



Event generator for Higgs pseudo-observables

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*in collaboration with David Marzocca

“WG2: Discussion of pseudo-observables for Higgs measurements”

07/07/2015

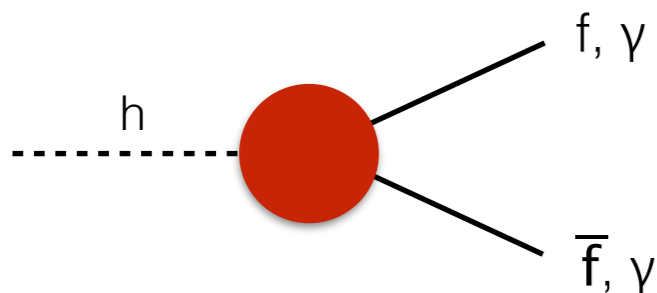
Preliminaries

- Construction of Higgs **P**seudo-**O**bservables (**PO**) in decays: [arXiv:1412.6038]
 1. h(125) is a spin 0 & zero width approximation
 - Factorisation of new physics effects in production and decay
 - *MC tool for Higgs decays*
 2. “On-shell” Higgs processes
PO defined from decomposition of “on-shell” amplitudes
 - *Straightforward relation to observable quantities $\sim |A|^2$*

HiggsPO_UFO

- Wish list for the MC tool:
 - A. **Simulate** parton level Higgs decays
 - B. **Input:** Higgs PO as (will be) defined in YR4
 - C. **Allow** for inclusion of radiative corrections (parton shower)
 - D. **Simple** to use
- Implementation:
 1. **FeynRules** [arXiv:1310.1921]
Define a set of effective interactions that reproduce a given amplitude at tree level
 2. Export **UFO** model [arXiv:1108.2040]
 3. To be used with **MadGraph** [arXiv:1405.0301] for specific processes only

Two body decays



$$\mathcal{A}[h \rightarrow \gamma(q, \epsilon)\gamma(q', \epsilon')] = i \frac{2 \epsilon_{\gamma\gamma}^{\text{SM,eff}}}{v_F} \epsilon'_\mu \epsilon_\nu [\kappa_{\gamma\gamma} (g^{\mu\nu} q \cdot q' - q^\mu q'^\nu) + \lambda_{\gamma\gamma}^{\text{CP}} \epsilon^{\mu\nu\rho\sigma} q_\rho q'_\sigma]$$

$$\mathcal{A}(h \rightarrow f\bar{f}) = -i \frac{y_{\text{eff}}^{f,\text{SM}}}{\sqrt{2}} \bar{f} (\kappa_f + i \lambda_f^{\text{CP}} \gamma_5) f$$

```
#####
## INFORMATION FOR HPO2F
#####
Block hpo2f
  1 1.000000e+00 # kb
  2 1.000000e+00 # kc
  3 1.000000e+00 # ktau
  4 1.000000e+00 # kmu
 11 0.000000e+00 # lb
 12 0.000000e+00 # lc
 13 0.000000e+00 # ltau
 14 0.000000e+00 # lmu

#####
## INFORMATION FOR HPOSM
#####
Block hposm
  1 3.800000e-03 # eAASM
  2 6.900000e-03 # eZASM
  3 1.770000e-02 # ybeff
  4 3.980000e-03 # yceff
  5 1.020000e-02 # ytaueff
  6 5.990000e-04 # ymueff
```

param_card.dat

- **HPOSM recover best up-to-date SM prediction**

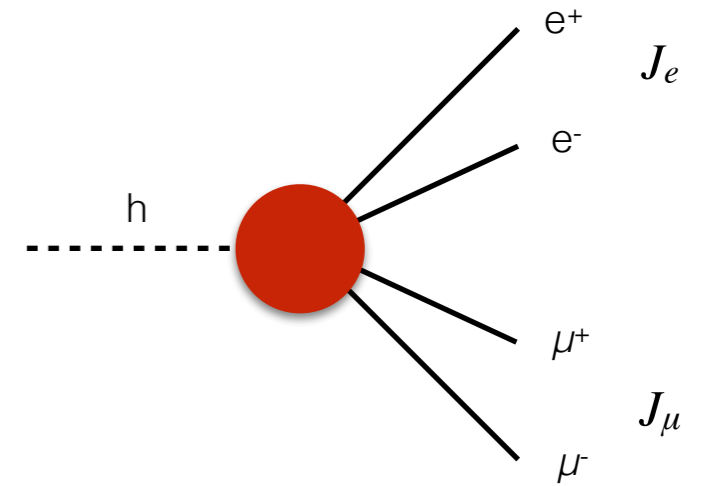
	$\bar{b}b$	$\bar{\tau}\tau$
$\text{Br}(h \rightarrow f\bar{f})$	5.77×10^{-1}	6.32×10^{-2}
$ y_{\text{eff}}^{f,\text{SM}} $	1.77×10^{-2}	1.02×10^{-2}
	$\bar{c}c$	$\bar{\mu}\mu$
$\text{Br}(h \rightarrow f\bar{f})$	2.91×10^{-2}	2.19×10^{-4}
$ y_{\text{eff}}^{f,\text{SM}} $	3.98×10^{-3}	5.99×10^{-4}
	$\gamma\gamma$	$Z\gamma$
$\text{Br}(h \rightarrow VV)$	2.28×10^{-3}	1.54×10^{-3}
$\epsilon_{VV}^{\text{SM,eff}}$	3.8×10^{-3}	6.9×10^{-3}

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR>

Four body decays: Example $h \rightarrow 2e2\mu$

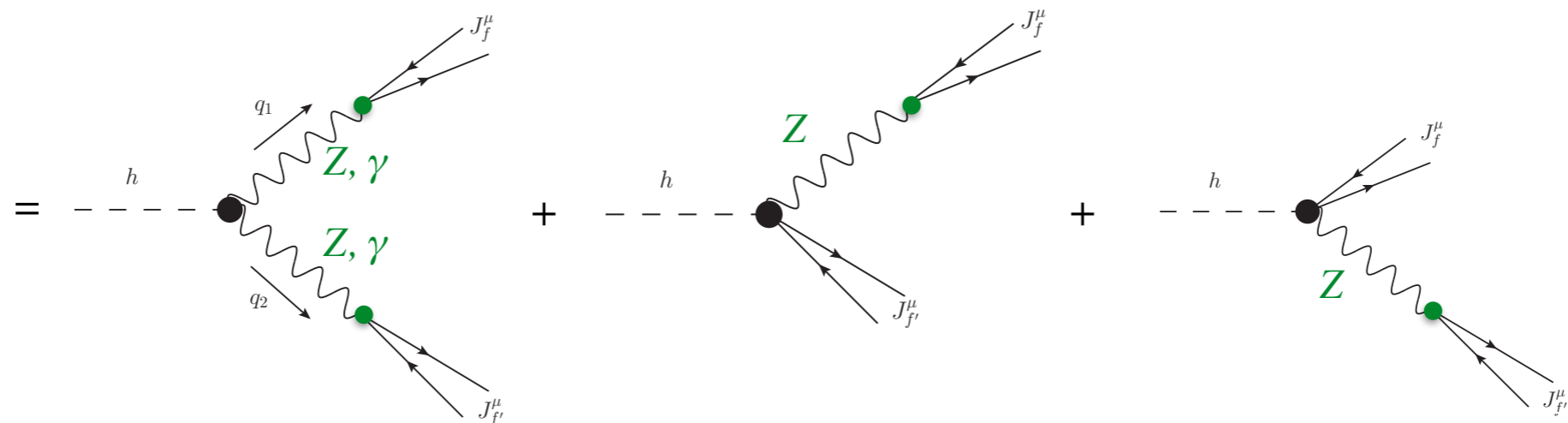
Decomposition of the (**helicity conserving**) amplitude:

$$A = i \frac{2m_Z^2}{v_F} \sum_{e=e_L, e_R} \sum_{\mu=\mu_L, \mu_R} (\bar{e} \gamma_\alpha e) (\bar{\mu} \gamma_\beta \mu) \times \left[F_1^{e\mu}(q_1^2, q_2^2) g^{\alpha\beta} + F_3^{e\mu}(q_1^2, q_2^2) \frac{q_1 \cdot q_2 g^{\alpha\beta} - q_2^\alpha q_1^\beta}{m_Z^2} + F_4^{e\mu}(q_1^2, q_2^2) \frac{\varepsilon^{\alpha\beta\rho\sigma} q_{2\rho} q_{1\sigma}}{m_Z^2} \right]$$

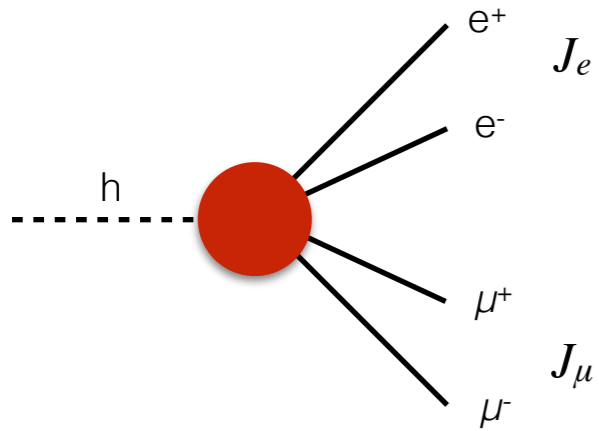


Momentum expansion of the form factors around the physical poles:


- Notion of an underlying Effective Field Theory (EFT) - smooth kinematical distortions from the SM.



Four body decays: Example $h \rightarrow 2e2\mu$



$$\mathcal{A} = i \frac{2m_Z^2}{v_F} \sum_{e=e_L, e_R} \sum_{\mu=\mu_L, \mu_R} (\bar{e} \gamma_\alpha e) (\bar{\mu} \gamma_\beta \mu) \times \left[F_1^{e\mu}(q_1^2, q_2^2) g^{\alpha\beta} + F_3^{e\mu}(q_1^2, q_2^2) \frac{q_1 \cdot q_2 g^{\alpha\beta} - q_2^\alpha q_1^\beta}{m_Z^2} + F_4^{e\mu}(q_1^2, q_2^2) \frac{\epsilon^{\alpha\beta\rho\sigma} q_{2\rho} q_{1\sigma}}{m_Z^2} \right]$$

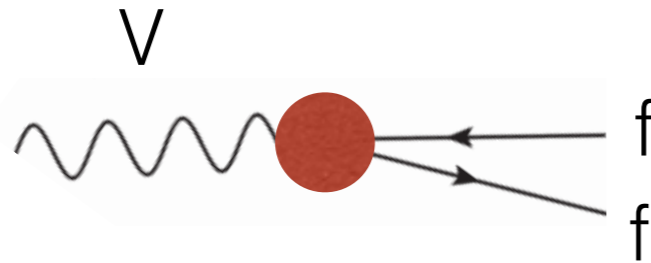

 Momentum expansion

$$\mathcal{A} = i \frac{2m_Z^2}{v_F} \sum_{e=e_L, e_R} \sum_{\mu=\mu_L, \mu_R} (\bar{e} \gamma_\alpha e) (\bar{\mu} \gamma_\beta \mu) \times \left[\left(\kappa_{ZZ} \frac{g_Z^e g_Z^\mu}{P_Z(q_1^2) P_Z(q_2^2)} + \frac{\epsilon_{Ze} g_Z^\mu}{m_Z^2 P_Z(q_2^2)} + \frac{\epsilon_{Z\mu} g_Z^e}{m_Z^2 P_Z(q_1^2)} \right) g^{\alpha\beta} + \left(\epsilon_{ZZ} \frac{g_Z^e g_Z^\mu}{P_Z(q_1^2) P_Z(q_2^2)} + \kappa_{Z\gamma} \epsilon_{Z\gamma}^{\text{SM-1L}} \left(\frac{e Q_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{e Q_e g_Z^\mu}{q_1^2 P_Z(q_2^2)} \right) + \kappa_{\gamma\gamma} \epsilon_{\gamma\gamma}^{\text{SM-1L}} \frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2} \right) \frac{q_1 \cdot q_2 g^{\alpha\beta} - q_2^\alpha q_1^\beta}{m_Z^2} + \left(\epsilon_{ZZ}^{\text{CP}} \frac{g_Z^e g_Z^\mu}{P_Z(q_1^2) P_Z(q_2^2)} + \epsilon_{Z\gamma}^{\text{CP}} \left(\frac{e Q_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{e Q_e g_Z^\mu}{q_1^2 P_Z(q_2^2)} \right) + \epsilon_{\gamma\gamma}^{\text{CP}} \frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2} \right) \frac{\epsilon^{\alpha\beta\rho\sigma} q_{2\rho} q_{1\sigma}}{m_Z^2} \right]$$

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

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

W and Z boson PO



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

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  
  
param_card.dat
```

Parameter counting

Consider decays: $h \rightarrow WW^*$, $h \rightarrow ZZ^*$, $h \rightarrow Z\gamma$, $h \rightarrow \gamma\gamma$

Neutral currents

$$h \rightarrow e^+e^-\mu^+\mu^-$$

$$h \rightarrow \mu^+\mu^-\mu^+\mu^-$$

$$h \rightarrow e^+e^-e^+e^-$$

$$h \rightarrow \gamma e^+e^-$$

$$h \rightarrow \gamma\mu^+\mu^-$$

$$h \rightarrow \gamma\gamma$$

11

Charged currents

$$h \rightarrow e^+\mu^- \nu\nu$$

$$h \rightarrow e^-\mu^+ \nu\nu$$

7

N. & C. interference

$$h \rightarrow e^+e^- \nu\nu$$

$$h \rightarrow \mu^-\mu^+ \nu\nu$$

2

```
#####  
## INFORMATION FOR HP04F  
#####  
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
```

- Compared to only 4 parameter in the present “kappa” formalism

Example: $h \rightarrow 2e2\mu$

MadGraph5_aMC@NLO

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

or

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

Analytic calculation

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

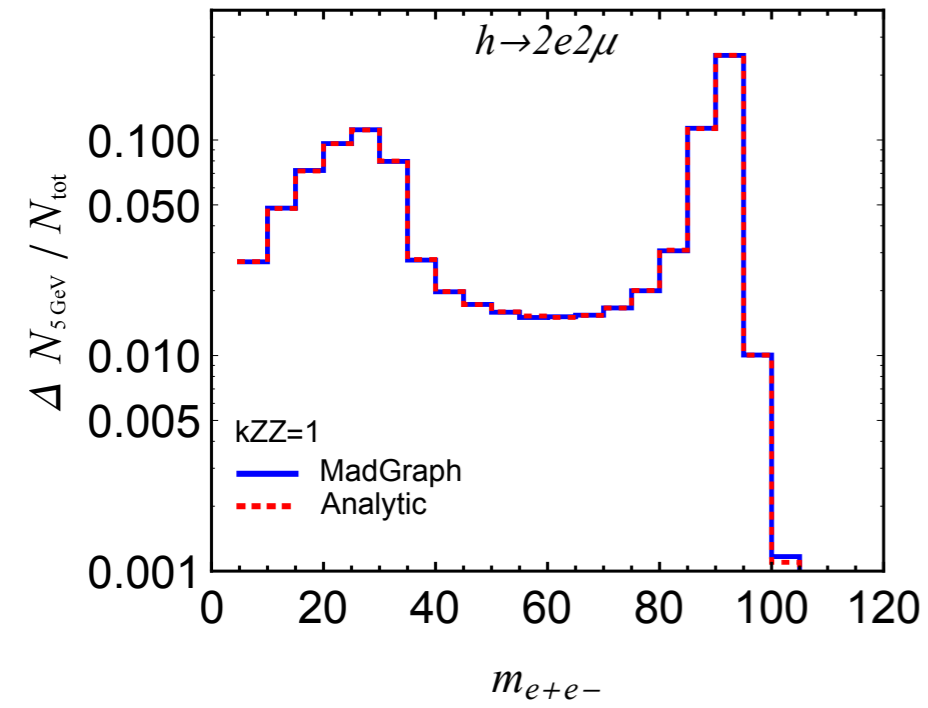
$$\begin{aligned} \sum_s \mathcal{A}\mathcal{A}^* &= \left(\frac{2m_Z^2}{v_F} \right)^2 \sum_{f,f'} \text{tr}(\not{p}_1 \gamma_\mu P^f \not{p}_2 \gamma_{\mu_1}) \\ &\quad \times \text{tr}(\not{p}_3 \gamma_\nu P^{f'} \not{p}_4 \gamma_{\nu_1}) \\ &\quad \times T_{ff'}^{\mu\nu}(q_1, q_2) T_{ff'}^{\mu_1\nu_1*}(q_1, q_2), \end{aligned}$$

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

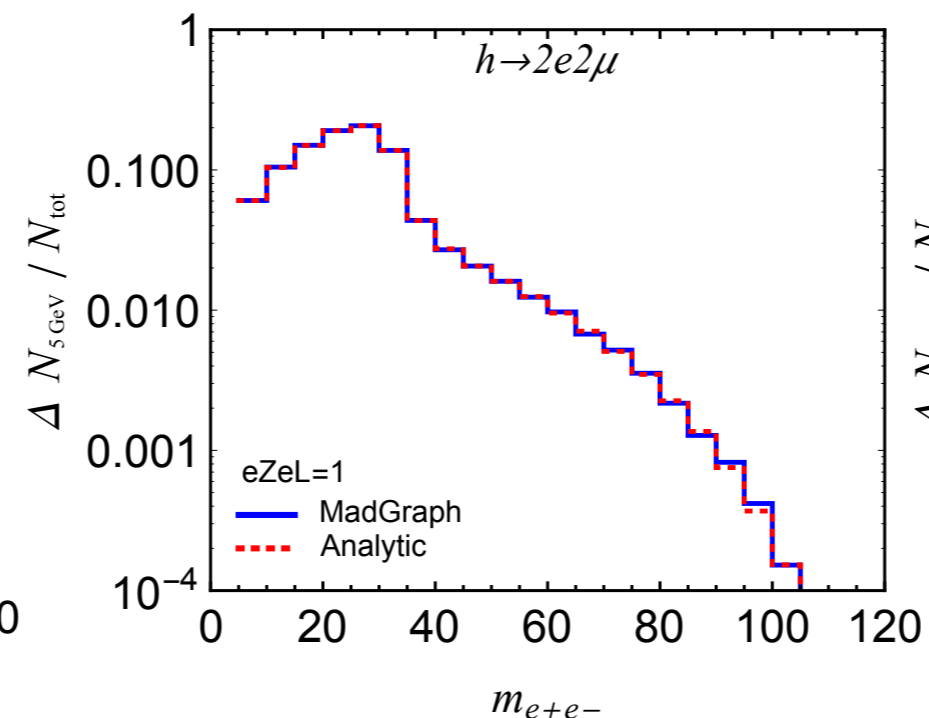
- Benchmark (a): $\kappa_{ZZ} = 1$ and all other Higgs PO zero. The decay width in MadGraph: $2.3241(7) \times 10^{-7} \text{ GeV}$ and analytic: $2.3232 \times 10^{-7} \text{ GeV}$. See Fig 1 (a).
- Benchmark (b): $\epsilon_{ZeL} = 1$ and all other Higgs PO zero. The decay width in MadGraph: $1.4919(5)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

Example: $h \rightarrow 2e2\mu$

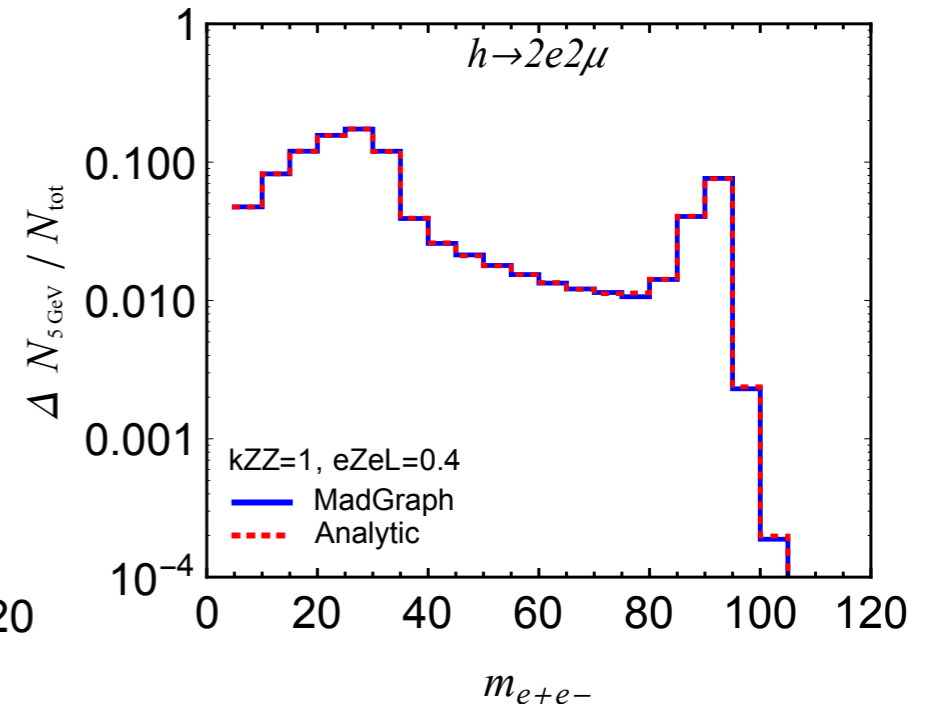
(a)



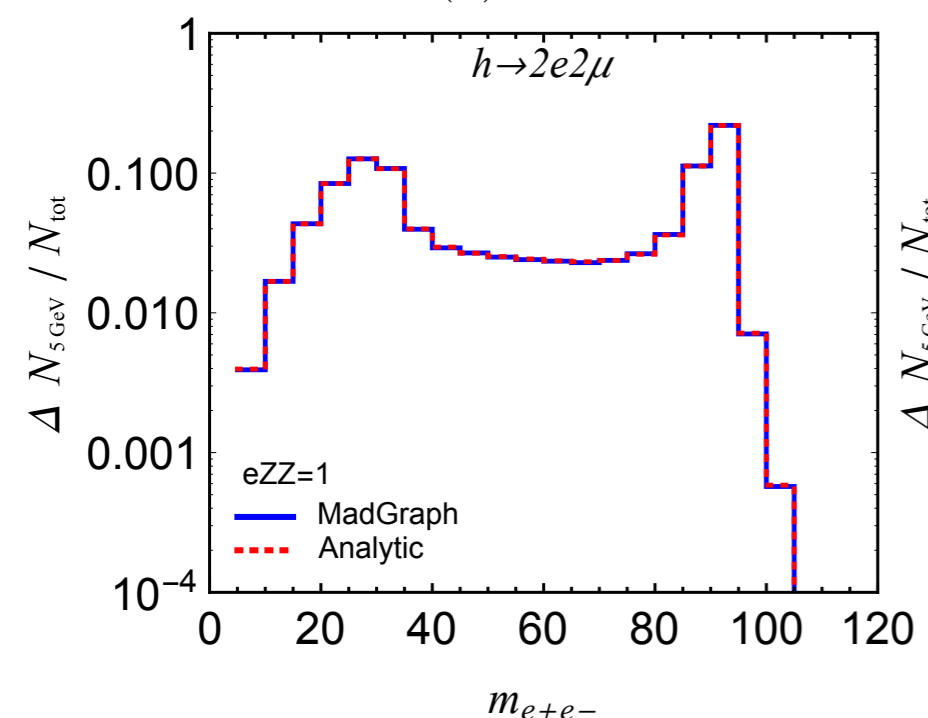
(b)



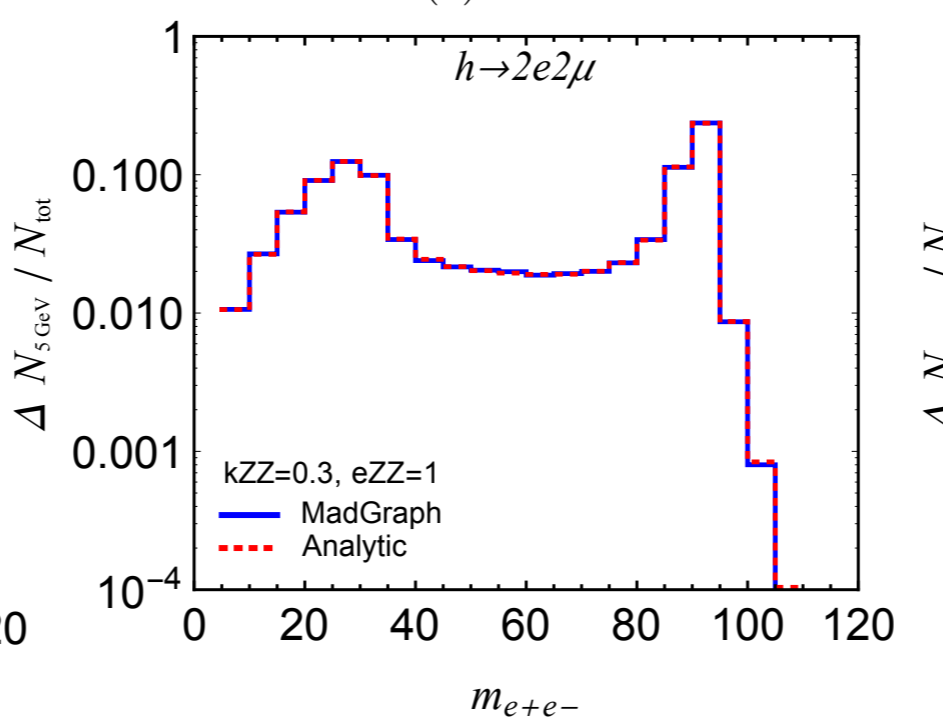
(c)



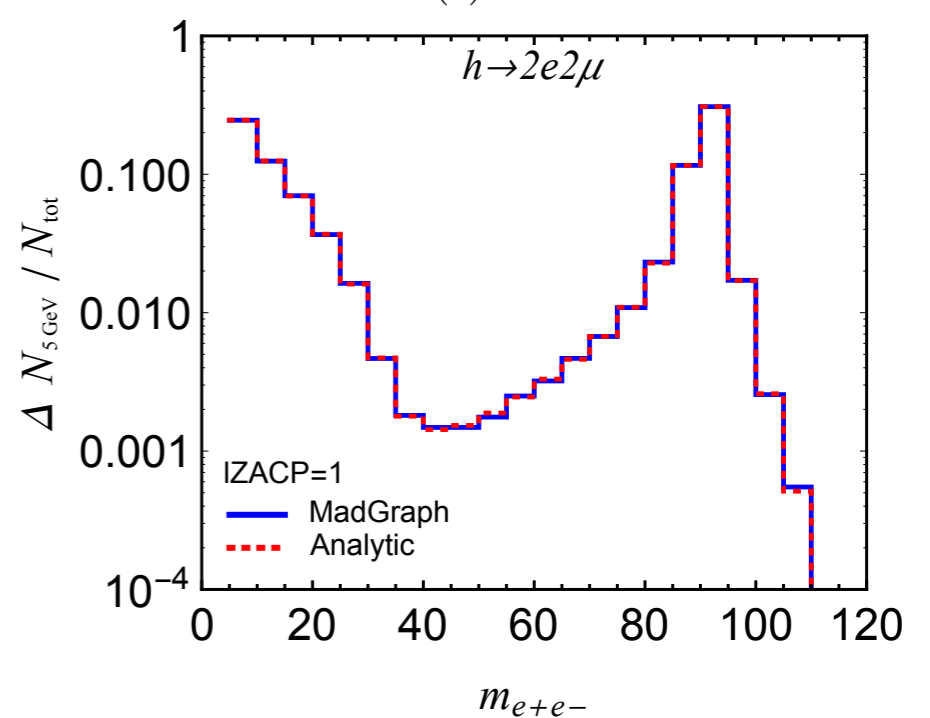
(d)



(e)



(f)



Final remarks

- We presented the MC tool for Higgs **P**seudo-**O**bservables (**PO**) in decays
- Publicly available at:
<http://www.physik.uzh.ch/data/HiggsPO/>
with the instructions note.
- Suggestions and comments welcome