Charting the Higgs Self-Coupling with the ATLAS Experiment

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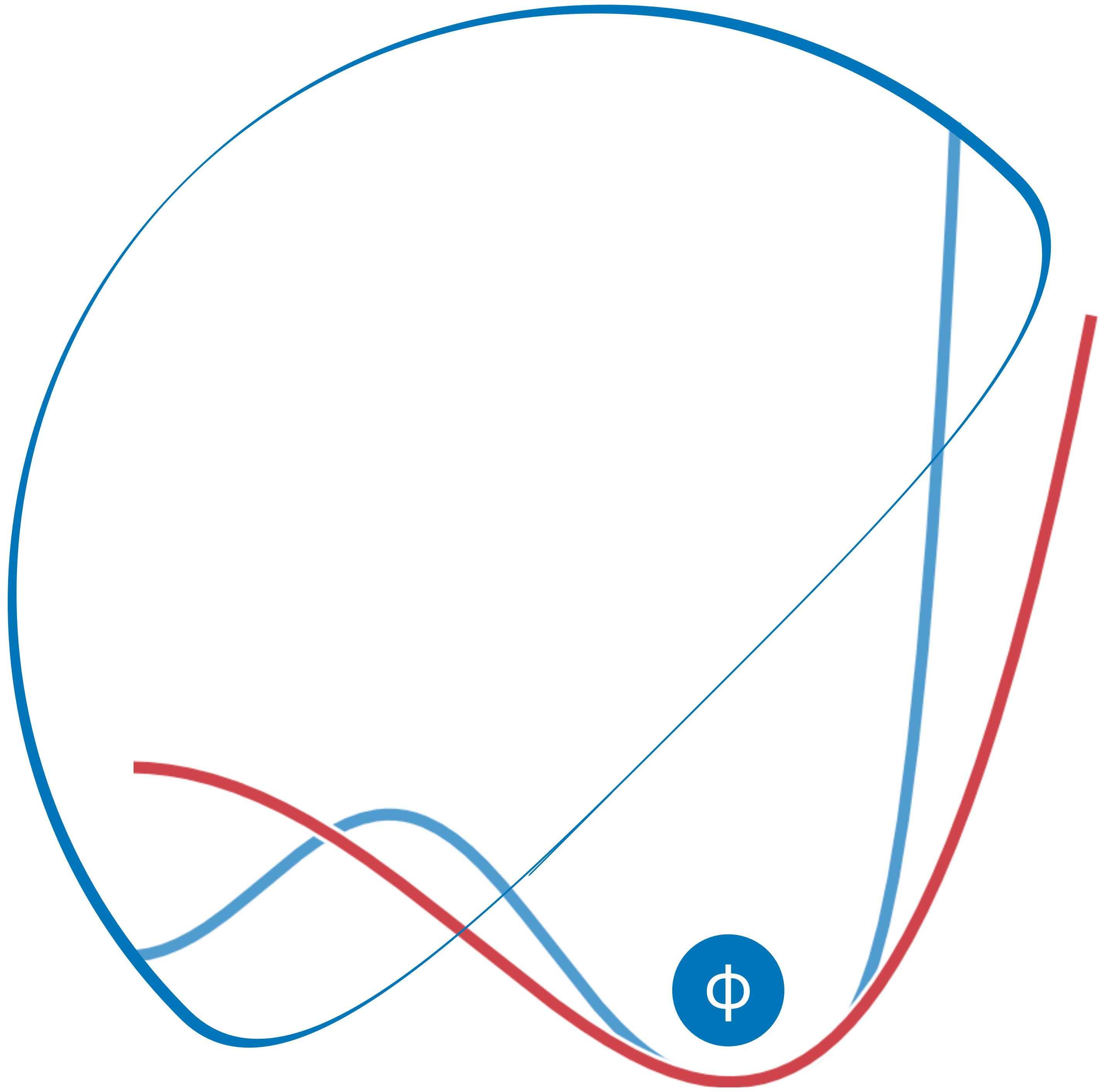


ATLAS EXPERIMENT

Nikhef

Introduction & Motivations

the key role of the Higgs scalar sector

Higgs self-interactions at the LHC

deep-dive in direct double-Higgs measurements

one example of indirect-probes

Looking towards the future

what can we say at the LHC

and shall we look towards future machines

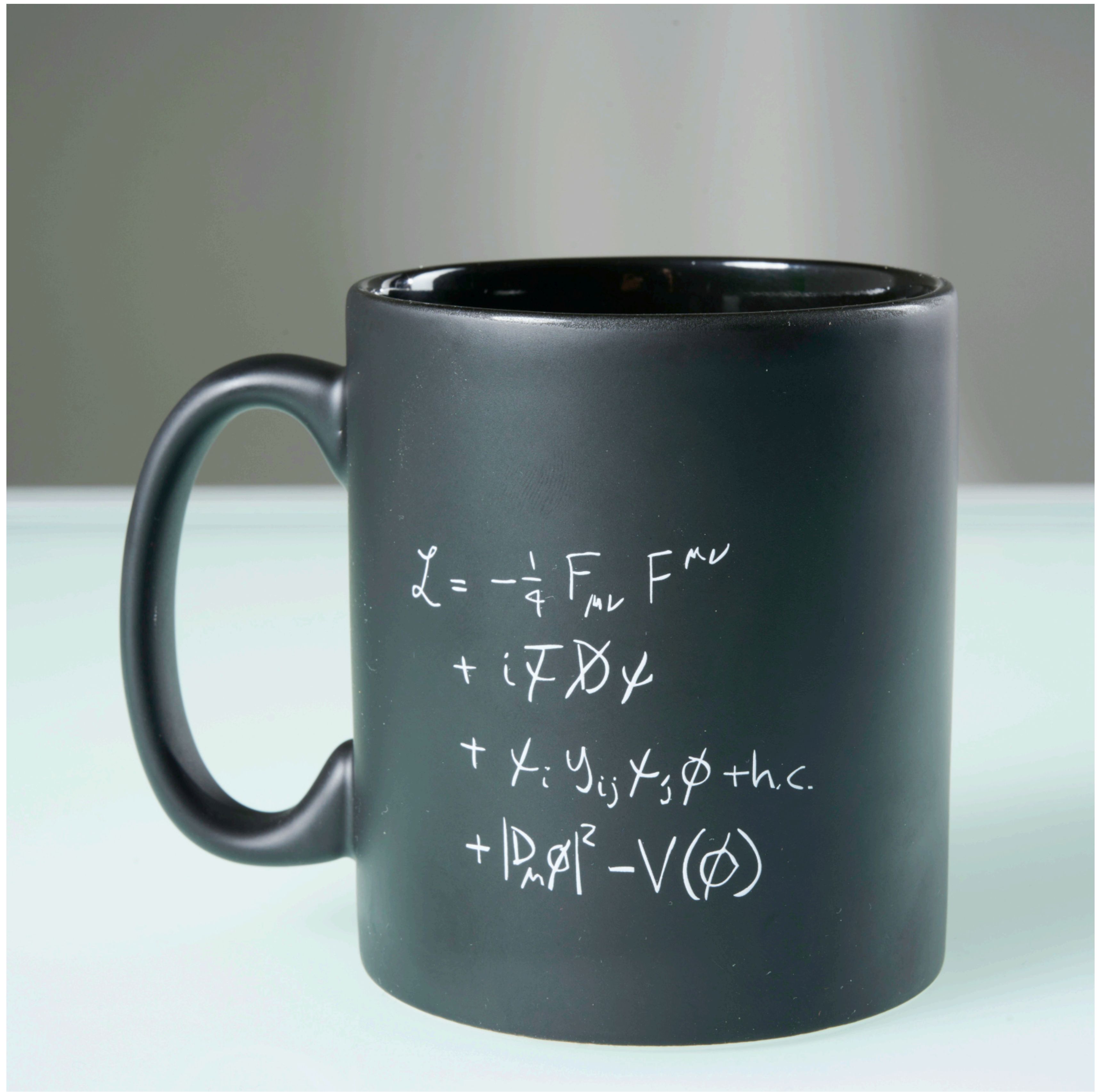
Motivations: the key role of the Higgs scalar sector

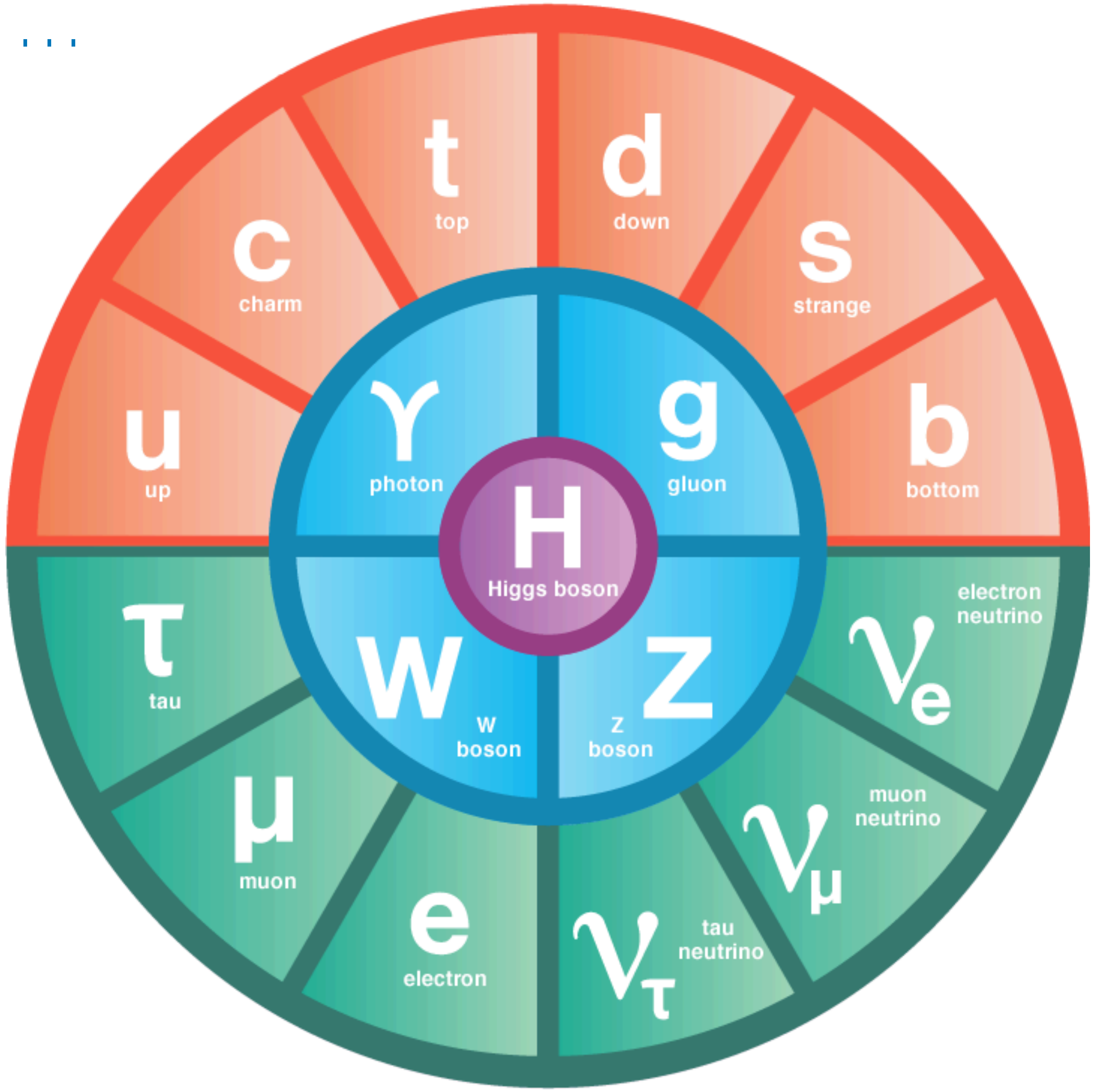
The Standard Model and the Higgs

The usual introduction from a CERN particle physicist …

The SM accurately describes fundamental particles and forces: natural, highly symmetric, precisely tested, …

(fits on a coffee mug)





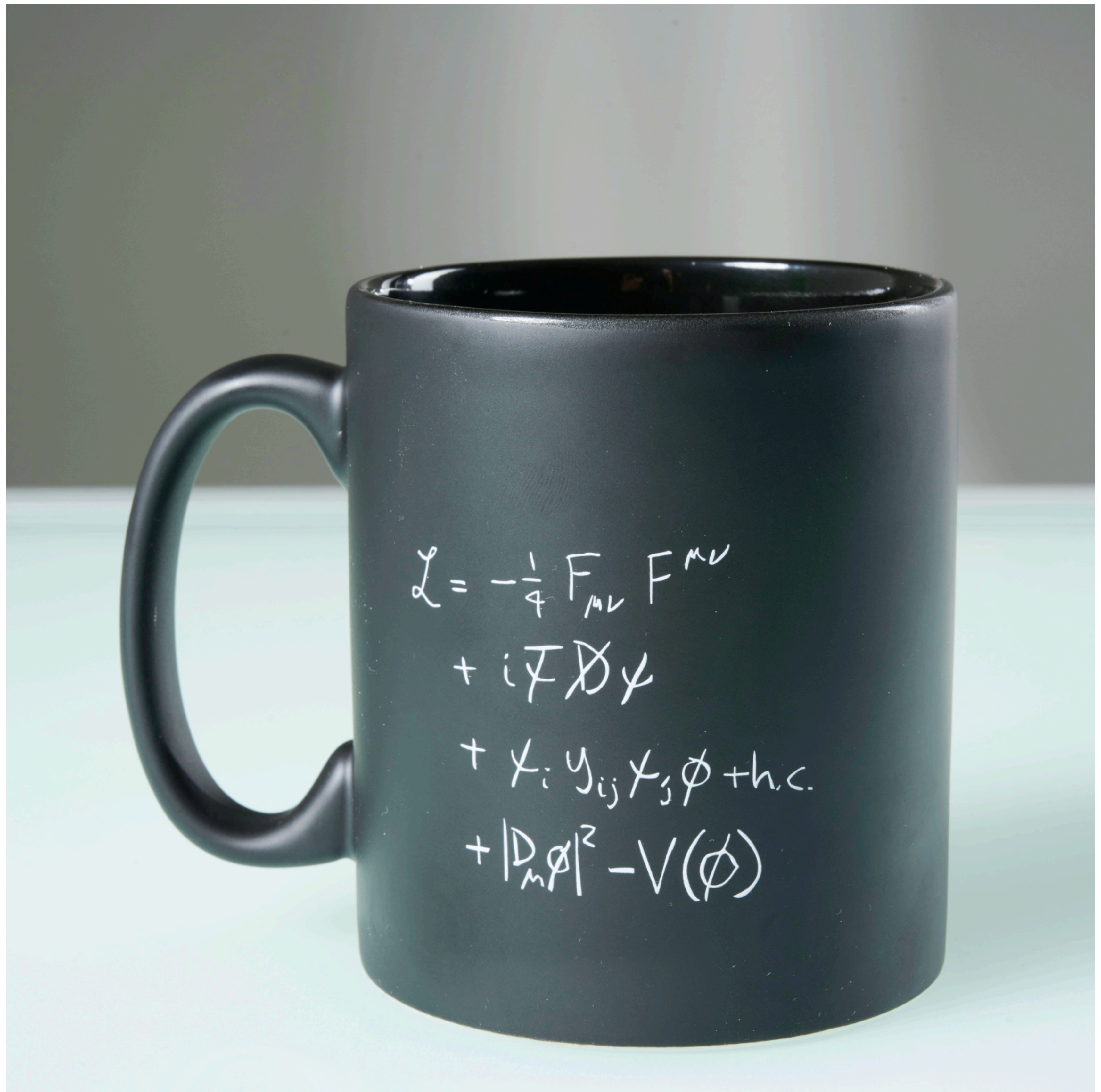
The **Higgs boson** is at the core of this description:

- necessary ingredient to break Electroweak Symmetry
- linked to many of particle physics open questions

The Standard Model and the Higgs

As elegant and compact as the Lagrangian can be

the Standard Model has a very intricate structure …



1

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

2

$$- \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^2_w}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^2_h 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^2_w}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^2 c^2_w(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s^2_w(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^2_w}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^2_w}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c^2_w}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \frac{1}{4}g^2\frac{1}{c^2_w}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s^2_w}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s^2_w}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c^2_w - 1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s^2_w A_\mu A_\mu\phi^+\phi^-$$

3

$$- \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right] + \frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s^2_w - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s^2_w - 1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s^2_w - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)]$$

4

$$+ \frac{ig}{2\sqrt{2}}\frac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j)$$

5

$$+ \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c^2_w})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c^2_w}\bar{X}^0 X^0 H] + \frac{1-2c^2_w}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

full SM lagrangian

… with the Higgs boson at its very core !

Symmetries of the Standard Model

The Standard Model is a **Quantum Field Theory** (QFT):
interactions are dictated by symmetries of spacetime + internal symmetries

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ \, i\bar{\psi} \not{D} \psi$$

$$+ \, \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

$$+ \, |D_\mu \phi|^2 - V(\phi)$$

- $-\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$: Interactions among SM bosons
- $i\bar{\psi} \not{D} \psi$: Interaction between force carriers and fermions
- $\bar{\psi}_i y_{ij} \psi_j \phi + h.c.$: Higgs coupling to fermions (quarks, leptons)
- $|D_\mu \phi|^2$: Higgs coupling to bosons
- $V(\phi)$: Higgs potential

… symmetries dictate interactions, plus free parameters …

Symmetries of the Standard Model

The Standard Model is a **Quantum Field Theory** (QFT):
interactions are dictated by symmetries of spacetime + internal symmetries

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

Gauge Interactions

$$+ i\bar{\psi} \not{D} \psi$$

Gauge Interactions

$$+ \psi_i y_{ij} \psi_j \phi + h.c.$$

Yukawa Interactions

$$+ |D_\mu \phi|^2 - V(\phi)$$

Gauge Interactions

Scalar Self-Interactions

… symmetries dictate interactions, plus free parameters …

Parameters of the Standard Model

1

$$-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g^2_s f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$

$$\tfrac{1}{2}ig^2_s(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$

2

$$M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c^2_w}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H -$$

$$\tfrac{1}{2}m^2_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+\phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c^2_w}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} +$$

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

$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu -$$

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

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

$$\tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$

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

$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$

$$\tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] -$$

$$gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c^2_w}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$

$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$

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

$$igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c^2_w}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$

$$igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$

$$\tfrac{1}{4}g^2\tfrac{1}{c^2_w}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s^2_w}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$

$$W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s^2_w}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$

$$W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c^2_w - 1)Z^0_\mu A_\mu\phi^+\phi^- -$$

$$g^1 s^2_w A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j -$$

3

$$\bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] +$$

$$\tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s^2_w - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s^2_w -$$

$$1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s^2_w - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$

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

$$\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$

4

$$\tfrac{g}{2}\tfrac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$

$$m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-$$

$$\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) -$$

$$\tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 -$$

5

$$\tfrac{M^2}{c^2_w})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- -$$

$$\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y -$$

$$\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -$$

$$\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c^2_w}\bar{X}^0 X^0 H] +$$

$$\tfrac{1-2c^2_w}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] +$$

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

Total of 19 (26) parameters …

- **g_1, g_2, g_3** - 3 gauge couplings (EW + QCD)
- QCD vacuum angle $\boldsymbol{\theta_{QCD}}$
- 3 **CKM angles** + 1 **phase**
- 6 quark masses + 3 charged lepton masses
  (or Yukawa couplings **Y_u, Y_d, Y_e** for each generation)
- Higgs mass **m_H** (or **μ**)
- Higgs vacuum expectation value **v**
- (neutrino masses or **Y_ν** Yukawa couplings)

… the Higgs is responsible for 15 (22) of them !

(or there must be a new source of EW symmetry breaking)

Higgs and the Standard Model

The Higgs boson is **central** in the Standard Model

Two **fundamentally new** type of interactions

- Yukawa couplings
- Scalar self-interactions

Responsible for the value of most of the Standard Model free parameters

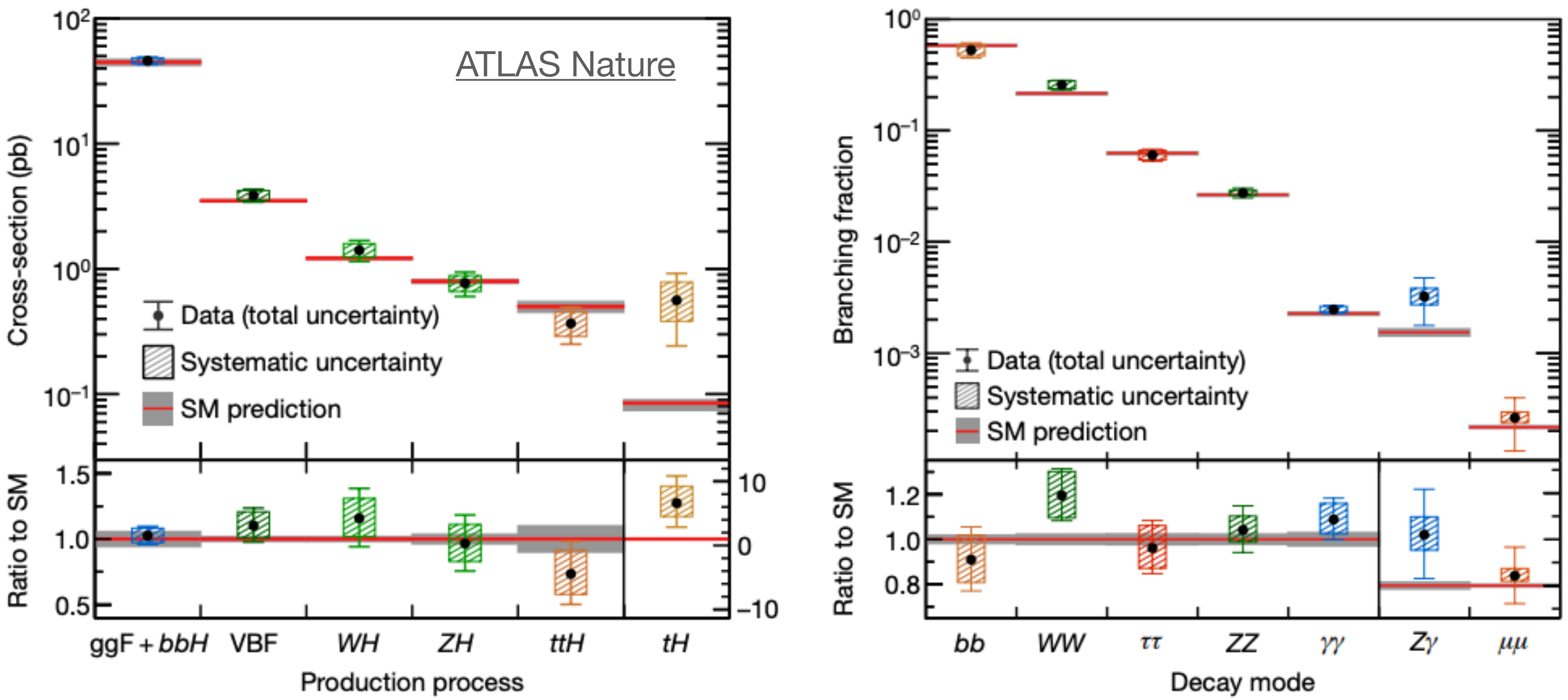
*Deviations from the predictions imply a **revolution** in our understanding of the Standard Model as a QFT*

The vast majority of possible deviations are linked to the Higgs Sector: it's all about the Higgs !

There is space for deviations

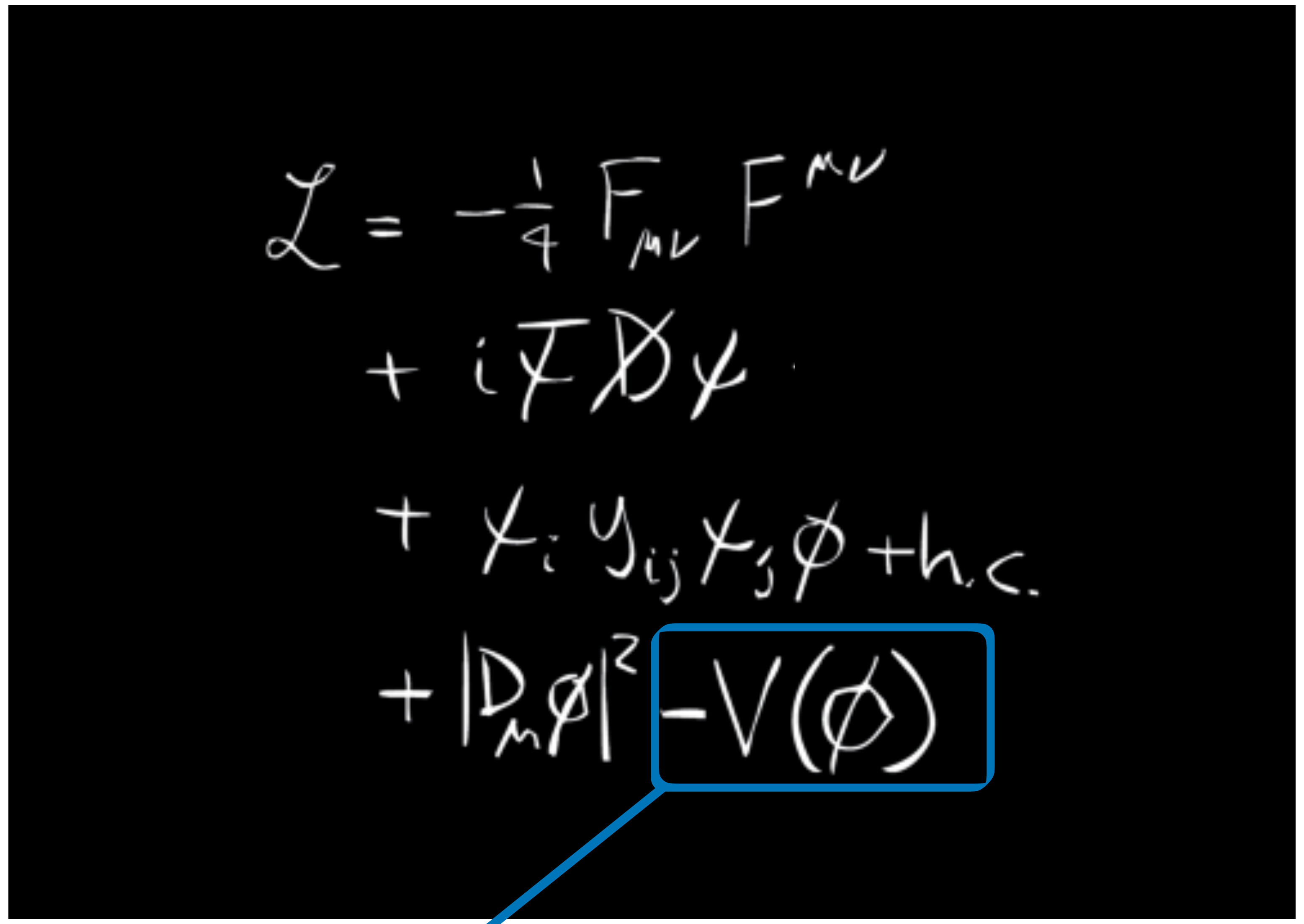
Many of SM parameters are probed with high precision at colliders
(EW and QCD measurements orders of magnitude more precise than Higgs physics)

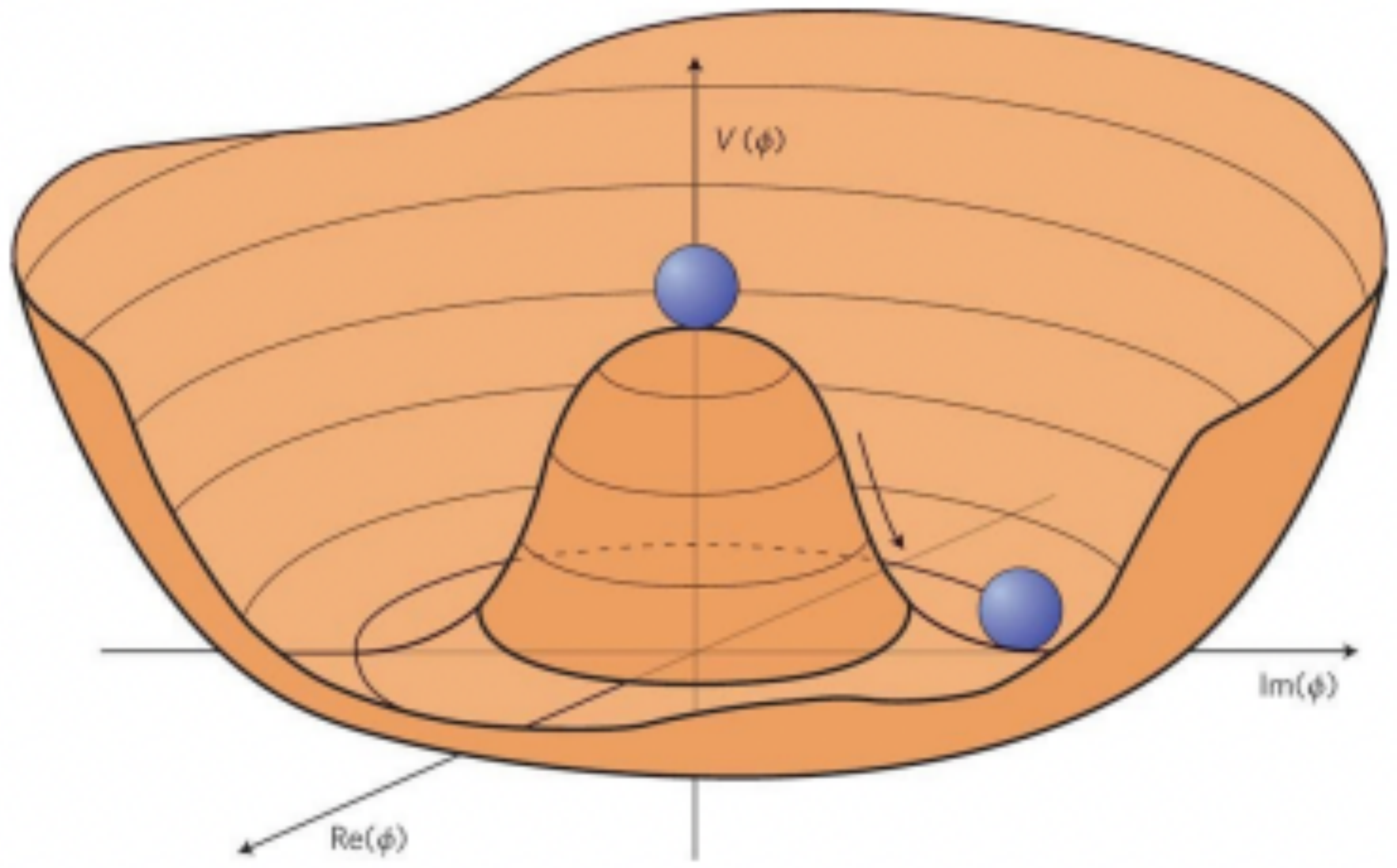
Several of the Higgs interactions & related parameters are still at ~**O(10%)** precision
(far from the percent level precision with which we know $\boldsymbol{\alpha_S(m_Z)}$ or even better $\boldsymbol{\alpha_{EW}}$)



While we are closing in on higher precision in Higgs Yukawa and Gauge couplings we have fewer answers on Scalar Self-Interactions

The Higgs Potential





Well known shape of the Higgs potential after EW symmetry breaking, that you'll find on all textbook

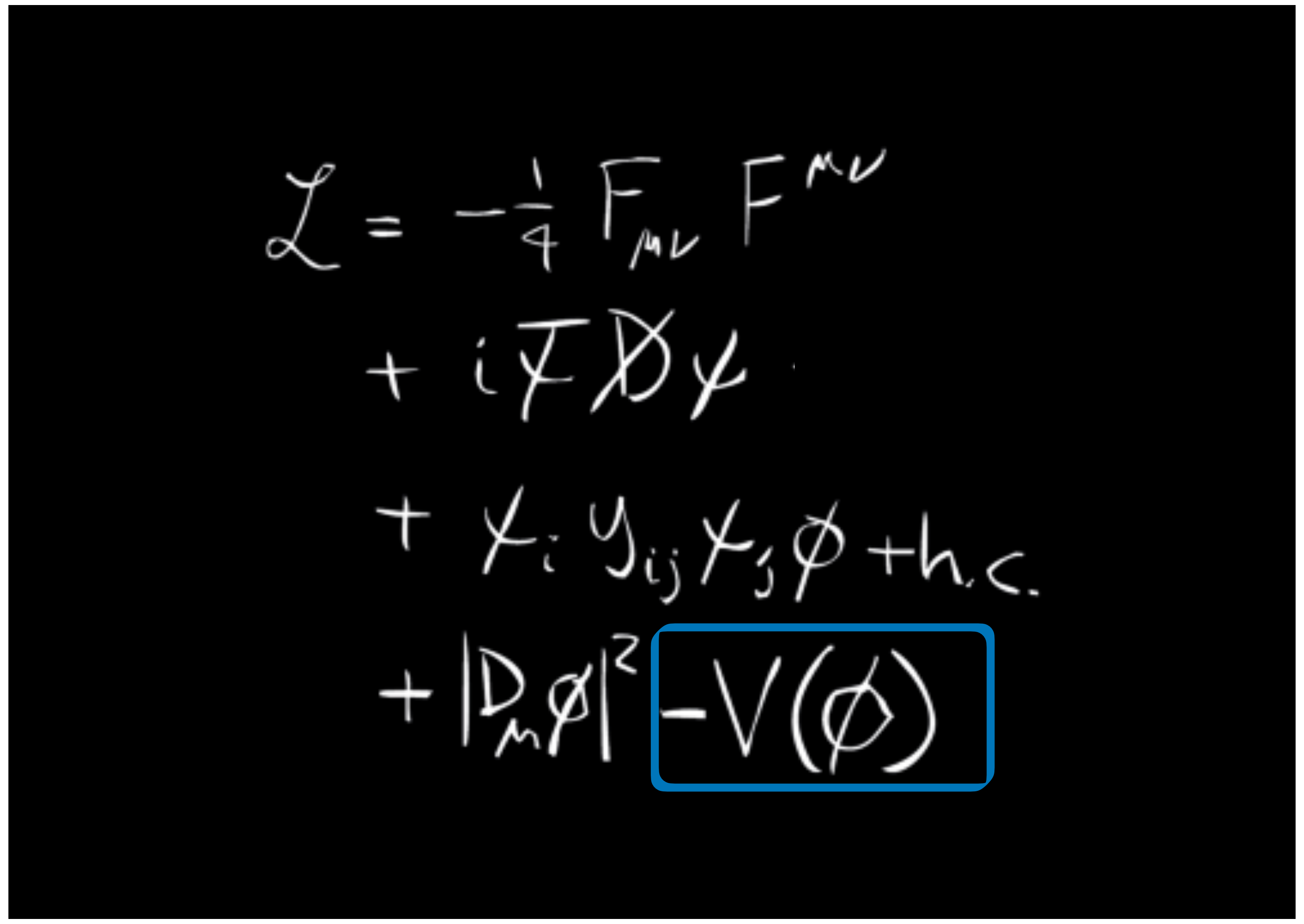
$$V(\phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi_1 + i\phi_2 \end{pmatrix}$$

Scalar-field potential
(complex doublet of scalar fields)

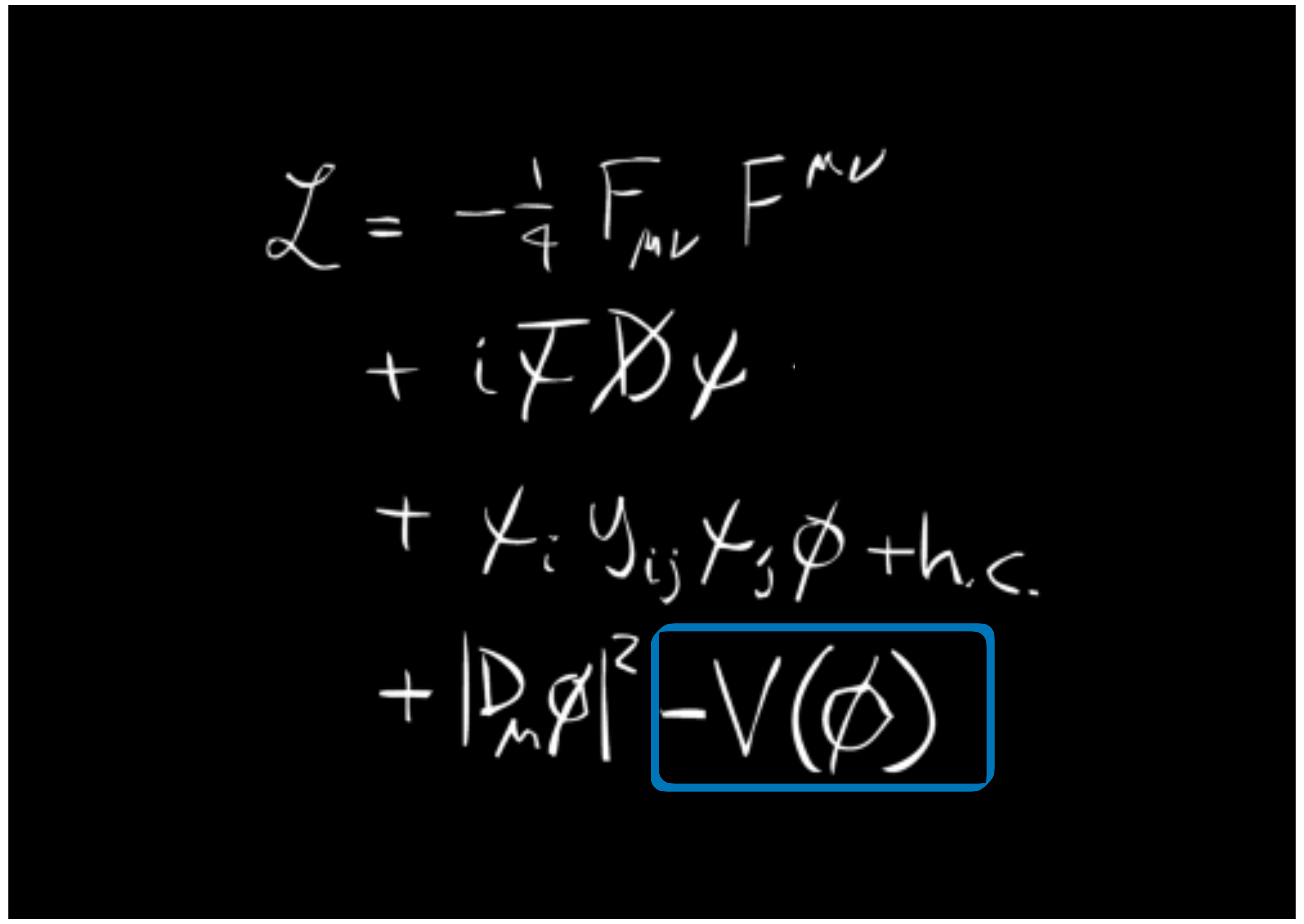
$$V(\Phi) = V_0 + \frac{1}{2} m_H^2 H^2 + \lambda \nu H^3 + \frac{1}{4} \lambda H^4$$

The Higgs Potential



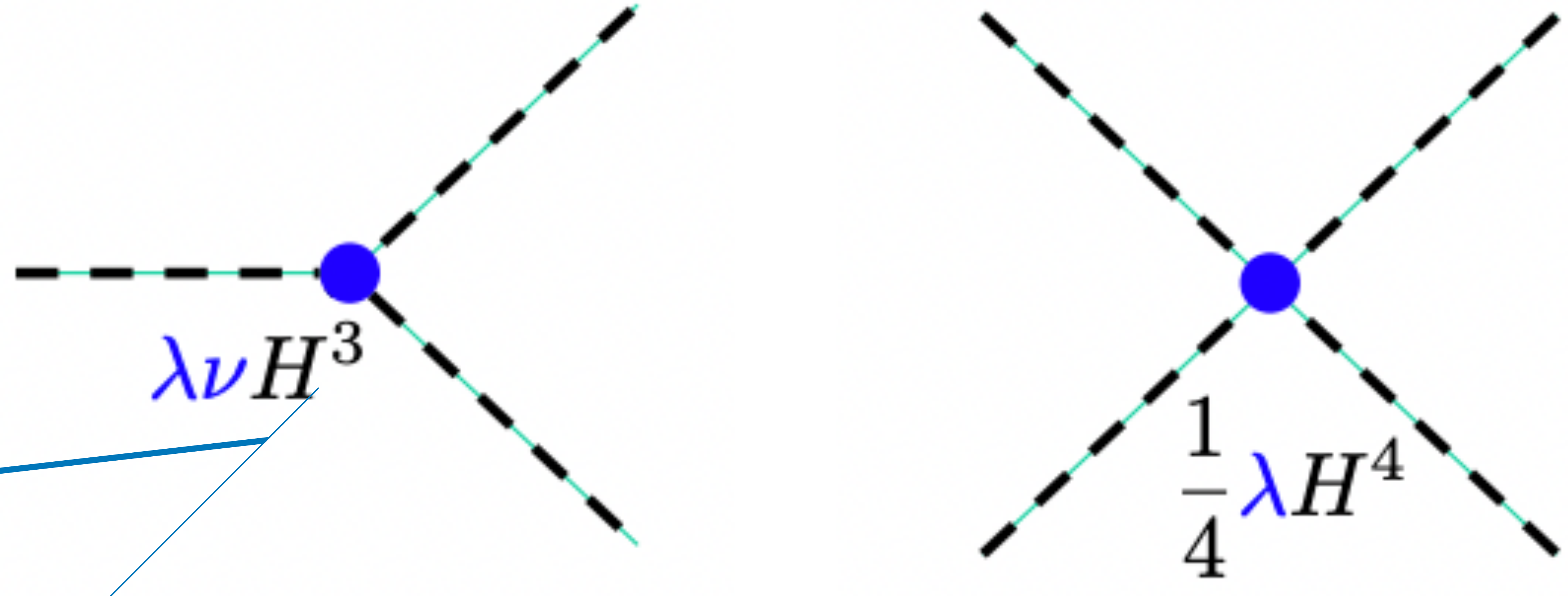
$$V(\Phi) = V_0 + \frac{1}{2} m_H^2 H^2 + \lambda \nu H^3 + \frac{1}{4} \lambda H^4$$

Scalar Self-Interactions



$$+ \lambda \nu H^3 + \frac{1}{4}\lambda H^4$$

Qualitatively new type of fundamental interactions:



In the Standard Model, the **λ** parameter is not free: determined by the measurement of $\mathbf{m_H}$ and **v**

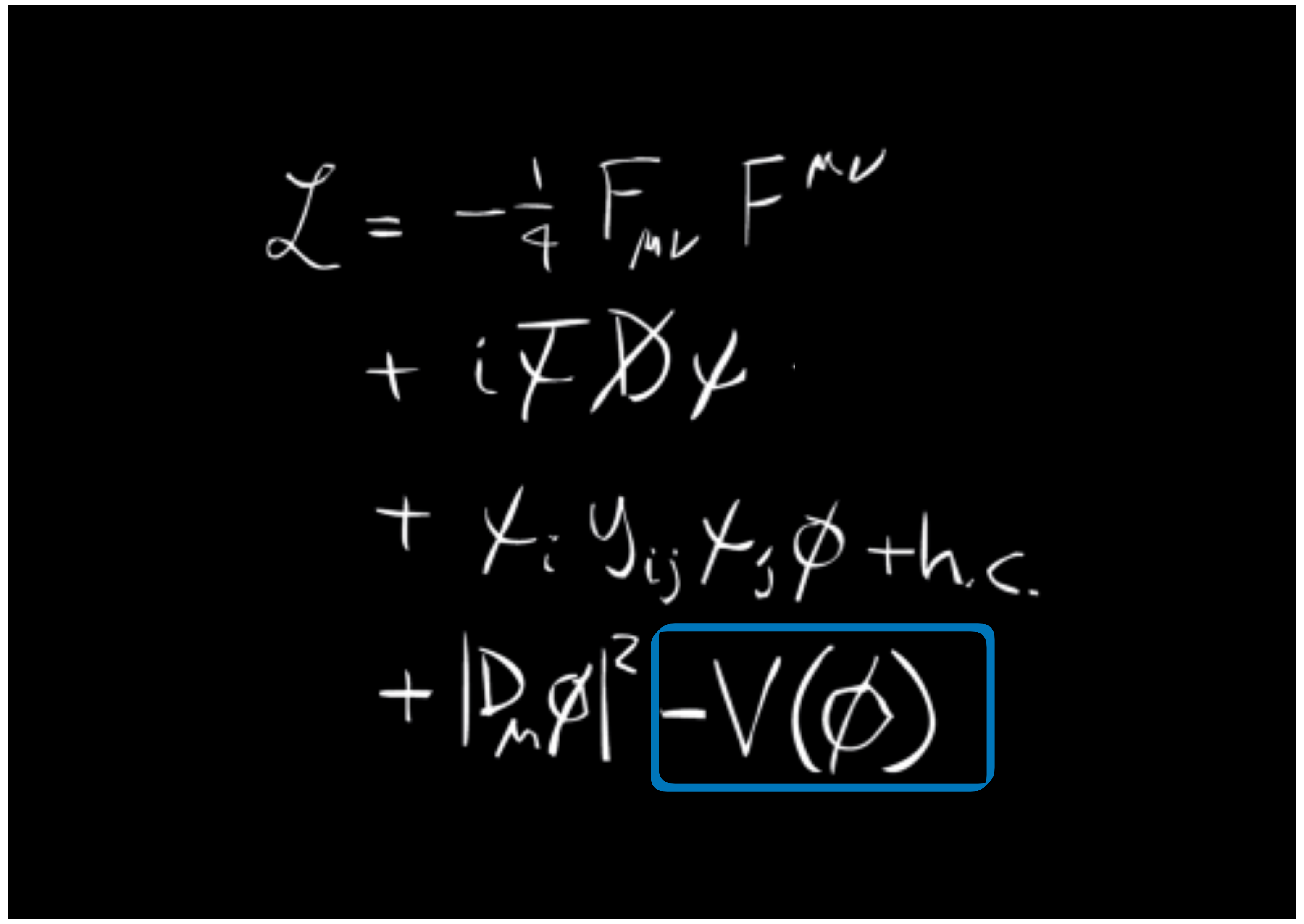
$$m_H = \sqrt{2}\mu = \sqrt{2\lambda}\nu$$

$\lambda_{HHH} \sim \lambda \mathbf{v}$

$\lambda_{HHHH} \sim \lambda$

$\sigma_{pp \to HH} \gg \sigma_{pp \to HHH}$

Scalar Self-Interactions



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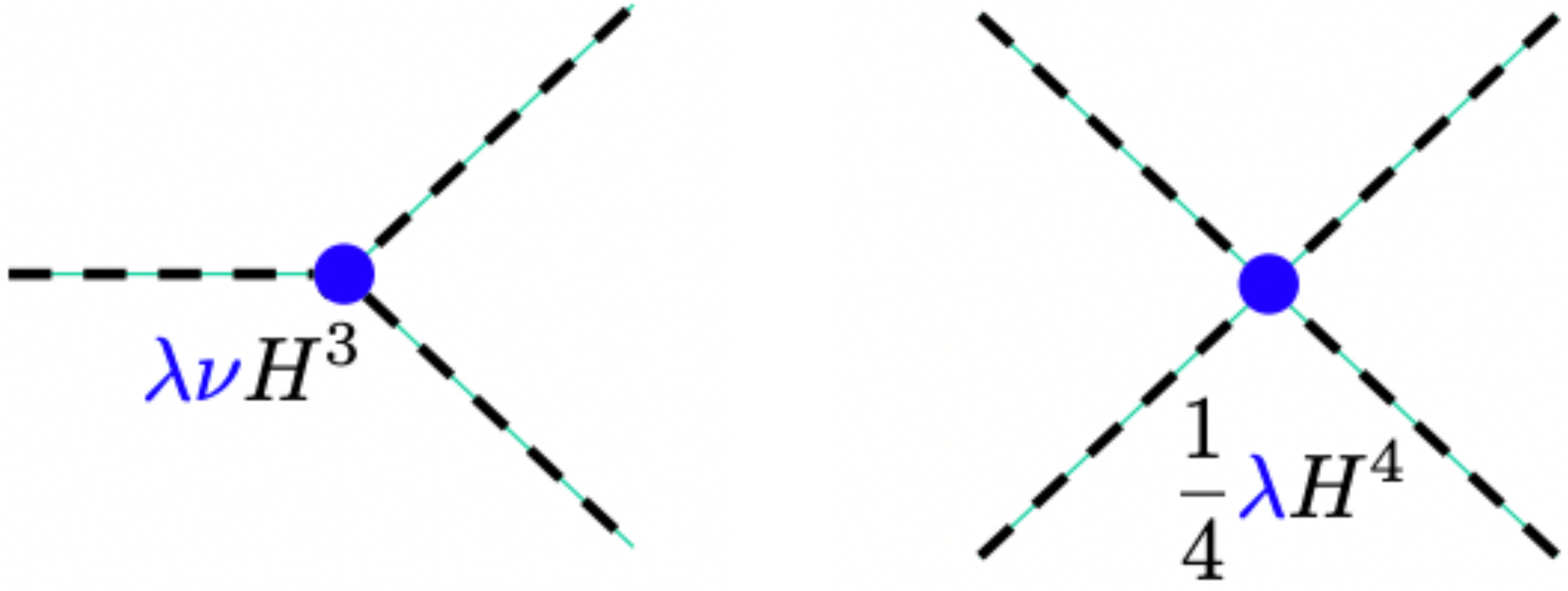
Qualitatively new type of fundamental interactions:

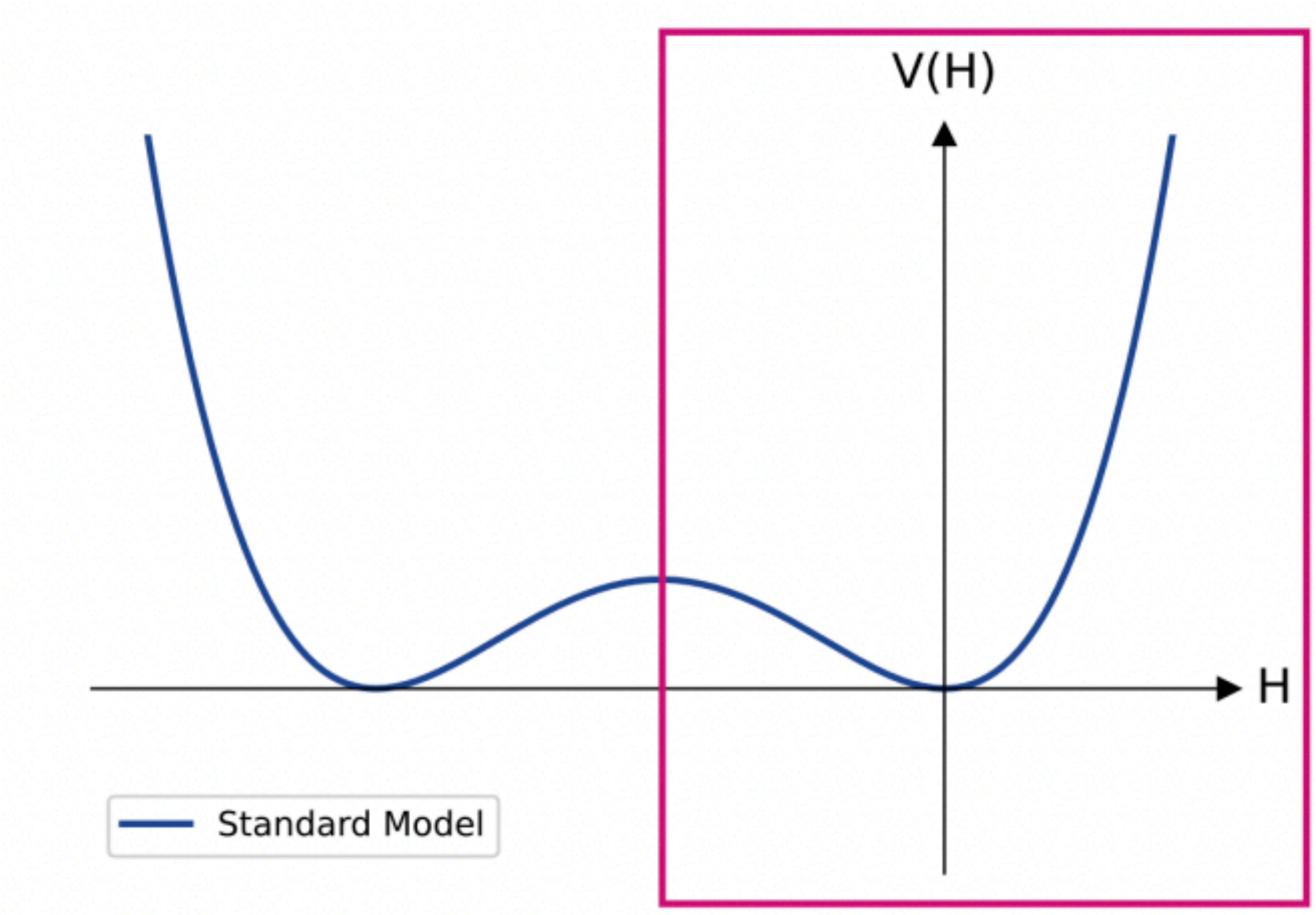


- Unique occurrence in nature of **scalar self-interactions** among **fundamental particles** (by itself a compelling argument)
- Key piece to determine the **shape of the Higgs potential** in the Standard Model

So far out of reach of **experimental measurements**

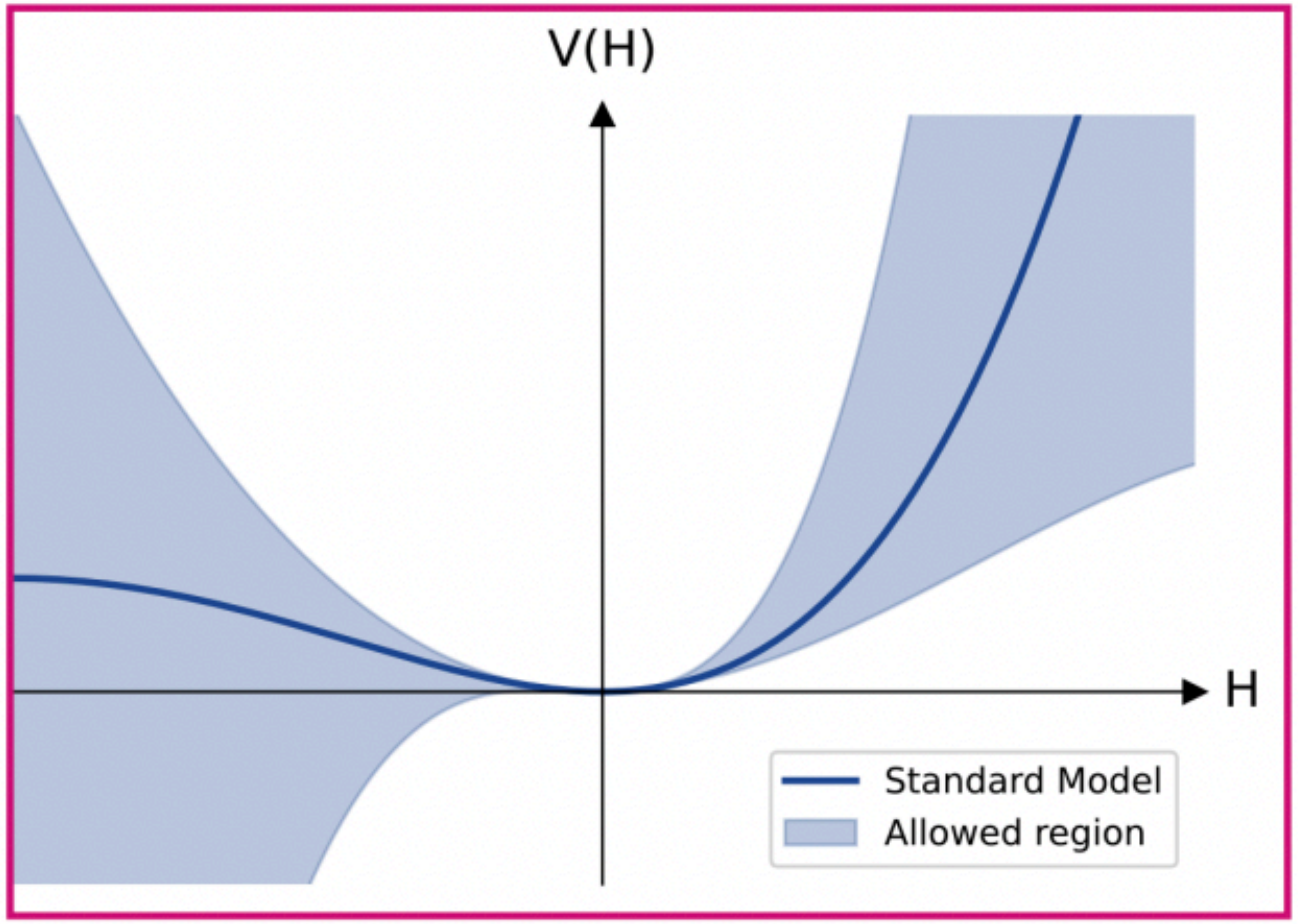
The Higgs Potential

The Higgs Potential in QFT textbooks
(what the SM predicts)



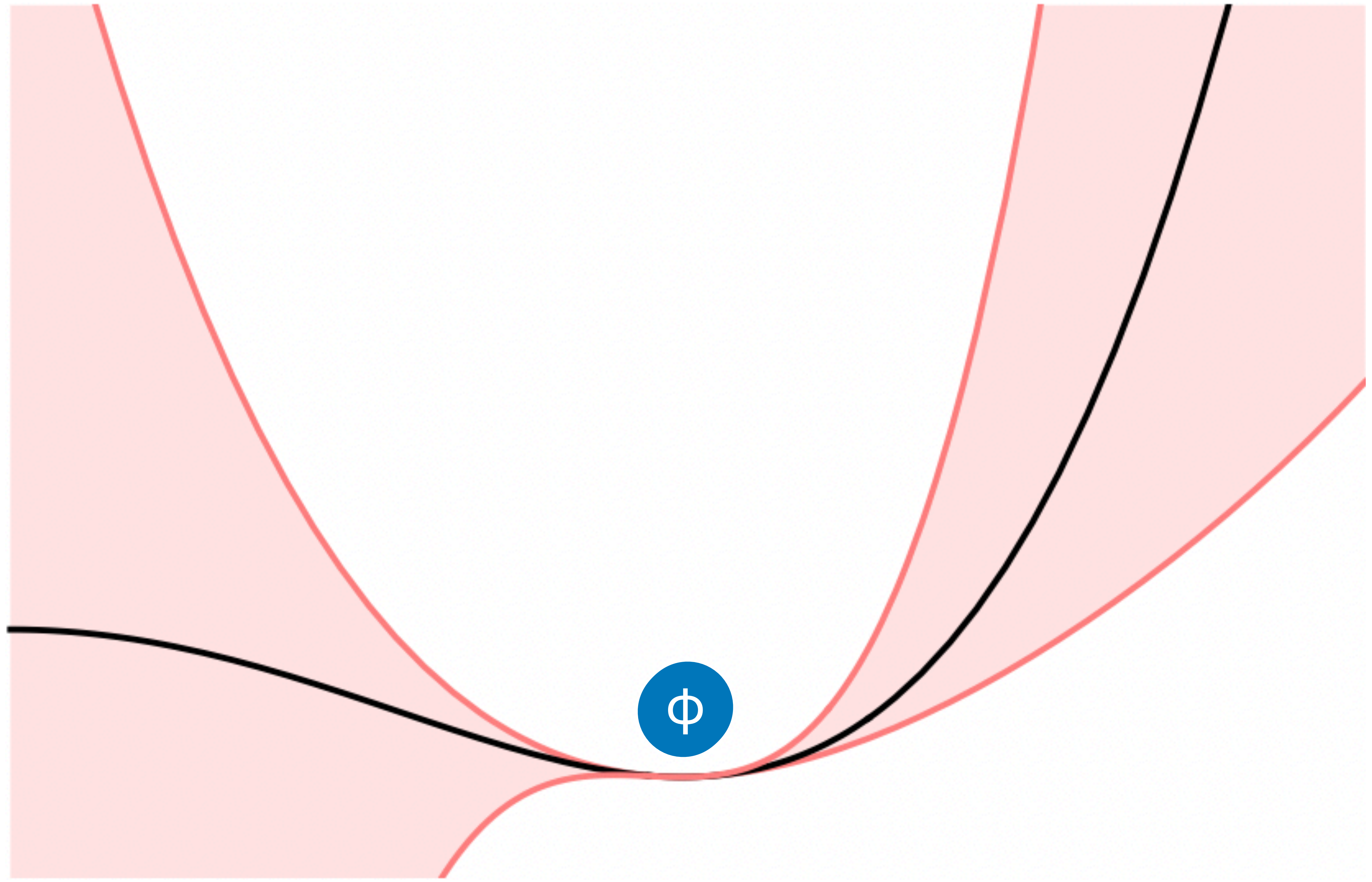
$$V(\Phi) = V_0 + \frac{1}{2}m_H^2 H^2 + \lambda \nu H^3 + \frac{1}{4}\lambda H^4$$

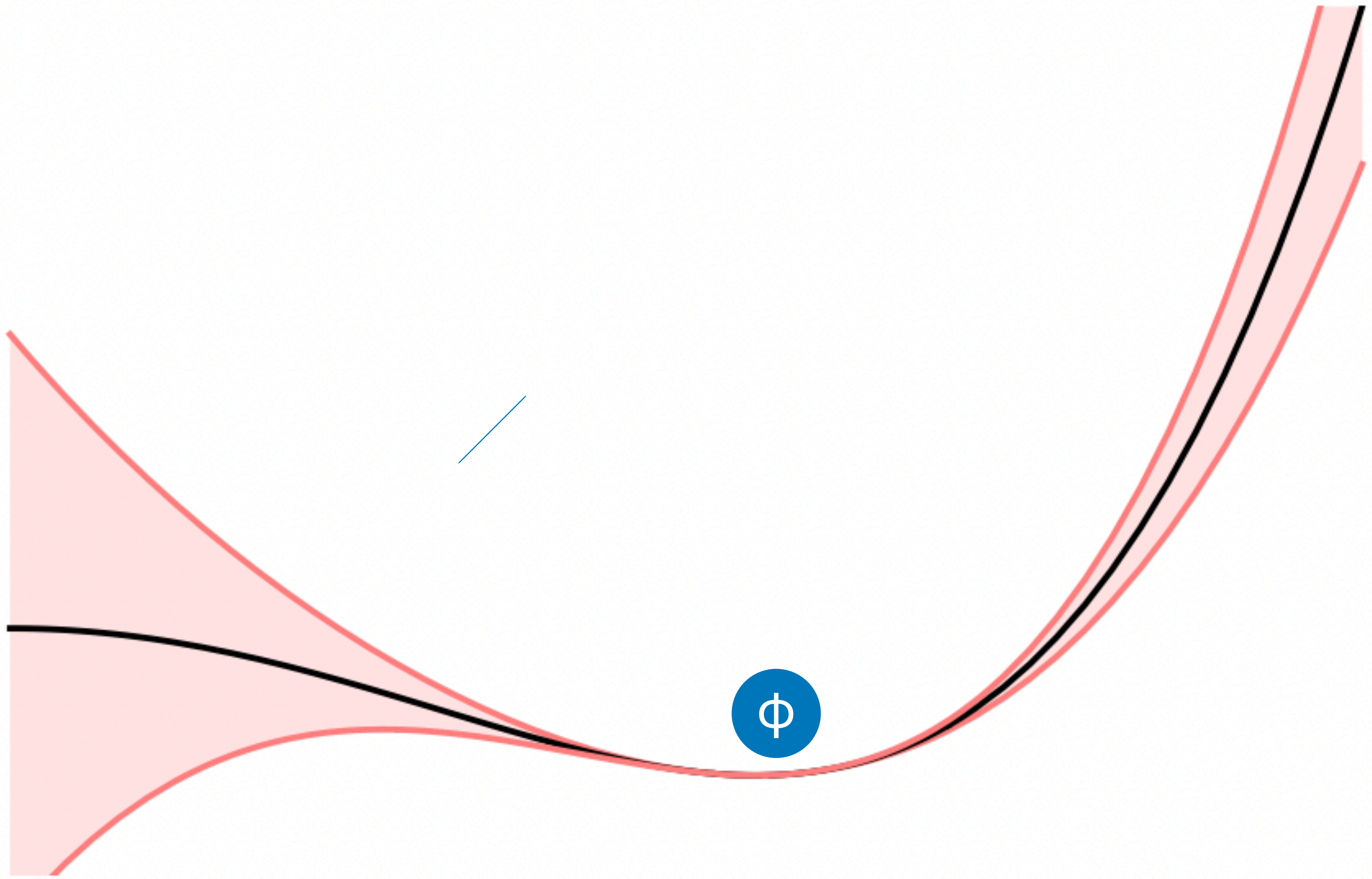
Current experimental knowledge of the Higgs potential



Using current ATLAS limits @ 95% CL

The Higgs Potential

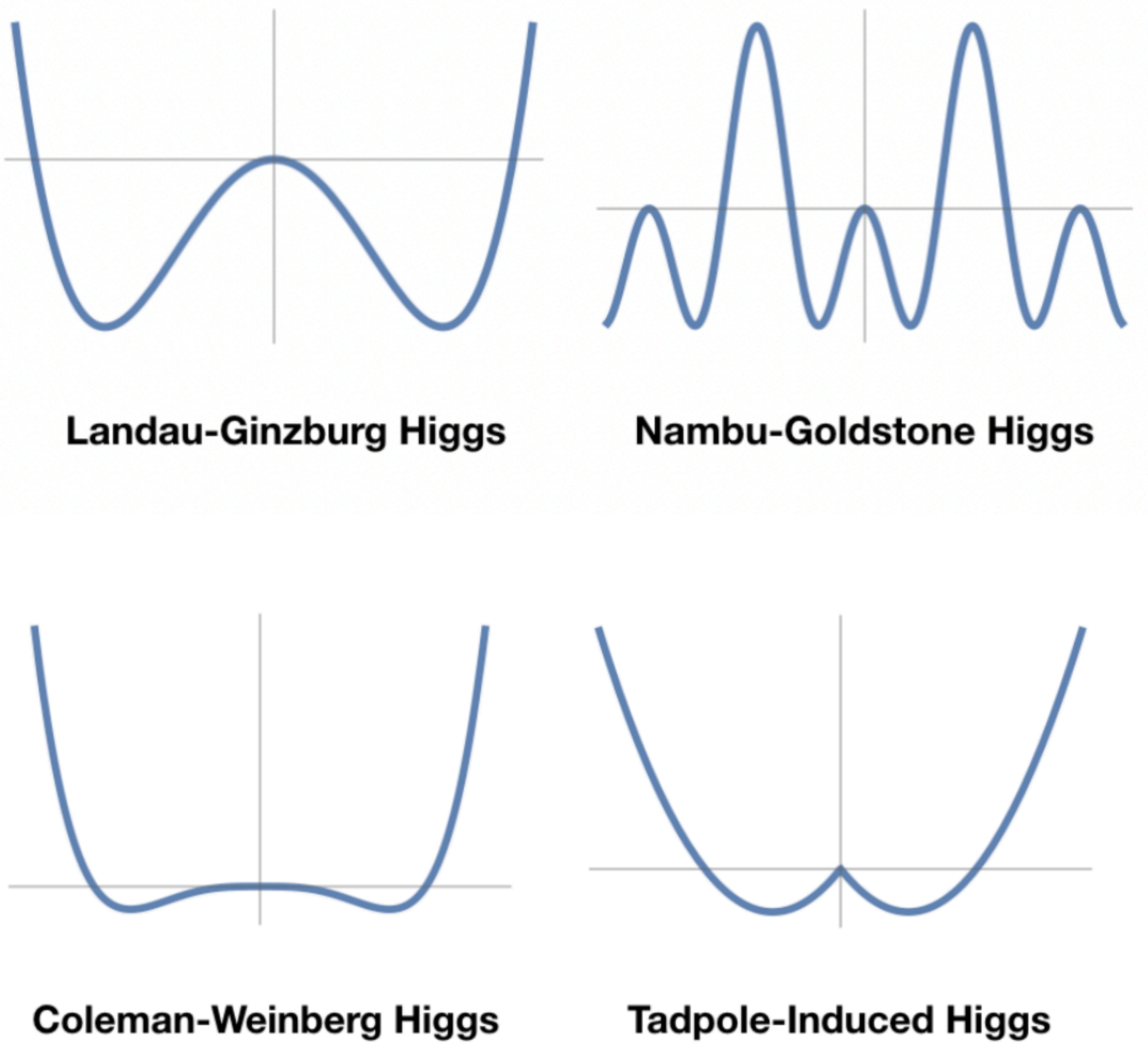


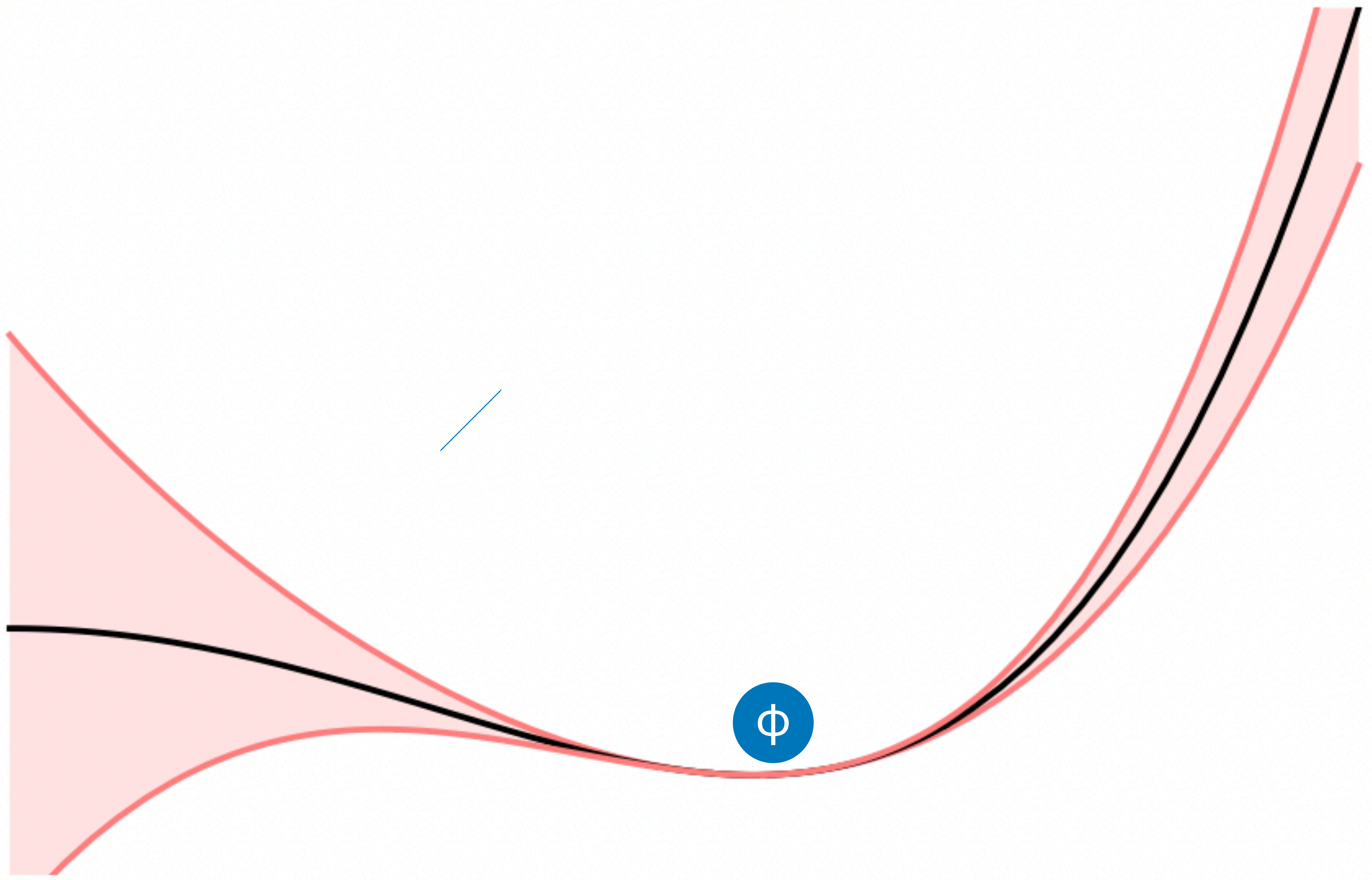


The more precisely we measure Higgs self-interactions

The Higgs Potential

The Higgs Potential in QFT textbooks of the future
(might still be the Standard Model realisation)



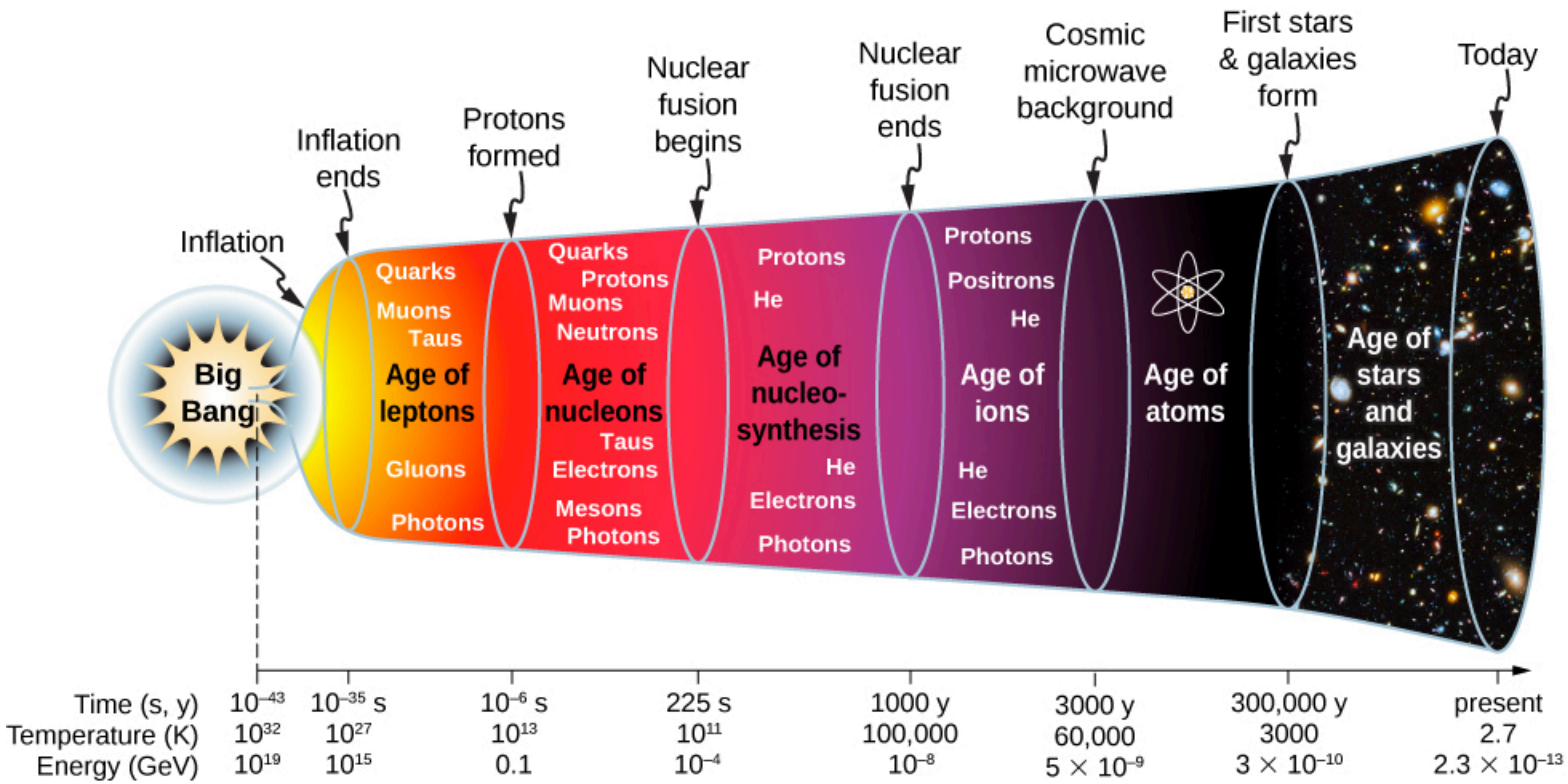


1907.02078

Why do we care? (on a fundamental level)

The Higgs provides a **simple and effective description of symmetry breaking**, but we don't have a deeper understanding of the **relevant dynamics** - which can furthermore inform us on some of the fundamental open questions of SM physics

One example: ***Electroweak baryogenesis and phase diagram of the EW symmetry***



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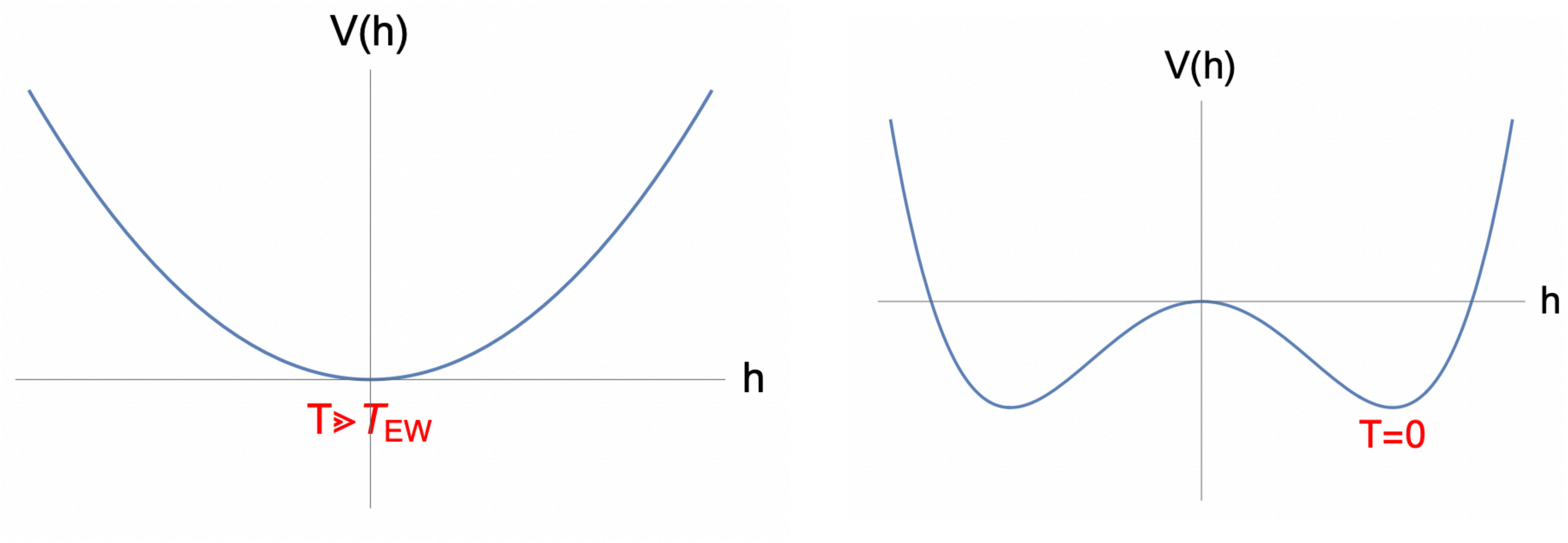


Evolution along the history of the universe (from higher T to current stability)

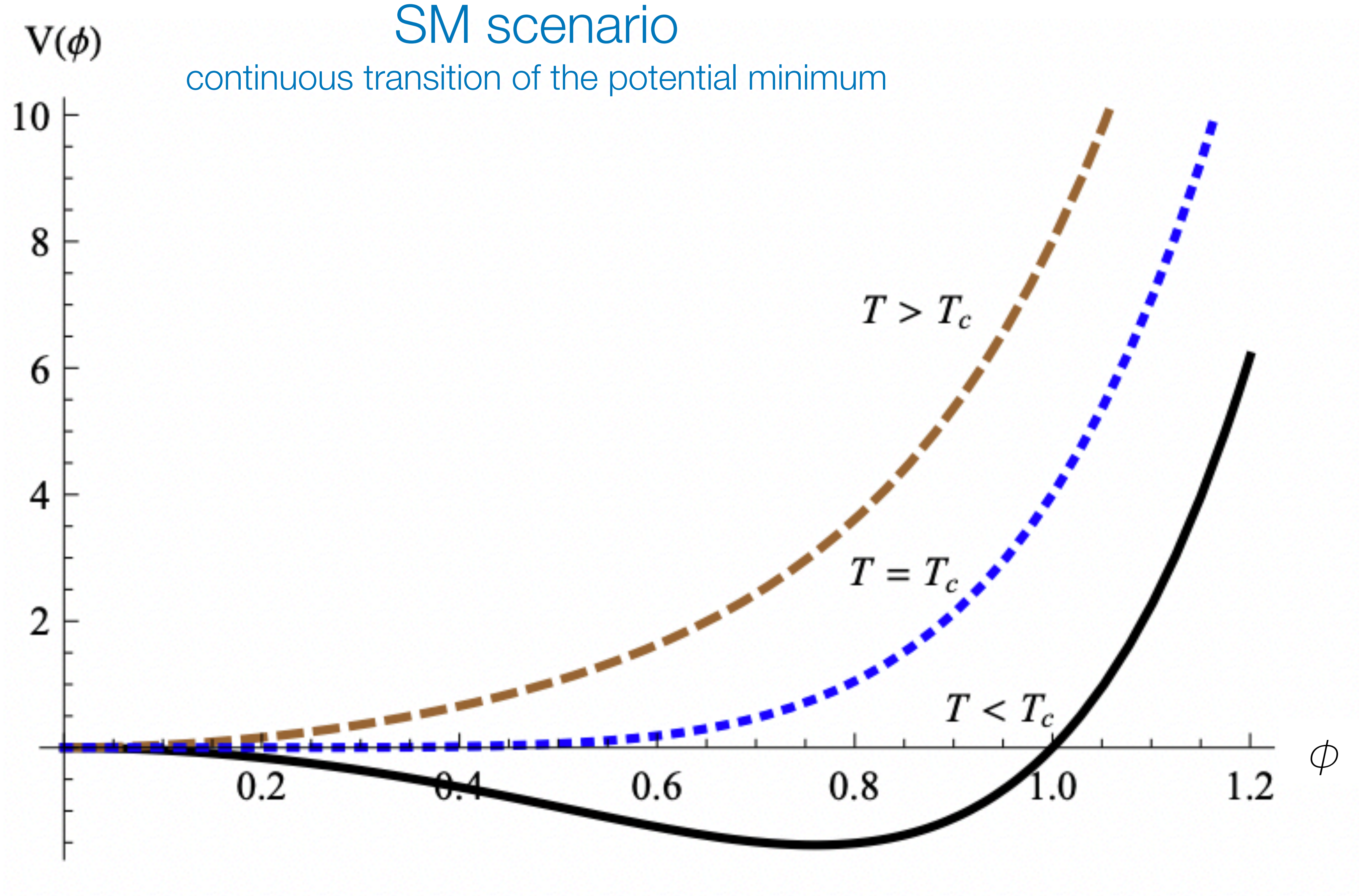
The phase transition between these two conditions strictly relates to baryogenesis

Why do we care? (on a fundamental level)

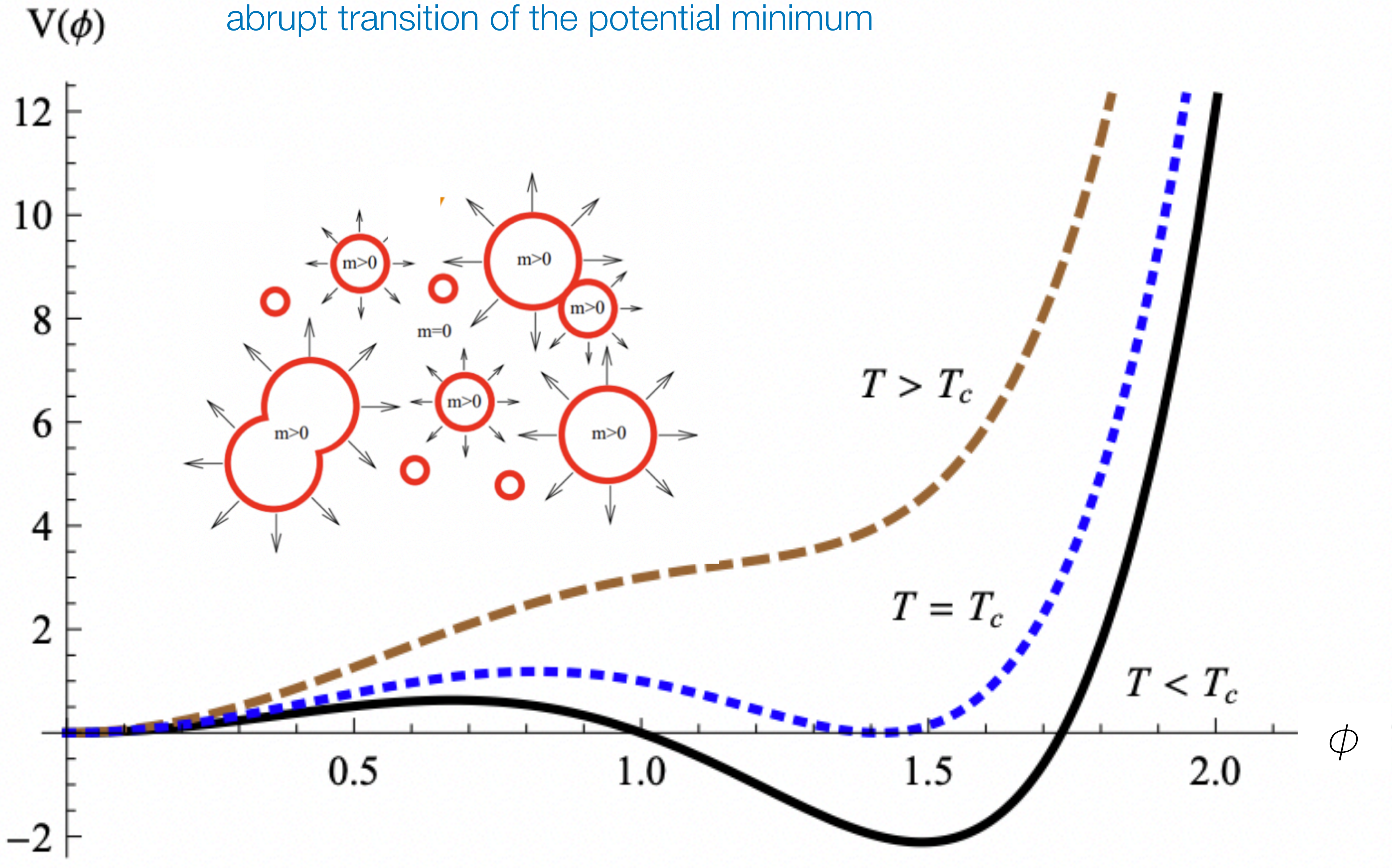
The Higgs provides a **simple and effective description of symmetry breaking**, but we don't have a deeper understanding of the **relevant dynamics** - which can furthermore inform us on some of the fundamental open questions of SM physics

One example: ***Electroweak baryogenesis and phase diagram of the EW symmetry***

2nd order phase transition
SM scenario
continuous transition of the potential minimum



1st order phase transition
BSM scenario
abrupt transition of the potential minimum

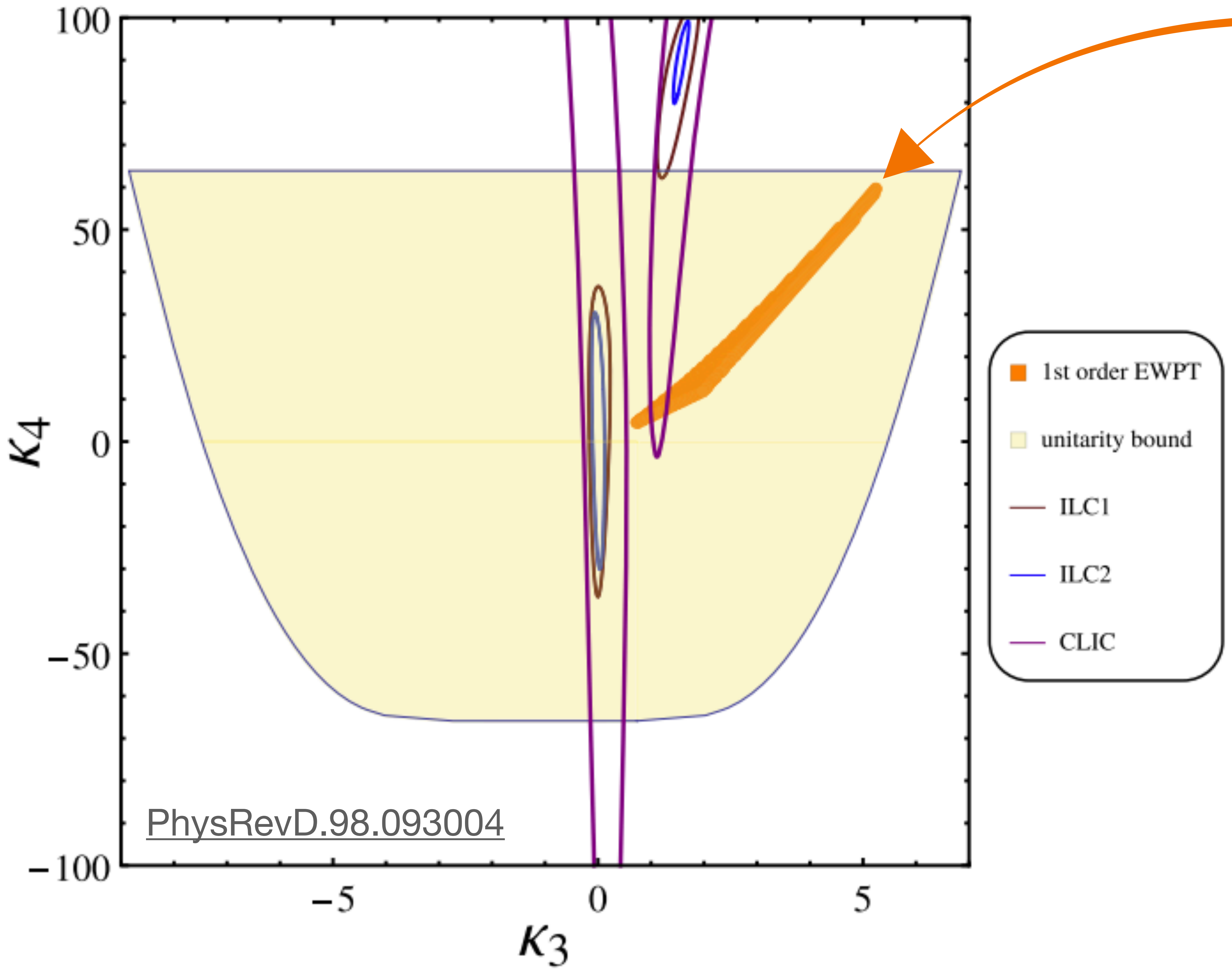


In presence of **FOPT expanding bubbles** (EWSB inside the bubble): B violation from sphalerons at high T, CP violation from chiral interactions at the bubble walls, large departure from thermal equilibrium in FOTP → **conditions for baryogenesis** 1710.04061

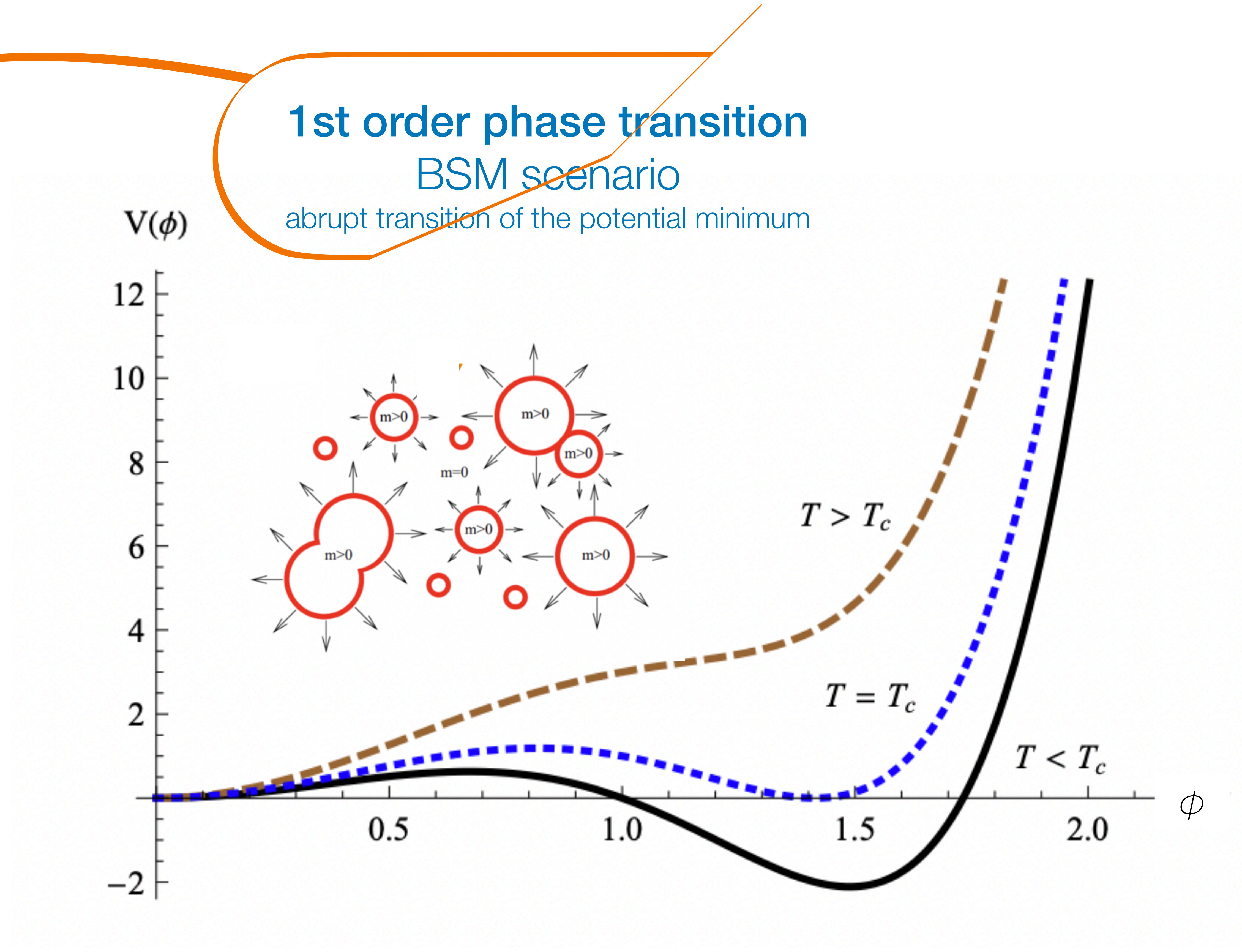
Why do we care? (on a fundamental level)

The Higgs provides a **simple and effective description of symmetry breaking**, but we don't have a deeper understanding of the **relevant dynamics** - which can furthermore inform us on some of the fundamental open questions of SM physics

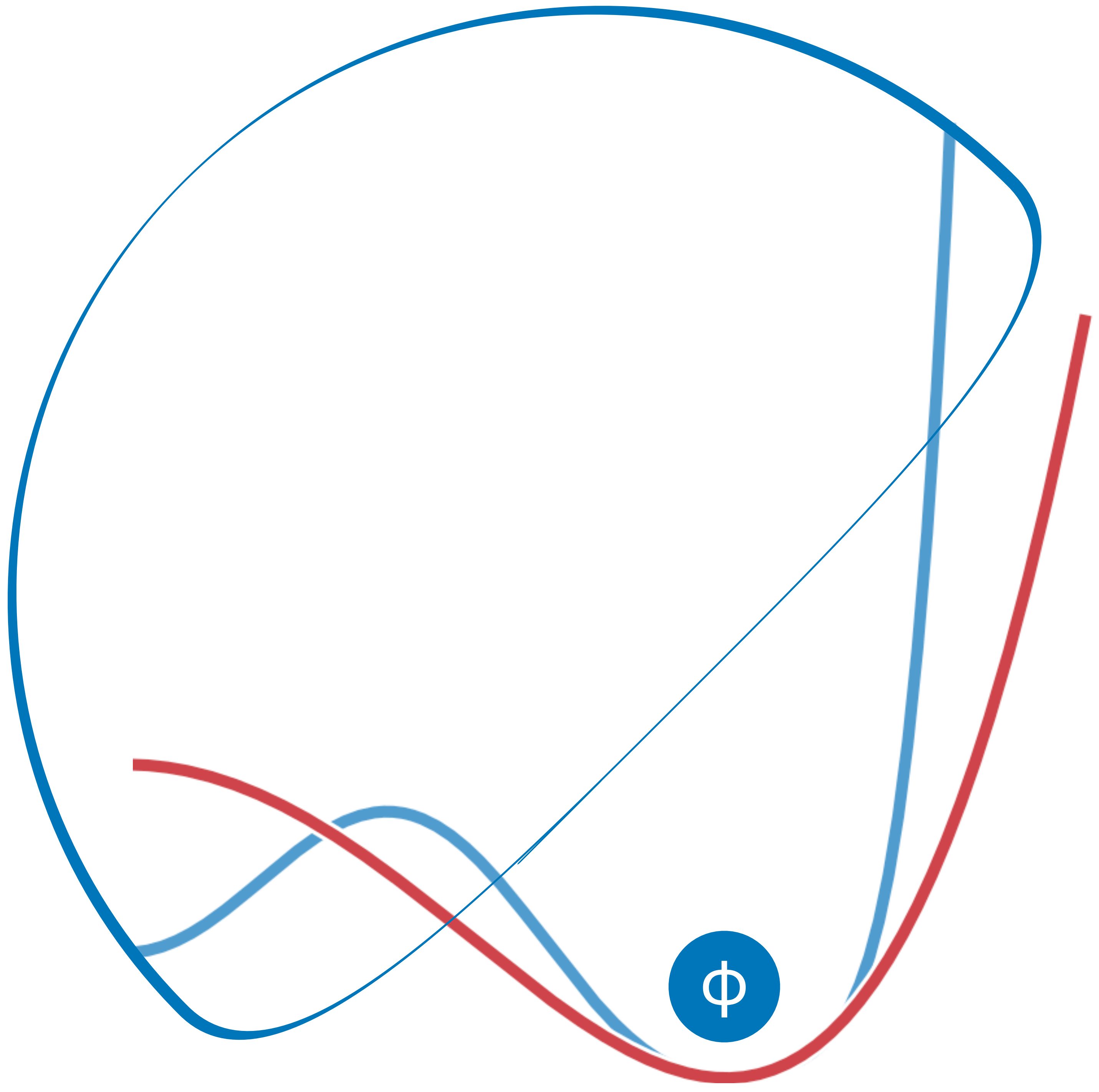
One example: ***Electroweak baryogenesis and phase diagram of the EW symmetry***



(k_3 and k_4 ratios between the measured triple and quartic H couplings and their SM predictions -1)

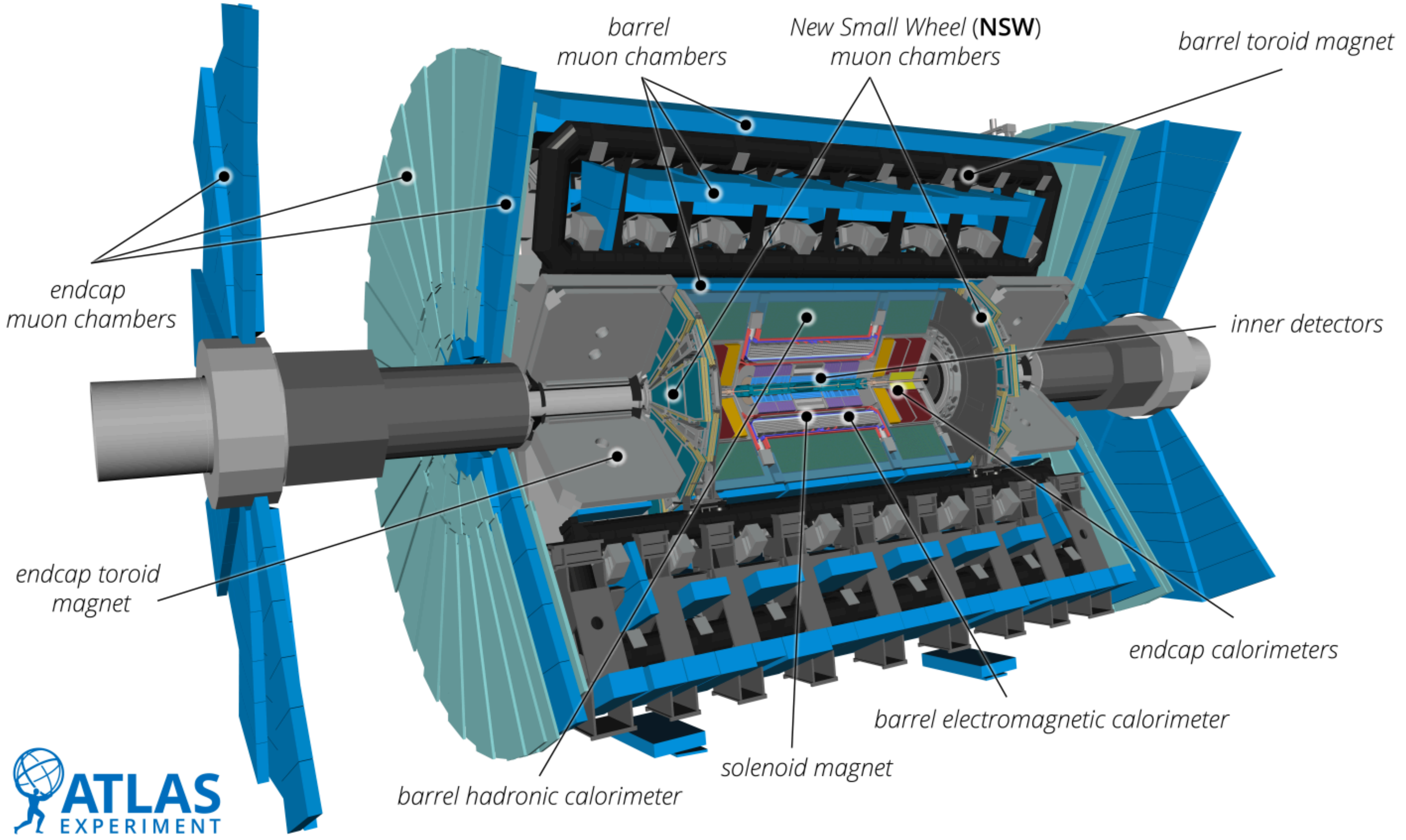


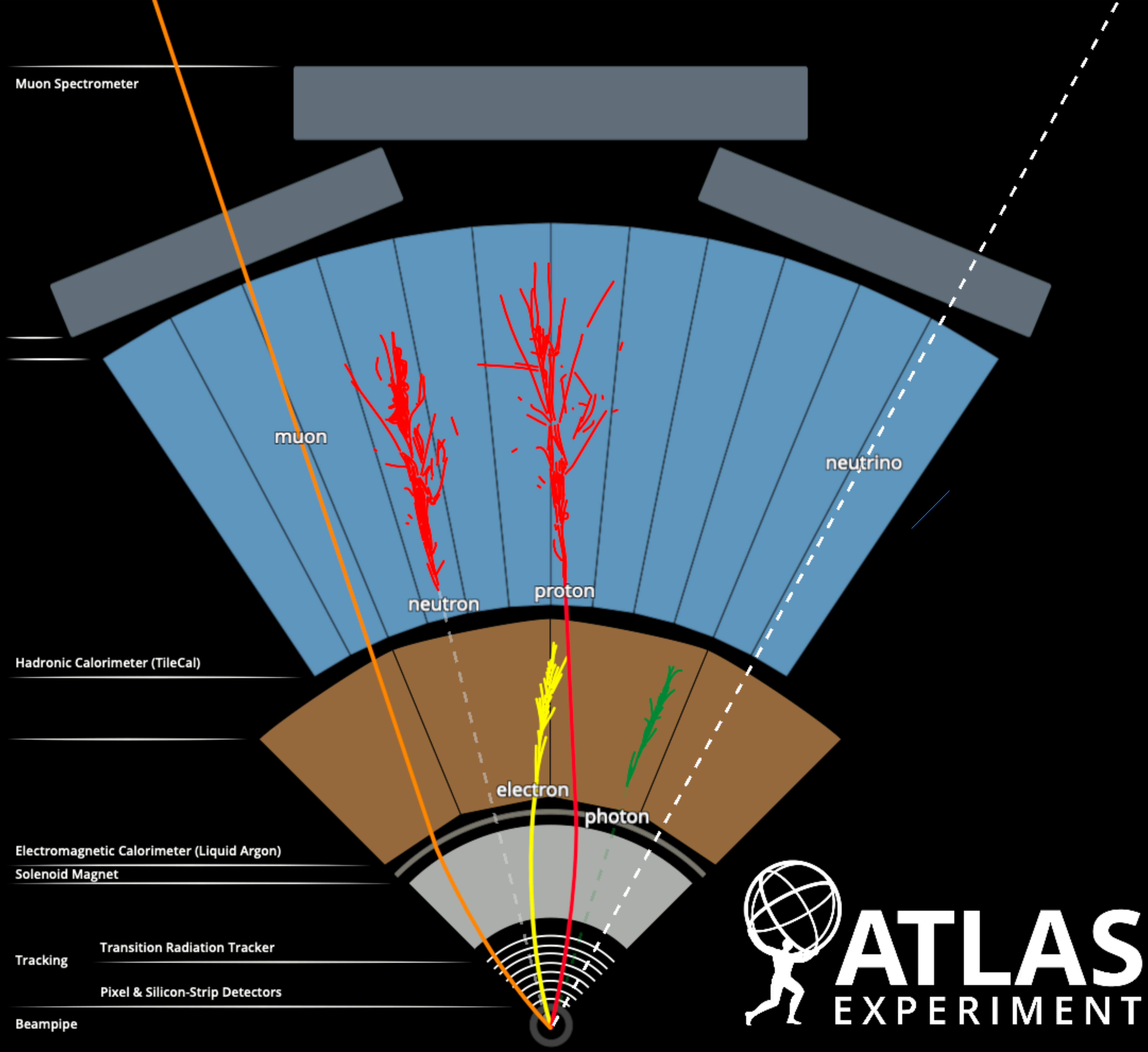
How do we explore all this (experimentally)?



LHC and ATLAS

From proton-proton collisions to Higgs self-interactions

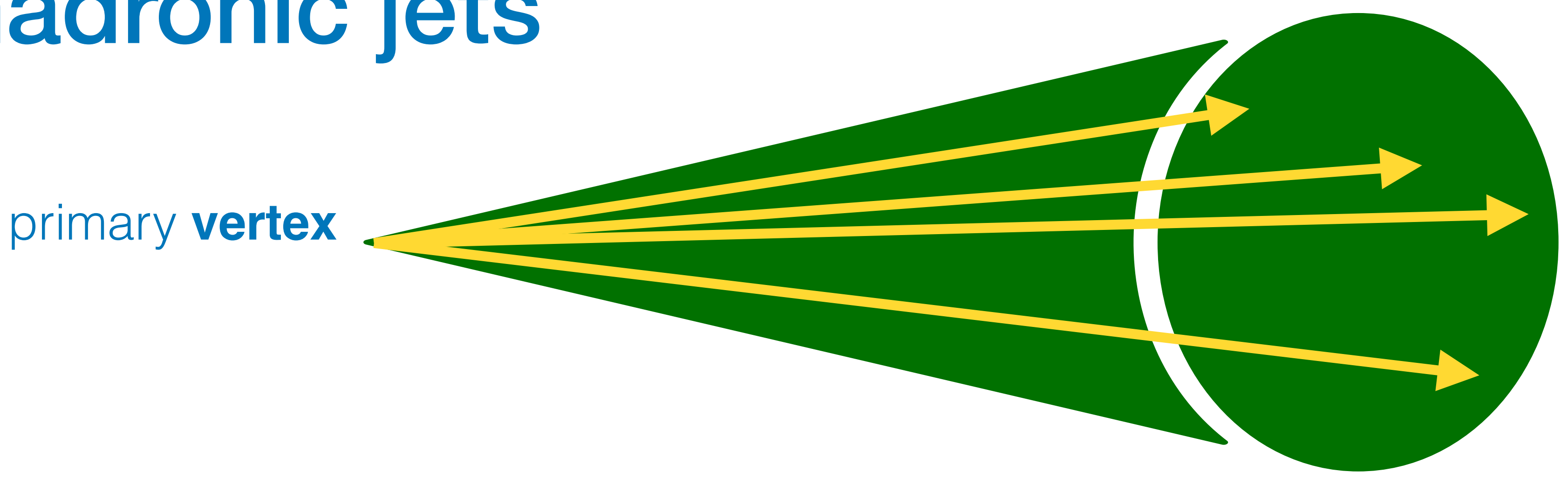




Muon Spectrometer
Hadronic Calorimeter (TileCal)
Electromagnetic Calorimeter (Liquid Argon)
Solenoid Magnet
Tracking
Transition Radiation Tracker
Pixel & Silicon-Strip Detectors
Beampipe
muon
neutron
proton
neutrino
electron
photon
ATLAS
EXPERIMENT

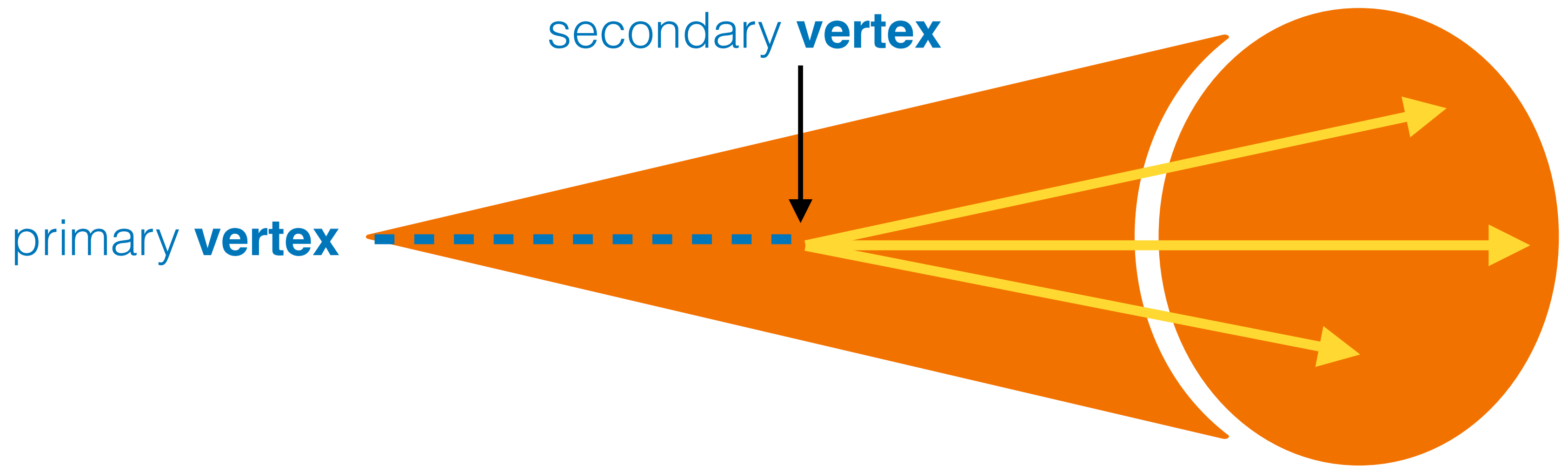
ATLAS ‘objects’ (important in this talk)

- **hadronic jets**



QCD particles radiates gluons and quarks, hadronize, and can be finally reconstructed as or sprays of QCD particles in the detectors (‘jets’)

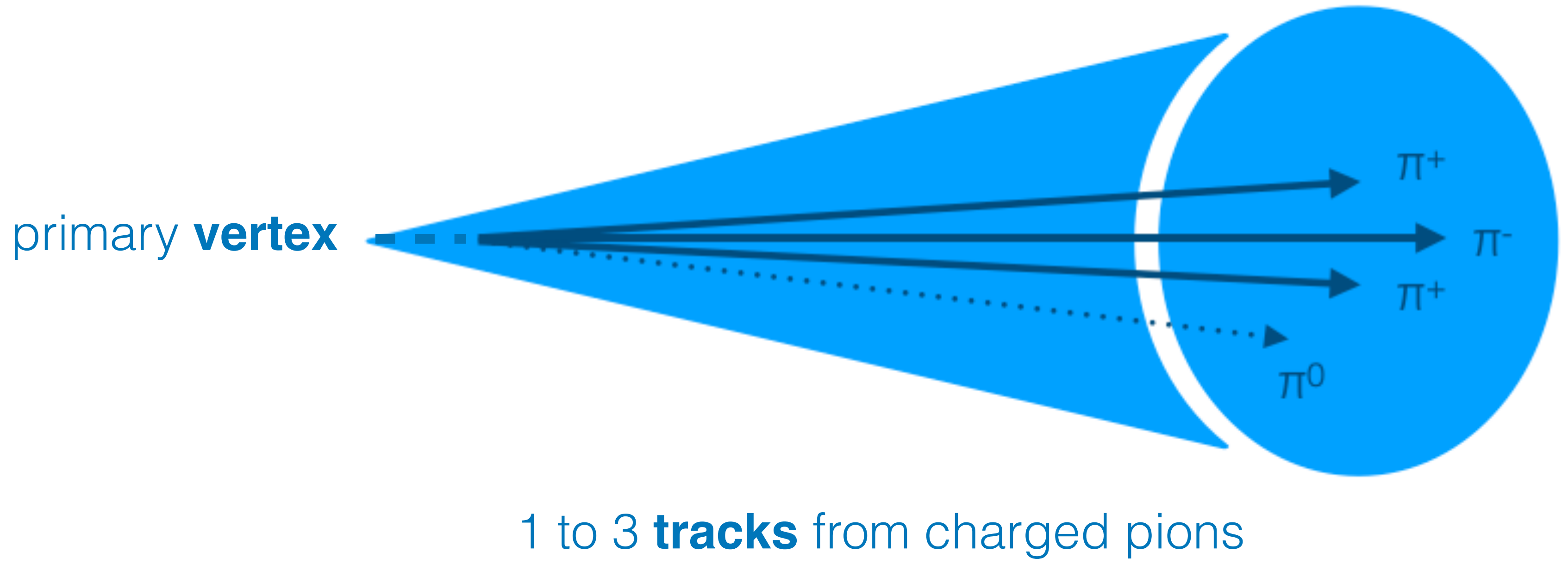
- **hadronic jets from bottom-quarks**



B-hadrons have a longer lifetime (~1.5ps)
and can travel O(mm) in the detector before decaying

σ [m(bb)] ~ 15GeV

- **τ leptons (hadronic decays)**



Tau leptons can decay leptonically
or hadronically (to charged and neutral hadrons)
Shorter lifetime than B-hadrons (~0.29ps)

σ [m($\tau\tau$)] ~ 15GeV

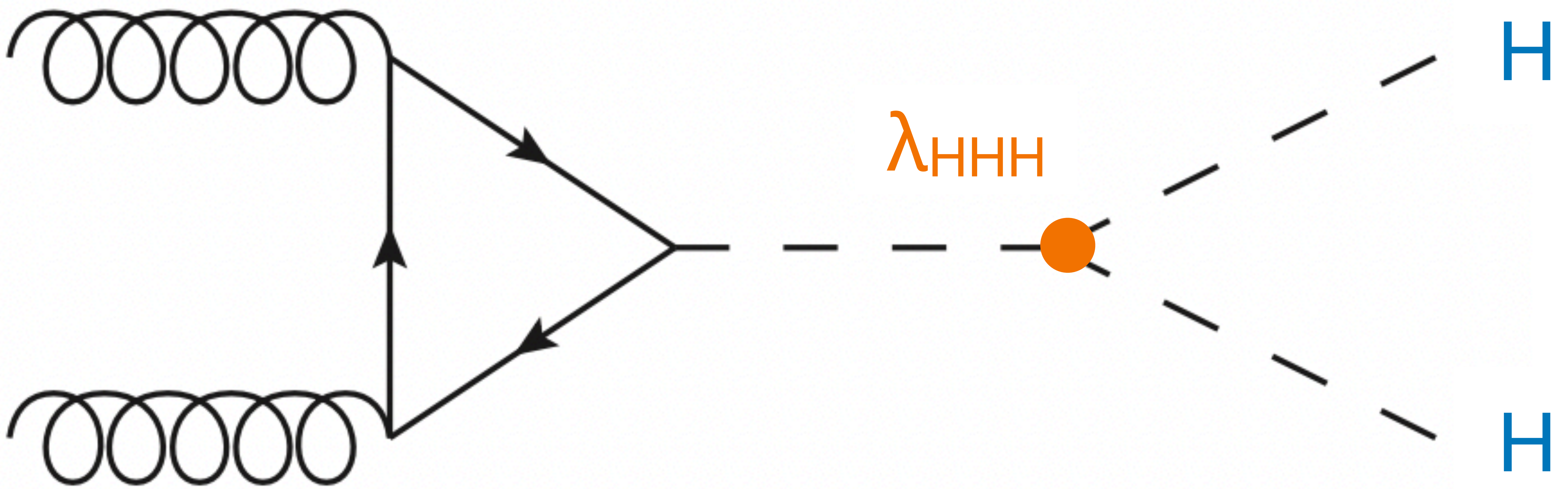
*Most jet-objects are reconstructed as a combination of information from the **tracker** and energy deposits from the EM and hadronic **calorimeters***

So what do we actually want to measure?

$$V(H) = \frac{1}{2} m_{\mathrm{H}}^2 H^2 + \lambda_{\mathrm{HHH}} v H^3 + \frac{1}{4} \lambda_{\mathrm{HHHH}} H^4$$

At the LHC… **Double** Higgs production

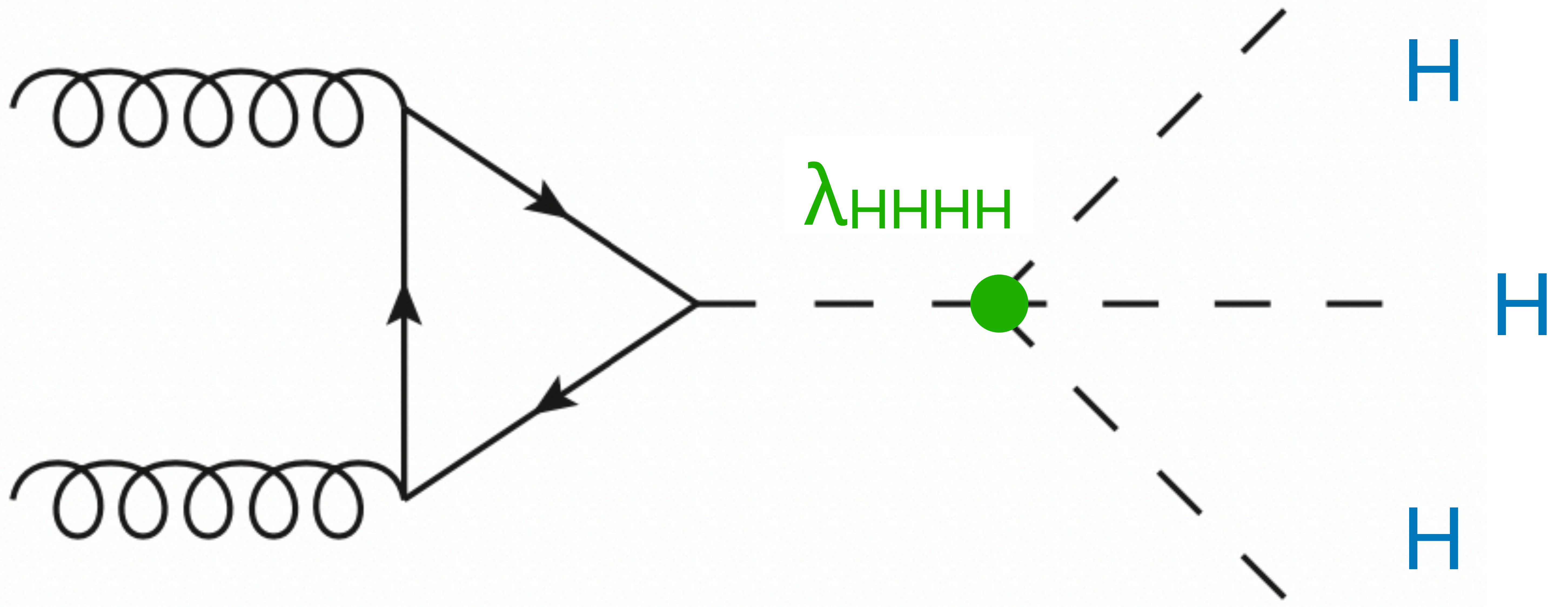
- gluon-fusion production of Higgs pairs
- very low cross-section: ~1000 smaller than single-Higgs
- ~**5000 HH events** produced in the whole **LHC Run-2**



$$V(H) = \frac{1}{2}m_{\mathrm{H}}^2 H^2 + \lambda_{\mathrm{HHH}} v H^3 + \frac{1}{4}\lambda_{\mathrm{HHHH}} H^4$$

At the LHC… **Triple** Higgs production

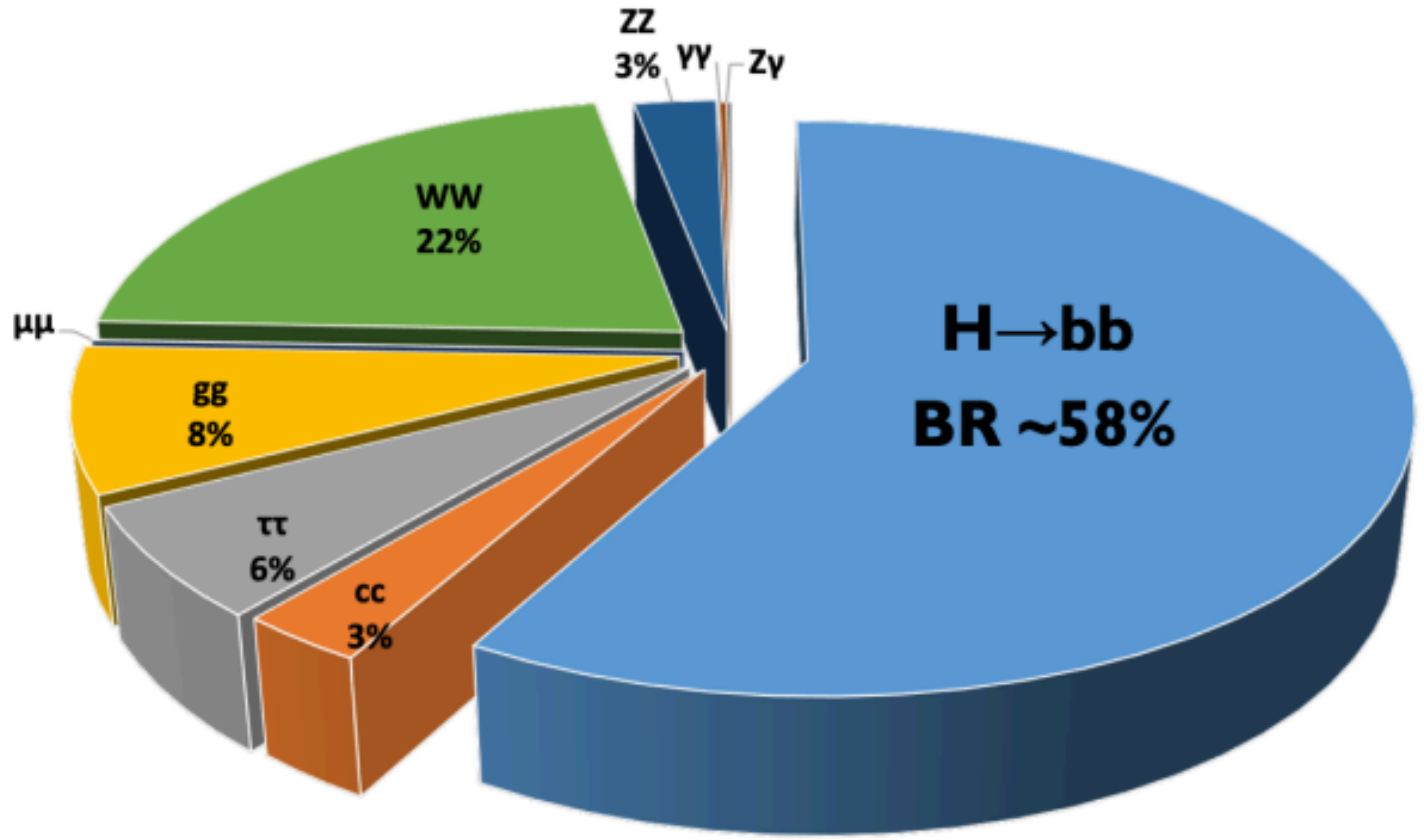
- gluon-fusion production of Higgs triplets
- minuscule cross-section: ~1000 smaller than double-Higgs!
- ~**5 HHH events** produced in the whole LHC Run-2

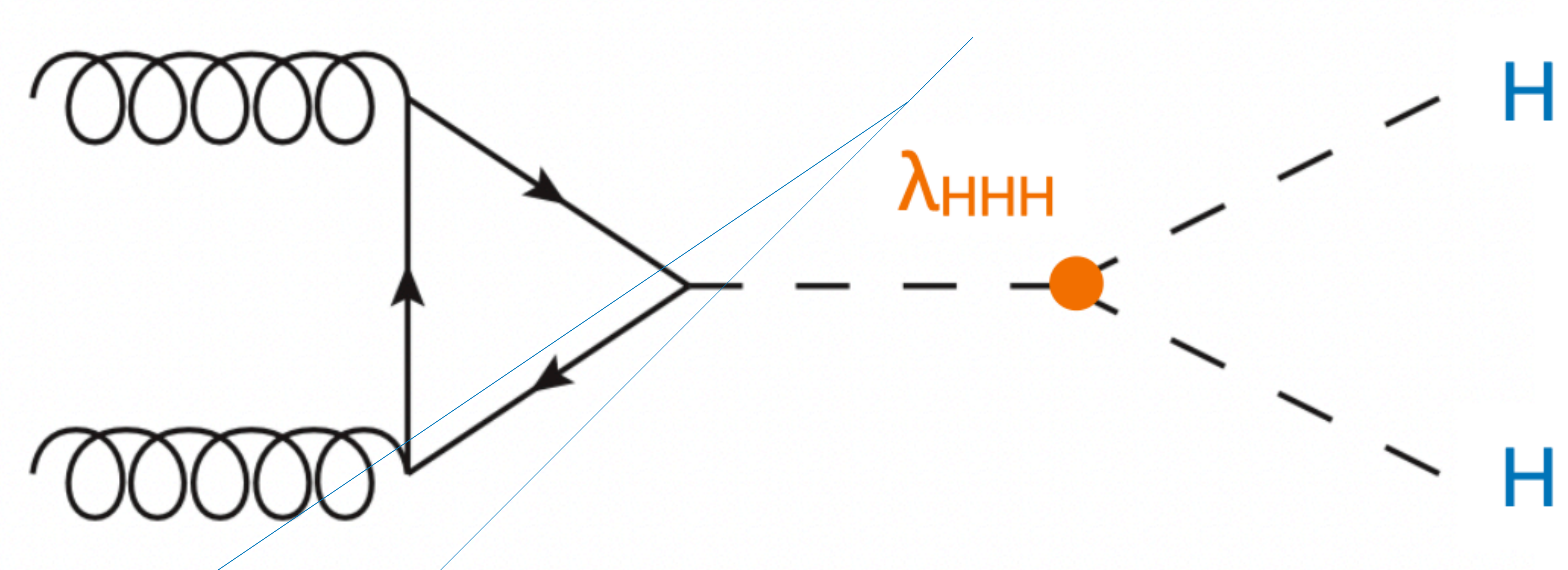


Higgs decays

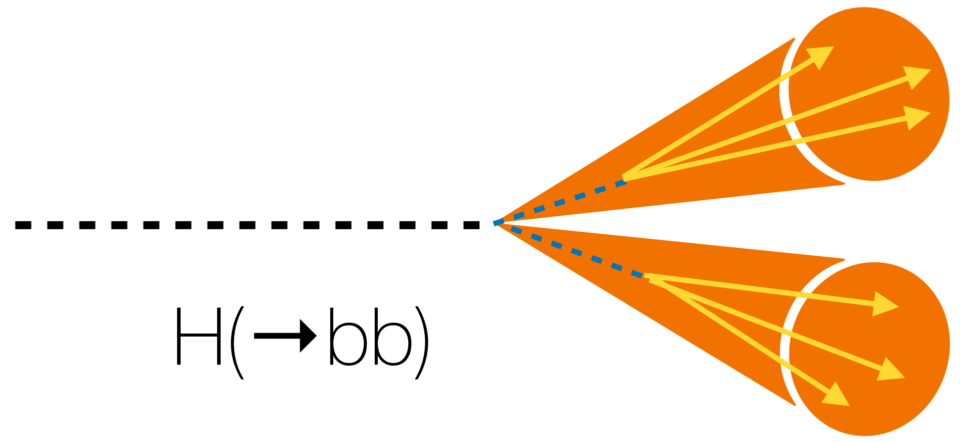
Higgs bosons decay immediately in the ATLAS detector, so the question is: what are we looking for?

(Higgs coupling proportional to the particles mass)

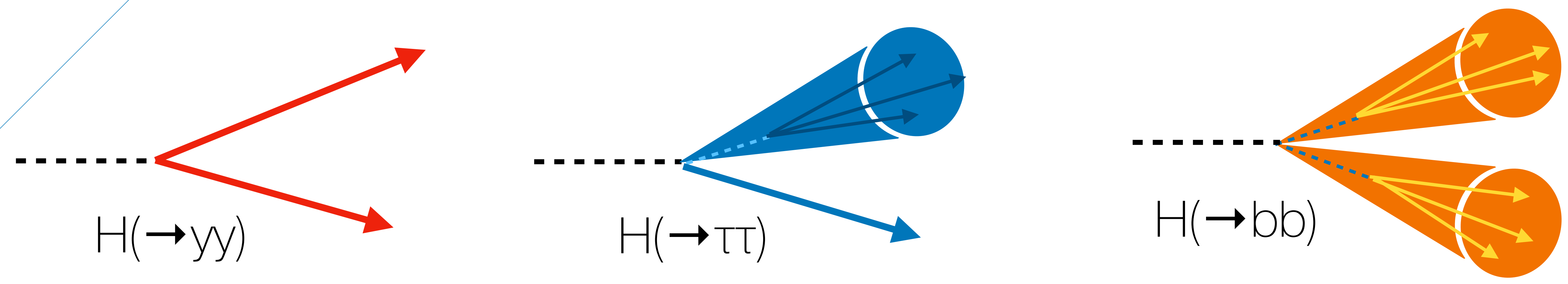




1st Higgs decaying to **bottom-quarks**:
largest branching ratio, coarse energy resolution



2nd Higgs determines the nature of the experimental search:
cleaner signature vs higher statistics …



Double-Higgs (HH) final states

Higgs bosons decay immediately in the ATLAS detector, so the question is: what are we looking for?
(Higgs coupling proportional to the particles mass)

BRs	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Three combinations are favoured

- **H(→bb)H(→bb)**
  largest branching ratio (34%)
  huge QCD multi-jet background
- **H(→bb)H(→ττ)**
  moderate branching ratio (7.3%)
  multi-jet rejected thanks to tau leptons
- **H(→bb)H(→γγ)**
  tiny branching ratio (<1%)
  clean signature and great resolution

A recent highlight: HH(bbττ) search

Rather than a lengthy review of HH results in ATLAS and CMS,
I will go deeper into the details of a single HH search in ATLAS

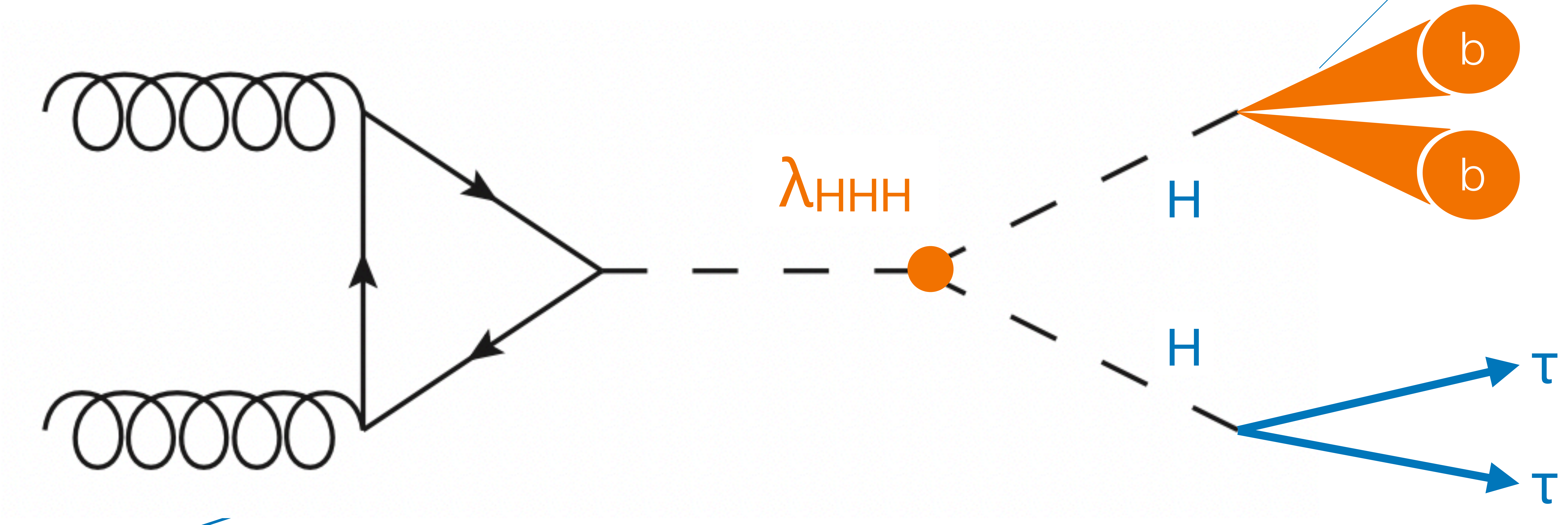
BRs	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

- the most sensitive channel to HH production so far
- a great example of the experimental challenges and techniques
- very recent results presented at Higgs 2023 (submission to PRD ongoing)
- ATLAS-CONF-2023-071
- (I worked and am working on it)

HH(bbττ) search with LHC Run-2 dataset

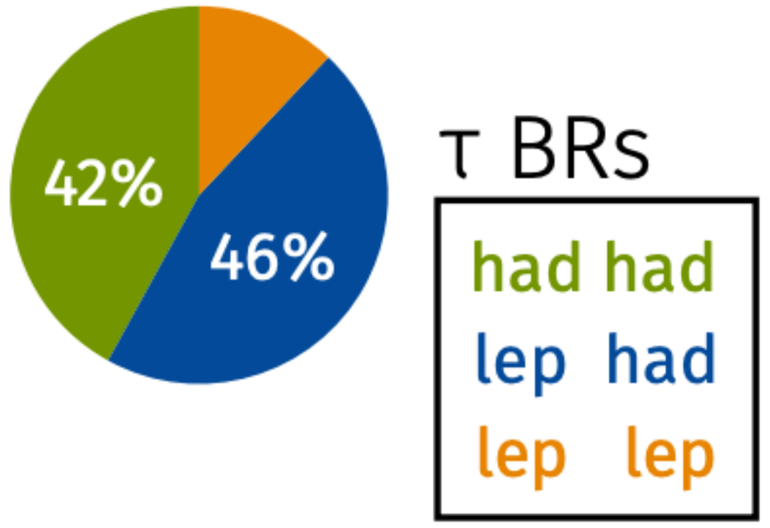
Results published by the ATLAS Collaboration in November 2023 on the full LHC Run-2 dataset

ATLAS-CONF-2023-071



Two analysis channels depending on τ decays:

- fully-hadronic ($\tau_{had}\tau_{had}$)
- semi-leptonic ($\tau_{lep}\tau_{had}$)

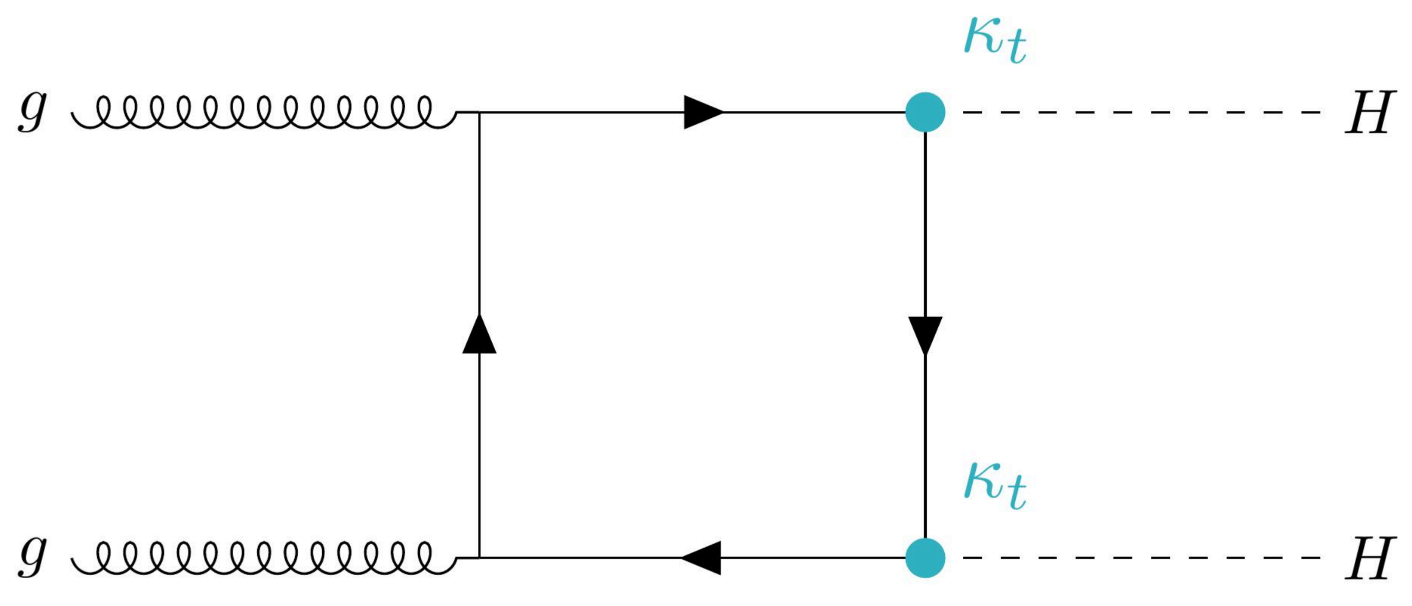


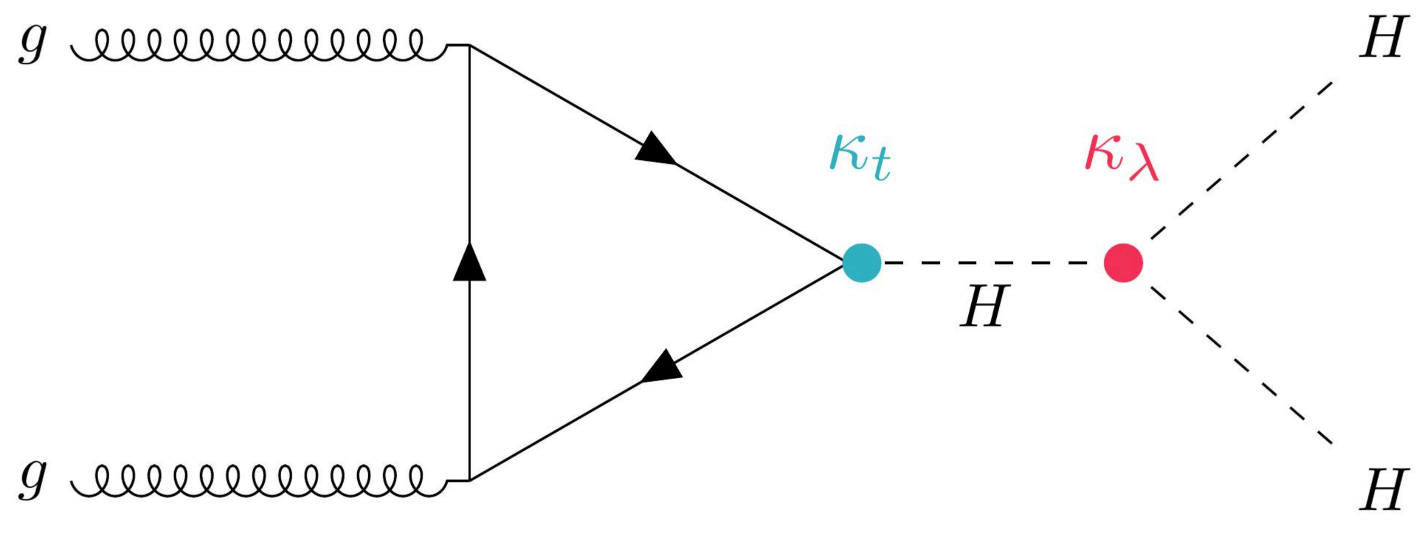
Double-Higgs (HH) production mechanisms

More into detail, we search from double-Higgs production via multiple production processes (and interacting diagrams)

- **gluon-fusion** (ggF) production of Higgs pairs

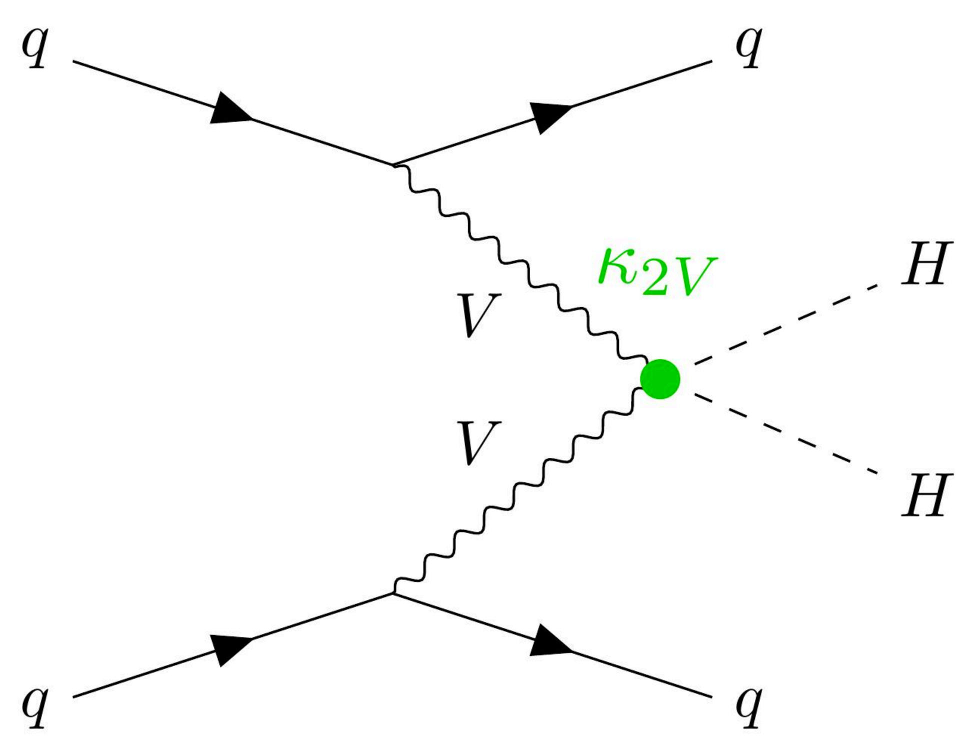
$\sigma_{ggF}(pp \rightarrow HH) = 31$ fb

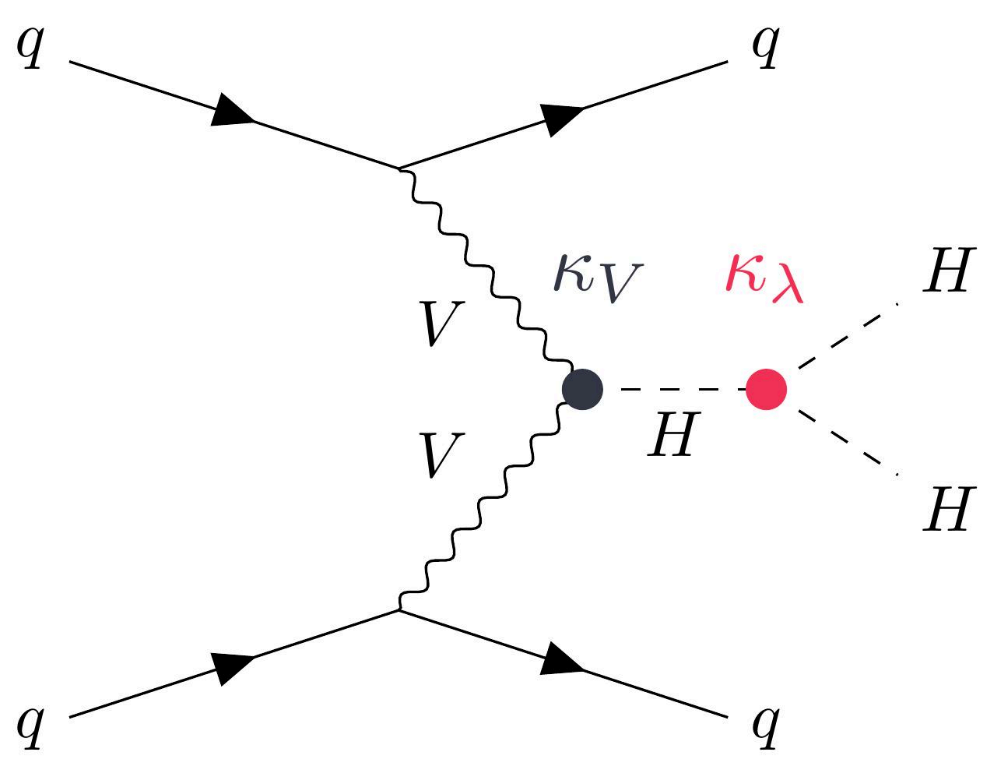


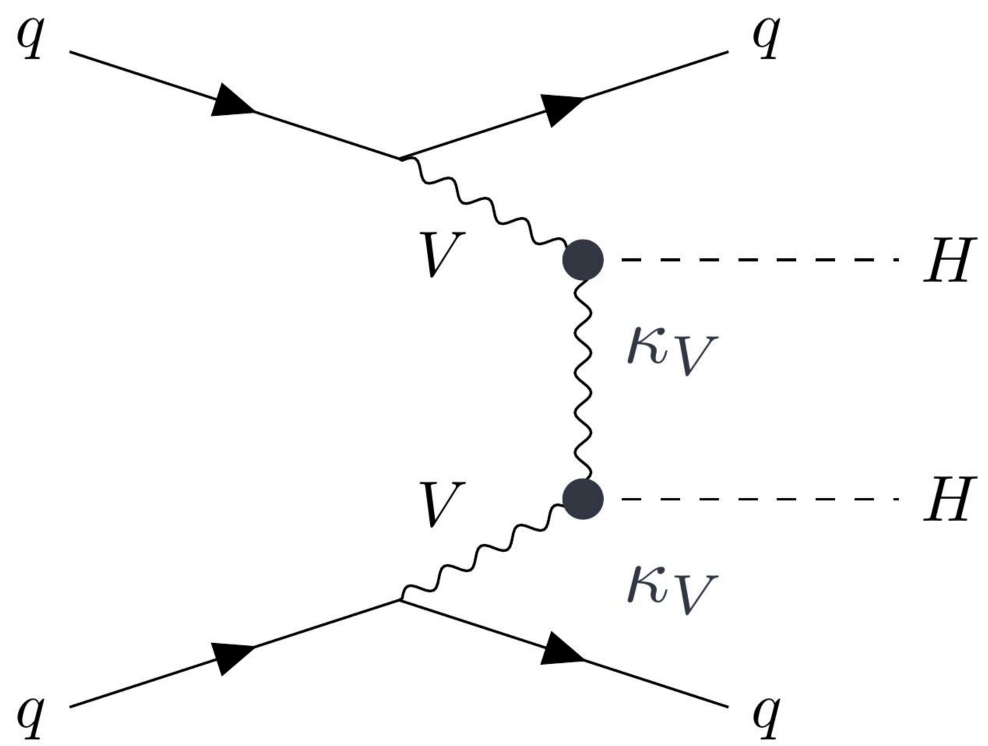


- **vector-boson-fusion** (VBF) production of Higgs pairs

$\sigma_{VBF}(pp \rightarrow HH) = 1.7$ fb





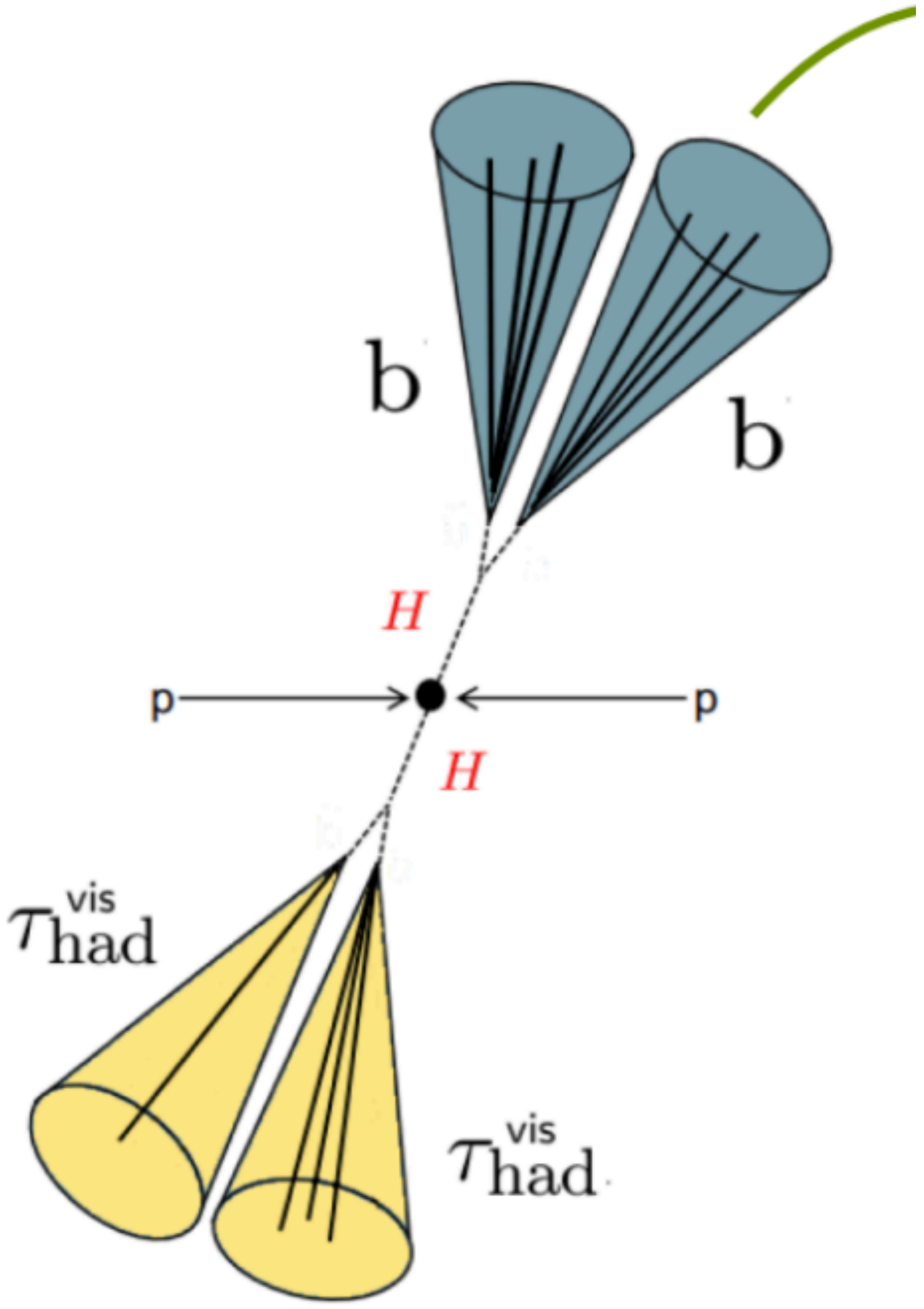


VBF events characterised by lower cross-section and production of hadronic QCD jets in the forward region

HH(bbττ) analysis strategy

Triggering on τ signatures, loose pre-selection, multivariate S/B discrimination

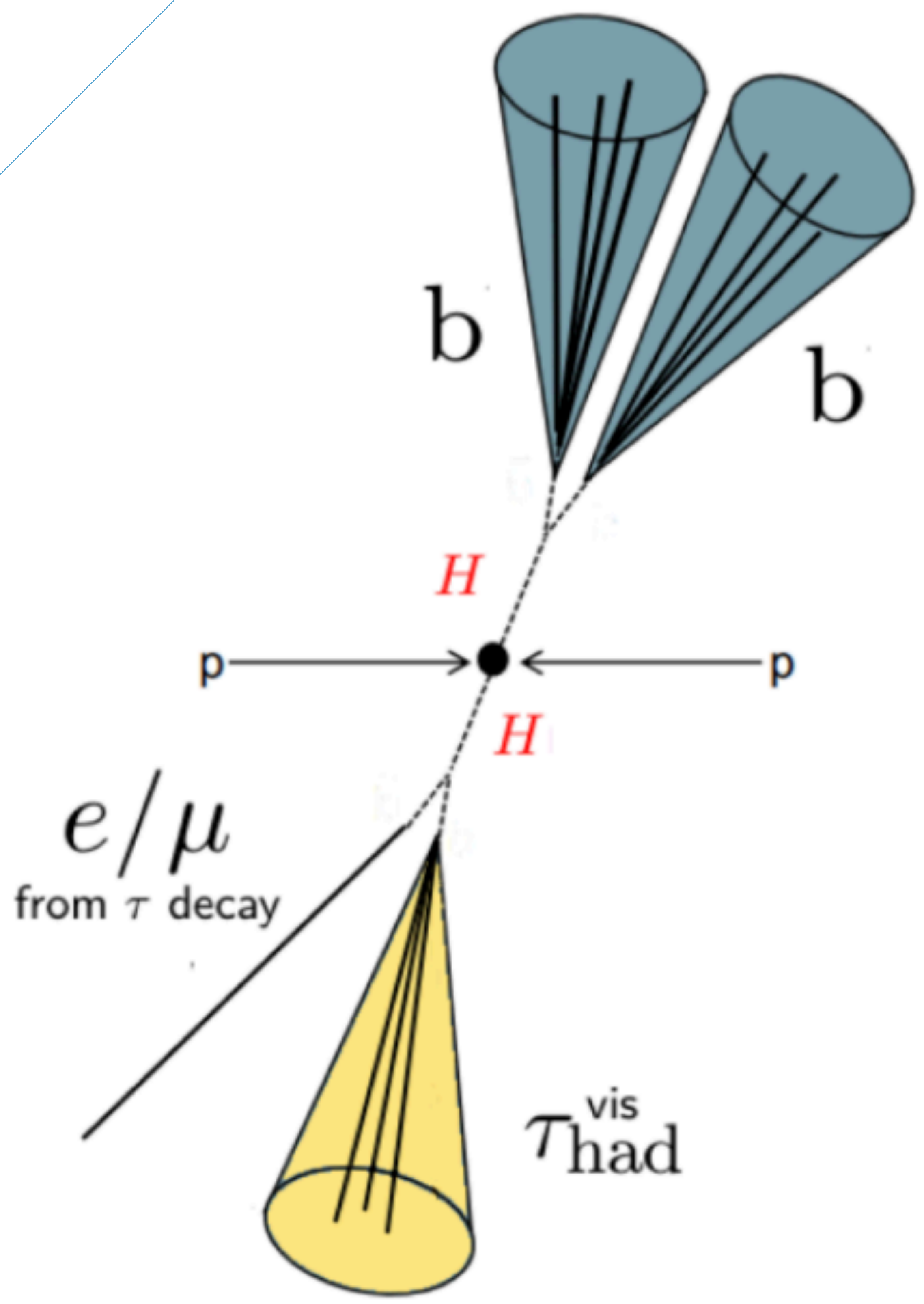
fully-hadronic (**$\tau_{had}\tau_{had}$**)



- trigger-**$\tau_{had}\tau_{had}$**: hadronic τ-leptons
- trigger-**$\tau_{lep}\tau_{had}$**: electrons/muons
- **$\tau_{had}\tau_{had}$**: lepton veto
- **$\tau_{lep}\tau_{had}$**: m_{bb} < 150 GeV

- m(ττ) > 60 GeV
- trigger-dependent pT threshold for b-jets and τ-leptons
- exactly 2 b-tagged jets (ε = 77%)
- opposite charged leptons

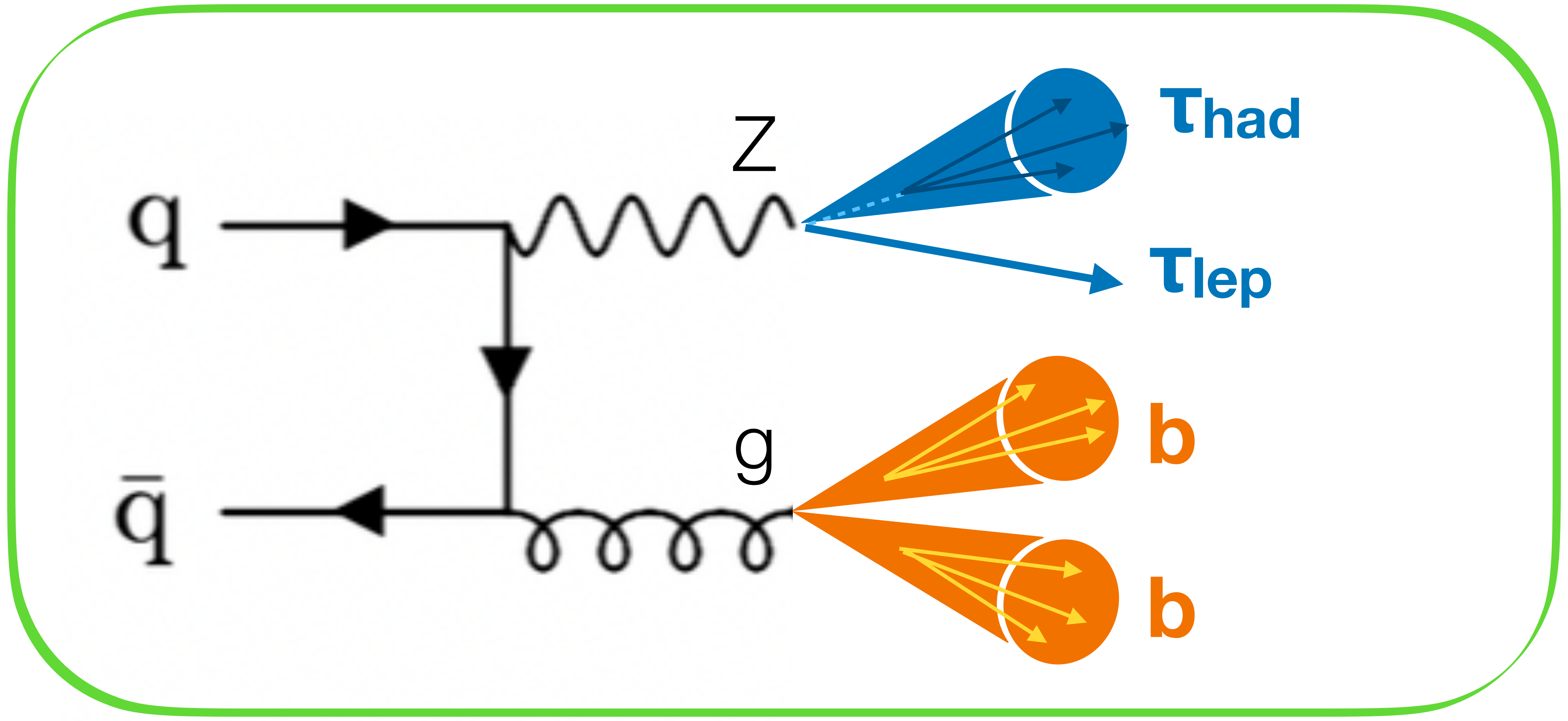
semi-leptonic (**$\tau_{lep}\tau_{had}$**)

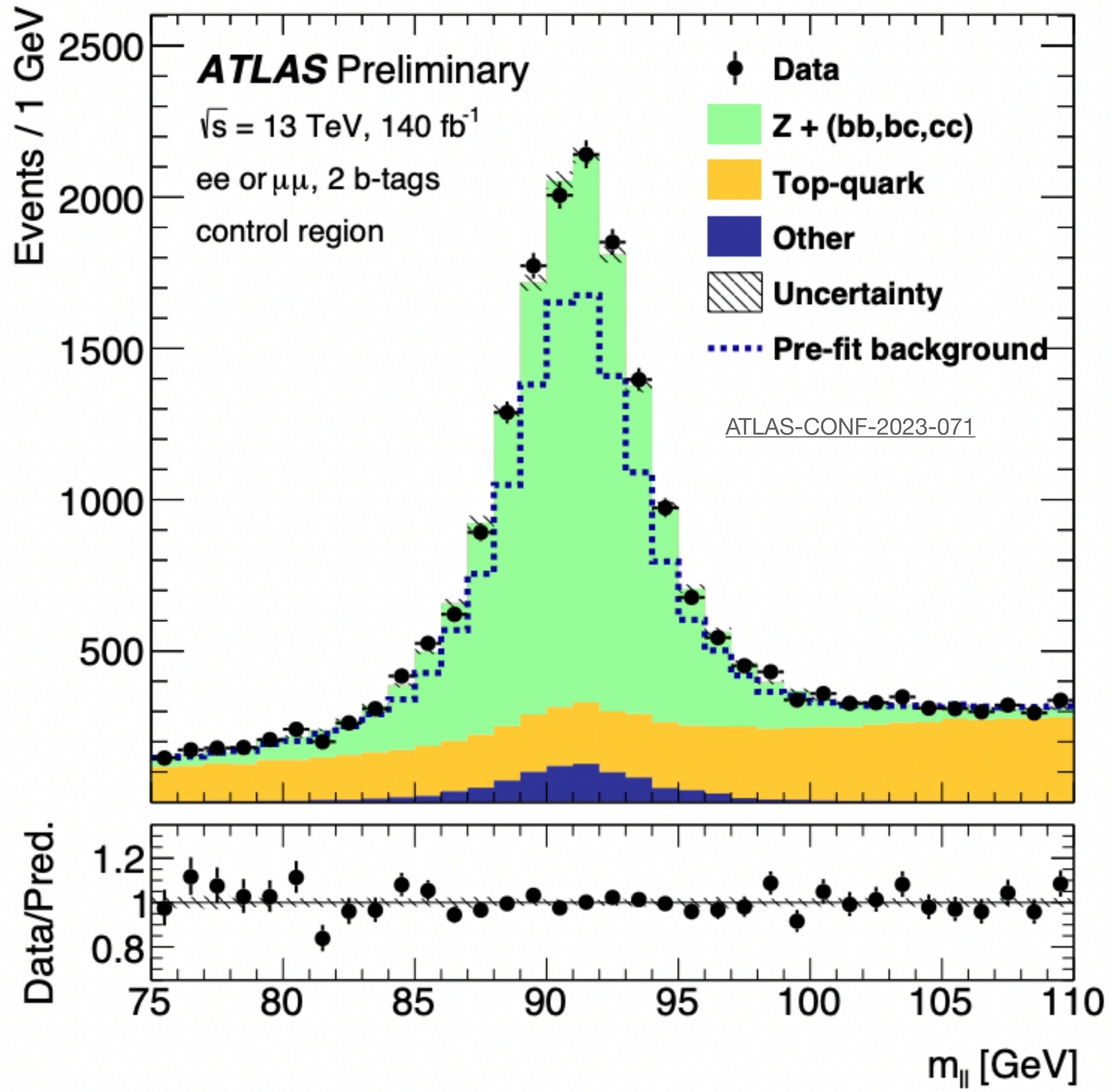


Analysis acceptance ~ 4%

A recent highlight: HH(bbττ) search

Large contribution from Standard Model background processes with similar signatures:
[top-quark-pair production, Z/W boson with heavy flavour, single-Higgs production, etc.]





- **Control region:**
  replacing bbττ with bbee / bbμμ
  to isolate the Z mass peak

  measure the main background contributions from data

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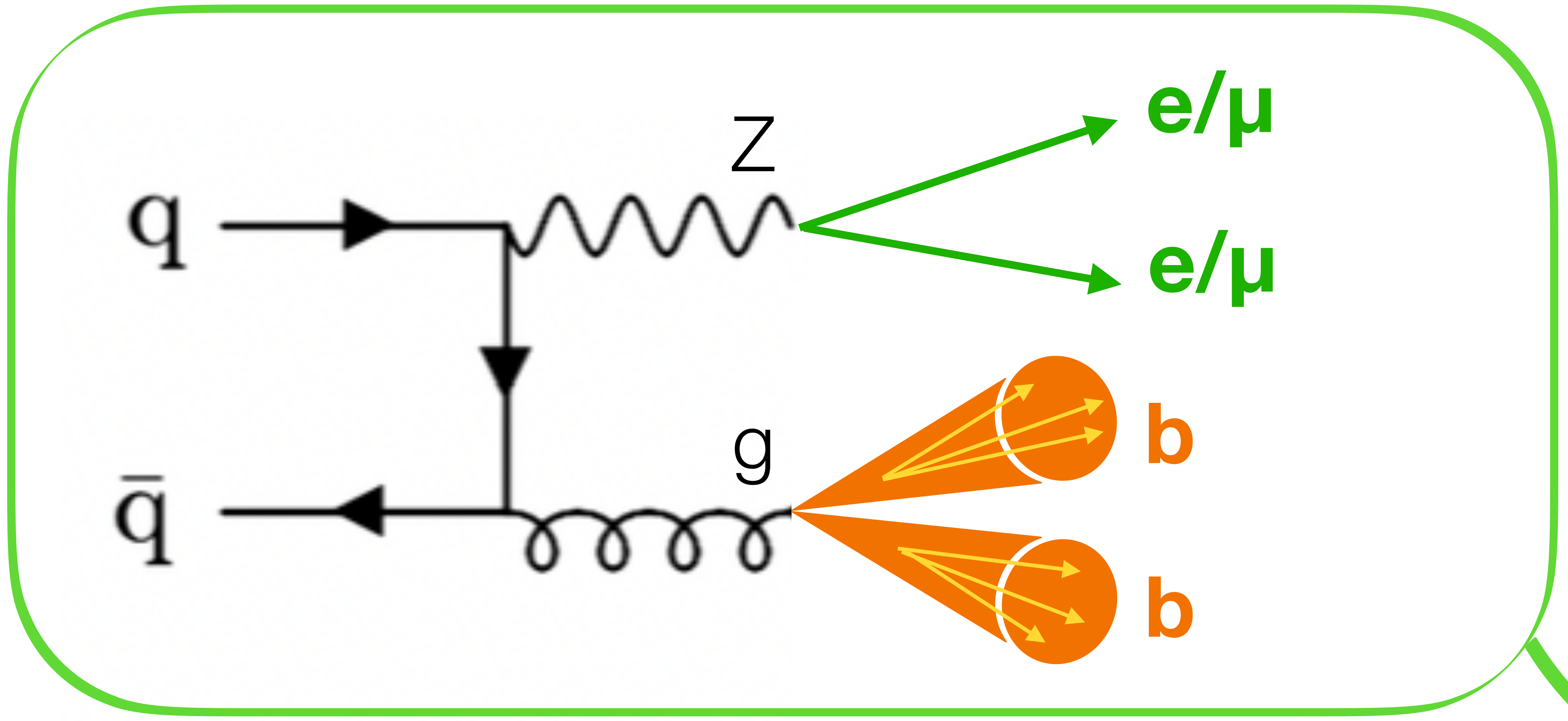
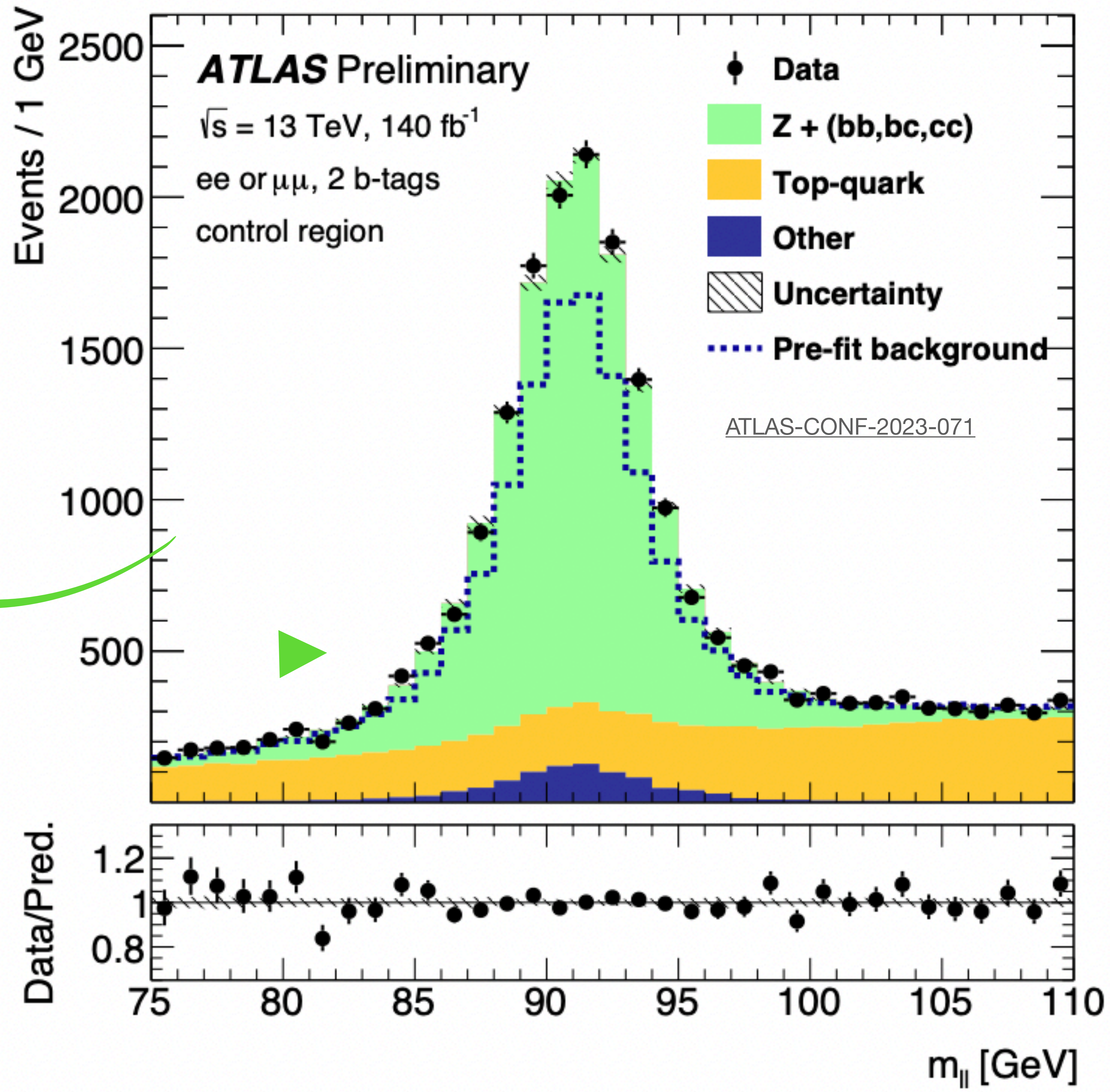




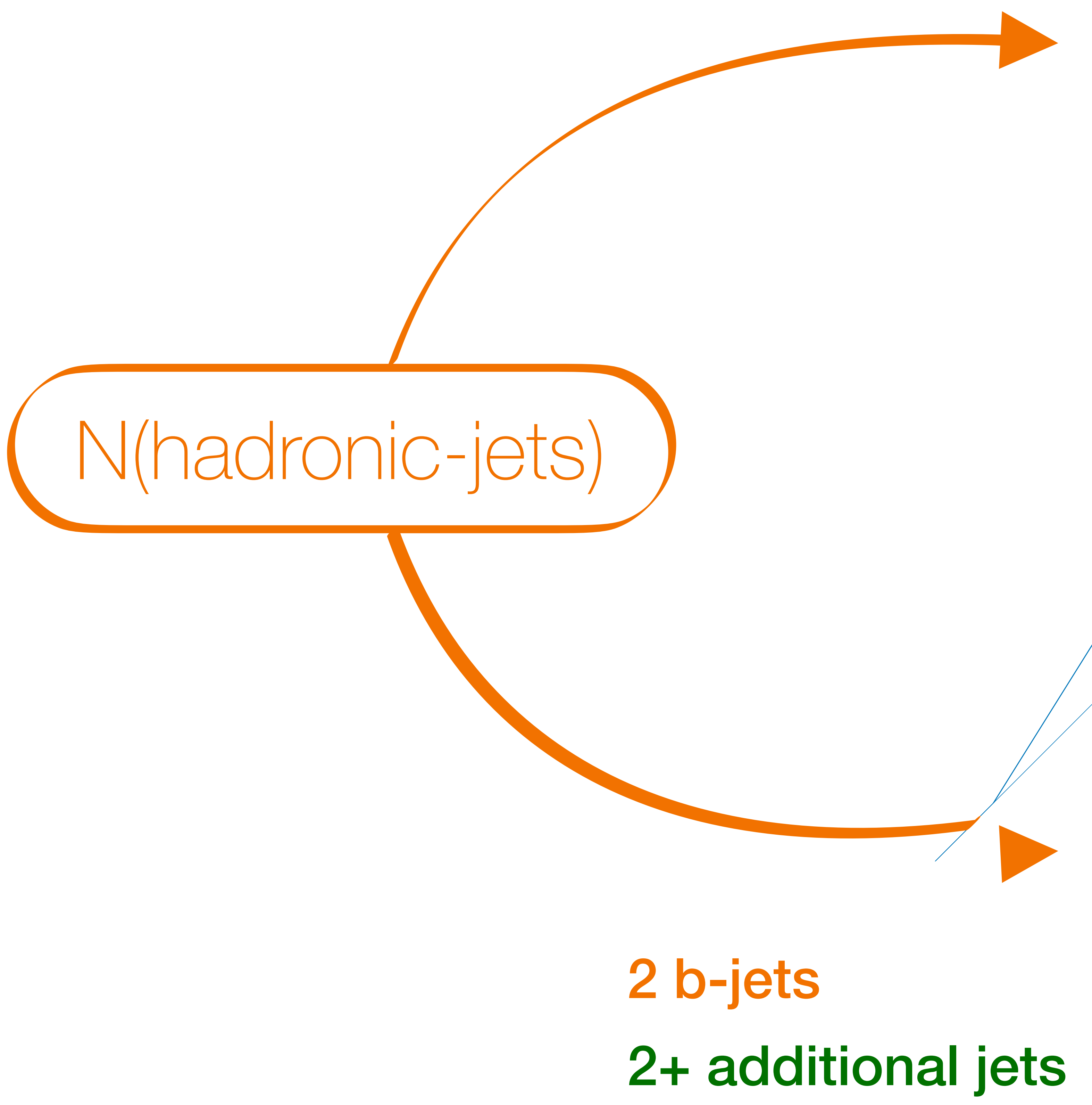
- **Control region:**
  replacing bbττ with bbee / bbμμ
  to isolate the Z mass peak

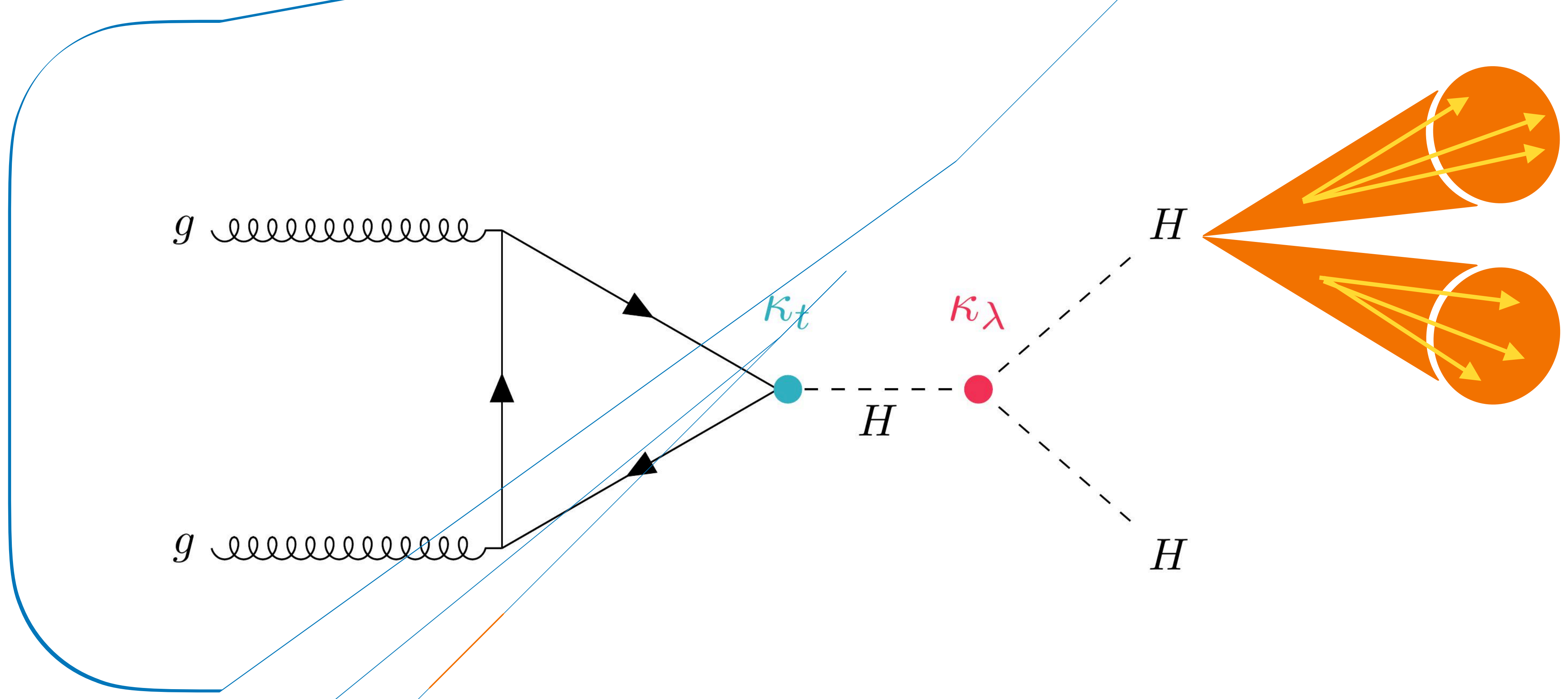
measure the main background contributions from data

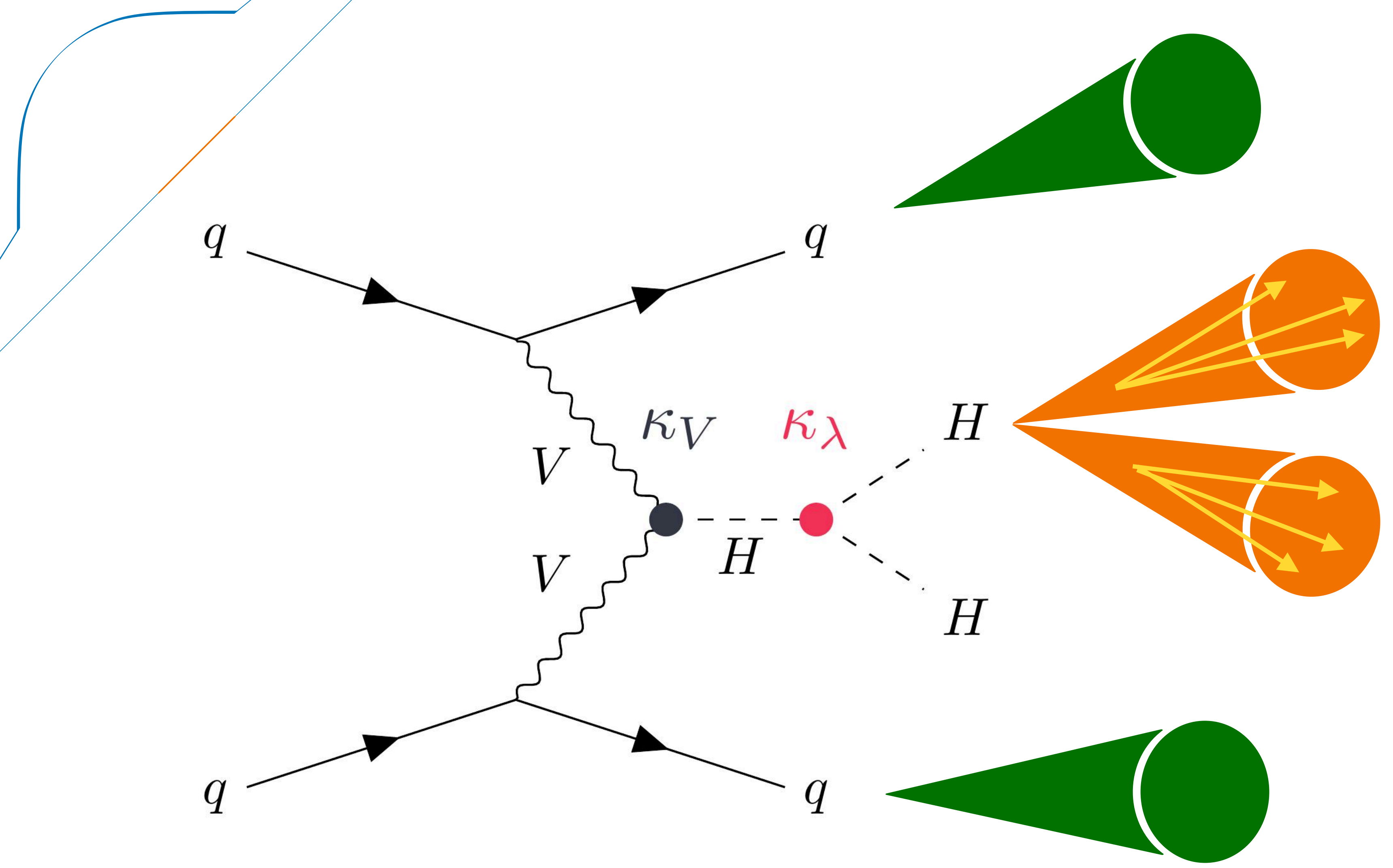
HH(bbττ) analysis category (I)

Events passing the loose pre-selection are divided into multiple categories

- **jet-multiplicity:**
  events with additional hadronic jets
  more likely to come from VBF production







HH(bbττ) analysis category (II)

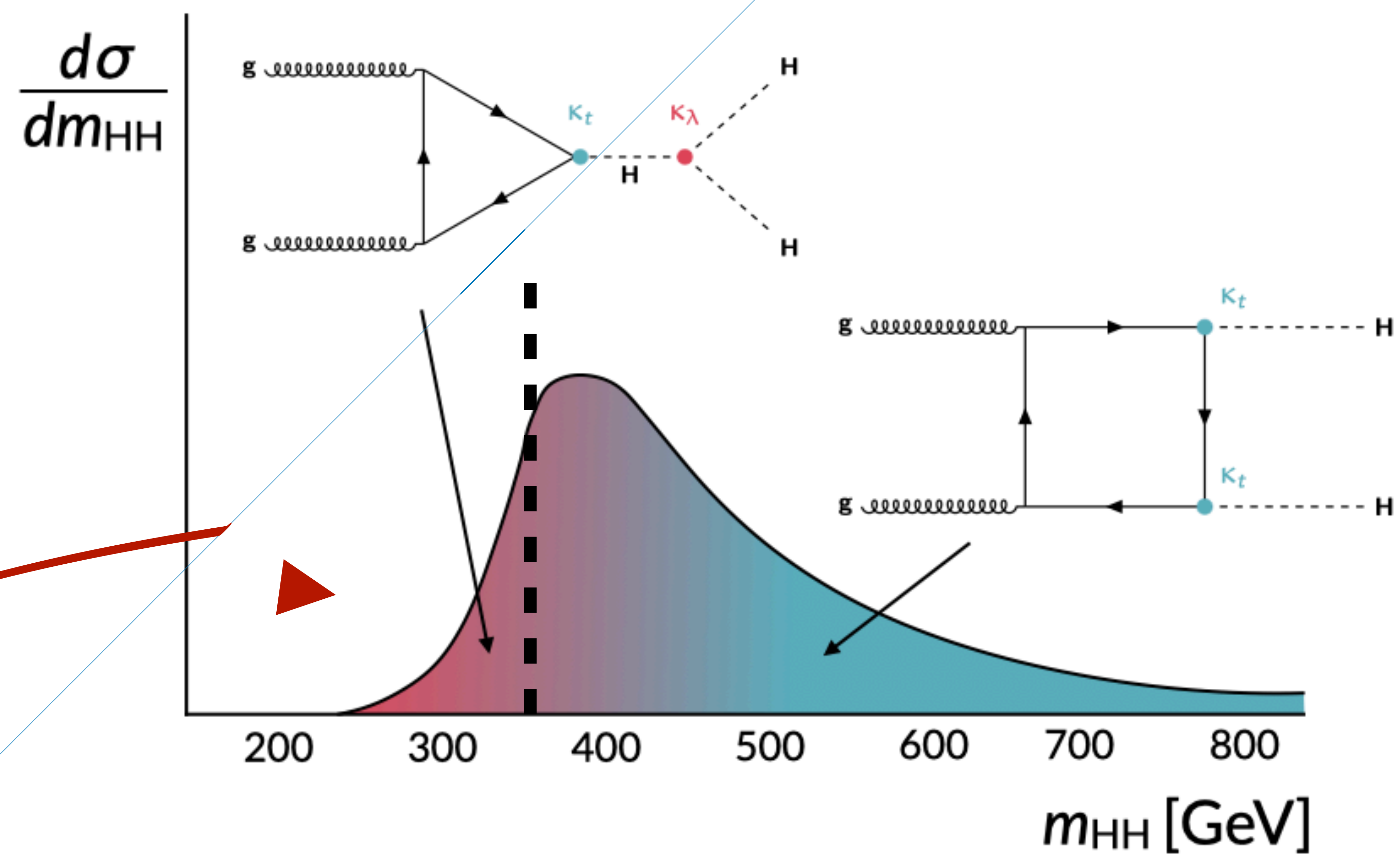
Events passing the loose pre-selection are divided into multiple categories

- **jet-multiplicity:**
  events with additional hadronic jets
  more likely to come from VBF production
- **reconstructed invariant mass m_{HH}**
  interference effects between box and triangle HH diagrams
  ggF production sensitive to the mass distribution

$m_{HH} < 350$ GeV — sensitivity to self-coupling variations

$m_{HH} > 350$ GeV

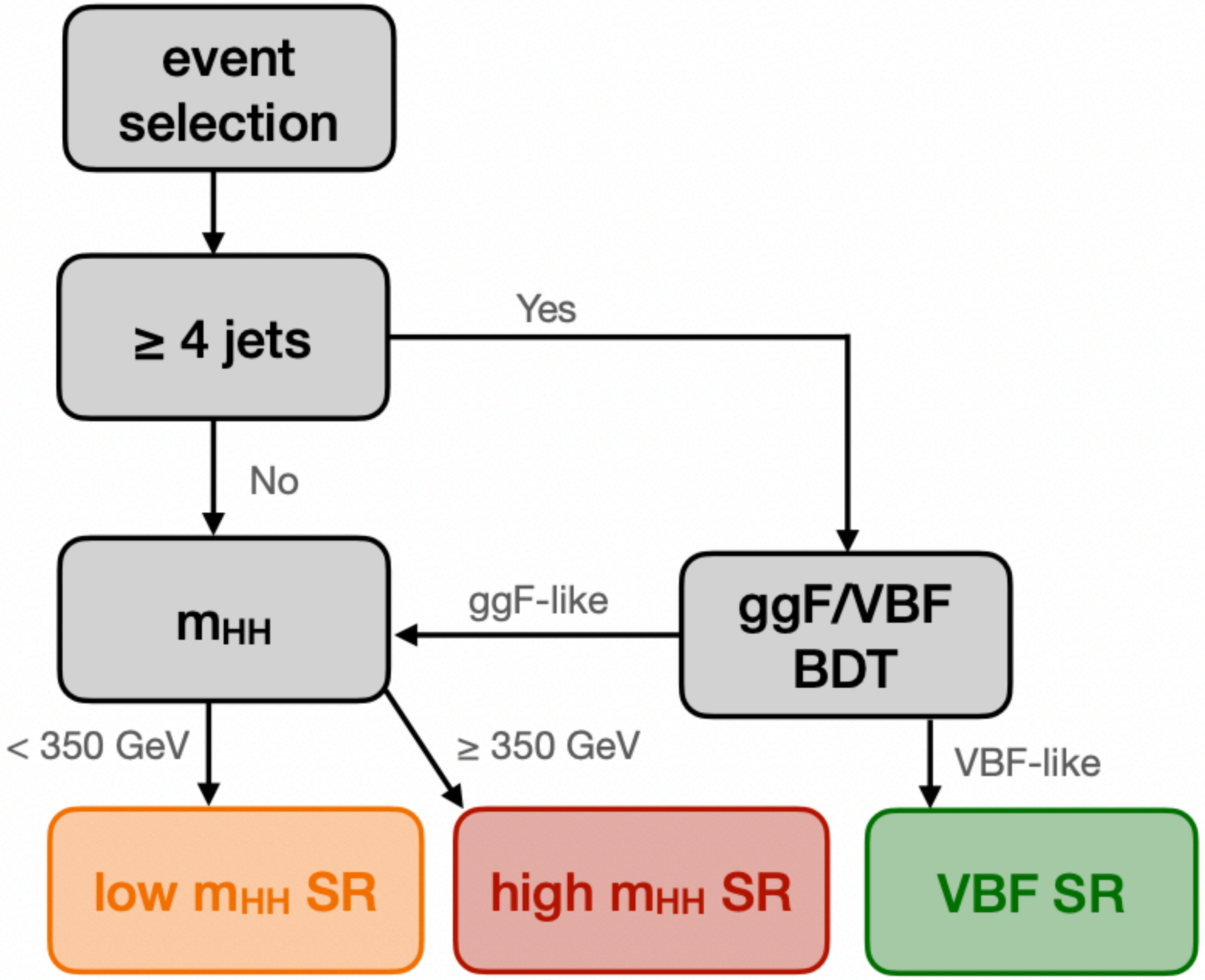
only for events with no additional jets



HH(bbττ) analysis category (III)

Events passing the loose pre-selection are divided into multiple categories

- **jet-multiplicity:**
  events with additional hadronic jets
  more likely to come from VBF production
- **reconstructed invariant mass m_{HH}**
  interference effects between box and triangle HH diagrams
  ggF production sensitive to the mass distribution
- **Boosted Decision Trees separation:**
  dedicated BDTs trained to separate
  ggF-like from VBF-like events
  only for events with at least 2 additional jets



Leading to 3 separate Signal Regions for each decay channel

A recent highlight: HH(bbττ) search

All events in the analysis Signal Regions are used to train **Boosted Decision Trees (MVA)** to separate the HH signal from the SM background. This is the variable we fit to collision data.

- fully-hadronic ($\tau_{had}\tau_{had}$)

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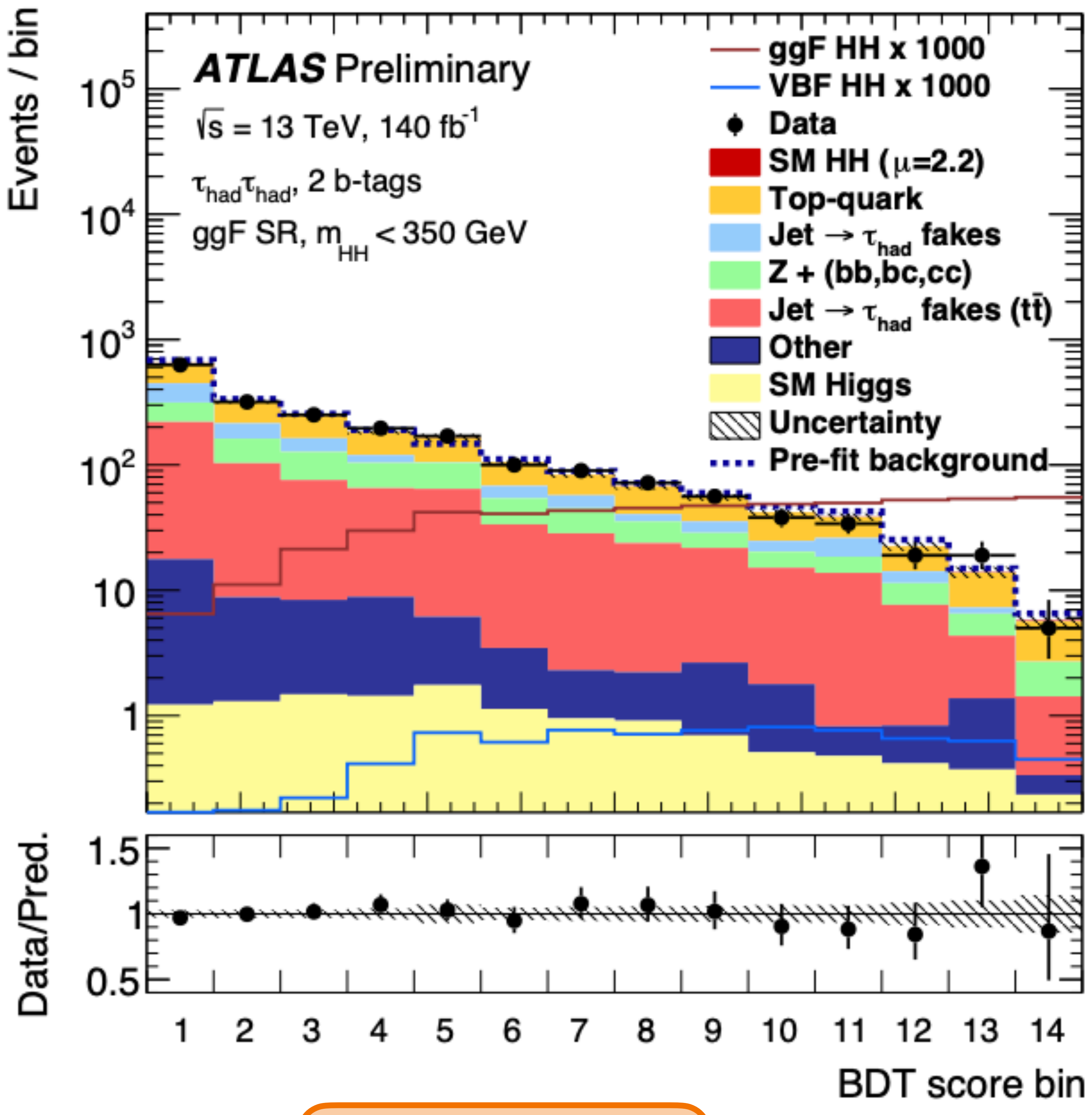
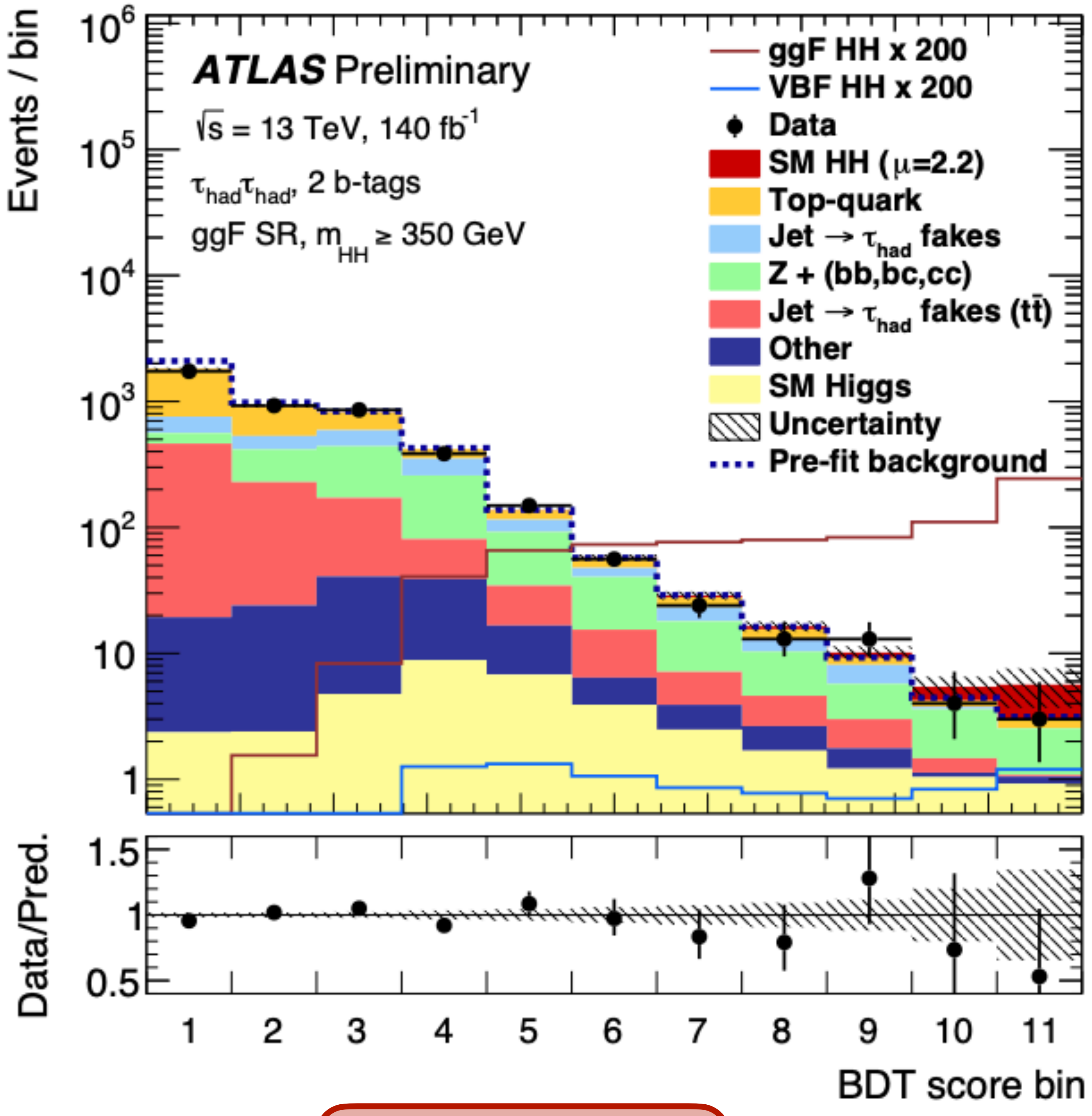
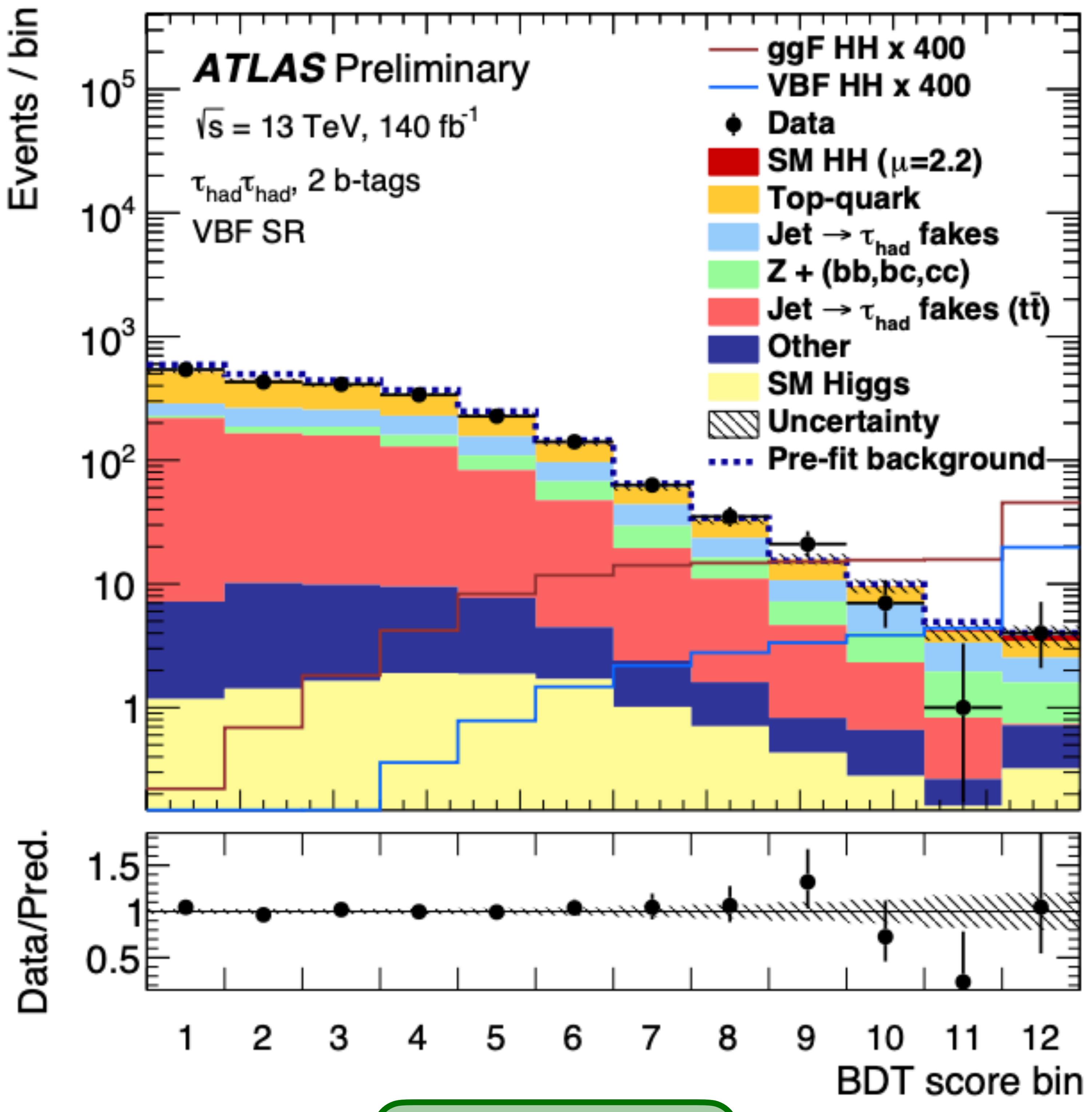


low mHH category



high mHH category



VBF category

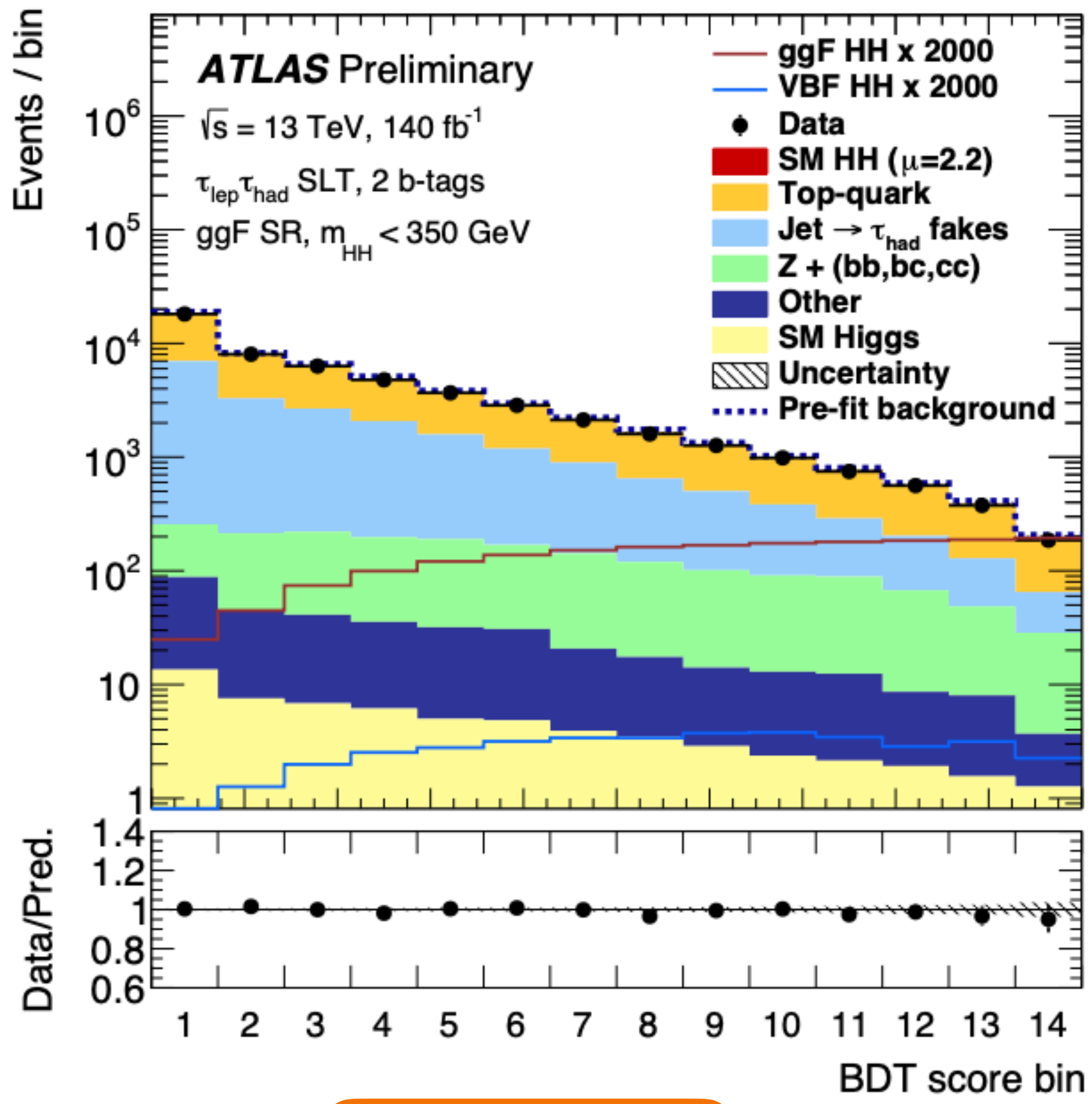
A recent highlight: HH(bbττ) search

All events in the analysis Signal Regions are used to train **Boosted Decision Trees (MVA)** to separate the HH signal from the SM background. This is the variable we fit to collision data.

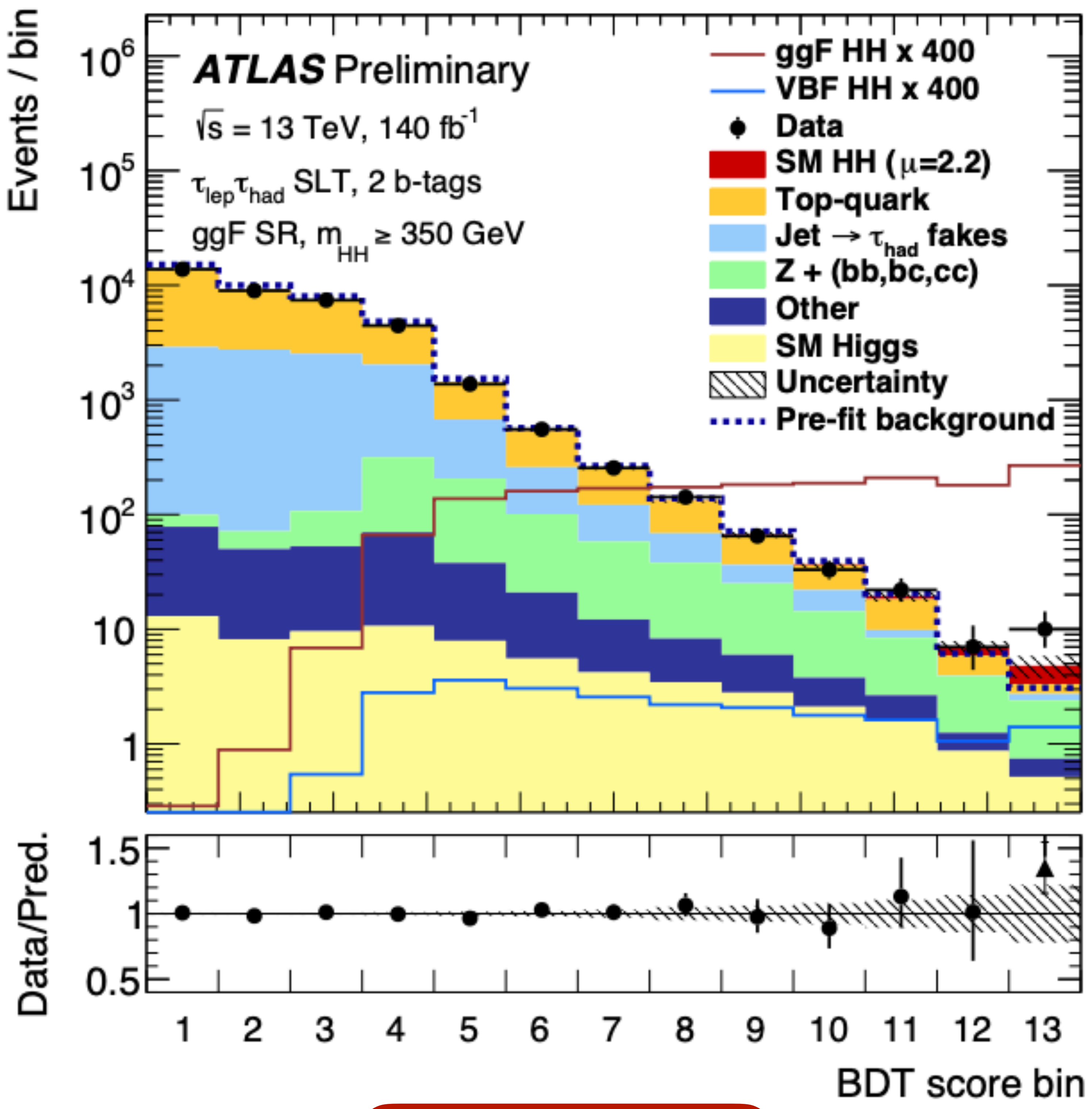
- semi-leptonic ($\tau_{lep}\tau_{had}$)

Mild excess observed in the semi-leptonic channel (high m_{HH} category) at 2.3σ

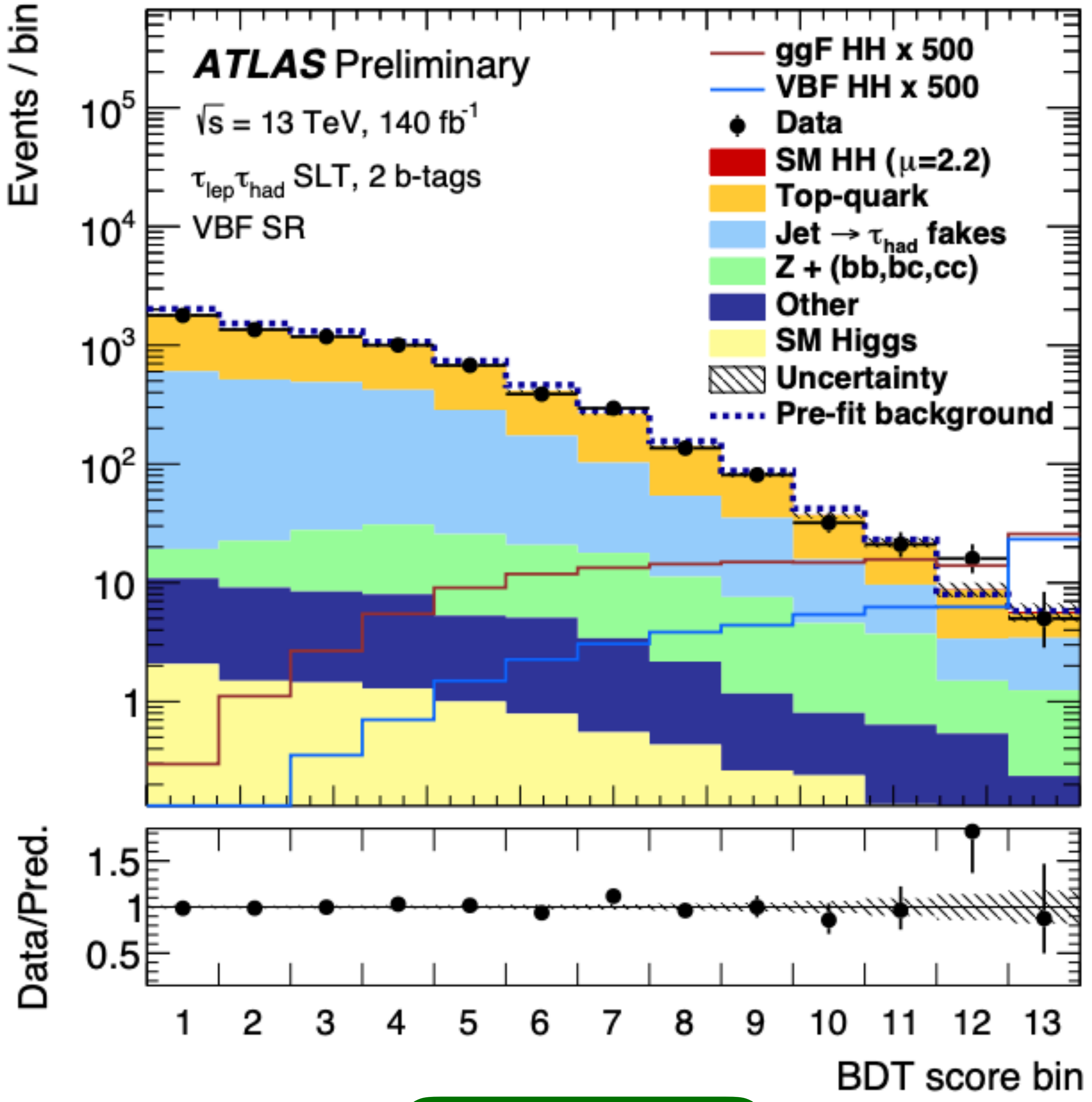
ATLAS-CONF-2023-071



low m_{HH} category



high m_{HH} category



VBF category

A recent highlight: HH(bbττ) search

We find no excess and we observe no signal - but we can set limits on the HH cross-section

Limits are set on the ratio between the measured cross-section and the SM prediction
(signal strength $\mu_{HH} = \sigma_{HH} / \sigma^{SM}_{HH}$)

HH cross-section

observed limit μ_{HH} < **5.9**
expected limit μ_{HH} < **3.1**

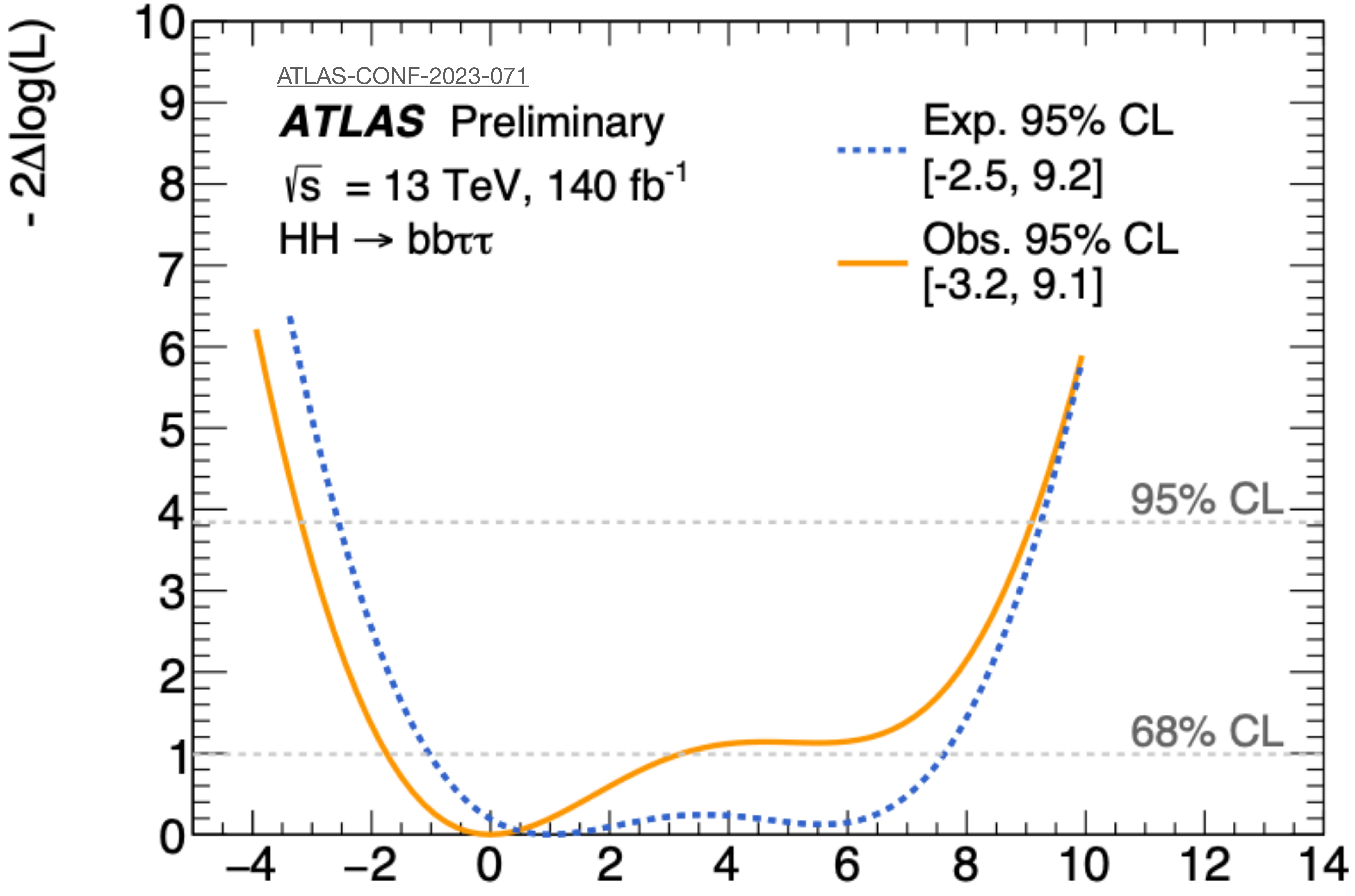
gluon-fusion HH

- observed limit μ_{HH} < **5.8**

vector-boson-fusion HH

- observed limit μ_{HH} < **91**
  (much tinier cross-section, looser limits)

Likelihood scan constraining the self-coupling parameter



$k_\lambda = \lambda / \lambda_{SM}$

$-3.2 < k_\lambda < 9.1$

A recent highlight: HH(bbττ) search

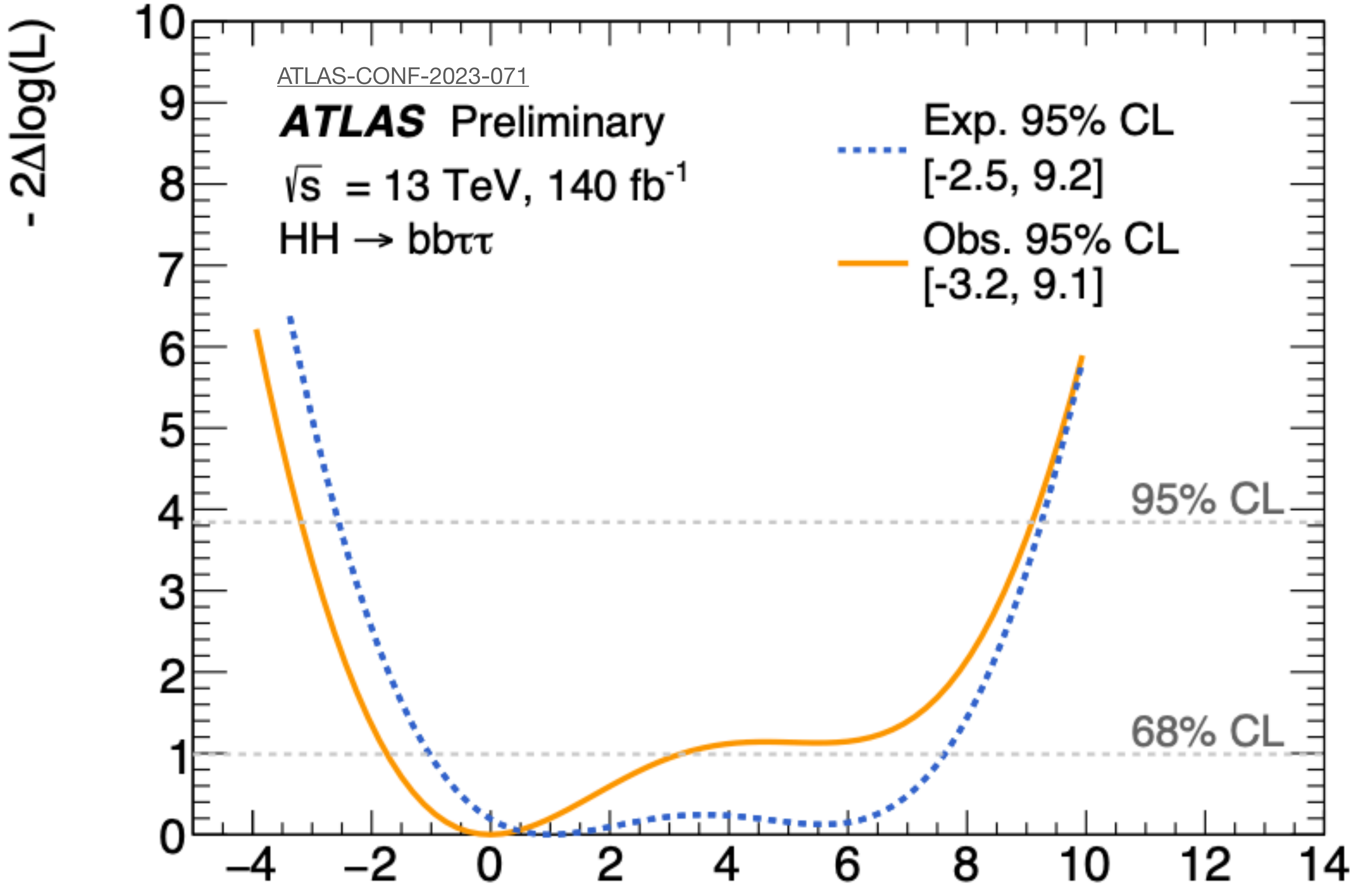
We find no excess and we observe no signal - but we can set limits on the HH cross-section

Limits are set on the ratio between the measured cross-section and the SM prediction
(signal strength $\mu_{HH} = \sigma_{HH} / \sigma^{SM}_{HH}$)

A good reference on theoretically allowed values of the self-coupling parameter (and scenarios with negative λ):

1704.02311
(Sec 2.1 in the context of EFT with additional $|H^6|$ potential terms)

Likelihood scan constraining the self-coupling parameter



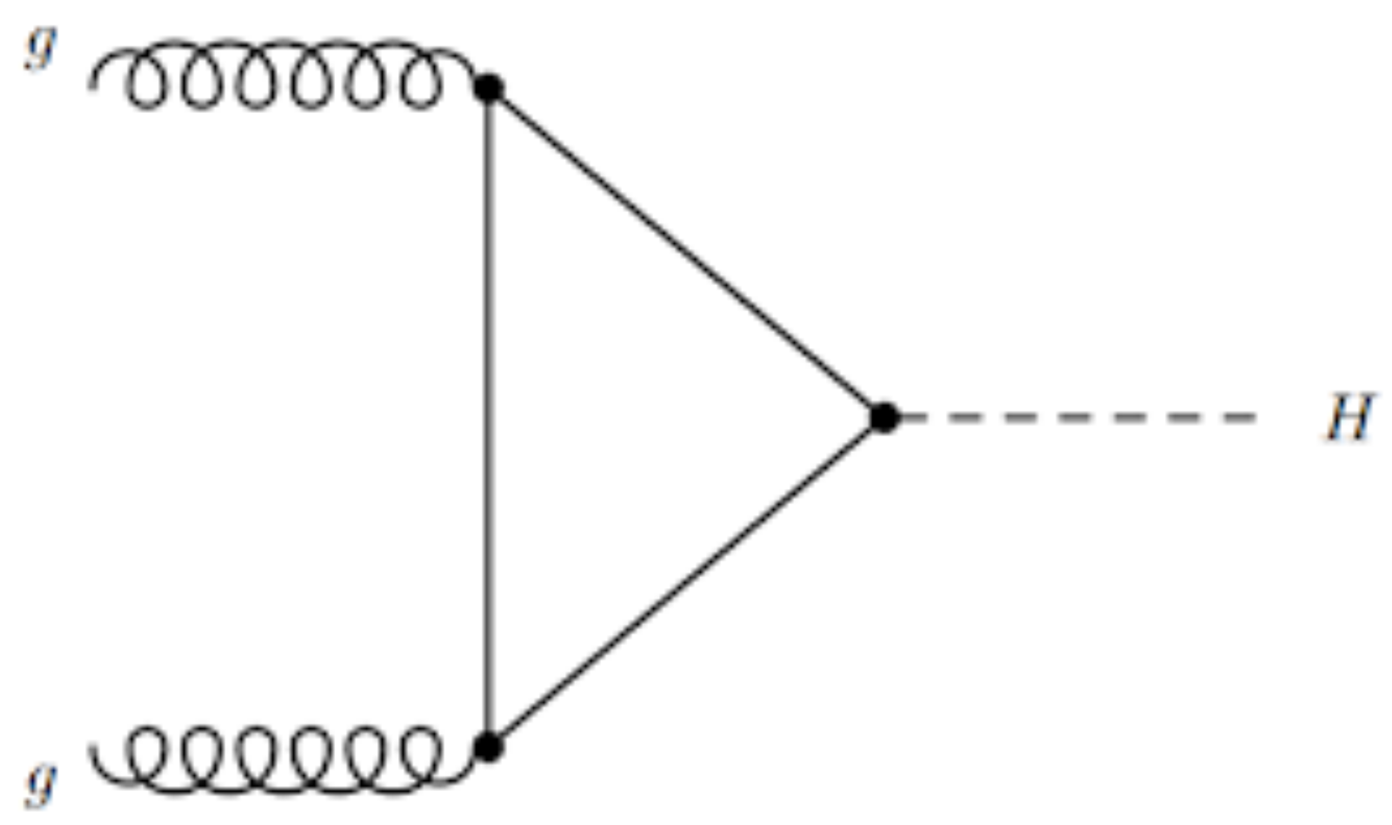
$k_\lambda = \lambda / \lambda_{SM}$

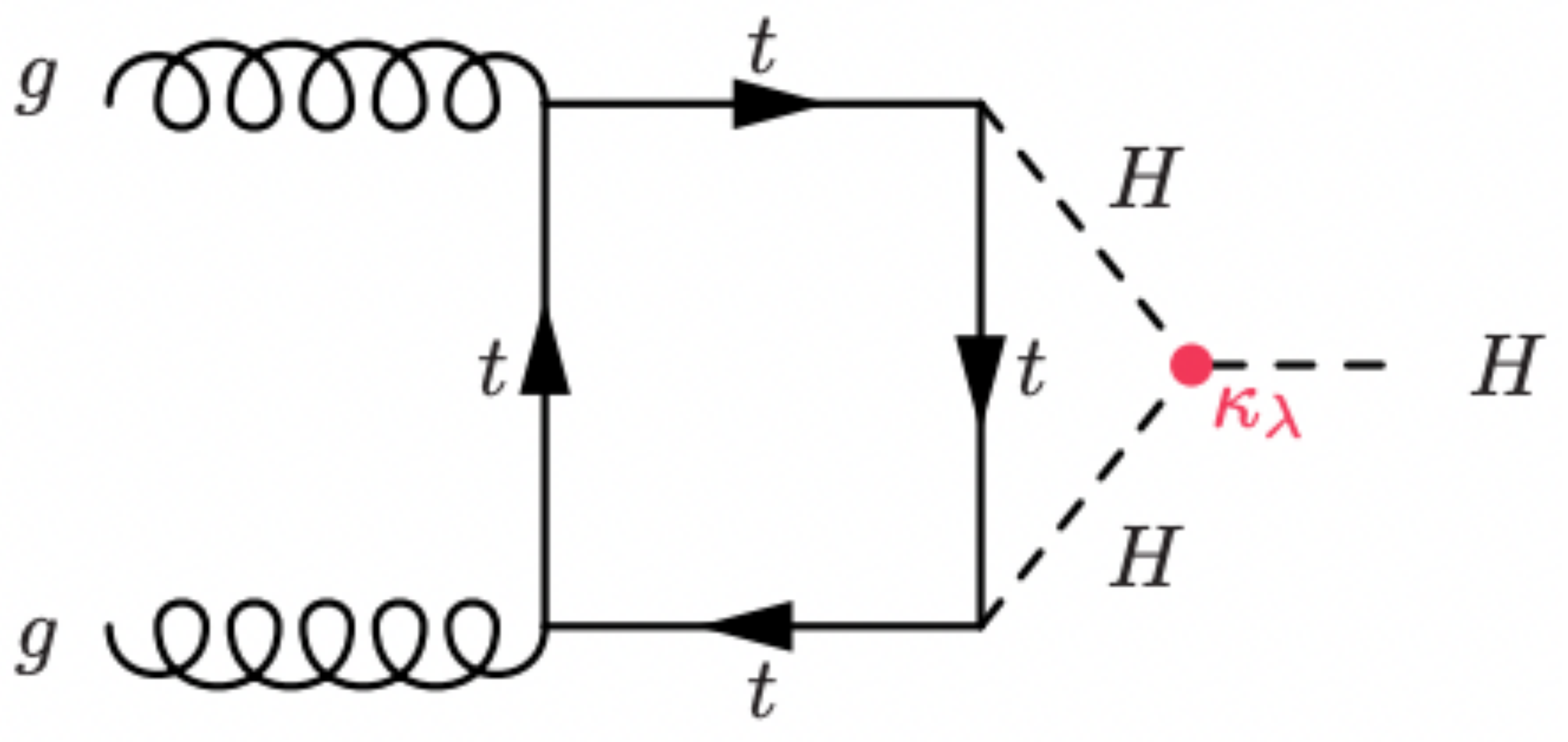
$-3.2 < k_\lambda < 9.1$

Indirect probes of self-interactions?

Indirect probes: single-Higgs corrections

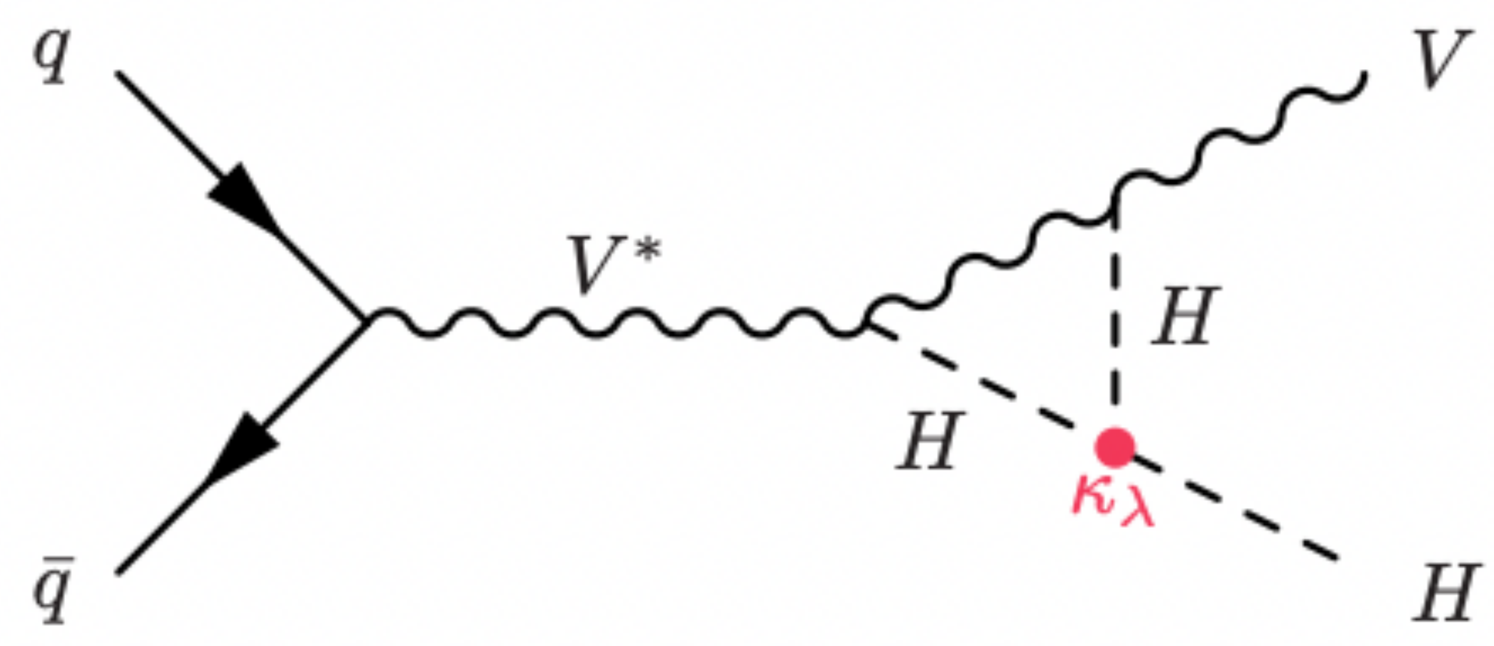
Consider the main Higgs production mechanism at the LHC: Higgs gluon-fusion ggH

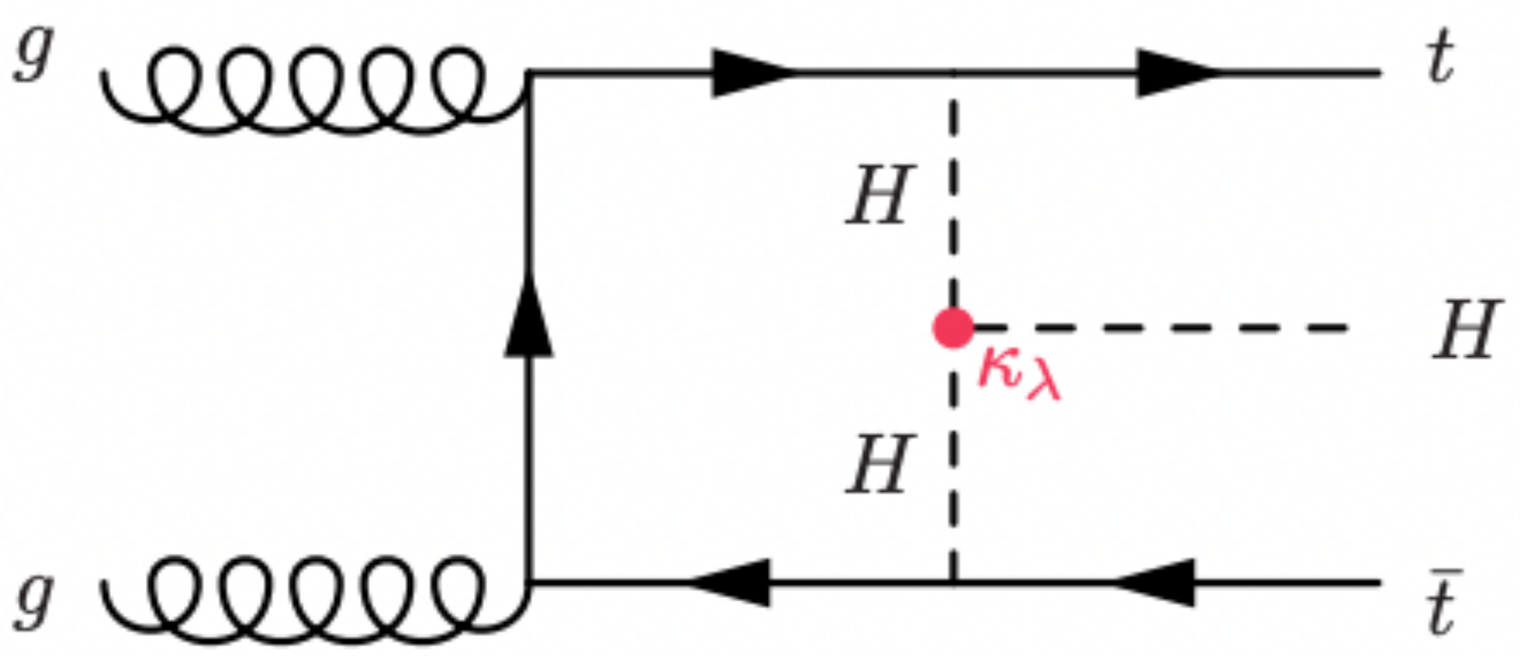




Higher-order corrections introduce a dependency on scalar-self-interactions !

(Higgs loops: much lower cross-section - but sizeable differential effects)

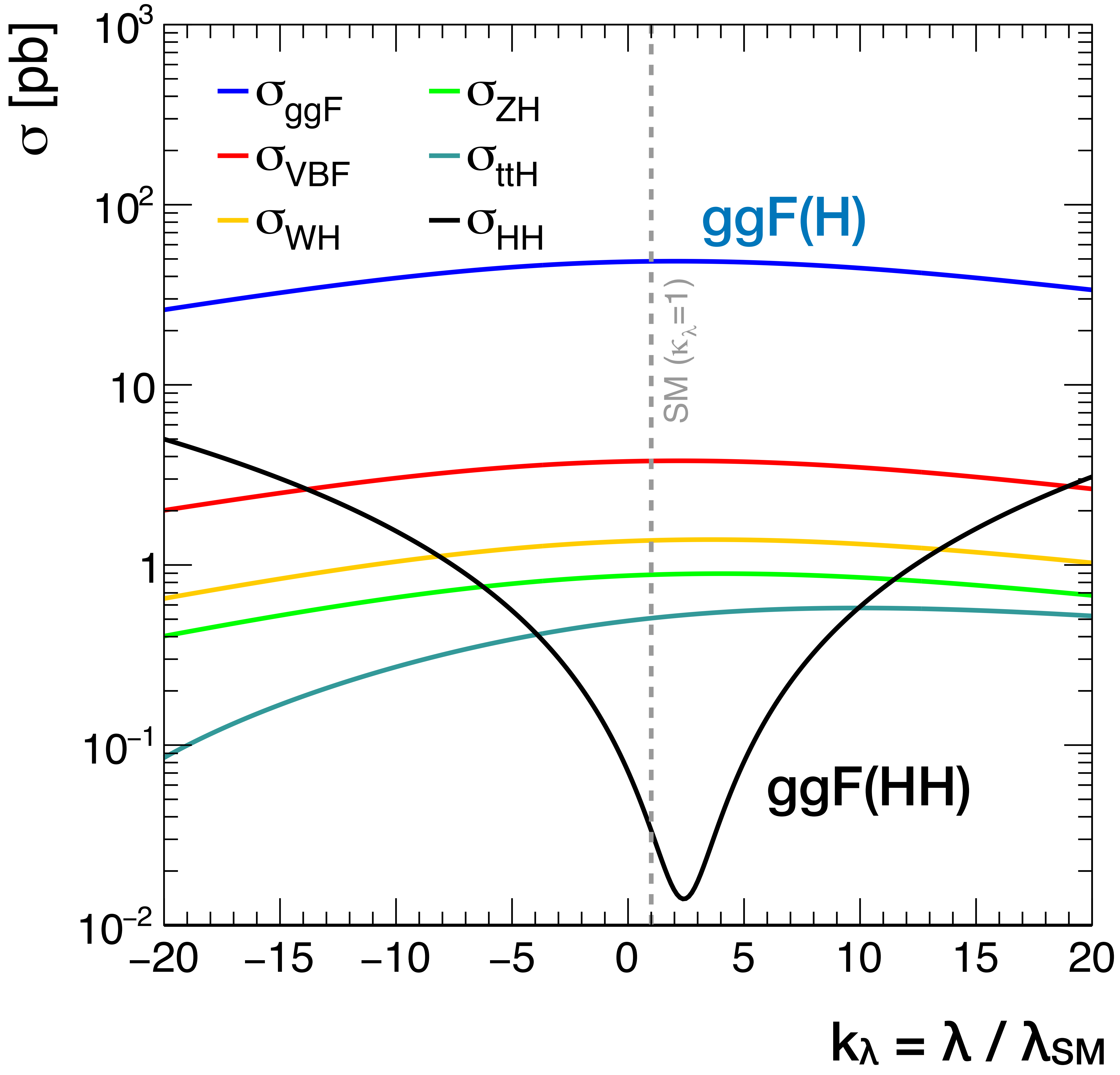




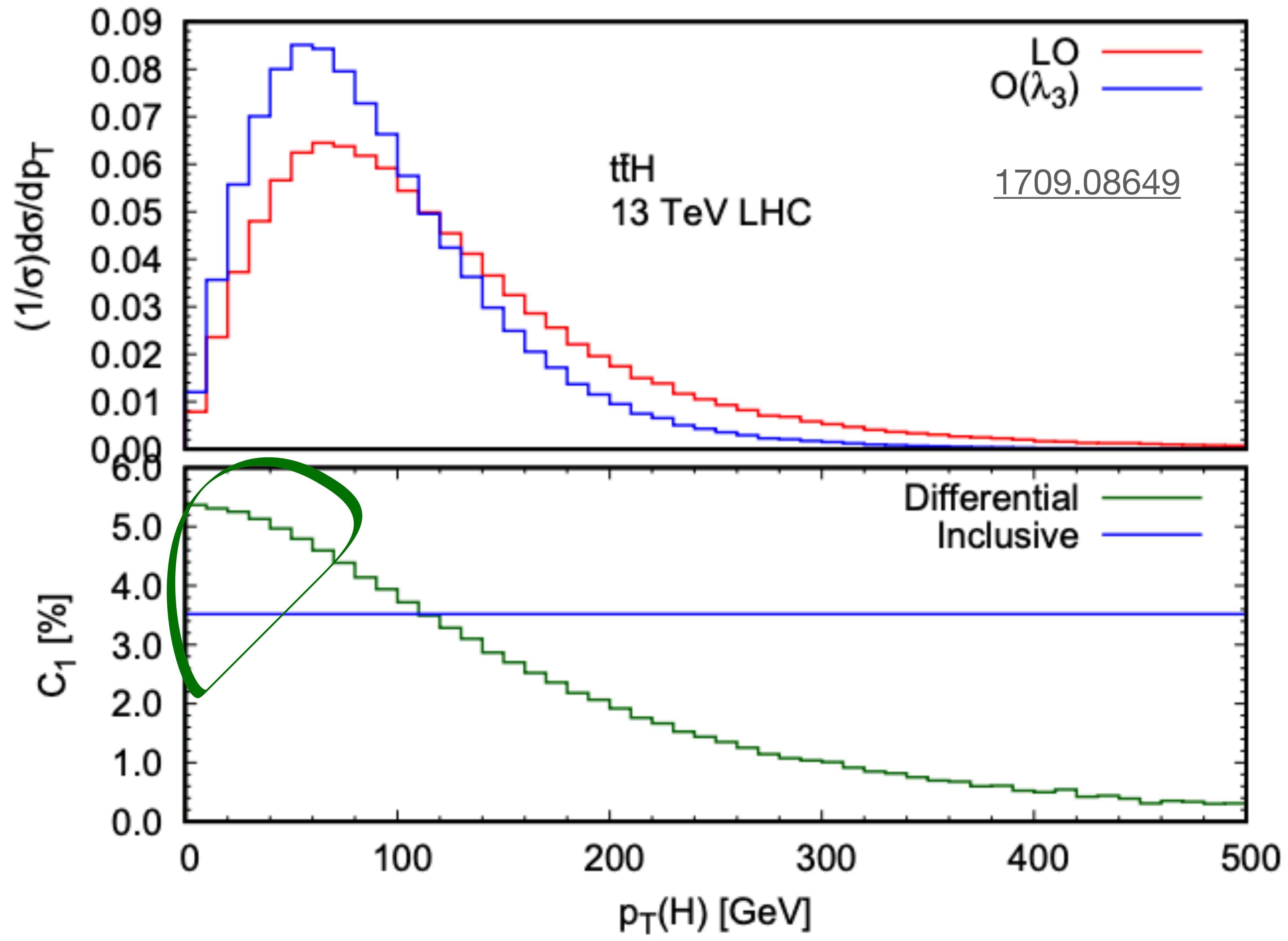
This is true for all Higgs production modes, as well as decay diagrams

Indirect probes: single-Higgs corrections

Total cross-section variations moderate compared to HH



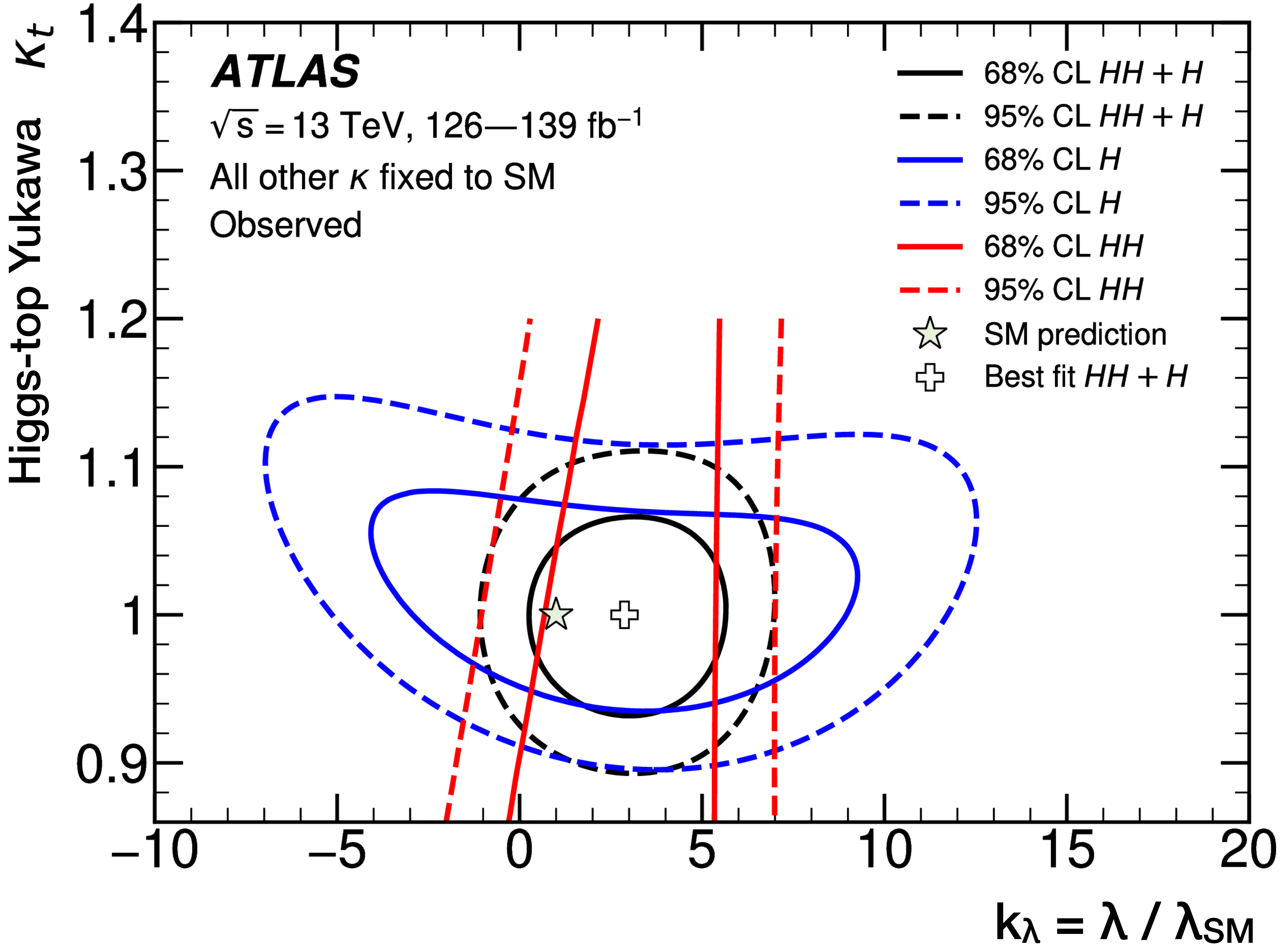
O(5%) effects on Higgs differential cross-sections

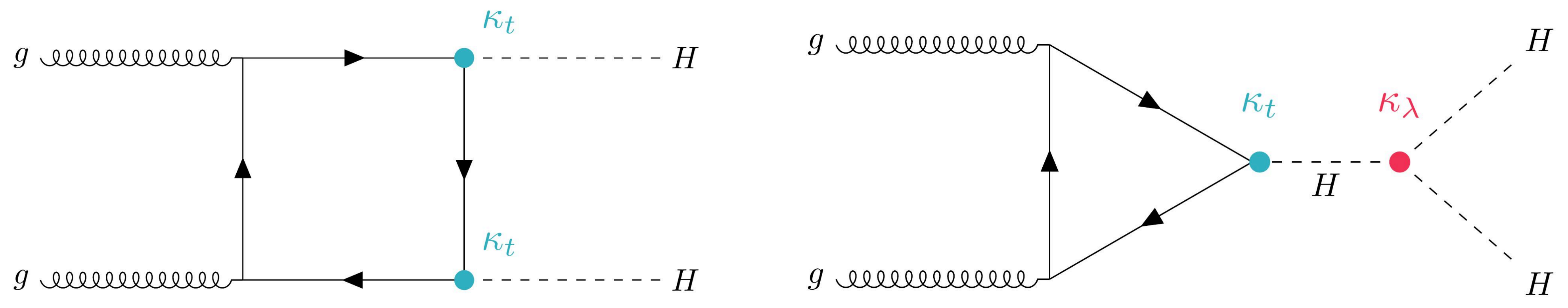


Single-Higgs measurements much more precise than HH: some sensitivity to moderate variations

Indirect probes: single-Higgs corrections

Simultaneous measurement of Higgs-top Yukawa and Higgs self-coupling





HH cross section

largely degenerate in the top-Yukawa and Higgs self-coupling

Single-H cross-section

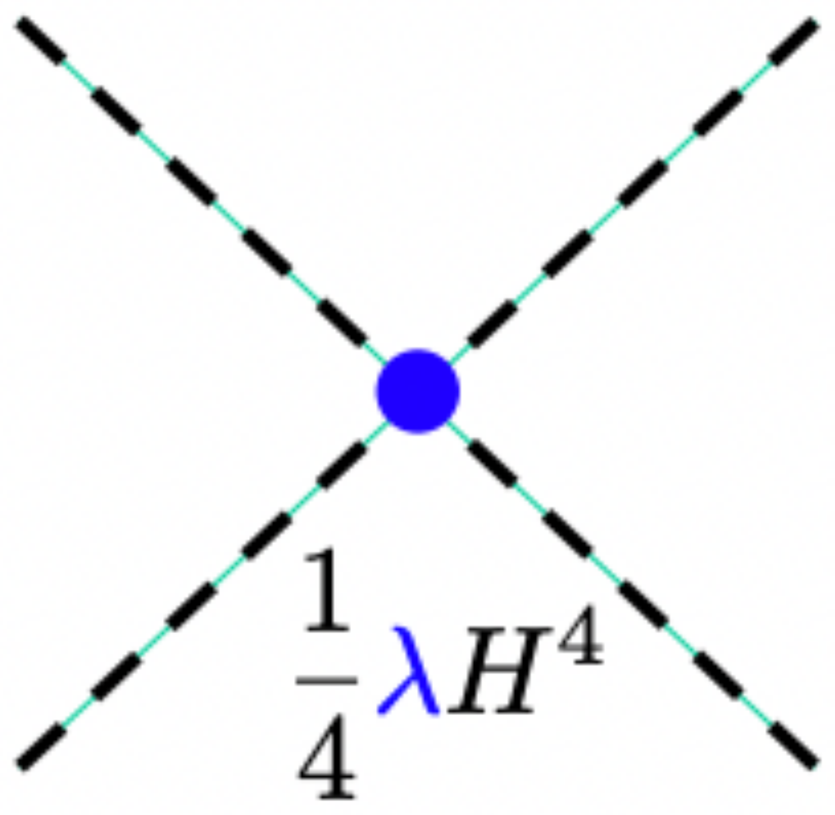
looser bounds on k_λ but sensitive to Higgs-top Yukawa

Combined H+HH

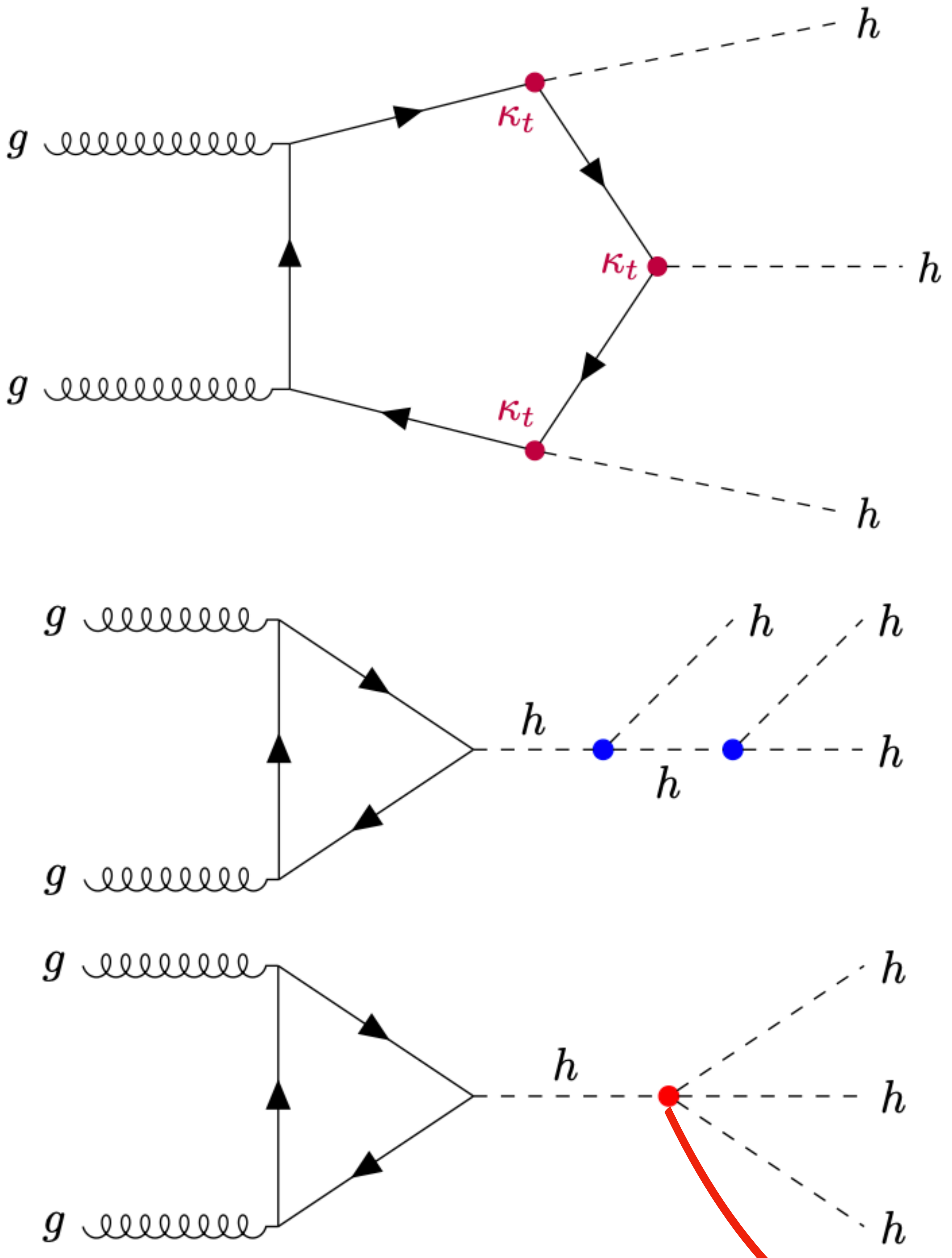
model independent constraints on Higgs coupling (Yukawa + gauge + self-interaction)

$$V(\Phi) = V_0 + \frac{1}{2}m_H^2 H^2 + \lambda \nu H^3 + \frac{1}{4}\lambda H^4$$

Can we make a statement on the quartic term?



Triple Higgs sensitivity



Tiny cross-section (~0.1fb) extremely challenging

- relying on H(bb) decays for maximum statistics
- non-trivial Higgs reconstruction (jet-pairing)
- large-radius-jet might bring large improvements

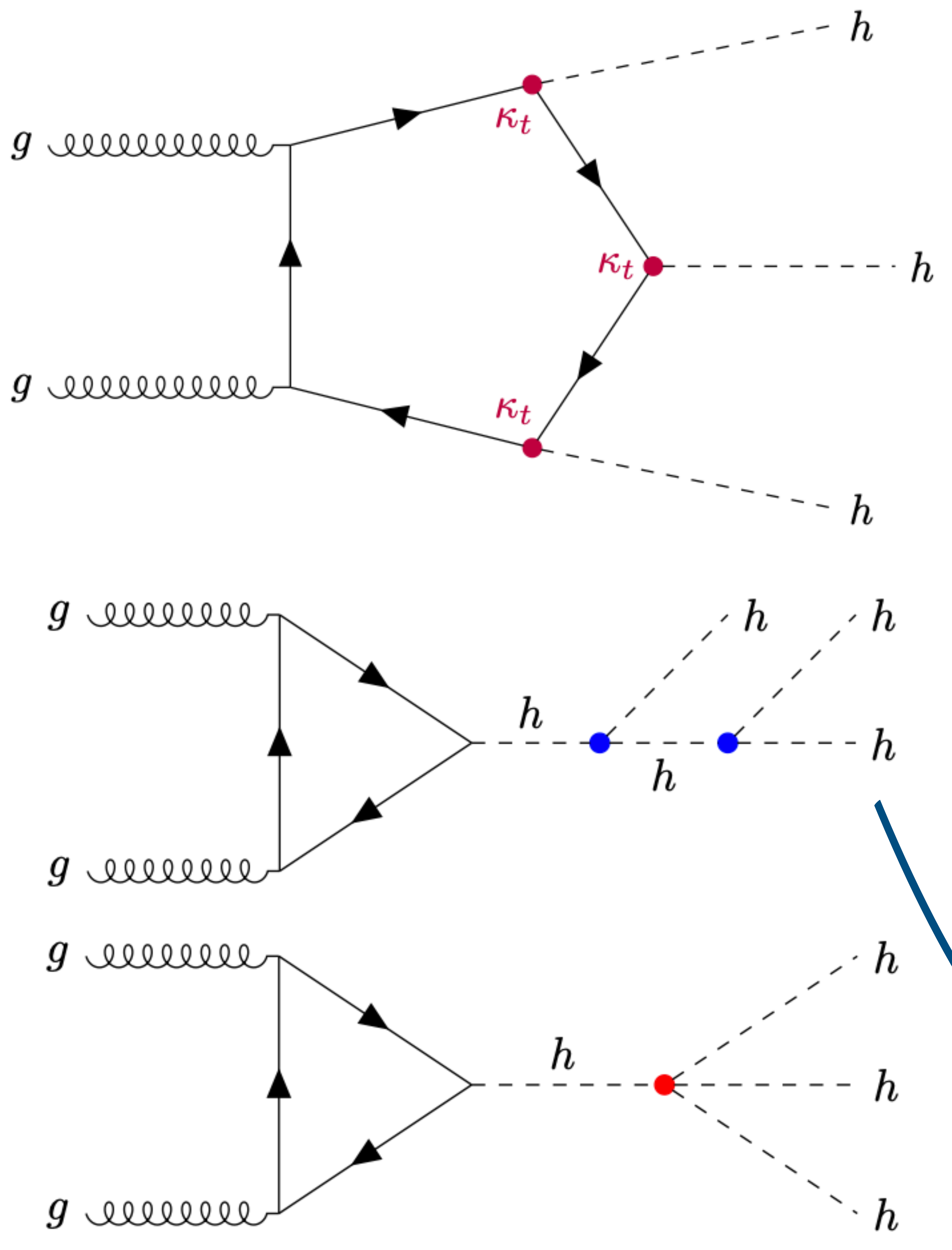
Current sensitivity estimates (LHC Run-2 dataset):
HHH cross-section limits ~ **300 x SM**

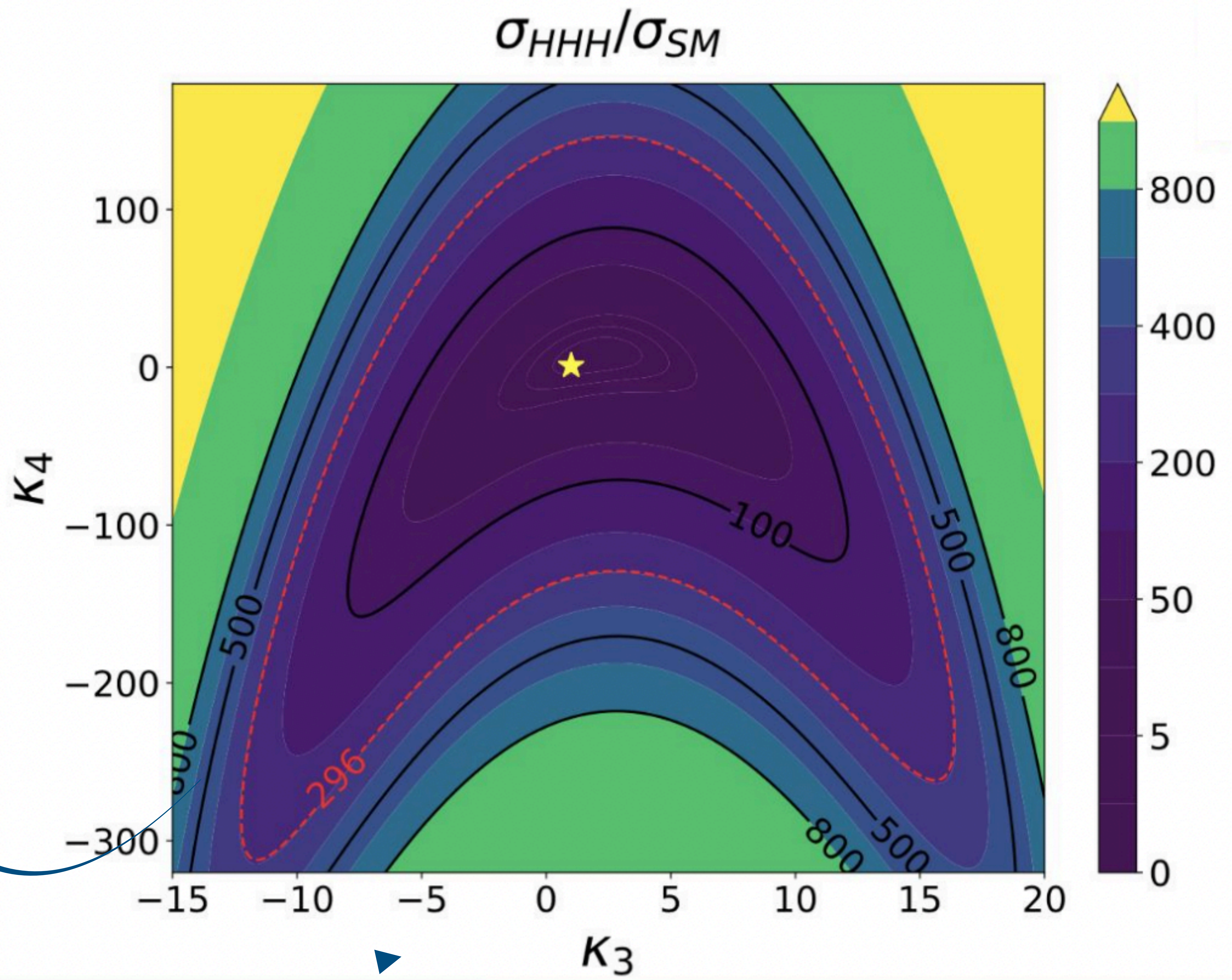
Bounds on the quartic coupling

$O(-150 < k_\lambda < 150)$

Triple Higgs sensitivity

HHH production shows actually good sensitivity to the trilinear coupling

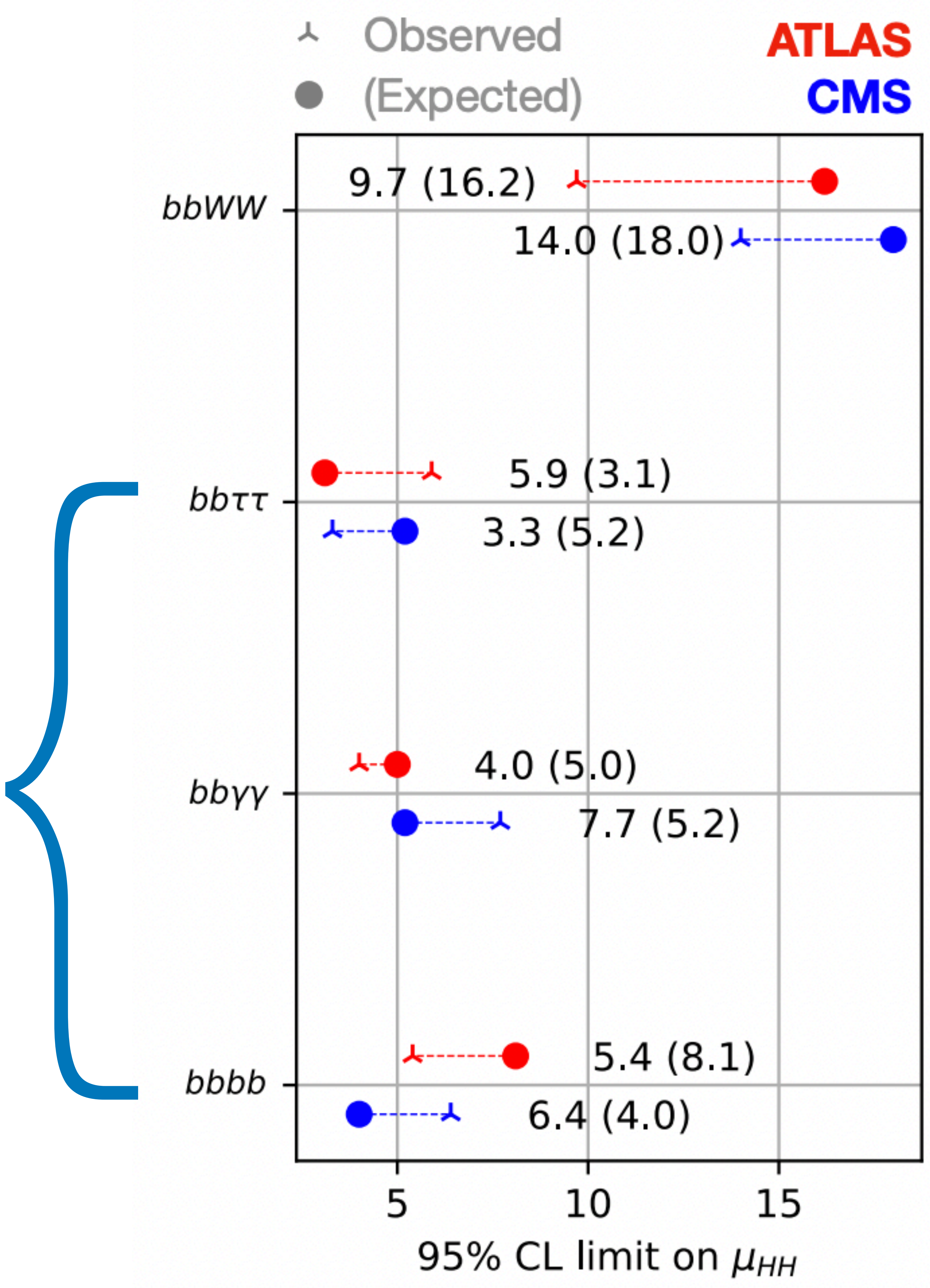




What is the general picture after the LHC Run-2?

HH searches in ATLAS: a general overview

(plots courtesy of Luca Cadamuro from ATLAS HH workshop)



- Cross-section limits at **O(3-5)** the SM expectation
  some differences between ATLAS and CMS
- Golden channels performing ~ similarly
- Combined limits from ATLAS: μ_{HH} < **2.4** (2.9)

Phys. Lett. B 843 (2023) 137745

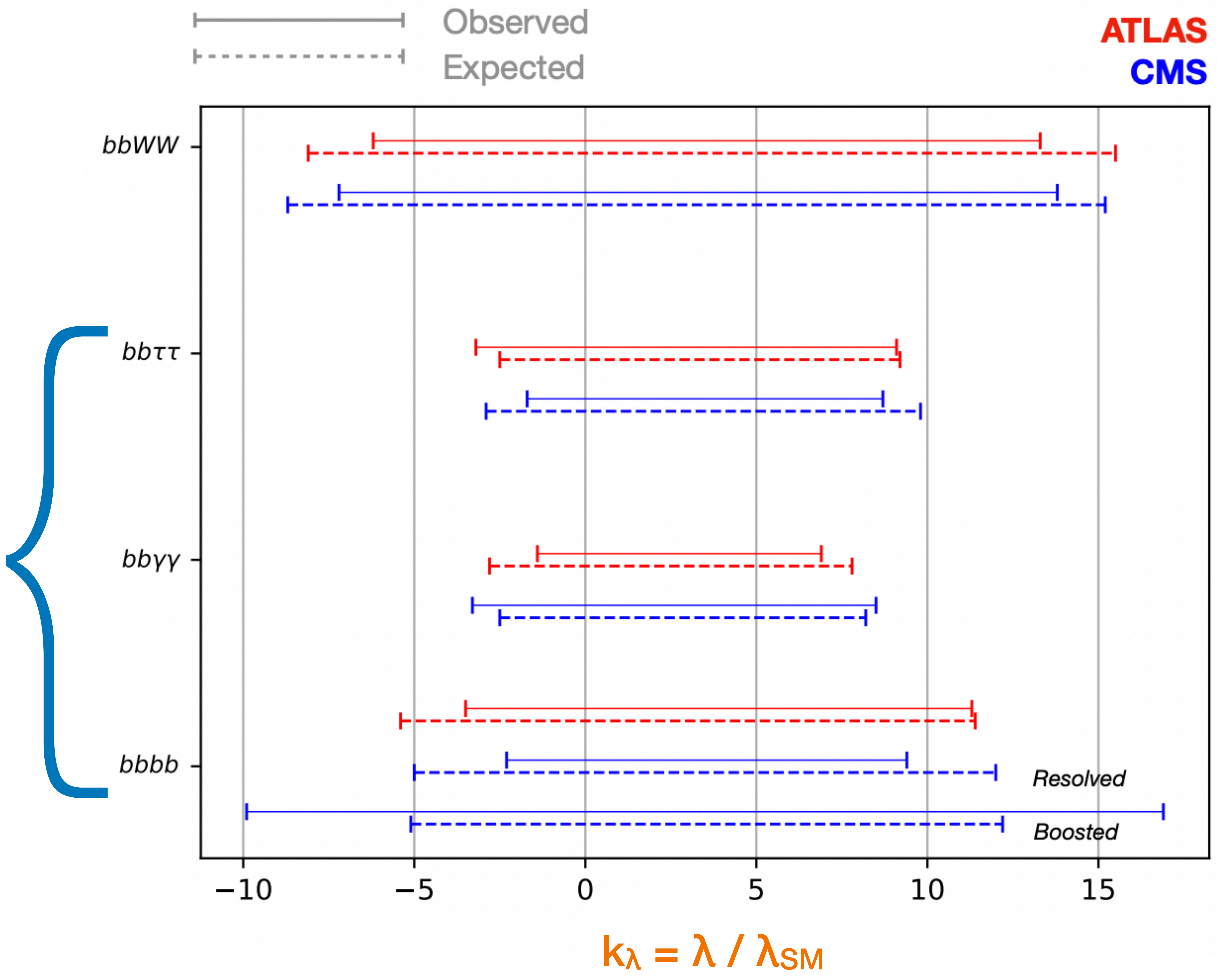
Remarkably:

back of the envelope combination +
scaling with LHC Run-3 luminosity (~300/fb) +
ATLAS & CMS combination

3σ evidence of HH production not out of reach

HH searches in ATLAS: a general overview

(plots courtesy of Luca Cadamuro from ATLAS HH workshop)



- Sensitivity to the Higgs self-coupling parameter still in the range of O(10)
- Combining all ATLAS analysis (plus single-Higgs, some assumptions)

$$-1.4 < \kappa_\lambda < 6.1$$

Phys. Lett. B 843 (2023) 137745

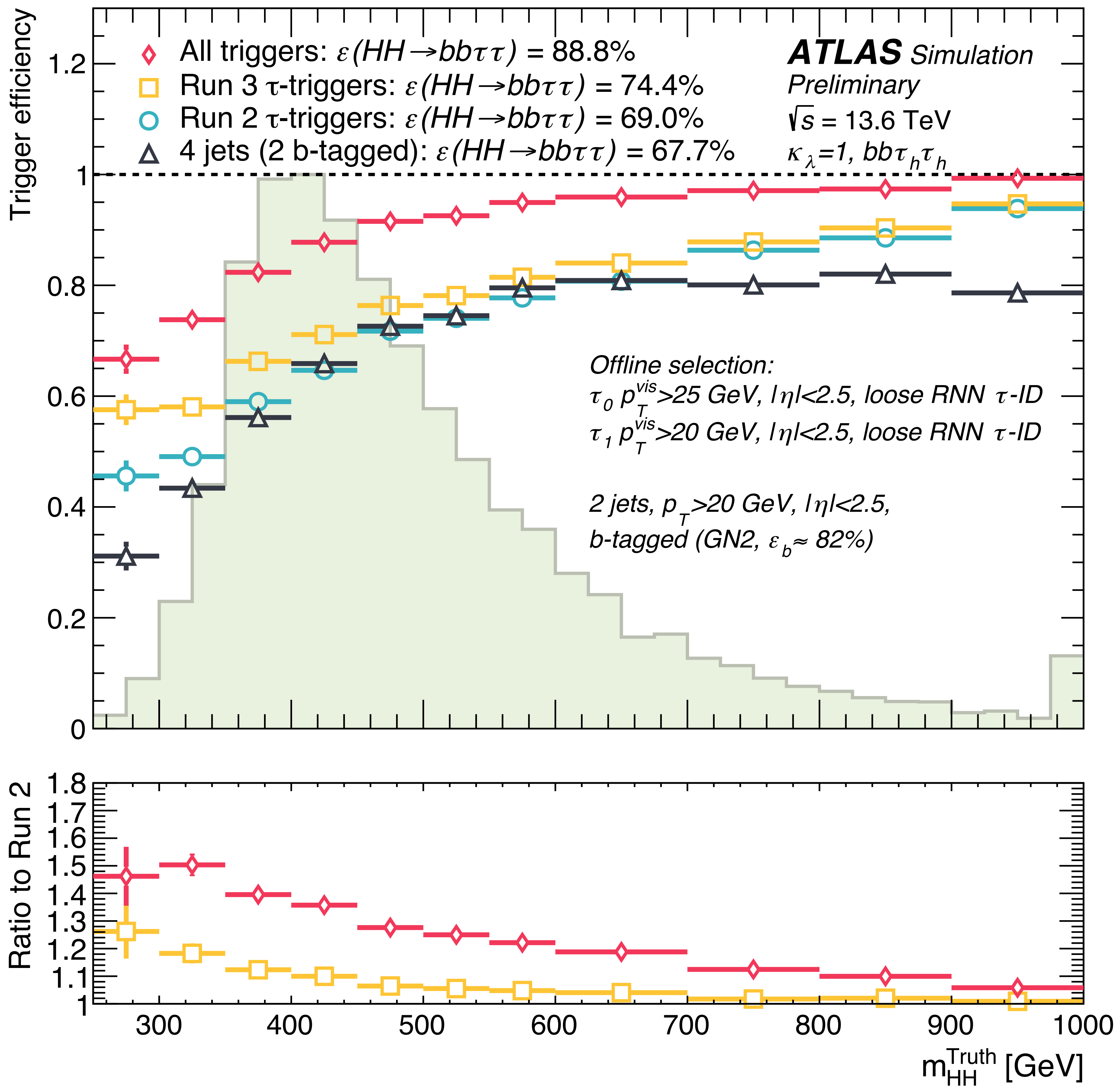
Looking to the future

Run-3: zoom on triggers

Di-Higgs searches are statistically limited: any additional luminosity directly impactful

O(300/fb) roughly double the available LHC Run-2 dataset, but of course we can do better

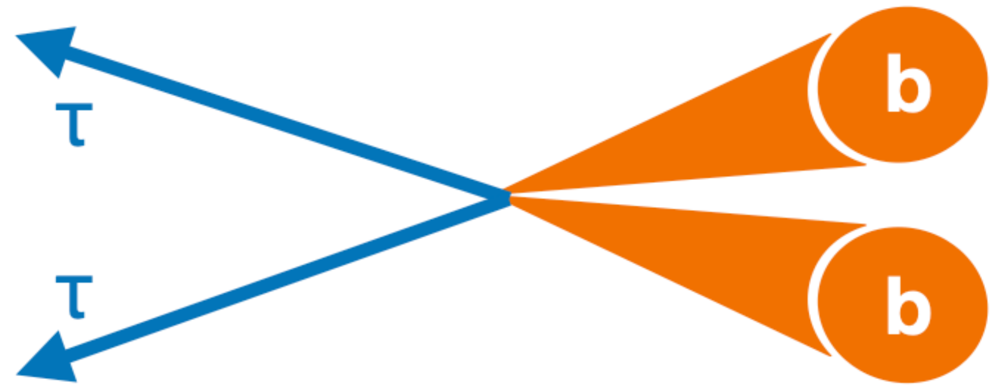
ATL-COM-DAQ-2023-100



Novel approach for HH(bbττ)

LHC collision events stored to tape based on hadronic jet activity

(rather than τ-leptons)



Trigger efficiency up to **+O(50%)** — up to 15/20% improved sensitivity

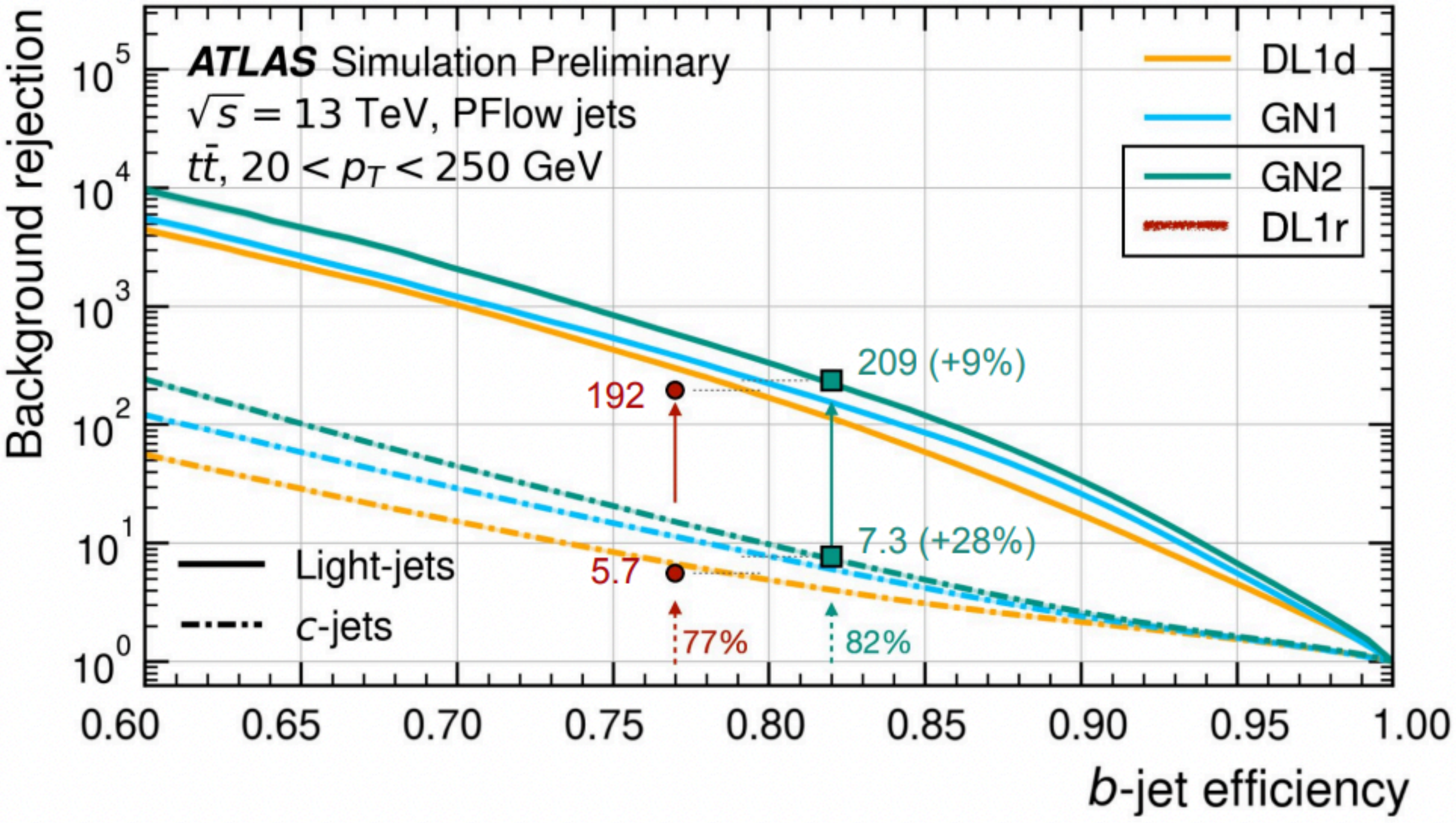
(effectively increasing the available luminosity)

Run-3: zoom on triggers

Di-Higgs searches are statistically limited: any additional luminosity directly impactful

O(300/fb) roughly double the available LHC Run-2 dataset, but of course we can do better

FTAG-2023-01



New algorithms for b-jet tagging

From **DL1r** to **GN2**

- ε(b-tag) = 77% → ε(b-tag) = 82%
- 30% improvement in charm-rejection
- 10% improvement in light rejection

These improvements don't come for free, work ongoing to calibrate and implement these new algorithms in the current (partial) **Run-3 dataset**

HL-LHC

HL-LHC

LHC schedule

2023-2028: Run-3	2029-2034: Run-4	2035-2039: Run-5	>2040: Run-6
$+O(300fb^{-1})$	$+O(1ab^{-1})$	$O(2ab^{-1})$	$O(3ab^{-1})$

Projections to the HL-LHC future become more guess-work

Estimates exist from ATLAS and CMS but they should be taken with a grain of salt (new detectors, …)

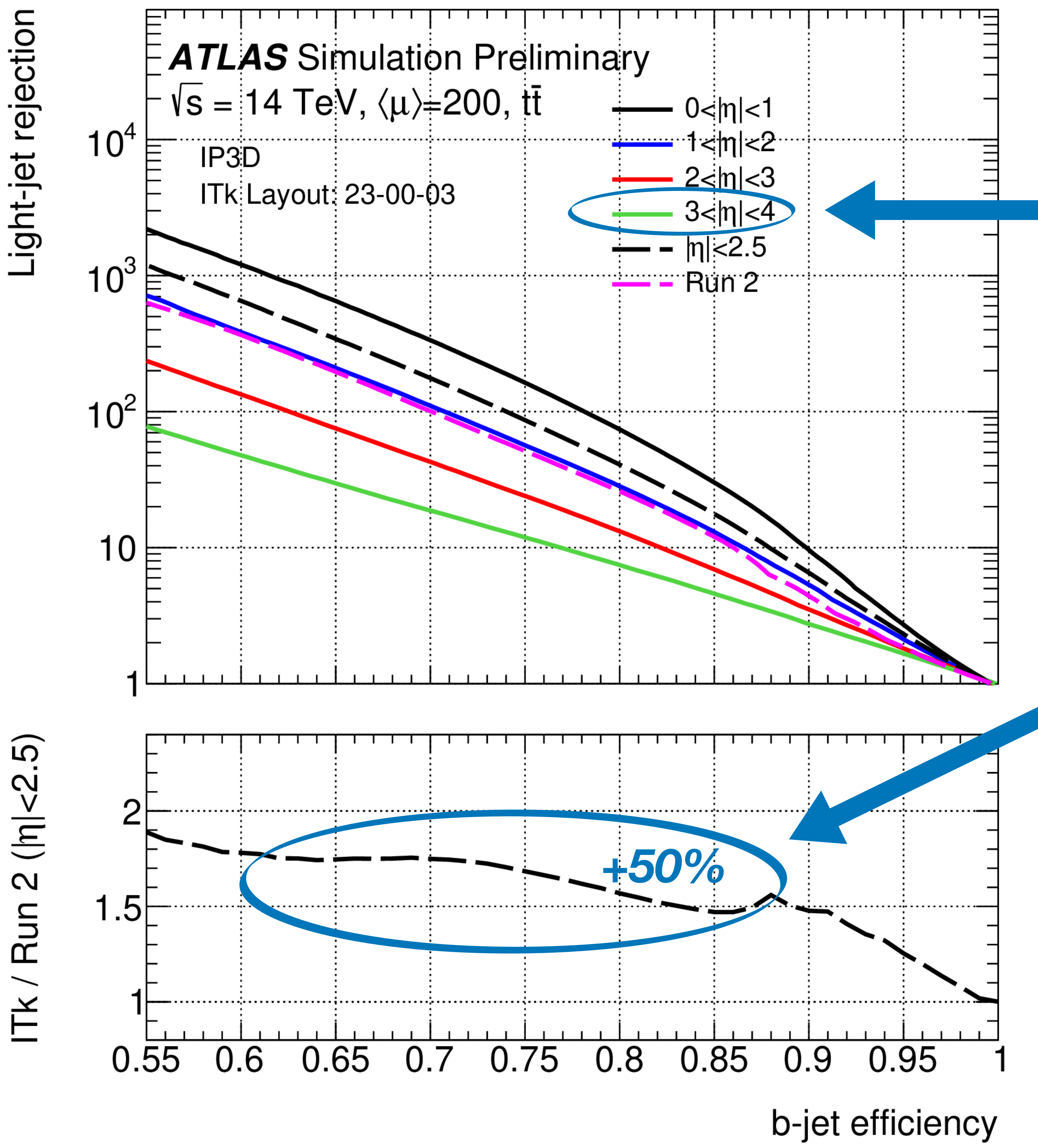
ATL-PHYS-PUB-2022-053

Medium Term: LHC Run-4

HH	5σ observation
$\delta\lambda_{HHH}$	<50%
λ_{HHHH}	<O(10)

potential targets in my view
(please don't quote this as ATLAS numbers!)

Example: new ATLAS tracker

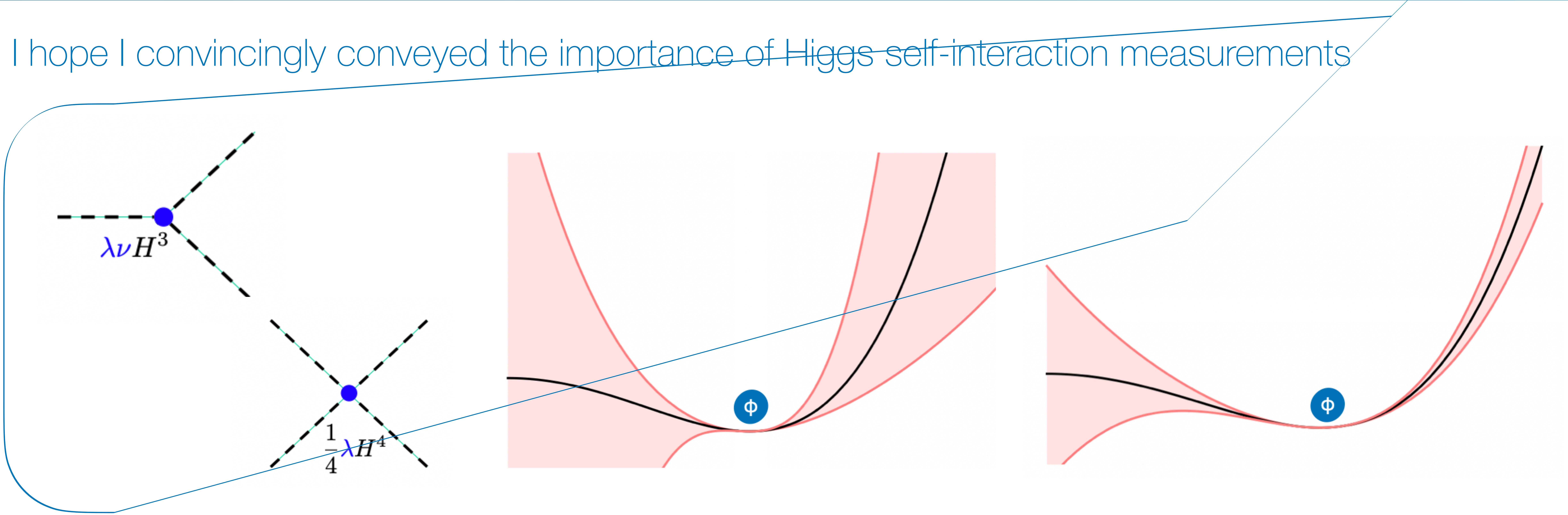


Tracking in the forward region |η|<4

b-tagging performance improved by O(>50%)

Conclusions

I hope I convincingly conveyed the importance of Higgs self-interaction measurements



- LHC Run-2 delivered first results, HH limit-setting and self-coupling $\delta\lambda_{HHH} \sim 10$
- LHC Run-3 started, dataset ~ same order of magnitude, 3σ evidence not out of reach
- HL-LHC is the final target, $\delta\lambda_{HHH}$ ~ potentially 50% in reach

Selle du Puy Gris, Belledonne