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KING'S College LONDON

Topology

Prediction (LEP)
Discovery (Tevatron)
Measurements (mass, decays, cross section, couplings)
Collapse of the Universe?
BSM? (SMEFT analysis)
CP violation?
Probing quantum predictions (spin correlations, entanglement)
Toponium?

1987

Estimating the Top Quark Mass

- **Needed as a partner of the bottom quark**
- Not discovered in 1975 or 1984
- Many speculations about its mass
- Indication of large mass from B physics
- Estimate from radiative corrections in neutral currents

"In the minimal standard model with $\rho = 1$ and equal Higgs and Z masses we find that ***$m_t < 168$ GeV*** *at 90% confidence level"*

- Not so bad!

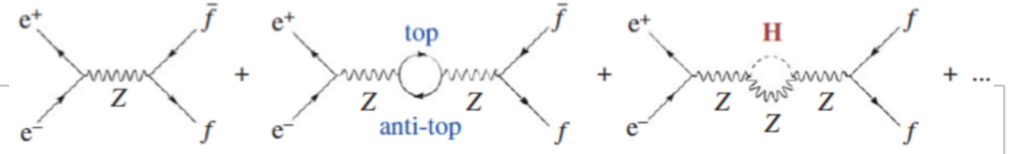
NEUTRAL CURRENTS WITHIN AND BEYOND THE STANDARD MODEL

G. COSTA[1], J. ELLIS[2], G.L. FOGLI[3], D.V. NANOPOULOS[4] and F. ZWIRNER[5]

CERN, Geneva, Switzerland

Received 29 June 1987

Where are the top and Higgs?



Estimating Masses with Electroweak Data

- High-precision electroweak measurements are sensitive to quantum corrections

$$m_W^2 \sin^2\theta_W = m_Z^2 \cos^2\theta_W \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}\mathrm{G}_F}(1+\Delta r)$$

Veltman

- Sensitivity to top mass is quadratic: $\frac{3\mathrm{G}_F}{8\pi^2\sqrt{2}}m_t^2$

- Sensitivity to Higgs mass is logarithmic:

$$\frac{\sqrt{2}\mathrm{G}_F}{16\pi^2}m_W^2\left(\frac{11}{3}\ln\frac{M_H^2}{m_Z^2}+...\right),\ M_H >> m_W$$

- Measurements at LEP et al. gave indications first on top mass, then on Higgs mass $\Delta\rho = 0.0026\frac{M_t^2}{M_Z^2} - 0.0015\ln\left(\frac{M_H}{M_W}\right)$

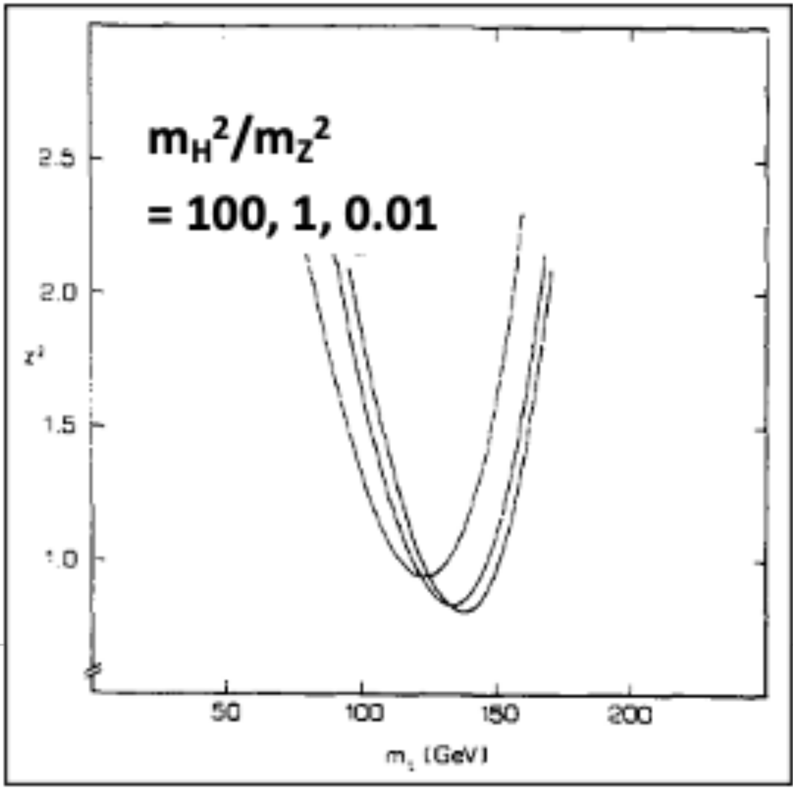
1989

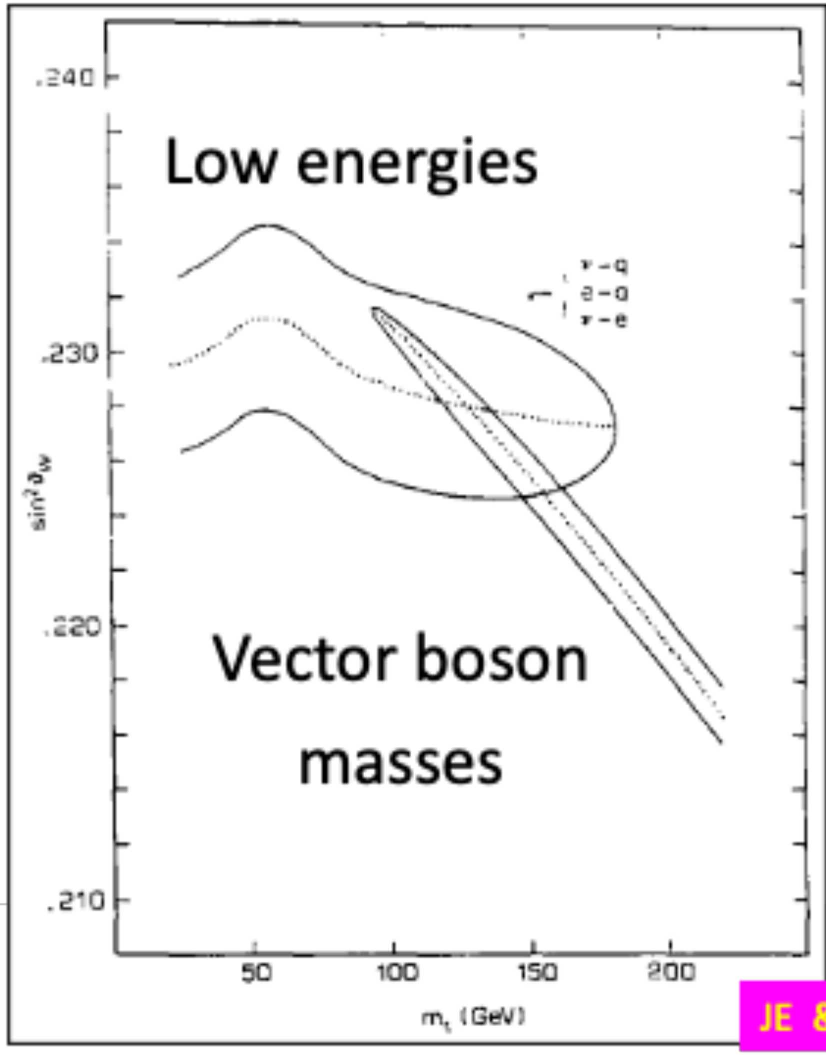
The Top Mass after First Precise m_Z

- In combination with low-energy measurements

$$m_t = 132^{+31}_{-37}\ \text{GeV}$$

- A first discussion of m_H



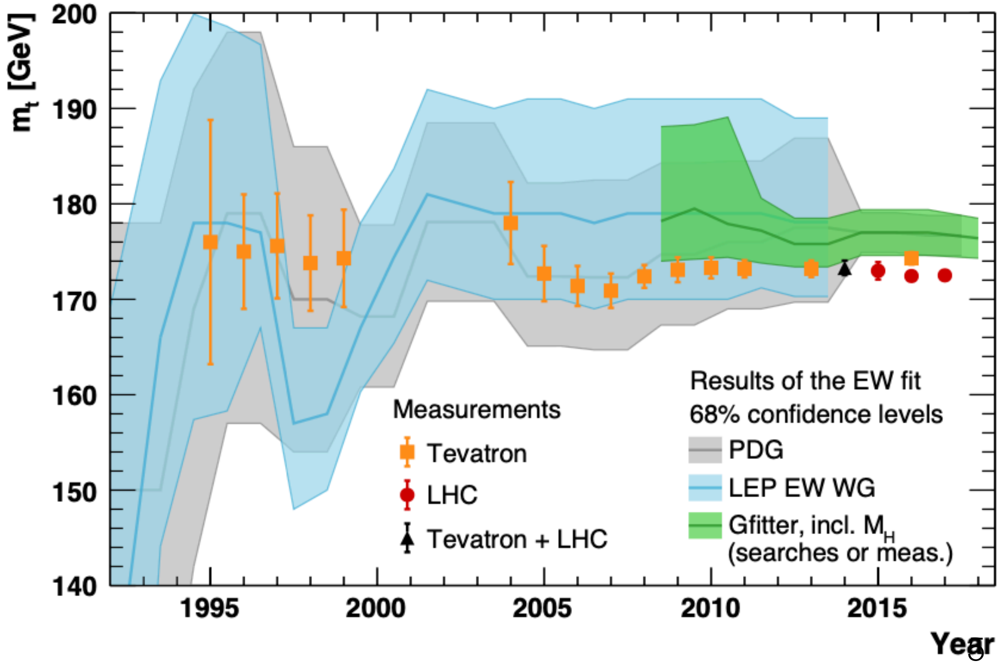


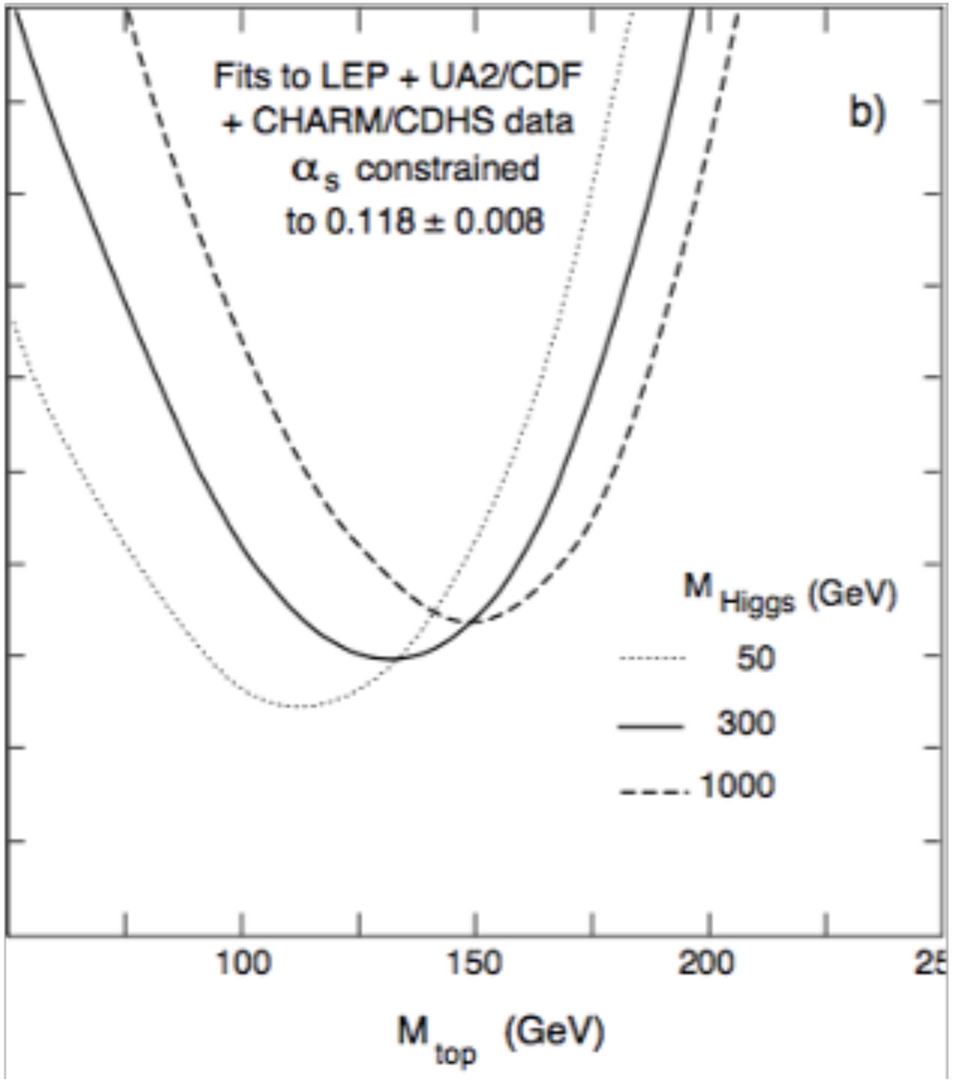
JE & Fogli

1991

	α_s unconstrained	α_s constrained	α_s unconstrained + Collider and ν data	α_s constrained + Collider and ν data
M_t (GeV) α_s	$94^{+53}_{-...}\ ^{+23}_{-24}$ $0.141 \pm 0.017\ \pm 0.002$	$124^{+40}_{-56}\ ^{+21}_{-21}$ 0.123 ± 0.007	$124^{+28}_{-31}\ ^{+16}_{-18}$ 0.138 ± 0.015	$132^{+27}_{-31}\ ^{+18}_{-19}$ 0.123 ± 0.007
$\chi^2/$ d.o.f.	0.3/2	2.2/3	1.5/5	3.0/6
$\sin^2\theta_{\rm eff}^{\rm lept}$ $\sin^2\theta_W \equiv 1 - M_W^2/M_Z^2$ M_W (GeV)	- - -	$0.2337 \pm 0.0014\ ^{+0.0001}_{-0.0004}$ $0.2299^{+0.0067}_{-0.0048}$ $80.01^{+0.27}_{-0.37}$	$0.2337 \pm 0.0010\ ^{+0.0003}_{-0.0004}$ 0.2299 ± 0.0033 80.01 ± 0.19	$0.2335 \pm 0.0009\ ^{+0.0001}_{-0.0004}$ 0.2290 ± 0.0033 80.06 ± 0.19

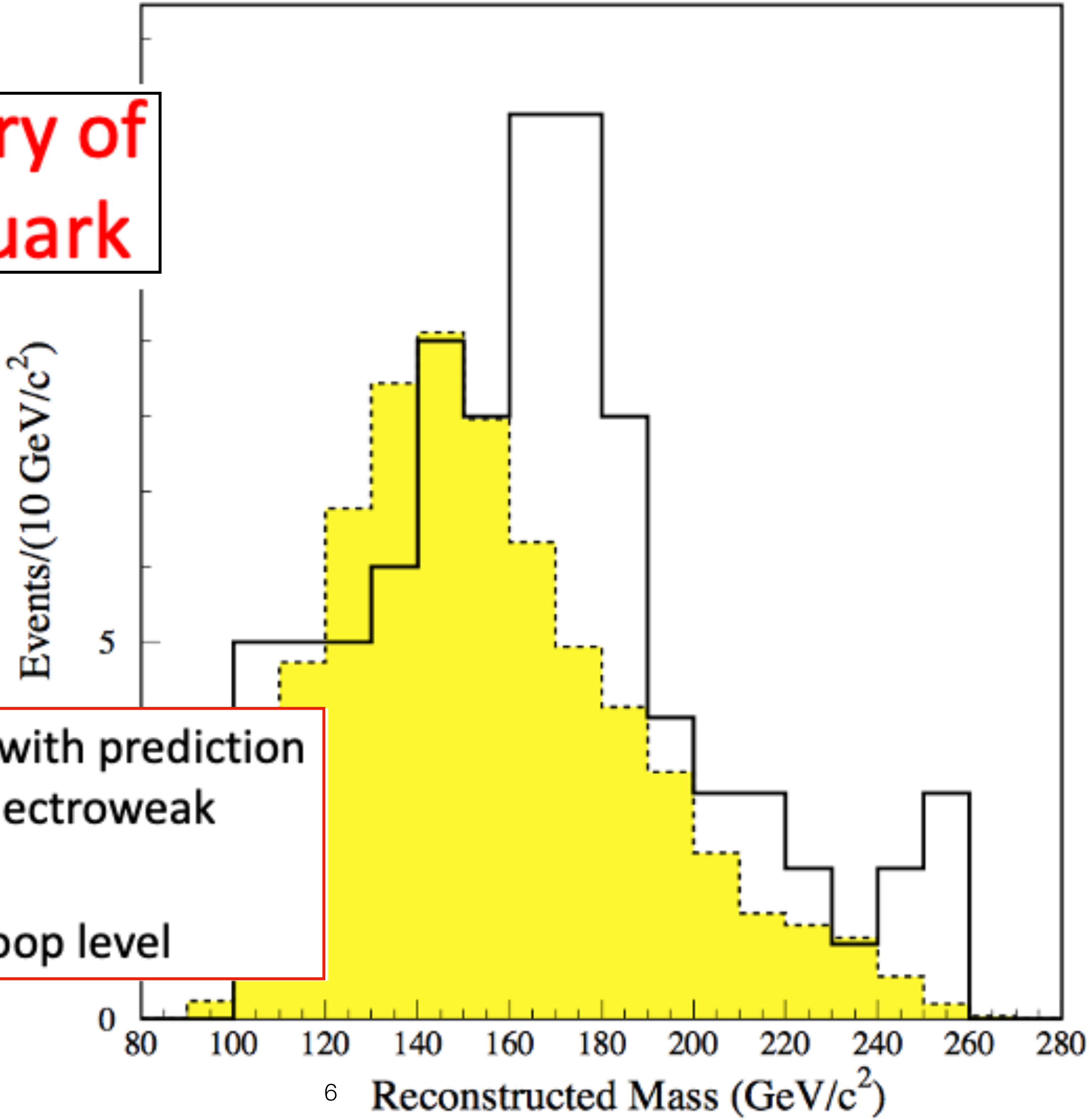
LEP Electroweak Working Group





1995

Discovery of the t Quark



- Mass consistent with prediction from precision electroweak data
- Check of SM at loop level

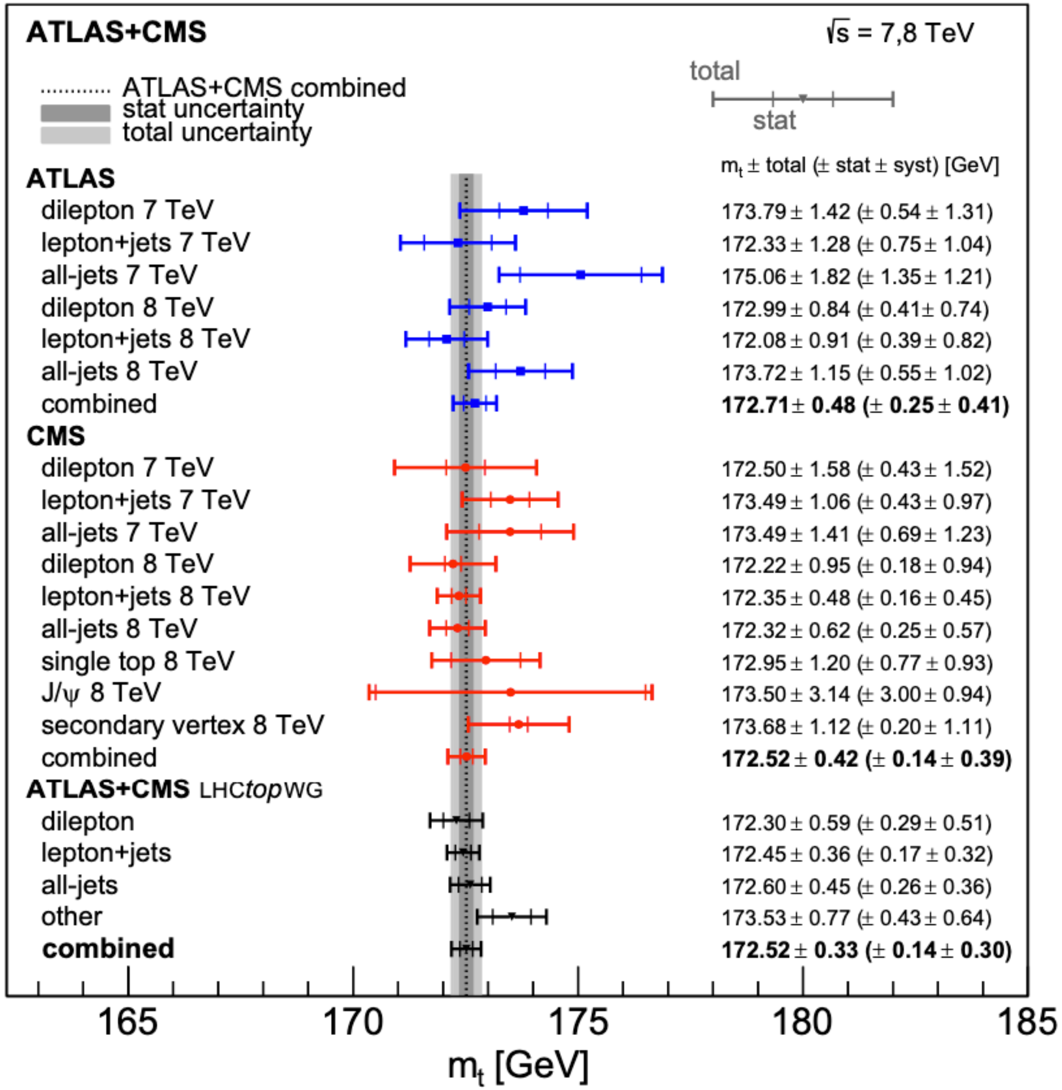
CDF Collaboration

Nobel Prize 1999

"The Theory's Predictions Verified"

- "… it was only through 't Hooft's and Veltman's work that more precise prediction of physical quantities involving properties of W and Z could start. **Large quantities of W and Z have recently been produced under controlled conditions at the LEP accelerator at CERN.** Comparisons between measurements and calculations have all the time showed great agreement, thus supporting the theory's predictions."
- "One particular quantity obtained with 't Hooft's and Veltman's calculation method **based on CERN results is the mass of the *top quark***, the heavier of the two quarks included in the third family in the model. **This quark was observed directly for the first time in 1995 at the Fermilab in the USA, but its mass had been predicted several years earlier.** Here too, agreement between experiment and theory was satisfactory."
- **"When can we expect the next great discovery?"**

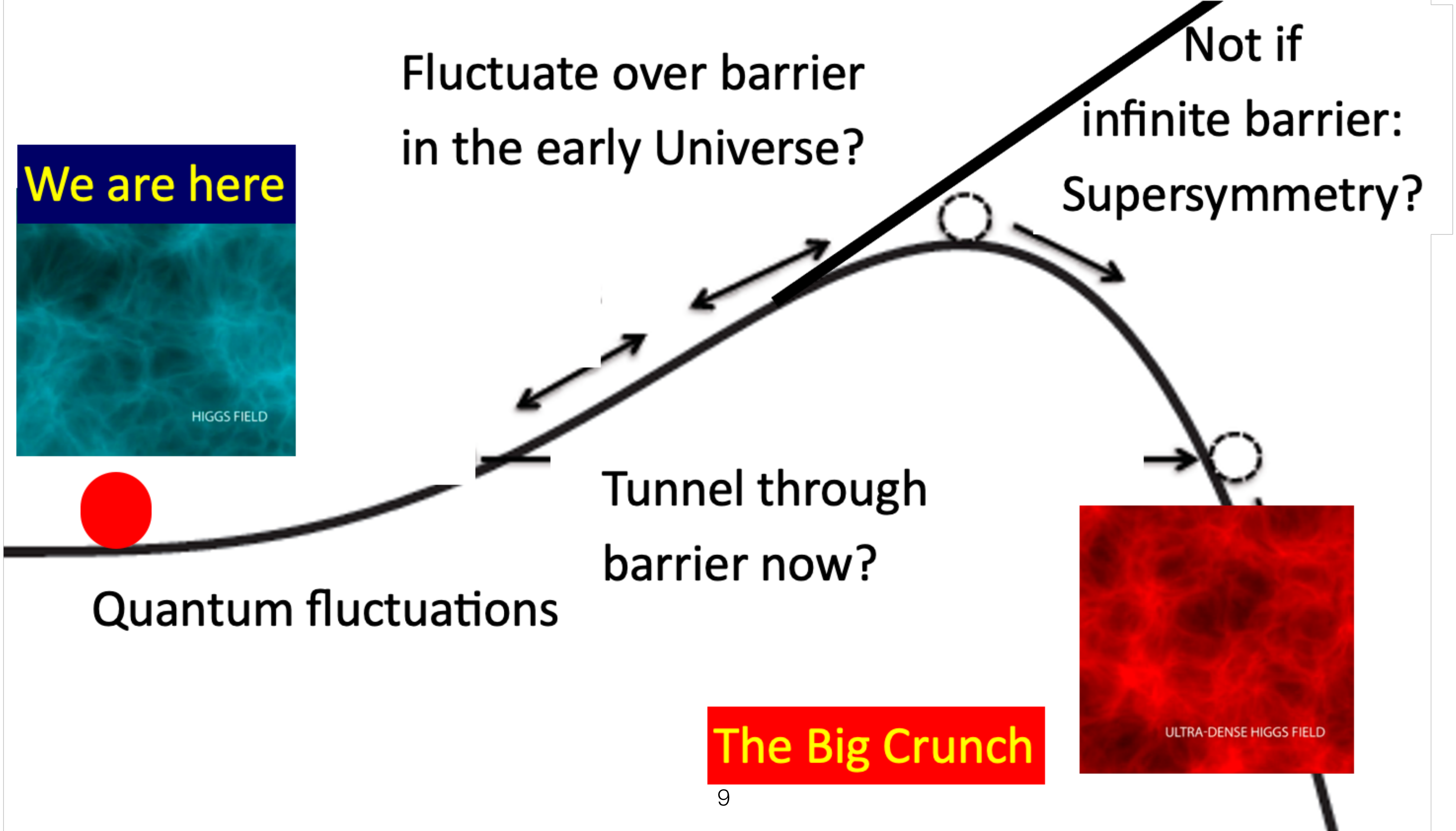
Measurement of Top Mass



$m_t = 172.53 \pm 0.33$ GeV: why is this important?

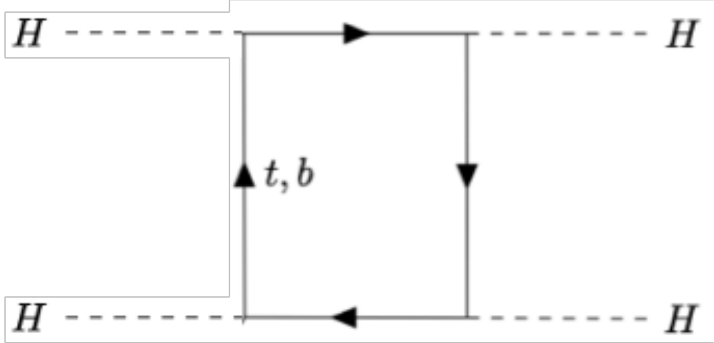
Will the Universe Collapse?

Should it have Collapsed already?



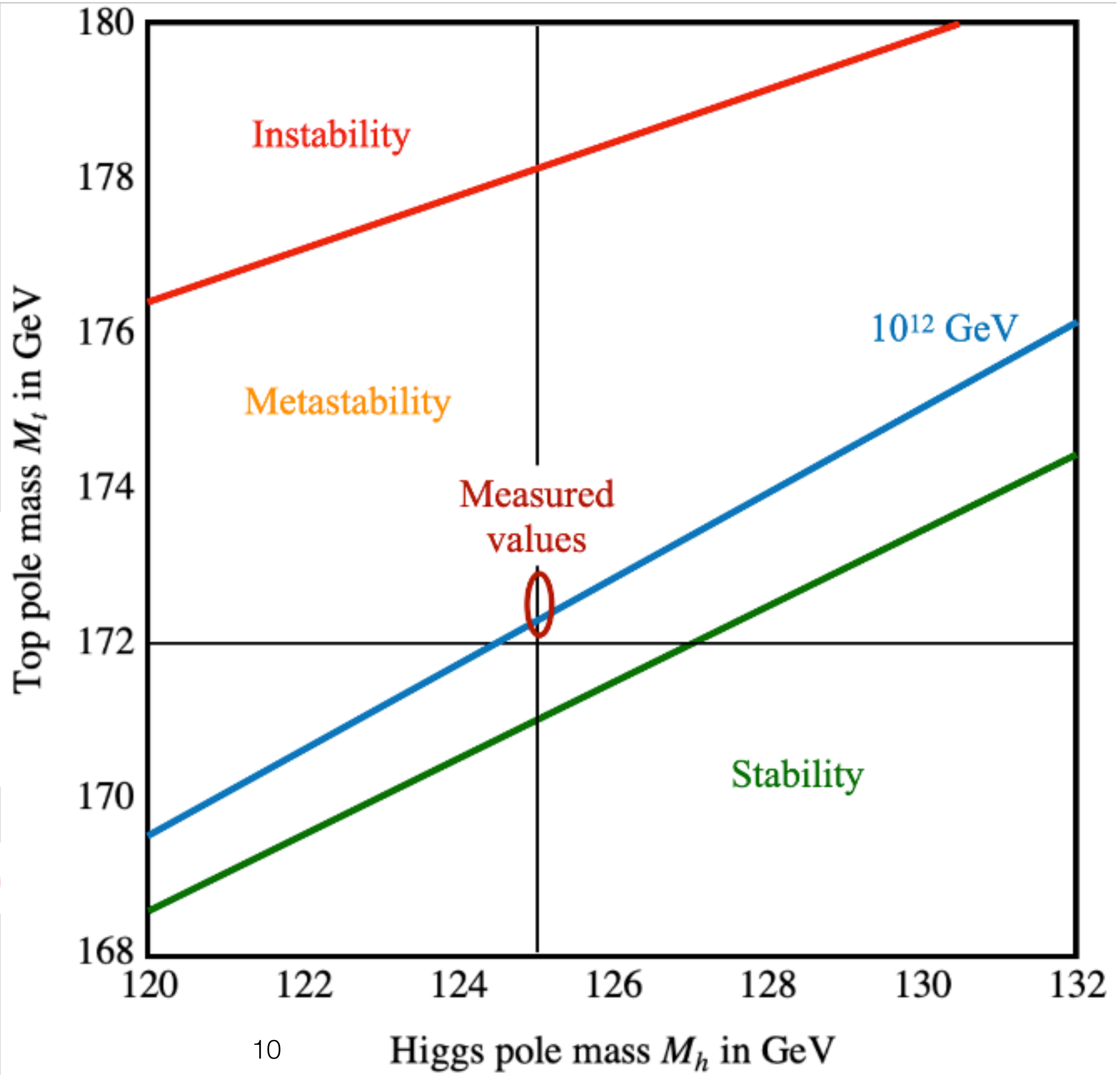
Is "Empty Space" Unstable?

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:

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

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:

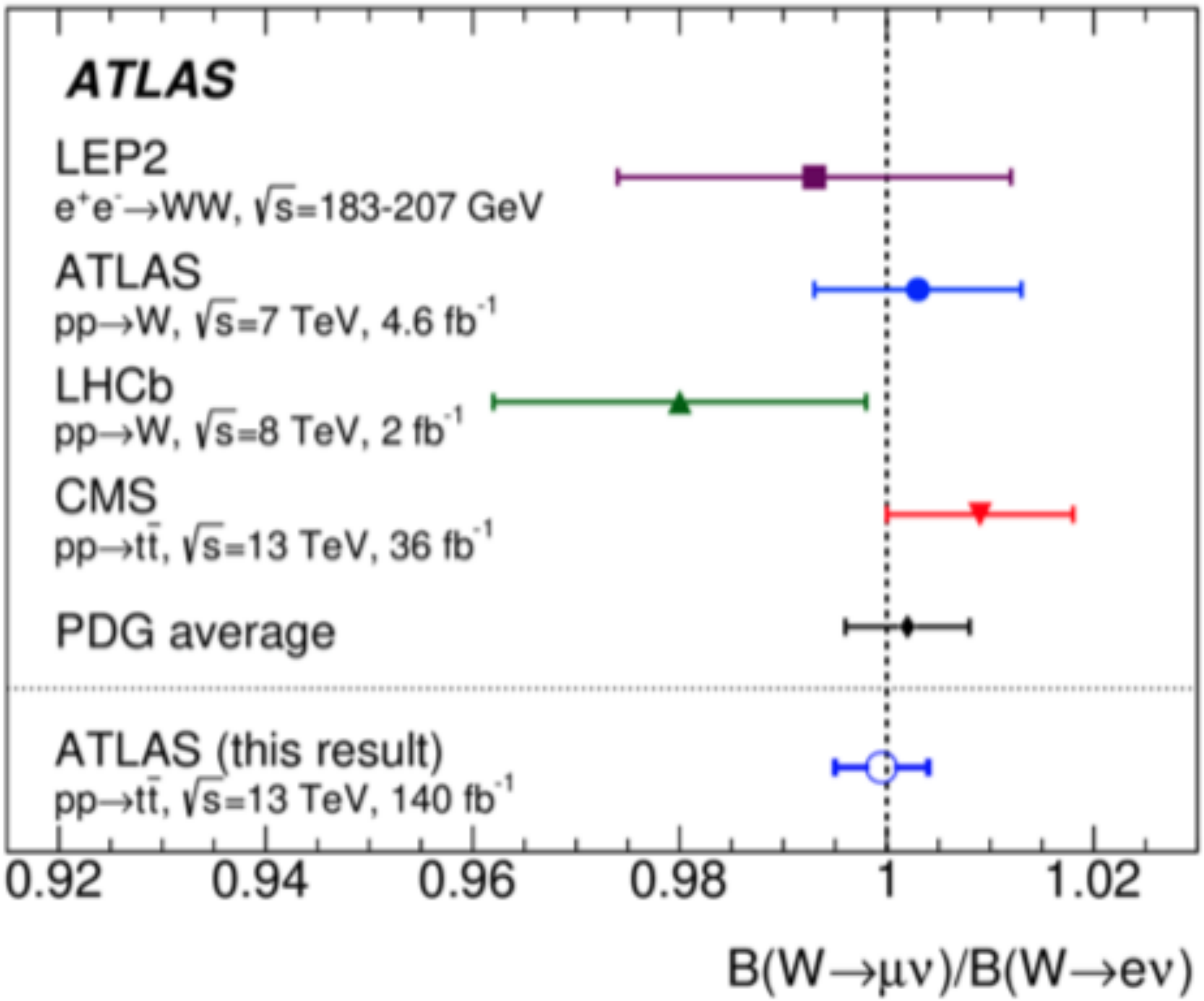
$$\log_{10}\frac{\Lambda}{\mathrm{GeV}} = 10.9 \pm 0.8$$

- Dominant uncertainties those in α_s and m_t

Top Decays

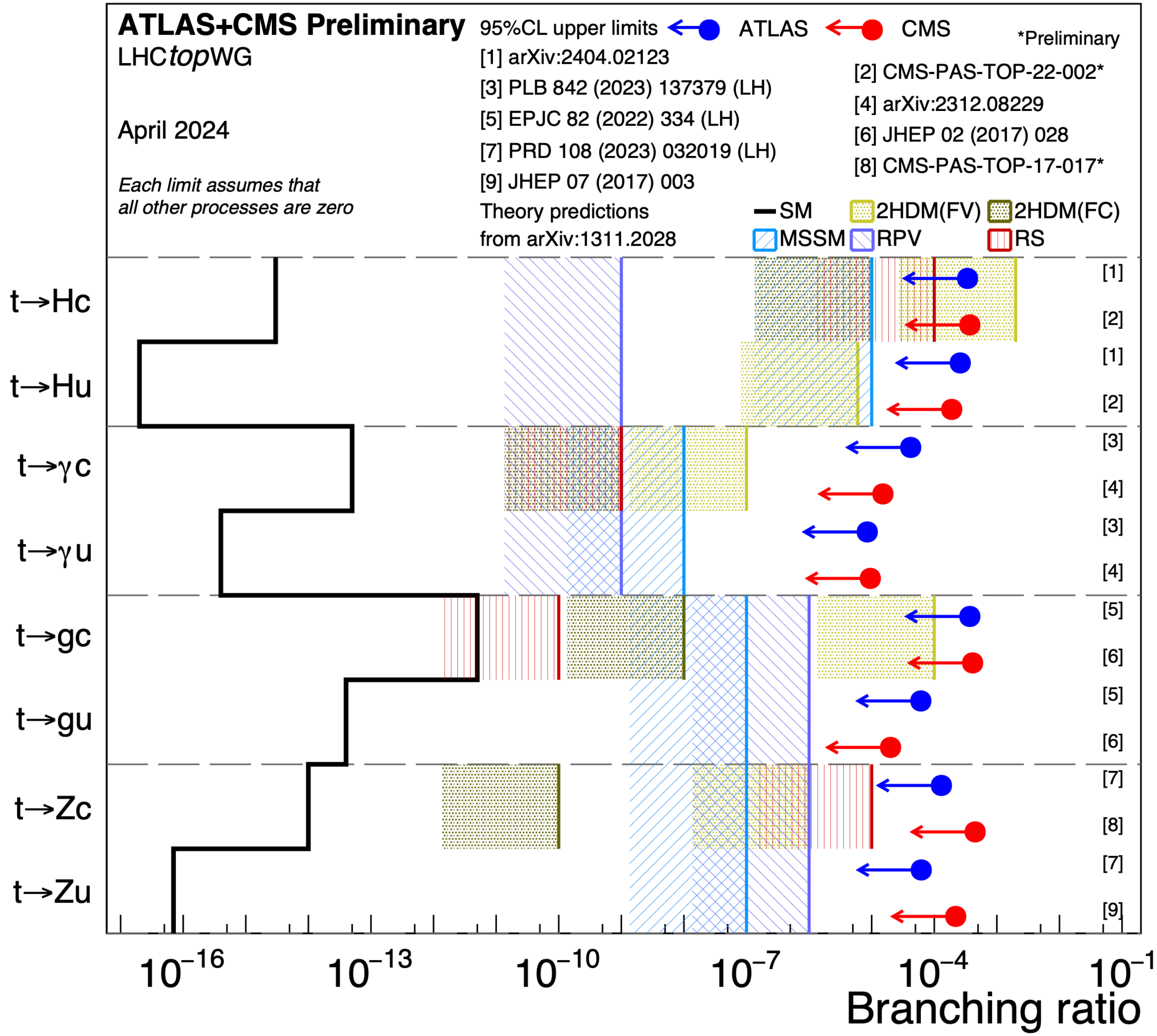
- Total decay width $1.42^{+0.19}_{-0.15}$ GeV (PDG)
- Dominant decays $t \to b + W^+$, followed by $W^+ \to \bar{q}q', \bar{\ell}\nu$
- $\Gamma(W^+b) = 0.957 \pm 0.034$ assuming no important BSM decays
- Most sensitive test of universality in $W \to e/\mu + \nu$ decays
- Most weakly constrained BSM decay mode (?):
  $\Gamma(H^+b, H^+ \to \bar{\tau}\nu)/\Gamma_{Tot} < 0.25$
- Strong constraints on flavour-changing decays:
  $\Gamma(t \to (\gamma, g, Z, H) + u, c) \lesssim 10^{-4}\ \Gamma_{Tot}$

Lepton Universality in Top Decays

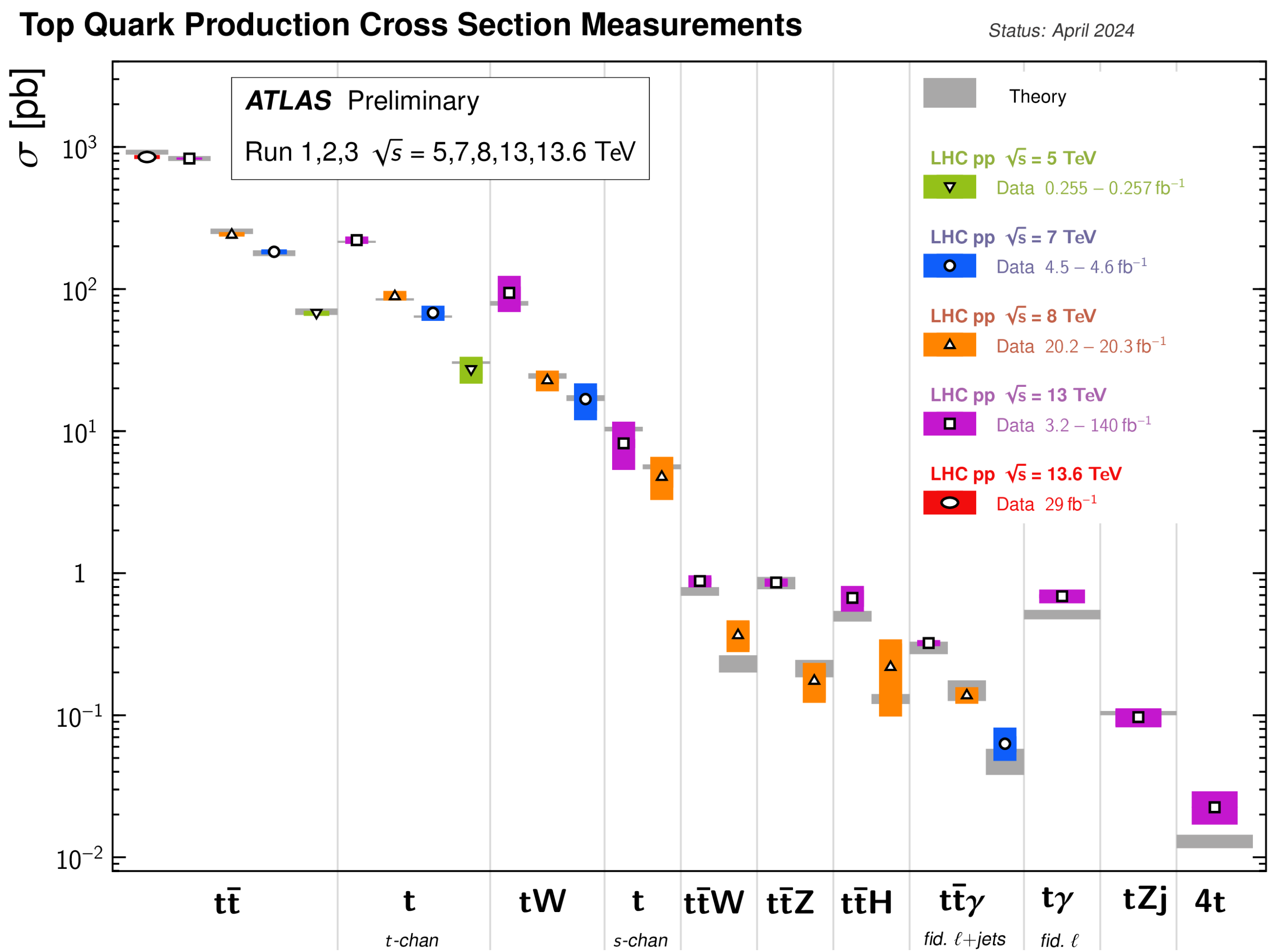


Most precise check of lepton universality in W decays

Searches for Flavour-Changing Top Decays

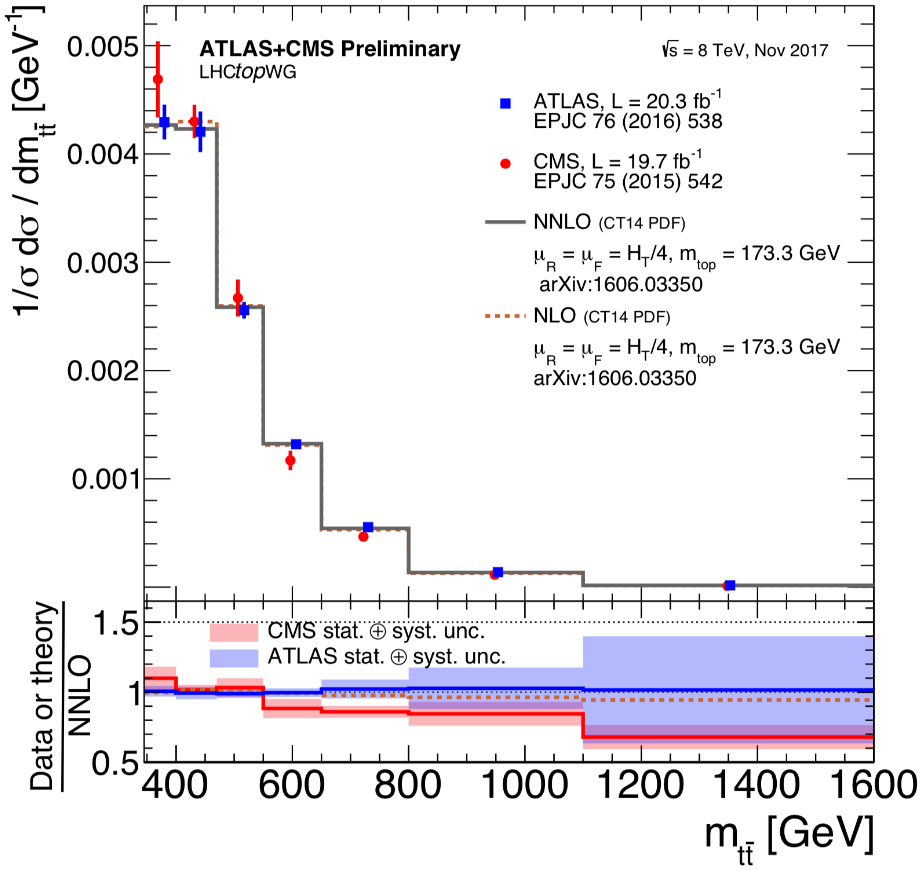


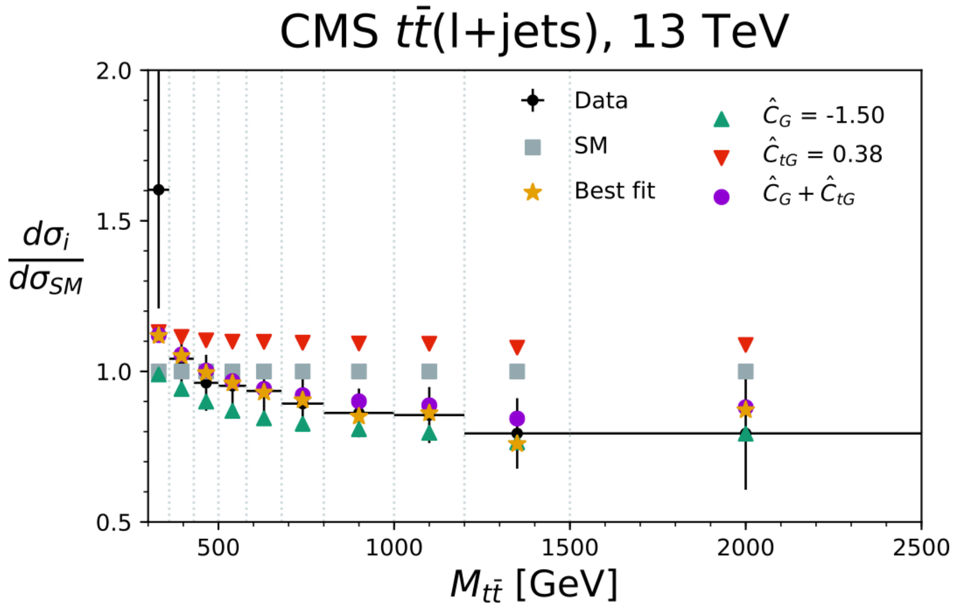
Top Production at the LHC



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

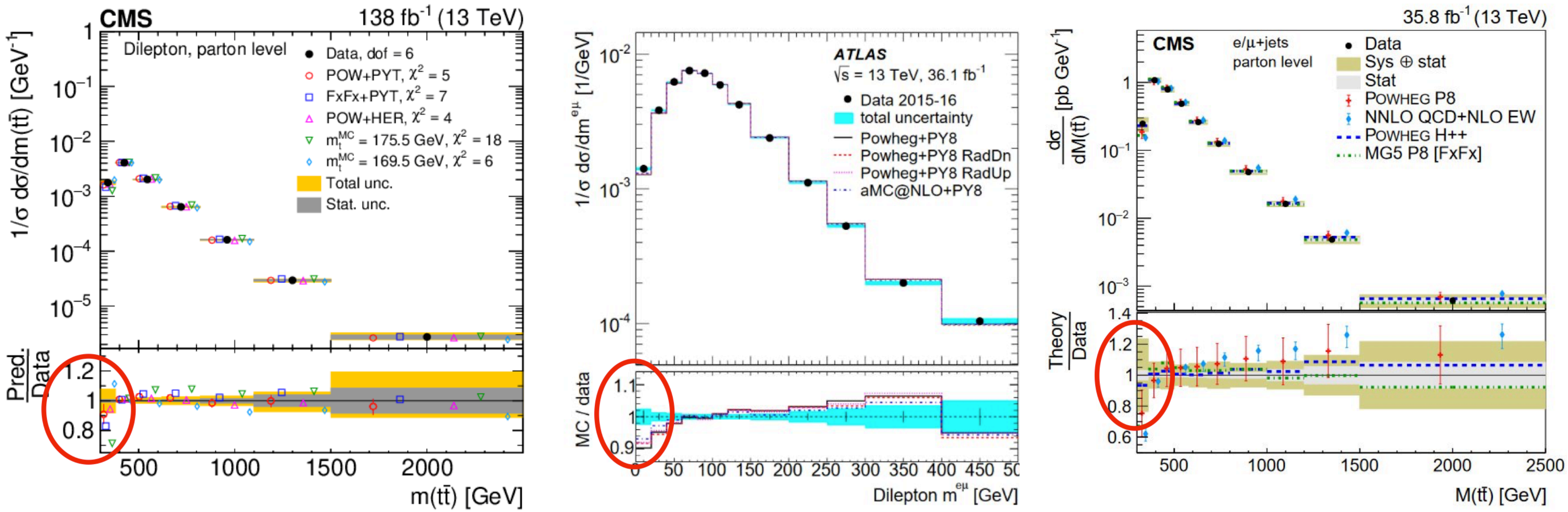
$t\bar{t}$ Cross Section as Function of $M_{t\bar{t}}$





- Good match to theory, except close to threshold?
- Can problem be fixed by BSM?
- No improvement with SMEFT
- Higher-order QCD effects?

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



Good match to theory, except close to threshold?

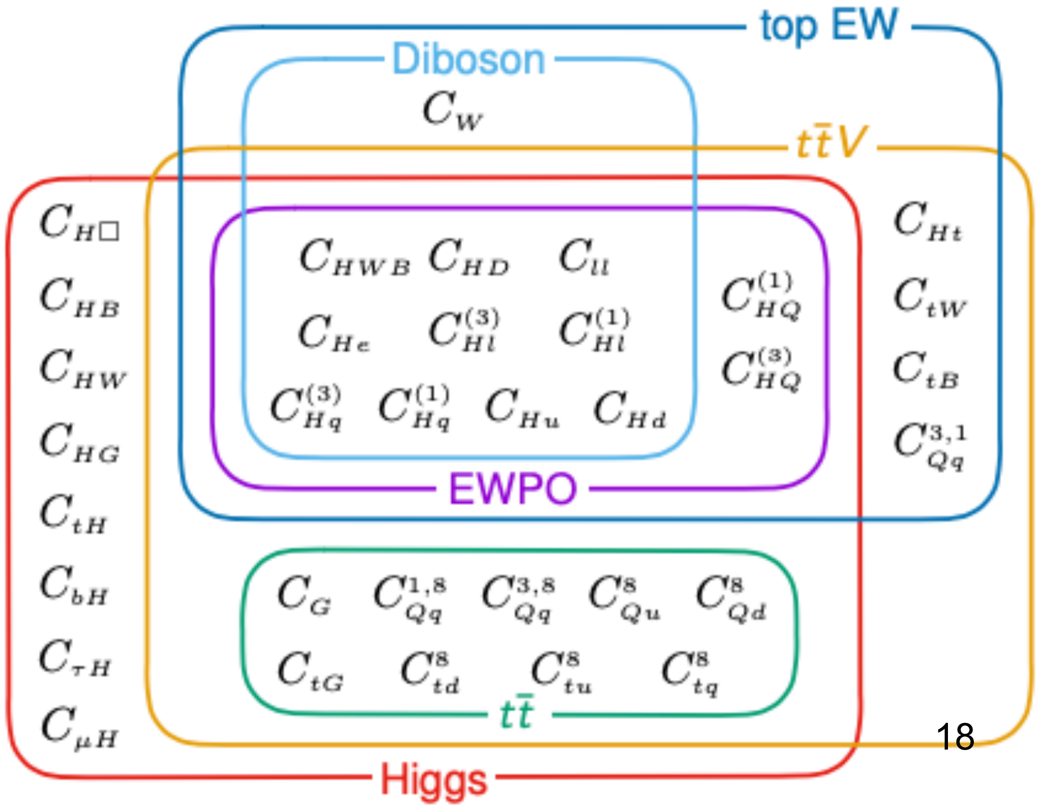
SMEFT Analysis:

Global Fit to Top, Higgs, Diboson, Electroweak Data

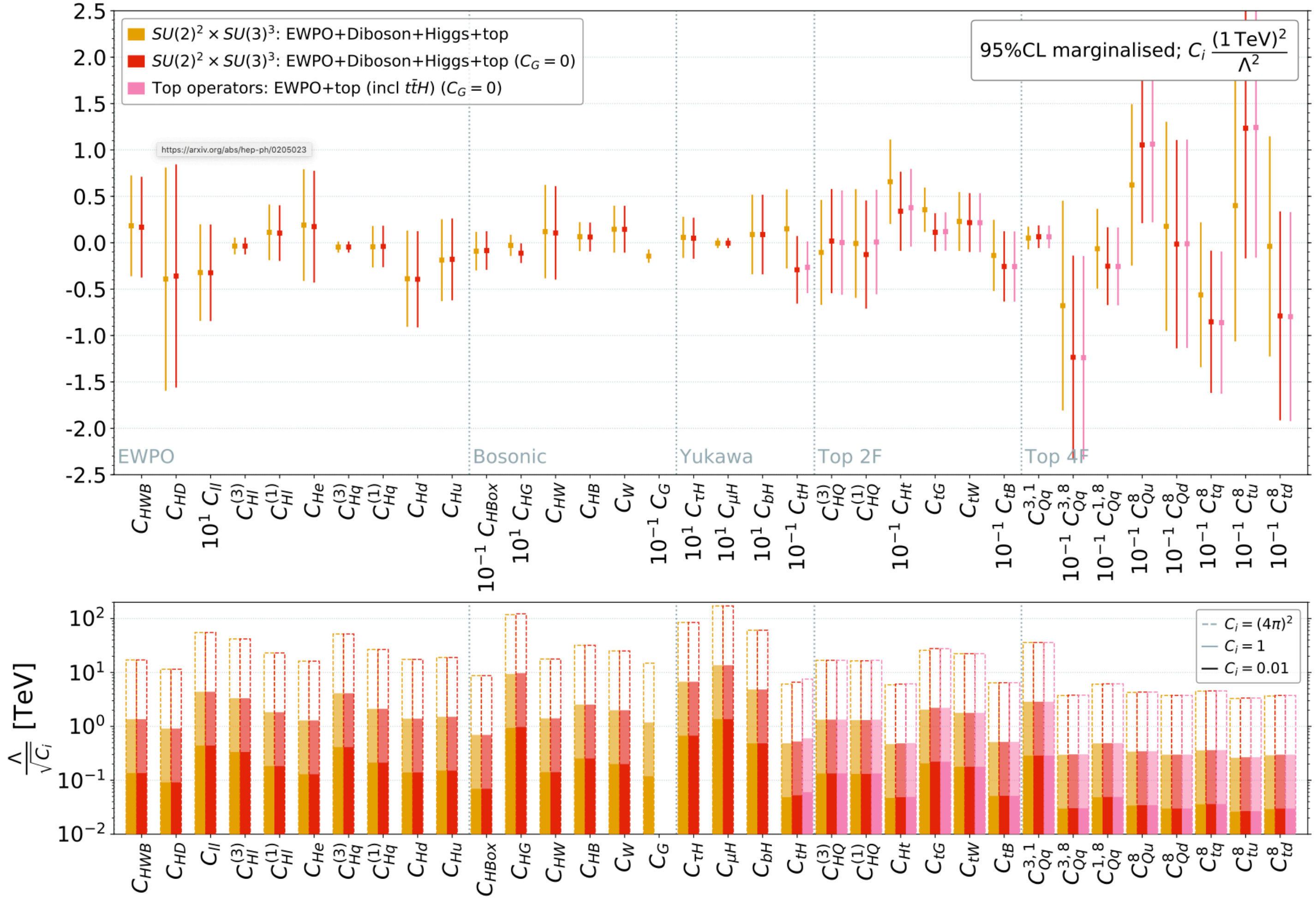
JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

- Global fit to dimension-6 operators using precision electroweak data, W^+W^- at LEP, top, Higgs and diboson data from LHC Runs 1, 2
- Search for BSM
- Constraints on BSM
  - At tree level
  - At loop level

341 measurements included in global analysis

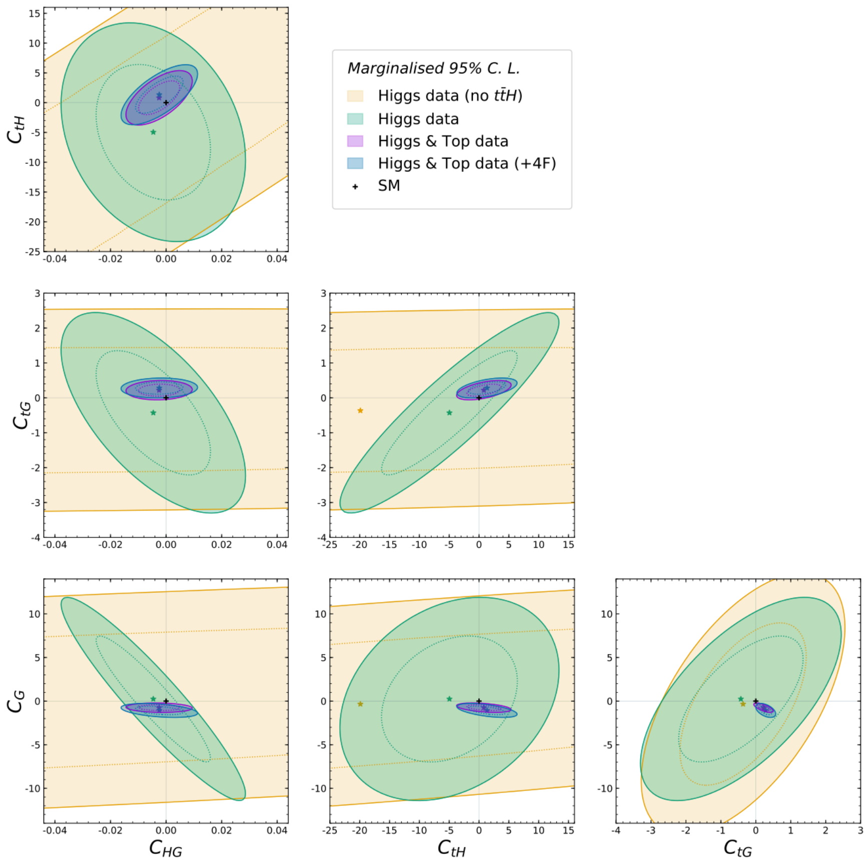


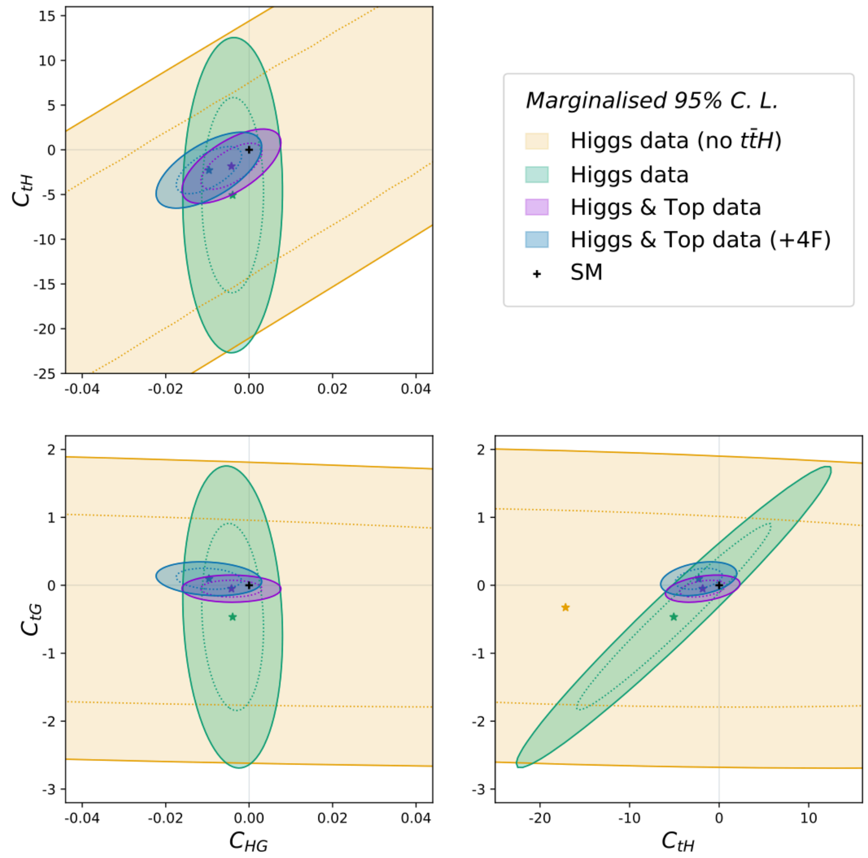
Global SMEFT Fit Including Top Data

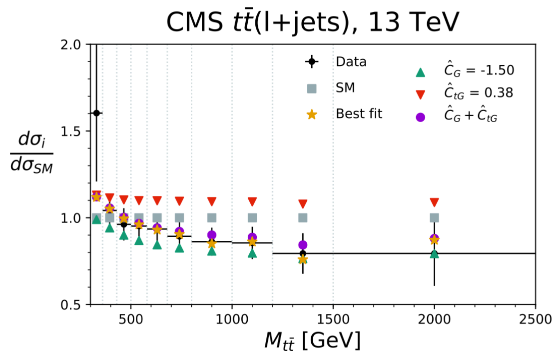


- Constraints on top operators weaker
- Fit prefers $C_G \neq 0$, but jet data (not included) want $C_G \simeq 0$

Tensions in SMEFT Analysis of Top Data

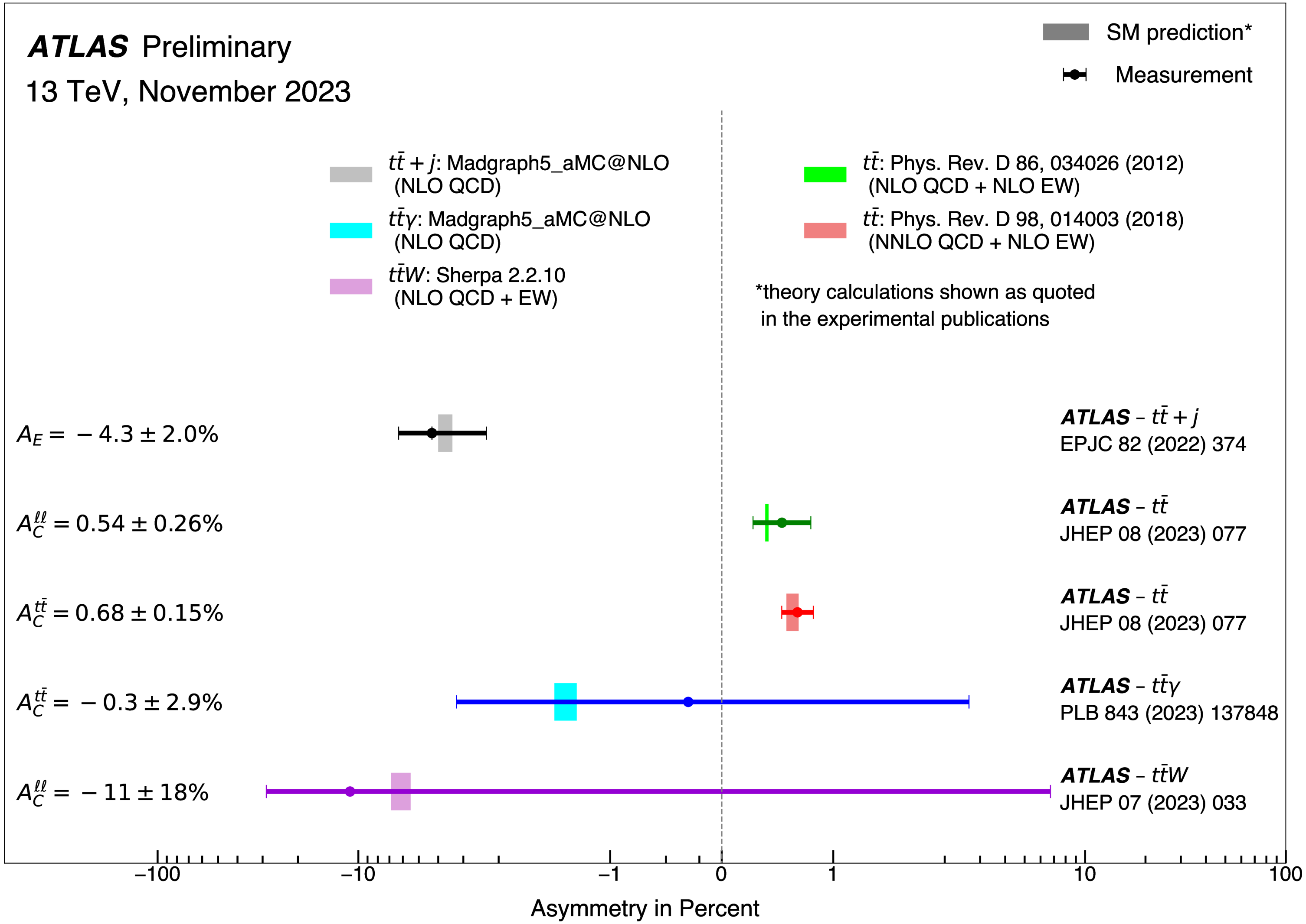






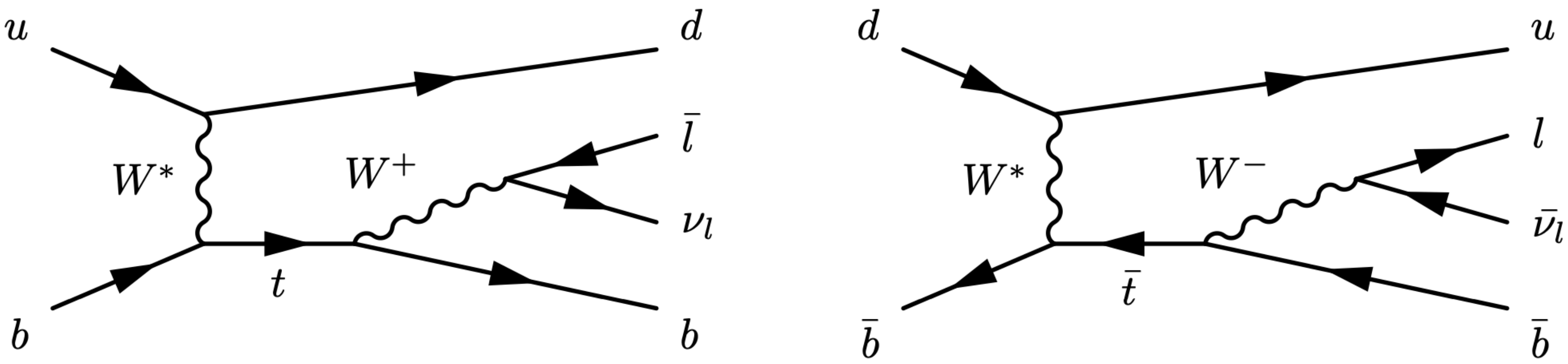
- Fit wants $C_G \neq 0$ (left), but jets want $C_G \simeq 0$ (right)
- Cannot help with threshold enhancement

$t\bar{t}$ Production Asymmetries

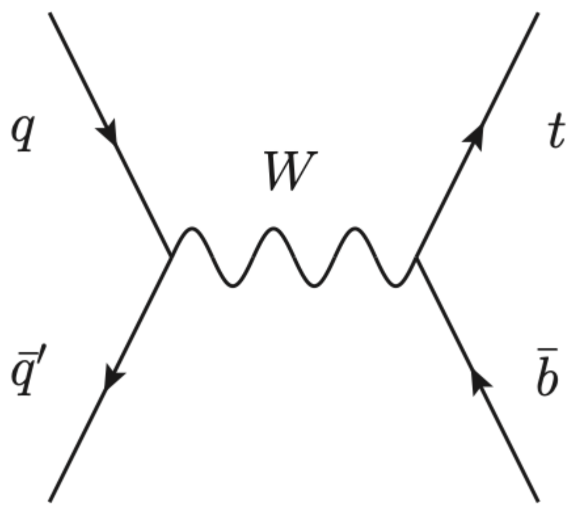


Consistent with theoretical predictions

Single-Top Production Diagrams in t- and s-Channels

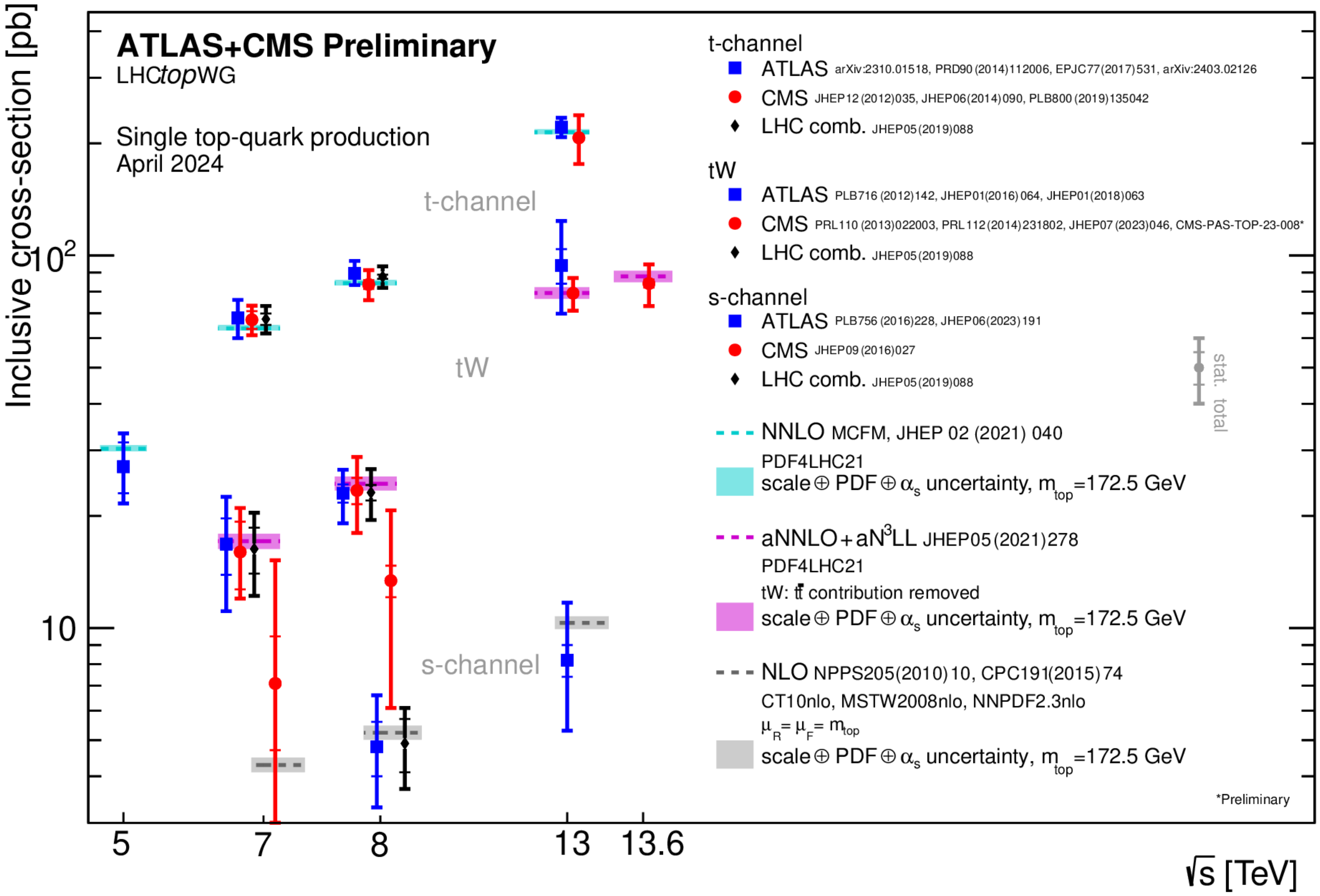


t-channel W exchange



s-channel W exchange

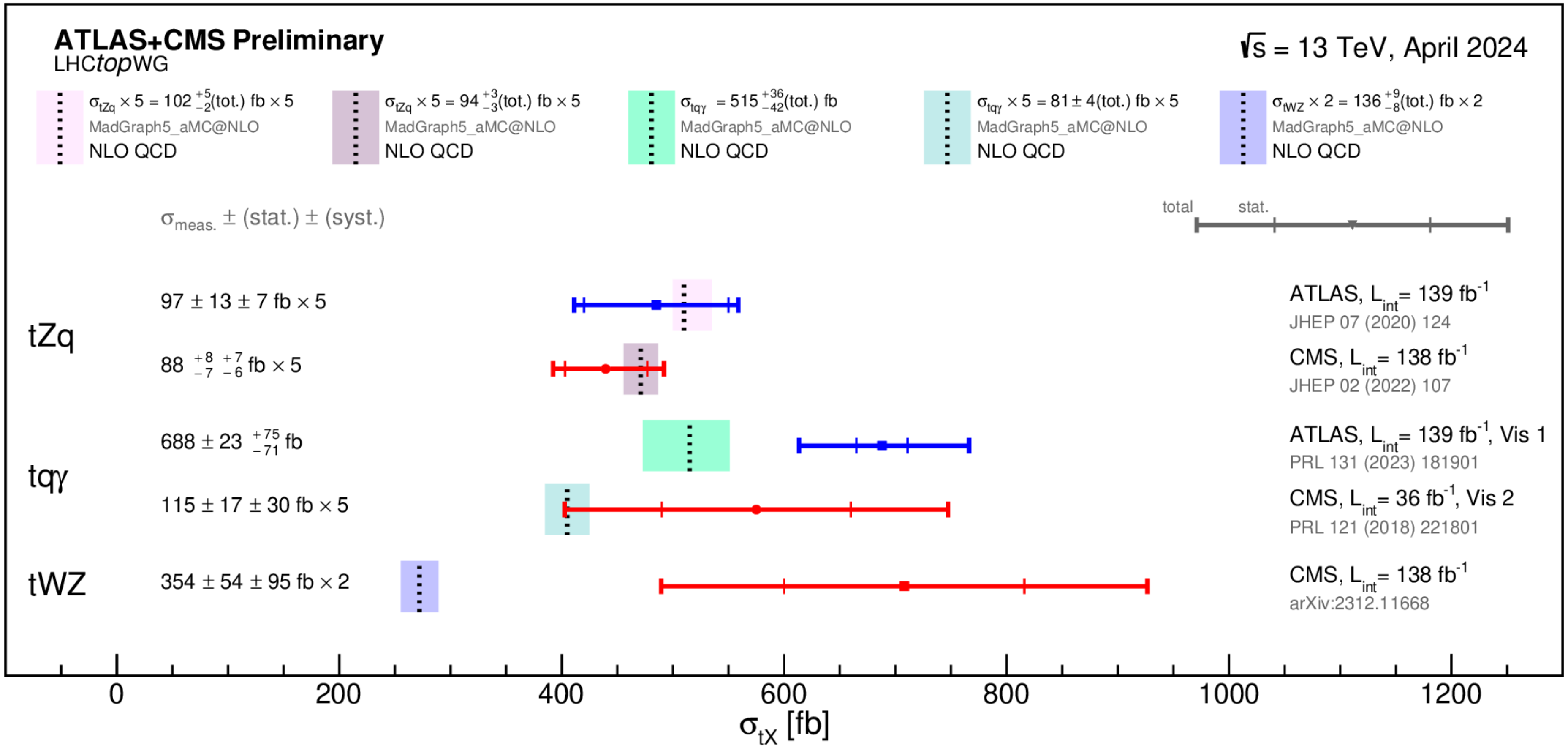
Single Top Production



Good agreement between theory and experiment

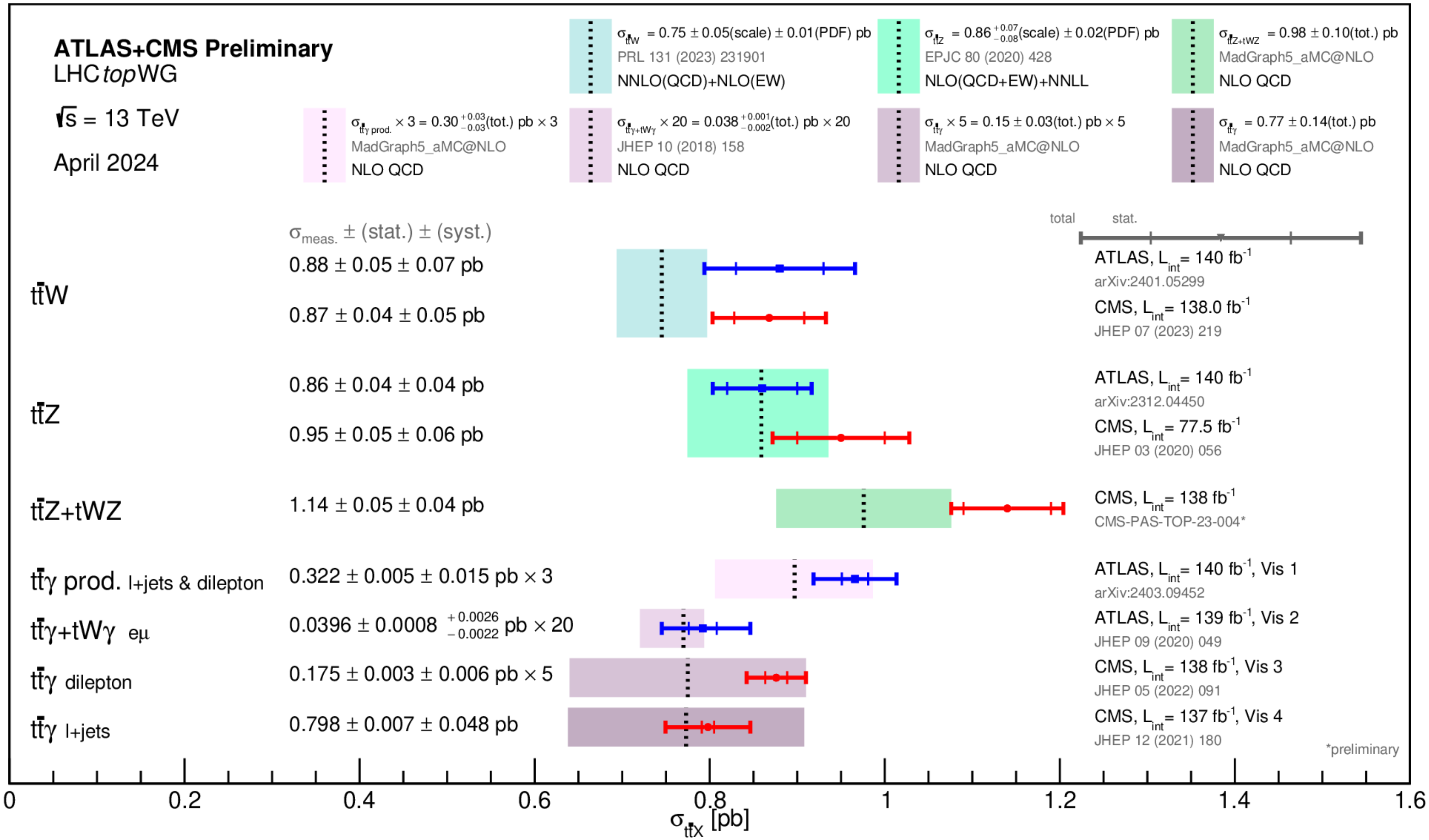
LHCtopWG

Single Top Associated Production



Mostly consistent with theoretical predictions

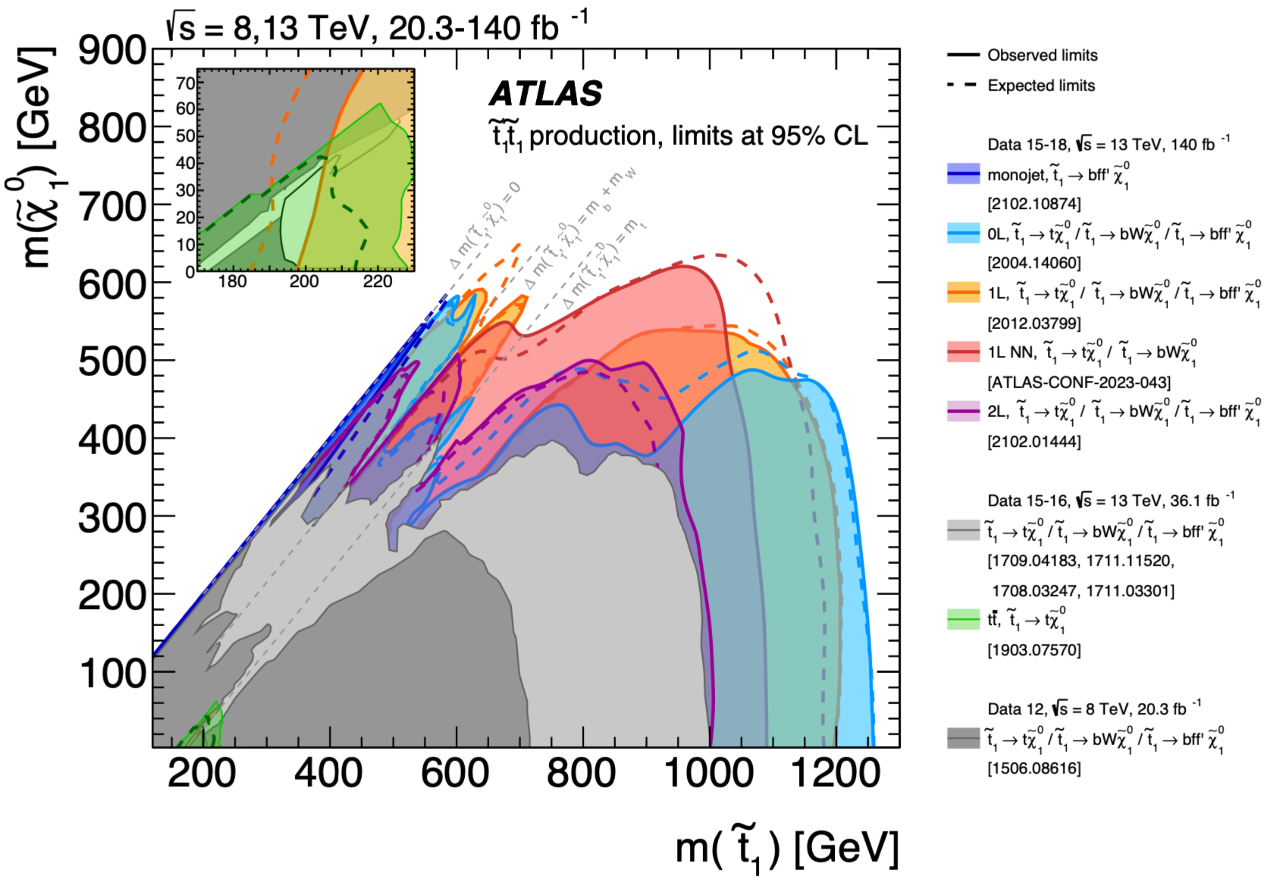
$t\bar{t}$ Associated Production



Consistent with theoretical predictions

Stop Searches at the LHC

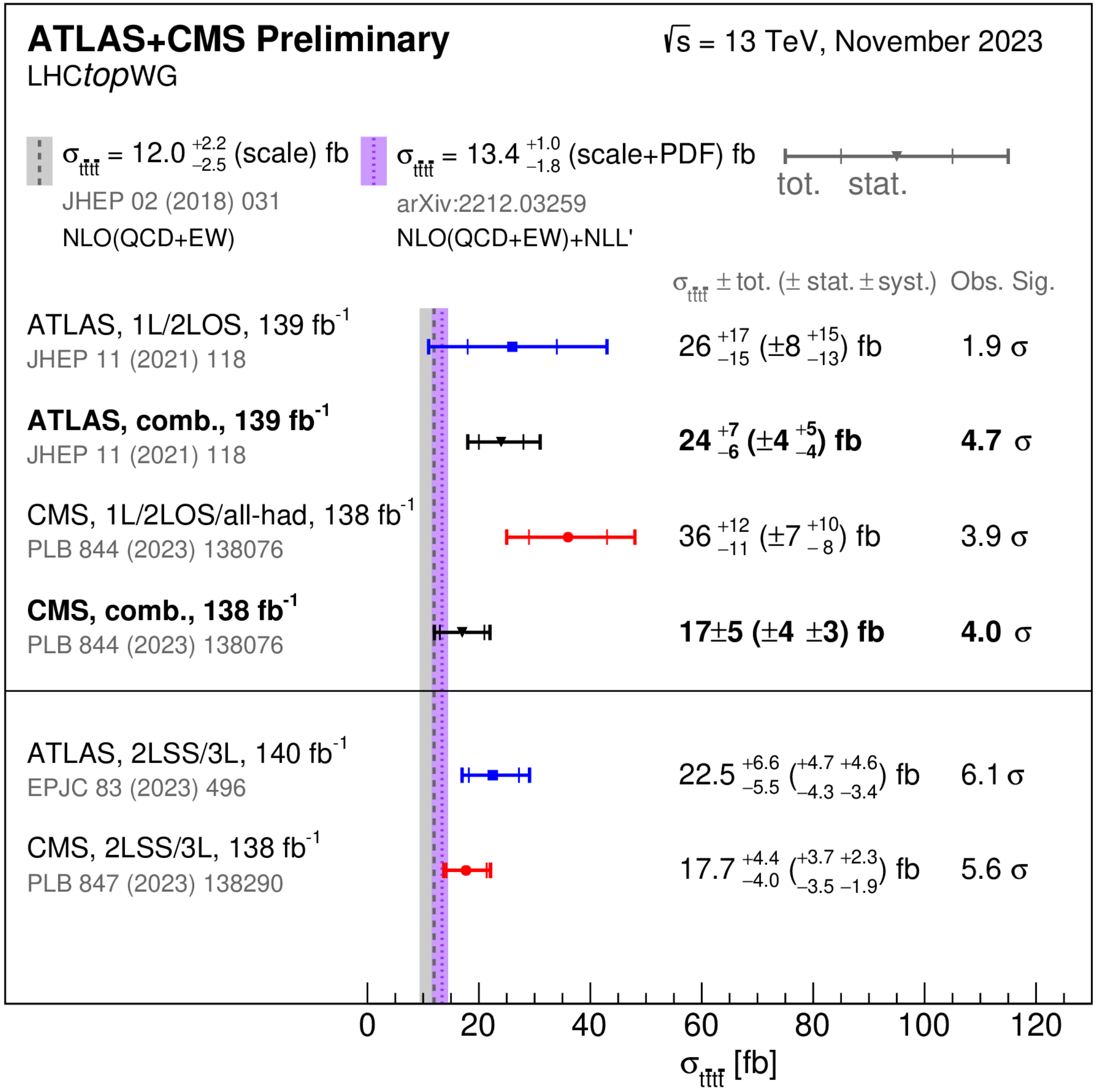
- Supersymmetric partners of top quark: $\tilde{t}_{L,R}$, may be lightest squarks (naturalness, large $\tilde{t}_L/\tilde{t}_R$ mixing)



- Lower mass limit depends on neutralino mass, decay pattern.

- Combination of decay modes in general: need to survey models

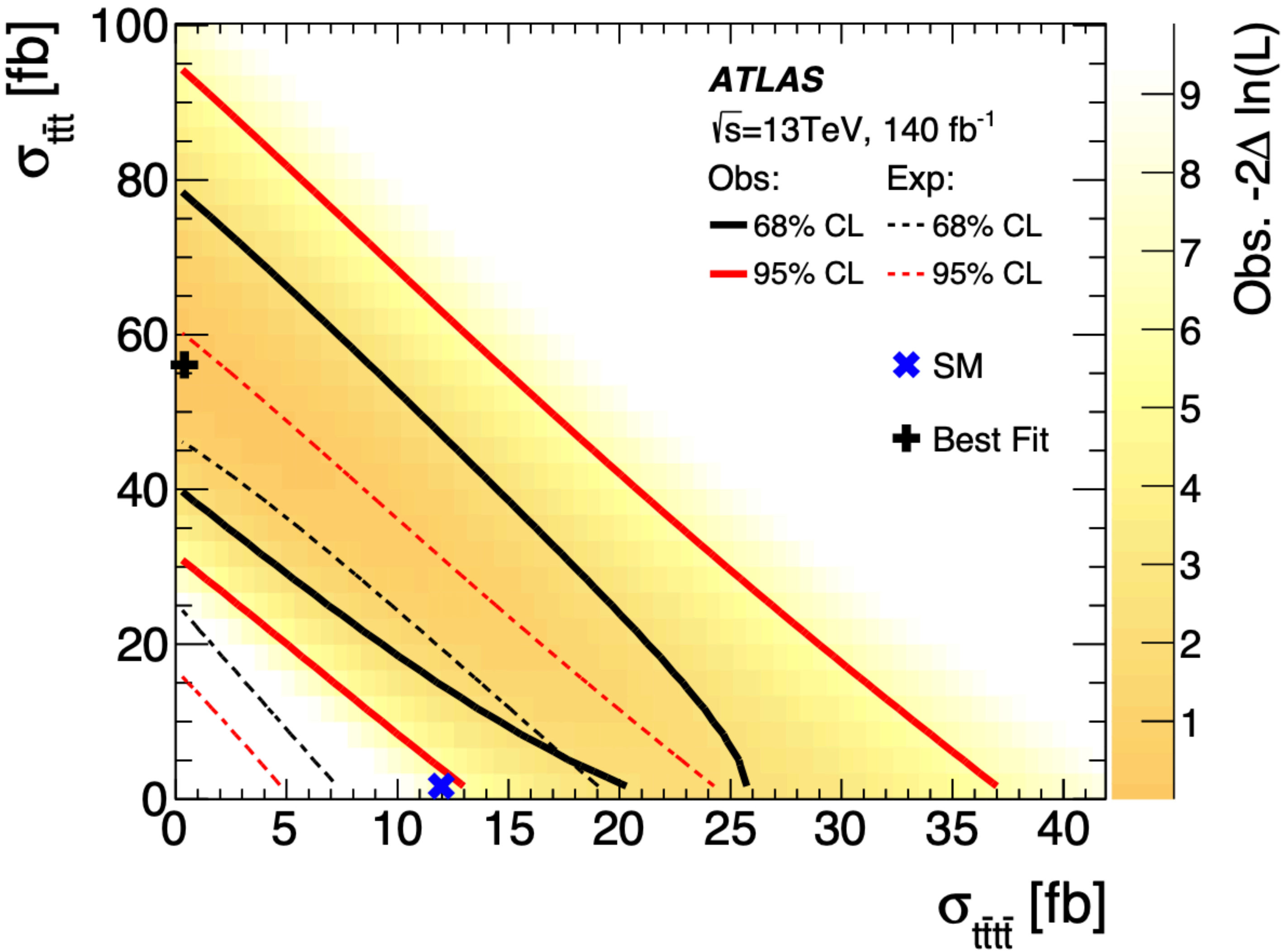
Measurements of $t\bar{t}t\bar{t}$ Production



LHCtopWG

ATLAS Collaboration, arXiv:2303.15061

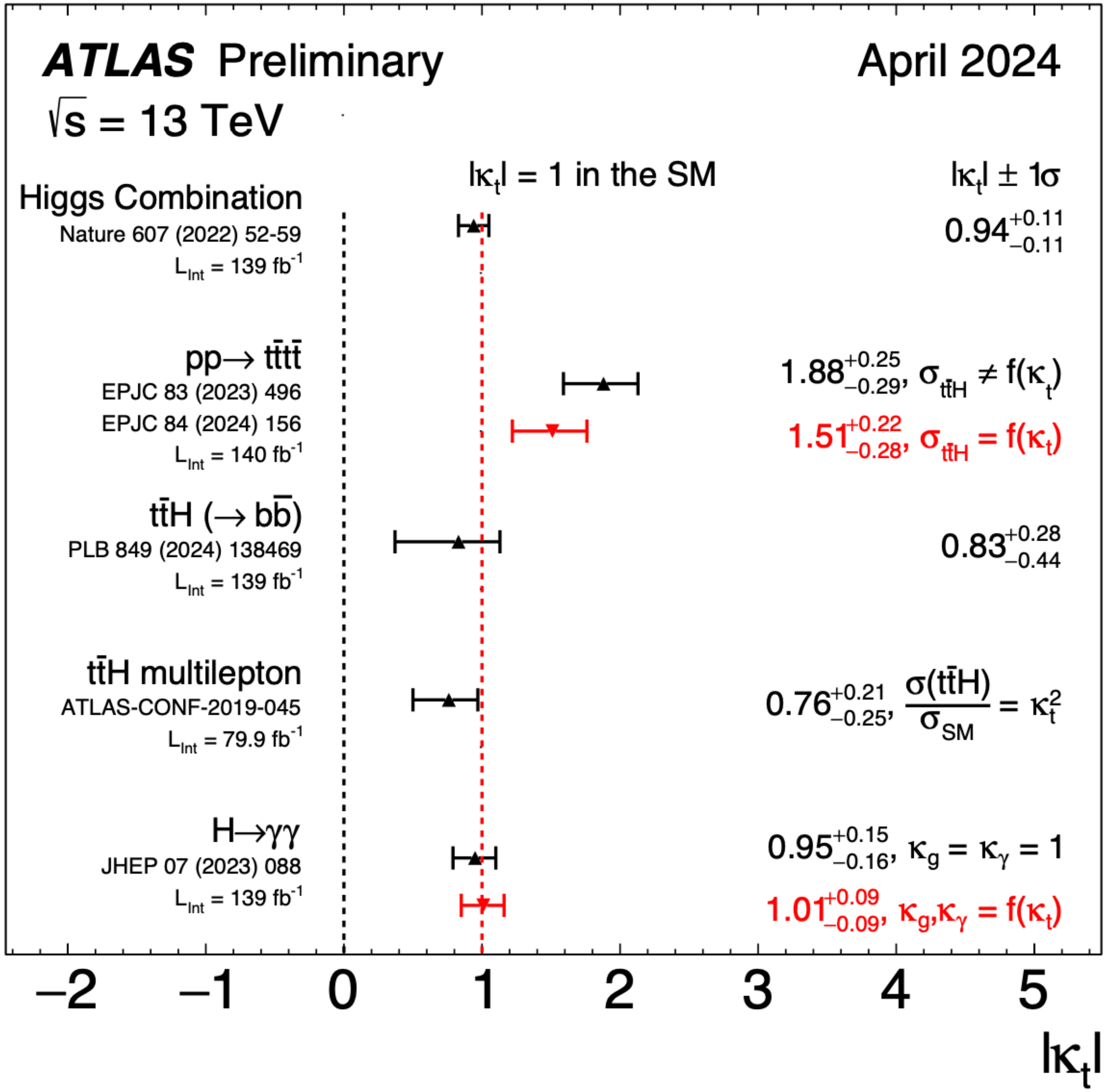
Constraints on $t\bar{t}t\bar{t}$ and $t\bar{t}t$ Production



Best fit prefers large $t\bar{t}t$ cross section: expected to be small

Central value of $t\bar{t}t\bar{t}$ cross section > Standard Model

Constraints on Top Yukawa Coupling



ATLAS Collaboration, ATL-PHYS-PUB-2024-005

Probes of CP Violation in $t\bar{t}H$ Coupling

- Two possible $t\bar{t}H$ couplings with different CP:

$$\mathcal{L}_t = -\frac{m_t}{v}\left(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t\right) H$$

- Expect $\kappa_t = 1, \tilde{\kappa}_t = 0$ in the Standard Model

- $\tilde{\kappa}_t$ constrained by the electric dipole moment of the electron, d_e, to which it contributes via 2-loop diagram

- Current upper limit $|d_e| < 4.1 \times 10^{-30}$ e.cm suggests $|\tilde{\kappa}_t| \lesssim 5 \times 10^{-4}$, if SM Higgs-electron coupling assumed, and no cancellation with other diagrams

- **Seek direct constraints on $\tilde{\kappa}_t$**

JE, Hwang, Sakurai & Takeuchi, arXiv:1312.5736

Observables Sensitive to $\tilde{\kappa}_t$

- Contributions to $Hgg, H\gamma\gamma$ couplings:

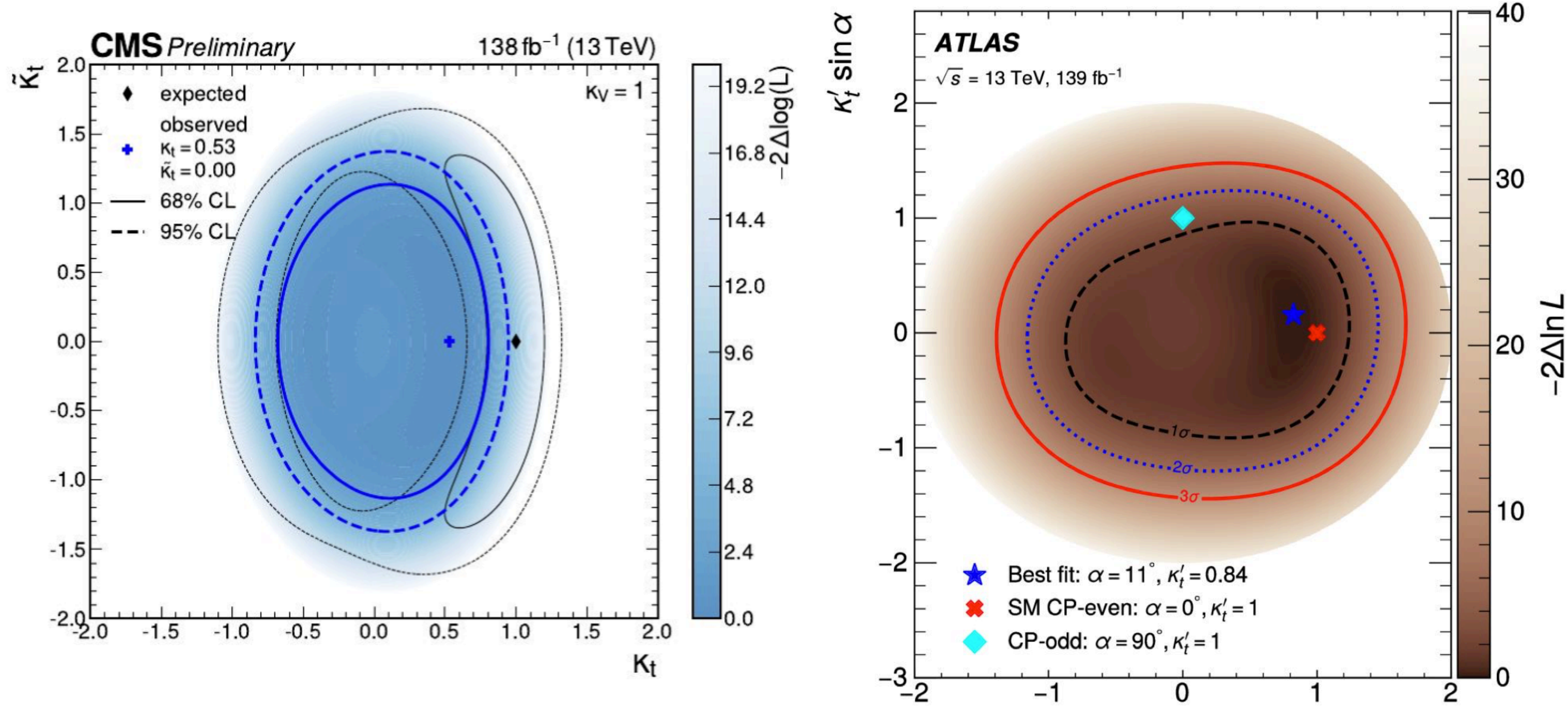
$$\mu_{gg} \simeq \kappa_t^2 + 2.6\tilde{\kappa}_t^2 + 0.11\kappa_t(\kappa_t - 1)$$
$$\mu_{\gamma\gamma} \simeq (1.28 - 0.28\kappa_t)^2 + (0.43\tilde{\kappa}_t)^2$$

- Affects ratios of $t\bar{t}H, tH, \bar{t}H$ cross sections
- Modifies invariant mass distributions
- Sensitivity in top quark polarisation and spin correlations

JE, Hwang, Sakurai & Takeuchi, arXiv:1312.5736

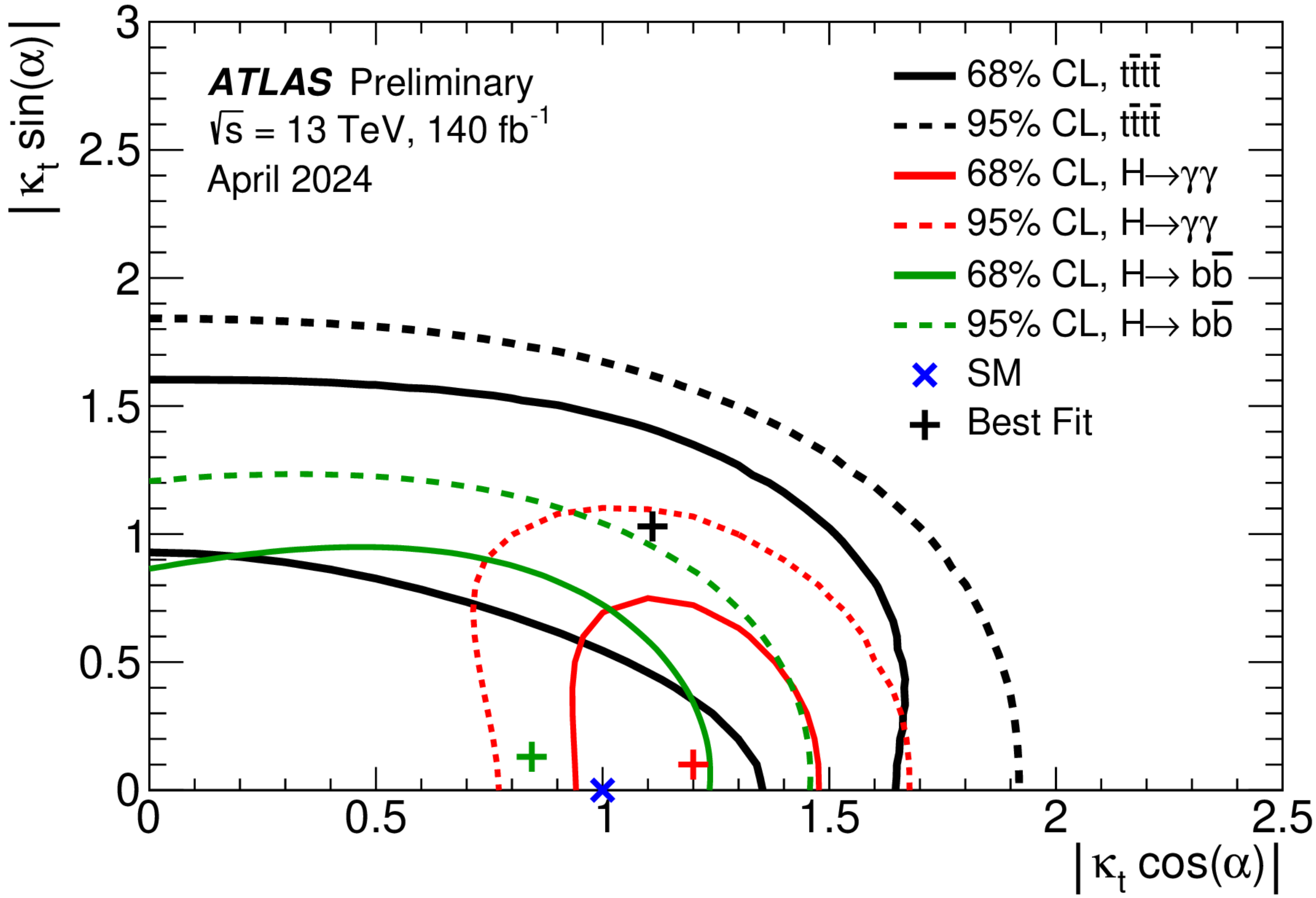
- Modifies cross section for $t\bar{t}t\bar{t}$ production

Search for CP Violation in $t\bar{t}H$ Coupling



$t\bar{t}$ measurements consistent with CP conservation, weak constraints on violation

Search for CP Violation in $t\bar{t}H$ Coupling



Some tension between $t\bar{t}t\bar{t}$ cross section and other measurements

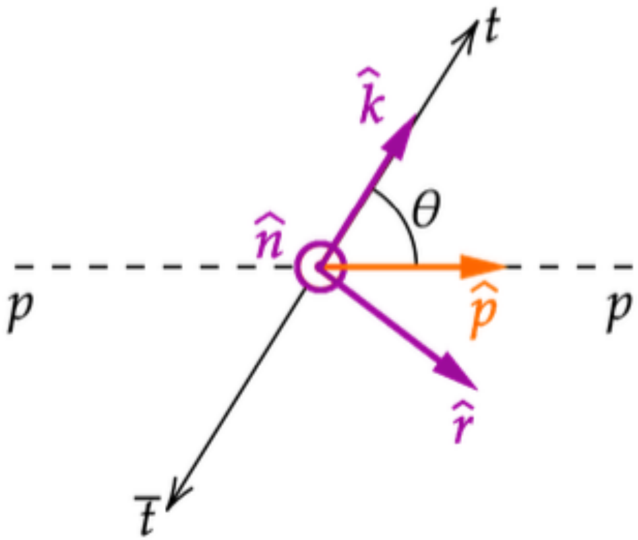
ATLAS Collaboration, arXiv:2303.15061

Entanglement

- 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: $\mathcal{B}_1 = \{B_{1i}\}_{i=1,2,3}, \quad \mathcal{B}_2 = \{B_{2j}\}_{j=1,2,3}$ ($= 0$ for $t, \bar{t}$)
- Singlet correlation matrix:

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



- Entanglement marker for spin 0:

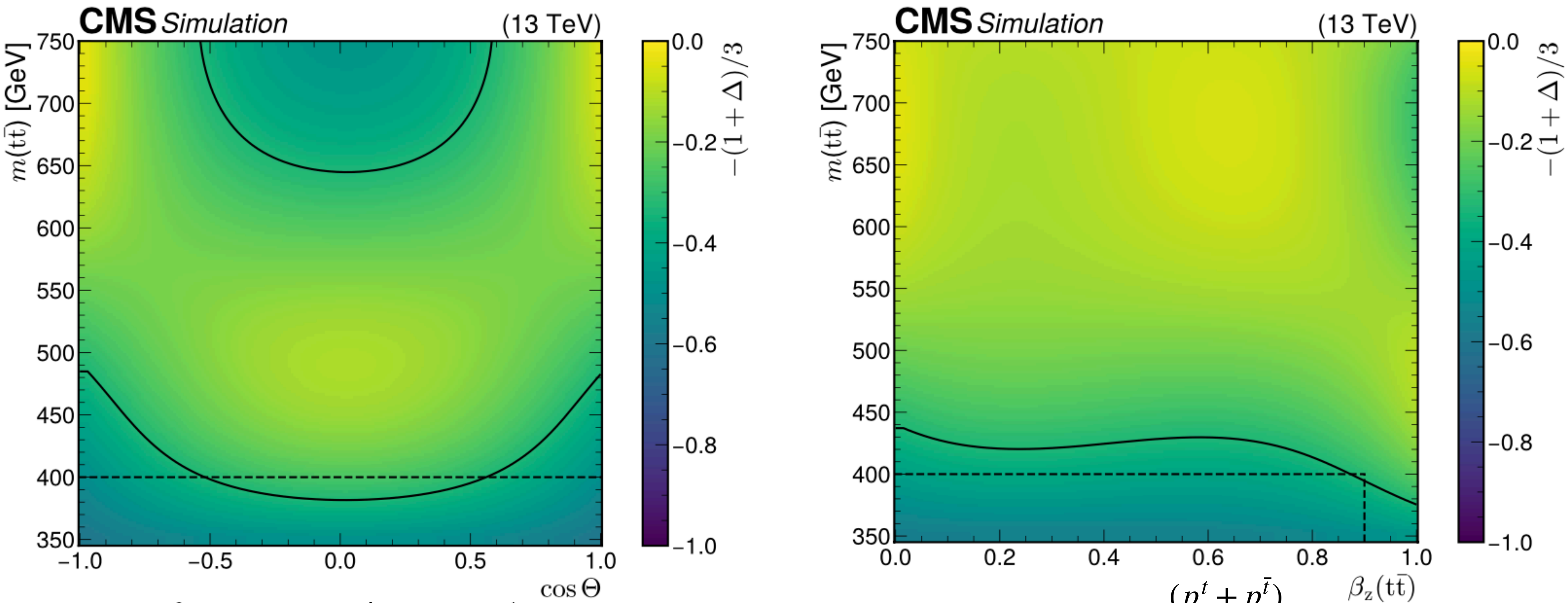
$$-C_{kk} - C_{rr} - C_{nn} \equiv -3\,D \qquad D = -\eta$$

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

Afik & de Nova, arXiv:2003.02280, 2203.05582;

Maltoni et al, arXiv:2401.08751

Values of Entanglement Marker in $t\bar{t}$



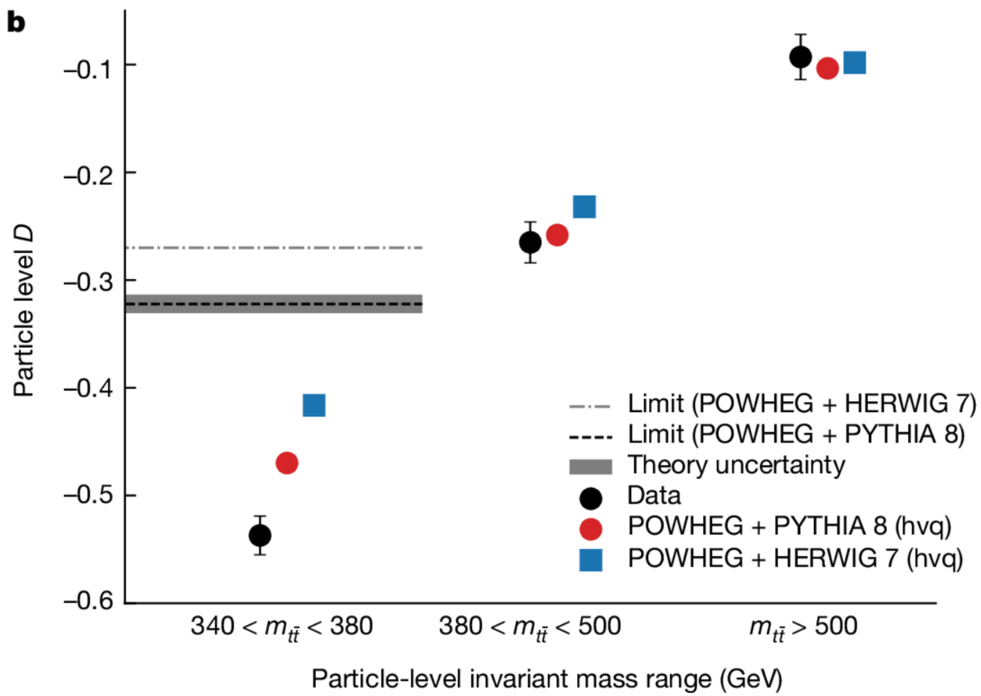
θ = scattering angle

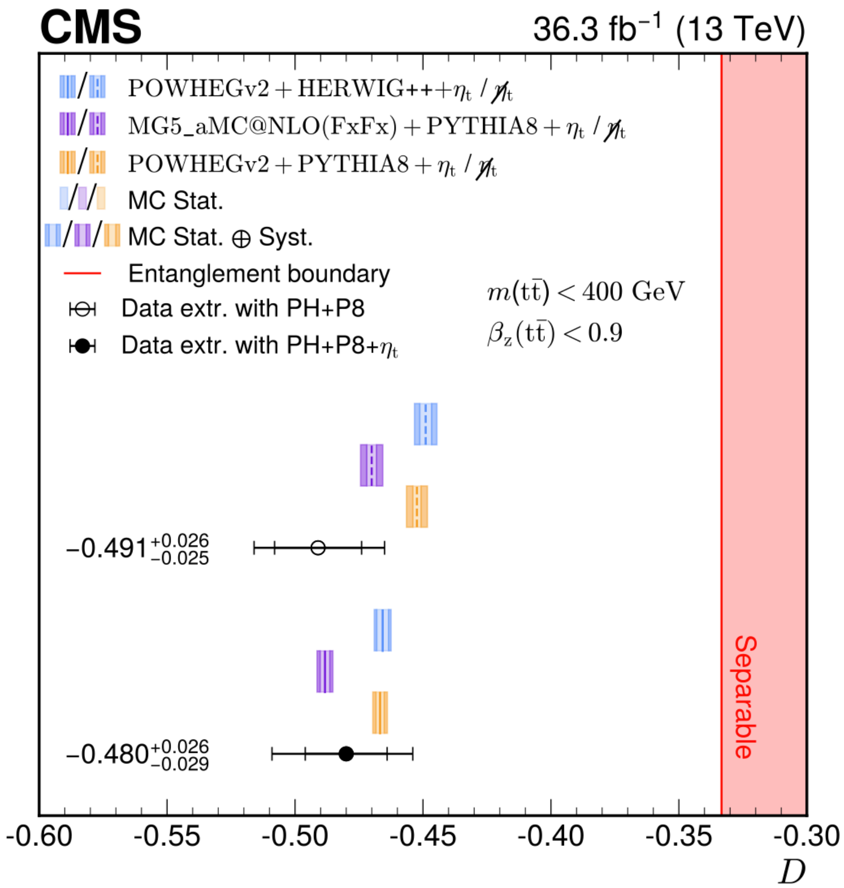
$$\beta_{zz}(t\bar{t}) = \frac{(p_z^t + p_z^{\bar{t}})}{(E^t + E^{\bar{t}})}$$

- Solid lines: entanglement boundary
- Dashed lines: phase space selected for analysis

CMS Collaboration, arXiv:2406.03976

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

More $t\bar{t}$ Entanglement Studies

- Entanglement marker for spin 0 (singlet):

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

- Entanglement marker for spin 1 (triplet):

$$\tilde{D} = \frac{1}{3}(C_{nn} - C_{rr} - C_{kk})$$

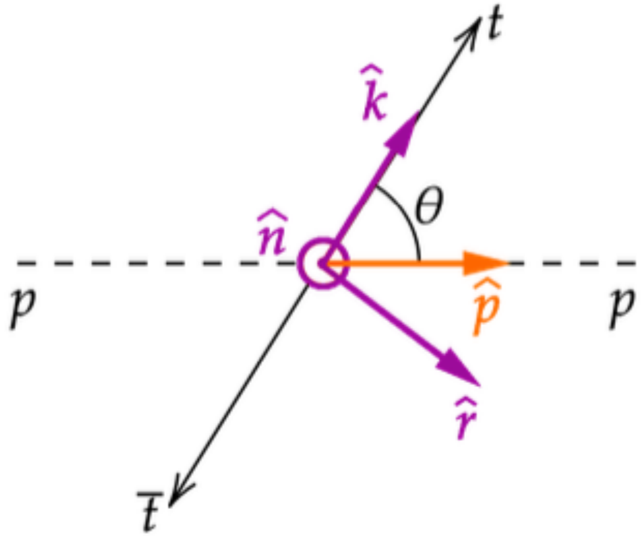
- Sufficient condition for entanglement:

$$\Delta_{\mathrm{E}} = C_{nn} + |C_{rr} + C_{kk}| > 1$$

- "Bell" (CHSH) inequality

$$\sqrt{2}\,\big|-C_{rr} + C_{nn}\big| \leq 2$$

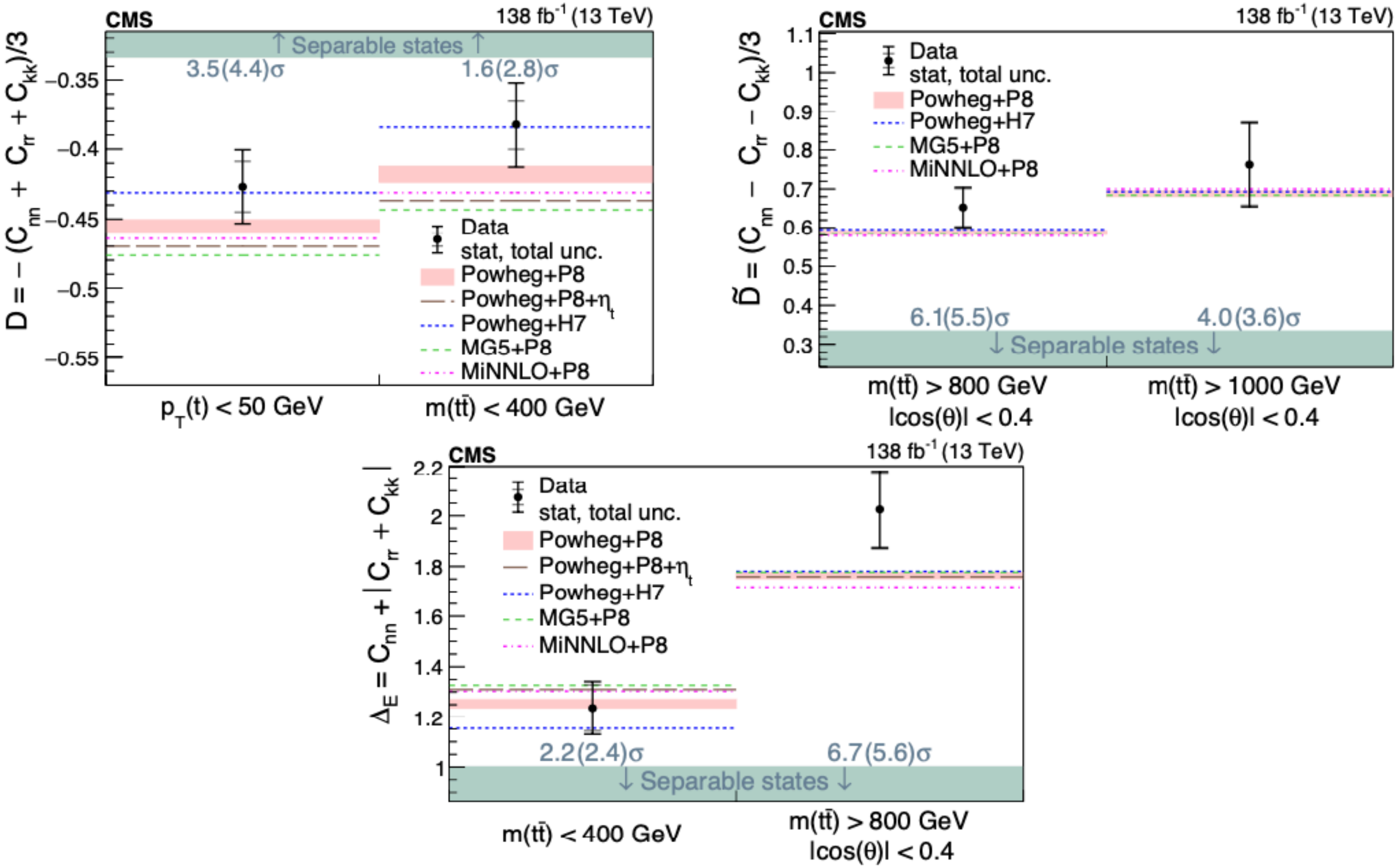
- Study in different kinematical regions



* Clauser, Horne, Shimony, Holt

Afik & de Nova, arXiv:2003.02280, 2203.05582;
CMS Collaboration, arXiv:2409.11067

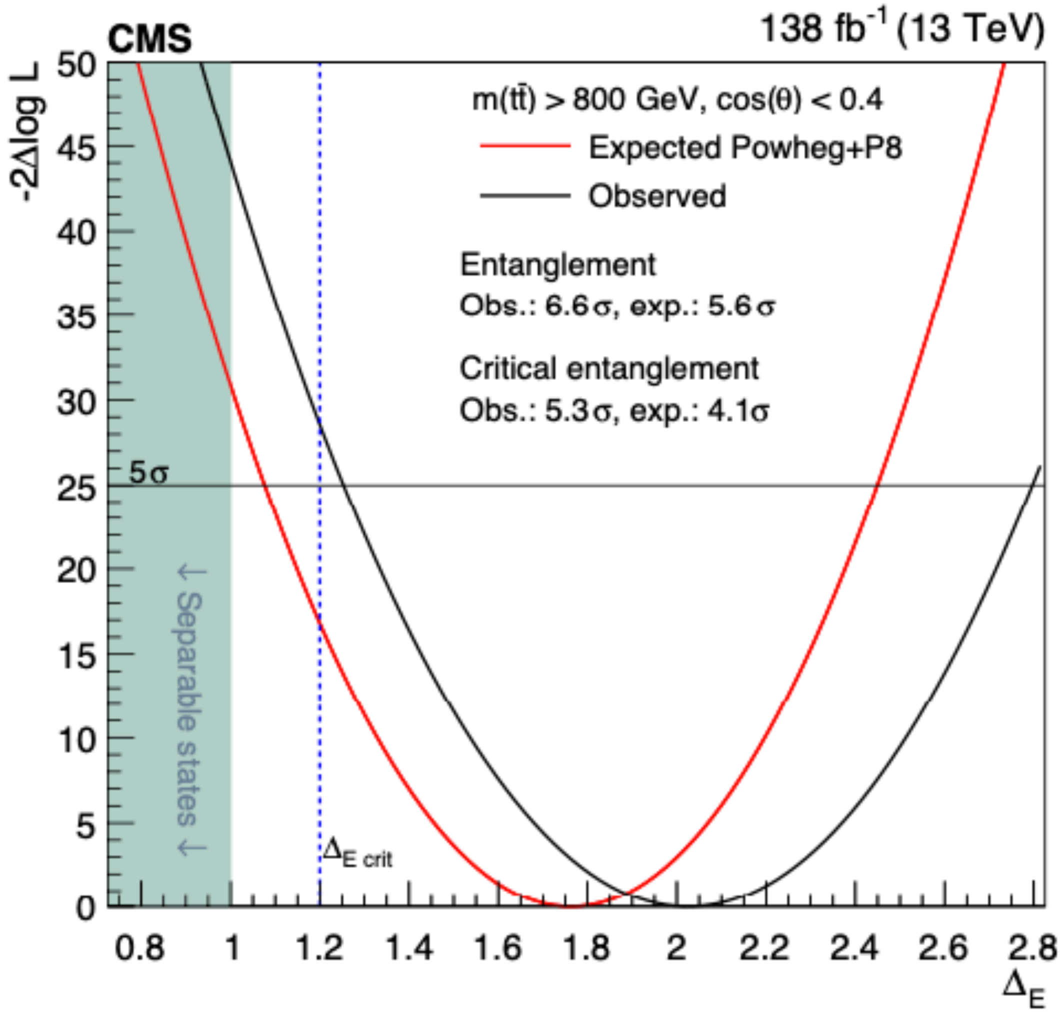
More $t\bar{t}$ Entanglement Studies



- Not separable = entangled: singlet entanglement at low mass, triplet entanglement at high mass

CMS Collaboration, arXiv:2409.11067

Entanglement at High $M_{t\bar{t}}$



- Blue dotted line: Maximum entanglement allowed by causal sharing of information

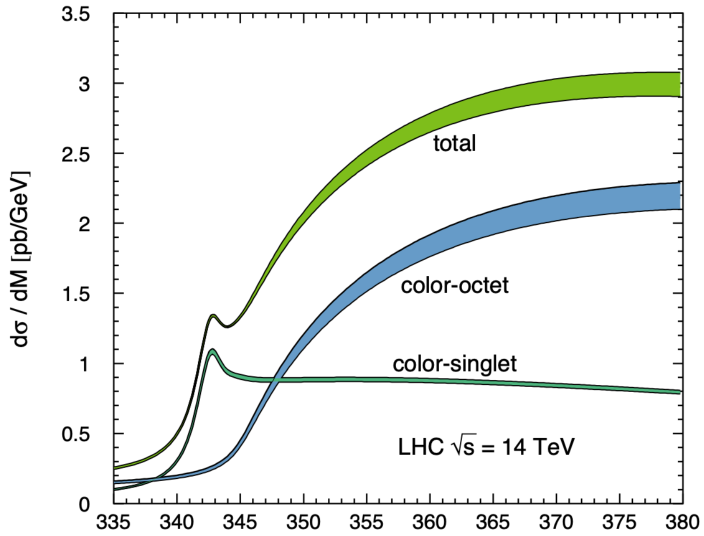
CMS Collaboration, arXiv:2409.11067

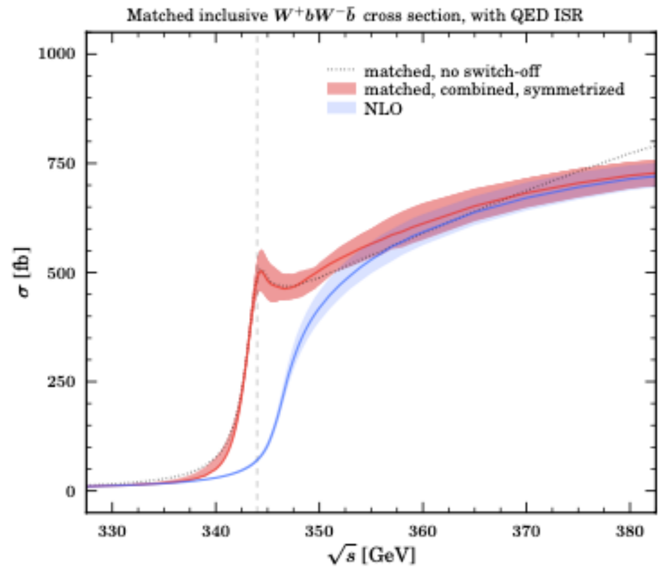
Interpretation

- These entanglement measurements verify predictions of quantum mechanics/ quantum field theory (QM/QFT)
- BUT, they do not exclude local hidden-variable theories (LHVTs)
- These QM/QFT predictions can be mimicked by suitable LHVT
- Discrimination between QM/QFT and LHVT could be provided by (generalised) Bell inequalities
- BUT, these entanglement measurements have other applications …

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

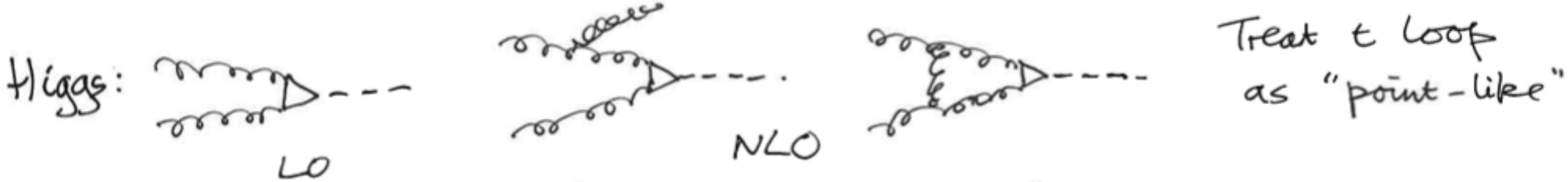
- Pseudoscalar toponium, not an elementary boson!
- Predicted to have a mass a few GeV below the $t\bar{t}$ threshold: 343.5 GeV
- Production of vector toponium in e^+e^- collisions studied in detail
- Relatively few studies for toponium in proton-proton collisions
- Fascinating QCD problem!



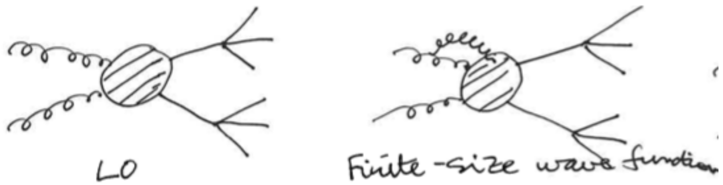


Toponium Production at the LHC

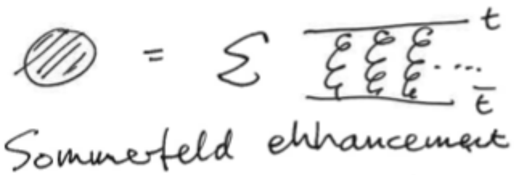
More complicated than Higgs production:



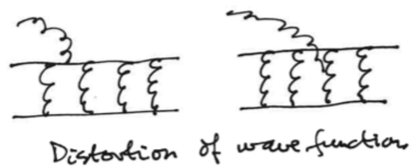
"Small" top loop replaced by "blob" of size $\sim 1/(M_t \alpha_s)$



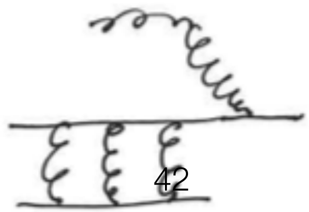
Sommerfeld enhancement of cross section close to $t\bar{t}$ threshold



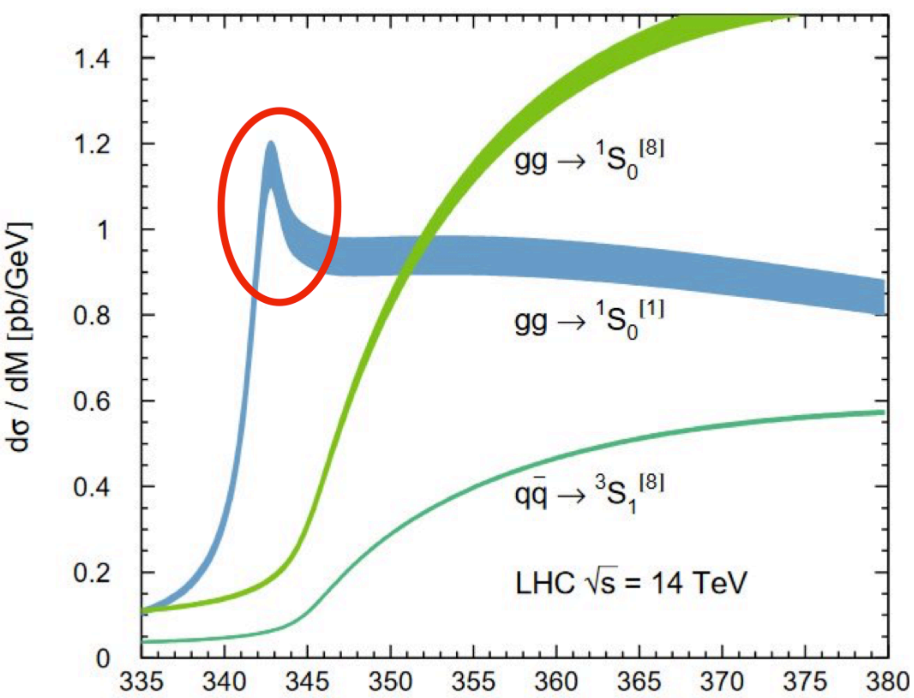
Distorted by gluon interactions

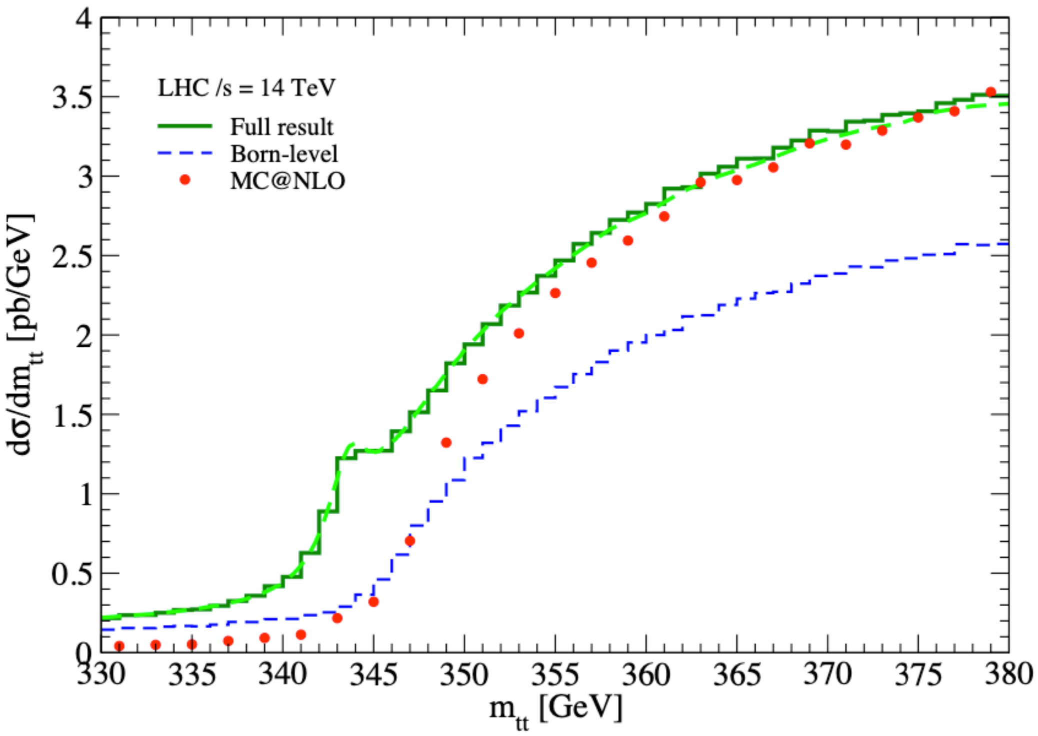


$t\bar{t}$ off-shell, unstable, gluon interactions



$t\bar{t}$ Sommerfeld Enhancement

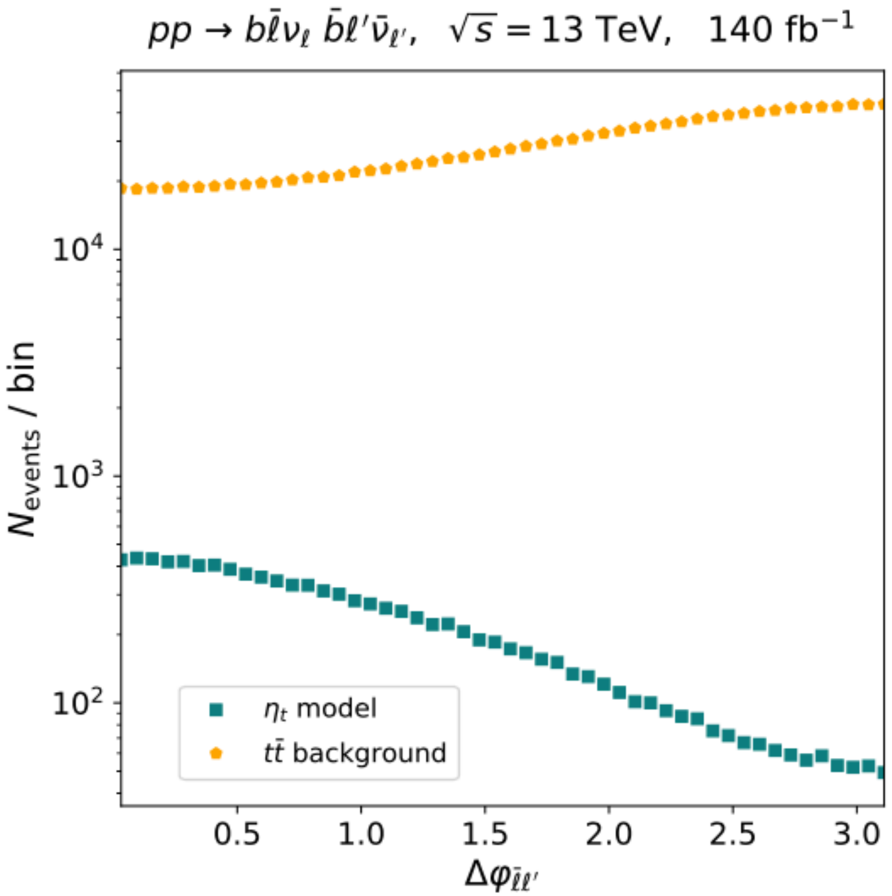




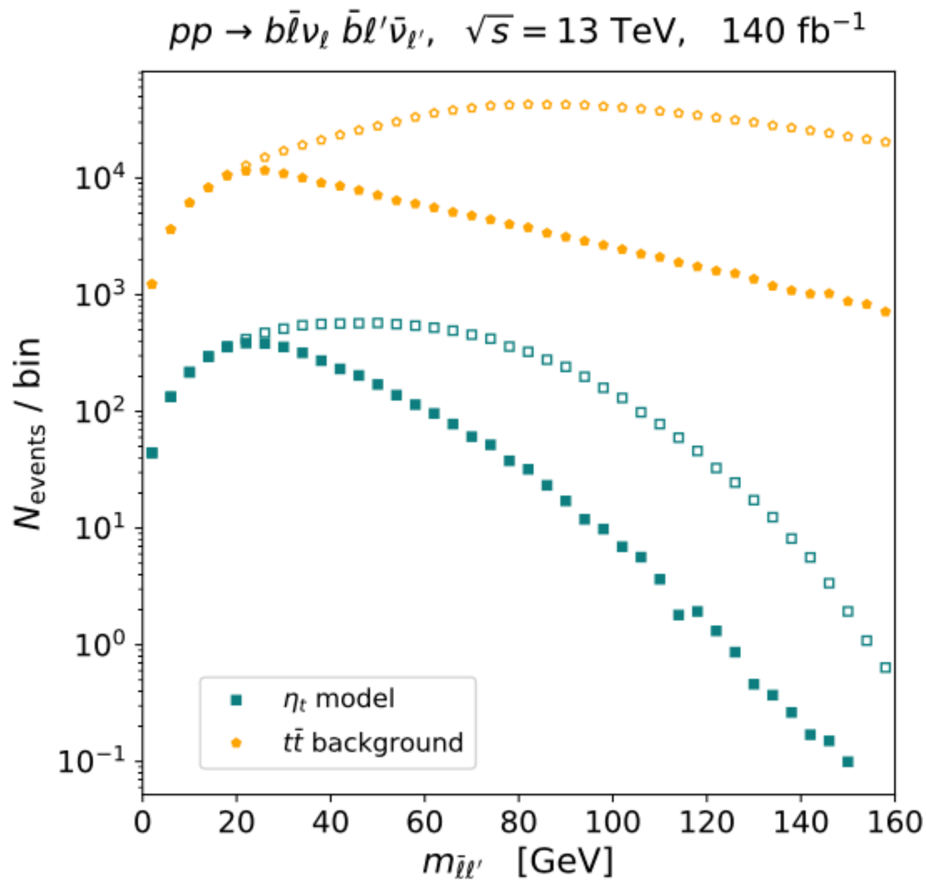
Sumino & Yokoya, arXiv:1007.0075

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

$t\bar{t}$ Threshold Kinematics



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

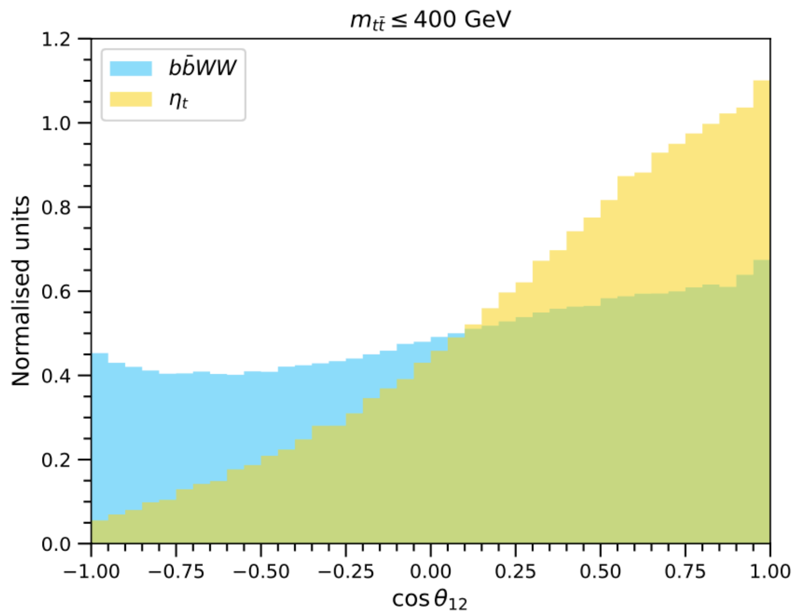


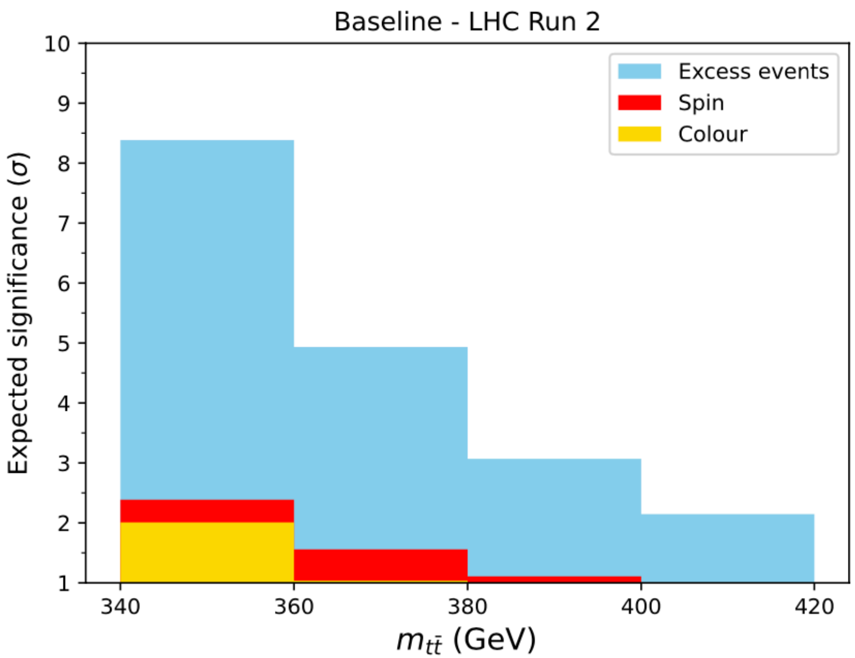
$m_{\bar{\ell}\ell'}$ with(out) azimuthal angle cut

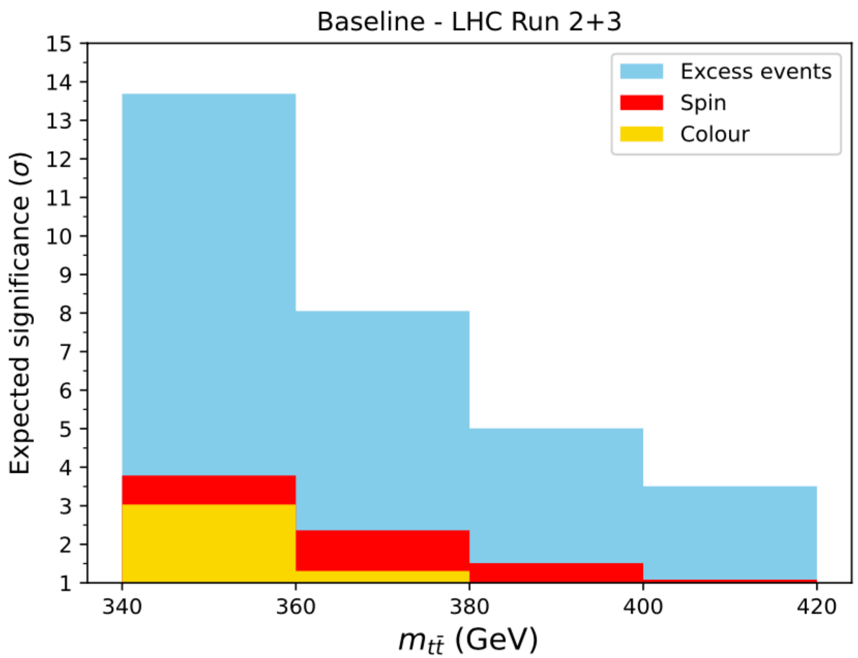
Fuks, Hagiwara, Ma & Zheng, arXiv:2102.11281

Theoretical Study of Toponium Search

- Using electron angular measurements: $\theta_{1,2}, \phi_{1,2}$
- Relative angle: θ_{12}
- Jet substructure
- Calculate statistical significance







Aguilar-Saavedra, arXiv:2407.20330

Search for η_t Signal

- Kinematical quantities:

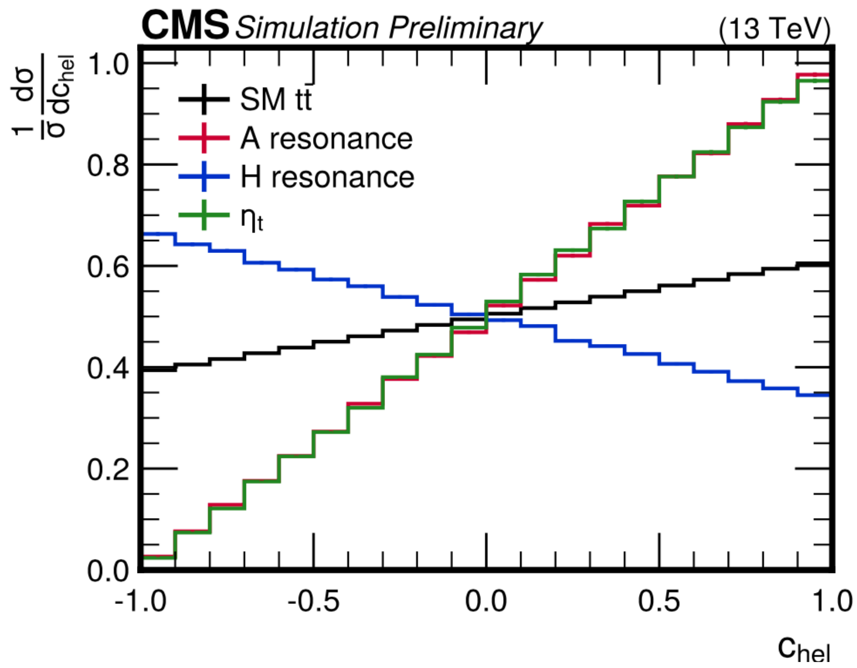
$$c_{\text{hel}} = -(\hat{\ell}^+)_k(\hat{\ell}^-)_k - (\hat{\ell}^+)_r(\hat{\ell}^-)_r - (\hat{\ell}^+)_n(\hat{\ell}^-)_n$$
$$c_{\text{han}} = +(\hat{\ell}^+)_k(\hat{\ell}^-)_k - (\hat{\ell}^+)_r(\hat{\ell}^-)_r - (\hat{\ell}^+)_n(\hat{\ell}^-)_n$$

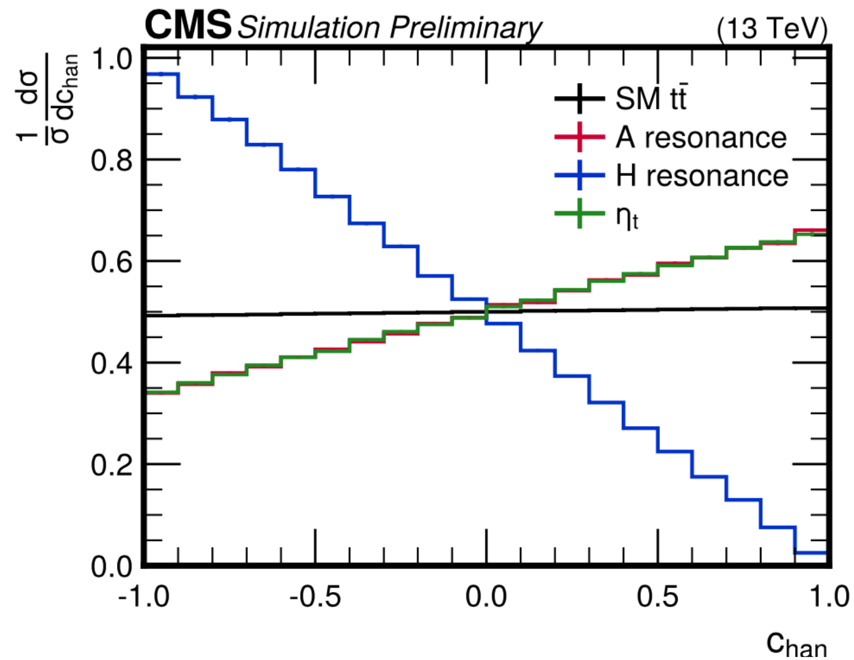
- Distributions

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

- Where

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

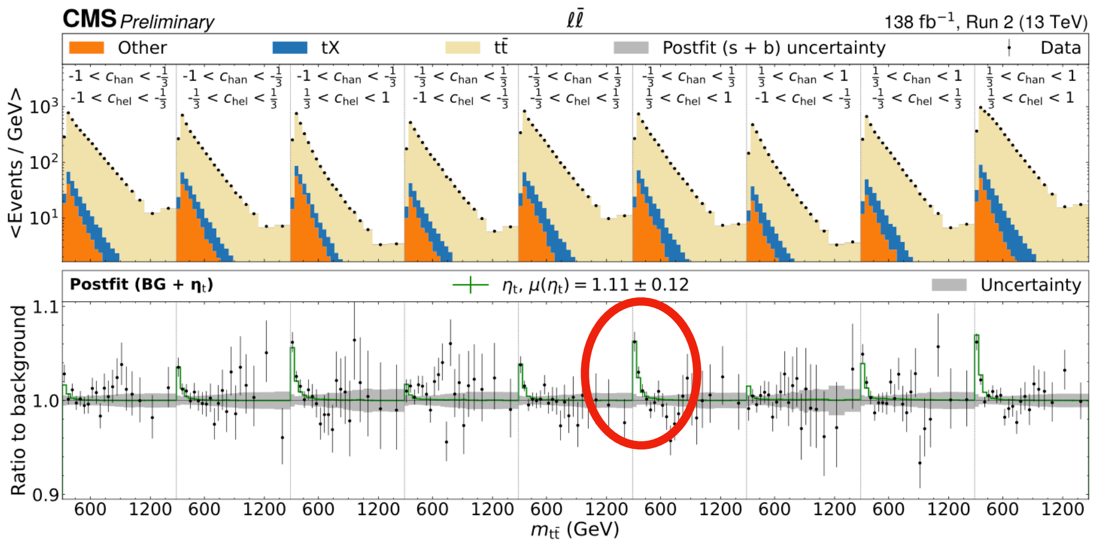


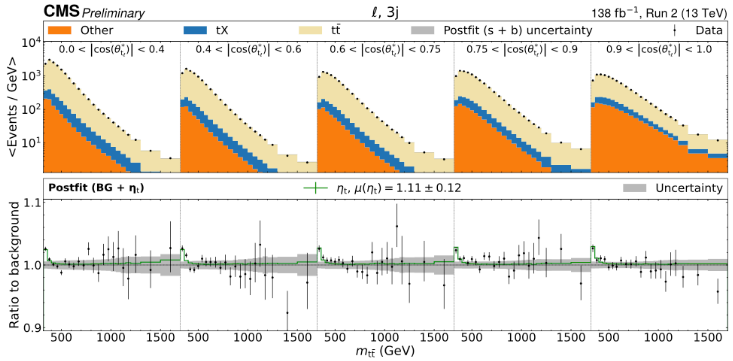


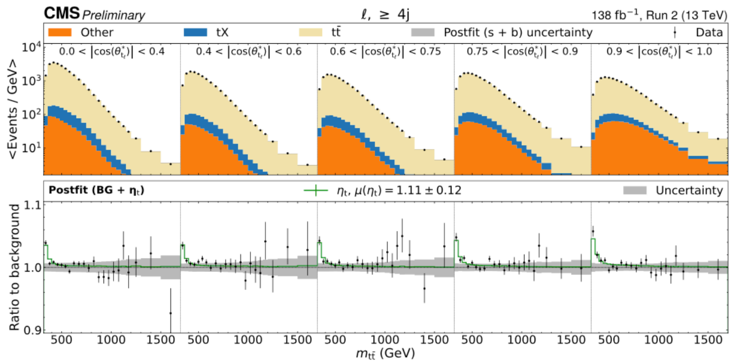
CMS Collaboration, CMS-PAS-HIG-22-013

Observation of η_t Signal?

SM + η_t hypothesis fits data well
Measured cross section $7.1\text{pb} \pm 11\,\%$
Consistent with theoretical calculation 6.43pb(*)
Nominal significance $> 5\sigma$





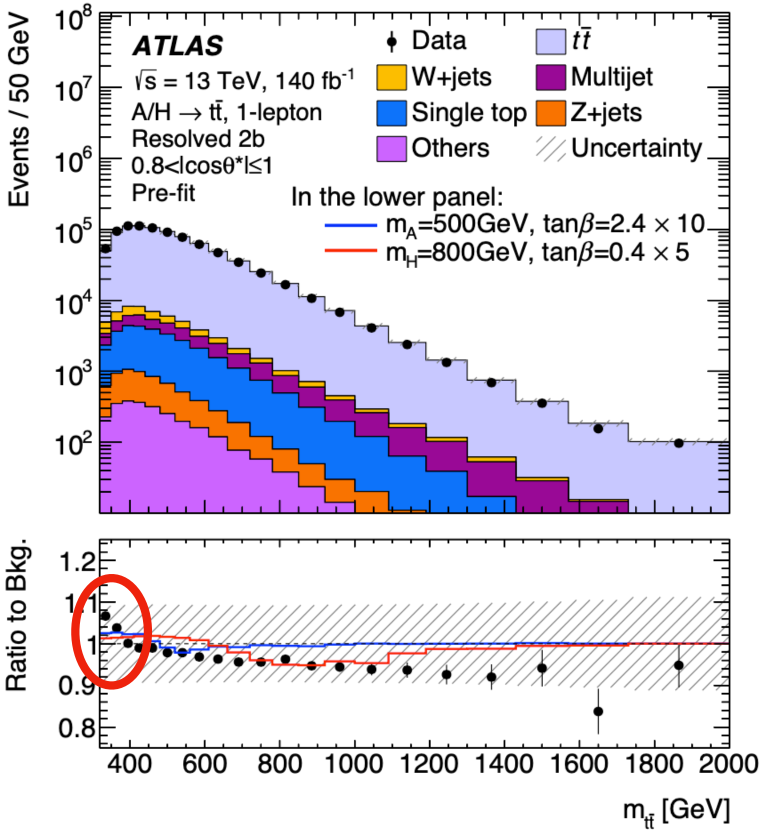


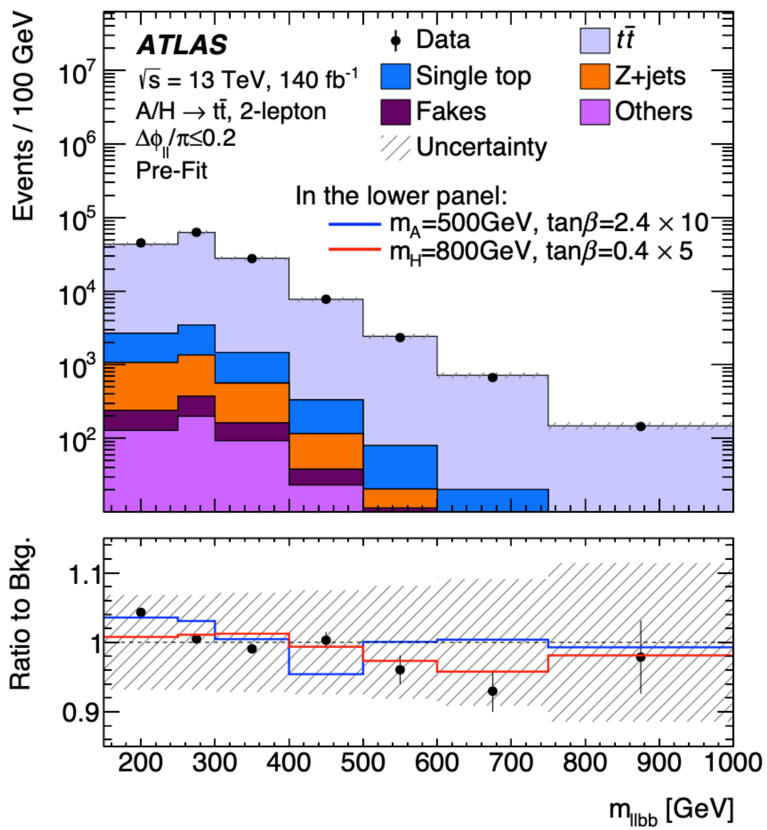
	Best-fit point	Difference in $-2\ln L$
η_t interpretation	$\mu(\eta_t) = 1.11$	-86.2
Single A interpretation	$m_A = 365\,\text{GeV}, \Gamma_A/m_A = 2\%, g_{At\bar{t}} = 0.78$	-72.6
Single H interpretation	$m_H = 365\,\text{GeV}, \Gamma_H/m_H = 2\%, g_{Ht\bar{t}} = 1.45$	-10.4

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

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

Hint of η_t Signal?





ATLAS Collaboration, arXiv:2404.18986