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Gluon fusion and quark annihilation
Recent progress (in `SusHi`)

If included in `SusHi`, this is marked by  .

[1512.04901: $Q'\overline{Q}\phi$]

[1605.03190: `SusHi Bento`]

[1608.02949: NMSSM distributions]

HDays 2016

Santander – September 2016

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676
DESY
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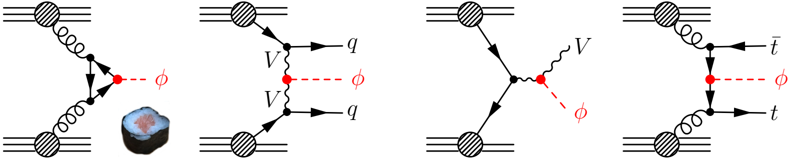
Outline

Production processes for Higgs bosons $H = \phi$

$pp \to \phi$ | $pp \to qq\phi$ | $pp \to W\phi/Z\phi$ | $pp \to t\bar{t}\phi$



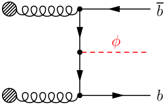
Gluon fusion
Quark annihilation

Vector boson fusion

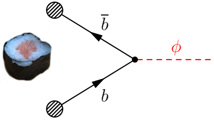
Higgsstrahlung

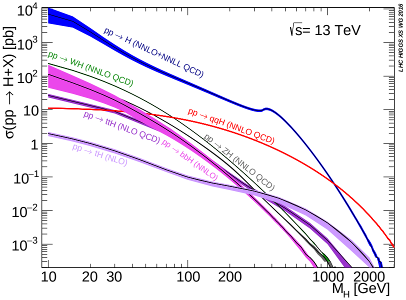
$t\bar{t}H$ production

4 flavour scheme (4FS):



5 flavour scheme (5FS):





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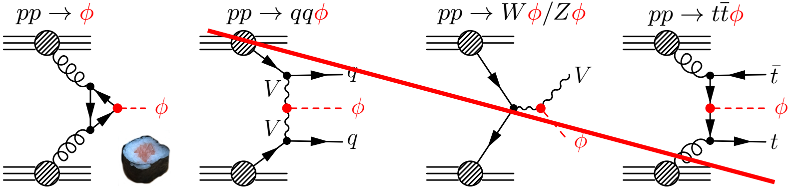

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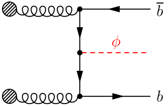

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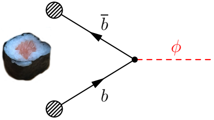
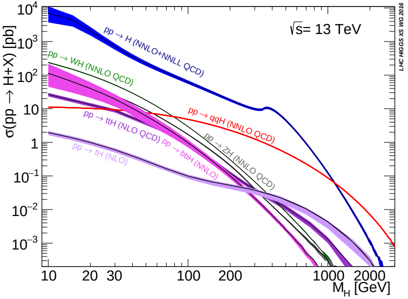
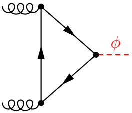


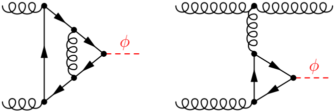


Outline

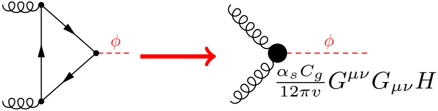
Gluon fusion: Leading order (LO) calculation:
involves quark loops in the SM



Next-to-leading order (NLO) QCD:
add also real contributions



Next-to-NLO (NNLO) QCD:
known in “heavy top-limit” $m_H \ll 2m_t$



Next-to-NNLO (N^3LO) QCD: soft expansion

σ^{LO} [Georgi et al. ’77]

Correction $> 100\%$

σ^{NLO} [Djouadi et al. ’91; Dawson et al. ’90; Spira et al. ’95]

Correction $20 - 30\%$

σ^{NNLO} [Harlander et al. ’02; Anastasiou et al. ’02; Ravindran et al. ’03]

Correction $2 - 5\%$

$\sigma^{\mathrm{N^3LO}}$ [Anastasiou et al. ’13 ’14 ’15 ’16; Hoeschele et al. ’12 ’14; Gehrmann et al. ’10 ’11; Kilgore et al. ’13; Duhr ’13 ’14; $+\ldots$]

Higher order top-quark contributions in the heavy top-limit

N^{3}LO results known in a soft expansion around the threshold $x = m_H^2/\hat{s}$:

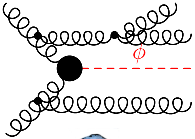
At LO the partonic CMS energy is $\hat{s} = m_H^2$, i.e. $x = 1$.

Real radiation allows for $\hat{s} > m_H^2$, i.e. $x < 1$.

Result presented as an expansion in $(1-x)^N$.

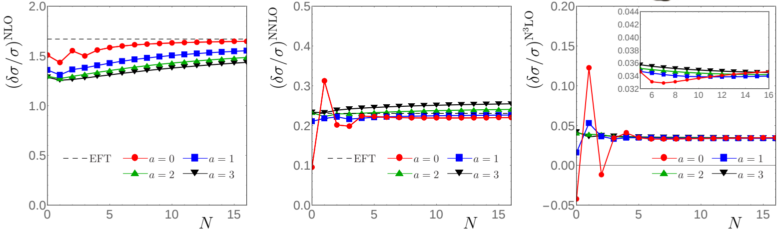
[Anastasiou et al. '13 '14 '15 '16, up to $N = 37$]

Most problematic:



Expansion with operator $\mathcal{T}_N^x$: $\quad x^a\, \mathcal{T}_N^x \left(\dfrac{\Delta\hat{\sigma}^t}{x^a}\right)$

Corrections w.r.t. previous order for SM Higgs at 13 TeV LHC:



$\rightarrow$ Good convergence at higher orders (gg better than qq, qg).

Control in `SusHi` through `Block GGHSOFT`:

```
Block GGHSOFT # parameters for soft expansion
 1   1   16   0    # NLO : [0/1=n/y] [N] [a]
 2   1   16   0    # NNLO: [0/1=n/y] [N] [a]
 3   1   16   0    # N3LO: [0/1=n/y] [N] [a]
```

Best prediction for $gg \to H$ in YR4 following [Anastasiou et al. '16]:

$$\sigma = 48.58\text{pb}^{+2.22\text{pb}(+4.56\%)}_{-3.27\text{pb}(-6.72\%)}(\text{theory}) \pm 1.56\text{pb}(3.20\%)(\text{PDF} + \alpha_s)$$

$$= (\underset{\text{LO}}{16.00} + \underset{\text{NLO}}{20.84} \underset{m_q@\text{NLO}}{- 2.05} + \underset{\text{NNLO}}{9.56} + \underset{1/m_t@\text{NNLO}}{0.34} + \underset{\text{EW}}{2.40} + \underset{\text{N}^3\text{LO}}{1.49})\text{pb}$$

for $m_H = 125\,\text{GeV}$, $\sqrt{s} = 13\,\text{TeV}$.
Theory uncertainties obtained from scale variation, truncation of the soft expansion, missing electroweak effects, missing quark-mass effects.
Suggestions in YR4: Added **F** (flat)- or **G** (gaussian) uncertainties ($\pm 4.5\%$)!

`SusHi 1.6.0` gives you in a single run ($\sim 30\,\text{sec}$):

$$\sigma = 48.28\text{pb} \pm 1.97\text{pb}(\mu_\text{R}\text{ variation})$$

including N^3LO QCD effects, EW effects, quark-mass effects (see later).
Main differences w.r.t. [Anastasiou et al. '16]: Wilson coefficients perturbatively expanded, EW correction factor, matching to high-energy behaviour, quark pole masses

Uncertainty estimate: Threshold resummation at N^3LL $(+\ldots)$
[Bonvini Marzani '14 + Muselli Rottoli '16; Bonvini Rottoli '14; Catani et al. '14; Schmidt Spira '15]

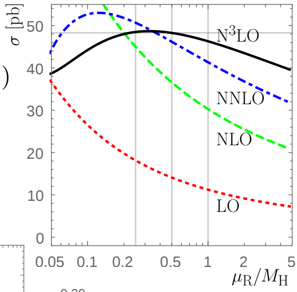
Discussion of effects and features:

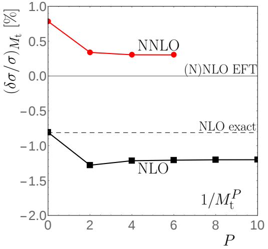
- ✓ Analytic calculation of μ_R dependence (for on-shell parameters):

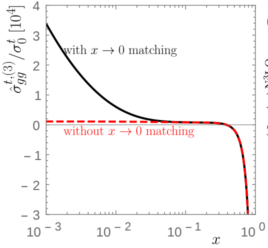
$$\sigma = \sum_{n\geq 0}\sum_{l=0}^{n}\left(\frac{\alpha_s(\mu_R)}{\pi}\right)^{n+2}\kappa_{nl}2^l\log^l(\mu_R/\mu_0)$$

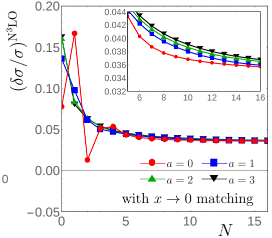
- ✓ $1/m_t^P$ terms at NNLO
- ✓ Matching to high-energy limit $x \to 0$ (problematic $\hat{s}/m_t^2$)

$pp \to H$ for $m_H = 125$ GeV at 13 TeV LHC (PDF4LHC15_100)









Mass effects beyond NLO:

Top-quark mass in inclusive XS:

NNLO $1/m_t^P$ expansion [Marzani et al. '08; Harlander Ozeren '09; Pak Rogal Steinhauser '09]

$+$ matching to high-energy limit [Marzani et al. '08; Harlander Mantler Marzani Ozeren '09]

More differential:

LO mass dependence of $H + 2$jets [Del Duca '01]

and $H + 3$jets [Campanario Kubocz '13; Greiner et al. '16]

NLO mass effects in high-energy limit in $H + 1$jet [Forte Muselli '15; Caola et al. '16]

NLO mass effects in $H + 1$jet in MCFM [Neumann Williams '16]

Two-loop planar master integrals for $H \to 3$ partons [Bonciani et al. '16 hoy!]

Bottom-quark mass

Troublesome logarithms of $\mathcal{L} = \log(m_b^2/Q^2)$ or differentially $\log(m_b^2/p_T^2)$, which are enhanced at $\mathcal{O}(\alpha_s^n \mathcal{L}^{2n})$ ($\leftrightarrow$ quark-pole masses)

Previous work: [Mantler Wiesemann '13; Grazzini Sargsyan '13; Banfi Monni Zanderighi '14]

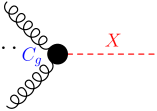
Resummation of abelian corrections: [Melnikov Penin '16; $\gamma\gamma$: Yakovlev et al. '98 '01]

Another ansatz: SCET [SL Stahlhofen Tackmann work with (slow) progress]

QCD	$\longrightarrow$	SCET I	$\longrightarrow$	SCET II$_m$	$\longrightarrow$	SCET II
$Q \sim 125$GeV		$\sqrt{\frac{m_b}{Q}}Q \sim 25$GeV		$\frac{m_b}{Q}Q \sim 5$GeV		$< m_b \sim 5$GeV

Scalar X (with $m_X = 750\,\text{GeV}$) with 'effective' Lagrangian:

$$\mathcal{L}_{\text{eff}}(m_X) \subset -\frac{C_g}{12\pi v}\alpha_s G^{\mu\nu}G_{\mu\nu}X \text{ with } C_g = C_g^{(0)} + \frac{\alpha_s}{\pi}C_g^{(1)} + \ldots$$



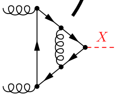
The $\mathrm{N^3LO}$ QCD results for $gg \to X$ can be applied.

`SusHi` allows to specify $C_g^{(k)}$ order by order, e.g. top-quark loop: $C_g^{(1)} = 11/4$.

Perturbative/resummed running of coefficients implemented.

Results obtained for $C_g^{(0)}(m_X) = 1$ with μ_R uncertainty (`MMHT2014nnlo`):

$\sigma(gg \to X)$ [fb]	$\mu_R = \mu_F = m_X/2$	$\mu_R = \mu_F = m_X$
LO	246.2 ± 52.8	185.8 ± 36.0
NLO	368.7 ± 43.1	316.3 ± 39.1
NNLO	410.0 ± 19.1	384.9 ± 24.0
$\mathrm{N^3LO}$	414.6 ± 5.4	407.2 ± 11.7



Control in `SusHi` through `Block DIM5` (also for pseudoscalars):

```
Block DIM5 # top example
     0    1        # Evolution of Wilson coefficients
    11    1.00     # c5h LO
   111    2.75     # c5h NLO
  # c5h = <11> + as/pi * <111>
```

check also `HIGLU` [Spira]

(Discussion of resonant contributions: [Bodwin Chung Wagner '16])

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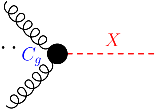

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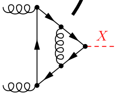


$\sigma(gg \to X)$ [fb]	
LO	
NLO	
NNLO	
$\mathrm{N^3LO}$	

Control in SusHi thr ... scalars):

```
Block DIM5 # top exa
     0     1      #
    11     1.00   #
   111     2.75   #
 # c5h = <11> + as/
```

... HIGLU [Spira]

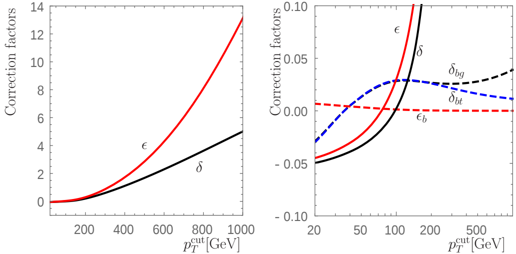
(Discussion of resonant contributions: [Bodwin Chung Wagner '16])

Dimension-5 operators in arbitrary models:

$$\mathcal{L} = \mathcal{L}_{\text{theory}} + \sum_{i=1}^{N_1} \frac{\alpha_s}{12\pi v} c_{5,1i}\, H_{1i} G^a_{\mu\nu} G^{a,\mu\nu} + \sum_{i=1}^{N_2} \frac{\alpha_s}{8\pi v} c_{5,2i}\, H_{2i} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$$

where $\mathcal{L}_{\text{theory}}$ describes any of the supported models.
Together with `BLOCK FACTORS` you can access κ_t, κ_b
and for example investigate the degeneracy between κ_t and $c_{5,H}$ at NLO:
Define $\sigma(p_T^{\text{cut}}) = \int_{p_T > p_T^{\text{cut}}} dp_T d\sigma / dp_T$ and look at

$$\frac{\sigma(p_T^{\text{cut}})}{\sigma(p_T^{\text{cut}})(\kappa_t = 1, \kappa_b = 0, c_{5,H} = 0)} = (\kappa_t + c^{(0)}_{5,H})^2 + \delta \kappa_t c^{(0)}_{5,H} + \epsilon (c^{(0)}_{5,H})^2 + \delta_{bt} \kappa_b \kappa_t + \delta_{bg} \kappa_b c^{(0)}_{5,H} + \epsilon_b \kappa_b^2$$



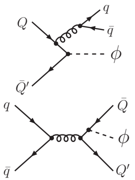
similar to
[Grojean Salvioni Schlaffer Weiler '13]
see also [Ellis et al. '87]

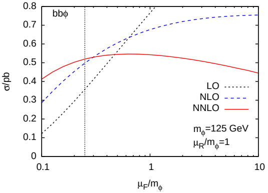
Outline

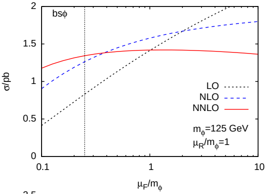
Heavy-quark annihilation  : [Harlander '15]

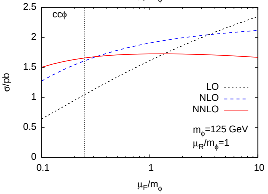
NNLO QCD partonic XS $Q'\overline{Q} \to \phi$ is independent of quark-flavor (apart from Yukawa coupling) due to vanishing interference terms for zero quark masses.

For $q \in \{Q, Q'\}$ no interference between:









Scale choice minimizing $(\mu_{\rm R}, \mu_{\rm F})$ dependence:

$\mu_{\rm R} \sim m_\phi$,$\mu_{\rm F} \sim 0.25 m_\phi$

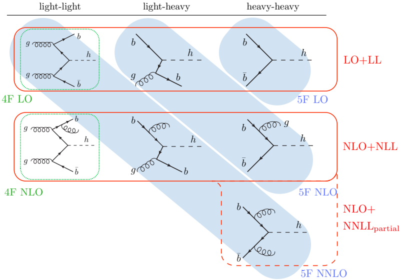
Control in `SusHi` through `Block QQH`:

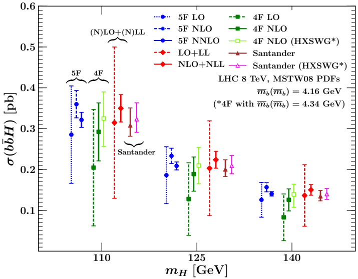
```
Block QQH # parameters for qq->H process
 1      5    # parton 1 = b
 2     -5    # parton 2 = bbar
11   4.18000000E+00 # Yukawa coupling
12   4.18000000E+00 # renorm.-scale Yuk.-coupl.
```

Santander matching between 4/5FS calculations: [Harlander Krämer Schumacher '11]

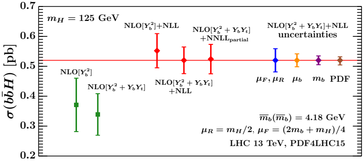
$$\sigma = \frac{\sigma^{4FS} + \omega\sigma^{5FS}}{1+\omega} \quad \text{with} \quad \omega = \ln\left(\frac{m_H}{m_b}\right) - 2$$

For bottom-quark annihilation recent progress in matching 5FS and 4FS:
FONLL scheme [Forte Napoletano Ubiali '15 '16]
SCET [Bonvini Papanastasiou Tackmann '15 '16]

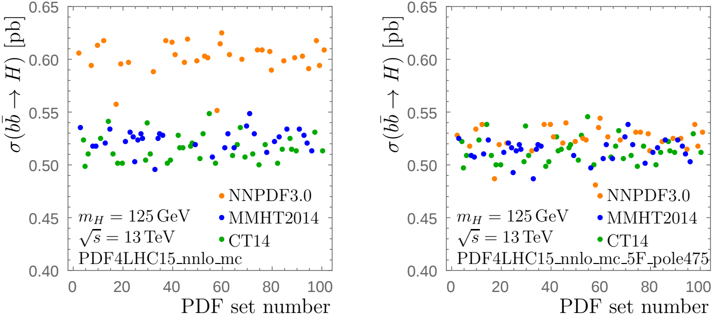




Matched predictions supersede Santander matched numbers.
FONLL-B $=$ NLO+NNLL$_{partial}$



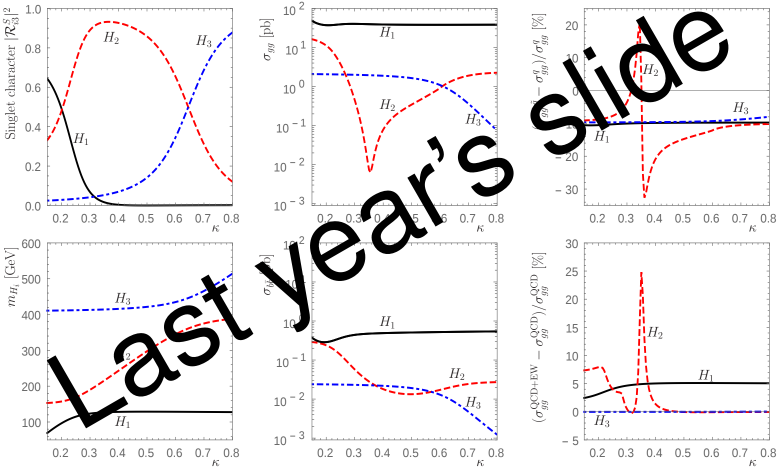
Warning: `PDF4LHC15` should not be used for 5FS calculations!
Instead use `APFEL` generated sets with well-defined bottom mass, see YR4!



Differential distributions at NLO combined with parton showers:
MC@NLO [Wiesemann Frederix Frixione Hirschi Maltoni Torrielli '14]
POWHEG box [Jäger Reina Wackeroth '15]

Outline

Results for the inclusive NMSSM cross section (CP-even Higgs bosons):
Spectrum generator NMSSMCALC [Baglio et al., '13], Details: [1502.07972: SL '15]



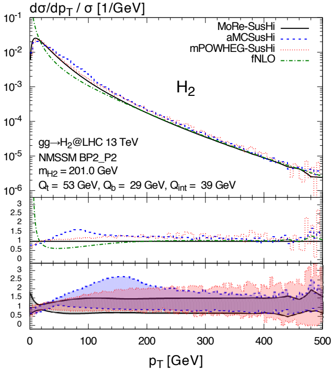
$\tan\beta = 2$, $A_\kappa = -20$ GeV, $\lambda = 0.62$, $\mu = 200$ GeV, $m_{H^\pm} = 400$ GeV, $M_3 = 1.5$ TeV

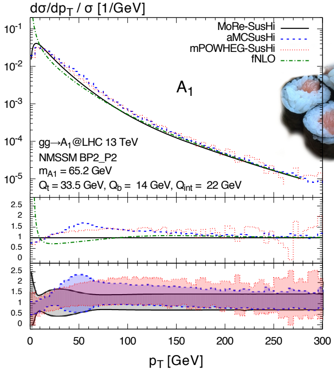
$m_{\tilde{t}_1} = 544.7$ GeV, $m_{\tilde{t}_2} = 941.2$ GeV, $m_{\tilde{b}_1} = 749.4$ GeV, $m_{\tilde{b}_2} = 757.4$ GeV, $\sqrt{s} = 8$ TeV

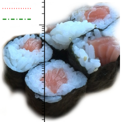
Goint differential in NMSSM Higgs production: [SL Mantler Wiesemann '16]

p_T Higgs distributions of POWHEG−SusHi [Mantler unp.], MoRe−SusHi [Harlander Mantler Wiesemann '14] and aMCSusHi [Mantler Wiesemann '15]

Example BP2_P2 in YR4: Singlets at $m_{H_2} = 201.0$ GeV, $m_{A_1} = 65.2$ GeV





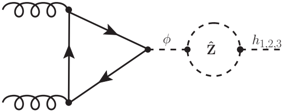


Similar findings as in MSSM, 2HDM for what concerns resummation scale choices: [Bagnaschi Harlander Mantler Vicini Wiesemann '15]

Higgs production in the MSSM with complex parameters:
Extension of SusHi with admixed Higgses: SusHiMi [SL Patel Weiglein '16?]
Main differences w.r.t. MSSM with real parameters:

- ✓ $\hat{\mathbf{Z}}$ factors describing CP-even and CP-odd mixing $\{h, H, A\}$ (obtained with FeynHiggs)
- ✓ non-vanishing couplings $g^A_{\tilde{q}ii}$ of squarks to pseudoscalar
- ✓ different left- and right-handed Yukawa couplings $g_{bR} = g^*_{bL}$

Partonic cross section at leading order:



$$\sigma_0^{h_a} = \frac{G_F \alpha_s^2(\mu_R)}{288\sqrt{\pi}} \left[\left| \mathcal{A}^{h_a,\mathrm{e}} \right|^2 + \left| \mathcal{A}^{h_a,\mathrm{o}} \right|^2 \right]$$

$$\text{with} \quad \mathcal{A}^{h_a,\mathrm{e}} = \hat{\mathbf{Z}}_{ah}\mathcal{A}^h_+ + \hat{\mathbf{Z}}_{aH}\mathcal{A}^H_+ + \hat{\mathbf{Z}}_{aA}\mathcal{A}^A_-$$

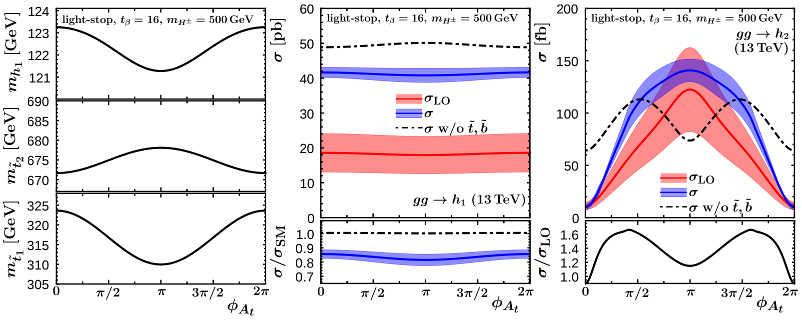
$$\text{and} \quad \mathcal{A}^{h_a,\mathrm{o}} = \hat{\mathbf{Z}}_{ah}\mathcal{A}^h_- + \hat{\mathbf{Z}}_{aH}\mathcal{A}^H_- + \hat{\mathbf{Z}}_{aA}\mathcal{A}^A_+$$

Squark contributions only to $\mathcal{A}^{h_a,\mathrm{e}}$.
$\mathcal{A}_-$ contributions proportional to $(g_L - g_R) \propto \gamma_5$.

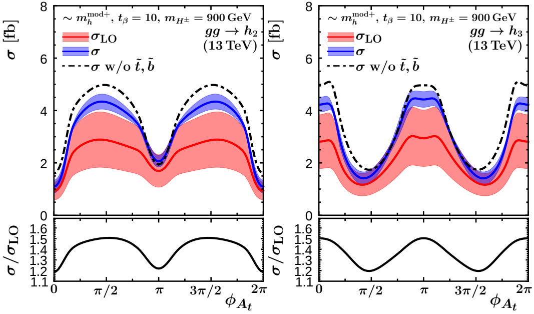
Higher orders:

- ✓ massive NLO top- and bottom-quark contributions ($g_L = g_R$)
- ✓ top up to N^{3}LO for the CP-even component of h_1, NNLO elsewhere
- ✓ Electroweak contributions mediated through light quarks
- ✓ Interpolated NLO contributions of squarks-gluinos (from phase 0 and π)

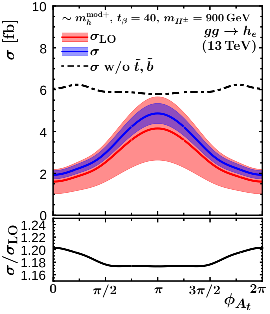
Numerical results I: $\sim$ light-stop scenario (Scale uncertainties)



Numerical results II: $\sim m_h^{\text{mod}+}$ scenario
Admixture of two heavy Higgs bosons



Δ_b corrections



Main effects:
1. Large effects from squarks and gluinos (also through Δ_b)
2. Large admixture of the two heavy Higgs bosons $\longleftrightarrow$ large interferences
Similarly bottom-quark annihilation is affected.

Outline

Conclusion:

Within the last year quite some progress was achieved in the calculation of gluon fusion and (heavy) quark-annihilation.

- ✓ $\mathrm{N^3LO}$ QCD corrections to gluon fusion
- ✓ Works on mass effects to gluon fusion (differentially)
- ✓ NNLO QCD predictions for heavy-quark annihilation
- ✓ Matched predictions for bottom-quark annihilation

Many new results were/are incorporated in `SusHi`!

- ✓ Inclusion of Dimension-5 operators
- ✓ Going differential for NMSSM Higgs bosons
- ✓ `SusHiMi` extension for MSSM with CP violation