Higgs Couplings @ High Scales

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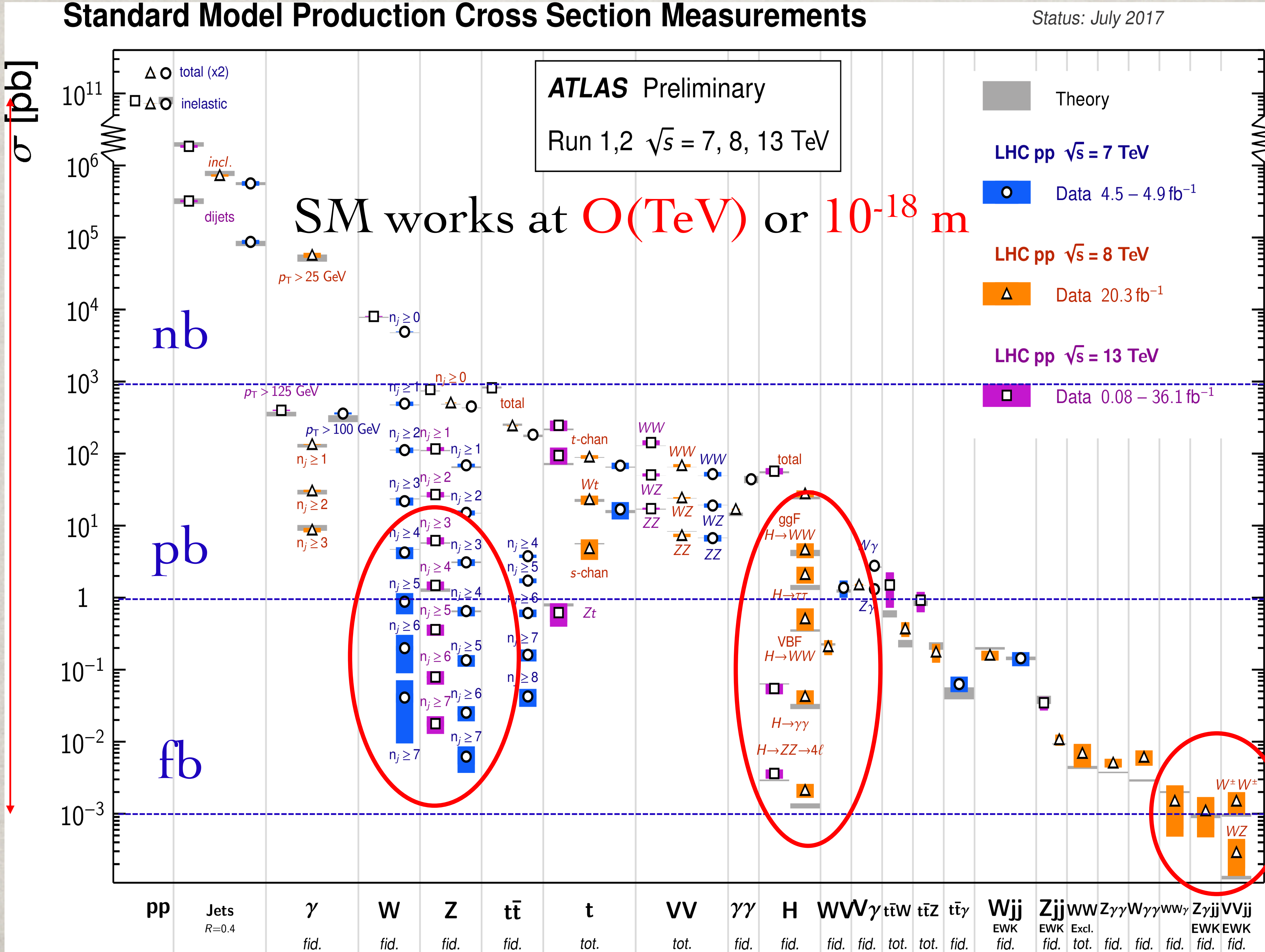
UW - Madison, April 3, 2018

D. Goncalves, TH, S. Mukhopadhyay, arXiv:1710.02149 (PRL,2017); arXiv:1803.09751.

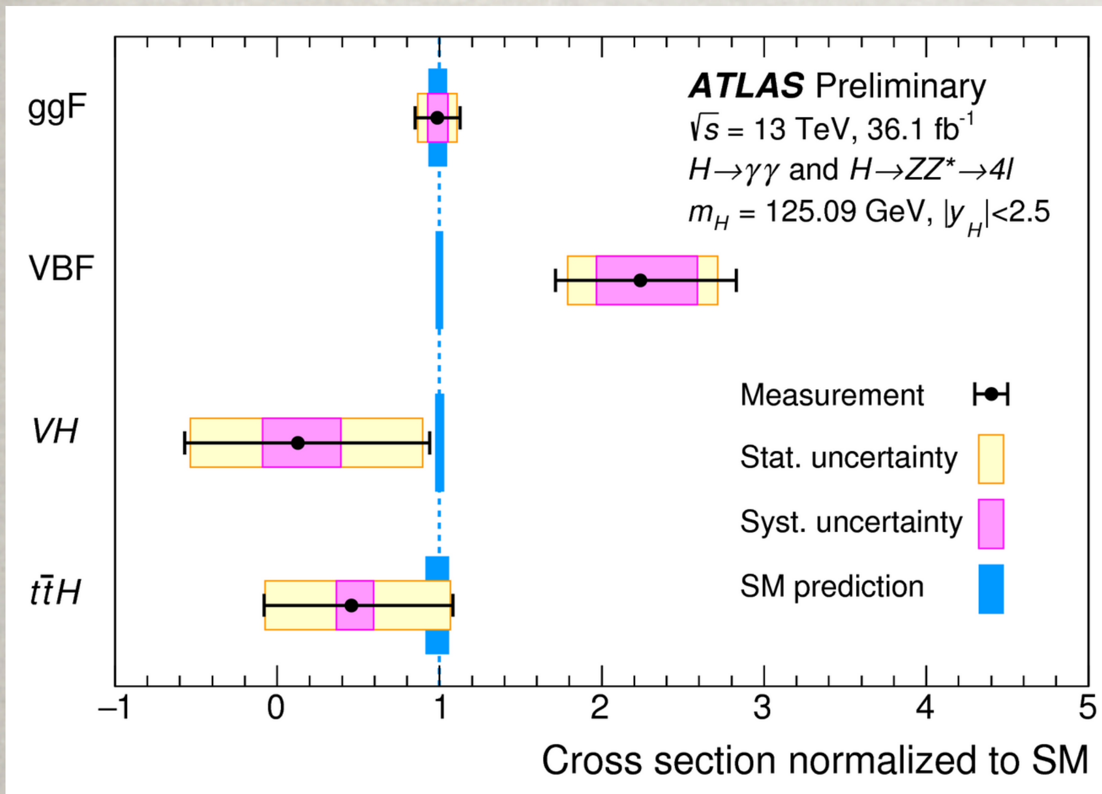
LHC Rocks!

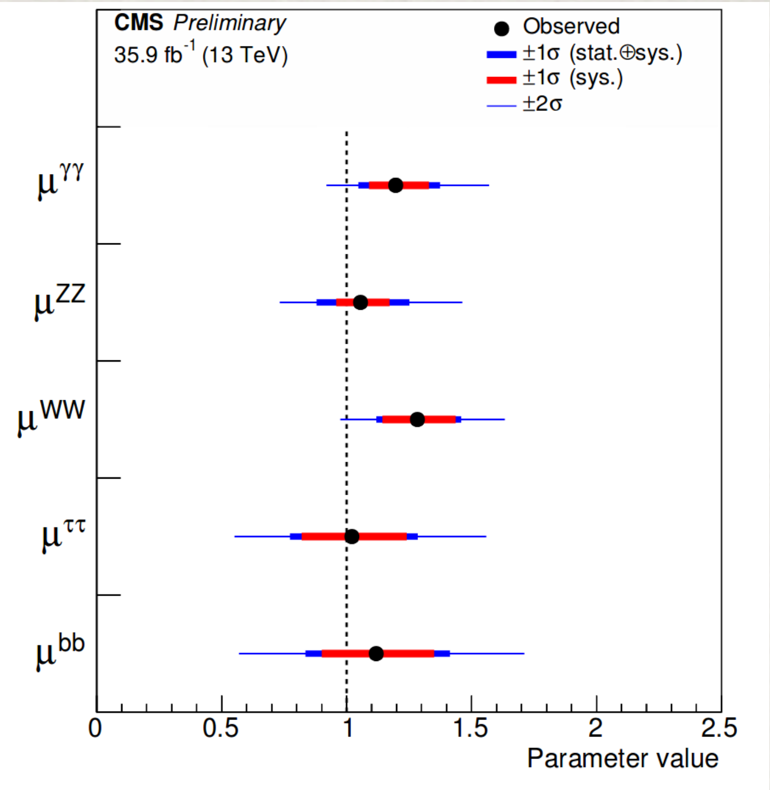


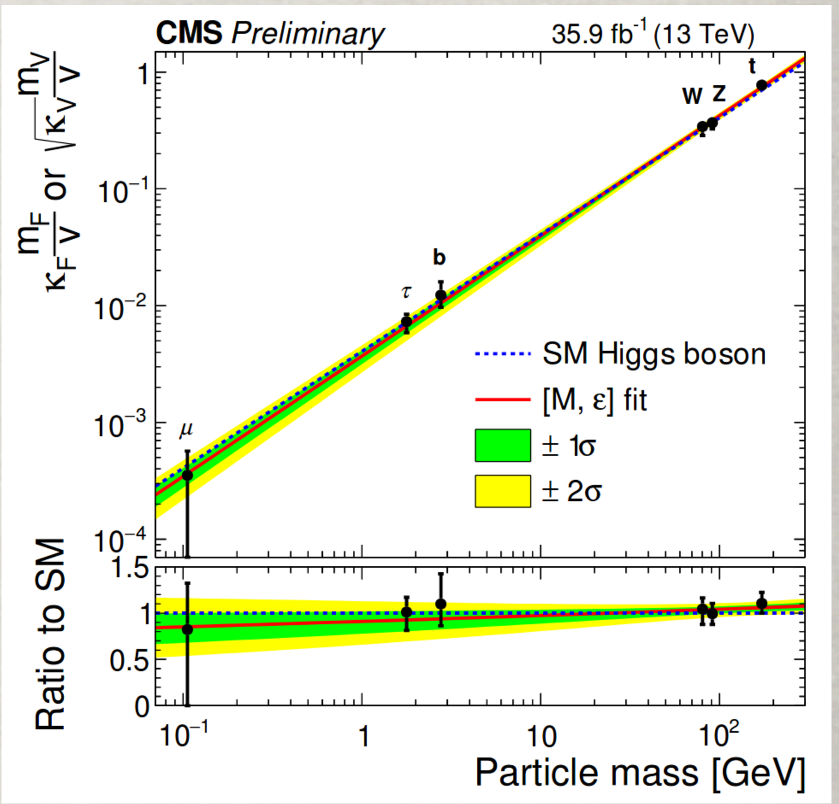
O(14)

Higgs Moriond update: (D. Sperka, ATLAS & CMS)

Four production channels with sensitivities;
Five decay channels observed;
Fermionic & bosonic couplings verified:







All indications → SM-like Higgs boson, "elementary" at a scale Λ < O(1 TeV)

→ SM self-consistent to exponentially high scales!

"... most of the grand underlying principles have been firmly established. An eminent physicist remarked that the future truths of physical science are to be looked for in the sixth place of decimals. "

--- Albert Michelson (1894)

Michelson–Morley experiments (1887):
"the moving-off point for the theoretical aspects of the second scientific revolution"

Will History repeat itself (soon)?

What We Wish to Know

1. V = -μ²|ϕ|² + λ|ϕ|⁴

the only dimensional parameter allowed by SM symmetry.

"… scalar particles are the only kind of free particles whose mass term does not break either an internal or a gauge symmetry." Ken Wilson, 1970

In the Wilsonian QFT formulation:

$$\mathcal{L} = \sum c_i \Lambda^n \mathcal{O}_n = c_0\Lambda^4 + c_2\Lambda^2\mathcal{O}_{\text{dim }2} + c_3\Lambda\mathcal{O}_{\text{dim }3}$$

$$+ c_4\mathcal{O}_{\text{dim }4} + \frac{c_6}{\Lambda^2}\mathcal{O}_{\text{dim }6} + \ldots$$

"Relevant operators" from observations:

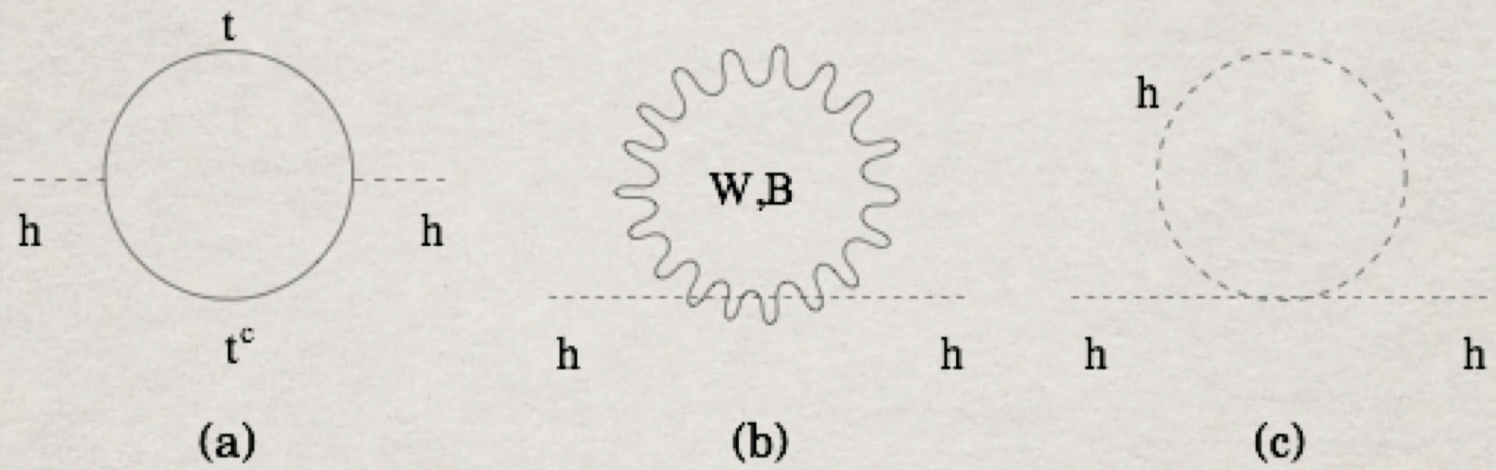
$$c_0\Lambda^4 \sim c.c.:\ (10^{-3}\text{ eV})^4 \sim (10^{-11}\Lambda_{\text{QCD}})^4 \sim (10^{-14}v)^4 \sim (10^{-30}M_{\text{Planck}})^4$$

$$c_2\Lambda^2 \sim m_h^2:\ \lambda v^2 \sim \mu^2 \sim (100\text{ GeV})^2 \sim (10^{-16}M_{\text{Planck}})^2$$

$$m_w^2:\ g^2v^2, \quad \delta m_w^2 \sim m_w^2 \ln(\Lambda/m_w)$$

$$c_3\Lambda \sim m_f:\ y_f v, \quad \delta m_f \sim m_f \ln(\Lambda/m_w)$$

The "large hierarchy" in perspectives:



$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t^2 \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

If $\Lambda^2 \gg m_H^2$, then unnaturally large cancellations must occur.

Cancelation in perspective:

$m_H{}^2$ = 36,127,890,984,789,307,394,520,932,878,928,933,023

–36,127,890,984,789,307,394,520,932,878,928,917,398

= $(125\ \text{GeV})^2$! ?

"Naturalness" → TeV scale new physics.

“Naturalness” in perspective:

Unbelievable!

$4\ mm^2 / 20\ cm^2 \sim 10^{-3}$ fine-tune.

“Naturalness” → TeV scale new physics.

2. $V = -\mu^2 |\phi|^2 + \lambda |\phi|^4$

It represents a weakly coupled new force (a fifth force):

- **In the SM, λ is a free parameter, now measured at collider energies $\lambda \approx 0.13$**
- **In SUSY, it is related to the gauge couplings tree-level: $\lambda = (g_L^2 + g_Y^2)/8 \approx 0.3/4$ ← a bit too small**
- **In composite/strong dynamics, harder to make λ big enough. (due to the loop suppression by design)**

Already possess challenge to BSM theories.

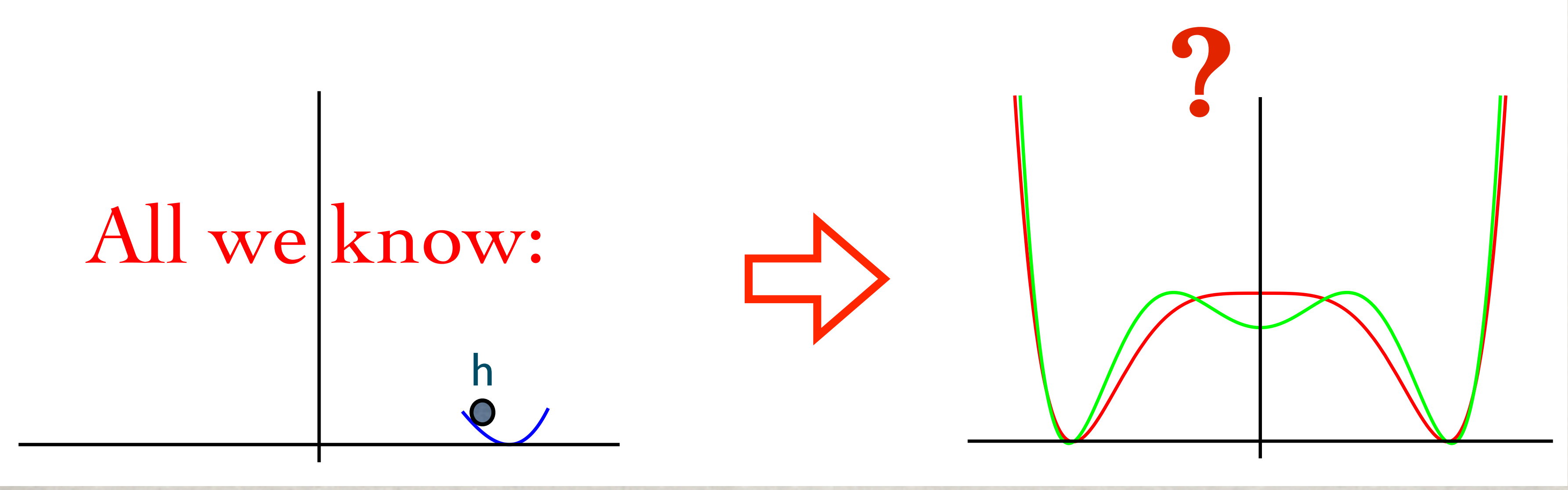
3. The Nature of EWSB

$$V(|\Phi|) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$
$$\Rightarrow \mu^2 H^2 + \lambda v H^3 + \frac{\lambda}{4}H^4$$

Fully determined at the weak scale:

$v = (\sqrt{2}G_F)^{-1/2} \approx 246$ GeV $\quad m_H \approx 126$ GeV

$$m_H^2 = 2\mu^2 = 2\lambda v^2 \quad \Rightarrow \quad \mu \approx 89 \text{ GeV}, \quad \lambda \approx \frac{1}{8}.$$



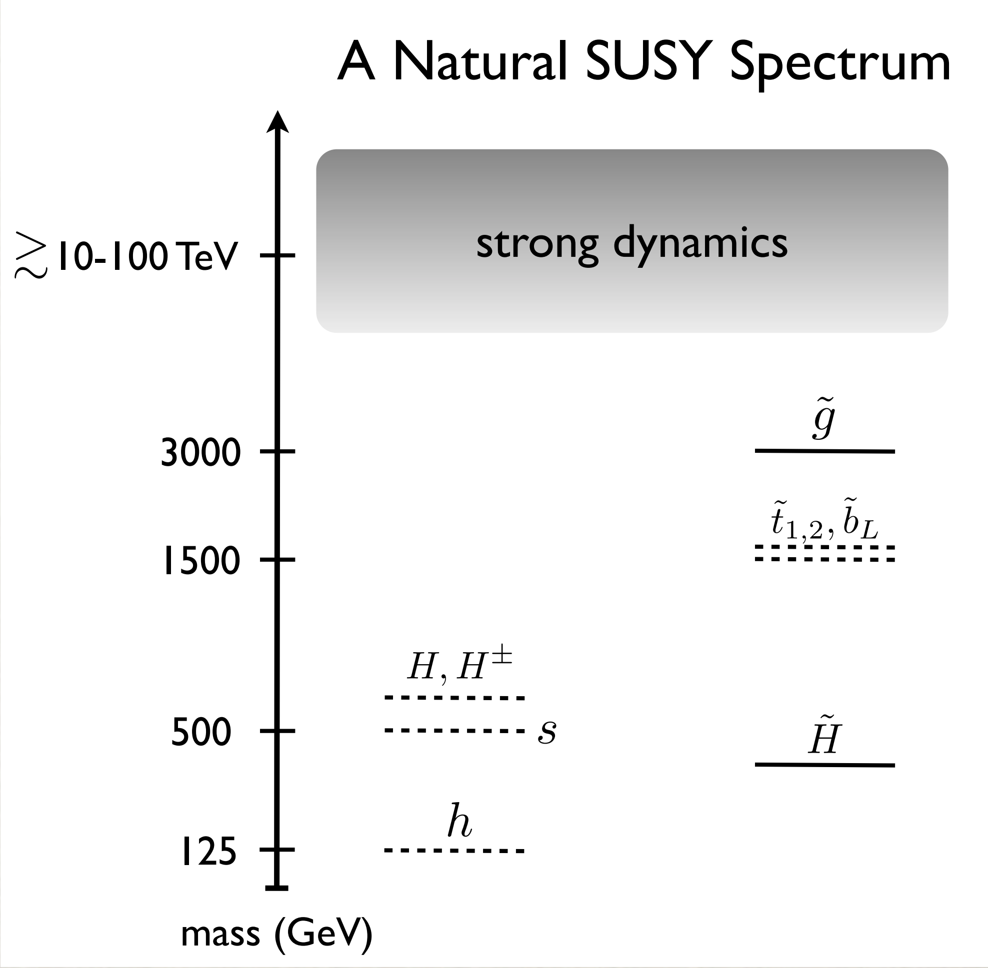
O(1) deviation on λ_{hhh} could make EW phase transition strong 1^{st} order!

X.M.Zhang (1993); C. Grojean et al. (2005); D. Chung, A. Long, L.-T. Wang (1209.1819).

4. A "NATURAL" EW THEORY?

- "Natural SUSY":

Cohen, Kaplan, Nelson, 1996
Hall, Pinner, Ruderman, 2012
Baer, Barger, Huang, Tata, 2012



Relevant to the Higgs and the "Most Wanted":

$\tilde{H}^{0,\pm},\ \tilde{t},\ \tilde{b},\ (\tilde{g});\ S,\ \tilde{S}...$

Current LHC bounds:

$m_{\tilde{t}} > 200 - 680$ GeV,

$m_{\tilde{\chi}^{\pm}} > 100 - 600$ GeV (depending on m_{χ^0})

- "Compositeness": the T', current ATLAS limit:

$M_T > 480$ GeV, for $M_A < 100$ GeV.

5. The Higgs portals to Cosmos?

(Dark Matter?)

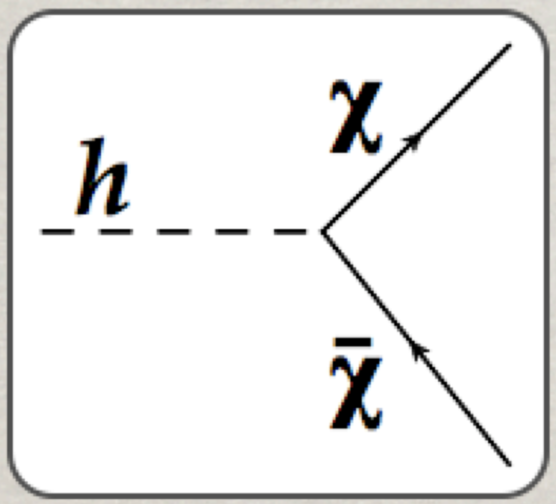
$H^\dagger H$ is the only bi-linear SM gauge singlet.

Bad: May lead to hierarchy problem w.r.t. high-scale physics;

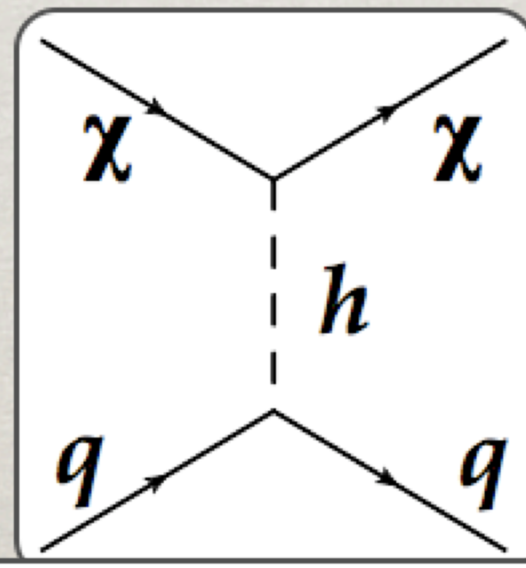
Good: May readily serve as a portal to the dark sector:

$$k_s H^\dagger H\ S^* S, \qquad \frac{k_\chi}{\Lambda} H^\dagger H\ \bar{\chi}\chi.$$

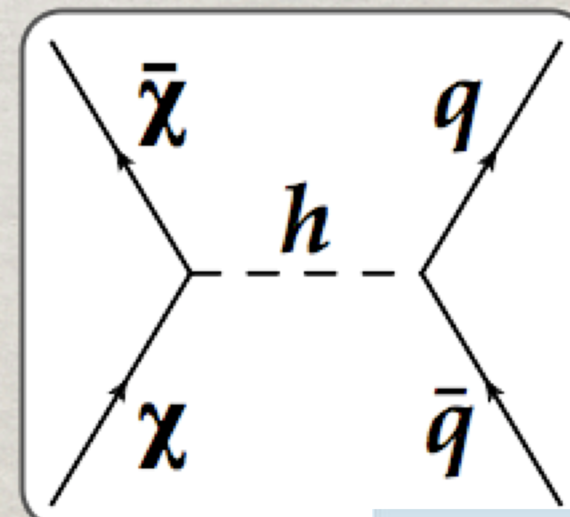
Missing energy at LHC

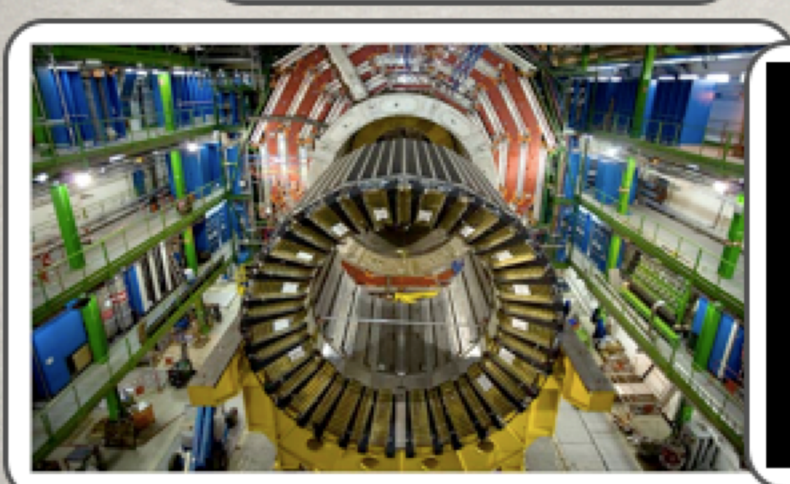


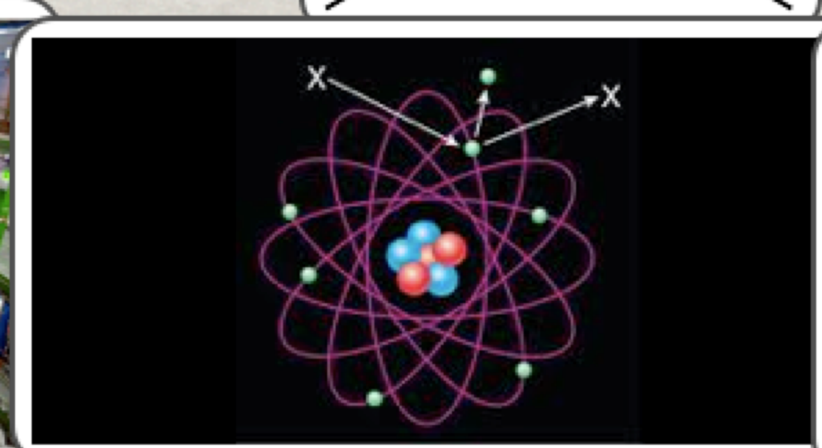
Direct detection

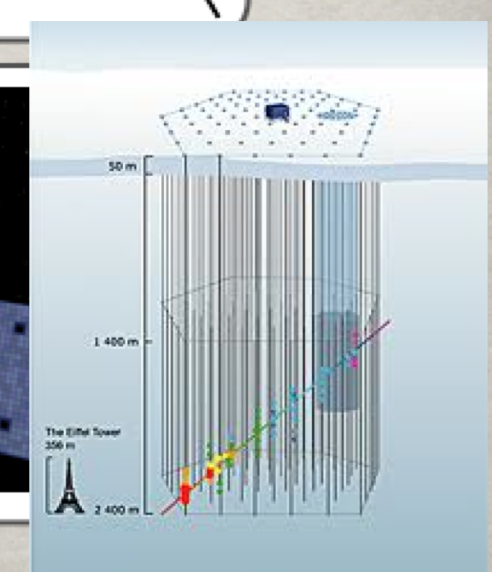


Indirect detection









The searches for BSM physics
under the Higgs lamppost will continue …

Precision Higgs measurements, on g_i at the scale M:

$$\Delta_i \equiv \frac{g_i}{g_{SM}} - 1 \sim \mathcal{O}(v^2/M^2)$$ ≈ a few % for M ≈ 1 TeV

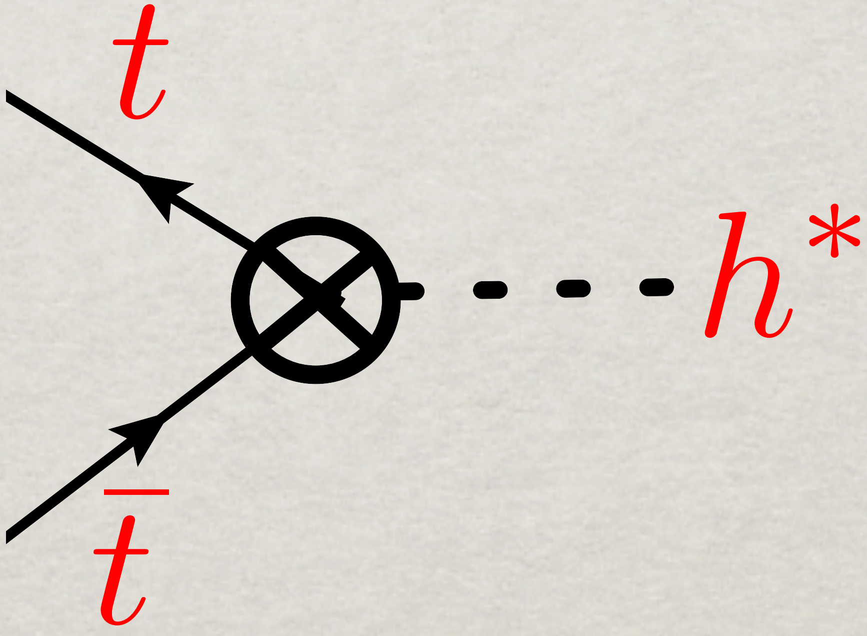
Higgs coupling deviations:

Δ:	VVH	bbH,ττH	ggH,γγH	HHH
Composite	(3-9)%	$(1\ \text{TeV}/f)^2$	(tree-level)	100%
H^0, A^0		6% $(500\ \text{GeV}/M_A)^2$		
T'			-10% $(1\ \text{TeV}/M_T)^2$ (loop)	
LHC 14 TeV, 3 ab^{-1}:	8%	15%	few%	50%
27 TeV, 15 ab^{-1}:	4%	7%	1%	<20%

In absence of new physics beyond the Standard Model from the current searches at the LHC,

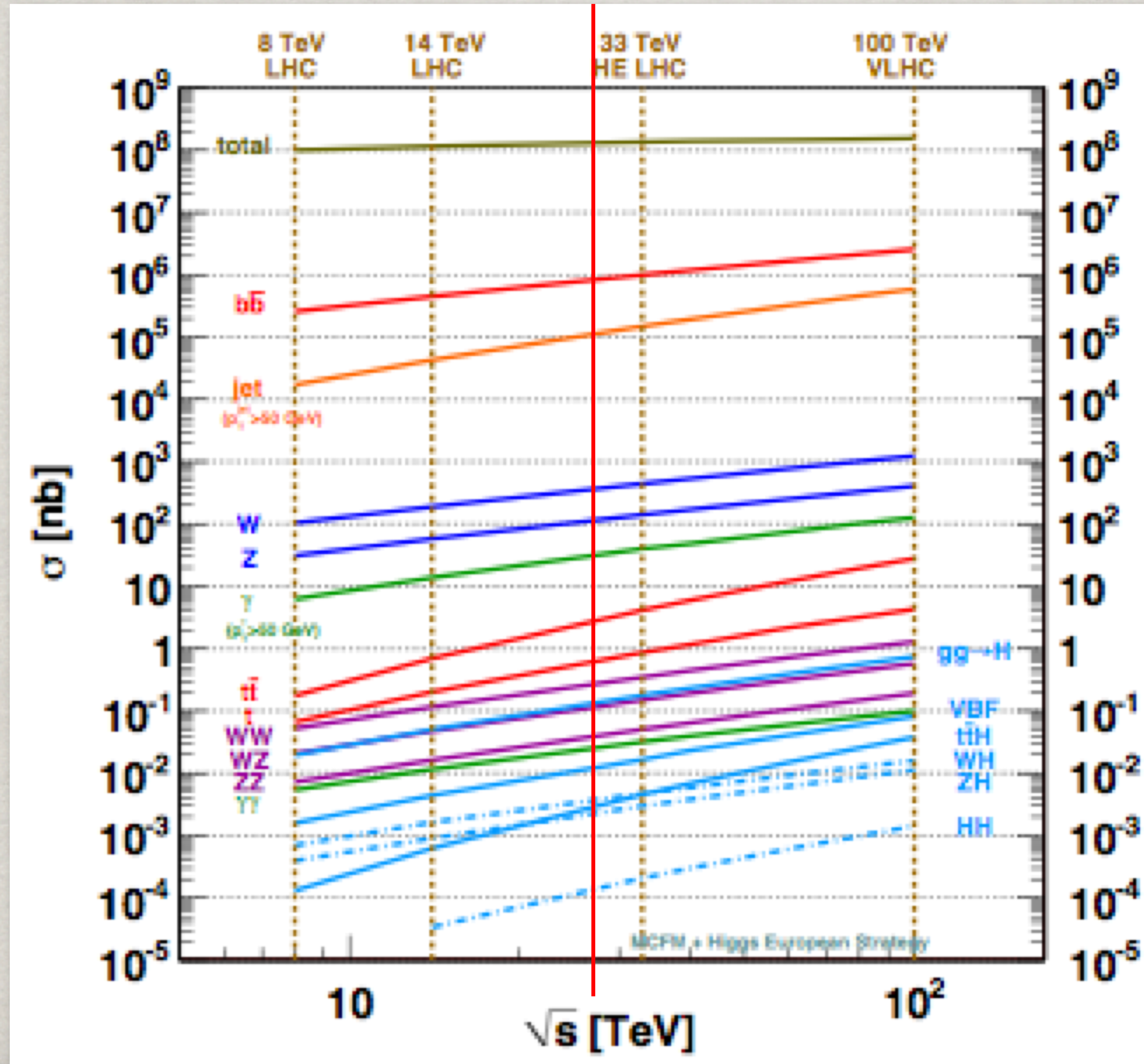
We propose to study the SM Higgs at high scales:

- Sensitive to new physics
- "Naturalness" is a UV problem.
- "Higgs portal" to a subtle sector.



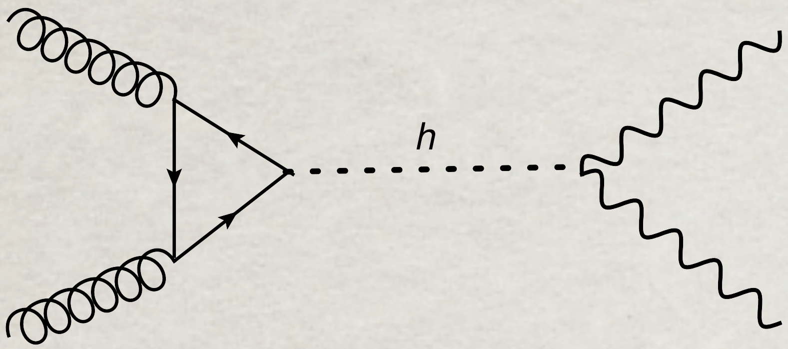
$$\sigma_{\rm on} \propto \frac{g_i^2(m_h^2)g_f^2(m_h^2)}{m_h\Gamma_h} \text{ and } \sigma_{\rm off} \propto \frac{g_i^2(Q^2)g_f^2(Q^2)}{Q^2}$$

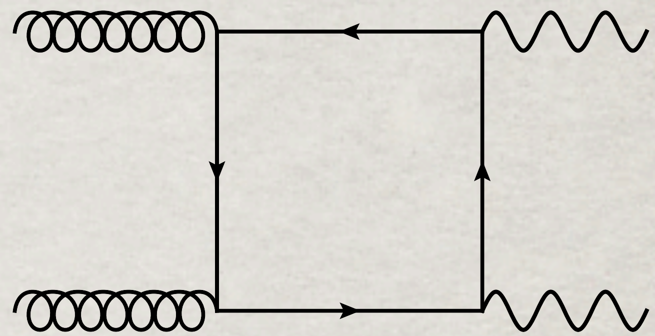
HL-LHC / HE-LHC:



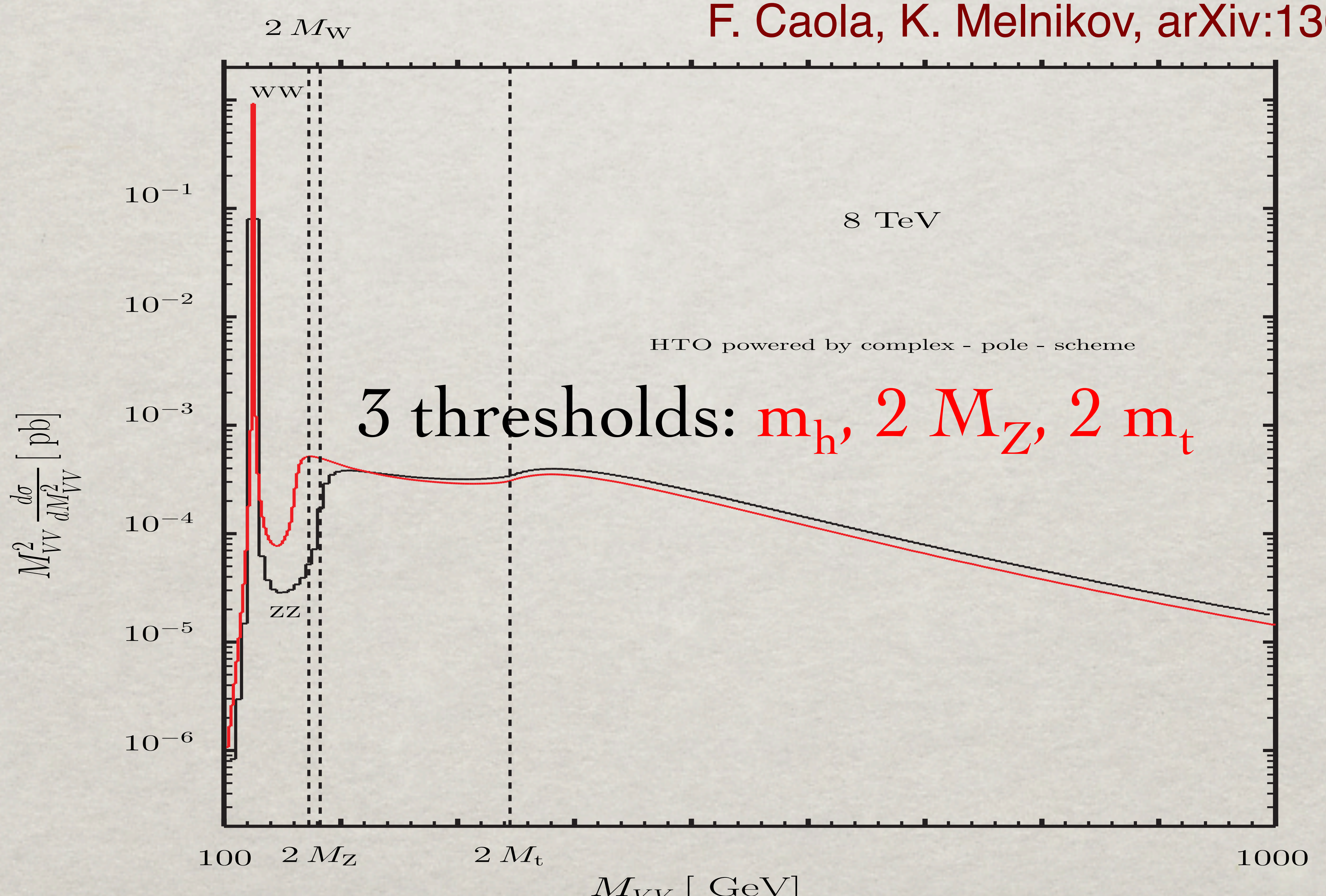
8 TeV LHC
14 TeV LHC
33 TeV HE LHC
100 TeV VLHC
total
bb̄
jet
W
Z
γ
tt̄
t
WW
WZ
ZZ
γγ
gg→H
VBF
tt̄H
WH
ZH
HH
MCFM + Higgs European Strategy
σ [nb]
√s [TeV]
10
10²
1
10⁹ 10⁸ 10⁷ 10⁶ 10⁵ 10⁴ 10³ 10² 10⁻¹ 10⁻² 10⁻³ 10⁻⁴ 10⁻⁵

gg → h* → WW, ZZ production:



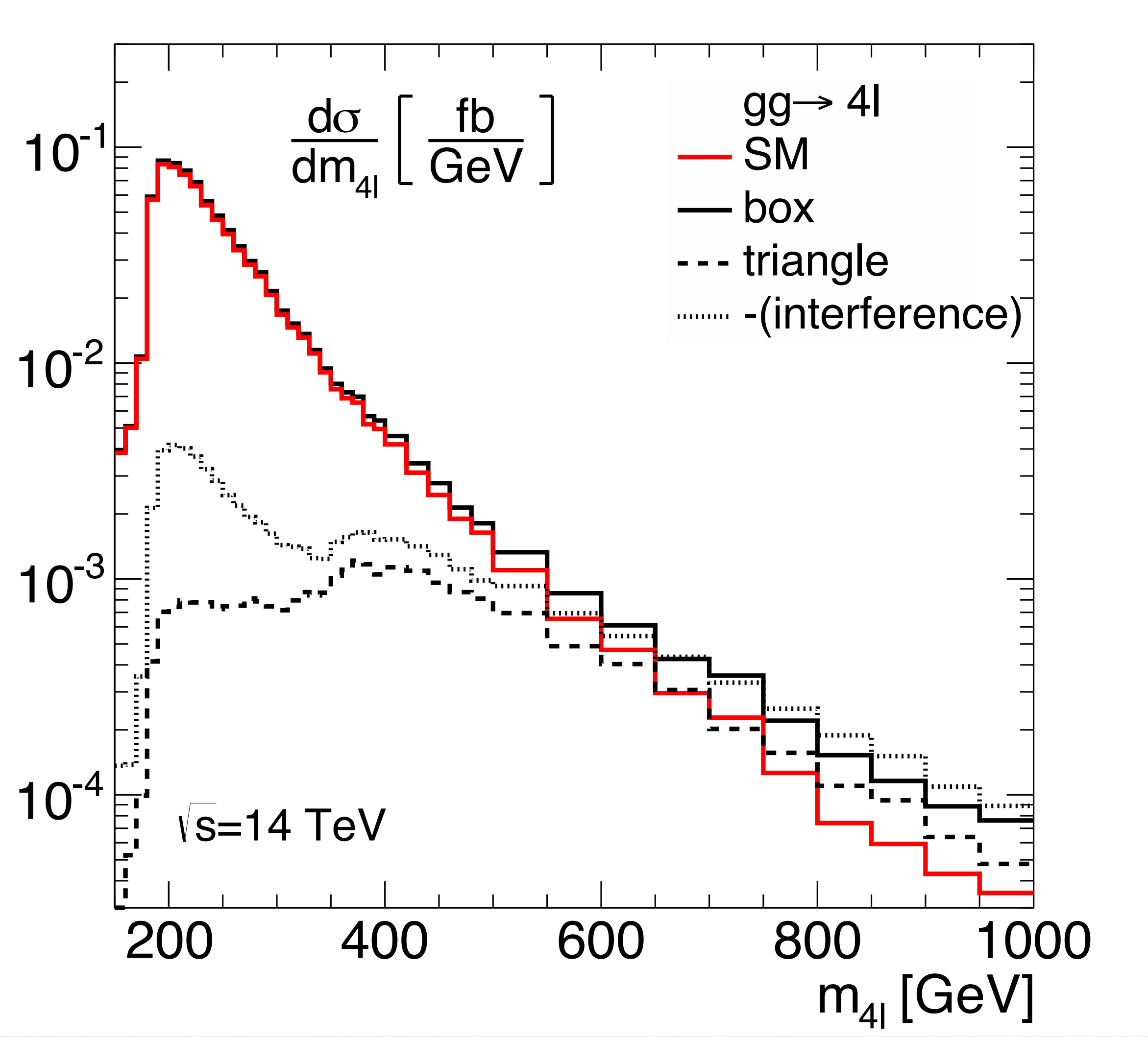


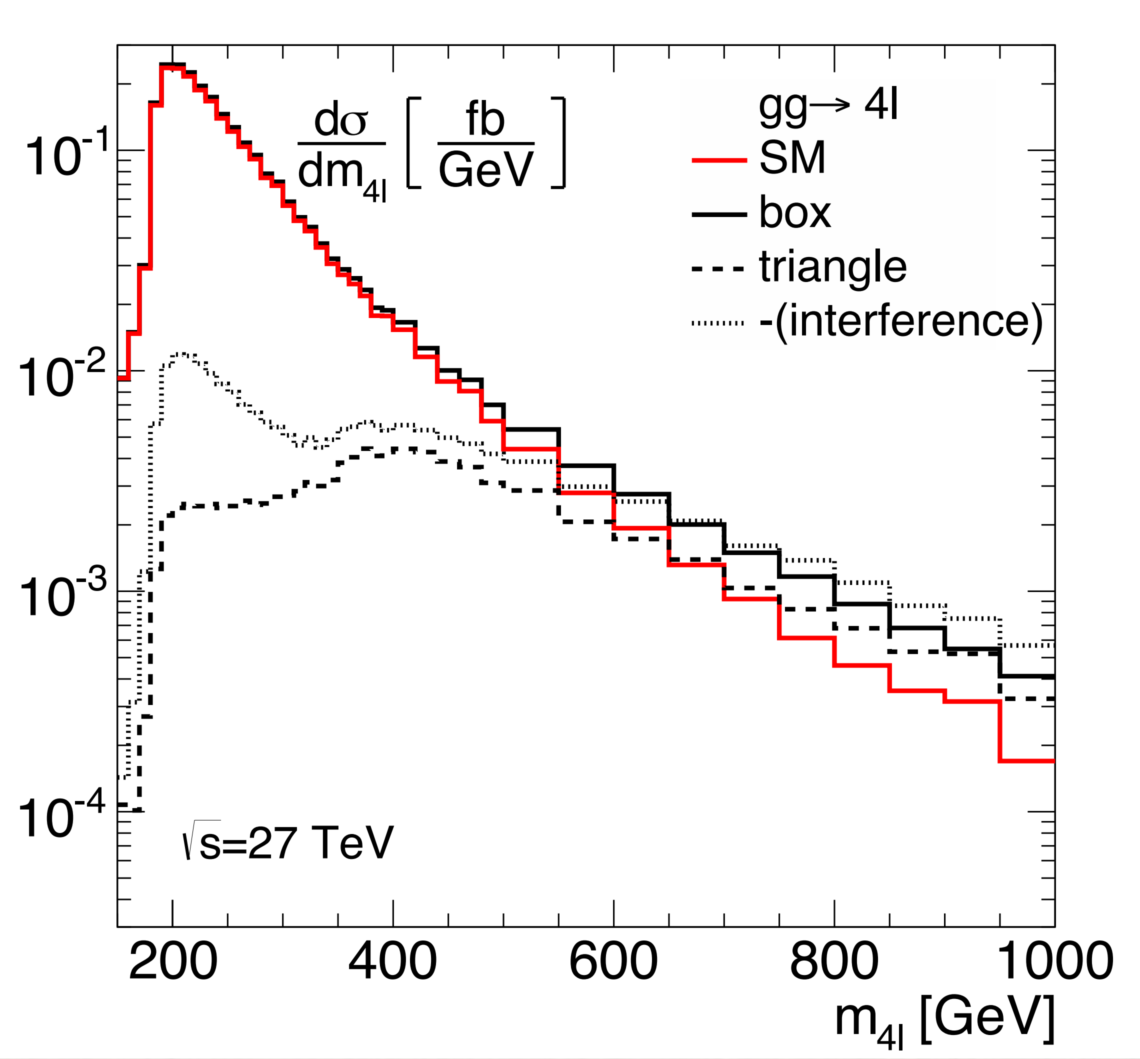
N. Kauer, G. Passarino, arXiv:1206.4803;
F. Caola, K. Melnikov, arXiv:1307.4935.



HL-LHC / HE-LHC:

gg → h* → ZZ → 4 l's





Significant destructive interference
between the box (B) & triangle diagram (S)
→ Linearly sensitive to modifications!

HL-LHC: 14 TeV, 3 ab^{-1}
HE-LHC: 27 TeV, 15 ab^{-1}

gg → h* → ZZ → 4 l's

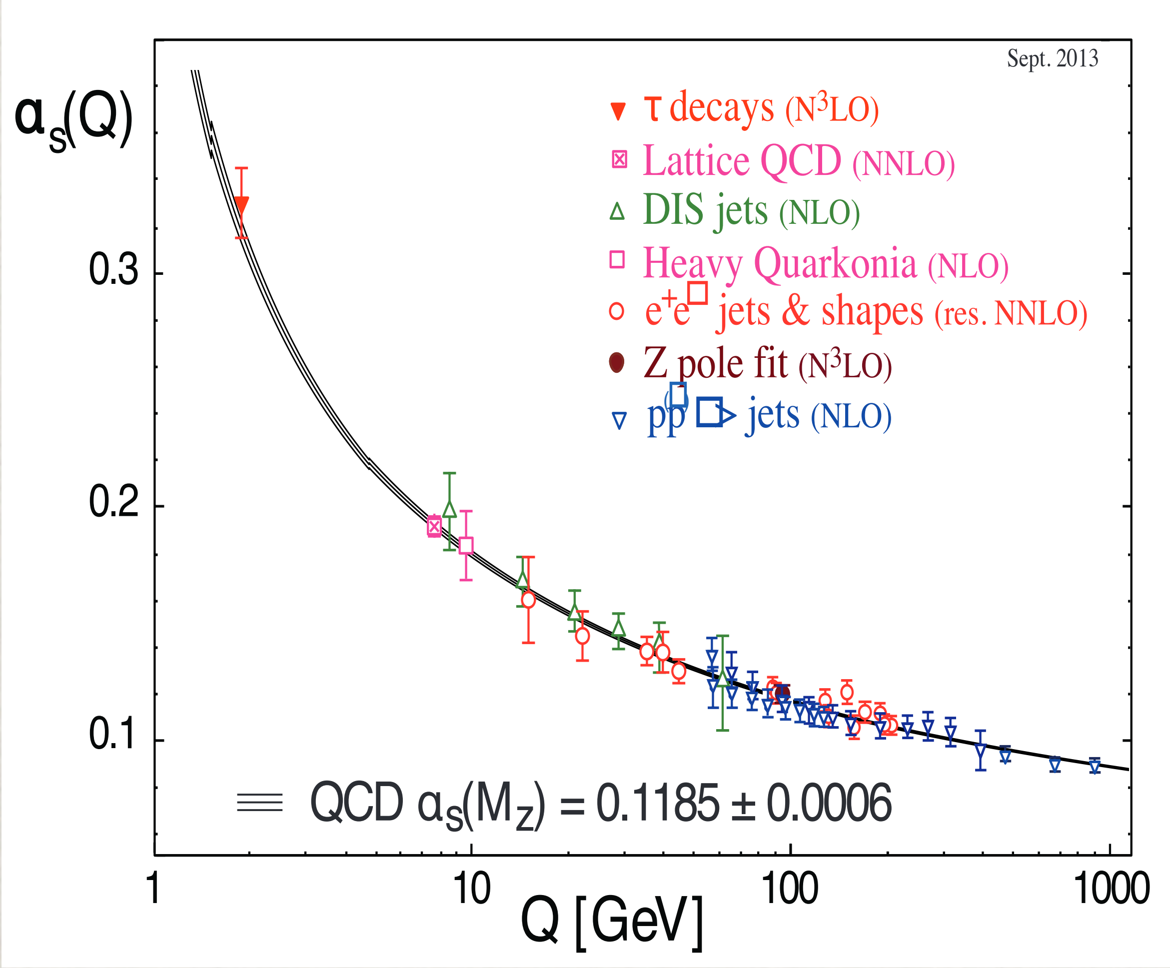
$$p_{T\ell} > 10 \;\; \text{GeV} \,, \qquad |\eta_\ell| < 2.5 \,,$$
$$m_{4\ell} > 150 \;\; \text{GeV} \,, \qquad m_{\ell\ell'} > 4 \;\; \text{GeV} \,,$$
$$m_{\ell\ell}^{(1)} = [40, 120] \;\; \text{GeV} \,, \qquad m_{\ell\ell}^{(2)} = [12, 120] \;\; \text{GeV}$$

Cross sections:	14 TeV	27 TeV
q qbar → ZZ → 4 l's:	18 fb	35 fb
gg → ZZ → 4 l's:	6.1 fb	19 fb

Case Study 1: Weakly coupled

Physical parameters in the theory evolve with scale → RGE.

The best example $\alpha_s(Q)$: Not only QCD verified, but also NO new physics contributions below the accessible scale!



- EW parameters verified: $\alpha_{\text{QED}}(Z),\ \sin^2\theta_W$
- Bottom quark mass (y_b) weak evidence: $m_b(\Upsilon) \to m_b(Z)$

The next target: top quark & Higgs!

The top quark Yukawa coupling:

SM:

$$\frac{dy_t}{dt} = \beta_{y_t}^{\rm SM} = \frac{y_t}{16\pi^2}\left(\frac{9}{2}y_t^2 - 8g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{20}g_1^2\right)$$

$$\beta_Q = \beta_Q^{\rm SM} + \sum_{\text{s: massive new states}} \theta(\mu - M_s)(N_s \beta_{s,Q}^{\rm NP})$$

MSSM:

$$\frac{dy_t}{dt} = \frac{y_t}{16\pi^2}\left(6y_t^2 - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{13}{15}g_1^2\right), \qquad \text{MSSM}$$

Gauge fields in Extra Dim:

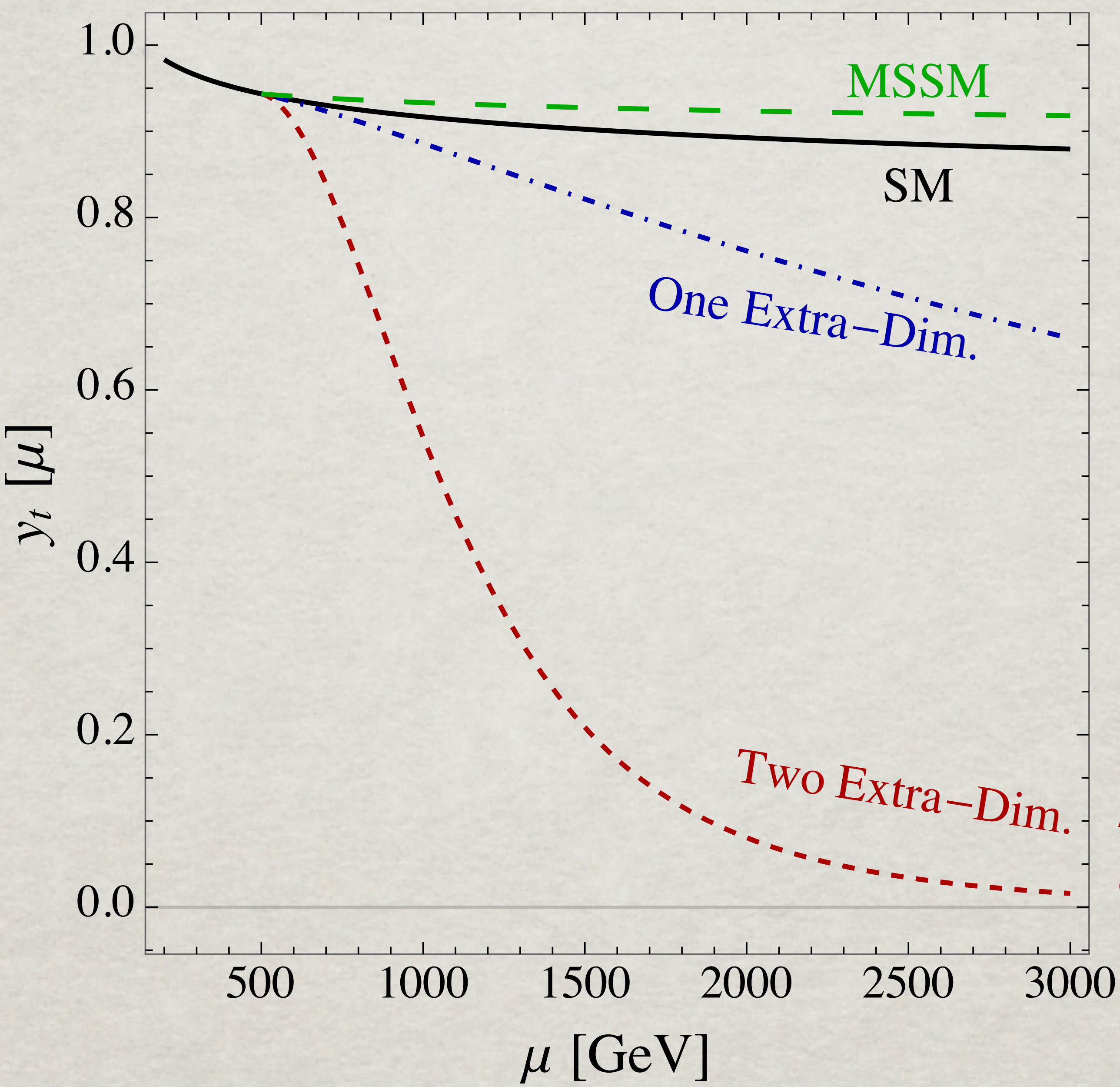
$$\frac{dy_t}{dt} = \beta_{y_t}^{\rm SM} + \frac{y_t}{16\pi^2}2(S(t)-1)\left(\frac{3}{2}y_t^2 - 8g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{20}g_1^2\right), \qquad \text{5D,}$$

$$\frac{dy_t}{dt} = \beta_{y_t}^{\rm SM} + \frac{y_t}{16\pi^2}4\pi(S(t)^2-1)\left(\frac{3}{2}y_t^2 - 8g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{20}g_1^2\right), \qquad \text{6D.}$$

$S(t) = e^t R$ ~ **μ**R: counts the number of states.

→ "volume", power-law running!

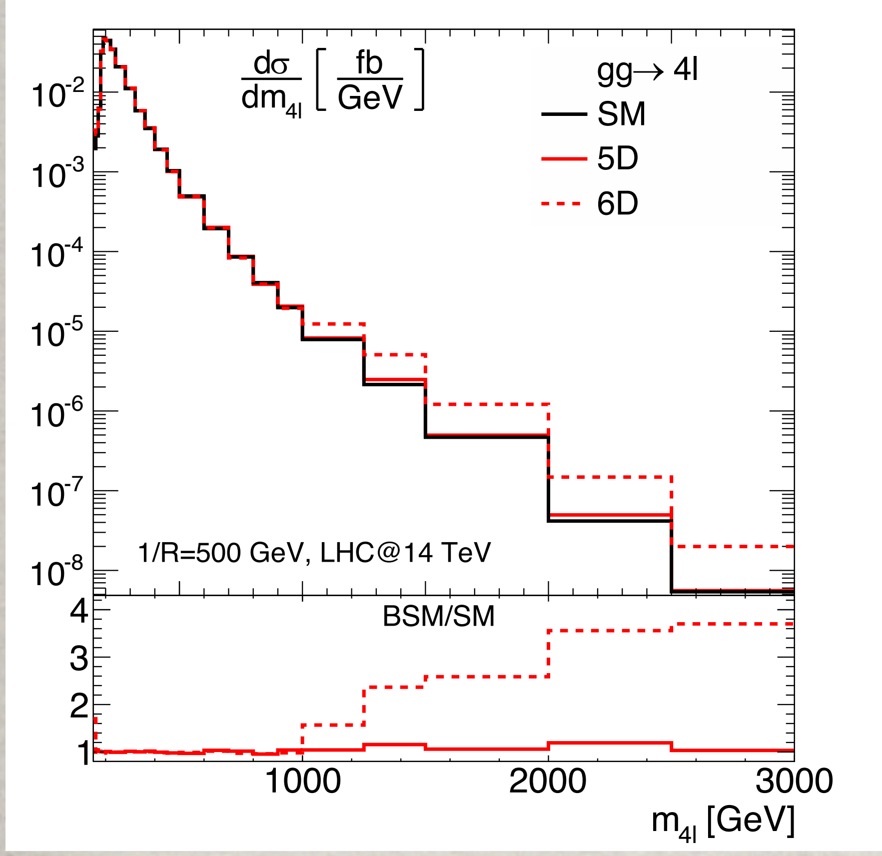
Top quark Yukawa coupling: RGE

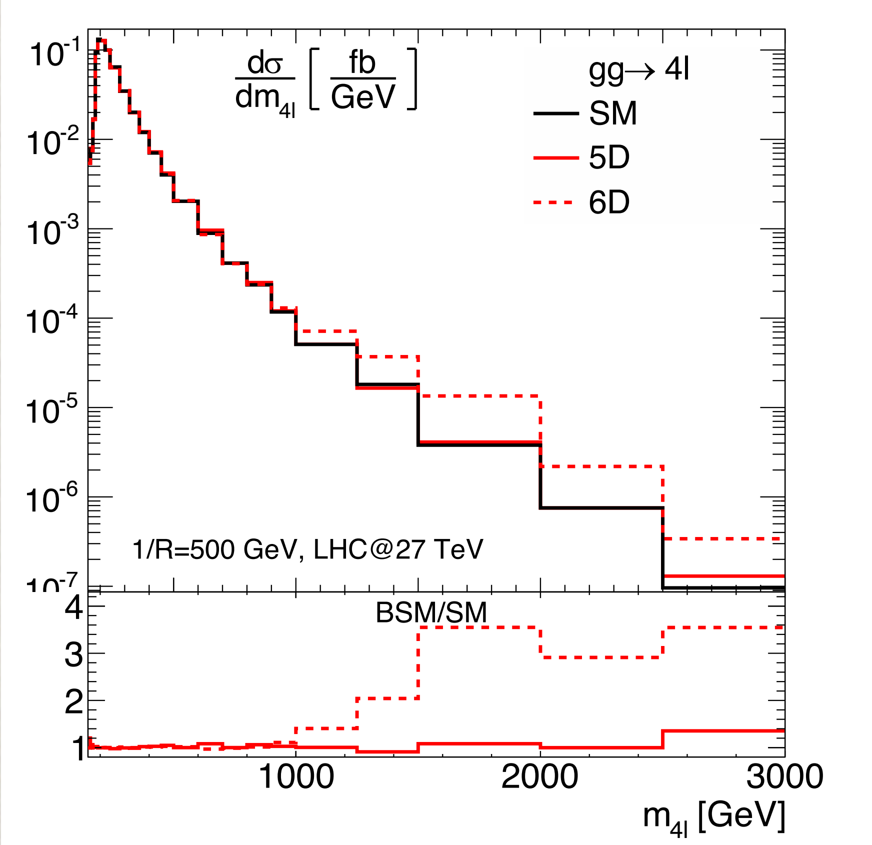


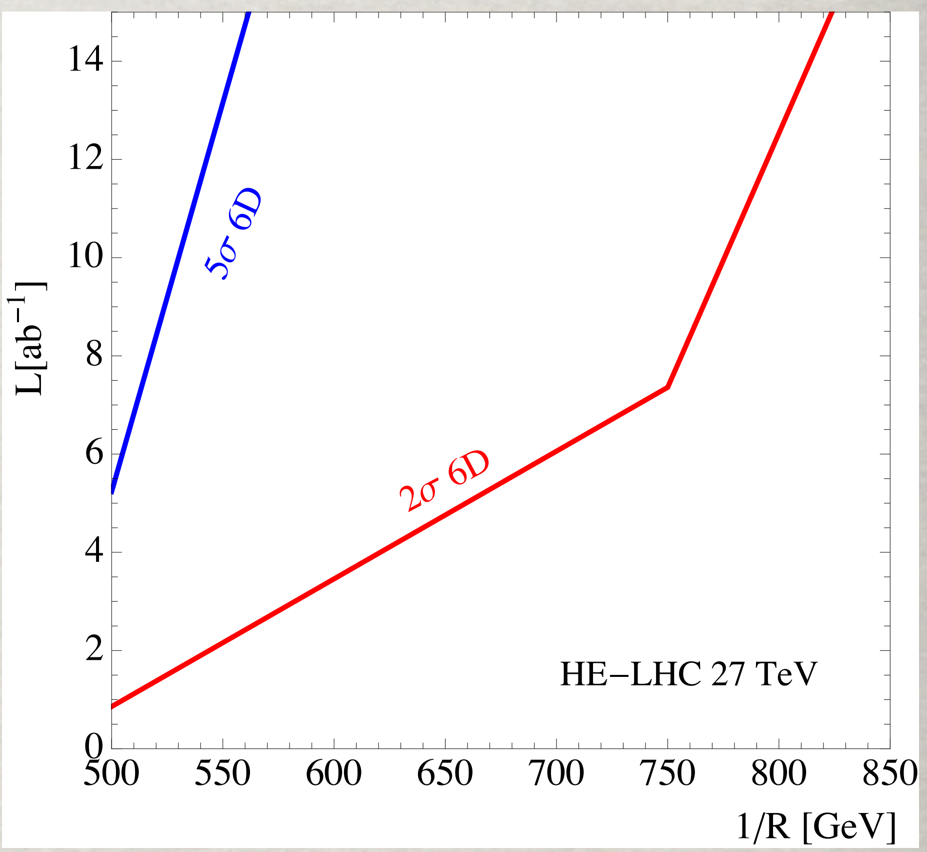
A.S. Cornell et al., arXiv:1209.6239.

Suppressed Yukawa coupling
→ smaller s-channel signal rate
→ weaker interference
→ larger ZZ signal!

LHC Sensitivity: Running of top quark Yukawa coupling







SM / MSSM too weak to be appreciable

- **5D signal rather weak: Little sensitivity.**
- **HL-LHC: Insensitive.**
- **HE-LHC @ 6D: a factor of 3-4 increase.**

Reach 1/R ~ 0.8 TeV @ 2σ; 0.6 TeV @ 5σ

Case Study 2: Strongly coupled

The Higgs boson may still be a composite state at a high scale Λ_c

The Goldstone-boson nature → $m_h << \Lambda_c$.

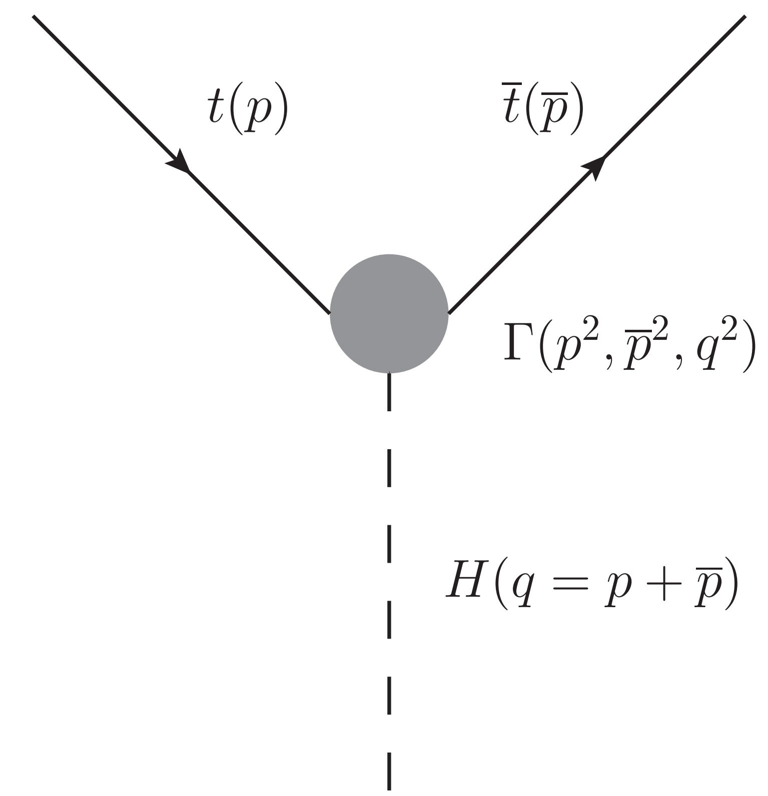
The deviation from the point-like interaction:

- Momentum-dependent Form Factor
- Non-local interactions
- Beyond simple QFT description
- Underlying dynamics → new constituents

M. Beneke et al., arXiv:1108.1876;
V. Punjabi et al., arXiv:1503.01452.

The Momentum-dependent Form Factor:

$$V_{ttH}(p^\mu, \bar{p}^\mu) = \frac{\sqrt{2}m_t}{v}\Gamma\left(p^2/\Lambda_c^2, \bar{p}^2/\Lambda_c^2, q^2/\Lambda_c^2\right)$$



Current 95%CL bound from the LHC Higgs signal:

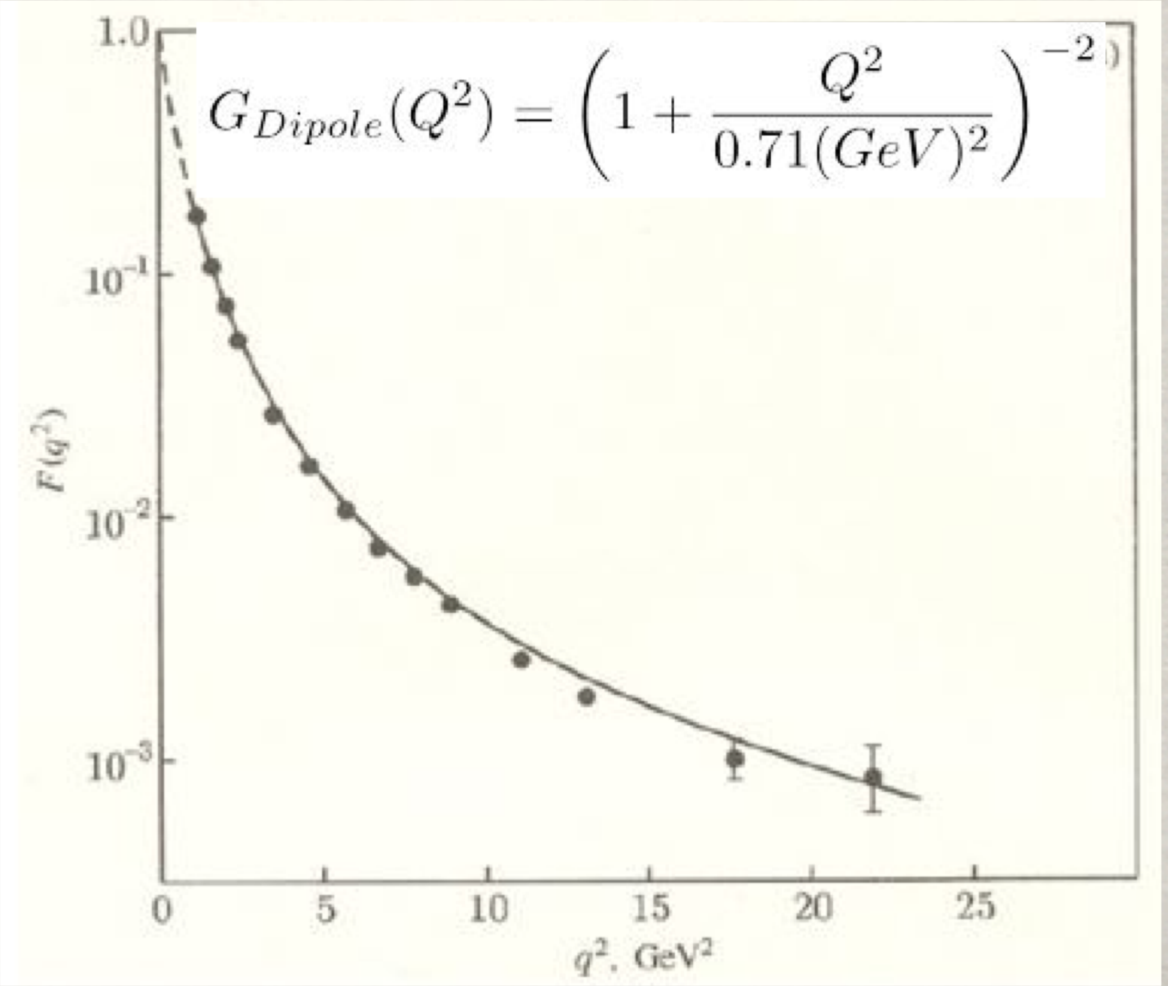
$$|\Gamma\left(m_h^2/\Lambda^2\right)^2 - 1| < 0.1$$

Nucleon form factor:

$$\Gamma\left(q^2/\Lambda_c^2\right) = \frac{1}{(1 + q^2/\Lambda_c^2\ )^n}$$

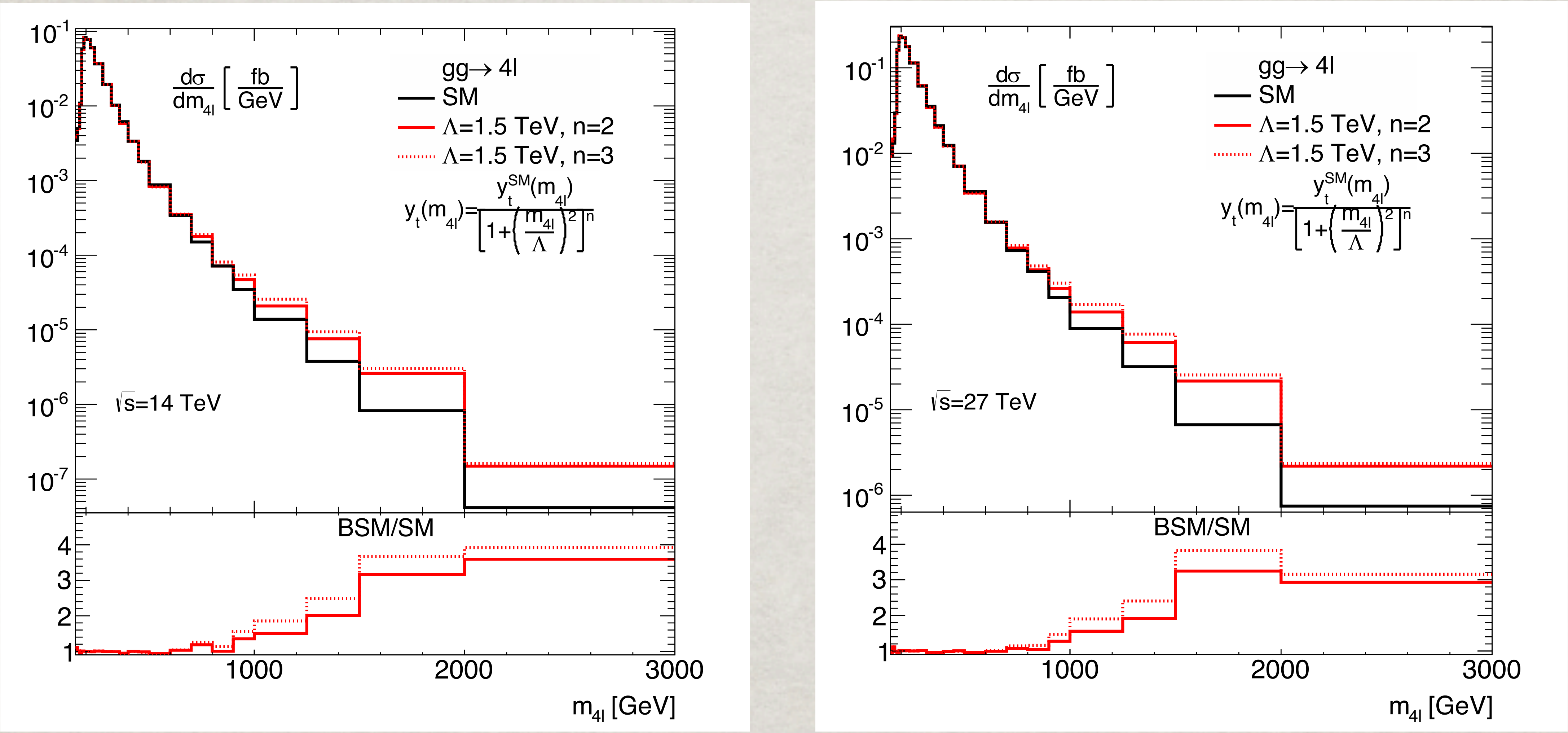
n=2 → "Dipole FF"

Leading to a suppressed ttH → Enhanced ZZ signal!



LHC distribution: top-Higgs Form Factor

(similar effects for n=2,3)



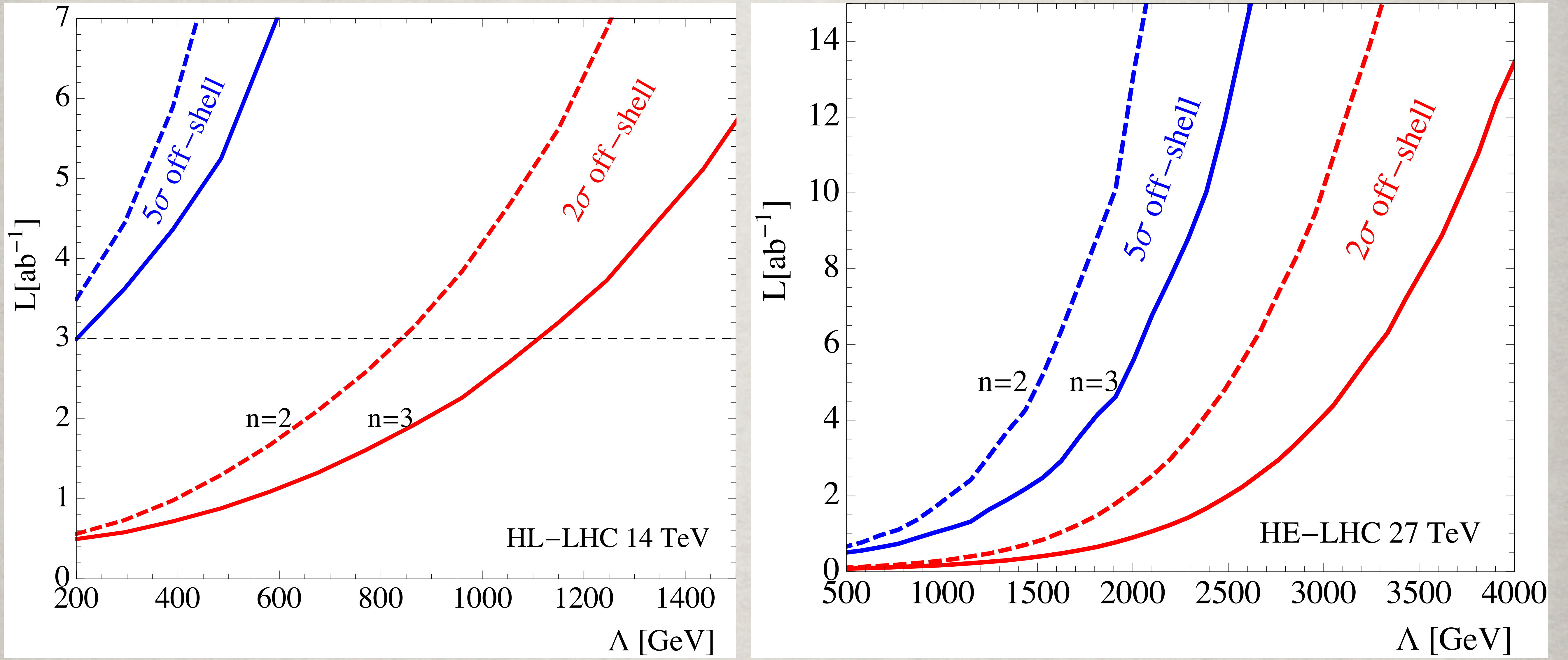
Form Factor suppression

→ smaller off-shell Higgs signal

→ weaker interference

→ larger ZZ signal: a factor of 3-4!

LHC Sensitivity: top-Higgs Form Factor



HL-LHC: Λ_c ~0.8 TeV @ 2σ

HE-LHC: Λ_c ~3.3 TeV @ 2σ; 2.1 TeV @ 5σ.

Case Study 3:
Higgs Portal: Scalar Singlet

The Higgs boson may serve as a "portal" to a "Hidden sector" (i.e., SM singlets)

$$\mathcal{L} \supset \partial_\mu S \partial^\mu S^* - \mu^2 |S|^2 - \lambda_S |S|^2 |H|^2$$

$$m_S^2 = \mu^2 + \lambda_S v^2/2$$

N. Craig et al. arXiv:1412.0258.

Contribution to the Higgs mass:

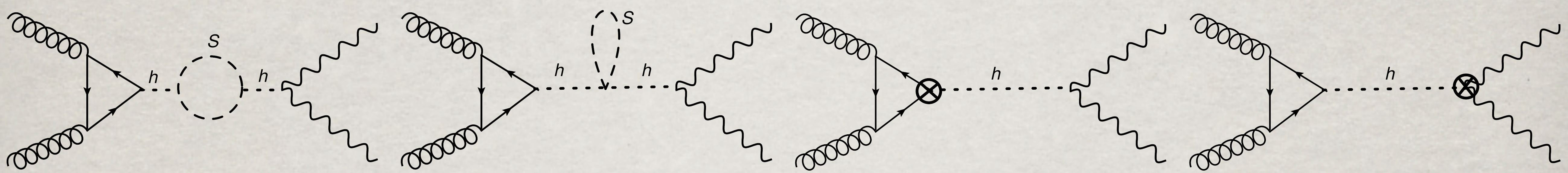
$$\delta M_h^2 = \frac{1}{16\pi^2}(\lambda_S - 2N_c y_t^2)\Lambda^2 + \frac{6N_c y_t^2}{16\pi^2} m_t^2 \log\frac{\Lambda^2}{m_t^2} - \frac{1}{16\pi^2}\left(\lambda_S m_S^2 + \lambda_S^2 v^2\right)\log\frac{\Lambda^2}{m_S^2},$$

IF $\lambda_S(\Lambda^2) = 6y_t^2(\Lambda^2)$ → act like top-squark !

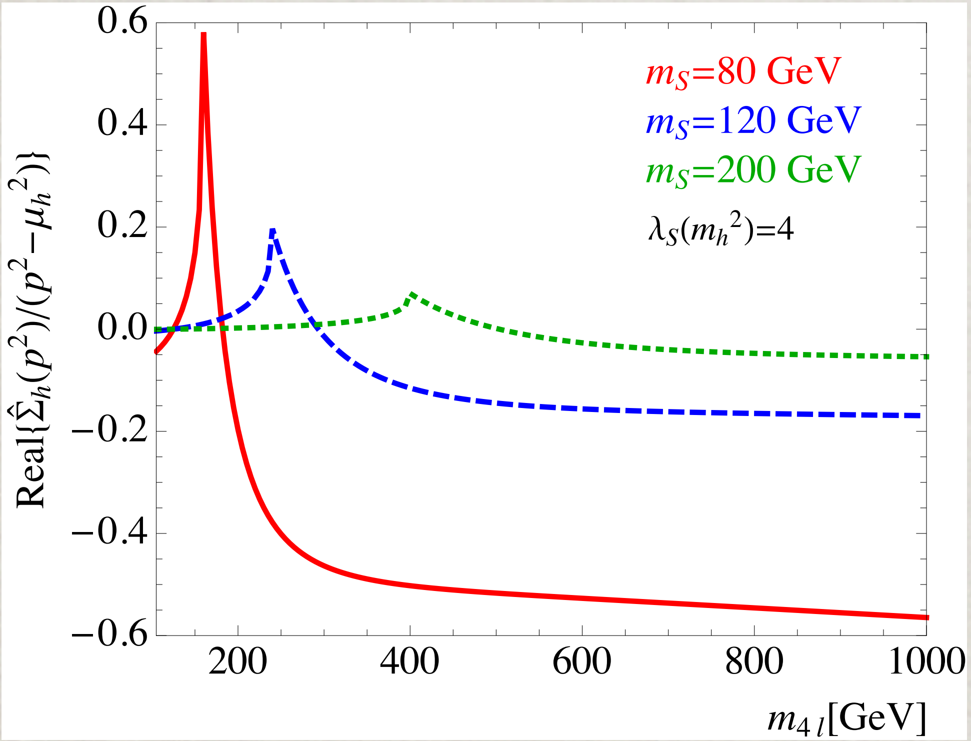
Will alleviate the "Little hierarchy" problem.

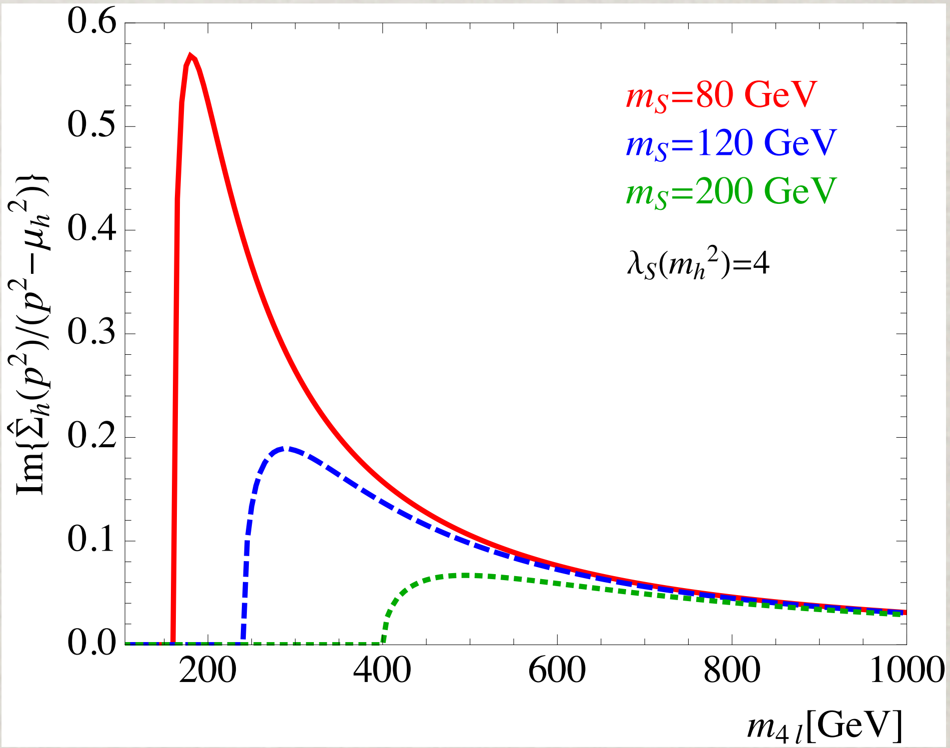
Twin Higgs; Neutral naturalness;…

When crossing the threshold → branch-cut contribution!



D. Goncalves, TH, S. Mukhopadhyay, PRL: arXiv:1710.0249.

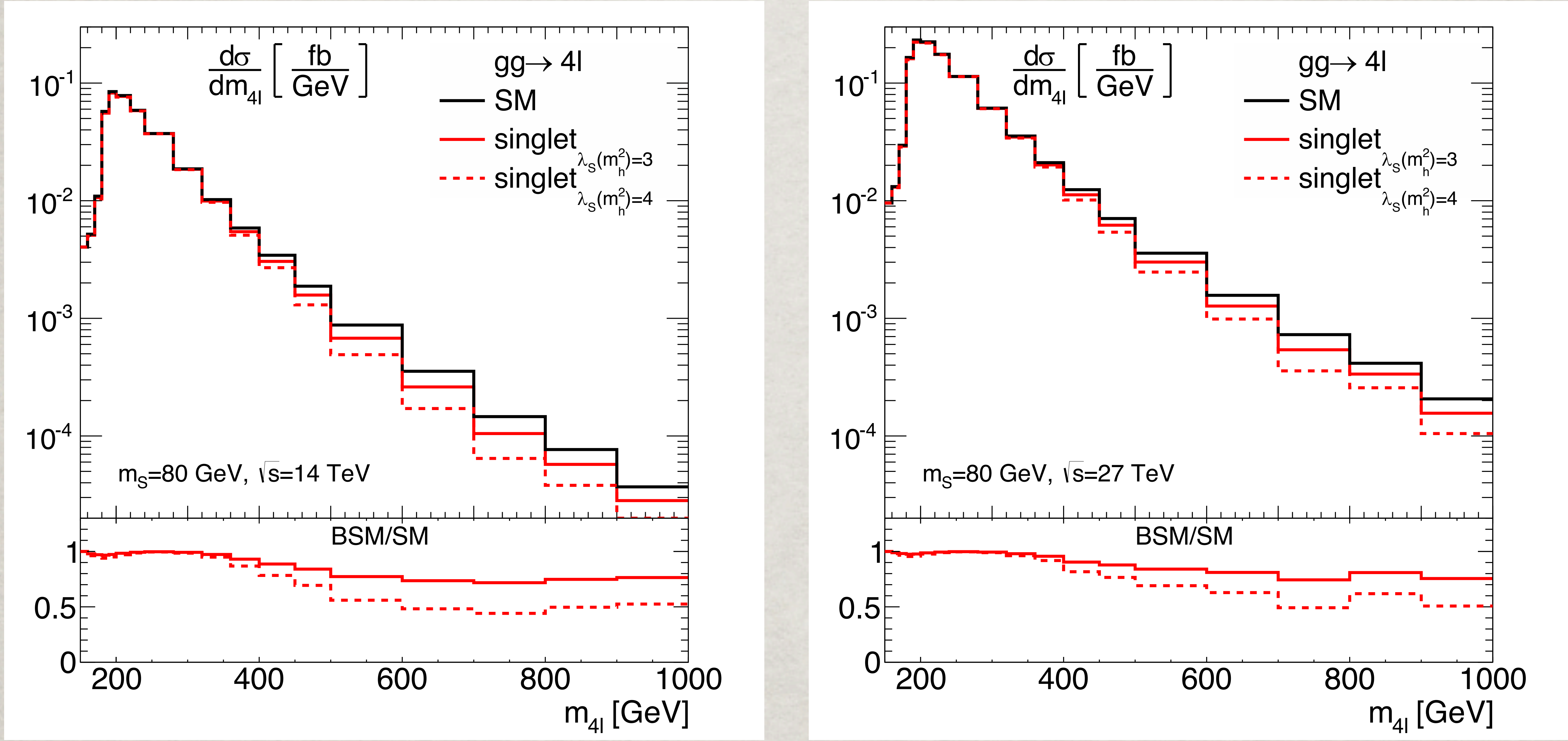




S-matrix singularities:

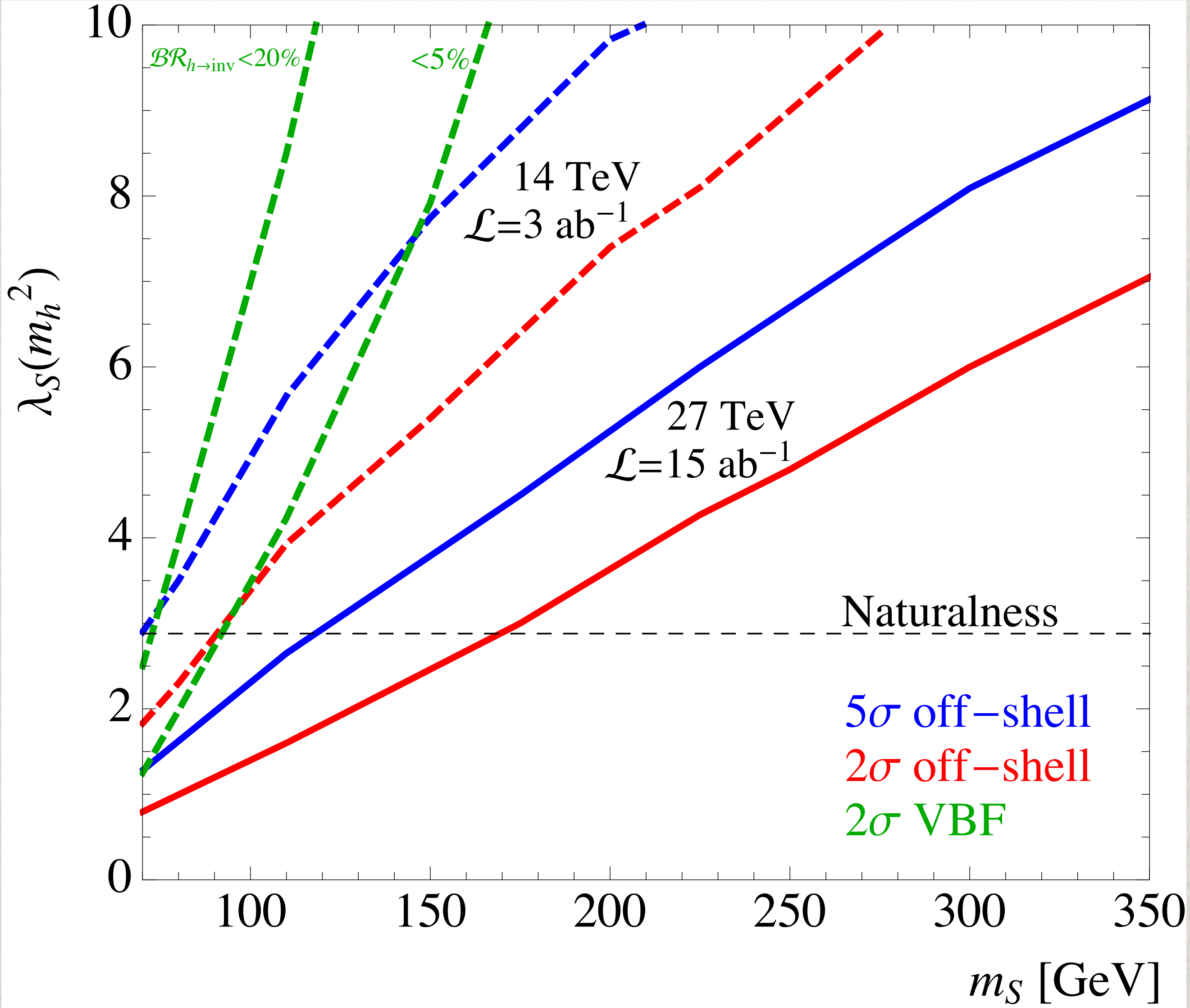
- s-channel resonant pole
- Pair-production branch-cut

LHC Sensitivity: Higgs portal via S



Due to the interference, the rate is reduced w.r.t. the SM (to 50%, potentially observable.)

LHC Sensitivity: Higgs portal via S



IF taking λs for "natural values":

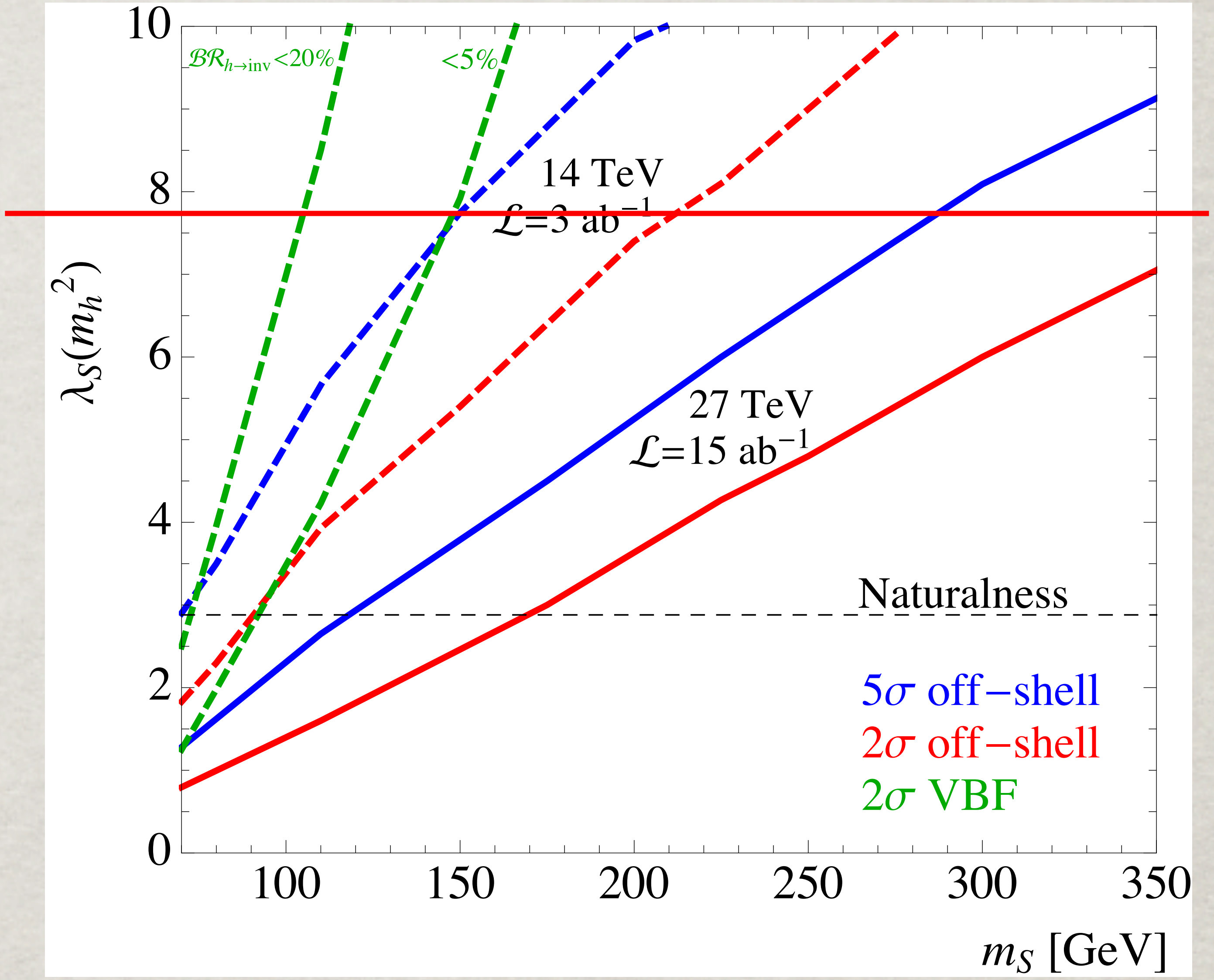
HL-LHC: m_s ~ 90 GeV @ 2σ; 70 GeV @ 5σ.

HE-LHC: m_s ~ 160 GeV @ 2σ; 120 GeV @ 5σ.

LHC Sensitivity: Higgs portal via S

Invisible Higgs in VBF:

N. Craig et al. arXiv:1412.0258.:
Systematics for jet + ET missing



Off-shell Higgs can do better than

- The "invisible searches" via VBF
- Higgs factory near ZH threshold: total width needed

The singlet has other motivations:

- Serves as a cold DM
- Modify EW phase transition to a strong 1st order transition

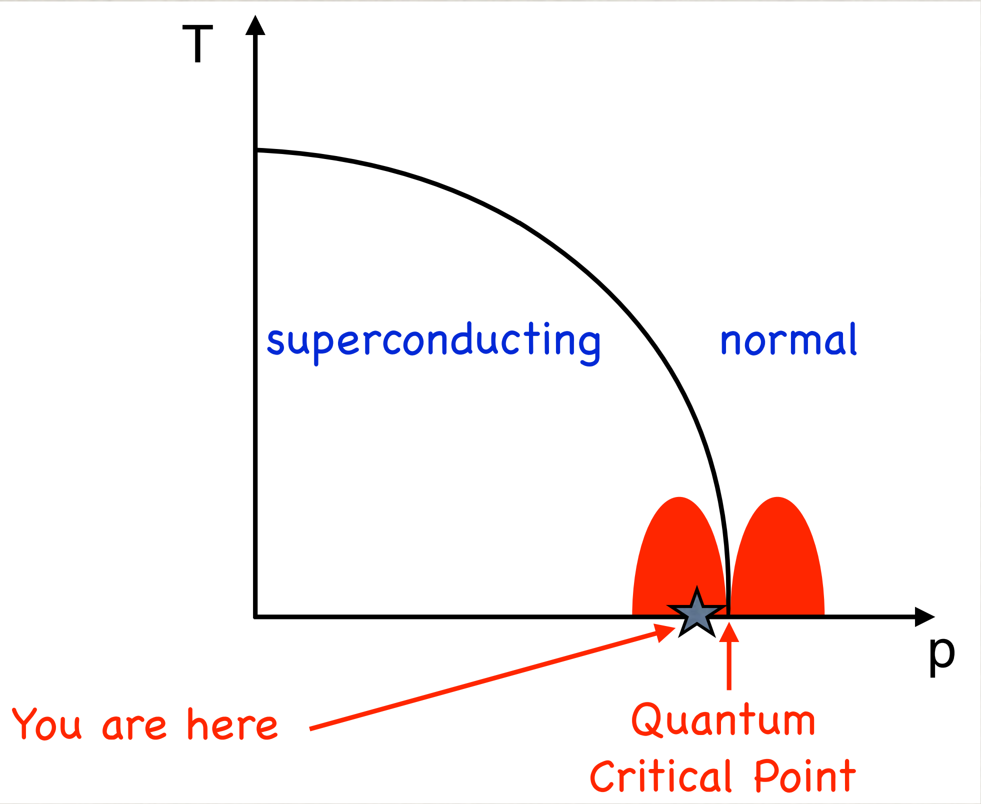
J. McDonald, hep-ph/0702043;
C.P. Burgess et al., hep-ph/0011335;
V. Barger et al. arXiv:0706.4311.

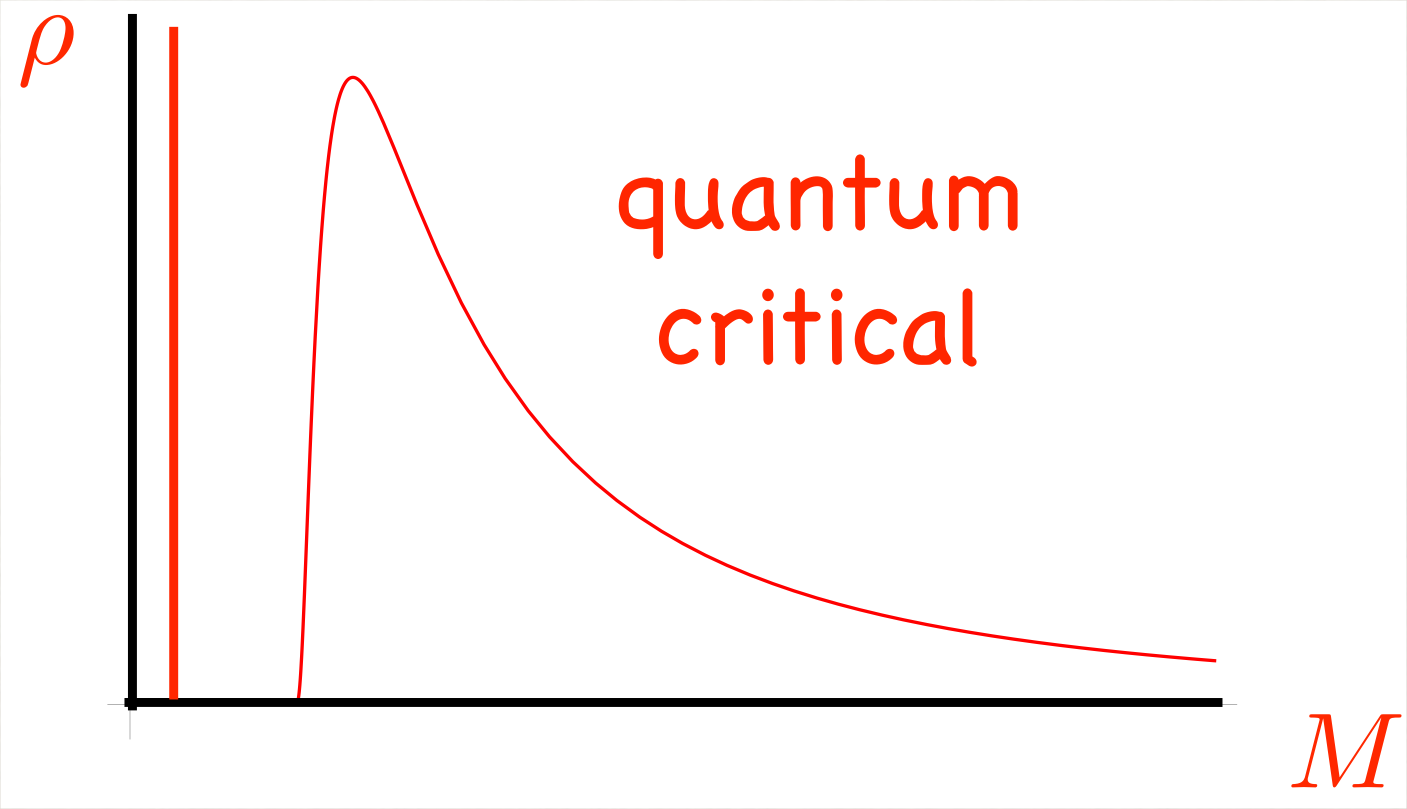
P. Fox et al., arXiv:1109.4398;
Batell, Gori, Wang, arXiv:1112.5280;
D. Chung, A. Long, L.-T. Wang (1209.1819);
…

Case Study 4: Quantum Critical Higgs

B. Bellazzini, C. Csaki, J. Terning et al., arXiv:1511.08218.

- Phase transition at zero temperature is called quantum phase transition (QPT).
- Dynamics of QPT is represented by a continuum spectrum from a scale ***μ***, associated with a strongly coupled conformal field theory (CFT).





Quantum Critical Higgs

B. Bellazzini, C. Csaki, J. Terning et al., arXiv:1511.08218.

- Large scaling dimension **Δ** makes a weaker dependence of the Higgs mass correction on the cutoff **Λ** :

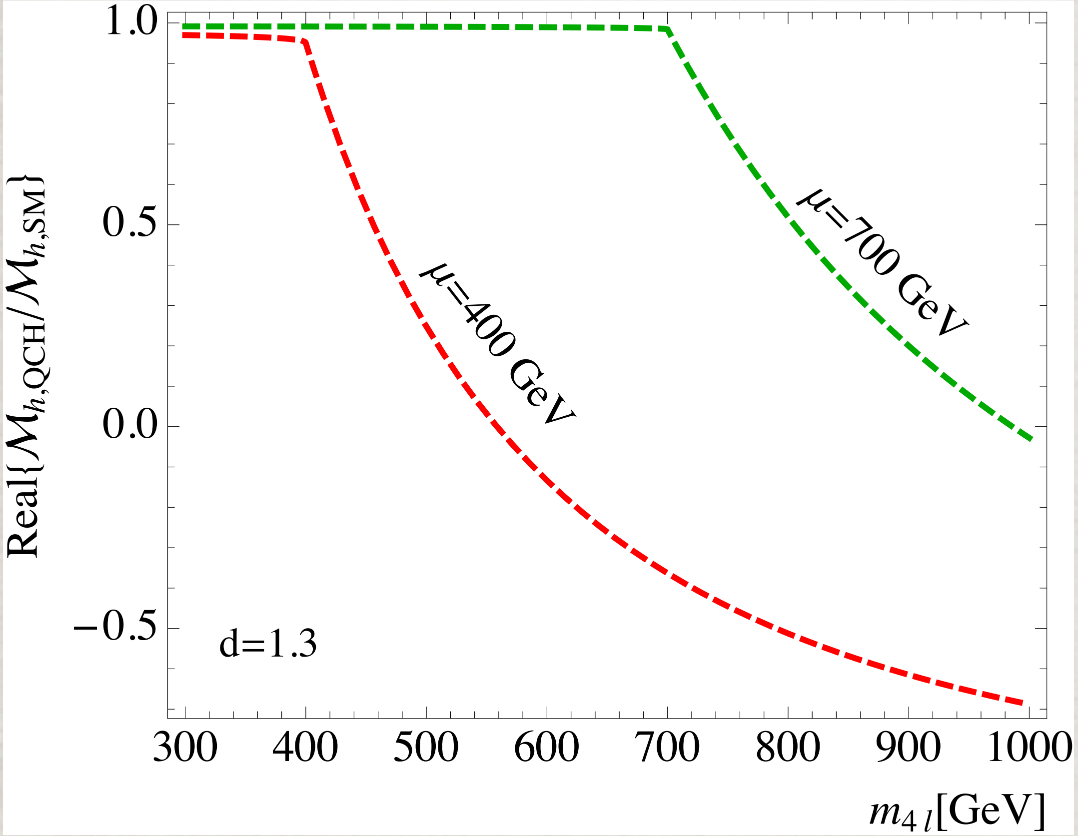
$$\delta m_h^{4-2\Delta} = \frac{3\lambda_t^2}{8\pi^2}\Lambda^{4-2\Delta}$$

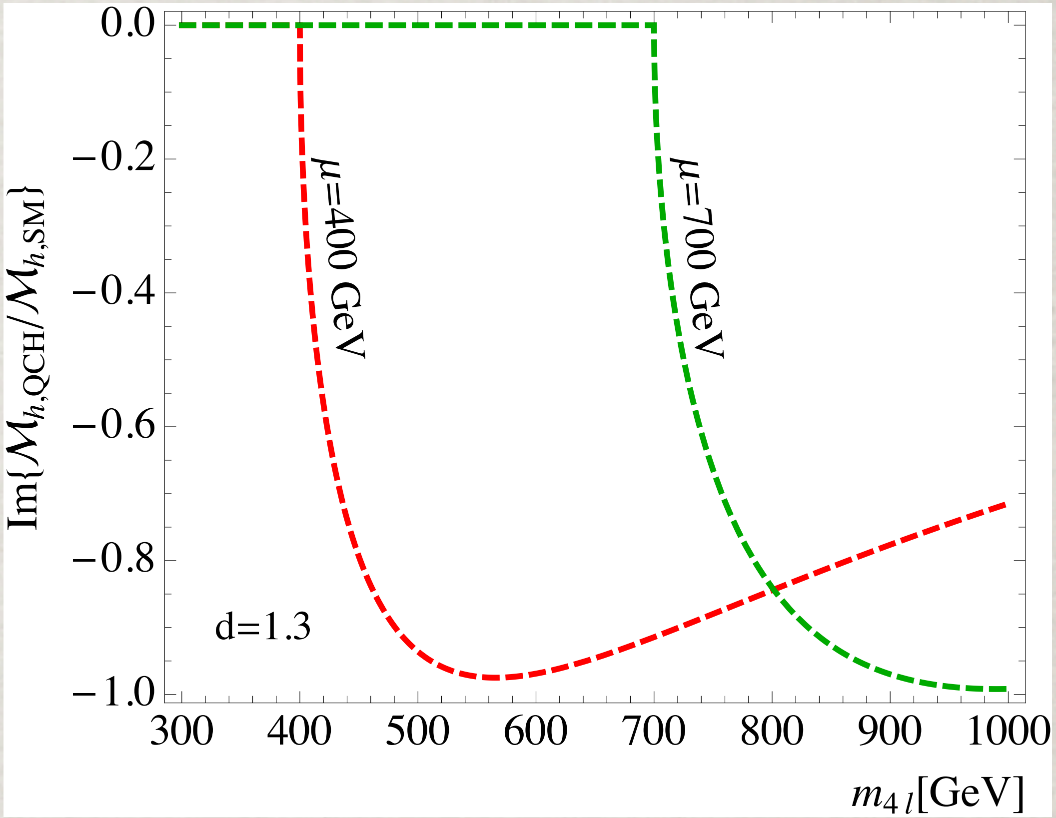
Spectral function (un-particle/un-Higgs):

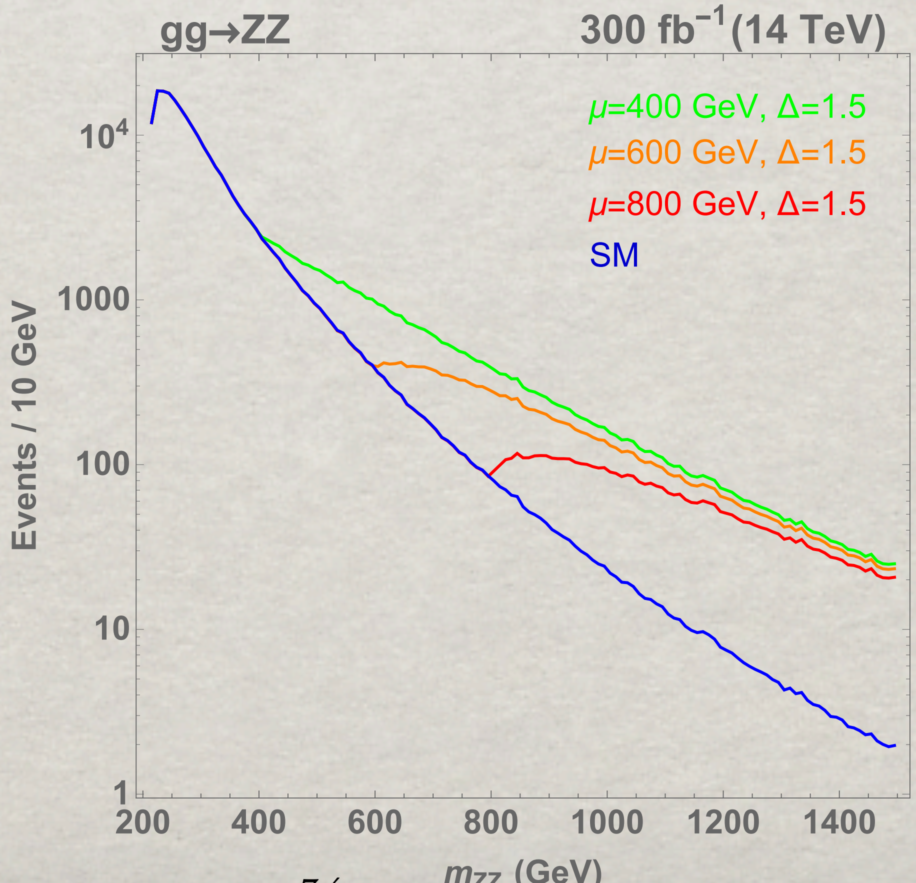
$$g_{ZZh} \sim (g^{\mu\nu} p_1 \cdot p_2 - p_1^{\mu} p_2^{\nu})\Gamma_{ZZh}, \quad \delta\lambda_t = \sqrt{2-\Delta}\left(\frac{\Lambda}{\mu}\right)^{\Delta-1},$$

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

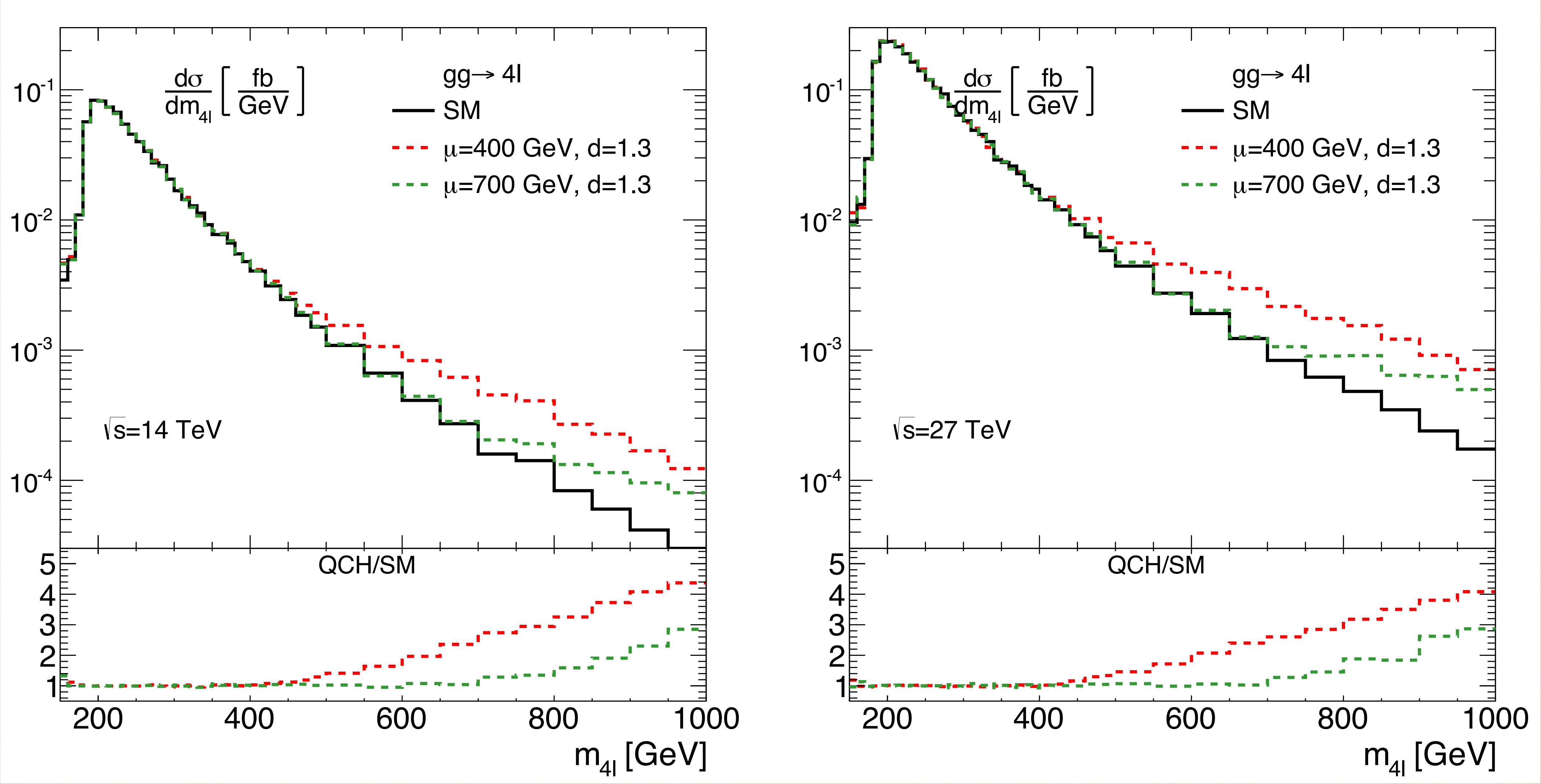
Threshold effects, distributions: QCH





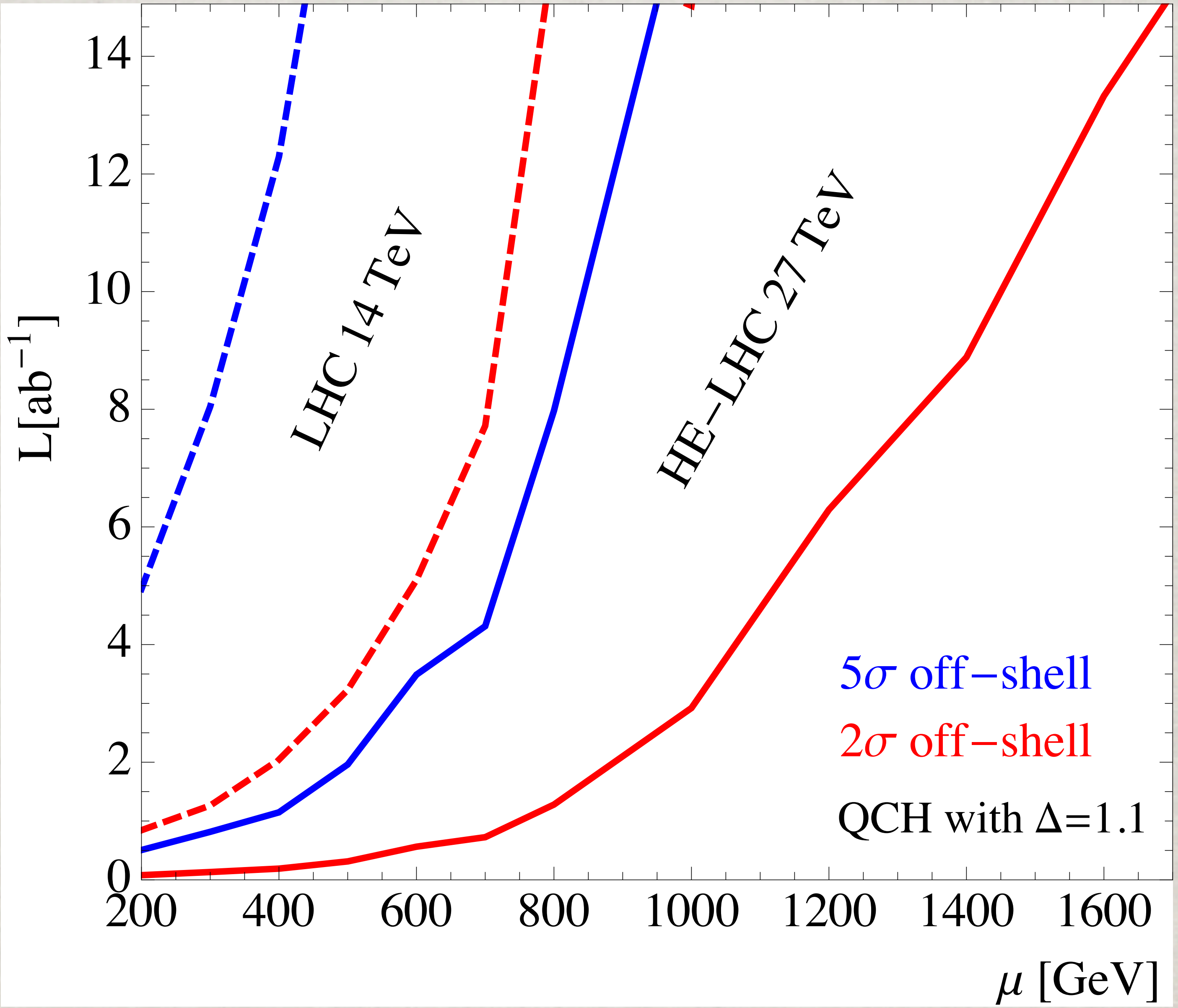


Threshold effects, distributions: QCH



Branch-cut suppression (Csaki et al.)
→ smaller off-shell Higgs signal
→ weaker interference
→ larger ZZ signal: a factor of 3-4!

LHC Sensitivity: QCH



HL-LHC: Λ_c ~0.5 TeV @ 2σ

HE-LHC: Λ_c ~1.6 TeV @ 2σ; 0.9 TeV @ 5σ.

Larger effects (signal) for larger: 1.0 < Δ < 1.5

Summary:

The Higgs boson is a new class,
likely a window to new physics.

In the absence of deviation from the SM, we propose to study Higgs physics at higher scales (off-shell): pp → h* → ZZ

In accordance with the "naturalness" considerations:

- Weakly coupled: RGE for SM; MSSM: weak effects.
- Extra dimensions → Power-law running!
- New states coming into Higgs propagation:
  scalar singlets; a continuum spectrum in QCH
- Strong dynamics/composite Higgs: Form Factor for tth.

Modifications may be observable at the LHC upgrades
2***σ*** - 5***σ*** level sensitivity.