Production of heavy Higgs bosons and decay into top quarks at the LHC

Peter Galler

Humboldt-Universität zu Berlin, Institut für Physik

in collaboration with

Werner Bernreuther, Clemens Mellein, Zong-Guo Si, Peter Uwer

based on PhysRevD.93.034032/ arXiv:1511.05584

LHCP 2016, 15.06.2016

Motivation

- 2012: Discovery of the Higgs [ATLAS, Phys. Lett. B716 (2012) 1; CMS, Phys. Lett. B716 (2012) 30]
  $\rightarrow$ at least 1 type of scalar elementary particle exists in nature
- Are there other types of spin-0 bosons (different masses, pseudoscalars)? For example: another Higgs-doublet $\rightarrow$ 2HDM, SUSY
- Heavy Higgs bosons are experimentally less constrained than additional light Higgs bosons
- high mass and Yukawa coupling $\sim m_f$ $\rightarrow$ study resonance in the $t\bar{t}$ decay channel

Motivation

- 2012: Discovery of the Higgs [ATLAS, Phys. Lett. B716 (2012) 1; CMS, Phys. Lett. B716 (2012) 30]
  $\rightarrow$ at least 1 type of scalar elementary particle exists in nature
- Are there other types of spin-0 bosons (different masses, pseudoscalars)? For example: another Higgs-doublet $\rightarrow$ 2HDM, SUSY
- Heavy Higgs bosons are experimentally less constrained than additional light Higgs bosons
- high mass and Yukawa coupling $\sim m_f$ $\rightarrow$ study resonance in the $t\bar{t}$ decay channel

Motivation

- 2012: Discovery of the Higgs [ATLAS, Phys. Lett. B716 (2012) 1; CMS, Phys. Lett. B716 (2012) 30]
  $\rightarrow$ at least 1 type of scalar elementary particle exists in nature
- Are there other types of spin-0 bosons (different masses, pseudoscalars)? For example: another Higgs-doublet $\rightarrow$ 2HDM, SUSY
- Heavy Higgs bosons are experimentally less constrained than additional light Higgs bosons
- high mass and Yukawa coupling $\sim m_f$ $\rightarrow$ study resonance in the $t\bar{t}$ decay channel

Motivation

- 2012: Discovery of the Higgs [ATLAS, Phys. Lett. B716 (2012) 1; CMS, Phys. Lett. B716 (2012) 30]
  $\rightarrow$ at least 1 type of scalar elementary particle exists in nature
- Are there other types of spin-0 bosons (different masses, pseudoscalars)? For example: another Higgs-doublet $\rightarrow$ 2HDM, SUSY
- Heavy Higgs bosons are experimentally less constrained than additional light Higgs bosons
- high mass and Yukawa coupling $\sim m_f$ $\rightarrow$ study resonance in the $t\bar{t}$ decay channel

2-Higgs-Doublet Model (2HDM) in a nutshell

- $\Phi_1 = \begin{pmatrix} \xi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \varphi_1 + i\chi_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \xi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \varphi_2 + i\chi_2) \end{pmatrix}$
- $\boxed{\tan\beta = \frac{v_2}{v_1}}$
- top-Yukawa coupling: $\mathcal{L}_{\mathrm{Yuk},t} = -\frac{m_t}{v} \sum_j \bar{t}(a_{jt} - i b_{jt} \gamma_5) t \phi_j$
- reduced Yukawa couplings a_t, b_t depend on α or α_1, α_2, α_3 and β
- use flavour conserving type-II 2HDM (d_R,ℓ_R couple to Φ_1, u_R couple to Φ_2) because of strong exp. constraints on FCNC

CP conserving case

$$\begin{aligned} h &= -\varphi_1 \sin\alpha + \varphi_2 \cos\alpha \\ H &= \varphi_1 \cos\alpha + \varphi_2 \sin\alpha \\ A &= -\chi_1 \sin\beta + \chi_2 \cos\beta \end{aligned}$$

CP violating case

$$\begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{pmatrix} = R(\alpha_1, \alpha_2, \alpha_3) \begin{pmatrix} \varphi_1 \\ \varphi_2 \\ A \end{pmatrix}$$

$$H^+ = -\xi_1^+ \sin\beta + \xi_2^+ \cos\beta$$

for details see, e.g.:[Branco, Ferreira, Lavoura, Rebelo, Sher, Silva, arXiv:1106.0034]

2HDM-Type-II Scenarios

CP-conserving scenario I and II

$$\tan\beta = 0.7, \quad \alpha = \beta - \frac{\pi}{2}$$

	h	H	A
a_t	1	1.43	0
b_t	0	0	1.43
f_{VV}	1	0	0
$m(\mathrm{I})$ [GeV]	125	**550**	**510**
$\Gamma(\mathrm{I})$ [GeV]	0.004	34.56	49.28
$m(\mathrm{II})$ [GeV]	125	**550**	**700**
$\Gamma(\mathrm{II})$ [GeV]	0.004	34.49	75.28

CP-violating scenario III

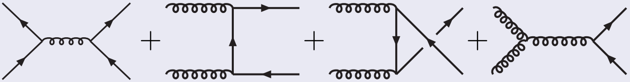
$$\tan\beta = 0.7, \alpha_1 = \beta,$$
$$\alpha_2 = \frac{\pi}{15}, \alpha_3 = \frac{\pi}{4}$$

	ϕ_1	ϕ_2	ϕ_3
a_t	0.98	0.86	-1.16
b_t	0.30	0.99	0.99
f_{VV}	0.98	-0.15	-0.15
$m(\mathrm{III})$ [GeV]	125	**500**	**800**
$\Gamma(\mathrm{III})$ [GeV]	0.004	36.55	128.16

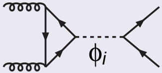
- h, ϕ_1 SM-like (alignment limit)
- H,A-Yukawa coupling to t quark $a_t, b_t = \cot\beta = 1.43 \Rightarrow$ enhanced
- H,A-Yukawa coupling to b quark $a_b, b_b = \tan\beta \Rightarrow$ suppressed $\rightarrow$ save to neglect
- f_{VV}: coupling to vector bosons
- m free parameter; Γ fixed by mass and couplings
- CPC-case I: mass degenerate; CPC-case II: mass non-degenerate

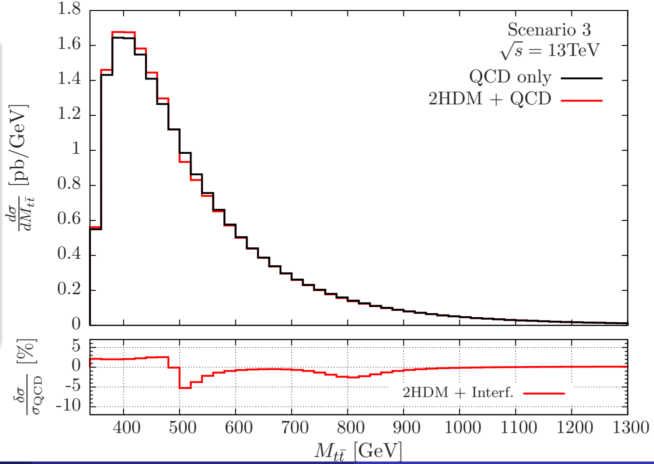
Leading Order

QCD contribution

$\mathcal{A}_{\text{QCD}} =$ 

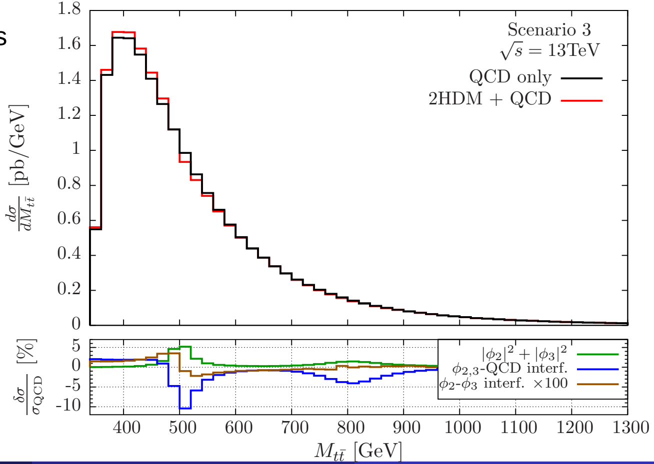
(pseudo-)scalar contribution

$\mathcal{A}_{\phi_j} =$ 



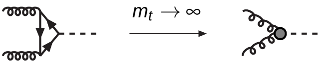
Different Contributions to the Leading Order

- effect of 2HDM most prominent in the resonant region
- interference with QCD important
- interference effects between different CPV scalars negligible
- How large are the contributions form the NLO QCD corrections?



Next-to-Leading Order – Heavy Top Quark Limit

- LO is already a 1-loop calculation
  $\Rightarrow$ NLO is a 2-loop calculation
- use effective $gg\phi$ vertex: $\mathcal{L}_{\text{eff}} = (f_S G^a_{\mu\nu} G^{\mu\nu}_a + f_P \varepsilon_{\mu\nu\rho\sigma} G^{\mu\nu}_a G^{\rho\sigma}_a)\phi$



- effective theory : leading order in the $1/m_t$ expansion of the $gg\phi$ vertex
- take higher orders of $1/m_t$ into account by using K-factor
  [Krämer, Laenen, Spira 1996]

$$\boxed{\sigma^{\text{approx}}_{\text{NLO}} = \frac{\sigma^{\text{eff}}_{\text{NLO}}}{\sigma^{\text{eff}}_{\text{LO}}} \sigma^{\text{full}}_{\text{LO}}}$$

- good approximation for $pp \to HX$
  Assumption: good approx. for $|pp \to \phi \to t\bar{t}|^2$
- no K-factor for QCD-interference

Next-to-Leading Order – Soft Gluon Approximation

- at LO: significant heavy Higgs contributions only in resonance region
- at NLO: redrestrict the calculation to the resonance region
- extract resonance/pole contribution by applying soft gluon approximation
- non-factorizing contributions from real and virtual corrections cancel exactly in soft gluon approximation [Fadin et al. '94, Melnikov et al. '96, Beenakker et al. '97, Dittmaier et al. 2014]

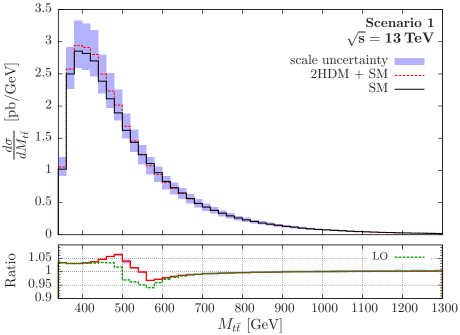
NLO Results - Inclusive Cross Section

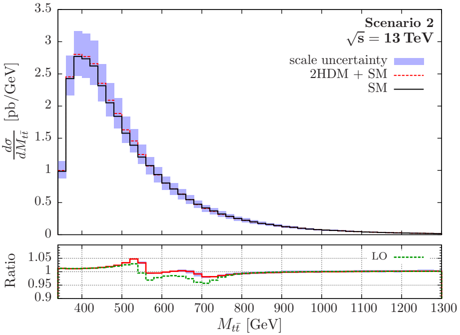
	Scenario 1	Scenario 2	Scenario 3
μ_0 [GeV]	265	312.5	325
σ_{QCDW} [pb]	$643.22^{+81.23}_{-77.71}$	$624.25^{+80.98}_{-76.19}$	$619.56^{+81.05}_{-75.72}$
σ_{2HDM} [pb]	$13.59^{+1.85}_{-1.64}$	$7.4^{+0.77}_{-0.78}$	$7.21^{+0.81}_{-0.77}$
$\sigma_{2HDM}/\sigma_{QCDW}$ [%]	2.1	1.2	1.2

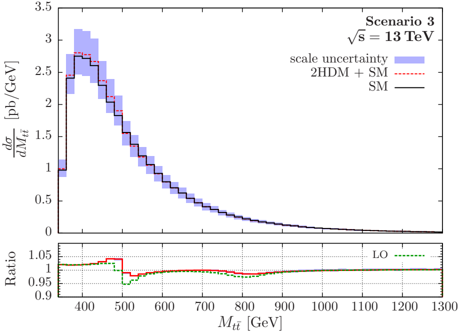
$$\mu_0 = \mu_R = \mu_F = \frac{m_2 + m_3}{4}$$

$$\mu \text{ variation: } \mu = \tfrac{\mu_0}{2}, \mu_0, 2\mu_0$$

- inclusive cross section shows only little sensitivity to heavy Higgs contribution (also good because $\delta\sigma_{t\bar{t}}^{\text{exp}} \sim 5\%$)
- study more sensitive observables

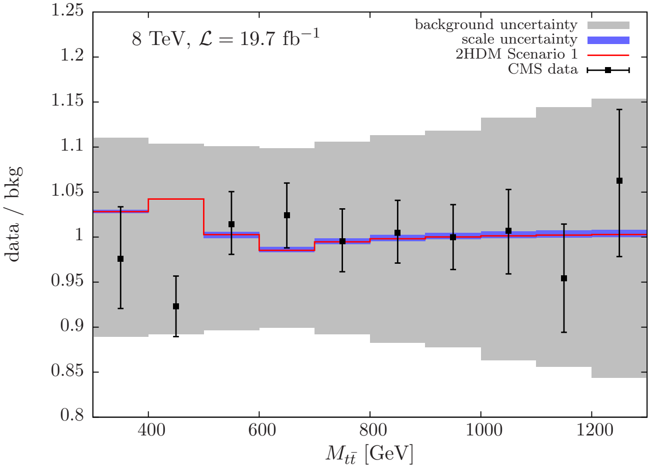






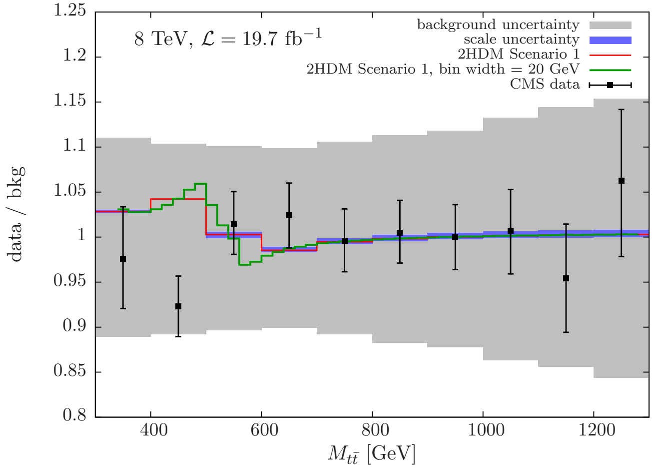
- heavy Higgs NLO corrections small w.r.t. to QCD background
- heavy Higgs NLO corrections important w.r.t. the heavy Higgs LO
- strongest effect in the mass degenerate case where resonances overlap

Comparison with CMS [arXiv:1309.2030]



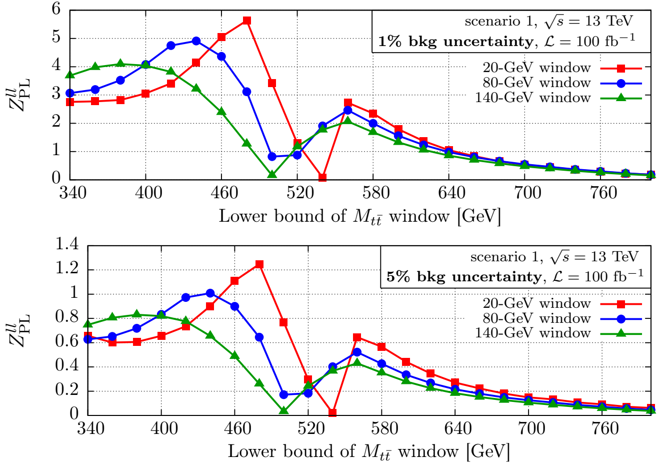
scenario 1 cannot be excluded by this measurement because of background uncertainty

Comparison with CMS [arXiv:1309.2030]



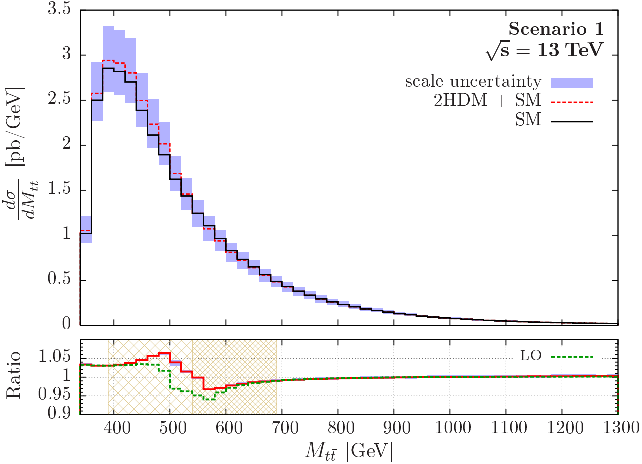
How to avoid peak-dip cancellation and find resonance experimentally?
$\Rightarrow$ sliding $M_{t\bar{t}}$ window

Signal Significance @NLO



- estimate significance form N_s and N_b in different $M_{t\bar{t}}$ windows
- smaller bin width $\rightarrow Z_{PL}$ larger
- smaller background uncertainty $\rightarrow Z_{PL}$ larger

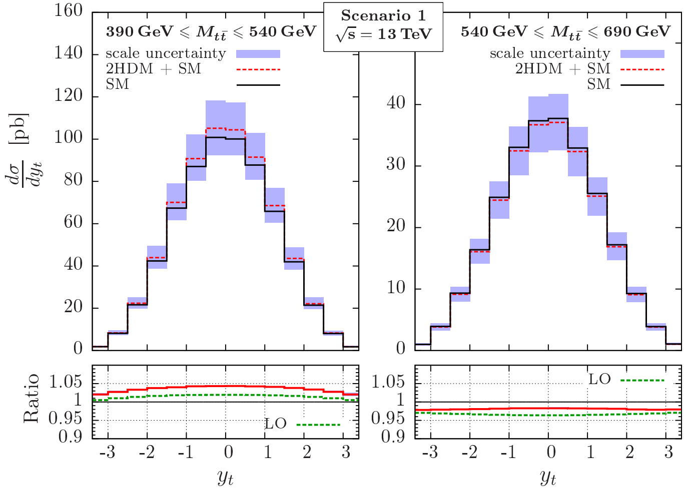
NLO Results – Applied Cuts



- strictly: approximation valid only in resonance region
- want to avoid peak-dip cancellation in other observables, e.g. y_t, $\cos\theta_{CS}$

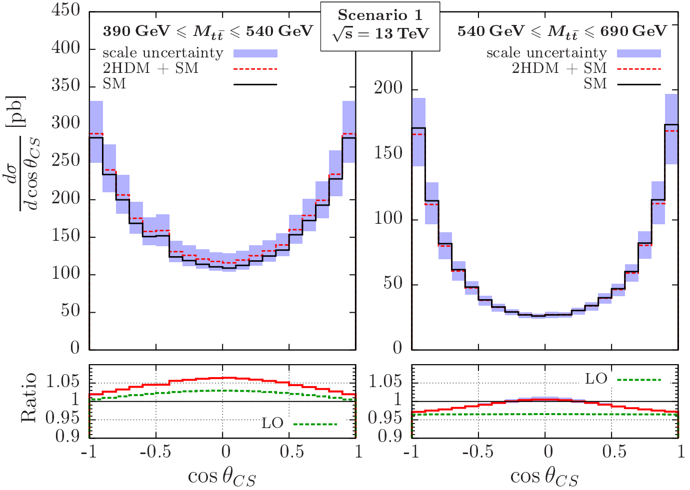
$\rightarrow$ apply cuts below and above the resonance to estimate maximal effect

Results – y_t



- NLO slightly increases effect above the resonance in the central region
  $\Rightarrow$ highest sensitivity in central region
- NLO decreases effect below the resonance

Results - $\cos\theta_{CS}$



- θ_{CS} defined in $t\bar{t}$ ZMF (@LO same as scattering angle)
- largest effects in central region: $\sim 7\%$ in lower $M_{t\bar{t}}$ bin
- $\geq 5\%$ for $-0.5 \leq \cos\theta_{CS} \leq 0.5$ (compare to: $\geq 5\%$ for 460GeV $\leq M_{t\bar{t}} \leq$ 500GeV)

Summary: Results on the Level of Stable Tops

- heavy Higgs-QCD interference must be taken into account
- NLO effect large w.r.t. Higgs-only cross section but small w.r.t. QCD background
- NLO corrections positive in resonance region
- NLO effects from heavy Higgs bosons can be enhanced by appropriate $M_{t\bar{t}}$ cuts (inclusive: 2% $\rightarrow$ with $M_{t\bar{t}}$-cut: $\sim$ 5% for scenario 1)
- m_{Φ} unknown $\rightarrow$ scan $M_{t\bar{t}}$ to avoid cancellation from peak-dip structure
- strong significance only achievable by reducing background uncertainty
- $\frac{d\sigma}{d\cos\theta_{CS}}$ is most sensitive observables studied so far
- studied $p_{\perp}^{t}$ distribution as well: heavy Higgs effect well below 5%

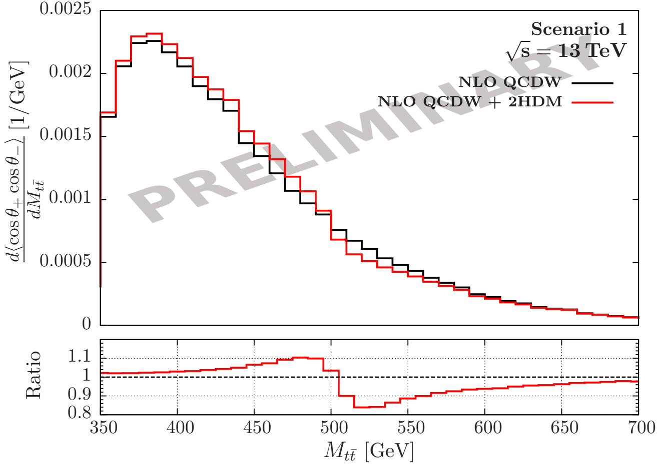
Outlook: Decay of the $t\bar{t}$ Pair

Further investigation by including the decay of the tops

Answer questions:

1. What can be learned about the CP nature of the spin-0 resonance?
2. Is it possible to increase the signal/background ratio by analysing spin dependent observables?
3. Would a 750 GeV resonance be experimentally accessible in the $t\bar{t}$ channel?

Expectation Value of Helicity Correlation vs. $M_{t\bar{t}}$



expectation value of helicity correlation: $\langle\cos\theta_+\cos\theta_-\rangle$

$\theta_\pm$: angle between $\ell^\pm$ and top (antitop) in top (antitop) rest frame

preliminary result: considerable increase in sensitivity when considering spin dependent observables with additional $M_{t\bar{t}}$ cuts

Thank you for your attention!

Additional Material

2-Higgs-Doublet Model (2HDM) – Yukawa Couplings

$$\mathcal{L}_{\Phi,\mathrm{Yuk}} \supset -\bar{Q}_L \left[\left(\lambda_1^d \Phi_1 + \lambda_2^d \Phi_2 \right) d_R + \left(\lambda_1^u \widetilde{\Phi}_1 + \lambda_2^u \widetilde{\Phi}_2 \right) u_R \right] + \text{h.c.}$$

$$\widetilde{\Phi}_i = i\tau_2 \Phi_i^*$$

Flavour conserving 2HDMs:

Type	u_R	d_R	ℓ_R
I	Φ_2	Φ_2	Φ_2
II	Φ_2	Φ_1	Φ_1
Lepton-specific (X)	Φ_2	Φ_2	Φ_1
Flipped (Y)	Φ_2	Φ_1	Φ_2

$\mathcal{L}_{\mathrm{Yuk}}$ in terms of Higgs mass eigenstates ϕ_j:

$$\mathcal{L}_{\mathrm{Yuk}} \supset -\sum_j \left[\frac{m_u}{v} \bar{u}(a_{ju} - i b_{ju}\gamma_5) u + \frac{m_d}{v} \bar{d}(a_{jd} - i b_{jd}\gamma_5) d \right] \phi_j$$

$$a_{ju} = \frac{R_{j2}}{\sin\beta}, \quad b_{ju} = R_{j3}\cot\beta, \quad a_{jd} = \frac{R_{j1}}{\cos\beta}, \quad b_{jd} = R_{j3}\tan\beta, \quad v = \sqrt{v_1^2 + v_2^2}$$

2-Higgs-Doublet Model (2HDM) – Gauge Couplings

Higgs-Gauge couplings are derived from $\mathcal{L}_{\Phi,\text{kin}}$

$$\begin{aligned}\mathcal{L}_{\Phi,\text{kin}} &= (D_\mu\Phi_1)^\dagger(D^\mu\Phi_1) + (D_\mu\Phi_2)^\dagger(D^\mu\Phi_2) \\ &= \mathcal{L}_{VV\Phi} + \mathcal{L}_{VV\Phi\Phi} + \mathcal{L}_{WZ\Phi\Phi} + \mathcal{L}_{W\gamma\Phi\Phi} + \mathcal{L}_{Z\Phi\Phi} + \mathcal{L}_{W\Phi\Phi} + \mathcal{L}_{\gamma\Phi\Phi}\end{aligned}$$

relevant terms for decay width

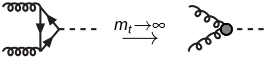
$$\begin{aligned}\mathcal{L}_{VV\Phi} &= f_{VV\phi_i}\left(\frac{2m_W^2}{v}W_\mu^+W^{-\mu} + \frac{m_Z^2}{v}Z_\mu Z^\mu\right)\phi_i \\ \mathcal{L}_{Z\Phi\Phi} &= \frac{m_Z}{v}f_{Z\phi_j\phi_k}(\phi_j \overleftrightarrow{\partial_\mu}\phi_k)Z^\mu\end{aligned}$$

with

$$\begin{aligned}f_{VV\phi_i} &= R_{i1}\cos\beta + R_{i2}\sin\beta \\ f_{Z\phi_j\phi_k} &= (R_{i2}R_{j3} - R_{i3}R_{j2})\cos\beta + (R_{i3}R_{j1} - R_{i1}R_{j3})\sin\beta\end{aligned}$$

Next-to-Leading Order – Effective $gg\phi$ Vertex

LO is already a 1-loop calculation
$\Rightarrow$ NLO is a 2-loop calculation
Use effective $gg\phi$ vertex:
$\mathcal{L}_{\text{eff}} = (f_S G^a_{\mu\nu} G^{\mu\nu}_a + f_P \varepsilon_{\mu\nu\rho\sigma} G^{\mu\nu}_a G^{\rho\sigma}_a)\phi$

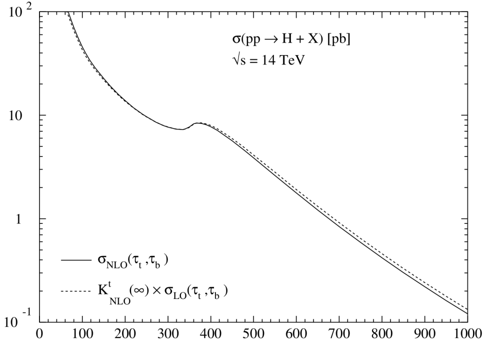


Effective theory : leading order in the $1/m_t$ expansion of the $gg\phi$ vertex
$\to$ take higher orders of $1/m_t$ into account by using K-factor

[Krämer, Laenen, Spira 1996]

$$\boxed{\sigma^{\text{approx}}_{\text{NLO}} = \frac{\sigma^{\text{eff}}_{\text{NLO}}}{\sigma^{\text{eff}}_{\text{LO}}} \sigma^{\text{full}}_{\text{LO}}}$$

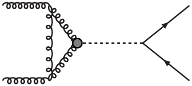
Good approximation for Higgs production:

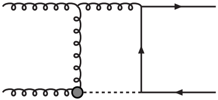


- major part of NLO QCD corrections originates from soft/collinear gluons which do not resolve the effective coupling
- here we assume that this is true for the process $pp \to \phi \to t\bar{t}$ as well

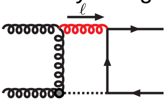
Next-to-Leading Order – Soft Gluon Approximation

- Seen in LO: significant contributions form the extended Higgs sector to $t\bar{t}$ production only in resonance region
- at NLO: restrict the calculation to the resonance region

   a) factorizing contributions, e.g. 

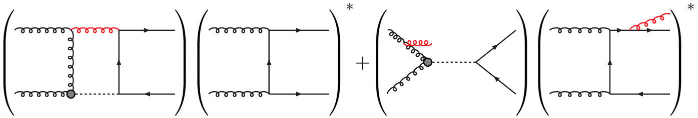
   b) non-factorizing contributions, e.g. 

- extract pole contribution by soft gluon approximation



$$\xrightarrow{\ell\to 0} \quad \sim \frac{1}{s - m_\phi^2 + i\Gamma_\phi m_\phi}$$

$\Rightarrow$ non-factorizing contributions from real and virtual corrections cancel



$$\Big|_{\text{soft-gluon approx.}} = 0$$

Leading Order Matrix Elements

$$|\overline{\mathcal{M}_\phi}|^2 = \frac{s^3 m_t^3}{2C_F v^2}\Big\{(|\tilde{f}_{S_2}|^2 + 4|\tilde{f}_{P_2}|^2)(a_{2t}^2\beta_t^2 + b_{2t}^2) + (|\tilde{f}_{S_3}|^2 + 4|\tilde{f}_{P_3}|^2)(a_{3t}^2\beta_t^2 + b_{3t}^2)$$

$$+ 2(\mathrm{Re}[\tilde{f}_{S_2}\tilde{f}_{S_3}^*] + \mathrm{Re}[\tilde{f}_{P_2}\tilde{f}_{P_3}^*])(a_{2t}a_{3t}\beta_t^2 + b_{2t}b_{3t})\Big\}$$

$$2\overline{\mathrm{Re}[\mathcal{A}_\phi\mathcal{A}_{\mathrm{QCD}}^*]} = -\frac{4\pi\alpha_s m_t^2 s}{C_A C_F v(1-\beta^2 z^2)}\Big\{(a_{2t}\beta_t^2\mathrm{Re}[\tilde{f}_{S_2}] - 2b_{2t}\mathrm{Re}[\tilde{f}_{P_2}])$$

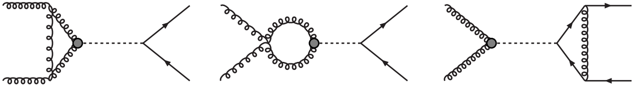
$$+ (a_{3t}\beta_t^2\mathrm{Re}[\tilde{f}_{S_3}] - 2b_{3t}\mathrm{Re}[\tilde{f}_{P_3}])\Big\}$$

Resonant Contributions

The resonant contributions can be divided into

1. Factorizing Diagrams

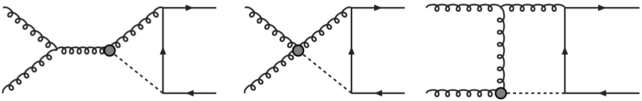
$\rightarrow$ scalar propagator as coefficient; divide into scalar prod. and decay



(simpler to calculate, known from literature)

2. Non-Factorizing Diagrams

$\rightarrow$ scalar propagator in loop; no division into scalar prod. and decay possible

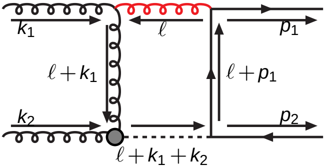


How to extract pole contribution $\frac{1}{s-m_\phi^2+i\Gamma_\phi m_\phi}$?

$\Rightarrow$ **soft-gluon approximation**

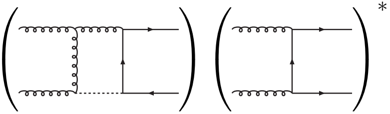
Soft-Gluon Approximation

Example: Box Diagram



$$\xrightarrow{\ell \to 0} \quad \sim \frac{1}{\hat{s} - m_\phi^2 + i\Gamma_\phi m_\phi} \text{ + non-resonant terms}$$

Soft-Gluon Approximation

Example for Virtual Correction: 

neglect loop momenta in the numerator $\rightarrow$ scalar integral:

$$\int \frac{d^4\ell}{(2\pi)^4} \frac{1}{(\ell^2+i\varepsilon)((\ell+k_1)^2+i\varepsilon)((\ell+k_1+k_2)^2-m_\phi^2+i\Gamma_\phi m_\phi)((\ell+p_1)^2-m_t^2+i\varepsilon)}$$

neglect ℓ^2 terms in the denominator where possible

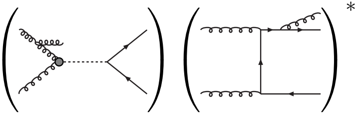
$$\int \frac{d^4\ell}{(2\pi)^4} \frac{1}{(\ell^2+i\varepsilon)(2\ell k_1+i\varepsilon)(2\ell(k_1+k_2)+\hat{s}-m_\phi^2+i\Gamma_\phi m_\phi)(2\ell p_1+i\varepsilon)}$$

perform contour integration

$$-i\int \frac{d^3\ell}{(2\pi)^3} \frac{1}{2|\vec{\ell}|\left[-2|\vec{\ell}|k_1^0+2\vec{\ell}\vec{k}_1+i\varepsilon\right]\left[-2|\vec{\ell}|(k_1^0+k_2^0)+2\vec{\ell}(\vec{k}_1+\vec{k}_2)+\hat{s}-m_\phi^2+i\Gamma_\phi m_\phi\right]\left[-2|\vec{\ell}|p_1^0+2\vec{\ell}\vec{p}_1+i\varepsilon\right]}$$

$$= +i\int \frac{d^3\ell}{(2\pi)^3} \frac{1}{2\ell^0\left[-2\ell k_1+i\varepsilon\right]\left[-2\ell(k_1+k_2)+\hat{s}-m_\phi^2+i\Gamma_\phi m_\phi\right]\left[2\ell p_1-i\varepsilon\right]}; \quad \ell^0=|\vec{\ell}|$$

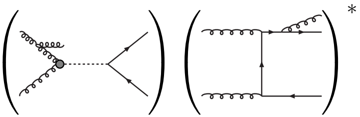
Soft-Gluon Approximation

Example Real Correction: 

$$\to - i \int \frac{d^3q}{(2\pi)^3\, 2q^0} \frac{1}{\left[-2qk_1 + i\varepsilon\right]\left[-2q(k_1+k_2) + \hat{s} - m_\phi^2 + i\Gamma_\phi m_\phi\right]\left[2qp_1 - i\varepsilon\right]}$$

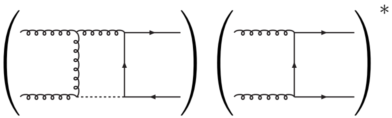
$$q^0 = |\vec{q}|$$

Soft-Gluon Approximation



$$\to -\,\mathrm{i} \int \frac{d^3q}{(2\pi)^3\, 2q^0}\, \frac{1}{\left[-2qk_1+i\varepsilon\right]\left[-2q(k_1+k_2)+\hat{s}-m_\phi^2+i\Gamma_\phi m_\phi\right]\left[2qp_1-i\varepsilon\right]}$$

$$q^0 = |\vec{q}|$$

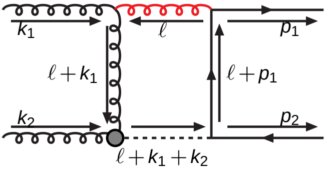


$$\to +\mathrm{i} \int \frac{d^3\ell}{(2\pi)^3}\, \frac{1}{2\ell^0\left[-2\ell k_1+i\varepsilon\right]\left[-2\ell(k_1+k_2)+\hat{s}-m_\phi^2+i\Gamma_\phi m_\phi\right]\left[2\ell p_1-i\varepsilon\right]}$$

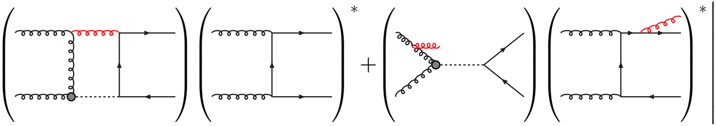
$$\ell^0 = |\vec{\ell}|$$

Soft-Gluon Approximation

Example: Box Diagram



$\xrightarrow{\ell\to 0} \quad \sim \frac{1}{\hat{s}-m_\phi^2+i\Gamma_\phi m_\phi}$ + non-resonant terms



soft-gluon approx. $= 0$

non-factorizing virtual corrections cancel with real corrections from initial and final state radiation in the soft-gluon approximation
(known effect from: [Beenakker, Chapovsky, Berends '97])

- only valid if observable is inclusive enough

Results – Inclusive Cross Section (LO & NLO)

			σ_{LO}^{ϕ}	σ_{NLO}^{ϕ}	K^{ϕ}	$\sigma_{LO}^{\phi+QCD}$	$\sigma_{NLO}^{\phi+QCD}$	$K^{\phi+QCD}$
I	8 TeV	w/o int	2.03	4.11	2.02	123.63	195.96	1.59
		w int	0.65	3.58	5.51	122.25	195.44	1.60
	13 TeV	w/o int	7.34	14.90	2.03	411.84	652.76	1.58
		w int	1.55	11.57	7.46	406.05	649.42	1.60
II	8 TeV	w/o int	0.79	1.56	1.97	115.05	187.25	1.63
		w int	0.52	1.91	3.67	114.79	187.59	1.63
	13 TeV	w/o int	3.05	6.03	1.98	385.65	624.94	1.62
		w int	1.41	6.33	4.49	384.01	625.24	1.63
III	8 TeV	w/o int	1.30	2.72	2.09	113.91	186.95	1.64
		w int	0.67	2.72	4.06	113.28	186.94	1.65
	13 TeV	w/o int	4.74	9.89	2.09	382.36	624.33	1.63
		w int	1.88	8.92	4.74	379.50	623.35	1.64

Heavy Higgs Widths

	Scenario 1		Scenario 2		Scenario 3	
	Γ_2 [GeV]	Γ_3 [GeV]	Γ_2 [GeV]	Γ_3 [GeV]	Γ_2 [GeV]	Γ_3 [GeV]
$\phi_j \to t\bar{t}$	34.48	49.15	34.41	71.97	32.31	85.05
$\phi_j \to VV$	0	0	0	0	1.12	5.11
$\phi_j \to \phi_1 Z$	0	0	0	0	0.65	3.24
$\phi_j \to \phi_2 Z$	0	0	0	3.14	0	31.28
$\phi_j \to \phi_1 \phi_1$	0	0	0	0	2.38	3.00
$\phi_j \to \phi_1 \phi_2$	0	0	0	0	0	0.31
$\phi_j \to gg$	0.08	0.13	0.08	0.17	0.08	0.17
Total	34.56	49.28	34.49	75.28	36.55	128.16