2HDM Effects in top-quark pair production

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Phenomenology of Elementary Particle Physics

in collaboration with

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based on Phys.Rev.D93,034032 [arXiv:1511.05584] and
Phys.Rev.D95,095012 [arXiv:1702.06063]

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Motivation

- Why study heavy Higgs bosons?
  - 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
  - Heavy Higgs bosons are experimentally less constrained than additional light Higgs bosons
- Why study the $t\bar{t}$ channel?
  - high mass and Yukawa coupling $\sim m_f \rightarrow$ resonance in the $t\bar{t}$ decay channel
  - $t\bar{t}$ pairs copiously produced at the LHC
  - SM $t\bar{t}$ production well understood in terms of higher order corrections (e.g. up to NNLO QCD)
  - $t\bar{t}$ spin polarization and correlation accessible

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]

2HDM Type-II Scenarios

studied several parameter scenarios
in this talk: show a CP-conserving scenario as an example

- h, ϕ_1 SM-like (by construction, so-called "alignment limit")
- H,A-Yukawa coupling to t quark
  $a_t, b_t = \cot\beta = 1 \Rightarrow$ SM-like
- H,A-Yukawa coupling to b quark
  $a_b, b_b = \tan\beta = 1$, but suppressed by $\mathcal{O}(\frac{m_b^2}{m_t^2}) < 0.1\% \rightarrow$ save to neglect
- f_{VV}: coupling to vector bosons
- m: free parameter; Γ fixed by mass and couplings

Parameters for example scenario

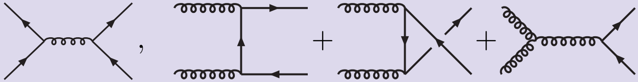
choose: $\tan\beta = 1, \quad \alpha = \beta - \frac{\pi}{2}$

	h	H	A
a_t	1	1	0
b_t	0	0	1
f_{VV}	1	0	0
m [GeV]	125	**600**	**900**
Γ [GeV]	0.004	20.69	80.94

Leading Order

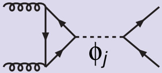
QCD contribution

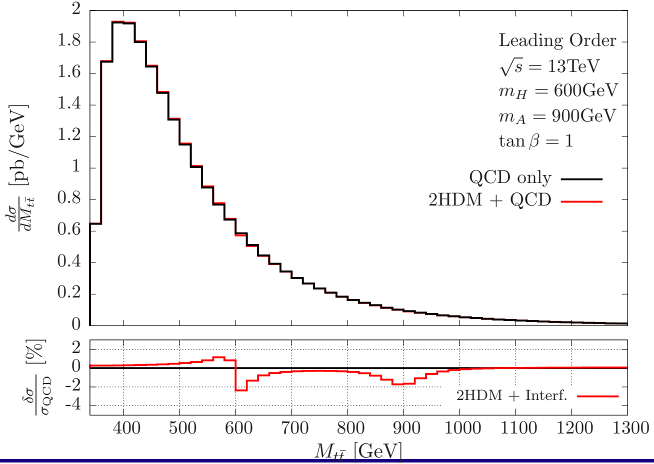
$\mathcal{A}_{\mathrm{QCD}} =$



(pseudo-)scalar contribution

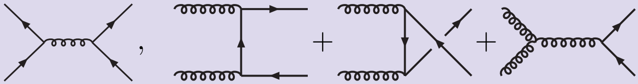
$\mathcal{A}_{\phi_j} =$



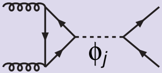


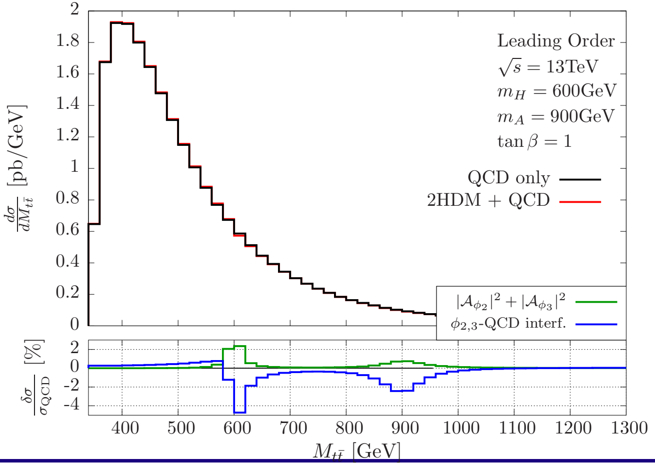
Leading Order

QCD contribution

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

(pseudo-)scalar contribution

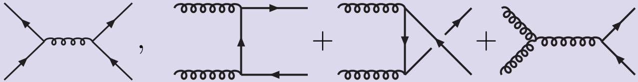
$\mathcal{A}_{\phi_j} =$ 



Leading Order

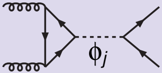
QCD contribution

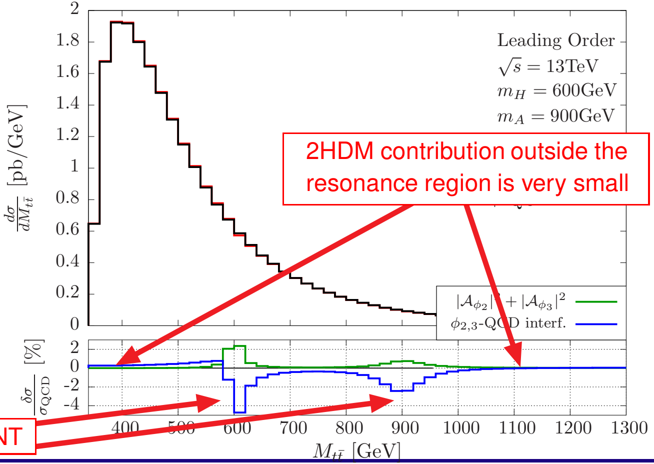
$\mathcal{A}_{\text{QCD}} =$



(pseudo-)scalar contribution

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

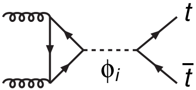




Interference IMPORTANT

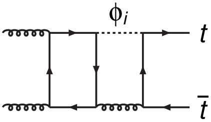
Next-to-Leading Order: Approximations

LO:

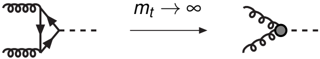


LO is already a 1-loop calculation ⇒ NLO requires a 2-loop calculation,e.g.

NLO:



→ simplify calculation by applying two approximations:

1. heavy top-mass limit 

   with an additional rescaling [Krämer, Laenen, Spira 1996]

2. restrict NLO calculation to the resonant region (dominant contribution) by applying soft gluon approximation

NLO Results: Inclusive $t\bar{t}$ Cross Section @ 13 TeV

	example scenario
μ_0 [GeV]	375
σ_{QCDW} [pb]	$522.78^{+79.84}_{-74.27}$
σ_{2HDM} [pb]	$2.30^{+0.21}_{-0.23}$
$\sigma_{\text{2HDM}}/\sigma_{\text{QCDW}}$ [%]	0.4

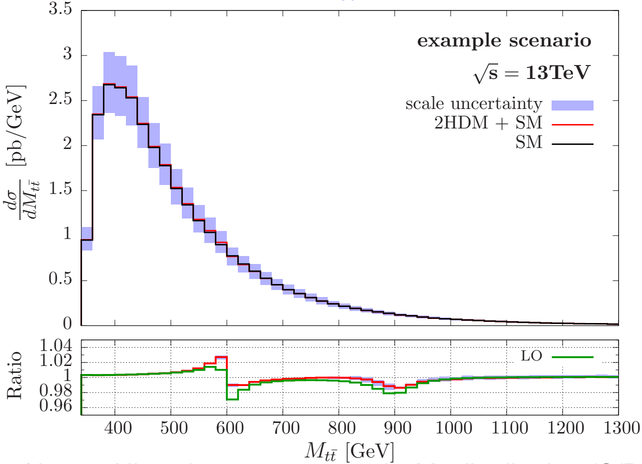
$\mu_0 = \mu_R = \mu_F = \frac{m_2+m_3}{4}$, μ variation: $\mu = \frac{\mu_0}{2}, \mu_0, 2\mu_0$

QCDW: QCD and weak corrections

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

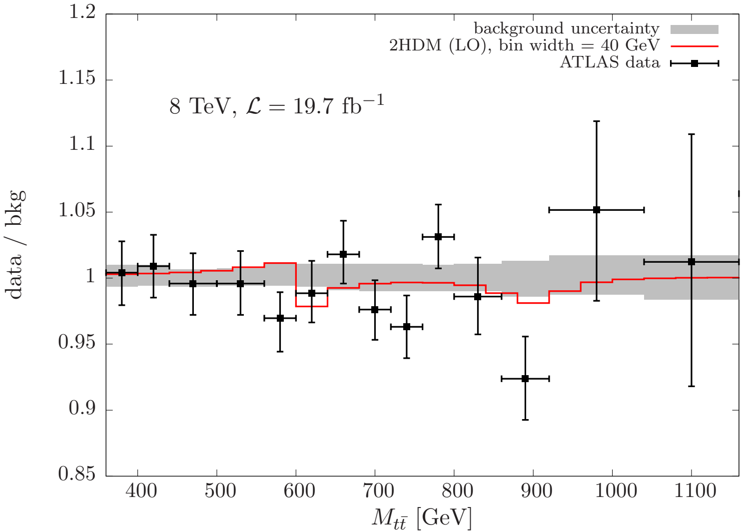
$\Rightarrow$ study more sensitive observables

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



- effects of heavy Higgs bosons stronger in $M_{t\bar{t}}$ distribution (S/B $\sim$ 3%)
- peak-dip cancellation for observables inclusive in $M_{t\bar{t}}$
- avoid peak-dip cancellation in other observables by binning in $M_{t\bar{t}}$
- checked spin independent observables, e.g. y_t, $\cos\theta_{CS}$ $\rightarrow$ sensitivity compareable to $M_{t\bar{t}}$

Comparison with ATLAS [ATLAS-CONF-2016-073]



ATLAS-CONF-2016-073
Fig. 7a

μ+jets, b-tag category 1

signal difficult to detect in the $M_{t\bar{t}}$ distribution

Results: Spin Dependent Observables

Try to increase signal/background ratio by analysing spin dependent observables, e.g. angular correlations in the dilepton decay channel of $t\bar{t}$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4}(1 + B_+^a \cos\theta_+ + B_-^b \cos\theta_- - C_{ab}\cos\theta_+\cos\theta_-)$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\varphi} = \frac{1}{2}(1 - D\cos\varphi)$$

$$\cos\theta_+ = \hat{\boldsymbol{\ell}}^+ \cdot \hat{\mathbf{a}}, \quad \cos\theta_- = \hat{\boldsymbol{\ell}}^- \cdot \hat{\mathbf{b}}, \quad \cos\varphi = \hat{\boldsymbol{\ell}}^+ \cdot \hat{\boldsymbol{\ell}}^-$$

C_{ab} is related to double spin asymmetry and spin correlations

$$C_{ab} \sim \frac{\sigma_{t\bar{t}}(\uparrow\uparrow) + \sigma_{t\bar{t}}(\downarrow\downarrow) - \sigma_{t\bar{t}}(\uparrow\downarrow) - \sigma_{t\bar{t}}(\downarrow\uparrow)}{\sigma_{t\bar{t}}(\uparrow\uparrow) + \sigma_{t\bar{t}}(\downarrow\downarrow) + \sigma_{t\bar{t}}(\uparrow\downarrow) + \sigma_{t\bar{t}}(\downarrow\uparrow)} = -4\langle(\mathbf{S}_t \cdot \hat{\mathbf{a}})\,(\mathbf{S}_{\bar{t}} \cdot \hat{\mathbf{b}})\rangle$$

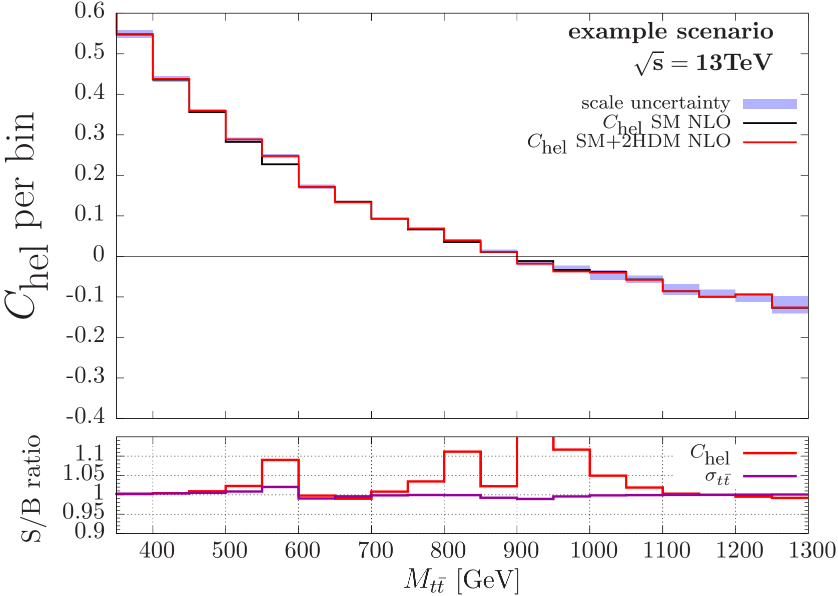
$\mathbf{S}_t$ and $\mathbf{S}_{\bar{t}}$ are the spin operators of t and $\bar{t}$, respectively

We choose three orthonormal reference axes: $\hat{\mathbf{a}} = \{\hat{\mathbf{k}}, \hat{\mathbf{n}}, \hat{\mathbf{r}}\}$

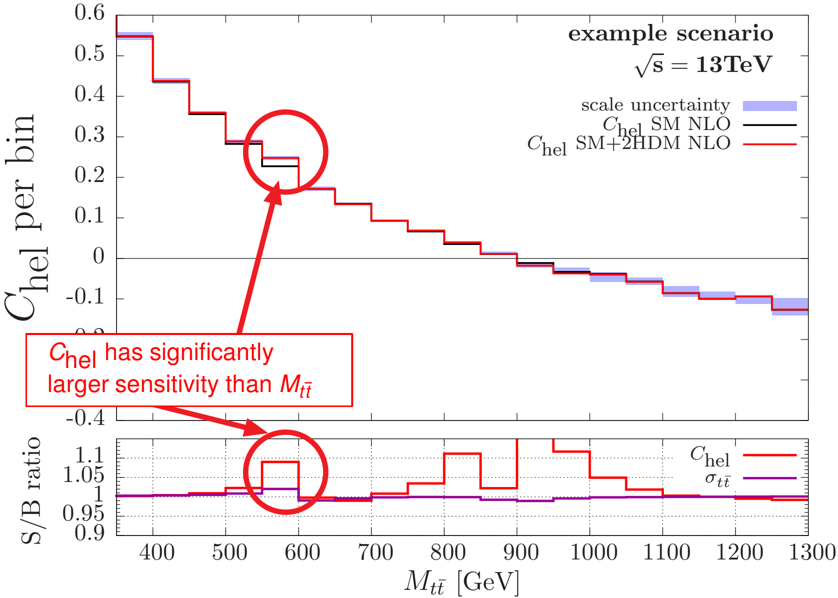
$\hat{\mathbf{k}}$: direction of top quark in $t\bar{t}$ ZMF, $\hat{\mathbf{n}}, \hat{\mathbf{r}}$ directions perpendicular to $\hat{\mathbf{k}}$

and study: $C_{\text{hel}} \equiv C_{kk}, \quad C_{nn}, \quad C_{rr}, \quad D = -\frac{1}{3}(C_{\text{hel}} + C_{nn} + C_{rr})$

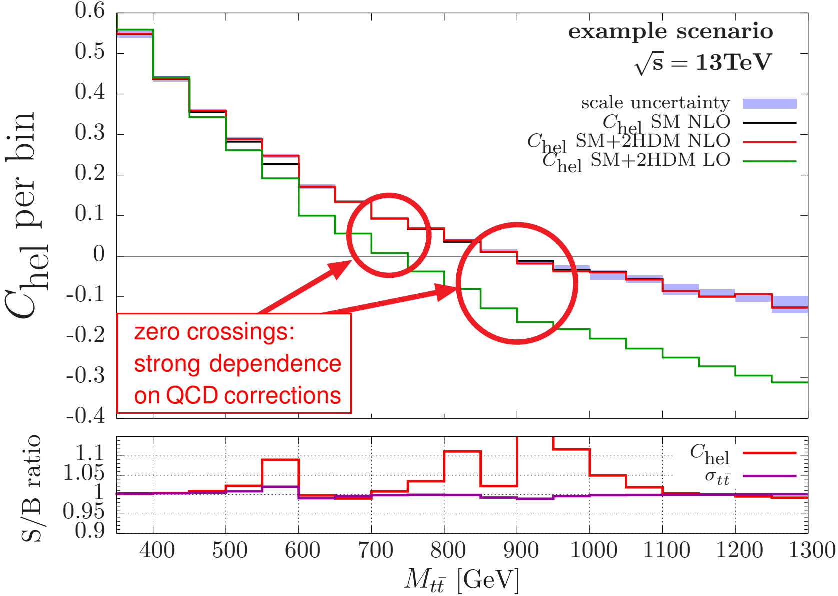
Results: Spin Correlations @NLO



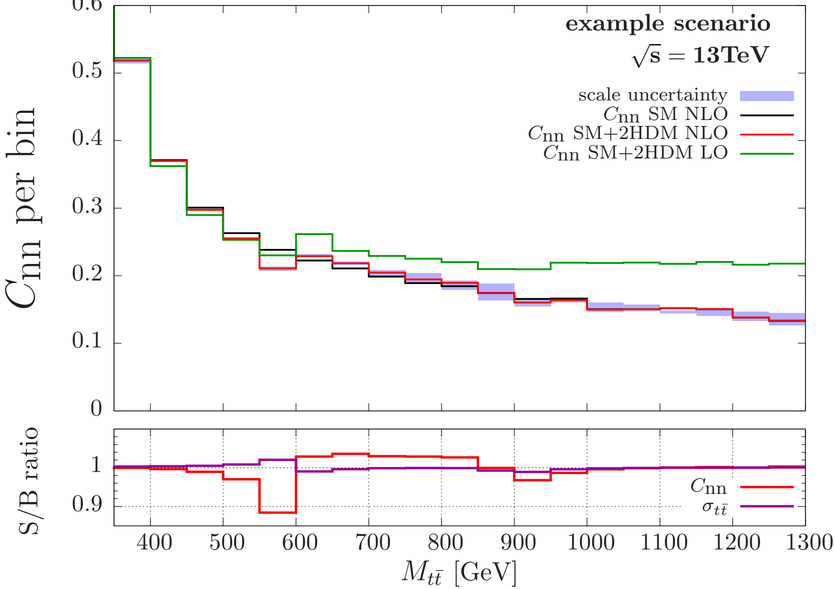
Results: Spin Correlations @NLO



Results: Spin Correlations @NLO



Results: Spin Correlations @NLO II



Summary

- heavy Higgs bosons in the 2HDM can be constrained in $t\bar{t}$ production (if $\tan\beta$ is not too large)
- heavy Higgs-QCD interference must be taken into account
- bin observables in $M_{t\bar{t}}$ to avoid peak-dip cancellation
- $t\bar{t}$ spin correlations can potentially be used to increase sensitivity significantly
  $\longleftarrow$ NLO corrections important to identify perturbatively robust spin dependent observables

Thank you for your attention!

Additional Material

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

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

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

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:

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

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

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

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

Leading Order Matrix Elements

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

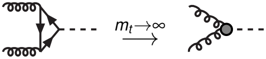
$$+ 2(\mathrm{Re}[\tilde{f}_{S_2}\tilde{f}_{S_3}^*] + \mathrm{Re}[\tilde{f}_{P_2}\tilde{f}_{P_3}^*])(a_{2t}a_{3t}\beta_t^2 + b_{2t}b_{3t})\Big\}$$

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

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

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

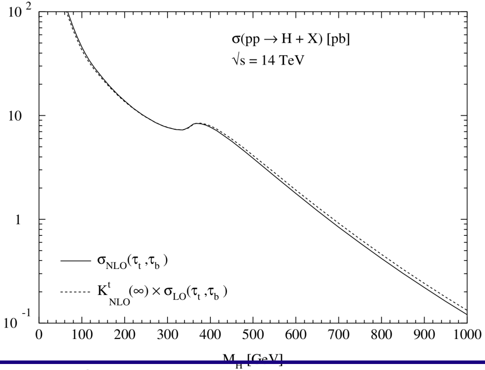


Effective theory : leading order in the $1/m_t$ expansion of the $gg\phi$ vertex
$\to$ take higher orders of $1/m_t$ into account by using K-factor

[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:

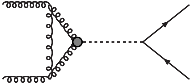


- major part of NLO QCD corrections originates from soft/collinear gluons which do not resolve the effective coupling
- here we assume that this is true for the process $pp \to \phi \to t\bar{t}$ as well

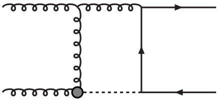
Next-to-Leading Order – Soft Gluon Approximation

- 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

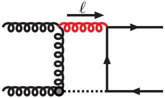
  a) factorizable contributions, e.g.

  b) non-factorizable contributions, e.g.

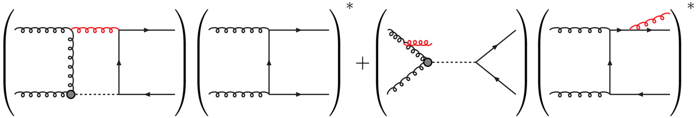
  

- extract pole contribution by soft gluon approximation



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

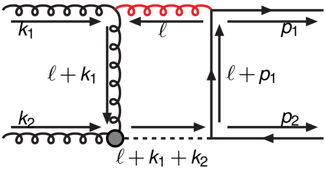
$\Rightarrow$ non-factorizable contributions from real and virtual corrections cancel



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

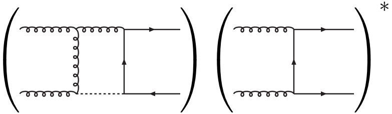
Soft-Gluon Approximation

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

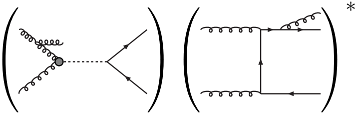
$$\int \frac{d^4\ell}{(2\pi)^4} \frac{1}{(\ell^2+i\varepsilon)(2\ell k_1+i\varepsilon)(2\ell(k_1+k_2)+\hat{s}-m_\phi^2+i\Gamma_\phi m_\phi)(2\ell p_1+i\varepsilon)}$$

perform contour integration

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

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

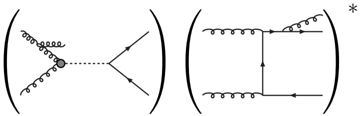
Soft-Gluon Approximation

Example Real Correction: 

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

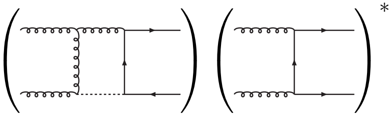
$$q^0 = |\vec{q}|$$

Soft-Gluon Approximation



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

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

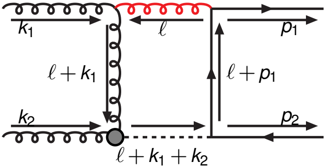


$$\to +\mathrm{i}\int \frac{d^3\ell}{(2\pi)^3}\,\frac{1}{2\ell^0\left[-2\ell k_1+i\varepsilon\right]\left[-2\ell(k_1+k_2)+\hat{s}-m_\phi^2+i\Gamma_\phi m_\phi\right]\left[2\ell p_1-i\varepsilon\right]}$$

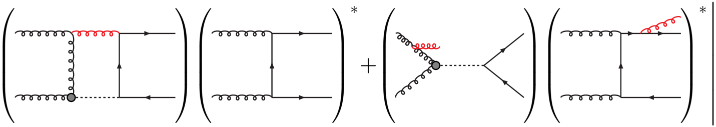
$$\ell^0=|\vec{\ell}|$$

Soft-Gluon Approximation

Example: Box Diagram



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



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

non-factorizable 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