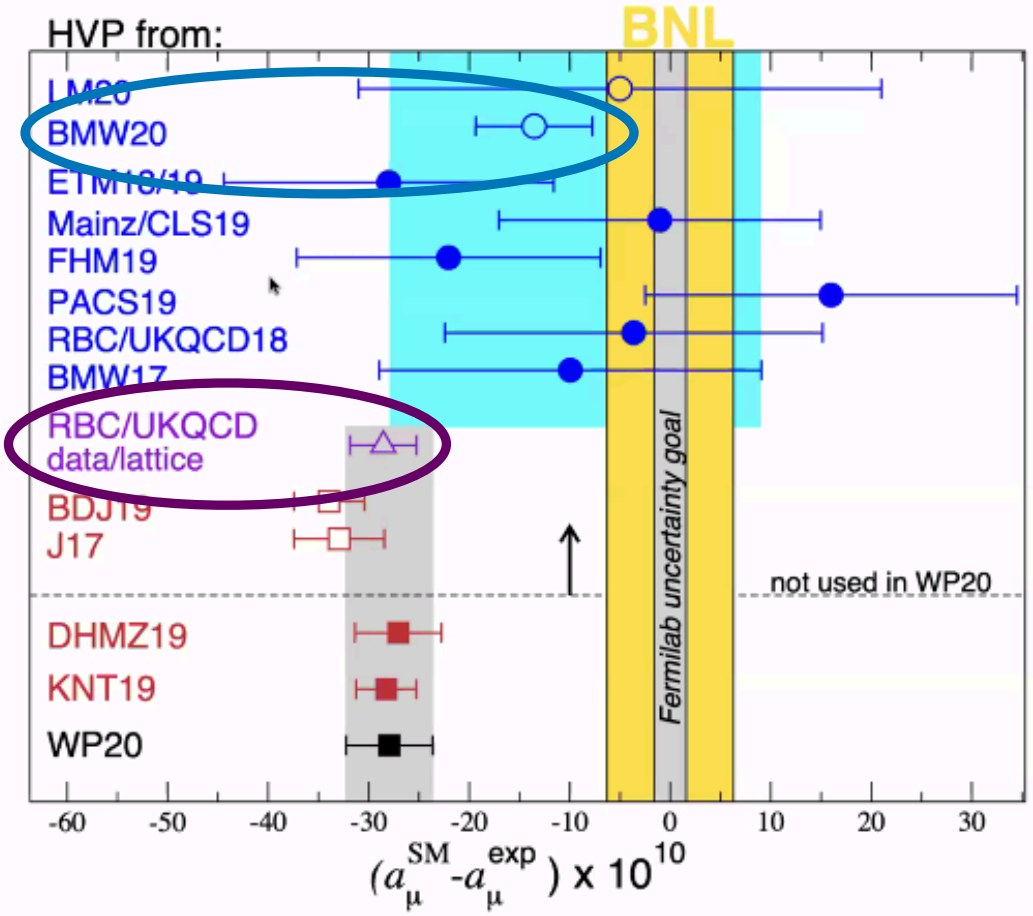
Aoyama et al, arXiv:2006.04822





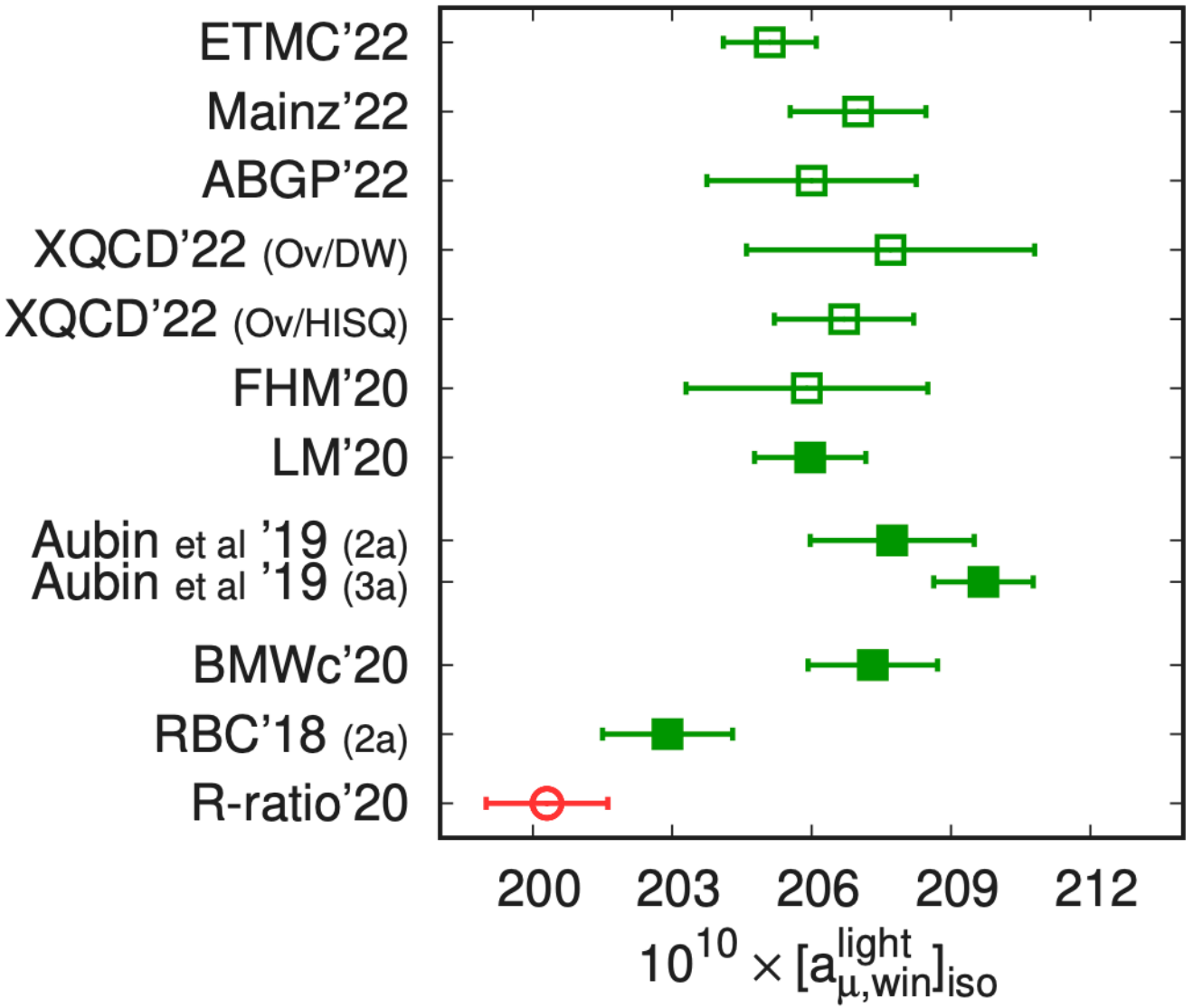
Lattice Calculations of Hadronic Vacuum Polarization

$$a_\mu^{\rm HVP} + \left[a_\mu^{\rm QED} + a_\mu^{\rm Weak} + a_\mu^{\rm HLbL}\right] \Rightarrow a_\mu^{\rm SM}$$



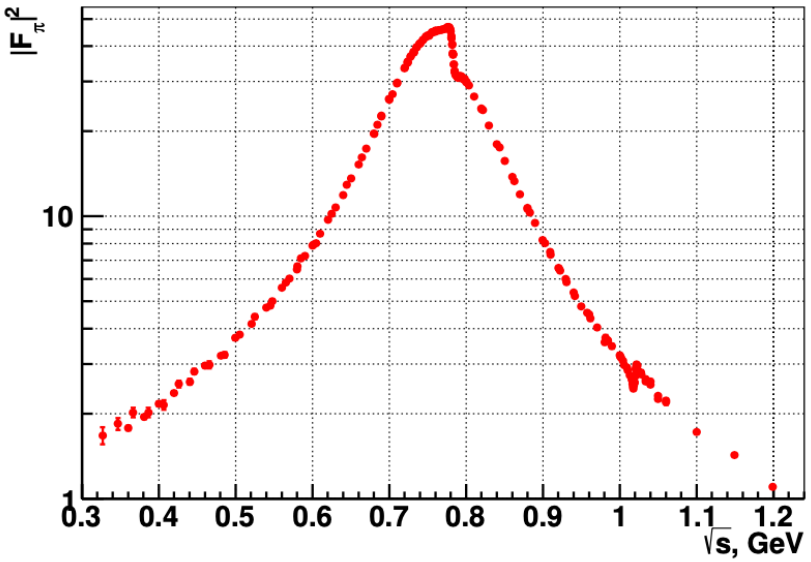
Aoyama et al, arXiv:2006.04822

Recent Lattice Calculations



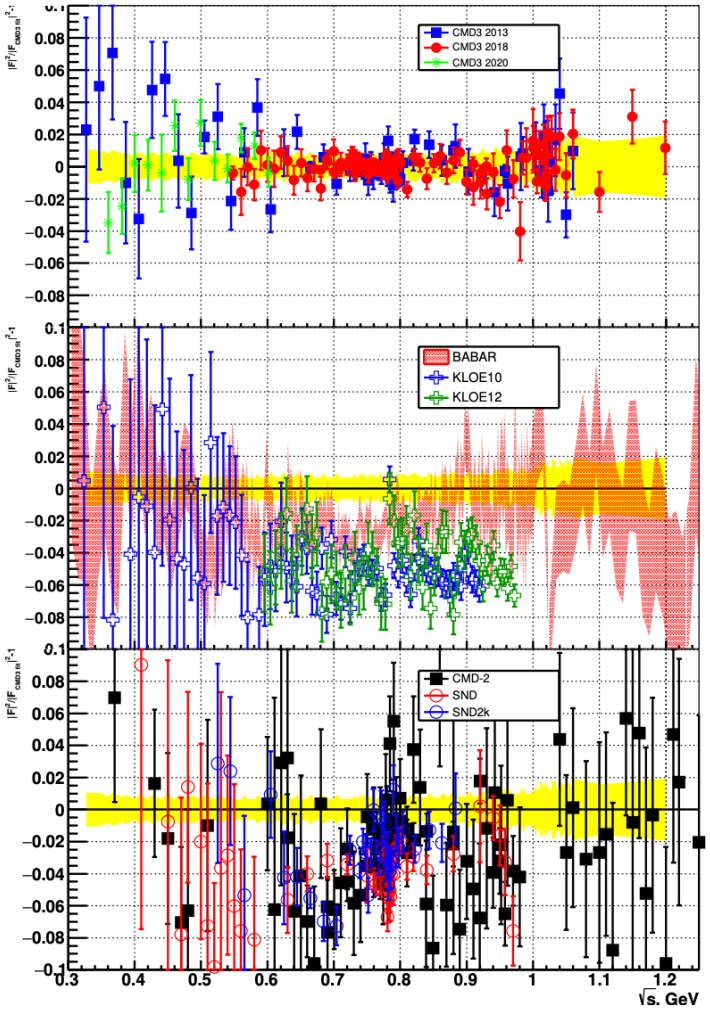
Updated CMD-3 Measurement of HVP

$e^+e^- \to \pi^+\pi^-$ form factor



CMD-3 Collaboration, arXiv:2309.12910

Comparison with previous results

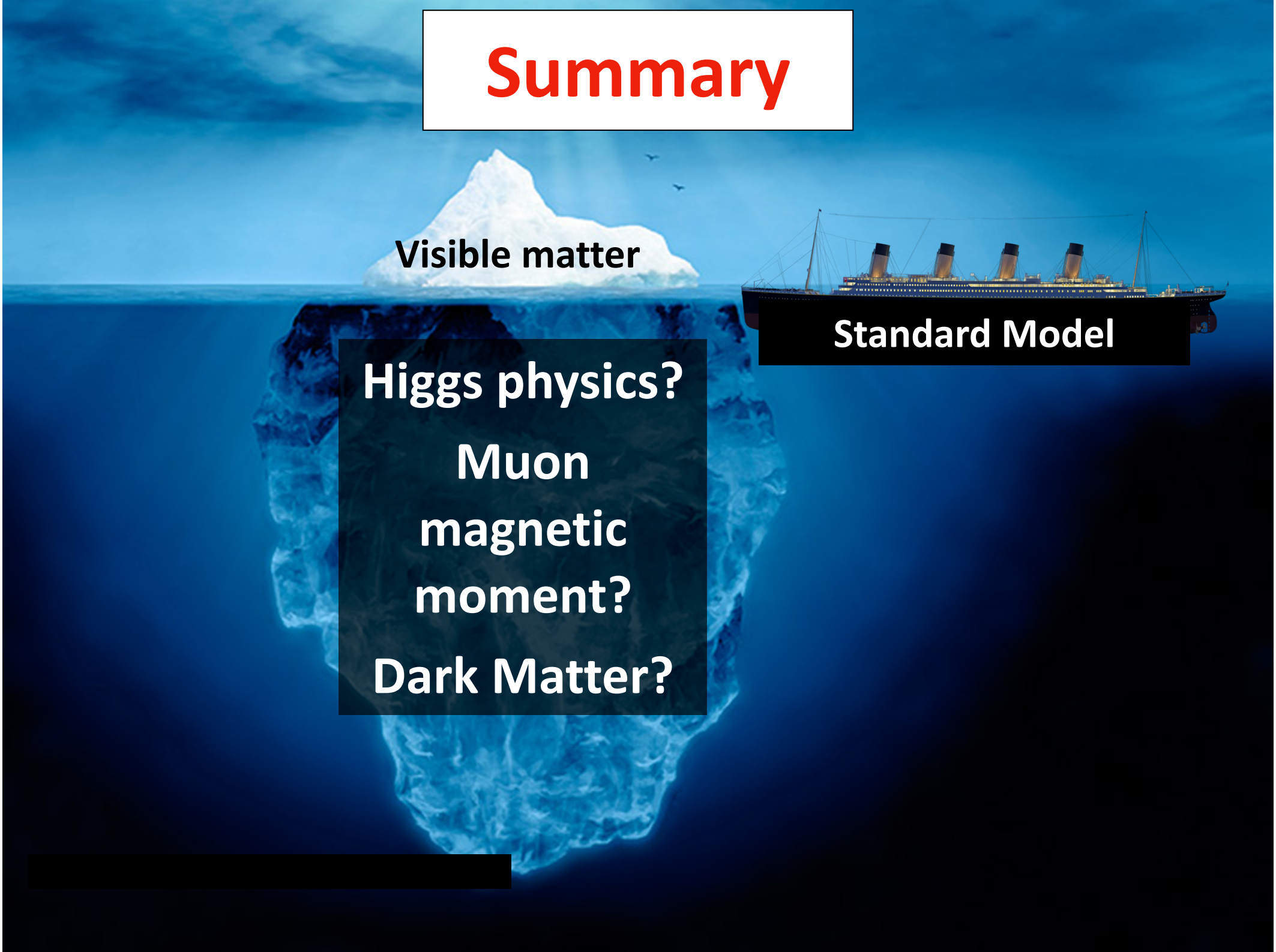


$(g_\mu - 2)$ – HVP discrepancy

$\Delta a_\mu = (49 \pm 55) \times 10^{-11}$

Consistent with no BSM signal

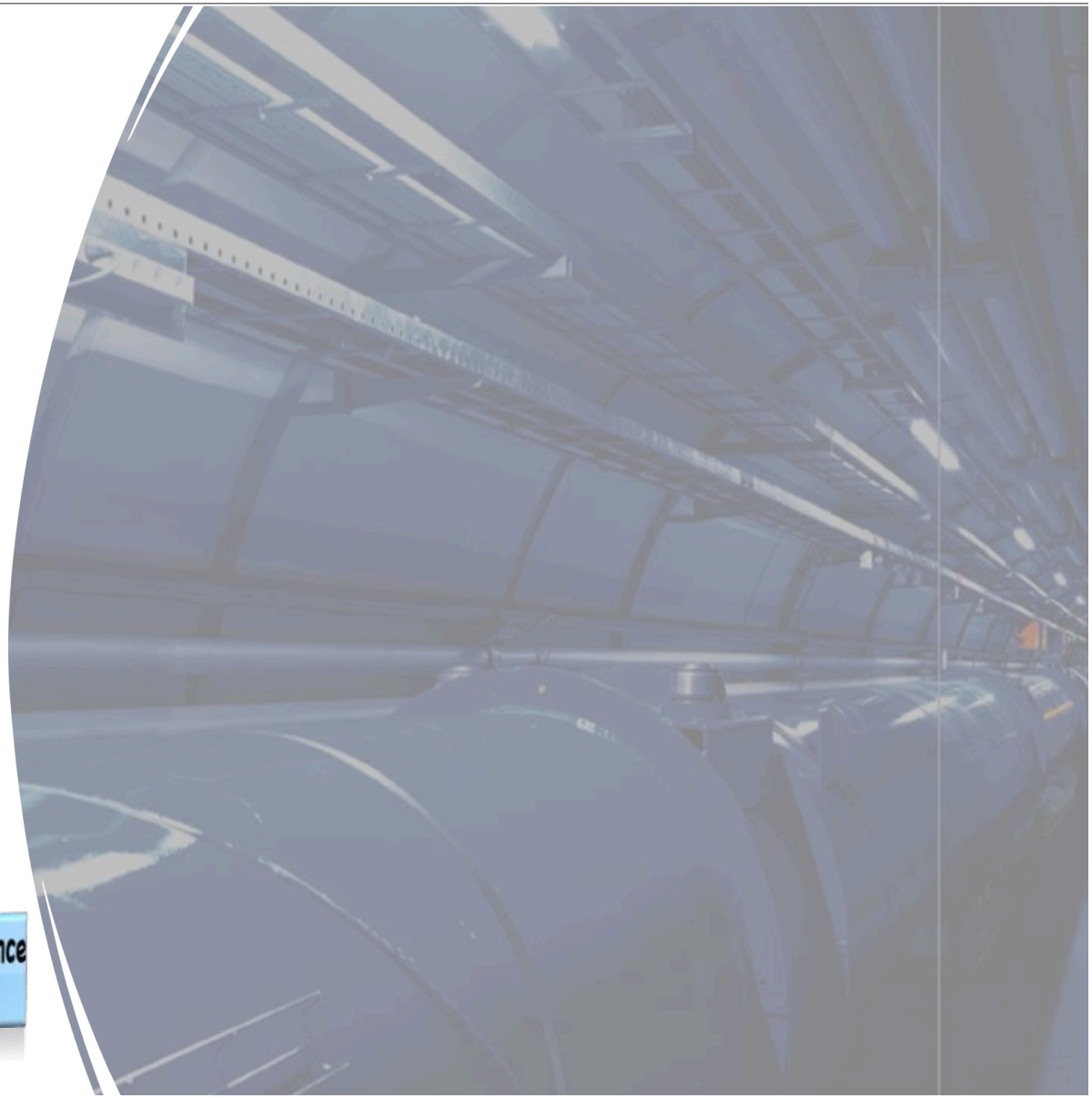
Summary


Visible matter
Standard Model
Higgs physics?
Muon magnetic moment?
Dark Matter?

Ireland in CERN (finally!)

Sinéad M. Ryan
Trinity College Dublin
&
Co-chair CERN-Ireland Users Group

Cosmology, Astrophysics, Theory and Collider Higgs 2024 conference (CATCH22+2)



"Should the CERN Member States determine the FCC-ee is likely to be CERN's next world-leading research facility following the high-luminosity Large Hadron Collider, the United States intends to collaborate on its construction and physics exploitation, subject to appropriate domestic approvals."