Finite top-mass effects for Higgs production with a jet-veto at NNLO

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LHCPhenoNet Final Meeting, Berlin (Germany)

24-26 November, 2014

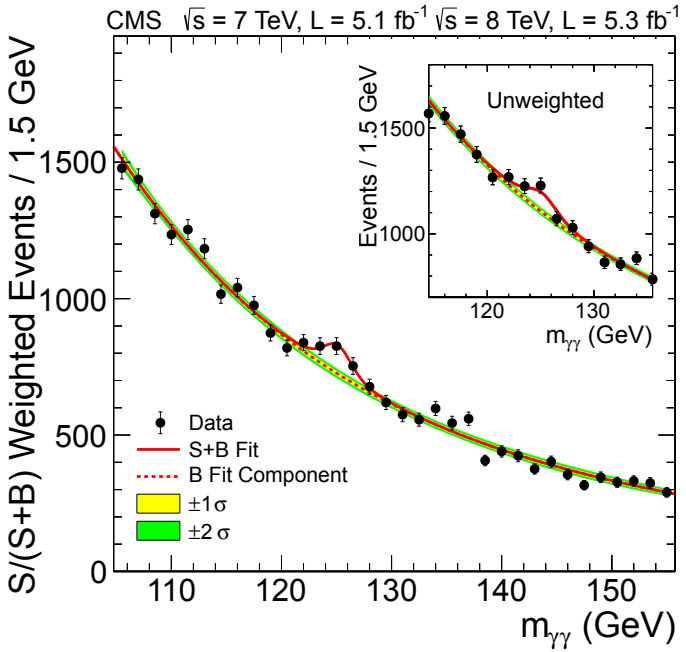
Outline

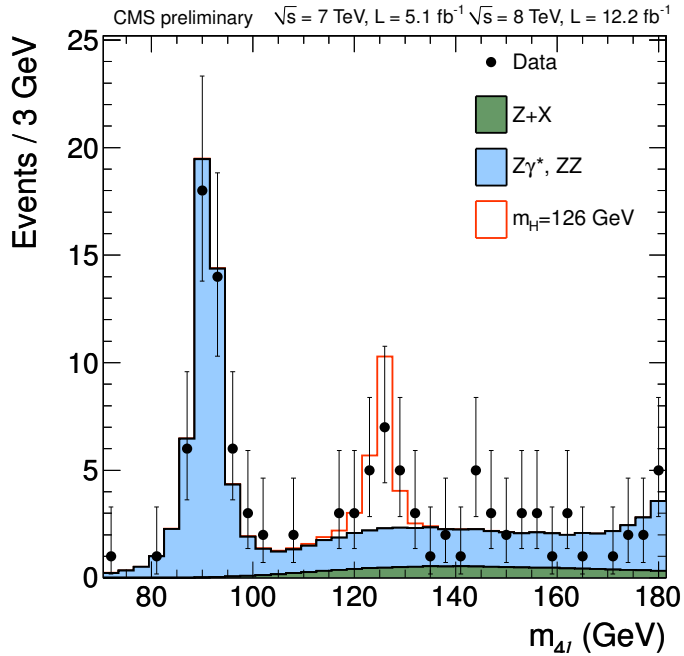
1. Motivation

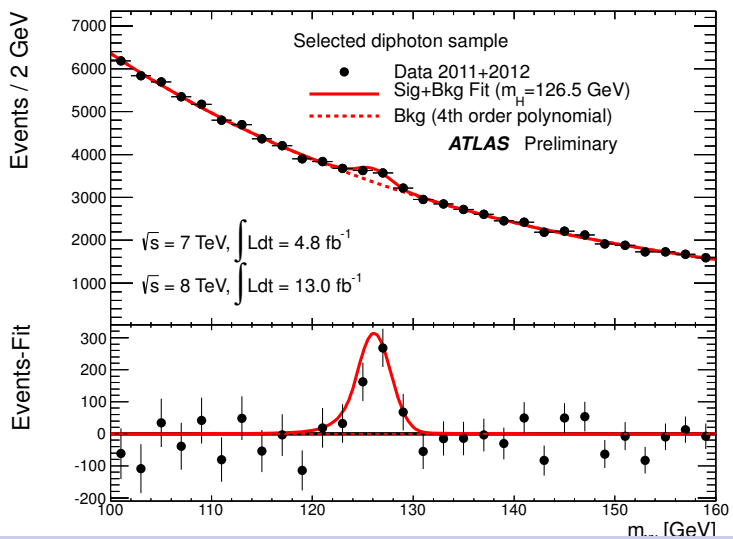
2. Outline of the calculation
   - Higgs+jet at NLO
   - Higgs with jet veto at NNLO

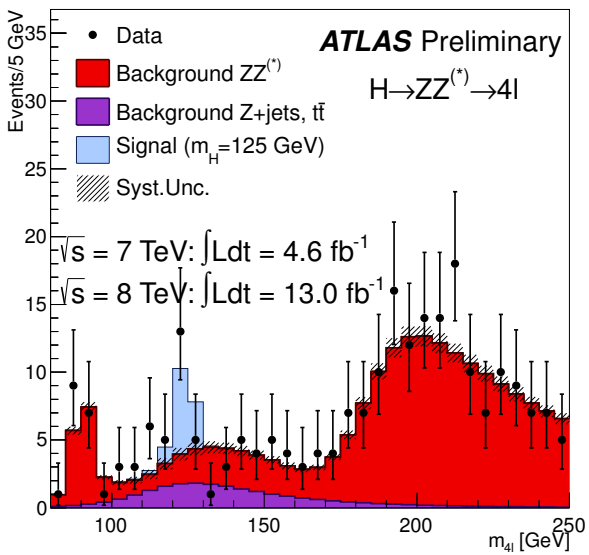
3. Results: Top-mass effects on
   - jet vetoed cross section
   - Higgs+jet cross section
   - Higgs/jet distributions

Motivation

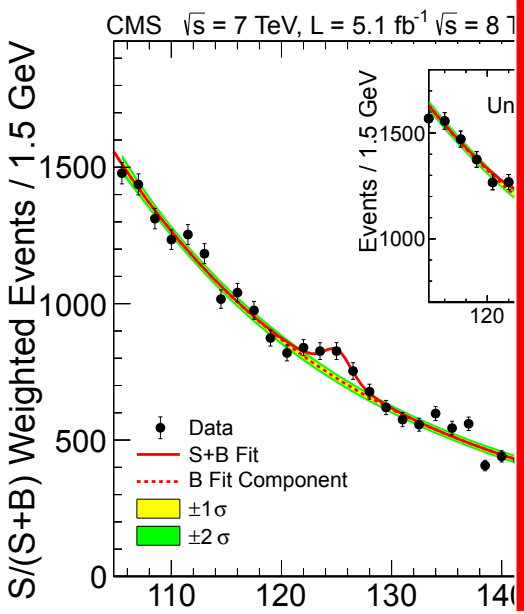

CMS √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 5.3 fb-1
S/(S+B) Weighted Events / 1.5 GeV
Unweighted
Events / 1.5 GeV
mγγ (GeV)
Data
S+B Fit
B Fit Component
±1σ
±2 σ


CMS preliminary √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 12.2 fb-1
Events / 3 GeV
Data
Z+X
Zγ*, ZZ
mH=126 GeV
m4l (GeV)


Events / 2 GeV
Selected diphoton sample
Data 2011+2012
Sig+Bkg Fit (mH=126.5 GeV)
Bkg (4th order polynomial)
ATLAS Preliminary
√s = 7 TeV, ∫Ldt = 4.8 fb-1
√s = 8 TeV, ∫Ldt = 13.0 fb-1
Events-Fit


Events/5 GeV
Data
Background ZZ(*)
Background Z+jets, tt̄
Signal (mH=125 GeV)
Syst.Unc.
ATLAS Preliminary
H→ZZ(*)→4l
√s = 7 TeV: ∫Ldt = 4.6 fb-1
√s = 8 TeV: ∫Ldt = 13.0 fb-1
m4l [GeV]

Motivation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S/(S+B) Weighted Events / 1.5 GeV
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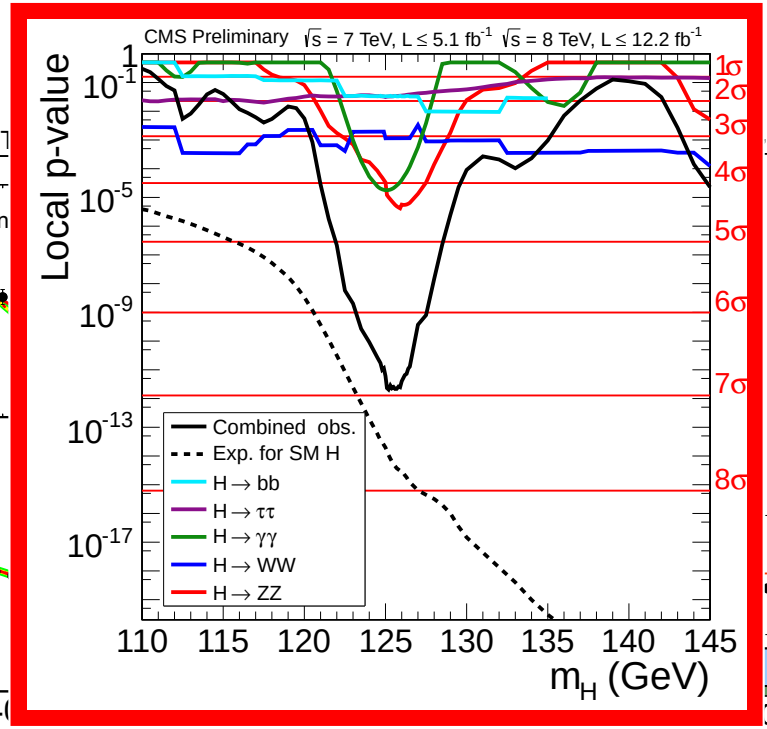
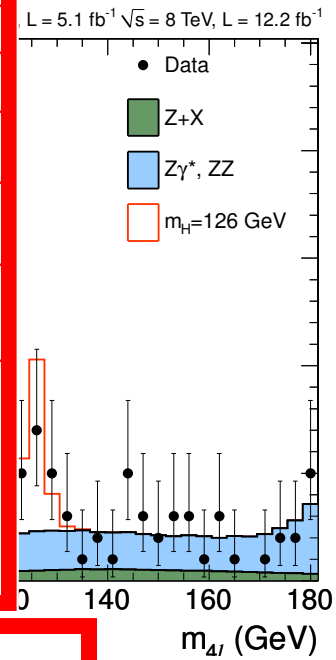
Data
S+B Fit
B Fit Component
±1σ
±2 σ


CMS Preliminary √s = 7 TeV, L ≤ 5.1 fb-1 √s = 8 TeV, L ≤ 12.2 fb-1
Local p-value
Combined obs.
Exp. for SM H
H → bb
H → ττ
H → γγ
H → WW
H → ZZ
mH (GeV)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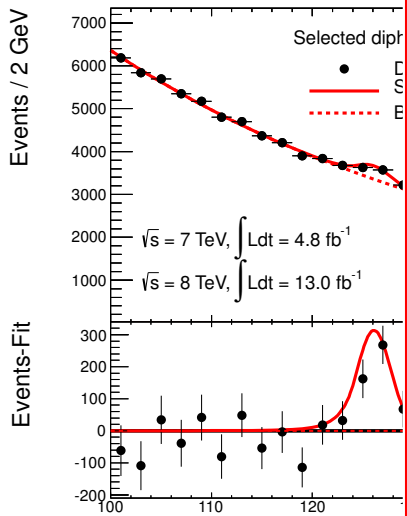
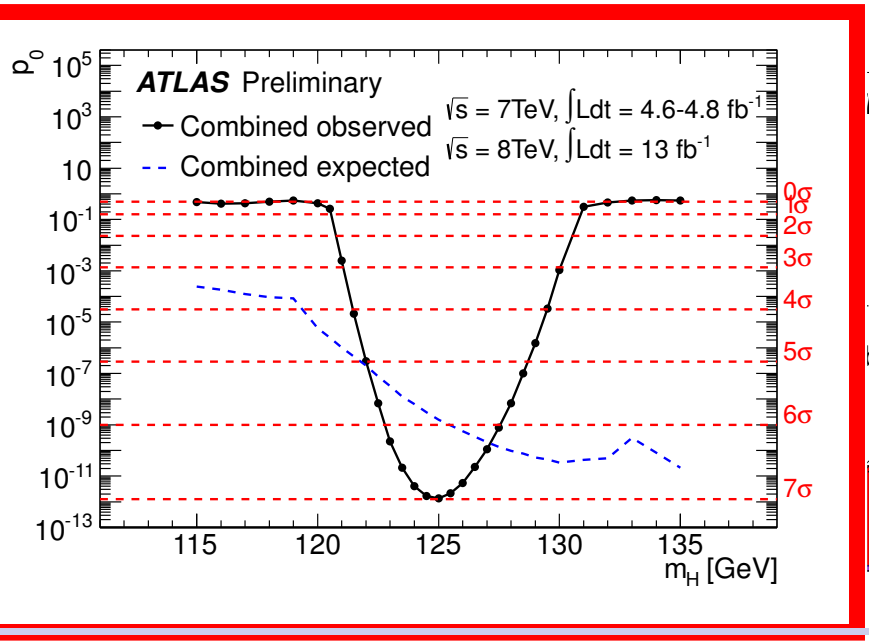
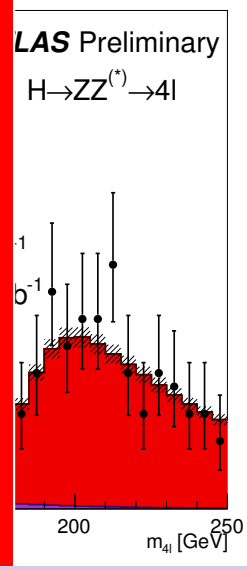
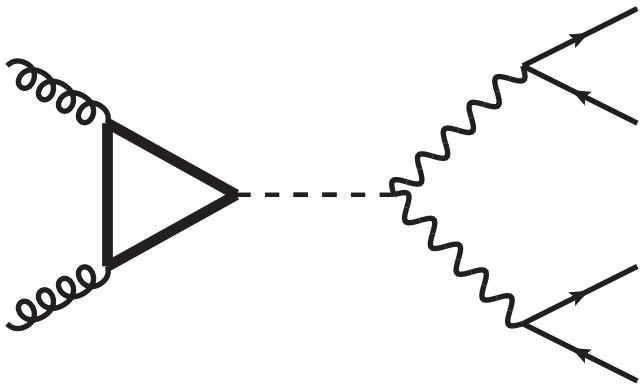

Events / 2 GeV
Selected dipl
√s = 7 TeV, ∫Ldt = 4.8 fb-1
√s = 8 TeV, ∫Ldt = 13.0 fb-1
Events-Fit


p0
ATLAS Preliminary
Combined observed
Combined expected
√s = 7TeV, ∫Ldt = 4.6-4.8 fb-1
√s = 8TeV, ∫Ldt = 13 fb-1
mH [GeV]


ATLAS Preliminary
H→ZZ(*)→4l
m4l [GeV]

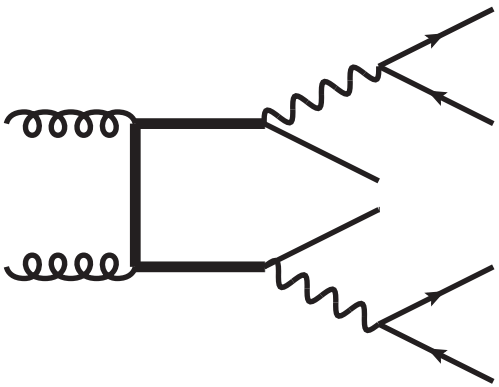
Motivation: $H \to WW^* \to 4l$ channel

- production:

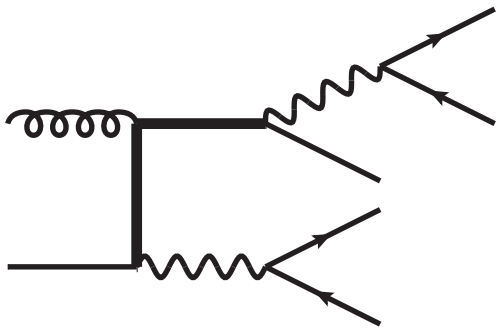


- backgrounds:

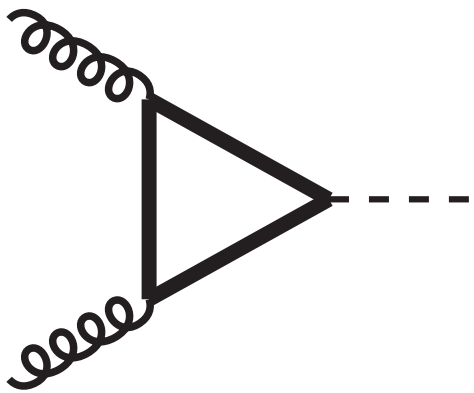
$t\bar{t} \to b\bar{b}WW^* \to b\bar{b}\,4l$

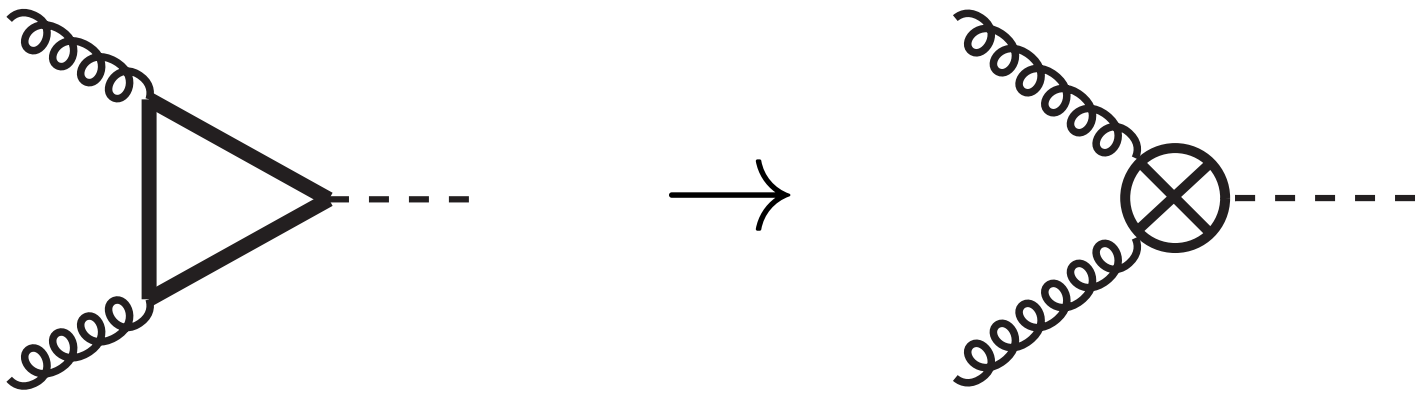


$tW \to bWW^* \to b\,4l$



- top decays to hard b-jets
- possibility 1: b-tagging
- possibility 2: Jet-veto (simpler)





Inclusive cross section

- **NNLO:**
  [Harlander, Kilgore '02]
  [Anastasiou, Melnikov '02]
  [Ravindran, Smith, v. Neerven '03]
- **NNLO+Resummation:**
  [Catani, de Florian, Grazzini, Nason '02]
  [Ahrens, Becher, Neubert, Zhang '08]
- **Electroweak corrections:**
  [Djouadi, Gambino '94]
  [Aglietti, Bonciani, Degrassi, Vicini '04]
  [Degrassi, Maltoni '04]
  [Actis, Passarino, Sturm, Uccirati '08]
- **Mixed EW/QCD corrections:**
  [Anastasiou, Boughezal, Petriello '09]
- **even: first steps towards N^{3}LO:**
  [Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Mistlberger '14 '14]
  [Ball, Bonvini, Forte, Marzani, Ridolfi '13 '14]
  [Florian, Mazzitelli, Moch, Vogt '14]

Differential cross section:

- **H+jet NLO:**
  [de Florian, Grazzini, Kunszt '99]
- **jet-veto NNLO(+NNLL):**
  [Catani, de Florian, Grazzini '01]
  [Berger, Marcantonini, Stewart, Tackmann, Waalewijn '11]
  [Banfi, Monni, Salam, Zanderighi '12]
  [Becher, Neubert '12]
- **Fully differential NNLO:**
  [Anastasiou, Melnikov, Petriello '04]
  [Catani, Grazzini '07]
- **p_T resummation at NNLL:**
  [Bozzi, Catani, de Florian, Grazzini '03 '05]
- **H+jet NNLO (gg channel):**
  [Chen, Gehrmann, Glover, Jaquier '14]

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all heavy-top limit

Mass effects?

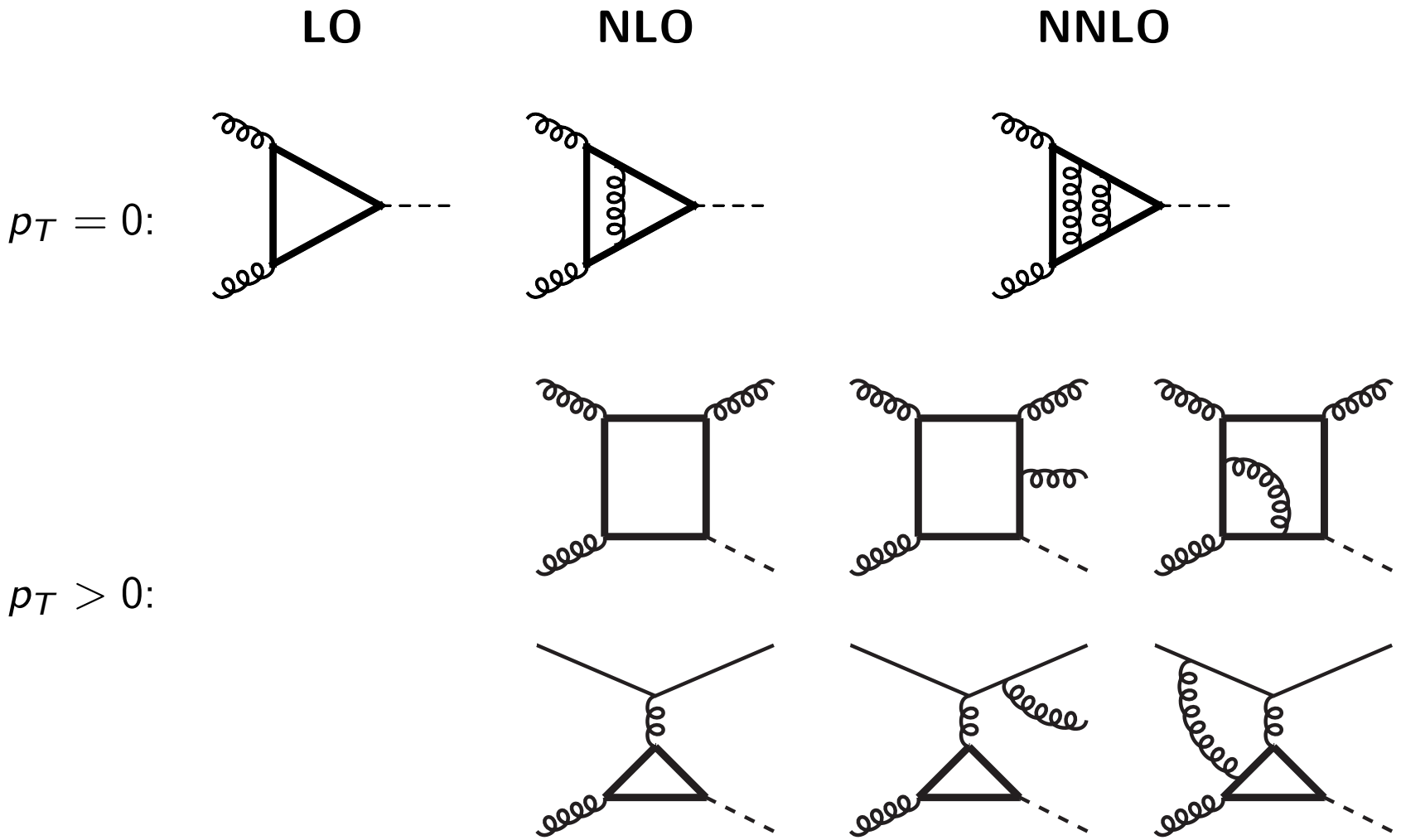
Top-mass effects

- considered to be small
- TRUE: $<1\%$ for NNLO corrections

  [Harlander, Mantler, Marzani, Ozeren '10], [Pak, Rogal, Steinhauser '10]
- BUT: only inclusive!
- HERE: validation of $m_{\text{top}} \to \infty$ for
  - Higgs+jet at NLO
  - Higgs with jet veto at NNLO
- METHOD: asymptotic expansion

  $\to$ subleading terms in $1/m_{\text{top}}^k$ expansion $(k = 0, 2, 4)$

Outline of the calculation



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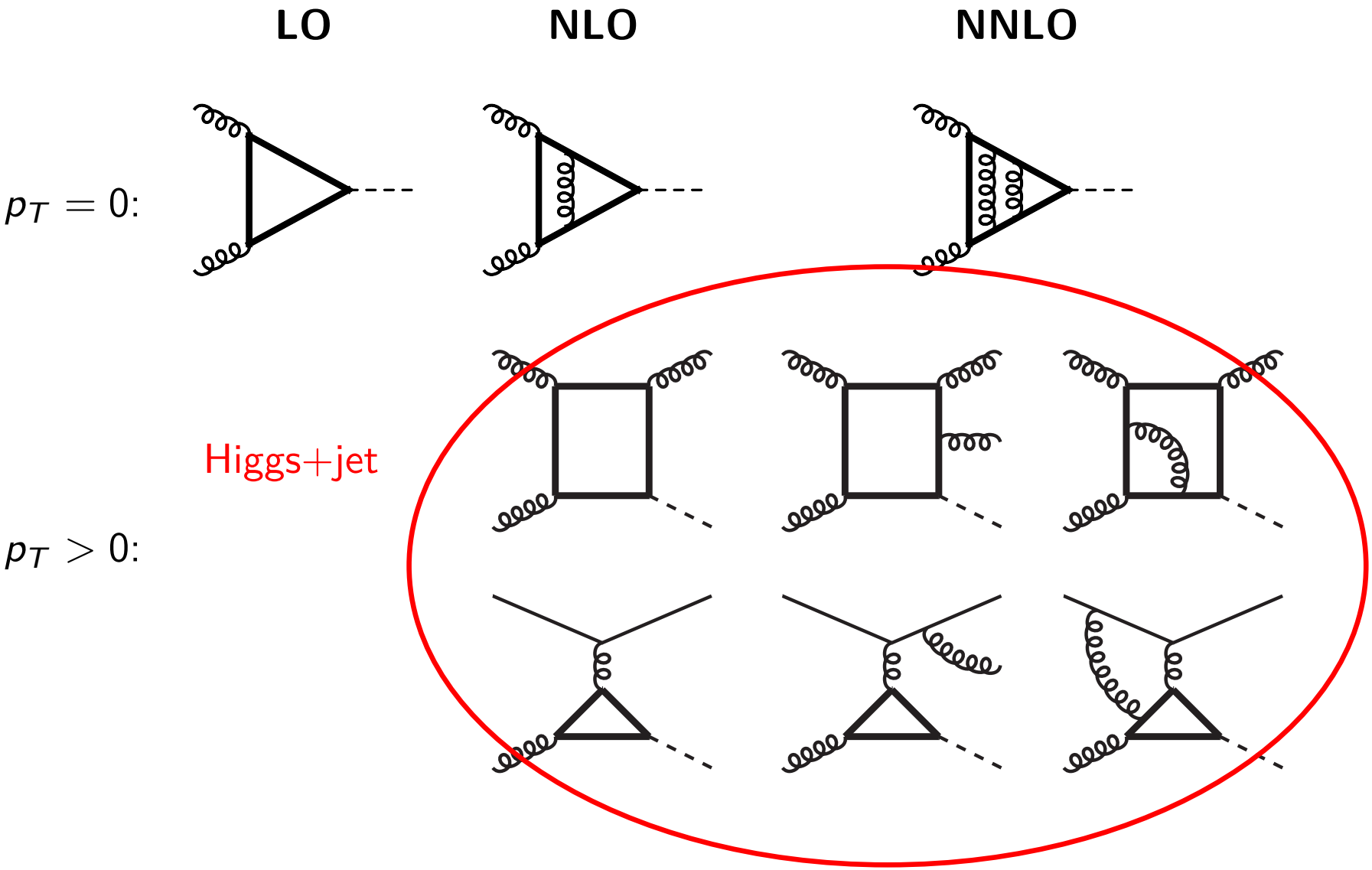
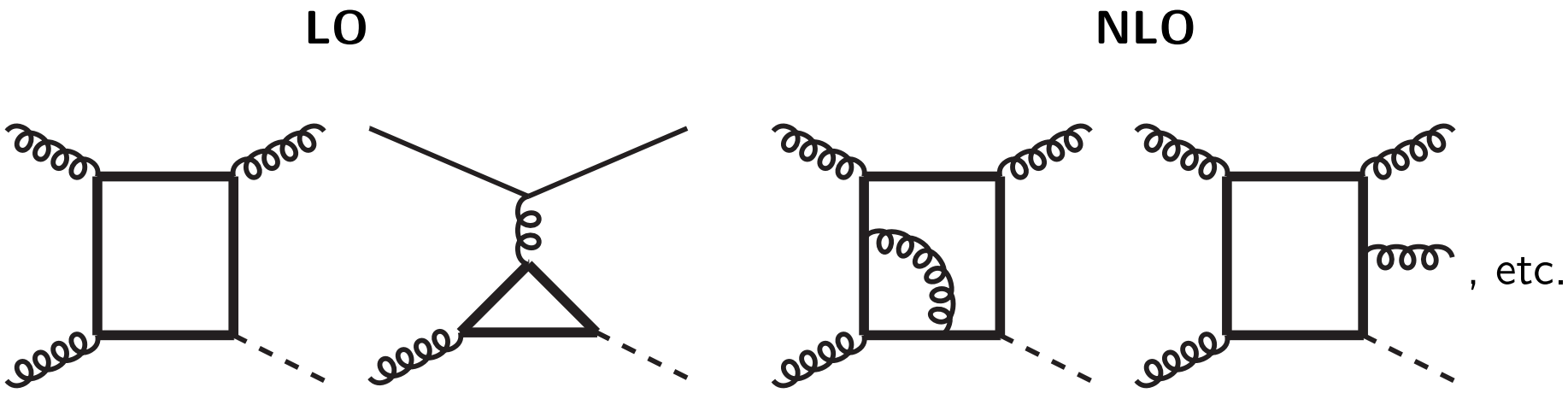


Outline of the calculation: Higgs+jet at NLO



- subleading $1/m_{\text{top}}^k$ terms in asymptotic expansion

  [Harlander, Mantler, Marzani, Ozeren '10]
- fully differential up to NLO

  [Harlander, Neumann, Ozeren, MW '12]
- dipole subtraction

  [Catani, Seymour '97]

Outline of the calculation: Jet-veto at NNLO

- NNLO total cross section known up to $1/m_{\text{top}}^8$

  [Harlander, Mantler, Marzani, Ozeren '10]

- combination with Higgs+jet $\rightarrow$ jet-veto through NNLO:

  cf. [Catani, de Florian, Grazzini '01]

$$\sigma^{\text{veto}} = \sigma^{\text{tot}} - \sigma[\text{1-jet}] - \sigma[\text{2-jet}]$$

- take σ^{tot} from `ggh@nnlo` and $\sigma[n\text{-jet}]$ from Higgs+jet calculation

  [Harlander, Kilgore '02]

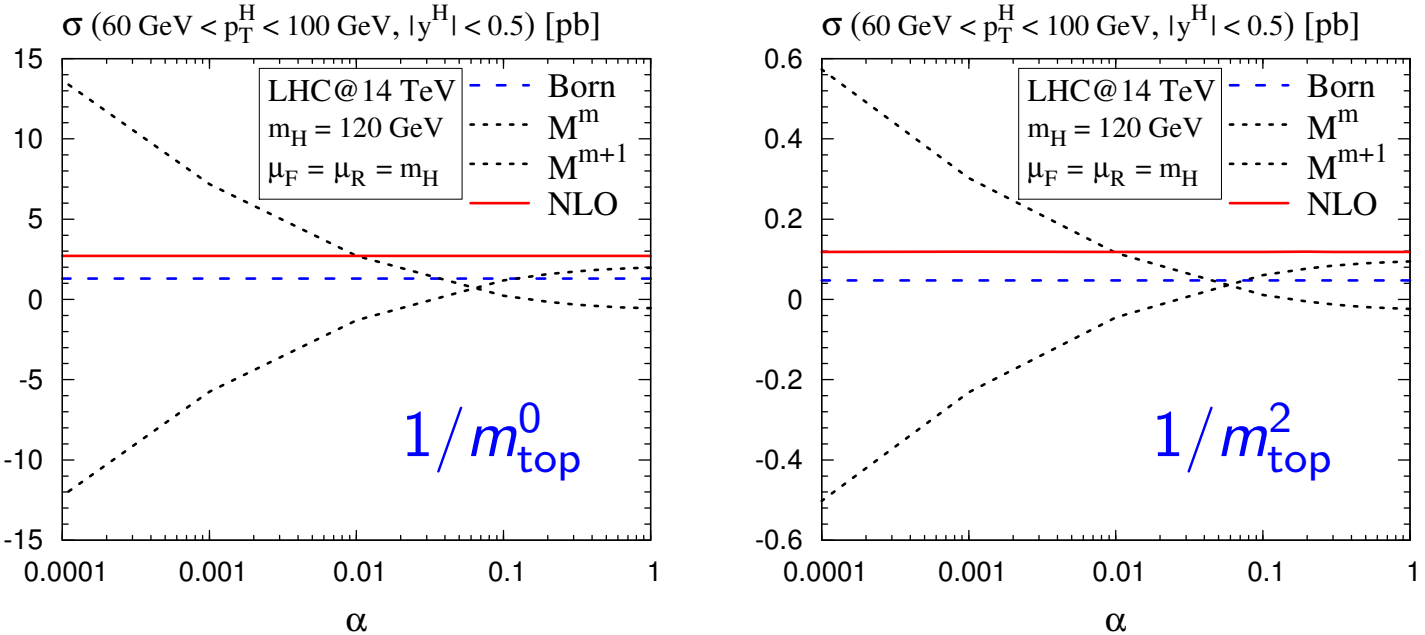
- implemented for $1/m_{\text{top}}^k$, $k = 0, 2, 4$
- jet definition: anti-k_T, $R = 0.5$, $p_{T,\text{min}}^{\text{jet}} = 30\,\text{GeV}$

$\Rightarrow$ Setup allows to validate heavy-top limit for Higgs+n-jet with $n = 0/1/2$ at NNLO/NLO/LO

Checks

- $1/m_{\text{top}}^k$ total x-section (amplitudes) checked against [Pak, Rogal, Steinhauser '10]
- α-parameter independence of Higgs+jet

  [Nagy, Trócsányi '00], [Nagy '03]



- agreement with existing codes for $m_{\text{top}} \to \infty$:
  - `HqT`: analytical fixed order p_T distribution

    [Bozzi, Catani, de Florian, Grazzini '03 '05]
  - `HNNLO`: jet-vetoed cross section

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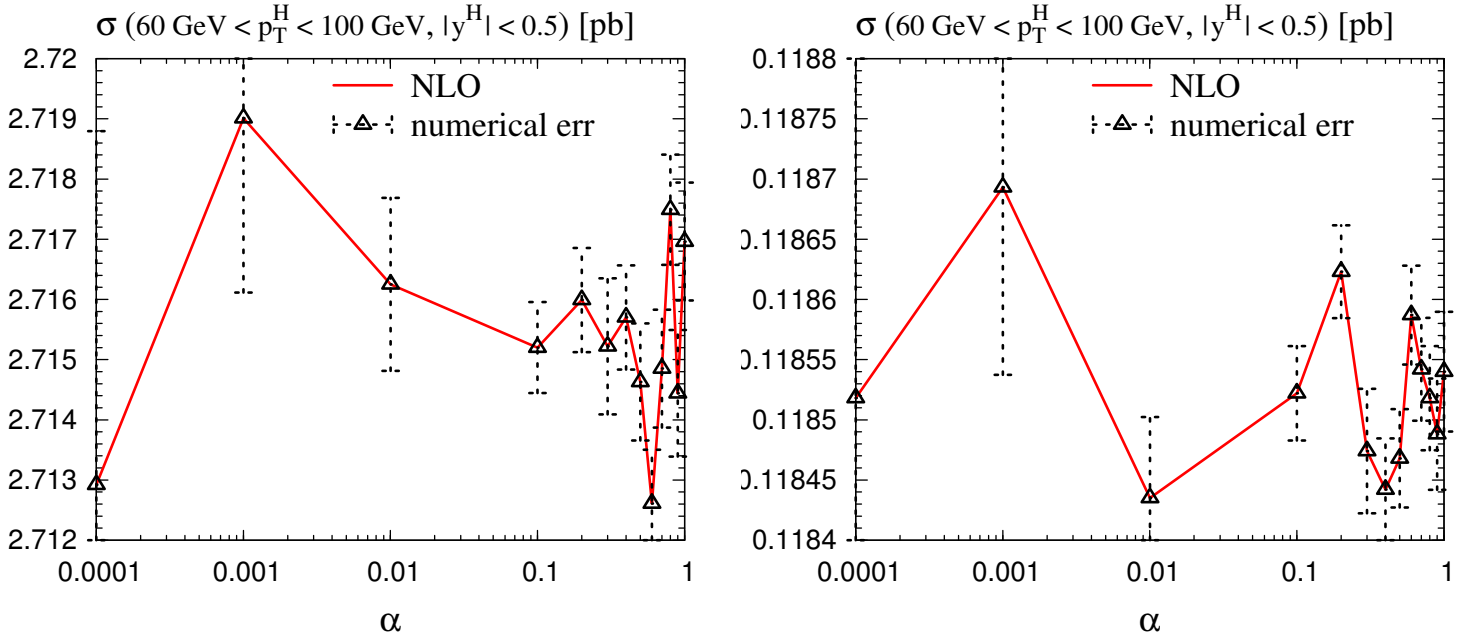

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Results: Jet-veto

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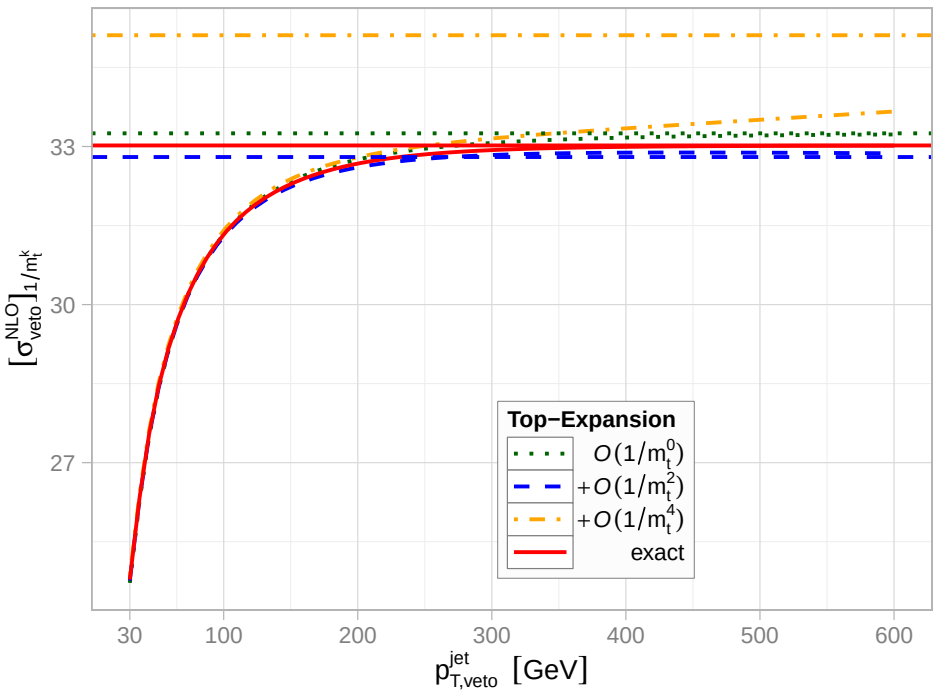
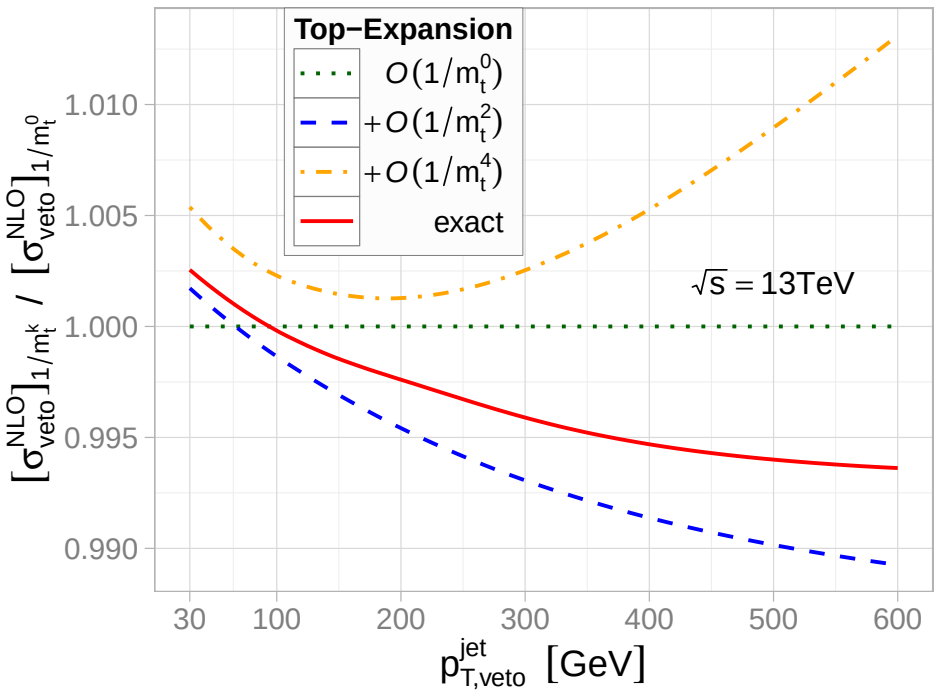
Jet-veto cut dependence at NLO:

[Neumann, MW '14]

$$\sigma^{\text{veto}} = \sigma^{\text{tot}} - \sigma[\text{1-jet}]$$

reweighted by exact top-mass dependence at born-level!





Results: Jet-veto

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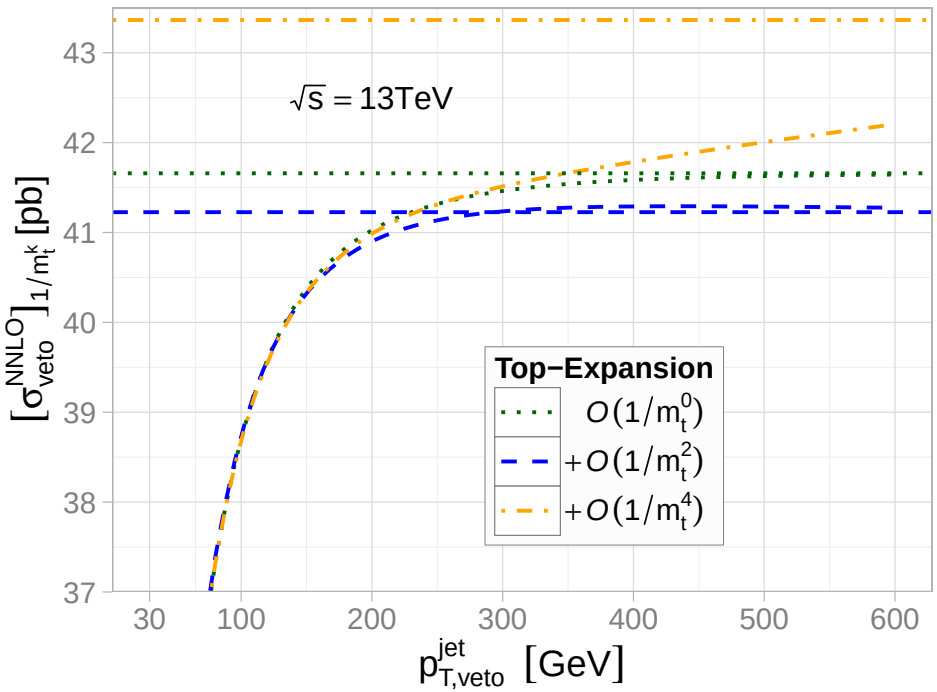

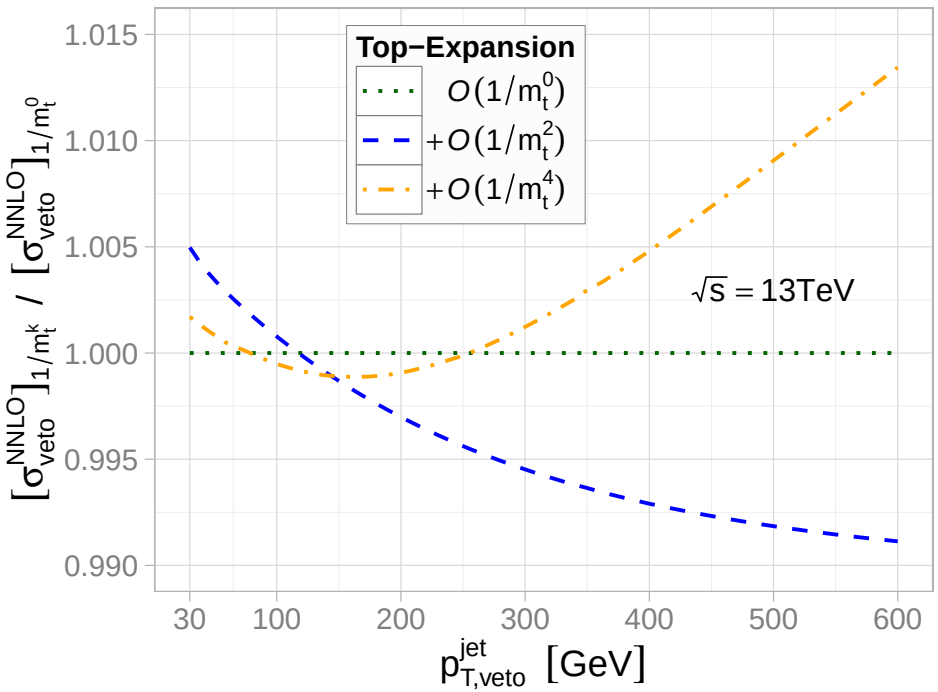

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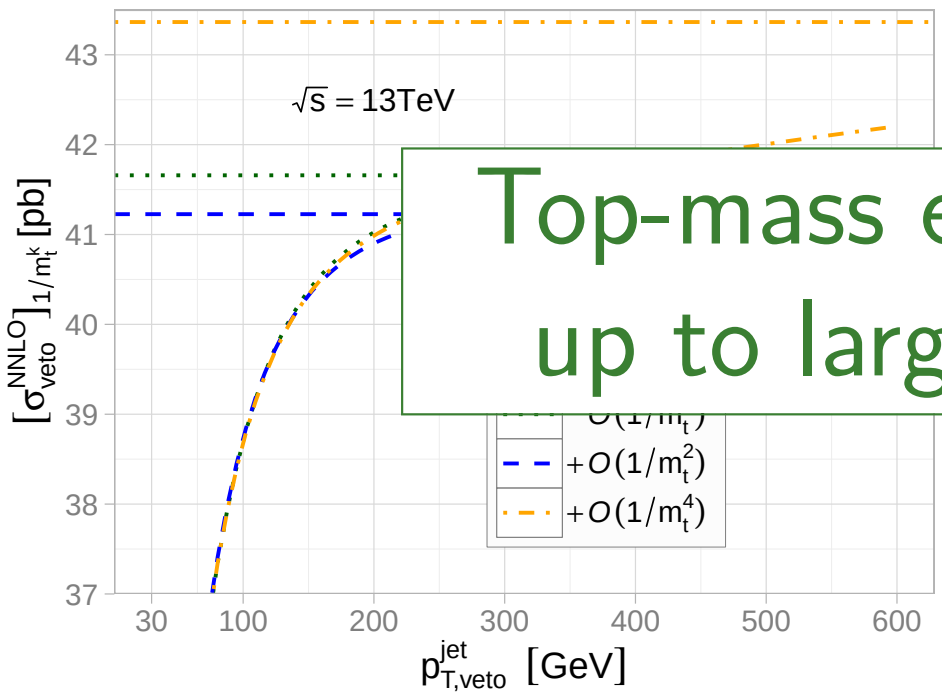
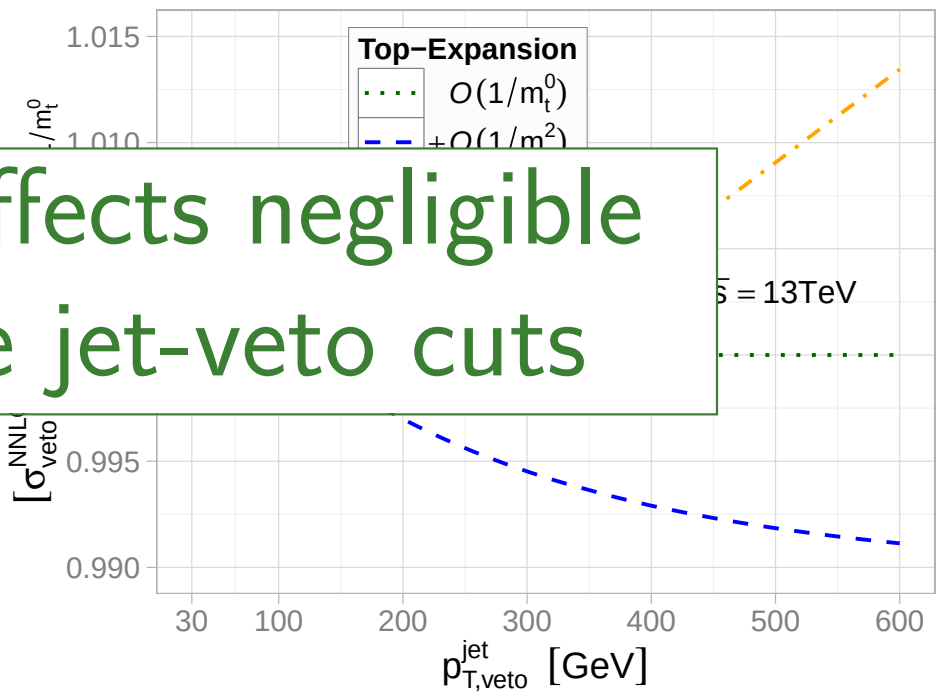




Top-mass effects negligible up to large jet-veto cuts

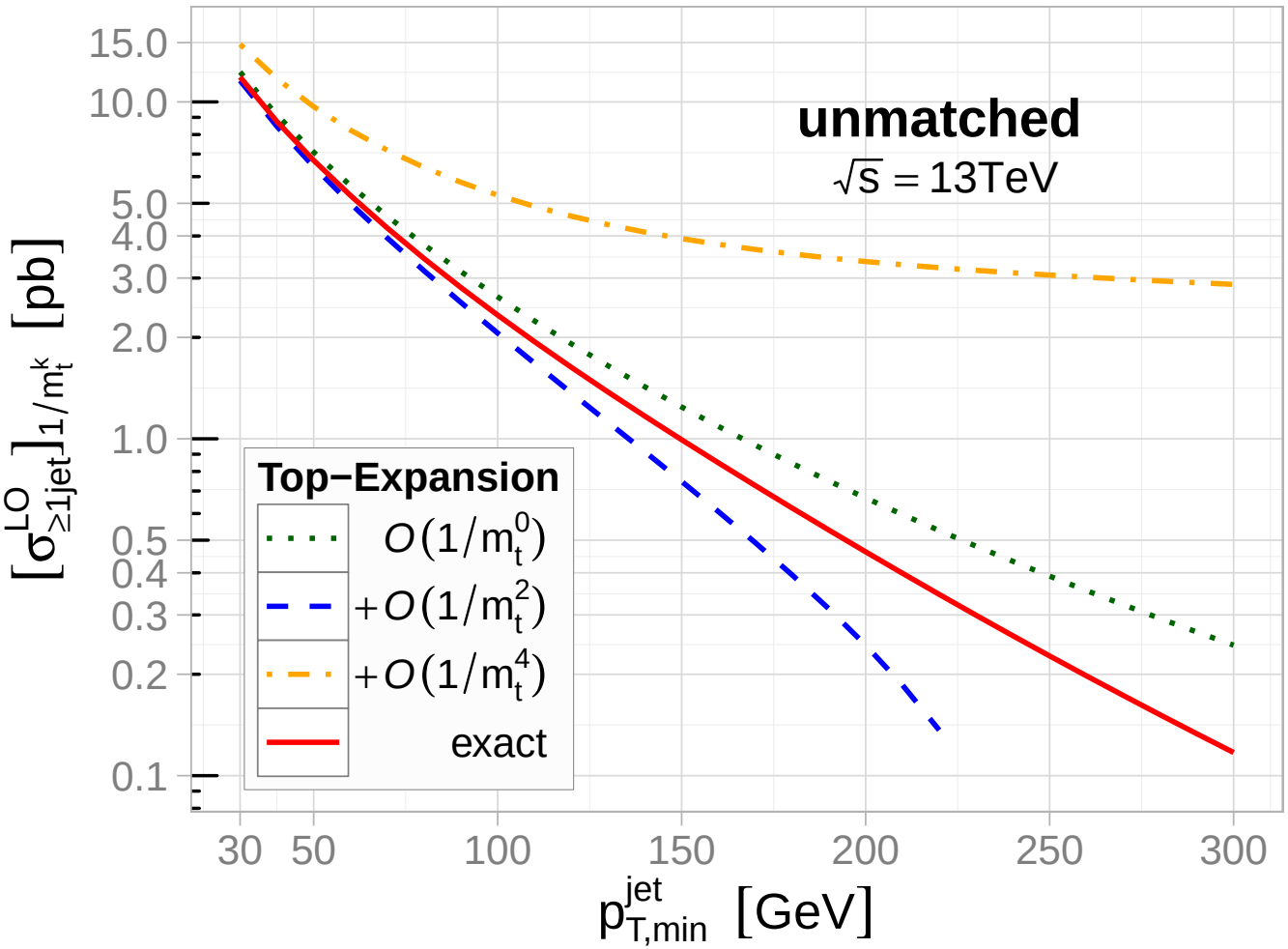
Results: Higgs+jet

Results: Higgs+jet

Minimal jet cut dependence at LO:

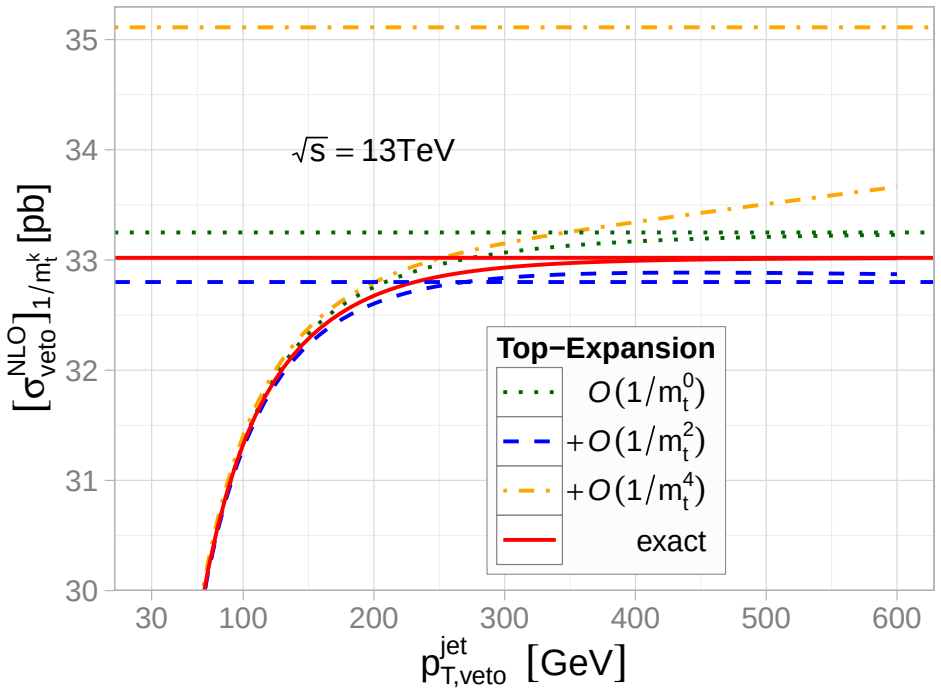
[Neumann, MW '14]

reweighted by exact top-mass dependence at born-level!



Introducing the matched Higgs+jet cross section

- observation: Higgs+jet and total integrated over problematic large-p_T region



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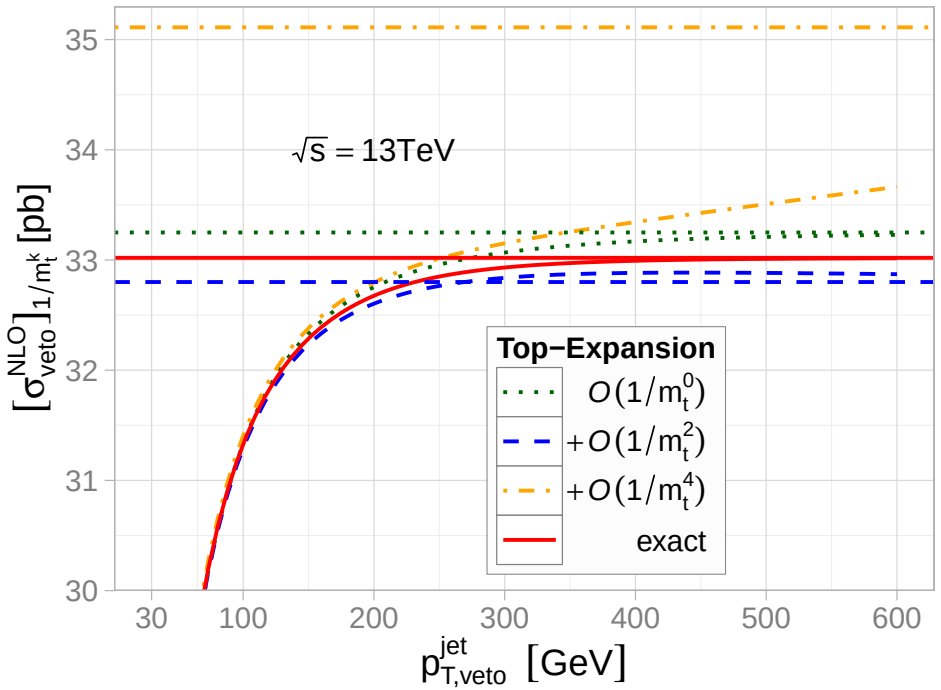

- solution for total: high-energy matching for $z \to \infty$ (known)

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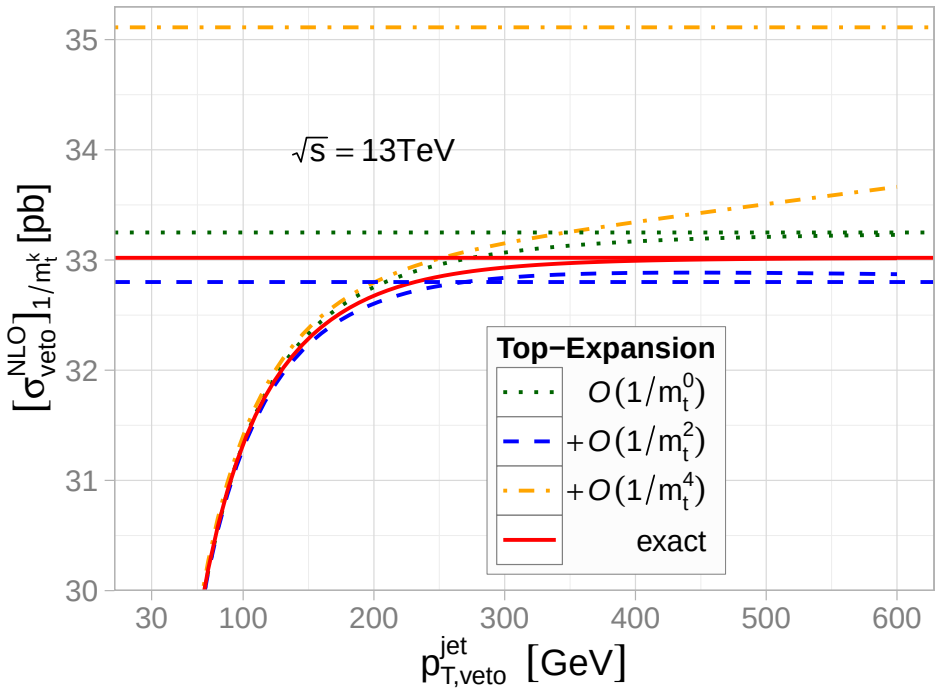


$[\sigma]_{1/m^k_{\text{top}}} \mathrel{\widehat{=}}$ cross section truncated at $1/m^k_{\text{top}}$

- solution for total: high-energy matching for $z \to \infty$ (known)
- Higgs+jet: similar matching for $p_T \to \infty$ (not known)
- assume it was known, then:

$$[\sigma^{\text{H+jet,matched}}_{LO}]_{1/m^k_{\text{top}}} - [\sigma^{\text{H+jet}}_{LO}]_{1/m^k_{\text{top}}} = [\sigma^{\text{tot,matched}}_{NLO}]_{1/m^k_{\text{top}}} - [\sigma^{\text{tot}}_{NLO}]_{1/m^k_{\text{top}}}$$

Introducing the matched Higgs+jet cross section

$\Rightarrow$ define matched Higgs+jet cross section:

$$[\sigma_{LO}^{\text{H+jet,matched}}]_{1/m_{\text{top}}^k} = [\sigma_{LO}^{\text{H+jet}}]_{1/m_{\text{top}}^k} - [\sigma_{NLO}^{\text{tot}}]_{1/m_{\text{top}}^k} + [\sigma_{NLO}^{\text{tot,matched}}]_{1/m_{\text{top}}^k}$$

$[\sigma]_{1/m_{\text{top}}^k} \mathrel{\widehat{=}}$ cross section truncated at $1/m_{\text{top}}^k$

- problematic effects canceled between 1. and 2. term on r.h.s.
- same possible at NLO with NNLO total cross section

$\rightarrow$ reliable prediction through well-behaved $1/m_{\text{top}}$ expansion?

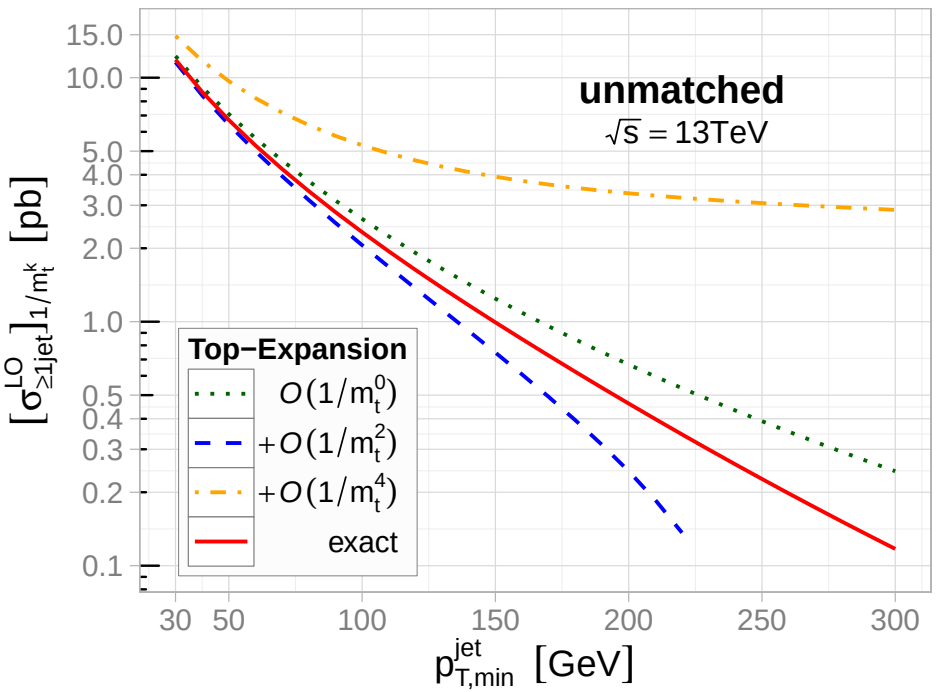
Results: Higgs+jet

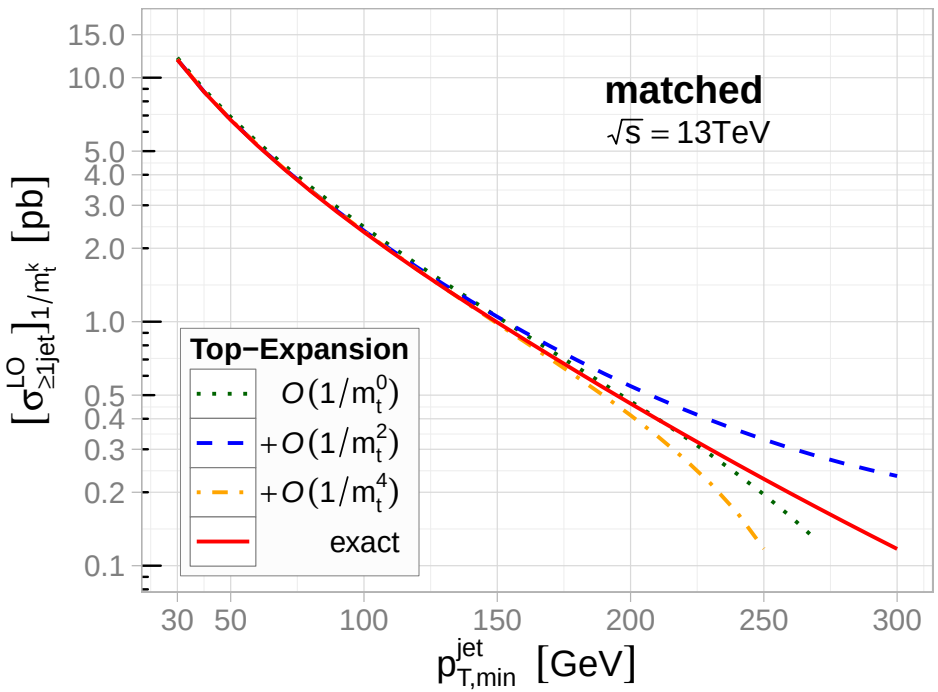
Minimal jet cut dependence at LO:

[Neumann, MW '14]

$$[\sigma_{LO}^{\text{H+jet,matched}}]_{1/m_{\text{top}}^k} = [\sigma_{LO}^{\text{H+jet}}]_{1/m_{\text{top}}^k} - [\sigma_{NLO}^{\text{tot}}]_{1/m_{\text{top}}^k} + [\sigma_{NLO}^{\text{tot,matched}}]_{1/m_{\text{top}}^k}$$

reweighted by exact top-mass dependence at born-level!





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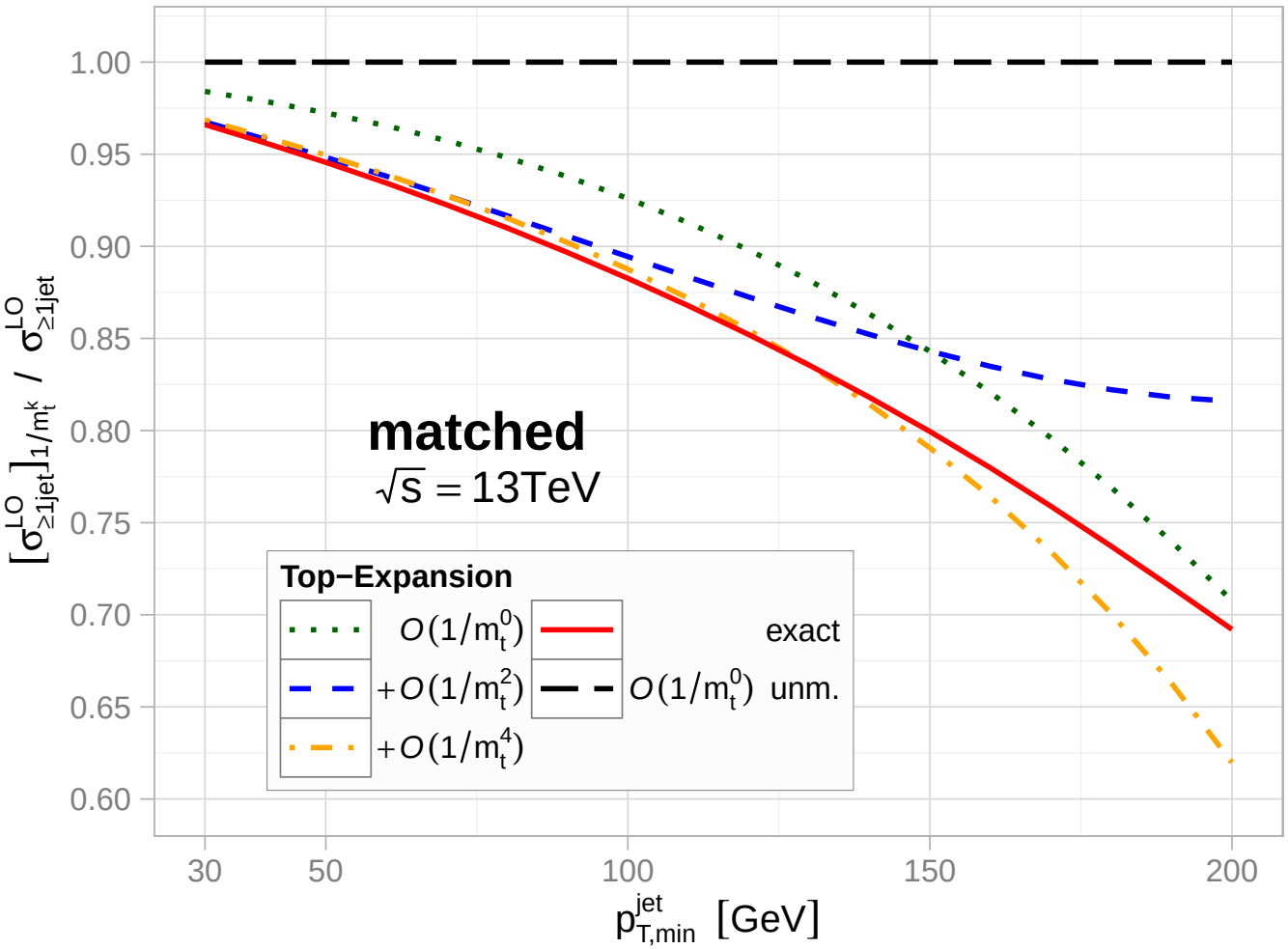

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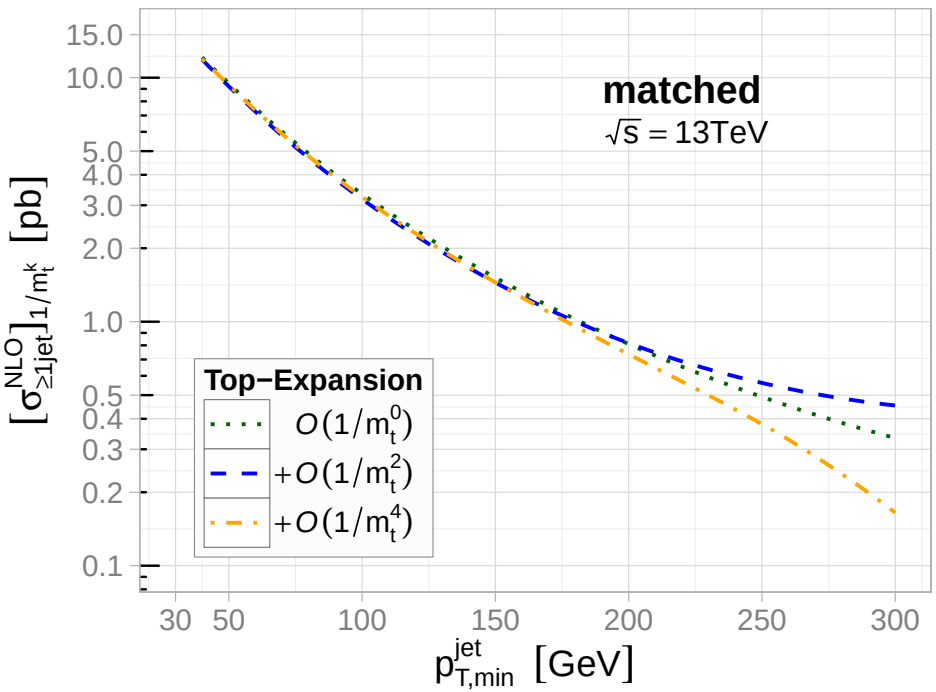
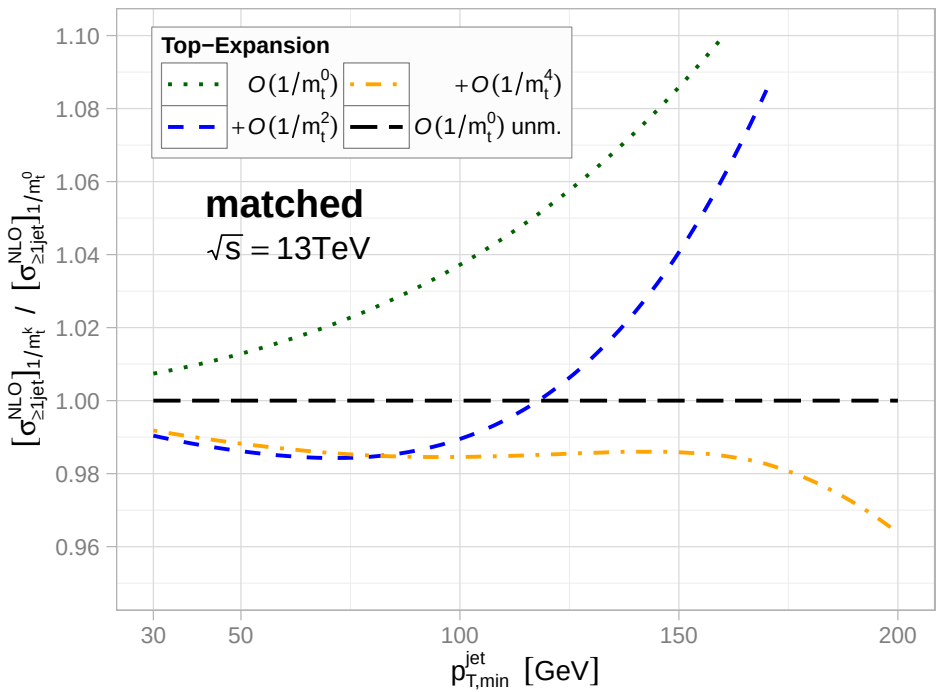
Minimal jet cut dependence at NLO:

[Neumann, MW '14]

$$[\sigma_{NLO}^{\text{H+jet,matched}}]_{1/m_{\text{top}}^k} = [\sigma_{NLO}^{\text{H+jet}}]_{1/m_{\text{top}}^k} - [\sigma_{NNLO}^{\text{tot}}]_{1/m_{\text{top}}^k} + [\sigma_{NNLO}^{\text{tot,matched}}]_{1/m_{\text{top}}^k}$$

reweighted by exact top-mass dependence at born-level!





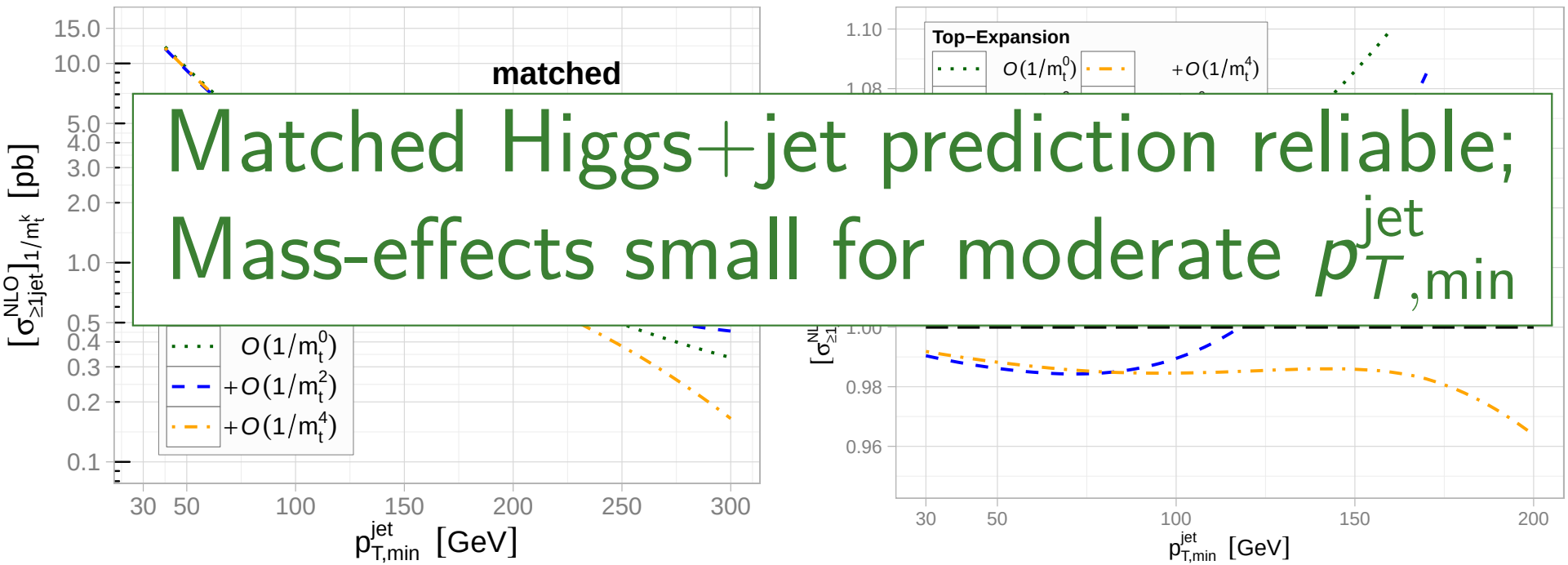
Results: Higgs+jet

Minimal jet cut dependence at NLO:

[Neumann, MW '14]

$$[\sigma_{NLO}^{\text{H+jet,matched}}]_{1/m_{\text{top}}^k} = [\sigma_{NLO}^{\text{H+jet}}]_{1/m_{\text{top}}^k} - [\sigma_{NNLO}^{\text{tot}}]_{1/m_{\text{top}}^k} + [\sigma_{NNLO}^{\text{tot,matched}}]_{1/m_{\text{top}}^k}$$

reweighted by exact top-mass dependence at born-level!



Matched Higgs+jet prediction reliable;
Mass-effects small for moderate $p_{T,\text{min}}^{\text{jet}}$

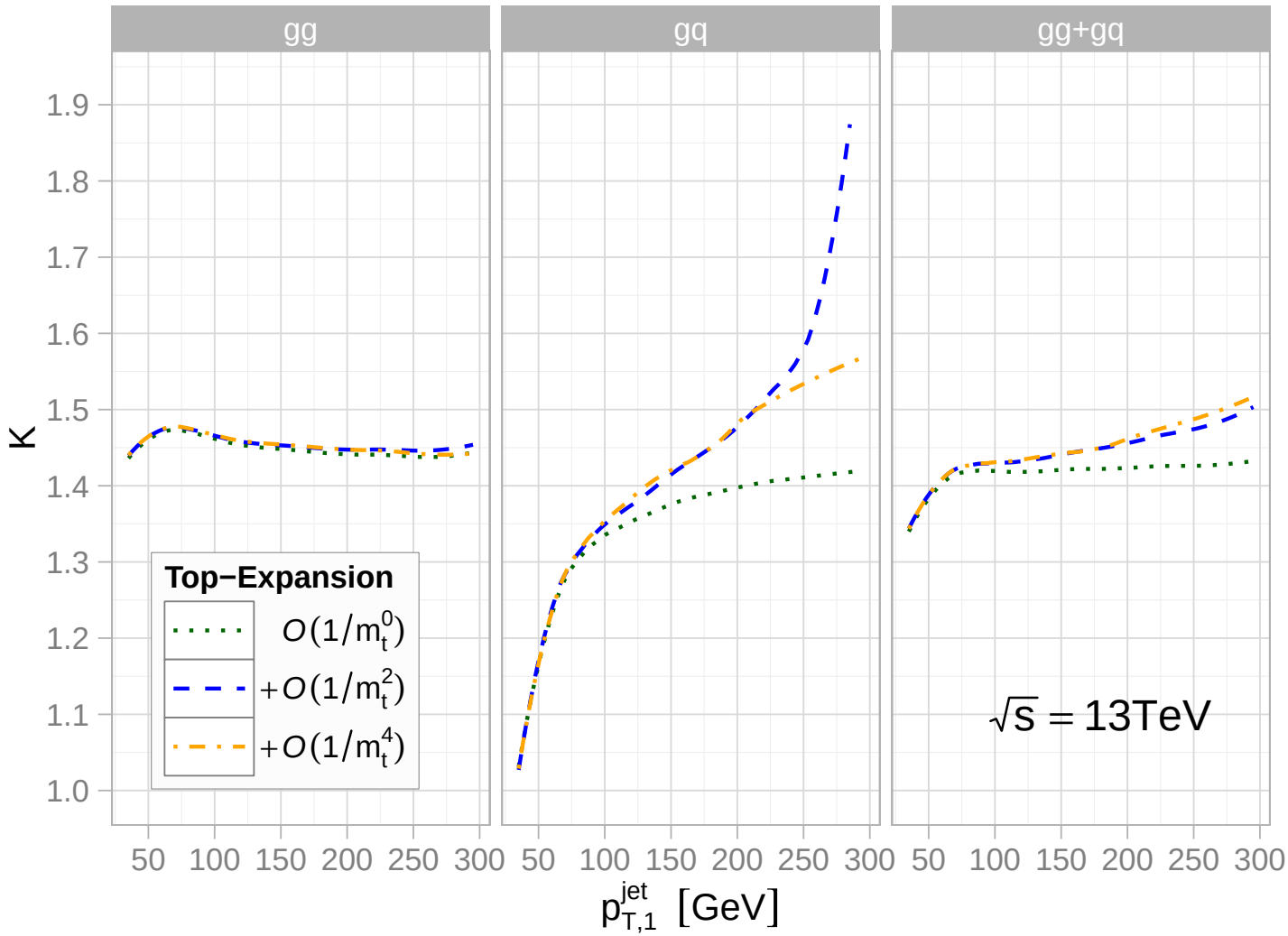
Results: distributions

Results: hardest jet distribution

Transverse momentum dependent K-factor:

[Neumann, MW '14]

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

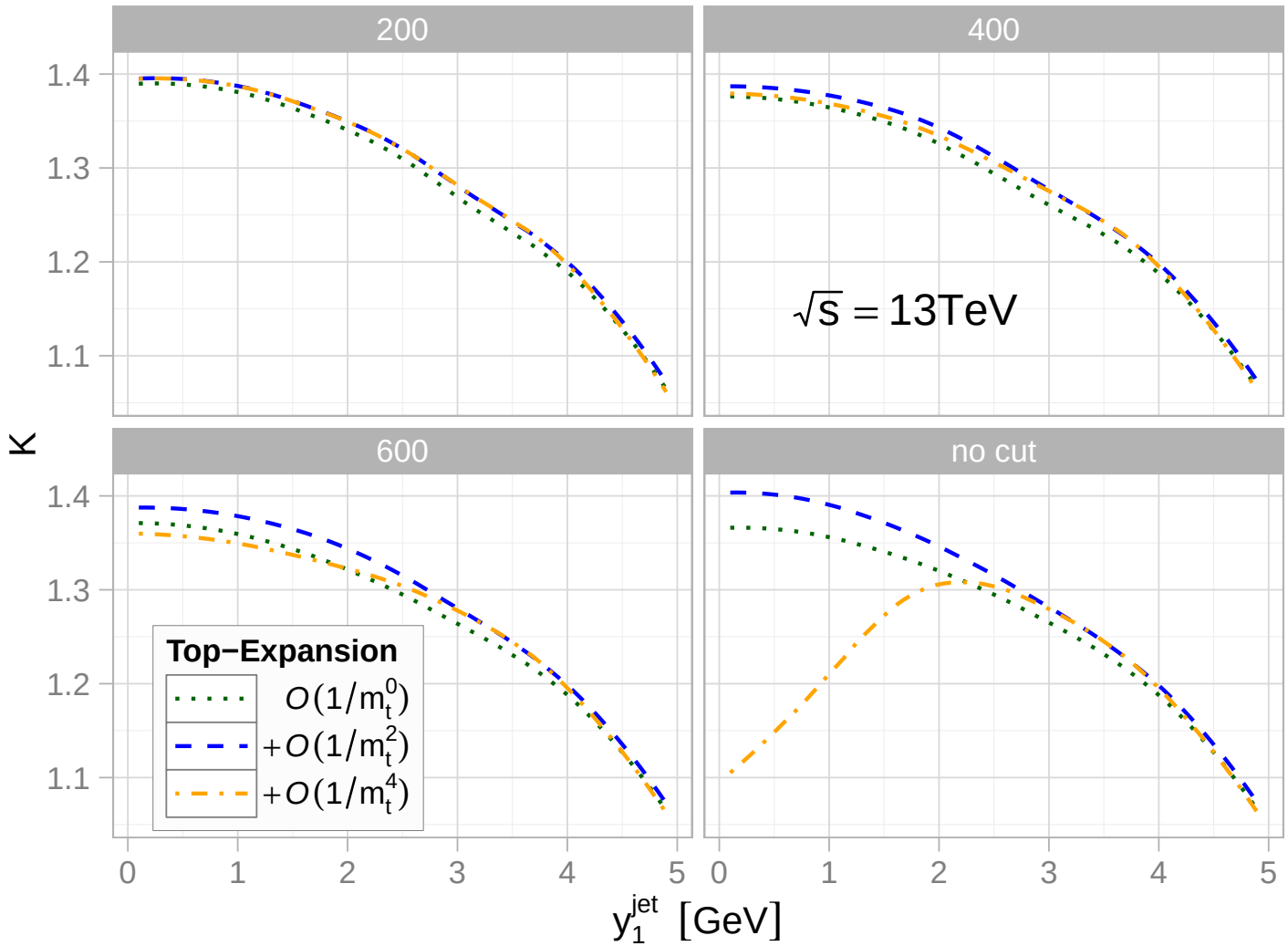


Results: hardest jet distribution

Rapidity dependent K-factor:

[Neumann, MW '14]

$$p_T^{\text{jet}} < p_{T,max}^{\text{jet}}, \quad K = d\sigma^{\text{NLO}}/d\sigma^{\text{LO}}$$

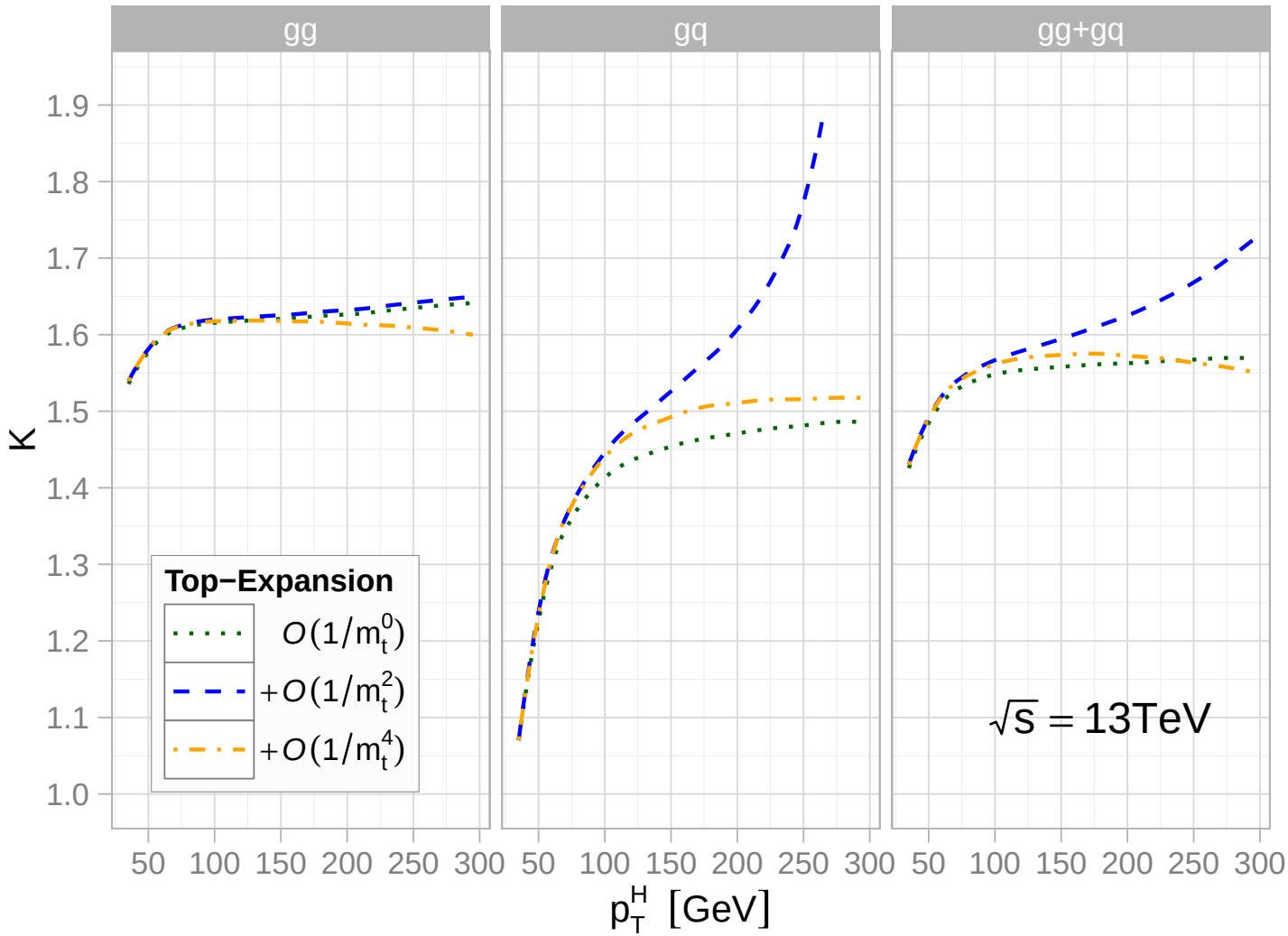


Results: Higgs distribution

Transverse momentum dependent K-factor:

[Harlander, Neumann, Ozeren, MW '12], Neumann, MW '14]

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



Results: Higgs distribution

Transverse momentum dependent K-factor:

[Harlander, Neumann, Ozeren, MW '12], Neumann, MW '14]

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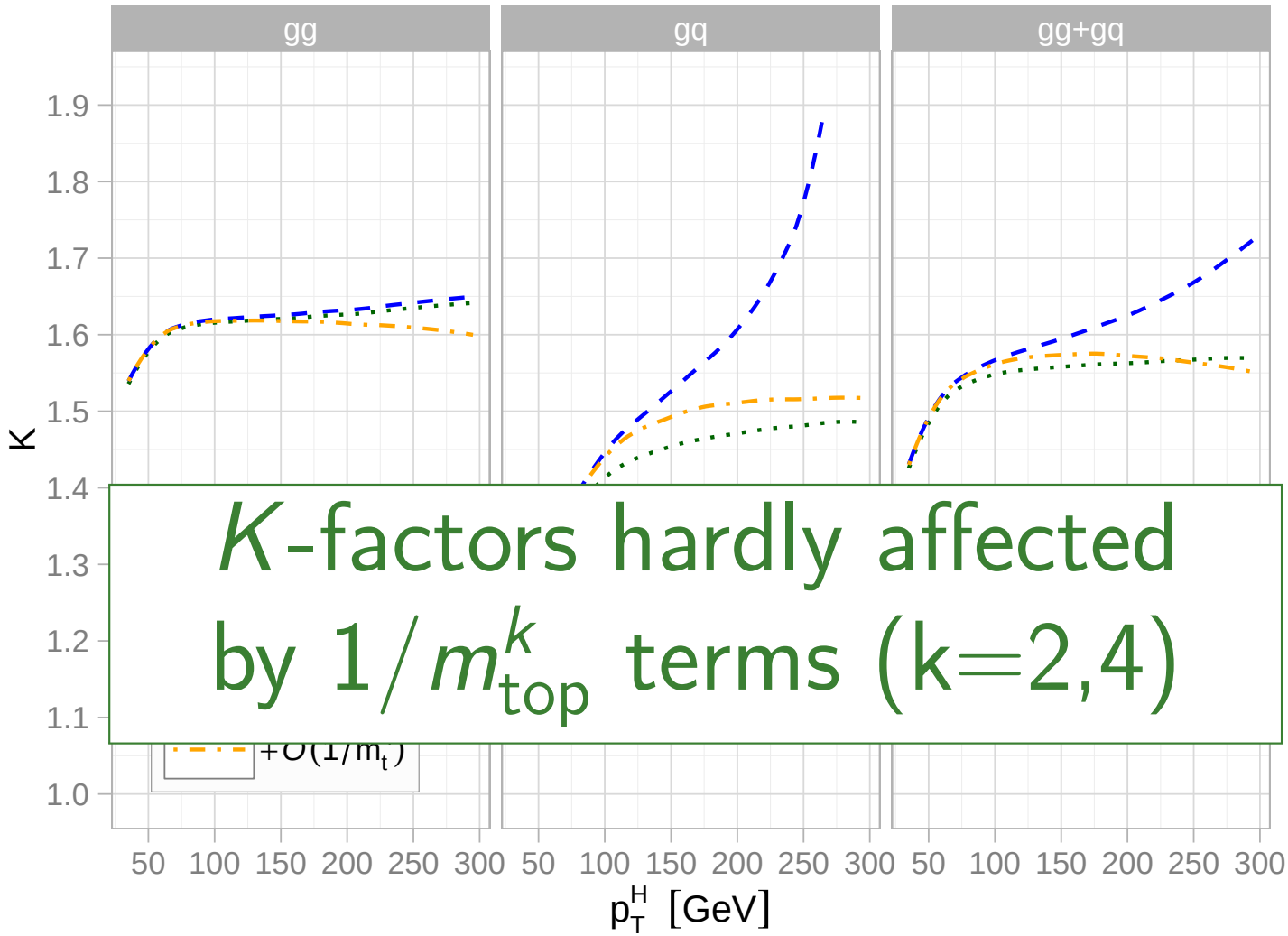


K-factors hardly affected by $1/m_{\mathrm{top}}^k$ terms (k=2,4)

Conclusions

- Subleading terms in $1/m_{\text{top}}$ for
  - Jet-veto at NNLO
  - Higgs+jet at NLO
  - Higgs and hardest jet distributions
- Jet-veto remarkably well described by heavy-top limit
- $1/m_{\text{top}}$ expansion not well behaved for Higgs+jet
- Definition of matched Higgs+jet rate $\Rightarrow$ reliable prediction
- Top-mass effects at NLO found to be small then ($p_{T,\text{min}}^{\text{jet}} \lesssim 100\,\text{GeV}$)
- Heavy-top limit valid for distributions ($p_T \lesssim 150\,\text{GeV}$)

BackUp

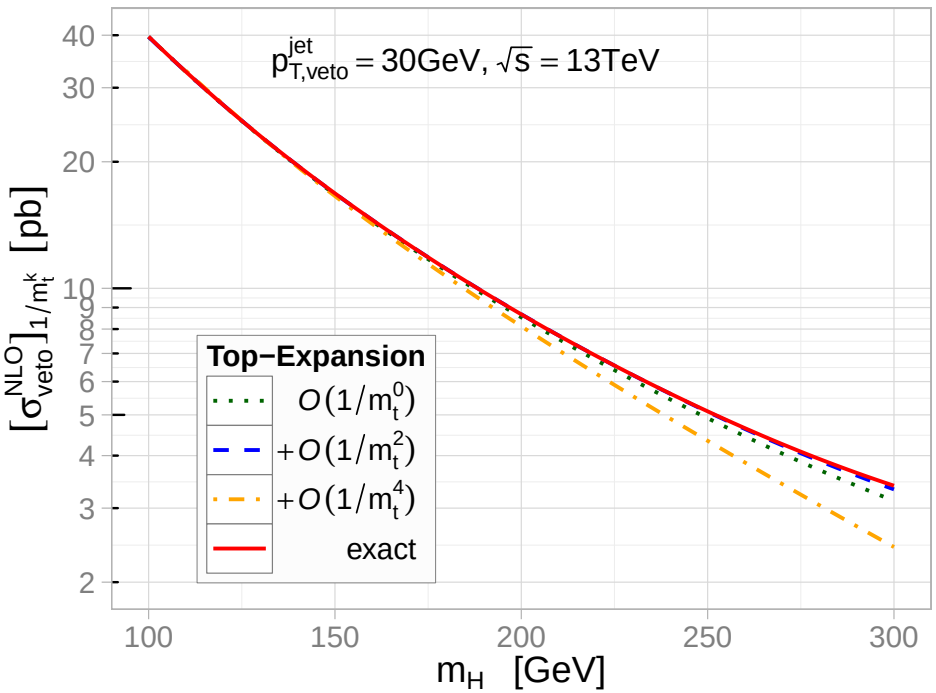
Results: Jet-veto

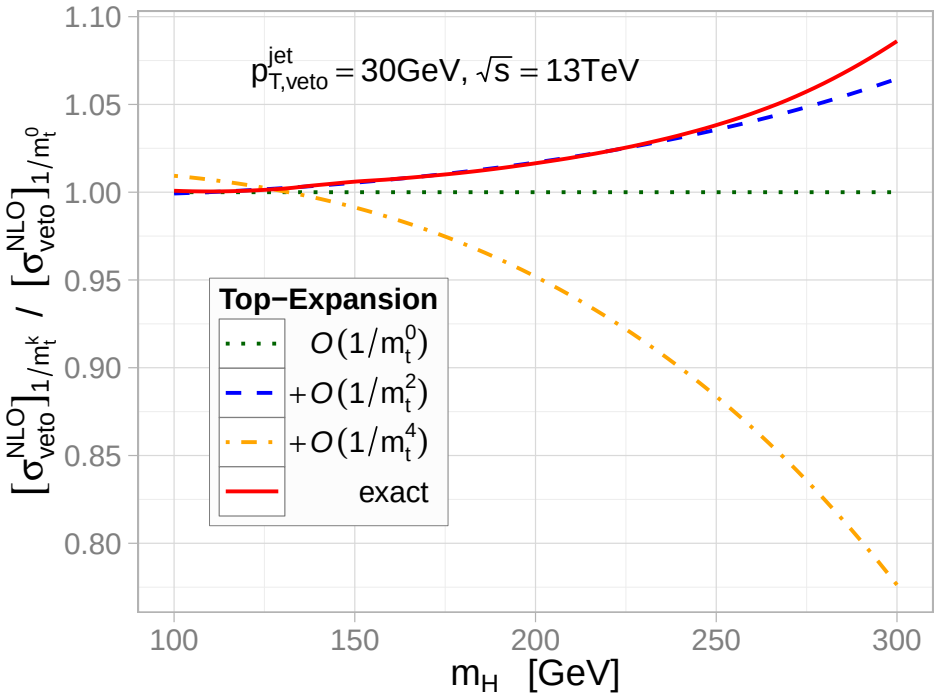
Higgs mass dependence at NLO:

[Neumann, MW '14]

$$\sigma^{\text{veto}} = \sigma^{\text{tot}} - \sigma[\text{1-jet}]$$

reweighted by exact top-mass dependence at born-level!



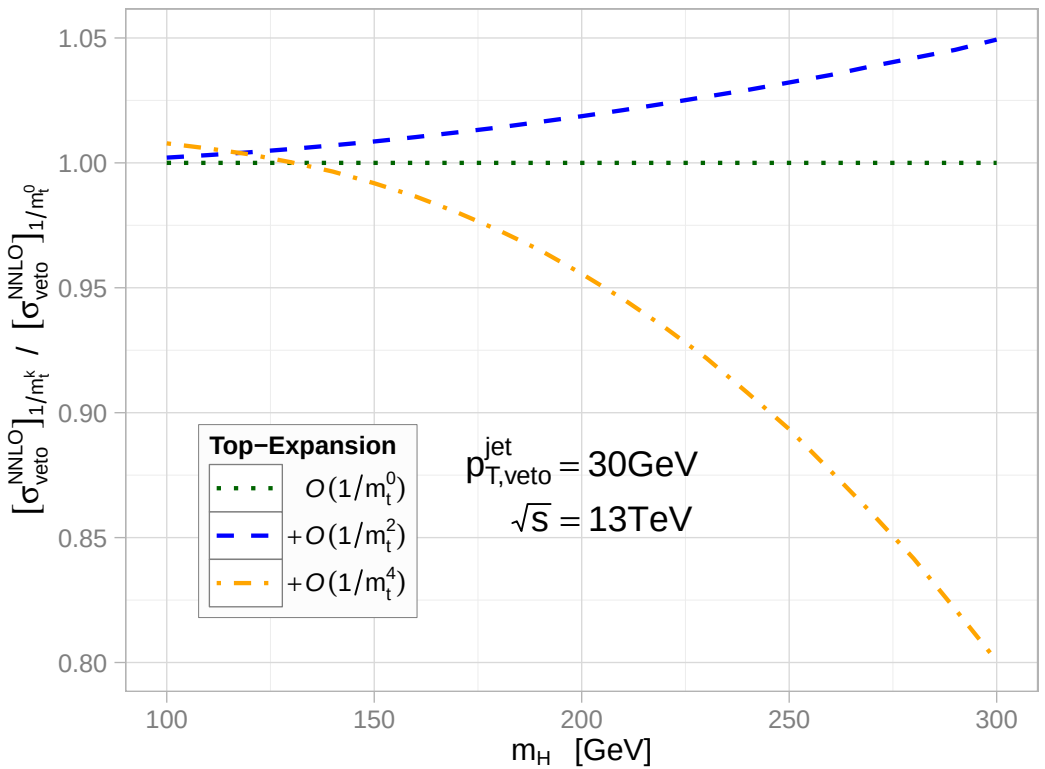


Results: Jet-veto

Higgs mass dependence at NNLO:

[Neumann, MW '14]

$$\sigma^{\text{veto}} = \sigma^{\text{tot}} - \sigma[\text{1-jet}] - \sigma[\text{2-jet}]$$



Results: Jet-veto

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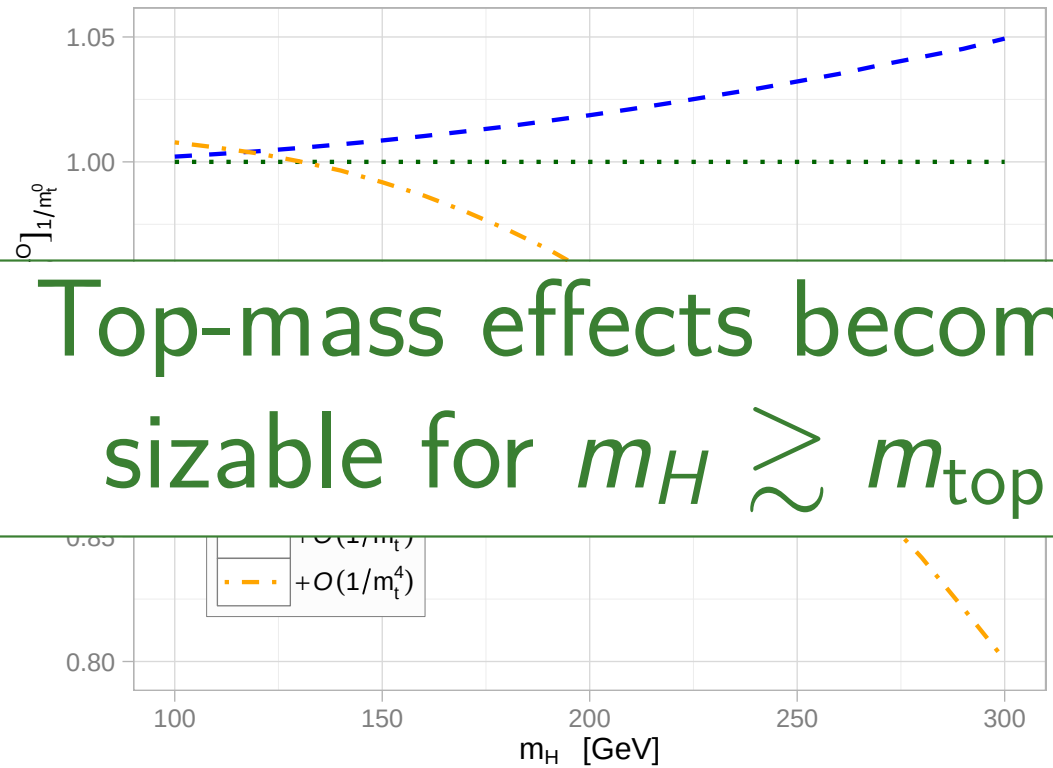


Top-mass effects become sizable for $m_H \gtrsim m_{\text{top}}$

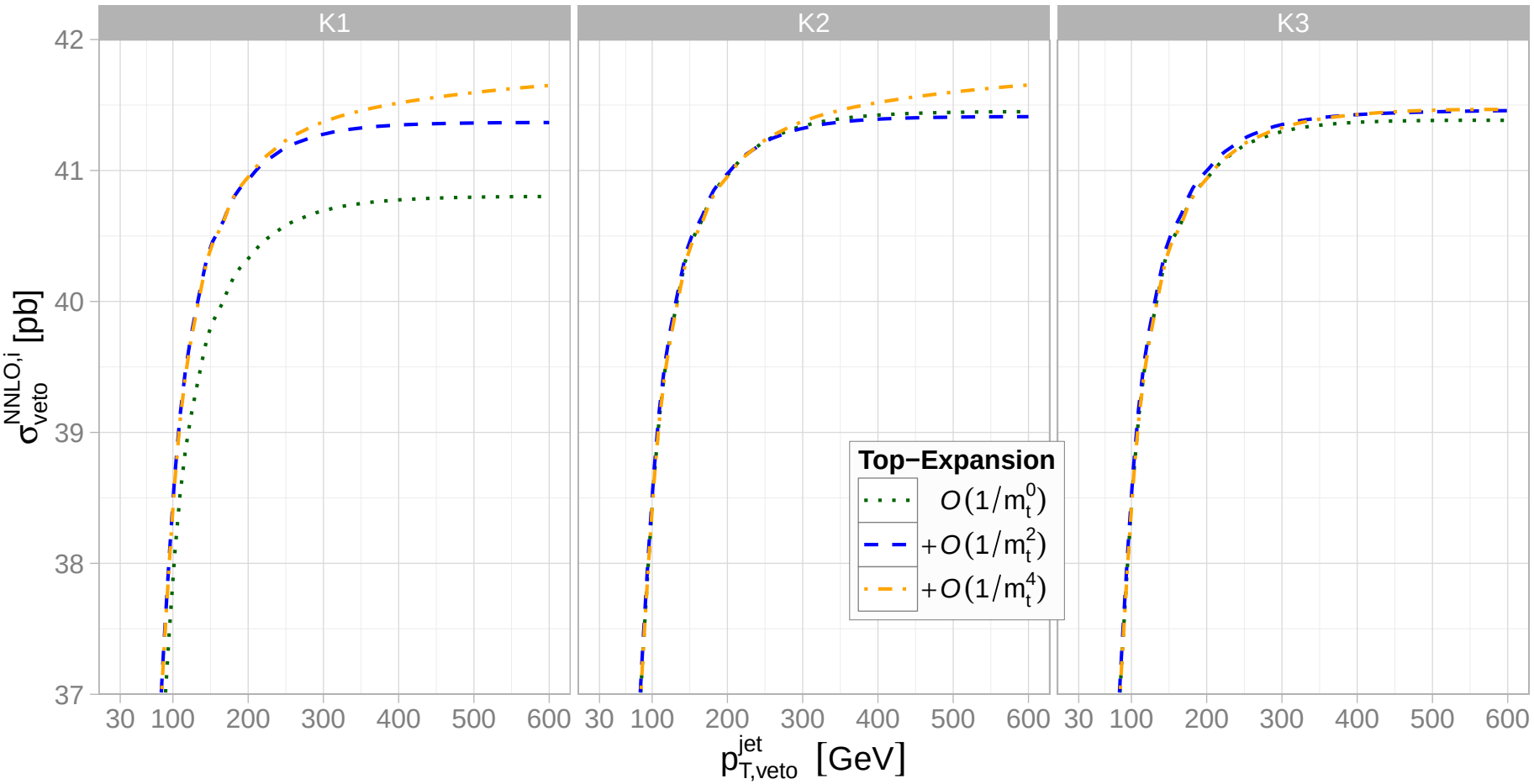
Results: Jet-veto

Other approximations:

[Neumann, MW '14]

$$\sigma^{\text{veto}} = \sigma^{\text{veto}}_{\text{NLO}} + \kappa_i \cdot \left([\sigma^{\text{veto}}_{\text{NNLO}}]_{1/m^k_{\text{top}}} - [\sigma^{\text{veto}}_{\text{NLO}}]_{1/m^k_{\text{top}}} \right)$$

$$\kappa_0 = 1, \ \kappa_1 = \sigma^{\text{veto}}_{\text{LO}} / [\sigma^{\text{veto}}_{\text{LO}}]_{1/m^k_{\text{top}}}, \ \kappa_2 = \sigma^{\text{veto}}_{\text{NLO}} / [\sigma^{\text{veto}}_{\text{NLO}}]_{1/m^k_{\text{top}}}$$



Results: Jet-veto

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