The Future of Particle Physics

The story so far

Higgs puzzles

Dark matter

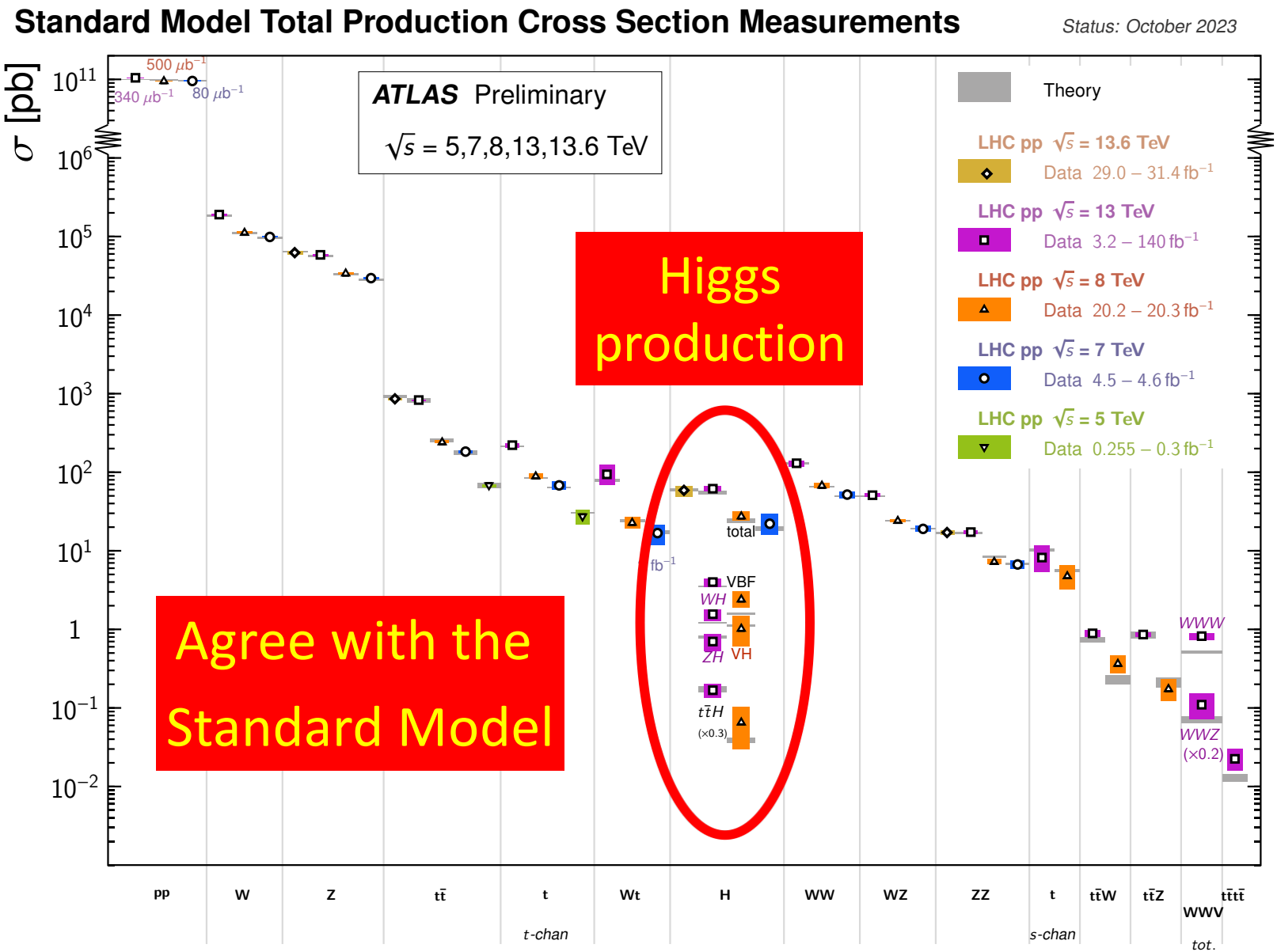
Direct and indirect approaches

Stop Press: More Higgs bosons or a new quarkonium?

John Ellis

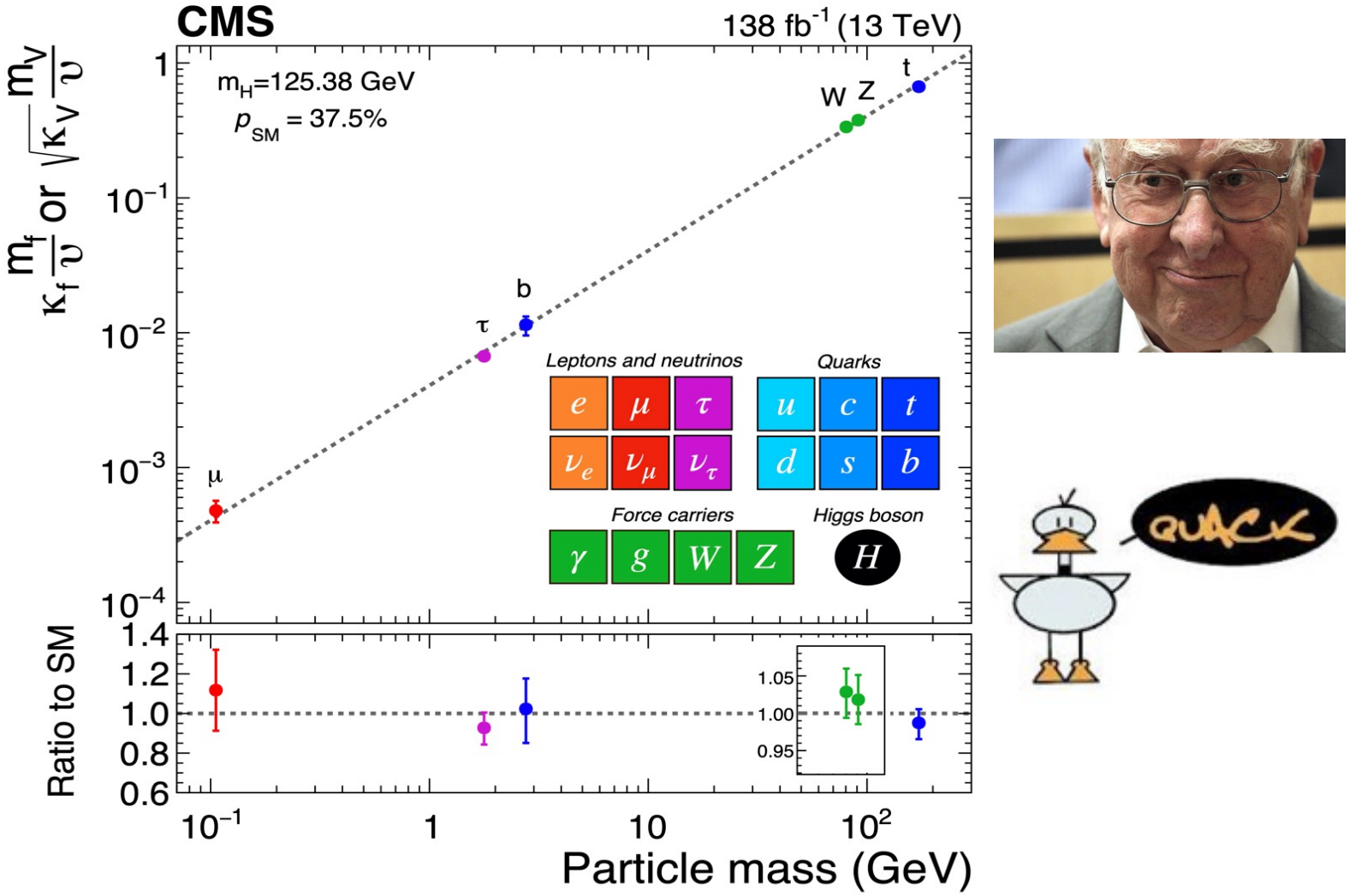
KING'S College LONDON

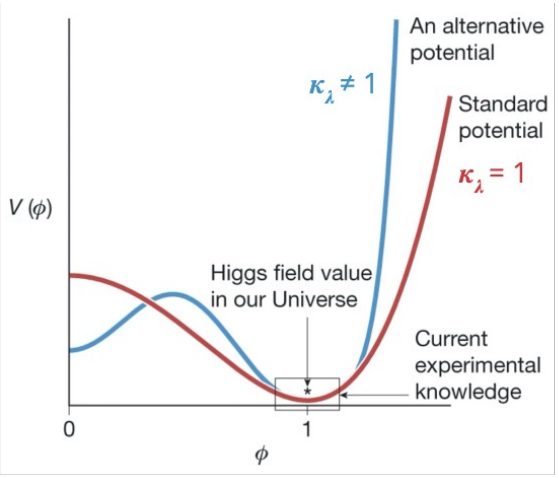
LHC Measurements



It Walks and Quacks like a Higgs

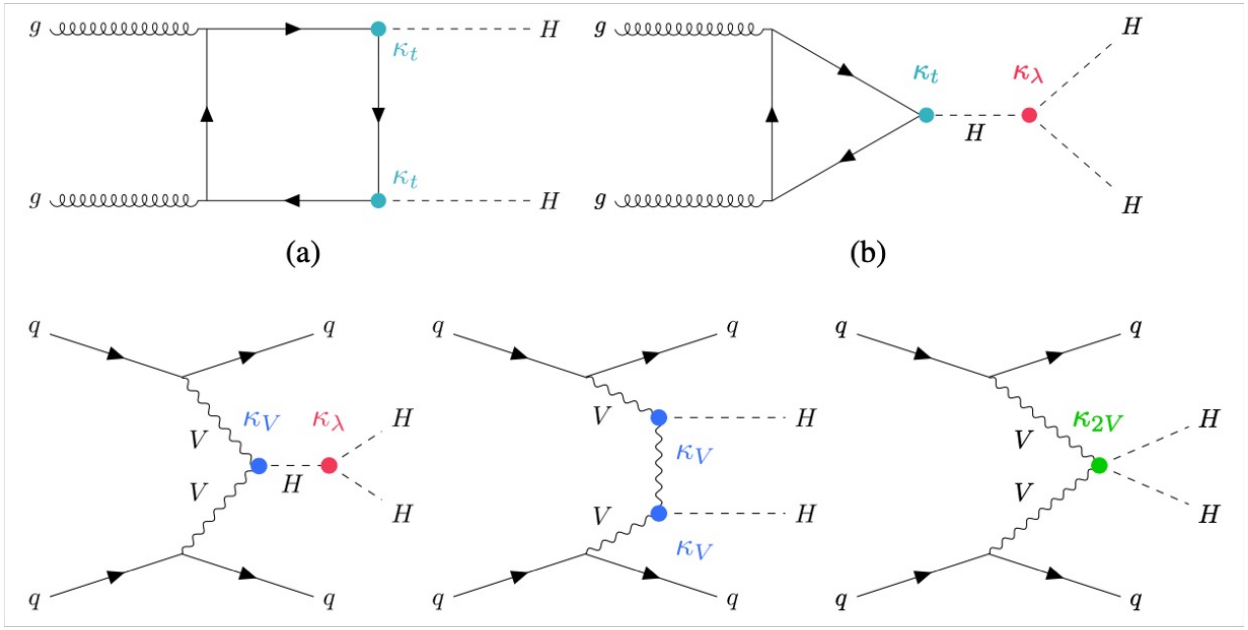
- Do couplings scale ~ mass? With scale = v?



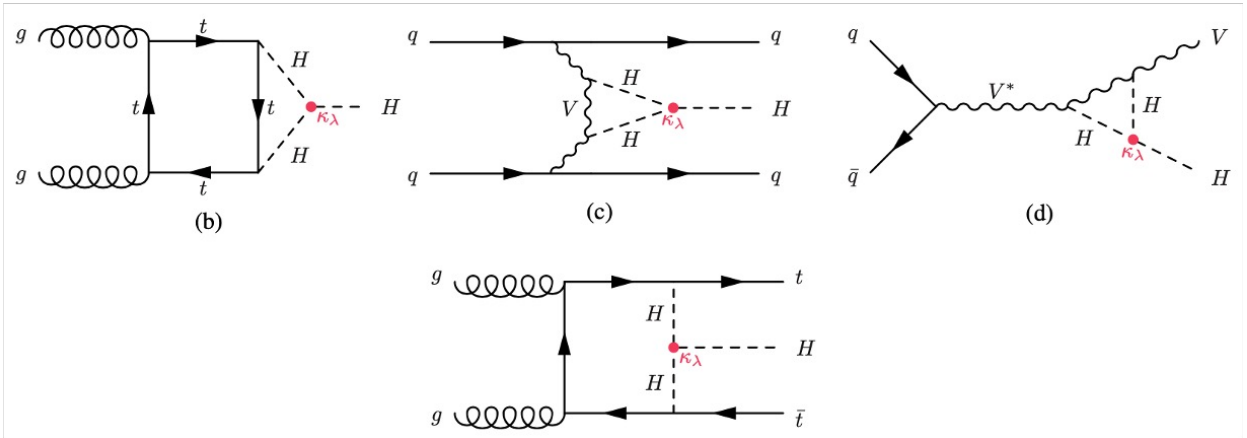


Search for Triple-H Coupling

Diagrams for double-Higgs production



Loop corrections to single Higgs production

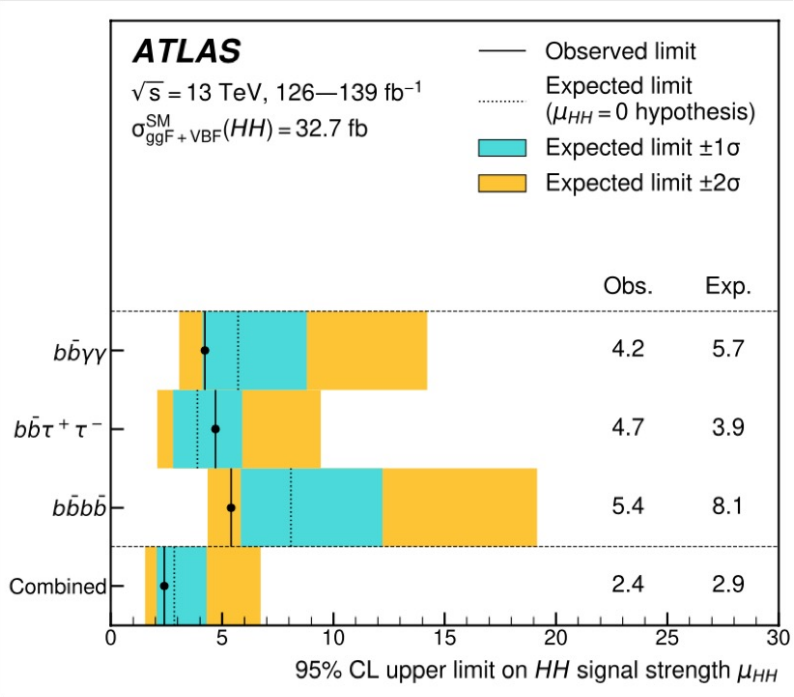


ATLAS Collaboration, arXiv: 2211.01216

Next frontier in Higgs measurements

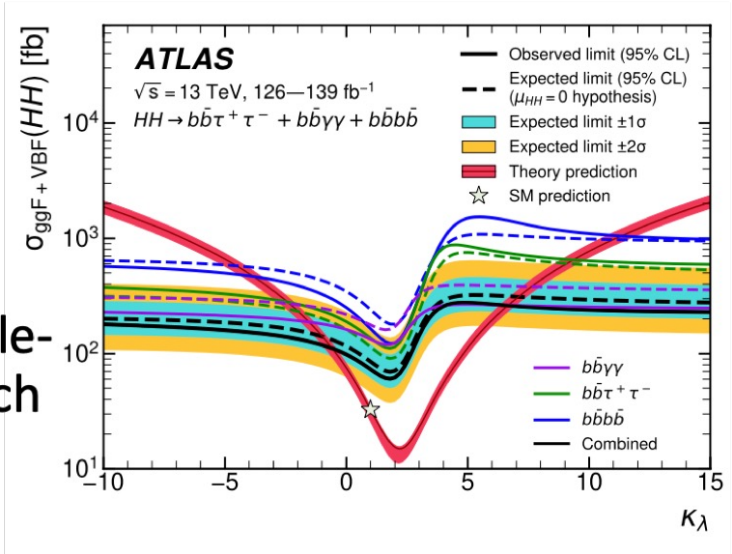
Search for HHH Coupling

Limit on double-Higgs production

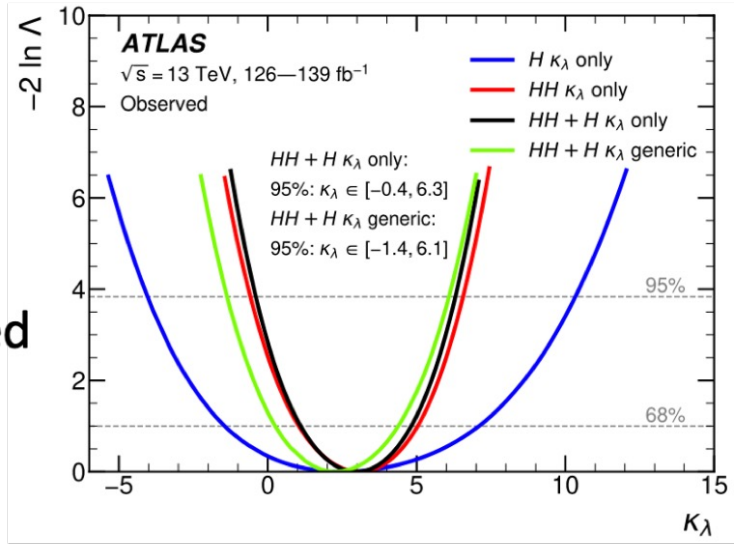


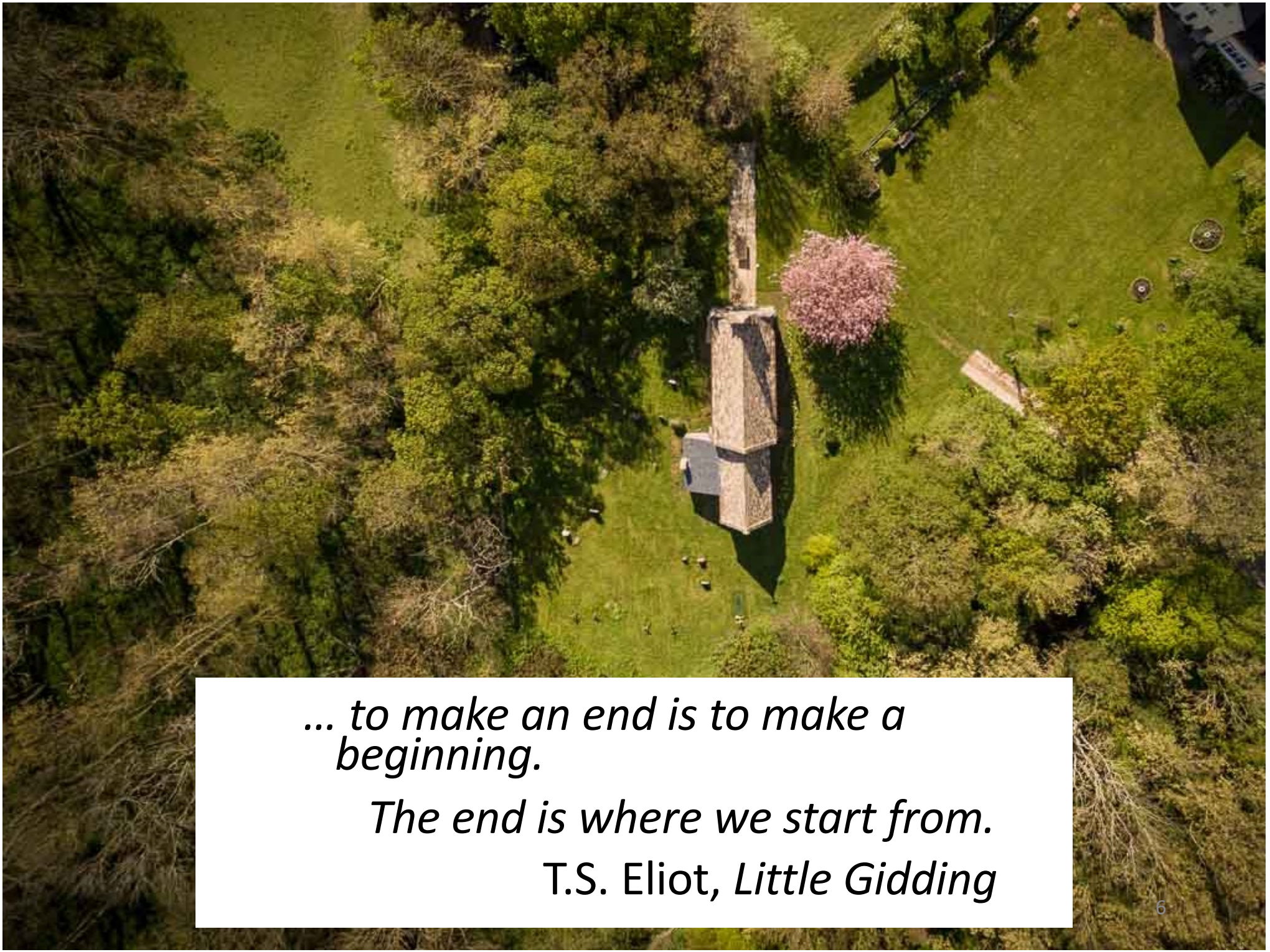
Limits on triple-Higgs coupling

From double-Higgs search



Combined limit





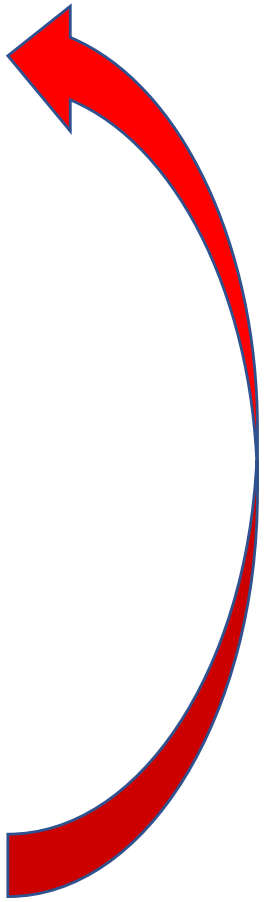
… to make an end is to make a beginning.

The end is where we start from.

T.S. Eliot, *Little Gidding*

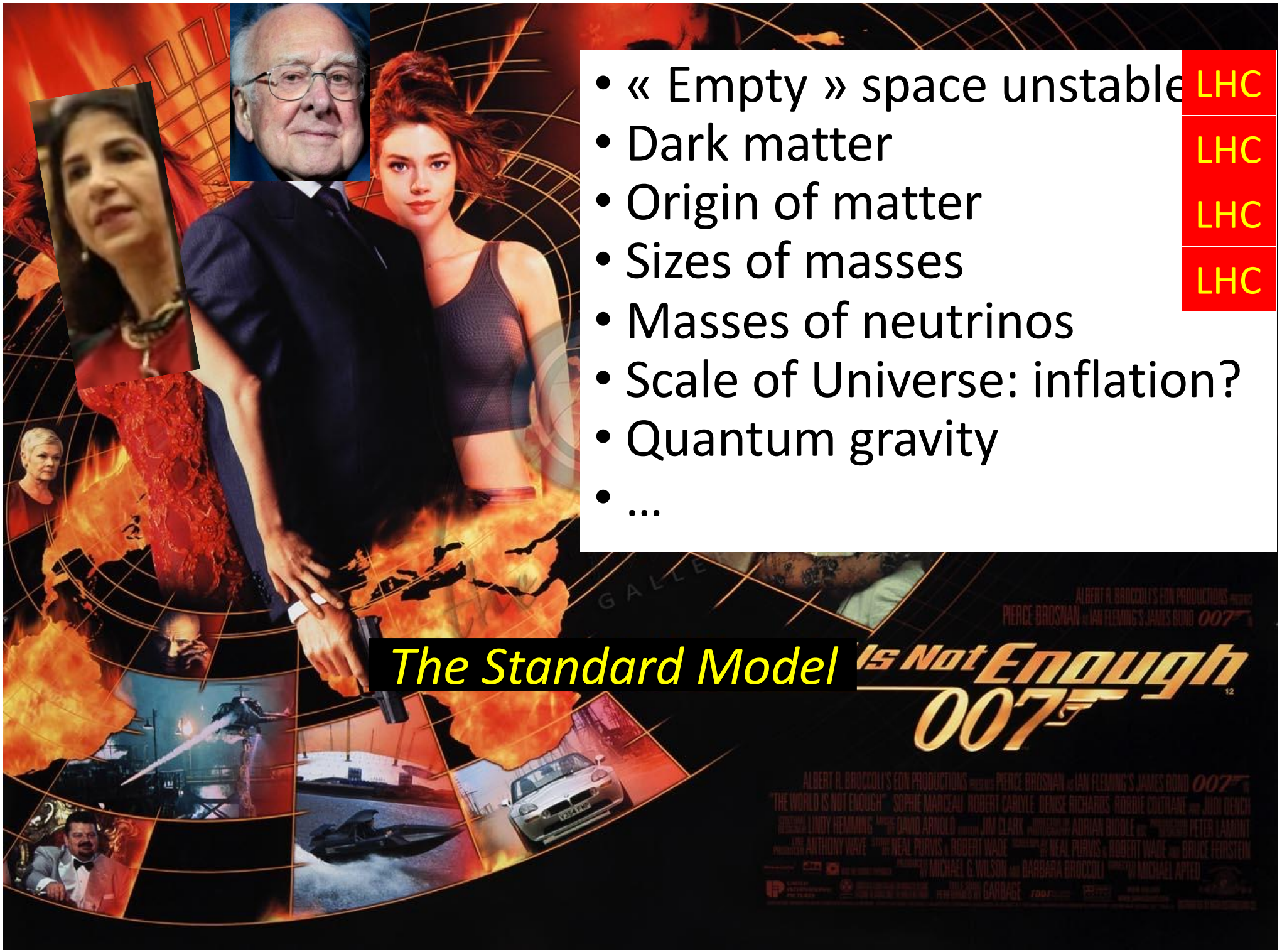
Higgstorical Summary

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



Time to repeat?


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
BRUCE FEIRSTEIN
MICHAEL G. WILSON
BARBARA BROCCOLI
MICHAEL APTED
GARBAGE


• « Empty » space unstable LHC
• Dark matter LHC
• Origin of matter LHC
• Sizes of masses LHC
• Masses of neutrinos
• Scale of Universe: inflation?
• Quantum gravity
• …
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?

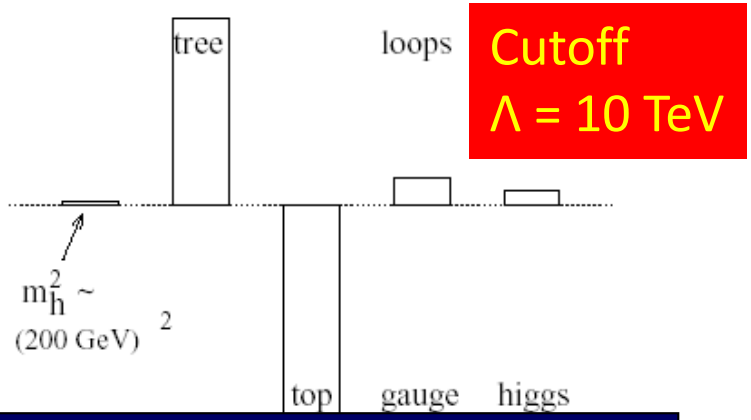
Theoretical worries about the Higgs boson

Elementary Higgs or Composite?

- Higgs field:

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

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



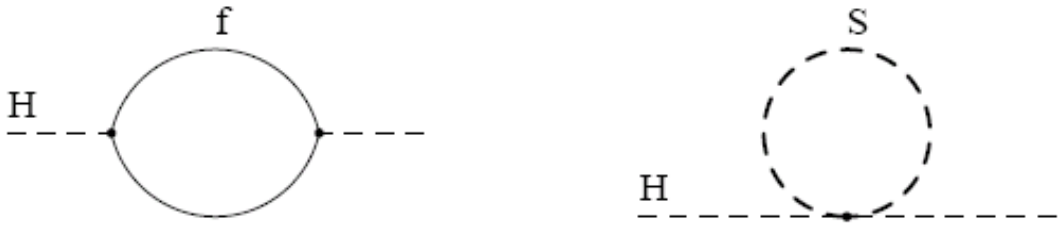
Cut-off Λ ~ 1 TeV with Supersymmetry?

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

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

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



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

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

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

- Leading divergence cancelled if

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

Supersymmetry!

What lies beyond the Standard Model?

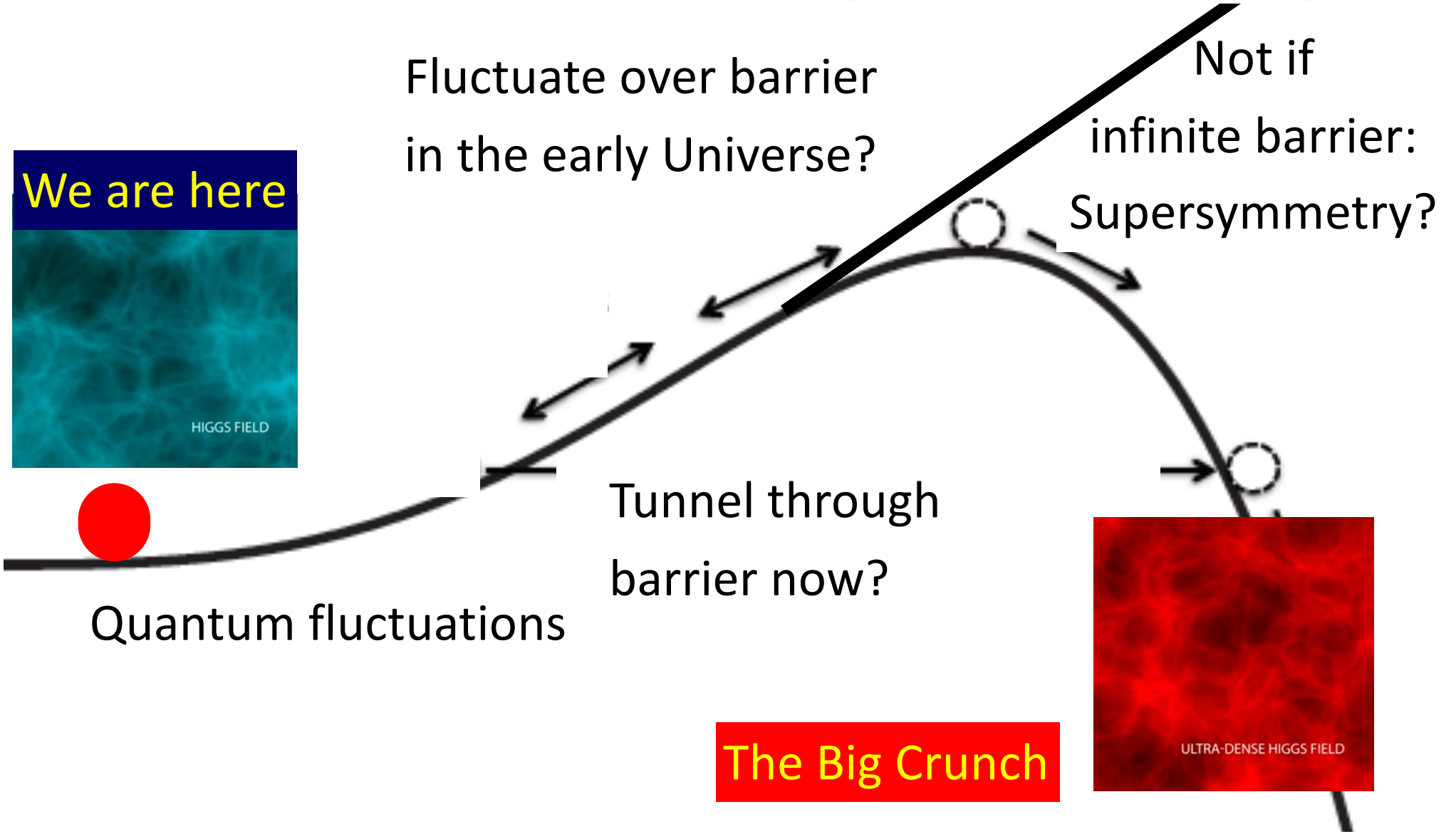
Supersymmetry

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**, $g_\mu - 2$, …

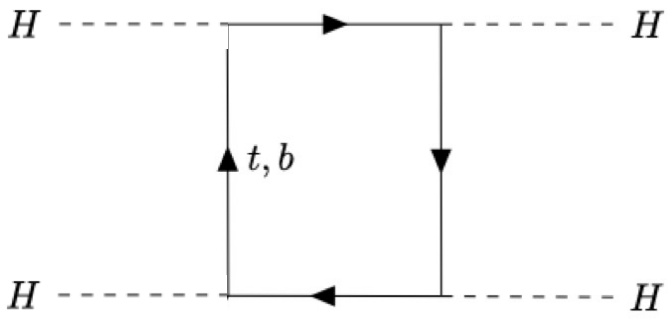
Will the Universe Collapse?

Should it have Collapsed already?



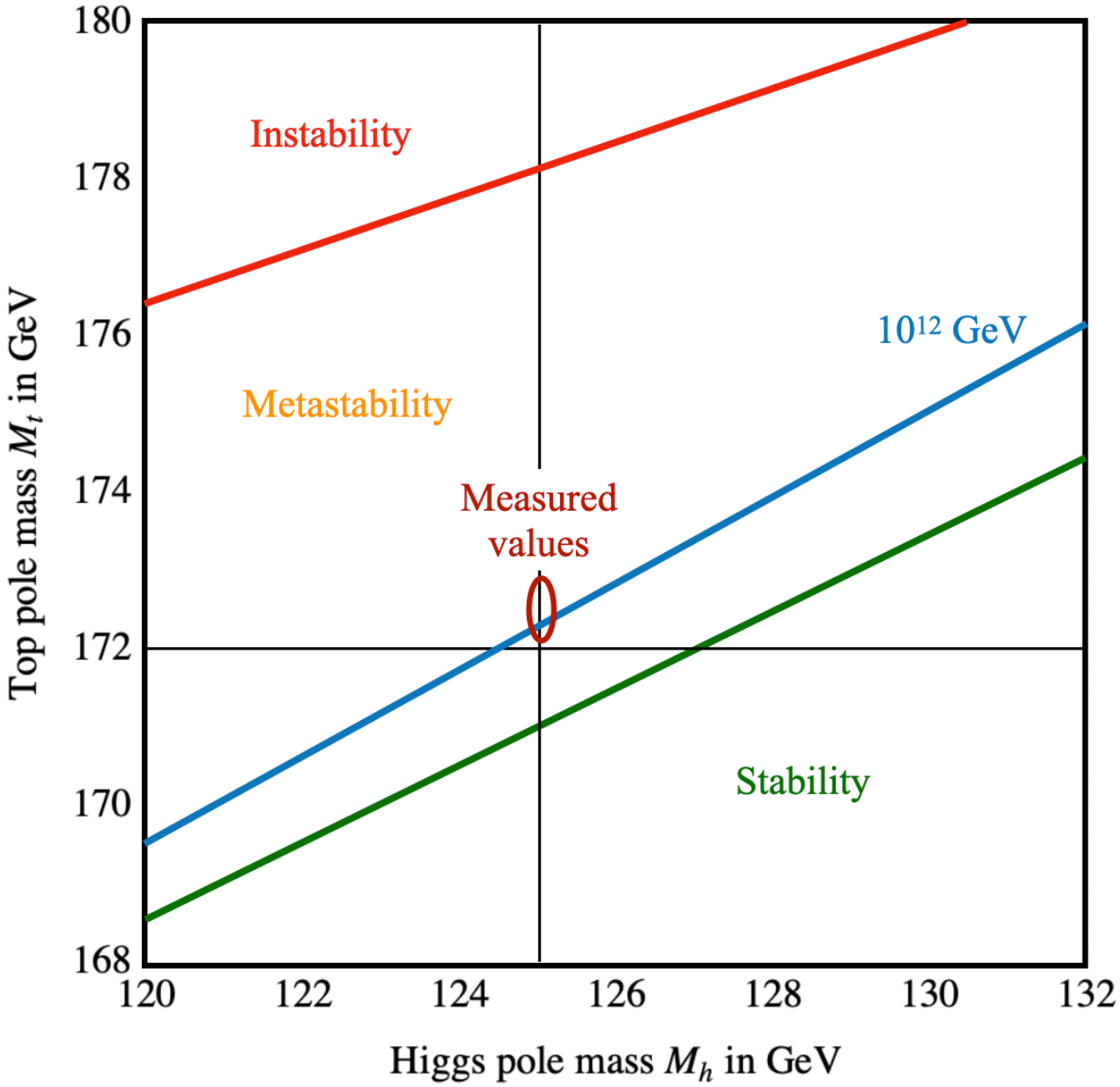
Is “Empty Space” Unstable?

Depends on masses of Higgs boson and top quark

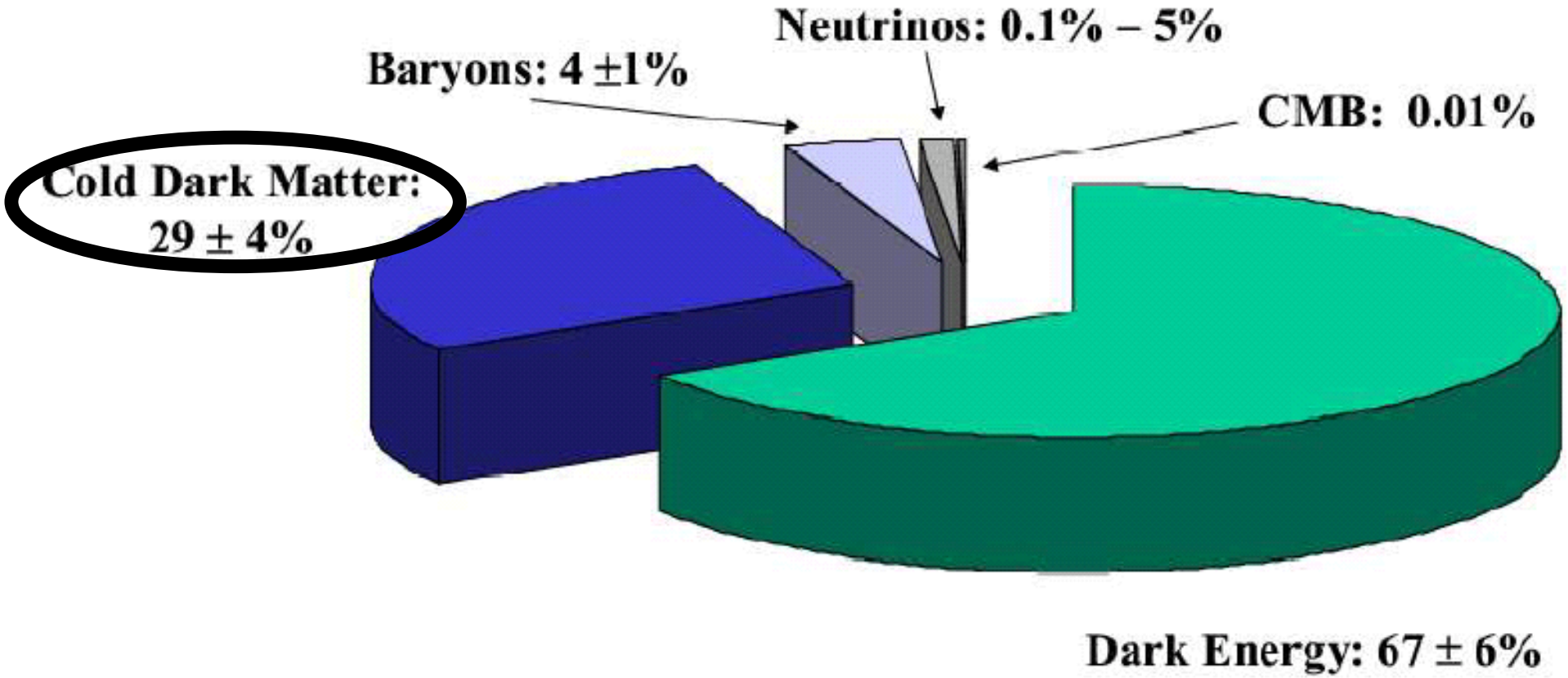


$$16\pi^2 \frac{d\lambda}{dt} = 12(\lambda^2 + h_t^2\ \lambda - h_t^4) + \mathcal{O}(g^4, g^2\lambda$$

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



Strange Recipe for a Universe



The ‘Standard Model’ of the Universe indicated by astrophysics and cosmology

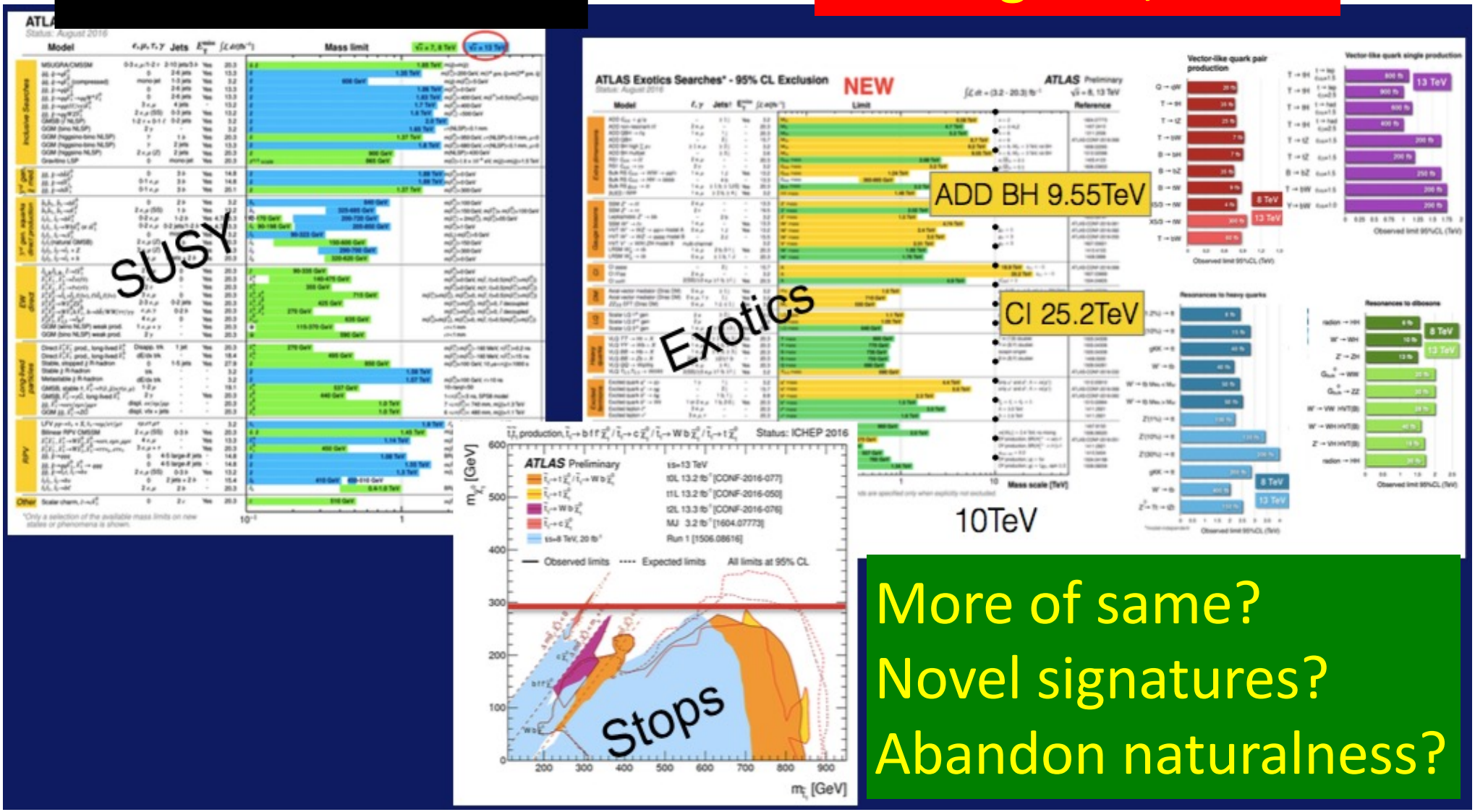
WIMP Candidates

- Could have right density if weigh 100 to 1000 GeV (accessible to LHC experiments?)
- Present in many extensions of Standard Model
- Particularly in attempts to understand strength of weak interactions, mass of Higgs boson
- Examples:
  - Extra dimensions of space
  - **Supersymmetry** 

Nothing (yet) at the LHC

No supersymmetry

Nothing else, either



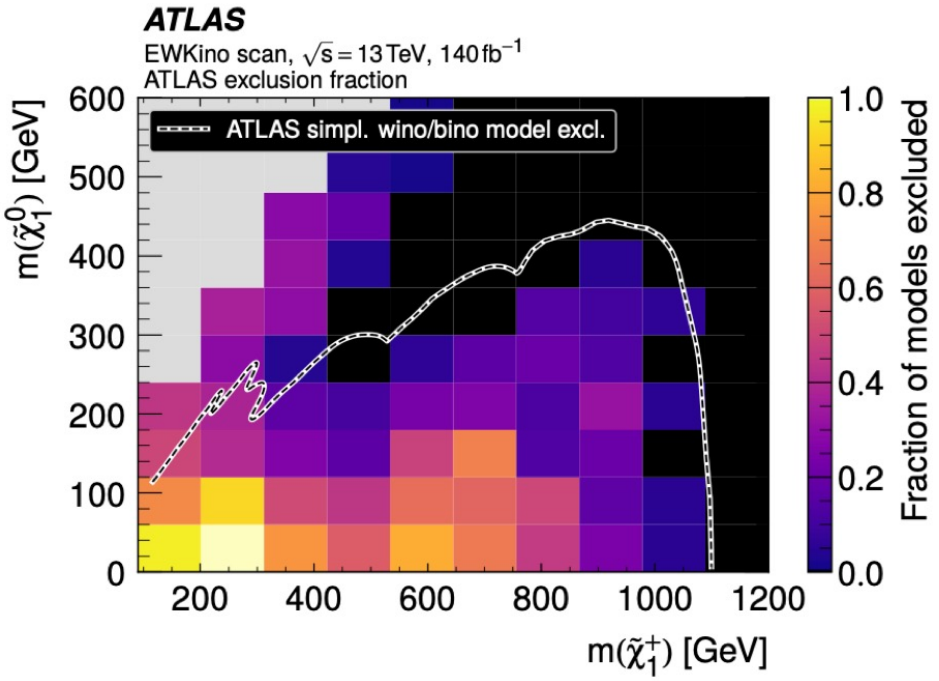
Fraction of Models Excluded

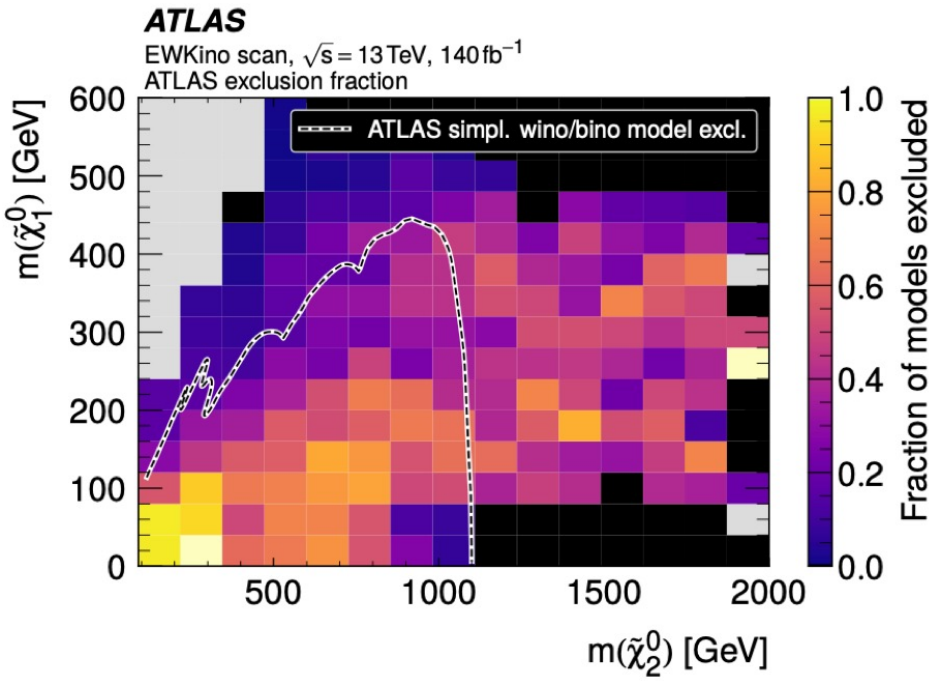
Exclusions not 100%, not as strong as often stated

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

Black = < 10% of pMSSM models excluded

Cream = > 90% of pMSSM models excluded



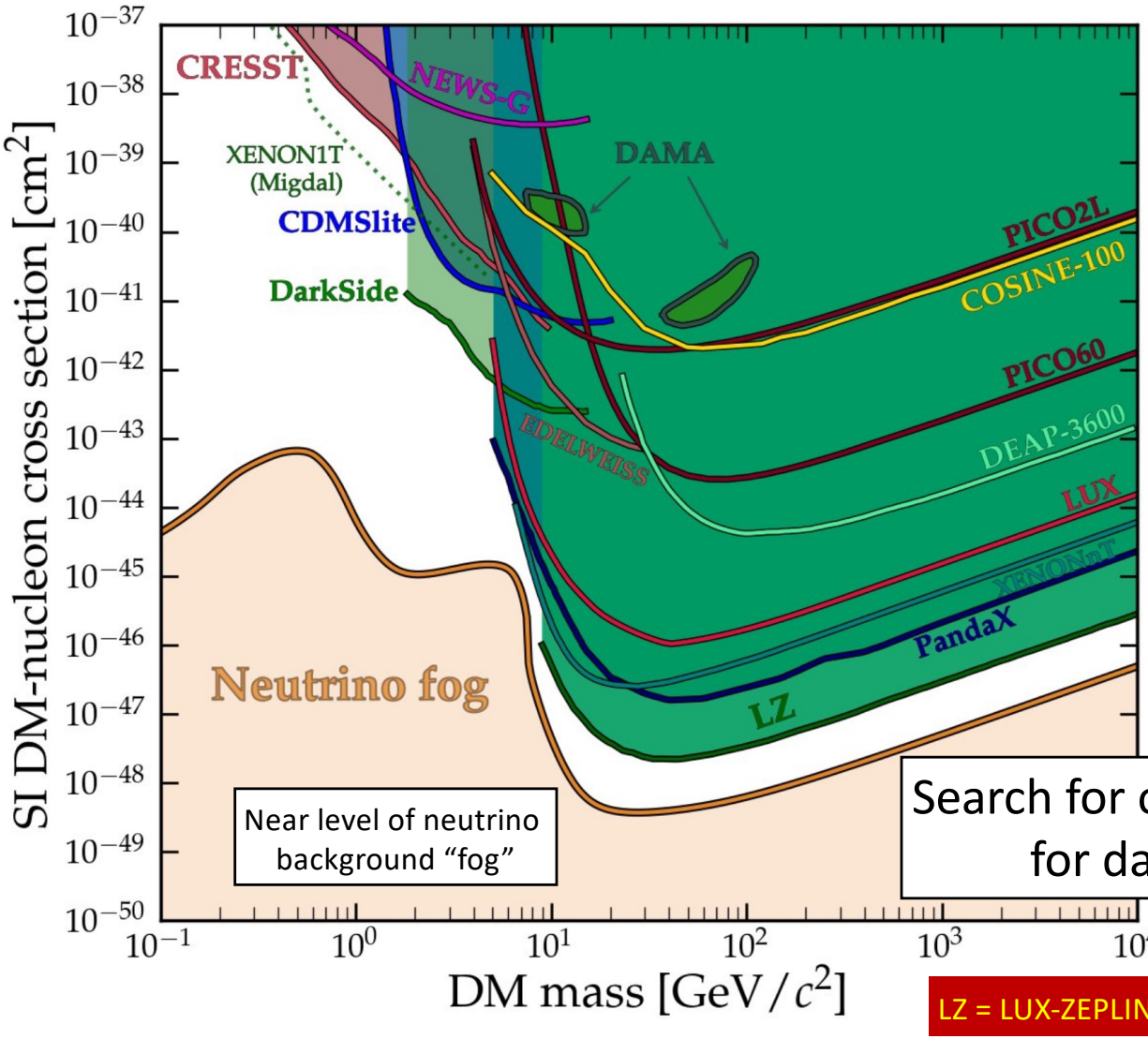


Many low-mass pMSSM models consistent with constraints

Hope springs eternal!

Direct Dark Matter Searches

Latest experimental results

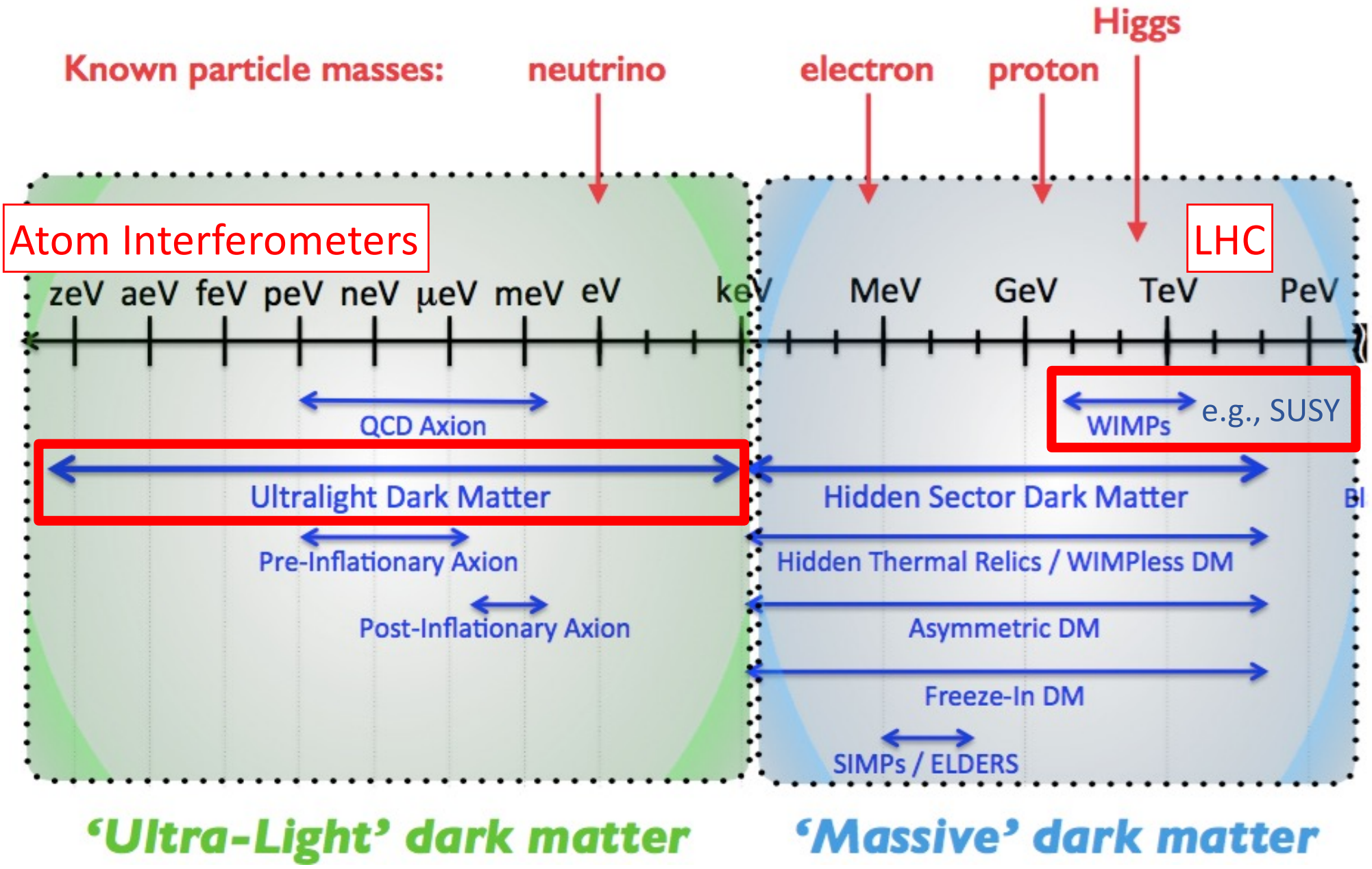


Near level of neutrino background "fog"

Search for other candidates for dark matter?

LZ = LUX-ZEPLIN collaboration, *preliminary*

Other Candidates for Dark Matter



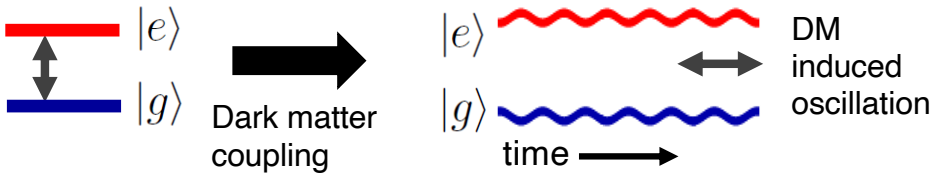
Searches for Light Dark Matter

AION

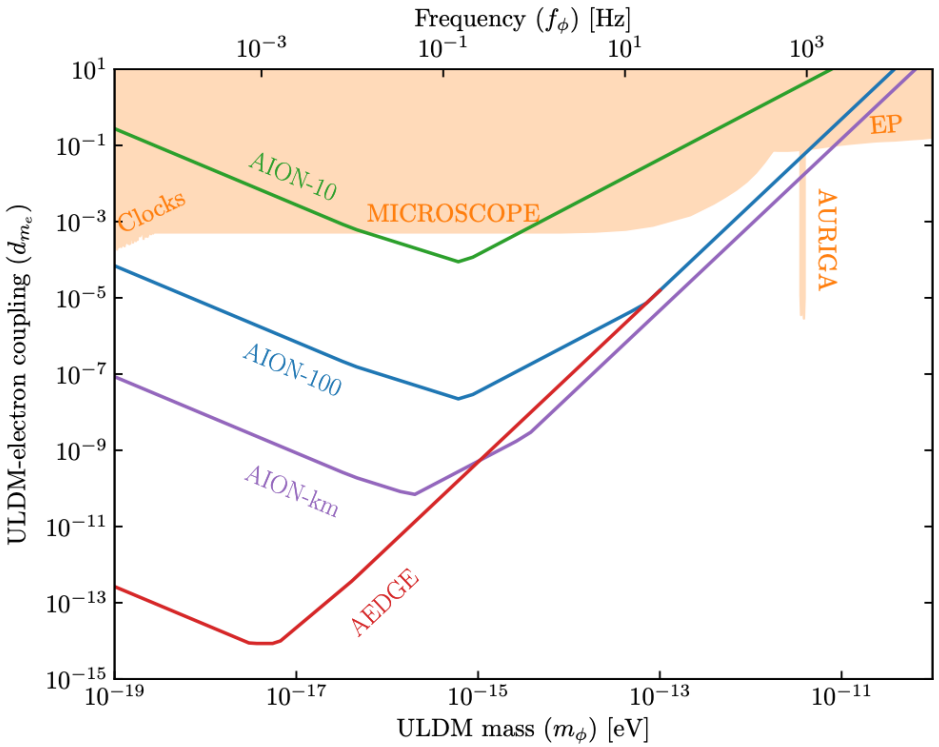
Linear couplings to gauge fields and matter fermions

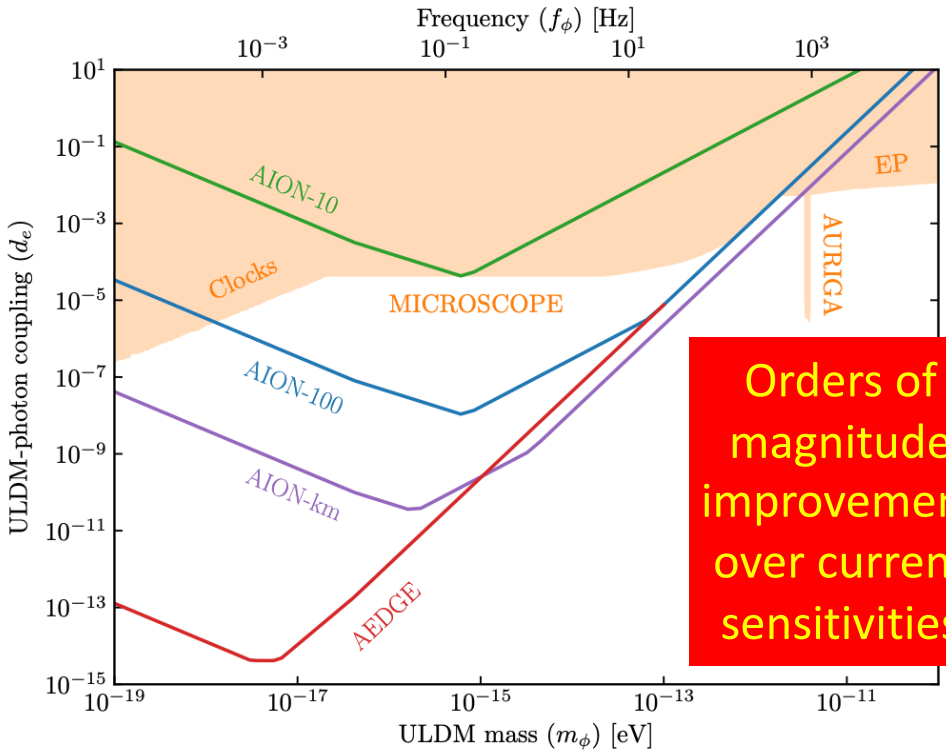
$$\mathcal{L}_{\mathrm{int}\phi} = \kappa\phi\left[+\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}F^A_{\mu\nu}F^{A\mu\nu} - \sum_{i=e,u,d}(d_{m_i}+\gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right]$$

Atom Interferometry



Affects E level Phase shift

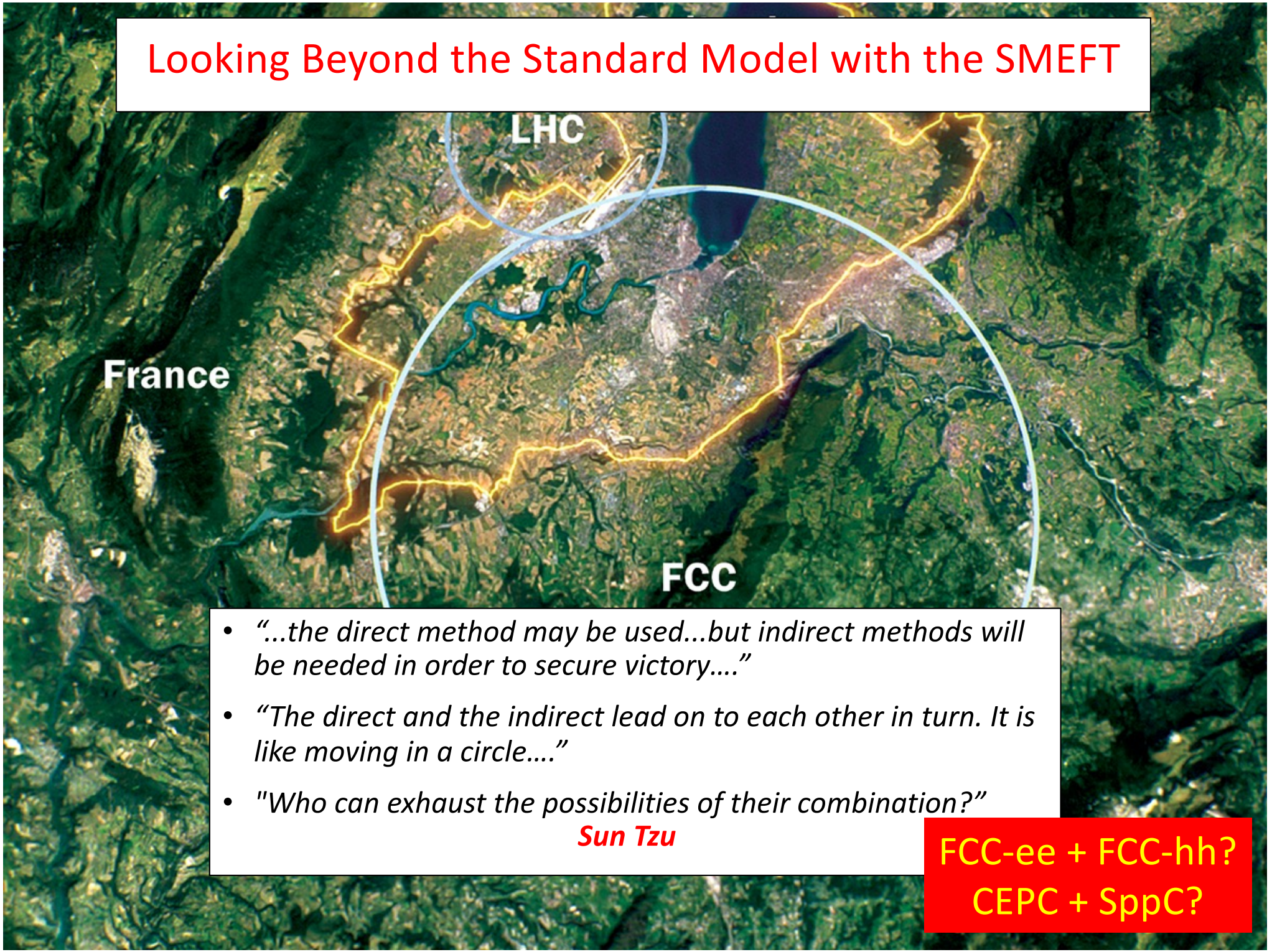




Orders of magnitude improvement over current sensitivities

AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755; Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

Looking Beyond the Standard Model with the SMEFT



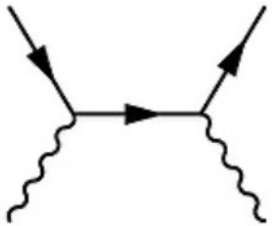
- *"...the direct method may be used...but indirect methods will be needed in order to secure victory...."*
- *"The direct and the indirect lead on to each other in turn. It is like moving in a circle...."*
- *"Who can exhaust the possibilities of their combination?"*

Sun Tzu

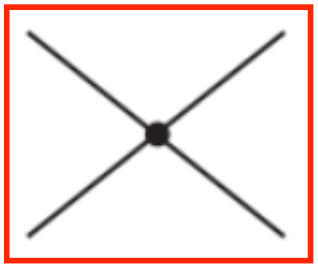
FCC-ee + FCC-hh?
CEPC + SppC?

Effective Field Theories (EFTs)

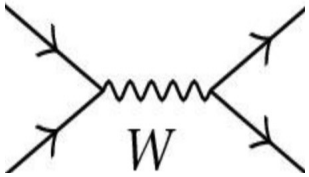
a long and glorious History



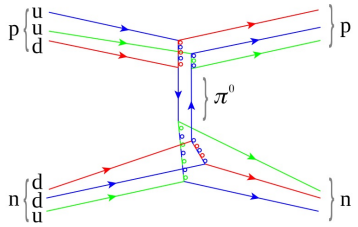
- 1930's: "Standard Model" of QED had d=4
- **Fermi's four-fermion theory of the weak force**



- 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

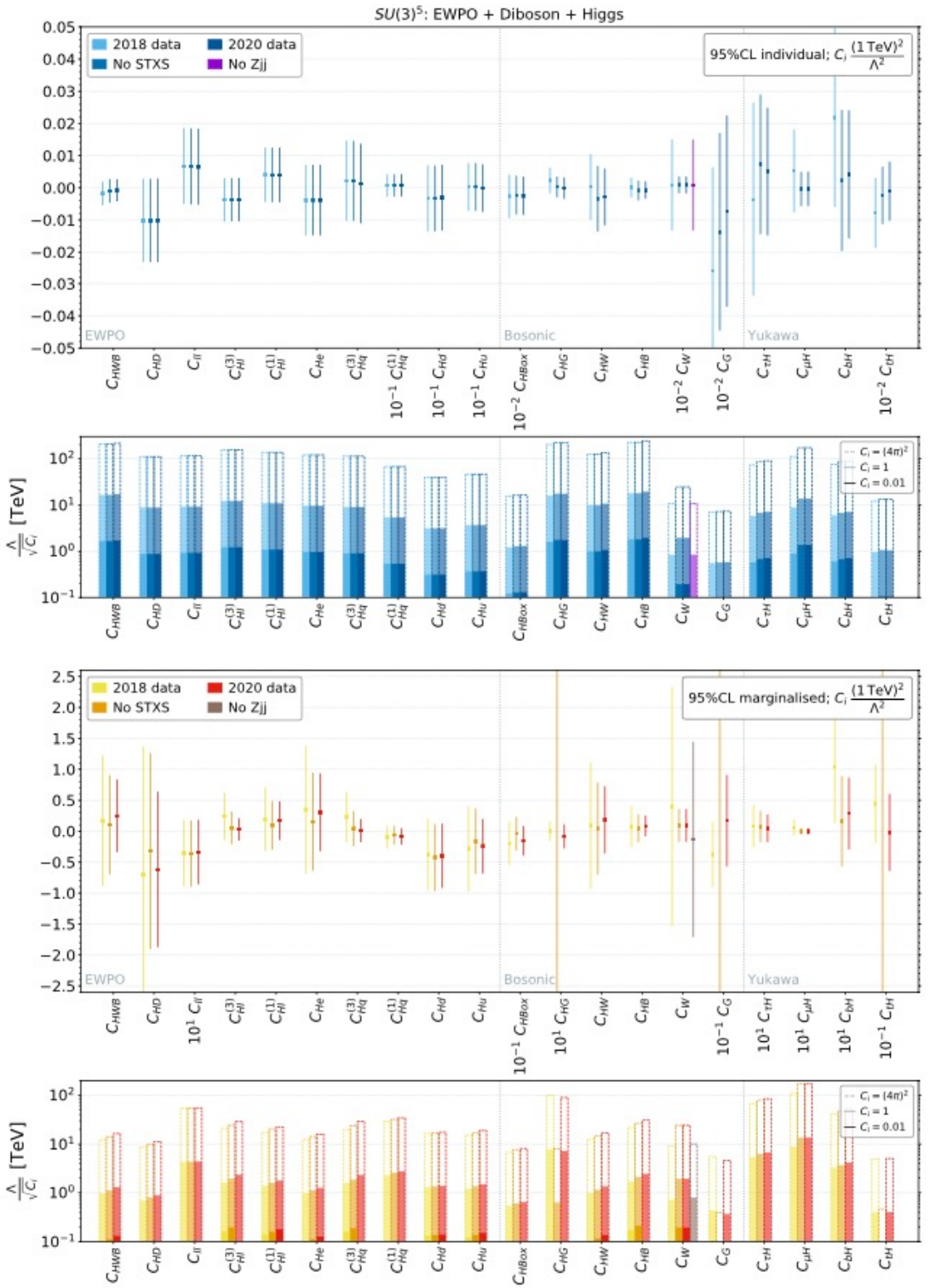
Standard Model Effective Field Theory

A powerful way to analyze the data

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

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

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

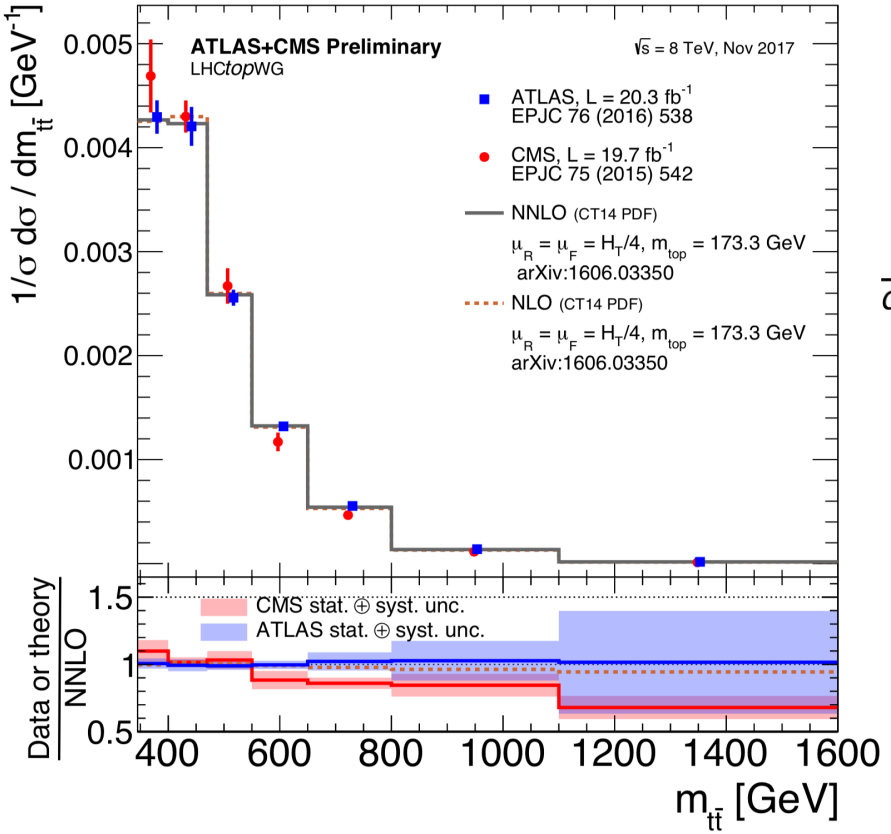


No significant deviations from SM

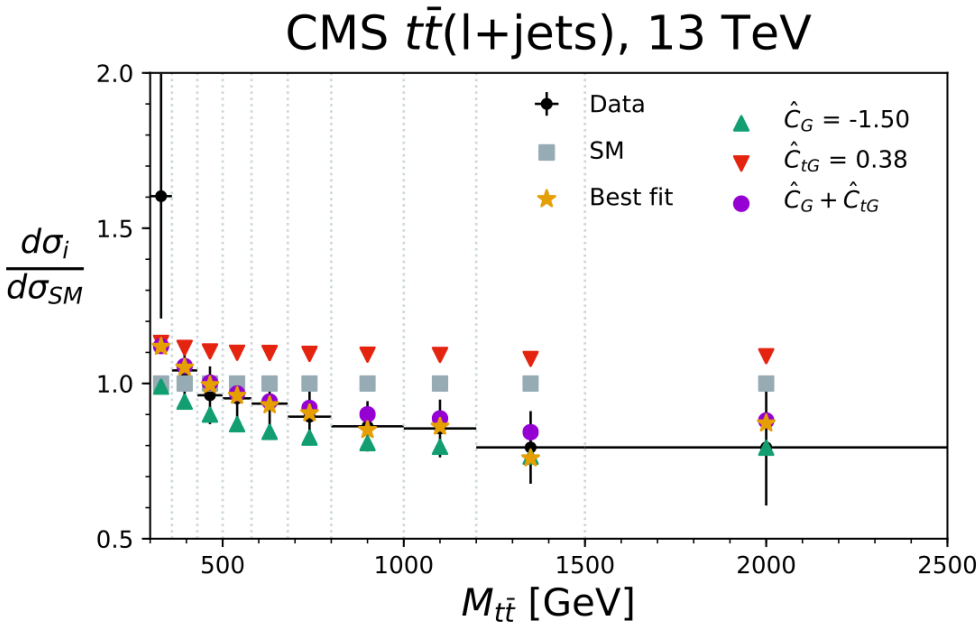
JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Stop press from the LHC!

$t\bar{t}$ Cross Section as Function of $M_{t\bar{t}}$



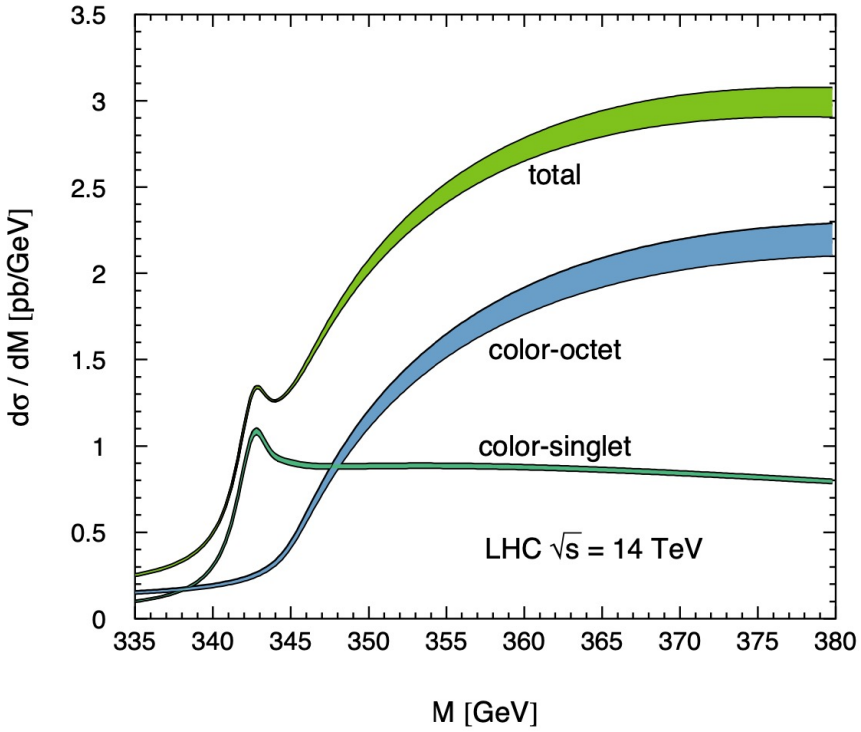
- Good match to theory, except close to threshold?



- Can problem be fixed by BSM?
- No improvement with SMEFT
- Higher-order QCD effects?

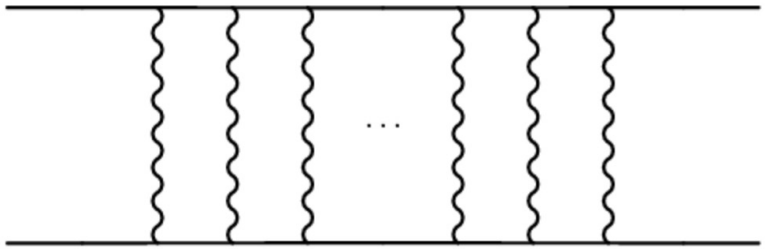
Is the LHC Discovering a Boson with Mass around 340 GeV?

- An elementary boson – or pseudoscalar toponium?
- Predicted to have a mass a few GeV below the $t\bar{t}$ threshold: 343.5 GeV
- Production of vector toponium in e^+e^- collisions studied in detail
- Relatively few studies for toponium in proton-proton collisions
- Fascinating QCD problem!



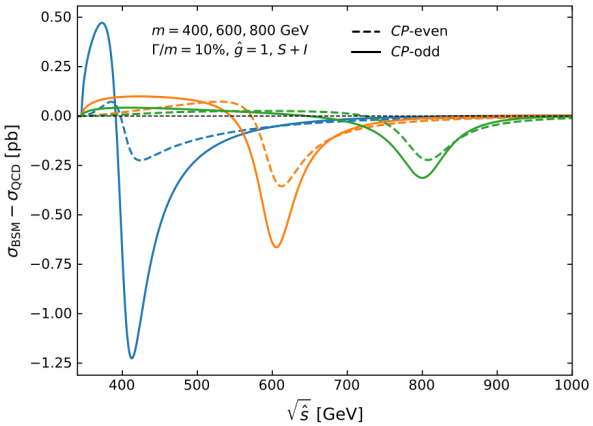
$t\bar{t}$ Bound State vs Additional Higgs?

- Prediction of QCD
- Sommerfeld enhancement: summation of $(\alpha_s/v)^n$



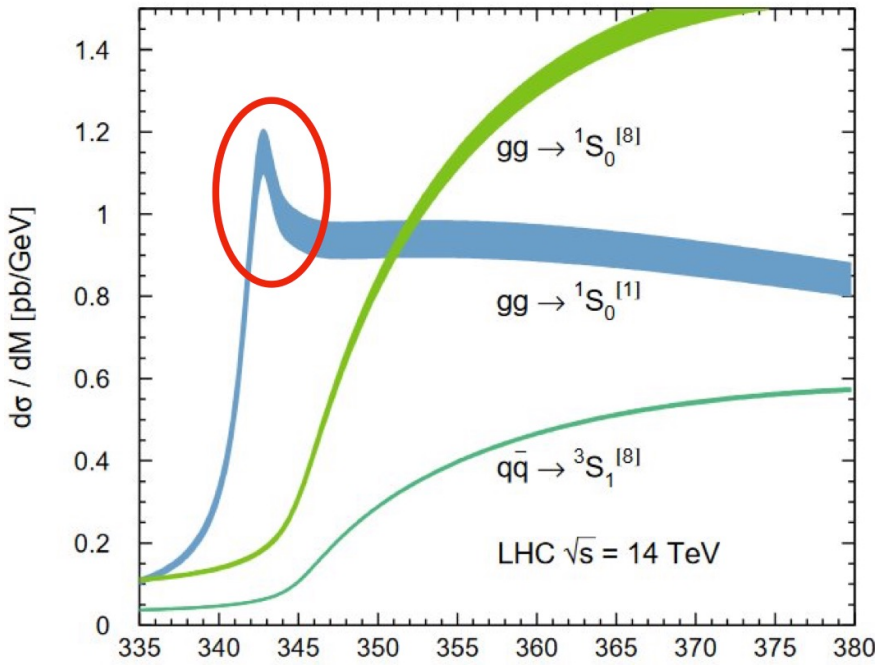
- Lowest-lying $t\bar{t}$ states in s-wave: $t\bar{t}$ $^1S_0$,$^3S_1$ (pseudoscalar, vector)
- Production of scalar $t\bar{t}$ $^3P_0$ suppressed

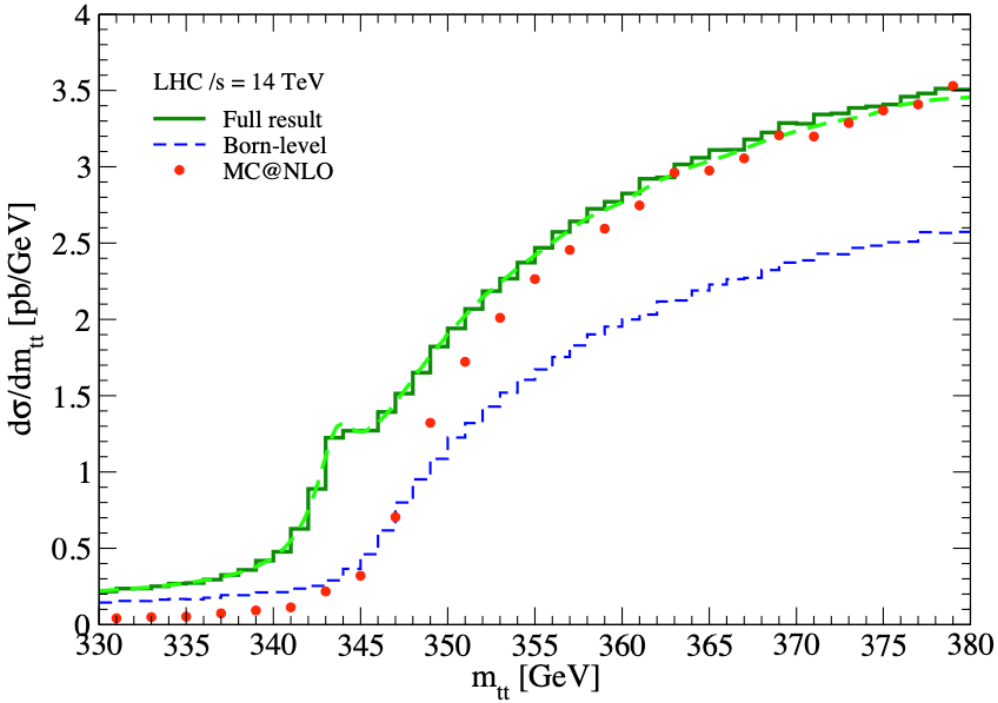
- BSM, e.g., 2 Higgs doublet model
- 4 extra physical Higgses: neutral pseudoscalar, scalar, charged $A, H, H^{\pm}$
- Expect *A,H* interference with QCD background (peaks & dips)



Djouadi, JE, Popov & Quevillon, arXiv:1901.03417

$t\bar{t}$ Sommerfeld Enhancement

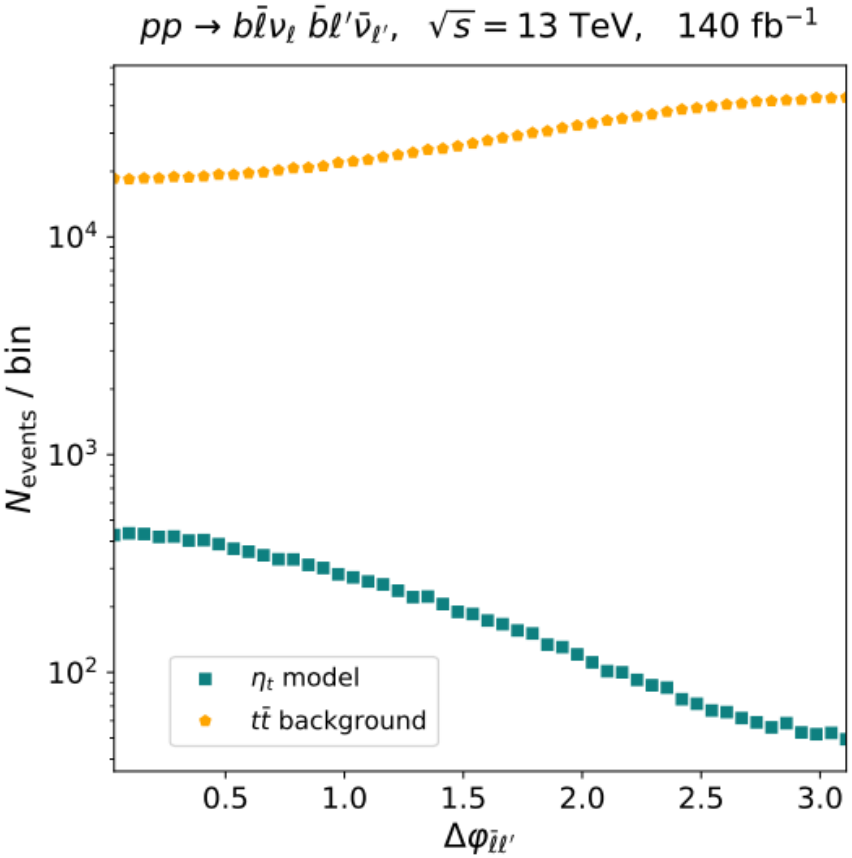




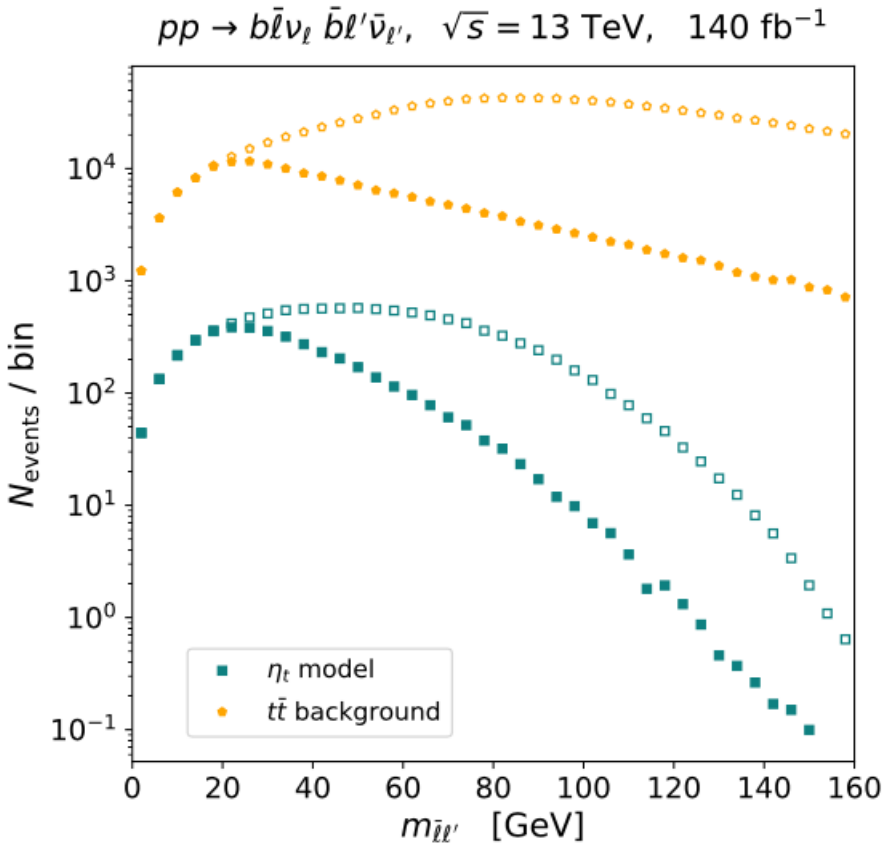
Sumino & Yokoya, arXiv:1007.0075

- Colour-singlet, η_t pole dominant below nominal $\bar{t}t$ threshold
- Cross-section >> perturbative QCD calculation of $d\sigma/dm_{\bar{t}t}$

Toponium Decay Kinematics



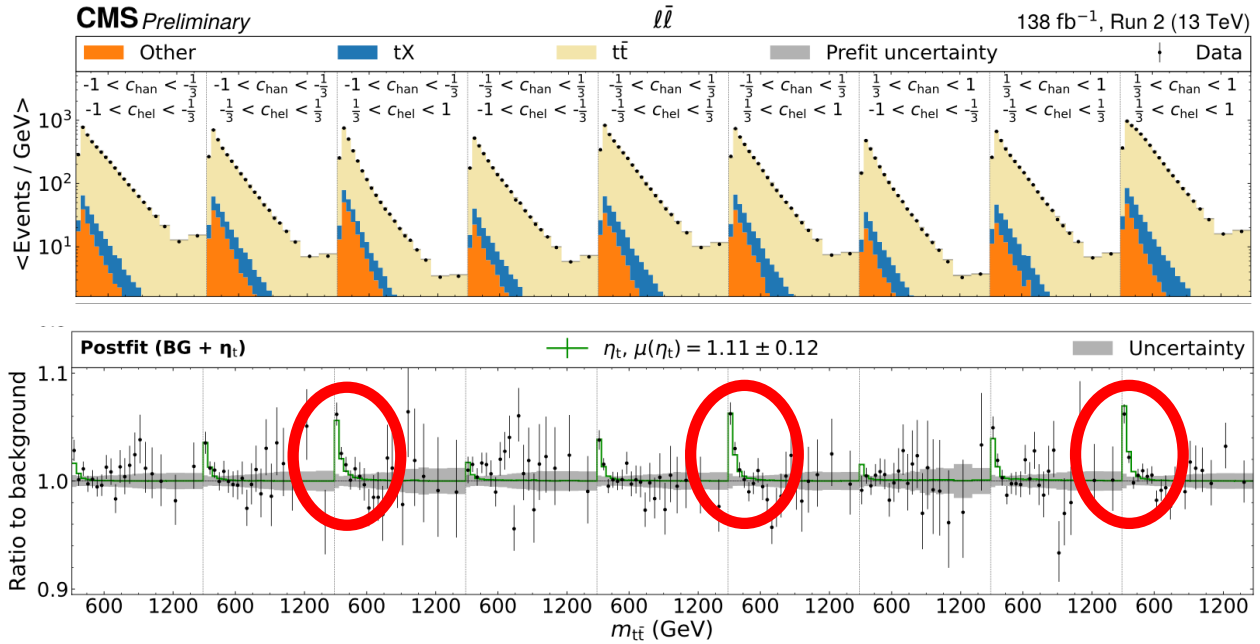
$\bar{\ell}\ell'$ azimuthal angle difference



$m_{\bar{\ell}\ell'}$ with(out) azimuthal angle cut

Fuks, Hagiwara, Ma & Zheng, arXiv:2102.11281

Observation of η_t Signal?



SM η_t hypothesis fits data well

Measured cross section 7.1pb($\pm$11%) consistent with theory: 6.43pb[(*)]

Nominal significance $> 5\sigma$

Fits data better than BSM Higgs boson

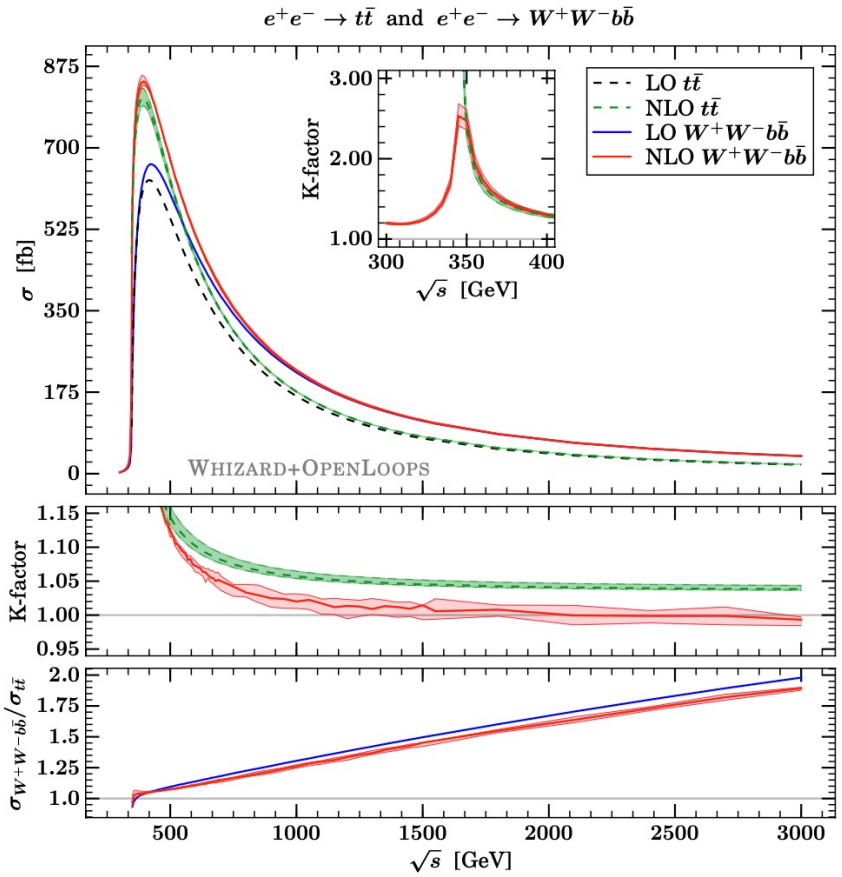
	Best-fit point	Difference in $-2\ln L$
η_t interpretation	$\mu(\eta_t) = 1.11$	-86.2
Single A interpretation	$m_A = 365\,\text{GeV}, \Gamma_A/m_A = 2\%, g_{At\bar{t}} = 0.78$	-72.6
Single H interpretation	$m_H = 365\,\text{GeV}, \Gamma_H/m_H = 2\%, g_{Ht\bar{t}} = 1.45$	-10.4

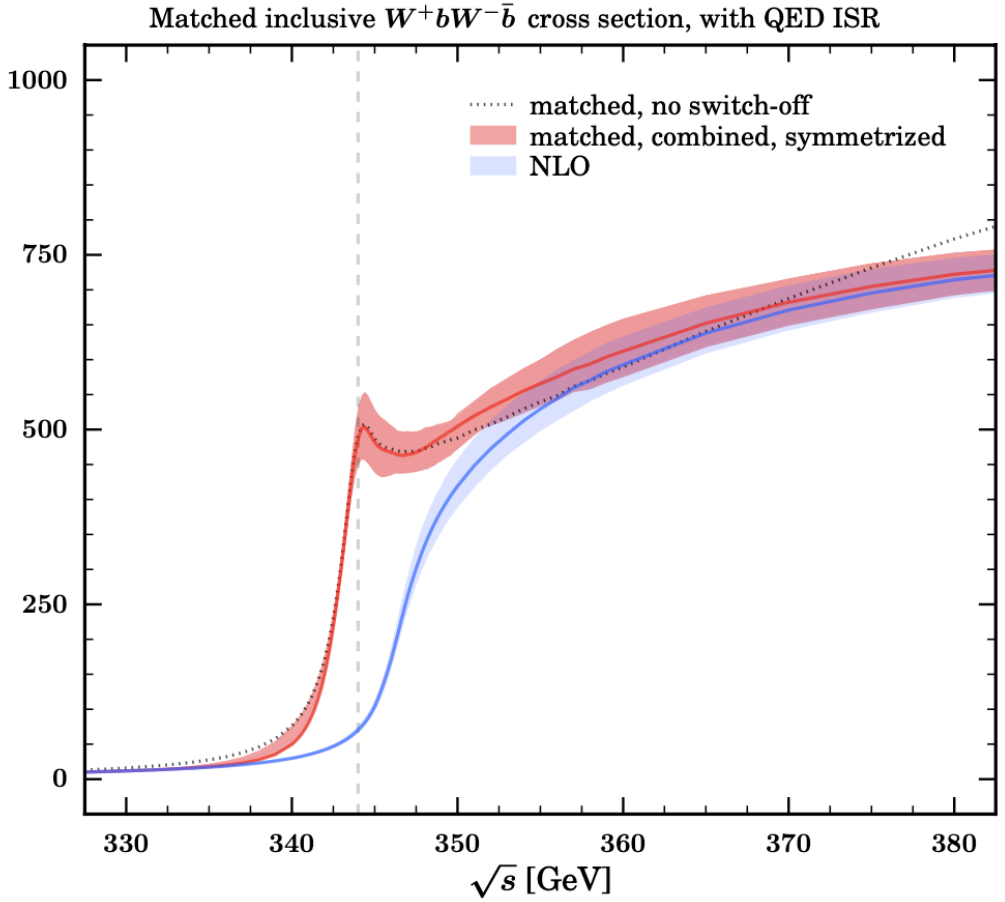
(*)Fuks, Hagiwara, Ma & Zheng, arXiv:2102.11281

CMS Collaboration, CMS-PAS-HIG-22-013,
DESY Colloquium, Oct. 15, 2024

Interesting possibility for the future?

Toponium in e^+e^- Annihilation





- Precise calculations available of vector toponium in $\sigma(e^+e^- \to \bar{t}t)$
- Need better calculations of pseudoscalar toponium in $pp \to \bar{t}t$ + X near threshold

Reuter et al, arXiv:1801.08083

Inconclusive Summary

- No shortage of puzzles indicating need for BSM
  - Everything about the Higgs is puzzling
    - Flavour, vacuum stability, EW mass scale, …
      - **Abandon naturalness? For what?**
- Dark matter
  - Heavy fermion (WIMP) or ultralight bosonic clouds?
    - No experimental sign of WIMP at LHC or elsewhere
      - **Broaden experimental search**
- Combine direct and indirect approaches for BSM
  - **FCC-ee/CEPC + FCC-hh/SppC**
- LHC stop press: More Higgs bosons or **toponium**?
  - **Great 50th birthday present for charmonium!**