Collaborative Research Center TRR 257
PHH
Particle Physics Phenomenology after the Higgs Discovery

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TTK Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

Higgs Cross Sections

Higgsstrahlung and Higgs production beyond the Standard Model

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Status quo

SusHi: Higgs production:

[Harlander, Liebler, Mantler: 2013][Harlander, Liebler, Mantler: 2016]

- gluon fusion: $gg \to H$ (`ggh@nnlo`)
- bottom annihilation: $b\bar{b} \to H$ (`bbh@nnlo`)

vh@nnlo: Higgs + Vector boson production ("Higgsstrahlung")

[Brein, Harlander, Zirke: 2012][Harlander, Liebler, Zirke: 2014][Harlander, Klappert, Liebler, Simon: 2020]

both:

- various BSM models (2HDM, MSSM, ...)
- SLHA input/output
- linkage to Spectrum Generators

$\Rightarrow$ merge vh@nnlo into SusHi

Cross Sections

Hadronic Cross Section

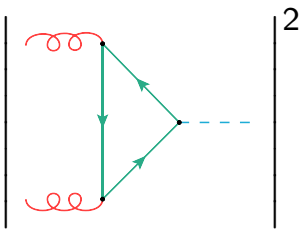
$$\sigma^{\mathrm{LO}}(s) = \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 \; f(x_1) \; f(x_2) \; \hat{\sigma}^{\mathrm{B}}(\hat{s}) \; \delta(\hat{s} - x_1 x_2 s)$$

Partonic Cross Section:

$$\hat{\sigma}^{\mathrm{B}}(\hat{s}) = \frac{1}{2\hat{s}} \int \mathrm{d}\Pi(\mathrm{D} = 4 - 2\epsilon) \, |\mathcal{M}_{\mathrm{Born}}|^2(\hat{s})$$

Matrix Element:

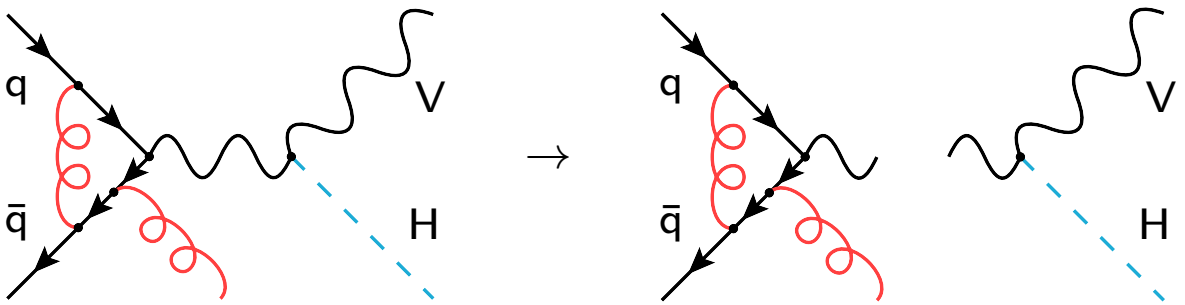
$$|\mathcal{M}_{\mathrm{Born}}|^2(\hat{s}) =$$

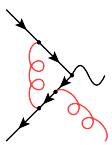


$$\hat{\sigma}_{ij}^{\mathrm{NLO}} = \hat{\sigma}_{ij}^{\mathrm{R}} + \hat{\sigma}_{ij}^{\mathrm{V}} + \hat{\sigma}_{ij}^{\mathrm{C}}$$

$$\hat{\sigma}_{ij}^{\mathrm{NNLO}} = \hat{\sigma}_{ij}^{\mathrm{RR}} + \hat{\sigma}_{ij}^{\mathrm{RV}} + \hat{\sigma}_{ij}^{\mathrm{VV}} + \hat{\sigma}_{ij}^{\mathrm{C1}} + \hat{\sigma}_{ij}^{\mathrm{C2}}$$

Drell-Yan like Higgsstrahlung

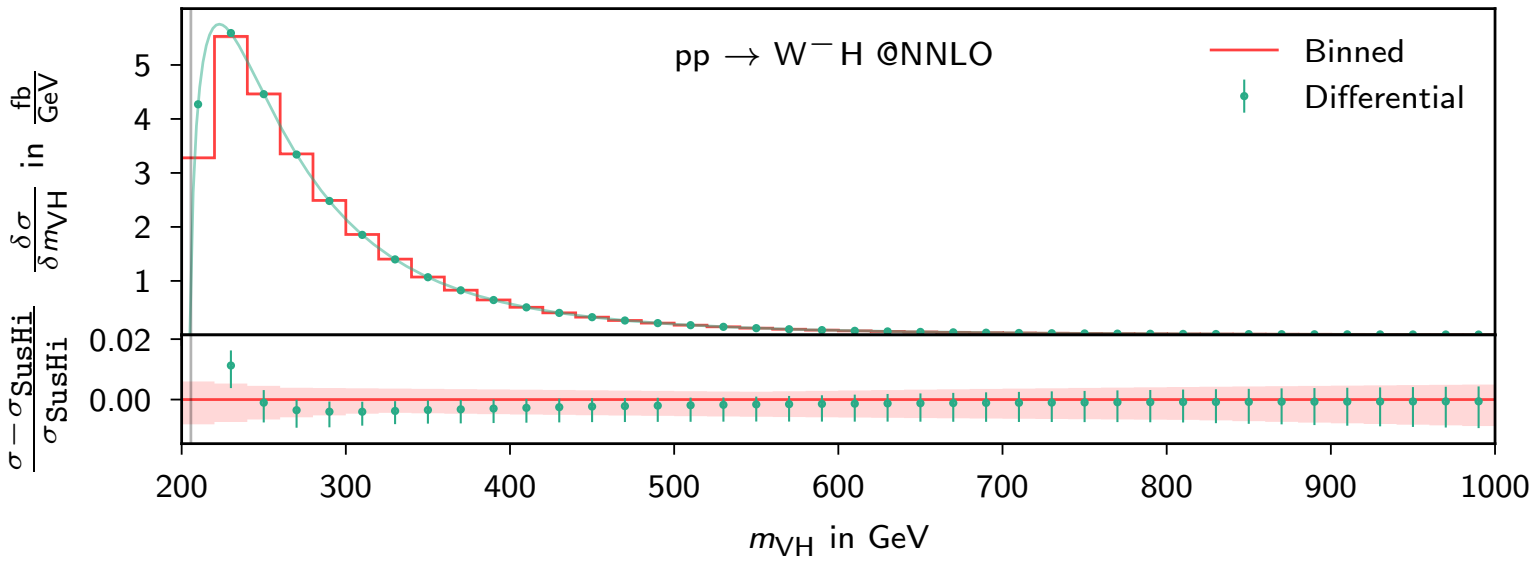


 : $\sigma_{pp\to V^*}$  : $\Gamma_{V^*\to VH}$

$$\sigma_{pp\to VH} = \int_{(m_H+m_V)^2}^{s} dq^2 \; \sigma_{pp\to V^*} \; d\Gamma_{V^*\to VH}/dq^2$$

$\hat{\sigma}_{pp\to V^*}$ up to α_s^3 available [Duhr, Mistlberger: 2021][Duhr, Dulat, Mistlberger: 2020]

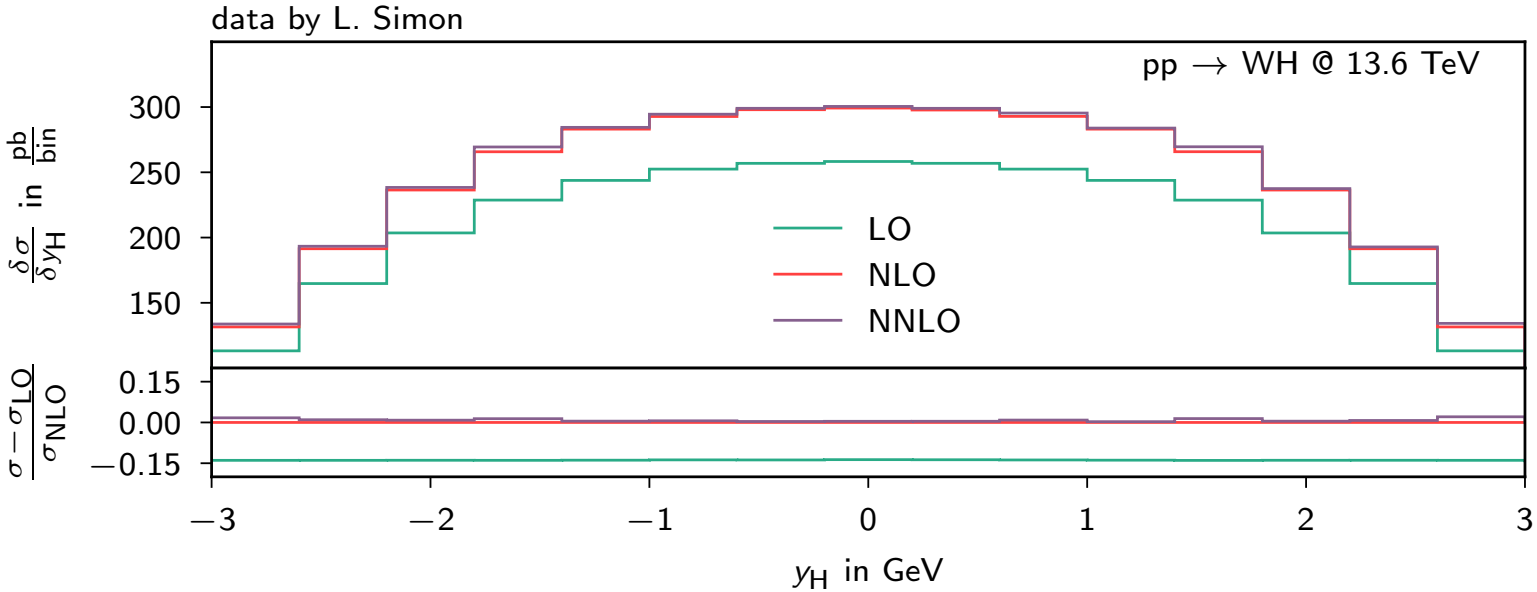
Invariant Mass Distribution



Binned: $\delta\sigma_{\mathrm{pp}\to\mathrm{VH}} = \int_{m^2_{\mathrm{VH}}-\frac{1}{2}\delta m^2_{\mathrm{VH}}}^{m^2_{\mathrm{VH}}+\frac{1}{2}\delta m^2_{\mathrm{VH}}} \mathrm{d}q^2 \; \sigma_{\mathrm{pp}\to\mathrm{V}^*} \; \mathrm{d}\Gamma_{\mathrm{V}^*\to\mathrm{VH}}/\mathrm{d}q^2$

Differential: $\frac{\mathrm{d}\sigma}{\mathrm{d}m^2_{\mathrm{VH}}} = \sigma_{\mathrm{pp}\to\mathrm{V}^*} \; \mathrm{d}\Gamma_{\mathrm{V}^*\to\mathrm{VH}}/\mathrm{d}m^2_{\mathrm{VH}}$

Fully Differential



`SusHi 2.0` like program for differential Cross Sections → `history`

Including:

- Higgs Production in Gluon Fusion
- Higgs Production in Heavy Quark Annihilation
- Drell-Yan Higgsstrahlung (done by L. Simon)
- Beyond the SM

Subtraction Schemes

Find `Waldo` such that

$$\int \mathrm{d}\Pi_R \left(|\mathcal{M}_R|^2 - \texttt{Waldo} \right) = \text{finite}$$

and

$$\int \mathrm{d}\Pi_R \texttt{Waldo} \text{ calculable and cancels poles in } \hat{\sigma}_V,\ \hat{\sigma}_C$$

and

$$\texttt{Waldo} \text{ Process independent}$$

$\Rightarrow$ `Waldo` subtracts singular behaviour of $|\mathcal{M}|^2$

Sector Decomposition [Heinrich: 2008]

FKS (NLO) [Frixione, Kunszt, Signer: 1996]

SecToR Improved Phase sPace for real Radiation [Czakon: 2010]

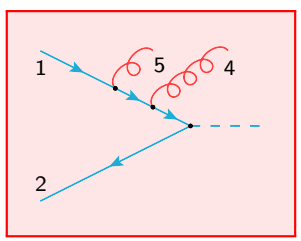
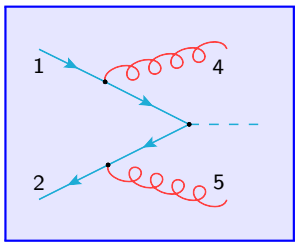
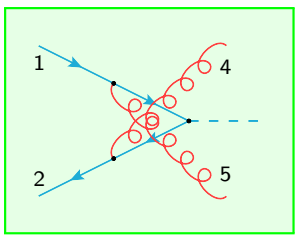
Nested Soft-Collinear Subtraction Scheme [Caola, Melnikov, Röntsch: 2017]

Antenna Subtraction [Gehrmann-De Ridder, Gehrmann, Glover: 2007], CoLoRfulNNLO Subtraction [Del Duca et al.: 2016], ...

Phase-Space Partitions

Double-real Radiation: many singular Phase-Space Configurations

`STRIPPER`: Separate Configurations

$$|\mathcal{M}_{\text{RR}}|^2 = \Bigg| \;  +  +  + \ldots \Bigg|^2$$

Introduce weights: $1 = \omega^{14,15} + \omega^{14,25} + \omega^{15,24} + \omega^{24,25}$

Such that $\omega^{14,25} \, |\mathcal{M}_{\text{RR}}|^2$ only singular when $1 \parallel 4$ or $2 \parallel 5$

$\Rightarrow$ Subtract only specific divergences
$\Rightarrow$ Use suitable parametrisation

From Higgsstrahlung to Higgs Production

Higgsstrahlung already implemented (by L. Simon)

Heavy Quark Annihilation:

- two-particle PS $\rightarrow$ one-particle PS
- also $q\bar{q}$ initial state

Gluon Fusion:

- two-particle PS $\rightarrow$ one-particle PS
- $q\bar{q}$ initial state $\rightarrow$ gg initial state

$\Rightarrow$

- Add gg Initial State
- Add General # FS Particles

$\Rightarrow$

- Completely general for Colour-Singlet Production

How to extend `history`

```
IF (ORDERGGH>=0) THEN
  ORDER = ORDERGGH
  FS_NUM = 1
  IS_CONF = GG
  PROC = GGH
  MASSES(1) = MH
  CALL SIGMA(SIGMAGGH, ERRORGGH)
ENDIF

IF (ORDERDY>=0) THEN
  ORDER = ORDERDY
  FS_NUM = 2
  IS_CONF = QQ
  PROC = DY
  MASSES(1) = MV
  MASSES(2) = MH
  CALL SIGMA(SIGMADY,ERRORDY)
ENDIF
```

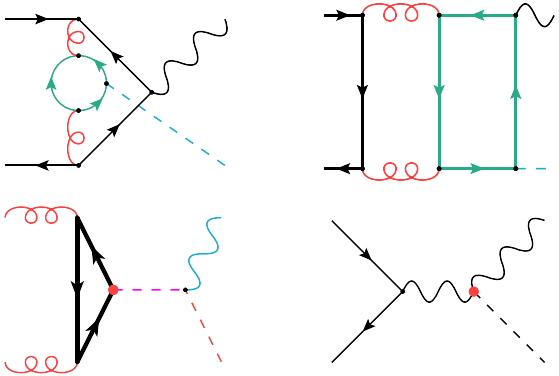
```
function flm(p1,p2,p3,pt1,pt2)

  if (proc == ggh) then
    res = flm_ggh(p1,p2,p3,pt1,pt2)
  else if (proc == qqh) then
    res = flm_qqh(p1,p2,p3,pt1,pt2)
  else if (proc == dy) then
    res = flm_dy(p1,p2,p3,pt1,pt2)
  end if

end function flm
```

⇒ Easily extendible

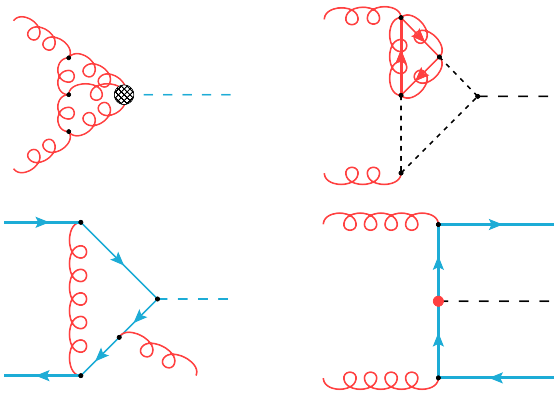
⇒ Include other processes (Colour-Singlet production only)

Summary

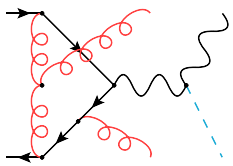
vh@nnlo



SusHi



VH DY @ N^{3}LO



SusHi 2.0

Nested Soft-Collinear Subtraction Scheme → history