HIGGS + 2 JETS VIA GLUON FUSION

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At values of $m_H > 100$ GeV, and at LHC energies, these are the two dominant processes for Higgs production: $gg$ fusion and weak-boson fusion (WBF).

WBF, characterized by two forward-backward jets, is important for the extraction of Higgs couplings with gauge bosons.

**Double real corrections** to $gg \rightarrow H$ can “fake” WBF $\iff$

- accurate evaluation of these corrections
- investigate the “goodness” of the large $m_t$ limit.
Diagrams

\[
\begin{align*}
q Q & \rightarrow q Q H & Q = q, q' \\
q g & \rightarrow q g H \\
g g & \rightarrow g g H \\
\text{plus crossed processes.}
\end{align*}
\]
Tensor integrals

All the scalar integrals (triangles, boxes and pentagons) are finite (the top mass $m_t$ protects from divergences) \(\Rightarrow\) we work in $D = 4$ dimensions.

Due to the presence of the $H$ vertex, we have for the tensor integrals

- triangles: at most two loop-momenta in the numerator $(k^\alpha k^\beta)$
- boxes: at most three loop-momenta in the numerator $(k^\alpha k^\beta k^\gamma)$
- pentagons: at most four loop-momenta in the numerator $(k^\alpha k^\beta k^\gamma k^\delta)$

For triangles and boxes we directly apply Passarino-Veltman formulae and we express the tensor integrals in the amplitudes as combination of scalar triangles and boxes.
Write the polarization vectors of the external gluons as a linear combination of external momenta. For the \( i \)-th gluon we have

\[
\epsilon_i = \epsilon_{i1} q_1 + \epsilon_{i2} q_2 + \epsilon_{i3} q_3 + \epsilon_{i4} q_4
\]

and contract the amplitudes. In this way, the tensor integrals depend only on scalar products of the type \( q_i \cdot q_j \) and \( k \cdot q_i \).

The \( \epsilon_{ij} \) coefficients are computed from the knowledge of the products \( \epsilon_i \cdot q_j \), once one assigns a definite polarization for the gluons.

All dot-products in the numerator of the tensor pentagons can be rewritten as a combination of propagators. For example:

\[
k \cdot q_2 = \frac{1}{2} \left\{ \left[ (k + q_1 + q_2)^2 - m_i^2 \right] - \left[ (k + q_1)^2 - m_i^2 \right] \right\} - q_1 \cdot q_2
\]

The tensor pentagons with 4 loop momenta in the numerator are written as a combination of

- tensor boxes with at most 3 loop momenta in the numerator \( \implies \) Passarino-Veltman tensor reduction formulae

- scalar pentagons
It can be shown that the generic scalar pentagon in \( D \) dimension, \( P^D \), can be written as

\[
P^D(q_i \cdot q_j, m_t) = c_0 (D - 4) P^{D+2}(q_i \cdot q_j, m_t) + \sum_{k=1}^{5} c_k B_k^D(q_i \cdot q_j, m_t)
\]

where \( B_k^D \) is the \( k \)-th box obtained by pinching the \( k \)-th propagator in the pentagon.

Since \( P^6(q_i \cdot q_j, m_t) \) is finite, we can safely put \( D = 4 \) and the scalar pentagon can be rewritten in terms of box integrals only, in 4 dimensions.
These two diagrams contribute

$$\text{Tr} \left(t^a_t^b_t^c_t^d\right) T + \text{Tr} \left(t^d_t^c_t^b_t^a\right) T$$

$T$ is the same (Furry’s theorem).

4 gluons $\Rightarrow$ 4! = 24 diagrams. But cyclic permutations give the same trace $\Rightarrow$ 3! = 6 non-cyclic permutations.

When we sum the pairs of diagrams with the same “tensor” part, we have only three independent colour structures

\[
\begin{align*}
  c_1 &= \text{Tr} \left(t^a_t^b_t^c_t^d\right) + \text{Tr} \left(t^a_t^d_t^c_t^b\right) \\
  c_2 &= \text{Tr} \left(t^a_t^c_t^d_t^b\right) + \text{Tr} \left(t^a_t^b_t^d_t^c\right) \\
  c_3 &= \text{Tr} \left(t^a_t^d_t^b_t^c\right) + \text{Tr} \left(t^d_t^c_t^b_t^d\right)
\end{align*}
\]

Boxes and Triangles

They have two independent colour structures: $(c_1 - c_2)$ and $(c_1 - c_3)$.

\[
\begin{align*}
  c_1 - c_2 &= -\frac{1}{2} f^{abl} f^{cdl} \\
  c_3 - c_1 &= -\frac{1}{2} f^{adl} f^{bcl} \\
  c_2 - c_3 &= -\frac{1}{2} f^{alc} f^{dbl}
\end{align*}
\]
Gauge-invariance checks

We will concentrate on the $gg \rightarrow ggH$ processes, being the most articulate.

**GAUGE CHECK:** the amplitude **MUST** vanish if we set

$$\epsilon_i \text{ proportional to } q_i$$

Two gauge checks

- **QED-type** check. If we substitute all the gluons with photons, only the pentagon contributions survive in the $\gamma \gamma \rightarrow \gamma \gamma H$ process.

  The other contributions being zero, due to the presence of three and four gluon vertices

  $\Longrightarrow$ the sum of the contributions coming from the tensor reduction of pentagon diagrams (with no colour structure) **MUST** vanish.

- **full QCD** check. When we add all the diagrams with all their colour structure.
Applied cuts

The cross section diverges for
- final-state partons become collinear with one another
- final-state partons become collinear with initial-state partons
- final-state partons become soft

- **Minimal set of cuts** to define $H + 2$ jets

\[ p_{Tj} > 20 \text{ GeV} \quad |\eta_j| < 5 \quad R_{jj} > 0.6 \]

where $R_{jj}$ describes the separation of the two partons in the pseudo-rapidity versus azimuthal angle plane.

\[ R_{jj} = \sqrt{(\eta_{j1} - \eta_{j2})^2 + (\phi_{j1} - \phi_{j2})^2} \]

- **WBF set of cuts.** In addition to the previous ones, we impose

\[ |\eta_{j1} - \eta_{j2}| > 4.2 \quad \eta_{j1} \cdot \eta_{j2} < 0 \quad m_{jj} > 600 \text{ GeV} \]

- the two tagging jets must be well separated, with 3 units of pseudo-rapidity between the jet definition cones
- they must reside in opposite detector hemispheres
- they must possess a large dijet invariant mass.

ALL THE RESULTS FOR LHC ENERGY
Total cross section: minimal cuts

$\sqrt{s} = 14$ TeV

- Solid $m_T=175$ GeV
- Dots $m_T=3$ TeV
- Dashes WBF

Bottom graph:
- Solid $gg$
- Dots $qg$
- Dashes $qq$

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Total cross section: WBF cuts

solid $m_T=175$ GeV
dots $m_T=3$ TeV
dashes WBF

$m_T=175$ GeV
solid $gg$
dots $qq$
dashes $qq$

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$P_{Tj}$ (max): minimal cuts

$m_H = 120$ GeV

solid $m_T = 175$ GeV
dashes $m_T = 3$ TeV

$max_p_T[j]$ [fb/GeV]

$m_H = 120$ GeV

solid $m_T = 175$ GeV
dashes $m_T = 3$ TeV

$P_{Tj}$ (max) [fb/GeV]

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Azimuthal angle between jets $\phi_{jj}$: WBF cuts

$m_H = 120$ GeV

solid $m_T = 175$ GeV
dots $m_T = 3$ TeV
dashes WBF