MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

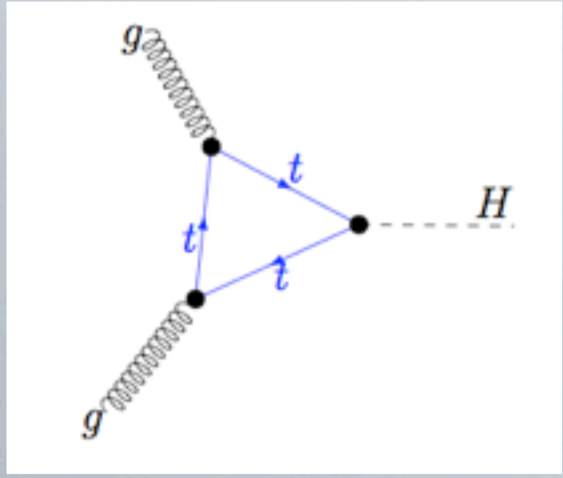
Mass effects in gg → H + jet(s) (fixed order)

Gudrun Heinrich
Max Planck Institute for Physics, Munich

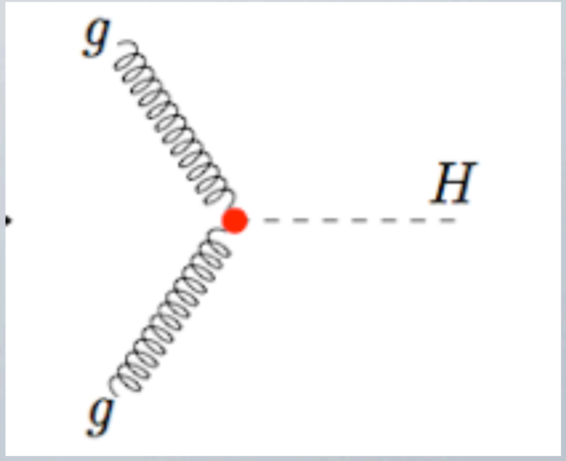
Higgs+jets workshop, IPPP Durham

December 9, 2014

Higgs Effective Theory (HEFT)



$$\xrightarrow[m_t \to \infty]{}$$



$$\mathcal{L}_{eff} = c_1 G^{\mu\nu,a} G_{\mu\nu,a} \, H$$

$$c_1(\mu)^{\overline{MS}} = \frac{\alpha_s(\mu)}{12\pi v} \left\{ 1 + \frac{\alpha_s(\mu)}{4\pi}(5C_A - 3C_F) + \mathcal{O}(\alpha_s^2) \right\}$$

- works very well for inclusive Higgs production

  (at NLO in HEFT: deviations to full theory below 1% for total cross section)

- fails for observables which are related to large momentum scales

  (e.g. Higgs pT at large transverse momenta, mT(H) in far off-shell region, ...)

  p_T/m_t not small, top loop "resolved"

how to obtain "Wilson coefficient" c_1 ?

$$\mathcal{L}_{ggH} = \frac{g_{ggH}}{v}\, G^{\mu\nu,a} G_{\mu\nu,a}\, H$$

$$\frac{g_{ggH}}{v} = \frac{\alpha_s}{8\pi}\frac{1}{v}\,\tau\,[1+(1-\tau)f(\tau)] \qquad \tau = 4m_t^2/m_H^2$$

$f(\tau)$: full top mass dependence from (one-)loop calculation

$$m_t \to \infty : f(\tau) \to \frac{1}{\tau} + \frac{1}{3\tau^2} + \mathcal{O}(\frac{1}{\tau^3}) \qquad \Longrightarrow \; g_{ggH} \to \frac{\alpha_s}{8\pi}\,\frac{2}{3}\; + \mathcal{O}(1/\tau)$$

how to obtain "Wilson coefficient" c_1 ?

$$\mathcal{L}_{ggH} = \frac{g_{ggH}}{v}\, G^{\mu\nu,a} G_{\mu\nu,a}\, H$$

$$\frac{g_{ggH}}{v} = \frac{\alpha_s}{8\pi}\frac{1}{v}\tau\,[1+(1-\tau)f(\tau)] \qquad \tau = 4m_t^2/m_H^2$$

$f(\tau)$: full top mass dependence from (one-)loop calculation

$$m_t \to \infty : f(\tau) \to \frac{1}{\tau} + \frac{1}{3\tau^2} + \mathcal{O}(\frac{1}{\tau^3}) \qquad \Longrightarrow \quad g_{ggH} \to \frac{\alpha_s}{8\pi}\frac{2}{3} + \mathcal{O}(1/\tau)$$

valid for on-shell Higgs, $2 \longrightarrow 1$ kinematics

how to obtain "Wilson coefficient" c_1 ?

$$\mathcal{L}_{ggH} = \frac{g_{ggH}}{v} G^{\mu\nu,a} G_{\mu\nu,a} H$$

$$\frac{g_{ggH}}{v} = \frac{\alpha_s}{8\pi} \frac{1}{v} \tau \left[1 + (1-\tau) f(\tau)\right] \qquad \tau = 4m_t^2/m_H^2$$

$f(\tau)$: full top mass dependence from (one-)loop calculation

$$m_t \to \infty : f(\tau) \to \frac{1}{\tau} + \frac{1}{3\tau^2} + \mathcal{O}(\frac{1}{\tau^3}) \qquad \Longrightarrow \quad g_{ggH} \to \frac{\alpha_s}{8\pi} \frac{2}{3} + \mathcal{O}(1/\tau)$$

valid for on-shell Higgs, 2 → 1 kinematics

corrections within the HEFT take into account higher orders in $1/m_t^2$ expansion

but this will not help for kinematic effects e.g. due to Higgs pT

Higgs+jet(s): logarithmic mtop dependence at large pT, $\mathcal{M} \sim m_t^2 \log^2 \frac{p_{T,H}^2}{m_t^2}$

incomplete list of available results

- inclusive Higgs production:

NLO (2 loops) with full top mass dependence:

mt dep. through one-dim integral representation: Spira, Djouadi, Graudenz, Zerwas ’93-95

analytic representation: Harlander, Kant ’05;

Anastasiou, Beerli, Bucherer, Daleo, Kunszt ’06; Aglietti, Bonciani, Degrassi, Vicini ’06

NNLO within HEFT: (inclusive cross section)

Harlander, Kilgore ’02; Anastasiou, Melnikov ’02; Ravindran, Smith, van Neerven ’03;

differential: Anastasiou, Melnikov, Petriello ’05; Catani, Grazzini ’07

mass effects in resummed jet veto efficiency: Mantler, Wiesemann ’12;

Grazzini, Sargsyan ’13; Banfi, Monni, Zanderighi ’13

incomplete list of available results

- inclusive Higgs production:

NLO (2 loops) with full top mass dependence:

mt dep. through one-dim integral representation: Spira, Djouadi, Graudenz, Zerwas '93-95

analytic representation: Harlander, Kant '05;

Anastasiou, Beerli, Bucherer, Daleo, Kunszt '06; Aglietti, Bonciani, Degrassi, Vicini '06

NNLO within HEFT: (inclusive cross section)

Harlander, Kilgore '02; Anastasiou, Melnikov '02; Ravindran, Smith, van Neerven '03;

differential: Anastasiou, Melnikov, Petriello '05; Catani, Grazzini '07

mass effects in resummed jet veto efficiency: Mantler, Wiesemann '12;

Grazzini, Sargsyan '13; Banfi, Monni, Zanderighi '13

top mass effects on **inclusive H** cross section:

see e.g. Spira et al; Harlander et al; Steinhauser et al; Anastasiou et al, ...
Neumann, Wiesemann '14;

HEFT accurate to about 1% for $p_{T,veto}^{j} < \sim$ 100 GeV

even better for more inclusive observables

can go up to 20-30% for larger values of $p_{T,veto}^{j}$

- Higgs plus one jet production:

LO (1 loop) with full top mass dependence:

R.K. Ellis, Hinchliffe, Soldate, van der Bij '88; Baur, Glover '89

NLO within HEFT:

DeFlorian, Grazzini, Kunszt '99; Ravindran, Smith, van Neerven '02; Glosser, Schmidt '02;

NNLO within HEFT: (gg channel)

Boughezal, Caola, Melnikov, Petriello, Schulze '13

Chen, Gehrmann, Glover, Jaquier '14 see Matthieu Jaquier's talk this afternoon

EW corrections within HEFT: Petriello, Keung '09

threshold expansion: Becher, Bell, Lorentzen, Marti '14 ; Huang, Li, Li, Wang '14

H to 4 leptons + 0,1 jet merged: Cascioli, Höche, Krauss, Maierhöfer, Pozzorini, Siegert '13

some recent studies of top mass effects:

Dawson, Lewis, Zeng '14; Neumann, Wiesemann '14; Grazzini, Sargsyan '13; Banfi, Monni, Zanderighi '13;

Harlander, Neumann, Ozeren, Wiesemann '12; Bagnaschi, Degrassi, Slavich, Vicini '12

- Higgs plus one jet production:

LO (1 loop) with full top mass dependence:

R.K. Ellis, Hinchliffe, Soldate, van der Bij ’88; Baur, Glover ’89

NLO within HEFT:

DeFlorian, Grazzini, Kunszt ’99; Ravindran, Smith, van Neerven ’02; Glosser, Schmidt ’02;

NNLO within HEFT: (gg channel)

Boughezal, Caola, Melnikov, Petriello, Schulze ’13

Chen, Gehrmann, Glover, Jaquier ’14 see Matthieu Jaquier’s talk this afternoon

EW corrections within HEFT: Petriello, Keung ’09

threshold expansion: Becher, Bell, Lorentzen, Marti ’14 ; Huang, Li, Li, Wang ’14

H to 4 leptons + 0,1 jet merged: Cascioli, Höche, Krauss, Maierhöfer, Pozzorini, Siegert ’13

some recent studies of top mass effects:

Dawson, Lewis, Zeng ’14; Neumann, Wiesemann ’14; Grazzini, Sargsyan ’13; Banfi, Monni, Zanderighi ’13; Harlander, Neumann, Ozeren, Wiesemann ’12; Bagnaschi, Degrassi, Slavich, Vicini ’12

upshot: difficult to assess as full mtop dependence at NLO is not known

for inclusive 1-jet rate better than ~2%

for more exclusive observables: very dependent on cuts, energy/pT range

for scales (e.g. p_T^H) $\leq \sim 2m_t$ HEFT accurate to about 1- 3% (see later)

- Higgs plus 2 jets (**gluon fusion**):

note: H+1jet and H+2 jet Higgs pT distributions have similar rates at large pT

- Higgs plus 2 jets (**gluon fusion**):

note: H+1jet and H+2 jet Higgs pT distributions have similar rates at large pT

LO (1 loop) with full top mass dependence: Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld '02

NLO within HEFT: Campbell, Ellis, Zanderighi '06;

van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, von Soden-Fraunhofen, Tramontano '13

matched NLO+shower predictions for H+0,1,2 jets:

MC@NLO: Alwall, Li, Maltoni '11;

MCFM+POWHEG/MG4: Campbell, Ellis, Frederix, Nason, Oleari, Williams '12

MCFM/OpenLoops/VBFNLO+Sherpa:

Buschmann, Goncalves-Netto, Krauss, Kuttimalai, Plehn, Schönherr '14

towards NNLO within HEFT: see James Currie's talk this afternoon

- Higgs plus 2 jets (**gluon fusion**):

note: H+1jet and H+2 jet Higgs pT distributions have similar rates at large pT

LO (1 loop) with full top mass dependence: Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld '02

NLO within HEFT: Campbell, Ellis, Zanderighi '06;

van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, von Soden-Fraunhofen, Tramontano '13

matched NLO+shower predictions for H+0,1,2 jets:

MC@NLO: Alwall, Li, Maltoni '11;

MCFM+POWHEG/MG4: Campbell, Ellis, Frederix, Nason, Oleari, Williams '12

MCFM/OpenLoops/VBFNLO+Sherpa:

Buschmann, Goncalves-Netto, Krauss, Kuttimalai, Plehn, Schönherr '14

towards NNLO within HEFT: see James Currie's talk this afternoon

- Higgs plus 3 jets (gluon fusion):

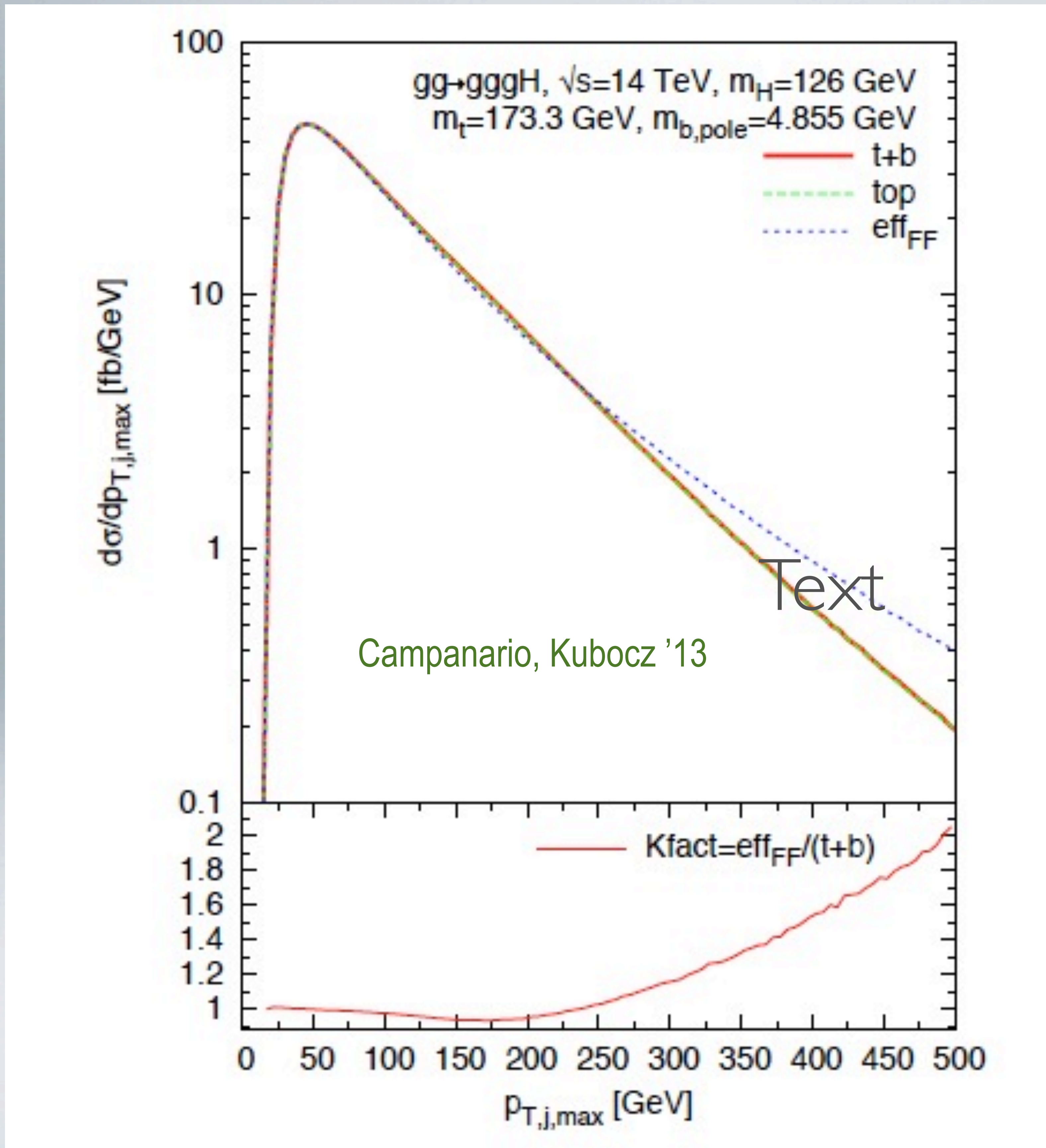
NLO within HEFT:

Cullen, van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Tramontano '13

pheno studies, Ntuples, etc: Greiner, Höche, Luisoni, Schönherr, Winter, Yundin

see Gionata Luisoni's talk this afternoon

LO (one loop) with quark mass dependence for gg to H ggg: Campanario, Kubocz '13

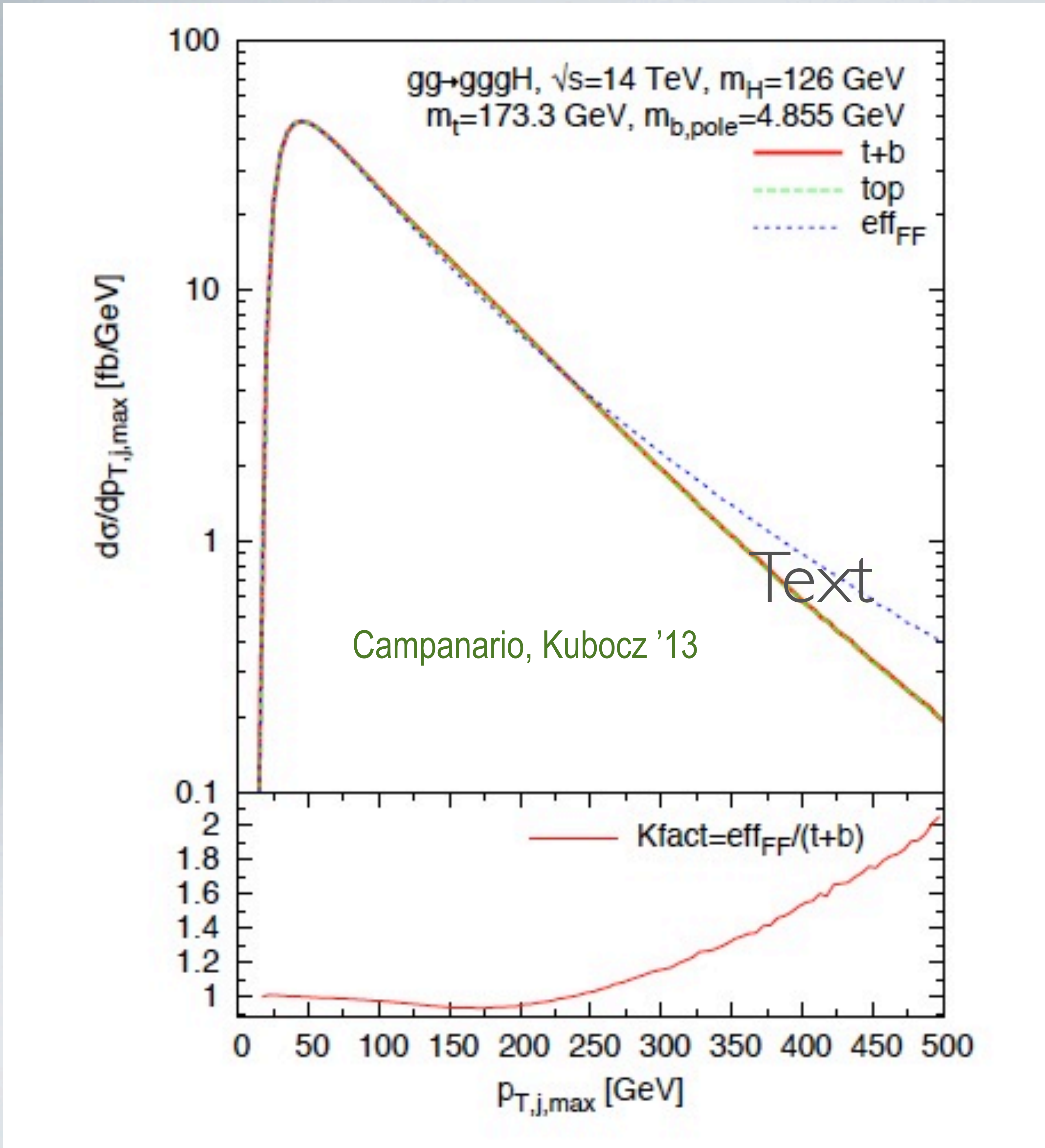


HEFT very good approximation up to

$p_t^j \sim 250\,\mathrm{GeV}$

for $p_t^j \sim 500\,\mathrm{GeV}$

corrections up to 100%



HEFT very good approximation up to

$p_t^j \sim 250\,\mathrm{GeV}$

for $p_t^j \sim 500\,\mathrm{GeV}$
corrections up to 100%

note that gg to H qqbar g and all quark initiated channels are missing

study fixed order perturbative and 1/mt^2 expansion, with jet veto

Neumann, Wiesemann 1408.6836

$$\left[\mathrm{d}\sigma^X\right]_{1/m_t^k}, \qquad X \in \{\mathrm{LO}, \mathrm{NLO}, \mathrm{NNLO}\}, \qquad k \in \{0, 2, 4, \ldots\}$$

within HEFT

all cross sections are reweighted by exact top mass dependence at LO

$$\left[d\sigma^X\right]_{1/m_t^k} = \sigma^{LO}(m_t)\ \left[d\bar{\sigma}^X\right]_{1/m_t^k} / \left[d\sigma^{LO}\right]_{1/m_t^k}$$

0-jet bin: $\sigma^X_{\text{veto}} = \sigma^X_{\text{tot}} - \sigma^{X'}_{\geq 1jet}$

if X=NNLO: X' = NLO with NNLO pdfs

study fixed order perturbative and 1/mt^2 expansion, with jet veto

Neumann, Wiesemann 1408.6836

$$[\mathrm{d}\sigma^X]_{1/m_t^k}, \qquad X \in \{\mathrm{LO}, \mathrm{NLO}, \mathrm{NNLO}\}, \qquad k \in \{0, 2, 4, \ldots\}$$

within HEFT

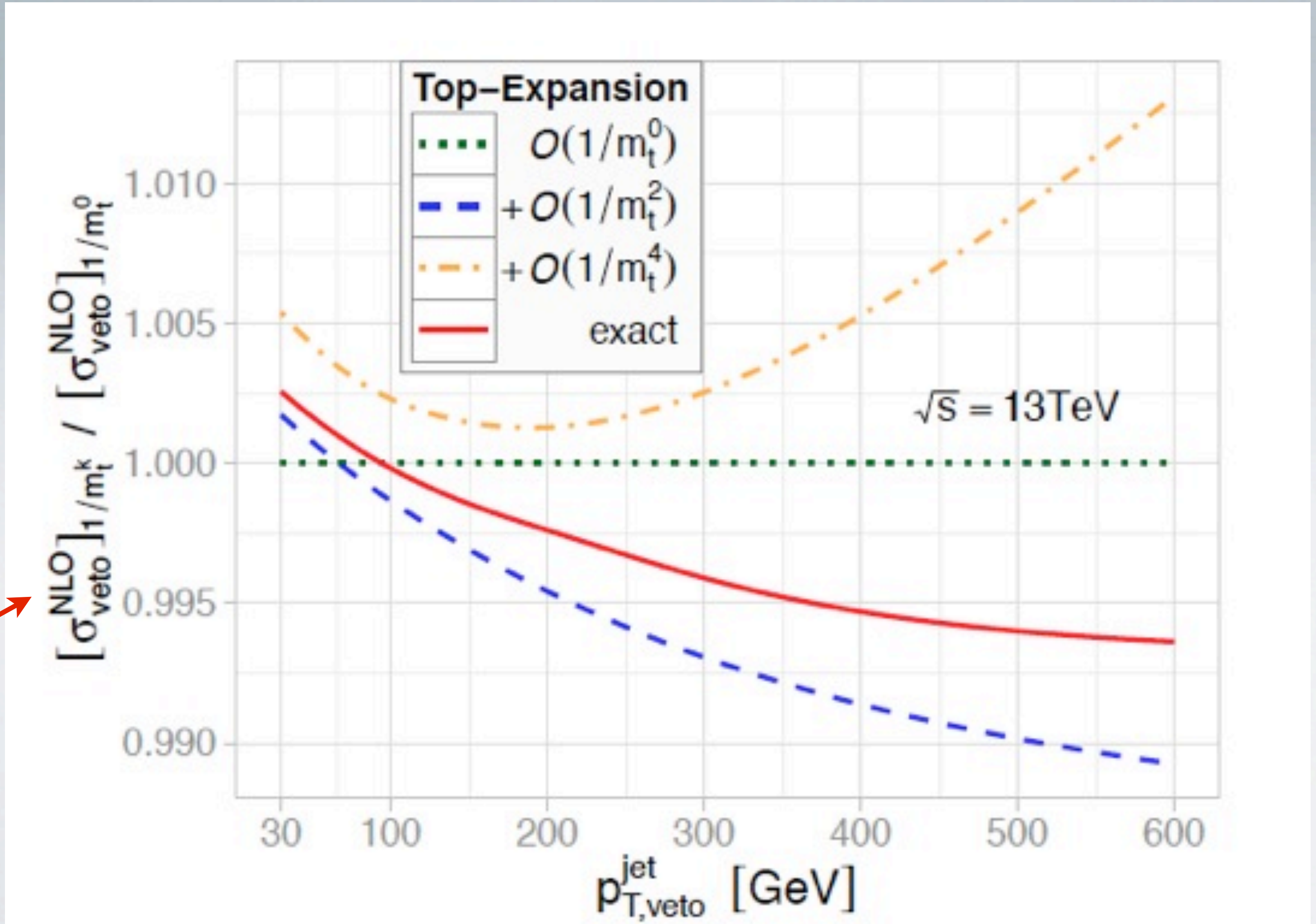
all cross sections are reweighted by exact top mass dependence at LO

$$[d\sigma^X]_{1/m_t^k} = \sigma^{LO}(m_t)\ [d\bar{\sigma}^X]_{1/m_t^k} / [d\sigma^{LO}]_{1/m_t^k}$$

0-jet bin: $\sigma^X_{\mathrm{veto}} = \sigma^X_{\mathrm{tot}} - \sigma^{X'}_{\geq 1 jet}$

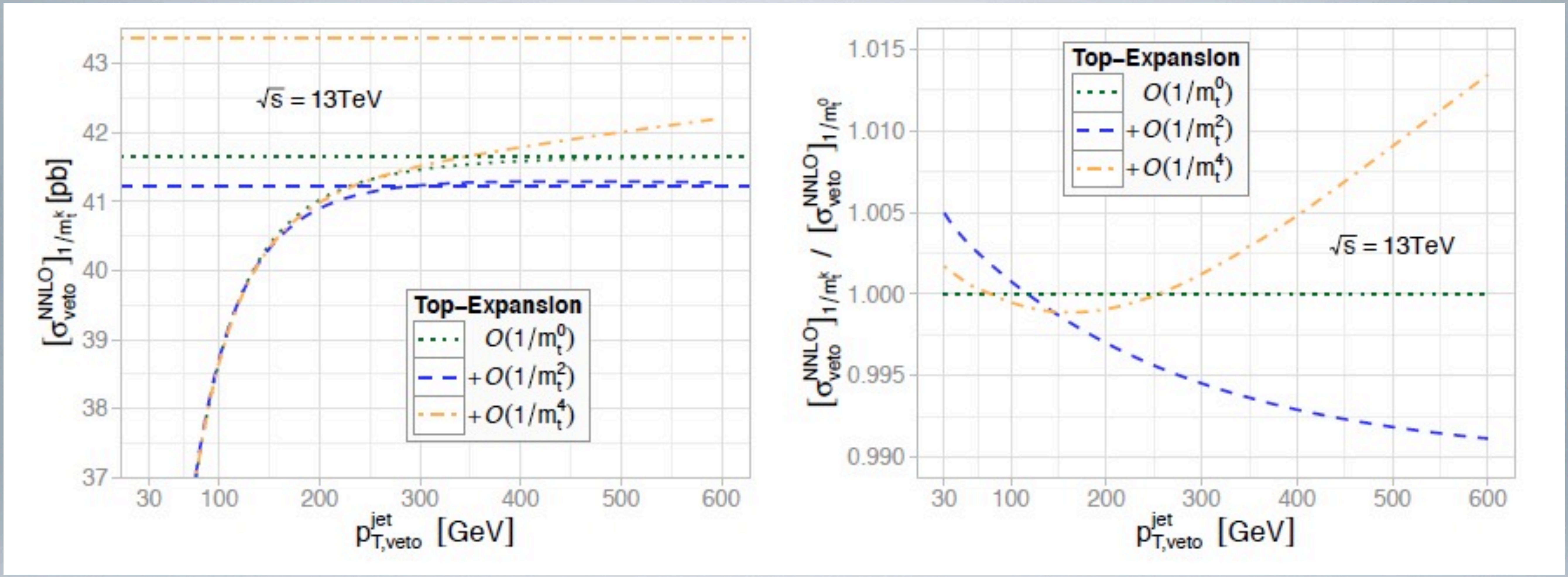
if X=NNLO: X' = NLO with NNLO pdfs

NLO



envelope below 2.5%

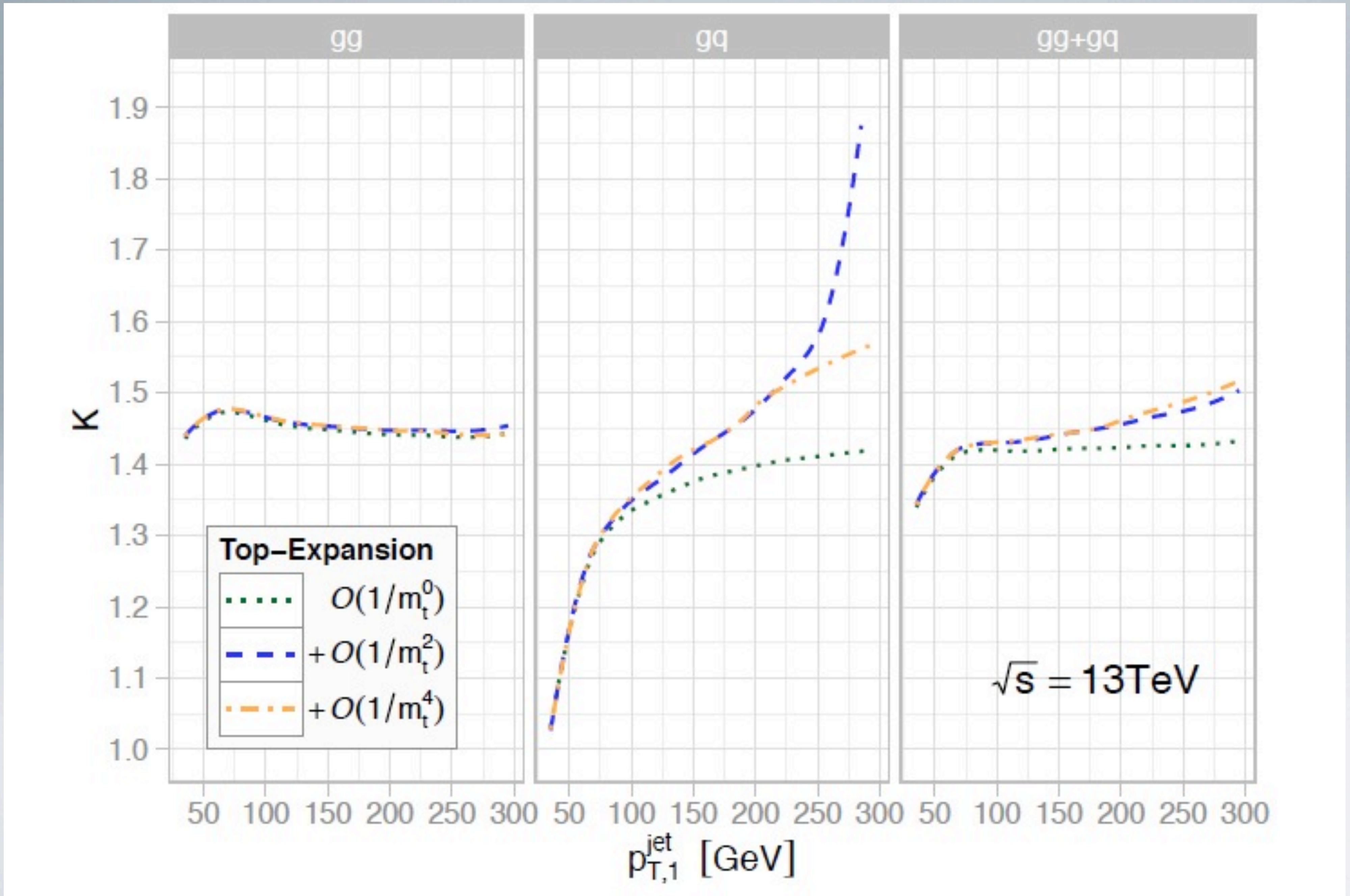
NNLO: $(\mu = m_H)$



rather small effects (below 3%) because contributions from large-pT jets are suppressed by phase space (jet veto)

K-factor for $p_{T,1}^{\rm jet}$, p_T^H

$$K_k^X(b) = \frac{\left[d\bar{\sigma}^X(b)\right]_{1/m_t^k}}{\left[d\bar{\sigma}^{LO}(b)\right]_{1/m_t^k}} \qquad \text{e.g.} \quad b = p_{T,1}^{\rm jet}$$

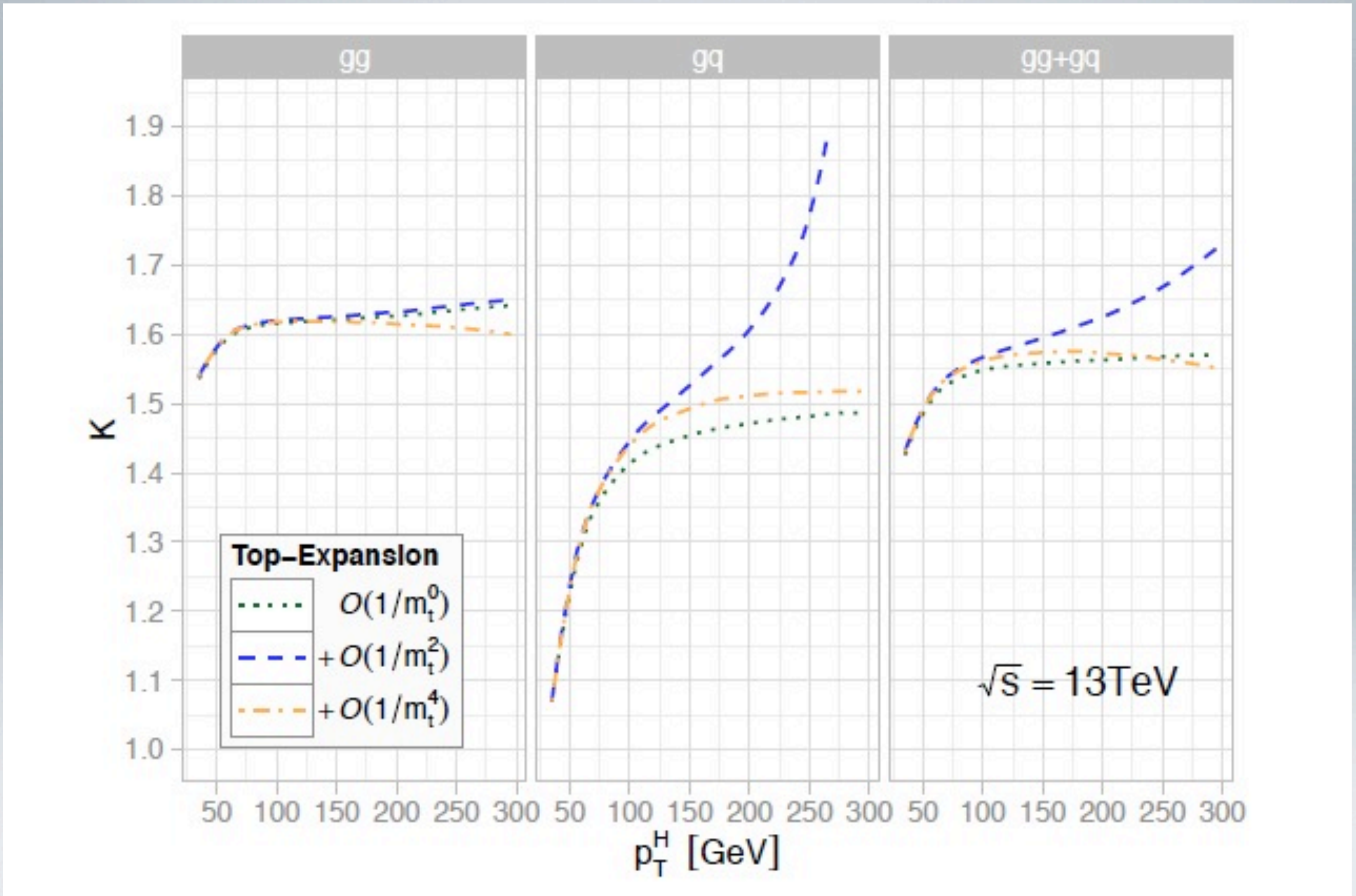


$\mu^2 = m_H^2 + (p_{T,1}^{\rm jet})^2$

X=NLO

difference in gg+qg ~ 7% at $p_{T,1}^{\rm jet} \sim 300\,\mathrm{GeV}$

Higgs pT:


gg
gq
gg+gq
K
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
Top−Expansion
$O(1/m_t^0)$
$+O(1/m_t^2)$
$+O(1/m_t^4)$
$\sqrt{s} = 13\mathrm{TeV}$
50 100 150 200 250 300
p_T^H [GeV]

what is meant by “NLO including top mass effects” for H+jet(s) ?

Alwall, Li, Maltoni 1110.1728

Buschmann, Goncalves-Netto, Krauss, Kuttimalai, Plehn, Schönherr 1410.5806 ★

reweighting: $$r^{(n)} = |\mathcal{M}^{(n)}(m_t)|^2 / |\mathcal{M}^{(n)}_{HEFT}|^2$$

for each event (jet multiplicity *n*) the HEFT (NLO) matrix elements are rescaled with the mass dependent loop (LO!) counterparts

findings: top mass effects seem to factorize as a constant factor in each pT bin

$\longrightarrow$ top mass effects are fully associated with the hard process, therefore reweighting procedure is justified

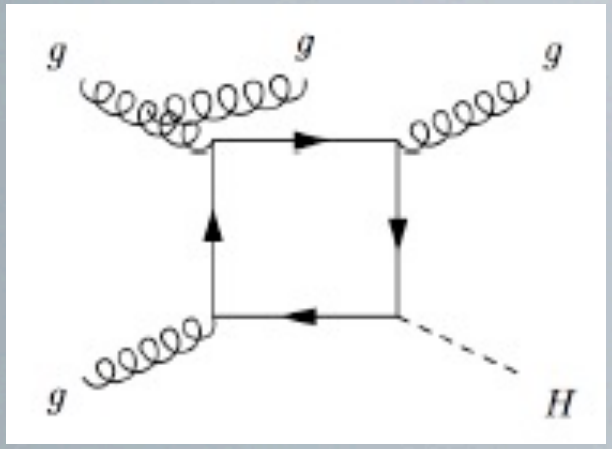
mass effects can lead to a factor ~4 at pT=600 GeV

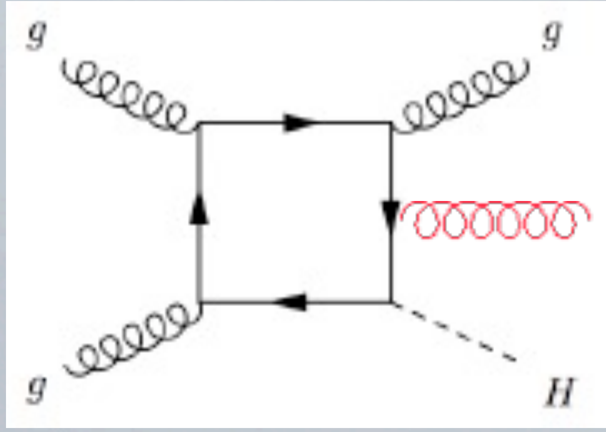
★refer to Maltoni, Vryonidou, Zaro 1408.6542 for HH production for this procedure

Maltoni, Vryonidou, Zaro 1408.6542:

full m_top dependence also in real radiation

transferred to H+jet means 1-loop diagrams combined with single real radiation, up to pentagon diagrams for H+1jet, hexagons for H+2jets





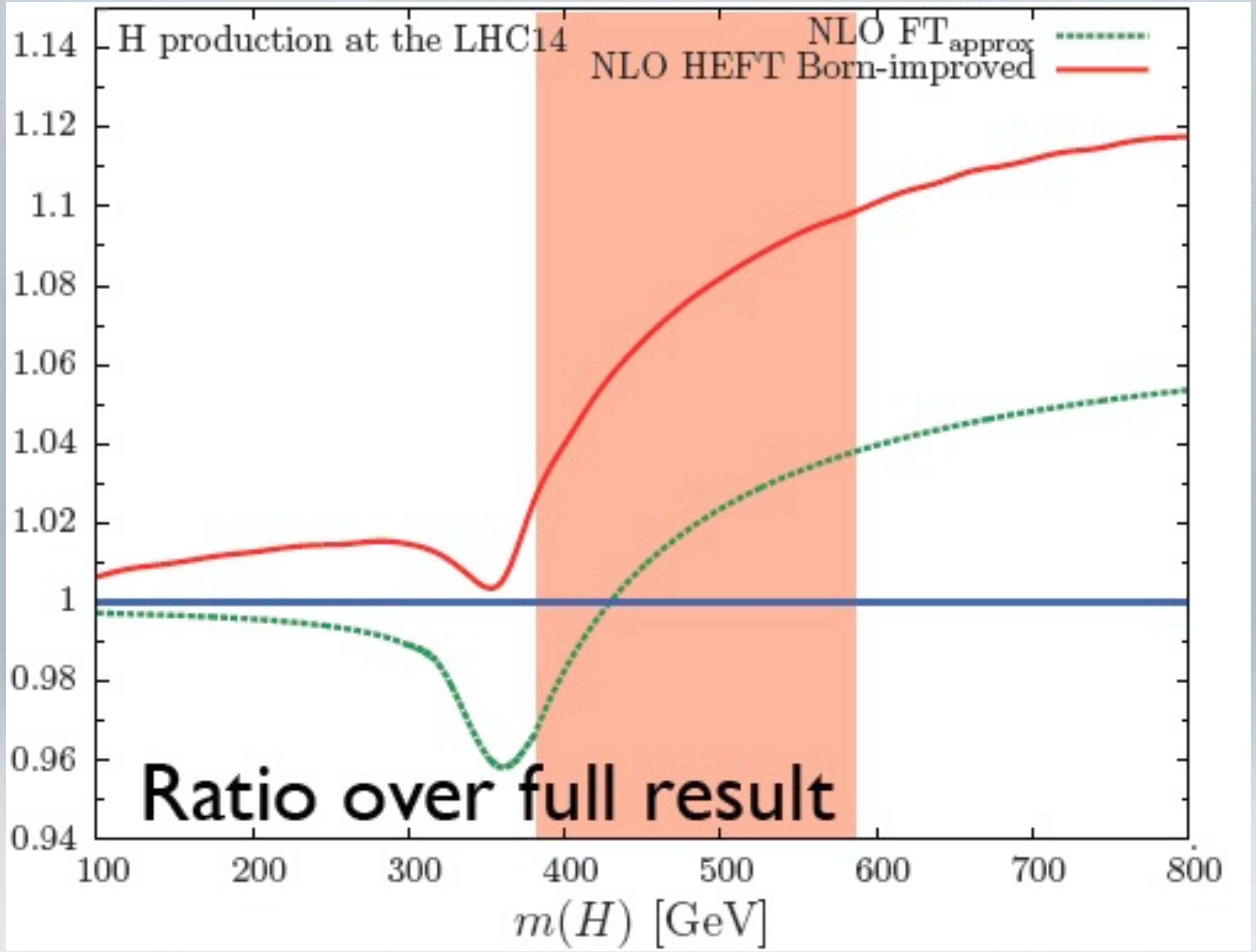
example diagrams for real radiation corrections to H+1jet

only missing ingredient for full NLO would be 2-loop virtual diagrams ⟶ “FT_approx”

compare to “Born improved HEFT” reweighting with $r = |\mathcal{M}_{loop}|^2/|\mathcal{M}_{HEFT}|^2$

LO (“Born”)

comparison "FT_approx" and "Born improved HEFT" for single Higgs case:

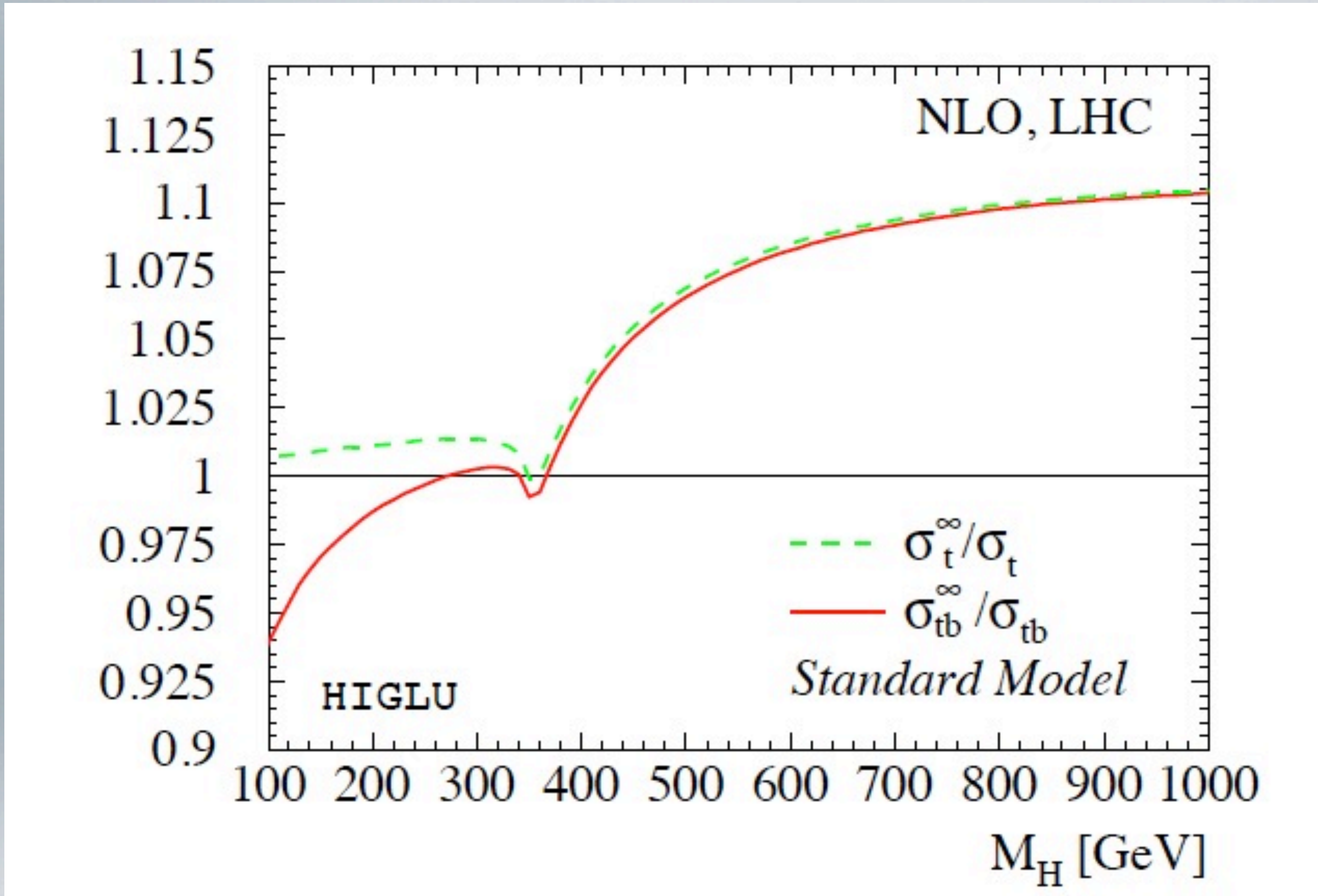


[M.Zaro, LHC XS WG meeting Nov '14]

inclusion of full mass dependence in real radiation

⟶ cancellations real-virtual spoilt or better approximation?

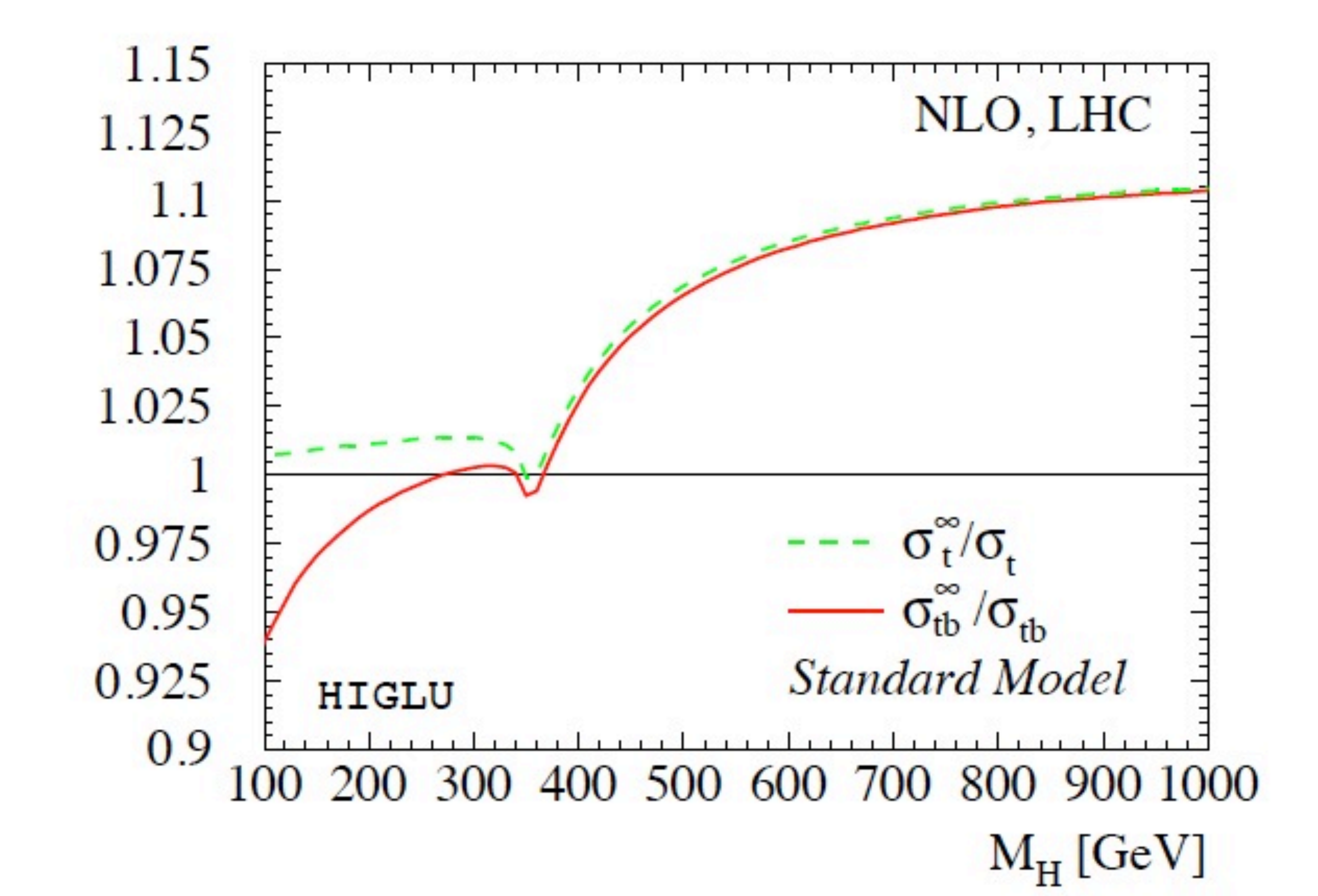
inclusive Higgs production: compare "Born improved HEFT" with full NLO



Harlander '03

based on HIGLU [Spira et al]

obvious cancellations between real and virtual contributions around the 2 mtop threshold because in this region "Born improved HEFT" is very close to full theory inclusive Higgs production: compare "Born improved HEFT" with full NLO



Harlander '03

based on HIGLU [Spira et al]

obvious cancellations between real and virtual contributions around the 2 mtop threshold because in this region "Born improved HEFT" is very close to full theory

beyond the threshold region it is unclear which is the better approximation for H+jet(s) until full mass dependence in virtual corrections (2 loops) is available

Conclusions

- H+jet: HEFT does rather well for observables which are sufficiently inclusive in pT (H, jet)

- less inclusive observables: top mass effects are important at large pT

Conclusions

- H+jet: HEFT does rather well for observables which are sufficiently inclusive in pT (H, jet)

- less inclusive observables: top mass effects are important at large pT

- studying only the gg channel, does not always capture the leading effects

Conclusions

- H+jet: HEFT does rather well for observables which are sufficiently inclusive in pT (H, jet)
- less inclusive observables: top mass effects are important at large pT
- studying only the gg channel, does not always capture the leading effects
- different approximations towards full NLO can lead to substantial differences in the predictions, not only at high pT