

Alexander von Humboldt Stiftung/Foundation

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 nonperturbative 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

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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**

EW corrections

Top pair transverse momentum

 $e^+e^-\mu^+\mu^-$ NLO (x10)

p
p_T(tt̄) [GeV]

 e^+

LO (x10)

LO

MadGraph5_aMC@NLO

MadGraph5_aMC@NLO

MadGraph5_aMC@NLO

ν_eμ[−]ν_μ NLO

- Just as one can have a perturbative series in the strong reserve coupling, one can also include higher order corrections in the electroweak (EW) coupling 10^{-6} 10^{-5} 10^{-4} 10−² LO (x3) \mathcal{P}_{α}^{0} \mathbf{m}_{α} in \mathbf{h}_{α} of \mathcal{P}_{α}^{0} σ per bin [pb] Z^2 _N \mathbf{D}^2 _(x3) ZZZNLO LO Hardest vector boson transverse momentum
- By comparing the strength of the strong to the EW_{\perp} coupling, one expects that NNLO @CD corrections of similar importance to NLO EW corrections 100 200 500 1000 2000 10^{-7} $\frac{1}{2}$ \mathbf{Q} NLO/LO 500 1000
 $p_T(V_1)$ [GeV]
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		- $\text{Close to EW resonances, radiation from decay.}$ products results in sizeable changes with $\mathbb{E}_{0.7}^{\frac{1}{2}}$ 10^{-5} 0.9 1.1 HU
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2 10 20 50 100 200 500 1000
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0.9
2 ^{0.8} 10 20 50 100 200 500
 $p_T(\|I\|/|V)$ [GeV] private version of MG5 aMC. The *p^T* (*tt*

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
	- O 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 , Mw and Mz (with α measured in Thomson scattering, and M_W and M_Z the on-shell weak boson masses)

O Other EW parameters are then predictions: vev, G_F, sin(θ_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 Schemes recap **VEDVIEW** As we said, one has to get rid of the *m^f* dependence, but not via the ↵MS-scheme. The

 $\{\alpha(0), M_W, M_Z\} \rightarrow \alpha(0)$ scheme $\{\alpha(M_Z), M_W, M_Z\} \rightarrow \alpha(M_Z)$ scheme ${G_{\mu}, M_W, M_Z} \rightarrow G_{\mu}$ scheme $\delta Z_e = -\frac{1}{2}$ 2 $\delta Z_{AA}-\frac{s_W}{c_W}$ c_W 1 2 δZ_{ZA} $\zeta z \perp z = \zeta z \perp \frac{1}{\Delta \alpha} (\Omega^2)$ $\sigma \mathcal{L}_{e}(\alpha(q^2)) = \sigma \mathcal{L}_{e}(\alpha(0))$ $2^{\frac{1}{\sigma}(\alpha(q^2))}$ In the on-shell scheme the weak mixing angle is a derived quantity. For a derived $\frac{1}{\sqrt{2}}$ is a derived $\frac{1}{\sqrt{2}}$ $\delta Z_e|_{G_\mu}\equiv\delta Z_e|_{\alpha(0)}-\frac{1}{2}\Delta r=$ sin² θ^W = s² ^W = 1 [−] ^M² \sim renormalized gauge boson masses. This definition is independent of a specific spe process and valid to all orders of perturbations of perturbation theory. The perturbation theory. The contract of per Since the dependent parameters s^W and c^W frequently appear, it is useful to introduce \vdots corresponding control G_{μ} $\delta Z_{\text{eff}} = -\frac{1}{2} \delta Z_{\text{eff}} - \frac{S_{W}}{2} \frac{1}{2} \delta Z_{Z_{\text{eff}}}$ alization of the condition of $2^{0.7}$ and $c_W 2^{0.7}$ $2^{0.7}$ The scheme ↵(*Q*2) is defined as $\delta Z_e|_{\alpha(Q^2)} \equiv \delta Z_e|_{\alpha(0)} - \frac{1}{2}$ 2 $\delta Z_e|_{\alpha(Q^2)} \equiv \delta Z_e|_{\alpha(0)} - \frac{1}{2}\Delta\alpha(Q^2)$ $\delta Z_e|_{\alpha(m^2)} - \frac{1}{e} \left(-\frac{c_W^2}{2} \Delta \rho + \Delta r_{\text{rem}} \right)$ $\sigma \Omega_e |\alpha(m_Z^2)| = \frac{1}{2} \left(\frac{-\frac{1}{2}}{s_W^2} \Delta \rho + \Delta r \text{ rem} \right)$ **A**
A *^T* (*k*2) $\mathcal{L}(\mathbf{q})$ change is defined as $\mathcal{L}(\mathbf{q})$ 2 $\delta Z_e|_{G_\mu} \equiv \delta Z_e|_{\alpha(0)} - \frac{1}{2}\Delta r = 0$ eqs. (5.3) and (5.6). Every time we have a *W* interaction with a quark the coupling is $g(x) = 1/127$ (14) $1/128$ (14.32) with *s*
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Another way to see this: every *g*² = ↵*/s*²

BACK

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) = *g*(*Z^e* +

*s*2

For example: consider di-jet production which can immediate graphic interpretation, depending interpretation, depicted in fig. 1. Such an interpretation, depending in fig. 1. Such an interpretation, depending in fig. 1. Such an interpretation, depending in the s

- ◆ "NLO EW" is a bit of a misnomer: NLO2 and NLO3 part of a "mixed" expansion
- "**Complete-NLO**" takes all the LO and NLO contributions in the mixed coupling expansion into account has the mixed coupling expansion into account in the mixed coupling expansion into account

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NLO dissection NLO DISSECTION

COMPLETE-NLO TO INCLUSIVE JET-PT .USIVE JET-PT

- eq. (2.25) + Inclusive jet-pr
	- Expectation (assume $\alpha_s=0.1$, $\alpha=0.01$): α and α and α α α on (assume $\alpha_{S} = 0.1, \alpha = 0.01$): α (2.26) α and α and α and α). π (assume u₅-0.1, u-0.01).

- $\big\{\quad$ $\big\}$ $\big\}$ $\big\}$ Size of corrections mostly follows what one expects from the coupling see indeed in the combinations on the left of that figure as representing $\frac{1}{2}$ $\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$ real-emission corrections to the $\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$ has a Feynman-diagram counterpart in the case of real-emission contributions, which is not real-emission contributions, which is not real- $\frac{1}{2}$ what one expects from the coupling
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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 1
- However, t- and s-channel differentiation needs to be revisited
	- At NLOEW, 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
	- O 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).

LO

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NLOQCD NLOEW

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

Off-shell effects

- Generate the process at complete-NLO $p p > e + v e j j$
- 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] 13

OFF-SHELL EFFECTS

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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

 $pp \rightarrow e^+v_e^+$ *v_e* bj , PDFs=LUXQED17 (82200)

$$
\mu_f^0 = \mu_r^0 = H_T/2
$$

[Work in progress: RF, D. Pagani, I. Tsinikos]¹⁴

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] ¹⁵

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] ¹⁶

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] 17

- 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 NLOEW corrections
- EW corrections to single-top production are small, but enhanced in tails of distributions. Also applying a jet-veto enhances the effects from higherorder corrections enormously, but here the EW corrections remain smaller than other effects