Universität Zürich[UZH]

HiggsPO event generator at NLO QCD

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in collaboration with:

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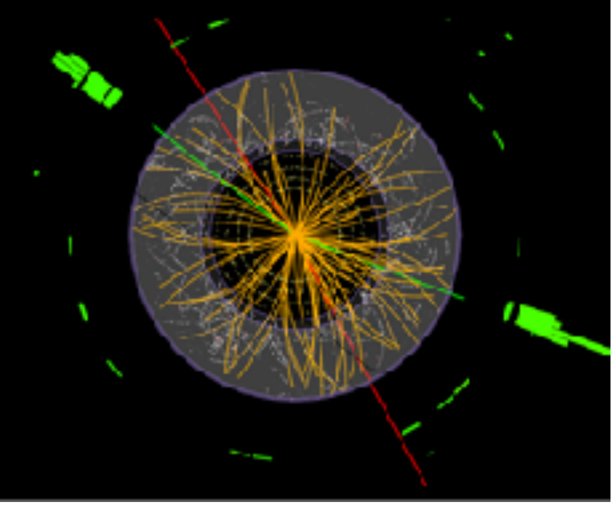
LHC Higgs Cross Section WG2 meeting, 08/05/2017, CERN

Outline

- *Introduction:* Higgs PO framework recap
- *Implementation* in a Monte Carlo tool
- ***HiggsPO*** tool at NLO in QCD **New**
- *Examples* and *validation*
- *Conclusions*



Experimental data

Fiblah

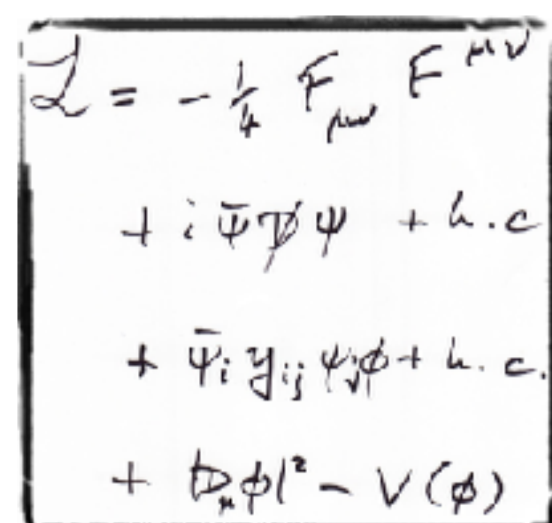
Fiducial cross sections, distributions, …

General encoding of the experimental results

Pseudo-Observables

*limited set of idealised observables

Applicable for large set of BSM theories



Theory

Couplings, masses, Wilson coeff., …

Q: How to get most out of the Higgs measurements?

*Higgs **PO** recap*

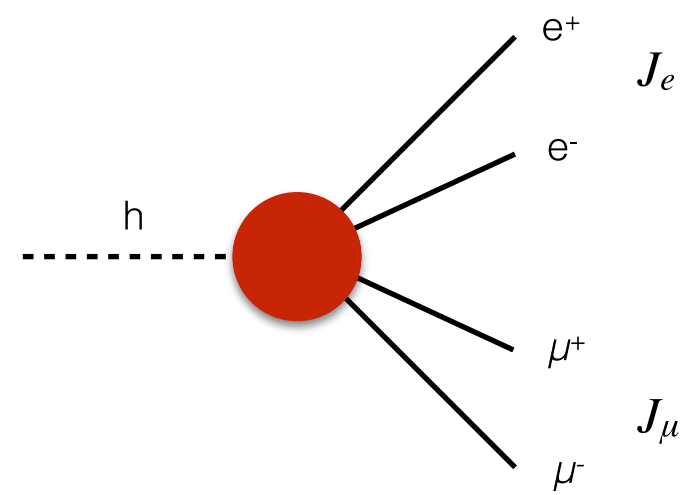
- Construction of Higgs **P**seudo-**O**bservables (**PO**) in Higgs decays [1412.6038] and EW production [1512.06135]. Summarised in the Yellow Report 4, Chapter III.1 [1610.07922]

1. h(125) is a spin 0 & zero width approximation
   → Factorisation of new physics effects in production and decay

2. *"On-shell"* Higgs processes
   PO are defined as pole residues in scattering amplitudes
   - Well-defined from the point of view of QFT
   - Improvable with (NP-free) soft QCD and QED radiation

Higgs **PO** recap

Example: h→2e2μ



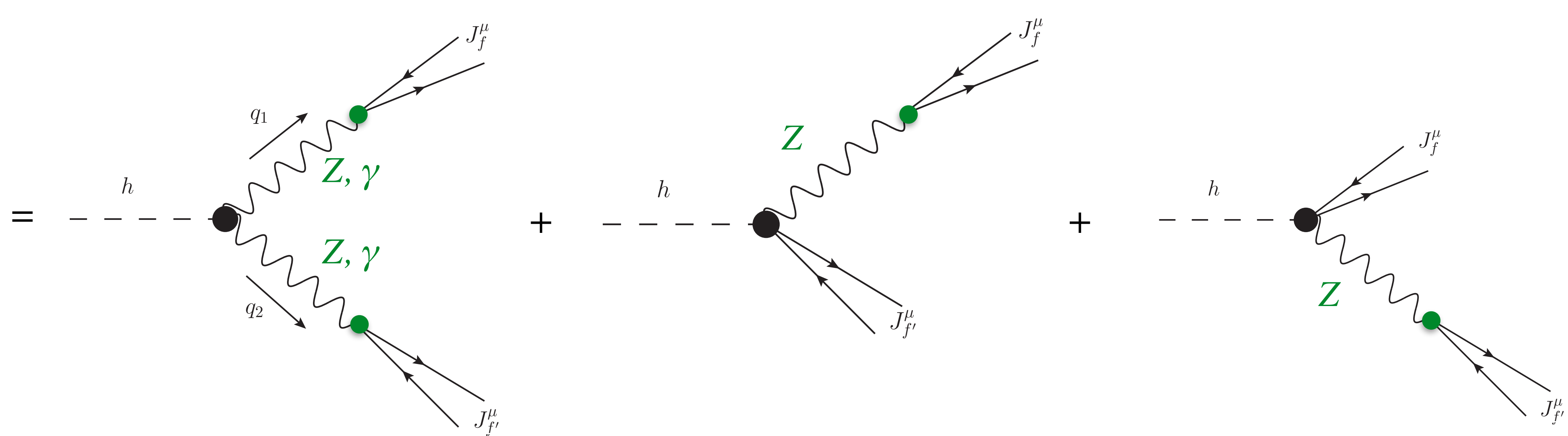
Decomposition of the ***(helicity-conserving)*** *amplitude:*

$$\mathcal{A} = i\frac{2m_Z^2}{v_F} \sum_{e=e_L,e_R} \sum_{\mu=\mu_L,\mu_R} (\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu)\times$$

$$\left[F_1^{e\mu}(q_1^2,q_2^2)g^{\alpha\beta} + F_3^{e\mu}(q_1^2,q_2^2)\frac{q_1\cdot q_2\ g^{\alpha\beta} - q_2{}^\alpha q_1{}^\beta}{m_Z^2} + F_4^{e\mu}(q_1^2,q_2^2)\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$

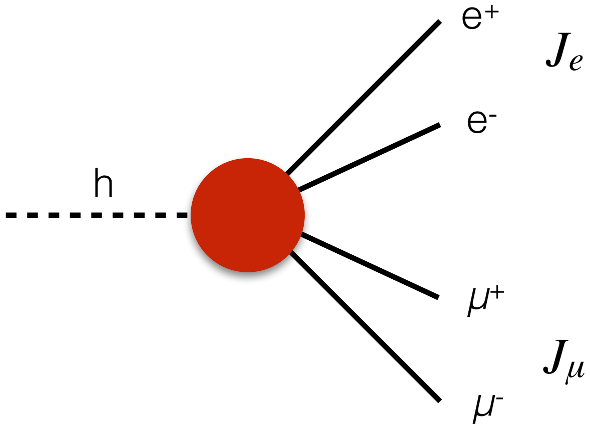
Momentum expansion of the form factors around the physical poles:

- Smooth kinematical distortions from the SM (heavy NP)



Higgs PO recap

Example: h→2e2μ



$$\mathcal{A} = i\frac{2m_Z^2}{v_F}\sum_{e=e_L,e_R}\sum_{\mu=\mu_L,\mu_R}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta\mu)\times$$

$$\left[F_1^{e\mu}(q_1^2,q_2^2)g^{\alpha\beta} + F_3^{e\mu}(q_1^2,q_2^2)\frac{q_1\cdot q_2\ g^{\alpha\beta} - q_2{}^\alpha q_1{}^\beta}{m_Z^2} + F_4^{e\mu}(q_1^2,q_2^2)\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$

Momentum expansion

$$\mathcal{A} = i\frac{2m_Z^2}{v_F}\sum_{e=e_L,e_R}\sum_{\mu=\mu_L,\mu_R}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta\mu)\times$$

$$\left[\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)}\right)g^{\alpha\beta} + \right.$$

$$+\left(\epsilon_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \kappa_{Z\gamma}\epsilon_{Z\gamma}^{\text{SM-1L}}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \kappa_{\gamma\gamma}\epsilon_{\gamma\gamma}^{\text{SM-1L}}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{q_1\cdot q_2\ g^{\alpha\beta} - q_2{}^\alpha q_1{}^\beta}{m_Z^2} +$$

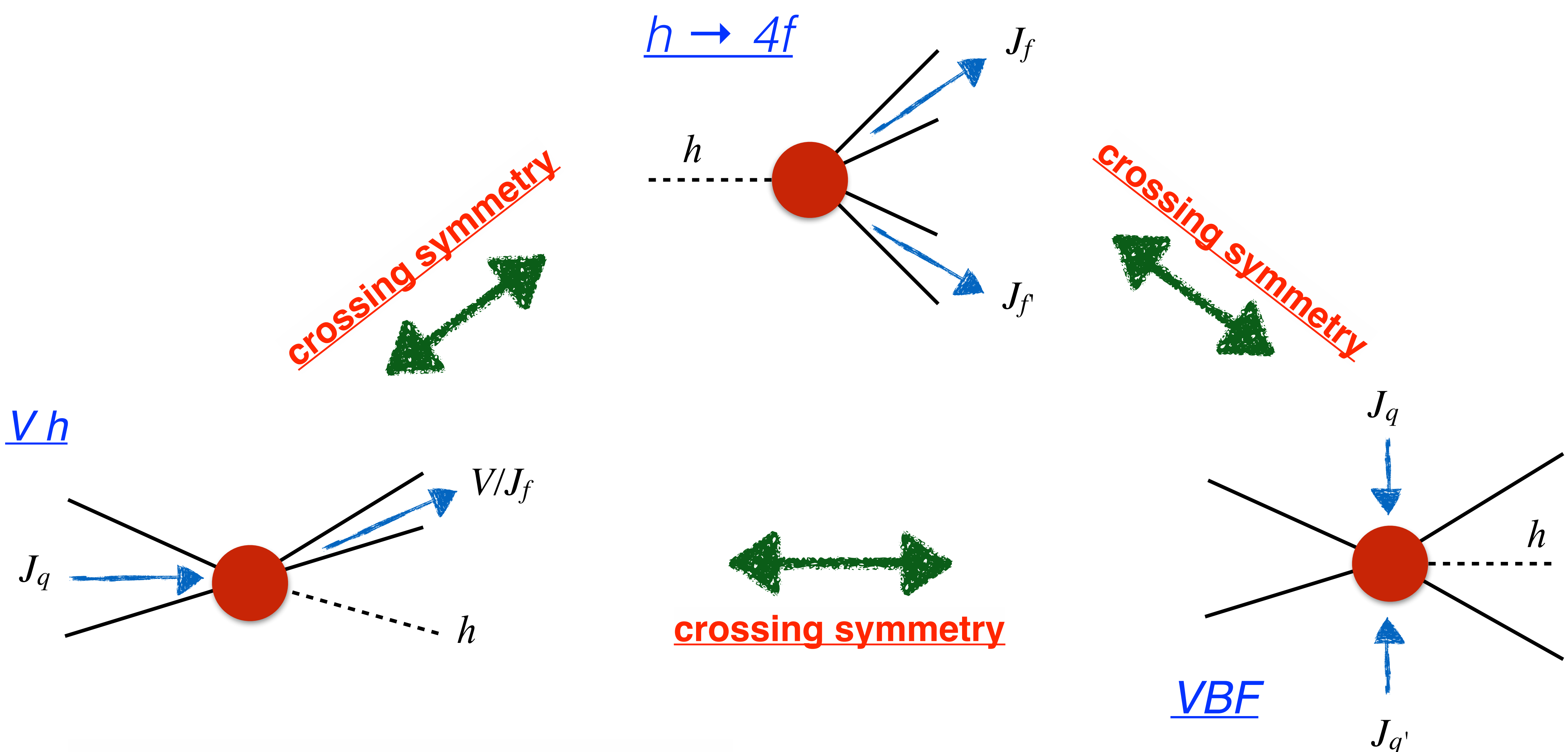
$$\left.+\left(\epsilon_{ZZ}^{\text{CP}}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \epsilon_{Z\gamma}^{\text{CP}}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \epsilon_{\gamma\gamma}^{\text{CP}}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$

In the SM: $\kappa_X \to 1,\ \epsilon_X \to 0$

$$P_Z(q^2) = q^2 - m_Z^2 + i m_Z\Gamma_Z$$

PO in EW Higgs production

- Production amplitudes related to decay amplitudes by **crossing symmetry**:
  - *Flavour universal* ***PO*** *exactly the same*
  - *Different fermion currents -* ***Quark contact terms***



- Different kinematical regions

[1512.06135]

Dedicated MC tool: ***HiggsPO***

- *Wish list for the Monte Carlo event generator:*

A. **Simulate** single Higgs production and decays

B. **Input parameters** Higgs PO as defined in **Yellow Report 4**

C. **Allow** for inclusion of (NP-free) radiative corrections

D. **Simple** to use. Rely on the well-known MC frameworks (and formats)

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- ***HiggsPO*** *model (Implementation)*

  1. ***FeynRules*** *[arXiv:1310.1921]*
     Define a set of effective interactions that at tree level generate exactly the scattering amplitude of interest (not to be used as a Lagrangian for arbitrary process and beyond tree level in HPO couplings)

  2. *Export model in the* ***Universal FeynRules Output*** *(**UFO**)* ***[arXiv:1108.2040]***

     To benefit from MG5_aMC@NLO [arXiv:1405.0301] or Sherpa [arXiv:0811.4622] frameworks

  3. *Partonic level events (e.g.* ***MadGraph5_aMC@NLO*** ***[arXiv:1405.0301]****)*
     To be used for a set of well-defined processes. Input lines documented in the HiggsPO Manual for each process separately.

  4. *Partonic events passed to a general purpose event generator (e.g.* ***Pythia*** ***[arXiv:1410.3012]****)*
     Automatic inclusion of (NP-free) radiative corrections. Final output in the well-known format e.g. "___.hep" (the STDHEP format).

HiggsPO at NLO in QCD

Implementation details

- QCD Lagrangian (including ghost terms) taken from the SM.fr
- SM fields defined in the mass (unitary) basis
- Effective Lagrangian of the EW sector — "HPO couplings"
  (at tree level reproduce the correct amplitudes)
- **NLOCT** package to calculate UV and R2 QCD counterterms
  [Degrande]
- No UV renormalisation of HPO couplings
- *R2 terms for flavour dependent contact-terms (hZqq) put by hand in the UFO model*

$$R_2^{\bar{f}_i f_i Z h} = -\frac{i g_s^2}{3\pi^2 v} \varepsilon_{Z,f^i} \; ,$$

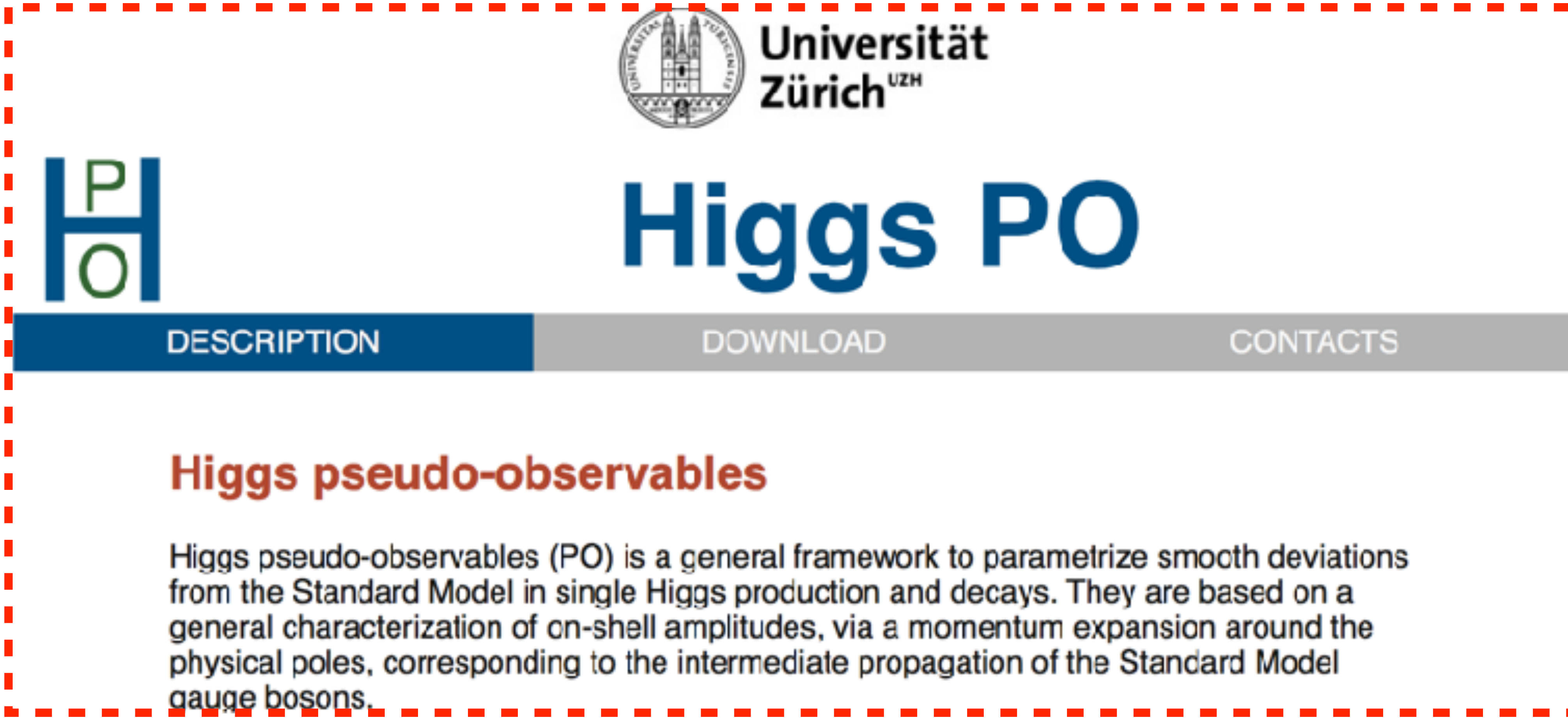
$$R_2^{\bar{u}_i d_j W^+ h} = -\frac{i g_s^2}{3\pi^2 v} \varepsilon_{W,u_L^i d_L^j} e^{-i\phi_{Wu}}$$

Note: Flavour dependent contact-terms terms are missing in similar UFO models (e.g. Higgs characterisation [1311.1829])

[AG, Isidori, Lindert, Marzocca]
to appear soon

Homepage: ***HiggsPO***

HiggsPO *can be downloaded from:* [*http://www.physik.uzh.ch/data/HiggsPO/*](http://www.physik.uzh.ch/data/HiggsPO/)



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Higgs PO

DESCRIPTION DOWNLOAD CONTACTS

Higgs pseudo-observables

Higgs pseudo-observables (PO) is a general framework to parametrize smooth deviations from the Standard Model in single Higgs production and decays. They are based on a general characterization of on-shell amplitudes, via a momentum expansion around the physical poles, corresponding to the intermediate propagation of the Standard Model gauge bosons.

Homepage: ***HiggsPO***

HiggsPO *can be downloaded from: http://www.physik.uzh.ch/data/HiggsPO/*

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Higgs PO

DESCRIPTION | DOWNLOAD | CONTACTS

Download the model

Version 1.0

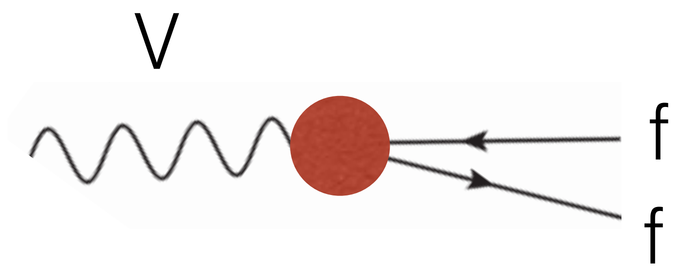
This model is suitable to simulate Higgs decay processes, as well as Higgs production in gluon-fusion.

- FeynRules model: HPO.fr
- UFO model: HiggsPO_UFO (zip)
- Manual: HiggsPO.pdf
- Slides (with examples of usage): link

Version 1.1

Extended to include electroweak Higgs production, see [1512.06135] for details.

W and Z boson PO



$$g_Z^f = \frac{2m_Z}{v_F} g_{Zf}^{\rm LEP} \;, \qquad g_W^f = \frac{\sqrt{2} m_W}{v_F} g_{Wf}^{\rm LEP} \;.$$

The default values taken from the experimental report:
[arXiv:1302.3415, hep-ex/0509008]

```
#####################################
## INFORMATION FOR WZPOLE
#####################################
Block wzpole
    1 -2.696000e-01 # gZeL
    2 -2.690000e-01 # gZmuL
    3 -2.693000e-01 # gZtauL
    4 2.315000e-01 # gZeR
    5 2.320000e-01 # gZmuR
    6 2.327000e-01 # gZtauR
    7 5.000000e-01 # gZv
    8 9.940000e-01 # gWe
    9 9.910000e-01 # gWmu
   10 1.025000e+00 # gWtau
   11 3.467000e-01 # gZuL
   12 -4.243000e-01 # gZdL
   15 -1.547000e-01 # gZuR
   16 7.735000e-02 # gZdR
   19 1.000000e+00 # gWuL
```

param_card.dat

Higgs PO — EW Higgs decays and production

```
####################################
## INFORMATION FOR HPOQUARK
####################################
Block hpoquark
   51 0.000000e+00 # eZuL
   52 0.000000e+00 # eZuR
   53 0.000000e+00 # eZdL
   54 0.000000e+00 # eZdR
   55 0.000000e+00 # eWuL
   56 0.000000e+00 # phiWuL
```

param_card.dat

Production: ***VBF, VH***

Decays: ***h*** **→** ***4*** ℓ, ***h*** **→** ***2q 2*** ℓ, ***h*** **→** ***2*** ν ***2*** ℓ, ***h*** **→** ***2*** ℓ γ, ***h*** **→** γγ

```
####################################
## INFORMATION FOR HPO4F
####################################
Block hpo4f
    1 1.000000e+00 # kZZ
    2 1.000000e+00 # kWW
    3 1.000000e+00 # kAA
    4 1.000000e+00 # kZA
    5 0.000000e+00 # eZZ
    6 0.000000e+00 # eWW
    7 0.000000e+00 # lAACP
    8 0.000000e+00 # lZACP
    9 0.000000e+00 # eZZCP
   10 0.000000e+00 # eWWCP
   11 0.000000e+00 # eZeL
   12 0.000000e+00 # eZmuL
   13 0.000000e+00 # eZtauL
   14 0.000000e+00 # eZeR
   15 0.000000e+00 # eZmuR
   16 0.000000e+00 # eZtauR
   17 0.000000e+00 # eZv
   18 0.000000e+00 # eWe
   19 0.000000e+00 # eWmu
   20 0.000000e+00 # eWtau
   21 0.000000e+00 # phiWe
   22 0.000000e+00 # phiWmu
   23 0.000000e+00 # phiWtau
```

param_card.dat

Examples and validation

Example: *h → 2e2μ*

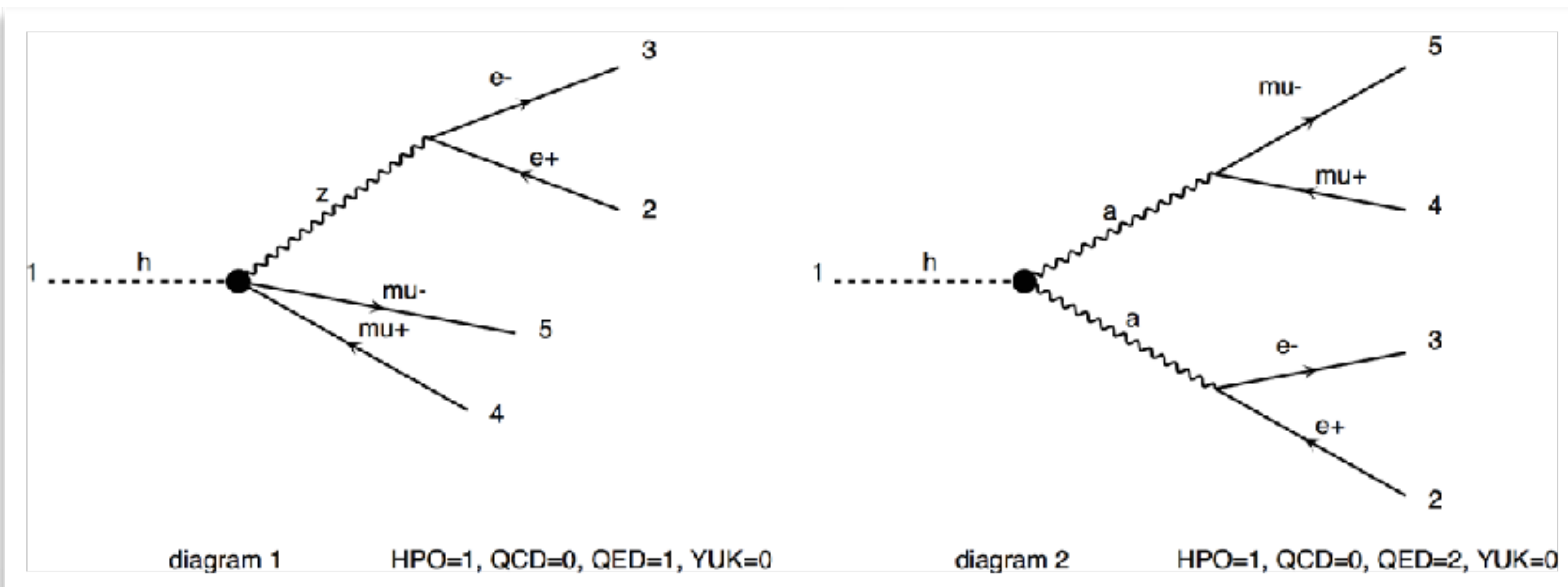
MadGraph5_aMC@NLO

```
> import model HiggsPO_UFO
> generate h > e+ e- mu+ mu- YUK=0
> output heemumu
```

Analytic calculation

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q_1^2\mathrm{d}q_2^2} = \Pi_{4l} \int \mathrm{d}\Omega \sum_s \mathcal{A}\mathcal{A}^*,$$

$$\sum_s \mathcal{A}\mathcal{A}^* = \left(\frac{2m_Z^2}{v_F}\right)^2 \sum_{f,f'} \mathrm{tr}(\not{p}_1\gamma_\mu P^f \not{p}_2\gamma_{\mu_1}) \times \mathrm{tr}(\not{p}_3\gamma_\nu P^{f'} \not{p}_4\gamma_{\nu_1}) \times \mathcal{T}^{\mu\nu}_{ff'}(q_1,q_2)\mathcal{T}^{\mu_1\nu_1 *}_{ff'}(q_1,q_2),$$



Example diagrams

Example: *h* → 2e2μ

MadGraph5_aMC@NLO

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> import model HiggsPO_UFO
> generate h > e+ e- mu+ mu- YUK=0
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Analytic calculation

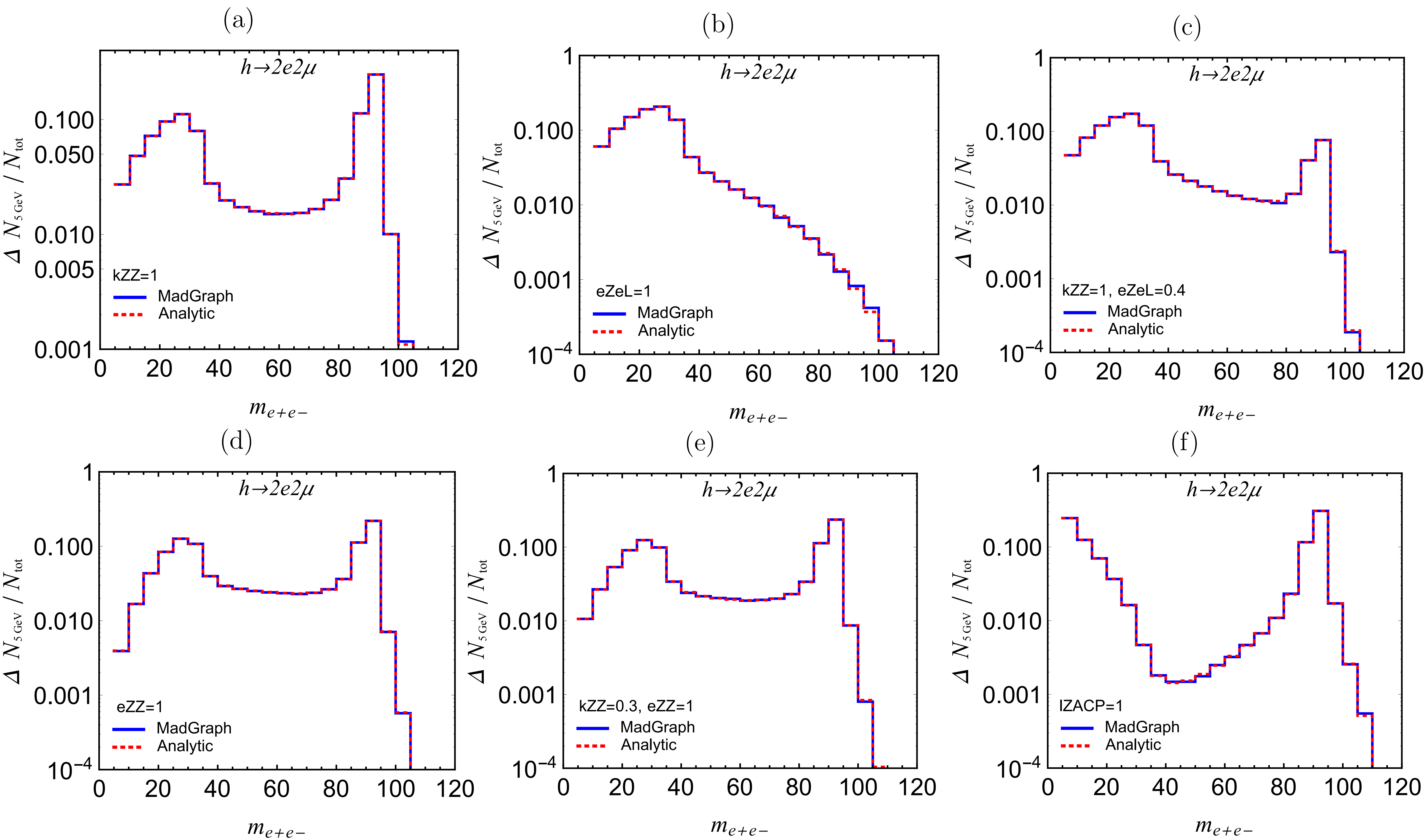
$$\frac{d\Gamma}{dq_1^2 dq_2^2} = \Pi_{4l} \int d\Omega \sum_s \mathcal{A}\mathcal{A}^*,$$

$$\sum_s \mathcal{A}\mathcal{A}^* = \left(\frac{2m_Z^2}{v_F}\right)^2 \sum_{f,f'} \mathrm{tr}(\not{p}_1 \gamma_\mu P^f \not{p}_2 \gamma_{\mu_1}) \times \mathrm{tr}(\not{p}_3 \gamma_\nu P^{f'} \not{p}_4 \gamma_{\nu_1}) \times \mathcal{T}^{\mu\nu}_{ff'}(q_1, q_2) \mathcal{T}^{\mu_1\nu_1 *}_{ff'}(q_1, q_2),$$

- Opposite sign same flavour lepton pair invariant mass cut: $m_{\ell\ell} > 5$ GeV

- Benchmark (a): $\kappa_{ZZ} = 1$ and all other Higgs PO zero. The decay width in MadGraph: $2.3241(7) \times 10^{-7}$ GeV and analytic: 2.3232×10^{-7} GeV. See Fig 1 (a).
- Benchmark (b): $\epsilon_{Ze_L} = 1$ and all other Higgs PO zero. The decay width in MadGraph: $1.4919(5) \times 10^{-6}$ GeV and analytic: 1.4917×10^{-6} GeV. See Fig 1 (b).
- Benchmark (c): $\kappa_{ZZ} = 1$, $\epsilon_{Ze_L} = 0.4$ and all other Higgs PO zero. The decay width in MadGraph: $7.449(2) \times 10^{-7}$ GeV and analytic: 7.447×10^{-7} GeV. See Fig 1 (c).
- Benchmark (d): $\epsilon_{ZZ} = 1$ and all other Higgs PO zero. The decay width in MadGraph: $2.1368(7) \times 10^{-8}$ GeV and analytic: 2.1368×10^{-8} GeV. See Fig 1 (d).
- Benchmark (e): $\kappa_{ZZ} = 0.3$, $\epsilon_{ZZ} = 1$ and all other Higgs PO zero. The decay width in MadGraph: $7.768(2) \times 10^{-8}$ GeV and analytic: 7.767×10^{-8} GeV. See Fig 1 (e).
- Benchmark (f): $\lambda^{CP}_{Z\gamma} = 1$ and all other Higgs PO zero. The decay width in MadGraph: $8.880(3) \times 10^{-10}$ GeV and analytic: 8.874×10^{-10} GeV. See Fig 1 (f).

Example: h → 2e2μ



Example: $h \to V\, q\, q$

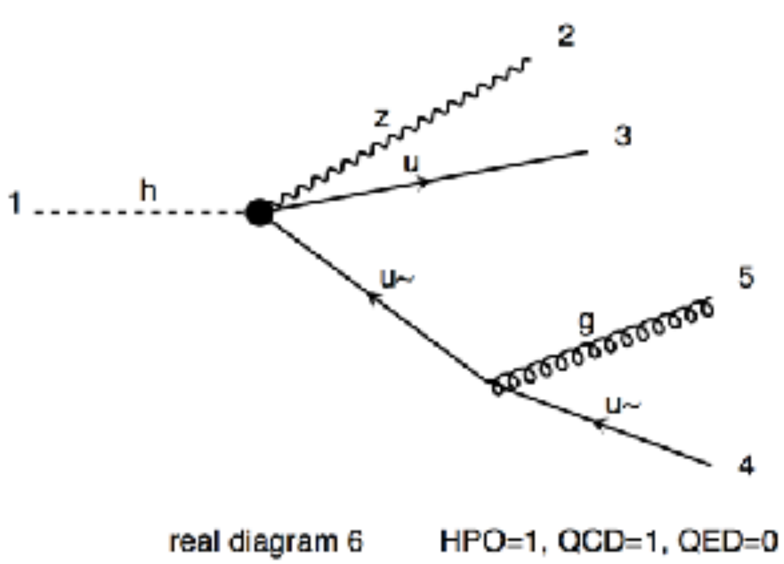
1) MadGraph5_aMC@NLO

2) Analytic calculation

$$K_F = 1 + \alpha_s/\pi \simeq 1.038$$

$$h \to W^- \bar{d} u + W^- \bar{d} c + W^- \bar{s} u + W^- \bar{s} c$$

kWW	eWuL	phiWuL	LO (an.)	LO	NLO	K_F
1	0	0	259.0	259.4(2)	269.1(3)	1.037(1)
0	1	0	883.1	883.0(7)	916.8(8)	1.038(1)
1	0.54	0	2.678	2.676(2)	2.782(3)	1.040(1)
1	0.54	$\pi/2$	500.8	501.1(4)	520.1(6)	1.038(1)
1	−0.54	$\pi/2$	532.3	531.8(4)	552.3(6)	1.039(1)
1	−0.54	0	1030	1030(1)	106.7(1)	1.036(1)



Example diagram

$$h \to Z\bar{u}u + Z\bar{c}c$$

Total inclusive decay rates are: in KeV

kZZ	eZuL	eZuR	LO (an.)	LO	NLO	K_F
1	0	0	19.83	19.84(2)	20.58(2)	1.037(1)
0	1	0	219.7	219.3(2)	228.2(2)	1.040(1)
0	0	1	219.7	219.6(2)	228.0(2)	1.039(1)
1	0.3	0	3.480	3.481(3)	3.606(5)	1.036(1)
1	−0.3	0	75.72	75.75(6)	78.64(7)	1.038(1)
1	0	0.3	55.72	55.70(5)	57.97(5)	1.038(1)
1	0	−0.3	23.48	23.51(2)	24.37(3)	1.037(1)

$$h \to Z\bar{d}d + Z\bar{s}s$$

Total inclusive decay rates are:

kZZ	eZdL	eZdR	LO (an.)	LO	NLO	K_F
1	0	0	25.59	25.60(2)	26.56(2)	1.037(1)
0	1	0	219.7	219.3(2)	228.2(3)	1.040(1)
0	0	1	219.7	219.6(2)	227.7(2)	1.037(1)
1	0.34	0	101.1	101.1(1)	104.7(1)	1.036(1)
1	−0.34	0	0.8869	0.8872(7)	0.9211(8)	1.038(1)
1	0	0.34	41.85	41.84(3)	43.55(4)	1.040(1)
1	0	−0.34	60.12	60.18(5)	62.38(6)	1.037(1)

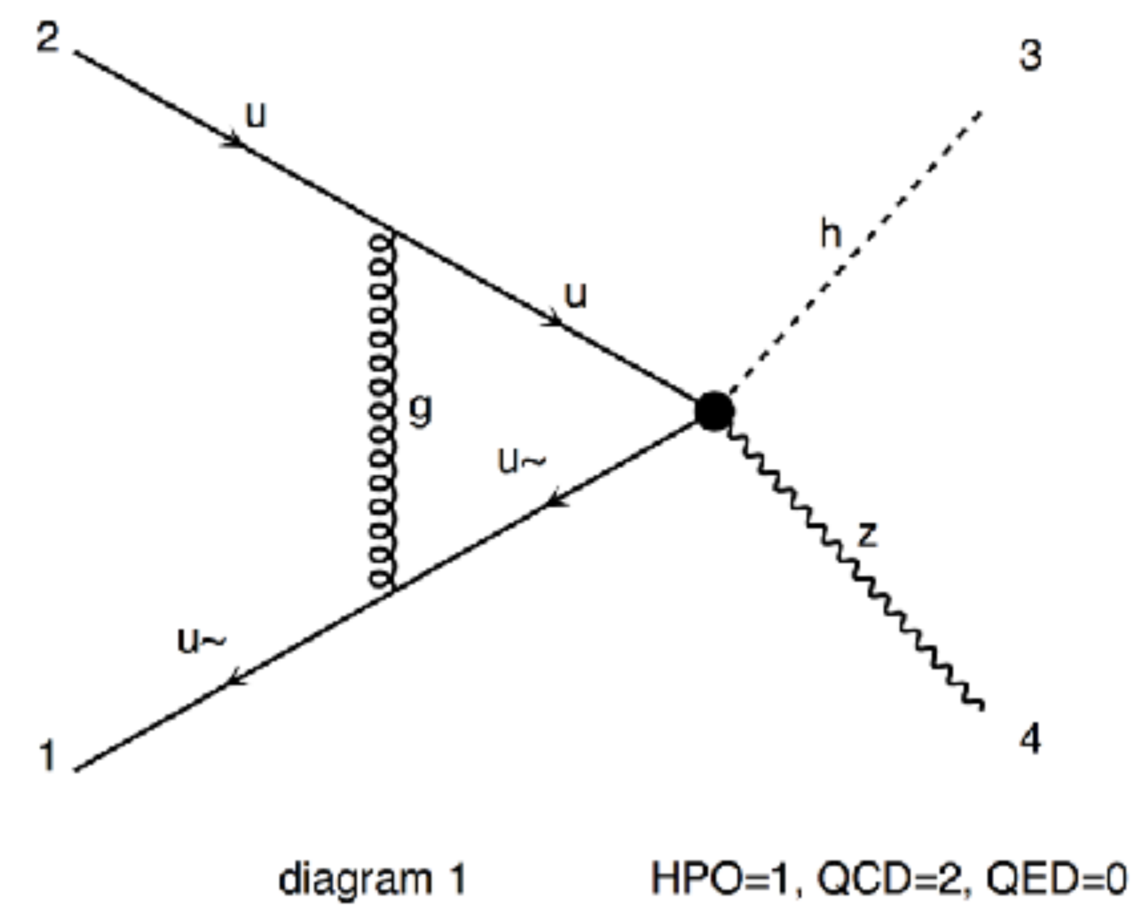
$p\, p \to Z\, h$ at NLO + PS

MADGRAPH5_AMC@NLO

```
import model HPO_ewk_prod_NLO
generate p p > h z HPO=1 QED=1 QCD=0 [QCD]
output ppHZnlo
```

Benchmarks

BP	kZZ	eZuL	eZuR	eZdL	eZdR
I	1	0	0	0	0
II	1	0.0195	0	0	0
III	1	0	0.0195	0	0
IV	1	0	0	0.0244	0
V	1	0	0	0	0.0244



Example diagram

[AG, Isidori, Lindert, Marzocca]
to appear soon

$p\,p \to Z\,h$ at NLO + PS

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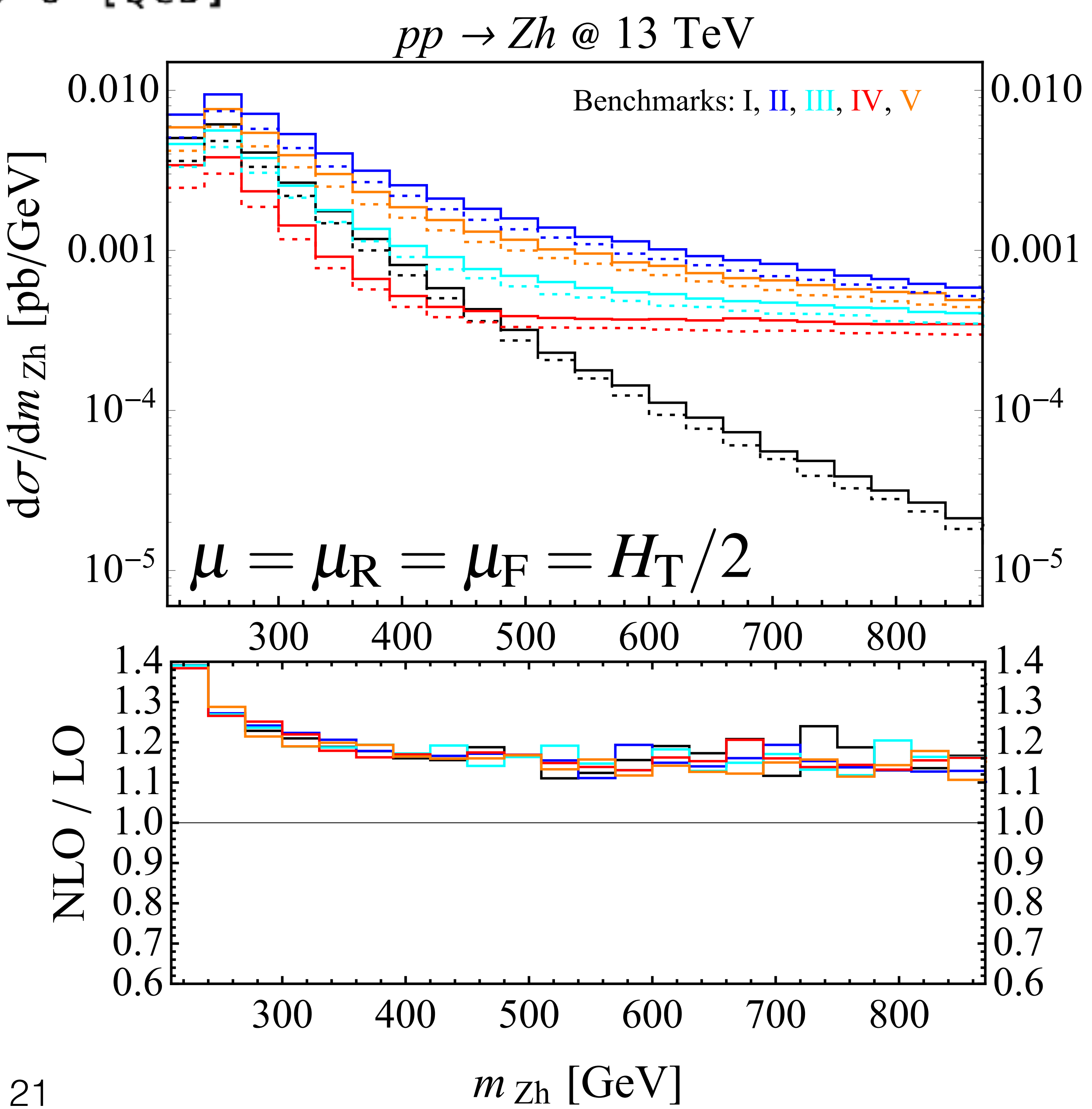
Benchmarks

BP	kZZ	eZuL	eZuR	eZdL	eZdR
I	1	0	0	0	0
II	1	0.0195	0	0	0
III	1	0	0.0195	0	0
IV	1	0	0	0.0244	0
V	1	0	0	0	0.0244

*Confirmed with SHERPA+OPENLOOPS

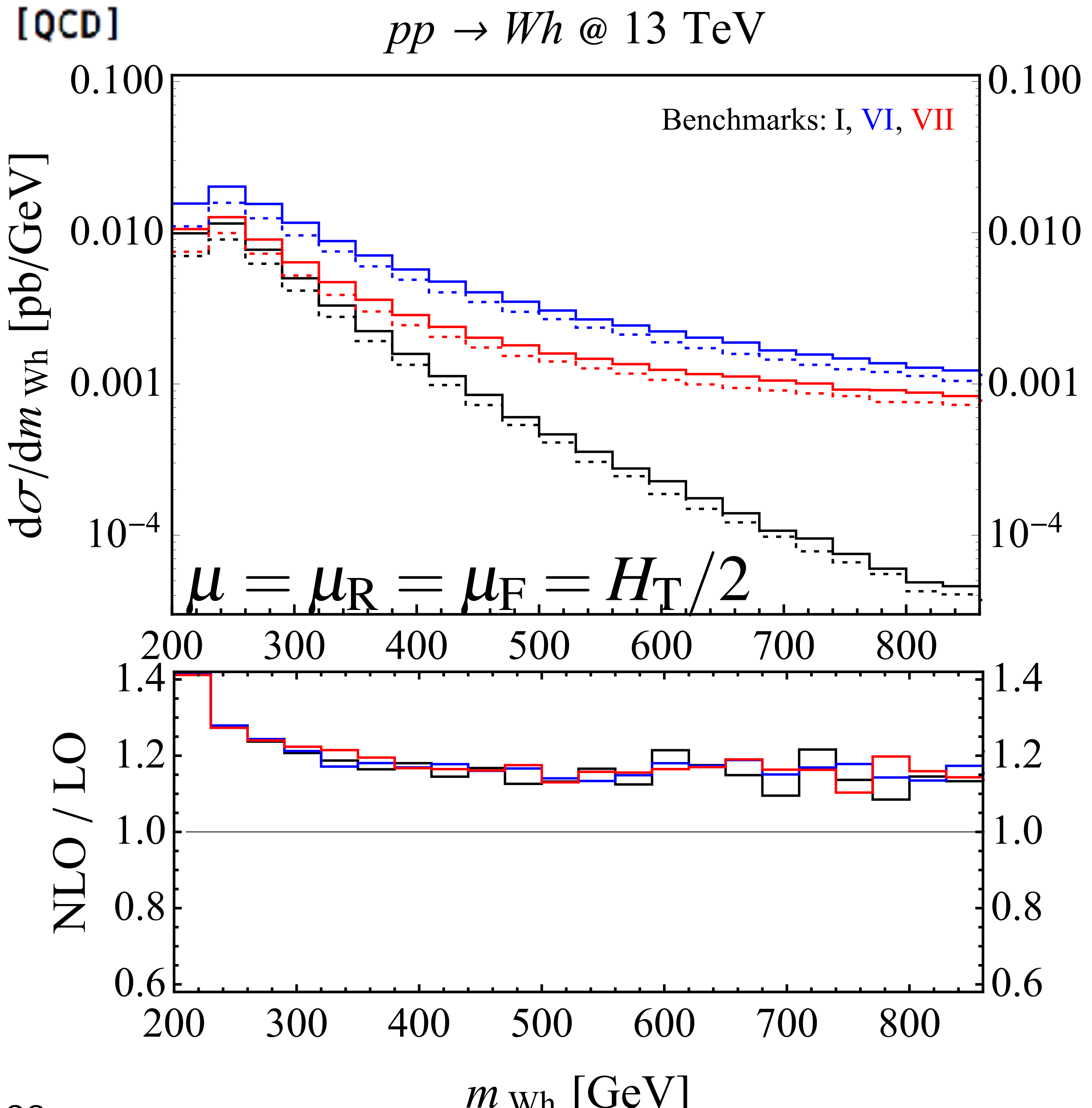


[AG, Isidori, Lindert, Marzocca]
to appear soon

$p\,p \to W\,h$ at NLO + PS

MADGRAPH5_AMC@NLO

```
import model HPO_ewk_prod_NLO
generate p p > h w+ HPO=1 QED=1 QCD=0 [QCD]
add process p p > h w- HPO=1 QED=1 QCD=0 [QCD]
output ppHWnlo
```



Benchmarks

	eWuL	phiWuL
VI	0.018	0
VII	0.018	$\frac{\pi}{2}$

*Confirmed with
SHERPA+OPENLOOPS

[AG, Isidori, Lindert, Marzocca]
to appear soon

Final remarks

- ***HiggsPO***: Event generator for Higgs **P**seudo-**O**bservables (**PO**) framework

- Publicly available at:
  http://www.physik.uzh.ch/data/HiggsPO/
  with the instructions note.

- Higgs decays fully implemented in *Version 1.0*

- Higgs EW production available in *Version 1.1*

- Upgrade to NLO in QCD available in *Version 1.2*

New