

EFT effects in the off-shell $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ decay channel: An experimentalist's perspective

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HXSWG Offshell Interpretations

Simulations and TH Uncertainties Meeting



Introduction:

Context: Investigation into EFT effects in the $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ decay channel, with an off-shell ($m_{ZZ} \geq 200$ GeV) Higgs boson.

Presentations during previous taskforce meetings highlighted operators of interest for this process (e.g. [Eleni](#))

At NLO: able to resolve to-quark look in ggF initiated Higgs. Allows us to probe top-related couplings. Operators effecting these vertices are loosely constrained.

Today:

Look at effects of selected EFT operators in m_T^{ZZ} distributions.

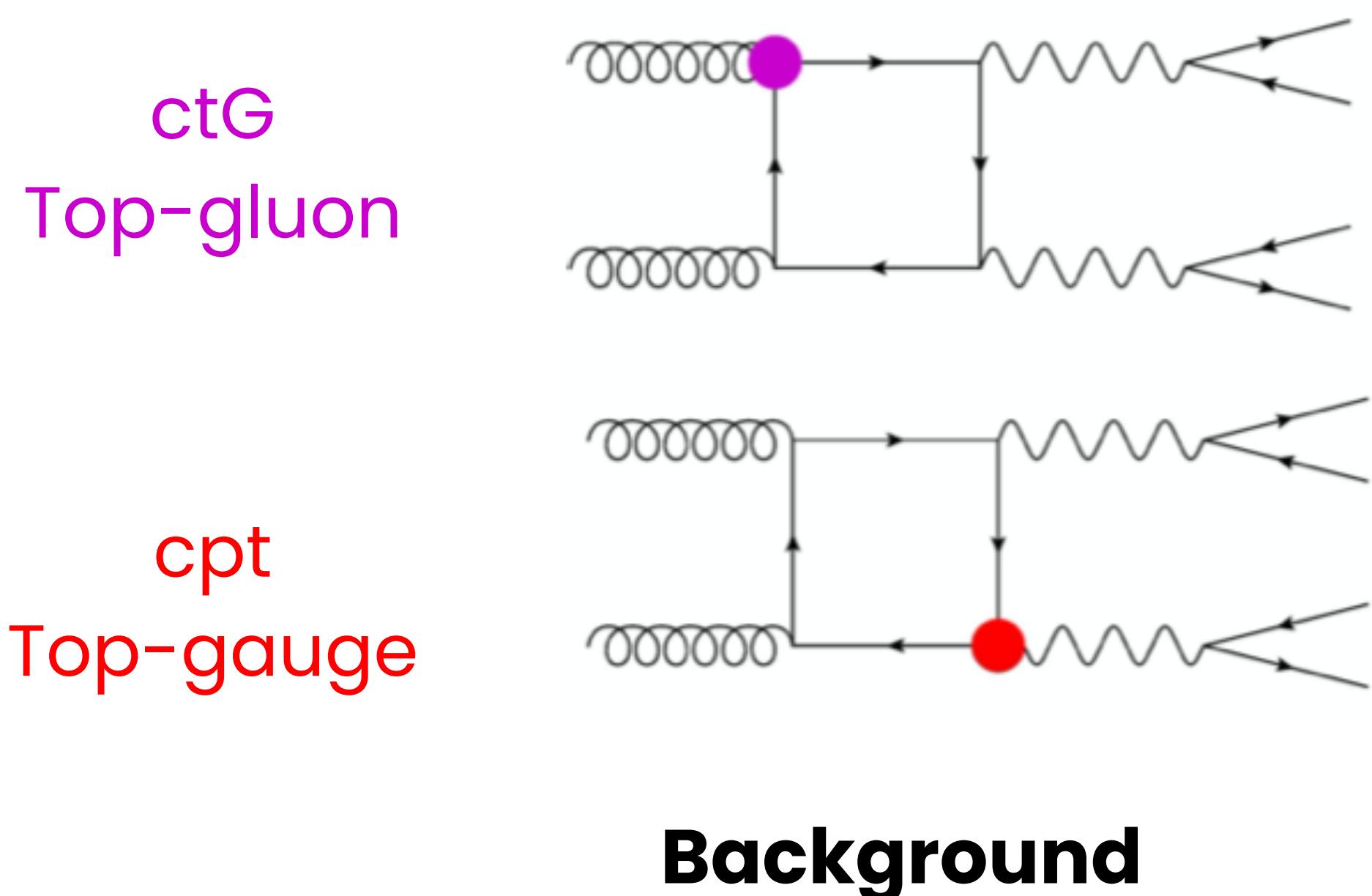
Idea being to investigate (check for cross-section and shape differences) with a somewhat experimentally realistic approach - i.e. similar event selection.



[Investigation is not yet complete, so comments and suggestions are most definitely welcome.](#)

Which operators contribute to process of interest?

- **Focus:** Higgs production (ggF) and decay.
- Turn on **only 1 operator** at a time.
- **Warsaw** basis.
- A snapshot – not complete set!

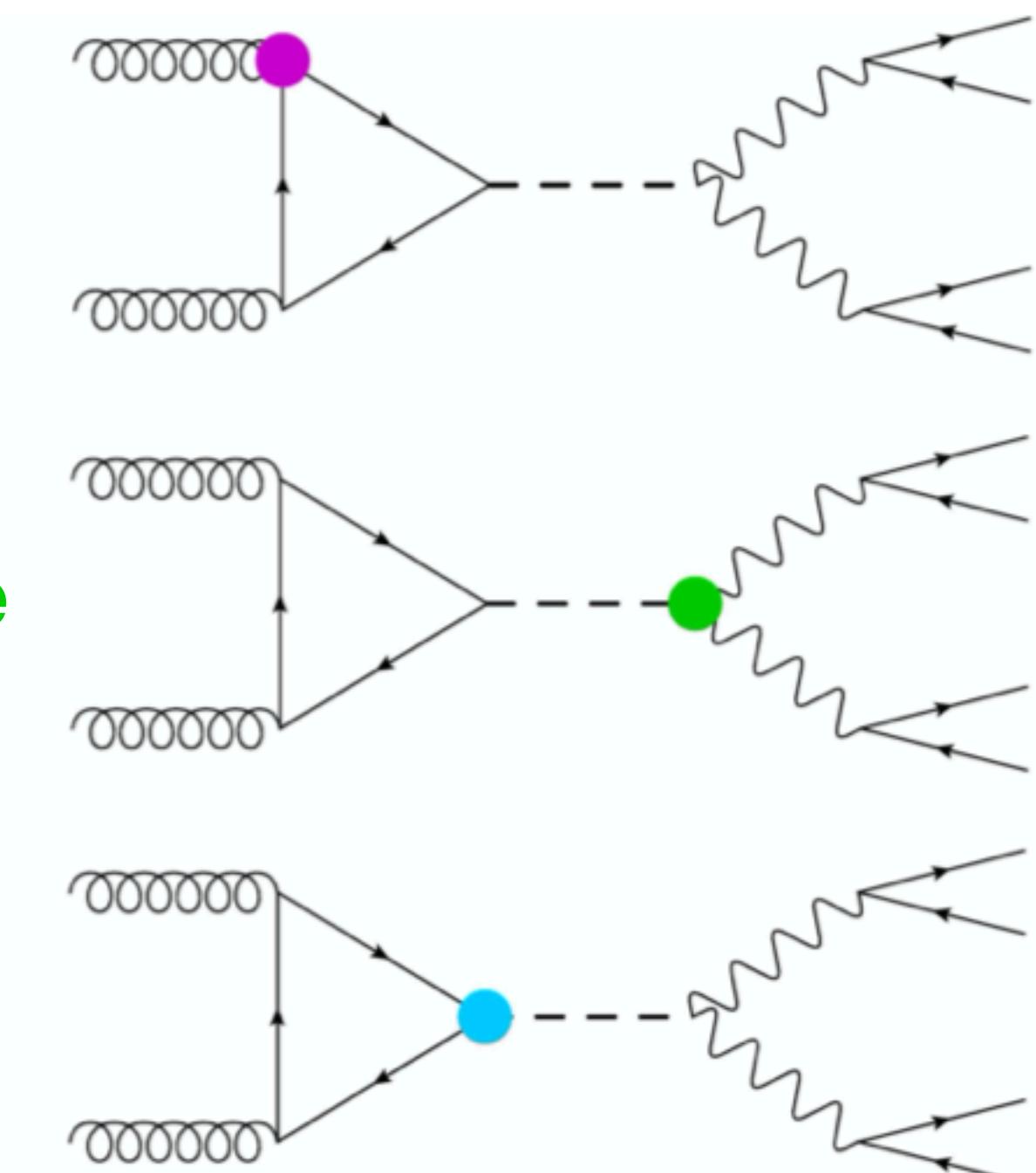


ctG
Top-gluon

cpW
Higgs-gauge
coupling

ctp
Top-Yukawa

Look at only these today



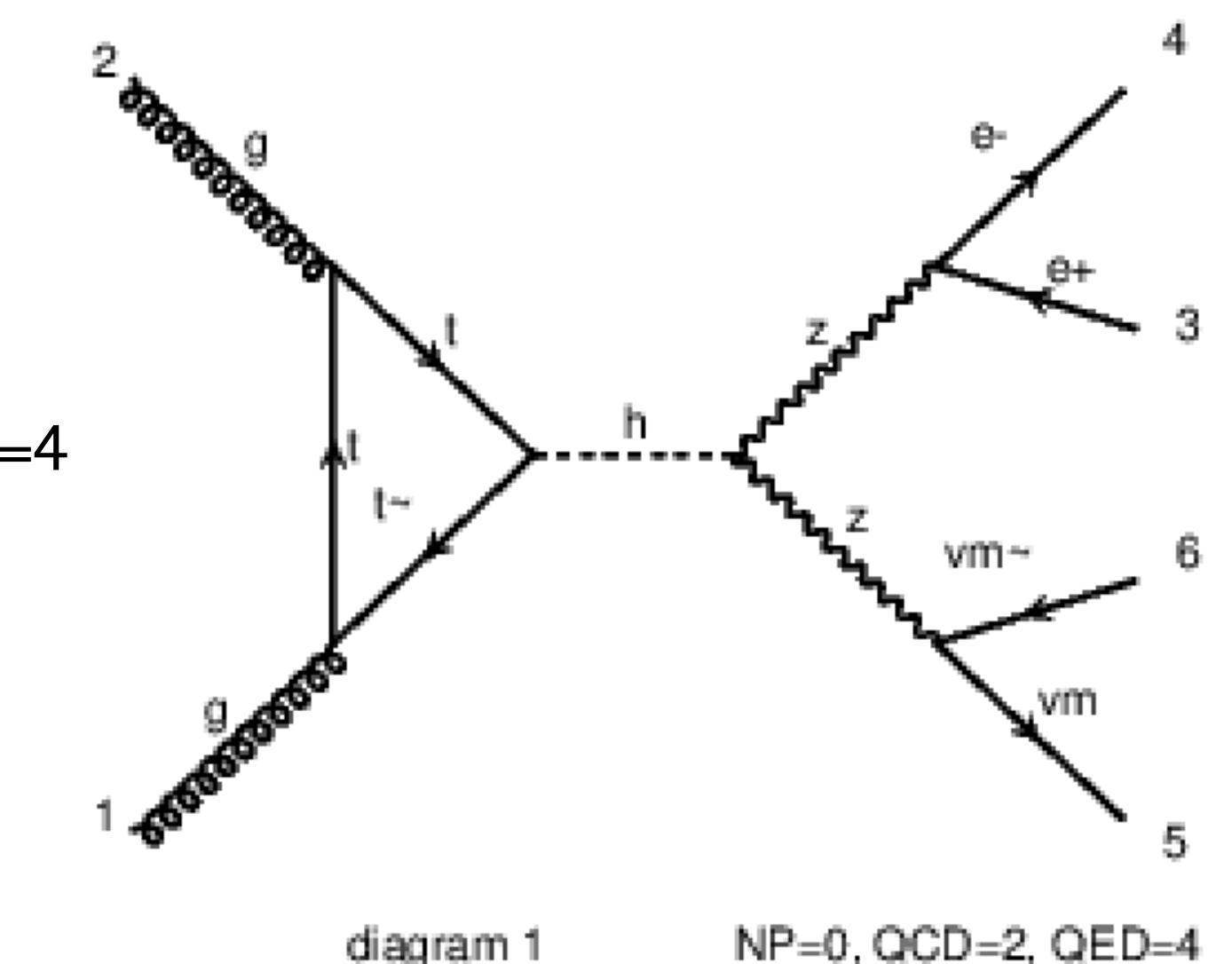
Signal

[Diagrams taken from [Eleni's talk](#)]

EFT sample generation:

- To obtain coefficients in parametrisation, require three samples.
Need to generate: SM, $NP^2 == 2$ (interference i.e. SM x ctG) and $NP^2 == 4$ (i.e. ctG x ctG) samples.
- **SMEFT@NLO** (v0.1) used for sample generation [[link](#)] in Warsaw basis.
- Model: SMEFTatNL0_U2_2_U3_3_cG_4F_L0_UF0-NL0
 - MadGraph5_aMC@NLO v2.7.3 , Generation commands:
 - **SM**: generate $g\ g \rightarrow h \rightarrow l^+ l^- v_l v_{l\bar{l}} / w^+ w^-$ [noborn=QCD] $NP=0$
 - **Int**: generate $g\ g \rightarrow h \rightarrow l^+ l^- v_l v_{l\bar{l}} / w^+ w^-$ [noborn=QCD] $NP^2==2$
 - **Quad**: generate $g\ g \rightarrow h \rightarrow l^+ l^- v_l v_{l\bar{l}} / w^+ w^-$ [noborn=QCD] $NP^2==4$
 - Pythia8 v.8.201, for the showering
 - HepMC v.2.06.09, to produce the output files from Pythia.
- Generator level cut in MadGraph: $E_T^{miss} > 80$ GeV.
- Some coefficients also required a $ptllmin$ cut > 10 GeV (cpW) to avoid divergences.
- Scale of new physics: $\Lambda = 1$ TeV.

$$\frac{\sigma}{\sigma_{SM}} = 1 + \sum_i \alpha_i c_i + \sum_{ij} \beta_{ij} c_i c_j$$



RIVET routine details:

- **Rivet** : toolkit to validate Monte Carlo event generators: [[info](#)]
- Routine running on hepmc.gz files - to perform event selection.
- 100k events per operator.
- Standalone Rivet2 v2.7.2 (which uses FastJet v3.3.2, YODAv1.7.7, hepmc v2.06.09)
- Object definitions generally follow the recommendations: [[git](#)], [[rivet](#)]
- Study conducted at **Truth** level (no detector simulation applied)

	Define FS leptons: $ \eta < 2.5, p_T > 10 \text{ GeV}$
	Veto e, μ from τ decays
Final state particle definitions	Overlap removal $\Delta R(e, \gamma) > 0.1$
	Overlap removal $\Delta R(\mu, \gamma) > 0.1$
	FS neutrinos, veto from τ decays
	FS jets defined using Anti-Kt with $\Delta R > 0.4$
	Jets required to have $p_T > 20 \text{ GeV}, \eta < 4.5$

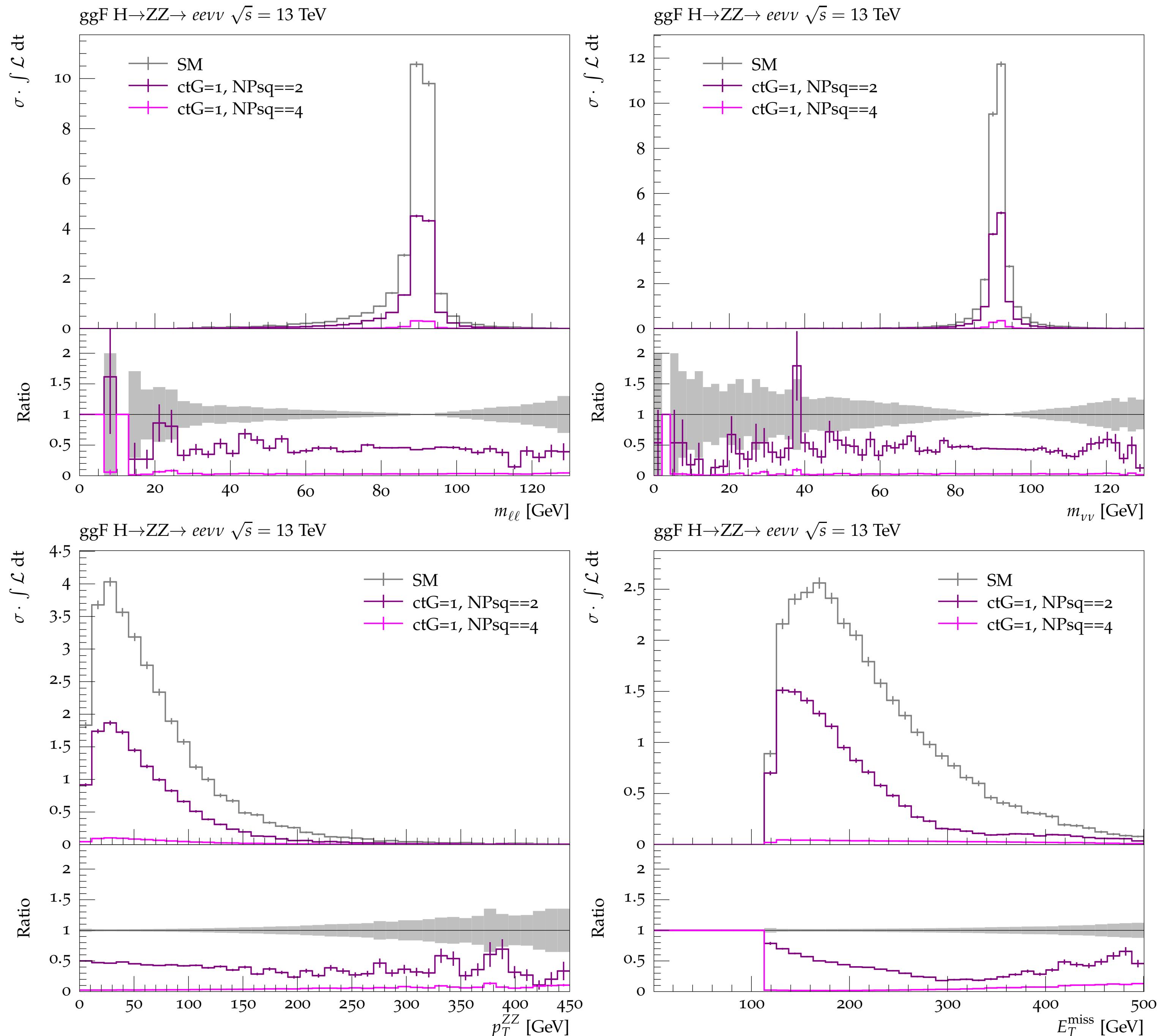
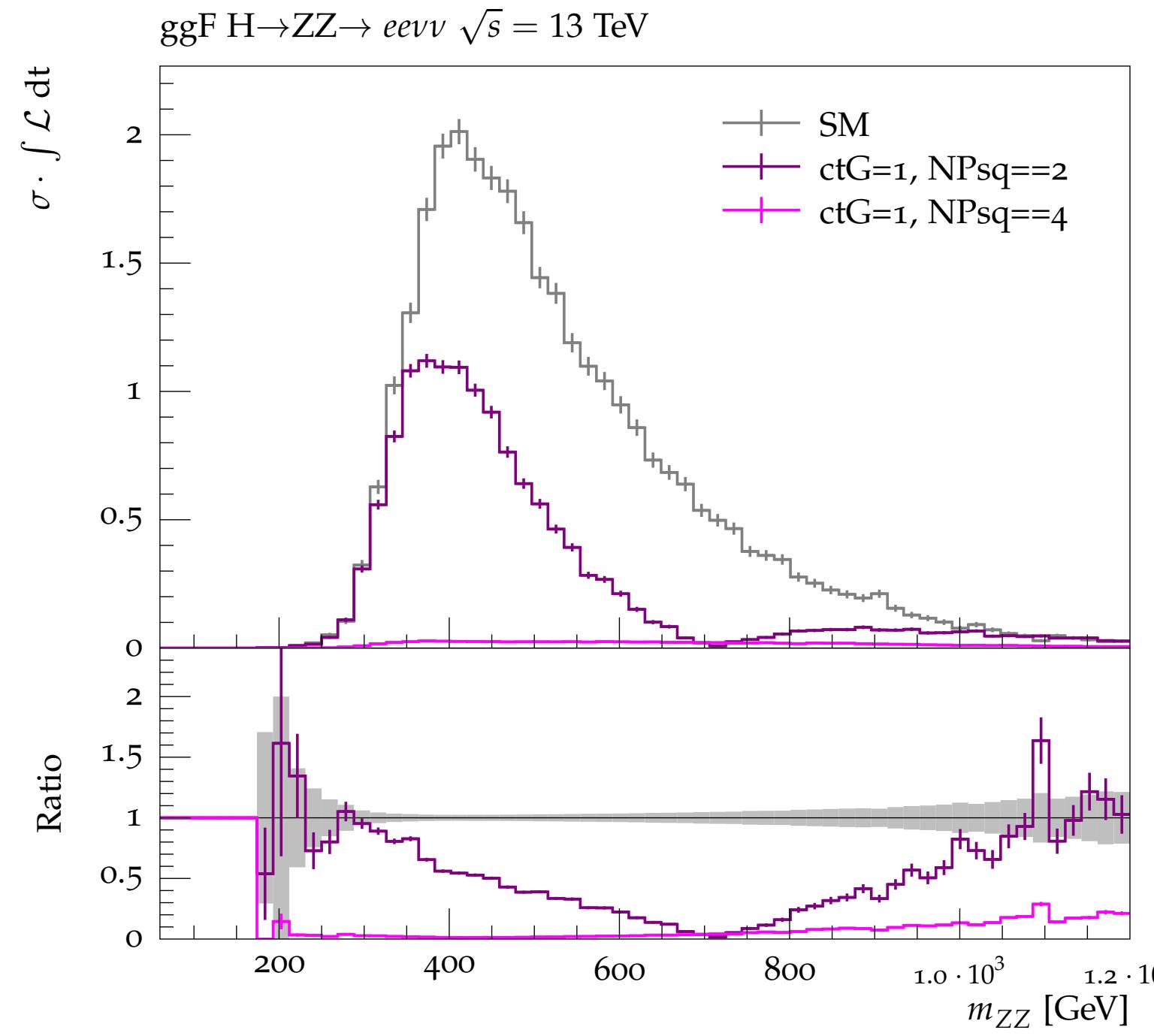
Event selection:

- Followed closely event selection from previous analyses in this channel.
[\[36fb⁻¹\]](#)

Event selection	FS: Exactly two e/ μ , exactly two ν SFOS leptons Overlap removal: $\Delta R > 0.2 (\ell, \text{jet})$	Mainly for correctly selecting final state particles of desired process
	$E_T^{\text{miss}} > 120 \text{ GeV}$	
	$\Delta R(\ell, \ell) < 1.8$	
	$\Delta\phi (\text{Z}, E_T^{\text{miss}}) > 2.5$	
	$\Delta\phi (\text{jet} \mid p_T > 100 \text{ GeV}, E_T^{\text{miss}}) > 0.4 \text{ or } < 0$	
	nbjets = 0	

Kinematic distributions:

- Look at range of kinematics to check samples are produced correctly.
- Here shown $ee\nu\nu$ only.
- Observe both Z bosons on-shell, and m_{ZZ} starts ~ 200 GeV.
- Will upload complete set of plots to [\[CERNbox\]](#) location once finalised.

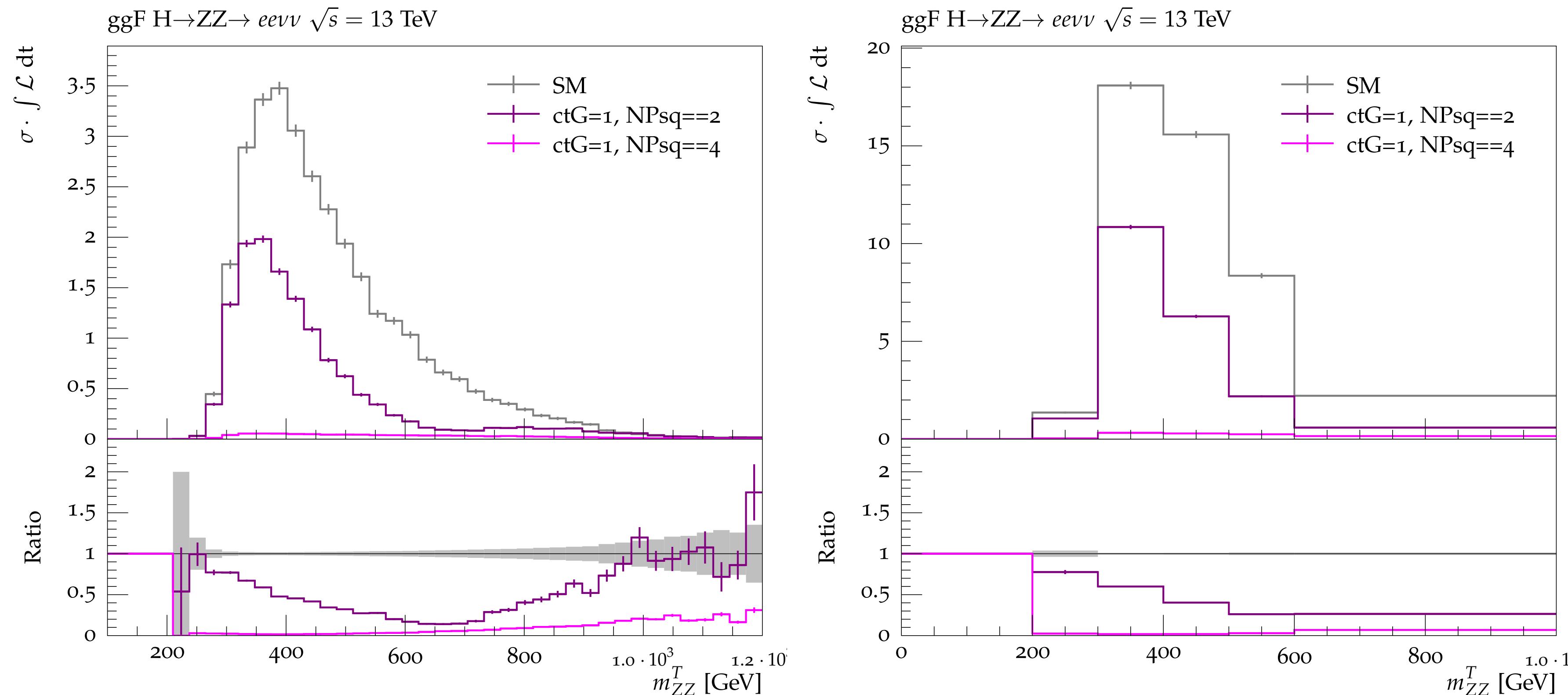


Observable of interest: m_T^{ZZ}

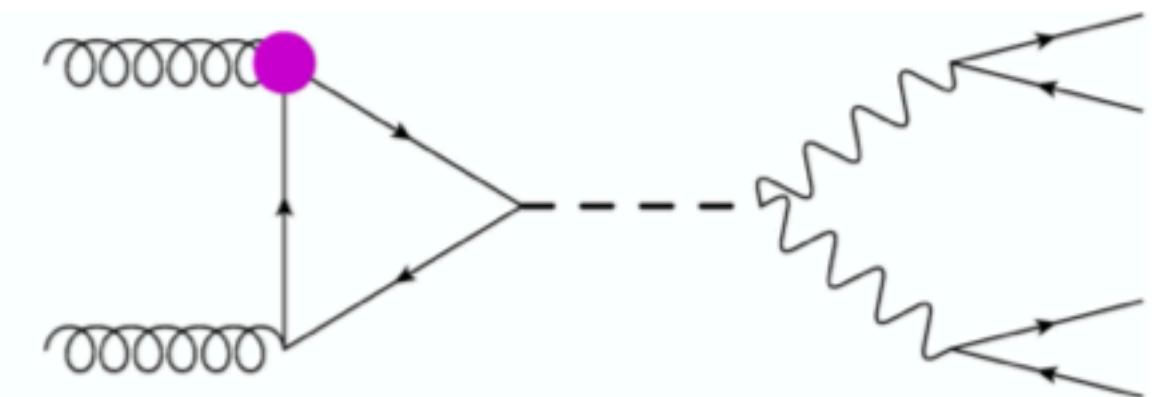
- Used in $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ analysis instead of m_{ZZ} due to presence of **missing energy**.

$$m_T^2 \equiv [\sqrt{m_Z^2 + |\vec{p}_T^{\ell\ell}|^2} + \sqrt{m_Z^2 + |\vec{p}_T^{\text{miss}}|^2}]^2 - [\vec{p}_T^{\ell\ell} + \vec{p}_T^{\text{miss}}]^2$$

- For signal strength fits: use a **slightly coarser binning**: optimise between having no bins with 0 entries (binning too fine) and too coarse (sensitivity suffers).



Top-gluon results: ctG



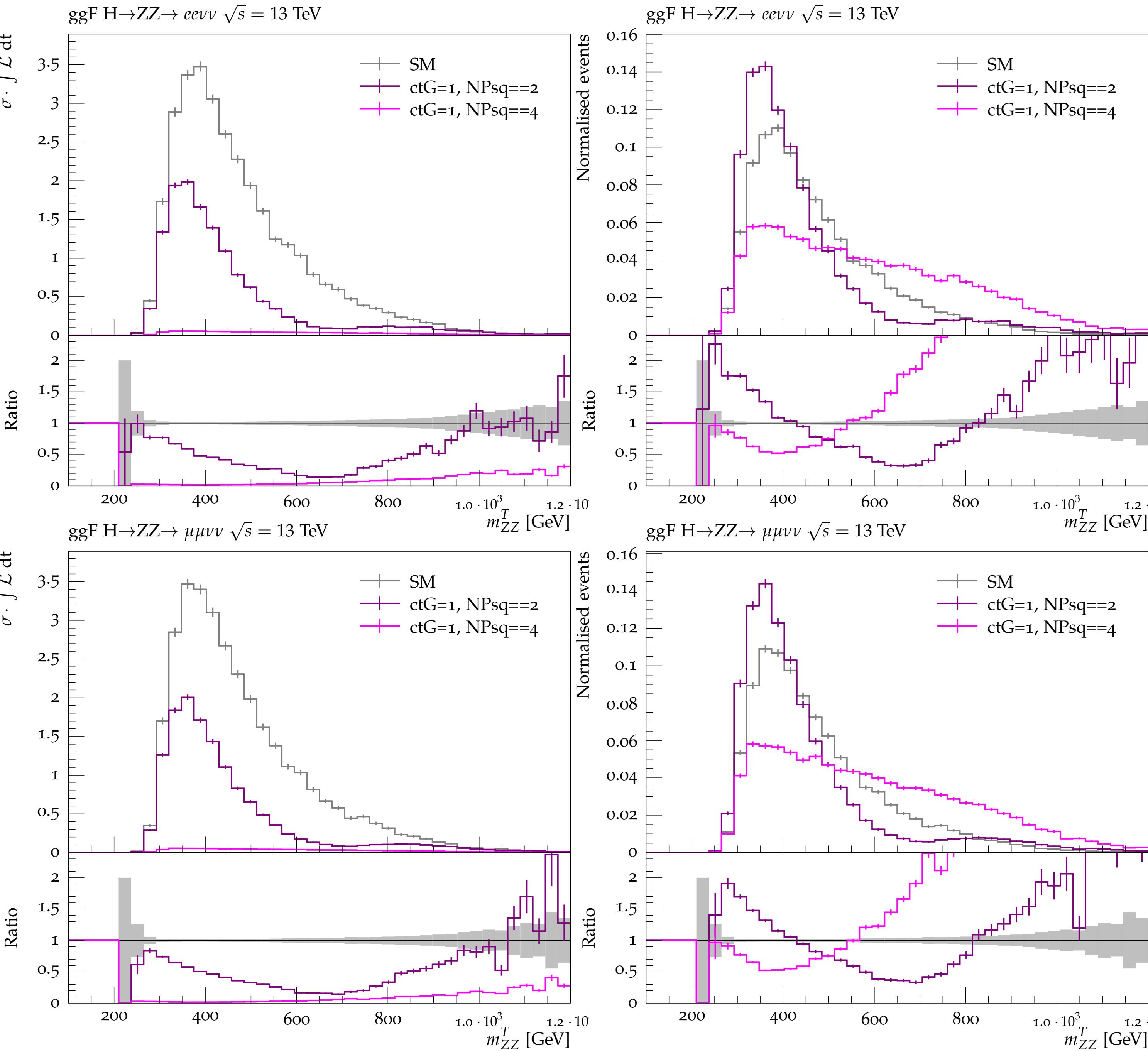
Enters **both** signal and interfering background process.

Parametrisation results obtained from m_T^{ZZ} distributions (normalised to 139fb^{-1}).

$$\frac{\sigma}{\sigma_{SM}} = 1 + \sum_i \alpha_i c_i + \sum_{ij} \beta_{ij} c_i c_j$$

Using
NPsq==2
sample

Using
NPsq==4
sample



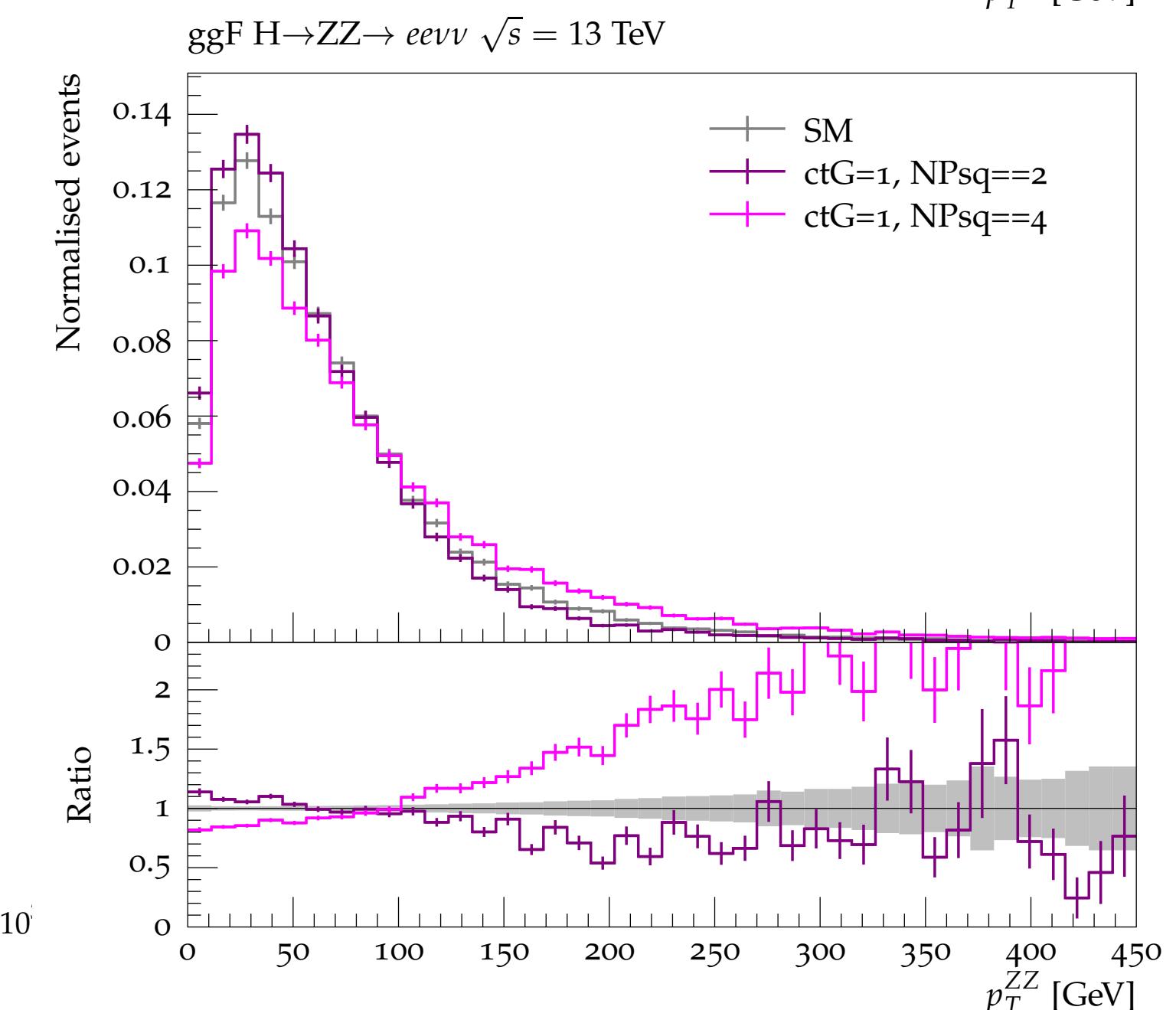
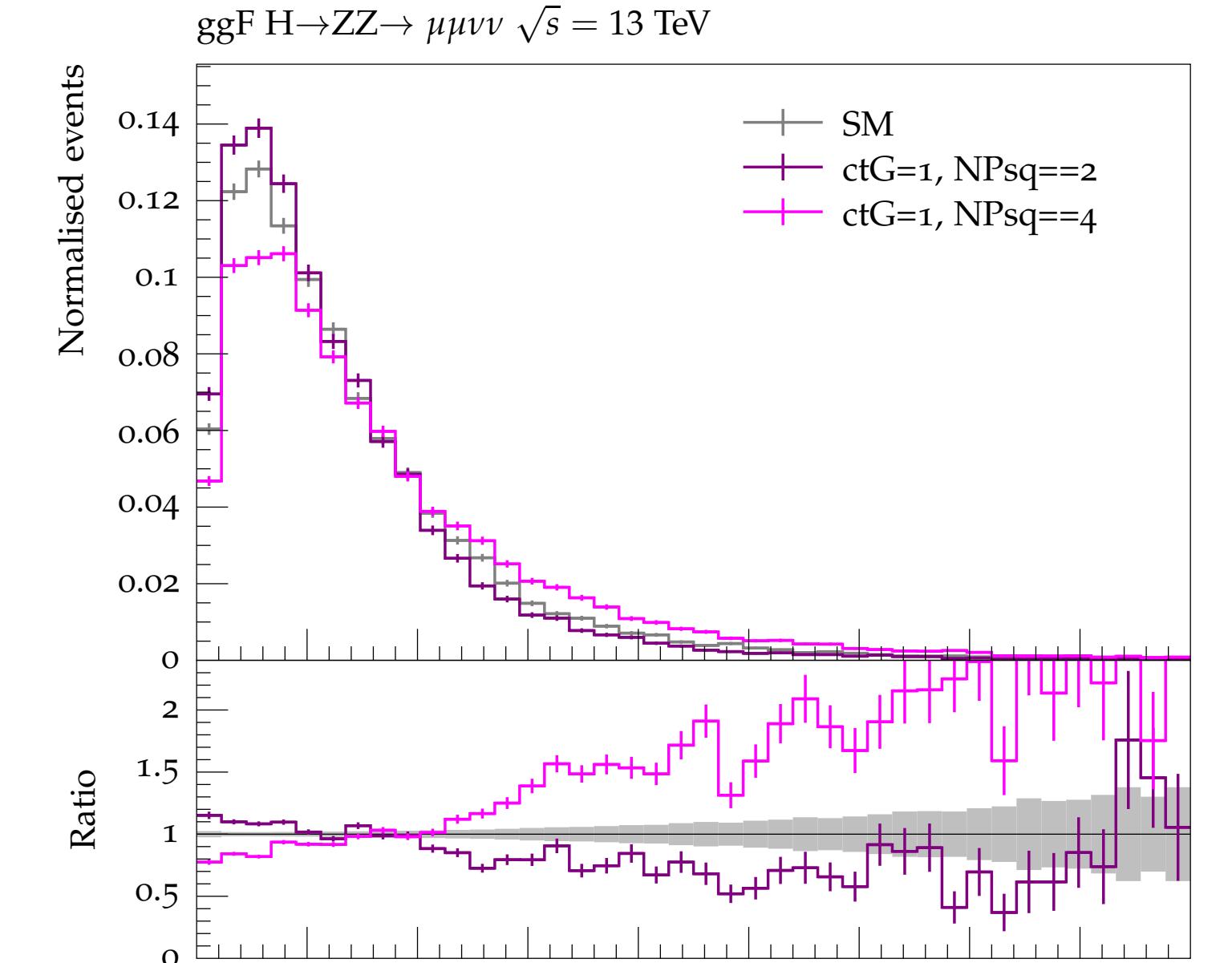
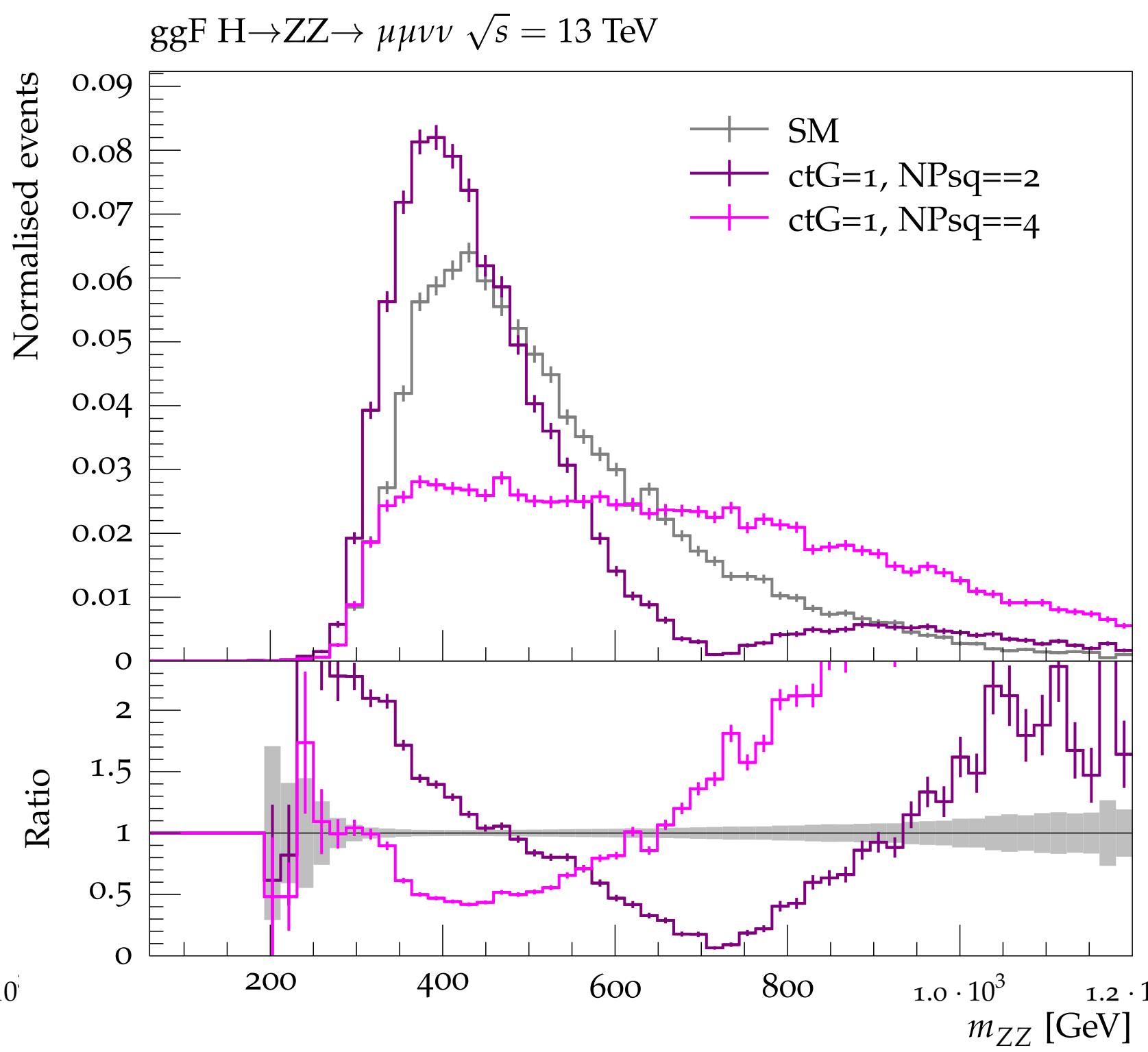
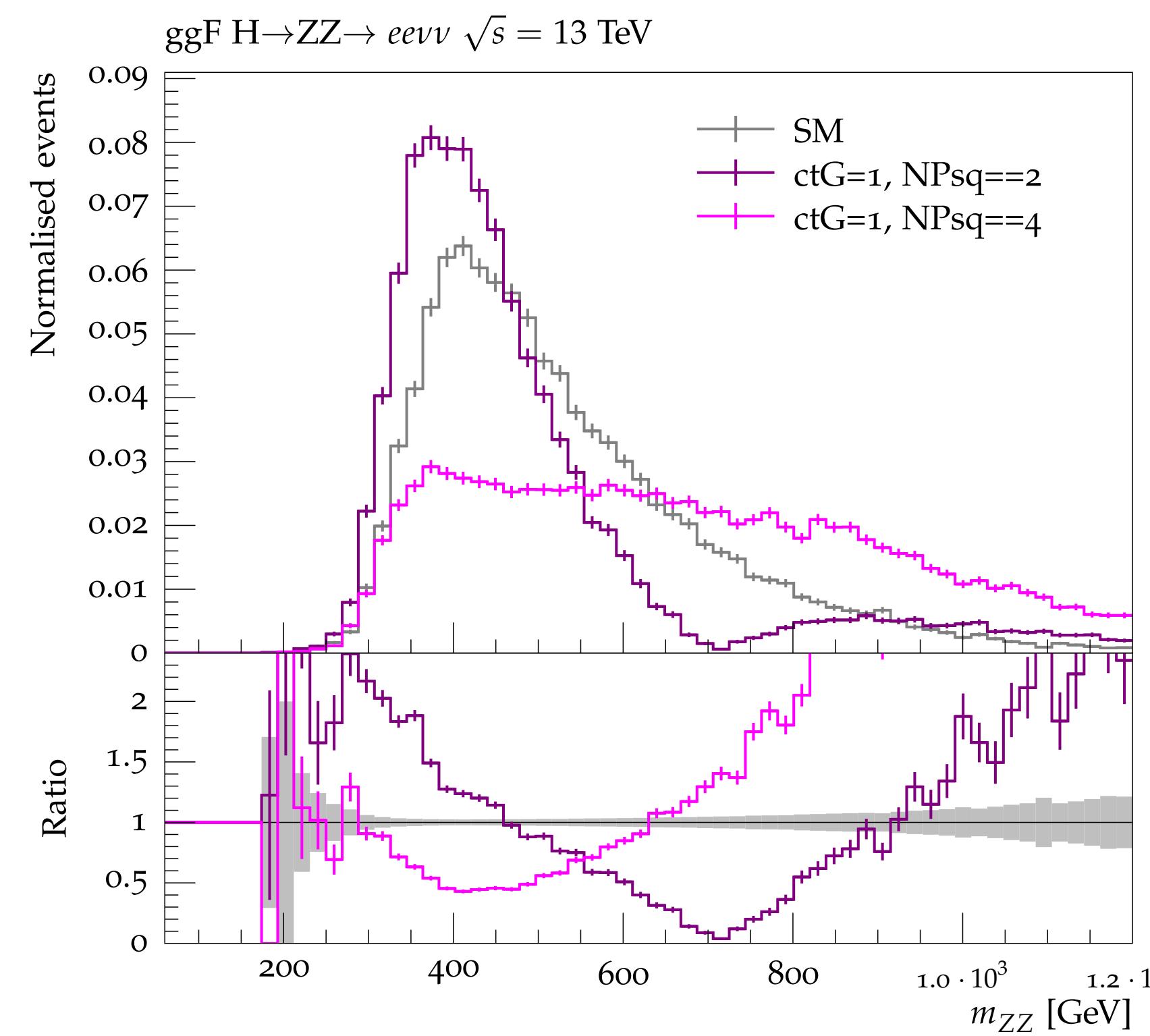
A closer look at ctG kinematics:

Notice significant difference between **shape** of SM and ctG samples.

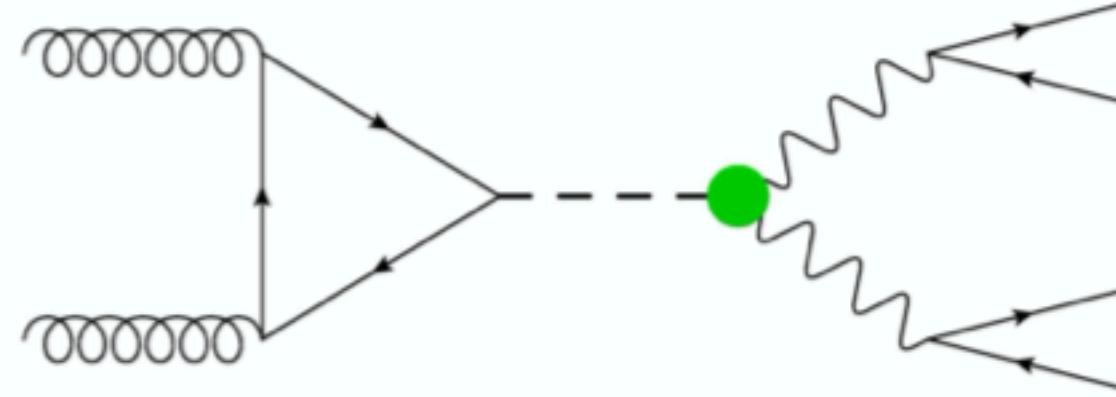
Take a look at normalise m_{ZZ} and p_T^{ZZ} distributions:

- Observe peak is shifted slightly higher for quadratic sample compare to SM
- Peak shifted slightly lower for interference sample.

Quite different shape in m_{ZZ} distribution for both samples.



Higgs-gauge results: cpW

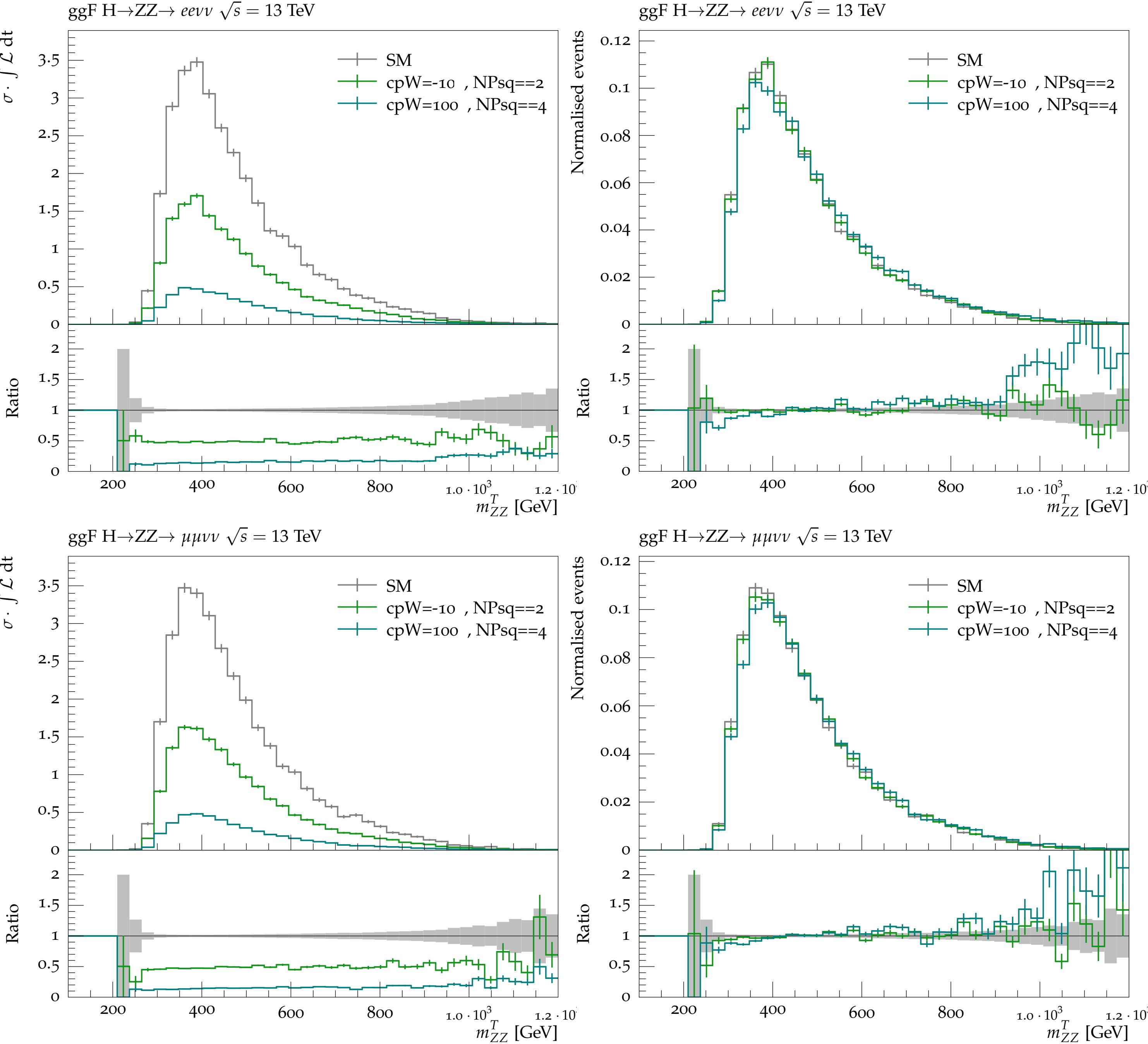


Parametrisation results obtained from m_T^{ZZ} distributions (normalised to 139fb^{-1}).

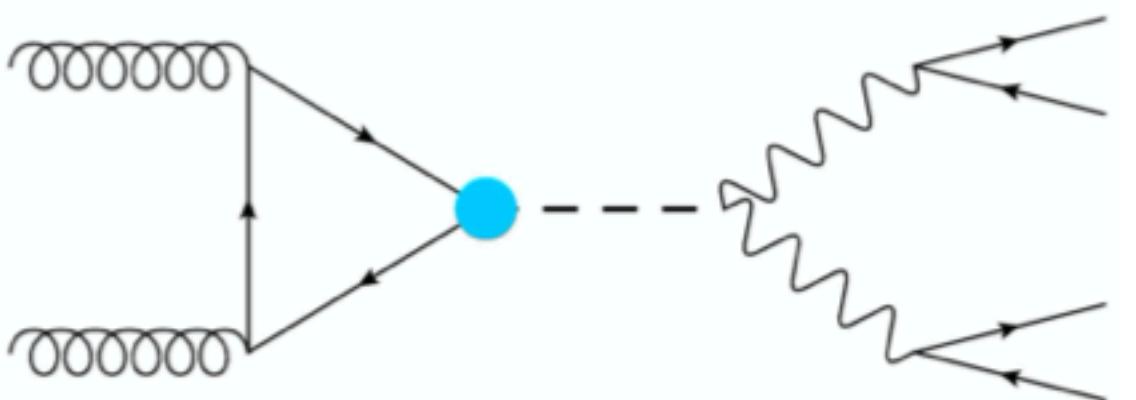
$$\frac{\sigma}{\sigma_{SM}} = 1 + \sum_i \alpha_i c_i + \sum_{ij} \beta_{ij} c_i c_j$$

Using
NPsq==2
sample

Using
NPsq==4
sample



Top-Yukawa results: ctp

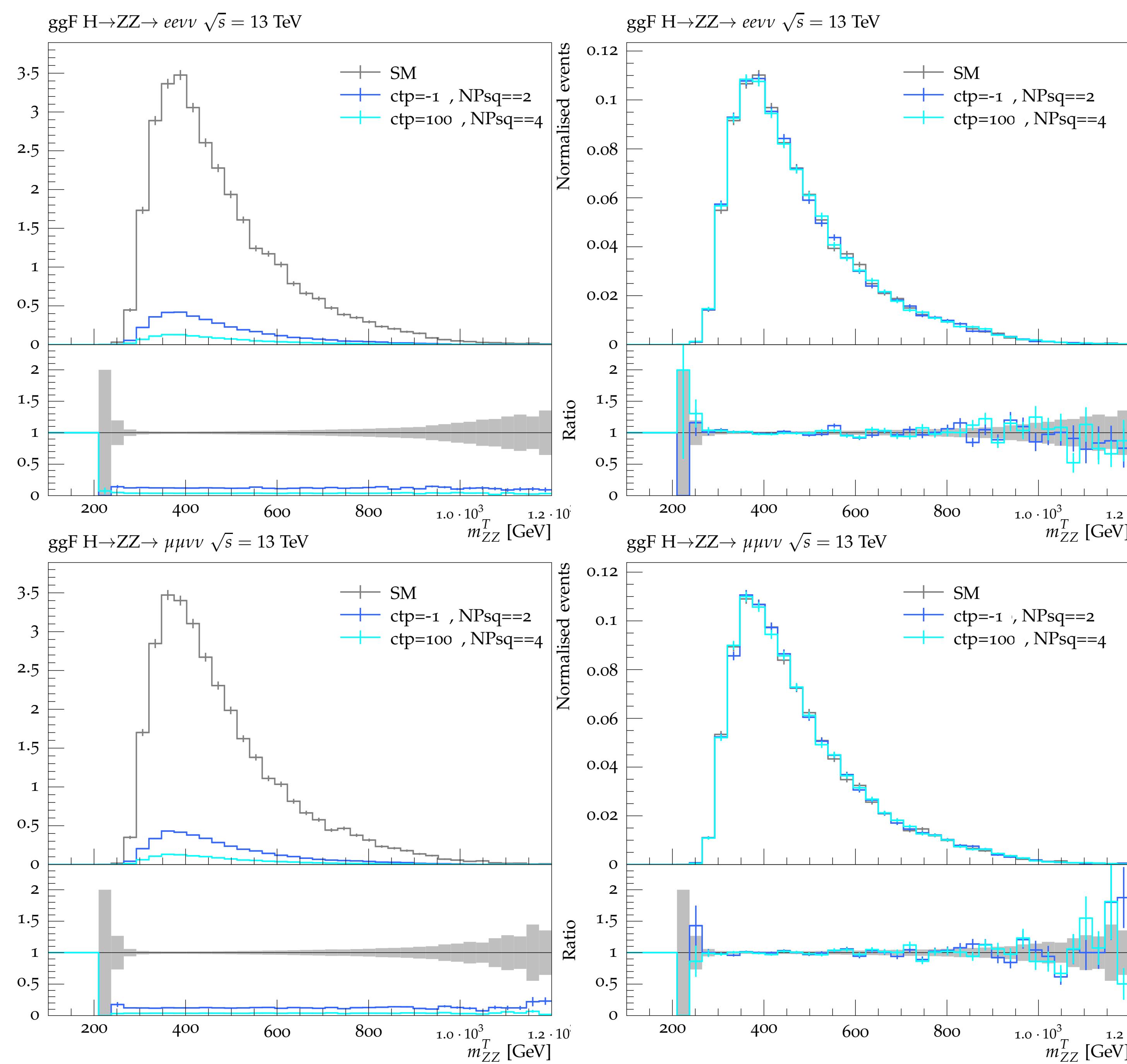


Parametrisation results obtained from m_T^{ZZ} distributions (normalised to 139fb^{-1}).

$$\frac{\sigma}{\sigma_{SM}} = 1 + \sum_i \alpha_i c_i + \sum_{ij} \beta_{ij} c_i c_j$$

Using
NPsq==2
sample

Using
NPsq==4
sample

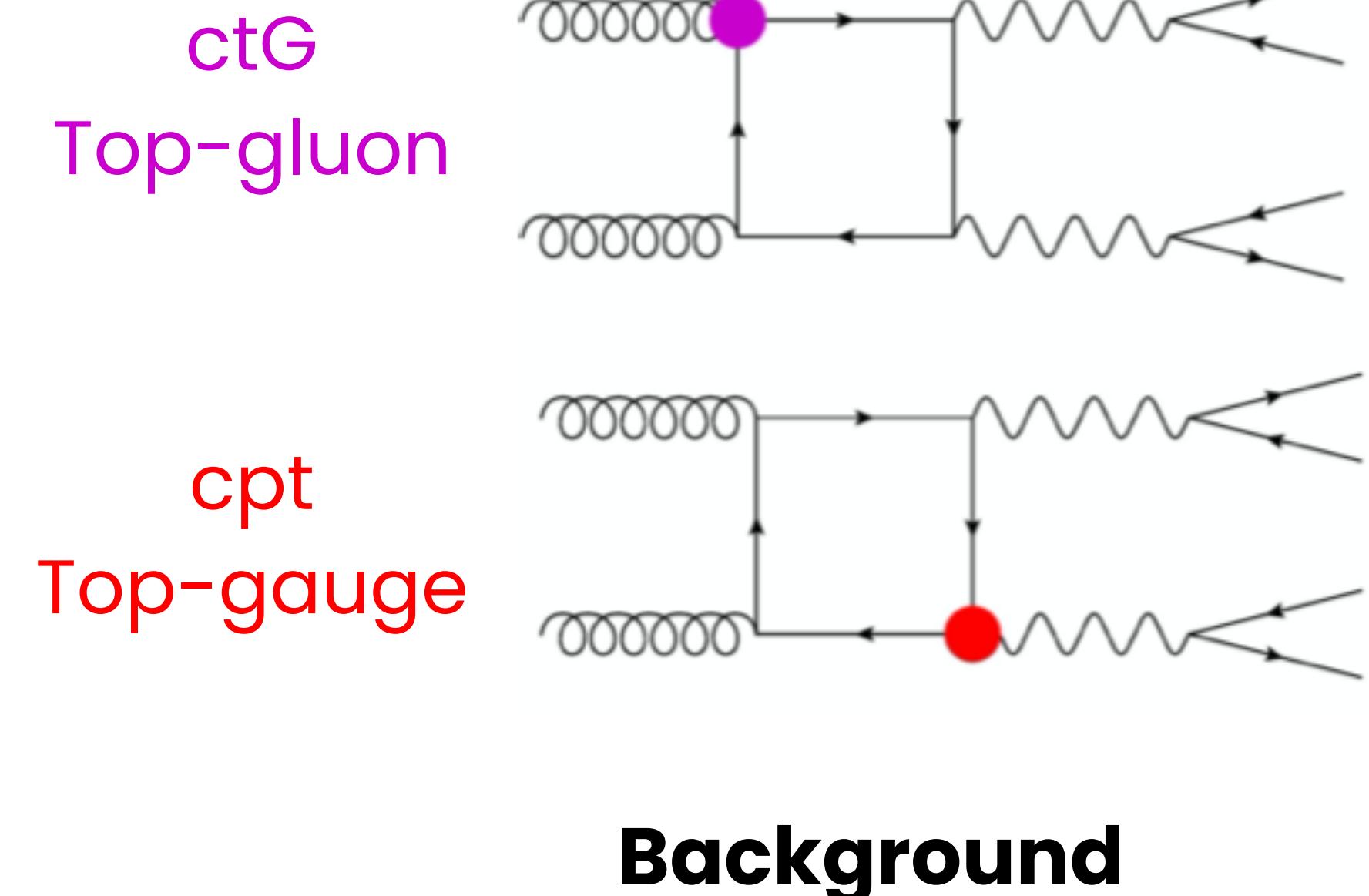


Conclusions:

- Looked at effect of XS and shapes due to EFT effects in off-shell region for $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ process.
- Coefficients shown today: ctG, cpW, cpt.
- Observe significant shape differences for ctG only.
- Also working on cpWB and cpG (Q: Observe large shape differences similar to ctG?) .

Further work:

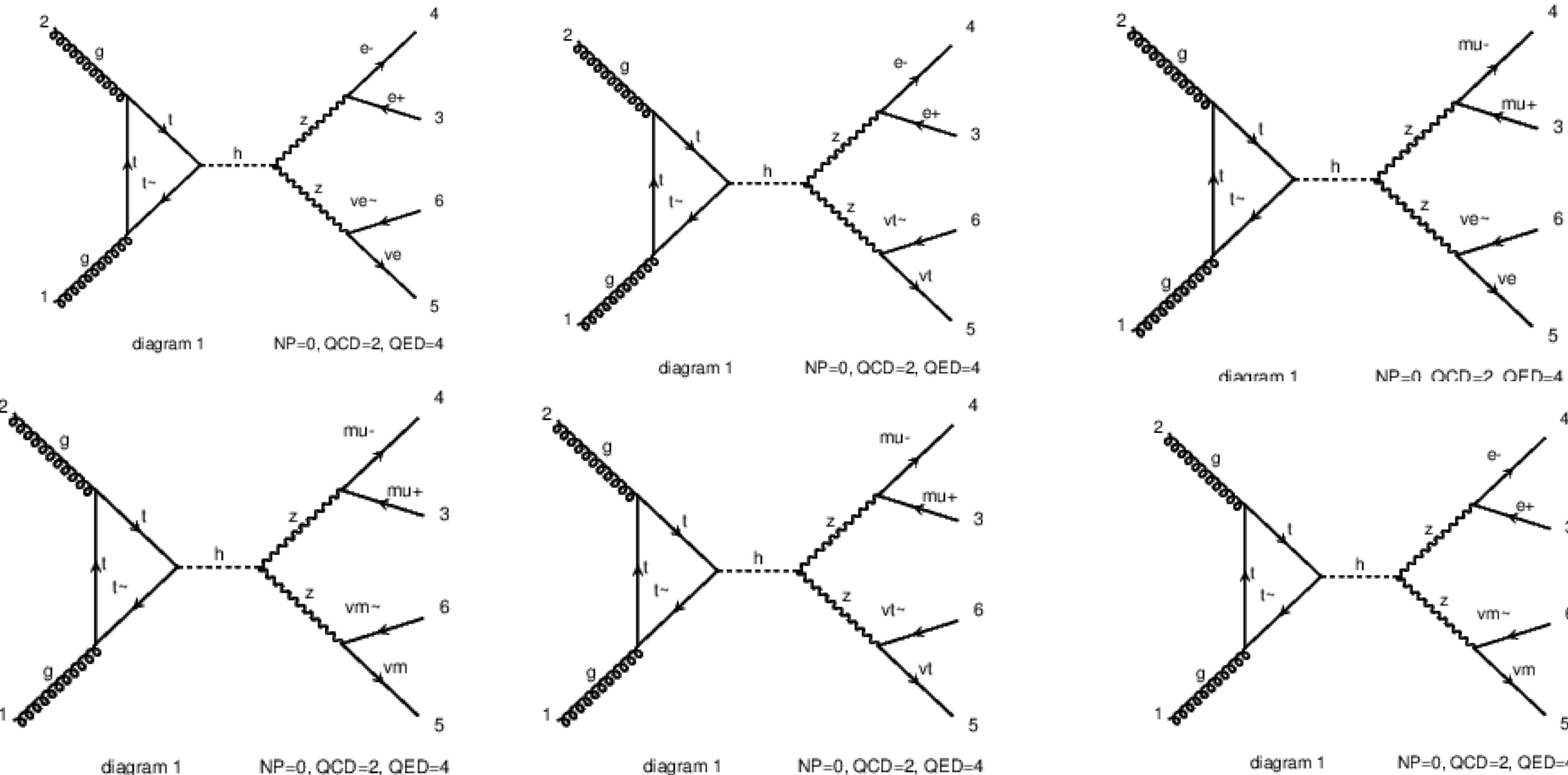
- Focussed on ggF production mode so far -> worth pursuing VBF production mode as well?
- Investigate more coefficients that contribute.
- Look also at background processes, especially that which interferes with the signal.
Particularly important for off-shell analysis since signal strength parametrisation is in terms of SIG+BKG+SBI processes.



Additional material

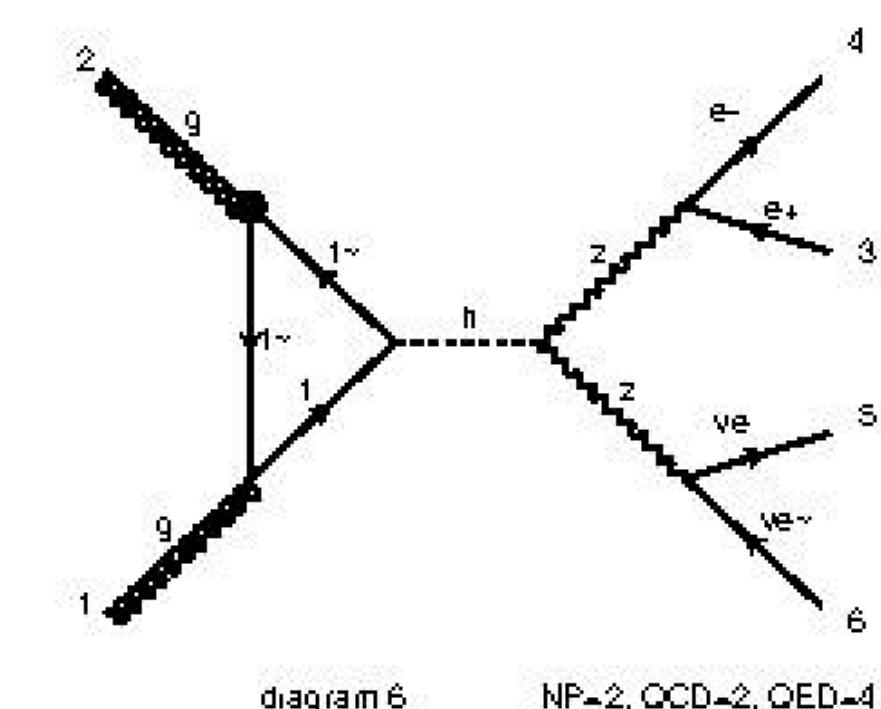
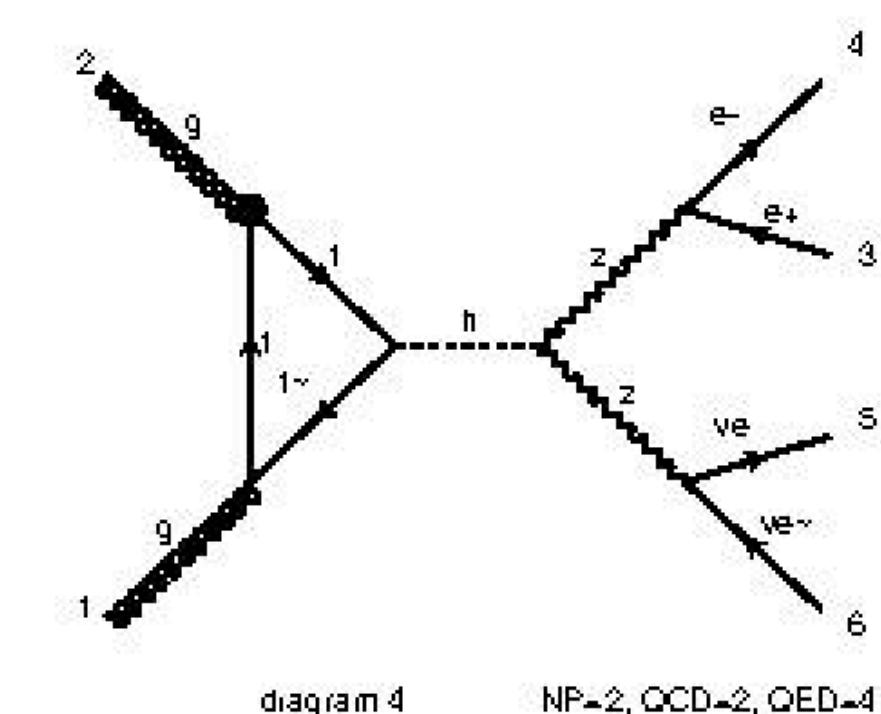
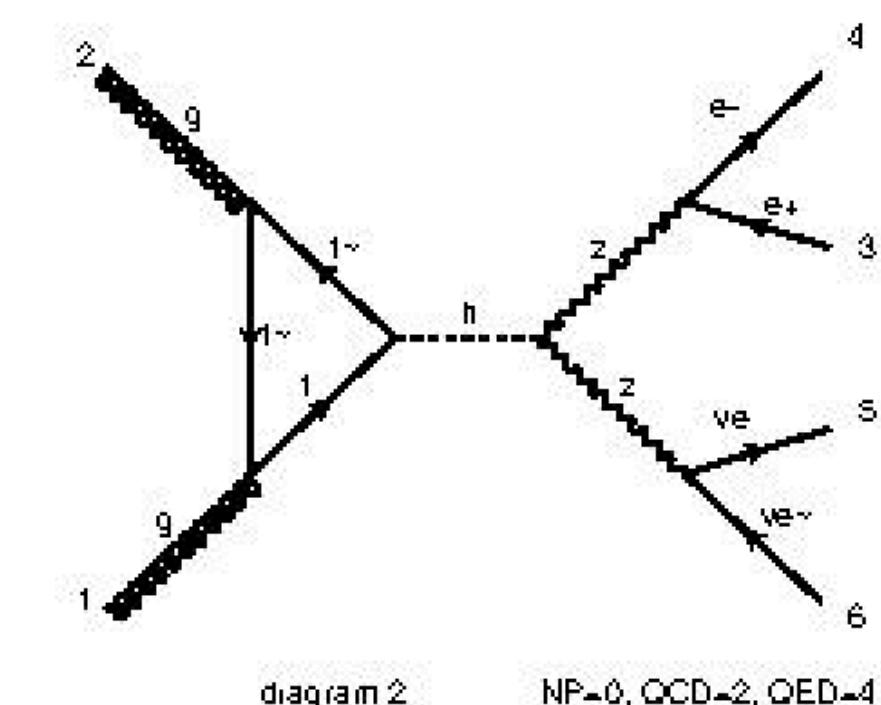
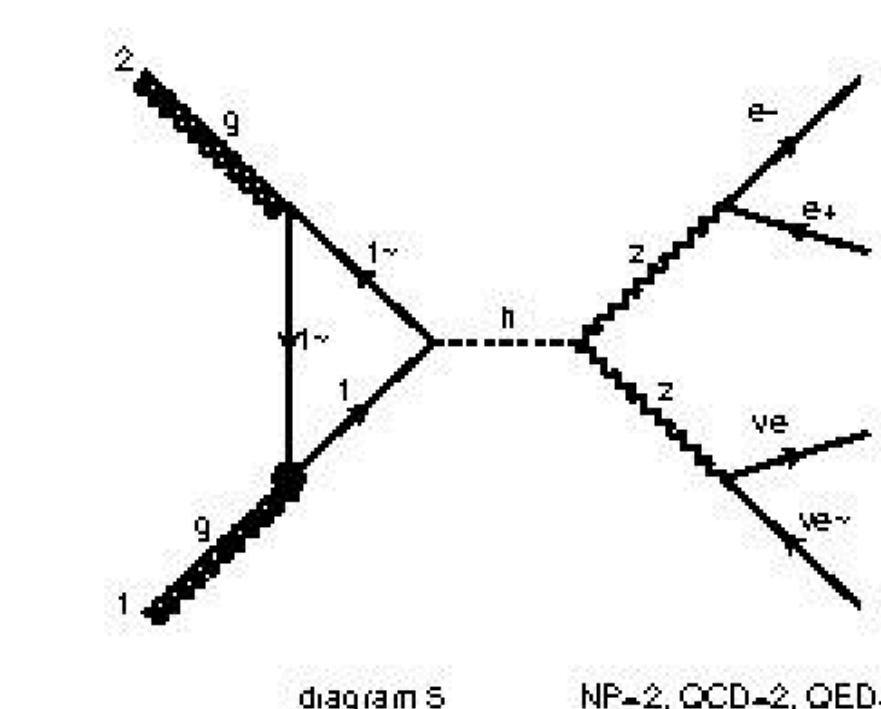
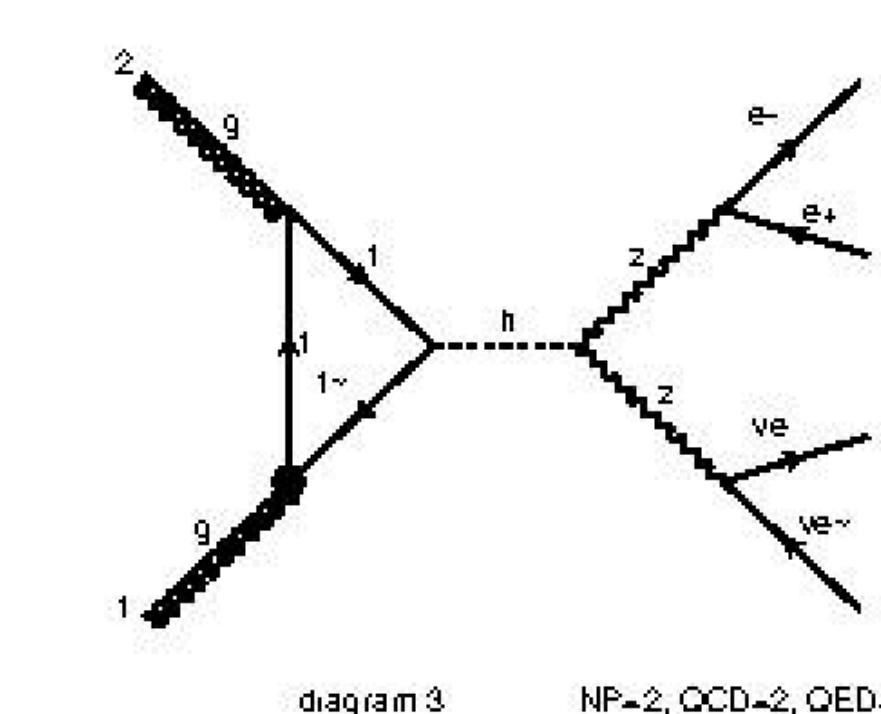
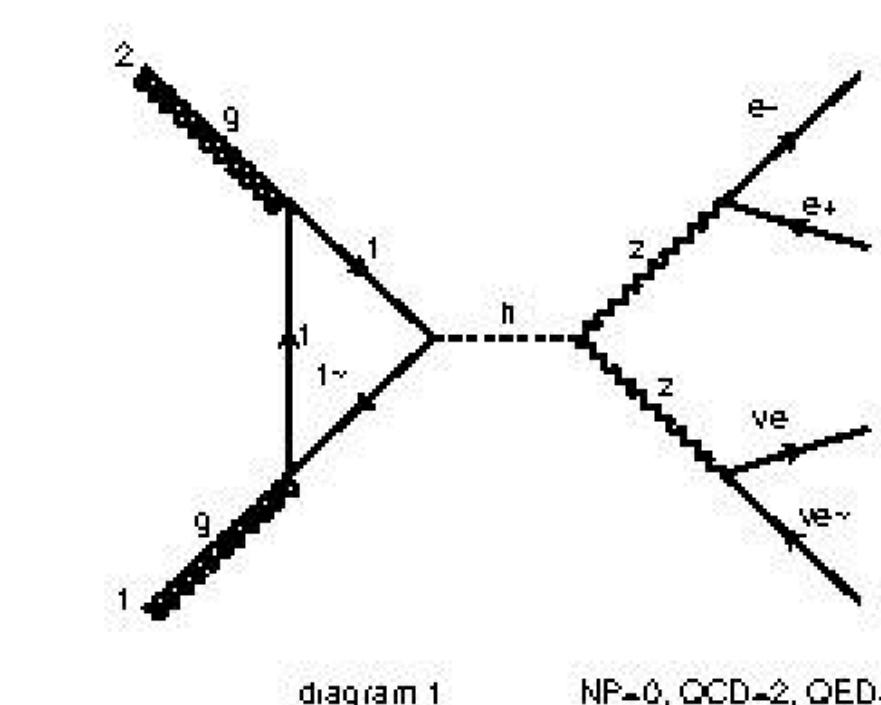
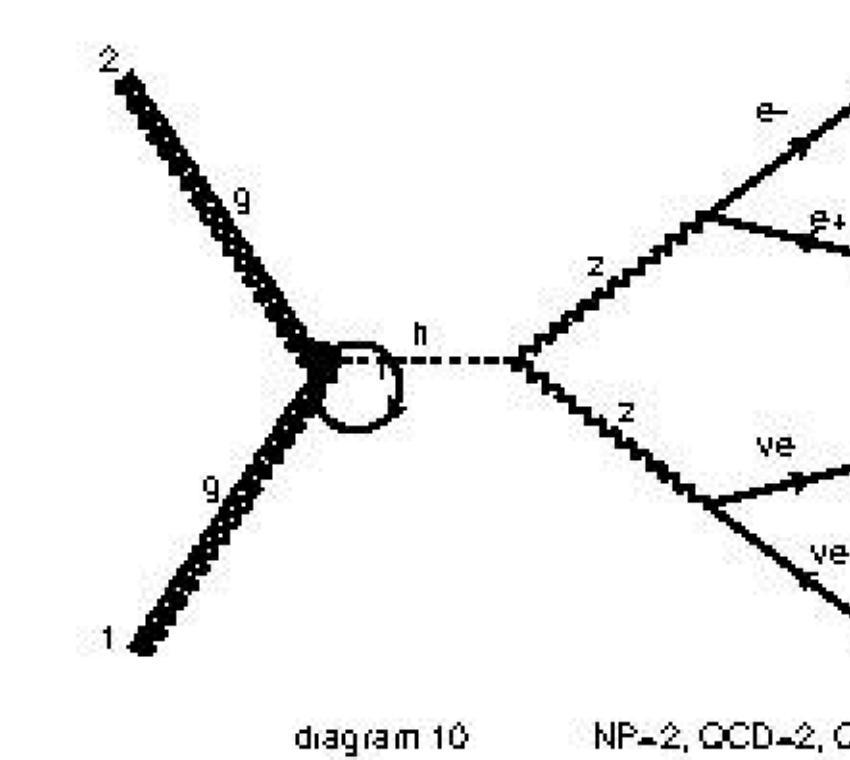
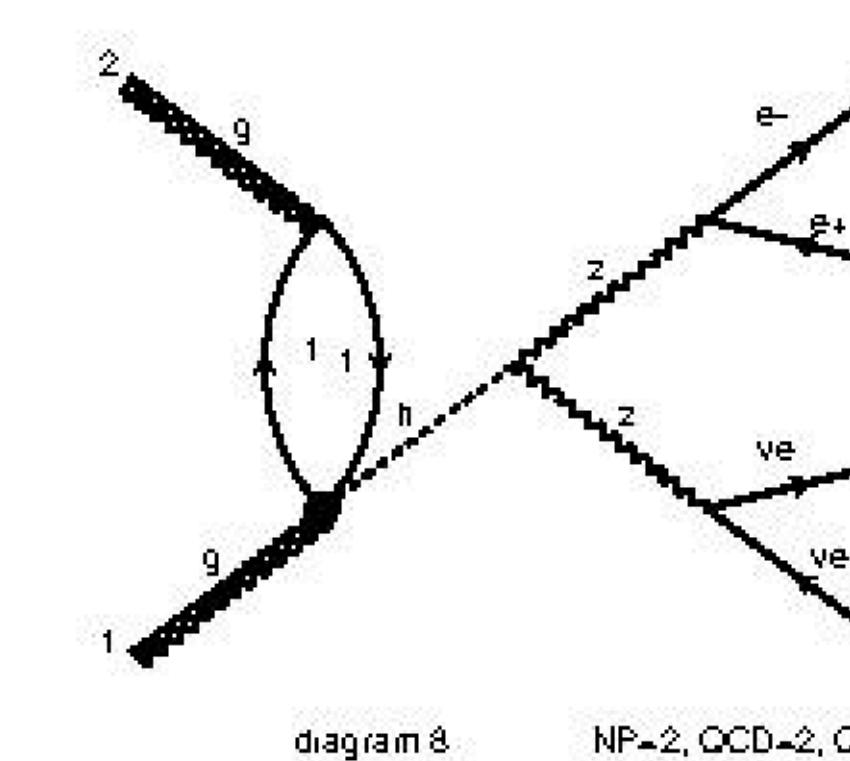
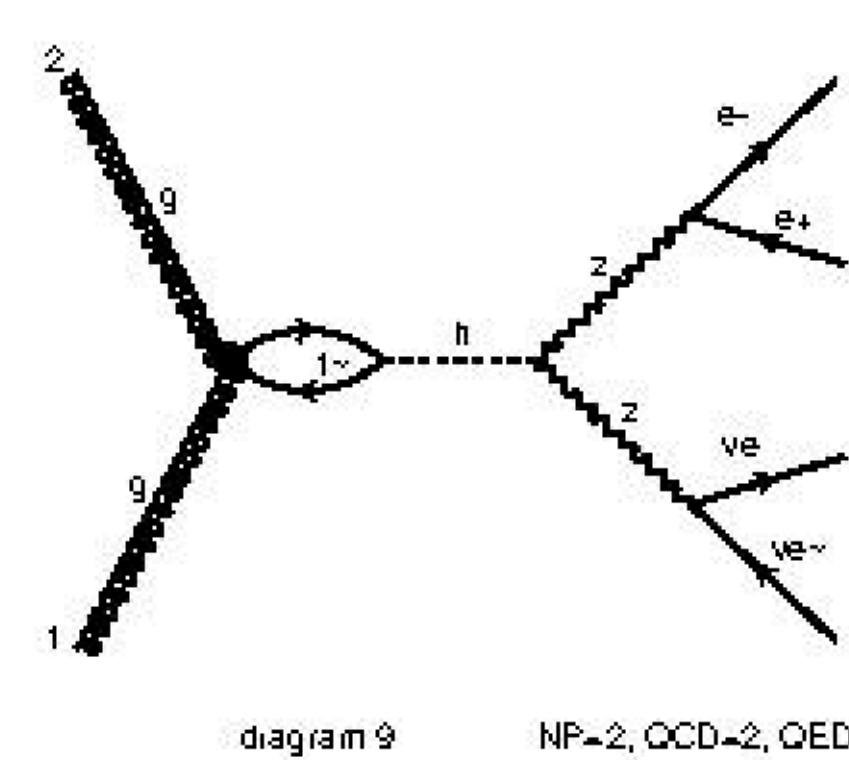
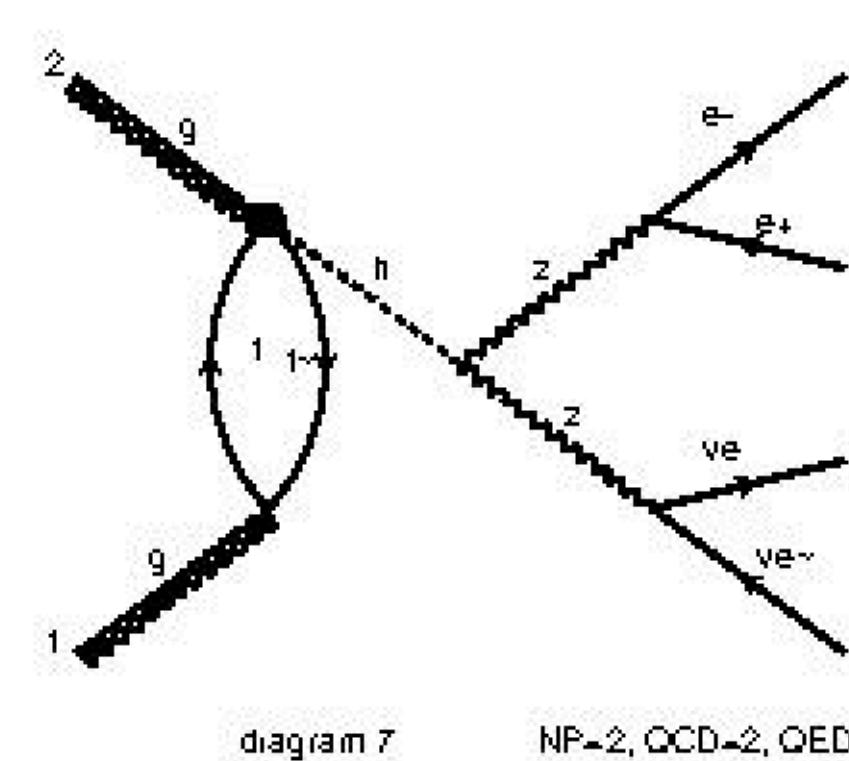
Feynman diagrams from MadGraph:

- SM sample. Loop is resolved.
- All combinations of ee & $\mu\mu$ with $\nu_e\nu_{e'}$ $\nu_\mu\nu_{\mu'}$ $\nu_\tau\nu_\tau$



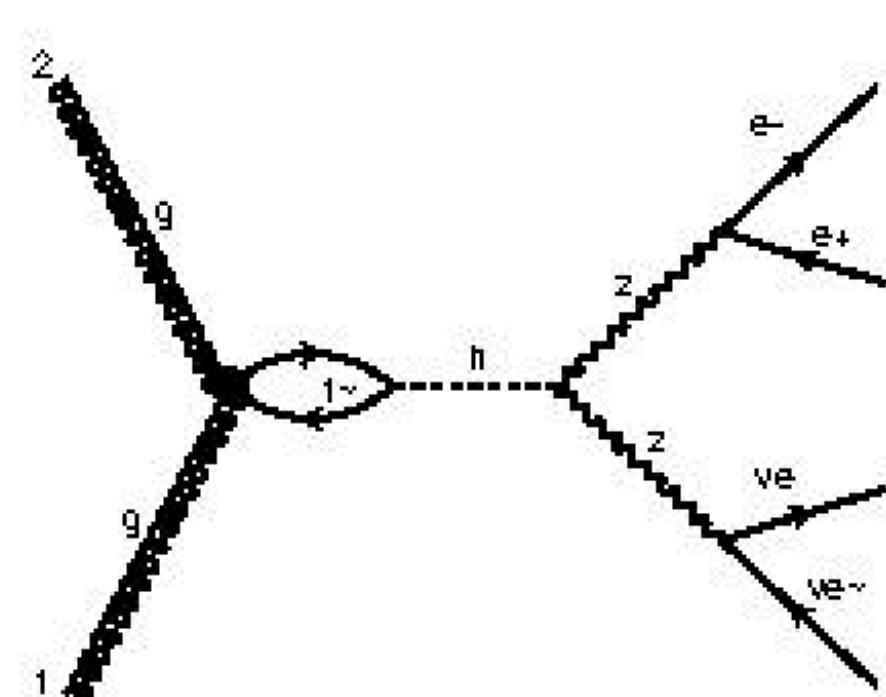
Feynman diagrams from MadGraph: For the remaining diagrams just display $ee\nu_e\nu_e$!

- ctG interference



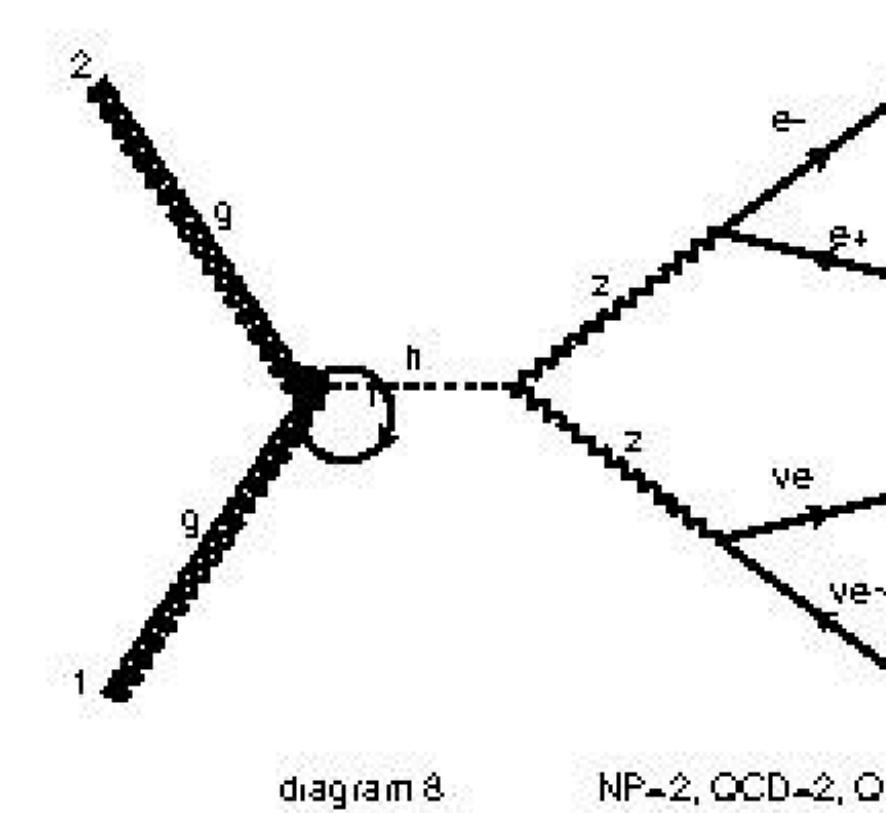
Feynman diagrams from MadGraph

- # ○ ctG quadratic



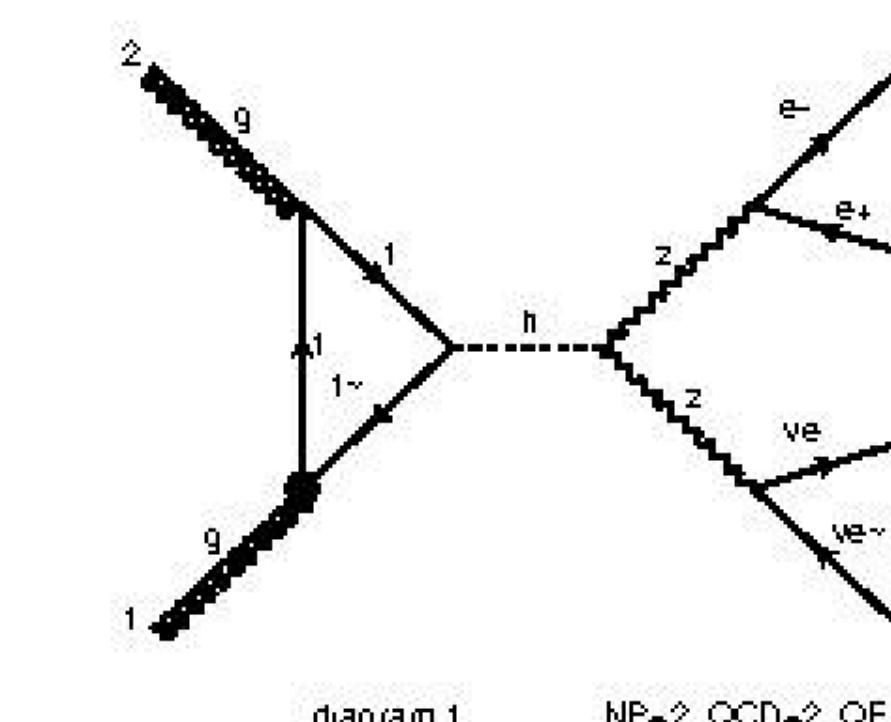
diagram

NP=2, QCD=2, QED=



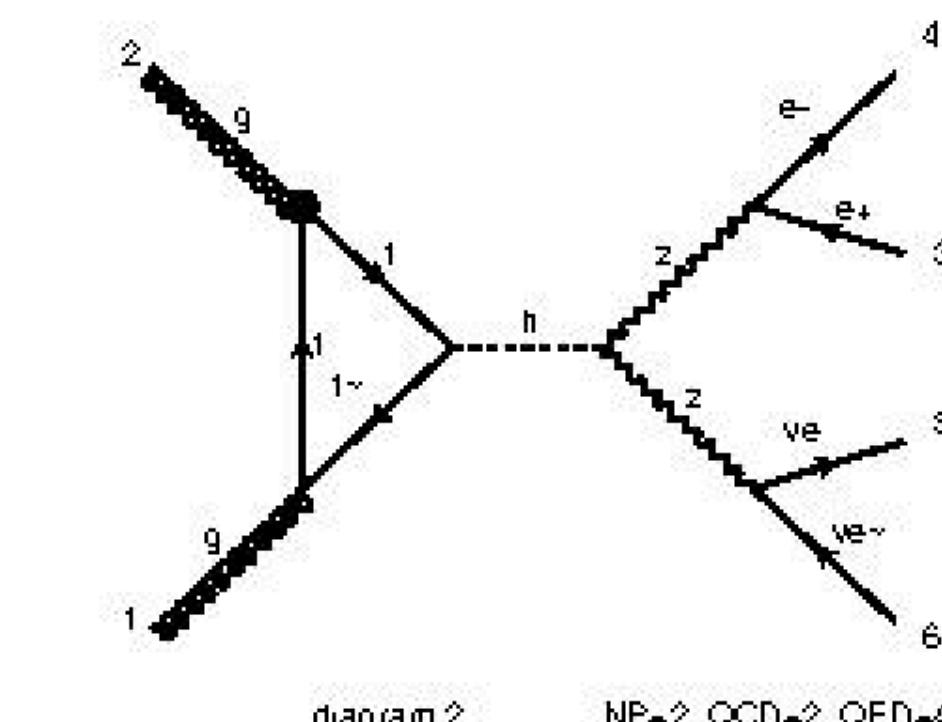
diag

NP=2, QCD=2, OE



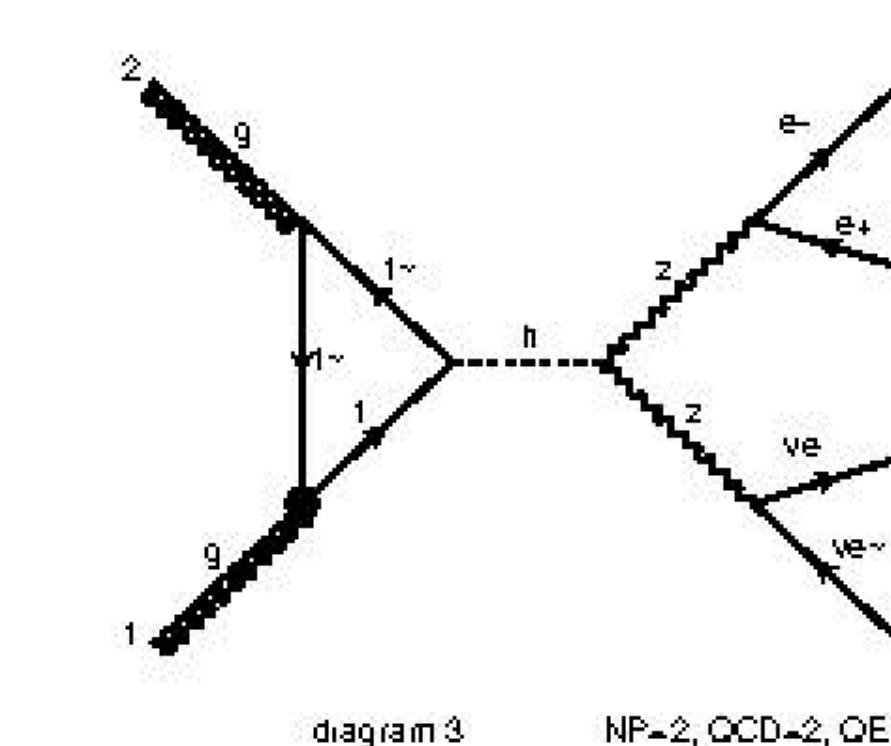
diag

NP=2, QCD=2, Q



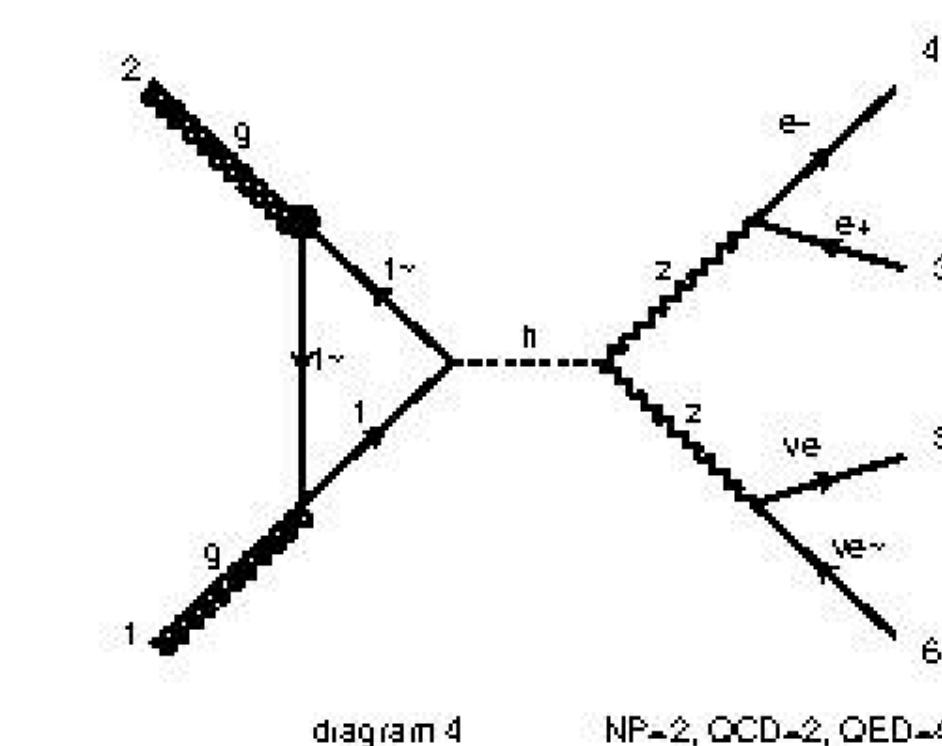
Diagram

NP=2, QCD=2, QED=



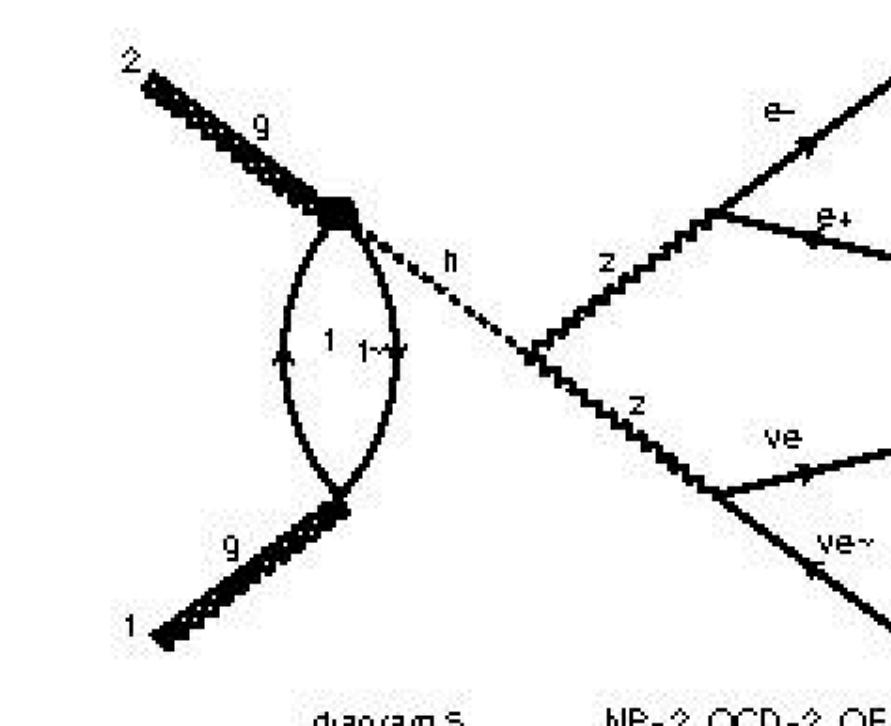
dia

NP=2, QCD=2, Q



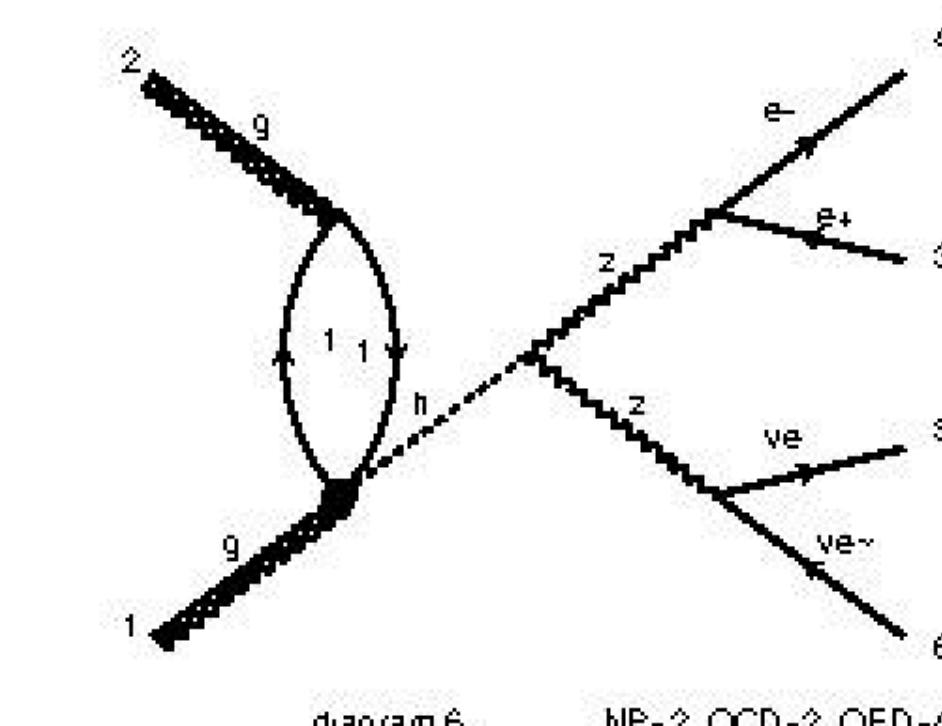
diagram

NP=2, QCD=2, QED=



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NP=2, QCD=2, Q

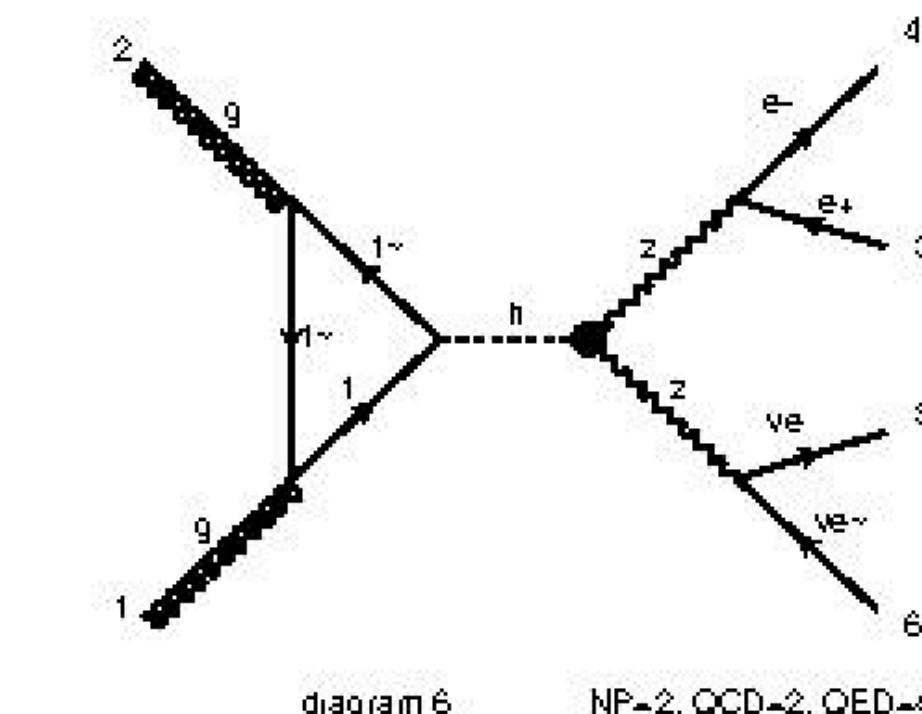
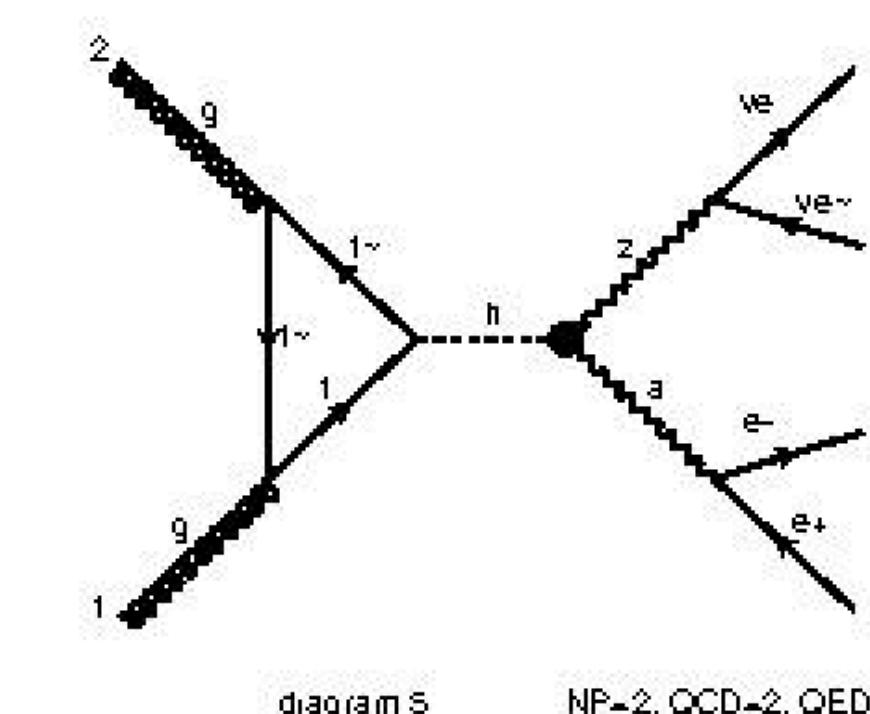
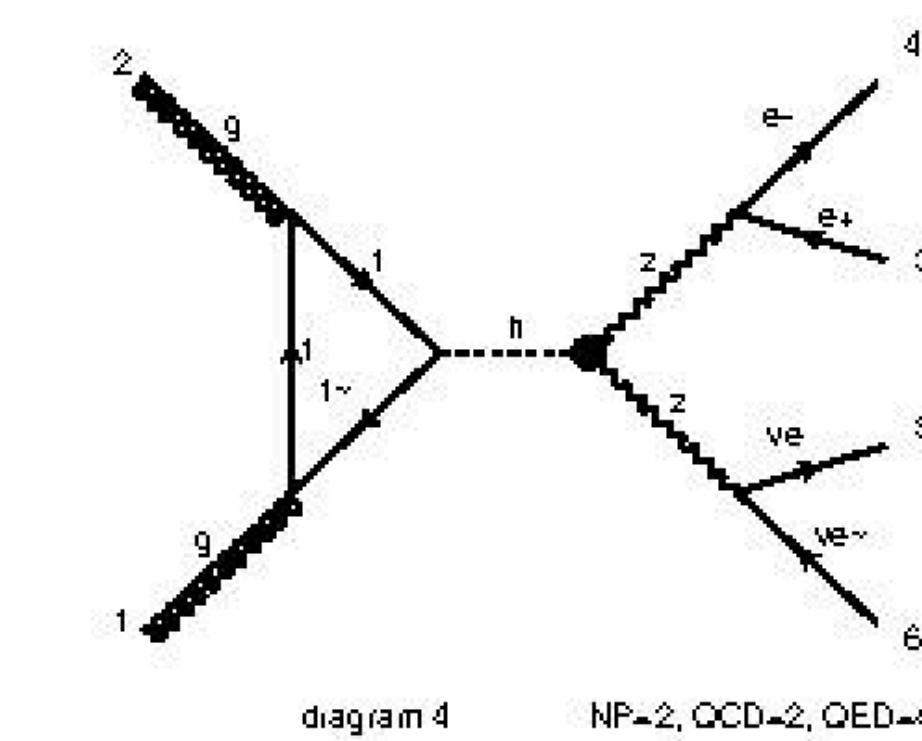
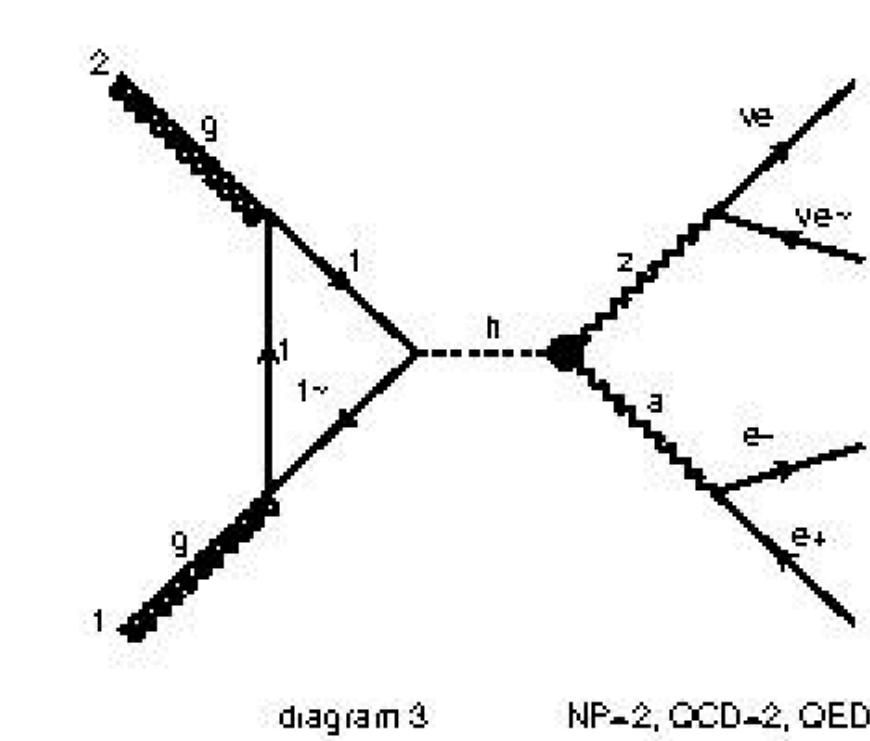
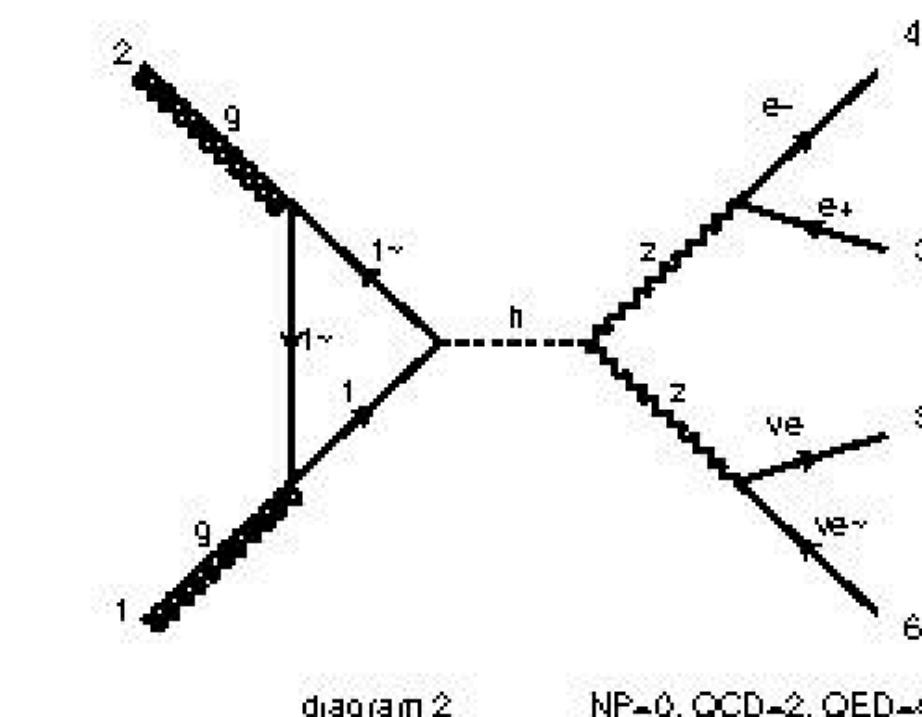
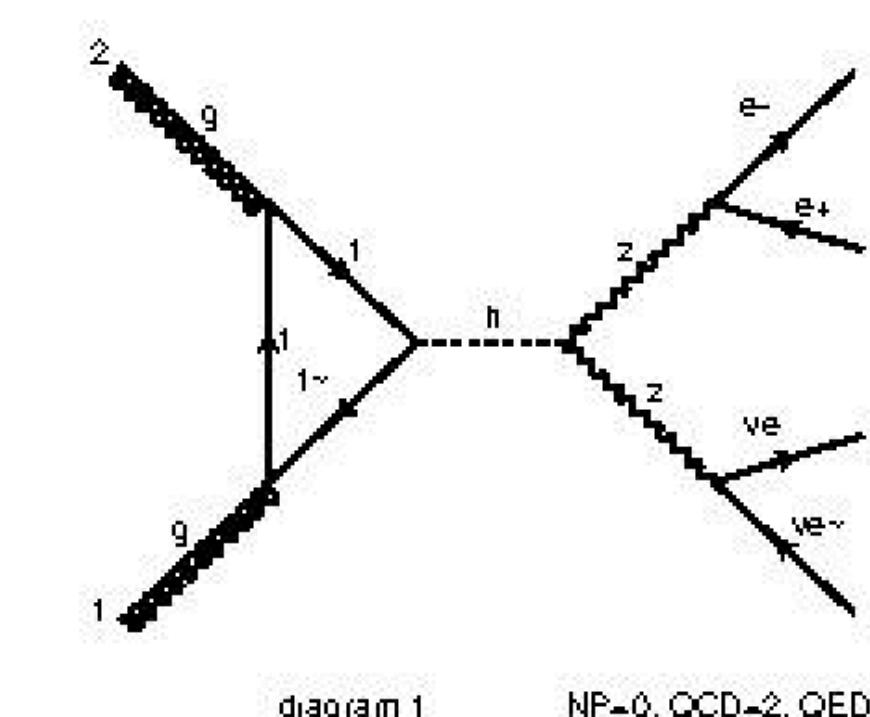


diagram

NP=2, QCD=2, QED=

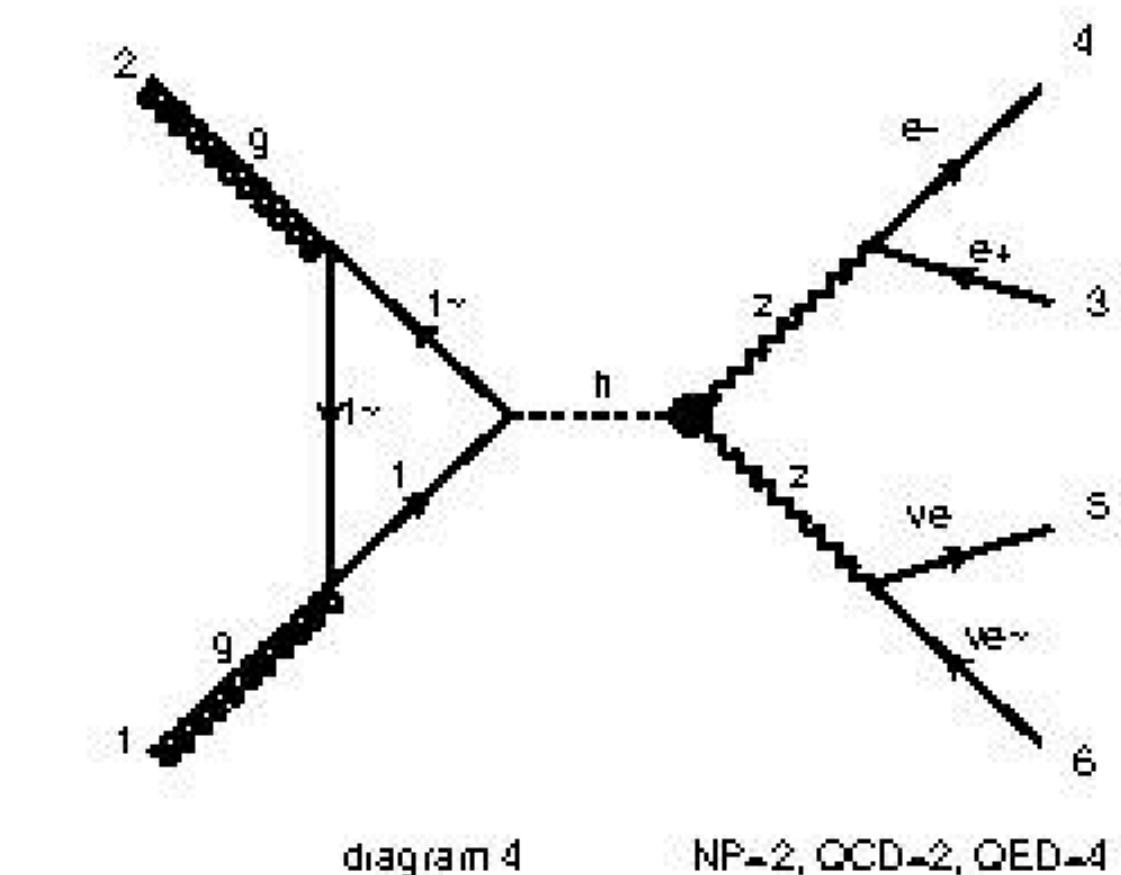
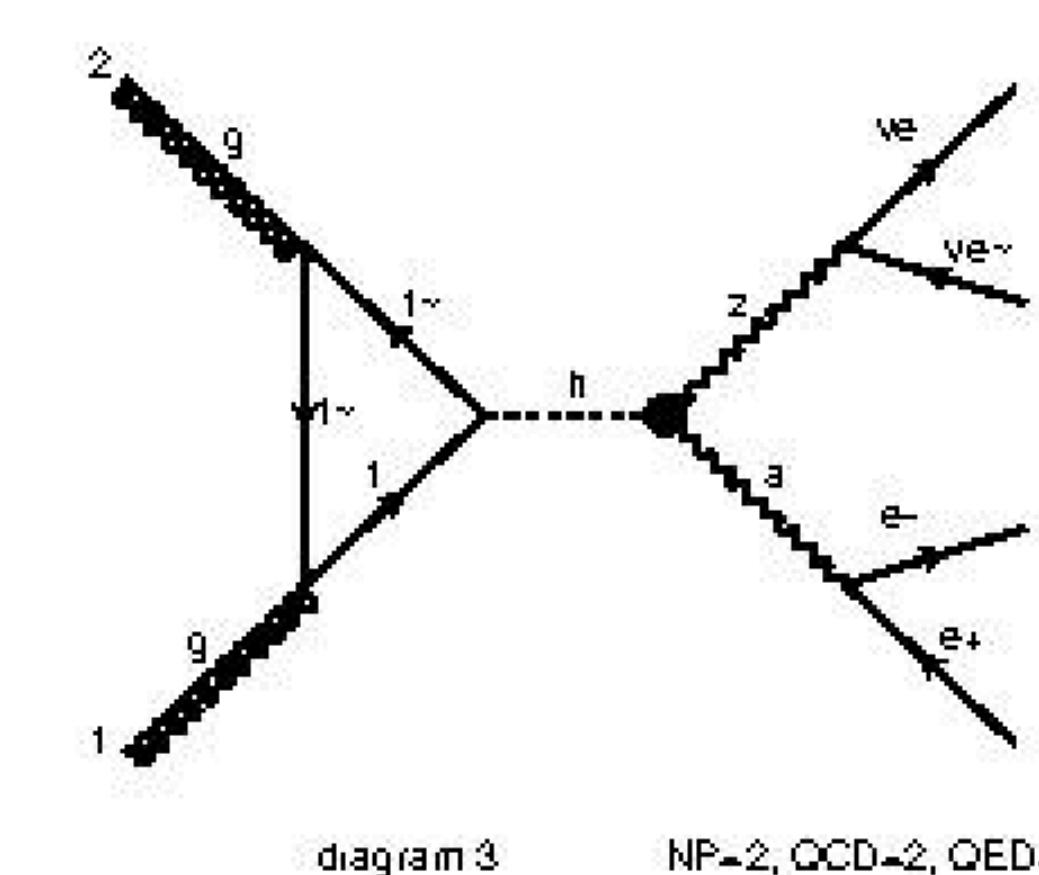
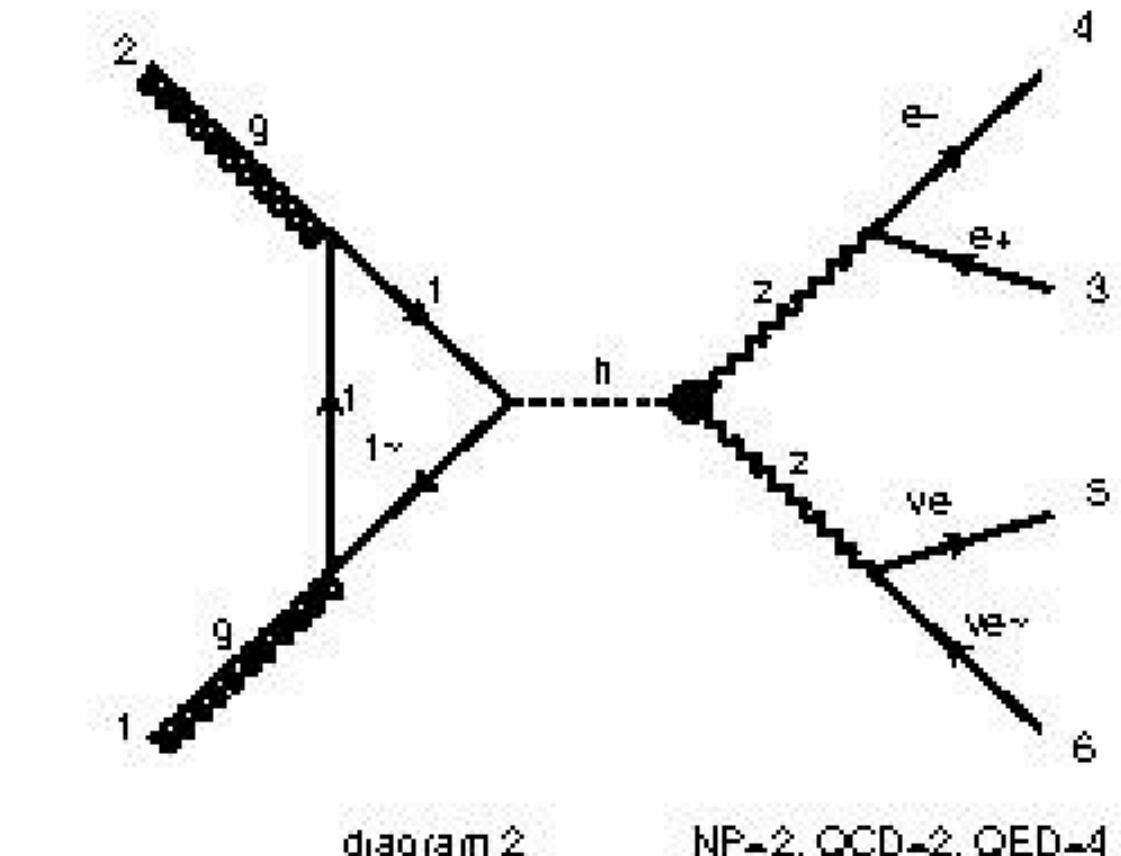
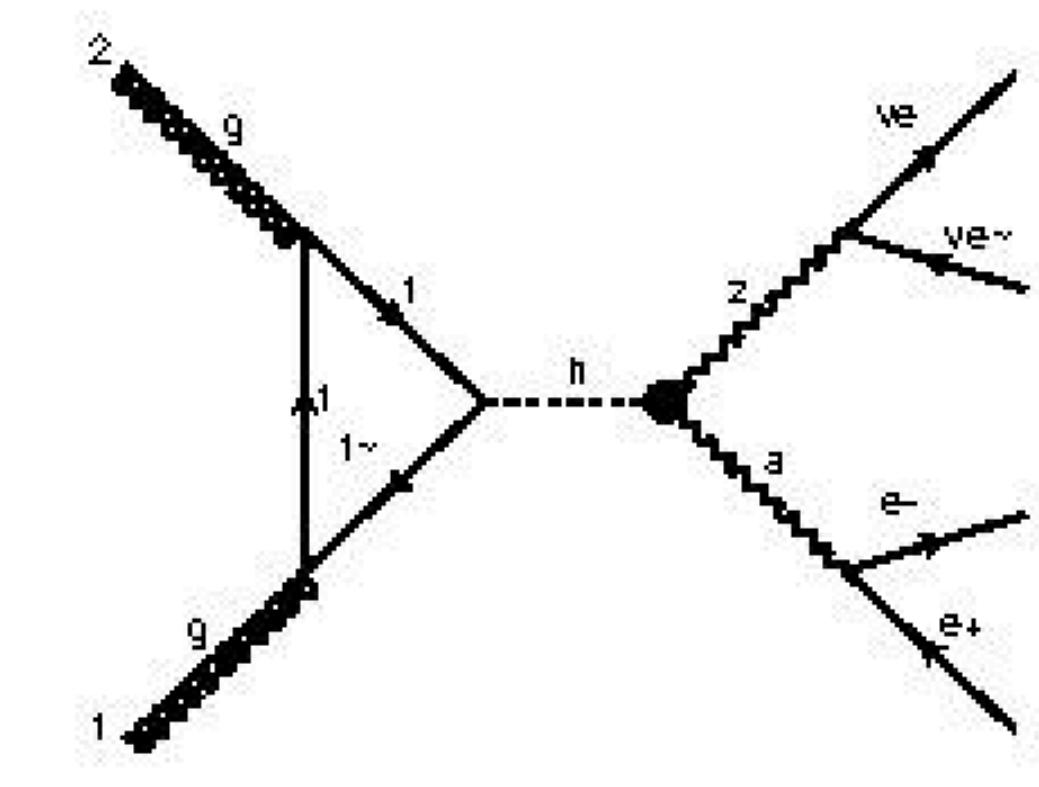
Feynman diagrams from MadGraph:

- cpW interference



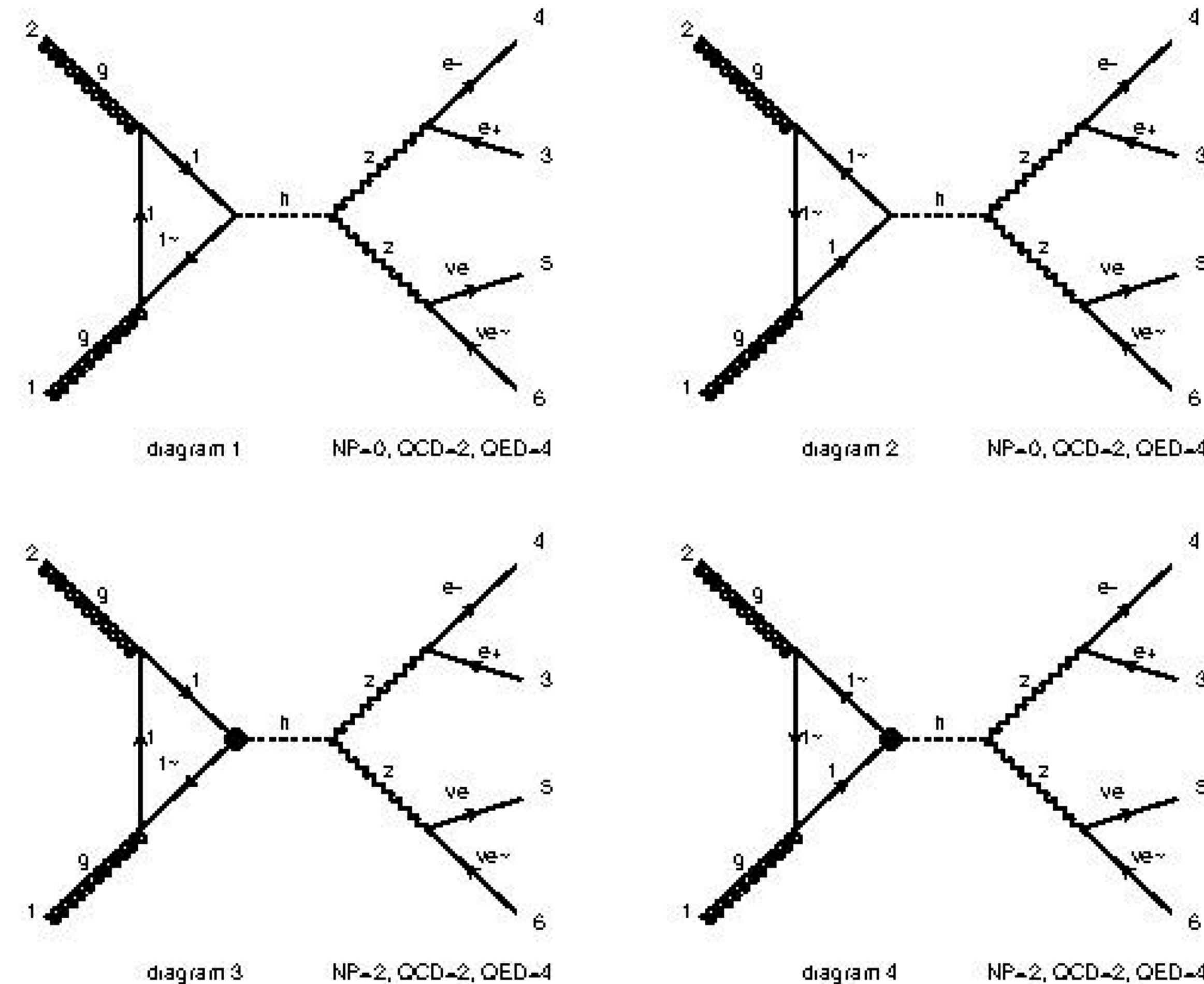
Feynman diagrams from MadGraph:

- cpW quadratic



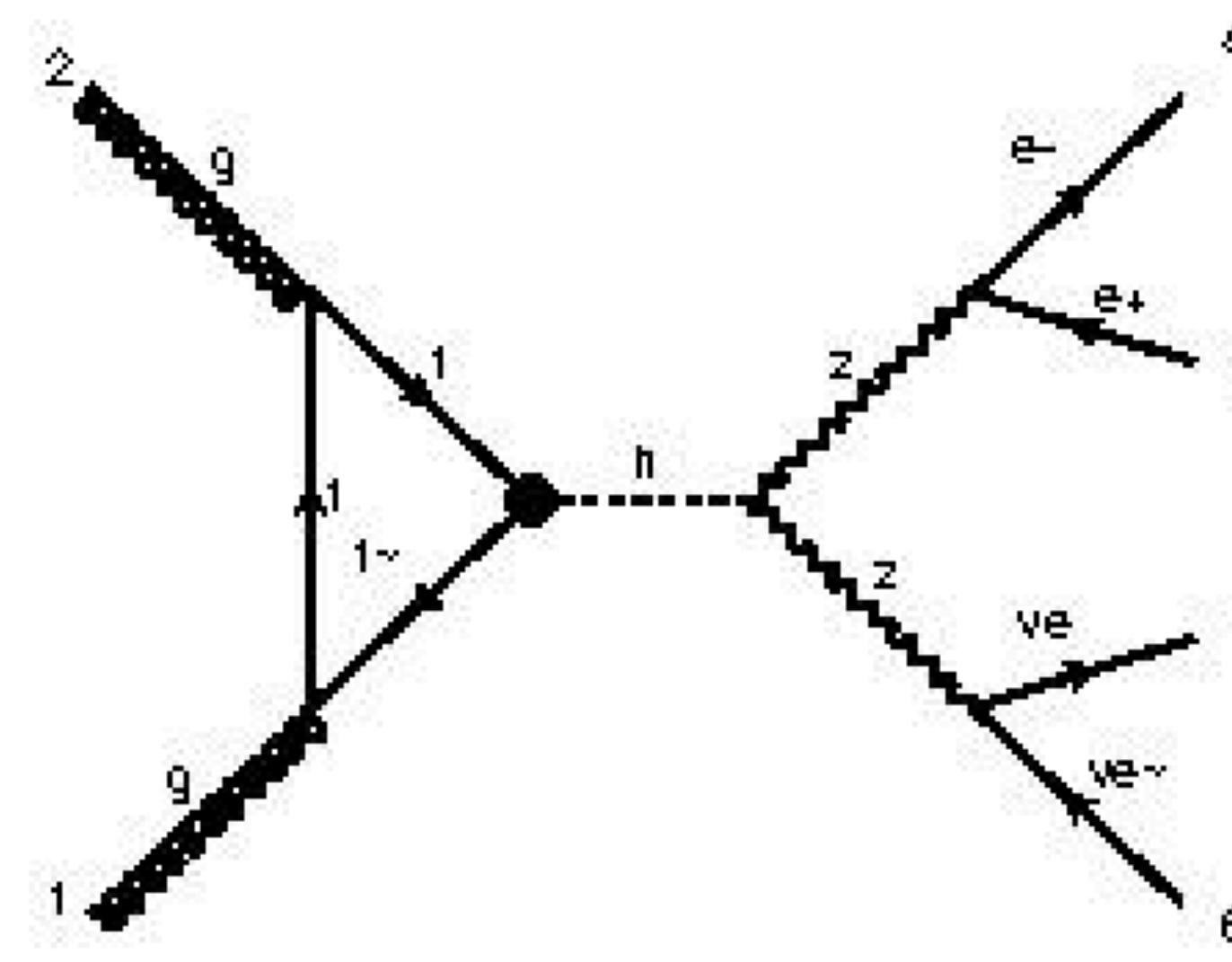
Feynman diagrams from MadGraph:

- ctp interference

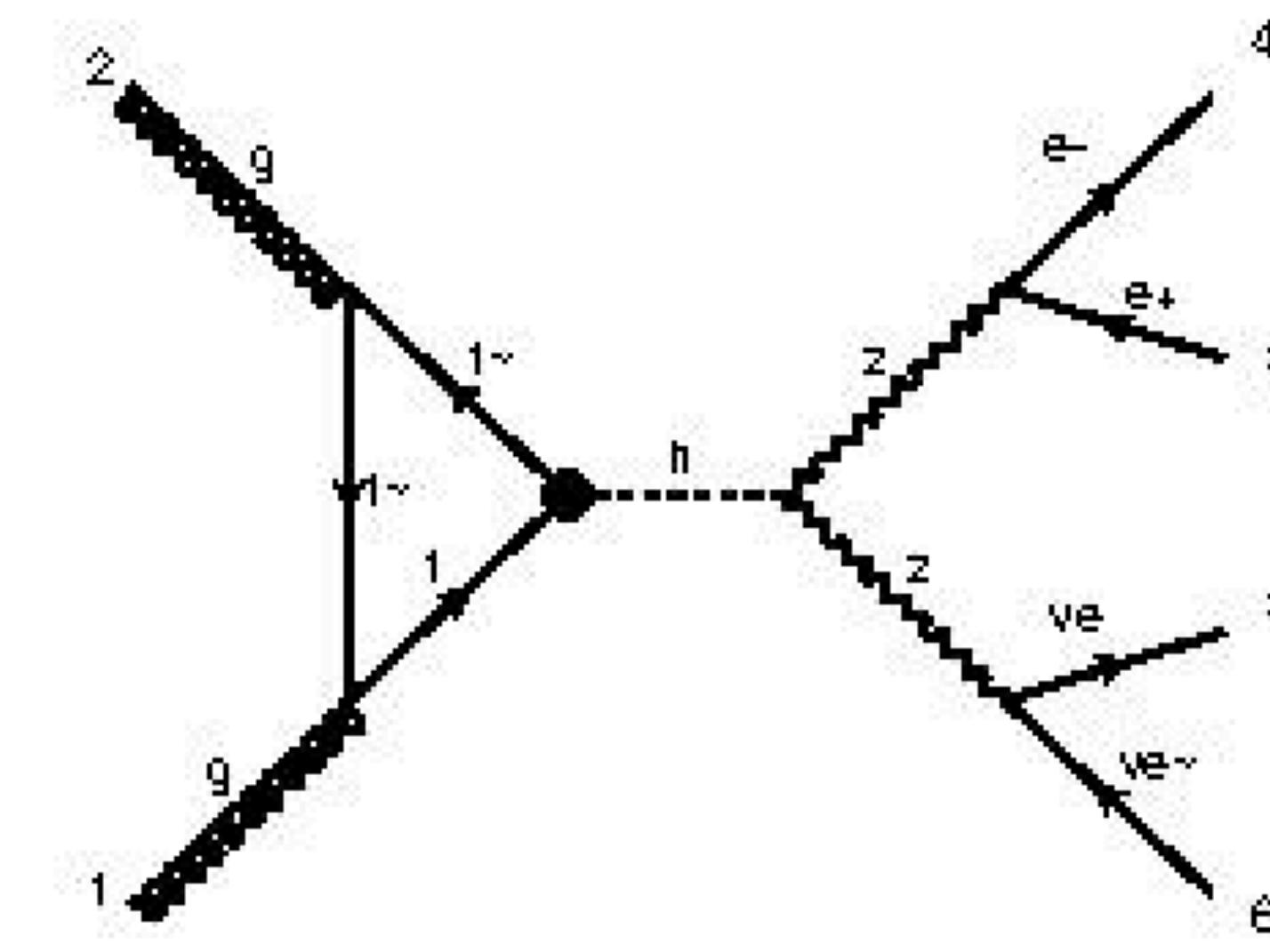


Feynman diagrams from MadGraph:

- ctp quadratic



NP=2, QCD=2, QED=4



NP=2, QCD=2, QED=4