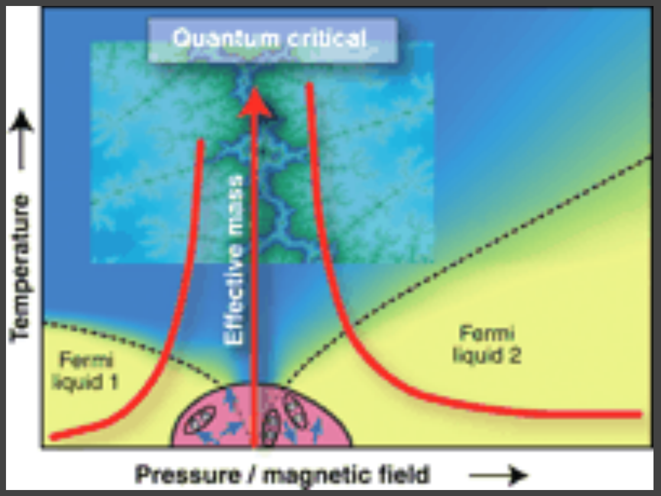
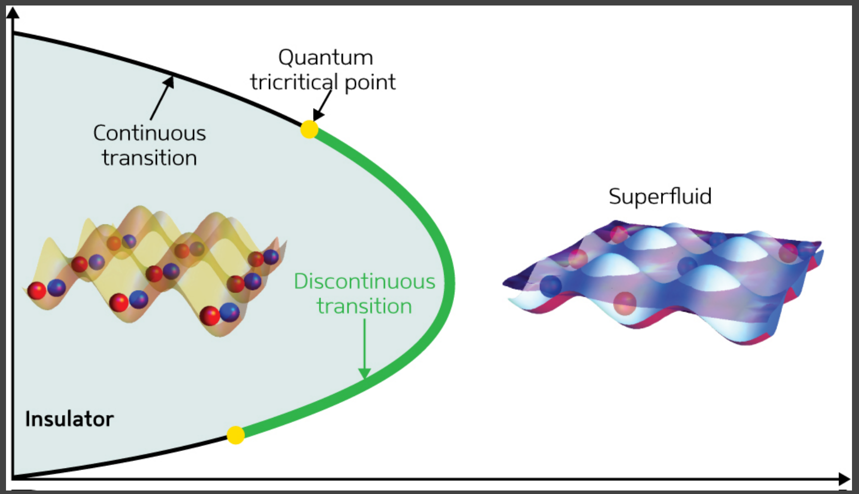
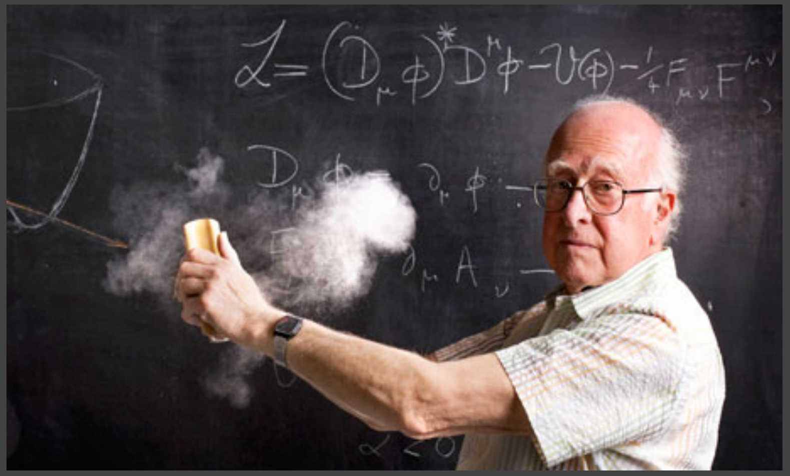
ERC Workshop: 09/13/2016
Effective Field Theories for Collider Physics, Flavor Phenomena and Electroweak Symmetry Breaking , Brug Crass, Eltville







A Natural Quantum Critical Higgs

Seung J. Lee

KOREA UNIVERSITY
1905

With B. Bellazzini, C. Csaki, J. Hubisz, J. Serra, J. Terning; arXiv:1511.08218
With C. Csaki, A. Parolini, Y. Shirman; work in progress
With C. Csaki, A. Parolini work in progress

Introduction

What Kind of New Physics could be nearby (near the EWSB scale), which is not described by EFT?

Not super-weakly coupled,
yet not inconsistent with the data?

Higgs Problem: way before it was even discovered

Weisskopf Phys. Rev.56 (1939) 72

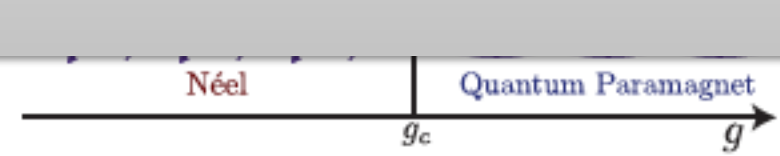
Higgs & Quantum Phase Transition

Condensed matter systems can produce a light scalar by tuning the parameters close ... rs.

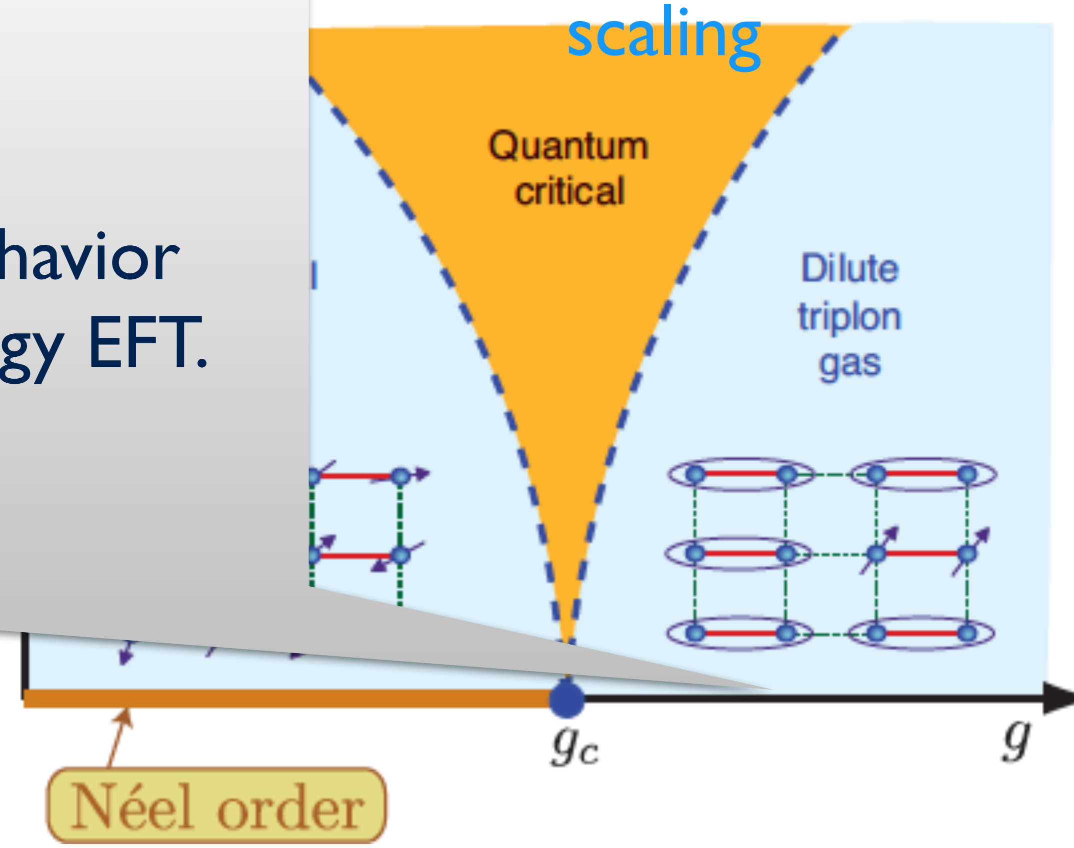
@2nd order QPT, @ critical point, all masses vanish & the theory is scale invariant, characterized by the dimensions of the field,

and at low energies we will see the universal behavior of some fixed point that constitutes the low-energy EFT.

scaling



Sachdev, arXiv:1102.4268



What is the nature of electroweak phase transition?

Does the underlying theory also have a QPT?

If so, is it more interesting than mean-field theory?

$$G(p) \sim \frac{i}{p^2} \quad \text{vs.} \quad G(p) \sim \frac{i}{(p^2)^{2-\Delta}} \quad \text{or} \quad G(p) \sim \frac{i}{(p^2-\mu^2)^{2-\Delta}}$$

Ising Model

$$H = -J\sum s(x)s(x+n)$$

$$s(x) = \pm 1$$

Low T

High T

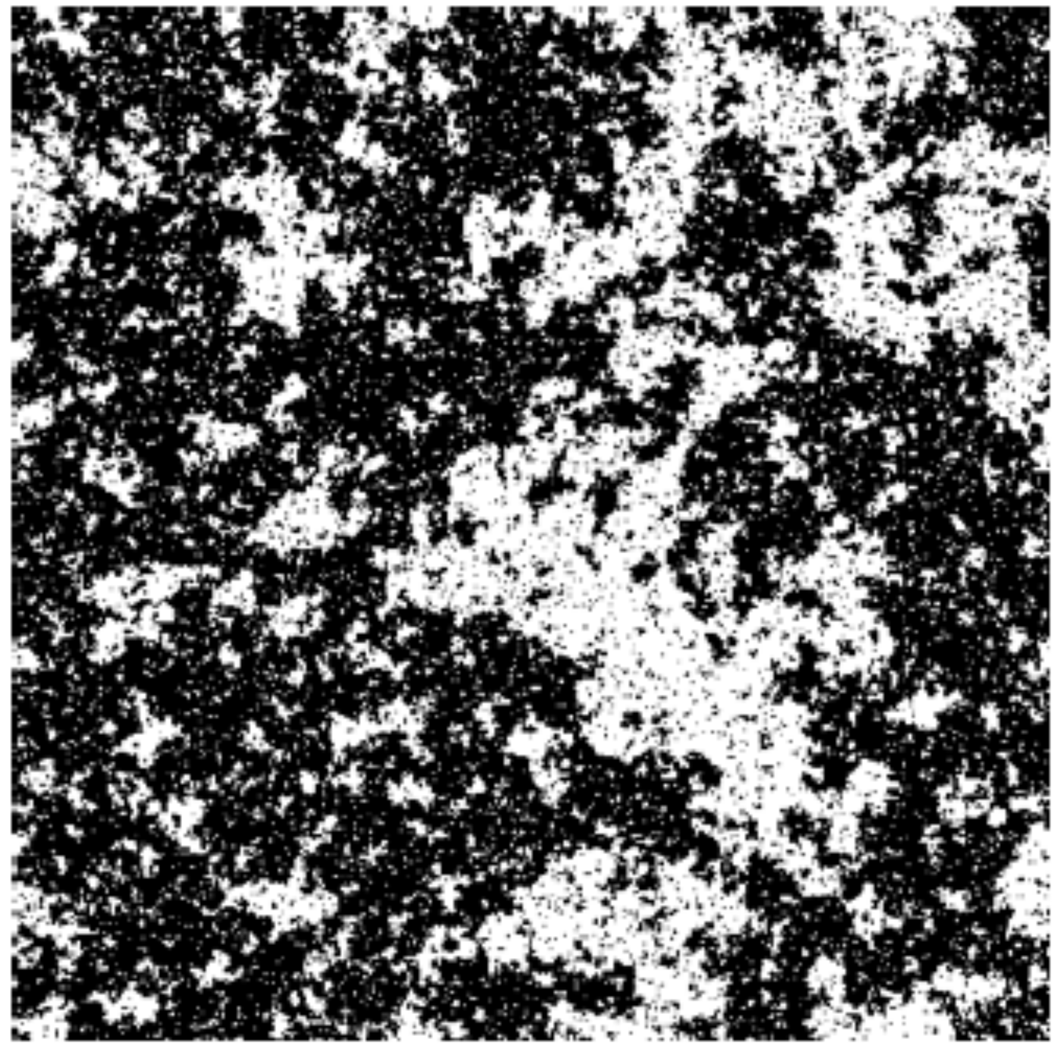
T_c

$$\langle s(0)s(x)\rangle = e^{-|x|/\xi}$$

at $T=T_c$ $\quad \xi \to \infty$

Courtesy of J. Terning

Critical Ising Model is Scale Invariant



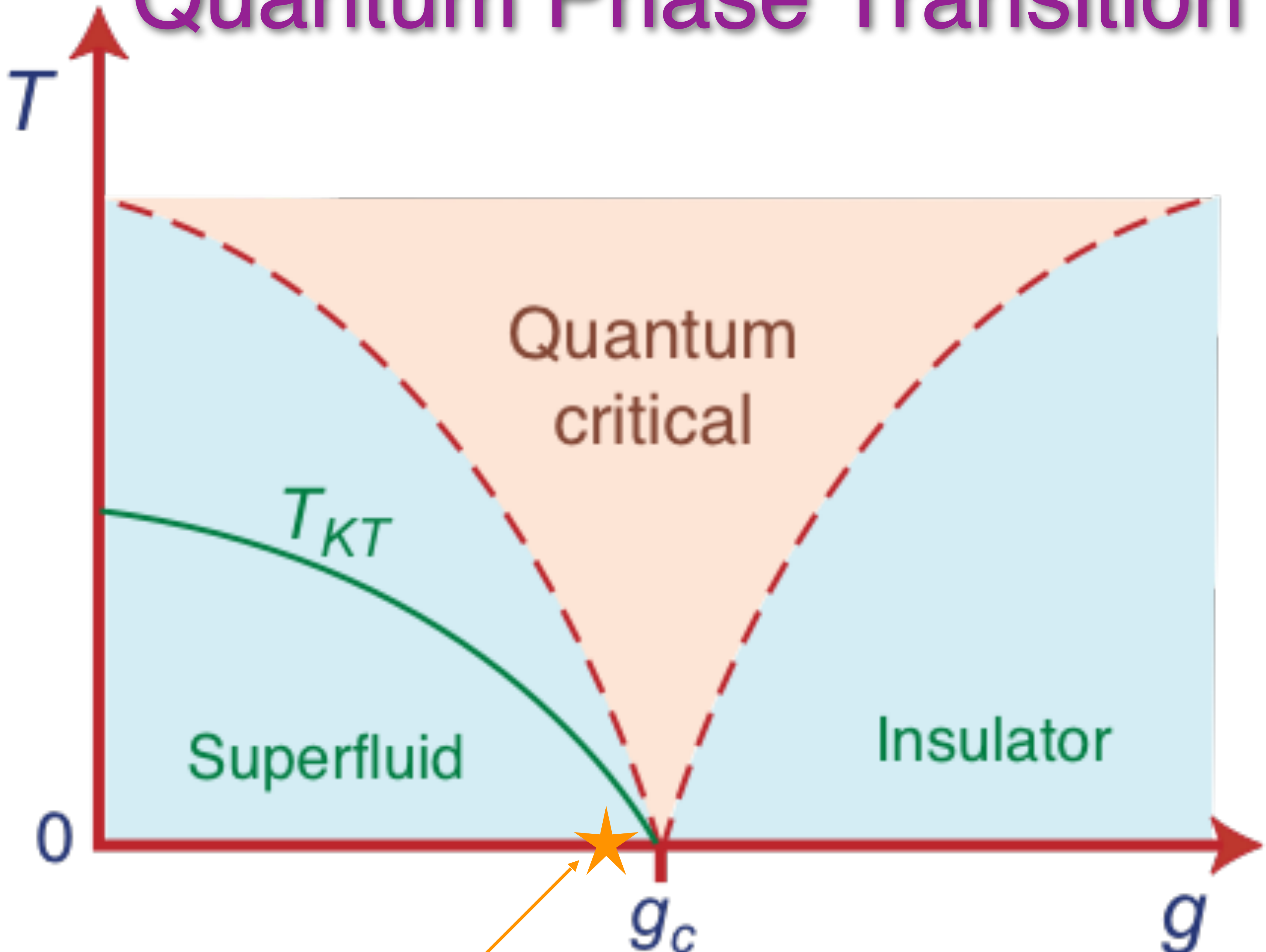
http://bit.ly/2Dcrit

at T=T$_c$ $\quad \langle s(0)s(x)\rangle \propto \frac{1}{|x|^{2\Delta-1}} = \int d^3p\, \frac{e^{ip\cdot x}}{|p|^{4-2\Delta}}$

critical exponent

Courtesy of J. Terning

Quantum Phase Transition



We are here

The Quantum Critical Higgs

- At a QPT the approximate scale invariant theory is characterized by the scaling dimension Δ of the gauge invariant operators.

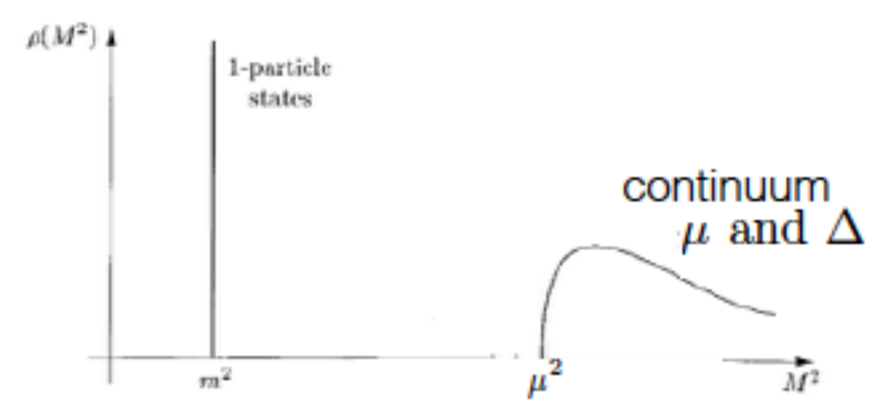
  SM: $\Delta = 1 + \mathcal{O}(\alpha/4\pi)$.

- We want to present a general class of theories describing a higgs field near a non-mean-field QPT.

- In such theories, in addition to the pole (Higgs), there can also be a higgs continuum, representing additional states associated with the dynamics underlying the QPT

$$G_h(p^2) = \frac{i}{p^2 - m_h^2} + \int_{\mu^2}^{\infty} dM^2 \frac{\rho(M^2)}{p^2 - M^2}$$

- One result of the presence of the non-trivial scaling dimension and continuum will be the appearance of form factors in couplings of the Higgs to the SM particles.



Modeling the QCH: generalized free fields

Generalized Free Fields

Polyakov, early '70s- skeleton expansions

CFT completely specified by 2-point function - rest vanish

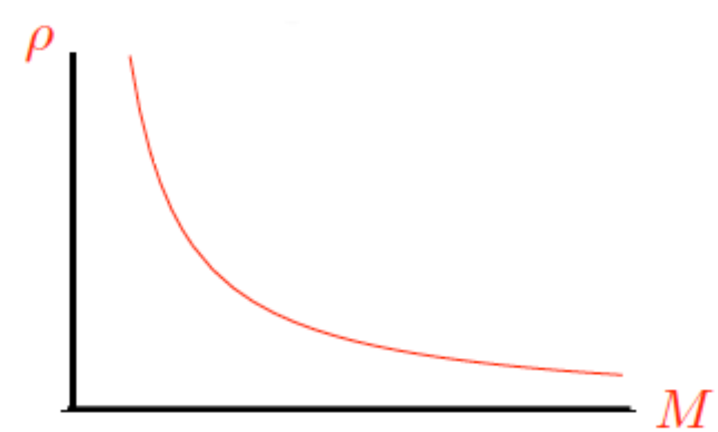
Scaling - 2-point function: $G(p^2) = -\dfrac{i}{(-p^2 + i\epsilon)^{2-\Delta}}$

Can be generated from: $\mathcal{L}_{\rm GFF} = -\hbar^\dagger \left(\partial^2\right)^{2-\Delta} \hbar$

Georgi
hep-ph/0703260

Branch cut starting at origin - spectral density purely a continuum:

$$G(p) \sim \int_{\mu^2}^{\infty} dM^2 \frac{\rho(M^2)}{p^2 - M^2}$$



Modeling the QCH: generalized free fields

With the discovery of Higgs, we need a pole (125 GeV) and a gap to BSM continuum

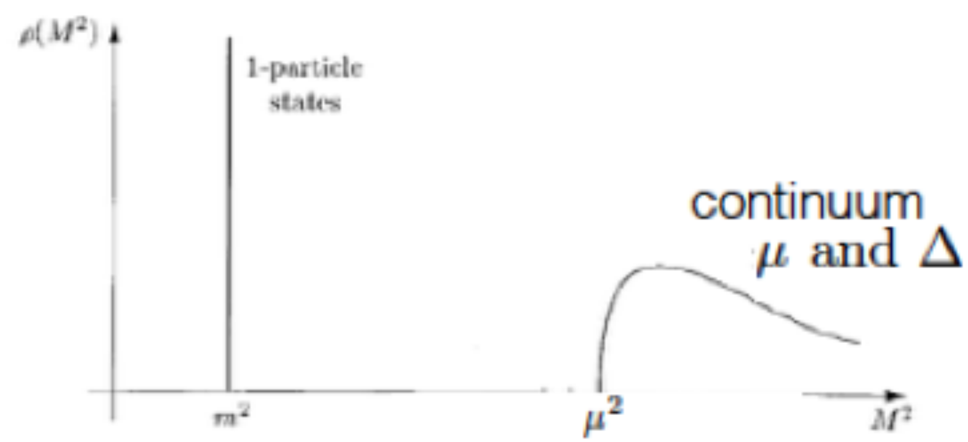
- A model with just two parameters:

$$\mathcal{L}_{\text{quadratic}} = -\frac{1}{2\,Z_{\hbar}}\hbar\left[\partial^2+\mu^2\right]^{2-\Delta}\hbar + \frac{1}{2\,Z_{\hbar}}(\mu^2-m_{\hbar}^2)^{2-\Delta}\hbar^2$$

Assuming $\hbar$ to be weakly coupled, the scaling dimension of $\hbar^2$ is 2Δ

Generally:

$$G_{\hbar}(p^2) = \frac{i}{p^2-m_{\hbar}^2} + \int_{\mu^2}^{\infty} dM^2\,\frac{\rho(M^2)}{p^2-M^2}$$



SM recovered in limits $\mu\to\infty$ and/or $\Delta\to 1$

Form Factors for the Quantum Critical Higgs

- When looking at observables, we need to use form factors to characterize the strong sector in generality, since there is no separation of scales.

This is not an EFT expansion, but rather an expansion in weak couplings that perturb the generalized free field theory.

Form Factors for the Quantum Critical Higgs

- We consider a QPT Higgs scenario where Higgs is (partially) imbedded into a strongly coupled sector (approximately conformal at scale well above the EW scale)

  => Higgs pick up a significant anomalous dimension, and there is a large mixing with the continuum

- The effects of Higgs emerging from the quantum critical point can be parametrized in terms of form factors in a model independent way.

- We assume that the SM fermions, the massless gauge bosons, and the transverse parts of the W and Z are external to the CFT, that is elementary, while the Higgs (Z_{long}, W_{long}) originates from or is mixed with the strong sector, corresponding to a theory with spontaneously or explicitly broken conformal symmetry.

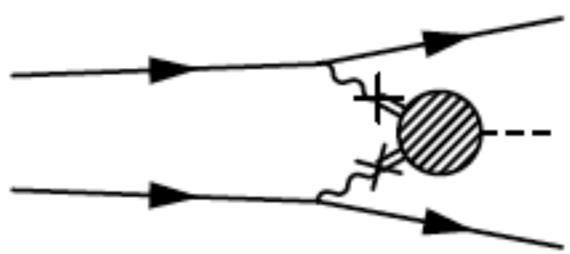
  => this strong sector is characterized by its n-point functions entering into form factors

Off-shell Form Factors for the Quantum Critical Higgs

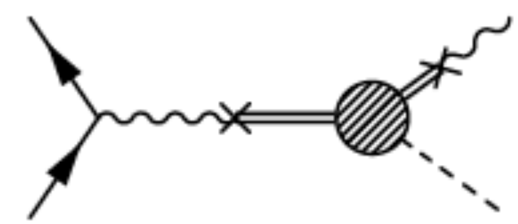
Off-shell behavior: nontrivial momentum dependent form factors

$$p_1^2 + p_2^2 = m_h^2 - 2p_1 \cdot p_2.$$

VBF



Higgsstrahlung: $p_2 \to -p_2$



$$\mathcal{M}_{VBF} \;=\; J_1^{\alpha} G^V_{\alpha\mu}(p_1)\; J_2^{\beta} G^V_{\nu\beta}(p_2) F^{\mu\nu}_{\mathrm{VVh}}(p_i;\mu)\, N_V$$

$$\mathcal{M}_{q\bar{q}\to Vh} \;=\; J_I^{\alpha} G^V_{\alpha\mu}(p_1)\, \bar{\epsilon}_{2\nu} F^{\mu\nu}_{\mathrm{VVh}}(p_1, -p_2;\mu)\, N_V$$

$$F^{\mu\nu}_{VVh}(p_i;\mu) = g^{\mu\nu}\,\Gamma_1 + (g^{\mu\nu} p_1\cdot p_2 - p_2^{\mu} p_1^{\nu})\,\Gamma_2 + (p_1^{\mu} p_1^{\nu} + p_2^{\mu} p_2^{\nu})\,\Gamma_3 + (p_1^{\mu} p_1^{\nu} - p_2^{\mu} p_2^{\nu})\,\Gamma_4 + p_1^{\mu} p_2^{\nu}\,\Gamma_5$$

$$\Gamma_i = \Gamma_i(p_1^2, p_2^2, p_1\cdot p_2)$$

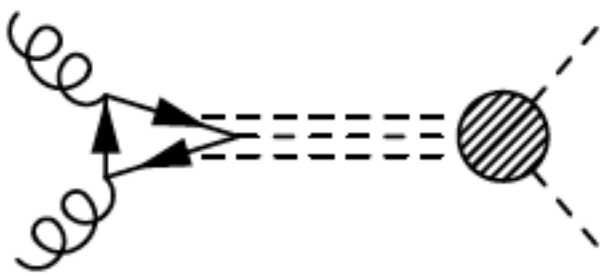
$$\Gamma_1^{(\mathrm{SM})} = 1 \text{ and } \Gamma_{i\neq 1}^{(\mathrm{SM})} = 0.$$

etc…

Off-shell Form Factors for the Quantum Critical higgs

Off-shell behavior: nontrivial momentum dependent form factors

$p_1 \cdot p_2 = s/2$



$p_1 \cdot p_3 = (m_h^2 - t)/2$

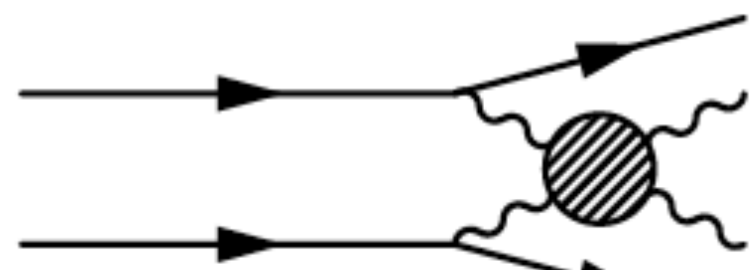
$$\mathcal{M}_{gghh} = \left[(\epsilon_1 \cdot p_2)(\epsilon_2 \cdot p_1) - (p_1 \cdot p_2)(\epsilon_1 \cdot \epsilon_2) \right] \Xi_1 (p_1 \cdot p_2, p_1 \cdot p_3; \mu)$$
$$+ \epsilon_2 \cdot [(p_1 \cdot p_2) p_3 - (p_2 \cdot p_3) p_1] \, \epsilon_1 \cdot [(p_1 \cdot p_2) p_3 - (p_1 \cdot p_3) p_2] \, \Xi_2 (p_1 \cdot p_2, p_1 \cdot p_3; \mu)$$

suppressed in the large top mass limit in the SM

Bose Symmetry: $\Xi_i (p_1 \cdot p_2, p_1 \cdot p_3; \mu) = \Xi_i (p_1 \cdot p_2, p_2 \cdot p_3; \mu)$

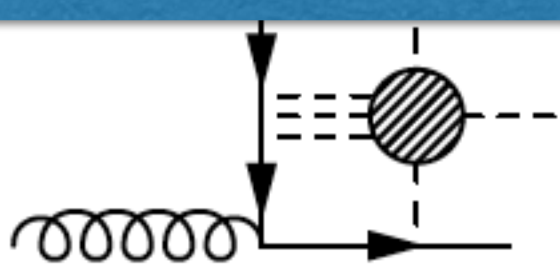
Off-shell Form Factors for the Quantum Critical higgs

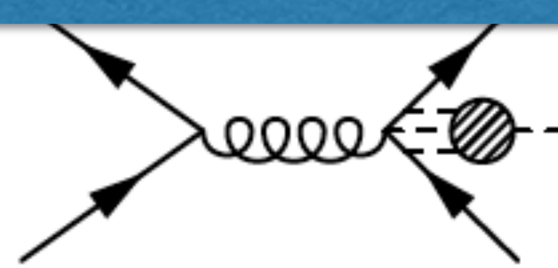
Off-shell behavior: nontrivial momentum dependent form factors



On can estimate from an EFT perspective, where Higgs is (the only) light degree of freedom surviving from the strongly coupled sector (below the scale \mu).

=> can estimate the size of the N-point Higgs correlator by considering the effect of loops on its renormalization.



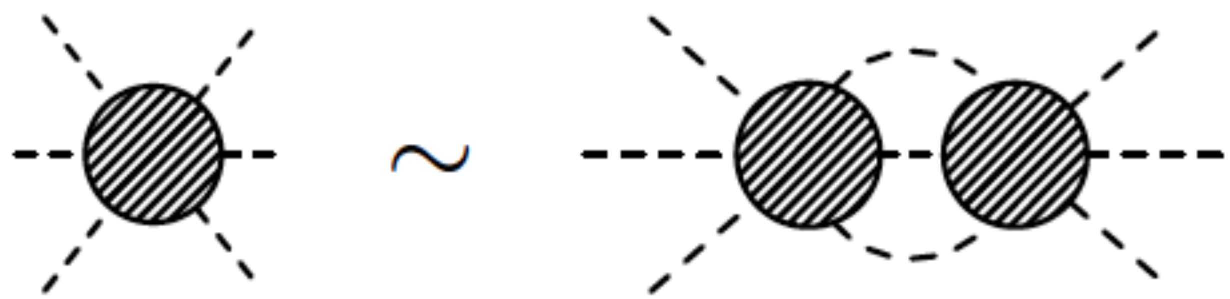


$\Theta_k = \Theta_k(p_1 \cdot p_2, p_1 \cdot p_3)\,, \quad \widehat{\Theta}_k^{ij} = \widehat{\Theta}_k^{ij}(p_1 \cdot p_2, p_1 \cdot p_3)$

Estimation of Form Factors

use low energy effective theory of 125 GeV resonance
apply tenets of NDA below onset of cut/continuum:

$$\mathcal{L} = \frac{\alpha_n}{\mu^{n-4}}\phi^n$$

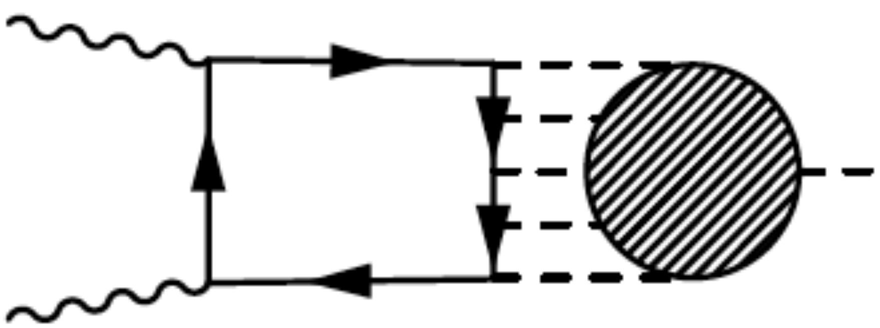


$$\alpha_n \sim (16\pi^2)^{n/2-1}$$

Counting:
n/2-1 loops cut off at IR scale and dimensional analysis

Estimation of Form Factors

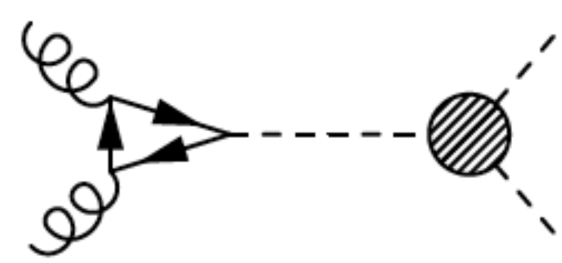
If top quark is external to strong dynamics:



$$g_n^{tth} \sim 4\pi \left(\frac{\lambda_t}{4\pi}\right)^{n-1}$$

Gluon fusion process involves (perturbative) coupling of top quark to Higgs field

e.g. double Higgs production through gluon fusion would be dominated by



dominant contribution comes from tree diagram

Generalized Free Fields via AdS/CFT

Cacciapaglia, Marandella and Terning 08'
Falkowski and Perez-Victoria 08'
Bellazzini, Csaki, Hubisz, SL, Serra, Terning 15'

- SO(4) global symmetry is gauged in the 5D bulk

$$S = \int d^4x dz \sqrt{g} \left[|D_M H|^2 - \frac{1}{4g_4^2} W^{a\,2}_{MN} - \phi(z) |H|^2 + \mathcal{L}_{\rm int}(H) \right] + \int d^4x \, \mathcal{L}_{\rm perturbative}.$$

$$ds^2 = a(z)^2 \left(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2 \right) \qquad a(z) = \frac{R}{z} e^{-\frac{2}{3}\mu(z-R)}$$

$$G_h(R,R,p^2) = i\tilde{Z}_h \left[\frac{\mu K_{1-\nu}(\mu R)}{R K_\nu(\mu R)} - \frac{\sqrt{\mu^2 - p^2} K_{1-\nu}(\sqrt{\mu^2-p^2}R)}{R K_\nu(\sqrt{\mu^2-p^2}R)} - M_0^2 \right]^{-1}$$

Soft wall terminates CFT with continuum, not set of KK modes

The bulk to brane propagator is then given by $G_h(R,z,p^2) = a^{-\frac{3}{2}}(z)(z/R)^{\frac{1}{2}} \dfrac{K_\nu(\sqrt{\mu^2-p^2}z)}{K_\nu(\sqrt{\mu^2-p^2}R)}$

=> reduce to the previous propagator in the limit pR <<1 :

$$G_{\hbar}(p) = -\frac{i\, Z_{\hbar}}{(\mu^2 - p^2 + i\epsilon)^{2-\Delta} - (\mu^2 - m_h^2)^{2-\Delta}} \qquad Z_{\hbar} = \frac{(2-\Delta)}{(\mu^2 - m_h^2)^{\Delta-1}}$$

obtain such propagator from a calculable model of this sort based on a Banks-Zaks fixed point in a supersymmetric QCD theory: Csaki, SL, Shirmanm, Parolini (in preparation)

A Natural Qauntum Critical Higgs

Csaki, SL, Parolini, work in progress

- The upshot is that there is a QPT (CFT) with non-trivial dynamics, and the pole (physical Higgs) arises as a composite bound state of CFT similar to composite Higgs models

A new 5D model: Higgs arises from CFT with a domain wall

$$ds^2 = a(z)^2(dx^2 - dz^2)$$

$$a_{UV}(z) = \frac{R}{z} e^{\frac{2}{3}(R-z)\mu_{UV}}\,, \quad a_{IR}(z) = \frac{R_p}{z} e^{\frac{2}{3}(R_p-z)\mu_{IR}}$$

$$a(z)^{-4}(a(z)a''(z) - 2a'(z)^2) \leq 0$$

wec
holographic a-theorem

$$\mu_{IR} - \mu_{UV} \geq 0.$$

A Natural Qauntum Critical Higgs

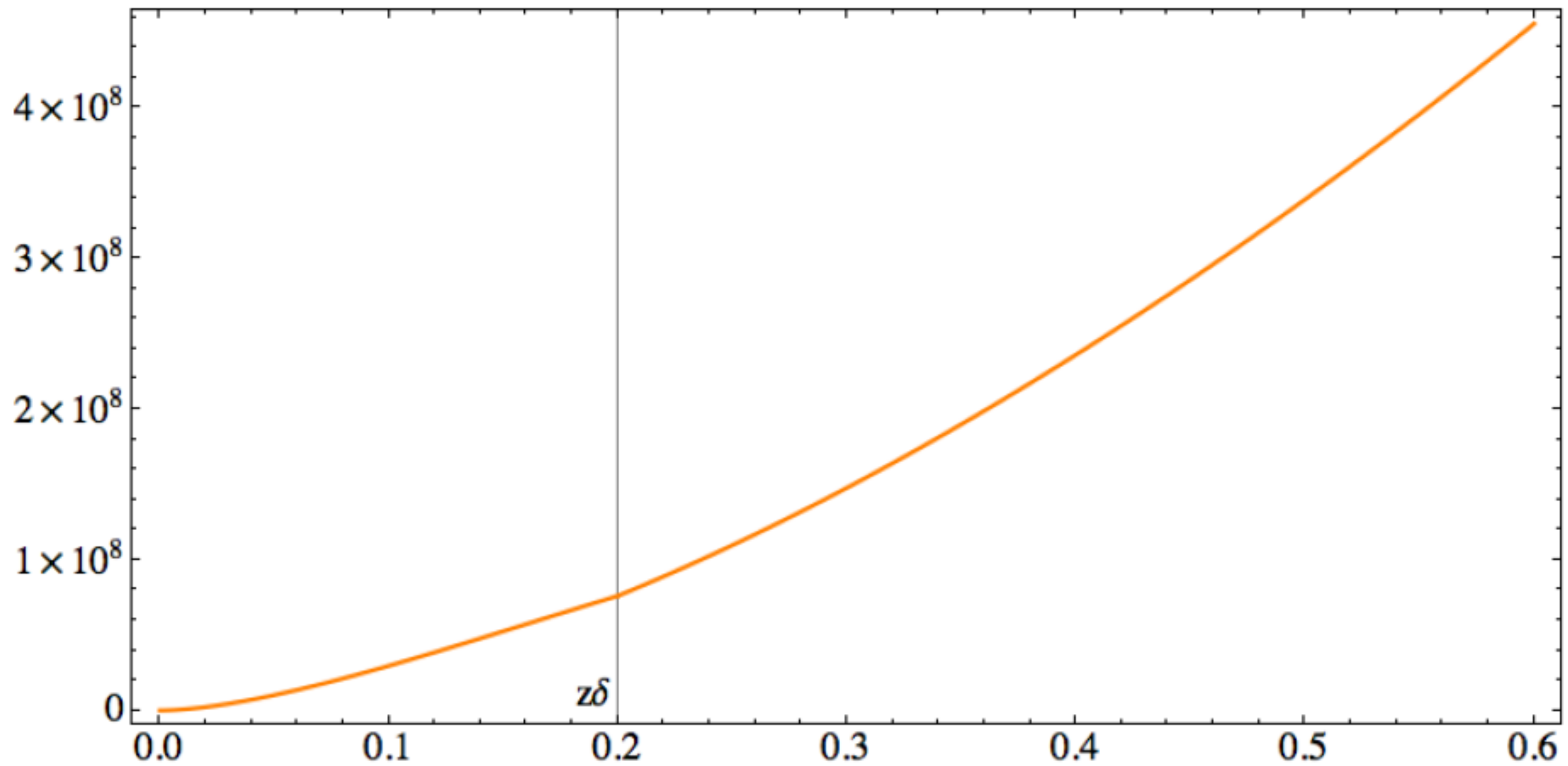
Csaki, SL, Parolini, work in progress

$$\mathcal{L} = \sqrt{g}\left[\frac{1}{2}g^{MN}D_M\Phi^\dagger D_N\Phi - V(\Phi)\right] \qquad \left(-\partial_z^2 + \hat{V}\right)\Psi = p^2\Psi$$

The Schrödinger potential

$$\hat{V} = \hat{M}^2 + \frac{3a''}{2a} + \frac{3(a')^2}{4a^2} \qquad \hat{M}^2 = a^2 R \frac{\partial^2 V(\hat{v})}{\partial \hat{v}^2}.$$

Profile of bulk higgs



A Natural Qauntum Critical Higgs

Csaki, SL, Parolini, work in progress

$$\left(-\partial_z^2 + \hat{V}\right)\Psi = p^2\Psi$$

$$S_{eff} = \frac{1}{2}\int \frac{\mathrm{d}^4 p}{(2\pi)^4} h(-p)\hat{\Pi}(p^2)h(p)$$

The propagator presents a pole for $p^2 = m_0^2$ and it develops a non zero imaginary part for $p^2 > \mu_{IR}^2$

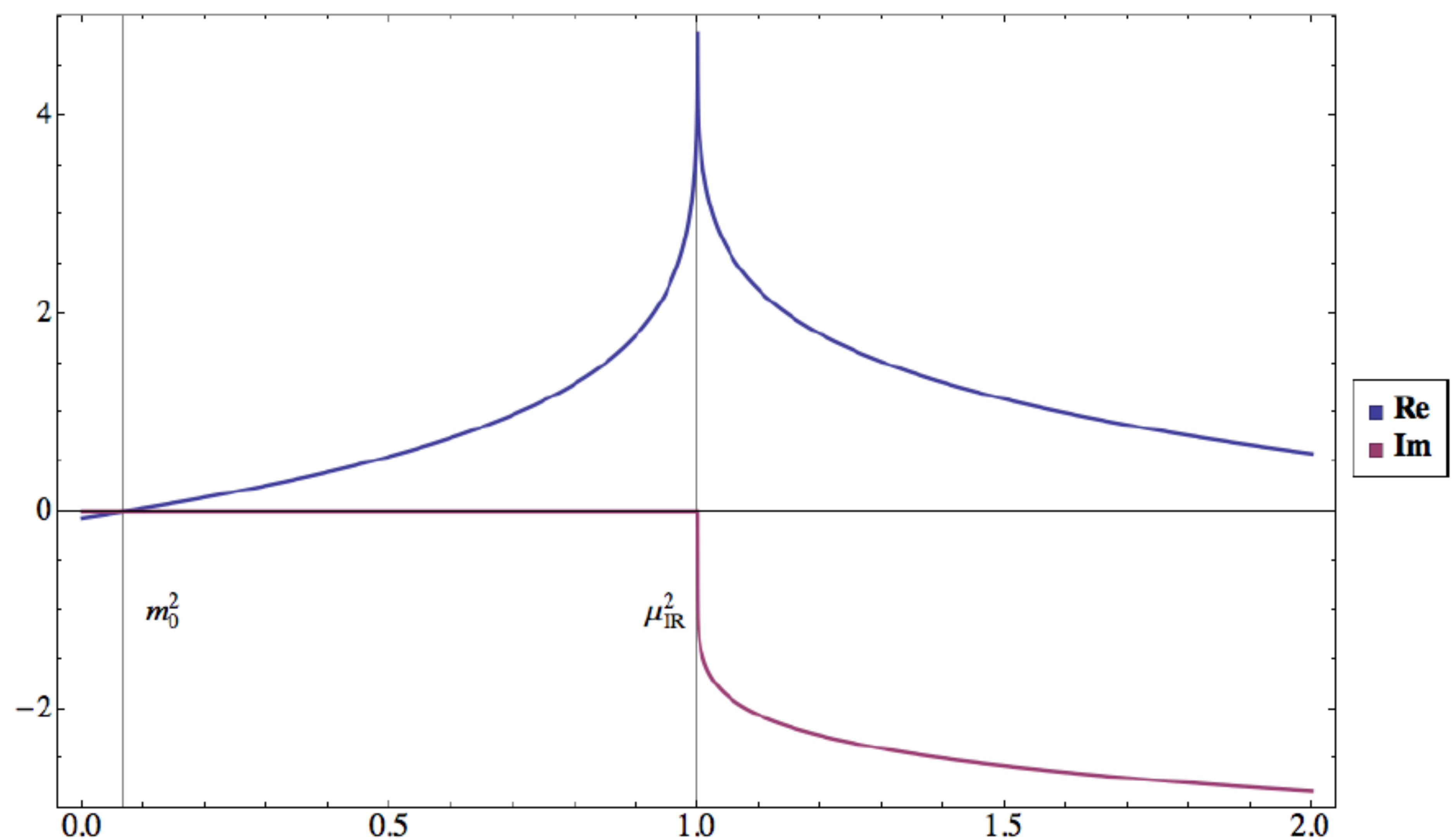
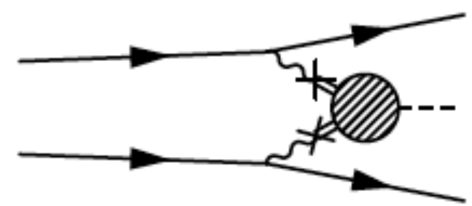
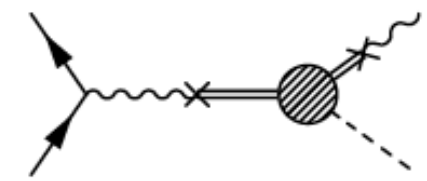


Figure 2: The inverse propagator $\Pi(p^2)$. It becomes zero in correspondence of $p^2 = m_0^2$ and it stays real for $p^2 < \mu_{IR}^2$.

Direct Signals

- Form factors



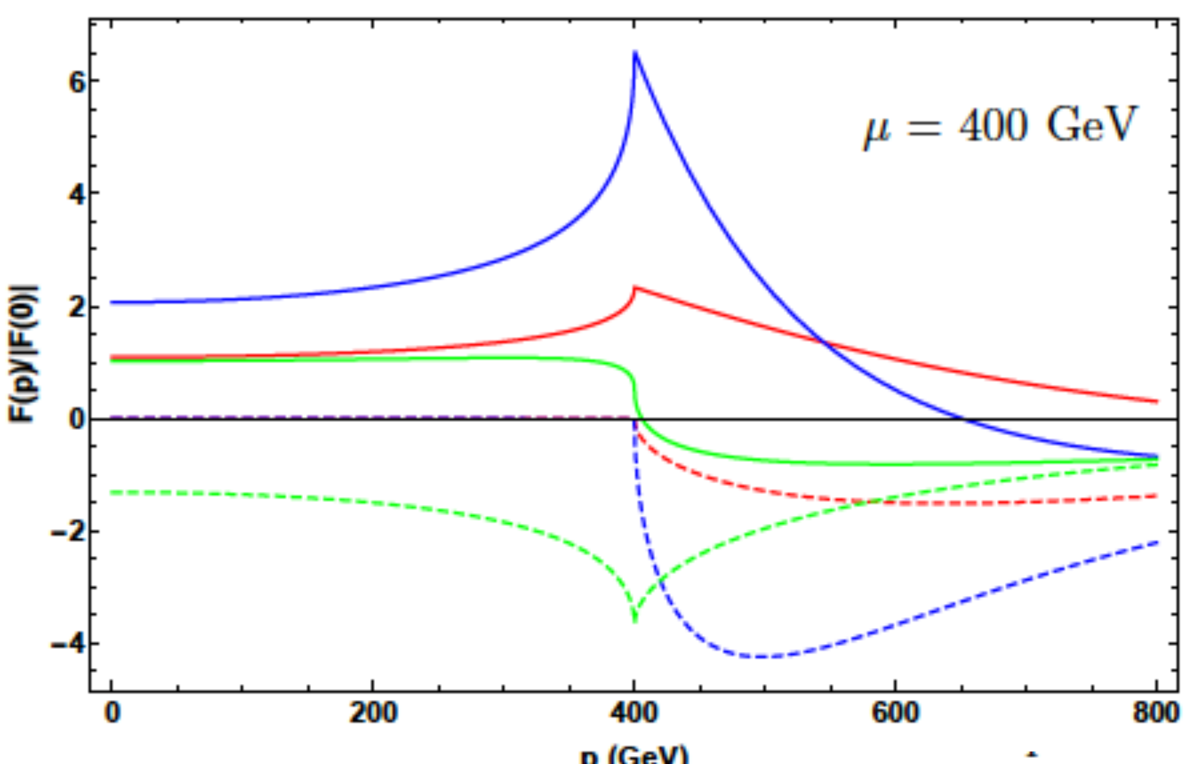


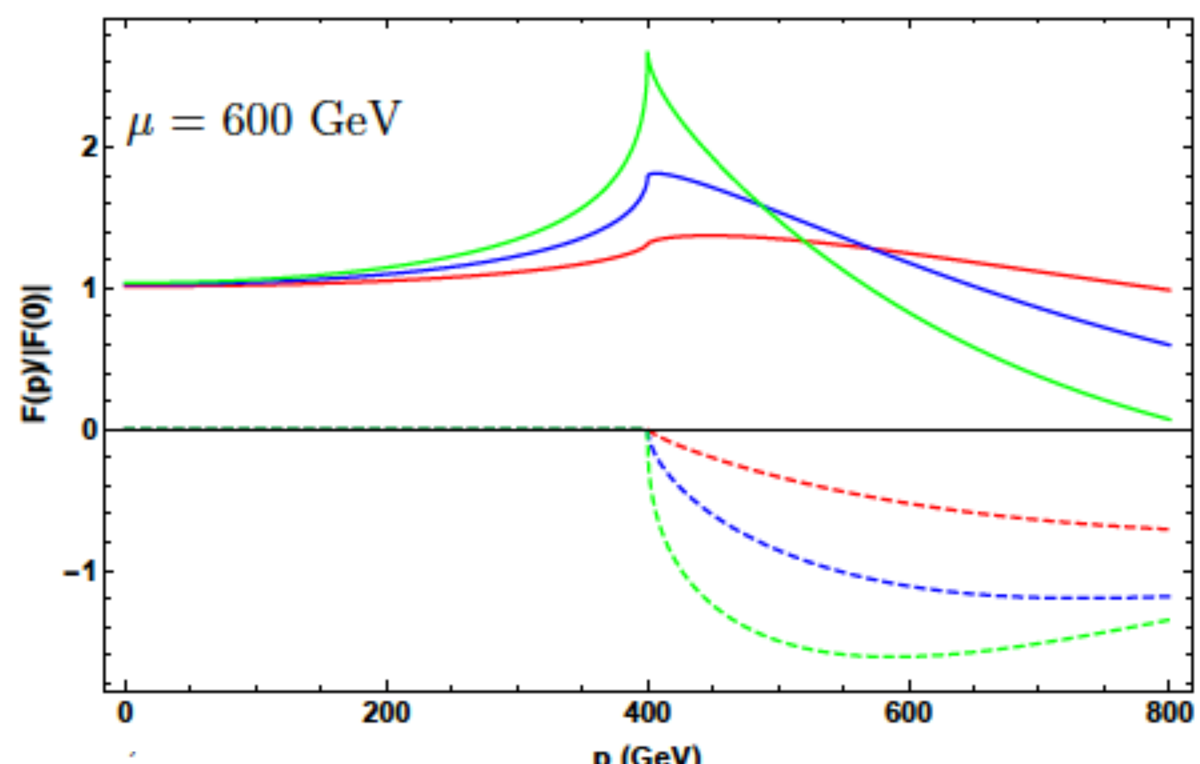
$$\mathcal{H} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \mathcal{V} + h \end{pmatrix}$$

$$\mathcal{M}_{VBF} = J_1^{\alpha} G^V_{\alpha\mu}(p_1)\; J_2^{\beta} G^V_{\nu\beta}(p_2) F^{\mu\nu}_{\mathrm{VVh}}(p_i;\mu)\, N_V$$

$$\mathcal{M}_{qq\to Vh} = J_I^{\alpha} G^V_{\alpha\mu}(p_1)\, \bar{\epsilon}_{2\nu} F^{\mu\nu}_{\mathrm{VVh}}(p_1,-p_2;\mu)\, N_V$$

$$F^{ab}_{VVh} = 2\frac{\mathcal{V}}{L\,M^2}\int_R^{\infty} dz\, a^2\left(\frac{z}{R}\right)\frac{K_{2-\Delta}(\sqrt{\mu^2-(p_1+p_2)^2}\,z)K_{2-\Delta}(\mu\, z)}{K_{2-\Delta}(\sqrt{\mu^2-(p_1+p_2)^2}\,R)K_{2-\Delta}(\mu\, R)}$$

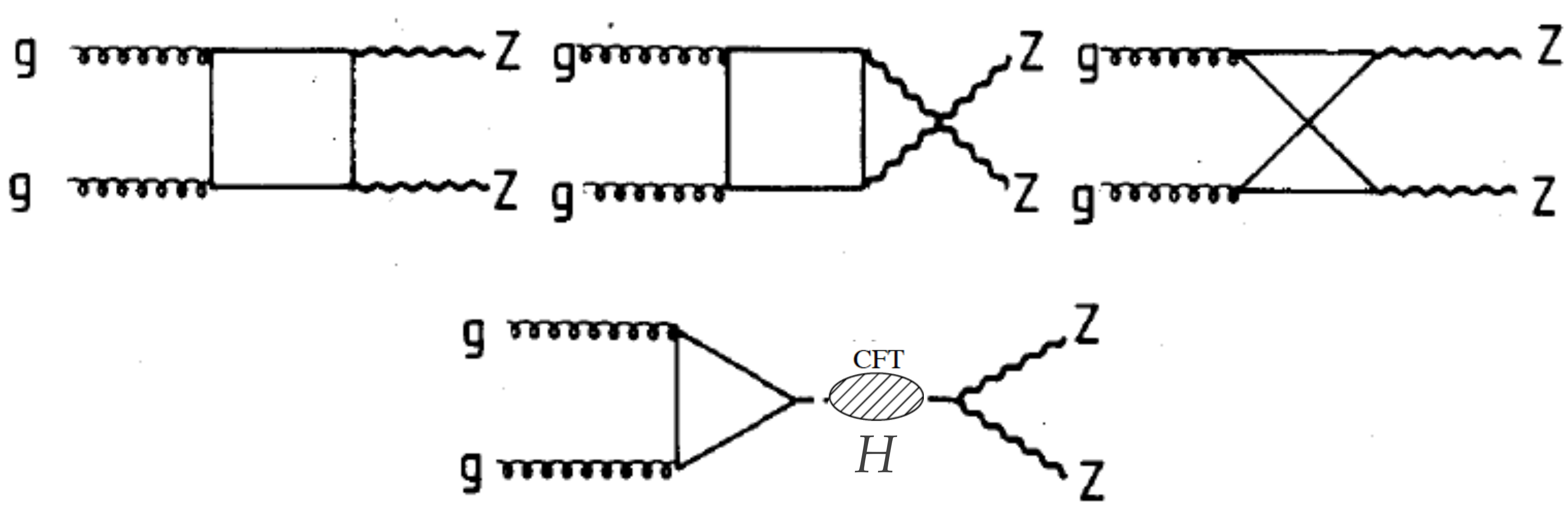




$\Delta = 1.2$ (Red), 1.4 (Blue), and 1.6 (Green)

Direct Signals

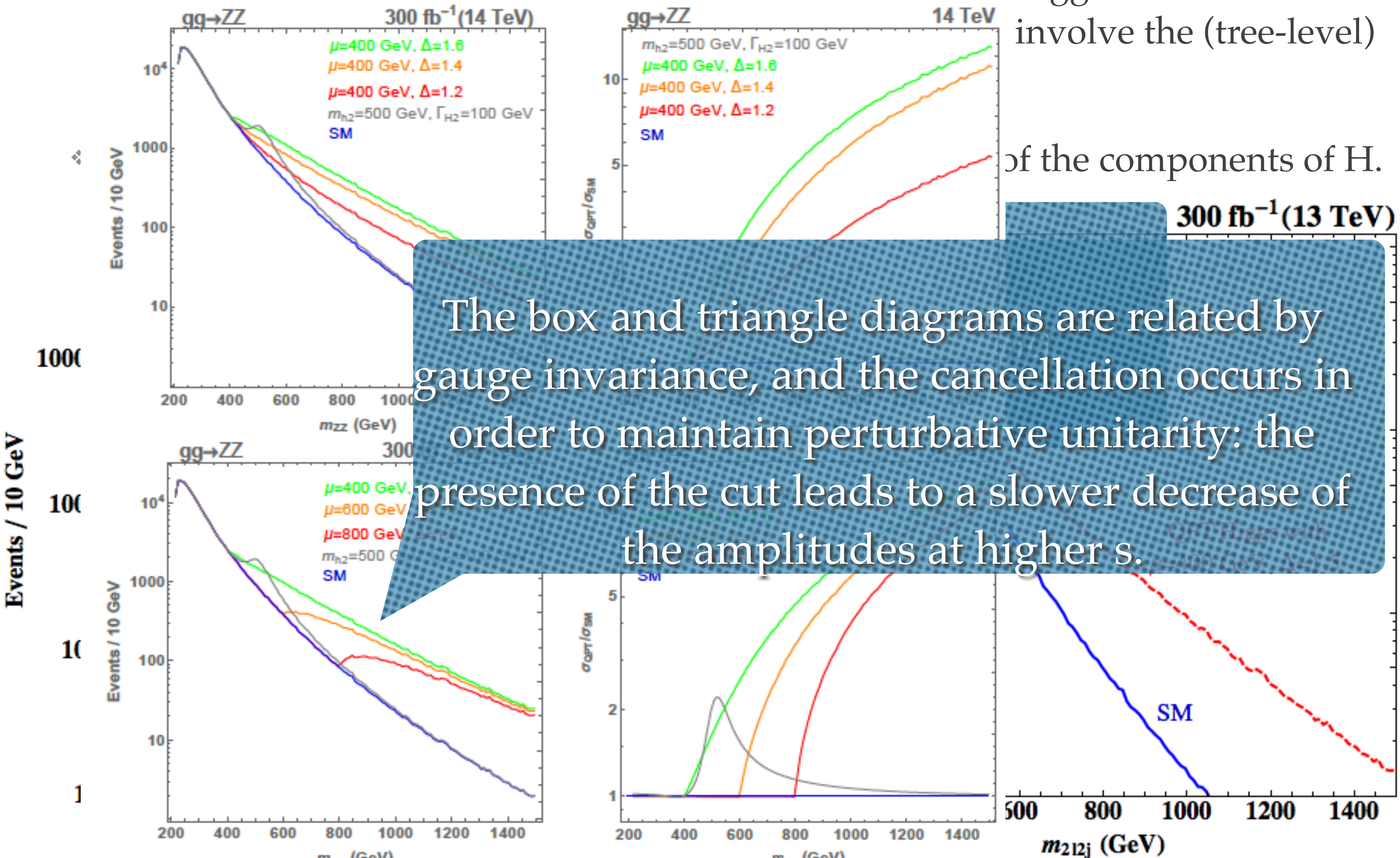
- Off-shell Higgs can be tested via interference.



sensitive to the
modifications of the Higgs two-point function

Direct Signals

- Single Higgs production: Production of the cut modifies Higgs cross sections
  involve the (tree-level)
- of the components of H.

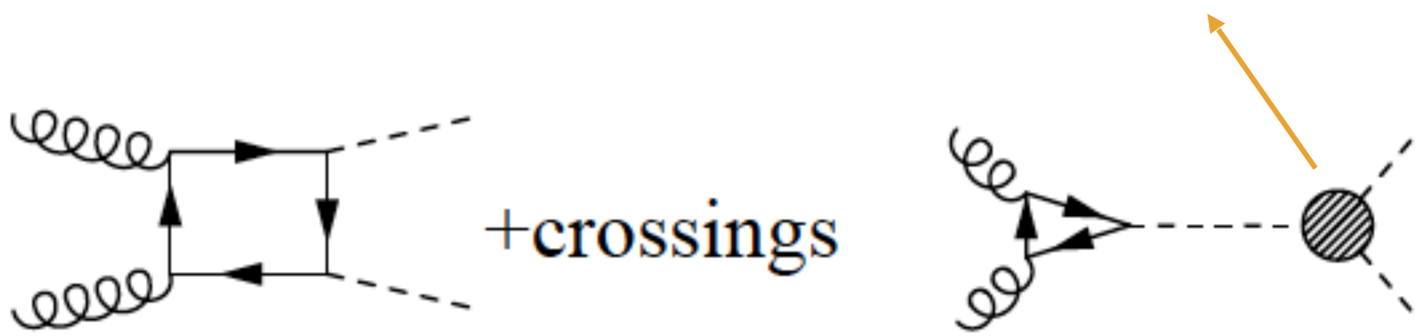


The box and triangle diagrams are related by gauge invariance, and the cancellation occurs in order to maintain perturbative unitarity: the presence of the cut leads to a slower decrease of the amplitudes at higher s.

Direct Signals

- Double Higgs production

probe the higher n-point correlators of the CFT.



$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}} = \frac{\alpha_{\mathrm{w}}^2 \alpha_{\mathrm{s}}^2}{2^{15}\pi M_{\mathrm{W}}^4 \hat{s}^2}\left(|\mathrm{gauge1}|^2 + |\mathrm{gauge2}|^2\right)$$

gauge1 = box + triangle (negative interference)

gauge2 = box (largest contribution)

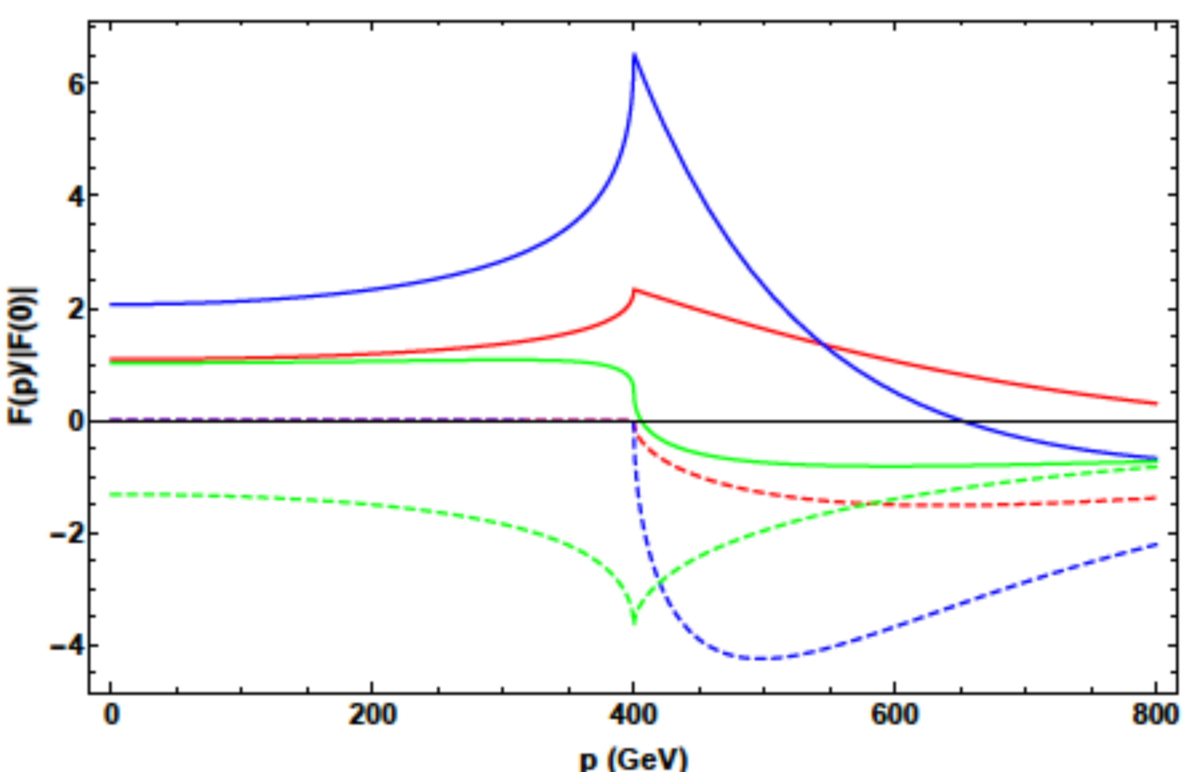
Direct Signals

- Form factors for trilinear Higgs self coupling $\lambda_5(H^\dagger H)^2$

$$F_{hhh} = \frac{\lambda_5}{L^2}\,\mathcal{V}\int_R^\infty dz\,\frac{1}{a}\left(\frac{z}{R}\right)^2\,\frac{K_{2-\Delta}(\mu\, z)}{K_{2-\Delta}(\mu\, R)}\prod_{i=1}^{3}\frac{K_{2-\Delta}(\sqrt{\mu^2-p_i^2}\,z)}{K_{2-\Delta}(\sqrt{\mu^2-p_i^2}\,R)}$$

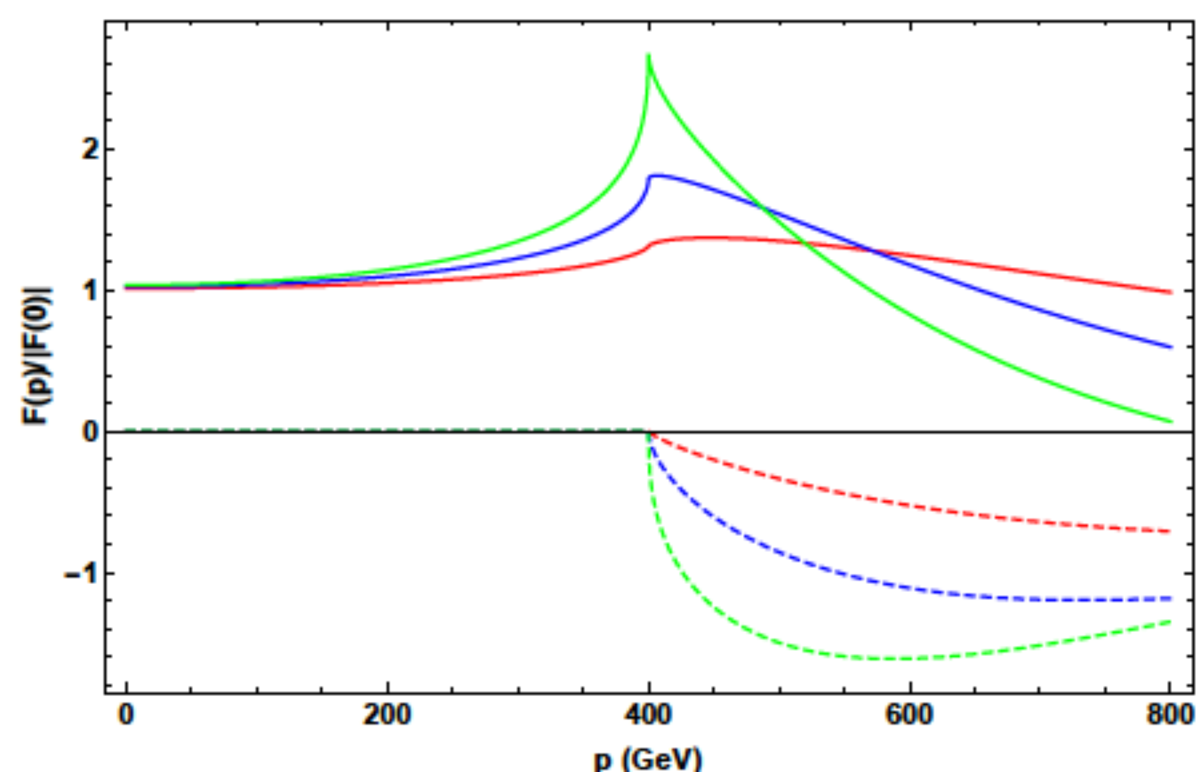
$\mu = 400, \quad \Delta = 1.5,$

Higgs momentum: 200 GeV (Red), 400 GeV (Blue), and 600 GeV (Green)



$\mu = 400,$

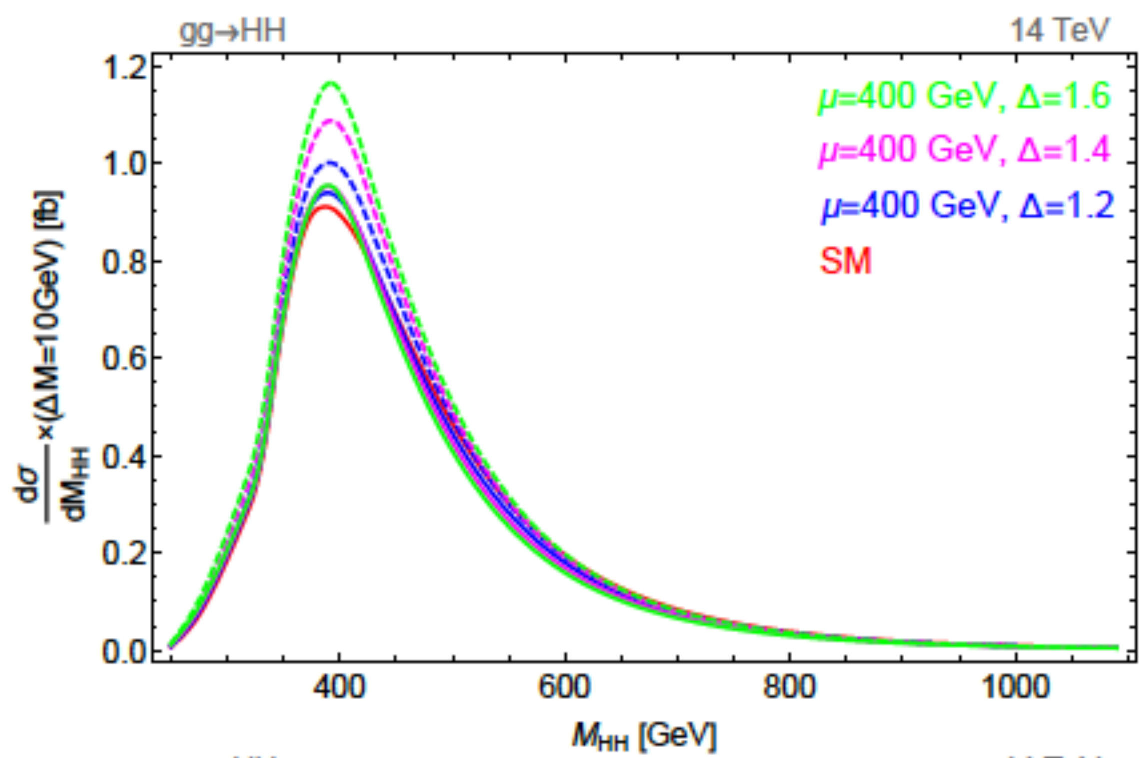
$\Delta = 1.2$ (Red) 1.4 (Blue), and 1.6 (Green).

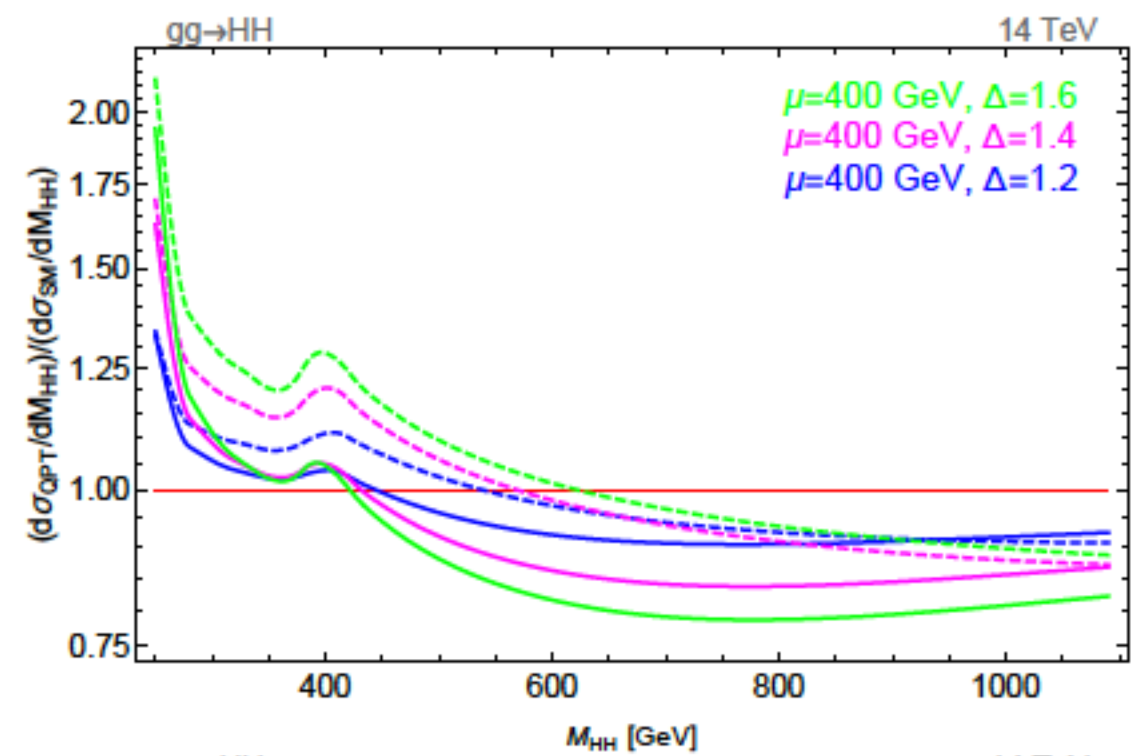


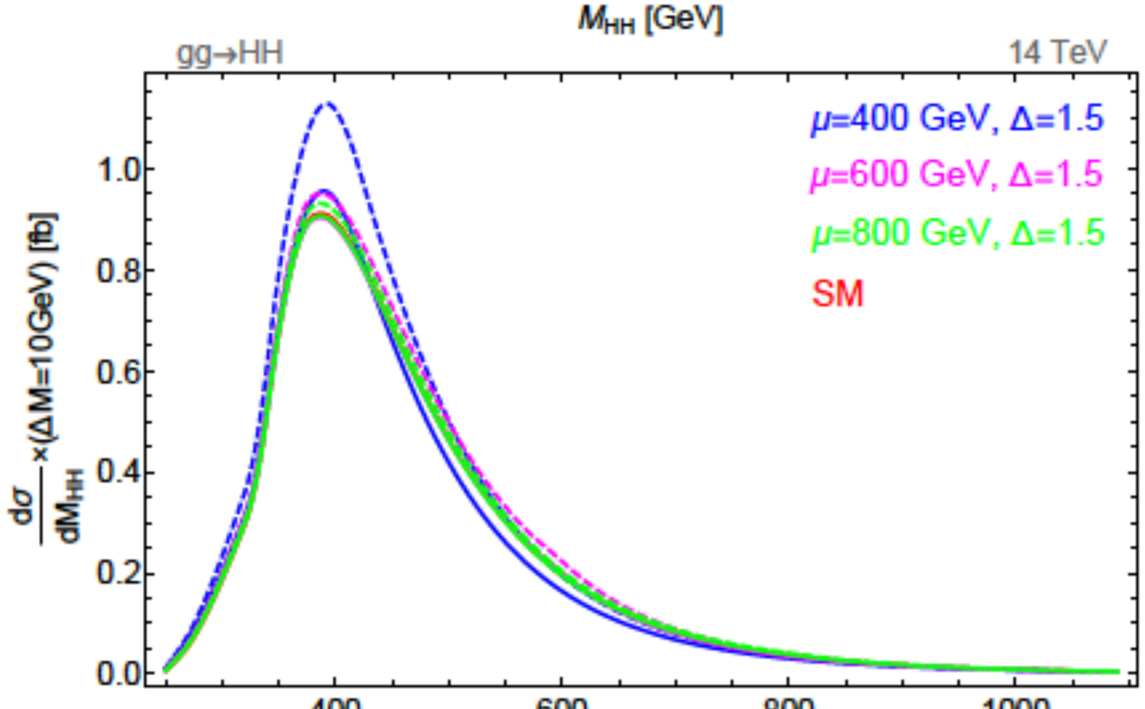
Direct Signals

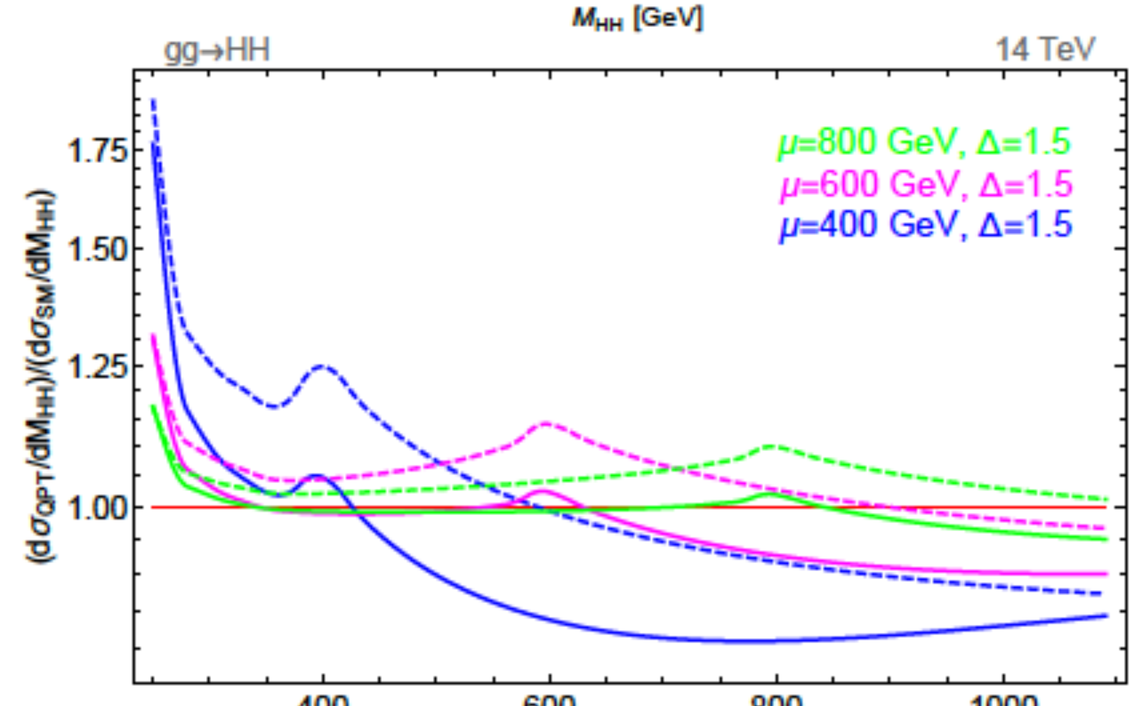
- Double Higgs production

dashed lines correspond to the case where only the Higgs two-point function has non-trivial behavior inherited from a sector with strong dynamics.









Summary

What Kind of New Physics could be nearby, which is not described by EFT?

Not super-weakly coupled, yet not inconsistent with the data?

Quantum Criticality <-> Fine-Tuning

Quantum Critical Higgs - a unified framework to look at Higgs sector in analogy of Quantum Phase Transition (Higgs sector may exhibit signs of quantum criticality with non-trivial non-mean-field behavior):

A very powerful dynamical assumption: Generalized Free Fields theory, where 2-pt function determines the theory

5D models: a natural quantum critical Higgs

Phenomenology: Not EFT, but form factors

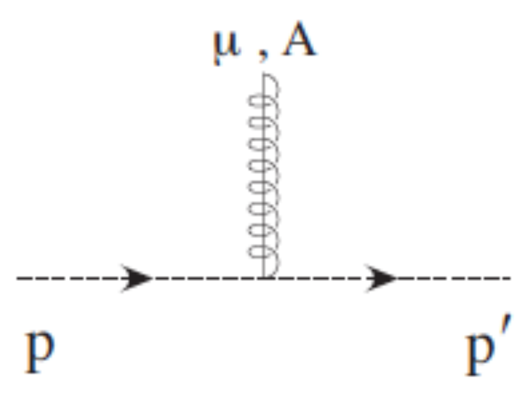
Back-up

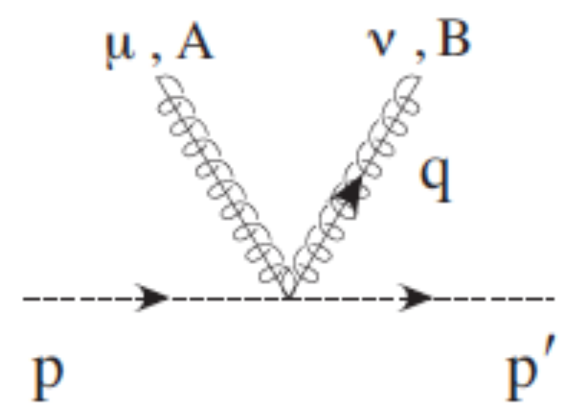
Non-local operators

$$\mathcal{L}_{\mathcal{H}} = -\mathcal{H}^\dagger \left[D^2+\mu^2\right]^{2-\Delta}\mathcal{H} + \mu^{4-2\Delta}\mathcal{H}^\dagger\mathcal{H} - V(|\mathcal{H}|)$$

$$[\partial^2-\mu^2]^{2-\Delta}\delta(x-y)$$

$$W(x,y) = P\exp\left[-igT^a \int_x^y A^a_\mu d\omega^\mu\right]$$





- e.g. for the trilinear interaction in momentum space: $\mathcal{H}^\dagger(p+q)A^a_\mu(q)\mathcal{H}(p)\Gamma^{\mu,a}(p,q)$

$$\Gamma^{\mu,a}(p,q) = gT^a\,(2p^\mu+q^\mu)\,F(p,q)\ ,$$

$$F(p,q) = -\frac{\left(\mu^2-(p+q)^2\right)^{2-\Delta}-\left(\mu^2-p^2\right)^{2-\Delta}}{2p\cdot q+q^2}$$

similar to SCET!