A Study of Weak Corrections to Drell-Yan, Top-quark pair and Di-jet Production at High Energies with MCFM

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Outline

- Introduction
- Implementation of Weak Corrections in `MCFM`
  - Exact One-loop Corrections
  - Leading and Subleading Logarithms in the Sudakov regime
- Impact of weak one-loop corrections and comparison with existing results
- Effectiveness of the Sudakov approximation
- Combination of QCD and Weak Corrections
- Conclusions

Introduction

- As the CERN Large Hadron Collider (LHC) is operating at an unprecedented high energy and is reaching unrivalled precision, the inclusion of electroweak (EW) corrections becomes increasingly important.
- This is equally true in tests of the Standard Model (SM) and in searches for signals of new physics, in particular in the high-energy and high-momentum regimes of kinematic distributions.
- Electroweak corrections at high energies may also play a significant role in the extraction of parton distribution functions (PDFs), e.g., in constraining the gluon PDF at high momentum fraction in di-jet production.

Introduction

- The importance of weak corrections at high energies is due to the occurrence of soft and collinear radiation of virtual and real W and Z bosons. These give rise to Sudakov-like corrections that take the form

$$\alpha_W^l \log^n(Q^2/M_{W,Z}^2),\ \alpha_W = \alpha/(4\pi \sin^2\theta_W)\ (n \leq 2l-1)$$

- Some automated tools such as `RECOLA`, `SHERPA/MUNICH+OPENLOOPS`, `GOSAM`, `MADGRAPH5_aMC@NLO`, `NLOX` have the ability to perform NLO EW calculations. However, dedicated and efficient computations for specific processes, including also QCD corrections in the same way, is still highly desirable for LHC studies.

Introduction

- We present calculations concerning weak effect to three key SM processes at the LHC:
  - Neutral-Current (NC) Drell-Yan (DY) process,
  - strong top-anti-top-quark pair ($t\bar{t}$)
  - di-jet

  in the framework of the widely used, publicly available parton-level Monte Carlo (MC) program `MCFM` [1]
- The implementation of weak one-loop corrections in `MCFM` includes both the exact weak corrections and their Sudakov approximation based on the general algorithm of Denner-Pozzorini [2].

[1] `http://mcfm.fnal.gov/`

[2] A.Denner, S.Pozzorini (2001)

Cross Section at Hadron Level

$2 \to 2$: $i(p_1) + j(p_2) \to k(p_3) + l(p_4)$

$$d\sigma\left(P_1, P_2\right) = \frac{1}{1+\delta_{ij}} \sum_{i,j} \Bigg[\int_0^1 dx_1 \int_0^1 dx_2 \times f_i\left(x_1, \mu_F^2\right) f_j\left(x_2, \mu_F^2\right) d\hat{\sigma}_{ij}\left(\mu_R^2\right) + i \leftrightarrow j \Bigg]$$

$$\hat{s} = \left(p_1 + p_2\right)^2 = \left(p_3 + p_4\right)^2, \ \hat{t} = \left(p_1 + p_3\right)^2 = \left(p_2 + p_4\right)^2, \ \hat{u} = \left(p_1 + p_4\right)^2 = \left(p_2 + p_3\right)^2$$

$$d\hat{\sigma} = dP_{kl} \overline{\sum} [|\mathcal{M}_0|^2 (\alpha^m \alpha_s^n) + 2\mathcal{R}e(\delta\mathcal{M} \times \mathcal{M}_0^*)(\alpha^{m+1}\alpha_s^n)]$$

- $(m, n) = (2, 0)$ for NC-DY, $(m, n) = (0, 2)$ for $\mathrm{t\bar{t}}$ and di-jet
- dP_{kl}: final-state phase space

Neutral-current Drell-Yan production

Weak one-loop corrections to the parton-level LO

- vertex correction: form factors $\hat{F}^{\lambda}(\hat{s}, M_{V^a}), \hat{G}^{\lambda}(\hat{s}, M_{V^a})$; self-energy correction: $\hat{\Sigma}_T^{V^aV^b}(\hat{s})$ [W.Hollik (1990)]
  [W.Beenakker, S.C.van der Marck, and W.Hollik (1991)]
- box correction: $Z/W^{\pm}$ pairs, recomputed in terms of scalar integrals valuated by `QCDLoop` [R.K.Ellis and G.Zanderighi (2008)]

Choice of EW input scheme:

- $\alpha(0)$, $\alpha(M_Z^2)$, and G_μ
- `MCFM` default - G_μ

$$\alpha_{G_\mu} = \alpha(0)/[1 - \Delta r]$$

$$\Delta r^{1-\text{loop}} = \Delta\alpha(M_Z^2) - \frac{c_w^2}{s_w^2}\Delta\rho + \Delta r_{rem} = \frac{\hat{\Sigma}_T^W(0)}{M_W^2} + \frac{\alpha}{4\pi s_\mathrm{W}^2}\left(6 + \frac{7 - 4s_\mathrm{W}^2}{4s_\mathrm{W}^2}\log c_\mathrm{W}^2\right)$$

Neutral-current Drell-Yan production

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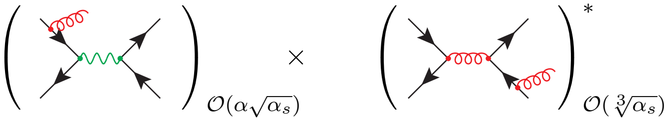
Top-quark pair production

[J.H.Kühn, A.Scharf, P.Uwer (2006)]
[J.H.Kühn, A.Scharf, P.Uwer (2007)]

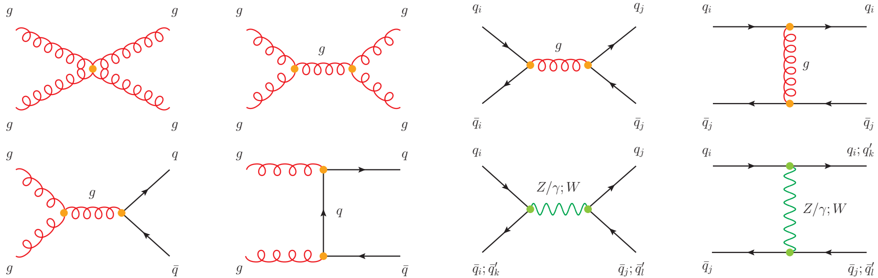
Weak one-loop contributions of $\mathcal{O}(\alpha\alpha_s^2)$ to total cross sections

- `MCFM` adopts published analytic expressions of virtual corrections to $q\bar{q}$ and gg
- real contributions are recomputed to cancel IR divergence from box contributions, where the cancellation of IR poles are performed by using Catani-Seymour dipole subtraction method [S.Catani, M.H.Seymour (1997)] [S.Catani, M.H.Seymour, Z. Trocsany (2002)]



Di-jet production

LO contributions of $\mathcal{O}\left(\alpha_s^2\right)$, $\mathcal{O}\left(\alpha^2\right)$ and $\mathcal{O}\left(\alpha_s\alpha\right)$



sample tree-level Feynman diagrams for di-jet production via QCD and EW interaction

Di-jet production

One-loop correction at fixed $\mathcal{O}(\alpha\alpha_s^2)$

$$d\hat{\sigma}(\alpha_s^2\alpha) \propto 2\mathrm{Re}\left[\delta\mathcal{M}(\alpha_s\alpha)\cdot\mathcal{M}_0^*(\alpha_s)+\delta\mathcal{M}(\alpha_s^2)\cdot\mathcal{M}_0^*(\alpha)\right]$$

- four-gluon: no EW correction
- four-quark: direct calculation $q_i\bar{q}_i \to q_j\bar{q}_j$ $(q_{i,j}\in\{u,d,c,s\})$
  - virtual correction: renormalized weak form factor $f_1(M_{V^a}/x)$ $(x=\hat{s},\ldots)$ [J.H.Kühn, A.Scharf, P.Uwer (2010)] rest are recomputed including QCD vertex and self-energy, as well as box contributions
  - real correction: $q_i\bar{q}_i \to q_j\bar{q}_j + g$ Catani-Seymour dipole subtraction [S.Catani, M.H.Seymour (1997)]

rest contribution obtained via crossing relation, e.g.
$|\mathcal{M}^{q_iq_j\to q_iq_j(g)}|^2_{\mathcal{O}(\alpha\alpha_s^2)} = |\mathcal{M}^{q_i\bar{q}_i\to q_j\bar{q}_j(g)}|^2_{\mathcal{O}(\alpha\alpha_s^2)}(2\to3\to4\to2)$

Di-jet production

One-loop correction at fixed $\mathcal{O}(\alpha\alpha_s^2)$

- two-gluon-two-quark: direction calculation $gg \to q\bar{q}$
  - virtual correction: renormalized vertex and self-energy
    $|\mathcal{M}^{V_i(gg\to q\bar{q})}|^2 = -2|\mathcal{M}^{\Sigma_i(gg\to q\bar{q})}|^2$
    box correction recomputed [J.H.Kühn, A.Scharf, P.Uwer (2010)]
    rest obtained via crossing relation, e.g.
    $|\mathcal{M}^{qg\to qg}|^2_{\mathcal{O}(\alpha\alpha_s^2)} = |\mathcal{M}^{gg\to q\bar{q}}|^2_{\mathcal{O}(\alpha\alpha_s^2)}(1 \leftrightarrow 4; \hat{s} \leftrightarrow \hat{t})$
  - real correction: via crossing relation of $q_i\bar{q}_i \to q_j\bar{q}_j + g$
    e.g.,
    $|\mathcal{M}^{q_i g\to q_i q_j \bar{q}_j}|^2_{\mathcal{O}(\alpha\alpha_s^2)} = -|\mathcal{M}^{q_i\bar{q}_i\to q_j\bar{q}_j g}|^2_{\mathcal{O}(\alpha\alpha_s^2)}(5 \to 2 \to 3 \to 4 \to 5)$
    trivial initial collinear singularities absorbed into PDF CTs

Formulism for EW logarithmic terms

Logarithmic correction factorize to Born amplitude dominant in Sudakov regime $|\hat{s}_{ij}| \sim \hat{s} \gg M_W^2$ [A.Denner, S.Pozzorini (2001)]

- double logarithms $\log^2(\hat{s}_{kl}/M_{V^a}^2)$: soft-collinear virtual gauge boson exchange between external legs k, l
- single logarithms: collinear mass singularities, wave function and parameter renormalizations

leading approximation (LA) limit of $\mathcal{O}(\alpha)$ weak correction to LO amplitude $\mathcal{M}_0$

$$\delta\mathcal{M} = \frac{\alpha}{4\pi}\left(\delta^{\mathrm{LSC}} + \delta^{\mathrm{SSC}} + \delta^{\mathrm{C}} + \delta^{\mathrm{PR}}\right)\mathcal{M}_0$$

Neutral-Current Drell-Yan Process

- LO amplitude in LA

$$\mathcal{M}_0^{q_\rho^\tau l_\sigma^\lambda} = 4\pi\alpha R_{q_\rho^\tau l_\sigma^\lambda} \frac{\mathcal{A}_{\tau\lambda}}{\hat{s}}\,, \quad \mathcal{A}_{\mathrm{LL}} = \mathcal{A}_{\mathrm{RR}} = \hat{u}\,, \quad \mathcal{A}_{\mathrm{LR}} = \mathcal{A}_{\mathrm{RL}} = \hat{t}$$

$$R_{q_\rho^\tau l_\sigma^\lambda} = \sum_{N=Z,\gamma} I^N_{q_\rho^\tau} I^N_{l_\sigma^\lambda} = \frac{Y_{q_\rho^\tau} Y_{l_\sigma^\lambda}}{4c_{\mathrm{W}}^2} + \frac{T^3_{q_\rho^\tau} T^3_{l_\sigma^\lambda}}{s_{\mathrm{W}}^2}\,, \quad Q = Y/2 + T^3$$

- logarithmic contributions

$$\delta^{\mathrm{LSC}}_{q_\rho^\tau l_\sigma^\lambda} = -\left(C^{\mathrm{wk}}_{q_\rho^\tau} + C^{\mathrm{wk}}_{l_\sigma^\lambda}\right)\log^2\left(\frac{\hat{s}}{M_W^2}\right) + 2\log\left(\frac{M_Z^2}{M_W^2}\right)\left[\left(I^Z_{q_\rho^\tau}\right)^2 + \left(I^Z_{l_\sigma^\lambda}\right)^2\right]\log\left(\frac{\hat{s}}{M_W^2}\right),$$

$$\begin{aligned}\delta^{\mathrm{SSC}}_{q_\rho^\tau l_\sigma^\lambda} = &- 4\left[\log\left(\frac{\hat{s}}{M_W^2}\right) - \log\left(\frac{M_Z^2}{M_W^2}\right)\right] R_{q_\rho^\tau l_\sigma^\lambda}\left(I^Z_{q_\rho^\tau} I^Z_{l_\sigma^\lambda}\right)\log\left(\frac{\hat{t}}{\hat{u}}\right) \\ &- \frac{\delta_{\tau\mathrm{L}}\delta_{\lambda\mathrm{L}}}{s_{\mathrm{W}}^4 R_{q_\rho^\tau l_\sigma^\lambda}}\log\left(\frac{\hat{s}}{M_W^2}\right)\left[\delta_{\rho\sigma}\log\left(\frac{|\hat{t}|}{\hat{s}}\right) - \delta_{-\rho\sigma}\log\left(\frac{|\hat{u}|}{\hat{s}}\right)\right],\end{aligned}$$

$$\delta^{\mathrm{C}}_{q_\rho^\tau l_\sigma^\lambda} = 3\left(C^{\mathrm{wk}}_{q_\rho^\tau} + C^{\mathrm{wk}}_{l_\sigma^\lambda}\right)\log\left(\frac{\hat{s}}{M_W^2}\right), \quad \delta^{\mathrm{PR}}_{q_\rho^\tau l_\sigma^\lambda} = \left(\frac{s_{\mathrm{W}}}{c_{\mathrm{W}}} b^{\mathrm{ew}}_{\mathrm{AZ}}\Delta_{q_\rho^\tau l_\sigma^\lambda} - b^{\mathrm{ew}}_{\mathrm{AA}}\right)\log\left(\frac{\hat{s}}{M_W^2}\right).$$

$$\Delta_{q_\rho^\tau l_\sigma^\lambda} := \left(-\frac{1}{4c_{\mathrm{W}}^2} Y_{q_\rho^\tau} Y_{l_\sigma^\lambda} + \frac{c_{\mathrm{W}}^2}{s_{\mathrm{W}}^4} T^3_{q_\rho^\tau} T^3_{l_\sigma^\lambda}\right) / R_{q_\rho^\tau l_\sigma^\lambda}\,, \quad b^{\mathrm{ew}}_{AZ} = -\frac{19 + 22 s_{\mathrm{W}}^2}{6 s_{\mathrm{W}} c_{\mathrm{W}}}\,, \quad b^{\mathrm{ew}}_{AA} = -\frac{11}{3}$$

$$C^{\mathrm{wk}}_{f^\kappa} = C^{ew}_{f^\kappa} - Q^2_{f^\kappa}\,, \quad I^Z_{f^\kappa} = \left(T^3_{f^\kappa} - s_{\mathrm{W}}^2 Q_{f^\kappa}\right) / \left(s_{\mathrm{W}} c_{\mathrm{W}}\right)$$

Top-quark Pair Production

- logarithmic contributions

$$\delta^{\mathrm{LSC}}_{q_1^\tau q_2^\lambda} = -\left(C^{\mathrm{wk}}_{q_1^\tau} + C^{\mathrm{wk}}_{q_2^\lambda}\right)\log^2\left(\frac{\hat{s}}{M_W^2}\right) + 2\log\left(\frac{M_Z^2}{M_W^2}\right)\left[\left(I^Z_{q_2^\lambda}\right)^2 + \left(I^Z_{q_2^\lambda}\right)^2\right]\log\left(\frac{\hat{s}}{M_W^2}\right),$$

$$\delta^{\mathrm{SSC}}_{q_1^\tau q_2^\lambda} = -\,4\left[\log\left(\frac{\hat{s}}{M_W^2}\right) - \log\left(\frac{M_Z^2}{M_W^2}\right)\right]\left(I^Z_{q_1^\tau} I^Z_{q_2^\lambda}\right)\log\left(\frac{\hat{t}}{\hat{u}}\right)\,\delta_{q_1 q},$$

$$\delta^{\mathrm{C}}_{q_1^\tau q_2^\lambda} = 3\left(C^{\mathrm{wk}}_{q_1^\tau} + C^{\mathrm{wk}}_{q_2^\lambda}\right)\log\left(\frac{\hat{s}}{M_W^2}\right) - \frac{1}{4s^2_{\mathrm{W}}}\left[\delta_{q_1 t}\,(1+\delta_{\tau R}) + \delta_{q_2 t}\,(1+\delta_{\lambda R})\right]\frac{m_t^2}{M_W^2}\log\left(\frac{\hat{s}}{m_t^2}\right)$$

- correction ($\delta\mathcal{M}$) interferes LO amplitude ($\mathcal{M}_0$)

$$\sum_{\tau,\lambda=\mathrm{L,R}}\left(\delta\mathcal{M}^{q_1 q_2}_{\tau\lambda}\right)\cdot\left(\mathcal{M}^{q_1 q_2}_{0,\tau\lambda}\right)^* = \frac{1}{4}\frac{1}{N^2_{q_1 q_2}}\frac{\alpha}{4\pi}\sum_{\tau,\lambda=\mathrm{L,R}}\left(\delta^{\mathrm{LSC}}_{q_1^\tau q_2^\lambda} + \delta^{\mathrm{SSC}}_{q_1^\tau q_2^\lambda} + \delta^{\mathrm{C}}_{q_1^\tau q_2^\lambda}\right)|\mathcal{M}^{q_1 q_2}_{0,\tau\lambda}|^2$$

$$N_{qt} = N_c = 3, \quad N_{tt} = N_c^2 - 1 = 8$$

Di-jet Production

- logarithmic contributions
  same part of contributions as in $\mathrm{t\bar{t}}$ with $m_t \to 0$, additional part of contributions involving W exchange in $\hat{t}, \hat{u}$ channels
- additional contribution to partonic differential cross section

$$(\delta\mathcal{M})_W \cdot (\mathcal{M}_0)^* = -\frac{\alpha}{2\pi s_{\mathrm{W}}^2}\left[\log\left(\frac{\hat{s}}{M_W^2}\right) - \log\frac{M_Z^2}{M_W^2}\right]\left[\log\left(\frac{-\hat{t}}{\hat{s}}\right)\delta_{q_i q_j}\left(|\mathcal{M}_{\mathrm{LL}}^{\mathrm{q\bar{q}}}|^2_{\mathrm{t\times t}} + |\mathcal{M}_{\mathrm{LL}}^{\mathrm{q\bar{q}}}|^2_{\mathrm{t\times s}}\right) - \log\left(\frac{-\hat{u}}{\hat{s}}\right)|V_{q_i q_j}|^2|\mathcal{M}_{\mathrm{LL}}^{\mathrm{q\bar{q}}}|^2_{\mathrm{t\times s}}\right].$$

$$(V_{ud} = V_{cs} = 1)$$

Neutral-current Drell-Yan production

Comparison with ZGRAD2 at 13 TeV

[U.Baur, O.Brein, W.Hollik, C.Schappacher, D.Wackeroth (2002)]

$$p_T(l^\pm) > 25 \text{ GeV}, \quad |\eta(l^\pm)| < 2.5\,, \quad M(l^+l^-) > 60 \text{ GeV}$$

- comparison of total cross section

	σ_{LO} (pb)	σ_{wk} (pb)	$\delta\sigma_{wk}$[3] (%)
MCFM	712.44(2)	4.474(3)	0.628
ZGRAD2	712.41(2)	4.483(3)	0.629

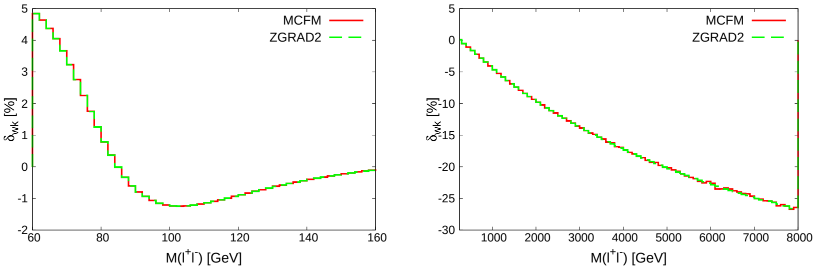
- comparison of differential cross section relative weak one-loop correction:

$$\delta_{\text{wk}} = \frac{d\sigma_{NLO}^{\text{wk}} - d\sigma_{LO}}{d\sigma_{LO}}$$

[3] $\delta\sigma_{wk} = \sigma_{wk}/\sigma_{LO}$

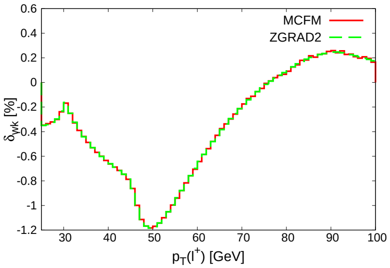
Neutral-current Drell-Yan production

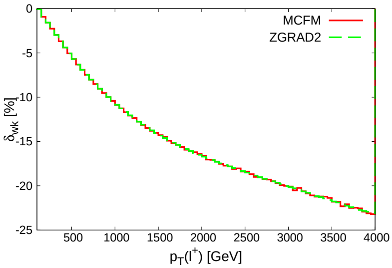
- invariant mass of the lepton pair ($l = e \, \mathrm{or} \, \mu$)



Neutral-current Drell-Yan production

- lepton transverse momentum ($p_T(l^+)$)



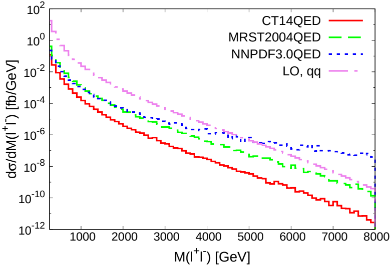


Neutral-current Drell-Yan production

- $\gamma\gamma \to l^+l^-$ at LO $\mathcal{O}\left(\alpha^2\right)$ at 14 TeV [S.Dittmaier, M.Huber (2010)]

$M(l^+l^-)$ [GeV]	50-∞	100-∞	200-∞	500-∞	1000 -∞	2000-∞
$\sigma^{MCFM}_{\gamma\gamma,0}$ [fb]	1287.98(7)	377.77(5)	63.88(1)	3.9809(7)	0.35407(7)	0.018759(4)
$\sigma^{DH}_{0}\vert_{FS/PS}$ [fb]	738773(6)	32726.8(3)	1484.92(1)	80.9489(6)	6.80008(3)	0.303767(1)
σ^{MCFM}_{0} [fb]	739272(13)	32881.5(6)	1484.37(30)	81.0745(16)	6.8103(1)	0.304209(5)
$\delta^{DH}_{\gamma\gamma,0}$[%]	0.17	1.15	4.30	4.92	5.21	6.17
$\delta^{MCFM}_{\gamma\gamma,0}$[%]	0.17	1.15	4.30	4.91	5.20	6.17

- invariant mass of photon-induced process compared with that of $q\bar{q}$ initiated process (13 TeV)



recent work with efforts to improve photon PDF
[A.D.Martin, M.G.Ryskin (2014)]
[L.A.Harland-Lang *et al* (2016)]
[A.Manohar *et al* (2016)]

Top-quark pair production

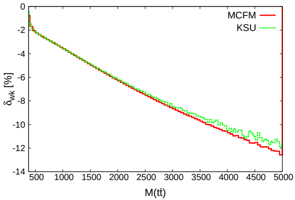
Comparison with KSU at parton- and hadron-level (13 TeV)

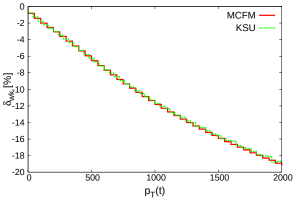
[J.H.Kühn, A.Scharf, P.Uwer (2015)]

- comparison of total cross section

	σ_{LO} (pb)	$\delta\sigma_{\rm wk}$ (%)	$\delta\sigma_{\rm wk} \times \sigma_{LO}$ (pb)
MCFM	474.60(4)	-2.01	-9.50
KSU	–	-2.00	-9.48

- comparison of differential cross section
  - kinematic distributions: $M_{\rm t\bar{t}}$, $p_T(t)$





Di-jet production

Comparison with DHS at the 14 TeV LHC

[S.Dittmaier, A.Huss, C.Speckner (2012)]

- comparison of $\delta_{\rm wk}$, $\delta^{\rm tree}_{\rm EW}$

$$\text{anti}-k_T,\ R = 0.6; \quad k_T(j) > 25\ \text{GeV}, \quad |y(j)| < 2.5$$

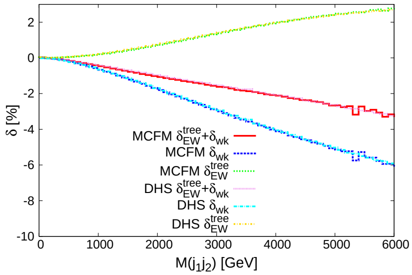
- in various ranges of $M(j_1 j_2)$, $k_T(j_1)$

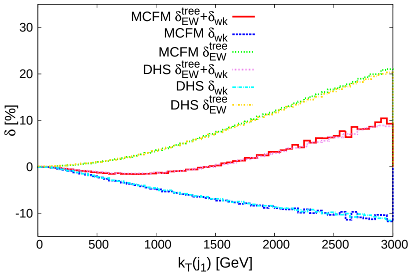
$M(j_1j_2)$	[GeV]	$50-\infty$	$100-\infty$	$200-\infty$	$500-\infty$	$1000-\infty$	$2000-\infty$	$5000-\infty$
$\delta_{\rm wk}[\%]$	DHS	-0.02	-0.03	-0.07	-0.31	-0.88	-2.20	-5.53
	MCFM	-0.02	-0.03	-0.07	-0.31	-0.88	-2.23	-5.57
$\delta^{\rm tree}_{\rm EW}[\%]$	DHS	0.03	0.01	0.02	0.10	0.34	1.00	2.56
	MCFM	0.03	0.01	0.02	0.08	0.30	0.96	2.61

$k_T(j_1)$	[GeV]	$25-\infty$	$50-\infty$	$100-\infty$	$200-\infty$	$500-\infty$	$1000-\infty$	$2500-\infty$
$\delta_{\rm wk}[\%]$	DHS	-0.02	-0.08	-0.28	-0.84	-2.72	-5.48	-10.49
	MCFM	-0.02	-0.08	-0.28	-0.83	-2.75	-5.64	-10.41
$\delta^{\rm tree}_{\rm EW}[\%]$	DHS	0.03	0.03	0.12	0.36	1.44	4.62	18.28
	MCFM	0.03	0.03	0.11	0.33	1.42	4.72	18.88

Di-jet production

- comparison of δ_{wk}, $\delta_{\mathrm{EW}}^{\mathrm{tree}}$
  - kinematic distributions: $M(j_1 j_2)$, $k_T(j_1)$



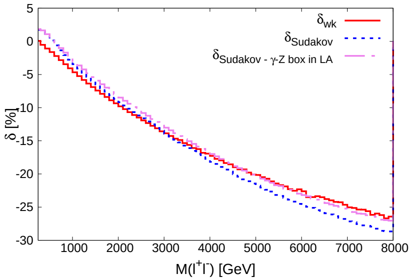


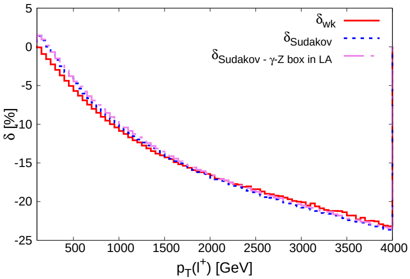
Neutral-Current Drell-Yan process

Relative weak Sudakov correction

$$\delta_{\text{Sudakov}} = \frac{d\sigma^{\text{Sudakov}}_{NLO} - d\sigma_{LO}}{d\sigma_{LO}}$$

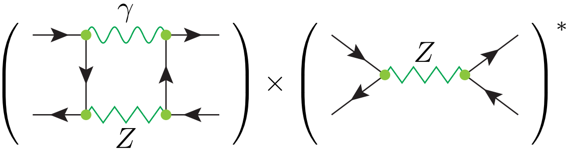
- kinematic distributions: $M(l^+l^-)$, $p_T(l^+)$ (13 TeV)





Neutral-Current Drell-Yan process

- exact weak one-loop corrections: γ-Z contribution excluded



- γ-Z box contribution in leading approximation (LA):

$$
\begin{aligned}
&\overline{\sum}\mathrm{Re}\left(\delta^{\mathrm{SSC,Z}}\mathcal{M}_0\times\mathcal{M}_0^*\right)=\frac{2}{3}\alpha^3\pi\cdot\frac{-16}{\hat{s}^2}\cdot\log\left(\frac{\hat{t}}{\hat{u}}\right)\log\left(\frac{\hat{s}}{M_Z^2}\right)\cdot\Bigg\{\\
&+Q_q^2Q_l^2\left[g_v^q g_v^l\left(\hat{t}^2+\hat{u}^2\right)-g_a^q g_a^l\left(\hat{t}^2-\hat{u}^2\right)\right]\\
&+2\,Q_qQ_l\left[\left(g_v^{q\,2}+g_a^{q\,2}\right)\left(g_v^{l\,2}+g_a^{l\,2}\right)\left(\hat{t}^2+\hat{u}^2\right)-4g_v^q g_v^q g_a^q g_a^l\left(\hat{t}^2-\hat{u}^2\right)\right]\\
&+\left(g_v^q g_v^l+g_a^q g_a^l\right)\left[\left(g_v^q g_v^l+g_a^q g_a^l\right)^2+3\left(g_v^q g_a^l+g_a^q g_v^l\right)^2\right]\hat{u}^2\\
&-\left(g_v^q g_v^l-g_a^q g_a^l\right)\left[\left(g_v^q g_v^l-g_a^q g_a^l\right)^2+3\left(g_v^q g_a^l-g_a^q g_v^l\right)^2\right]\hat{t}^2\Bigg\}
\end{aligned}
\tag{1}
$$

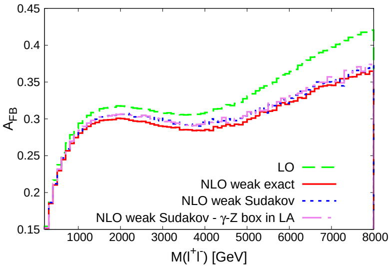
Neutral-Current Drell-Yan process

- Forward-Backward asymmetry A_{FB}:

$$A_{\mathrm{FB}} = \frac{F-B}{F+B}, \quad F = \int_0^1 \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*}\,\mathrm{d}\cos\theta^*,\ B = \int_{-1}^0 \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*}\,\mathrm{d}\cos\theta^*$$

$$\cos\theta^* = \frac{|p_z(l^+l^-)|}{p_z(l^+l^-)} \frac{2}{M(l^+l^-)\sqrt{M^2(l^+l^-)+p_T^2(l^+l^-)}}\left[p^+(l^-)p^-(l^+) - p^-(l^-)p^+(l^+)\right]$$

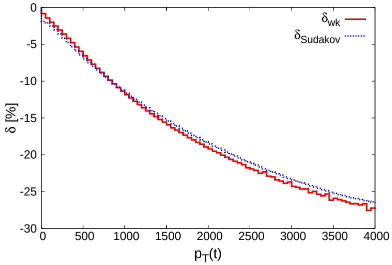
  - the search for extra gauge boson (Z') in the high-invariant mass region [E. Accomando *et al* (2016)]

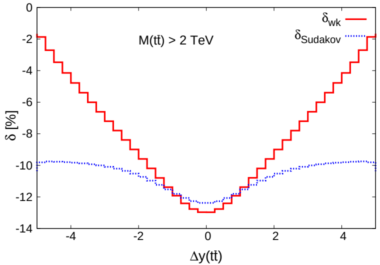


Top-quark pair production

Comparison of Sudakov approximation with exact weak one-loop at 13 TeV

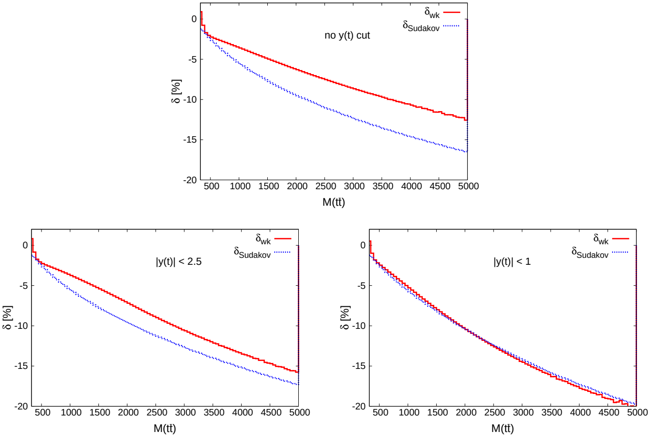
- kinematic distributions: $p_T(t)$, $\Delta y(t\bar{t})$





Top-quark pair production

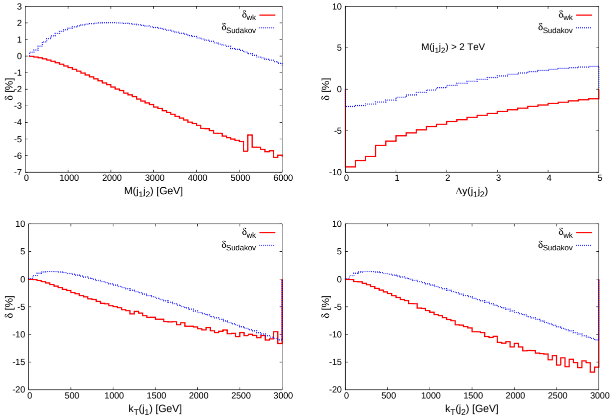
- kinematic distribution: $M(t\bar{t})$



Di-jet production

Comparison performed at the 13 TeV LHC

- kinematic distributions: $M(j_1 j_2)$, $\Delta y(j_1 j_2)$, $k_T(j_{1,2})$



Combination of QCD and Weak Corrections

Two procedures for combining the corrections

- additive

$$\sigma_{QCD+\mathrm{wk}} = \sigma_{(N)NLO\,QCD} + \sigma_{\mathrm{wk}}$$
$$\delta_{\mathrm{add}} = \frac{\sigma_{QCD+\mathrm{wk}} - \sigma_{(N)NLO\,QCD}}{\sigma_{(N)NLO\,QCD}} = \frac{\sigma_{\mathrm{wk}}}{\sigma_{(N)NLO\,QCD}}$$

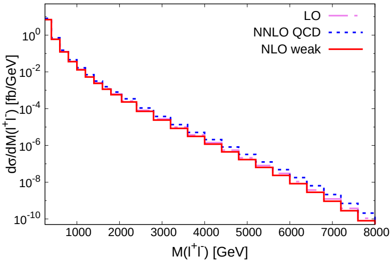
- multiplicative

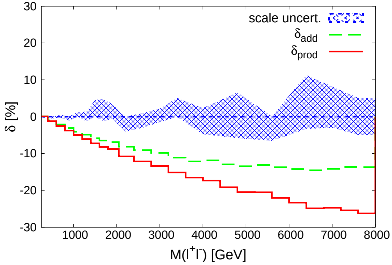
$$\sigma_{QCD\times\mathrm{wk}} = \sigma_{(N)NLO\,QCD}\left(1 + \frac{\sigma_{\mathrm{wk}}}{\sigma_{LO}}\right)$$
$$\delta_{\mathrm{prod}} = \frac{\sigma_{QCD\times\mathrm{wk}} - \sigma_{(N)NLO\,QCD}}{\sigma_{(N)NLO\,QCD}} = \frac{\sigma_{\mathrm{wk}}}{\sigma_{LO}}$$

NNLO QCD and Weak Corrections to the NC-DY

NNLO QCD to NC-DY in MCFM [R.Boughezal *et al* (2016)]

- same input parameter setup; PDF set: MSTW2008NNLO





$$(\mu_F/M_Z, \mu_R/M_Z) = \{(0.5, 0.5),\ (2,2),\ (0.5,1),\ (0.5,2),\ (1,0.5),\ (2,0.5)\}$$

NNLO QCD and Weak Corrections to $t\bar{t}$

NNLO QCD results in existing work

[M.Czakon, D.Heymes, A.Mitov (2016)]
[M.Czakon, P.Fiedler, D.Heymes, A.Mitov (2016)]

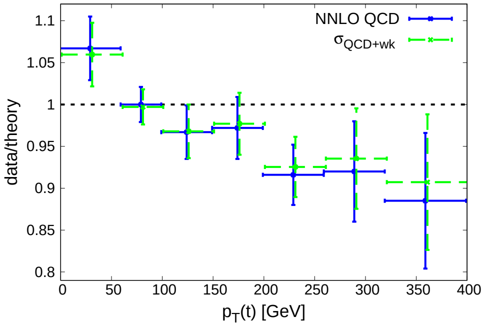
- comparison with NNLO QCD at Tevatron

$M(t\bar{t})$ [GeV]	$d\sigma/dM(t\bar{t})$ [pb/bin]		
	NLO QCD	NNLO QCD corr	NLO weak corr
[240 ; 412.5]	2.96×10^{0}	0.17×10^{0}	0.05×10^{0}
[412.5 ; 505]	2.47×10^{0}	0.12×10^{0}	-0.01×10^{0}
[505 ; 615]	9.20×10^{-1}	0.30×10^{-1}	-0.15×10^{-1}
[615 ; 750]	2.66×10^{-1}	0.07×10^{-1}	-0.08×10^{-1}
[750 ; 1200]	6.20×10^{-2}	0.16×10^{-2}	-0.27×10^{-2}
[1200 ; ∞]	1.07×10^{-4}	0.20×10^{-4}	-0.10×10^{-4}

[M.Czakon, P.Fiedler, D.Heymes, A.Mitov (2016)]

NNLO QCD and Weak Corrections to $t\bar{t}$

- Combination of NNLO QCD and NLO weak compared with 8 TeV CMS data[4] ($19.6 fb^{-1}$)

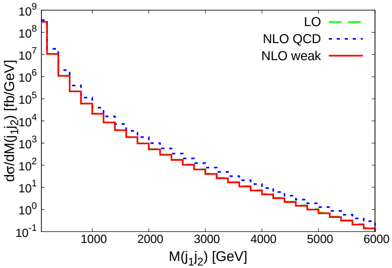


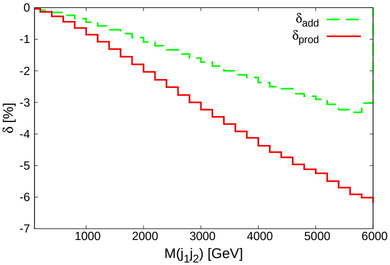
[4] V. Khachatryan *et al*, EPJ,C75(11):542, 2015

NLO QCD and Weak Corrections to Di-jet

NLO QCD public code `MEKS` [J. Gao *et al* (2013)]

- comparison and combination on invariant mass $M(j_1 j_2)$ distribution at 13 TeV



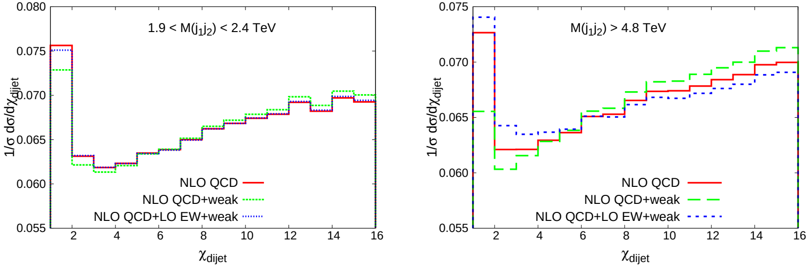


NLO QCD and Weak Corrections to Di-jet

NLO QCD+NLO weak for normalized $\chi_{\rm dijet}$ distribution (13 TeV)

- same setup as in CMS [5] analysis
- anti-k_T algorithm with $R = 0.4$

$$\chi_{\rm dijet} = \exp\left(|y(j_1) - y(j_2)|\right), \; y_{\rm boost} = \frac{1}{2}|y(j_1) + y(j_2)| < 2.22$$



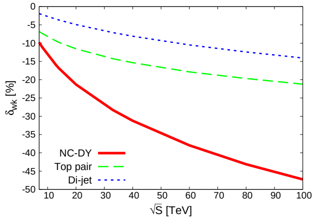
[5] CMS-PAS-EXO-15-009 (2015)

Conclusions

- Implementation of one-loop EW corrections in `MCFM`
- Comparison of exact with approximated results ⇒ efficacy of Sudakov approximation
- Combination of (N)NLO QCD and NLO EW

Conclusions

- The proper consideration of EW corrections is even more important for any future hadron colliders operating at higher energies. The relative EW correction in the high-energy region (defined by $M_{final} > \sqrt{S}/4$) becomes more of significance as the increase of machine energies. Particularly in NC-DY process, the inclusion of EW effects is mandatory in order to have an accurate theoretical prediction for the heigh-energy cross section at a 100 TeV pp machine.



Backup - input setups

NC-DY

- input parameters (same as in di-jet)

$M_W = 80.3695$ GeV	$\Gamma_W = 2.1402$ GeV
$M_Z = 91.1535$ GeV	$\Gamma_Z = 2.4943$ GeV
$M_H = 126$ GeV	$m_t = 172.5$ GeV
$m_b = 4.82$ GeV	$m_c = 1.2$ GeV
$m_s = 150$ MeV	$m_u = 66$ MeV
$m_d = 66$ MeV	$m_e = 0.51099892$ MeV
$m_\mu = 105.658369$ MeV	$m_\tau = 1.777$ GeV
$G_\mu = 1.16637 \times 10^{-5}$ GeV^{-2}	$\alpha_{G_\mu} = 1/132.4525902$
$\sin^2\theta_W = 1 - M_W^2/M_Z^2$	

- choice of PDF set and scales

$$\text{MSTW2008NLO} : \alpha_s(M_Z) = 0.12018;\ \mu_F = \mu_R = M_Z$$

- acceptance cuts

$$p_T(l^\pm) > 25 \text{ GeV}, \quad |\eta(l^\pm)| < 2.5\,, \quad M(l^+l^-) > 60 \text{ GeV}$$

Backup - input setups

$t\bar{t}$ production

- input parameters

$M_W = 80.385\,\mathrm{GeV}$	$M_Z = 91.1876\,\mathrm{GeV}$
$M_H = 126\,\mathrm{GeV}$	$m_t = 173.2\,\mathrm{GeV}$
$m_b = 4.82\,\mathrm{GeV}$	$\alpha(m_t) = 1/127$
$\sin^2\theta_W = 1 - M_W^2/M_Z^2$	$\alpha_s(m_t) = 0.106823$

- choice of PDF set and scales

$$\mathrm{MSTW2008NNLO} : \alpha_s(M_Z) = 0.11707;\ \mu_F = \mu_R = m_t$$

Backup - input setups

Di-jet production

- input parameter: same as in NC-DY
- choice of PDF set and scales

$$\text{CTEQ6L1} : \alpha_s(M_Z) = 0.129783; \quad \mu_F = \mu_R = k_T(j_1)$$

- jet algorithm and acceptance cuts

$$\text{anti}-k_T,\ R = 0.6; \quad k_T(j) > 25\ \text{GeV}, \quad |y(j)| < 2.5$$