

The background of the slide features a dark, monochromatic image of a mountain peak, possibly Mount Fuji, rendered in shades of gray against a black sky.

Very boosted Higgs

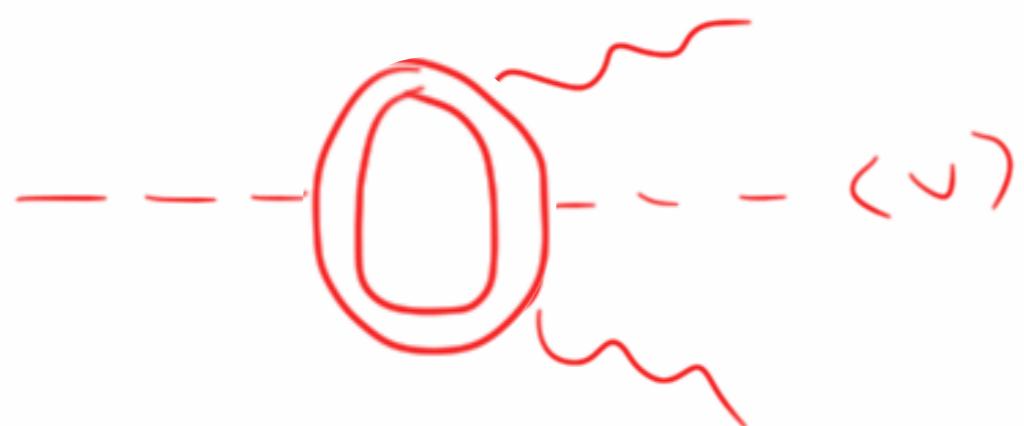
Andreas Weiler (CERN/DESY)

Hierarchy problem

$$\text{---} \circ \text{---} + \text{---} \circ \text{---} \approx 0$$

t **NP**
 T', \tilde{t}, \dots

motivates deviations in

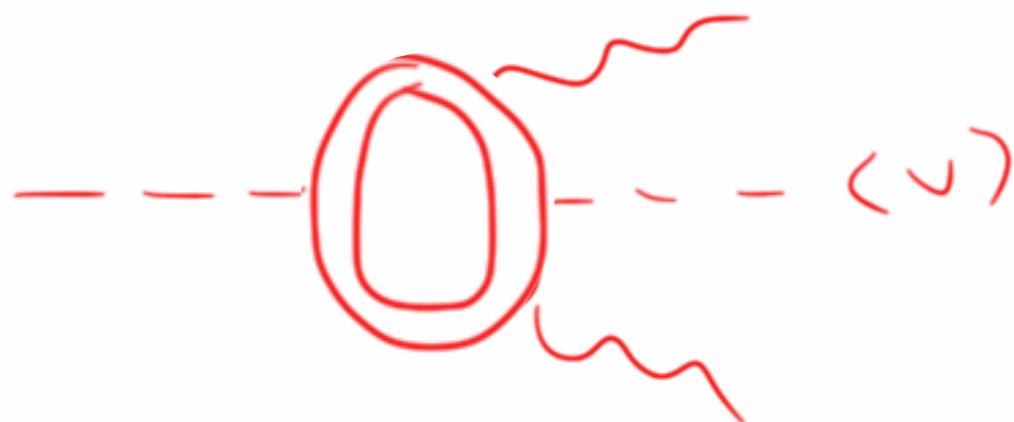


see e.g. Low, Vichi, Rattazzi

Hierarchy problem

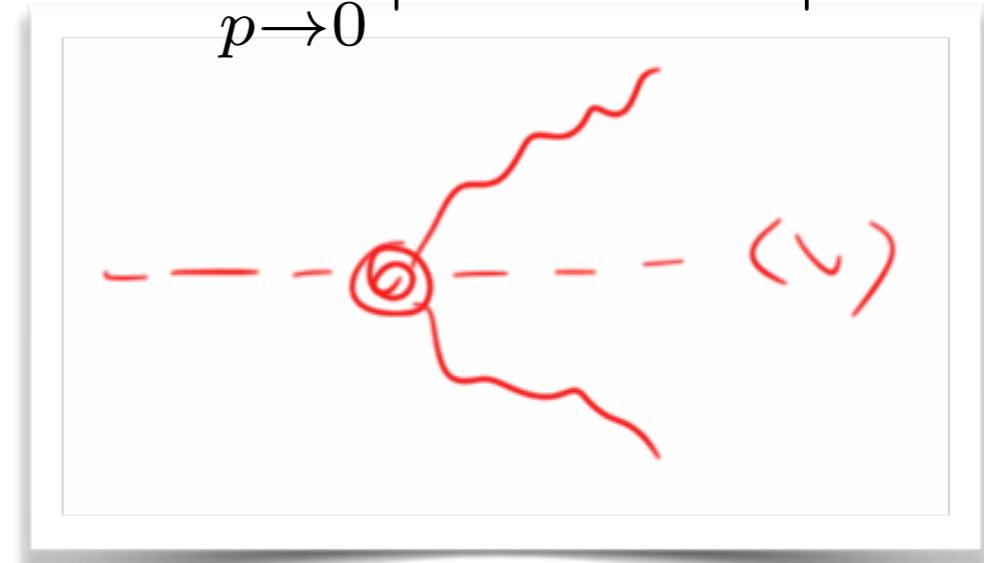
$$t \quad \text{NP}$$
$$+ \approx 0$$
$$T', \tilde{t}, \dots$$

motivates deviations in



we actually measure:

$$\propto \lim_{p \rightarrow 0} |\text{SM} + \text{NP}|^2$$



see e.g. Low, Vichi, Rattazzi

19 = 8+3+8

change Higgs
kin. term:

$VV \rightarrow h$

$h \rightarrow \gamma\gamma$

$GG \rightarrow h$

$h \rightarrow ff$

$$\mathcal{O}_H = \frac{1}{2}(\partial^\mu |H|^2)^2$$

$$\mathcal{O}_T = \frac{1}{2} \left(H^\dagger \overset{\leftrightarrow}{D}_\mu H \right)^2$$

$$\mathcal{O}_6 = \lambda |H|^6$$

All were new doors,
probed for the first time
at the LHC!

$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W_{\mu\nu}^a$$

$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{O}_{GG} = g_s^2 |H|^2 G_{\mu\nu}^A G^{A\mu\nu}$$

$$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W_\mu^a W_\nu^b W_\rho^c$$

Main focus
here

$$\mathcal{O}_{y_u} = y_u |H|^2 \bar{Q}_L \tilde{H} u_R$$

$$\mathcal{O}_{y_d} = y_d |H|^2 \bar{Q}_L H d_R$$

$$\mathcal{O}_{y_e} = y_e |H|^2 \bar{L}_L H e_R$$

$$\mathcal{O}_R^u = (iH^\dagger \overset{\leftrightarrow}{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$$

$$\mathcal{O}_R^d = (iH^\dagger \overset{\leftrightarrow}{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$$

$$\mathcal{O}_R^e = (iH^\dagger \overset{\leftrightarrow}{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$$

$$\mathcal{O}_L^q = (iH^\dagger \overset{\leftrightarrow}{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$$

$$\mathcal{O}_L^{(3)q} = (iH^\dagger \sigma^a \overset{\leftrightarrow}{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$$

$$\mathcal{O}_{LL}^{(3)l} = (\bar{L}_L \sigma^a \gamma^\mu L_L)(\bar{L}_L \sigma^a \gamma_\mu L_L)$$

Operator not visible in vacuum (redefinition of input parameter)

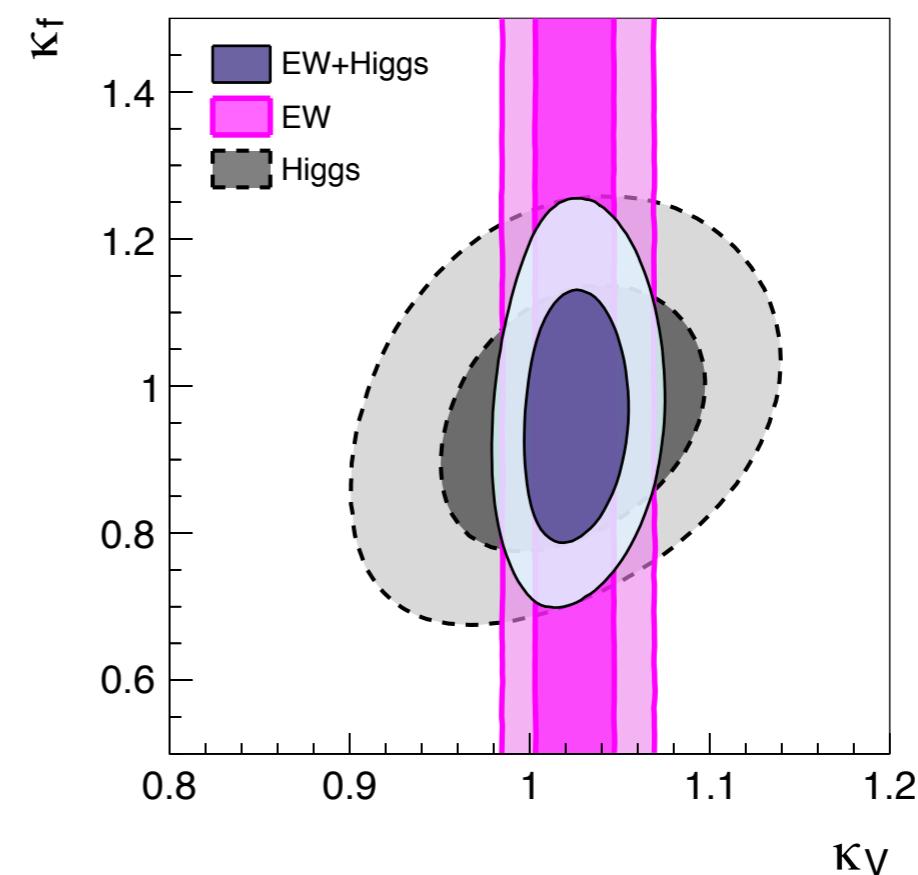
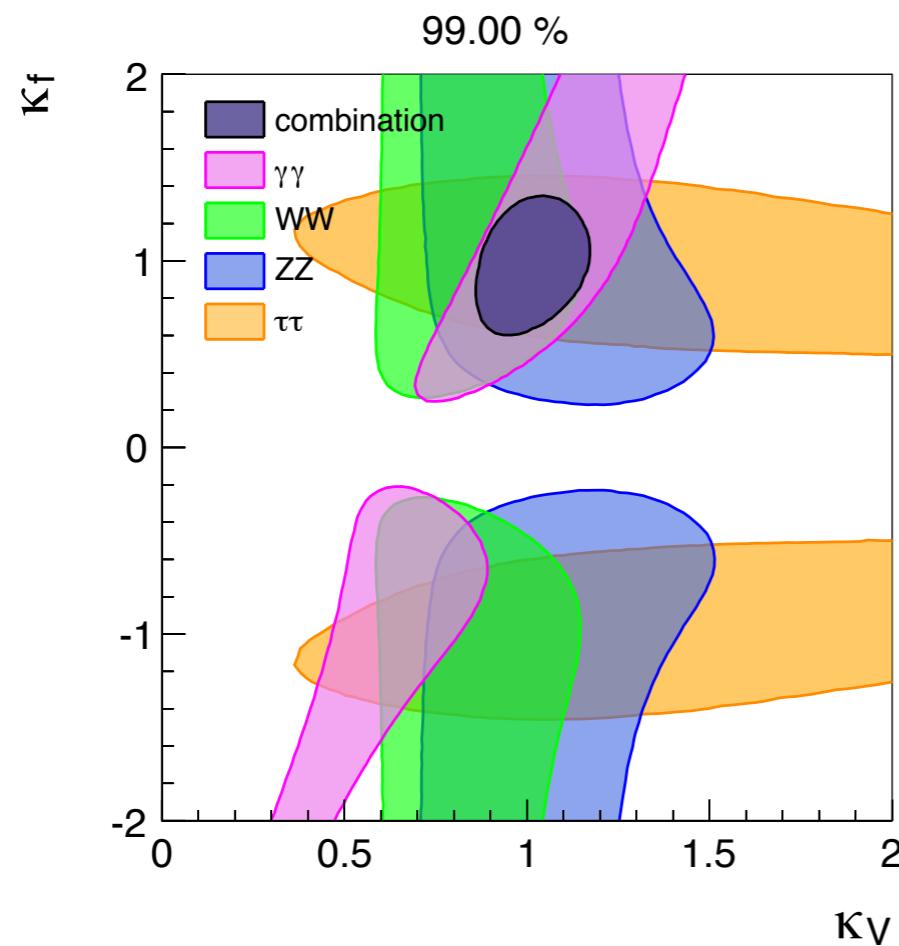
e.g. $\frac{1}{g_s^2} G_{\mu\nu}^2 + \frac{|H|^2}{\Lambda^2} G_{\mu\nu}^2 \rightarrow \left(\frac{1}{g_s^2} + \frac{v^2}{\Lambda^2} \right) G_{\mu\nu}^2$



But can affect h physics:



Higgs fit



beyond inclusive Higgs production

- So far mostly produced on-shell Higgs at a characteristic scale $\mu \approx m_H$
- want to test Higgs couplings at large energy
- analog to LEP1 (on-shell $Z \Rightarrow S, T$) vs. LEP2 (off-shell $Z \Rightarrow W, Y$)

Higgs EFT

$$\mathcal{O}_t = \frac{y_t}{v^2} |H|^2 \bar{Q}_L \tilde{H} t_R\,, \qquad \mathcal{O}_g = \frac{\alpha_s}{12\pi v^2} |H|^2 G_{\mu\nu}^a G^{a\,\mu\nu}\,,$$

$$\mathcal{L}=\mathcal{L}_{SM}+(1-c_t)\mathcal{O}_t+k_g\mathcal{O}_g\;.$$

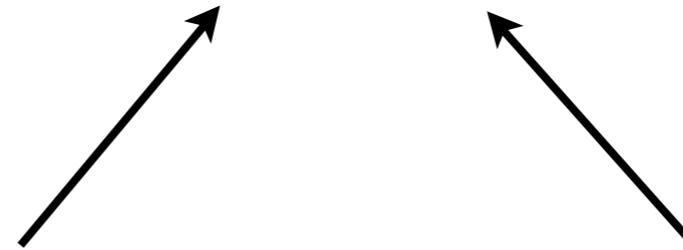
$$\frac{\sigma_{\rm incl}(\kappa_t,\kappa_g)}{\sigma_{\rm incl}^{\rm SM}} \simeq (\kappa_t+\kappa_g)^2 \left(1-\frac{7}{15}\,\frac{\kappa_g}{\kappa_t+\kappa_g}\,\frac{m_h^2}{4m_t^2}\right) \simeq (\kappa_t+\kappa_g)^2$$

Higgs EFT

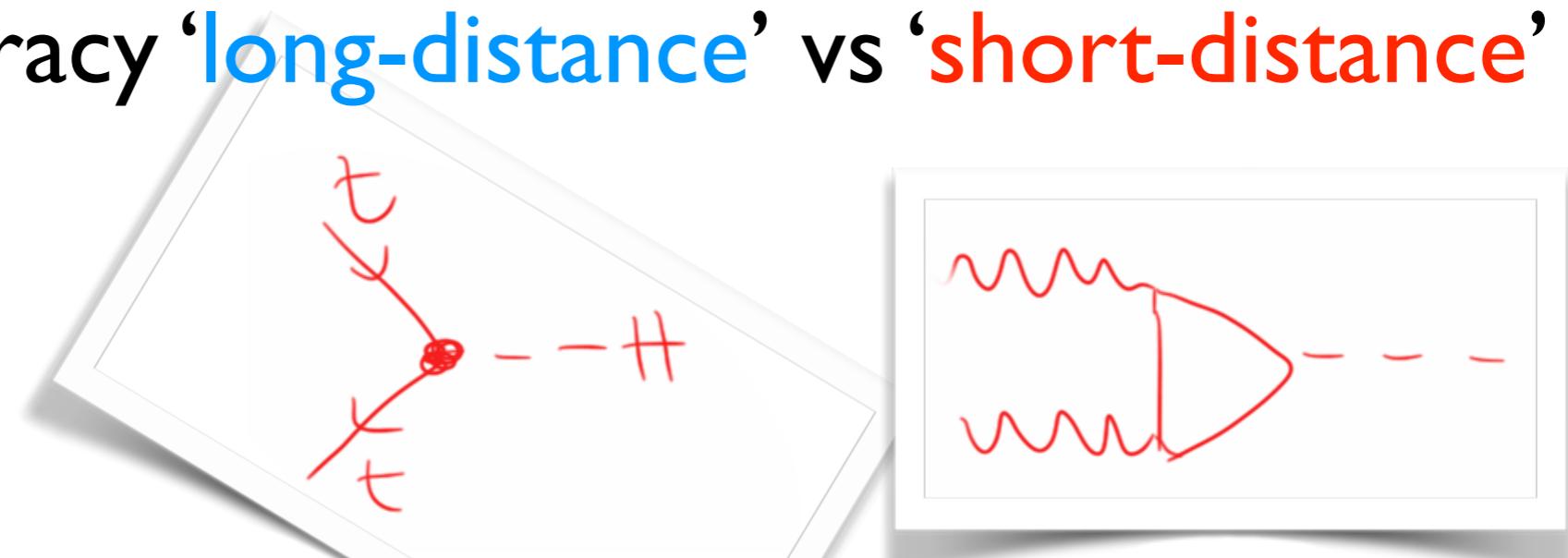
$$\mathcal{O}_t = \frac{y_t}{v^2} |H|^2 \bar{Q}_L \tilde{H} t_R, \quad \mathcal{O}_g = \frac{\alpha_s}{12\pi v^2} |H|^2 G_{\mu\nu}^a G^{a\mu\nu},$$

$$\mathcal{L} = \mathcal{L}_{SM} + (1 - c_t) \mathcal{O}_t + k_g \mathcal{O}_g.$$

$$\mu_{\text{incl}}(c_t, k_g) = \frac{\sigma_{\text{incl}}^{\text{BSM}}(c_t, k_g)}{\sigma_{\text{incl}}^{\text{SM}}} = (c_t + k_g)^2$$



Degeneracy ‘long-distance’ vs ‘short-distance’



Higgs EFT

$$\mathcal{O}_t = \frac{y_t}{v^2} |H|^2 \bar{Q}_L \tilde{H} t_R, \quad \mathcal{O}_g = \frac{\alpha_s}{12\pi v^2} |H|^2 G_{\mu\nu}^a G^{a\mu\nu},$$

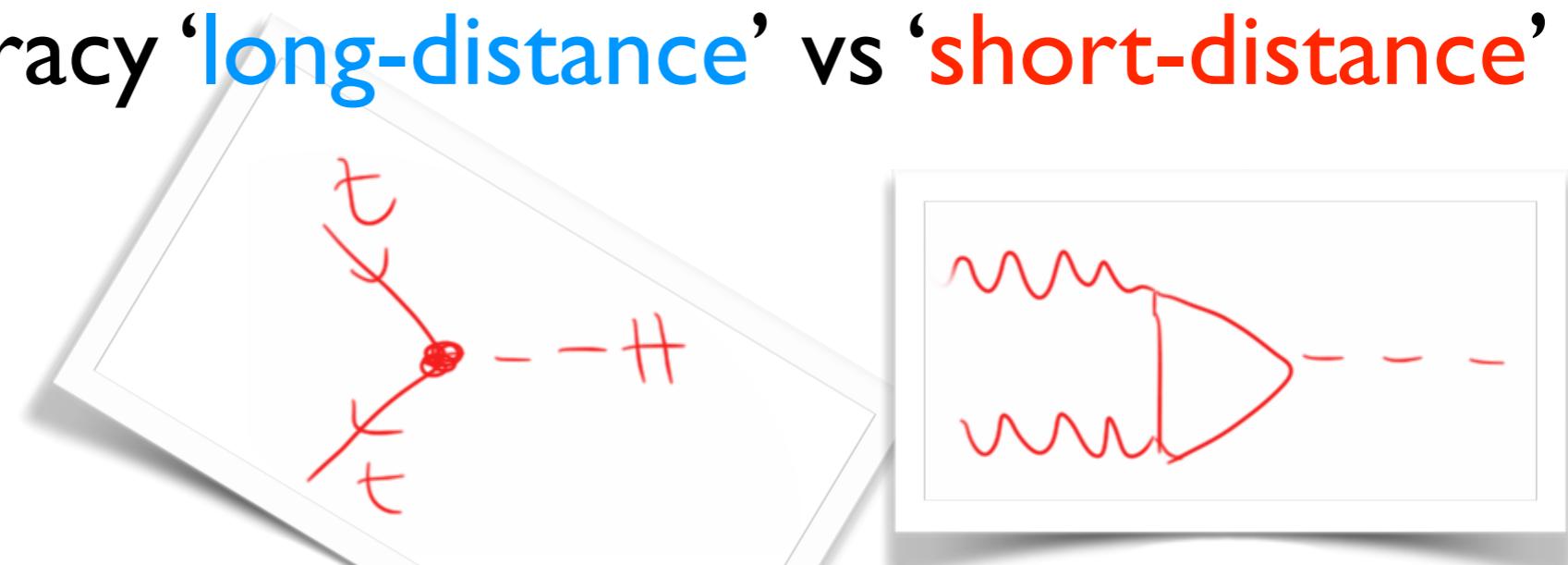
$$\mathcal{L} = \mathcal{L}_{SM} + (1 - c_t) \mathcal{O}_t + k_g \mathcal{O}_g.$$

$$\mu_{\text{incl}}(c_t, k_g) = \frac{\sigma_{\text{incl}}^{\text{BSM}}(c_t, k_g)}{\sigma_{\text{incl}}^{\text{SM}}} = (c_t + k_g)^2$$

top-partners in
composite Higgs

$$\Delta c_t = \Delta c_g = \frac{9}{4} \Delta c_\gamma$$

Degeneracy ‘long-distance’ vs ‘short-distance’



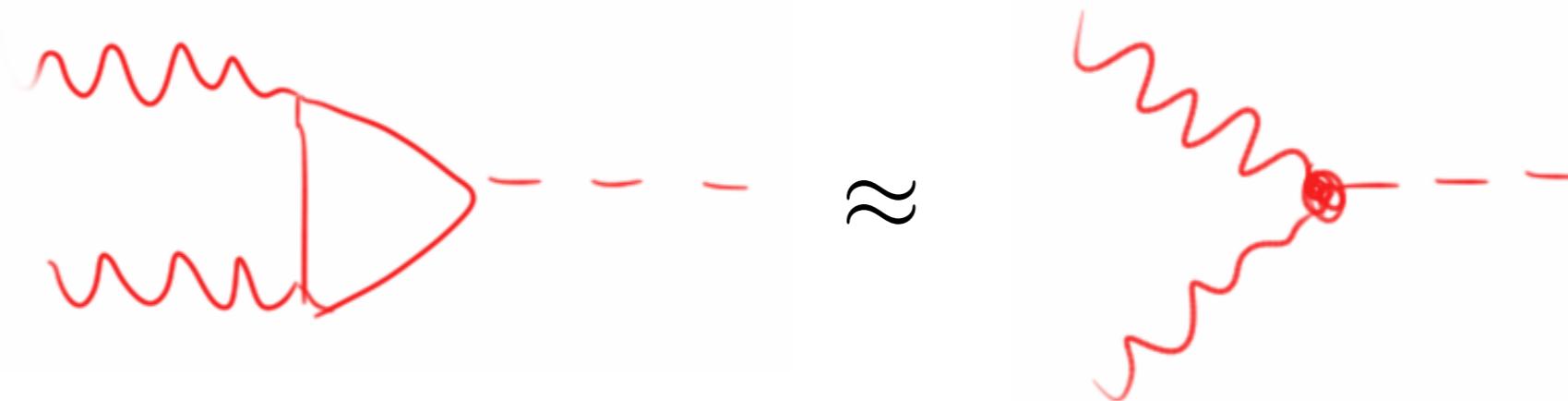
fermionic top-partners in composite Higgs models exactly lead to $\Delta c_t = \Delta c_g = \frac{9}{4} \Delta c_\gamma$.

having access to $h\bar{t}\bar{t}$ final state will resolve this degeneracy
but notoriously difficult channel

14%-4% @ LHC₃₀₀¹⁴-LHC₃₀₀₀¹⁴ vs 10%-4% @ ILC₅₀₀⁵⁰⁰-ILC₁₀₀₀¹⁰⁰⁰

$$\sigma(pp \rightarrow H + X)_{\text{inclusive}}$$

Does not resolve short-distance physics

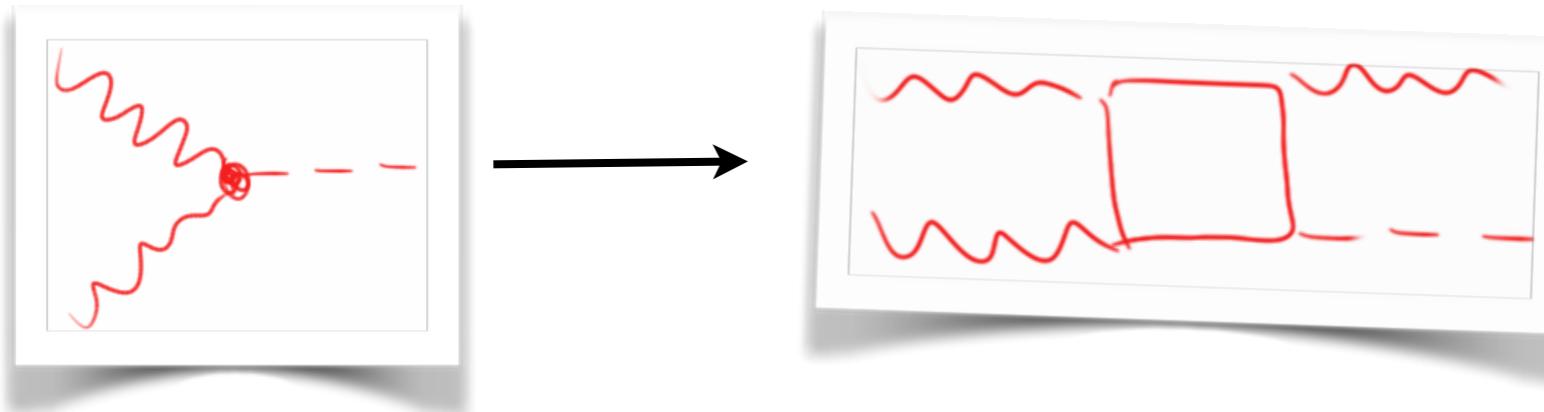


$m_H(\text{GeV})$	$\frac{\sigma_{NLO}(m_t)}{\sigma_{NLO}(m_t \rightarrow \infty)}$	$\frac{\sigma_{NLO}(m_t, m_b)}{\sigma_{NLO}(m_t \rightarrow \infty)}$
125	1.061	0.988
150	1.093	1.028
200	1.185	1.134

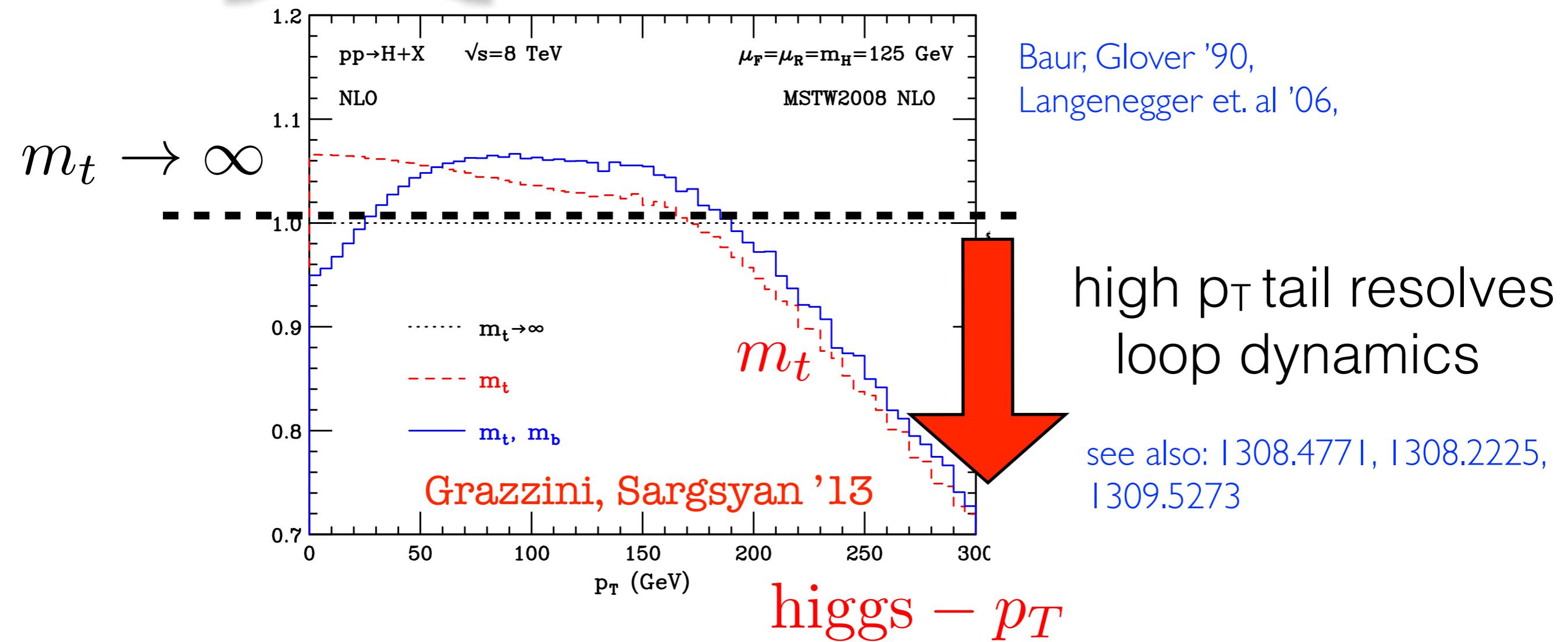
e.g. [1306.4581](#)

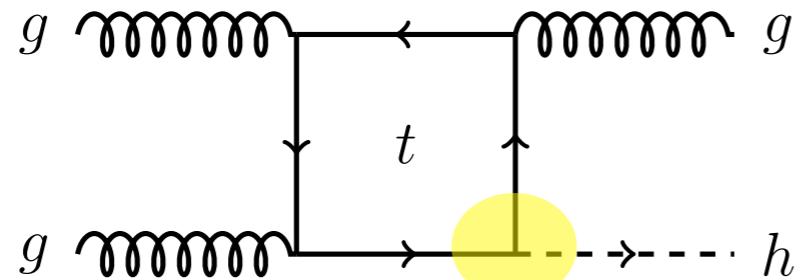
Beyond current observables

Resolve the loop, recoil against hard jet

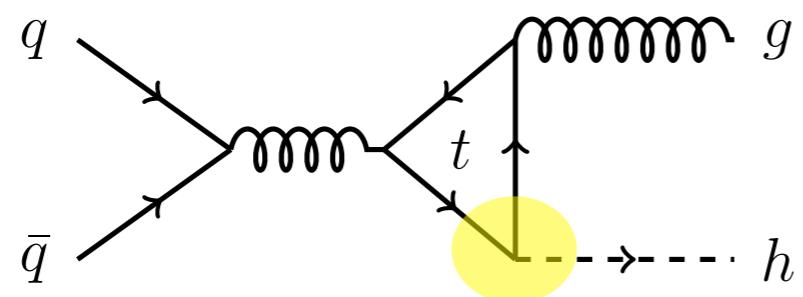
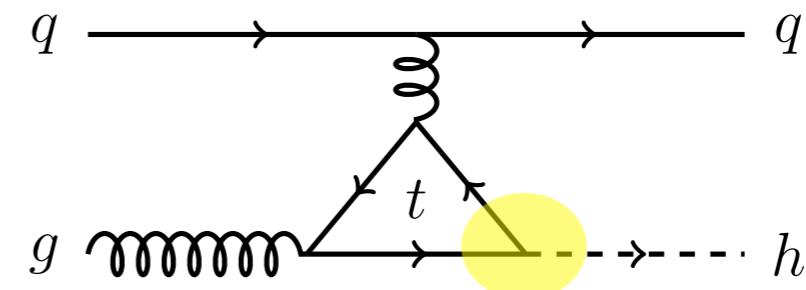


$$p_T \gg m_t$$



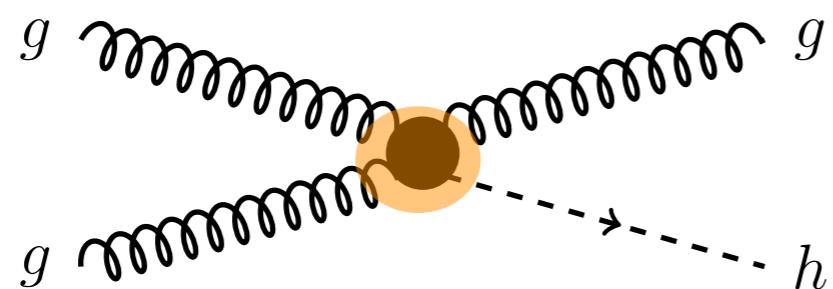


IR



$$\hat{\sigma}_{p_T^{min}}(c_t, k_g, \hat{s}) \propto \frac{1}{16 \pi \hat{s}^2} \int_{t_{min}}^{t_{max}} dt |c_t \mathcal{M}_{IR} + k_g \mathcal{M}_{UV}|^2$$

UV



$$t_{\frac{min}{max}} = \frac{1}{2} \left(m_h^2 - \hat{s} \mp \sqrt{m_h^4 - 2 \hat{s} (m_h^2 + 2 (p_T^{min})^2) + \hat{s}^2} \right)$$

$$\frac{\sigma_{p_T^{min}}(c_t, k_g)}{\sigma_{p_T^{min}}^{SM}} = (c_t + k_g)^2 + \delta c_t k_g + \kappa k_g^2$$

degeneracy

$$\sigma_{p_T^{min}}(c_t, k_g) = \int_{s_{min}/s}^1 d\tau \mathcal{L}_{part}(\tau) \hat{\sigma}_{p_T^{min}}(c_t, k_g, \tau s)$$

resolve UV vs IR

p_T^{min} [GeV]	$\sigma_{p_T^{min}}^{SM}$ [fb]	δ	κ
100	2200	0.016	0.023
150	840	0.069	0.13
200	350	0.20	0.31
250	160	0.39	0.56
300	75	0.61	0.89
350	38	0.86	1.3
400	20	1.1	1.8
450	11	1.4	2.3
500	6.3	1.7	2.9
550	3.7	2.0	3.6
600	2.2	2.3	4.4
650	1.4	2.6	5.2
700	0.87	3.0	6.2
750	0.56	3.3	7.2
800	0.37	3.7	8.4

$$\tilde{\kappa}_g \frac{\alpha_s}{12\pi} \frac{h}{v} G_{\mu\nu}^a \tilde{G}^{\mu\nu a} \quad i \frac{m_t}{v} \bar{u} \gamma_5 u A^0$$

$$\frac{\sigma_{p_T^{min}}(c_t, k_g)}{\sigma_{p_T^{min}}^{SM}} = (c_t + k_g)^2 + \delta c_t k_g + \kappa k_g^2 \quad \text{add CPV coupling}$$

$$\frac{\sigma_{p_T^{min}}}{\sigma_{p_T^{min}}^{SM}} = \tilde{\gamma} \tilde{\kappa}_t^2 + \tilde{\delta} \tilde{\kappa}_t \tilde{\kappa}_g + \tilde{\epsilon} \tilde{\kappa}_g^2$$

\sqrt{s} [TeV]	p_T^{min} [GeV]	$\sigma_{p_T^{min}}^{SM}$ [fb]	δ	ϵ	gg, qg [%]	$\tilde{\gamma}$	$\tilde{\delta}$	$\tilde{\epsilon}$
14	100	2200	0.016	0.023	67, 31	2.3	-3.8	2.3
	150	830	0.069	0.13	66, 32	2.3	-4.0	2.5
	200	350	0.20	0.31	65, 34	2.3	-4.4	2.9
	250	160	0.39	0.56	63, 36	2.3	-4.9	3.5
	300	75	0.61	0.89	61, 38	2.3	-5.7	4.2
	350	38	0.86	1.3	58, 41	2.3	-6.6	5.1
	400	20	1.1	1.8	56, 43	2.3	-7.6	6.2
	450	11	1.4	2.3	54, 45	2.4	-8.9	7.4
	500	6.3	1.7	2.9	52, 47	2.4	-10	8.8
	550	3.7	2.0	3.6	50, 49	2.4	-12	10
	600	2.2	2.3	4.4	48, 51	2.4	-14	12
	650	1.4	2.6	5.2	46, 53	2.4	-16	14
	700	0.87	3.0	6.2	45, 54	2.4	-18	16
	750	0.56	3.3	7.2	43, 56	2.4	-20	18
	800	0.37	3.7	8.4	42, 57	2.5	-23	21
100	500	970	1.8	3.1	72, 28			
	2000	1.0	14	78	56, 43			

p_T dependence
resolves CP odd
couplings

Top partner models

- Supersymmetry (stops)
- Composite Higgs (M_{CHM_5})

Composite pGB Higgs

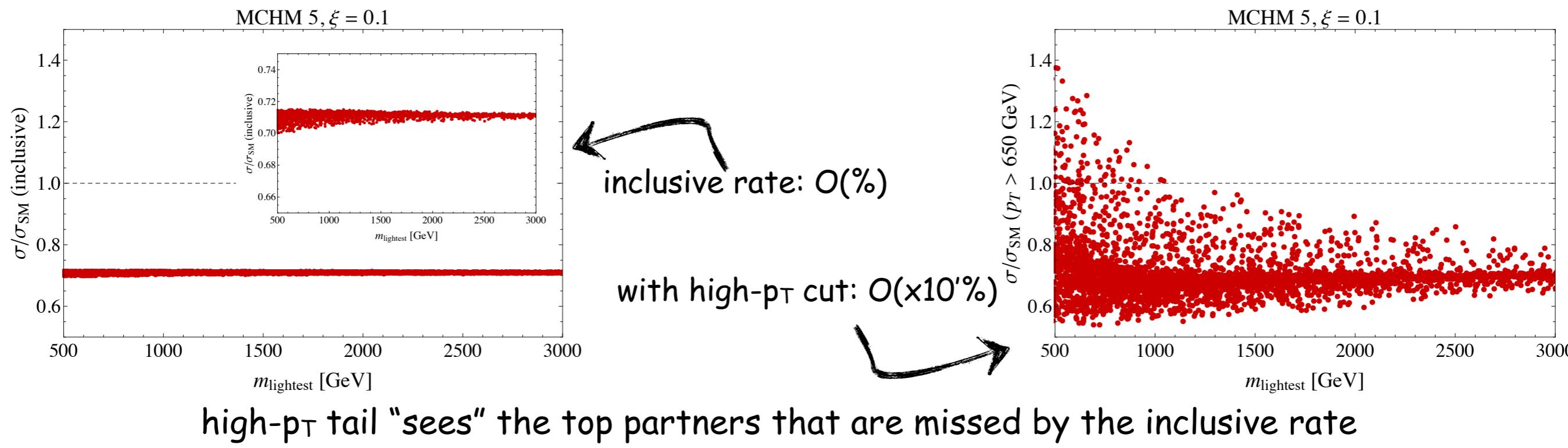
$$c_t + k_g = v \left(\frac{\partial}{\partial h} \log \det \mathcal{M}_t(h) \right)_{\langle h \rangle}$$

MCHM₅

$$c_t + k_g = (1 - 2\xi) / \sqrt{1 - \xi} \quad \sqrt{\xi} = v/f$$

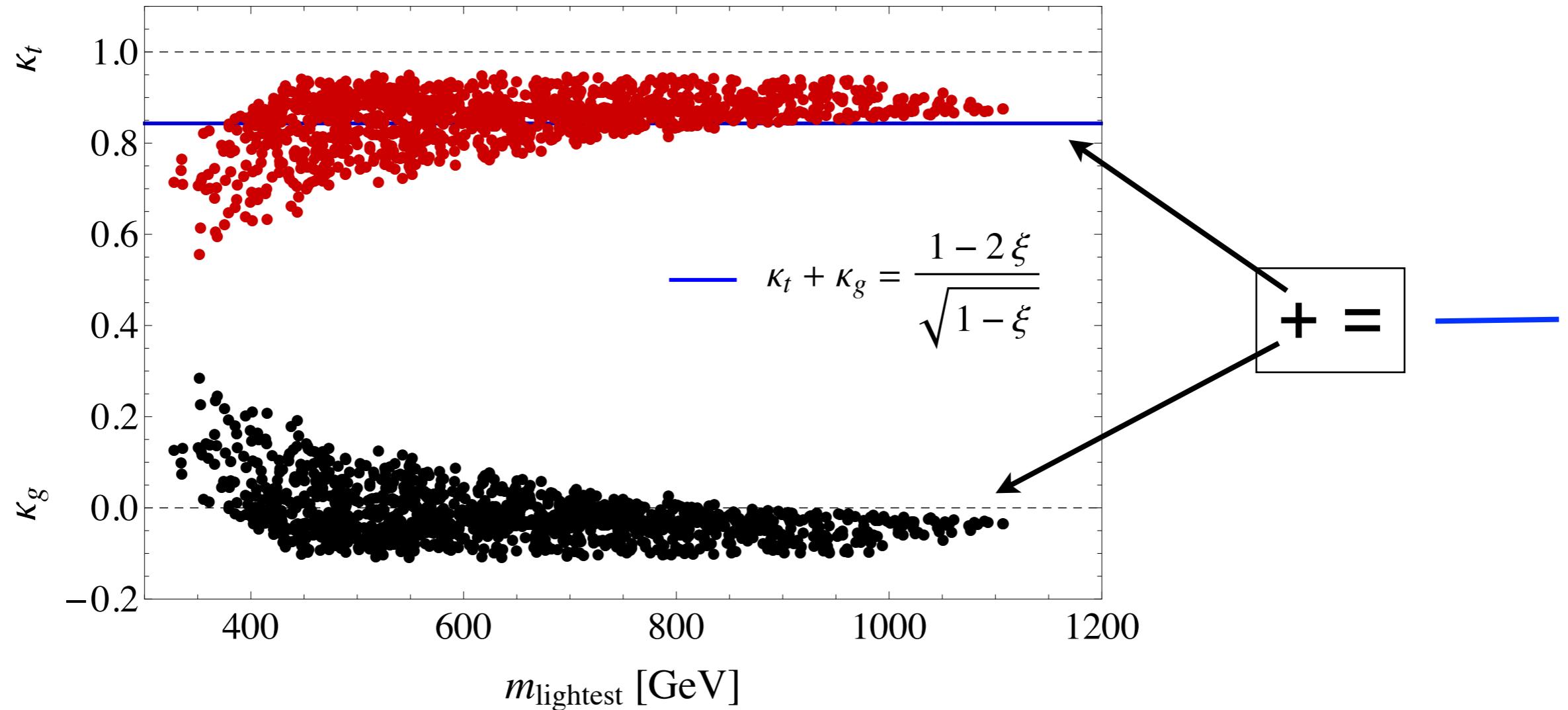
see e.g. Low Vichi & Azatov, Galloway

independent of top partner
spectrum and couplings



see also Azatov, Paul '13
Banfi, Martin, Sanz '13

MCHM₅, $\xi = 0.1$, $110 \text{ GeV} < m_h < 140 \text{ GeV}$



Supersymmetry

$$m_h^2 = m_Z^2 \cos^2 \beta + \frac{3y_t^2 m_t^2}{(4\pi)^2} \left[\log \left(\frac{m_S^2}{m_t^2} \right) + X_t^2 \left(1 - \frac{X_t^2}{12} \right) \right]$$

$$\frac{\Gamma(gg \rightarrow h)}{\Gamma(gg \rightarrow h)_{SM}} = (1 + \Delta_t)^2,$$

$$\Delta_t \approx \frac{m_t^2}{4} \left(\frac{1}{m_{\tilde{t}_1}^2} + \frac{1}{m_{\tilde{t}_2}^2} - \frac{A_t - \frac{\mu}{\tan \beta}}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2} \right)$$

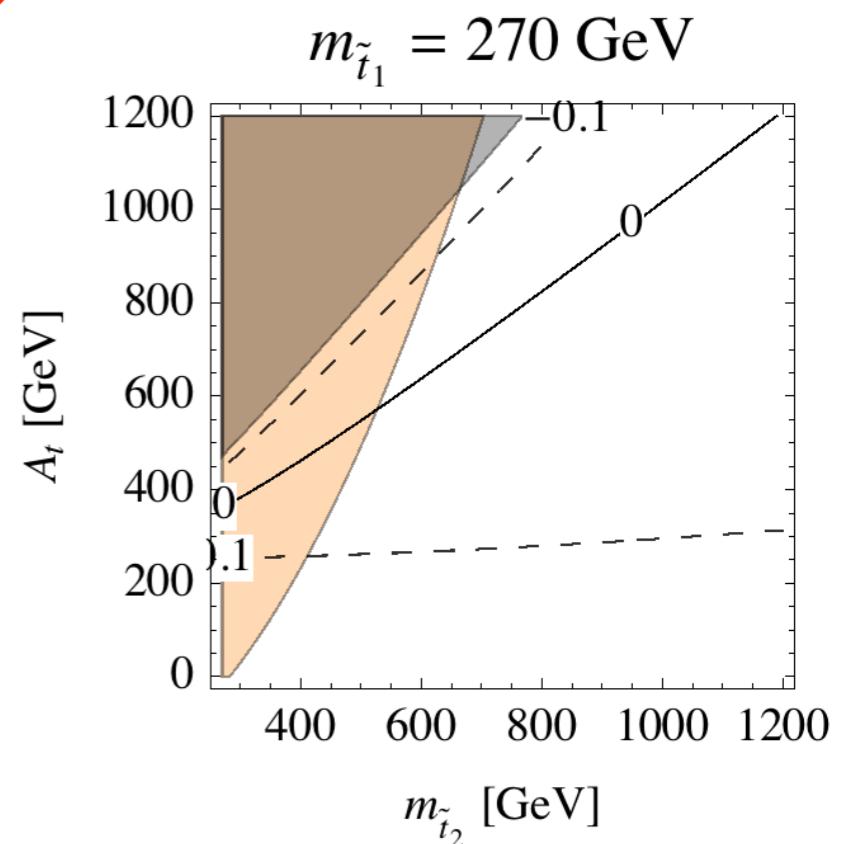
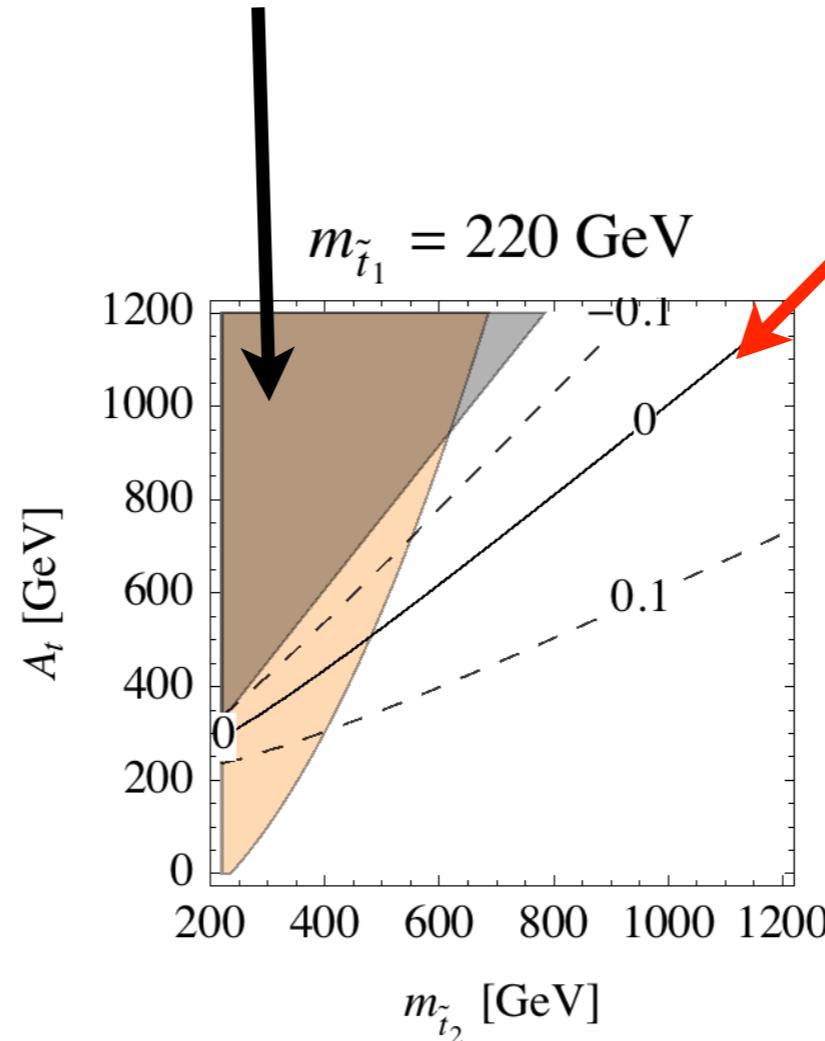
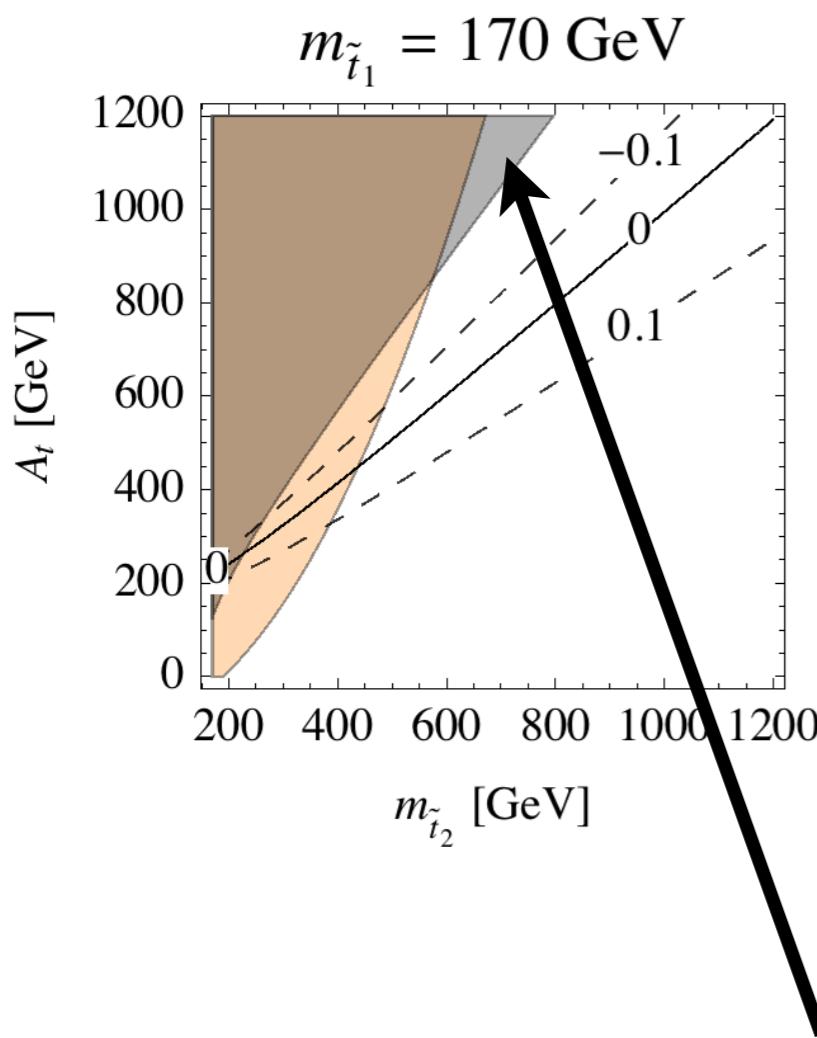
flat direction

flat direction

Real soft masses

$$m_Q, m_U \in \mathbb{R}$$

$$\Delta_t \approx 0$$

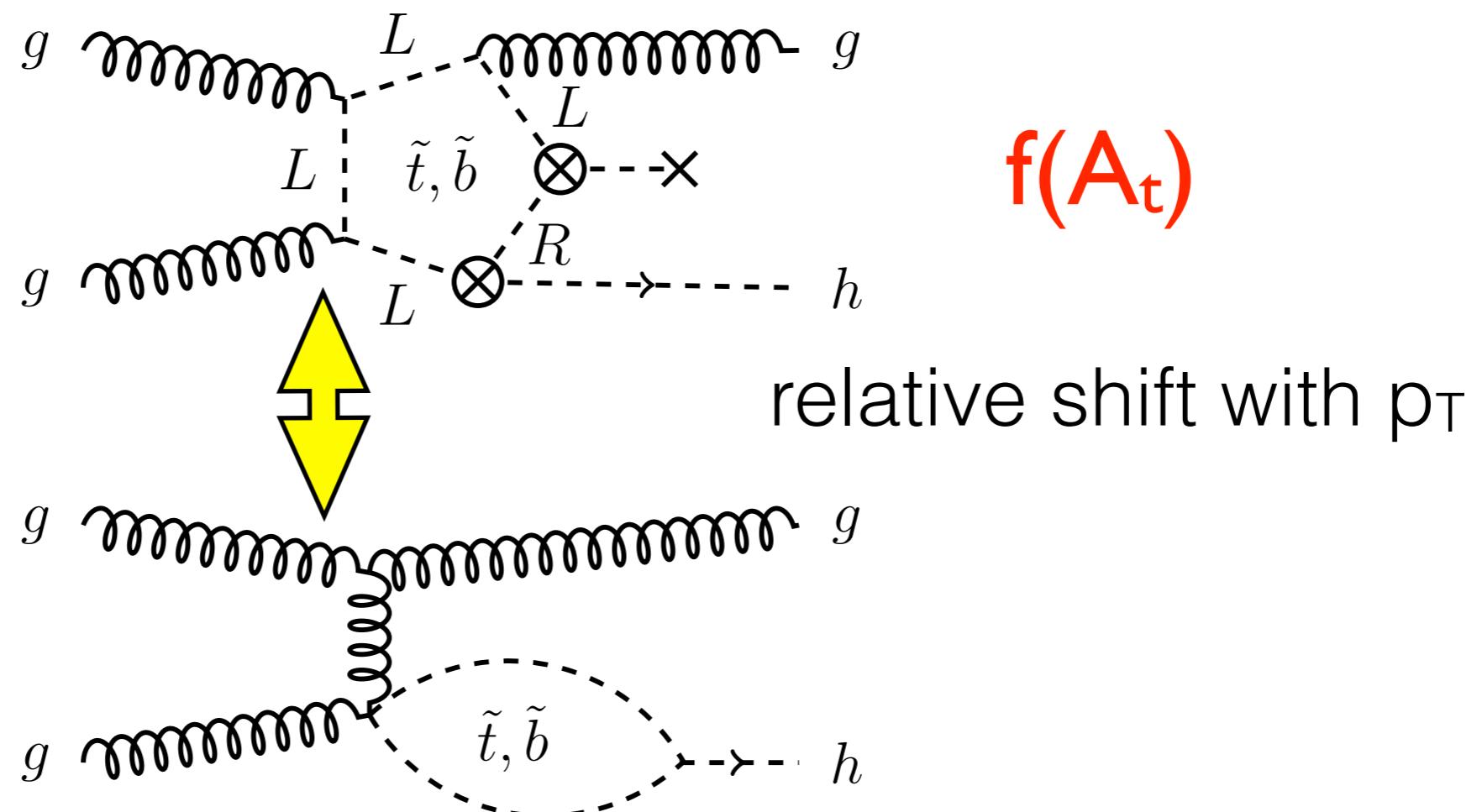


Charge-color breaking vacua

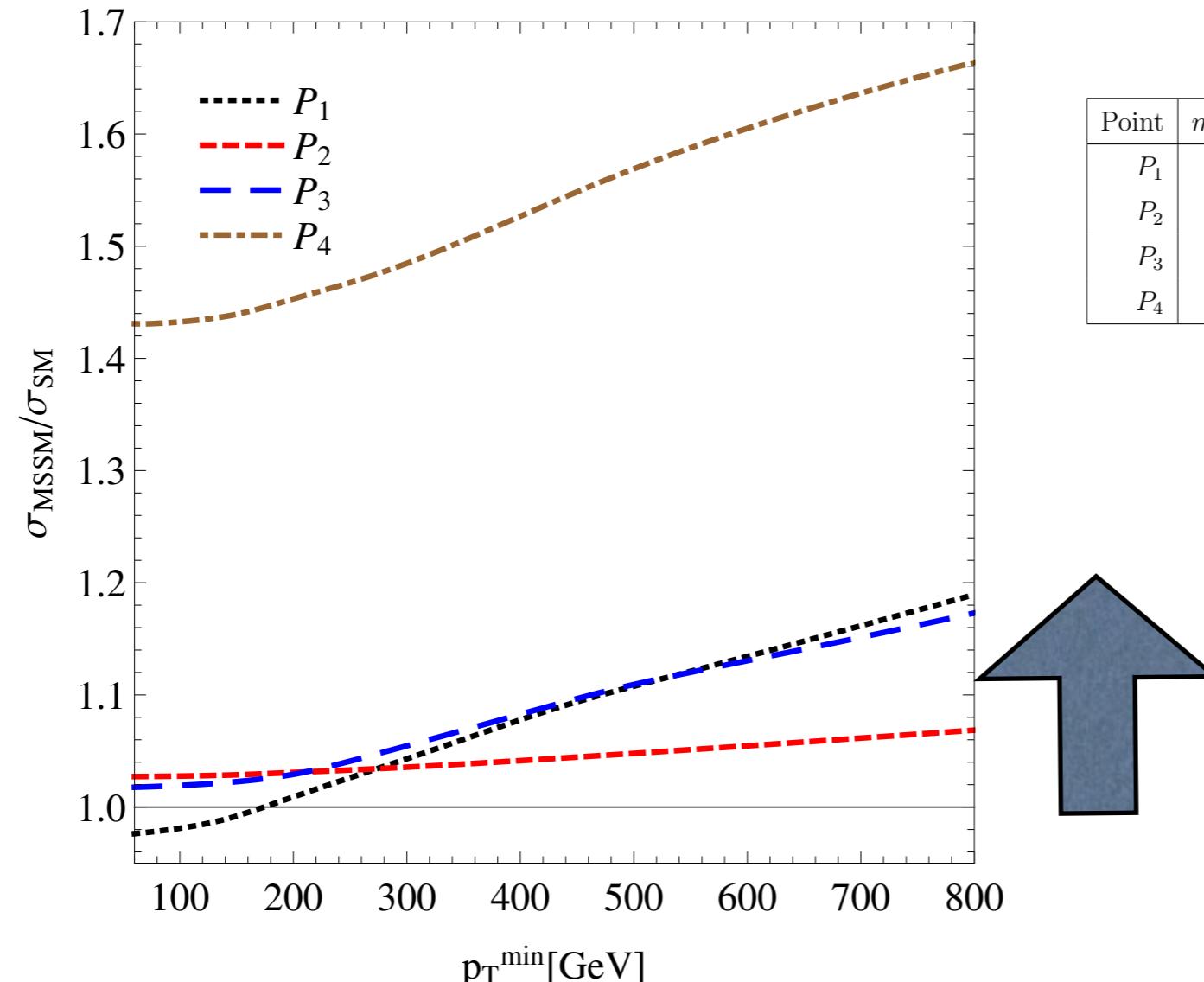
$$A_t^2 + 3\mu^2 > a \cdot \left(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 \right)$$

$$h A_t \tilde{t}_L \tilde{t}_R^*$$

Break flat direction



p_T dependent shift mostly from
 A_t independent diagrams



flat direction
 $\Delta_t \approx 0$

Ratio of cross-sections

$$\mathcal{R}(c_t, k_g) = \frac{\sigma_{650\text{ GeV}}}{\sigma_{150\text{ GeV}}}(c_t, k_g) \frac{K_{650}}{K_{150}}$$

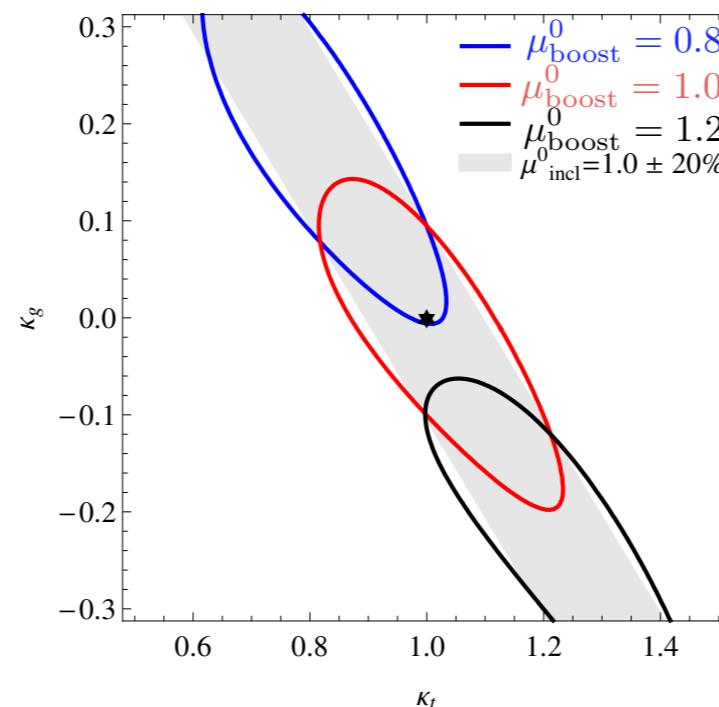
reduced th-uncertainty
(estimate using MCFM, LO → NLO large m_t)

Fit assuming estimated stat. & sys. errors

$$\chi^2(c_t, k_g) = \left(\frac{\mathcal{R}(c_t, k_g) - \mathcal{R}^*}{\delta\mathcal{R}} \right)^2 + \left(\frac{\mu_{\text{incl}}(c_t, k_g) - \mu_{\text{incl}}^*}{\delta\mu_{\text{incl}}} \right)^2$$

$$\delta\mathcal{R} = \mathcal{R}^* \sqrt{\frac{1}{N_{150\text{ GeV}}} + \frac{1}{N_{650\text{ GeV}}} + 2 \cdot 0.1^2}$$

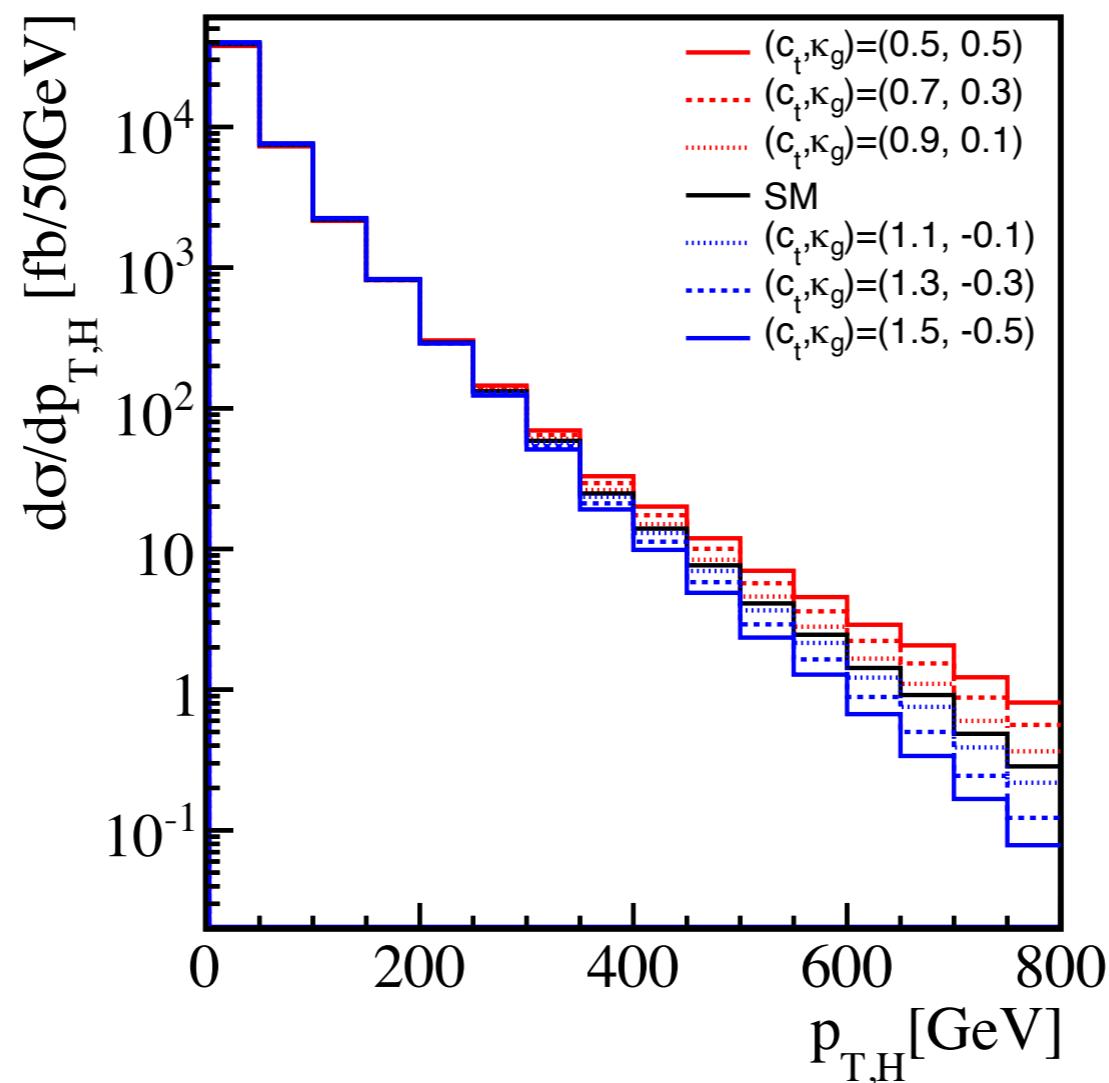
high p_T tail discriminates short and long distance physics contribution to $gg \rightarrow h$
 $\sqrt{s} = 14$ TeV, $\int dt \mathcal{L} = 3ab^{-1}$, $p_T > 650$ GeV
(partonic analysis in the boosted "ditau-jets" channel)



- NLO_{mt} recently calculated (1410.5806),
uncertainty still unknown, will it spoil the sensitivity ?
- Realistic study with backgrounds at reco-level

(HL)-LHC14

try to resolve worst case:
inclusive cross-section = SM



BOOSTED $H \rightarrow 2\ell + \not{p}_T$

M. Schlaffer, M. Spannowsky, M. Takeuchi, AW

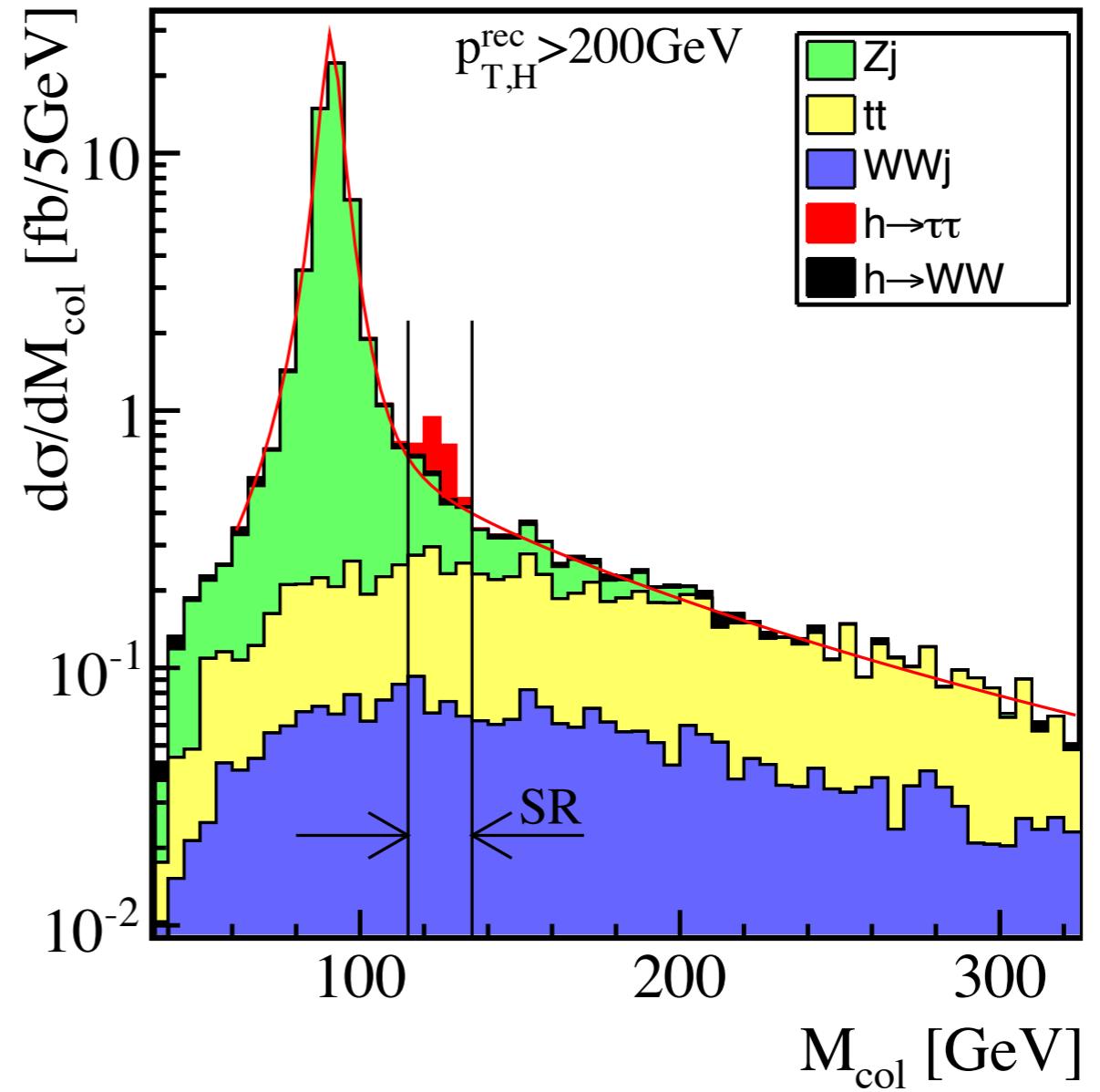
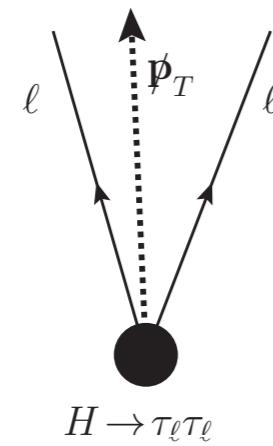
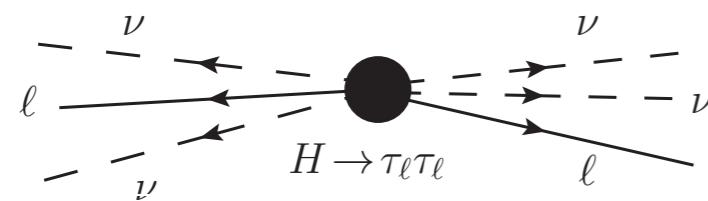
$$H \rightarrow WW^* \rightarrow 2\ell + \nu\bar{\nu}$$

$$H \rightarrow \tau_\ell \tau_\ell$$

see also Buschmann et al for
Higgs + 2j,

Collinear mass

$$H \rightarrow \tau_\ell \tau_\ell$$



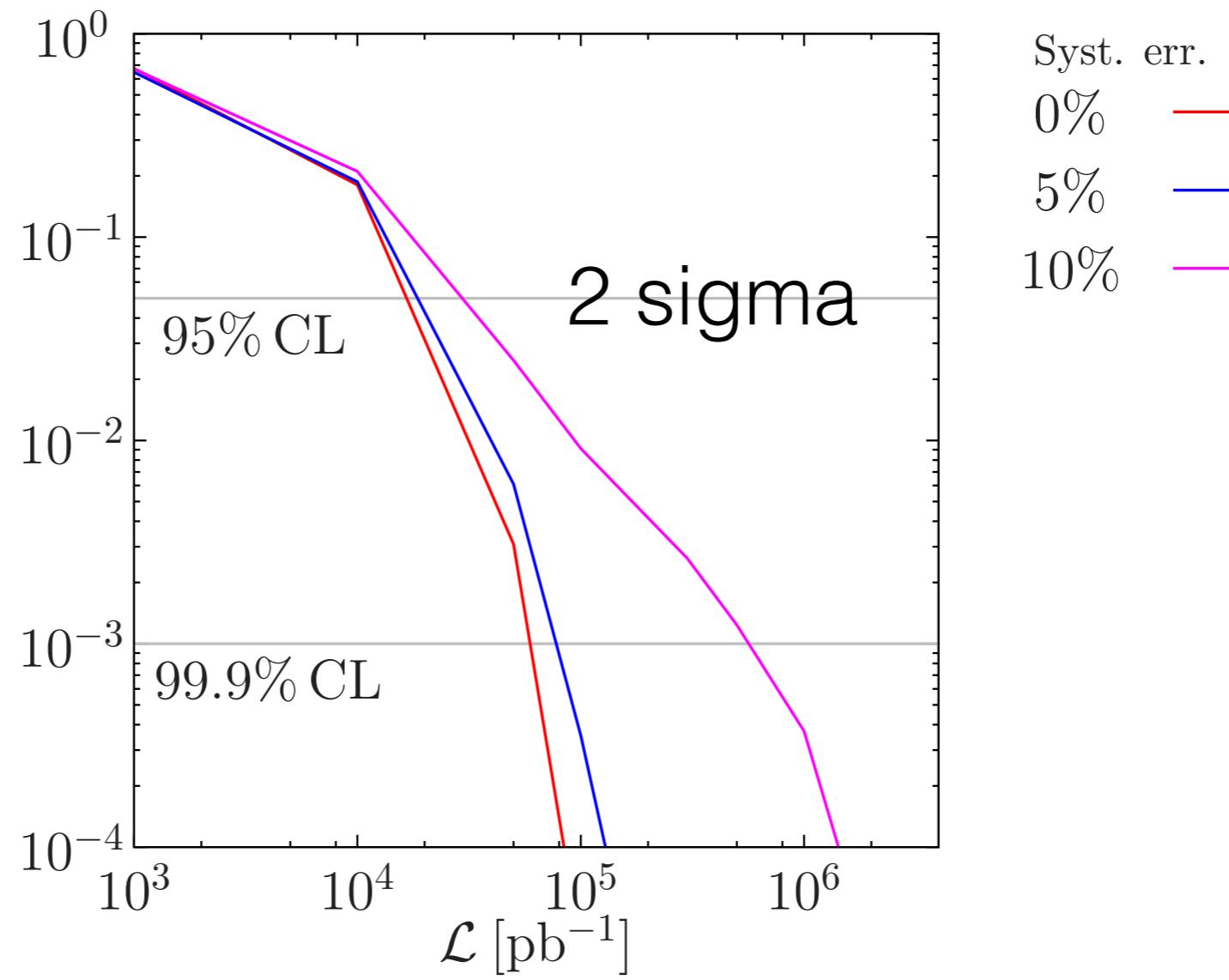
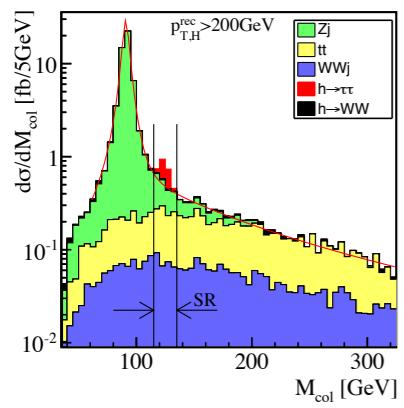
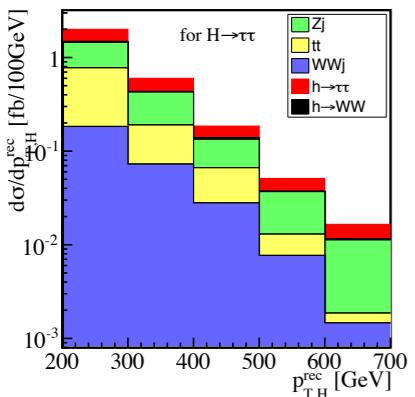
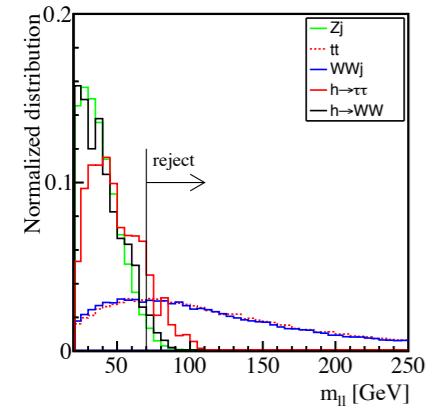
$$\not{p}_T = \mathbf{p}_{T,\nu_1,\text{col}} + \mathbf{p}_{T,\nu_2,\text{col}} : \quad \mathbf{p}_{\nu_1,\text{col}} = \alpha_1 \mathbf{p}_{\ell_1}, \quad \mathbf{p}_{\nu_2,\text{col}} = \alpha_2 \mathbf{p}_{\ell_2}.$$

$$p_{\text{col}} = p_{\nu_1,\text{col}} + p_{\nu_2,\text{col}} + p_{\ell_1} + p_{\ell_2}, \quad M_{\text{col}}^2 = p_{\text{col}}^2.$$

Cut flow for H -> tau tau

Event rate [fb]	$H \rightarrow \tau\tau$	$H \rightarrow WW^*$	$W_\ell W_\ell + \text{jets}$	$Z_{\rightarrow \tau\tau} + \text{jets}$	$t_\ell \bar{t}_\ell + \text{jets}$	S/B	S/\sqrt{B}
0. Nominal cross section	3149.779	10719.207	580.000	$1.01 \cdot 10^4$	$1.02 \cdot 10^5$	—	—
1. $n_\ell = 2$, opposite-sign	118.043	323.531	195.033	347.516	$3.72 \cdot 10^4$	—	—
2. $m_{\ell\ell} > 20$ GeV	117.733	264.723	189.522	315.201	$3.57 \cdot 10^4$	—	—
3. $p_{T,H}^{\text{rec}} > 200$ GeV	1.987	3.834	91.273	104.434	$1.28 \cdot 10^3$	0.004	2.62
4. $n_j^{\text{fat}} = 1$ ($p_{T,j} > 200$ GeV)	0.957	1.858	50.443	58.810	395.602	0.006	2.17
5. $n_b = 0$	0.940	1.825	48.855	57.068	105.851	0.01	3.29
6. \not{p}_T inside the two leptons	0.923	0.533	20.215	55.551	44.050	0.01	2.30
7. $m_{\ell\ell} < 70$ GeV	0.796	0.490	3.860	53.985	8.511	0.02	2.73
8. $ M_{\text{col}} - m_H < 10$ GeV	0.749	0.046	0.298	1.019	0.758	0.38	9.56
$p_{T,H}^{\text{rec}} > 300$ GeV	0.234	0.012	0.115	0.343	0.166	0.39	5.40
$p_{T,H}^{\text{rec}} > 400$ GeV	0.068	0.006	0.042	0.106	0.049	0.38	2.88
$p_{T,H}^{\text{rec}} > 500$ GeV	0.021	0.001	0.014	0.038	0.010	0.36	1.55
$p_{T,H}^{\text{rec}} > 600$ GeV	0.008	0.001	0.006	0.014	0.005	0.32	0.89

Example: $k_g = 0.5$

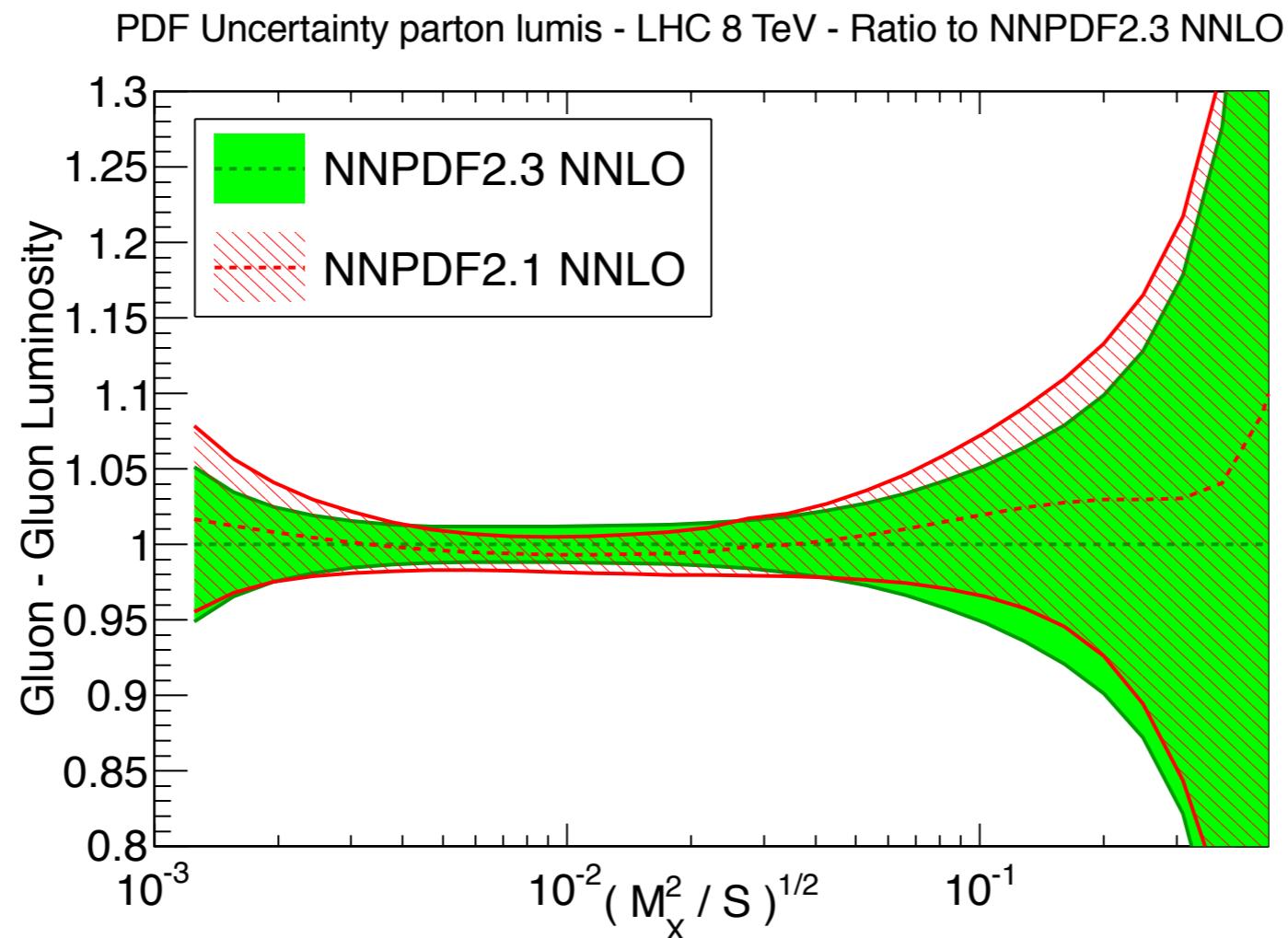


Boosted Higgs breaks degeneracy!

Conclusion

- Boosted gluon fusion gives additional insights
- Resolves loop dynamics, complementary to ttH and off-shell Higgs ($H^* \rightarrow ZZ \rightarrow 4l$)
- Breaks degeneracies in EFT, Susy and MCHM
- NLO_{mt} desirable

pdf uncertainties



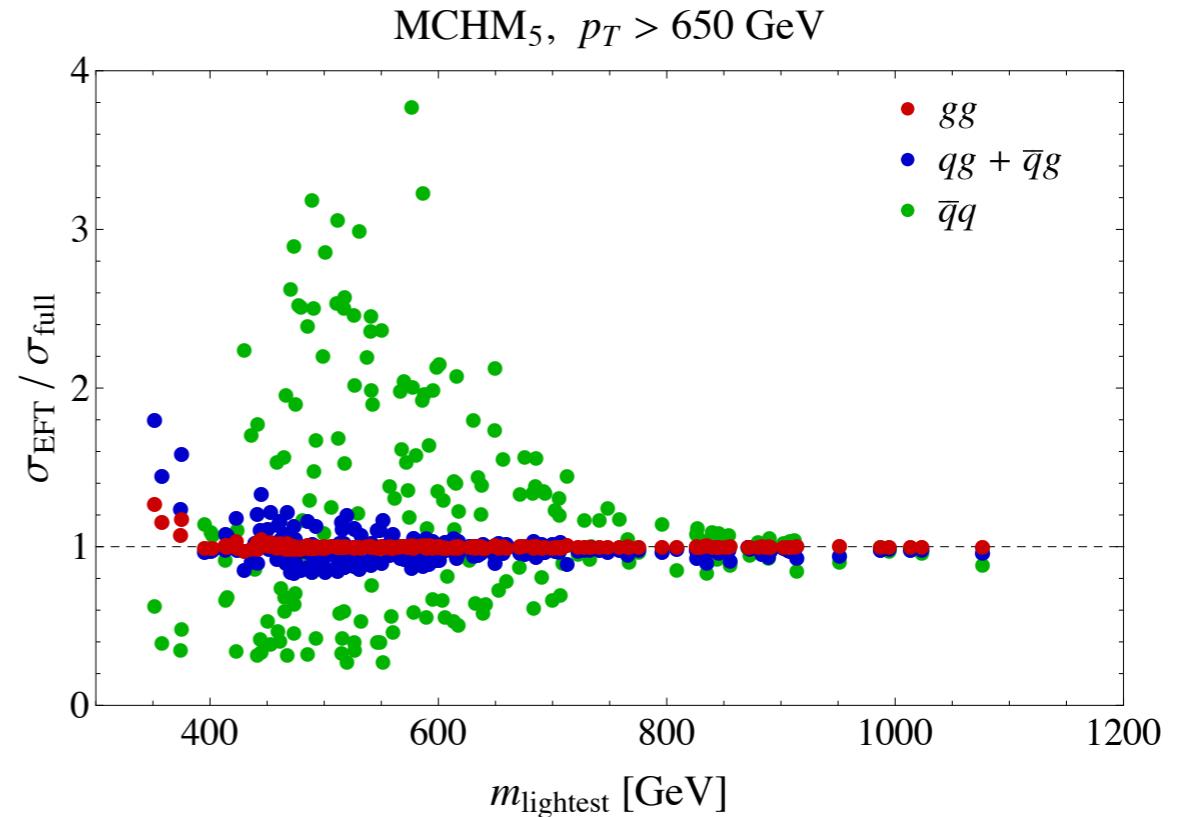
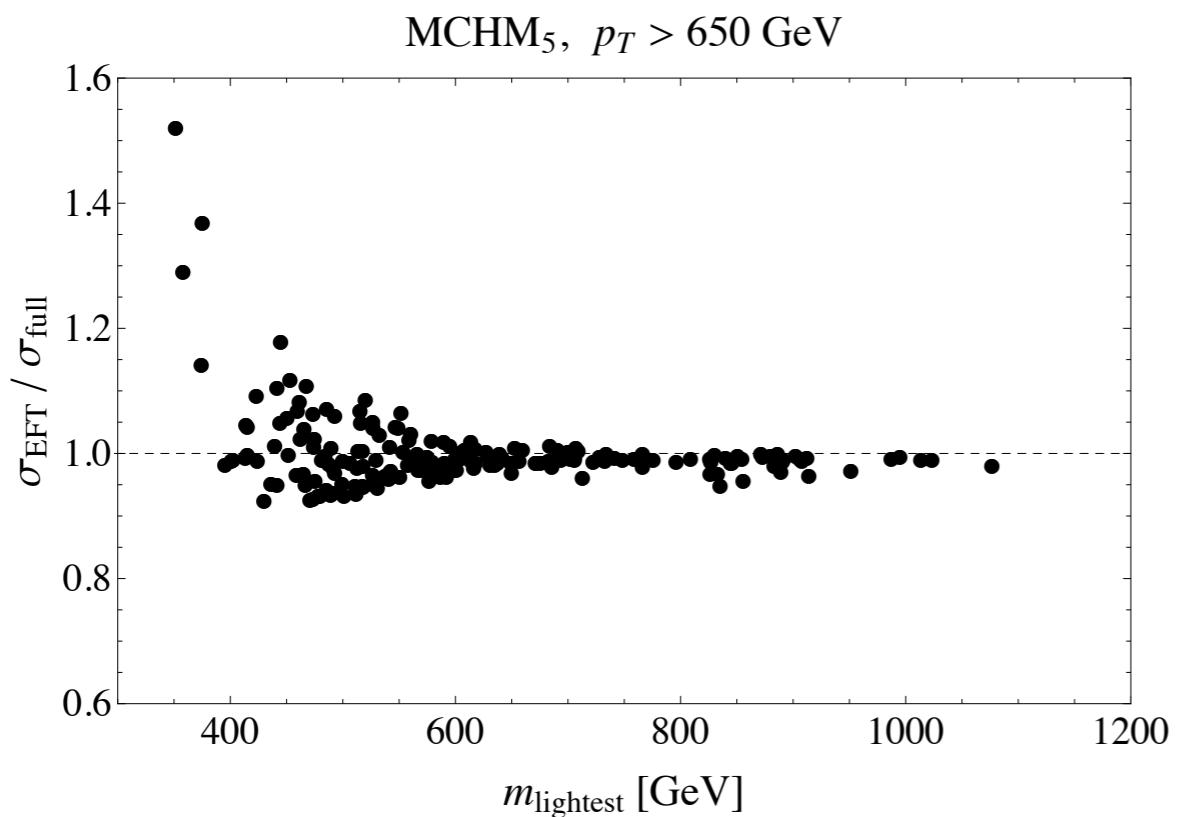


Figure 4: Ratio of the boosted Higgs cross section computed within the effective theory to the exact cross section computed retaining the complete form factors, versus the mass of the lightest top partner, for a sample set of points in the parameter space of MCHM₅. A transverse momentum cut $p_T > 650$ GeV is applied. The left panel shows the total cross section $pp \rightarrow h + \text{jet}$, whereas the right panel shows the three partonic channels $gg, qg, q\bar{q} \rightarrow h + \text{jet}$ individually.

