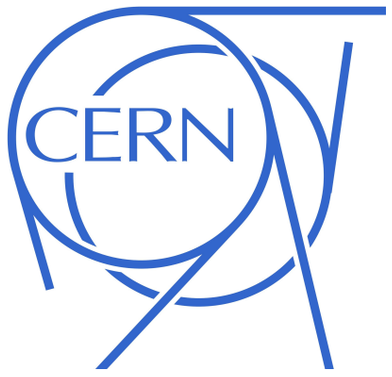
Overview:
Quark-mass effects and higher-dimensional OPs in gg→H

Marius Wiesemann



Les Houches 2017 (France)

10. June, 2017

Outline

1. Mass effects

- **Top-mass effects through $1/m_{top}$ expansion at $O(\alpha_s^4)$**
- **(Top- and) Bottom-mass in the resummed Higgs p_T spectrum**
- **Bottom-mass effects in the p_T spectrum at NLO**
- **Monte Carlos?**

2. Higher-dimensional OPs in the Higgs p_T spectrum

- **Focus on how to model the "leading" effects**

Total cross section at NNLO

top-mass effects by $1/m_{top}$ expansion:

$$\sigma = \sum_{k=0}^{\infty} \frac{1}{m_{\rm top}^{2k}} \, \sigma^{(k)}$$

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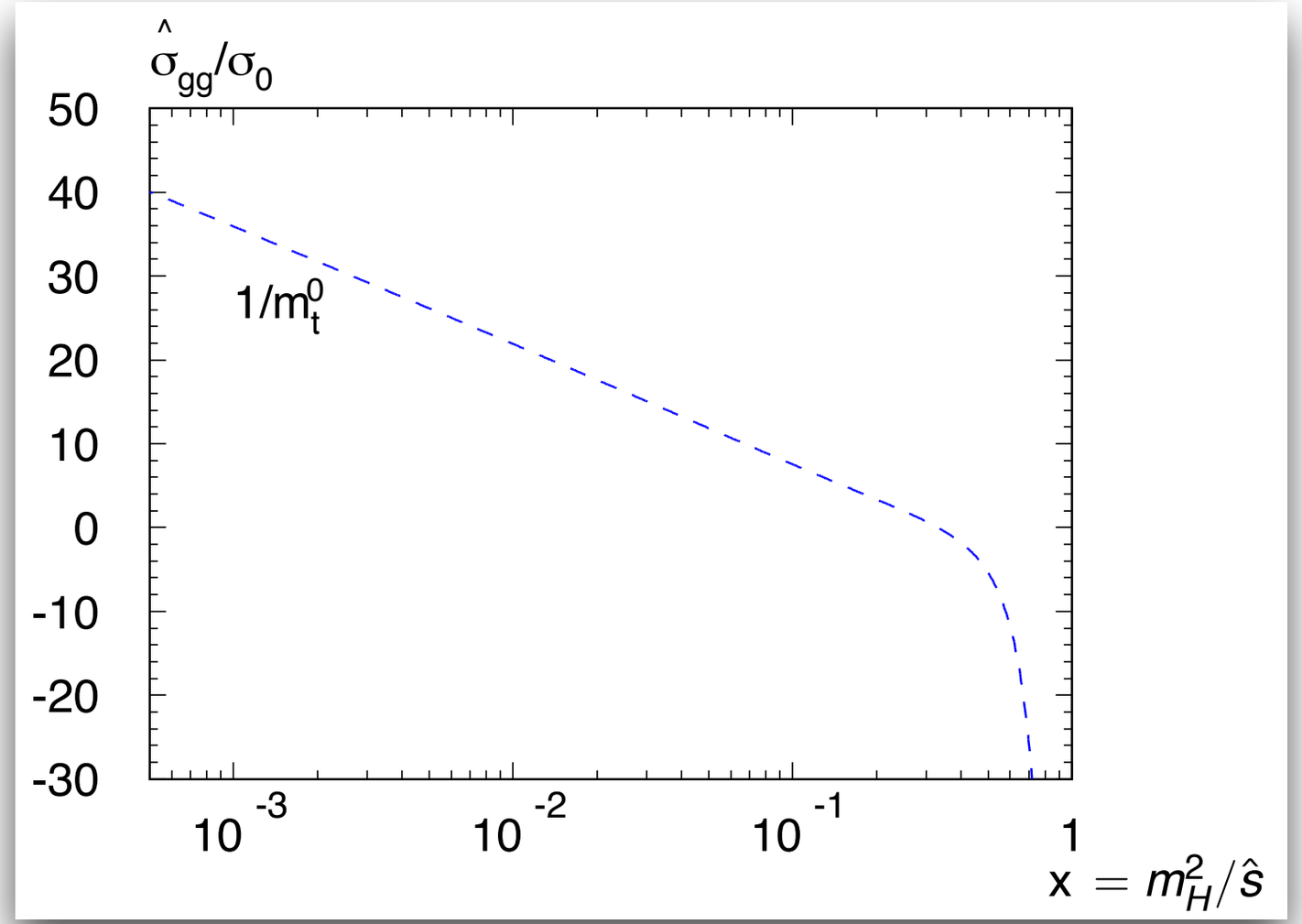
[Harlander, Mantler, Marzani, Ozeren '10]



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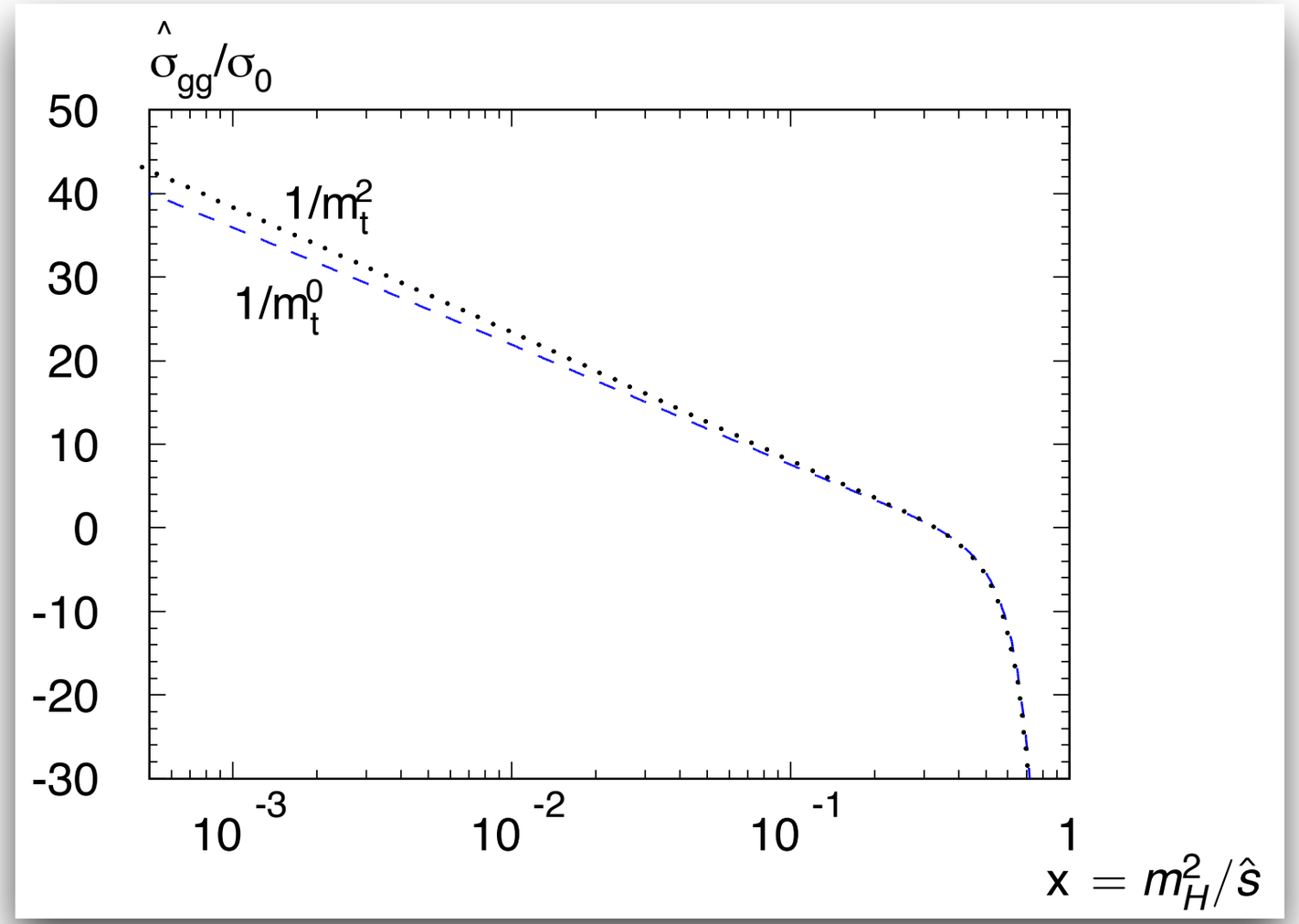

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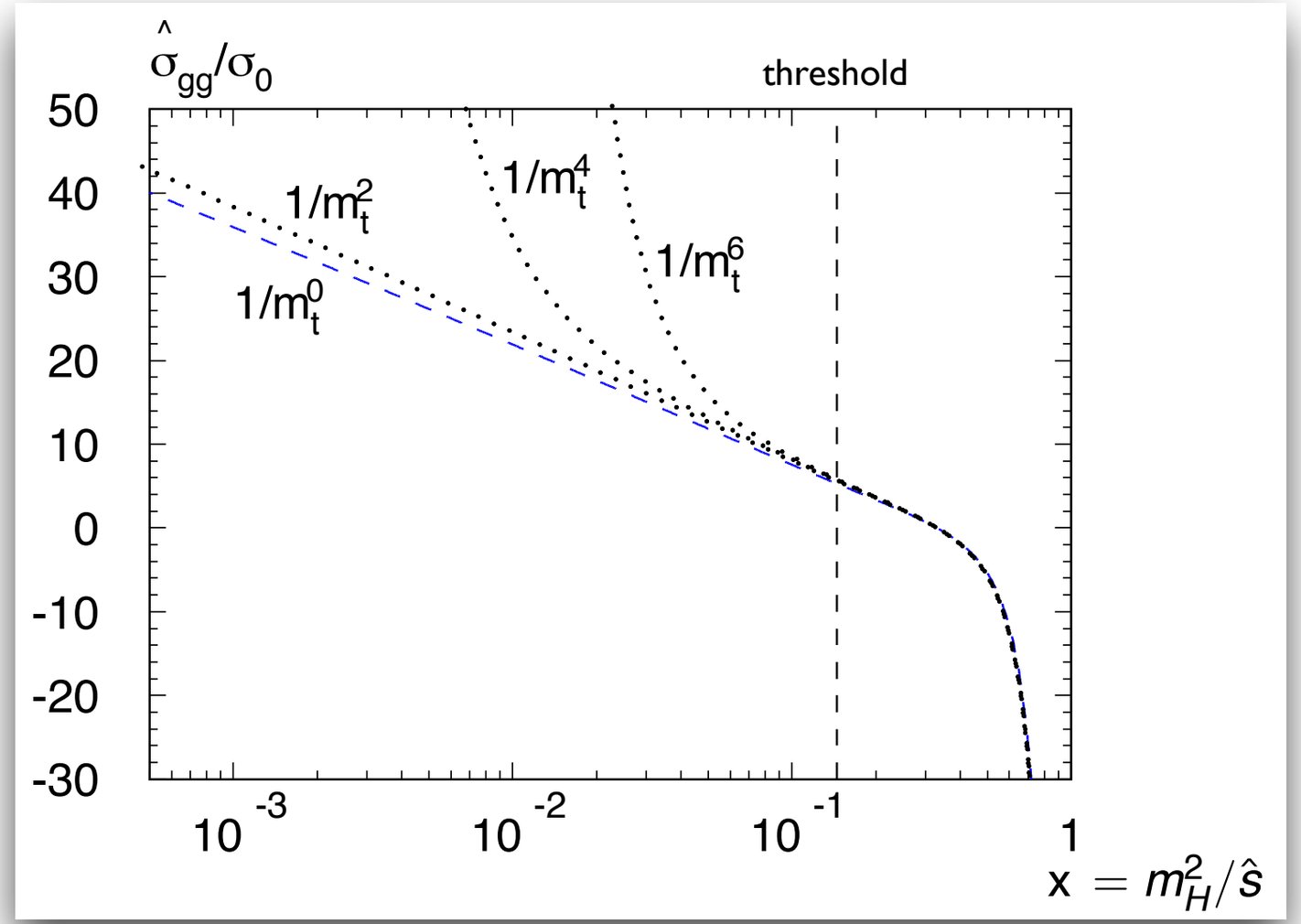

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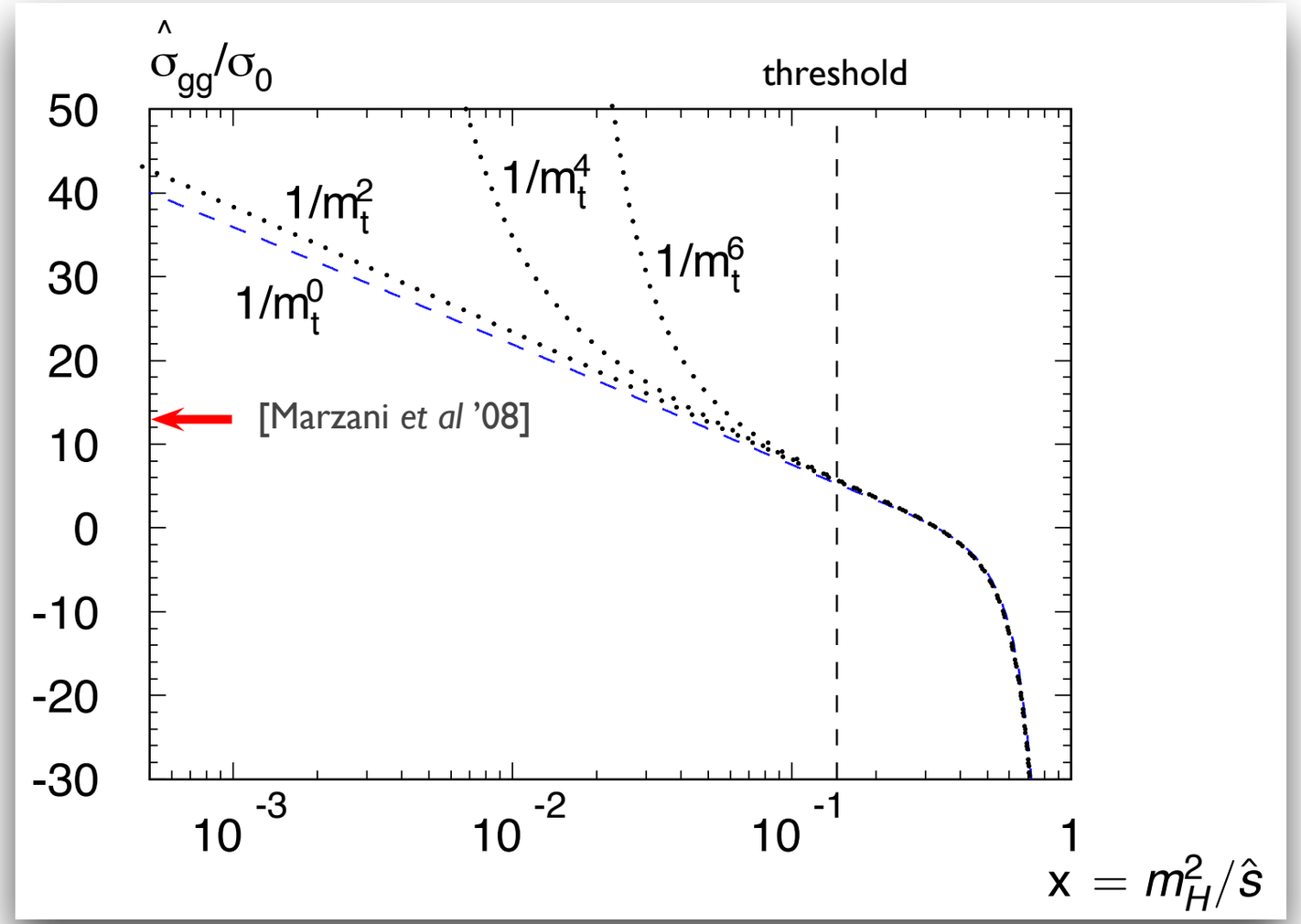

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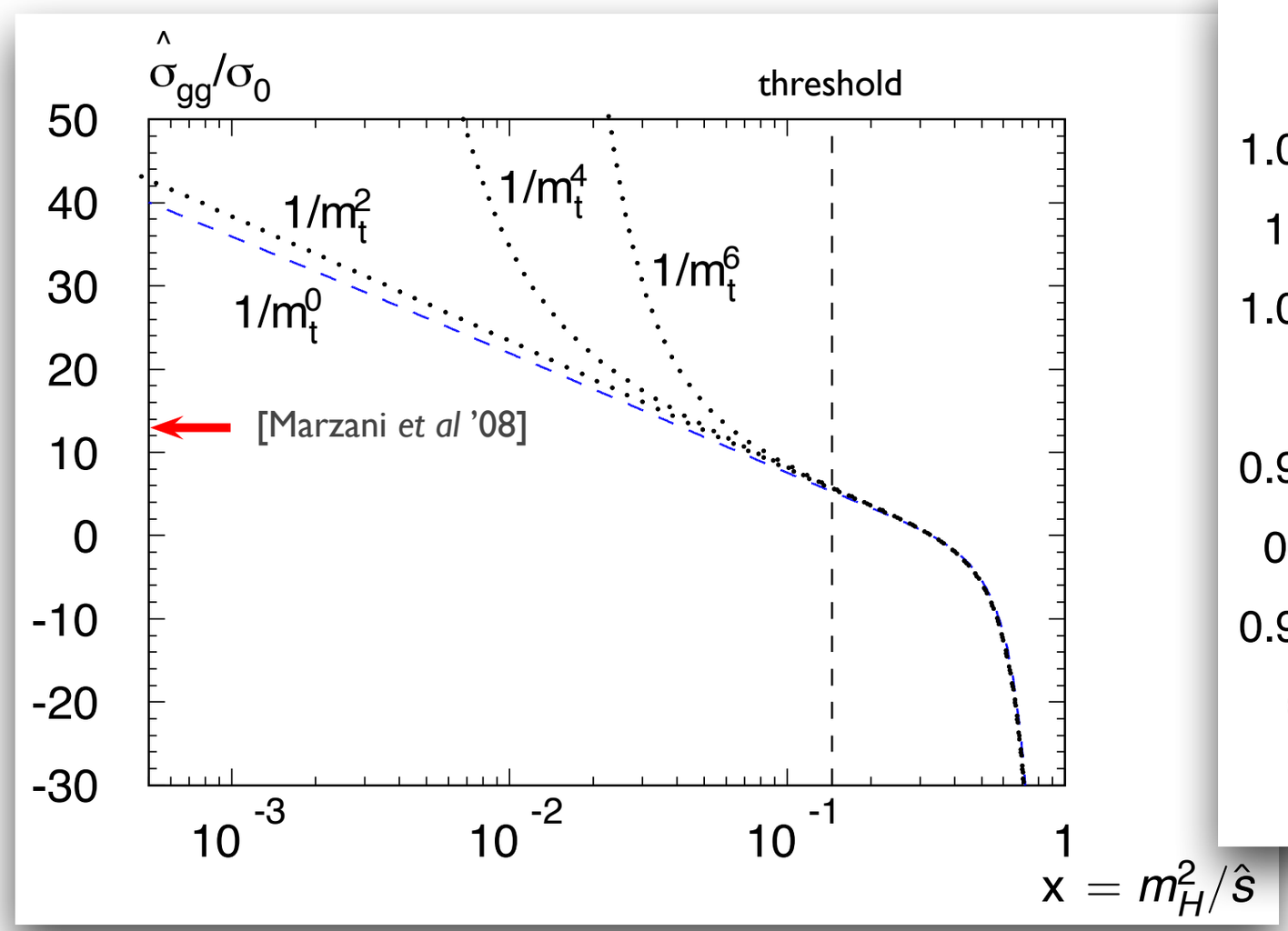

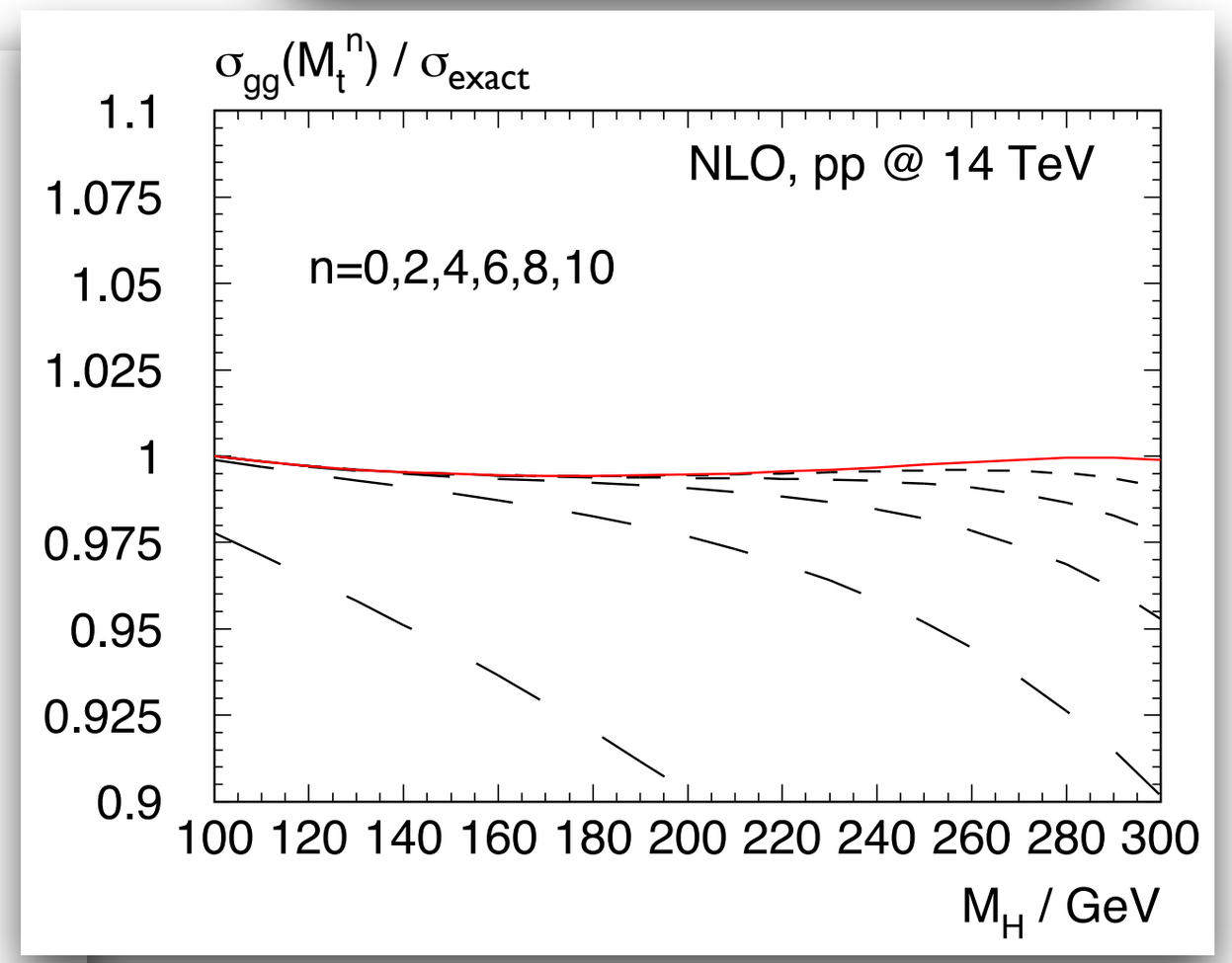

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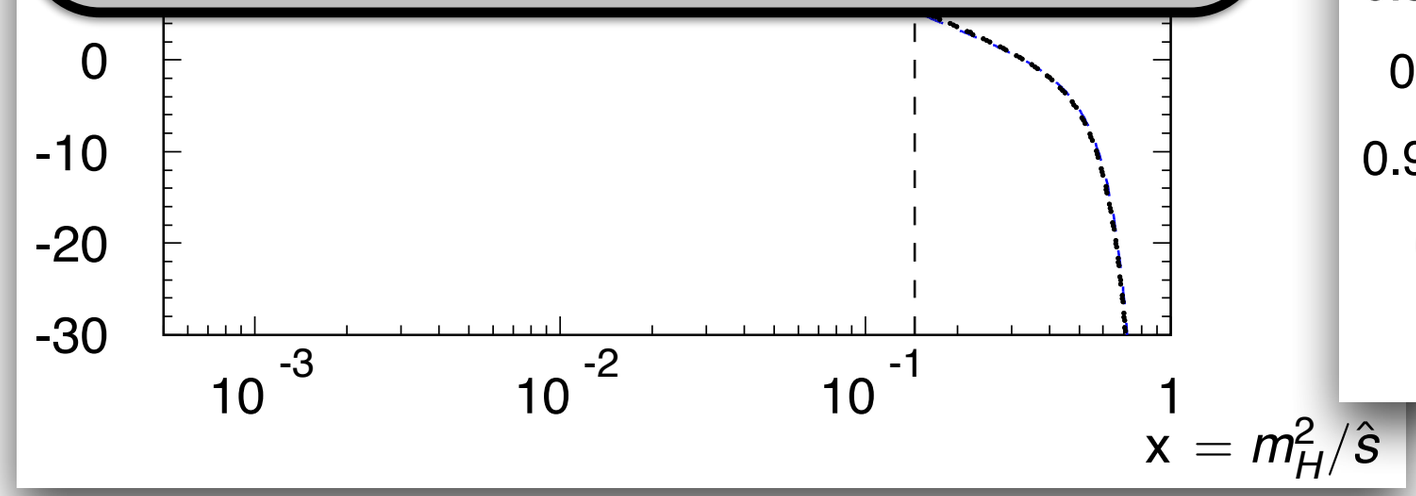
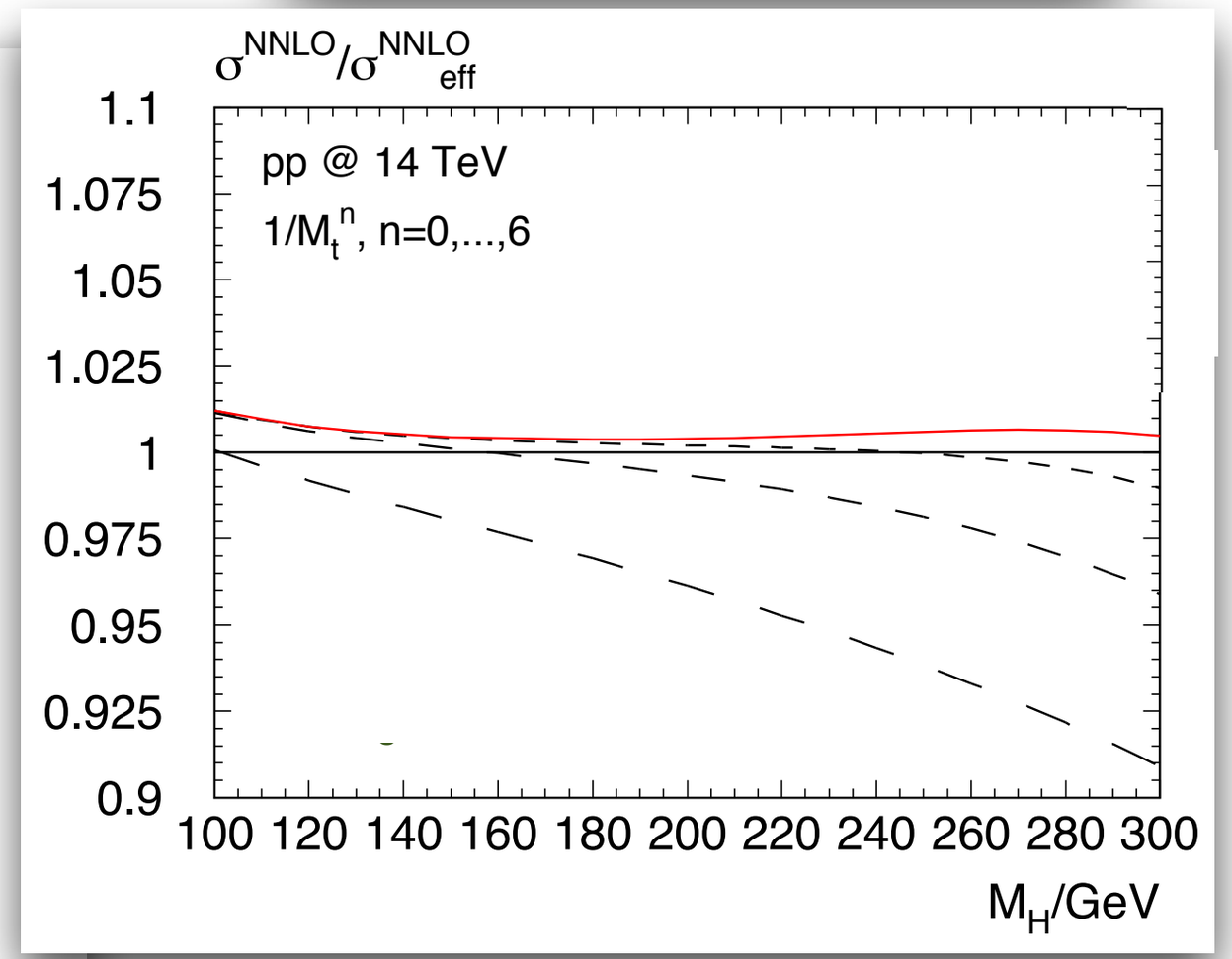
[Harlander, Mantler, Marzani, Ozeren '10]

$$\sigma^{\rm NNLO}_{\rm eff} = \sigma^{\rm LO}(m_{\rm top}) \cdot K^{\rm NNLO}_{\rm htl}$$

$$K^{\rm NNLO}_{\rm htl} \equiv \left(\frac{\sigma^{\rm NNLO}}{\sigma^{\rm LO}} \right)_{m_{\rm top} \to \infty}$$





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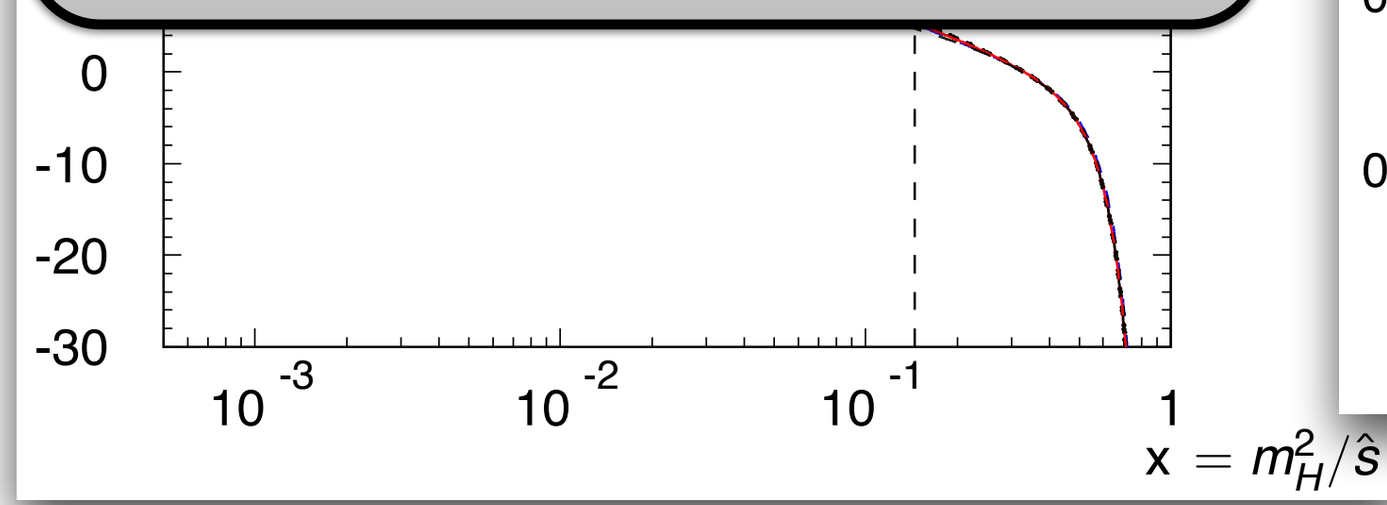
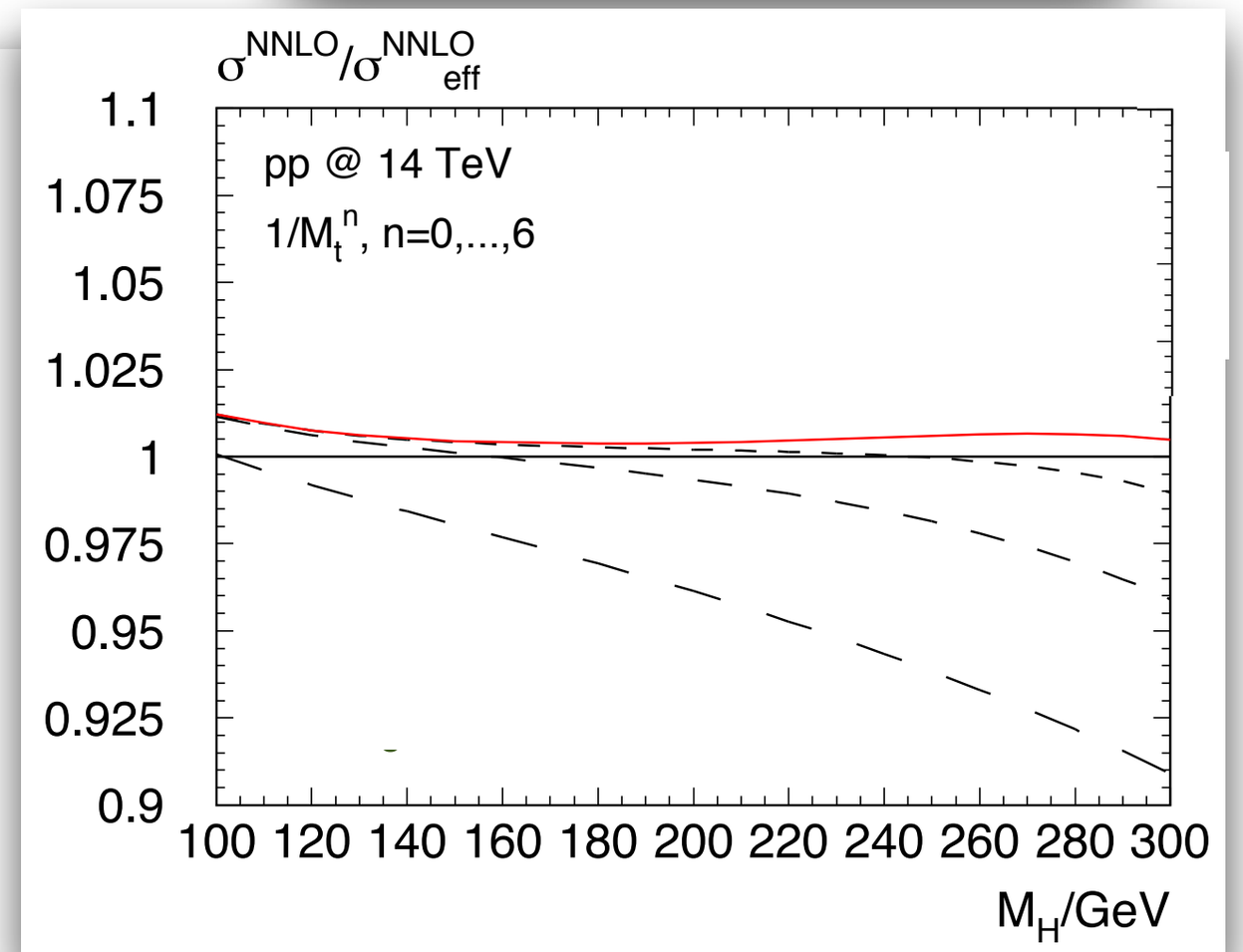
good approximation !





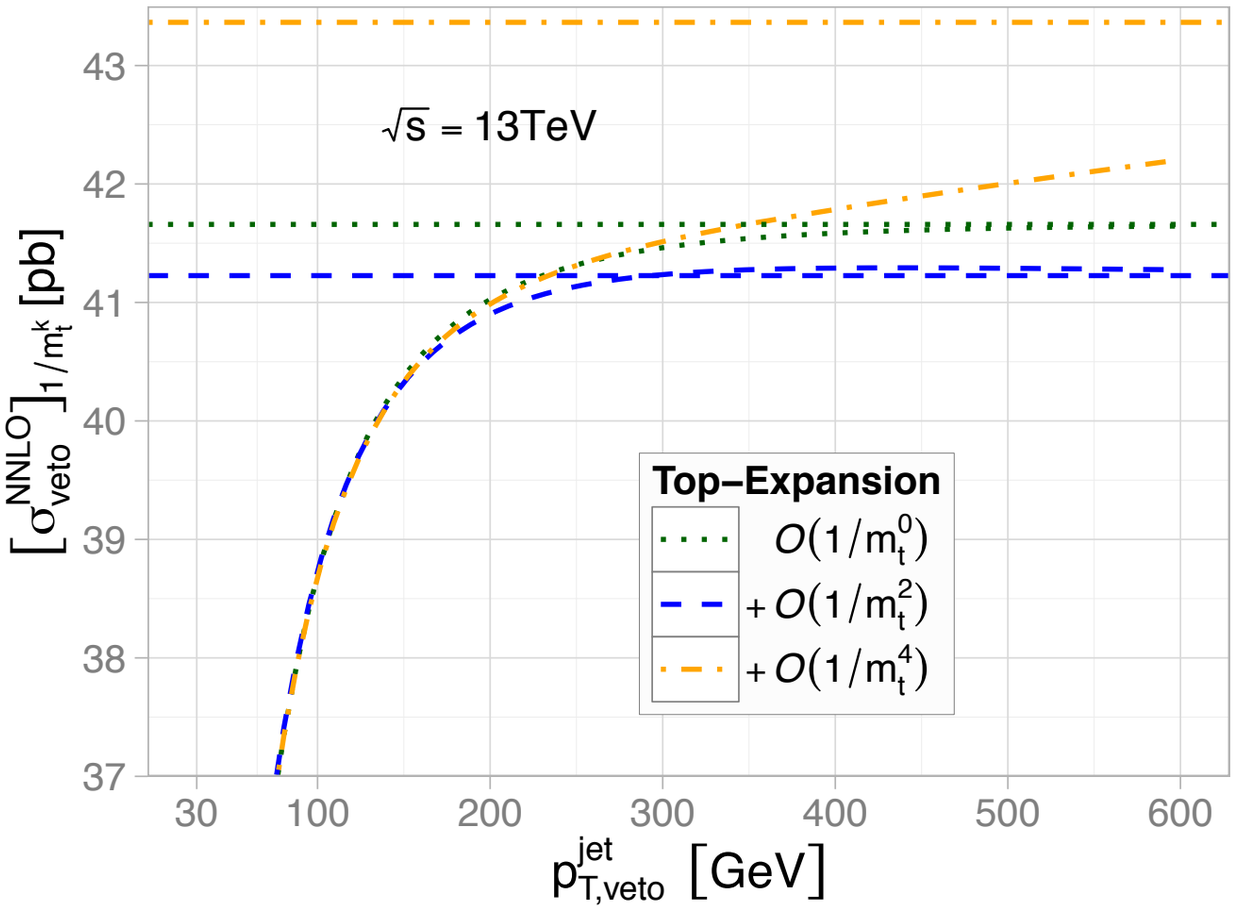
→ top-mass effects <1%

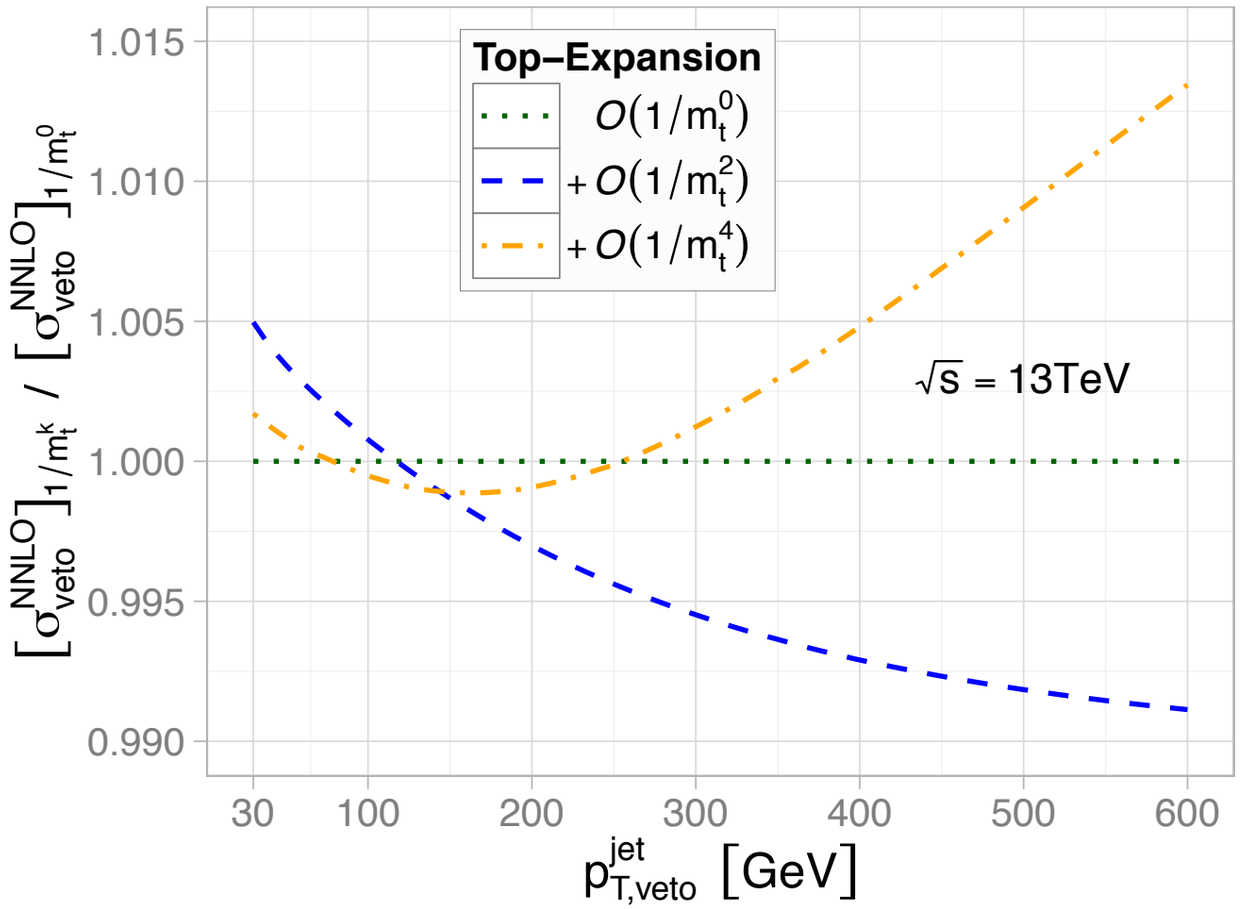
see also: [Pak, Rogal, Steinhauser '10]

Jet-veto at NNLO

$$\sigma^{\rm NNLO}_{\rm veto} \equiv \sigma^{\rm NNLO}_{\text{0-jet}} = \sigma^{\rm NNLO}_{\rm tot} - \sigma^{\rm NLO'}_{\geq \text{1-jet}}$$

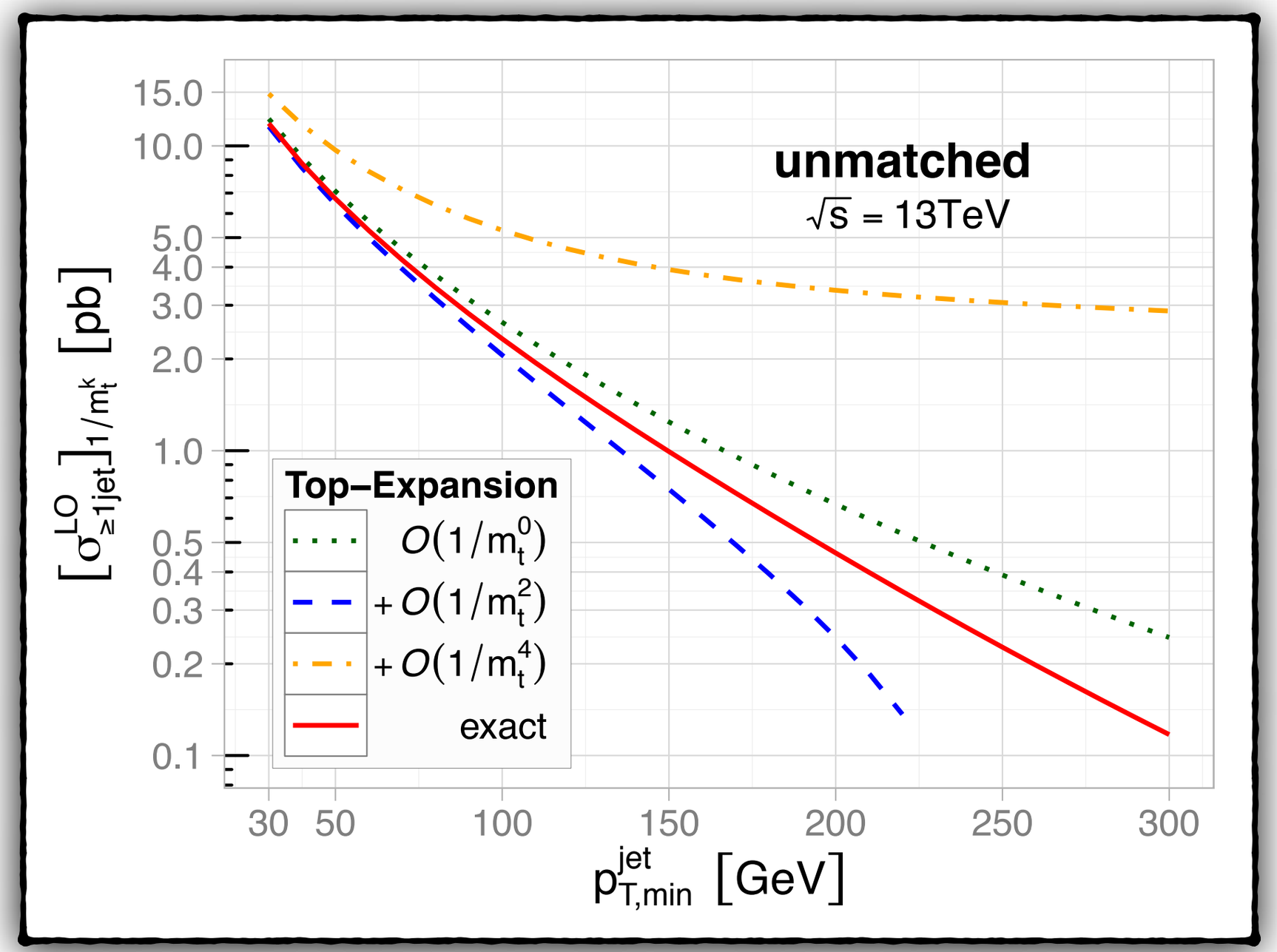
[Neumann, MW '14]





H+jet at LO

[Neumann, MW '14]



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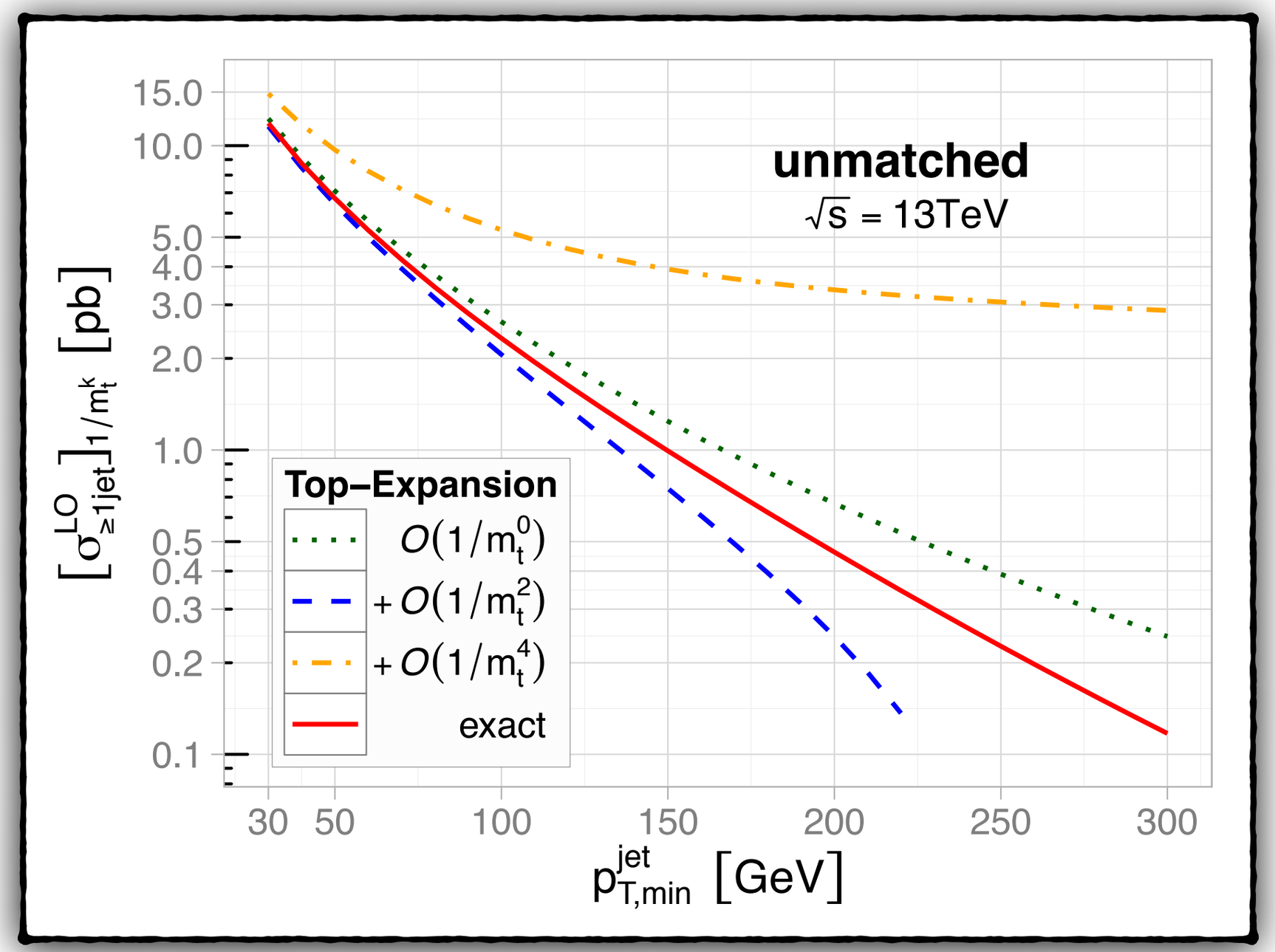

$$[\sigma^{\text{matched}}_{\text{tot}}]_{1/m^k_{\text{top}}} - [\sigma^{\text{unmatched}}_{\text{tot}}]_{1/m^k_{\text{top}}} = [\sigma^{\text{matched}}_{\geq 1\text{jet}}]_{1/m^k_{\text{top}}} - [\sigma^{\text{unmatched}}_{\geq 1\text{jet}}]_{1/m^k_{\text{top}}}$$

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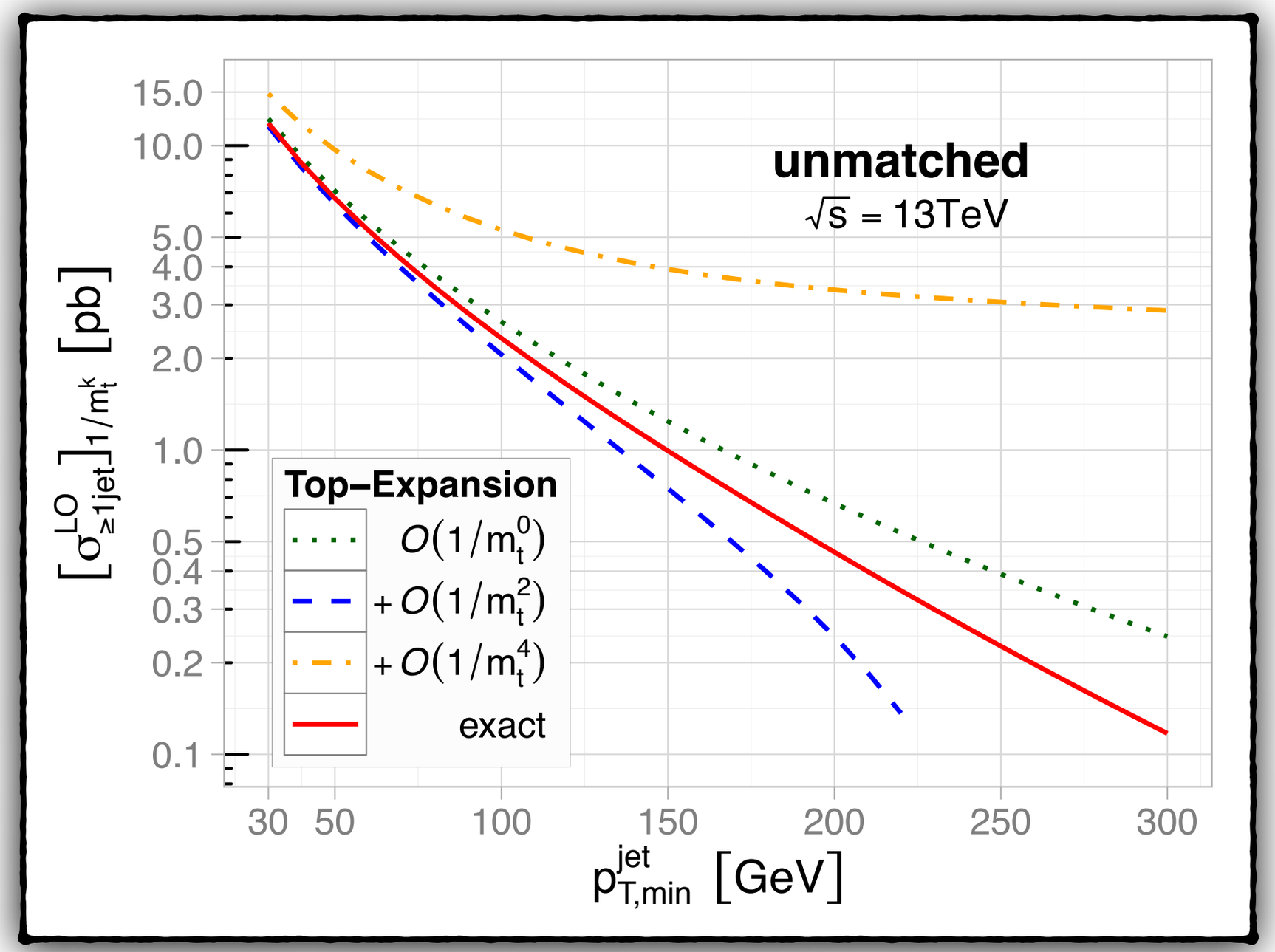

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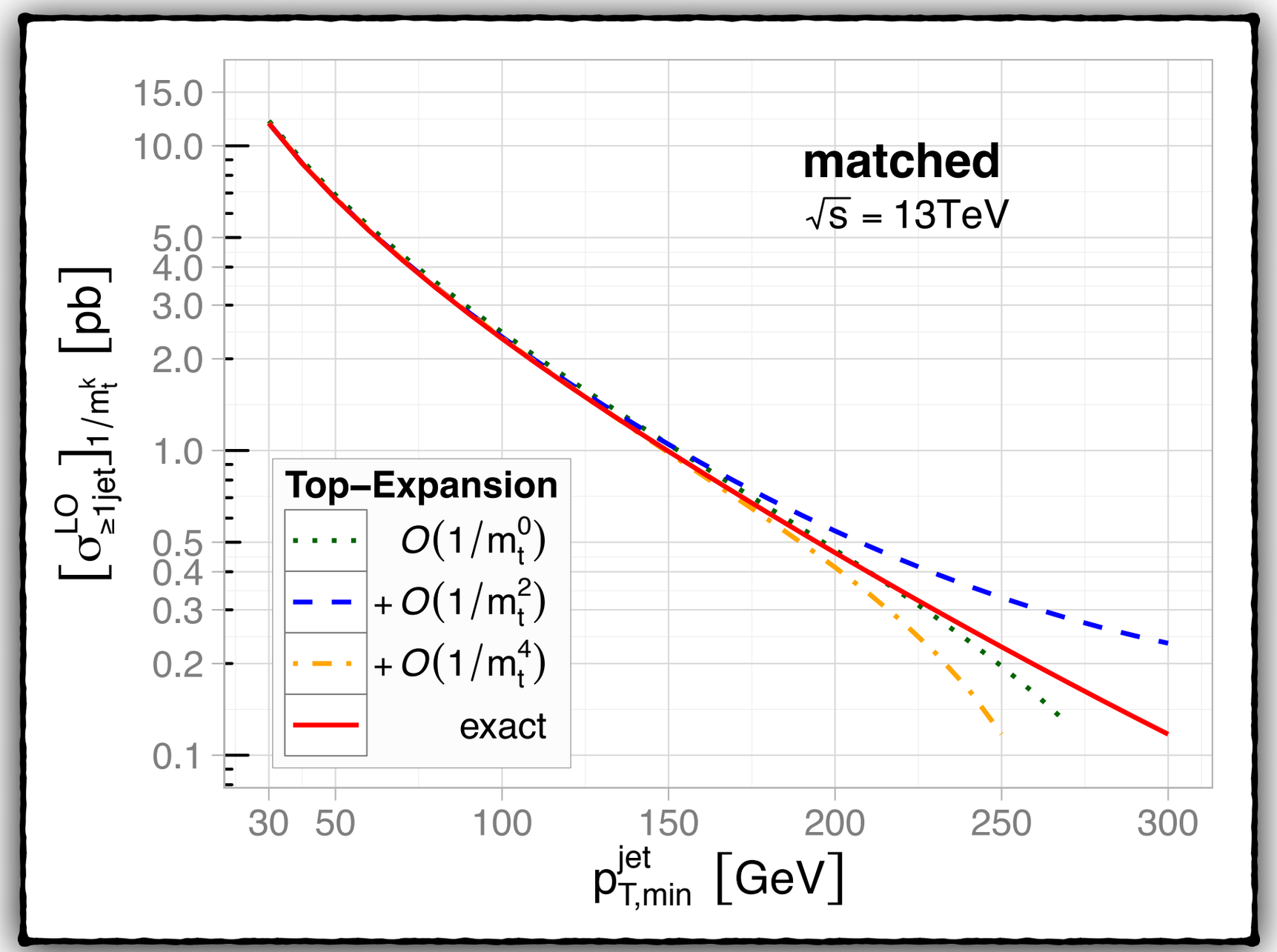

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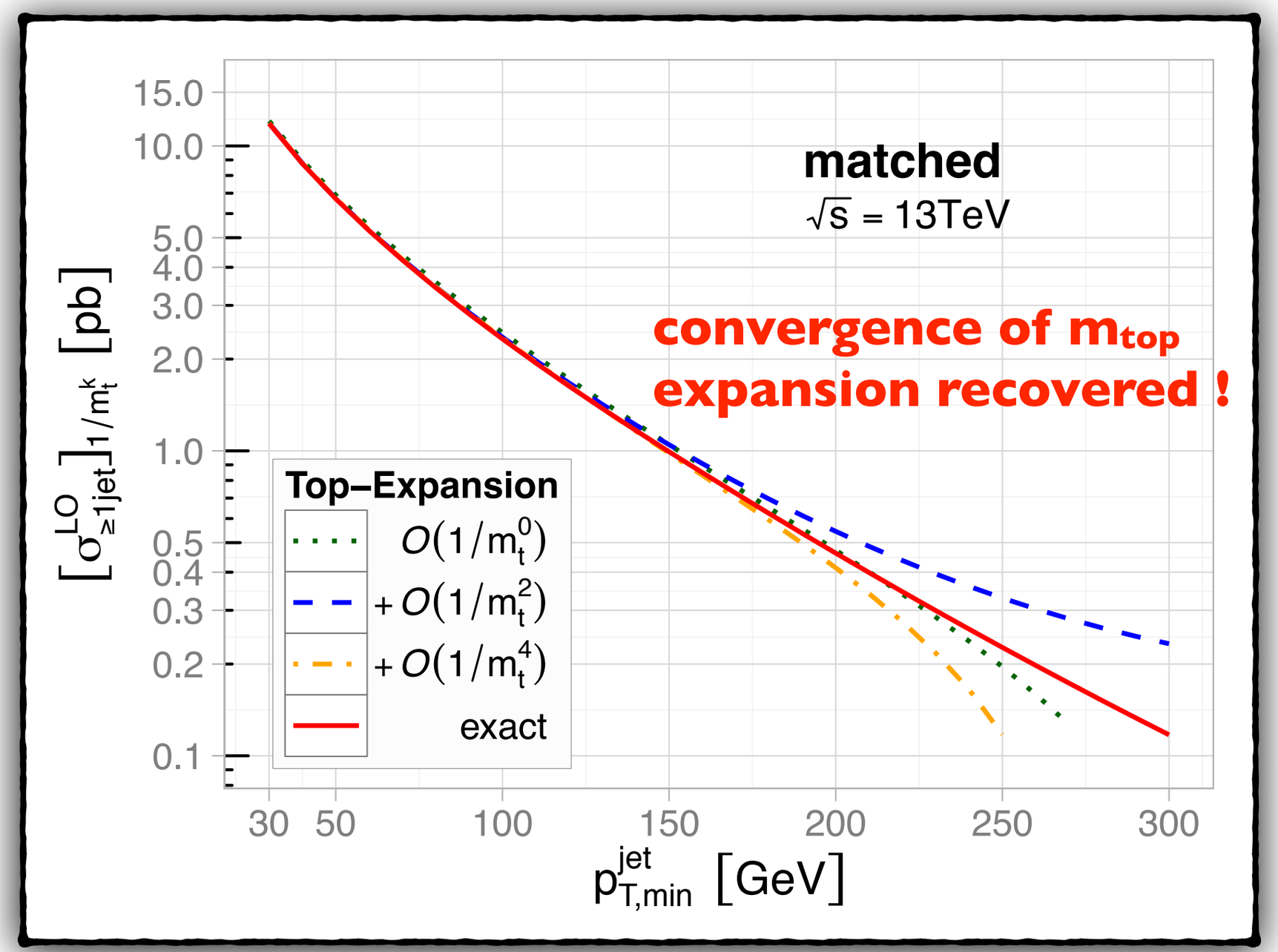

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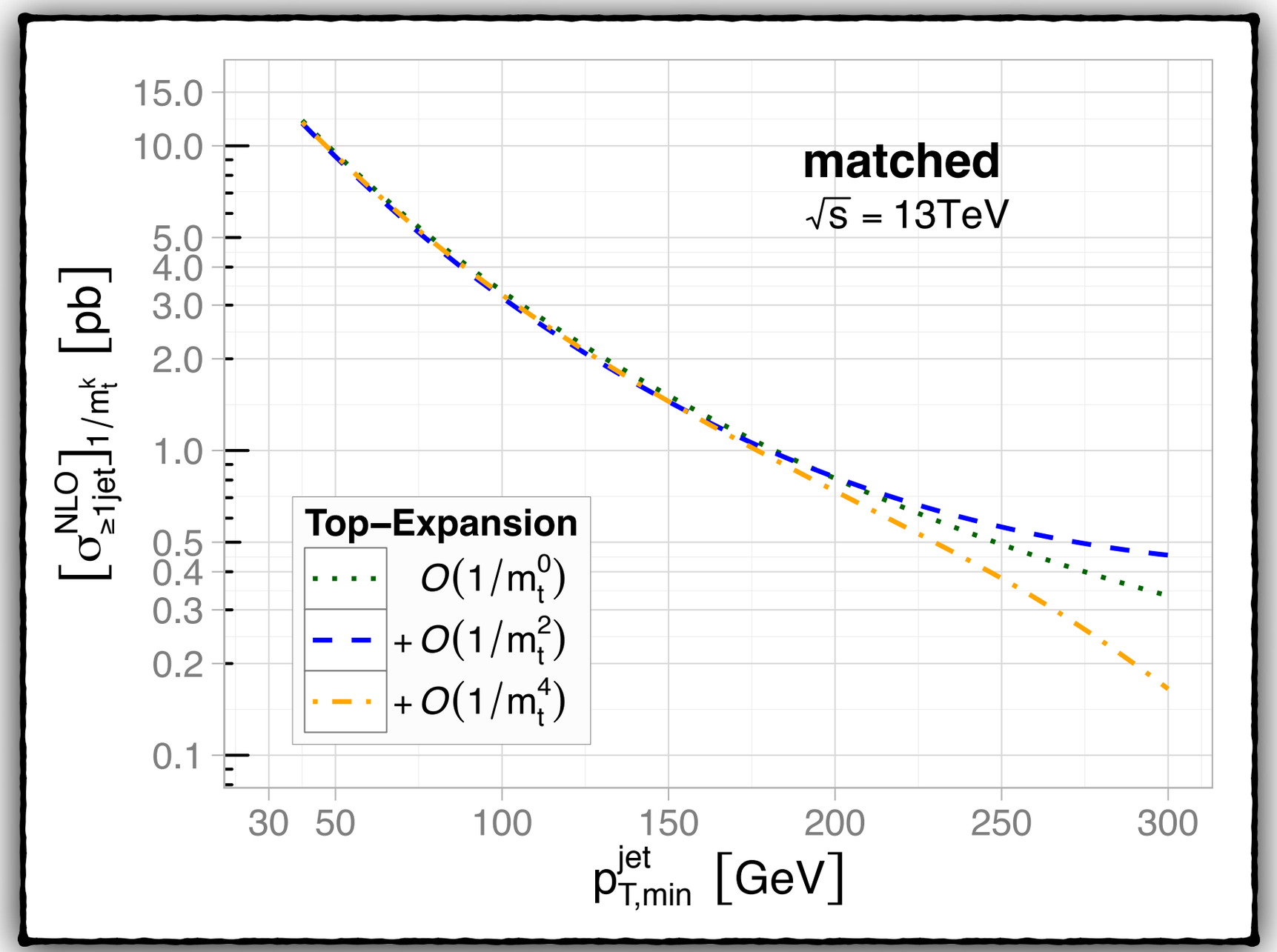
H+jet at NLO

[Neumann, MW '14]



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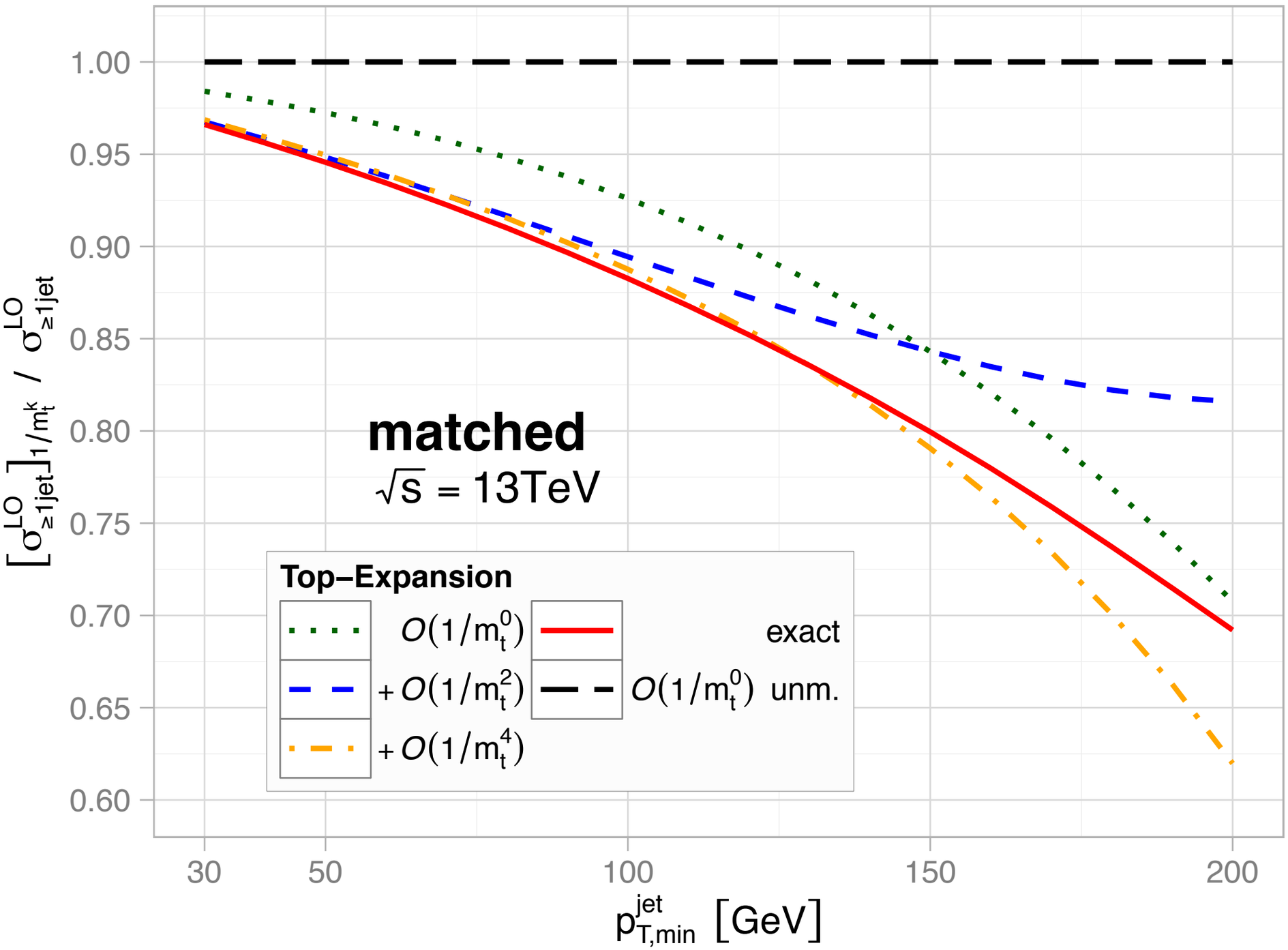

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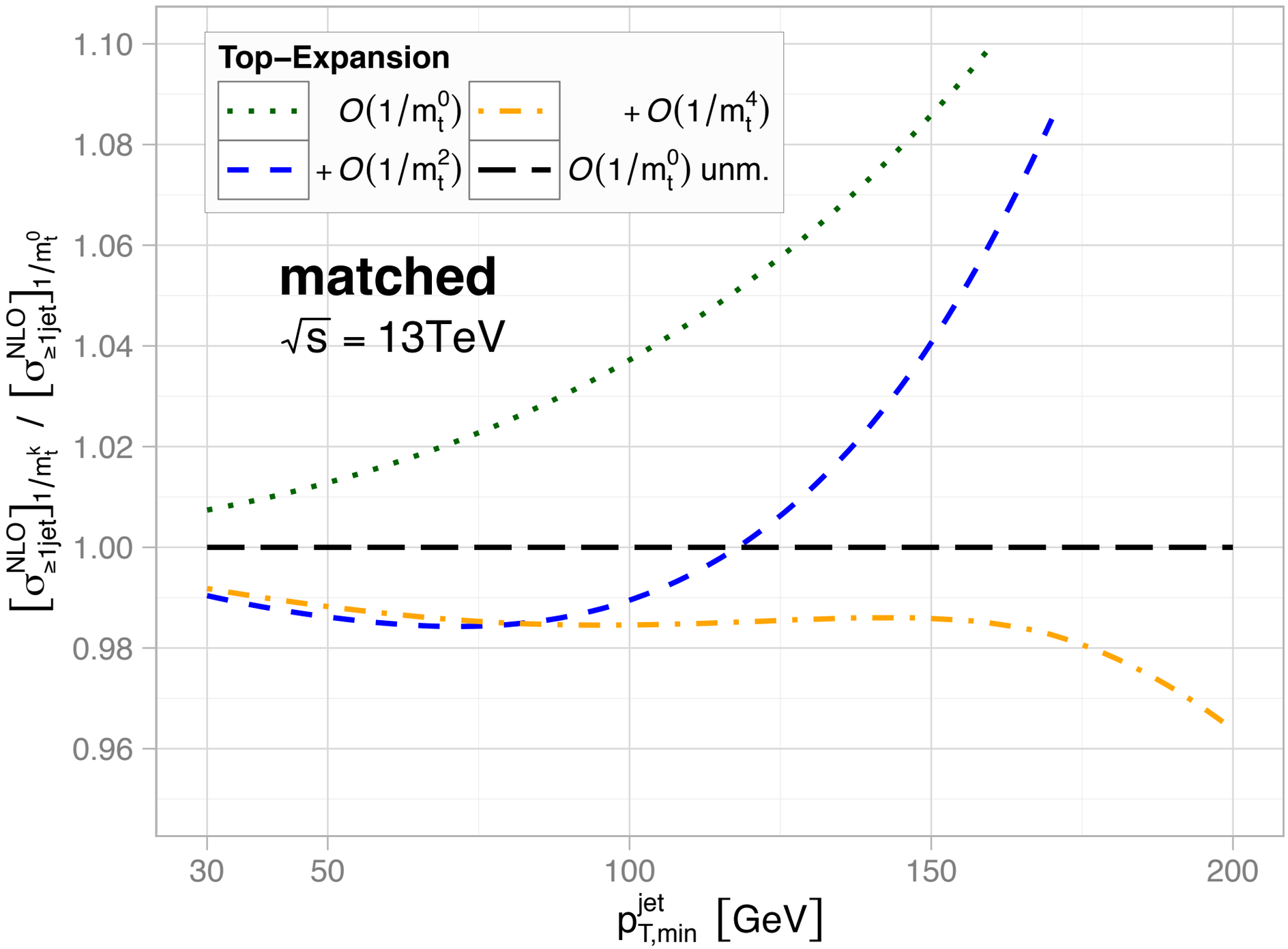
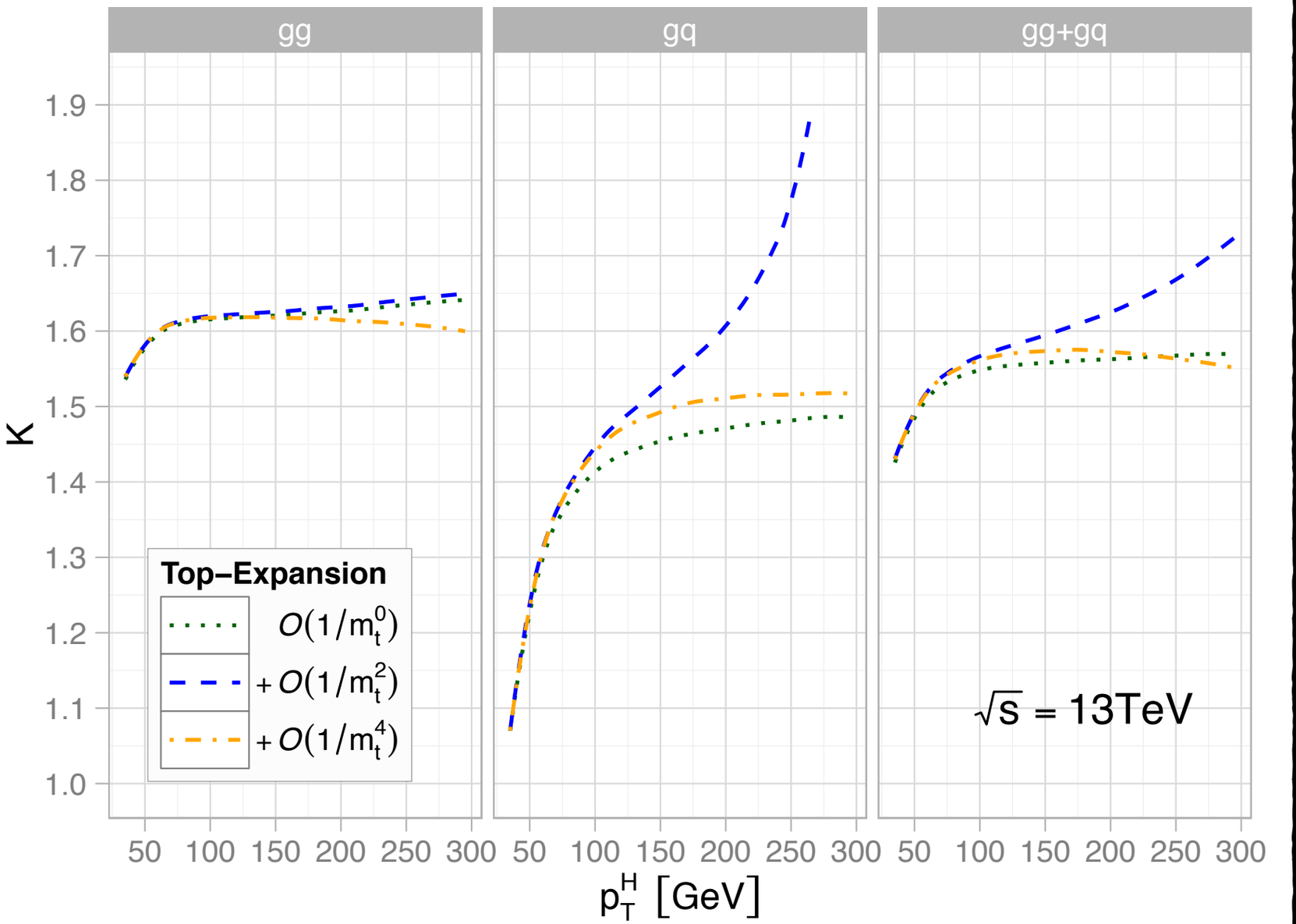
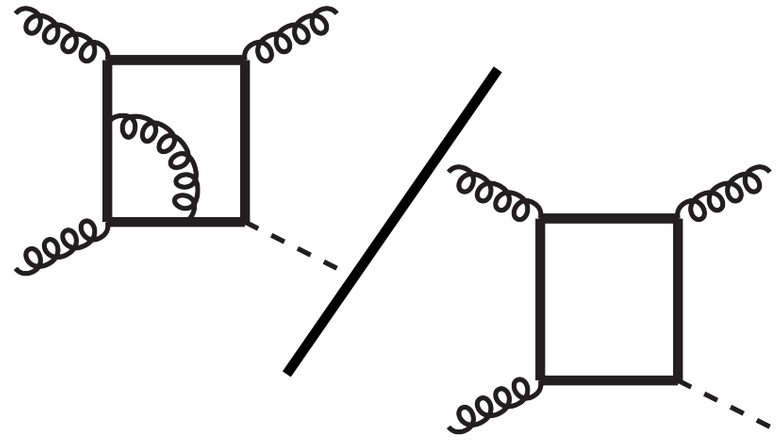


Higgs p_T at NLO

[Neumann, MW '14]
see also:
[Harlander, Neumann, MW '12]



$$K = \mathrm{d}\sigma^{\mathrm{NLO}} / \mathrm{d}\sigma^{\mathrm{LO}}$$



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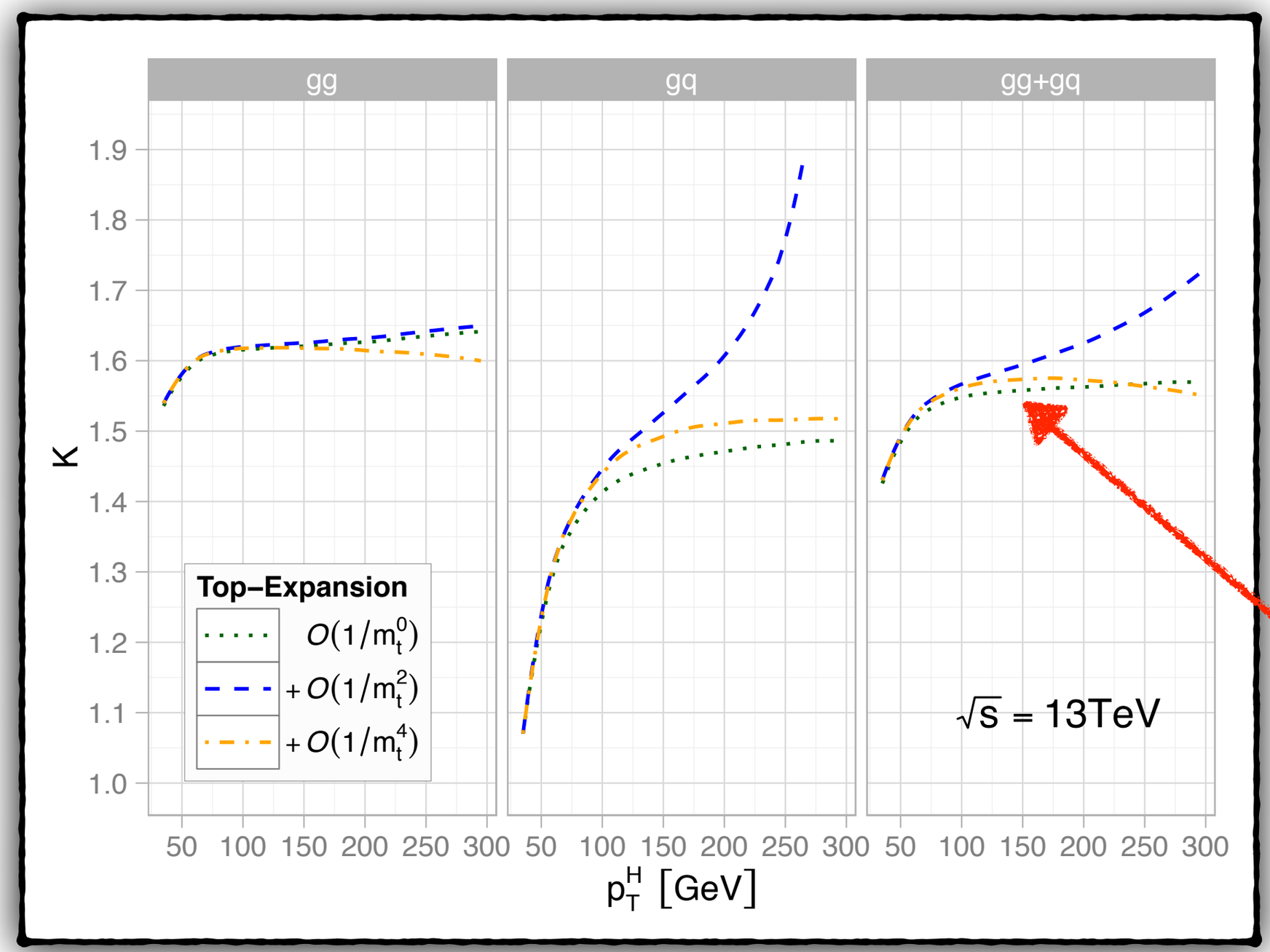

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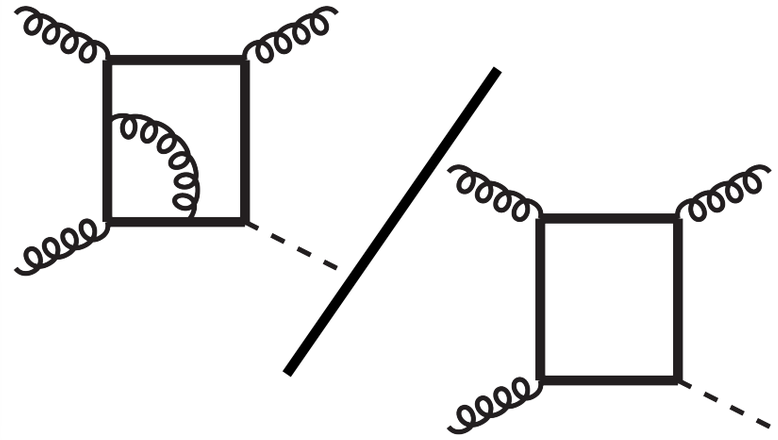
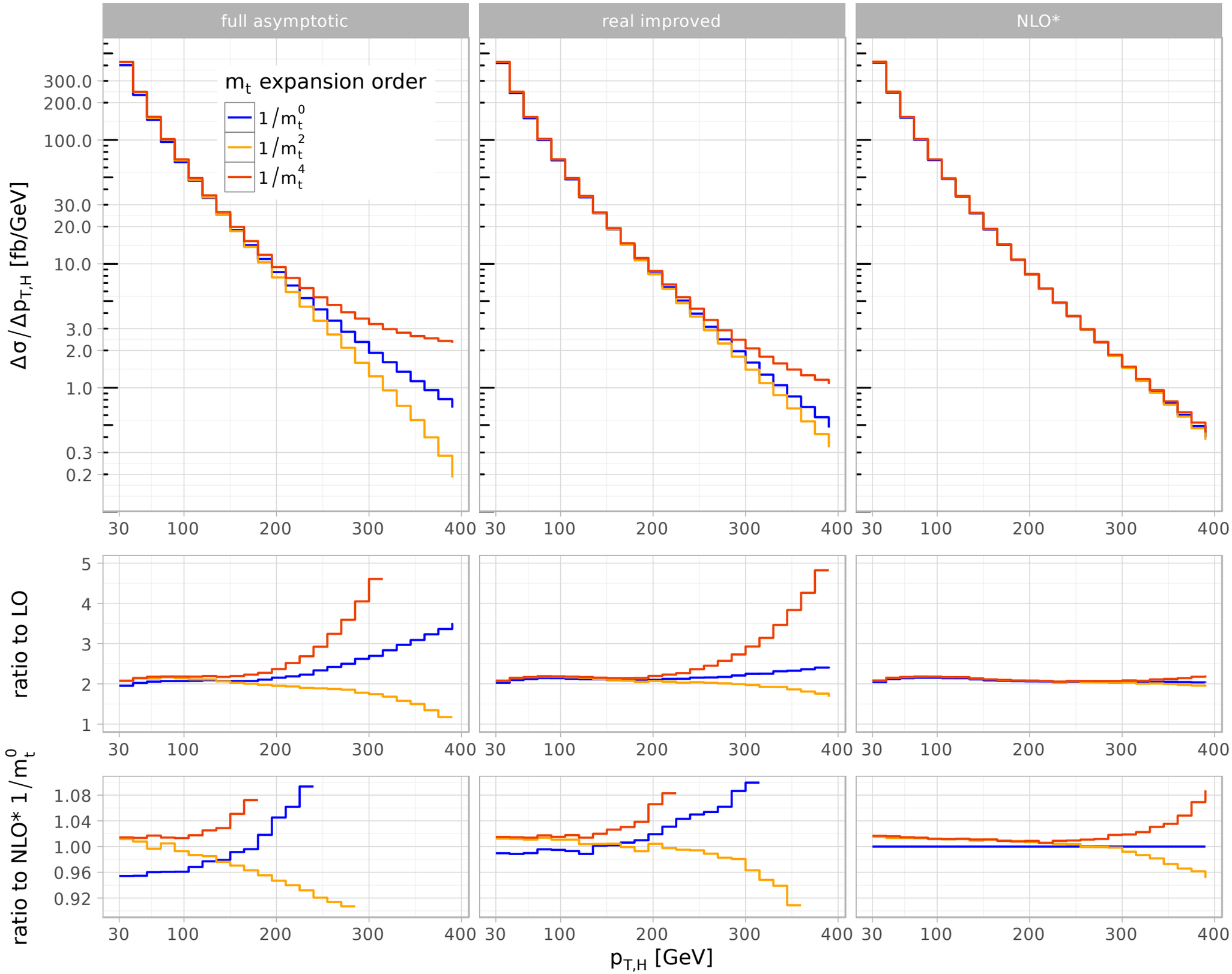


m_{top} effects below ~2% for $p_T < 150$ GeV

Higgs p_T at NLO

[Neumann, Williams '16]



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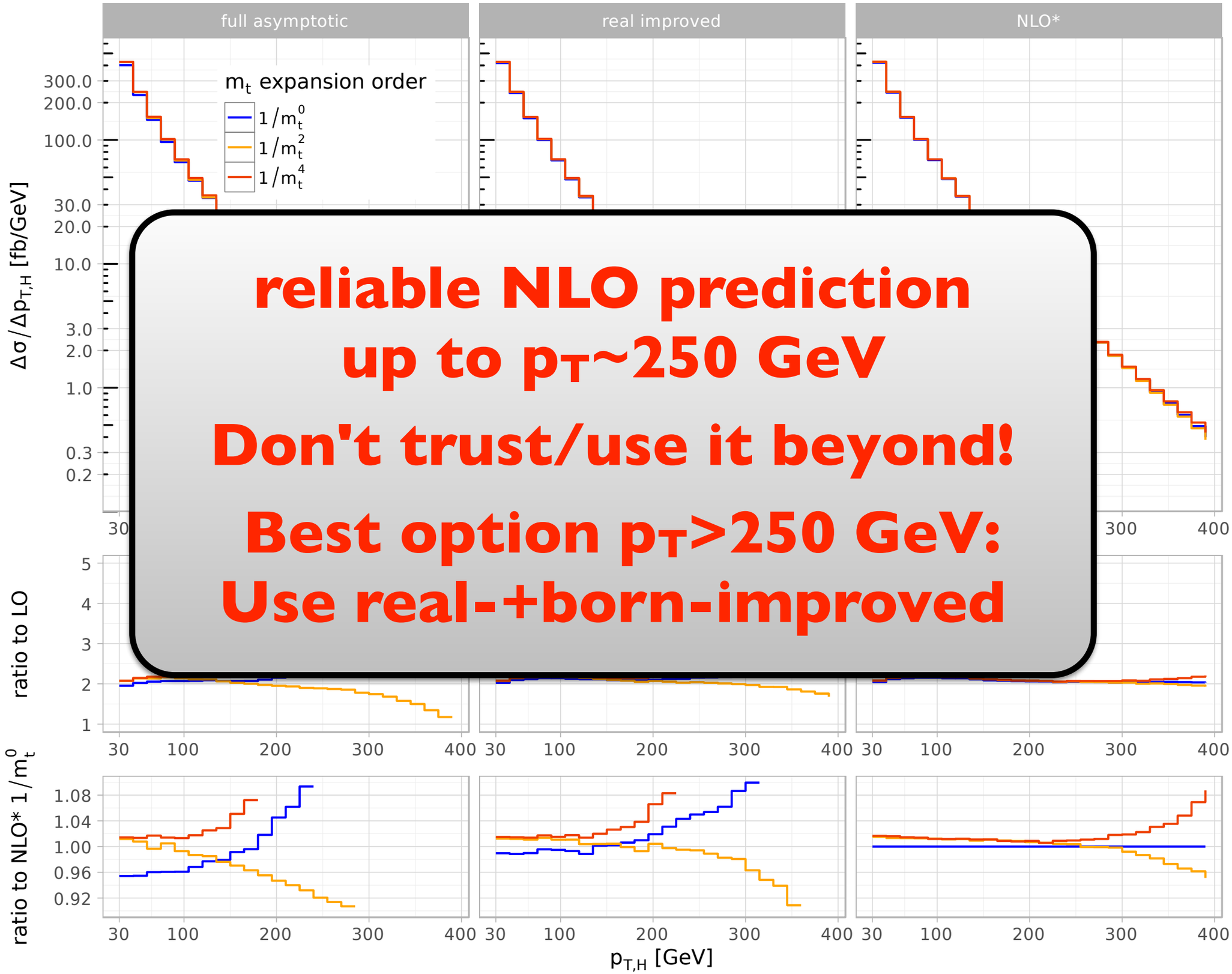
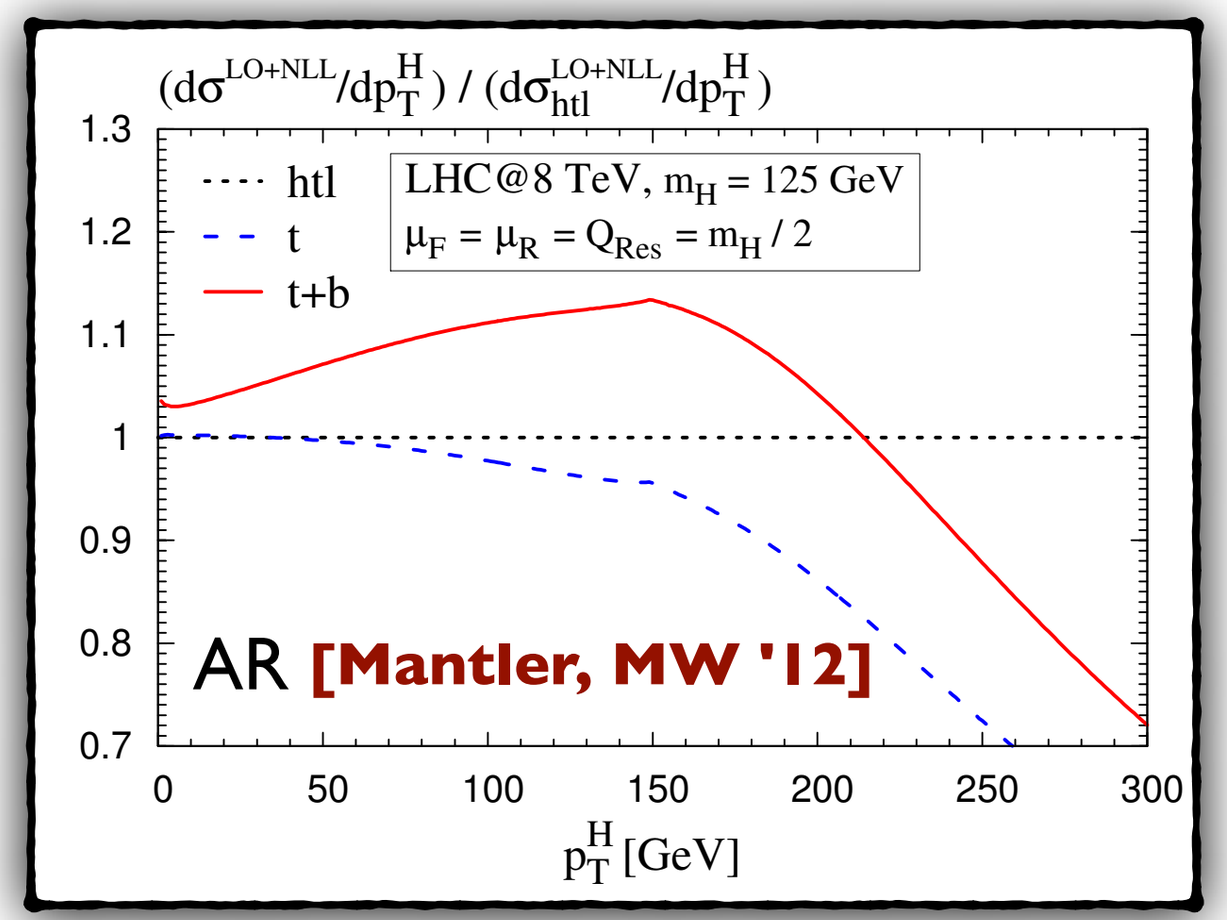


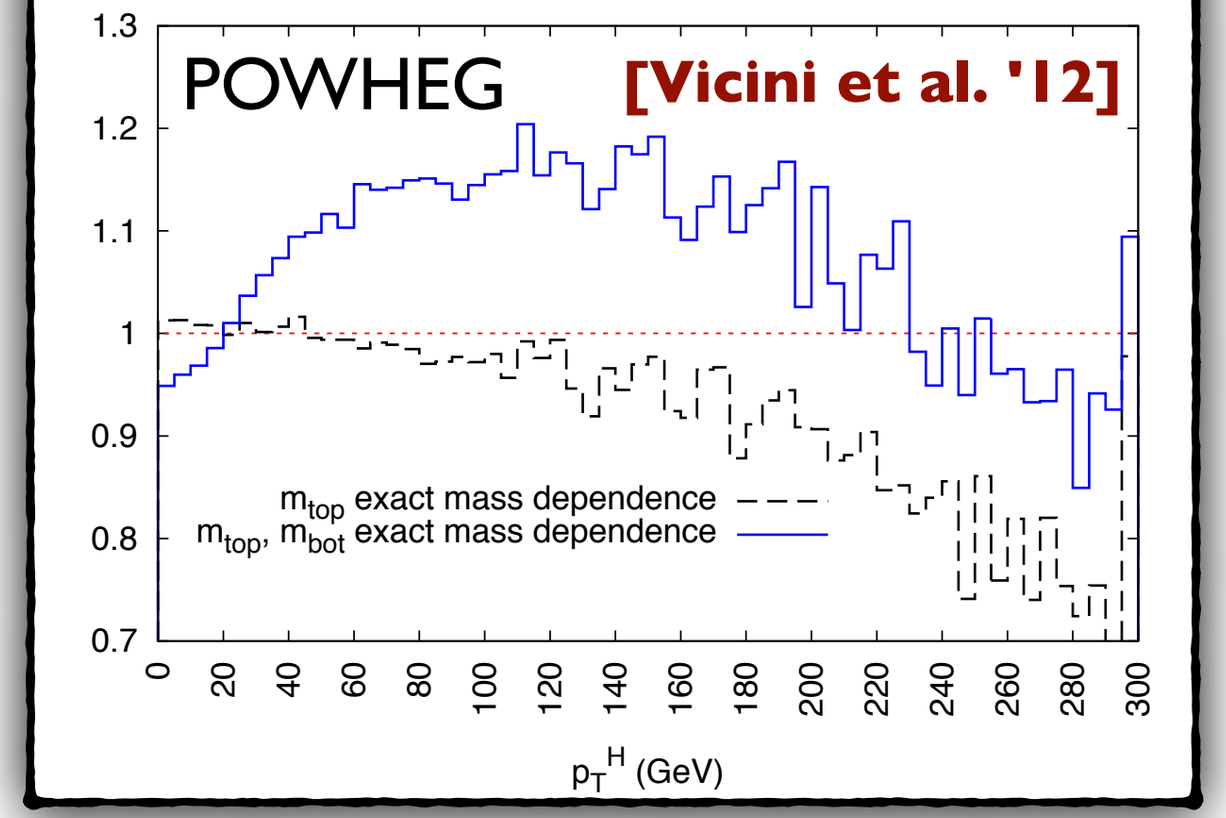
reliable NLO prediction up to p_T~250 GeV

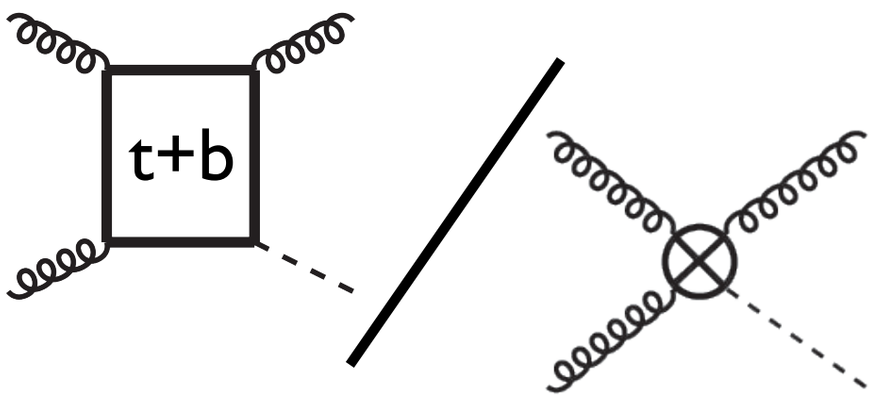
Don't trust/use it beyond!

Best option p_T>250 GeV: Use real-+born-improved

b-mass in resummed Higgs p_T



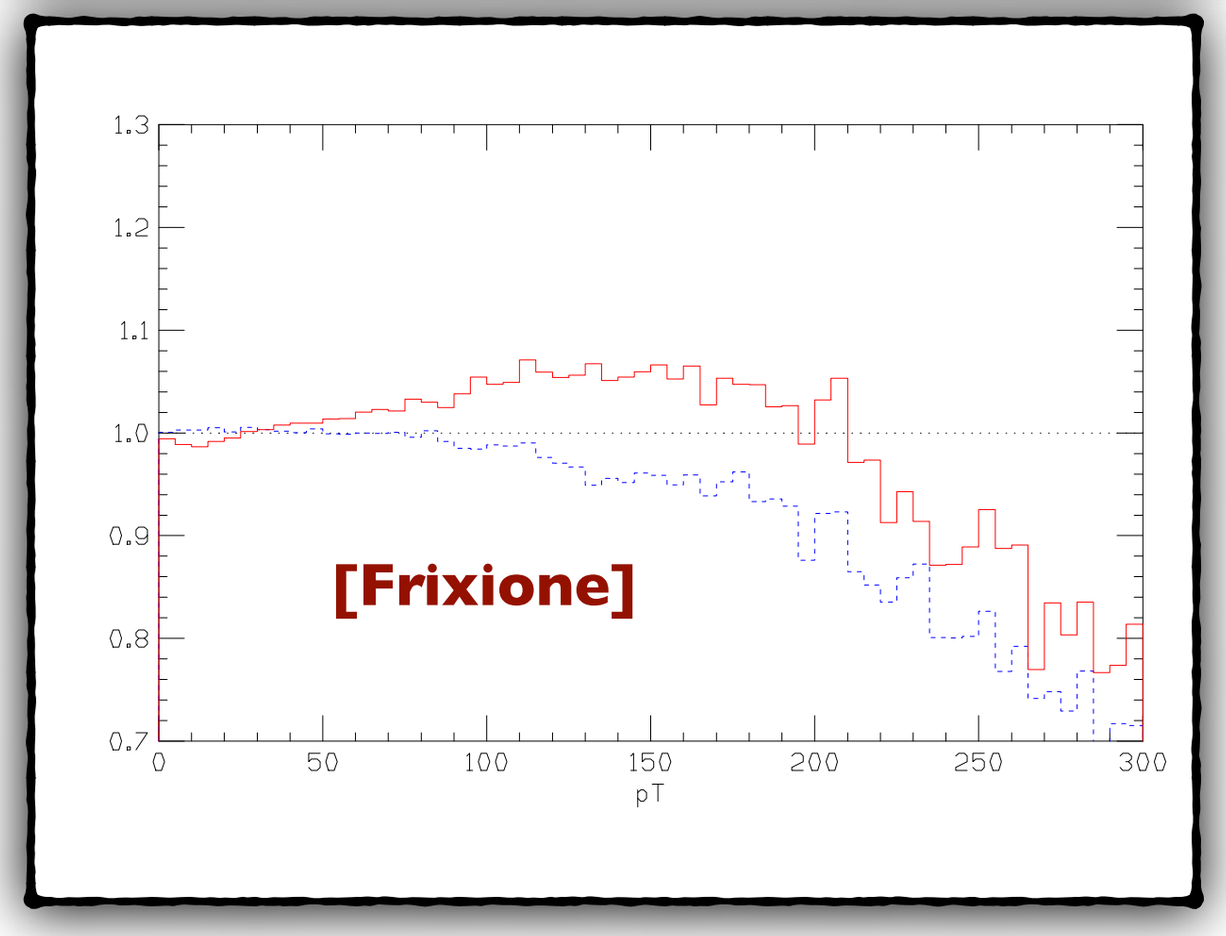


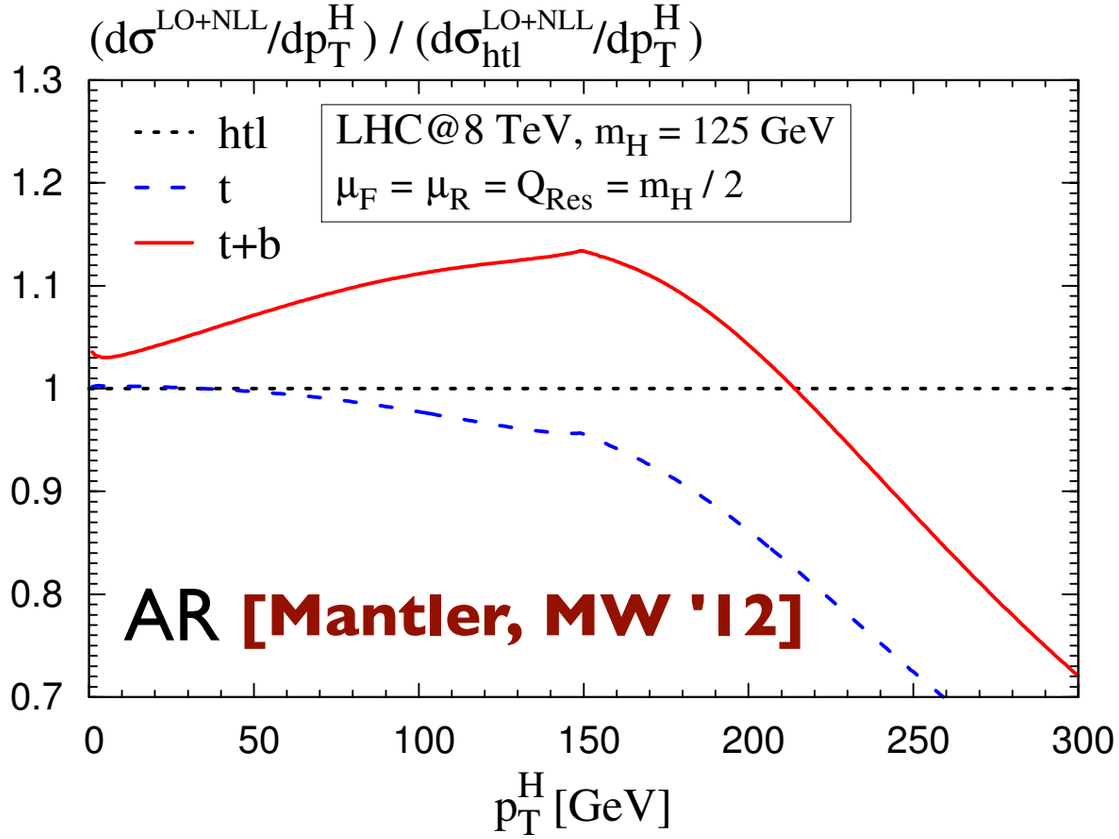


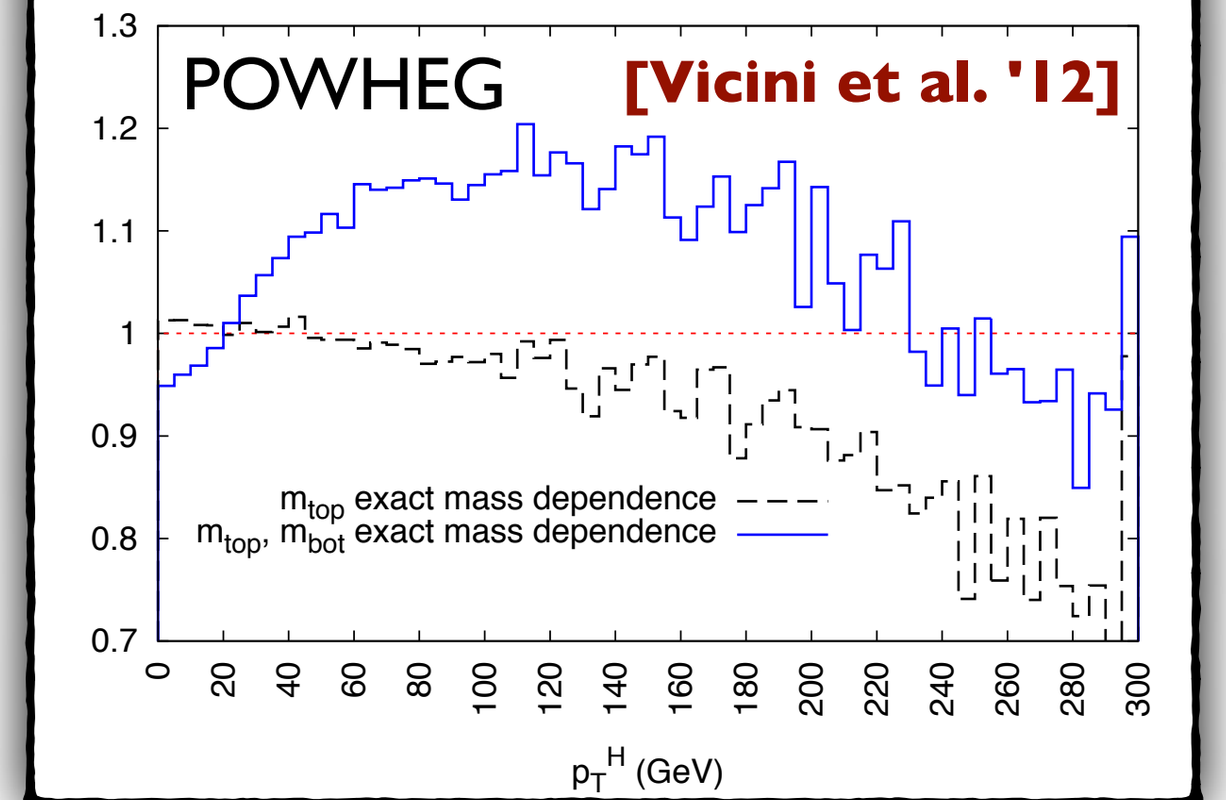
see also:

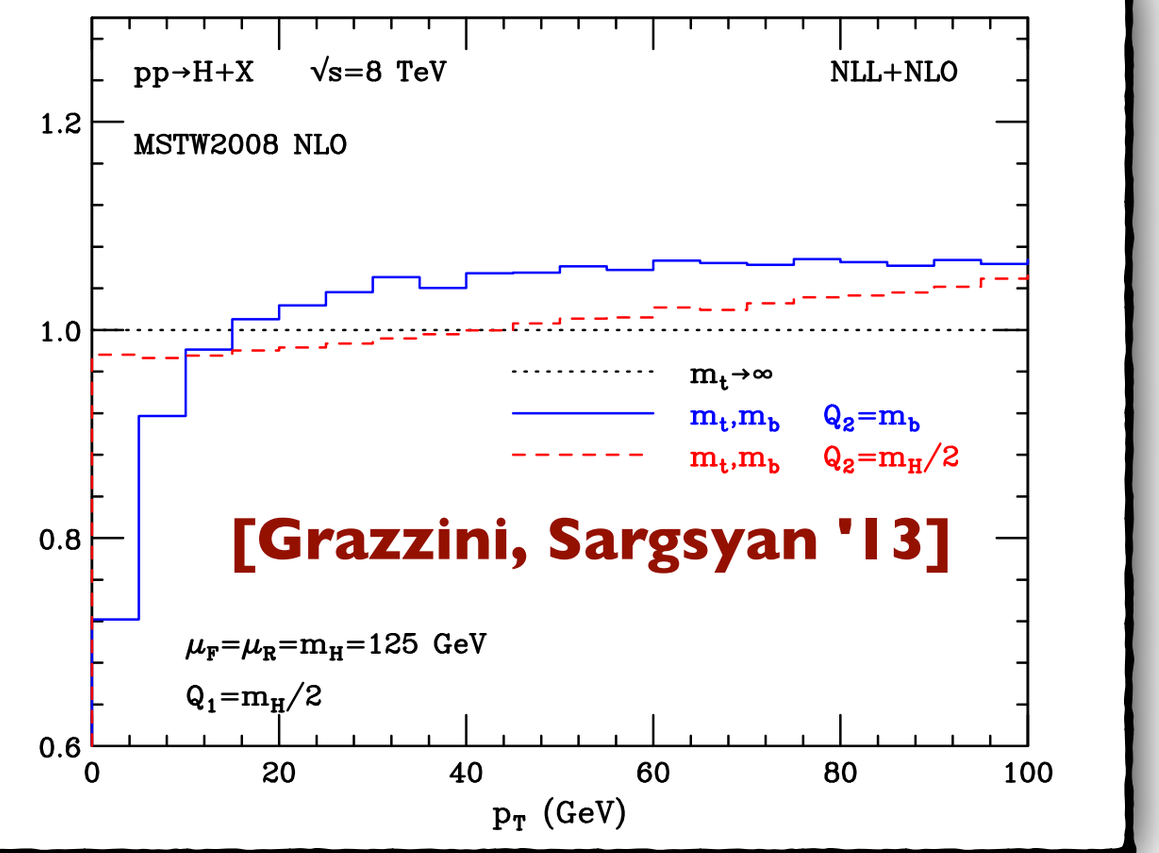
[Banfi, Monni, Zanderighi '13]

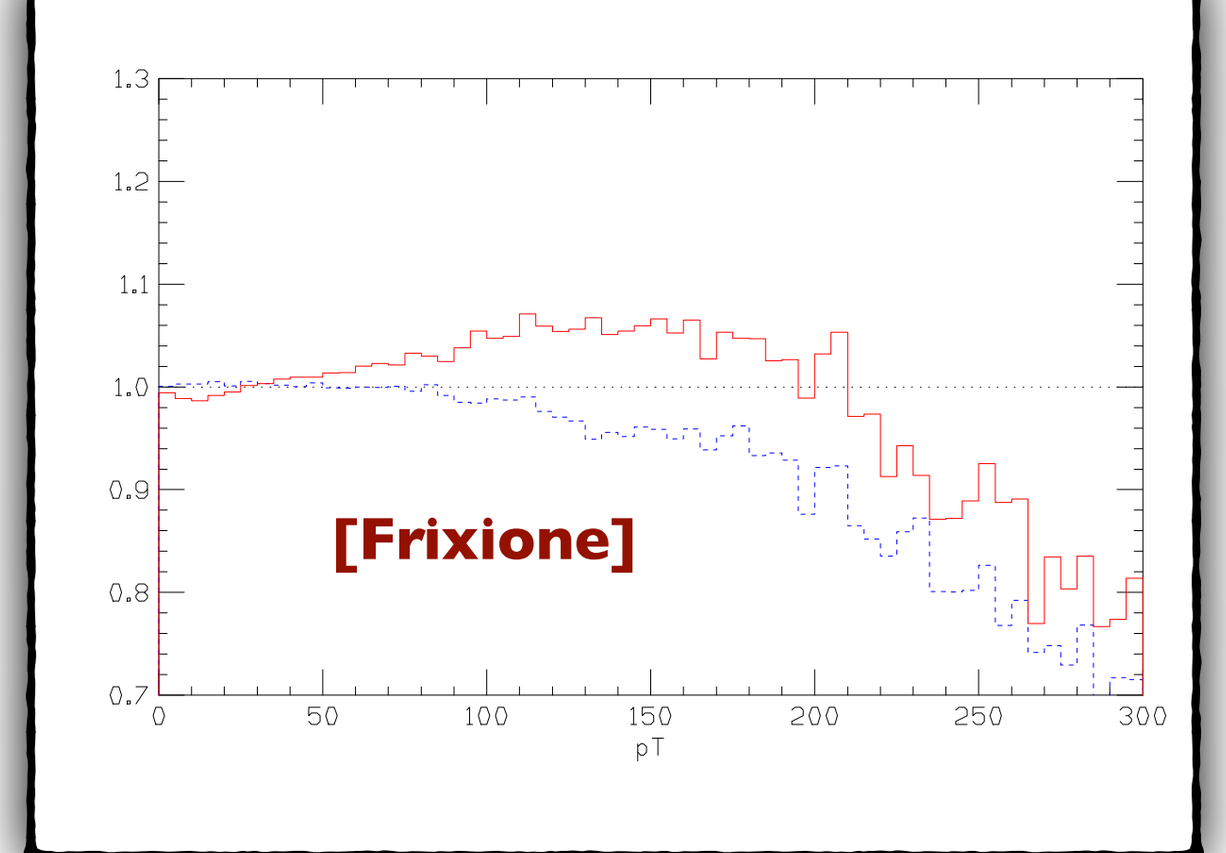
[Hamilton, Nason, Zanderighi '15]

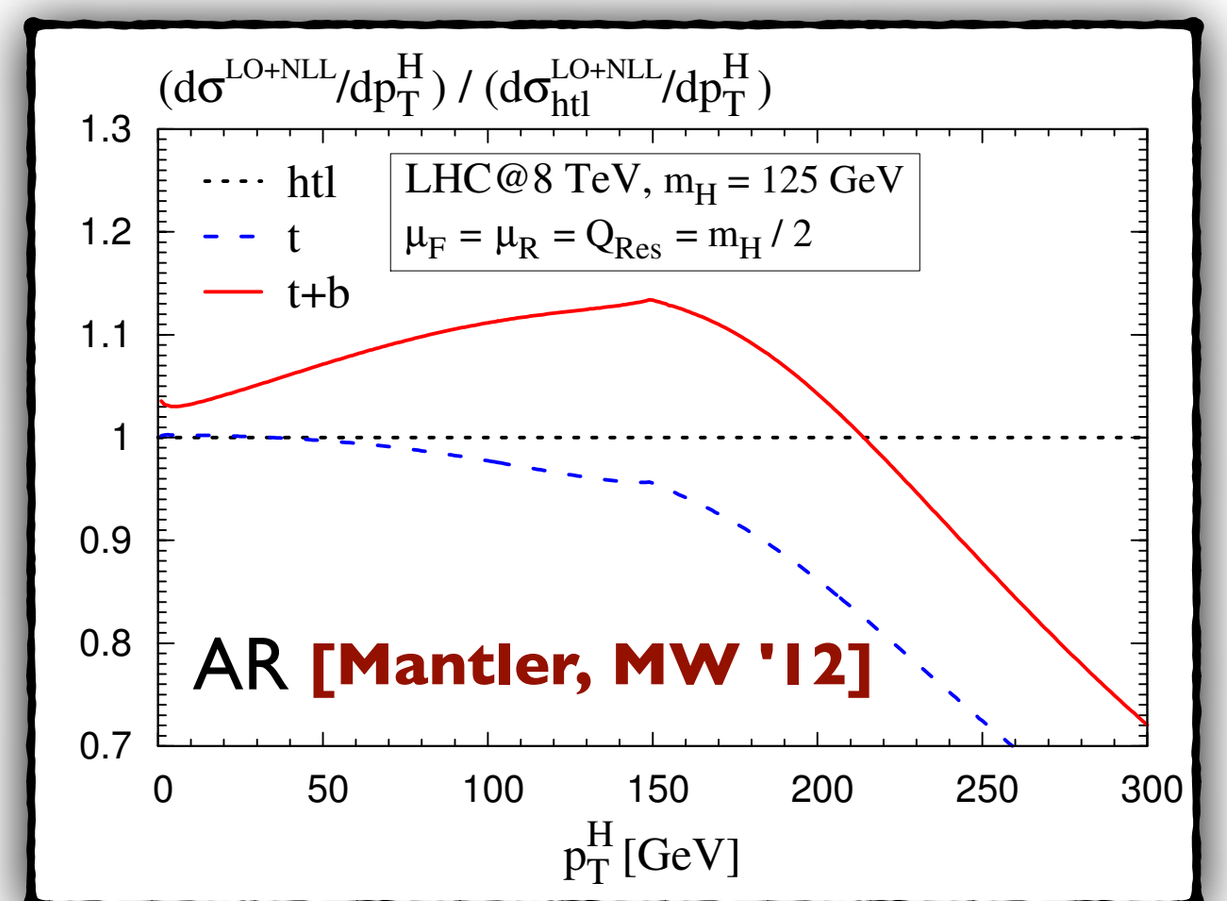


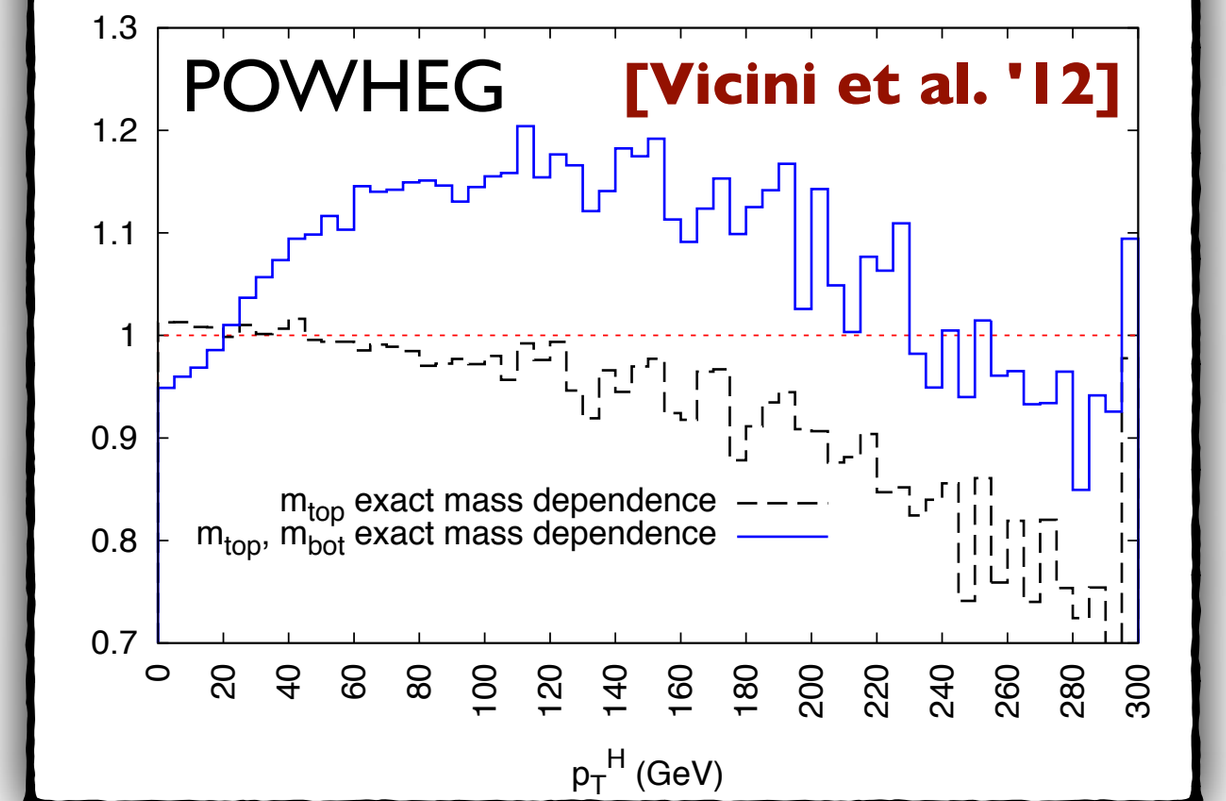

htl
t
t+b
LHC@8 TeV, m_H = 125 GeV
μ_F = μ_R = Q_Res = m_H / 2
AR [Mantler, MW '12]
p_T^H [GeV]

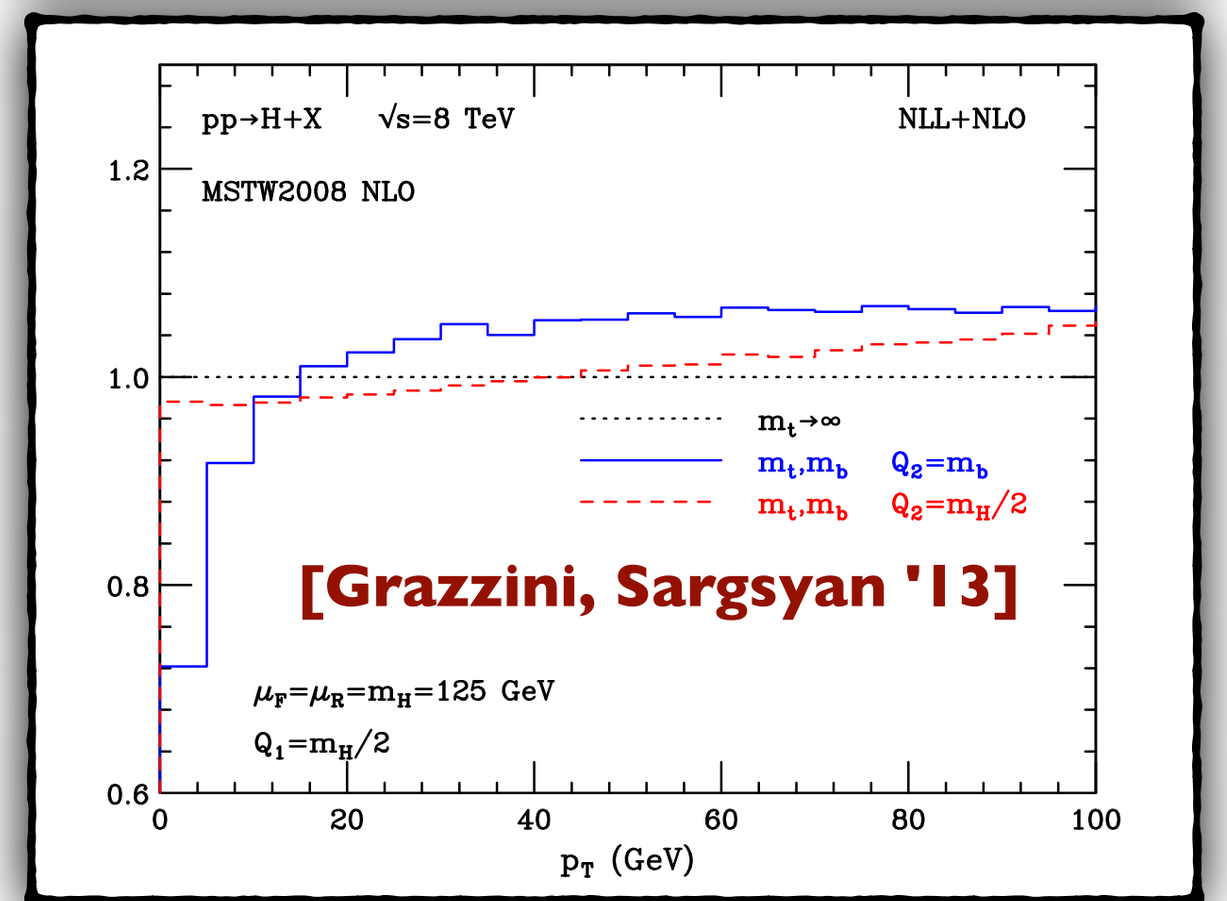

POWHEG
[Vicini et al. '12]
m_top exact mass dependence
m_top, m_bot exact mass dependence
p_T^H (GeV)

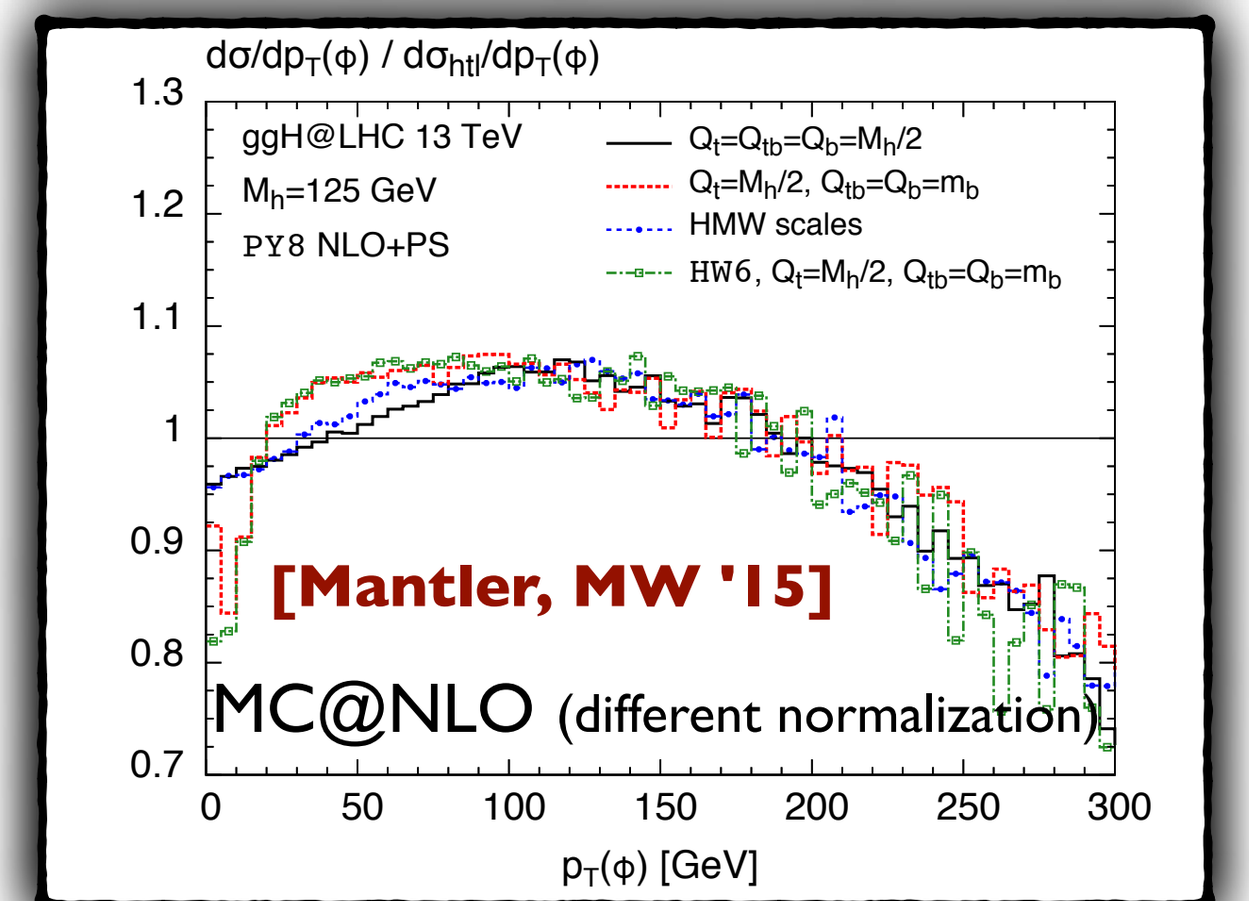

pp→H+X √s=8 TeV NLL+NLO
MSTW2008 NLO
m_t→∞
m_t,m_b Q_2=m_b
m_t,m_b Q_2=m_H/2
[Grazzini, Sargsyan '13]
μ_F=μ_R=m_H=125 GeV
Q_1=m_H/2
p_T (GeV)

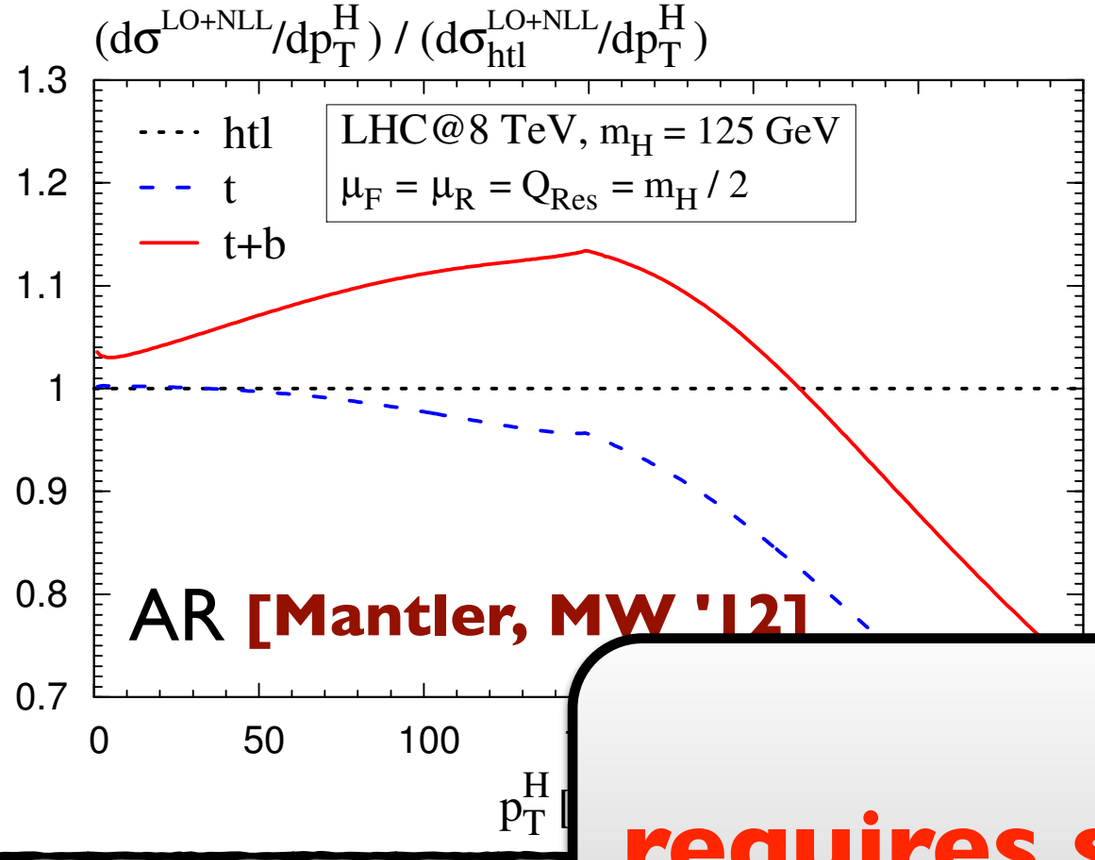

[Frixione]
pT

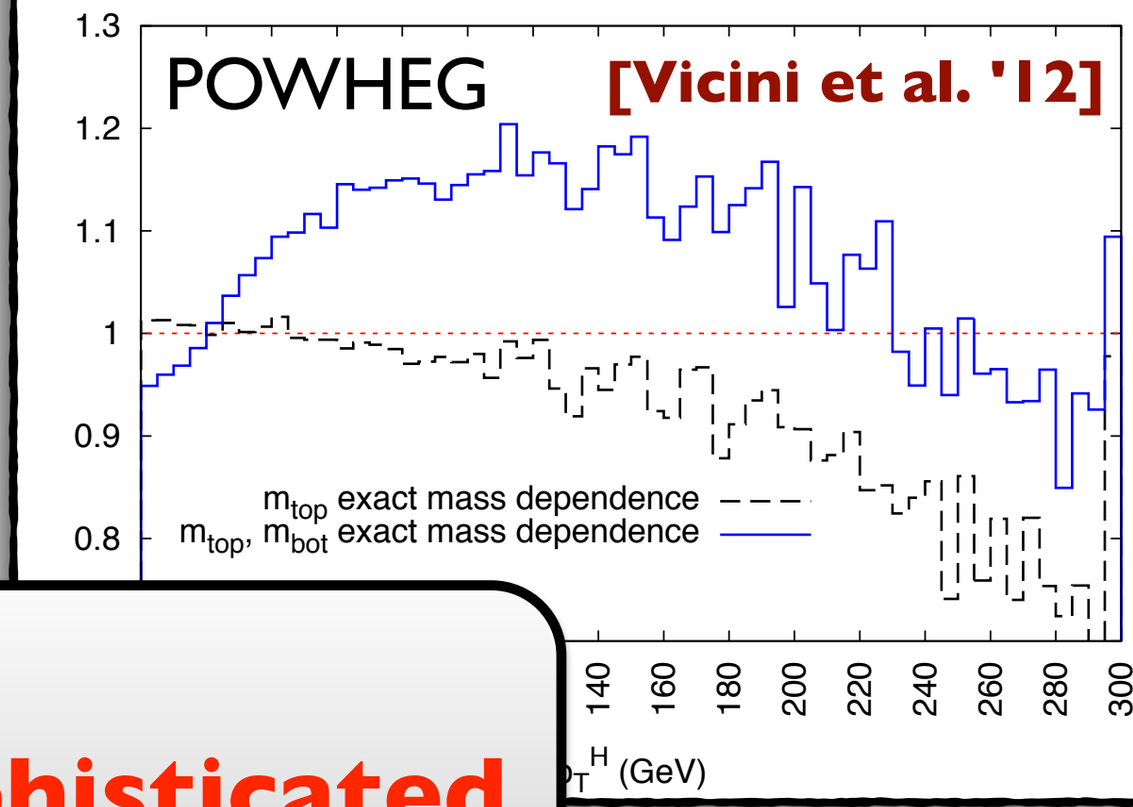

$(d\sigma^{LO+NLL}/dp_T^H) / (d\sigma_{htl}^{LO+NLL}/dp_T^H)$
htl
t
t+b
LHC@8 TeV, m_H = 125 GeV
$\mu_F = \mu_R = Q_{Res} = m_H / 2$
AR [Mantler, MW '12]
p_T^H [GeV]


POWHEG
[Vicini et al. '12]
m_{top} exact mass dependence
m_{top}, m_{bot} exact mass dependence
p_T^H (GeV)

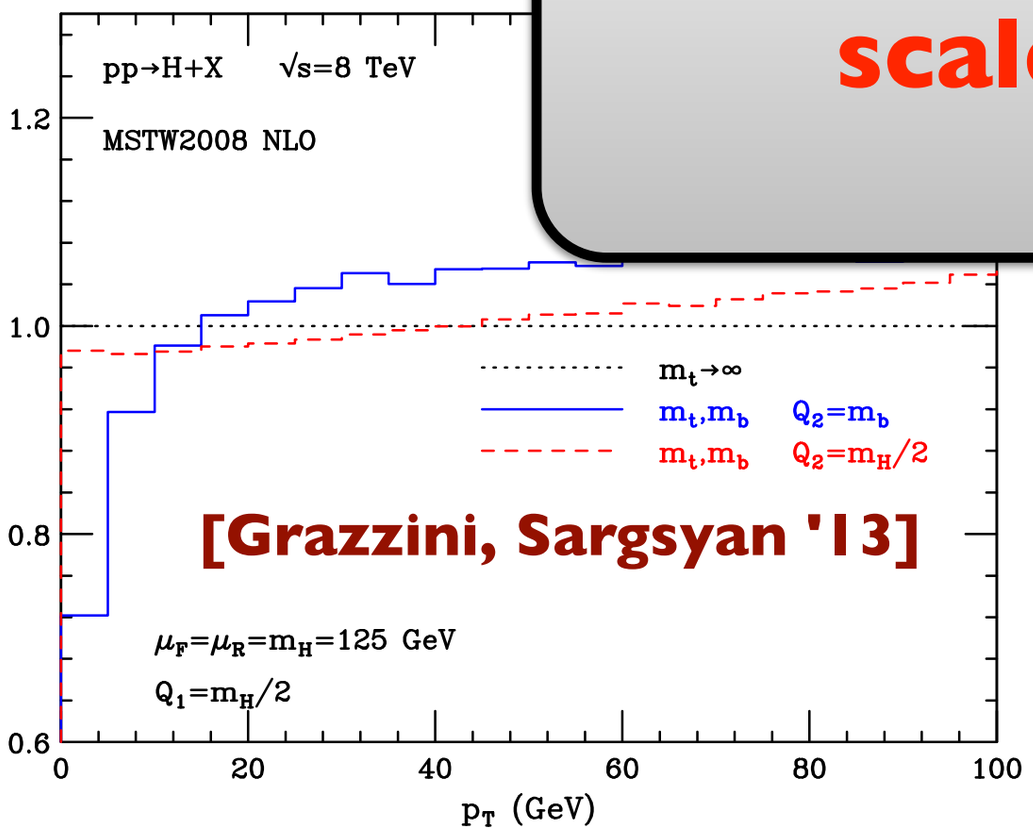

pp→H+X √s=8 TeV NLL+NLO
MSTW2008 NLO
$m_t \to \infty$
m_t, m_b $Q_2 = m_b$
m_t, m_b $Q_2 = m_H/2$
[Grazzini, Sargsyan '13]
$\mu_F = \mu_R = m_H$=125 GeV
$Q_1 = m_H/2$
p_T (GeV)

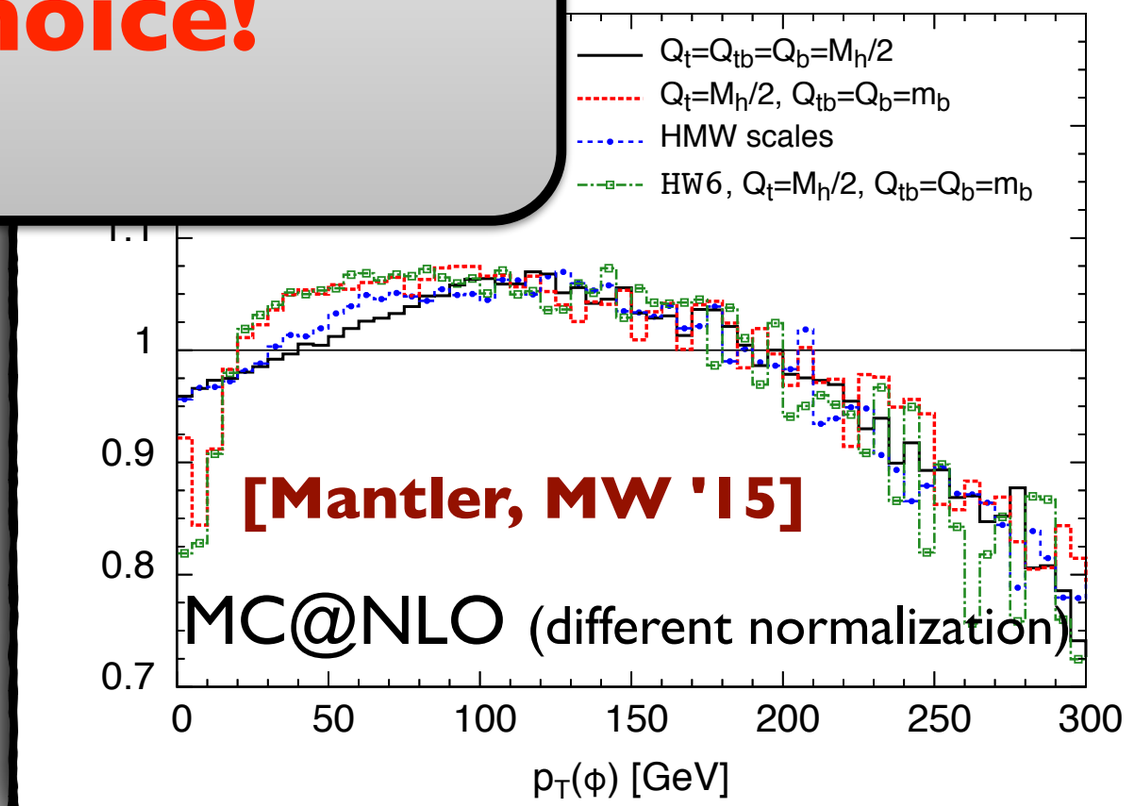

$d\sigma/dp_T(\phi) / d\sigma_{htl}/dp_T(\phi)$
ggH@LHC 13 TeV
M_h=125 GeV
PY8 NLO+PS
$Q_t = Q_{tb} = Q_b = M_h/2$
$Q_t = M_h/2$, $Q_{tb} = Q_b = m_b$
HMW scales
HW6, $Q_t = M_h/2$, $Q_{tb} = Q_b = m_b$
[Mantler, MW '15]
MC@NLO (different normalization)
$p_T(\phi)$ [GeV]





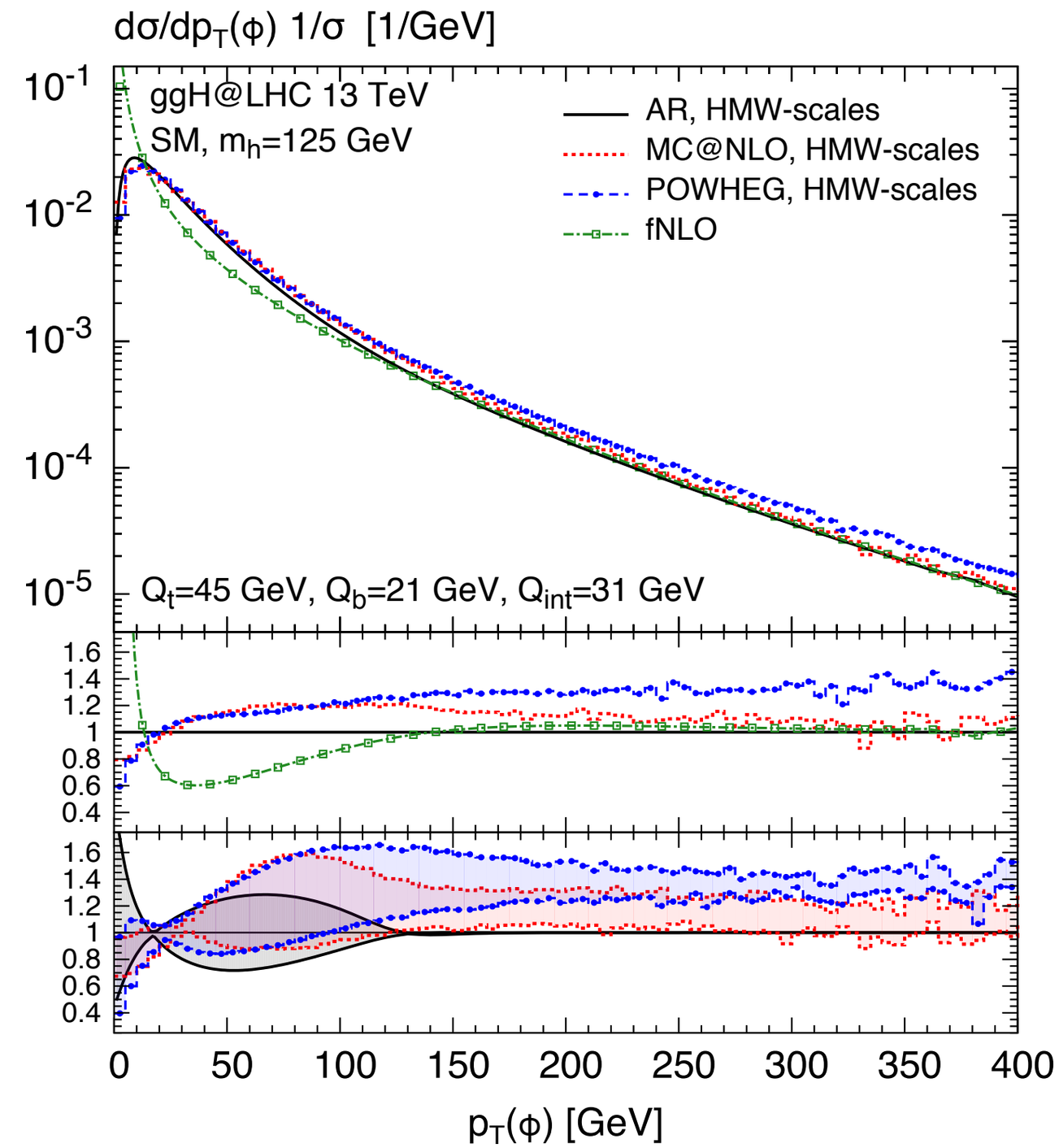
requires sophisticated scale choice!

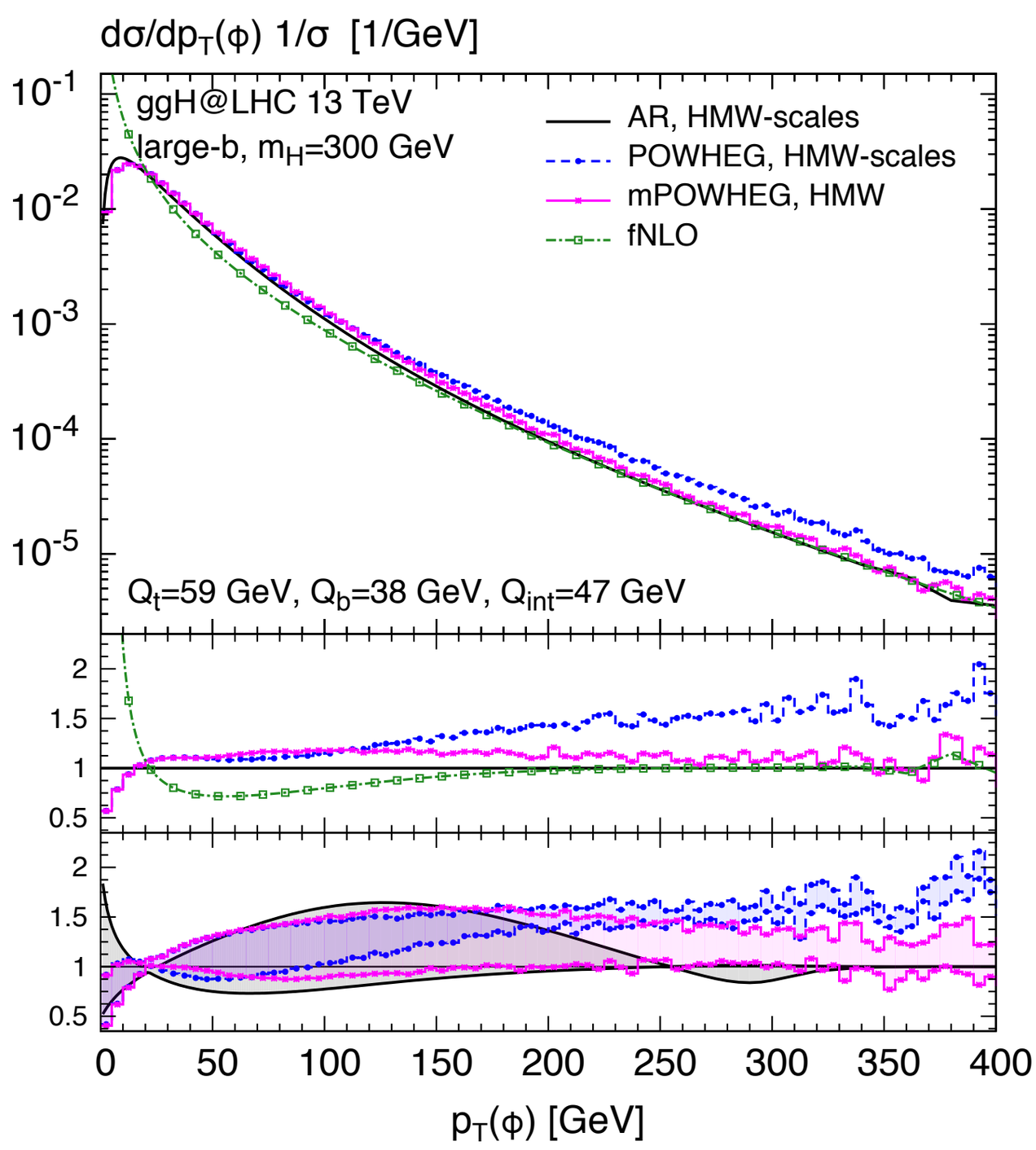




Resummation scale setting

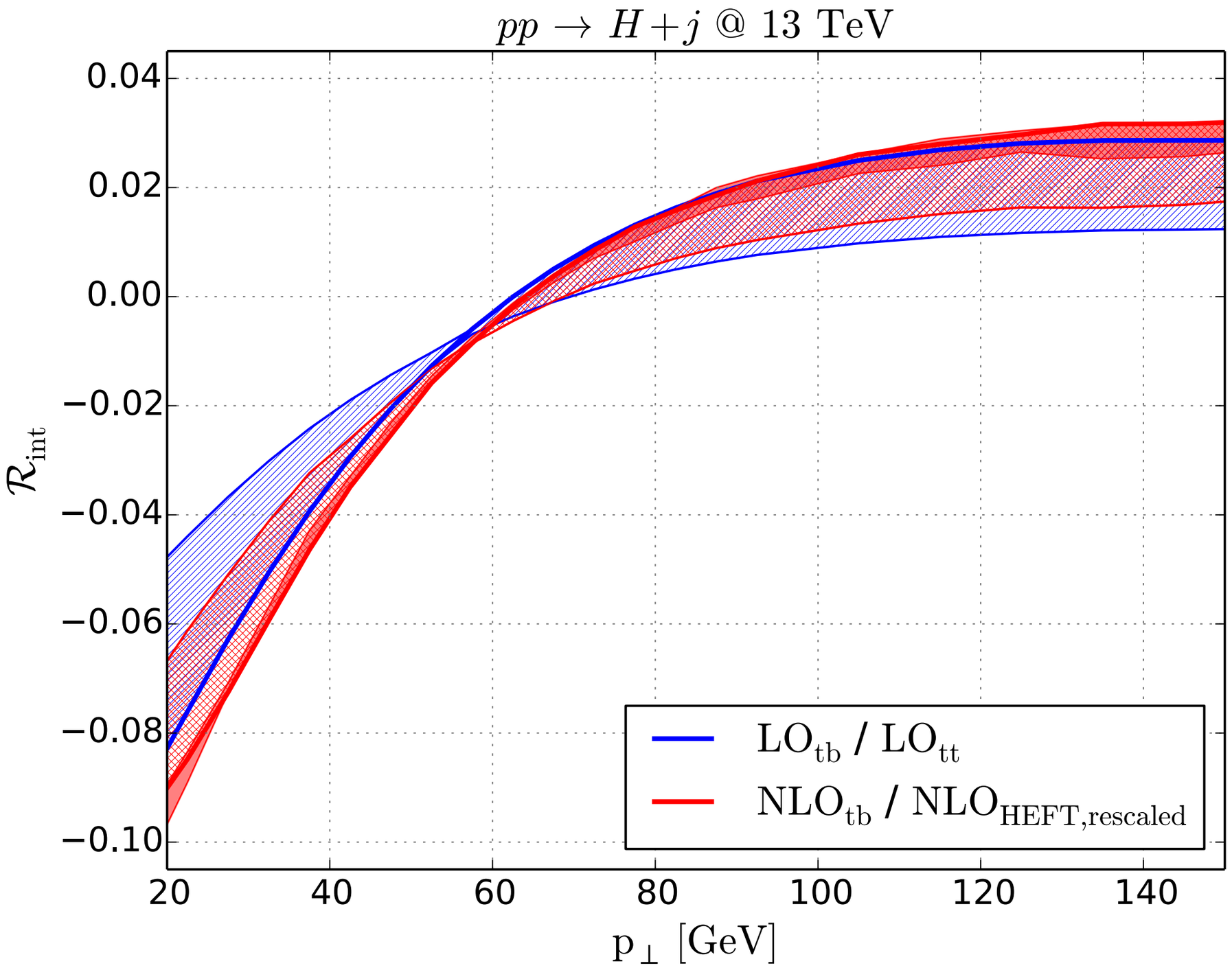
[Bagnaschi, Harlander, Mantler, Vicini, MW '15]





b-mass in Higgs p_T at NLO

[Lindert, Melnikov, Tancredi, Wever '17]



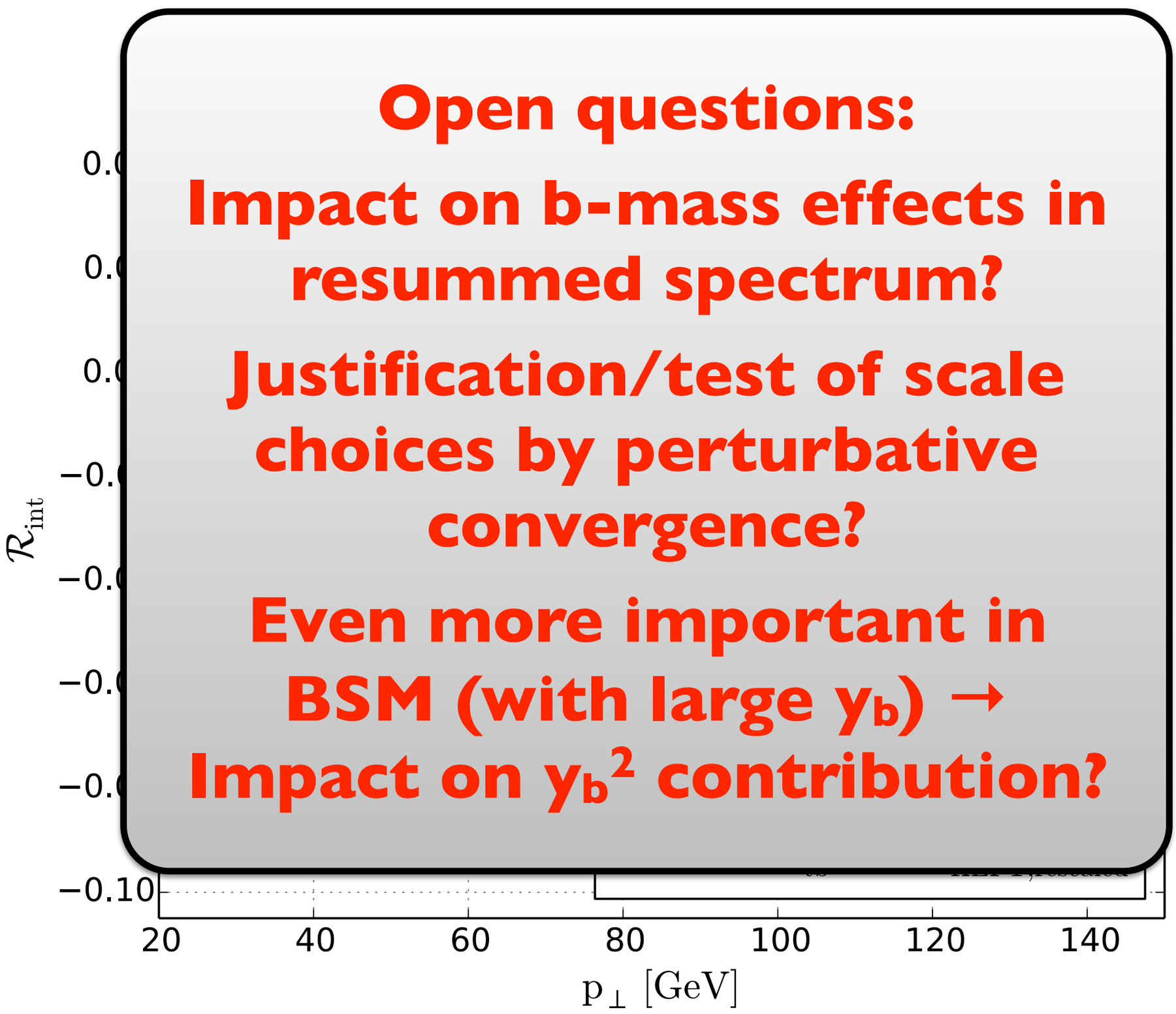
b-mass in Higgs p_T at NLO

Open questions:

Impact on b-mass effects in resummed spectrum?

Justification/test of scale choices by perturbative convergence?

Even more important in BSM (with large y_b) → Impact on y_b^2 contribution?



Mass effects in Monte-Carlos

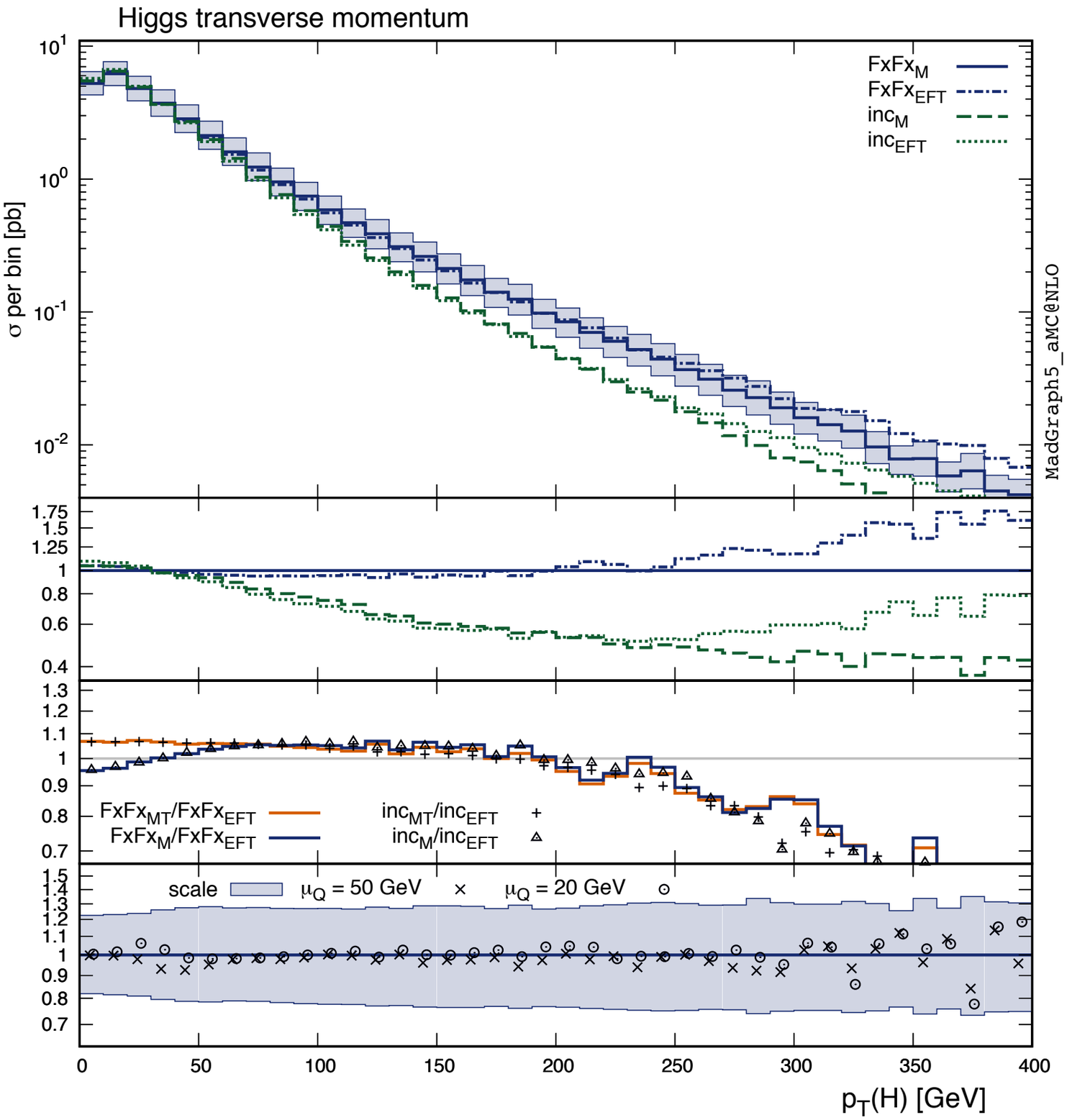
- **MG5_aMC@NLO** [Frederix, Frixione, Vryonidou, MW '16]
  - H+0/1/2-jets @ NLO (FxFx)
  - m_{top} in H+0-jet & 1-loop (borns, reals); H+≥1-jet virtuals (2-loop) reweighted by full (m_{top}) born
  - EFT not valid for m_{bottom} → full m_{bottom} dependence in H+0-jet @ NLO with aMCSusHi [Mantler, MW '15]

- **Sherpa** [Krauss et al.]
  - H+0/1/2-jets @ NLO (MEPS)
  - m_{top}, m_{bottom} included via reweighting of NLO EFT with LO

- **NNLOPS** [Hamilton, Nason, Zanderighi '14 '15]
  - H+0/1-jets @ NLO (POWHEG-MINLO) + NNLO normalization by reweighting in Higgs-y from HNNLO [Catani, Grazzini '07]
  - NLO H+1-jet in EFT reweighted with LO m_{top}, optional: same for m_{bottom} or only at LO H+1-jet

Mass effects in Monte-Carlos

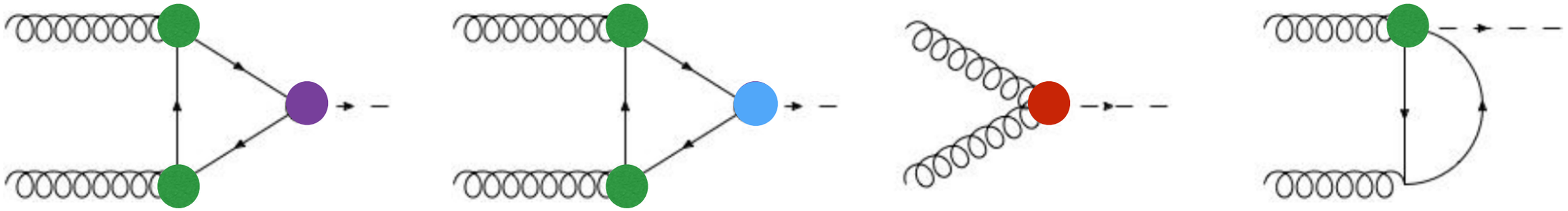
[Frederix, Frixione, Vryonidou, MW '16]



Higher-dimensional OPs

- **"right" way combine "leading" effects in SM prediction:**
  - **start from SM amplitudes for Higgs process**
  - **take consistent set of Operators (all dim-6 OPs)**
  - **compute BSM amplitudes that contribute**
  - **interference of SM with BSM amplitudes gives leading effect**
  - **may argue wether or not to include BSM^2 (SILH vs.)**
- **examples where this approach is followed:**
  - **LO at high Higgs p_T [Grojean, Salvioni, Schlaffer, Weiler '13]**
  - **NLO+NLL resummed (LO in p_T) [Grazzini, Ilnicka, Spira, MW '16]**
- **many similar studies:**
  - **[Azatov, Paul '13]**
  - **[Harlander, Neumann '13]**
  - **[Maltoni, Vryonidou, Zhang '16]**
  - **...**

Higher-dimensional OPs



$$\mathcal{O}_1 = |H|^2 G^a_{\mu\nu} G^{a,\mu\nu}$$
$$\mathcal{O}_2 = |H|^2 \bar{Q}_L H^c u_R + h.c.$$
$$\mathcal{O}_3 = |H|^2 \bar{Q}_L H d_R + h.c.$$
$$\mathcal{O}_4 = \bar{Q}_L H \sigma^{\mu\nu} T^a u_R G^a_{\mu\nu} + h.c.$$

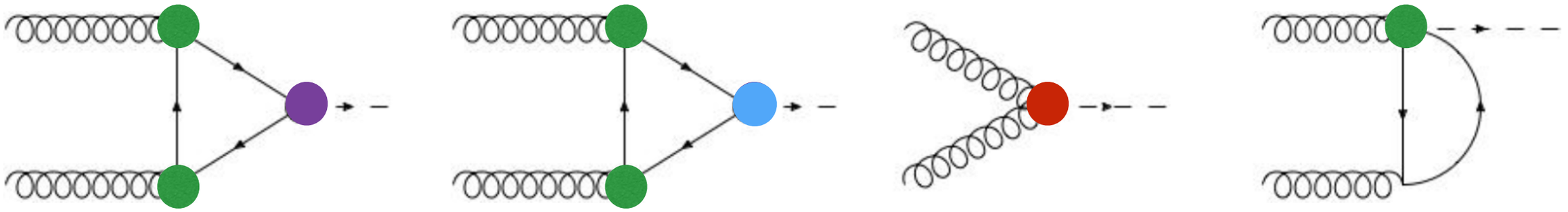
$$\frac{\alpha_S}{\pi v} c_g h G^a_{\mu\nu} G^{a,\mu\nu}$$ ◀····· as HTL in SM

$$\frac{m_t}{v} c_t h \bar{t}t$$ ◀····· modified top/bottom

$$\frac{m_b}{v} c_b h \bar{b}b$$ ◀····· Yukawa coupling

$$c_{tg} \frac{g_S m_t}{2v^3} (v+h) G^a_{\mu\nu} (\bar{t}_L \sigma^{\mu\nu} T^a t_R + h.c)$$

Higher-dimensional OPs



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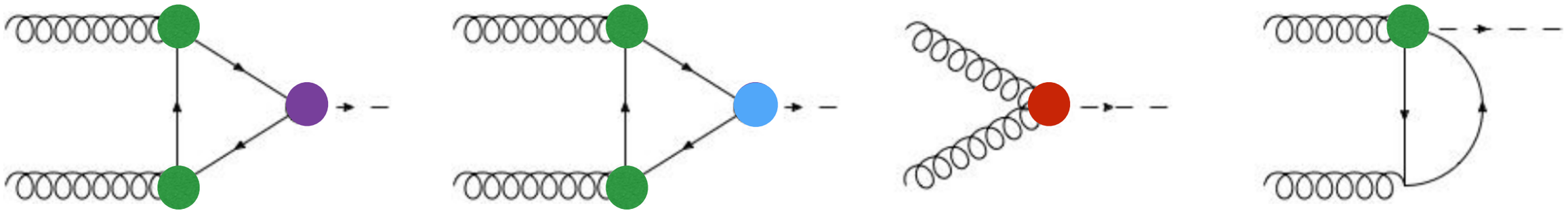
can be bounded from *tth* production

Higher-dimensional OPs



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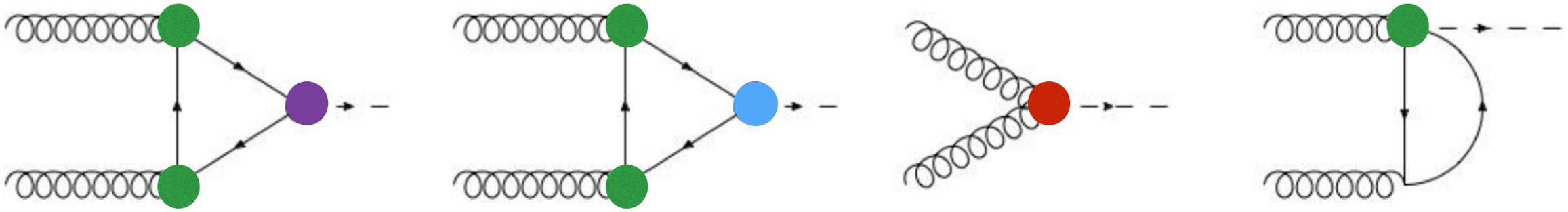
modified top/bottom Yukawa coupling

$$c_{tg} \frac{g_S m_t}{2v^3} (v+h) G^a_{\mu\nu} (\bar{t}_L \sigma^{\mu\nu} T^a t_R + h.c)$$

can be bounded from h->bb decay (and *bbh* production)

Higher-dimensional OPs



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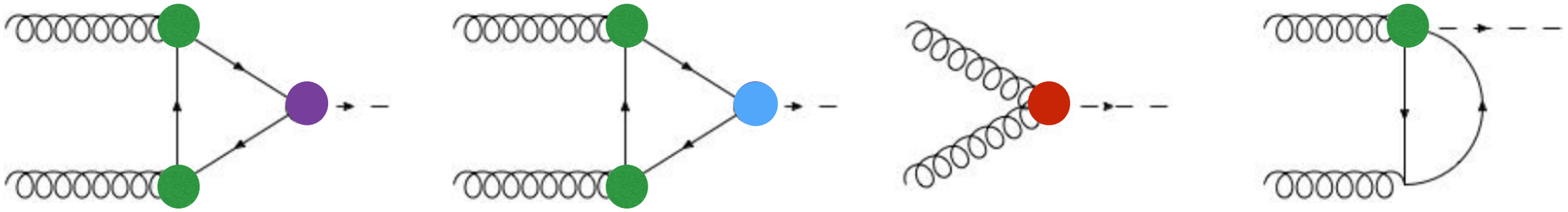
can be bounded from *tt* production

Higher-dimensional OPs



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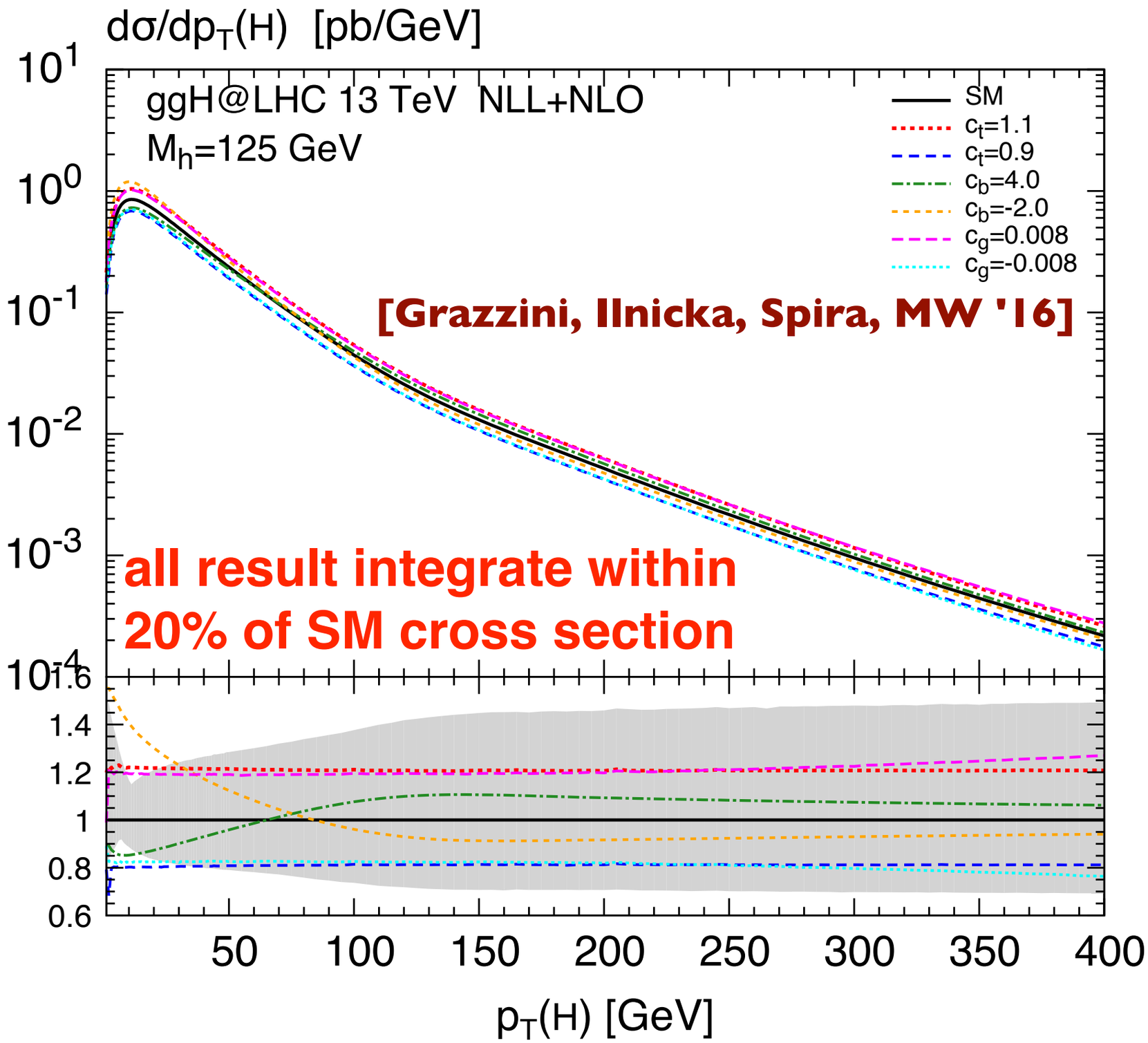
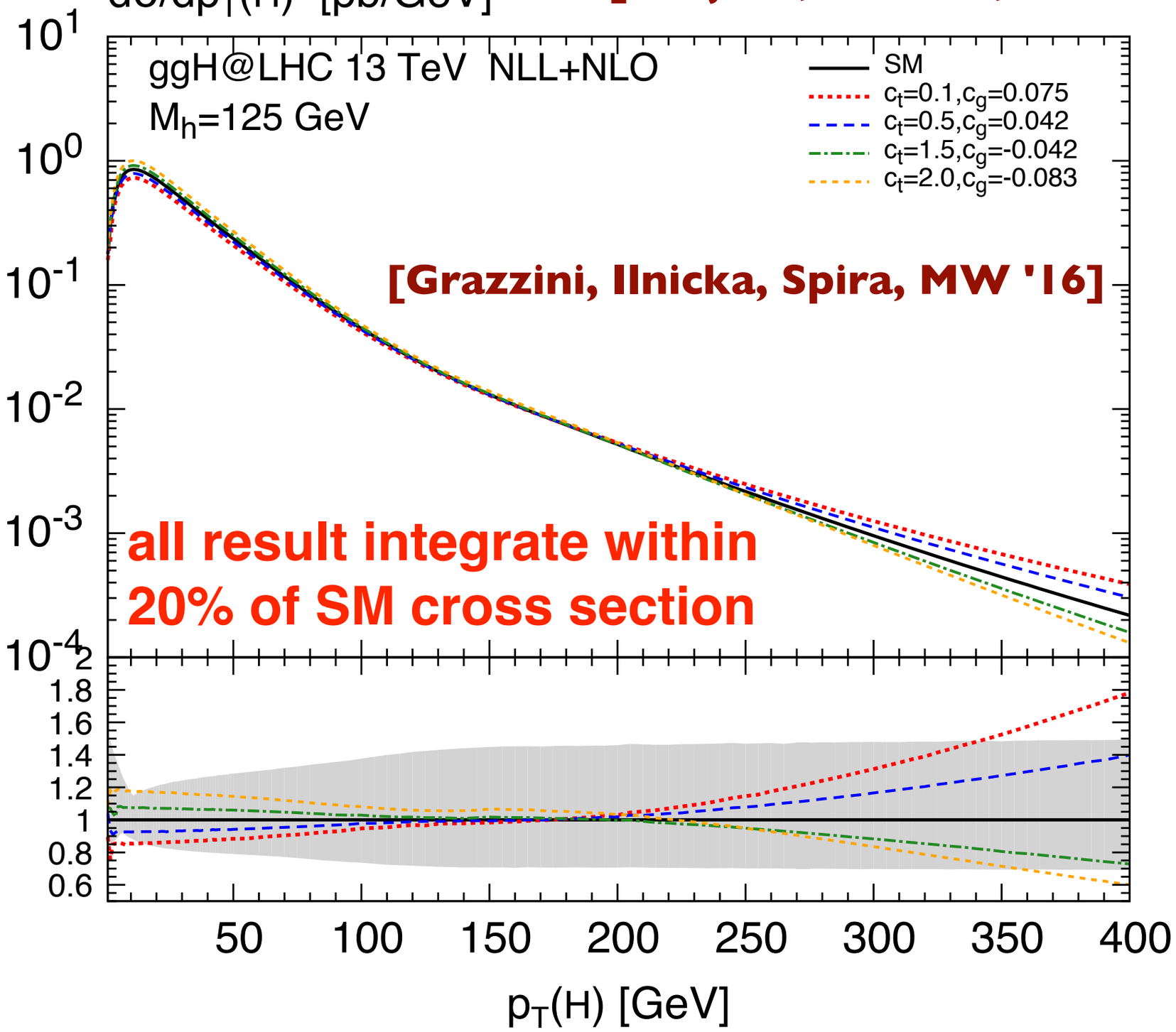
Easiest to bound from the Higgs pT spectrum

Higher-dimensional OPs



Higher-dimensional OPs

see also:
[Grojean, Salvioni, Schlaffer, Weiler '13]



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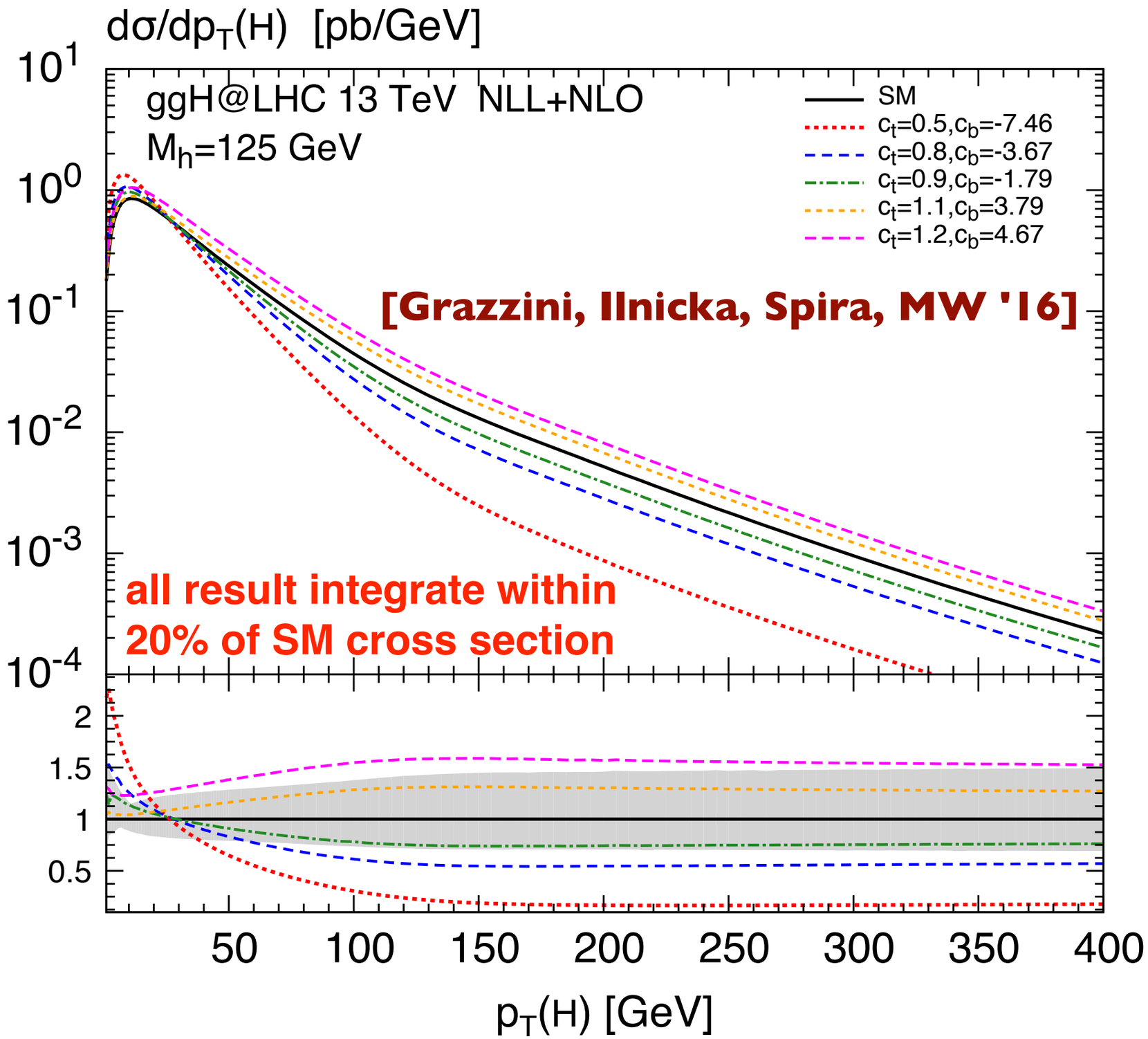

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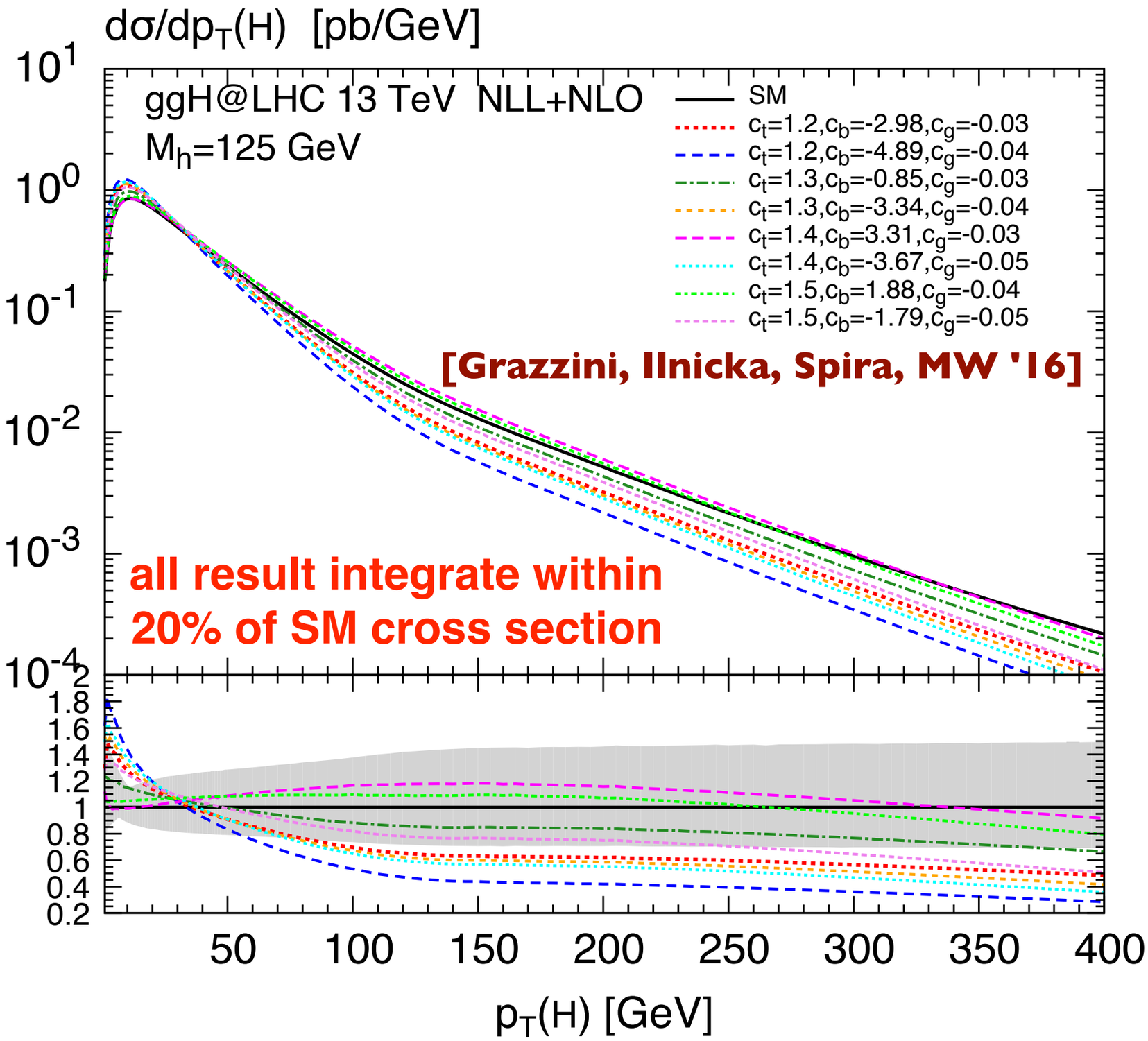

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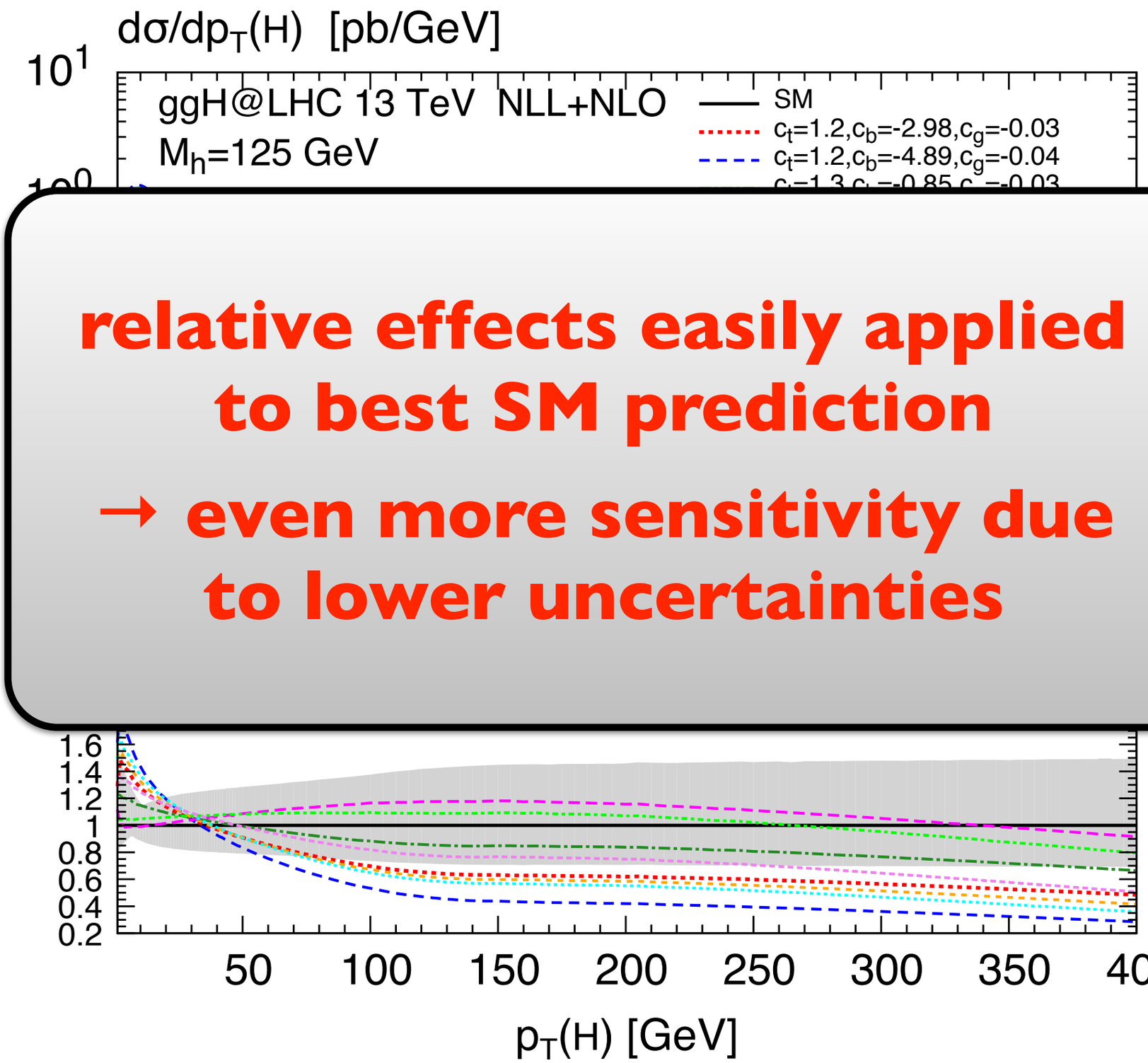


relative effects easily applied to best SM prediction

→ even more sensitivity due to lower uncertainties

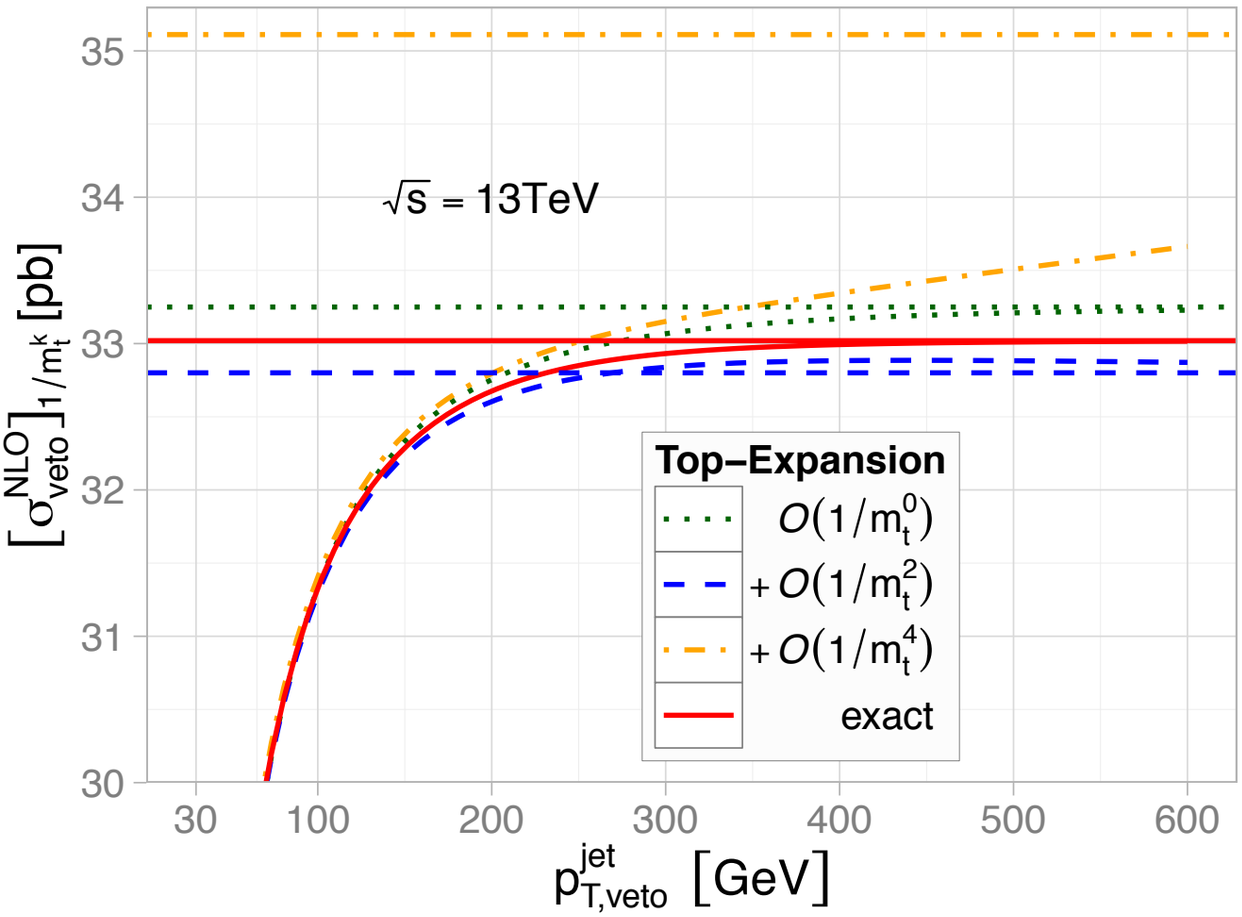
Conclusions

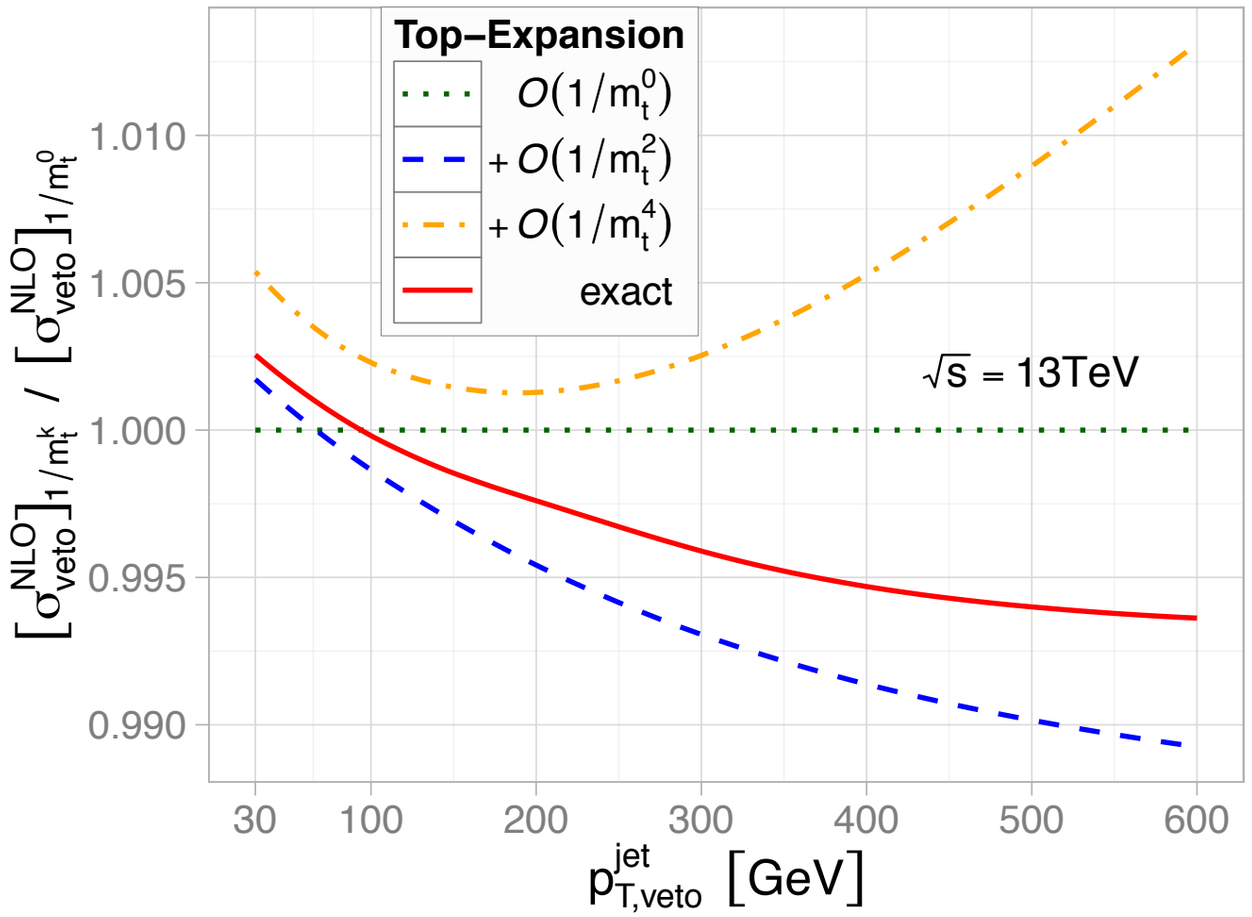
1. **Top-mass effects under good control at low scales/for inclusive observables through $1/m_{top}$ expansion at $O(\alpha_s^4)$**
   - **NEW: NLO p_T distribution but only up to 250 GeV**
2. **Bottom-mass effects tricky in (resummed) p_T spectrum**
   - **No general solution to 3-scale problem yet**
     → Resummation-scale choice important
   - **NEW: NLO corrections in massless limit**
     → Impact on resummed spectrum?
     → Justification/test of resummation-scale setting?
     → Impact on y_b^2 contribution (relevant BSM with large y_b)?
3. **Higher-dimensional OPs in the Higgs p_T spectrum**
   - **"Leading" effects computed at NLO+NLL**
   - **Straightforward combination with best SM prediction**
     → Effects well beyond scale uncertainties

Back Up

Jet-veto at NLO

[Neumann, MW '14]





Resummation scale setting

three scale problem!
(no complete solution yet)

bottom-mass effects at small p_T:

→ two approaches to choose matching/resummation scale:

[Harlander, Mantler, MW '14]	**[Bagnaschi, Vicini '15]**
separate scales for top, bottom and top-bottom interference term	
hadron level	**parton level**
resummation scales as large as possible, while requiring high-p_T matching	**matching scale choosen where collinear approximation fails (by >10%)**

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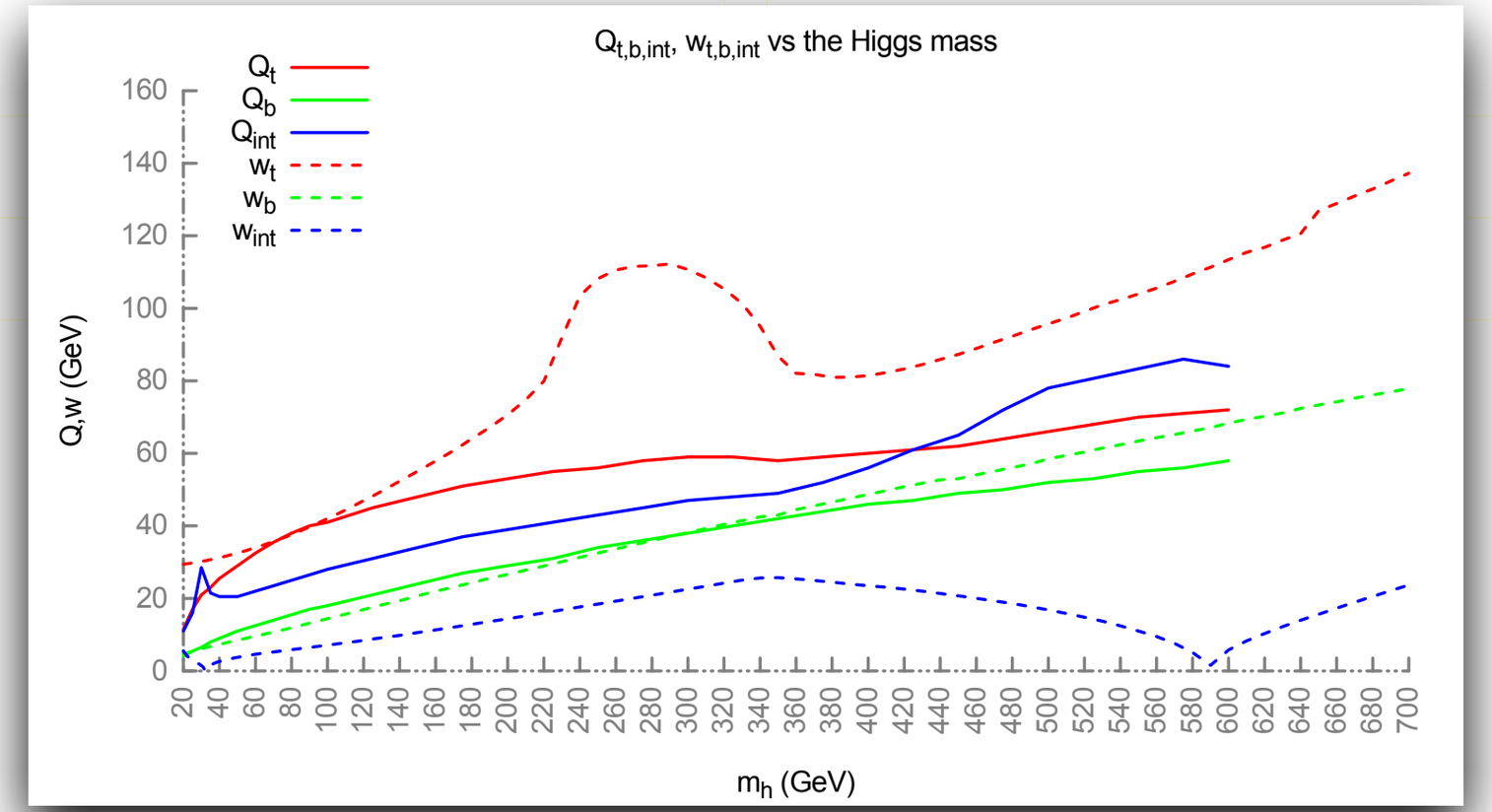

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