H+jets part I

aMCSusHi: combining MG5_aMC@NLO with SusHi

Marius Wiesemann

University of Zürich

ERC miniworkshop

CERN (Switzerland), 1-2 June, 2015

aMCSusHi [Mantler, MW '15]

- Higgs production at NLO+PS
- Combines the enormous capabilities of MG5_aMC@NLO (no need to tell you about) with matrix elements provided by SusHi

SusHi (**Su**persymmetric **Hi**ggs) [Harlander, Liebler, Mantler '12], [Liebler '15]

- inclusive Higgs cross sections (y/p_T distributions at NLO/LO)
- $gg \to \phi$ (NLO full, NNLO htl, EW effects), 5FS $bb \to \phi$ (NNLO)
- models: SM, 2HDM, MSSM and NMSSM
- MoRe-SusHi (**Mo**mentum **Re**summed SusHi):
  Analytical p_T resummation [Mantler, MW '12], [Harlander, Mantler, MW '14]

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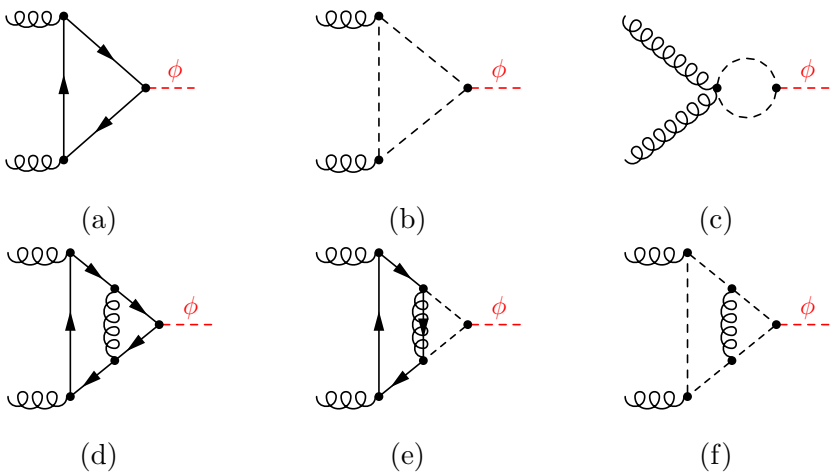
- MoRe-SusHi (**Mo**mentum **Re**summed SusHi): Analytical p_T resummation [Mantler, MW '12], [Harlander, Mantler, MW '14]
- Relevant for aMCSusHi: $gg \to \phi$ NLO Core of SusHi



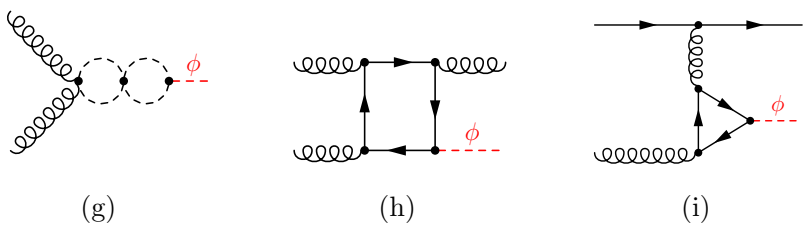


Figure 1: A sample of Feynman diagrams for $gg \to \phi$ contributing to the NLO cross section; (a-c) LO, (d-g) virtual and (h-i) real corrections. The graphical notation for the lines is: solid straight $\widehat{=}$ quark; spiraled $\widehat{=}$ gluon; dashed $\widehat{=}$ scalar (squark or Higgs); spiraled with line $\widehat{=}$ gluino.

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- setup extremely simple:

```
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```

aMCSusHi-script

```
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```

- <ggH-folder> must be subfolder of MG5_aMC@NLO
- sets up MG5_aMC@NLO $gg > h$ HEFT folder (no virtuals)

```
MG5_aMC>import model heft-no_b_mass
MG5_aMC>define p = p b b~
MG5_aMC>generate p p > h [real=QCD]
MG5_aMC>output <ggH-folder>
MG5_aMC>exit
```

- downloads and installs SusHi and FeynHiggs fully automatic (possible to provide their paths if already installed)
- links them to MG5_aMC@NLO and replaces matrix elements
  - adds SusHi and FeynHiggs libraries to makefile(s)
  - initializes SusHi in SOURCE/SETRUN.F
  - replaces matrix elements (born, virtuals, reals) in P0_* folders
- Running in <ggH-FOLDER> as in the ordinary MG5_aMC@NLO (except SusHi input blocks in param_card.dat)

Example for SM (Cards/param_card.dat):

```
#####################################
## INFORMATION FOR MASS
#####################################
Block mass
   15 1.777000e+00 # MTA
   23 9.118800e+01 # MZ
   25 1.250000e+02 # MH -- only effective if FEYNHIGGS Block is absent
[...]
#####################################
## INFORMATION FOR SMINPUTS
#####################################
Block sminputs
    1 1.325070e+02 # aEWM1
    2 1.166390e-05 # Gf
    3 1.180000e-01 # aS
# additional information needed for SusHi
    4 9.118760e+01 # m_Z(pole)
    5 0.416000e+01 # m_b(m_b)  -- only used if m_b is not on-shell
    6 1.730000e+02 # m_t(pole) -- top mass is set here
[...]
#####################################
## INFORMATION FOR SUSHI
#####################################
Block sushi
  1   0          # model: 0 = SM, 1 = MSSM, 2 = 2HDM
  2   0          # 0 = light Higgs (h), 1 = pseudoscalar (A), 2 = heavy Higgs (H)
Block renormbot # Renormalization of the bottom sector
  1   0          # m_b used for bottom Yukawa:  0 = OS, 1 = MSbar(m_b), 2 = MSbar(muR)
  4   4.75d0     # mbOS fixed -- used if m_b is on-shell (default)
Block factors
  1   0.d0       # factor for yukawa-couplings: c
  2   1.d0       # t
  3   1.d0       # b
```

aMCSusHi-folder (<ggH-folder>)

Example for 2HDM (Cards/param_card.dat):

```
#####################################
## INFORMATION FOR MASS
#####################################
Block mass
   25 1.250000e+02 # Higgs mass h for 2HDM in SusHi
   35 3.000000e+02 # Higgs mass H for 2HDM in SusHi
   36 2.700000e+02 # Pseudoscalar Higgs mass A for 2HDM in SusHi
[...]
#####################################
## INFORMATION FOR SUSHI
#####################################
Block sushi
  1    2          # model: 0 = SM, 1 = MSSM, 2 = 2HDM
  2    2          # 0 = light Higgs (h), 1 = pseudoscalar (A), 2 = heavy Higgs (H)
Block renormbot # Renormalization of the bottom sector
  1    0          # m_b used for bottom Yukawa:  0 = OS, 1 = MSbar(m_b), 2 = MSbar(muR)
  2    2          # tan(beta)-res. of Y_b: 0 = no, 1 = naive, 2 = full (for OS only)
  4    4.75d0     # mbOS fixed
Block 2hdm # 2HDM version according to arXiv:1106.0034
  2               # (1=I,2=II ,3=III ,4=IV)
Block minpar
  3    50d0       # tanb
Block alpha
  0.0247d0        # mixing in Higgs sector
Block factors
  1    0d0        # factor for yukawa-couplings: c
  2    1d0        # t
  3    1d0        # b
```

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- What can we compute?

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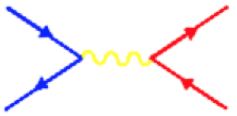
- What can we compute?
  - official version: NLO+PS Higgs cross sections in SM (top+bottom mass effects), 2HDM and MSSM
  - consistent treatment of all MSSM parameter (`FeynHiggs` link)
  - any (new) `SusHi` capabilities available (eg, $\tan\beta$ resummation)
  - already available but yet to be published: NMSSM (in collaboration with Stefan Liebler)

https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/aMCSushi

MadGraph



aMCSusHi: Hadronic Higgs production through NLO+PS in the SM, the 2HDM and the MSSM

This page contains the code to generate events for Higgs production at the LHC through gluon fusion.

NLO+PS Higgs production via gluon fusion (g g > h) in the SM with exact quark masses and in 2HDM/MSSM is built by a script. The script has to be used directly in the main folder (of the proper version) of MadGraph5_aMC@NLO (MG5_aMC homepage). The matrix elements are taken from SusHi (SusHi homepage). Compiled versions of SusHi and FeynHiggs (FeynHiggs homepage) are required. These codes can be either downloaded and installed automatically by this script or set up by the user beforehand. The script then modifies the proper MG5_aMC files and links SusHi and FeynHiggs.

More information can be found in the README.

Authors : Hendrik Mantler and Marius Wiesemann

Reference:

Hadronic Higgs production through NLO+PS in the SM, the 2HDM and the MSSM

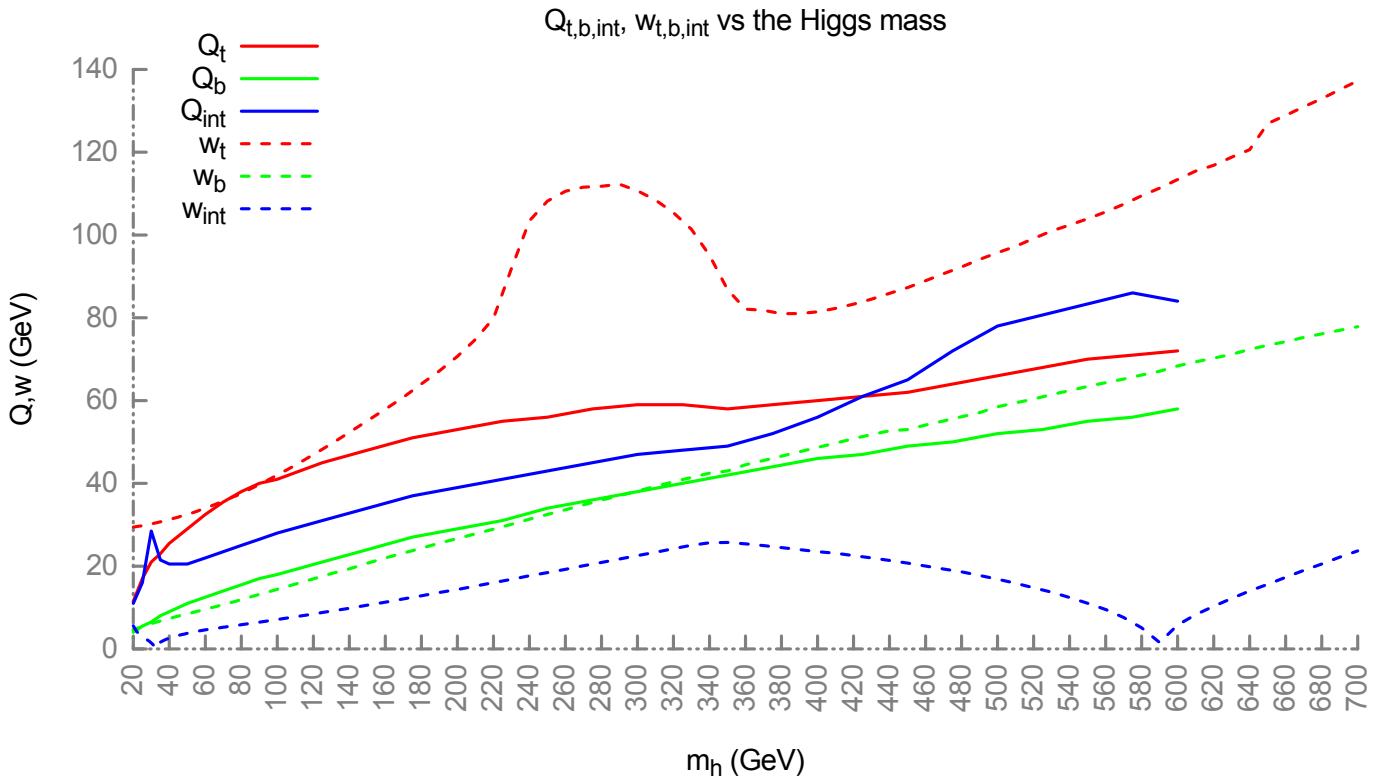
H. Mantler and M. Wiesemann. Apr 28, 2015. 25 pp.

e-Print: arXiv:1504.06625 [hep-ph]

Download instructions and script here

NLO+PS Higgs production: Matching Scales

- b-loop: non-factorizing terms for $p_T > m_b$ [Grazzini, Sargsyan '13]
- treatment as finite remainder [Banfi, Monni, Zanderighi '13]
- adjustment of matching scales (generally lower than for top quark) [Harlander, Mantler, MW '14], [Bagnaschi, Vicini '15]



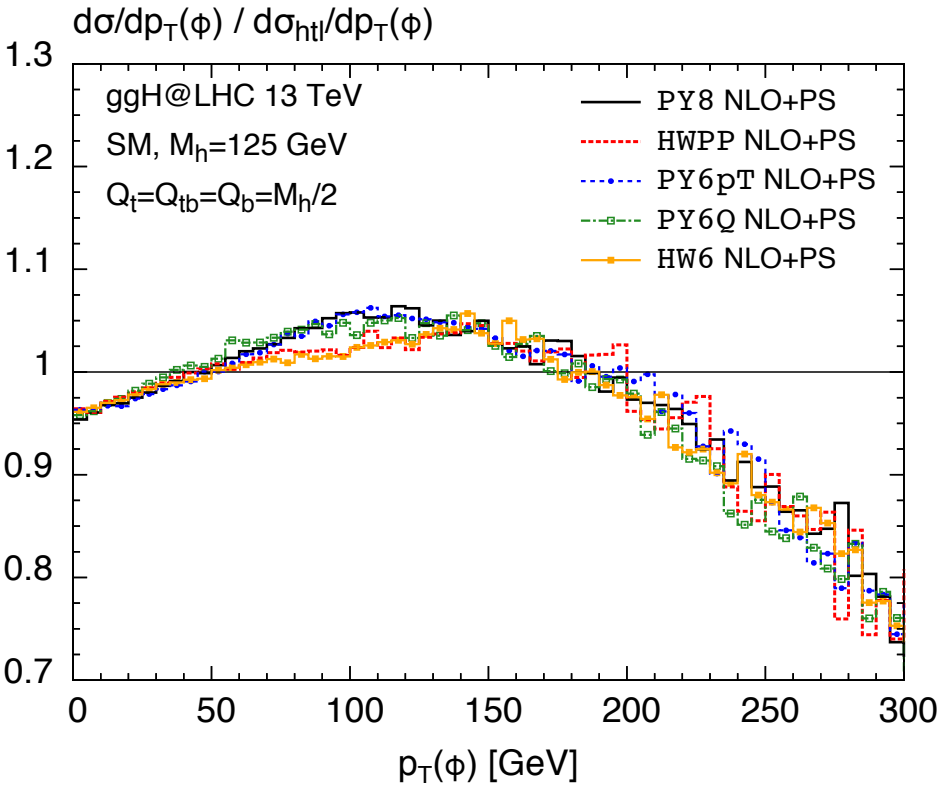
- ongoing comparison of scales and tools (applying `aMCSusHi`)

  [Bagnaschi, Harlander, Mantler, Vicini, MW 'to be published]

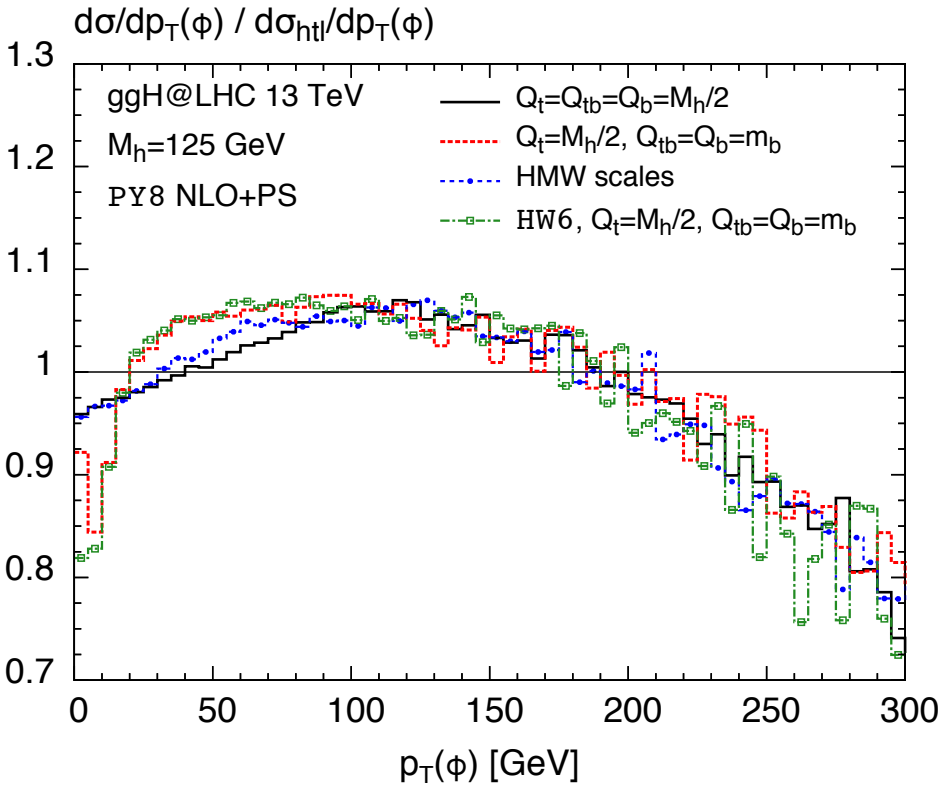
Results: NLO+PS Higgs production [Mantler, MW '15]

SM mass effects (full theory/heavy top limit)

different Monte Carlos



different scales



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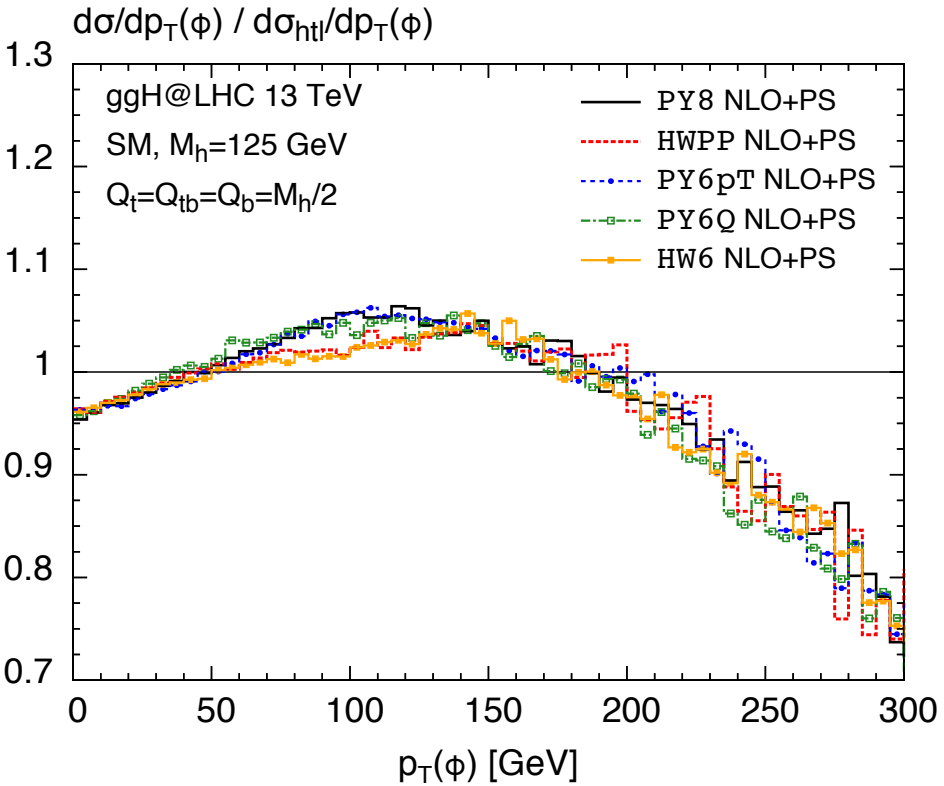

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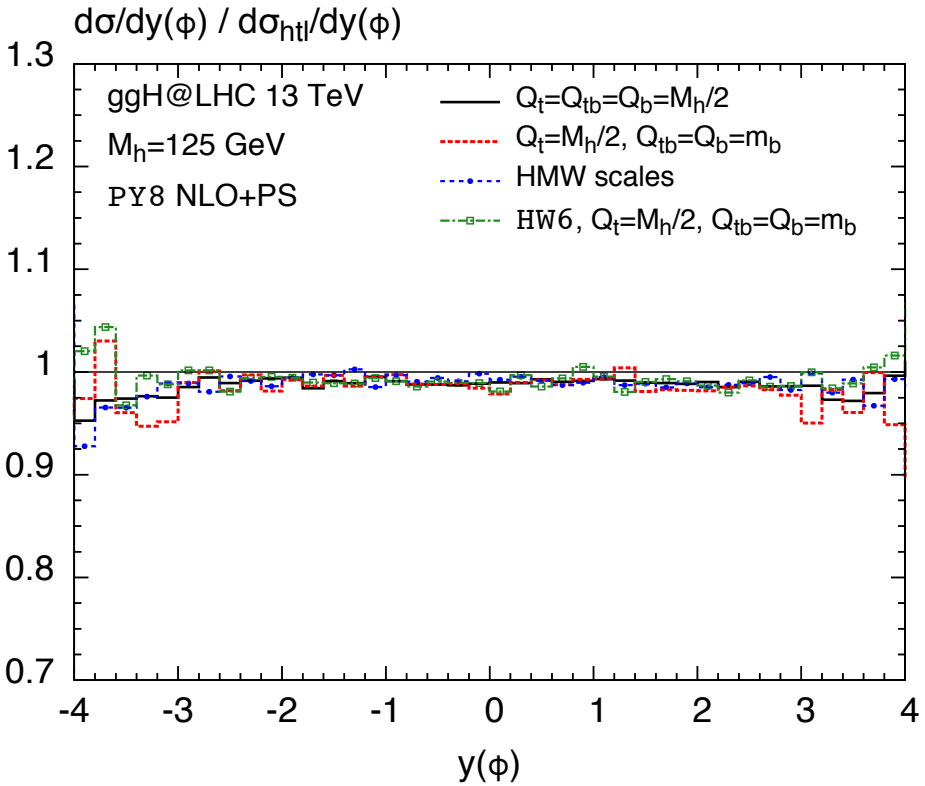

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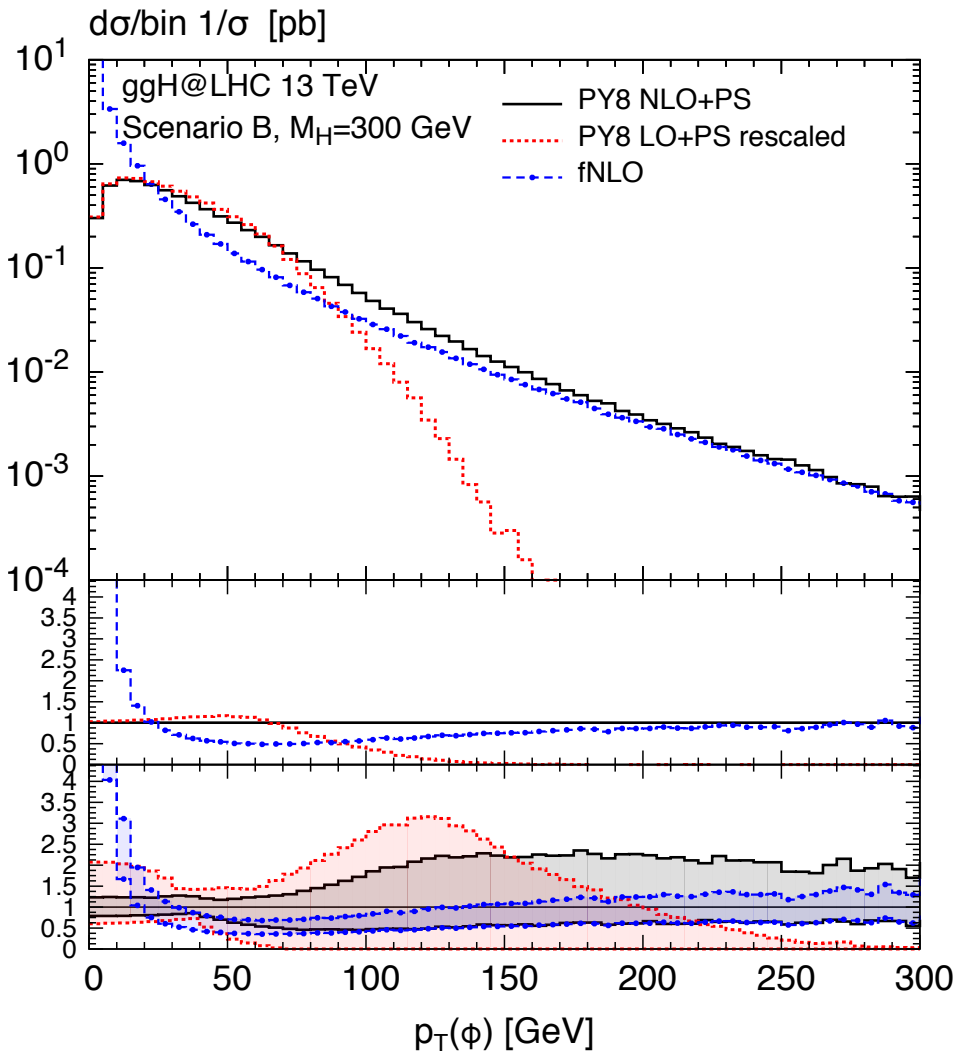
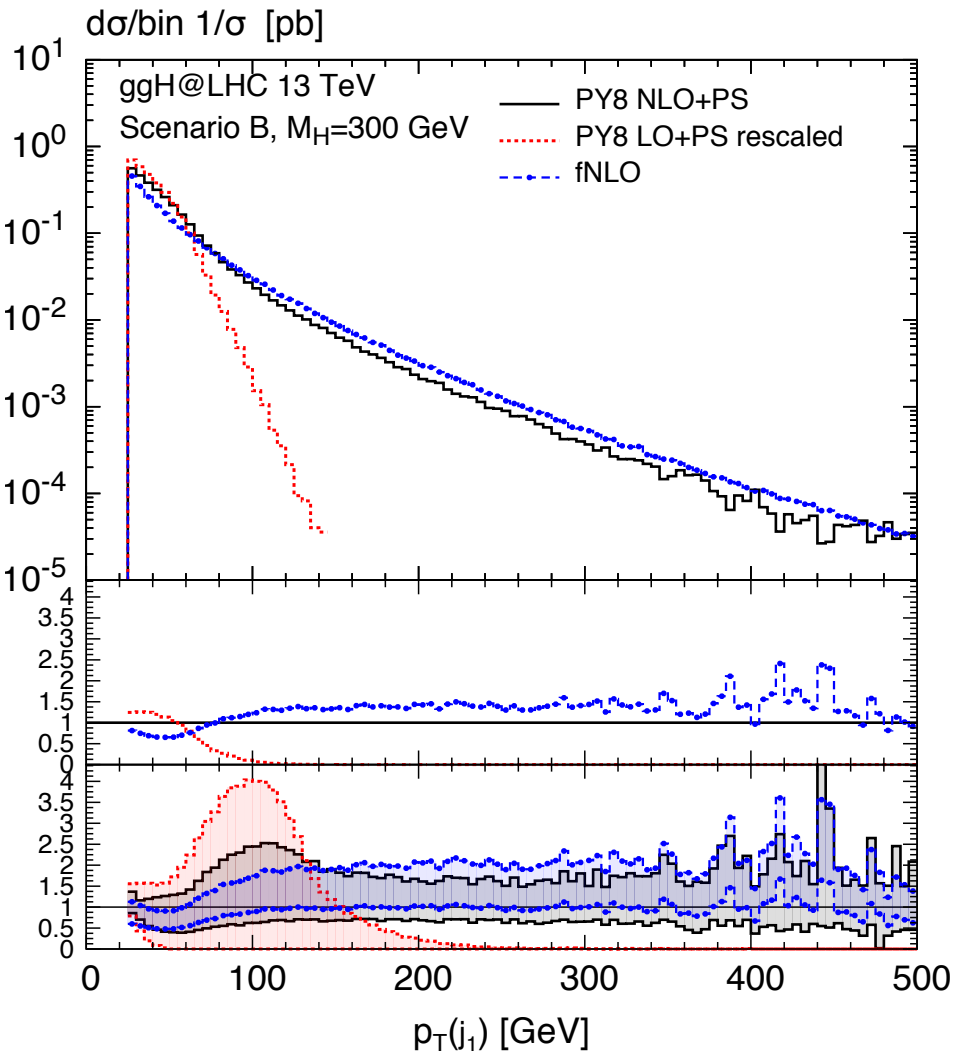
Heavy Higgs boson
in bottom-loop dominated 2HDM scenario





Higgs+jets in SM: Merging higher multiplicities (FxFx)

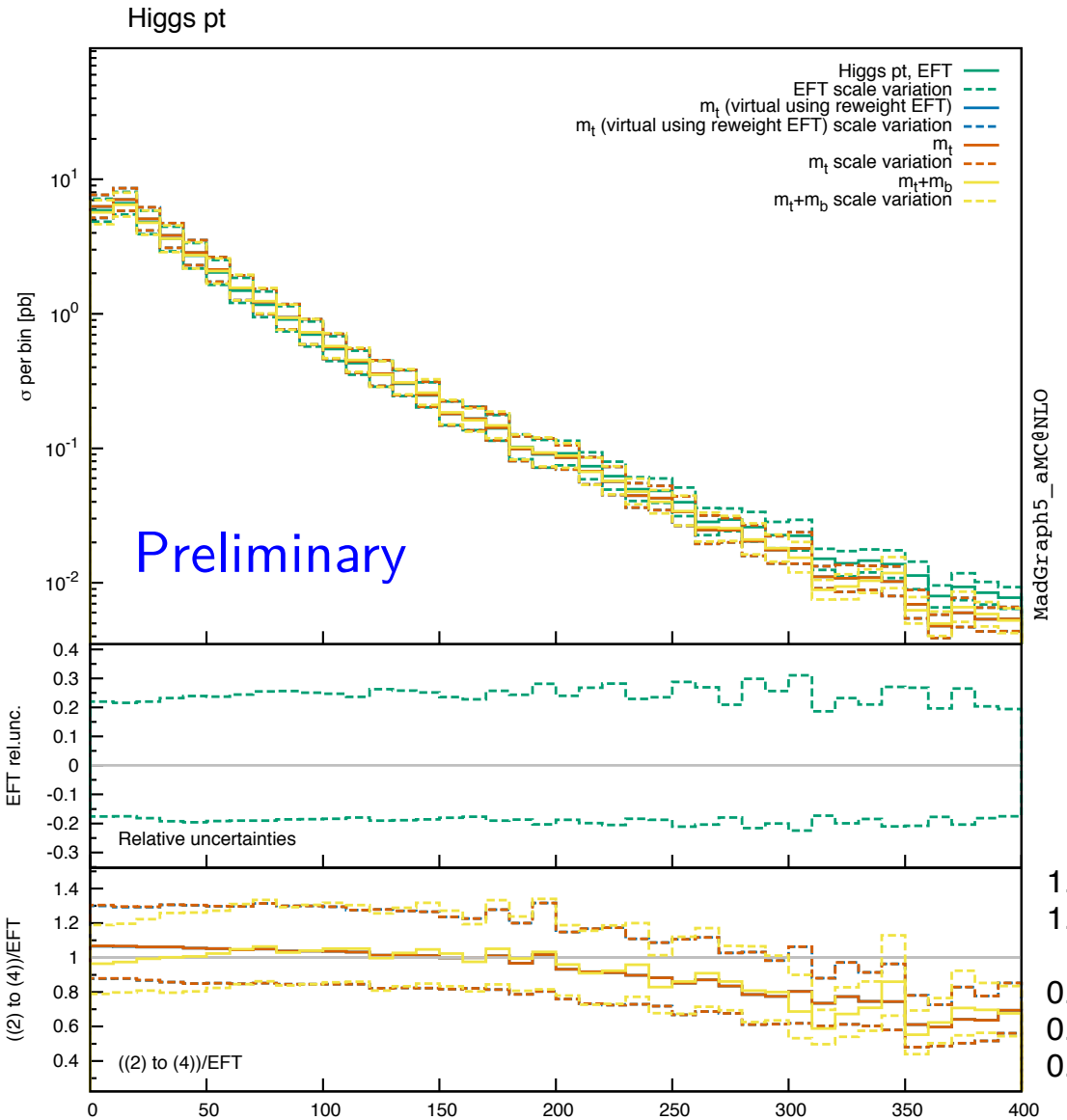
in collaboration with Rikkert Frederix, Stefano Frixion and Eleni Vryonidou

- We use the HEFT-NLO model
- 0-jet NLO exact matrix elements from `aMCSusHi` (modified script for HEFT-NLO model)
- FxFx merging of 1 and 2 jets at NLO in HEFT
- replacing all one-loop contributions by exact top mass (details by Eleni)
- how to account for bottom-quark loop?
  merged top result + bottom and interference from `aMCSusHi`:

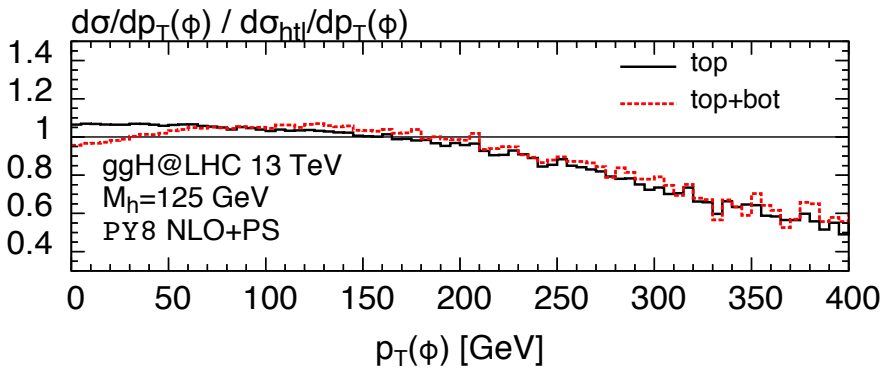
$$\sigma_{(y_t+y_b)^2} = \sigma_{y_t^2}(0,1,2\text{-jet},\text{FxFx}) + \sigma_{y_t\, y_b}(0\text{-jet}, Q_{tb}) + \sigma_{y_b^2}(0\text{-jet}, Q_b)$$

Results: Combination of top (merged) and bottom (0-jet)

0,1-jet merged:



aMCSusHi:



to be continued by Eleni...

H+jets Part II
Merging higher multiplicities at NLO with top mass effects

Eleni Vryonidou
Université catholique de Louvain

In collaboration with: R. Frederix, S. Frixione and M. Wiesemann

ERC Miniworkshop
CERN, 1/6/15

Higgs plus jets at NLO

Available relevant pieces:

- H+0jet contribution computed exactly at NLO and matched to the parton shower with aMCSushi (see Marius' talk, arxiv:1504.06625)
- H+1,2… jets available at NLO in the HEFT (HC model: arxiv:1306.6464)
- Merging possible at NLO in MG5_aMC@NLO with FxFx (arxiv:1209.6215)
- Possibility to compute 1-loop amplitudes for H+1,2,3 jets with MadLoop

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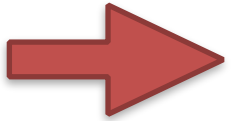
✺ Higher multiplicity samples provide better description of hard emissions which are poorly described by the parton shower

✺ Top mass effects also important in the high p_T tails

The main idea

Combine 1) the exact 0j NLO result: top and bottom included (aMCSusHi)
2) higher multiplicities at NLO in HEFT



Merged H+jets NLO samples with FxFx

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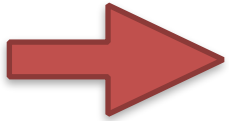

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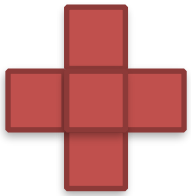


Include the **exact top mass dependence in the real corrections** of the higher multiplicities
2-loop amplitudes only available for H+0j:
Born-normalised HEFT virtual corrections for all higher multiplicities

(similar to what we did for HH arxiv:1408.6542,1407.0281,1401.7340)

Technical details (1)

Direct generation at NLO with loop-induced processes not feasible:

- extremely time consuming due to PS scanning with loop amplitudes
- possibly unstable due to loop instabilities in the soft and collinear regions

Reweighting is currently the only viable option:
i.e. generate all the events in HEFT and adjust weights afterwards

- Use weights stored internally for scale and pdf reweighting (arxiv:1110.4738)

- New intermediate event format in version 2.3 allows easier identification of various weights:

$$d\sigma^{(\mathbb{H})} = d\phi_{n+1}\left(\mathcal{R} - \mathcal{C}_{MC}\right) ,$$
$$d\sigma^{(\mathbb{S})} = d\phi_{n+1}\left[\left(\mathcal{B} + \mathcal{V} + \mathcal{C}^{int}\right)\frac{d\phi_n}{d\phi_{n+1}} + \left(\mathcal{C}_{MC} - \mathcal{C}\right)\right]$$

MC@NLO formalism

i.e. Born, real, virtual, counterterms

$$\begin{array}{rcl} \mathcal{B}, \mathcal{V}, \mathcal{C}^{(int)}, \mathcal{C}_{MC} & \times & \mathcal{B}_{FT}/\mathcal{B}_{HEFT} \\ \mathcal{R} & \times & \mathcal{R}_{FT}/\mathcal{R}_{HEFT} \end{array}$$

New event weight

Technical details (2)

Each weight accompanied by the PDG numbers of the particles in the relevant process: i.e. weight associated with g g > h g g comes with a “21 21 25 21 21” tag

Allows us to identify the relevant process and call the corresponding loop amplitude in a more straightforward way

1) Loop Amplitude library

Aim: To provide results for all 1-loop matrix elements (Born and real)

- Created and compiled beforehand using a script
- Input: all the processes (in PDG codes) that will be needed for H+1,2,3 jets
- Similar to the usual MadLoop standalone output but now all combined in a dynamic library (only tops in the loops)
- Library wrapper takes PDG codes as inputs, checks for permutations of PDG codes/ momenta to call the right amplitude

2) 0-jet contribution

- Not reweighted, obtained by linking the exact matrix elements (1-loop and 2-loop) from aMCSusHi (Marius’ talk)
- Top x bottom contribution and bottom^2 included
- Events generated separately, showered with the appropriate/different scales (1409.0531)
- Results added at the end at the plot level

Run setup and parameters

Merge H+0,1 jet (for now) at NLO

Automatic computation of the scale and pdf uncertainties (as usual in MG5_aMC@NLO)

$$\mu_{hard} \simeq m_T(H)$$

Merging scale variations: Q_{FxFx}=30, 45, 60 GeV
PYTHIA8 for the shower

Shower scales for various contributions:

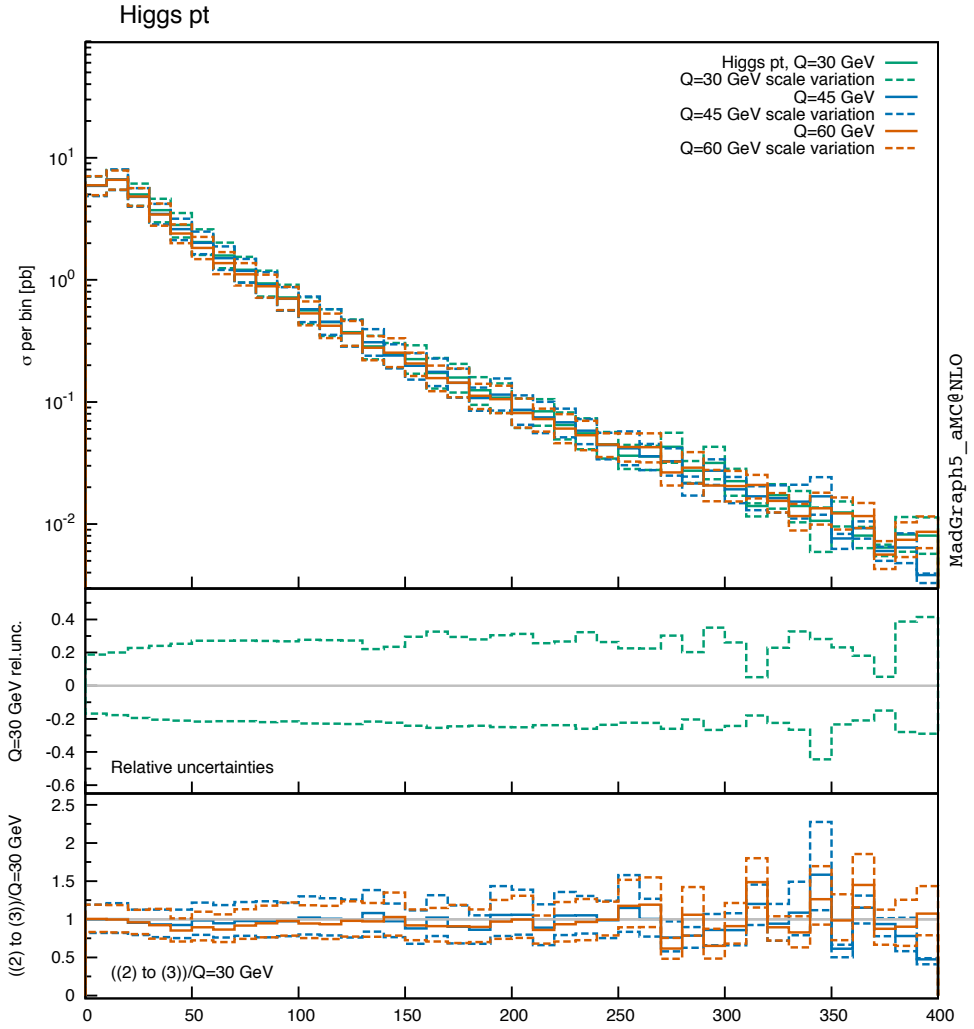
$$\langle Q_{sh}^{t^2} \rangle \sim \sqrt{\hat{s}}/2;\ \langle Q_{sh}^{b^2} \rangle = 23\ \text{GeV};\ \langle Q_{sh}^{b*t} \rangle = 34\ \text{GeV}$$ (arxiv:1409.0531)

Comparison only for H+0,1-jet samples for the moment:

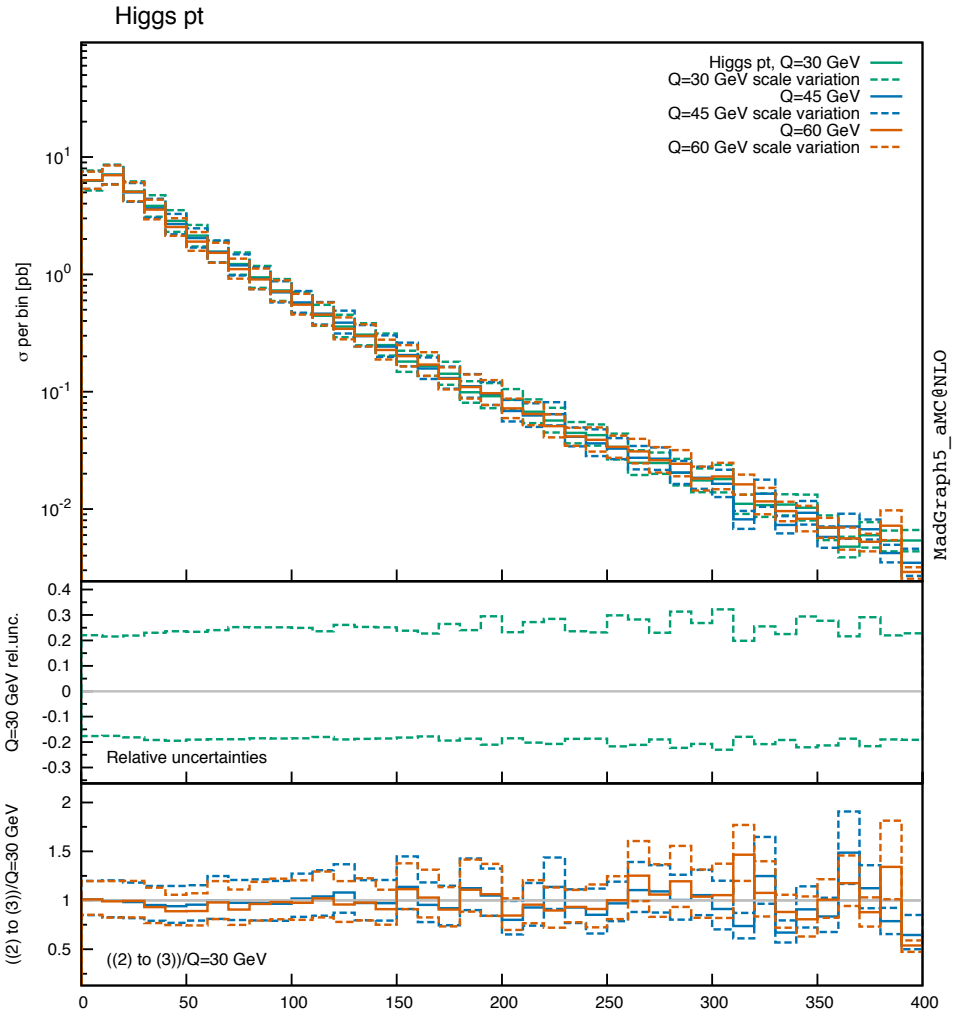
- top exact in reals, EFT-Born rescaled virtuals (all reweighted), no bottom
- top exact for 0-jet (from aMCSusHi)
- top and bottom exact for 0jet ("best" predictions)
- HEFT

Special thanks to Rikkert for all the plots
All results are preliminary

Merging scale variations



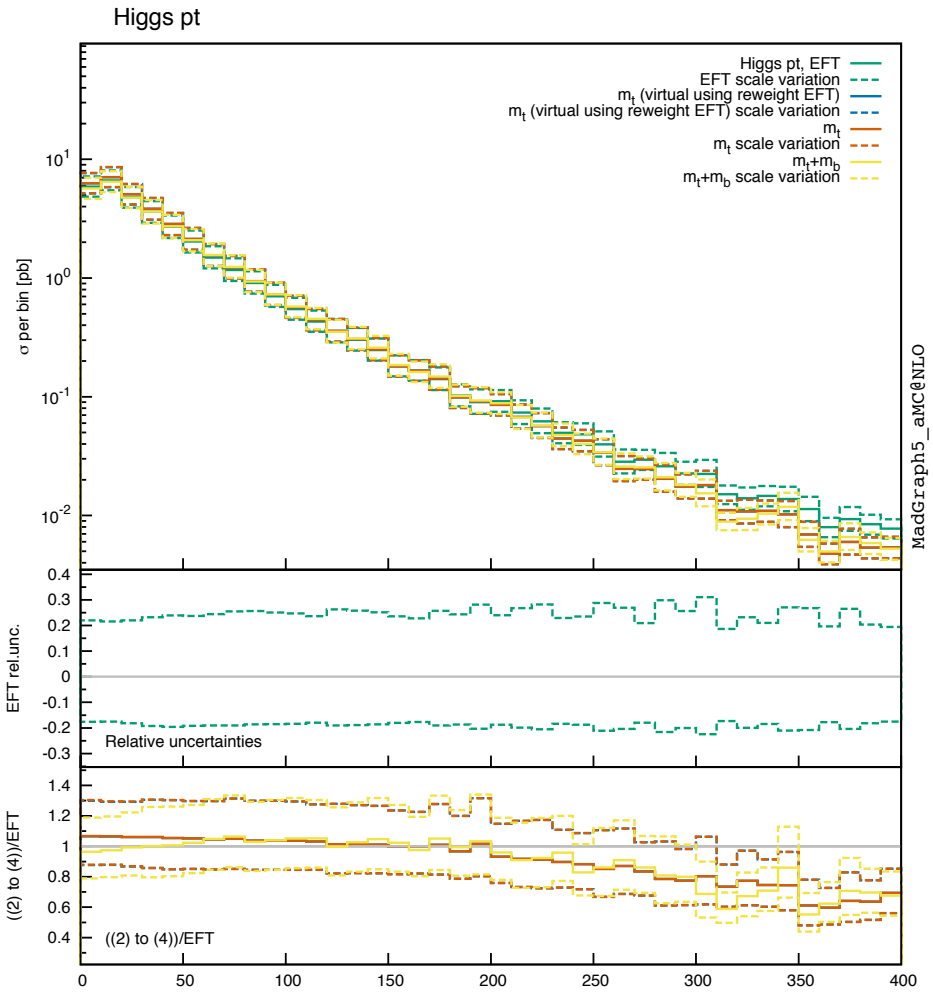
HEFT

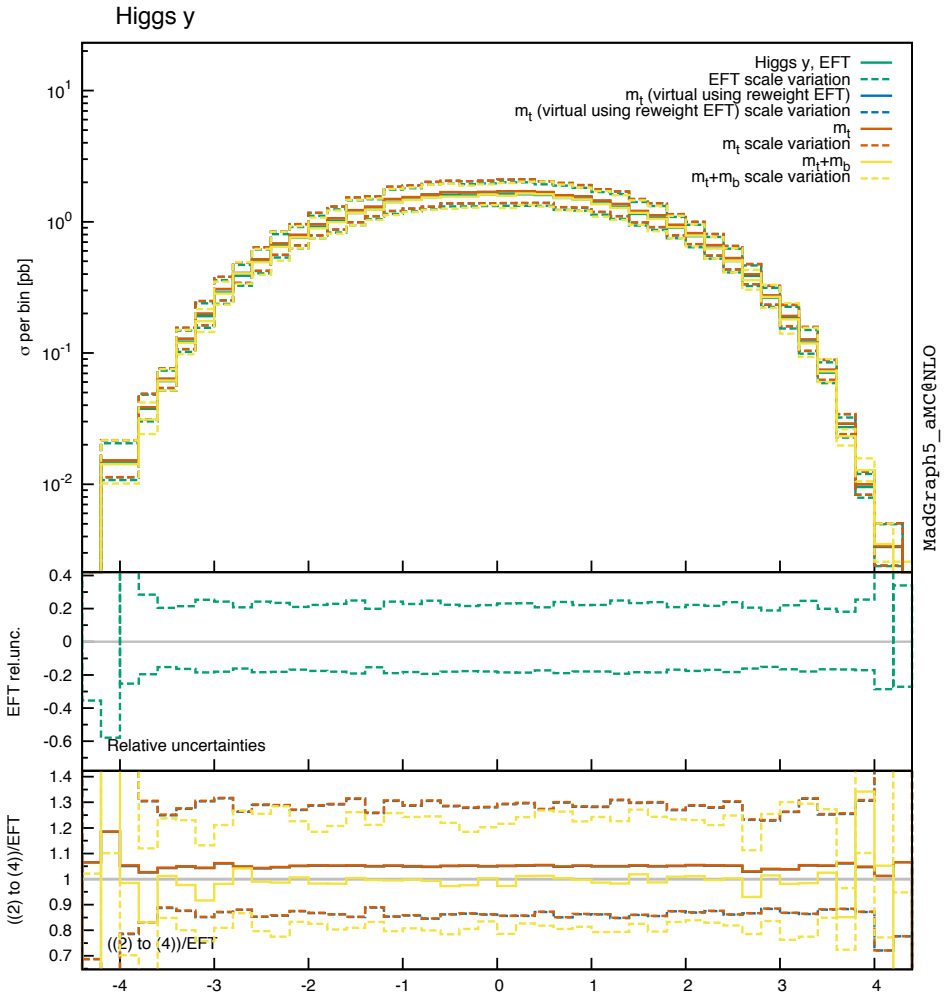


Mass effects included

Merging scale uncertainty always within the hard scale ($\mu_{R,F}$) variations

Results (1): Higgs pt and rapidity





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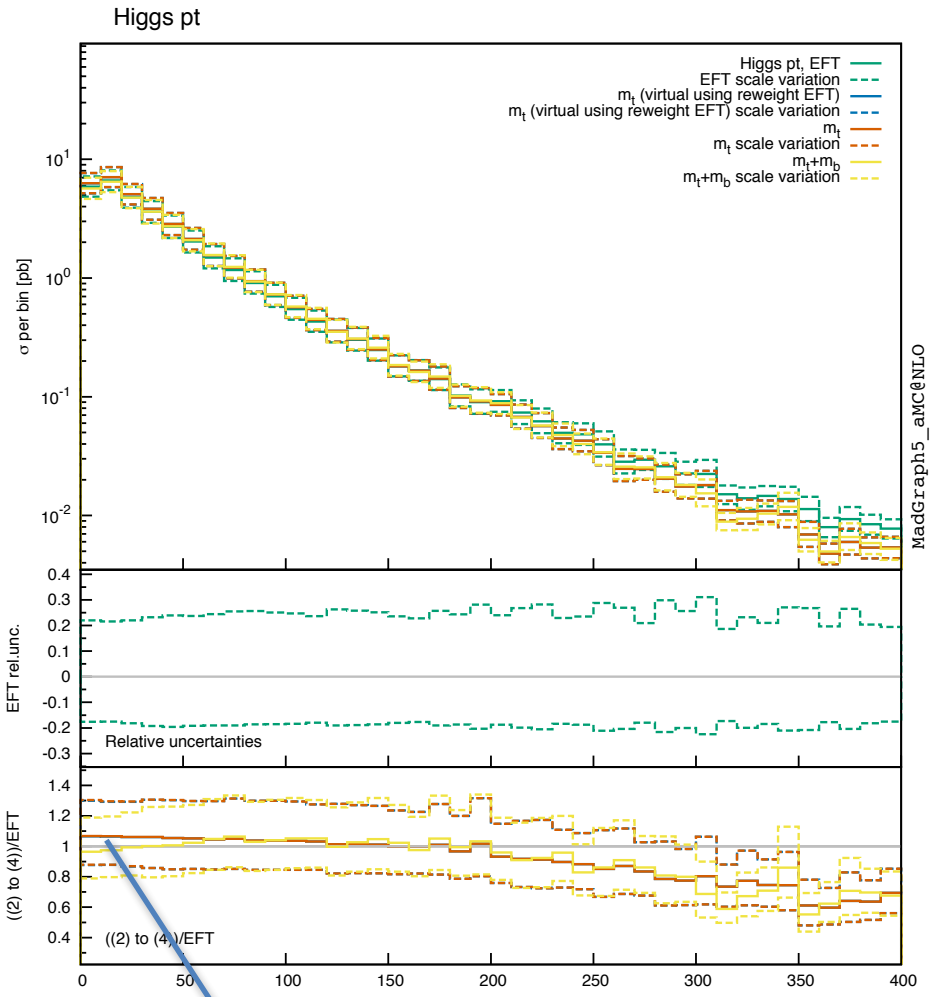

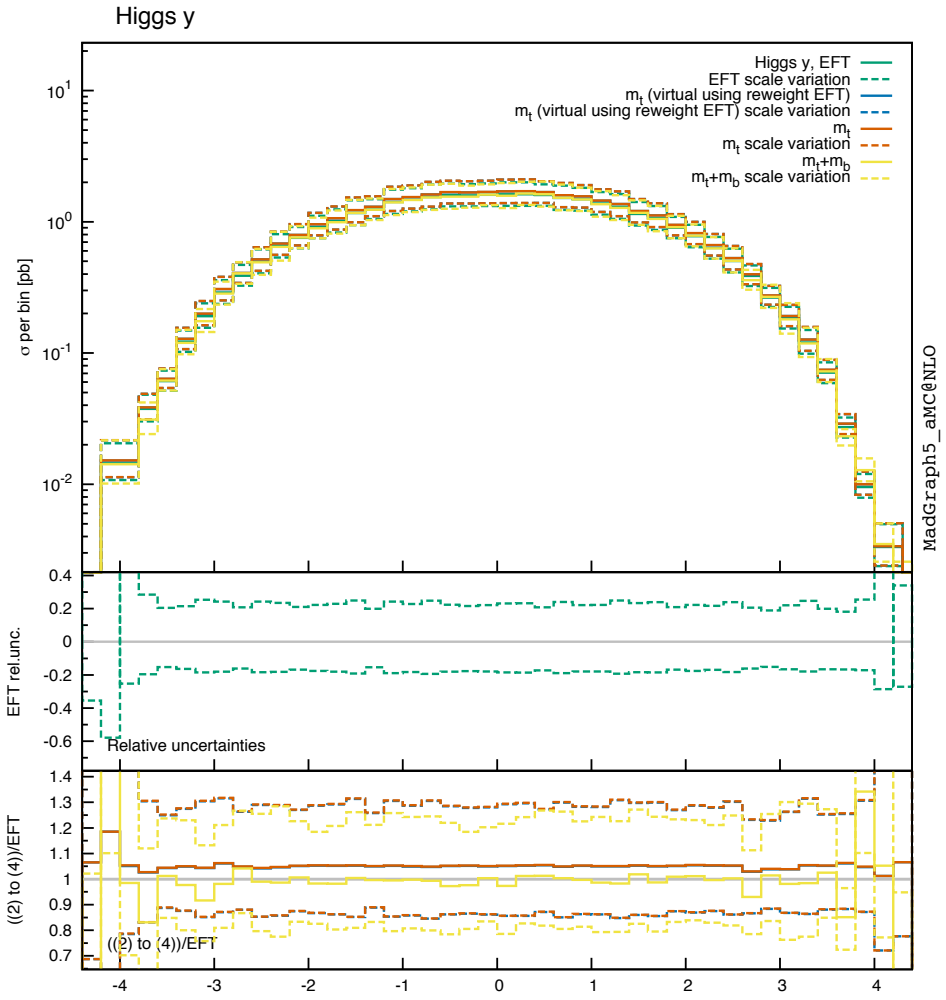

Bottom contribution relevant only at low p_T and in agreement with non merged results (as discussed by Marius)

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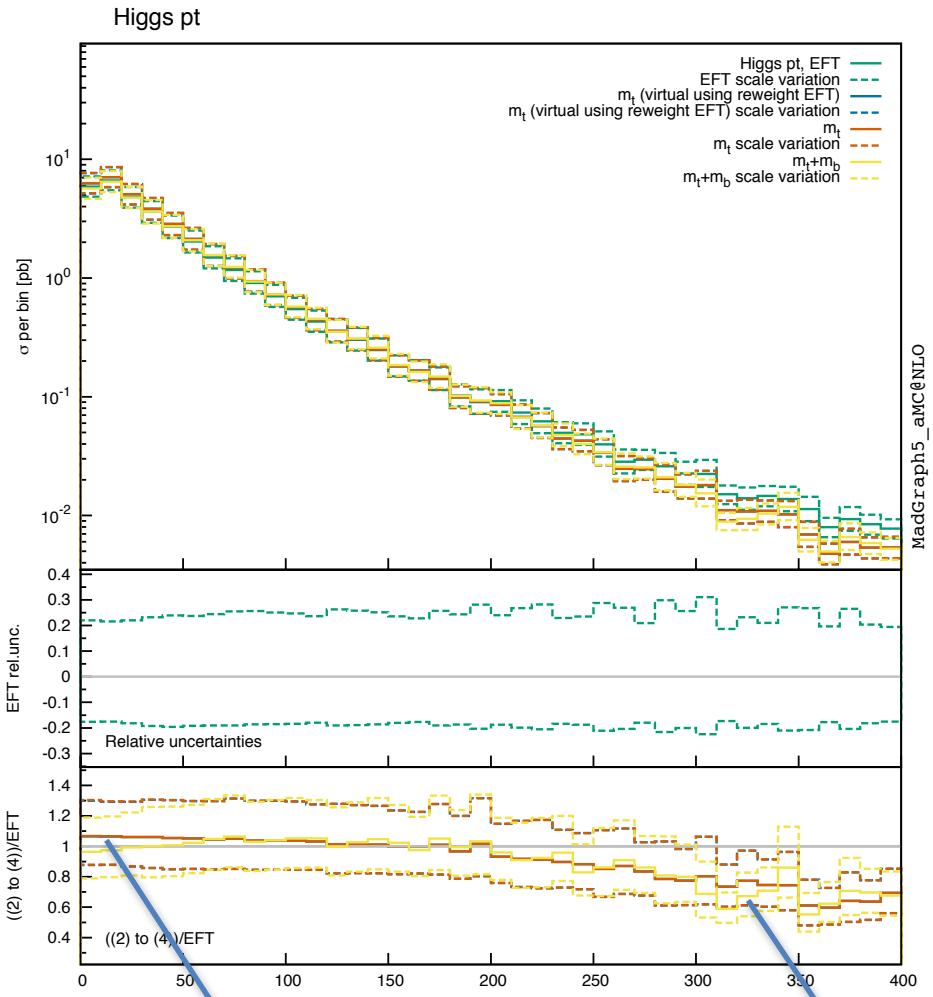

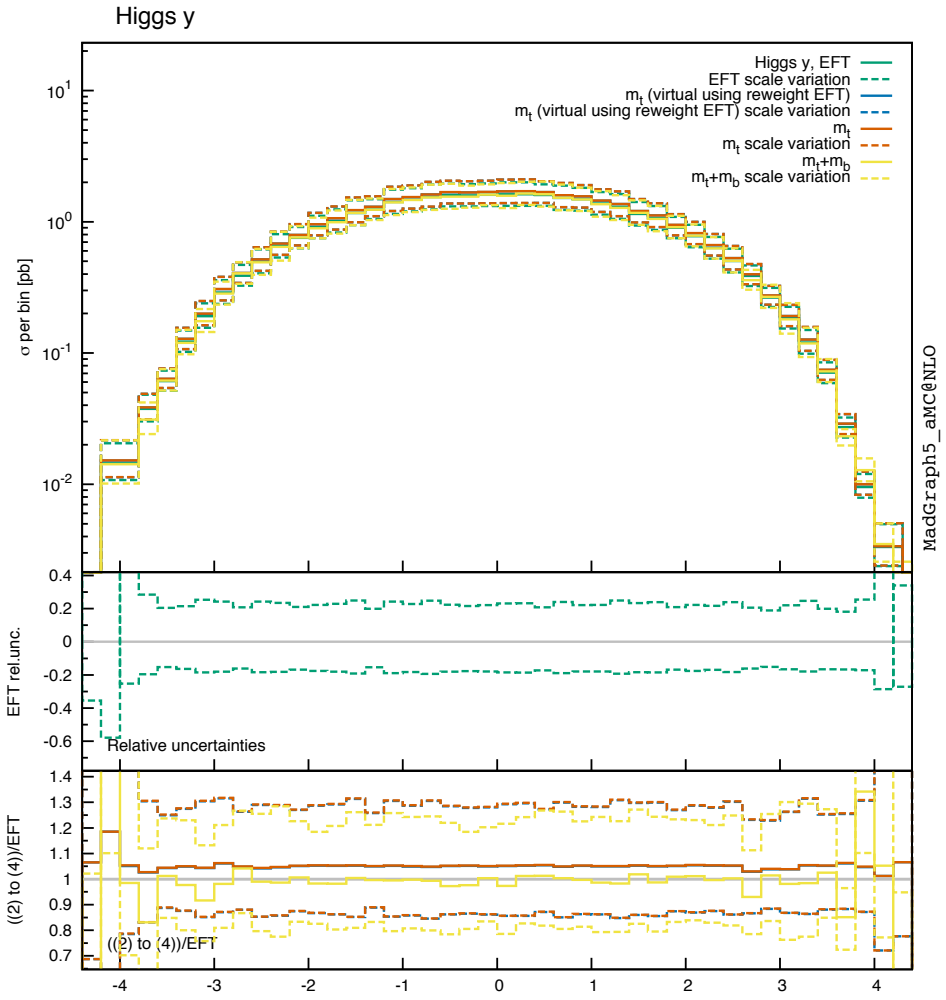

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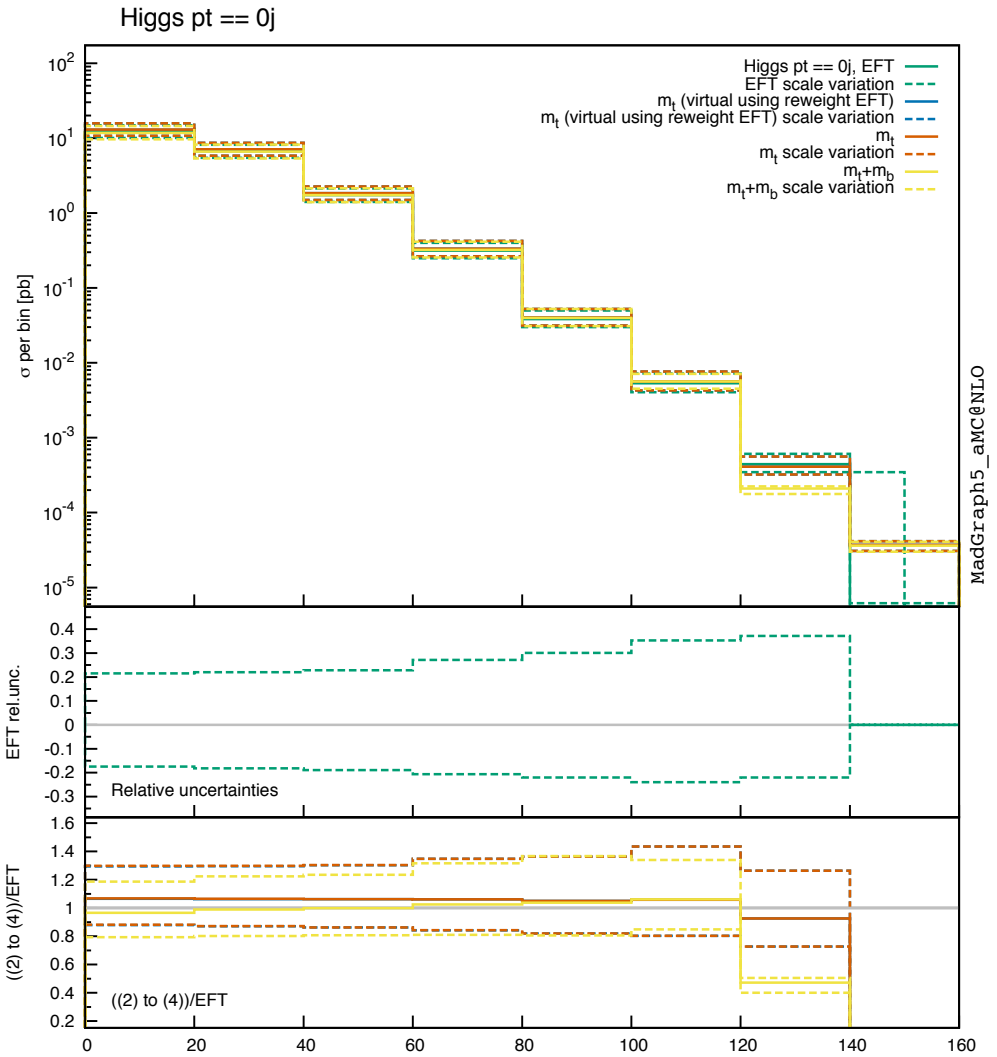
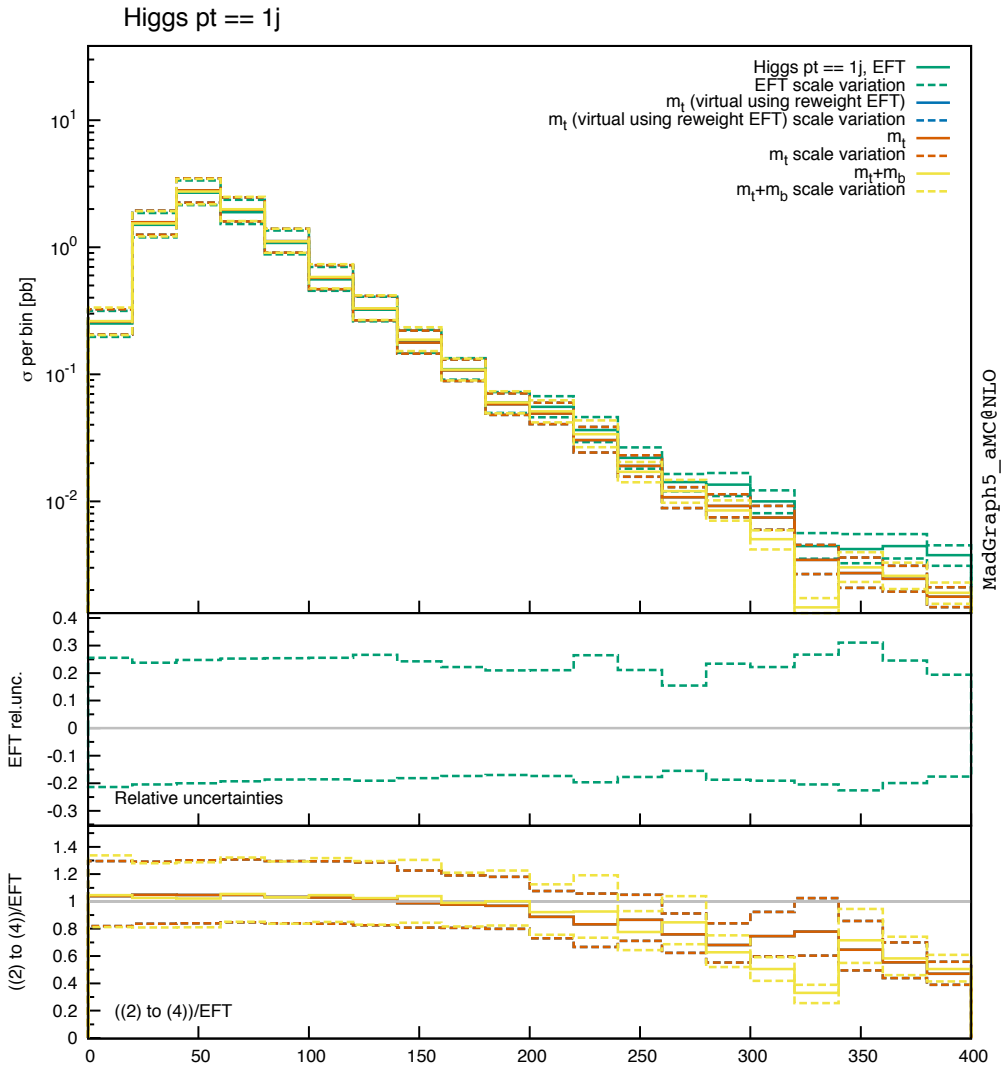
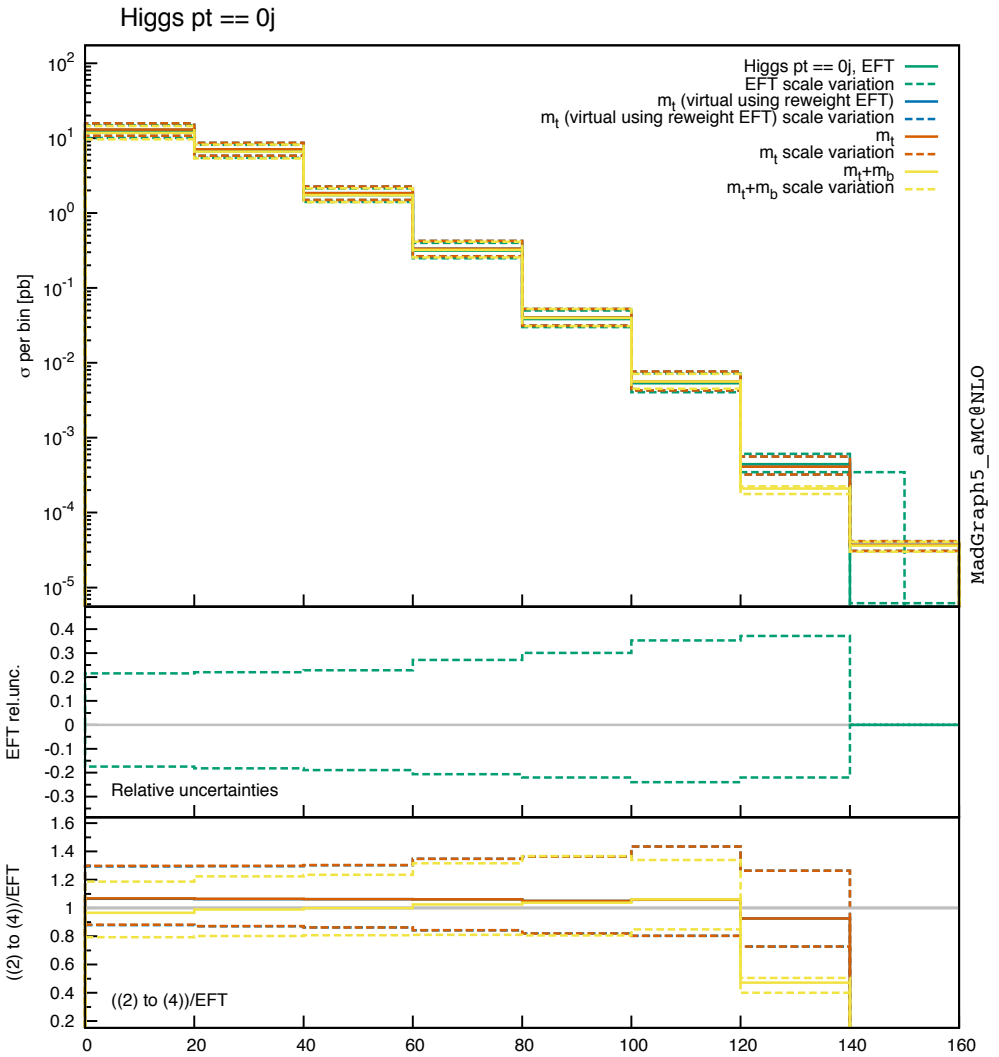
High p_T tail top mass effect

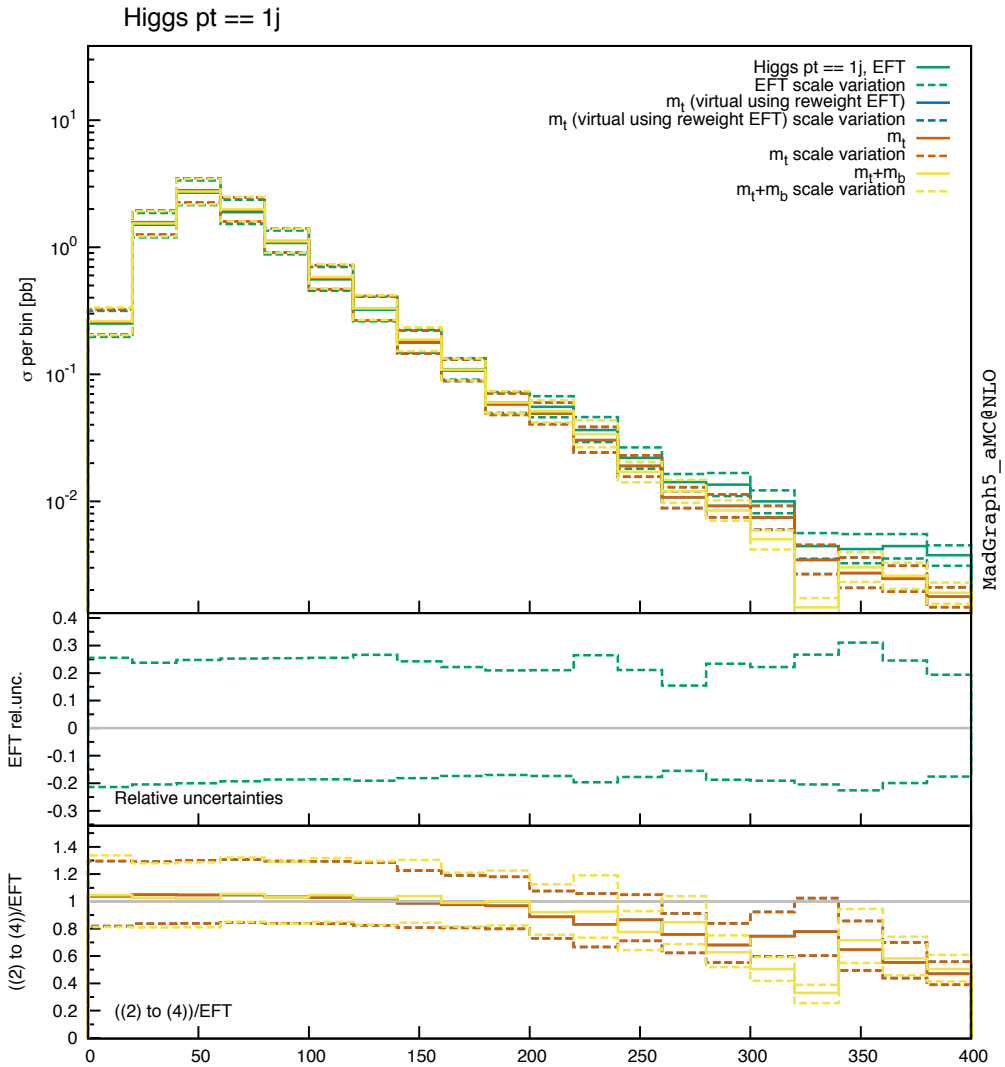
Results (2): Higgs p_T with jet binning





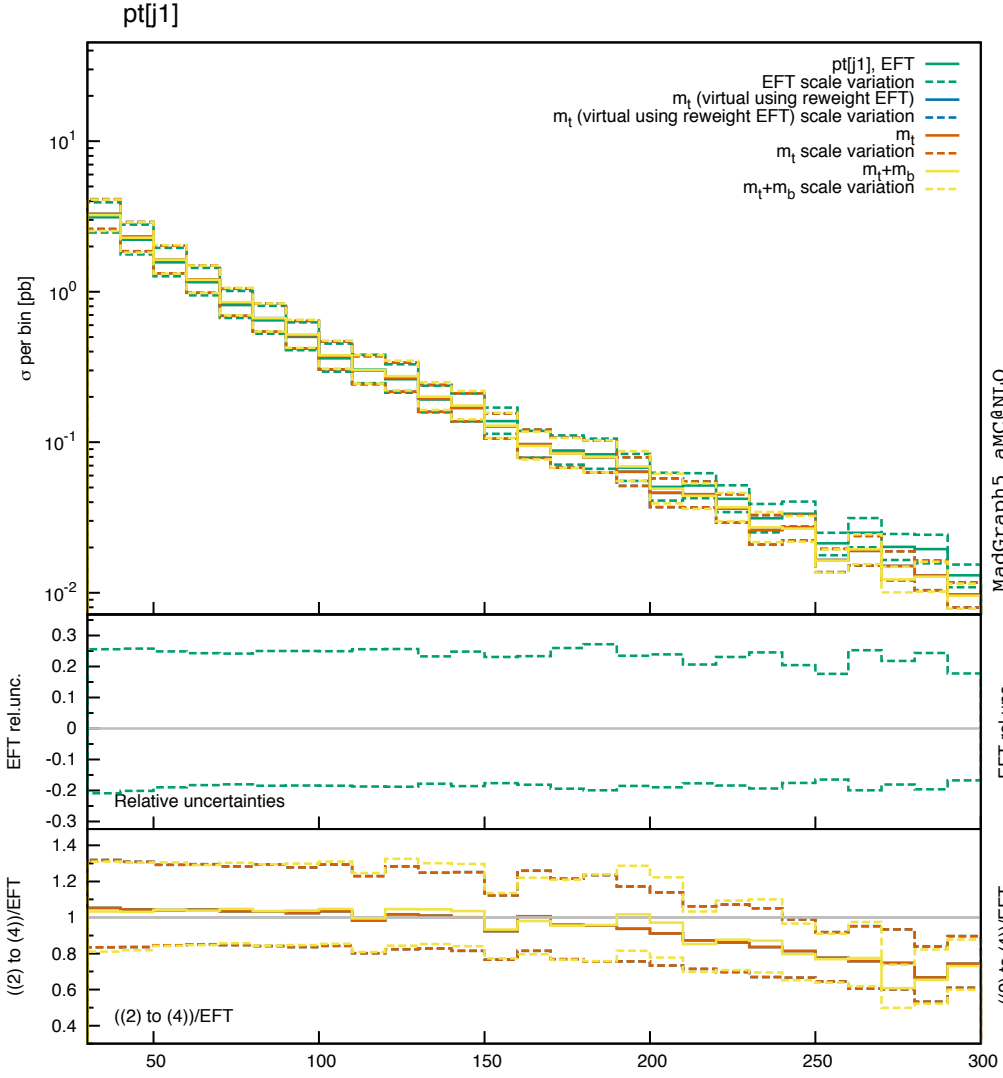
Results (2): Higgs p_T with jet binning

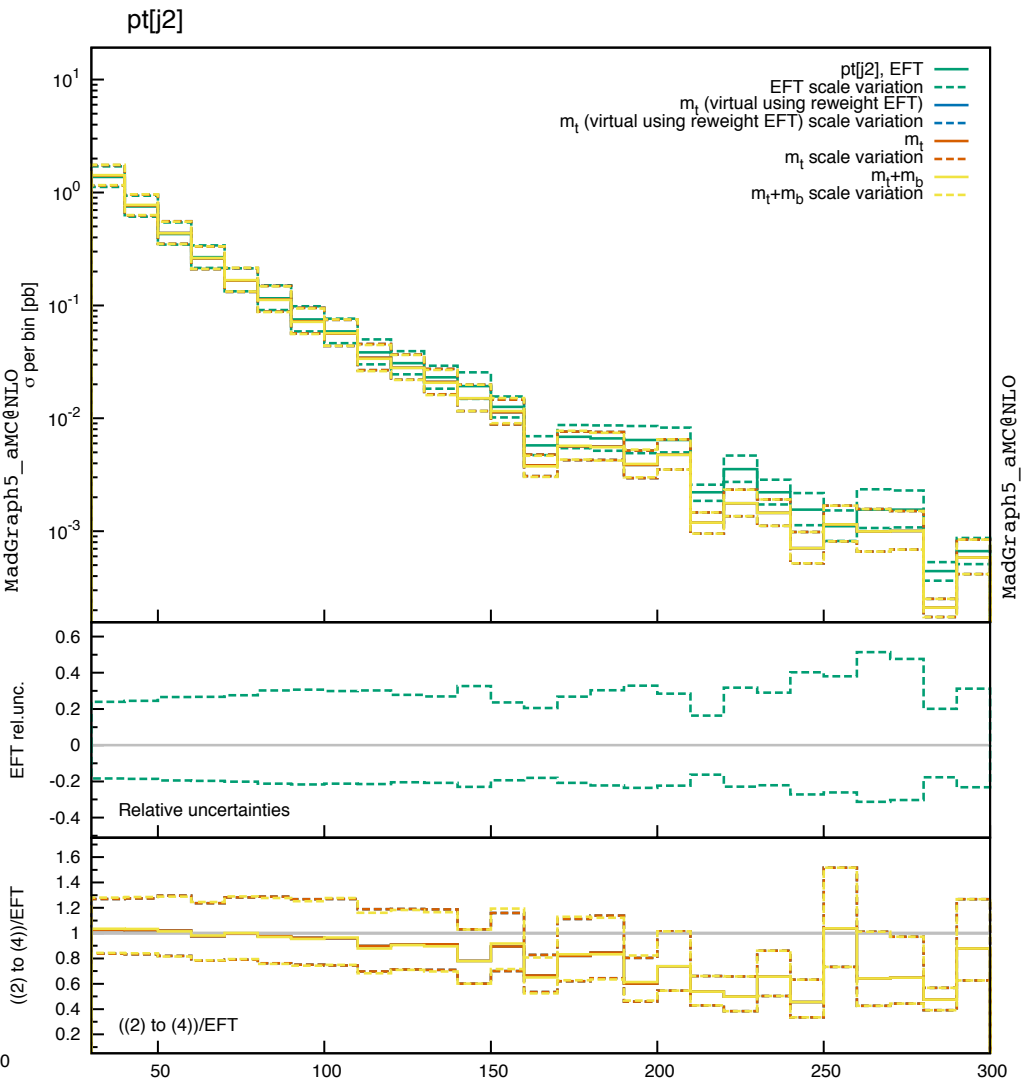




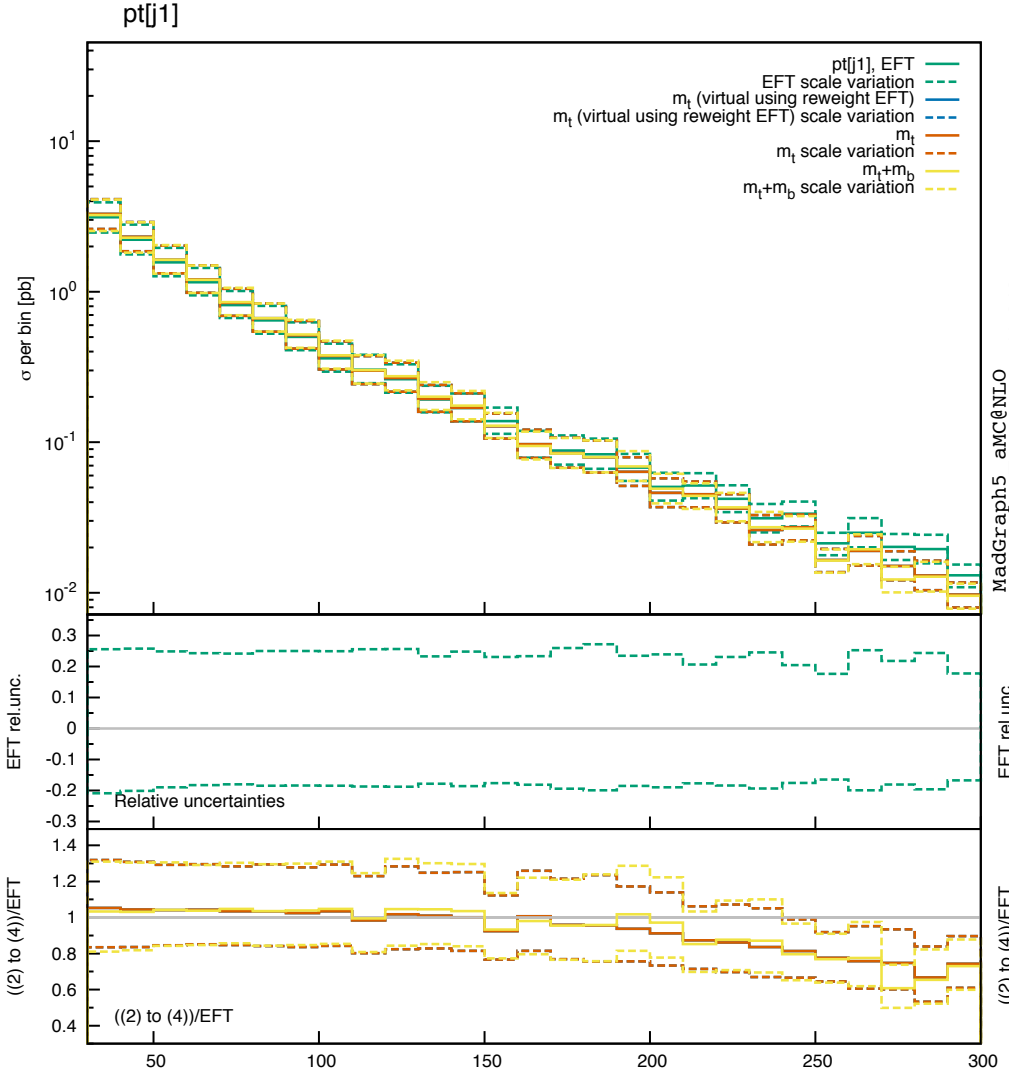
Top mass effects more important for 1-jet bin (30GeV p_T for the jets)
Two-loop virtual have a non-visible effect (blue → red)

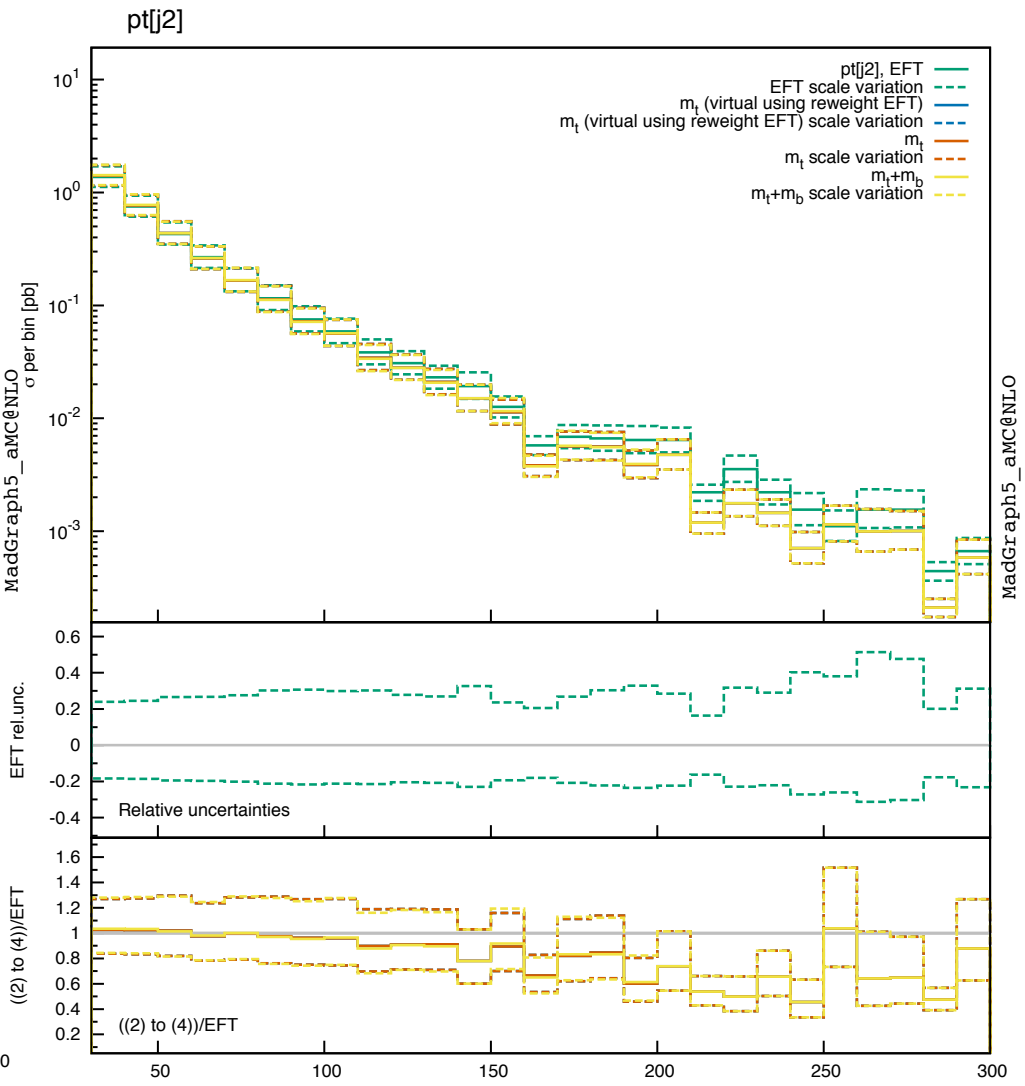
Results (1): Jets p_T





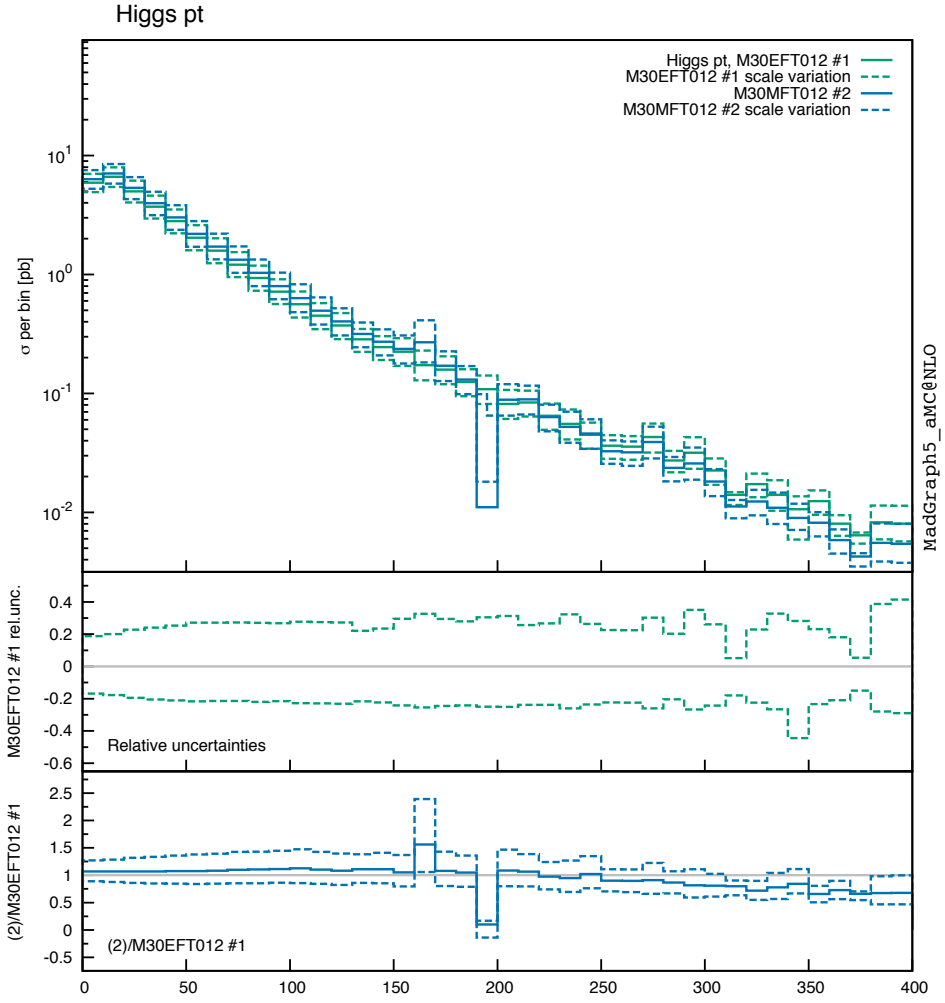
Results (1): Jets p_T

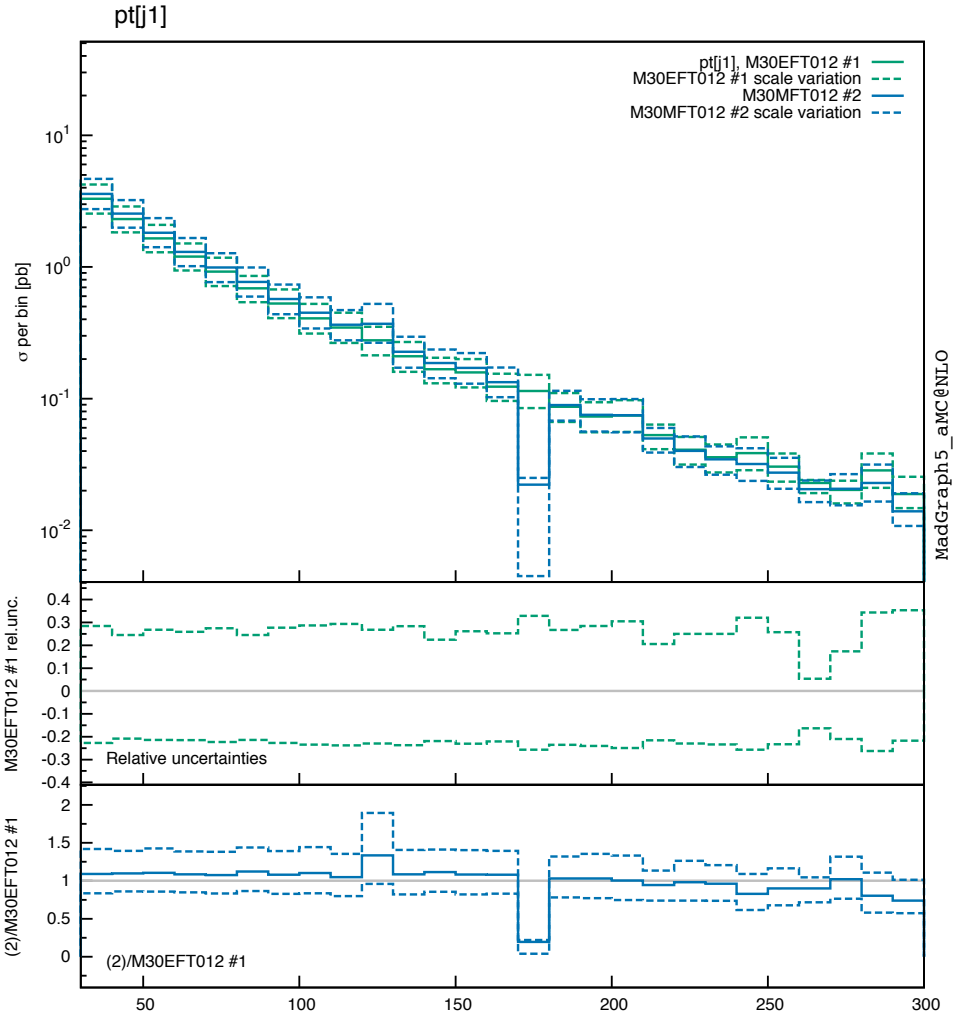




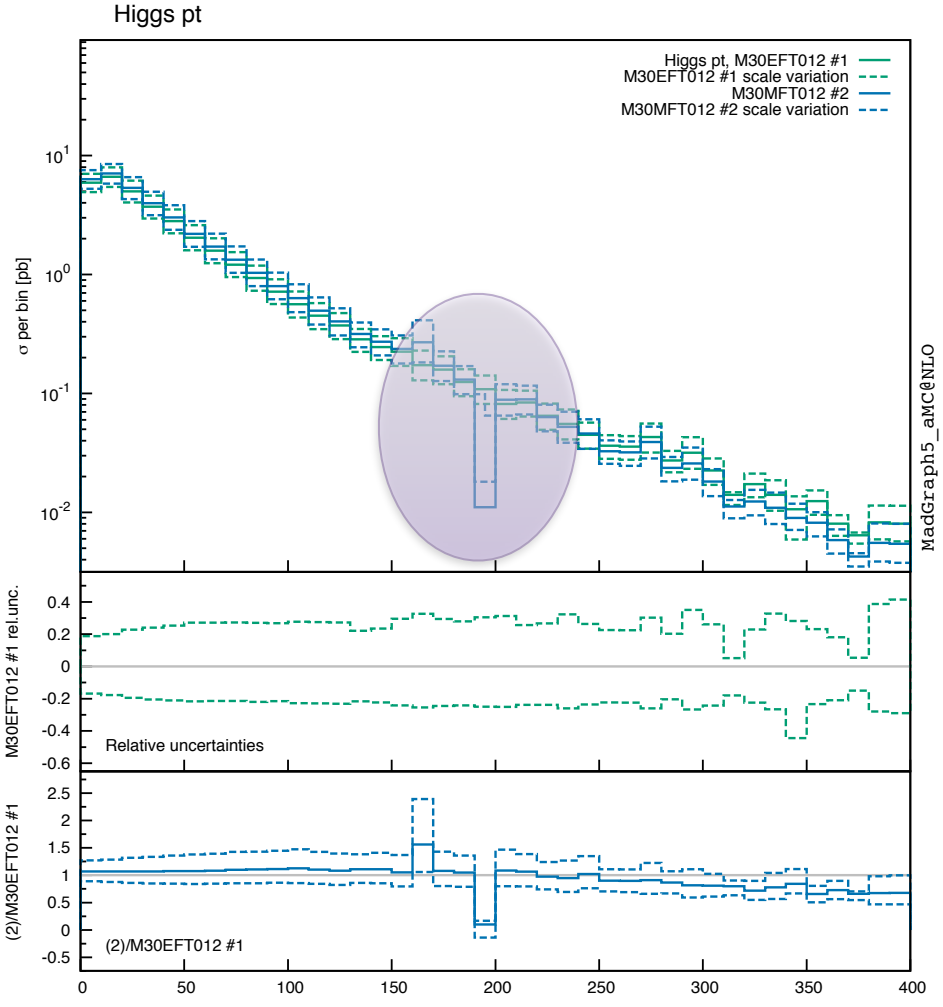
Again: top mass effects are important in the high pt tails with deviations reaching 30-40%

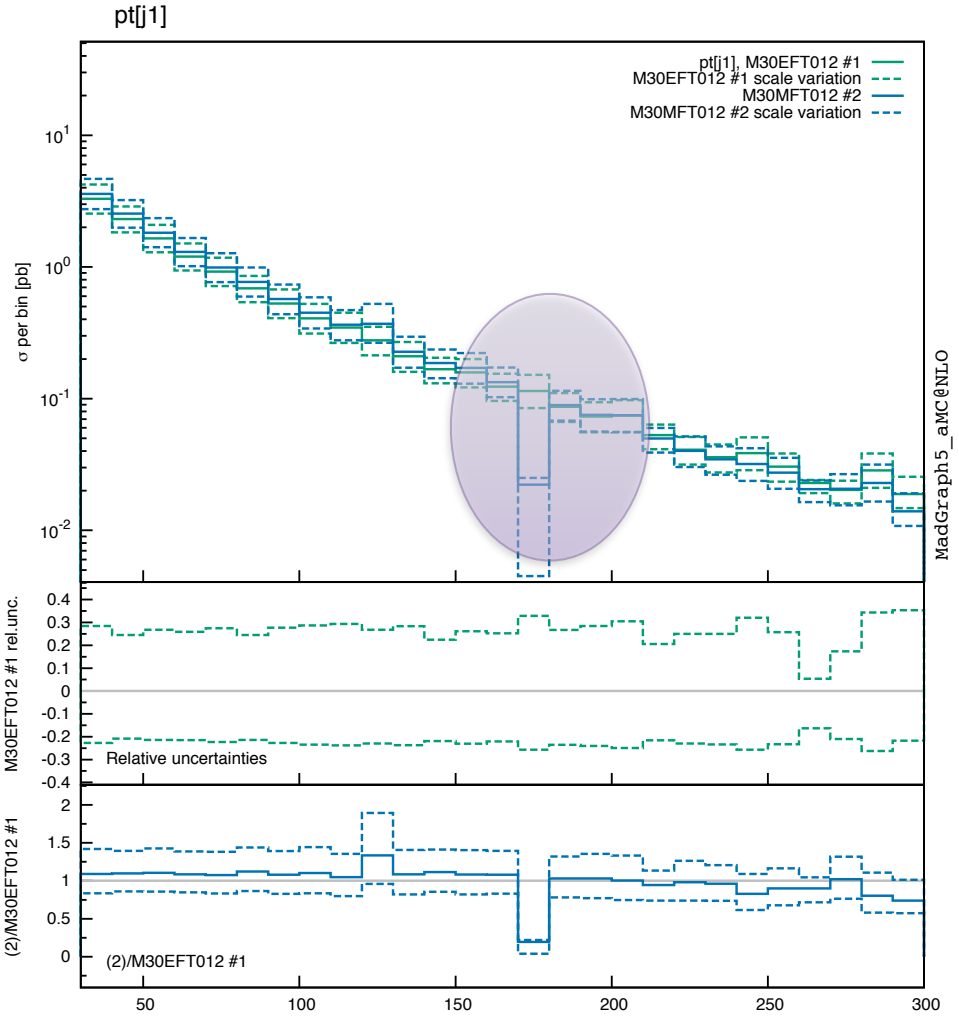
Extremely preliminary H+0,1,2 jet results





Extremely preliminary H+0,1,2 jet results

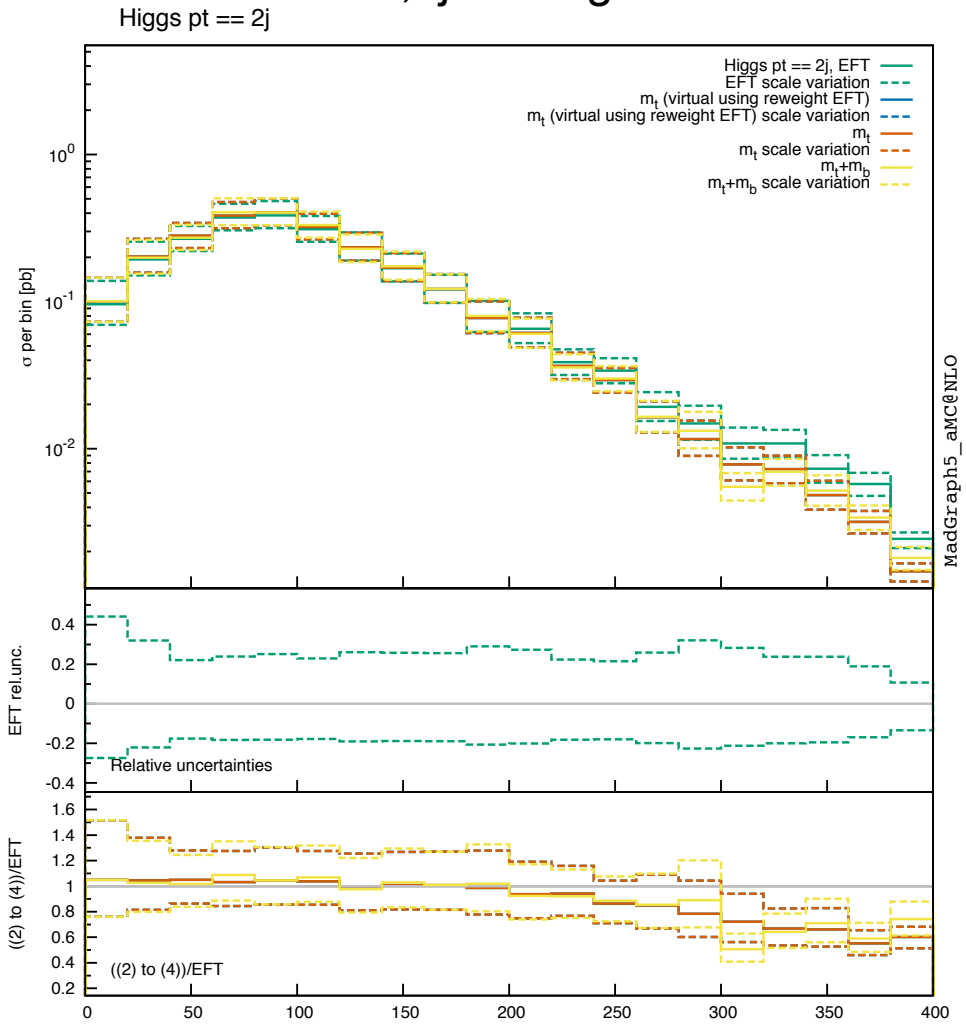




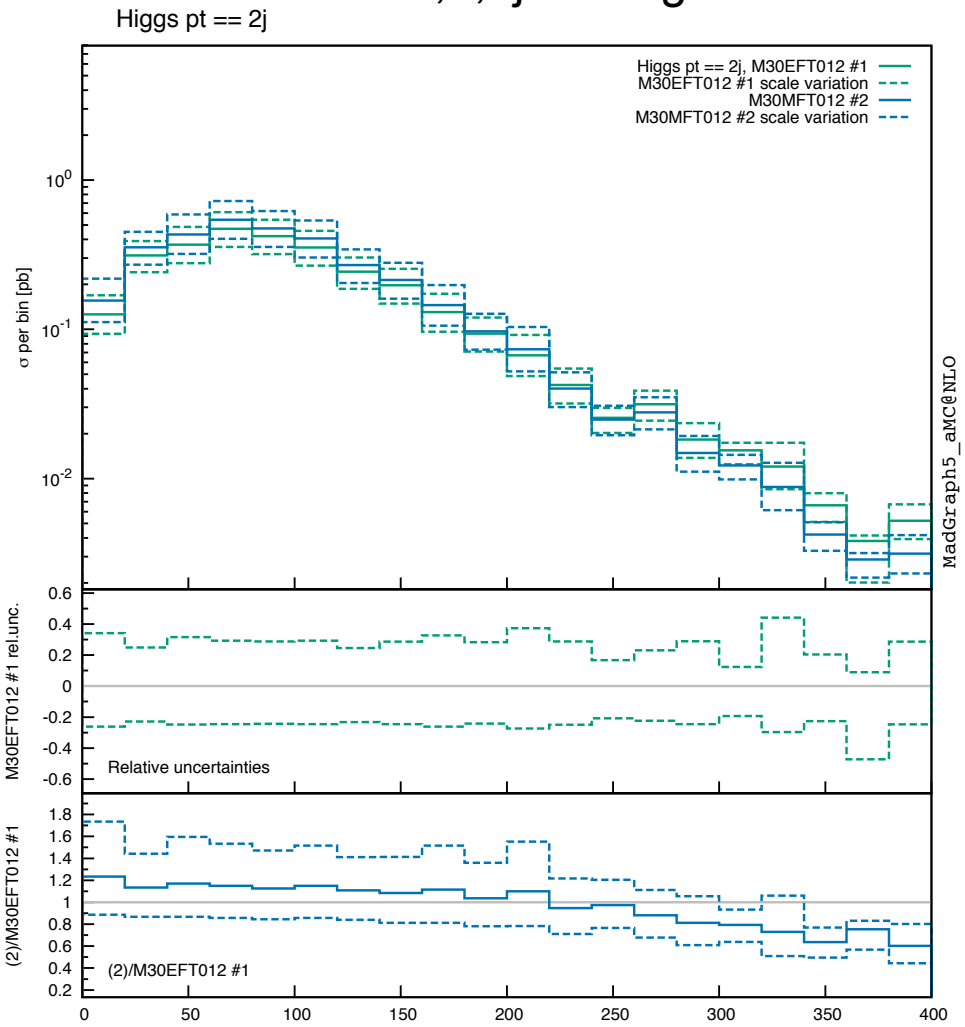
Some fluctuations: possibly instabilities in the loop amplitudes? More care needed with soft and collinear cut-offs? Further investigation required…

Extremely preliminary H+0,1,2 jet results

H+0,1jet merged



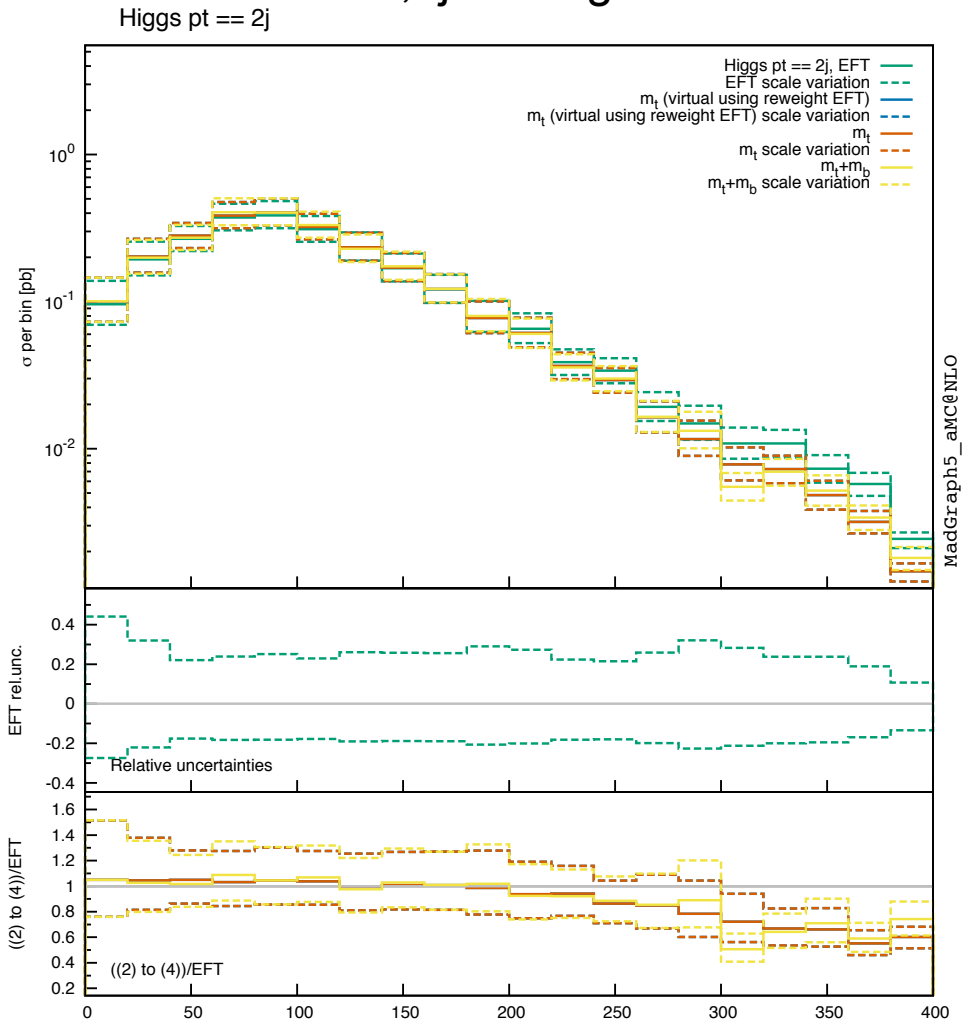
H+0,1,2jet merged



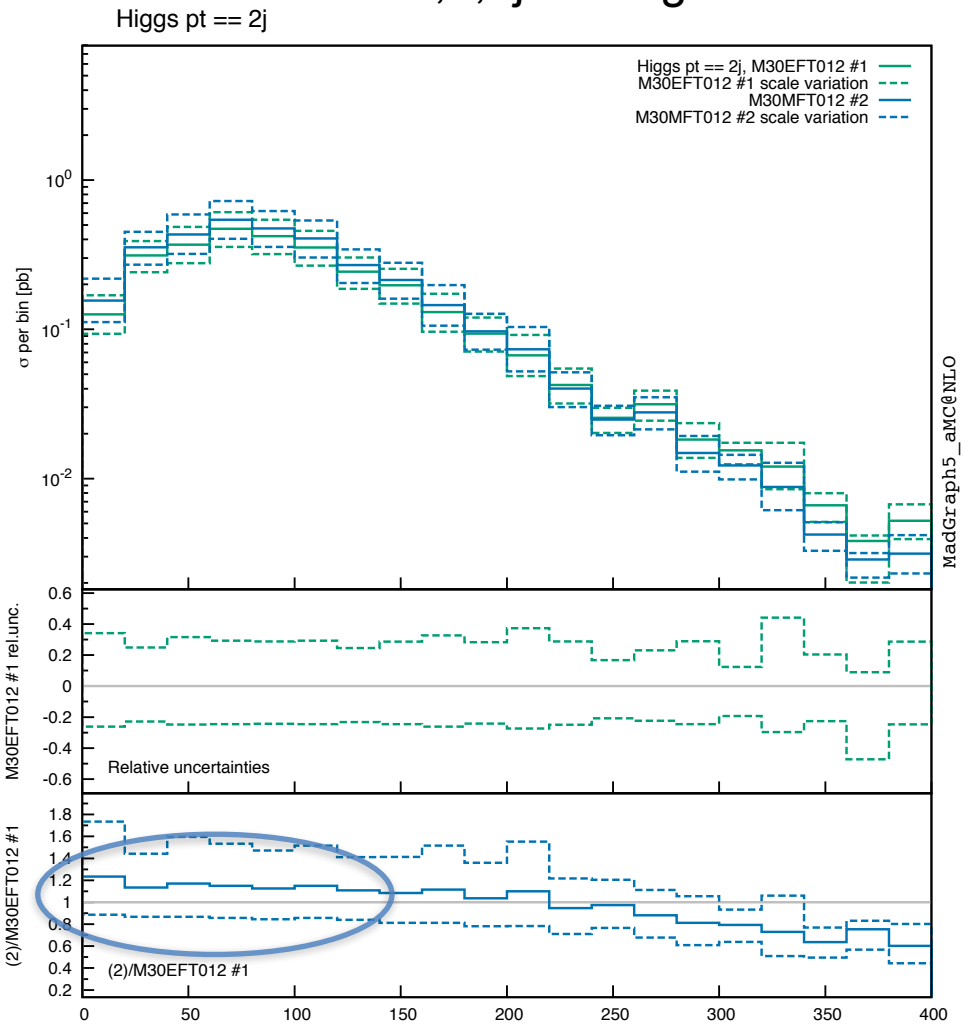
Larger deviation from EFT results in the low p_T region in the H+2jets bin

Extremely preliminary H+0,1,2 jet results

H+0,1jet merged



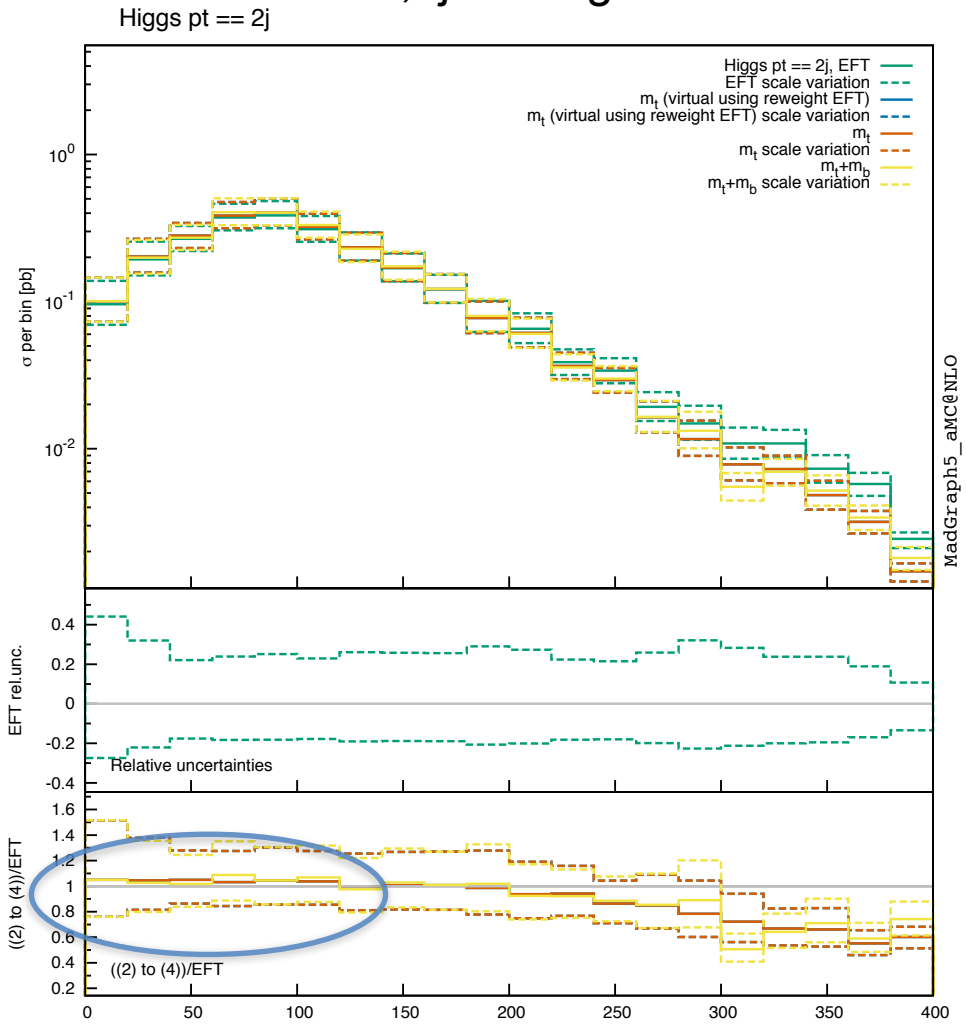
H+0,1,2jet merged



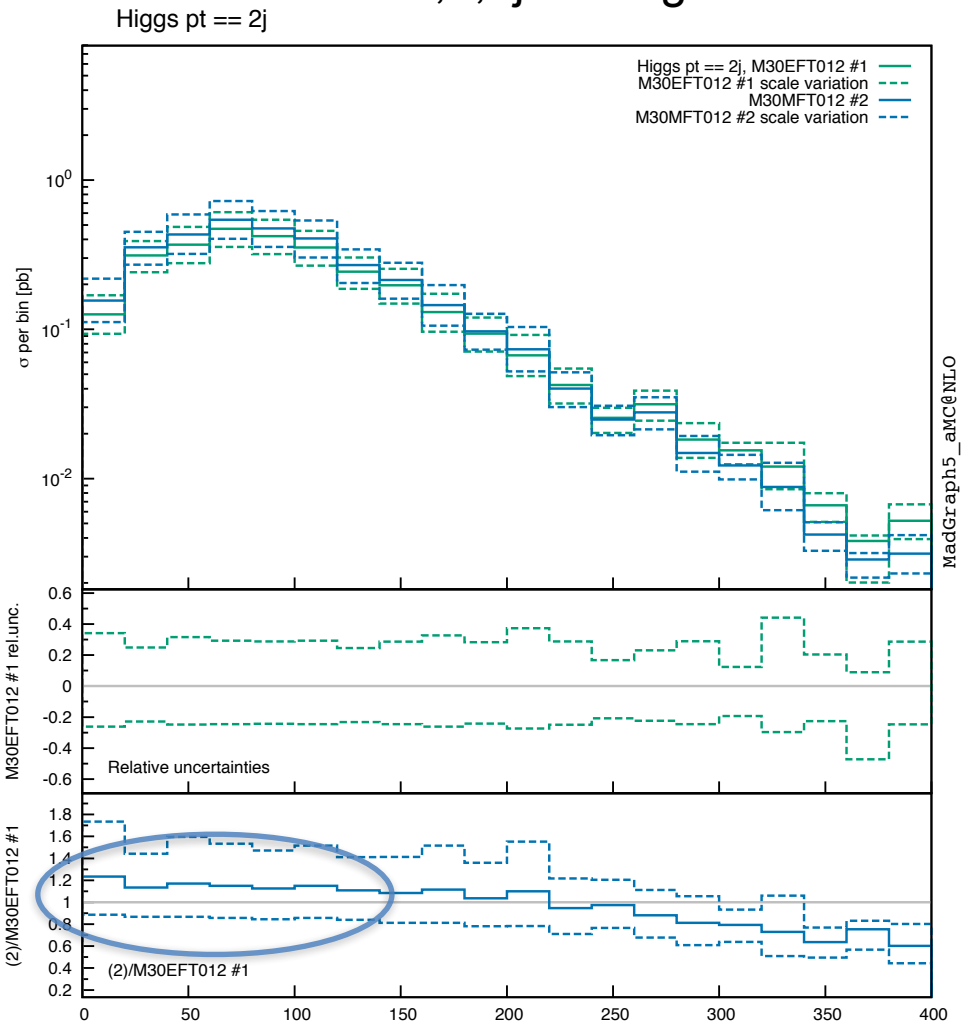
Larger deviation from EFT results in the low p_T region in the H+2jets bin

Extremely preliminary H+0,1,2 jet results

H+0,1jet merged



H+0,1,2jet merged



Larger deviation from EFT results in the low p_T region in the H+2jets bin

Conclusions-Outlook

Observations

- Top mass effects important at high pT tails
- 0-jet exact two loops virtual corrections impact very small, bottom quark contributions important at low pt
- 2-jets at NLO might be important for exclusive observables
- Merging scale uncertainty small compared to hard scale uncertainties

TODO

- Increase statistics for more exclusive quantities
- Investigate instabilities in results including 2-jets at NLO
- Release user-friendly script like aMCSusHi
- Include bottom masses in higher multiplicities(?)…

Thanks for your attention...