NLO QCD corrections to Heavy Higgs boson production and decay into $t\bar{t}$ within the 2HDM

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GRADUIERTEN KOLLEG

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Introduction

- general idea:
  investigate impact of additional heavy Higgs bosons on $t\bar{t}$ production
- choose specific model featuring heavy Higgs bosons: 2HDM
- study different observables and compare their sensitivity to heavy Higgs bosons
- take NLO QCD corrections into account

2HDM Type-II Scenarios

studied 3 parameter scenarios

in this talk: show as an example CP-conserving scenario 1

- h, ϕ_1 SM-like (by construction, so-called "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

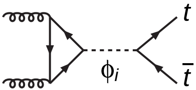
Parameters for Scenario 1

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

	h	H	A
a_t	1	1.43	0
b_t	0	0	1.43
f_{VV}	1	0	0
m [GeV]	125	**550**	**510**
Γ [GeV]	0.004	34.56	49.28

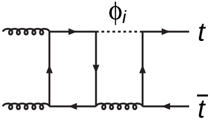
Next-to-Leading Order: Approximations

LO:

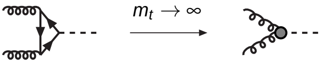


LO is already a 1-loop calculation $\Rightarrow$ NLO requires a 2-loop calculation,e.g.

NLO:



$\rightarrow$ simplify calculation by applying two approximations:

1. heavy top-mass limit 

2. restrict NLO calculation to the resonant region (dominant contribution)

NLO Results: Inclusive $t\bar{t}$ Cross Section

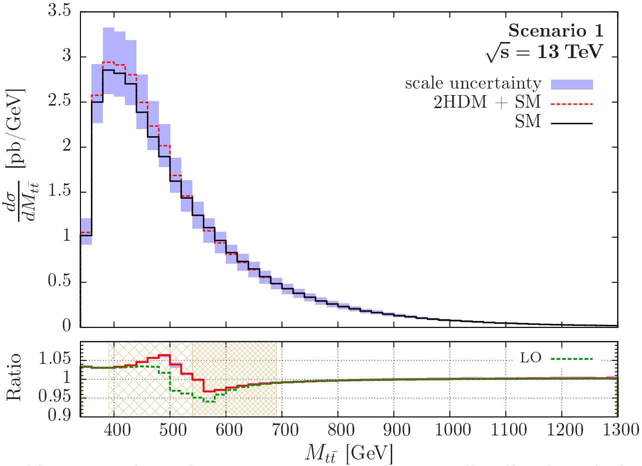
	Scenario 1	Scenario 2	Scenario 3
μ_0 [GeV]	265	312.5	325
σ_{QCDW} [pb]	$643.22^{+81.23}_{-77.71}$	$624.25^{+80.98}_{-76.19}$	$619.56^{+81.05}_{-75.72}$
σ_{2HDM} [pb]	$13.59^{+1.85}_{-1.64}$	$7.4^{+0.77}_{-0.78}$	$7.21^{+0.81}_{-0.77}$
$\sigma_{2HDM}/\sigma_{QCDW}$ [%]	2.1	1.2	1.2

$$\mu_0 = \mu_R = \mu_F = \frac{m_2+m_3}{4}, \quad \mu \text{ variation: } \mu = \frac{\mu_0}{2}, \mu_0, 2\mu_0$$

inclusive cross section shows only little sensitivity to heavy Higgs contribution (not yet constrained by measurement: $\delta\sigma^{exp}_{t\bar{t}} \sim 5\%$)

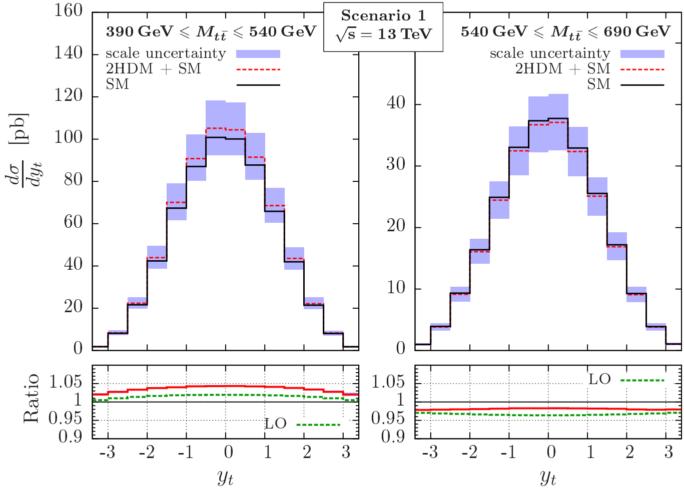
$\Rightarrow$ study more sensitive observables

$t\bar{t}$ Invariant Mass Distribution $M_{t\bar{t}}$



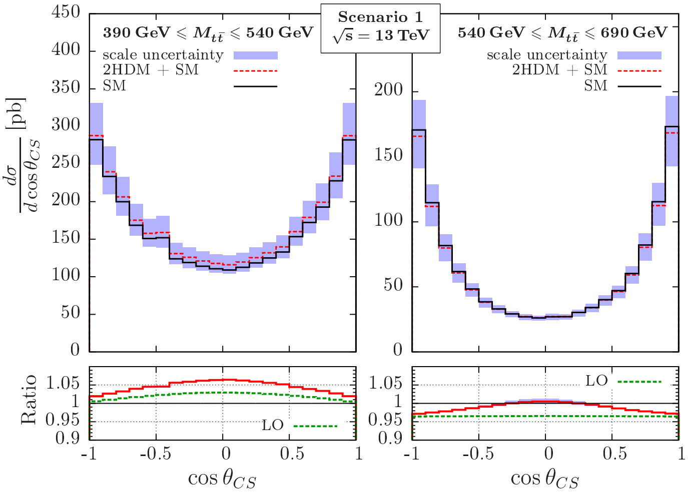
- effects of heavy Higgs bosons stronger in $M_{t\bar{t}}$ distribution (S/B $> 6\%$)
- peak-dip cancellation for observables inclusive in $M_{t\bar{t}}$
- avoid peak-dip cancellation in other observables, e.g. y_t, $\cos\theta_{CS}$ by applying cuts below and above the resonance to estimate maximal effect

Results: Top-Quark Rapidity Distribution 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: Cosine of Collins-Soper Angle $\cos\theta_{CS}$



- 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

Results: Spin Dependent Observables

Try to increase signal/background ratio by analysing spin dependent observables, e.g. spin correlations

$$C_{aa} = -4\langle(\mathbf{S}_t \cdot \hat{\mathbf{a}})(\mathbf{S}_{\bar{t}} \cdot \hat{\mathbf{a}})\rangle$$

$\mathbf{S}_t$ and $\mathbf{S}_{\bar{t}}$ are the spin operators of t and $\bar{t}$, respectively

choosing three different axes

$$\hat{\mathbf{a}} = \{\hat{\mathbf{k}}, \hat{\mathbf{n}}, \hat{\mathbf{r}}\}$$

$\hat{\mathbf{k}}$: direction of top quark in $t\bar{t}$ ZMF, $\hat{\mathbf{n}}, \hat{\mathbf{r}}$ directions perpendicular to $\hat{\mathbf{k}}$

correlations have direct interpretation as expectation values of angular distributions, e.g. in the dileptonic decay of $t\bar{t}$

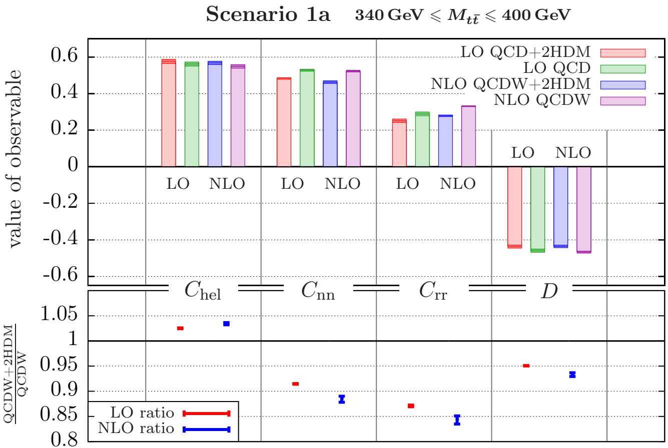
$$C_{kk} \sim \langle\cos\theta_+ \cos\theta_-\rangle$$

$\theta_\pm$: angle between $\ell^\pm$ and t ($\bar{t}$) in the t ($\bar{t}$) rest frame

From C_{aa} construct opening angle correlation:

$$D = \langle\mathbf{S}_t \cdot \mathbf{S}_{\bar{t}}\rangle = -\frac{1}{3}(C_{kk} + C_{nn} + C_{rr})$$

Results: Spin Correlations @NLO



- model: scalar heavy Higgs boson, $m_H = 400$ GeV, SM Yukawa couplings
- chosen $M_{t\bar{t}}$ cut to enhance signal/background ratio
- C_{rr} shows strongest effect: Sig./Bkg. ratio $\sim$ 15%
- compare with Sig./Bkg. ratio of cross section in the same $M_{t\bar{t}}$ bin: $\sim$ 4%

Summary

Heavy Higgs bosons (2HDM) can be constrained in the $t\bar{t}$ channel
(depends on Yukawa coupling / $\tan\beta$)

- use $M_{t\bar{t}}$ cuts to enhance signal from heavy Higgs bosons
- $t\bar{t}$ spin correlations show great potential to increase sensitivity significantly
- S/B ratio of spin correlations seem to be less sensitive to NLO QCD corrections

Outlook

Up to now: Only rough estimate ($\approx 10\%$) of uncertainties due to applied approximations $\rightarrow$ investigate these uncertainties further

Thank you for your attention!

Additional Material

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

- $$\Phi_1 = \begin{pmatrix} \xi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \varphi_1 + i\chi_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \xi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \varphi_2 + i\chi_2) \end{pmatrix}$$

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

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

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

- $\tan\beta = \frac{v_2}{v_1}$
- top-Yukawa coupling: $\mathcal{L}_{\text{Yuk},t} = -\frac{m_t}{v} \sum_j \bar{t}(a_{jt} - i b_{jt} \gamma_5) t \phi_j$
- 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

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

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

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

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

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

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

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

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

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

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

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

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

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

2HDM Type-II Scenarios

CP-conserving scenario I and II

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

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

CP-violating scenario III

study: $\tan\beta = 0.7, \alpha_1 = \beta,$

$\alpha_2 = \frac{\pi}{15}, \alpha_3 = \frac{\pi}{4}$

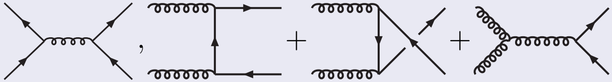
	ϕ_1	ϕ_2	ϕ_3
a_t	0.98	0.86	-1.16
b_t	0.30	0.99	0.99
f_{VV}	0.98	-0.15	-0.15
$m(\mathrm{III})$ [GeV]	125	**500**	**800**
$\Gamma(\mathrm{III})$ [GeV]	0.004	36.55	128.16

- h, ϕ_1 SM-like (by construction, so-called “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

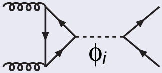
QCD contribution

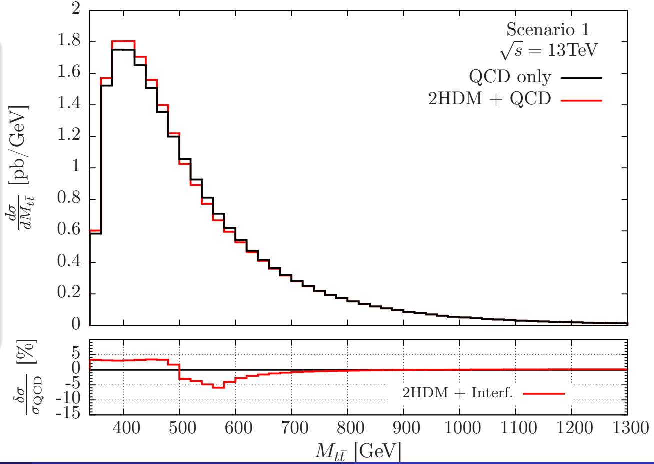
$\mathcal{A}_{\text{QCD}} =$



(pseudo-)scalar contribution

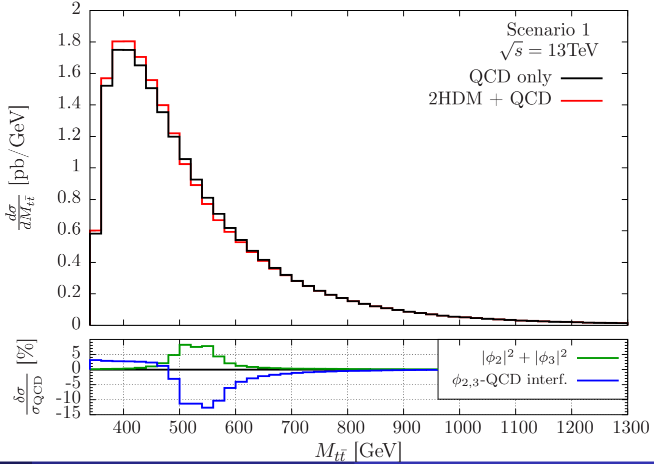
$\mathcal{A}_{\phi_j} =$





Interference Effects

- effect of 2HDM most prominent in the resonant region
- interference with QCD very important (peak-dip instead of bump)



Leading Order Matrix Elements

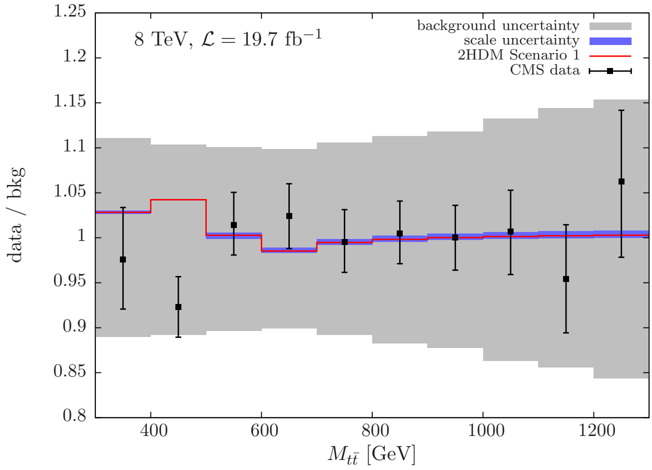
$$|\overline{\mathcal{M}}_\phi|^2 = \frac{s^3 m_t^3}{2C_F v^2}\Bigg\{(|\tilde{f}_{S_2}|^2 + 4|\tilde{f}_{P_2}|^2)(a_{2t}^2\beta_t^2 + b_{2t}^2) + (|\tilde{f}_{S_3}|^2 + 4|\tilde{f}_{P_3}|^2)(a_{3t}^2\beta_t^2 + b_{3t}^2)$$

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

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

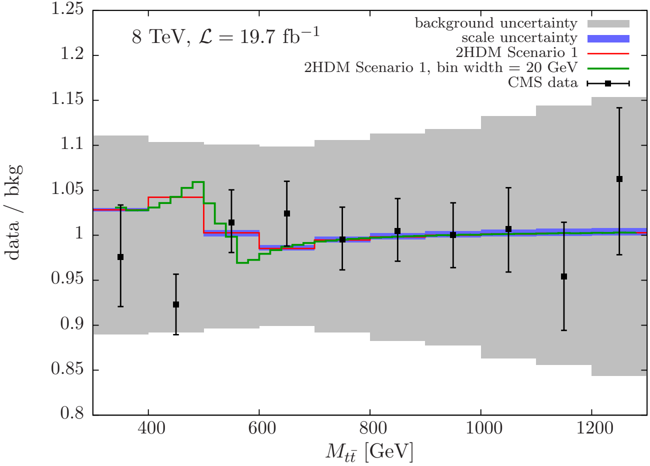
$$+ (a_{3t}\beta_t^2\mathrm{Re}[\tilde{f}_{S_3}] - 2b_{3t}\mathrm{Re}[\tilde{f}_{P_3}])\Bigg\}$$

Comparison with CMS [arXiv:1309.2030]

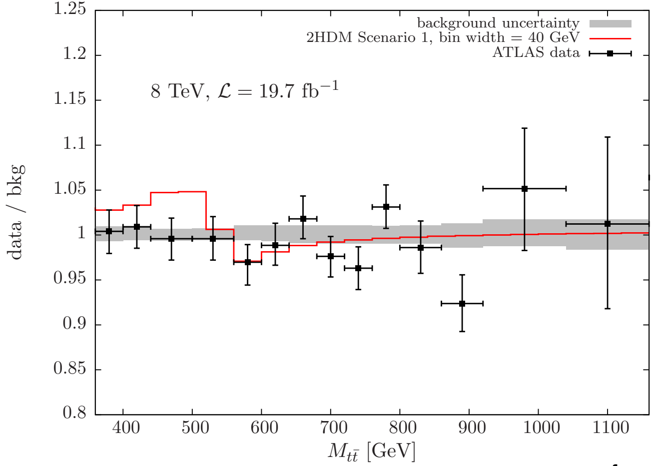


background uncertainty too large to exclude scenario 1

Comparison with CMS [arXiv:1309.2030]



peak-dip cancellation due to large bin width



ATLAS-CONF-2016-073
Fig. 7a

μ+jets, b-tag category 1

- strong reduction of background uncertainty
- small bin width
- interference effects taken into account

$\rightarrow$ exclude scenario 1 at $> 95\%$ CL

for details about

ATLAS-CONF-2016-073

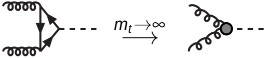
see

Katharina's talk

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:

$$\mathcal{L}_{\text{eff}} = (f_S G^a_{\mu\nu} G^{\mu\nu}_a + f_P \varepsilon_{\mu\nu\rho\sigma} G^{\mu\nu}_a G^{\rho\sigma}_a)\phi$$

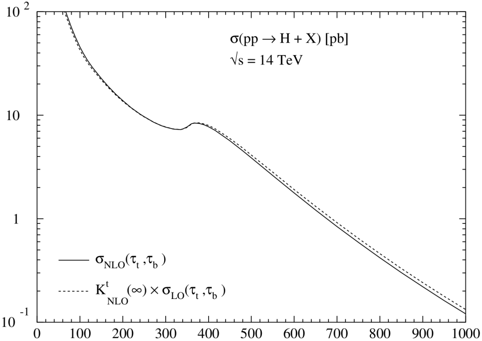


Effective theory : leading order in the $1/m_t$ expansion of the $gg\phi$ vertex
$\rightarrow$ take higher orders of $1/m_t$ into account by using K-factor

[Krämer, Laenen, Spira 1996]

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

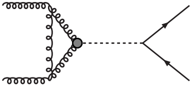
Good approximation for Higgs production:

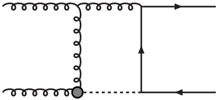


- major part of NLO QCD corrections originates from soft/collinear gluons which do not resolve the effective coupling
- here we assume that this is true for the process $pp \to \phi \to t\bar{t}$ as well

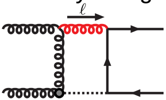
Next-to-Leading Order – Soft Gluon Approximation

- Seen in LO: significant contributions from 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. 

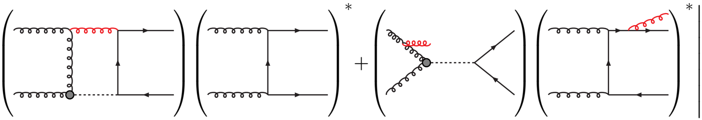
  b) non-factorizing contributions, e.g. 

- extract pole contribution by soft gluon approximation



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

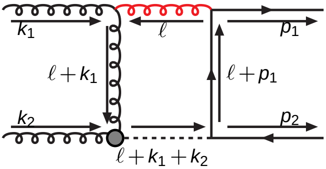
$\Rightarrow$ non-factorizing contributions from real and virtual corrections cancel



soft-gluon approx. $= 0$

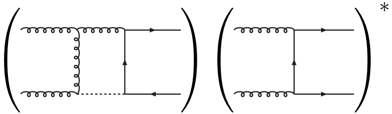
Soft-Gluon Approximation

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:

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

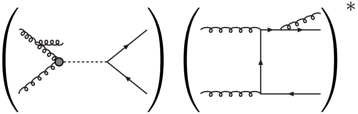
neglect ℓ^2 terms in the denominator where possible

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

perform contour integration

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

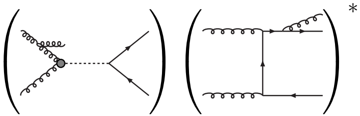
Soft-Gluon Approximation

Example Real Correction: 

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

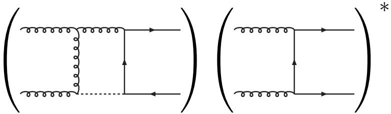
$$q^0 = |\vec{q}|$$

Soft-Gluon Approximation



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

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

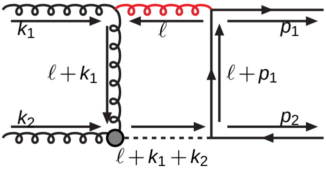


$$\to +\mathrm{i}\int \frac{d^3\ell}{(2\pi)^3}\,\frac{1}{2\ell^0\left[-2\ell k_1+i\varepsilon\right]\left[-2\ell(k_1+k_2)+\hat{s}-m_\phi^2+i\Gamma_\phi m_\phi\right]\left[2\ell p_1-i\varepsilon\right]}$$

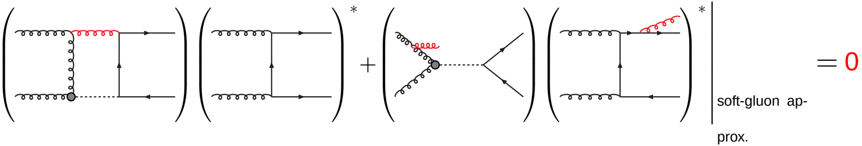
$$\ell^0=|\vec{\ell}|$$

Soft-Gluon Approximation

Example: Box Diagram



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



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

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
Mass [GeV]	550	510	550	700	500	800