Higgs Couplings @ High Scales

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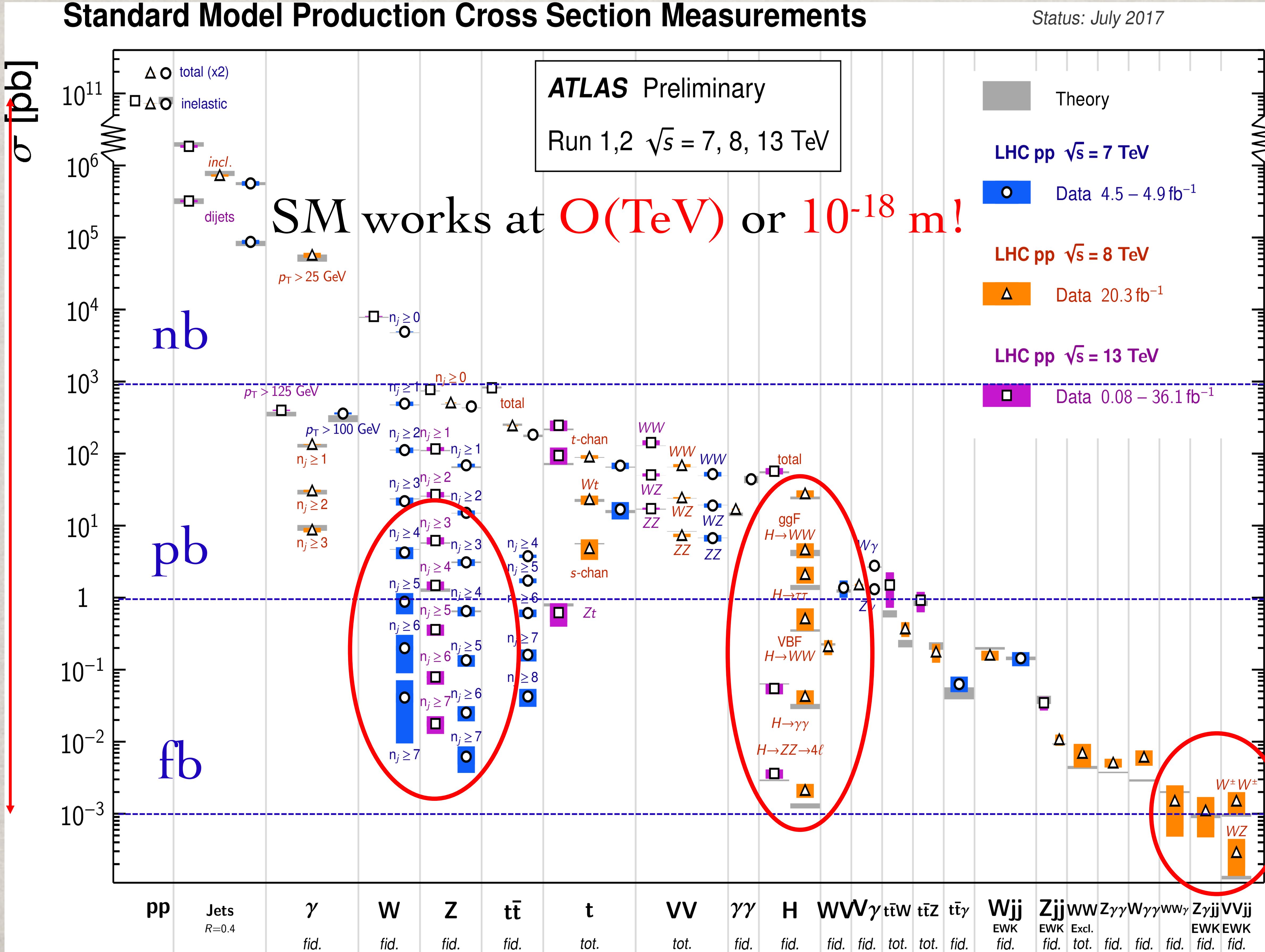
PITT PACC, Univ. of Pittsburgh

Beyond BSM Workshop

伊香保，天坊 Hotel, Oct. 2, 2018

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

LHC Rocks!



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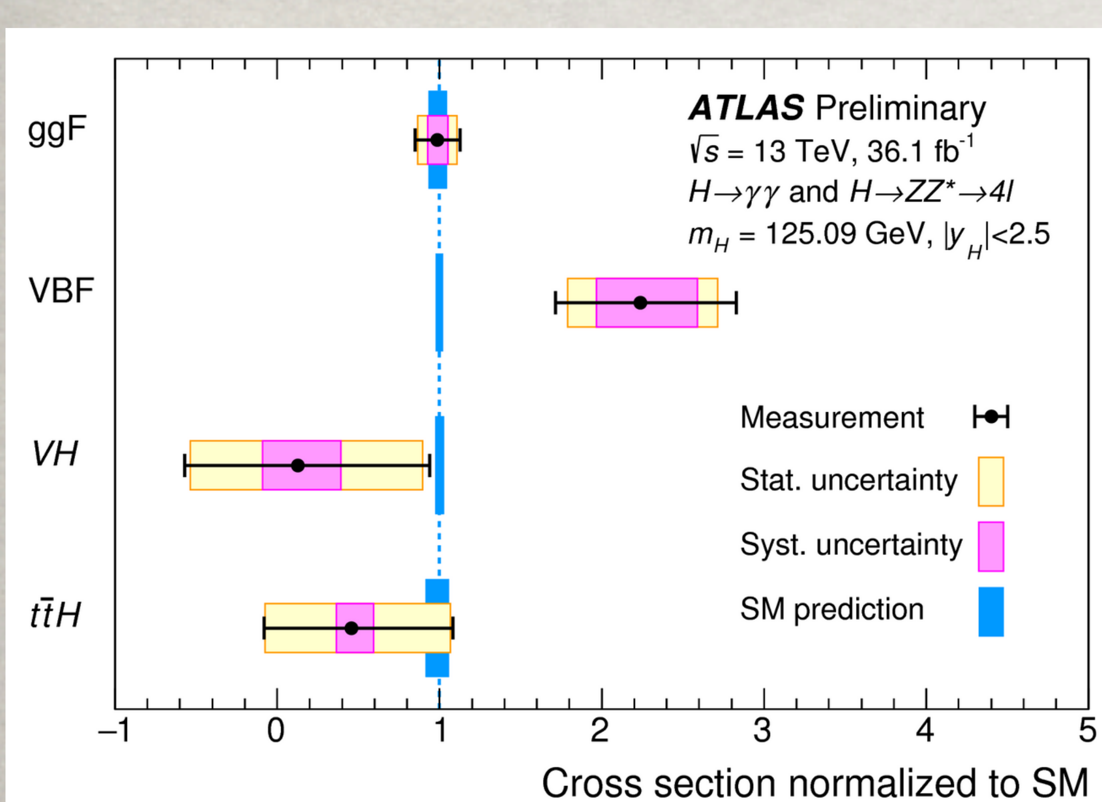
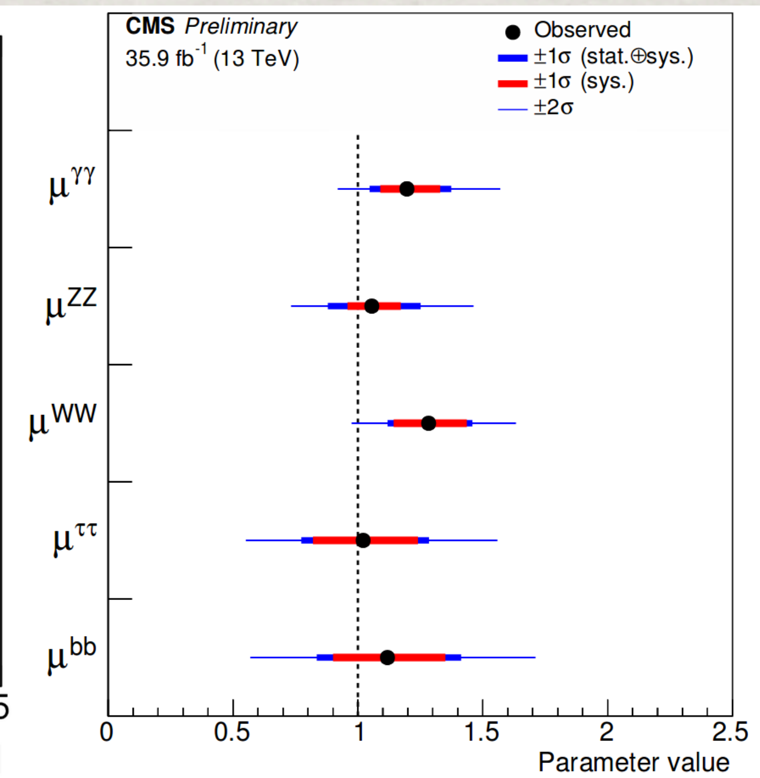
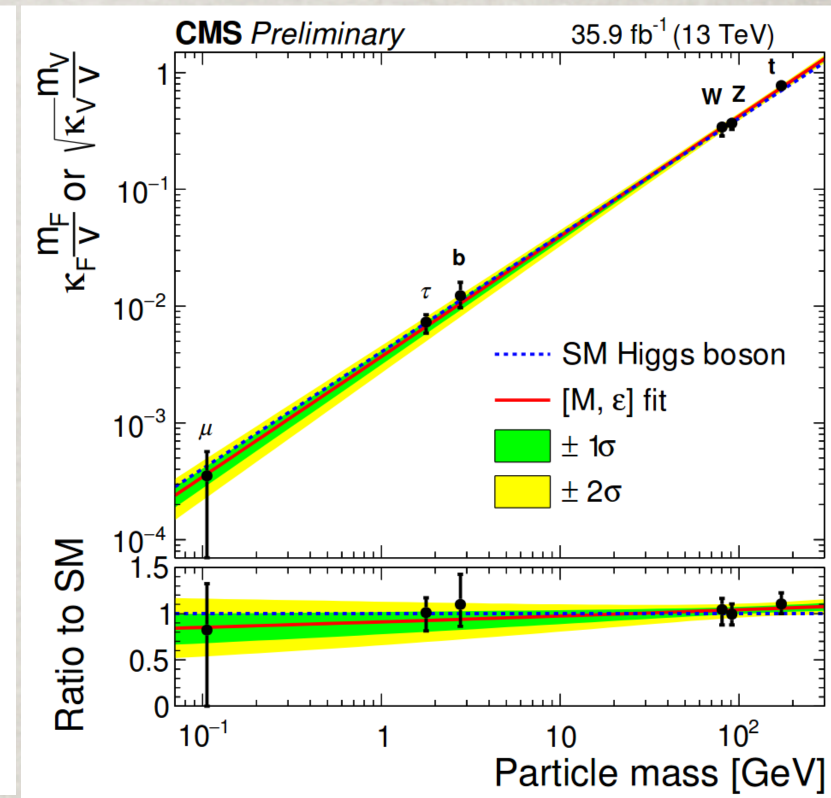
Higgs Moriond update: (D. Sperka, ATLAS & CMS)

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







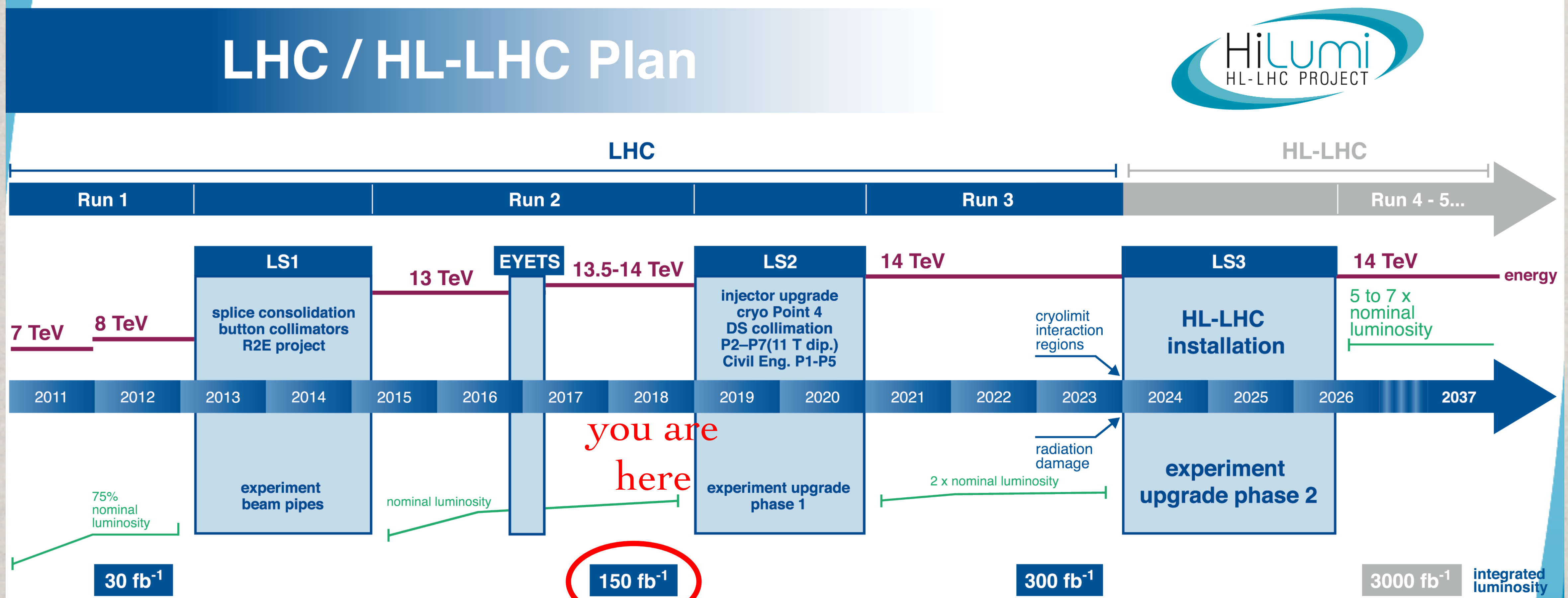
All indications → SM-like Higgs boson, "elementary" at a scale Λ < O(1 TeV)

→ SM self-consistent to exponentially high scales! Next?

HL-LHC:
The Energy & Precision Frontier

(Sasha Valishev, FNAL workshop)

Timeline & Goal:
Commissioning 2026; 3 ab^{-1} by 2037 (250 fb^{-1}/y)



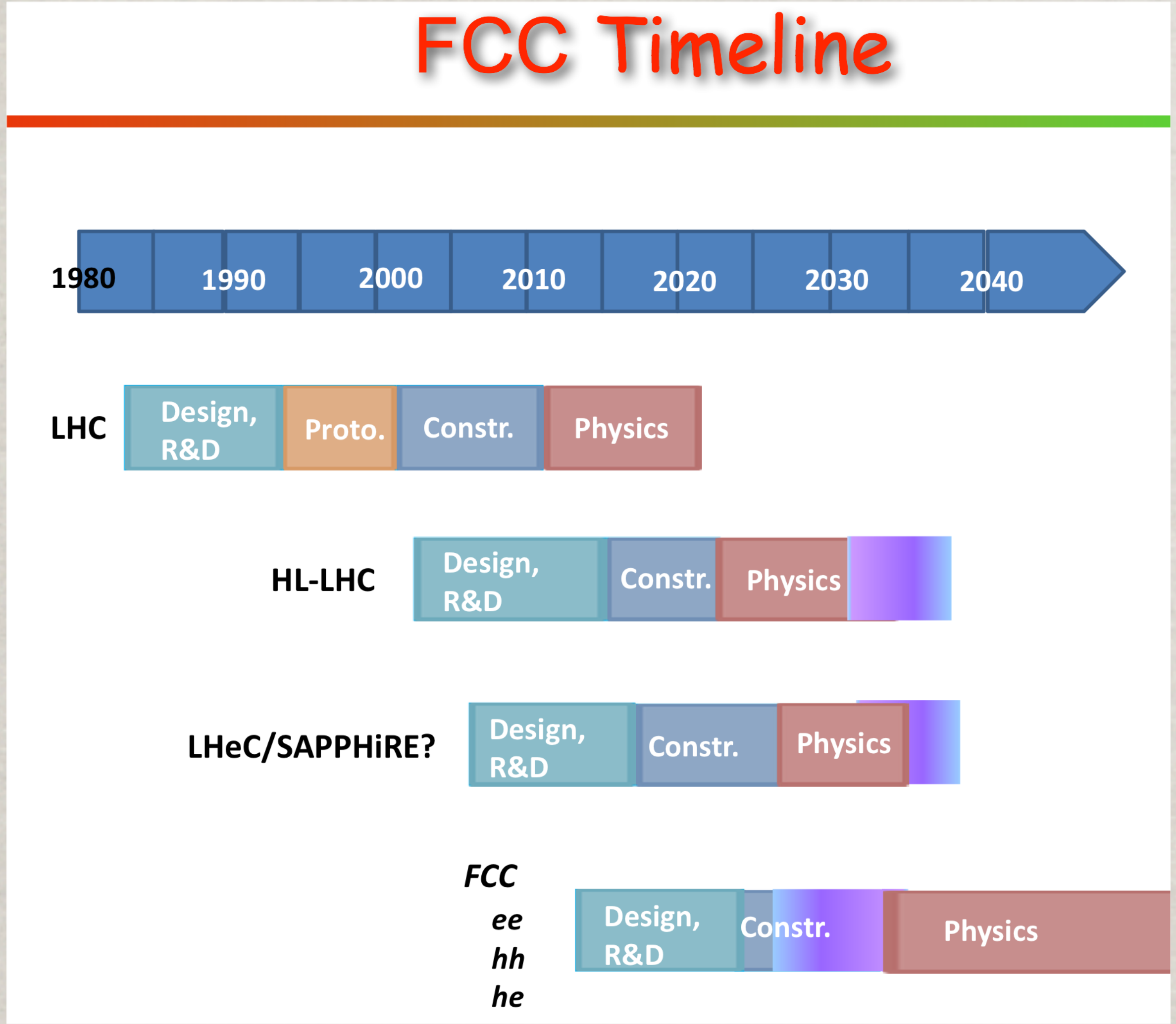
A factor of 20x to come!

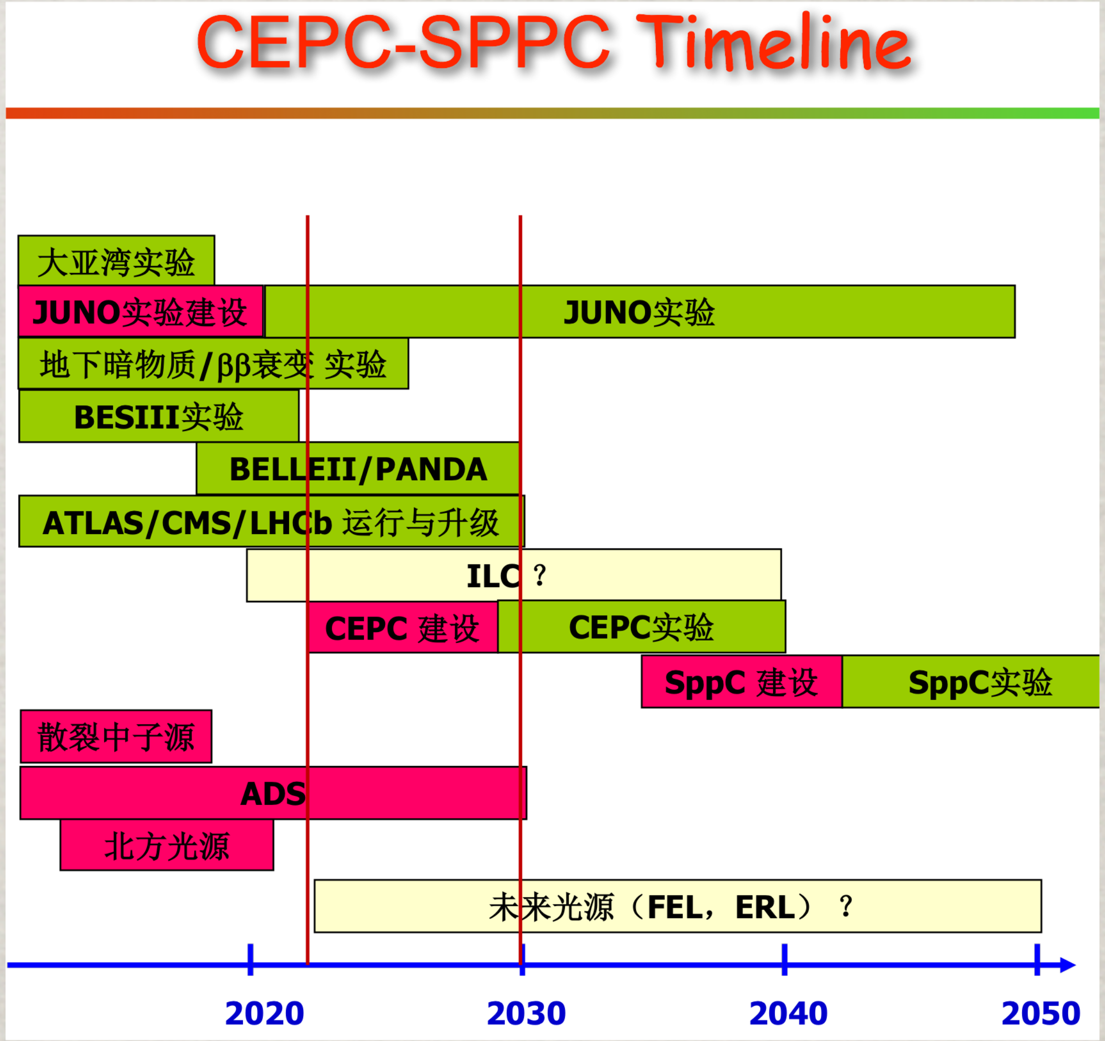
Levelled Luminosity $L = 5{\times}10^{34} cm^{-2} s^{-1}$

HE-LHC: The New Energy Frontier

physics goals:

- 2x LHC collision energy with FCC-hh magnet technology
- c.m. energy = 27 TeV ~ 14 TeV x 16 T/8.33T
- target luminosity ≥ 4 x HL-LHC (cross section $\propto 1/E^2$)



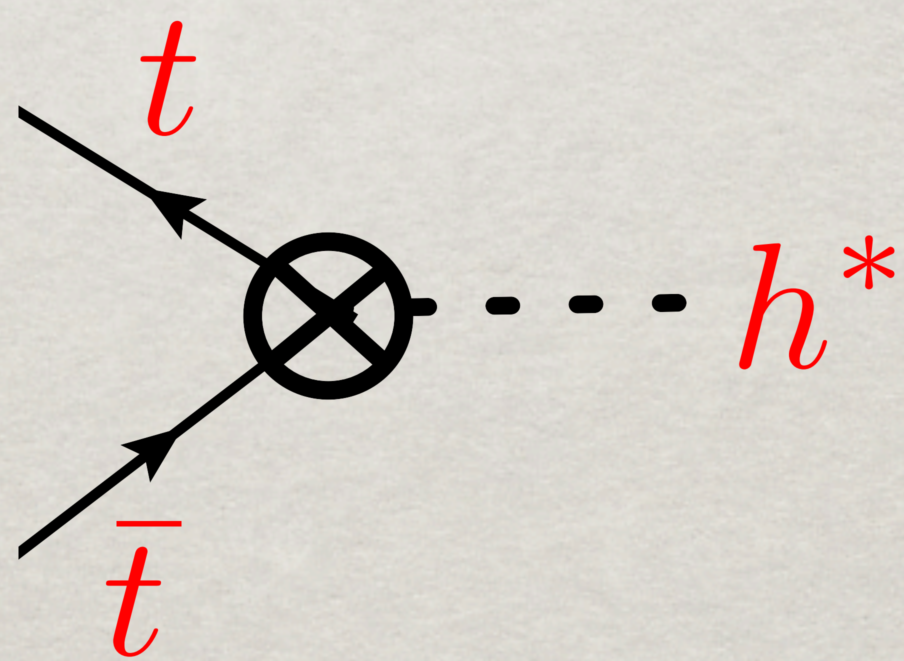


Great potential for Beyond BSM physics!

In absence of "Beyond the Standard Model" physics from the current searches at the LHC, we are forced to look for "Beyond BSM" physics!

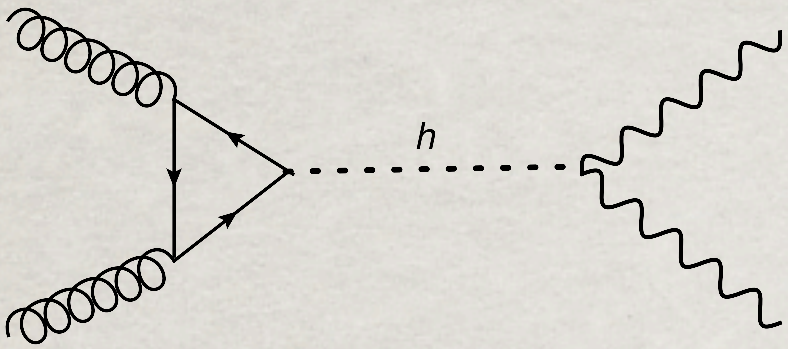
We propose to study the Higgs boson at high scales:

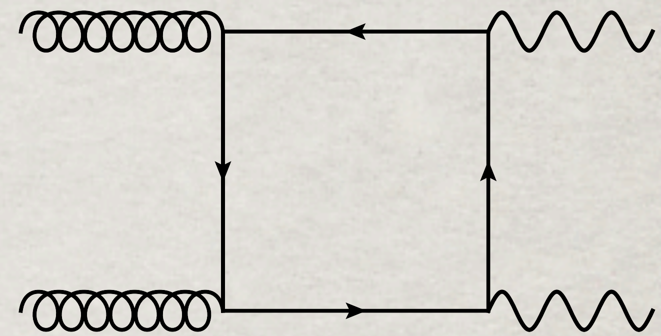
- Sensitive to new physics
- "Naturalness" is a UV problem.
- "Higgs portal" to a subtle sector.



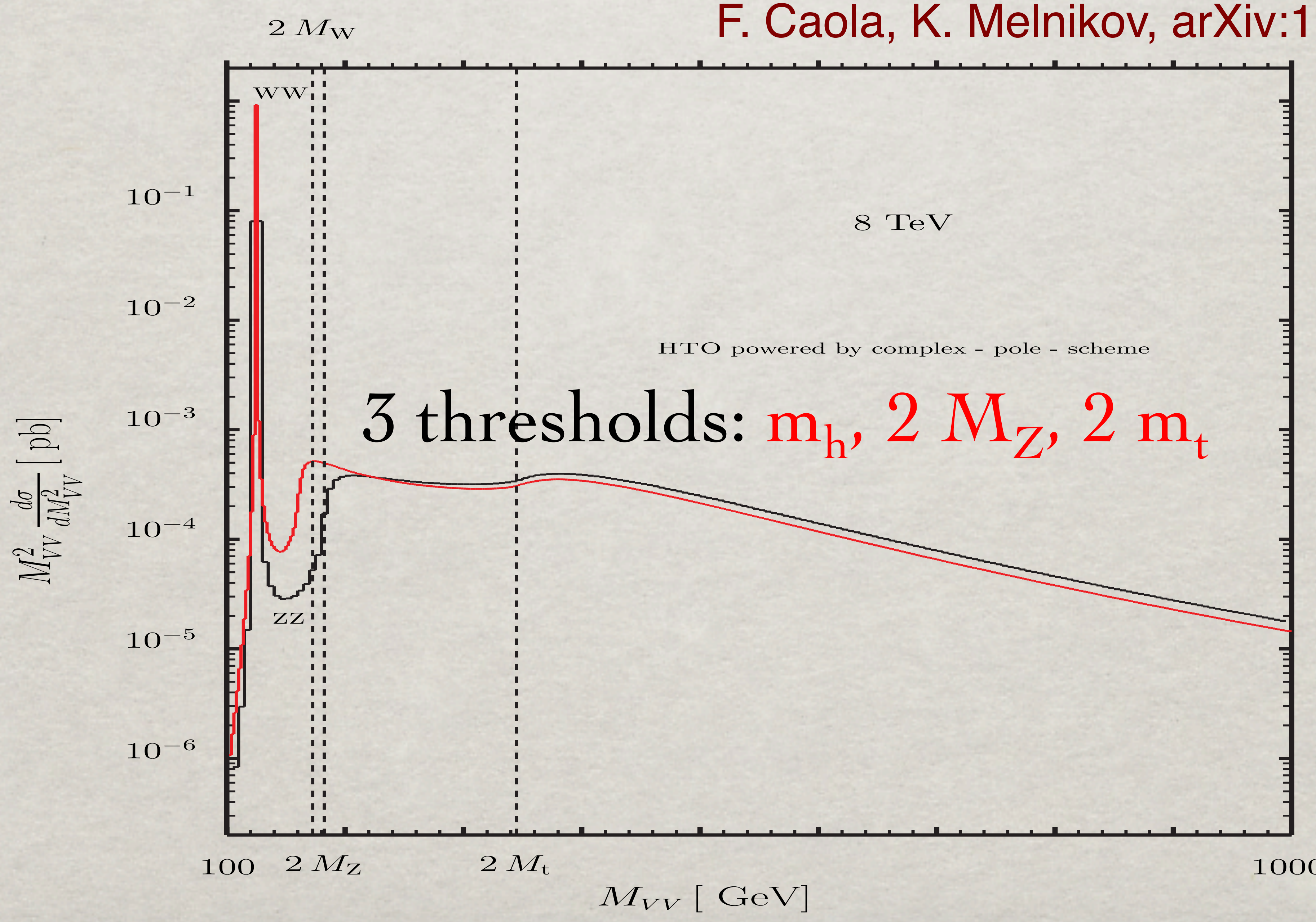
$$\sigma_{\rm on} \propto \frac{g_i^2(m_h^2)g_f^2(m_h^2)}{m_h\Gamma_h} \text{ and } \sigma_{\rm off} \propto \frac{g_i^2(Q^2)g_f^2(Q^2)}{Q^2}$$

gg → h* → WW, ZZ production:



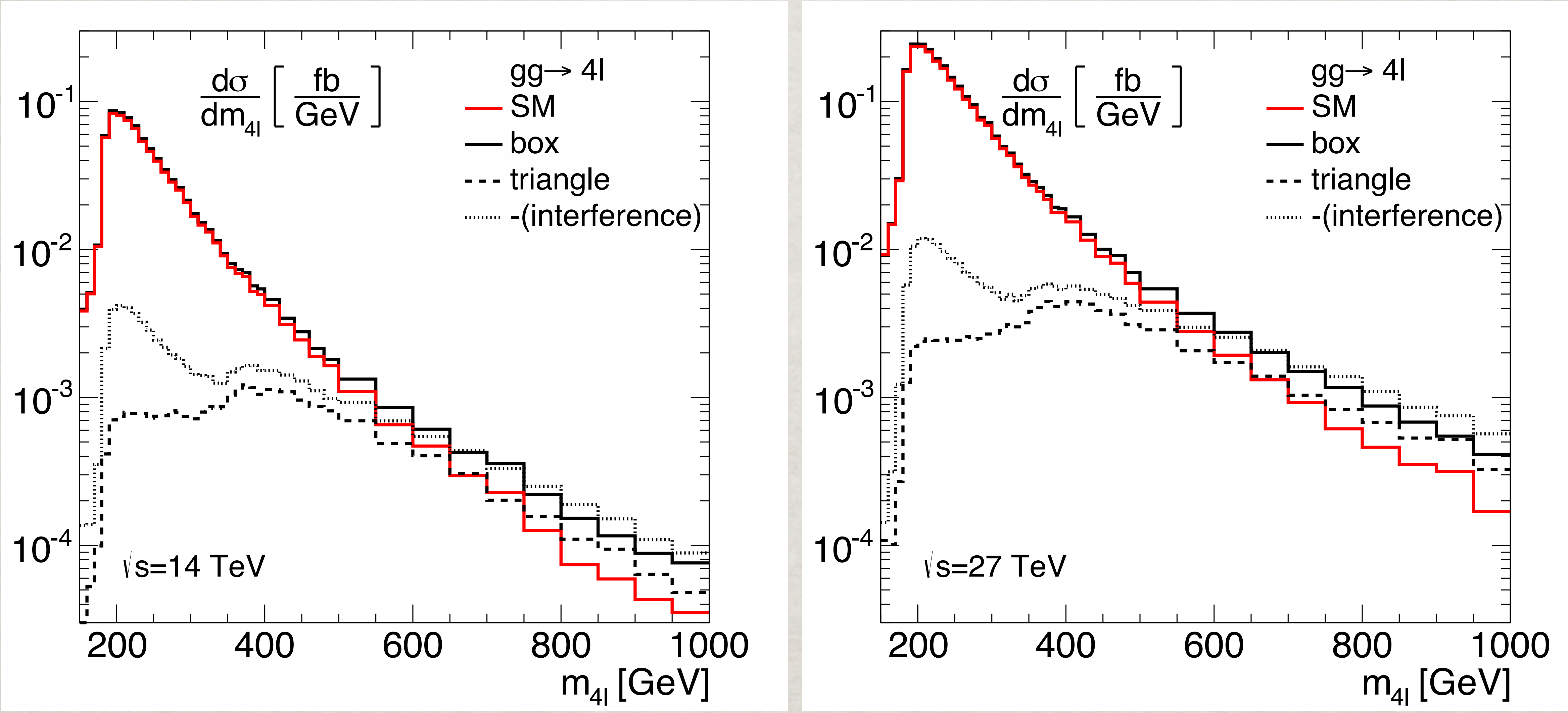


N. Kauer, G. Passarino, arXiv:1206.4803;
F. Caola, K. Melnikov, arXiv:1307.4935.



3 thresholds: m_h, 2 M_Z, 2 m_t

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

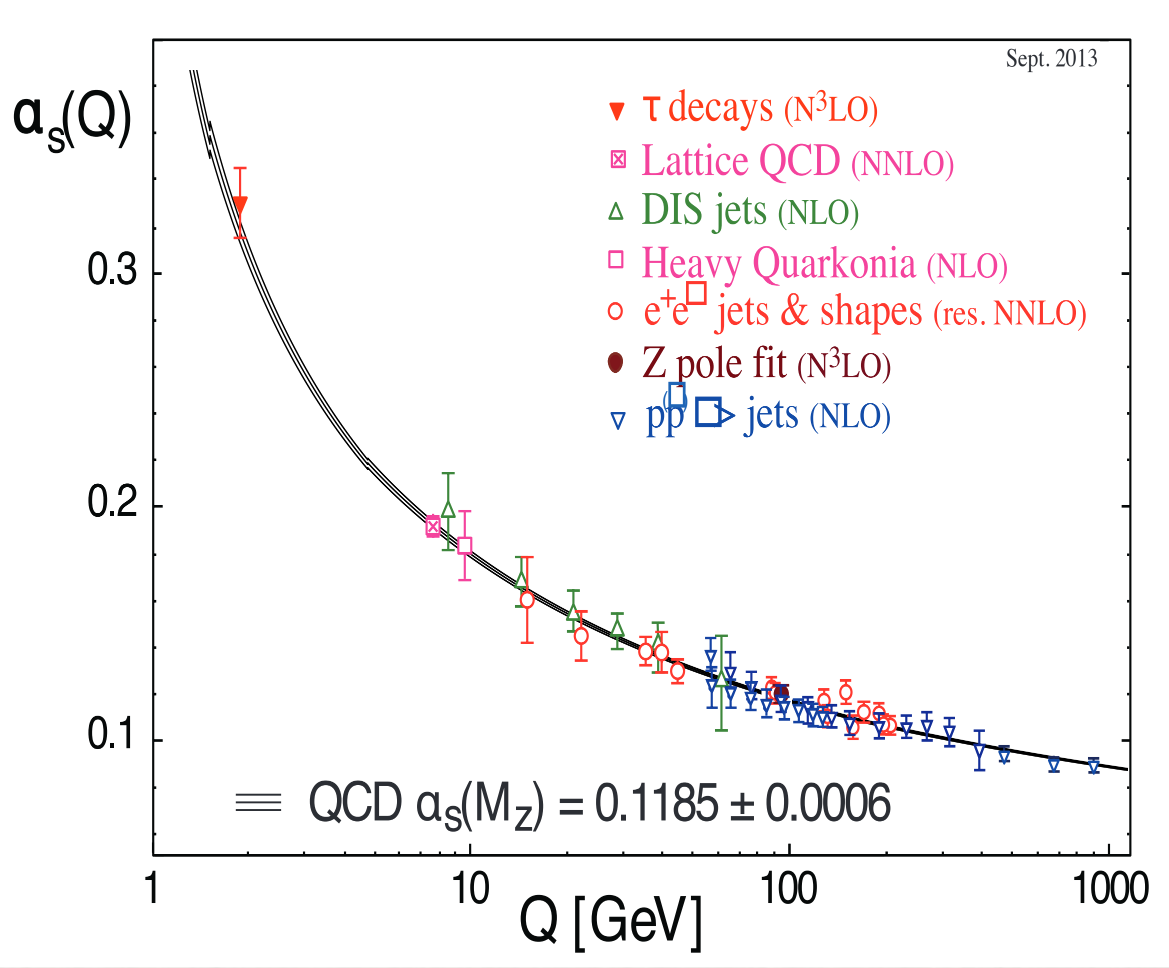
$$p_{T\ell} > 10 \quad \text{GeV} \,, \qquad |\eta_\ell| < 2.5 \,,$$
$$m_{4\ell} > 150 \quad \text{GeV} \,, \qquad m_{\ell\ell'} > 4 \quad \text{GeV} \,,$$
$$m_{\ell\ell}^{(1)} = [40, 120] \quad \text{GeV} \,, \qquad m_{\ell\ell}^{(2)} = [12, 120] \quad \text{GeV}$$

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.

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



- EW parameters verified: $\alpha_{\rm QED}(Z),\ \sin^2\theta_W$
- Bottom quark mass (y_b) evidence at M_Z, m_h.

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:

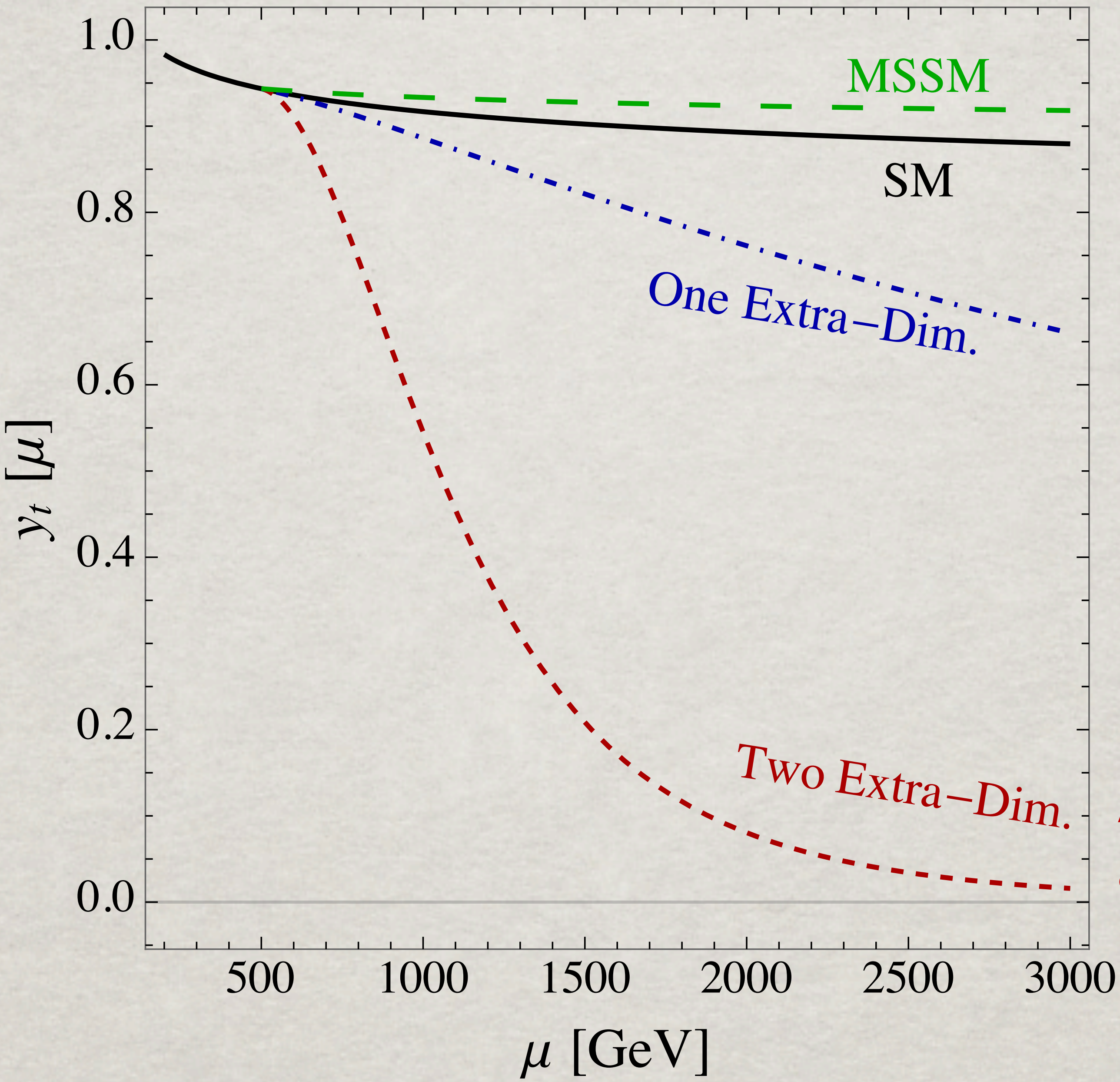
$$\frac{dy_t}{dt} = \beta_{y_t}^{\rm SM} + \frac{y_t}{16\pi^2} 2(S(t)-1)\left(\frac{3}{2}y_t^2 - 8g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{20}g_1^2\right), \qquad \text{5D},$$

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

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

→ "volume", power-law running!

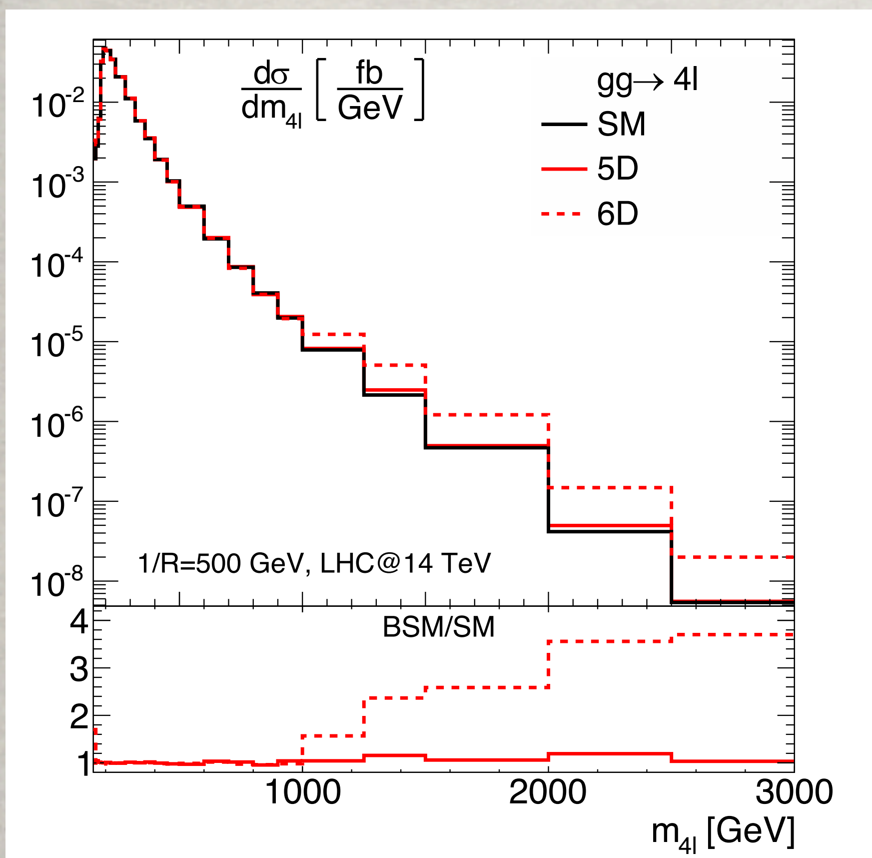
Top quark Yukawa coupling: RGE

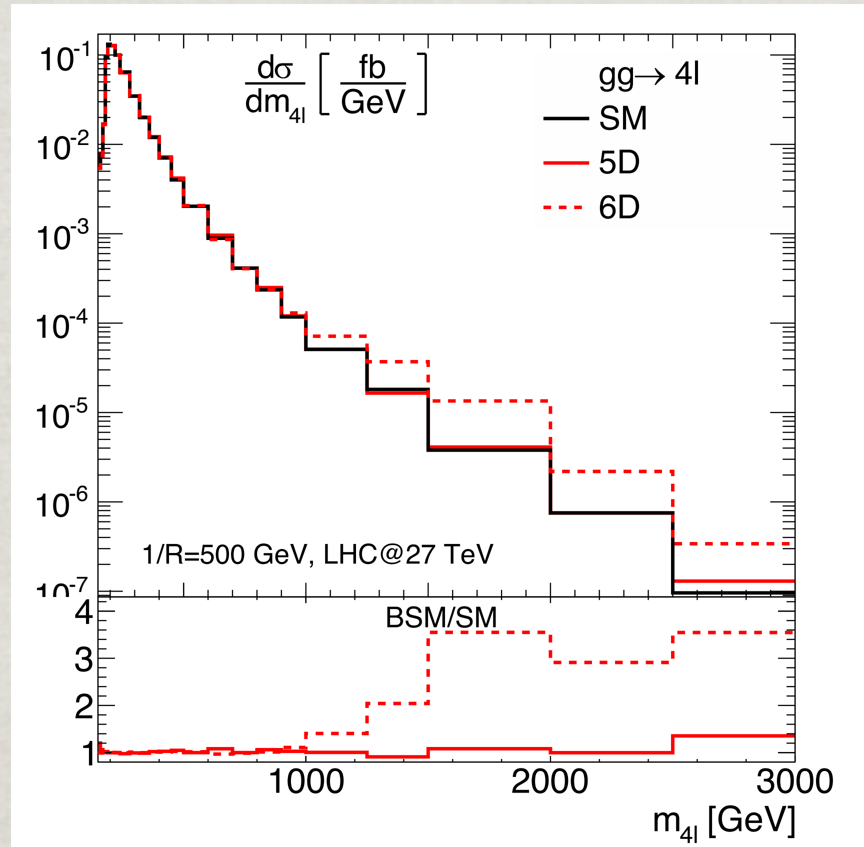


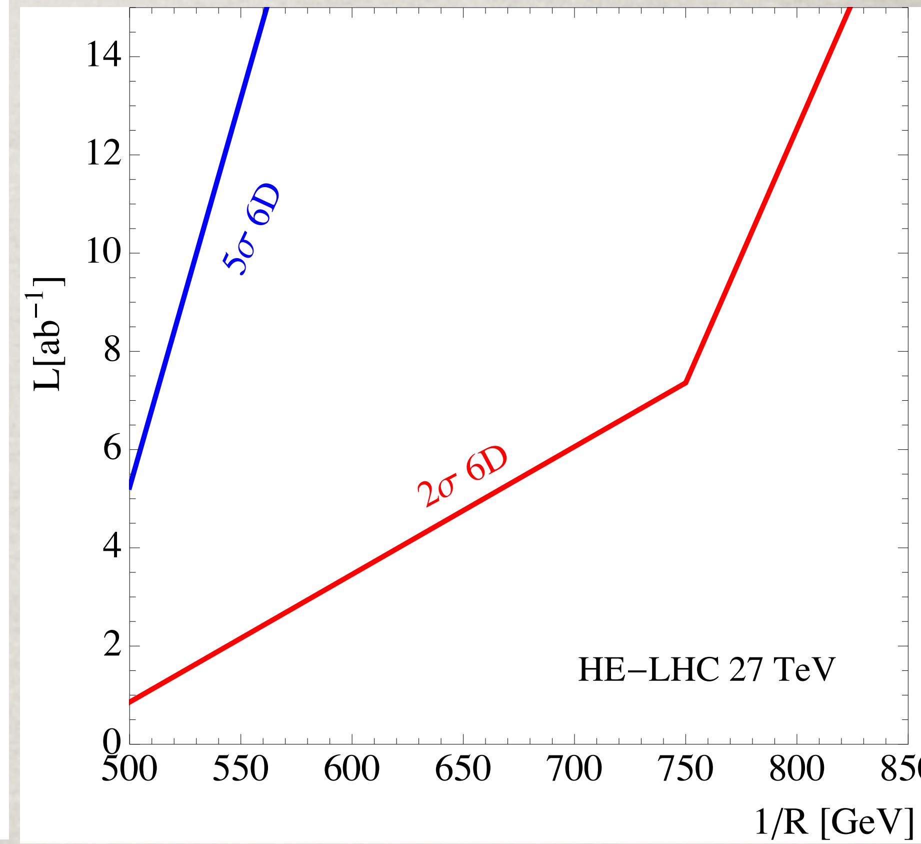
A.S. Cornell et al., arXiv:1209.6239.

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

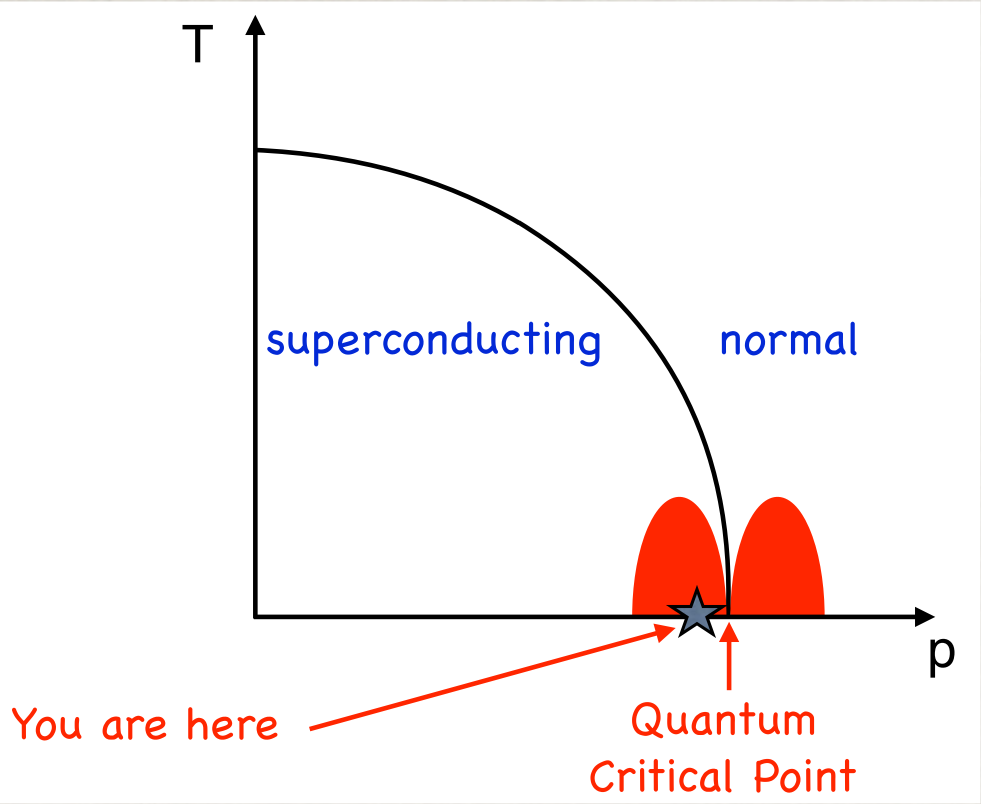
- **5D signal rather weak: Little sensitivity.**
- **HL-LHC: Insensitive.**
- **HE-LHC @ 6D: a factor of 3-4 increase.**

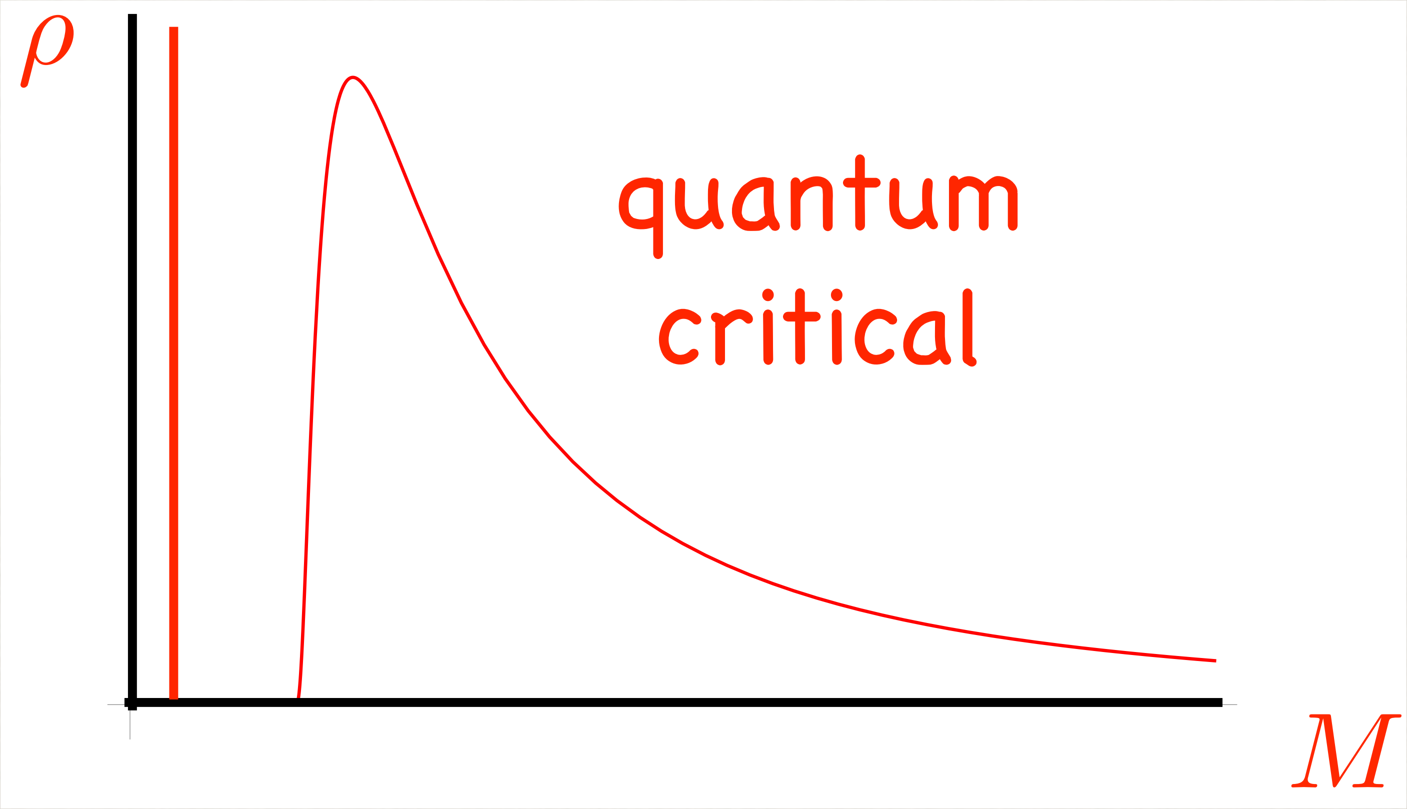
Reach 1/R ~ 0.8 TeV @ 2σ; 0.6 TeV @ 5σ

Case Study 2: 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 strongly coupled conformal field theory (CFT).





J. Terning's Aspen talk (2016)

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** :

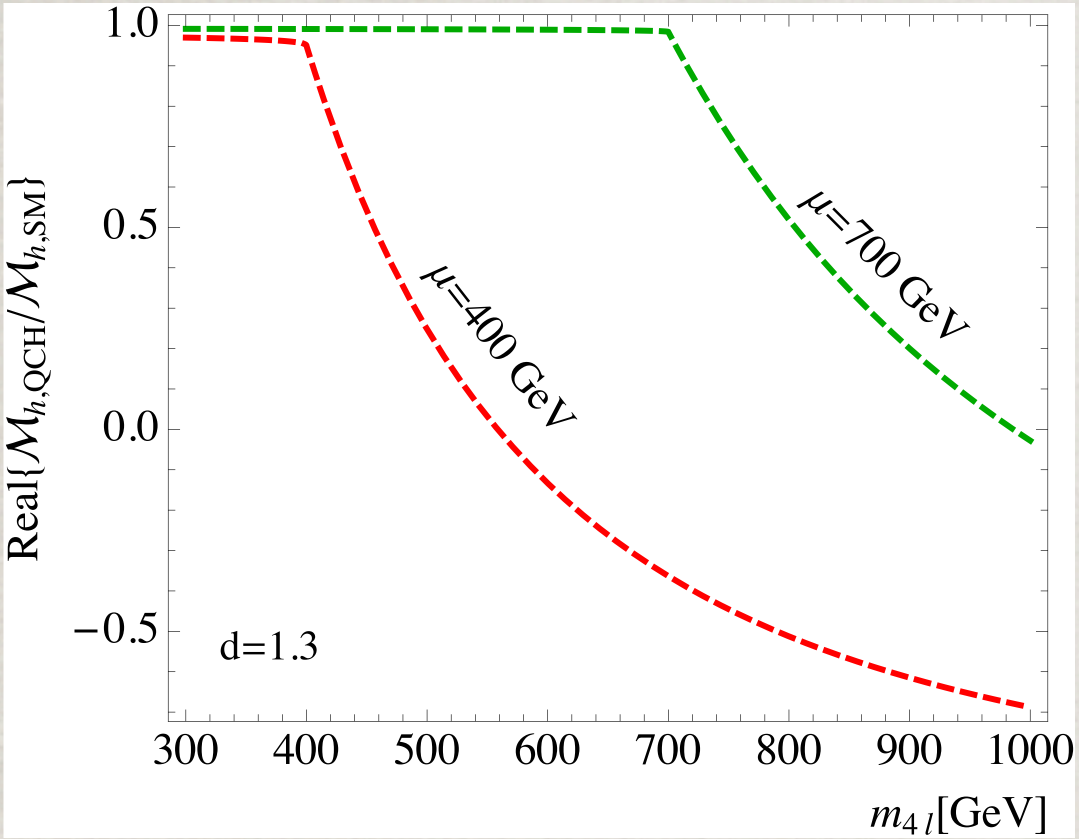
$$\delta m_h^{4-2\Delta} = \frac{3\lambda_t^2}{8\pi^2}\Lambda^{4-2\Delta}$$

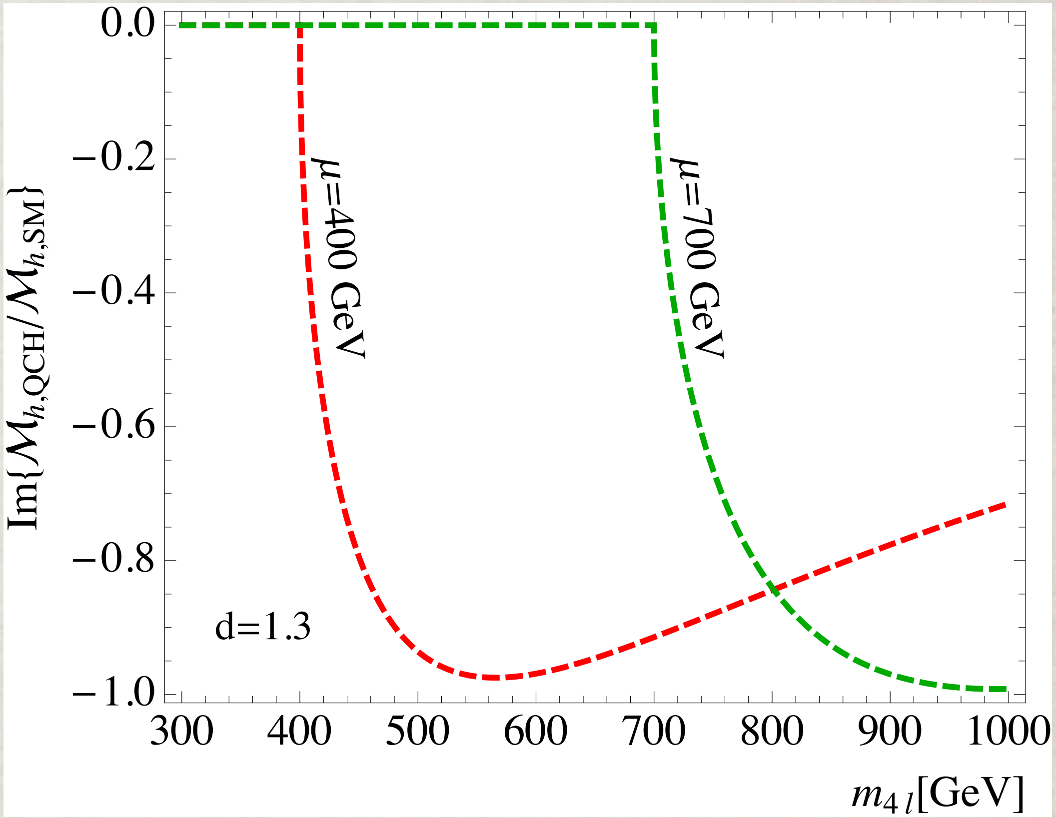
Spectral function (un-particle/un-Higgs):

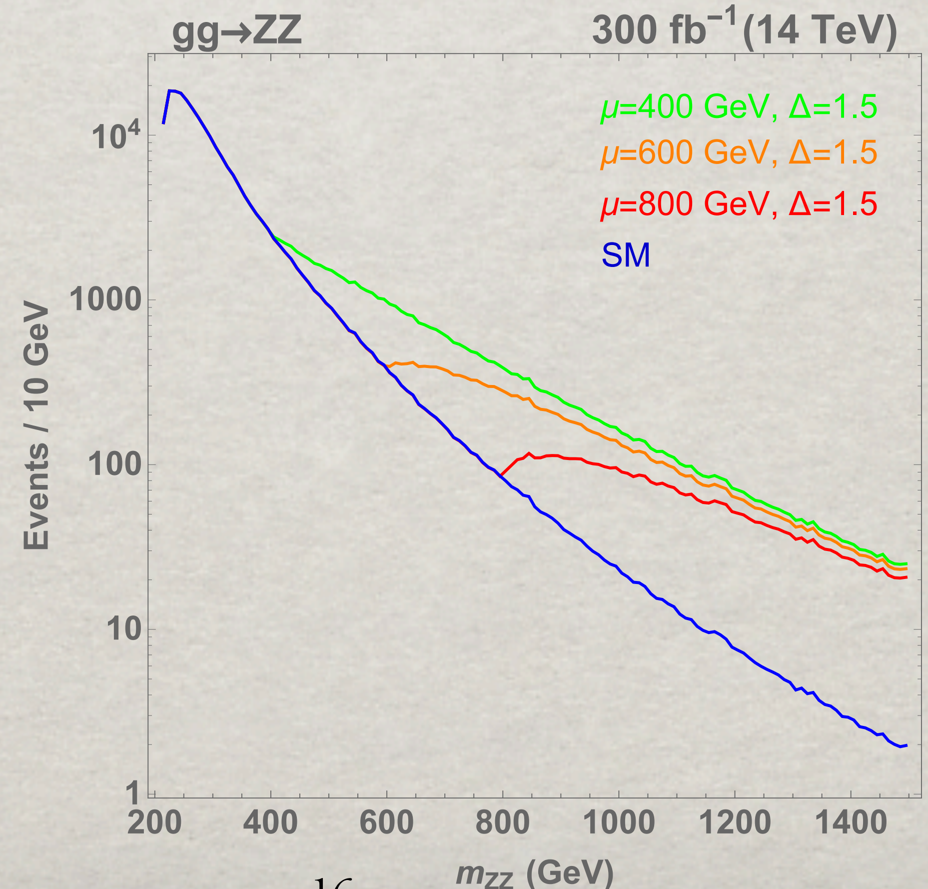
$$g_{ZZh} \sim (g^{\mu\nu} p_1 \cdot p_2 - p_1^\mu p_2^\nu)\Gamma_{ZZh}, \quad \delta\lambda_t = \sqrt{2-\Delta}\left(\frac{\Lambda}{\mu}\right)^{\Delta-1},$$

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

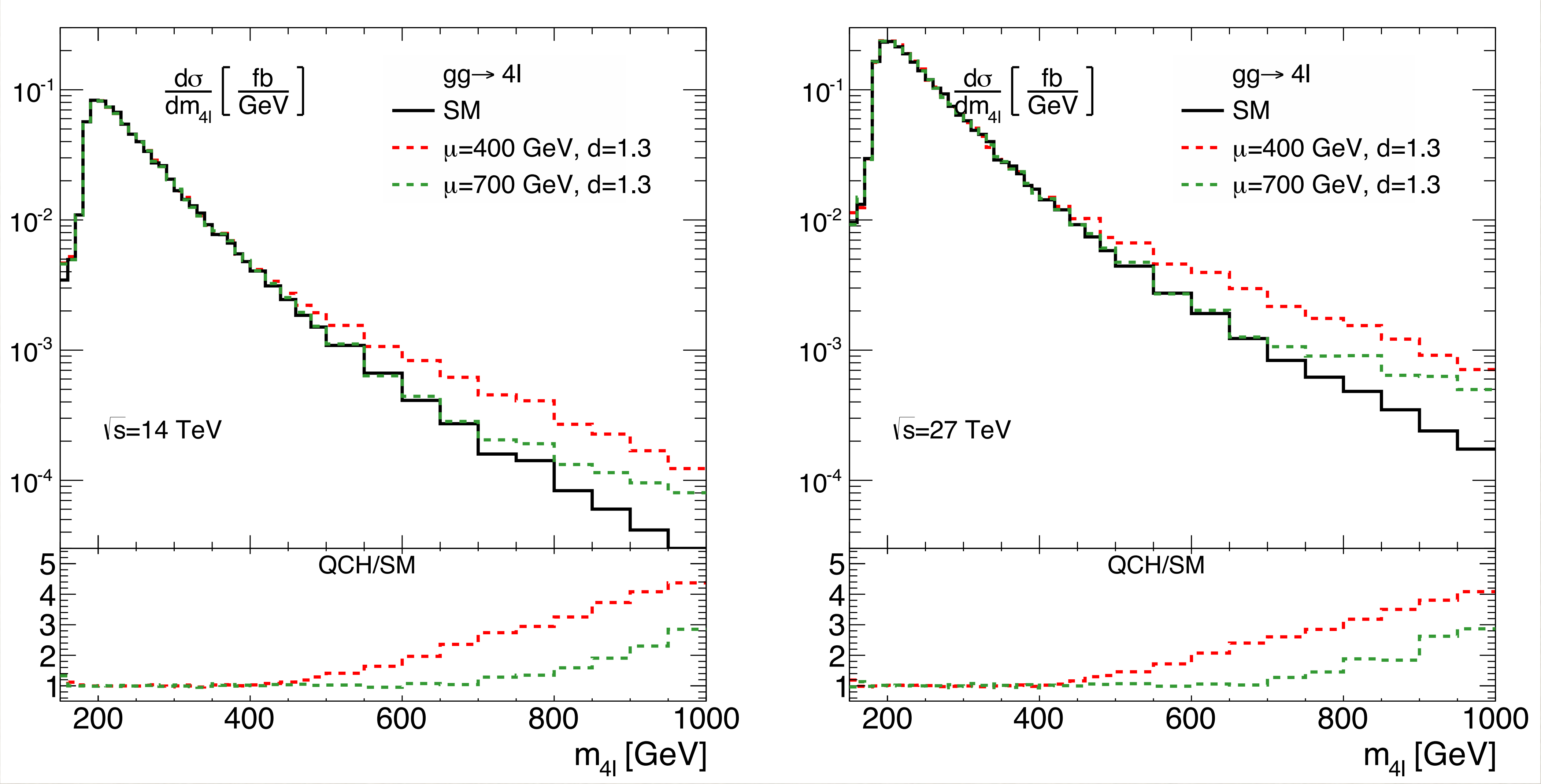
Threshold effects, distributions: QCH







Threshold effects, distributions: QCH



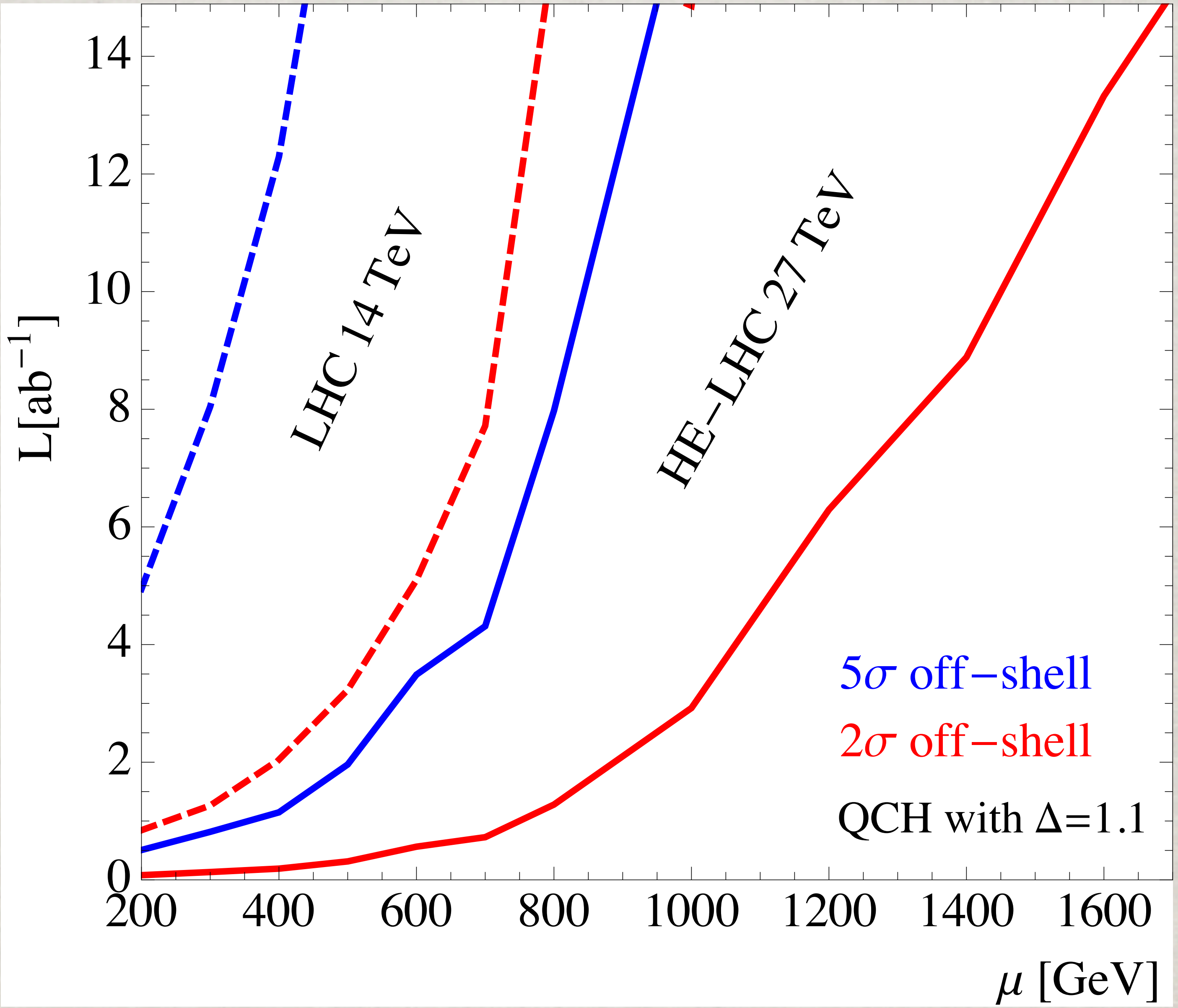
Branch-cut suppression (Csaki et al.)

→ 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

Case Study 3:
Strongly coupled

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

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

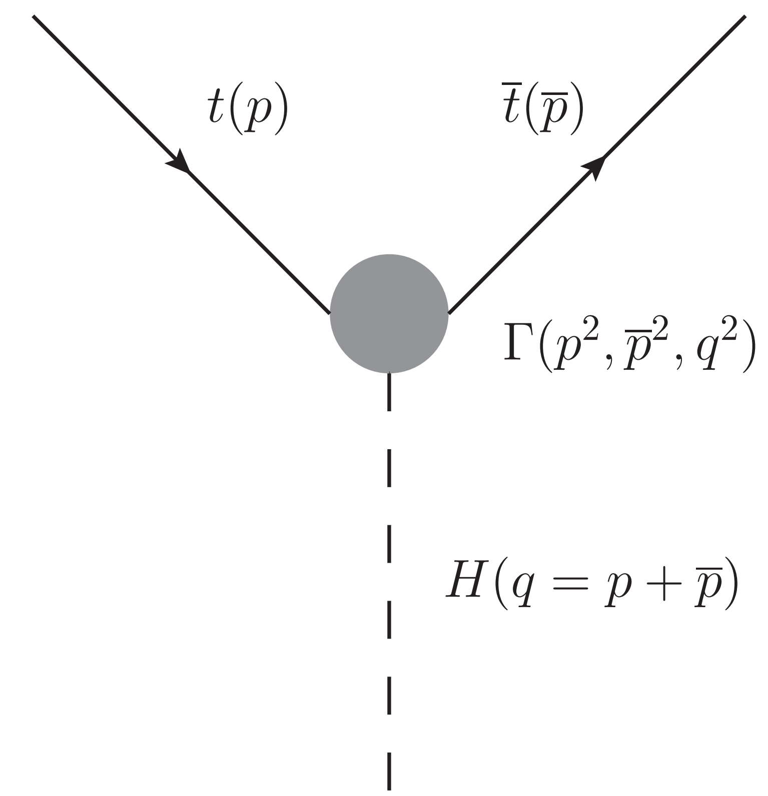
The deviation from the point-like interaction:

- 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:

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

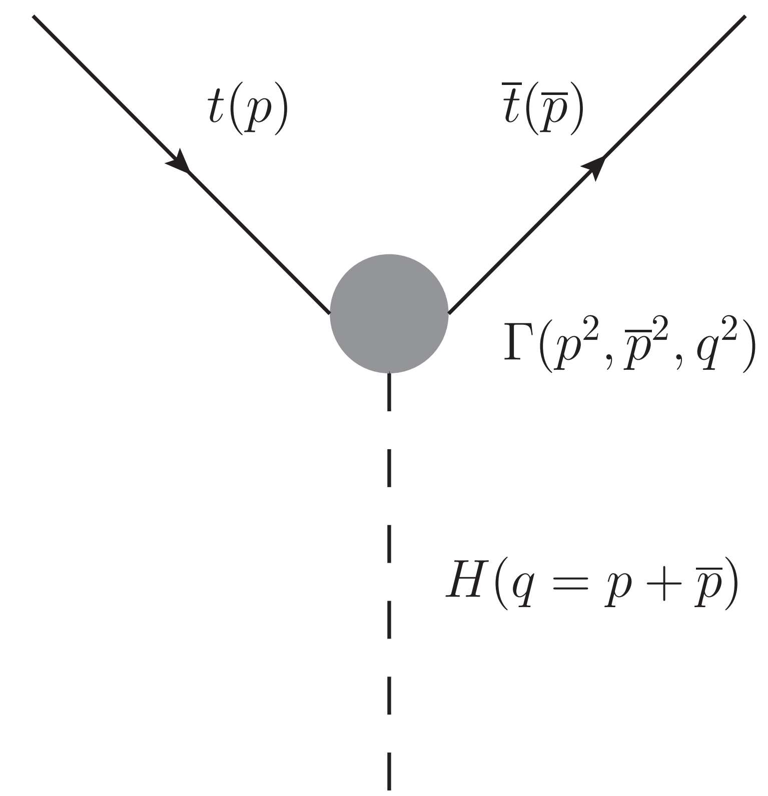


Current 95%CL bound
from the LHC Higgs signal:

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

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:

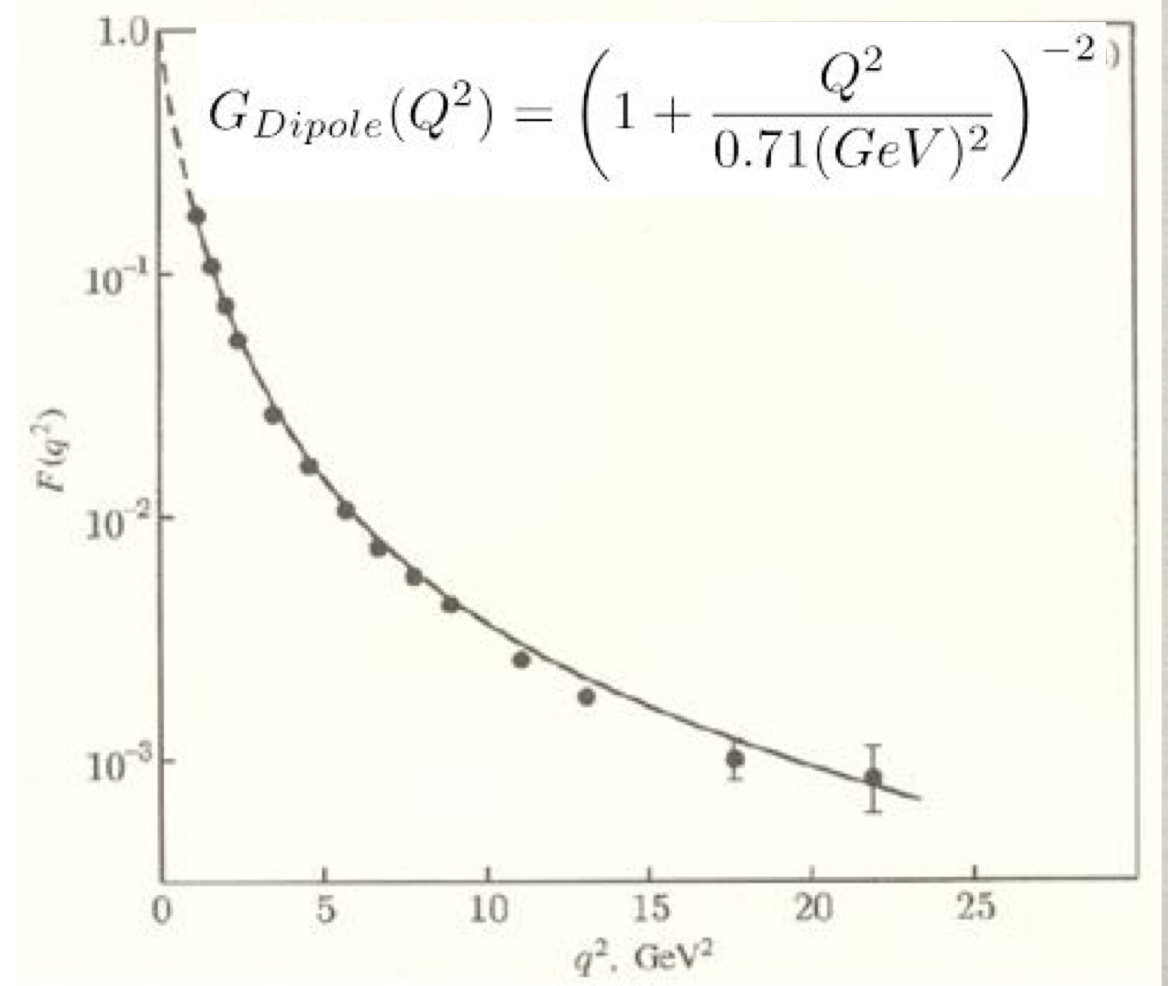
$$\left|\Gamma\left(m_h^2/\Lambda^2\right)^2 - 1\right| < 0.1$$

Nucleon form factor:

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

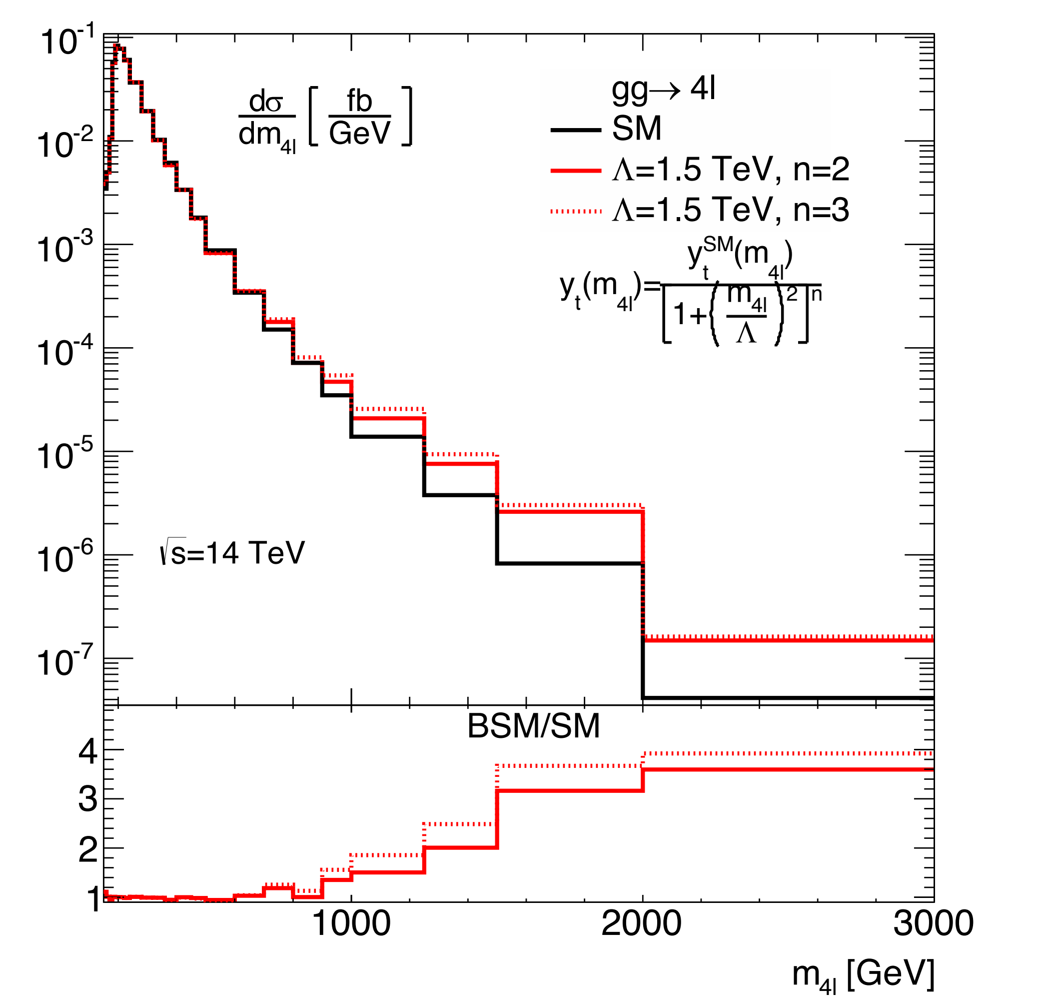
n=2 → "Dipole FF"

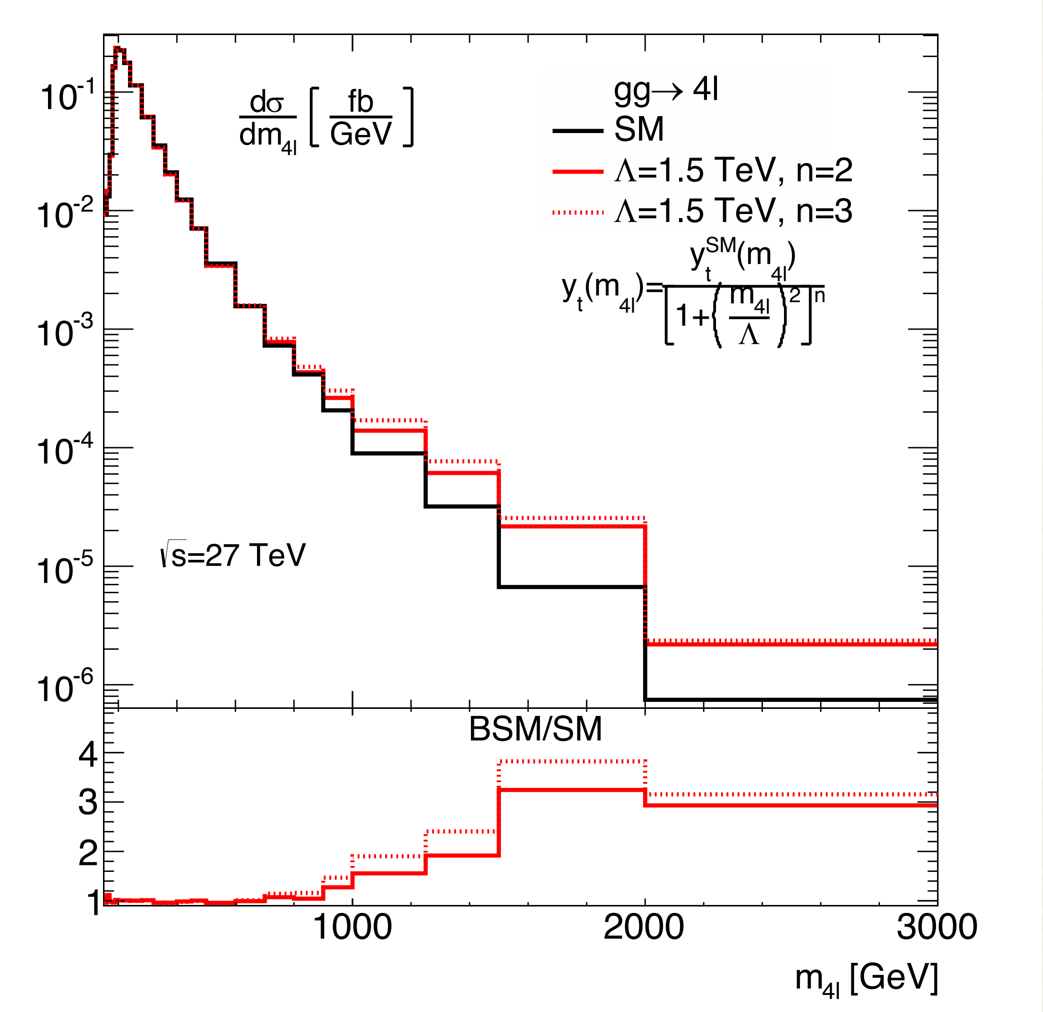
Leading to a suppressed ttH → Enhanced ZZ signal!



LHC distribution: top-Higgs Form Factor

(similar effects for n=2,3)





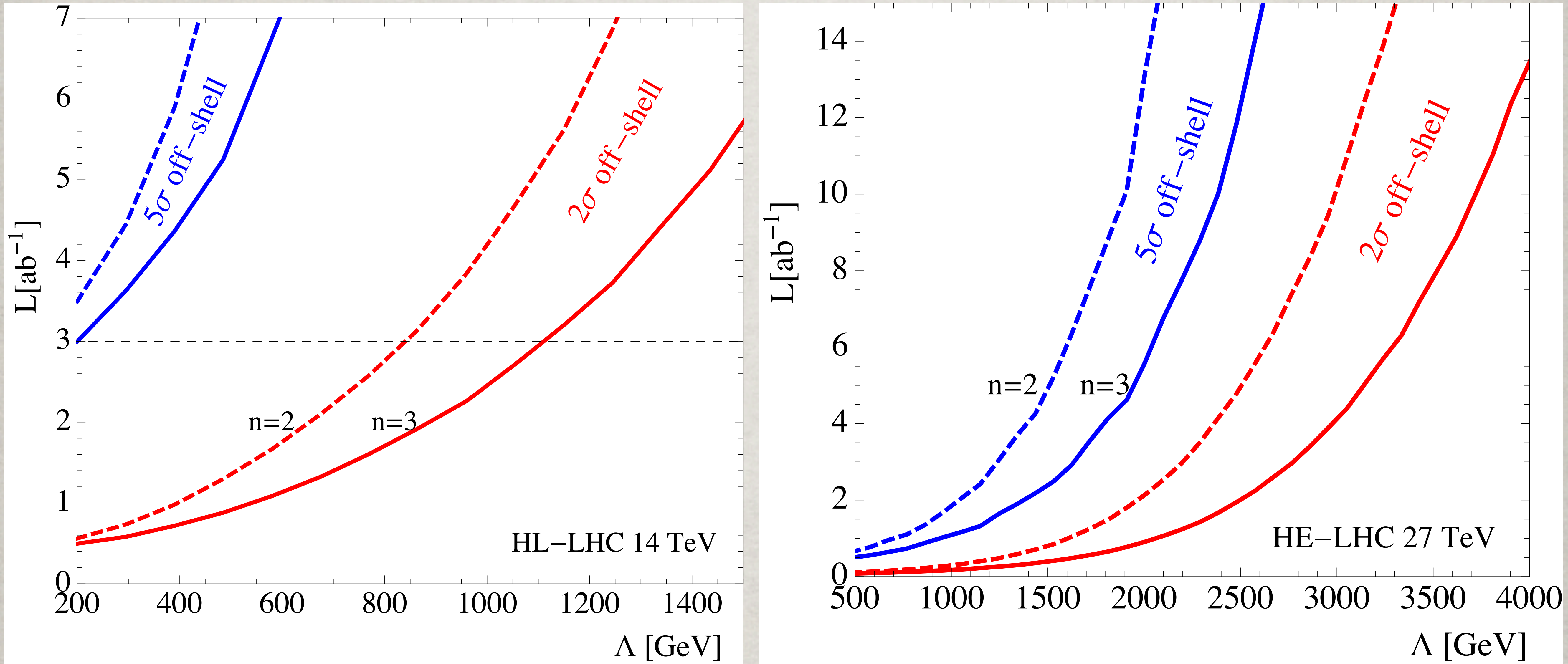
Form Factor suppression

→ 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 4:
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:

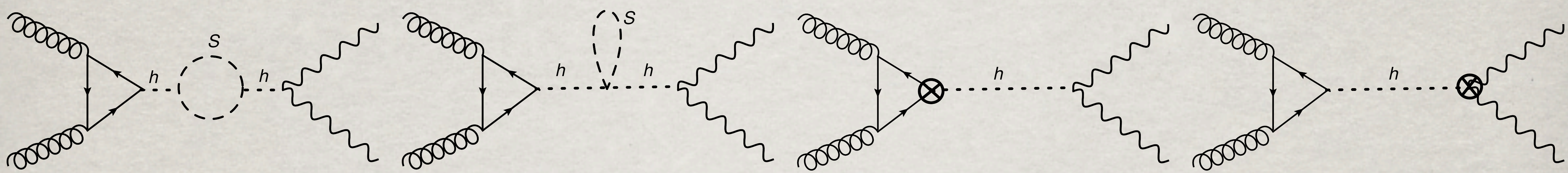
$$\delta M_h^2 = \frac{1}{16\pi^2}(\lambda_S - 2N_c y_t^2)\Lambda^2 + \frac{6N_c y_t^2}{16\pi^2} m_t^2 \log\frac{\Lambda^2}{m_t^2} - \frac{1}{16\pi^2}\left(\lambda_S m_S^2 + \lambda_S^2 v^2\right)\log\frac{\Lambda^2}{m_S^2},$$

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

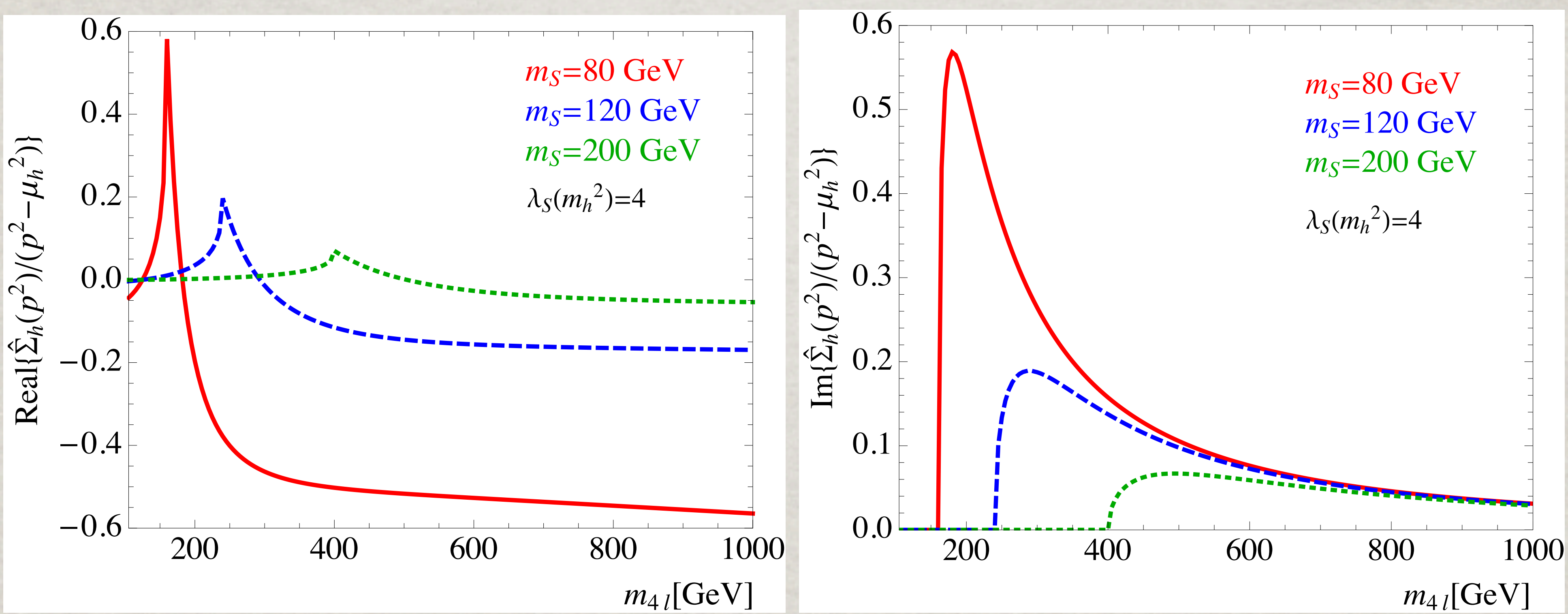
Will alleviate the "Little hierarchy" problem.

Twin Higgs; Neutral naturalness;…

When crossing the threshold → branch-cut contribution!



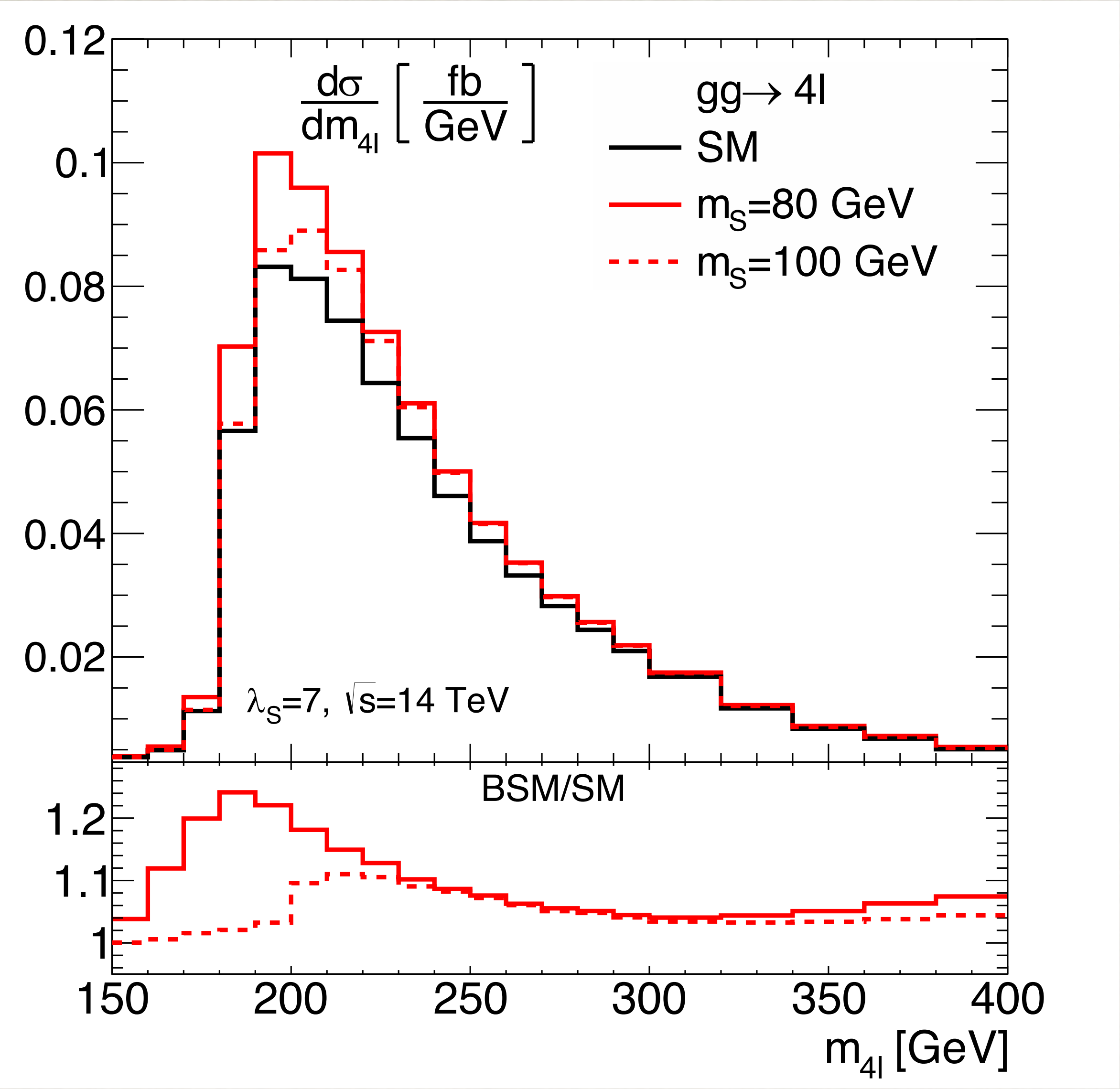
D. Goncalves, TH, S. Mukhopadhyay, PRL: arXiv:1710.0249.

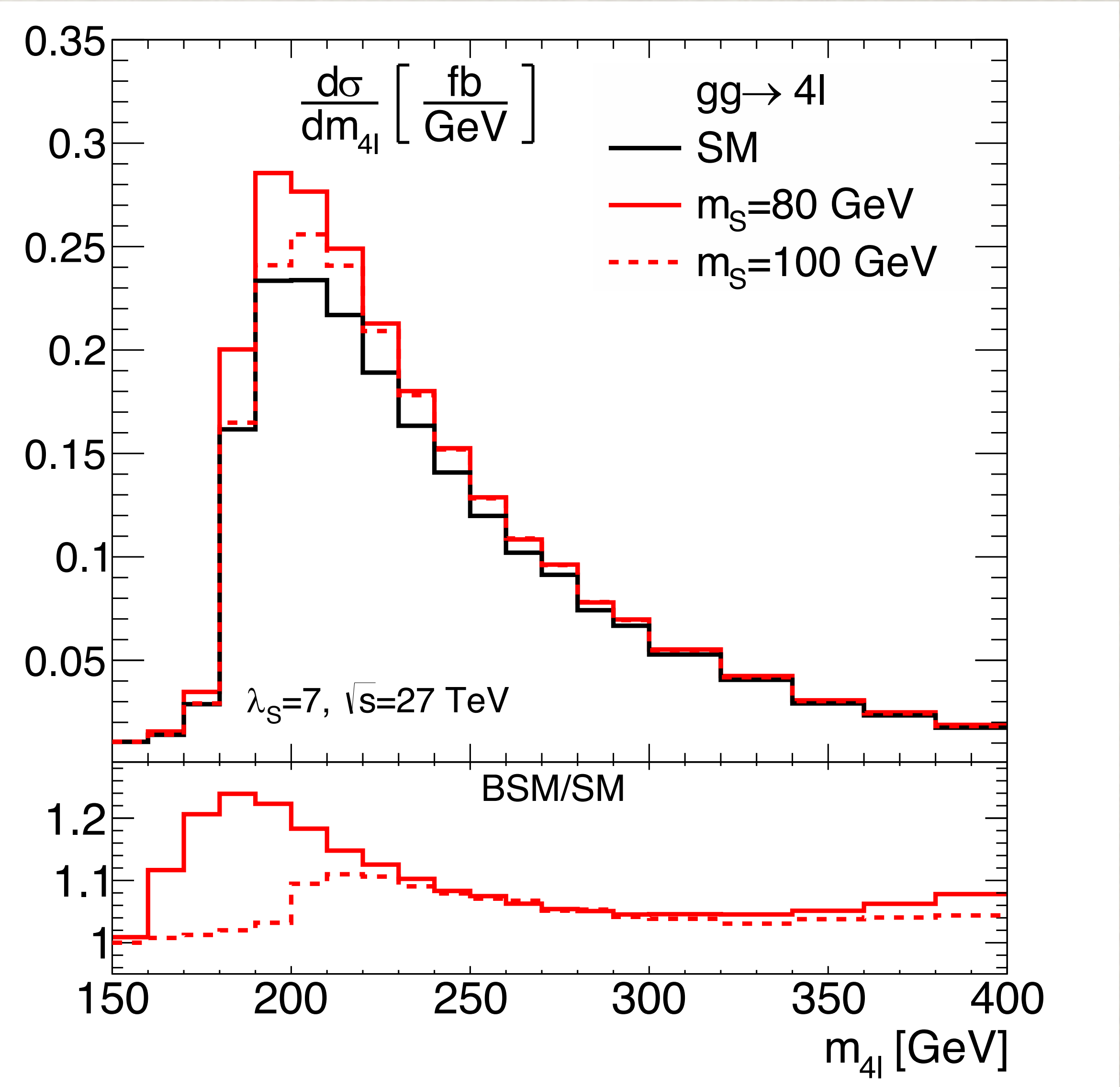


S-matrix singularities:

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

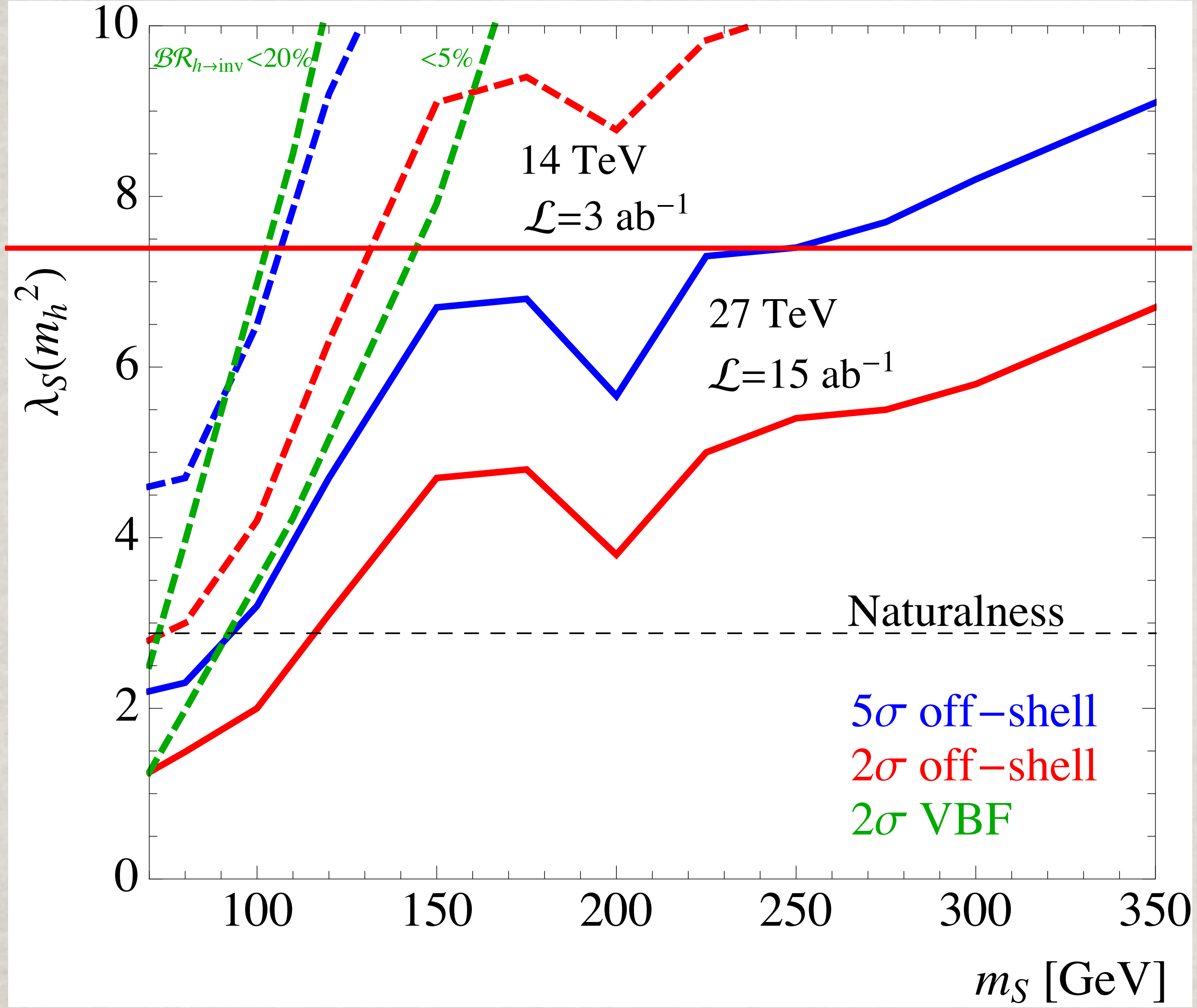
LHC Sensitivity: Higgs portal via S





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

LHC Sensitivity: Higgs portal via S



Invisible Higgs in VBF:

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

IF taking λs for "natural values":

HL-LHC: m_s ~ 70 GeV @ 2σ.

HE-LHC: m_s ~ 120 GeV @ 2σ; 100 GeV @ 5σ.

Summary:

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

In the absence of deviation from 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 → small effects
- Extra dimensions → Power-law running: significant change
- New states coming into Higgs propagation:
  scalar singlets; a continuum spectrum
- Strong dynamics/composite Higgs: Form Factor for tth.

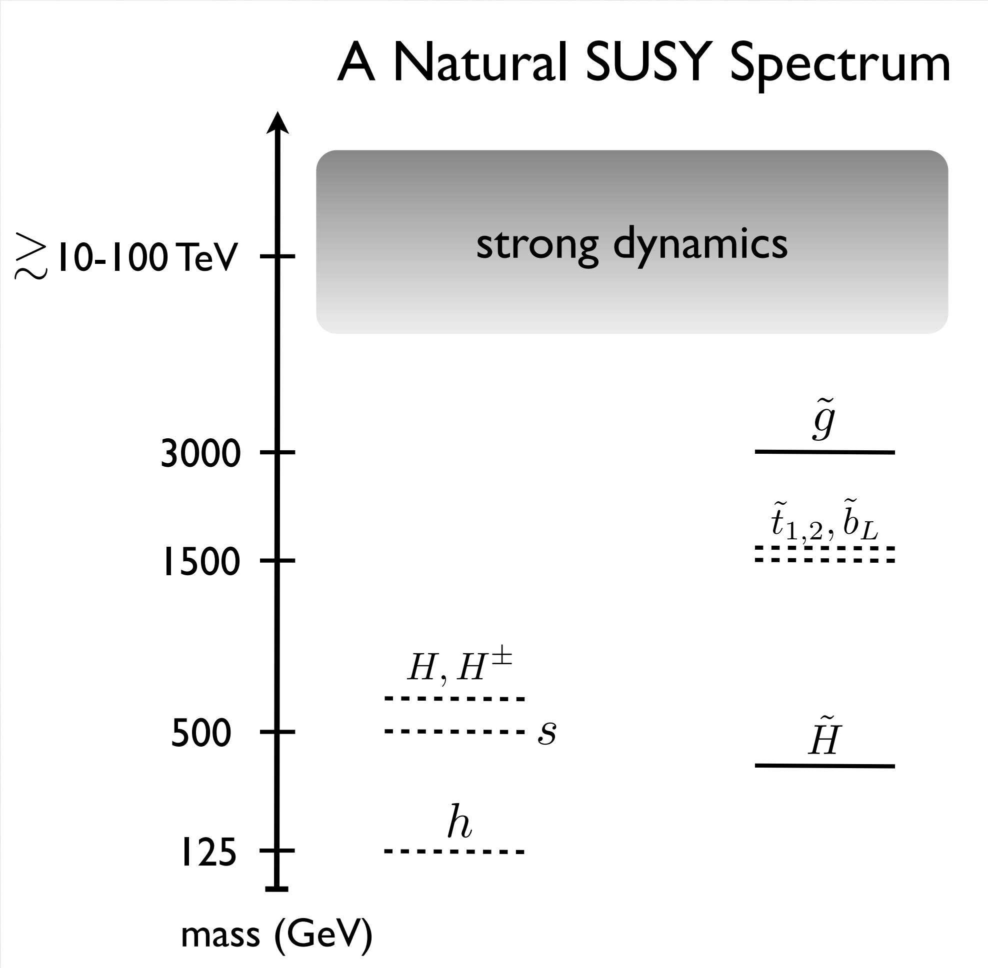
Modifications may be observable at the LHC upgrades
2$\boldsymbol{\sigma}$ -- 5$\boldsymbol{\sigma}$ level sensitivity.

The Searches Will Continue ...

- "Natural SUSY":

Relevant to the Higgs and the "Most Wanted":

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



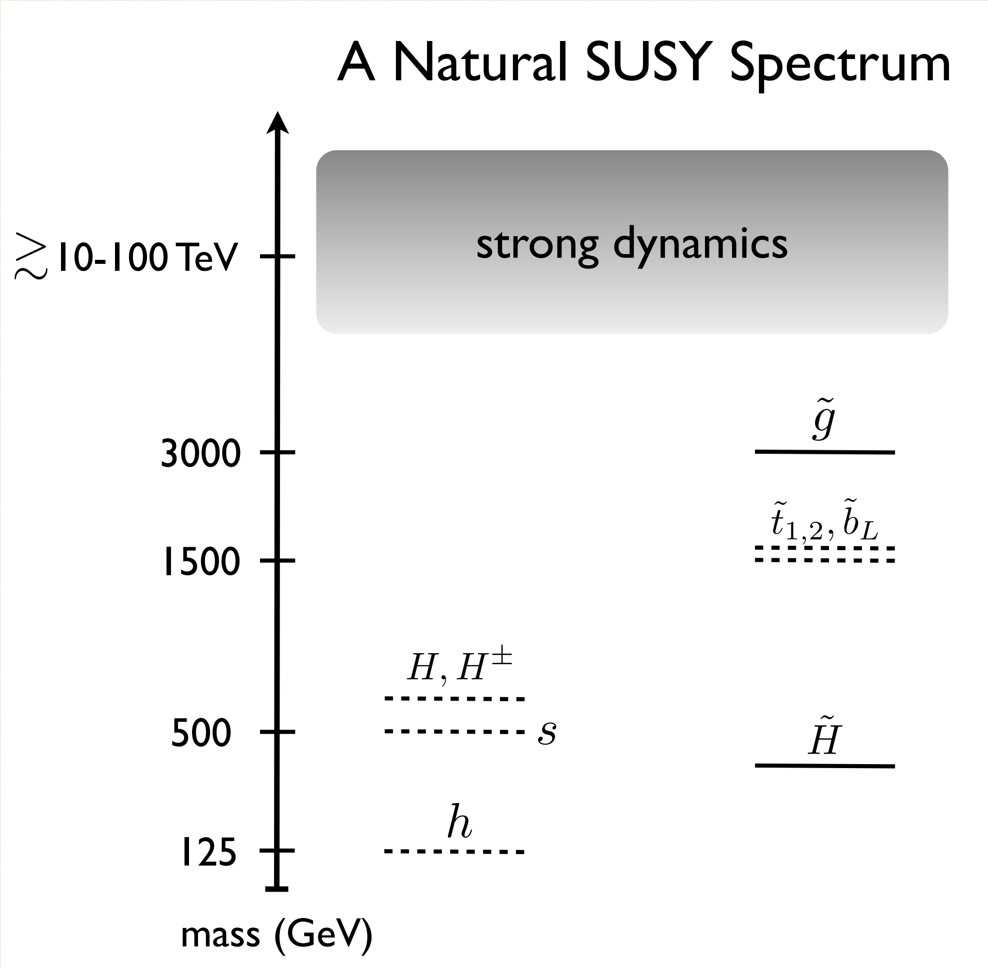
Current LHC bounds:

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

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

THE SEARCHES WILL CONTINUE ...

- "Natural SUSY":



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

Current LHC bounds:

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

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

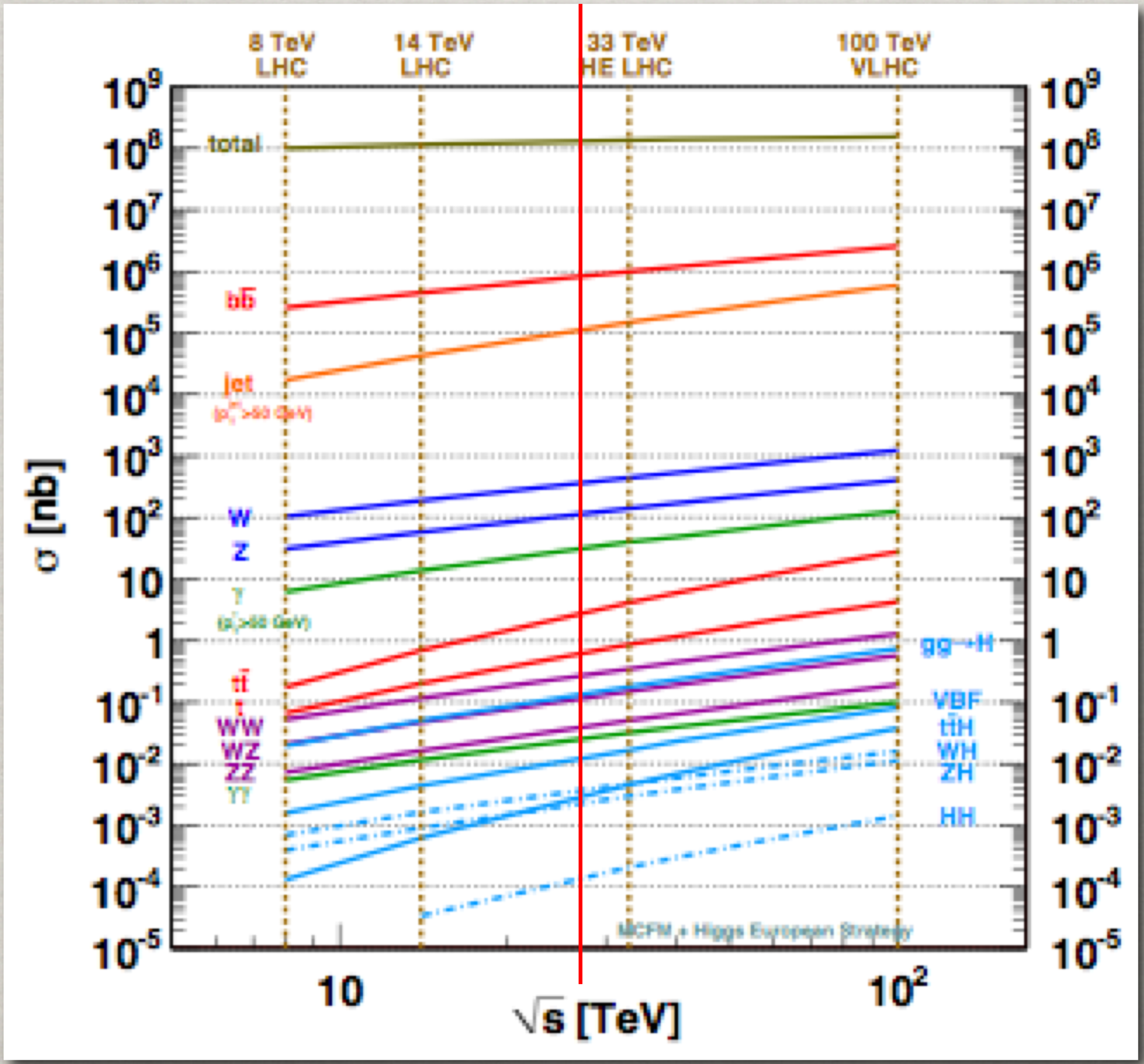
- New strong dynamics, "Compositeness":

The top-quark partner T',

Current ATLAS limit:

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

HL-LHC / HE-LHC:



8 TeV
LHC
14 TeV
LHC
33 TeV
HE LHC
100 TeV
VLHC
total
$b\bar{b}$
jet
W
Z
γ
$t\bar{t}$
WW
WZ
ZZ
γγ
gg→H
VBF
$t\bar{t}H$
WH
ZH
HH
MCFM + Higgs European Strategy
σ [nb]
√s [TeV]
10
10^2