The automation of EW corrections in MadGraph5_aMC@NLO

Marco Zaro

Nikhef

NWO
Netherlands Organisation
for Scientific Research

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Road to precision: where are we?

- Higgs cross section at N^{3}LO in QCD (ggF and VBF)
  Anastasiou et al, arXiv:1503.06056, Dreyer, Karlberg, arXiv:1606.00840
- NNLO available for all 2→2 processes, general subtraction techniques available
  see e.g Del Duca et al, arXiv:1501.07226, Caola et al, arXiv:1702.01352
- Bottleneck to go to higher multiplicities is the lack of 2-loop amplitudes
  5g amplitude available, all helicities, leading col, Badger et al, arXiv:1712.02229, Abrey et al, arXiv:1712.03946, Chawdhry et al, arXiv:1805.09182
- NLO automated since a couple of years ago
- Since $\alpha \simeq \alpha_s^2$, NLO EW corrections cannot be neglected and have to be included.
- EW corrections are enhanced in certain kinematics regimes (e.g. by Sudakov logarithms at large scales) or for very exclusive observables. Automation in a very advanced stage
  see e.g.: Kallweit et al, arXiv:1412.5157 (Sherpa+OpenLoops), Biedermann et al, arXiv:1704.05783 (Sherpa+Recola+Collier), LesHouches2015+2017, arXiv:1605.04692 & 1803.07977 (Tool comparison), Frederix, Frixione, Hirschi, Pagani, Shao, MZ, arXiv:1804.10017 (MadGraph5_aMC@NLO)

Steps towards the automation of EW corrections

- IR subtraction: techniques established for QCD corrections can be extended to EW ones.
  - Replace color factors with charges ($C_F \to q_i^2$, $C_A \to 0$, $T_F \to N_{C,i}\, q_i^2$)
  - Replace color-linked Borns with charge-linked ones
- Loop amplitudes: one-loop techniques can be exploited for EW loops.
  - UV/R_2 counterterms for the EW interactions are needed
  - Higher ranks appear, integrand-reduction may lead to unstable results Switch to other techniques (Tensor-integral reduction, Laurent-series expansion,…)
    TIR: Passarino, Veltman, Nucl. Phys. B160 (1979), Davydychev, Phys. Lett. B263 (1991), Denner, Dittmaier, hep-ph/0509141
    Laurent Exp.: Mastrolia et al, arXiv:1203.0291,1312.6678
  - Use scalar-integral libraries that support complex masses
    OneLoop: van Hameren, arXiv:1007.4716
    QCDLoop: Carrazza et al, arXiv:1605.03181

Automation in MadGraph5_aMC@NLO

Frixione, Frederix, Hirschi, Pagani, Shao, MZ, 1804.10017

- The FKS subtraction has been extended to handle mixed QCD/EW corrections
- The NLO-capable model features all R_2/UV counterterms. The complex-mass scheme can be activated.
- Models exist both in the $\alpha(M_Z)$ and G_μ scheme
- Collier and Ninja have been linked to MadLoop
  Collier: Denner et al, arXiv:1604.06792 Ninja: Peraro, arXiv:1403.1229, +Hirschi, arXiv:1604.01363
- Formulas have been worked out to include FFs in the FKS subtraction. Still to be implemented → processes with *tagged* photons in the final state cannot be generated
- The code has been extensively tested against results in literature
- The process generation can be done exactly as for the QCD case:

```
> import model loop_qed_qcd_sm_Gmu
> set complex_mass_scheme True
> generate p p > e+ e- mu+ mu- [QED] # or [QED QCD]
> output pp_4lep
> launch NLO
```

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- The FKS su … /EW correction…
- The NLO-… complex-mass scheme ca…
- Models ex…
- Collier and…
  Collier: Denner… 01363
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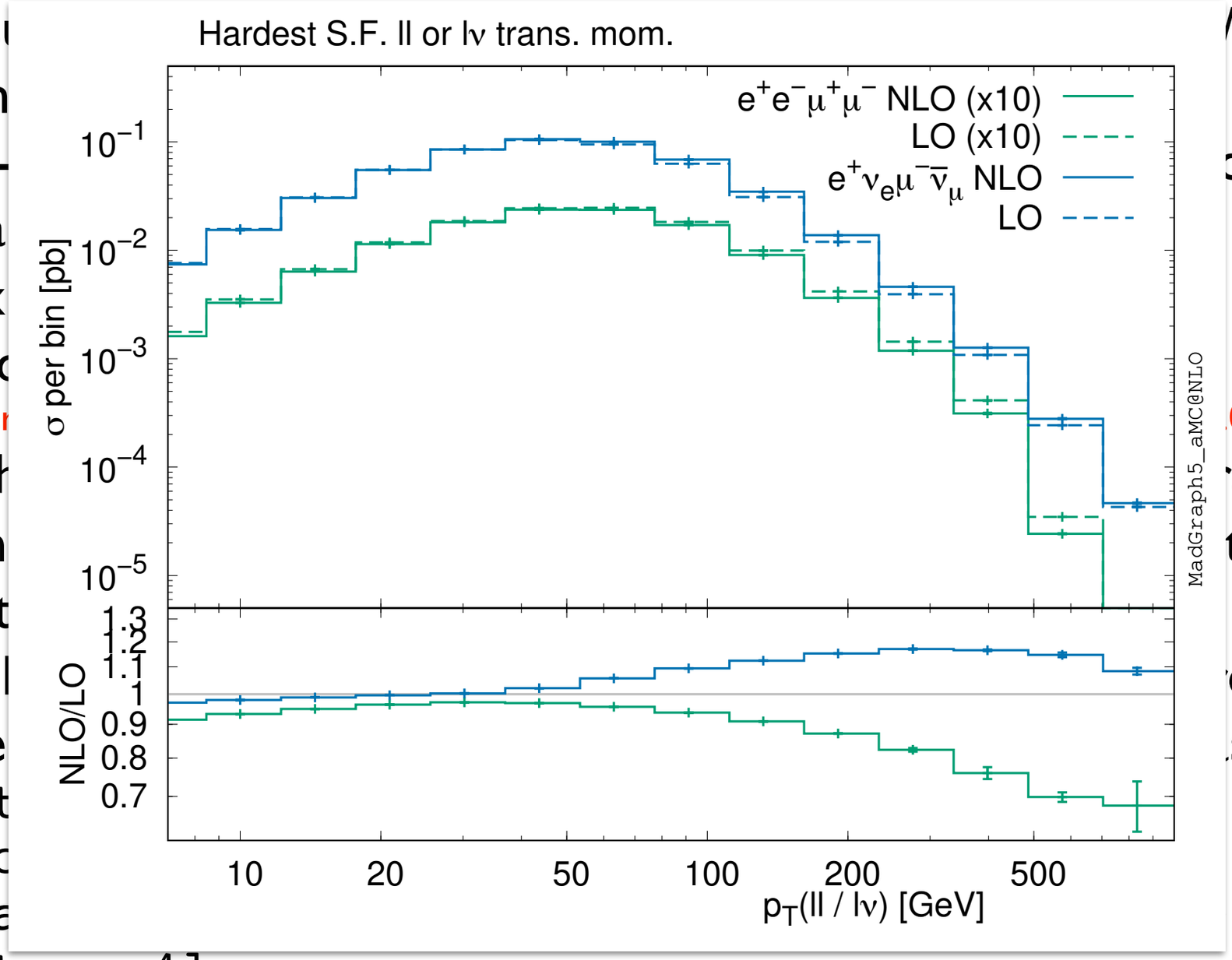
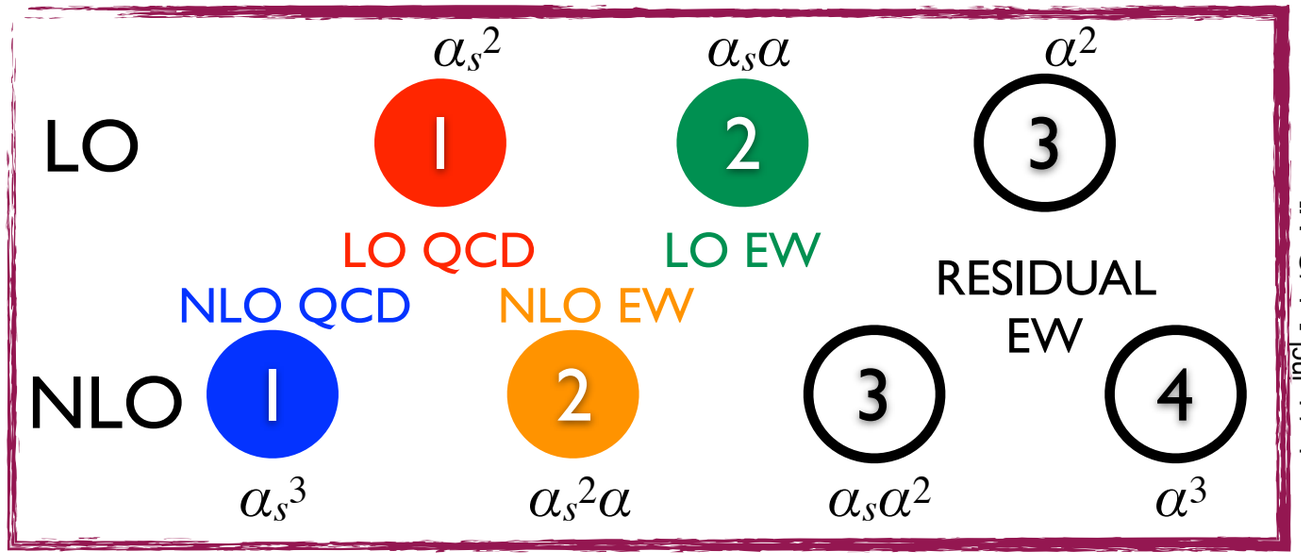
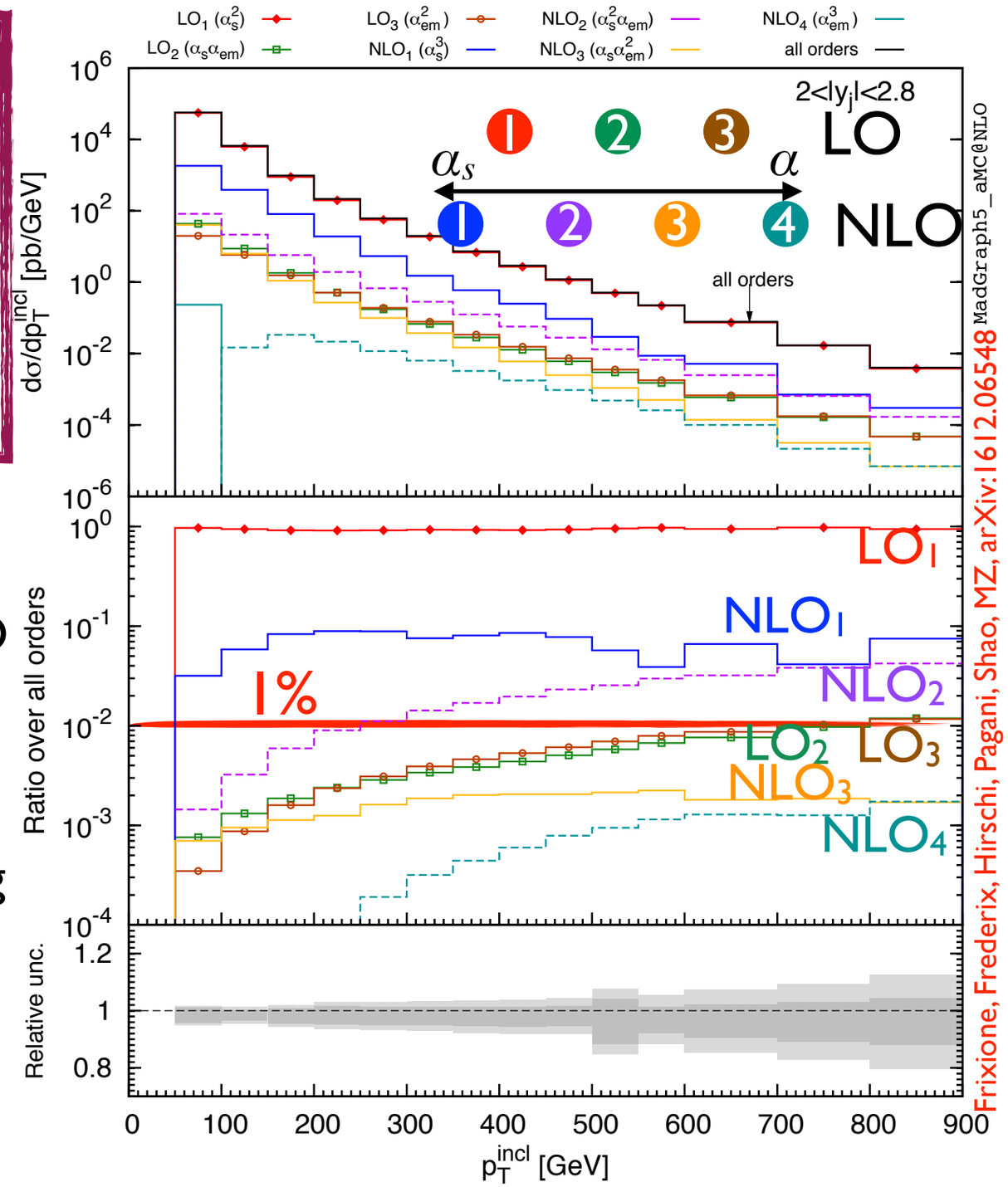


Beyond EW-corrections: complete-NLO accuracy

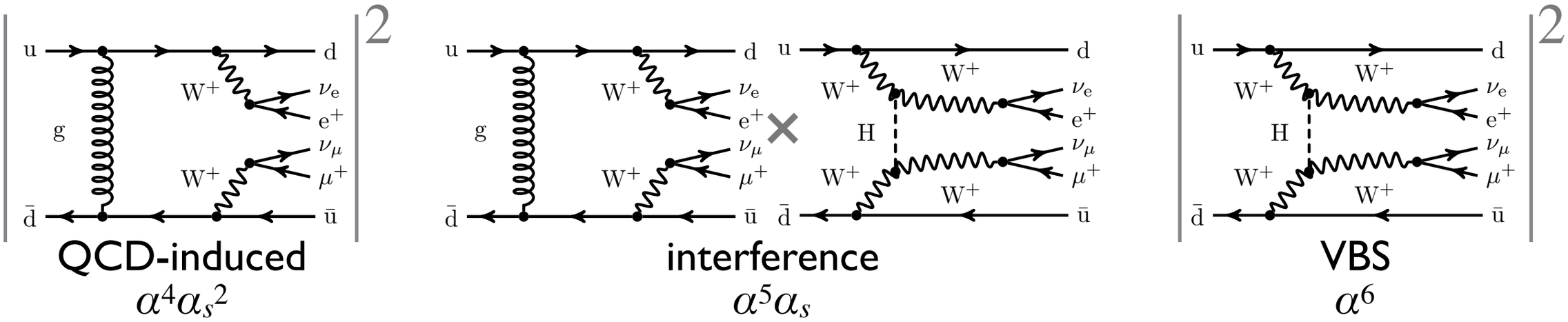




- In general a process proceeds through different coupling combinations at LO.
- Such a structure induces a similar one at NLO
- Usually the contribution with the largest power of s is considered as 'LO' and contributions with larger powers of are expected to be subheading by power counting
- This is the case e.g. for di-jet, or top pair production
- But…

A particular case: W^+W^+ production

- W^+W^+jj has three coupling combinations at LO, four at NLO:



- The vector-boson scattering (VBS) contribution is typically considered the signal, while the QCD-induced is a background
- At LO, even before applying cuts to enhance VBS, the size of VBS and of the QCD background is comparable Kulesza, Stirling, hep-ph/9912232
  The coupling hierarchy is not respected at LO

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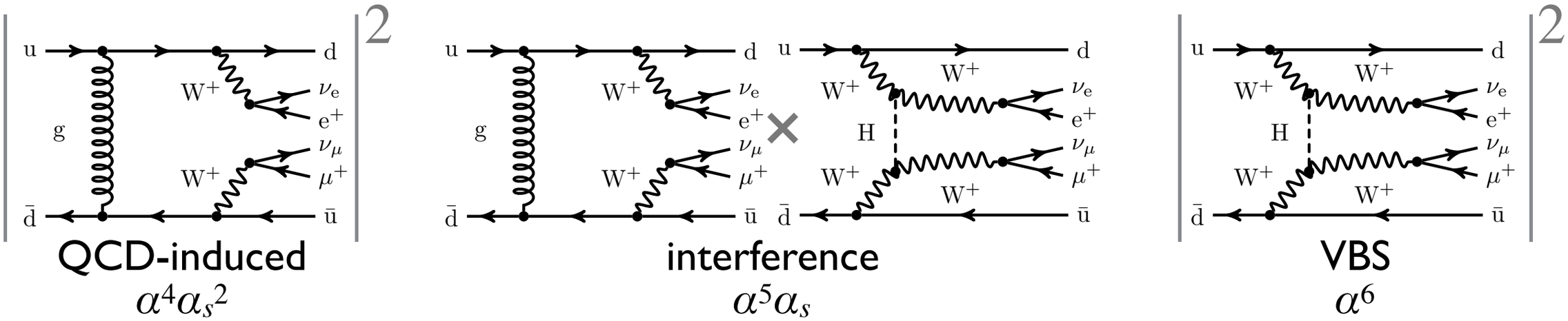

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What happens at NLO?

Complete NLO corrections to W^+W^+ scattering

Biedermann, Denner, Pellen, arXiv:1708.00268

- The complete-NLO corrections for this 2→6 process have been computed with Recola+Collier, including all contributions (non/single/double-resonant diagrams, s/t/u-channel diagrams, …) and employing the complex-mass scheme

Recola: Actis et al, arXiv:1211.6316 &1605.01090
Collier: Denner et al, arXiv:1407.0087 &1604.6792

- When VBS cuts are imposed, the coupling hierarchy is flipped!

VBS cuts

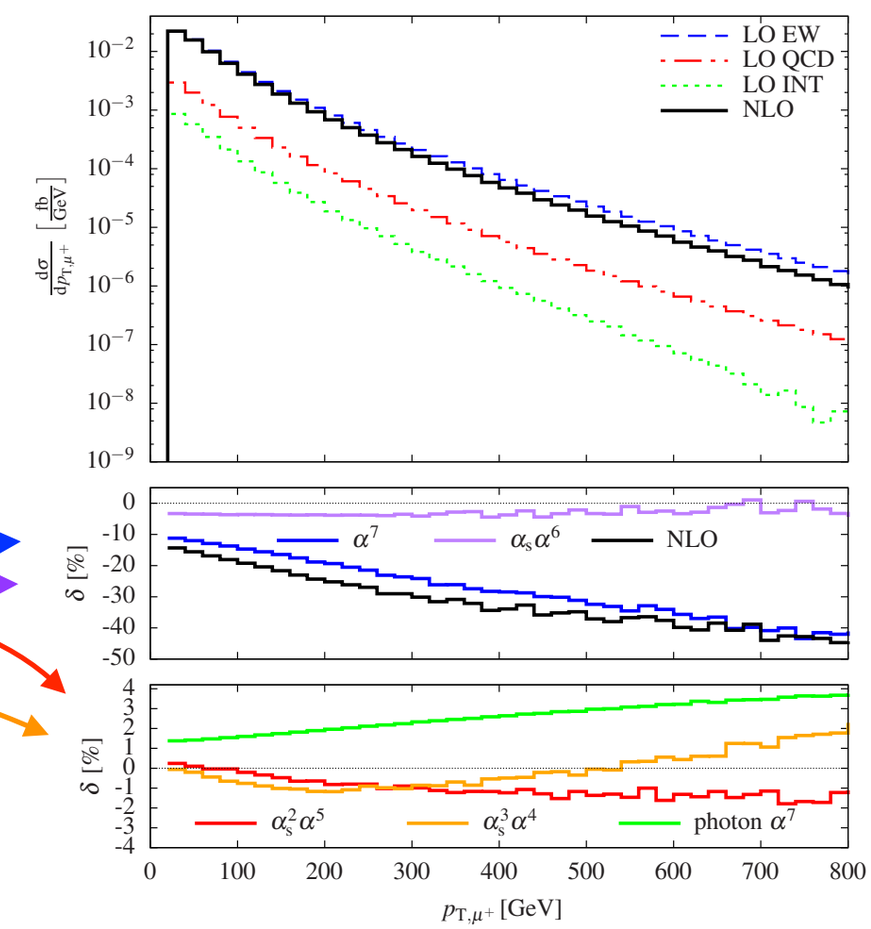
$$p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}, \qquad |y_\ell| < 2.5, \qquad \Delta R_{\ell\ell} > 0.3.$$
$$E_{\mathrm{T,miss}} = p_{\mathrm{T,miss}} > 40\,\mathrm{GeV}$$
$$p_{\mathrm{T,j}} > 30\,\mathrm{GeV}, \qquad |y_\mathrm{j}| < 4.5, \qquad \Delta R_{\mathrm{j}\ell} > 0.3,$$
$$m_{\mathrm{jj}} > 500\,\mathrm{GeV}, \qquad |\Delta y_{\mathrm{jj}}| > 2.5.$$

VBS (86%) Int. (3%) QCD (11%)

Order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$	Sum
σ_{LO} [fb]	1.4178(2)	0.04815(2)	0.17229(5)	1.6383(2)

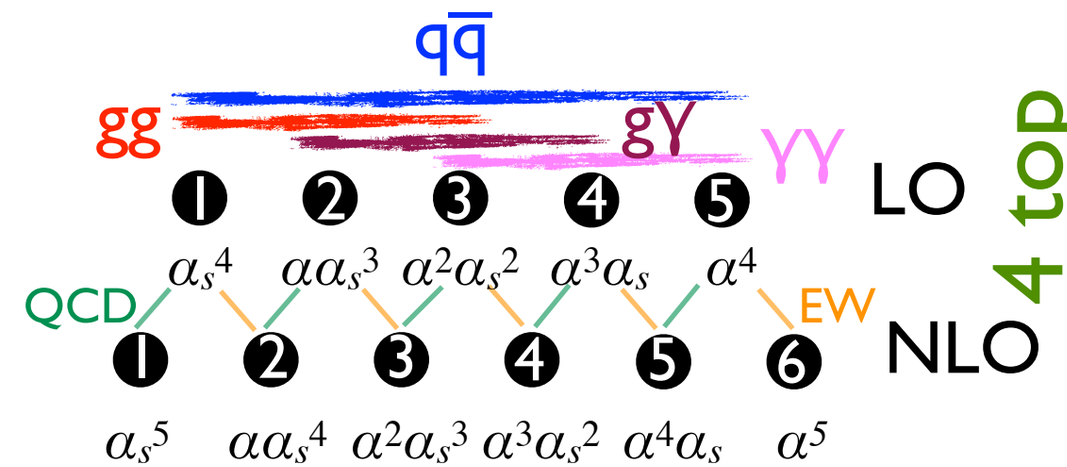
Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$
$\delta\sigma_{\mathrm{NLO}}$ [fb]	−0.2169(3)	−0.0568(5)	−0.00032(13)	−0.0063(4)
$\delta\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$ [%]	−13.2	−3.5	0.0	−0.4

VBS, EW corr. VBS, QCD corr.



Complete-NLO corrections for 4-top (and ttW)

Frederix, Pagani, MZ, arXiv:1711.02116



13 TeV

$\delta[\%]$	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$
LO_2	-26.0	-28.3	-30.5
LO_3	32.6	39.0	45.9
LO_4	0.2	0.3	0.4
LO_5	0.02	0.03	0.05
NLO_1	14.0	62.7	103.5
NLO_2	8.6	-3.3	-15.1
NLO_3	-10.3	1.8	16.1
NLO_4	2.3	2.8	3.6
NLO_5	0.12	0.16	0.19
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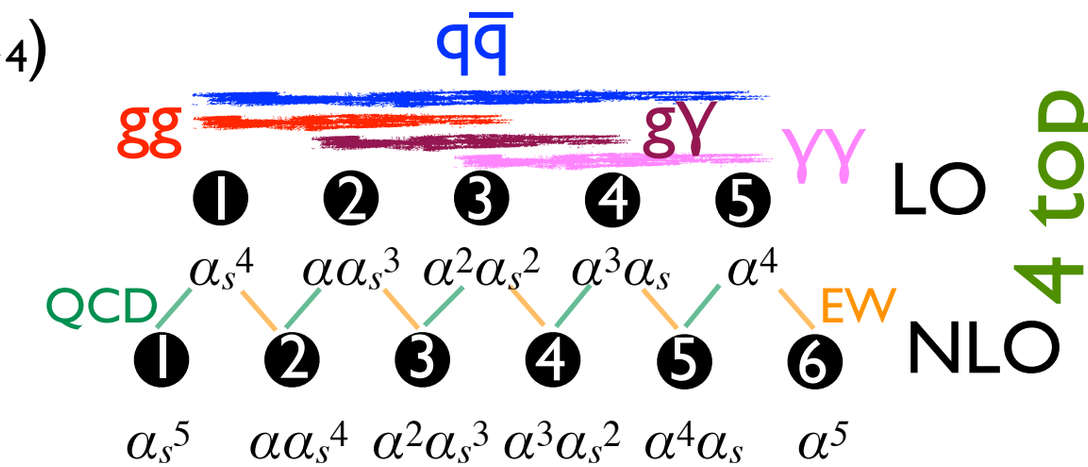

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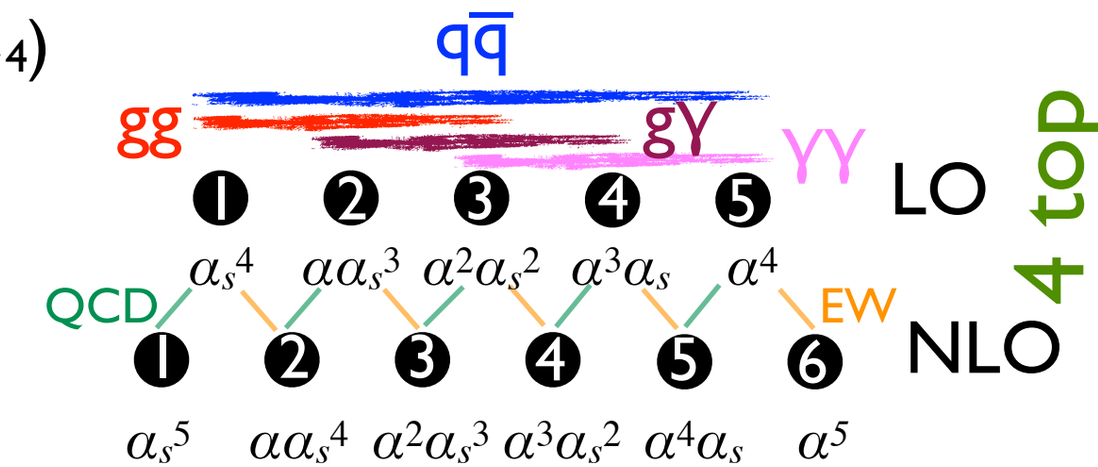

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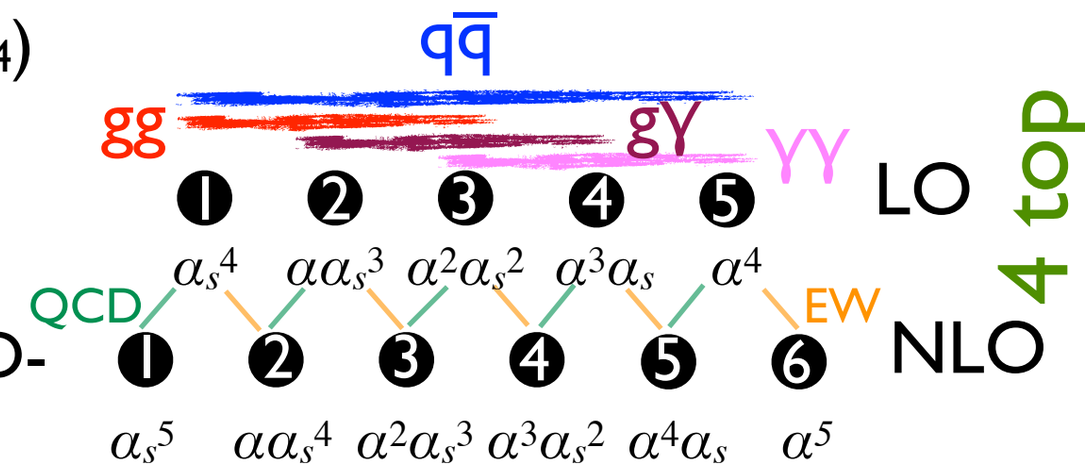

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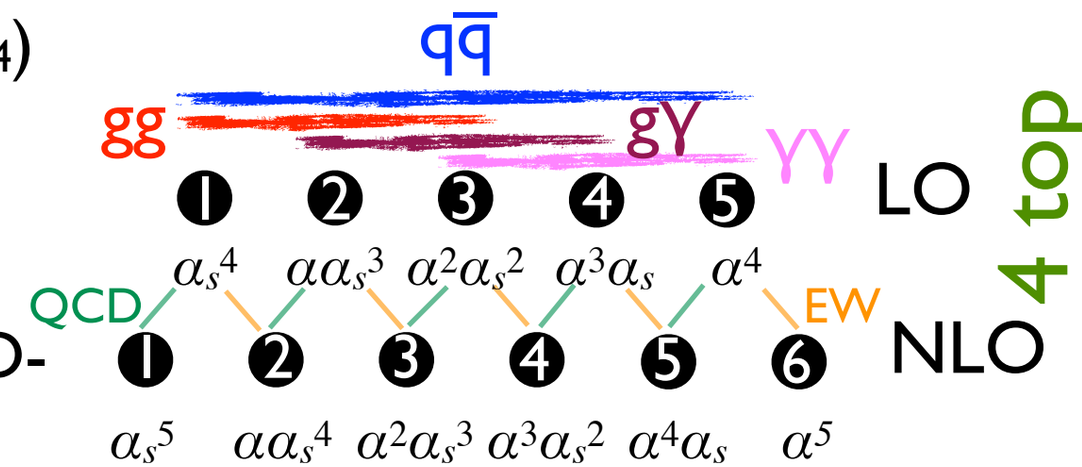

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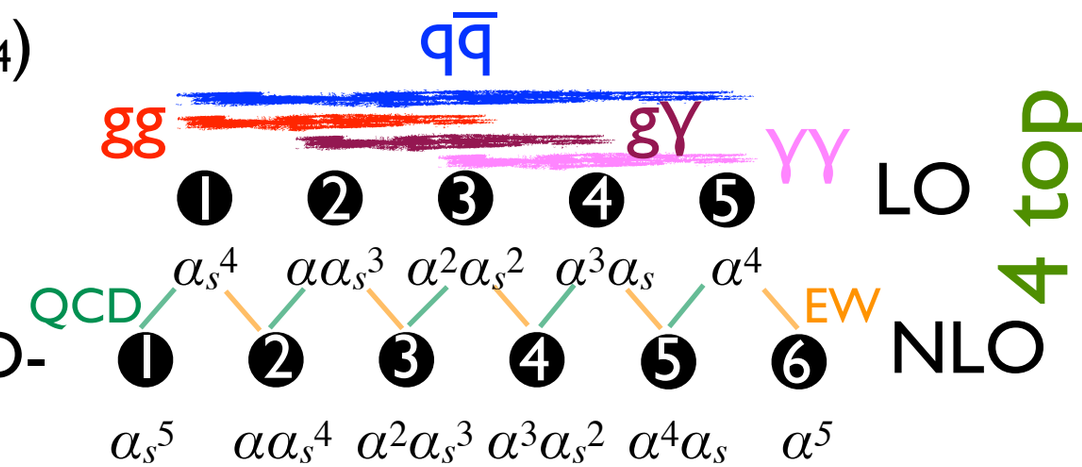
  A LO-based study may not capture the correct behaviour of the cross section



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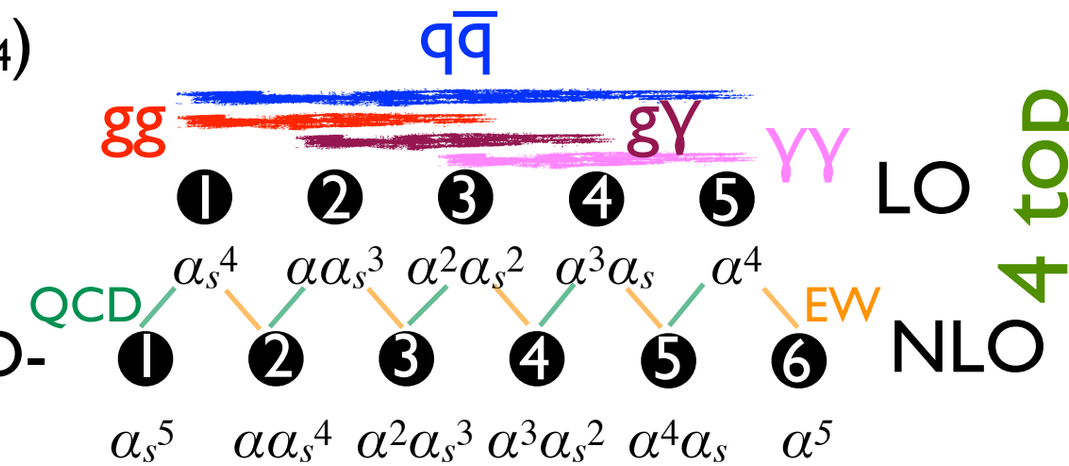
- Increasing the energy to 100 TeV reduces the relative effects both at LO and NLO



100 TeV

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LO_3	26.3	31.8	37.8
LO_4	0.05	0.07	0.09
LO_5	0.03	0.05	0.08
NLO_1	33.9	68.2	98.0
NLO_2	-0.3	-5.7	-11.6
NLO_3	-3.9	1.7	8.9
NLO_4	0.7	0.9	1.2
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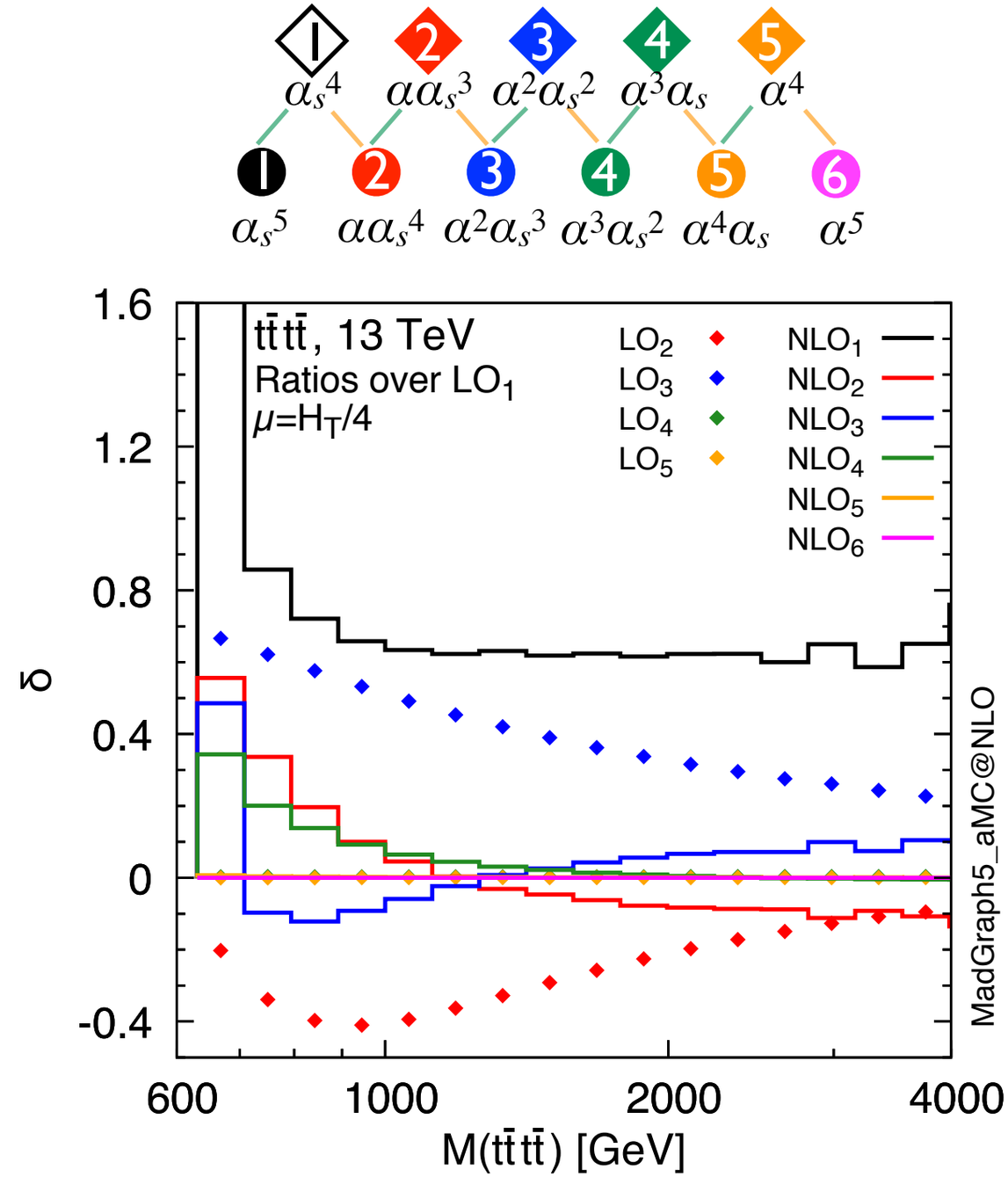
The 4-top invariant mass at the LHC



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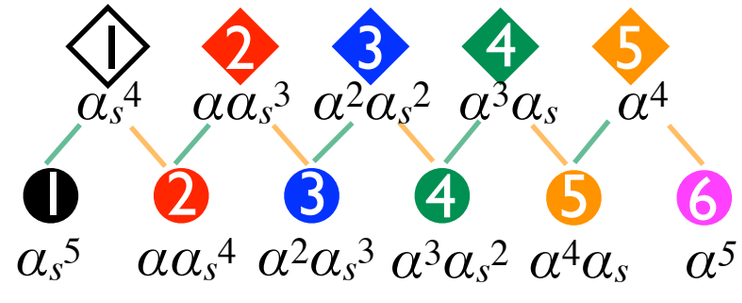

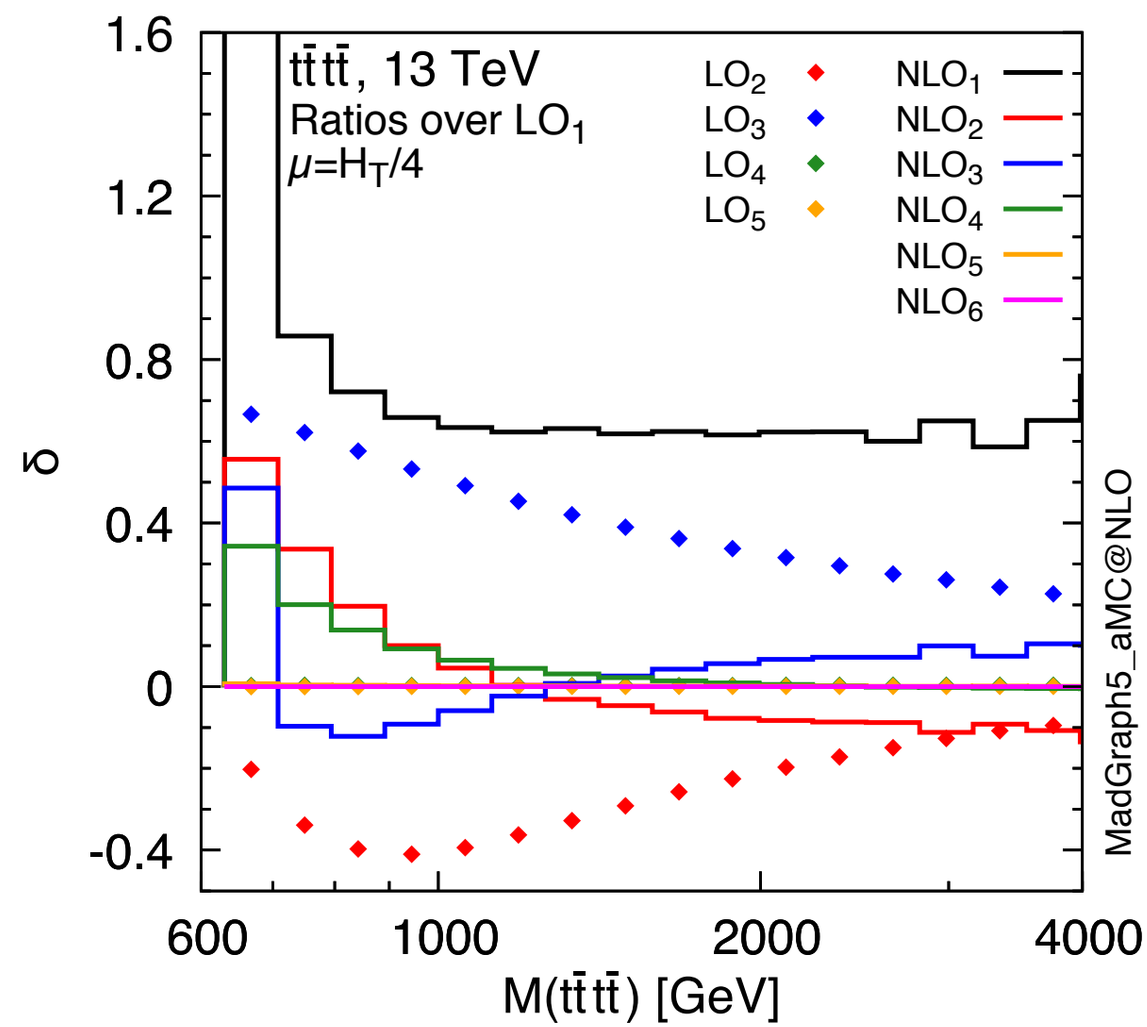

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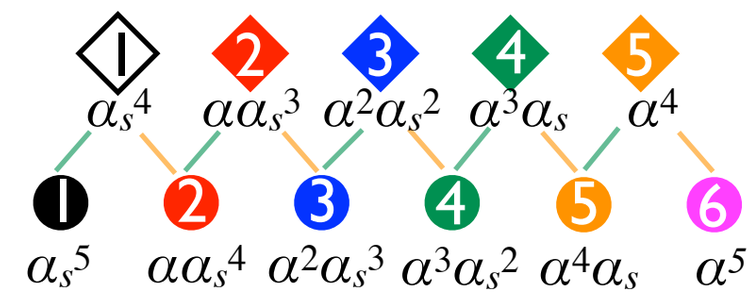

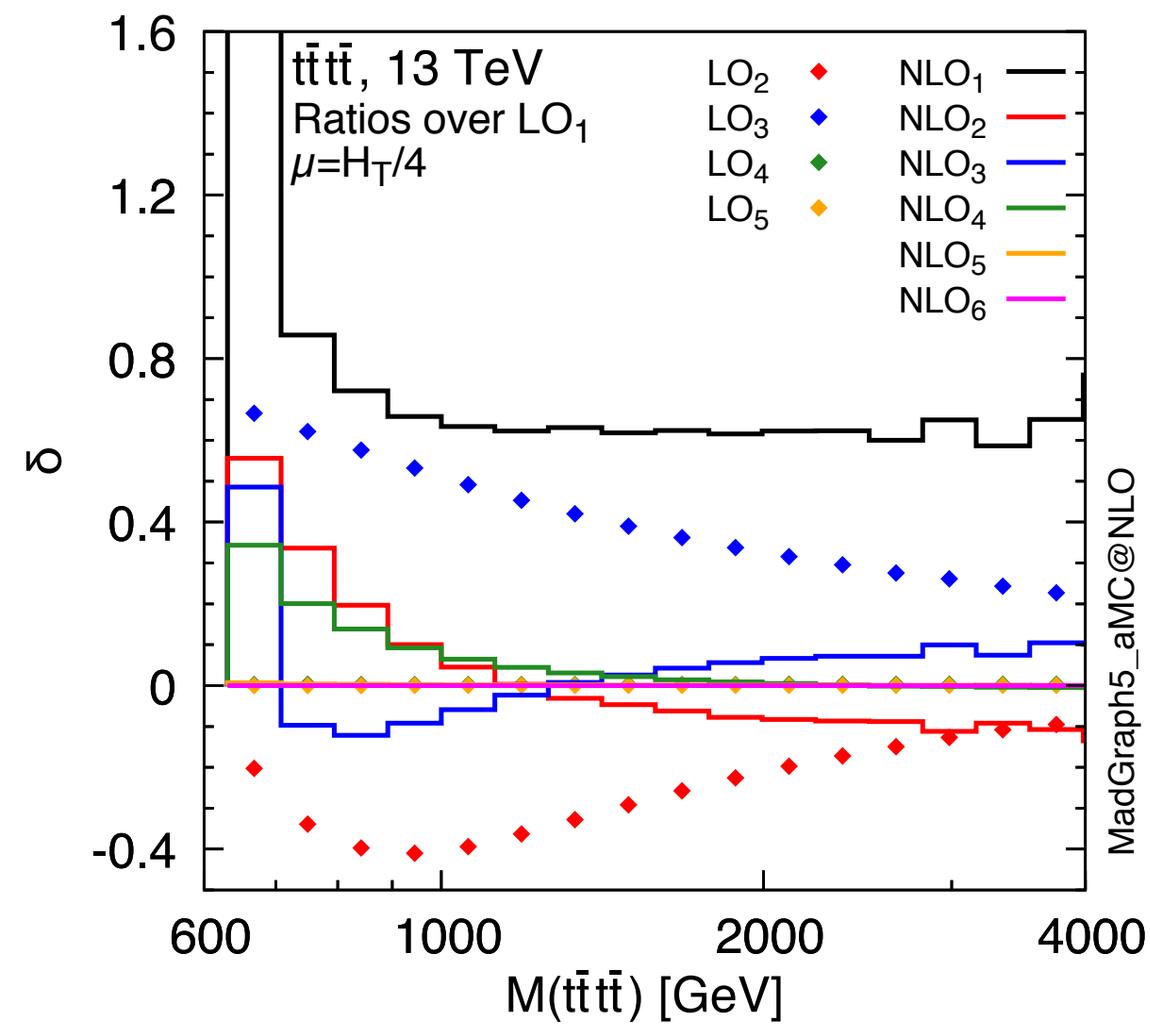

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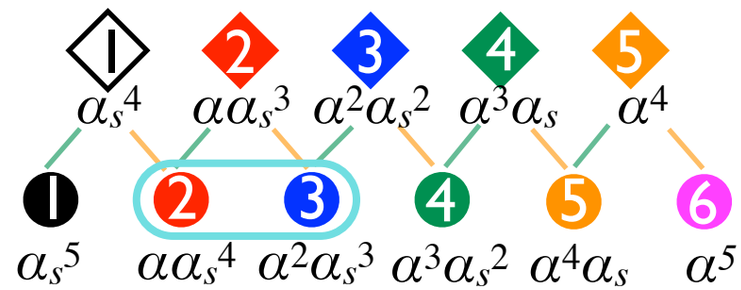

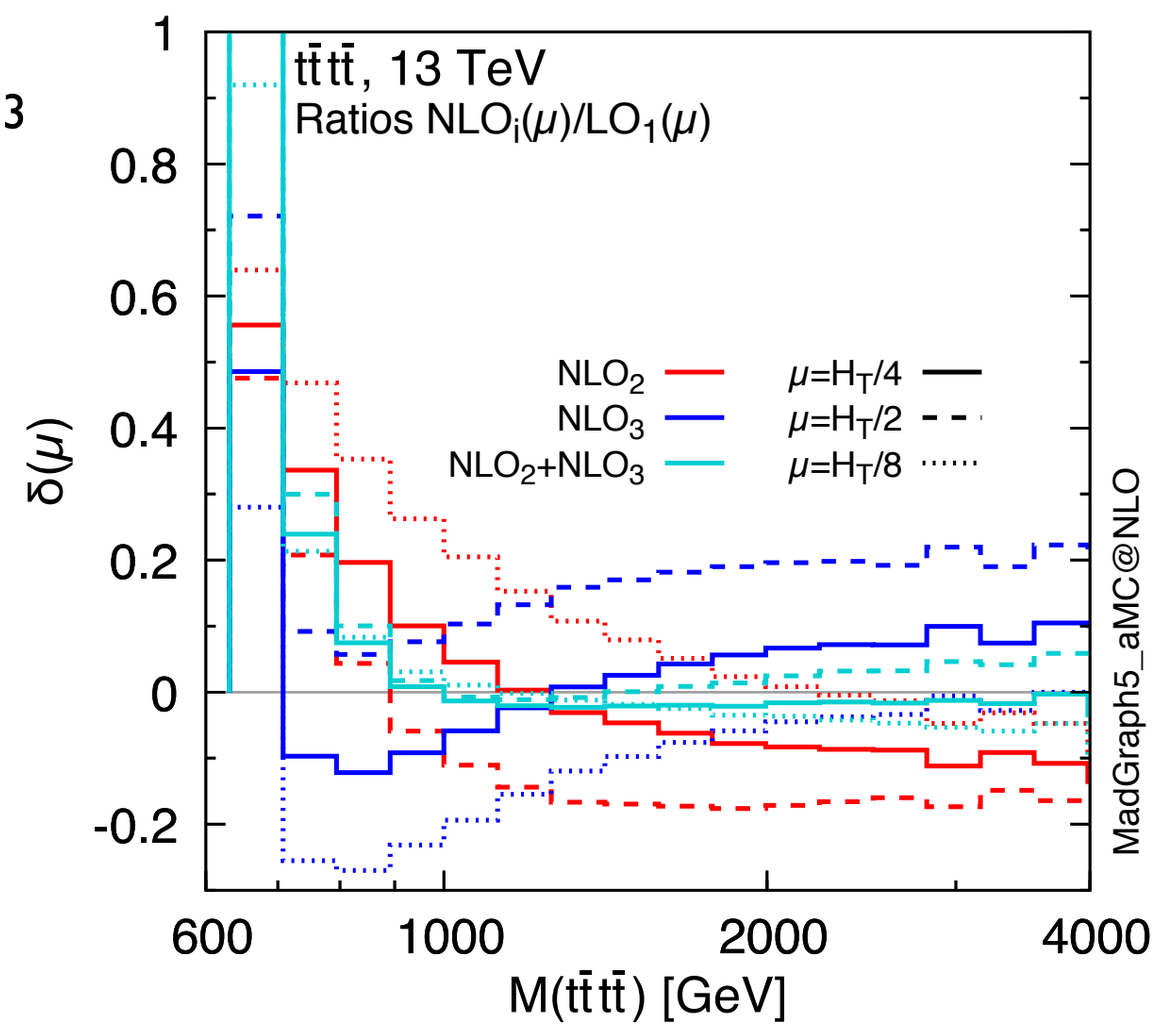

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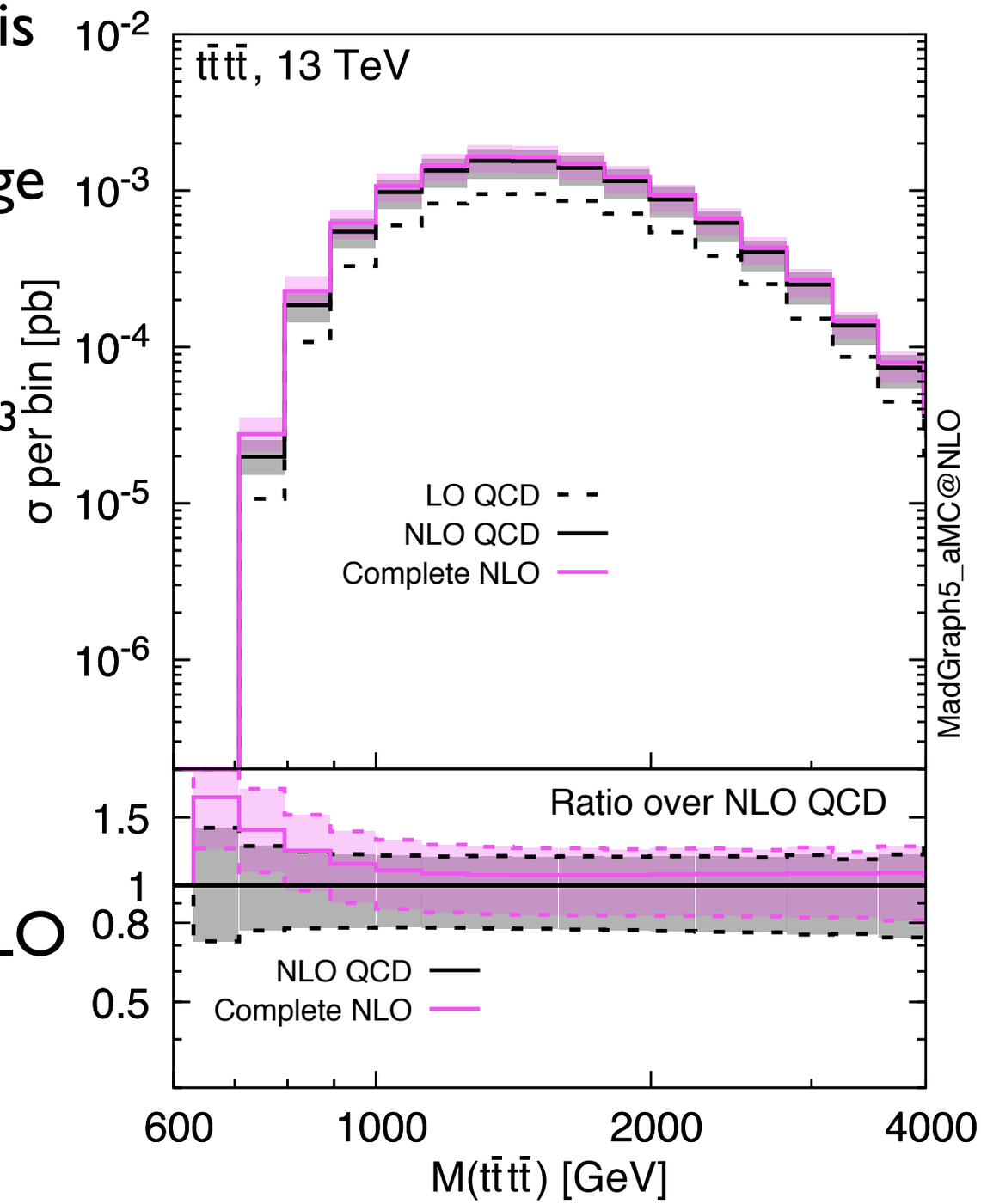
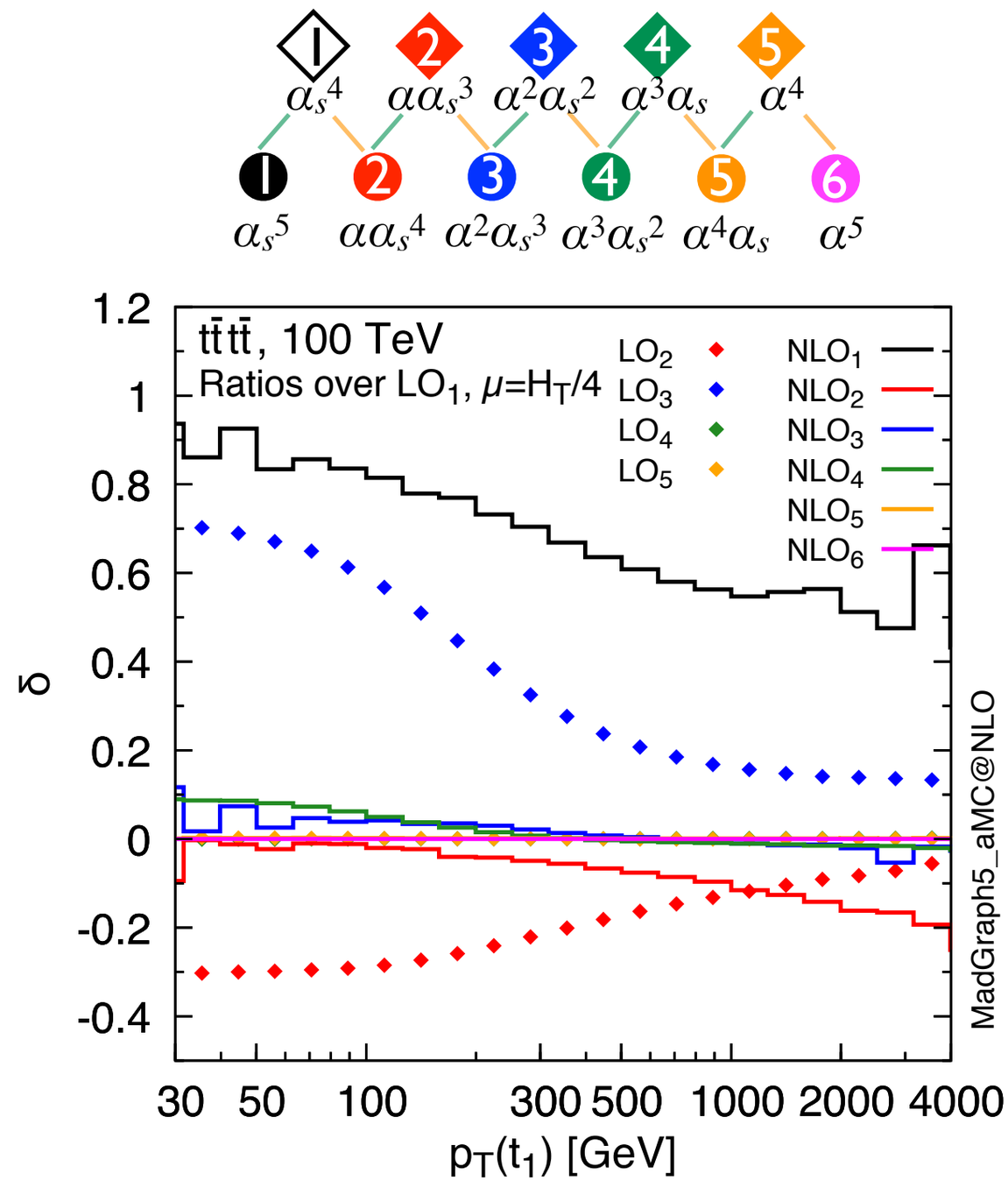
- This makes the complete-NLO correction remarkably close to the NLO QCD one, except for at threshold



The p_T of the hardest top at the FCC



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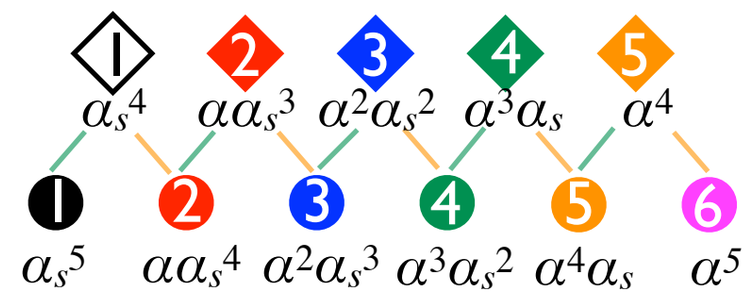
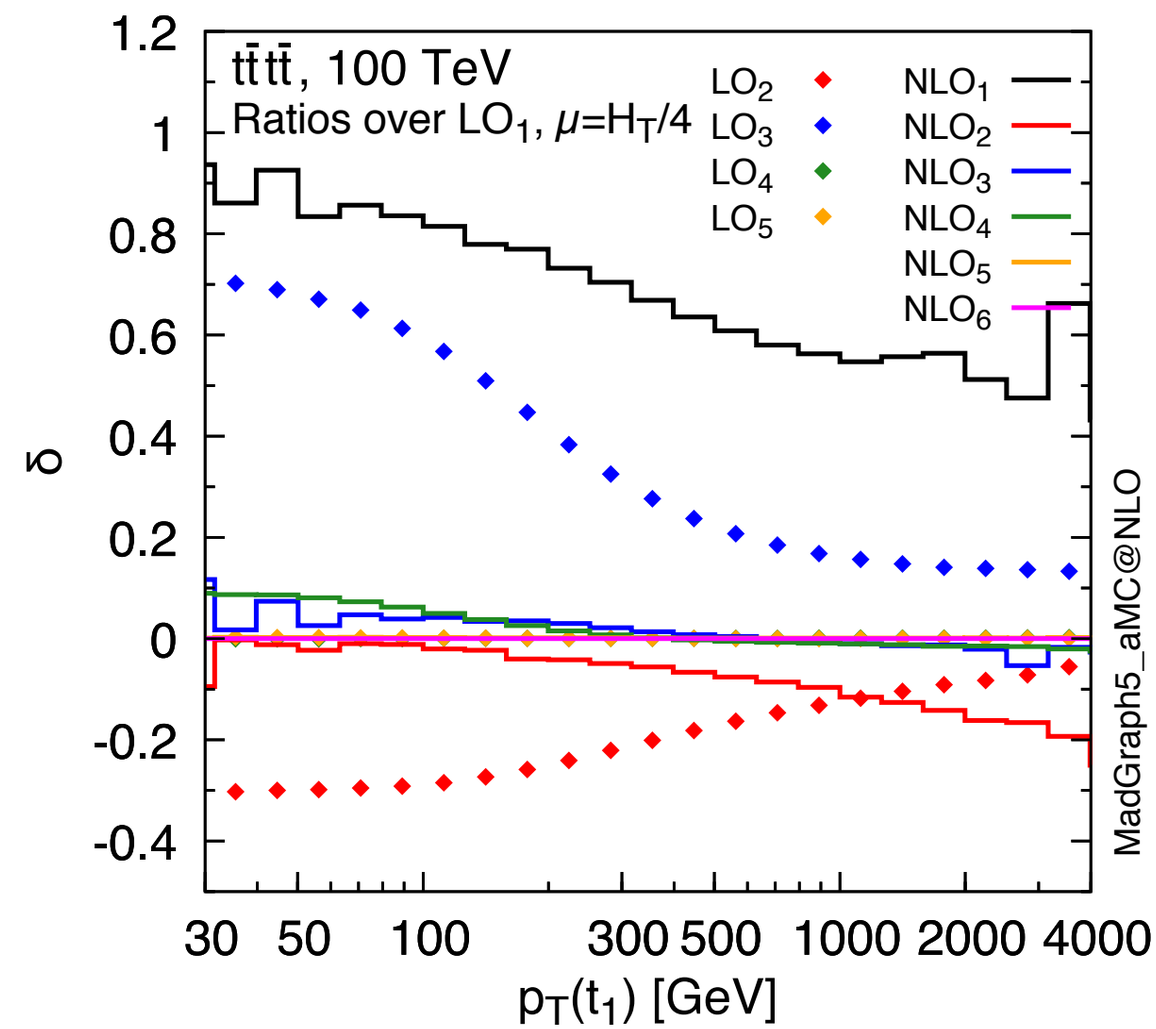
- No threshold enhancement is present for this observable
- At large p_T, NLO_2 shows the typical effect of the Sudakov logarithms of EW origin





The p_T of the hardest top at the FCC

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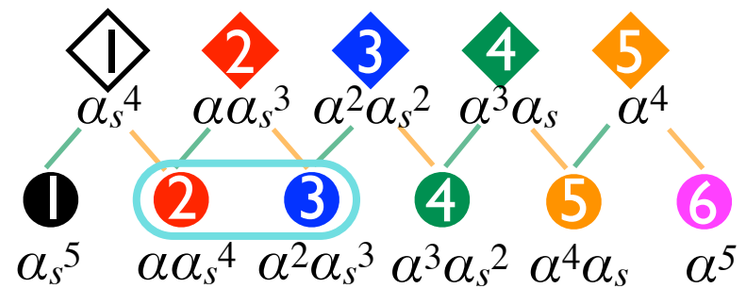

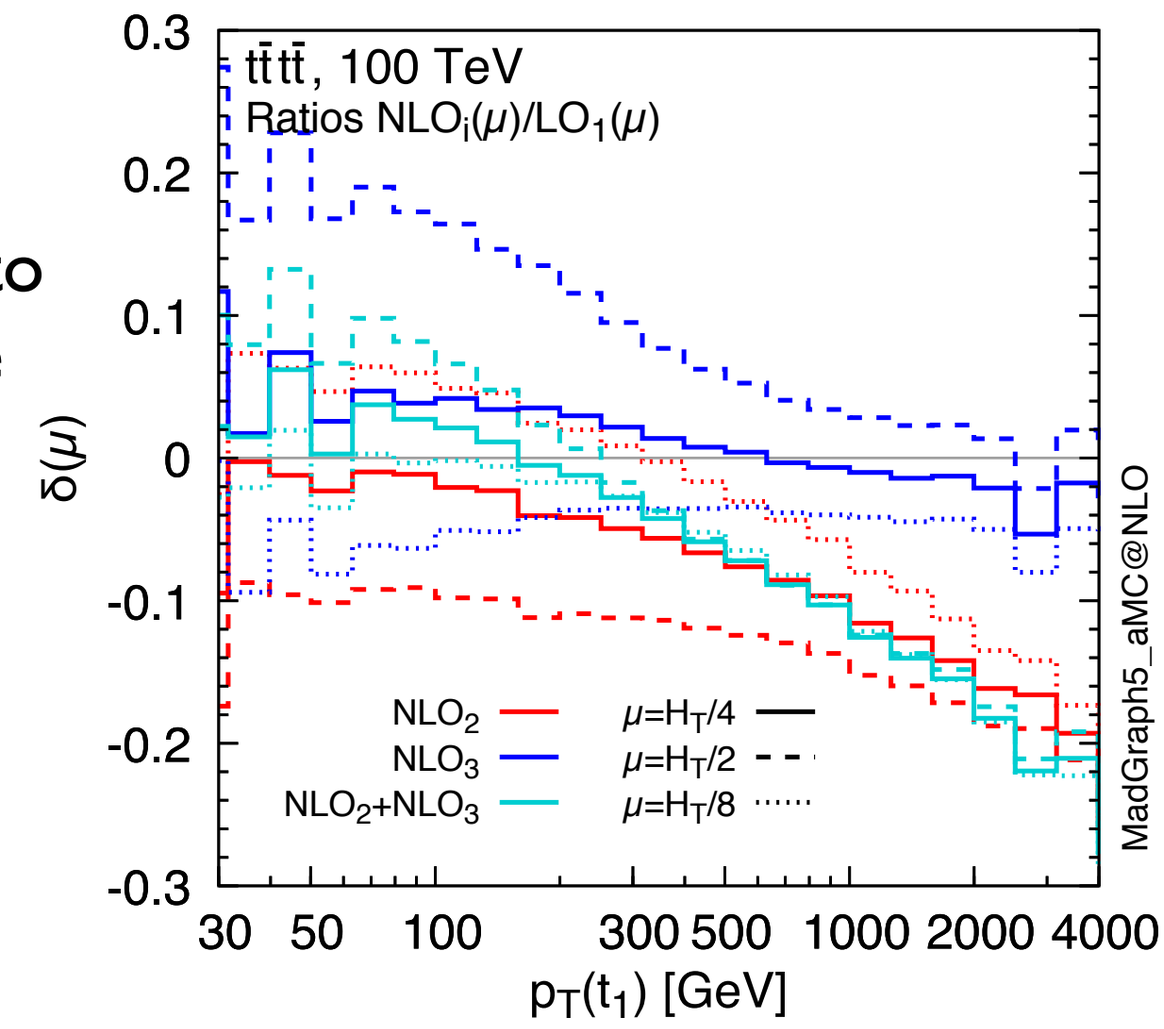

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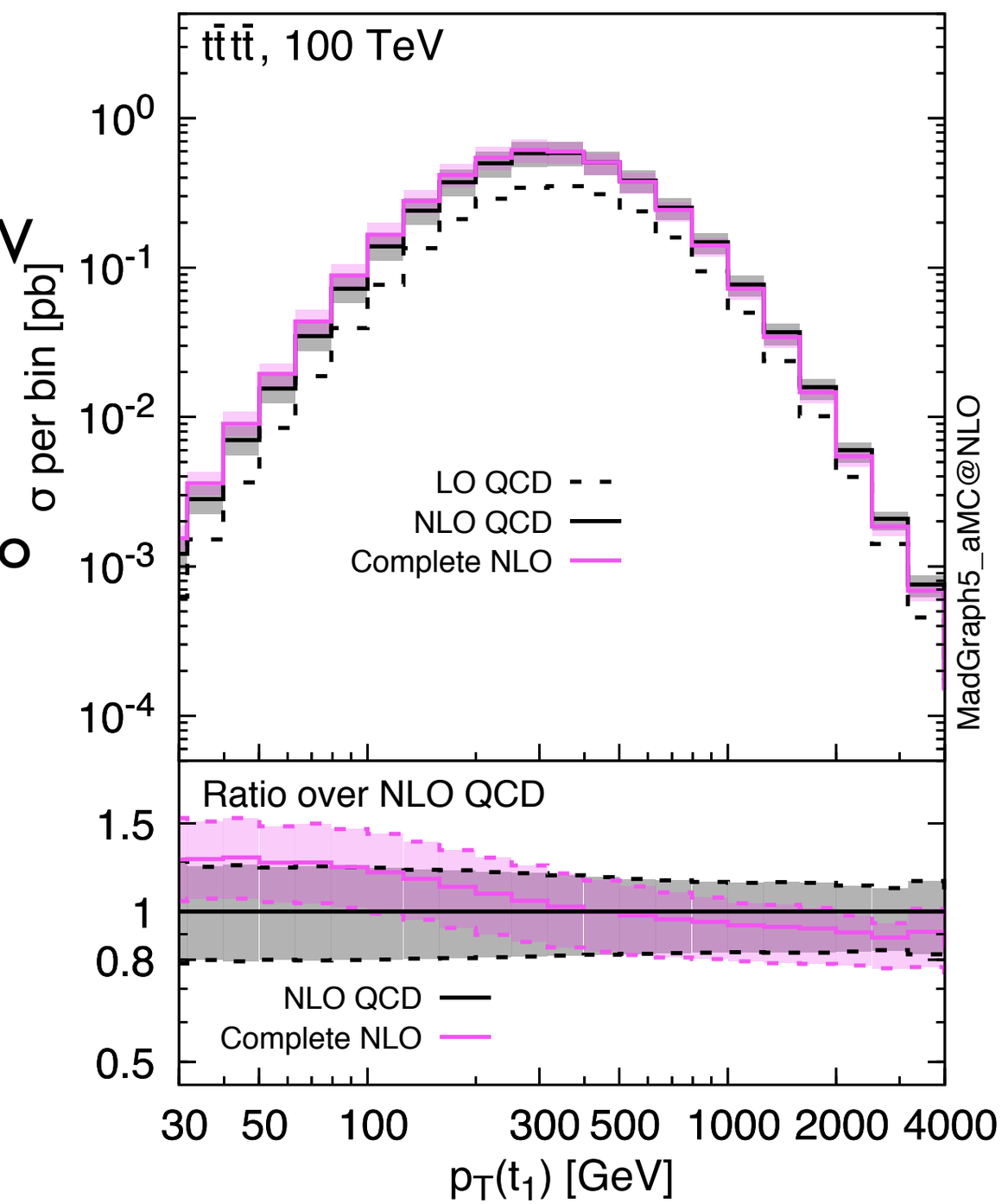


Conclusions and outlook

- Accurate predictions are becoming of utmost importance for the LHC programme
- Focusing on QCD corrections is not enough: EW effects can be large
- The automation of EW corrections has become an hot topic in the recent years
- Within `MadGraph5_aMC@NLO`, the automation has been achieved, and the code is public (as `MG5_aMC v3`)! https://launchpad.net/mg5amcnlo
- The code has some limitations (no EW corrections in processes with tagged photons), which will be lifted in the future
- A by-product of the automation is the possibility to compute the complete NLO corrections for arbitrary processes
- Despite the coupling suppression, they can be important for some processes (e.g. VBS, ttW and 4-top)
- In particular for 4-top production, subheading contributions show important cancelations which may be spoiled by BSM effects

Backup

EW renormalisation schemes in a nutshell

The renormalisation of α can be performed in different schemes:

- $\alpha(0)$: α is measured in the Thompson scattering, in the zero-momentum limit. Terms $\sim\log(Q/m_f)$ appear in the cross section, except for external photons. Fermion masses must be retained.
- $\alpha(M_Z)$: α is measured at the Z peak (e.g. at LEP). It removes the dependence on the fermion masses, which can be set to zero.
- G_μ scheme: the Fermi constant is measured from the muon lifetime, then α is extracted. W.r.t. the $\alpha(M_Z)$ scheme, also contributions of weak origin $(\Delta\rho)$ are resummed

The G_μ scheme is generally preferred for processes without final-state photons at the LO.

Final-state photons

At variance with the QCD case, when EW corrections are turned on, short-distance photons are not IR safe. They can split into a (collinear) pair of massless fermions

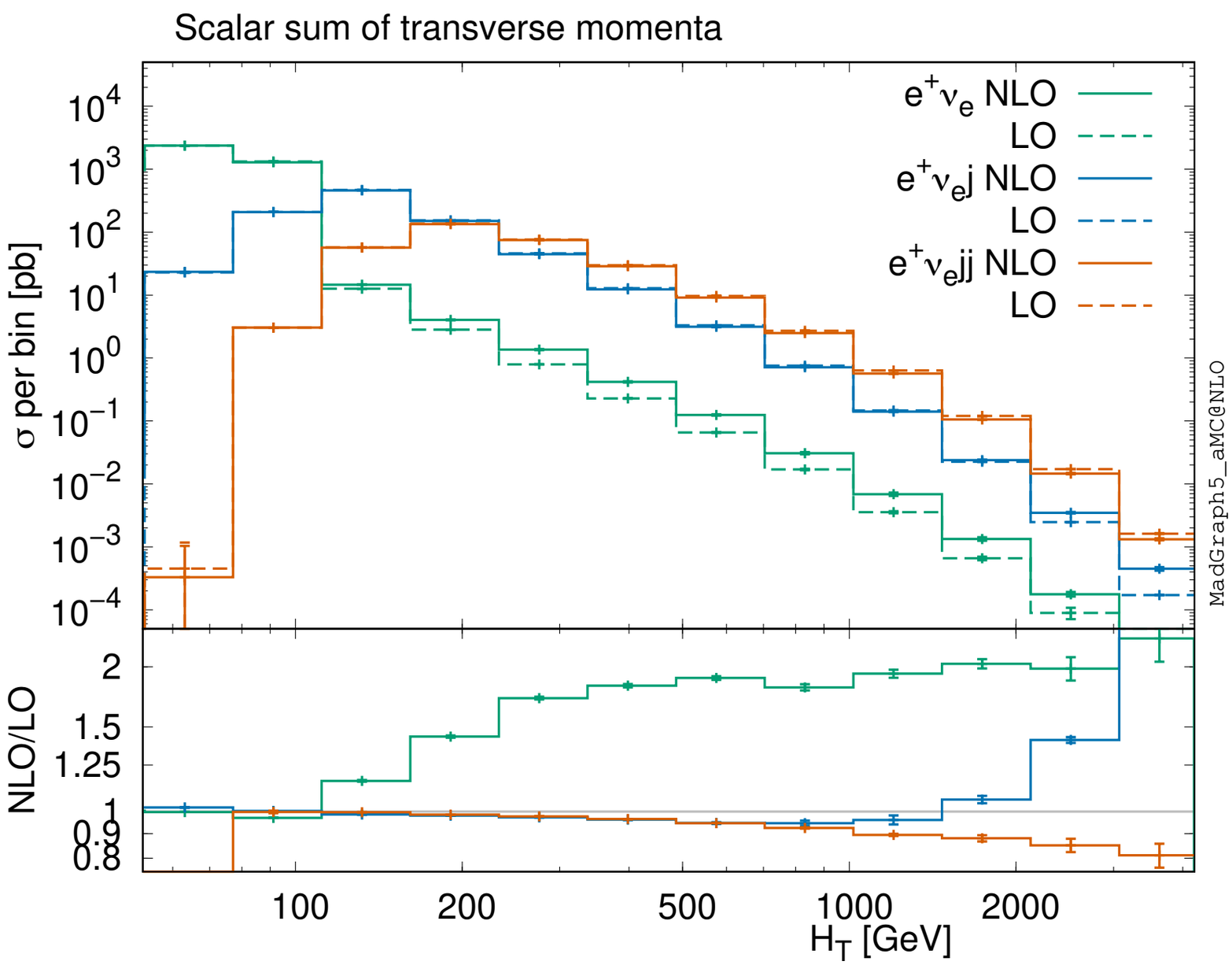
Two solutions can be adopted

- Use the $\alpha(0)$ scheme,for the vertices where photons are emitted
  see e.g. Les Houches 2013, arXiv:1405.1067, Sect.2
  - This assumes finite fermion masses, even if they are discarded elsewhere in the computation. $\gamma \to f\bar{f}$ splittings are not included
  - Not sure that this works in general, when complete-NLO corrections are considered
- Use fragmentation functions. Physical photons are those which come after fragmentation.
  - IR-subtraction scheme must be extended to include FFs
  - FFs can be used also for other particles. E.g. for leptons, where $\log(Q/m_f)$ can be resumed as for heavy quarks Mele, Nason, Nucl.Phys.B361

Other results: Setup

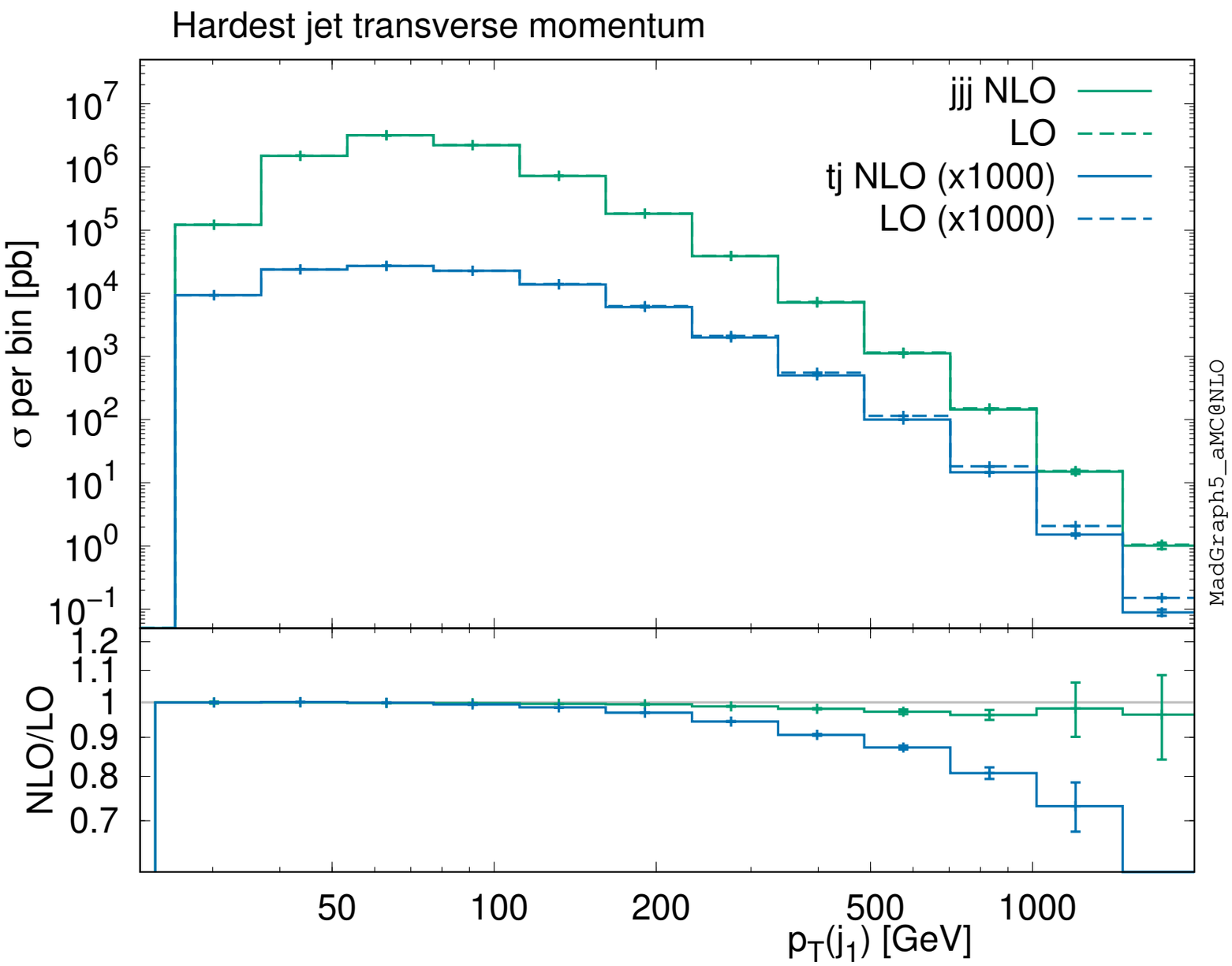
- G_μ scheme, complex-mass scheme, G_μ=1.6639 · 10^{-5} GeV^{-2}
- On-shell masses and widths:
  M_W=80.385 GeV, Γ_W=2.0897 GeV, M_Z=91.1876 GeV Γ_Z=2.4955 GeV,
  M_t=173.34 GeV, Γ_t=1.369 GeV, M_H=125 GeV, Γ_H=4.07 MeV
- `LUXqed_plus_PDF4LHC_nnlo_100` PDF set, $\mu_{r/f}=H_T/2$
- Photons and charged fermions are combined if $R_{\gamma f}<0.1$ dressed fermions
- Leptons must have $p_T(l)>10$ GeV, $|\eta(l)|<2.5$. OSSF pairs must satisfy $\Delta R_{ll}>0.4$, $M_{ll}>30$ GeV
- Quarks, gluon and non-recombined photons are clustered into anti-k_T jets, $\Delta R=0.4$, $p_T(j)>30$ GeV, $|\eta(j)|<4.5$
- Only NLO EW corrections will be shown (except for the complete-NLO results)

Results: W(→e⁺νₑ)+jets



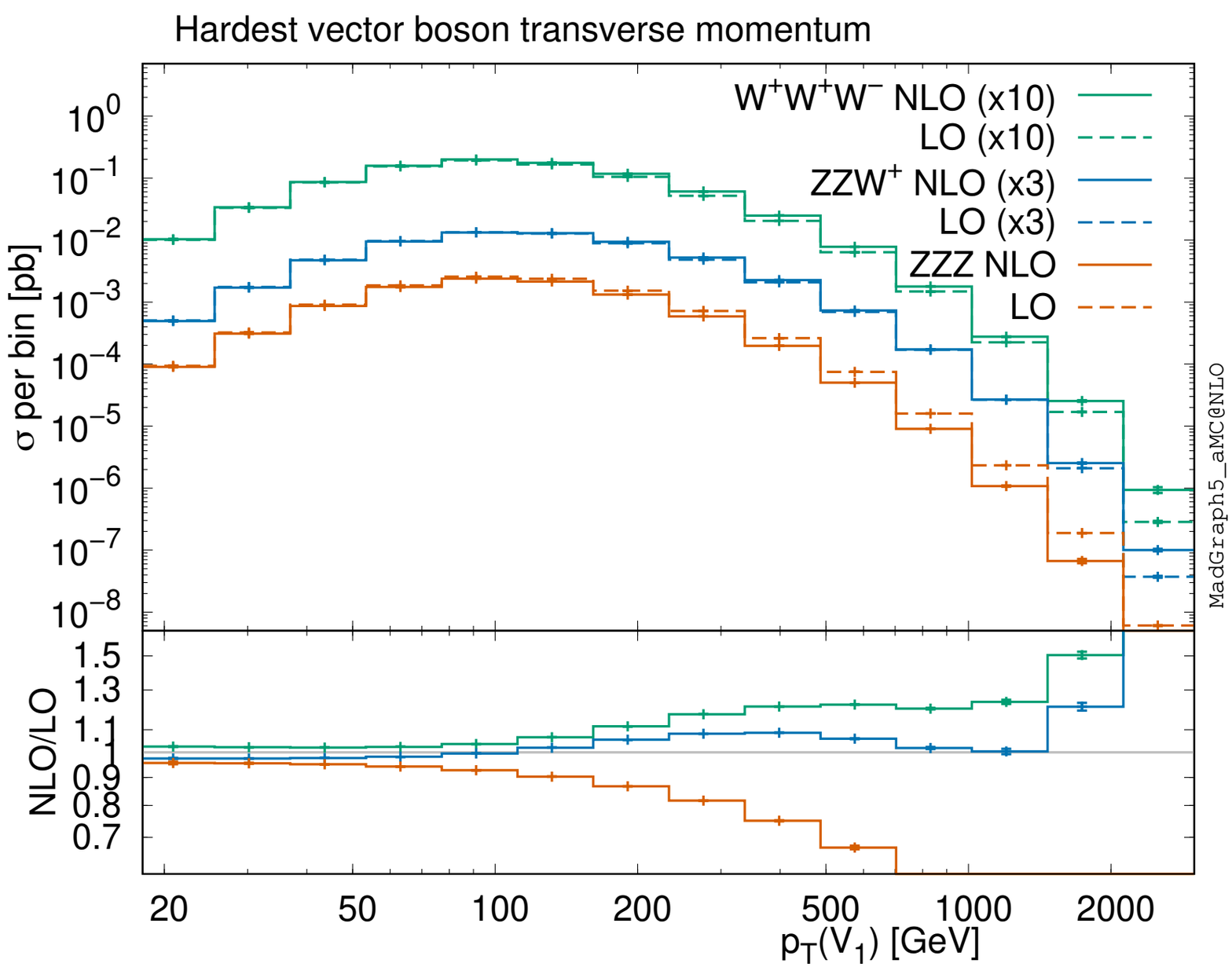
- With 0 extra jets, $H_T > M_W$ is populated only by off-shell configurations at LO; large K-factor come from real emissions
- With 1 jet, giant K-factors appear at large scale. Dominant topology is dijet+soft/collinear W
- With 2 jets EW corrections display the expected Sudakov suppression at large H_T

Results: single-top and 3-jet production



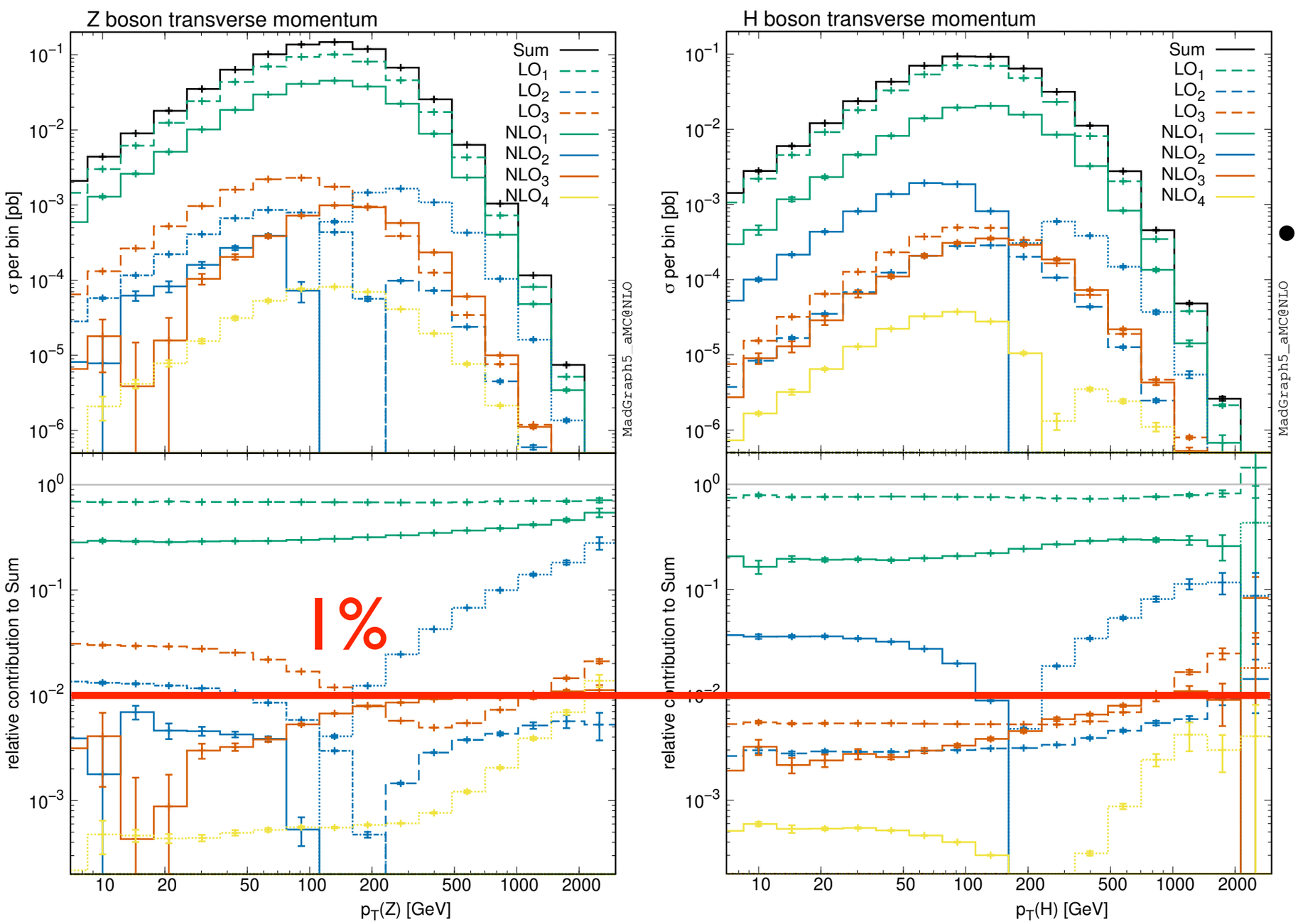
- In three-jet production, EW corrections appear to be totally negligible (also for $p_T(j_2/j_3)$)
- For single-top (both s- and t-channel), EW corrections display the typical suppression at large scales.
- EW corrections for three-jet production have never been computed in the literature

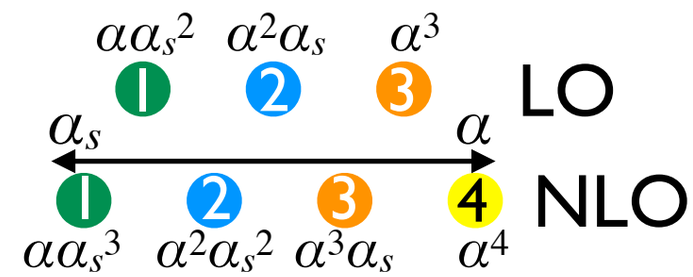
Results: triple vector-boson production



- Unlike for ZZZ, ZZW and WWW can have contributions where photons in the initial state couples directly to the vector boson.
- This makes EW corrections for ZZW and WWW positive at large p_T
- Vector bosons are treated as stable (Γ_V=0)

Results:
complete-NLO corrections to $t\bar{t}Z$ and $t\bar{t}H$

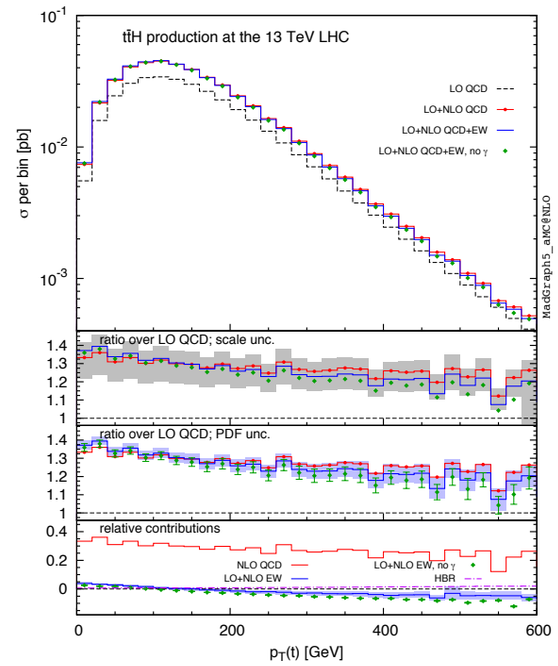


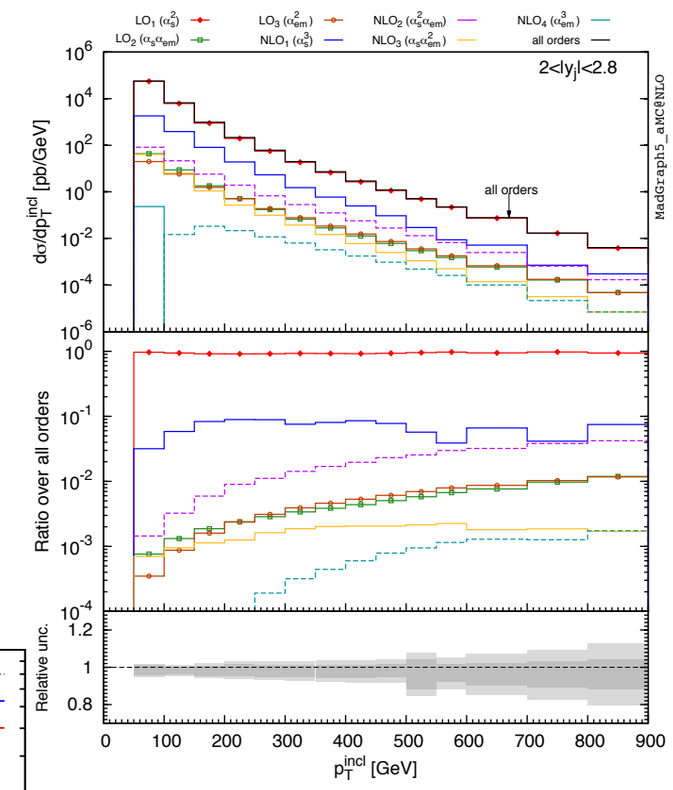


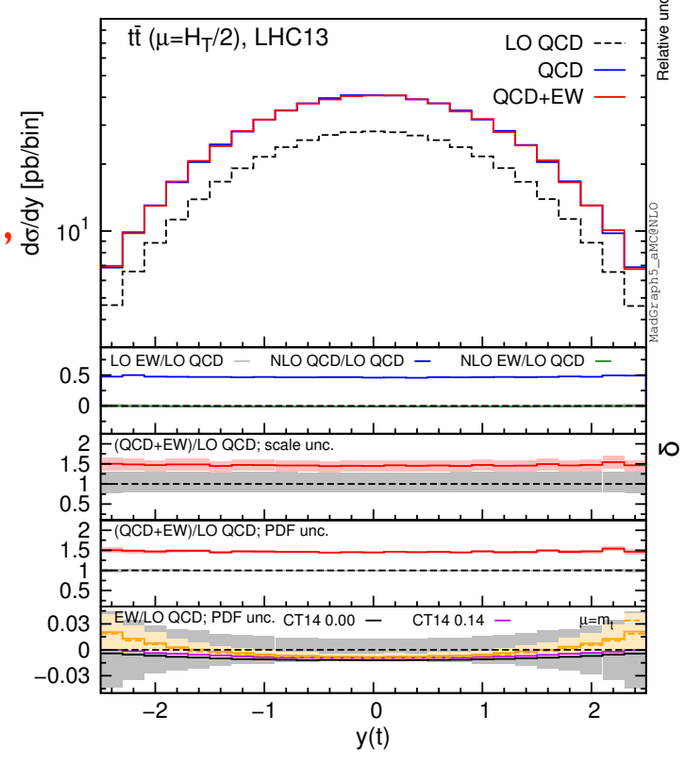
- Unlike $t\bar{t}W$ (Davide's talk), for $t\bar{t}H$ and $t\bar{t}Z$ subleading contributions are well suppressed, mostly because the gg-initial state is already accessible at LO

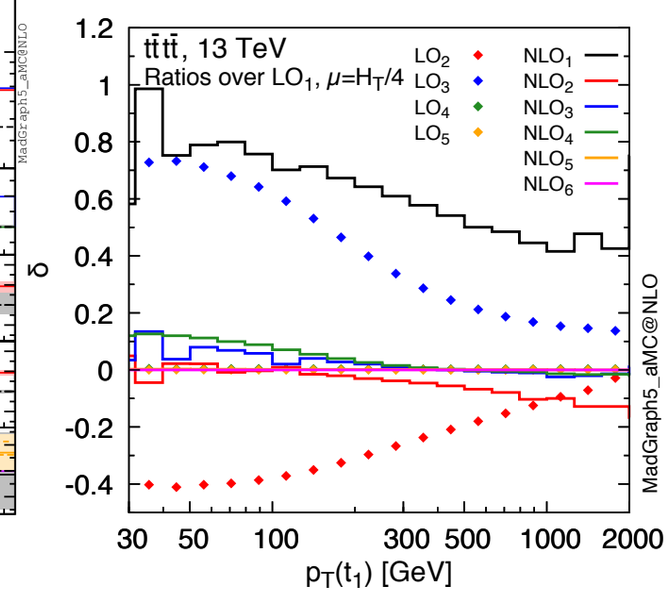
Other published results

- NLO EW and QCD corrections for $t\bar{t}H$, $t\bar{t}W$ and $t\bar{t}Z$
  Frixione, Hirshi, Pagani, Shao, MZ, arXiv:1504.03446
- Complete-NLO corrections for di-jet
  Frederix, Frixione, Hirshi, Pagani, Shao, MZ, arXiv: 1612.06548
- NLO EW and complete-NLO corrections for $t\bar{t}$
  + NNLO QCD combination
  Pagani, Tsinikos, MZ, arXiv:1606.01915, +Czakon, Heymes, Mitov, arXiv:1705.04105, 1711.03945, 1712.04842
- Complete-NLO corrections for $t\bar{t}W$ and four tops
  Frederix, Pagani, MZ, arXiv:1711.02116, Davide's talk







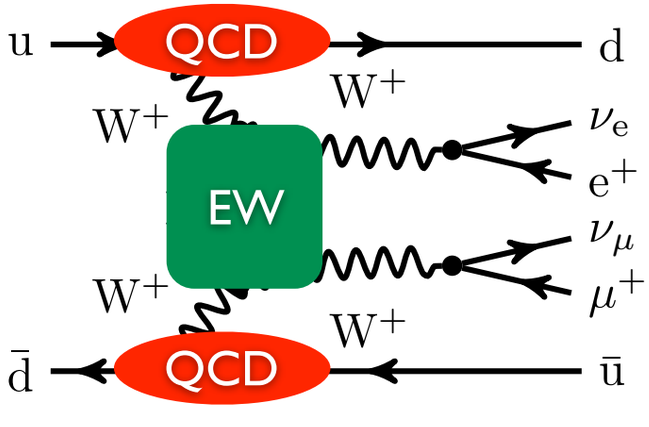


What is happening in VBS?

- Already without VBS cuts, VBS is comparable to the QCD background despite the coupling powers. This is due to the larger number of diagrams in VBS Kulesza, Stirling, hep-ph/9912232
- VBS cuts are designed to enhance VBS over QCD background, further reducing also the VBS-QCD interference.
  De facto, VBS and the QCD background are two different processes.
- EW corrections are dominated by corrections in the WW→WW scattering process, which probes large scales (m_{4l}~400 GeV).
  The bulk of the EW corrections is due to Sudakov logarithms
  details can be found in Biedermann et al, arXiv:1611.02951

$$\sigma_{\rm LL} = \sigma_{\rm LO}\left[1 - \frac{\alpha}{4\pi} 4 C_{\rm W}^{\rm ew} \log^2\left(\frac{Q^2}{M_{\rm W}^2}\right) + \frac{\alpha}{4\pi} 2 b_{\rm W}^{\rm ew} \log\left(\frac{Q^2}{M_{\rm W}^2}\right)\right]$$

$$C_{\rm W}^{\rm ew} = \frac{2}{s_{\rm w}^2} \qquad b_{\rm W}^{\rm ew} = \frac{19}{6 s_{\rm w}^2}$$



- QCD corrections only affect the quark lines

Complete-NLO corrections for $t\bar{t}W$

Frederix, Pagani, MZ, arXiv:1711.02116

13 TeV

$\delta[\%]$	$\mu = H_T/2$
LO_2	-
LO_3	0.9
NLO_1	50.0 (25.7)
NLO_2	−4.2 (−4.6)
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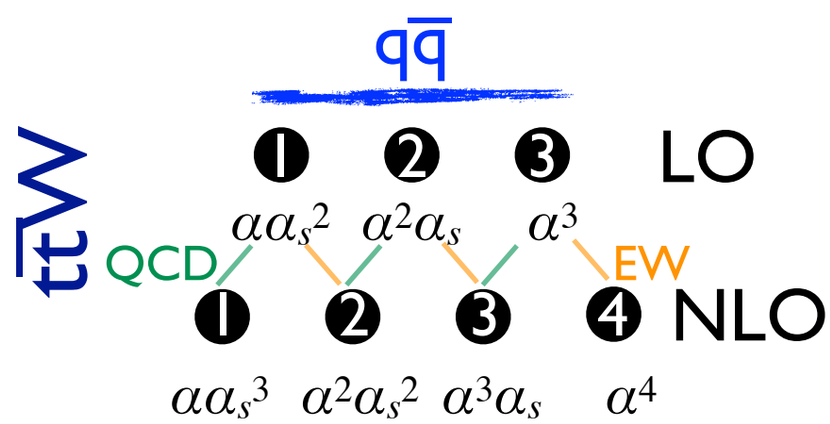
NLO_4	0.04 (−0.02)



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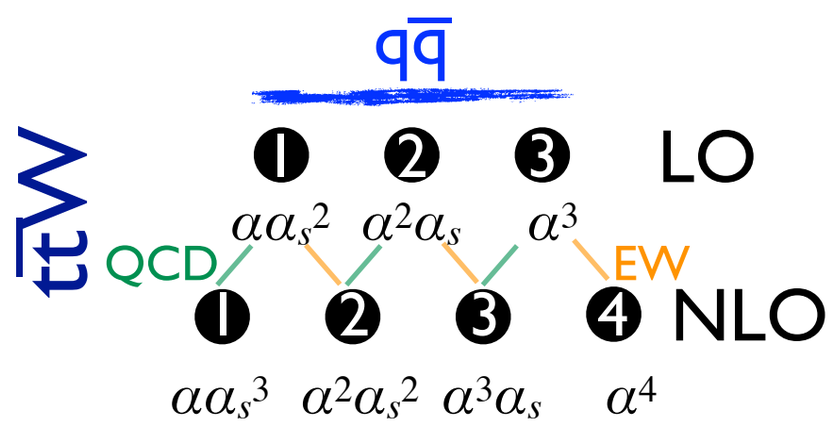

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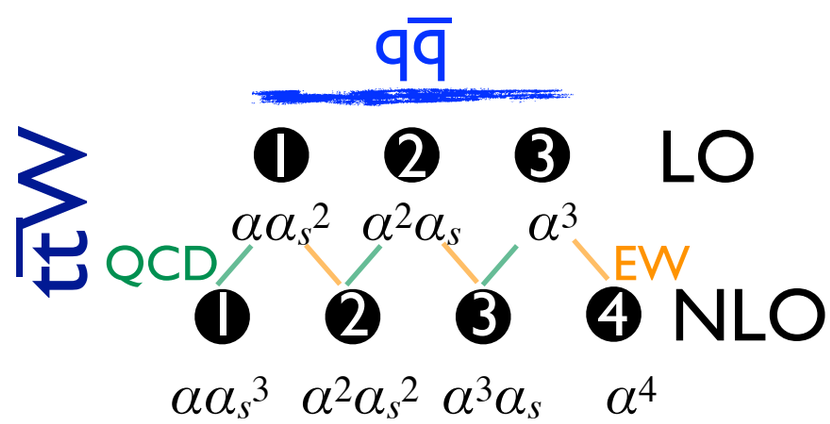

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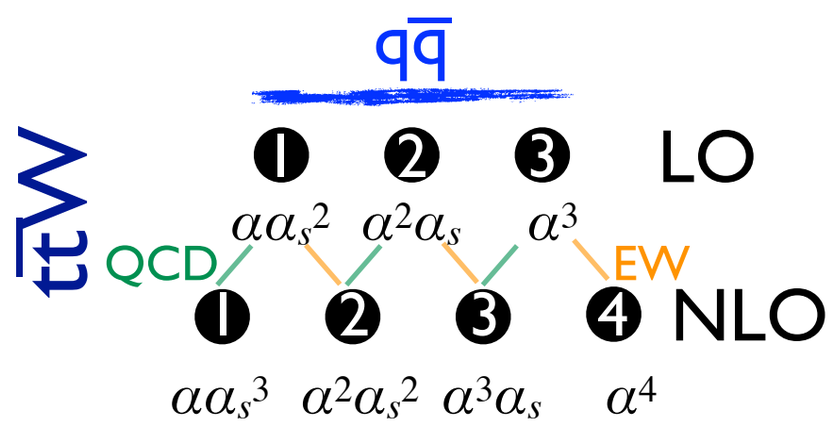

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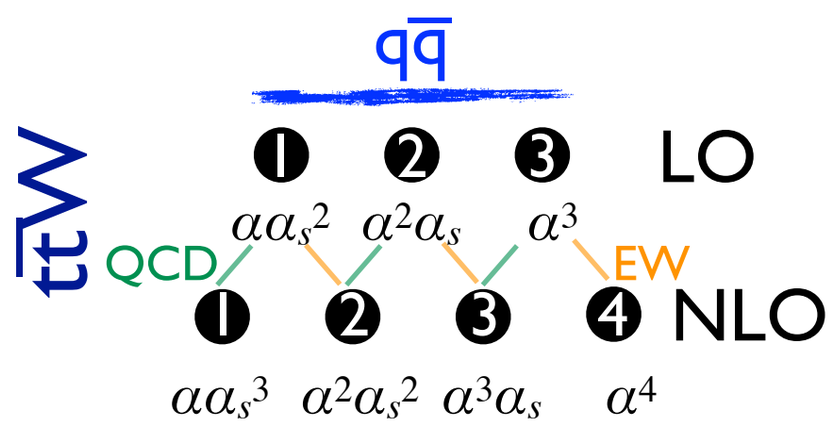

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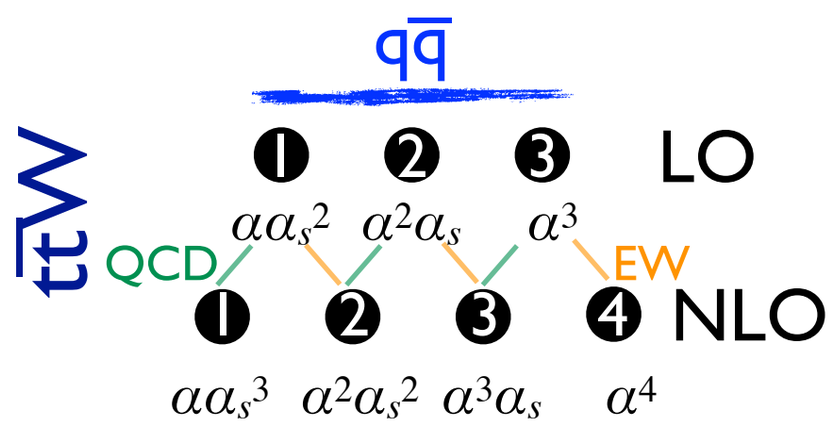

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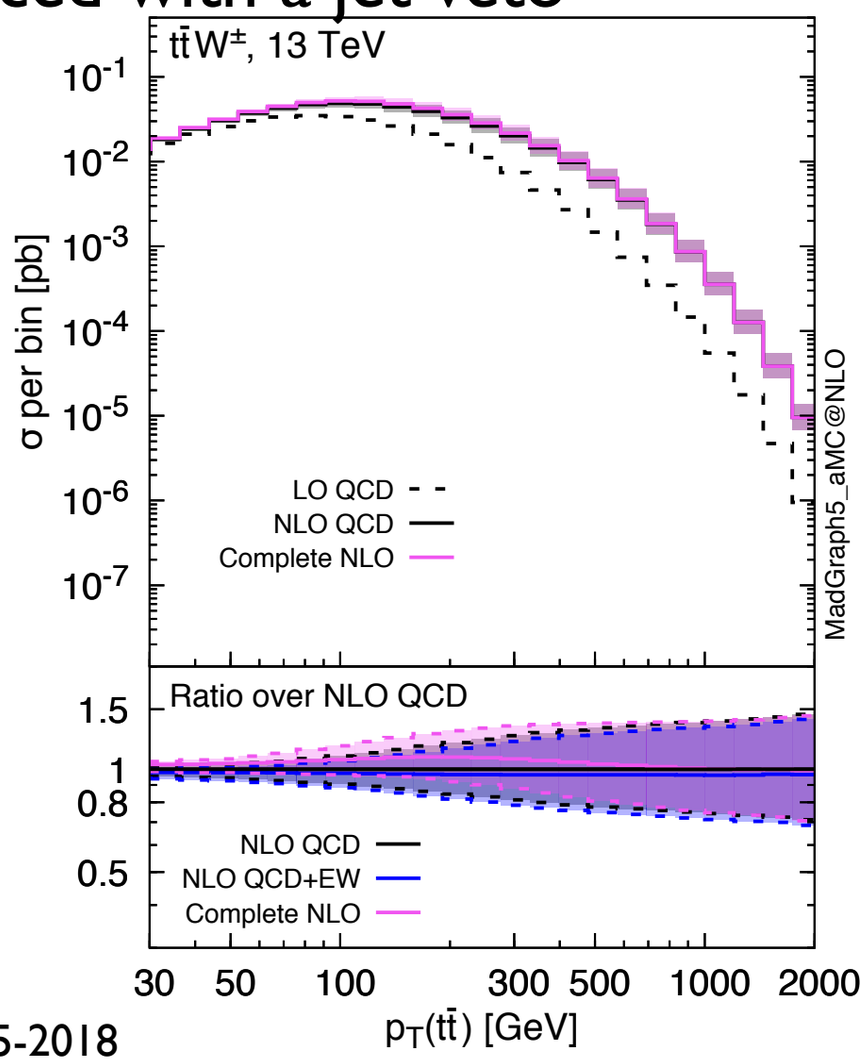
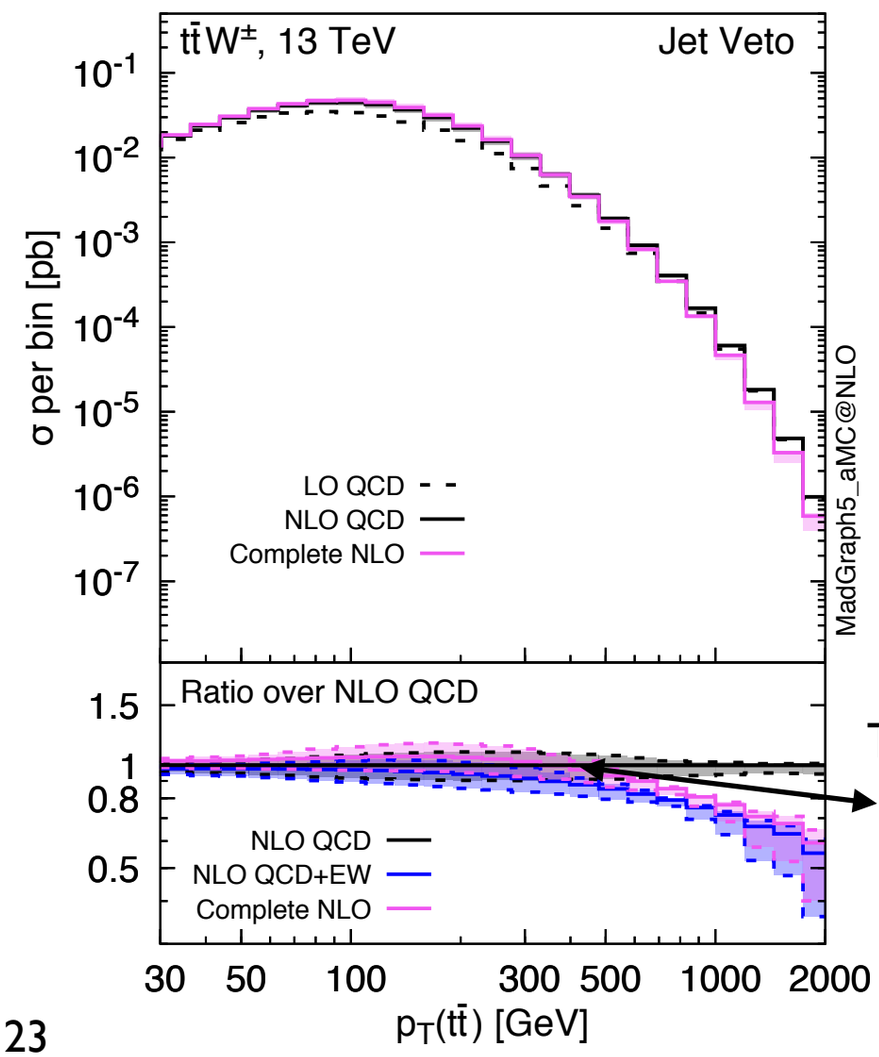
- The jet veto greatly reduces the NLO_1 (QCD corrections), which is dominated by hard radiation, and only mildly affects the other contributions
- At 100 TeV, NLO_3/LO_1~60% → almost as large as NLO_1 with the jet veto

$p_T(t\bar{t})$ and the effect of the jet veto

- QCD corrections to $t\bar{t}W$ are dominated by real emissions recoiling against the $t\bar{t}$ pair, with the W collinear to the emission or soft
- This leads to giant K-factors for the $p_T(t\bar{t})$ distribution, which are greatly reduced with a jet veto





The NLO QCD+EW and complete NLO uncertainty band barely overlap

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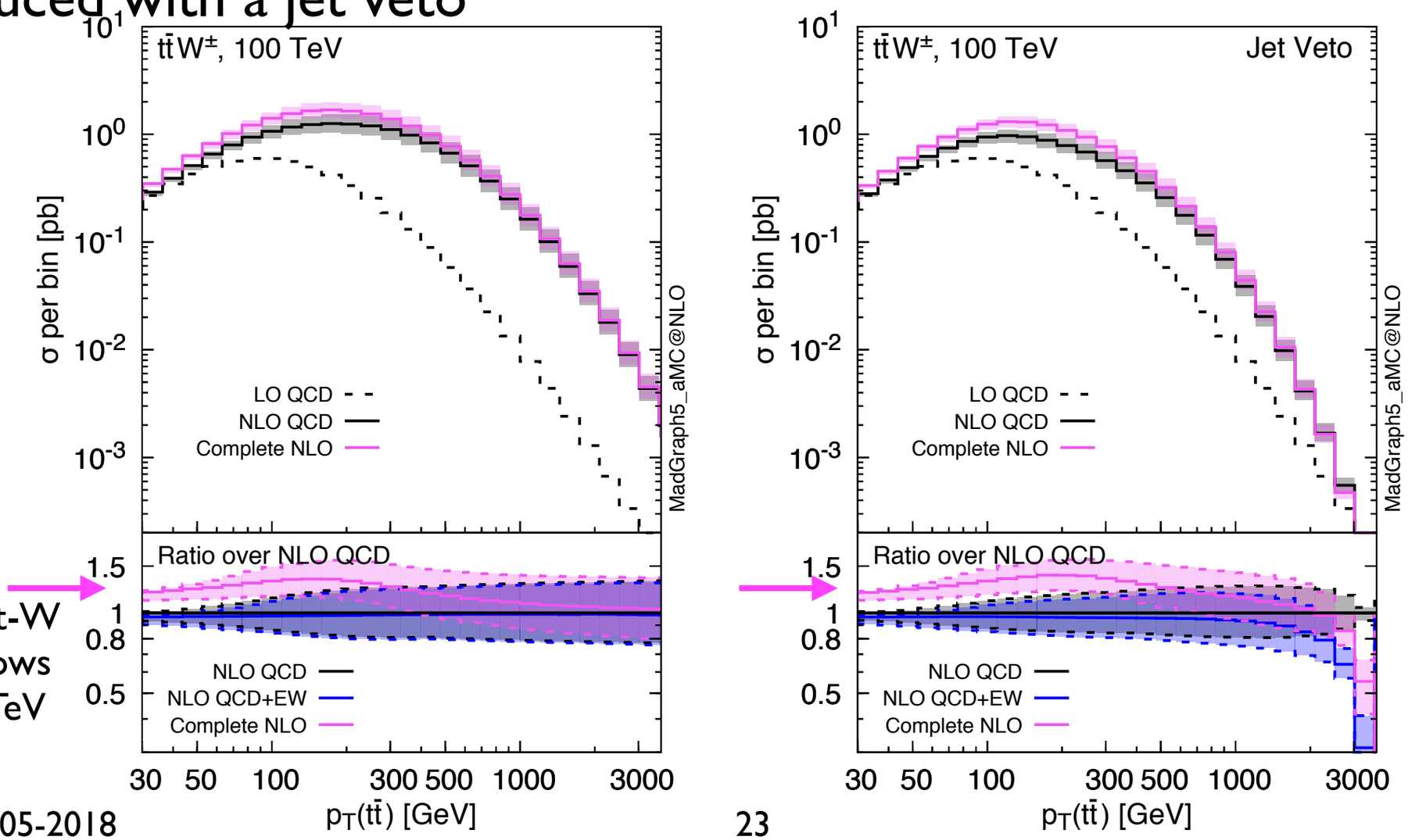

The effect of t-W scattering grows huge at 100 TeV