Higgs Physics @ High Scales

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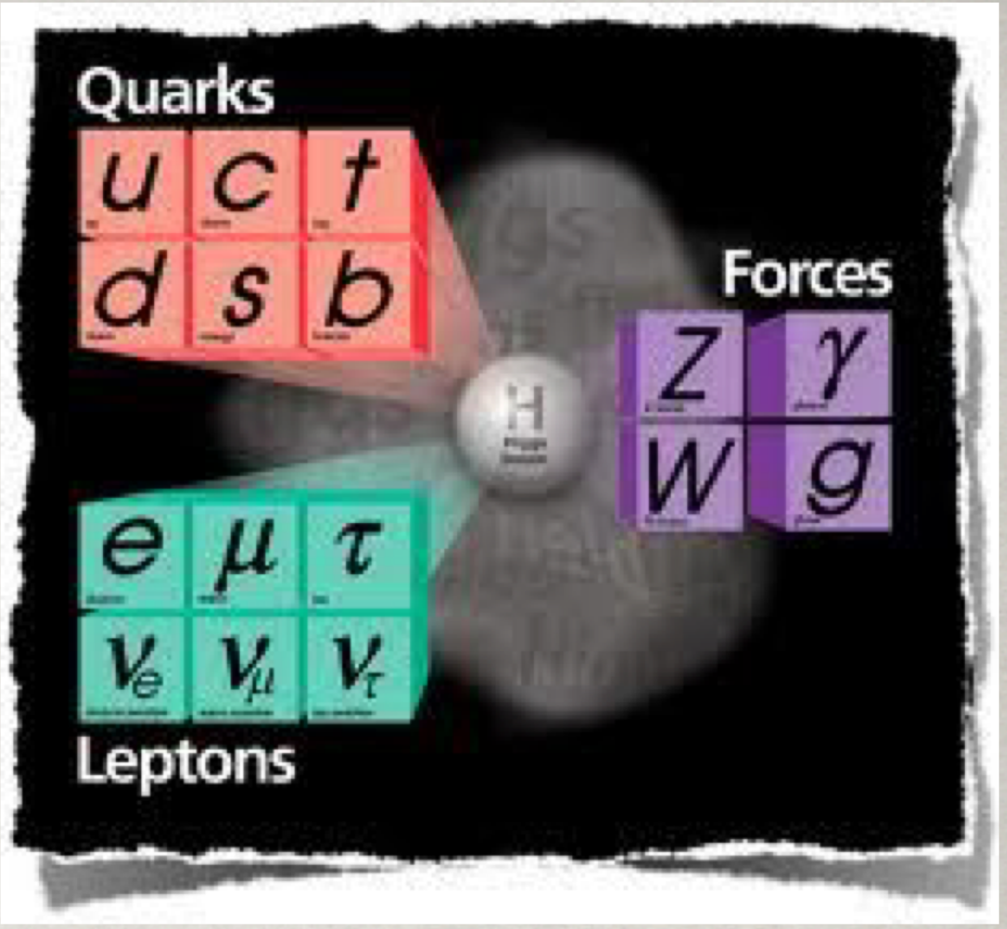
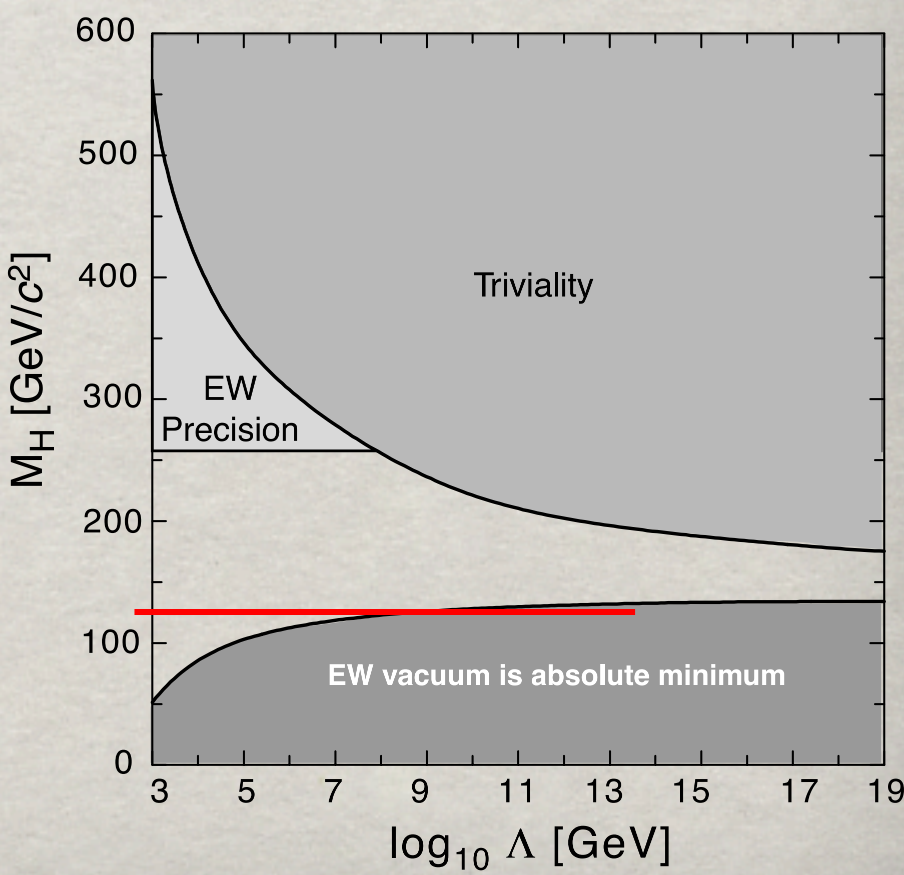
D. Goncalves, TH, S. Mukhopadhyay, arXiv:1710.02149 (PRL, 2017); arXiv:1803.09751; D. Goncalves, TH, S.C.I. Leung, H. Qin, arXiv:2012.05272; R. Abraham, D. Goncalves, TH, S.C.I. Leung, H. Qin, to appear.

The completion of the SM:

First time ever, we have a consistent relativistic/ quantum mechanical theory: weakly coupled, unitary, renormalizeable, vacuum (quasi?) stable.



Valid up to an exponentially high scale, perhaps to the Planck scale M_{Pl}!



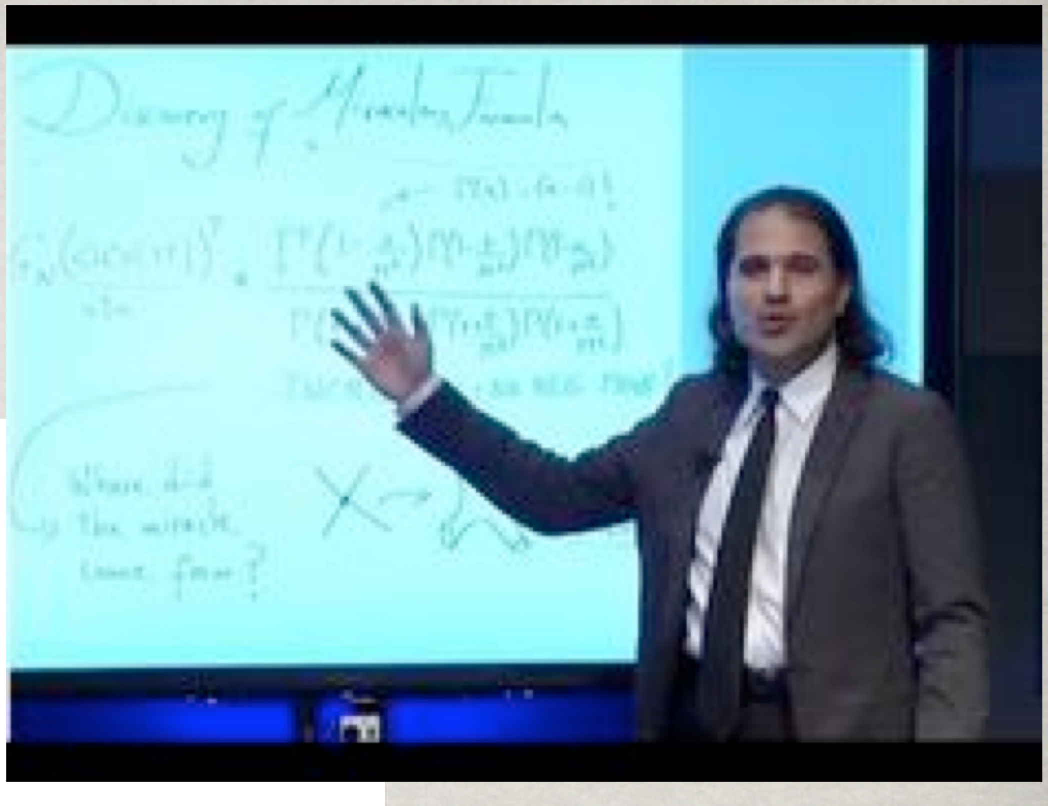
"… most of the grand underlying principles have been firmly established.
… the future truths of physical science are to be looked for in the sixth place of decimals. "

--- Albert Michelson (1894)

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

Will History repeat itself (soon)?

Nima Arkani-Hamed:



The central questions today are not details — but structural: origin of spacetime, UV/IR connection, standard model → real theory

SM as an Effective Field Theory

"The present educated view of the standard model, and of general relativity, is again that these are the leading terms in effective field theories." S. Weinberg, hep-th/9702027

"We are all Wilsonians now."

- J. Preskill, Quantum Frontier (2013)

In terms of a new physical scale Λ , below which the theory is valid:

(relevant operators)

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

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

(marginal operators) (irrelevant operators)

The 1st (most) "relevant operator": $c_0\Lambda^4$

Known physics scales and the observation:

$$(M_{PL}/\Lambda_{cosm})^4 \sim 10^{120}\,! \quad (\Lambda_{QCD}/\Lambda_{cosm})^4 \sim 10^{44}\,!$$

Wilsonian argument failed (badly)!

"… I do not understand (quantum) gravity" --- William Bardeen

The 2nd "relevant operator": the Higgs boson mass

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

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

"… 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

The "Hierarchy problem" between m_h & M_{Planck}

→ Higgs as a Probe of New Physics !

Immediate target: Precision Higgs physics $v^2/\Lambda^2 \sim 2\%$

- Cross sections/branching fractions → Higgs couplings
- Rare processes → search new phenomena

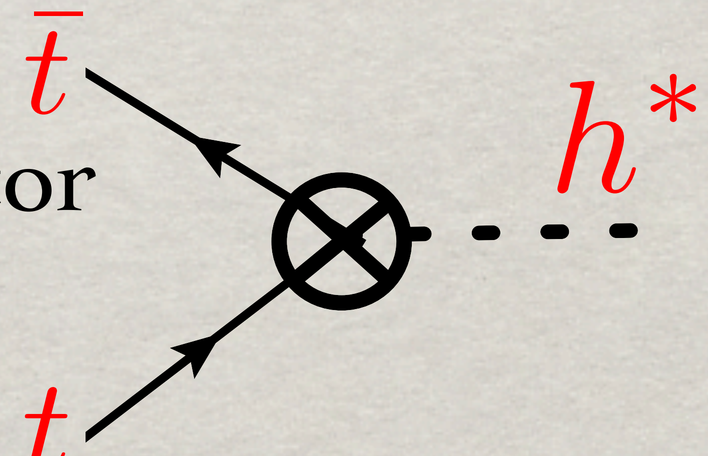
Much work/talks in this workshop …

Complementary Approach: Higgs physics at high scales

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

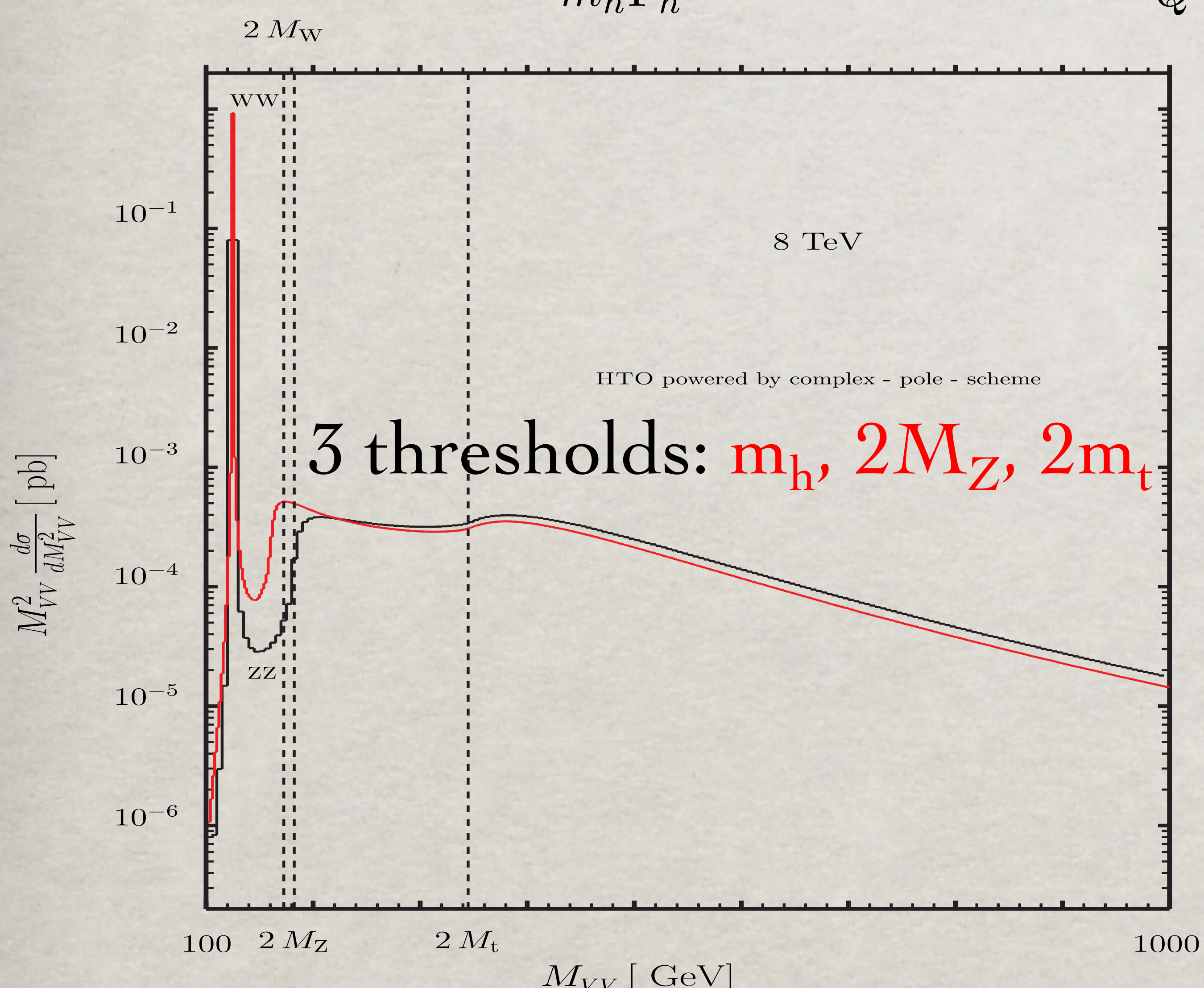
Focus on *ttH* coupling @ high scales:

a. Yukawa $y_t(Q)$ RGE running
b. EFT probe
c. Composite form factor

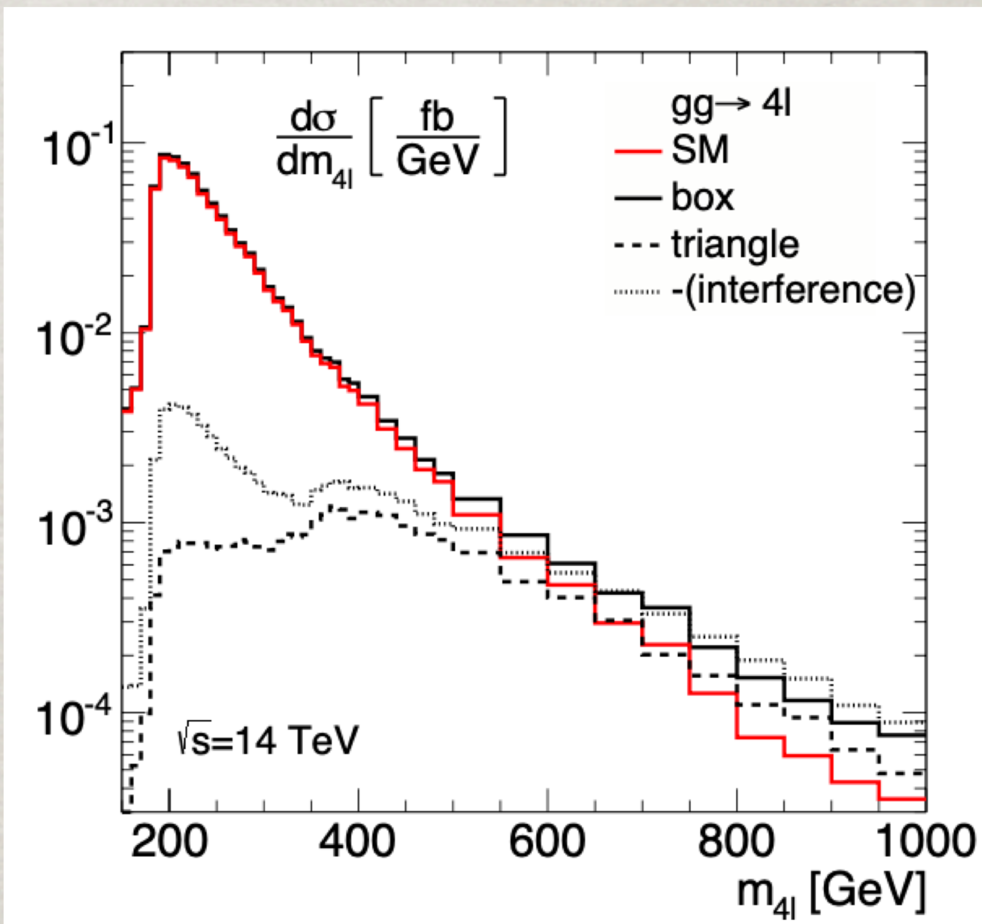


High-scale Higgs Physics I:
far off-shell Higgs gg → h* → WW, ZZ

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



3 thresholds: m_h, $2M_Z$, $2m_t$



Significant destructive interference between the box & triangle diagrams

N. Kauer, G. Passarino, arXiv:1206.4803
F. Caola, K. Melnikov, arXiv:1307.4935
Campbell, Ellis, Williams 1312.1628

a. Top quark Yukawa coupling $y_t(Q)$:

SM:

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

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

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-dimensions:

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

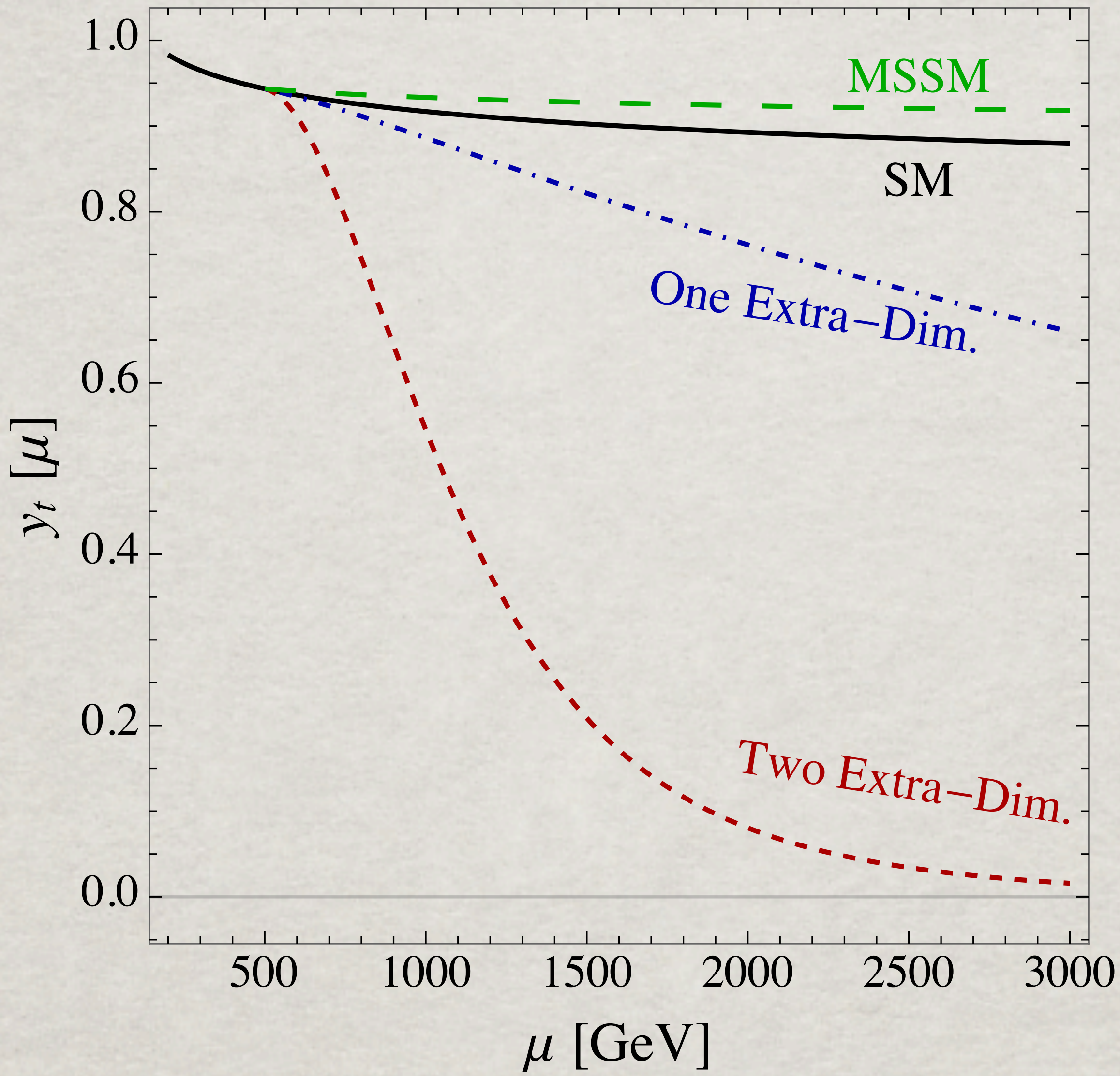
$$\frac{dy_t}{dt} = \beta^{\rm SM}_{y_t} + \frac{y_t}{16\pi^2}4\pi(S(t)^2-1)\left(\frac{3}{2}y_t^2 - 8g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{20}g_1^2\right), \qquad \text{6D.}$$

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

→ "volume", power-law running!

K. Dienes, E. Dudas, T. Gherghetta, 1998

Top quark Yukawa coupling $y_t(Q)$: RGE



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

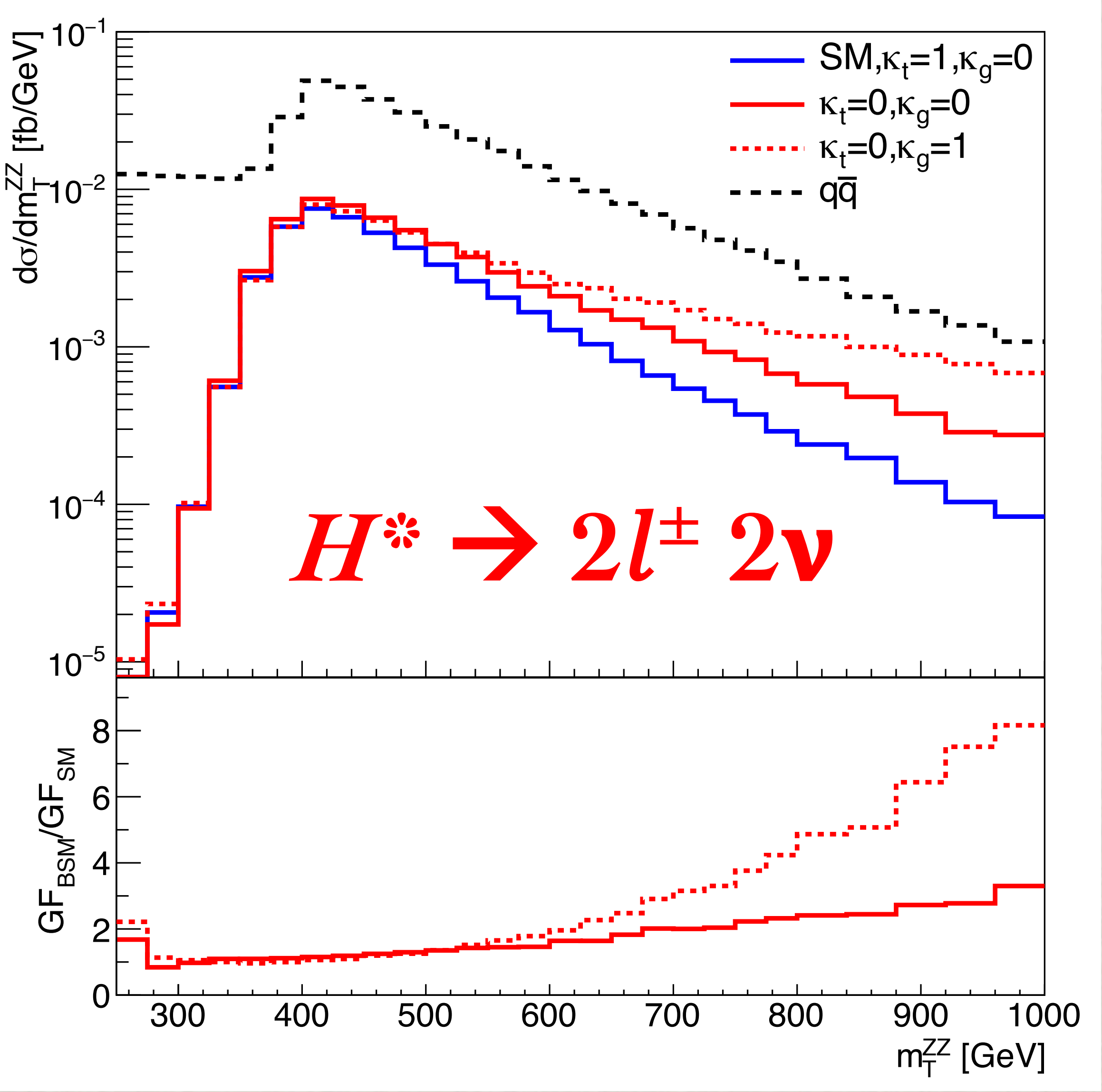
- **Suppressed Yukawa coupling → larger ZZ signal**
- **HL-LHC: rather insensitive to SM/MSSM/5D**
- **HE-LHC/FCC-hh @ 6D → Reach 1/R ~ 1 TeV**

D. Goncalves, TH, S. Mukhopadhyay, arXiv:1710.02149 (PRL, 2017); arXiv:1803.09751 (PRD, 2018).

b. Effective Field Theory description:

$$\mathcal{L} \supset c_g \frac{\alpha_s}{12\pi v^2}|\mathcal{H}|^2 G_{\mu\nu}G^{\mu\nu} + c_t \frac{y_t}{v^2}|\mathcal{H}|^2 \bar{Q}_L \tilde{\mathcal{H}} t_R + \text{h.c.}$$

$\mathcal{M}_{\rm BSM} \sim \mathcal{M}_{\rm SM}\,(1+m^2_{zz}/\Lambda^2)$



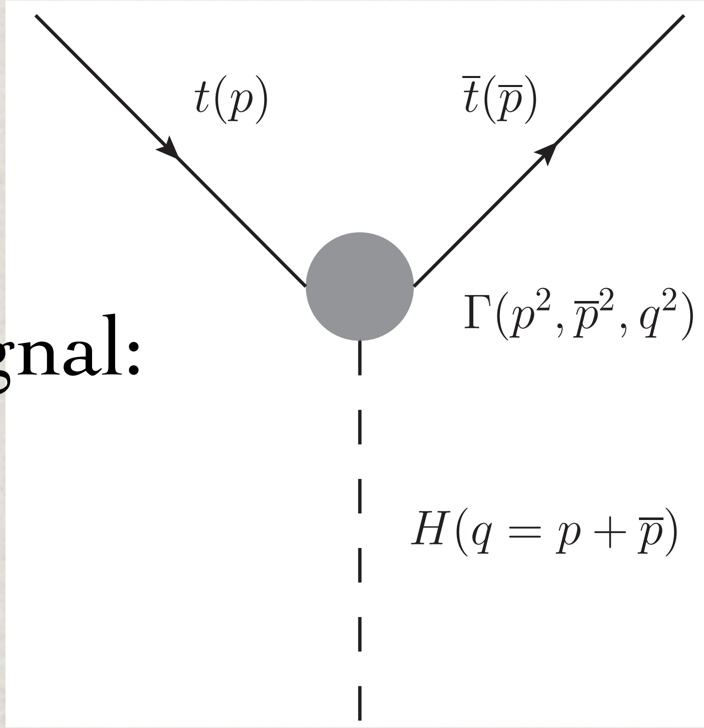
	Γ_H/Γ_H^{SM}	Λ_{EFT}
$H^* \to ZZ \to \ell\ell\nu\nu$	1.31	0.8 TeV
$H^* \to ZZ \to 4\ell$	1.3 (68% CL) [33]	0.55 TeV [34]

D. Goncalves, TH, S. Mukhopadhyay, arXiv:1710.02149 (PRL, 2017); arXiv:1803.09751 (PRD, 2018).
D. Goncalves, TH, S.C.I. Leung, H. Qin, arXiv:2012.05272.

c. The Momentum-dependent Form Factor:

Deviation from point-like interactions:

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



Current 95% CL bound from the LHC Higgs signal:

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

Analogue: Nucleon form factor

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

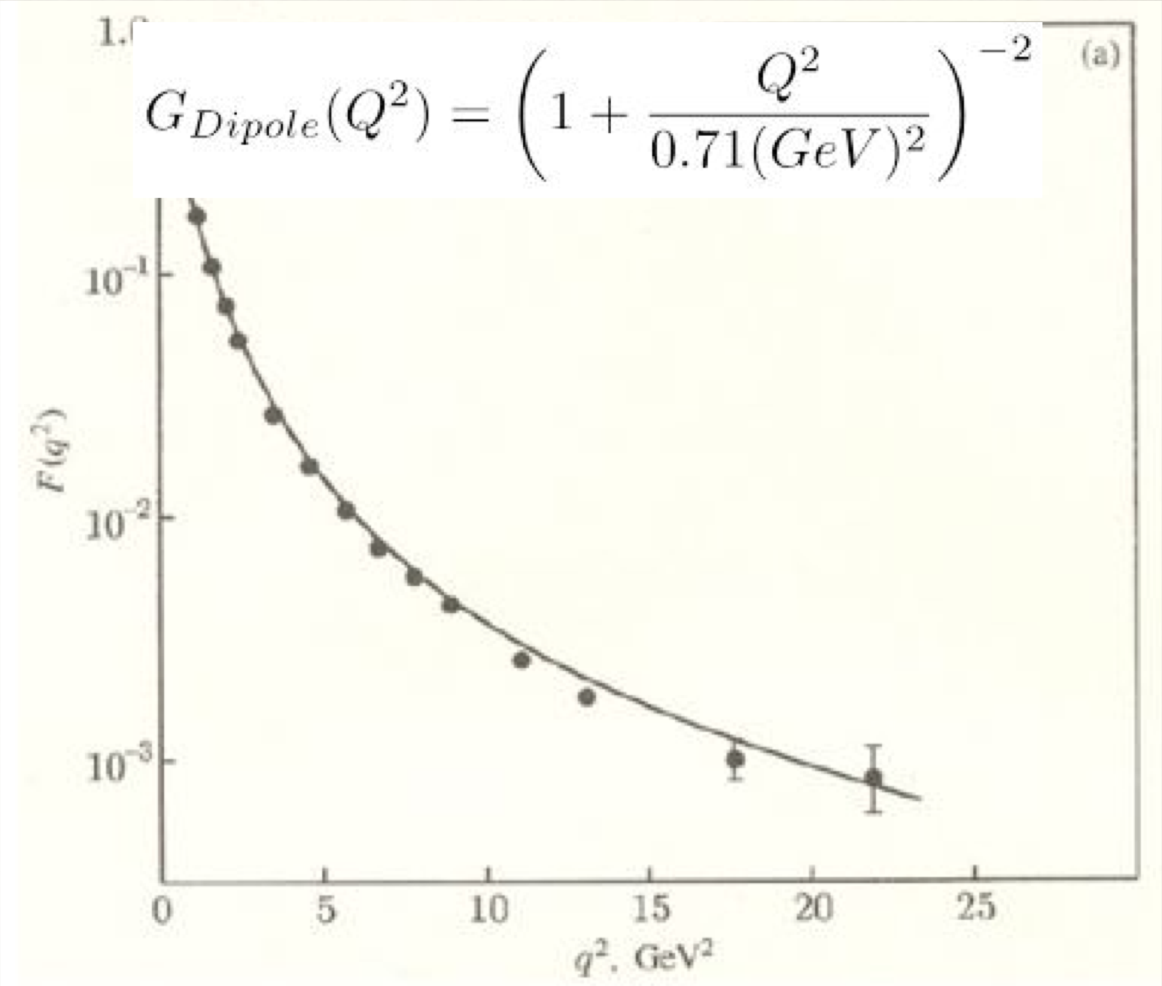
n=2 → "Dipole FF"

1-particle exchange potential;

a spatial exponential distribution.

Leading to a suppressed ttH

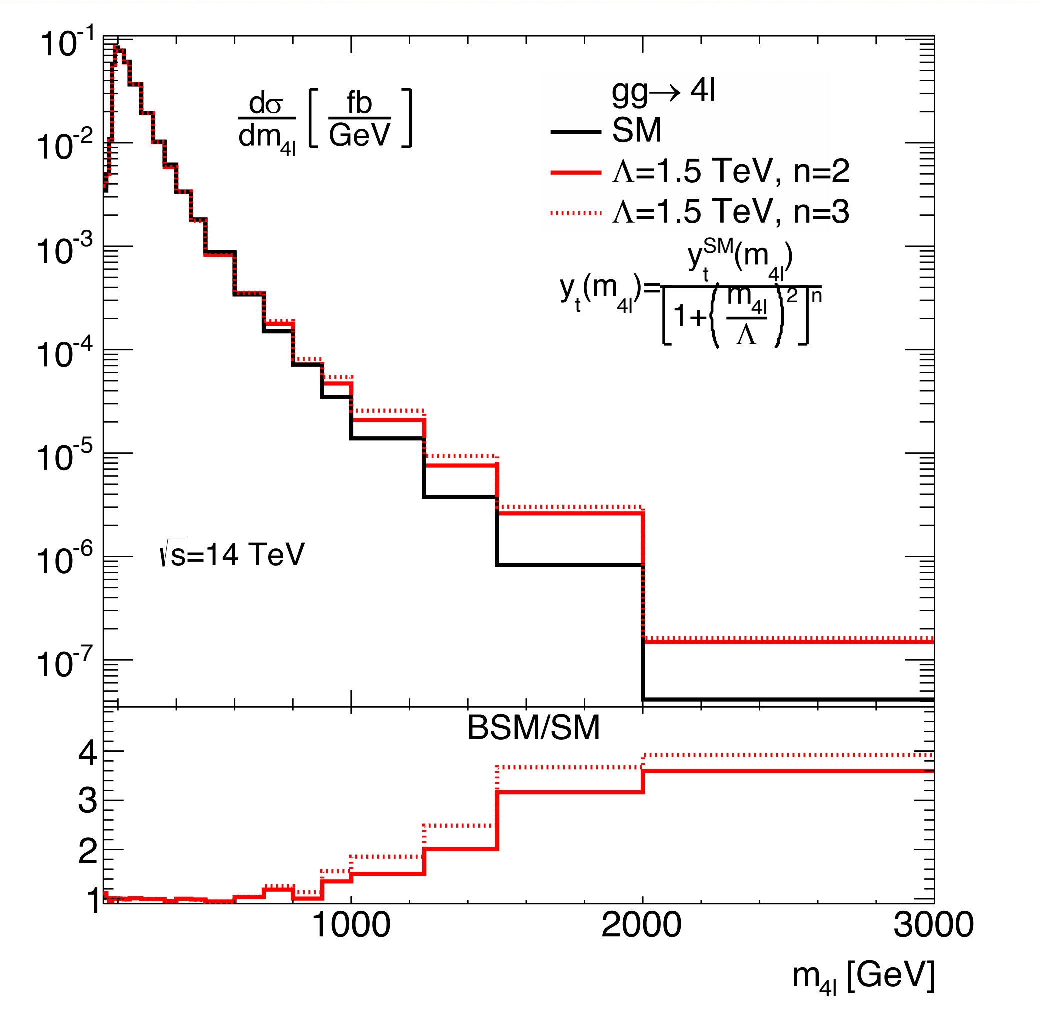
→ Enhanced ZZ signal!



LHC distribution: top-Higgs Form Factor

(similar effects for n=2,3)

$H^* \rightarrow 4\, l^{\pm}$



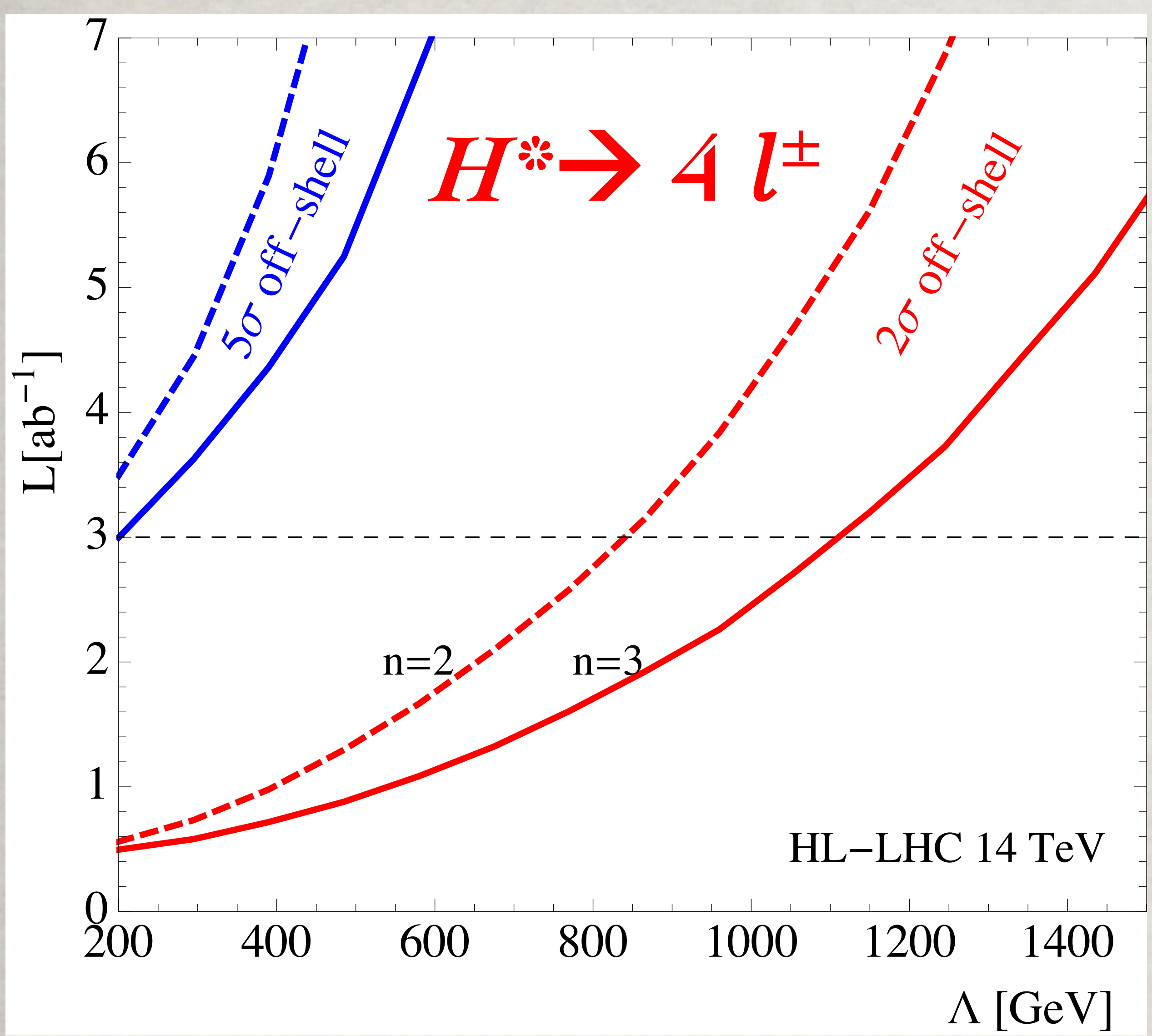
Form Factor suppression

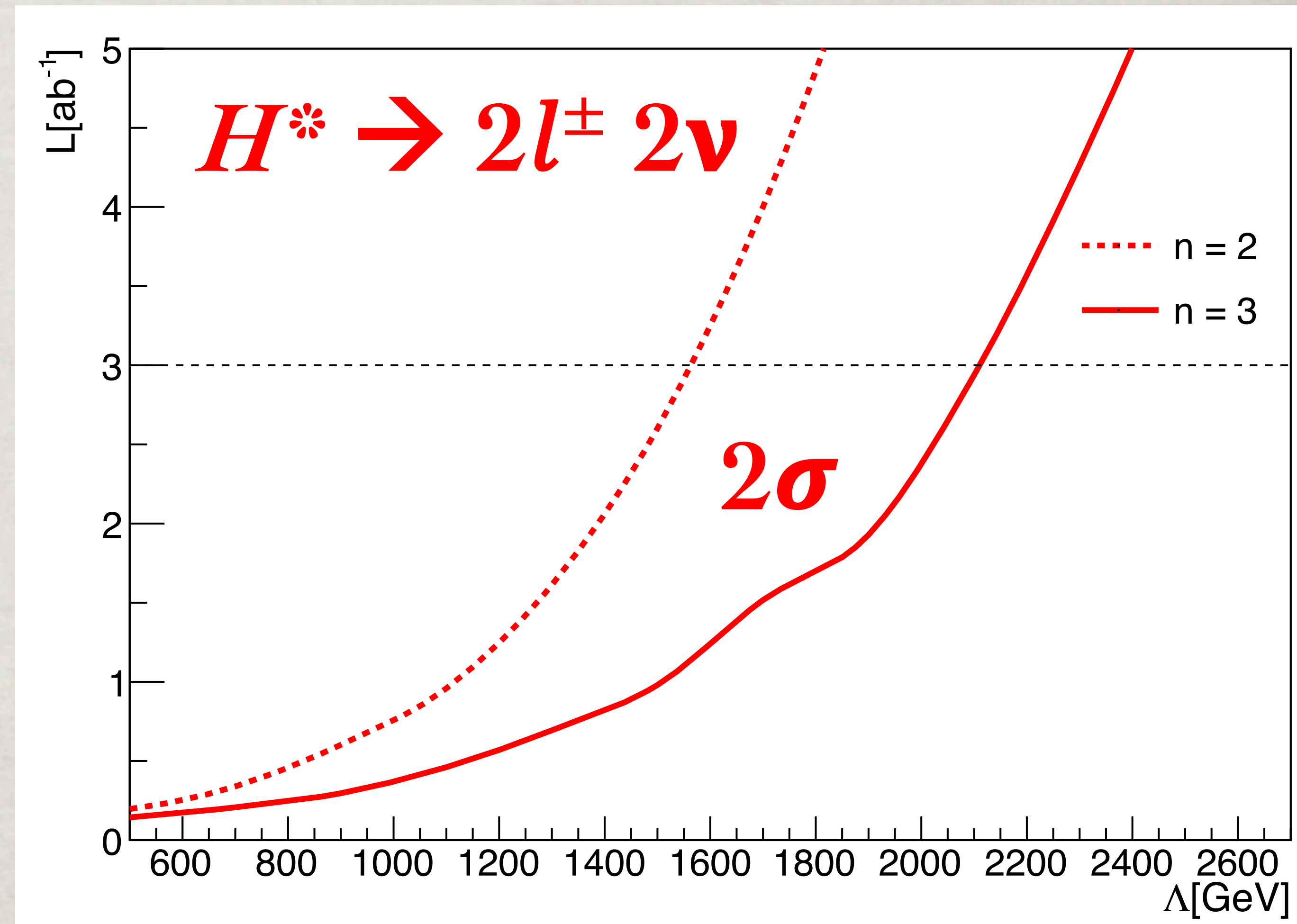
→ smaller off-shell Higgs signal

→ weaker interference

→ larger ZZ signal: a factor of 3-4!

LHC Sensitivity: top-Higgs Form Factor

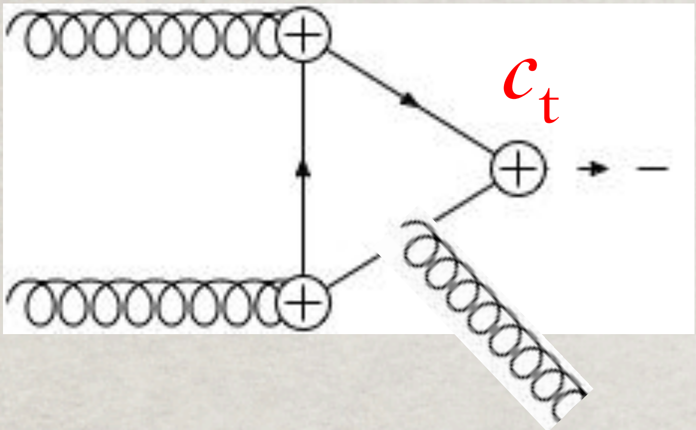


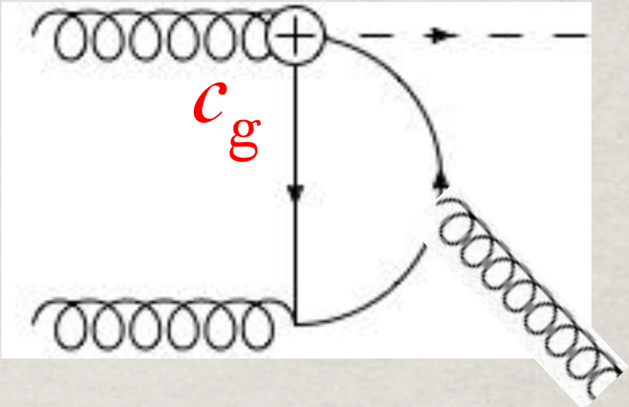


	Γ_H/Γ_H^{SM}	Λ_{EFT}	$\Lambda^{n=2}_{Composite}$
$H^* \to ZZ \to \ell\ell\nu\nu$	1.31	0.8 TeV	1.5 TeV
$H^* \to ZZ \to 4\ell$	1.3 (68% CL) [33]	0.55 TeV [34]	0.8 TeV [18]

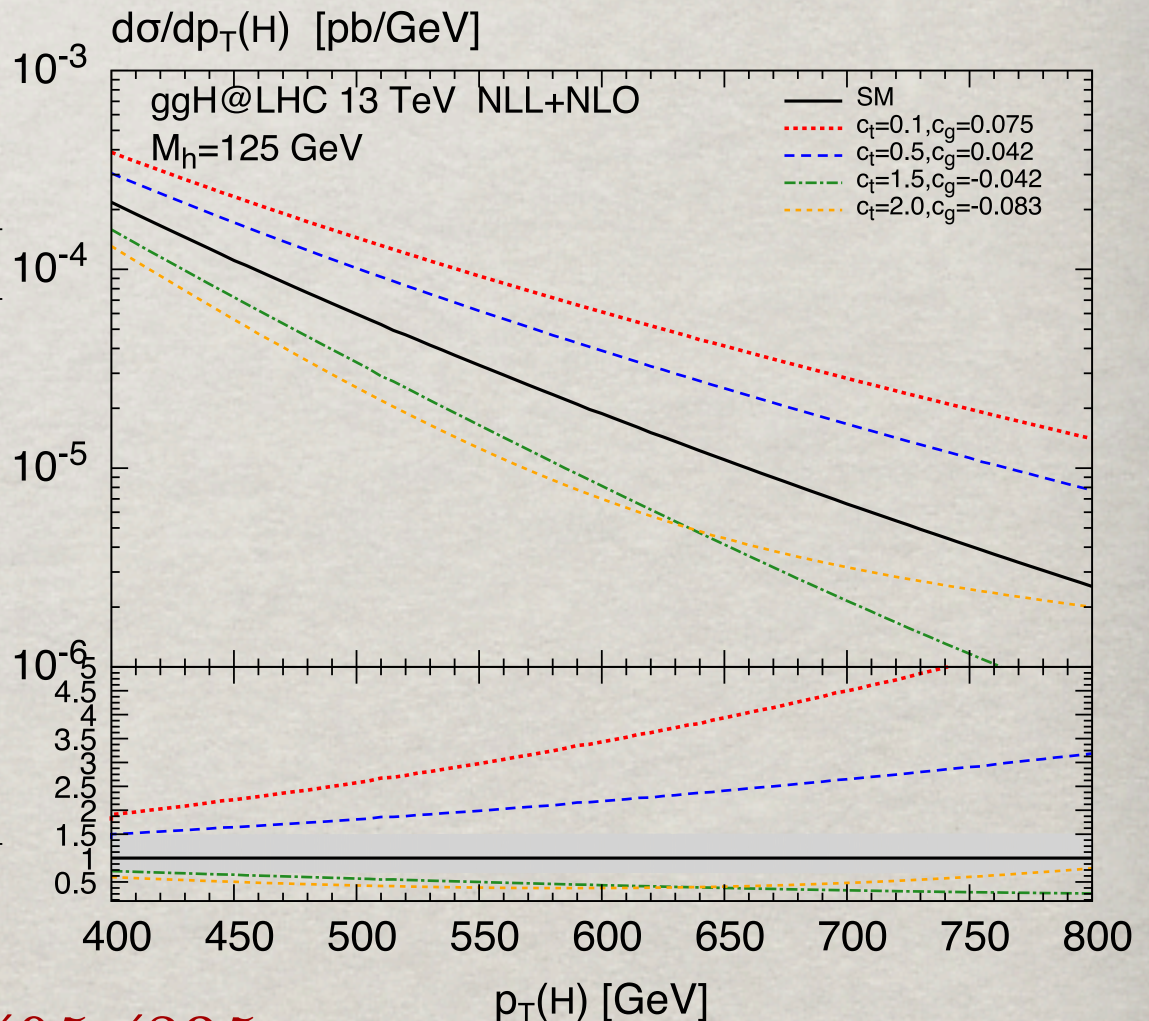
High-scale Higgs Physics II

Higgs @ high-P_T in gg →H+j





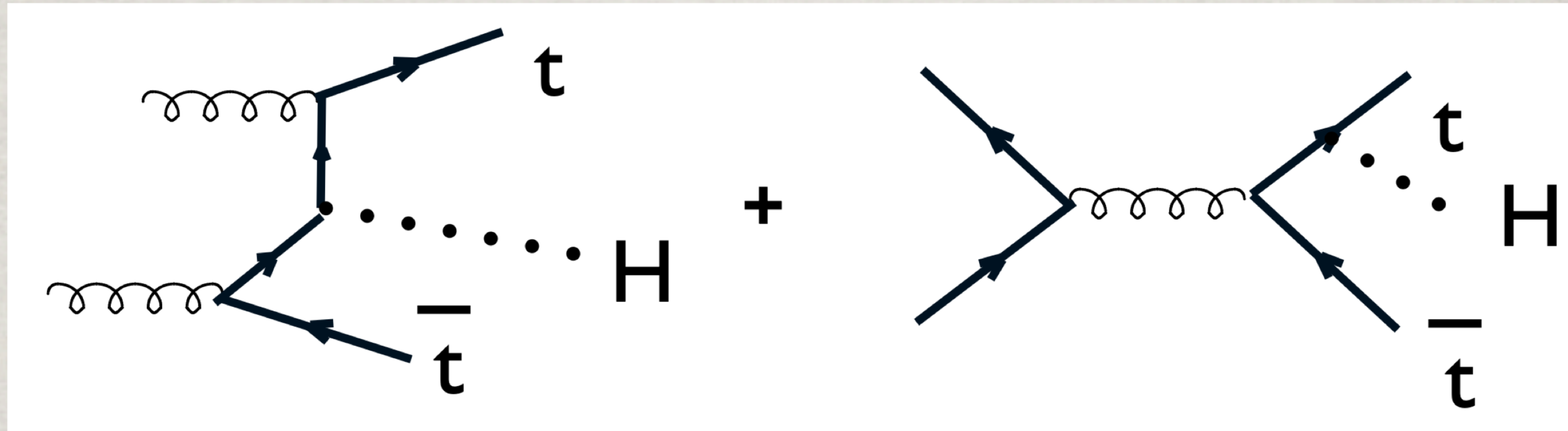
	(0.5,0.5)	(0.7,0.3)	(0.9,0.1)	**SM**	(1.1,-0.1)	(1.3,-0.3)	(1.5,-0.5)
$p_{T,H} > 10$ GeV	0.9733	0.9838	0.9945	1.0000	1.0055	1.0167	1.0281
$p_{T,H} > 100$ GeV	1.0044	1.0012	0.9999	1.0000	1.0006	1.0031	1.0076
$p_{T,H} > 200$ GeV	1.1166	1.0646	1.0198	1.0000	0.9820	0.9513	0.9277
$p_{T,H} > 300$ GeV	1.3450	1.1921	1.0591	1.0000	0.9459	0.8526	0.7791
$p_{T,H} > 400$ GeV	1.6531	1.3590	1.1087	1.0000	0.9023	0.7397	0.6210
$p_{T,H} > 500$ GeV	2.0233	1.5520	1.1633	1.0000	0.8573	0.6340	0.4932
$p_{T,H} > 600$ GeV	2.4869	1.7871	1.2274	1.0000	0.8076	0.5279	0.3882
$p_{T,H} > 700$ GeV	3.1213	2.1003	1.3093	1.0000	0.7482	0.4172	0.3161
$p_{T,H} > 800$ GeV	3.7427	2.3989	1.3841	1.0000	0.6981	0.3411	0.3129



M. Schlaffer, M. Spannowsky et al., arXiv:1405.4295;
M. Grazzini, A. Ilnicka, M. Spira, M. Wiesemann, arXiv:1612.00283 …

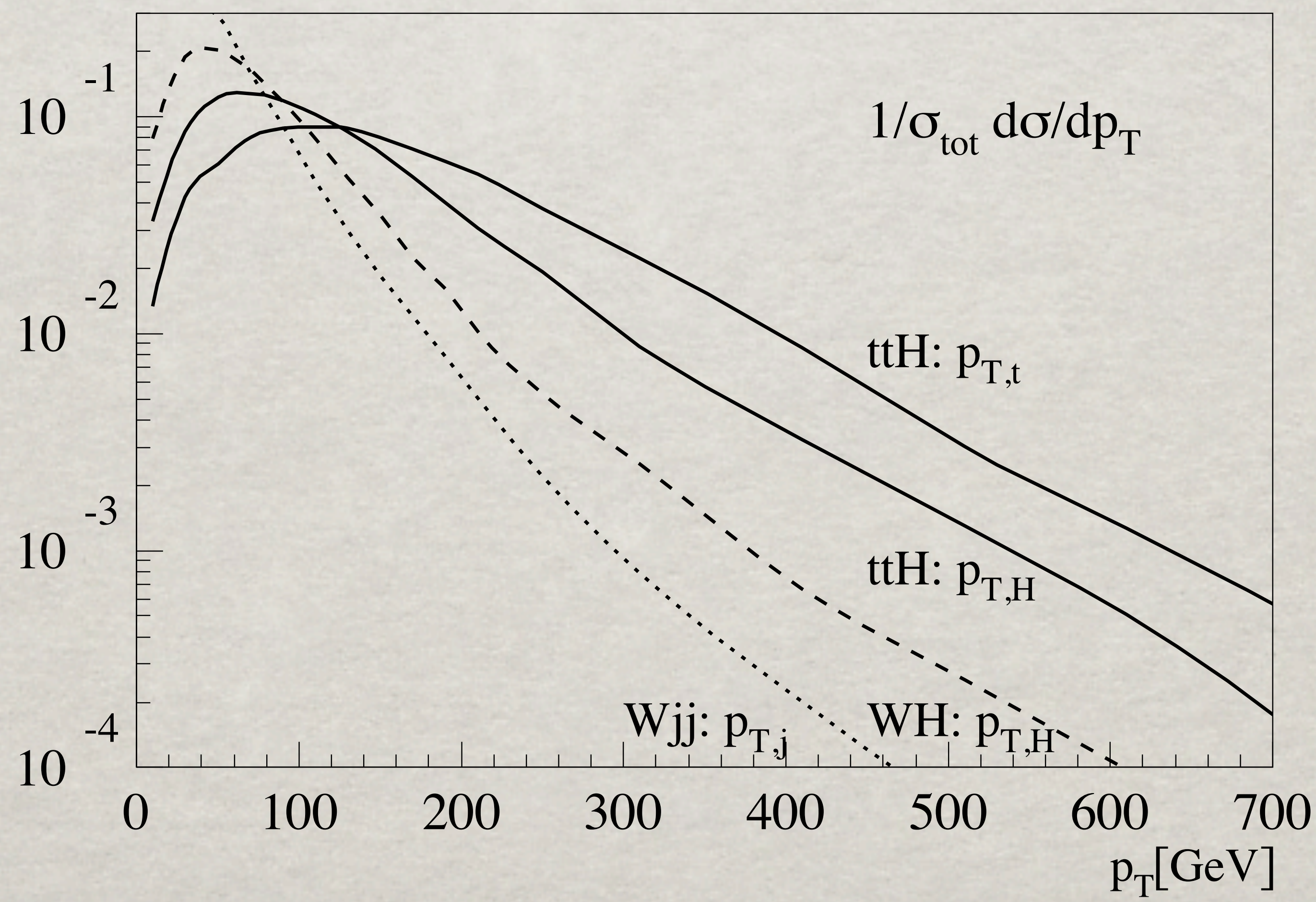
High-scale Higgs Physics III

Higgs @ high-P_T in gg → tt H



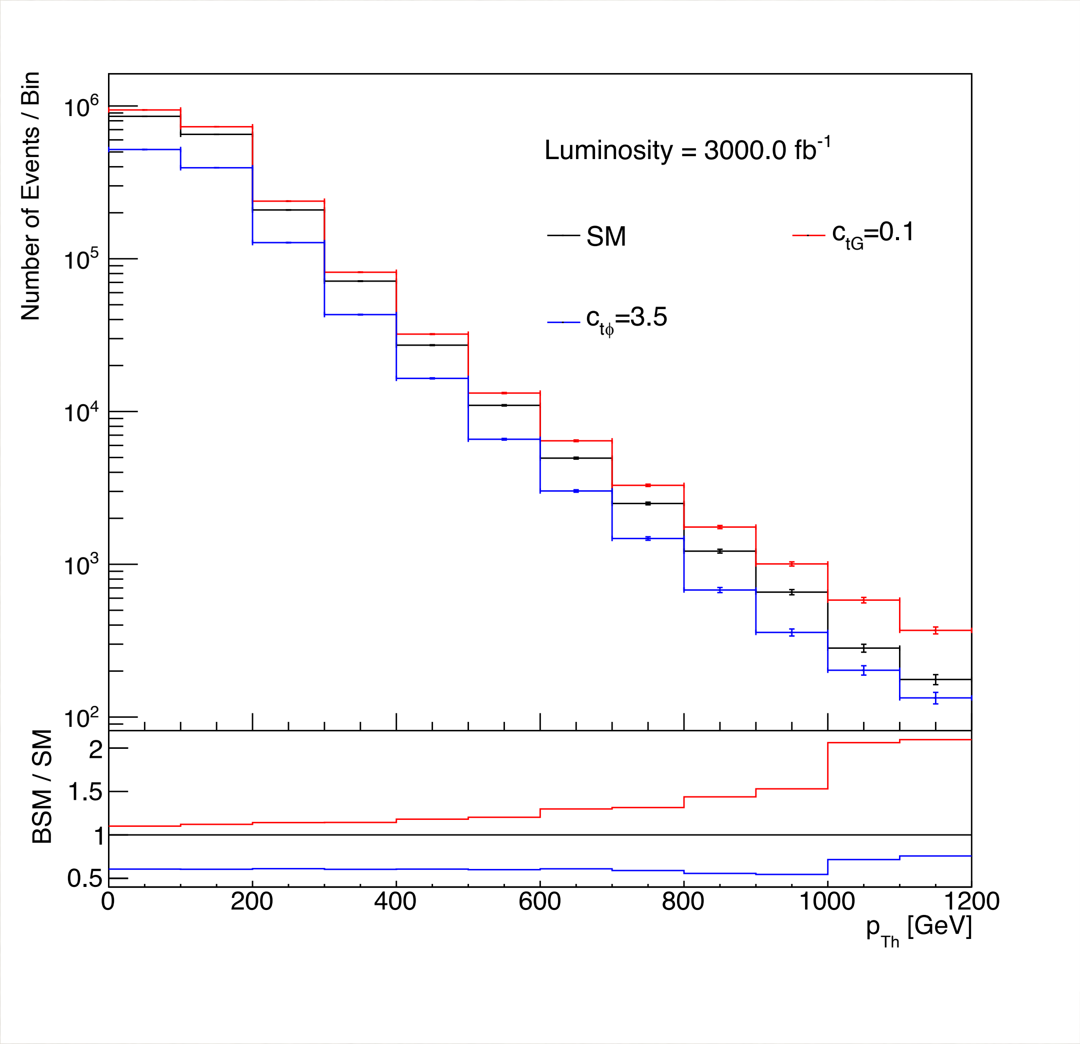
Event rate for *gg →tth* comparable to *gg →h* at high pT
at HL-LHC / FCC-hh

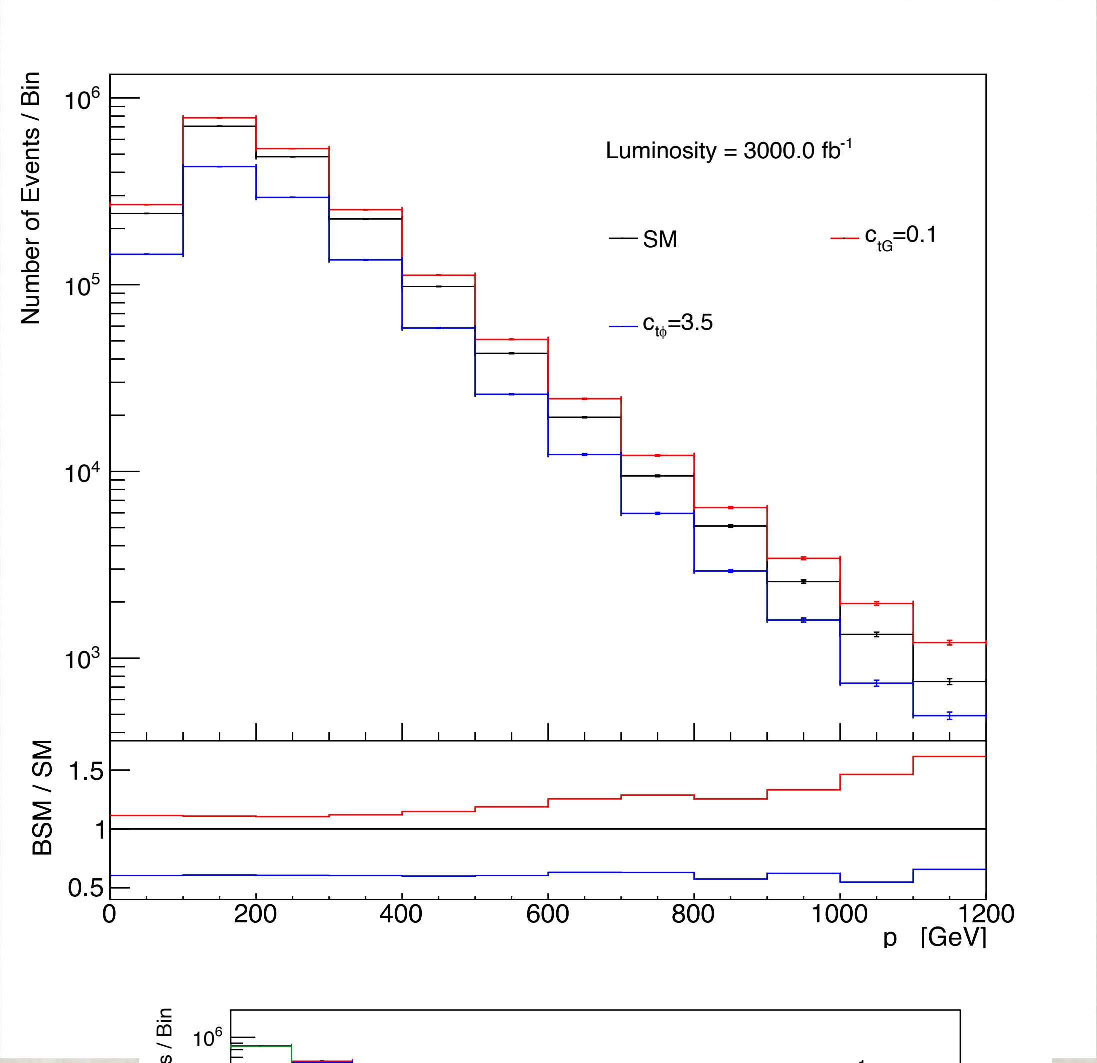
M. Mangano, 2018
FCC Report



T. Plehn, G. Salam, M. Spannowsky, arXiv:0910.5472

$$\mathcal{O}_{t\phi} = (H^\dagger H)(\bar{Q}t)\tilde{H} \qquad \mathcal{O}_{tG} = (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{H}G^A_{\mu\nu}$$

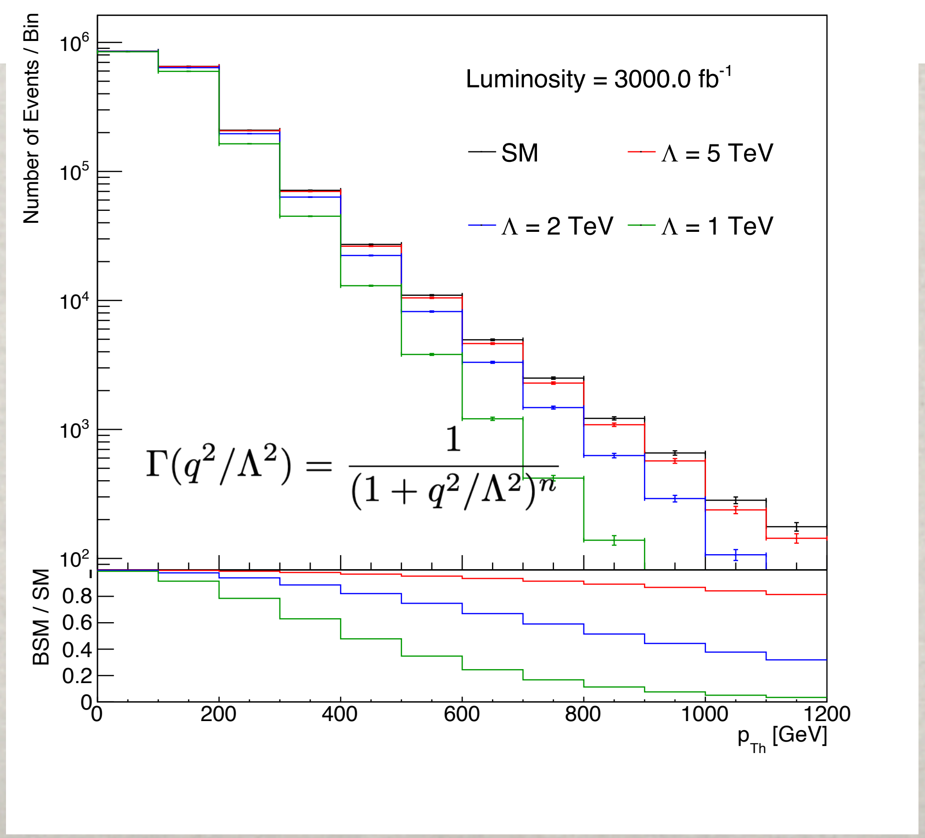




$gg \rightarrow ttH$

Direct probe of space-like regime (no BR's & cuts)

R. Abraham, D. Goncalves, TH, S.C.I. Leung, H. Qin, to appear.



Summary:

Under the Higgs lamppost
→ HPNP

Prevision Higgs measurements → 1% for ***Λ*** ~ 1 TeV – 2 TeV

Strong motivation to target on *ttH* coupling @ High scales
- Weakly coupled: RGE for SM; MSSM: weak effects.
- Extra dimensions → Power-law running!
- Strong dynamics / composite Higgs / EFT / Form Factor
- New states coming into Higgs propagation:
  scalar singlets; a continuum spectrum …

-

Modifications may be observable at the HL-LHC/FCC

2***σ*** - 5***σ*** level sensitivity.

Exciting journey on HPNP !