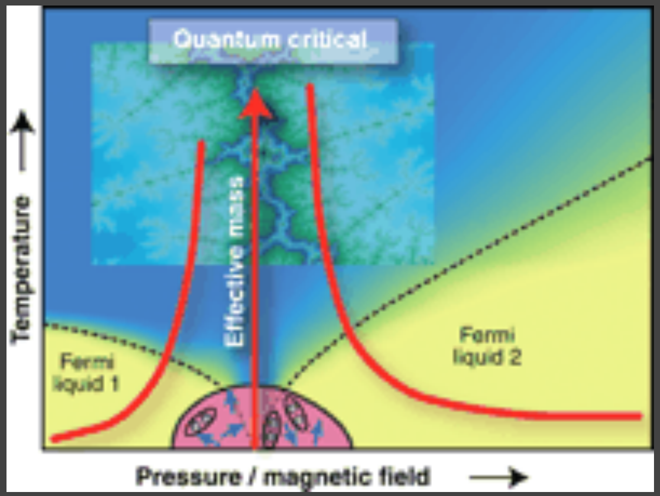
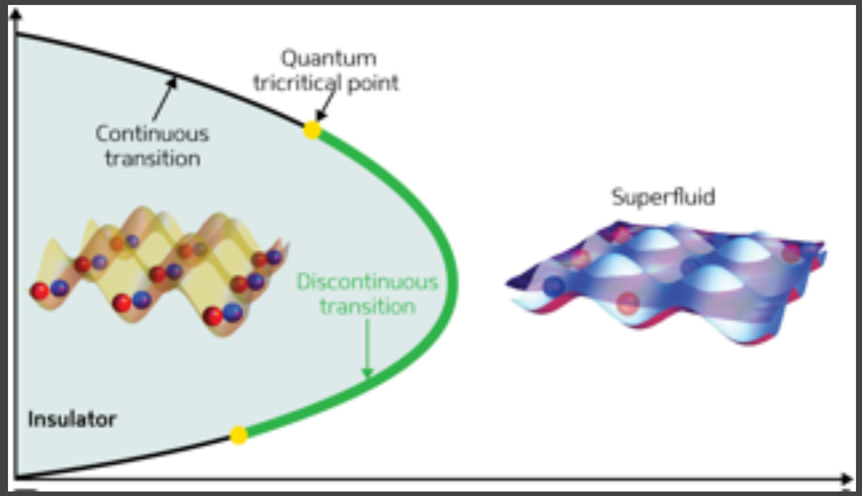
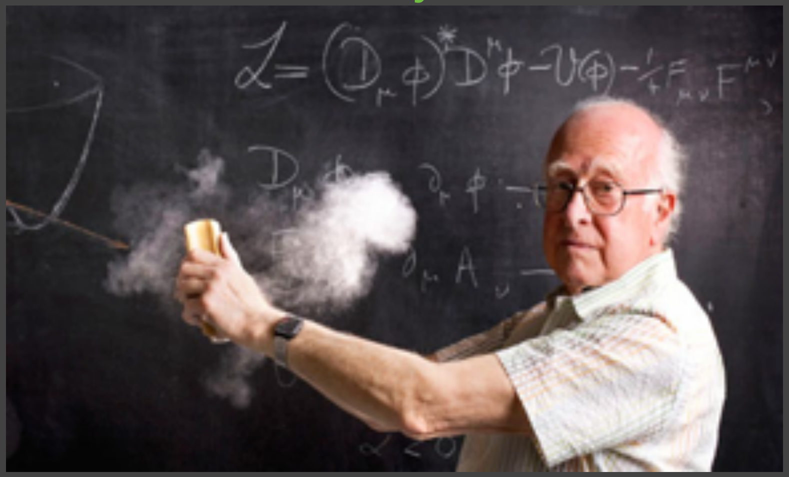
Charting the Unknown: interpreting LHC data from the energy frontier, CERN, July 29, 2016







A Natural Quantum Critical Higgs

Seung J. Lee

KOREA UNIVERSITY

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?

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(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

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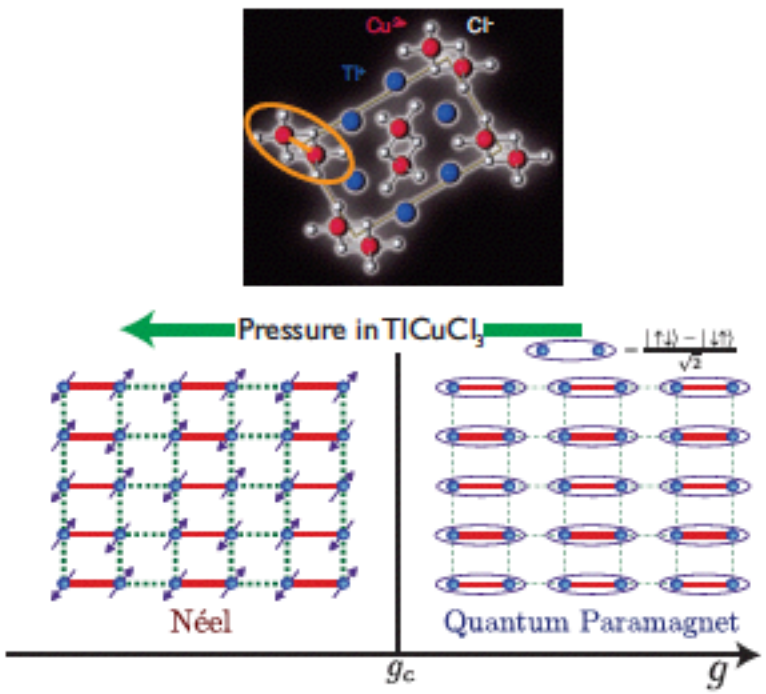
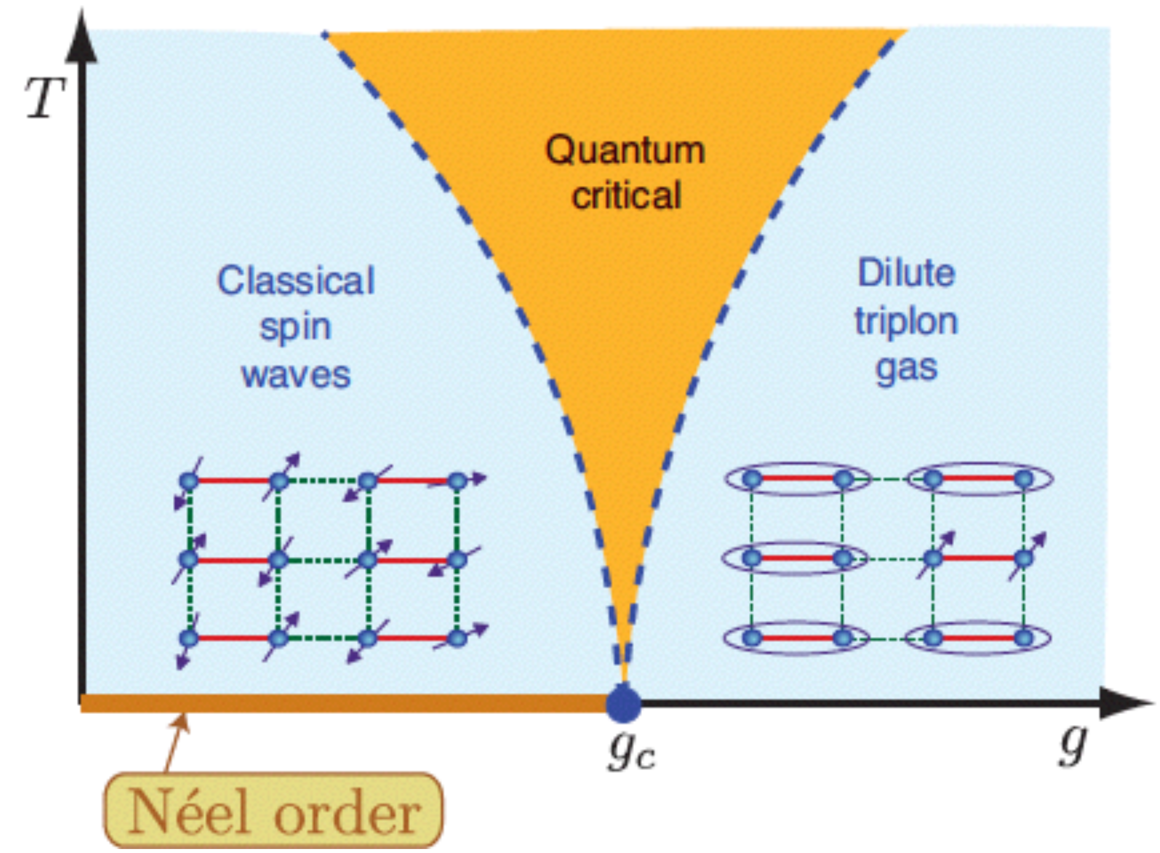
Higgs & Quantum Phase Transition

Condensed matter systems can produce a light scalar by tuning the parameters close to a critical value where a continuous phase transition occurs.



Sachdev, arXiv:1102.4268



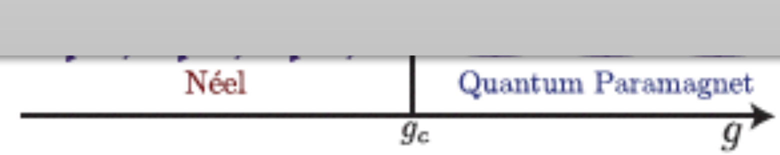
Higgs & Quantum Phase Transition

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.



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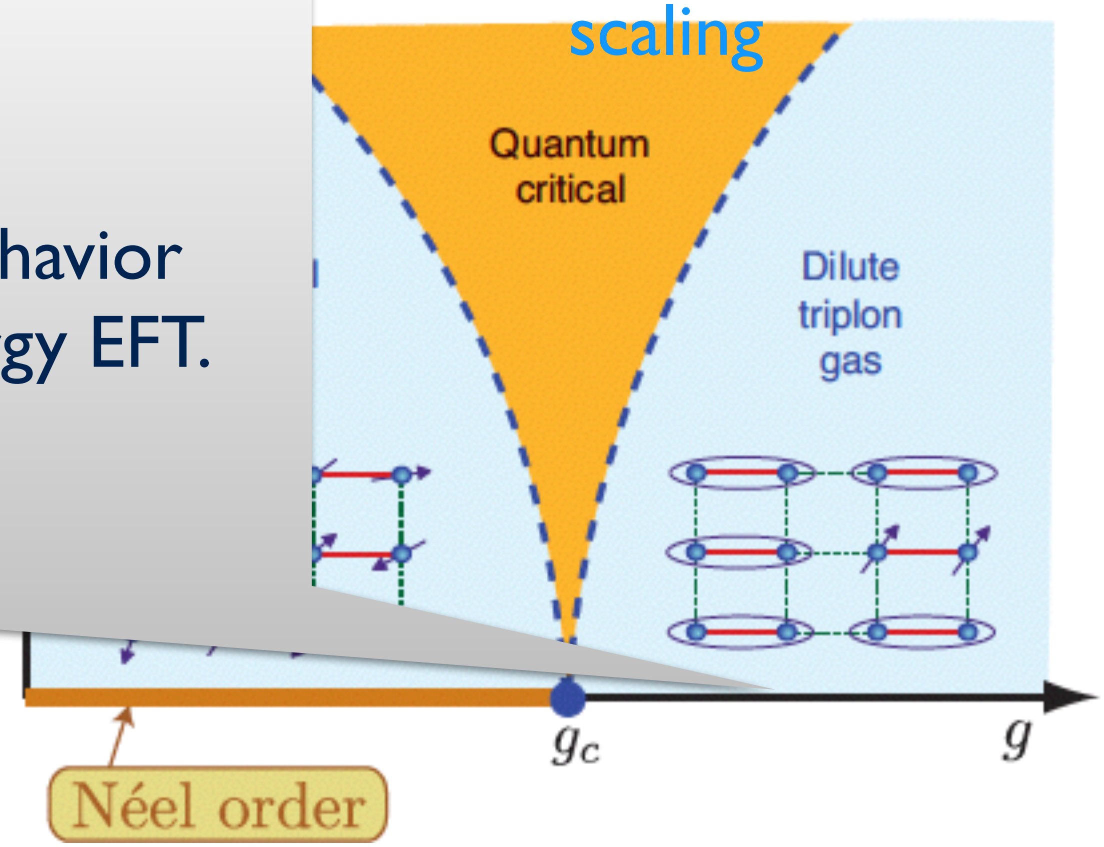

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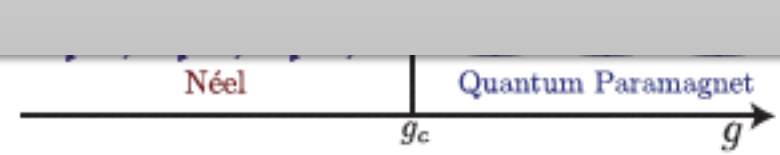
scaling



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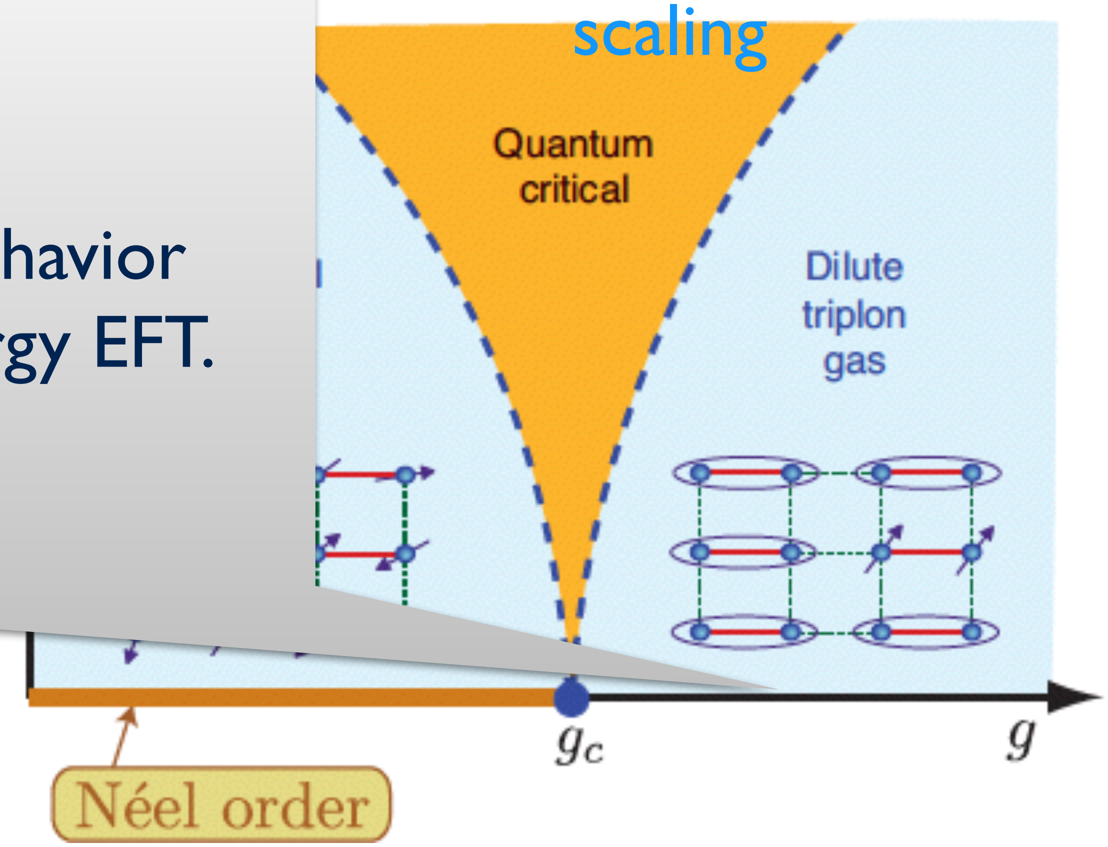

What is the nature of electroweak phase transition?

Does the underlying theory also have a QPT?

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

Higgs & Quantum Phase Transition

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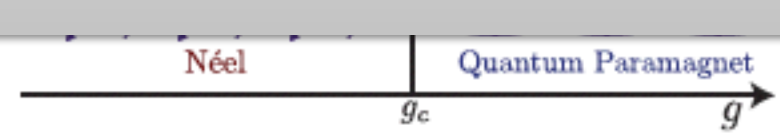

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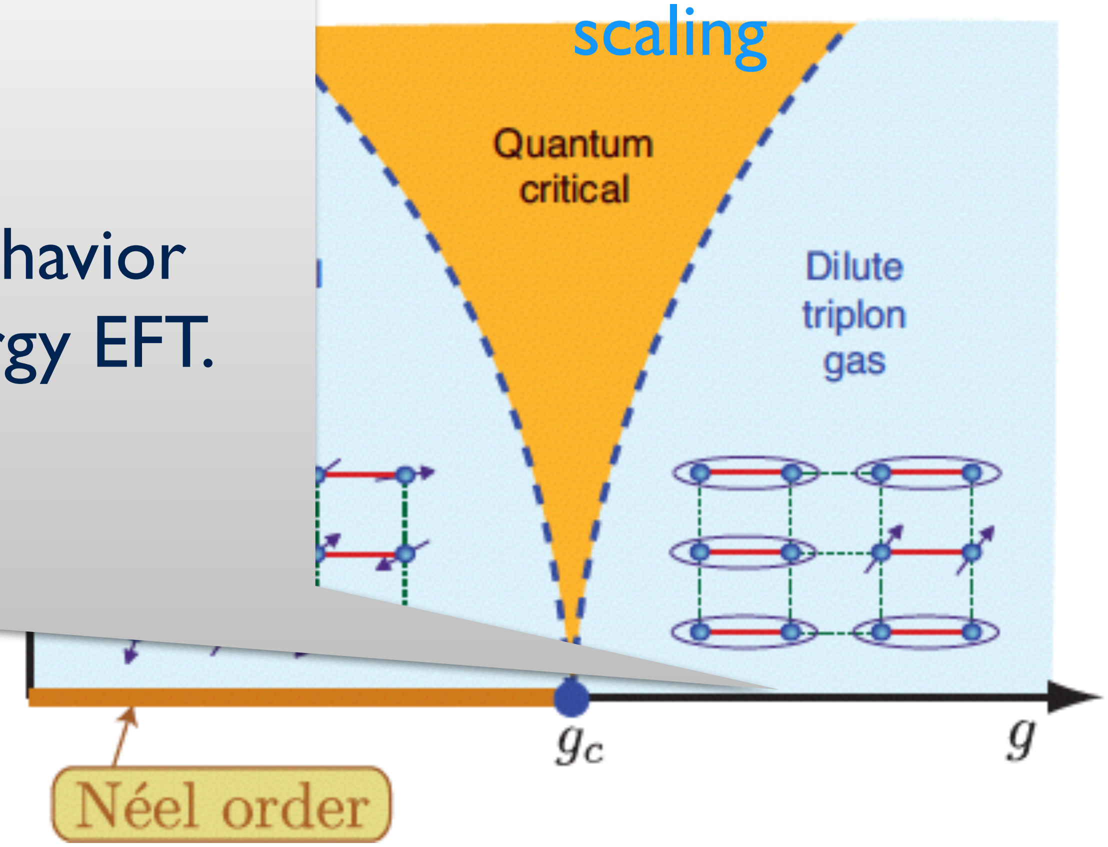


What is the nature of electroweak phase transition?

Does the underlying theory also have a QPT?

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

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

Ising Model

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

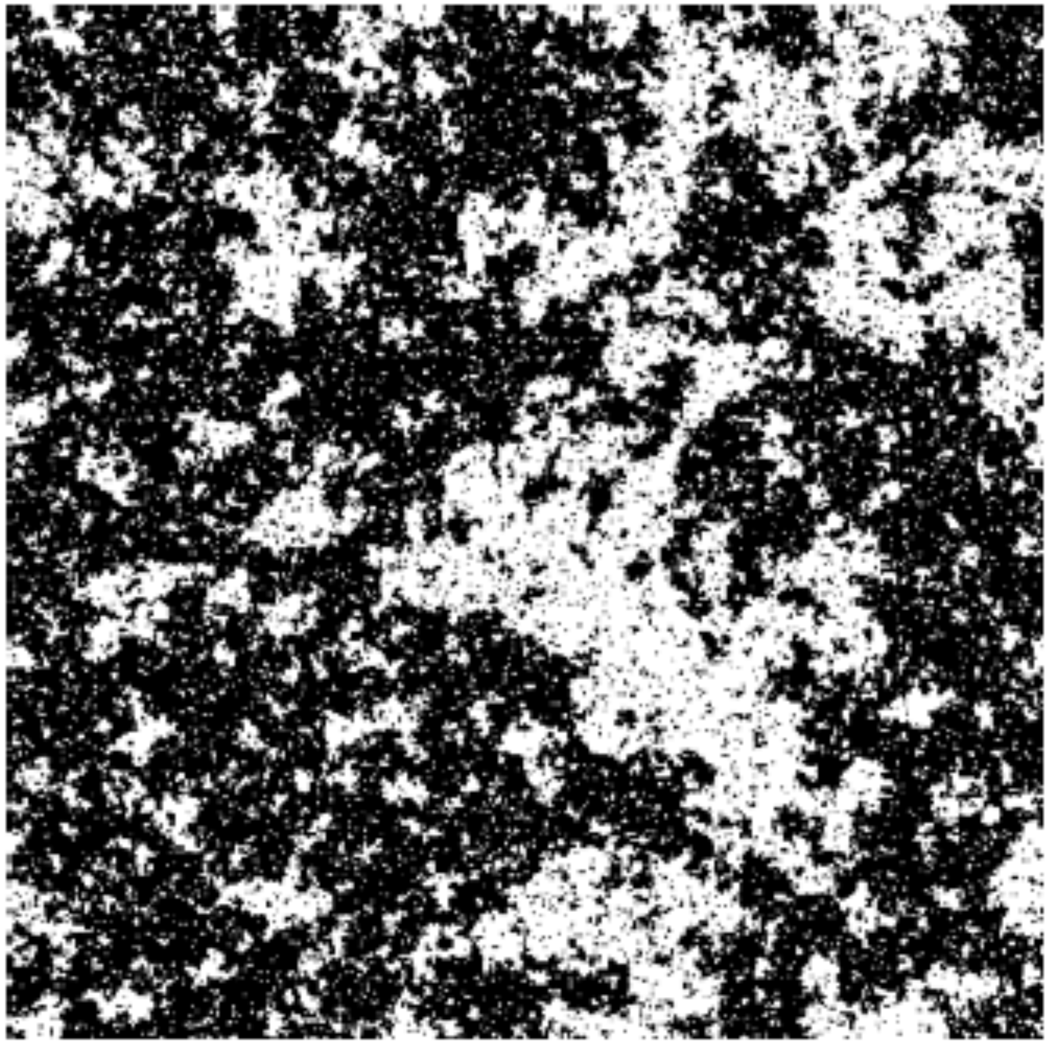
$$s(x) = \pm 1$$

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

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

Courtesy of J. Terning

Critical Ising Model is Scale Invariant



http://bit.ly/2Dcrit

at $T=T_c$ $\quad \langle s(0)s(x)\rangle \propto \frac{1}{|x|^{2\Delta-1}}$

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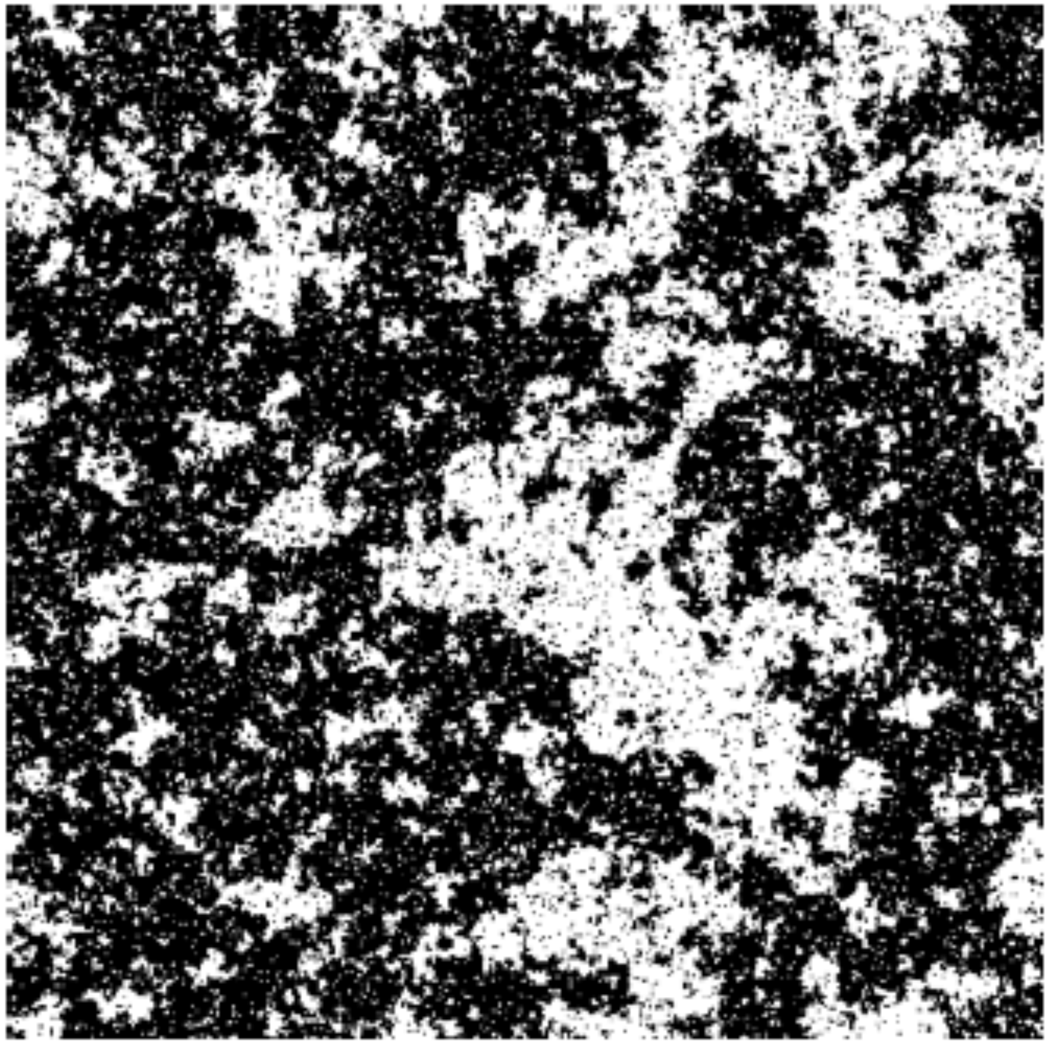


http://bit.ly/2Dcrit

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

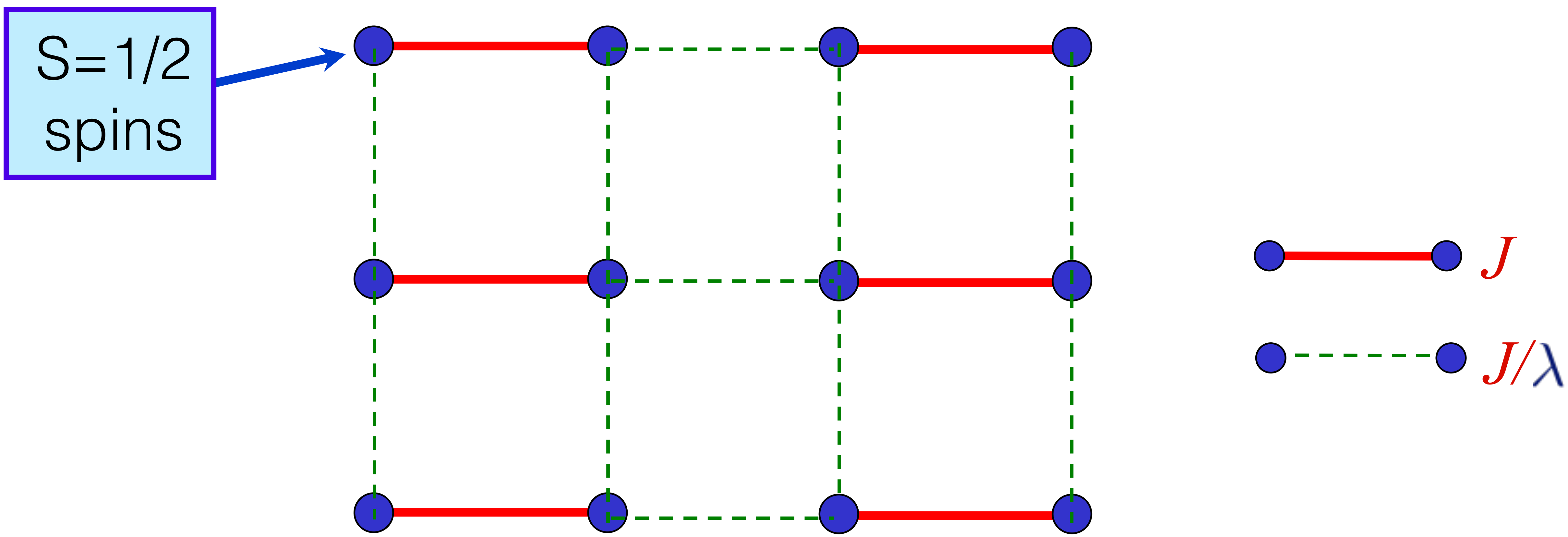
critical exponent

Courtesy of J. Terning

Spinning electrons localized on a cubic lattice

Sachdev, arXiv:1102.4268

$$H = \sum_{\langle ij \rangle} J_{ij} \vec{S}_i \cdot \vec{S}_j$$



Examine ground state as a function of λ

Spinning electrons localized on a cubic lattice

Sachdev, arXiv:1102.4268

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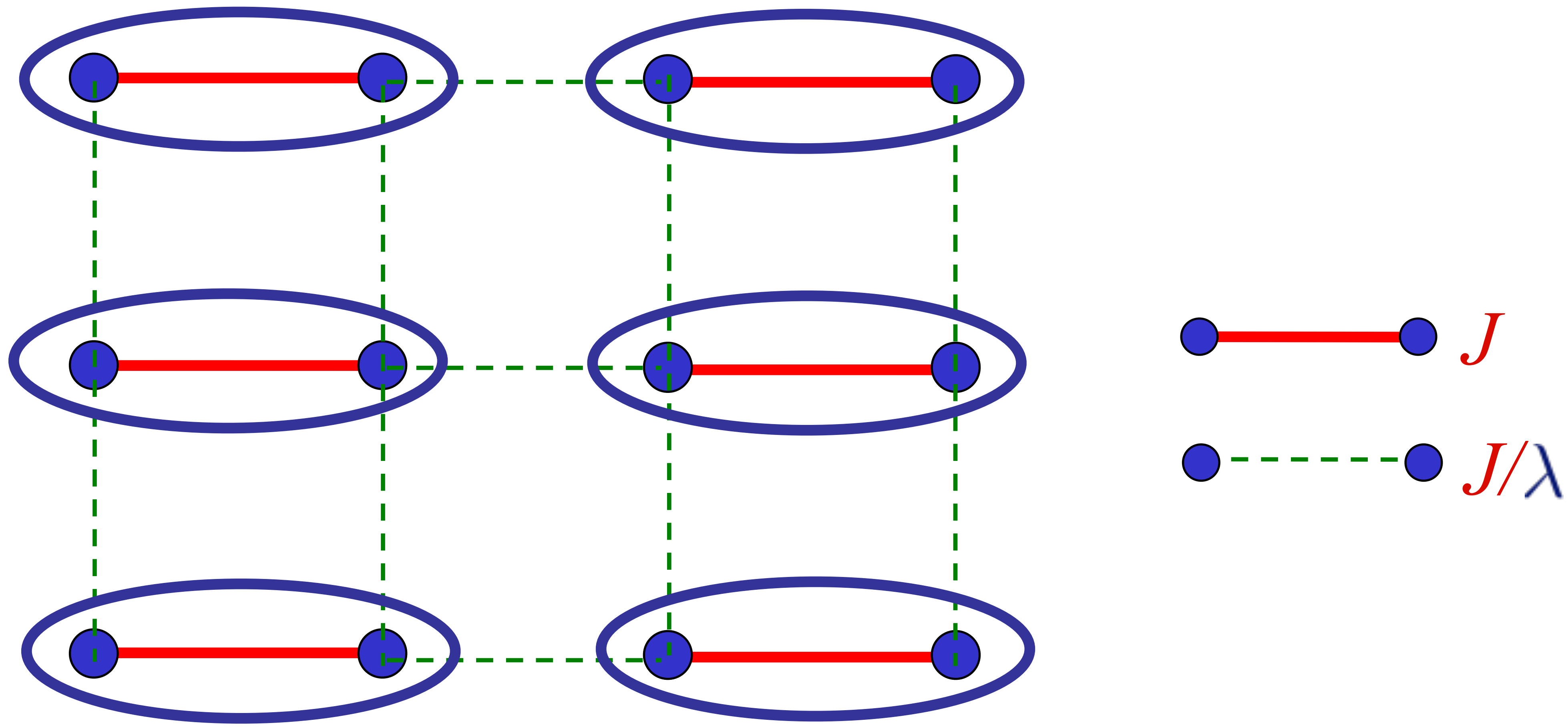

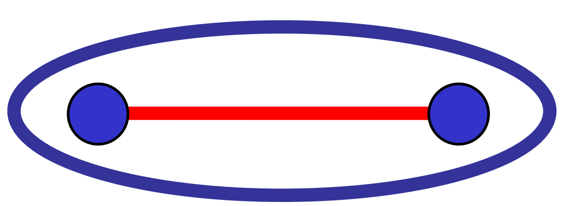

$$= \frac{1}{\sqrt{2}} \Big(\left| \uparrow\downarrow \right\rangle - \left| \downarrow\uparrow \right\rangle \Big)$$

At large λ ground state is a "quantum paramagnet" with spins locked in valence bond singlets

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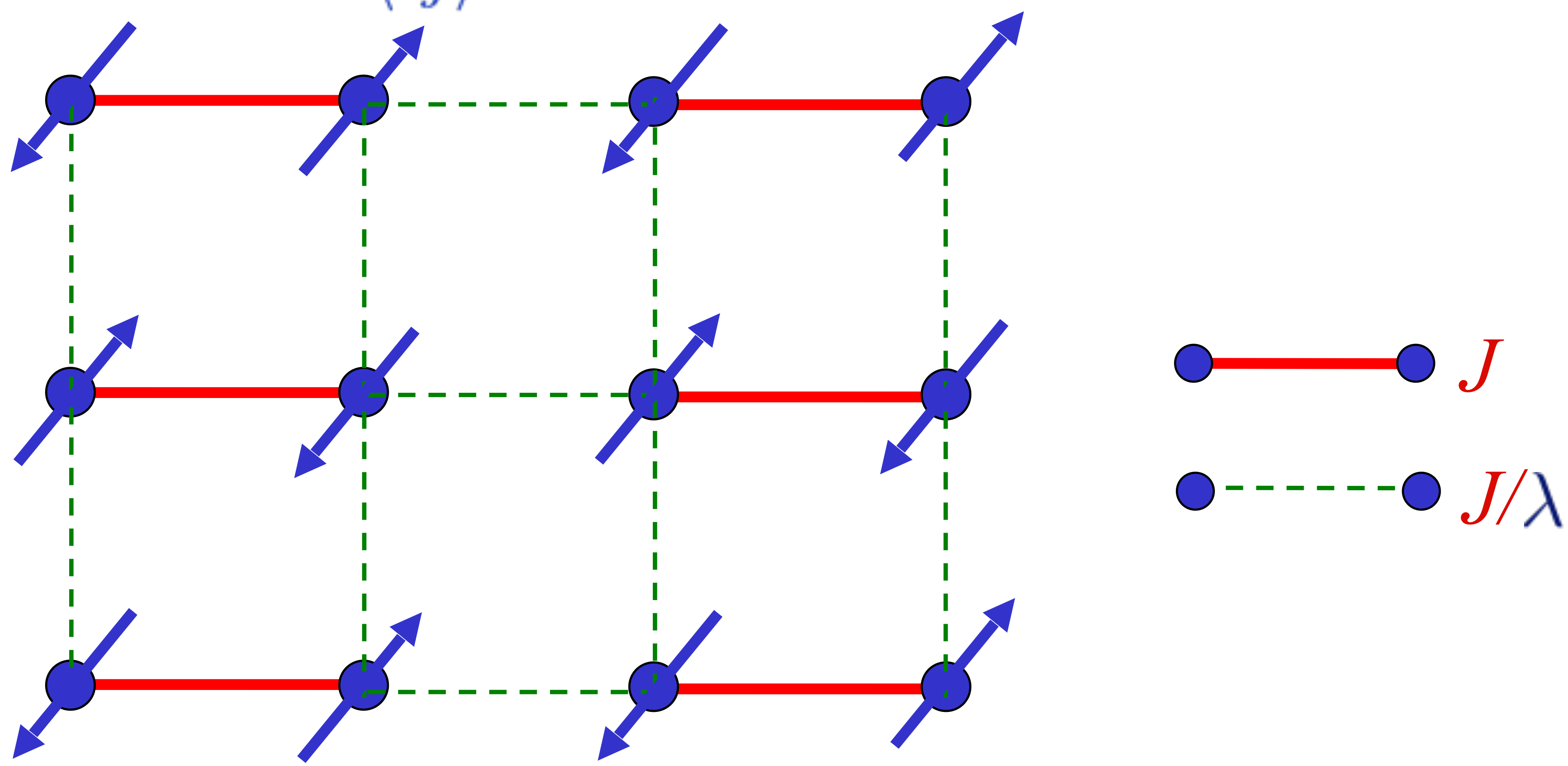
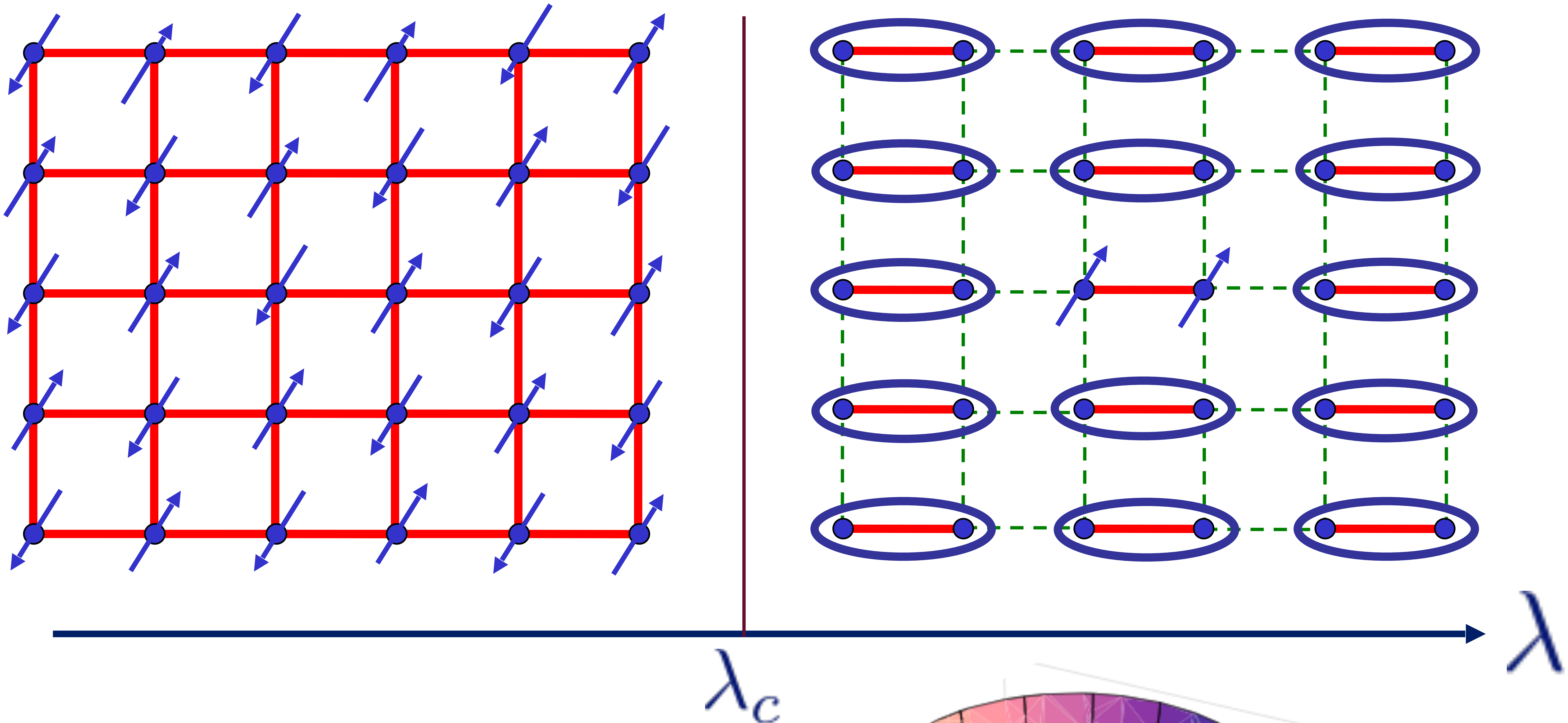


For $\lambda \approx 1$, the ground state has antiferromagnetic ("Néel") order, and the spins align in a checkerboard pattern.

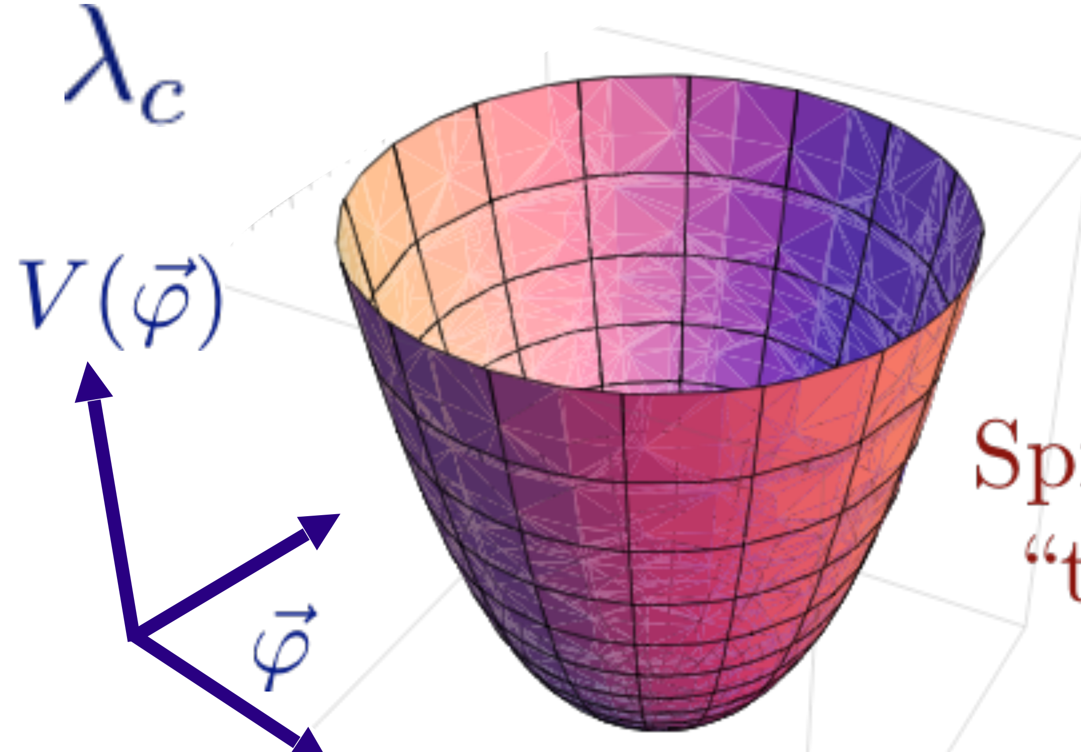
There is a broken O(3) symmetry characterized by an order parameter $\vec{\varphi} \sim (-1)^{i_x + i_y} \vec{S}_i$

Excitation spectrum in the paramagnetic phase



$$V(\vec{\varphi}) = (\lambda - \lambda_c)\vec{\varphi}^2 + u\left(\vec{\varphi}^2\right)^2$$

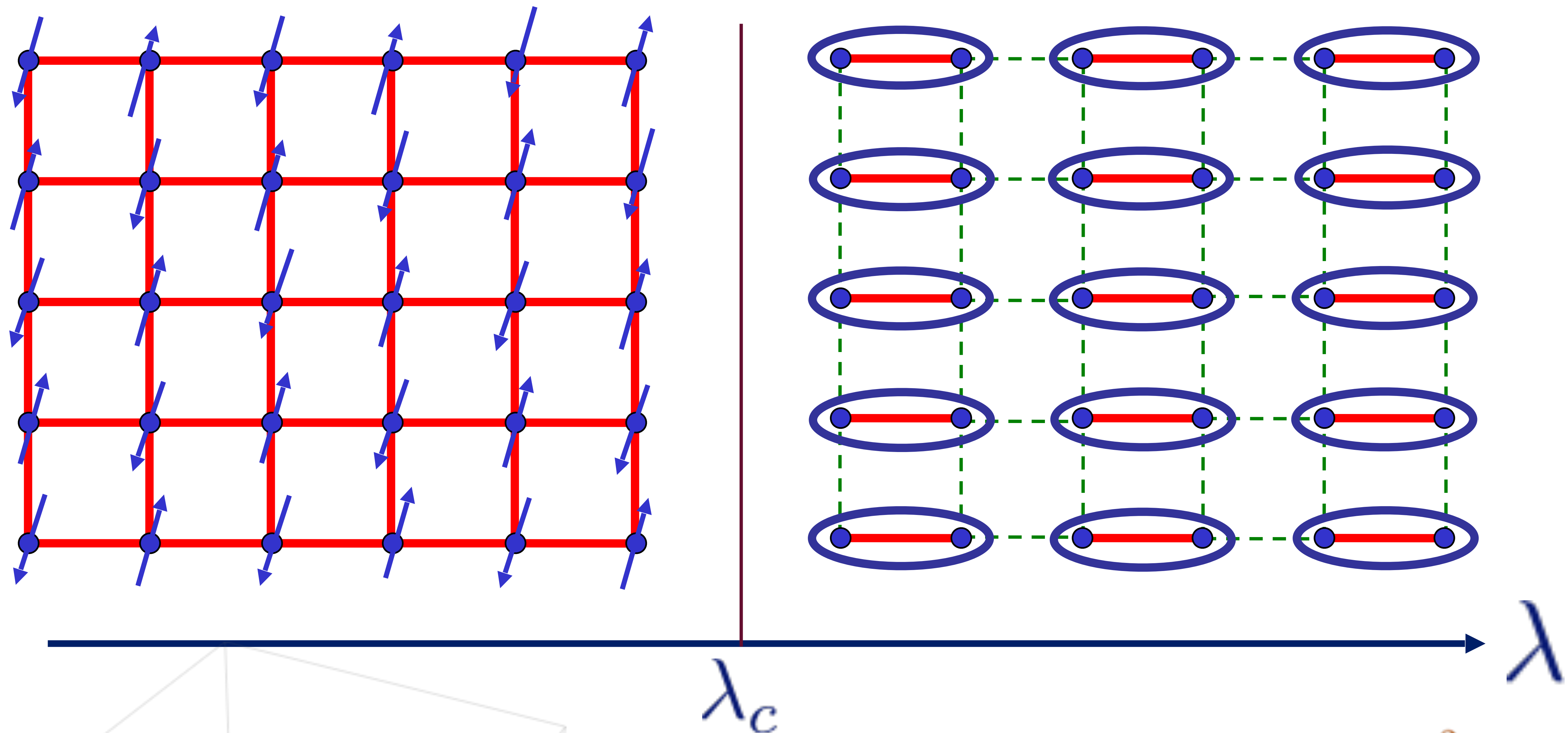
$$\lambda > \lambda_c$$

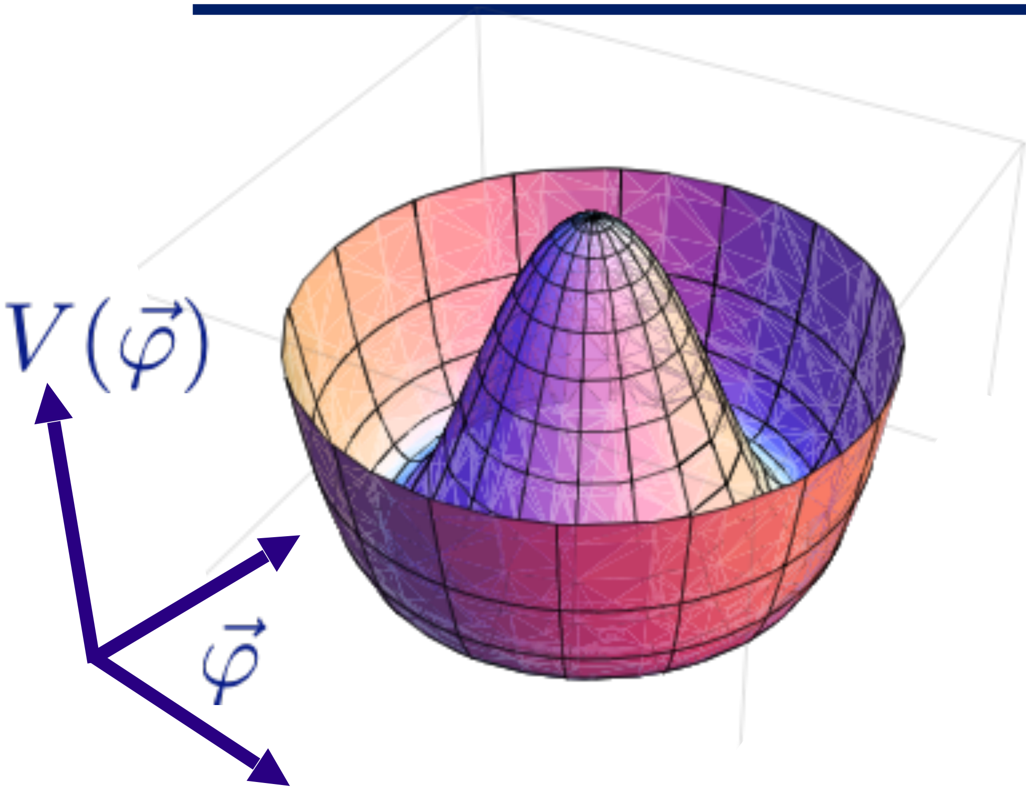


Spin $S = 1$
"triplon"

Sachdev, arXiv:1102.4268

Excitation spectrum in the Néel phase





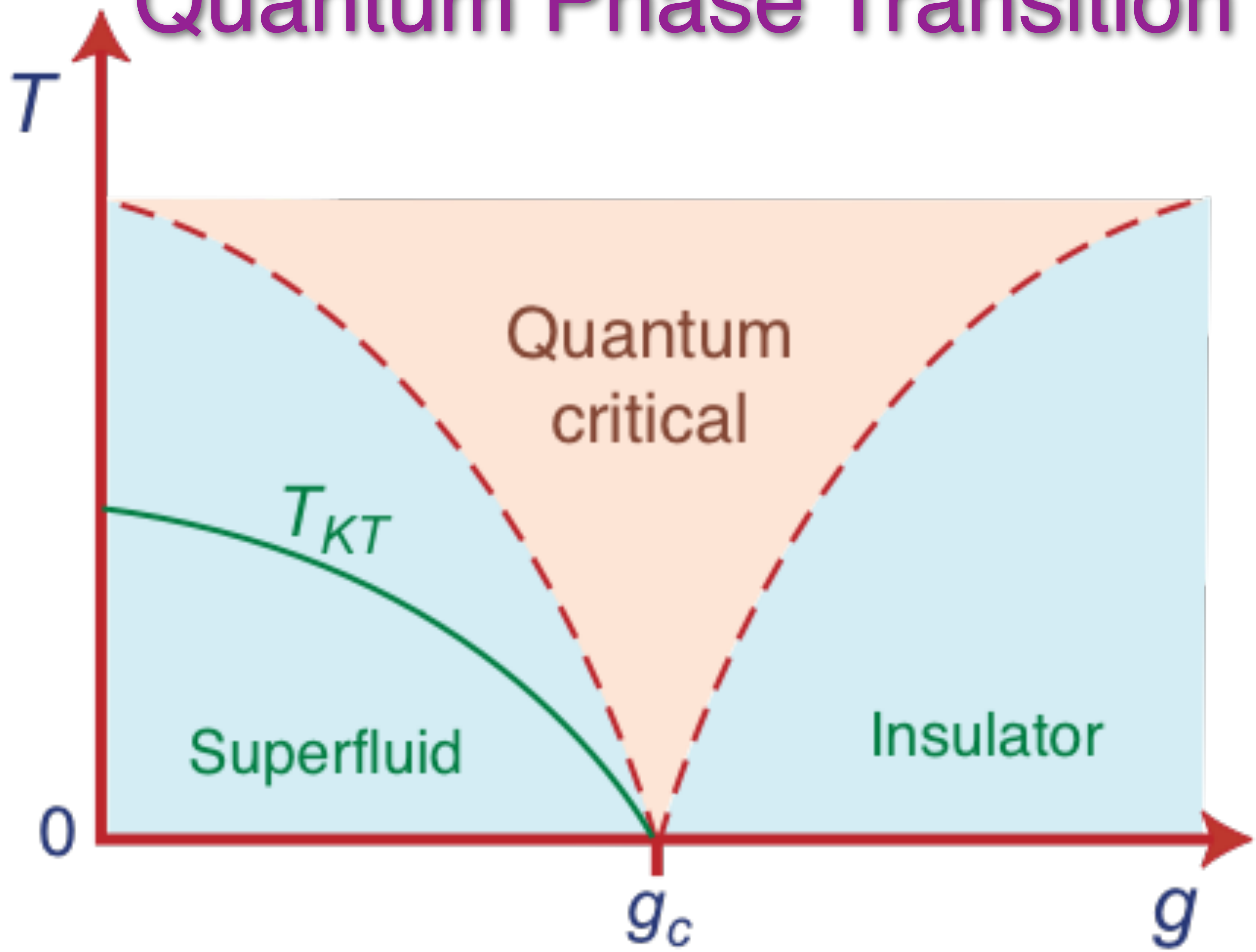
$$V(\vec{\varphi}) = (\lambda - \lambda_c)\vec{\varphi}^2 + u\left(\vec{\varphi}^2\right)^2$$

$$\lambda < \lambda_c$$

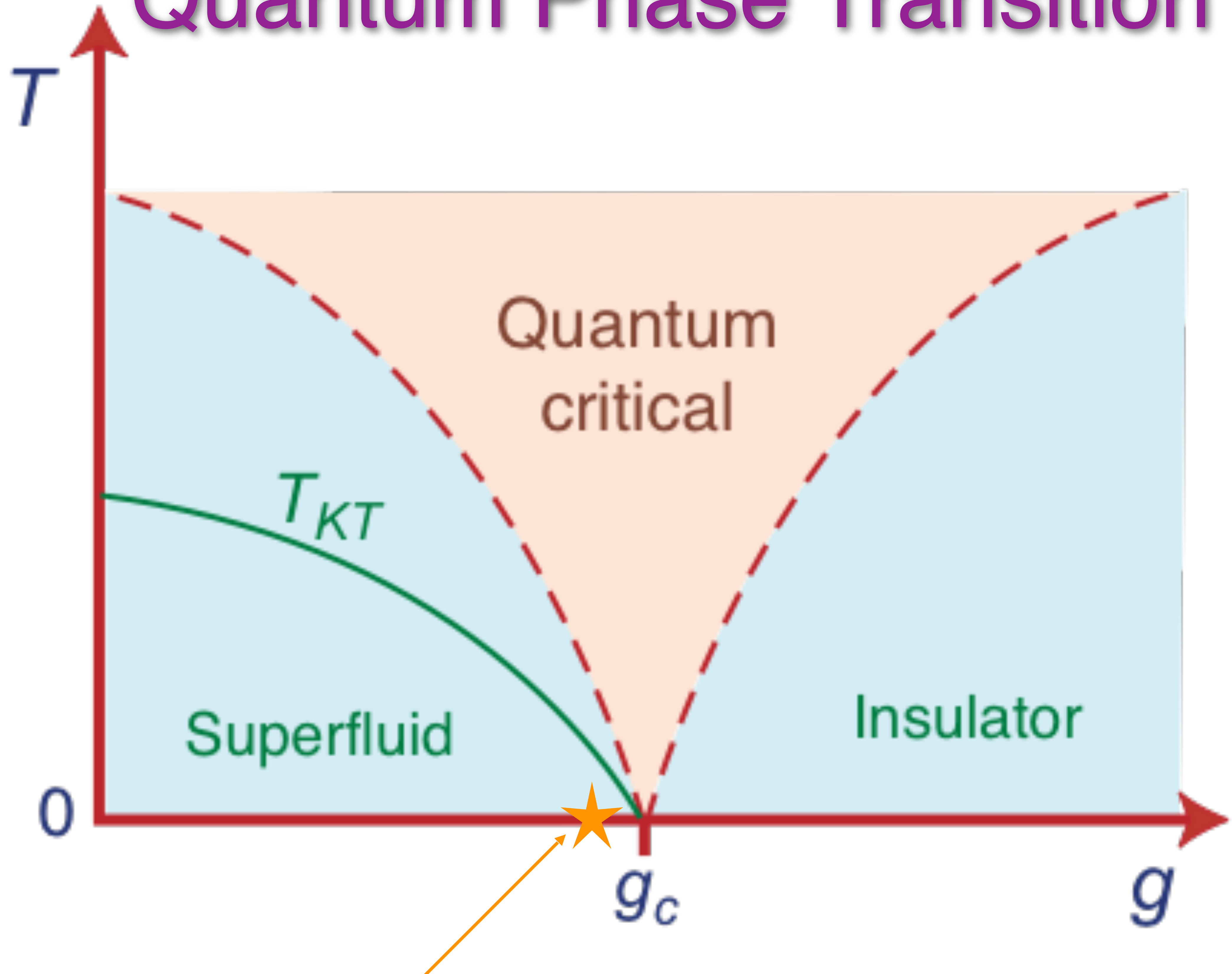
Spin waves (Goldstone boson)
and a longitudinal Higgs boson

Sachdev, arXiv:1102.4268

Quantum Phase Transition



Quantum Phase Transition



The Quantum Critical higgs

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

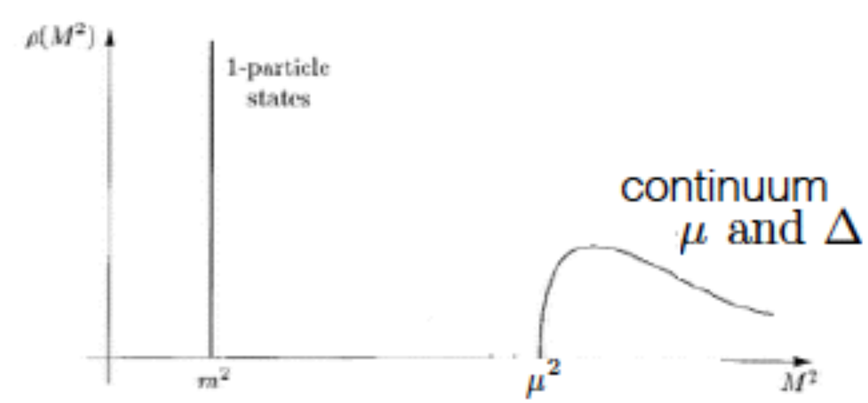
SM: $\Delta = 1 + \mathcal{O}(\alpha/4\pi)$.

- 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

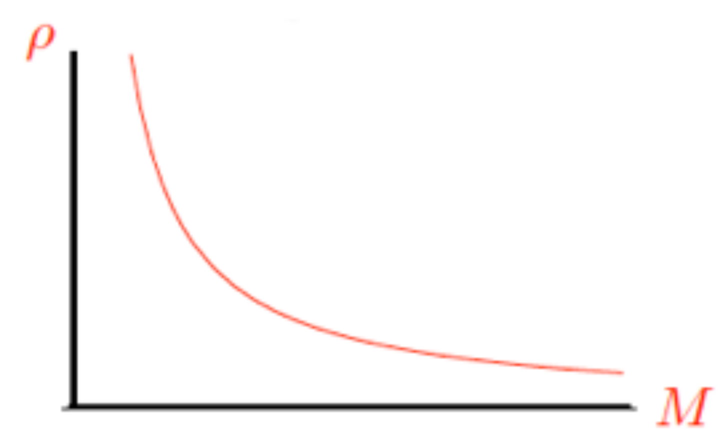
Scaling - 2-point function: $G(p^2) = -\frac{i}{(-p^2 + i\epsilon)^{2-\Delta}}$

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

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

Assuming $\mathcal{h}$ to be weakly coupled, the scaling dimension of $\mathcal{h}^2$ is 2Δ

The momentum space propagator for the physical Higgs scalar can be written as

$$G_h(p) = -\frac{i\,Z_h}{(\mu^2 - p^2 + i\epsilon)^{2-\Delta} - (\mu^2 - m_h^2)^{2-\Delta}}\,; \qquad Z_h = \frac{(2-\Delta)}{(\mu^2 - m_h^2)^{\Delta-1}}$$

c.f. unparticle propagator

Modeling the QCH: generalized free fields

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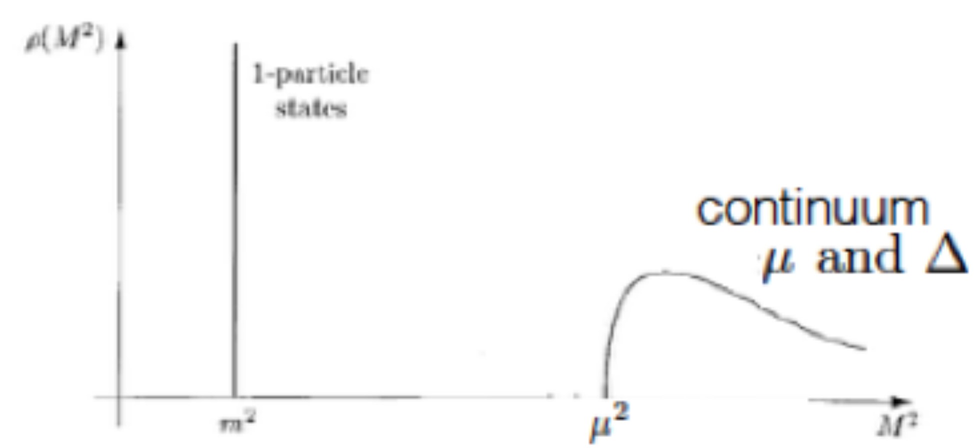
$$\mathcal{L}_{\rm quadratic} = -\frac{1}{2\,Z_{\hbar}}\hbar\left[\partial^2+\mu^2\right]^{2-\Delta}\hbar + \frac{1}{2\,Z_{\hbar}}(\mu^2-m_{\hbar}^2)^{2-\Delta}\hbar^2$$

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.

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

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- 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.

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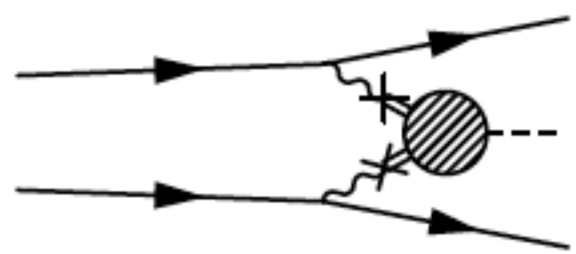
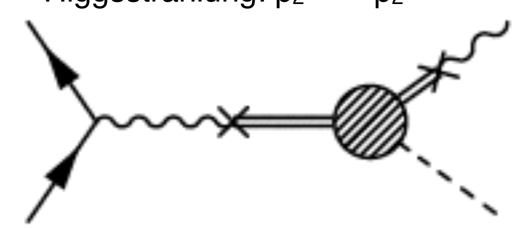
  => this strong sector is characterized by its n-point functions entering into form factors

Off-shell Form Factors for the Quantum Critical higgs

Off-shell behavior: nontrivial momentum dependent form factors

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





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

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

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

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

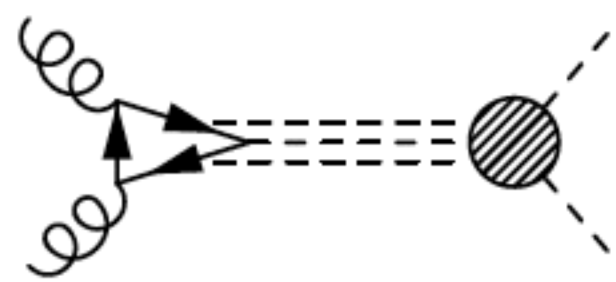
$$\Gamma_1^{(\rm SM)} = 1 \text{ and } \Gamma_{i\neq 1}^{(\rm SM)} = 0.$$

etc…

Off-shell Form Factors for the Quantum Critical higgs

Off-shell behavior: nontrivial momentum dependent form factors

$p_1 \cdot p_2 = s/2$



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

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

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

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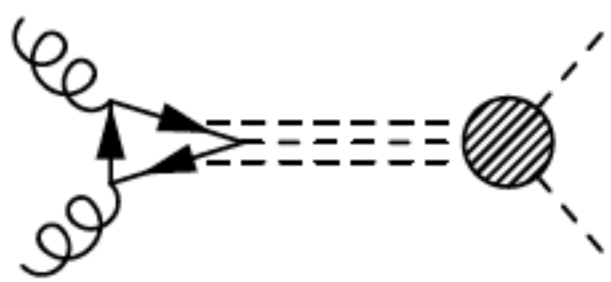

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$$+\epsilon_2 \cdot [(p_1 \cdot p_2)p_3 - (p_2 \cdot p_3)p_1] \, \epsilon_1 \cdot [(p_1 \cdot p_2)p_3 - (p_1 \cdot p_3)p_2] \, \Xi_2 (p_1 \cdot p_2, p_1 \cdot p_3; \mu)$$

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

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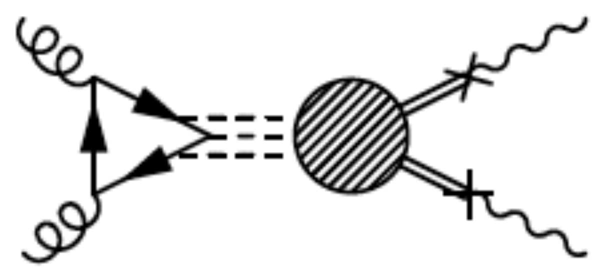
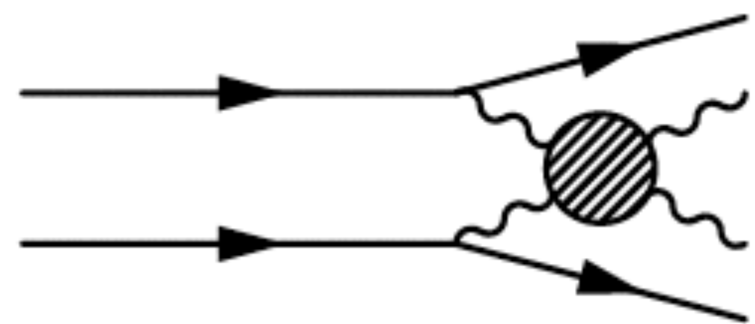
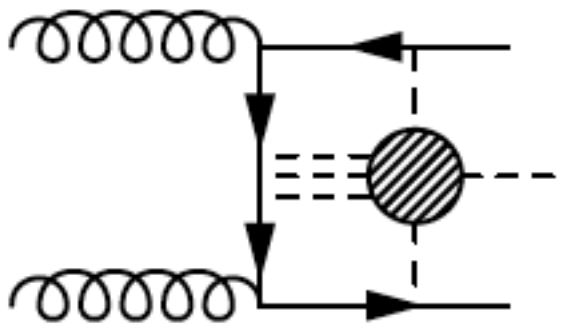
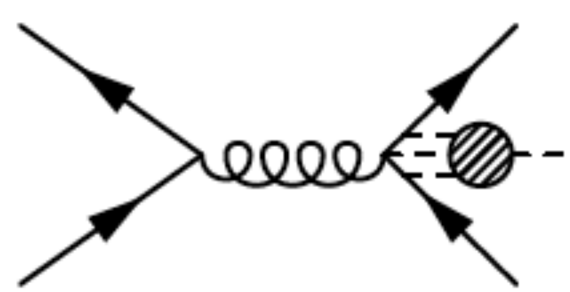




$$\mathcal{M}_{ggVV} = \epsilon_{1\,\mu}\epsilon_{2\,\nu}\left[F^{\mu\nu\rho\sigma}_{ggVV}(p_i;\mu) + \widehat{F}^{\mu\nu\rho\sigma}_{ggVV}(p_i;\mu)\right]\bar{\epsilon}_{3\,\rho}\bar{\epsilon}_{4\,\sigma}$$

$$\begin{aligned}
F^{\mu\nu\rho\sigma}_{ggVV}(p_i;\mu) = {} & \left[g^{\mu\nu}(p_1\cdot p_2) - p_1^\nu p_2^\mu\right]\left(g^{\rho\sigma}\Theta_1 + p_1^\rho p_1^\sigma\Theta_2 + p_2^\rho p_2^\sigma\Theta_3\right) \\
& + \left[g^{\mu\rho}g^{\nu\sigma}(p_1\cdot p_2) + g^{\mu\nu}p_1^\rho p_2^\sigma - g^{\mu\rho}p_1^\nu p_2^\sigma - g^{\nu\sigma}p_2^\mu p_1^\rho\right]\Theta_4 \\
& + g^{\rho\sigma}\left[g^{\mu\nu}(p_1\cdot p_3)(p_2\cdot p_3) - p_3^\mu p_3^\nu(p_1\cdot p_2) + p_3^\mu p_1^\nu(p_2\cdot p_3) + p_2^\mu p_3^\nu(p_1\cdot p_3)\right]\Theta_5 \\
& + p_3^\sigma\left[g^{\mu\nu}p_2^\rho(p_1\cdot p_3) + g^{\nu\rho}p_3^\mu(p_1\cdot p_2) - g^{\nu\rho}p_2^\mu(p_1\cdot p_3) - p_3^\mu p_1^\nu p_2^\rho\right]\Theta_6 \\
& + \left[g^{\mu\sigma}p_1^\nu p_1^\rho(p_2\cdot p_3) - g^{\mu\rho}p_1^\nu p_1^\sigma(p_2\cdot p_3) + g^{\mu\rho}p_1^\sigma p_3^\nu(p_1\cdot p_2) - g^{\mu\sigma}p_1^\rho p_3^\nu(p_1\cdot p_2)\right]\Theta_7 \\
& + \left[g^{\nu\sigma}p_2^\mu p_2^\rho(p_1\cdot p_3) - g^{\nu\rho}p_2^\mu p_2^\sigma(p_1\cdot p_3) + g^{\mu\rho}p_1^\sigma p_3^\nu(p_1\cdot p_2) - g^{\mu\sigma}p_1^\rho p_3^\nu(p_1\cdot p_2)\right]\Theta_8 \\
\widehat{F}^{\mu\nu\rho\sigma}_{ggVV}(p_i;\mu) = {} & p_{1\,\alpha}p_{2\,\beta}p_{i\,\gamma}p_{j\,\delta}\left(\epsilon^{\mu\nu\alpha\beta}\epsilon^{\rho\sigma\gamma\delta}\widehat{\Theta}_1^{ij} + \epsilon^{\mu\rho\alpha\gamma}\epsilon^{\nu\sigma\beta\delta}\widehat{\Theta}_2^{ij} + \epsilon^{\mu\sigma\alpha\gamma}\epsilon^{\nu\rho\beta\delta}\widehat{\Theta}_3^{ij}\right. \\
& \left. + \delta_1^i\delta_3^j\epsilon^{\mu\alpha\rho\sigma}\epsilon^{\nu\beta\gamma\delta}\widehat{\Theta}_4 + \delta_2^i\delta_3^j\epsilon^{\nu\beta\rho\sigma}\epsilon^{\mu\alpha\gamma\delta}\widehat{\Theta}_5\right), \\
& \Theta_k = \Theta_k(p_1\cdot p_2, p_1\cdot p_3), \quad \widehat{\Theta}_k^{ij} = \widehat{\Theta}_k^{ij}(p_1\cdot p_2, p_1\cdot p_3)
\end{aligned}$$



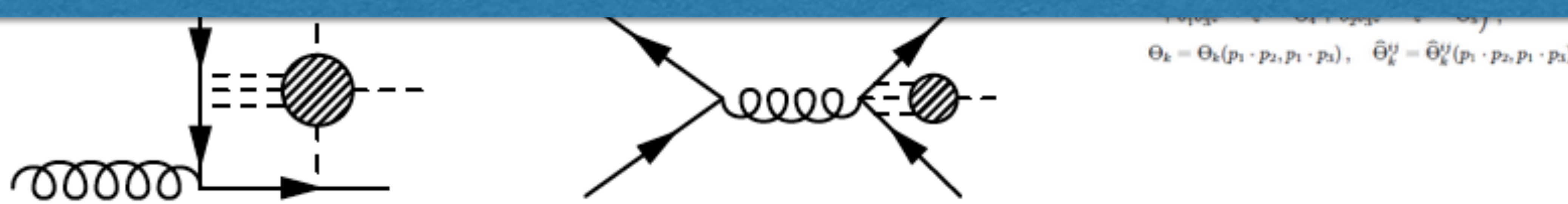


Off-shell Form Factors for the Quantum Critical higgs

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 μ.

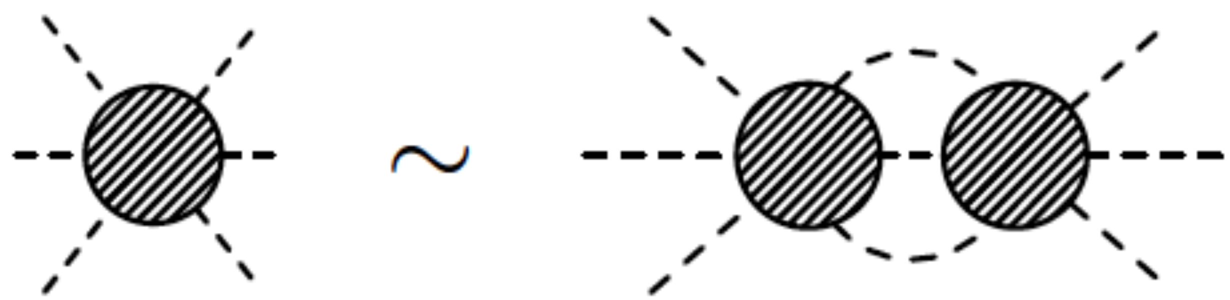
=> can estimate the size of the N-point Higgs correlator by considering the effect of loops on its renormalization.



Estimation of Form Factors

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

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

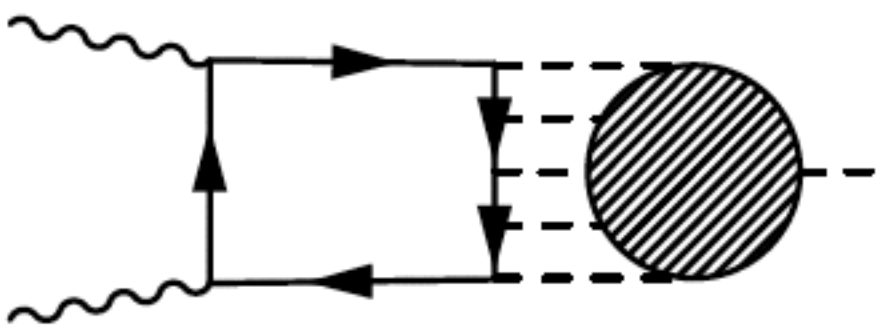


$$\alpha_n \sim (16\pi^2)^{n/2-1}$$

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

Estimation of Form Factors

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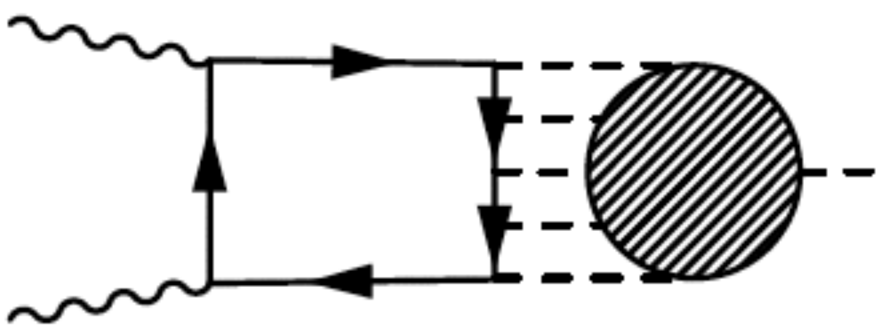

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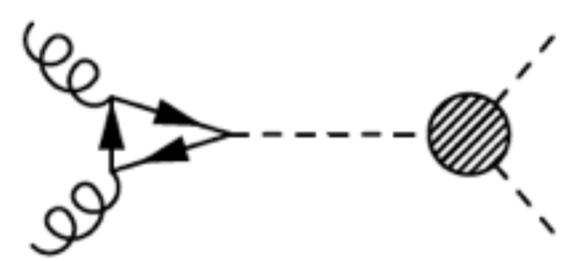
e.g. double Higgs production through gluon fusion would be dominated by



→ 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 $G_h(R,z,p^2) = a^{-\frac{3}{2}}(z)(z/R)^{\frac{1}{2}} \frac{K_\nu(\sqrt{\mu^2-p^2}z)}{K_\nu(\sqrt{\mu^2-p^2}R)}$

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

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

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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

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

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

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

A Natural Qauntum Critical Higgs

Csaki, SL, Parolini, work in progress

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

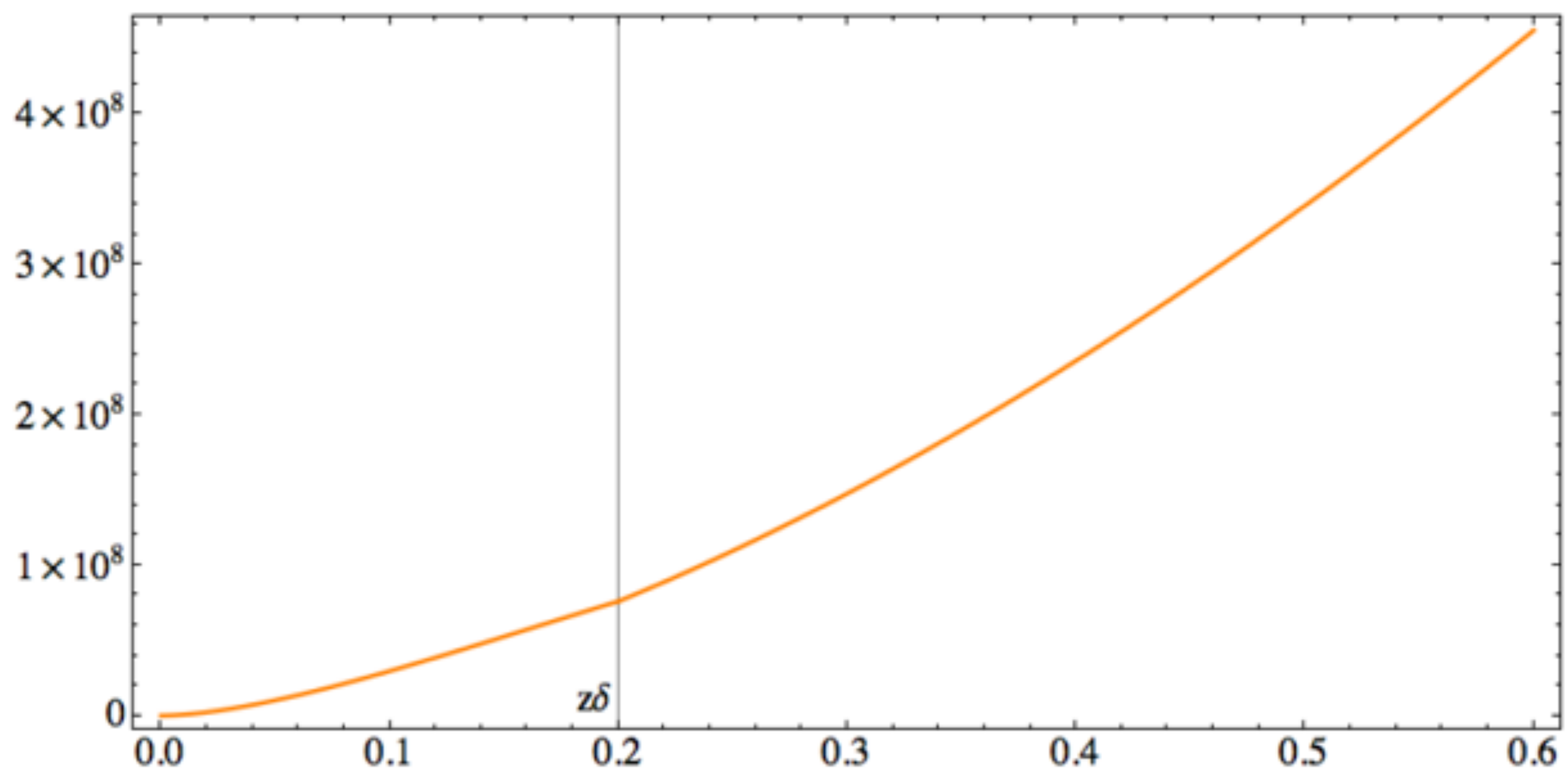
$$\left(-\partial_z^2 + \hat{V}\right)\Psi = p^2\Psi$$

The Schrödinger potential

$$\hat{V} = \hat{M}^2 + \frac{3a''}{2a} + \frac{3(a')^2}{4a^2}$$

$$\hat{M}^2 = a^2 R \frac{\partial^2 V(\hat{v})}{\partial \hat{v}^2}.$$

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 $p^2 > \mu_{IR}^2$

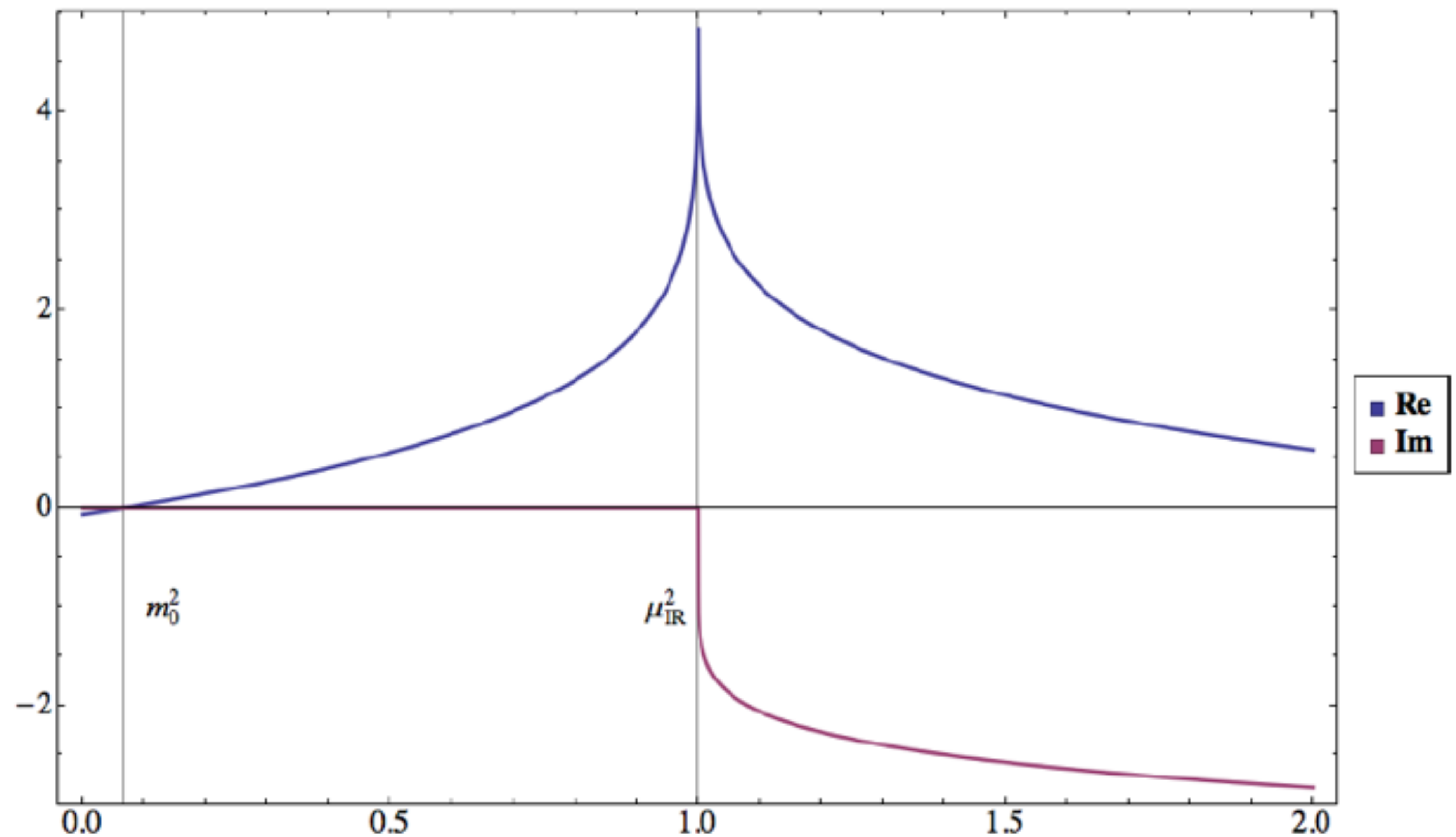
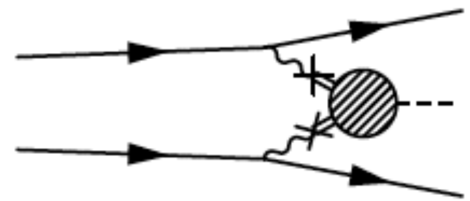
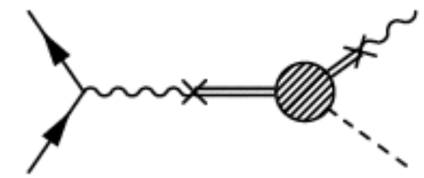


Figure 2: The inverse propagator $\Pi(p^2)$. It becomes zero in correspondence of $p^2 = m_0^2$ and it stays real for $p^2 < \mu_{IR}^2$.

Direct Signals

- Form factors



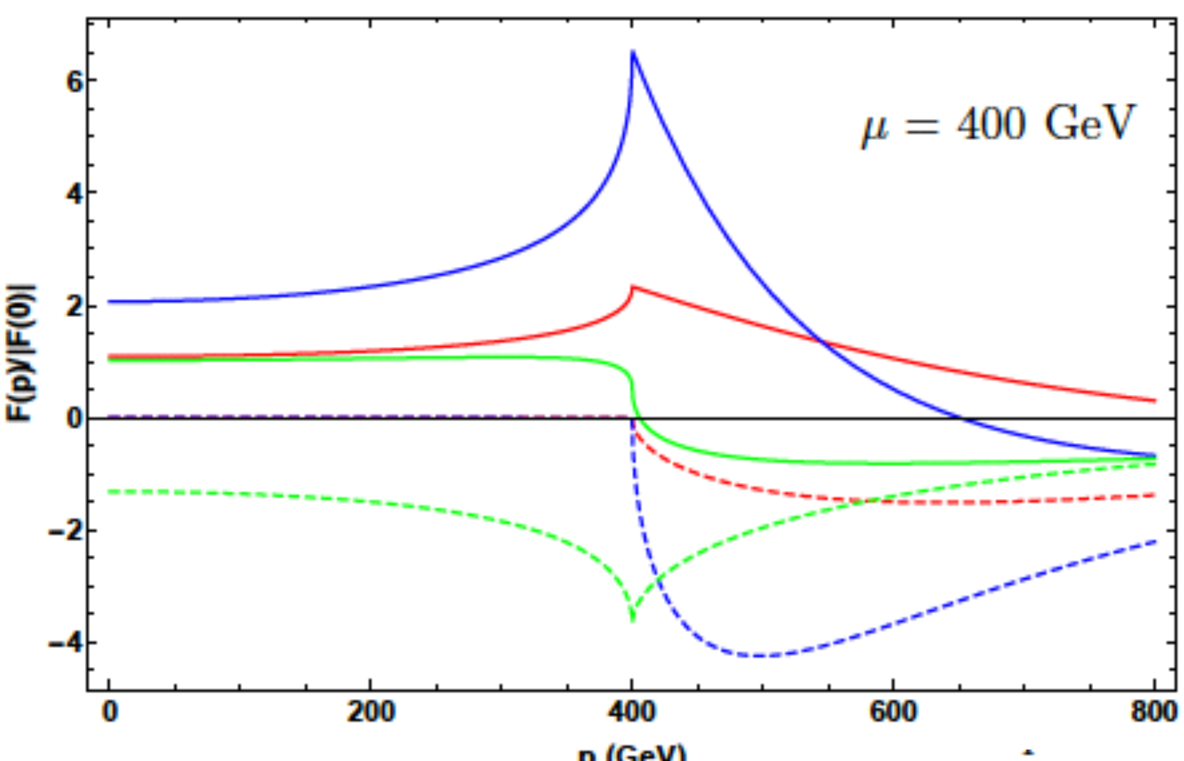


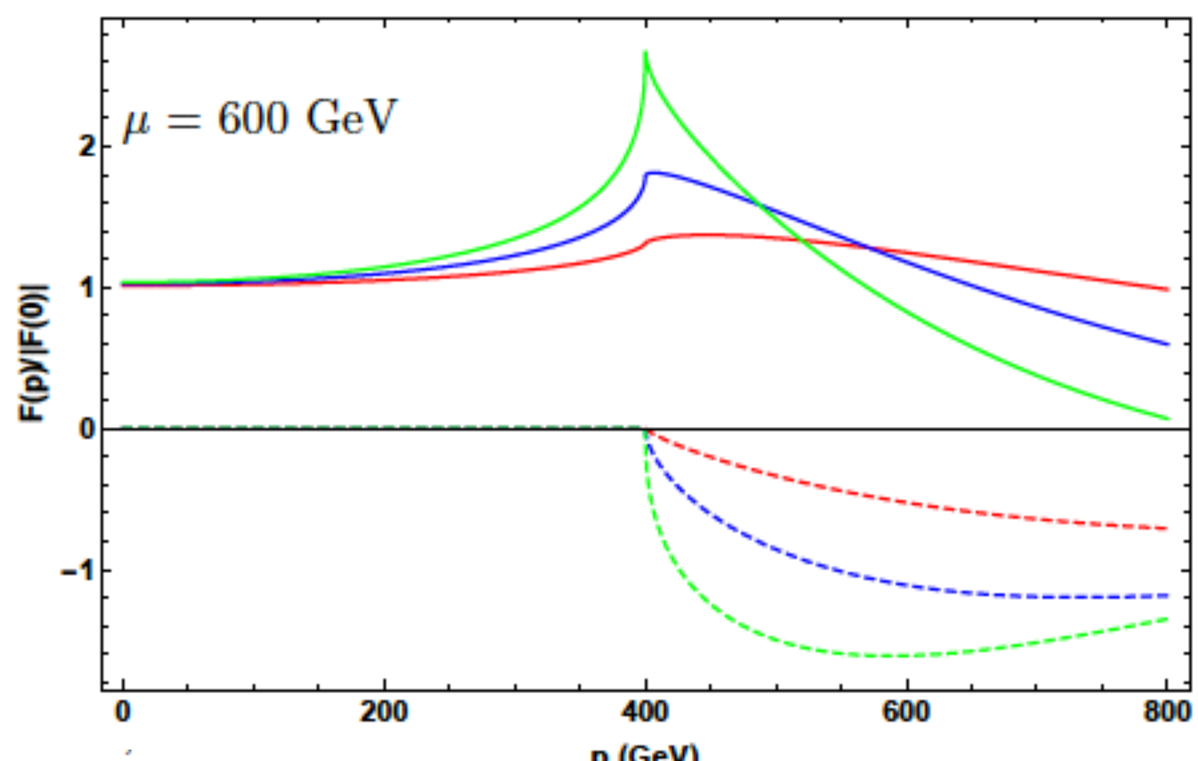
$$\mathcal{H} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \mathcal{V} + h \end{pmatrix}$$

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

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

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

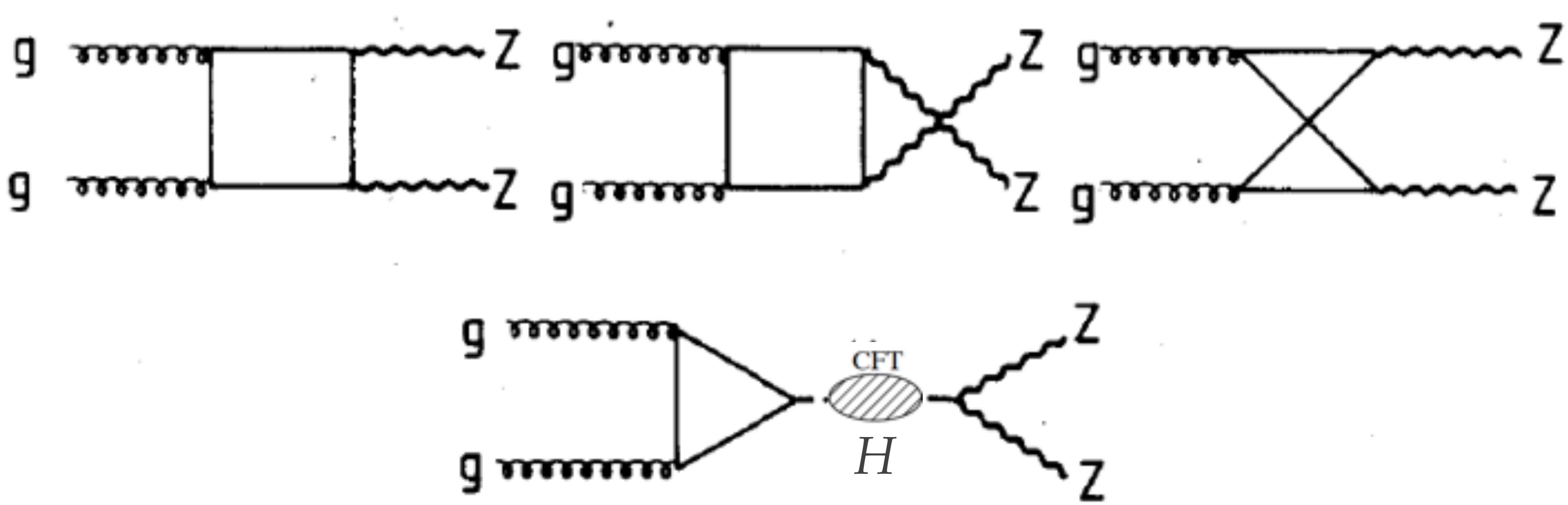




$\Delta = 1.2$ (Red), 1.4 (Blue), and 1.6 (Green)

Direct Signals

- Off-shell Higgs can be tested via interference.

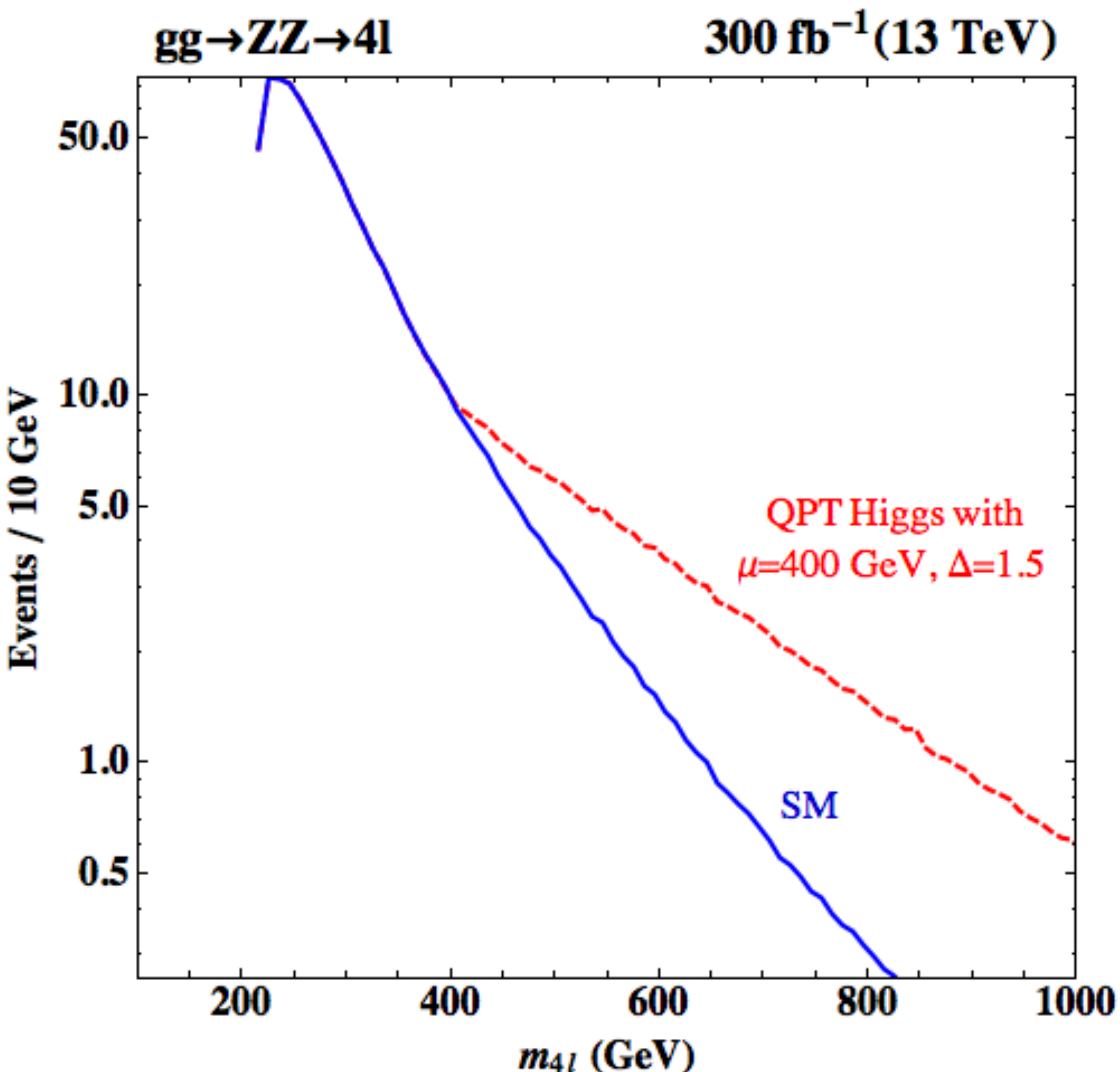


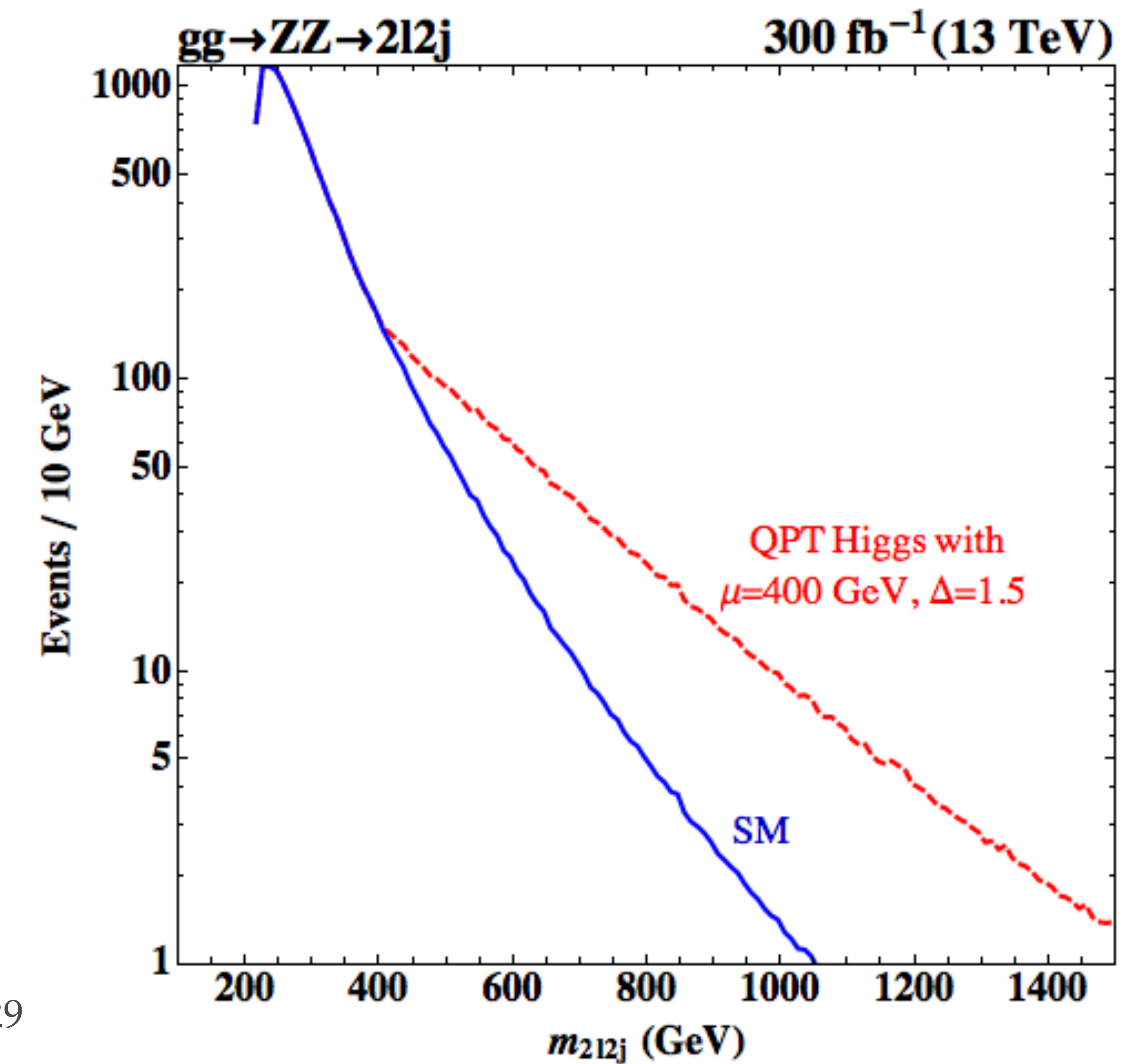
sensitive to the
modifications of the Higgs two-point function

Direct Signals

- Single Higgs production: Production of the cut modifies Higgs cross sections for energies above μ => modifies any cross sections that involve the (tree-level) exchange of the components of Higgs

- any cross sections that involve the (tree-level) exchange of the components of H.





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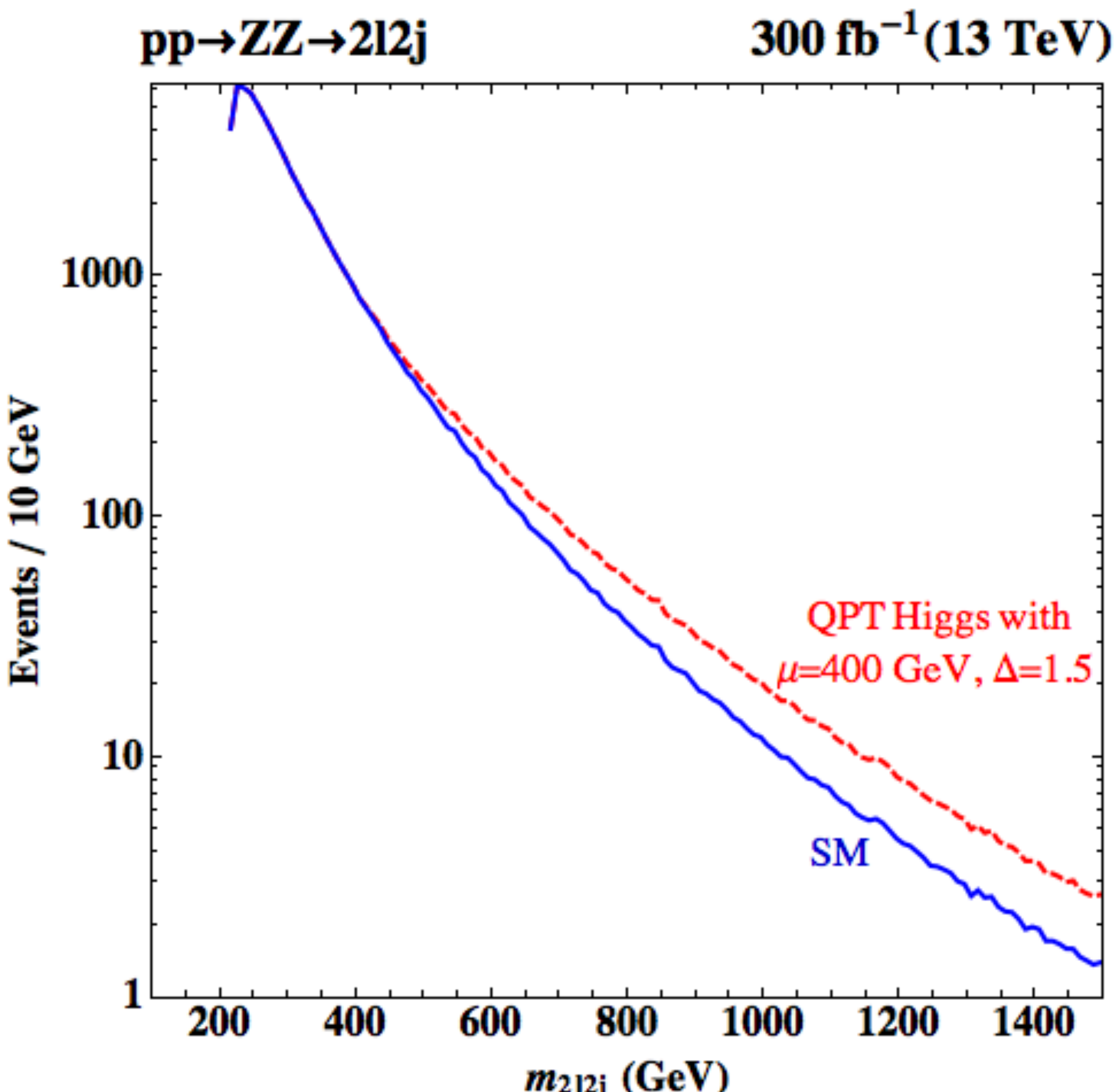

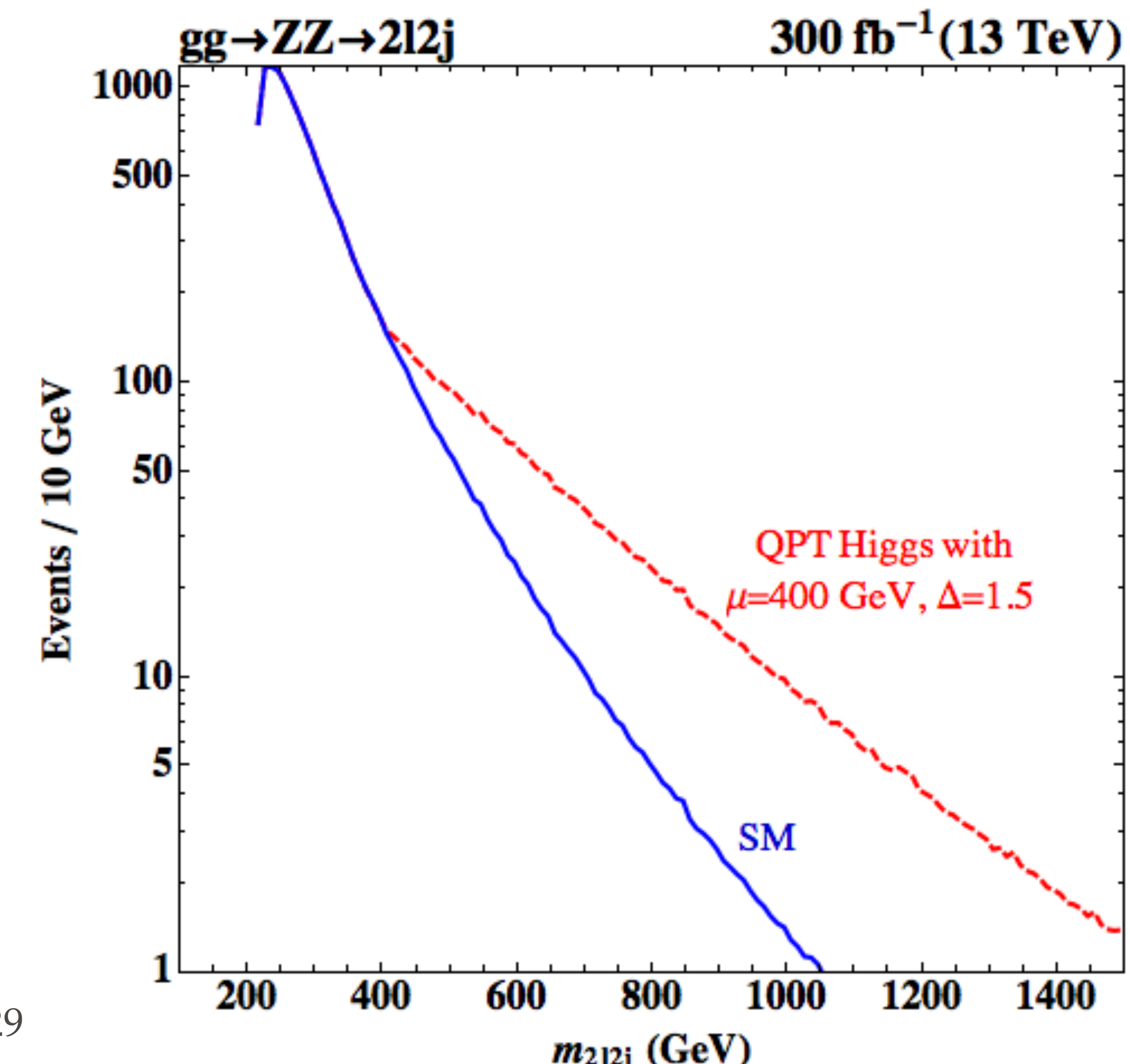

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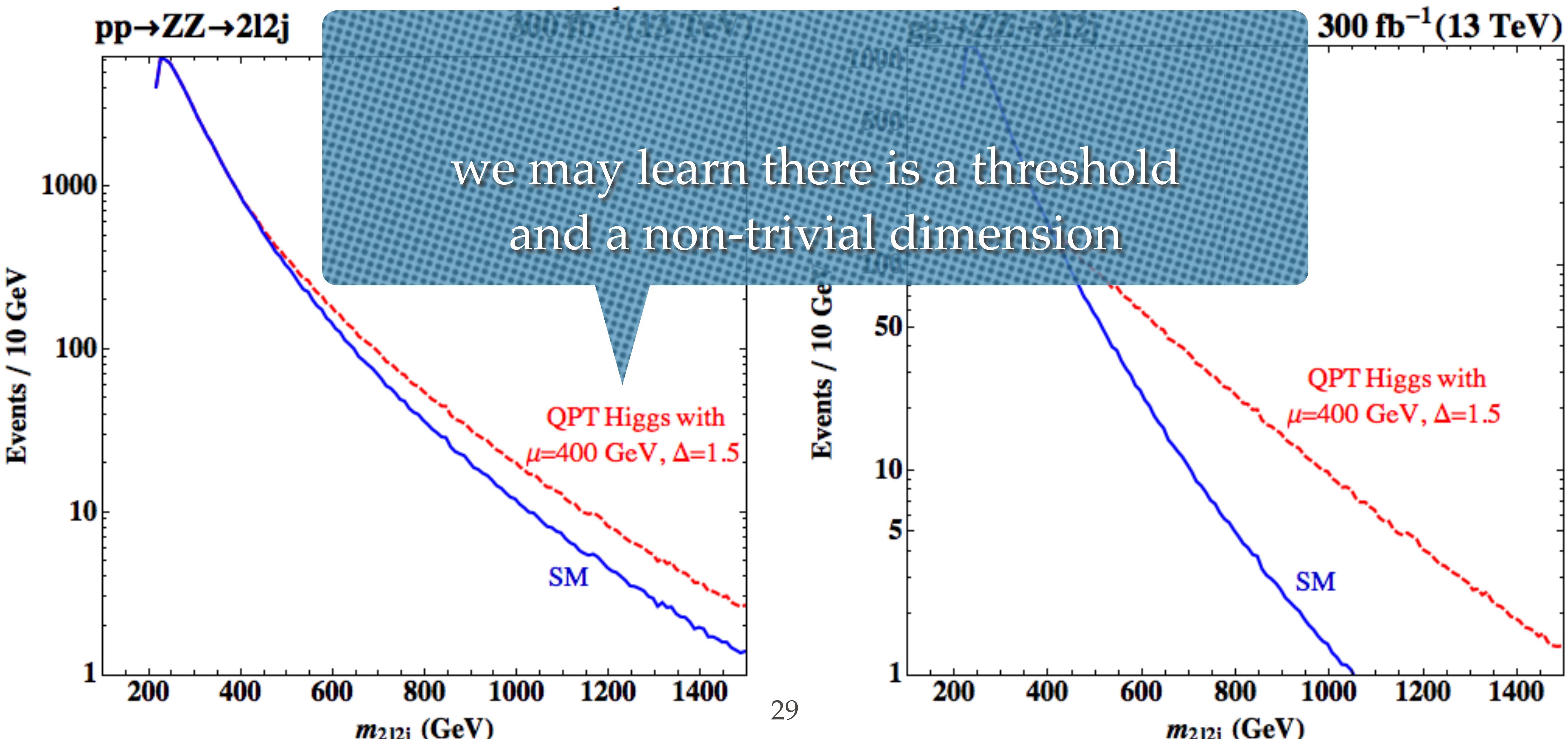

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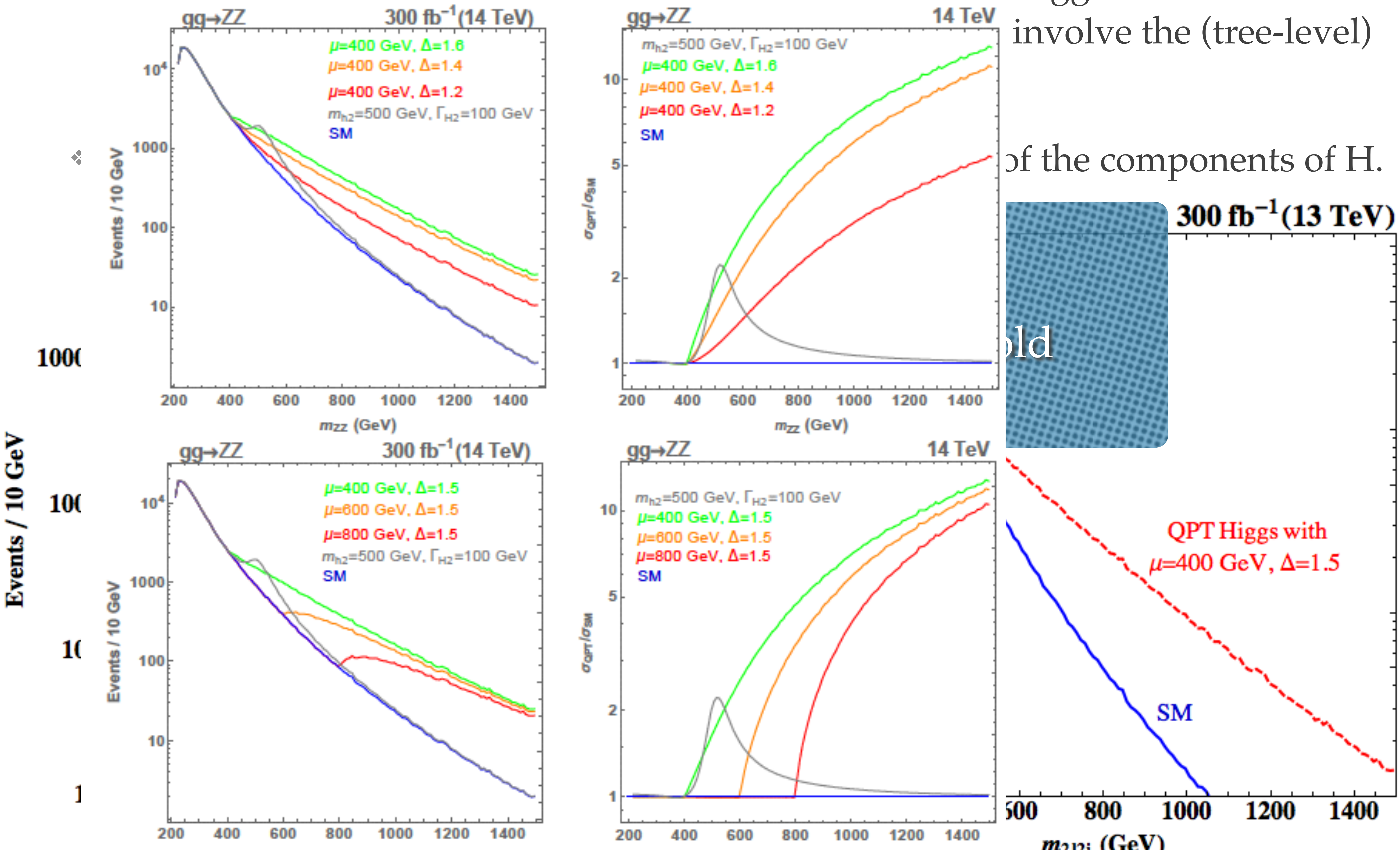

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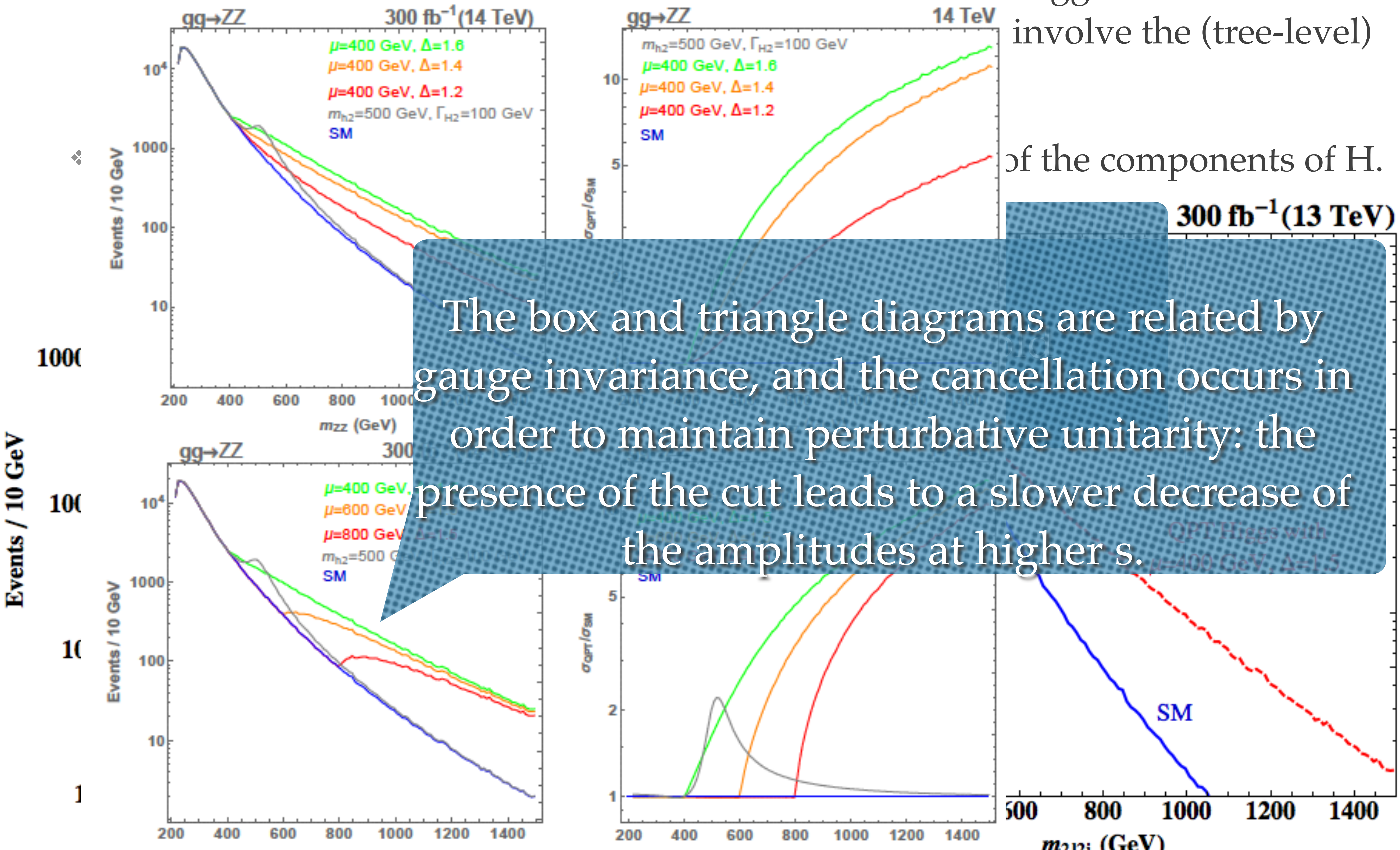
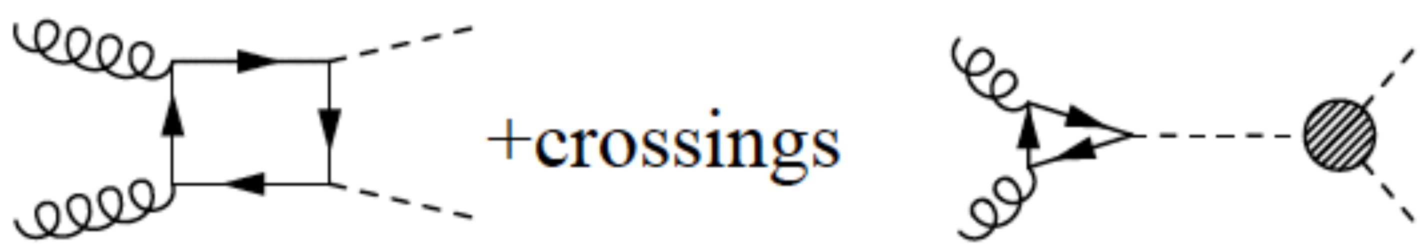


The box and triangle diagrams are related by gauge invariance, and the cancellation occurs in order to maintain perturbative unitarity: the presence of the cut leads to a slower decrease of the amplitudes at higher s.

Direct Signals

- Double Higgs production



$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{\alpha_w^2 \alpha_s^2}{2^{15}\pi M_W^4 \hat{s}^2}\left(|\text{gauge1}|^2 + |\text{gauge2}|^2\right)$$

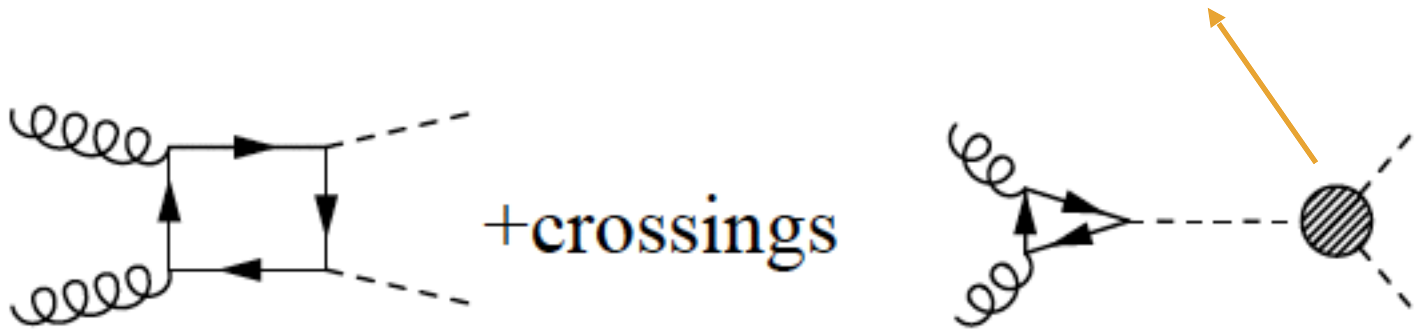
gauge1 = box + triangle (negative interference)

gauge2 = box (largest contribution)

Direct Signals

- Double Higgs production

probe the higher n-point correlators of the CFT.



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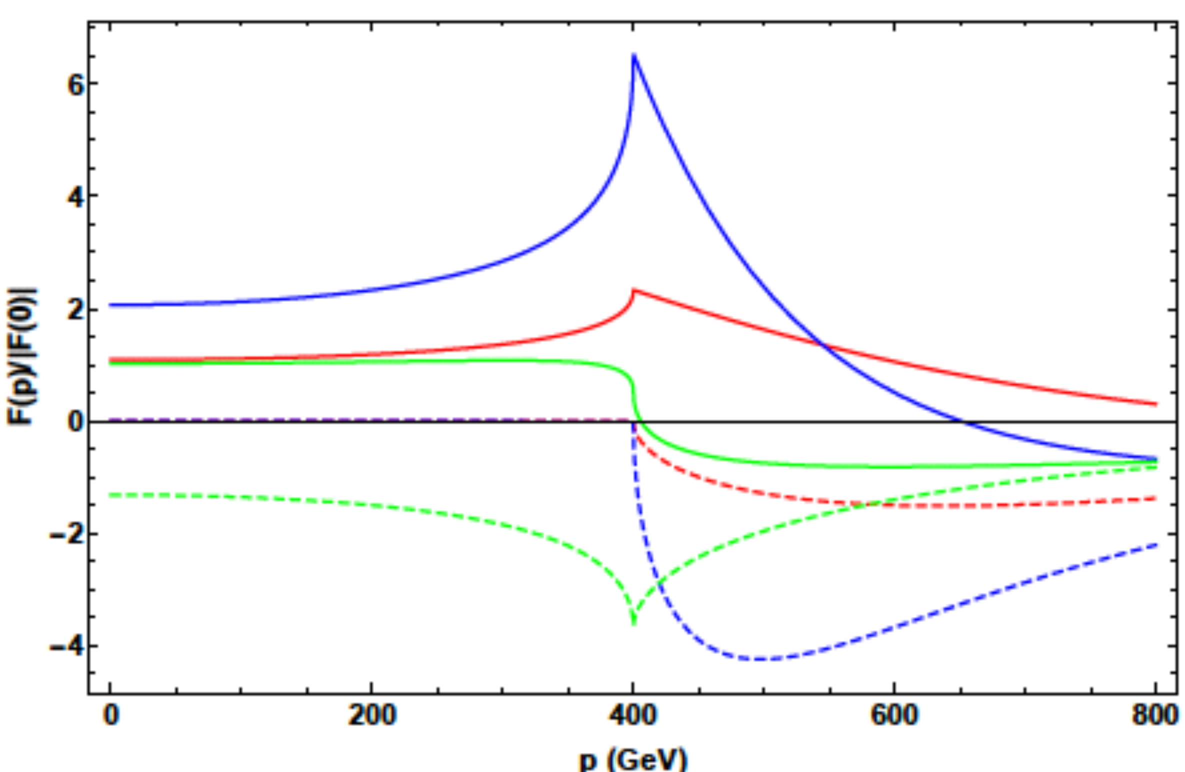
Direct Signals

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

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

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

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



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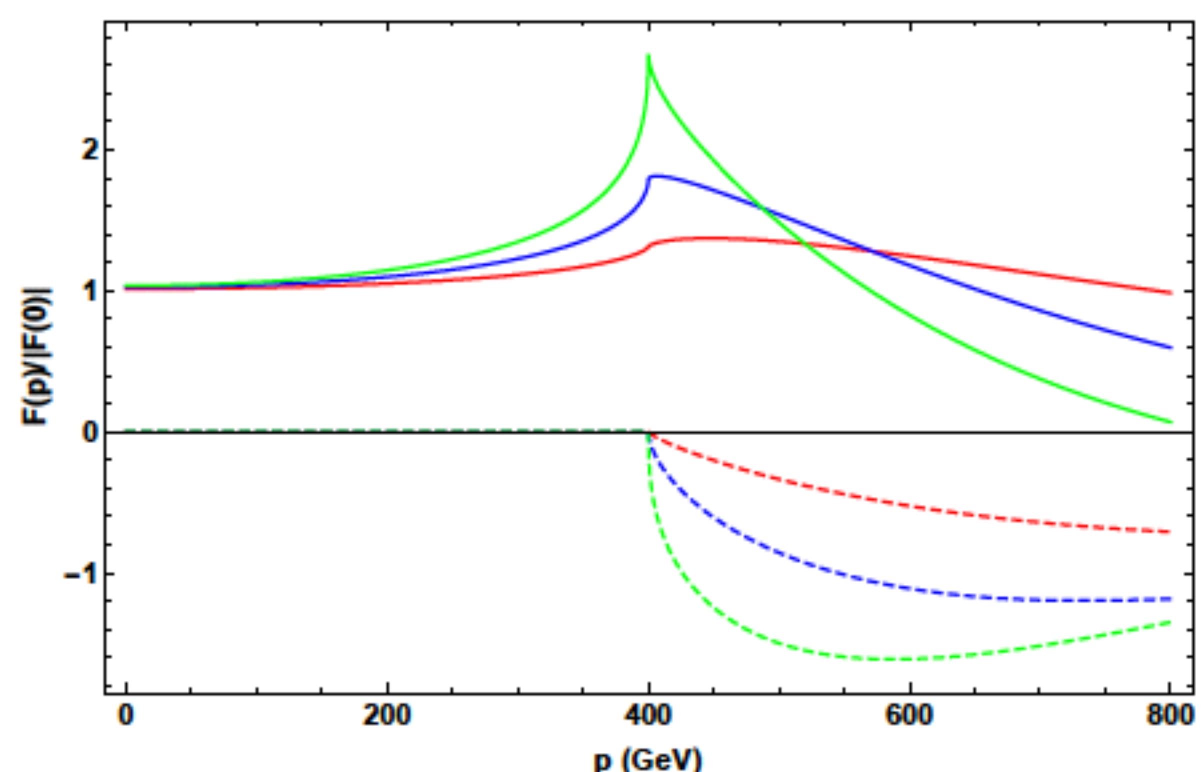
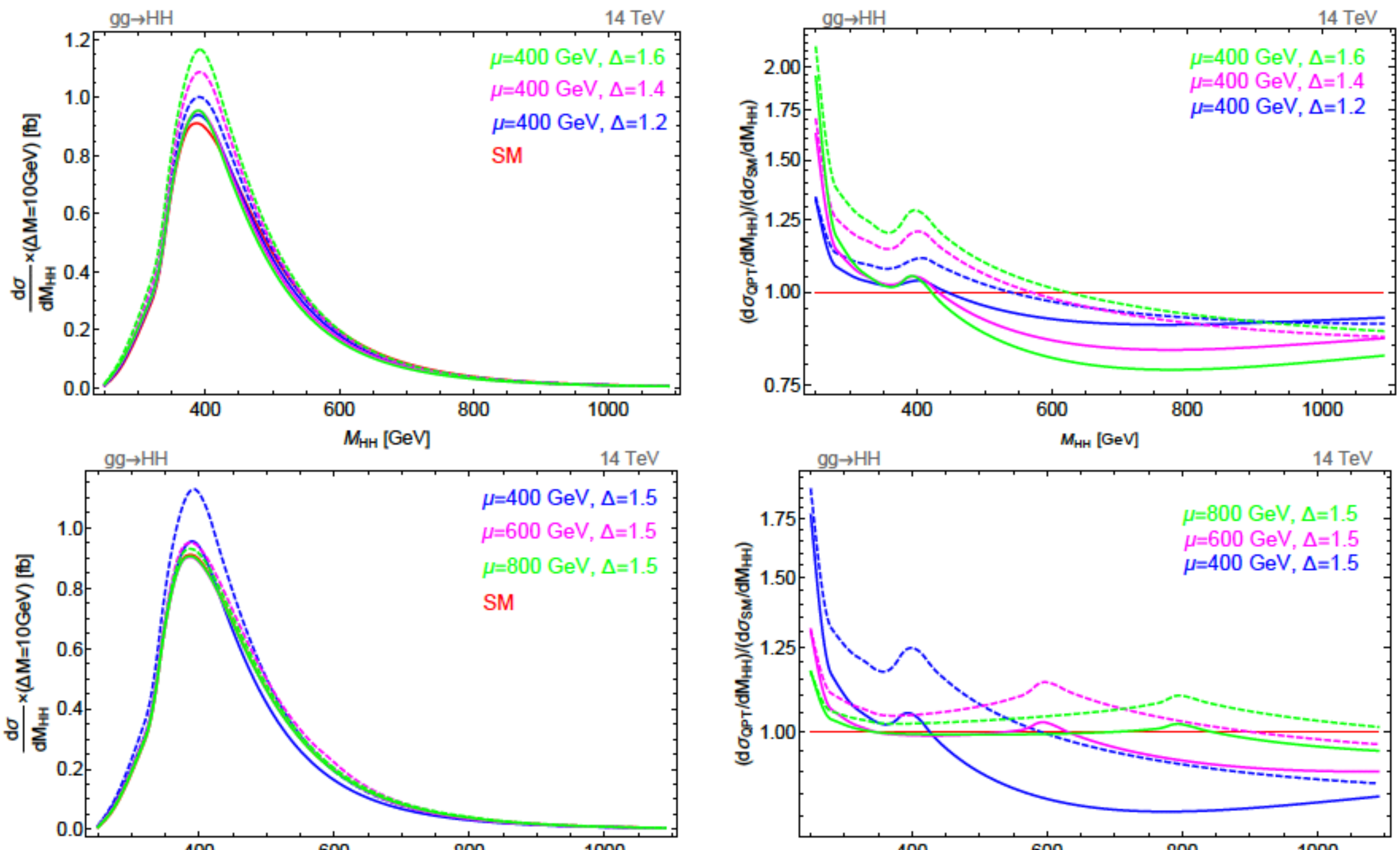


Direct Signals

- 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

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

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Phenomenology: Not EFT, but form factors

Back-up

Non-local operators

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

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

similar to SCET!

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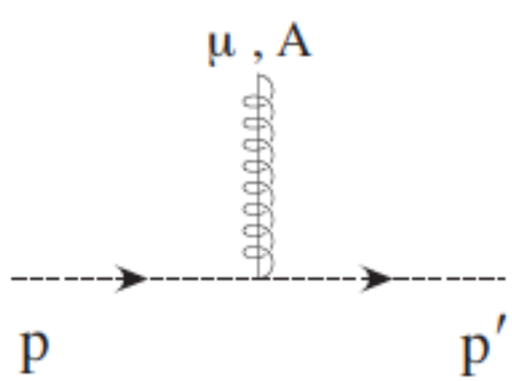
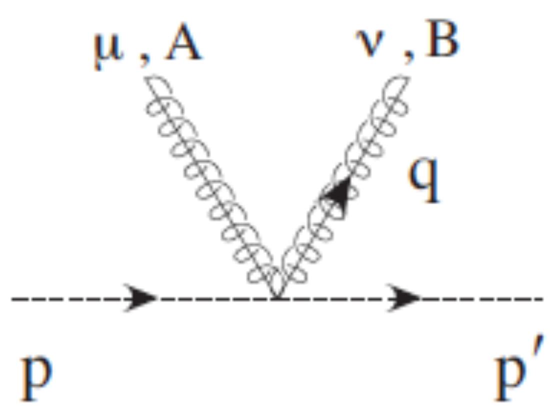




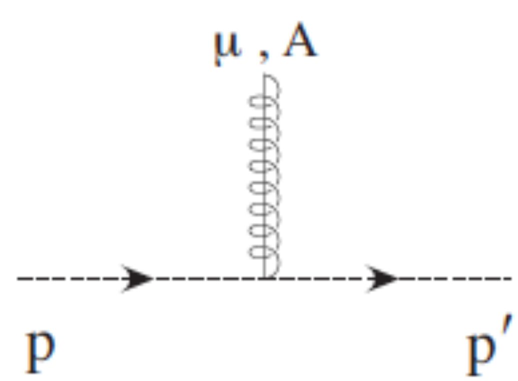
similar to SCET!

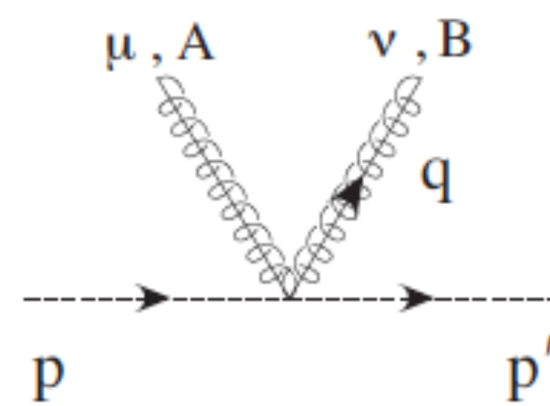
Non-local operators

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

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

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





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

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

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

similar to SCET!