HIGGS EXPERIMENT

A. David (CERN)

CERN-FERMILAB HADRON COLLIDER PHYSICS Summer School


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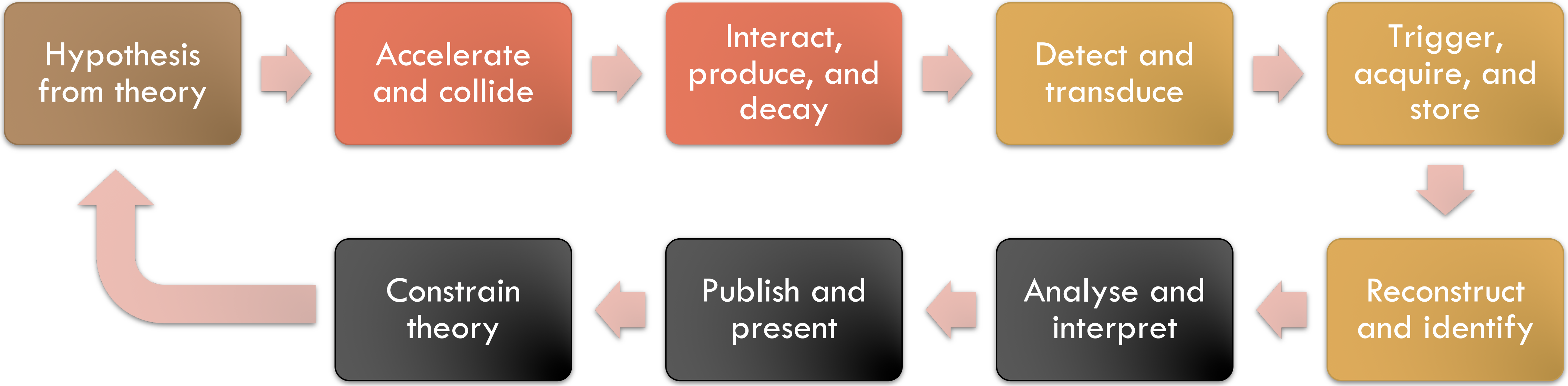
Hypothesis from theory
Accelerate and collide
Interact, produce, and decay
Detect and transduce
Trigger, acquire, and store
Reconstruct and identify
Analyse and interpret
Publish and present
Constrain theory

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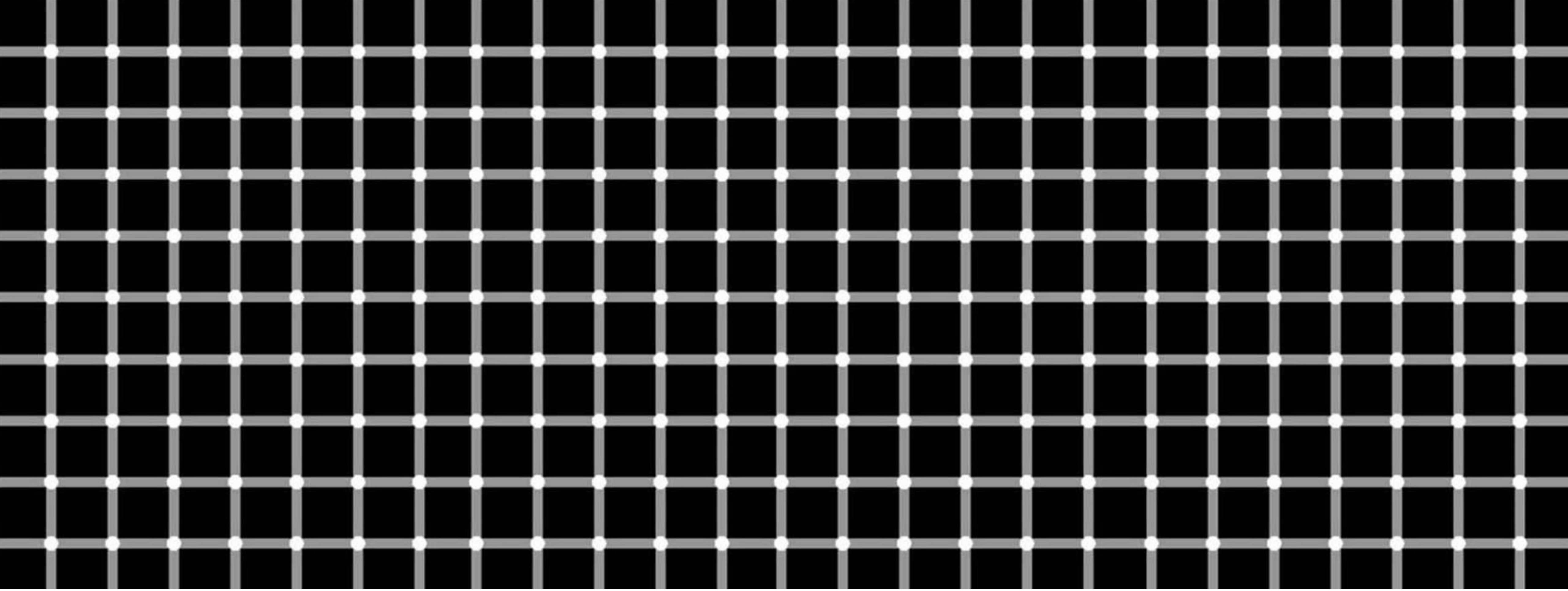

ELEMENTARY SCALAR EXPERIMENT

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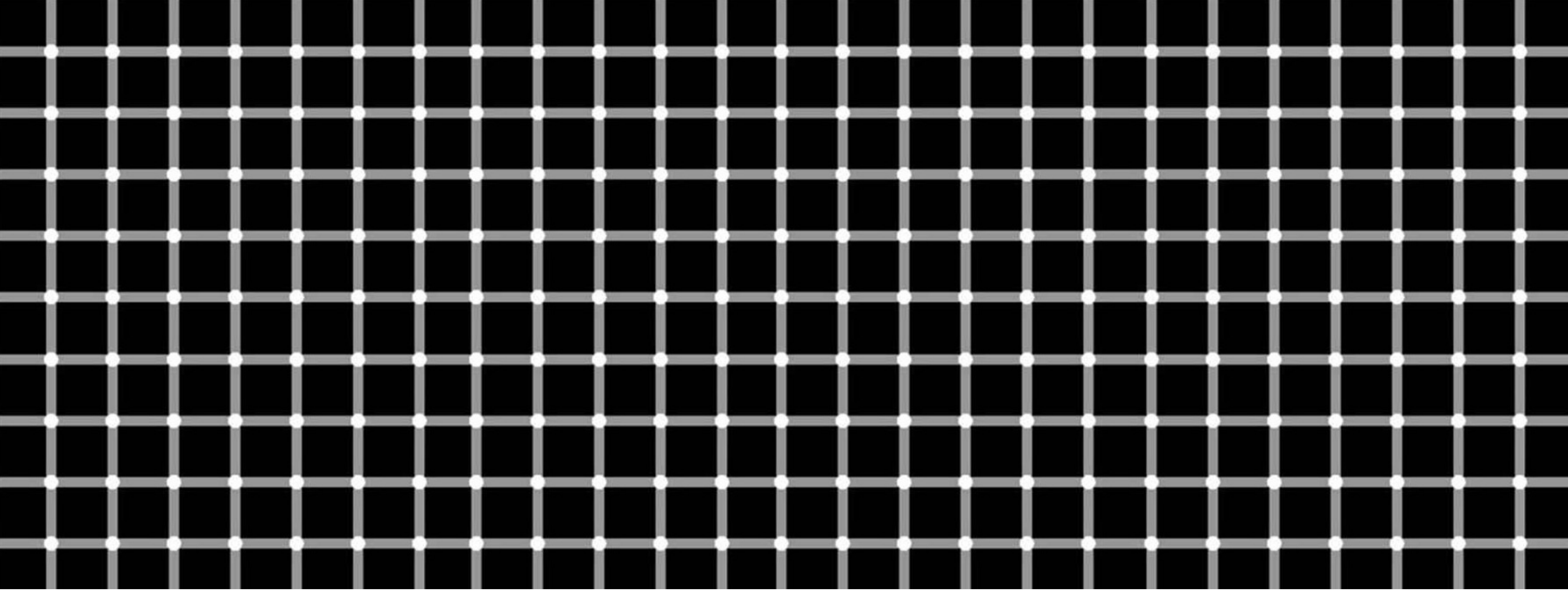

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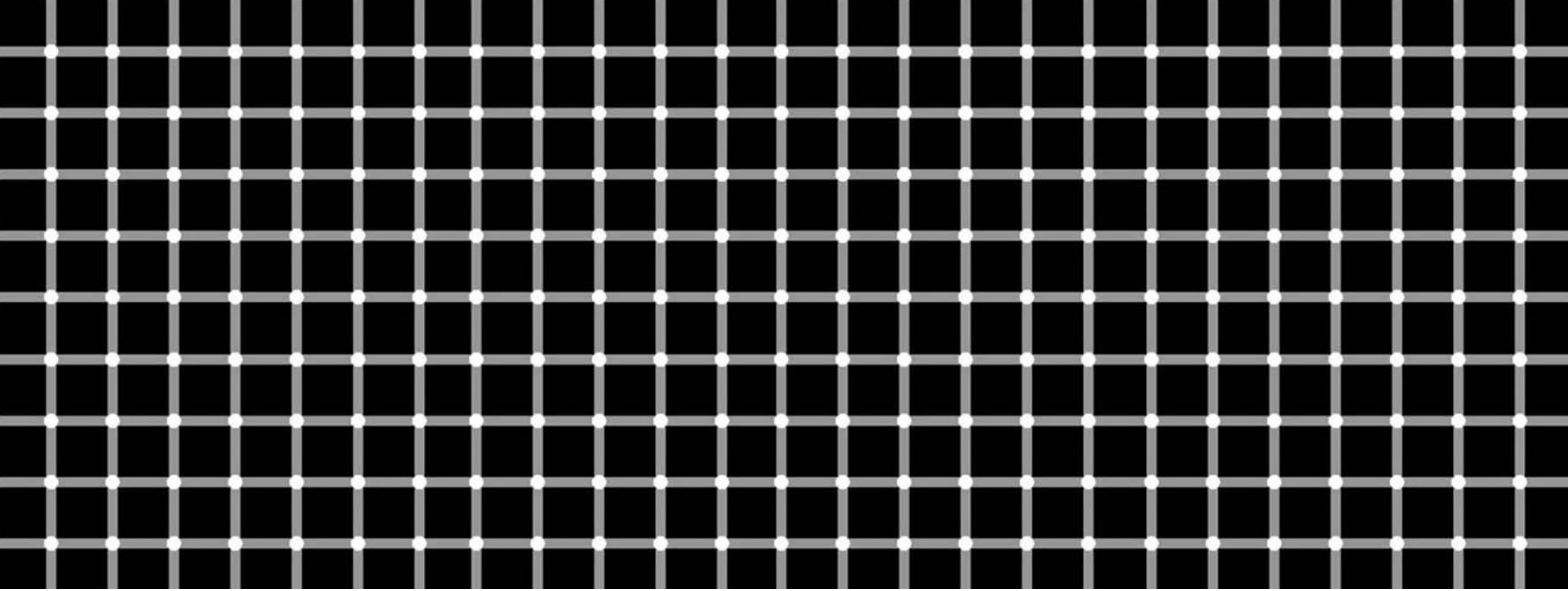
ELEMENTARY SCALAR EXPERIMENTAL SITUATION

A. David (CERN)

The choice of topics, results, and any mistakes are solely my doing.



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ES^2

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ES^2 – THE PANORAMA

Precision

- Mass
- Spin-parity
- Cross-sections

Discovery

- Couplings to fermions
- Rare decays

Known unknowns

- Self-coupling
- Off-shell production

Unknown unknowns

- BSM decays
- Anomalous couplings
- Portals

Other scalars

- Neutral
- Charged
- Heavy
- Light

TODAY AND TOMORROW

Episode VII – The Force Awakens

The scalar solution.

The scalar discovery.

Com{plex,bined} measurements.

Present of this many-faced scalar.

Coming up at the horizon.

Episode VIII – The Last Jedi

Constraining other scalars.

Sharpening the exploration tools.

Going differential.

Seeing self-double.

Going beyond the horizon.

EPISODE VII – THE FORCE AWAKENS

The scalar solution.
The scalar discovery.
Com{plex,bined} measurements.
Present of this many-faced scalar.
Coming up at the horizon.

A MASSIVE PROBLEM, A "SPHERICAL" SOLUTION

W and Z bosons not light, unlike the photon.

- **Mass mechanism** – the mexican hat field, first published by Brout and Englert (1964).
- **Higgs boson** – the field's massive radial excitation, tacit to Brout and Englert, massless via approximations in Guralnik et al., and explicitly mentioned by Higgs (1964).
- **Viability** – photons and massive weak bosons can coexist, shown by Kibble (1967).

An inspired extra.

- **Fermions** – quark & lepton masses via Yukawa interactions, by Weinberg (1967).

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu -$$

$$\partial_\nu W^+_\mu\partial_\nu W^-_\mu - M^2W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \frac{1}{2}\partial_\mu H\partial_\mu H - \frac{1}{2}m_h^2H^2 - \partial_\mu\phi^+\partial_\mu\phi^- -$$

$$M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) -$$

$$A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2W^+_\mu W^-_\nu W^+_\mu W^-_\nu +$$

$$g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2s_wc_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- +$$

$$4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] +$$

$$\frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- -$$

$$W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) -$$

$$\frac{1}{4}g^2W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$

$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) -$$

$$g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - g^1s_w^2A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j +$$

$$igs_wA_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 -$$

$$1-\gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1-\frac{8}{3}s_w^2-\gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+$$

$$\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) +$$

$$i\phi^0(\bar{e}^\lambda\gamma^5e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_jC_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_jC_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) -$$

$$m_u^\kappa(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_ju^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_jd^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5d^\lambda_j) + \bar{X}^+(\partial^2 -$$

$$M^2)X^+ + \bar{X}^-(\partial^2-M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- -$$

$$\partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) +$$

$$igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) - \frac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c_w^2}\bar{X}^0X^0H] + \frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ -$$

$$\bar{X}^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$

STANDARD MODEL OF PARTICLE PHYSICS

$$-\frac{1}{2}\partial_\nu g^a_\mu\partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar{q}_i^\sigma\gamma^\mu q_j^\sigma)g^a_\mu + \bar{G}^a\partial^2G^a + g_s f^{abc}\partial_\mu\bar{G}^aG^bg^c_\mu -$$

$$\partial_\nu W^+_\mu\partial_\nu W^-_\mu - M^2W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \frac{1}{2}\partial_\mu H\partial_\mu H - \frac{1}{2}m_h^2H^2 - \partial_\mu\phi^+\partial_\mu\phi^- -$$

$$M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h\left[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)\right] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) -$$

$$A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2W^+_\mu W^-_\nu W^+_\mu W^-_\nu +$$

$$g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2s_wc_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- +$$

$$4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] +$$

$$\frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- -$$

$$W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) -$$

$$\frac{1}{4}g^2W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$

$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) -$$

$$g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - g^1s_w^2A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}_j^\lambda(\gamma\partial + m_u^\lambda)u_j^\lambda - \bar{d}_j^\lambda(\gamma\partial + m_d^\lambda)d_j^\lambda +$$

$$igs_wA_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda\gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda\gamma^\mu d_j^\lambda)] + \frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar{u}_j^\lambda\gamma^\mu(\frac{4}{3}s_w^2 -$$

$$1-\gamma^5)u_j^\lambda) + (\bar{d}_j^\lambda\gamma^\mu(1-\frac{8}{3}s_w^2-\gamma^5)d_j^\lambda)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}_j^\lambda\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d_j^\kappa)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+$$

$$\gamma^5)\nu^\lambda) + (\bar{d}_j^\kappa C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u_j^\lambda)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) +$$

$$i\phi^0(\bar{e}^\lambda\gamma^5e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}_j^\lambda C_{\lambda\kappa}(1-\gamma^5)d_j^\kappa) + m_u^\lambda(\bar{u}_j^\lambda C_{\lambda\kappa}(1+\gamma^5)d_j^\kappa] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}_j^\lambda C^\dagger_{\lambda\kappa}(1+\gamma^5)u_j^\kappa) -$$

$$m_u^\kappa(\bar{d}_j^\lambda C^\dagger_{\lambda\kappa}(1-\gamma^5)u_j^\kappa] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}_j^\lambda\gamma^5u_j^\lambda) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}_j^\lambda\gamma^5d_j^\lambda) + \bar{X}^+(\partial^2 -$$

$$M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- -$$

$$\partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) +$$

$$igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) - \frac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c_w^2}\bar{X}^0X^0H] + \frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ -$$

$$\bar{X}^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$

STANDARD MODEL OF PARTICLE PHYSICS

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu -$$

$$\partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- -$$

$$M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h\left[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)\right] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) -$$

$$A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu +$$

$$g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- +$$

$$4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] +$$

$$\frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- -$$

$$W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) -$$

$$\frac{1}{4}g^2W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$

$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) -$$

$$g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - g^1s_w^2A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j +$$

$$igs_wA_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 -$$

$$1-\gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1-\frac{8}{3}s_w^2-\gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+$$

$$\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_jC^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) +$$

$$i\phi^0(\bar{e}^\lambda\gamma^5e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_jC_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_jC_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) -$$

$$m_u^\kappa(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_ju^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_jd^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5d^\lambda_j) + \bar{X}^+(\partial^2 -$$

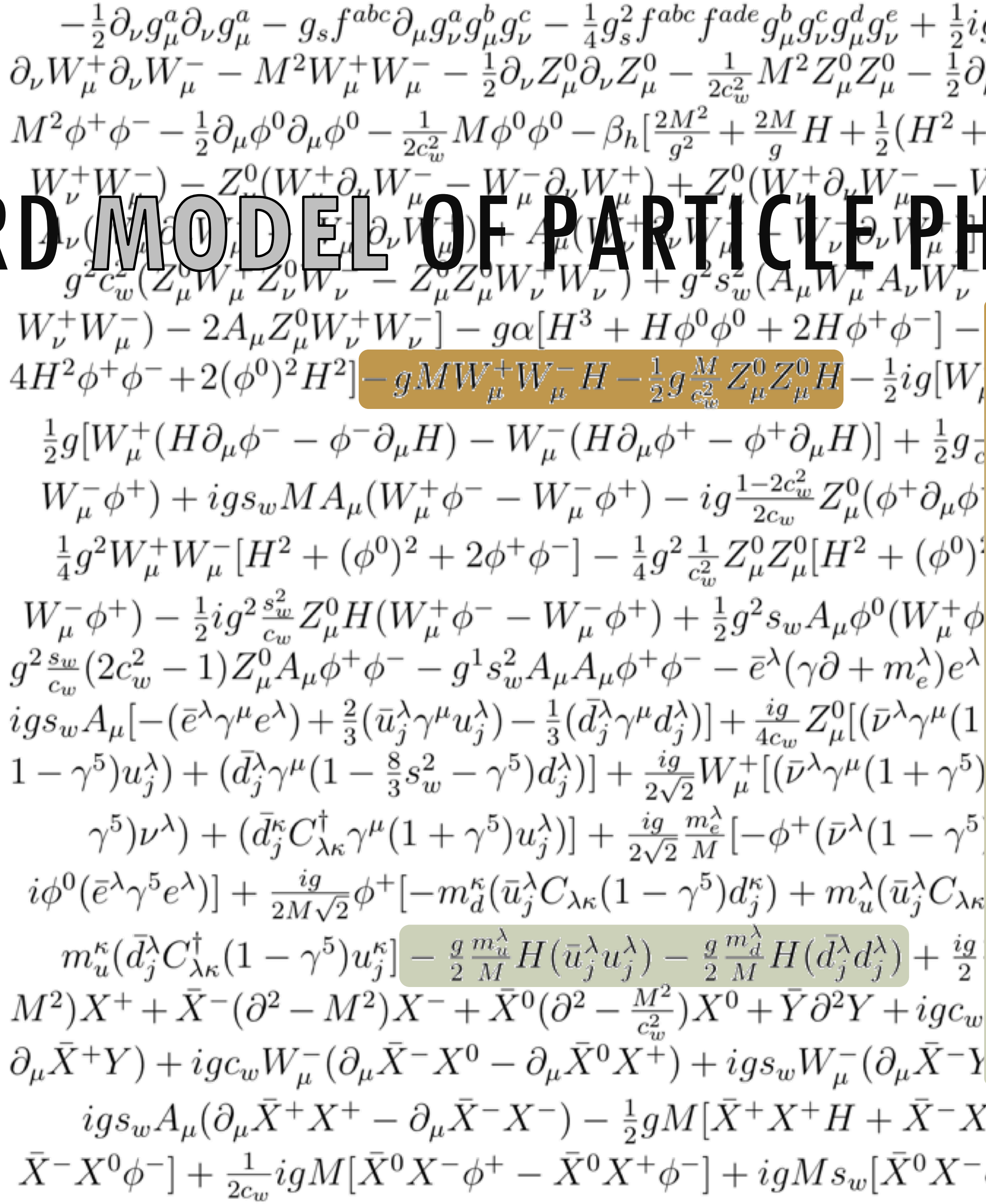
$$M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- -$$

$$\partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) +$$

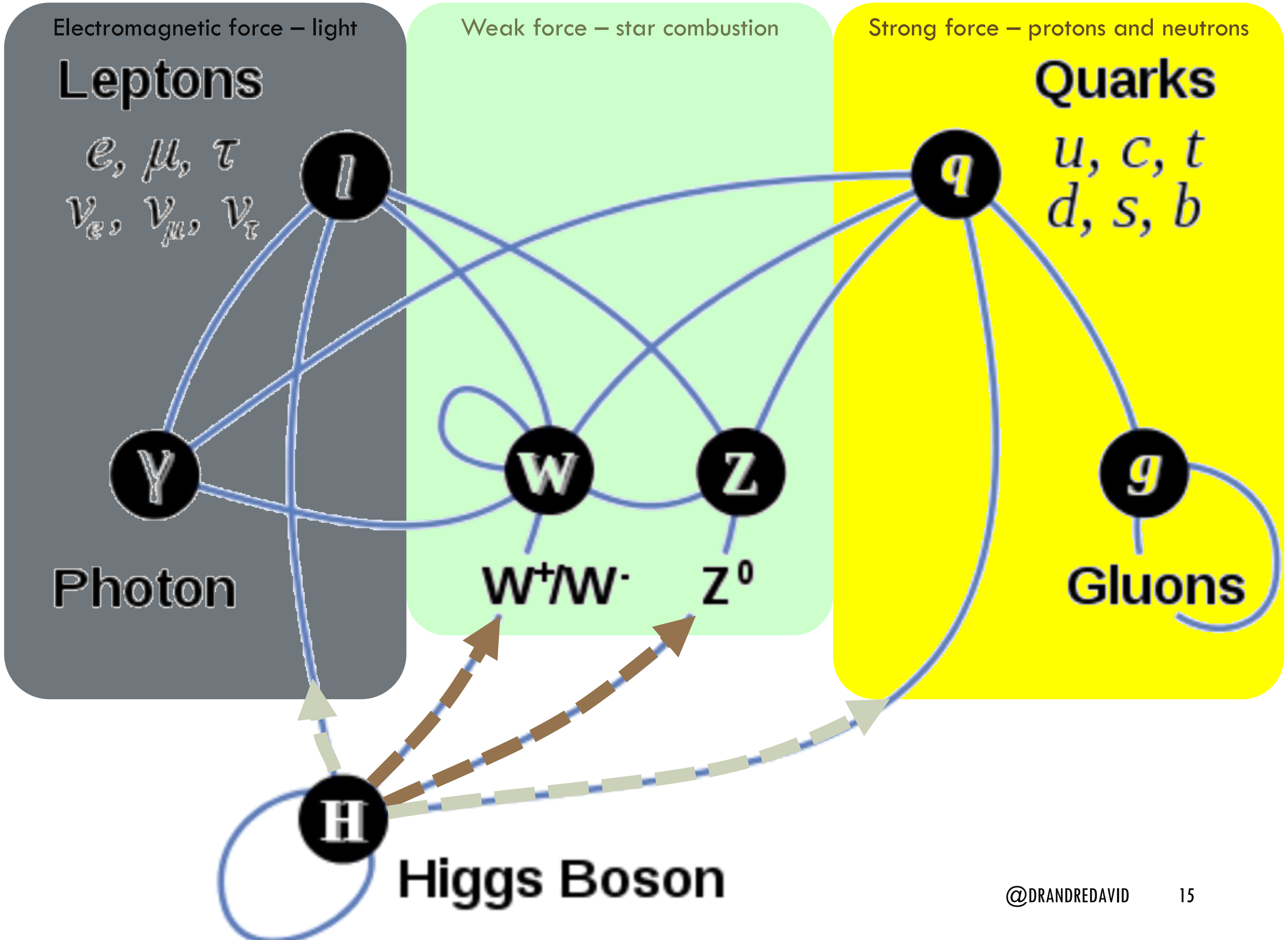
$$igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) - \frac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c_w^2}\bar{X}^0X^0H] + \frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ -$$

$$\bar{X}^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$

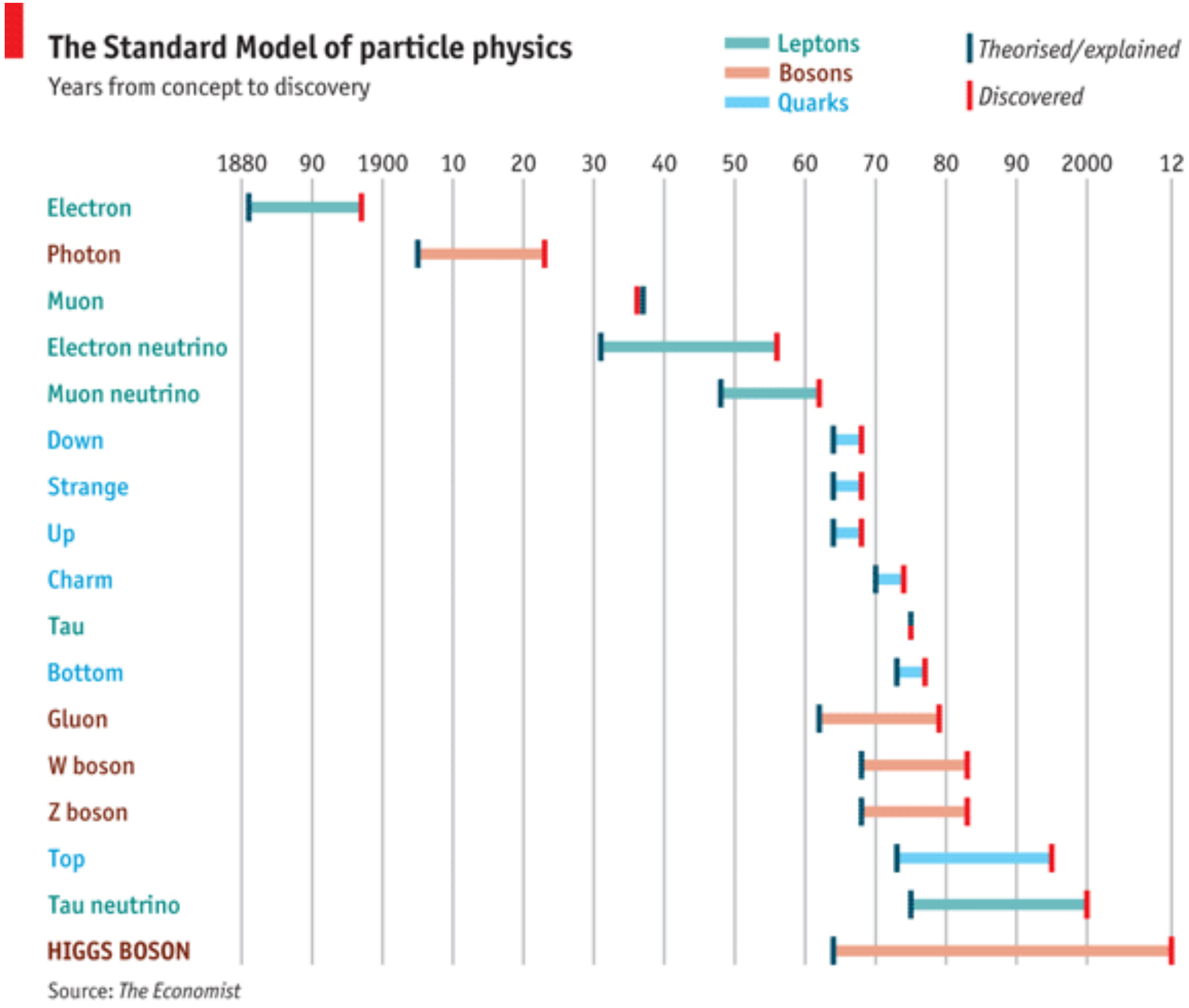
STANDARD MODEL OF PARTICLE PHYSICS



CLEAR PREDICTIONS

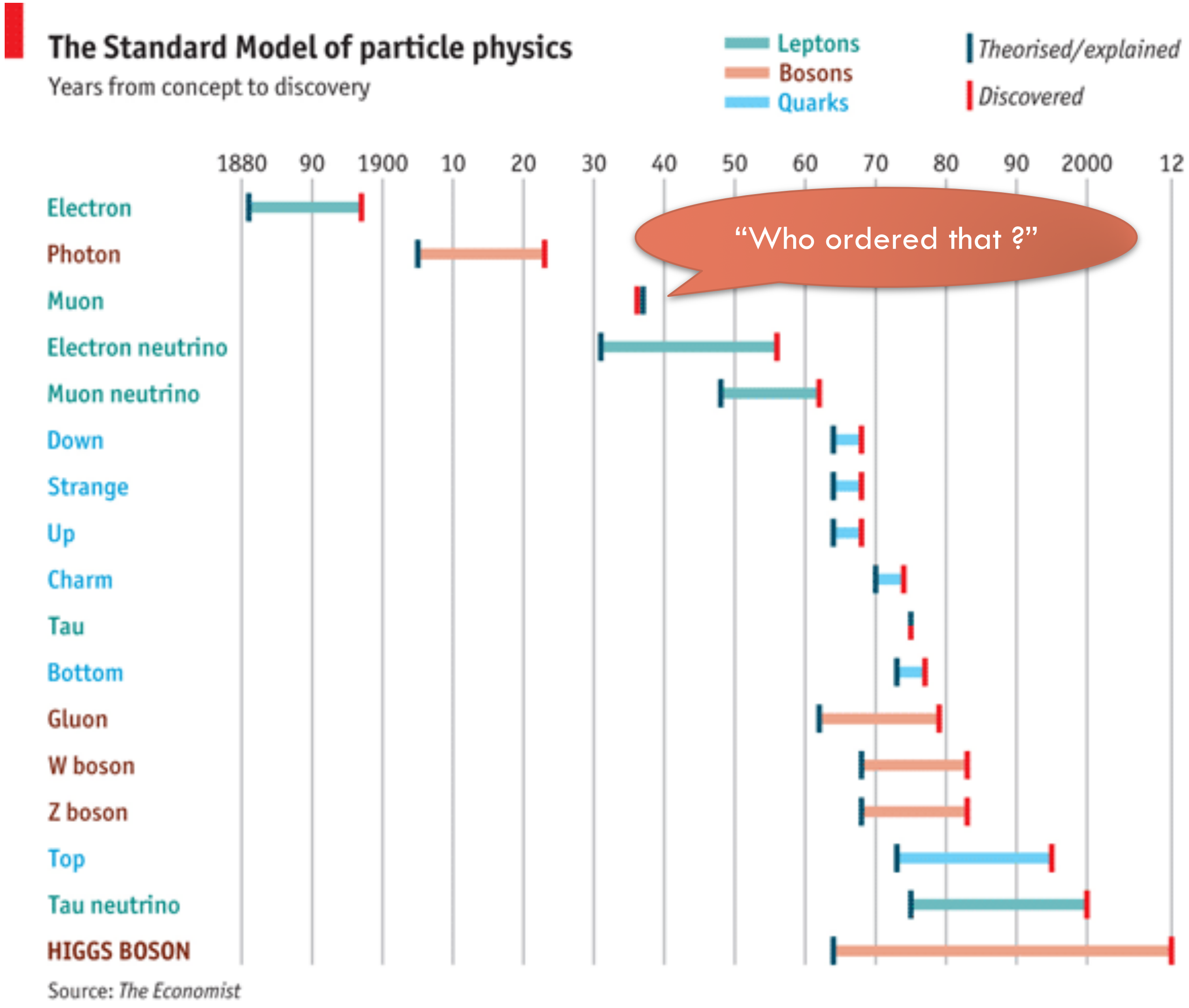


A LONG WAY



The Standard Model of particle physics
Years from concept to discovery
Leptons
Bosons
Quarks
Theorised/explained
Discovered
1880
90
1900
10
20
30
40
50
60
70
80
90
2000
12
Electron
Photon
Muon
Electron neutrino
Muon neutrino
Down
Strange
Up
Charm
Tau
Bottom
Gluon
W boson
Z boson
Top
Tau neutrino
HIGGS BOSON
Source: The Economist

A LONG WAY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Z boson
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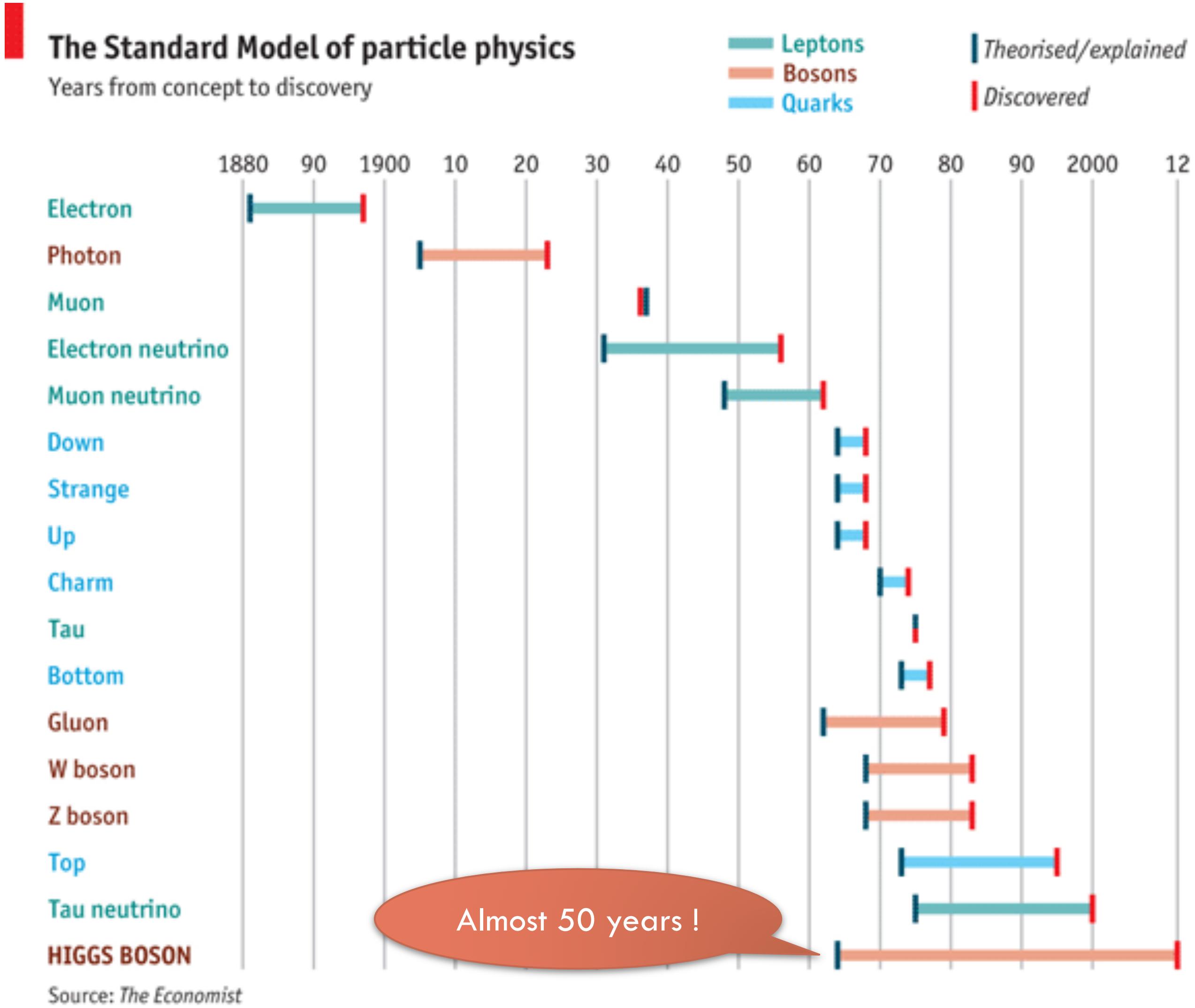
Source: The Economist
“Who ordered that ?”

A LONG WAY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W boson
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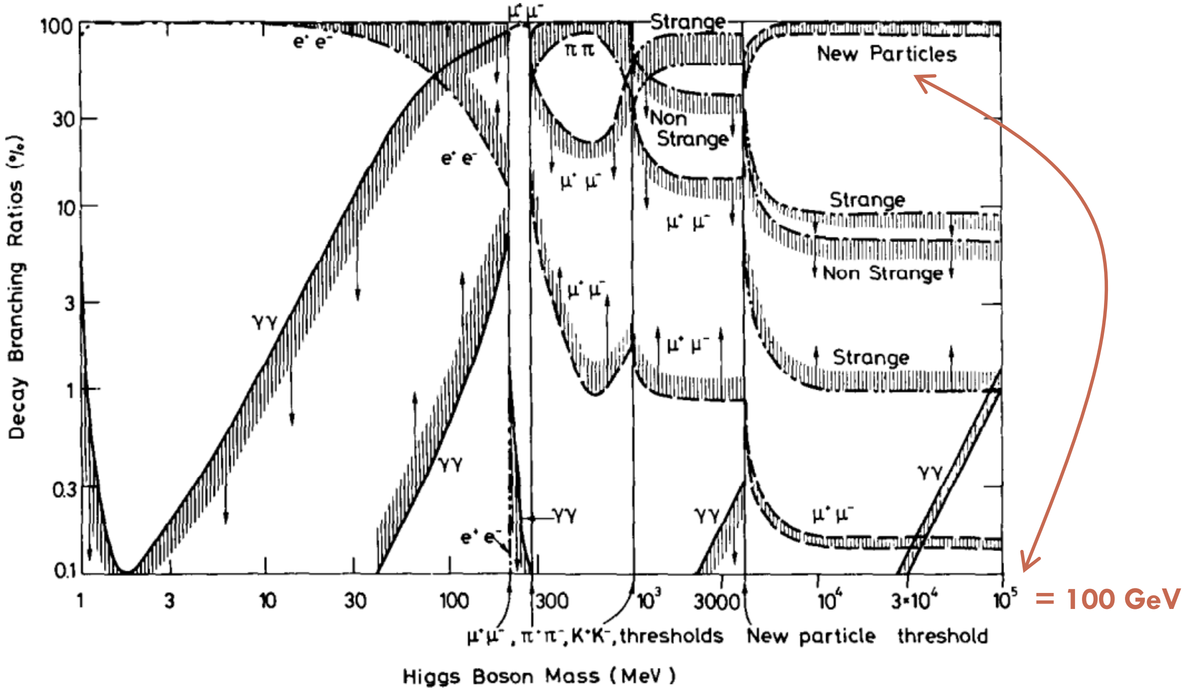
HIGGS BOSON
Almost 50 years !
Source: The Economist

"MASSA INCOGNITA"



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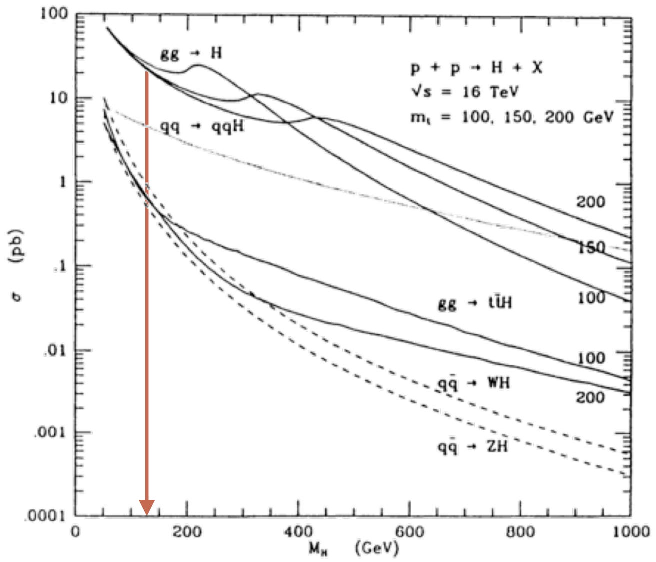
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

10.5170/CERN-1990-010-V-2 arXiv:1610.07922

A LEARNING PROCESS



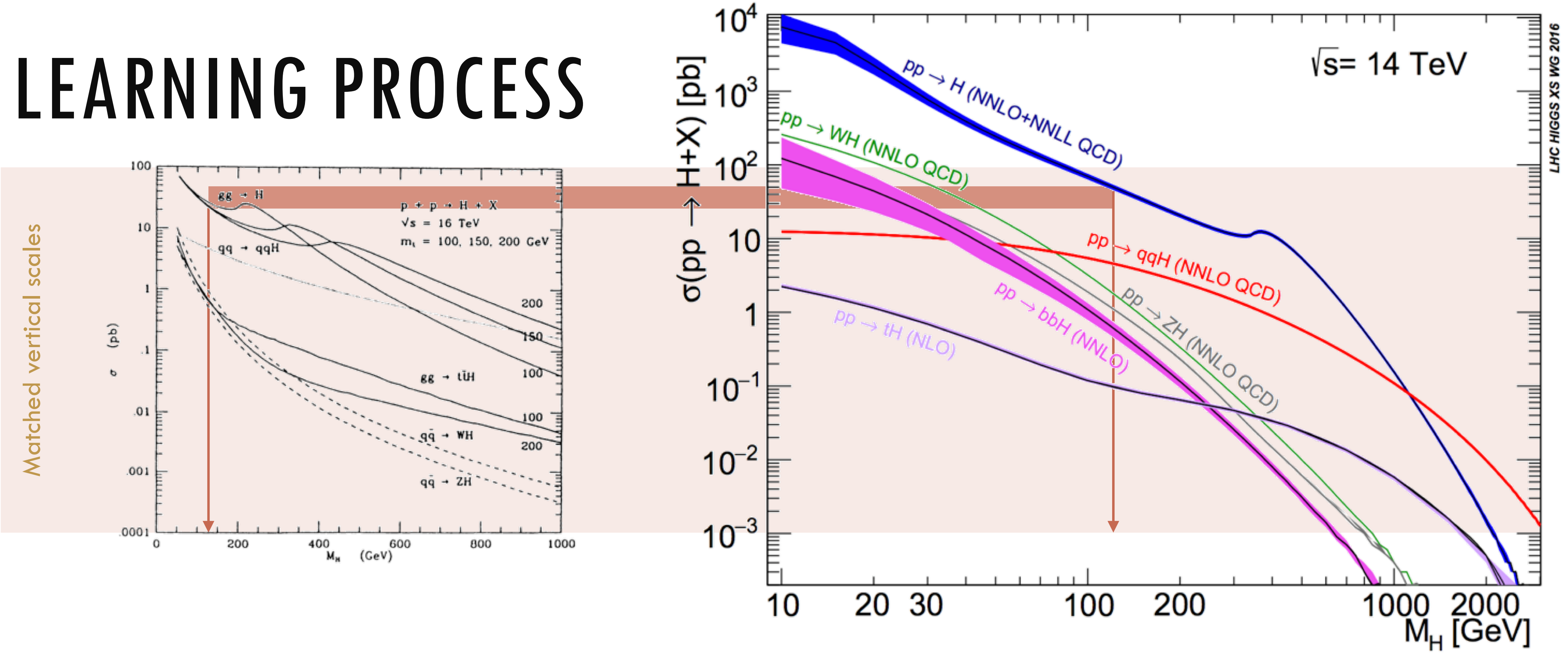
1990

m_{top} unknown

σ_{ggH} ~ **25 pb**

10.5170/CERN-1990-010-V-2 arXiv:1610.07922

A LEARNING PROCESS



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$m_{top} = 172.5 \pm 1.0$ GeV

σ_{ggH} (N^3LO+N^3LL) ~ **50 pb**

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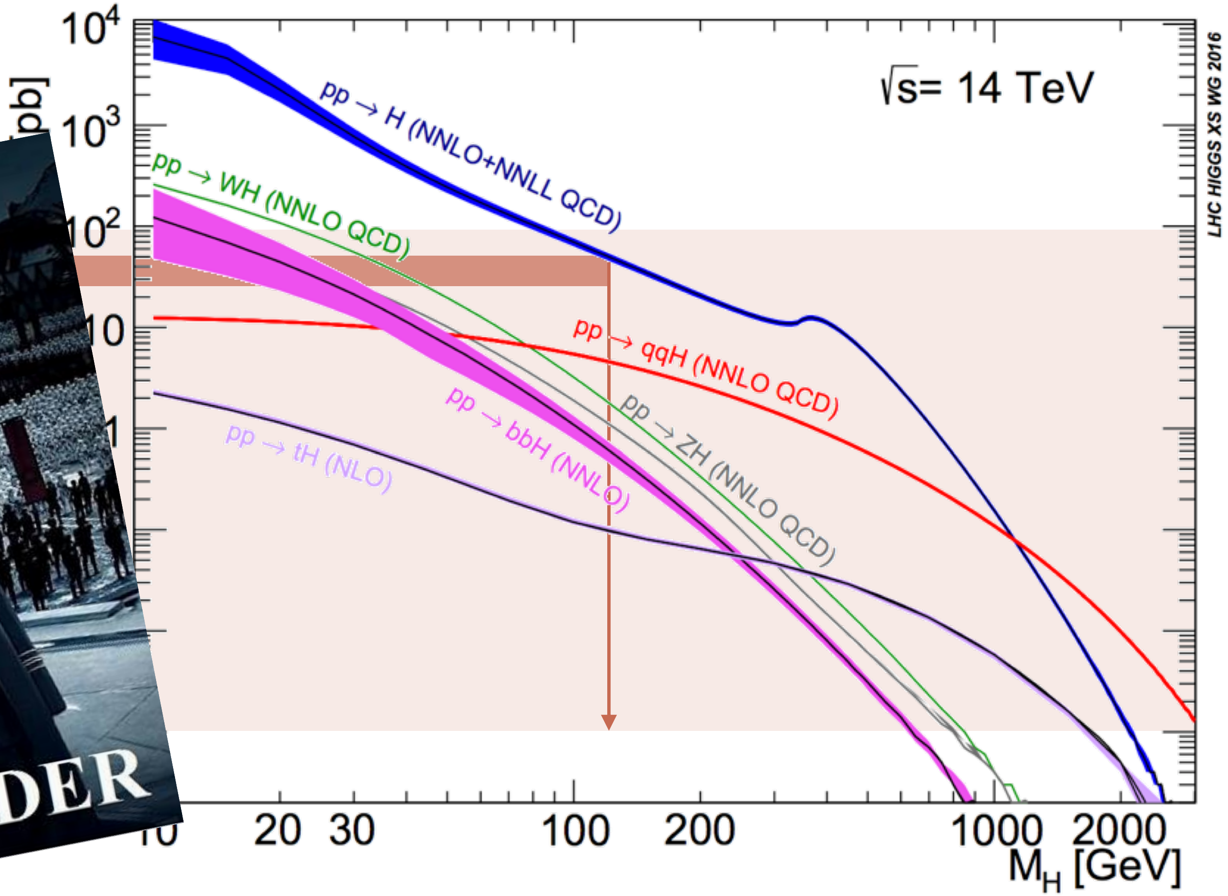

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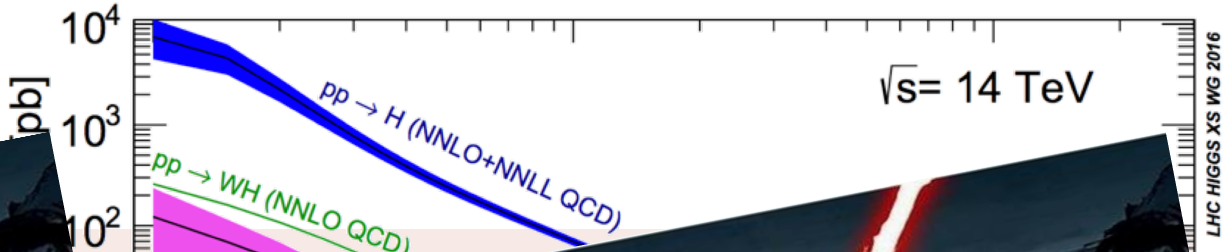

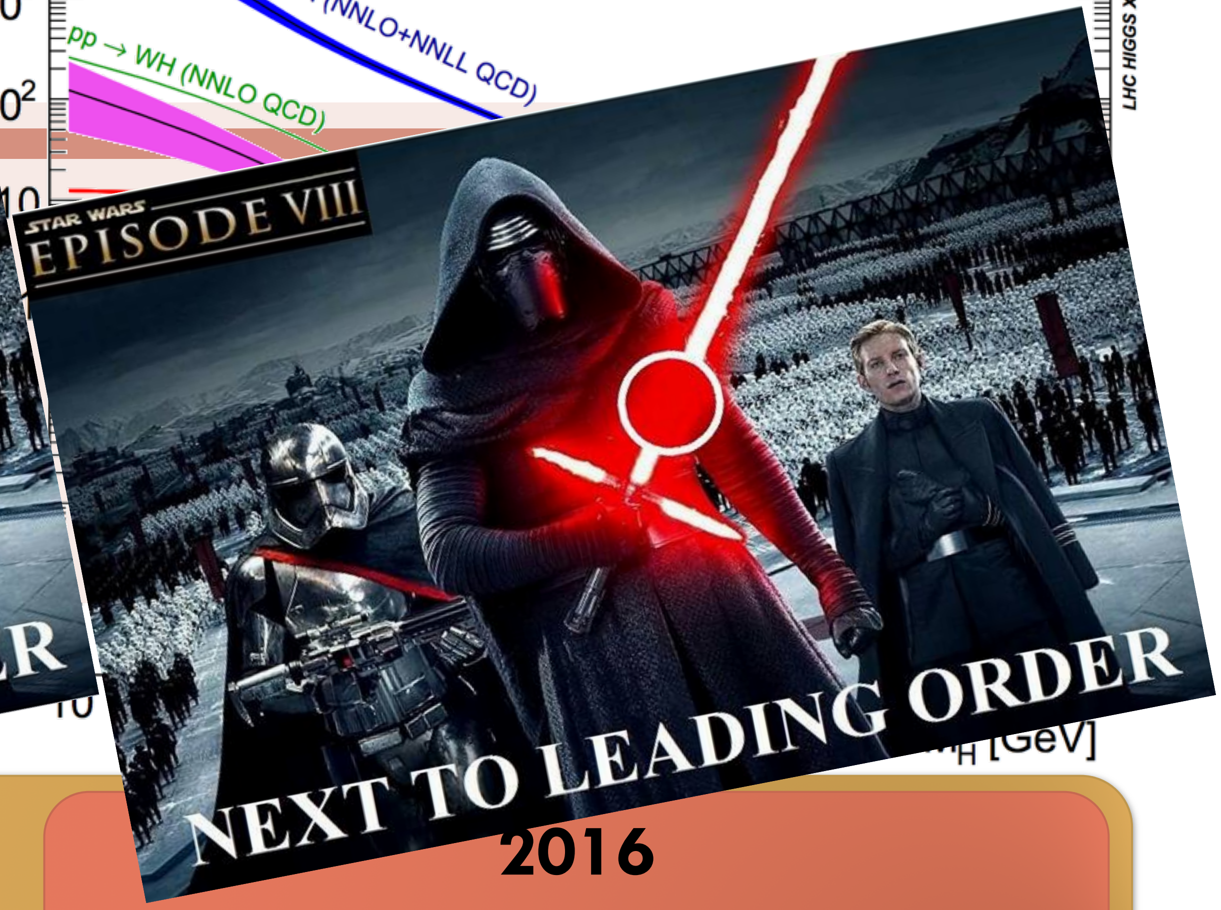

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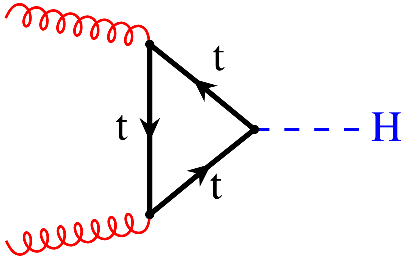
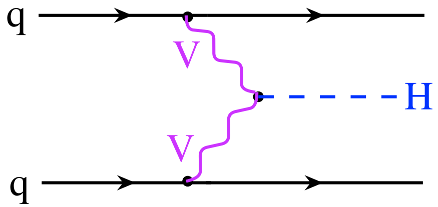
HOW SM HIGGSES ARE BORN

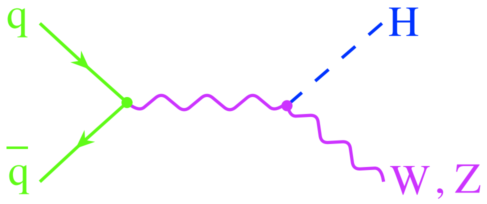
Gluon fusion



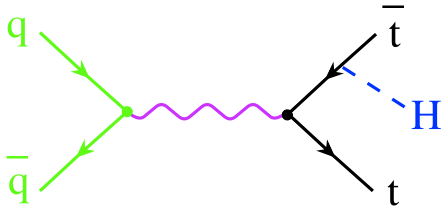
VBF

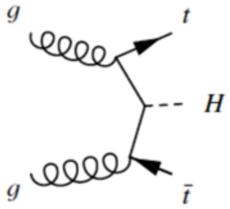


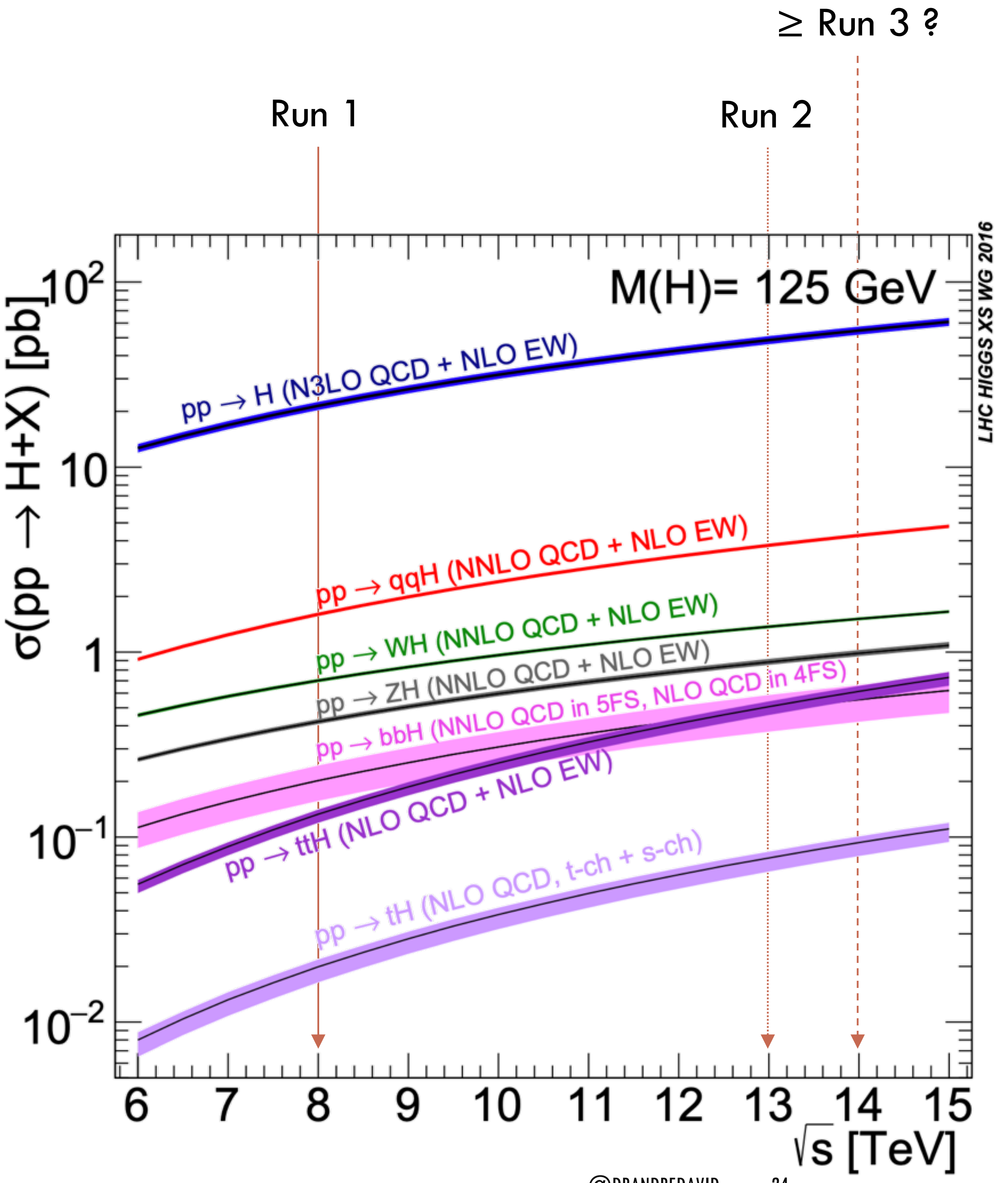
WH, ZH



bbH, ttH

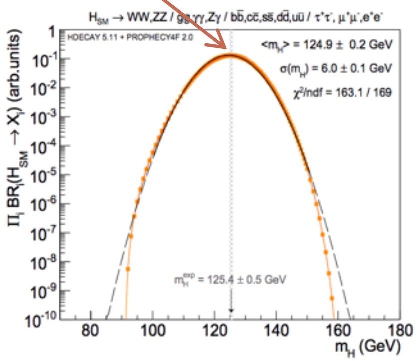






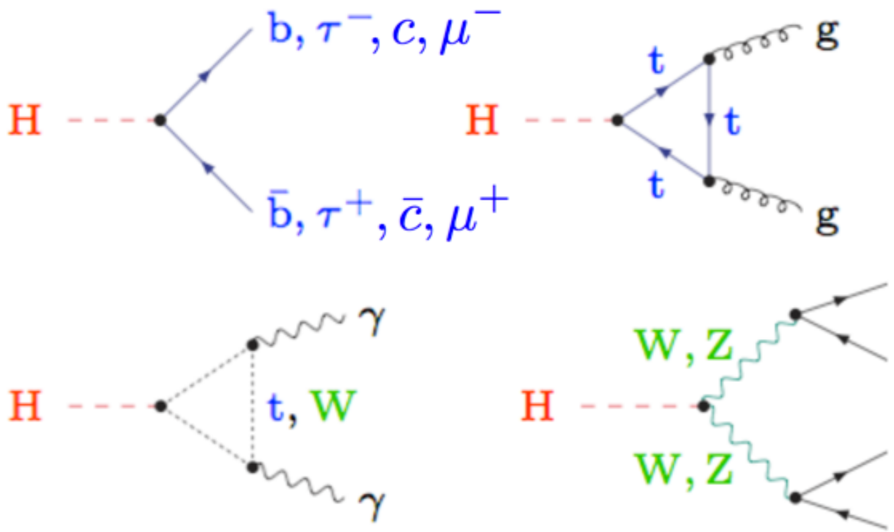
HOW SM HIGGSES DIE

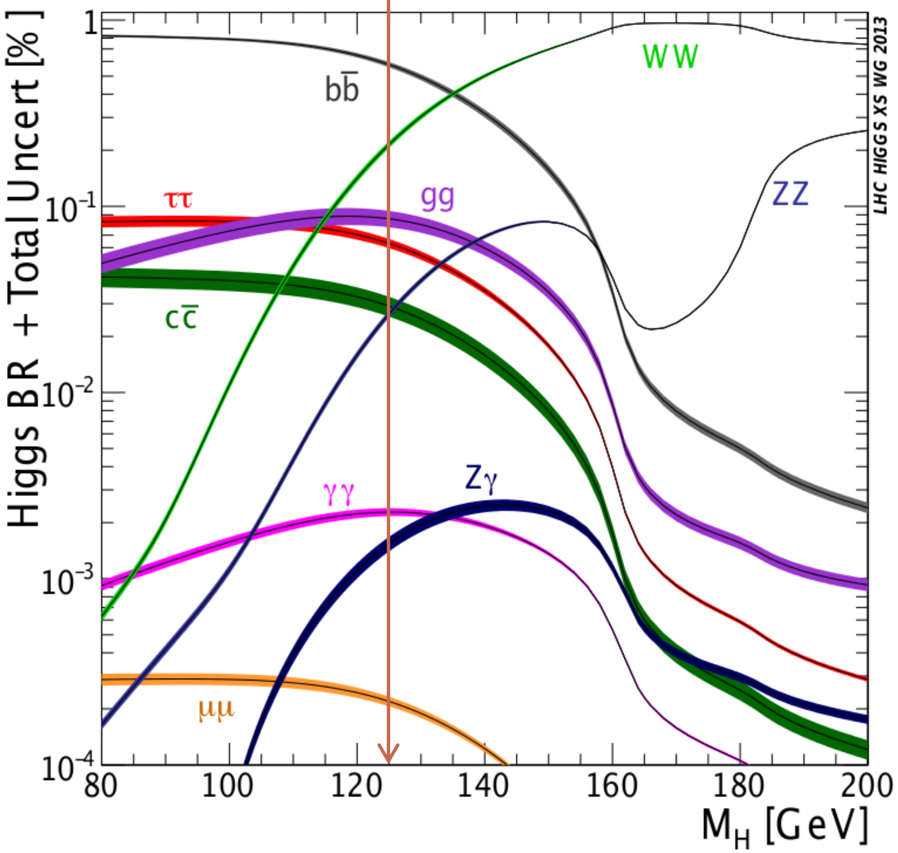
Near to maximal $\Pi\ BR_i$ ⟶



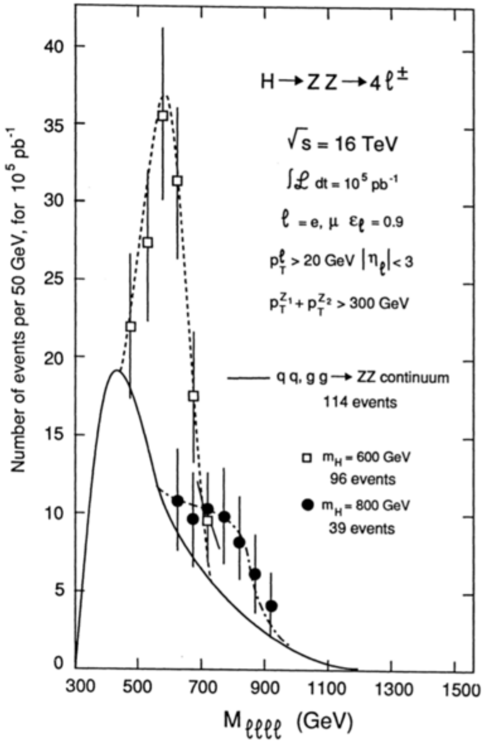
Couplings and kinematics drive BR ($b\bar{b}$, WW, ττ, ZZ).

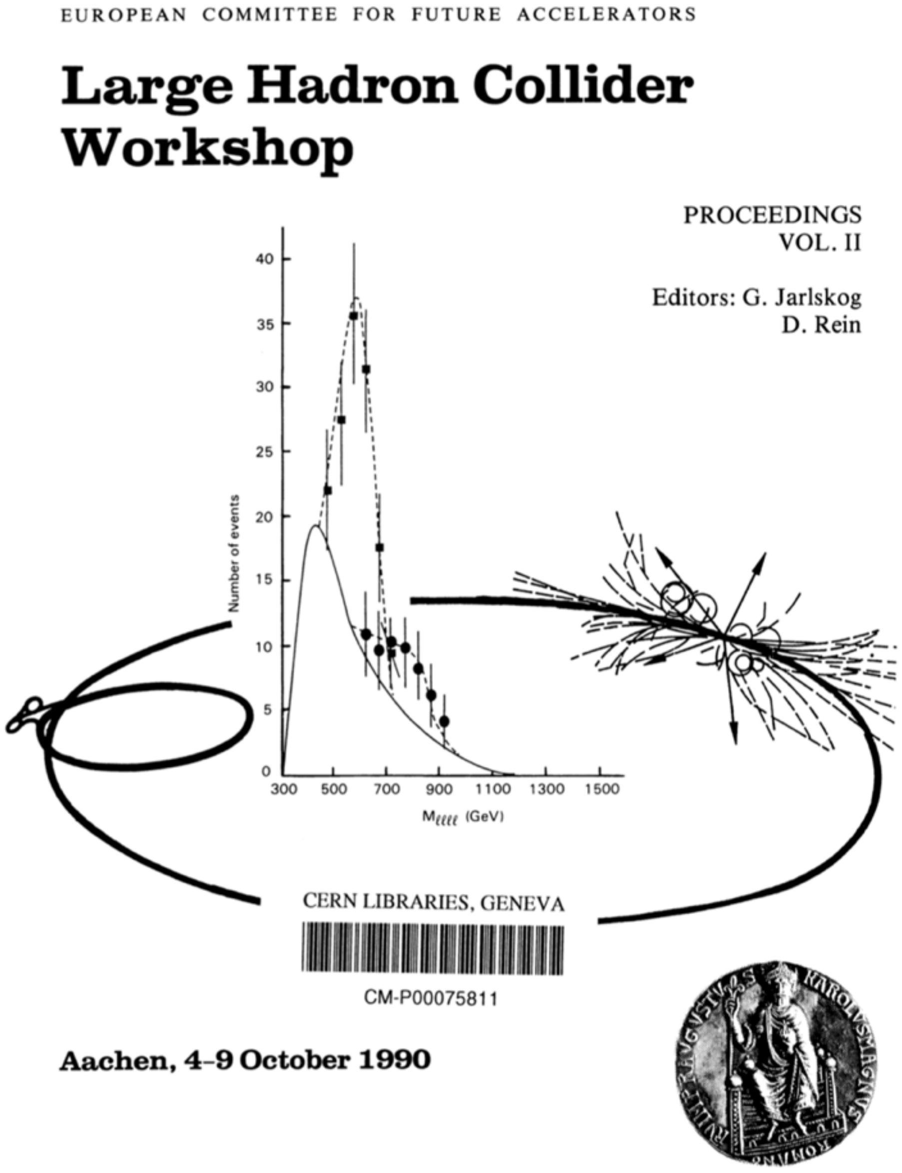
- Decays with photons (γγ, Zγ) through loops.





EXPERIMENTALISTS UNITE




EUROPEAN COMMITTEE FOR FUTURE ACCELERATORS

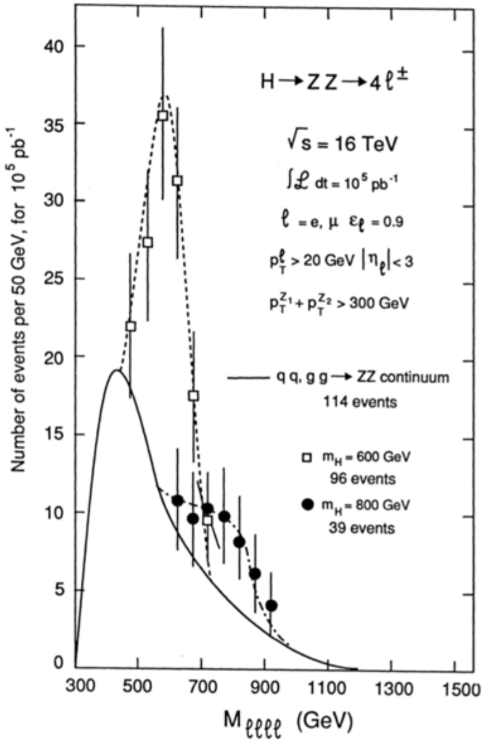
Large Hadron Collider Workshop

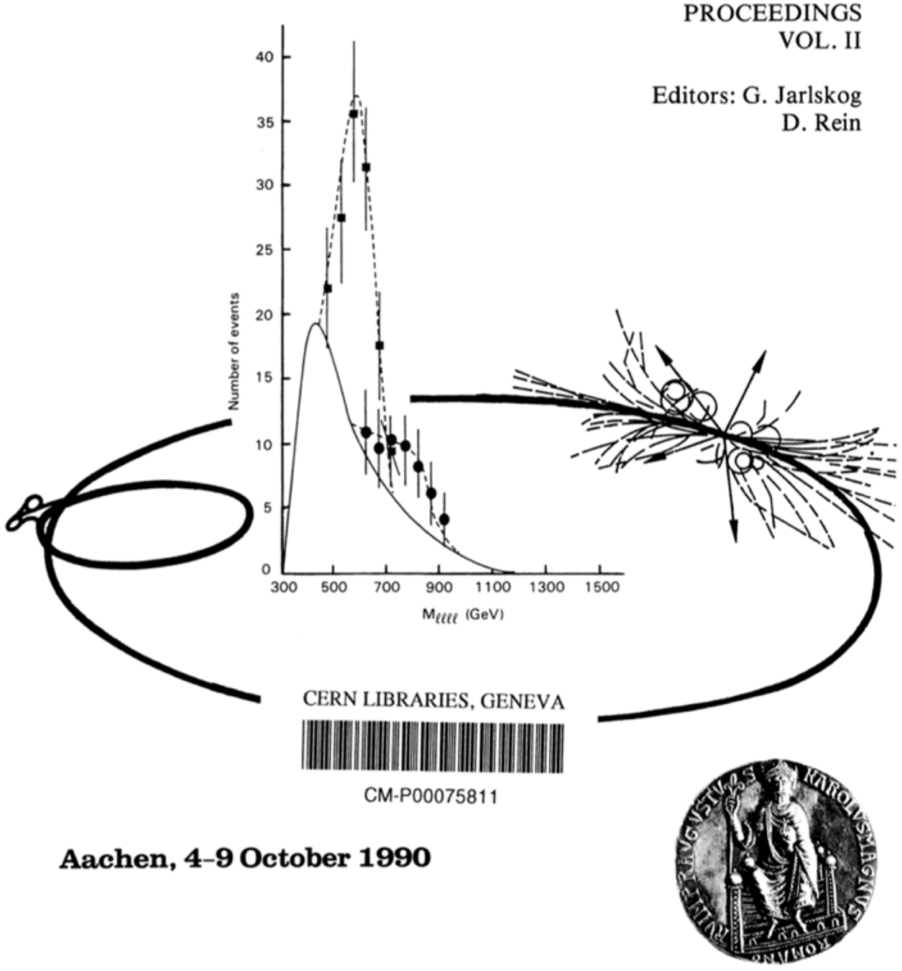
PROCEEDINGS
VOL. II

Editors: G. Jarlskog
D. Rein

Aachen, 4-9 October 1990

EXPERIMENTALISTS ASSEMBLE

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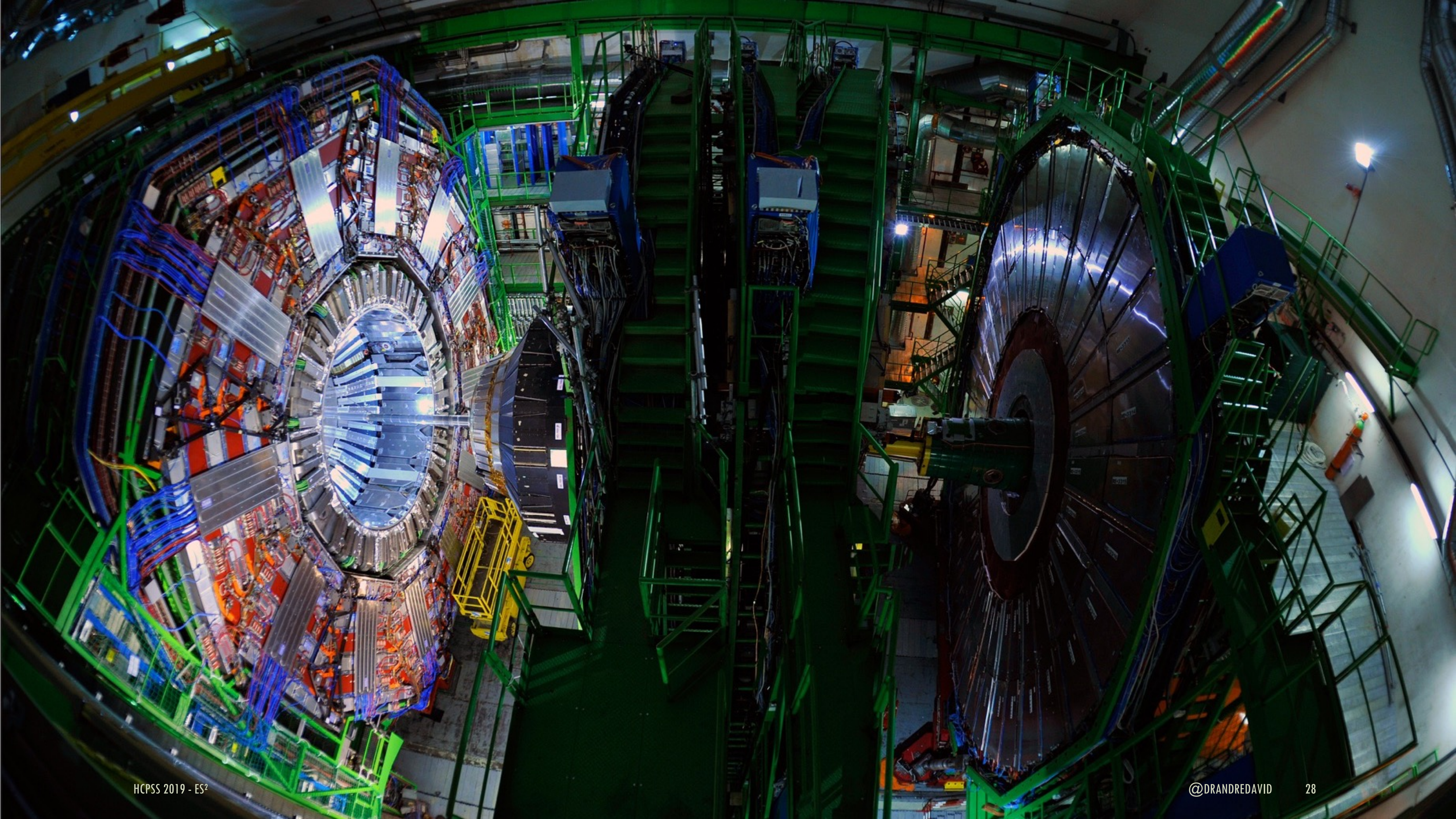
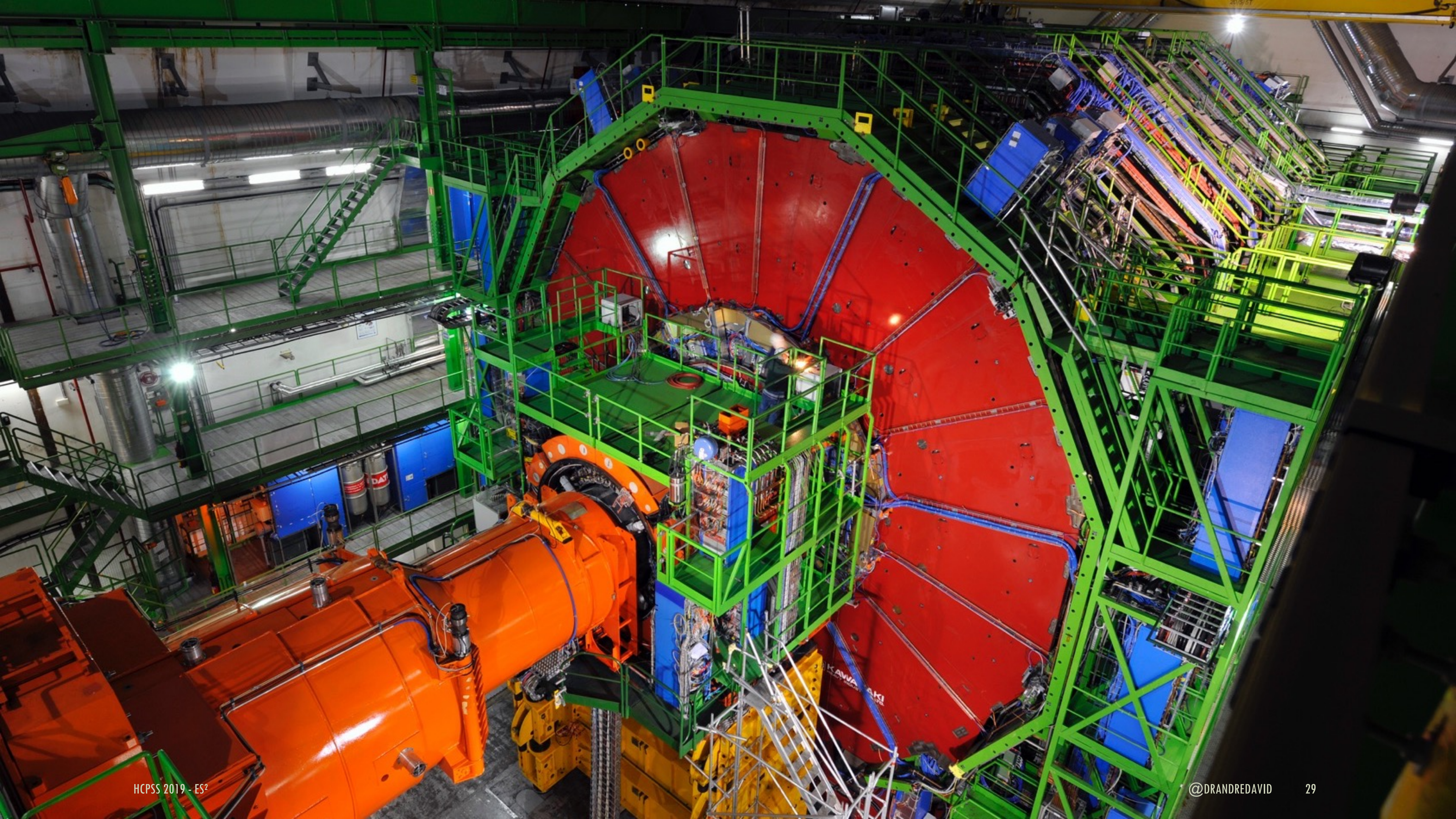
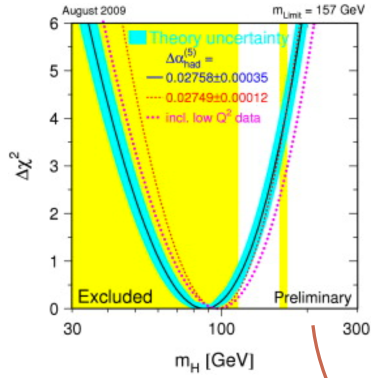
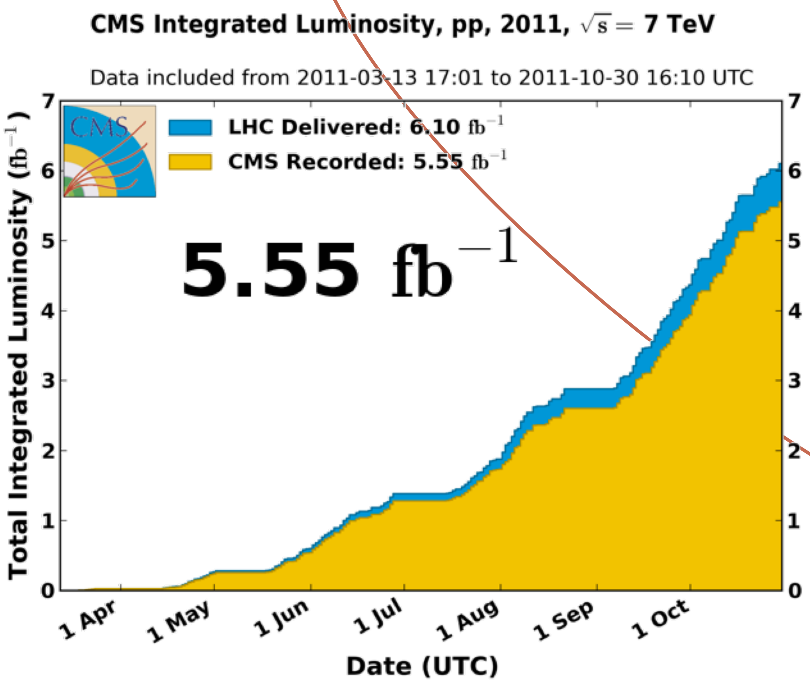
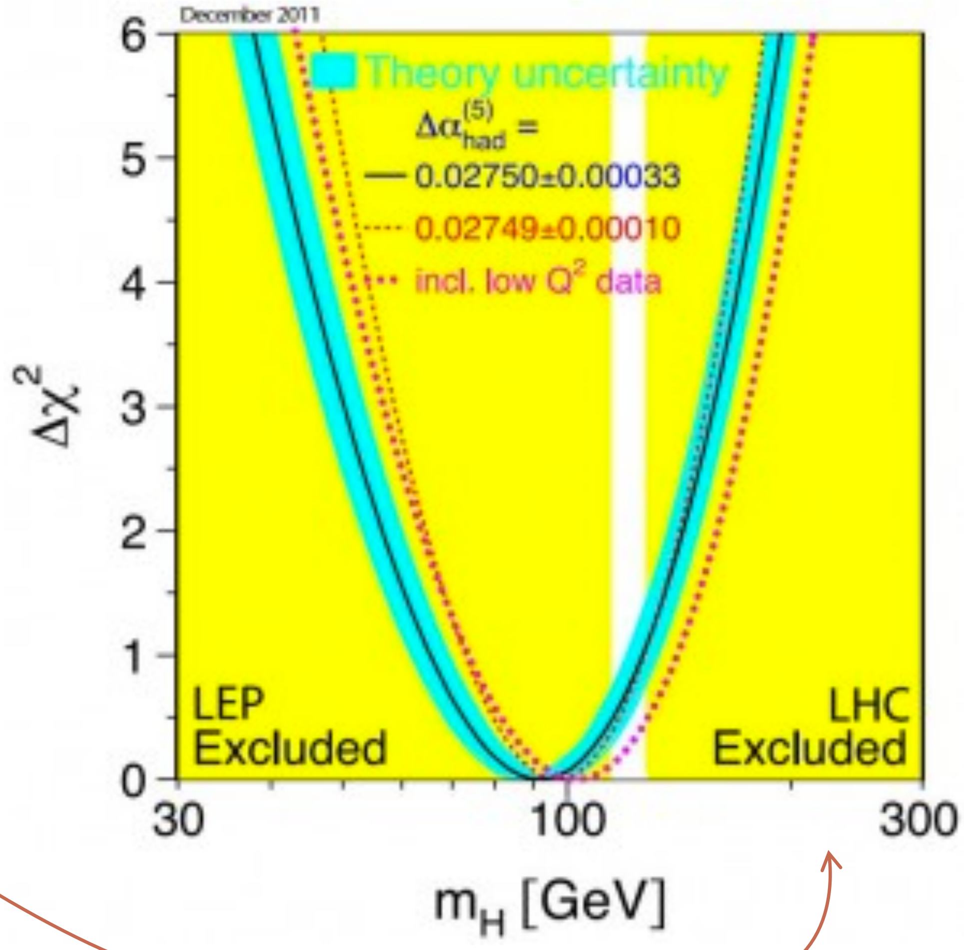


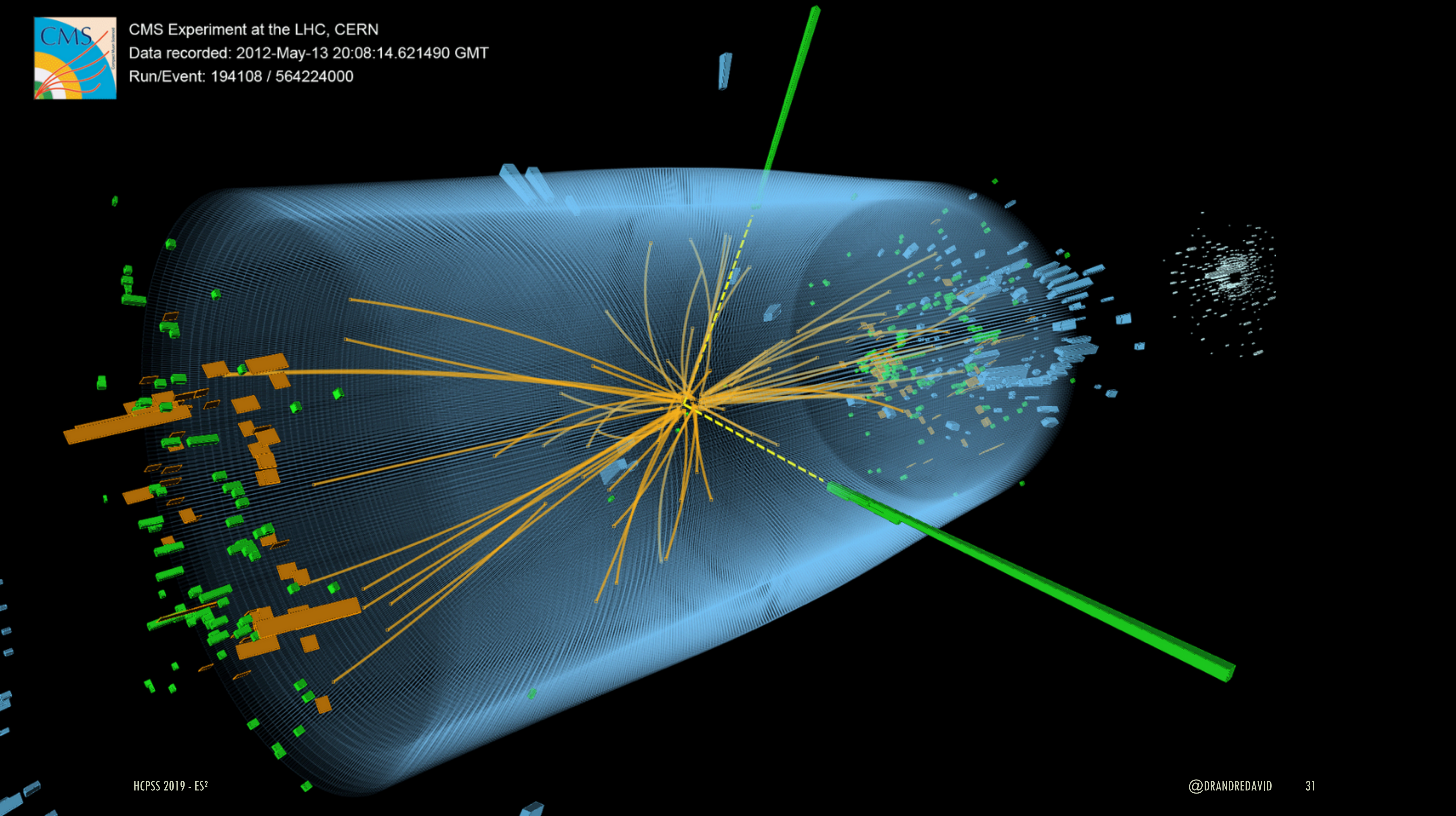


2011: STATUS AFTER THE FIRST LHC DATA

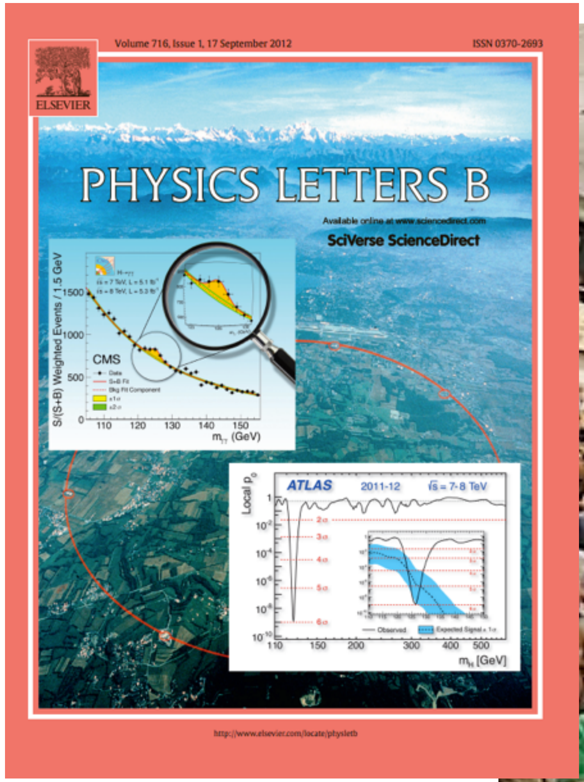







CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

JULY 4, 2012 – LOOKING UP TO A NEW BOSON



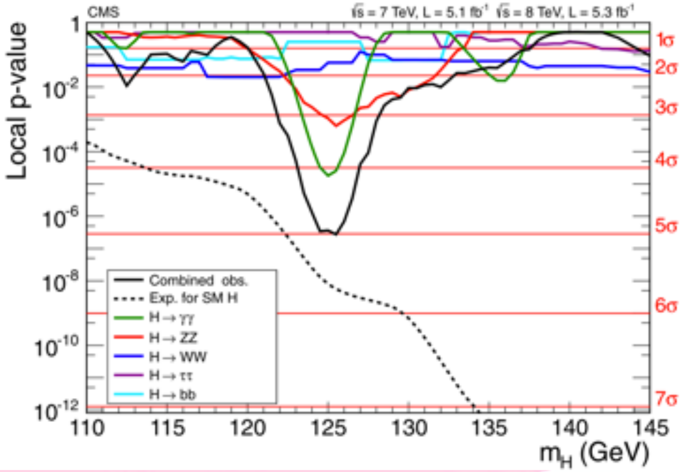
"HIGGSDEPENDENCE" DAY

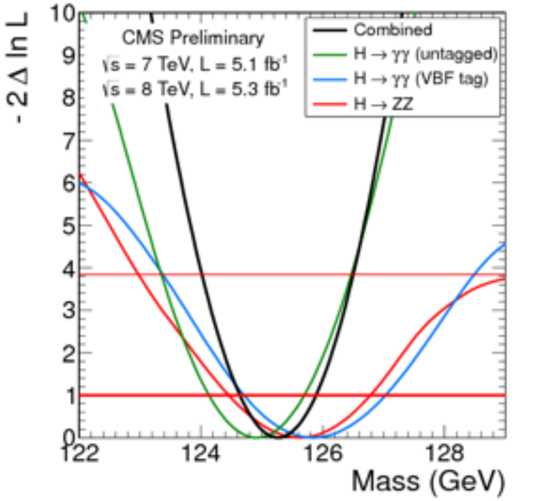
5σ significance.

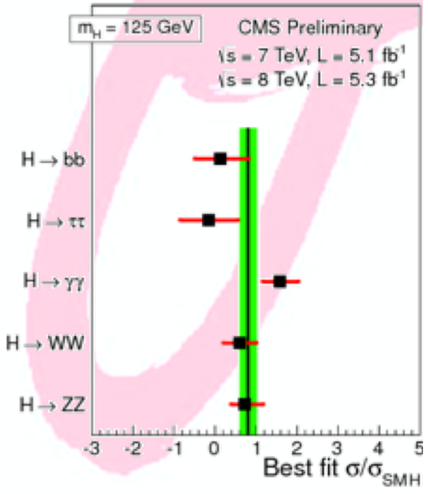
- Just under the SM expectation: $\mu = \sigma/\sigma_{SM} = 0.80 \pm 0.20$ (at 125 GeV).
- $m_X = 125.3 \pm 0.6$ GeV.
- "Proto-couplings" compatible with SM.
- Many channels.

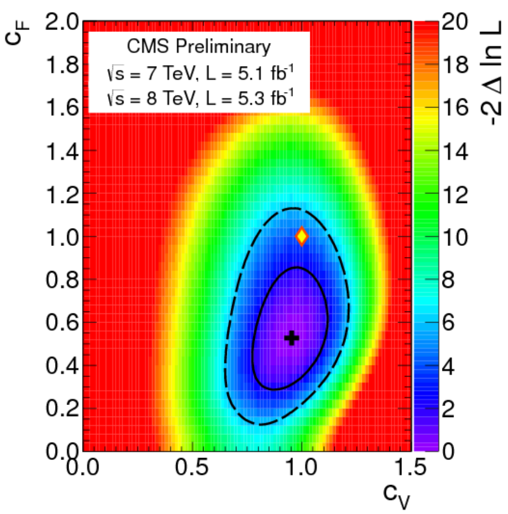
Two independent experiments.

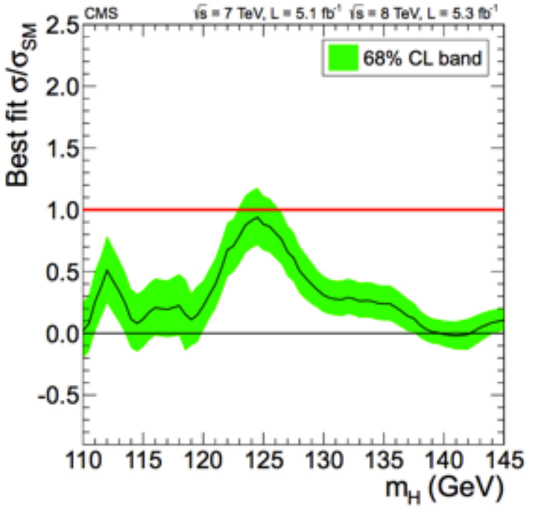
"More data needed…"











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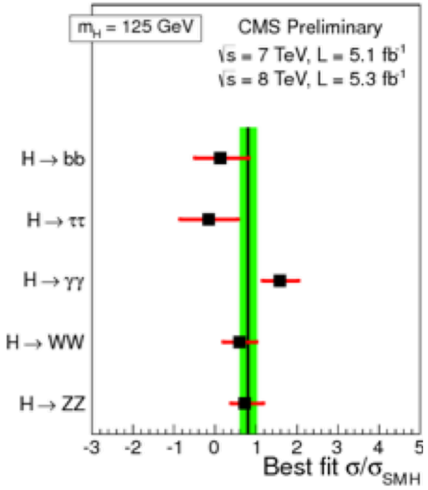

THE ANATOMY OF DEVIATIONS

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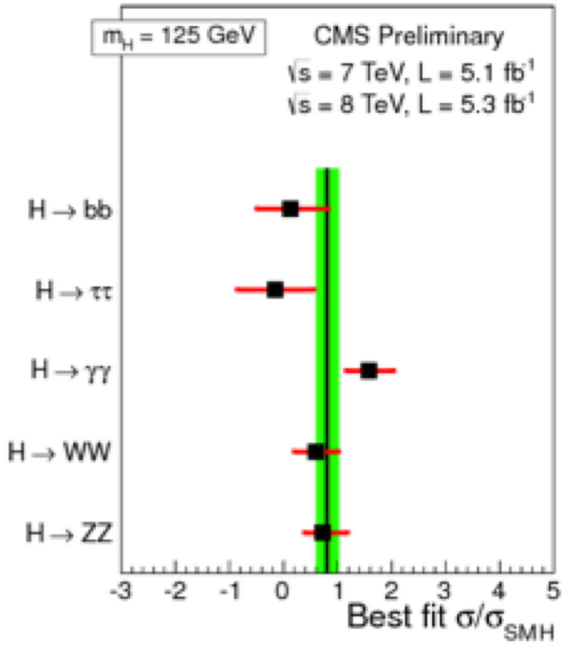


THE ANATOMY OF DEVIATIONS

$$\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{observed}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{expected}}}$$

Deviations are searched relative to SM expectation.

Conclusions are only as good
as the accuracy and precision
of the numerator and denominator.

THE ANATOMY OF DEVIATIONS

$$\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{observed}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{expected}}}$$

Production

Decay

Deviations are searched relative to SM expectation.

Conclusions are only as good
as the accuracy and precision
of the numerator and denominator.

THE ANATOMY OF DEVIATIONS

$$\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{observed}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{expected}}}$$

Data

Deviations are searched relative to SM expectation.

Conclusions are only as good
as the accuracy and precision
of the numerator and denominator.

THE ANATOMY OF DEVIATIONS

$$\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{observed}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{expected}}}$$

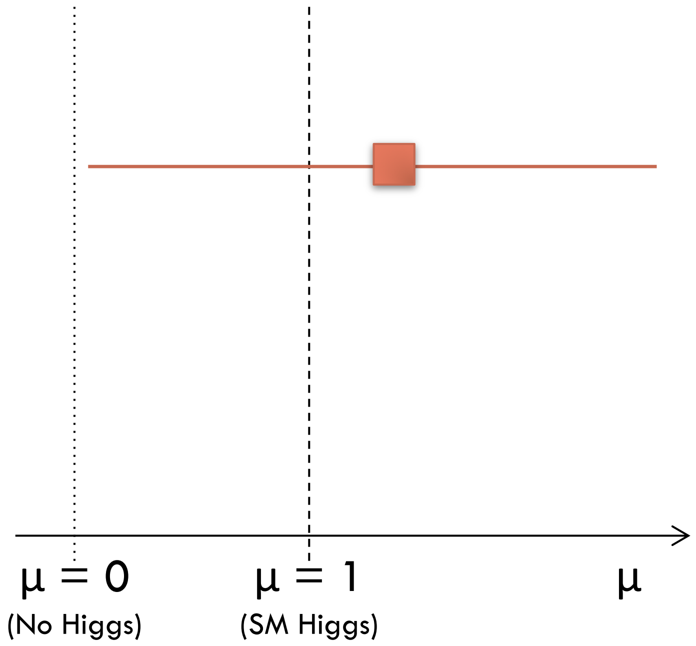
Data

Standard Model

Deviations are searched relative to SM expectation.

Conclusions are only as good
as the ***accuracy and precision***
of the ***numerator and denominator.***

READING DEVIATIONS

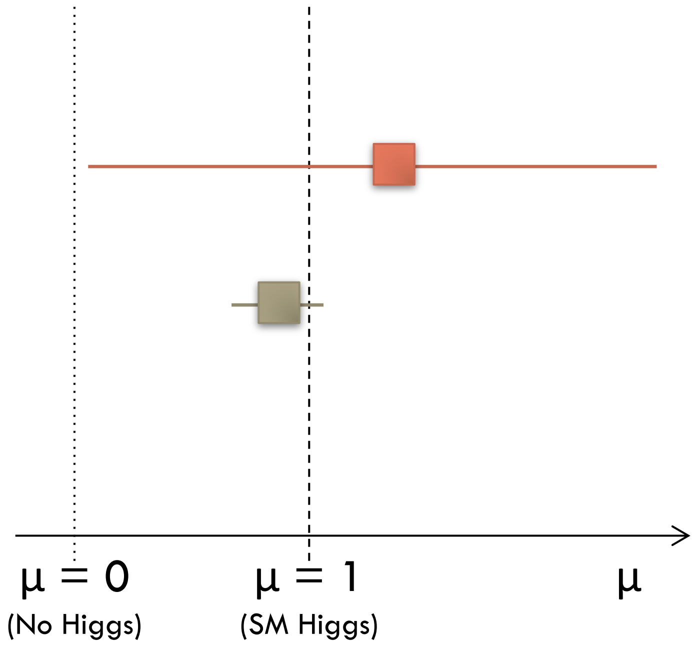


Imprecise measurement compatible with 0 and 1.
Inconclusive, "more data needed".

$\mu = 1$ means that the data match the SM.

- Uncertainty on μ quantifies the compatibility with the SM:
  - **$\mu = 1.3 \pm 1.2$ is inconclusive and "more data is needed"**, but
  - $\mu = 2.0 \pm 0.2$ could mean New Physics (or a systematic effect).

READING DEVIATIONS



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Large deviations excluded!

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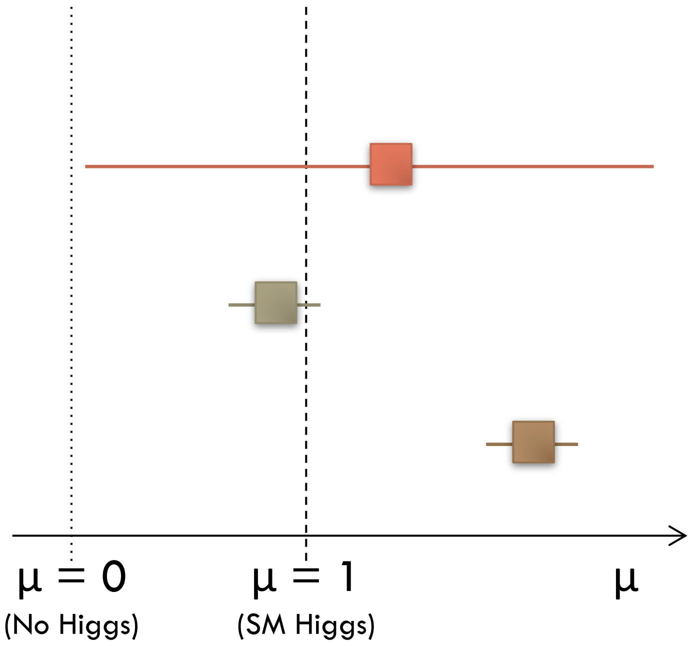

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Precise measurement **incompatible** with the SM!
Evidence of a deviation.

"New Physics ⇒ Deviation" but "Deviation ⇏ New Physics"
See, e.g., http://cern.ch/go/W8wW

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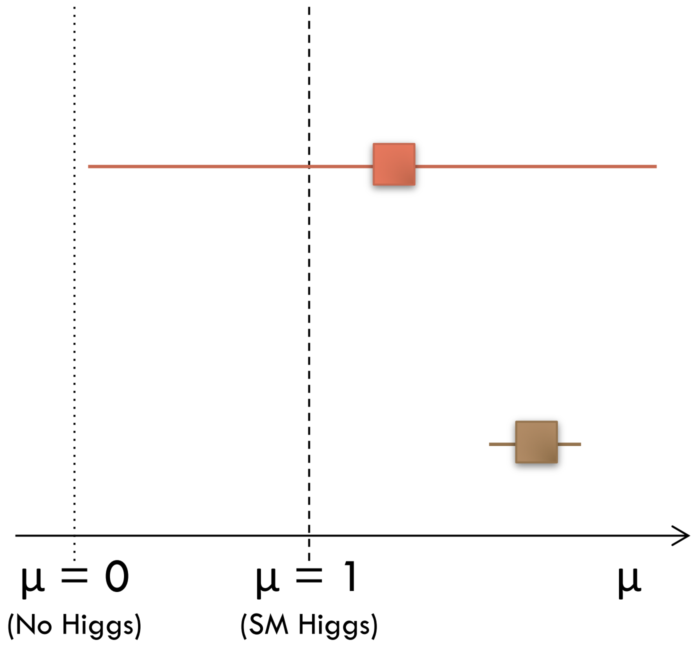


Imprecise measurement compatible with 0 and 1.
Inconclusive, “more data or better theory needed”.

Precise measurement **incompatible** with the SM!
Evidence of a deviation or exp./theory bias.

“New Physics ⇒ Deviation” but “Deviation ⇏ New Physics”
See, e.g., http://cern.ch/go/W8wW

Who Should Be TIME's Person of the Year 2012?

As always, TIME's editors will choose the Person of the Year, but that doesn't mean readers shouldn't have their say. Cast your vote for the person you think most influenced the news this year for better or worse. Voting closes at 11:59 p.m. on Dec. 12, and the winner will be announced on Dec. 14.

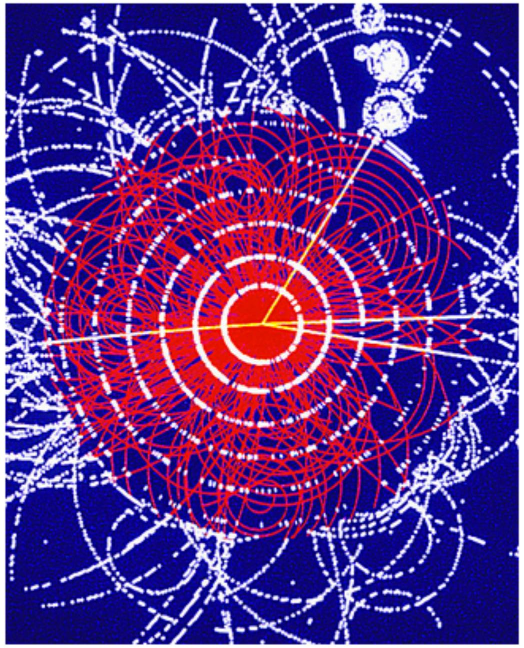
Like 1.5k | Tweet 536 | +1 20 | Share 7

THE CANDIDATES

The Higgs Boson

18 of 40

By Jeffrey Kluger | Monday, Nov. 26, 2012



SSPL/GETTY IMAGES

Simulation of a Higgs-Boson decaying into four muons, CERN, 1990.

What do you think?

Should **The Higgs Boson** be TIME's Person of the Year 2012?

Definitely   No Way

VOTE

Take a moment to thank this little particle for all the work it does, because without it, you'd be just inchoate energy without so much as a bit of mass. What's more, the same would be true for the entire universe. It was in the 1960s that Scottish physicist Peter Higgs first posited the existence of a particle that causes energy to make the jump to matter. But it was not until last summer that a team of researchers at Europe's Large Hadron Collider — Rolf Heuer, Joseph Incandela and Fabiola Gianotti — at last sealed the deal and in so doing finally fully confirmed Einstein's general theory of relativity. The Higgs — as particles do — immediately decayed to more-fundamental particles, but the scientists would surely be happy to collect any honors or awards in its stead.

Photos: Step inside the Large Hadron Collider.

WHO SHOULD BE TIME'S PERSON OF THE YEAR 2012?

The Candidates

Video

Poll Results

PAST PERSONS OF THE YEAR

2011: The Protester

2010: Facebook's Mark Zuckerberg

2009: Ben Bernanke

2008: Barack Obama

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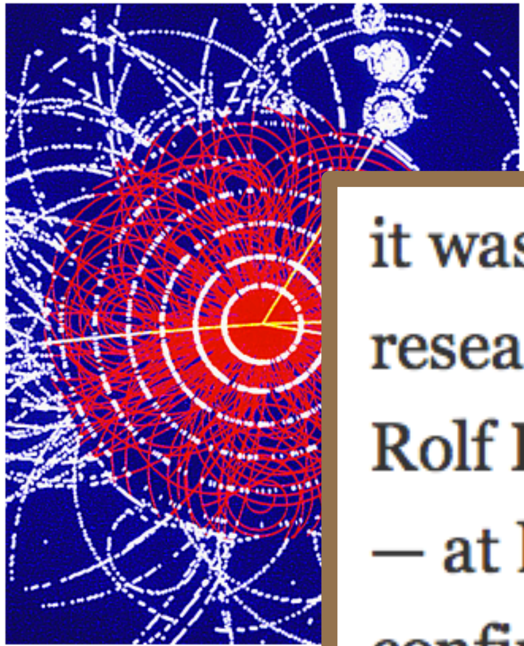

Simulation of a Higgs-Boson decaying int... 1990.

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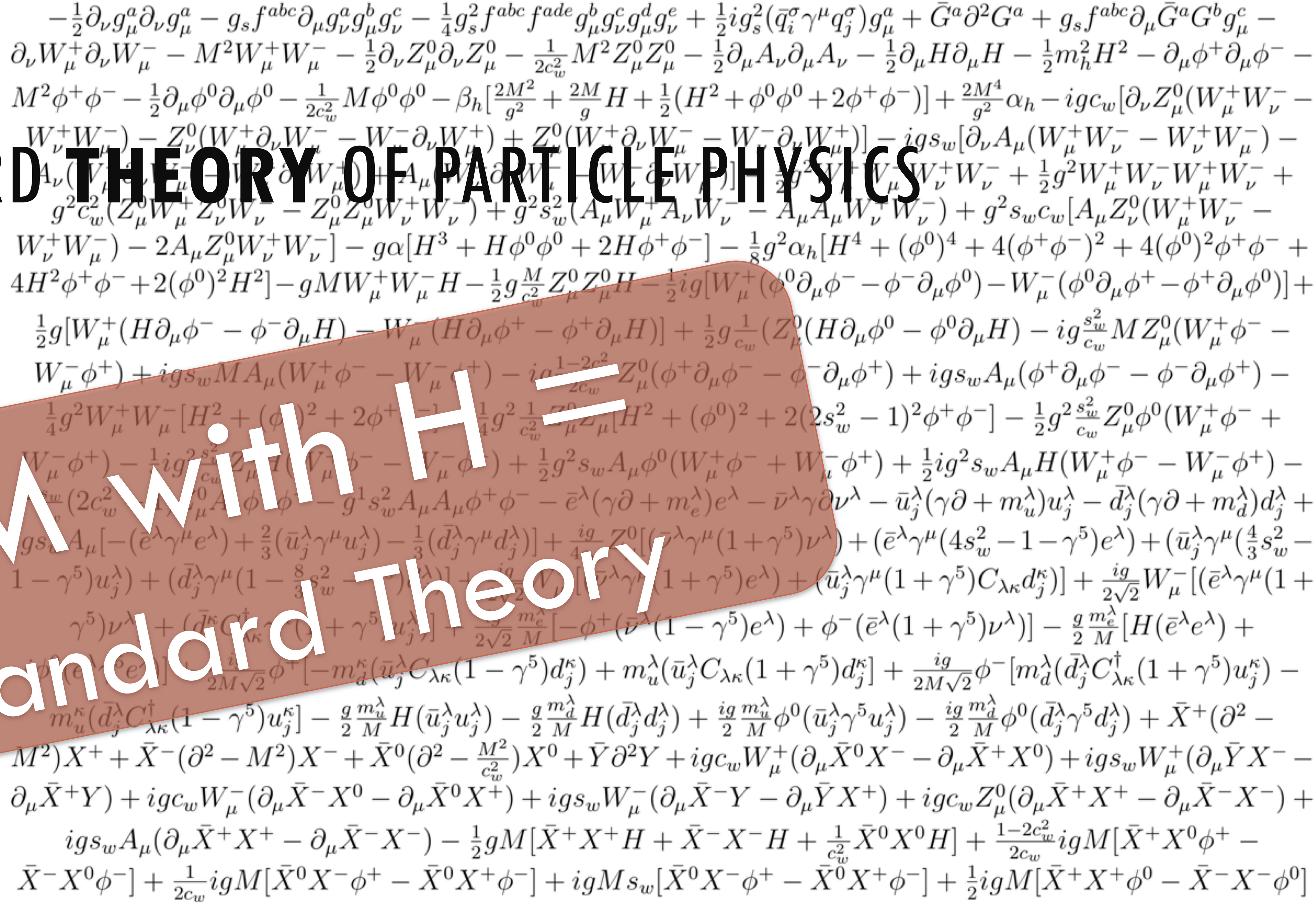
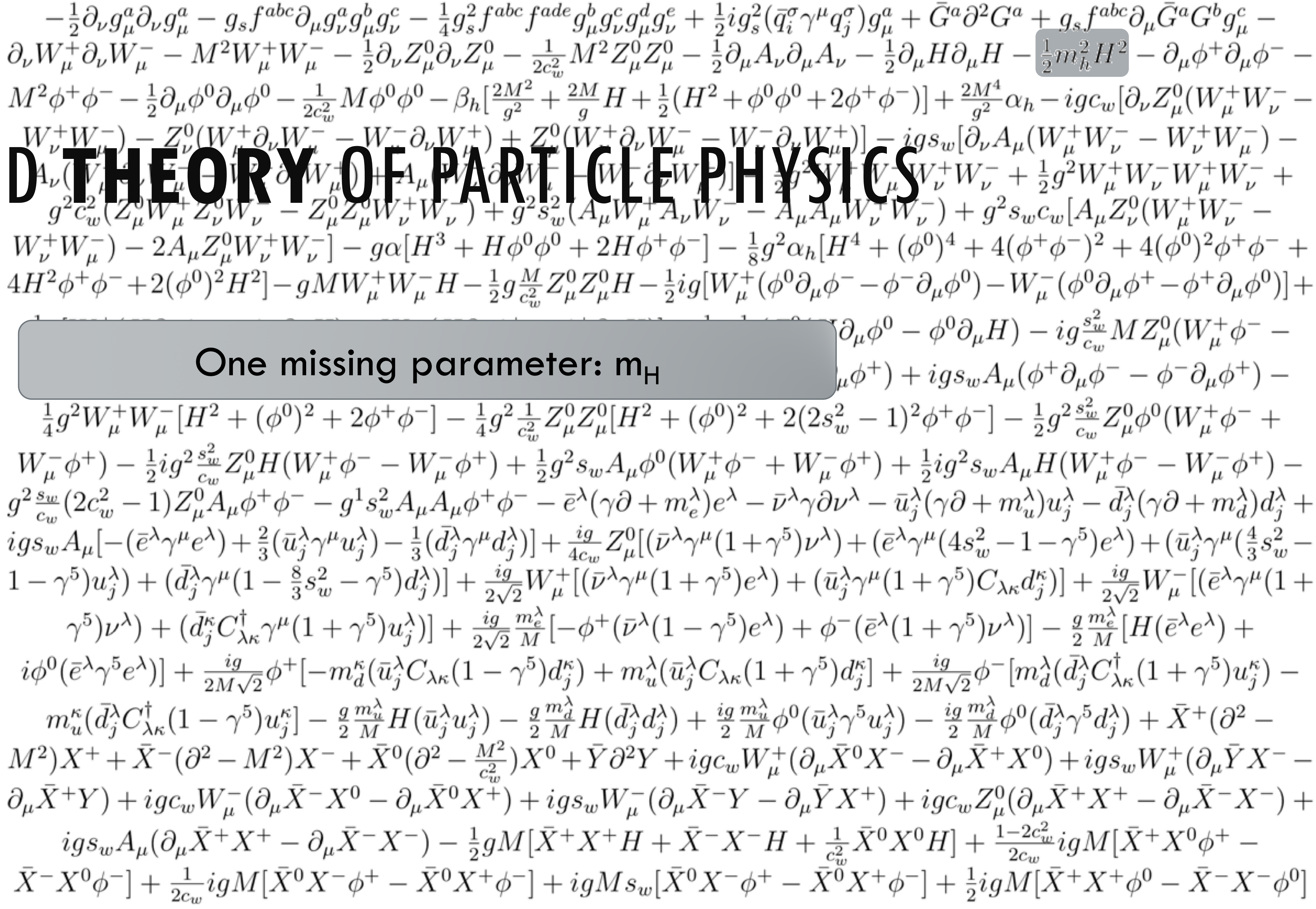
STANDARD **THEORY** OF PARTICLE PHYSICS



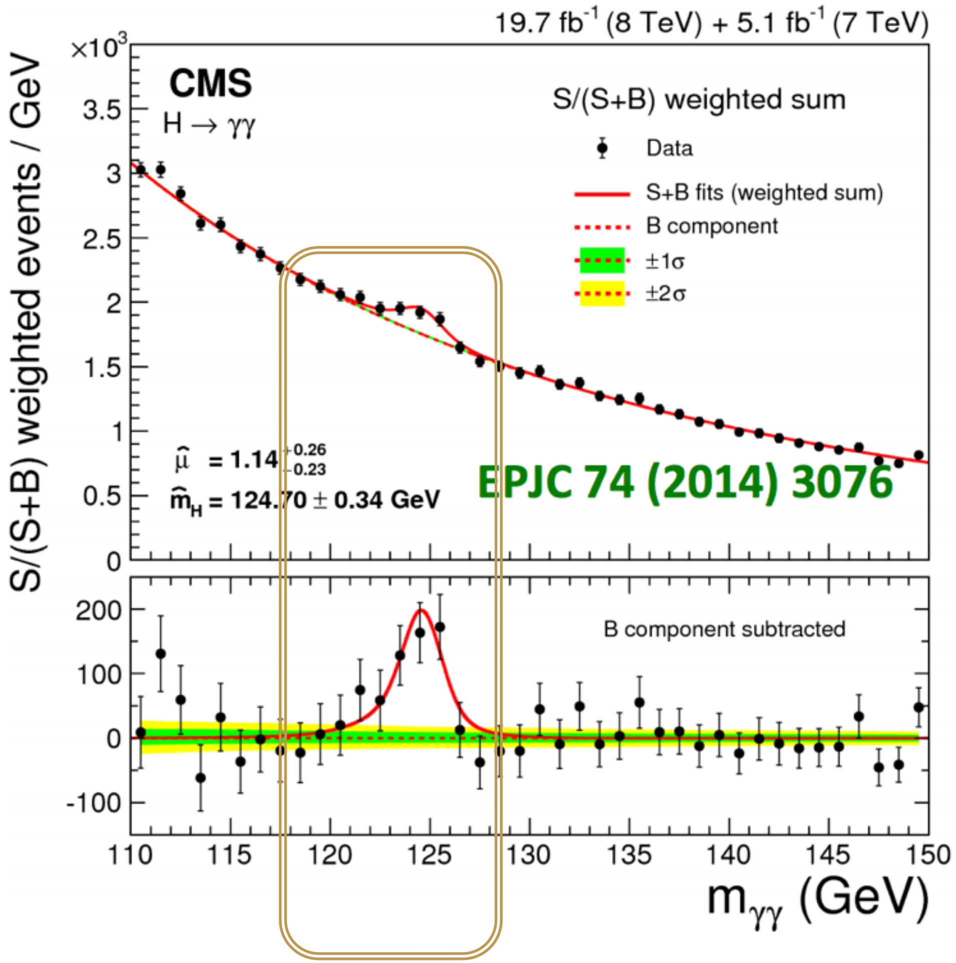
SM with H = Standard Theory

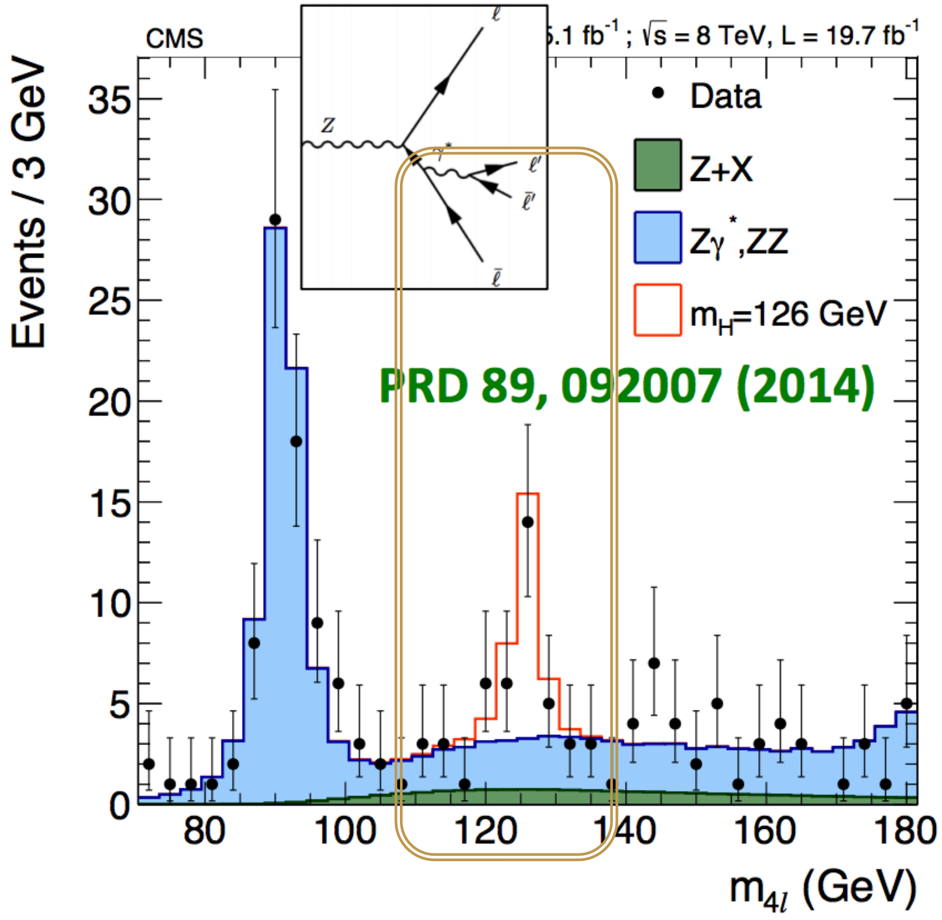
STANDARD THEORY OF PARTICLE PHYSICS



One missing parameter: m_H

MASS PEAKS: MASS MEASUREMENTS





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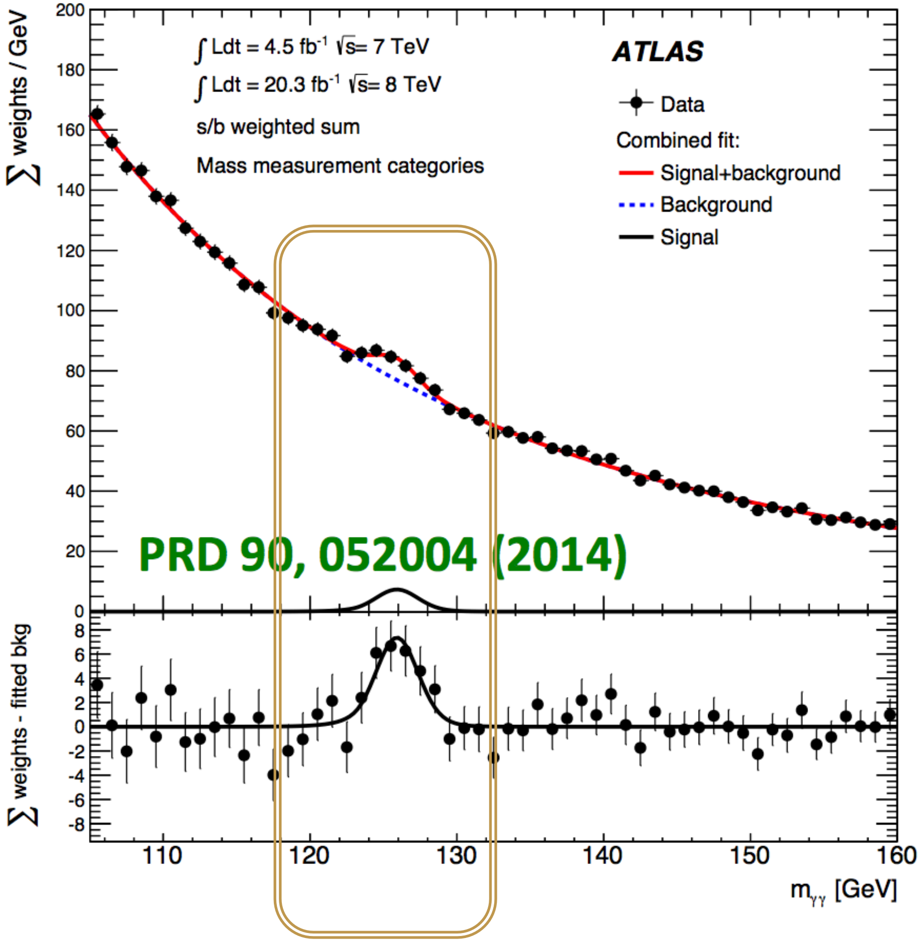
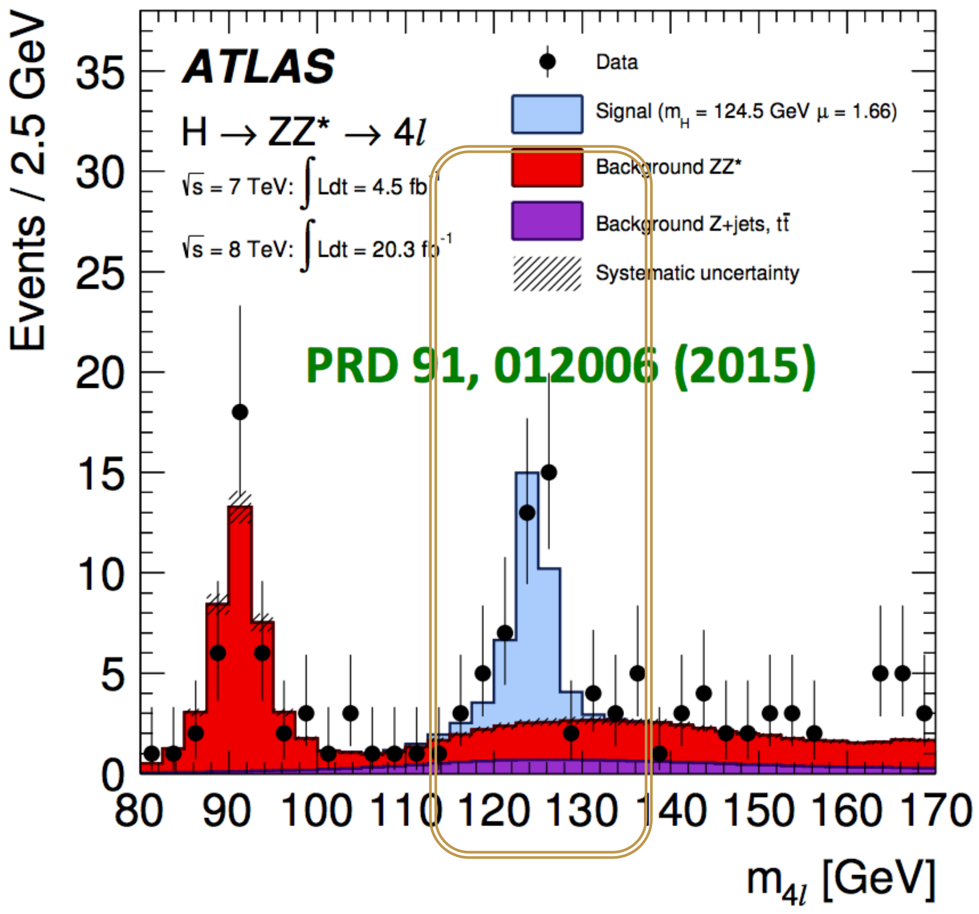
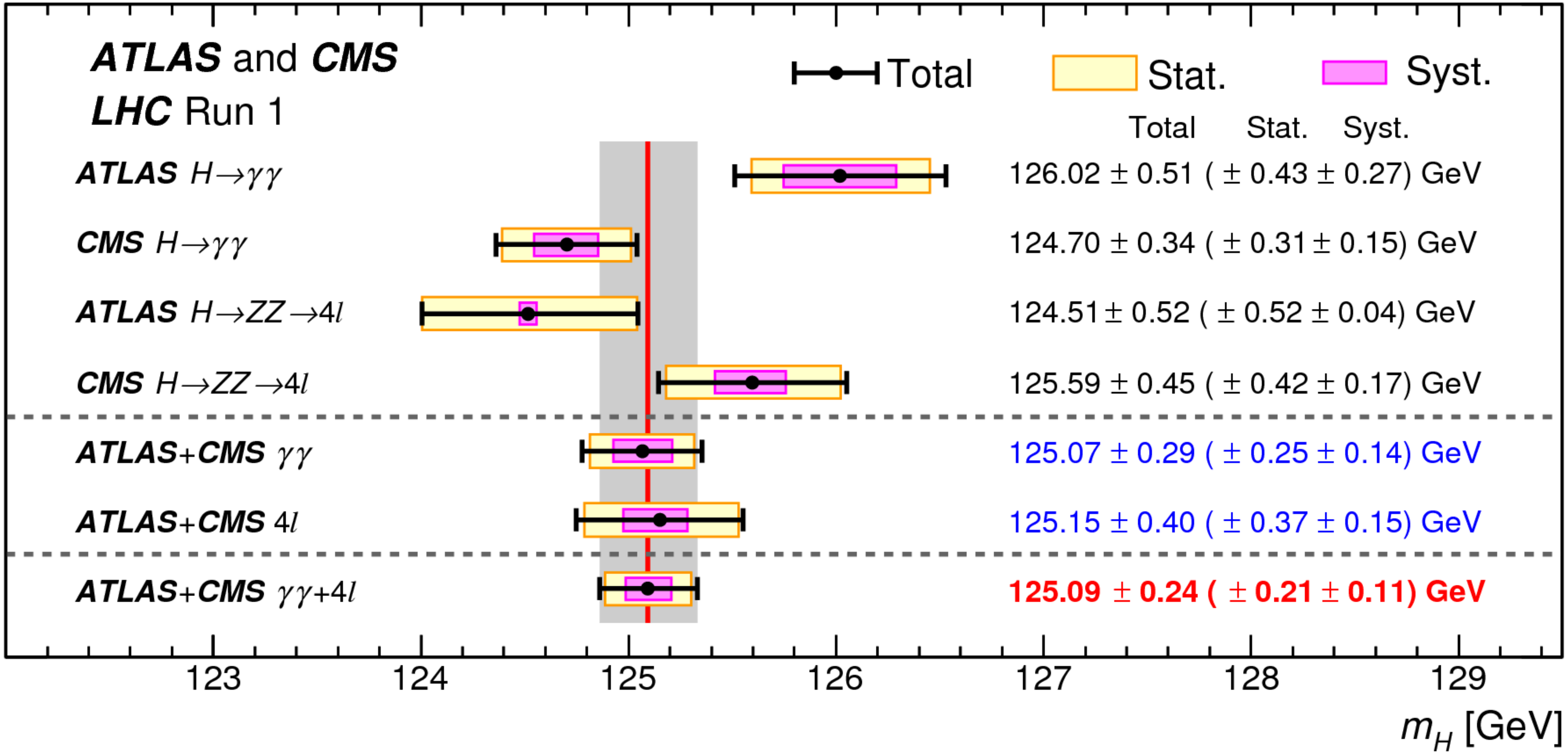




LHC COMBINED MASS MEASUREMENT



SO MUCH MORE THAN JUST ONE PLOT

m_H ~ **peak position.**

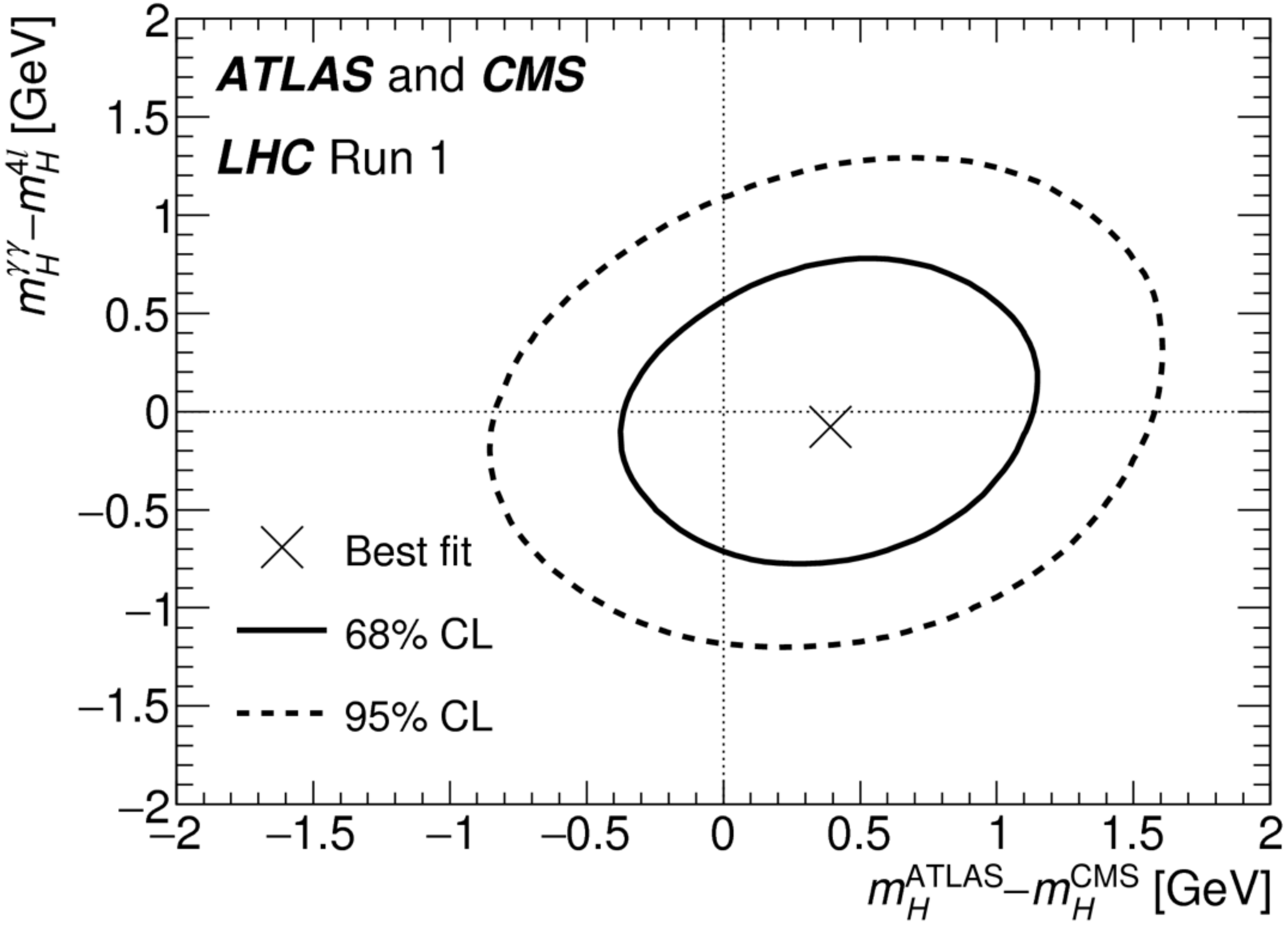
- But **peaks mean yields.**

Freely-float production yields (μ_{ggH}, μ_{VBF}).

- Assume as little as possible for the signal strength.
- Also called "unconstrained nuisance parameters".
- ⇒ m_H measurement ~ independent from production assumptions.

And compatibility cross-checks…

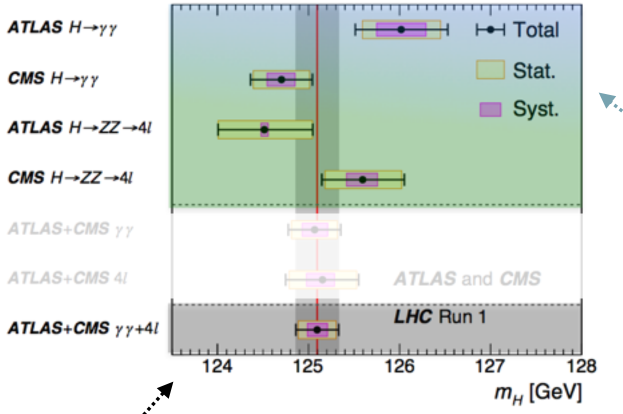
- Mass differences across channels and across experiments. →

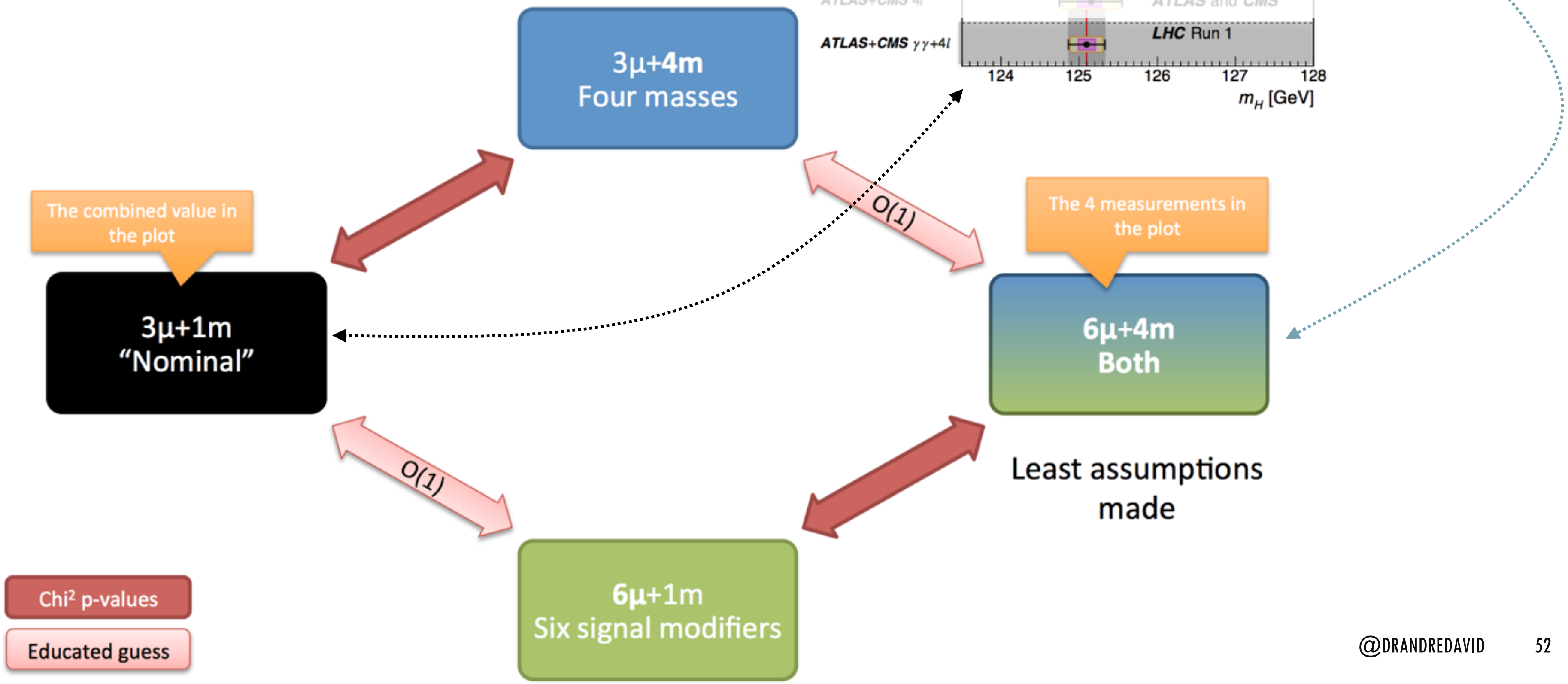


BEHIND THE SCENES

Compatibility

A number of different models to check compatibility of the result …





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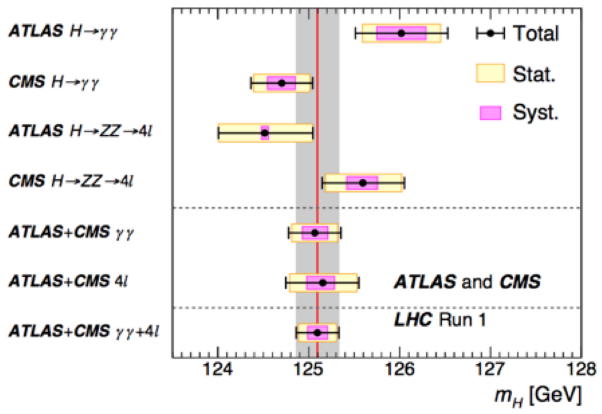
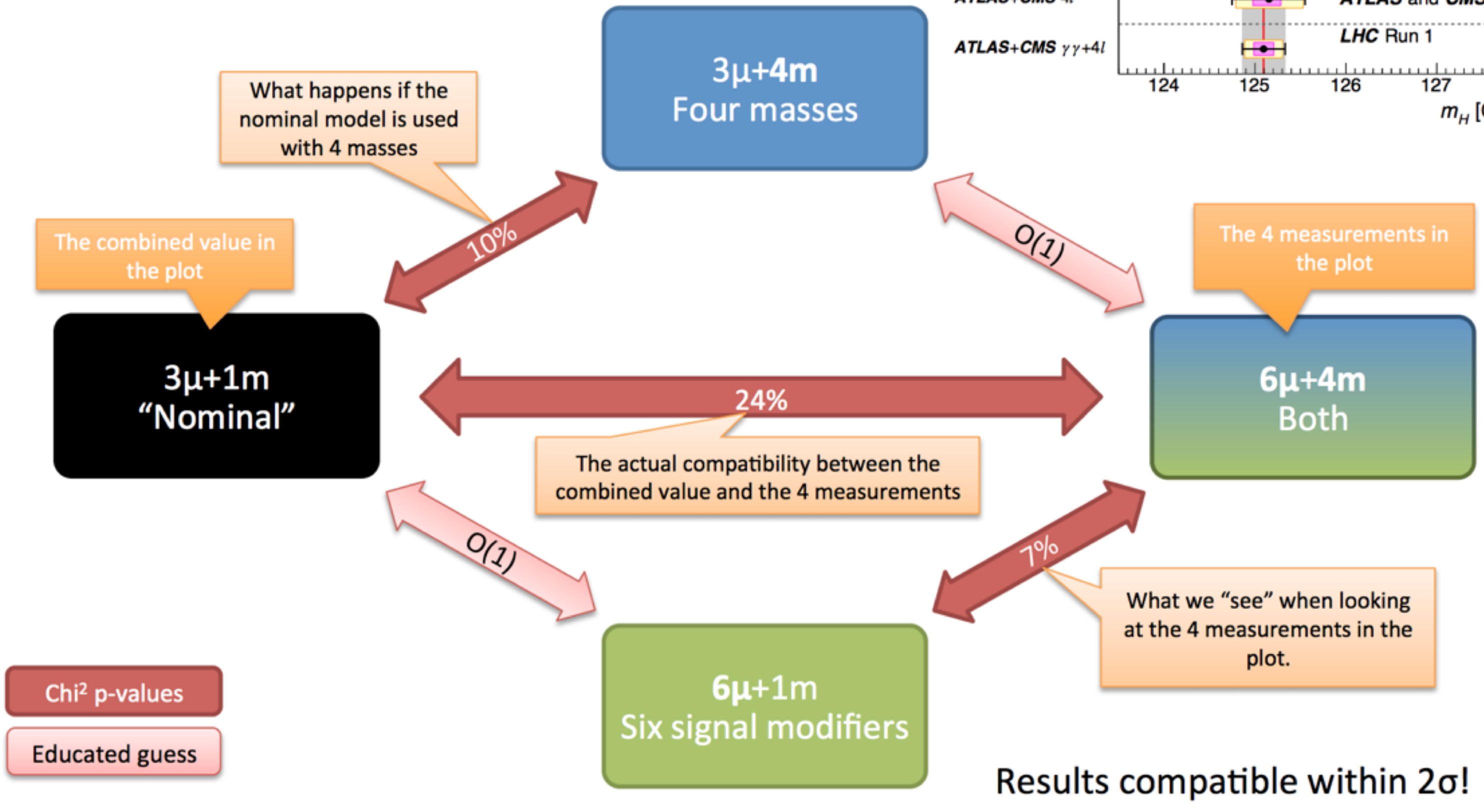
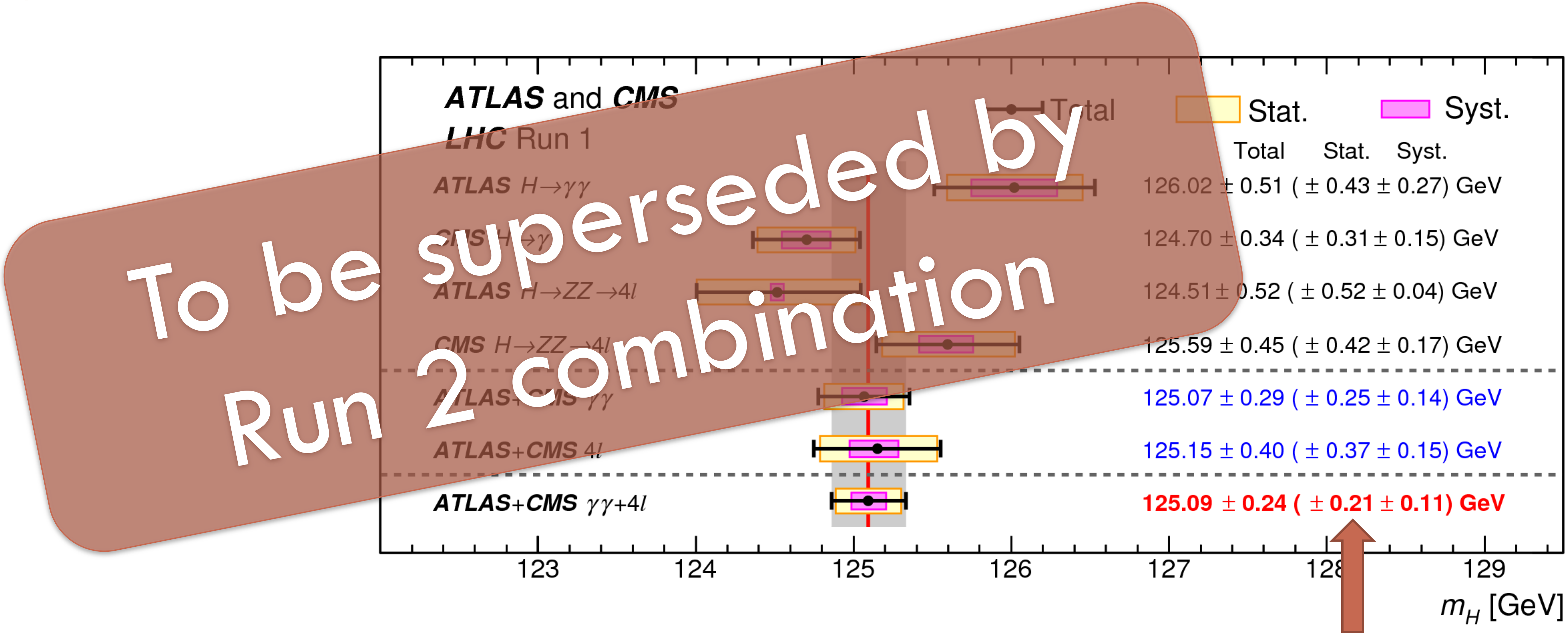




Results compatible within 2σ!

COMBINED LHC MASS MEASUREMENT



UNCERTAINTIES AND BIASES

Statistical uncertainty

Reduced by the amount of data (1/√N):

- Amount of signal process events.
- Amount of background process events in data-driven estimation from control region.

🏃‍♀️ **Not cheap to improve: needs more (perhaps higher-energy) data.**

Systematic uncertainty

Introduced by removing biases:

- Detector calibration, e.g. energy scales and resolutions.

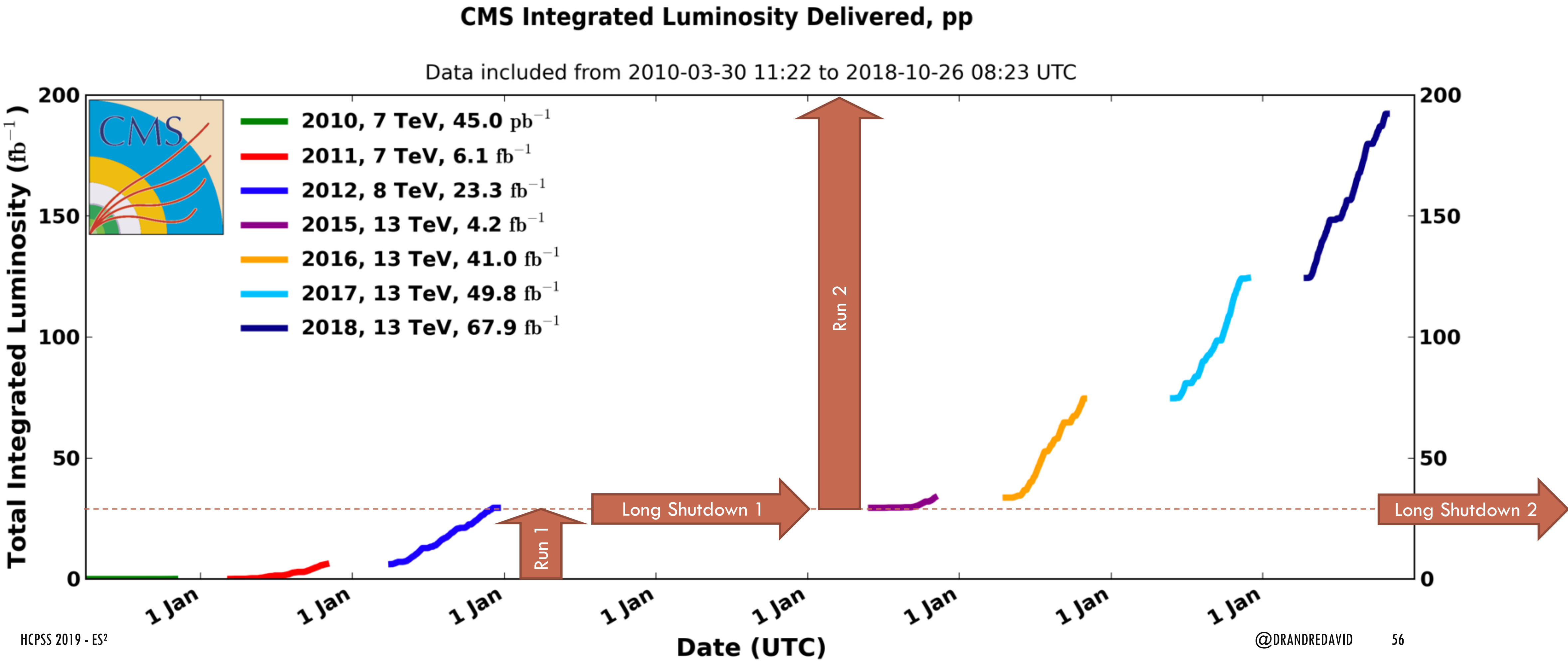
Introduced by adding information:

- PDF set fits, a data-theory hybrid.
- Theory-driven extrapolation from control region to signal region.
- Background estimation from theory prediction.

Caveat: some systematic uncertainties are actually statistical in nature.

🧠 **Hard to improve: requires much human ingenuity.**

UP, UP, AND AWAY



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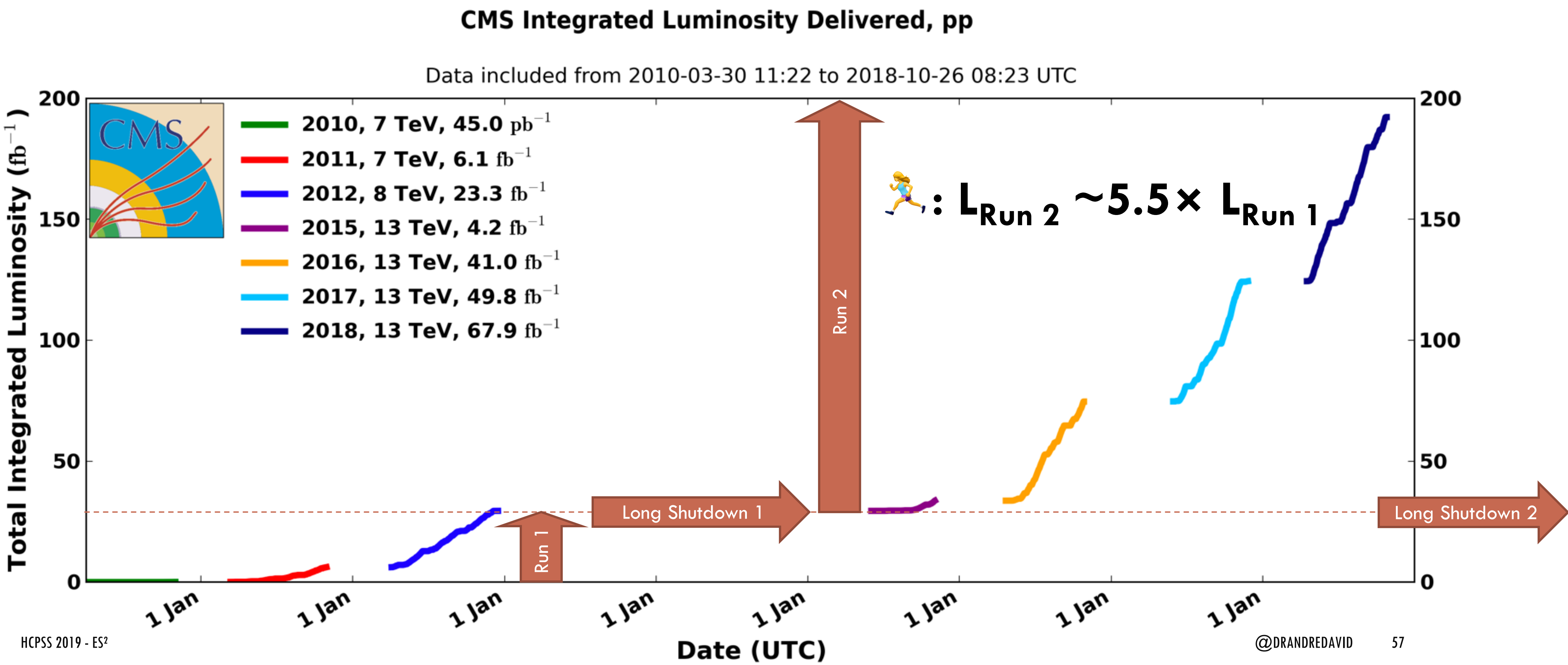
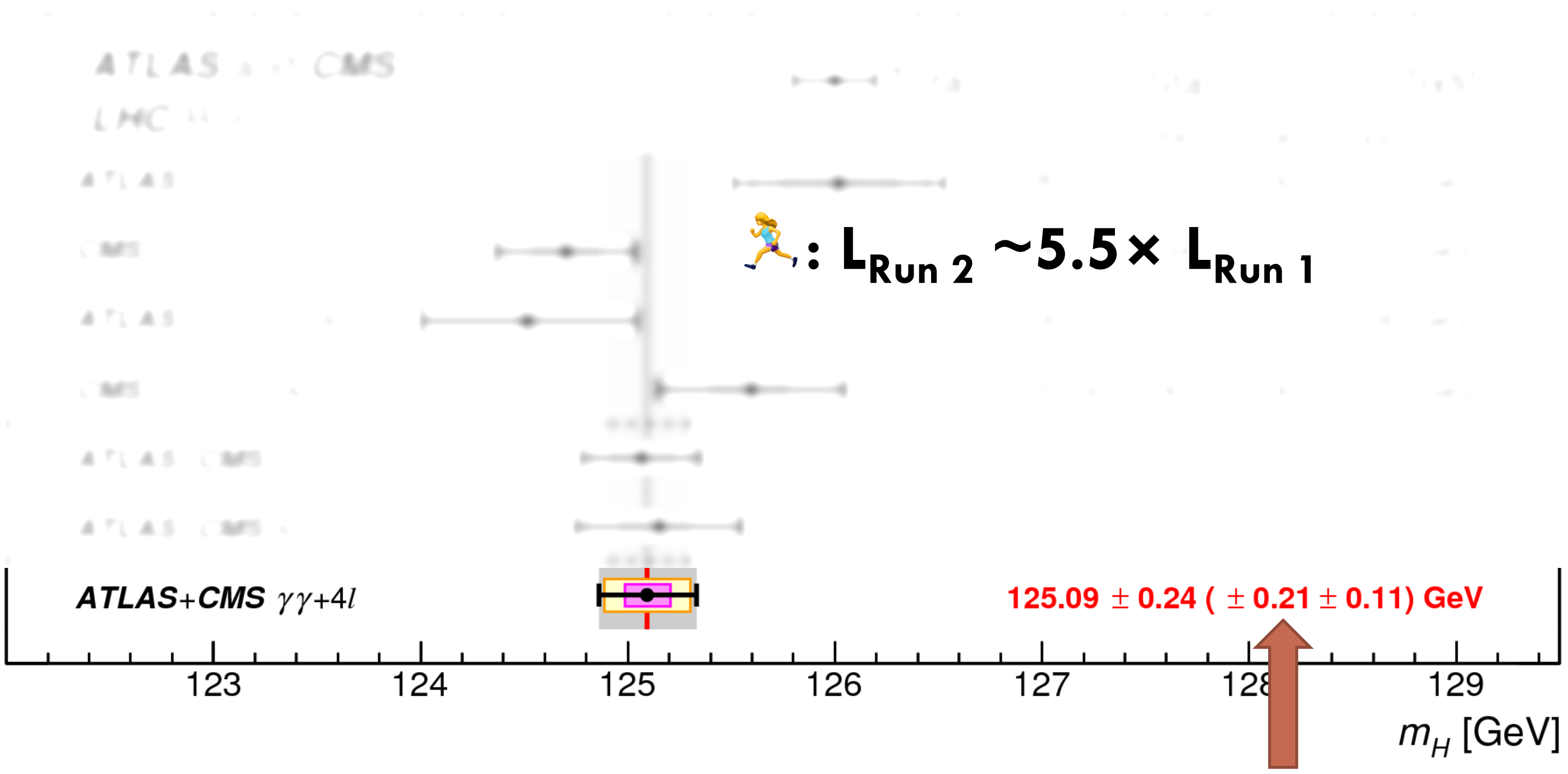
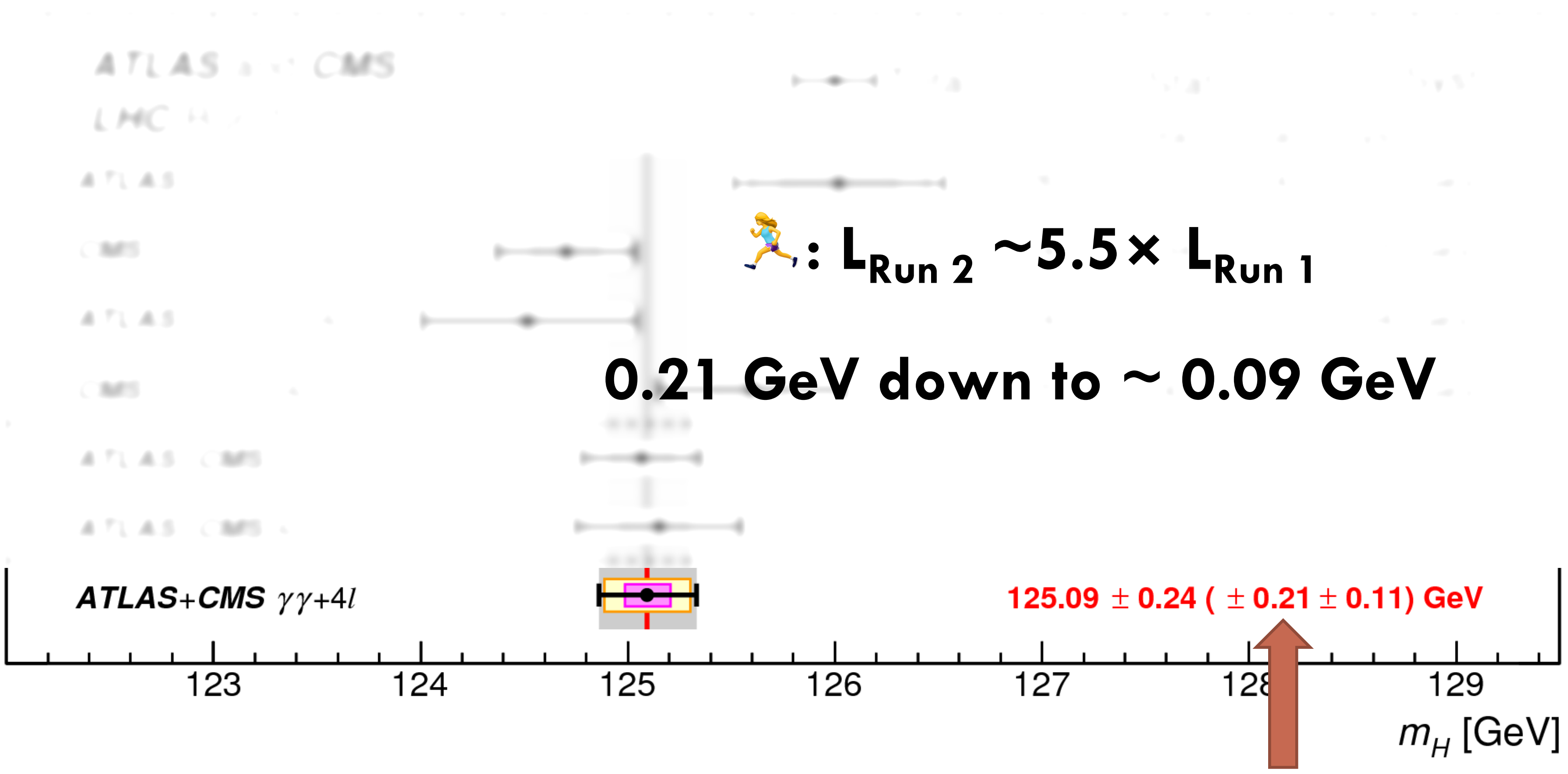


COMBINED LHC MASS MEASUREMENT



🏃‍♀️: $L_{Run\ 2}$ ~5.5× $L_{Run\ 1}$

COMBINED LHC MASS MEASUREMENT



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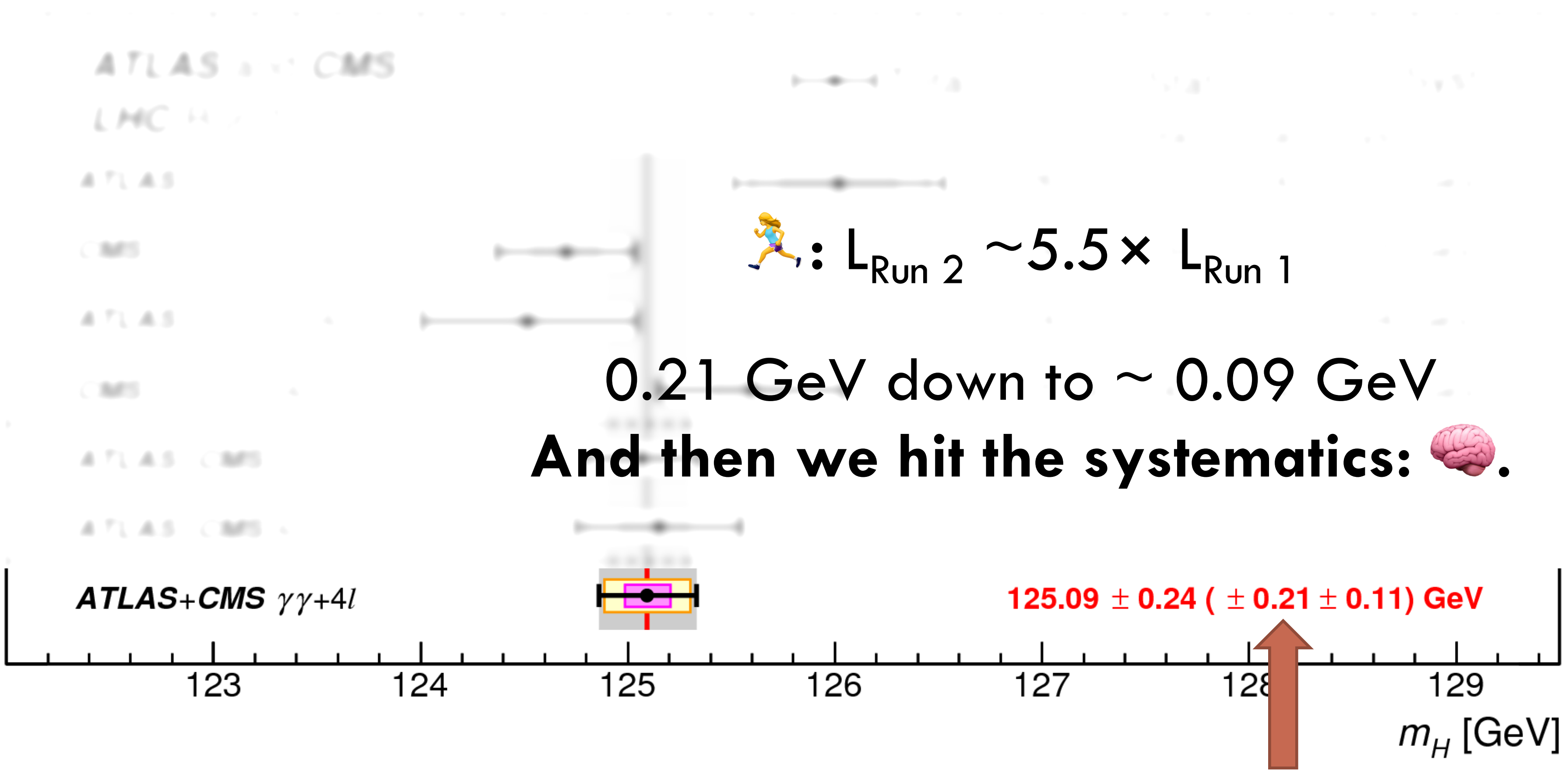

🏃‍♀️: $L_{Run\ 2} \sim 5.5 \times L_{Run\ 1}$

0.21 GeV down to ~ 0.09 GeV

And then we hit the systematics: 🧠.

FOR THE RECORD

~5 kiloauthors.

Found that there are two:

- Archana Sharma
  (both in CMS)
- Andrea Bocci
- Muhammad Ahmad
- F. M. Giorgi
  (one in CMS, one in ATLAS)

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NATURE | NEWS

Physics paper sets record with more than 5,000 authors

Detector teams at the Large Hadron Collider collaborated for a more precise estimate of the size of the Higgs boson.

Davide Castelvecchi

15 May 2015

CERN

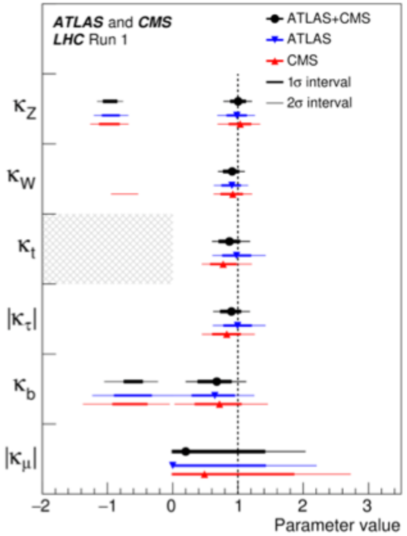
Thousands of scientists and engineers have worked on the Large Hadron Collider at CERN.

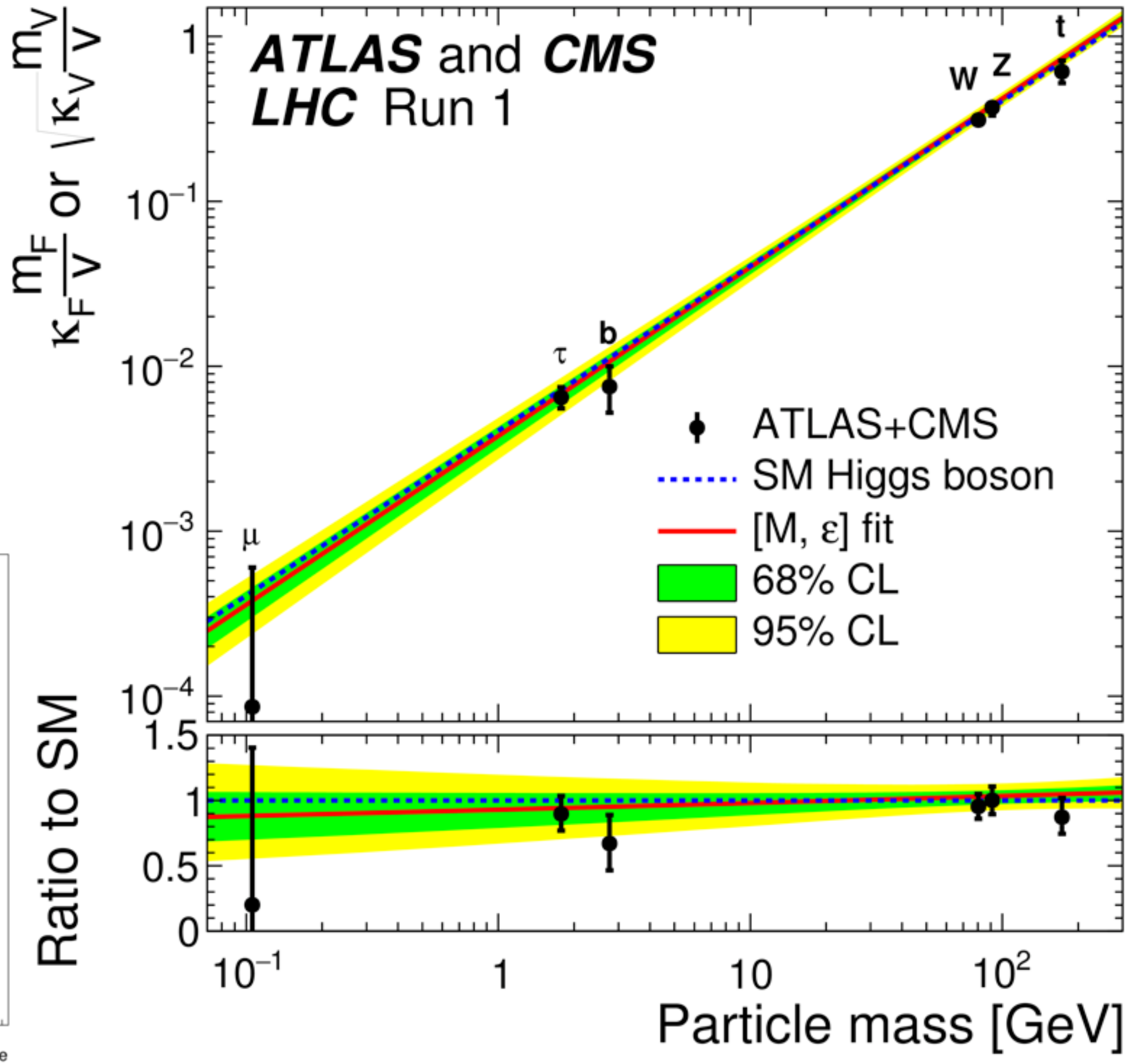
A physics paper with 5,154 authors has — as far as anyone knows — broken the record for the largest number of contributors to a single research article.

RUN1 IN ONE PLOT

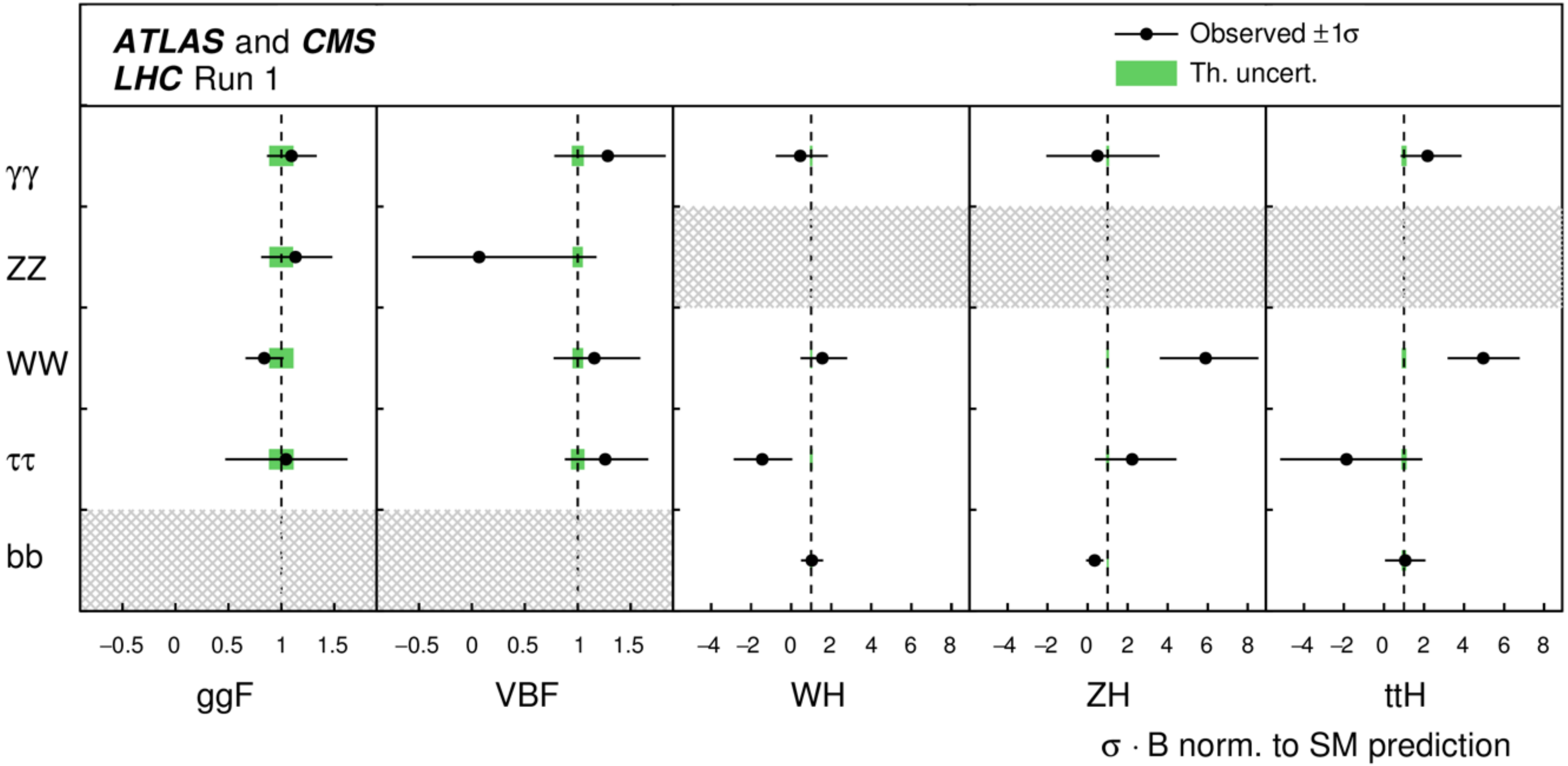
Scale individual Higgs couplings independently.

- Assumptions on total width.
- SM assumptions on gluon, photon coupling loop structures.

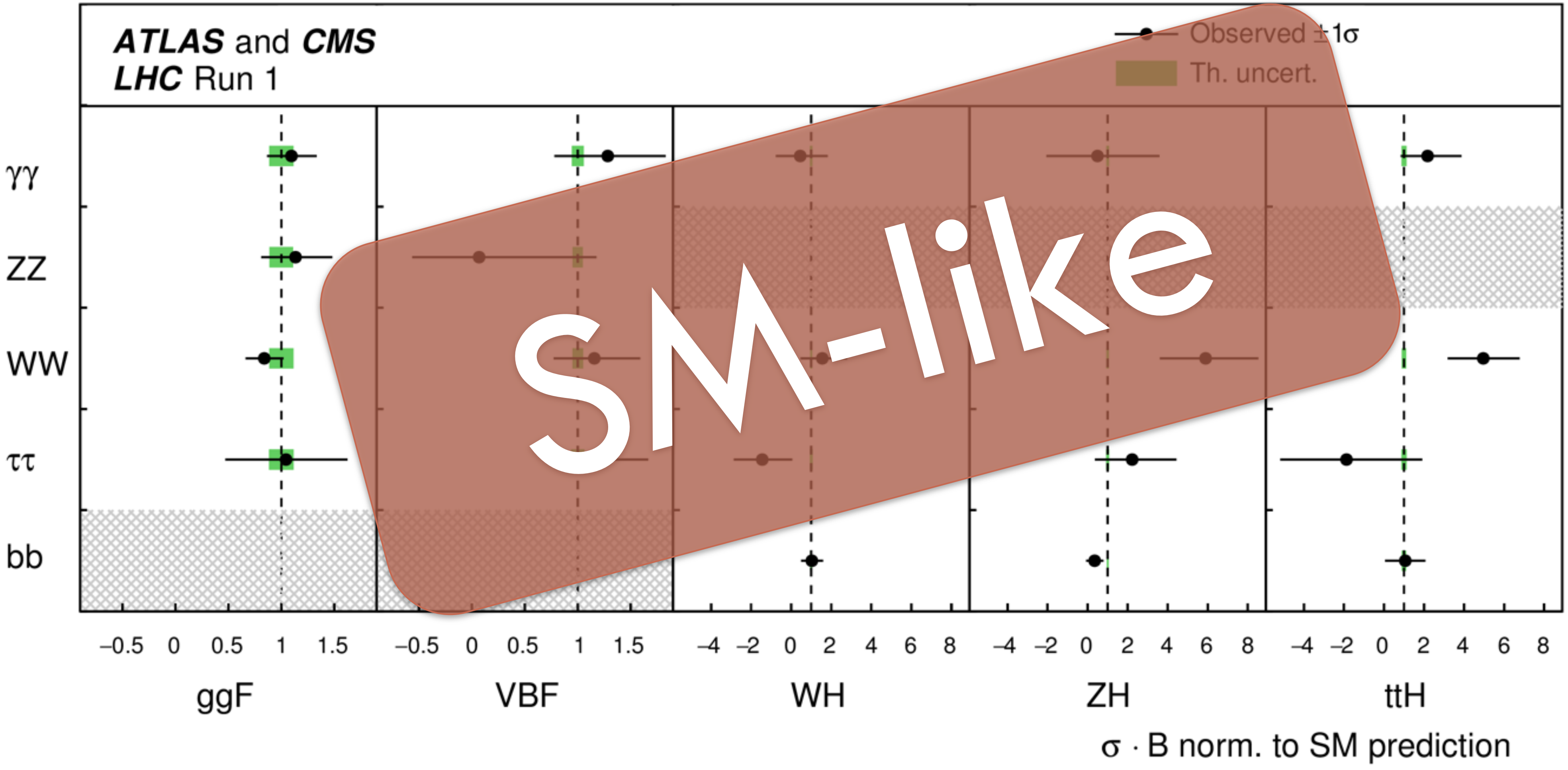




RUN1 IN ONE LESS MODEL-DEPENDENT PLOT



RUN1 IN ONE LESS MODEL-DEPENDENT PLOT



FAST FORWARD THROUGH RUN 2

Broader exploration enabled by large $O(100\ fb^{-1})$ datasets at 13 TeV.

Selected milestones of the last 5 years:

- Observation of $H \to \tau\tau$ decays.
- Observation of $H \to bb$ decays.
- Observation of ttH production.
- Reaching SM-level limits on $H \to \mu\mu$.

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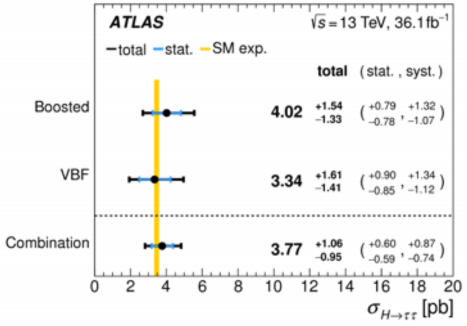

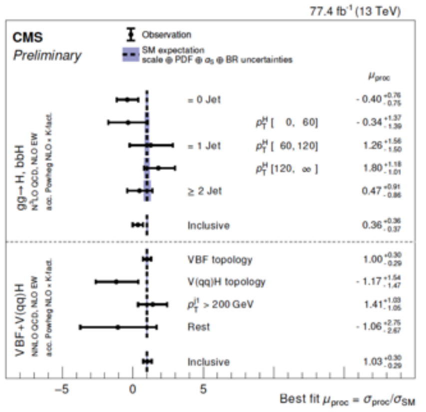

Production	ATLAS σ (36 fb^{-1})	CMS σ/μ (77 fb^{-1})
ggF (boosted)	4.02 ± 0.79 ± 1.3	σ= 1.11 ± 0.81 ± 0.78
VBF	3.34 ± 0.9 ± 1.34	σ=0.34 ± 0.08 ± 0.09
V(ll)H	-	μ=2.5 ± 1.4
comb	3.77 ± 0.6 ± 0.8	μ=1.24 ± 0.29

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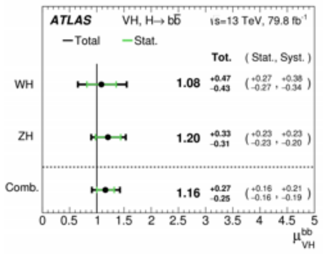

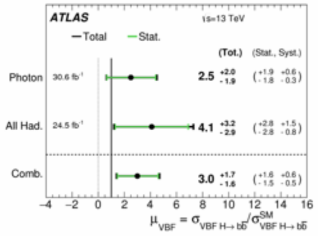

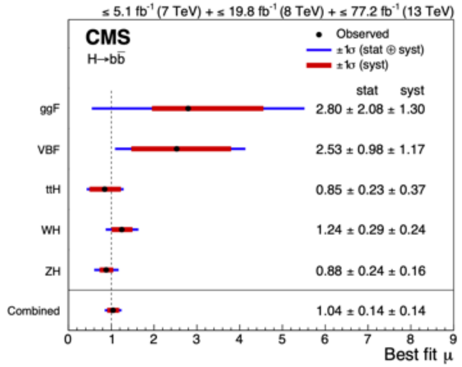

Production	ATLAS μ (Run I + *80 fb^{-1}(36fb^{-1}$))	CMS μ (Run I + 41 fb^{-1})
WH	1.08 ± 0.24 ± 0.29*	1.24 ± 0.29 ± 0.24
ZH	0.92 ± 0.21 ± 0.19*	0.88 ± 0.24 ± 0.16
VBF	2.5 ± 1.3 ± 0.5$	2.52 ± 0.98 ± 1.17
ttH	1.00 ± 0.28 ± 0.48$	0.85 ± 0.23 ± 0.37
ggF	5.8 ± 3.1 ± 2.5*	2.80 ± 2.08 ± 1.30
comb	1.01 ± 0.12 ± 0.16	1.01 ± 0.14 ± 0.14

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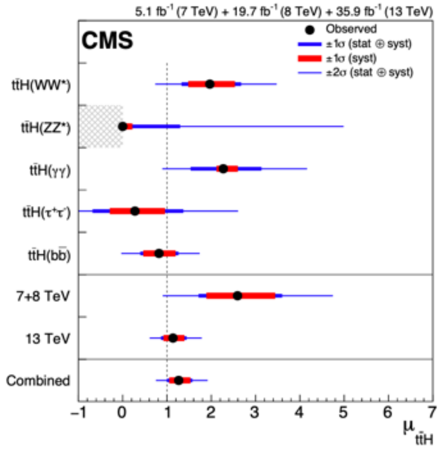

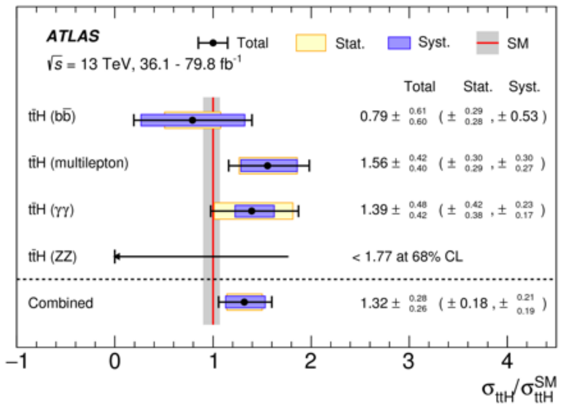

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ttH Run-2	CMS “μ + expected, total-only, uncertainties”		ATLAS “Cross-sections galore”	
Combination	Run-1 + 36 fb^{-1}	μ= 1.26 ±0.29 (±0.16 stat) 4.2σ exp (5.2σ obs)	Run-1 + 36–80 fb^{-1}	μ= 1.32 ±0.27 (±0.18 stat) 5.1σ exp (6.3σ obs)
H→bb	UP! 77 fb^{-1}	μ= 1.15 ±0.15 ±0.27 3.5σ exp (3.9σ obs)	36 fb^{-1}	μ= 0.84 ±0.29 ±0.56 1.6σ exp (1.4σ obs)
H→multi-ℓ	UP! 77 fb^{-1}	μ= 0.96 ±0.32 4.0σ exp (3.2σ obs)	36 fb^{-1}	μ= 1.6 ±0.4 ±0.4 2.8σ exp (4.1σ obs)
H→γγ	UP! 77 fb^{-1}	μ= 1.7 ±0.6 (±0.5 stat) 2.7σ exp (4.1σ obs)	UP! 139 fb^{-1}	μ= 1.38 ±0.39 (±0.33 stat) 4.2σ exp (4.9σ obs)
H→4ℓ	UP! 137 fb^{-1}	μ= 0.13 ± ~1	UP! 139 fb^{-1}	μ*= 1.2 ±1.2 ± 0.2 *STXS 0, |η|<2.5.

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H→γγ	UP! **77 fb^{-1}**	μ= 1.7 ±0.6 (±0.5 stat) **2.7σ exp**	UP! **139 fb^{-1}**	μ= 1.38 ±0.39 (±0.33 stat) **4.2σ exp** (4.9σ obs)
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Hard √2 ✅ – much work on systs.

~√2 ✅ on stat.-limited channel

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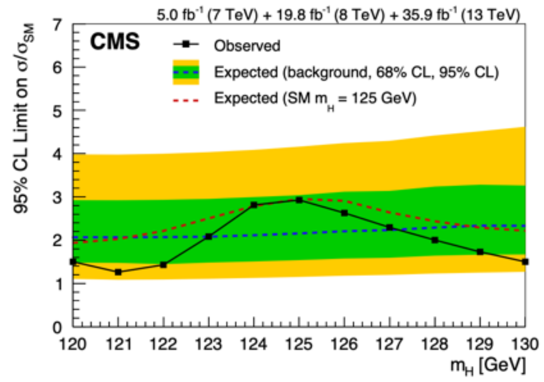
H→bb	UP! 77 fb^{-1}	μ= 1.15 ±0.15 **±0.27** **3.5σ exp** (	36 fb^{-1}	μ= 0.84 ±0.29 **±0.56** **1.6σ exp** (1.4σ obs)
H→multi-ℓ	UP! 77 fb^{-1}	μ= 0.96 ±0.32 4.0σ exp (3.2σ obs)	36 fb^{-1}	μ= 1.6 ±0.4 ±0.4 2.8σ exp (4.1σ obs)
H→γγ	UP! 77 fb^{-1}	μ= 1.7 ±0.6 (±0.5 stat) 2.7σ exp (4.1σ obs)	UP! 139 fb^{-1}	μ= 1.38 ±0.39 (±0.33 stat) 4.2σ exp (4.9σ obs)
H→4ℓ	UP! 137 fb^{-1}	μ= 0.13 ± ~1	UP! 139 fb^{-1}	μ*= 1.2 ±1.2 ± 0.2 *STXS 0, |η|<2.5.

tt+HF modeling

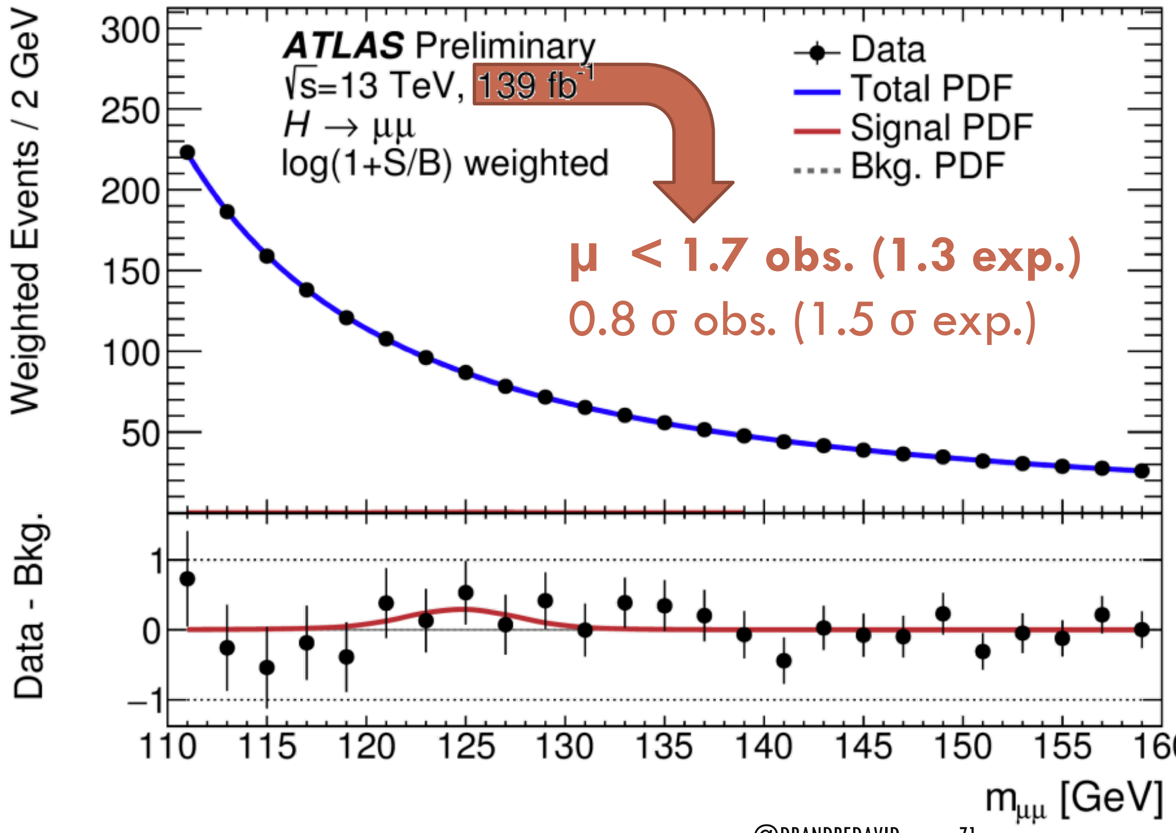
FAST FORWARD THROUGH RUN 2



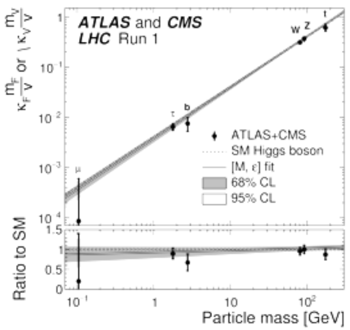
Broader exploration enabled by large O(100 fb^{-1}) datasets at 13 TeV.

Selected milestones of the last 5 years:

- Observation of H→ττ decays.
- Observation of H→bb decays.
- Observation of ttH production.
- **Reaching SM-level limits on H→μμ.**



FAST FORWARD THROUGH RUN 2



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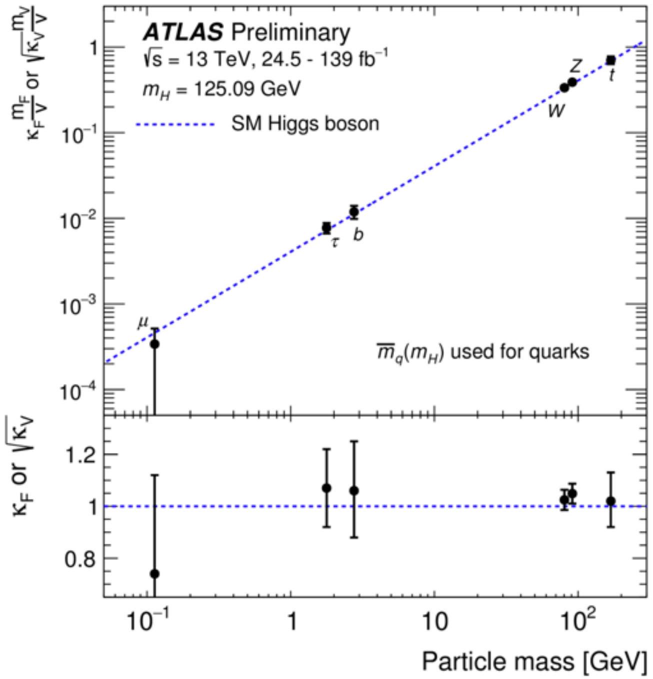
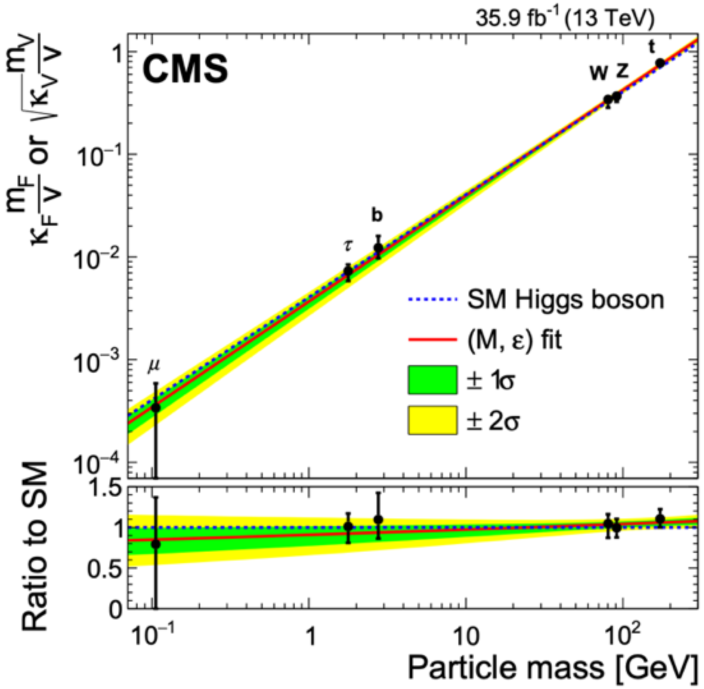
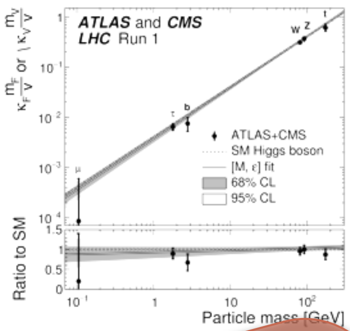




FAST FORWARD THROUGH RUN 2



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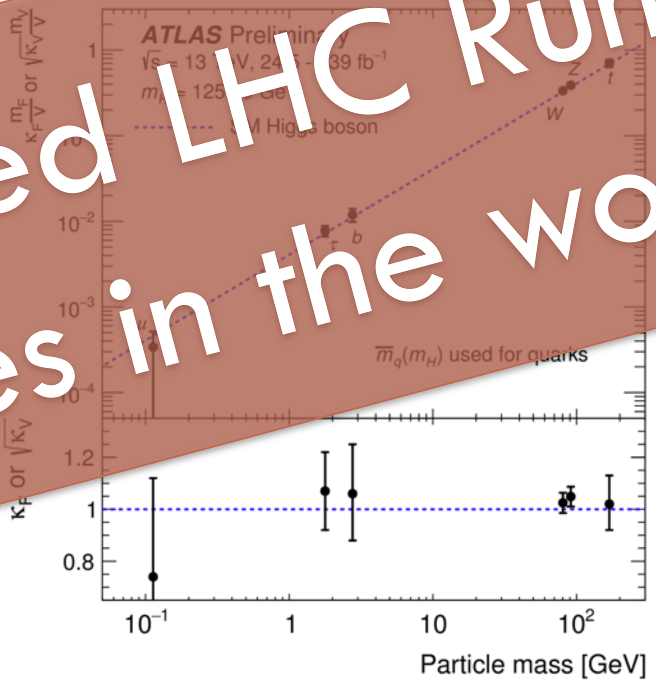
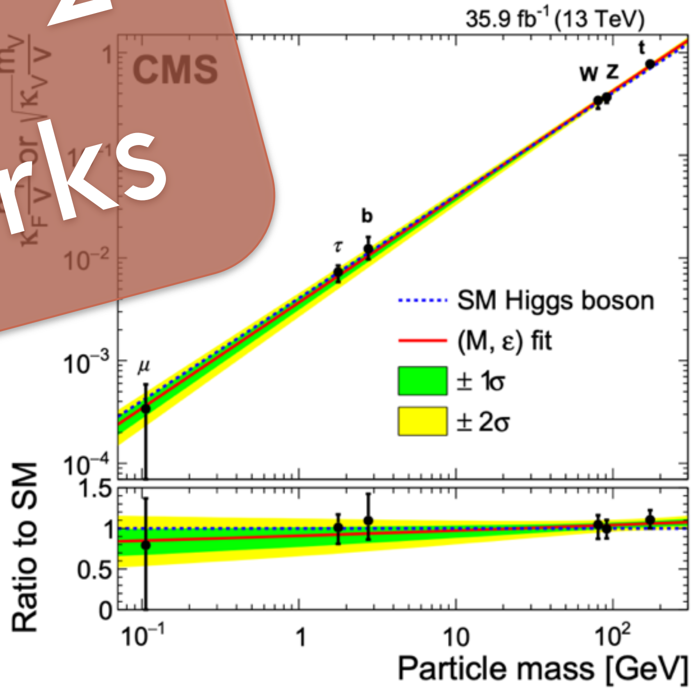
Combined LHC Run 2 analyses in the works





2010-2011
Test statistics
Nuisance parameters
RooWorkspace exchange

Setting the stage

2014-2016
m_H
Kappa-framework

Run-1 combinations

2019-2020
Fiducial and differential
m_H
STXS stage 1.1
...

Run-2 combinations

2023–2024?
…
SMEFT?

Run-3 combinations?

Post-fit observation: the LHC HGC has strong interactions every 4 to 5 years…

LHC HIGGS COMBINATION GROUP

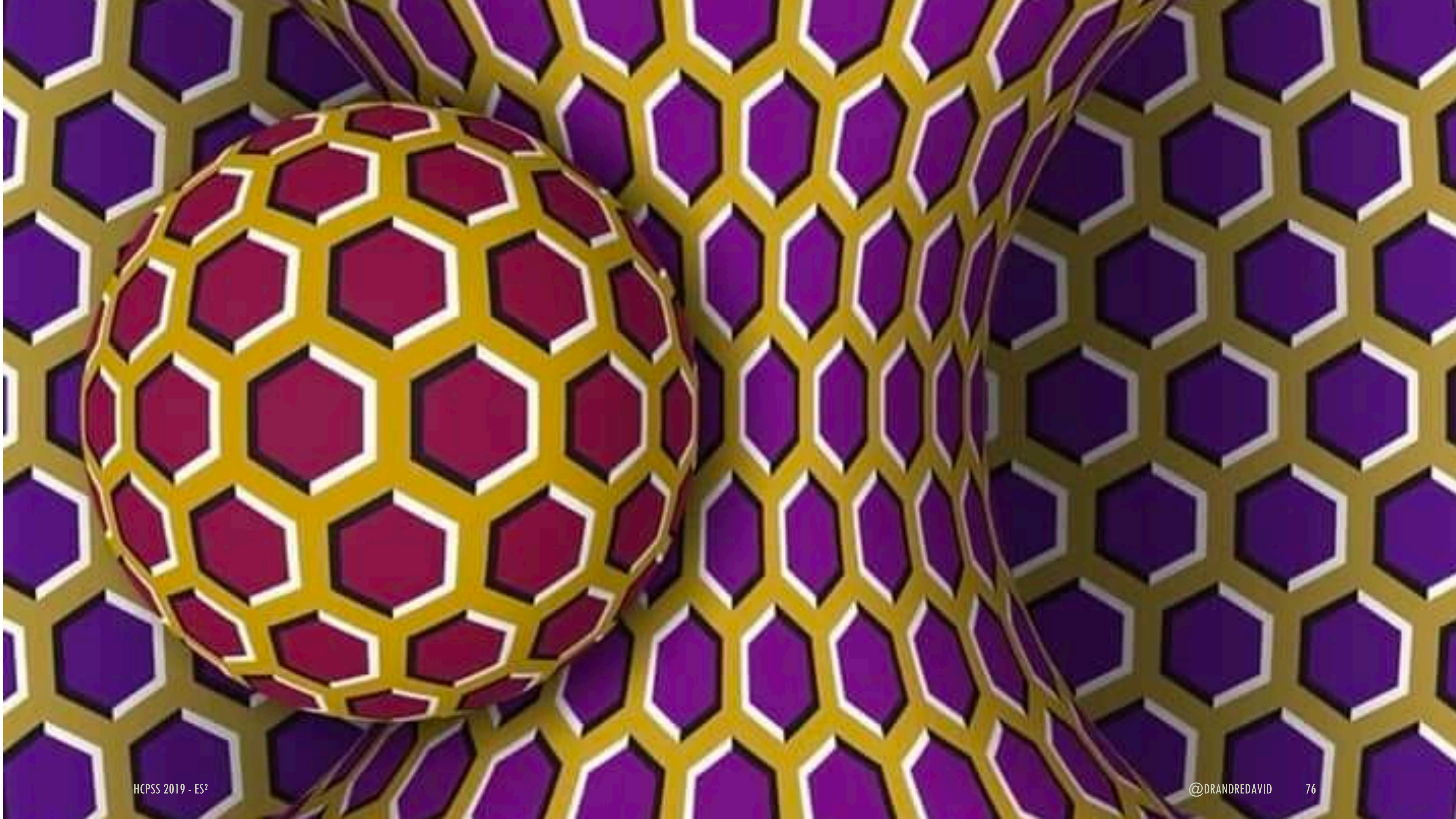
EPISODE VII – THE FORCE AWAKENS

Predicted in 1964, an elementary scalar was discovered in 2012.

- *Primus inter pares* (or pariah) of elementary particles.
  - Coupling to electron: **atomic radii.**
  - Coupling to up/down: **proton stability.**
  - Self-coupling: **EWK phase transition** of Universe.
  - Coupling to top: **stability of EWK vacuum.**
- **The "spherical cow" of particle physics.**
  - No charge, no spin, no structure (that we can presently resolve).

All measurements to date set H(125) as compatible with the SM.

- With more data, different and more detailed analyses of its properties become possible…



EPISODE VIII – THE LAST JEDI

Constraining other scalars.
Sharpening the exploration tools.
Going differential.
Seeing self-double.
Going beyond the horizon.

YESTERDAY AND TODAY

Episode VII – The Force Awakens

The scalar solution.

The scalar discovery.

Com{plex,bined} measurements.

Present of this many-faced scalar.

Coming up at the horizon.

Episode VIII – The Last Jedi

Constraining other scalars.

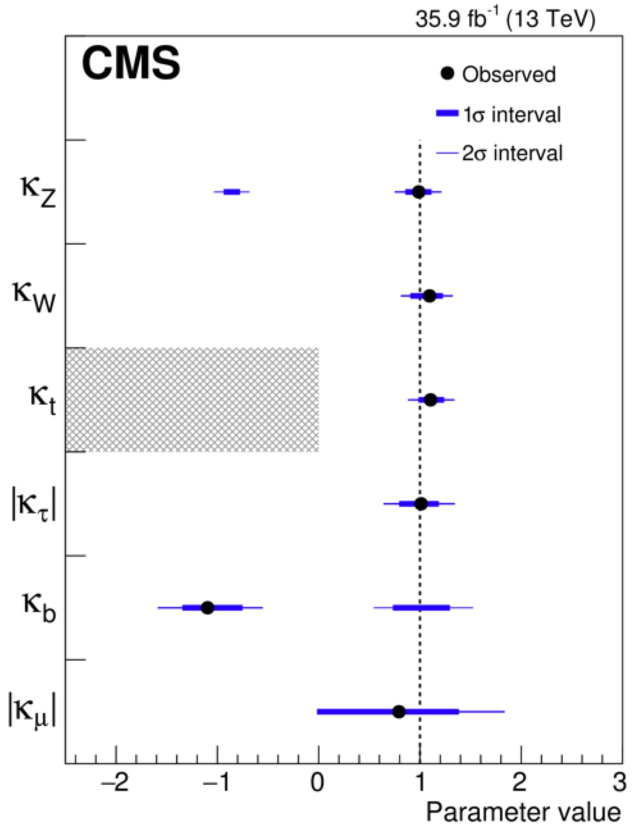
Sharpening the exploration tools.

Going differential.

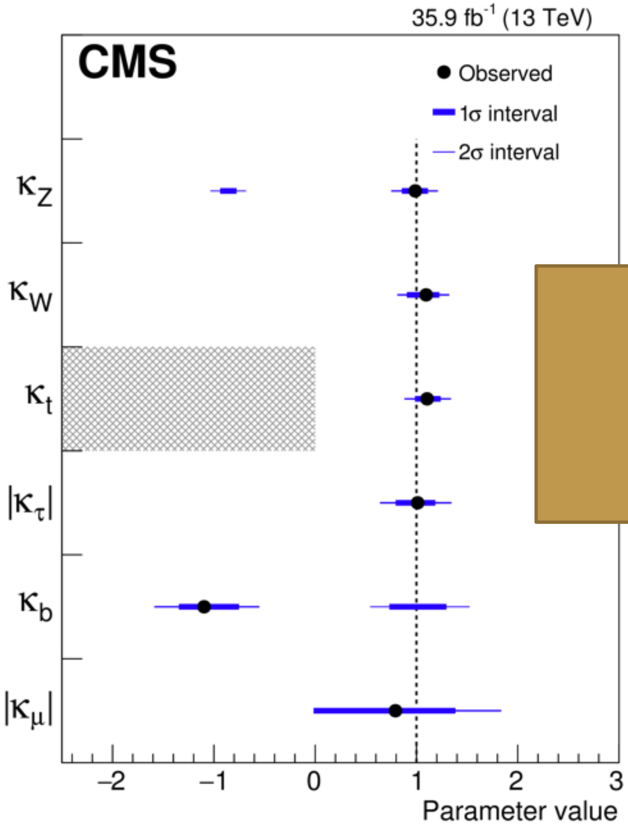
Seeing self-double.

Going beyond the horizon.

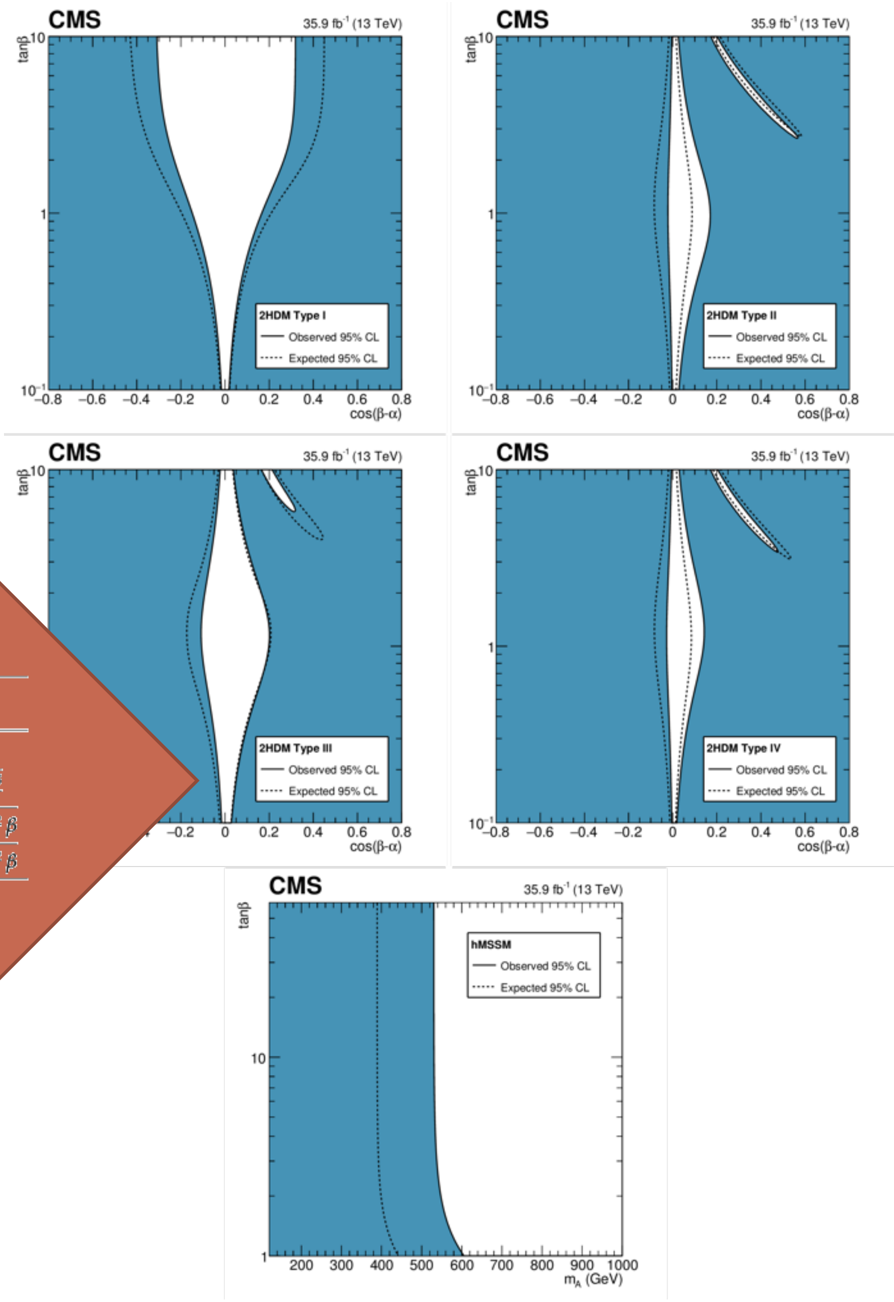
H(125) PROPERTIES CONSTRAIN OTHER SCALARS



SCALARS CAN MIX, SHARE VEV

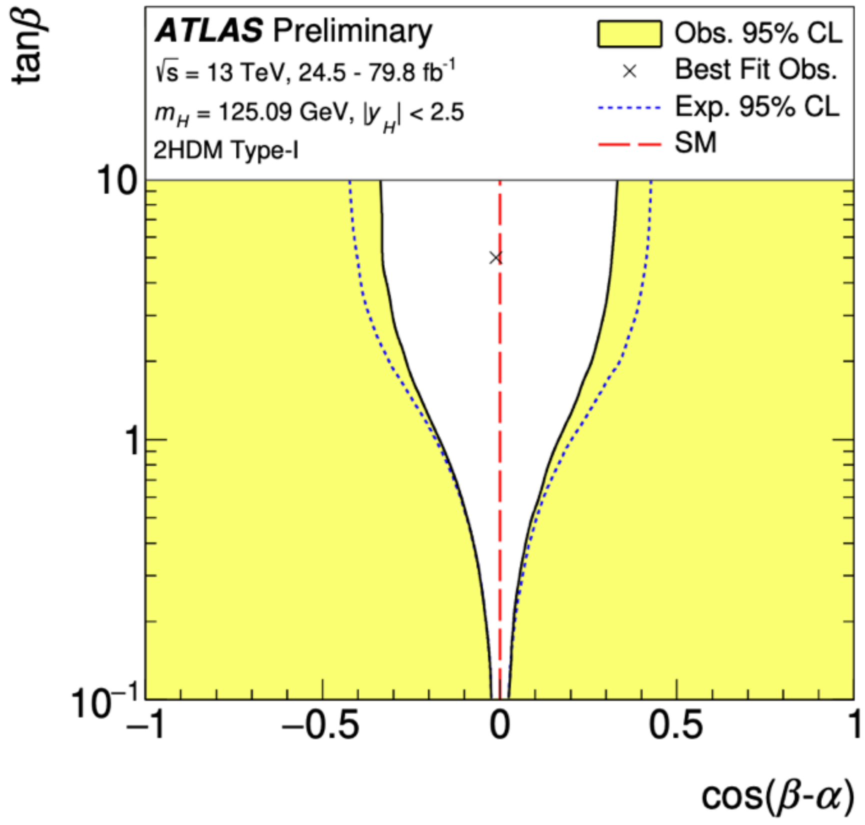


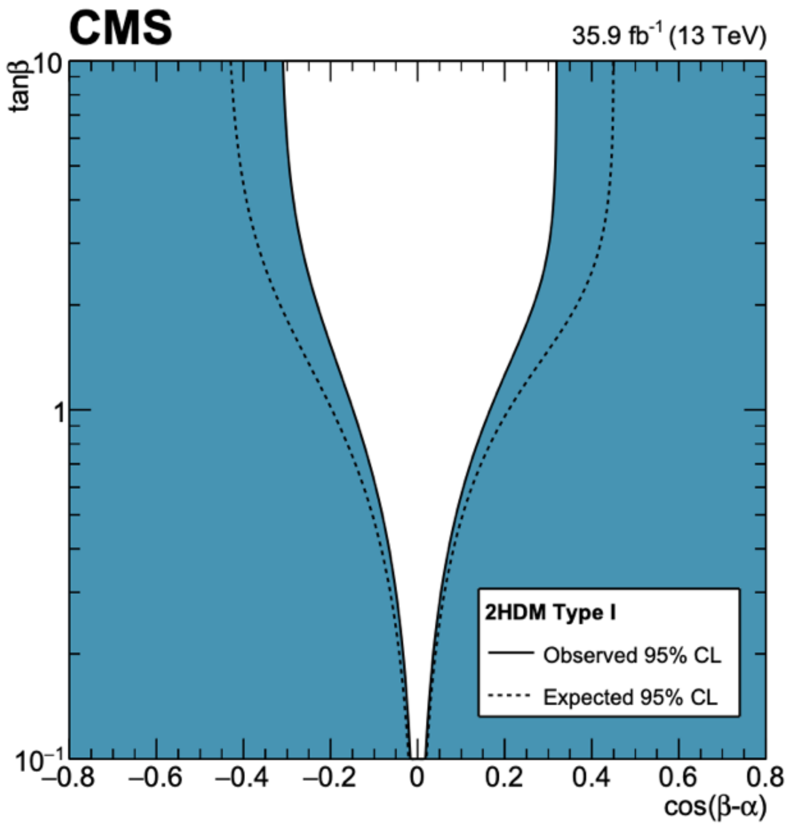
	2HDM				hMSSM
	Type I	Type II	Type III	Type IV	
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\frac{s_d+s_u\tan\beta}{\sqrt{1+\tan^2\beta}}$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$s_u\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$s_d\sqrt{1+\tan^2\beta}$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$s_d\sqrt{1+\tan^2\beta}$



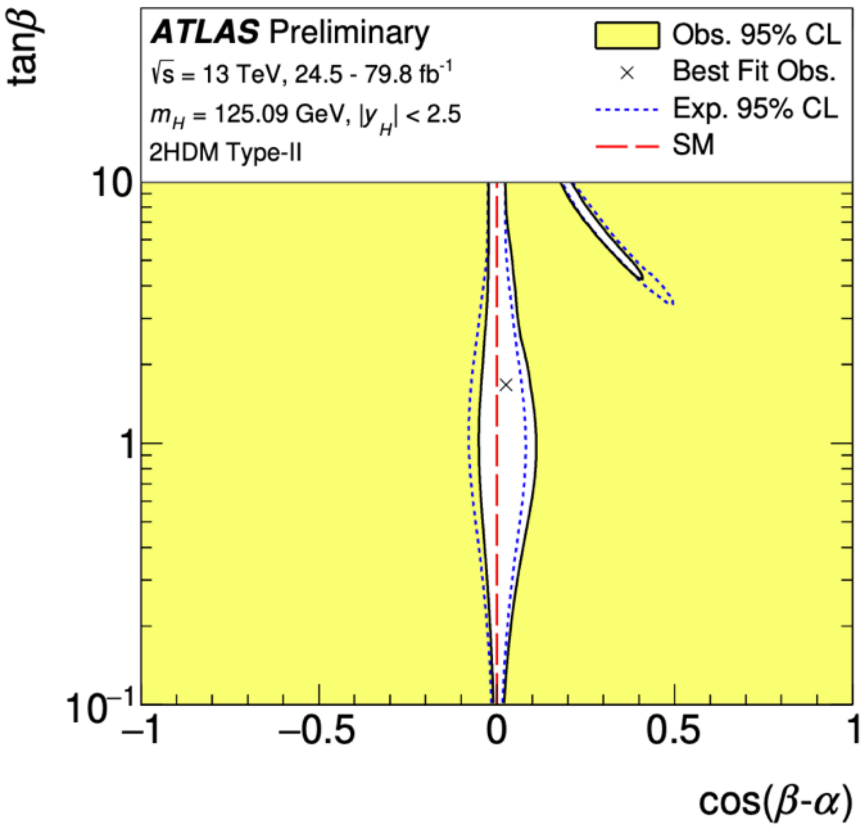
2HDM ∋ h, H, A, H$^\pm$

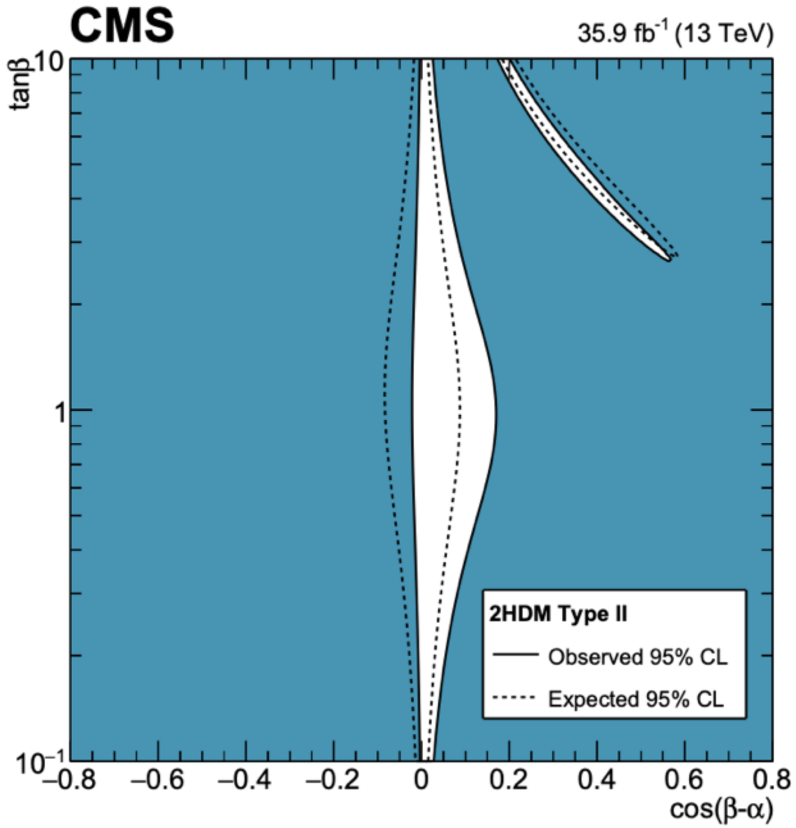
EXTENDED SCALAR SECTORS – 2HDM TYPE-I





EXTENDED SCALAR SECTORS – 2HDM TYPE-II





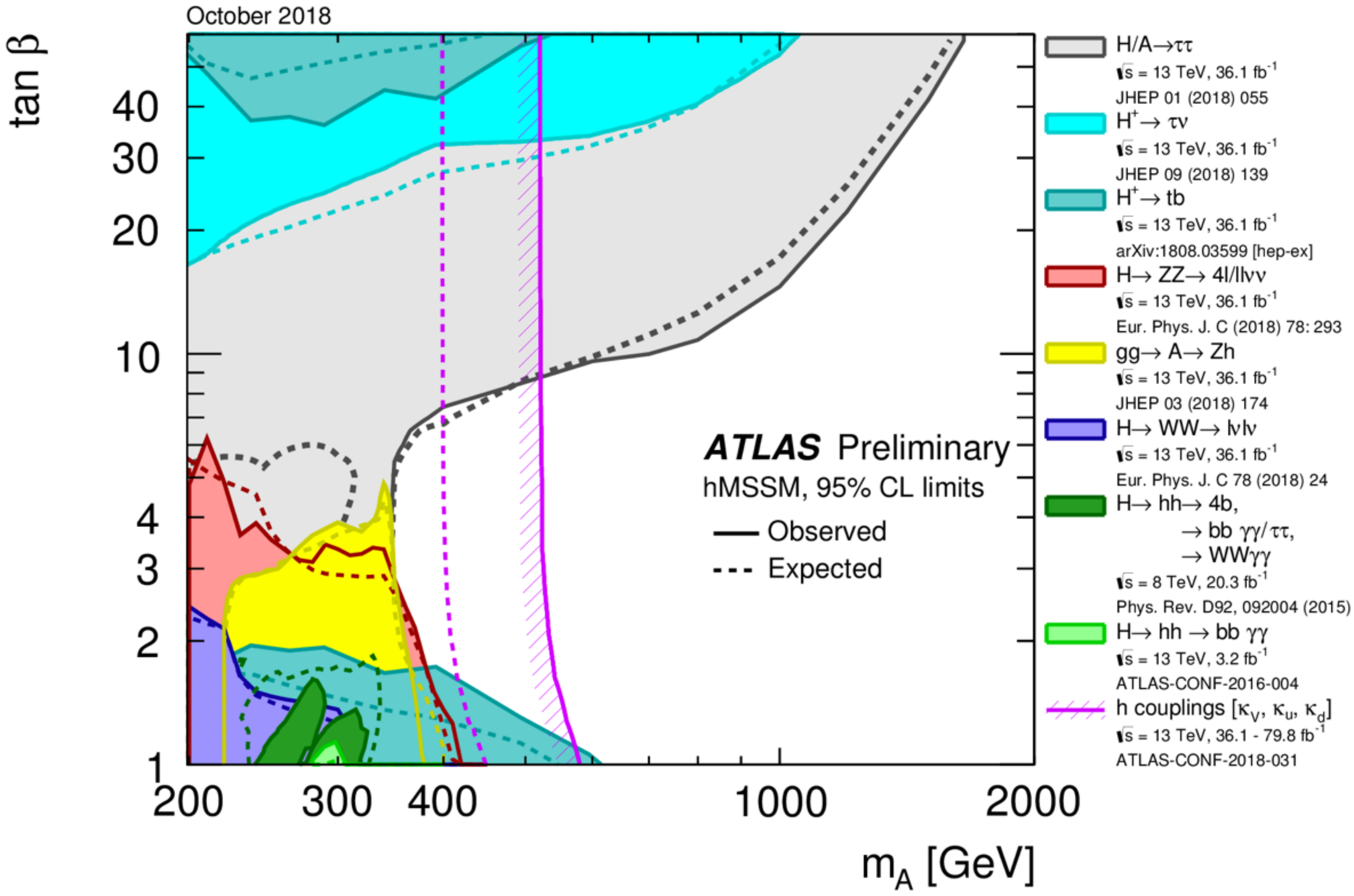
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/HIGGS/

EXTENDED SCALAR SECTORS – DIRECT SEARCHES

hMSSM interpretation example.

- Dozens of direct searches.
- Relevance of H(125) indirect limits.

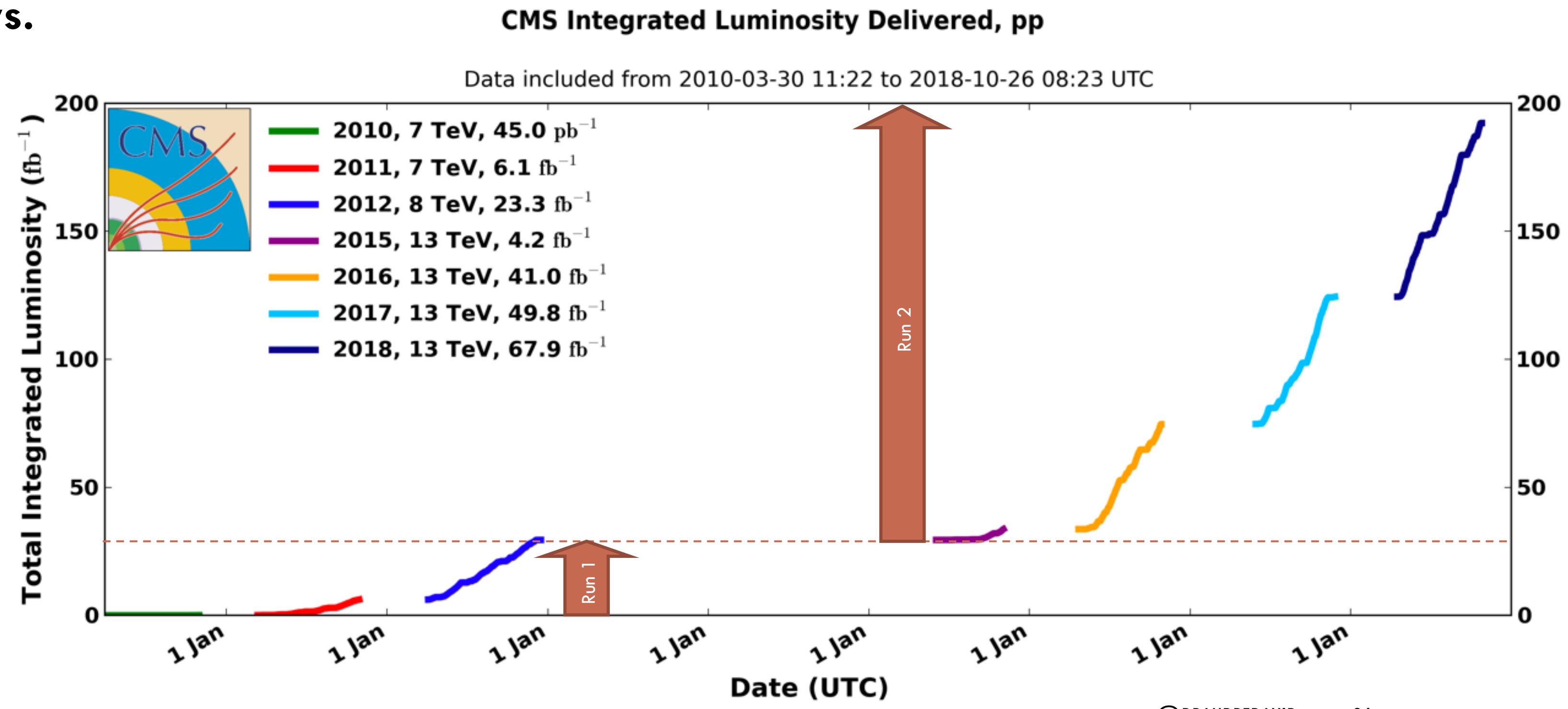
Dozens more searches to be discovered in the literature.



RUN 2 DATASET: BREADTH AND **DEPTH**

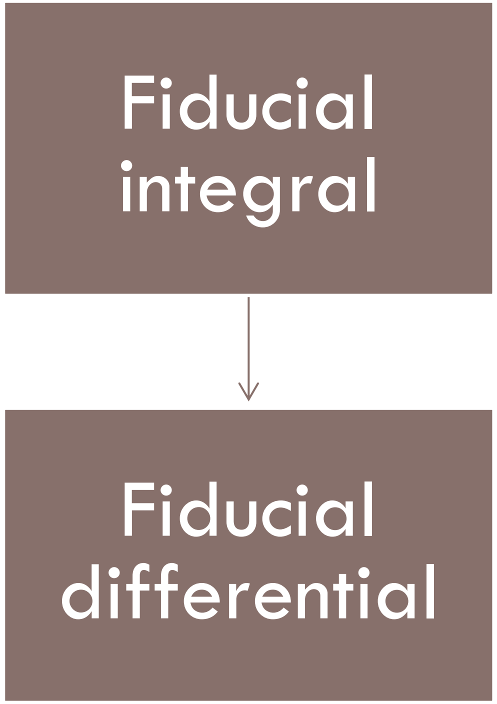
More data allows:

- To do more things the same way.
- To do **other things in new ways.**

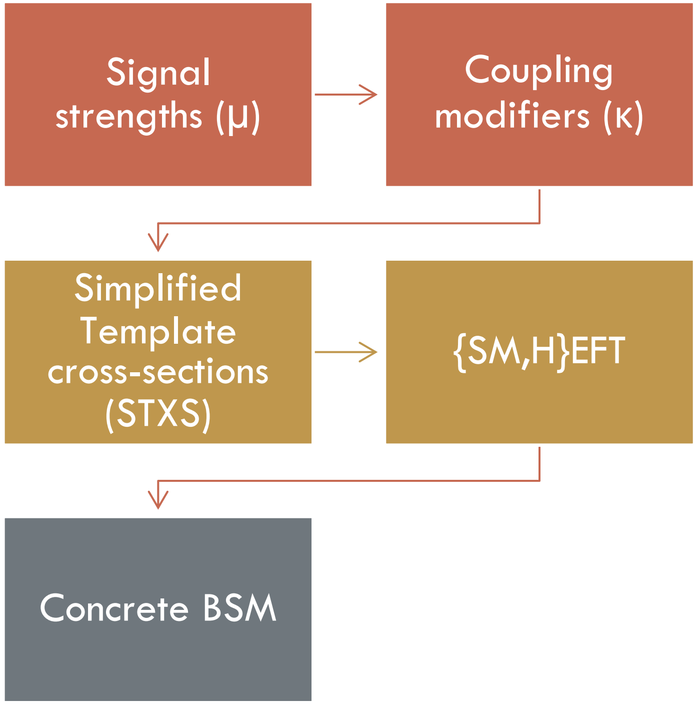


TWO COMPLEMENTARY AVENUES

Perennial measurements
(~ independent from theory)



Tools to find deviations from SM
(depend on theory tools)



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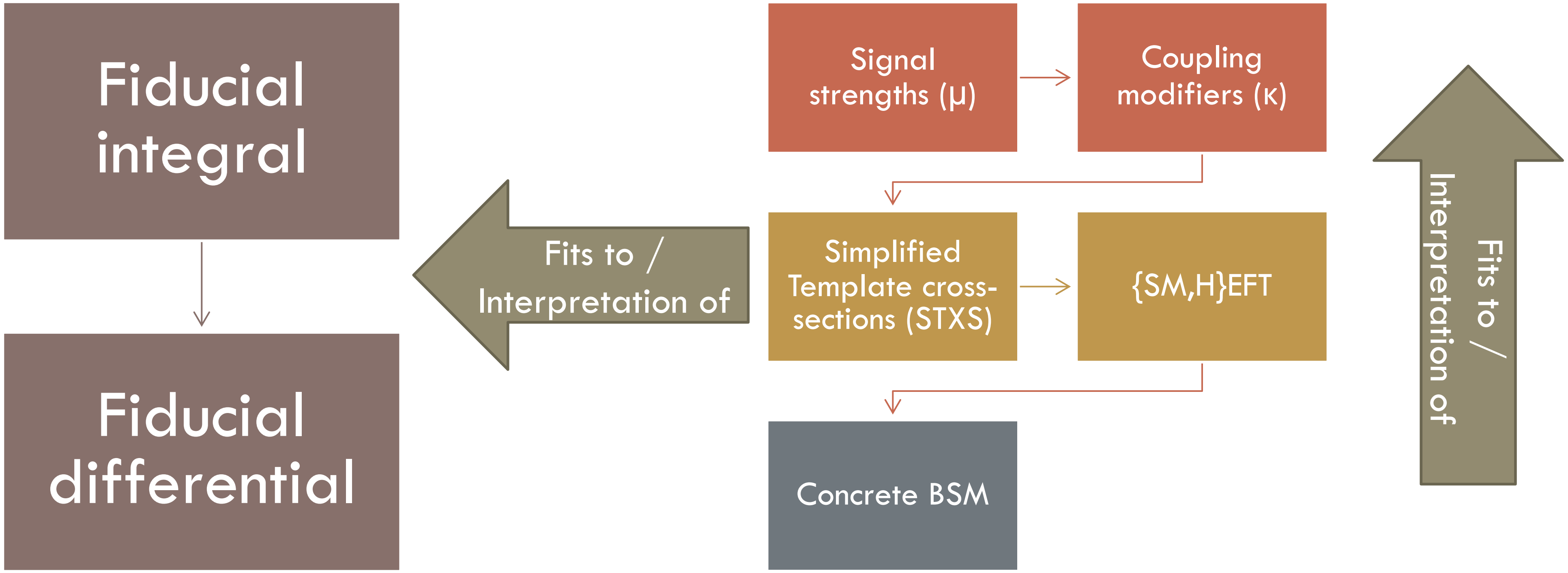
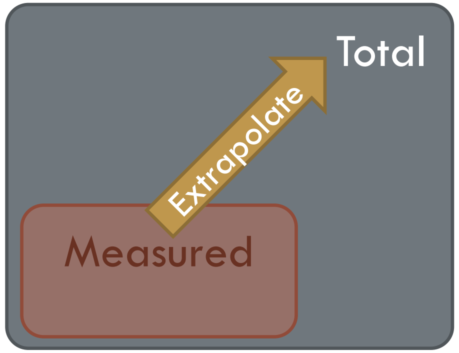


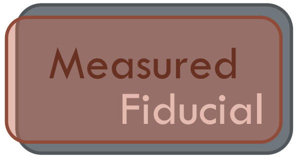
CROSS-SECTION MEASUREMENTS



Total

- Detectors have limited acceptance (A<1) for processes.
- A≪1 implies large, model-dependent, extrapolation.

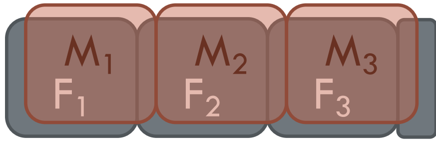
$$\sigma = \frac{N}{A \times \epsilon \times L}$$



Fiducial integral

- Fiducial volume chosen such that $A_{fid} \sim 1$.
- Careful "fid" definition can keep ε_{fid} model-independent.

$$\sigma_{\text{fid}} = \frac{N}{(A_{\text{fid}} \sim 1) \times (\epsilon_{\text{fid}} \sim \text{const}) \times L}$$



Fiducial differential

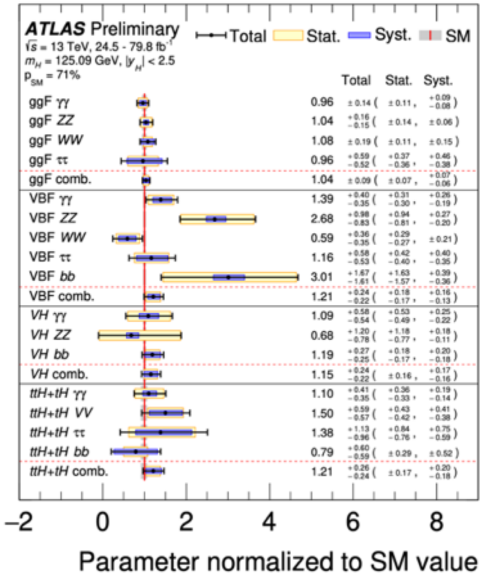
- Many contiguous fiducial cross-sections.
- Migration across contiguous bins.
  - Unfolding reconstruction (Simulation^{-1}) accounts for that.

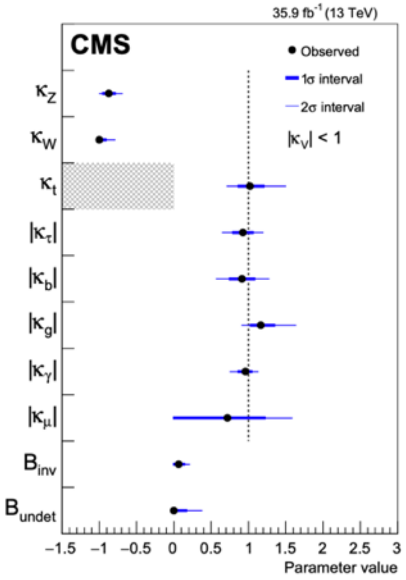
$$\vec{\sigma}_{\text{gen}} = \text{Simulation}^{-1}\left(\frac{\vec{N}}{\vec{\epsilon} \times L}\right)$$

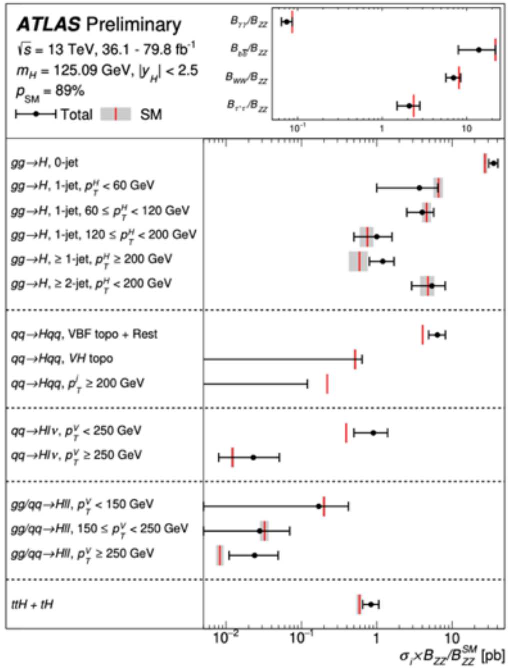
$$\vec{\sigma}_{\text{reco}} = \frac{\vec{N}}{\vec{\epsilon} \times L}, \vec{\sigma}_{\text{reco}} = \text{Simulation}(\vec{\sigma}_{\text{gen}})$$

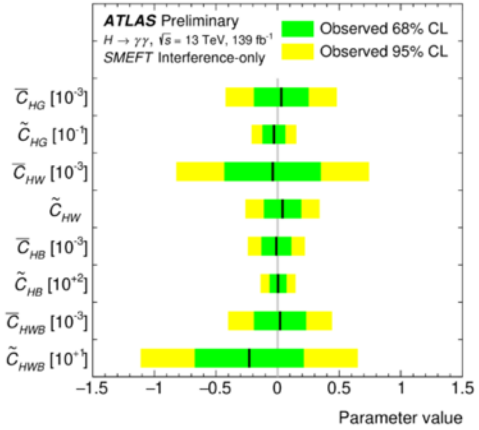
{CONSTRAIN,DISCOVER}ING BSM

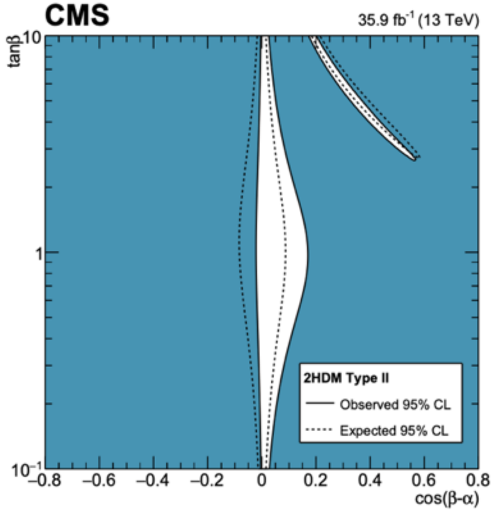
Signal strengths (μ) → Coupling modifiers (κ) → Simplified Template cross-sections (STXS) → {SM,H}EFT → Concrete BSM











DEFORMING THE SM

Signal strengths (μ) → Coupling modifiers (κ) → Simplified Template cross-sections (STXS) → {SM,H}EFT → Concrete BSM

μ and κ basically change only overall normalizations.

No refined interpretation, but μ = κ = 1 recovers the best SM prediction.

STXS are regions with high BSM potential (tails) or complex theory uncertainties like QCD resummation.

EFT Wilson coefficients change shapes in multidimensional differential distributions in a correlated way.

Not applicable.

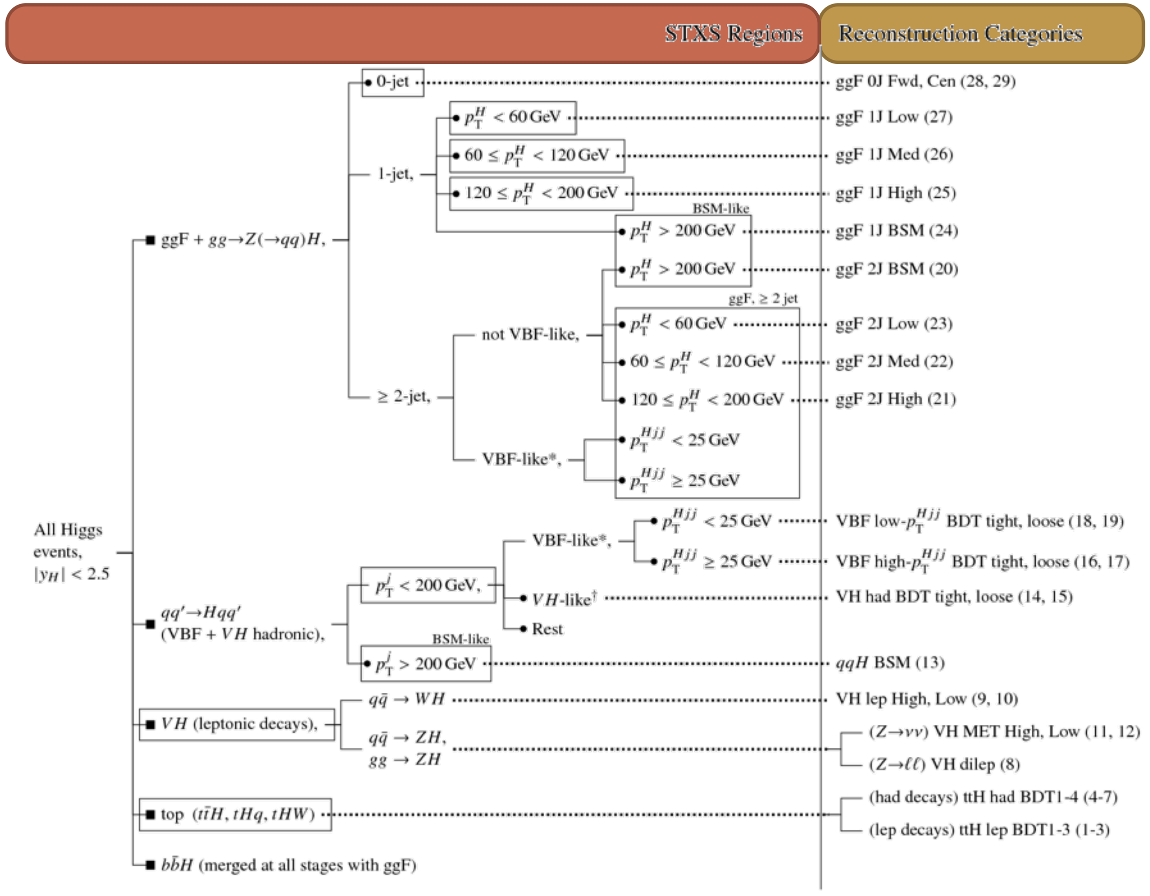
It's a whole different theory after all.

DEFORMING THE SM

Signal strengths (μ) → Coupling modifiers (κ) → **Simplified Template cross-sections (STXS)** → {SM,H}EFT → Concrete BSM

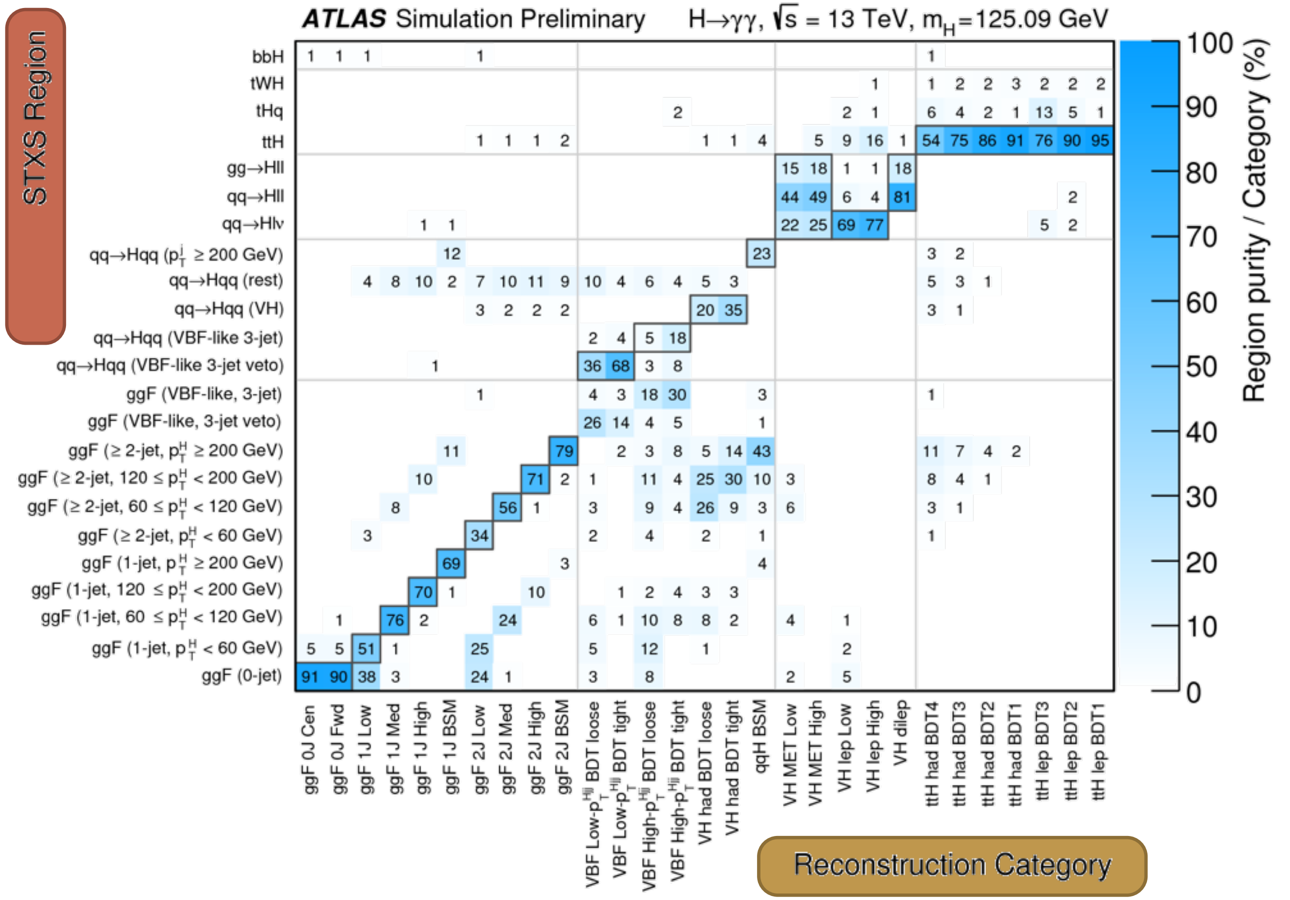
STXS are regions with high BSM potential (tails) or complex theory uncertainties like QCD resummation.

SIMPLIFIED FOR SOME, TEMPLATES FOR OTHERS

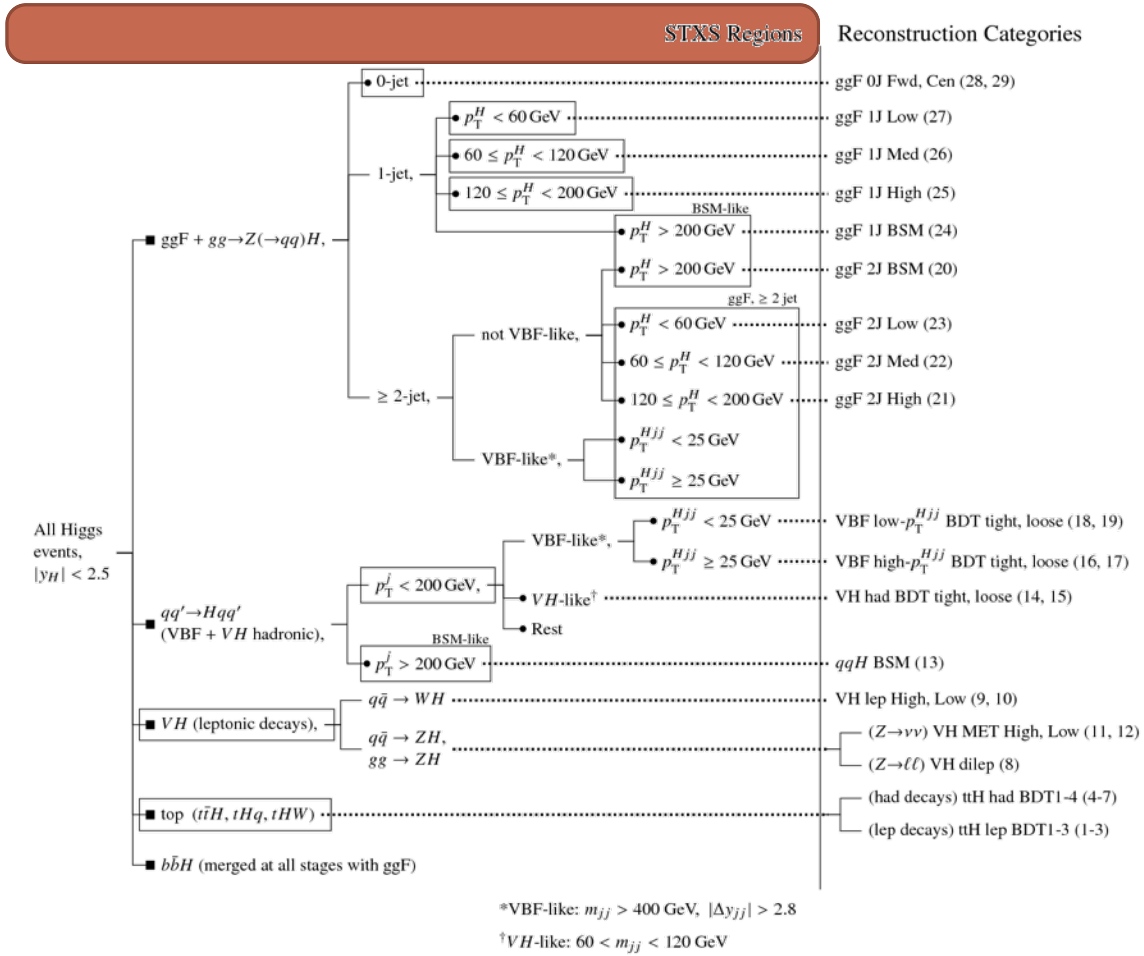


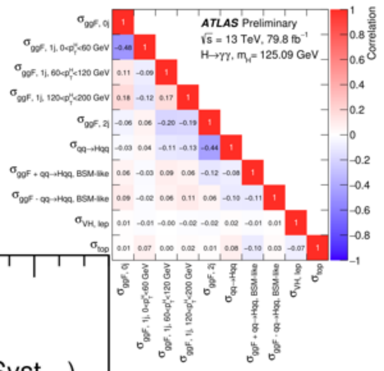
*VBF-like: $m_{jj} > 400$ GeV, $|\Delta y_{jj}| > 2.8$

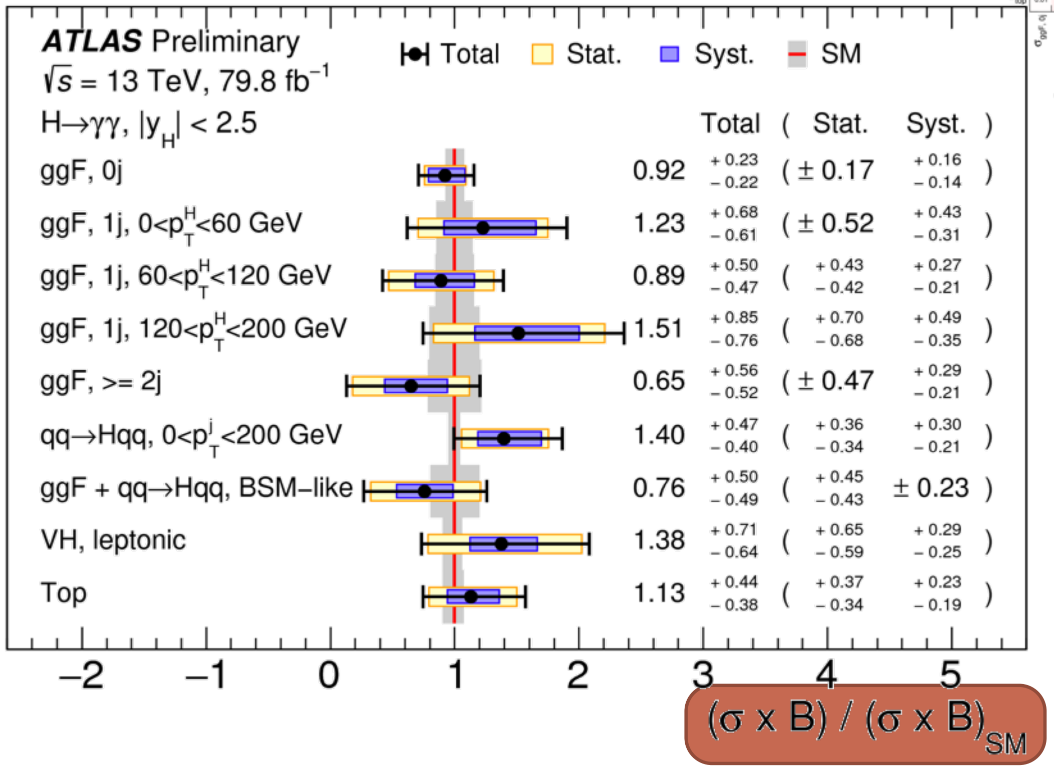
†VH-like: $60 < m_{jj} < 120$ GeV



SIMPLIFIED FOR SOME, TEMPLATES FOR OTHERS







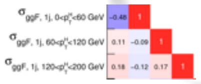
SIMPLIFIED FOR SOME, TEMPLATES FOR OTHERS

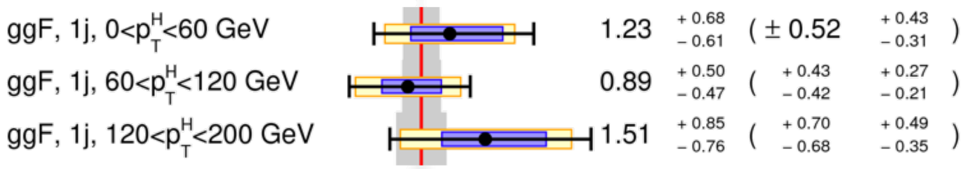
Can recompute ggF 1-jet XS *a posteriori*.

- E.g., if QCD theory uncertainties change.

"Just" needs **STXS measurements**.

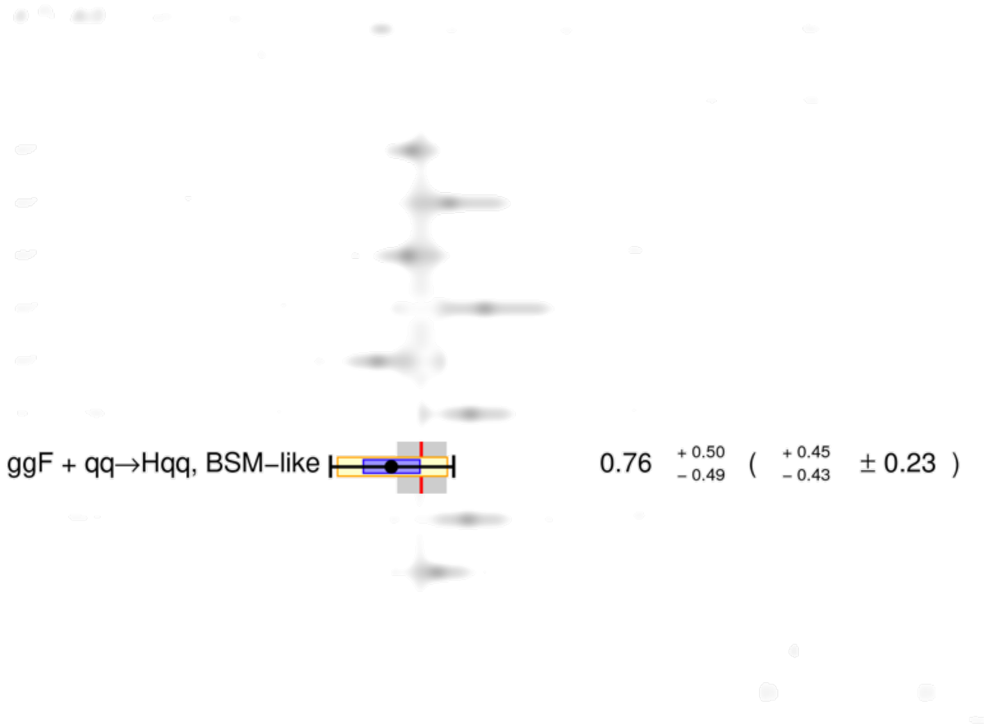
- And their **covariance**.





SIMPLIFIED FOR SOME, TEMPLATES FOR OTHERS

Single out high-p_T, BSM-sensitive, regions.



DEFORMING THE SM

Signal strengths (μ) → Coupling modifiers (κ) → Simplified Template cross-sections (STXS) → {SM,H}EFT → Concrete BSM

EFT Wilson coefficients change shapes in multidimensional differential distributions in a correlated way.

SMEFT

Super Mega Epic Fun Time

NOT ALL EFT ARE BORN THE SAME

⬇️ Top-down EFT

Full theory known: 🤓

- Matching conditions bridge EFT and full theory.

NOT ALL EFT ARE BORN THE SAME

⬇️ Top-down EFT

Full theory known: 🤓

- Matching conditions bridge EFT and full theory.

NOT ALL EFT ARE BORN THE SAME

⬇️ Top-down EFT

Full theory known: 🤓

- Matching conditions bridge EFT and full theory.

⬆️ Bottom-up EFT

Full theory unknown: 🤔

- Add operators as theory can calculate and data can discern.

NOT ALL EFT ARE BORN THE SAME

⬇️ Top-down EFT

Full theory known: 🤓

⬆️ Bottom-up EFT

Full theory **unknown**: 🤔

https://arxiv.org/abs/1412.1837

IN PRACTICE

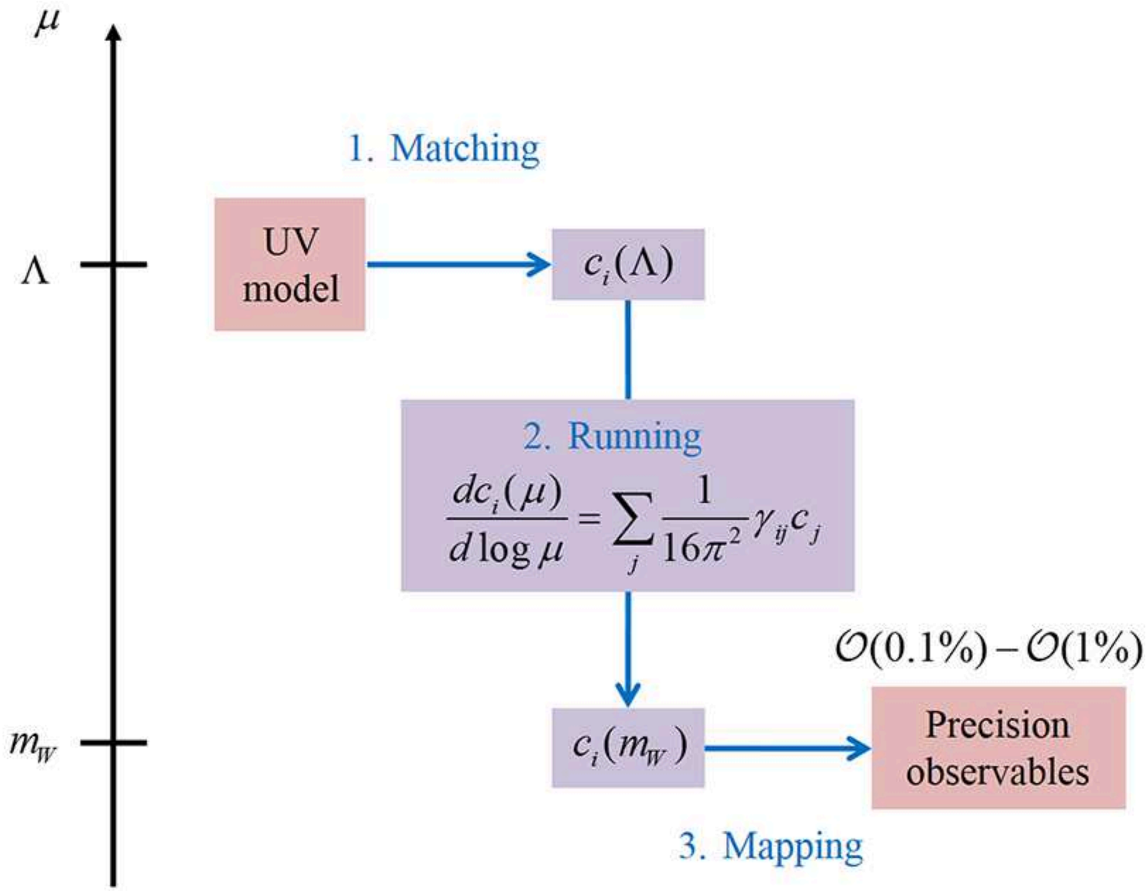
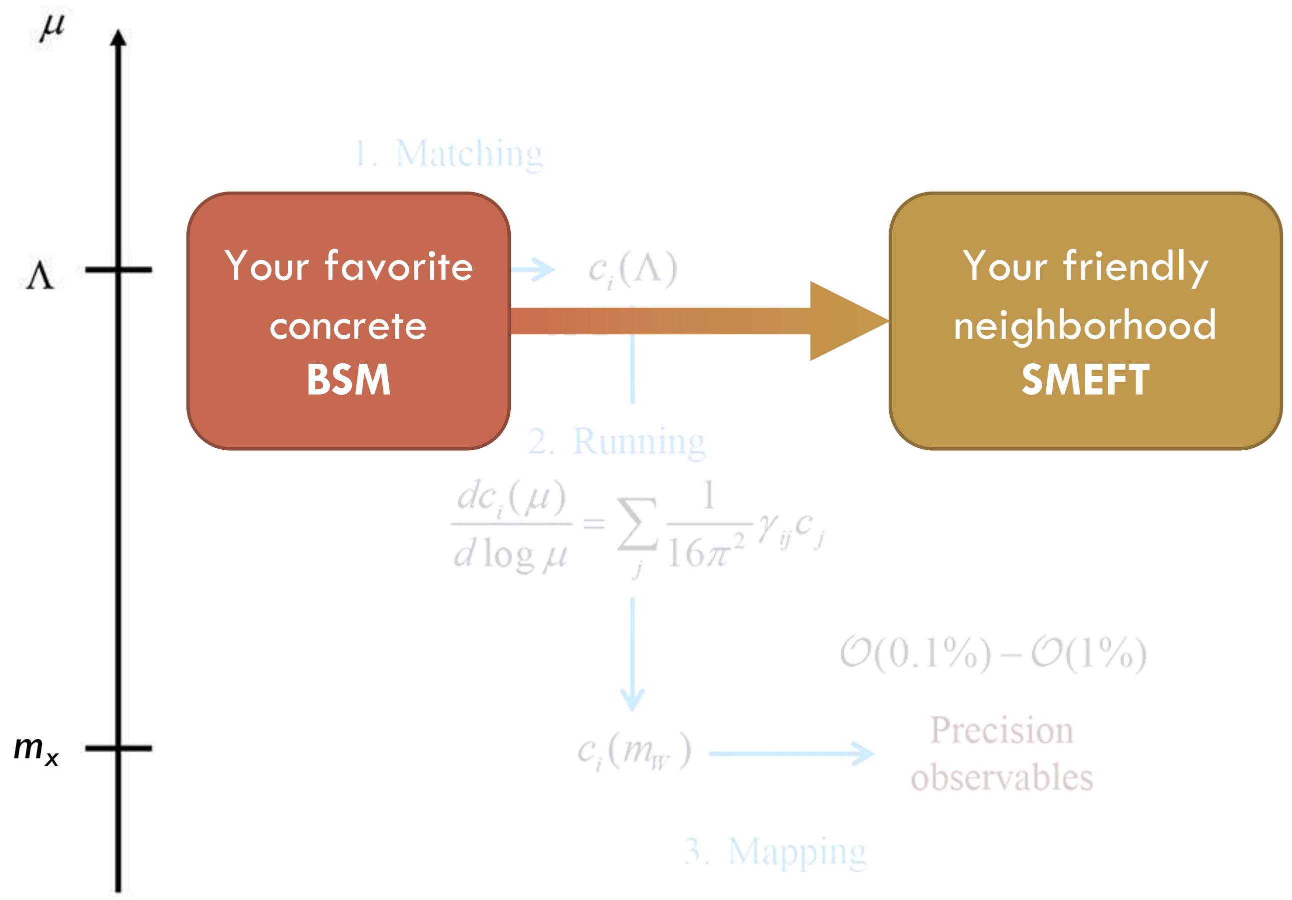
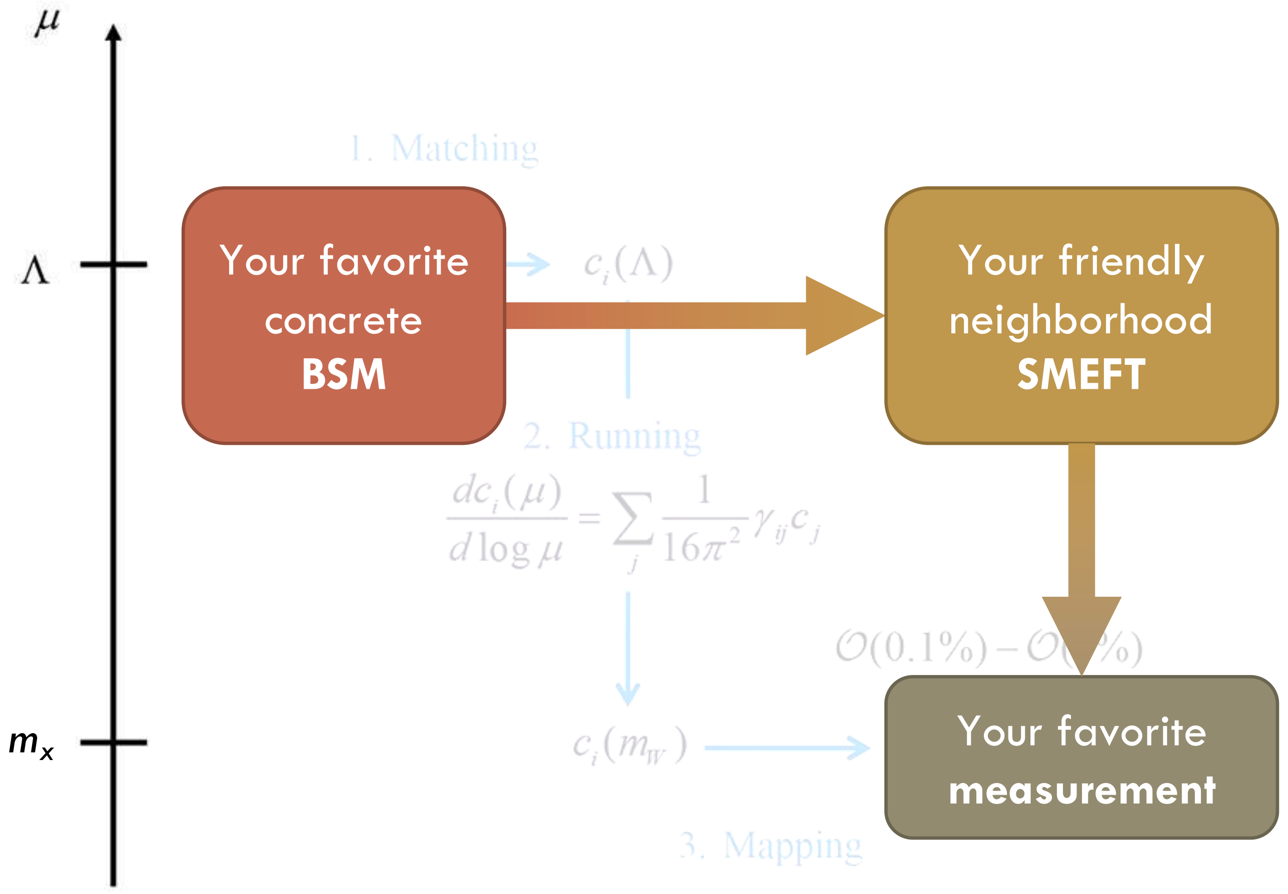


Figure 1. SM EFT as a bridge to connect UV models and weak scale precision observables.

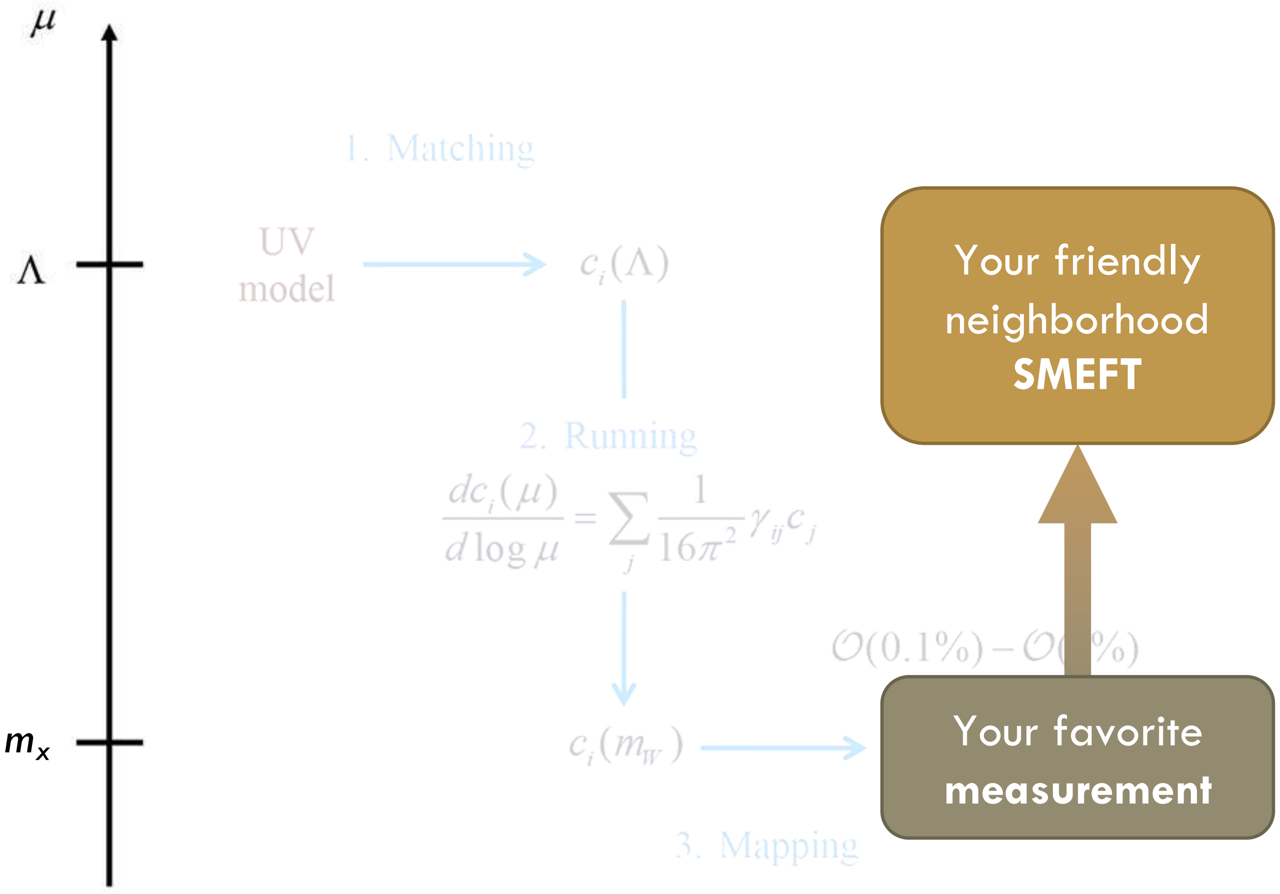
IN PRACTICE: 💻 COMPUTE ⟶ PREDICT



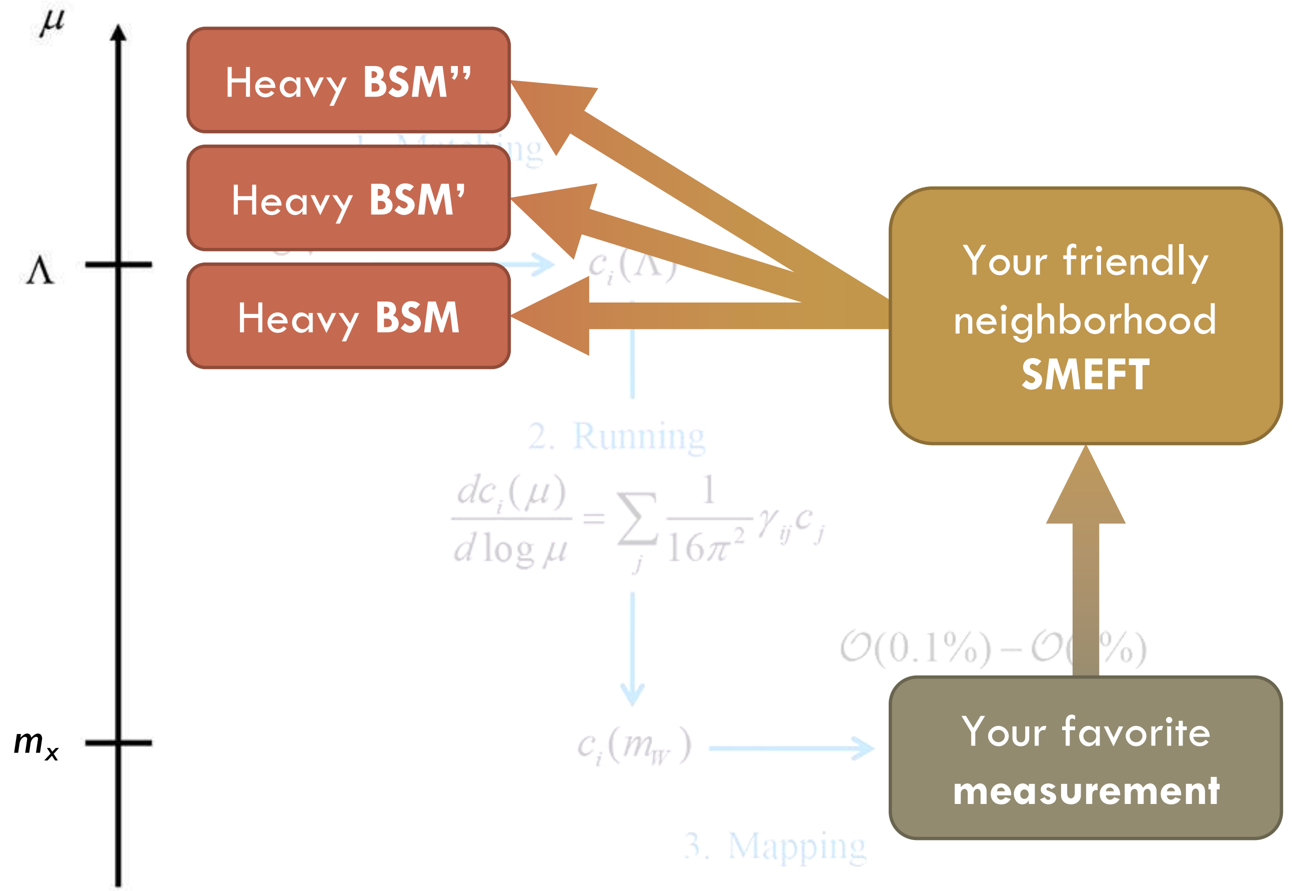
IN PRACTICE: 💻 COMPUTE ⟶ PREDICT



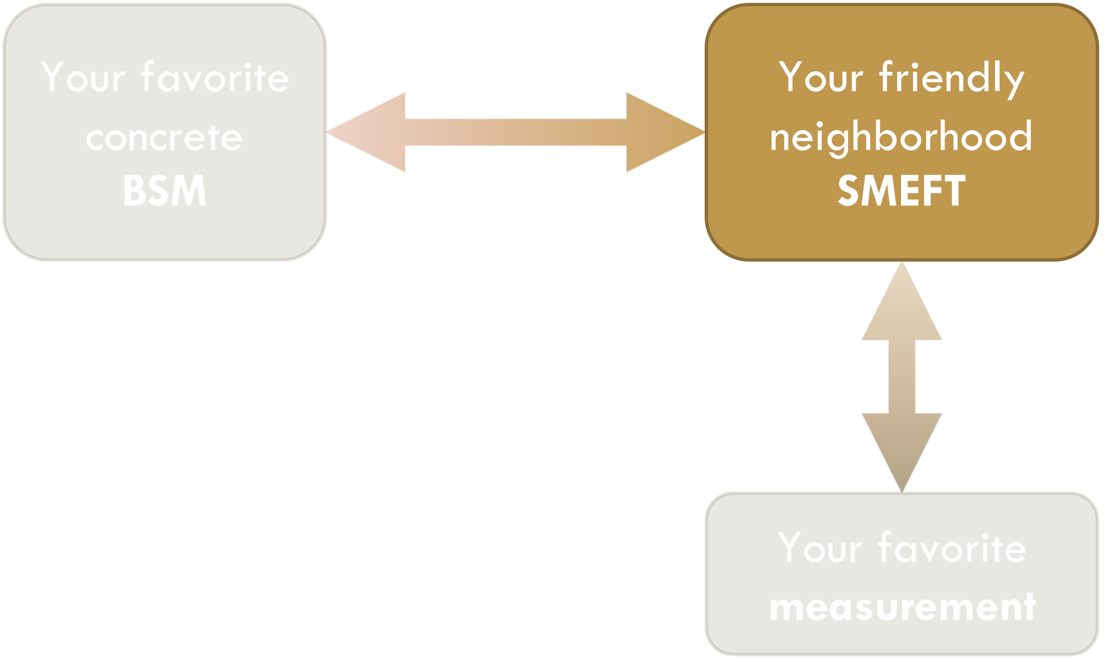
IN PRACTICE: 📏 MEASURE → CONSTRAIN



IN PRACTICE: 📏 MEASURE → CONSTRAIN



SMEFT


Your favorite concrete **BSM**
Your friendly neighborhood **SMEFT**
Your favorite **measurement**

SMEFT – SM FIELDS, ONE SCALAR DOUBLET

$$\mathcal{L} = \mathcal{L}_{\text{SM}}$$

Your friendly neighborhood **SMEFT**

SMEFT – … AND ADD HIGHER-DIM OPERATORS

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L \neq 0}}\mathcal{L}_5 + \frac{1}{\Lambda^2_{\delta B = 0}}\mathcal{L}_6 + \frac{1}{\Lambda^2_{\delta B \neq 0}}\mathcal{L}'_6 + \frac{1}{\Lambda^3_{\delta L \neq 0}}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \ldots$$

Your friendly neighborhood **SMEFT**

SMEFT – SM FIELDS AND NEW OPERATORS

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L \neq 0}} \mathcal{L}_5 + \frac{1}{\Lambda^2_{\delta B = 0}} \mathcal{L}_6 + \frac{1}{\Lambda^2_{\delta B \neq 0}} \mathcal{L}'_6 + \frac{1}{\Lambda^3_{\delta L \neq 0}} \mathcal{L}_7 + \frac{1}{\Lambda^4} \mathcal{L}_8 + \ldots$$

4 – The SM, SU(3)×SU(2)×U(1)

- **Glashow 1961; Weinberg 1967; Salam 1967**

5 – Majorana mass

- Weinberg 1979; Zee, Wilczek 1979

6 – The Good

- **Leung, Love, Rao 1984; Buchmuller Wyler 1986; Grzadkowski, Iskrzynski, Misiak, Rosiek 2010**

6' – The Bad

- Weinberg 1979; Abbott Wise 1980

7 – The Ugly

- Lehman 1410.4193; Henning et al. 1512.03433

8 – The next level

- **Lehman, Martin 1510.00372; Henning et al. 1512.03433**

SMEFT – WHAT'S USUALLY DISCUSSED

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2_{\delta B=0}} \mathcal{L}_6 + \frac{1}{\Lambda^4} \mathcal{L}_8 + \ldots$$

6 – The Good

- Leung, Love, Rao 1984; Buchmuller Wyler 1986; Grzadkowski, Iskrzynski, Misiak, Rosiek 2010

8 – The next level

- Lehman, Martin 1510.00372; Henning et al. 1512.03433

SMEFT – A CONSISTENT, IMPROVABLE, QFT

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2_{\delta B=0}} \mathcal{L}_6$$

Heavy lifting in the last 6 years

114 papers found, 106 of them citeable (published or arXiv)

Citation summary results	Citeable papers
Total number of papers analyzed:	106
Total number of citations:	2,636
Average citations per paper:	24.9
Breakdown of papers by citations:	
Renowned papers (500+)	0
Famous papers (250-499)	1
Very well-known papers (100-249)	2
Well-known papers (50-99)	14
Known papers (10-49)	39
Less known papers (1-9)	36
Unknown papers (0)	14
h_{HEP} index [?]	29

1. **Renormalization Group Evolution of the Standard Model Dimension Six Operators II: Yukawa Dependence**
Elizabeth E. Jenkins, Aneesh V. Manohar (UC, San Diego), Michael Trott (CERN). Oct 17, 2013. 16 pp.
Published in **JHEP 1401 (2014) 035**
DOI: 10.1007/JHEP01(2014)035
e-Print: **arXiv:1310.4838** **[hep-ph]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; Link to Article from SCOAP3
Detailed record - Cited by 237 records 100+

• • •

114. **The Higgs width in the SMEFT**
Ilaria Brivio, Tyler Corbett, Michael Trott. Jun 17, 2019. 41 pp.
e-Print: **arXiv:1906.06949** **[hep-ph]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record

SMEFT AT DIM=6 – WELL BEYOND SCALAR

🚀 LHC Top WG

- "Interpreting top-quark LHC measurements in [SMEFT]" https://arxiv.org/abs/1802.07237
- dim6top (LO).

🛬 LHC Higgs WG

- STXS as intermediate step, parametrized as function of Wilson coefficients.
- Studying concrete models plus SMEFTsim (LO) and SMEFT@NLO.

🚧 LHC Electroweak WG

- Mostly WG3 "Multi-bosons", working toward Yellow Report.
- V+jets: QCD uncertainties vs non-EWK BSM.

59 OPERATORS – 76 PARAMETERS*

$$\frac{1}{\Lambda^2_{\delta B=0}}\mathcal{L}_6$$

* For three flavor generations there are 2499, "but that's just copy-pasting".

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

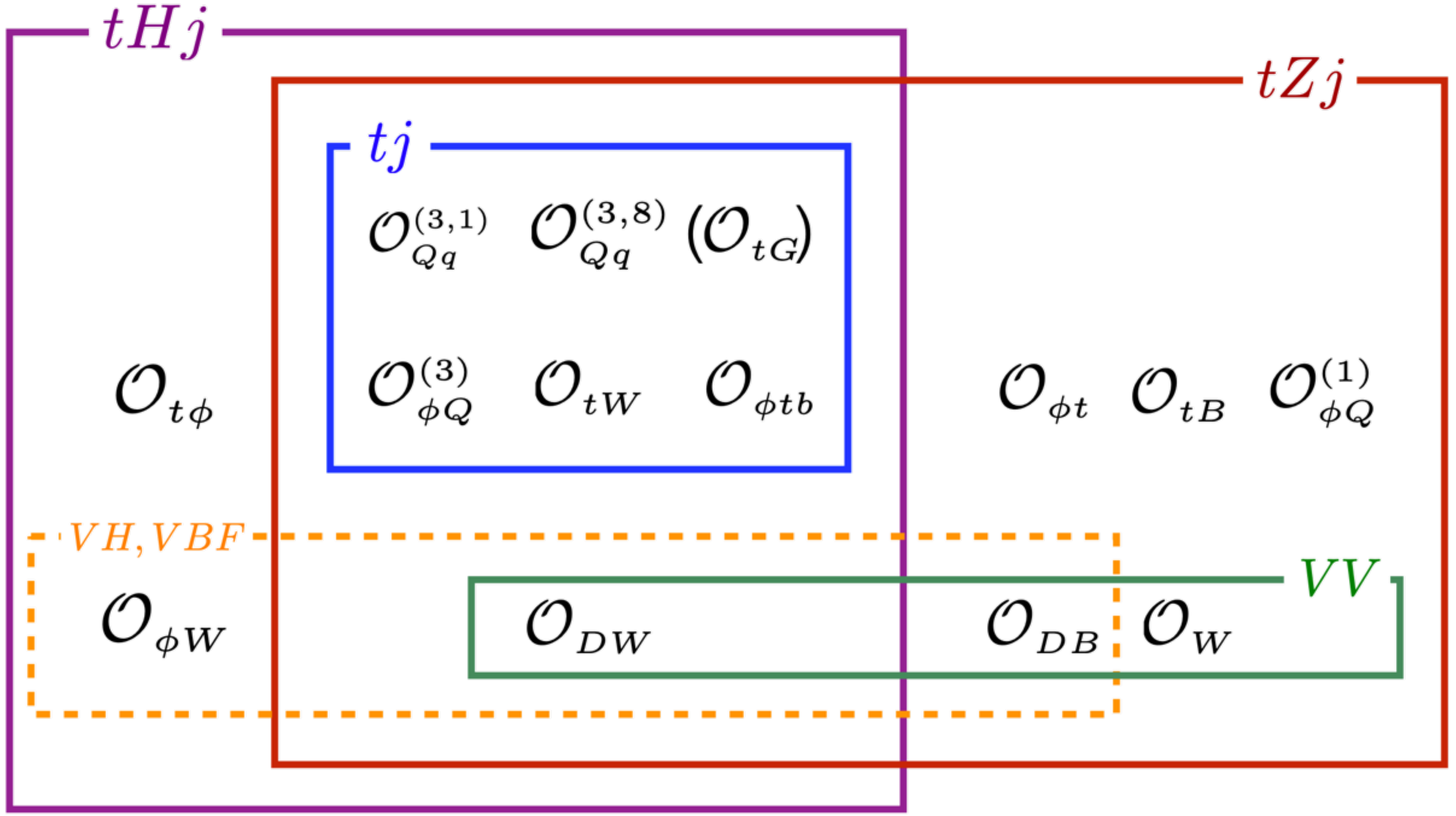
Table 2: Dimension-six operators other than the four-fermion ones.

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu \tau^I q_r)(\bar q_s\gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu \tau^I l_r)(\bar q_s\gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q [illegible]	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	[illegible] $\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]$ [illegible]		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta}$ [illegible] $(q^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q [illegible]	[illegible] $\left[(d_p^\alpha)^T C u_r^\beta\right]$ [illegible]		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$				

Table 3: Four-fermion operators.

https://indico.cern.ch/event/727560/contributions/3019707/attachments/1672341/2683328/BEHEP_KM_20180621.pdf

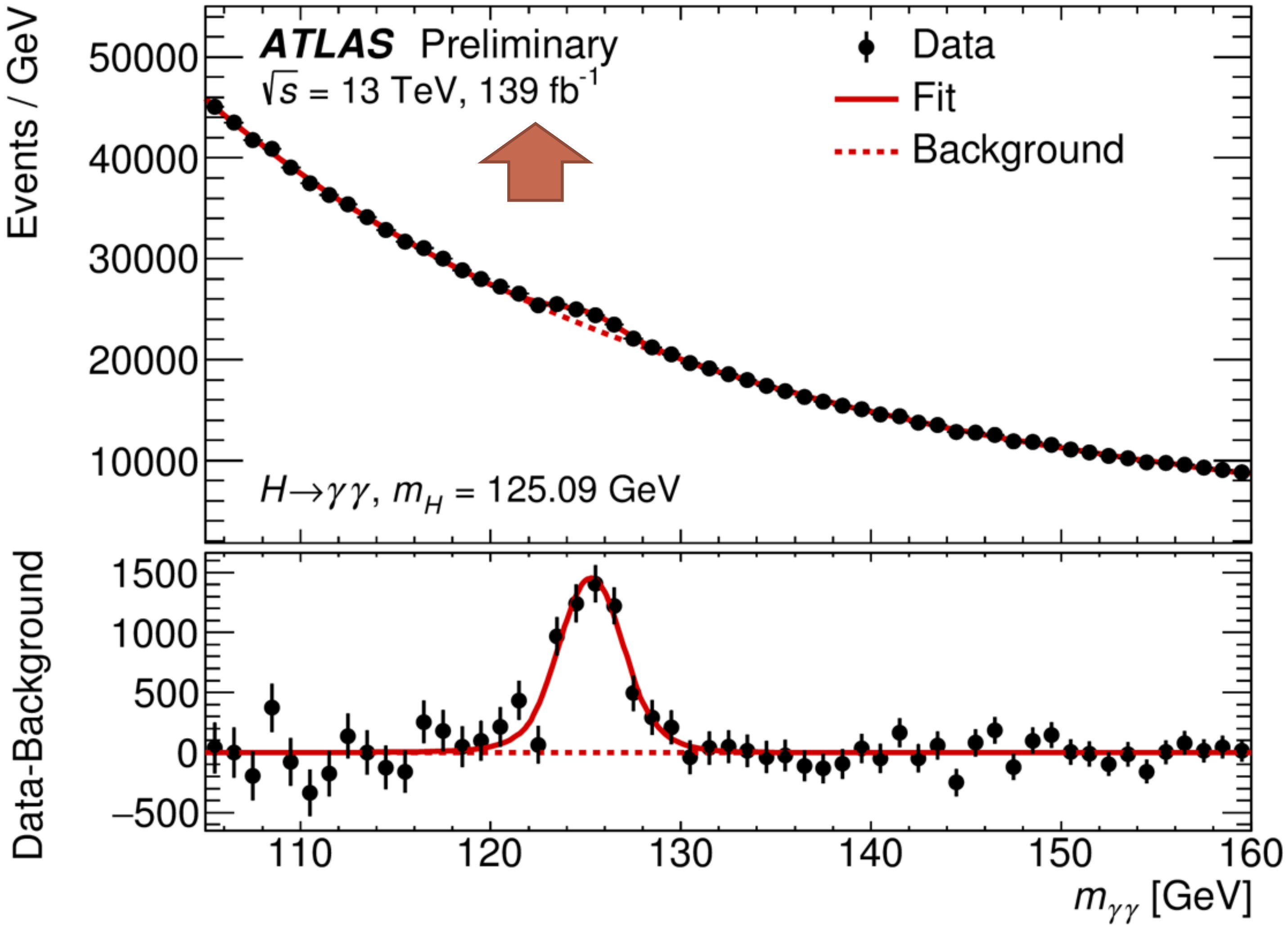
OPERATE ME THIS – THJ AND TZJ PRODUCTION



https://indico.cern.ch/event/727560/contributions/3019707/attachments/1672341/2683328/BEHEP_KM_20180621.pdf

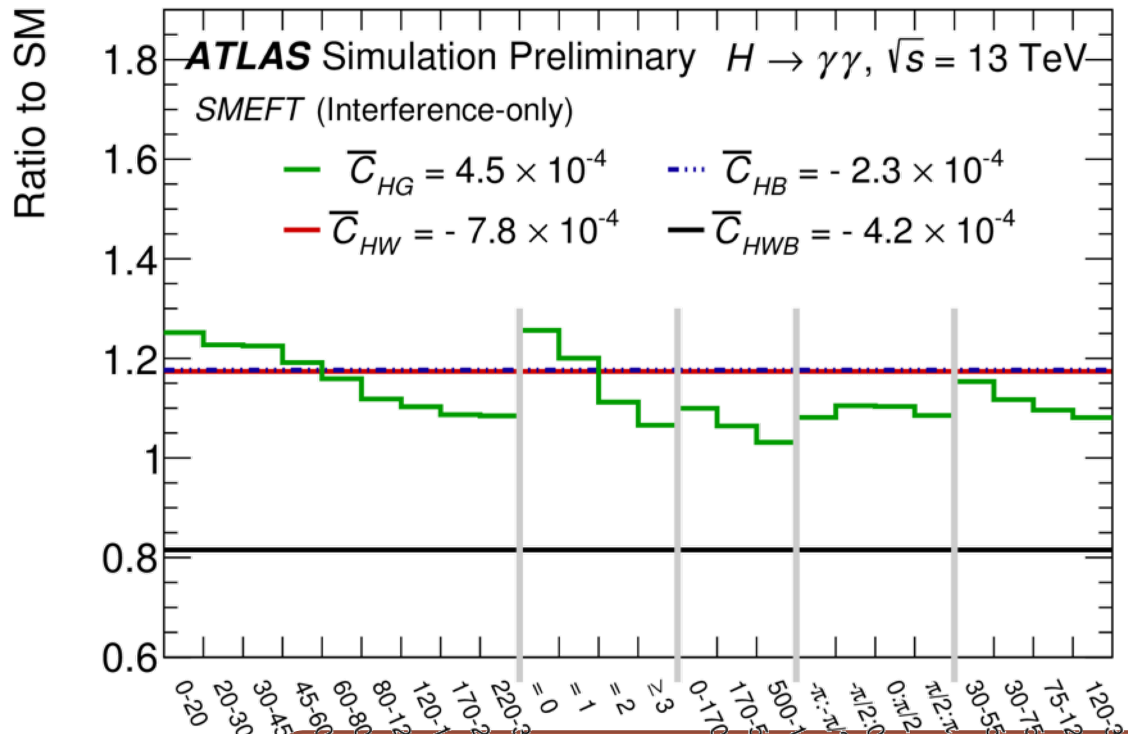
OPERATE ME THIS – THJ AND TZJ PRODUCTION

SMEFT IN HIGGS TO DIPHOTON – FULL RUN 2



SMEFT – CORRELATED EFFECT ON OBSERVABLES

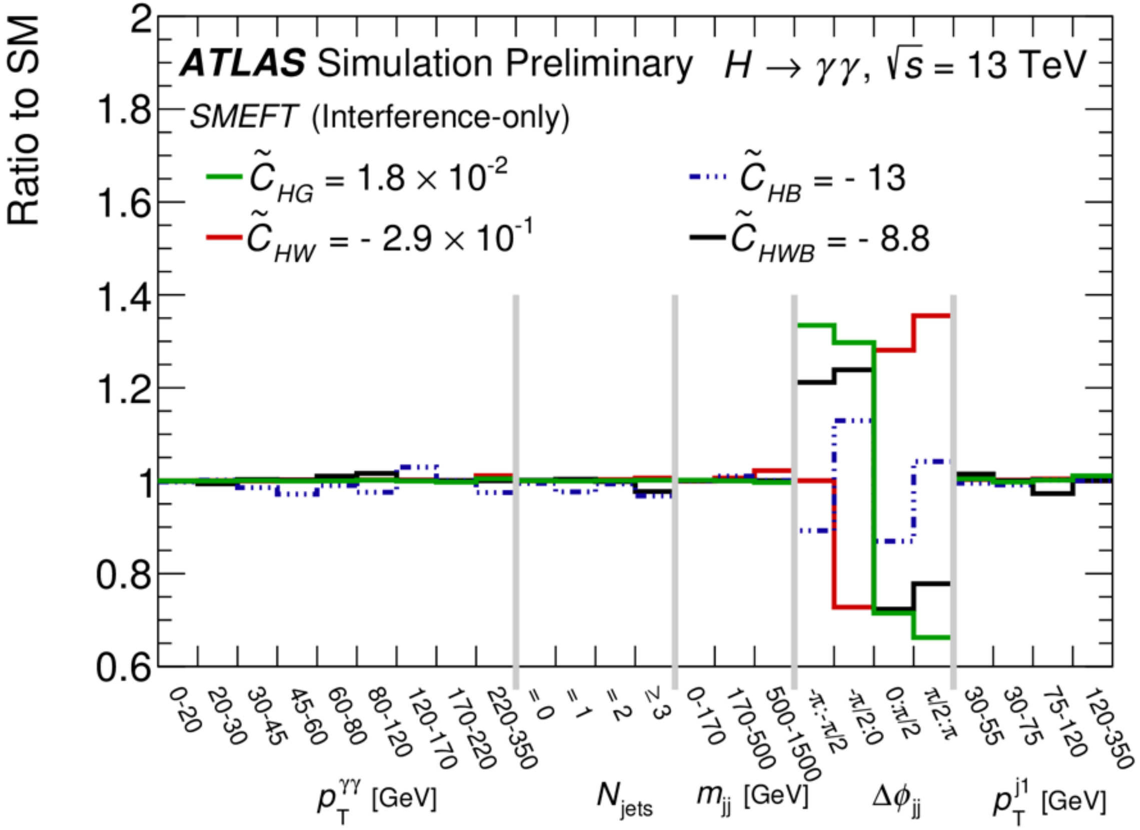
CP-even operators: effects on normalization and shape



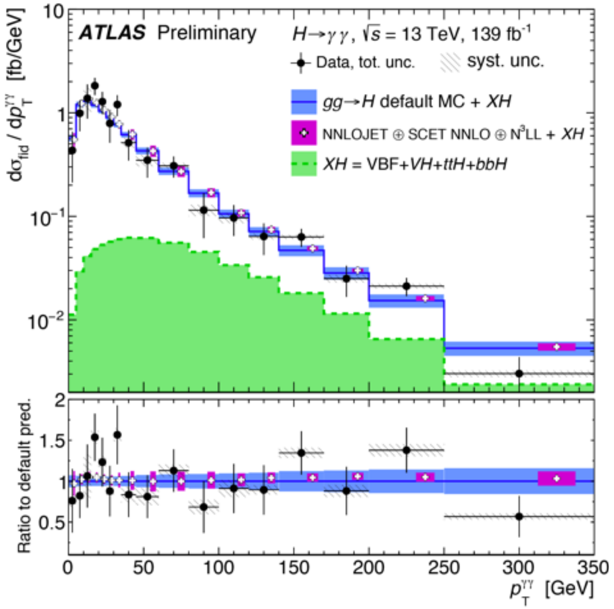
$p_T^{\gamma\gamma}$ [GeV] N_{jets} m_{jj} [GeV] $\Delta\phi_{jj}$ p_T^{j1} [GeV]

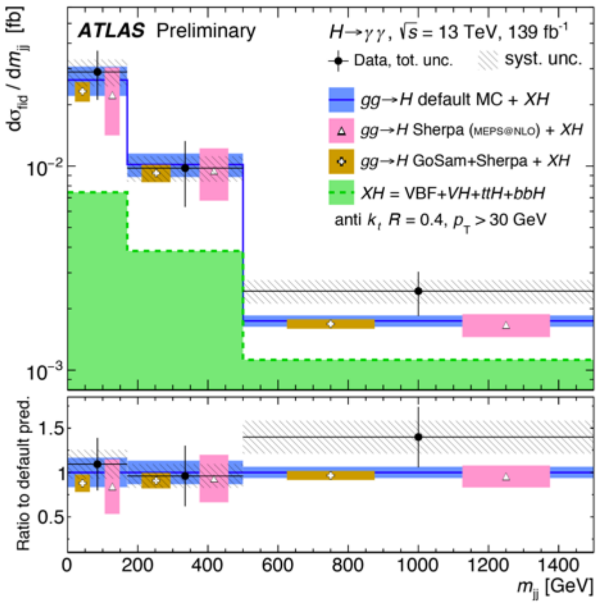
Five differential observables

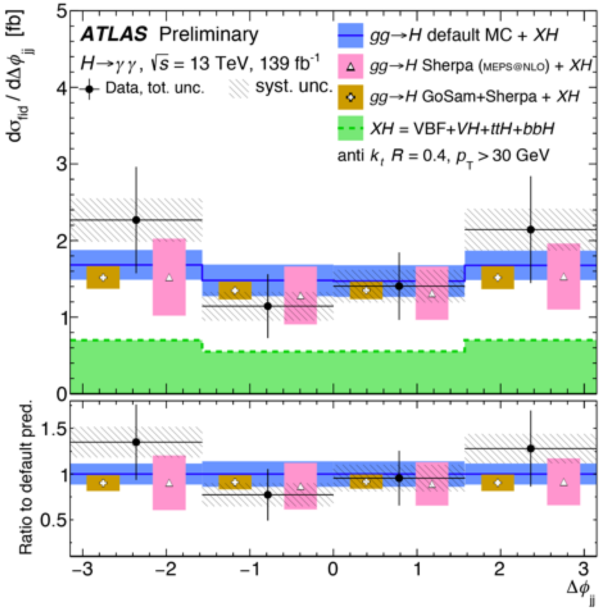
CP-odd operators: effects on $\Delta\phi_{jj}$ shape

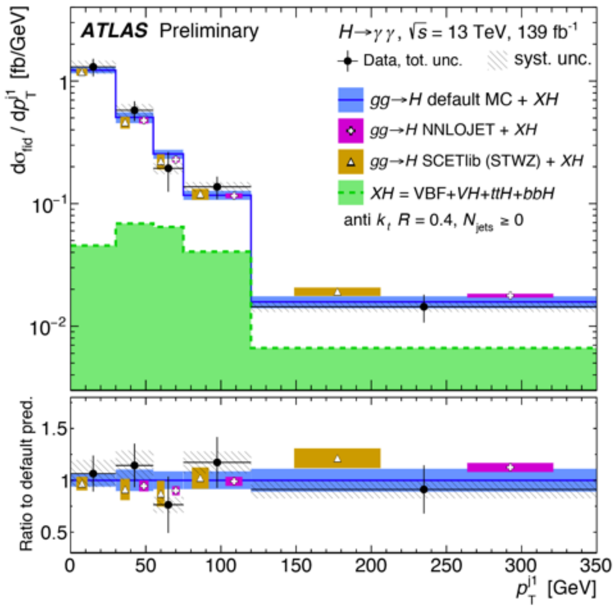


FIDUCIAL DIFFERENTIAL CROSS-SECTIONS





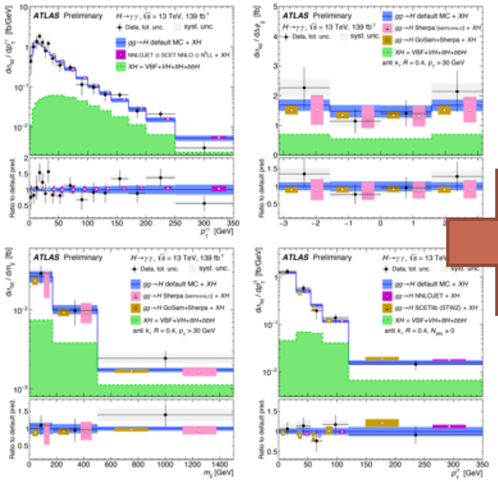


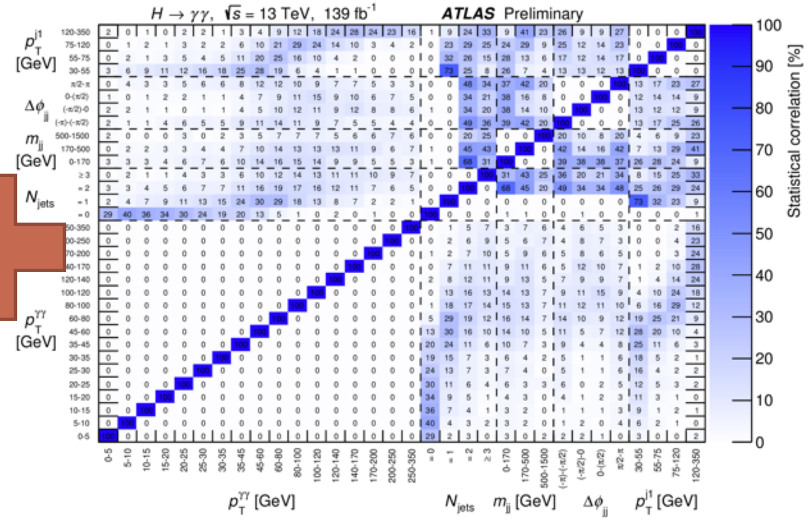


Unfolded measurements probing wide kinematics ranges.

Overall, excellent agreement with different SM predictions.

1ST LHC SMEFT RESULTS – A SET OF OPERATORS

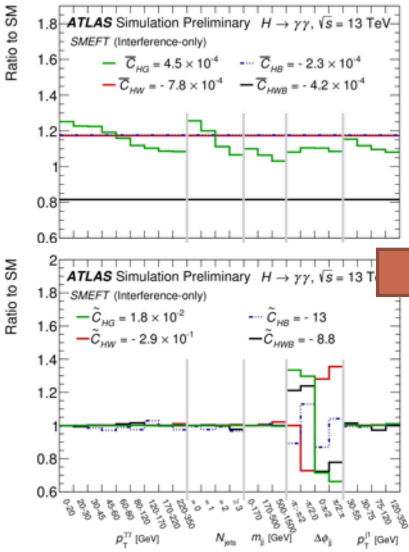


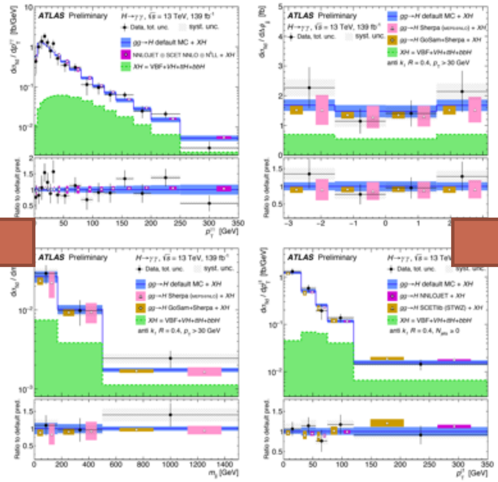


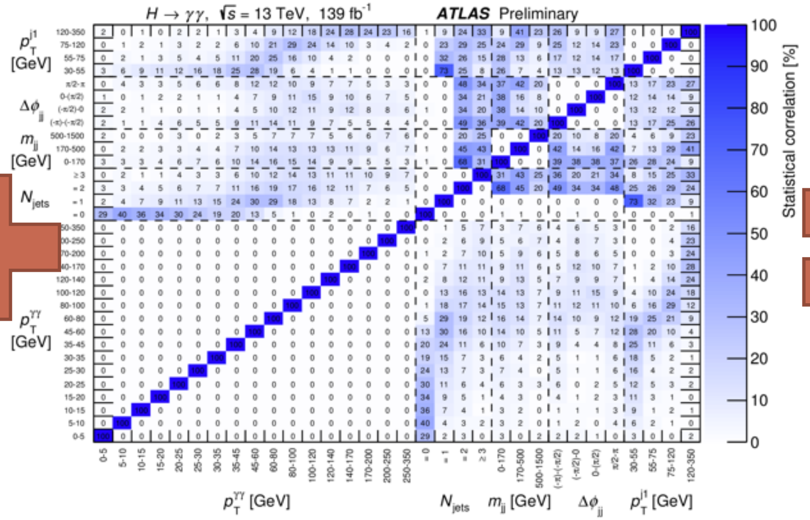
Fit for a set of Wilson coefficients using:

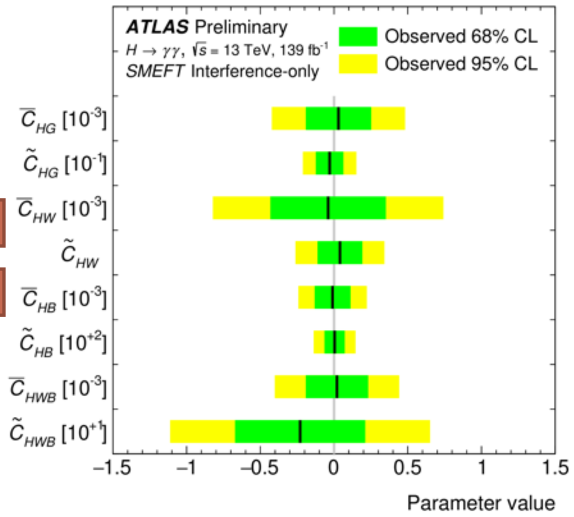
- Templates of SMEFT effects on differential observables.
- Unfolded fiducial differential cross-section measurements.
- Statistical correlation between bins, since events can contribute to multiple bins.

1ST LHC SMEFT RESULTS – A SET OF OPERATORS





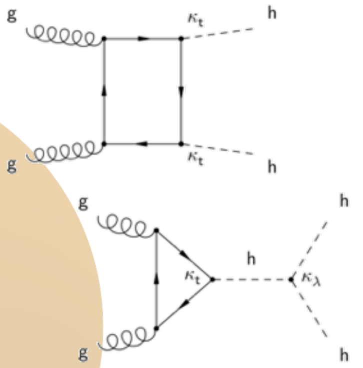




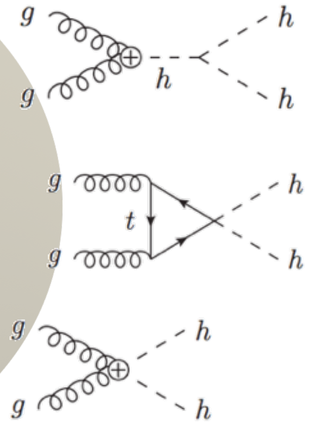
Fit for a set of Wilson coefficients using:

- Templates of SMEFT effects on differential observables.
- Unfolded fiducial differential cross-section measurements.
- Statistical correlation between bins, since events can contribute to multiple bins.

TWO-HIGGS – THE SCALAR POTENTIAL & MORE

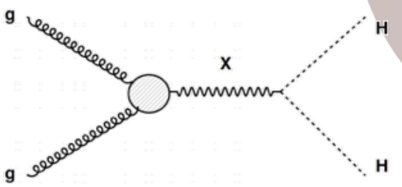


SM λ_{HHH}
- Destructive interference

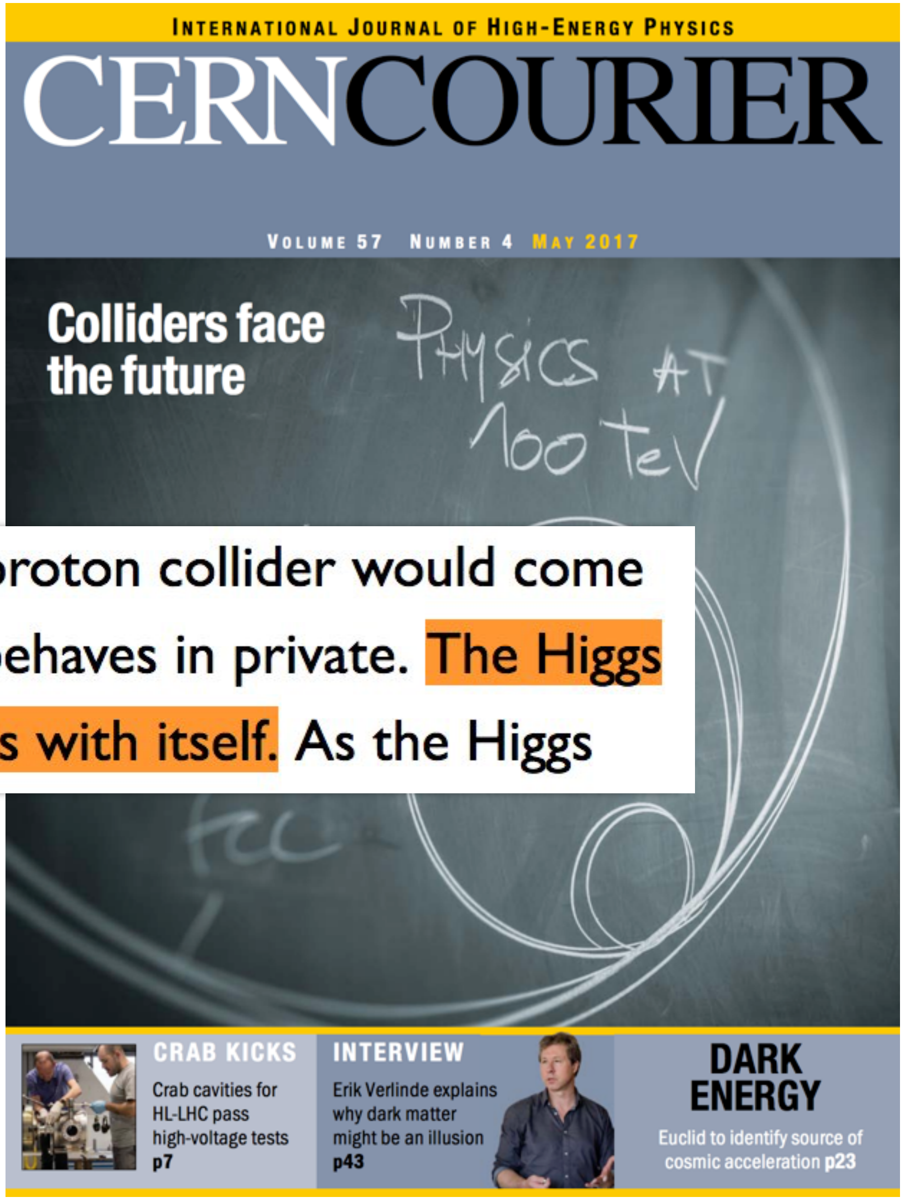


Resonant production
- spin-0 radion
- spin-2 graviton

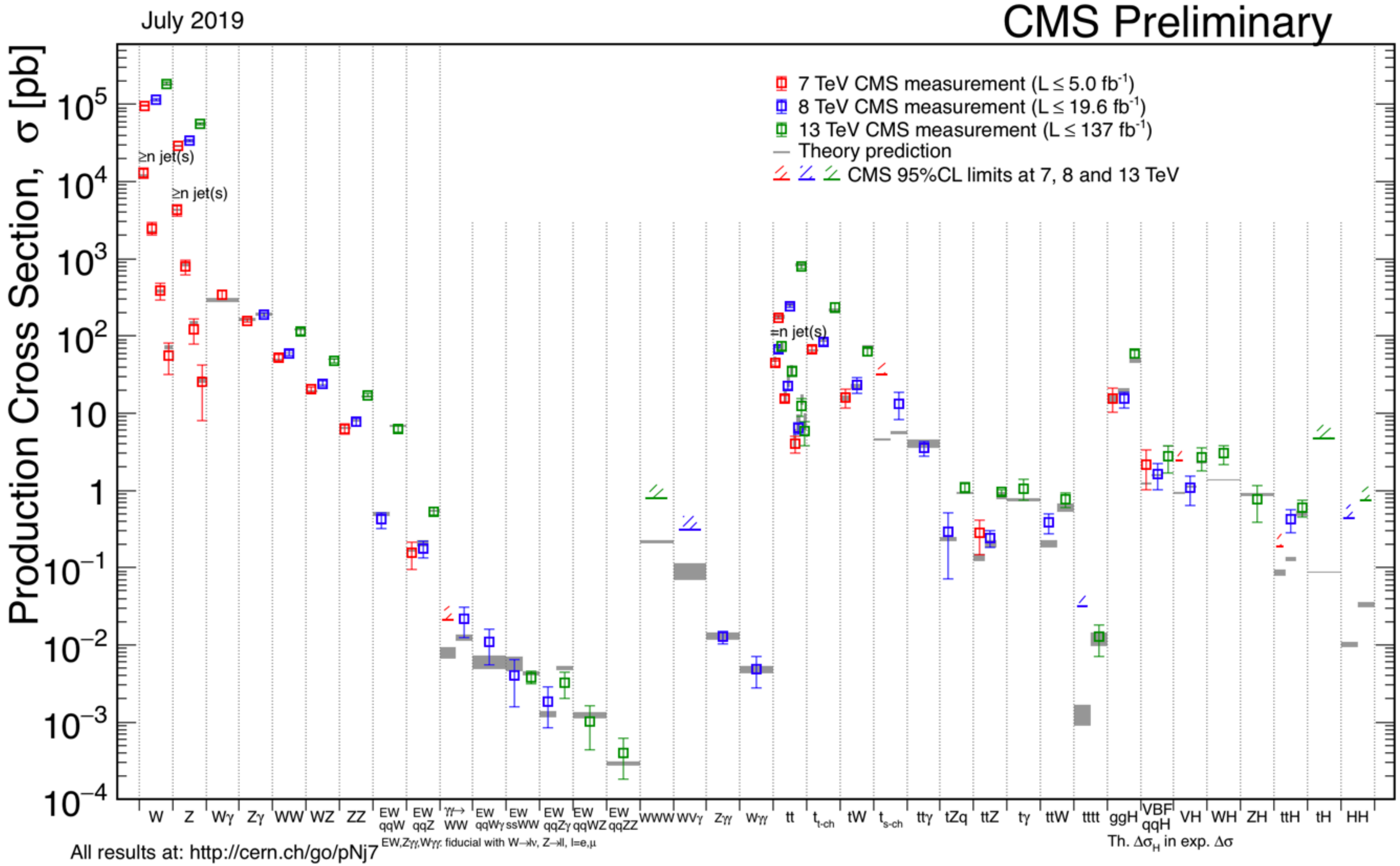
BSM couplings
- Effective Lagrangian

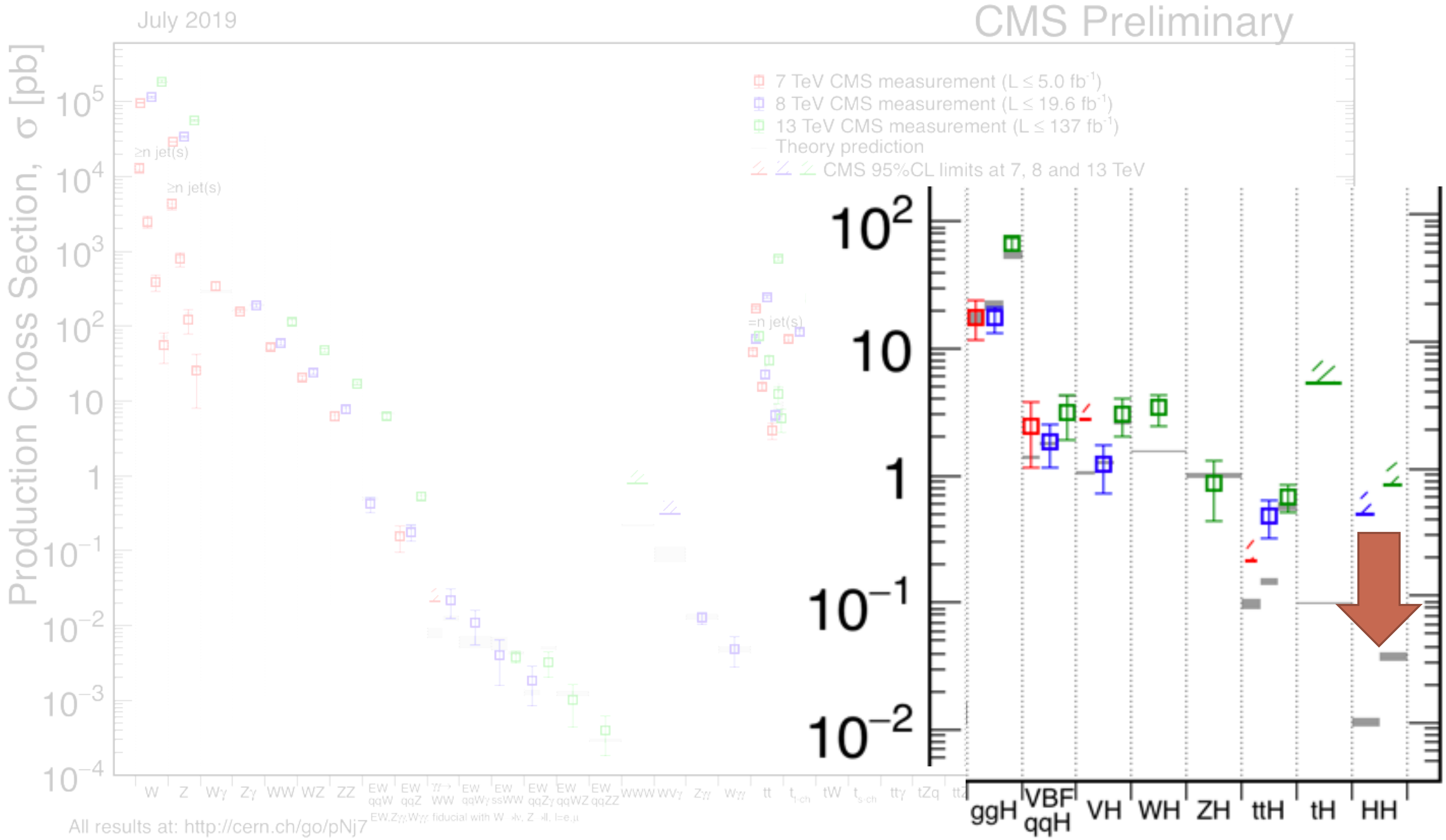


MORE EXCEPTIONAL ASPECTS

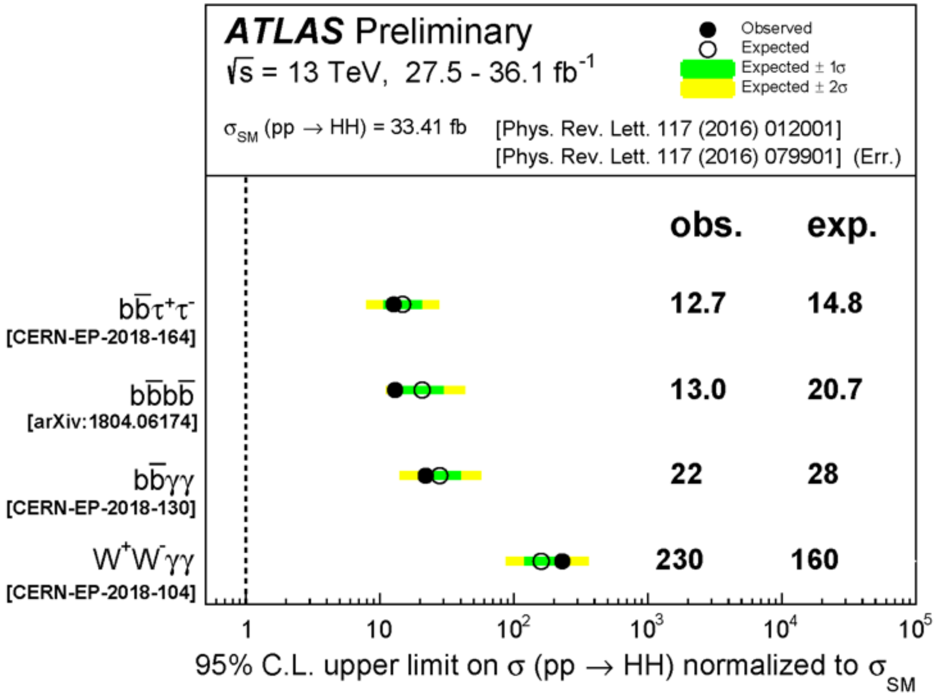


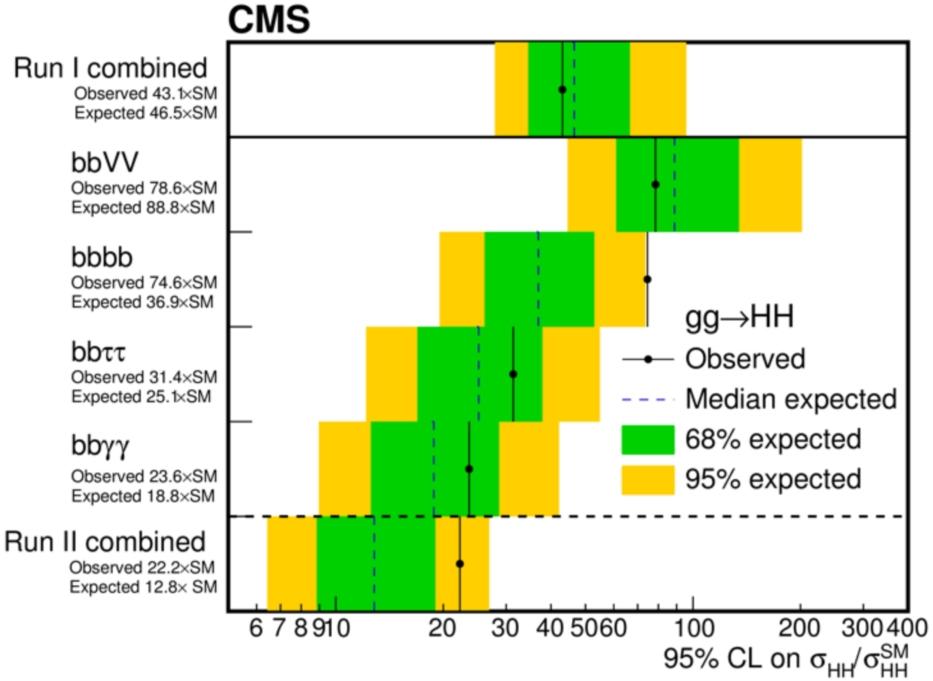
One respect in which a 100 TeV proton–proton collider would come to the fore is in revealing how the Higgs behaves in private. The Higgs is the only particle in the SM that interacts with itself. As the Higgs

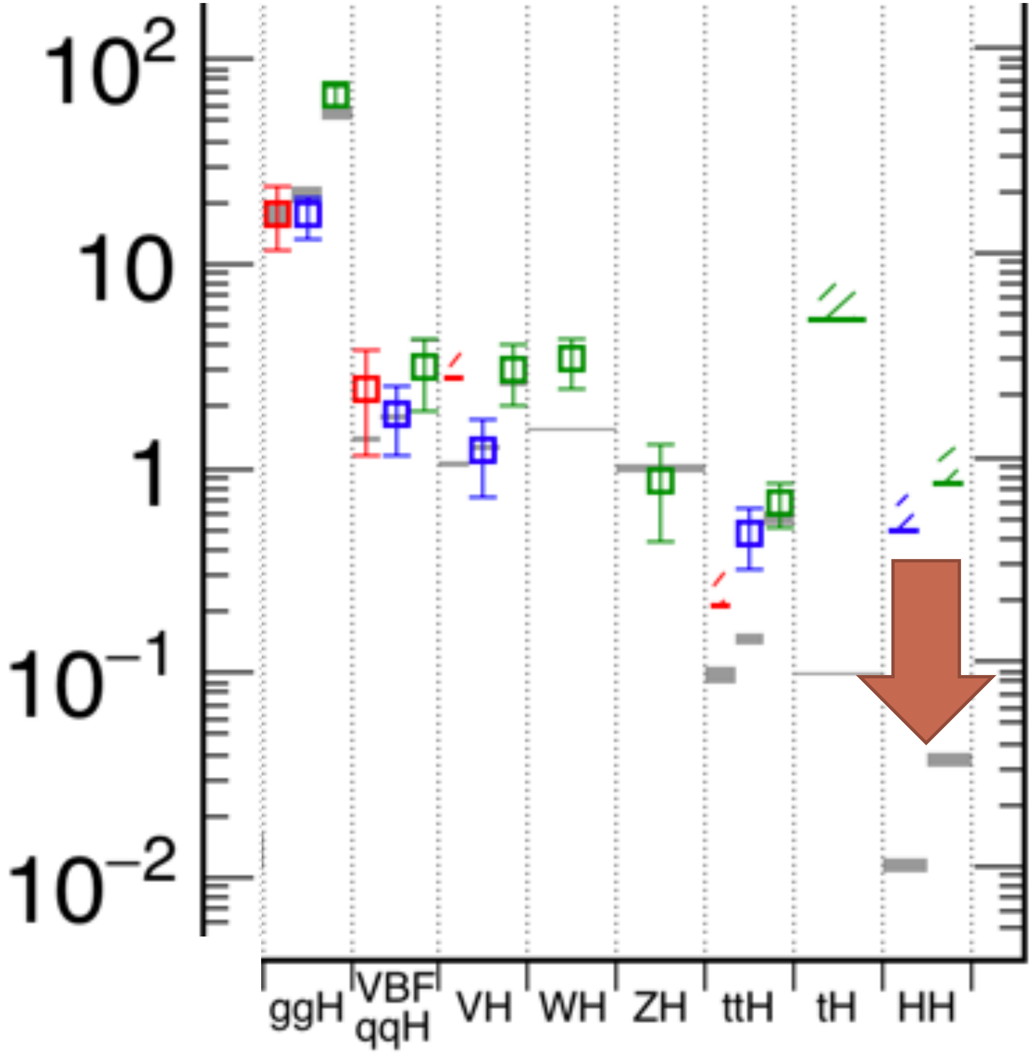

July 2019
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
13 TeV CMS measurement (L ≤ 137 fb-1)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
≥n jet(s)
≥n jet(s)
≥n jet(s)
W Z Wγ Zγ WW WZ ZZ EW qqW EW qqZ γγ→WW EW qqWγ EW ssWW EW qqZγ EW qqWZ EW qqZZ WWW WVγ Zγγ Wγγ tt t-ch tW ts-ch ttγ tZq ttZ tγ ttW tttt ggH VBF qqH VH WH ZH ttH tH HH
EW,Zγγ,Wγγ: fiducial with W→lν, Z→ll, l=e,μ
Th. Δσ_H in exp. Δσ
All results at: http://cern.ch/go/pNj7

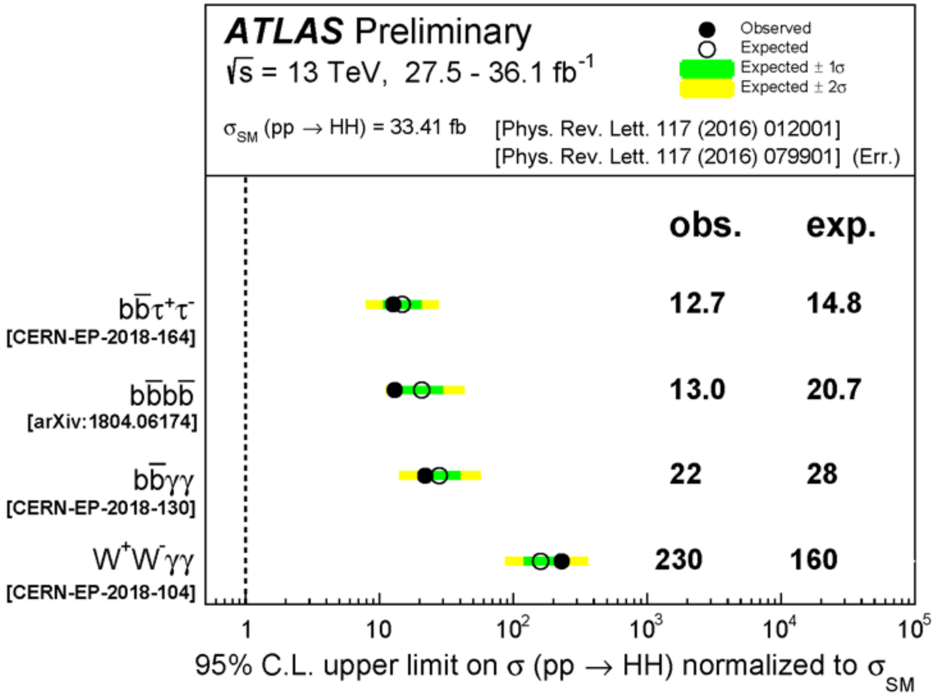


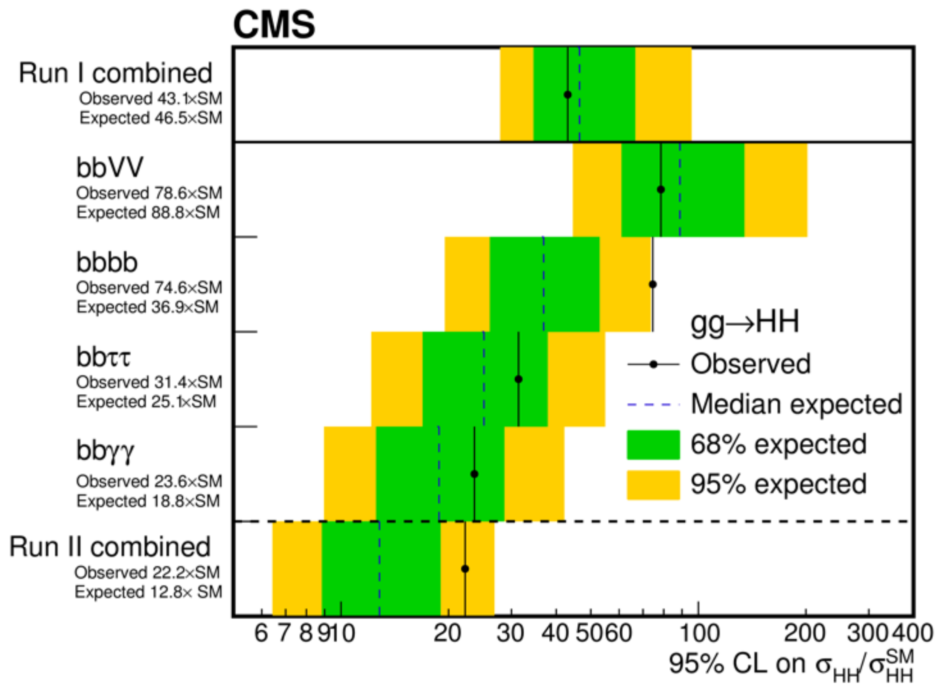
July 2019
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb⁻¹)
8 TeV CMS measurement (L ≤ 19.6 fb⁻¹)
13 TeV CMS measurement (L ≤ 137 fb⁻¹)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
All results at: http://cern.ch/go/pNj7
ggH
VBF qqH
VH
WH
ZH
ttH
tH
HH


ATLAS Preliminary
√s = 13 TeV, 27.5 - 36.1 fb-1
Observed
Expected
Expected ± 1σ
Expected ± 2σ
σSM (pp → HH) = 33.41 fb
[Phys. Rev. Lett. 117 (2016) 012001]
[Phys. Rev. Lett. 117 (2016) 079901] (Err.)
obs.
exp.
bb̄τ+τ-
[CERN-EP-2018-164]
12.7
14.8
bb̄bb̄
[arXiv:1804.06174]
13.0
20.7
bb̄γγ
[CERN-EP-2018-130]
22
28
W+W-γγ
[CERN-EP-2018-104]
230
160
95% C.L. upper limit on σ (pp → HH) normalized to σSM


CMS
Run I combined
Observed 43.1×SM
Expected 46.5×SM
bbVV
Observed 78.6×SM
Expected 88.8×SM
bbbb
Observed 74.6×SM
Expected 36.9×SM
bbττ
Observed 31.4×SM
Expected 25.1×SM
bbγγ
Observed 23.6×SM
Expected 18.8×SM
Run II combined
Observed 22.2×SM
Expected 12.8× SM
gg→HH
Observed
Median expected
68% expected
95% expected
95% CL on σHH/σHH SM

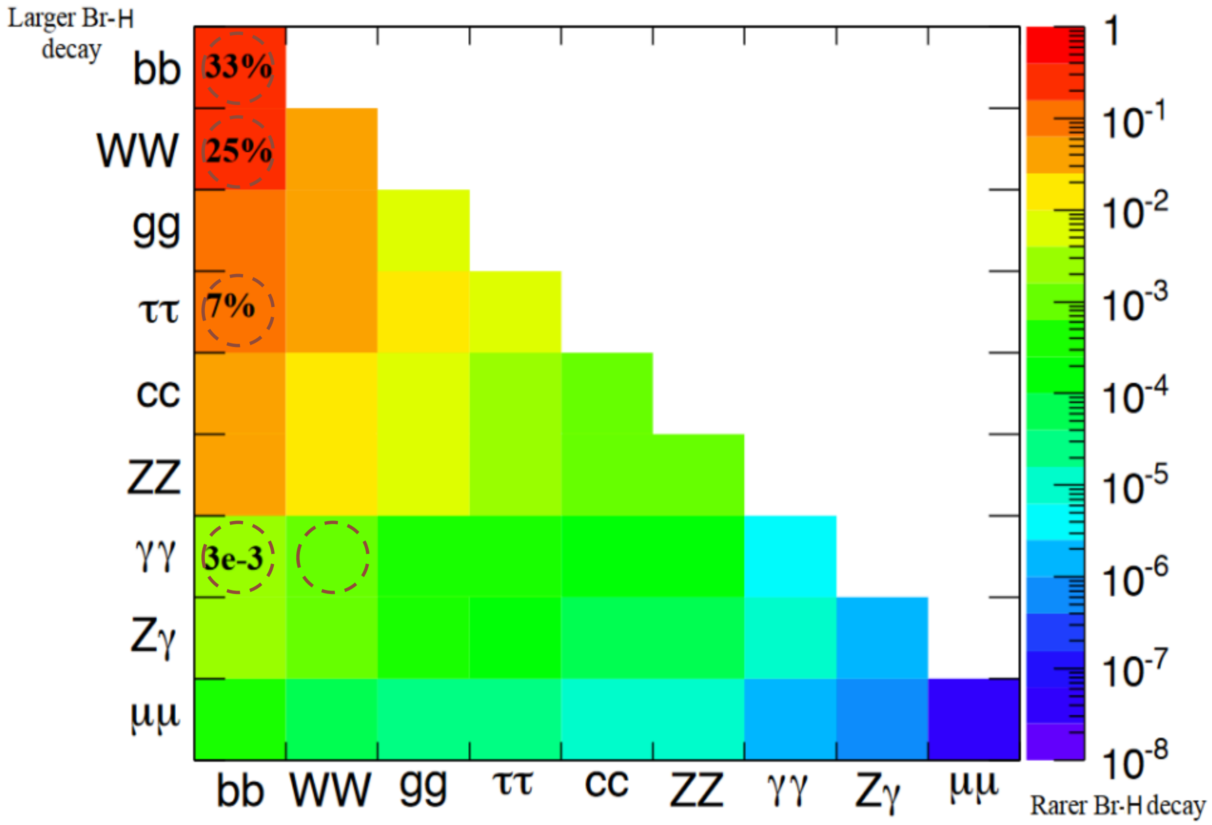

ggH
VBF qqH
VH
WH
ZH
ttH
tH
HH





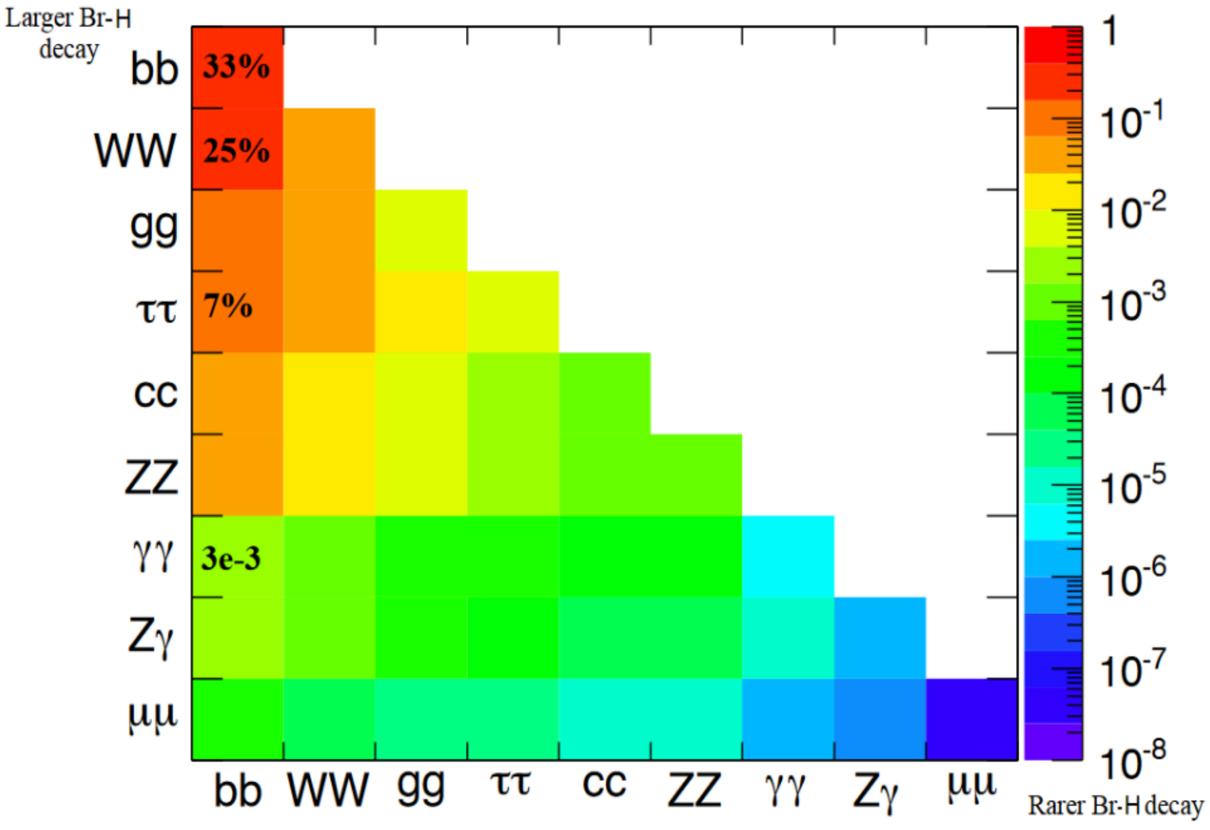
Tradeoff between:

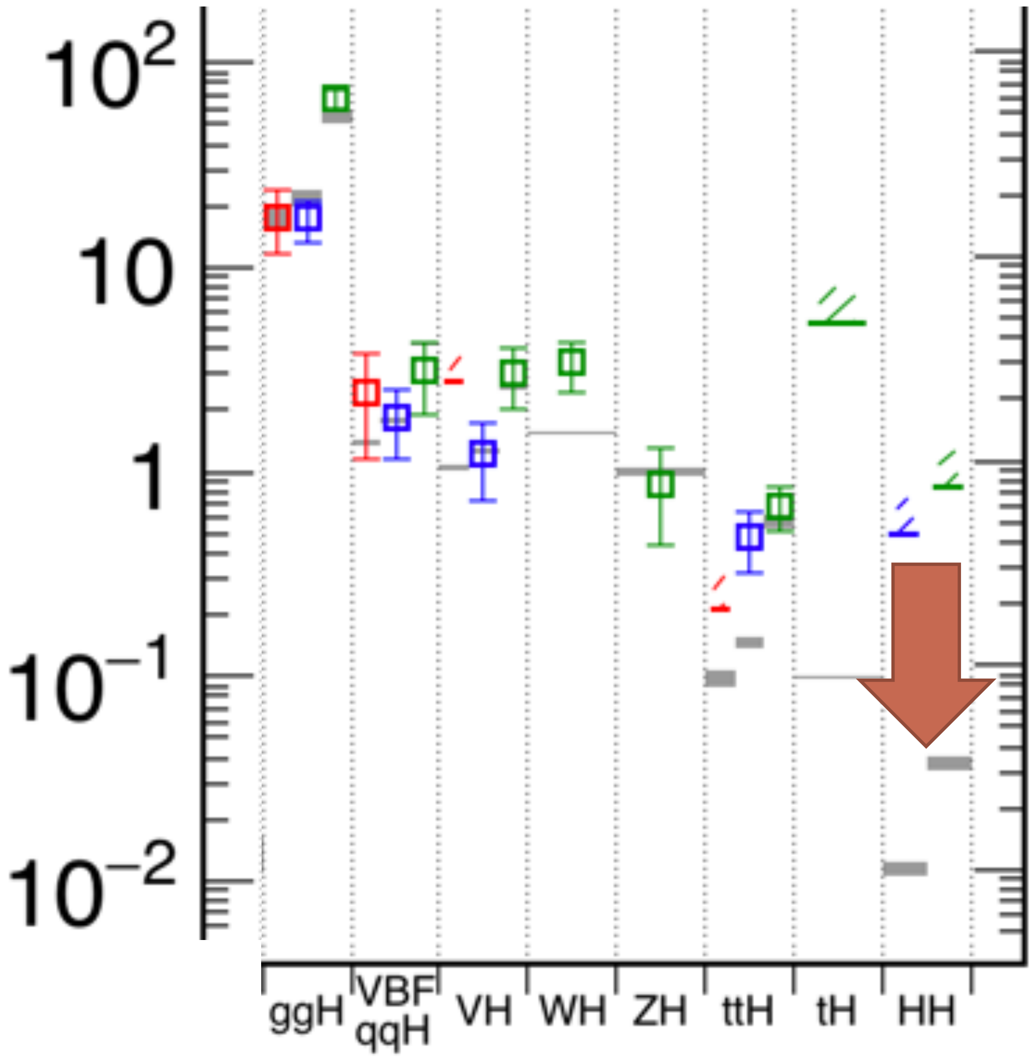
1. Resolution (S/B)
2. Yield (branching fraction)



Tradeoff between:

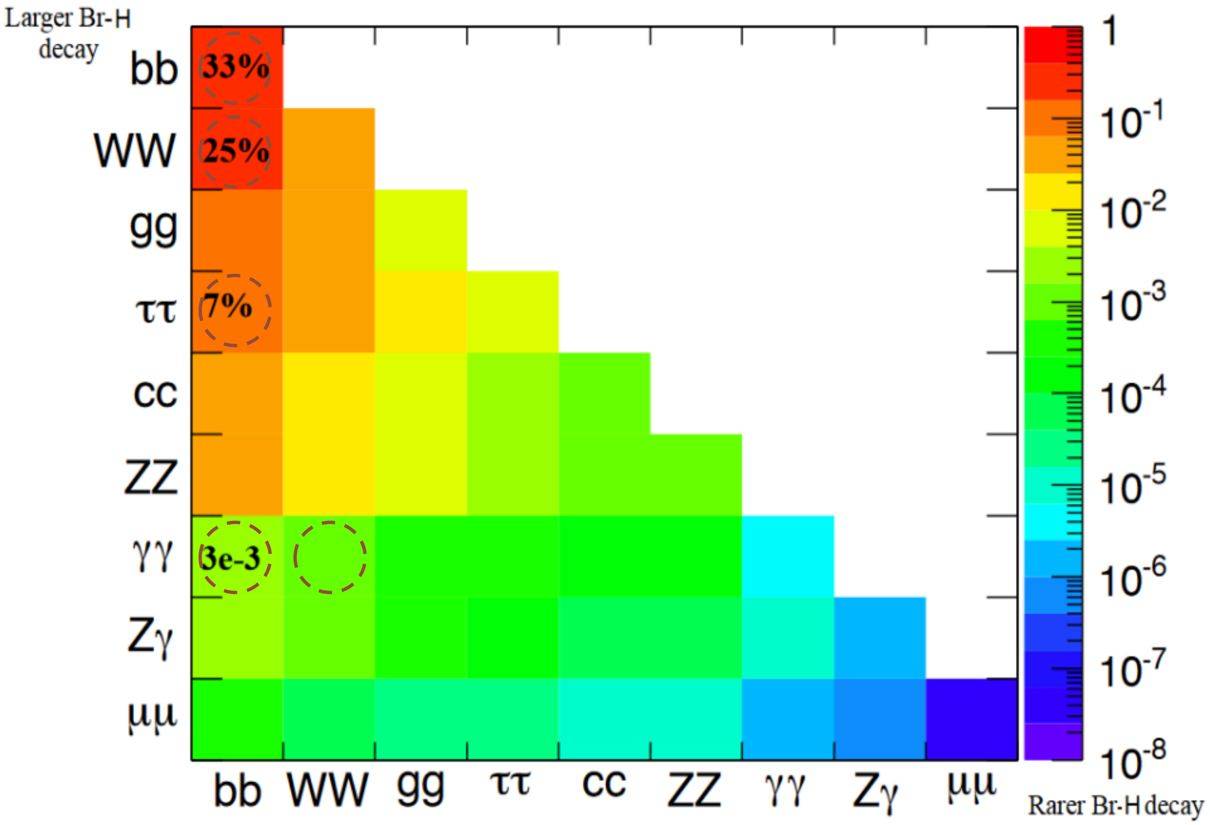
1. Resolution (S/B)
2. Yield (branching fraction)

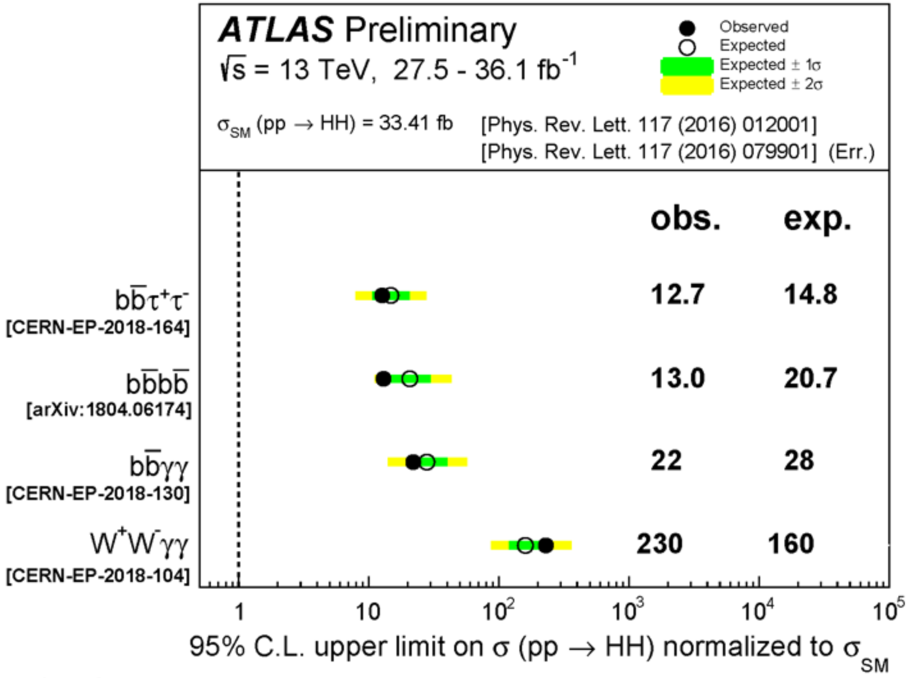


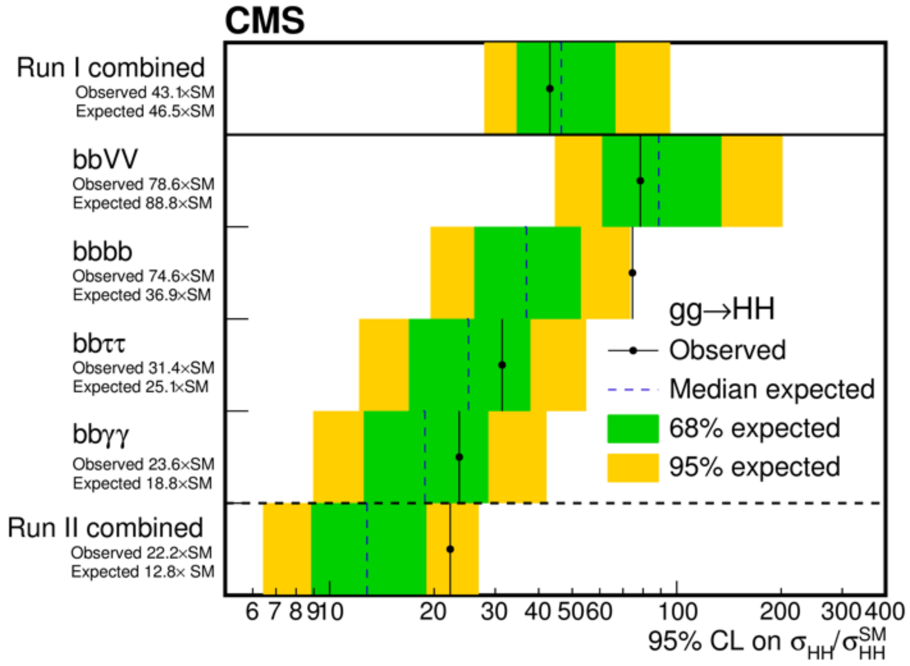


Tradeoff between:

1. Resolution (S/B)
2. Yield (branching fraction)

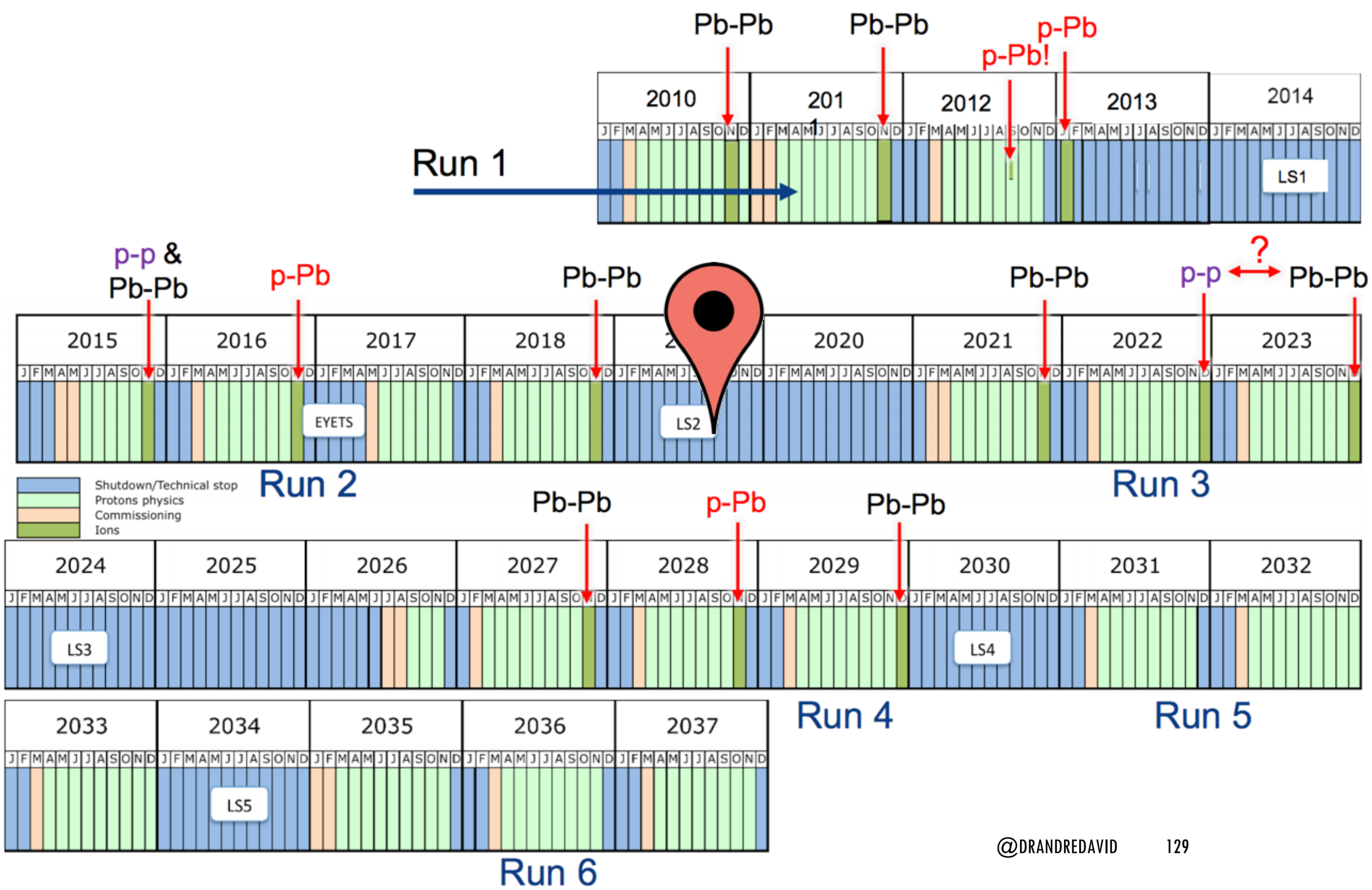






LHC NOW AT

10 / 28 (35.71%)



UNTIL THE (HL-)LHC IS OVER – EXPECTATIONS

Right now, expect 4.0σ.

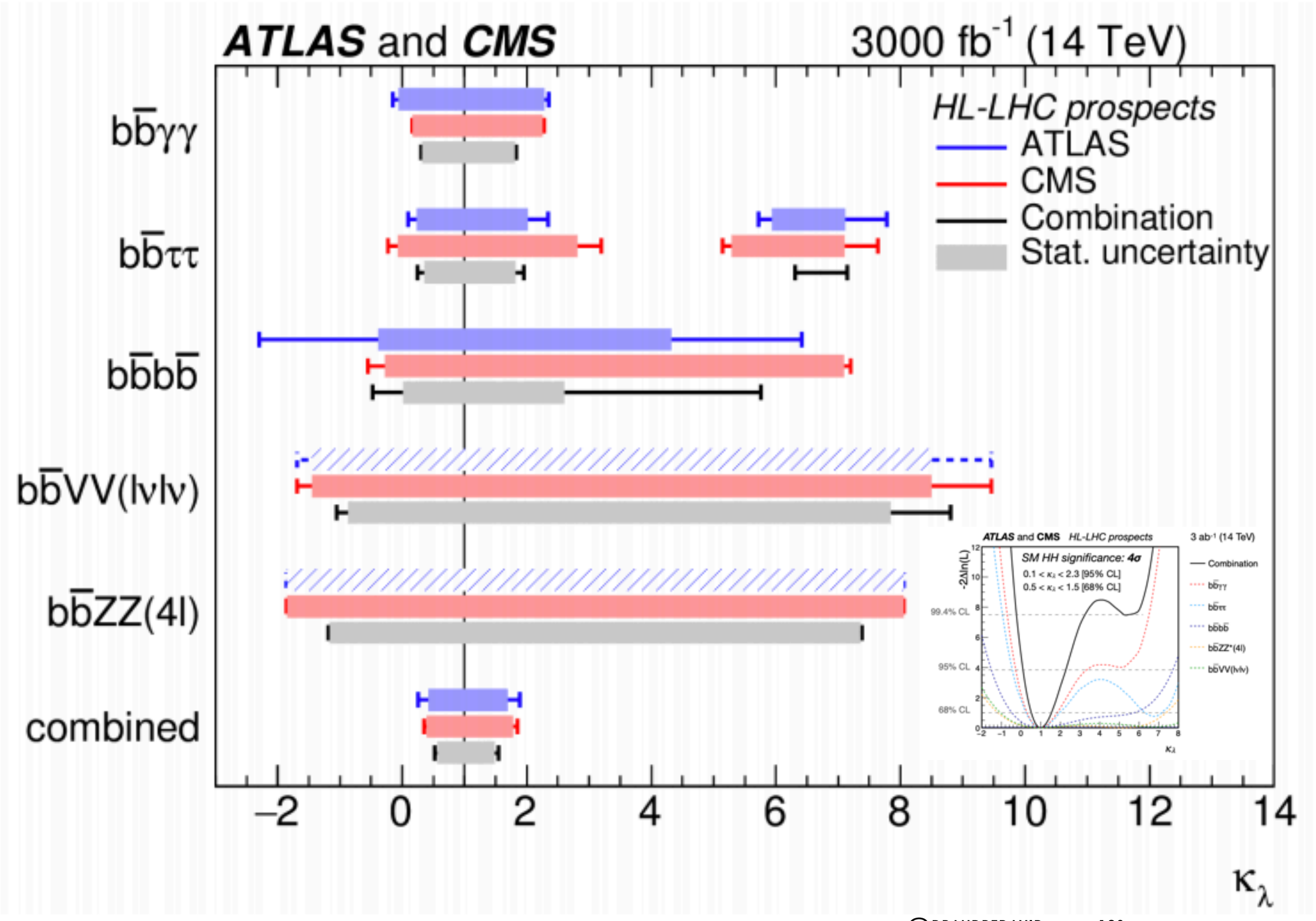
Statistical uncertainty dominates:

- Need more 🏃…

Still, room for more 🧠:

- Making better use of statistics.
- Adding more channels; every drop counts.

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

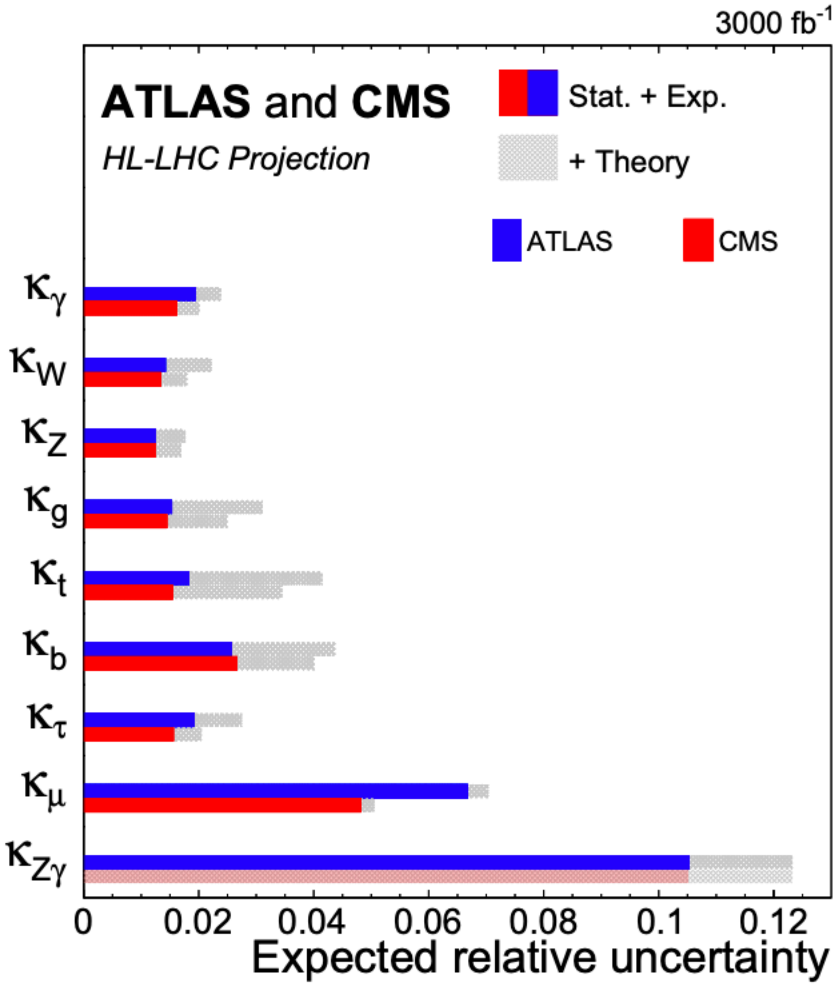


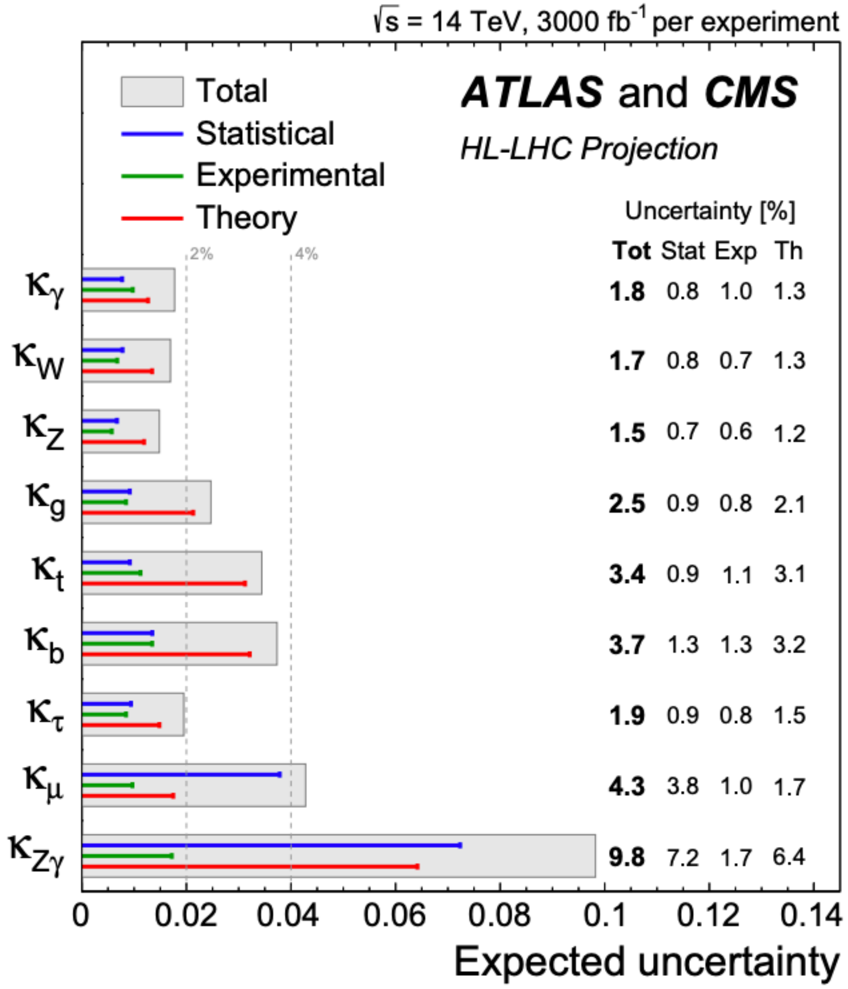
UNTIL THE (HL-)LHC IS OVER – EXPECTATIONS

Down to the few percent.

- Improved BSM sensitivity.

Theory uncertainties play relevant role.





EPISODE VIII – THE LAST JEDI

Direct searches for extended scalar sectors.

- H(125) still alone.

Differential measurements and SMEFT interpretation are quantum leap.

- Different channels at different stages.
- Sweeping BSM interpretations.
- Menagerie of EFT options with different generality.
  - SMEFT and Warsaw basis well understood.
- **Global, combined, EFT program clearly coming.**

Higgs self-coupling, scalar potential.

- Ultimate test at the heart of the SM structure.

THE (HL-LHC) IS CLEARLY NOT ENOUGH

$$N(ZH, H \to 4\ell) \propto \sigma_{ZH} \times \mathrm{BR}(H \to 4\ell)$$
$$\propto g^2_{HZZ} \times \frac{g^2_{HZZ}}{\Gamma_H}$$

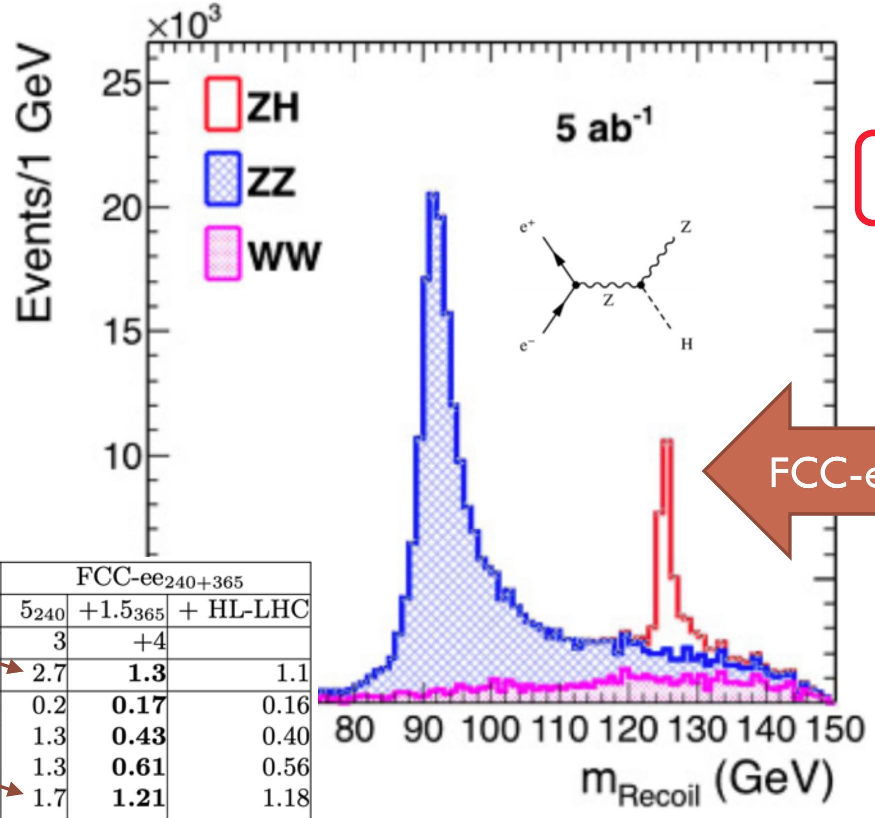
$$N(ZH) \propto \sigma_{ZH} \propto g^2_{HZZ}$$

Must measure Higgs total width.

- (HL-)LHC cannot do it.

$e^+e^- \to Z+H$

- Recoil mass Higgs peak.
- Independent of Higgs decay mode.



FCC-ee example

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$LEP3_{240}$	$CEPC_{250}$	$FCC\text{-}ee_{240+365}$		
Lumi (ab^{-1})	3	2	1	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	15	8	6	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.7	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.8	1.3	1.3	**0.61**	0.56
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	2.3	2.2	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	2.1	1.5	1.6	**1.01**	0.90
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.9	1.5	1.4	**0.74**	0.67
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	12	8.7	10.1	**9.0**	3.8
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	6.1	3.7	4.8	**3.9**	1.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	–	–	3.1
BR_{EXO} (%)	SM	<1.7	<2.1	<1.6	<1.2	<1.2	$<$**1.0**	$<$**1.0**

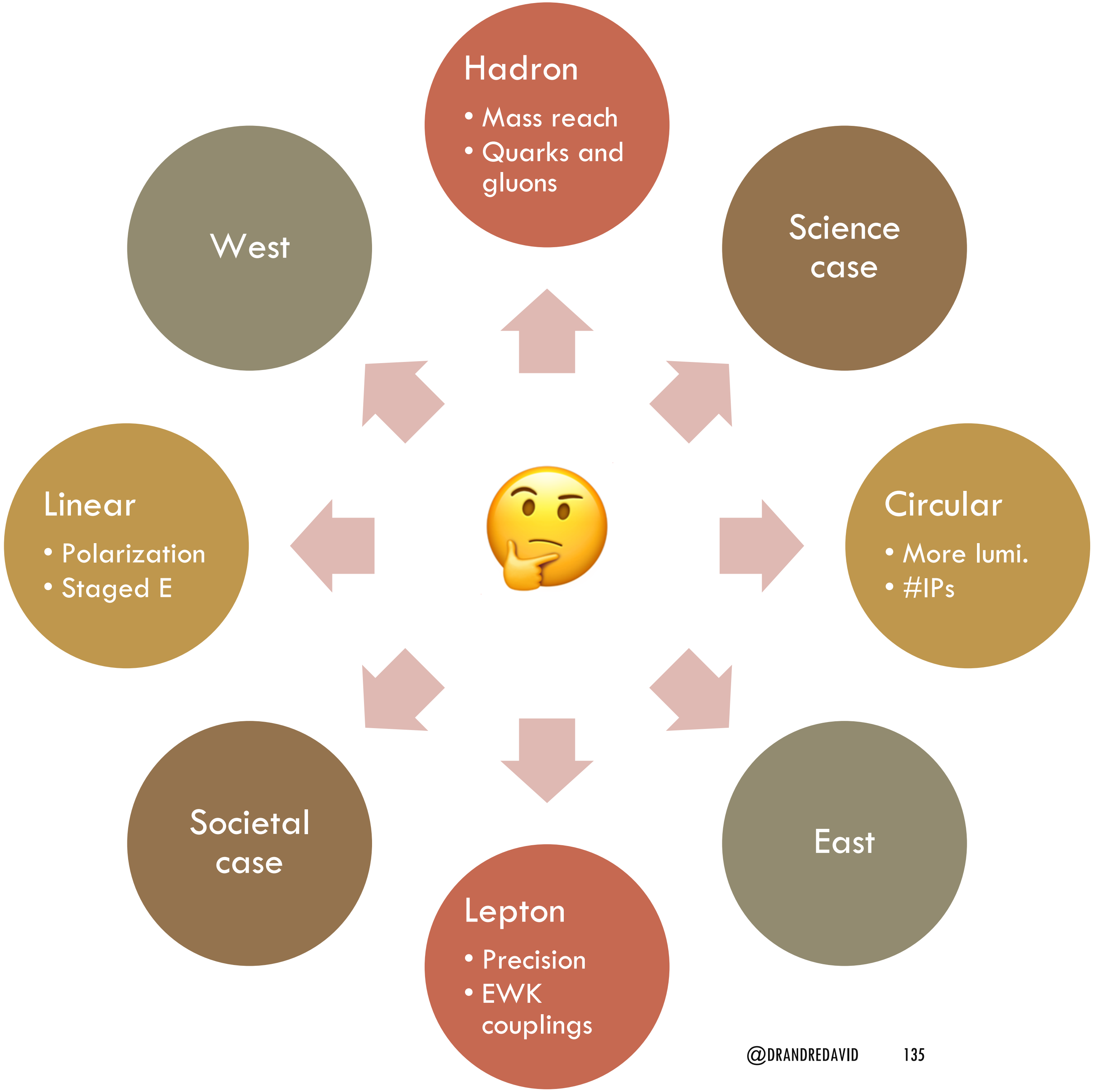
CIRCULAR? LINEAR?

Not simple.

LINEAR? CIRCULAR?

Not simple.

- Beware anyone who tells you so.



https://arxiv.org/abs/1905.03764

CIRCULAR? LINEAR?

Not simple.

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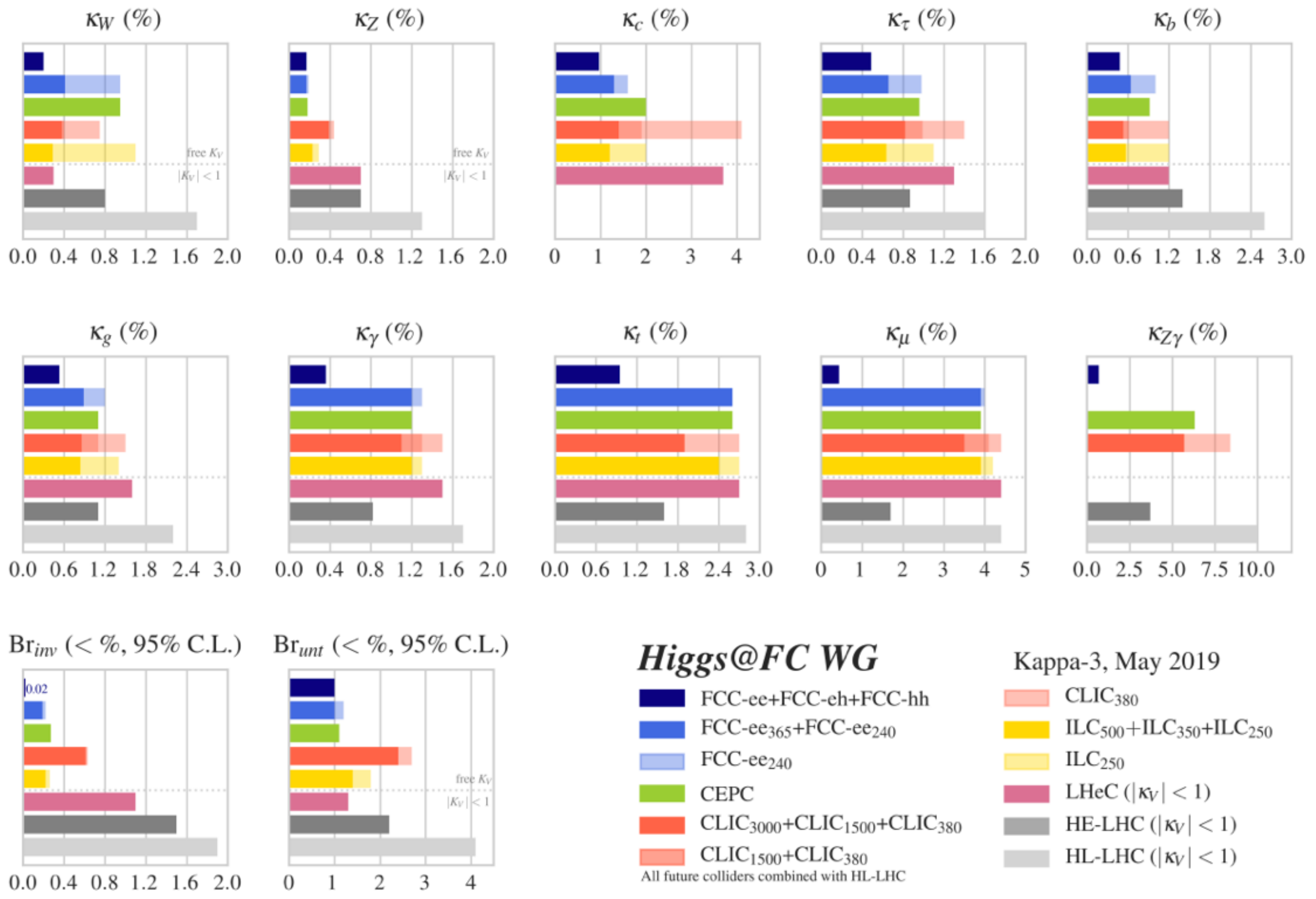
Clear complementarity between lepton and hadron machines.

- **Muon and top coupling.**
- **Invisible branching fraction.**



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LINEAR? CIRCULAR?

Not simple.

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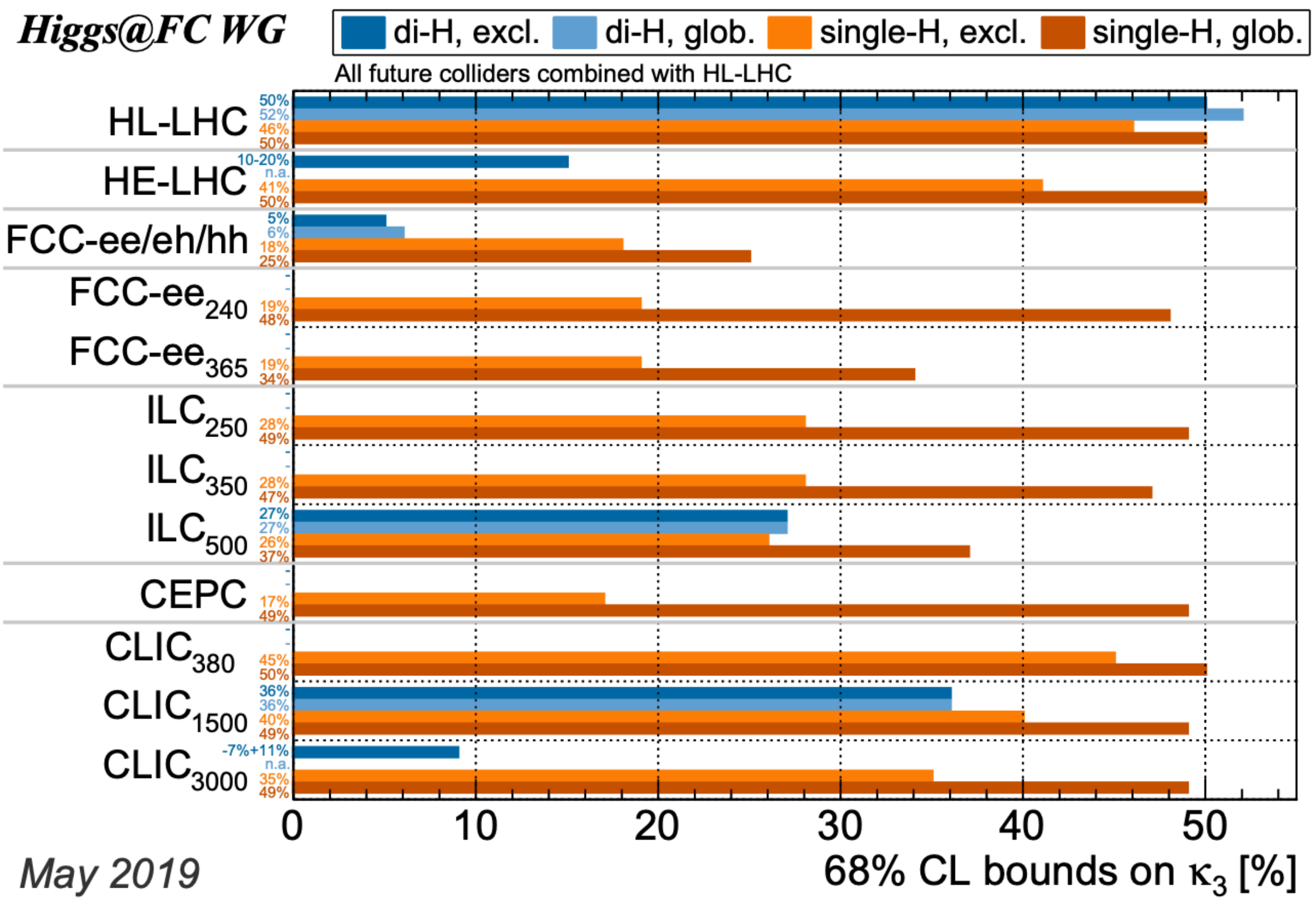
Clear complementarity between lepton and hadron machines.

- Muon and top coupling.
- Invisible branching fraction.

Higgs self-coupling prospects differ.

Discovery from other sectors also important.



EPISODE IX – THE RISE OF SKYWALKER

An episode for us to write together.

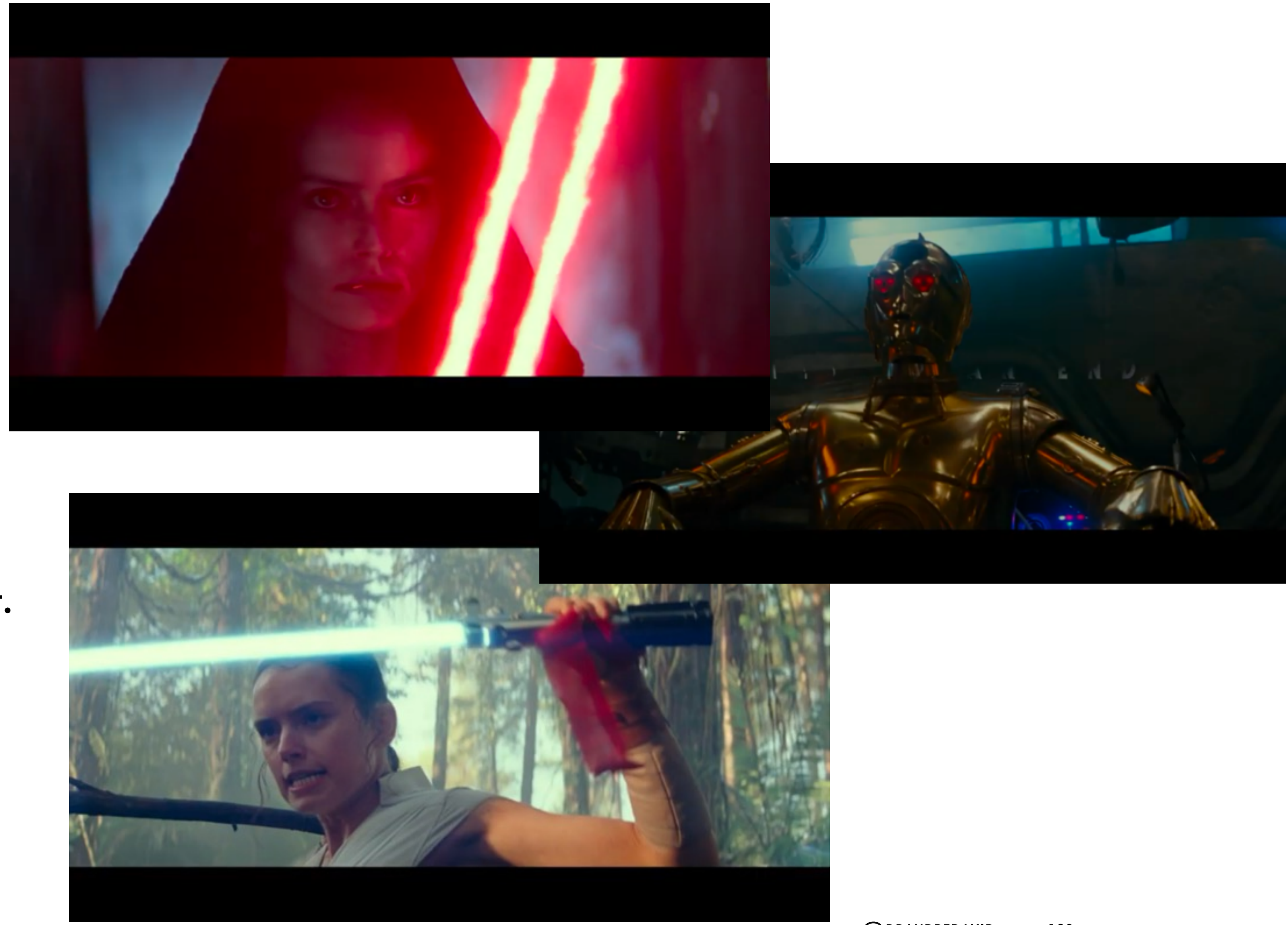
- Is it the rise of other scalars?
- Is it the rise of this scalar heralding BSM physics?

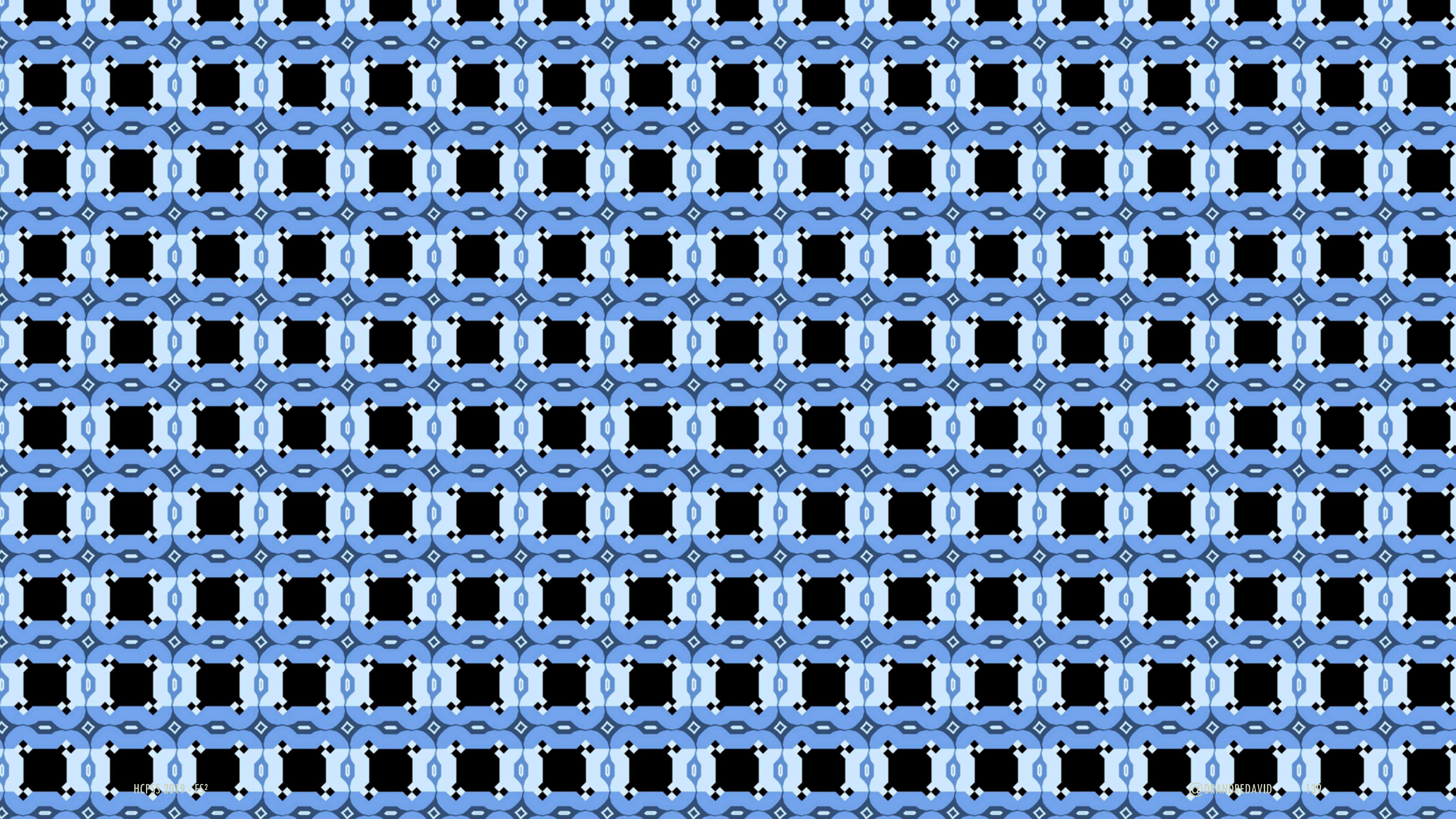
Path of exploration for this scalar is clear.

- We have to be brave enough to tread it 🏃‍♀️.
- It requires ingenuity 🧠 to make the most of it.

SM is undefeated. SM is incomplete.

- Brace yourself for the uncharted.





TOPICS NOT COVERED

SO YOU KNOW WHAT WAS LEFT OUT

SM

Rare processes like Zγ decays or tH production.

Spin and CP, which are highly-differential measurements.

All the H→ZZ→4ℓ exploration of the 8D decay space.

Total width at the LHC, including interpretation of off-shell H(125) production.

Coupling to charm (second generation) from direct searches and indirect measurements of $p_T(H)$.

Couplings to light quarks.

Self-coupling from loop effects (assuming SM for other couplings).

Boosted ggH with H→bb, fat jets, and reach of p_T = 1 TeV.

Signal-continuum interference in H→γγ.

BSM

Invisible decays (other than H→ZZ→4ν).

Decays into lepton-flavor violating final states.

Most the extended scalar searches.

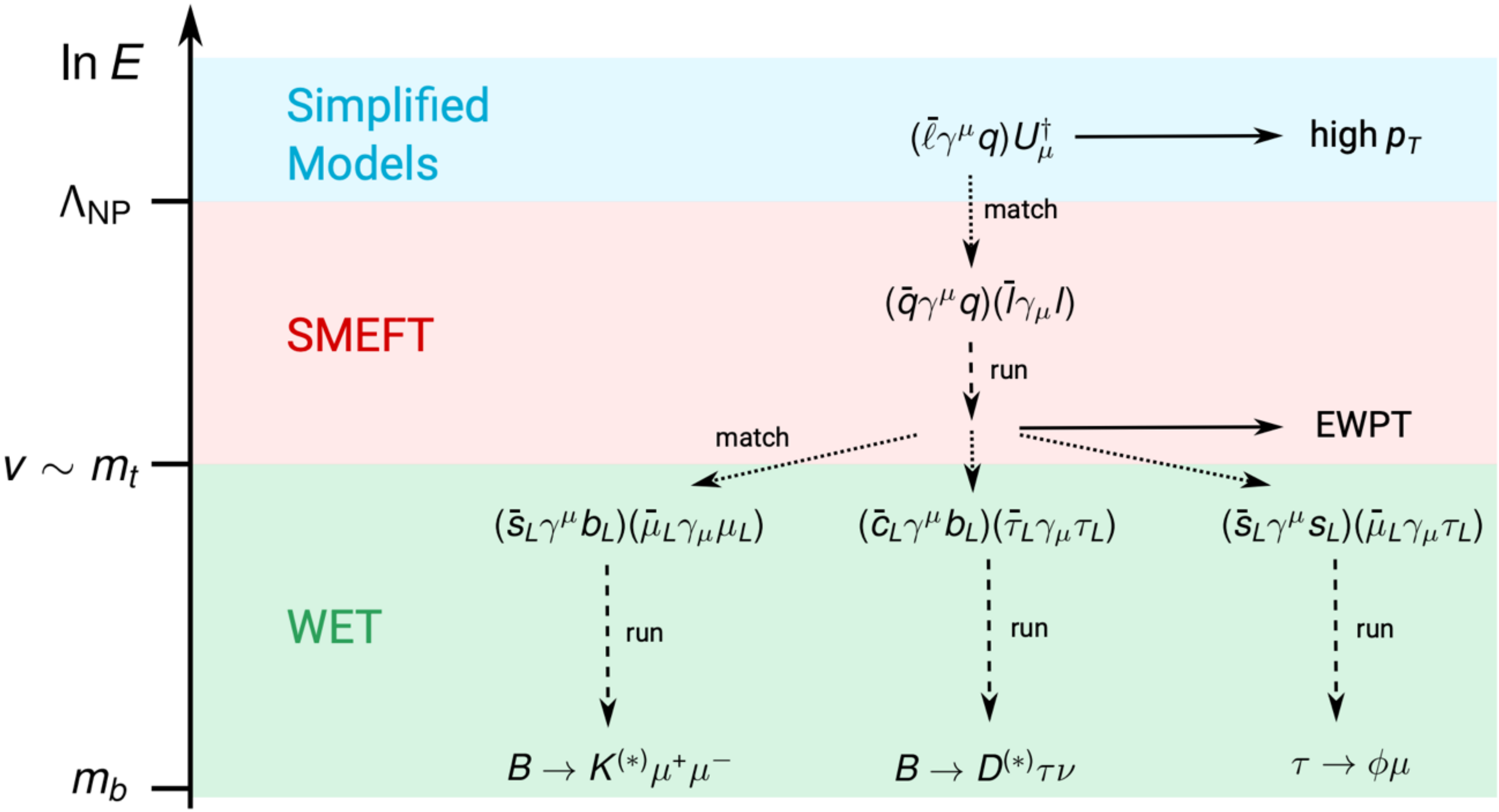
- Low-mass/high-mass, charged/neutral, singlets, etc.

EFT issues.

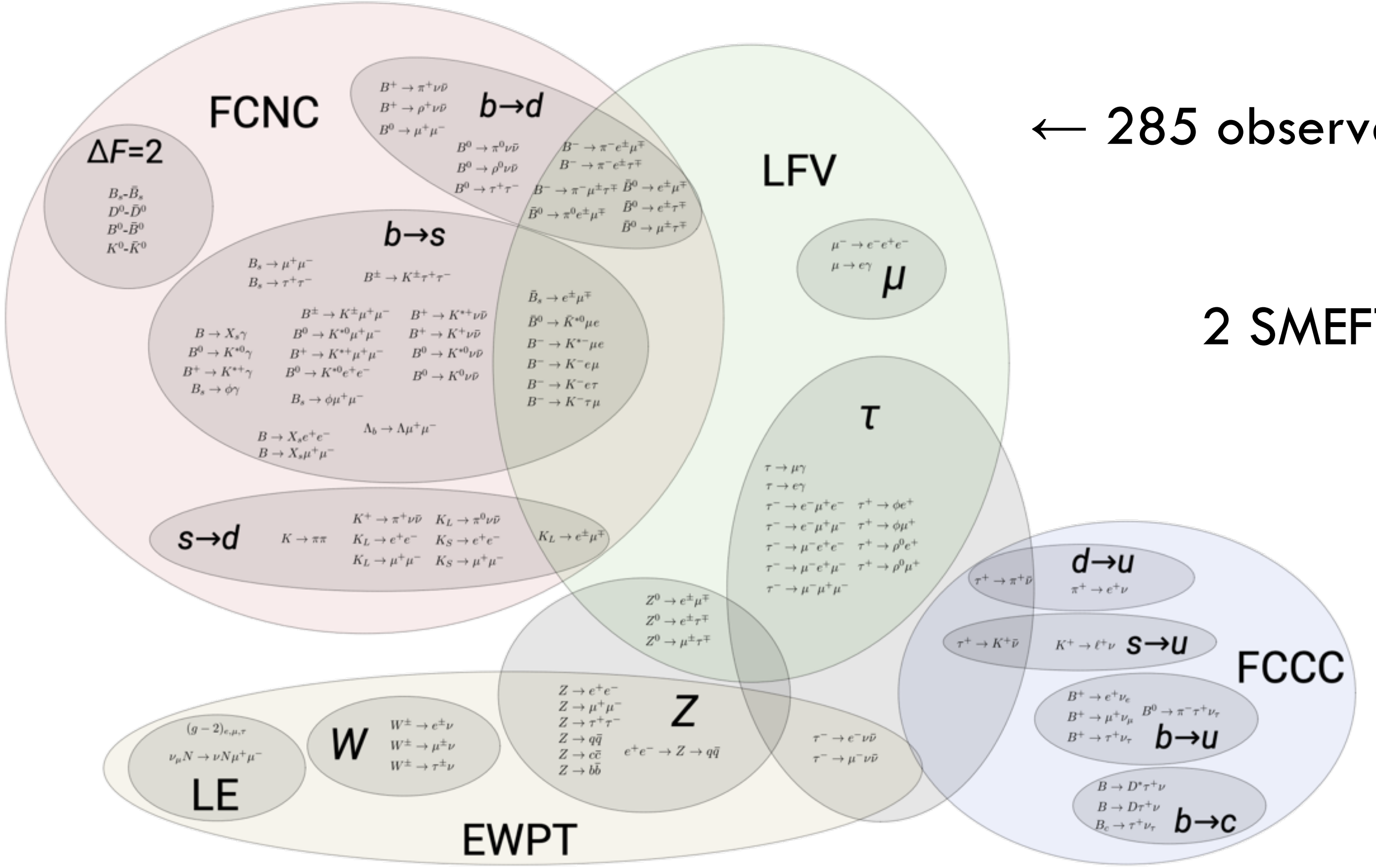
- Validity, quadratic/linear, Dim-4-6-interference and Dim-6^2, LO vs NLO, etc.

🌋 FOR DISCUSSION

$U_1 \sim (3, 1)_{2/3}$ VECTOR LQ – SMEFT – B PHYSICS

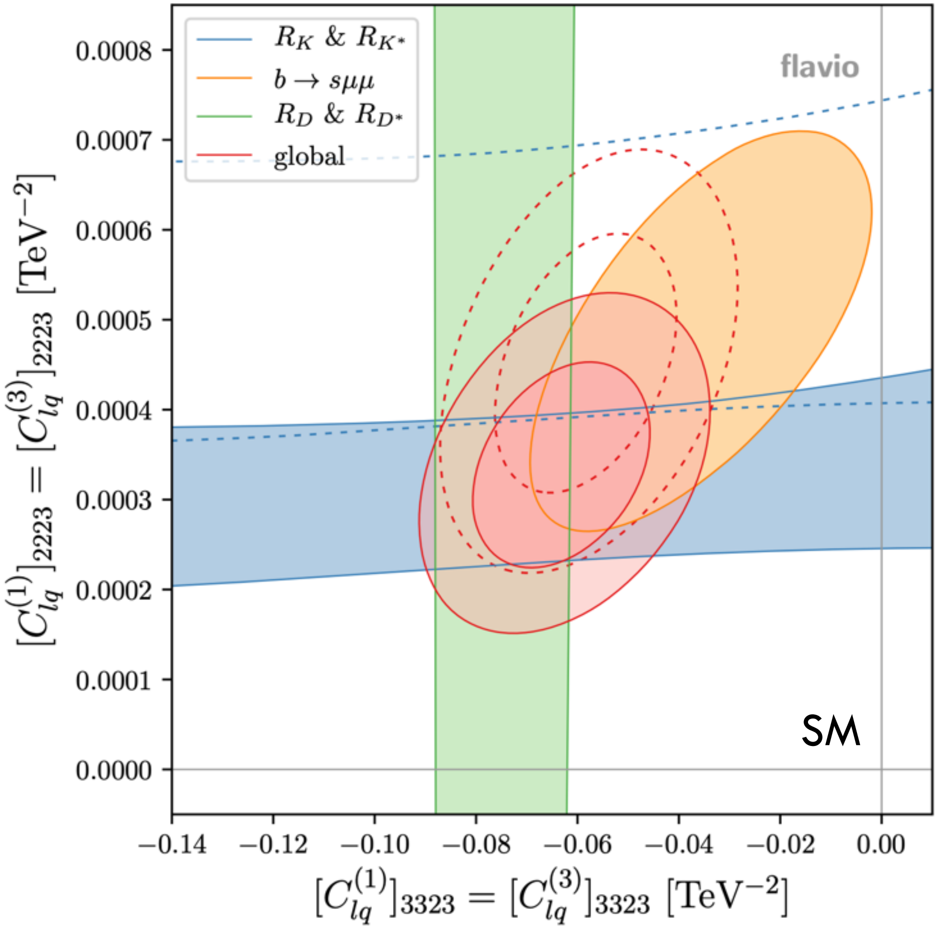


🎢 A WILD RIDE THROUGH OBSERVABLE LAND



← 285 observables

2 SMEFT ops. ⟶



BUT IT'S NOT JUST POLES – TAILS ARE 💎

For H decays, or inclusive production, $\mu \sim O(v, m_H)$

$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\text{TeV}}{\Lambda}\right)^2$$

⇒ **precision** probes large Λ

e.g. $\delta O = 1\% \Rightarrow \Lambda \sim 2.5$ TeV

For H production off-shell or with large momentum transfer Q, $\mu \sim O(Q)$

$$\delta O_Q \sim \left(\frac{Q}{\Lambda}\right)^2$$

⇒ **kinematic reach** probes large Λ even if precision is low

e.g. $\delta O_Q = 15\%$ at Q=1 TeV ⇒ $\Lambda \sim 2.5$ TeV https://indico.cern.ch/event/559310/contributions/2257037/attachments/1329680/1997635/Mangano-SM.pdf

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BUT IT'S NOT JUST POLES — TAILS ARE

…decays, or inclusive production, $\mu \sim O(v, m_H)$

…ision probes large Λ

Just a Higgs example.

Applicable to **large-Q^2 processes** and **differential distributions.**

For H productio…

$$\delta O_Q \sim \left(\frac{Q}{\Lambda}\right)^2$$

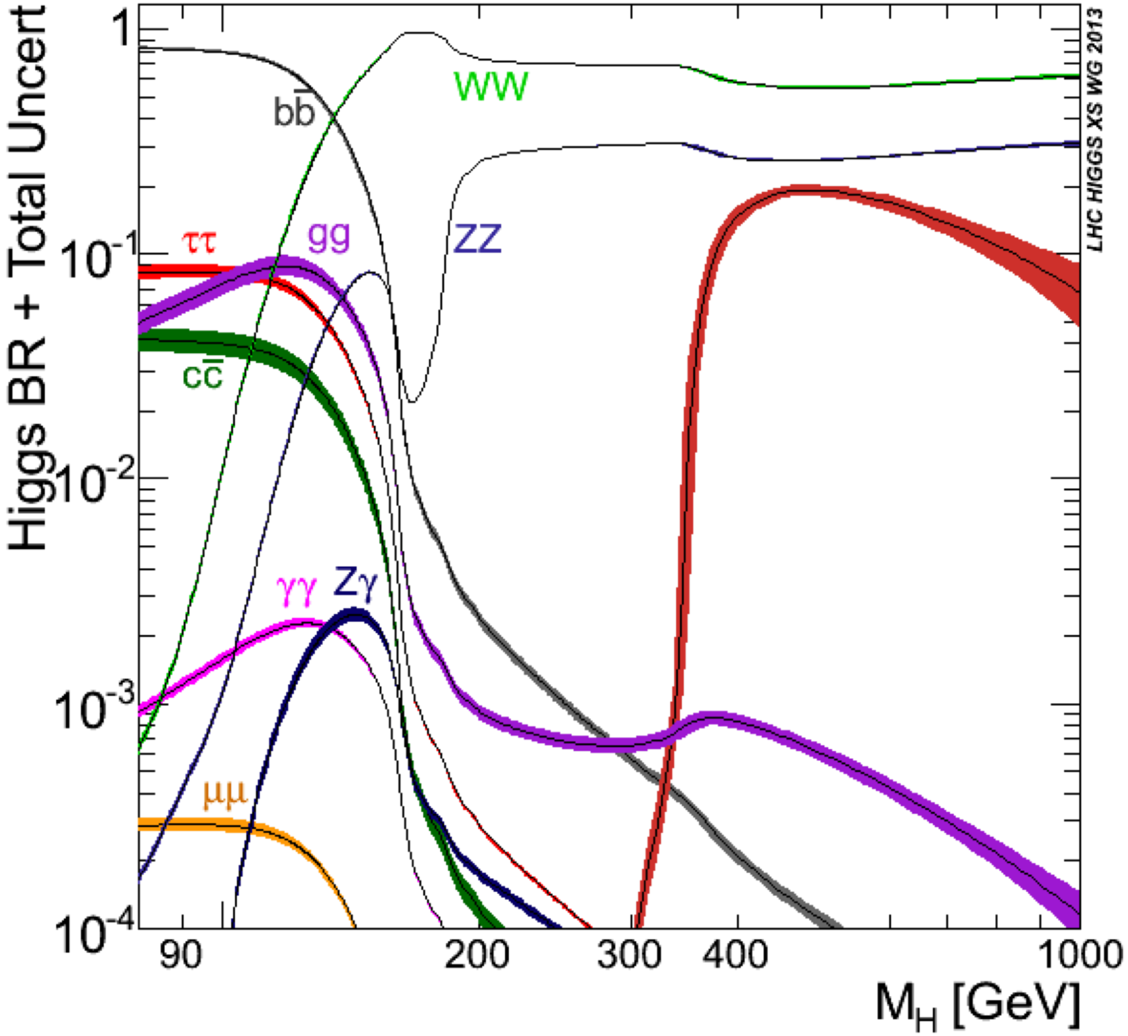
⇒ kine…

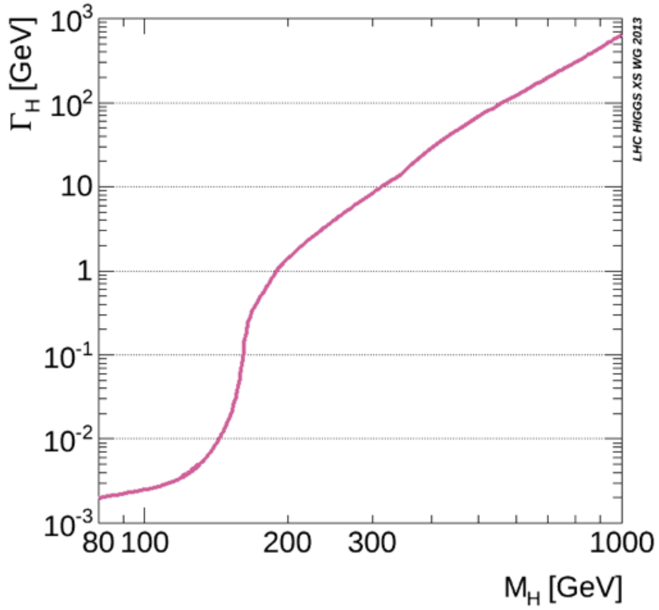
if precision is low

e.g. δO_Q =15% at Q=1 TeV ⇒ Λ~2.5 TeV

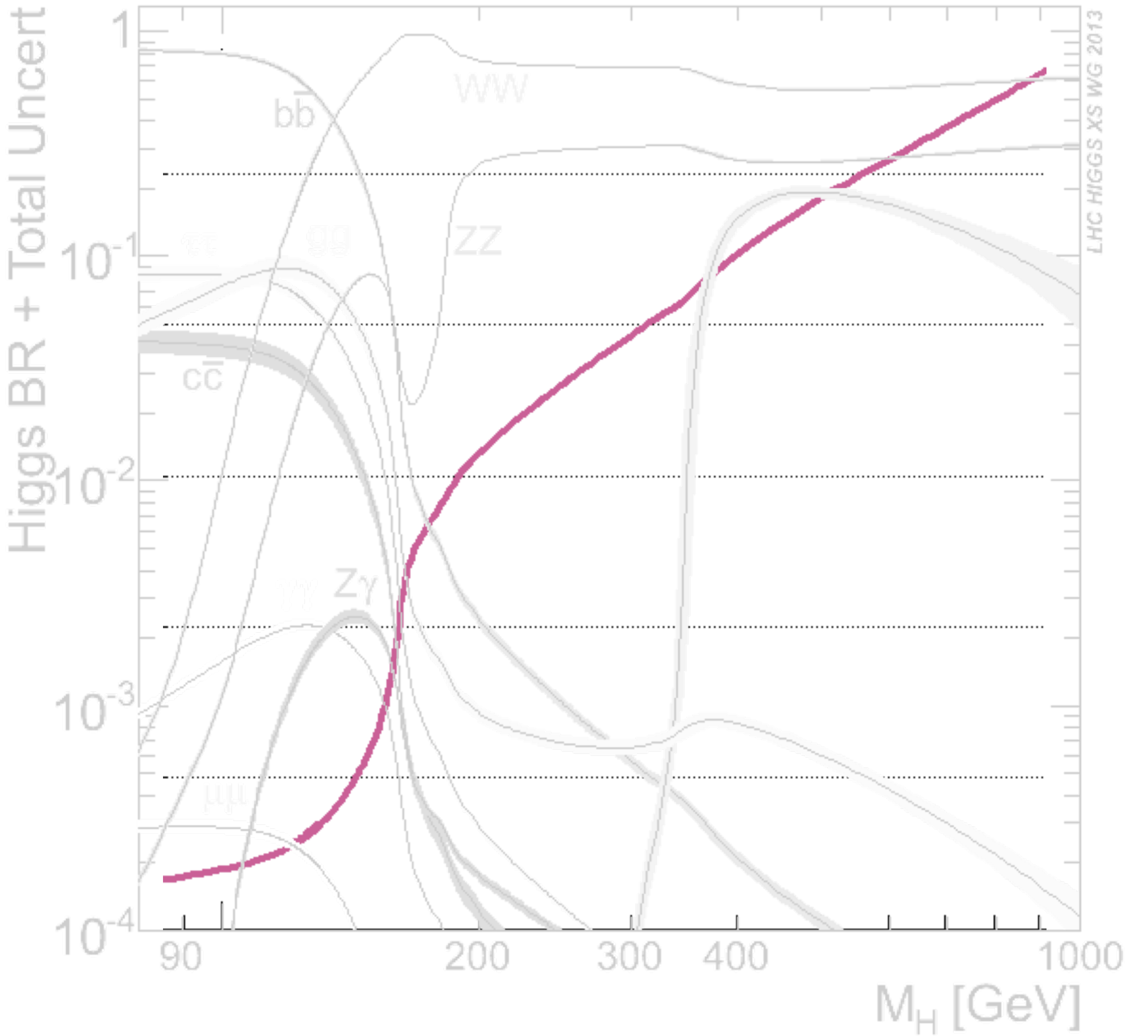
☢️ FOR EVEN MORE DISCUSSION

TOTAL WIDTH, (PARTIAL WIDTHS), AND BRANCHING FRACTIONS





TOTAL WIDTH, PARTIAL WIDTH, AND BRANCHING FRACTIONS



COMPUTING FOR THE UNMEASURABLE – QED

Spin and polarization sums

We have seen that the probability of scattering, and hence the cross-section, is proportional to $|\mathcal{M}|^2$. The initial and final states involve definite spins u_s or v_s and polarizations ϵ^r_μ. These are often not measured experimentally in which case they are summed or averaged over. We

sum over spin or polarization of final states

average over spin or polarization of initial states

In QCD there's another quantum number: color.
So, which particle has no color, no spin, and no polarization?