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UNDER THE HIGH PATRONAGE OF THE PRESIDENT OF THE ITALIAN REPUBLIC

Rome, April 12, 2016

Prospects for the measurement of the Higgs Potential @ FCC

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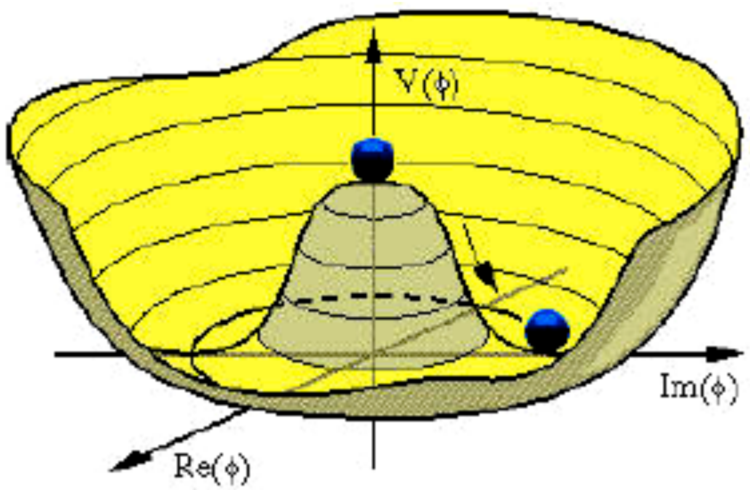
1905

Based on collaboration with Benjamin Fuks, Jeong Han Kim (arXiv:1510.07697)
Higgs Chapter of the report on Physics at 100 TeV (R. Contino et al.)
And also with B. Bellazzini, C. Csaki, J. Hubisz, J. Serra, J. Terning (arXiv:1511.08218)

How well do we understand the EWSB, i.e. Higgs Potential?



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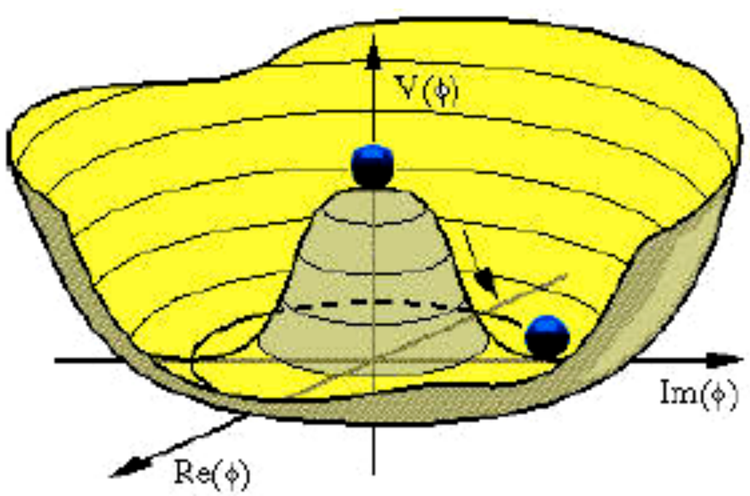

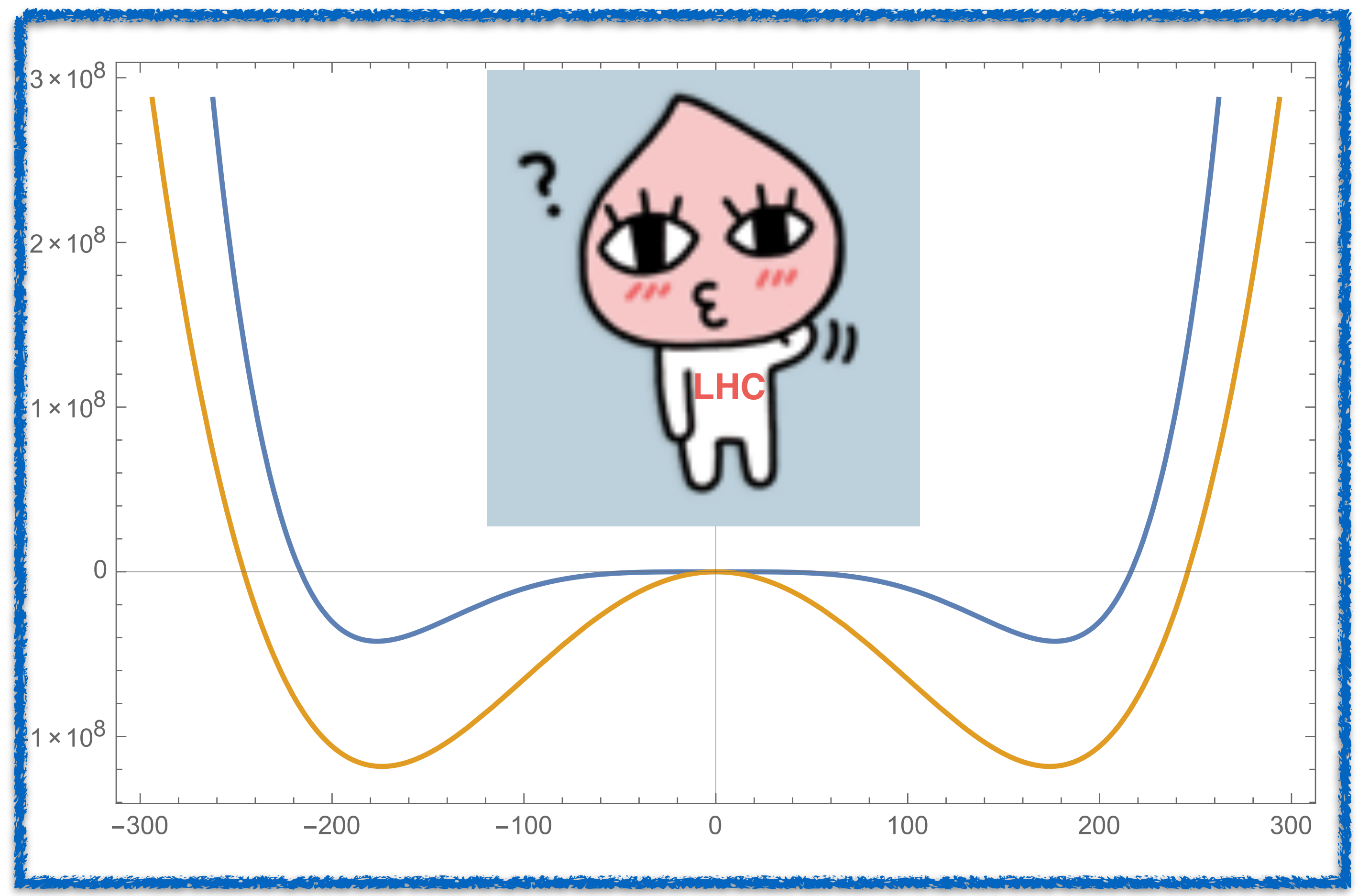

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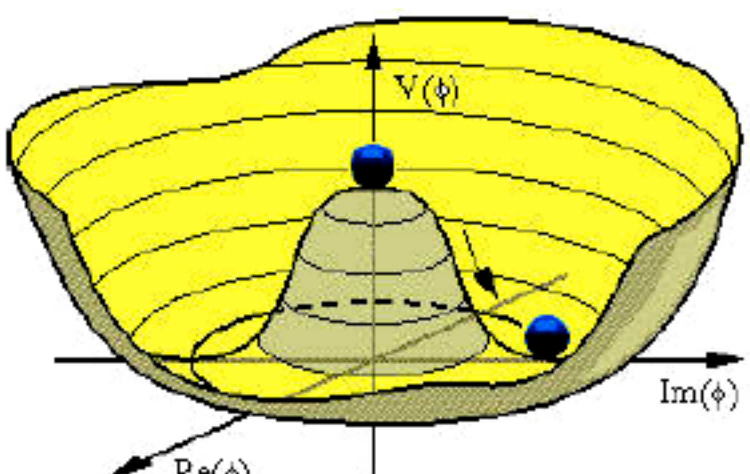
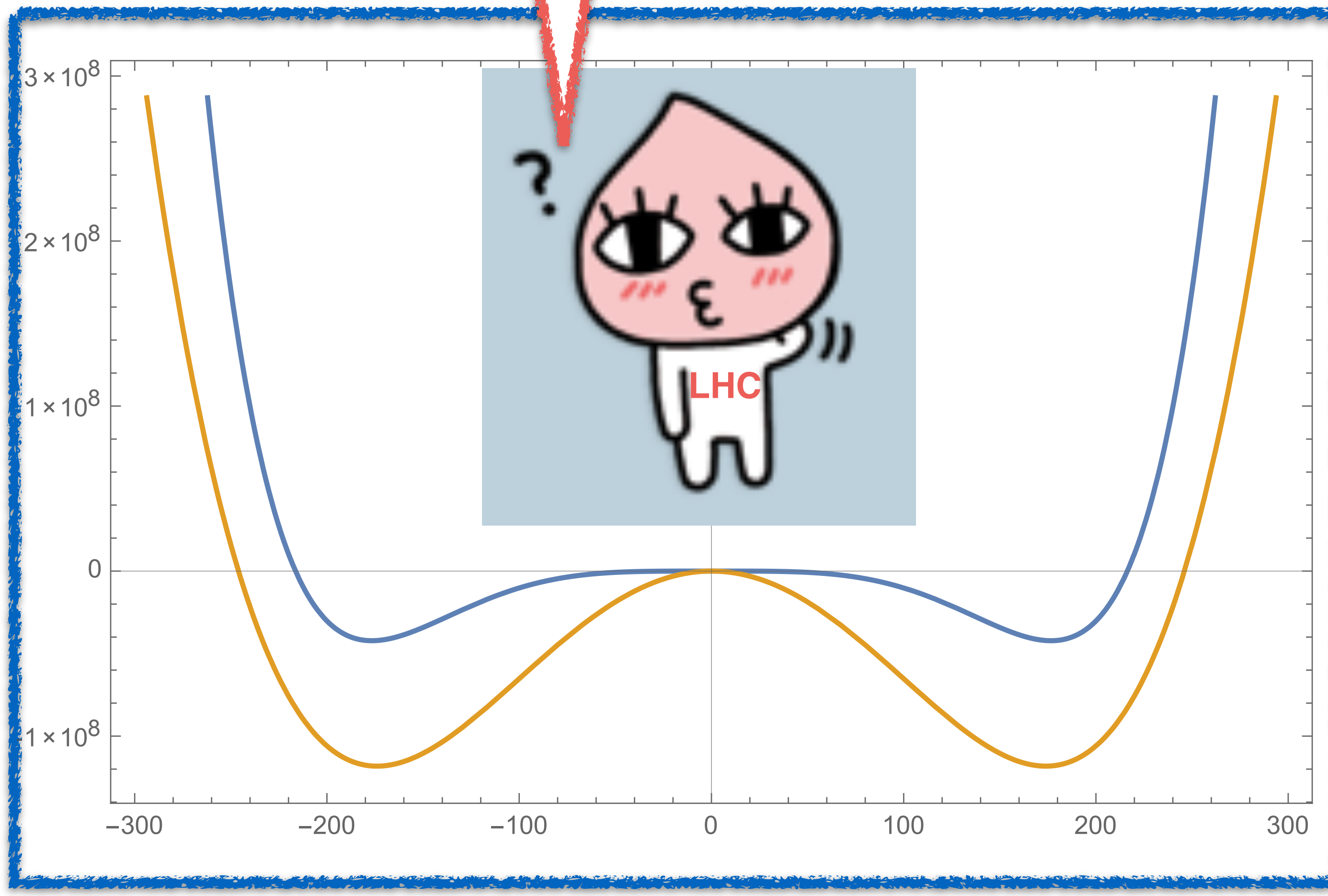


$$V(\tilde{h}) \overset{?}{=} \tilde{v}^{2\Delta}\tilde{m}^{4-2\Delta}\sum_{n=0}^{\infty}\frac{c_n}{n!}\left(\frac{\tilde{h}}{\tilde{v}^{\Delta}}\right)^n$$



Higgs Potential is unknown: e.g. a toy model

$$V_{SM}(H) = -\mu^2 H^+ H + \lambda (H^+ H)^2$$

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$$\tilde{V}(H) = -\lambda |H|^4 + c_6 |H|^6 \qquad c_6 \sim \Lambda^{-2}$$

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- With this potential the VEV and mass of the Higgs are given by, $v^2 = \frac{4}{3}\frac{\lambda}{c_6}\,, \quad \frac{m_h^2}{v^2} = 2\lambda$ ⟶ experimentally $\lambda \approx 0.13$

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This is just one simple example that shows that the form of the Higgs potential is completely undetermined

Higgs Potential: toy model

- However, FCC can potentially distinguish between the two possibilities just presented.

- In particular, via double Higgs production, the triple Higgs coupling can be probed: i.e.

$$\lambda_{hhh} = 3\frac{m_h^2}{v} \longleftrightarrow \tilde{\lambda}_{hhh} = 7\frac{m_h^2}{v}$$

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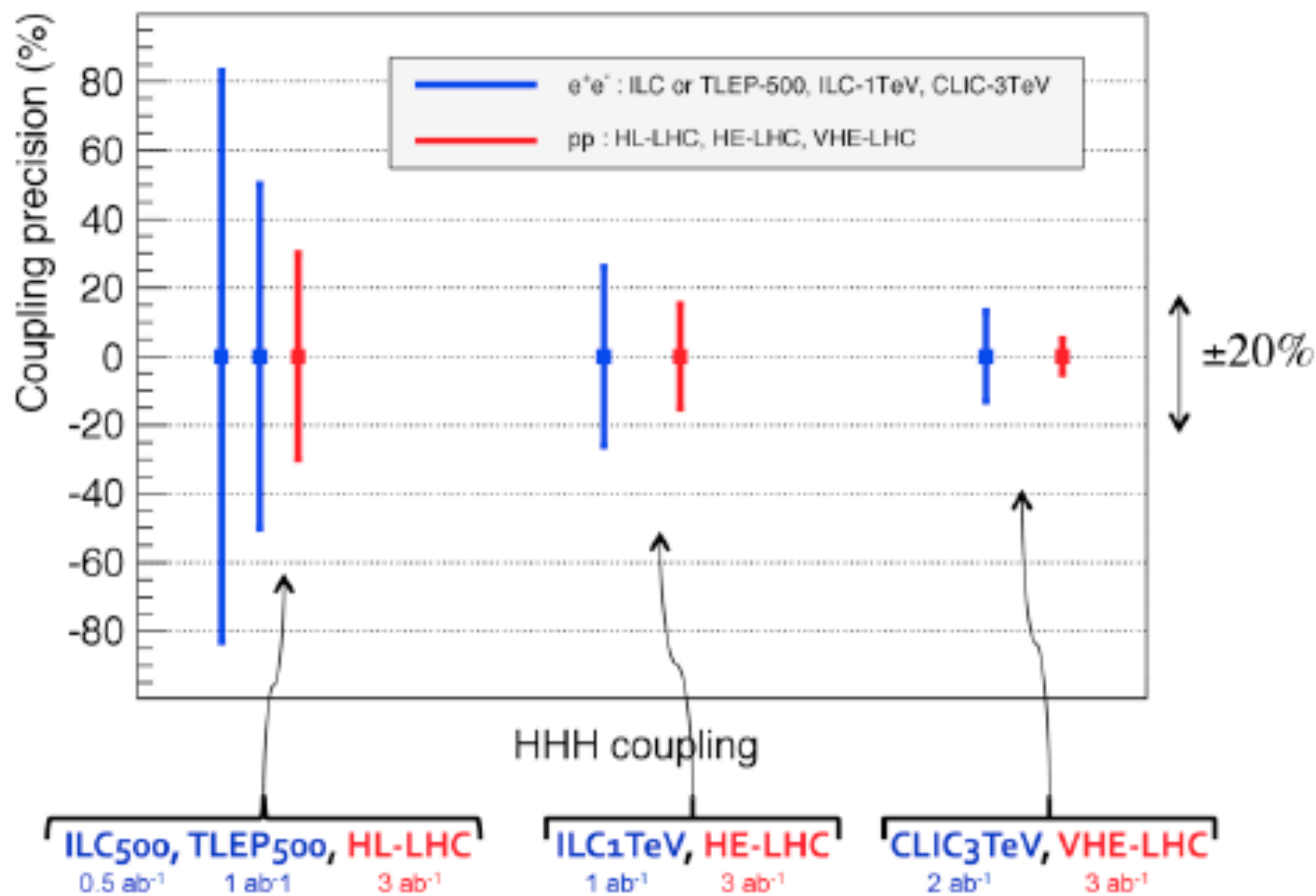
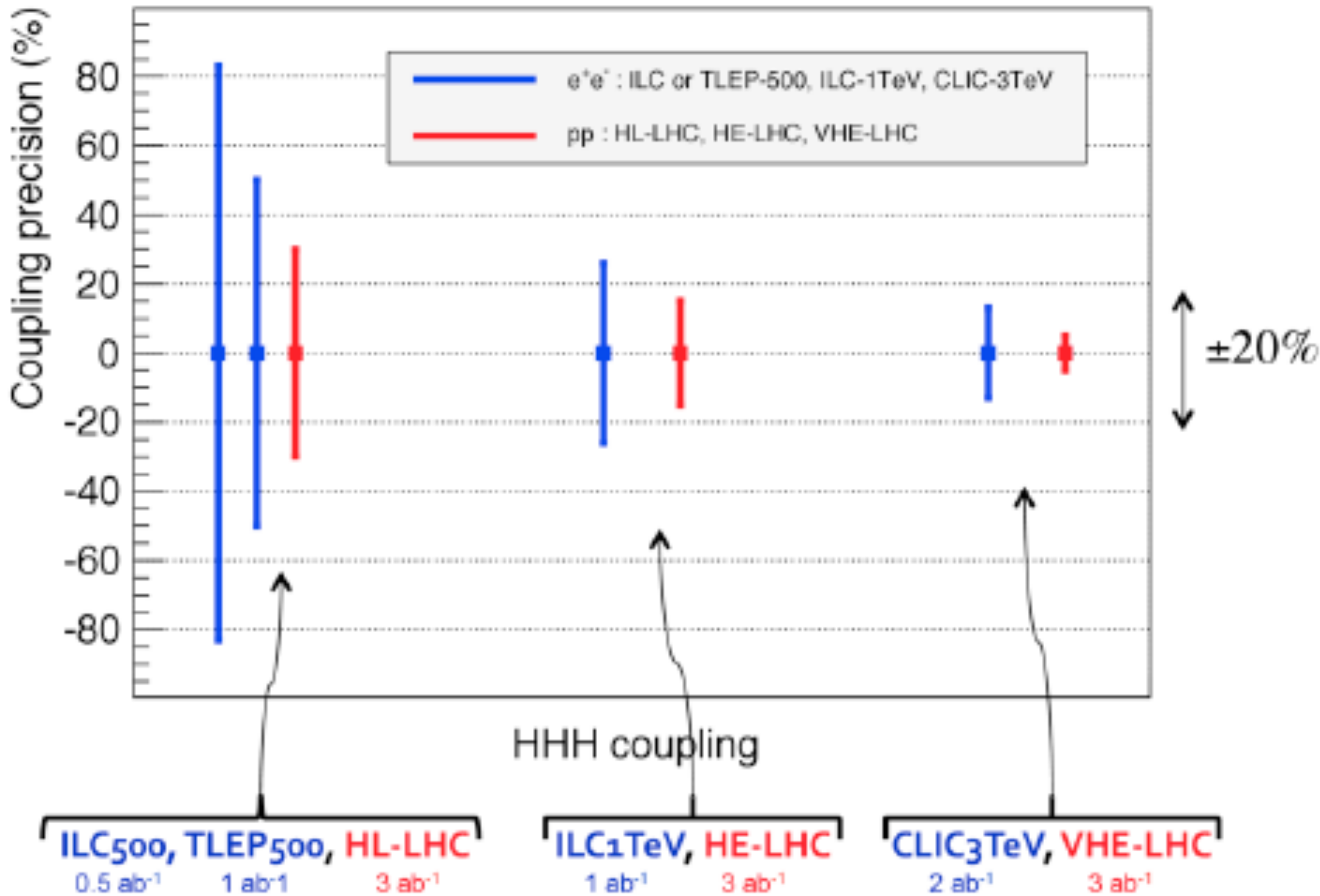
λ_{hhh}



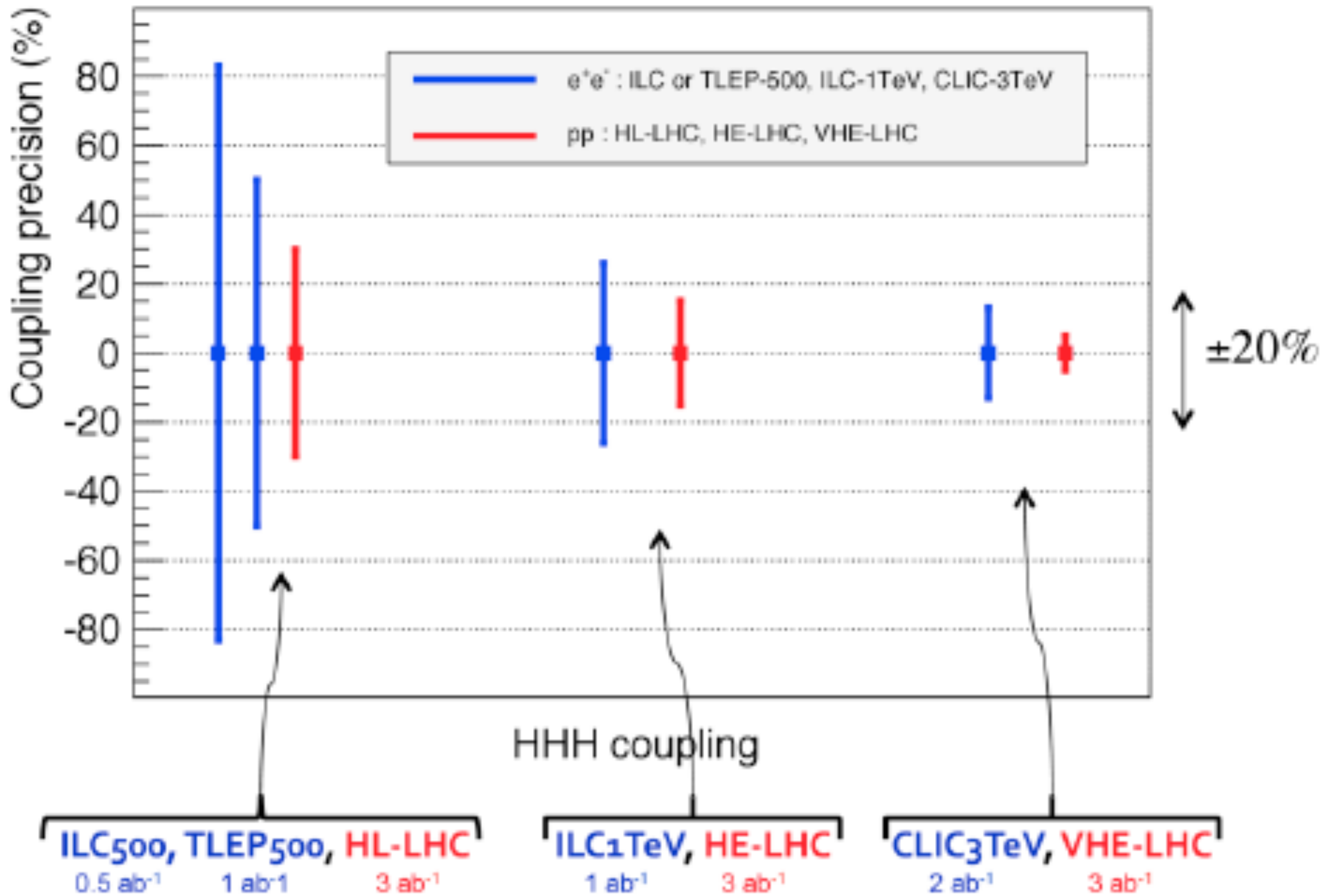
Higgs Potential



- ✦ we need future colliders to understand the underlying dynamics of the EWSB

Higgs Potential

see Roberto Contino's talk!



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Probing the EWSB mechanism

with Benjamin Fuks, Jeong Han Kim

- Establishing the SM nature of the electroweak symmetry breaking mechanism
  - Finding a Higgs is the first step ✅
  - Deriving the form of the scalar potential is necessary ❌
- Establishing the SM nature of the Higgs boson ?
  - Measurements of the Yukawa interaction strengths (*i.e.*, the fermion masses)

- The scalar potential

$$V_h = \boxed{\frac{m_h^2}{2}h^2} + \boxed{(1+\kappa_3)\lambda_{hhh}^{SM} v h^3} + \boxed{\frac{1}{4}(1+\kappa_4)\lambda_{hhhh}^{SM} h^4} \quad \text{with} \quad \lambda_{hhh}^{SM} = \lambda_{hhhh}^{SM} = \frac{m_h^2}{2v^2}$$

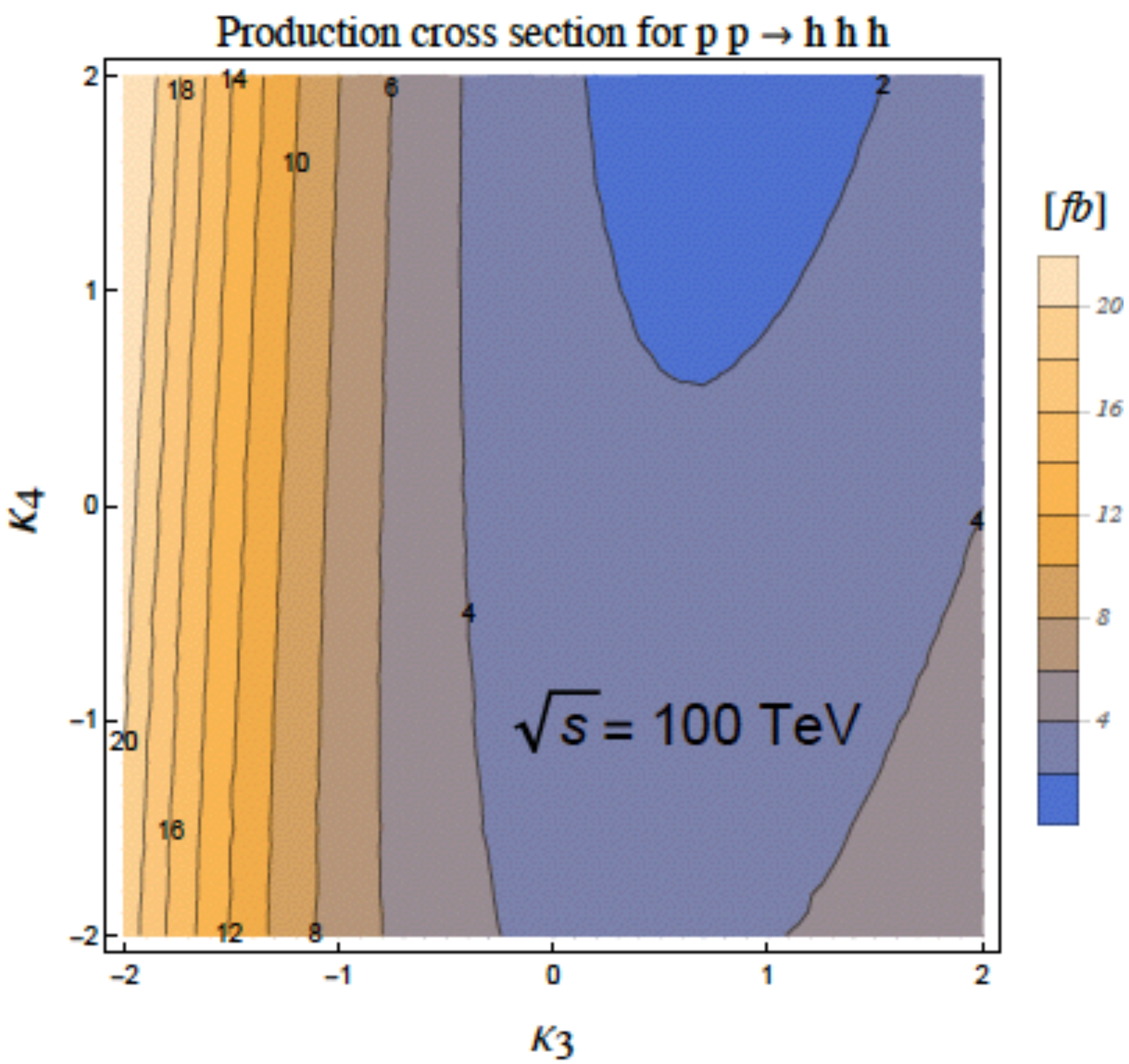
Measured

is $\kappa_3 = 0$?
Di-Higgs production
at the LHC can help

is $\kappa_4 = 0$?
No way for the LHC
(hhh cross section of ~0.01 fb)

Idea: probing triple-Higgs production at the FCC → Sensitivity to both κ parameters

Triple Higgs production at the FCC

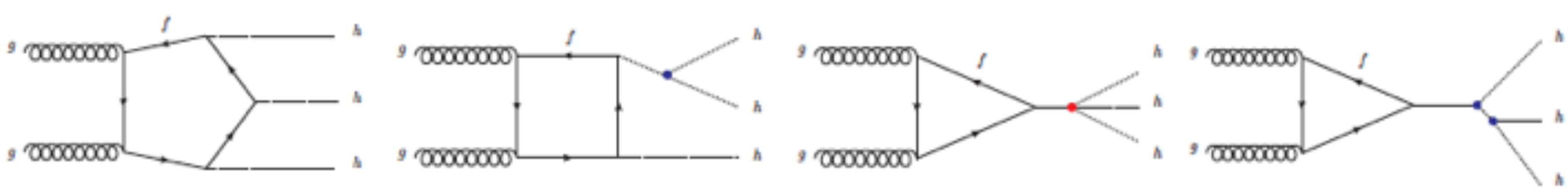


- **Triple Higgs production total rate**
  - Small in the Standard Model (~ 3-4 fb)
  - Could be much larger with new physics

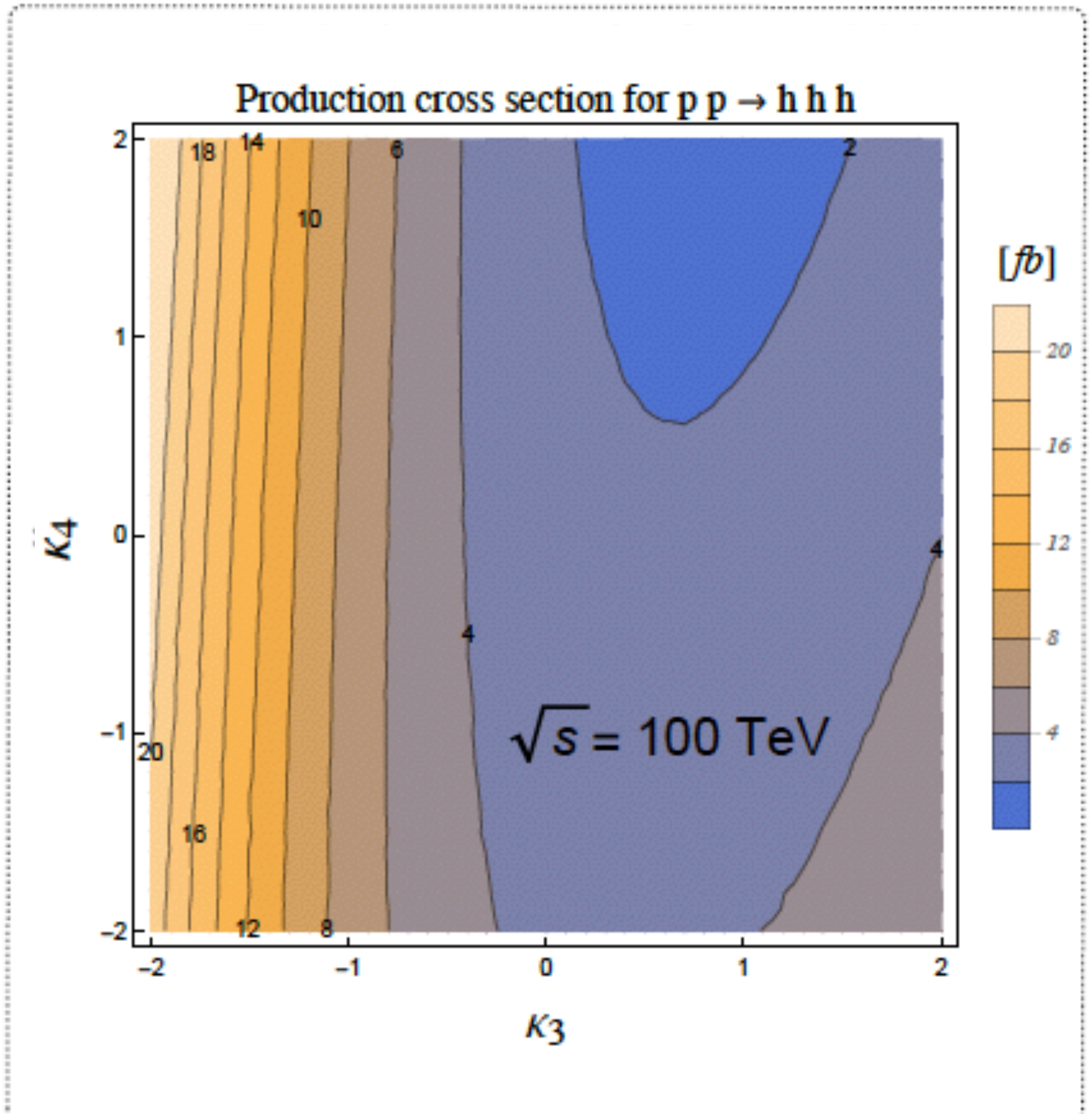
- **Dependence on the κ parameters**
  - κ_3: very strong
    - Can reach 20 fb for large and negative values
  - κ_4: milder (but not negligible)

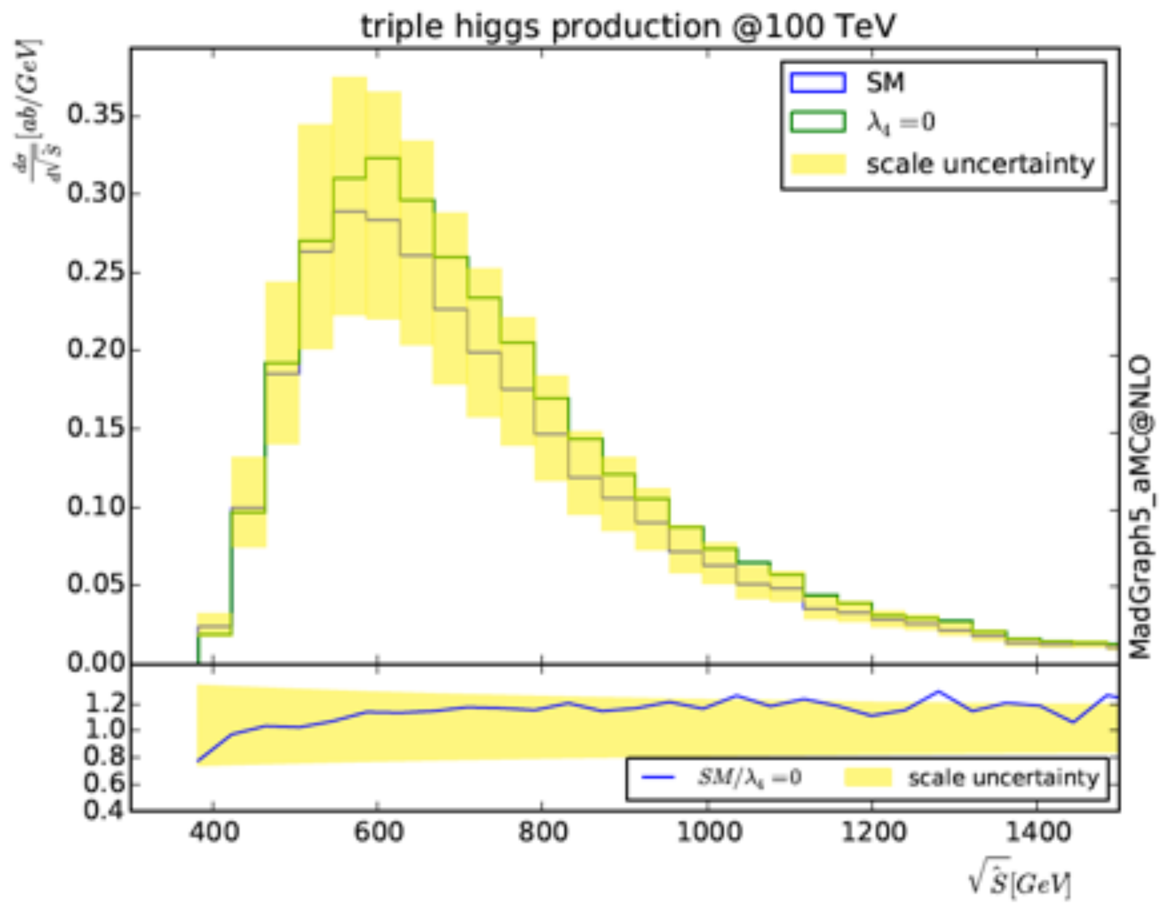
Could it be constrained?

$$\boxed{(1+\kappa_3)\lambda^{SM}_{hhh} v h^3} + \boxed{\frac{1}{4}(1+\kappa_4)\lambda^{SM}_{hhhh} h^4}$$



Triple Higgs production at the FCC

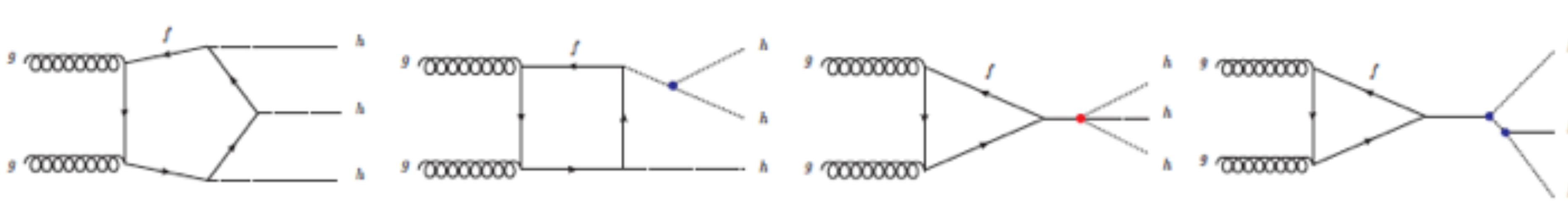




values

Could it be constrained?

$$\boxed{(1+\kappa_3)\lambda^{\rm SM}_{hhh} v h^3} + \boxed{\frac{1}{4}(1+\kappa_4)\lambda^{\rm SM}_{hhhh} h^4}$$



Considered triple Higgs signals

✦ Decay modes with the larger branching ratios

- ✤ 4 b-jets and a 2 W's (22%): boosted techniques?
  - ➢ see the di-Higgs case at the LHC
- ✤ 6 b-jets (19.5%): boosted techniques or angular information?
  - ➢ see the di-Higgs case at the LHC

Necessitates FCC detector details → Study of other channels

✦ Decay in the 4b + 2γ channel

- ✤ Clean, low background (*cf.* the diphoton)
- ✤ Small branching fraction (0.232%)
- ✤ Only studied channel so far [Papaefstathiou & Sakurai] [Chen, Yan, Zhao, Zhong & Zhao]

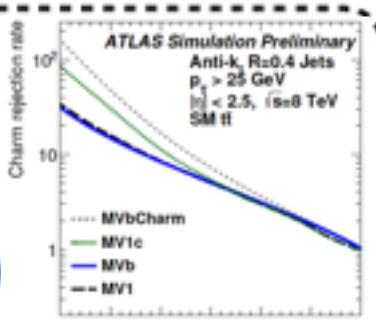
✦ Decay in the 4b + 2τ channel

- ✤ Large branching fraction (6.46%)
- ✤ Not studied yet, but the 2b+2τ channel is interesting in the di-Higgs case at the LHC

Why not at the FCC?

The 4b + 2γ channel: generalities

✦ Simulation details



- Parton-level study + smearing of the four-momenta (*à la* ATLAS)
- b-tagging performance: two LHC-inspired working points
  - ★ Very efficient (70%) with larger fake rates (18%, for c-jets, 1% for lighter jets)
  - ★ Less efficient (60%) with smaller fake rates (1.8%, for c-jets, 0.1% for lighter jets)

How good should the b-tagging be to observe a triple-Higgs signal

✦ Selection strategy for 20 ab^{-1}

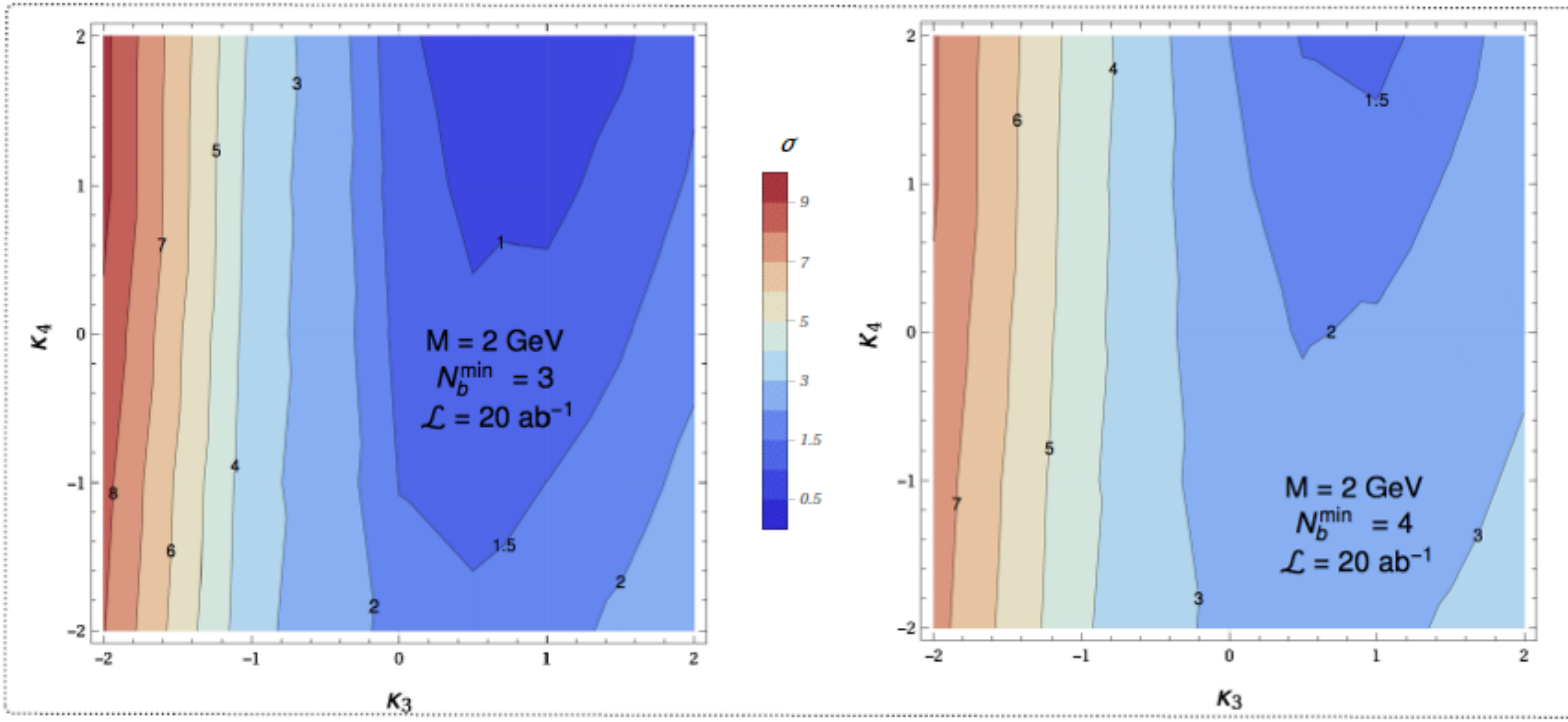
- Four jets (with an invariant mass smaller than 600 GeV), 2 photons
- Two dijet systems compatible with a Higgs ($m_{jj} \in [105, 140]$ GeV)
- The diphoton system compatible with a Higgs ($m_{\gamma\gamma} \in [125\text{-}M, 125\text{+}M]$ GeV)

What is the best M-value?

- At least $N_b^{\min}$ b-tagged jets

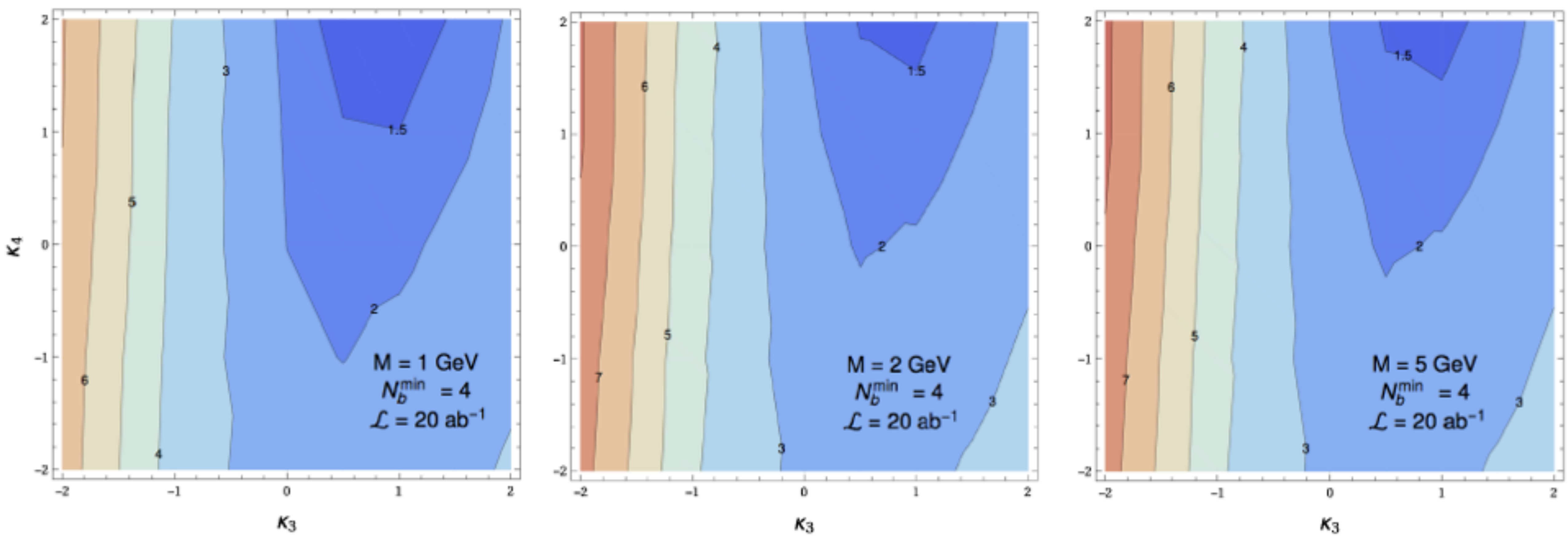
What is the best choice?

The 4b + 2γ channel: b-tagging considerations



- A low fake rate is primordial for a good sensitivity (1.8%/0.1% for a 60% efficiency)
  - Requiring at least 4 b-jets gives slightly better results (the background efficiency drops faster than the signal one)
  - Poorer results for a fake rate of 18%/1% for a 70% efficiency
    - Better signal acceptance
    - Much worse background contamination due to the fakes

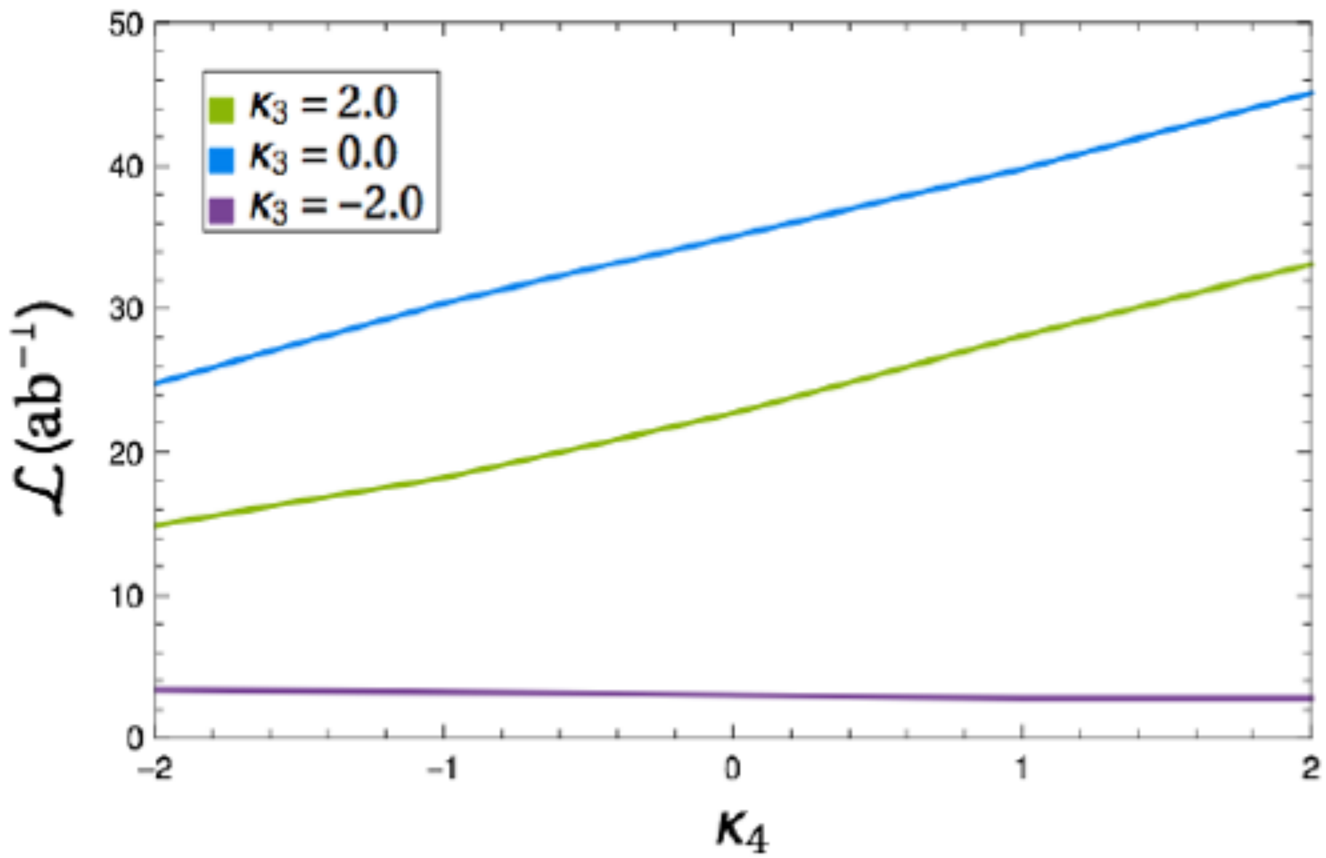
The 4b + 2γ channel: diphoton mass resolution



- ✦ Photons with a p_T greater than 20 GeV are very well reconstructed ($\sigma/E \sim 0.1/\sqrt{E}$)
  - ✤ A loss of signal efficiency implies to maintain M not too small
  - ✤ A too large M implies a more important background contamination
    - ★ However, mild effects on the sensitivity

M = 2 GeV gives the best results

The 4b + 2γ channel: luminosity goals for 3σ



- At least 4 b-tags
- M = 2 GeV
- b-tagging: 60% / 1.8% / 0.1%

- Large and negative κ_3 ⇔ huge cross section ⇔ BSM hints reachable with low luminosity
- Other κ_3 values ⇔ more luminosity is required
  - The scanned region of the parameter space cannot be entirely covered

The 4b + 2τ channel: generalities

✦ Simulation details

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  - ★ Less efficient (60%) with smaller fake rates (1.8%, for c-jets, 0.1% for lighter jets)
- tau-tagging performance: two LHC-inspired working points
  - ★ Very efficient (80%) with a small fake rate (0.1%)
  - ★ More conservative (50%) with a larger fake rates (1%,)

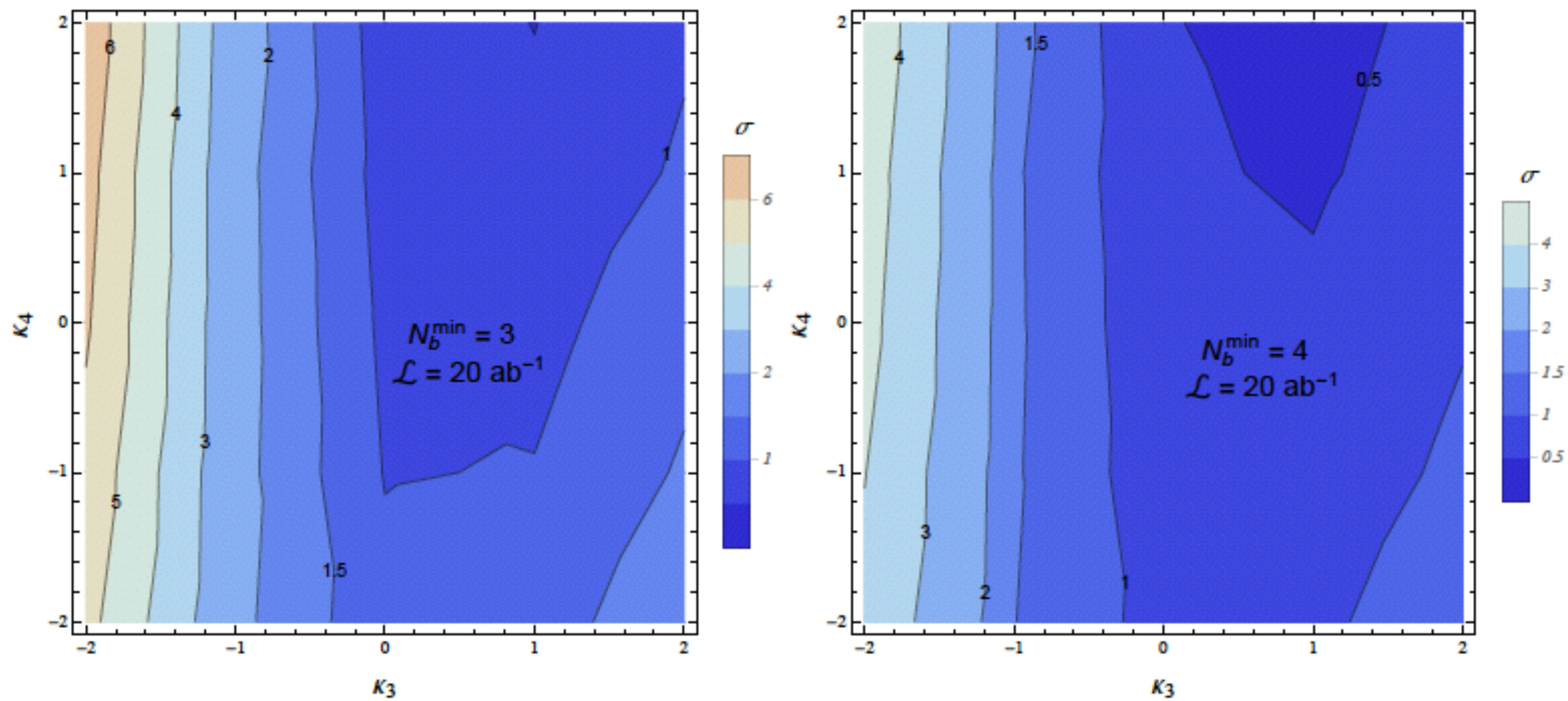
How good should the b- and tau-tagging be to observe a triple-Higgs signal

✦ Selection strategy for 20 ab^{-1}

- Four jets, 2 taus
- Two dijet systems compatible with a Higgs ($m_{jj} \in [105, 140]$ GeV)
- The ditau system compatible with a Higgs ($m_{\tau\tau} \in [115, 135]$ GeV)
- At least $N_b^{\min}$ b-tagged jets

What is the best choice?

The 4b + 2τ channel: b- and tau-tagging



- ✦ A good b-tagging efficiency is essential (70% for an 18% / 1% fake rate)
  - ✤ Requiring at least 3 b-jets gives slightly better results (better signal efficiency)
  - ✤ Smaller fake rate and efficiency: the signal efficiency drops faster than the background one
- ✦ A very efficient tau-tagger is essential (80% for a 0.1% fake rate)
  - ✤ All sensitivity is lost for a more conservative choice of (50% / 1%)

Summary

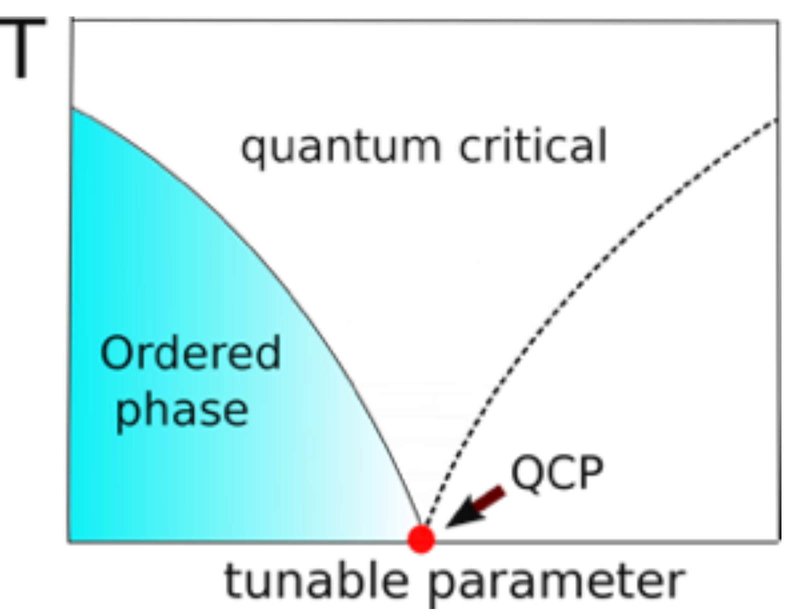
- We considered triple Higgs production at the FCC
  - Decay in the $4b + 2\gamma$ and $4b + 2\tau$ channels
  - Effects of the b-tagging and tau-tagging performances on the sensitivity
  - Effect of the diphoton mass resolution

- The diphoton channel yields the best sensitivity
  - Controlling the b-tagging fake rate is mandatory
  - The diphoton mass requirement cannot be too tight
  - A good fraction of the parameter space can be covered (but not the SM case)
    - A small part even with a few ab^{-1}
- The ditau channel could be complementary
  - An excellent tau-tagger is required

Post Higgs quesiton: The Quantum Critical Higgs

with B. Bellazzini, C. Csaki, J. Hubisz, J. Serra, J. Terning (arXiv:1511.08218)

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



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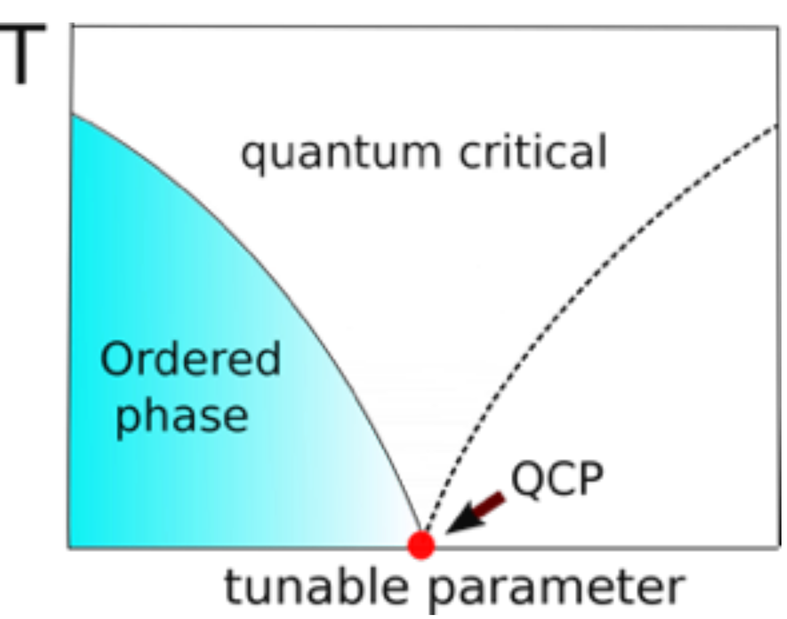

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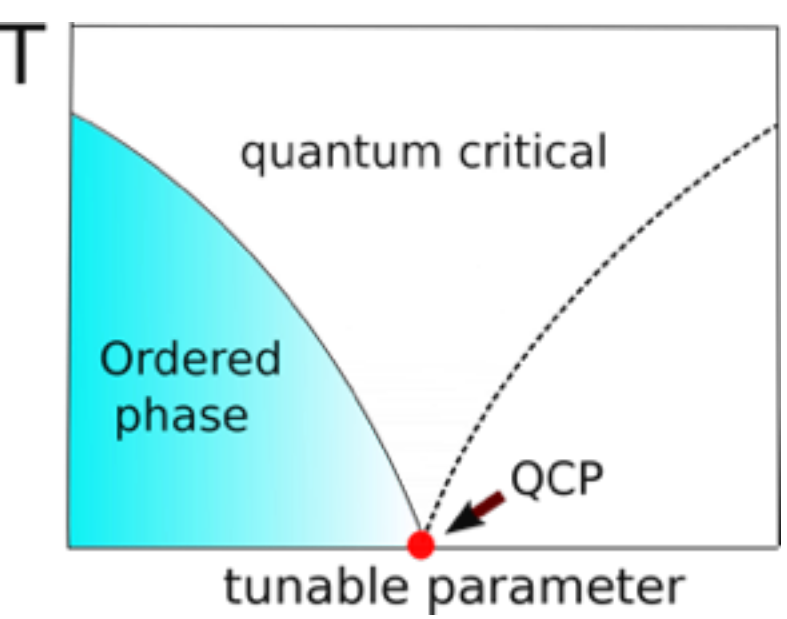

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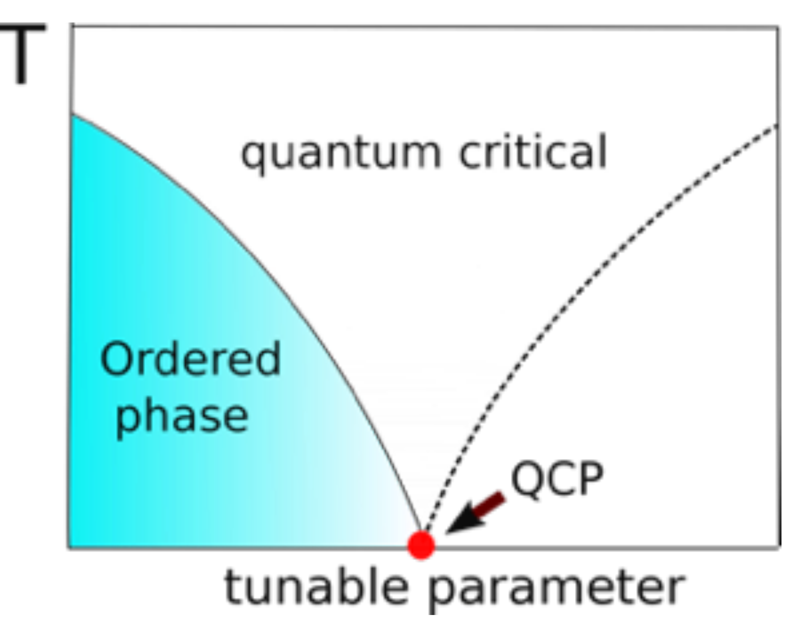

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✤and at low energies we will see the universal behavior of some fixed point that constitutes the low-energy EFT.

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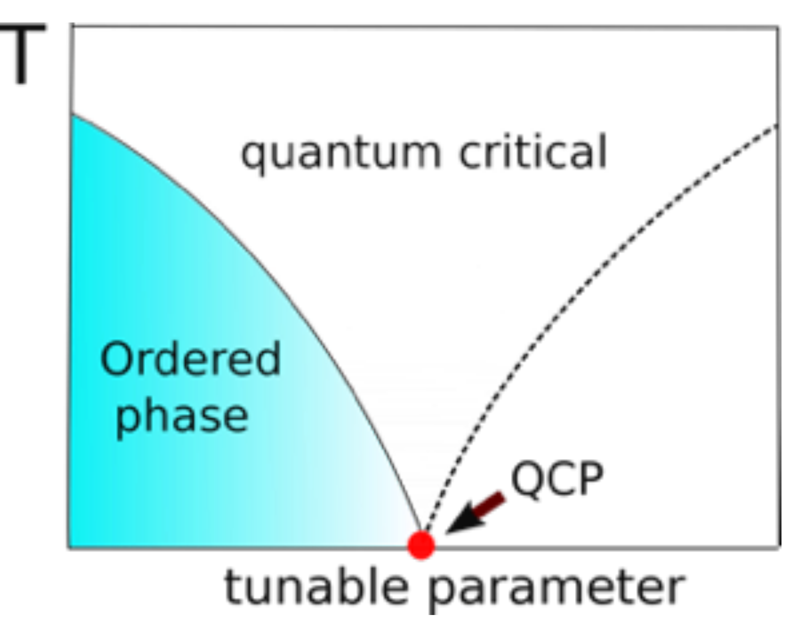

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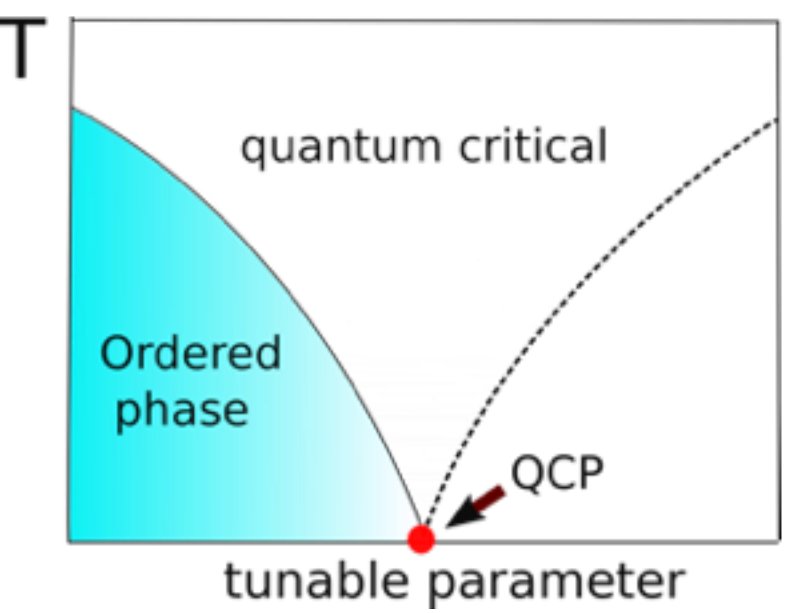

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✦It is important to know whether the underlying theory has a QPT

✤and if so, whether it is more interesting than mean-field theory like the Standard Model of particle physics.

Ising Model

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

Low T

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

High T

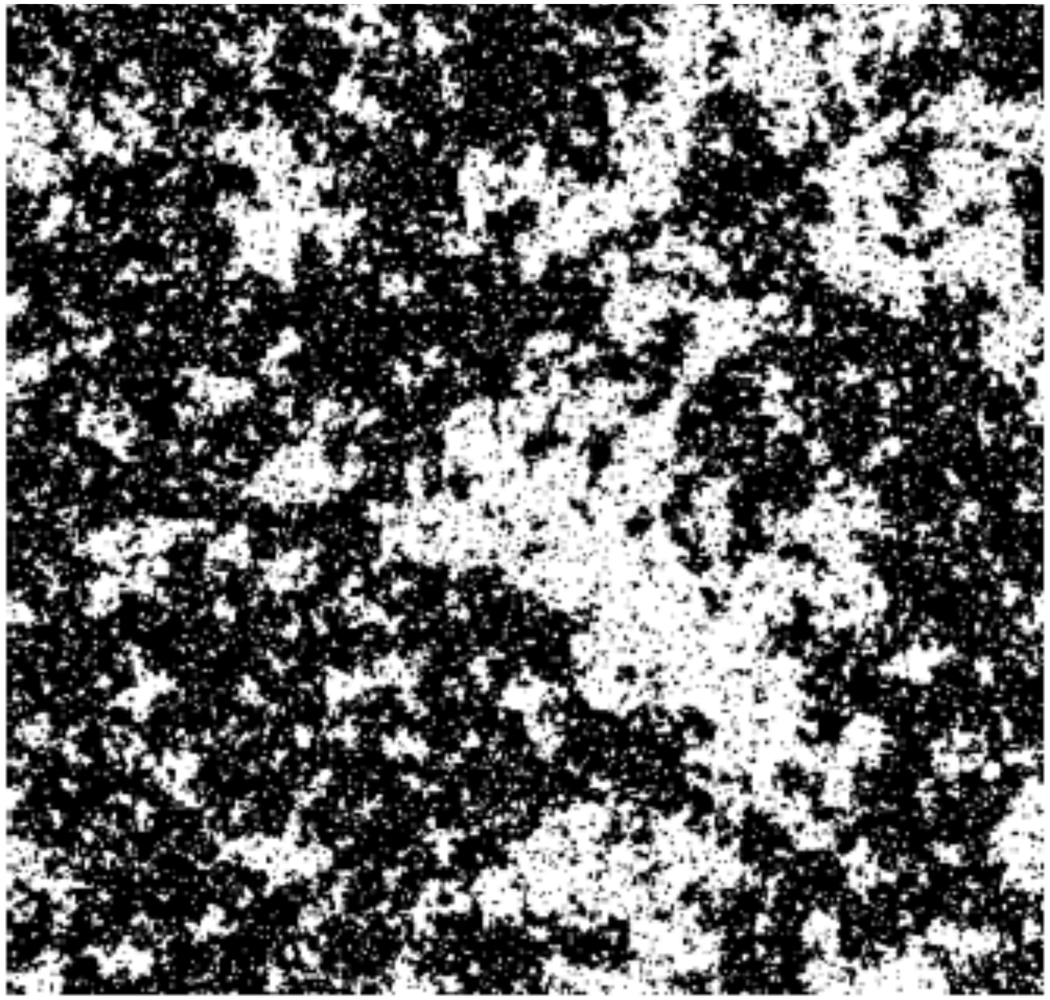
T_c

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

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$_c$ $\langle s(0)s(x)\rangle \propto \dfrac{1}{|x|^{2\Delta-1}}$

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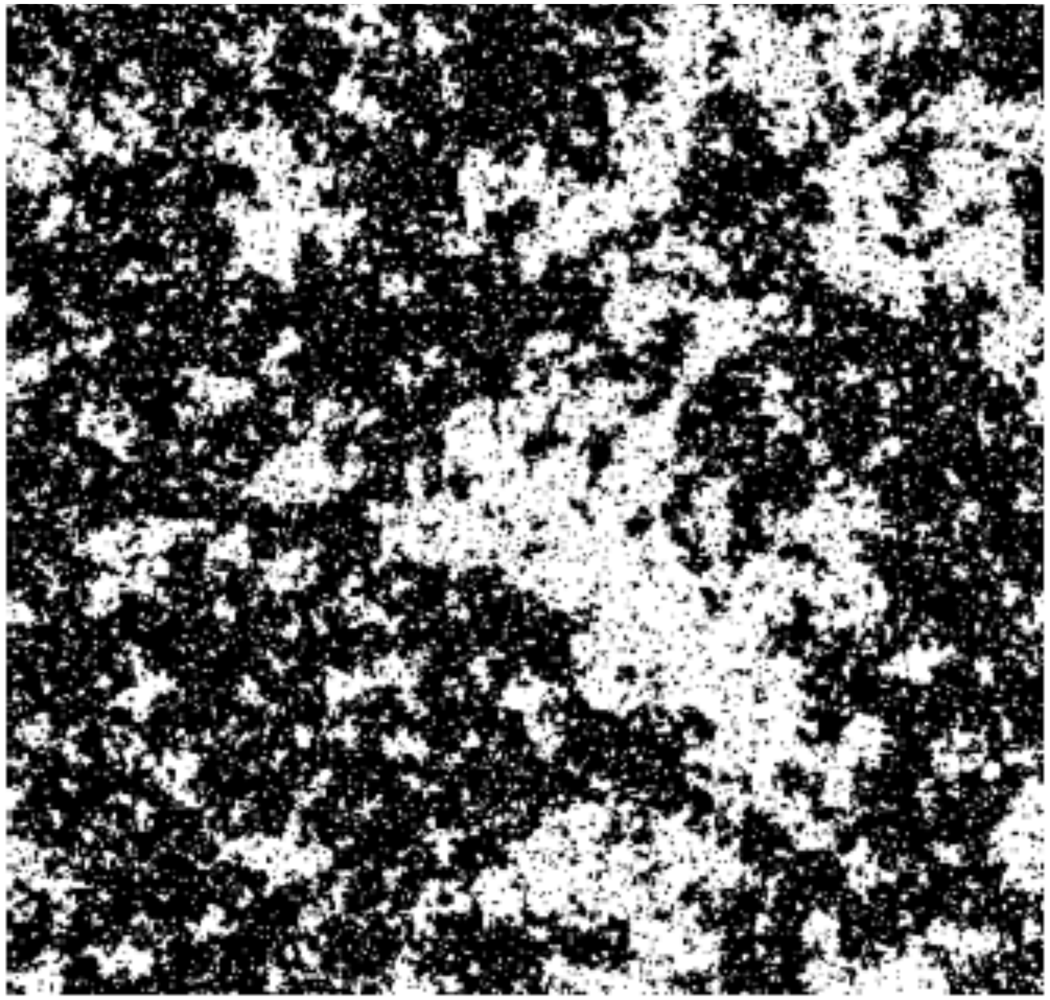
Critical Ising Model is Scale Invariant



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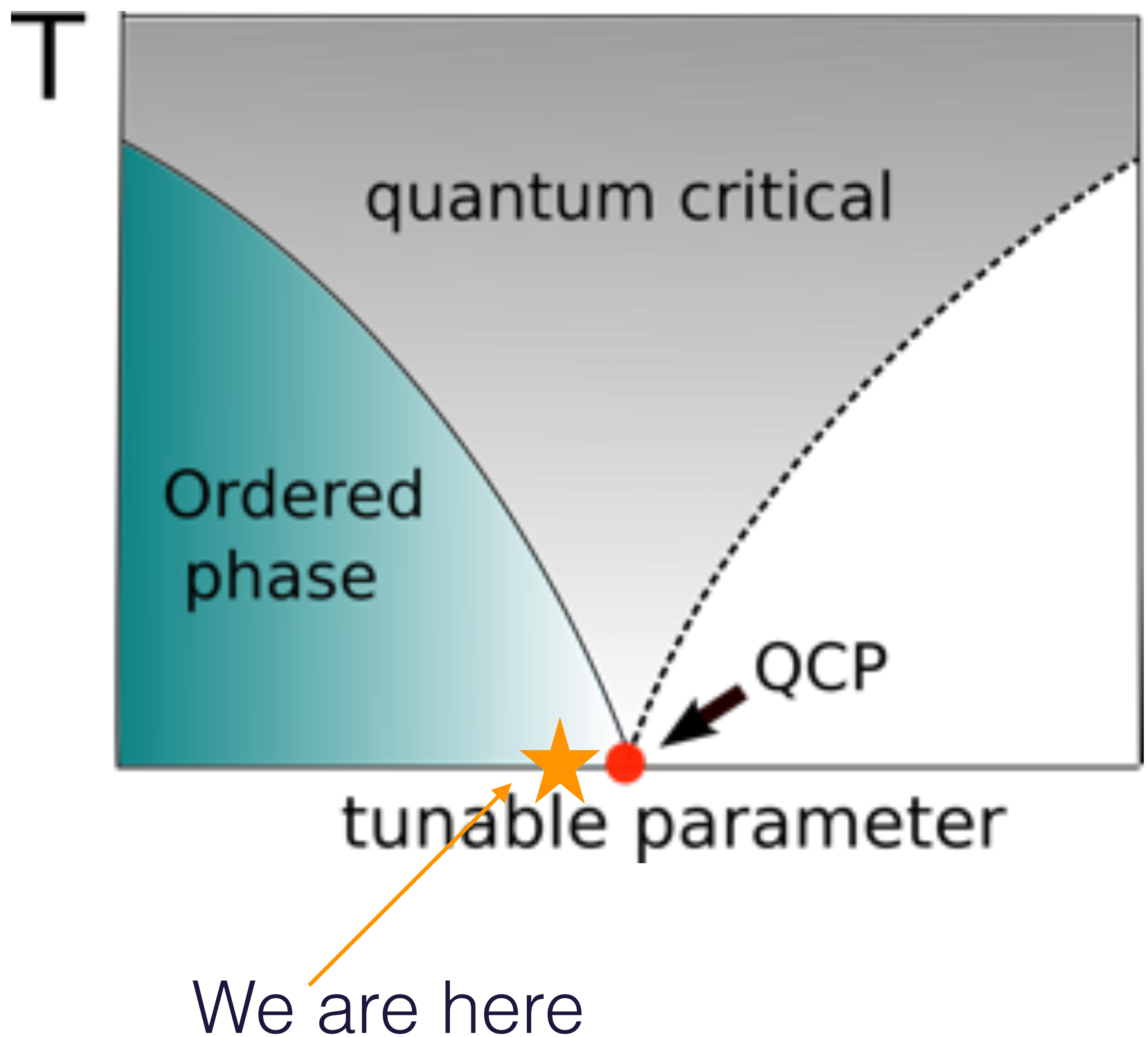
at T=Tc $\quad \langle s(0)s(x)\rangle \propto \frac{1}{|x|^{2\Delta-1}} = \int d^3p\, \frac{e^{ip\cdot x}}{|p|^{4-2\Delta}}$

critical exponent

Courtesy of J. Terning

Quantum Phase Transition



The Quantum Critical Higgs

✦At a QPT the approximate scale invariant theory is characterized by the scaling dimension Δ of the gauge invariant operators, where $1 < \Delta < 2$. In general, the two point function of a scalar with scaling dimension Δ in a CFT is

$$G_{\mathrm{CFT}}(p) = -\frac{i}{(-p^2 + i\epsilon)^{2-\Delta}} \qquad \text{SM: } \Delta = 1 + \mathcal{O}(\alpha/4\pi).$$

✦We propose 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 continuum will be the appearance of form factors in couplings of the Higgs to the SM particles.

Form Factors for QCH

- What would be a general low-energy EFT consistent with a QPT and no new massless particles?

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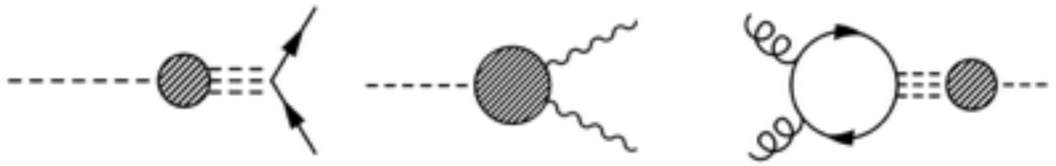
On-shell behavior:
constant form factors



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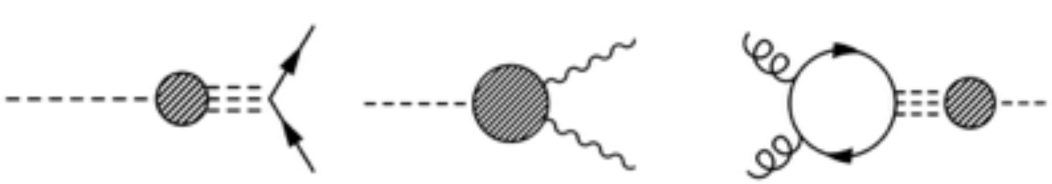
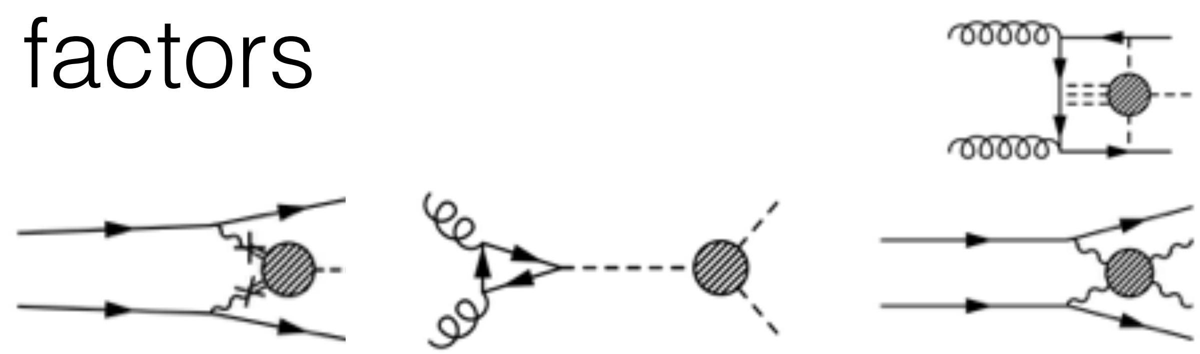
On-shell behavior: constant form factors



Off-shell behavior: nontrivial momentum dependent form factors



Form Factors for QCH

- ✦What would be a general low-energy EFT consistent with a QPT and no new massless particles?

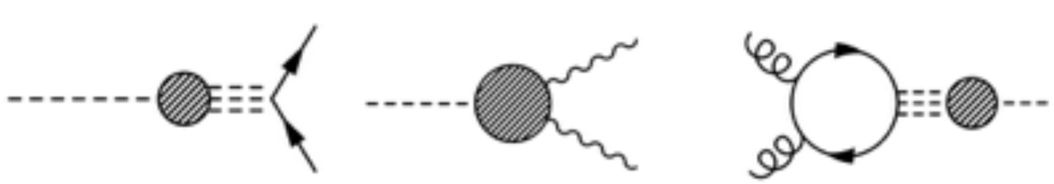
- ✦We consider a QPT Higgs scenario where Higgs is (partially) imbedded into a strongly coupled sector (approximately conformal at scale well above the EW scale)

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

- ✦The effects of H [illegible] can be parametrized in terms of form factors in a model independent way.

need build a general low-energy EFT !

On-shell behavior: constant form factors



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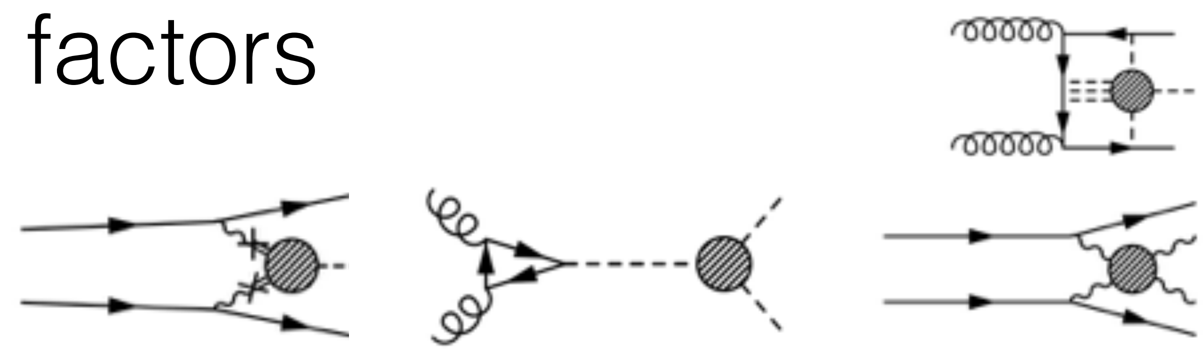
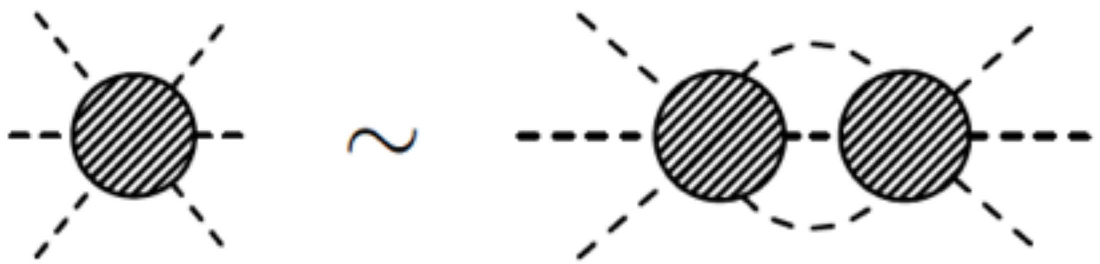


(NDA) Expectations of the size of the form factors

In **NDA**, loop corrections ~ original n-point function. e.g. n = 6:



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

loop contribution with two insertions of this operator (that contributes to the same n-point) would be one in which each vertex has n/2 external lines, and n/2 propagators exchanged in n/2 -1 loops.

quantum corrections: $\alpha_n \to \alpha_n \left(1 + \frac{\alpha_n}{(16\pi^2)^{n/2-1}}\right)$

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

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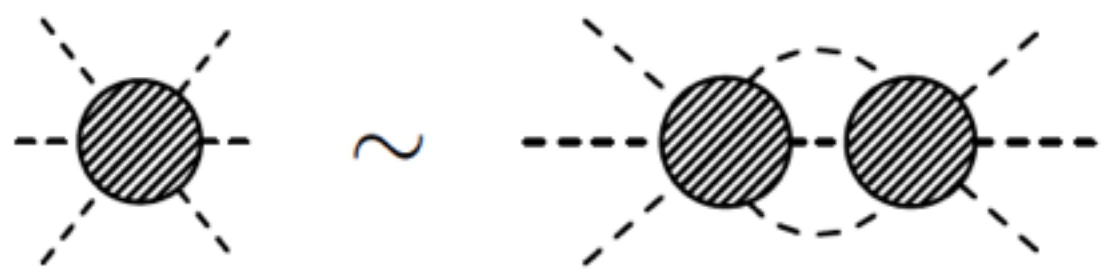

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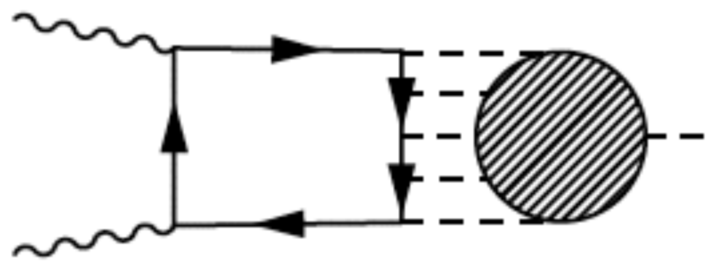
quantum corrections

e.g. with this, we can see that the n-point contribution to the gluon fusion process is suppressed by insertions of the perturbative coupling of the top-quark to the strongly coupled sector, along with a loop factor that is only partially cancelled by the large coefficient

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

Off-shell Form Factors for the Quantum Critical Higgs



If the shaded region corresponds to the n-point function, there are n - 1 insertions of the top Yukawa, and n - 2 loops. There are n - 1 scalar propagators and n - 2 fermionic propagators running in these loops.

estimate for the contribution of the n-point correlator to the $h\bar{t}t$ coupling:

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

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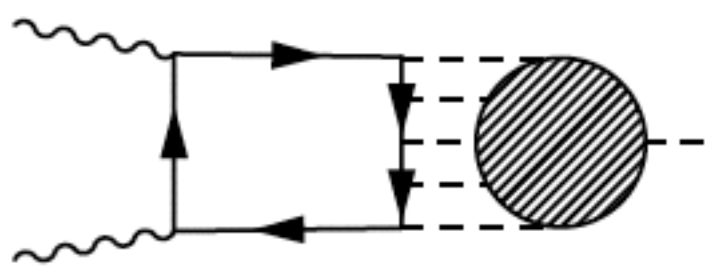

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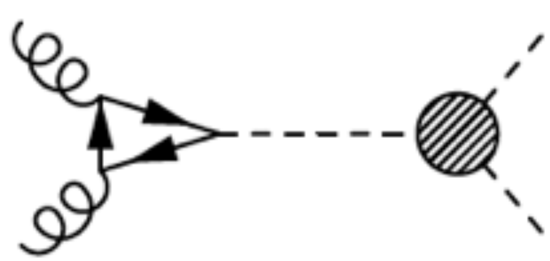
e.g. double Higgs production through gluon fusion would be dominated by



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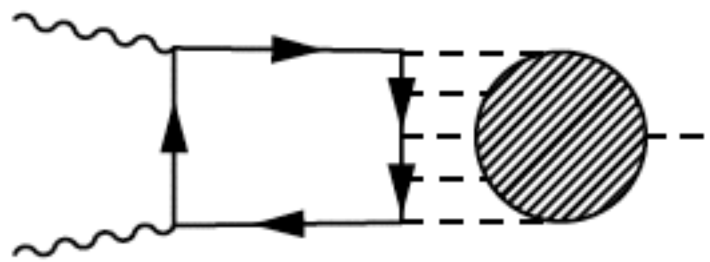

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dominant contribution comes from tree diagram

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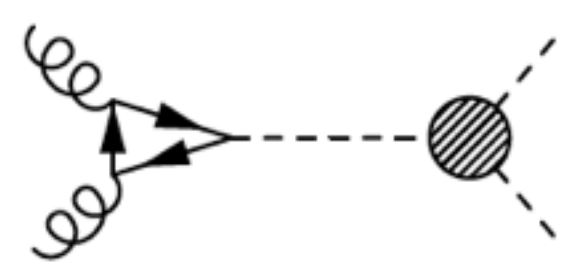
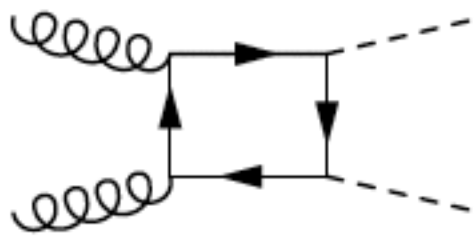


Direct Signal (e.g. Holographic Generalized Free Fields)

- Form factors for trilinear Higgs self coupling
  - SO(4) global symmetry is gauged in the 5D bulk

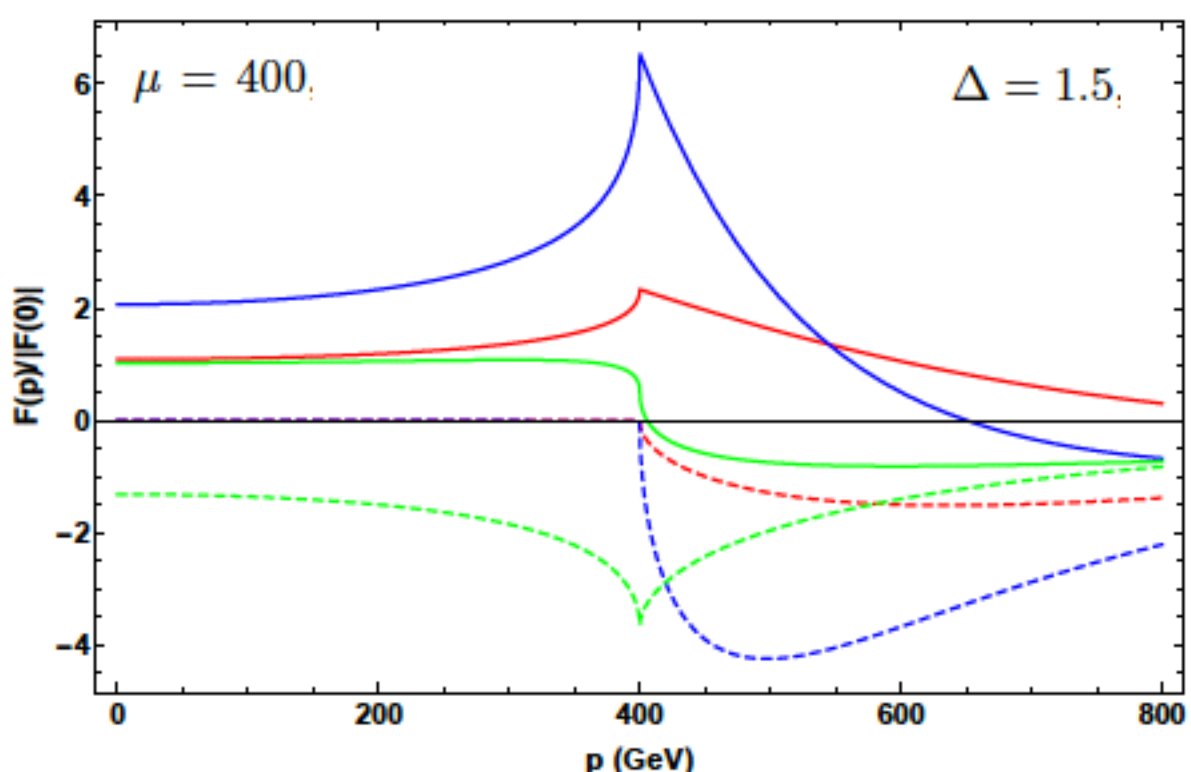
$\lambda_5(H^\dagger H)^2$



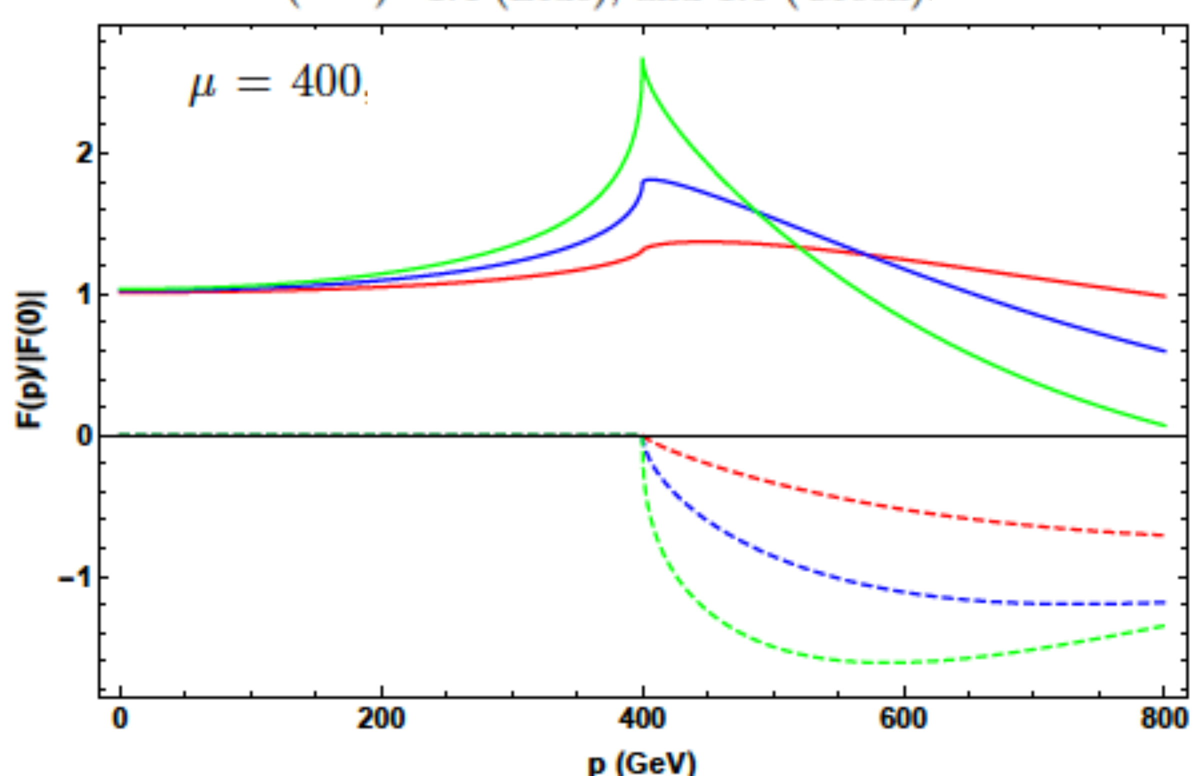
+crossings

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

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



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



Direct Signal (e.g. Holographic Generalized Free Fields)

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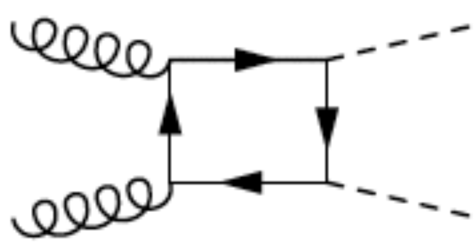
probe the higher n-point correlators of the CFT.

$\lambda_5 (H^\dagger H)^2$



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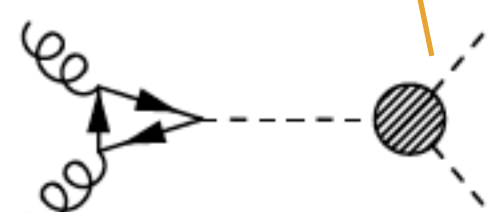

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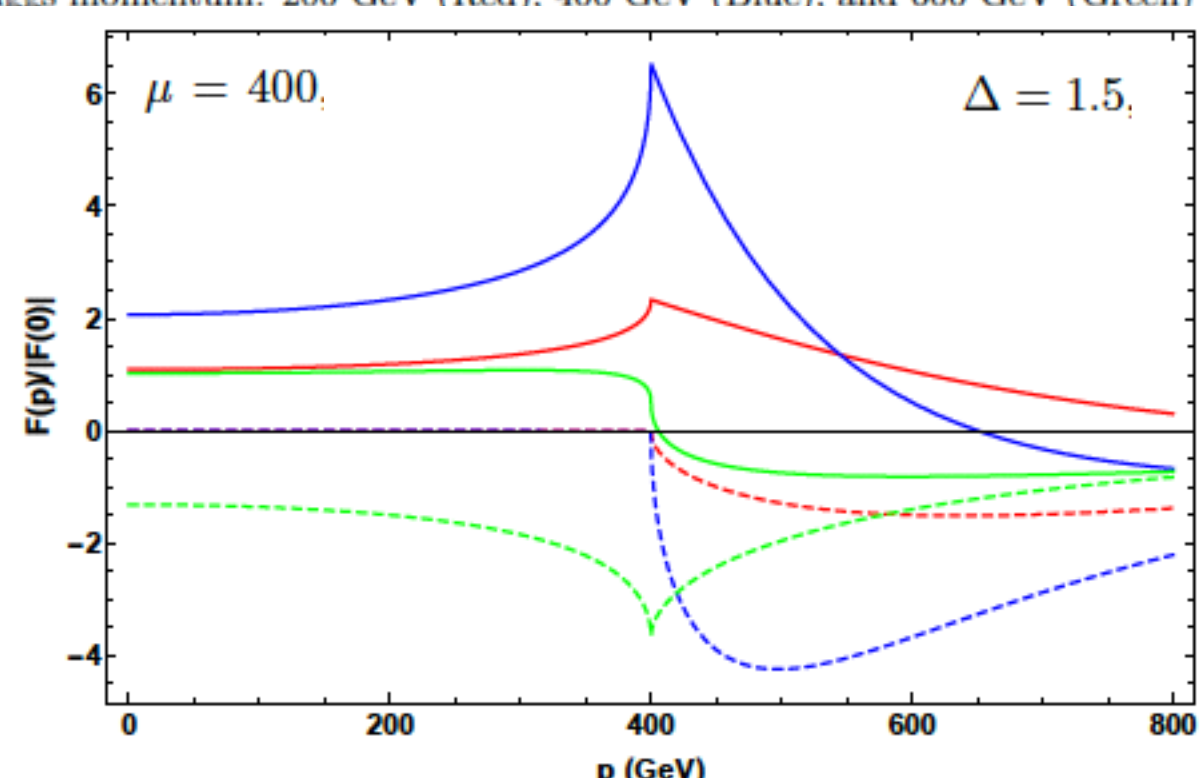

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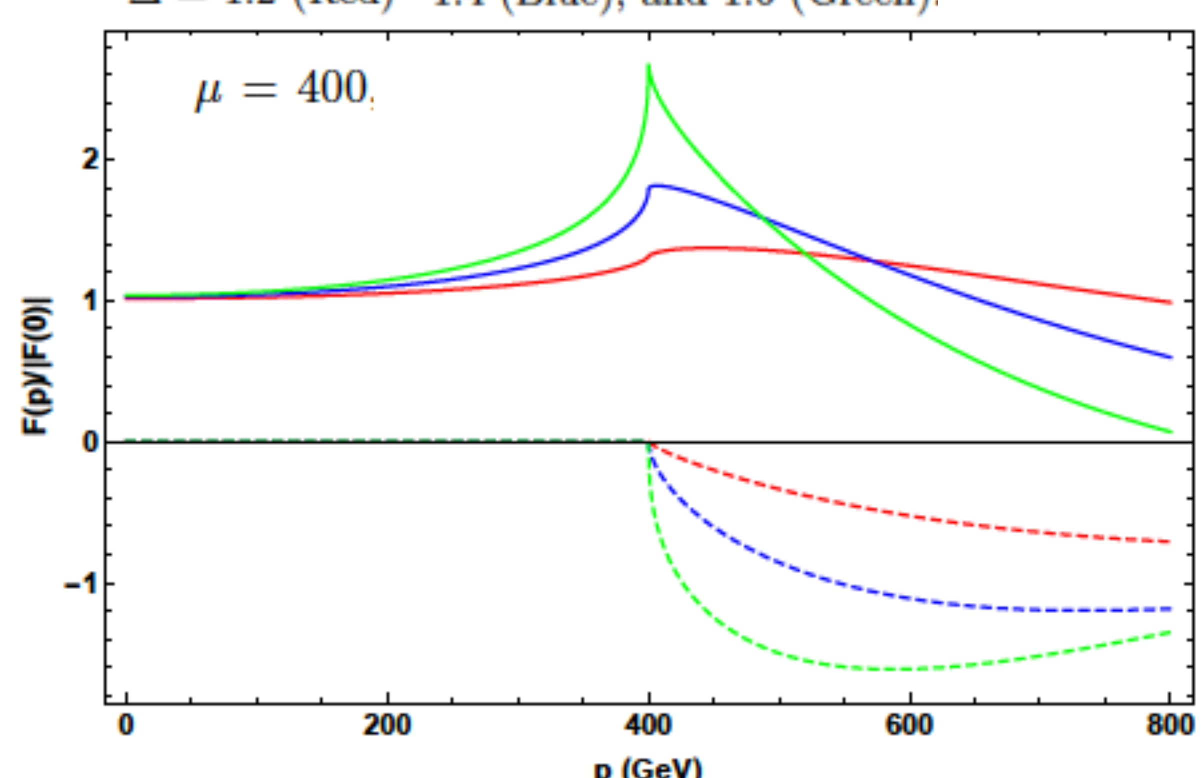
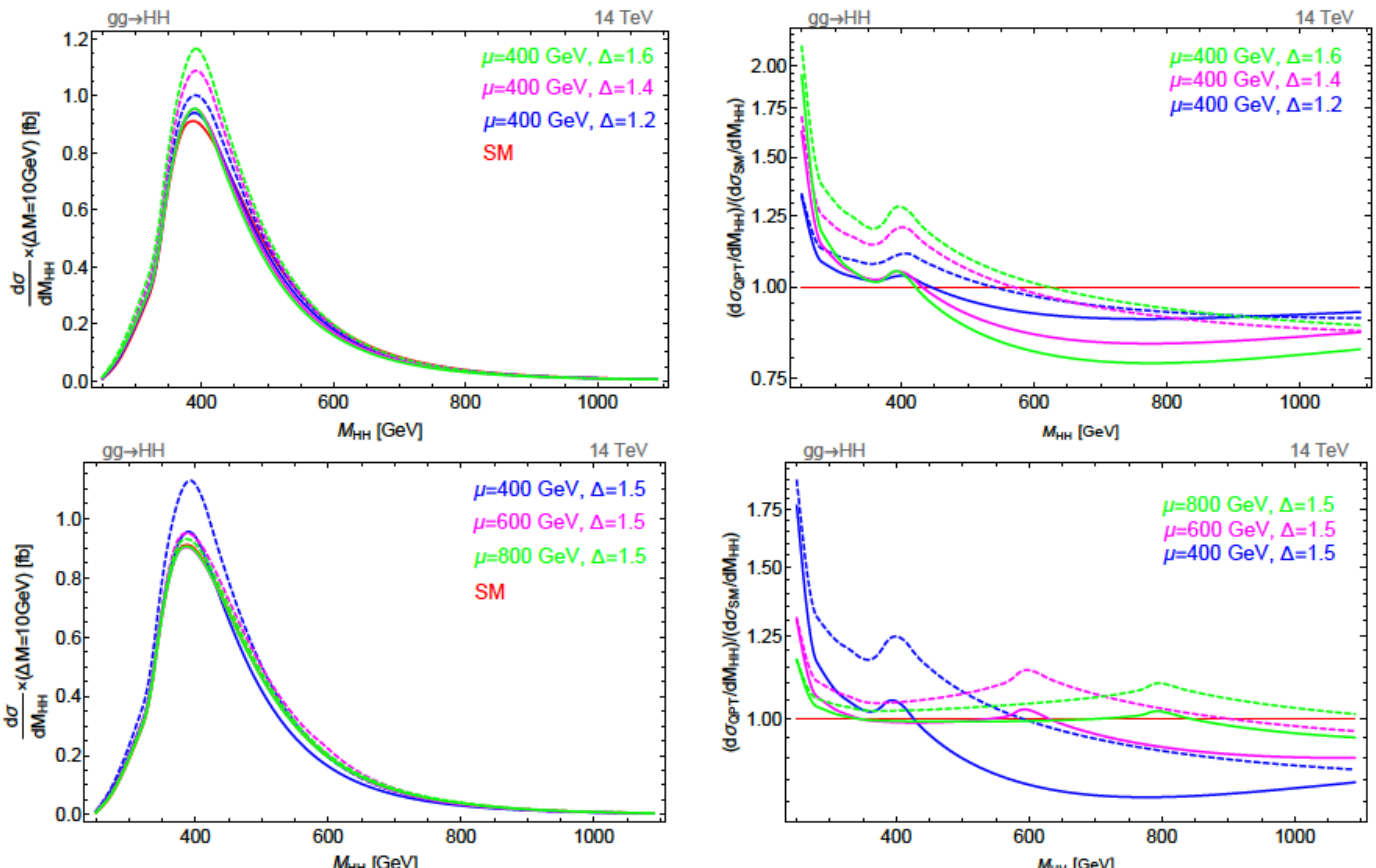


Direct Signal (e.g. Holographic Generalized Free Fields)

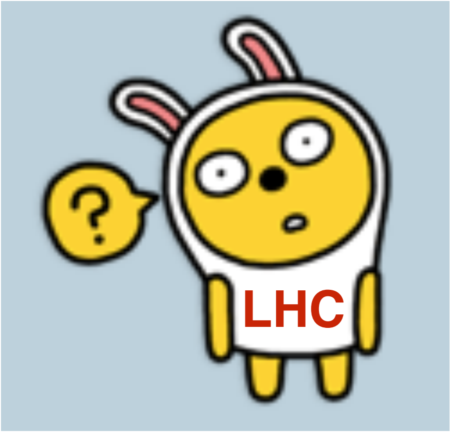
- Double Higgs production

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: Higgs Potential

$$V(\tilde{h}) \overset{?}{=} \tilde{v}^{2\Delta}\tilde{m}^{4-2\Delta}\sum_{n=0}^{\infty}\frac{c_n}{n!}\left(\frac{\tilde{h}}{\tilde{v}^{\Delta}}\right)^n$$



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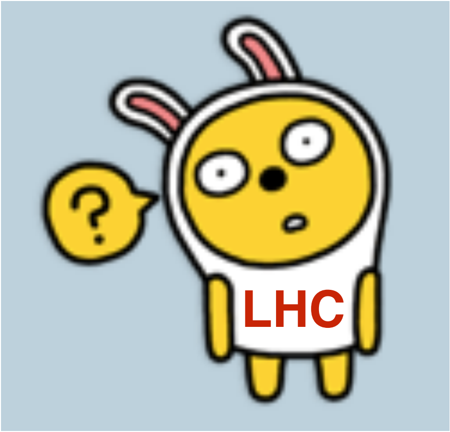

- We need FCC to really understand the EWSB!