MIDDLE WAY

KAPPAS
FIDUCIAL CROSS-SECTIONS

EFFECTIVE FIELD THEORY
WILSON COEFFICIENTS

RENCONTRES DE MORIOND 50 since 1966

André David (CERN)

Lunch – Waldorf-Astoria style

[http://cern.ch/go/Ns8X]

“Two waiters serve two steel workers lunch, on a girder high above New York City, 1930. (Photo by Keystone/Getty Images)”

4-box summary

Fiducial cross-sections are a lot of bins.

Kappas cannot describe many SM deformations.

Wilson coefficients deeply rooted in TH.

Need to **extend kappas** to something **between the other two.**

Standard Model of Particle Physics

[http://cern.ch/go/dW6z]

$$
\begin{aligned}
&-\tfrac{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 - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \tfrac{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 - \tfrac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H\partial_\mu H - \tfrac{1}{2}m_h^2H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - \\
&M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \tfrac{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)] - \tfrac{1}{2}g^2W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{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^-] - \tfrac{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 - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{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)] + \\
&\tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - \\
&W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{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^+) - \\
&\tfrac{1}{4}g^2W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \tfrac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - \\
&g^2\tfrac{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) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \tfrac{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(\tfrac{4}{3}s_w^2 - \\
&1-\gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1-\tfrac{8}{3}s_w^2-\gamma^5)d^\lambda_j)] + \tfrac{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)] + \tfrac{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)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + \\
&i\phi^0(\bar{e}^\lambda\gamma^5e^\lambda)] + \tfrac{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] + \tfrac{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] - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}^\lambda_ju^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}^\lambda_jd^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5u^\lambda_j) - \tfrac{ig}{2}\tfrac{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 - \tfrac{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^-) - \tfrac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H] + \tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \\
&\bar{X}^-X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]
\end{aligned}
$$

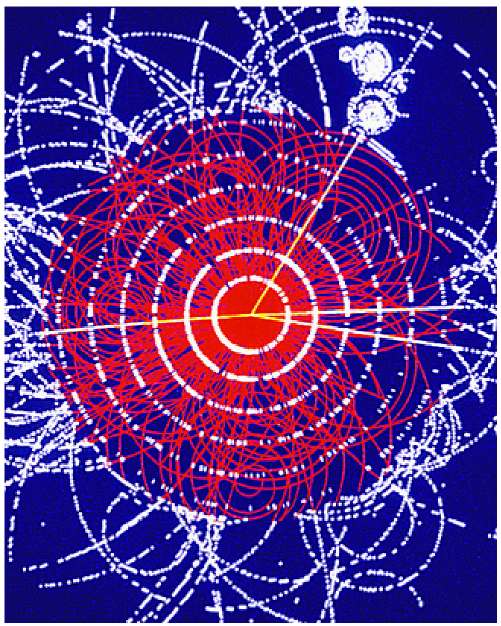
Who Should Be TIME's Person of the Year 2012?

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.

THE CANDIDATES

The Higgs Boson

By Jeffrey Kluger | Monday, Nov. 26, 2012



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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

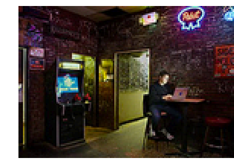
Take a moment to thank this little particle for all the work it does, because without it, you'd be just inchoate energy without so much as a bit of mass. What's more, the same would be true for the entire universe. It was in the 1960s that Scottish physicist Peter Higgs first posited the existence of 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.

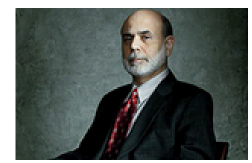
WHO SHOULD BE TIME'S PERSON OF THE YEAR 2012?
The Candidates
Video
Poll Results

PAST PERSONS OF THE YEAR

2011: The Protester



2010: Facebook's Mark Zuckerberg



2009: Ben Bernanke

2008: Barack Obama

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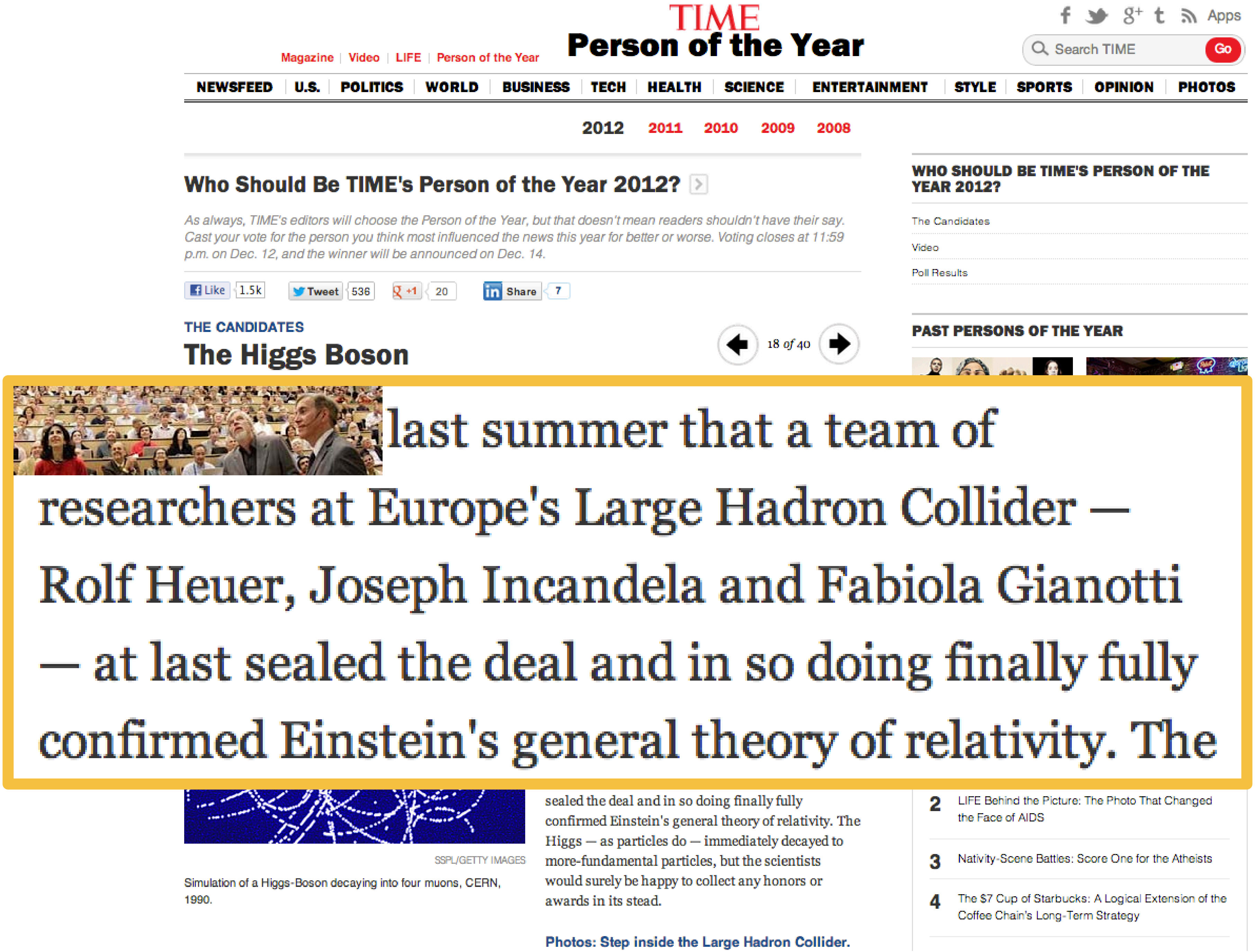
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Who Should Be TIME's Person of the Year 2012?

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THE CANDIDATES

The Higgs Boson

18 of 40

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SSPL/GETTY IMAGES

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Photos: Step inside the Large Hadron Collider.

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PAST PERSONS OF THE YEAR

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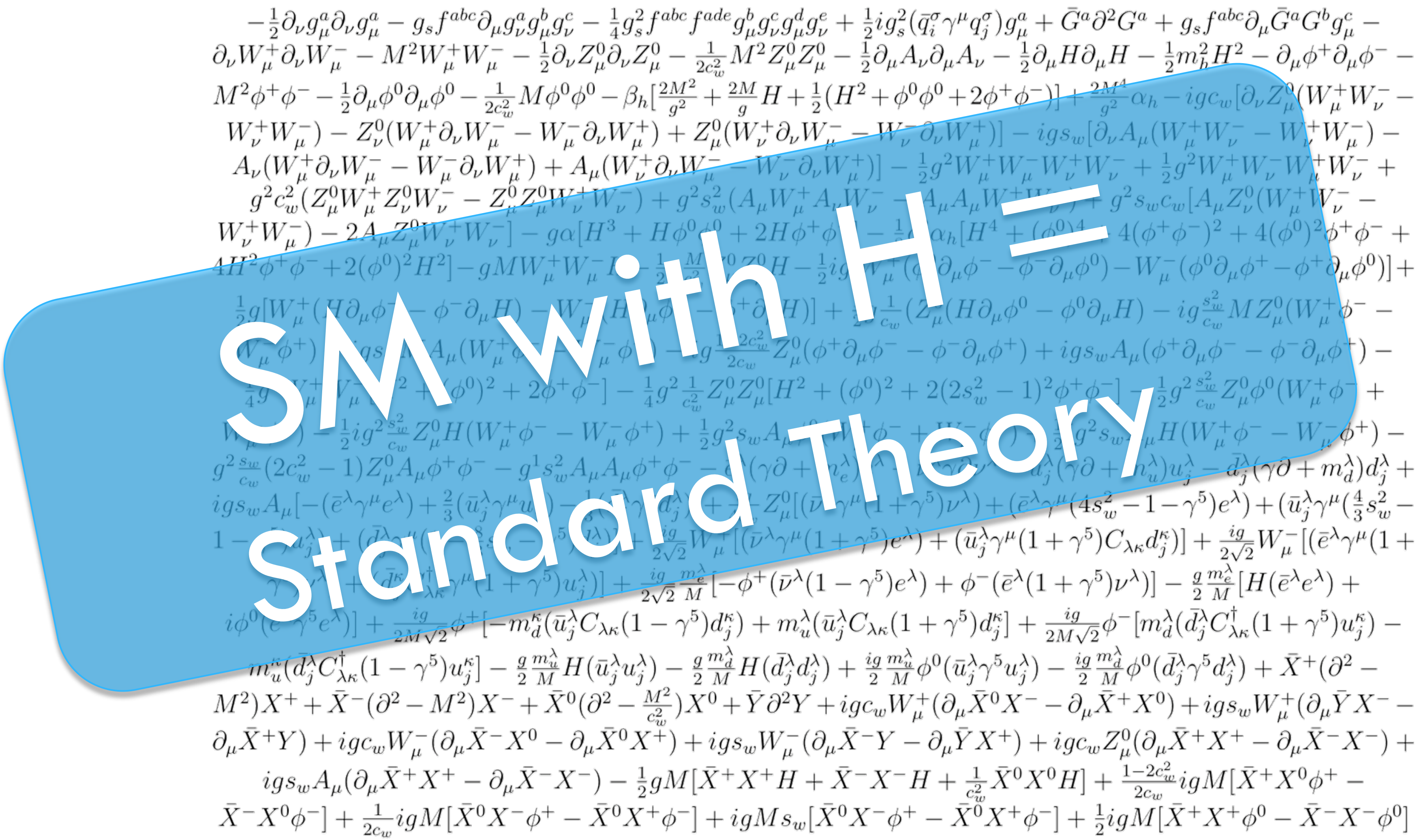
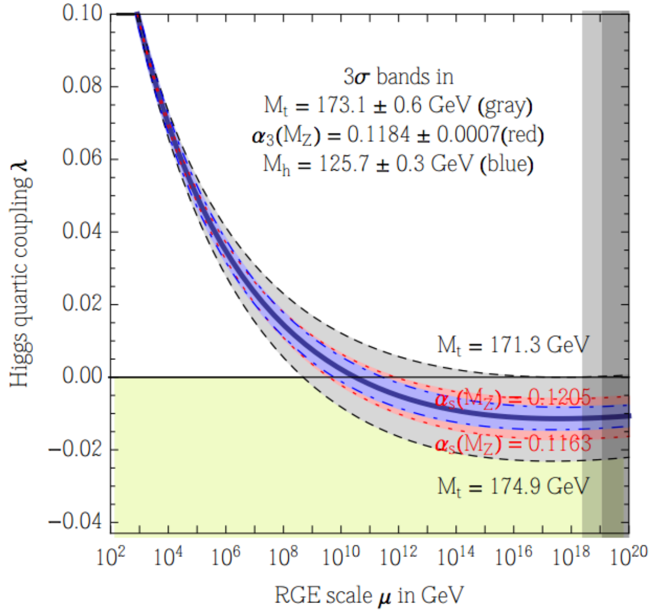
Standard **Theory** of Particle Physics

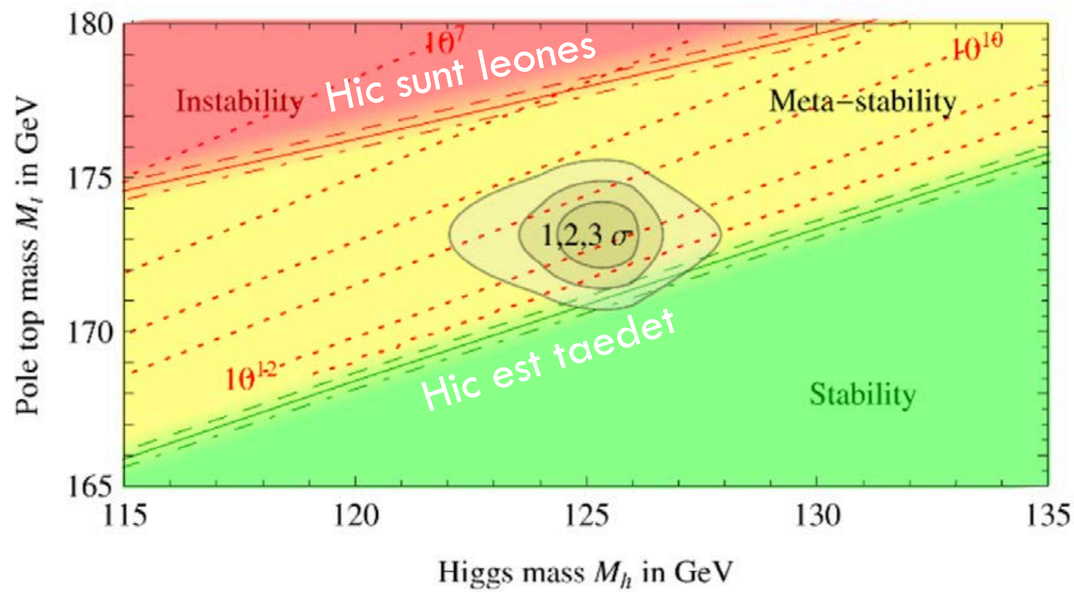
[http://cern.ch/go/dW6z]



The fate/character of the Universe

[JHEP 1208 (2012) 098]





- Standard Theory seems self-consistent up to large scales.
  - …though the Universe might decay.

Standard **Theory** of Particle Physics

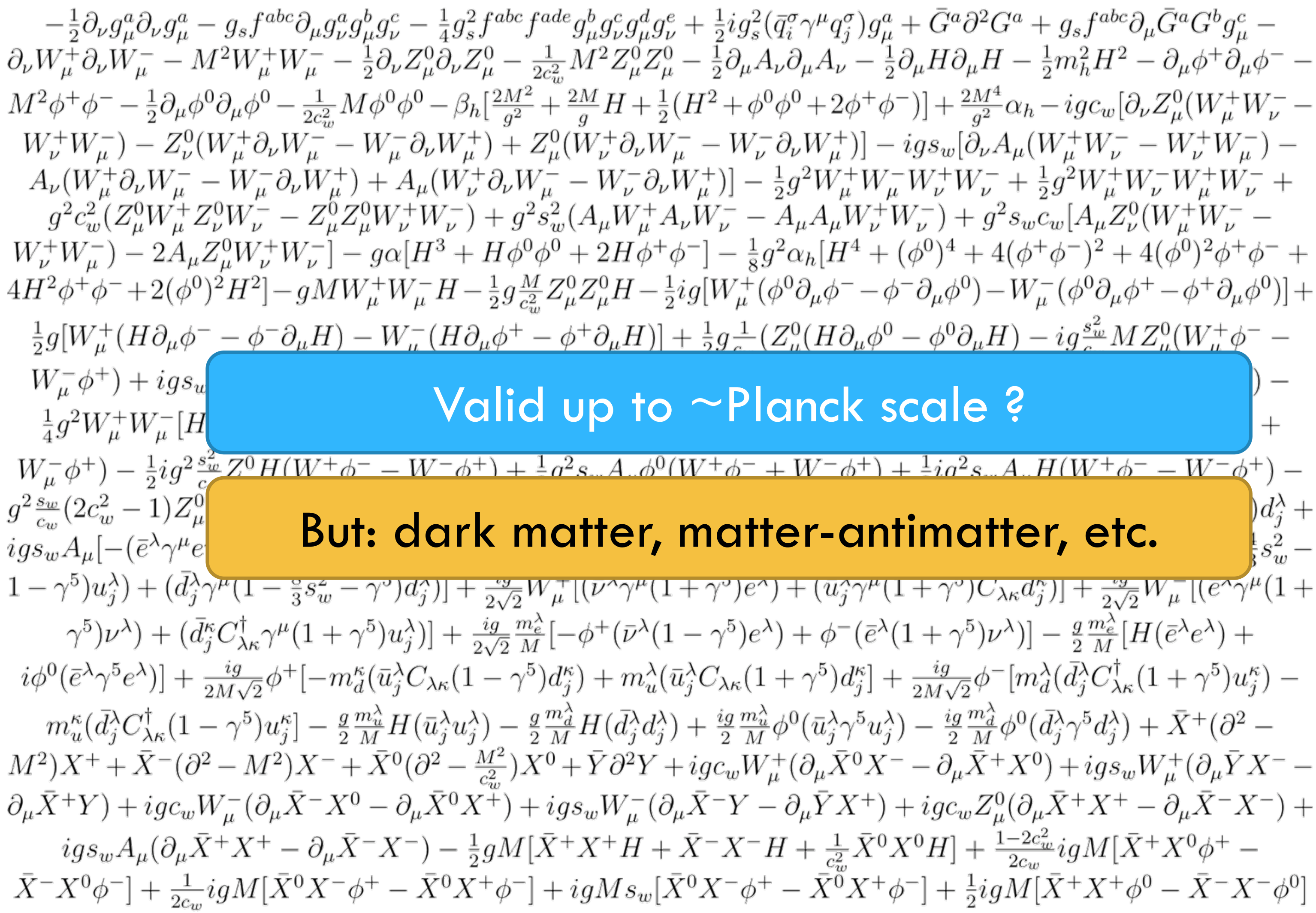
[http://cern.ch/go/dW6z]

$$-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu -$$
$$\partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \tfrac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- -$$
$$M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) -$$
$$A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu +$$
$$g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- +$$
$$4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] +$$
$$\tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- -$$
$$W^-_\mu\phi^+) + igs_w \text{[illegible]}) -$$
$$\tfrac{1}{4}g^2W^+_\mu W^-_\mu[H \text{[illegible]} +$$
$$W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) -$$
$$g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}_j^\lambda(\gamma\partial + m_u^\lambda)u_j^\lambda - \bar{d}_j^\lambda(\gamma\partial + m_d^\lambda)d_j^\lambda +$$
$$igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}_j^\lambda\gamma^\mu u_j^\lambda) - \tfrac{1}{3}(\bar{d}_j^\lambda\gamma^\mu d_j^\lambda)] + \tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}_j^\lambda\gamma^\mu(\tfrac{4}{3}s_w^2 -$$
$$1 - \gamma^5)u_j^\lambda) + (\bar{d}_j^\lambda\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d_j^\lambda)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}_j^\lambda\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d_j^\kappa)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+$$
$$\gamma^5)\nu^\lambda) + (\bar{d}_j^\kappa C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u_j^\lambda)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) +$$
$$i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}_j^\lambda C_{\lambda\kappa}(1-\gamma^5)d_j^\kappa) + m_u^\lambda(\bar{u}_j^\lambda C_{\lambda\kappa}(1+\gamma^5)d_j^\kappa] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}_j^\lambda C^\dagger_{\lambda\kappa}(1+\gamma^5)u_j^\kappa) -$$
$$m_u^\kappa(\bar{d}_j^\lambda C^\dagger_{\lambda\kappa}(1-\gamma^5)u_j^\kappa] - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}_j^\lambda u_j^\lambda) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}_j^\lambda d_j^\lambda) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}_j^\lambda\gamma^5 u_j^\lambda) - \tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}_j^\lambda\gamma^5 d_j^\lambda) + \bar{X}^+(\partial^2 -$$
$$M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- -$$
$$\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) +$$
$$igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H] + \tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ -$$
$$\bar{X}^-X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$

Valid up to ~Planck scale ?

Standard **Theory** of Particle Physics

[http://cern.ch/go/dW6z]

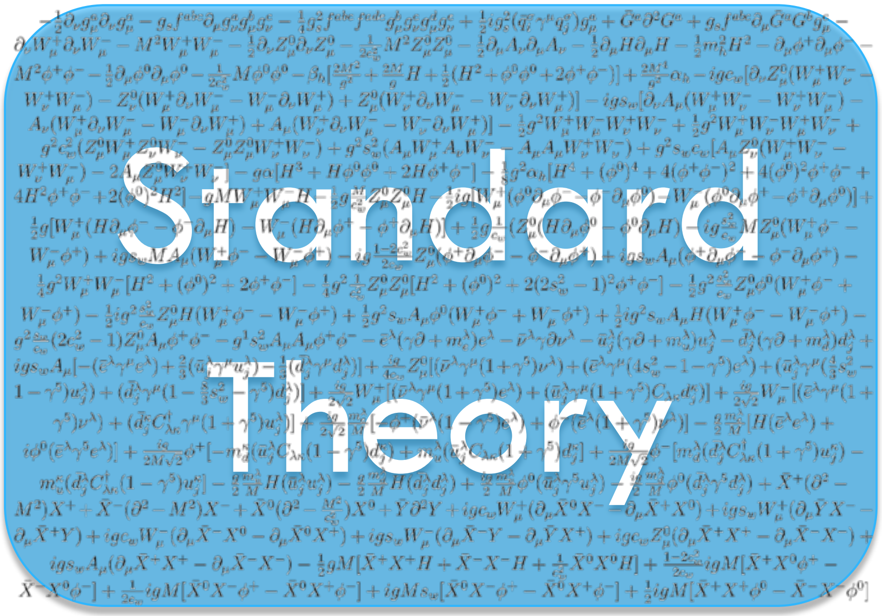


Valid up to ~Planck scale ?

But: dark matter, matter-antimatter, etc.

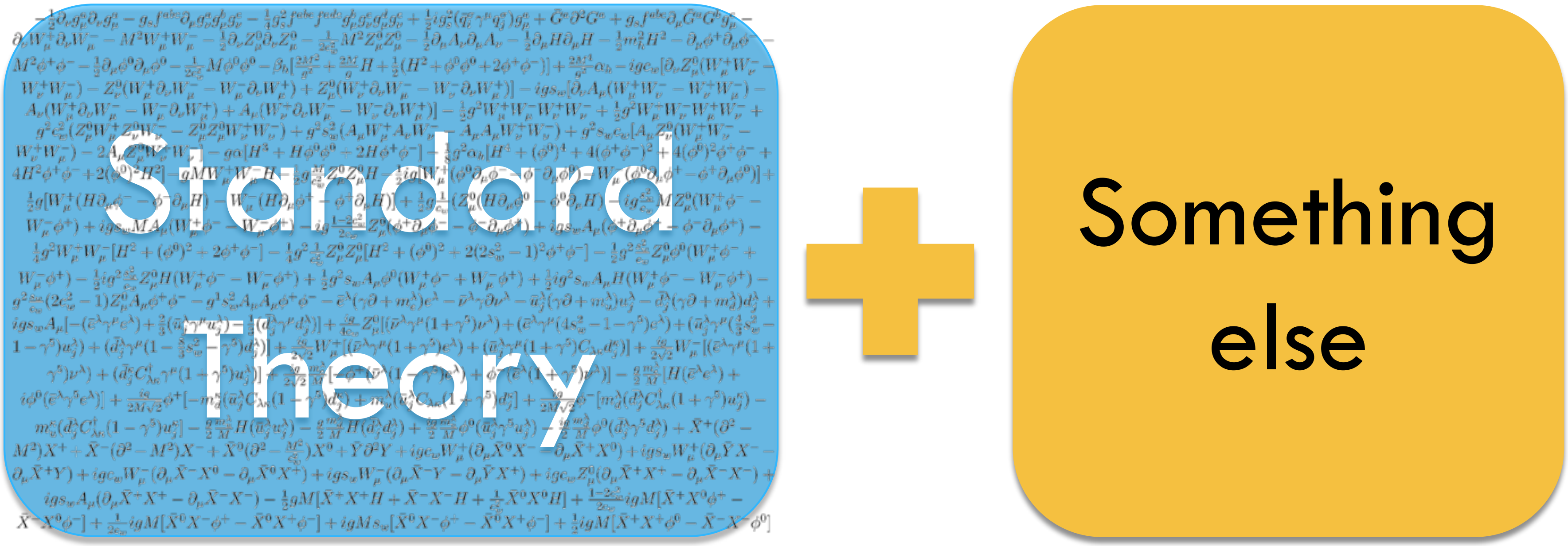
The Next Standard Model

[http://cern.ch/go/dW6z]



The Next Standard Model

[http://cern.ch/go/dW6z]



H(125) – looking for “*something else*”

- Mass
  - Exp. Uncertainties
  - SM consistency: (m_H, m_W, m_{top})
- Spin
  - J=0 ok for everyone?
- Charge
  - Zero. (That was easy.)
- Parity
  - Amplitude decomposition → EFT
- Scalar couplings
  - $\kappa \rightarrow \kappa(q) \rightarrow f(q) \rightarrow$ EFT

Handles on deviations

- **Mass**
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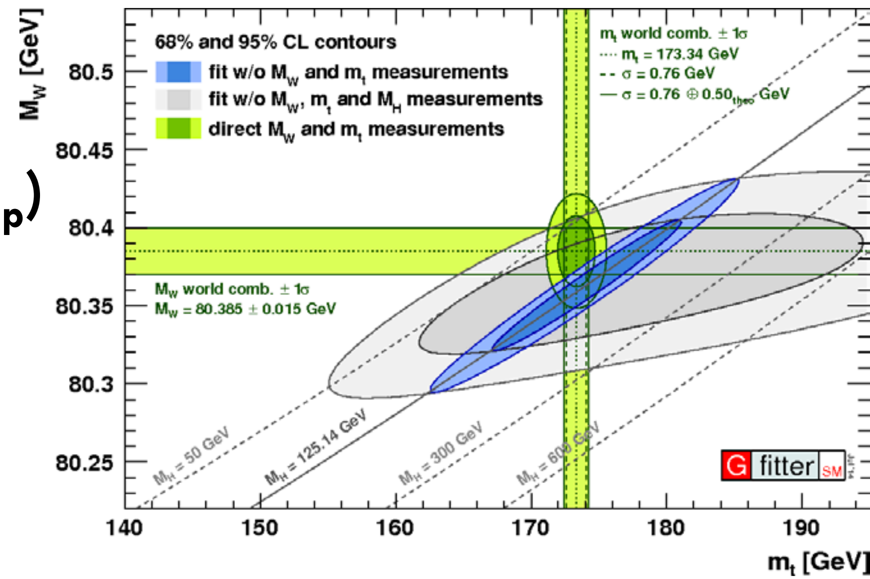

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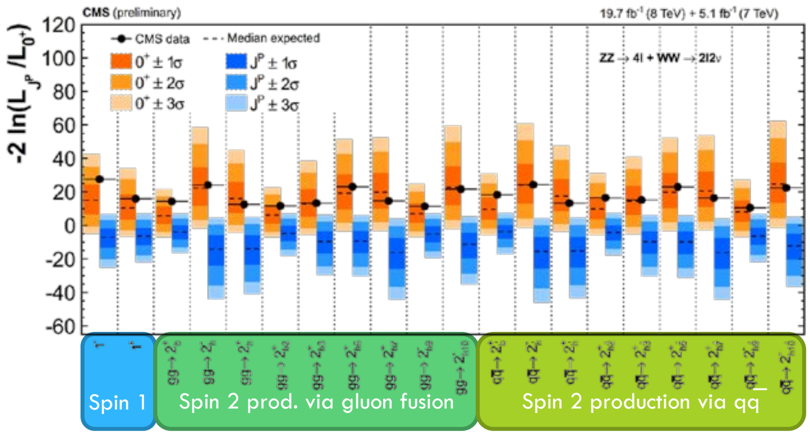

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0

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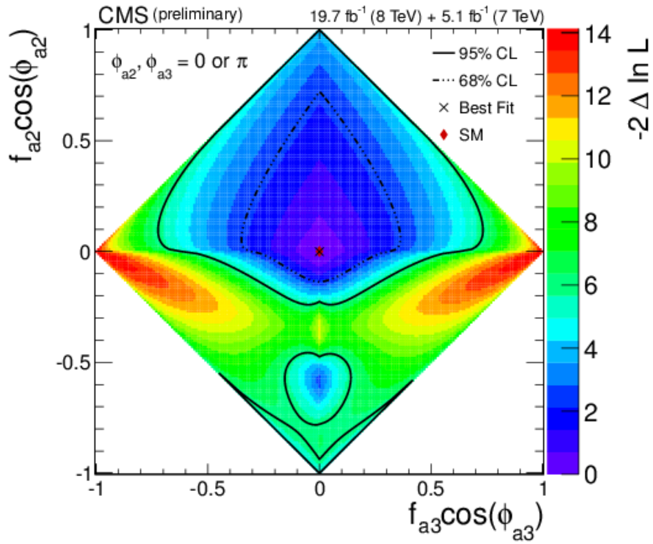
- **Parity**
  - **Amplitude decomposition → EFT**
- Scalar couplings
  - κ→ κ(q) → f(q) → EFT

$$A(X_{J=0} \to V_1 V_2) \sim v^{-1}\left(\left[a_1 - e^{i\phi_{\Lambda_1}}\frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2}\right] m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^* + a_2 f_{\mu\nu}^{*(Z_1)} f^{*(Z_2),\mu\nu} + a_3 f_{\mu\nu}^{*(Z_1)} \tilde{f}^{*(Z_2),\mu\nu} + a_2^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu} + a_2^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} \tilde{f}^{*(\gamma_2),\mu\nu}\right)$$



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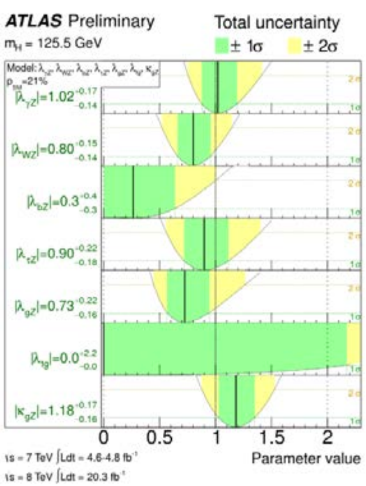

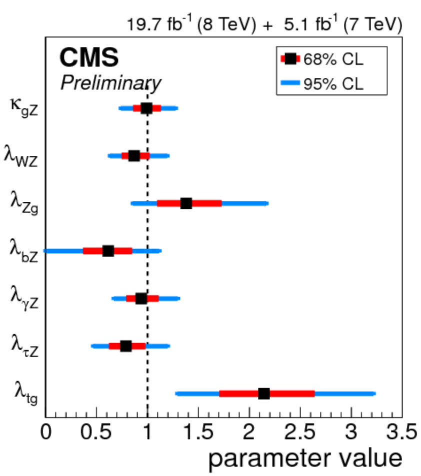

Kappas: scalar coupling deviations

[arXiv:1307.1347]

Production modes

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa_W^2$$

$$\frac{\sigma_{ZH}}{\sigma_{ZH}^{SM}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{SM}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}^{SM}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{SM}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{SM}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}} : \text{see Section 3.1.2}$$

$$\frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma_{s\bar{s}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{SM}} = \kappa_\tau^2$$

Total width

$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

- Single state, spin 0, and CP-even.
- Narrow-width approximation: $(\sigma \times BR) = \sigma \cdot \Gamma / \Gamma_H$

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$$= \kappa_t^2$$

see Section 3.1.2

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Kappas do not change shapes.
Only overall yields.

- Single state, spin 0, and CP-even.
- Narrow-width approximation: $(\sigma \times BR) = \sigma \cdot \Gamma / \Gamma_H$

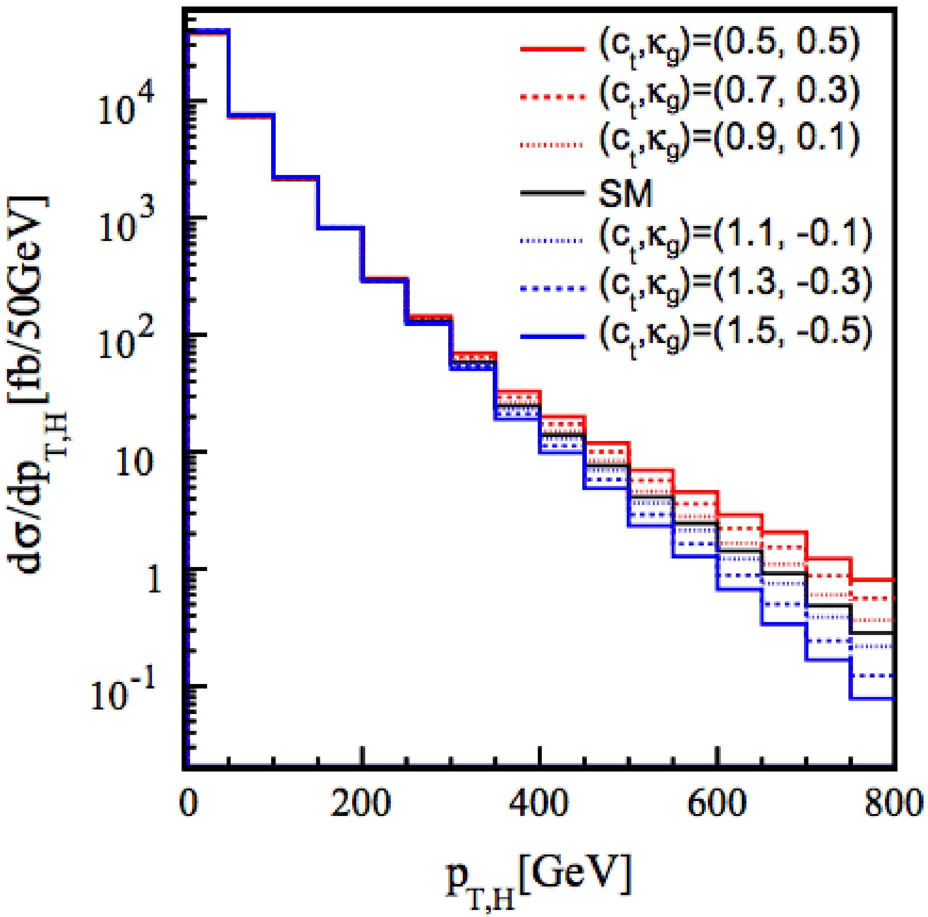
Kappas do not change shapes

[Spannowsky et al. arXiv:1405.4295]

- Scaling the **SM line** would not capture **gluon-gluon-H** vertex effects:

$$\mathcal{L}_{\rm eff} = -c_t \frac{m_t}{v} \bar{t} t H + \kappa_g \frac{\alpha_S}{12\pi} \frac{h}{v} G^a_{\mu\nu} G^{a\,\mu\nu} + \mathcal{L}_{\rm QCD}$$

$$\mathcal{M}(c_t, \kappa_g) = c_t \mathcal{M}_{\rm IR} + \kappa_g \mathcal{M}_{\rm UV}$$



Deviations are on a diet

[arXiv:1306.6352]

- SUSY (tanβ=5): $$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$
- Composite scalar: $$\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$$
- Top partners: $$\frac{g_{hgg}}{g_{h_{SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2, \quad \frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2$$

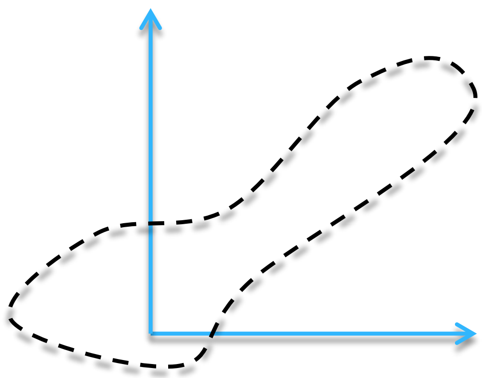
Effective field theory (EFT): the idea

[NPB 268 (1986) 621] [JHEP 10 (2010) 085]

- **Experimentally-driven set of parameters** vs. basis of QFT operators that may be better aligned with the **Next SM features.**

- EFT allows to perform accurate calculations:
  - NLO EWK effects, etc.
  - More sensitive interpretation.

- >59 dim-6 operators already mapped out in 1986.
  - **Which operators to keep ?**
  - **What about dim-8 ?**
  - **What about loop processes ?**



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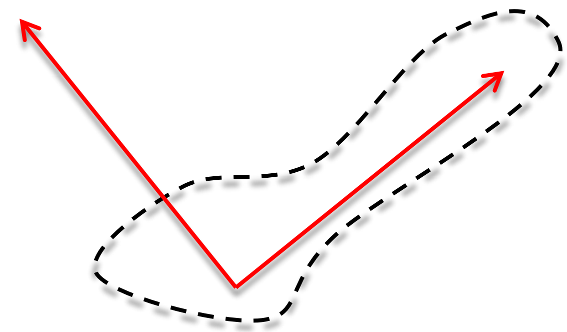

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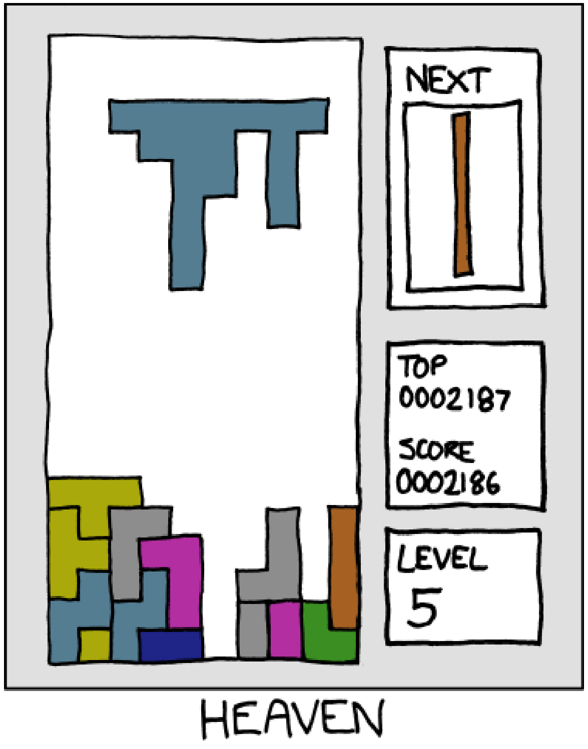
LHC Higgs Cross Section WG

[http://xkcd.com/888/]

- Experimentalists and theorists joined to produce the best pieces for a common puzzle.

- This talk draws heavily from discussions in and around **WG2.**
  - Special thanks to G. Passarino, G. Isidori, A. Falkowski, M. Duehrssen, M. Trott, F. Riva, F. Maltoni, and C. Grojean.
  - Inaccuracies are still my own.



Supplementing the Standard Theory

Concrete BSM

- SUSY: MSSM, NMSSM, etc.
- Possibly:
  - Light new physics.
  - Other states.
  - Non-decoupled.
- Specific benchmarks.
  - LHC HXSWG WG3.

EFT expansion

- Add higher-dimensional operators.
- Assumes:
  - Heavy new physics.
  - Indirect effects, loops.
  - Decoupled.
- Generic interpretation.
  - LHC HXSWG WG2.

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  - LHC HXSWG **WG2.**

Not all EFT are born the same

[http://cern.ch/go/L98Q]

Top-down EFT	Bottom-up EFT
Full theory known: Matching conditions bridge EFT and full theory.	Full theory **un**known: Add operators as theory can calculate and data can discern.

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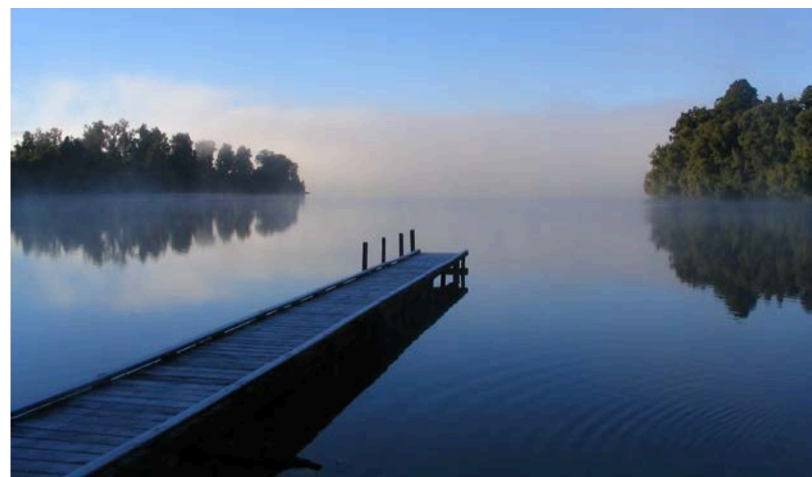

A taxonomy of dim-6 operators

[Trott et al. JHEP 04 (2014) 159]

Class	N_{op}	CP-even n_g	1	3	CP-odd n_g	1	3
$1: X^3$	4	2	2	2	2	2	2
$2: H^6$	1	1	1	1	0	0	0
$3: H^4 D^2$	2	2	2	2	0	0	0
$4: X^2 H^2$	8	4	4	4	4	4	4
$5: \psi^2 H^3 + \text{h.c.}$	3	$3n_g^2$	3	27	$3n_g^2$	3	27
$6: \psi^2 X H + \text{h.c.}$	8	$8n_g^2$	8	72	$8n_g^2$	8	72
$7: \psi^2 H^2 D$	8	$\frac{1}{2} n_g (9n_g + 7)$	8	51	$\frac{1}{2} n_g (9n_g - 7)$	1	30
$8: (\overline{L}L)(\overline{L}L)$	5	$\frac{1}{4} n_g^2 (7n_g^2 + 13)$	5	171	$\frac{7}{4} n_g^2 (n_g - 1)(n_g + 1)$	0	126
$8: (\overline{R}R)(\overline{R}R)$	7	$\frac{1}{8} n_g (21n_g^3 + 2n_g^2 + 31n_g + 2)$	7	255	$\frac{1}{8} n_g (21n_g + 2)(n_g - 1)(n_g + 1)$	0	195
$8: (\overline{L}L)(\overline{R}R)$	8	$4n_g^2 (n_g^2 + 1)$	8	360	$4n_g^2 (n_g - 1)(n_g + 1)$	0	288
$8: (\overline{L}R)(\overline{R}L)$	1	n_g^4	1	81	n_g^4	1	81
$8: (\overline{L}R)(\overline{L}R)$	4	$4n_g^4$	4	324	$4n_g^4$	4	324
$8:$ All	25	$\frac{1}{8} n_g (107n_g^3 + 2n_g^2 + 89n_g + 2)$	25	1191	$\frac{1}{8} n_g (107n_g^3 + 2n_g^2 - 67n_g - 2)$	5	1014
Total	59	$\frac{1}{8} (107n_g^4 + 2n_g^3 + 213n_g^2 + 30n_g + 72)$	53	1350	$\frac{1}{8} (107n_g^4 + 2n_g^3 + 57n_g^2 - 30n_g + 48)$	23	1149

Table 2. Number of CP-even and CP-odd coefficients in $\mathcal{L}^{(6)}$ for n_g flavors. The total number of coefficients is $(107n_g^4 + 2n_g^3 + 135n_g^2 + 60)/4$, which is 76 for $n_g = 1$ and 2499 for $n_g = 3$.

EFT questions

- From 2499 dim-6 operators to ~60 operators.
  - **Symmetries** guide the culling:
    - Flavour, ~custodial, CP.
    - Each assumption needs **testing** measurements/observables.

- But to go down from ~60:
  - Guidance from **experimental sensitivity.**
  - Use **complementary information:**
    - LEP, Tevatron, etc experimental constraints.
    - aTGC/aQGC, top quark, EDM searches, etc.

Working out the details

[http://cern.ch/go/6xk9]

"A construction worker crouches over the end of a girder high above the streets of New York. (Photo by General Photographic Agency/Getty Images). Circa 1930"

EFT challenges

- $|\text{dim-4} + \text{dim-6} + \text{dim-8} + \dots|^2 =$
  $= \mathbf{d4^2} + d4 \times d6 \ (+\ d6^2 + d4 \times d8)\ (+\ d6 \times d8 + d8^2) + \dots$
  - Weeding of the negligible, keeping of the sizable.

- Delicate choices because of:
  - Tails of large Q^2 values where dim-8 may not be so small.
  - Where there is no dim-6 tree contribution, dim-8 is leading.

- And let's not forget interferences.
  - Signals and backgrounds are physics processes all alike.

Delicate choices

[Passarino http://cern.ch/go/nT7n]

- $|\text{dim-4} + \text{dim-6} + \text{dim-8} + \ldots|^2 =$
  $= d4^2 + \mathbf{d4 \times d6}$ $(+\, d6^2 + \mathbf{d4 \times d8})$ $(+\, d6 \times d8 + d8^2) + \ldots$

1 Λ^{-2} Λ^{-4} Λ^{-4} Λ^{-6} Λ^{-8}

LO: g_{d4}
NLO: g_{d4}^{3}
NNLO: g_{d4}^{5}
...

If $\Lambda < 3$ TeV, **dim-8** should not be neglected w.r.t. **dim-6**.

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$d4^2$	$d4 \times d6$	$d6^2$	$d4 \times d8$	$d6 \times d8$	$d8^2$
1	Λ^{-2}	Λ^{-4}	Λ^{-4}	Λ^{-6}	Λ^{-8}

LO: g_{d4}
NLO: g_{d4}^3
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…

If $\Lambda > 5$ TeV, **SM NNLO** should not be neglected w.r.t. **dim-6**.

Delicate choices

[http://cern.ch/go/Ks9T]

- $|\text{dim-4} + \text{dim-6} + \text{dim-8} + \ldots|^2 =$
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LO: g_{d4}
NLO: g_{d4}^{3}
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…

VH, VBF, Hjj can probe very large Q^2, where d4 ~ 0.
Work in progress.
Many ideas.

Towards a conventional basis

[LHCHXSWG-INT-2015-001] [Falkowski http://cern.ch/go/Ks9T]

- Effort in the LHC HXSWG WG2 to **standardize the dim-6 operator language.**
  - Incorporate constraints from **LEP precision data.**
  - Link to **aTGC/aQGC** LHC EWWG.
  - **Basically, any data fit using dim-6 EFT can be "rotated in".**
- Design choice: align tree-level dim-6 effect with straightforward H(125) experimental observables.
  - **Beyond tree-level, not that simple.**

NLO EFT meets kappas

[Passarino http://cern.ch/go/nT7n]

$\mathbf{H \to \gamma\gamma}$ *Ad usum Delphini* (does not mean former member of Delphi)

is PTG

$$\Delta\kappa^{\gamma\gamma} = -\frac{1}{2\,s_\theta^2}\left(a_{\phi D} - 4\,s_\theta^2\,a_{\phi\Box}\right)$$

$$\Delta\kappa_W^{\gamma\gamma} = \Delta\kappa \quad \Delta\kappa_t^{\gamma\gamma} = \Delta\kappa^{\gamma\gamma} + a_{t\phi} \quad \Delta\kappa_b^{\gamma\gamma} = \Delta\kappa^{\gamma\gamma} + a_{b\phi}$$

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$$\mathscr{A}\left(\mathrm{H}\to\gamma\gamma\right) = \kappa^{\gamma\gamma}\,\mathscr{A}^{(4)} + \kappa_{\mathrm{t}}^{\gamma\gamma}\,\mathscr{A}_{\mathrm{t}}^{(4)} + \kappa_{\mathrm{b}}^{\gamma\gamma}\,\mathscr{A}_{\mathrm{b}}^{(4)} + 2\,i\,g g_6\,\frac{M_{\mathrm{H}}^2}{M_{\mathrm{W}}}\,a_{\mathrm{AA}}$$

NLO EFT meets kappas

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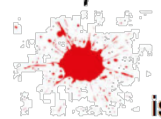
$\mathbf{H} \to \boldsymbol{\gamma\gamma}$ *Ad usum Delphini* (does not mean former member of Delphi)



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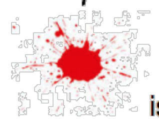
[Passarino http://cern.ch/go/nT7n]

$\mathbf{H} \rightarrow \boldsymbol{\gamma\gamma}$ *Ad usum Delphini* (does not mean former member of Delphi)



is PTG

$$\Delta\kappa^{\gamma\gamma} = -\frac{1}{2\,s_\theta^2}\left(a_{\phi D} - 4\,s_\theta^2\,a_{\phi\Box}\right)$$

$$\Delta\kappa_{\mathrm{W}}^{\gamma\gamma} = \Delta\kappa \quad \Delta\kappa_{\mathrm{t}}^{\gamma\gamma} = \Delta\kappa^{\gamma\gamma} + a_{\mathrm{t}\phi} \quad \Delta\kappa_{\mathrm{b}}^{\gamma\gamma} = \Delta\kappa^{\gamma\gamma} + a_{\mathrm{b}\phi}$$

$$\mathscr{A}\,(\mathrm{H} \rightarrow \gamma\gamma) = \kappa^{\gamma\gamma}\,\mathscr{A}^{(4)} + \kappa_{\mathrm{t}}^{\gamma\gamma}\,\mathscr{A}_{\mathrm{t}}^{(4)} + \kappa_{\mathrm{b}}^{\gamma\gamma}\,\mathscr{A}_{\mathrm{b}}^{(4)} + 2\,i\,g g_6\,\frac{M_{\mathrm{H}}^2}{M_{\mathrm{W}}}\,a_{\mathrm{AA}}$$

LHC season 2 premieres next week

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5 March 2015 Last updated at 00:15 GMT

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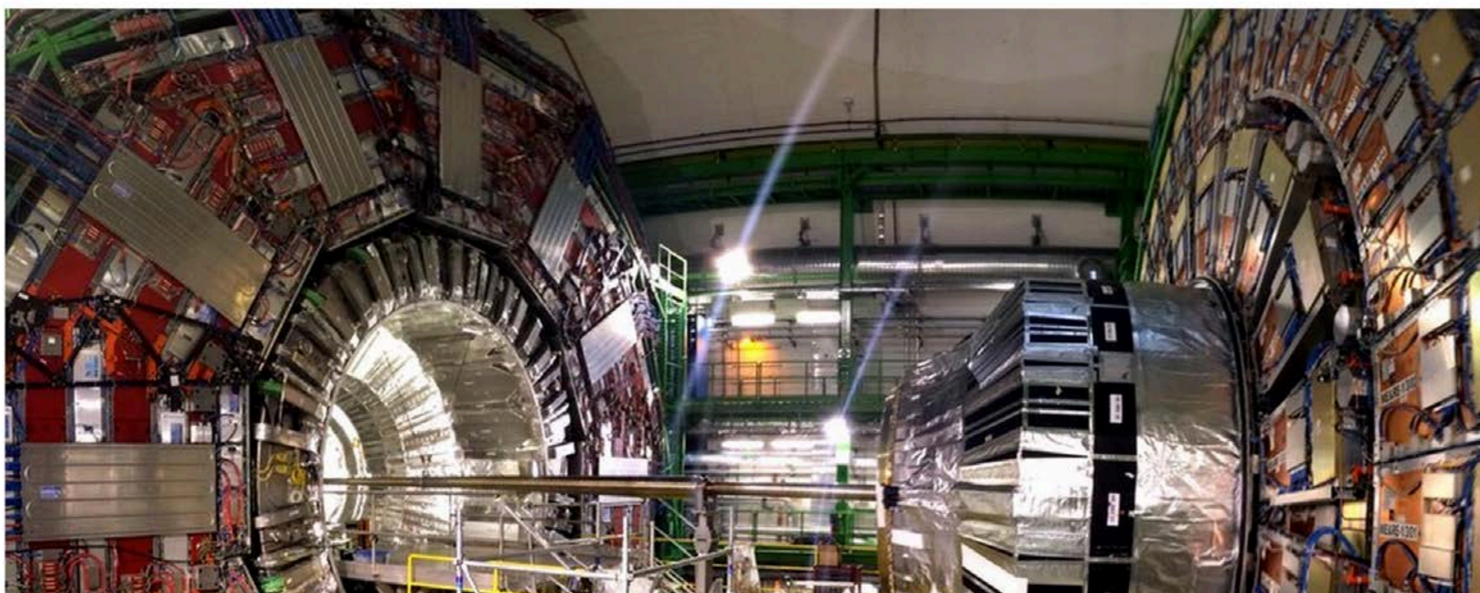
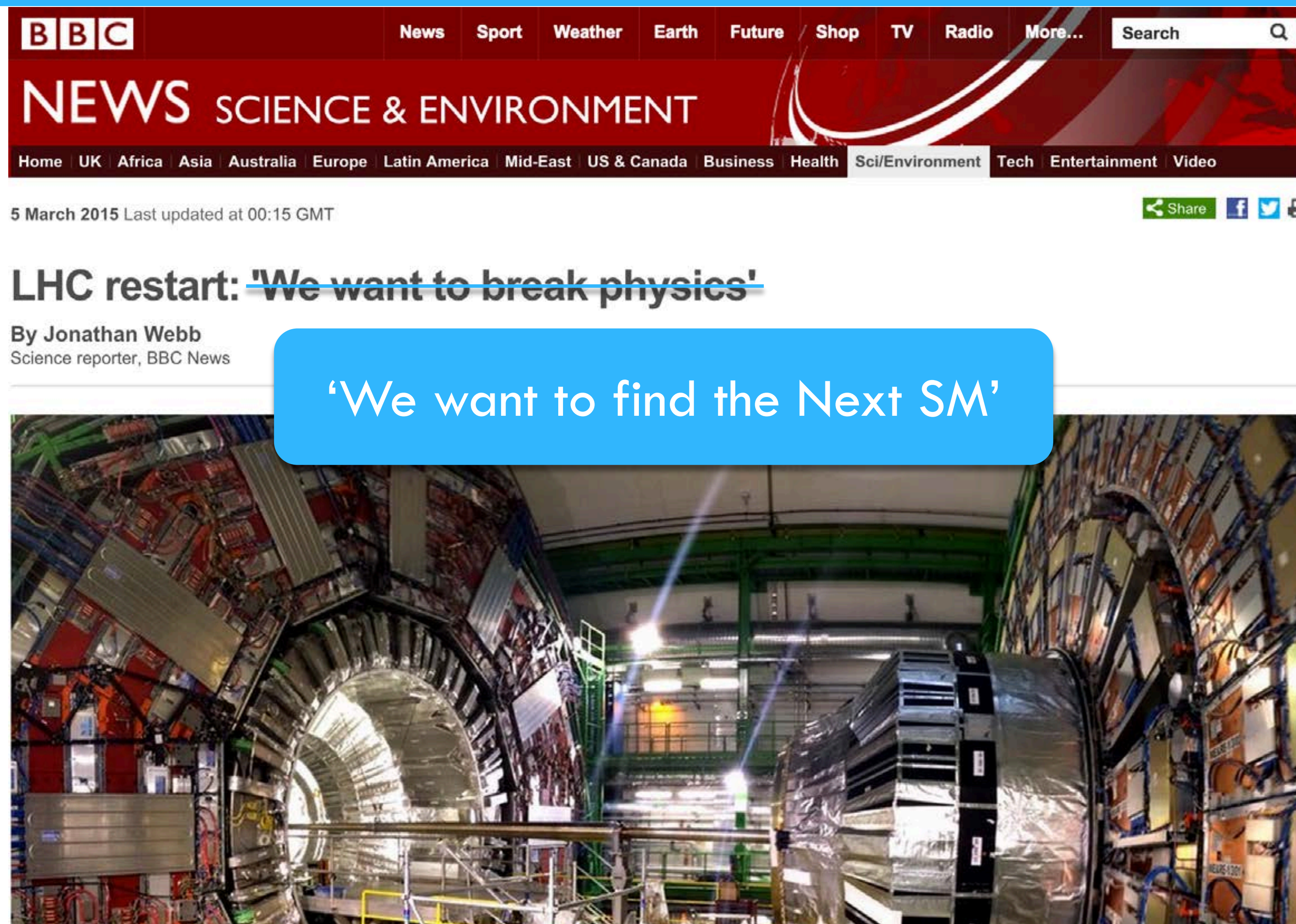
LHC restart: 'We want to break physics'

By Jonathan Webb
Science reporter, BBC News

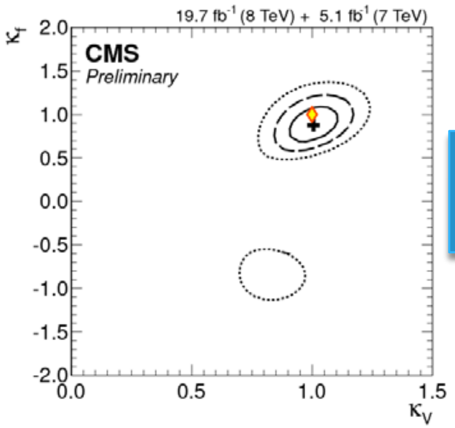


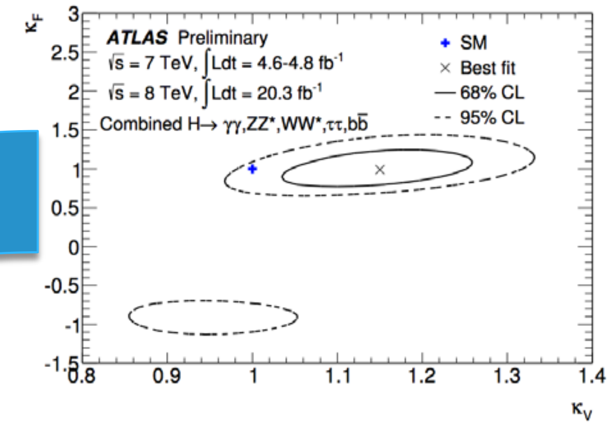
LHC season 2 premieres next week

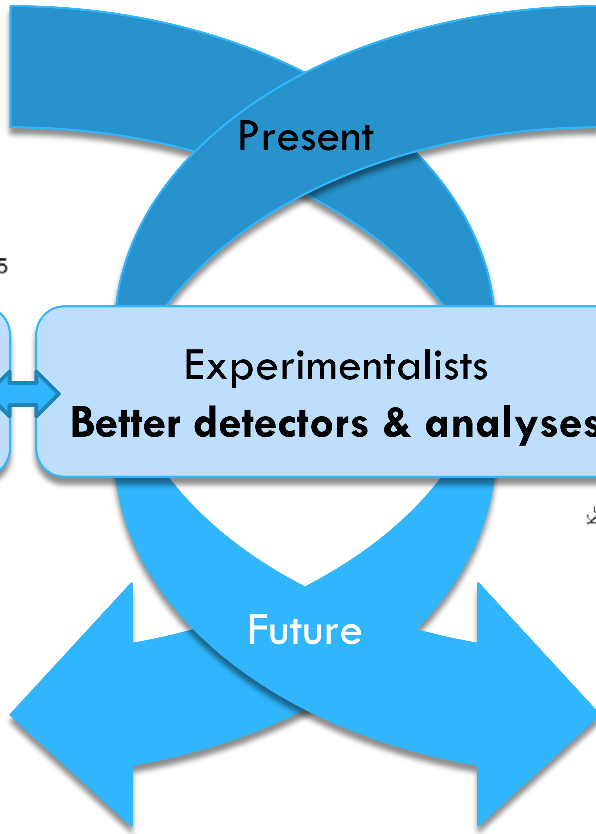


‘We want to find the Next SM’

The future is in precision and accuracy



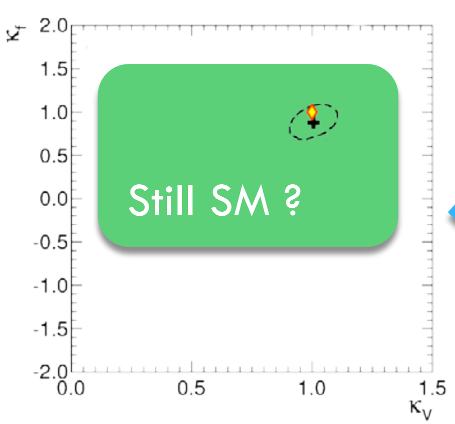


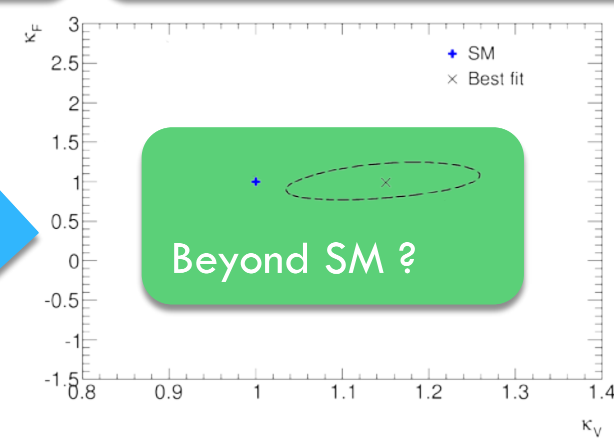


Accelerator physicists
More collisions

Experimentalists
Better detectors & analyses

Theorists
Better predictions





The future is in precision and accuracy

EFT cuts across

colliders (ee, eh),

sectors (multi-bosons, top),

and **searches** (LFV, EDM)…

Looking for the middle way

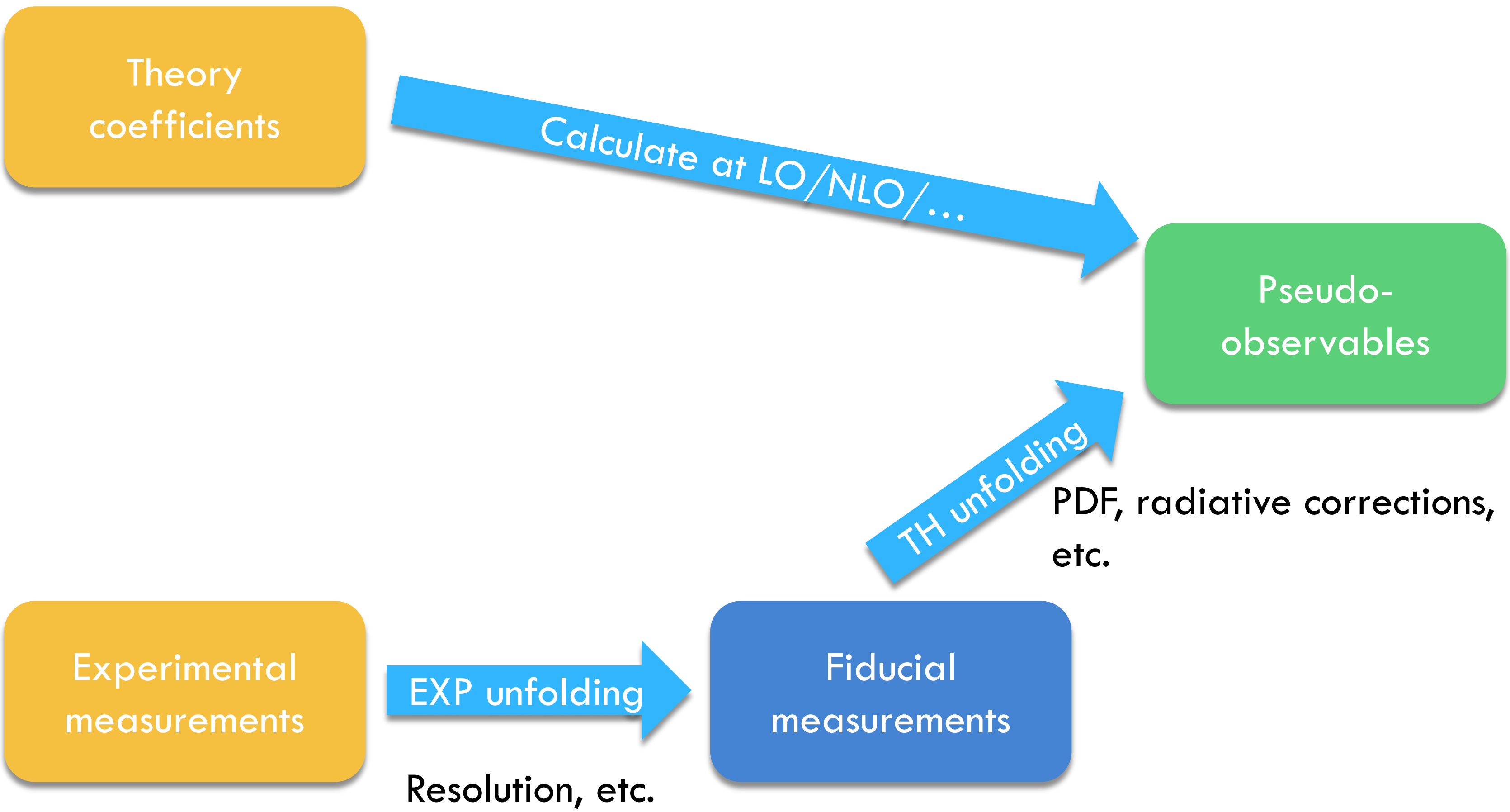
[http://cern.ch/go/6xk9]

“The eleventh most dangerous occupation in America is that of the rivet tosser. ***Insurance companies will not issue life or accident insurance cover to these people.*** *(Photo by Evans/Three Lions/Getty Images). Circa 1950”*

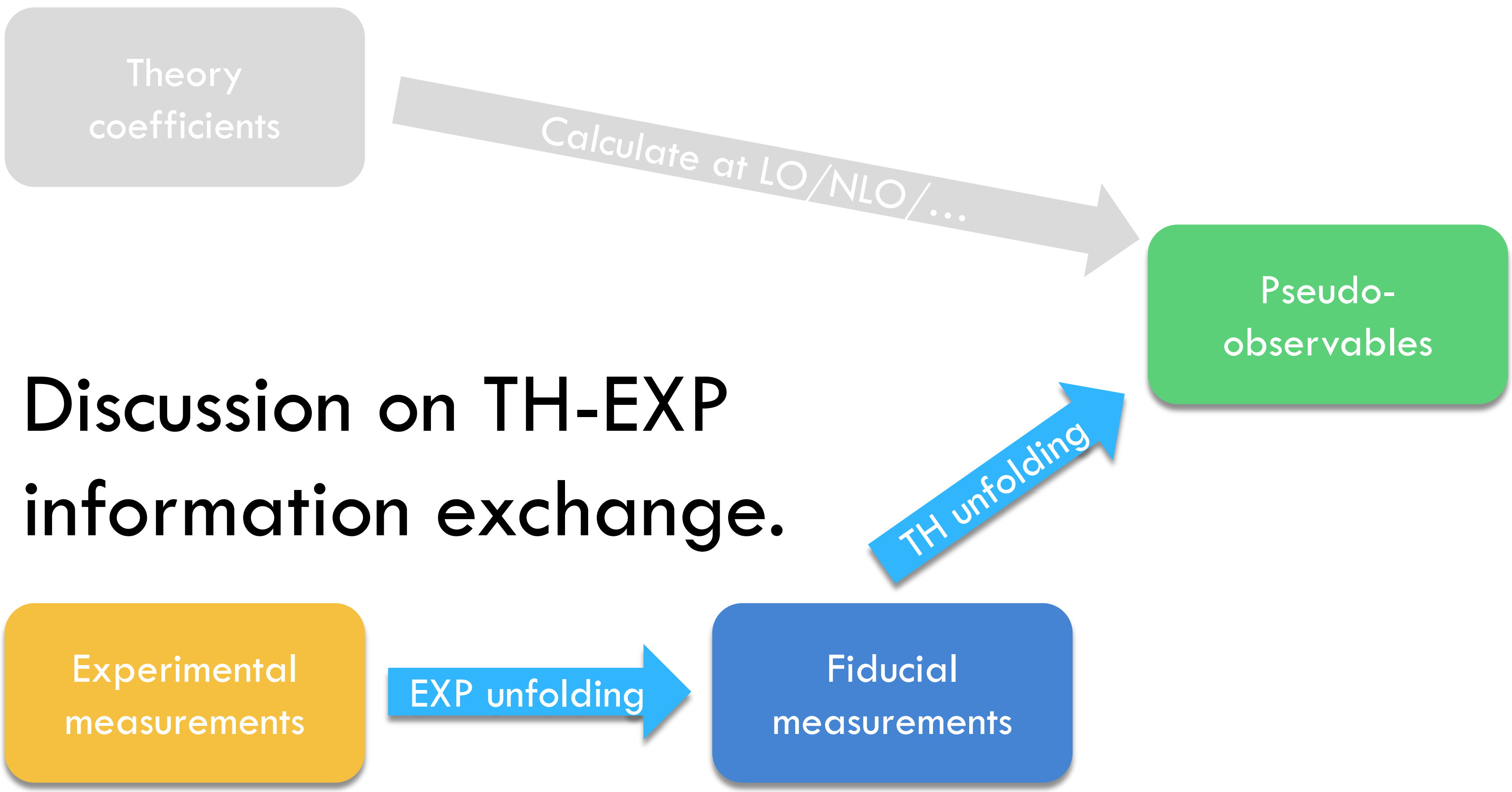
The need for the middle way

- **EFT** is all-encompassing, calculable, and evolving.
  - **But** too costly to redo all analyses if/when higher order calculations become available.
- **Fiducial cross-section** could be produced differentially for many quantities.
  - **But** no physical interpretation of every single bin by itself.
- **The middle way: pseudo-observables (PO).**
  - LEP-inspired scheme where theory and experiment intersect at clearly-defined points.

With some LEP inspiration

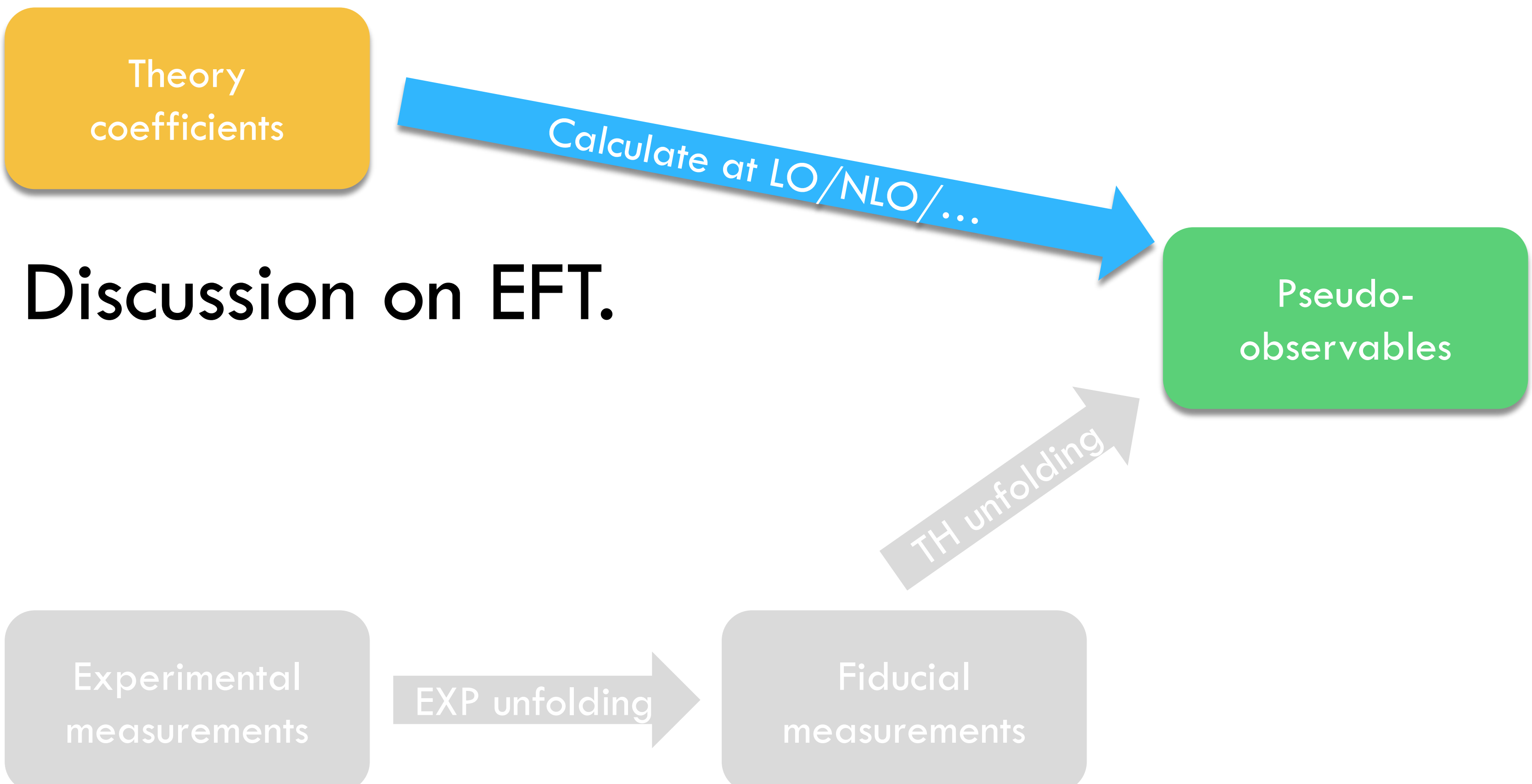


With some LEP inspiration



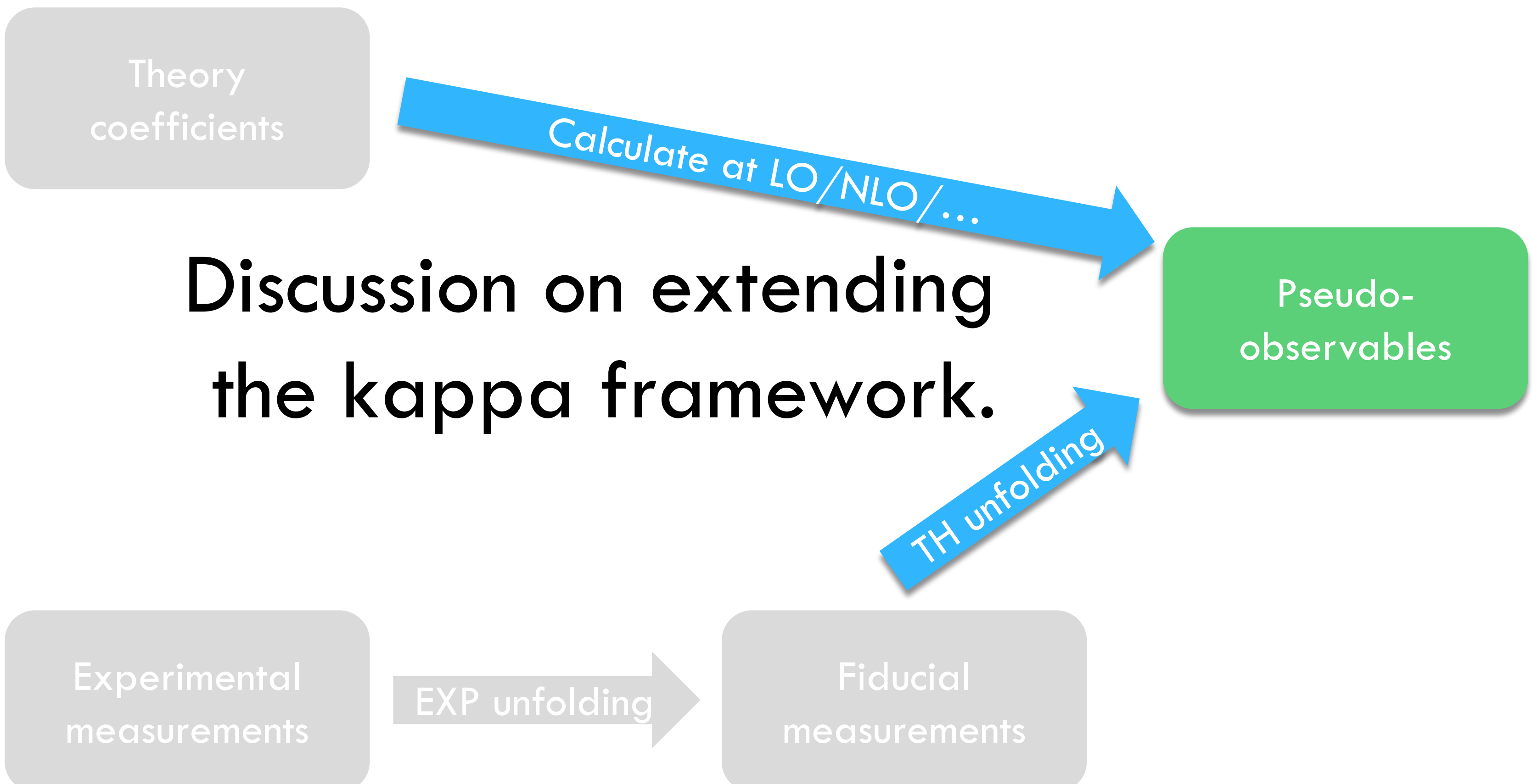
Discussion on TH-EXP information exchange.

With some LEP inspiration



Discussion on EFT.

With some LEP inspiration



Discussion on extending the kappa framework.

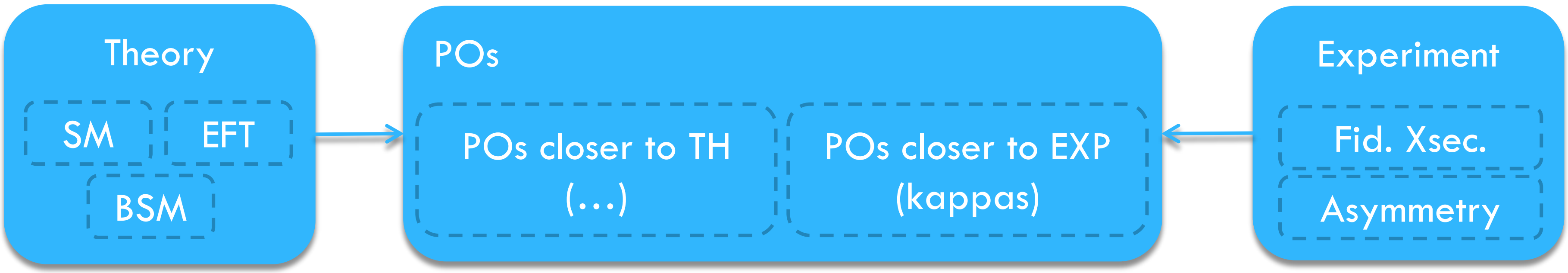
From kappas that fit little stuff…

...to kappas that fit more stuff.

Kappas might have been our first POs

- Kappas **must be extended** to:
  - Differential quantities.
  - Remove some assumptions.
  - Cover smooth deviations from the SM.

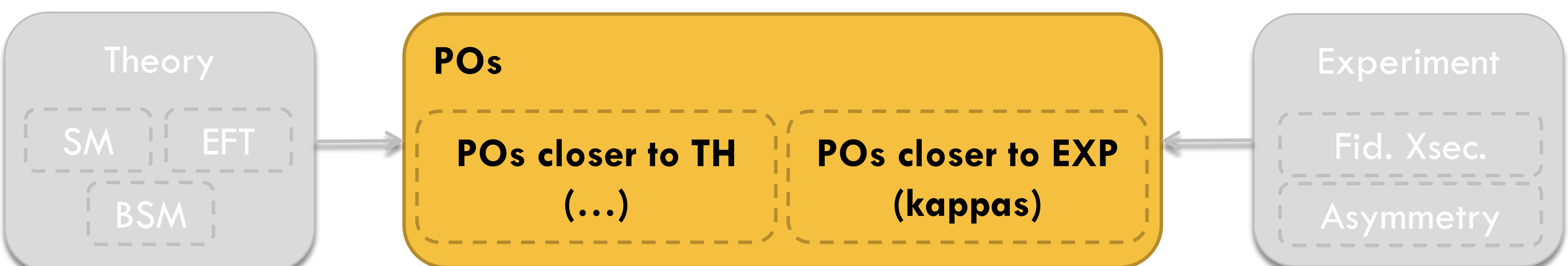
- With better/more POs, kappas may remain as part of the PO framework:



Inspiration for building PO

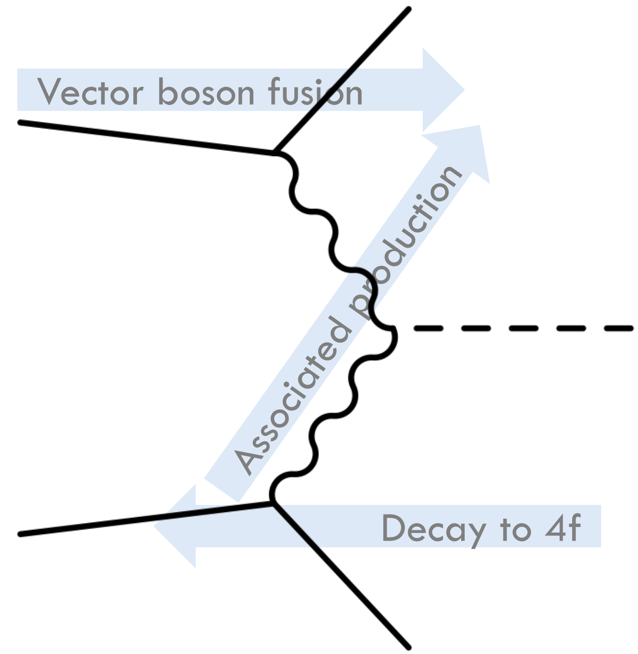
- If we assume that:
  Next SM ~ |dim-4 + dim-6 + dim-8 + … |²

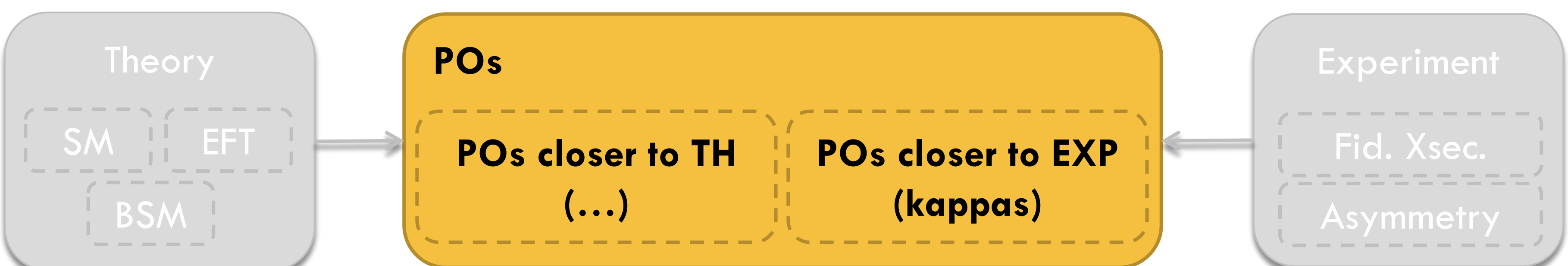
- Then POs can be motivated to parametrize:
  $\delta(PO_i) \sim (Data - d4^2) = d4 \times d6 + d6^2 + d4 \times d8 + \ldots$



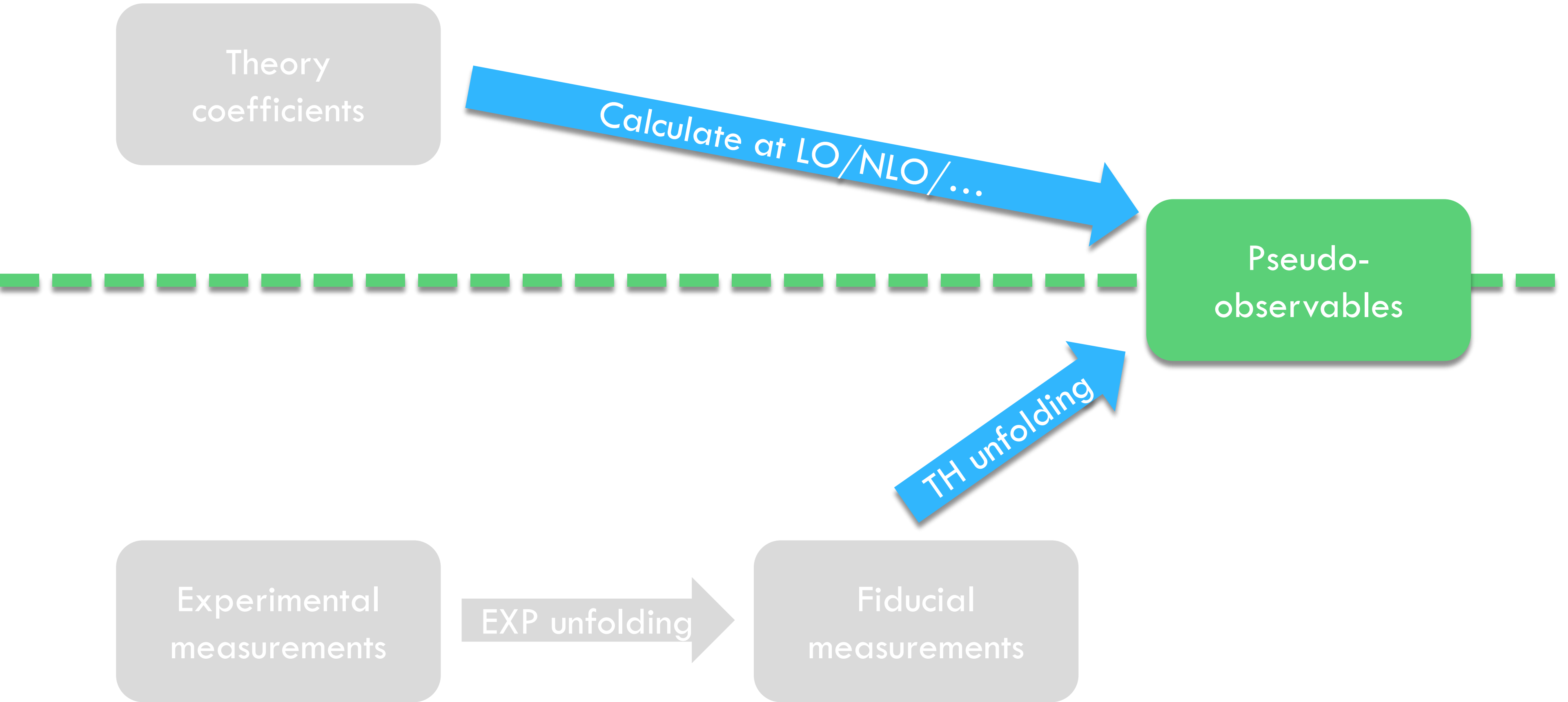
Inspiration for building PO

- Many practical issues to be solved.
- Many conceptual issues to be tackled.
- Many discussions to be held.



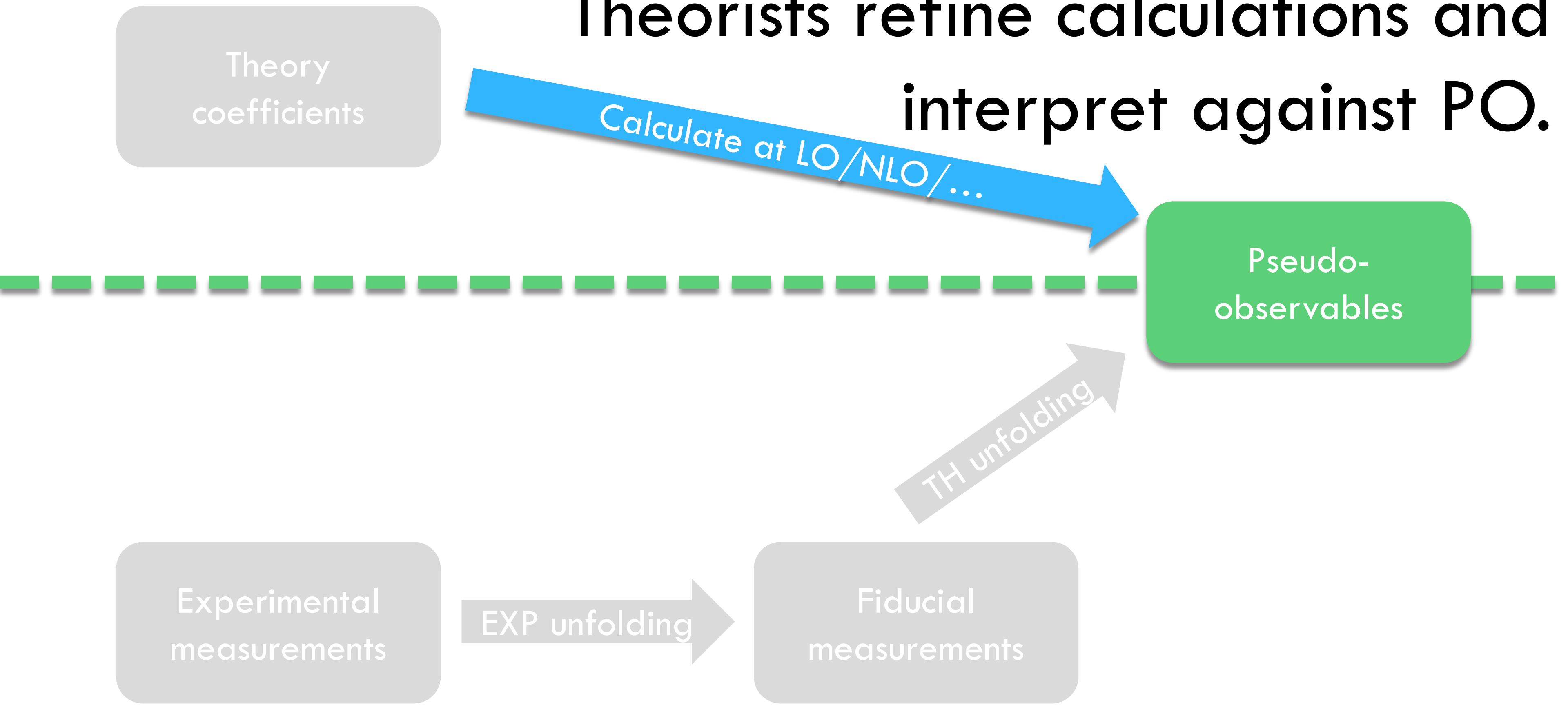


The middle way in action



The middle way in action

Theorists refine calculations and interpret against PO.



The middle way in action

Theory coefficients

Calculate at LO/NLO/…

Pseudo-observables

If SM predictions improve, experiments may redo PO.

TH unfolding

Experimental measurements

EXP unfolding

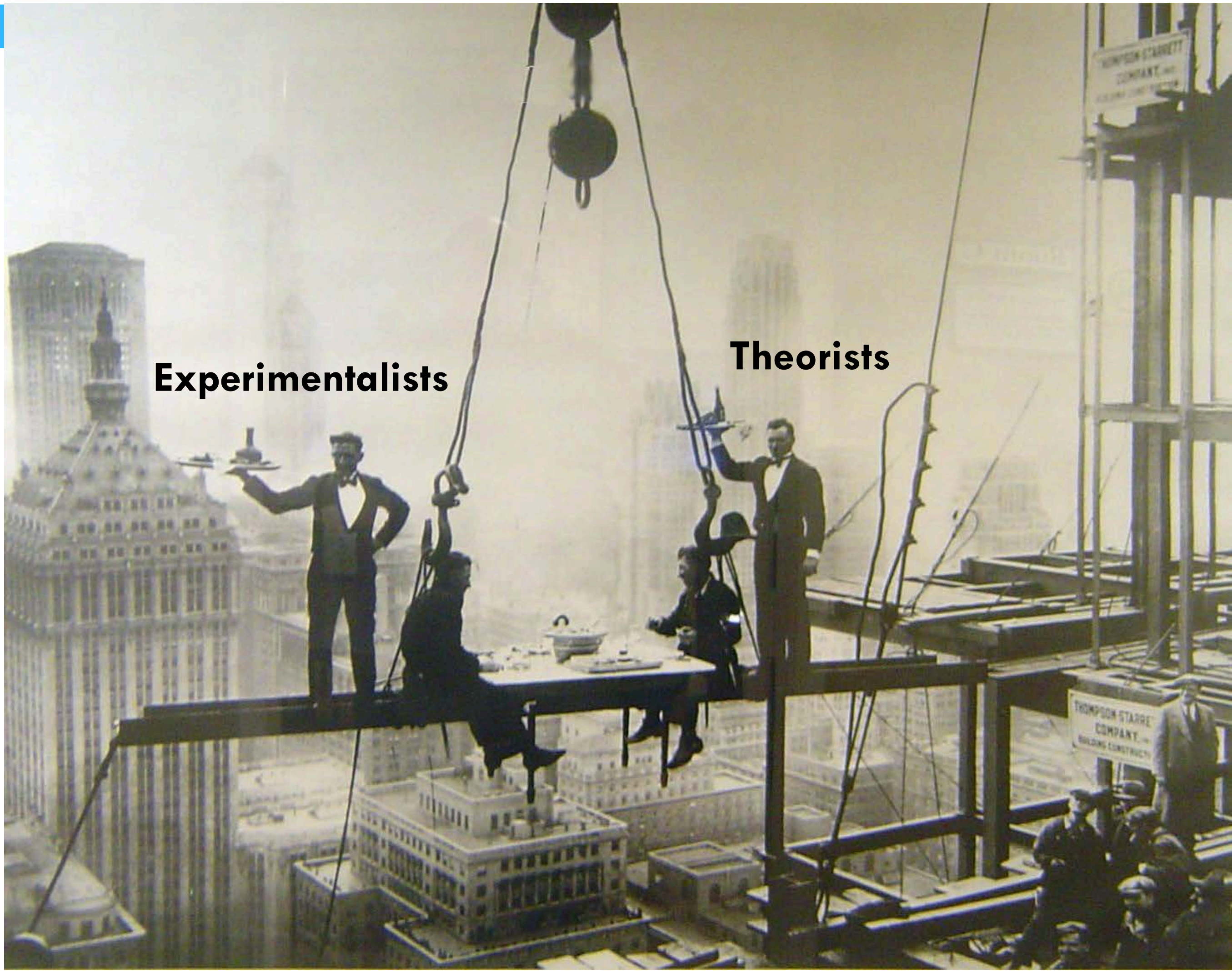
Fiducial measurements

POs are served in style

[http://cern.ch/go/Ns8X]

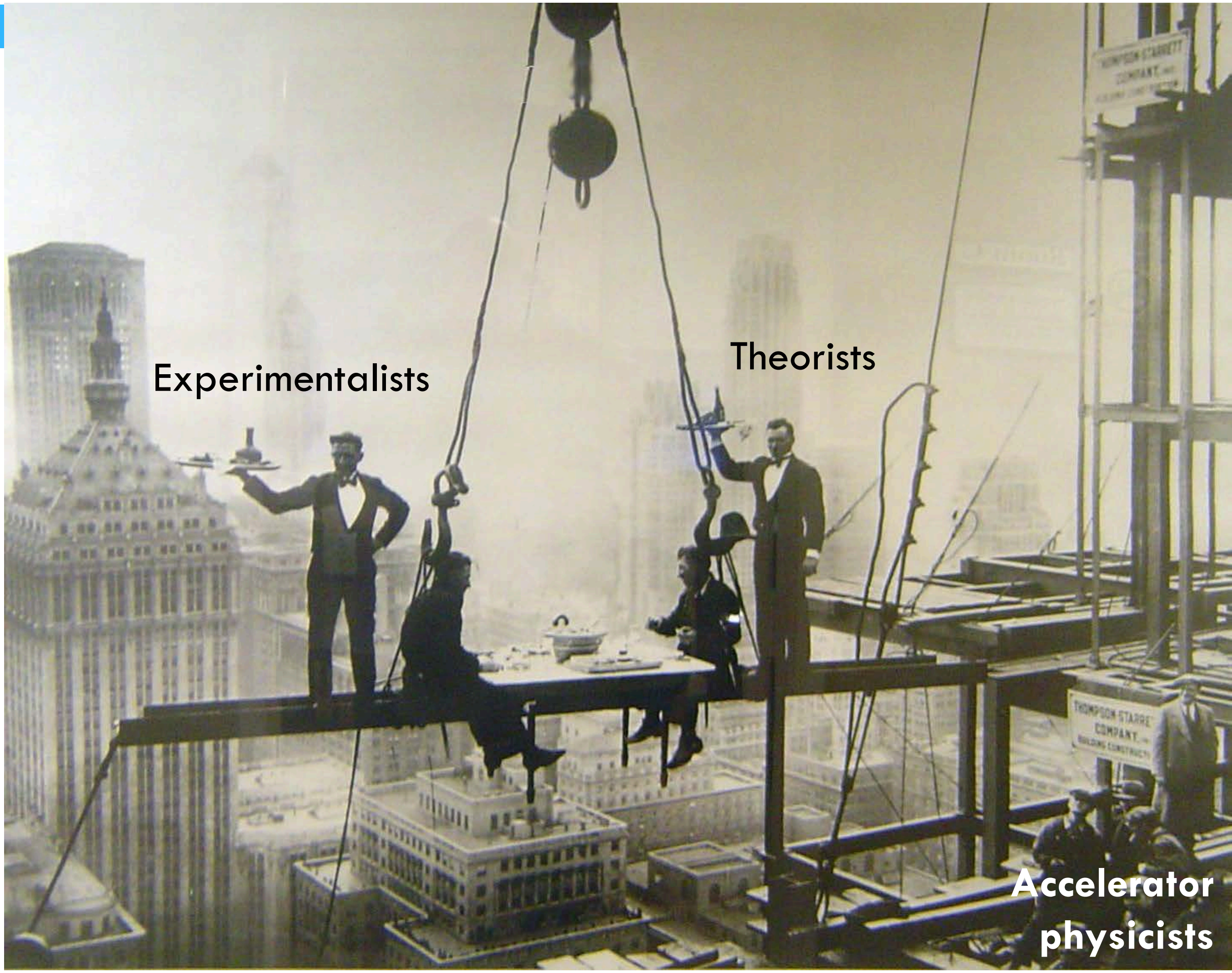
POs are served in style

[http://cern.ch/go/Ns8X]



POs are served in style

[http://cern.ch/go/Ns8X]



Reaching new heights

- **Standard Theory is complete and remarkably self-consistent.**
  - But challenged to describe reality.
  - Challenge: deviations are not expected to be large.

- **Bottom-up EFT tackles heavy new physics in general way.**
  - Applies to other colliders & other physics sectors.
  - Can affect any physics process: signal or background.

- **PO: a middle way between Experiment and Theory.**
  - Crafting of useful and meaningful PO on-going.
  - Up and coming discussions:
    - March 27 “Pseudo-Observables in Higgs decays” http://cern.ch/go/9Pw7
    - April 9-10 “Pseudo-observables: from LEP to LHC” http://cern.ch/go/77HM

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KEEP
CALM
AND
ASK
QUESTIONS

References

"…and references therein."

- Experiments' pages on results:
  - ATLAS: http://cern.ch/go/7IDT
  - CMS: http://cern.ch/go/6qmZ
  - Tevatron: http://cern.ch/go/h9jX
    - CDF: http://cern.ch/go/q8NV
    - D0: http://cern.ch/go/9Djq
- LHC HXSWG WG2: http://cern.ch/go/pj7d
- Incomplete list of conferences and workshops:
  - Higgs Days 2013: http://cern.ch/go/6zBp
  - ECFA HL-LHC workshop: http://cern.ch/go/SFW6
  - Higgs EFT 2013: http://cern.ch/go/bR7w
  - Higgs Couplings 2013: http://cern.ch/go/THp9
  - Moriond 2014: http://cern.ch/go/k8FP
  - Bernasque 2014: http://cern.ch/go/Pz7I
  - ICHEP 2014: http://cern.ch/go/8Btf
  - Rencontres du Vietnam 2014: http://cern.ch/go/9ZJJ
  - Zuoz Summer School 2014: http://cern.ch/go/9SHw
  - Higgs Couplings 2014: http://cern.ch/go/ctN6

KEEP CALM AND DISCUSS

5 steps for 4ℓ ~~addicts~~ aficionados

[Isidori et al. http://cern.ch/go/9GxP]

I. Kappa formalism → κ_i

- Non-trivial kinematical structure [e.g. h → 4ℓ, pp → Vh, ...]
- 3-body on-shell processes, unique Lorentz structure [e.g. h → bb, h → ττ]

II. Form factors → $f_i(s)$

III. EFT parameterization of the $f_i(s)$

e.g.: $f_i(s) = f_{i0}\,(1+ \lambda_i s)$

IV. Simplified EFT for a sub-set of observables (→ *correlations*)

V. Full EFT fit, including EW observables → C_i

A possible roadmap

κ

- NWA
- 0^+
- Single state
- 1 d.o.f./SM particle

κ_∞

- Short-distance contribution to loops.
- Appears in at least $p_T(H)$ and m_{VV}.
- Just one more d.o.f.

κ(q)

- $q = p_T(H)$, m_{34}, m_{VV}, m_{ZH}, …
- "differential μ"
- 1 d.o.f./bin

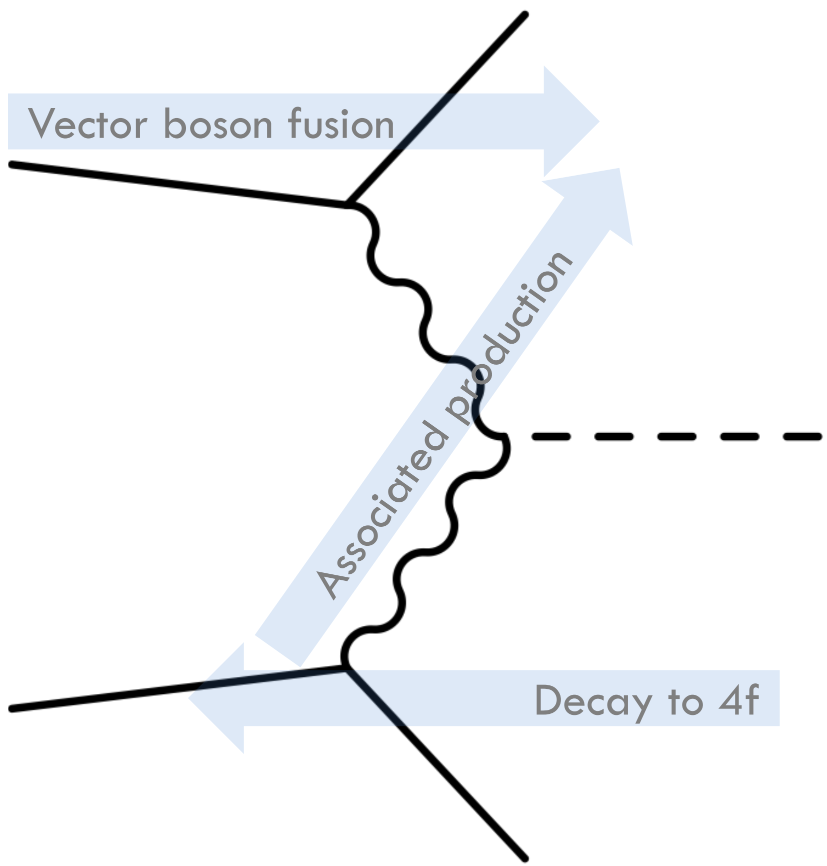
f(q) × Lorentz structures

- $f = f_0 + \lambda q$
- As done in flavour physics?
- 2 d.o.f./observable

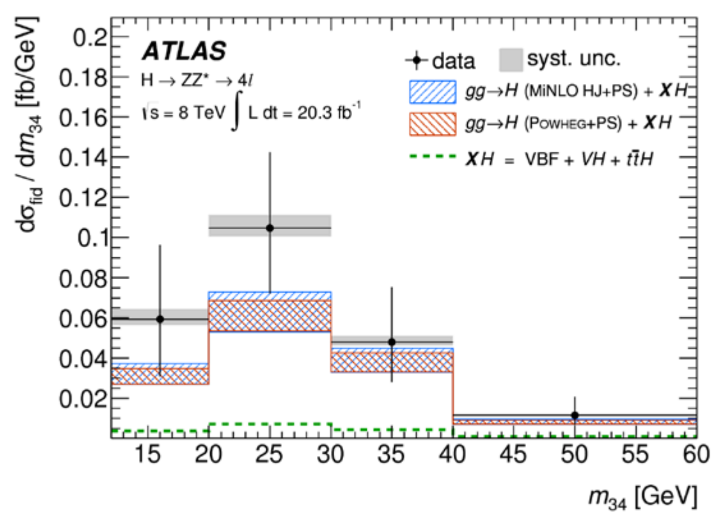
Full EFT

- Wilson coefficients c_i.
- Which ones?
- Which sets?
- Which assumptions?

The many facets of HVV



Decay	γ	γ*/Z*	Z
γ	✓	✓	✓
γ*/Z*		? (VBF)	✓(VH)
Z			✓ (H*)



PO at LEP: the A_{FB} example

[hep-ph/9902452] [hep-ex/0509008]

For the peak asymmetry, the presence of ρ's is irrelevant since they will cancel in the ratio. We have

$$\hat{A}^{0f}_{FB} = \frac{3}{4}\hat{A}_e\,\hat{A}_f,$$
$$\hat{A}_f = \frac{2\,\mathrm{Re}\left[\mathcal{G}^f_V\,(\mathcal{G}^f_A)^*\right]}{\left(|\mathcal{G}^f_V|^2+|\mathcal{G}^f_A|^2\right)}\,. \quad (20)$$

The question is what to do with imaginary parts in Eq.(20). For partial widths, as they absorb all corrections, the convention is to use

$$|\mathcal{G}^f_{V,A}|^2 = (\mathrm{Re}\mathcal{G}^f_{V,A})^2 + (\mathrm{Im}\mathcal{G}^f_{V,A})^2. \quad (21)$$

On the contrary, the PO peak asymmetry A^{0f}_{FB} will be defined by an analogy of equation Eq.(20) where *conventionally* imaginary parts are not included

$$A^{0f}_{FB} = \frac{3}{4}\mathcal{A}_e\,\mathcal{A}_f,$$
$$\mathcal{A}_f = \frac{2(g^f_V g^f_A)}{(g^f_V)^2+(g^f_A)^2}\,. \quad (22)$$

We note, that Eq.(22) is not an approximation of Eq.(20). Both are POs and both could be used as the *definition*. Numerically, they give very similar results: ZFITTER calculates for the two definitions in Eq.(20) and Eq.(22), $\hat{A}^{0l}_{FB} = 0.0160692$ and $A^{0l}_{FB} = 0.0160739$. The absolute difference, 0.0000047, is more than two orders of magnitude smaller than the current experimental error of 0.00096 [13].

PO at LEP: the A_{FB} example

[hep-ph/9902452] [hep-ex/0509008]

error. The difference between $A_{\rm FB}^{0,\ell}$ and the QED deconvoluted forward-backward asymmetry at the peak is dominated by a contribution of 0.0015 from the imaginary part of $\alpha(m_{\rm Z}^2)$, which accounts, via the optical theorem, for the decay of a massive photon to fermion pairs. The remaining electroweak contribution in the SM is -0.0005, again smaller than the LEP combined error on $A_{\rm FB}^{0,\ell}$.

It is therefore important to treat these complex parts correctly, but the measurements have no sensitivity to SM parameters entering through these components: the effects on the remnants are much smaller than the experimental uncertainties.

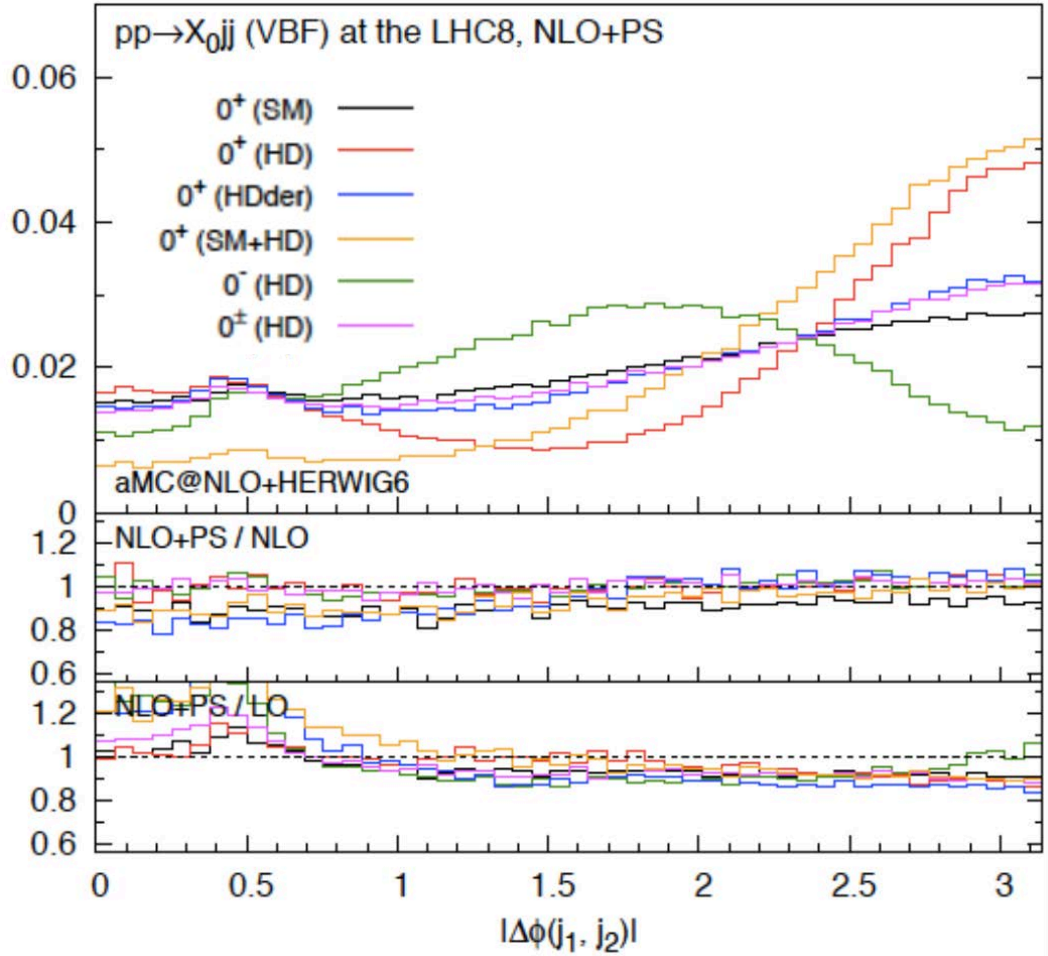
Since one of the main goals of the Z-pole analysis is to test theory with experimental results, considerable effort has been expended to make the extraction of the pseudo-observables describing the Z resonance as model-independent as possible, so that the meanings of "theory" and "experiment" remain distinct. Since the pseudo-observables do depend slightly on SM assumptions, as explained above, a more precise definition of what we mean by "model-independence" is that our analysis is valid in any scenario in which the predicted remnants remain small. The very small uncertainties arising from ambiguities in the theoretical definition of the pseudo-observables are discussed in Section 2.4.4, and quantified in Table 2.8.

Small remnants (imaginary parts), no problems.

Kappas do not change shapes

[Maltoni et al. http://cern.ch/go/8cPB]

- Scaling the **SM line** would not capture other spin-0 angular correlations in VBF.



Taxonomy of dim-6 operators

[Trott et al. JHEP 04 (2014) 159]

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$(H^\dagger D_\mu H)^* (H^\dagger D_\mu H)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8: (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

Table 1. The 59 independent dimension-six operators built from Standard Model fields which conserve baryon number, as given in Ref. [9]. The operators are divided into eight classes: X^3, H^6, etc. Operators with +h.c. in the table heading also have hermitian conjugates, as does the $\psi^2 H^2 D$ operator Q_{Hud}. The subscripts p, r, s, t are flavor indices.

First steps in YR3

[arXiv:1307.1347]

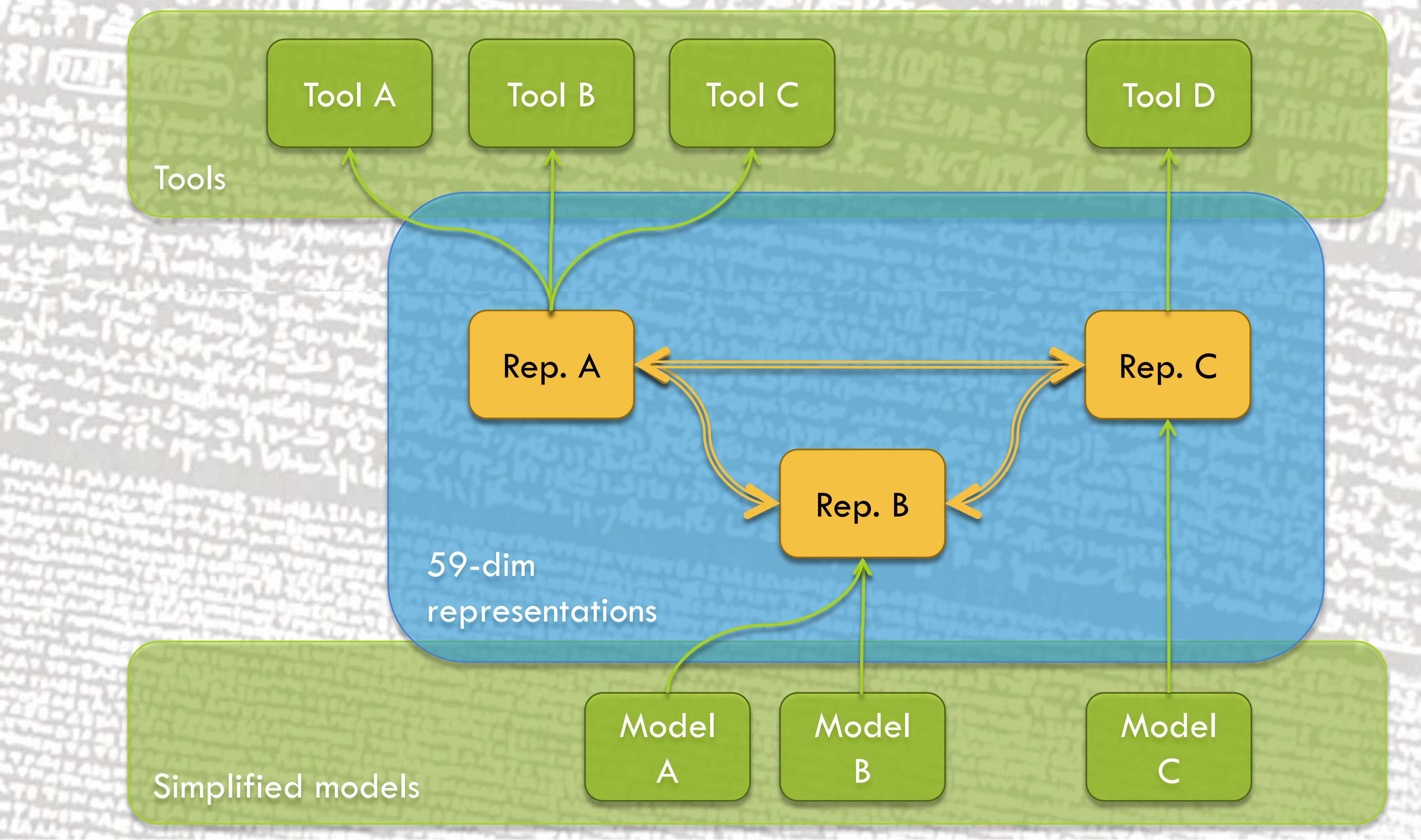
Table 52: Dimension-6 operators involving Higgs doublet fields or gauge-boson fields. For all $\psi^2\Phi^3$, $\psi^2 X\Phi$ operators and for $\mathcal{O}_{\Phi\mathrm{ud}}$ the hermitian conjugates must be included as well.

Φ^6 and $\Phi^4 D^2$	$\psi^2\Phi^3$	X^3
$\mathcal{O}_\Phi = (\Phi^\dagger\Phi)^3$	$\mathcal{O}_{\mathrm{e}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{l}}\,\Gamma_\mathrm{e}\mathrm{e}\Phi)$	$\mathcal{O}_G = f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$\mathcal{O}_{\mathrm{u}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{q}}\,\Gamma_\mathrm{u}\mathrm{u}\widetilde{\Phi})$	$\mathcal{O}_{\widetilde{G}} = f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)$	$\mathcal{O}_{\mathrm{d}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{q}}\,\Gamma_\mathrm{d}\mathrm{d}\Phi)$	$\mathcal{O}_\mathrm{W} = \varepsilon^{IJK}\mathrm{W}_\mu^{I\nu}\mathrm{W}_\nu^{J\rho}\mathrm{W}_\rho^{K\mu}$
		$\mathcal{O}_{\widetilde{\mathrm{W}}} = \varepsilon^{IJK}\widetilde{\mathrm{W}}_\mu^{I\nu}\mathrm{W}_\nu^{J\rho}\mathrm{W}_\rho^{K\mu}$
$X^2\Phi^2$	$\psi^2 X\Phi$	$\psi^2\Phi^2 D$
$\mathcal{O}_{\Phi G} = (\Phi^\dagger\Phi)G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{\mathrm{u}G} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_\mathrm{u}\mathrm{u}\widetilde{\Phi})G^A_{\mu\nu}$	$\mathcal{O}^{(1)}_{\Phi\mathrm{l}} = (\Phi^\dagger\mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{l}}\gamma^\mu\mathrm{l})$
$\mathcal{O}_{\Phi\widetilde{G}} = (\Phi^\dagger\Phi)\widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{\mathrm{d}G} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_\mathrm{d}\mathrm{d}\Phi)G^A_{\mu\nu}$	$\mathcal{O}^{(3)}_{\Phi\mathrm{l}} = (\Phi^\dagger\mathrm{i}\overleftrightarrow{D}^I_\mu\Phi)(\bar{\mathrm{l}}\gamma^\mu\tau^I\mathrm{l})$
$\mathcal{O}_{\Phi\mathrm{W}} = (\Phi^\dagger\Phi)\mathrm{W}^I_{\mu\nu}\mathrm{W}^{I\mu\nu}$	$\mathcal{O}_{\mathrm{eW}} = (\bar{\mathrm{l}}\sigma^{\mu\nu}\Gamma_\mathrm{e}\mathrm{e}\tau^I\Phi)\mathrm{W}^I_{\mu\nu}$	$\mathcal{O}_{\Phi\mathrm{e}} = (\Phi^\dagger\mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{e}}\gamma^\mu\mathrm{e})$
$\mathcal{O}_{\Phi\widetilde{\mathrm{W}}} = (\Phi^\dagger\Phi)\widetilde{\mathrm{W}}^I_{\mu\nu}\mathrm{W}^{I\mu\nu}$	$\mathcal{O}_{\mathrm{uW}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_\mathrm{u}\mathrm{u}\tau^I\widetilde{\Phi})\mathrm{W}^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{\Phi\mathrm{q}} = (\Phi^\dagger\mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{q}}\gamma^\mu\mathrm{q})$
$\mathcal{O}_{\Phi\mathrm{B}} = (\Phi^\dagger\Phi)\mathrm{B}_{\mu\nu}\mathrm{B}^{\mu\nu}$	$\mathcal{O}_{\mathrm{dW}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_\mathrm{d}\mathrm{d}\tau^I\Phi)\mathrm{W}^I_{\mu\nu}$	$\mathcal{O}^{(3)}_{\Phi\mathrm{q}} = (\Phi^\dagger\mathrm{i}\overleftrightarrow{D}^I_\mu\Phi)(\bar{\mathrm{q}}\gamma^\mu\tau^I\mathrm{q})$
$\mathcal{O}_{\Phi\widetilde{\mathrm{B}}} = (\Phi^\dagger\Phi)\widetilde{\mathrm{B}}_{\mu\nu}\mathrm{B}^{\mu\nu}$	$\mathcal{O}_{\mathrm{eB}} = (\bar{\mathrm{l}}\sigma^{\mu\nu}\Gamma_\mathrm{e}\mathrm{e}\Phi)\mathrm{B}_{\mu\nu}$	$\mathcal{O}_{\Phi\mathrm{u}} = (\Phi^\dagger\mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{u}}\gamma^\mu\mathrm{u})$
$\mathcal{O}_{\Phi\mathrm{WB}} = (\Phi^\dagger\tau^I\Phi)\mathrm{W}^I_{\mu\nu}\mathrm{B}^{\mu\nu}$	$\mathcal{O}_{\mathrm{uB}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_\mathrm{u}\mathrm{u}\widetilde{\Phi})\mathrm{B}_{\mu\nu}$	$\mathcal{O}_{\Phi\mathrm{d}} = (\Phi^\dagger\mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{d}}\gamma^\mu\mathrm{d})$
$\mathcal{O}_{\Phi\widetilde{\mathrm{W}}\mathrm{B}} = (\Phi^\dagger\tau^I\Phi)\widetilde{\mathrm{W}}^I_{\mu\nu}\mathrm{B}^{\mu\nu}$	$\mathcal{O}_{\mathrm{dB}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_\mathrm{d}\mathrm{d}\Phi)\mathrm{B}_{\mu\nu}$	$\mathcal{O}_{\Phi\mathrm{ud}} = \mathrm{i}(\widetilde{\Phi}^\dagger D_\mu\Phi)(\bar{\mathrm{u}}\gamma^\mu\Gamma_\mathrm{ud}\mathrm{d})$

Table 53: Alternative basis of dimension-6 operators involving Higgs doublet fields or gauge-boson fields.

Φ^6 and $\Phi^4 D^2$	$\psi^2\Phi^3$	X^3
$\mathcal{O}'_6 = (\Phi^\dagger\Phi)^3$	$\mathcal{O}'_{\mathrm{e}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{l}}\,\Gamma_\mathrm{e}\mathrm{e}\Phi)$	$\mathcal{O}'_G = f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$\mathcal{O}'_\Phi = \partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi)$	$\mathcal{O}'_{\mathrm{u}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{q}}\,\Gamma_\mathrm{u}\mathrm{u}\widetilde{\Phi})$	$\mathcal{O}'_{\widetilde{G}} = f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$\mathcal{O}'_\mathrm{T} = (\Phi^\dagger\overleftrightarrow{D}_\mu\Phi)(\Phi^\dagger\overleftrightarrow{D}^\mu\Phi)$	$\mathcal{O}'_{\mathrm{d}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{q}}\,\Gamma_d\mathrm{d}\Phi)$	$\mathcal{O}'_\mathrm{W} = \varepsilon^{IJK}\mathrm{W}_\mu^{I\nu}\mathrm{W}_\nu^{J\rho}\mathrm{W}_\rho^{K\mu}$
		$\mathcal{O}'_{\widetilde{\mathrm{W}}} = \varepsilon^{IJK}\widetilde{\mathrm{W}}_\mu^{I\nu}\mathrm{W}_\nu^{J\rho}\mathrm{W}_\rho^{K\mu}$
$X^2\Phi^2$	$\psi^2 X\Phi$	$\psi^2\Phi^2 D$
$\mathcal{O}'_{\mathrm{D}W} = \left(\Phi^\dagger\tau^I\mathrm{i}\overleftrightarrow{D^\mu}\Phi\right)(D^\nu\mathrm{W}_{\mu\nu})^I$	$\mathcal{O}'_{\mathrm{u}G} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_\mathrm{u}\mathrm{u}\widetilde{\Phi})G^A_{\mu\nu}$	$\mathcal{O}'^{(1)}_{\Phi\mathrm{l}} = (\Phi^\dagger\mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{l}}\gamma^\mu\mathrm{l})$
$\mathcal{O}'_{D\mathrm{B}} = \left(\Phi^\dagger\mathrm{i}\overleftrightarrow{D^\mu}\Phi\right)(\partial^\nu\mathrm{B}_{\mu\nu})$	$\mathcal{O}'_{\mathrm{d}G} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_\mathrm{d}\mathrm{d}\Phi)G^A_{\mu\nu}$	$\mathcal{O}'^{(3)}_{\Phi\mathrm{l}} = (\Phi^\dagger\mathrm{i}\overleftrightarrow{D}^I_\mu\Phi)(\bar{\mathrm{l}}\gamma^\mu\tau^I\mathrm{l})$
$\mathcal{O}'_{D\Phi\mathrm{W}} = \mathrm{i}(D^\mu\Phi)^\dagger\tau^I(D^\nu\Phi)\mathrm{W}^I_{\mu\nu}$	$\mathcal{O}'_{\mathrm{eW}} = (\bar{\mathrm{l}}\sigma^{\mu\nu}\Gamma_\mathrm{e}\mathrm{e}\tau^I\Phi)\mathrm{W}^I_{\mu\nu}$	$\mathcal{O}'_{\Phi\mathrm{e}} = (\Phi^\dagger\mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{e}}\gamma^\mu\mathrm{e})$
$\mathcal{O}'_{D\Phi\widetilde{\mathrm{W}}} = \mathrm{i}(D^\mu\Phi)^\dagger\tau^I(D^\nu\Phi)\widetilde{\mathrm{W}}^I_{\mu\nu}$	$\mathcal{O}'_{\mathrm{uW}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_\mathrm{u}\mathrm{u}\tau^I\widetilde{\Phi})\mathrm{W}^I_{\mu\nu}$	$\mathcal{O}'^{(1)}_{\Phi\mathrm{q}} = (\Phi^\dagger\mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{q}}\gamma^\mu\mathrm{q})$
$\mathcal{O}'_{D\Phi\mathrm{B}} = \mathrm{i}(D^\mu\Phi)^\dagger(D^\nu\Phi)\mathrm{B}_{\mu\nu}$	$\mathcal{O}'_{\mathrm{dW}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_\mathrm{d}\mathrm{d}\tau^I\Phi)\mathrm{W}^I_{\mu\nu}$	$\mathcal{O}'^{(3)}_{\Phi\mathrm{q}} = (\Phi^\dagger\mathrm{i}\overleftrightarrow{D}^I_\mu\Phi)(\bar{\mathrm{q}}\gamma^\mu\tau^I\mathrm{q})$
$\mathcal{O}'_{D\Phi\widetilde{\mathrm{B}}} = \mathrm{i}(D^\mu\Phi)^\dagger(D^\nu\Phi)\widetilde{\mathrm{B}}_{\mu\nu}$	$\mathcal{O}'_{\mathrm{eB}} = (\bar{l}\sigma^{\mu\nu}\Gamma_\mathrm{e}\mathrm{e}\Phi)B_{\mu\nu}$	$\mathcal{O}'_{\Phi\mathrm{u}} = (\Phi^\dagger\mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{u}}\gamma^\mu\mathrm{u})$
$\mathcal{O}'_{\Phi\mathrm{B}} = (\Phi^\dagger\Phi)B_{\mu\nu}\mathrm{B}^{\mu\nu}$	$\mathcal{O}'_{\mathrm{uB}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_\mathrm{u}\mathrm{u}\widetilde{\Phi})\mathrm{B}_{\mu\nu}$	$\mathcal{O}'_{\Phi\mathrm{d}} = (\Phi^\dagger\mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{d}}\gamma^\mu\mathrm{d})$
$\mathcal{O}'_{\Phi\widetilde{\mathrm{B}}} = (\Phi^\dagger\Phi)\mathrm{B}_{\mu\nu}\widetilde{\mathrm{B}}^{\mu\nu}$	$\mathcal{O}'_{\mathrm{dB}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_\mathrm{d}\mathrm{d}\Phi)\mathrm{B}_{\mu\nu}$	$\mathcal{O}'_{\Phi\mathrm{ud}} = \mathrm{i}(\widetilde{\Phi}^\dagger D_\mu\Phi)(\bar{\mathrm{u}}\gamma^\mu\Gamma_\mathrm{ud}\mathrm{d})$
$\mathcal{O}'_{\Phi G} = \Phi^\dagger\Phi G^A_{\mu\nu}G^{A\mu\nu}$		
$\mathcal{O}'_{\Phi\widetilde{G}} = \Phi^\dagger\Phi G^A_{\mu\nu}\widetilde{G}^{A\mu\nu}$		

A Rosetta stone for HEFT



Experiments Falsify Theories

Precision (uncertainties) vs. **accuracy** (higher orders).

Tools: **calculators** vs. **generators.**

- **LHC Run 2:**
  - more exclusive.
  - more differential.
  - more off-shell.
  - more Yukawas.
    - Discover ttH !
  - more HVV.
- **HVV systematization:**
  - γγ, γγ*, Zγ*, ZZ.
    - Plus the W…
  - The VBF, VH, HVV triangle.
- **EFT:**
  - Devise tests for every assumption.
  - Which loops to keep?
    - Even-higher-dimensional niches?
  - Observables vs. "inferrables". Global fit of EWPD, a{T,Q}GC, scalars.
  - Some physics processes not more equal than others.
    - EFT vs. "backgrounds", SMH as a background,…

Experiment-Theory **information interchange** interface.

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.*

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.*

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.*

Anatomy of deviations

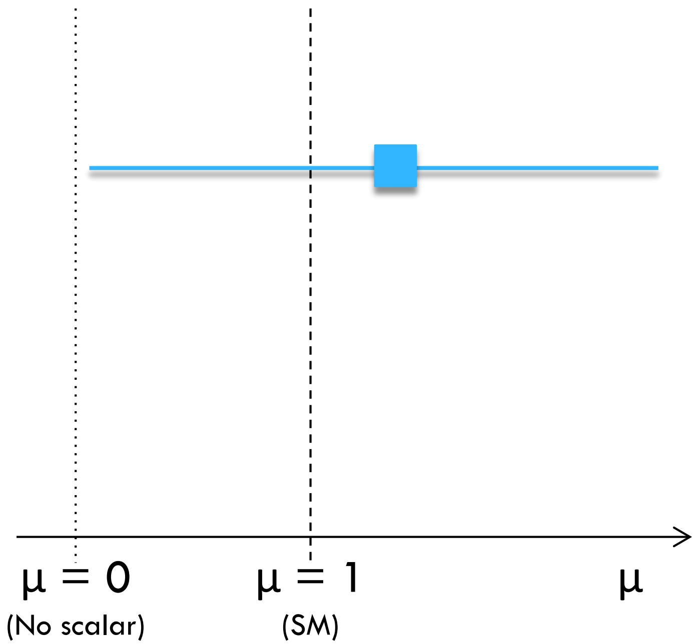
$$\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{observed}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{expected}}}$$

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.***

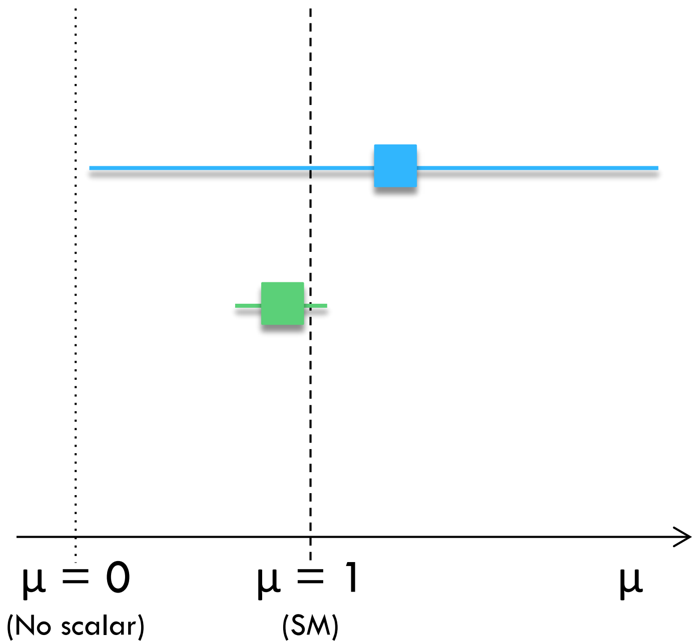
The anatomy of deviations



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).

The anatomy of deviations

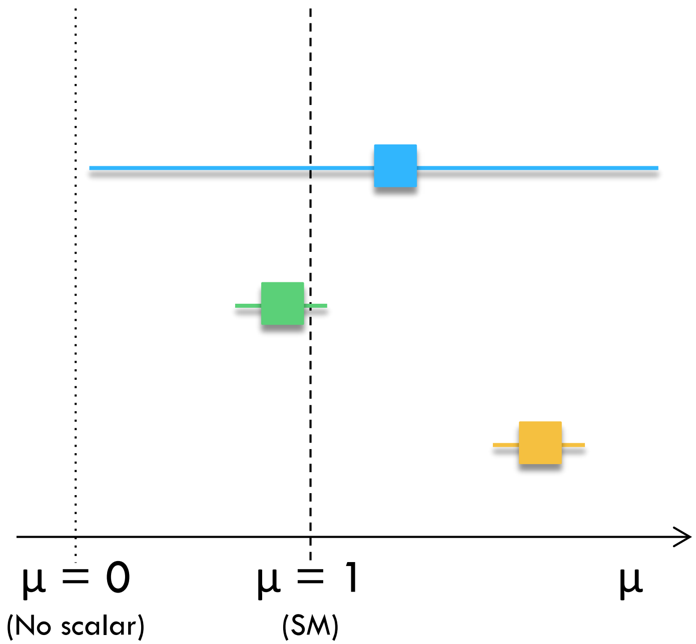


Imprecise measurement compatible with anything.
Inconclusive, "more data needed".

Precise measurement **compatible** with the SM.
Large deviations excluded!

- **$\mu = 1$ means that the data match the SM.**
  - Uncertainty on μ quantifies the compatibility with the SM:
    - $\mu = 1.3 \pm 1.2$ usually means "more data needed", but
    - $\mu = 2.0 \pm 0.2$ could mean New Physics (or a systematic effect).

The anatomy of deviations



Imprecise measurement compatible with anything.
Inconclusive, "more data needed".

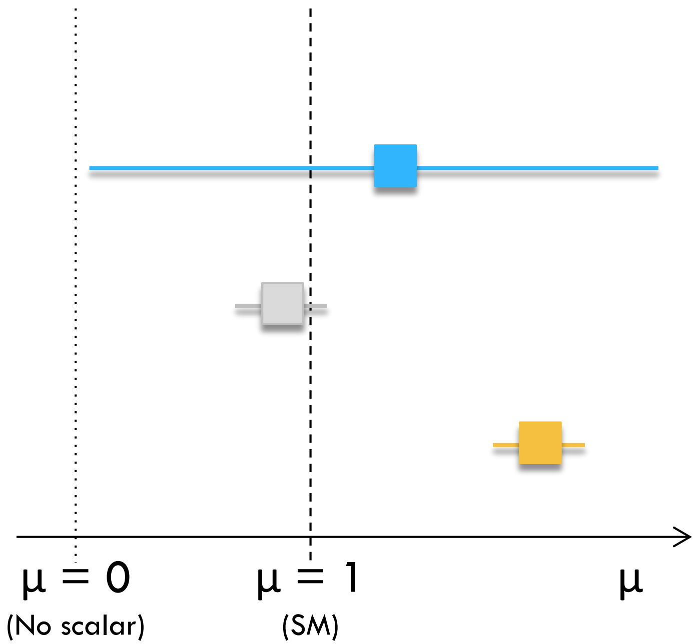
Precise measurement **compatible** with the SM.
Large deviations excluded!

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

- $\mu = 1$ means that the data match the SM.
  - Uncertainty on μ quantifies the compatibility with the SM:
    - $\mu = 3 \pm 5$ usually means "more data needed", but
    - **$\mu = 2.0 \pm 0.2$ could mean New Physics (or a systematic effect).**

The anatomy of deviations



Imprecise measurement compatible with anything.
Inconclusive, "more data **or better theory** needed".

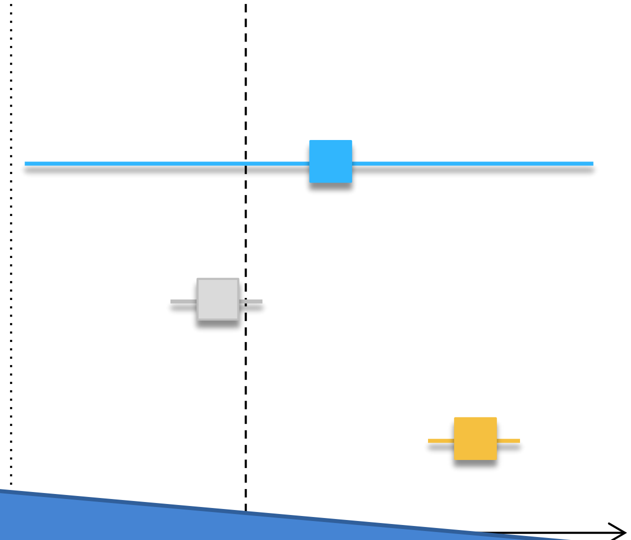
Precise measurement **compatible** with the SM.
Large deviations excluded!

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

- μ = 1 means that the data match the SM.
  - Uncertainty on μ quantifies the compatibility with the SM:
    - μ = 3 ±5 usually means "more data needed", but
    - **μ = 2.0 ±0.2 could mean New Physics (or a systematic effect).**

The anatomy of deviations



Imprecise measurement compatible with anything.
Inconclusive, “more data **or better theory** needed”.

Precise measurement **compatible** with the SM.
Large deviations excluded!

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

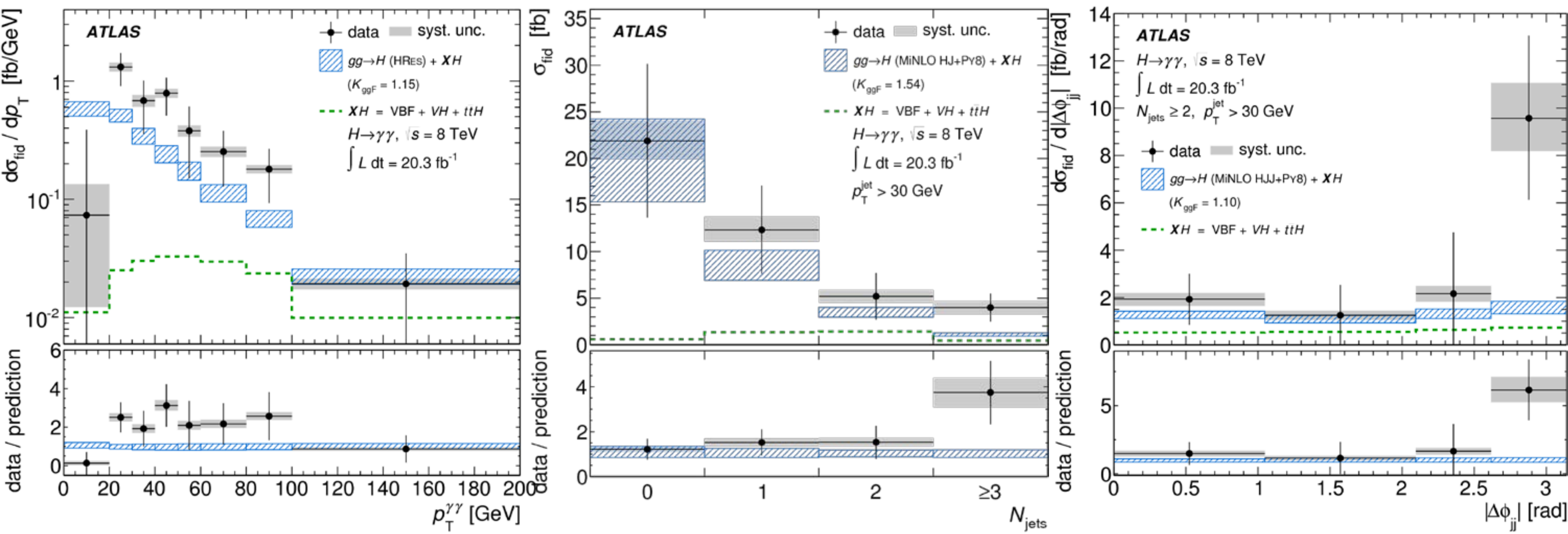
Theory contributes as much to the conclusions as experiments !

- $\mu = 2.0 \pm 0.2$ could mean

Differential distributions

[arXiv:1407.4222][arXiv:1408.3226]

- Differential picture directly touches fundamental aspects:
  - The loop structure where new particles may be running (p_T shape).
  - The QCD structure of the calculations (N_{jets}).
- ATLAS H→γγ and ZZ results and the adventure of unfolding.
  - Illustrates the power of having more statistics (signal-like excess).



Differential distributions

[arXiv:1407.4222][arXiv:1408.3226]

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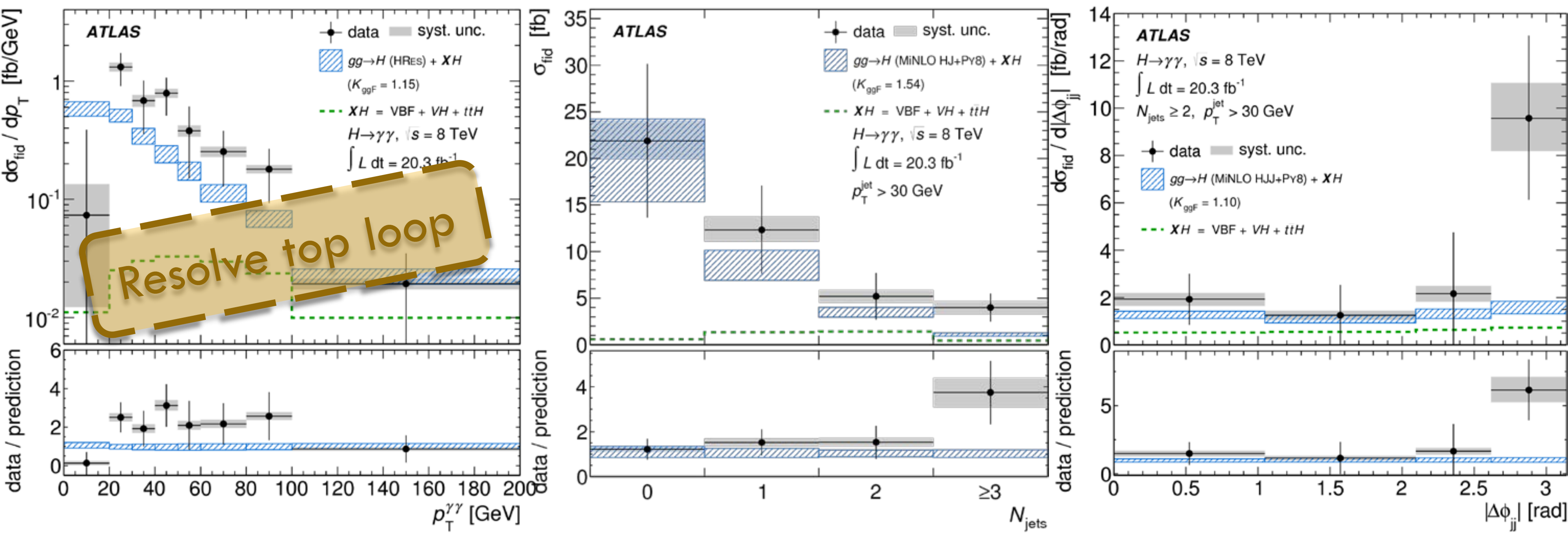

Differential distributions

[arXiv:1407.4222][arXiv:1408.3226]

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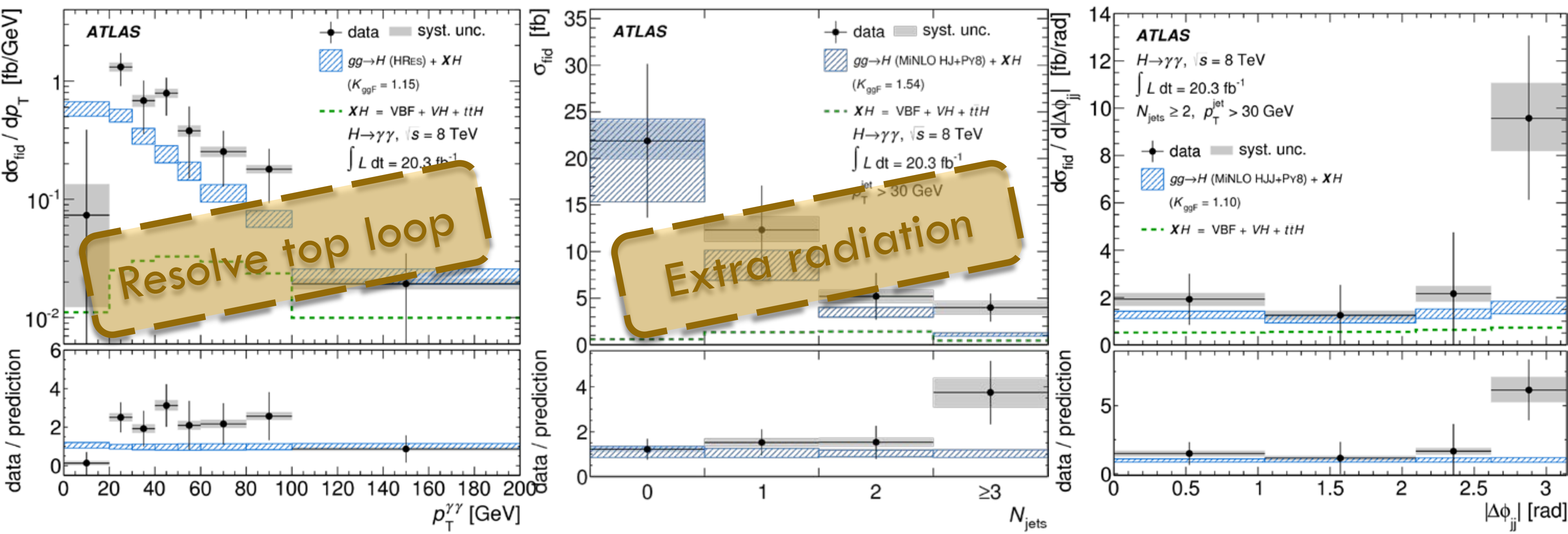

Differential distributions

[arXiv:1407.4222][arXiv:1408.3226]

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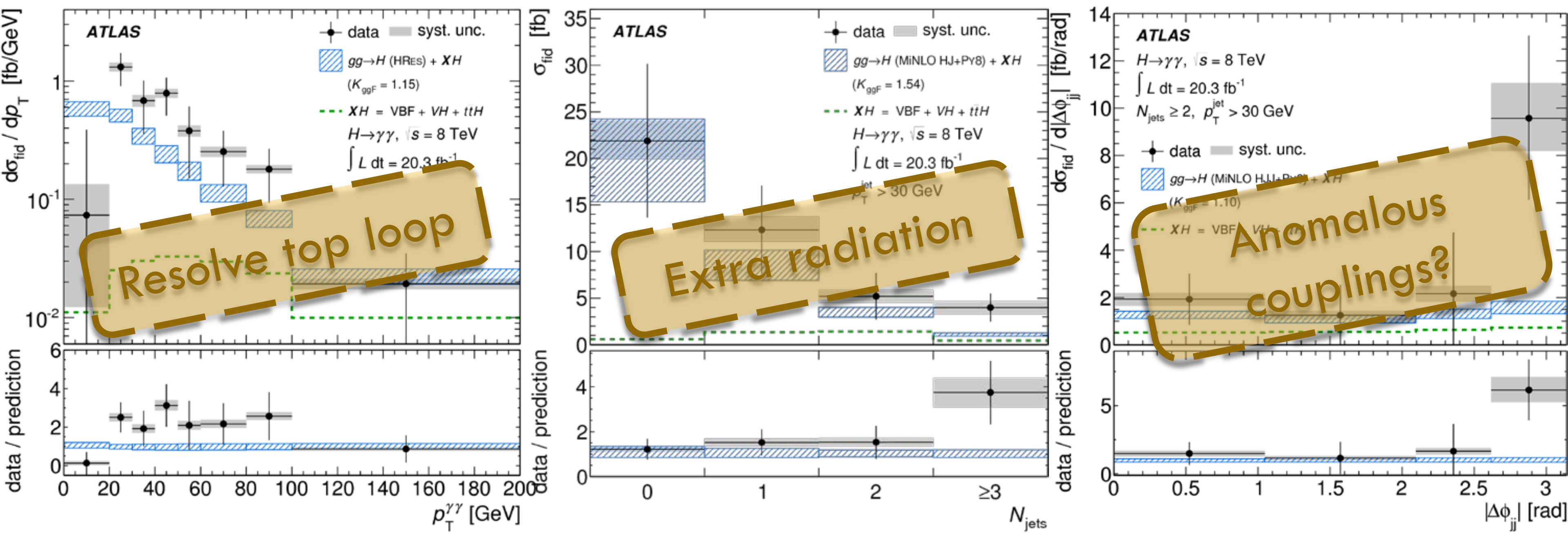
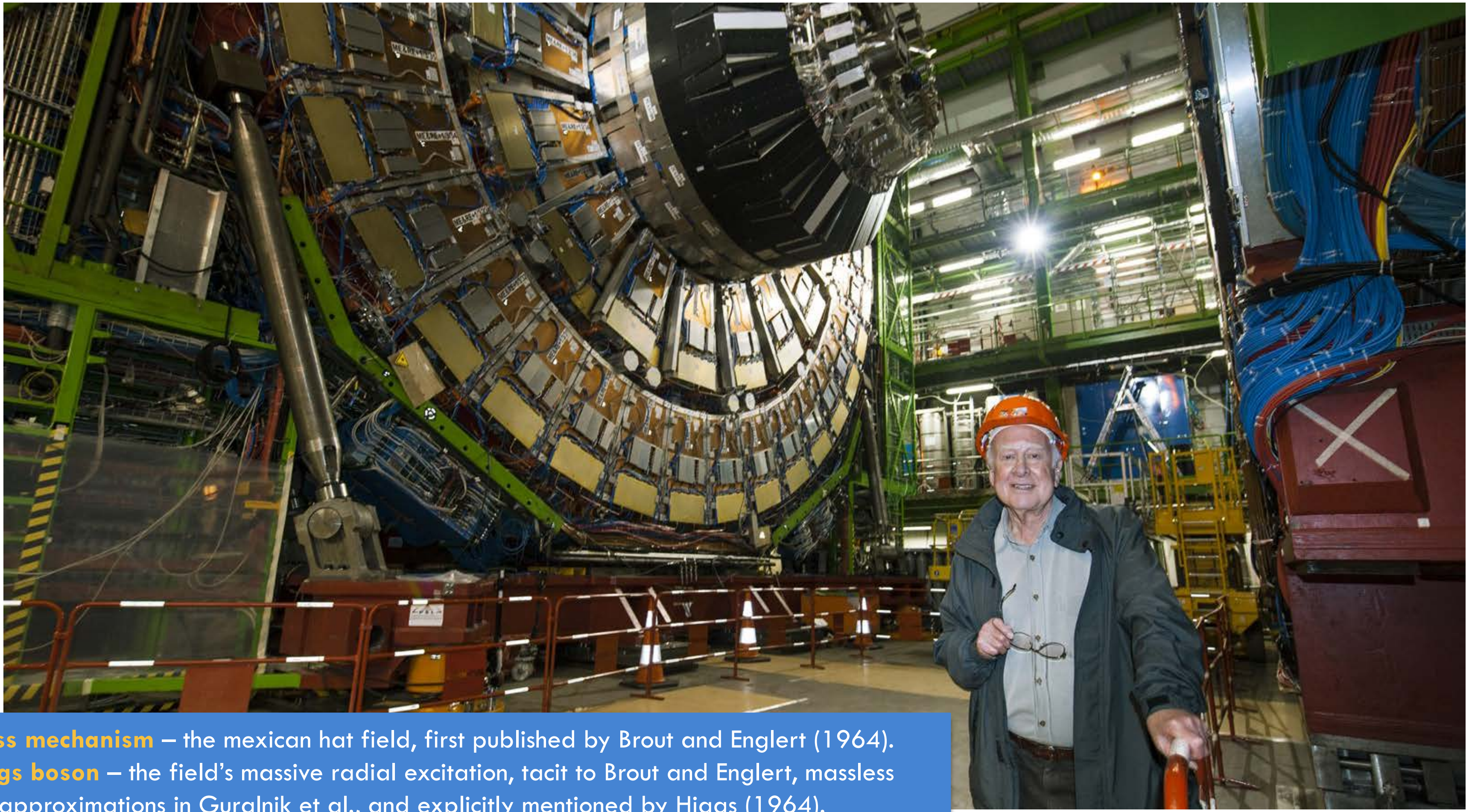


For discussion

Higgs in CMS – ca. 2008

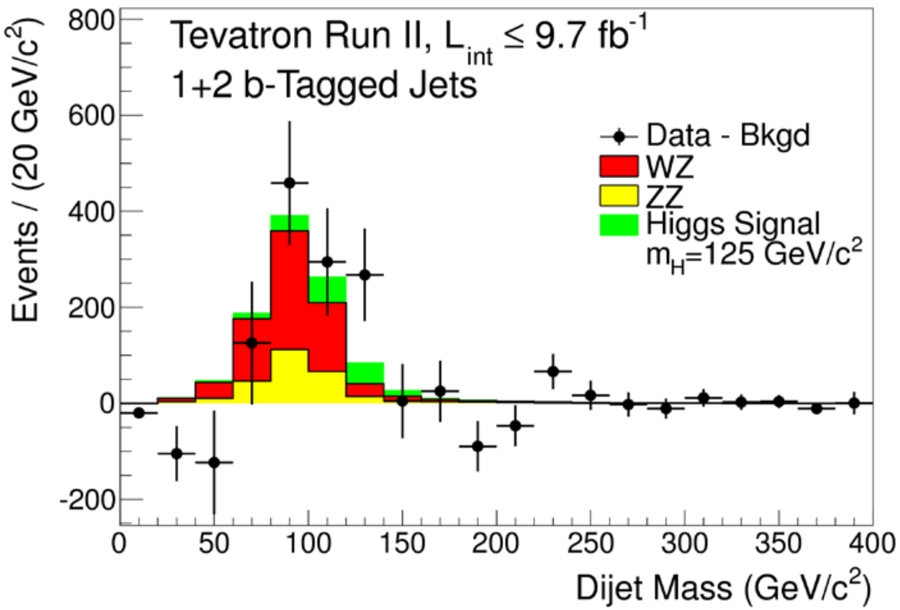
[http://cern.ch/go/dJf7][http://cern.ch/go/Sx8m]

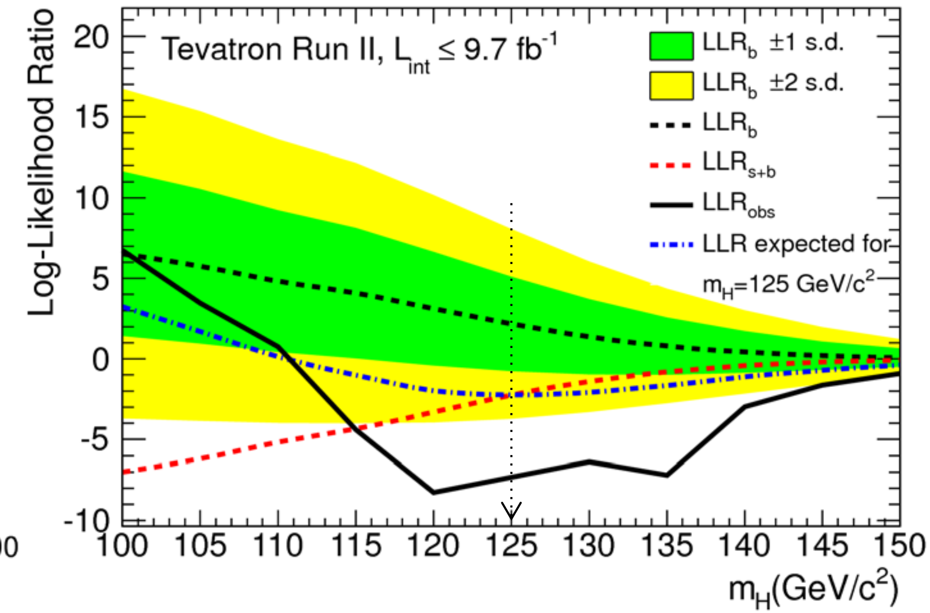


- **Mass mechanism** – the mexican hat field, first published by Brout and Englert (1964).
- **Higgs boson** – the field's massive radial excitation, tacit to Brout and Englert, massless via approximations in Guralnik et al., and explicitly mentioned by Higgs (1964).
- **Viability** – photons and massive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

From the other side of the pond

[arXiv:1207.6436]

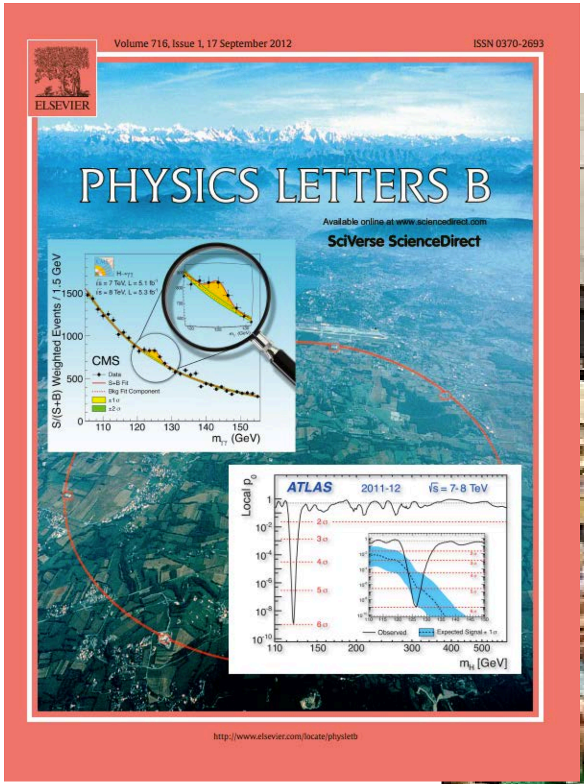




- Combination of Tevatron VH⟶$b\bar{b}$ searches, in July 2012:
  - **2.8σ local significance at m_H=125 GeV.**

Looking up to a new boson

[http://cern.ch/go/q8jx]



A 2012 hit

[http://goo.gl/49c0c][http://goo.gl/suJzZ][http://goo.gl/ShJJG]

symmetry dimensions of particle physics

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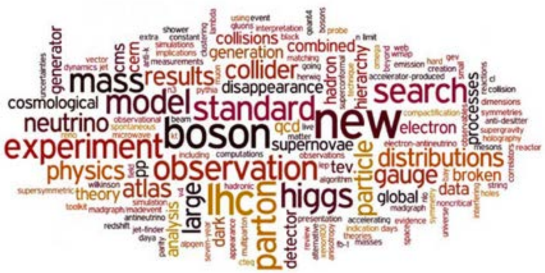

signal to background

May 12, 2013

The top 40 physics hits of 2012

The Higgs boson is a popular subject among the most-cited physics papers of 2012, but a particle simulation manual takes the top spot.

2012 reports for eprints

1. 568 citations in 2012
Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC
ATLAS Collaboration (Georges Aad (Freiburg U.) *et al.*). Jul 2012. 24 pp.
Published in **Phys.Lett. B716 (2012) 1-29**
CERN-PH-EP-2012-218
DOI: 10.1016/j.physletb.2012.08.020
e-Print: **arXiv:1207.7214 [hep-ex]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; Link to all figures including auxiliary figures

2. 558 citations in 2012
Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC
CMS Collaboration (Serguei Chatrchyan (Yerevan Phys. Inst.) *et al.*). Jul 2012.
Published in **Phys.Lett. B716 (2012) 30-61**
CMS-HIG-12-028, CERN-PH-EP-2012-220
DOI: 10.1016/j.physletb.2012.08.021
e-Print: **arXiv:1207.7235 [hep-ex]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; ADS Abstract Service; Link to PRESSRELEASE

3. 433 citations in 2012
Combined results of searches for the standard model Higgs boson in pp collisions at $\sqrt{s}=7$ TeV
CMS Collaboration (Serguei Chatrchyan (Yerevan Phys. Inst.) *et al.*). Feb 2012.
Published in **Phys.Lett. B710 (2012) 26-48**
CMS-HIG-11-032, CERN-PH-EP-2012-023
DOI: 10.1016/j.physletb.2012.02.064
e-Print: **arXiv:1202.1488 [hep-ex]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; ADS Abstract Service

4. 381 citations in 2012
Combined search for the Standard Model Higgs boson using up to 4.9 fb^{-1} of pp collision data at $\sqrt{s}=7$ TeV with the ATLAS detector at the LHC
ATLAS Collaboration (Georges Aad (Freiburg U.) *et al.*). Feb 2012. 8 pp.
Published in **Phys.Lett. B710 (2012) 49-66**
CERN-PH-EP-2012-019
DOI: 10.1016/j.physletb.2012.02.044
e-Print: **arXiv:1202.1408 [hep-ex]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; ADS Abstract Service; Link to all figures including auxiliary figures

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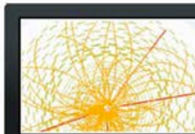
Breakthrough of the Year, 2012

Every year, crowning one scientific achievement as Breakthrough of the Year is no easy task, and 2012 was no exception. The year saw leaps and bounds in physics, along with significant advances in genetics, engineering, and many other areas. In keeping with tradition, *Science*'s editors and staff have selected a winner and nine runners-up, as well as highlighting the year's top news stories and areas to watch in 2013.



FREE ACCESS

The Discovery of the Higgs Boson

A. Cho

Exotic particles made headlines again and again in 2012, making it no surprise that the breakthrough of the year is a big physics finding: confirmation of the existence of the Higgs boson. Hypothesized more than 40 years ago, the elusive particle completes the standard model of physics, and is arguably the key to the explanation of how other fundamental particles obtain mass. The only mystery that remains is whether its discovery marks a new dawn for particle physics or the final stretch of a field that has run its course.

Read more about the Higgs boson from the research teams at CERN.

Runners-Up FREE WITH REGISTRATION

This year's runners-up for Breakthrough of the Year underscore feats in engineering, genetics, and other fields that promise to change the course of science.

More on scalar couplings

Scalar coupling deviations framework

[arXiv:1307.1347]

Production modes

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ggH}}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma^{\mathrm{SM}}_{\mathrm{VBF}}} = \kappa^2_{\mathrm{VBF}}(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma^{\mathrm{SM}}_{\mathrm{WH}}} = \kappa_W^2$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ZH}}} = \kappa_Z^2$$

$$\frac{\sigma_{\mathrm{t\bar{t}H}}}{\sigma^{\mathrm{SM}}_{\mathrm{t\bar{t}H}}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{\mathrm{WW^{(*)}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{WW^{(*)}}}} = \kappa_W^2$$

$$\frac{\Gamma_{\mathrm{ZZ^{(*)}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{ZZ^{(*)}}}} = \kappa_Z^2$$

$$\frac{\Gamma_{\mathrm{b\bar{b}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{b\bar{b}}}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{\mathrm{SM}}_{\tau^-\tau^+}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{\mathrm{SM}}_{\gamma\gamma}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{\mathrm{Z}\gamma}}{\Gamma^{\mathrm{SM}}_{\mathrm{Z}\gamma}} = \begin{cases} \kappa_{(\mathrm{Z}\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(\mathrm{Z}\gamma)}^2 \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{\mathrm{t\bar{t}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{t\bar{t}}}} = \kappa_t^2$$

$$\frac{\Gamma_{\mathrm{gg}}}{\Gamma^{\mathrm{SM}}_{\mathrm{gg}}} : \text{see Section 3.1.2}$$

$$\frac{\Gamma_{\mathrm{c\bar{c}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{c\bar{c}}}} = \kappa_t^2$$

$$\frac{\Gamma_{\mathrm{s\bar{s}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{s\bar{s}}}} = \kappa_b^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma^{\mathrm{SM}}_{\mu^-\mu^+}} = \kappa_\tau^2$$

Total width

$$\frac{\Gamma_{\mathrm{H}}}{\Gamma^{\mathrm{SM}}_{\mathrm{H}}} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

- Single state, spin 0, and CP-even.
- Narrow-width approximation: $(\sigma \times BR) = \sigma \cdot \Gamma / \Gamma_H$

Scalar coupling deviations framework

[arXiv:1307.1347]

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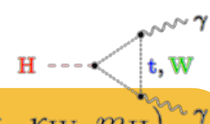

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

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$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}} \; : \; \text{see Section 3.1.2}$$

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Total width

$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

- Loops resolved at NLO QCD and LO EWK accuracy.
- Peg the as-of-yet unmeasured to “closest of kin”.

Scalar coupling deviations framework

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$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{SM}} = \kappa_\tau^2$$

Total width

$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

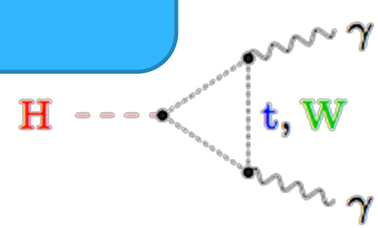
- Total width as dependent function of all κ_i.
- Total width scaled as free parameter: κ_H. **(invisible decays)**

Weak bosons and fermions

 [arXiv:1307.1347]

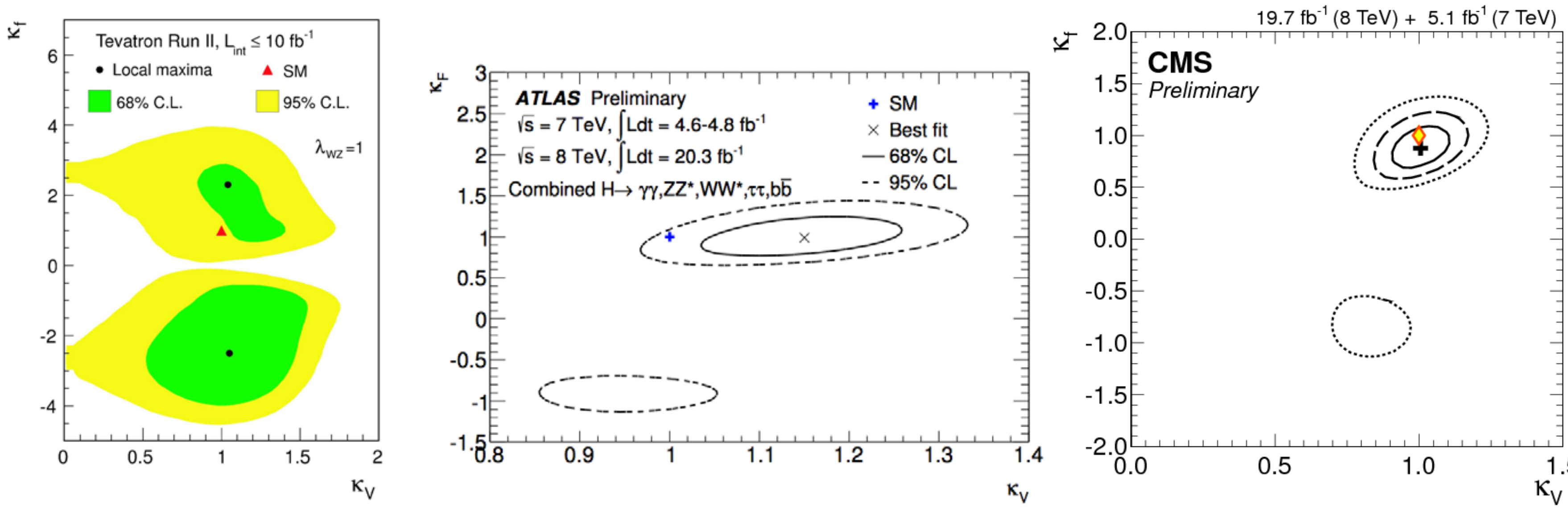
Boson and fermion scaling assuming no invisible or undetectable widths Free parameters: $\kappa_V(=\kappa_W=\kappa_Z)$, $\kappa_f(=\kappa_t=\kappa_b=\kappa_\tau)$.					
	$H\to\gamma\gamma$	$H\to ZZ^{(*)}$	$H\to WW^{(*)}$	$H\to b\bar{b}$	$H\to\tau^-\tau^+$
ggH $t\bar{t}H$	$\frac{\kappa_f^2\cdot\kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2\cdot\kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_f^2\cdot\kappa_f^2}{\kappa_H^2(\kappa_i)}$	
VBF WH ZH	$\frac{\kappa_V^2\cdot\kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2\cdot\kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_V^2\cdot\kappa_f^2}{\kappa_H^2(\kappa_i)}$	

H→γγ resolved into top-loop, b-loop, τ-loop, and W-loop.



Weak bosons and fermions

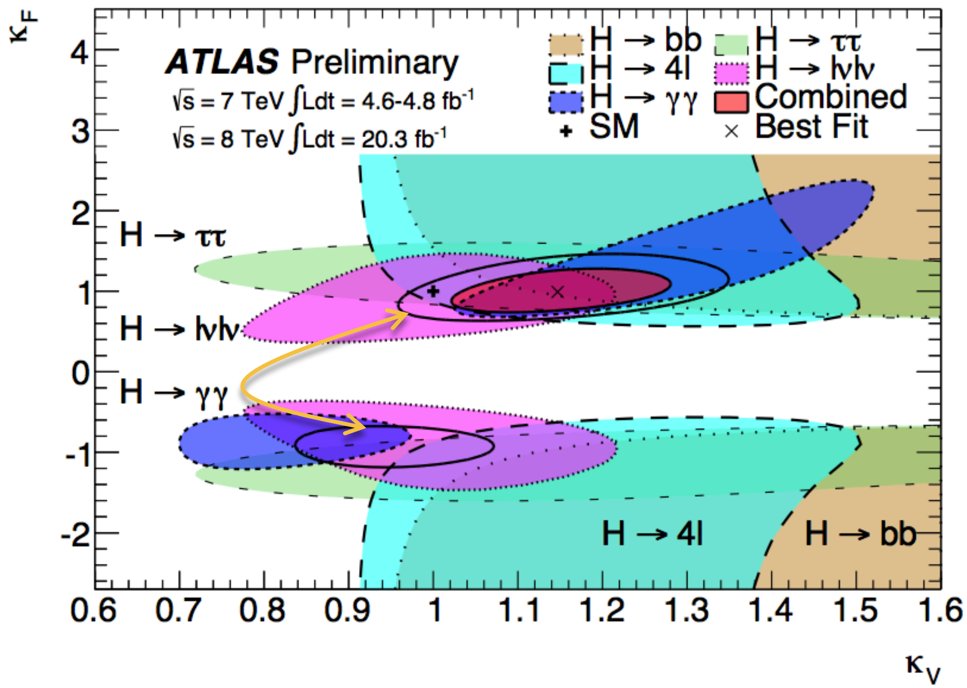
[arXiv:1303.6346][ATLAS-CONF-2014-009][CMS-PAS-HIG-14-009]

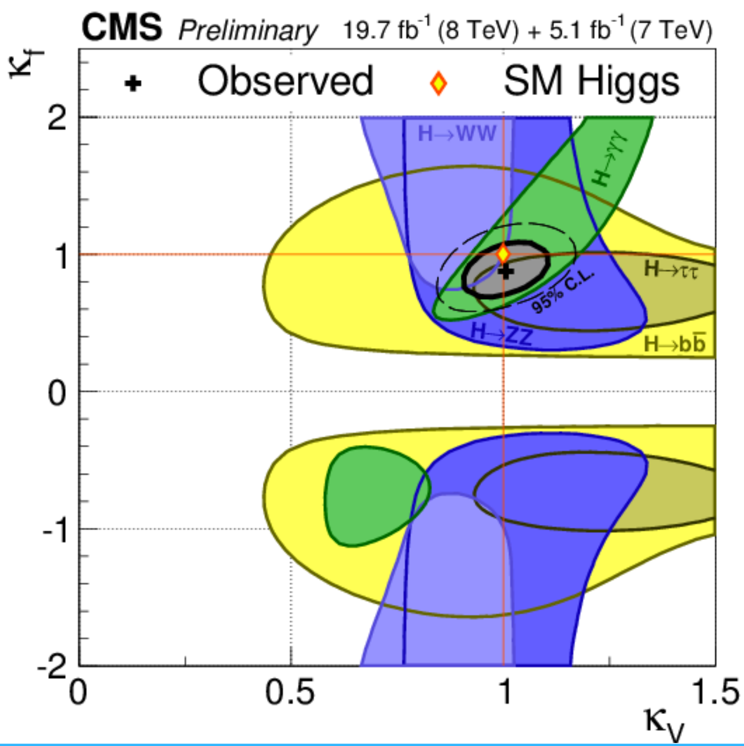


	Tevatron	ATLAS	CMS
p(SM)	-	10%	< 1σ

Weak bosons and fermions

[ATLAS-CONF-2014-009][CMS-PAS-HIG-14-009]

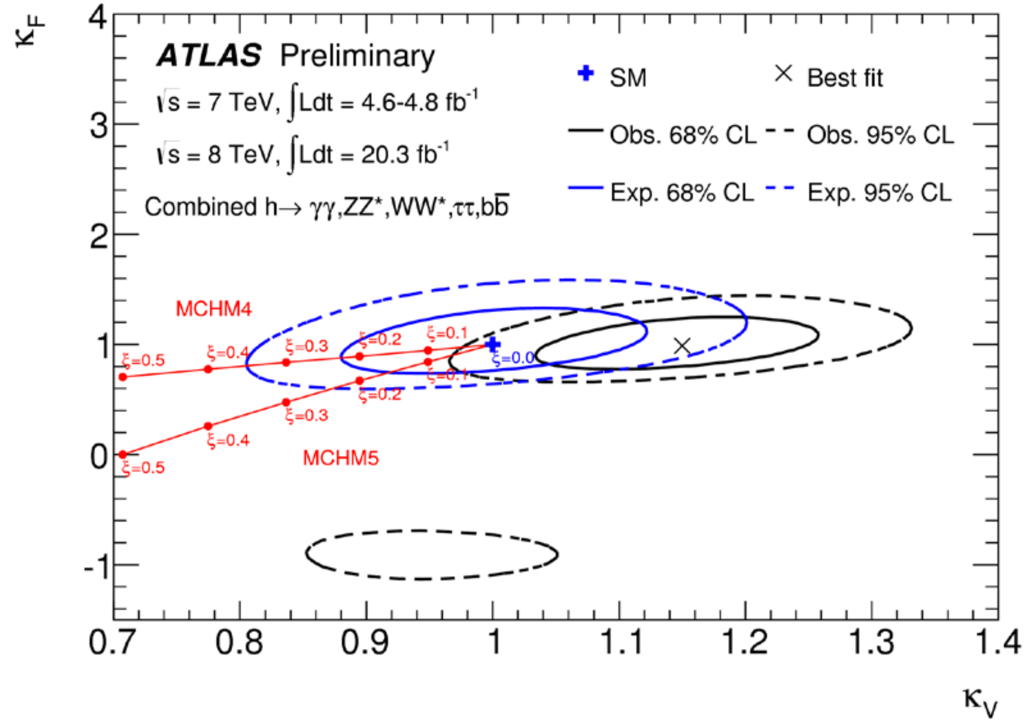




	ATLAS	CMS
P(SM)	**10%**	**< 1σ**

Testing for a composite scalar

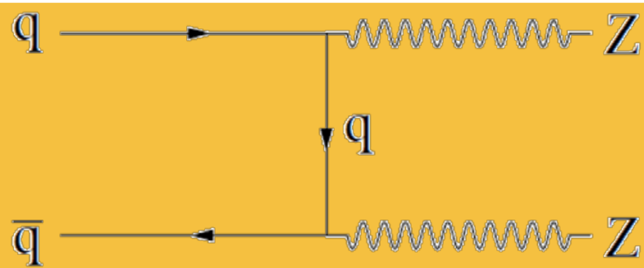
[ATLAS-CONF-NOTE-2014-010]



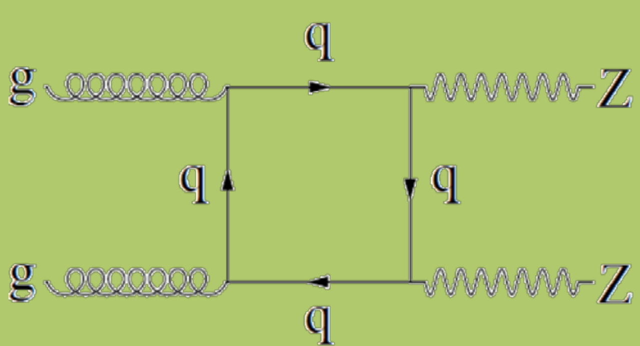
- Example of one BSM alternative being directly tested on the outcome of these fits.

Odds and ends

Off-shell – involved processes

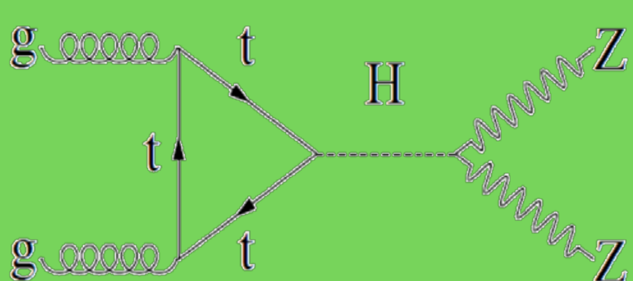


Backgrounds



Strong interference

NNLO/LO k-factors depend on m_{ZZ}
[G. Passarino, arXiv:1312.2397]
Use the same k-factors for signal and gg continuum
[M. Bonvini et al., PRD 88 2013]



Signal

H* – off-shell

[PLB 736 (2014) 64][JHEP 08 (2012) 116][PRD 88 2013][arXiv:1311.3589]

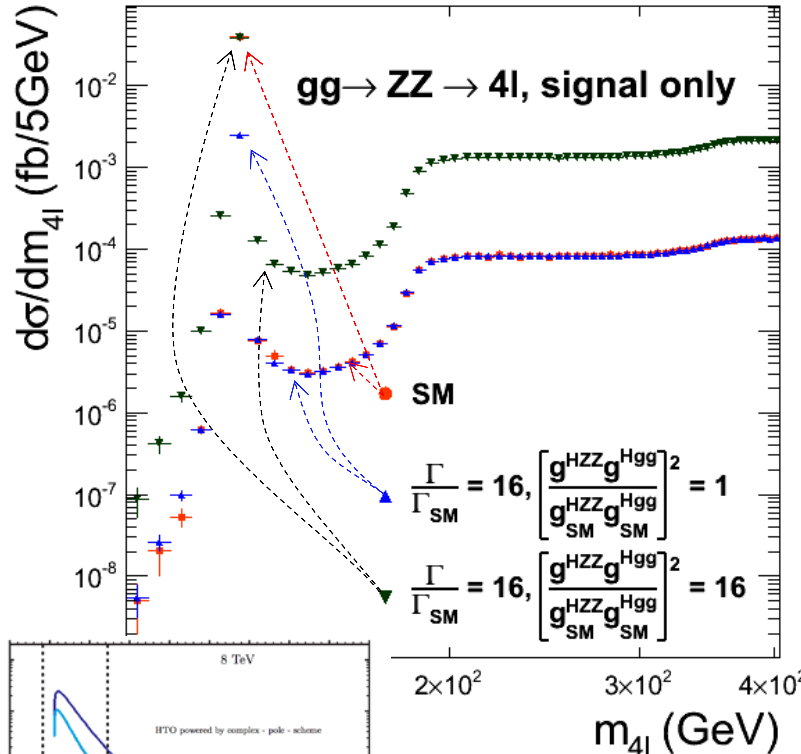
- Define $r = \Gamma_H / \Gamma_H^{SM}$
- On-mass-shell we have

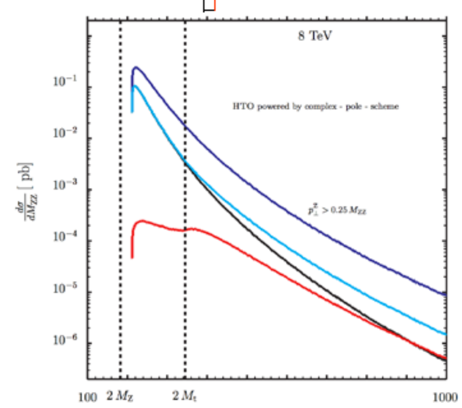
$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} = \frac{\kappa_g^2 \kappa_Z^2}{r} (\sigma \cdot \mathcal{B})_{SM}$$

- Off-mass-shell there is no ***r***:

$$\frac{d\sigma^{\text{off-peak}}_{gg\to H\to ZZ}}{dm_{ZZ}} = \kappa_g^2 \kappa_Z^2 \cdot \frac{d\sigma^{\text{off-peak,SM}}_{gg\to H\to ZZ}}{dm_{ZZ}}$$

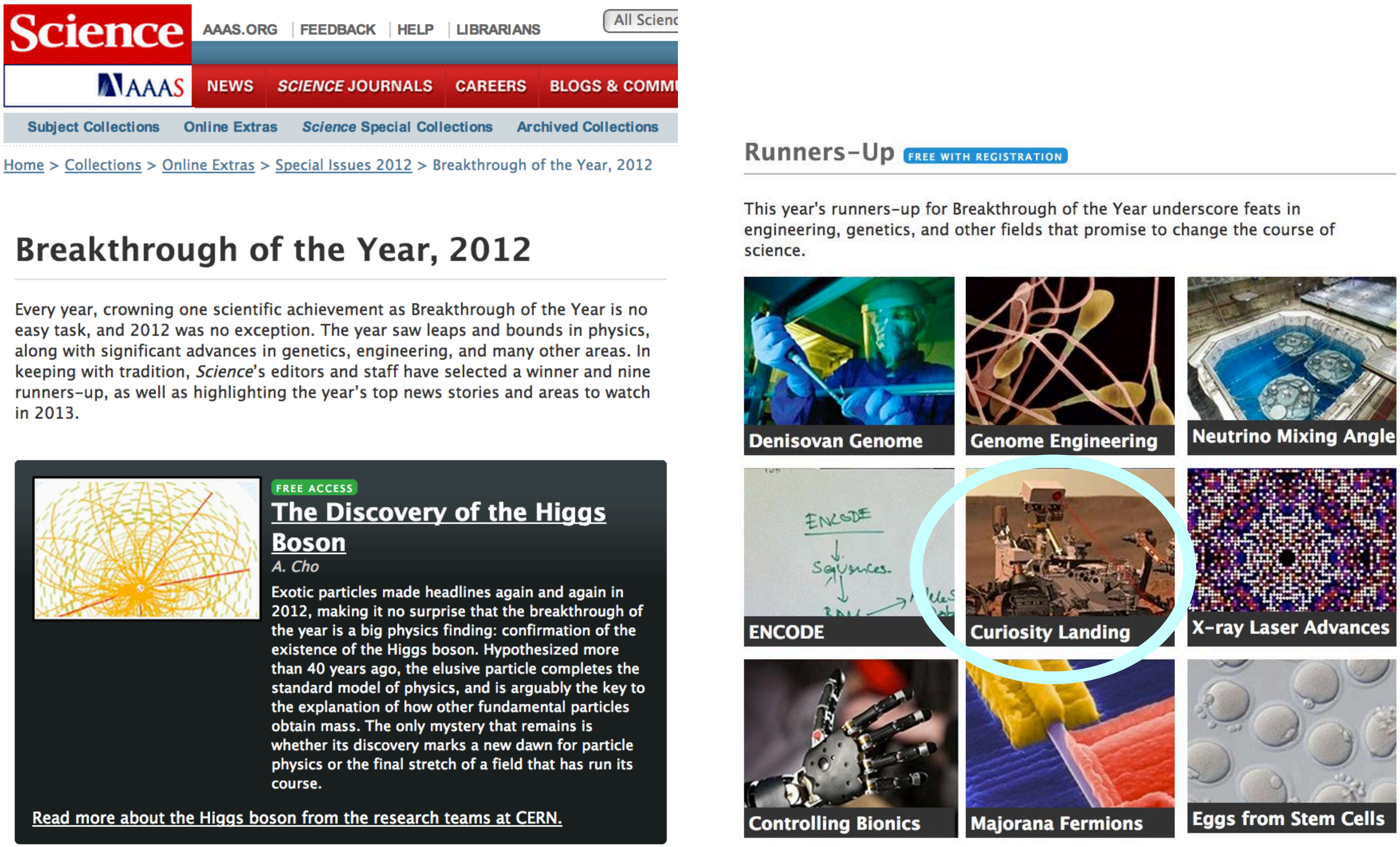
- Can make inference on ***r*** from on- **and** off-shell **assuming:**
  - $\mu_{\text{on-shell}} = \mu_{\text{off-shell}}$
  - Only SM processes → ZZ:
    - gg→H*
    - **gg** = |gg→H* + gg→non-H|²
    - |gg→H*|² + |gg→non-H|²
    - **Total** = **gg** + $q\bar{q}$





A 2012 hit

[http://goo.gl/ShJJG]



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Breakthrough of the Year, 2012

Every year, crowning one scientific achievement as Breakthrough of the Year is no easy task, and 2012 was no exception. The year saw leaps and bounds in physics, along with significant advances in genetics, engineering, and many other areas. In keeping with tradition, *Science*'s editors and staff have selected a winner and nine runners-up, as well as highlighting the year's top news stories and areas to watch in 2013.

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The Discovery of the Higgs Boson

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Runners-Up

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This year's runners-up for Breakthrough of the Year underscore feats in engineering, genetics, and other fields that promise to change the course of science.

Denisovan Genome | Genome Engineering | Neutrino Mixing Angle

ENCODE | Curiosity Landing | X-ray Laser Advances

Controlling Bionics | Majorana Fermions | Eggs from Stem Cells

Delayed unitarization: until when?

[http://cern.ch/go/q8Gq]

- Assume that WW scattering is $\delta^{-1/2}$ that of SM.
- Things can look like the SM for a long time.
  - **Time ~ Energy.**