Higgs pair production with EFT Modeling at NLO

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Karlsruher Institut für Technologie (KIT)

LHC-HH Subgroup Meeting

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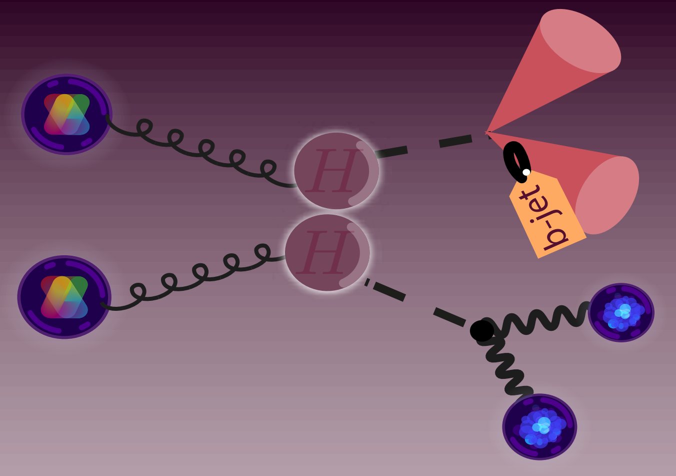
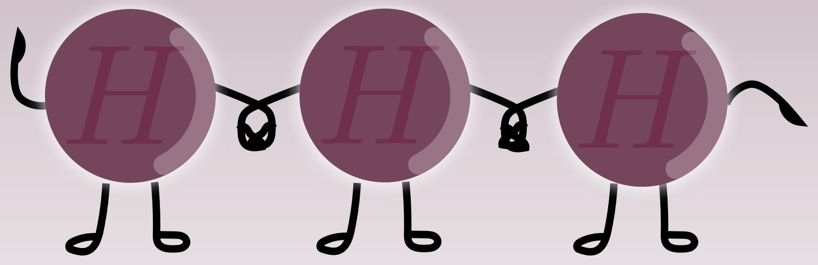
Why looking for Higgs pairs ?



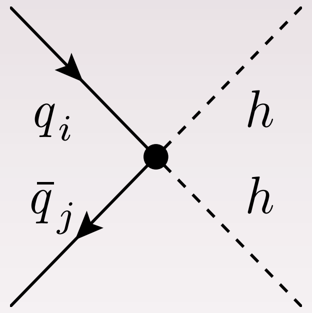
- The natural " next-step" after finding the Higgs.

- Essential for probing the trilinear coupling.



S. Di Vita, et al (2017)

- Provides a direct measurement of Higgs coupling to light quarks



[L.A, R. Corral Lopez and R Gröber '19]

- Sensitive to non-linearity in couplings with the Higgs

- Probe some of the Higgs EFT operators

Could we save computational power by reweighting SM MC samples to become EFT ones ?

Both ATLAS and CMS are now trying to implement the reweighting procedure

HH production in Effective Field Theories

There are 2- famous- EFT's for the Higgs pair process

- Higgs Effective Field Theory - non-linear- a.k.a. Chiral Lagrangian [Ionso et al '12 and Buchalla et al '13]

$$\mathcal{L}_{\rm HEFT} = -m_t \left(c_t \frac{h}{v} + c_{tt} \frac{h^2}{v^2} \right) (\bar{t}_R t_L + h.c.) - c_{hhh} \frac{m_h^2}{2v^2} h^3 + \frac{\alpha_s}{8\pi} \left(c_{ggh} \frac{h}{v} + c_{gghh} \frac{h^2}{v^2} \right) {\rm tr}(G_{\mu\nu} G^{\mu\nu})$$

- SM Effective Field Theory, strongly interacting light Higgs (SILH) basis [R. Contino, et al.'13]

$$\mathcal{L}_{\rm SILH} = \frac{\bar{c}_H}{2v^2} \partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H) - \frac{\bar{c}_6 \lambda}{v^2} (H^\dagger H)^3 + \left(\frac{\bar{c}_u}{v^2} y_u H^\dagger H \bar{q}_L H^c t_R + h.c. \right) + \frac{\bar{c}_g g_s^2}{m_W^2} H^\dagger H {\rm tr}(G_{\mu\nu} G^{\mu\nu})$$

- SM Effective Field Theory, Warsaw basis [B. Grzadkowski, et al.'10]

$$\begin{aligned}\mathcal{L}_{\rm SMEFT} = & \, C_{H,\Box} (H^\dagger H) \Box (H^\dagger H) + C_{H\,D} |(H^\dagger D_\mu H)|^2 + C_H (H^\dagger H)^3 + C_{uH} \left(H^\dagger H \bar{q}_L H^c t_R + h.c. \right) \\ & + C_{HG} H^\dagger H {\rm tr}(G_{\mu\nu} G^{\mu\nu})\end{aligned}$$

SILH and Warsaw are the same except for the choice of which operators are removed by E.o.M !

ATLAS

by

C. Dimitriadi, L. Pereira Sanchez and A. Ferrari

Reweighting in HEFT

- The weights for the total, and differential cross sections are available for LO and NLO [G. Heinrich, et al. '17] [G. Heinrich, et al. '20]

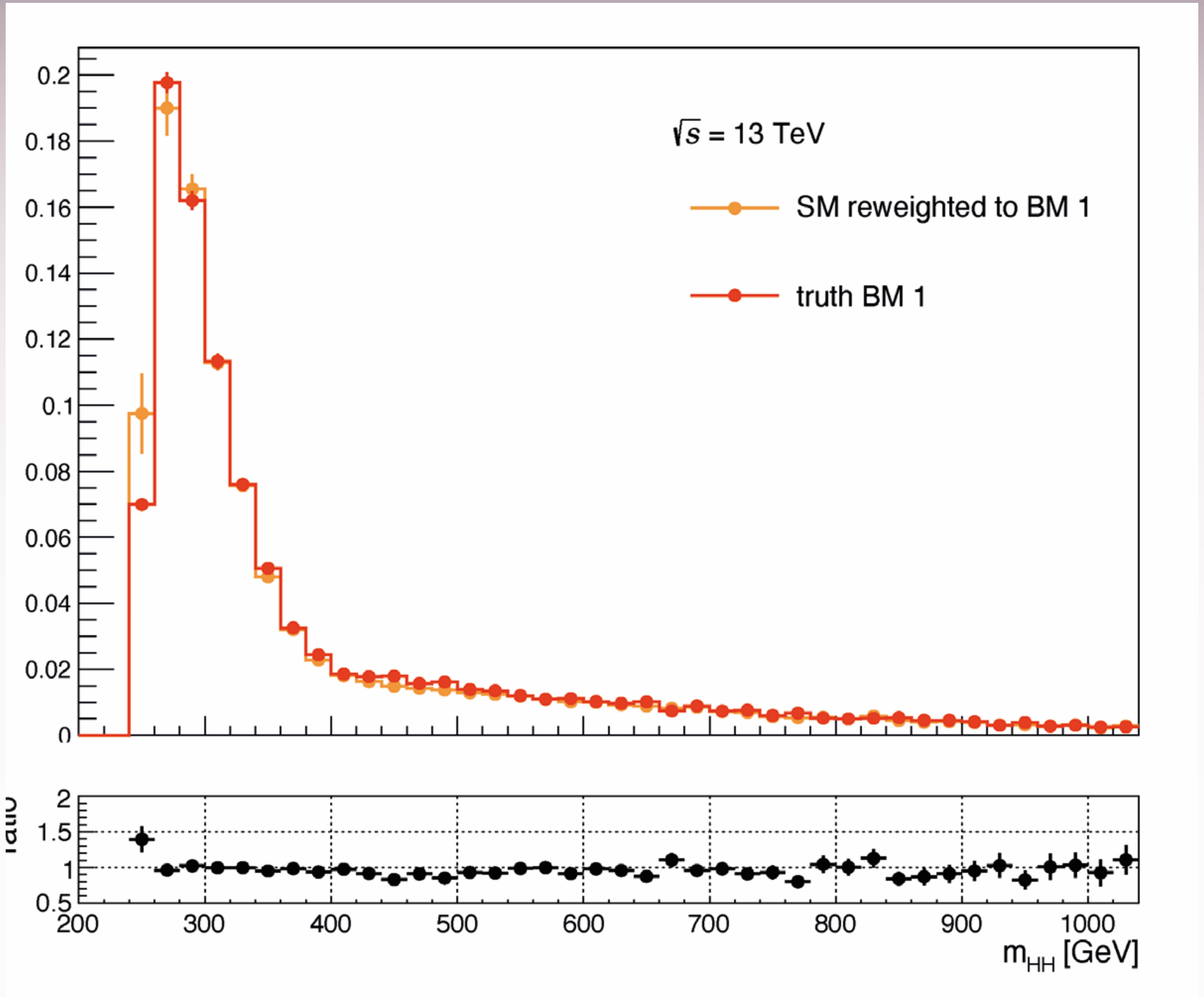
- Reweighting of M_{hh} distributions were done for 7 benchmarks as a cross-check.

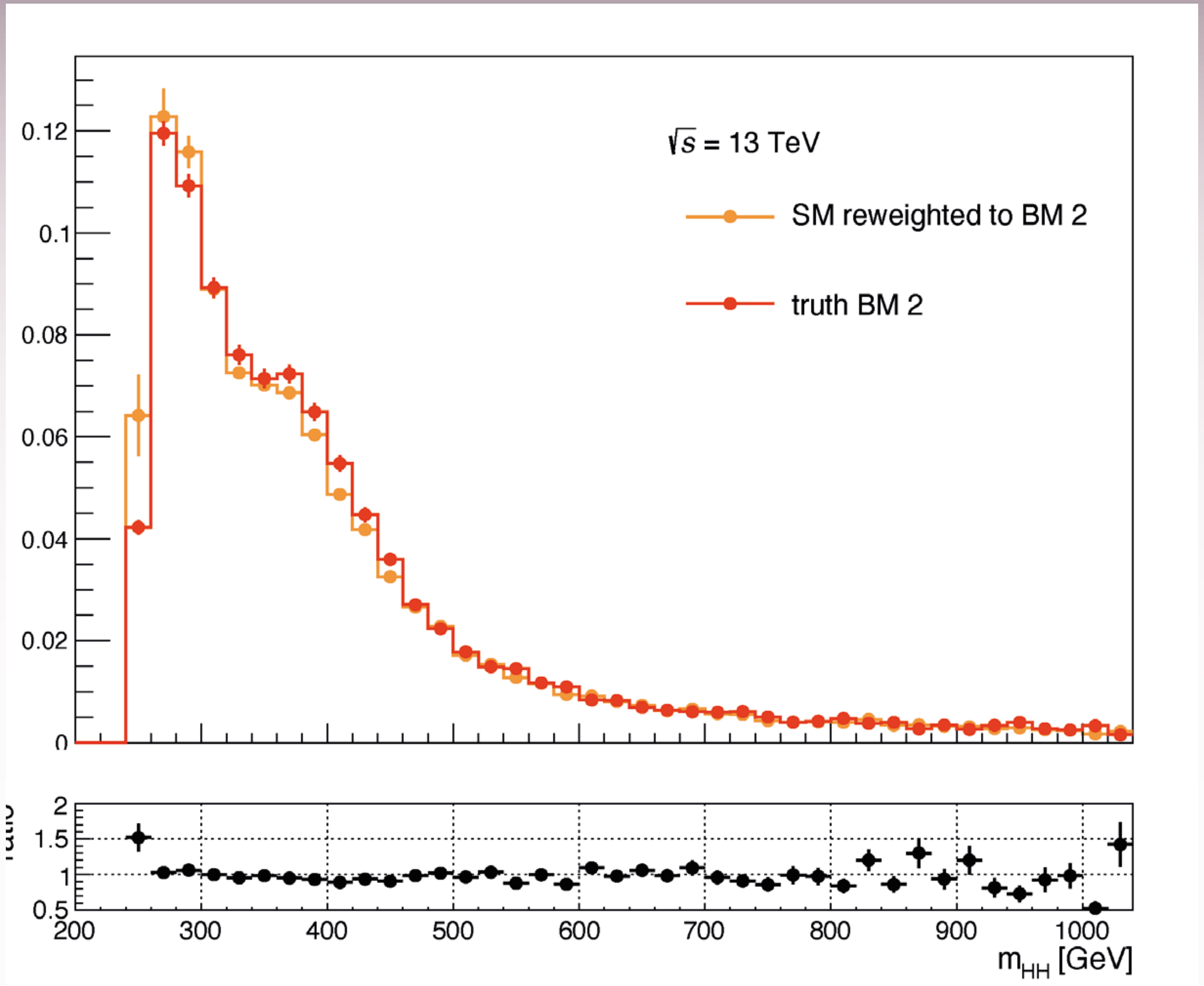
benchmark	ct	chhh	ctt	cggh	cgghh
SM	1	1	0	0	0
1	0.94	3.94	-0.333	0.5	0.333
2	0.61	6.84	0.333	0	-0.333
3	1.05	2.21	-0.333	0.5	0.5
4	0.61	2.79	0.333	-0.5	0.167
5	1.17	3.95	-0.333	0.167	-0.5
6	0.83	5.68	0.333	-0.5	0.333
7	0.94	-0.10	1	0.167	-0.167

Weights are given by an analytic parametrisation

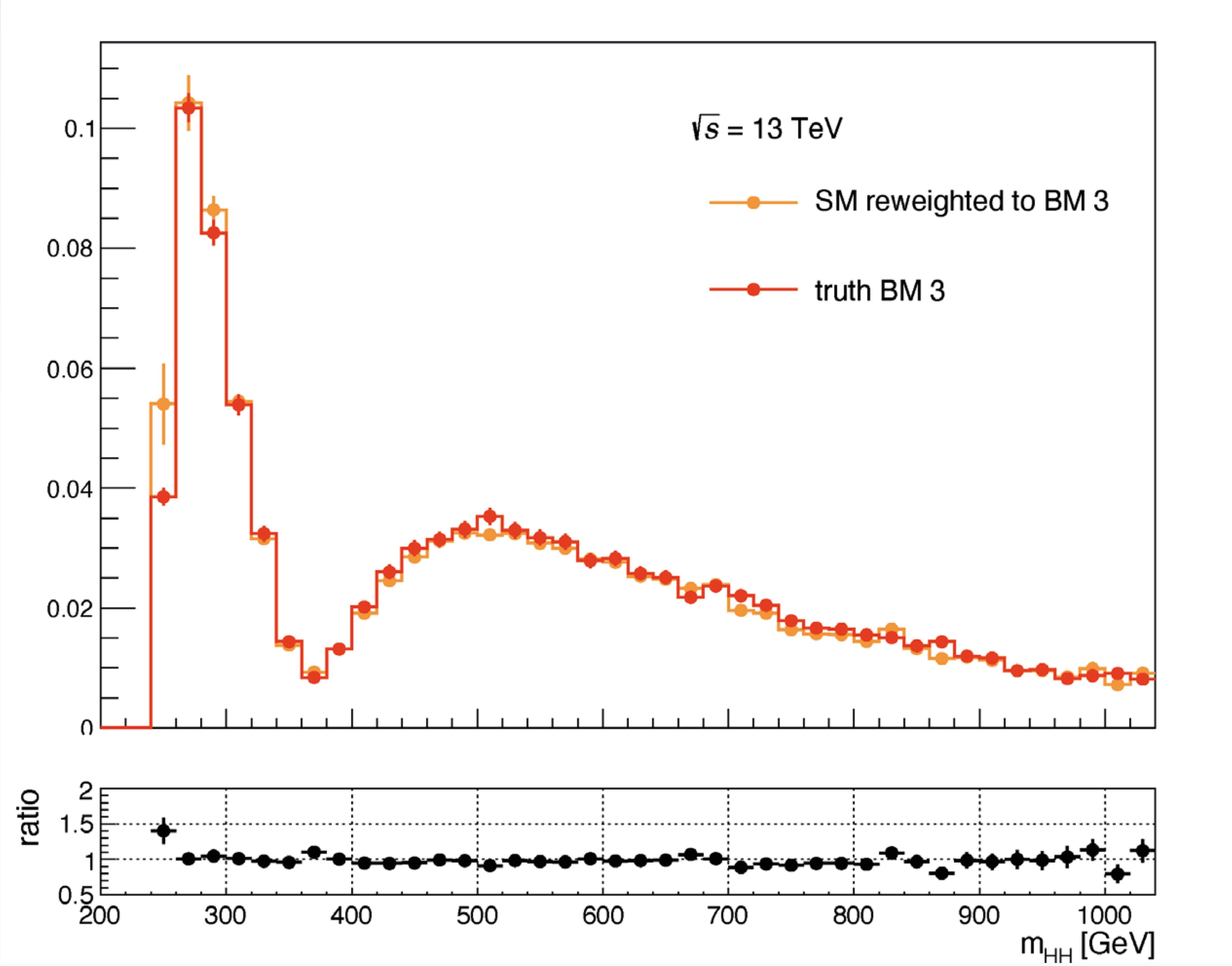
$$\frac{d\sigma}{dM_{hh}} \Big/ \frac{d\sigma^{SM}}{dM_{hh}} = \sum_i A_i c_i$$

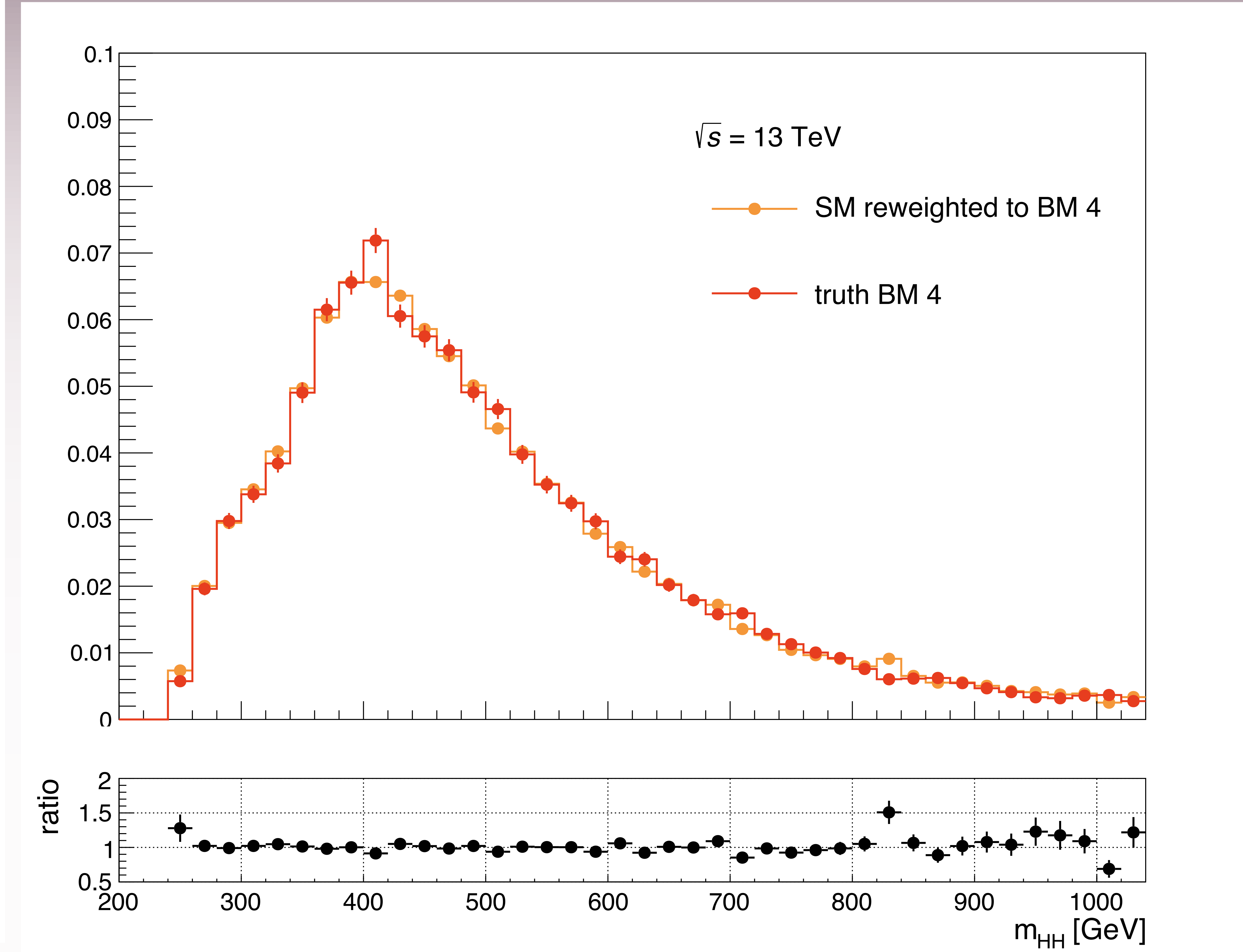
Reweighting validation @ NLO



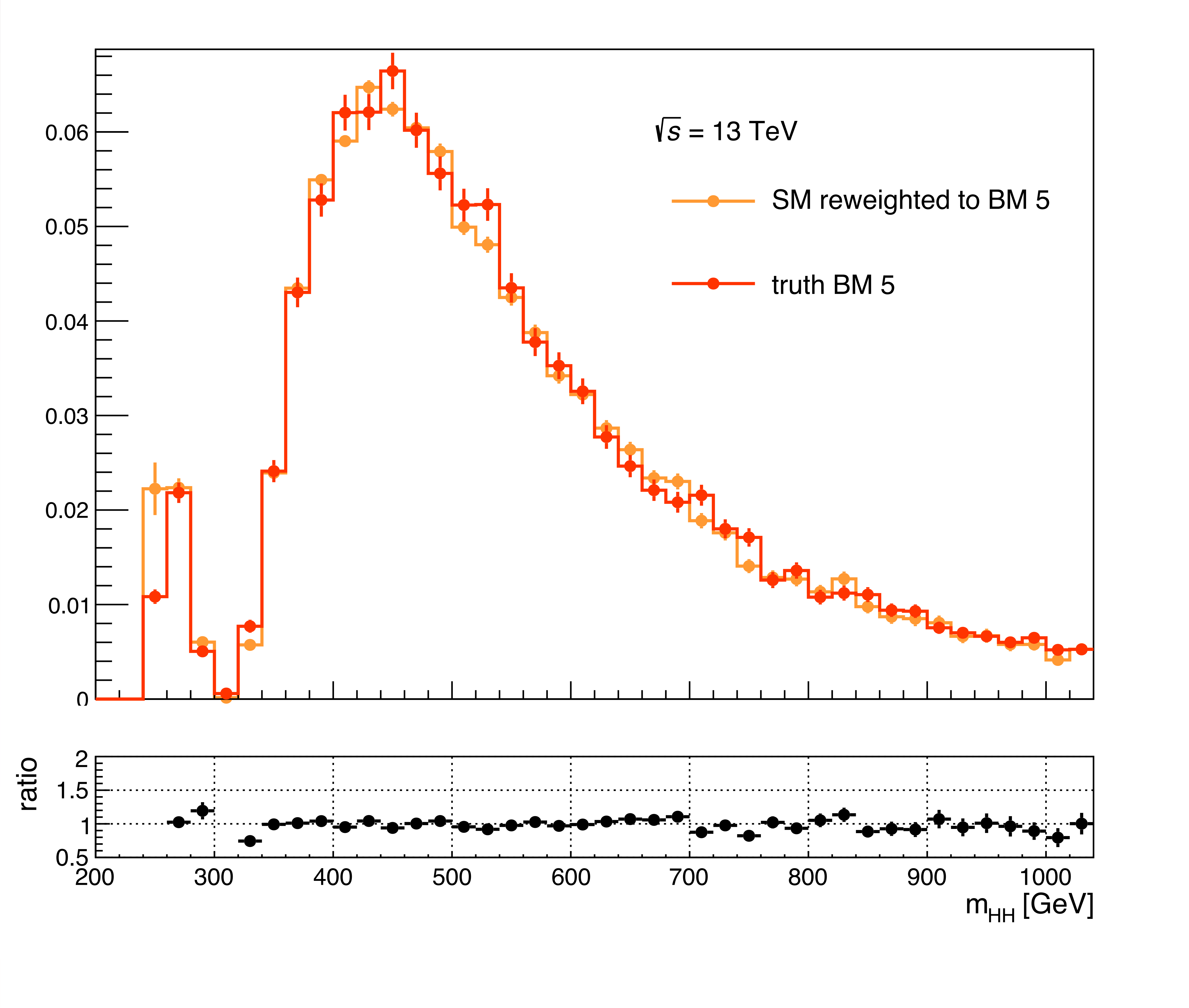


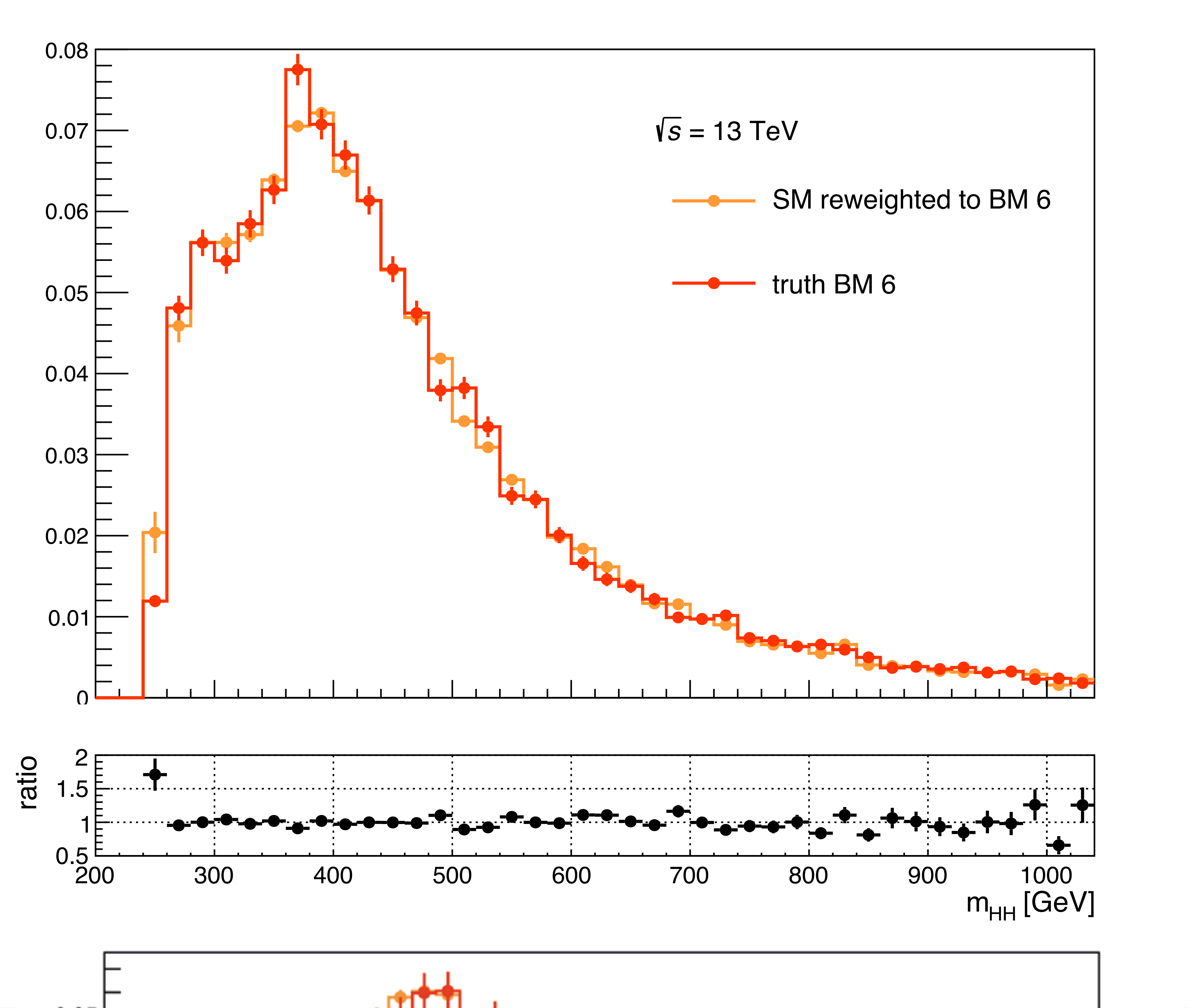
Reweighting validation @ NLO

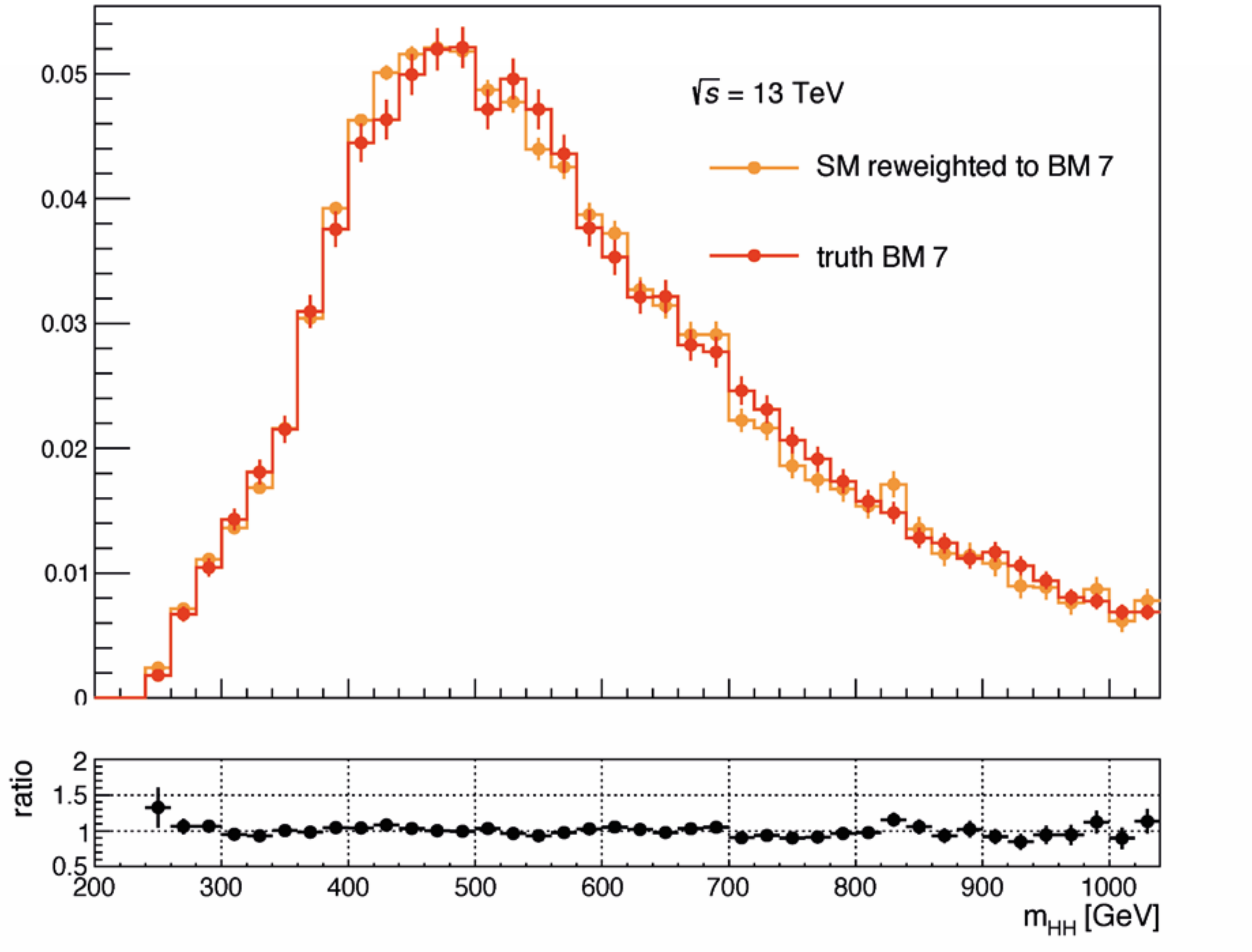




Reweighting validation @ NLO







CMS

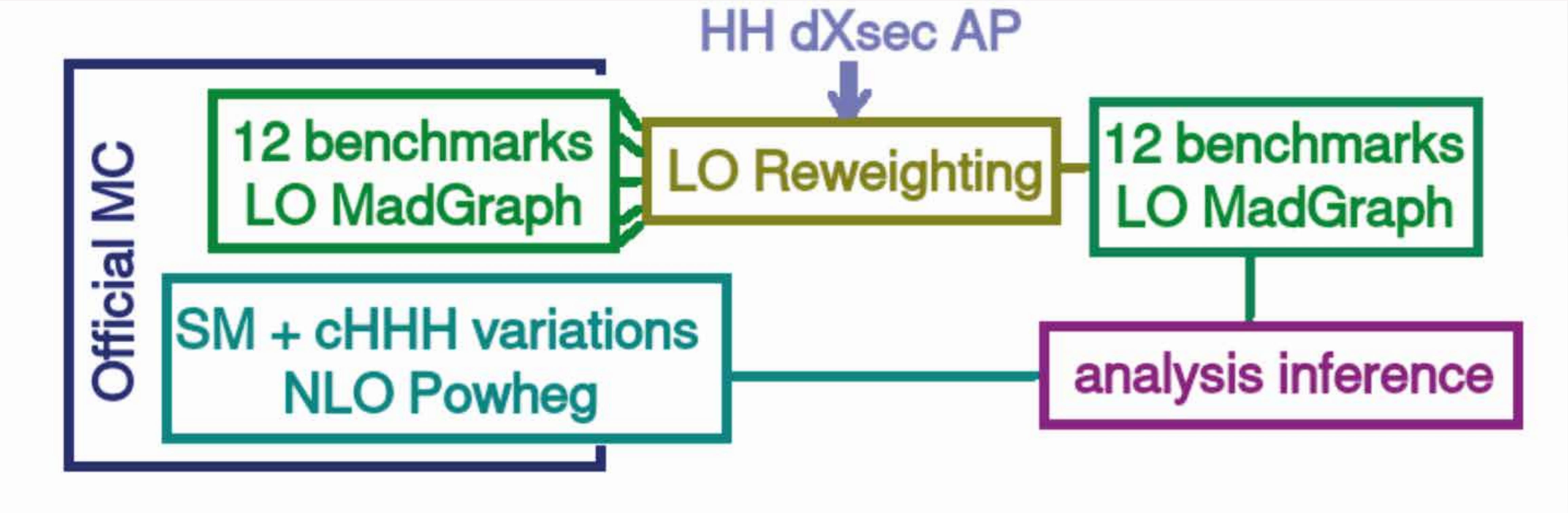
by
P. Mandrik and S. Slabospitskii

Typical CMS non-resonant ggF HH workflow

at the moment :

- Official MC for representative benchmarks in MadGraph at LO only

- Powheg NLO generator and analytical parametrisation (AP) of ggF HH of differential cross section are available



Can we incorporate NLO reweighting of LO MadGraph/NLOPowheg samples into ongoing analyses and how will it work?

Input

Samples produced privately for SM + 12 EFT benchmarks + extra benchmarks (43 EFT points in total):

- Madgraph LO MC private samples, input configuration cards

  https://github.com/pmandrik/HH_pair/tree/master/generation

- Powheg LO MC private samples, 100K events, generated at full theory, User-Processes-V2/ggHH, input configuration cards (13 TeV)

  https://github.com/pmandrik/HH_pair/tree/master/generation

- Powheg NLO MC private samples, up to 100K events, generated at full theory, User-Processes-V2/ggHH, input configuration cards (13 TeV):

  https://github.com/pmandrik/HH_pair/tree/master/generation

- Analytical parameterization of $\frac{d\sigma}{dM_{hh}}$

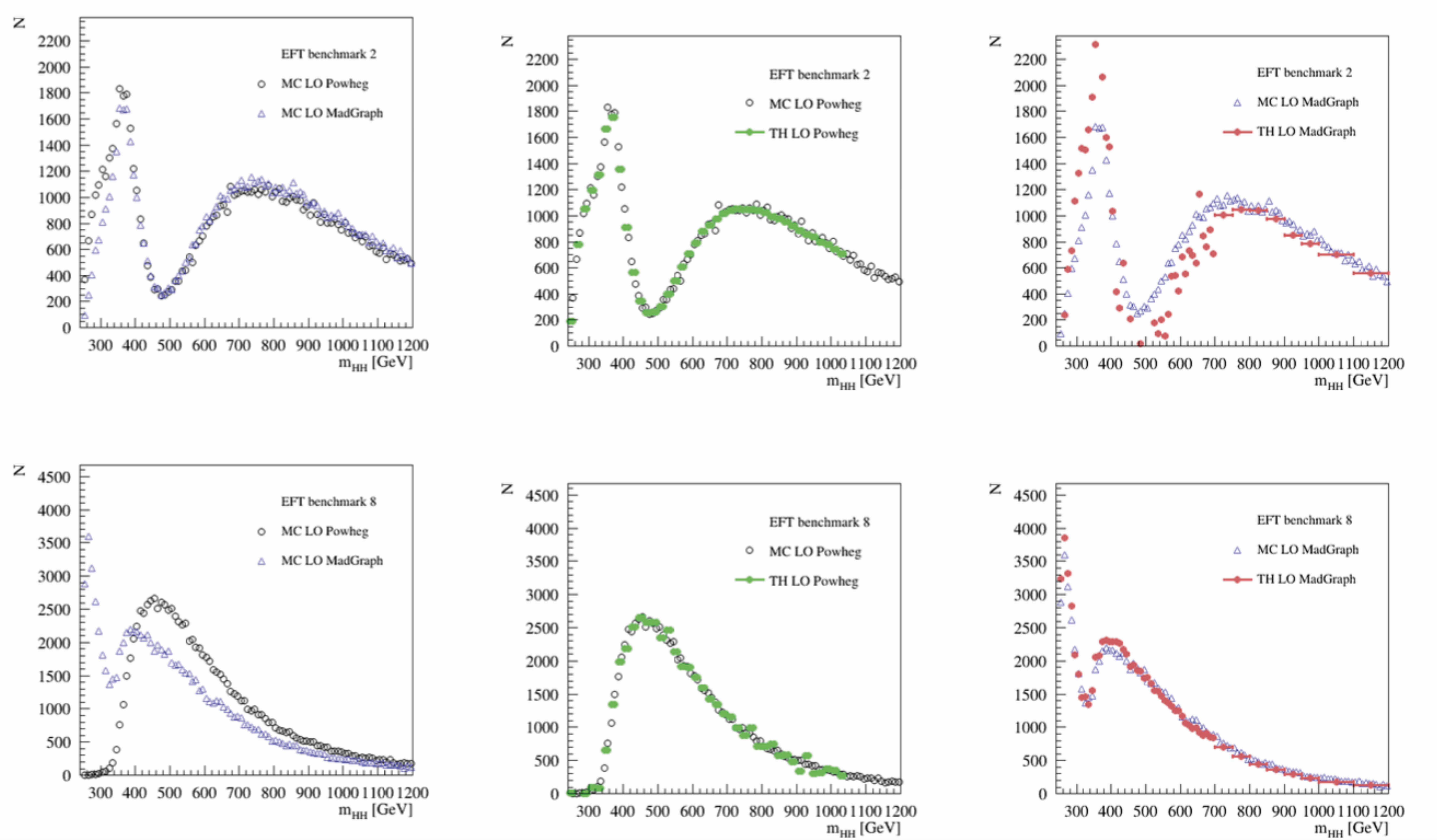
at LO (Madgraph & Powheg based) [A. Carvalho et al '15] MG and [G.Buchalla et al ´18] Powheg

at NLO (Powheg based) [G.Buchalla et al ´18]

Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1	1
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1	-1
12	15.0	1.0	1.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0

C + + implementation of the prediction from analytical parametrisations is available in https://github.com/pmandrik/VSEVA/blob/master/HHWWgg/reweight/reweight_HH.C

M_{hh}@LO


EFT benchmark 2
MC LO Powheg
MC LO MadGraph
TH LO Powheg
TH LO MadGraph
EFT benchmark 8
N
m_{HH} [GeV]

Intermediate conclusions

- Good Powheg/MadGraph and MC/AP agreement for most of the benchmark, but BM-8 for MadGraph vs Powheg and BM-2 for MG vs AP

- CMS official MC samples generated using MadGraph & NLO k-factors from Powheg
Then reweight to take differences in generators/models prediction

(MadGraph LO) → (Powheg LO) → (Powheg NLO)

- Analytical parameterization from MadGraph is defined for LO only

- Analytical parameterization from Powheg is defined up to $M_{hh} < 1040\,\mathrm{GeV}$ and does not take into account dependence on $\cos\theta^*$

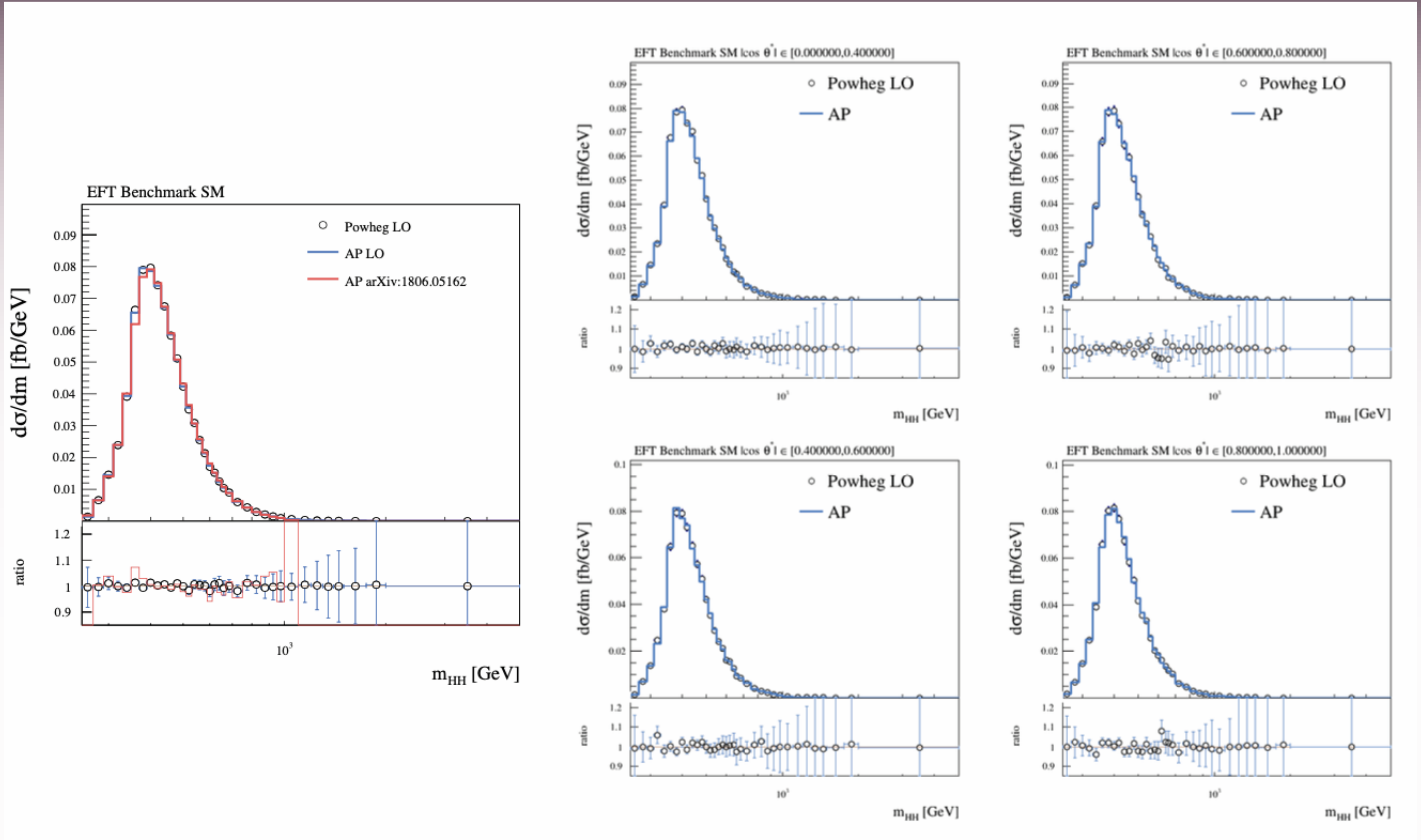
Solution:

- Derive custom A_* coefficients using private MC (35/9 benchmarks for fit/validation with $\approx 10^6$ events) for analytical parameterization:

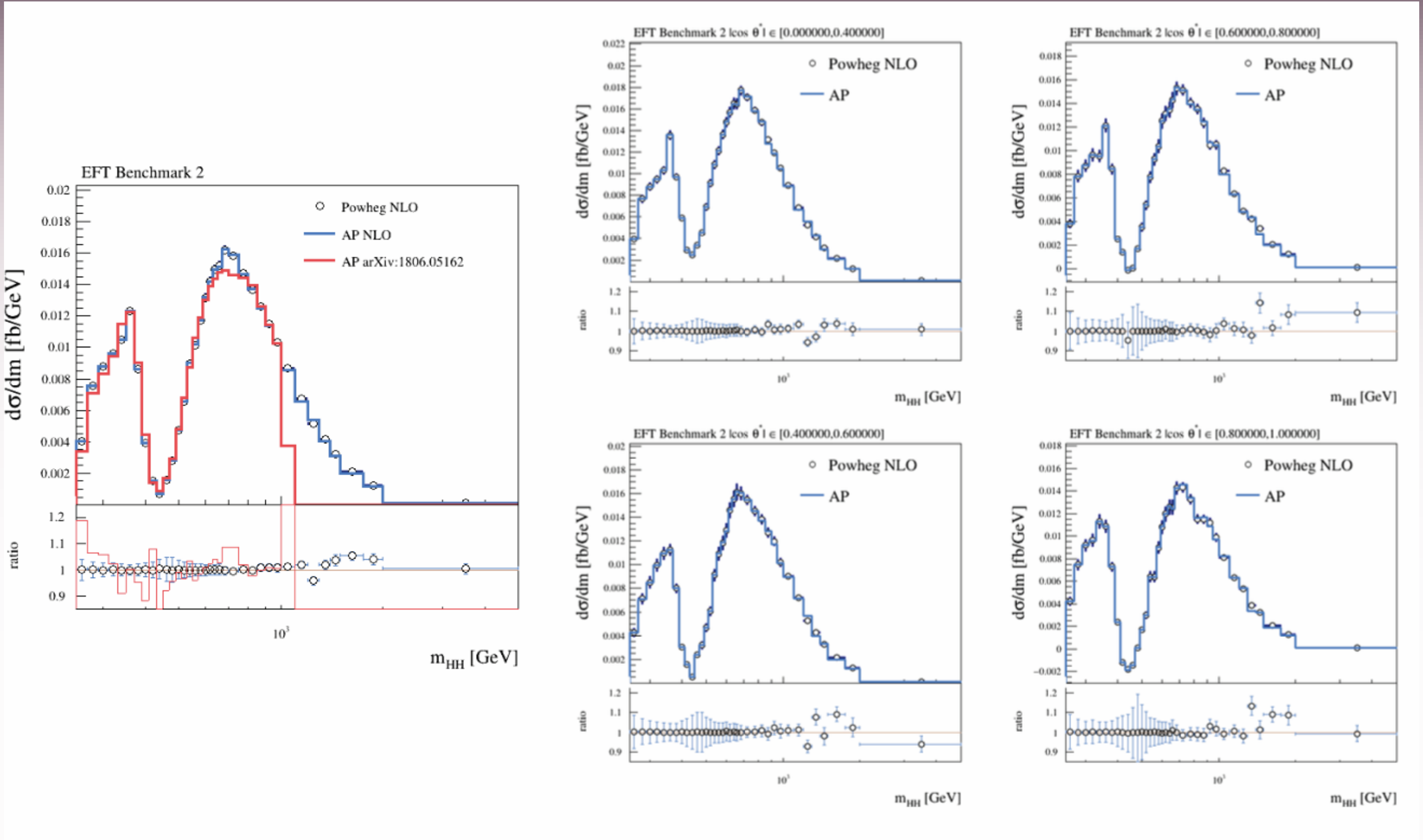
$$\frac{d\sigma}{dM_{hh}d|\cos\theta^*|} = \sum A_i(M_{hh}, |\cos\theta^*|)c_i$$

- To extract the $A_i(M_{hh}, |\cos\theta^*|)$ coefficients the system of equations is solved by performing a minimisation in ROOT MINUIT.

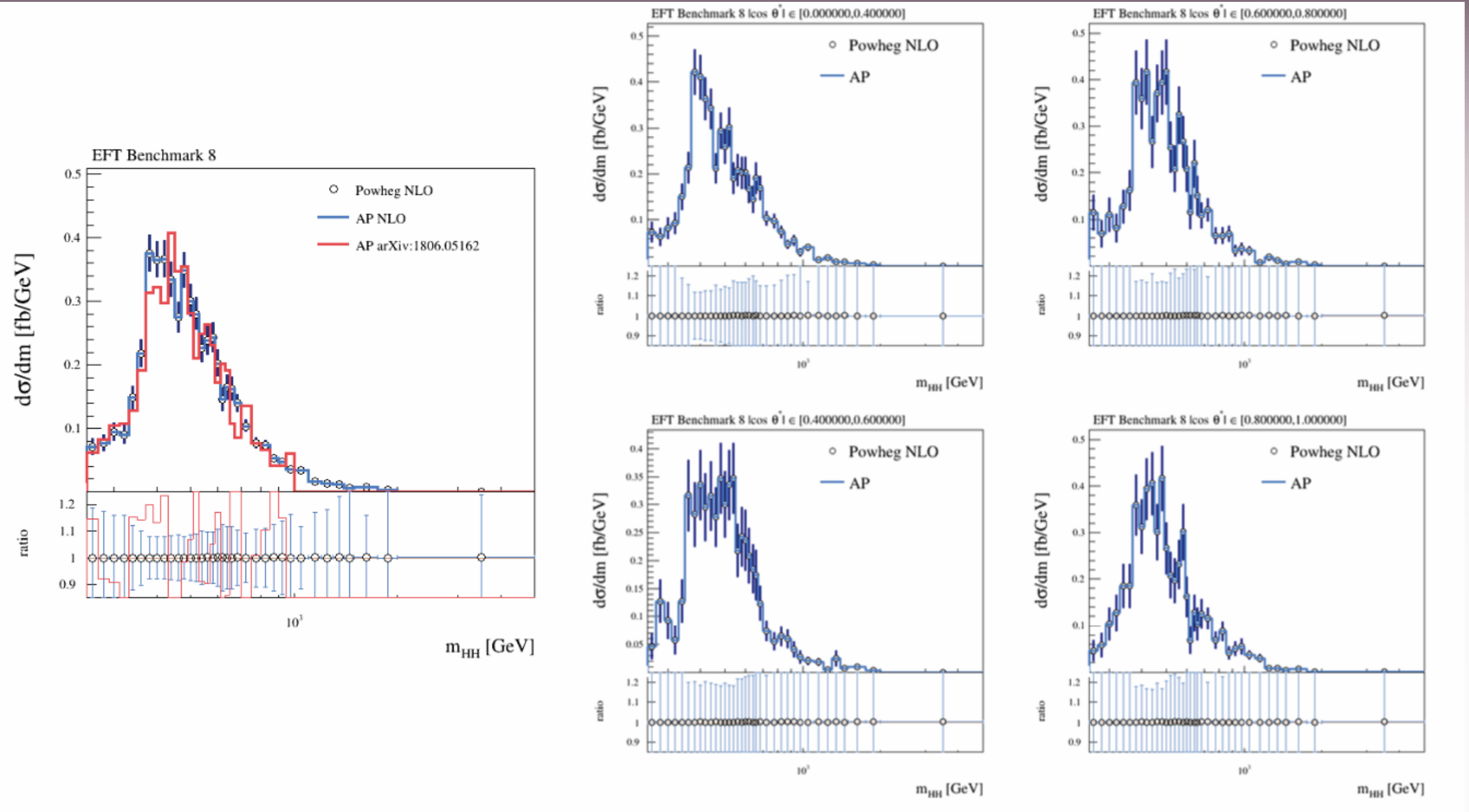
AP @ LO results



AP @ LO results

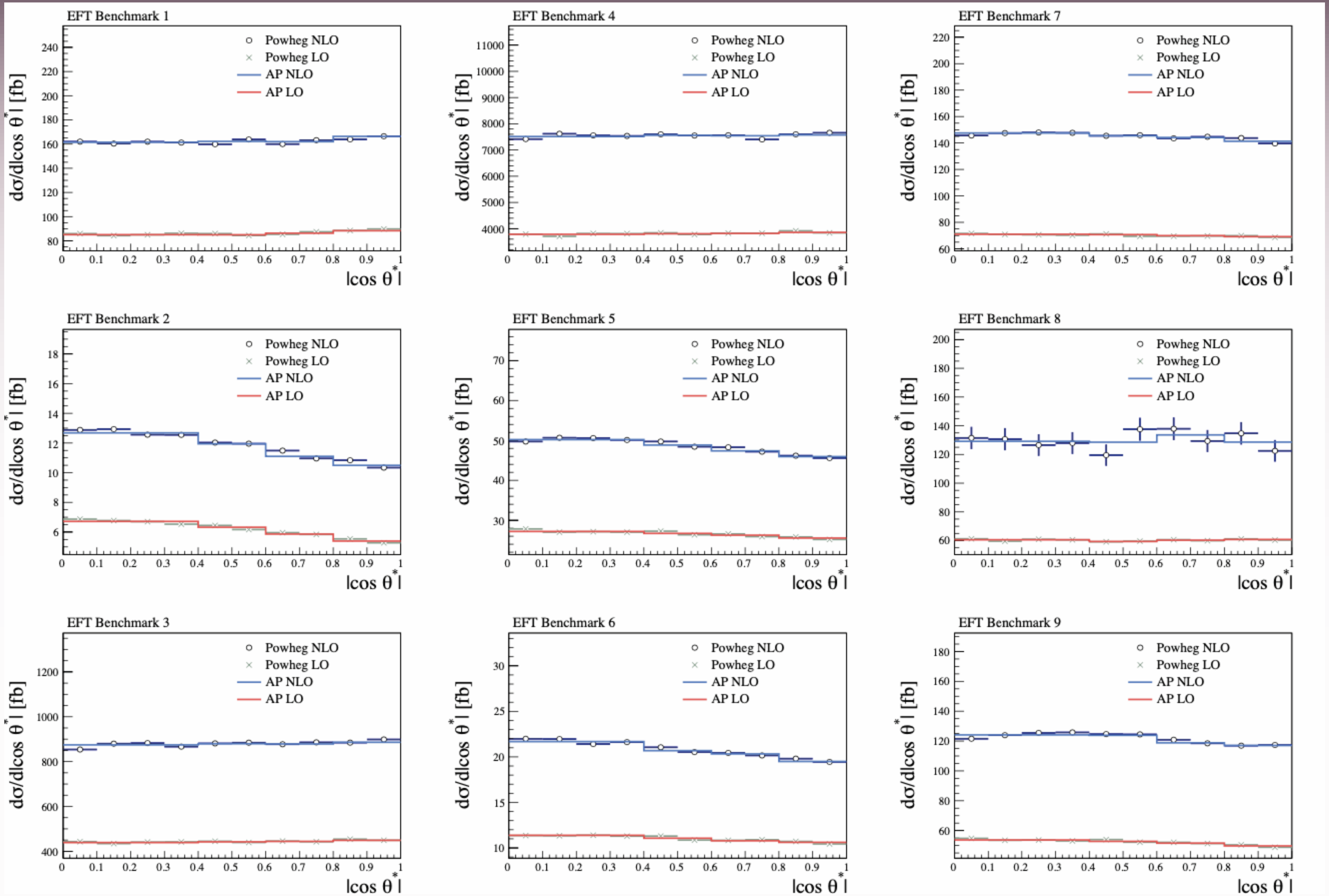


Benchmark 8, a special one

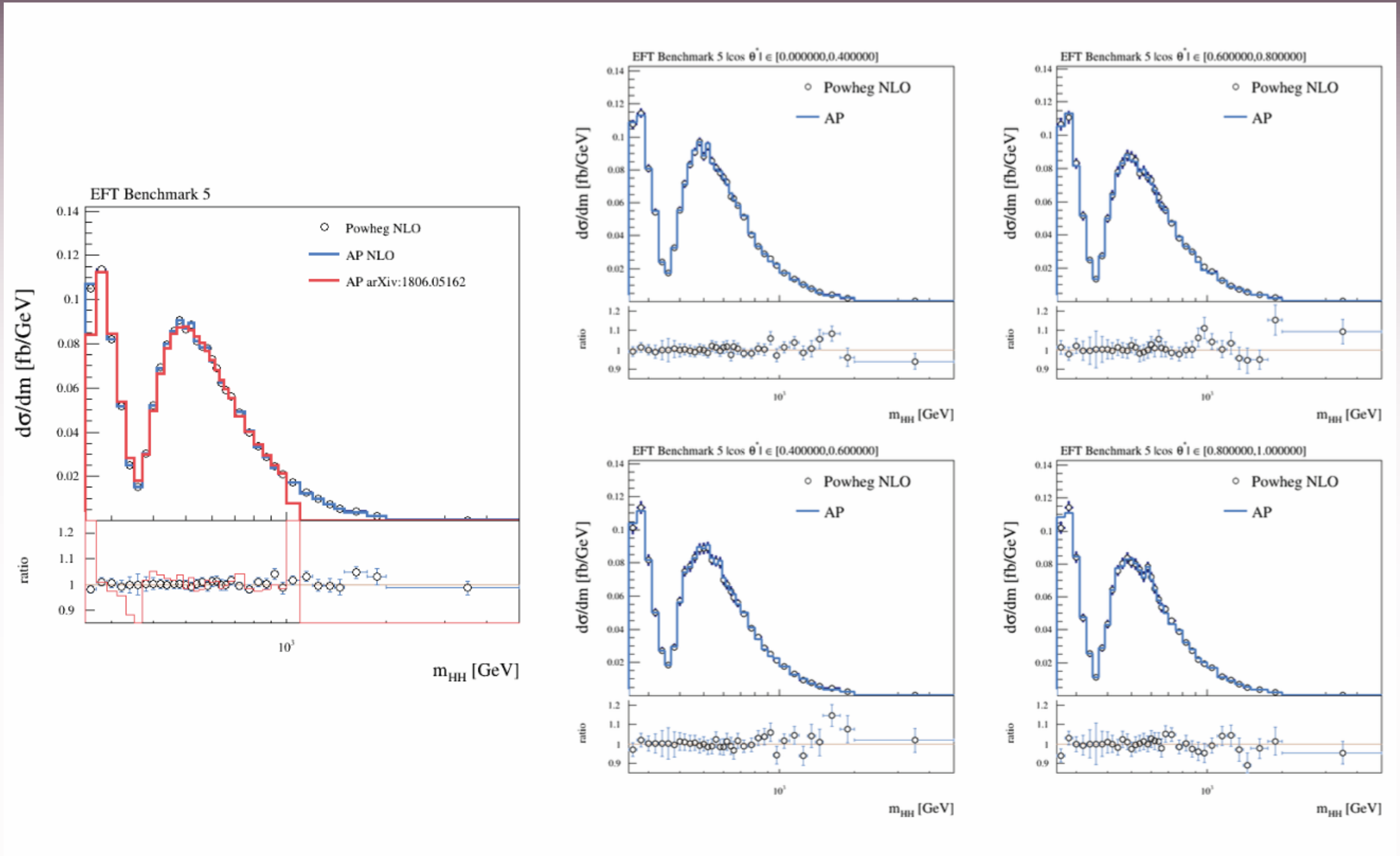


- In addition, generation of events for this benchmark at least ≈ 10 times slower

NLO results


EFT Benchmark 1
EFT Benchmark 2
EFT Benchmark 3
EFT Benchmark 4
EFT Benchmark 5
EFT Benchmark 6
EFT Benchmark 7
EFT Benchmark 8
EFT Benchmark 9
Powheg NLO
Powheg LO
AP NLO
AP LO
dσ/d|cos θ*| [fb]
|cos θ*|

NLO results



EFT Benchmark 5
Powheg NLO
AP NLO
AP arXiv:1806.05162
dσ/dm [fb/GeV]
ratio
m_HH [GeV]
EFT Benchmark 5 |cos θ*| ∈ [0.000000,0.400000]
EFT Benchmark 5 |cos θ*| ∈ [0.600000,0.800000]
EFT Benchmark 5 |cos θ*| ∈ [0.400000,0.600000]
EFT Benchmark 5 |cos θ*| ∈ [0.800000,1.000000]
Powheg NLO
AP

Theory

by
L. Alasfar, R. Gröber and G. Heinrich

Translation between the EFT's

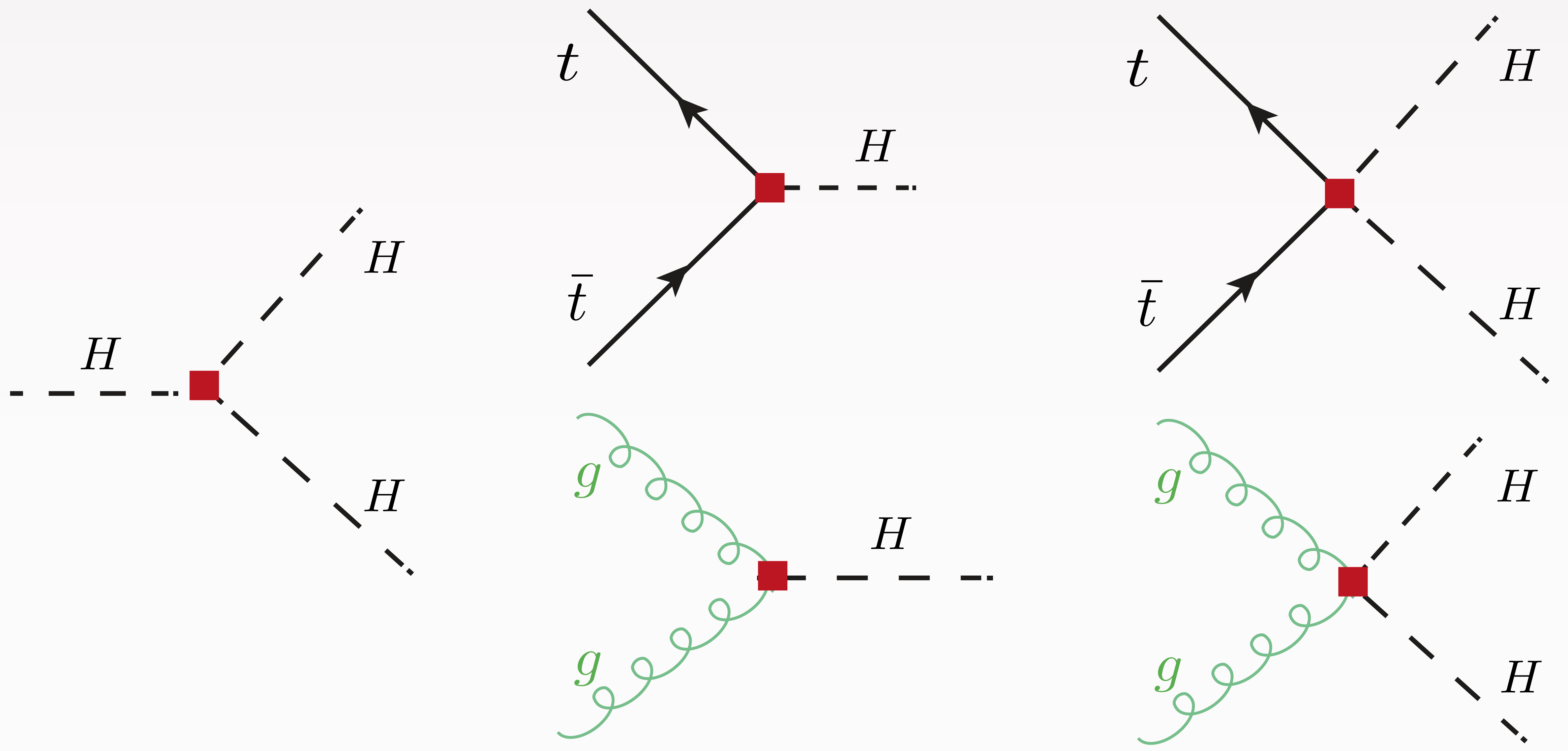
Equiv. use field redefinition

$$h \to h + C_{H,kin}\left(h + h^2/v + h^3/(3v^2)\right)$$

One can use the equations of motions for the Higgs to eliminate some of the Warsaw basis operators

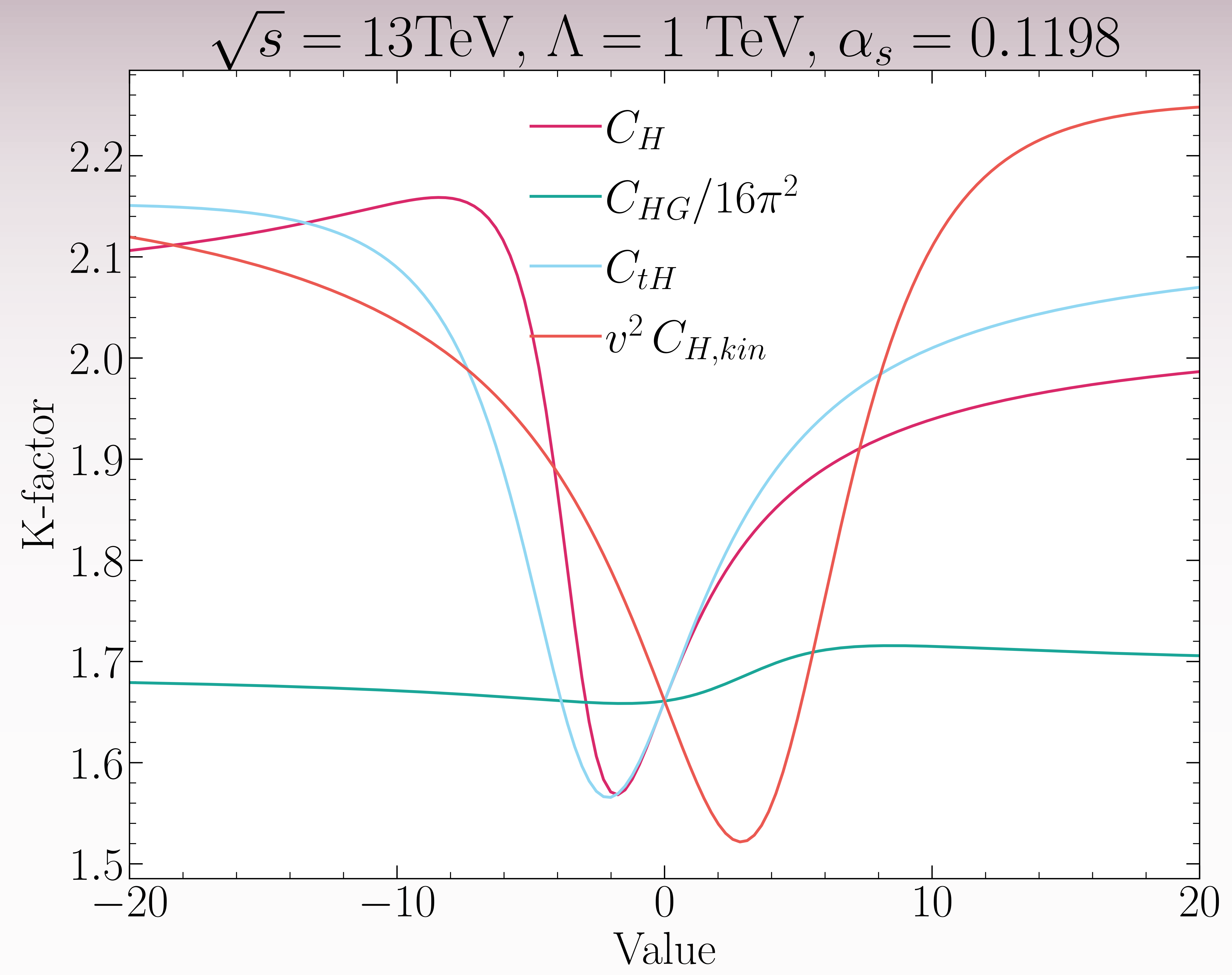
We define the Wilson coefficient for Warsaw basis $$C_{H,kin} = \left(C_{H,\Box} - \frac{1}{4}C_{HD}\right)v^2$$

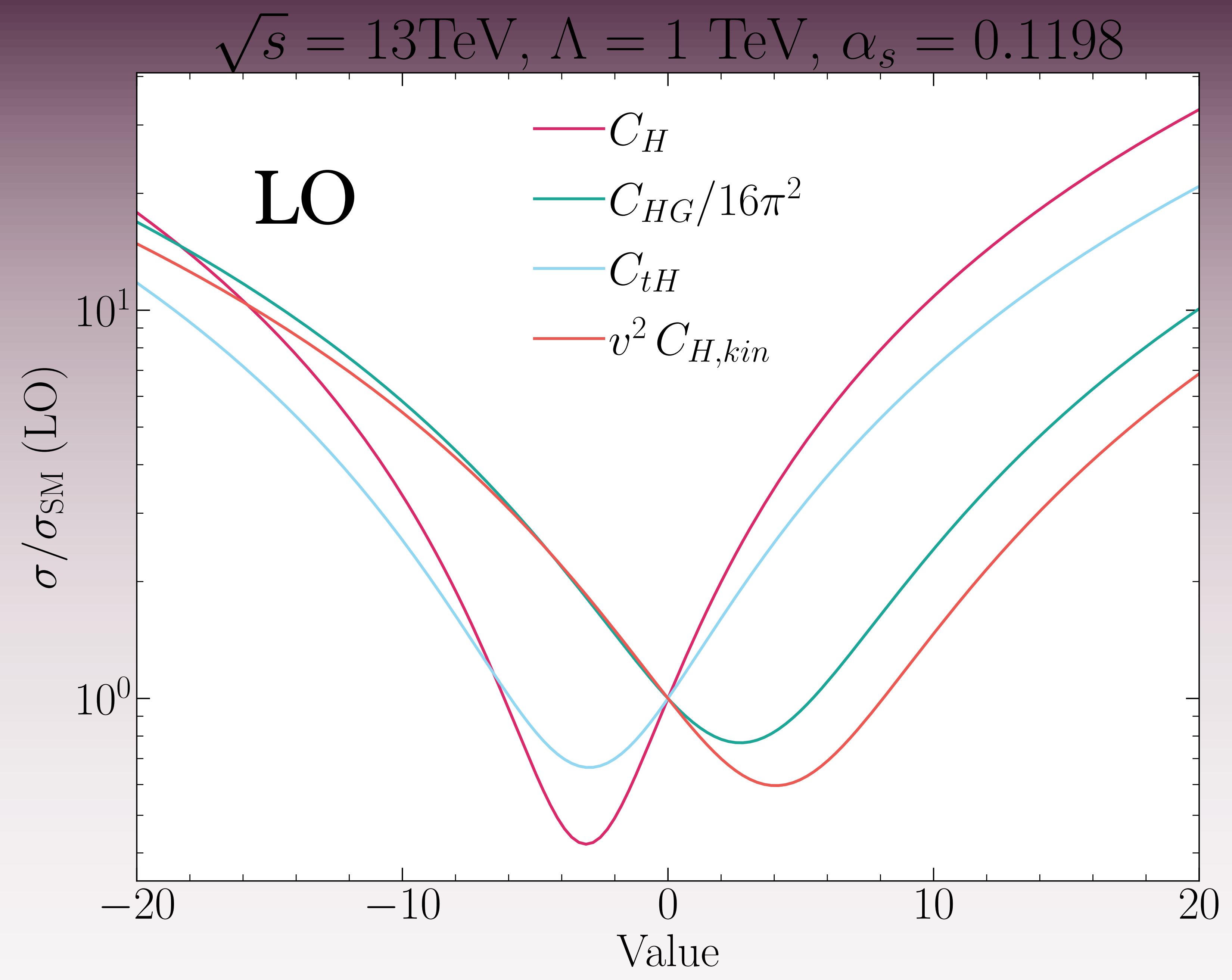
HEFT	SILH	Warsaw
c_{hhh}	$1+\bar{c}_6-\frac{3}{2}\bar{c}_H$	$1-2\frac{v^4}{m_h^2}C_H+3c_{H,kin}$
c_t	$1-\frac{\bar{c}_H}{2}-\bar{c}_u$	$1+c_{H,kin}-C_{uH}\frac{v^3}{\sqrt{2}m_t}$
c_{tt}	$-\left(\frac{3}{2}\bar{c}_u+\frac{\bar{c}_H}{2}\right)$	$-C_{uH}\frac{3v^3}{2\sqrt{2}m_t}+c_{H,kin}$
c_{ggh}	$\frac{128\pi^2}{g_2^2}\bar{c}_g$	$\frac{8\pi}{\alpha_s}v^2C_{HG}$
c_{gghh}	$\frac{64\pi^2}{g_2^2}\bar{c}_g$	$\frac{4\pi}{\alpha_s}v^2C_{HG}$

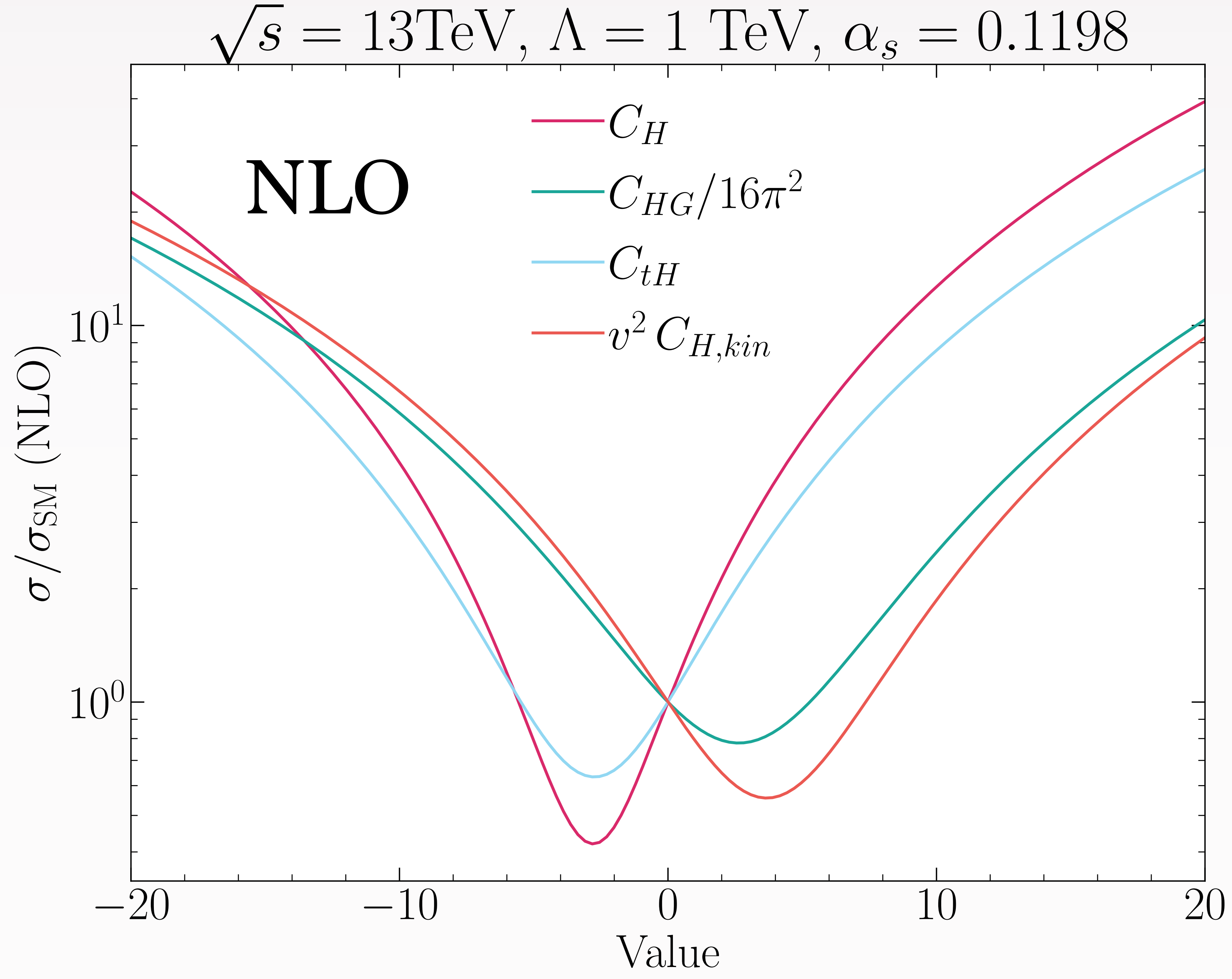


Cross-sections and K-factors

We redefine the SMEFT operators such that $C \to \dfrac{C}{\Lambda^2}$

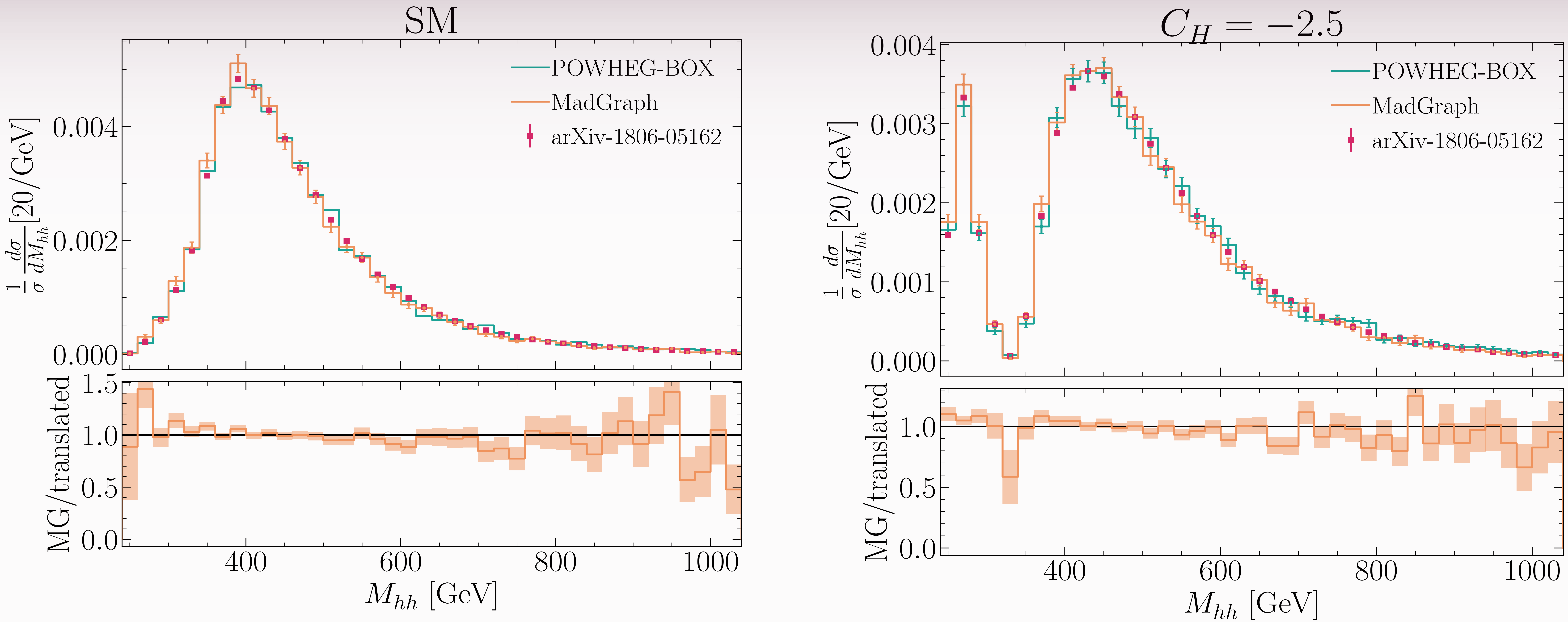




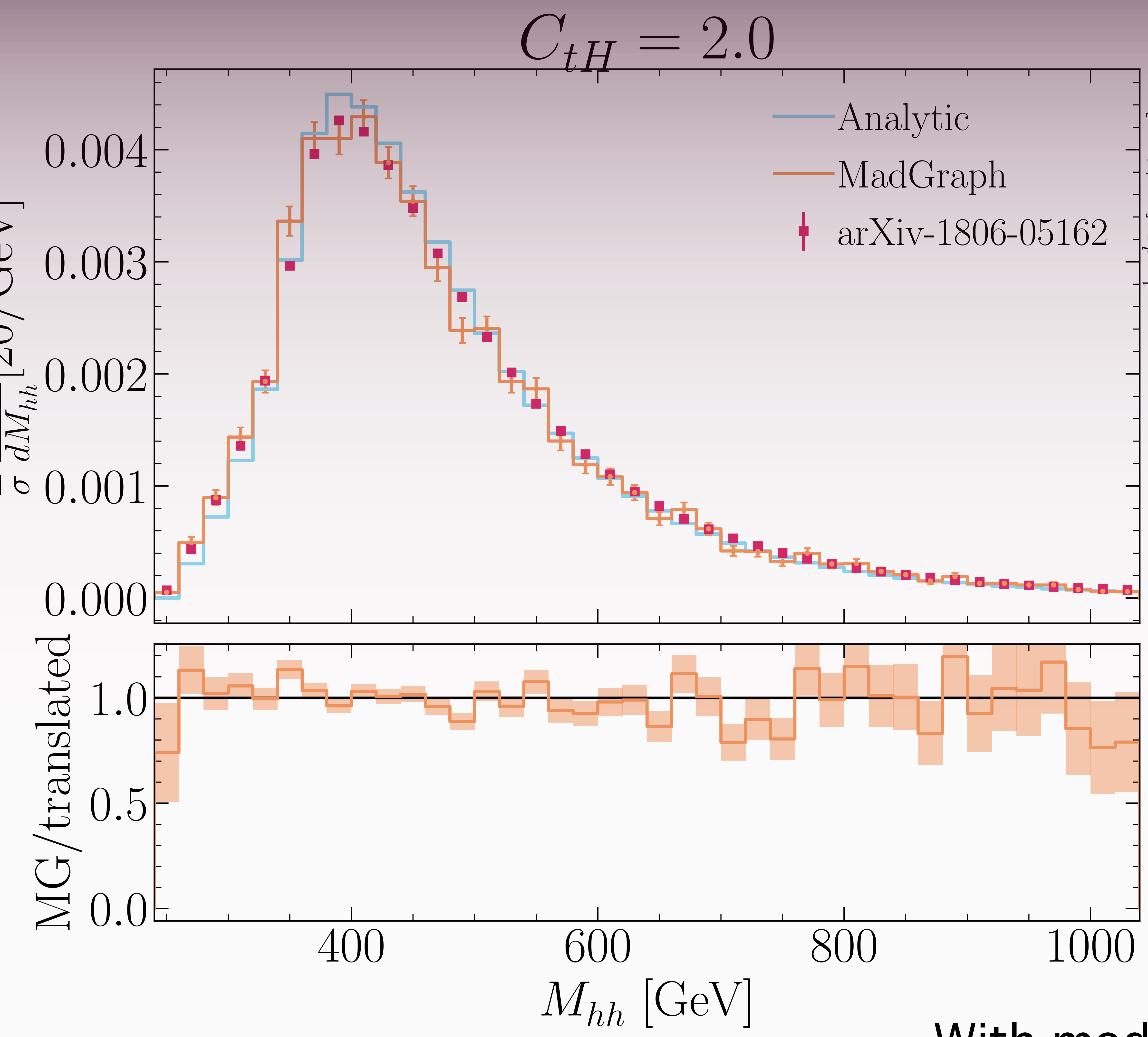


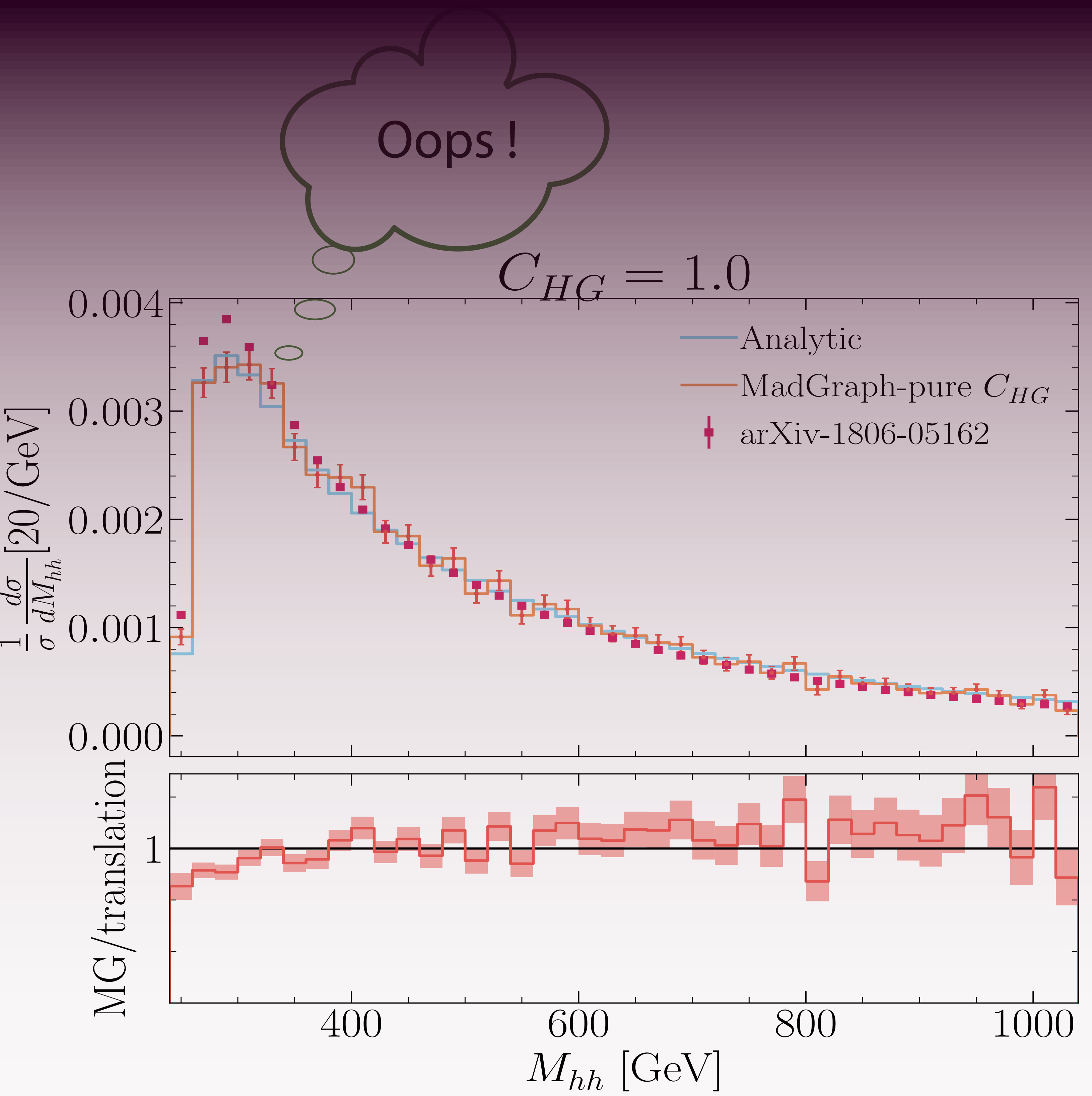
These plots are obtained from the translation from HEFT from [G. Buchalla, et al. '18] arXiv:1806.05162 (hep-ph)

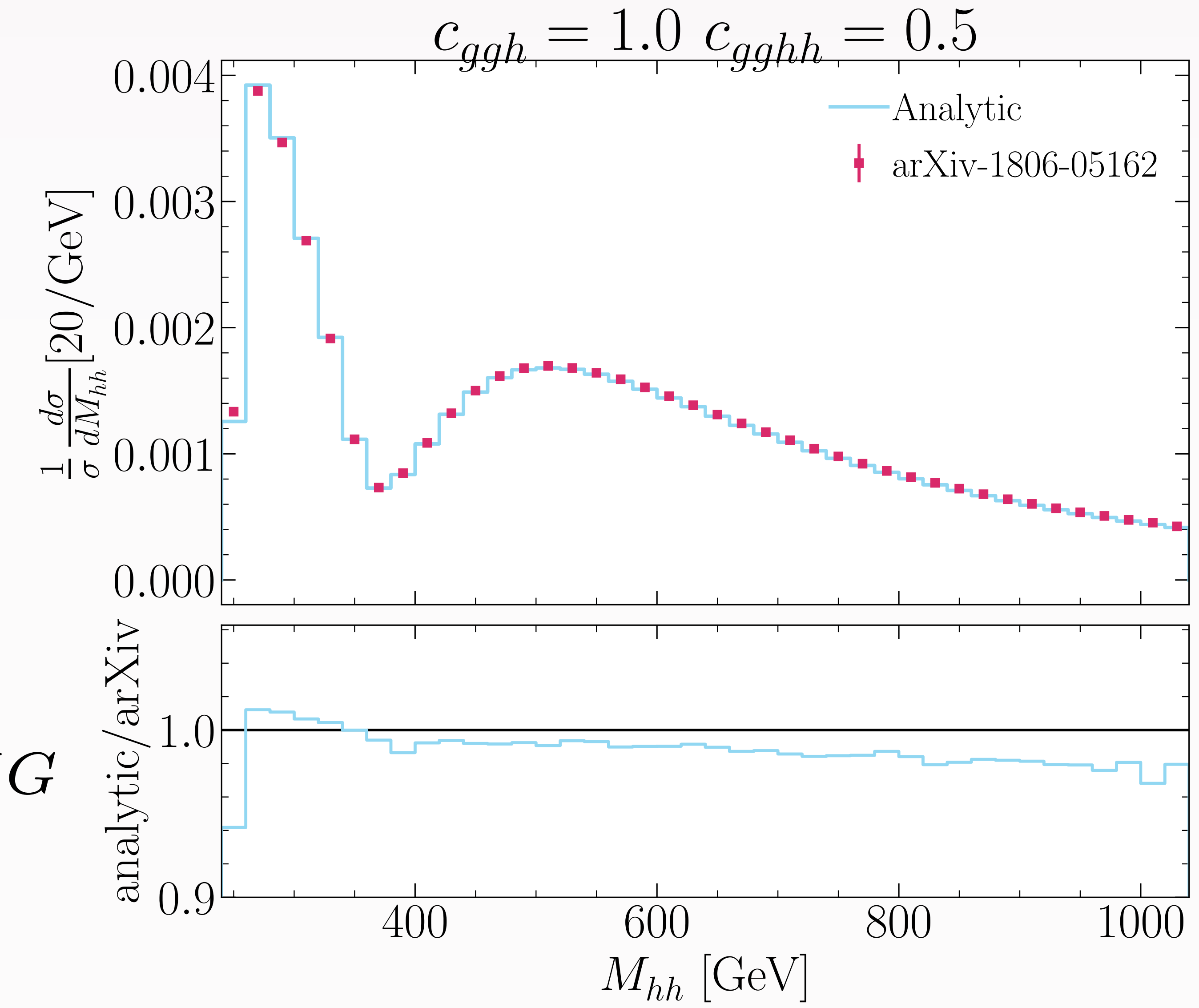
Validation plots (LO only)



Validation plots (LO only)







With modified definition of C_{HG}

Conclusion

- Reweighting MC samples (LO and NLO) was achieved for HEFT.

- Low statistics in the 1st bin is noticed to affect some benchmarks. Moreover, some benchmarks show disagreement between MG and Powheg derived AP's.

- Custom coefficients of the AP of the differential NLO and LO Powheg cross sections as a function of M_{hh} and $\cos\theta^*$ are derived, allowing to increase reweighting range from M_{hh} < 1040 up to M_{hh} < 5000 GeV and take into account $\cos\theta^*$ dependence.

- Predictions for the SM and 12 EFT benchmarks are in a good agreement with MC $\Longrightarrow$ suitable for the analysis of 12 benchmarks

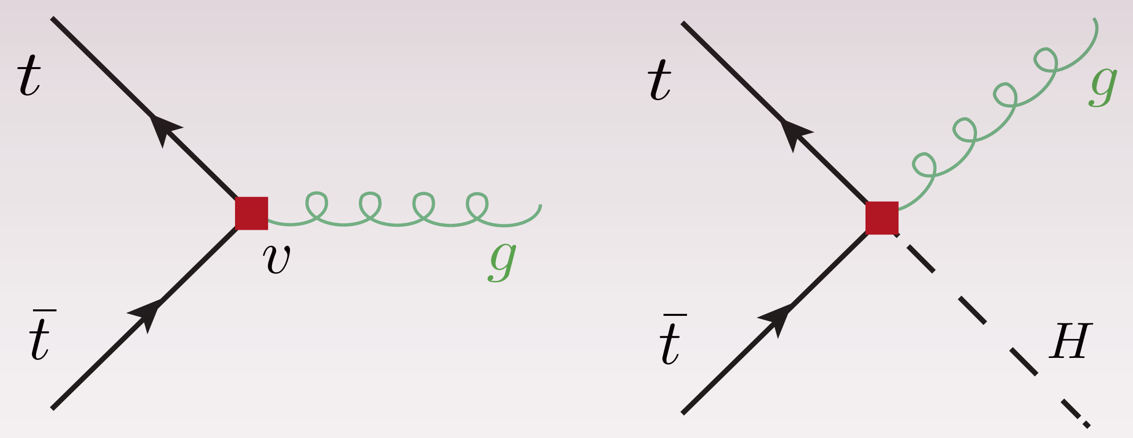
- Constraints on NLO A_{16}-A_{23} coefficients are limited by statistical fluctuations $\Longrightarrow$ EFT parameter scan with care

- The issue with HEFT to Warsaw for C_{HG}, where the translation depends on α_s can be avoided by redefining the SMEFT operator.

Outlook

- To include or not to include the chromomagnetic operator, in SMEFT

$$\hat{O}_{tG} := y_t g_s (\bar{q}_L \sigma^{\mu\nu} T_A t_R) H^c G^A_{\mu\nu}$$



- NLO SMEFT event generator, via POWHEG-BOX

- Better statistics for the 1st bin and NLO coefficients.

Backup

Reminder

For the following EFT Lagrangian:

$$\mathcal{L}_{ggF} = -\,\kappa_\lambda \lambda_{HHH}^{SM} v H^3 - \frac{m_t}{v}(\kappa_t H + \frac{\kappa_2}{v} H^2)(\bar{t_L} t_R + h.c.) \; + \frac{\alpha_S}{12\pi v}(\kappa_g H - \frac{\kappa_{2g}}{2v} H^2) G^a_{\mu\nu} G^{a,\,\mu\nu}$$

the cross section for ggf HH production in pp can be parameterized as a polynomial of the κ's:

$$\begin{aligned}\sigma_{LO} = & A_1\,\kappa_t^4 + A_2\,\kappa_2^2 + A_3\,\kappa_t^2\kappa_\lambda^2 + A_4\,\kappa_g^2\kappa_\lambda^2 + A_5\,\kappa_{2g}^2 + A_6\,\kappa_2\kappa_t^2 + A_7\,\kappa_t^3\kappa_\lambda \\ & + A_8\,\kappa_2\kappa_t\,\kappa_\lambda + A_9\,\kappa_2\kappa_g\kappa_\lambda + A_{10}\,\kappa_2\kappa_{2g} + A_{11}\,\kappa_t^2\kappa_g\kappa_\lambda + A_{12}\,\kappa_t^2\kappa_{2g} \\ & + A_{13}\,\kappa_t\kappa_\lambda^2\kappa_g + A_{14}\,\kappa_t\kappa_\lambda\kappa_{2g} + A_{15}\,\kappa_g\kappa_\lambda\kappa_{2g}\,.\end{aligned}$$

$$\begin{aligned}\sigma_{NLO} = & \ldots + A_{16}\,\kappa_t^3\kappa_g + A_{17}\,\kappa_t\kappa_2\kappa_g + A_{18}\,\kappa_t\kappa_g^2\kappa_\lambda + A_{19}\,\kappa_t\kappa_g\kappa_{2g} \\ & + A_{20}\,\kappa_t^2\kappa_g^2 + A_{21}\,\kappa_2\kappa_g^2 + A_{22}\,\kappa_g^3\kappa_\lambda + A_{23}\,\kappa_g^2\kappa_{2g}\,.\end{aligned}$$

to take into account differences in the shapes a binned parametrisation of the cross section, for example, as a function of m_{HH} can be used:

$$\frac{d\sigma}{dm_{HH}} = \sum A_i(m_{HH})\,c_i$$

To extract the $A_i(m_{HH}, |\cos\theta^*|)$ coefficients the system of equations is solved by performing a minimisation in ROOT MINUIT. In every bin $\boldsymbol{b} = (m_{HH}, |\cos\theta^*|)$:

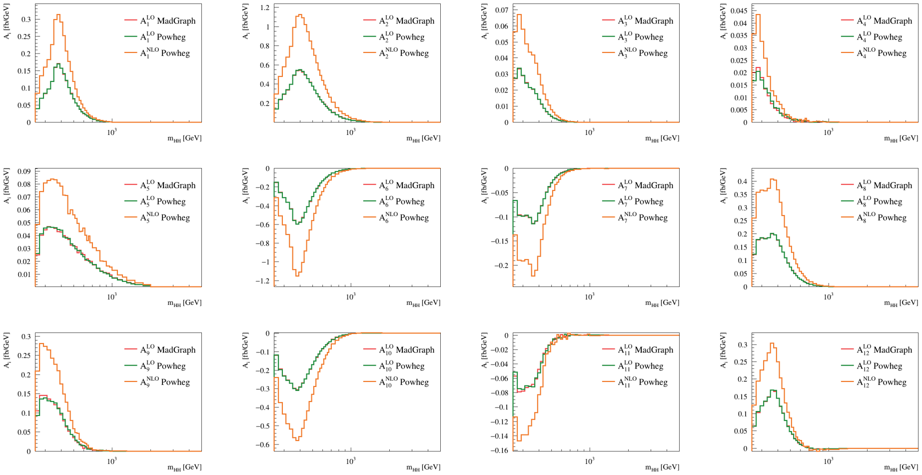
Edges in $m_{HH} = [\ 250, 270, 290, 310, 330, 350, 370,$
$390, 410, 430, 450, 470, 490, 510,$
$530, 550, 570, 590, 610, 630, 650,$
$670, 700, 750, 800, 850, 900, 950,$
$1000, 1100, 1200, 1300, 1400, 1500, 1750,$
$2000, 5000\ ]$ Gev

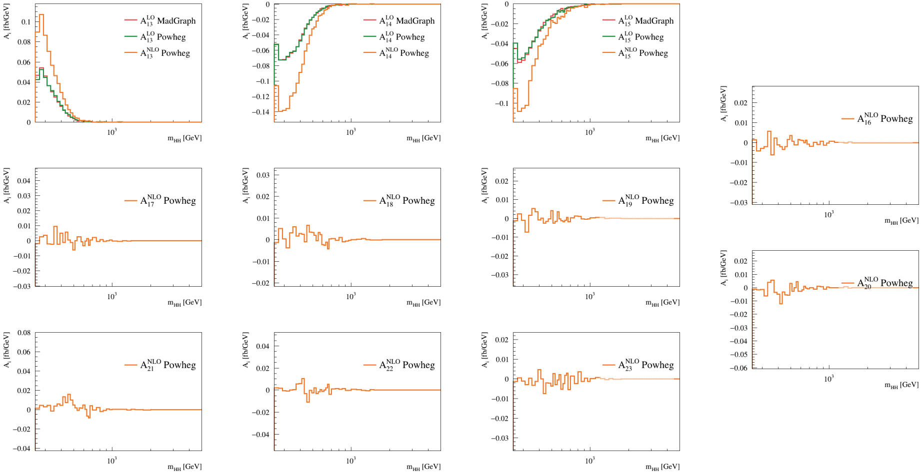
Edges in $|\cos\theta^*| = [\ 0, 0.4, 0.6, 0.8, 1\ ]$

following function is minimized :

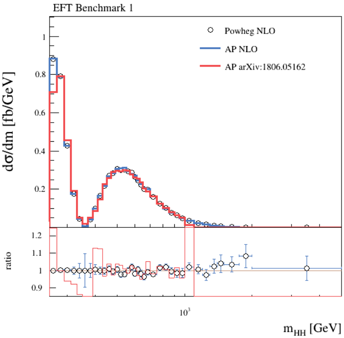
$$f(\boldsymbol{b}) = \sum_{i}^{N_{samples}} \left(\frac{\frac{d\sigma_i^{MC}(\boldsymbol{b})}{d\boldsymbol{b}} - \frac{d\sigma_i^{AP}(\boldsymbol{b})}{d\boldsymbol{b}}}{0.1 \cdot \frac{d\sigma_i^{MC}(\boldsymbol{b})}{d\boldsymbol{b}}} \right)^2$$

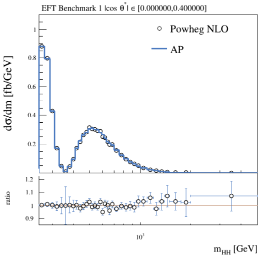
A_i from the fit, explicitly

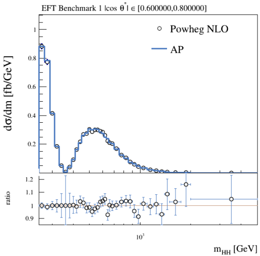


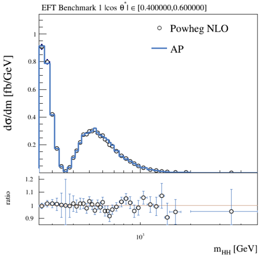


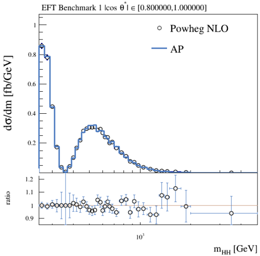
Constraints on NLO A_{16}-A_{23} coefficients are limited by statistical fluctuations!

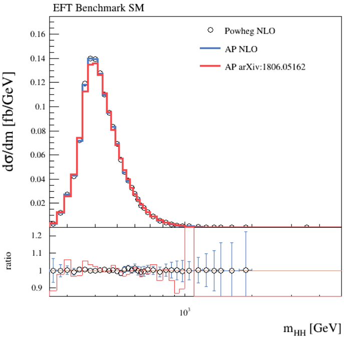

EFT Benchmark 1
Powheg NLO
AP NLO
AP arXiv:1806.05162
dσ/dm [fb/GeV]
ratio
m_HH [GeV]

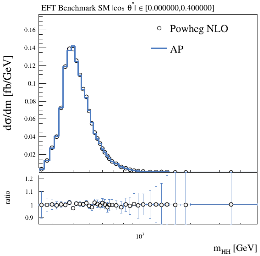

EFT Benchmark 1 |cos θ*| ∈ [0.000000,0.400000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_HH [GeV]

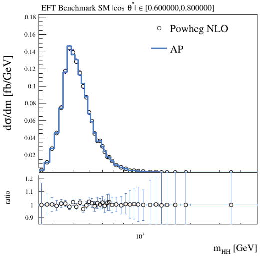

EFT Benchmark 1 |cos θ*| ∈ [0.600000,0.800000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_HH [GeV]

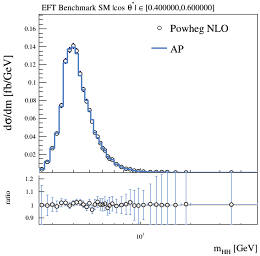

EFT Benchmark 1 |cos θ*| ∈ [0.400000,0.600000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_HH [GeV]

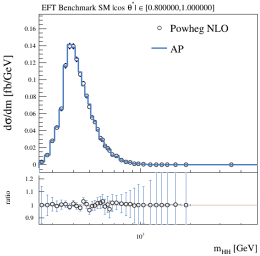

EFT Benchmark 1 |cos θ*| ∈ [0.800000,1.000000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_HH [GeV]

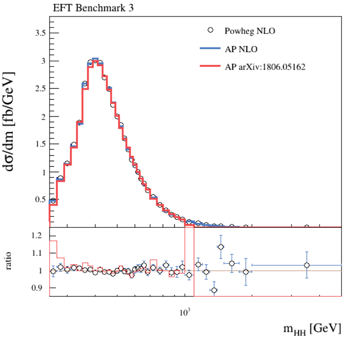

EFT Benchmark SM
Powheg NLO
AP NLO
AP arXiv:1806.05162
dσ/dm [fb/GeV]
ratio
m_HH [GeV]

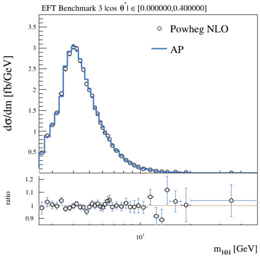

EFT Benchmark SM |cos θ*| ∈ [0.000000,0.400000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_HH [GeV]

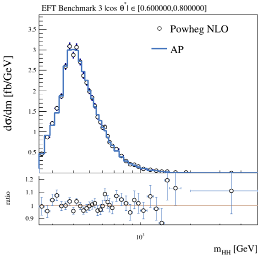

EFT Benchmark SM |cos θ*| ∈ [0.600000,0.800000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_HH [GeV]

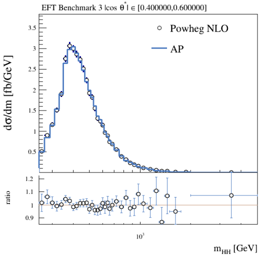

EFT Benchmark SM |cos θ*| ∈ [0.400000,0.600000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_HH [GeV]

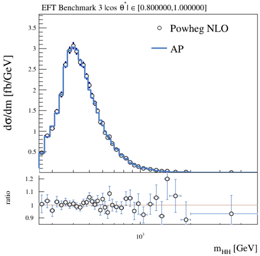

EFT Benchmark SM |cos θ*| ∈ [0.800000,1.000000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_HH [GeV]

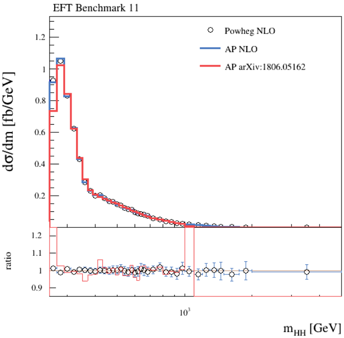

EFT Benchmark 3
Powheg NLO
AP NLO
AP arXiv:1806.05162
dσ/dm [fb/GeV]
ratio
m_{HH} [GeV]

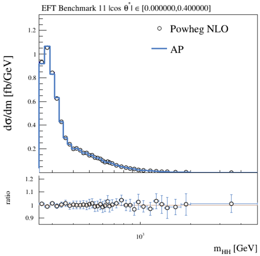

EFT Benchmark 3 |cos θ*| ∈ [0.000000,0.400000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_{HH} [GeV]

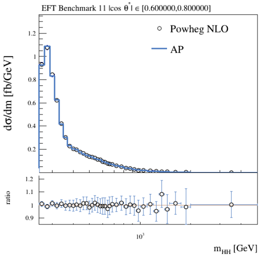

EFT Benchmark 3 |cos θ*| ∈ [0.600000,0.800000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_{HH} [GeV]

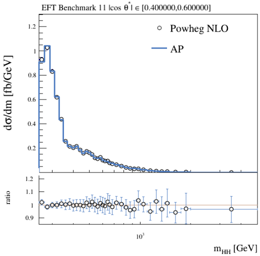

EFT Benchmark 3 |cos θ*| ∈ [0.400000,0.600000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_{HH} [GeV]

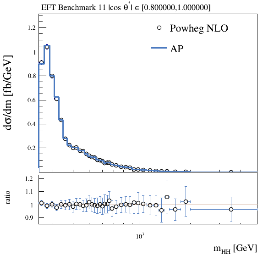

EFT Benchmark 3 |cos θ*| ∈ [0.800000,1.000000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_{HH} [GeV]

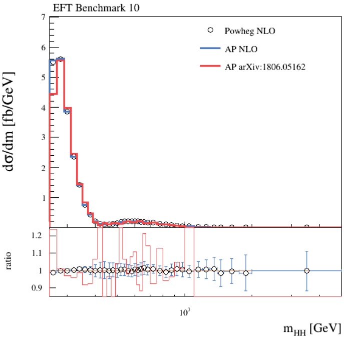

EFT Benchmark 11
Powheg NLO
AP NLO
AP arXiv:1806.05162
dσ/dm [fb/GeV]
ratio
m_{HH} [GeV]

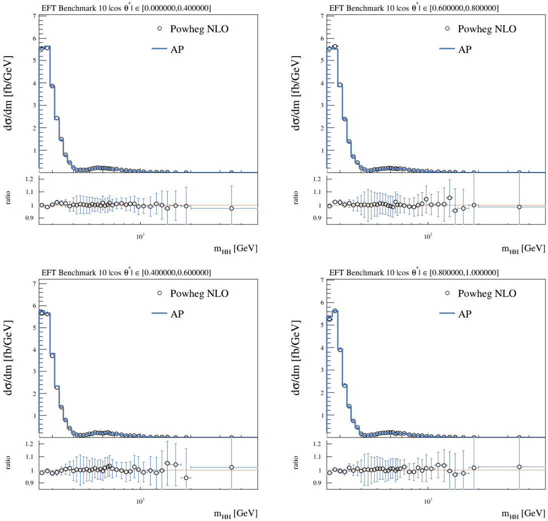

EFT Benchmark 11 |cos θ*| ∈ [0.000000,0.400000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_{HH} [GeV]

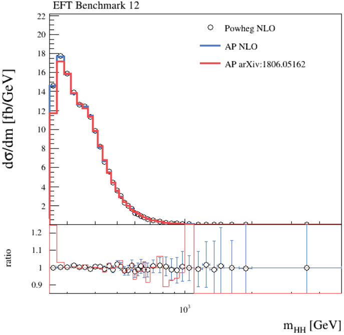

EFT Benchmark 11 |cos θ*| ∈ [0.600000,0.800000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_{HH} [GeV]


EFT Benchmark 11 |cos θ*| ∈ [0.400000,0.600000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_{HH} [GeV]

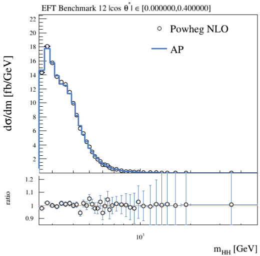

EFT Benchmark 11 |cos θ*| ∈ [0.800000,1.000000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_{HH} [GeV]


EFT Benchmark 10
Powheg NLO
AP NLO
AP arXiv:1806.05162
dσ/dm [fb/GeV]
ratio
m_{HH} [GeV]
10^3

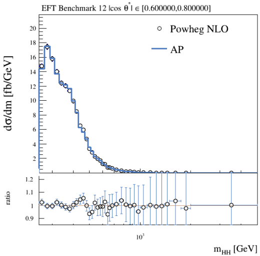

EFT Benchmark 10 |cos θ*| ∈ [0.000000,0.400000]
EFT Benchmark 10 |cos θ*| ∈ [0.600000,0.800000]
EFT Benchmark 10 |cos θ*| ∈ [0.400000,0.600000]
EFT Benchmark 10 |cos θ*| ∈ [0.800000,1.000000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_{HH} [GeV]
10^3



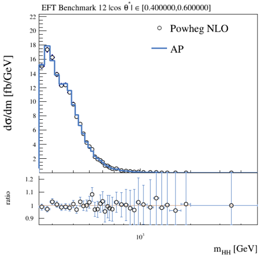
EFT Benchmark 12
Powheg NLO
AP NLO
AP arXiv:1806.05162
dσ/dm [fb/GeV]
ratio
m_HH [GeV]



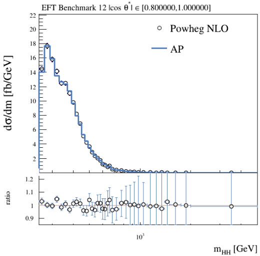
EFT Benchmark 12 |cos θ*| ∈ [0.000000,0.400000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_HH [GeV]



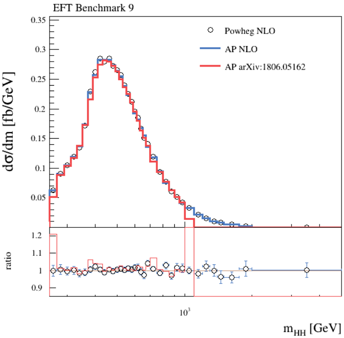
EFT Benchmark 12 |cos θ*| ∈ [0.600000,0.800000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_HH [GeV]

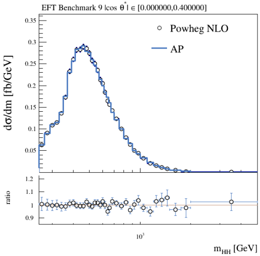


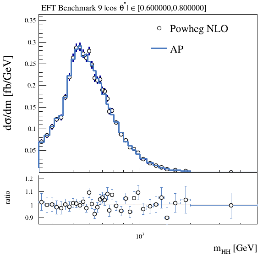
EFT Benchmark 12 |cos θ*| ∈ [0.400000,0.600000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_HH [GeV]

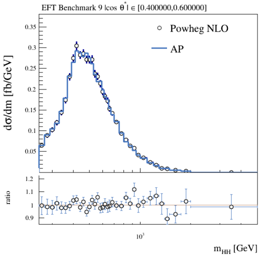


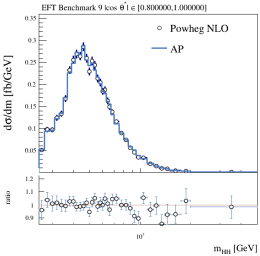
EFT Benchmark 12 |cos θ*| ∈ [0.800000,1.000000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_HH [GeV]

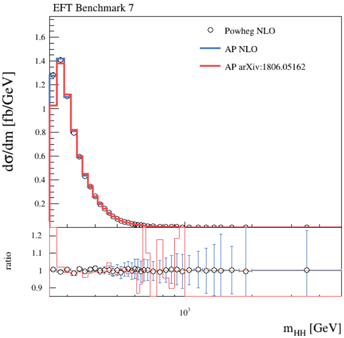

EFT Benchmark 9
Powheg NLO
AP NLO
AP arXiv:1806.05162
dσ/dm [fb/GeV]
ratio
m_{HH} [GeV]

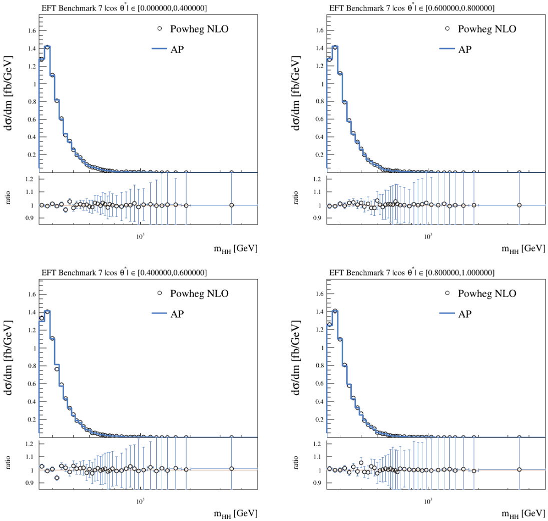

EFT Benchmark 9 |cos θ*| ∈ [0.000000,0.400000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_{HH} [GeV]

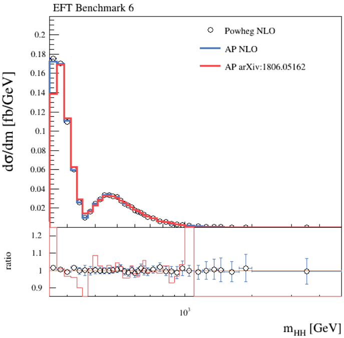

EFT Benchmark 9 |cos θ*| ∈ [0.600000,0.800000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_{HH} [GeV]

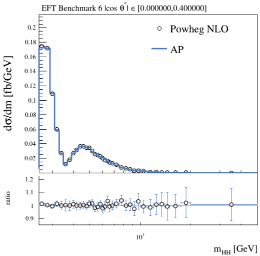

EFT Benchmark 9 |cos θ*| ∈ [0.400000,0.600000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_{HH} [GeV]

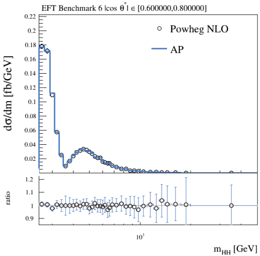

EFT Benchmark 9 |cos θ*| ∈ [0.800000,1.000000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_{HH} [GeV]

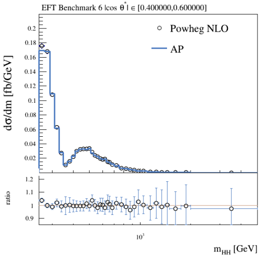

EFT Benchmark 7
Powheg NLO
AP NLO
AP arXiv:1806.05162
dσ/dm [fb/GeV]
ratio
m_HH [GeV]

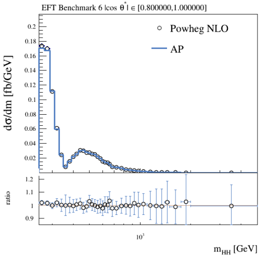

EFT Benchmark 7 |cos θ*| ∈ [0.000000,0.400000]
Powheg NLO
AP
EFT Benchmark 7 |cos θ*| ∈ [0.600000,0.800000]
Powheg NLO
AP
EFT Benchmark 7 |cos θ*| ∈ [0.400000,0.600000]
Powheg NLO
AP
EFT Benchmark 7 |cos θ*| ∈ [0.800000,1.000000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_HH [GeV]

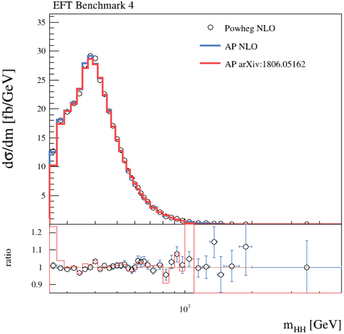

EFT Benchmark 6
Powheg NLO
AP NLO
AP arXiv:1806.05162
dσ/dm [fb/GeV]
ratio
m_{HH} [GeV]

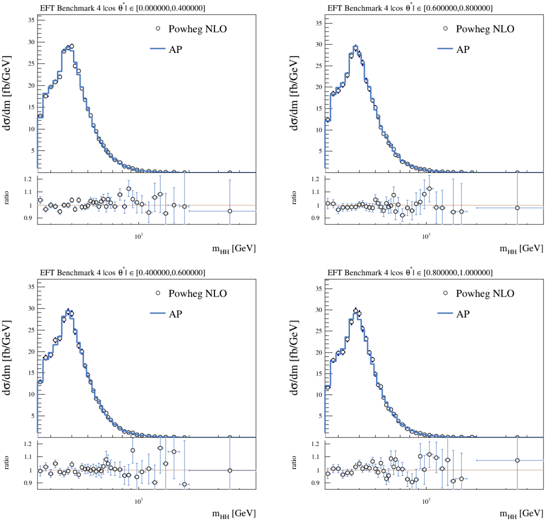

EFT Benchmark 6 |cos θ*| ∈ [0.000000,0.400000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_{HH} [GeV]


EFT Benchmark 6 |cos θ*| ∈ [0.600000,0.800000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_{HH} [GeV]

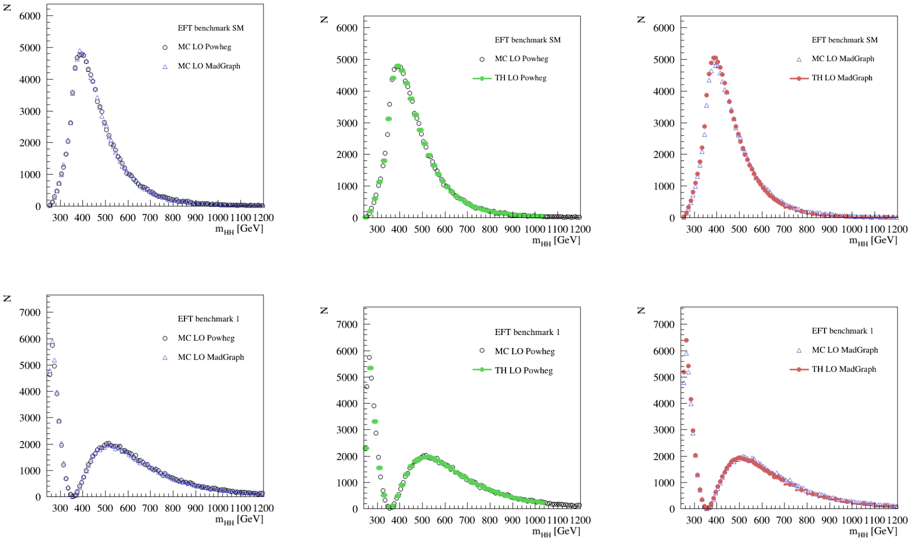

EFT Benchmark 6 |cos θ*| ∈ [0.400000,0.600000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_{HH} [GeV]


EFT Benchmark 6 |cos θ*| ∈ [0.800000,1.000000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_{HH} [GeV]

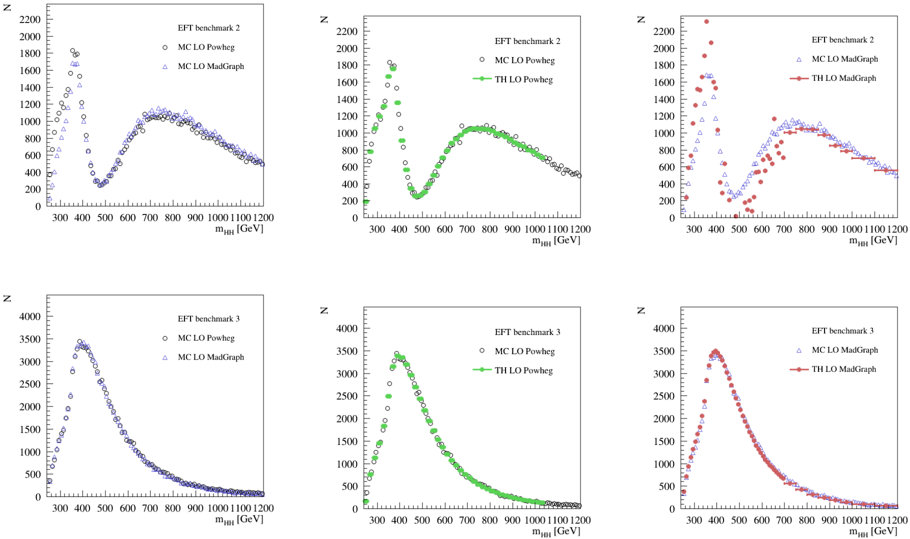

EFT Benchmark 4
Powheg NLO
AP NLO
AP arXiv:1806.05162
dσ/dm [fb/GeV]
ratio
m_HH [GeV]


EFT Benchmark 4 |cos θ*| ∈ [0.000000,0.400000]
EFT Benchmark 4 |cos θ*| ∈ [0.600000,0.800000]
EFT Benchmark 4 |cos θ*| ∈ [0.400000,0.600000]
EFT Benchmark 4 |cos θ*| ∈ [0.800000,1.000000]
Powheg NLO
AP
dσ/dm [fb/GeV]
ratio
m_HH [GeV]

M_{HH} @ LO

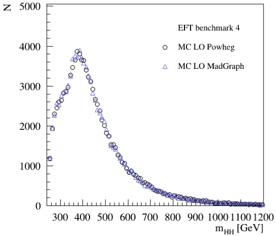

EFT benchmark SM
MC LO Powheg
MC LO MadGraph
EFT benchmark SM
MC LO Powheg
TH LO Powheg
EFT benchmark SM
MC LO MadGraph
TH LO MadGraph
EFT benchmark 1
MC LO Powheg
MC LO MadGraph
EFT benchmark 1
MC LO Powheg
TH LO Powheg
EFT benchmark 1
MC LO MadGraph
TH LO MadGraph
N
m_HH [GeV]

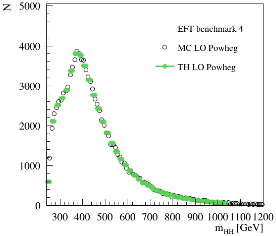
M_{HH} @ LO

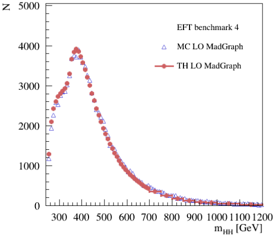


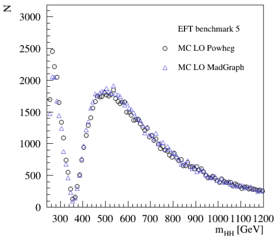
N
EFT benchmark 2
MC LO Powheg
MC LO MadGraph
TH LO Powheg
TH LO MadGraph
EFT benchmark 3
m_{HH} [GeV]
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
500
1500
2500
3000
3500
4000
300
700
900
1100

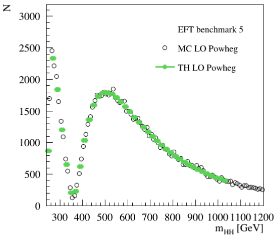
M_{HH} @ LO

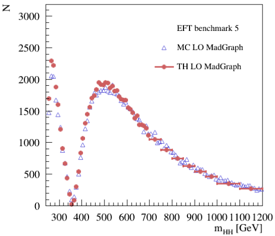

N
EFT benchmark 4
MC LO Powheg
MC LO MadGraph
m_HH [GeV]


N
EFT benchmark 4
MC LO Powheg
TH LO Powheg
m_HH [GeV]

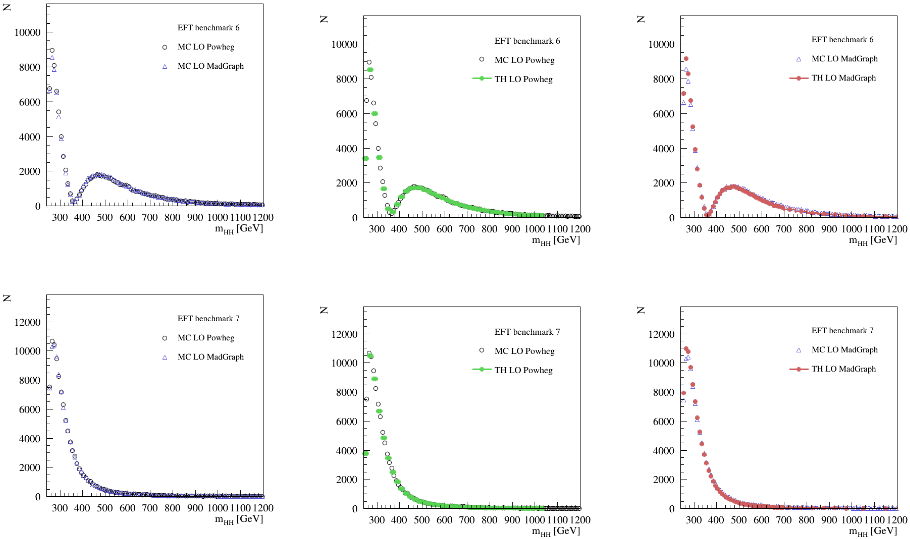

N
EFT benchmark 4
MC LO MadGraph
TH LO MadGraph
m_HH [GeV]


N
EFT benchmark 5
MC LO Powheg
MC LO MadGraph
m_HH [GeV]


N
EFT benchmark 5
MC LO Powheg
TH LO Powheg
m_HH [GeV]

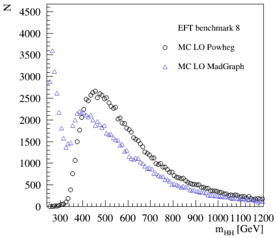

N
EFT benchmark 5
MC LO MadGraph
TH LO MadGraph
m_HH [GeV]

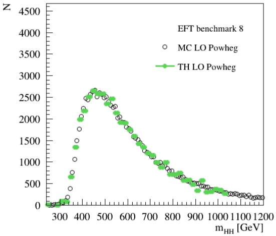
M_{HH} @ LO

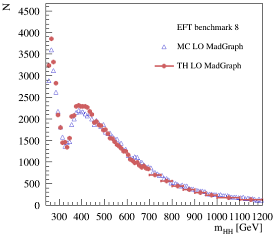


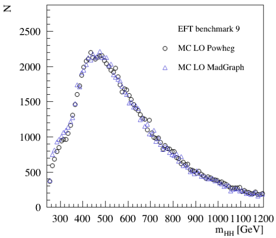
EFT benchmark 6
MC LO Powheg
MC LO MadGraph
EFT benchmark 6
MC LO Powheg
TH LO Powheg
EFT benchmark 6
MC LO MadGraph
TH LO MadGraph
EFT benchmark 7
MC LO Powheg
MC LO MadGraph
EFT benchmark 7
MC LO Powheg
TH LO Powheg
EFT benchmark 7
MC LO MadGraph
TH LO MadGraph
N
m_{HH} [GeV]

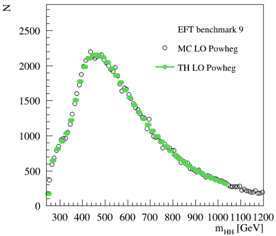
M_{HH} @ LO

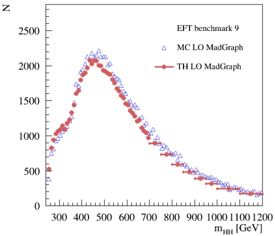

N
EFT benchmark 8
MC LO Powheg
MC LO MadGraph
m_HH [GeV]


N
EFT benchmark 8
MC LO Powheg
TH LO Powheg
m_HH [GeV]

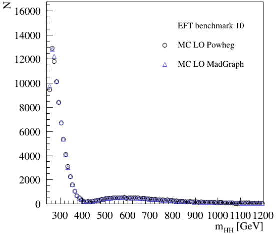

N
EFT benchmark 8
MC LO MadGraph
TH LO MadGraph
m_HH [GeV]

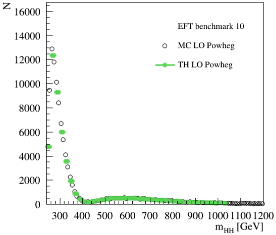

N
EFT benchmark 9
MC LO Powheg
MC LO MadGraph
m_HH [GeV]

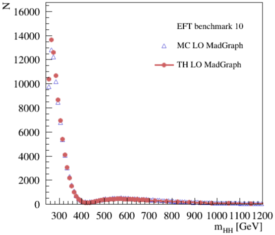

N
EFT benchmark 9
MC LO Powheg
TH LO Powheg
m_HH [GeV]

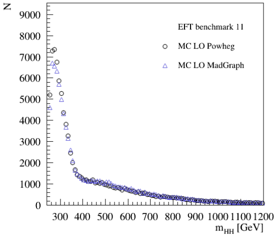

N
EFT benchmark 9
MC LO MadGraph
TH LO MadGraph
m_HH [GeV]

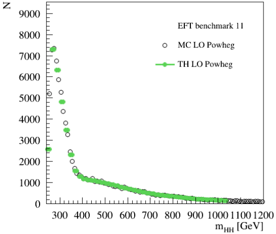
M_{HH} @ LO

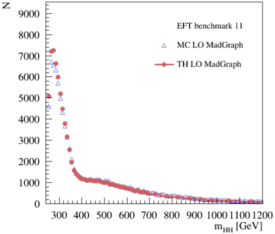

EFT benchmark 10
MC LO Powheg
MC LO MadGraph
N
m_{HH} [GeV]


EFT benchmark 10
MC LO Powheg
TH LO Powheg
N
m_{HH} [GeV]

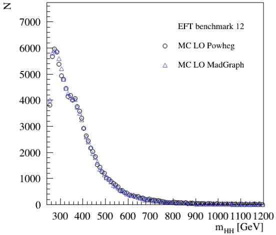

EFT benchmark 10
MC LO MadGraph
TH LO MadGraph
N
m_{HH} [GeV]

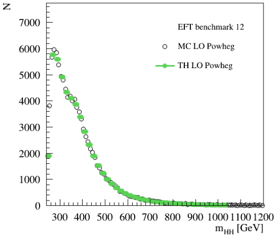

EFT benchmark 11
MC LO Powheg
MC LO MadGraph
N
m_{HH} [GeV]

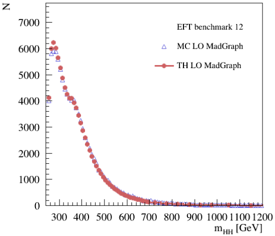

EFT benchmark 11
MC LO Powheg
TH LO Powheg
N
m_{HH} [GeV]


EFT benchmark 11
MC LO MadGraph
TH LO MadGraph
N
m_{HH} [GeV]

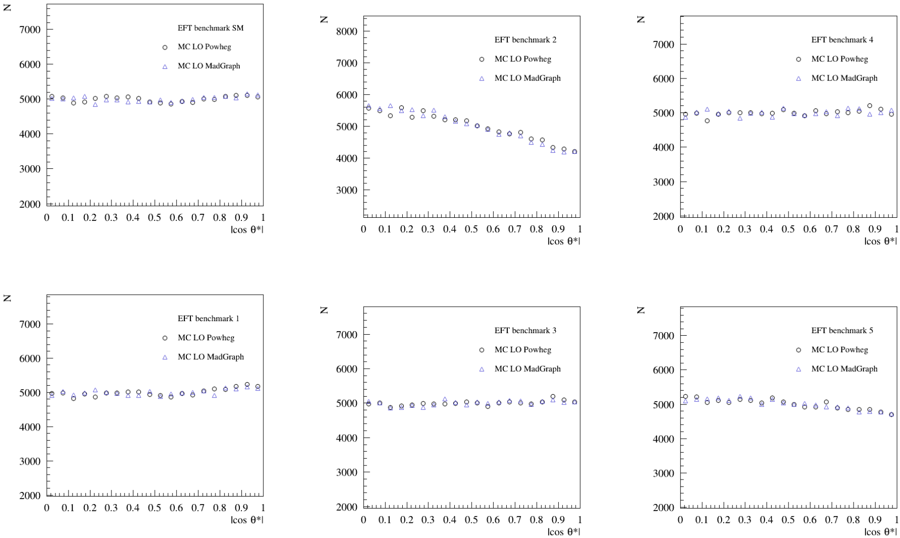
M_{HH} @ LO


N
EFT benchmark 12
MC LO Powheg
MC LO MadGraph
m_HH [GeV]

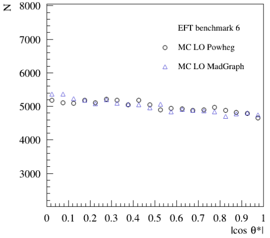

N
EFT benchmark 12
MC LO Powheg
TH LO Powheg
m_HH [GeV]

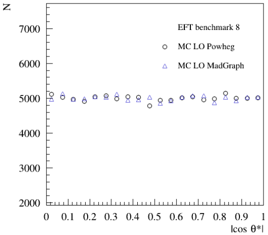

N
EFT benchmark 12
MC LO MadGraph
TH LO MadGraph
m_HH [GeV]

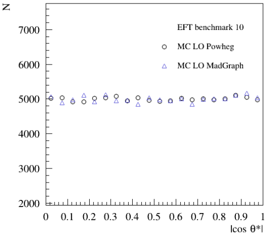
$\cos\theta^*$ @ LO

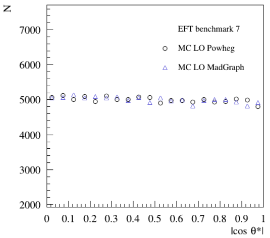

EFT benchmark SM
MC LO Powheg
MC LO MadGraph
EFT benchmark 2
MC LO Powheg
MC LO MadGraph
EFT benchmark 4
MC LO Powheg
MC LO MadGraph
EFT benchmark 1
MC LO Powheg
MC LO MadGraph
EFT benchmark 3
MC LO Powheg
MC LO MadGraph
EFT benchmark 5
MC LO Powheg
MC LO MadGraph
N
|cos θ*|

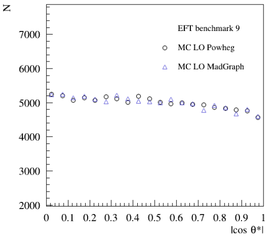
$\cos\theta^*$ @ LO

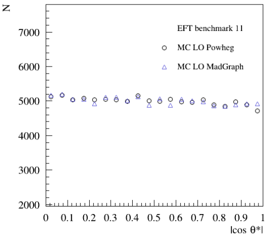

N
EFT benchmark 6
MC LO Powheg
MC LO MadGraph
|cos θ*|


N
EFT benchmark 8
MC LO Powheg
MC LO MadGraph
|cos θ*|

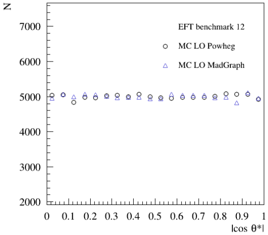

N
EFT benchmark 10
MC LO Powheg
MC LO MadGraph
|cos θ*|


N
EFT benchmark 7
MC LO Powheg
MC LO MadGraph
|cos θ*|


N
EFT benchmark 9
MC LO Powheg
MC LO MadGraph
|cos θ*|


N
EFT benchmark 11
MC LO Powheg
MC LO MadGraph
|cos θ*|

$\cos\theta^*$ @ LO



N
7000
6000
5000
4000
3000
2000
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
|cos θ*|
EFT benchmark 12
MC LO Powheg
MC LO MadGraph