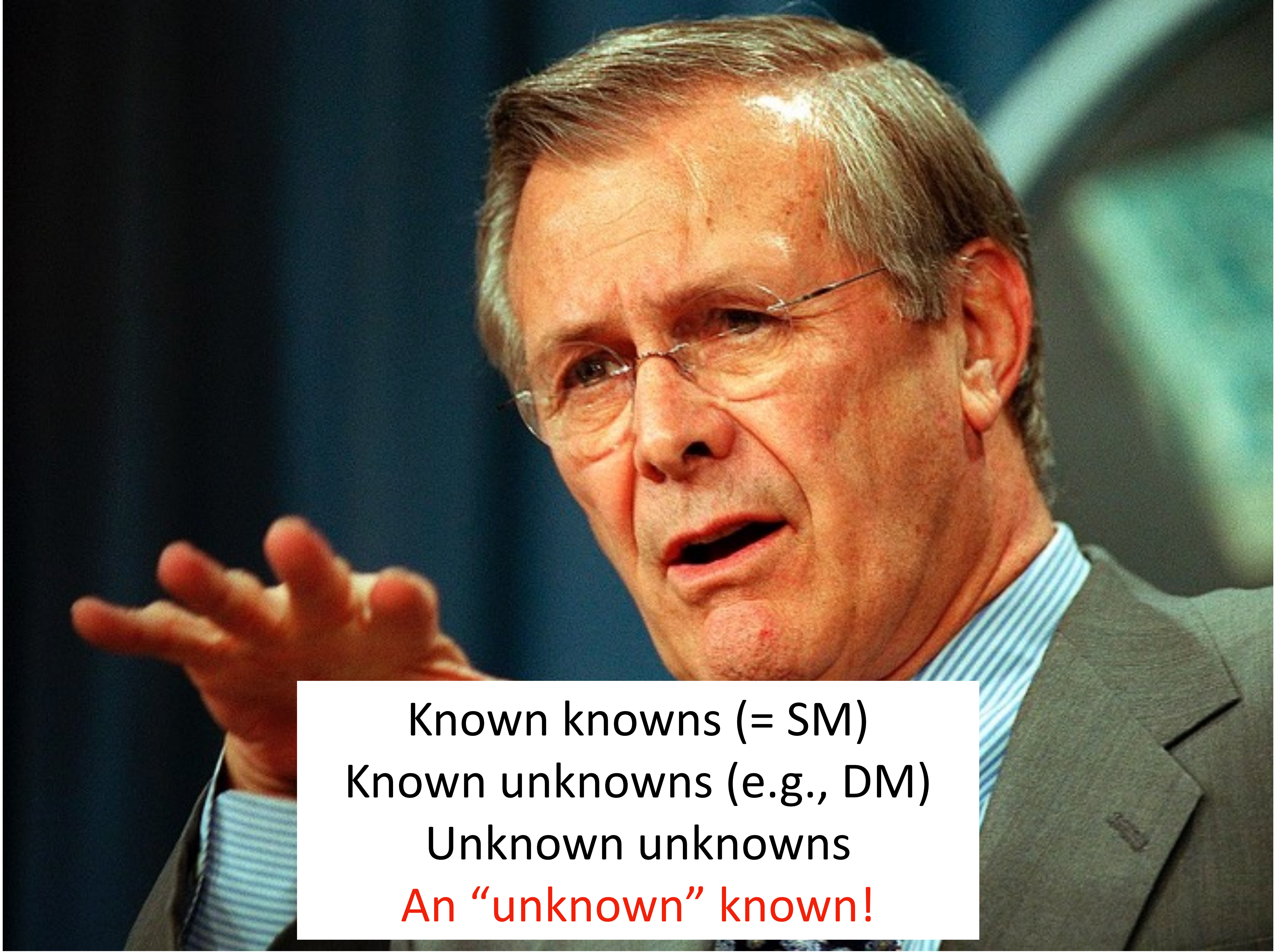
LHC physics: the first 15 years

Introduction
Review of Higgs physics
Motivations for physics beyond the SM:
Higgs mysteries
SM Effective Field Theory to scan for new physics
Top physics
Discovery of another boson?

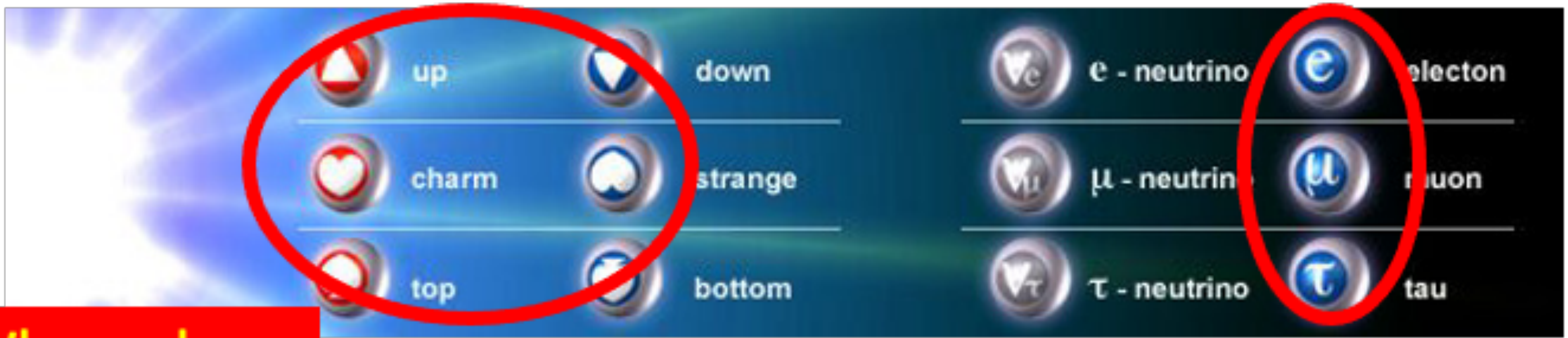
YEARS /ANS CERN
1954-2024

John Ellis
KING'S College LONDON


Known knowns (= SM)
Known unknowns (e.g., DM)
Unknown unknowns
An "unknown" known!

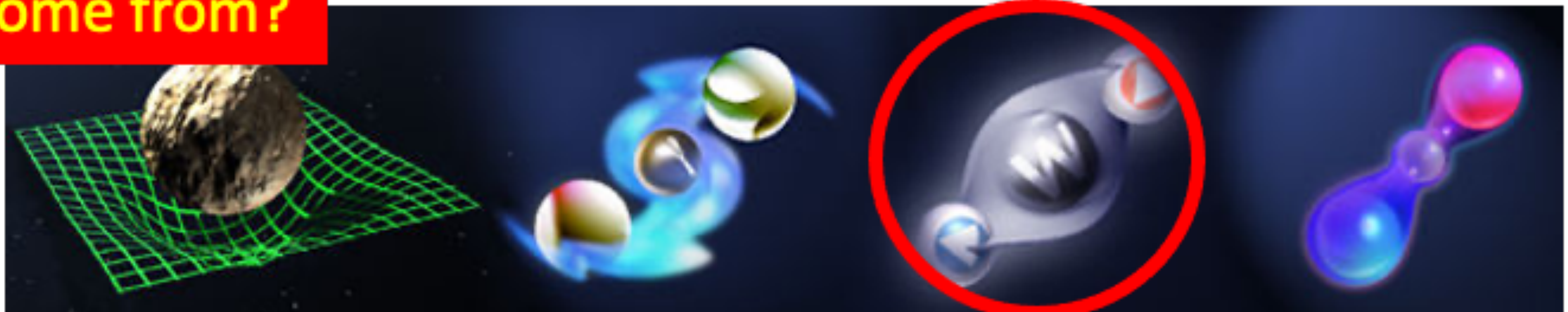
The 'Standard Model'

The matter particles



Where does mass come from?

The fundamental interactions



Gravitation electromagnetism weak nuclear force strong nuclear force

Why do Things Weigh?

Newton:

Weight proportional to Mass

Einstein:

Energy related to Mass

Neither explained origin of Mass

Where do the masses come from?

Are masses due to Higgs boson? (the physicists' Holy Grail)

Some Key LHC Dates

- 1994: LHC approved by CERN Council
- 2008: LHC start-up
- 2009: First low-energy collisions
- 2010: First high-energy collisions at 7 TeV
- 2011: First hints of the Higgs boson
- 2012: LHC at 8 TeV, discovery of the Higgs boson
- 2013: Nobel Prize for Peter Higgs and François Englert
- 2015 - 2018: Run 2 of the LHC at 13 TeV
- 2022 - 2026: Run 3 of the LHC at 13.6 TeV

Summary of the Standard Model

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

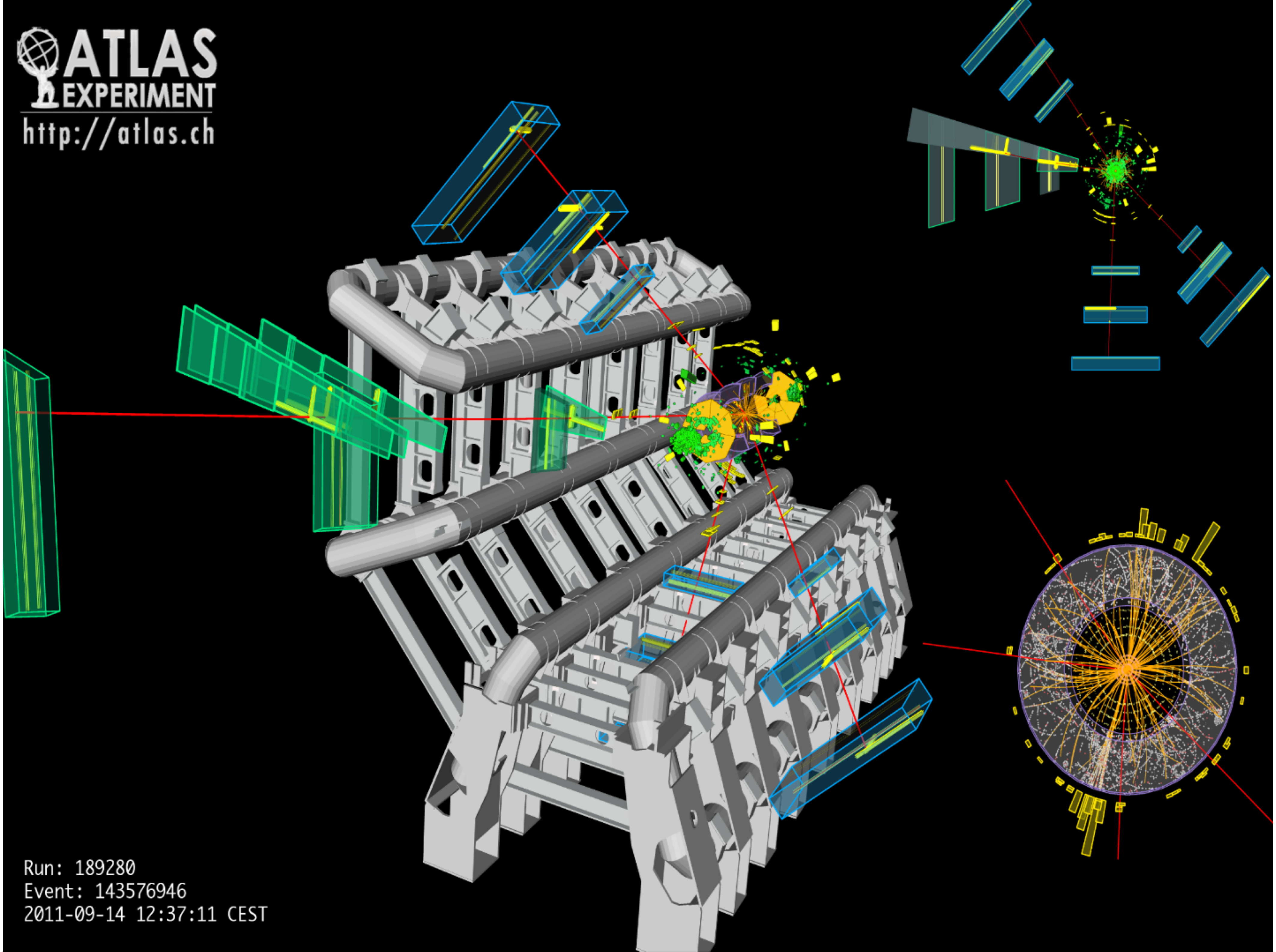
L_L	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$	$(\mathbf{1},\mathbf{2},-1)$
E_R	$e^-_R , \mu^-_R , \tau^-_R$	$(\mathbf{1},\mathbf{1},-2)$
Q_L	$\begin{pmatrix} u \\ d \end{pmatrix}_L , \begin{pmatrix} c \\ s \end{pmatrix}_L , \begin{pmatrix} t \\ b \end{pmatrix}_L$	$(\mathbf{3},\mathbf{2},+1/3)$
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:

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

Tested < 0.1% before LHC

Testing now in progress


ATLAS
EXPERIMENT
http://atlas.ch
Run: 189280
Event: 143576946
2011-09-14 12:37:11 CEST

Higgsdependence Day!

Scientists from around the World

Member States 7446

Austria 97 – Belgium 102 – Bulgaria 83 – Czech Republic 207 - Denmark 50 – Estonia 20 – Finland 76 – France 801 - Germany 1131 – Greece 220 – Hungary 84 – Israel 56 – Italy 2013 - Netherlands 154 – Norway 60 – Poland 370 – Portugal 125 – Romania 141 – Serbia 50 – Slovakia 122 – Spain 497 - Sweden 76 – Switzerland 196 – United Kingdom 715

Associate Member States in the pre-stage to Membership 55

Cyprus 18 – Slovenia 37

Associate Member States 1064

Brazil 157 – Croatia 51 – India 463 – Latvia 18 – Lithuania 27 – Pakistan 70
Türkiye 187 – Ukraine 91

Observers 2200

Japan 230 – (Russia 824) – USA 1146

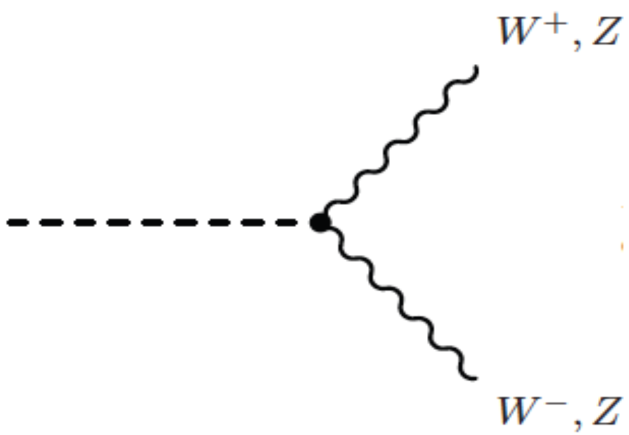
International Co-operation Agreements:

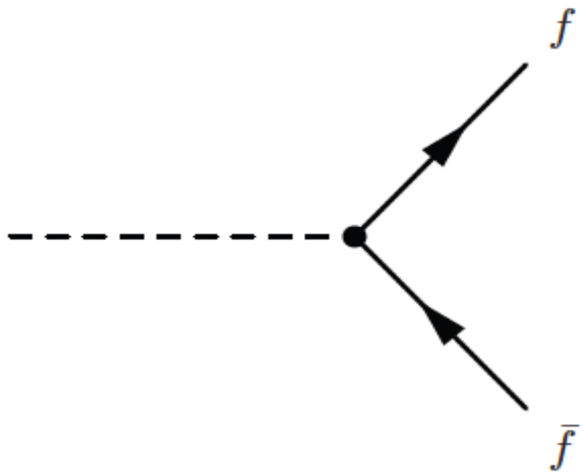
AB, AE, AL, AM, AR, AU, AZ, BD, BH, BO, BR, BY, CA, CL, CN, CO, CR, DZ, EC, EE, EG, GE, GH, HK, HO, IC, ID, IR, IS, JO, KR, KZ, LB, LT, MA, MD, ME, MK, MO, MT, MY, MX, MZ, NP, NZ, PA, PE, PH, PK, PR, RK, RW, QA, SA, SI, SL, SN, TL, TN, TU, TW, VN, UZ, ZA

Non-Member States and Territories 1975

Afghanistan 3 – Albania 6 – Algeria 15 – Argentina 22 – Armenia 17 – Australia 35 – Azerbaijan 5 – Bahrain 11 Bangladesh 11 – Belarus 26 – Bolivia 2 – Bosnia and Herzegovina 1 – Botswana 1 – Burundi 1 – Canada 149, Chile 43 – Colombia 57 – Congo 1 – Costa Rica 4 – Cuba 16 – Democratic Republic of the Congo 1 – Ecuador 13 Egypt 38 – El Salvador 1 – Georgia 58 – Guatemala 2 – Honduras 3 – Hong Kong 5 – Iceland 3 – Indonesia 11 – Iran 45 Ireland 33 – Jamaica 1 – Jordan 5 – Kazakhstan 15 – Kenya 2 – Kuwait 1 – Kyrgyzstan 2 – Lebanon 23 – Lesotho 1 Luxembourg 2 – Madagascar 4 – Macao 2 – Malaysia 11– Malta 3 – Mauritius 1 – Mexico 97 – Mongolia 3 – Montenegro 7 Morocco 31 – Myanmar 1 – Nepal 13 – New Zealand 2 – Nigeria 6 – North Macedonia [illegible] – Palestine 5 – People's Republic of China 701 – Paraguay 2 – Peru 11 – Philippines 2 – Republic of Korea 197 - Saint Kitts and Nevis 1 – Saudi Arabia 4 Senegal 2 – South Africa 49 – Sri Lanka 9 – Syrian Arab Republic 4- Taiwan 57 – Thailand 20 – Trinidad and Tobago 1 Tunisia 6 – Uganda 1 – Uruguay 1 - Uzbekistan 2 – Venezuela 7 - Viet Nam 12 – Yemen 1 – Zambia 1 – Zimbabwe 3

Higgs Boson Couplings





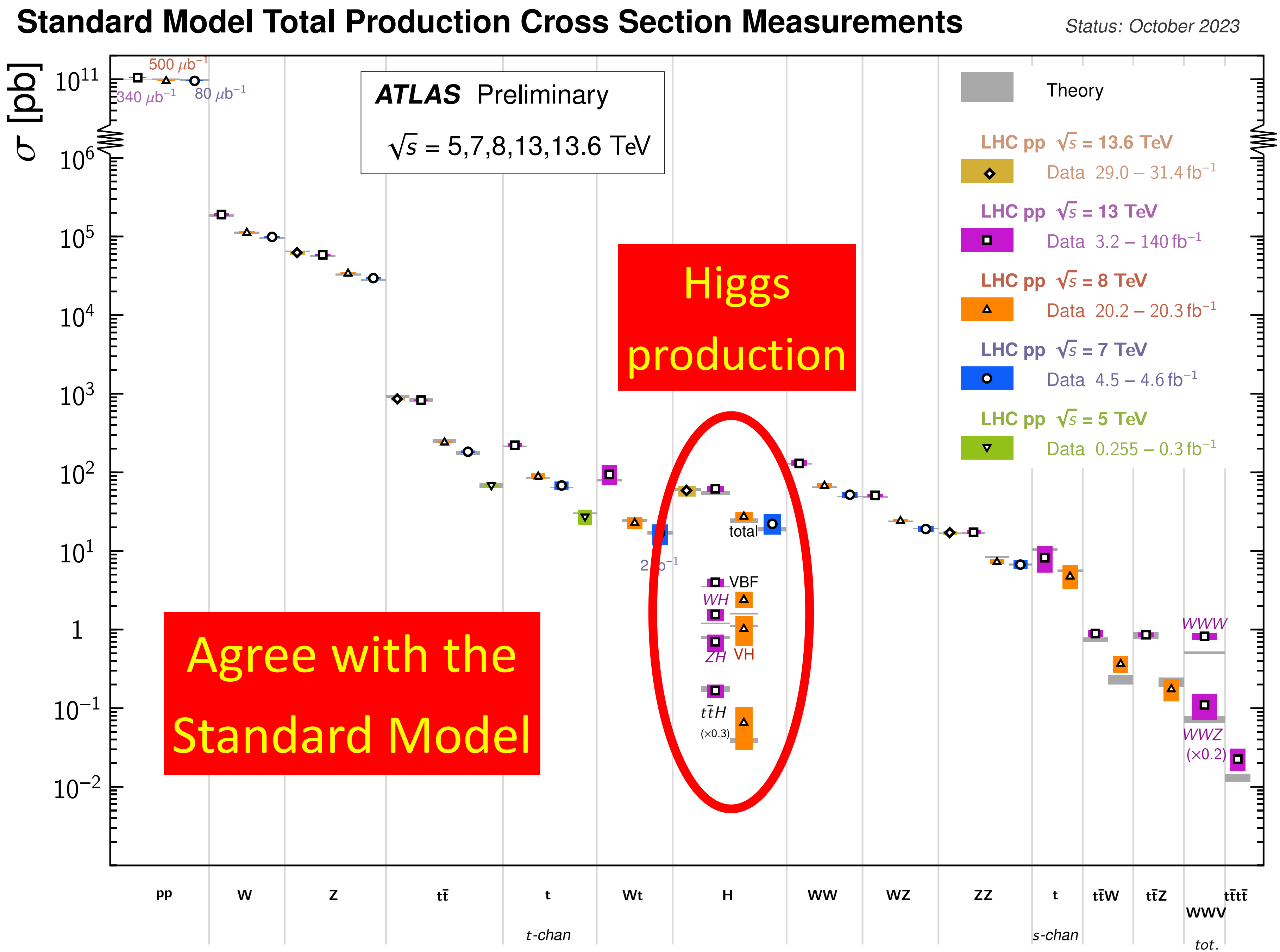
$$g_2 M_W \ , \quad g_2 \frac{M_Z}{c_W}$$

$$\frac{m_f}{v} = \frac{g_2 m_f}{2M_W}$$

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

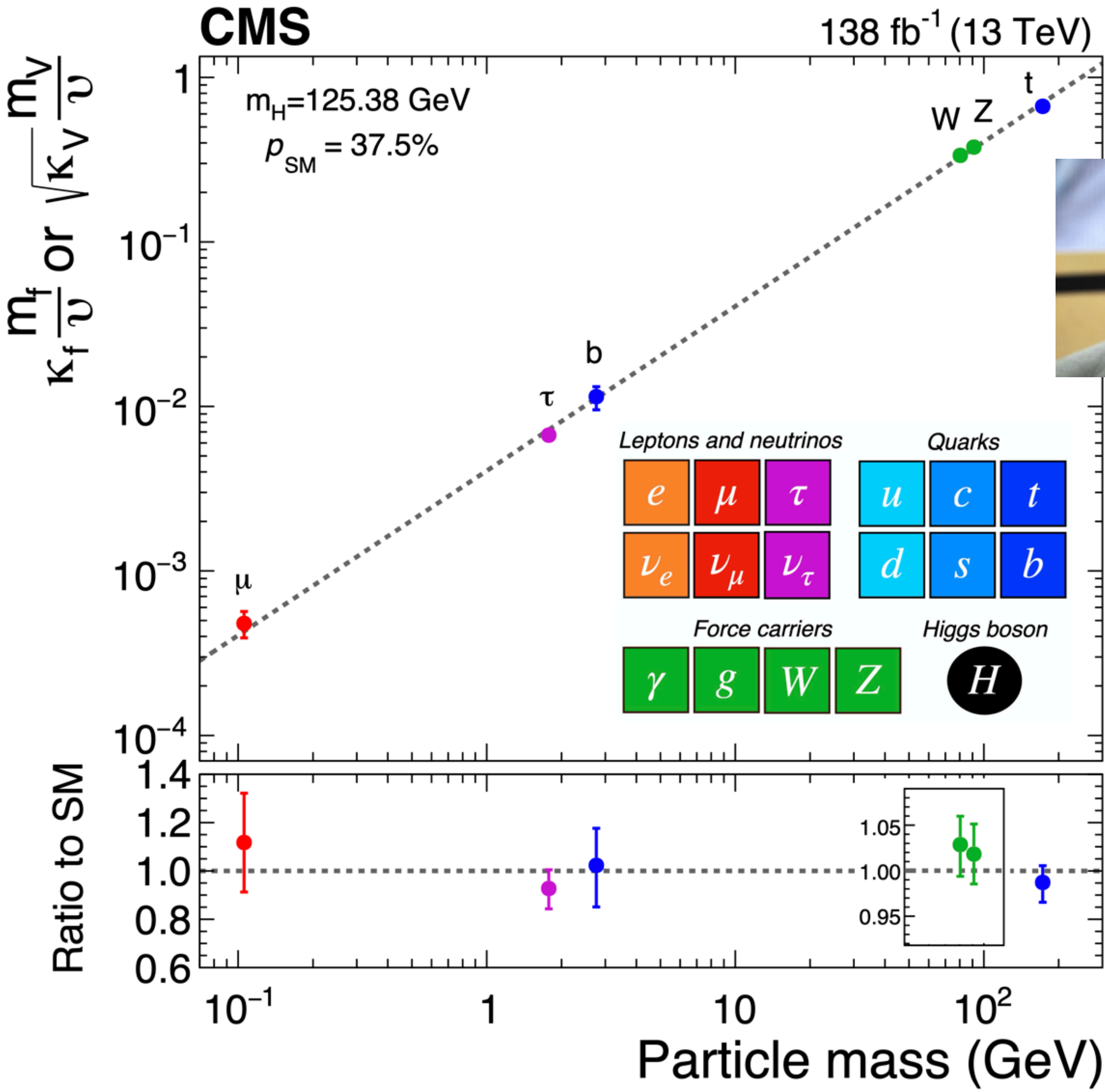
$$\Gamma(H \to VV) = \frac{G_F M_H^3}{8\pi\sqrt{2}} F(r) \left(\frac{1}{2}\right)_Z , \quad r = \frac{M_V}{M_H}$$

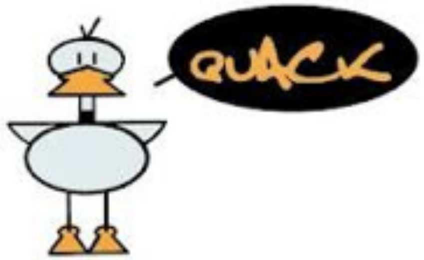
LHC Measurements



It Walks and Quacks like a Higgs

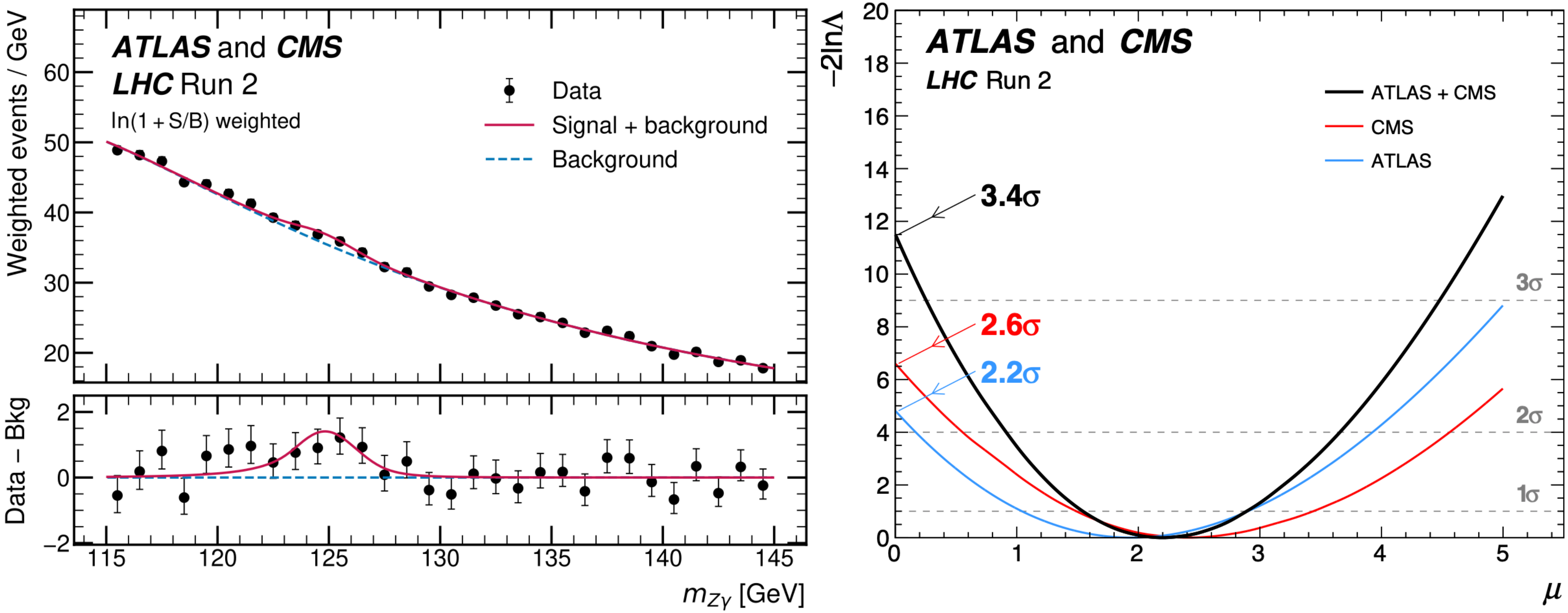
- Couplings scale ~ mass, with scale ~ v





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

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

Higher-order EW unimportant

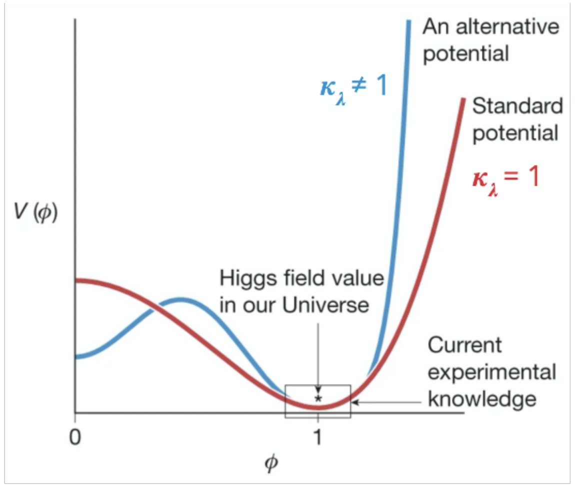
Chen, Chen, Qiao & Zhu, arXiv:2404.11441

Statistics? BSM physics?

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

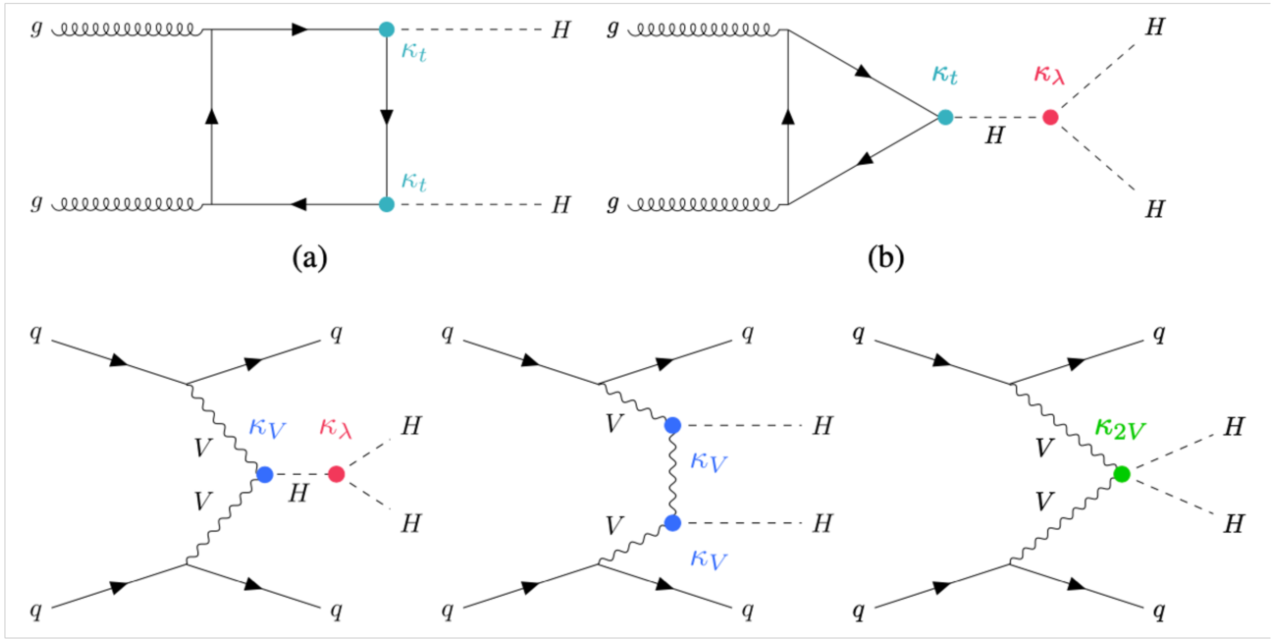
Higher-Order Higgs Couplings

- 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**

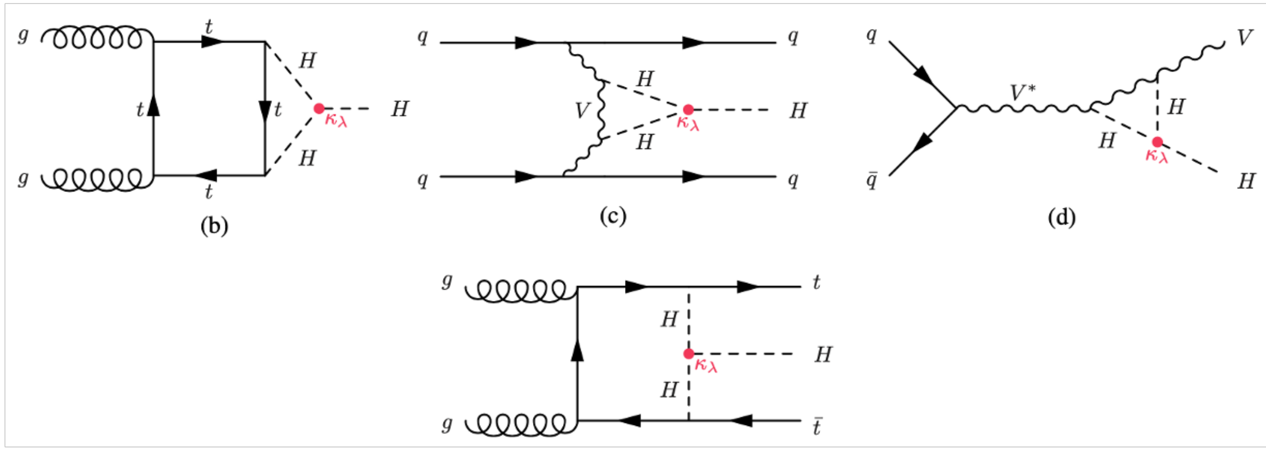


Search for Triple-H Coupling

Diagrams for double-Higgs production



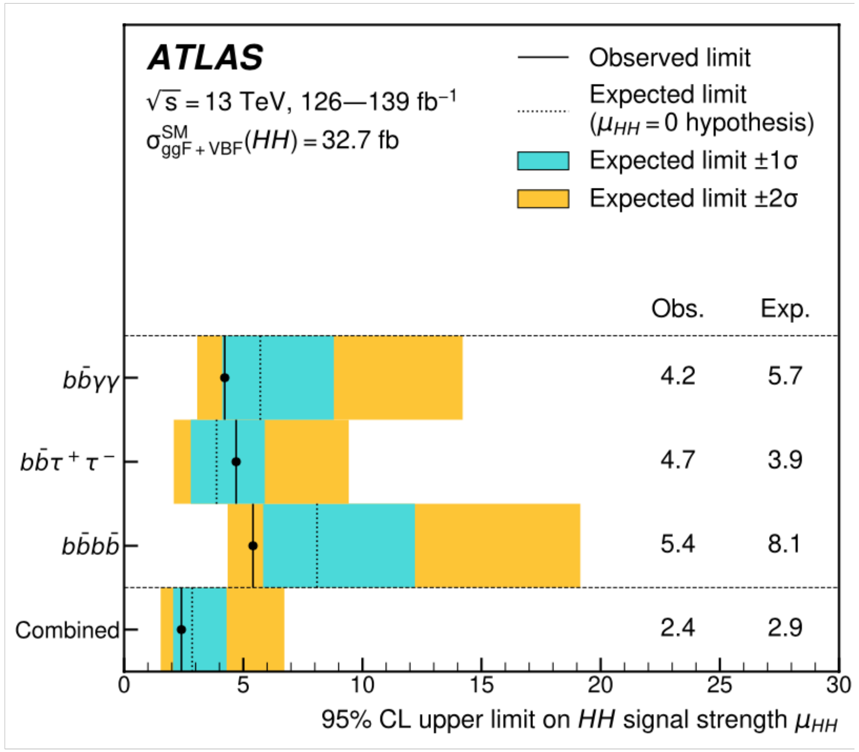
Loop corrections to single Higgs production



ATLAS Collaboration, arXiv: 2211.01216

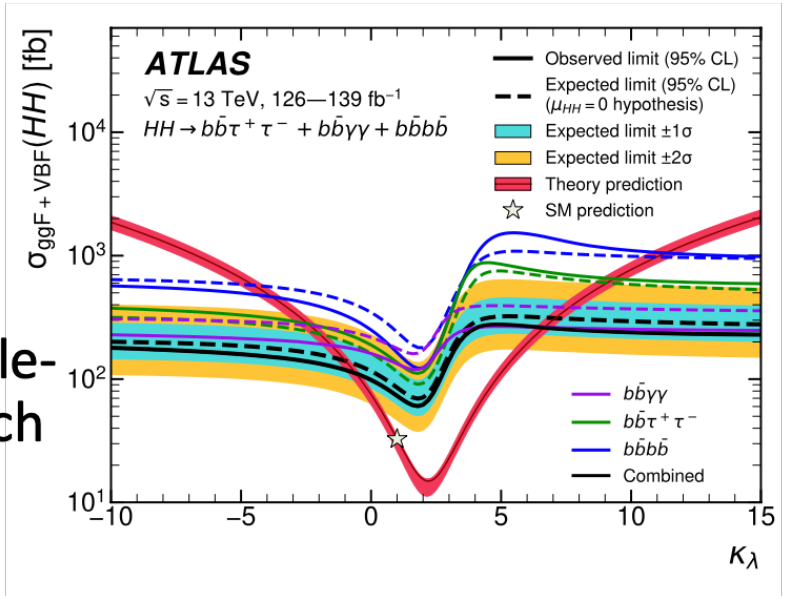
Search for HHH Coupling

Limit on double-Higgs production

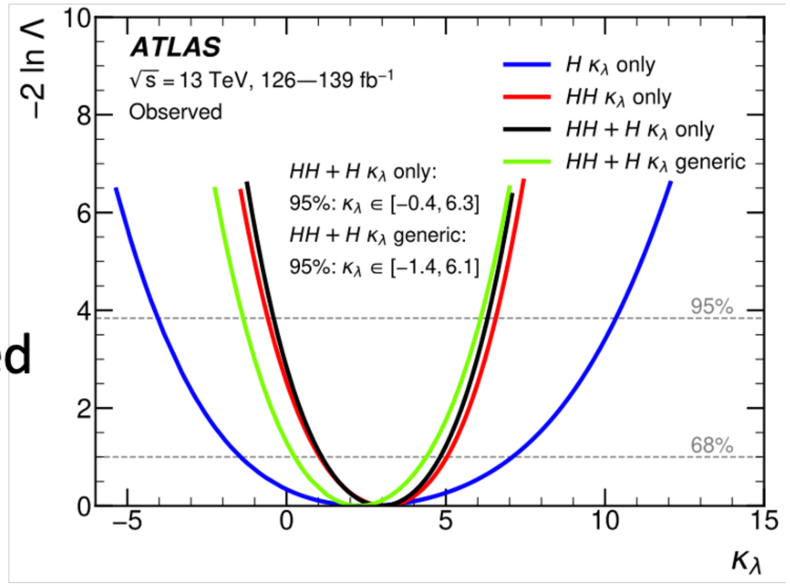


Limits on triple-Higgs coupling

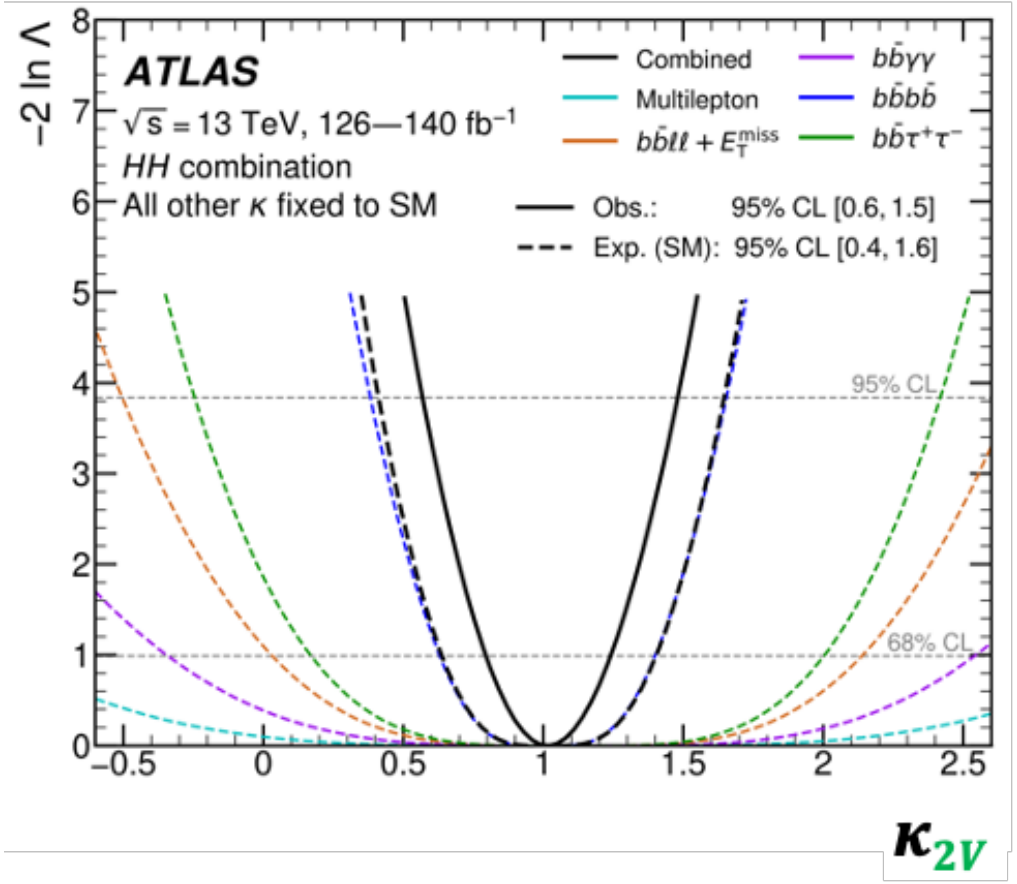
From double-Higgs search

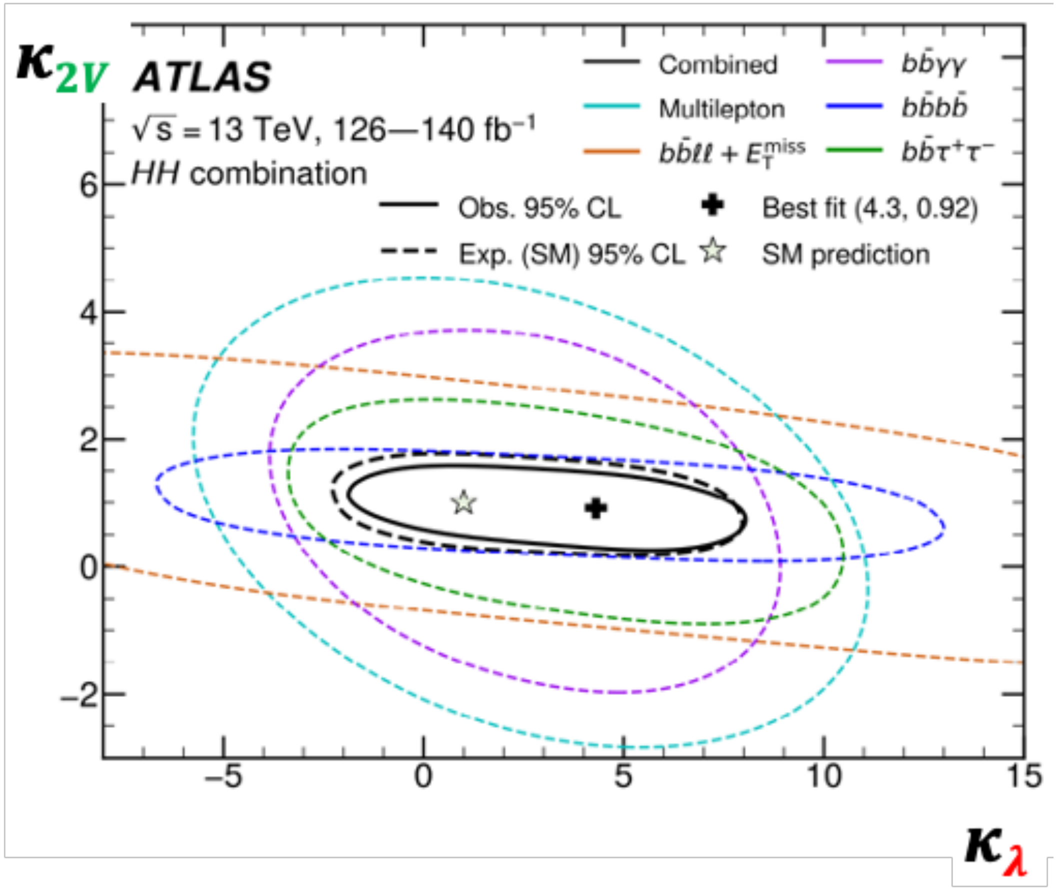


Combined limit



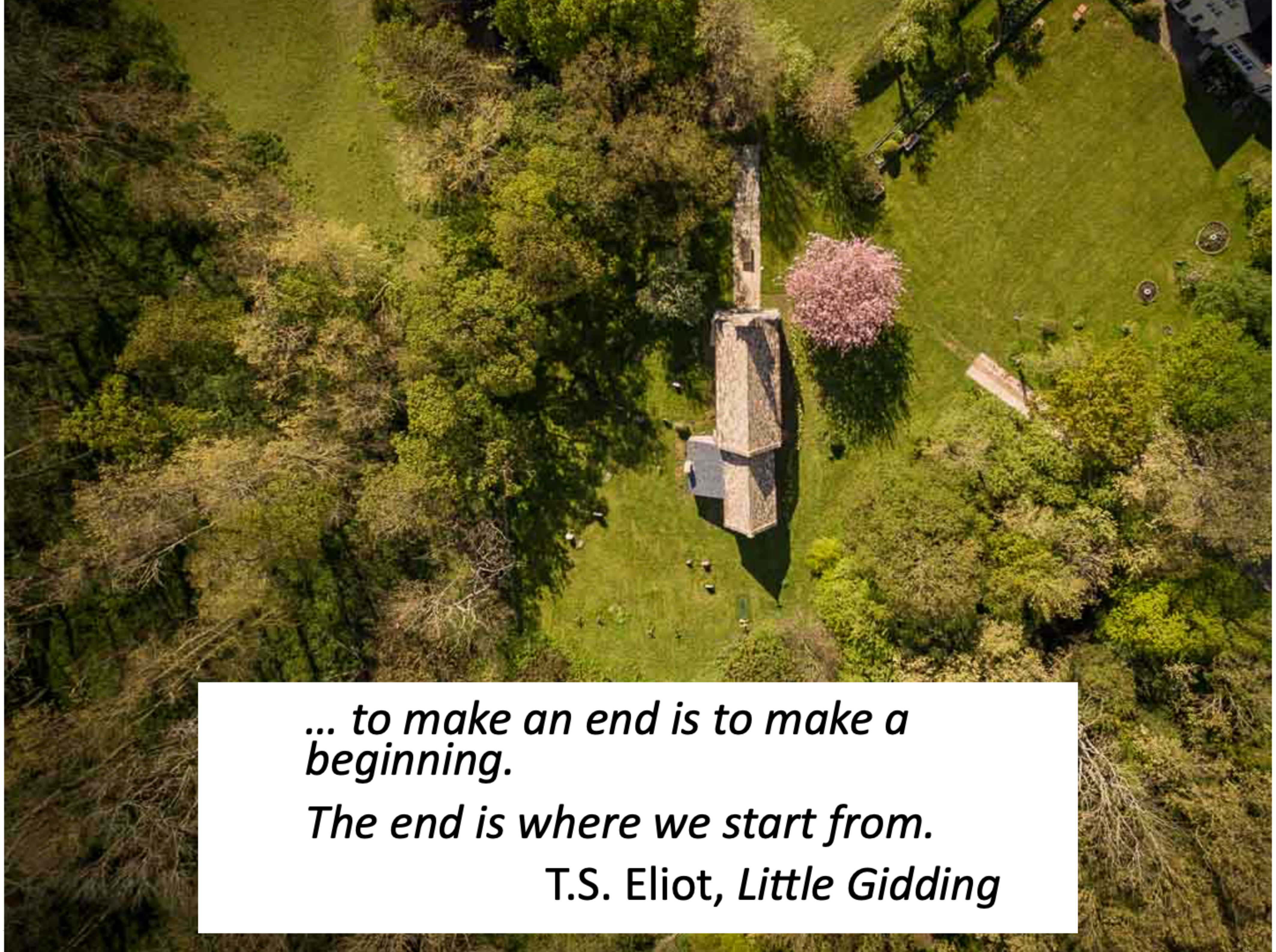
Evidence for VVHH Coupling





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

ATLAS Collaboration, arXiv:2406.09971


… 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 — LHC
- Dark matter — LHC
- Origin of matter — LHC
- Sizes of masses — LHC
- Masses of neutrinos
- Inflation
- Quantum gravity
- …

Everything about Higgs is Puzzling

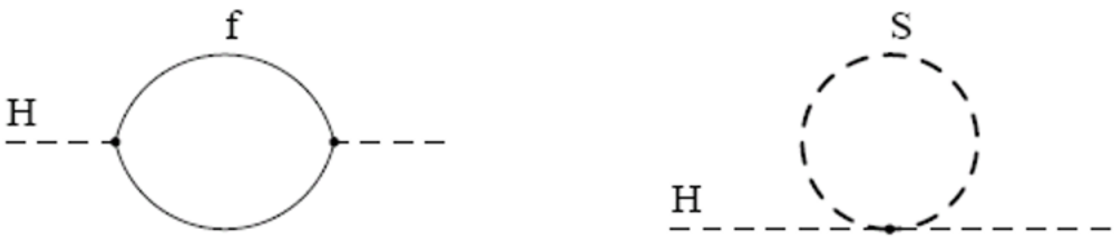
$$\mathcal{L} \; = \; yH\psi\overline{\psi} + \mu^2|H|^2 - \lambda|H|^4 - V_0 \; + \ldots$$

- 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?

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!

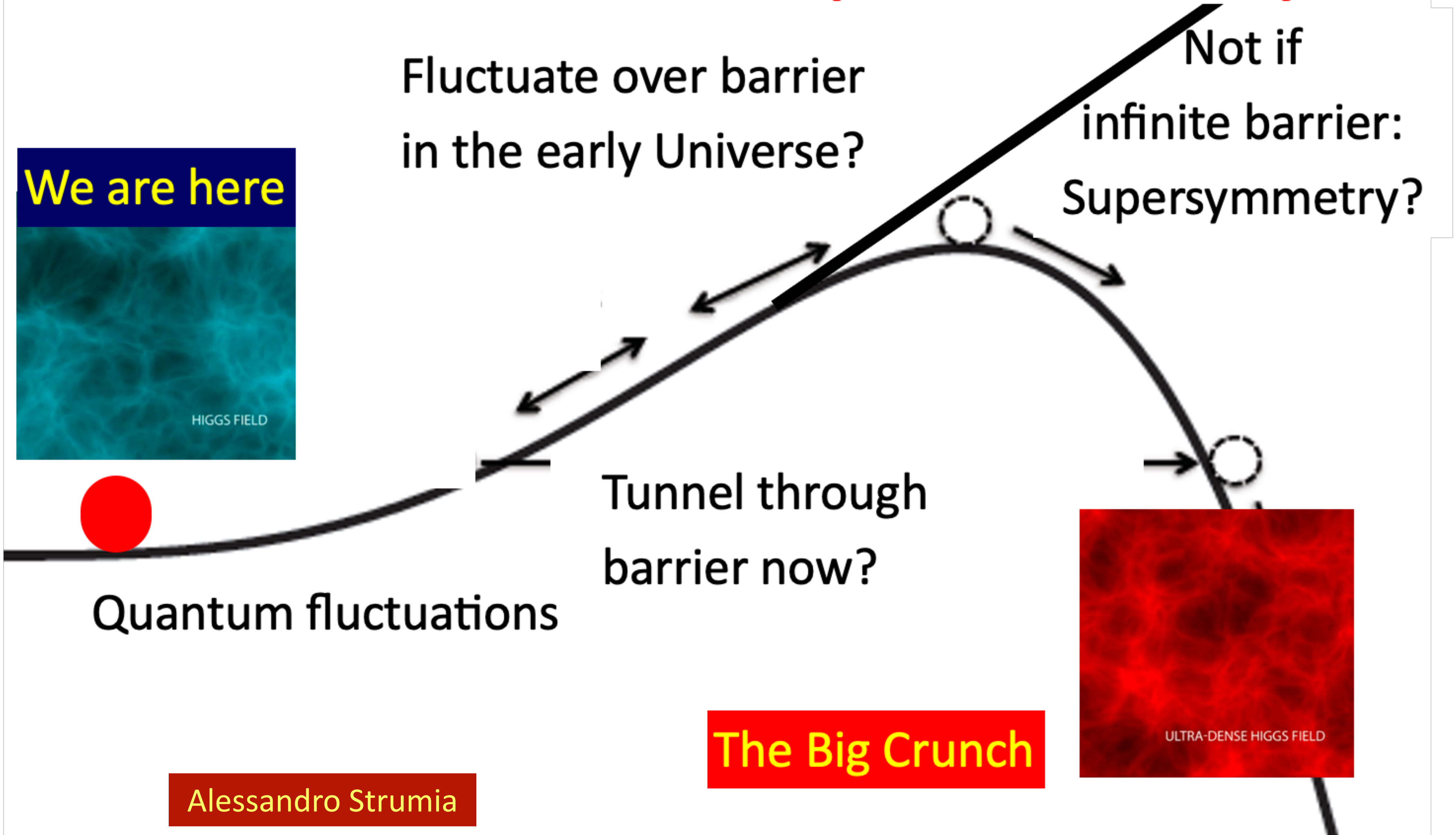
What lies beyond the Standard Model?

Supersymmetry?

New motivations from LHC

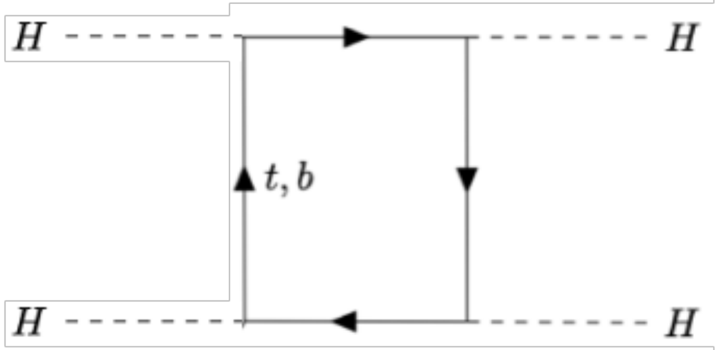
- Stabilize electroweak vacuum
- Successful prediction for Higgs mass
  - Should be < 130 GeV in simple models
- Successful predictions for couplings
  - Should be within few % of SM values
- Naturalness, GUTs, string, **dark matter**, $g_\mu - 2?$... ,

Will the Universe Collapse?
Should it have Collapsed already?



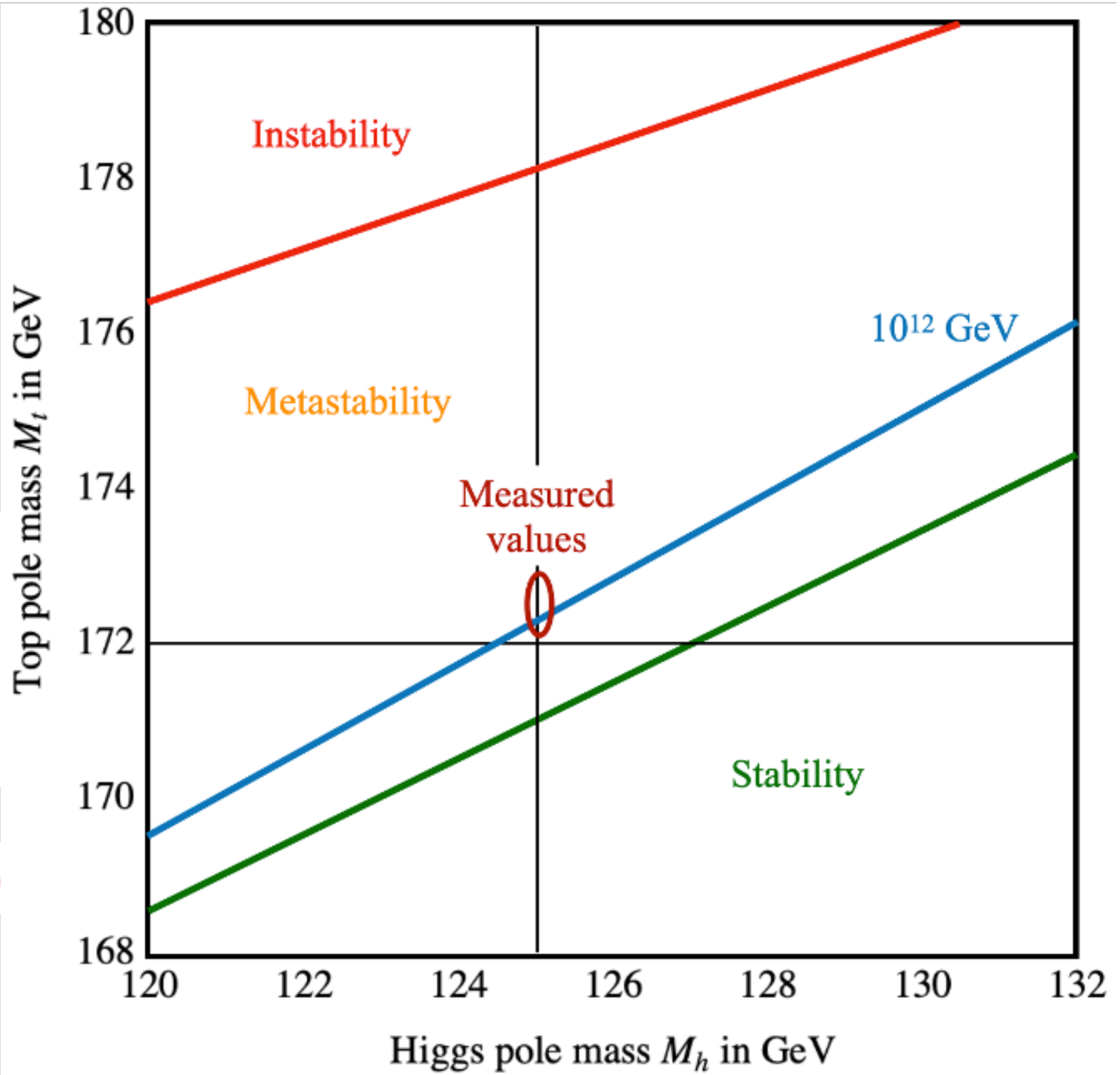
Is "Empty Space" Unstable?

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:

$$\mathrm{Log}_{10}\frac{\Lambda}{\mathrm{GeV}} = 10.5 - 1.3\left(\frac{m_t}{\mathrm{GeV}} - 172.6\right) + 1.1\left(\frac{m_H}{\mathrm{GeV}} - 125.1\right)\right) + 0.6\left(\frac{\alpha_s(m_Z) - 0.1179}{0.0009}\right)$$

Buttazzo et al, arXiv:1307.3536; Franceschini et al, 2203.17197

- New LHC value of m_t :

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

ATLAS & CMS, CERN-LPCC-2023-02

- Latest experimental values:

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

ATLAS & CMS

ATLAS, arXiv:2309.12986

- Instability scale:

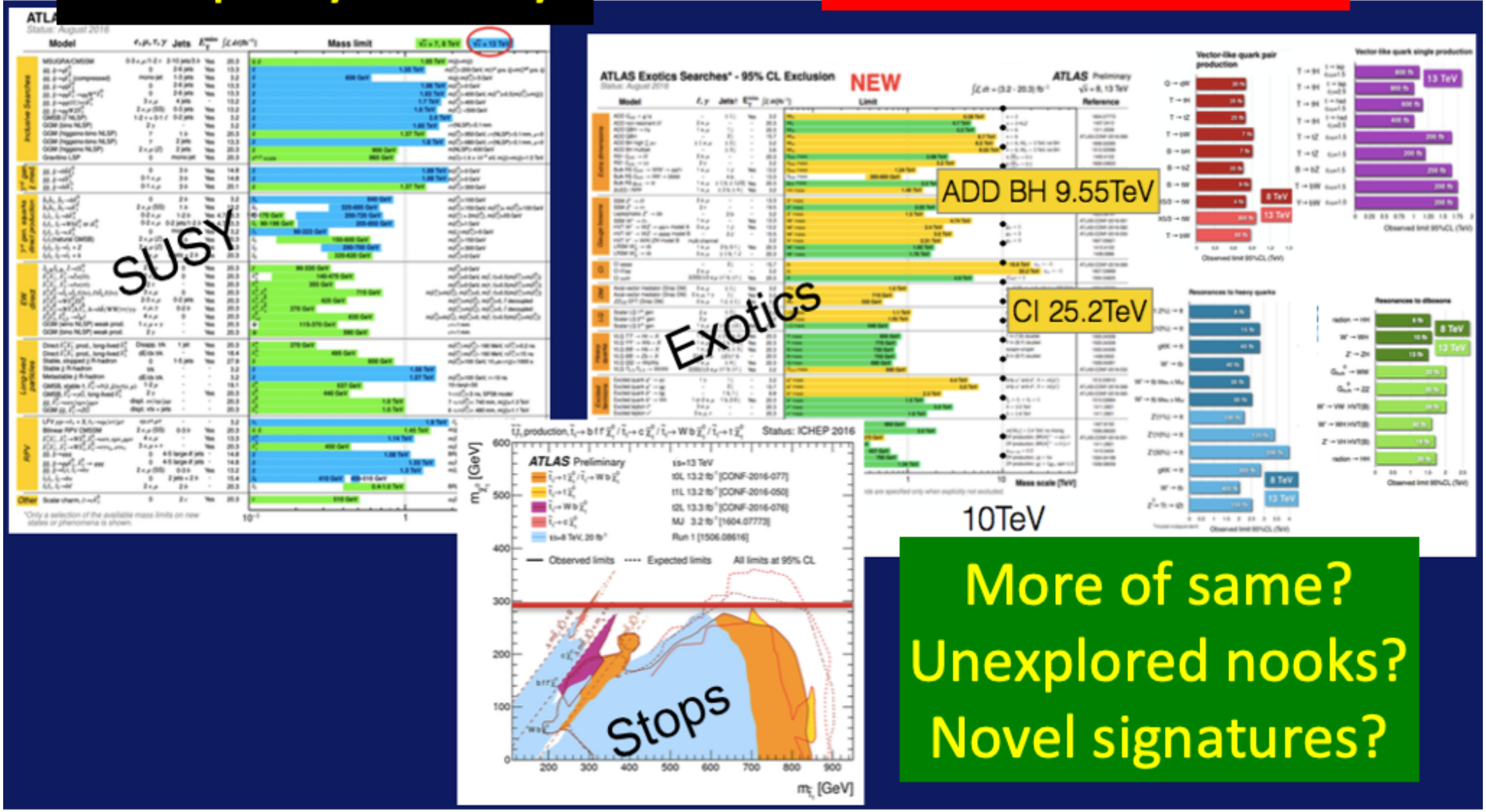
$$\log_{10}\frac{\Lambda}{\mathrm{GeV}} = 10.9 \pm 0.8$$

- Dominant uncertainties those in α_s and m_t

Nothing (yet) at the LHC

No supersymmetry

Nothing else, either



More of same?
Unexplored nooks?
Novel signatures?

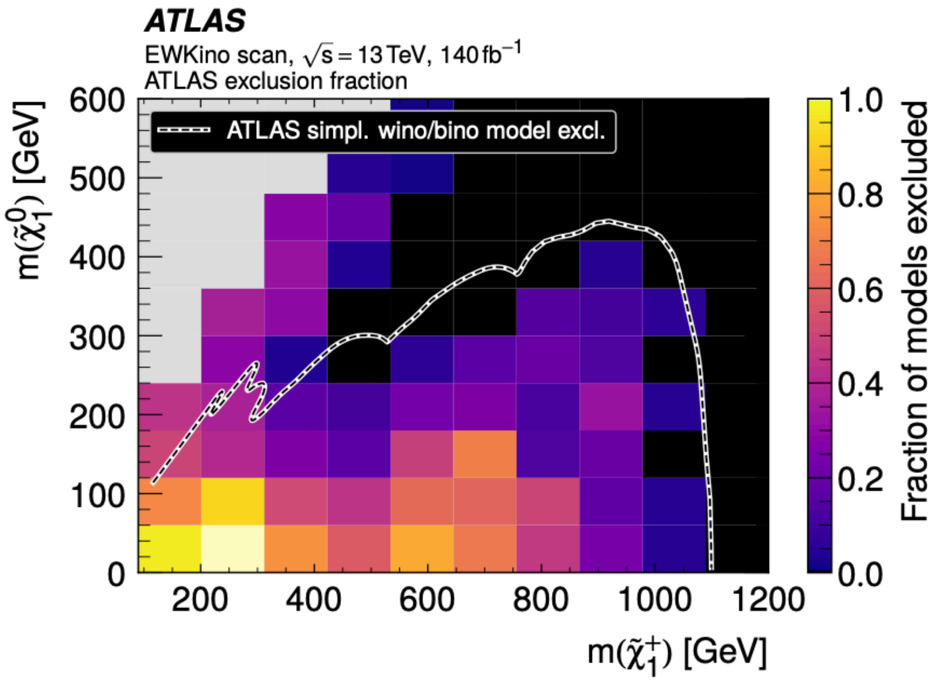
ATLAS Collaboration, arXiv:2402.01392

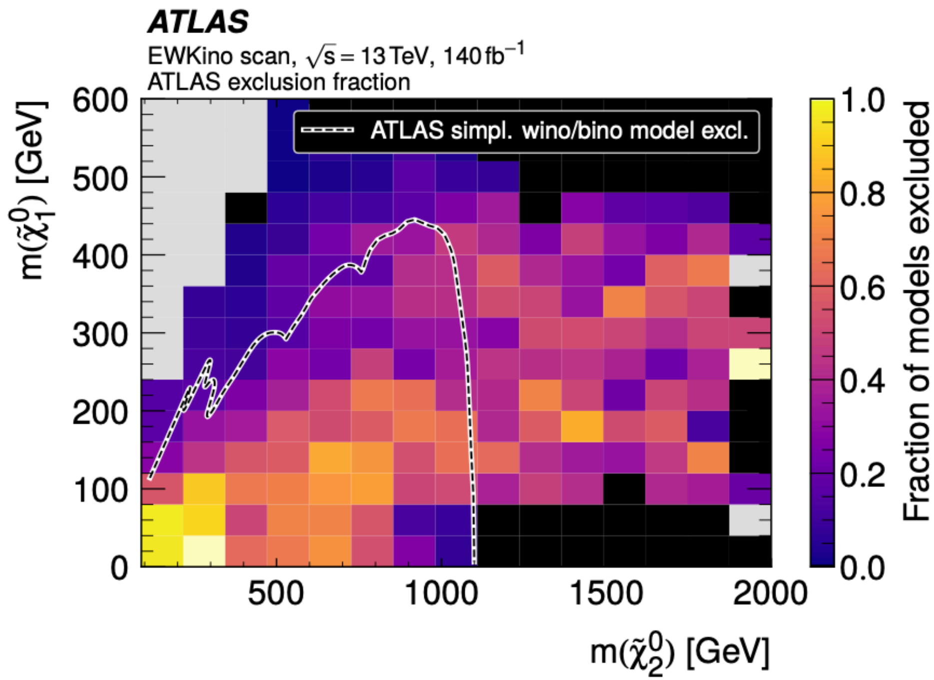
Survey of SUSY searches in pMSSM

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



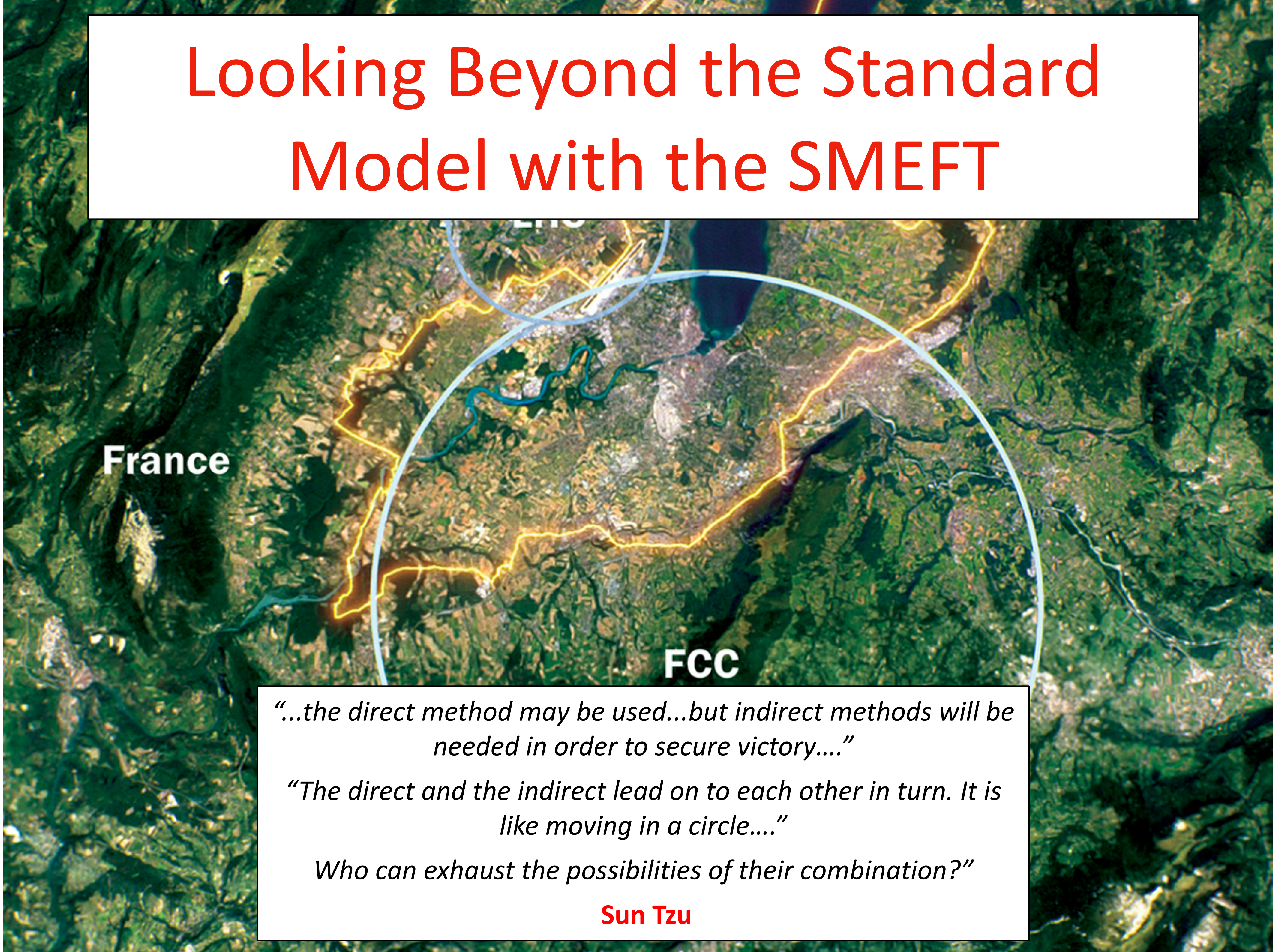


Many low-mass pMSSM models consistent with constraints

“Not dead yet”

Monty Python and the Holy Grail

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...."

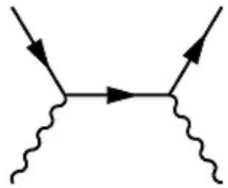
"The direct and the indirect lead on to each other in turn. It is like moving in a circle...."

Who can exhaust the possibilities of their combination?"

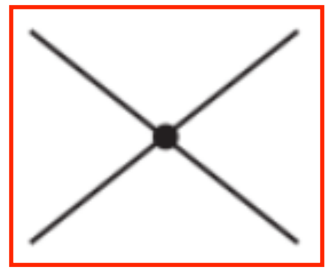
Sun Tzu

Effective Field Theories (EFTs)
a long and glorious History

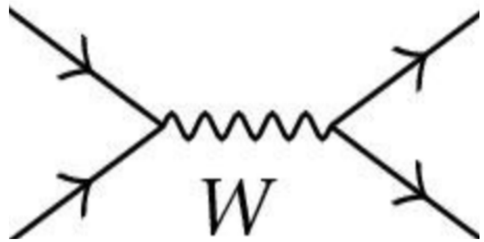
- 1930's: "Standard Model" of QED had d=4



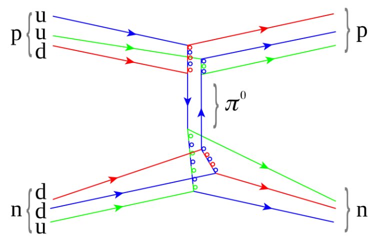
- **Fermi's four-fermion theory of the weak force**



- 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

Standard Model Effective Field Theory

a more 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 SMEFT Operators

- Including 2- and 4-fermion operators
- Different colours for different data sectors
- Grey cells violate SU(3)^5 symmetry
- Important when including top observables

X^3		H^6 and H^4D^2		ψ^2H^3	
$\mathcal{O}_G$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar l_p e_r H)$
$\mathcal{O}_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
$\mathcal{O}_W$	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\star(H^\dagger D_\mu H)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar q_p d_r H)$
$\mathcal{O}_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

X^2H^2		ψ^2XH		ψ^2H^2D	
$\mathcal{O}_{HG}$	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I H W^I_{\mu\nu}$	$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p\gamma^\mu l_r)$
$\mathcal{O}_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar l_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar l_p\tau^I\gamma^\mu l_r)$
$\mathcal{O}_{HW}$	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde H\, G^A_{\mu\nu}$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p\gamma^\mu e_r)$
$\mathcal{O}_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde H\, W^I_{\mu\nu}$	$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p\gamma^\mu q_r)$
$\mathcal{O}_{HB}$	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde H\, B_{\mu\nu}$	$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q_p\tau^I\gamma^\mu q_r)$
$\mathcal{O}_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar q_p\sigma^{\mu\nu}T^A d_r)H\, G^A_{\mu\nu}$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p\gamma^\mu u_r)$
$\mathcal{O}_{HWB}$	$H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I H\, W^I_{\mu\nu}$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p\gamma^\mu d_r)$
$\mathcal{O}_{H\widetilde WB}$	$H^\dagger\tau^I H\, \widetilde W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar q_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde H^\dagger D_\mu H)(\bar u_p\gamma^\mu d_r)$

Anomalous magnetic moments

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
$\mathcal{O}_{ll}$	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

Flavour anomalies

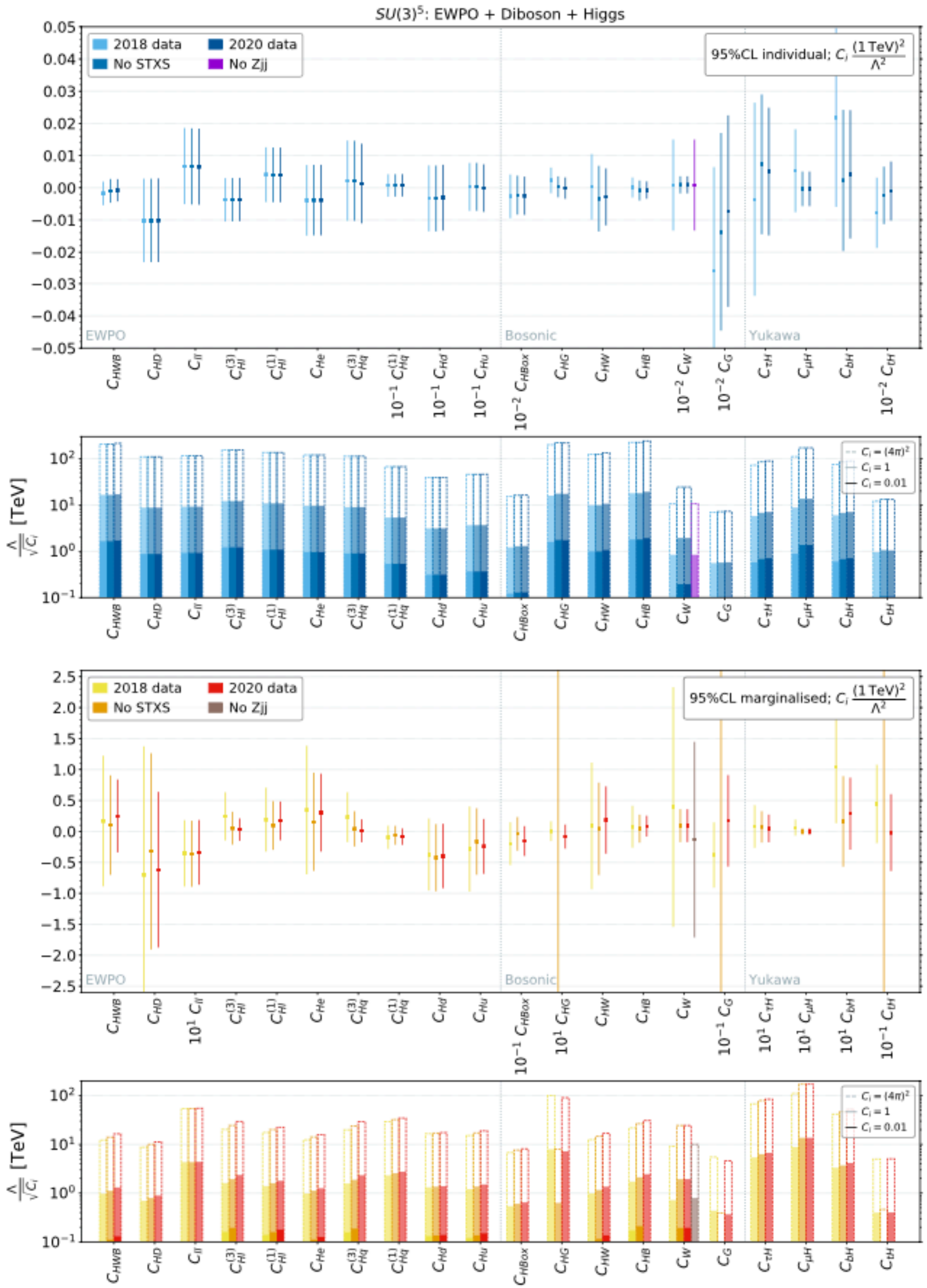
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
$\mathcal{O}_{ledq}$	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$\mathcal{O}_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$\mathcal{O}_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$\mathcal{O}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$\mathcal{O}_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$\mathcal{O}_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$		

Baryon decay

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

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

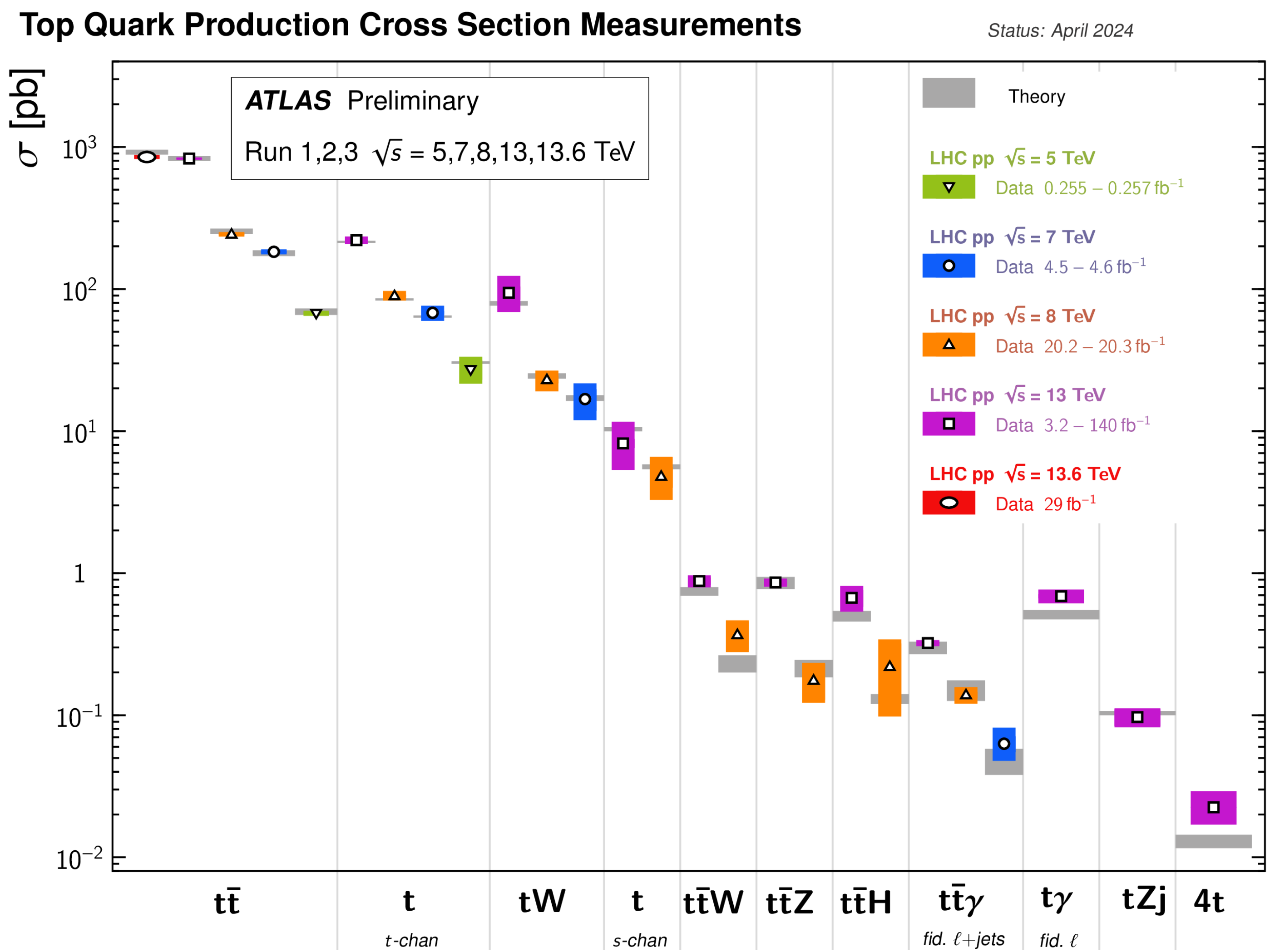
- **Individual operator coefficients**
- **Marginalised over all other operator coefficients**



No significant deviations from SM

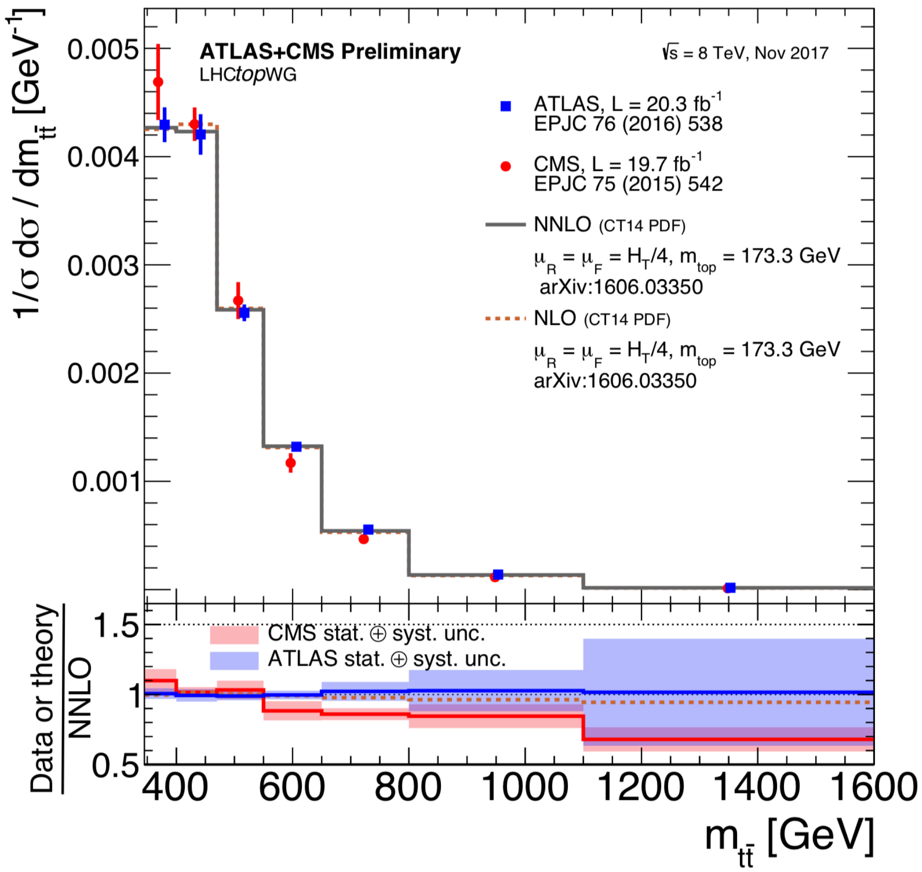
JE, Madigan, Mimasu, Sanz & You,
arXiv:2012.02779

Top Production at the LHC

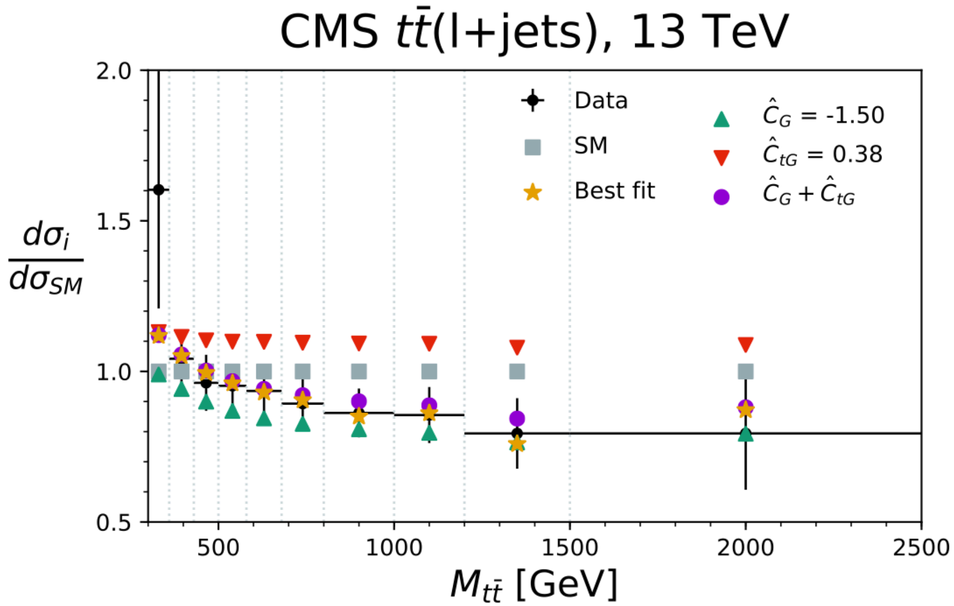


- Many different final states: most measurements agree with NNLO+NNLL theory

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



- Good match to theory, except close to threshold?



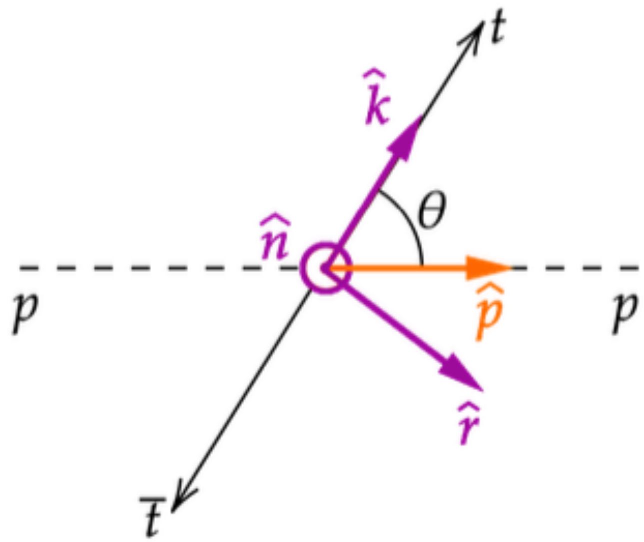
- Can problem be fixed by BSM?
- No improvement with SMEFT
- Higher-order QCD effects?

Spin Correlations

- Correlation between two polarised quantum-mechanical subsystems $$\rho = \frac{1}{4}(\mathbf{1}\otimes\mathbf{1} + \mathcal{B}_1\cdot\boldsymbol{\sigma}\otimes\mathbf{1} + \mathcal{B}_2\cdot\mathbf{1}\otimes\boldsymbol{\sigma} + \mathcal{C}\cdot\boldsymbol{\sigma}\otimes\boldsymbol{\sigma})$$
- Correlation matrix: $\mathcal{C} = \{C_{ij}\}_{i,j=1,2,3}$

  Net subsystem polarisations: $\mathcal{B}_1 = \{B_{1i}\}_{i=1,2,3}$, $\mathcal{B}_2 = \{B_{2j}\}_{j=1,2,3}$ ($= 0$ for $t, \bar{t}$)
- Spin singlet correlation matrix (pseudoscalar):

$$\mathcal{C}^{(\text{singlet})} = \begin{pmatrix} -\eta & 0 & 0 \\ 0 & -\eta & 0 \\ 0 & 0 & -\eta \end{pmatrix}$$



- Entanglement marker for spin 0:

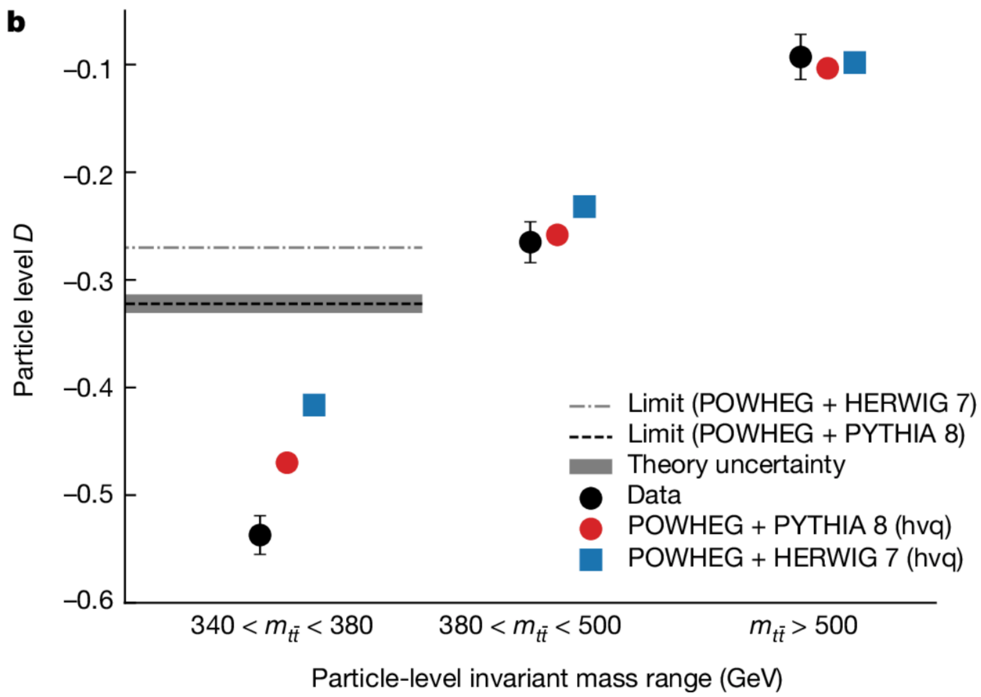
$$-C_{kk} - C_{rr} - C_{nn} \equiv -3\,D \qquad D = -\eta$$

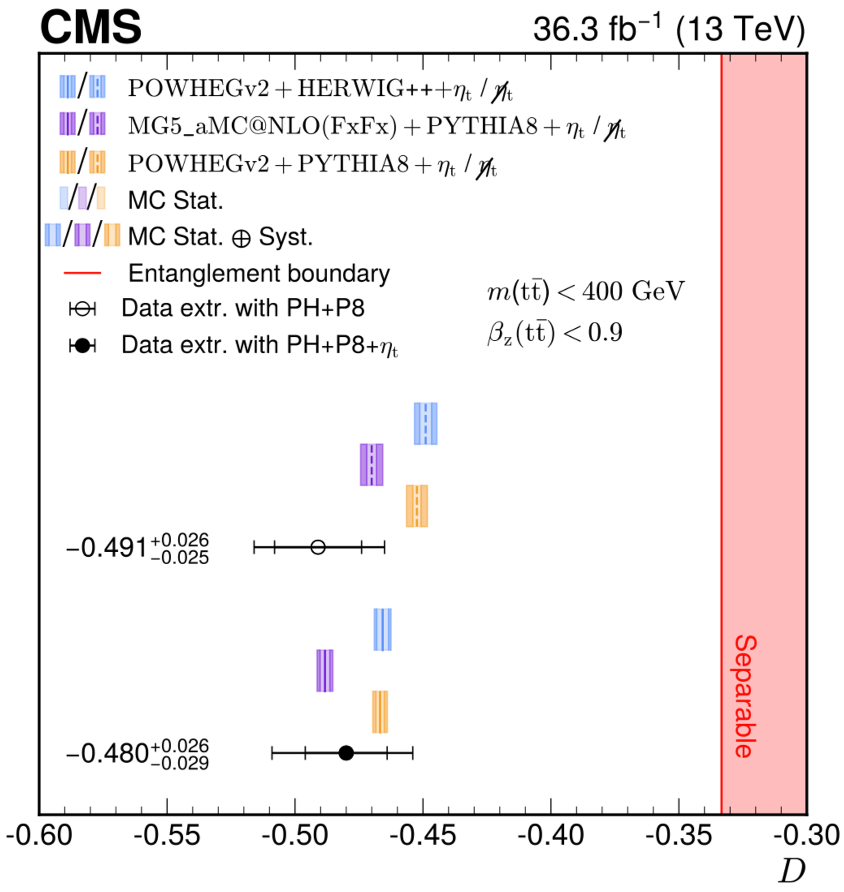
$$\eta > \frac{1}{3} \implies \text{entanglement,}$$

Afik & de Nova, arXiv:2003.02280, 2203.05582;

Maltoni et al, arXiv:2401.08751

Entanglement at $t\bar{t}$ Threshold





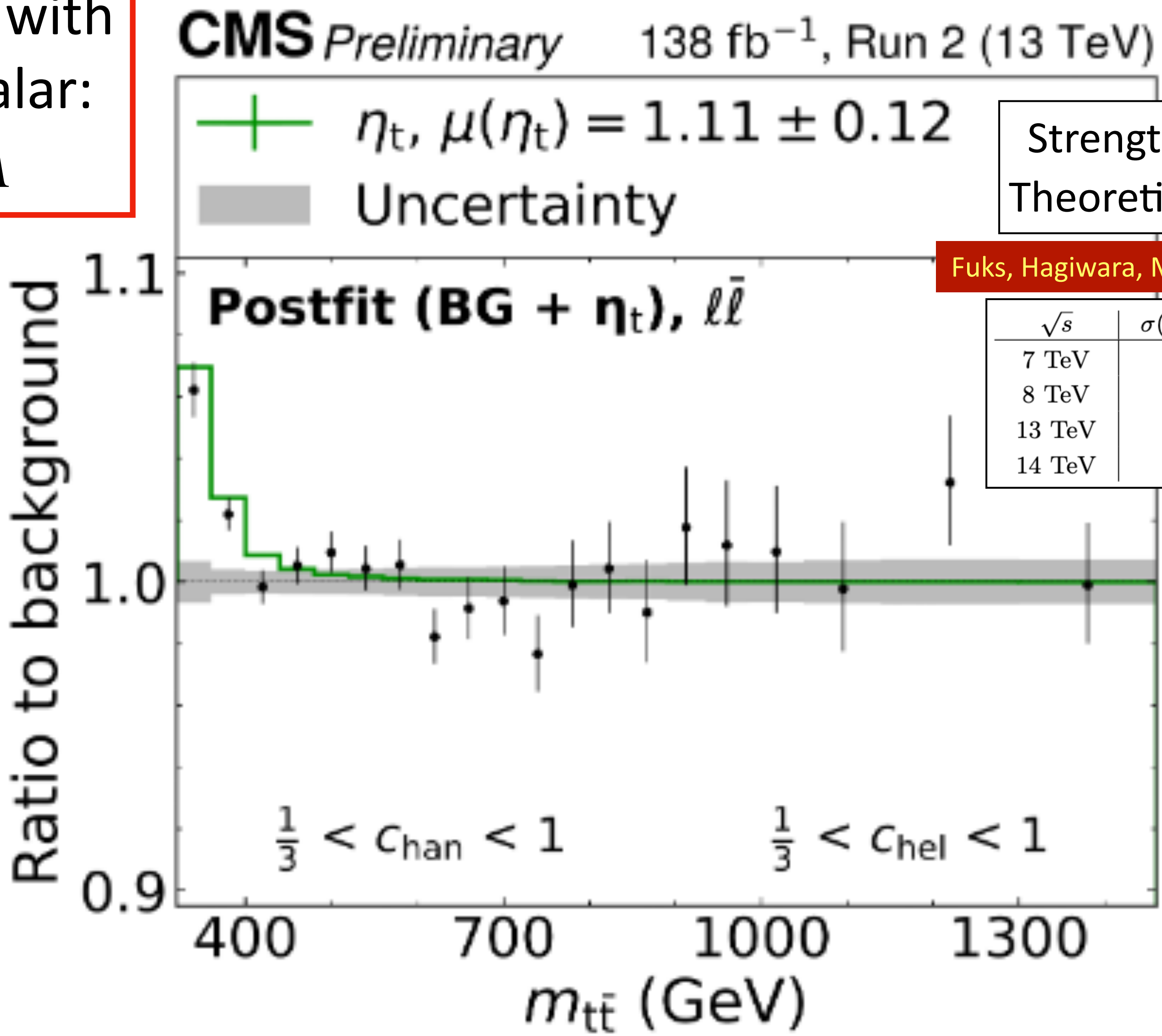
ATLAS Collaboration, Nature 633, 542

CMS Collaboration, arXiv:2406.03976

Significant spread in predictions of QCD Monte Carlo codes

CMS Signal

Consistent with pseudoscalar: η_t or A



Strength Compatible with Theoretical Prediction for η_t

Fuks, Hagiwara, Ma & Zheng, arXiv:2102.11281

$\sqrt{s}$	$\sigma(\eta_t)$ [pb]	$\sigma(t\bar{t})$ [pb]	Ratio
7 TeV	1.55	172	0.0090
8 TeV	2.19	246	0.0089
13 TeV	6.43	810	0.0079
14 TeV	7.54	954	0.0079

CMS Collaboration, CMS-PAS-HIG-22-013

Correlations used to Analyze Enhancement

- Entanglement markers

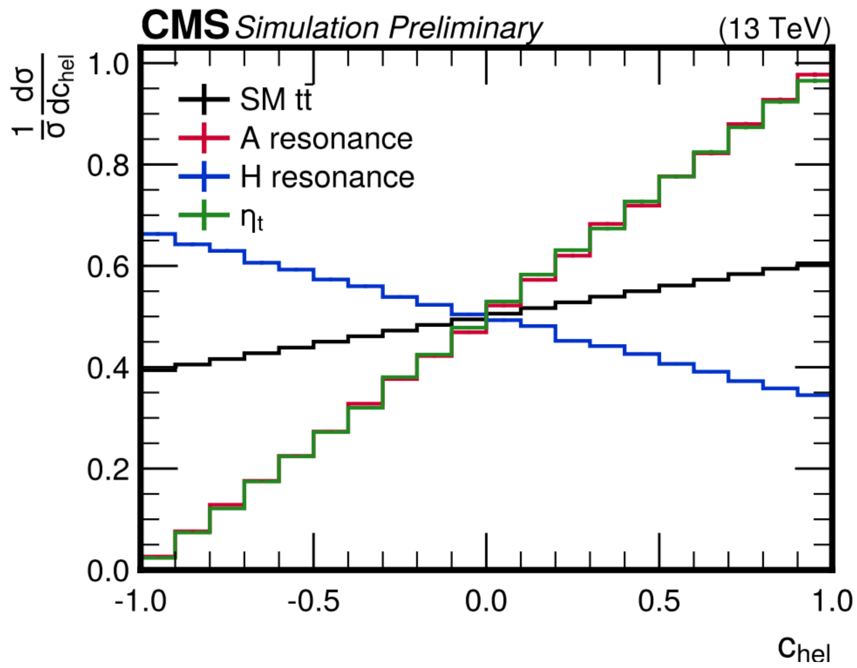
$$c_{\mathrm{hel}} = -(\hat{\ell}^{+})_k(\hat{\ell}^{-})_k - (\hat{\ell}^{+})_r(\hat{\ell}^{-})_r - (\hat{\ell}^{+})_n(\hat{\ell}^{-})_n$$
$$c_{\mathrm{han}} = +(\hat{\ell}^{+})_k(\hat{\ell}^{-})_k - (\hat{\ell}^{+})_r(\hat{\ell}^{-})_r - (\hat{\ell}^{+})_n(\hat{\ell}^{-})_n$$

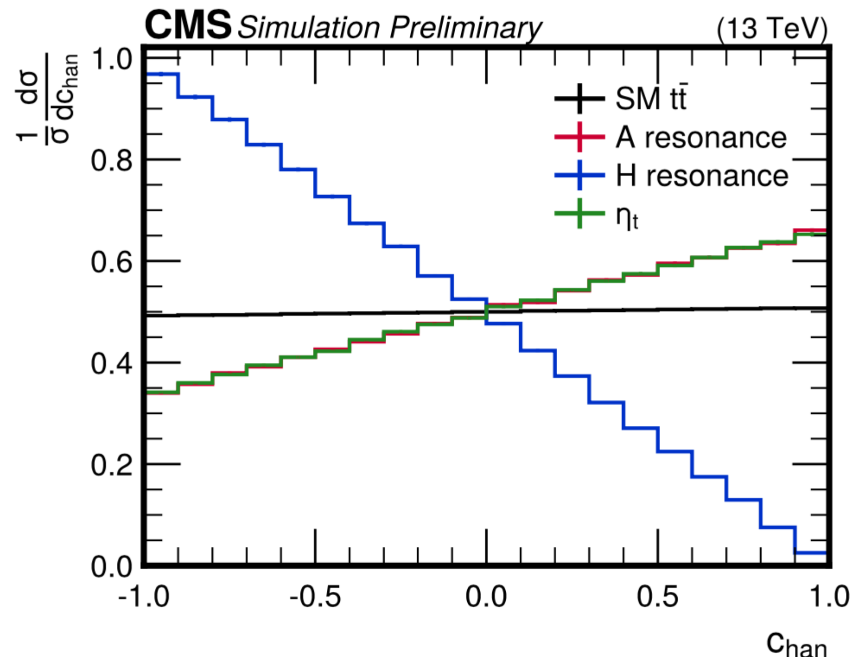
- Distributions

$$\frac{1}{\sigma}\frac{d\sigma}{dc_{\mathrm{hel}}} = \frac{1}{2}(1 - D\, c_{\mathrm{hel}}) \qquad \frac{1}{\sigma}\frac{d\sigma}{dc_{\mathrm{han}}} = \frac{1}{2}\left(1 + D^{(k)}\, c_{\mathrm{han}}\right)$$

- Where

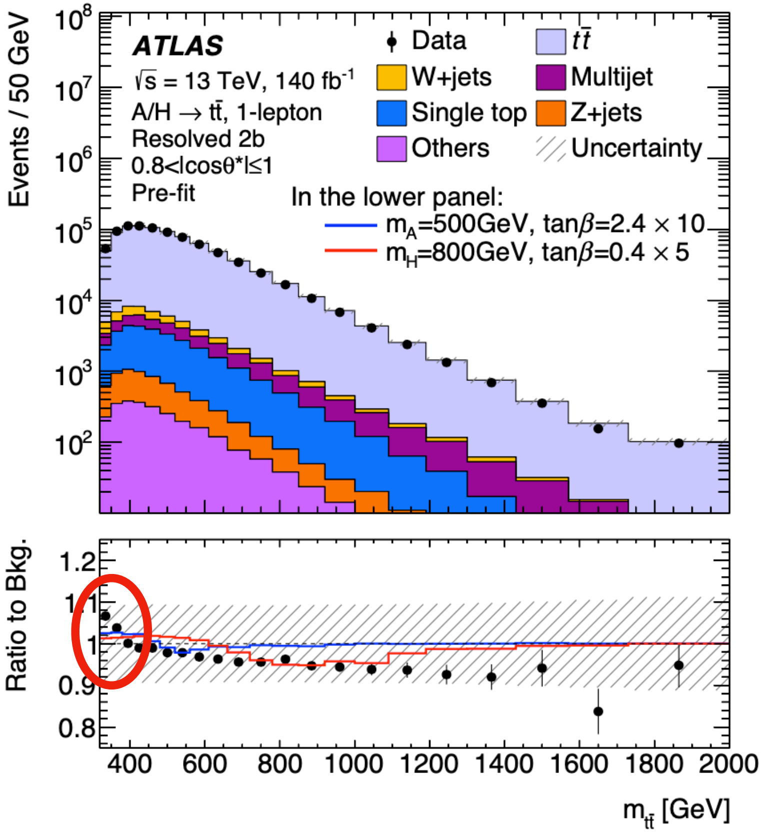
$$-C_{kk} - C_{rr} - C_{nn} \equiv -3\,D$$
$$-C_{kk} + C_{rr} + C_{nn} \equiv -3\,D^{(k)}$$

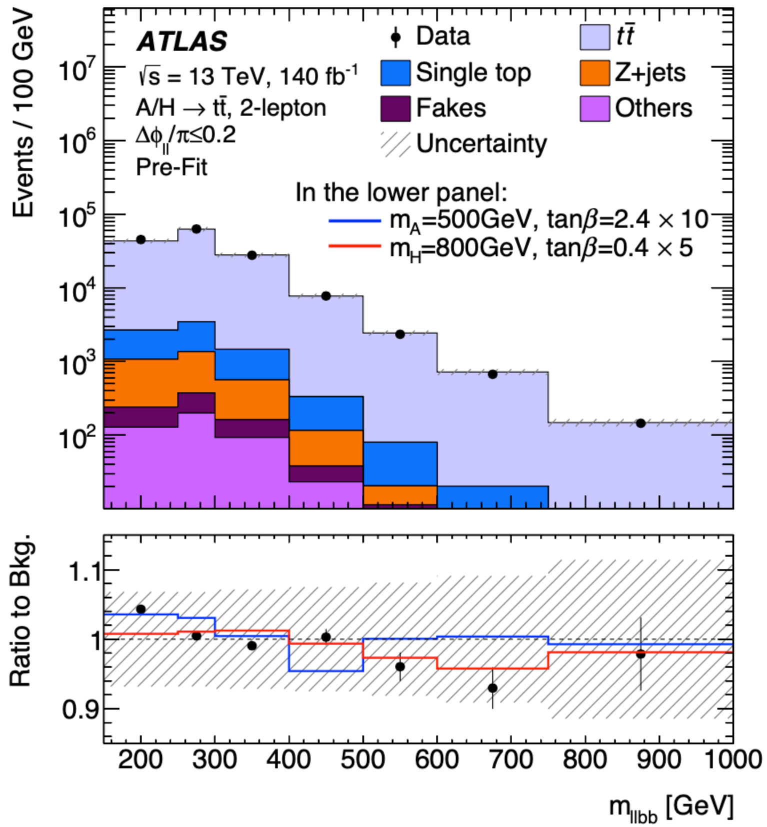




CMS Collaboration, CMS-PAS-HIG-22-013

Signal in ATLAS Data?

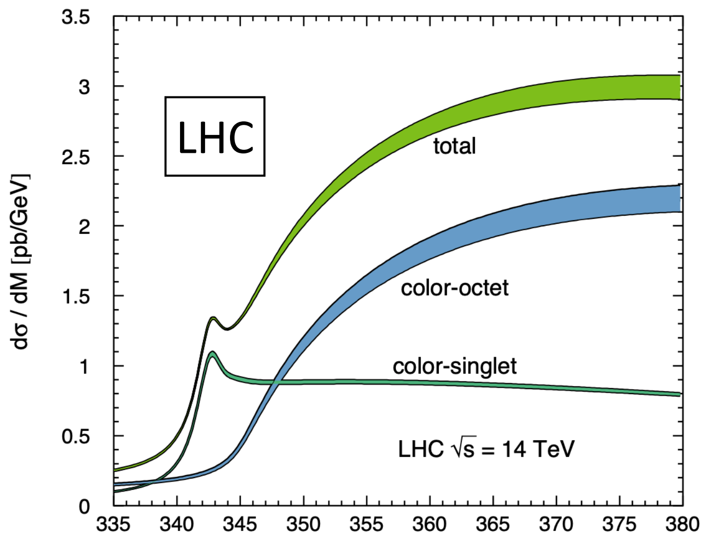


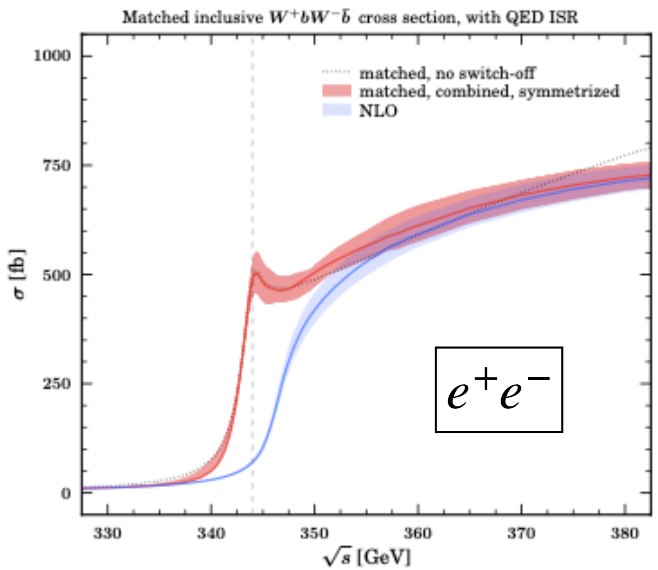


ATLAS Collaboration, arXiv:2404.18986

Has CMS Discovered a Boson with Mass around 340 GeV?

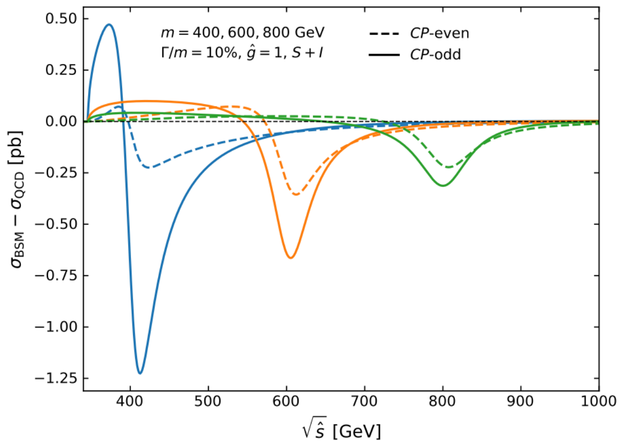
- An elementary boson?
  - Extended Higgs sector, …
- or toponium?
  - Predicted to have a mass a few GeV below the $t\bar{t}$ threshold: 343.5 GeV
  - Production of vector toponium in e^+e^- collisions studied in detail
  - Relatively few studies for toponium in proton-proton collisions
  - Fascinating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





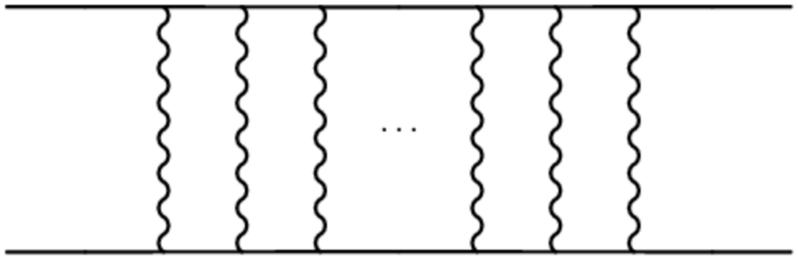
Additional Higgs or $t\bar{t}$ Bound State?

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



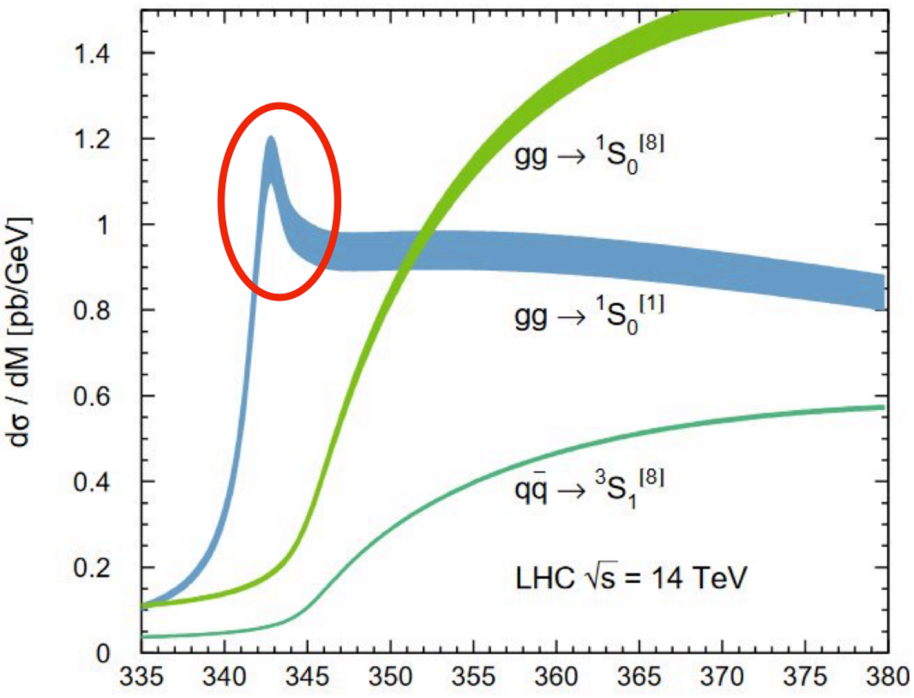
Djouadi, JE, Popov & Quevillon, arXiv:1901.03417

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

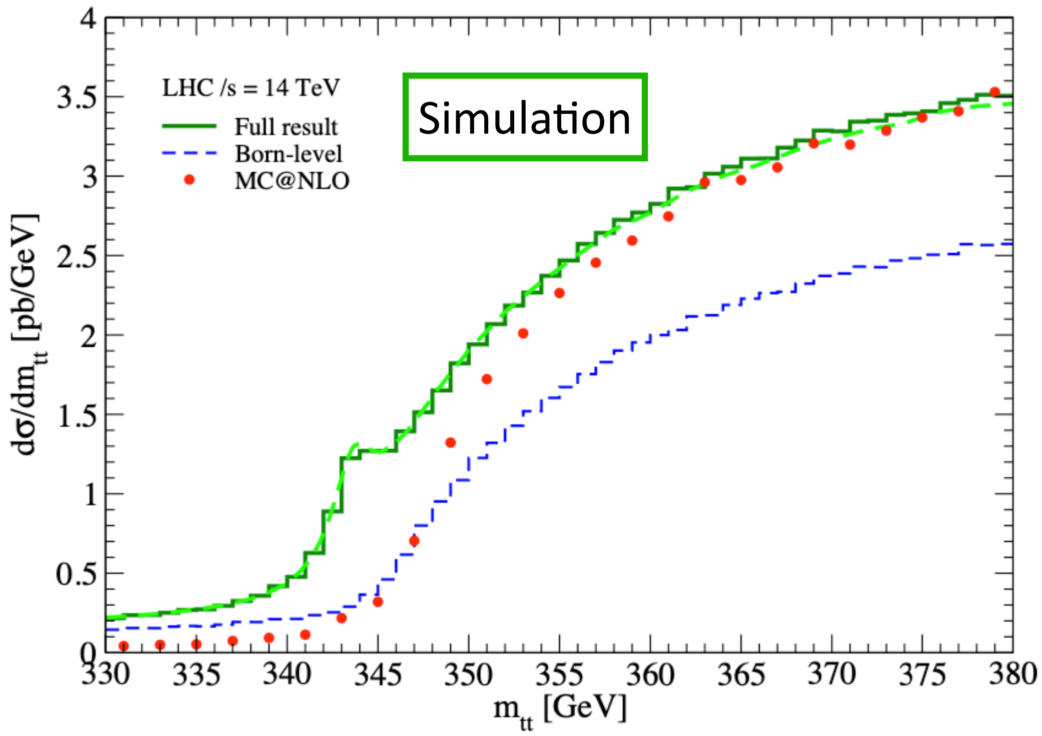


- Lowest-lying $t\bar{t}$ states in s-wave: ${}^1S_0, {}^3S_1$ (pseudoscalar, vector)
- Production of scalar ${}^3P_0$ suppressed
  - No wavefunction at origin
  - Forbidden in gg collisions (Landau-Yang)

η_t Enhancement below Threshold



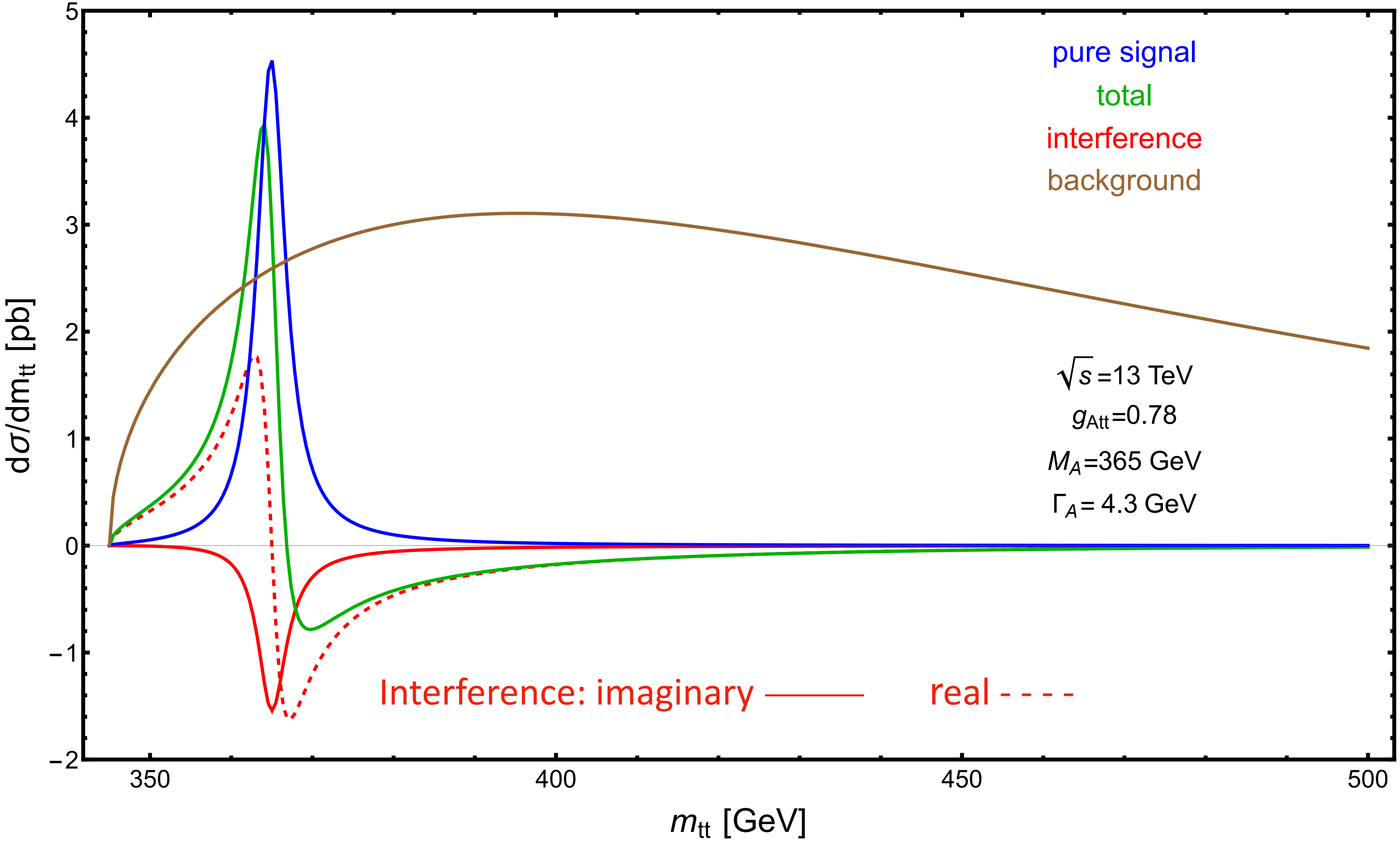
Kiyo, Kühn, Moch, Steinhauser & Uwer, arXiv:0812.0919 [hep-ph]



Sumino & Yokoya, arXiv:1007.0075

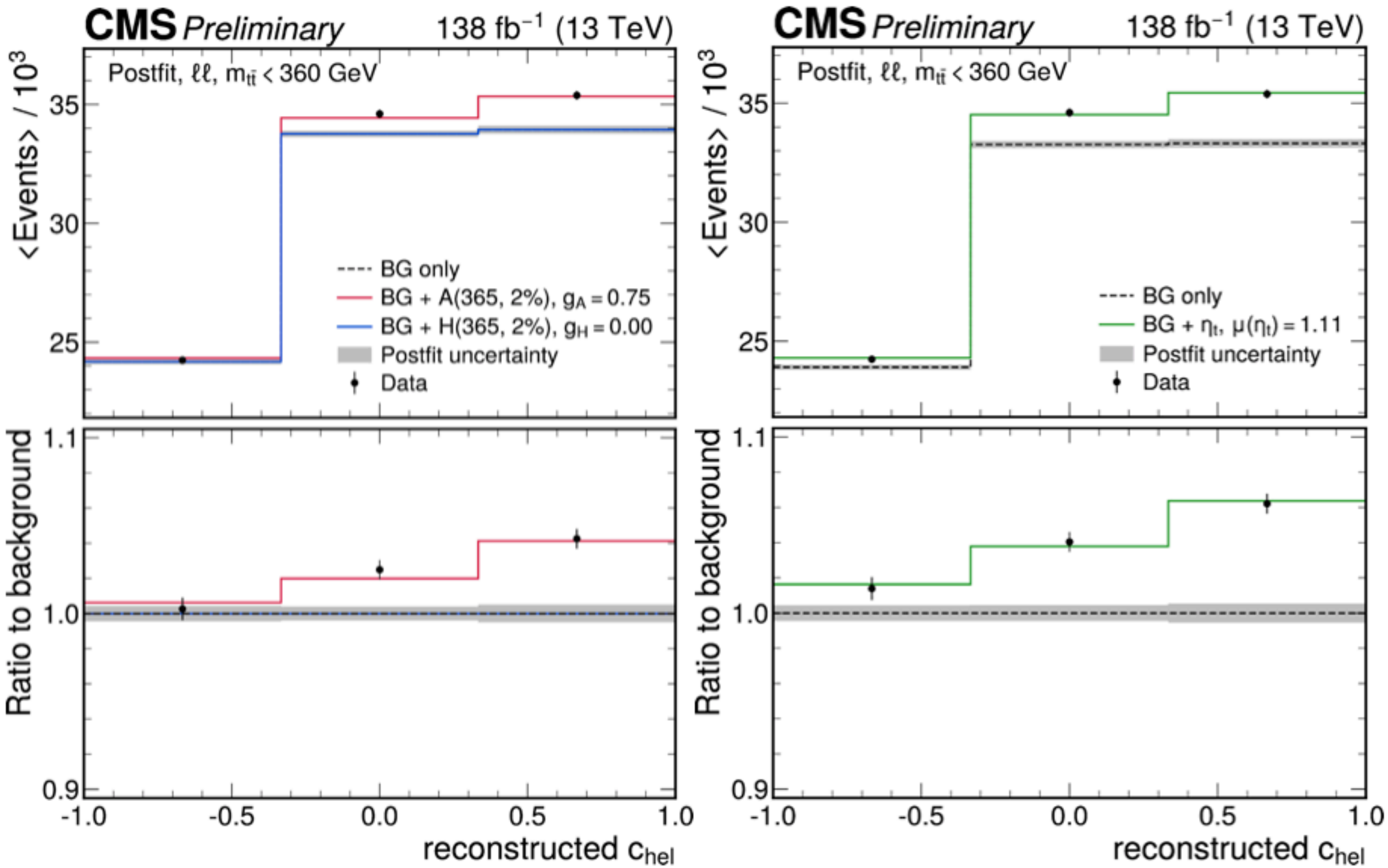
- Colour-singlet, η_t pole dominant below nominal $\bar{t}t$ threshold
- Cross-section >> perturbative QCD calculation of $d\sigma/dm_{\bar{t}t}$

A Pseudoscalar Boson?



Djouadi, JE & Quevillon, arXiv:2412.15138

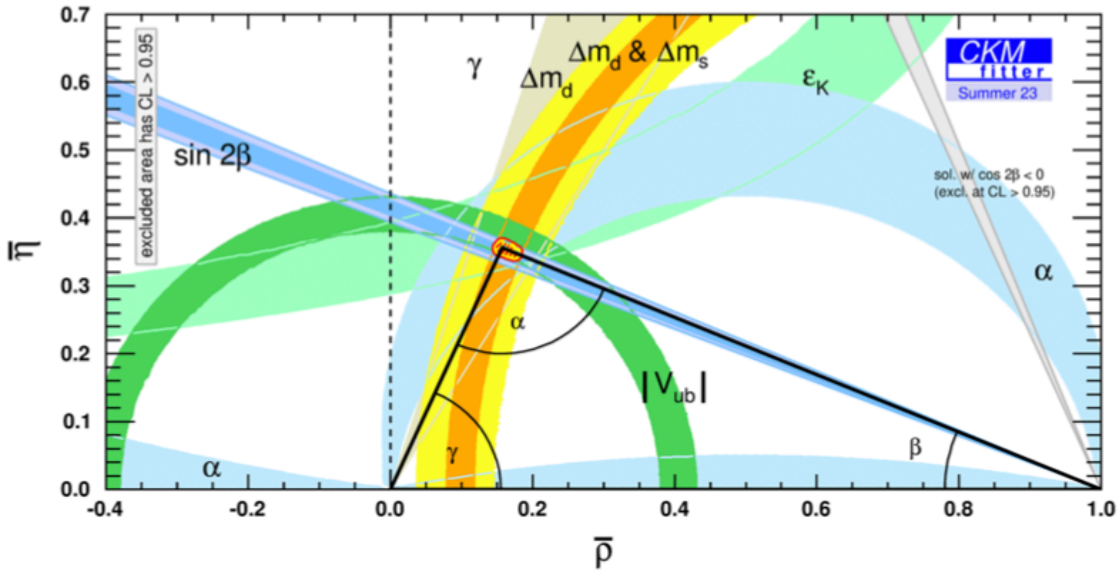
A and η_t both Consistent with Data



CMS Collaboration, CMS-PAS-HIG-22-013

Measurements of CP Violation

World-leading measurements of CKM angles in B decays



$$\sin 2\beta = 0.717 \pm 0.013 \pm 0.008$$

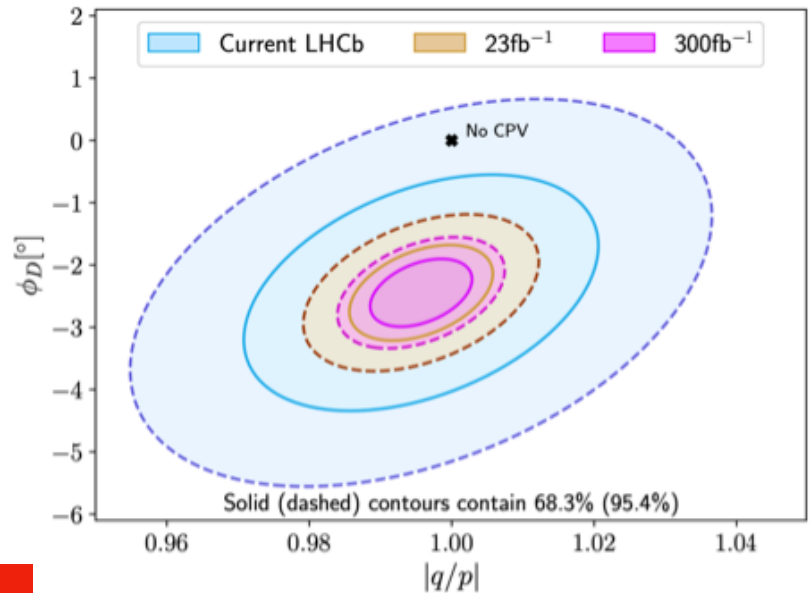
$$\gamma = 63.8^{+3.5}_{-3.7} \text{ degrees}$$

Discovery of CP violation in D decays

$$\Delta A_{CP} \equiv A_{CP}(D^0 \to K^- K^+) - A_{CP}(D^0 \to \pi^- \pi^+)$$
$$= (-15.4 \pm 2.9) \times 10^{-4}$$

Larger than SM expectation,
but significant QCD uncertainties

Good prospects for future studies

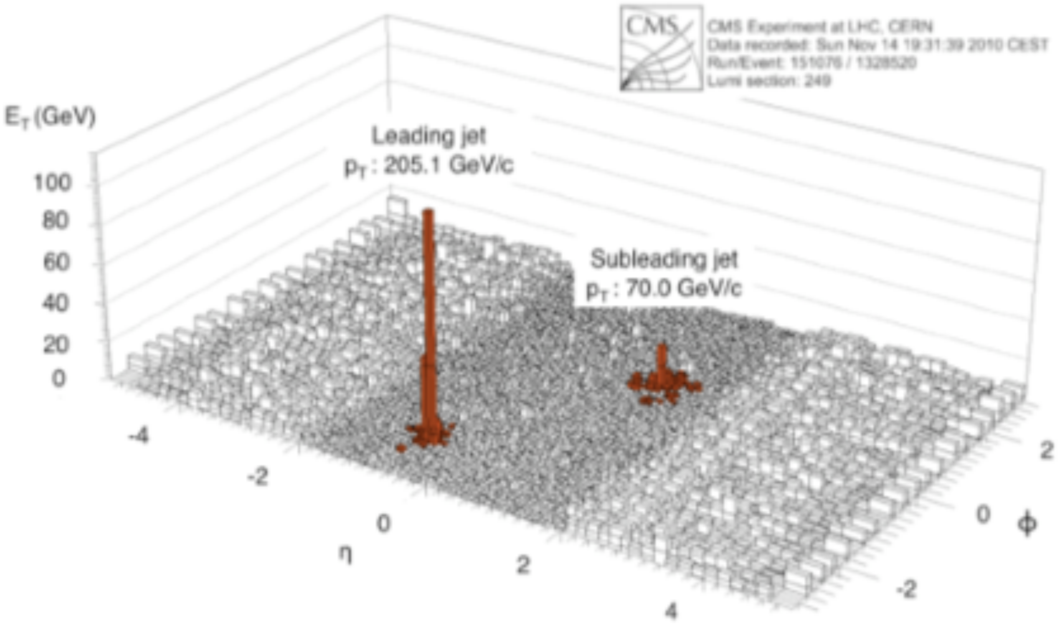


LHCb Collaboration

Highlights of Heavy-Ion Physics

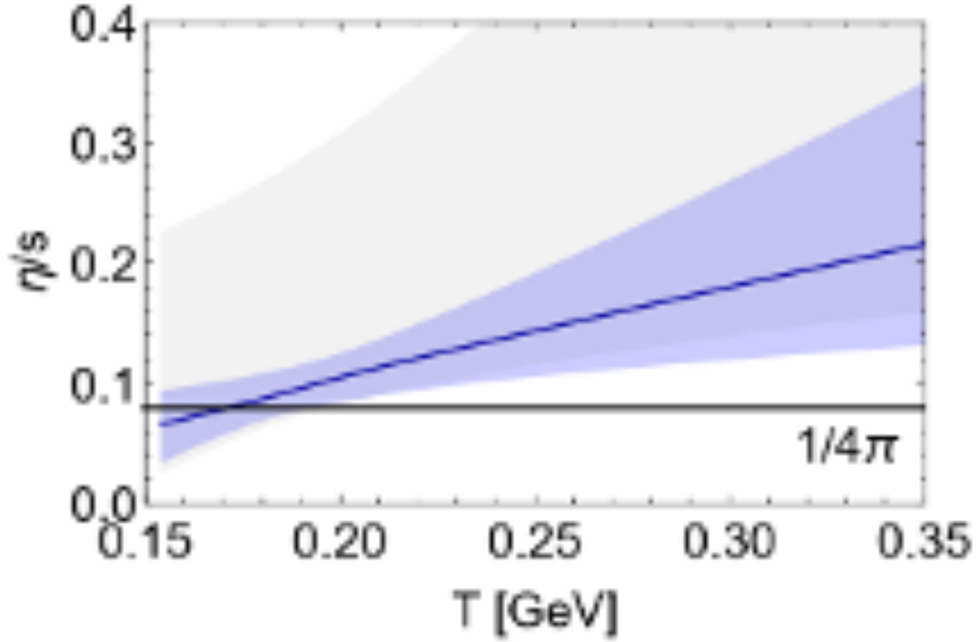
Urs Wiedemann

Jet quenching



In QCD vacum, jets hadronise
In QCD plasma, jets thermalise

Small (but increasing?) viscosity



QCD plasma is most perfect fluid known
Higher viscosity at higher temperature?

Nijs, Gursoy, v.d. Schee, Snellings, arXiv:2010.15130, arXiv:2010.15134

Summary

[redacted]