# Beyond the Standard Model

Review of Higgs physics
Motivations for physics beyond the SM:
Higgs mysteries
Status of $g_\mu - 2$

SM Effective Field Theory to scan for new physics
Dark matter: heavy fermions or light bosons?
New physics in gravitational waves?

70 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:

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

- Lagrangian:

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu}$$ gauge interactions

$$+ \; i\bar{\psi} \not{D} \psi + h.c.$$ matter fermions

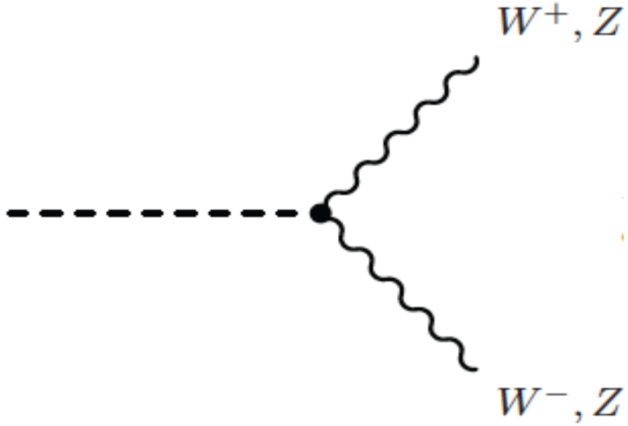
$$+ \; \psi_i y_{ij} \psi_j \phi + h.c.$$ Yukawa interactions

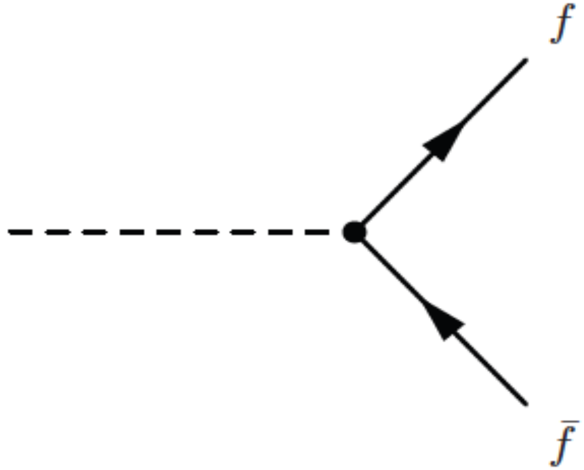
$$+ \; |D_\mu \phi|^2 - V(\phi)$$ Higgs potential

Tested < 0.1% before LHC

Testing now in progress

# Higgs Boson Couplings



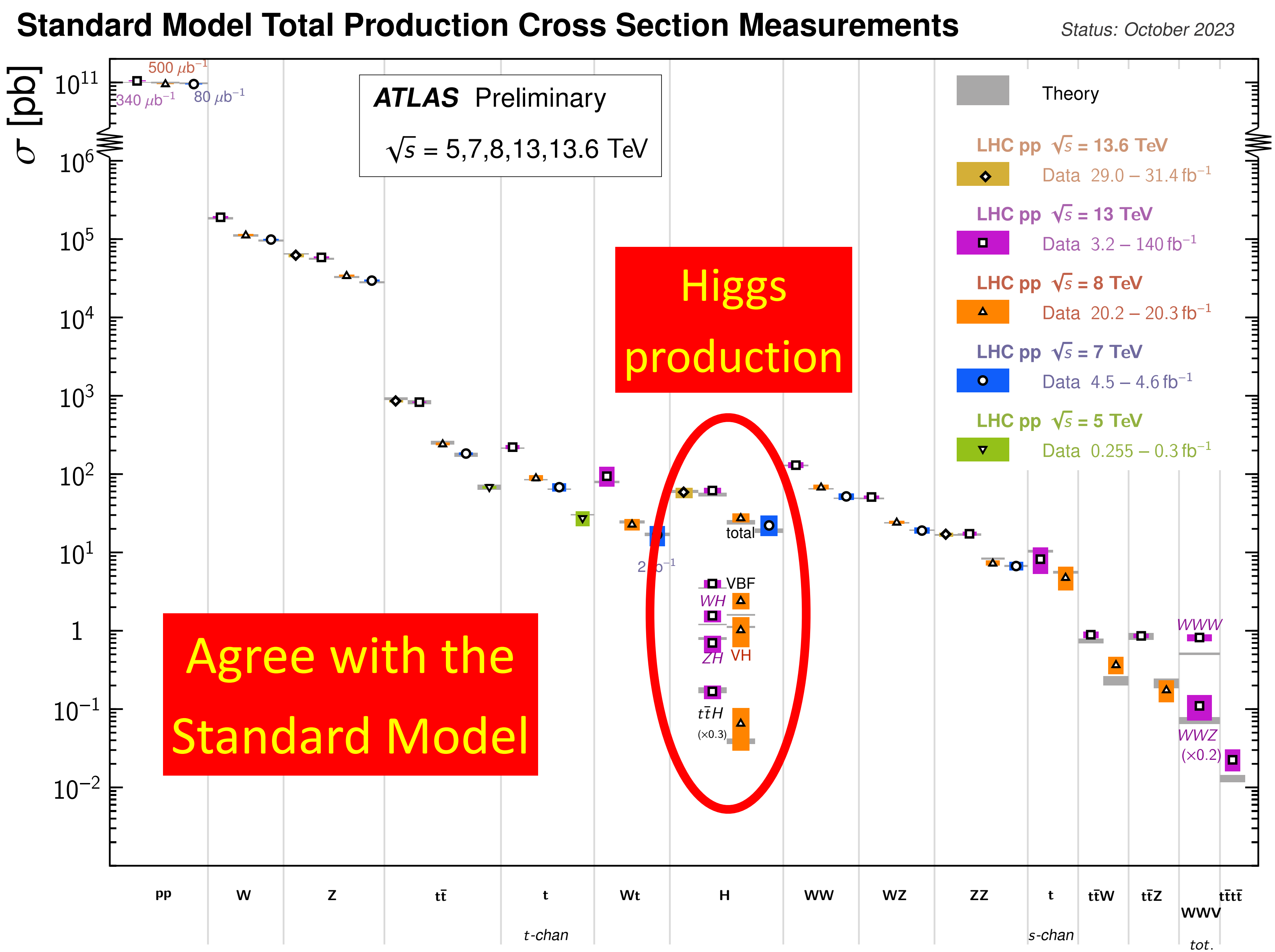




$g_2 M_W \; , \quad g_2 \frac{M_Z}{c_W}$ $\qquad\qquad$ $\frac{m_f}{v} = \frac{g_2 m_f}{2M_W}$

$$\Gamma(H \to f\bar{f}) = N_c \frac{G_F M_H}{4\pi\sqrt{2}} m_f^2, \quad N_C = 3\,(1) \text{ for quarks (leptons)}$$

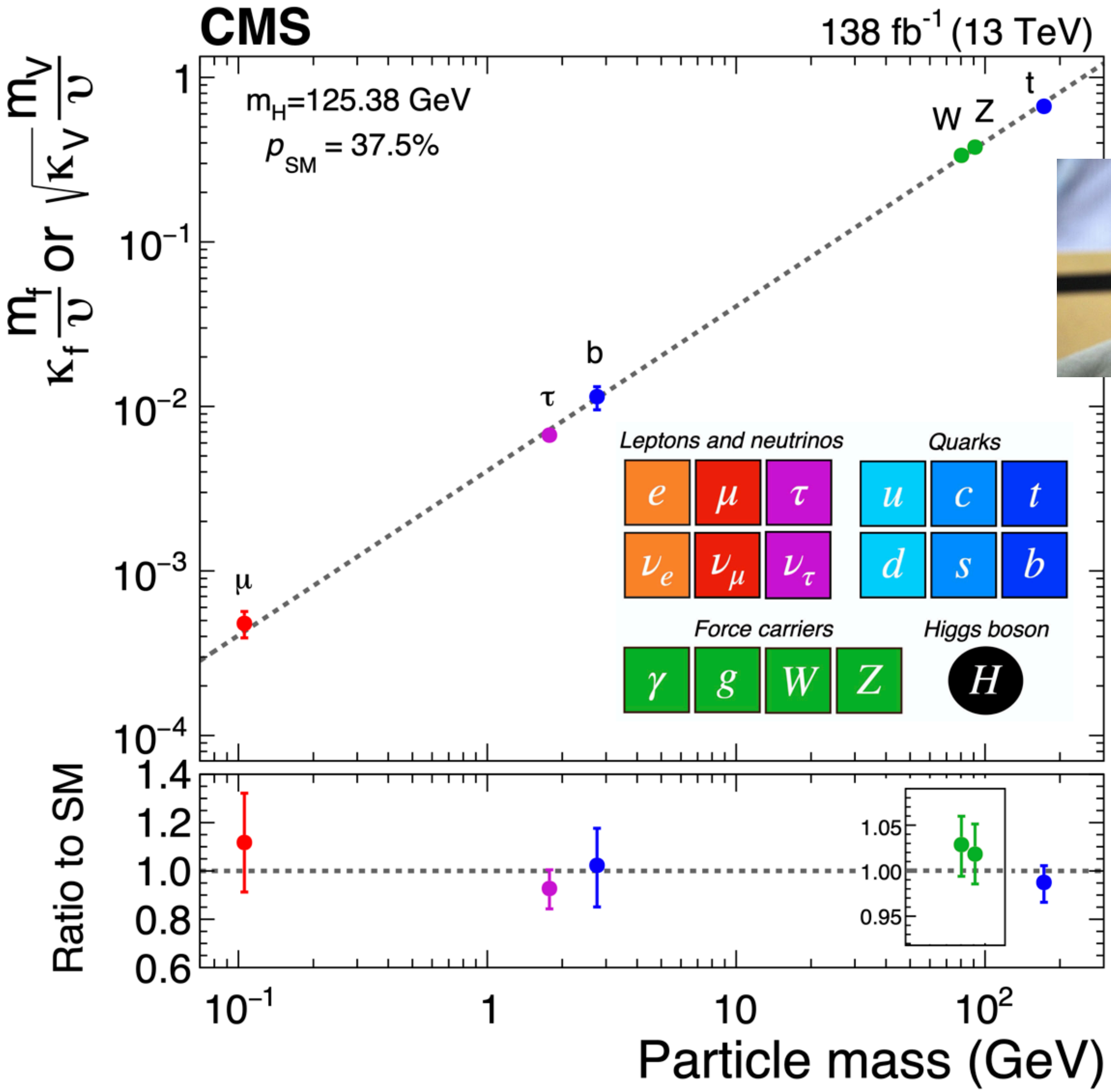
$$\Gamma(H \to VV) = \frac{G_F M_H^3}{8\pi\sqrt{2}} F(r) \left(\frac{1}{2}\right)_Z, \quad r = \frac{M_V}{M_H}$$

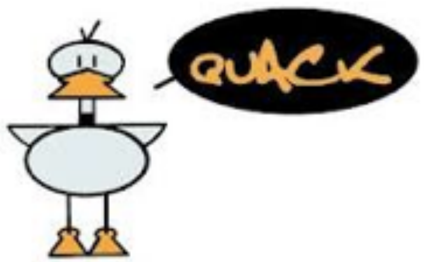
# LHC Measurements



# It Walks and Quacks like a Higgs

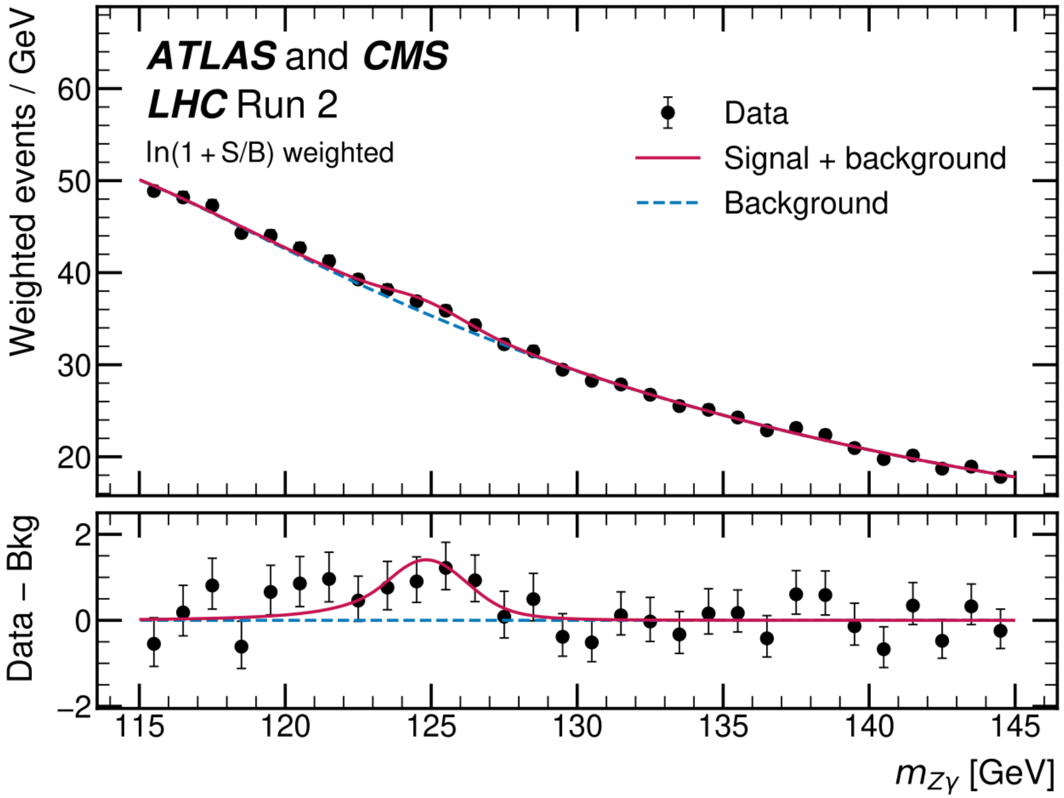
- Couplings scale ~ mass, with scale ~ v

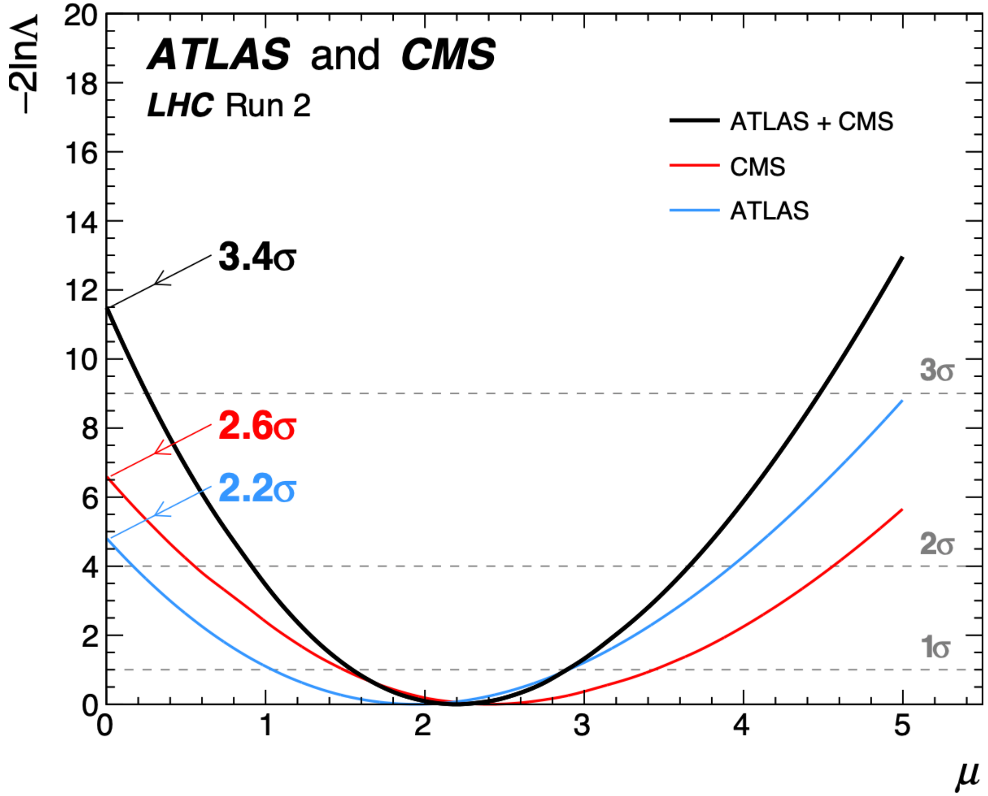


ATLAS & CMS, arXiv:2309.03501

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




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

Negligible change in NLO QCD

Higher-order EW unimportant

Statistics? BSM physics?

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

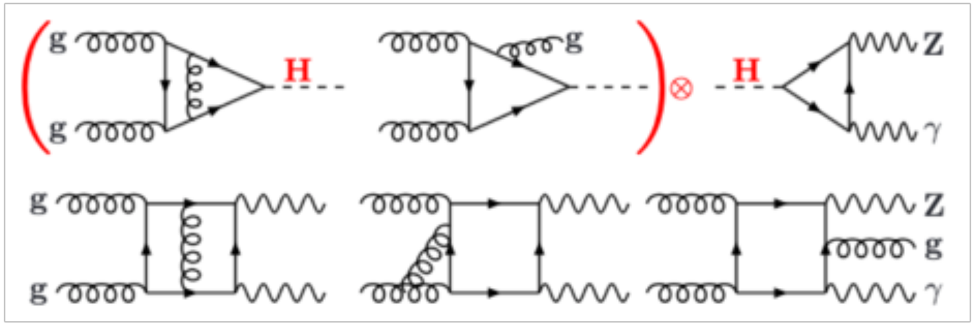
Chen, Chen, Qiao & Zhu, arXiv:2404.11441

Boto, Das, Romão, Saha & Silva, arXiv:2312.13050

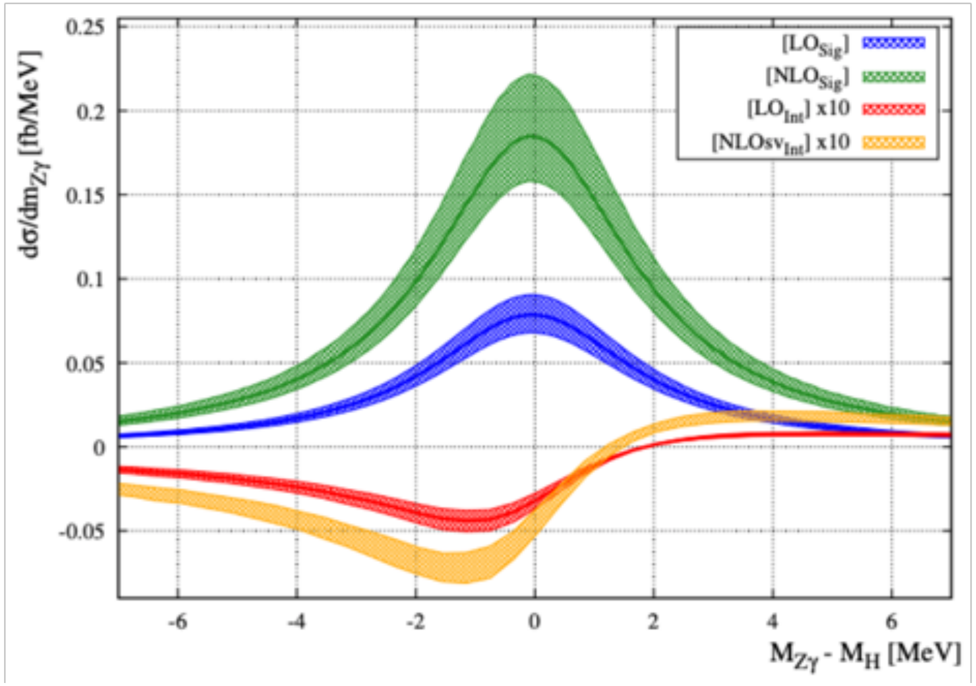
Buccioni, Devoto, Djouadi, JE, Quevillon, Tancredi, arXiv:2312.12384

# QCD Corrections to $H \to Z\gamma$

NLO QCD diagrams for signal and background




NLO QCD increases cross-section by factor ~ 2



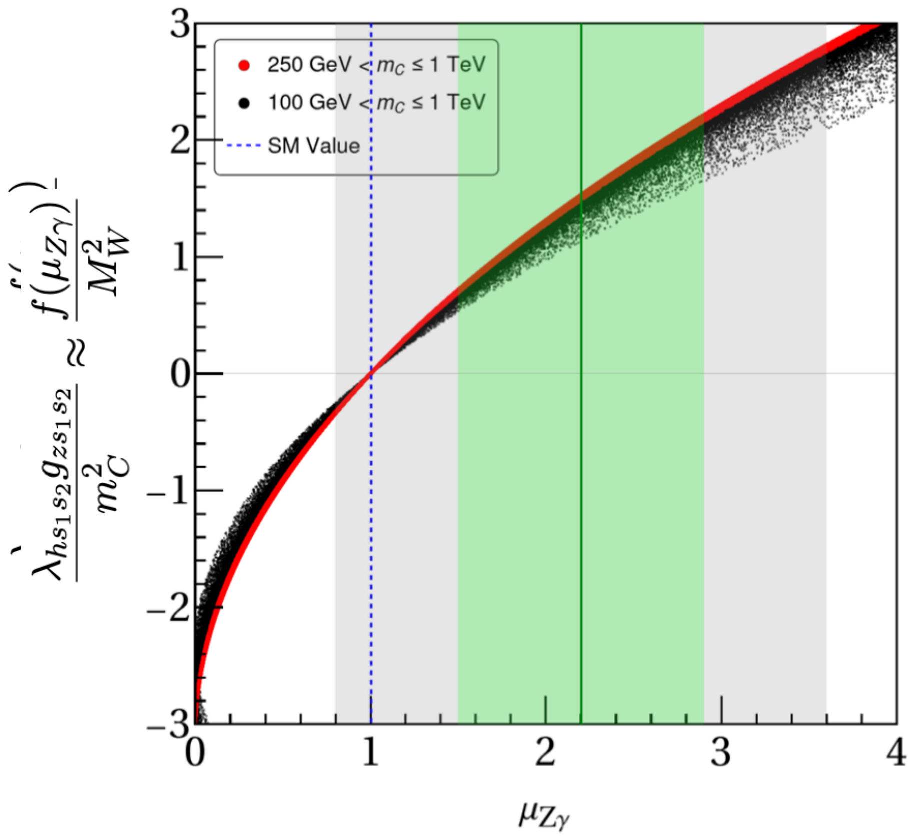

Negative interference – but blown up by factor 10 in plot

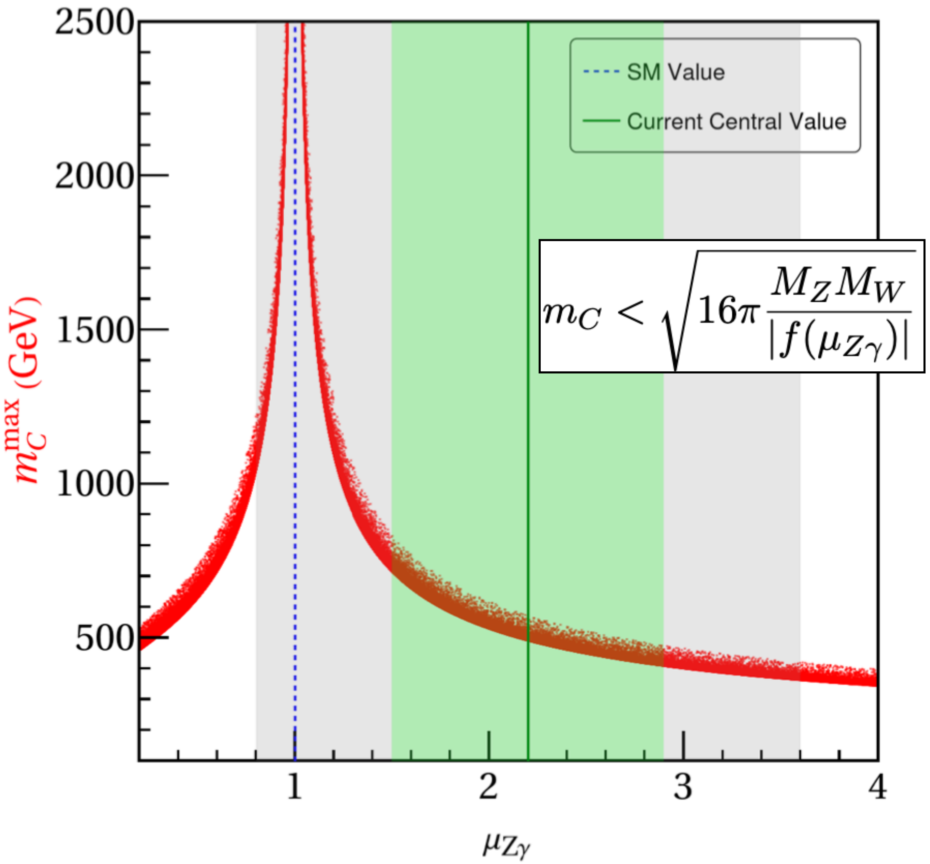
Reduces cross-section by 3%: $\sigma_{\rm Sig}^{\rm NLO} = 1.207^{+20\%}_{-15\%}$ fb, $\sigma_{\rm Int}^{\rm NLOsv} = -0.0344^{+12\%}_{-12\%}$ fb

# BSM Scenario for $H \to Z\gamma$

$$\mathscr{L}_S^{\rm int} = \lambda_{hs_is_j} M_W\, h\, S_i^{+Q} S_j^{-Q} + i\, g_{zs_is_j} Z^\mu \left\{ \left(\partial_\mu S_i^{+Q}\right) S_j^{-Q} - \left(\partial_\mu S_j^{-Q}\right) S_i^{+Q} \right\}$$
$$+ eQ g_{zs_is_j} A^\mu Z_\mu S_i^{+Q} S_j^{-Q} + g_{zzs_is_j} Z^\mu Z_\mu S_i^{+Q} S_j^{-Q} + \text{h.c.}\,,$$

Mixing parameter: $\dfrac{\lambda_{hs_1s_2} g_{zs_1s_2}}{m_C^2} \approx \dfrac{f(\mu_{Z\gamma})}{M_W^2}$



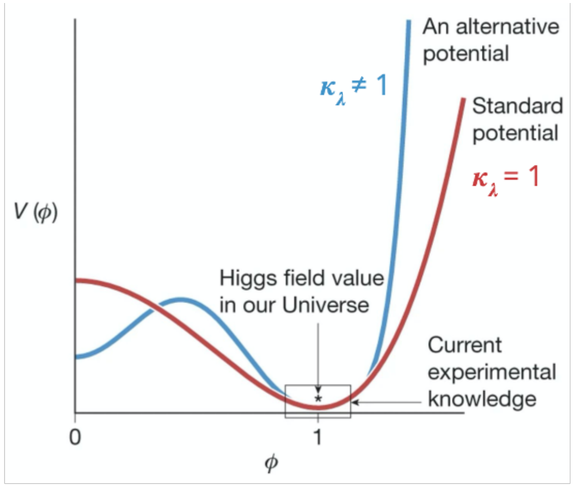




Boto, Das, Romão, Saha & Silva, arXiv:2312.13050

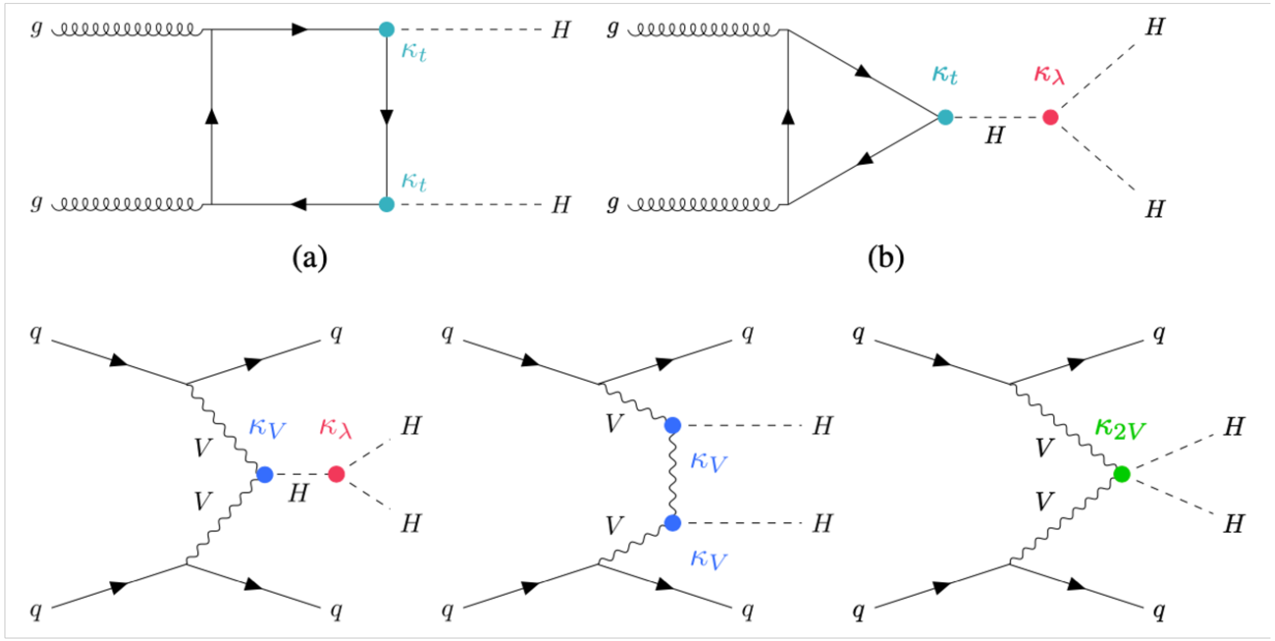
# Higher-Order Higgs Couplings

- 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 $|H|^2|D_\mu H|^2$ **BSM physics?**
- Parameterized by $\kappa_\lambda, \kappa_{2V}$, respectively
- **Measuring them is next frontier in Higgs measurements**

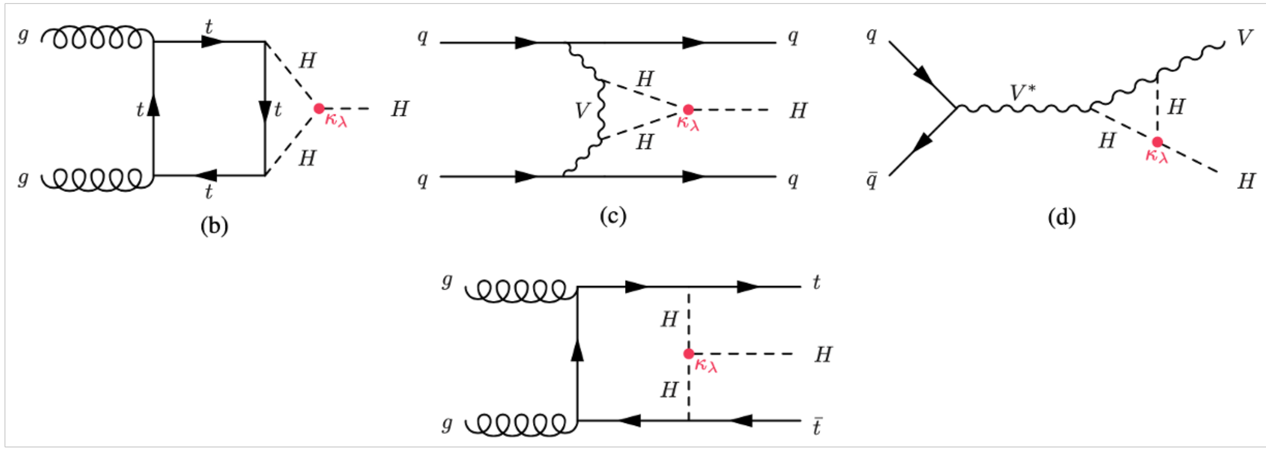
# Search for Triple-H Coupling




Diagrams for double-Higgs production



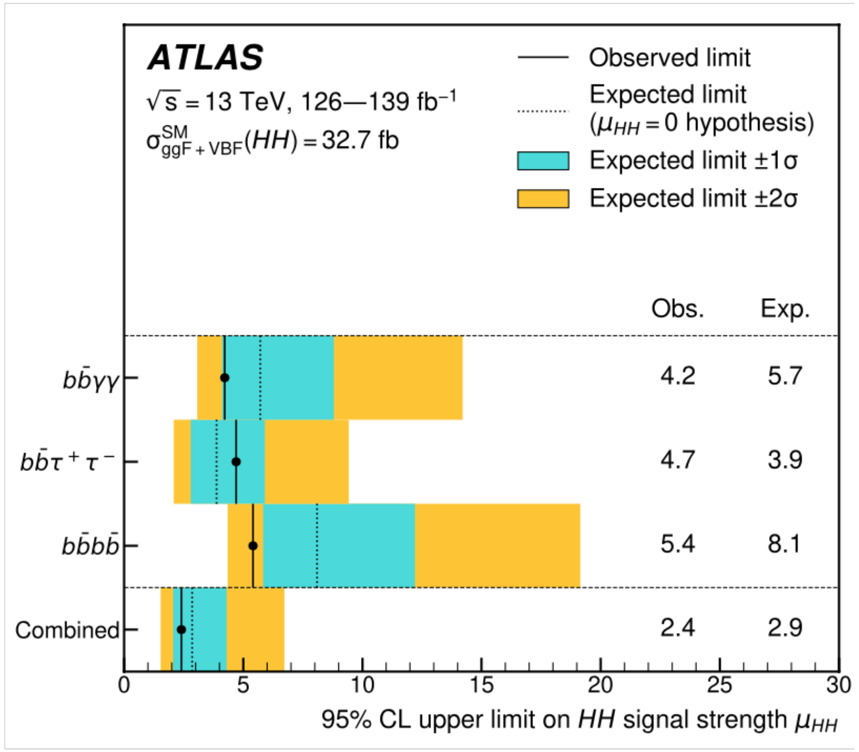

Loop corrections to single Higgs production



ATLAS Collaboration, arXiv: 2211.01216

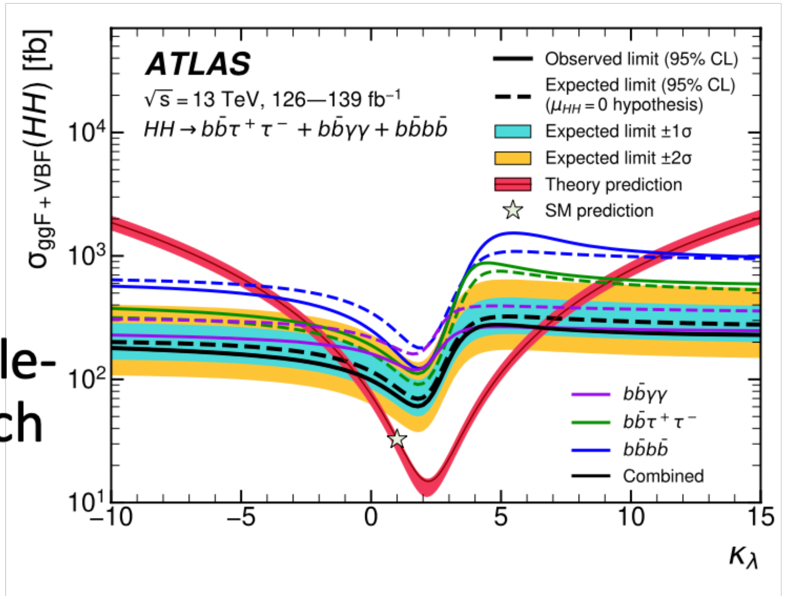
# Search for HHH Coupling

## Limit on double-Higgs production

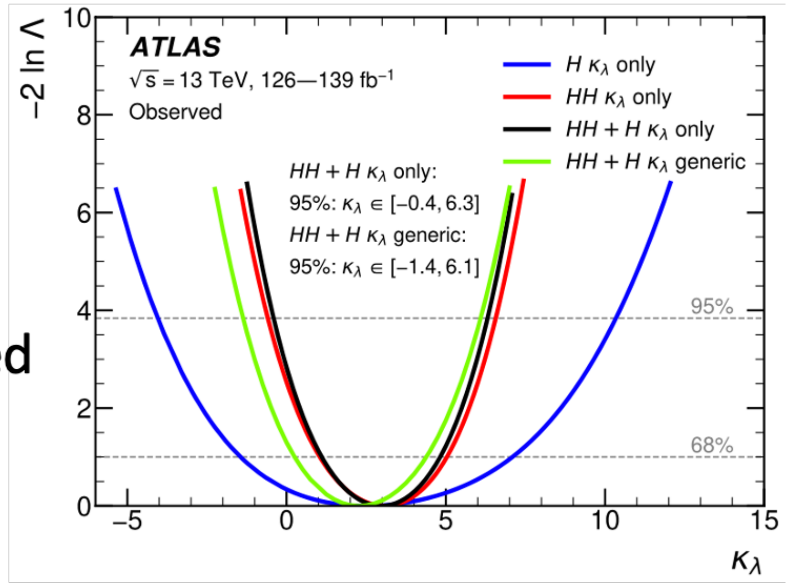



## Limits on triple-Higgs coupling

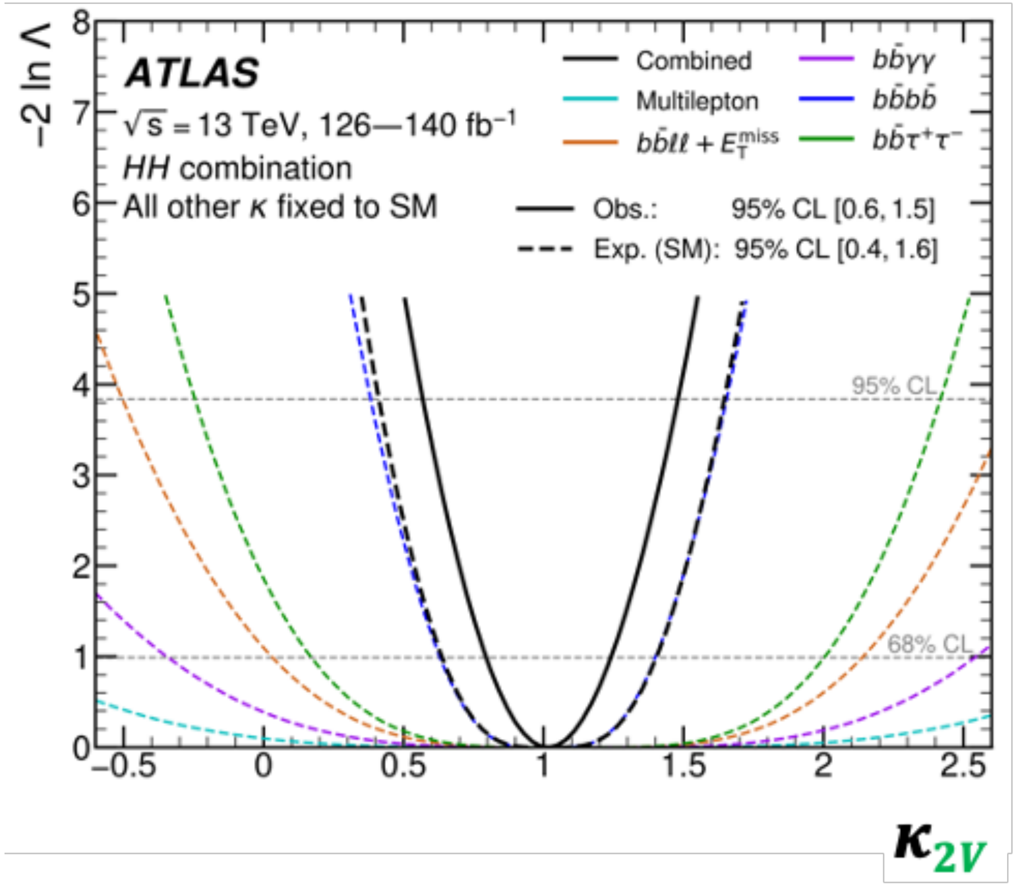
From double-Higgs search

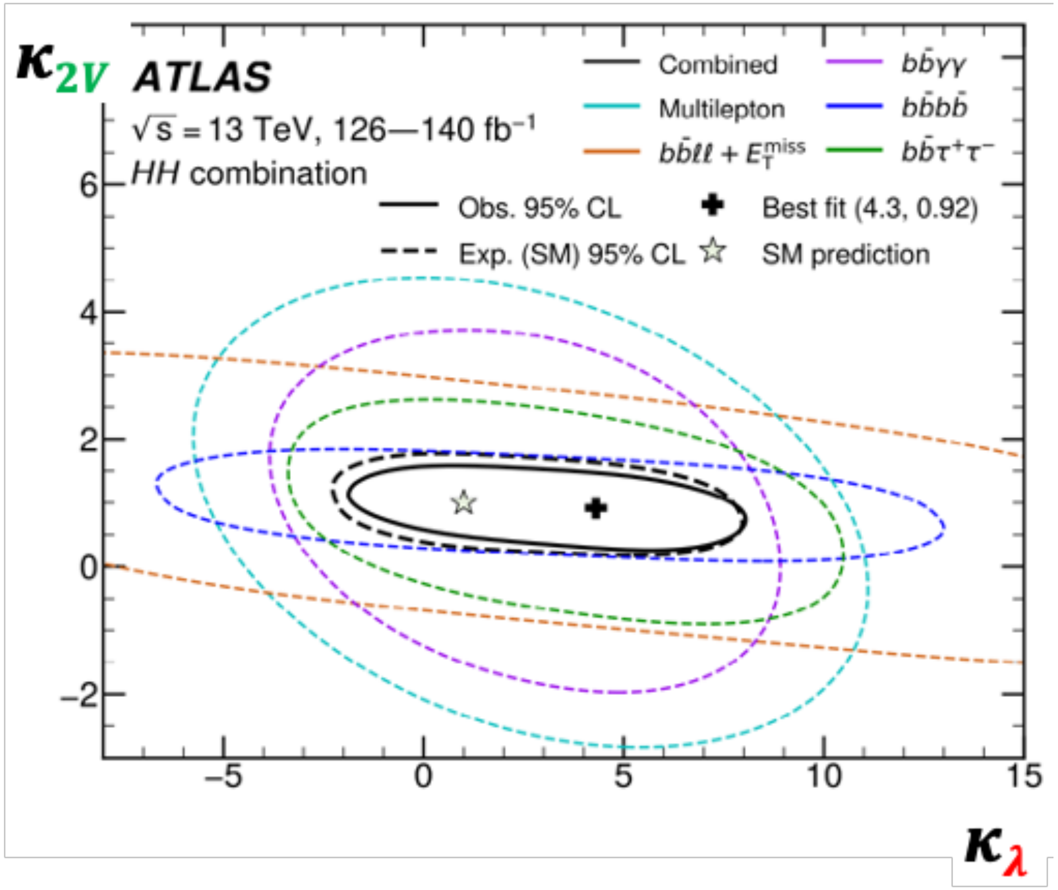



Combined limit



# Evidence for VVHH Coupling

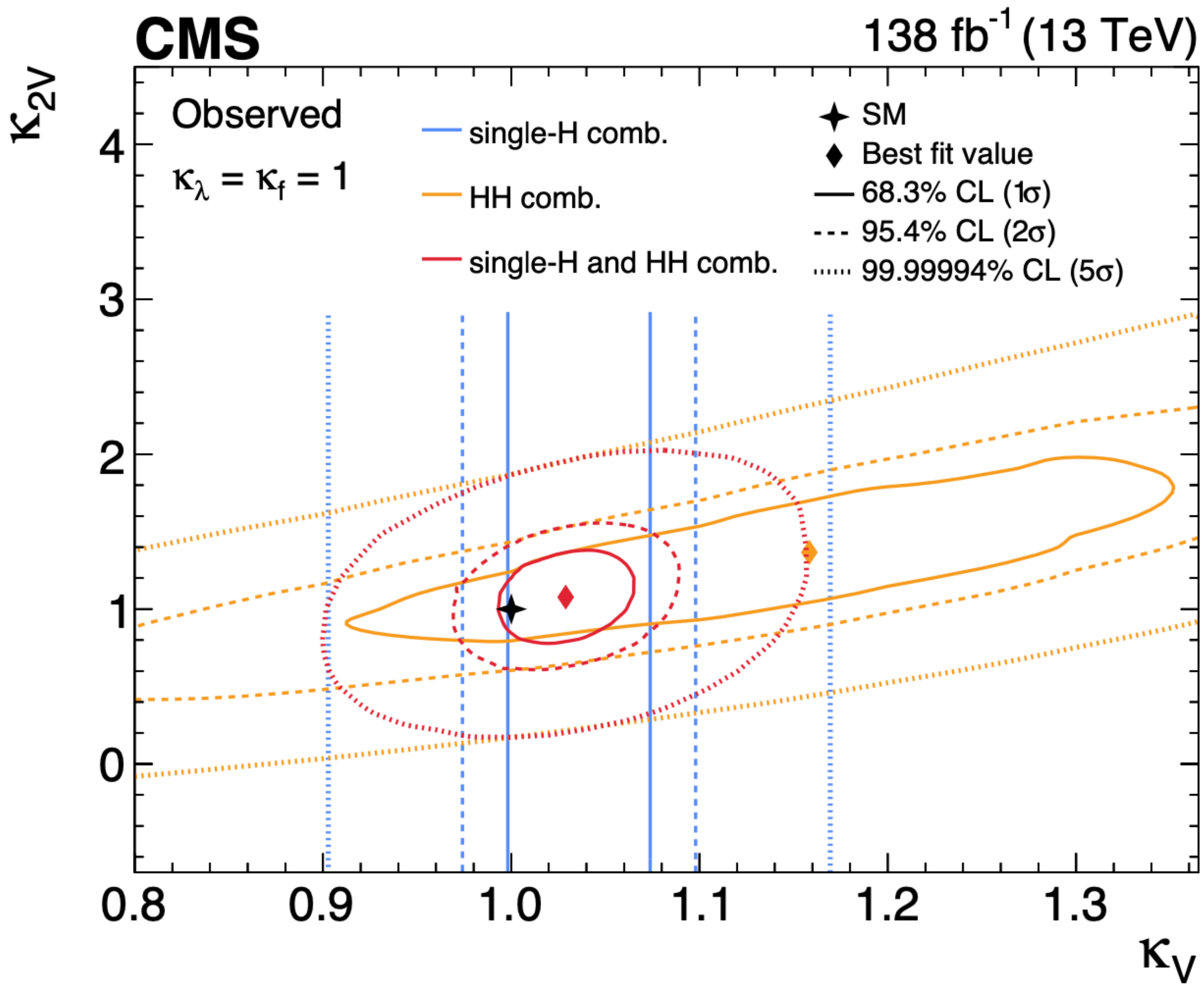



$\kappa_{2V} = 1.02 \pm 0.23$ if other Higgs couplings have Standard Model values

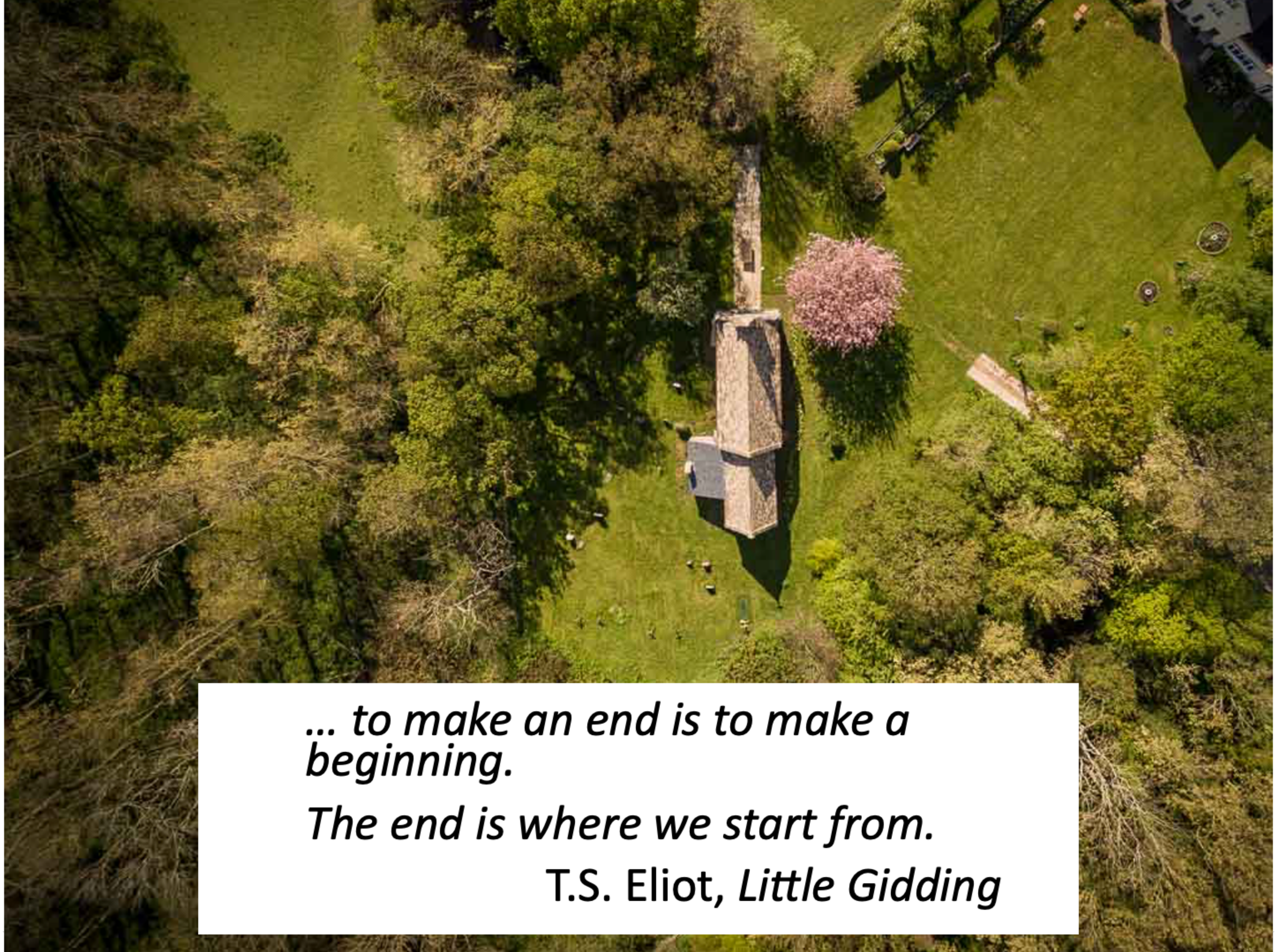
ATLAS Collaboration, arXiv:2406.09971

# Evidence for VVHH Coupling




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

CMS Collaboration, arXiv:2407.13554



*… 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 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
• Dark matter
• Origin of matter
• Sizes of masses
• Masses of neutrinos
• Inflation
• Quantum gravity
• …
LHC
LHC
LHC
LHC
The Standard Model
Not Enough
007

# Everything about Higgs is Puzzling

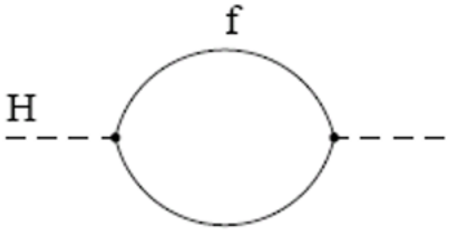
$$\mathcal{L} = yH\psi\overline{\psi} + \mu^2|H|^2 - \lambda|H|^4 - V_0 \quad + \ldots$$

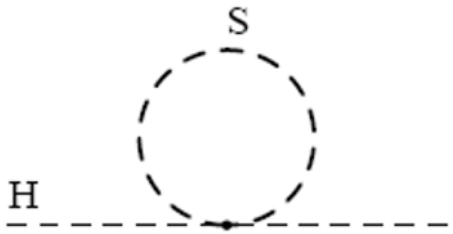
- Pattern of Yukawa couplings y:
  - **Flavour problem**
- Magnitude of mass term μ:
  - **Naturalness/hierarchy problem**
- Magnitude of quartic coupling λ:
  - **Stability of electroweak vacuum**
- Cosmological constant term $V_0$:
  - **Dark energy**

Higher-dimensional interactions?

# 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

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

**Supersymmetry!**

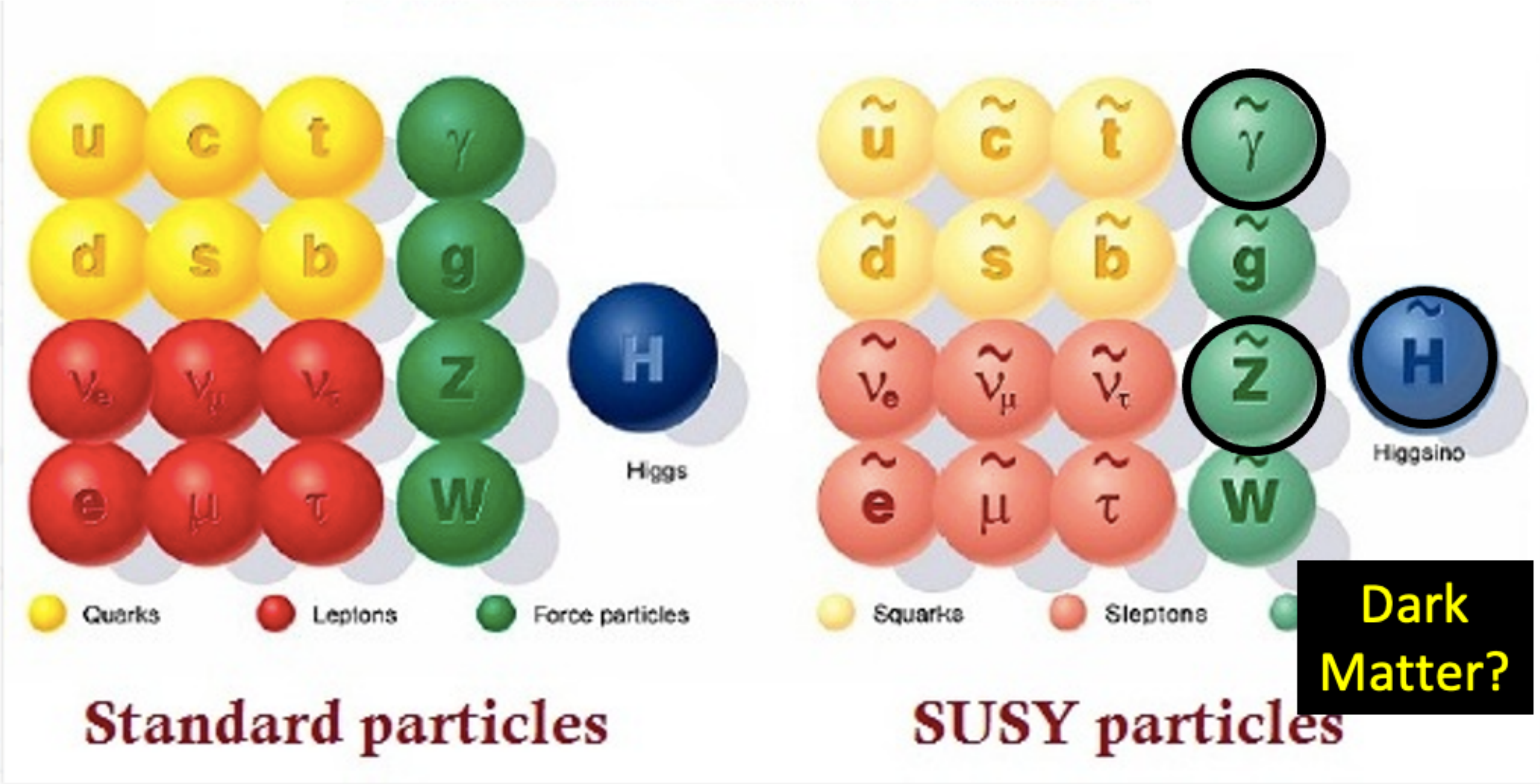
# What lies beyond the Standard Model?

# 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**, $g_\mu - 2$?… ,

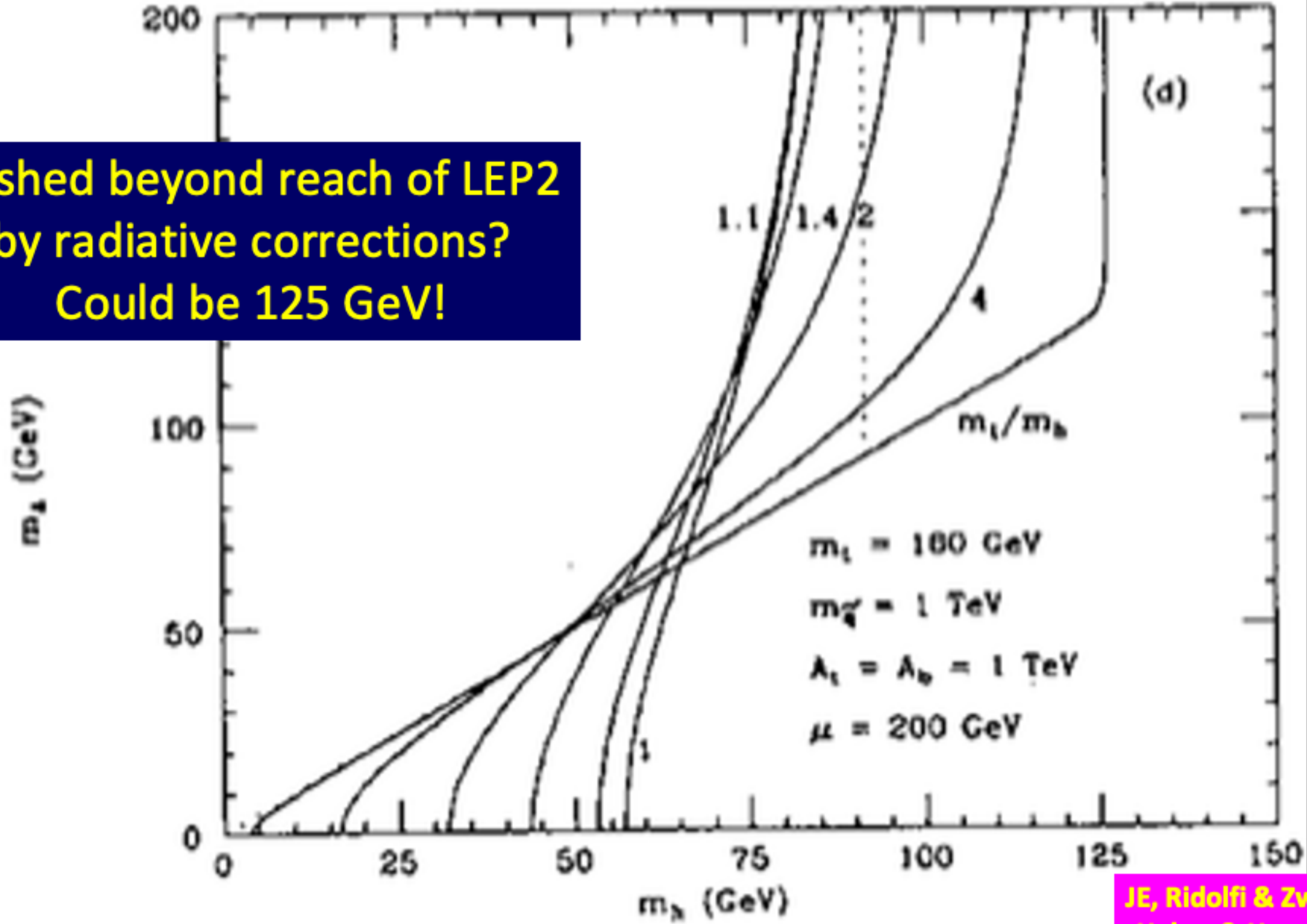
# Minimal Supersymmetric Extension of the Standard Model



1990/1

# Higgs Mass in Supersymmetry

Pushed beyond reach of LEP2 by radiative corrections? Could be 125 GeV!




JE, Ridolfi & Zwirner; Haber & Hempfling

# Grand Unification

- At one-loop order without/**with** supersymmetry:

$$b_i = \begin{pmatrix} 0 \\ -\frac{22}{3} \\ -11 \end{pmatrix} + N_g \begin{pmatrix} \frac{4}{3} \\ \frac{4}{3} \\ \frac{4}{3} \end{pmatrix} + N_H \begin{pmatrix} \frac{1}{10} \\ \frac{1}{6} \\ 0 \end{pmatrix}$$

$$b_i = \begin{pmatrix} 0 \\ -6 \\ -9 \end{pmatrix} + N_g \begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix} + N_H \begin{pmatrix} \frac{3}{10} \\ frac12 \\ 0 \end{pmatrix}$$

- At two-loop order without/**with** supersymmetry:

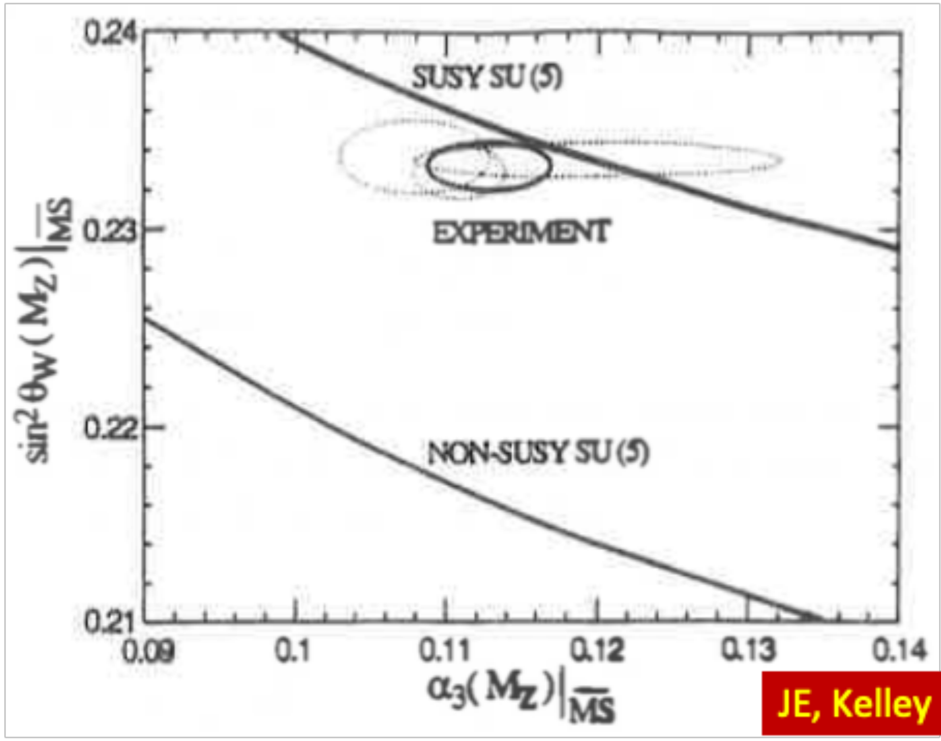
$$b_{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -\frac{136}{3} & 0 \\ 0 & 0 & -102 \end{pmatrix} + N_g \begin{pmatrix} \frac{19}{15} & \frac{3}{5} & \frac{44}{15} \\ \frac{1}{5} & \frac{49}{3} & 4 \\ \frac{4}{30} & \frac{3}{2} & \frac{76}{3} \end{pmatrix} + N_H \begin{pmatrix} \frac{9}{50} & \frac{9}{10} & 0 \\ \frac{3}{10} & \frac{13}{6} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$b_{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -24 & 0 \\ 0 & 0 & -54 \end{pmatrix} + N_g \begin{pmatrix} \frac{38}{15} & \frac{6}{5} & \frac{88}{15} \\ \frac{2}{5} & 14 & 8 \\ \frac{11}{5} & 3 & \frac{68}{3} \end{pmatrix} + N_H \begin{pmatrix} \frac{9}{50} & \frac{9}{10} & 0 \\ \frac{3}{10} & \frac{7}{2} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

- At three-loop order …

1991

# LEP Data Consistent with Supersymmetric Grand Unification




JE, Kelley & Nanopoulos

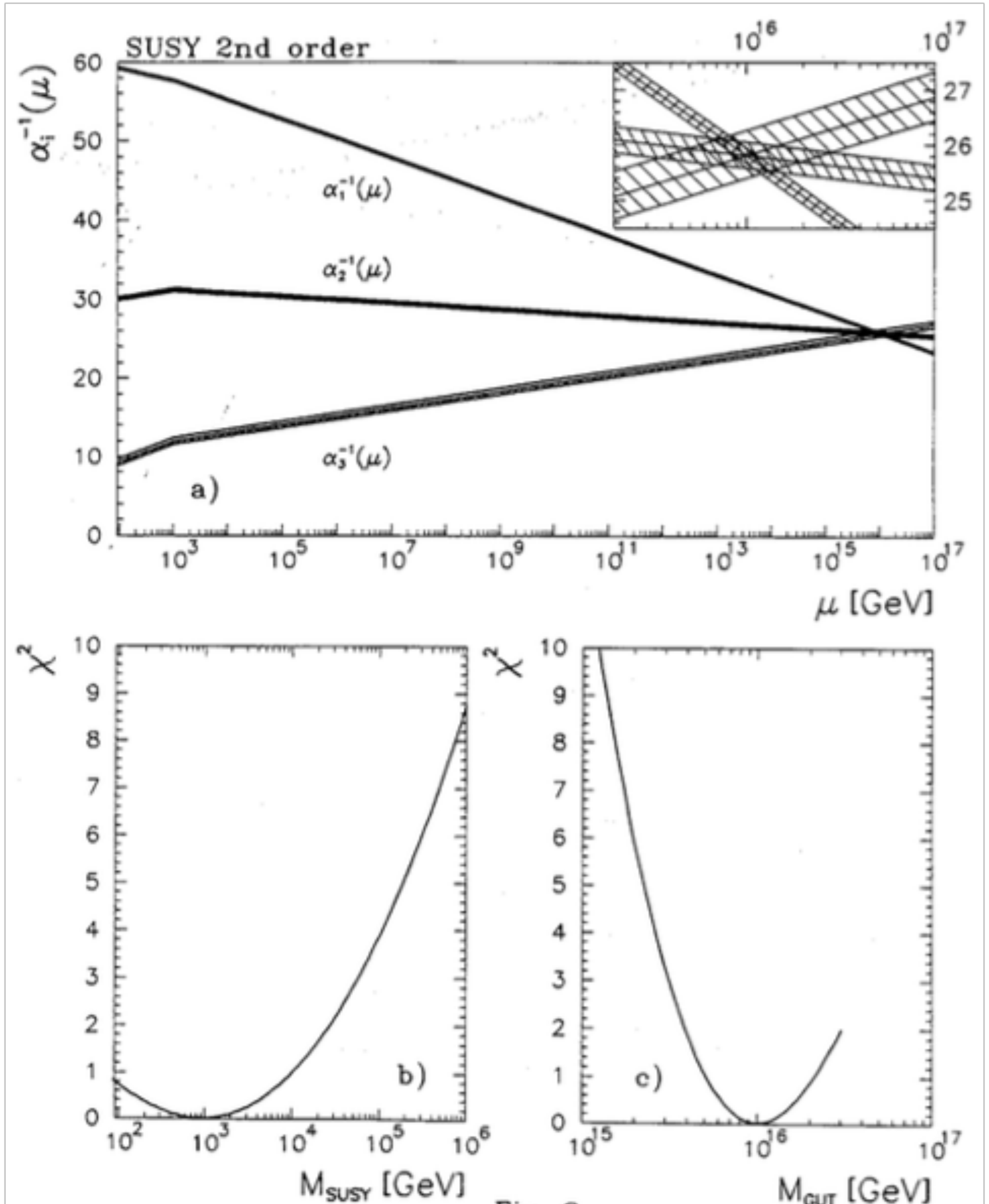
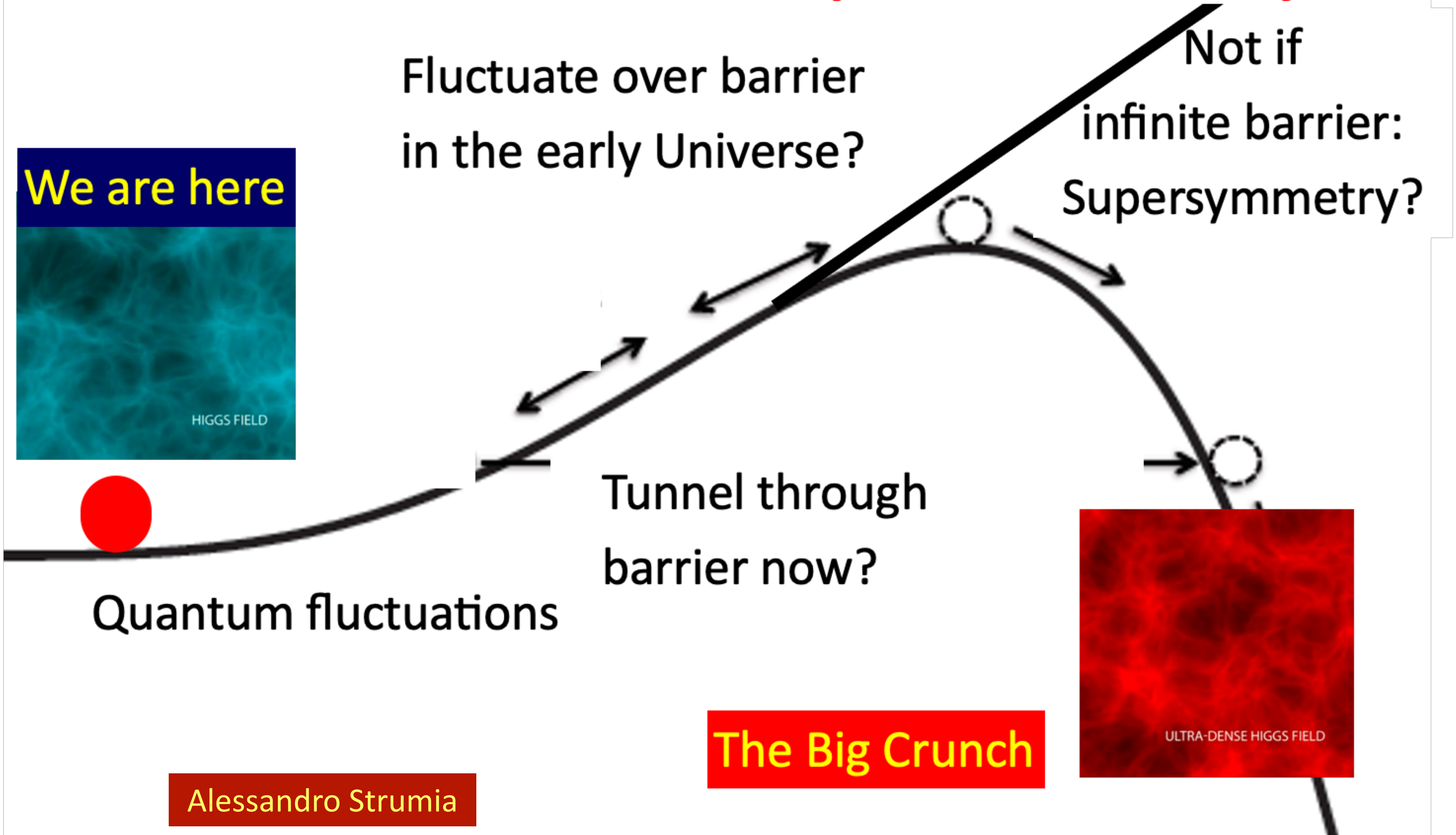



Fig. 2

Amaldi, de Boer & Furstenau

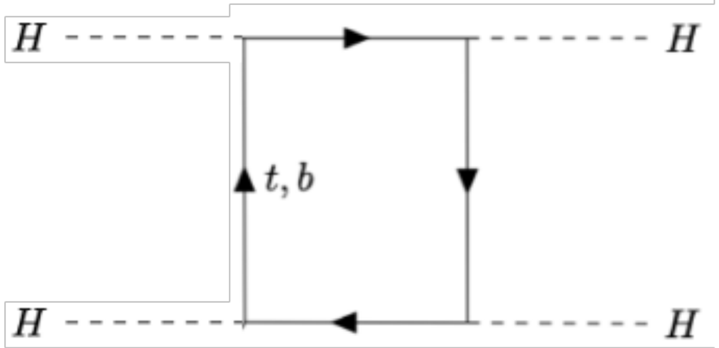
# Will the Universe Collapse?

# Should it have Collapsed already?



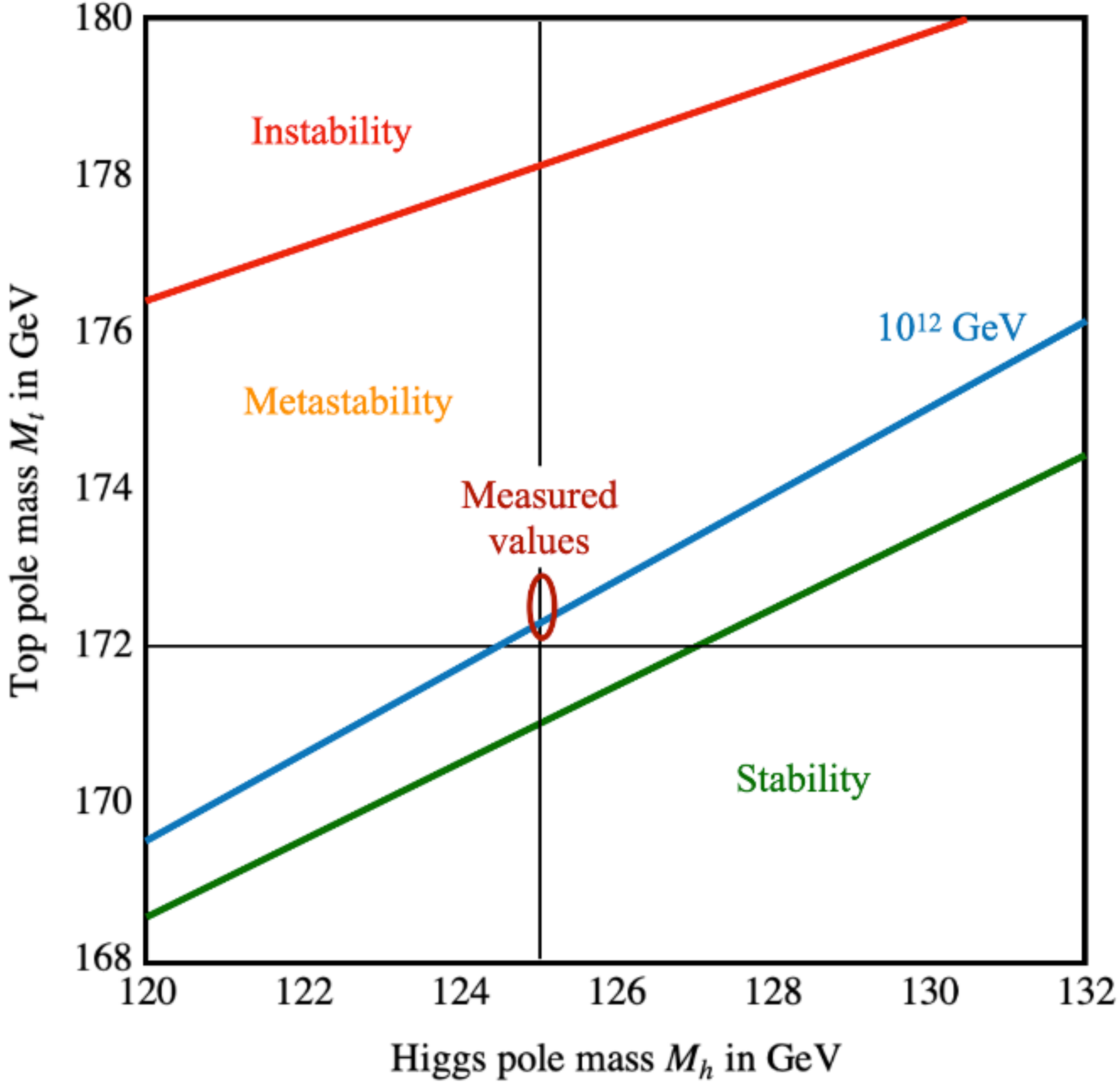
# Is “Empty Space” Unstable?

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

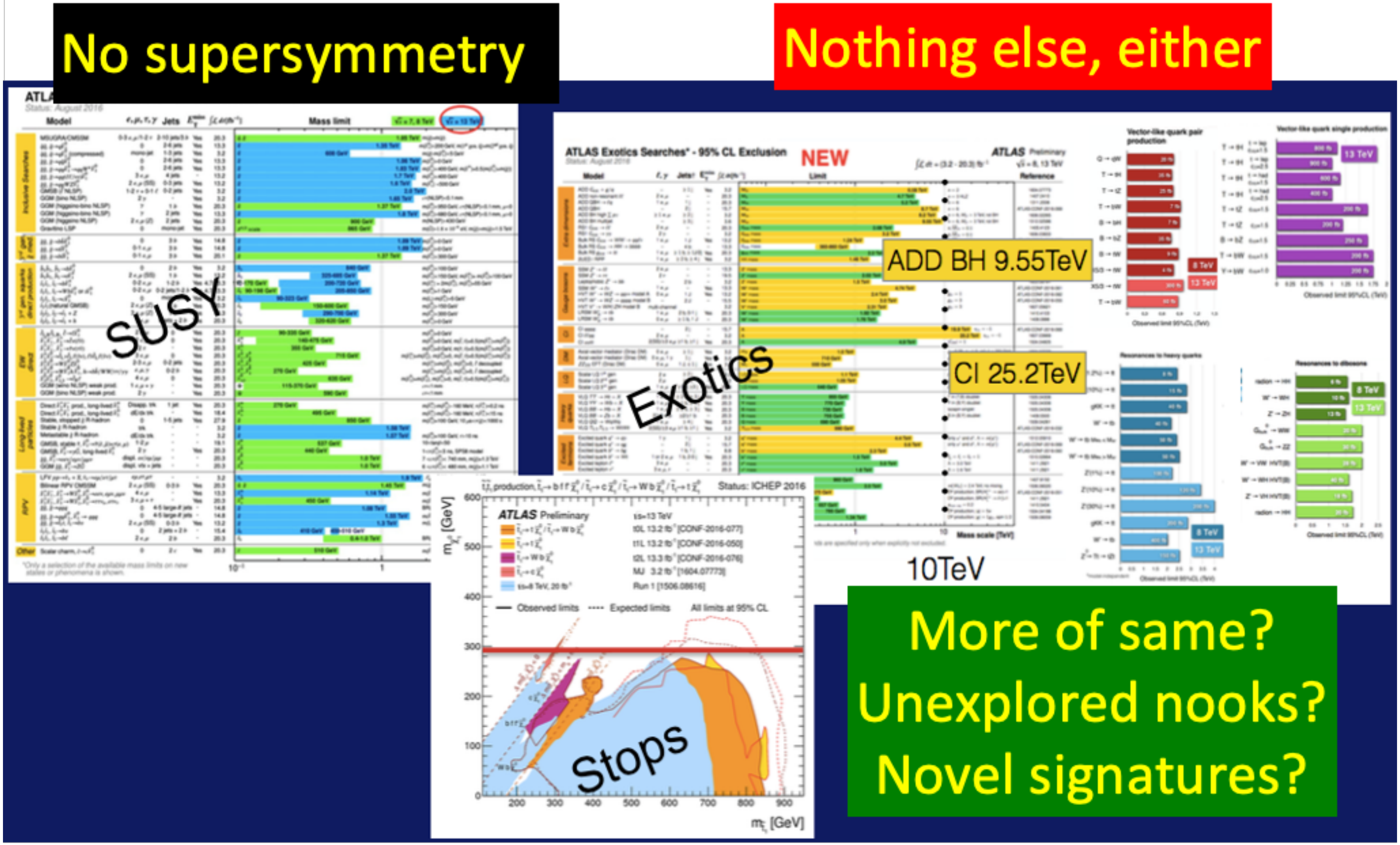
ATLAS, arXiv:2309.12986

- Instability scale:

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

- Dominant uncertainties those in $\alpha_s$ and $m_t$

# Nothing (yet) at the LHC

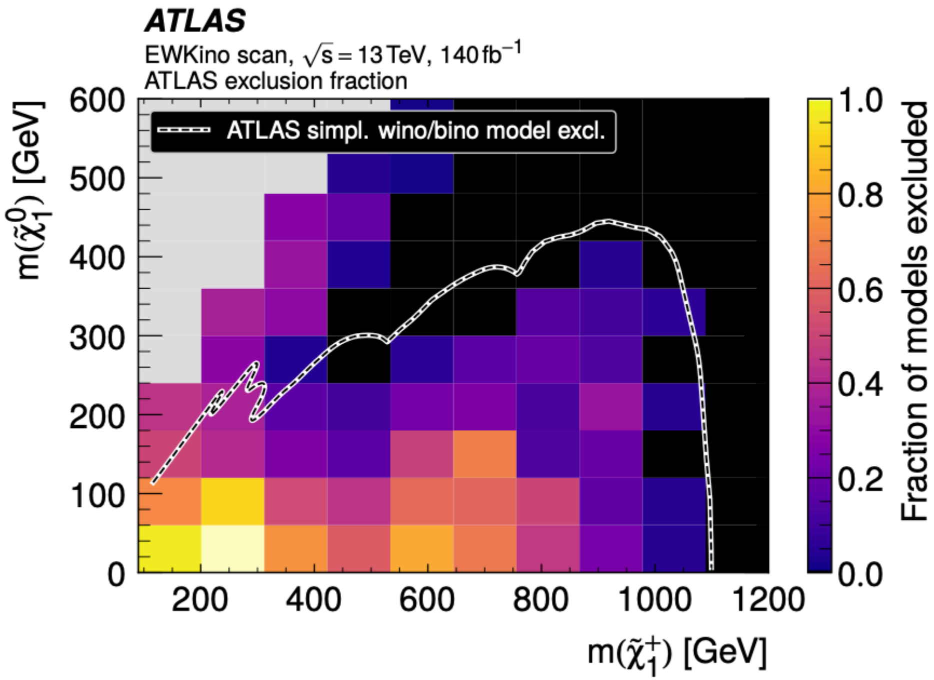


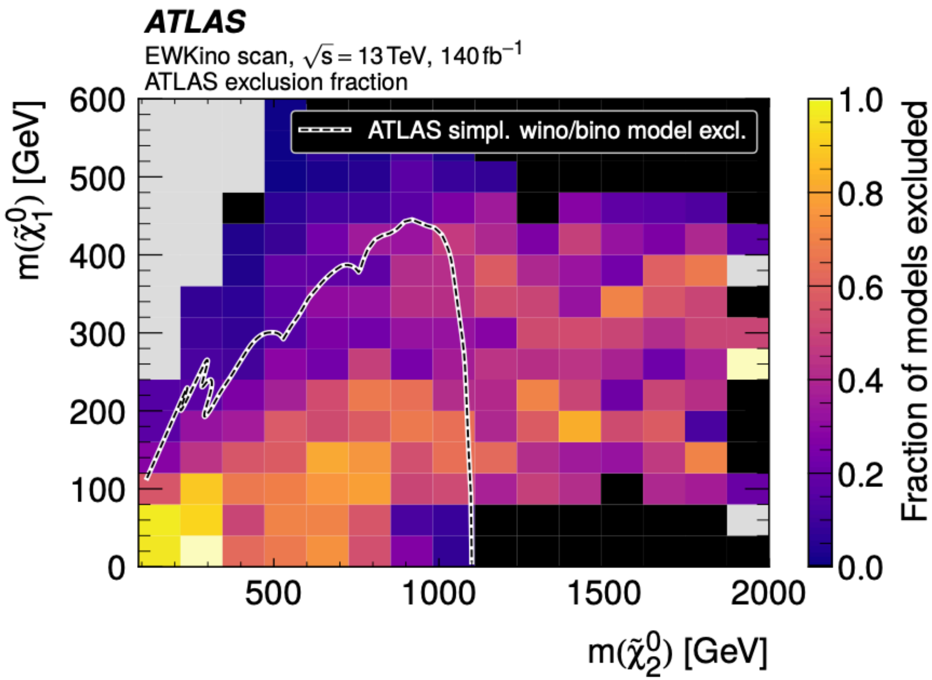
# Survey of SUSY searches in pMSSM

Lines = chargino/neutralino 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

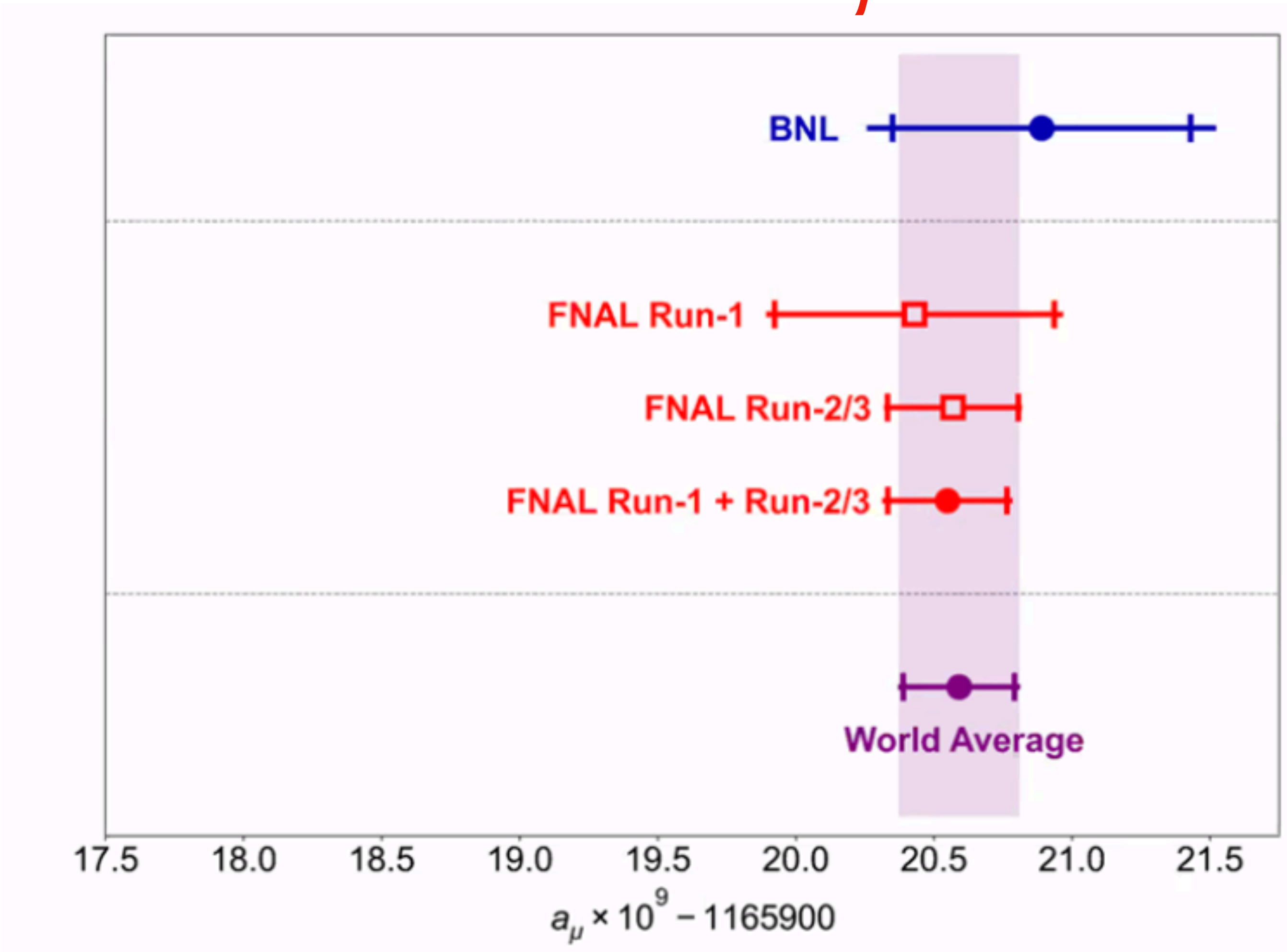
**“Not dead yet”**

Monty Python and the Holy Grail


# $g_\mu - 2$:

## Dawn of new physics or its sunset?

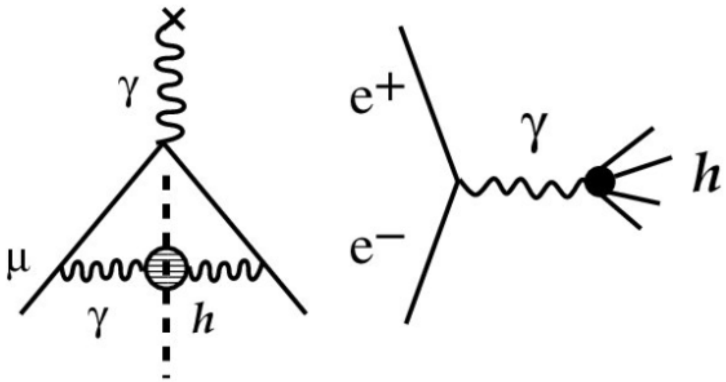
# Quo Vadis $g_\mu - 2$?




- 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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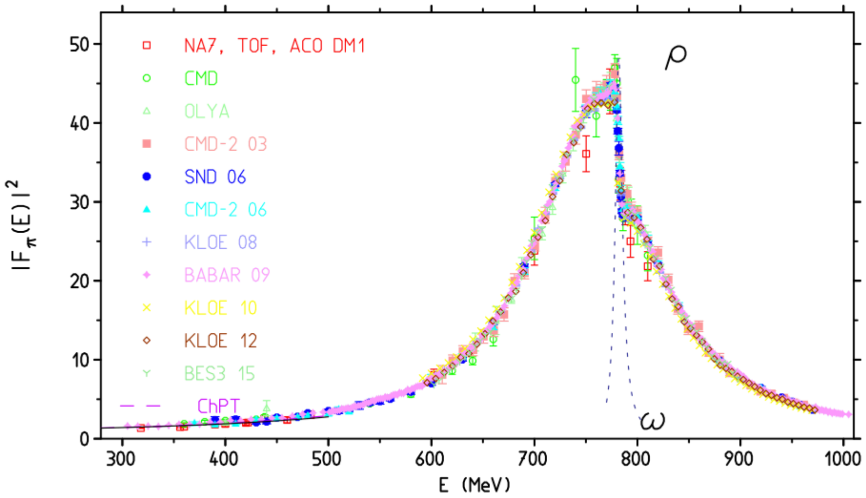
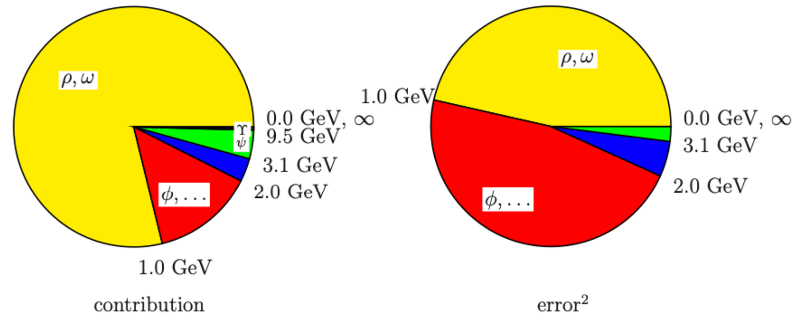
# Hadronic Vacuum Polarization

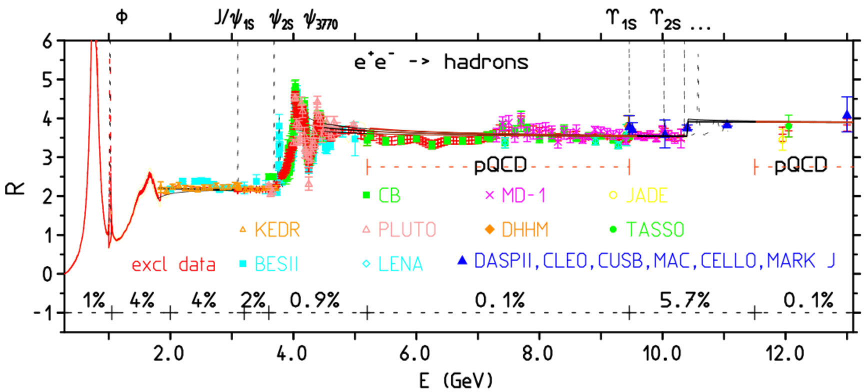
- Most important contribution is from low energies $\lesssim 1$ GeV, dominated by $\rho$ and $\omega$ peaks, taking account of interference effects




- Uncertainties dominated by $\rho$ and $\omega$ region, and by region between 1 and 2 GeV ($\phi$, etc.)



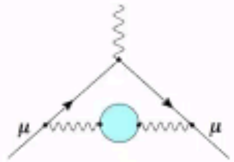

- High energies under good control from perturbative QCD



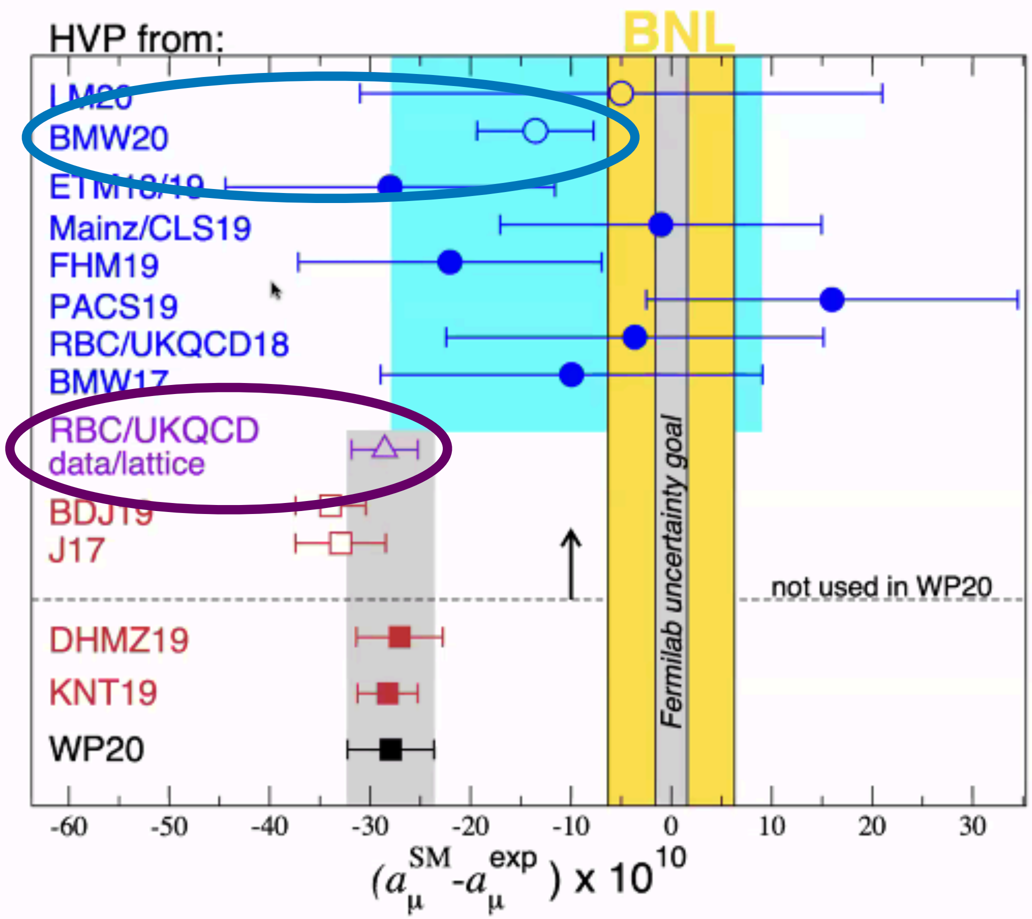

$$a_\mu^{\text{HVP, LO}} = 693.1(2.8)_{\text{exp}}(2.8)_{\text{sys}}(0.7)_{\text{DV+QCD}} \times 10^{-10}$$
$$= 693.1(4.0) \times 10^{-10}\,.$$

Aoyama et al, arXiv:2006.04822

# Lattice Calculations of Hadronic Vacuum Polarization

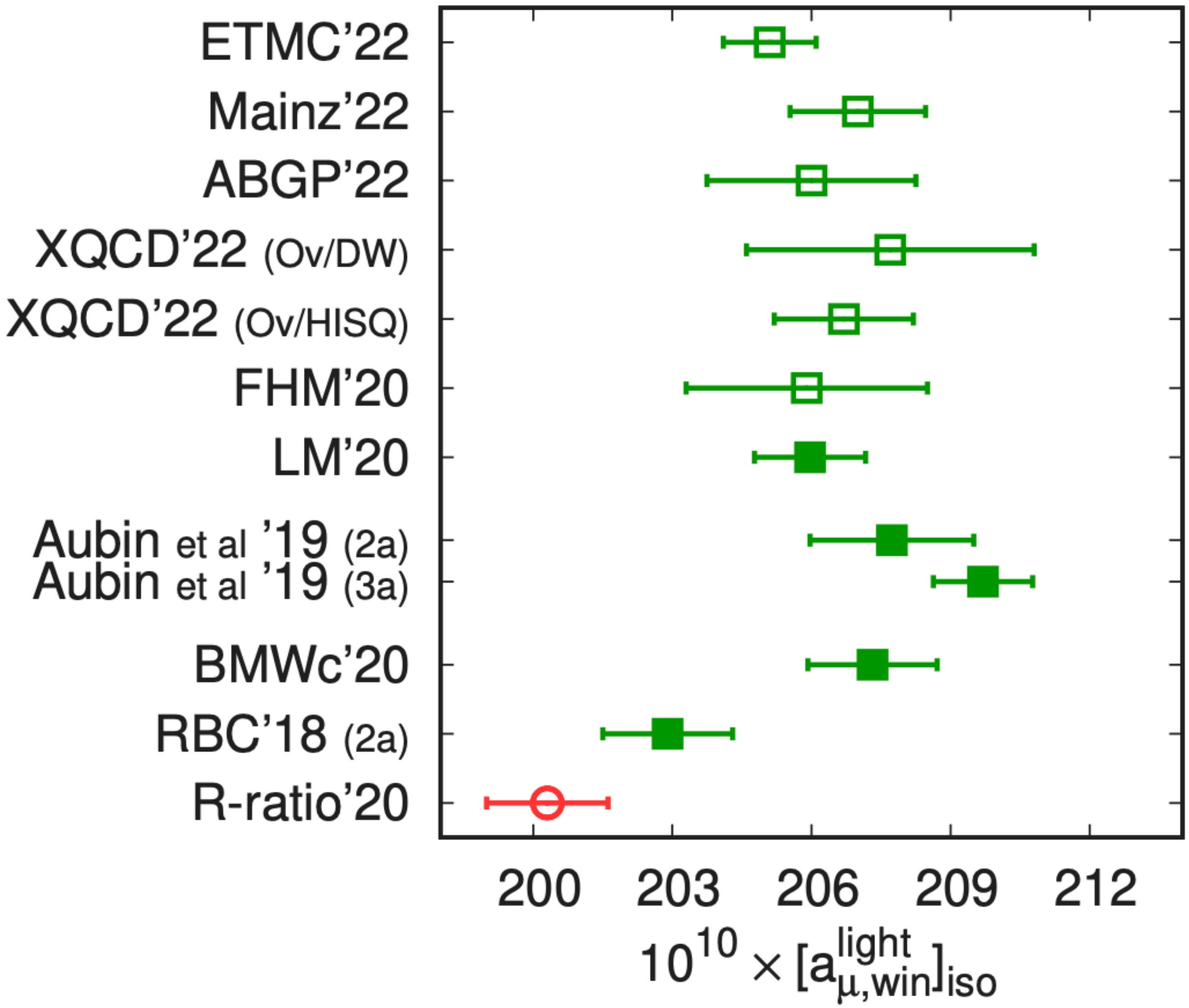



$$a_\mu^{\mathrm{HVP}} + [a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{Weak}} + a_\mu^{\mathrm{HLbL}}] \rangle\ a_\mu^{\mathrm{SM}}$$



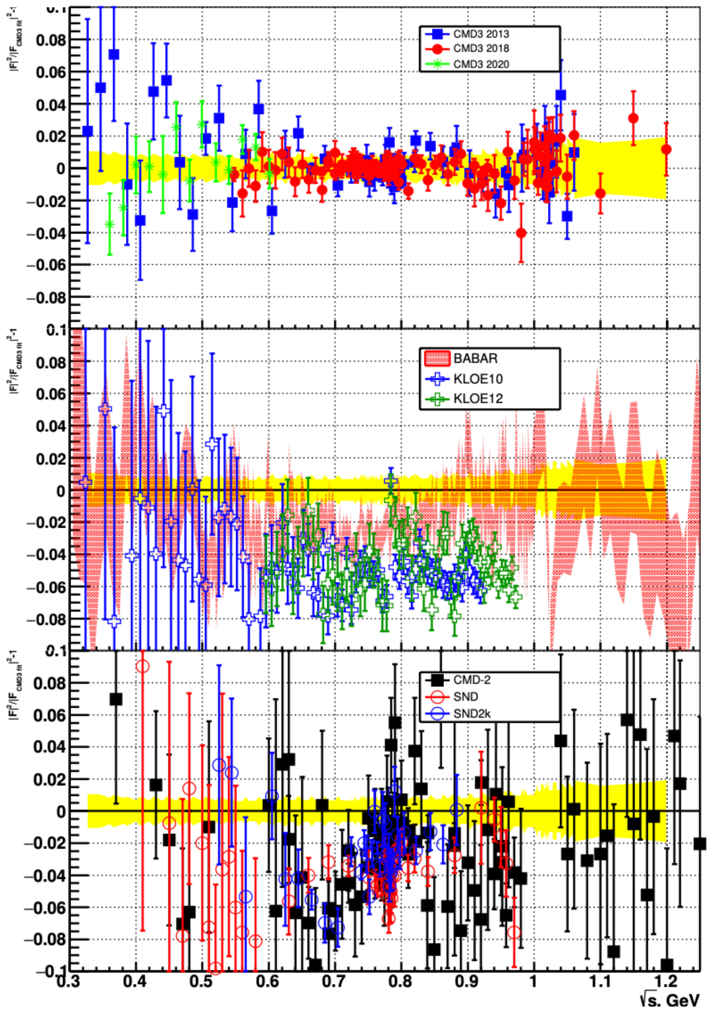

Aoyama et al, arXiv:2006.04822

# Recent Lattice Calculations

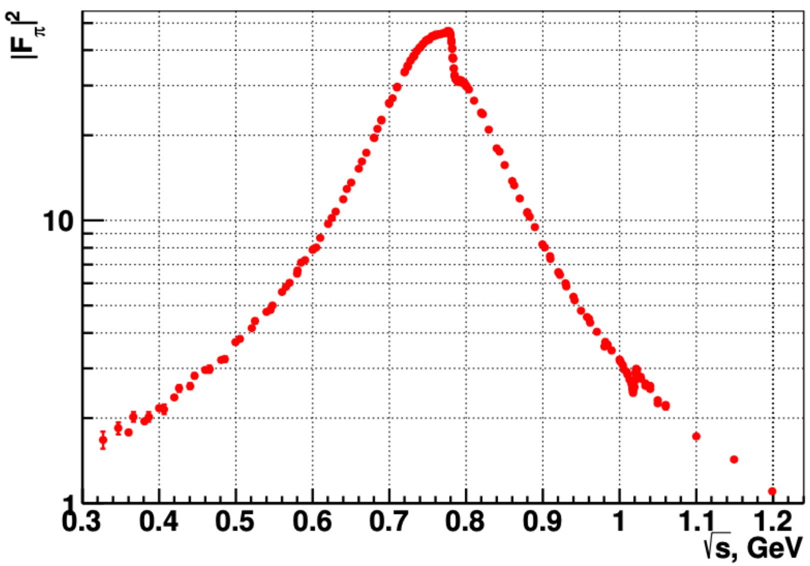


# Updated CMD-3 Measurement of HVP

Comparison with previous results




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



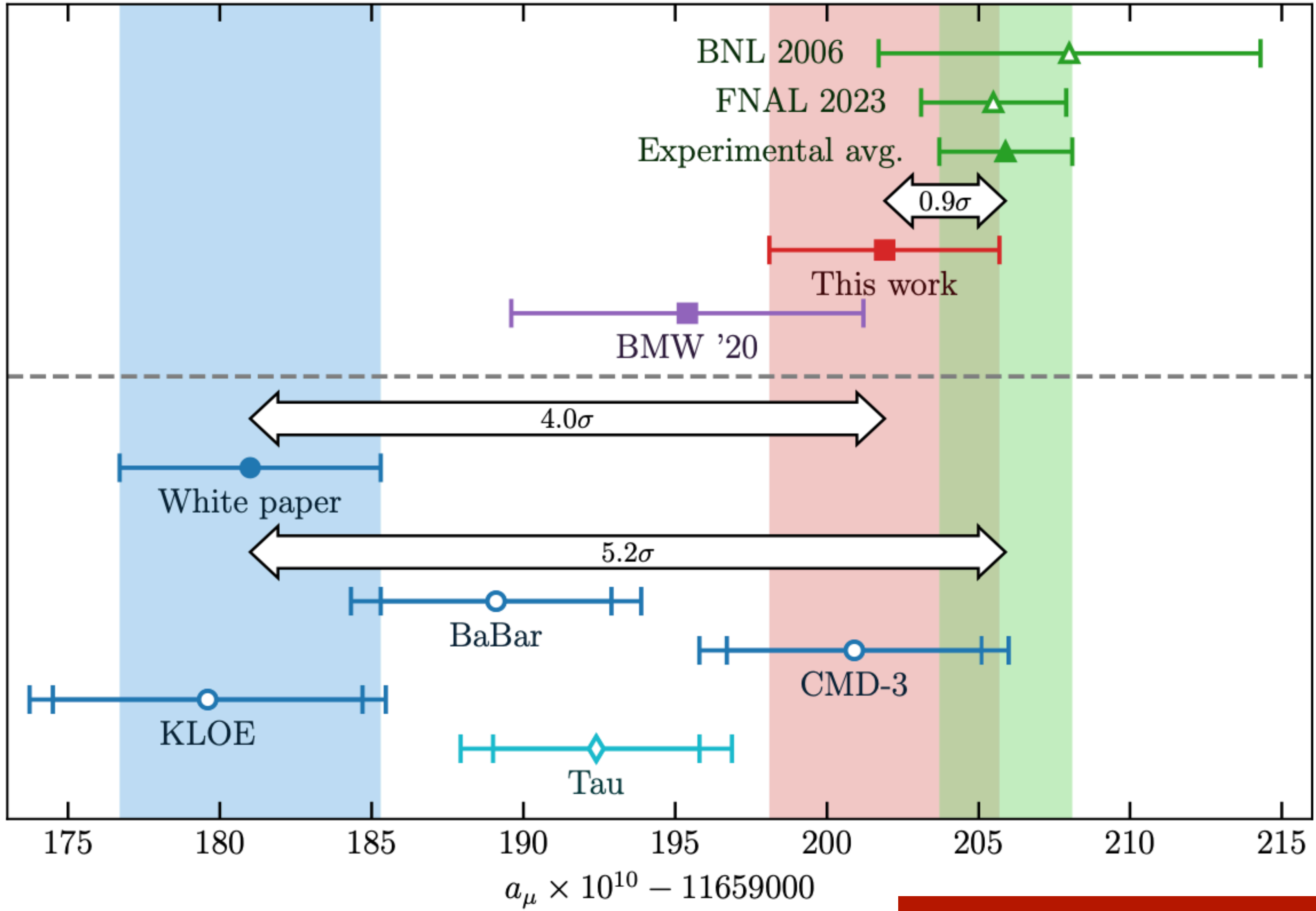

$(g_\mu - 2)$ – HVP discrepancy

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

**Consistent with no BSM signal**

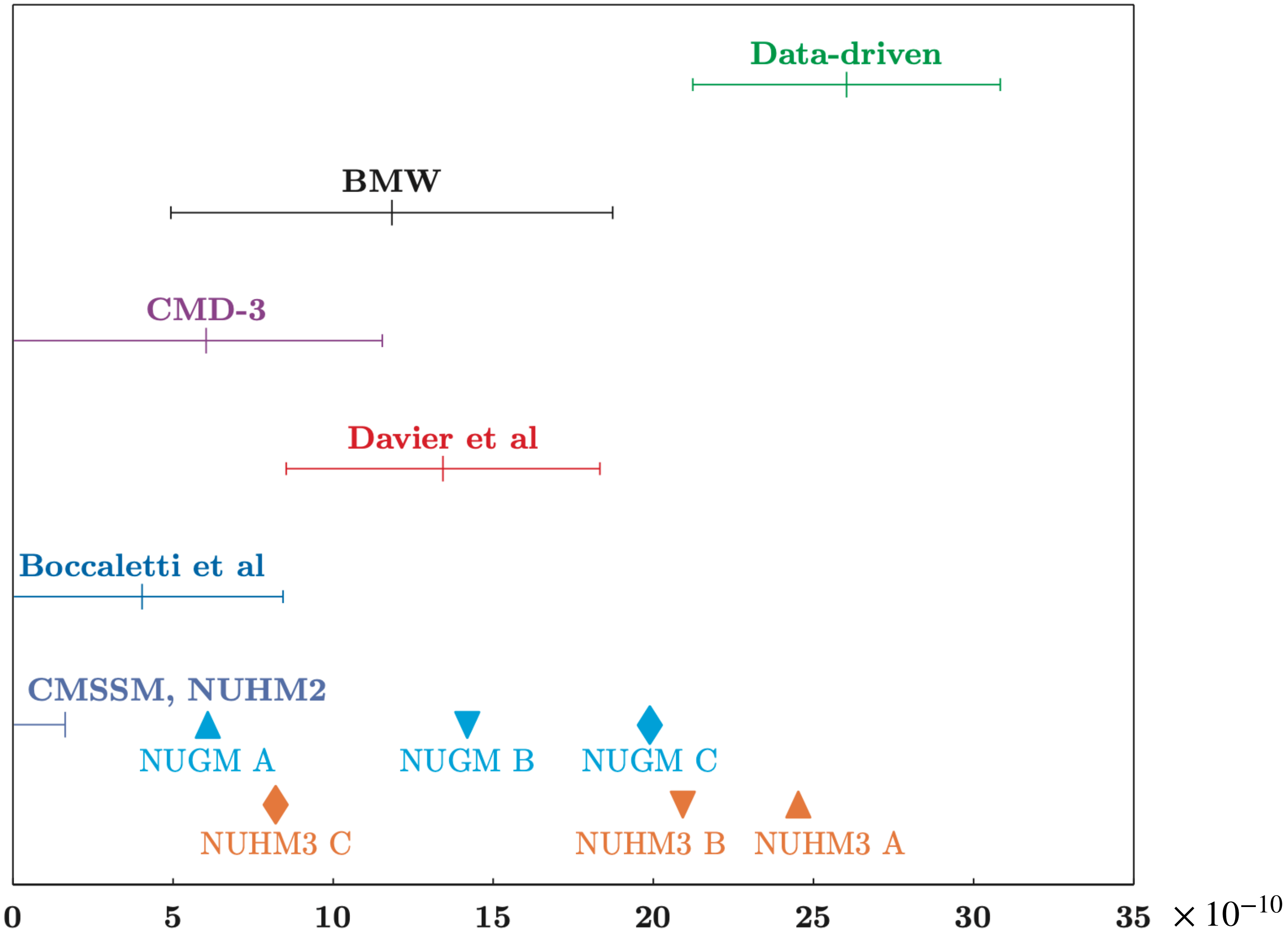
CMD-3 Collaboration, arXiv:2309.12910

# New Lattice Calculation of $g_\mu - 2$




Boccaletti et al, arXiv:2407.10913

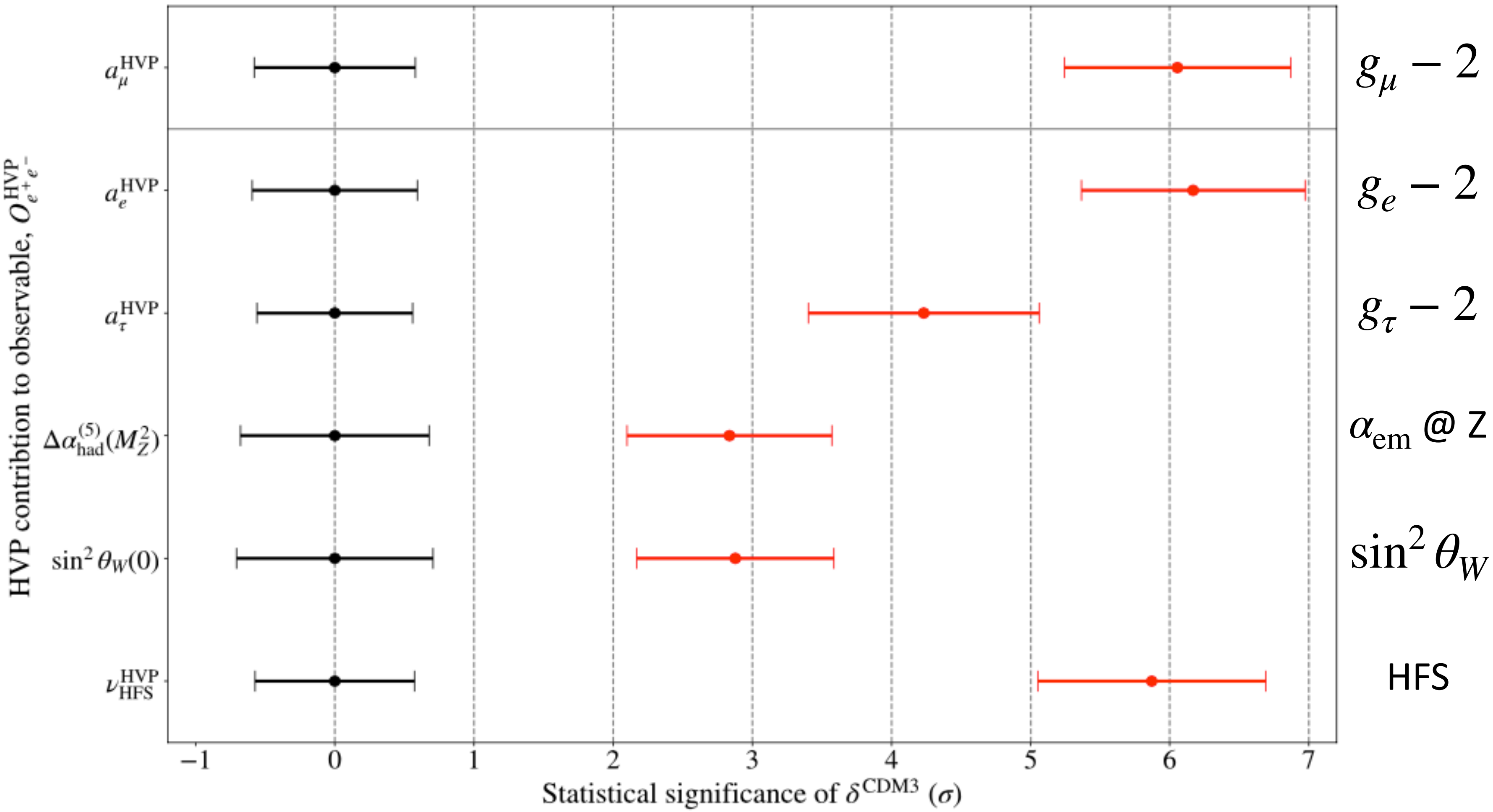
# $g_\mu - 2$ in Benchmark SUSY Scenarios




Comparison of experimental and theoretical estimates of $\Delta a_\mu$ with calculations in supersymmetric models including benchmarks

JE, Olive, Spanos, arXiv:2407.08679

# Impacts on Other Observables




- Important effects on $g_e - 2$, HFS, lesser effects on $\alpha_{\text{em}}$, $\sin^2\theta_W$

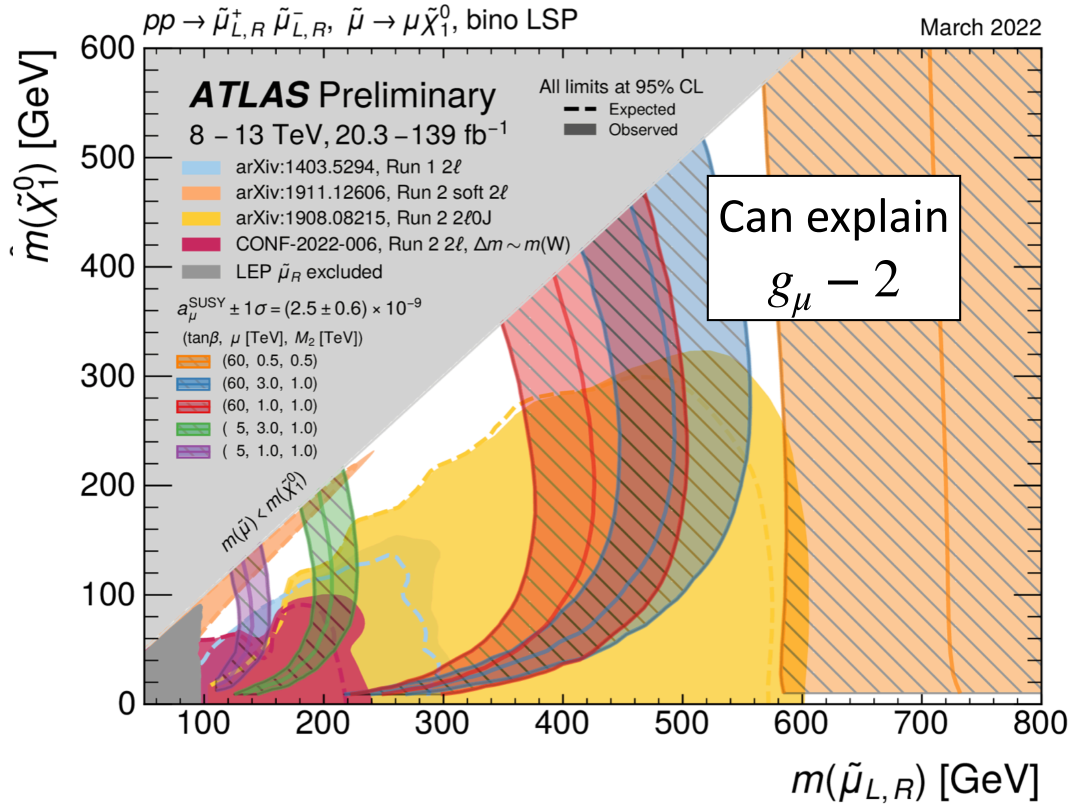
Luzio, Keshavarzi, Masiero & Paradisi, arXiv:2407.01123

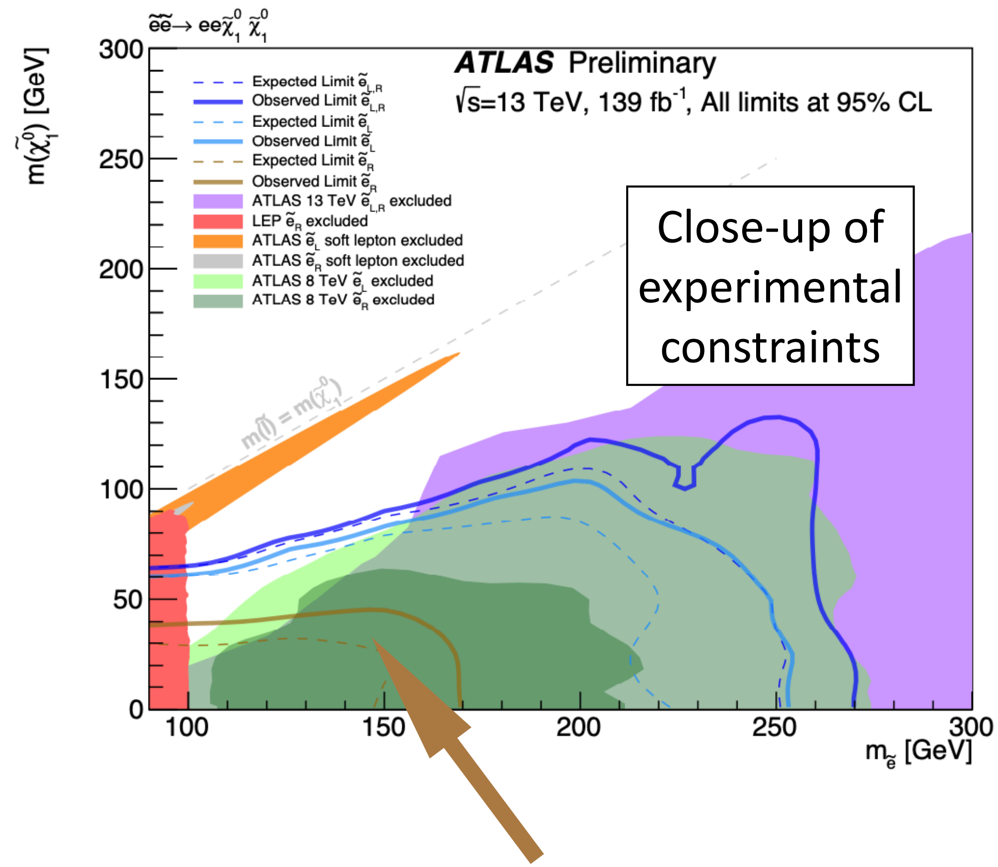
# $g_\mu - 2$ in SUSY Models

- LHC constraints on strongly-interacting sparticles exclude significant contribution to $g_\mu - 2$ in CMSSM
- Violate universality in gaugino masses: $M_1 \neq M_2 \neq M_3$? NUGM
- Violate universality in sfermion and Higgs supersymmetry-breaking masses: $m_{\tilde{t}}, m_{\tilde{b}}, m_{\tilde{\tau}} \neq$ other squarks, sleptons and Higgs masses? NUHM3
- Can accommodate "any" value of $g_\mu - 2$

# LHC vs Supersymmetry

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



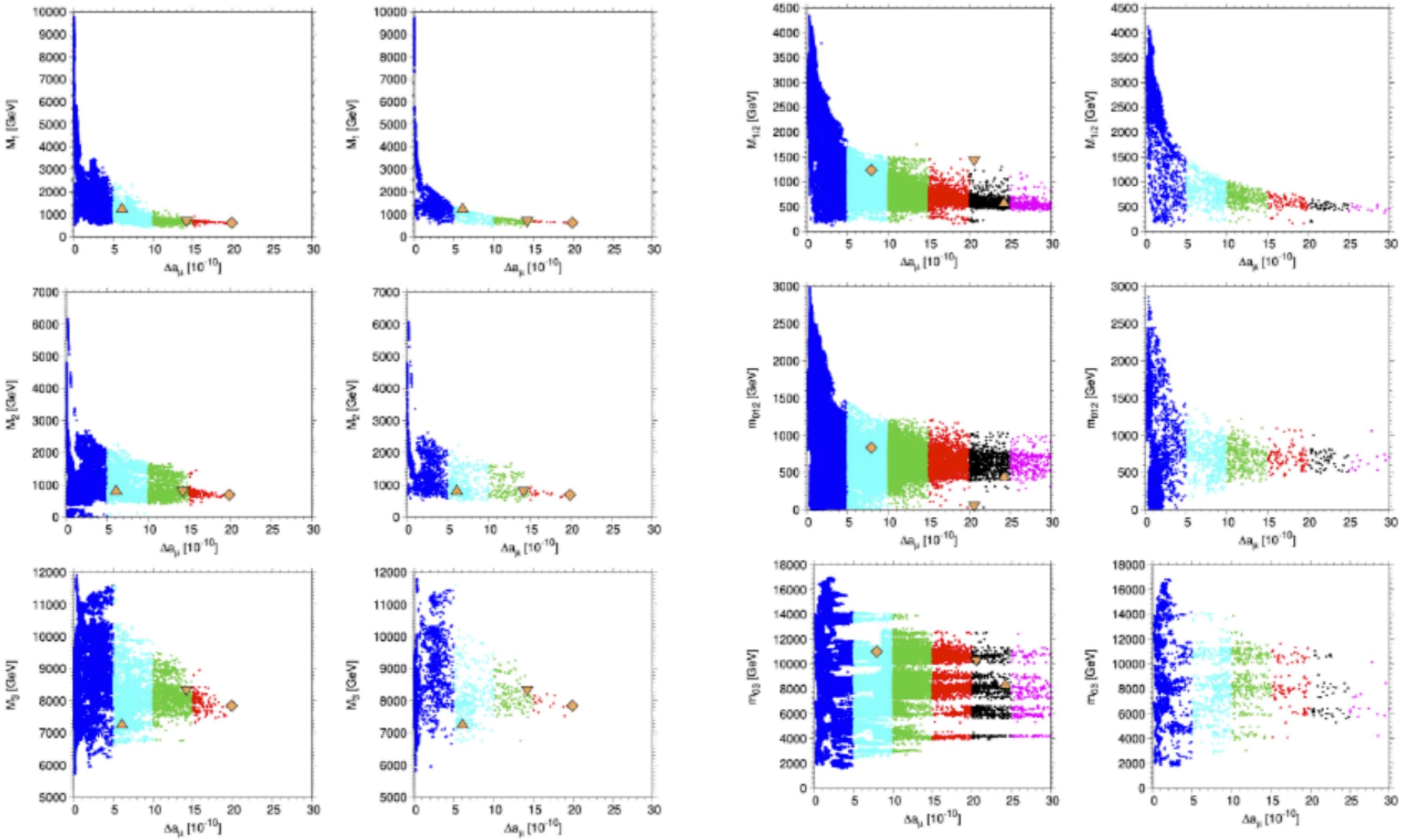

- Most models have $m_{\tilde{\mu}_L} > m_{\tilde{\mu}_R}$ but $m_{\tilde{\mu}_R} \simeq m_{\tilde{e}_R}$: **relevant constraint**

ATLAS Collaboration

# Non-Universal SUSY Scenarios

NUGM

NUHM3



Colour-coded according to $g_\mu - 2$ values

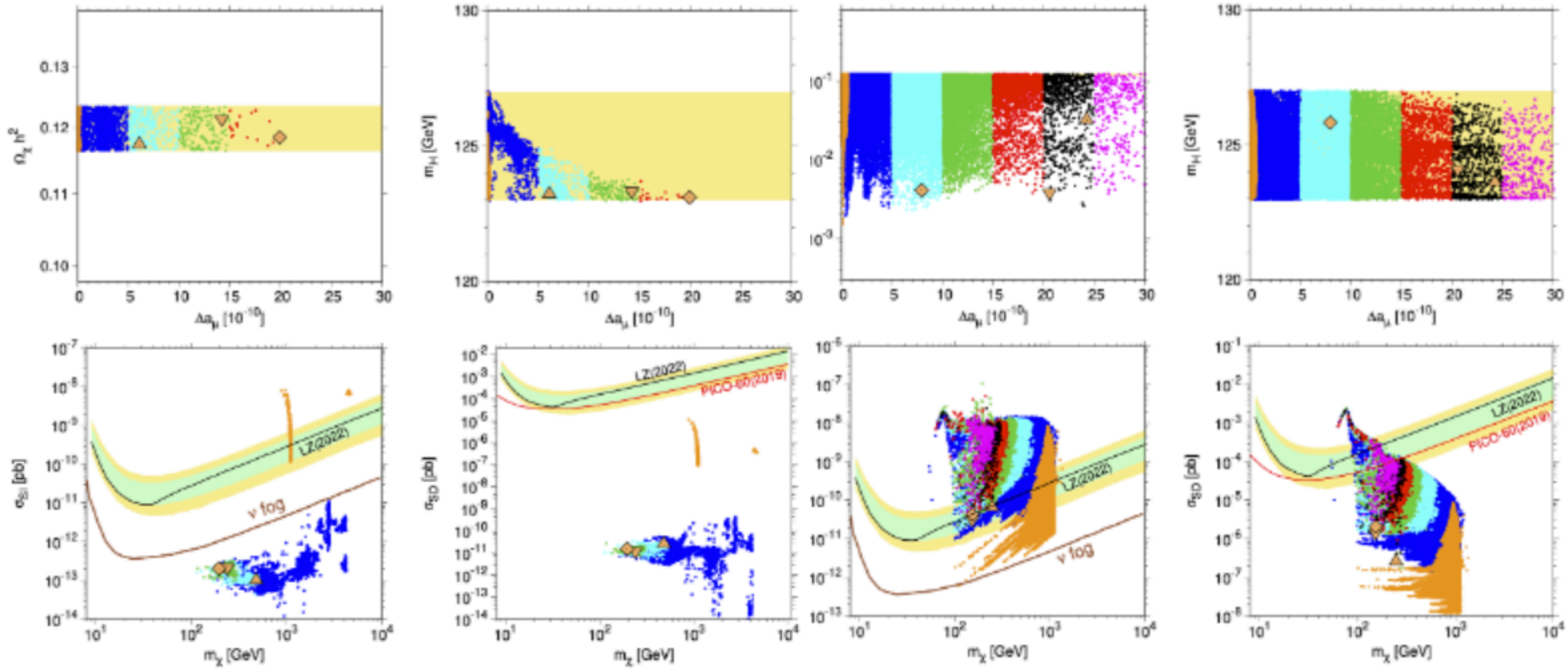
(Benchmarks indicated by triangles)

JE, Olive, Spanos, arXiv:2407.08679

# Non-Universal SUSY Scenarios

NUGM

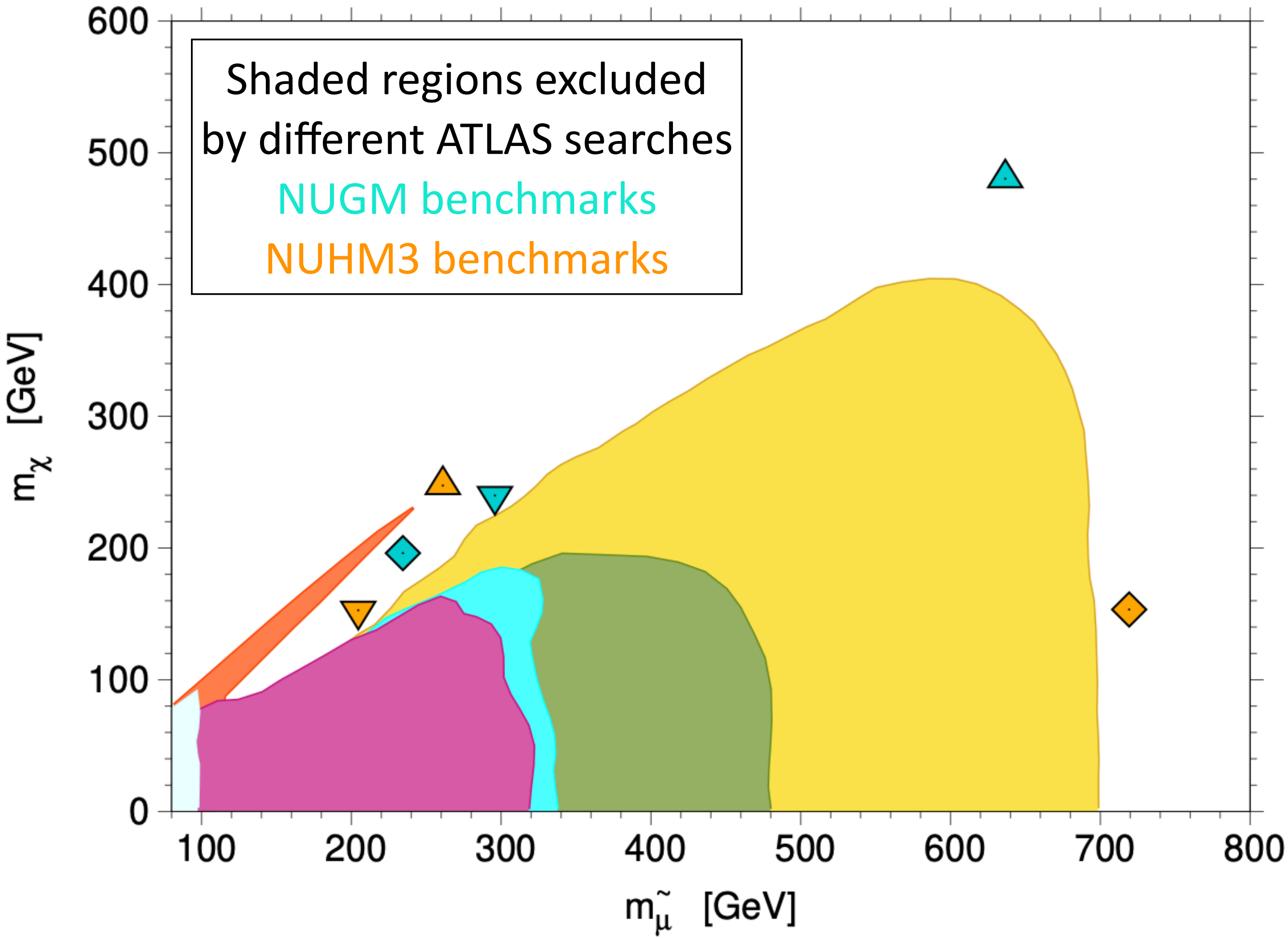
NUHM3




Dark matter density, $m_H$ and scattering cross sections

JE, Olive, Spanos, arXiv:2407.08679

# Comparison of Benchmarks with ATLAS Limits




Prospects for future discovery

JE, Olive, Spanos, arXiv:2407.08679