Madgraph5_aMC@NLO simulation for the muon collider

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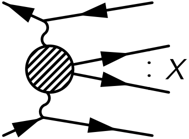
The muon collider

$\mu^+\mu^- \to X$

- High energy!
- VBF processes grow as energy grows! $\sigma \sim (\ln \frac{s}{m_W^2})^x$



- Z boson fusion suppressed comparing to W boson fusion.

$$g_{\mu\mu Z} \ll g_{\mu\nu_\mu W}$$
$$\sigma(\mu^+\mu^- \to \mu^+\mu^- X) \ll \sigma(\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu X)$$

Simulating electroweak processes

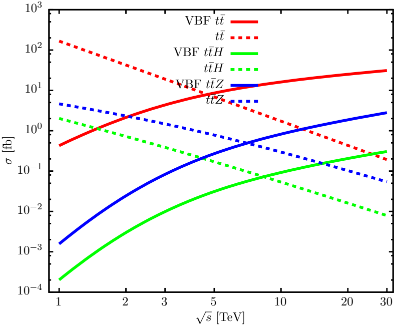
- $W^{\pm}, Z$ are massive
- For n external particles, individual diagrams: $\mathcal{M} \propto E^m, m > 4 - n$
- Perturbative unitarity:$\mathcal{M}^{\text{full}} \leq \mathcal{O}(E^{4-n})$
- Gauge invariance ensures cancellation between different diagrams
- For example, considering W boson propagator in unitarity gauge:

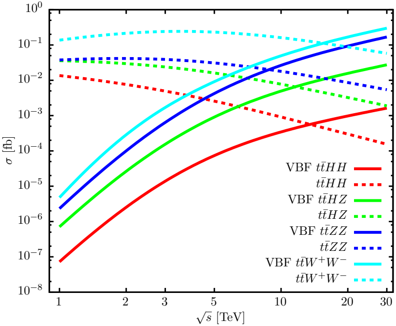
$$-i\frac{g^{\mu\nu} - \frac{k^\mu k^\nu}{m_W^2}}{k^2 - m_W^2}$$

and $\mathrm{SU}(2)$ coupling $g_2 = \frac{m_W}{2v}$, we must adopt $m_W^2 = m_W^2 = m_W^2 = m_W^2 - im_W\Gamma_W$, where the decay width Γ_W can be set to be zero or non-zero.

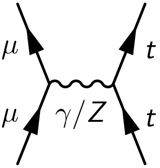
- $\Gamma_W = 0 \rightarrow$ the zero-width scheme, W boson cannot decay. $\mu^+\mu^- \rightarrow W^+W^-$
- $\Gamma_W \neq 0 \rightarrow$ the complex mass scheme, W boson must decay $\mu^+\mu^- \rightarrow e^+\nu_e\tau^-\bar{\nu}_\tau$
- Similar for Z boson

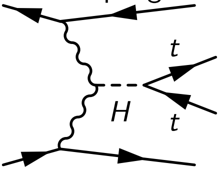
top pair processes



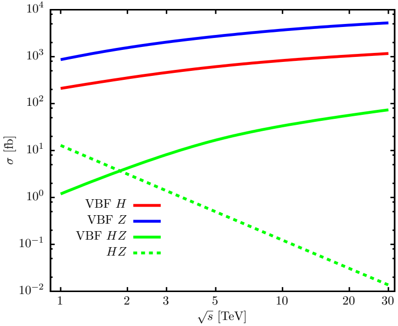


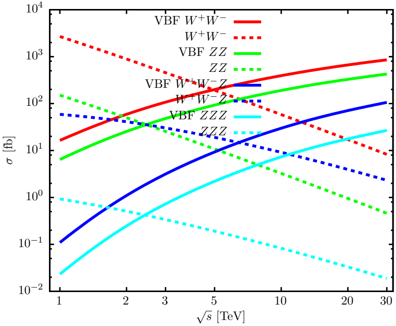
Also access to more couplings:



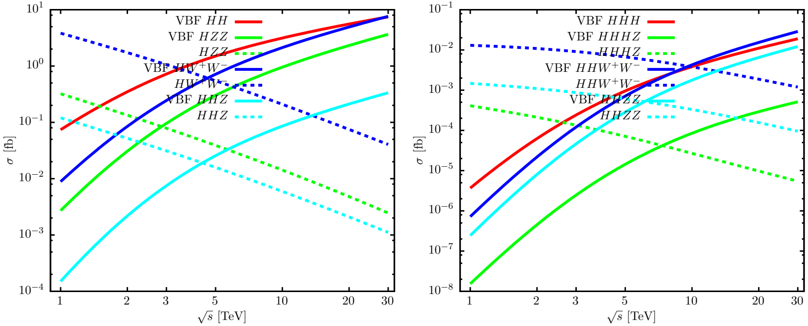


Higgs and vector bosons

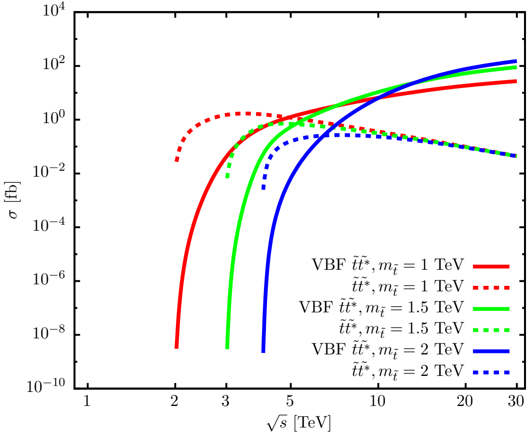




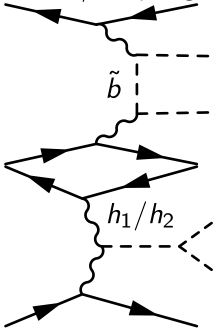
Multi-Higgs and Higgs self-couplings



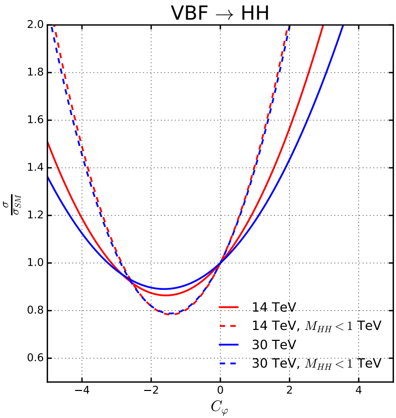
$\tilde{t}\tilde{t}^*$ production



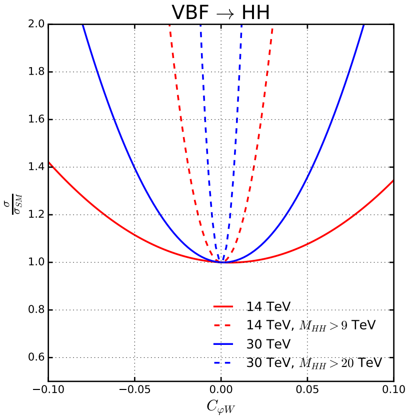
And also probing other NP particles/couplings:



VBF HH in SMEFT

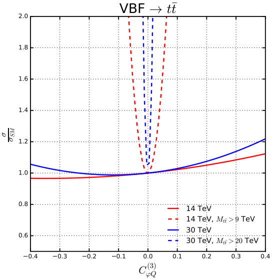


$$(\phi^\dagger\phi - \frac{v^2}{2})^3$$

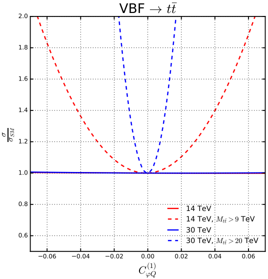


$$(\phi^\dagger\phi - \frac{v^2}{2}) W_I^{\mu\nu} W^I_{\mu\nu}$$

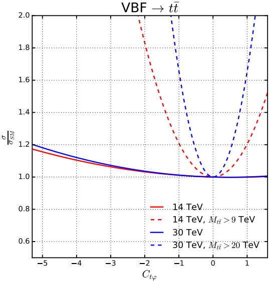
VBF $t\bar{t}$ in SMEFT



$$i(\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi)(\bar{Q}\gamma^\mu \tau^I Q)$$



$$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{Q}\gamma^\mu Q)$$



$$i(\phi^\dagger \phi - \frac{v^2}{2})\bar{Q}t\tilde{\phi} + h.c.$$

Effective W approximation

- W boson fusion process
- For $\sqrt{s} \gg \sqrt{s_{WW}} \gg m_W$, and "low"-$p_T$ W boson(collinear splitting)

$$\sigma(\mu^- \mu^+ \xrightarrow{W^- W^+ \to X} X) \approx f_{W^-/\mu^-} \otimes f_{W^+/\mu^+} \otimes \hat{\sigma}(W^- W^+ \to X)$$

- $f_{W^-/\mu^-}, f_{W^+/\mu^+}$: W boson PDF
- Implemented in Madgraph5_aMC@NLO and under validating

```
c w boson splitting function: longitudinal polarization
      double precision function ewa_w0(x)
      implicit none
      double precision x
      double precision coup
^^^^^^
      include 'ElectroweakFlux.inc'
^^^^^^
c     P_W(x,lambda=0) = (gW/4pi)**2 (1-x)/x
      coup = ewa_gW2/(16d0*pi2)
      ewa_w0 = coup * (1d0-x)/x
      return
      end
```

$$f_{W_L^\pm/\mu^\pm}(x) = \frac{g_W^2}{16\pi^2} \frac{1-x}{x}$$

[with F. Maltoni, L. Mantani, O. Mattelaer, R. Ruiz]

EWA example

syntax:

```
MG5_aMC>generate w+ w- > h h
MG5_aMC>output ewa-hh
MG5_aMC>launch
```

In the run card:

```
#*********************************************************************
# Collider type and energy                                           *
# lpp: 0=No PDF, 1=proton, -1=antiproton, 2=photon from proton,      *
#                                         3=photon from electron     *
#*********************************************************************
  -4|    = lpp1 ! beam 1 type^
  4|= lpp2 ! beam 2 type
  15000.0|   = ebeam1 ! beam 1 total energy in GeV
  15000.0|   = ebeam2 ! beam 2 total energy in GeV
```

4 means muons, and -4 means anti-muons.

Conclusion and outlook

- Large VBF cross section
- Madgraph5_aMC@NLO: checking various VBF processes in the SM
- and various BSM
- Effective W approximation: implementing and checking, for better understanding of physics, and simulation

Backup slides