Top mass effects at NLO

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Recap & Motivation

- Lot of progress in HEFT approach since first NLO calculation [Dawson, Dittmaier, Spira '98]:
  - NNLO [de Florian, Mazzitelli '13, Grigo, Melnikov, Steinhauser '14]
  - NLO+NNLL [Shao, Li, Li, Wang '13],
  - NNLO+NNLL [de Florian, Mazzitelli '15], remaining scale uncertainty 5-6%
- Mass effects beyond LO only partially understood:
  - in NLO real radiation [Maltoni, Vryonidou, Zaro '14]: -10%
  - from $1/m_t^2$ expansion [Grigo, Hoff, Steinhauser '15]: +/-10% at NLO, +/- 5% at NNLO
- PDF + α_s uncertainties (PDF4LHC15): 3-4% [Javier's talk in Nov.]
- Largest uncertainty from missing mass effects,
  ☞ full NLO calculation needed

Effects from NLO real radiation ✅

- *gg* → *HHg* and *qg* → *HHq* one-loop matrix elements from GoSam [Greiner, Heinrich, Jahn, Luisoni, Mastrolia, Ossola, Peraro, Schlenk, von Soden-Fraunhofen, Tramontano]
- Dipole subtraction [Catani, Seymour ’97]
- Phase-space integration using parton-level Monte-Carlo
- Checks:
  - *gg* → *Hg* etc. reproduced and compared to Sushi [Harlander, Liebler, Mantler ’13]
  - Independence of dipole-cut α parameter [Nagy ’03]
  - Compare with MG5_aMC@NLO result [Maltoni, Vryonidou, Zaro ’14] ☞ later in this talk

Effects from virtual two-loop amplitude

- Generate diagrams with **qgraf** [Nogueira '93] ✅
- Generate amplitude within extended **GoSam** framework using **form** [Vermaseren] ✅
- (Partial) reduction to master integrals with **Reduze** [von Manteuffel, Studerus] ✅
- Checks:
  - Amplitude generated in second framework ✅
  - $gg \to H$ reproduced and compared to **Sushi** ✅
- Numerical evaluation of (master) integrals with **SecDec** [Borowka, Heinrich, Jahn, Jones, Kerner, Schlenk, TZ]

  ☞ needs more time + validation ⏳

meanwhile…

Approximate top-mass effects at NLO

$$\sigma^{NLO}(p) = \int d\phi_3 \left[\left(d\sigma^R(p) \right)_{\epsilon=0} - \left(\sum_{\text{dipoles}} d\sigma^{LO}(p) \otimes dV_{\text{dipole}} \right)_{\epsilon=0} \right] \checkmark$$

$$+ \int d\phi_2 \left[d\sigma^V(p) + d\sigma^{LO}(p) \otimes \mathbf{I} \right]_{\epsilon=0}$$

$$+ \int_0^1 dx \int d\phi_2 \left[d\sigma^{LO}(xp) \otimes (\mathbf{P} + \mathbf{K})(x) \right]_{\epsilon=0} \checkmark$$

$$d\sigma^V + d\sigma^{LO}(\epsilon) \otimes \mathbf{I} \approx d\sigma^V_{\text{exp},N} \frac{d\sigma^{LO}(\epsilon)}{d\sigma^{LO}_{\text{exp},N}(\epsilon)} + d\sigma^{LO}(\epsilon) \otimes \mathbf{I}$$

$$= \left(d\sigma^V_{\text{exp},N} + d\sigma^{LO}_{\text{exp},N}(\epsilon) \otimes \mathbf{I} \right) \frac{d\sigma^{LO}(\epsilon)}{d\sigma^{LO}_{\text{exp},N}(\epsilon)}$$

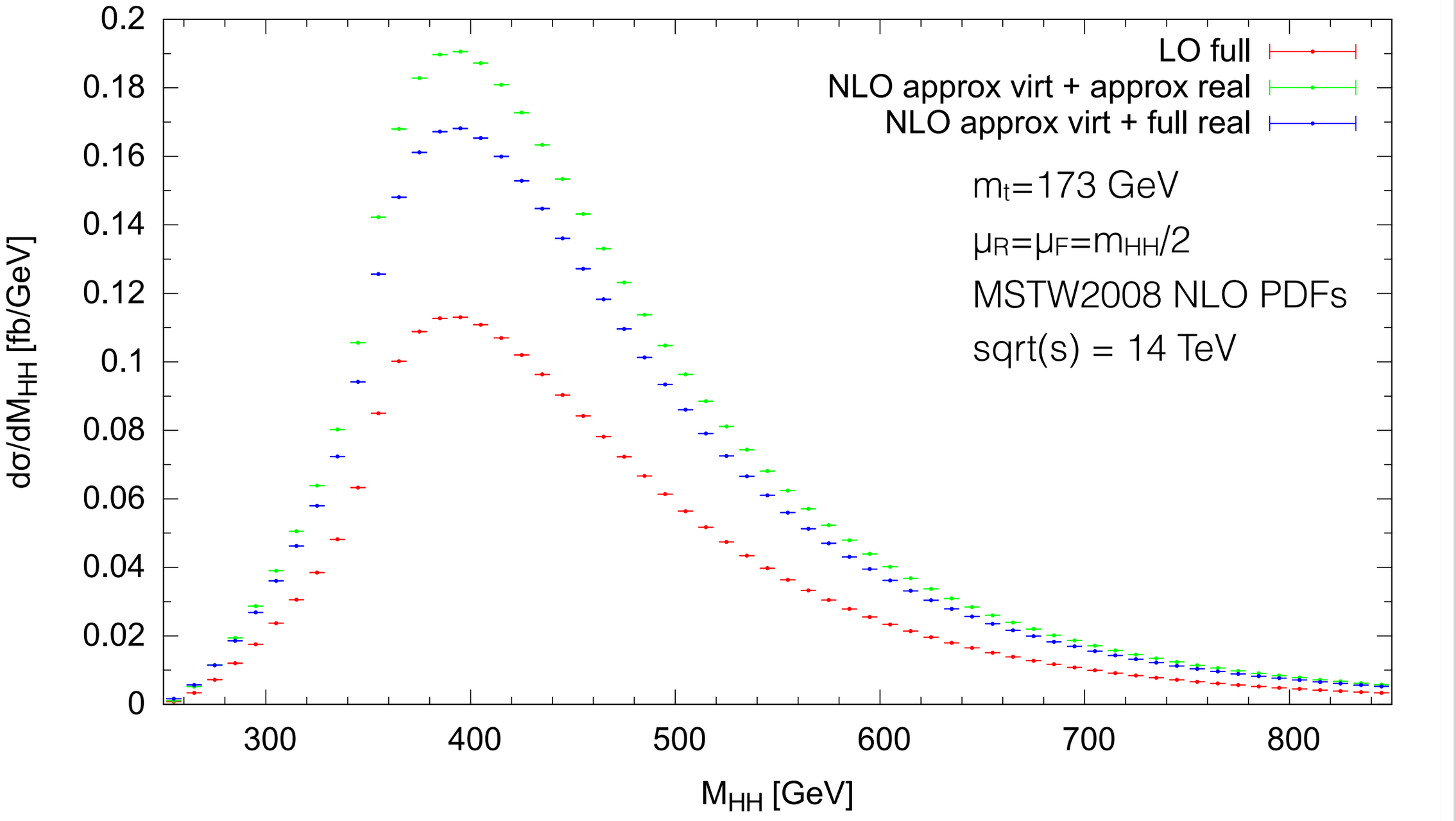
$$= \left(d\sigma^V_{\text{exp},N} + d\sigma^{LO}_{\text{exp},N}(\epsilon) \otimes \mathbf{I} \right) \frac{d\sigma^{LO}(\epsilon=0)}{d\sigma^{LO}_{\text{exp},N}(\epsilon=0)} + \mathcal{O}(\epsilon)$$

$$d\sigma_{\text{exp},N} = \sum_{k=0}^{N} d\sigma^{(k)} \left(\frac{\Lambda}{m_t} \right)^{2k}$$

$$\Lambda \in \left\{ \sqrt{s}, \sqrt{t}, \sqrt{u}, m_h \right\}$$

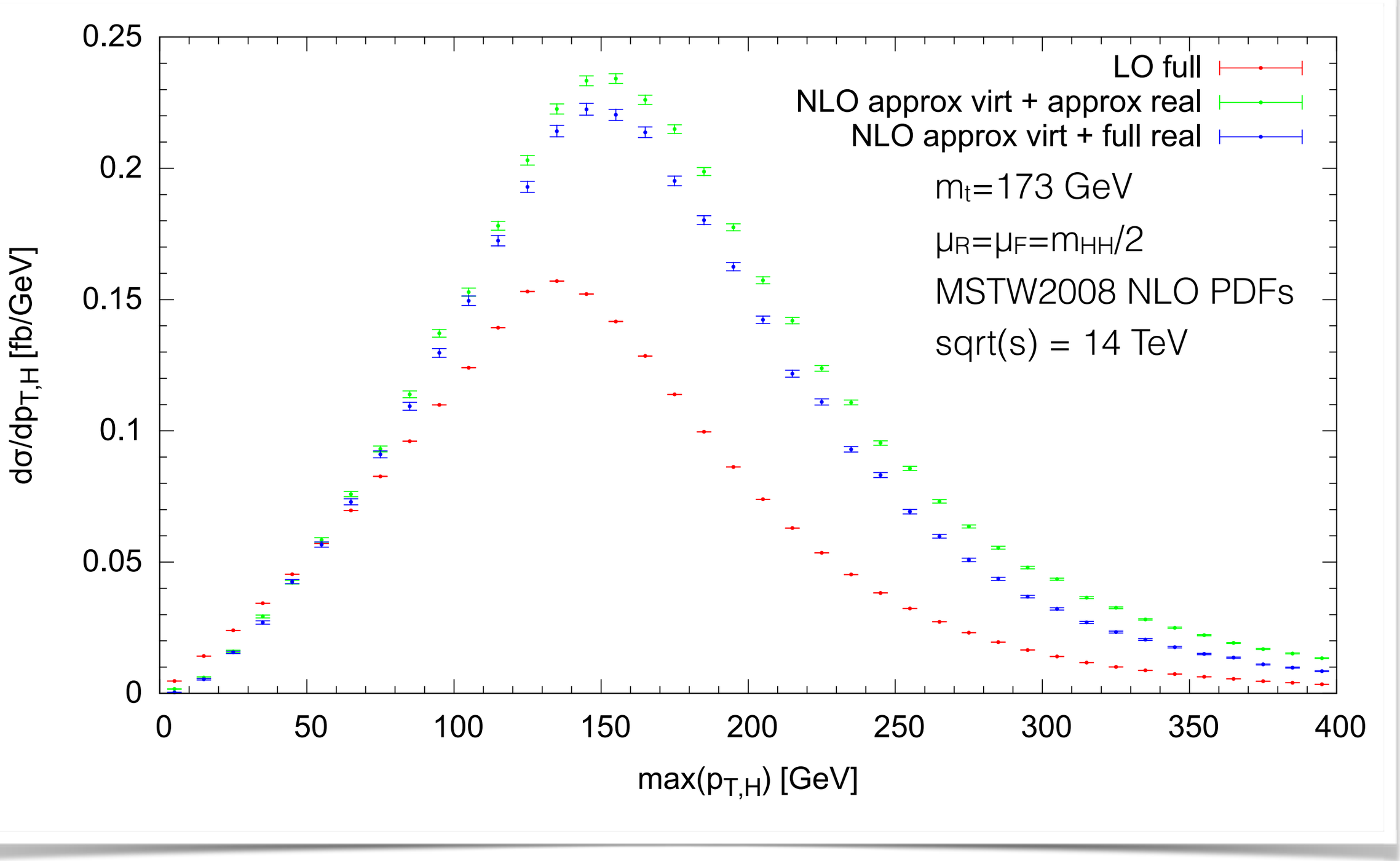
- full real-emission matrix elements and dipoles
- virtual corrections as asymptotic expansion in $1/m_t^2$ with `q2e/exp` [Harlander, Seidensticker, Seidensticker] + `Reduze` [von Manteuffel, Studerus] + `matad` [Steinhauser]
- not directly comparable with [Grigo, Hoff, Steinhauser], (real radiation treated differently, expansion parameter $(m_H/m_t)^2$)

Mass effects in M_{HH} distribution (I)

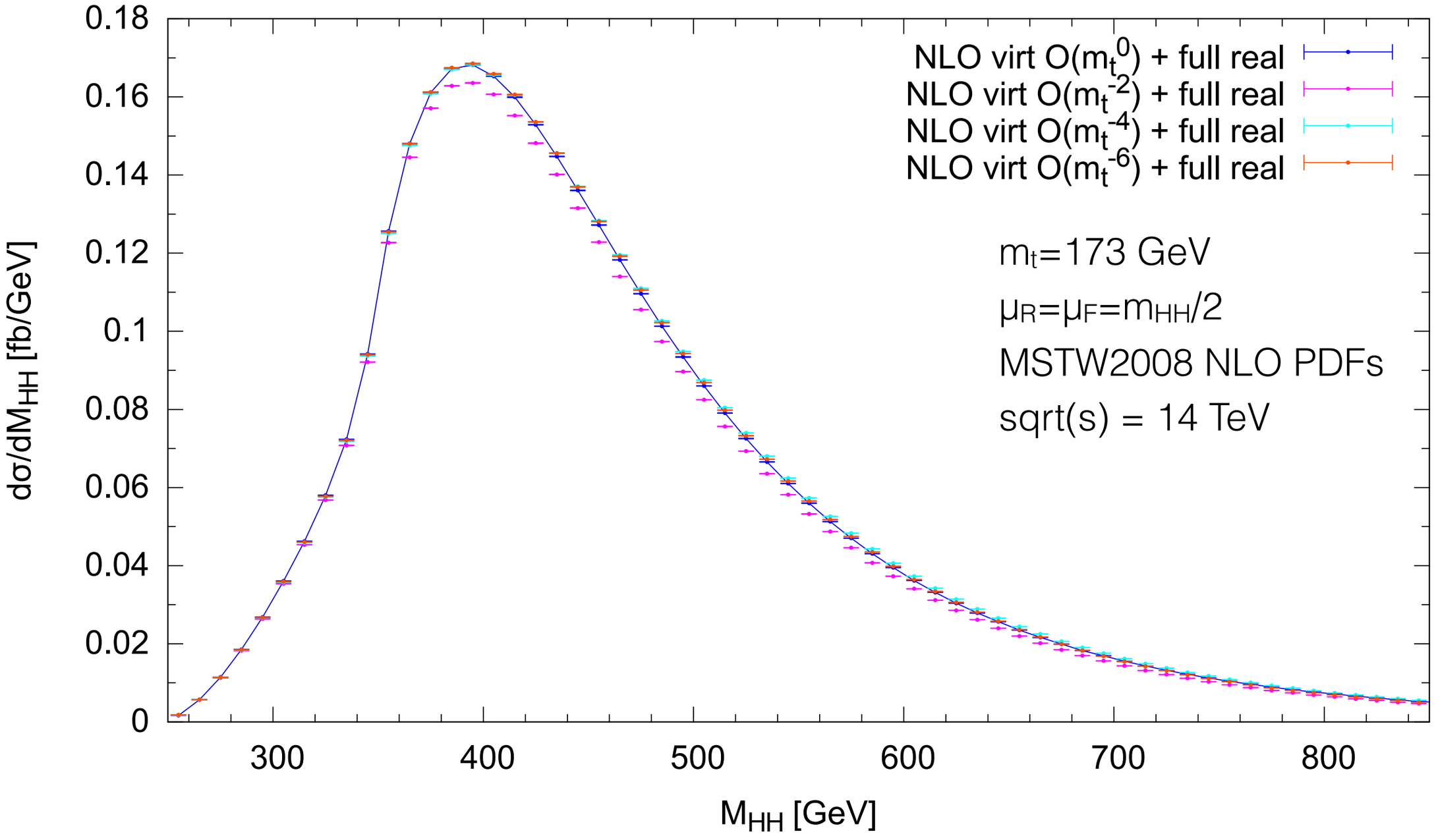


- „approx“ ≙ rescaled expansion with N=0
- Known negative mass effects from real radiation

Mass effects in p_T distribution (I)

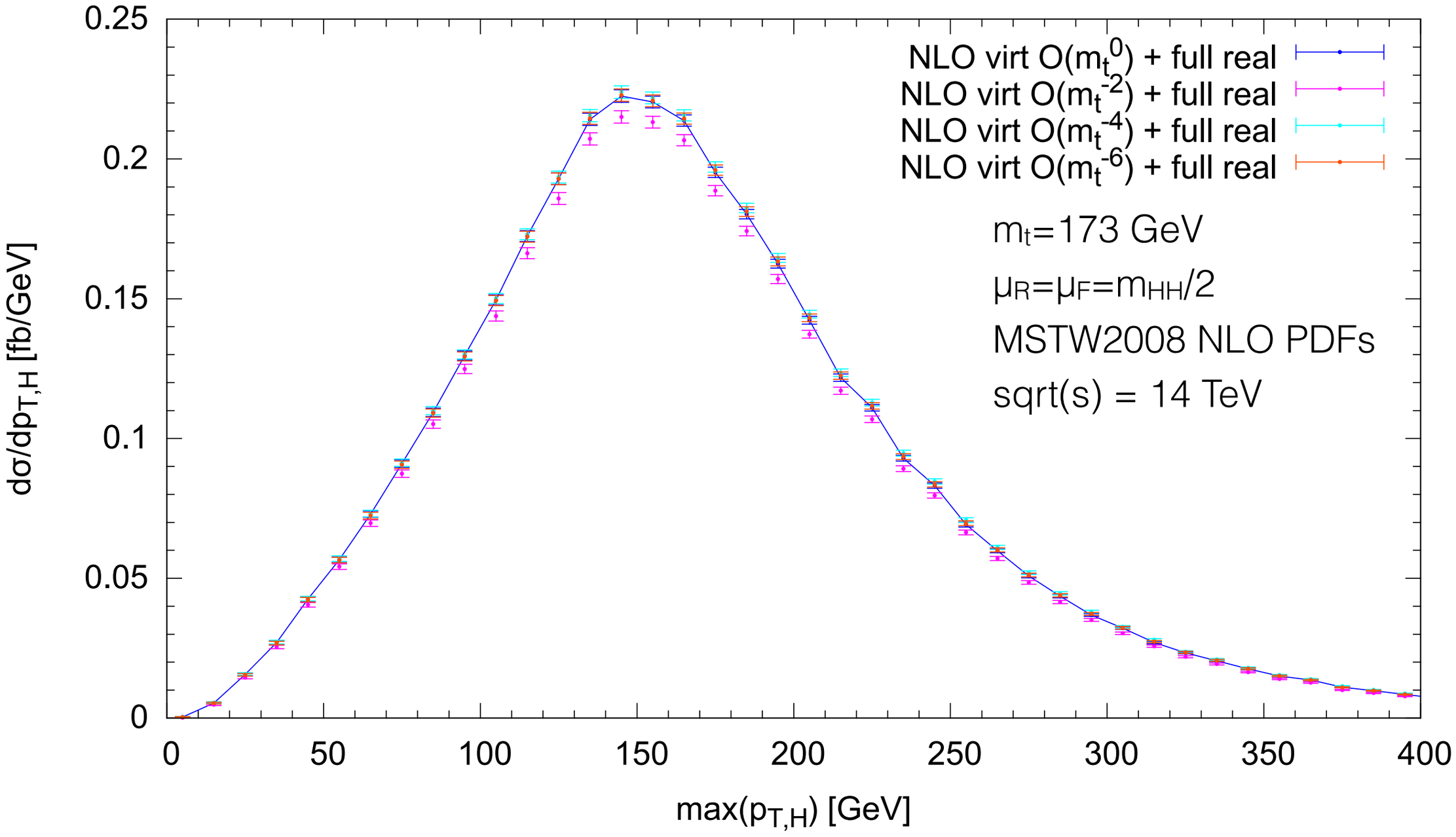


Mass effects in M_{HH} distribution (II)



- Slight tendency that -10% effect persists, but: spoilt cancellations? threshold effects?

Mass effects in p_T distribution (II)



Preliminary results for cross-check

- full real-emission matrix elements
- virtual corrections in HEFT (≙ expansion with N=0)
- m_t=172.5 GeV, $\mu_0=m_{HH}$, $\mu_R=\mu_F \in [\mu_0/2, 2\mu_0]$
- PDF4LHC15_nlo_30_pdfas PDFs with (without) α_s variation

	$gg \to HH$ total cross section [fb]			
	$m_H = 124.5$ GeV	$m_H = 125.0$ GeV	$m_H = 125.09$ GeV	$m_H = 125.5$ GeV
$\sqrt{s} = 7$ TeV	5.047	$5.011^{+19\%}_{-16\%} \pm 4.5\%(\pm 4.2\%)$	5.004	4.975
$\sqrt{s} = 8$ TeV	7.343	$7.292^{+18\%}_{-15\%} \pm 4.2\%(\pm 3.8\%)$	7.283	7.241
$\sqrt{s} = 13$ TeV	25.13	$24.97^{+15\%}_{-14\%} \pm 3.2\%(\pm 2.8\%)$	24.94	24.80
$\sqrt{s} = 14$ TeV	29.85	$29.66^{+18\%}_{-15\%} \pm 3.1\%(\pm 2.6\%)$	29.62	29.47

- compare to **MG5_aMC@NLO** results (for m_H = 125 GeV):

	$\sqrt{s} = 8$ TeV NLO	$\sqrt{s} = 13$ TeV NLO
HH (NLO_approx)	$7.28^{+18\%}_{-15\%} \pm 0.7\%$	$24.9+15\%_{-13\%} \pm 0.5\%$

(borrowed from Eleni's talk on Nov. 19)

Conclusions

- Reproduced -10% mass effects from NLO real radiation
- Setup for full NLO calculation ready
- Results with full top-mass dependence within close reach