The Higgs Boson & Beyond

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

YEARS /ANS CERN
1954-2024

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

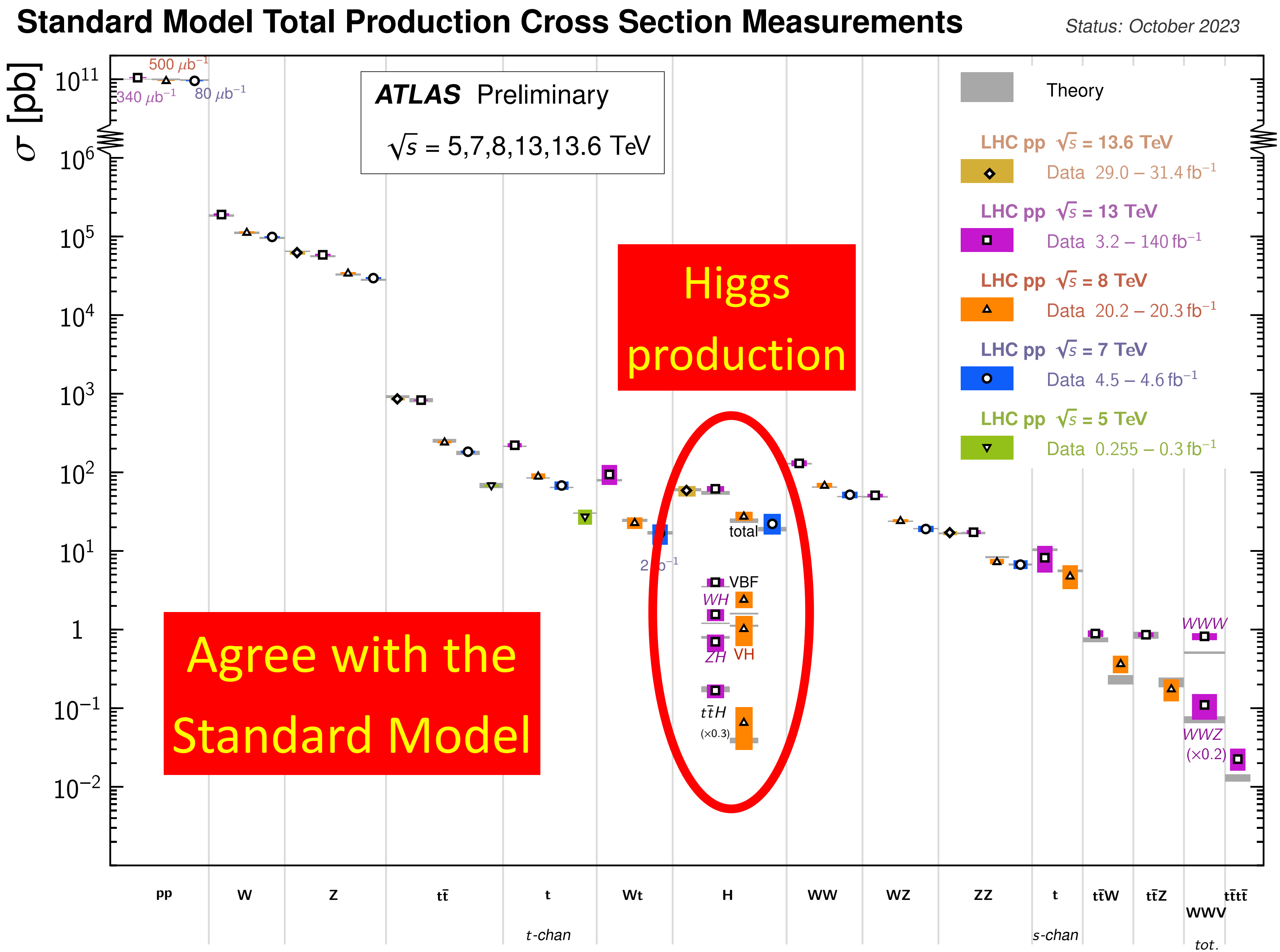
- Lagrangian:

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

Tested < 0.1% before LHC

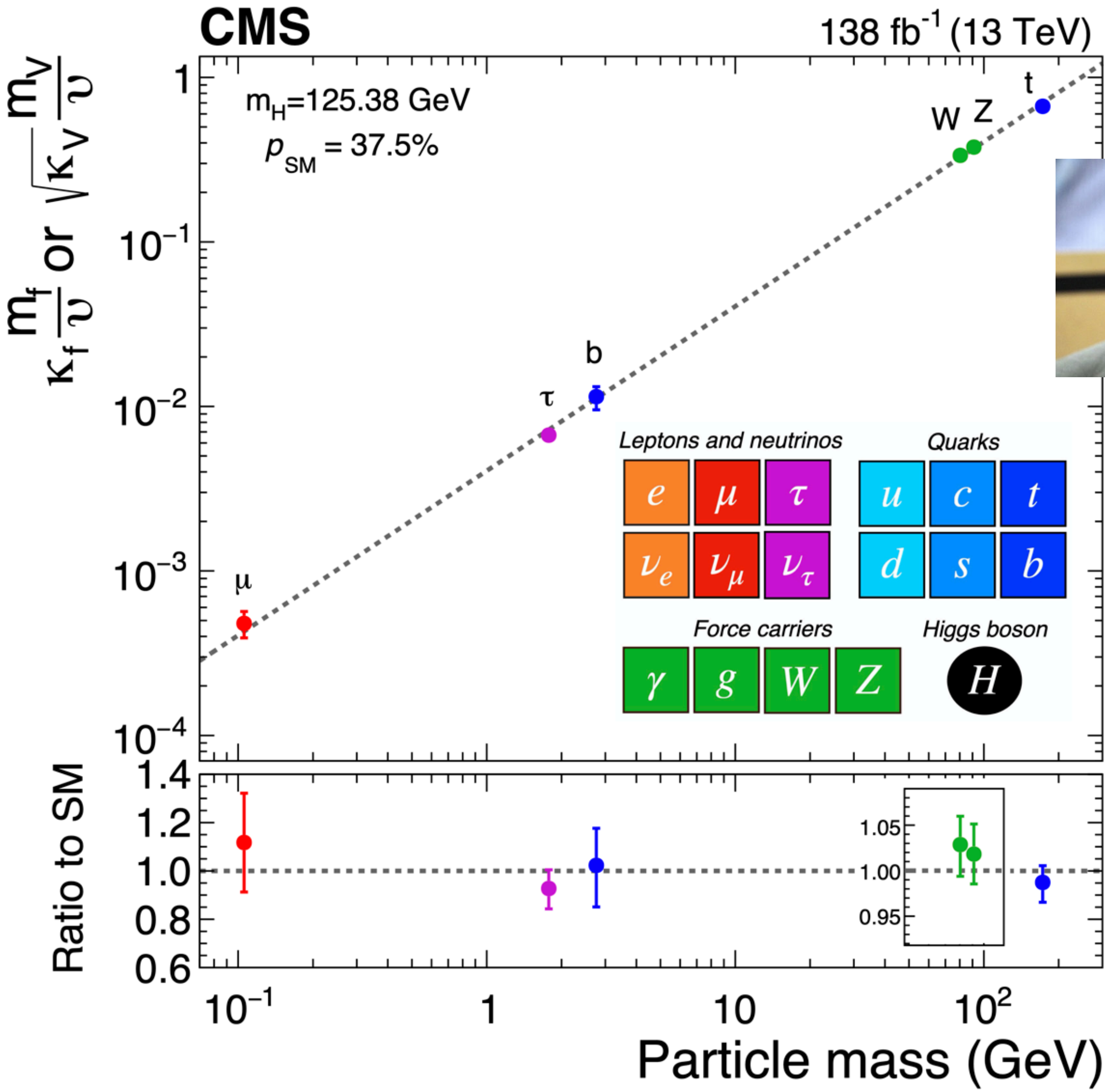
Testing now in progress

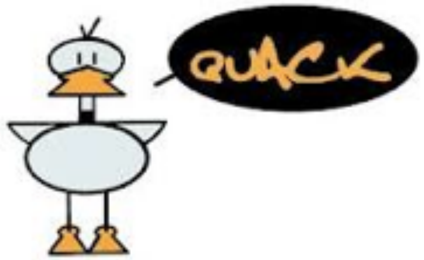
LHC Measurements



It Walks and Quacks like a Higgs

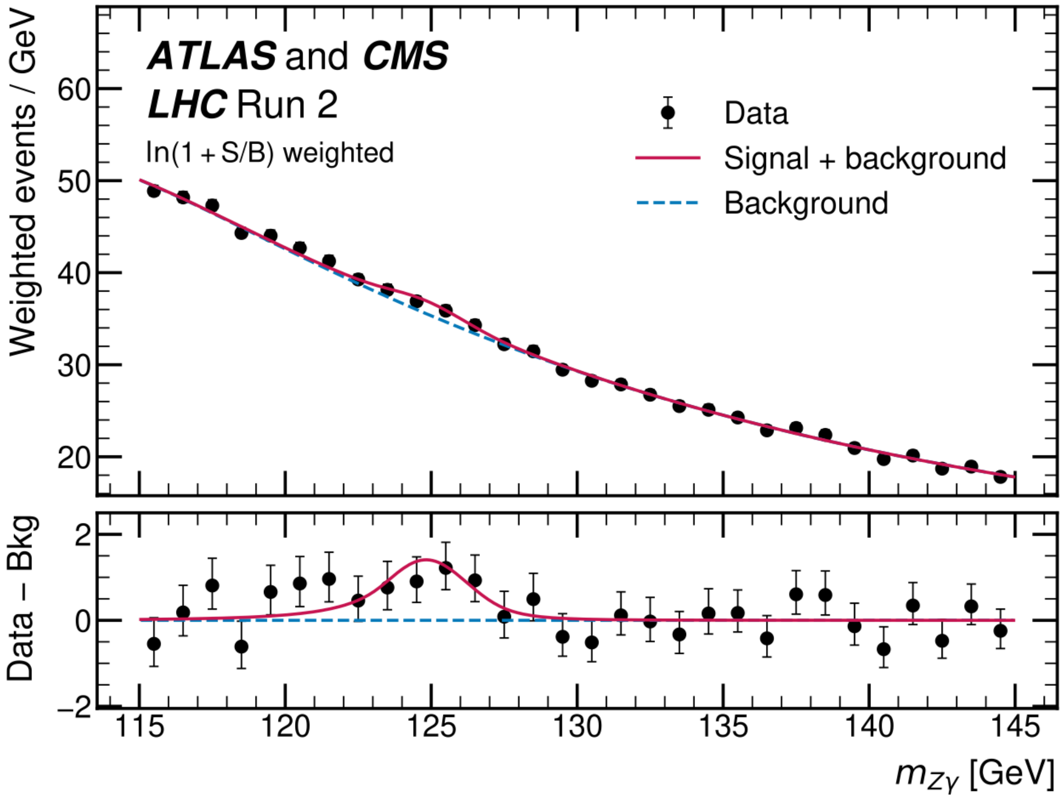
- Couplings scale ~ mass, with scale ~ v

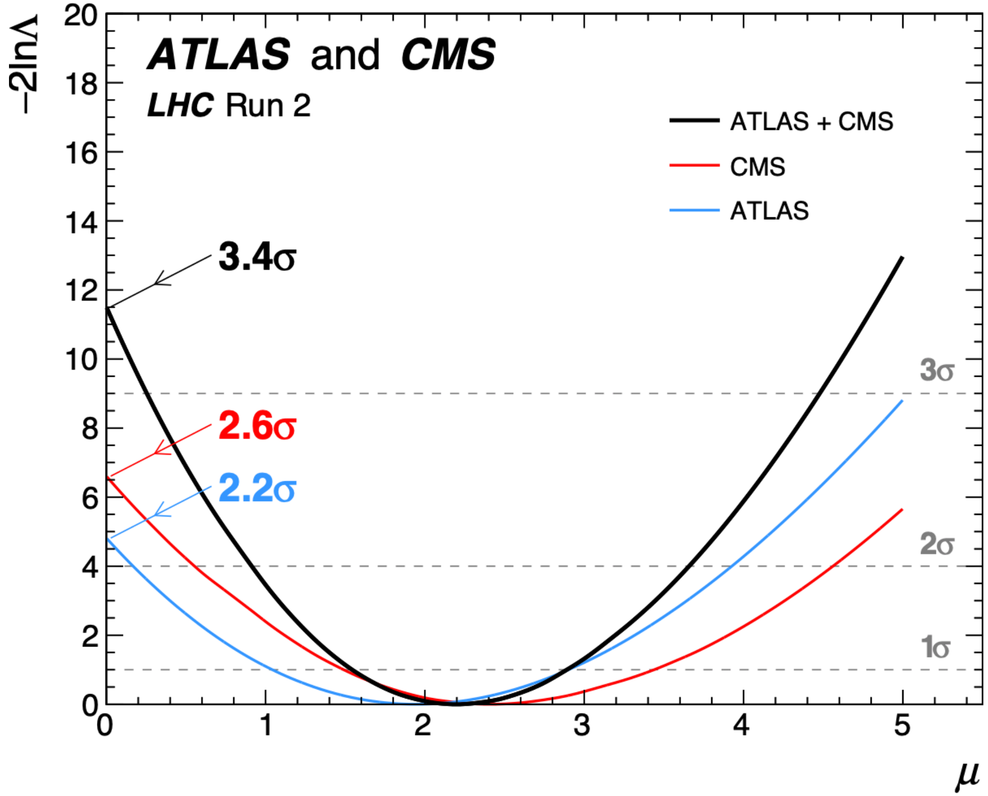




ATLAS & CMS, arXiv:2309.03501

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

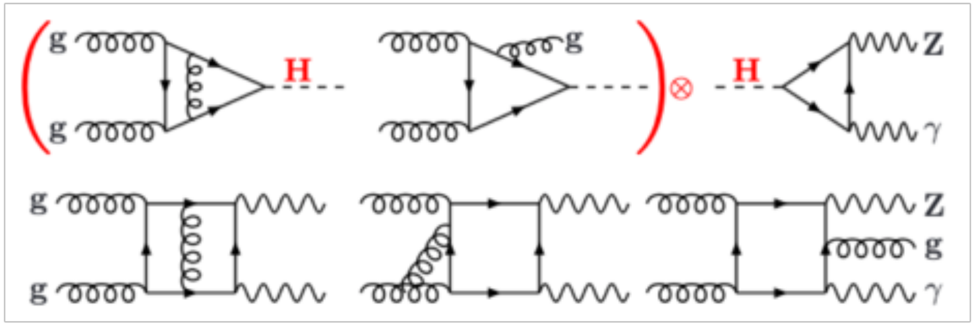
Chen, Chen, Qiao & Zhu, arXiv:2404.114441

Statistics? BSM physics?

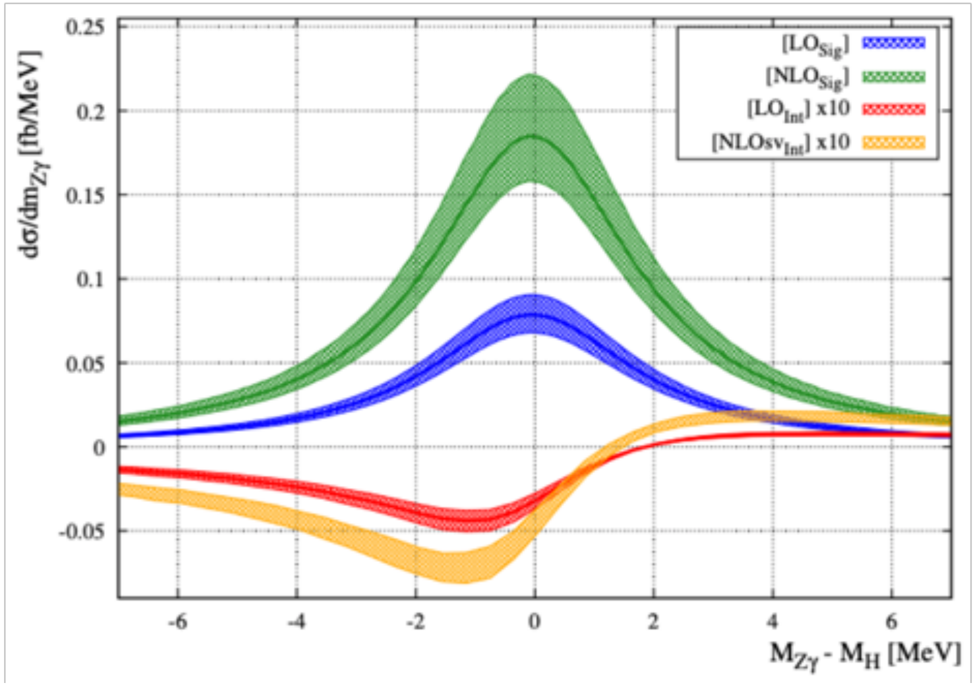
Buccioni, Devoto, Djouadi, JE, Quevillon, Tancredi, arXiv:2312.12384

QCD Corrections to $H \to Z\gamma$

NLO QCD diagrams for signal and background



NLO QCD increases cross-section by factor ~ 2

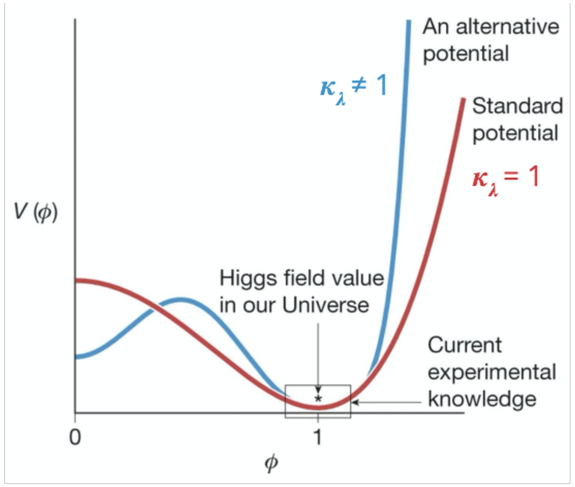


Negative interference – but blown up by factor 10 in plot

Reduces cross-section by 3%: $\sigma^{\mathrm{NLO}}_{\mathrm{Sig}} = 1.207^{+20\%}_{-15\%}$ fb, $\sigma^{\mathrm{NLOsv}}_{\mathrm{Int}} = -0.0344^{+12\%}_{-12\%}$ fb

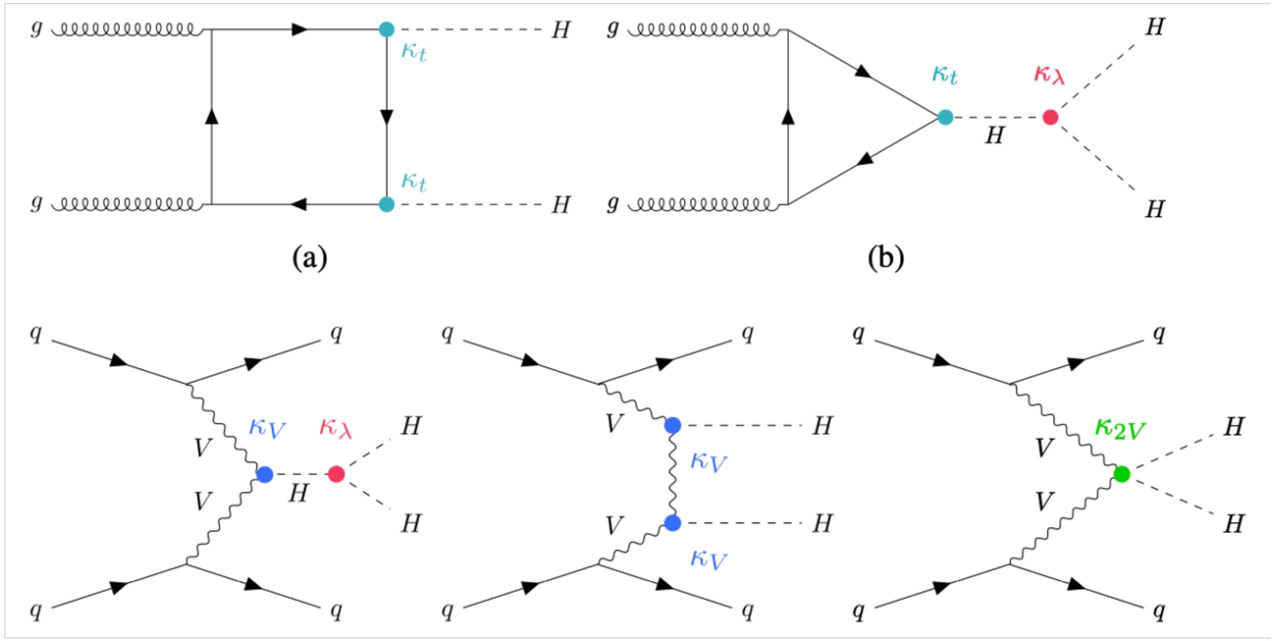
Higher-Order Higgs Couplings

- Standard Model Lagrangian contains $HHH, VVHH$ couplings in Higgs potential $V(H)$, Higgs kinetic term $|D_\mu H|2$, respectively
- Directly related to (m_H, m_W) and VVH, respectively
- Absence/modification would destroy consistency (renormalizability) of Standard Model
- Could be modified by, e.g., higher-order terms in effective field theory, e.g., H^6 or $|H|^2|D_\mu H|^2$
- Parameterized by $\kappa_\lambda, \kappa_{2V}$, respectively
- **Measuring them is next frontier in Higgs measurements**

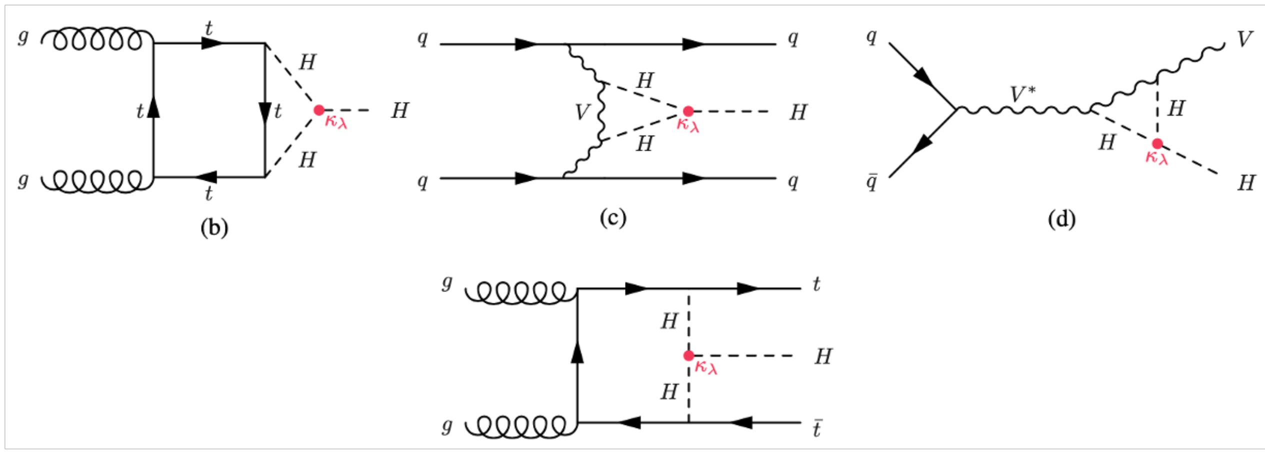


Search for Triple-H Coupling

Diagrams for double-Higgs production



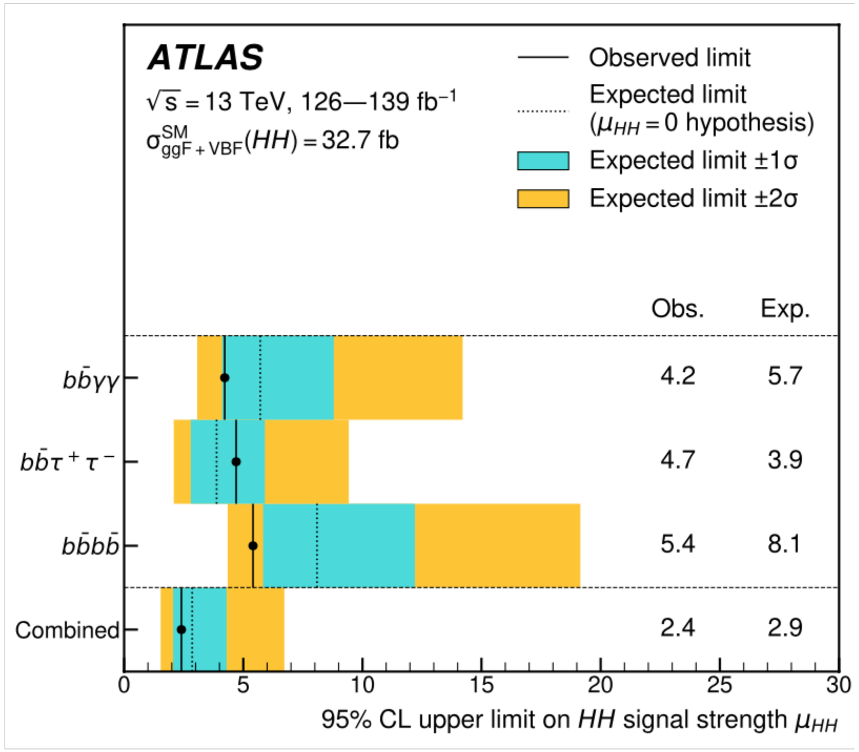
Loop corrections to single Higgs production



ATLAS Collaboration, arXiv: 2211.01216

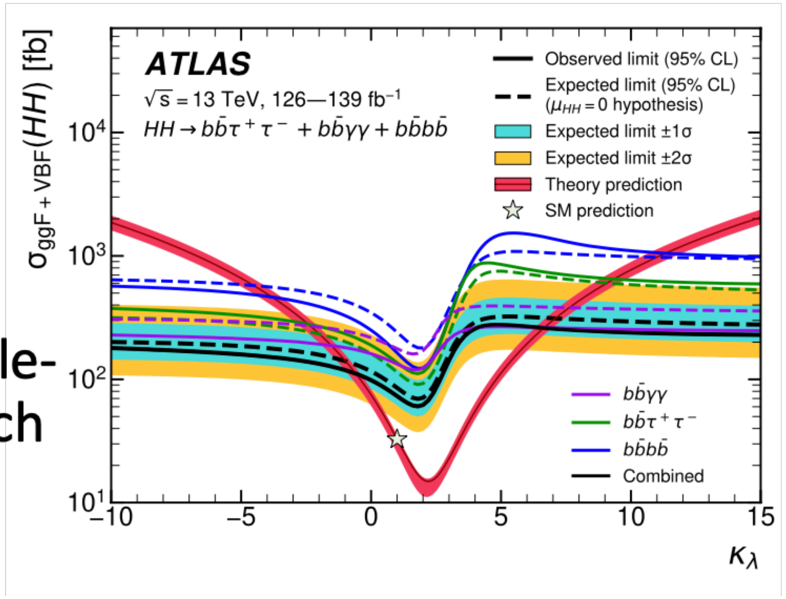
Search for HHH Coupling

Limit on double-Higgs production

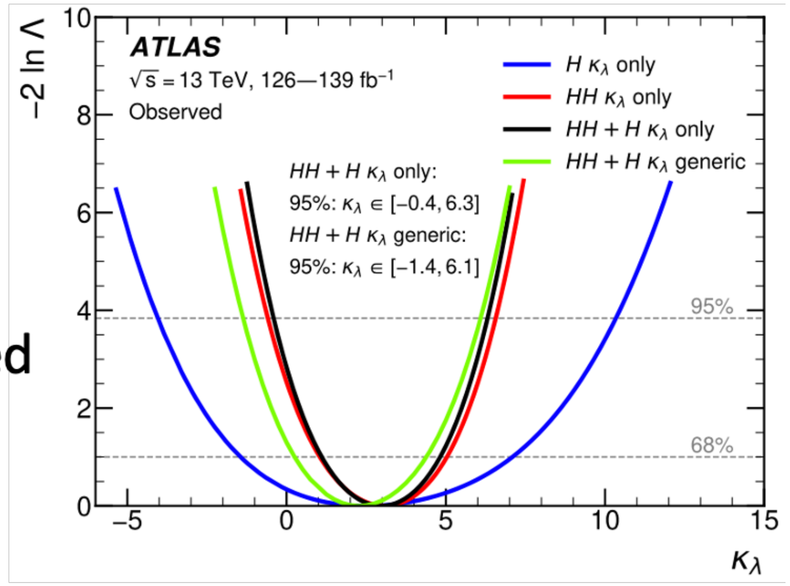


Limits on triple-Higgs coupling

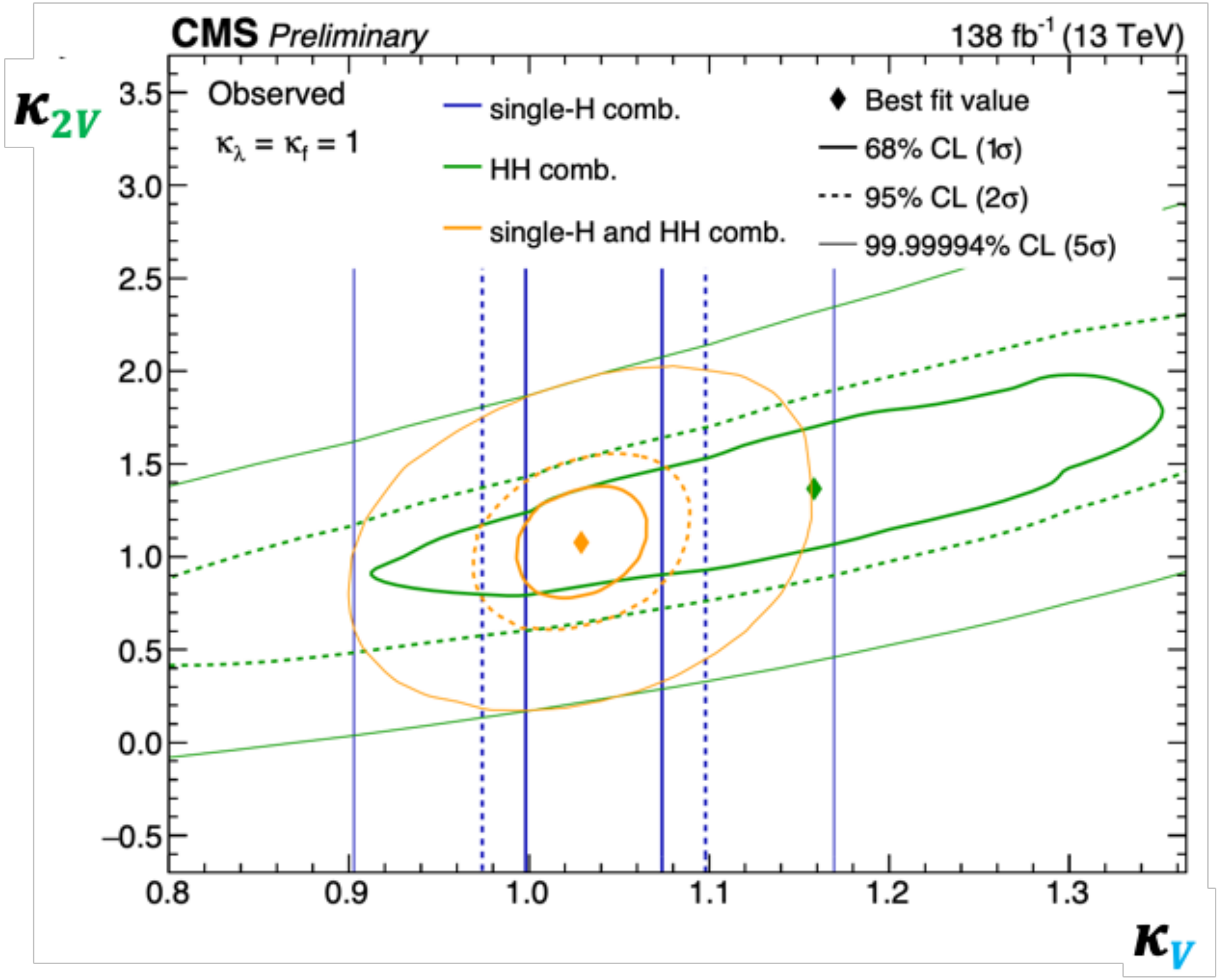
From double-Higgs search



Combined limit



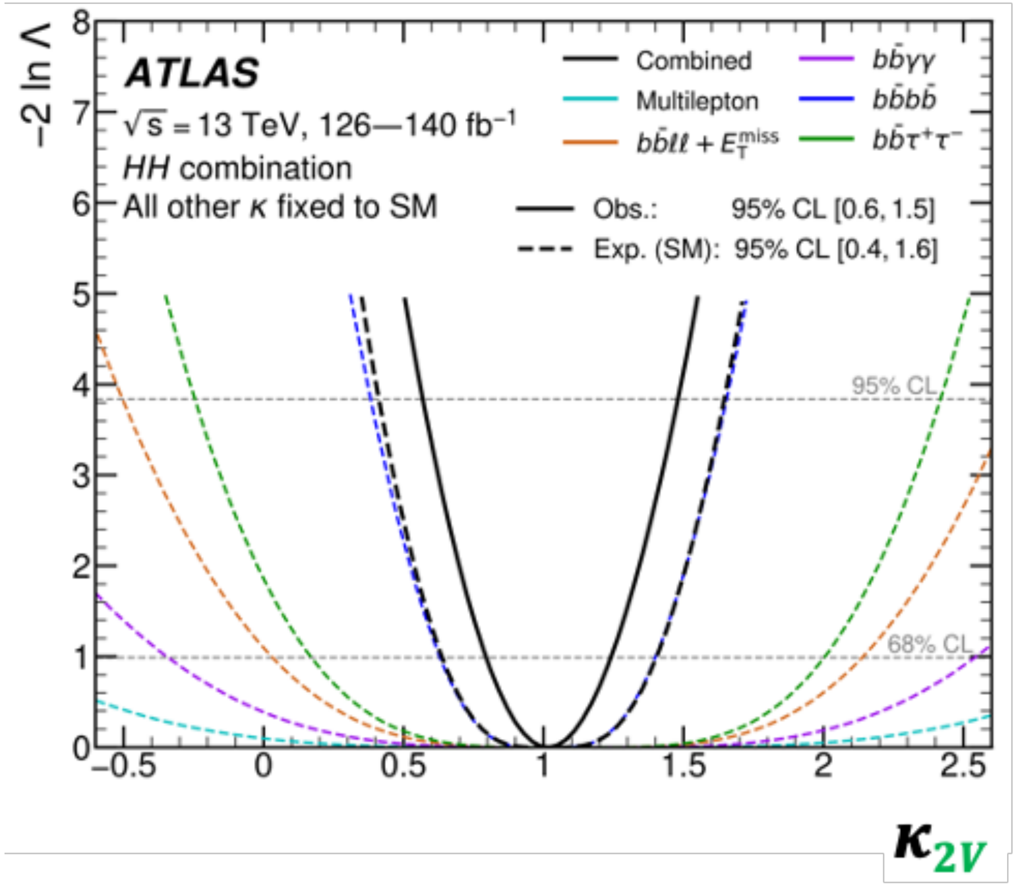
Evidence for VVHH Coupling

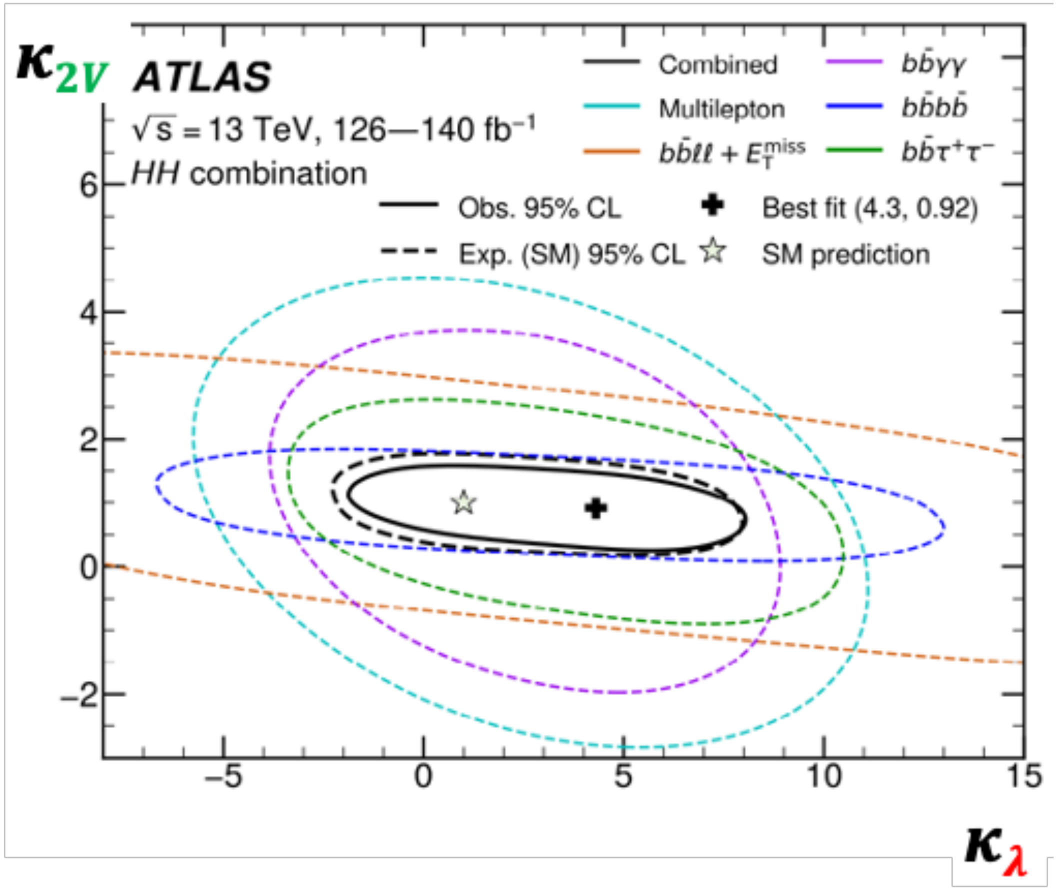


$5-\sigma$ exclusion of $\kappa_{2V} = 0$ if other Higgs couplings have Standard Model values

CMS Collaboration, HIG-23-006-pas

Evidence for VVHH Coupling

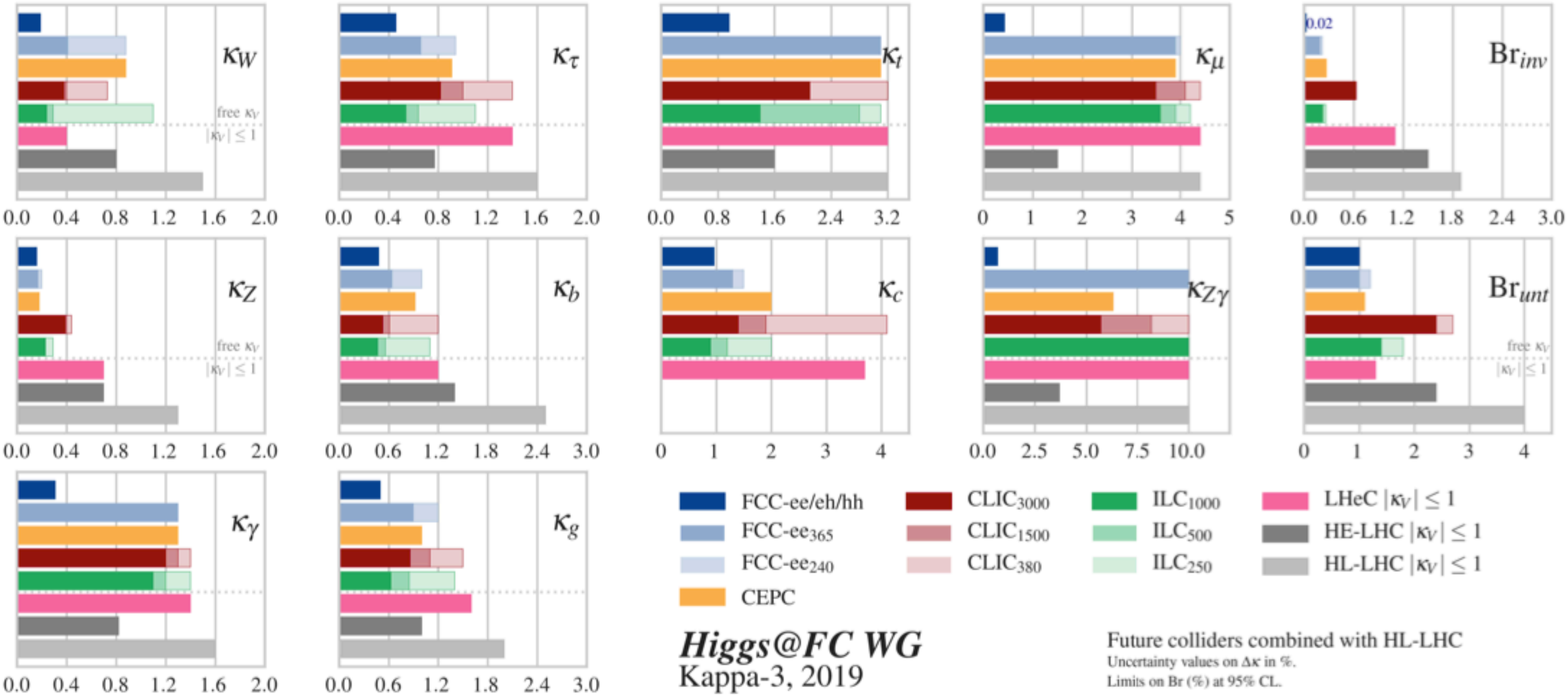




$\kappa_{2V} = 1.02 \pm 0.23$ if other Higgs couplings have Standard Model values

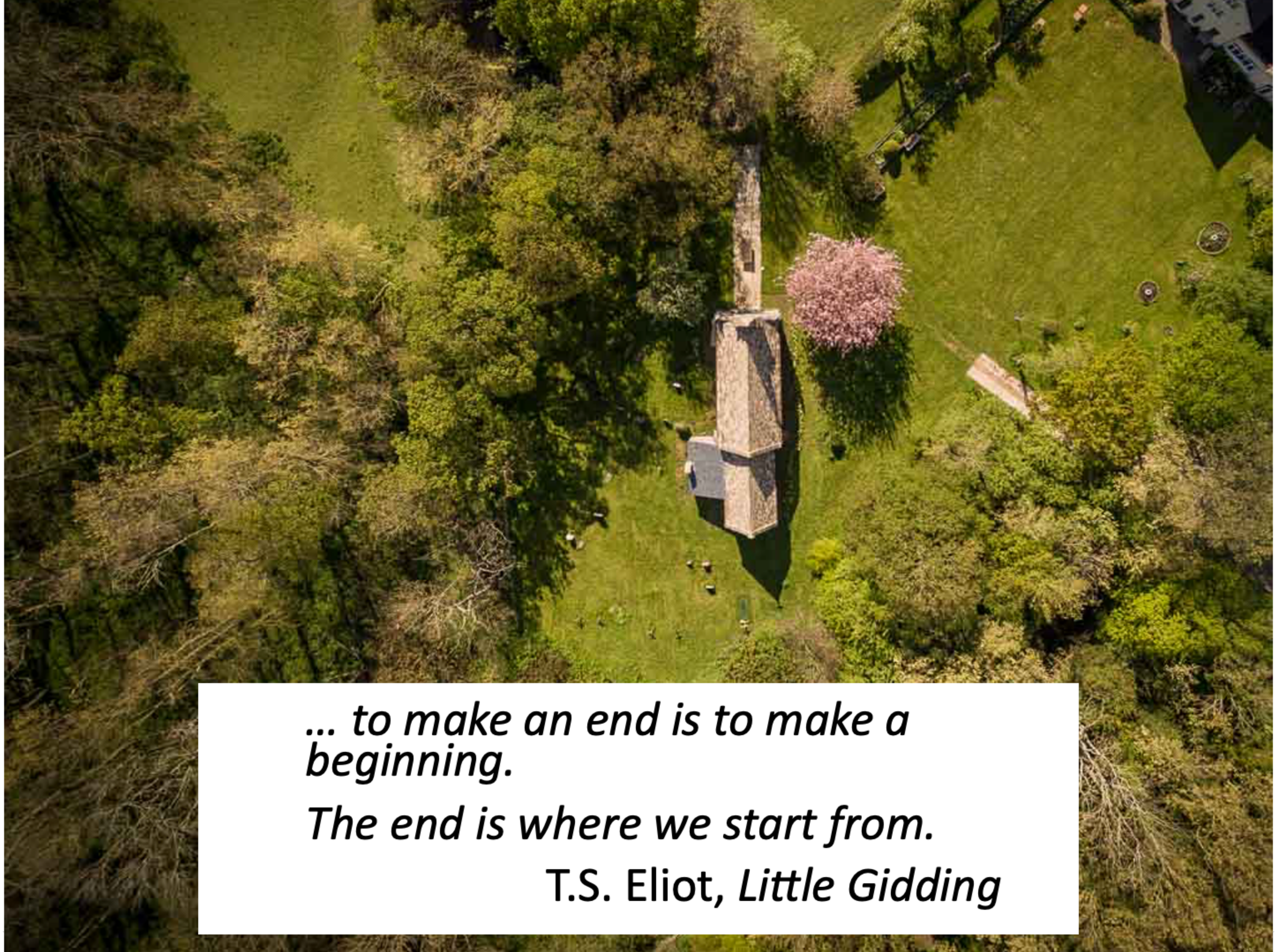
ATLAS Collaboration, arXiv:2406.09971

Future Prospects



Coupling modifiers κ_i: strengths relative to SM predictions

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

- « Empty » space is unstable — LHC
- Dark matter — LHC
- Origin of matter — LHC
- Sizes of masses — LHC
- Masses of neutrinos
- Inflation
- Quantum gravity
- …

The Standard Model

Everything about Higgs is Puzzling

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

- 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?

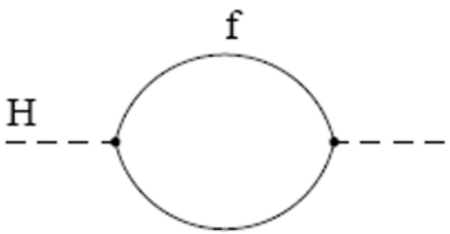
Supersymmetry?

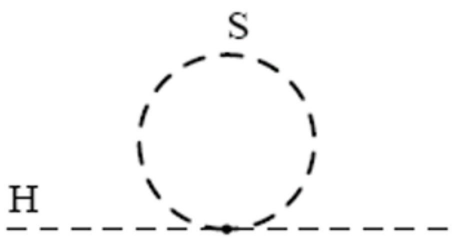
New motivations from LHC

- 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**, $g_\mu - 2$?… ,

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:





- Each is quadratically divergent: $\int^{\Lambda} d^4k/k^2$

$$\Delta m_H^2 = -\frac{y_f}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + \ldots]$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + \ldots]$$

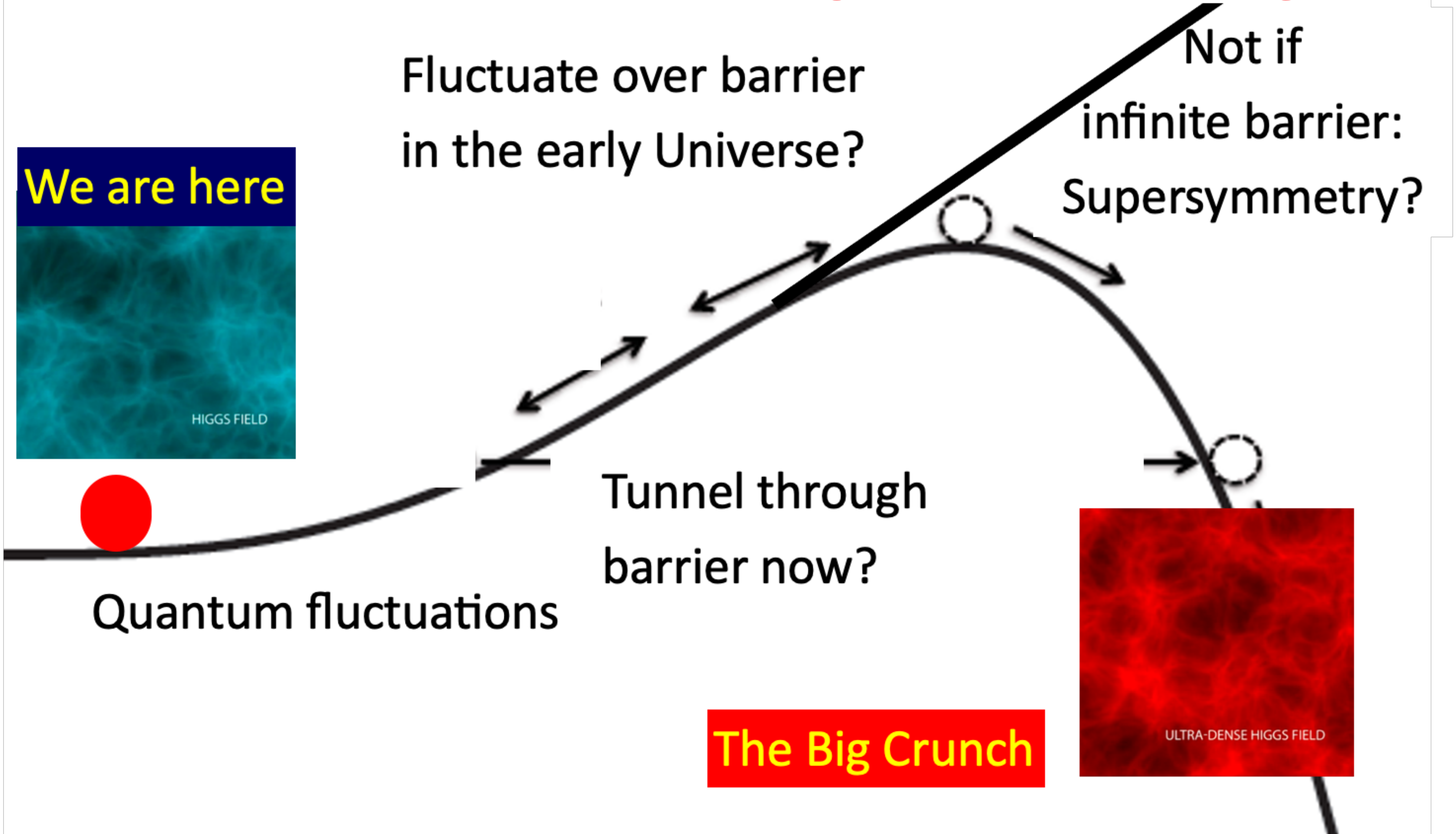
- Leading divergence cancelled if

Supersymmetry!

$$\lambda_S = y_f^2 \text{ x } 2$$

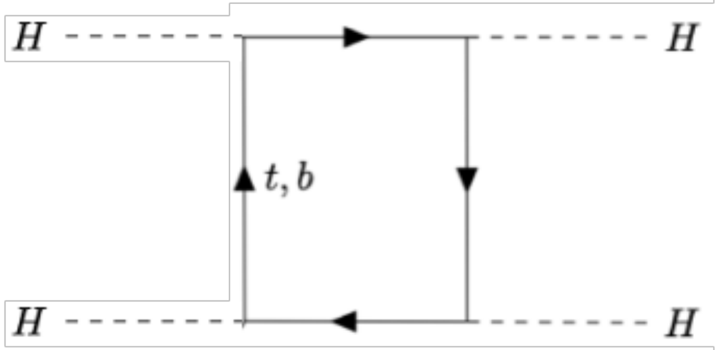
Will the Universe Collapse?

Should it have Collapsed already?



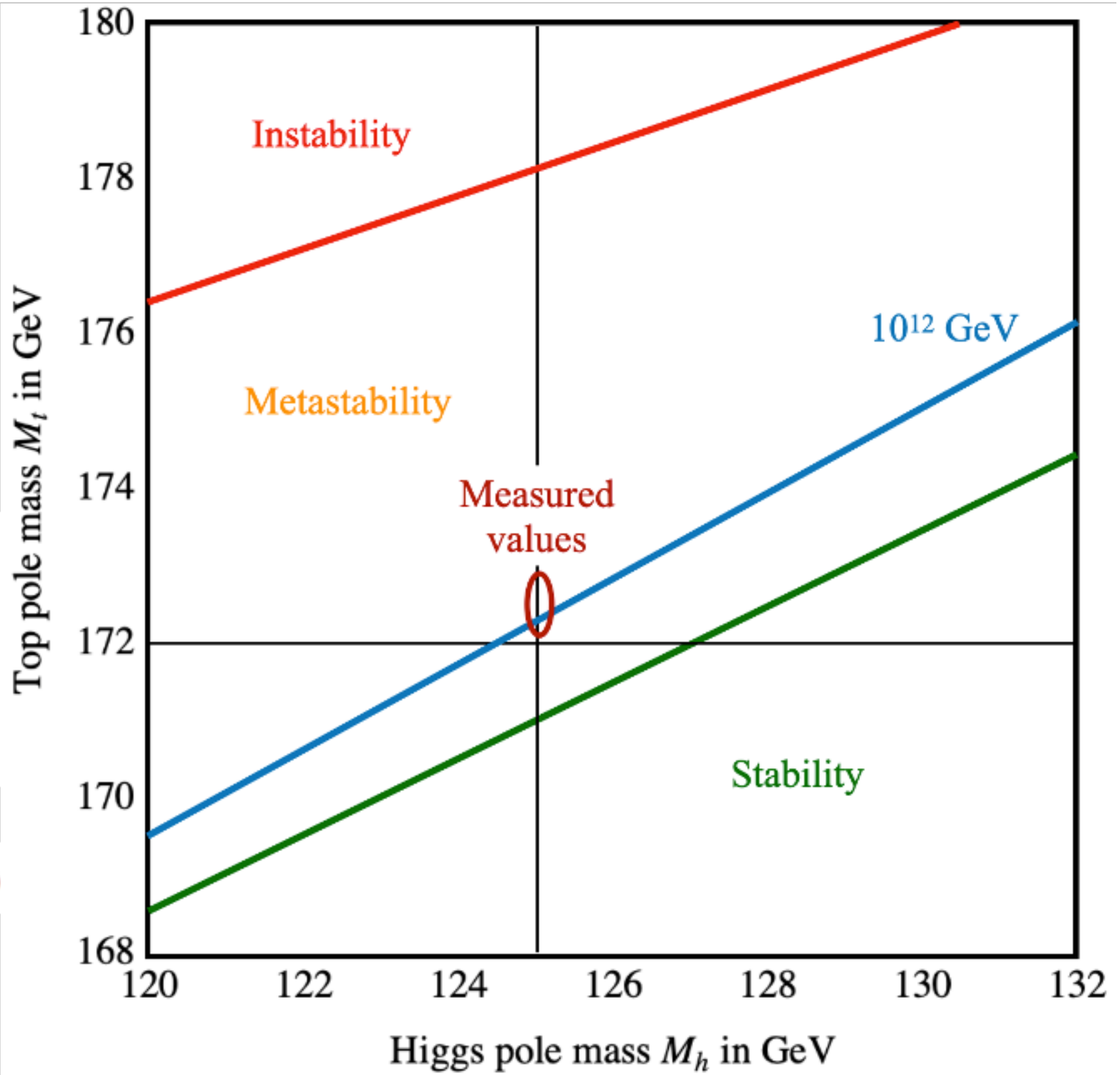
Is "Empty Space" Unstable?

Depends on masses of Higgs boson and top quark



$$16\pi^2 \frac{d\lambda}{dt} = 12(\lambda^2 + h_t^2\,\lambda - h_t^4) + \mathcal{O}(g^4, g^2\lambda$$

$$t = \log(Q^2)$$



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

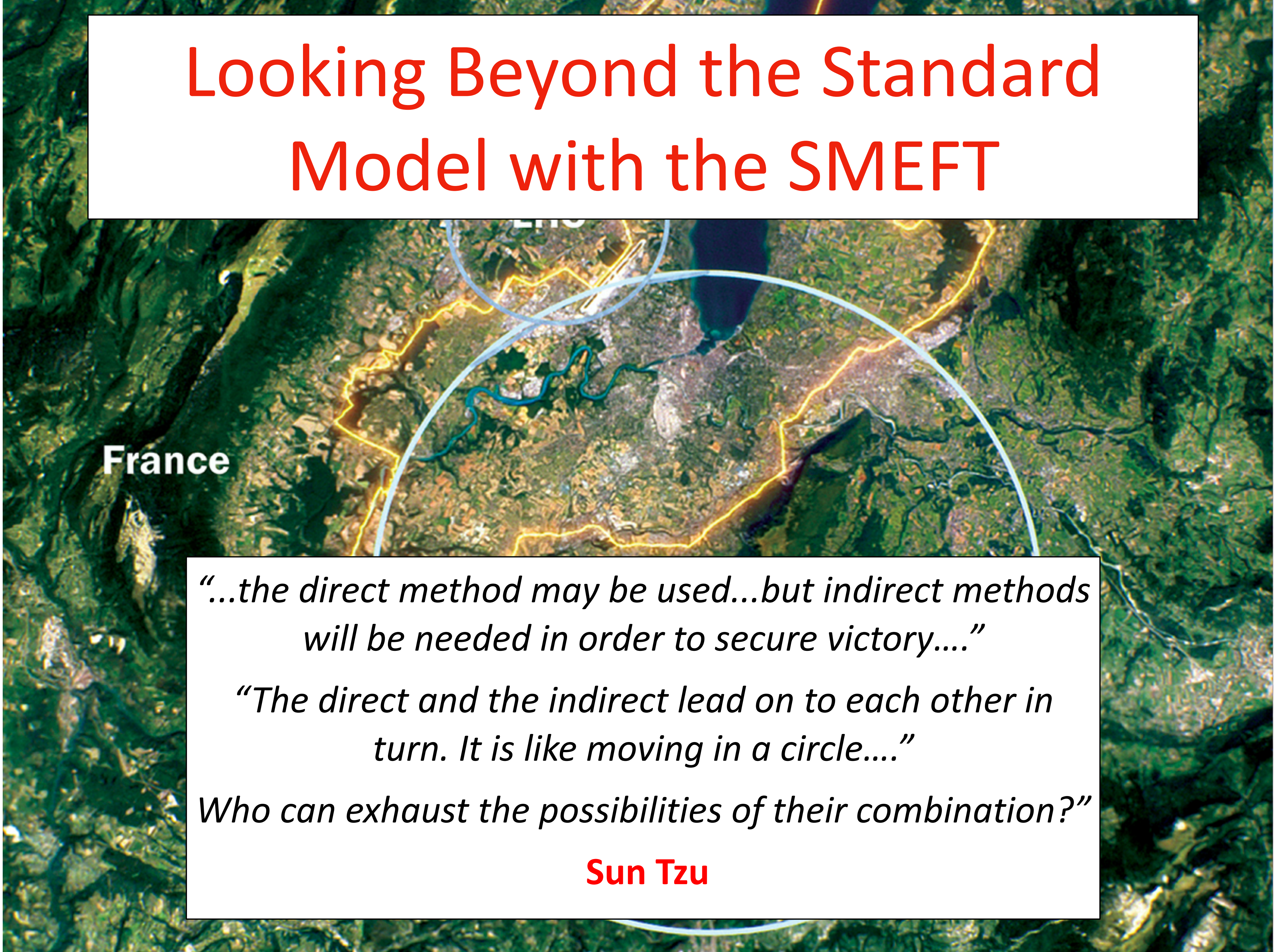
ATLAS, arXiv:2309.12986

- Instability scale:

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

- Dominant uncertainties those in α_s and m_t

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…."

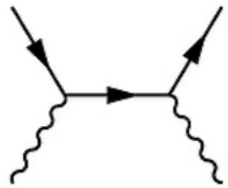
"The direct and the indirect lead on to each other in turn. It is like moving in a circle…."

Who can exhaust the possibilities of their combination?"

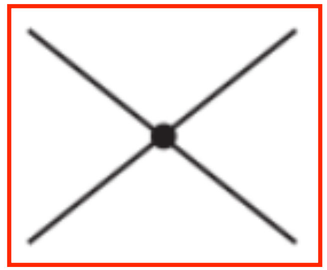
Sun Tzu

Effective Field Theories (EFTs)
a long and glorious History

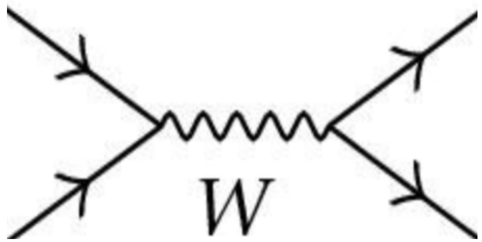
- 1930's: "Standard Model" of QED had d=4



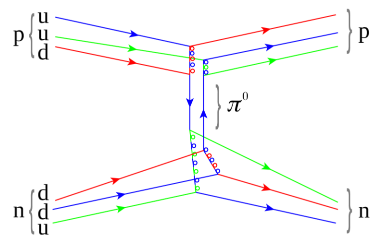
- **Fermi's four-fermion theory of the weak force**



- 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: (∂π∂π)ππ clue ➔ QCD

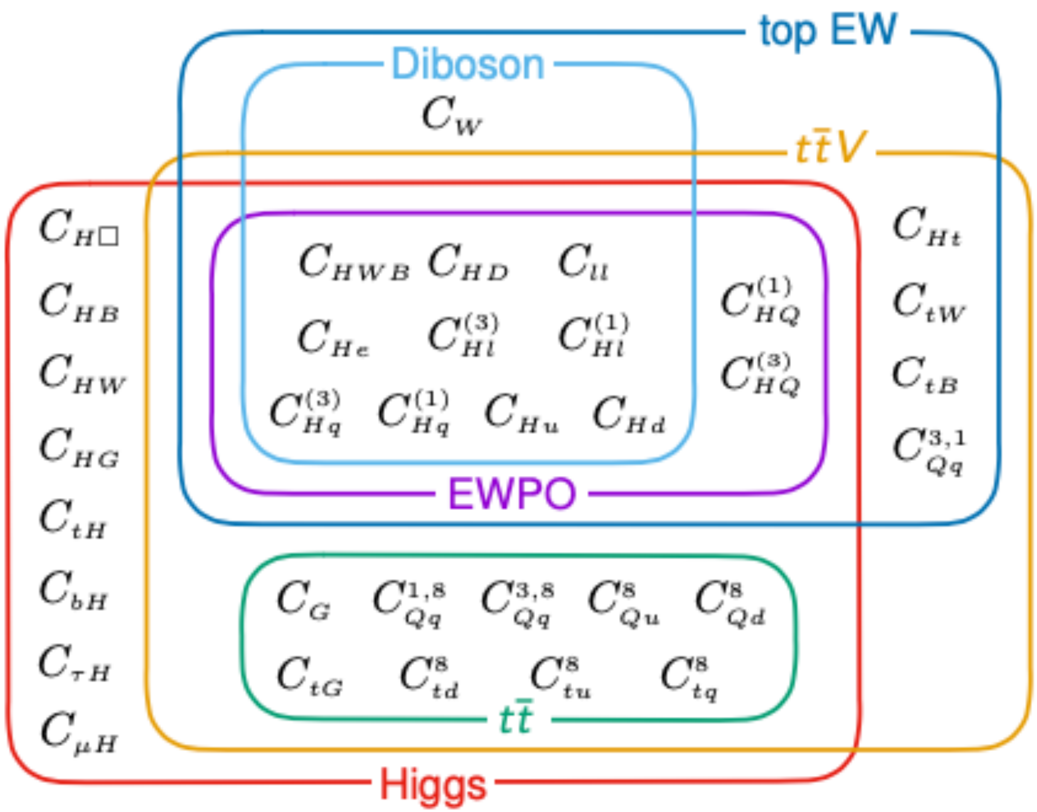
Global SMEFT Fit

to Top, Higgs, Diboson, Electroweak Data

JE, Madigan, Mimasu, Sanz & You, arXiv:2022.02779

- 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

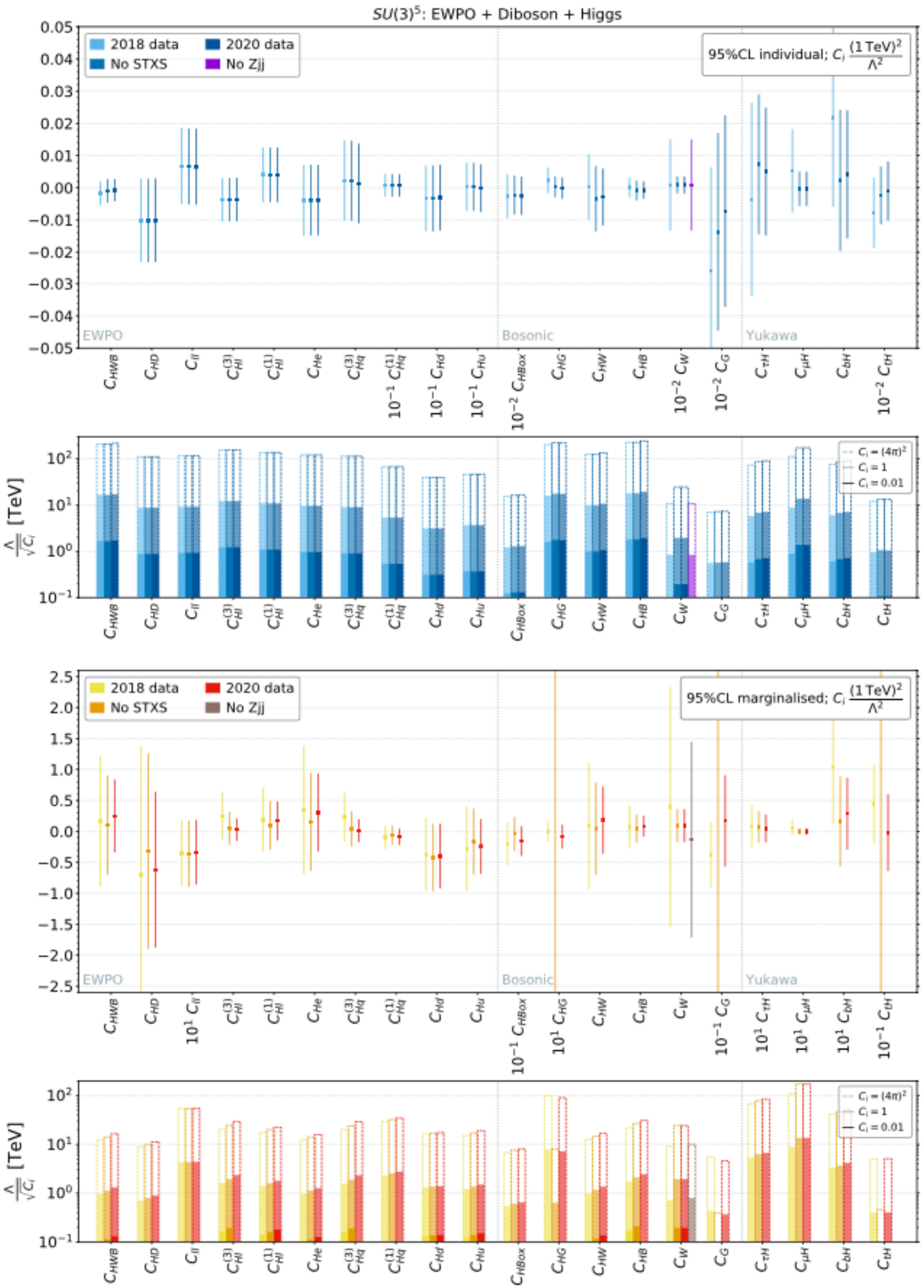


Dimension-6 Constraints with Flavour-Universal SU(3)^5 Symmetry

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

No significant deviations from SM

JE, Madigan, Mimasu, Sanz & You, arXiv:2022.02779



Single-Field Extensions of the Standard Model

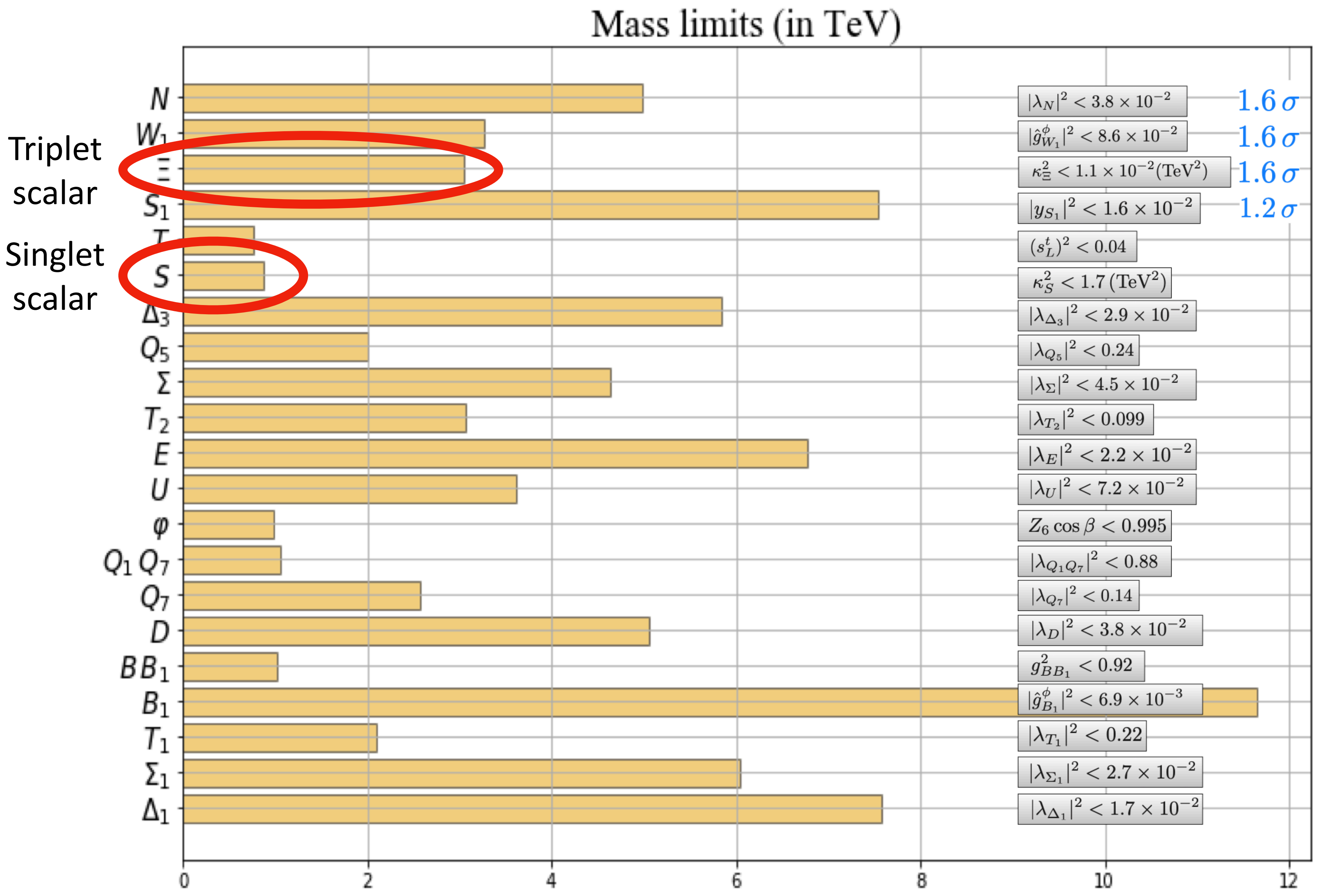
Name	Spin	SU(3)	SU(2)	U(1)	Name	Spin	SU(3)	SU(2)	U(1)
S	0	1	1	0	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
S_1	0	1	1	1	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
φ	0	[illegible]	2	$\frac{1}{2}$	Σ	$\frac{1}{2}$	1	3	0
Ξ	0	1	3	0	Σ_1	$\frac{1}{2}$	1	3	-1
Ξ_1	0	1	3	1	U	$\frac{1}{2}$	3	1	$\frac{2}{3}$
B	1	1	1	0	D	$\frac{1}{2}$	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

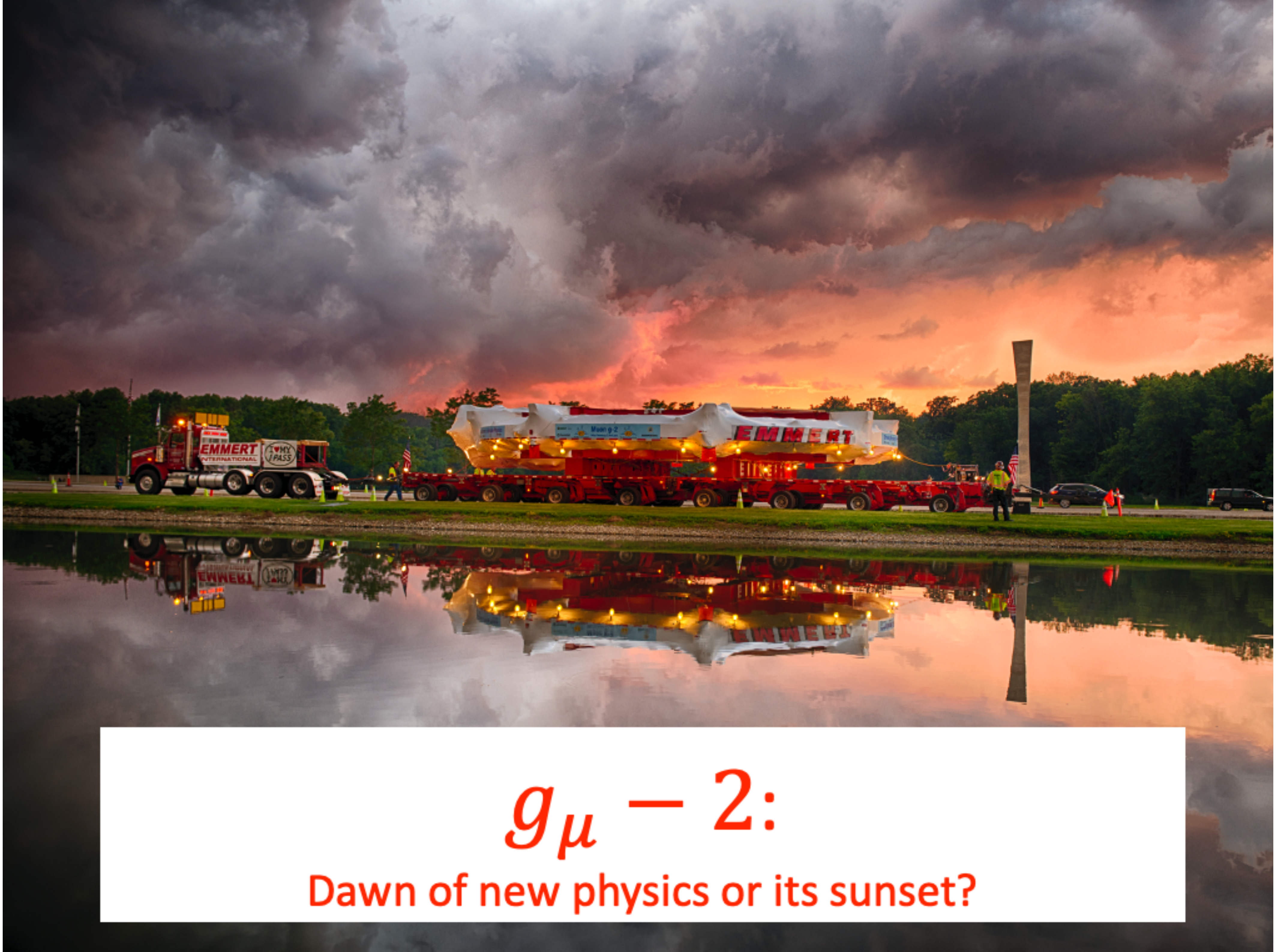
Vector

JE, Madigan, Mimasu, Sanz & You, arXiv:2022.02779

Single-Field Extensions of the Standard Model



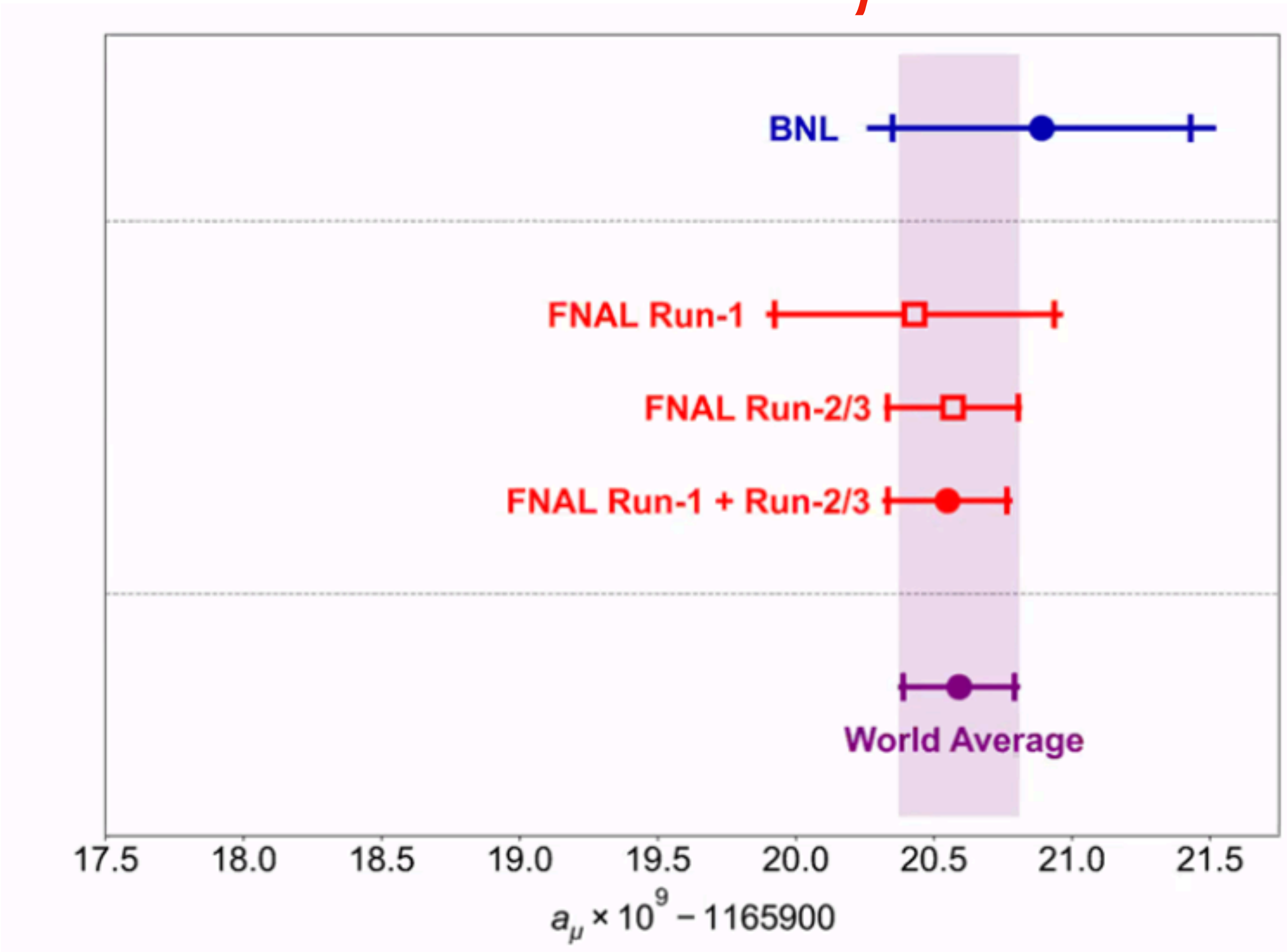
JE, Madigan, Mimasu, Sanz & You, arXiv:2022.02779



$g_\mu - 2$:

Dawn of new physics or its sunset?

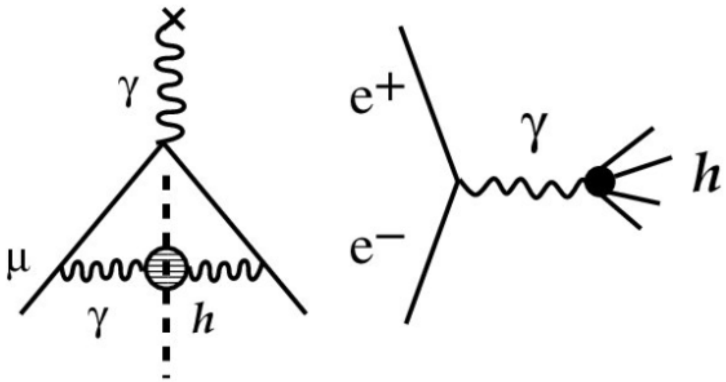
Quo Vadis $g_\mu - 2$?



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

Theory Initiative

- Comprehensive review of calculations of the Standard Model contributions to $g_\mu - 2$
- Including discussion of the uncertainties
- Particularly in calculation of leading-order vacuum polarisation



Aoyama et al, arXiv:2006.04822

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The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama [1,2,3], N. Asmussen [4], M. Benayoun [5], J. Bijnens [6], T. Blum [7,8], M. Bruno [9], I. Caprini [10], C.M. Carloni Calame [11], M. Cè [9,12,13], G. Colangelo [14,*], F. Curciarello [15,16], H. Czyż [17], I. Danilkin [12], M. Davier [18,*], C.T.H. Davies [19], M. Della Morte [20], S.I. Eidelman [21,22,*], A.X. El-Khadra [23,24,*], A. Gérardin [25], D. Giusti [26,27], M. Golterman [28], Steven Gottlieb [29], V. Gülpers [30], F. Hagelstein [14], M. Hayakawa [31,2], G. Herdoíza [32], D.W. Hertzog [33], A. Hoecker [34], M. Hoferichter [14,35,*], B.-L. Hoid [36], R.J. Hudspith [12,13], F. Ignatov [21], T. Izubuchi [37,8], F. Jegerlehner [38], L. Jin [7,8], A. Keshavarzi [39], T. Kinoshita [40,41], B. Kubis [36], A. Kupich [21], A. Kupść [42,43], L. Laub [14], C. Lehner [26,37,*], L. Lellouch [25], I. Logashenko [21], B. Malaescu [5], K. Maltman [44,45], M.K. Marinković [46,47], P. Masjuan [48,49], A.S. Meyer [37], H.B. Meyer [12,13], T. Mibe [1,*], K. Miura [12,13,3], S.E. Müller [50], M. Nio [2,51], D. Nomura [52,53], A. Nyffeler [12,*], V. Pascalutsa [12], M. Passera [54], E. Perez del Rio [55], S. Peris [48,49], A. Portelli [30], M. Procura [56], C.F. Redmer [12], B.L. Roberts [57,*], P. Sánchez-Puertas [49], S. Serednyakov [21], B. Shwartz [21], S. Simula [27], D. Stöckinger [58], H. Stöckinger-Kim [58], P. Stoffer [59], T. Teubner [60,*], R. Van de Water [24], M. Vanderhaeghen [12,13], G. Venanzoni [61], G. von Hippel [12], H. Wittig [12,13], Z. Zhang [18], M.N. Achasov [21], A. Bashir [62], N. Cardoso [47], B. Chakraborty [63], E.-H. Chao [12], J. Charles [25], A. Crivellin [64,65], O. Deineka [12], A. Denig [12,13], C. DeTar [66], C.A. Dominguez [67], A.E. Dorokhov [68], V.P. Druzhinin [21], G. Eichmann [69,47], M. Fael [70], C.S. Fischer [71], E. Gámiz [72], Z. Gelzer [23], J.R. Green [9], S. Guellati-Khelifa [73], D. Hatton [19], N. Hermansson-Truedsson [14], S. Holz [36], B. Hörz [74], M. Knecht [25], J. Koponen [1], A.S. Kronfeld [24], J. Laiho [75], S. Leupold [42], P.B. Mackenzie [24], W.J. Marciano [37], C. McNeile [76], D. Mohler [12,13], J. Monnard [14], E.T. Neil [77], A.V. Nesterenko [68], K. Ottnad [12], V. Pauk [12], A.E. Radzhabov [78], E. de Rafael [25], K. Raya [79], A. Risch [12], A. Rodríguez-Sánchez [6], P. Roig [80], T. San José [12,13], E.P. Solodov [21], R. Sugar [81], K. Yu. Todyshev [21], A. Vainshtein [82], A. Vaquero Avilés-Casco [66], E. Weil [71], J. Wilhelm [12], R. Williams [71], A.S. Zhevlakov [78]

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Hadronic Vacuum Polarization

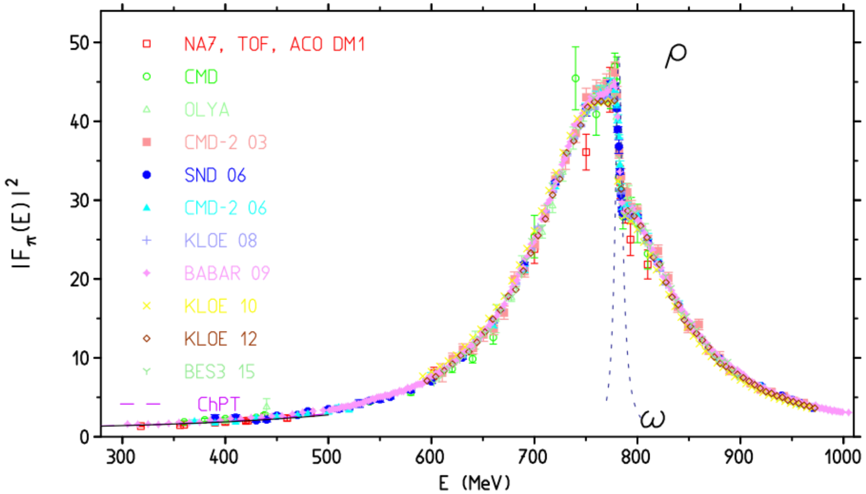
- Most important contribution is from low energies $\lesssim 1$ GeV, dominated by ρ and ω peaks, taking account of interference effects

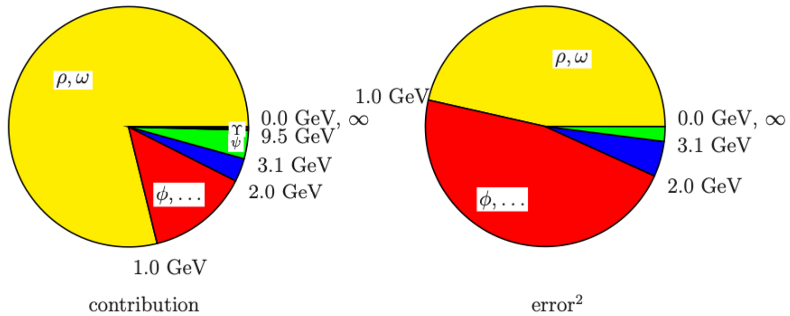
- Uncertainties dominated by ρ and ω region, and by region between 1 and 2 GeV (ϕ, etc.)

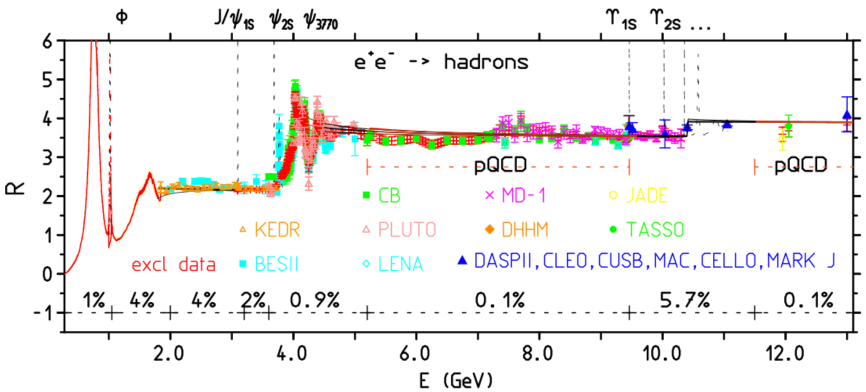
- High energies under good control from perturbative QCD

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

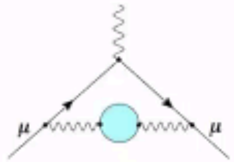
Aoyama et al, arXiv:2006.04822



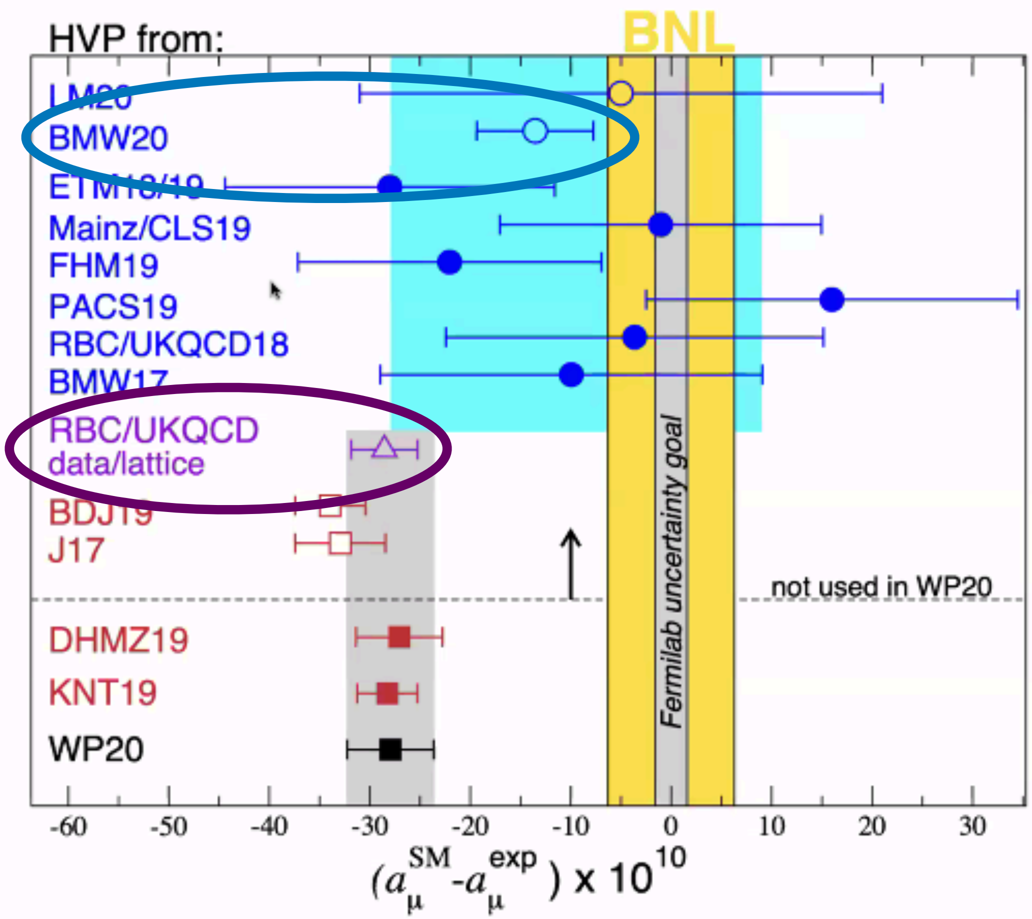




Lattice Calculations of Hadronic Vacuum Polarization

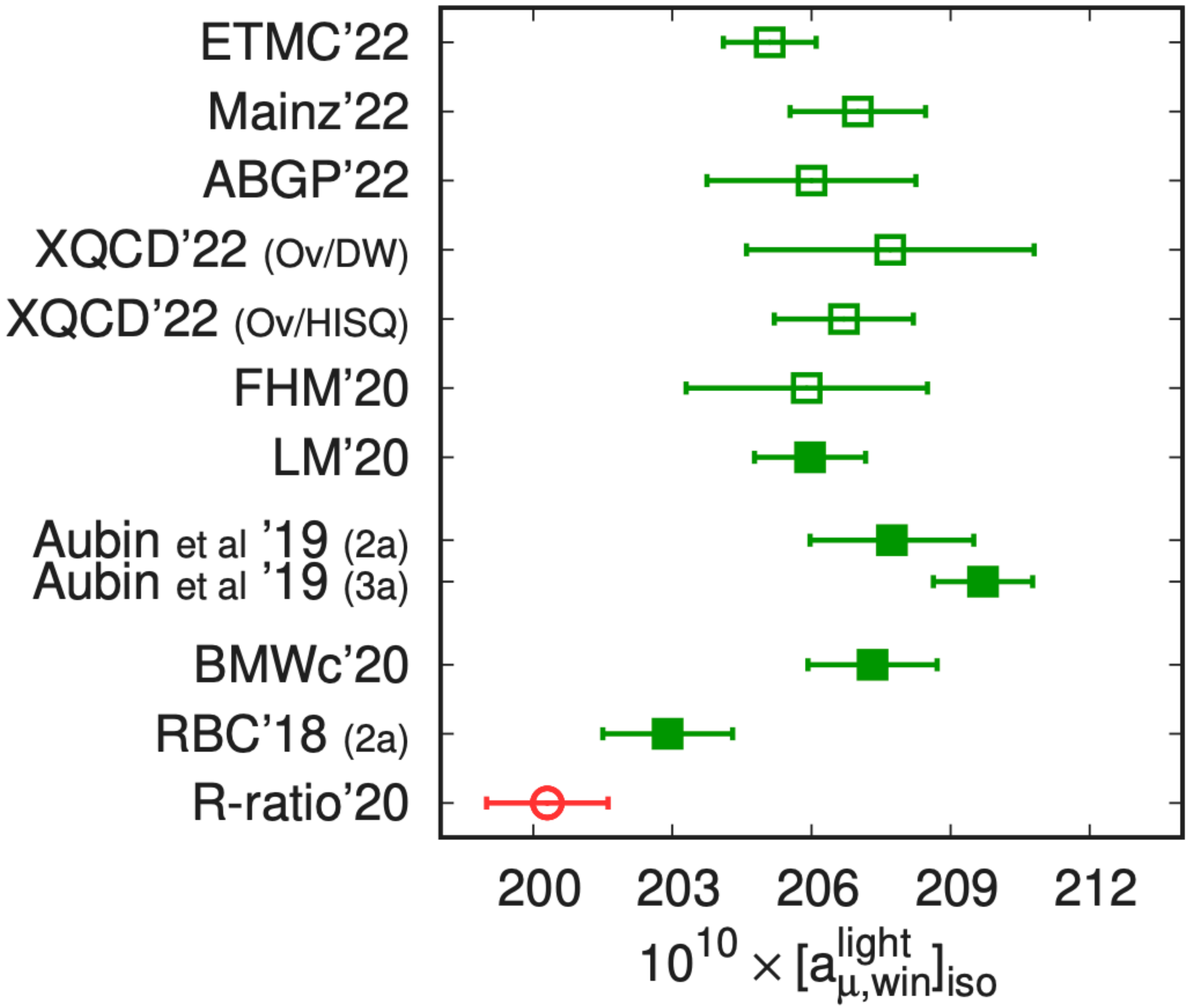


$$a_\mu^{\rm HVP} + \left[a_\mu^{\rm QED} + a_\mu^{\rm Weak} + a_\mu^{\rm HLbL}\right] > a_\mu^{\rm SM}$$



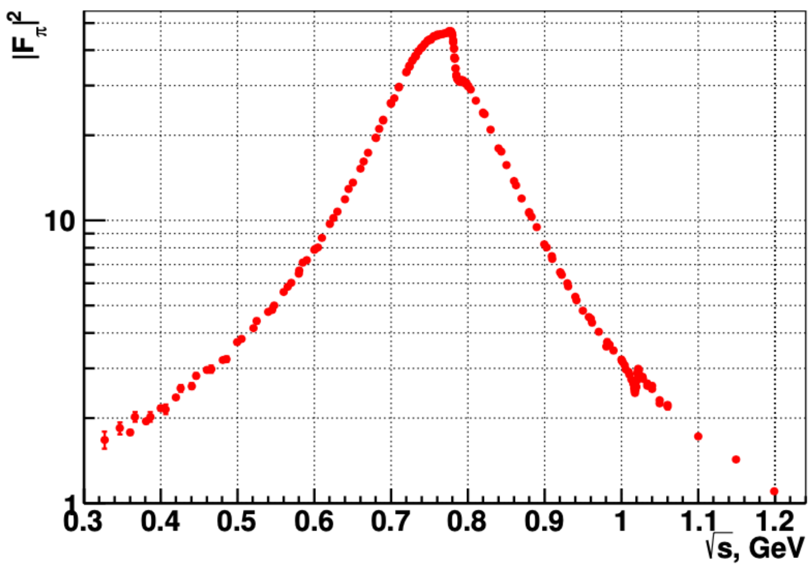
Aoyama et al, arXiv:2006.04822

Recent Lattice Calculations



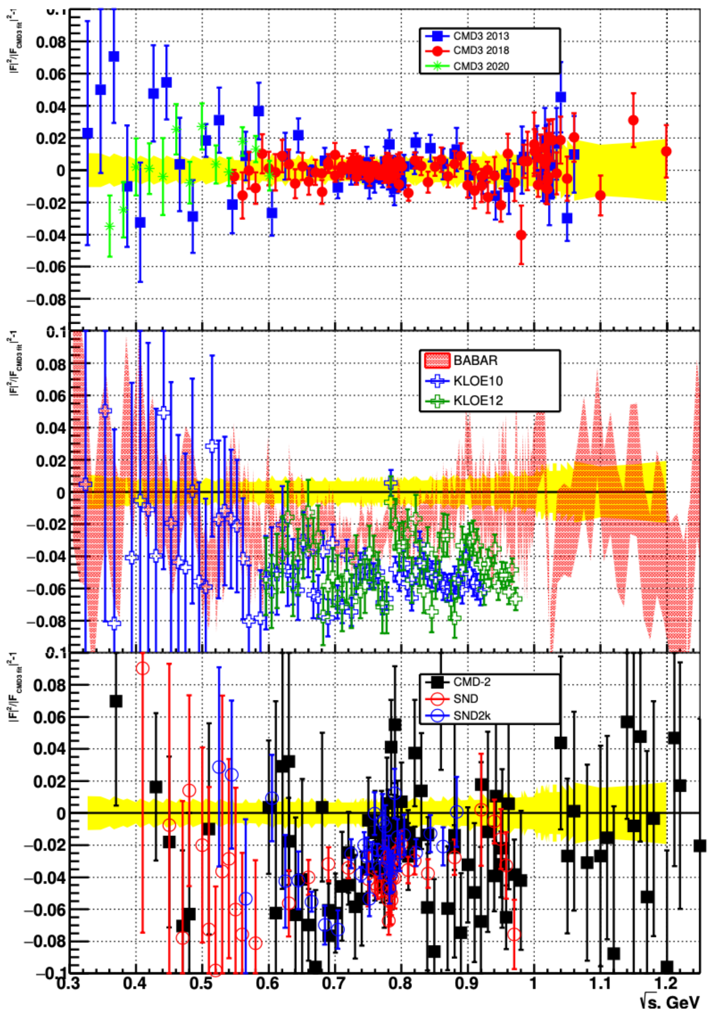
Updated CMD-3 Measurement of HVP

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



CMD-3 Collaboration, arXiv:2309.12910

Comparison with previous results



$(g_\mu - 2)$ – HVP discrepancy

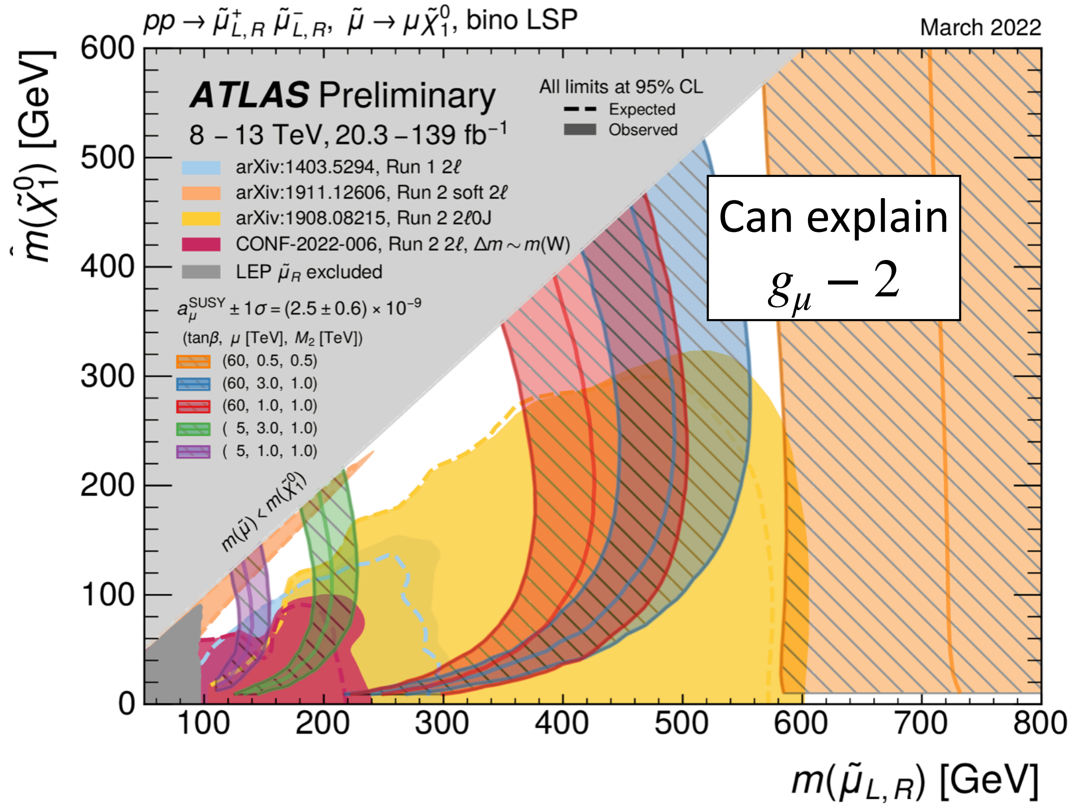
$\Delta a_\mu = (49 \pm 55) \times 10^{-11}$

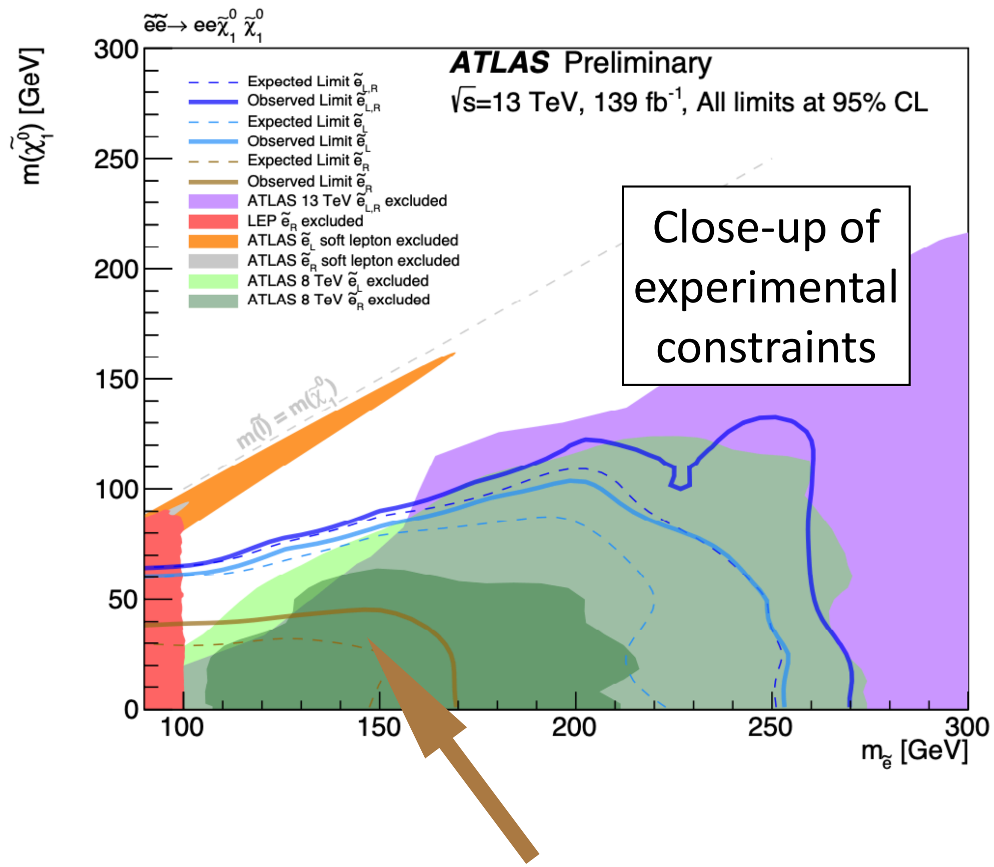
Consistent with no BSM signal

LHC vs Supersymmetry

- LHC favours squarks & gluinos > 2 TeV (but loopholes)

- Does not exclude lighter electroweakly-interacting particles, e.g., sleptons

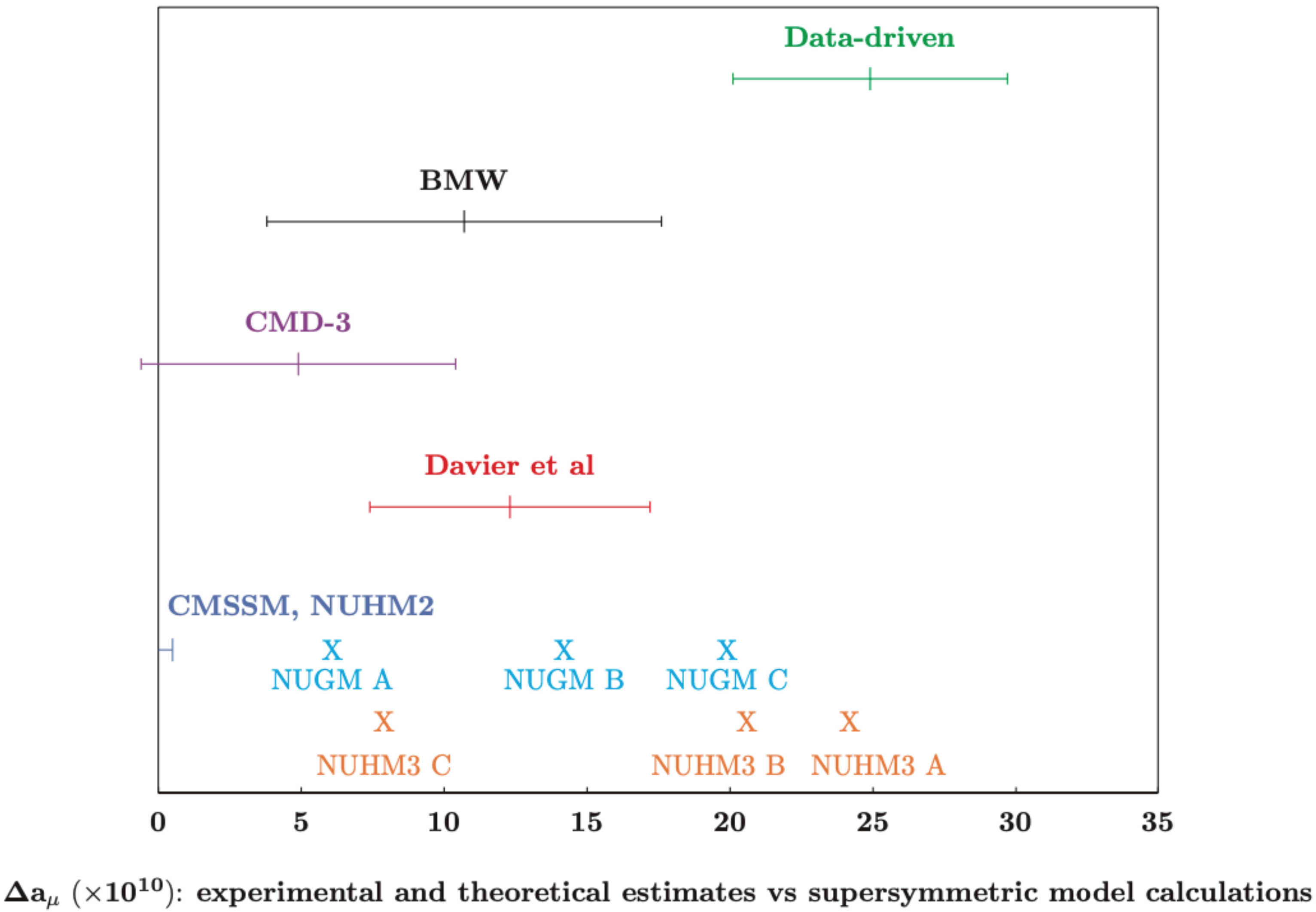




- Most models have $m_{\tilde{\mu}_L} > m_{\tilde{\mu}_R}$ but $m_{\tilde{\mu}_R} \simeq m_{\tilde{e}_R}$: **relevant constraint**

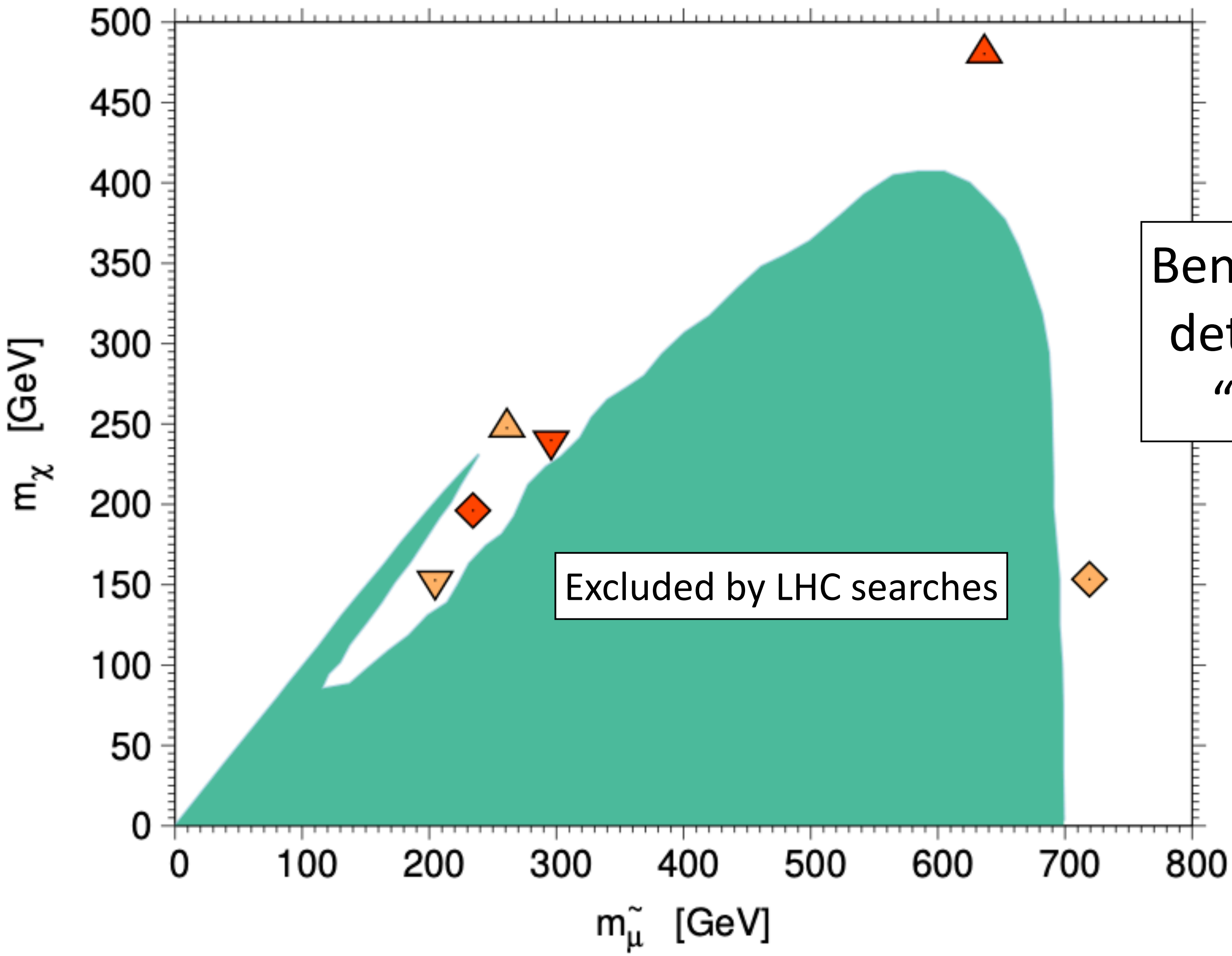
ATLAS Collaboration

$g_\mu - 2$ in Benchmark SUSY Scenarios



JE, Olive, Spanos, *in preparation*

Smuon & Neutralino Masses in Benchmarks



Benchmarks detectable "soon"

JE, Olive, Spanos, *in preparation*

The Dark Matter Hypothesis

- Proposed by Fritz Zwicky, based on observations of the Coma galaxy cluster
- The galaxies move too quickly
- The observations require a

  stronger gravitational field

  than provided by the visible matter
- **Dark matter?**

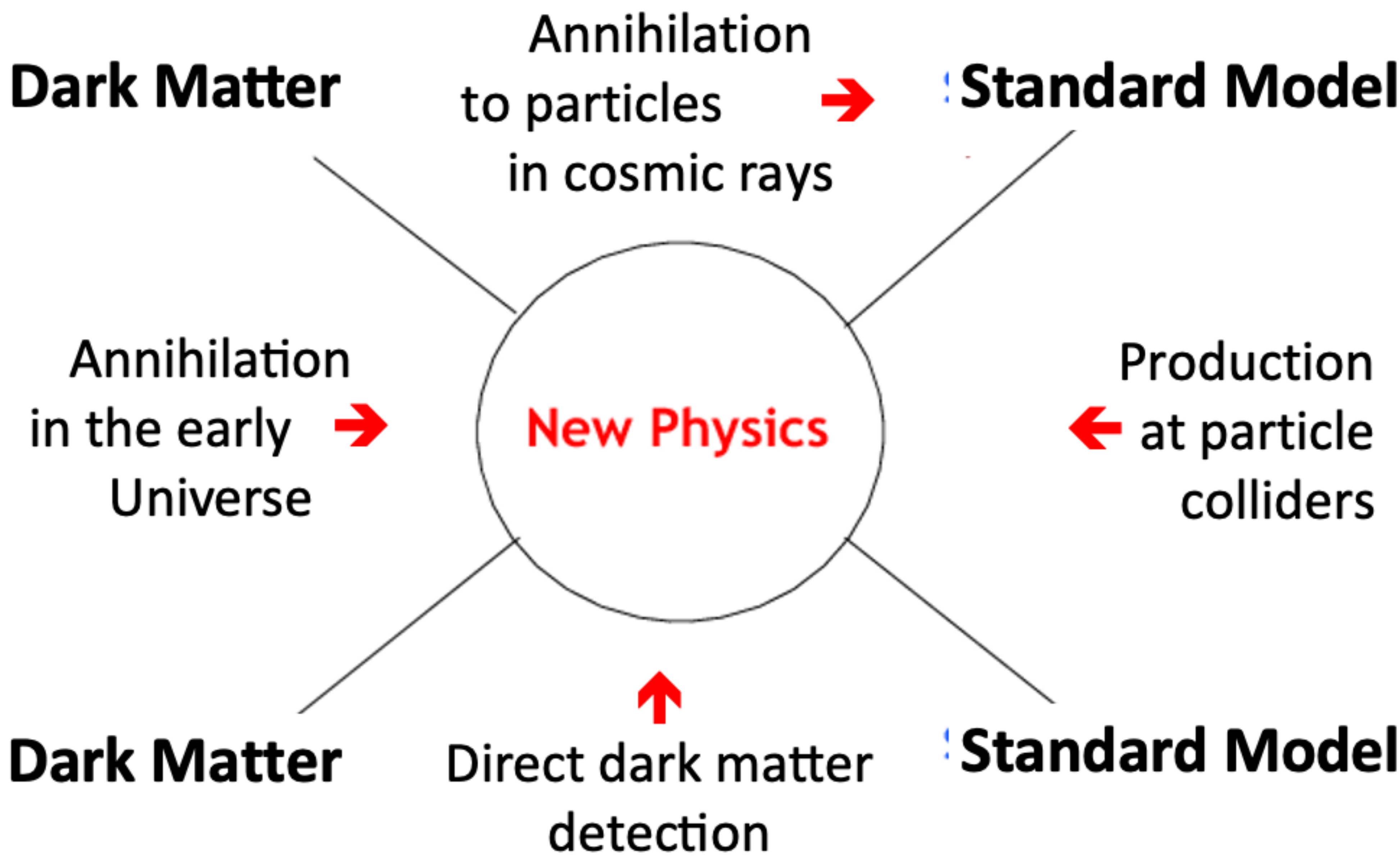
The Rotation Curves of Galaxies

- Measured by Vera Rubin
- The stars also orbit 'too quickly'
- Her observations also required a stronger gravitational field than provided by the visible matter

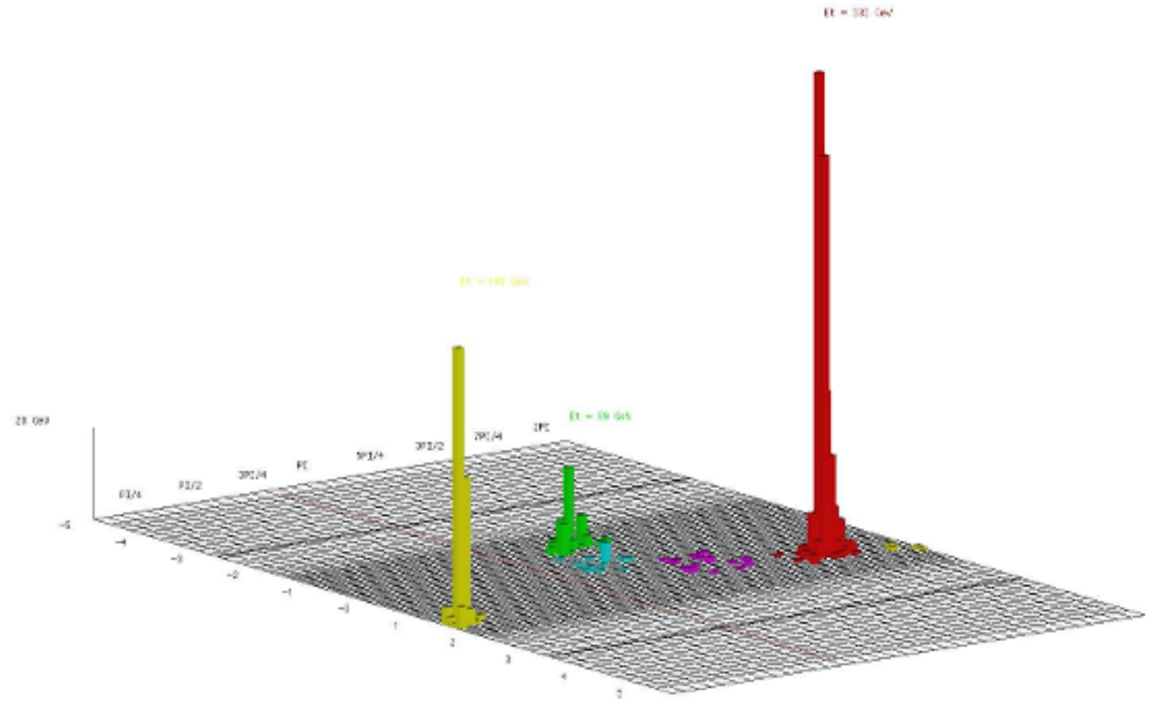
Scanned at the American Institute of Physics

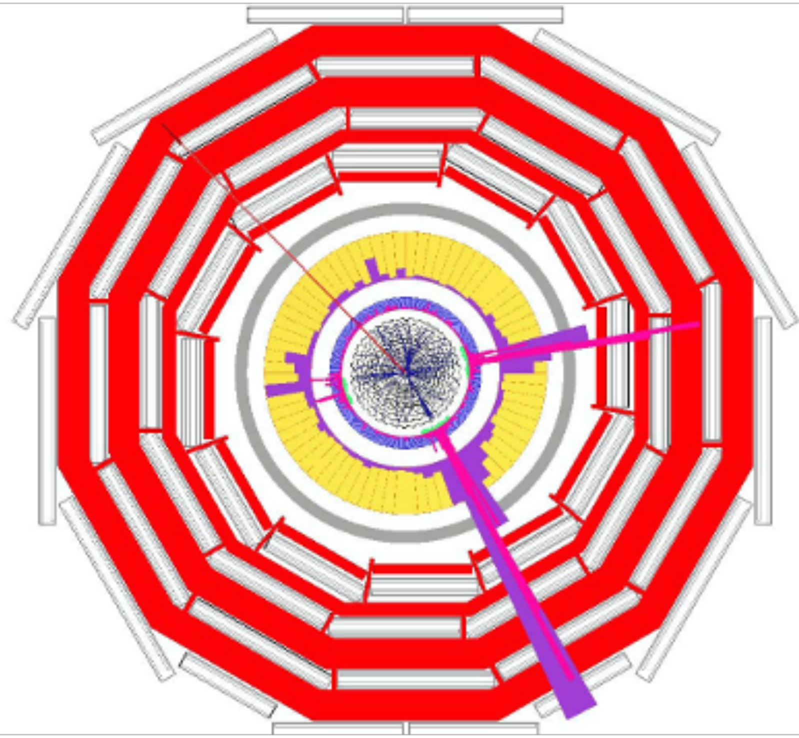
- **Further strong evidence for dark matter**
- Also:
  - Structure formation, cosmic background radiation, …

Searches for Dark Matter



Classic Dark Matter Signature



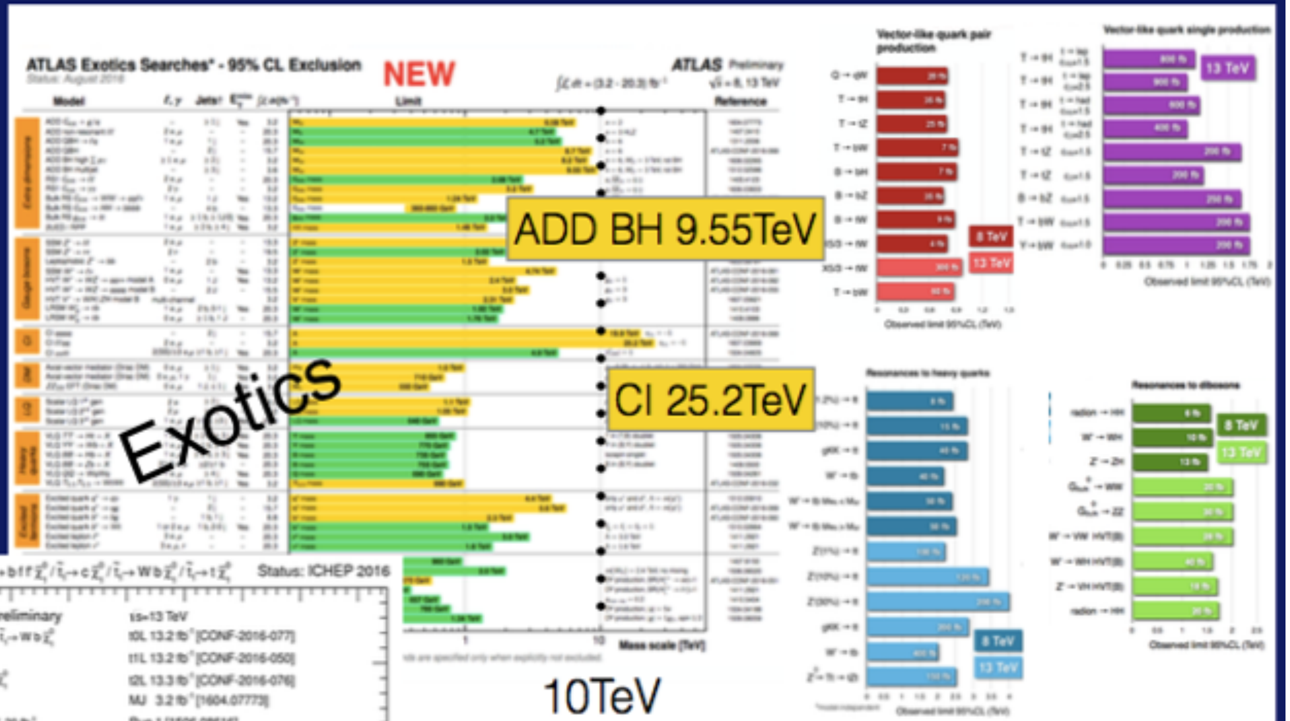


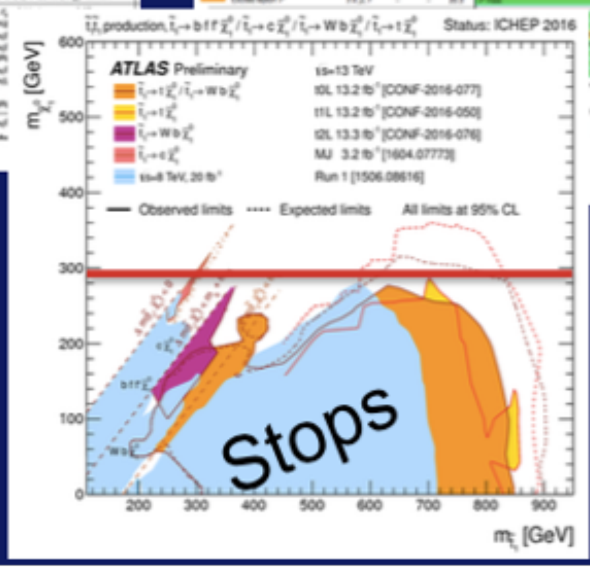
Missing transverse energy
carried away by dark matter particles

Nothing (yet) at the LHC

No supersymmetry

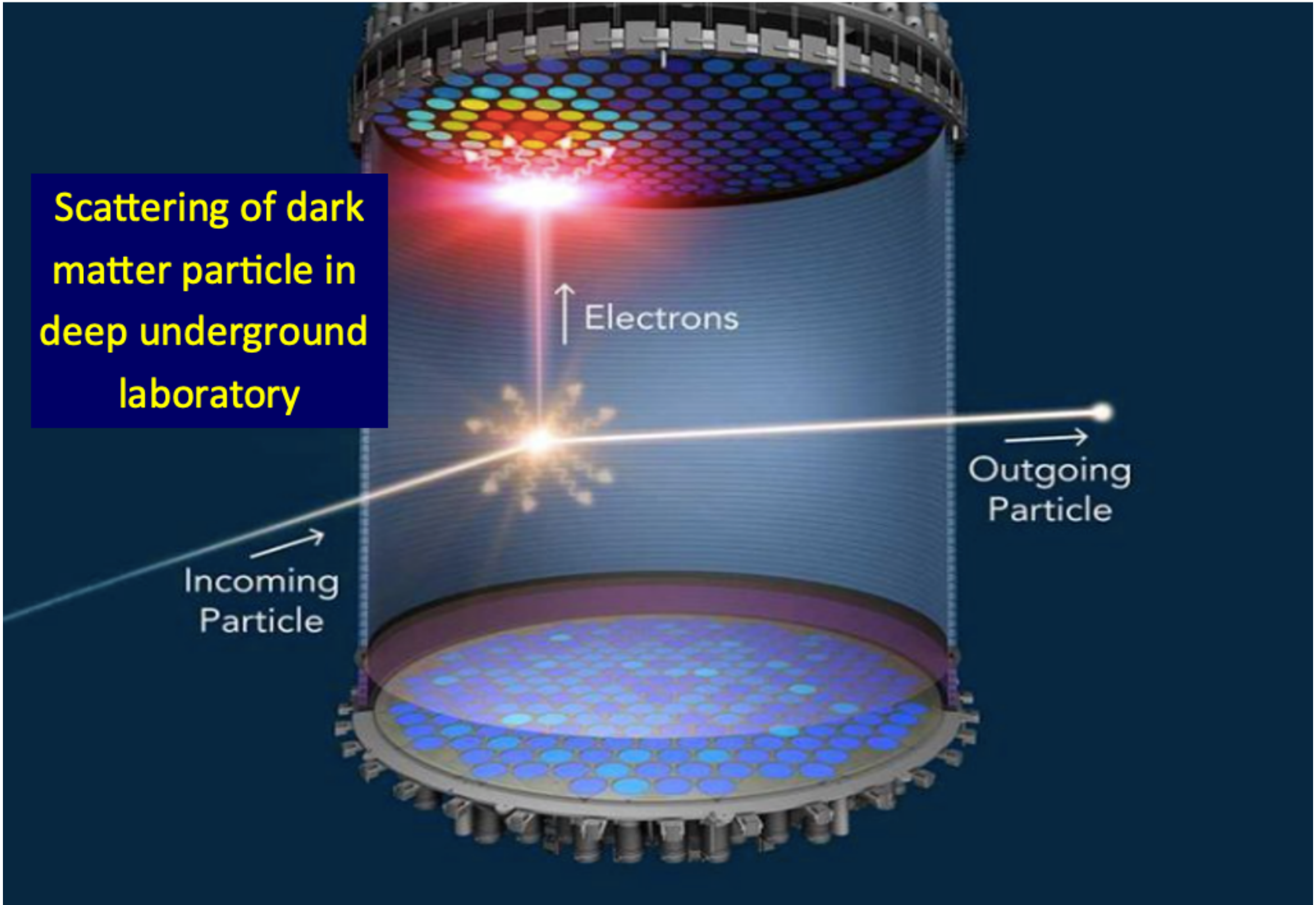
Nothing else, either





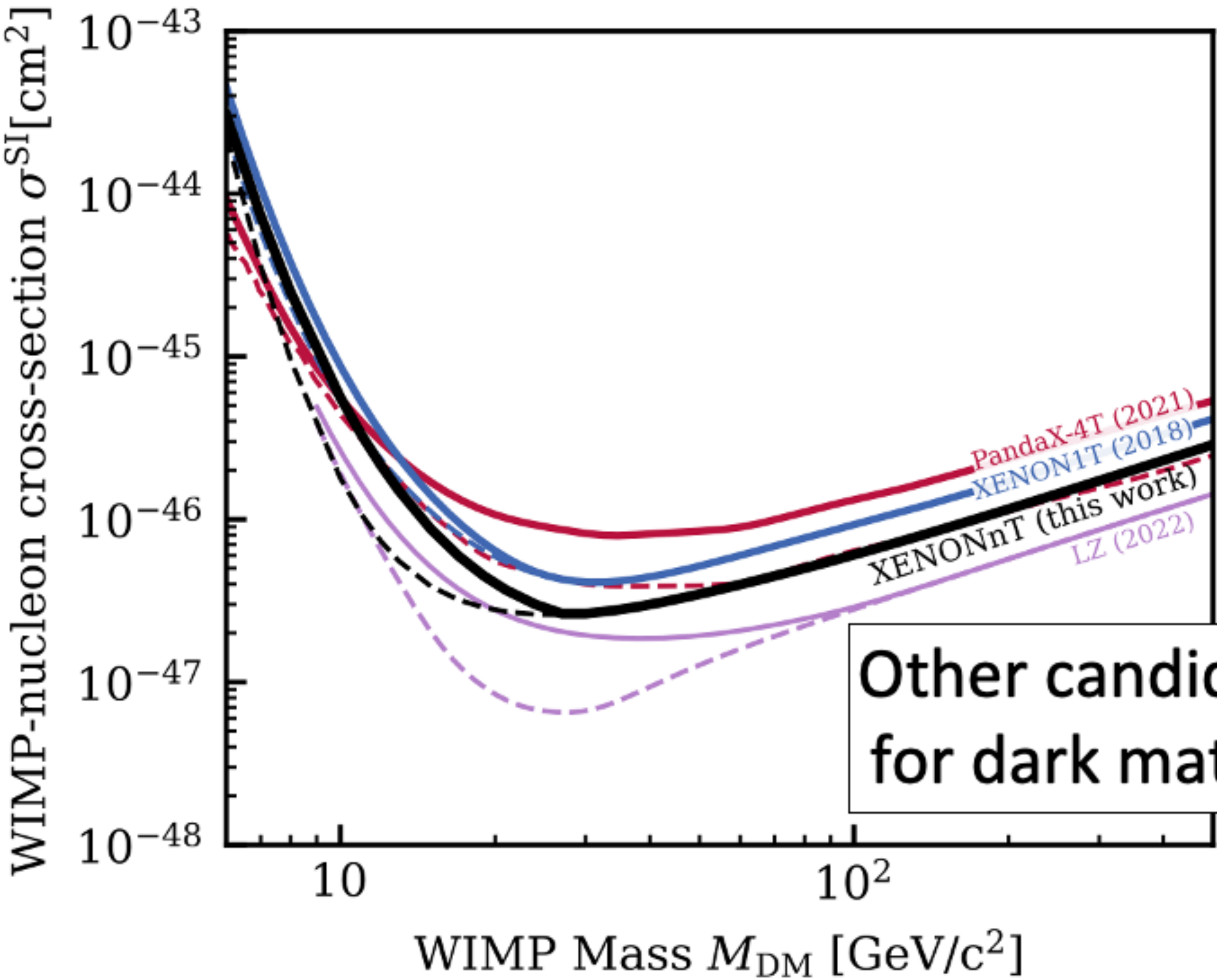
More of same?
Unexplored nooks?
Novel signatures?

Direct Dark Matter Detection

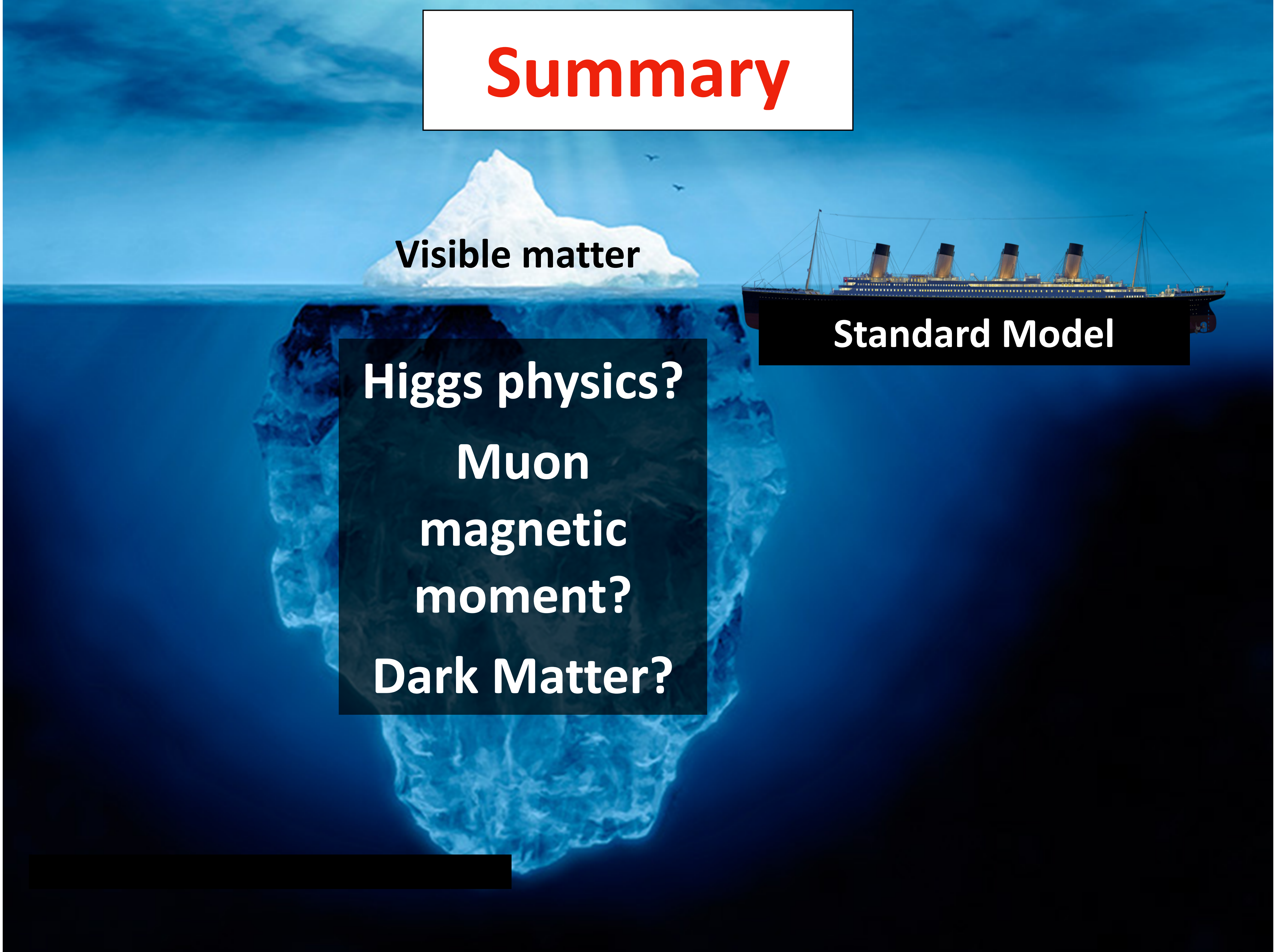


Direct Dark Matter Searches

Latest experimental results



Other candidates for dark matter?


Summary
Visible matter
Standard Model
Higgs physics?
Muon magnetic moment?
Dark Matter?
[redacted]