Gluon fusion contribution to HBB (B = H,γ, Z,W) processes at the LHC

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Overview

Introduction

- There are many standard model (decay/scattering) processes which begin at loop-level at the leading order itself.
- Such loop-induced standard model processes are expected to be sensitive to new physics scales.
- Due to a large gluon flux, the gluon initiated processes can be important at high energy hadron colliders such as the LHC and its future upgrades.

Introduction

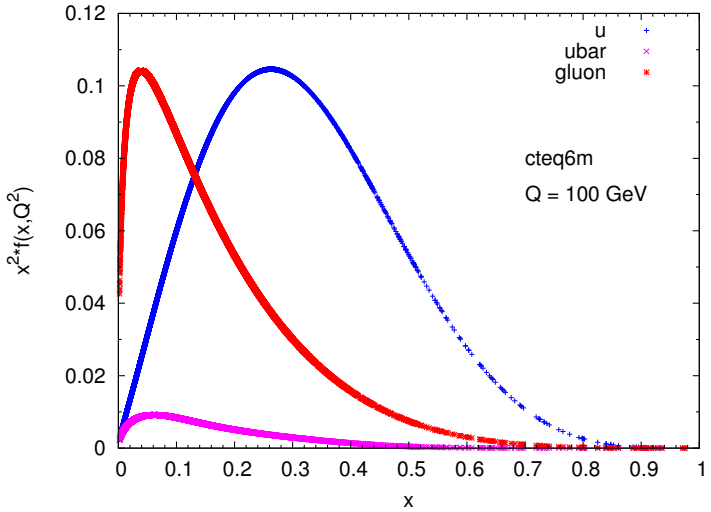

Figure: A comparison of parton distribution functions at a fixed scale.

- In the past we have studied $\mathrm{gg} \to \mathrm{VVj}, \mathrm{VHj}(\mathrm{V} = \gamma, \mathrm{Z}, \mathrm{W})$ processes at the LHC 1207.2927, 1208.2593, 1409.8059. In this talk we will focus on $\mathrm{gg} \to \mathrm{HBB}(\mathrm{B} = \mathrm{H}, \gamma, \mathrm{Z})$ processes. Some results on these processes are reported in hep-ph/0507321, hep-ph/0608057, 1408.6542, 0903.2885, 1507.00020, 1508.06524.

Introduction

- Observing HHH channel would provide us information on quartic self-Higgs coupling.
- HHZ is a background to HHH in $\mathrm{Z} \to \mathrm{bb}$ mode.
- VVH $(\mathrm{V} = \gamma, \mathrm{Z}, \mathrm{W})$ channels are backgrounds to $\mathrm{gg} \to \mathrm{HH}$ when one of the two Higgs bosons decays into a pair of vector bosons $(\gamma\gamma, \gamma\mathrm{Z}, \mathrm{ZZ}^*, \mathrm{WW}^*)$.

The Amplitudes

- These processes are one-loop at the leading order and proceed via quark loop diagrams.

- We have triangle, box and pentagon one-loop amplitudes to be calculated.

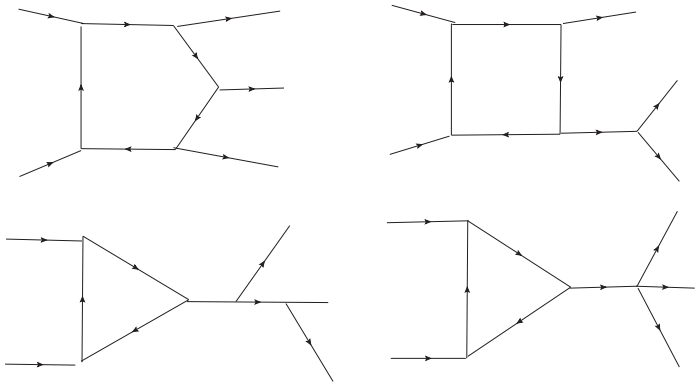

Figure: Classes of diagrams contributing to $\mathrm{gg} \to \mathrm{HBB}$.

- In most cases, we can identify prototype diagrams/amplitudes and generate all other diagrams by permuting the external legs.

The Amplitudes

- Various symmetries can be utilized to simplify the (complex) calculation.
- For example, due to charge conjugation, $\mathcal{M}(\mathrm{gg} \to \mathrm{HH}\gamma) = 0$. For the same reason in $\mathrm{gg} \to \mathrm{HHZ}$ case only the axial-vector part of qqZ coupling contributes, while in $\mathrm{gg} \to \mathrm{H}\gamma\mathrm{Z}$ and $\mathrm{gg} \to \mathrm{HZZ}$ cases only the vector type of amplitude gives non-zero contribution.
- Except top quark, all others are taken massless. Inclusion of finite b-quark mass is trivial.

Calculation and Checks

- The quark loop traces are calculated in FORM in $n-$dimensions. A suitable prescription for γ_5 (where applicable) is needed.
- One of the most difficult parts of the calculation is the reduction of one-loop tensor integrals into a suitable set of scalar integrals.
- We have one-loop five point tensor integral of rank four as the most complicated tensor structure.

$$\mathcal{E}_{\mu\nu\rho\sigma} = \int \frac{d^n l}{(2\pi)^n} \frac{l_\mu l_\nu l_\rho l_\sigma}{D_0 D_1 D_2 D_3 D_4} \tag{1}$$

Calculation and Checks

- Reduction of tensor integrals into appropriate scalars is done using methods of Oldenborgh and Vermaseren (Z. Phys. C 46 (1990)). Using Schouten Identity, we reduce penta-tensor and scalar integrals into lower rank box-tensor and scalar integrals.

$$\mathcal{E}_0(0,1,2,3,4) = \sum_I c_I \, \mathcal{D}_0^{(I)} + \mathcal{O}(\epsilon) \tag{2}$$

(Physics Letters 137B, 241)

Calculation and Checks

- After all the above reductions, the amplitude has following general structure of any one-loop amplitude in 4−dimensions.

$$\mathcal{M}^{1-loop} = \sum_i d_i \, \mathcal{D}_0^i + \sum_i c_i \, \mathcal{C}_0^i + \sum_i b_i \, \mathcal{B}_0^i + \sum_i a_i \, \mathcal{A}_0^i + \mathcal{R} \quad (3)$$

  $\mathcal{R}$ is know as the rational term. It is an artifact of UV regularization of tensor integrals and it is independent of the quark masses in the loop.

- Scalar integrals are calculated using the `OneLOop` package 1007.4716.

Calculation and Checks

- The amplitudes are expected to be free from UV and IR (due to massless quarks) singularities. This is an important check on the amplitudes.

- As an ultimate check, we can check the gauge invariance of amplitudes with respect to the gauge currents. It can be done numerically by replacing the polarizations with their respective 4-momenta, $\epsilon_\mu(k) \to k_\mu$.

- Because of a very large and complicated expression of the amplitudes, we calculate the (helicity/ polarized) amplitudes before squaring them $\Rightarrow |\mathcal{M}|^2 \Rightarrow$ partonic & hadronic cross sections.

Calculation and Checks

- Such calculations often suffer from numerical instabilities due to vanishing Gram Determinants which appear in the reduction of tensor integrals.

- The issue can be understood with the help of following simple example,

$$C^{\mu}(p_1, p_2) = \int \frac{d^n l}{(2\pi)^n} \frac{l^{\mu}}{D_0 \; D_1 \; D_2} = \overline{l^{\mu}} \tag{4}$$

$$= p_1^{\mu} \; C_1 + p_2^{\mu} \; C_2. \tag{5}$$

Calculation and Checks

$$\begin{pmatrix} C_1 \\ C_2 \end{pmatrix} = \begin{pmatrix} p_1.p_1 & p_1.p_2 \\ p_1.p_2 & p_2.p_2 \end{pmatrix}^{-1} \begin{pmatrix} \overline{l.p1} \\ \overline{l.p2} \end{pmatrix}. \tag{6}$$

- The reduction assumes linear independence of external momenta, however, the phase space generation only cares the 4-momentum conservation for a given process.
- Due to limited precision the issue becomes more severe in the reduction of higher point and higher rank tensor integrals.

Calculation and Checks

- Switching to quad-precision calculation can improve the situation. However, the computation time is huge in this case. Separate tensor reduction routines can be employed for the phase space points which give rise to numerical instability.

- We take a more economic route and check the gauge invariance of the amplitude for each phase space point. We ignore all those phase space points which do not satisfy the gauge invariance test beyond an appropriately chosen tolerance value.

Results (Preliminary)

- Kinematic cuts:

$$\mathrm{p_T^{H/Z}} > 1\ \mathrm{GeV}, \mathrm{p_T^{\gamma}} > 20\ \mathrm{GeV},$$
$$|\eta_{\mathrm{H/Z}}| < 5.0, |\eta_{\gamma}| < 2.5, \Delta\mathrm{R}_{\gamma\gamma} > 0.4 \tag{7}$$

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- Scale choice:

$$\mu_{\mathrm{F}} = \mu_{\mathrm{R}} = \sqrt{\hat{\mathrm{s}}} \tag{8}$$

and, scale uncertainty is reported by changing the scale by a factor of two about the central scale.

Results (Preliminary)

$\sqrt{s}$(TeV)	8	13	100
σ (HHH)	$7.048^{+34\%}_{-24\%}$	$31.87^{+30\%}_{-22\%}$	$3093^{+17\%}_{-14\%}$
σ (HHZ)	$8.385^{+34\%}_{-24\%}$	$36.12^{+30\%}_{-22\%}$	$3024^{+17\%}_{-14\%}$
σ (H$\gamma\gamma$)	$1.240^{+37\%}_{-23\%}$	$4.852^{+29\%}_{-22\%}$	$265.8^{+16\%}_{-13\%}$
σ (HZγ)	$1.401^{+32\%}_{-22\%}$	$4.931^{+28\%}_{-21\%}$	$241.3^{+15\%}_{-13\%}$
σ (HZZ)	$83.7000^{+36\%}_{-21\%}$	$471.636^{+36\%}_{-24\%}$	$102573^{+20\%}_{-15\%}$

Table: SM cross sections at various collider center-of-mass energies with scale uncertainties. All cross sections in *ab*.

Results (Preliminary)

	PEN	BX	TR	FULL
σ (HHH)	8110	4319	274.2	3039 (Destructive)
σ (HHZ)	16837.3	111645	123713	3024.33 (Strong Destructive)
σ (H$\gamma\gamma$)	265.8	–	–	265.8
σ (HZγ)	78.04	216.2	–	241.3 (Mild Destructive)
σ (HZZ)	18677.3	23684.9	31998.7	102573 (Constructive)

Table: Contributions from pentagon, box and triangle amplitudes at $\sqrt{s} = 100$ TeV. All cross sections in *ab*.

Results (Preliminary)

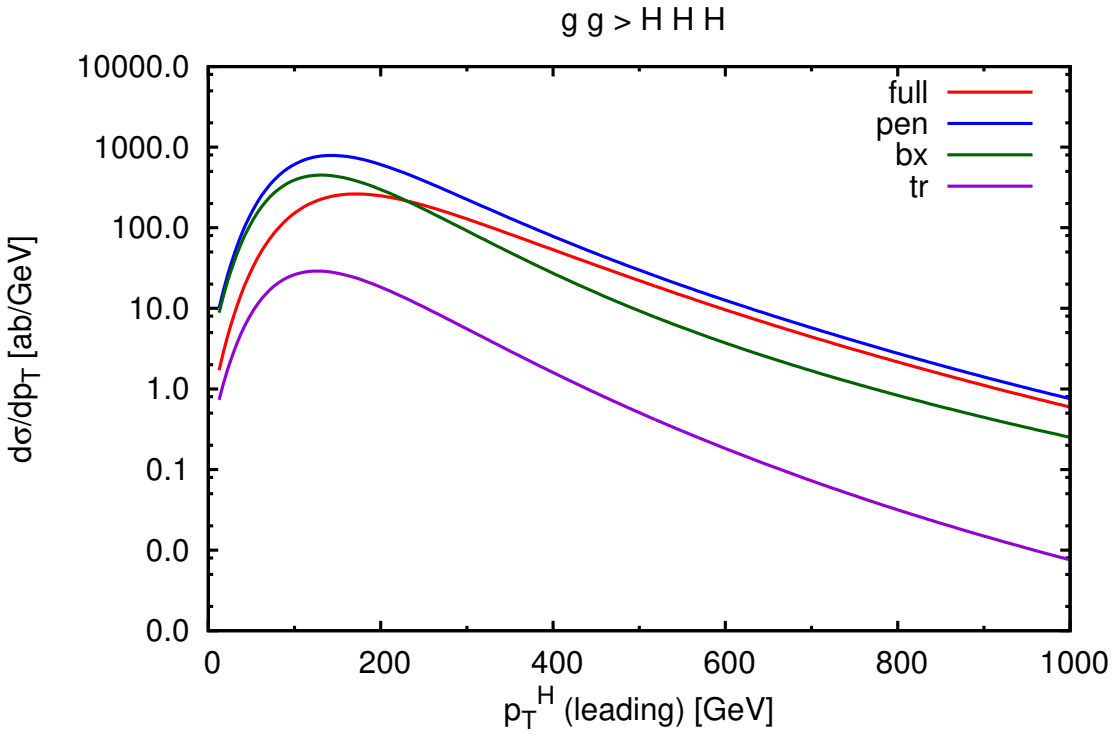
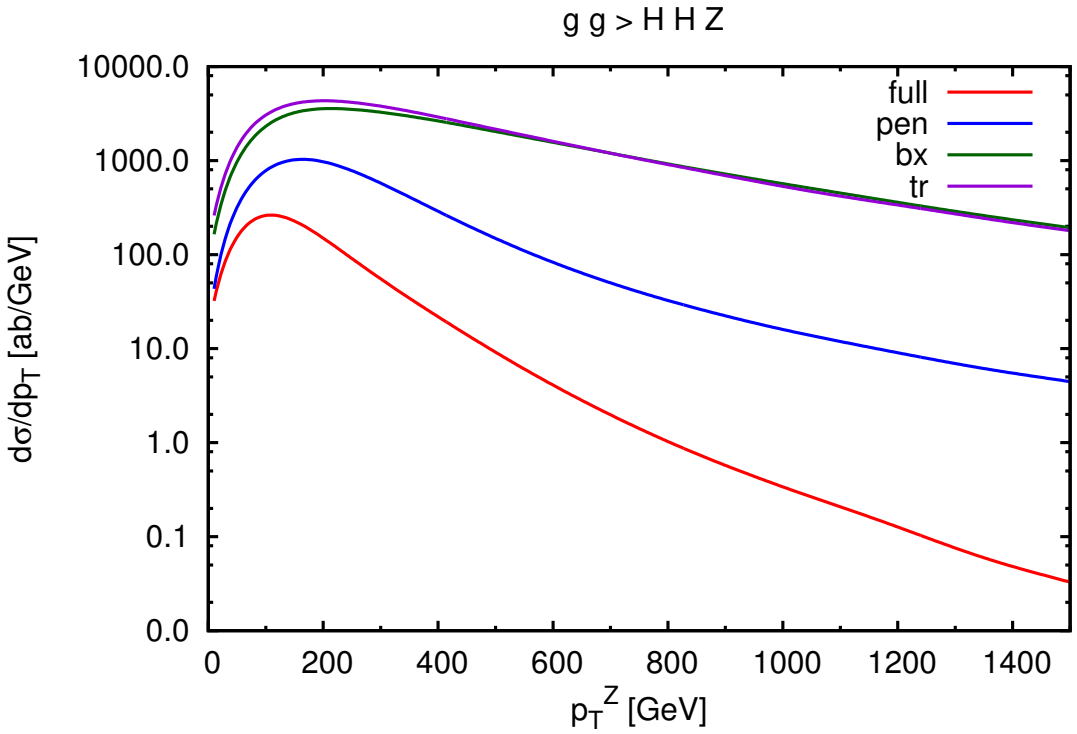


Figure: A comparison among various pieces of the amplitude.

Results (Preliminary)



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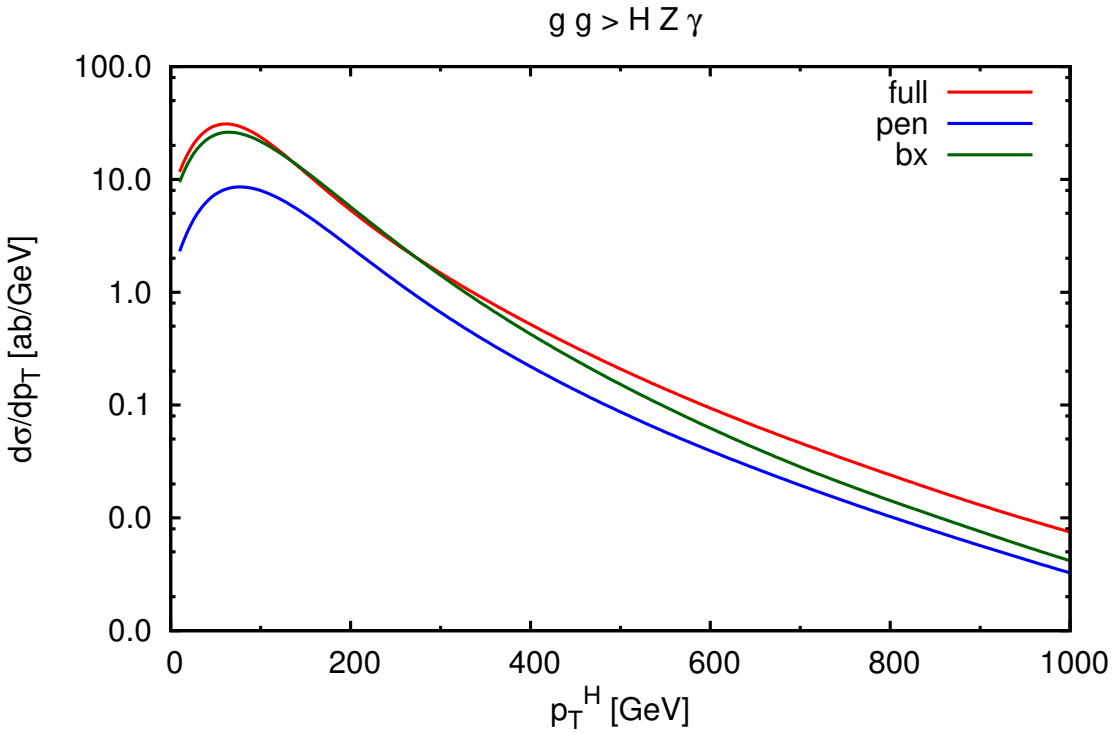

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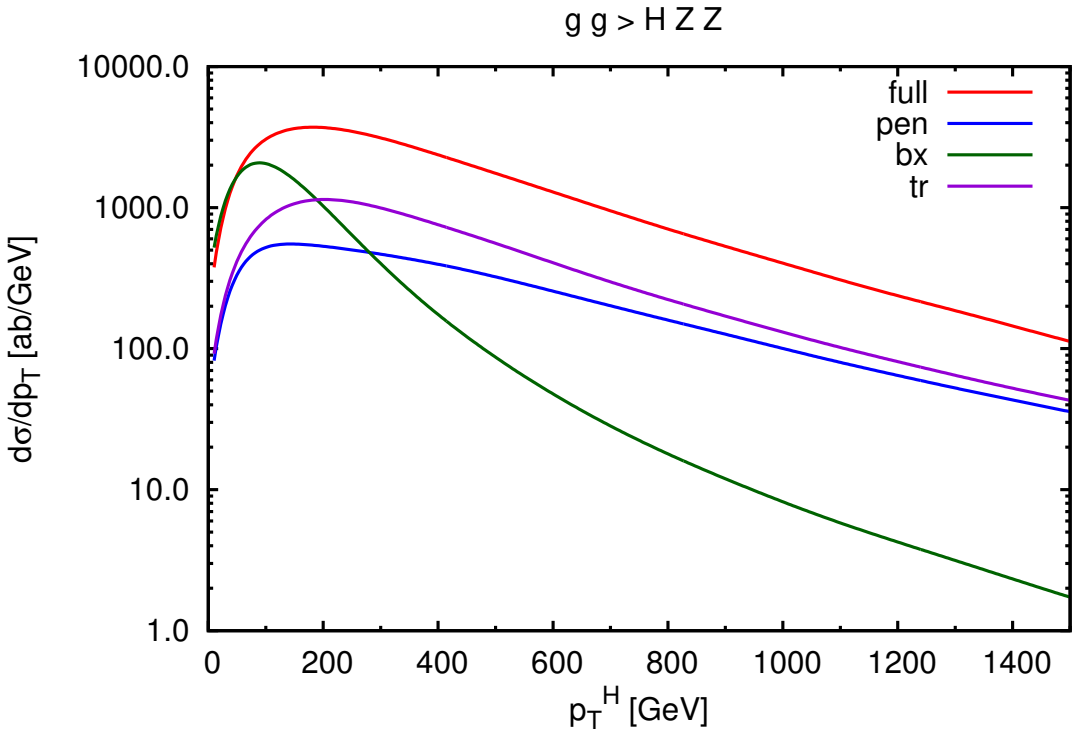

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Results (Preliminary)

ANML (0.9,1.1)	C_{tth}	C_{3h}	C_{4h}	C_{zzh}	C_{zzhh}
HHH	$(-52\%, +92\%)$	$(+8\%, -5\%)$	$(+1\%, -1\%)$	–	–
HHZ	$(+33\%, +83\%)$	$(-1.6\%, +1.9\%)$	–	$(+138\%, +167\%)$	$(-4.9\%, +19\%)$
$\mathrm{H}\gamma\gamma$	$(-1\%, +1\%)$	–	–	–	–
$\mathrm{HZ}\gamma$	$(-4\%, +4\%)$	–	–	$(-15\%, +15\%)$	–
HZZ	$(-21\%, +25\%)$	$(+0.5\%, -0.4\%)$	–	$(-26\%, +34\%)$	$(+4\%, -3\%)$

Table: The effect of changing various couplings by 10% of their SM values at $\sqrt{\mathrm{s}}$ = 100 TeV. All cross sections in *ab*. Correlations among couplings are not considered here.

Summary and Outlook

- We have computed loop-induced gluon fusion contributions to HBB $(\mathrm{B} = \mathrm{H}, \gamma, \mathrm{Z})$ processes. Due to small rates, their observation would require very large luminosity.

- Some of these processes display a strong interference between different (gauge invariant) sets of diagrams. Any modification to these SM couplings due to new physics effects can spoil the interference effect and lead to a very different prediction.

- The effect of anomalous couplings can be studied more systematically using higher dimension operators which would inherently take care of possible correlations among various couplings.

Thank You.