Electroweak NLO calculations

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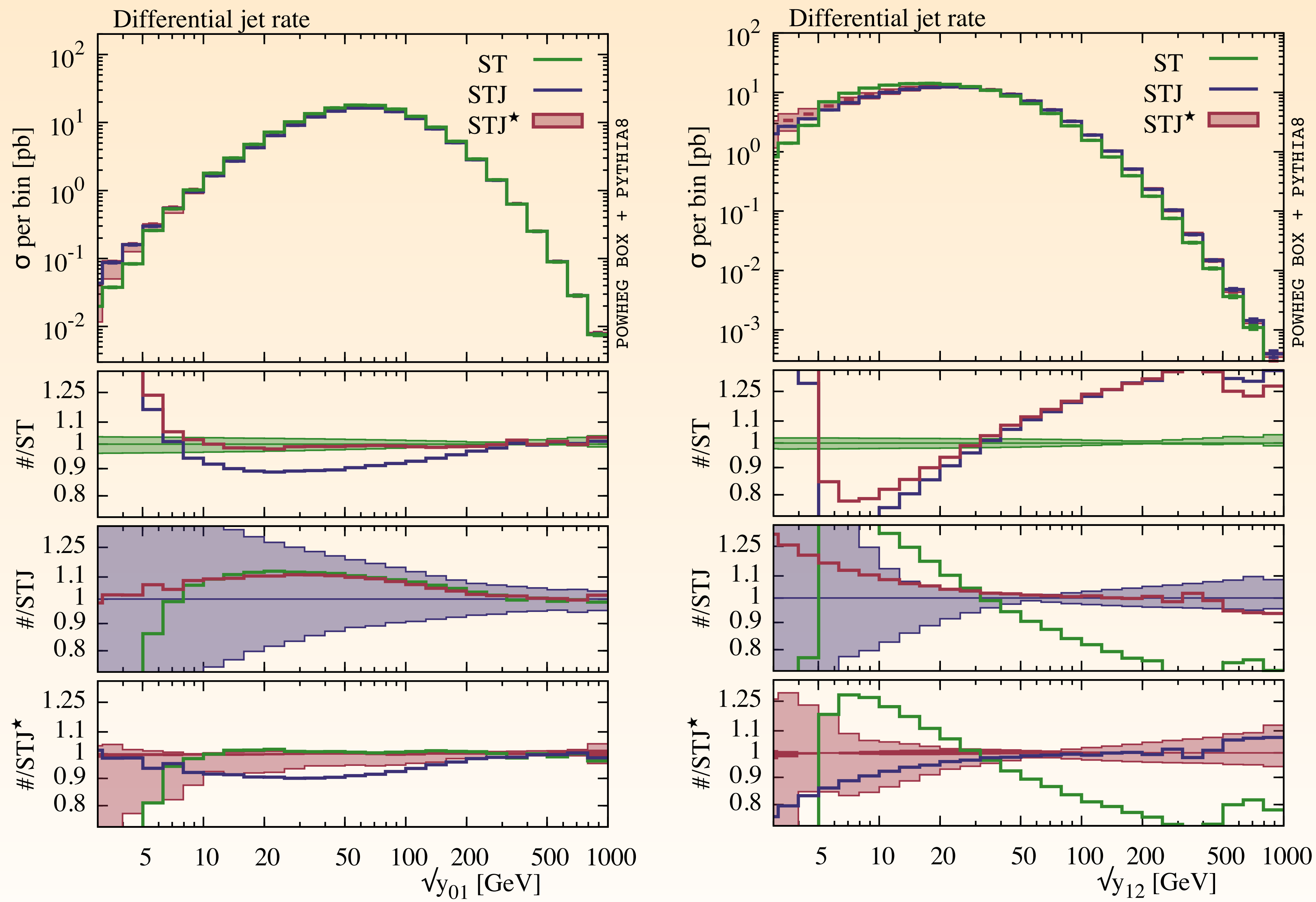
Minlo' t-channel single-top

- ST: default POWHEG NLO t-channel single-top predictions
  STJ: new t-channel single-top+jet NLO in POWHEG
  STJ*: Minlo' merged ST+STJ (without merging scale through enforcing unitarity)

- Small differences between ST/STJ and STJ* at small scales, but this is deep in the Sudakov region, where higher accurate resummation is needed (and non-perturbative effects play an important role as well)

- Uncertainty band for ST y_{12} is too small -> artefact of POWHEG methodology



- **The preferred (i.e. most-accurate) predictions for t-channel single-top production**

[S. Carrazza, RF, K. Hamilton and G. Zanderighi, arXiv:1805.09855]

NLO EW corrections

EW corrections

- Just as one can have a perturbative series in the strong coupling, one can also include higher order corrections in the electroweak (EW) coupling
- By comparing the strength of the strong to the EW coupling, one expects that NNLO QCD corrections of similar importance to NLO EW corrections
  - On top of that, EW corrections can be enhanced in certain kinematical regions, where they can result in several tens of percents:
    - Close to EW resonances, radiation from decay products results in sizeable changes
    - When photon luminosity is important
    - Large transverse) momenta or invariants result in large EW corrections
      - Important in BSM searches, **particularly when understanding shapes of backgrounds is a must**

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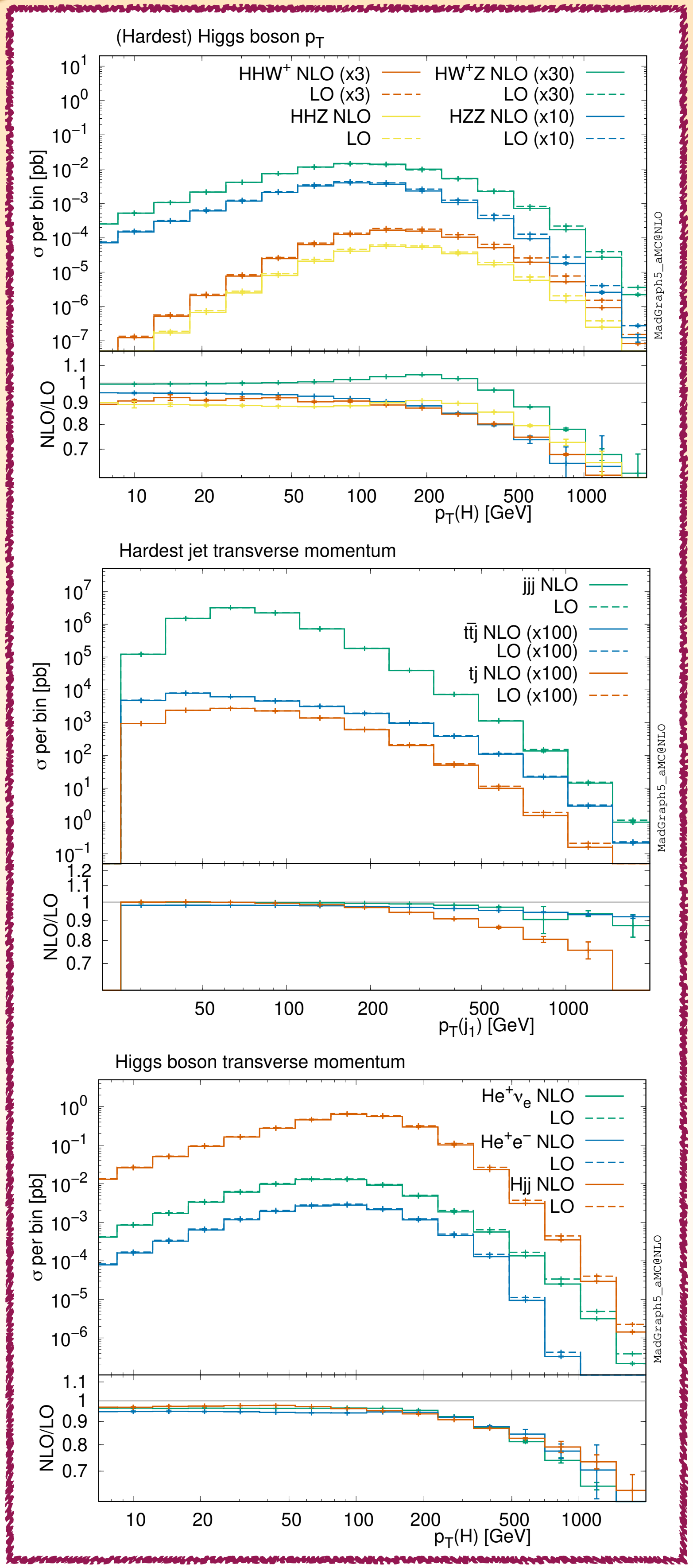

EW vs Strong corrections

- When including higher order corrections in the strong coupling, renormalisation (and factorisation) scale dependence is reduced in the predictions
- This is not the case for EW corrections: scale dependence is effectively the same in LO and NLO EW computations
  - Instead, scheme dependence is reduced
  - Note that scheme dependence is typically not considered to be an uncertainty: it is quite obvious which scheme is preferred

EW scheme choices

- The EW sector of the SM has 3 independent parameters for the gauge interactions. Historically taken to be α, M_W and M_Z (with α measured in Thomson scattering, and M_W and M_Z the on-shell weak boson masses)
  - Other EW parameters are then predictions: vev, G_F, $\sin(\theta_W)$, λ, ρ, …
- Alternatively, by using other input parameters, and updating the renormalisation conditions accordingly, one resums some important higher order contributions
  - At LO, scheme dependence is only through the numerical value of the input parameters (which effectively means the value of α)

Common EW schemes: overview

$\{\alpha(0)\,,\ M_W\,,\ M_Z\} \to \alpha(0)$ scheme

$$\delta Z_e = -\frac{1}{2}\delta Z_{AA} - \frac{s_W}{c_W}\frac{1}{2}\delta Z_{ZA}$$

$\{\alpha(M_Z)\,,\ M_W\,,\ M_Z\} \to \alpha(M_Z)$ scheme

$$\delta Z_e|_{\alpha(Q^2)} \equiv \delta Z_e|_{\alpha(0)} - \frac{1}{2}\Delta\alpha(Q^2)$$

$\{G_\mu\,,\ M_W\,,\ M_Z\} \to G_\mu$ scheme

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$$\delta Z_e|_{\alpha(m_Z^2)} - \frac{1}{2}\left(-\frac{c_W^2}{s_W^2}\Delta\rho + \Delta r_{\rm rem}\right)$$

$\alpha(0) \sim 1/137 \qquad \alpha(M_Z) \sim 1/128 \qquad \alpha|_{G_\mu} \sim 1/132$

As a rule of thumb, for a generic process at the LHC, the Gmu scheme is superior and has to be preferred. However, if a photon is present in the Born final-state, alpha(0) and the corresponding renormalisation should be used for the associated QED vertex.

[Slide by D. Pagani]

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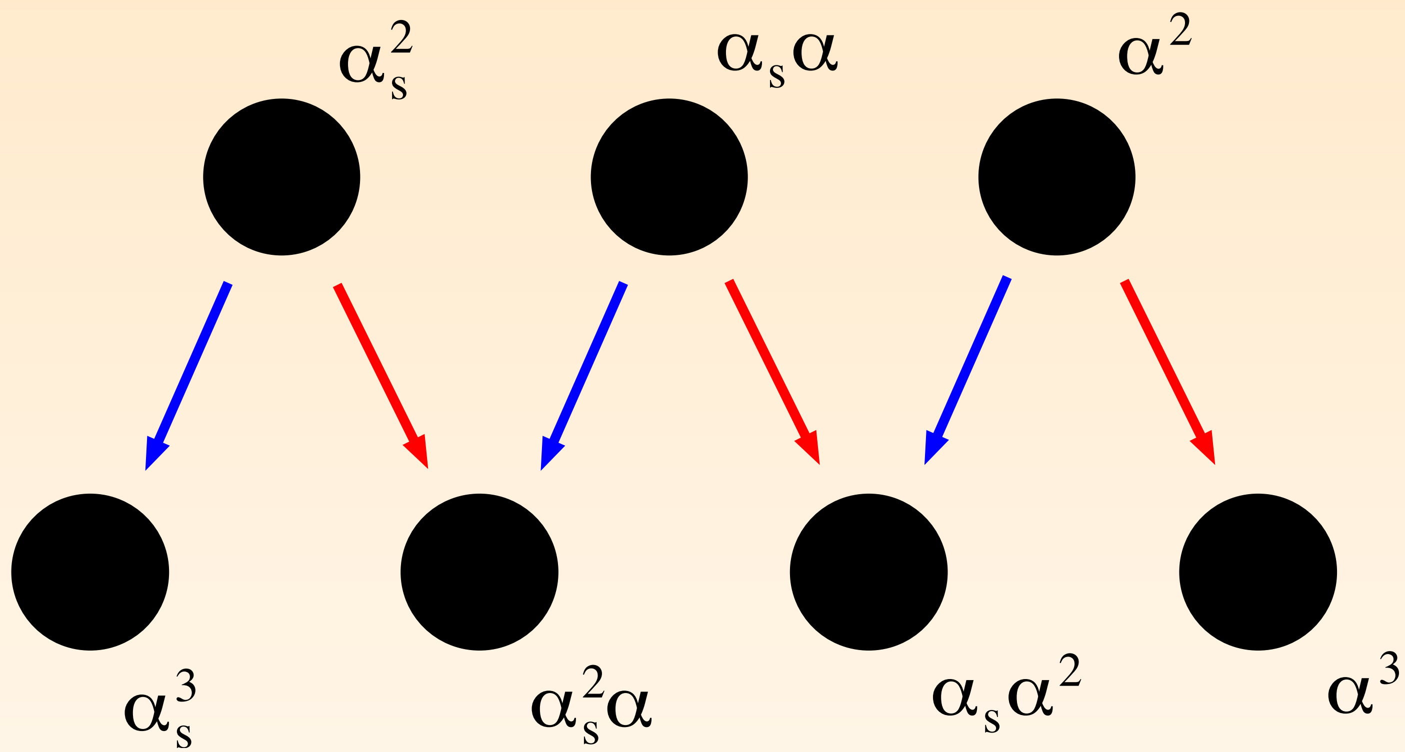
NLO DISSECTION

- For example: consider di-jet production



- "NLO EW" is a bit of a misnomer:
  NLO_2 and NLO_3 part of a "mixed" expansion
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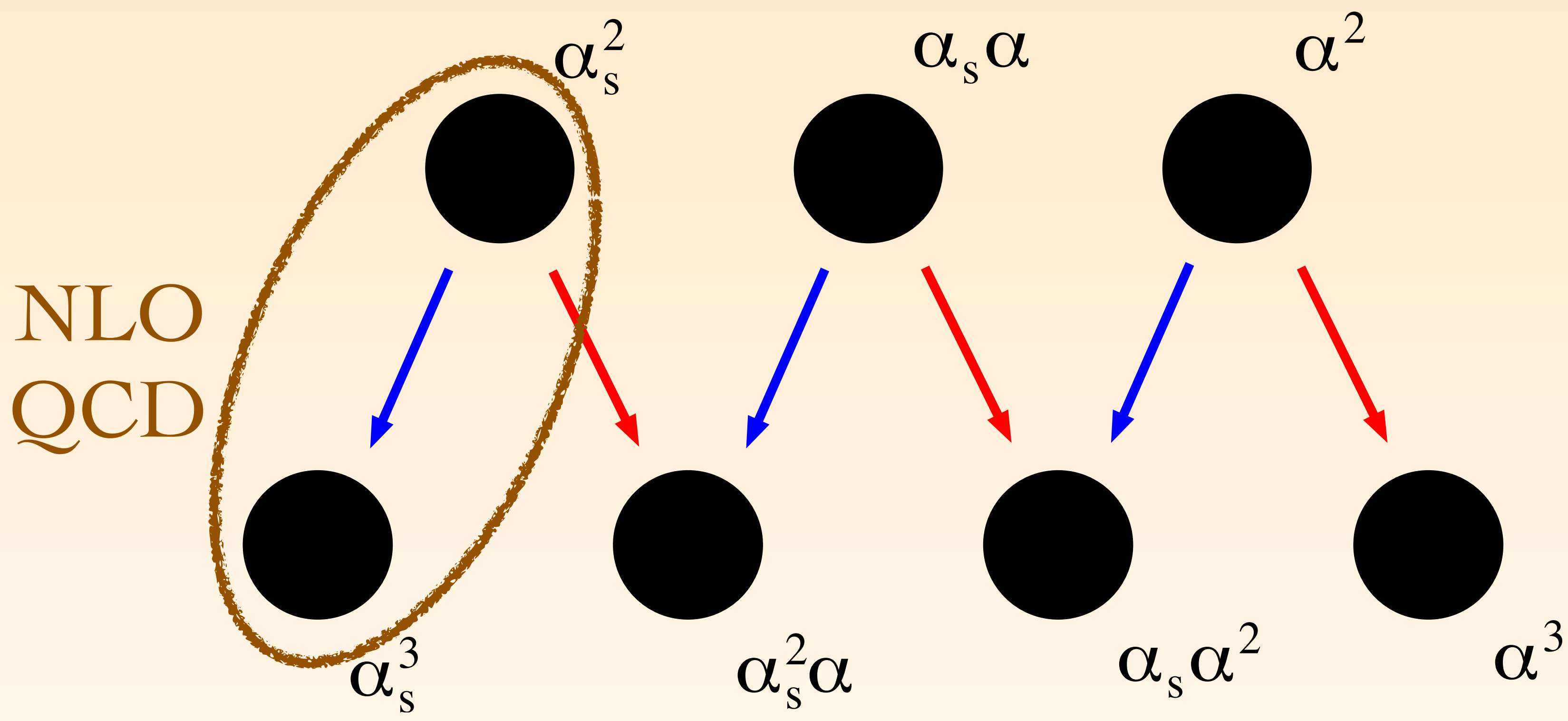

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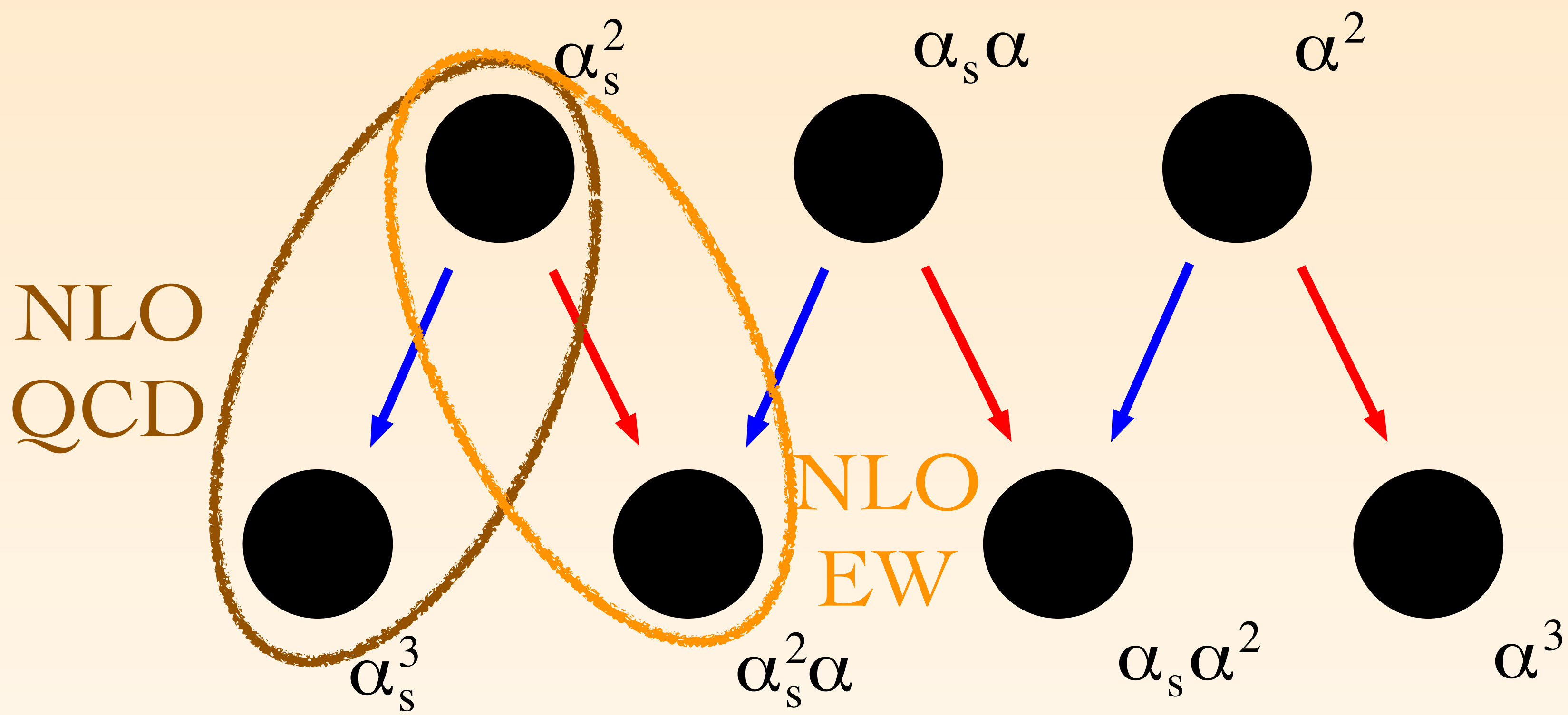

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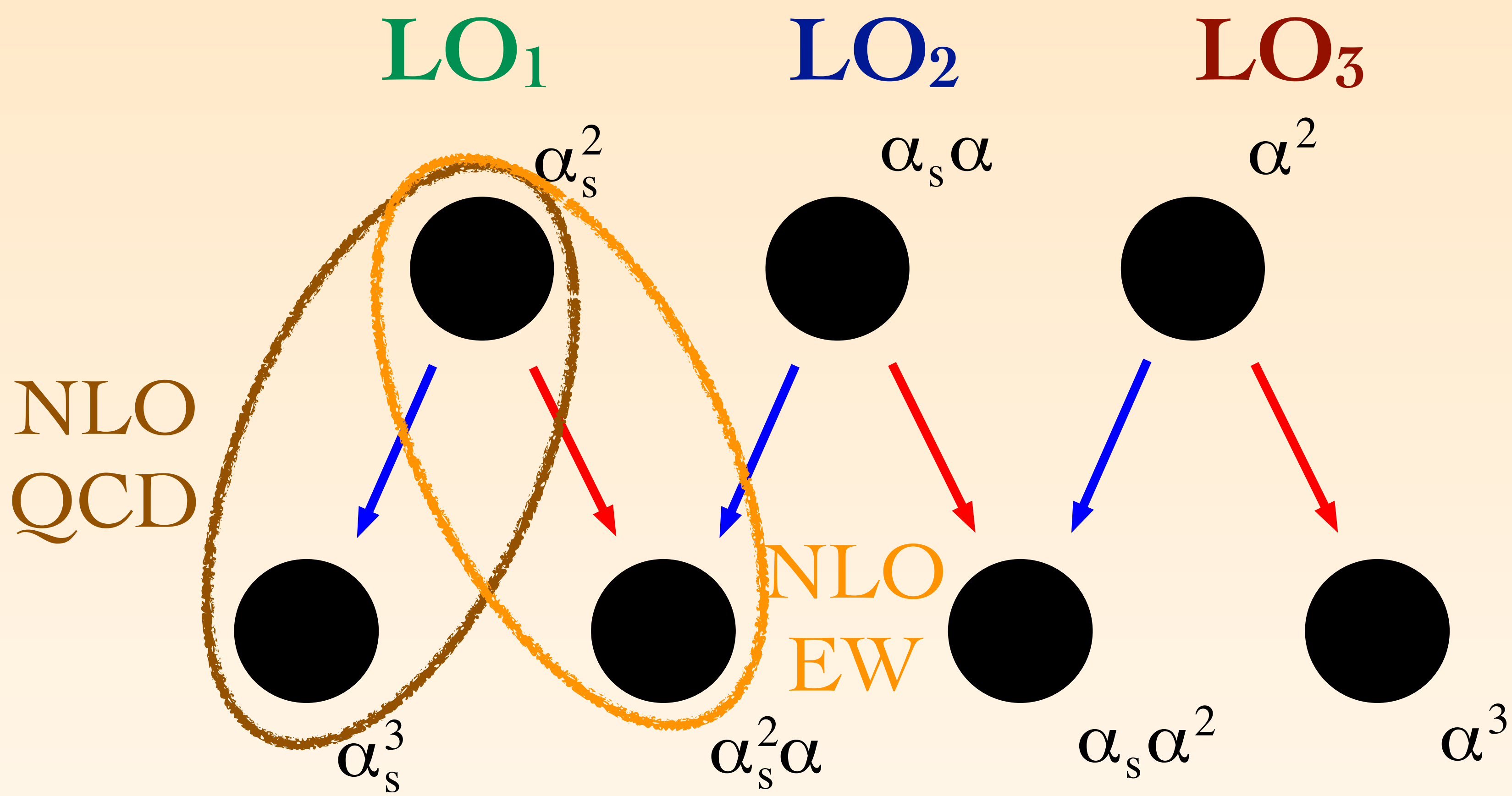

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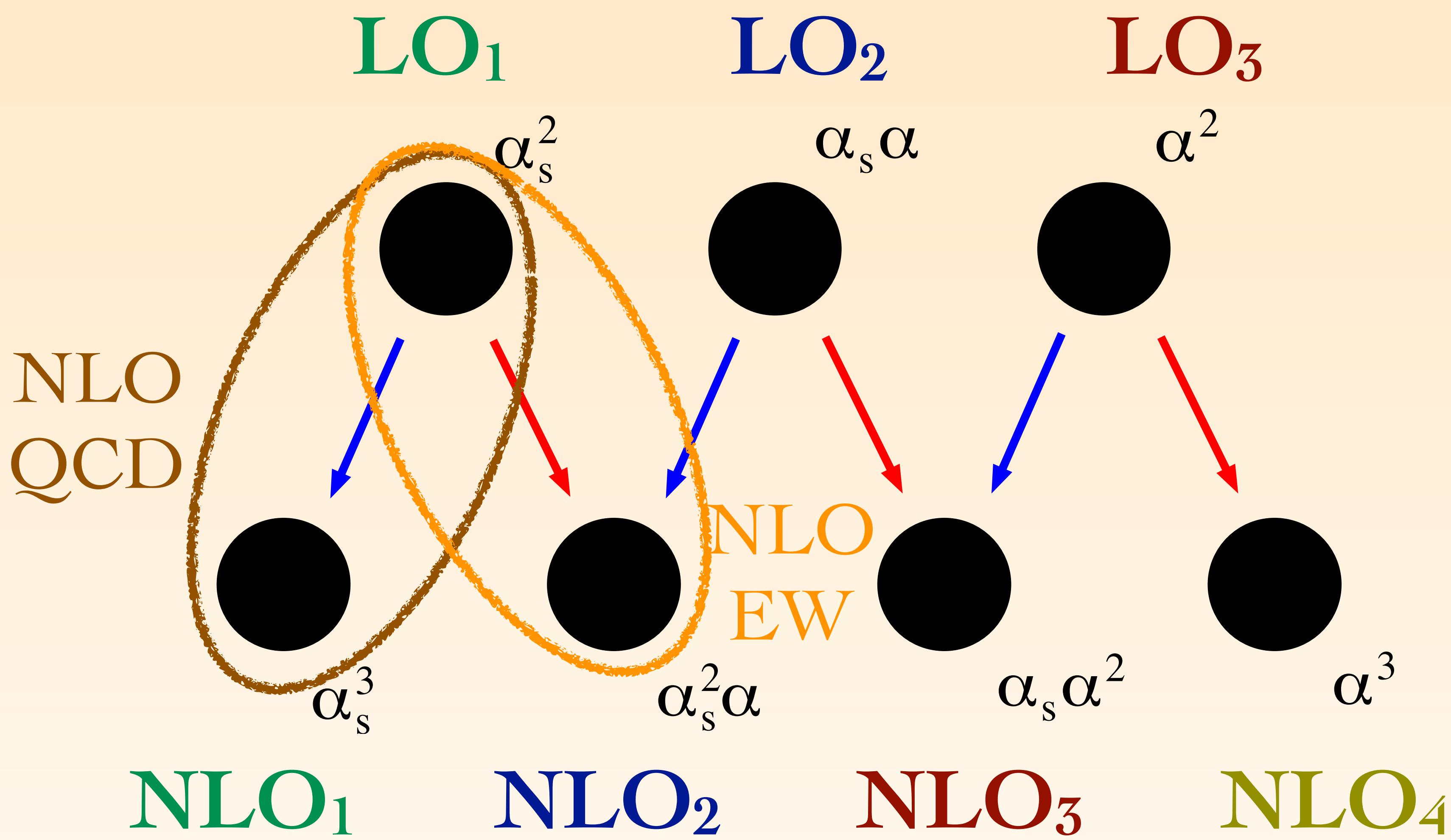

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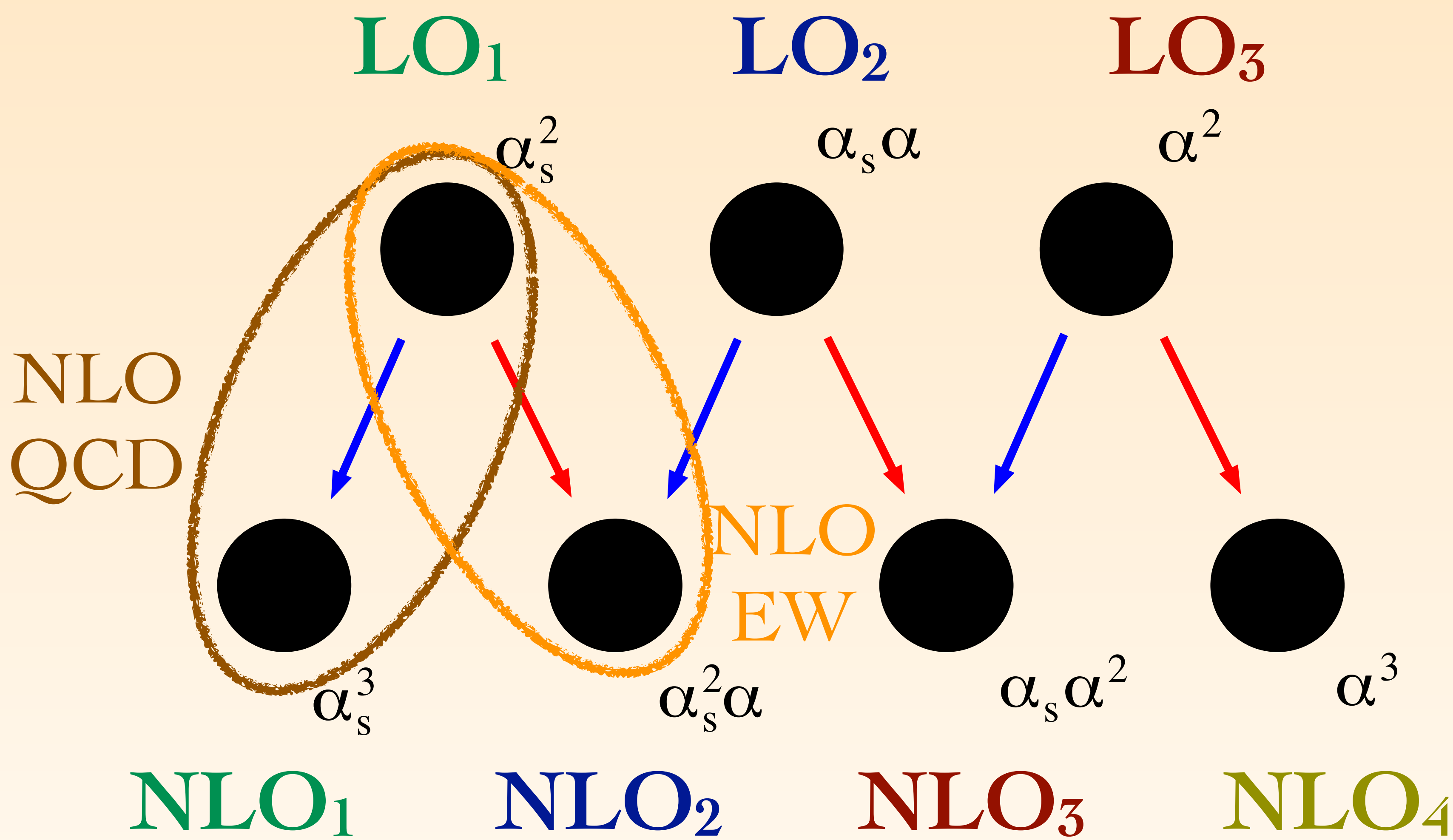

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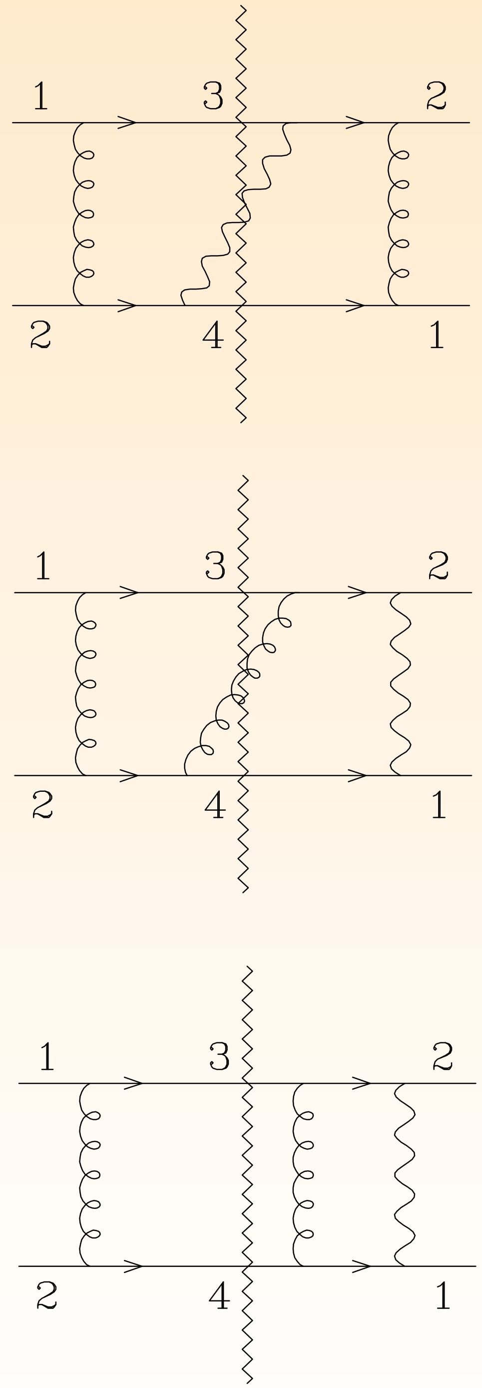
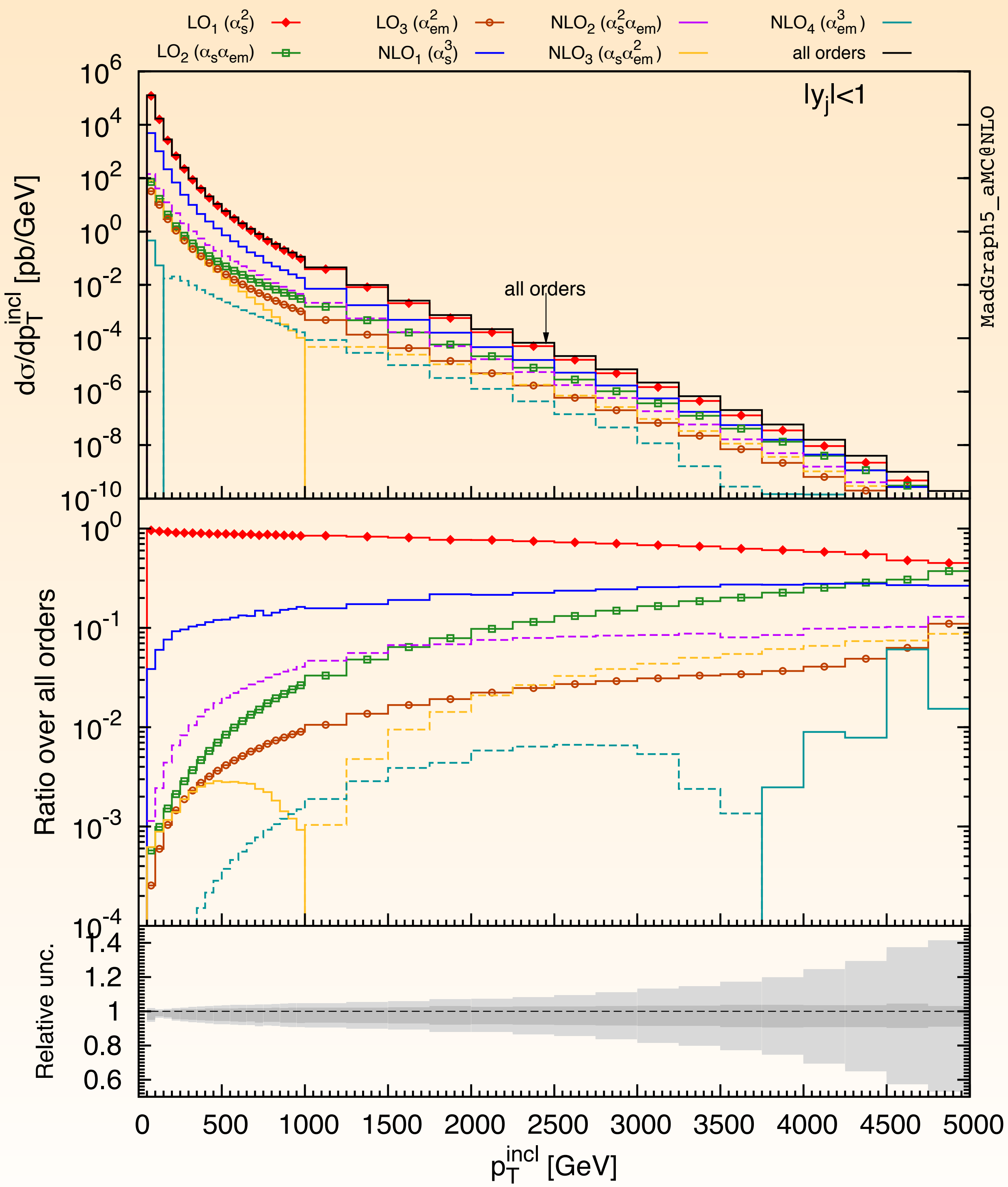
For example: NLO2 has both "QCD" and "EW" contributions

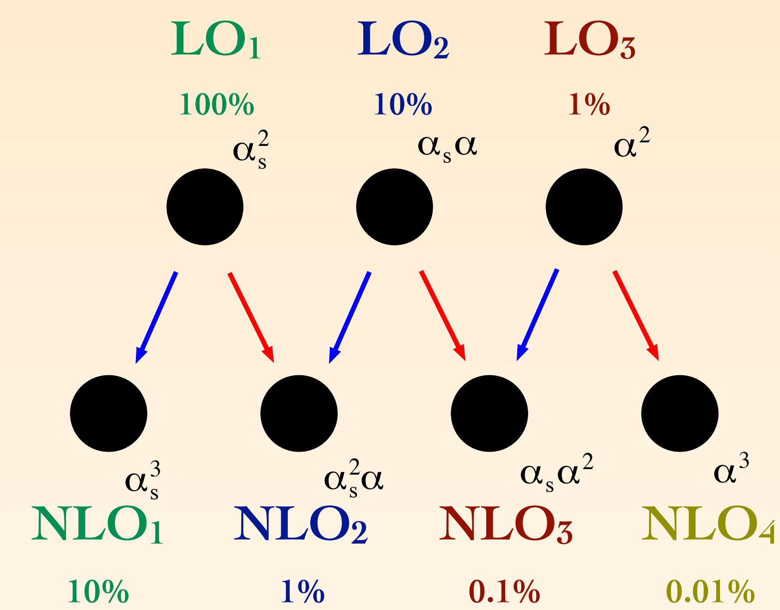


Complete-NLO to inclusive jet-p_T

[RF, Frixione, Hirschi, Pagani, Shao, Zaro, 2017]



- Inclusive jet-p_T
- Expectation (assume α_S=0.1, α=0.01):



- Size of corrections mostly follows what one expects from the coupling combinations
  - Apart from the very far tail where NLO$_3$ is slightly larger then one would expect

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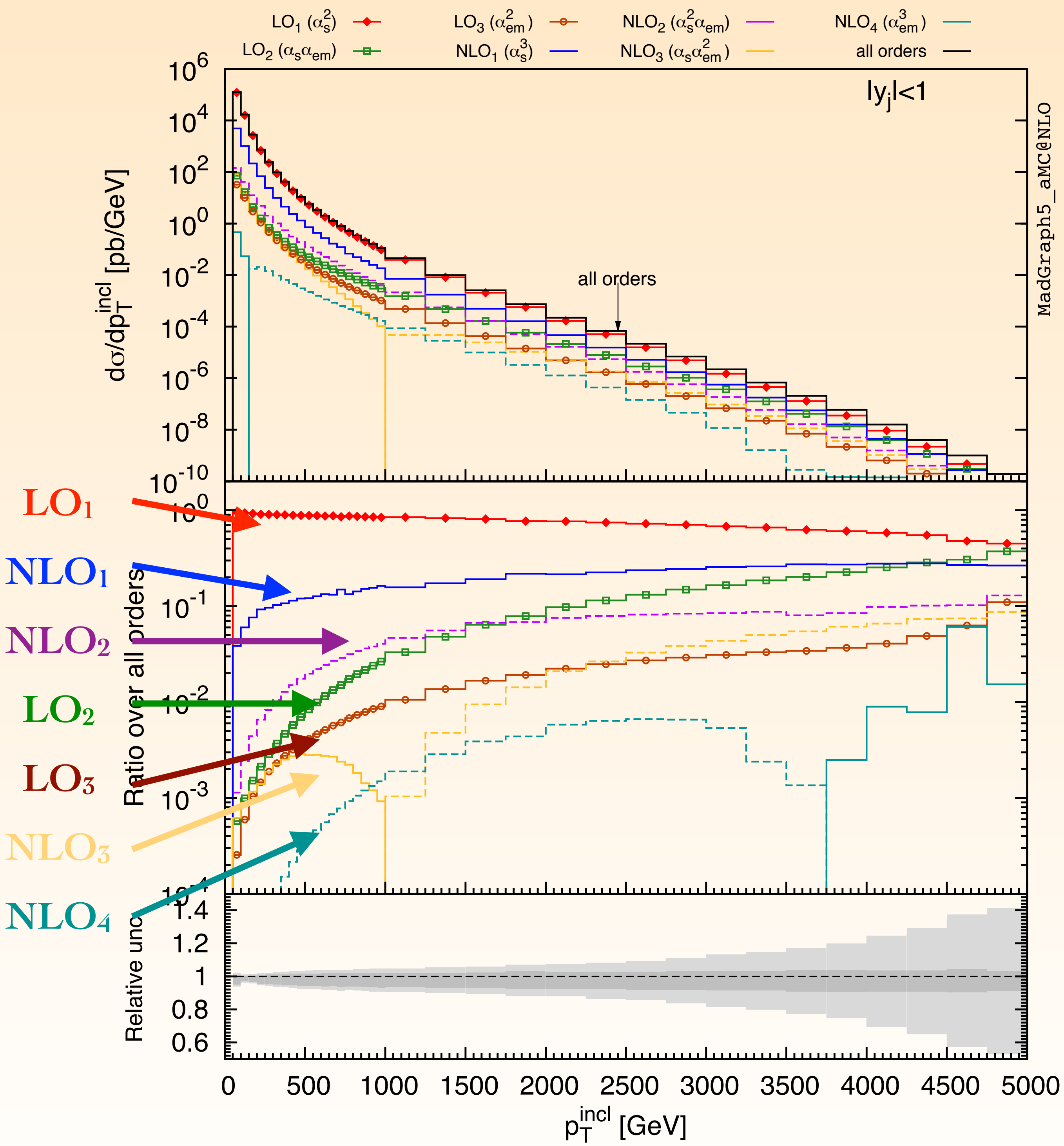

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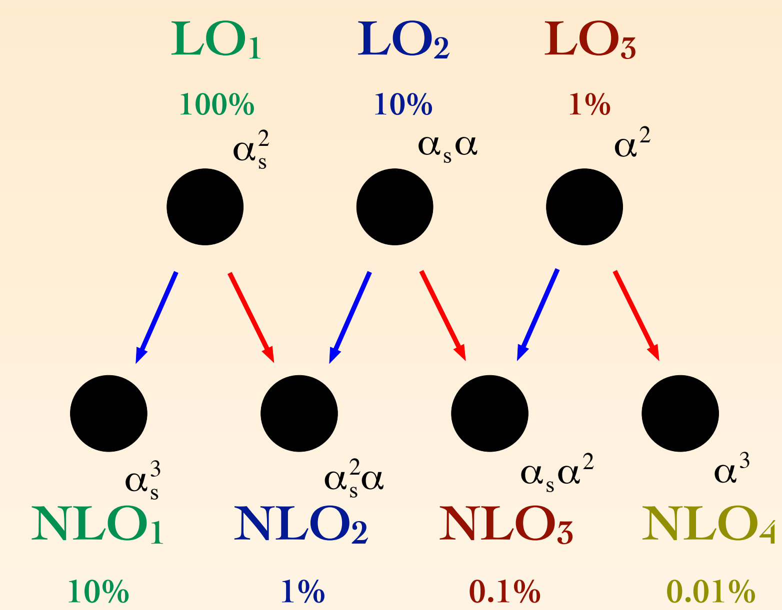

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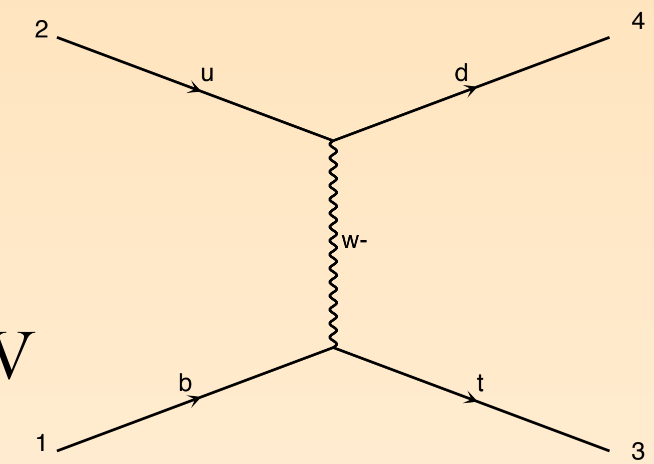
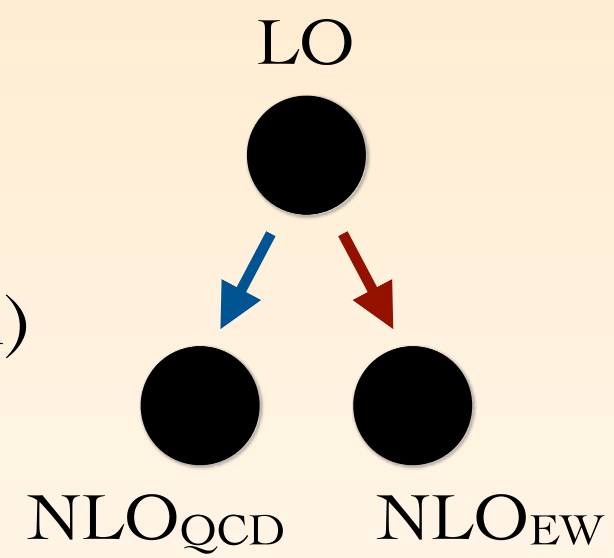
Single-top production

T- AND S-CHANNEL

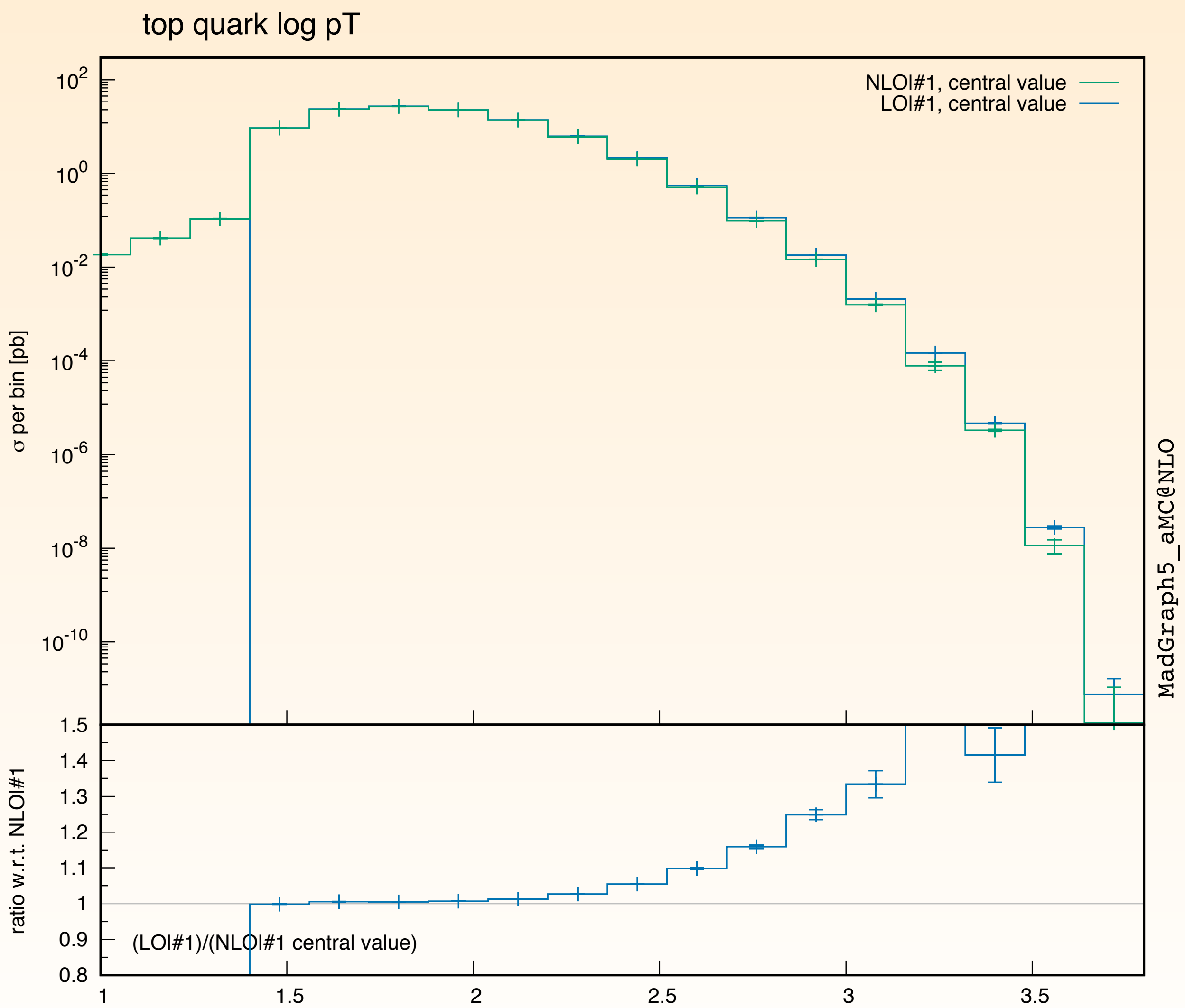


- Single-top production (with on-shell top quark) is a purely EW process. Hence, no difficulties in defining NLO QCD & EW
- However, t- and s-channel differentiation needs to be revisited
  - At NLO_{EW}, Initial state photon results in diagrams that contain both an t-channel and an s-channel W-boson (but one can probably still use parton flavours for differentiation)
- In the next results, no attempt in updating the differentiation will be made. We will only consider the sum
  - If necessary, one could always subtract the s-channel contribution at LO to obtain an NLO t-channel prediction
- NLO EW corrections for single-top production first studied by M. Beccaria et al. (2006), Mirabella (2008) and Bardin et al. (2011).

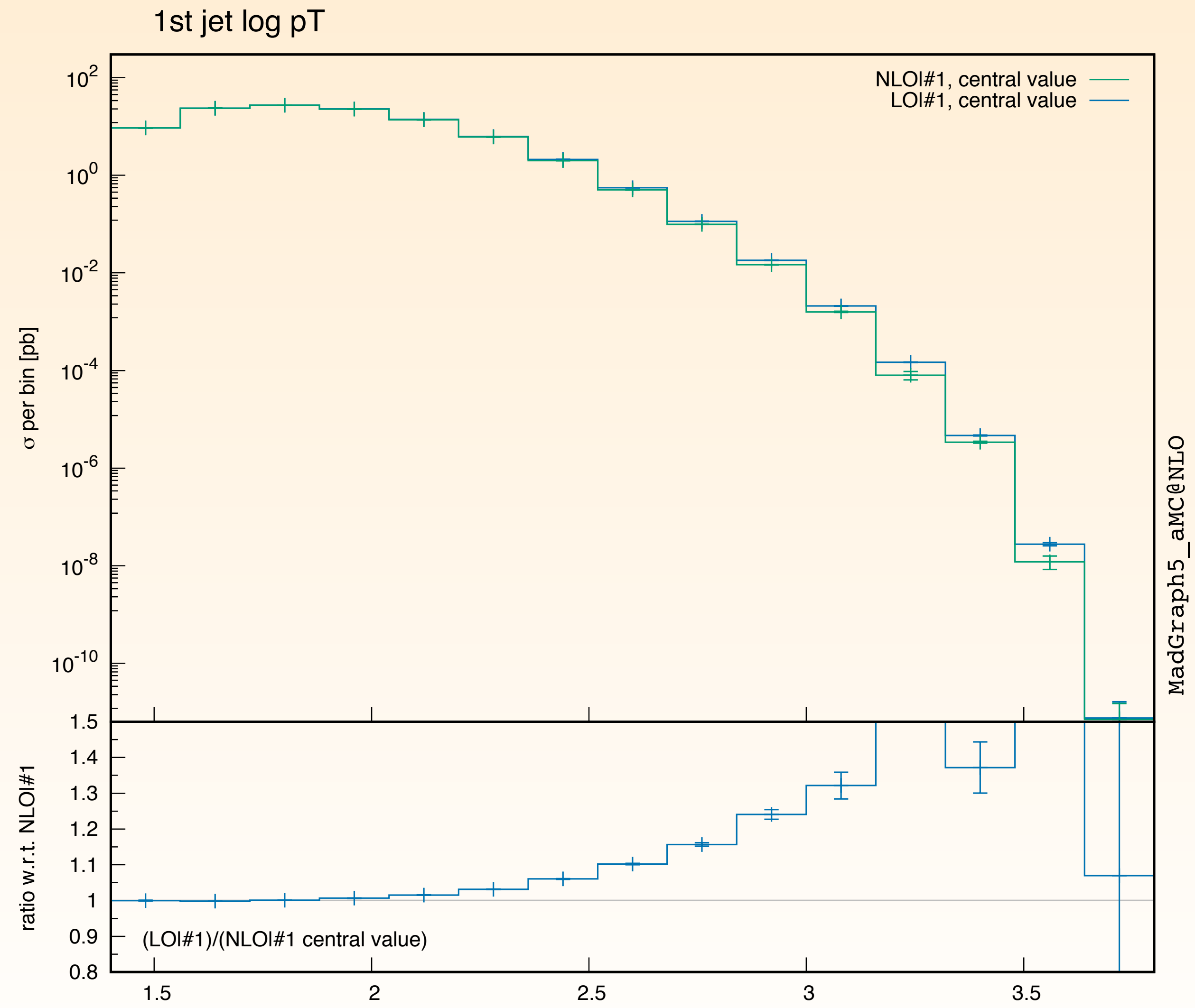


Inclusive rates

- For inclusive rates, the contributions from NLO EW corrections are small (less than a percent)
- This does no longer hold for the (extreme) tails of distributions, where the corrections can reach tens of percents



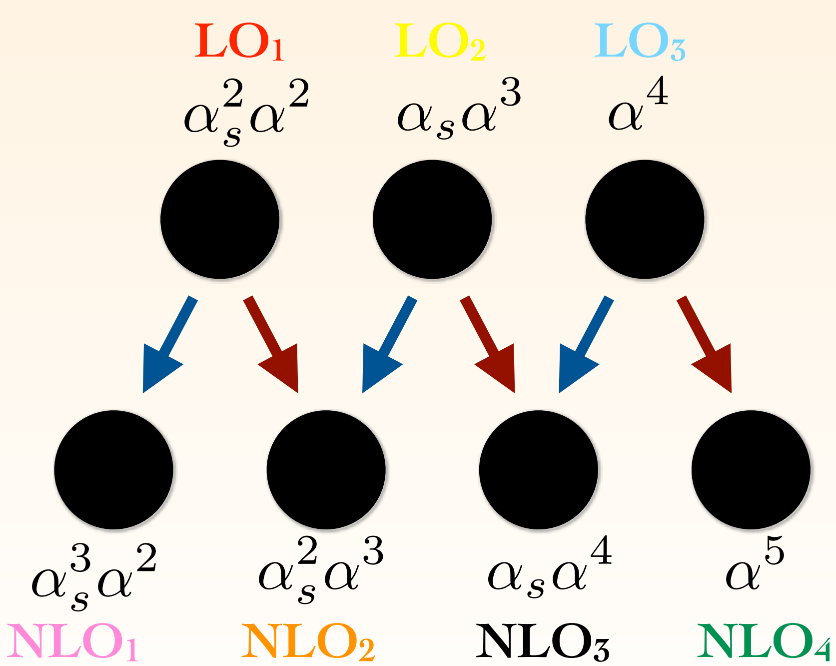
log10(pT(top)/GeV)

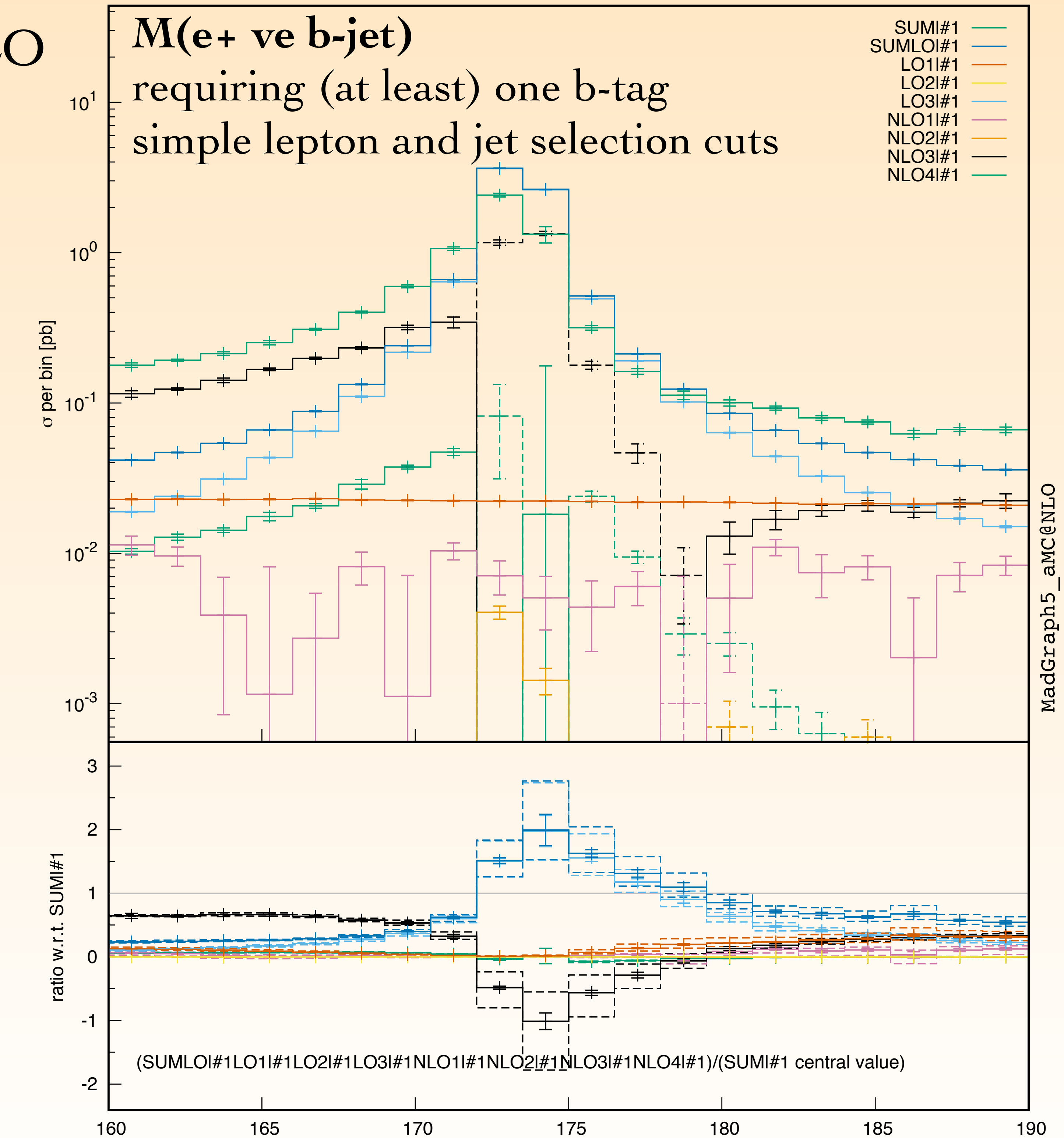


log10(pT(jet)/GeV)

Off-shell effects

- Generate the process at complete-NLO
  p p > e+ ve j j
- This includes single-top production, but also background processes, with possible interferences
- Straightforward to generate, but difficult to interpret, assess uncertainties and to make use of





[Work in progress: RF, D. Pagani, I. Tsinikos]

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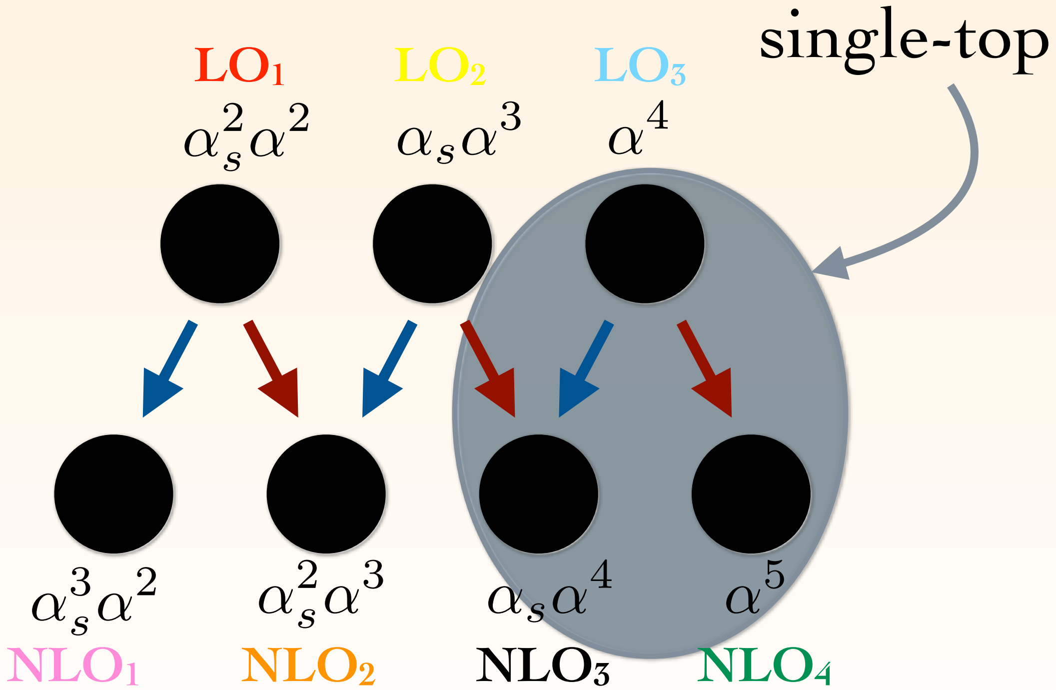

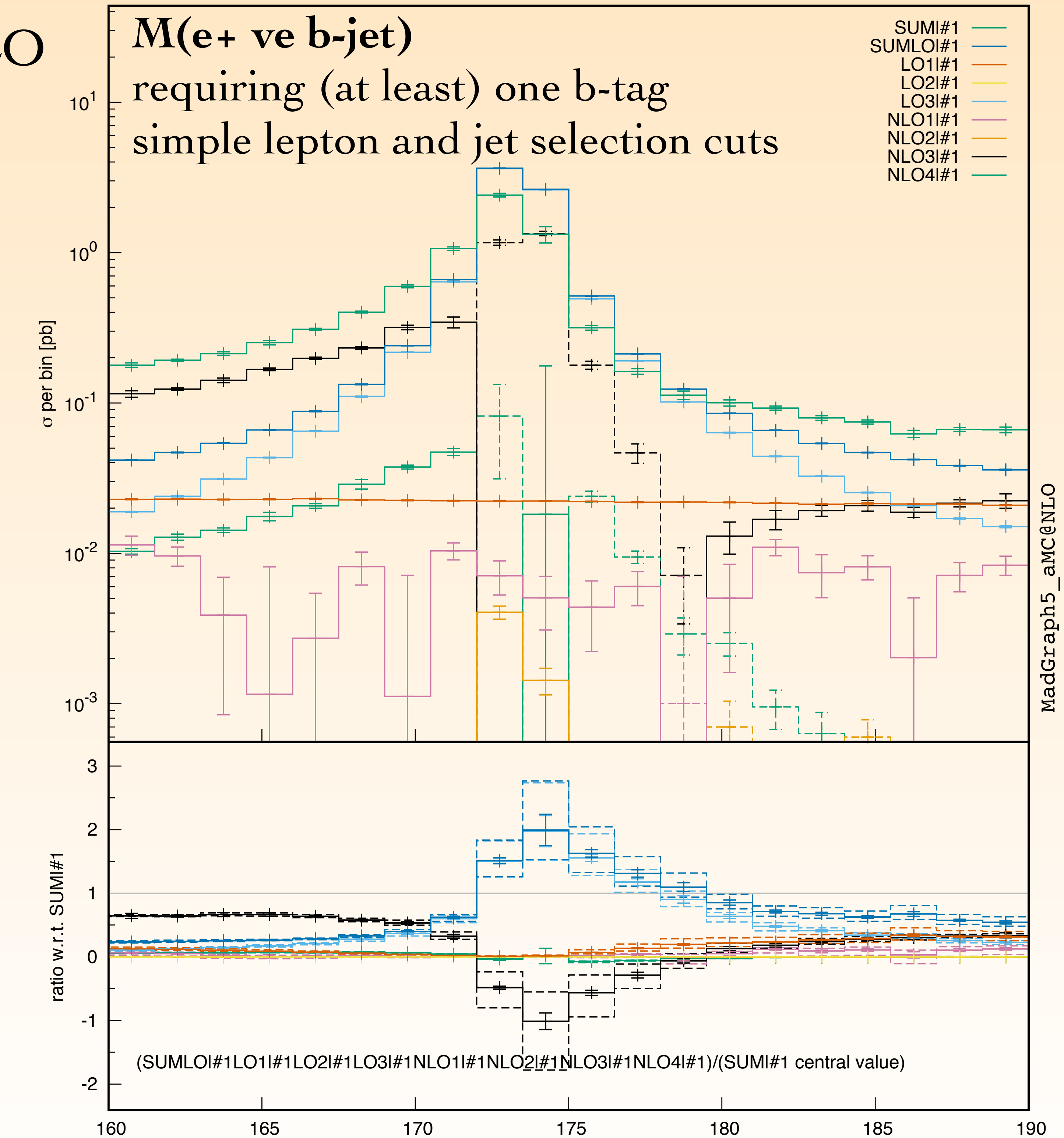

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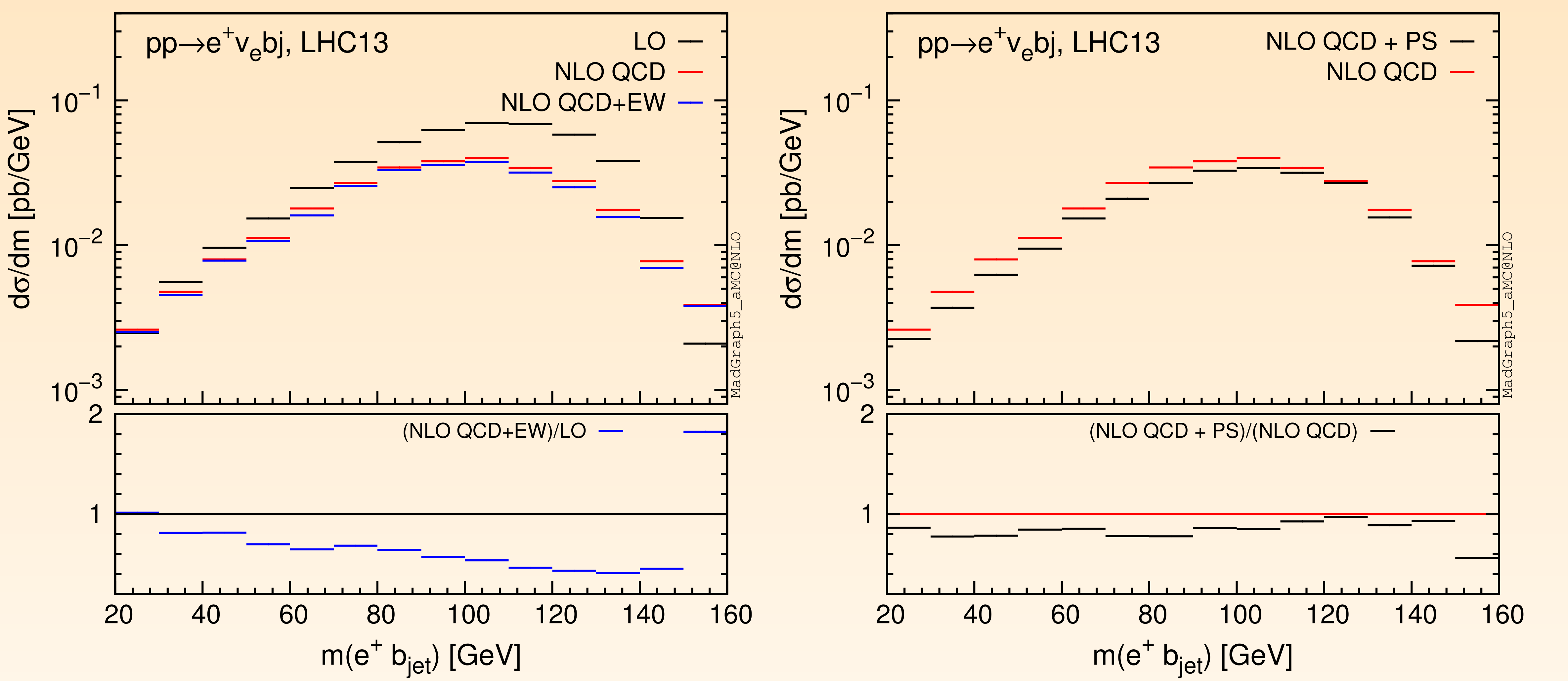
Jet veto enhances corrections

- Let's ignore possible interferences and focus again on single-top as signal: LO_3 + NLO_3 & NLO_4
- To enhance single-top signal, typically (b-)jet-veto is applied
    - require exactly one lepton, one b-jet, and one additional non-b-tagged jet
- In particular, the jet vetos enhance the effects from NLO corrections enormously
- Including higher orders does not solve the problem. Also at NNLO QCD ([Berger et al.]) the corrections remain large
- Resummation through parton shower improves the situation considerably, however not available for the EW corrections

$pp \to e^+ v_e b j$, PDFs=LUXQED17 (82200), $\mu_f^0 = \mu_r^0 = H_T/2$	
Order	σ [fb]
LO QCD	$4.616(4)^{+0.415(+9.0\%)}_{-0.532(-11.5\%)}$
NLO QCD	$2.75(3)^{+0.22(+8.2\%)}_{-0.24(-8.8\%)}$
NLO QCD+EW	$2.57(3)^{+0.22(+8.5\%)}_{-0.25(-9.6\%)}$
LO QCD + PS	$3.038(6)^{+0.280(+9.2\%)}_{-0.357(-11.7\%)}$
NLO QCD + PS	$2.36(2)^{+0.12(+5.0\%)}_{-0.10(-4.0\%)}$

[Work in progress: RF, D. Pagani, I. Tsinikos]

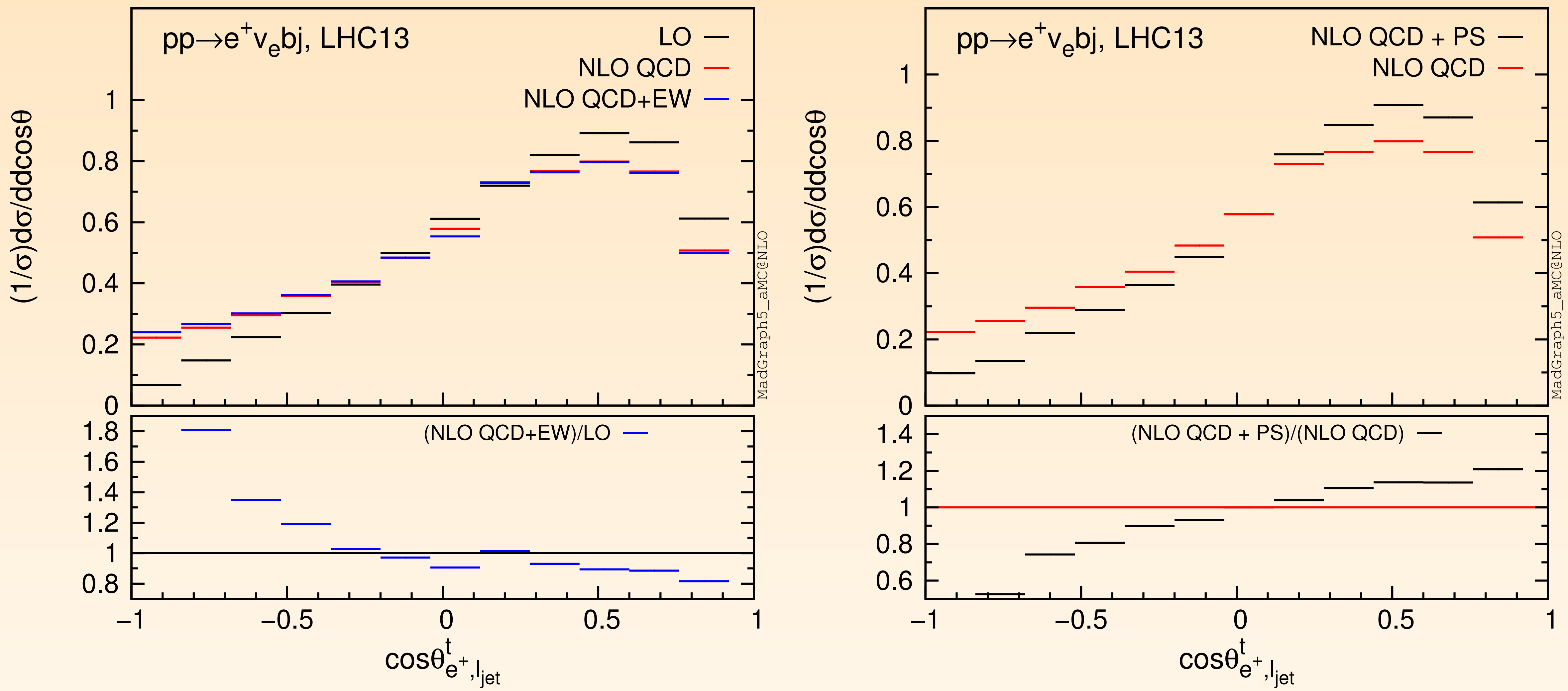
Differential distributions 1



- ✦ Lepton + b-jet invariant mass
- ✦ *left*: Fixed order comparison; *right*: NLO vs NLO+PS (with QCD corrections)
- ✦ EW corrections small compared to other effects

[Work in progress: RF, D. Pagani, I. Tsinikos]

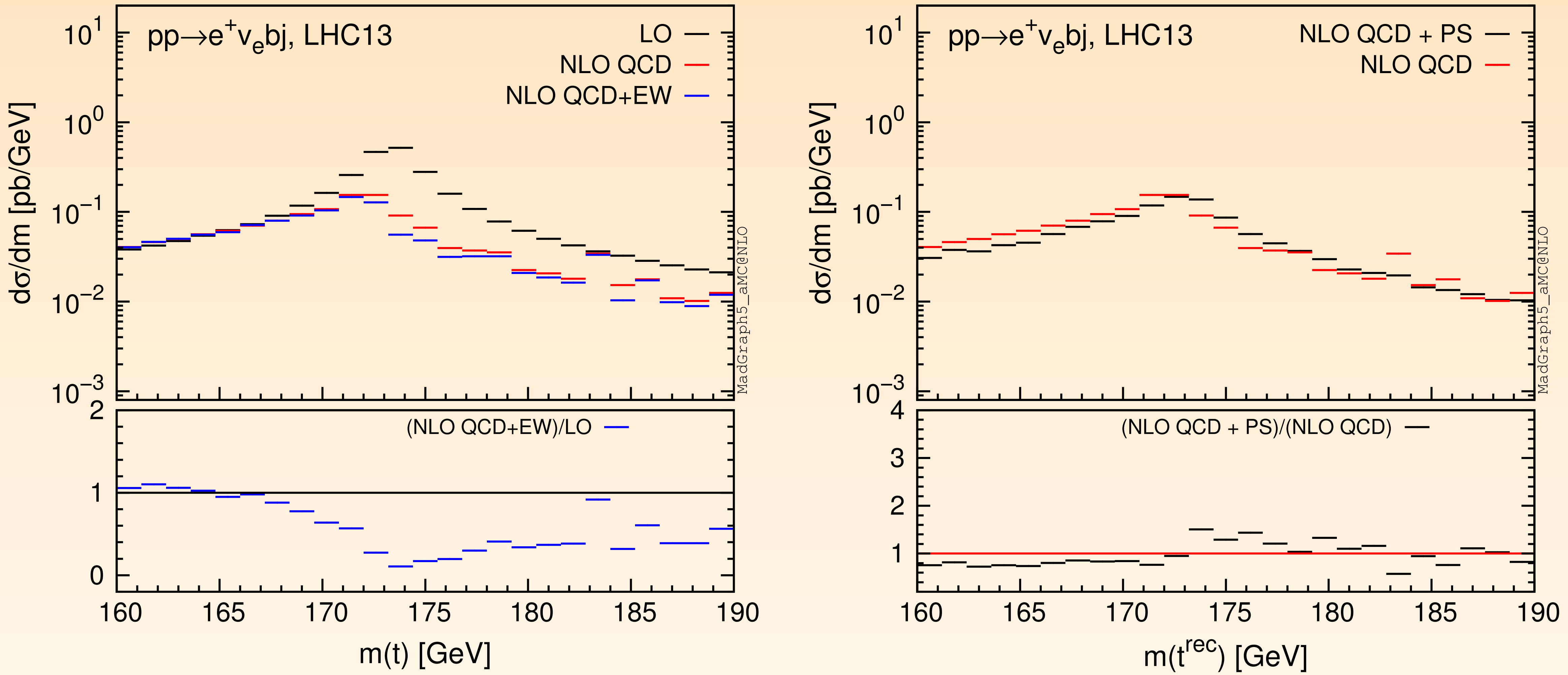
Differential distributions 2



- Angle between lepton, in the top rest-frame, and light jet: very sensitive to spin correlations
- Effects from parton shower again larger than from EW corrections

[Work in progress: RF, D. Pagani, I. Tsinikos]

Differential distributions 3



- ✦ Reconstructed to quark mass from lepton, b-jet and missing energy, using W-boson mass constraint
- ✦ EW corrections are of similar size as compared to effects from parton shower

[Work in progress: RF, D. Pagani, I. Tsinikos]

Conclusions

- NLO EW corrections are a part of a family of NLO corrections due to the mixed coupling expansion of the perturbative series (**complete-NLO**)
- Automation of **complete-NLO** for all* relevant SM processes (e.g. in MadGraph5_aMC@NLO v3_beta)
- Not covered: beyond NLO_{QCD} the distinction between jets, photons and leptons becomes non-trivial without fragmentation functions (work in progress)
- Work-in-progress: consistent matching to parton showers when including NLO_{EW} corrections
- EW corrections to single-top production are small, but enhanced in tails of distributions. Also applying a jet-veto enhances the effects from higher-order corrections enormously, but here the EW corrections remain smaller than other effects