EW Corrections at the LHC

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LHC Processes

Typical LHC processes being studied such as jet production, t-quark pair production, W or Z production proceed via energetic parton processes

$$q\bar{q} \to \mu^+\mu^-, \quad qq \to qq, \quad q\bar{q} \to t\bar{t},\ q\bar{q} \to WW, \quad gg \to t\bar{t}$$

with $E_{\text{cm}} = \sqrt{s} = Q$ of order (few) TeV.

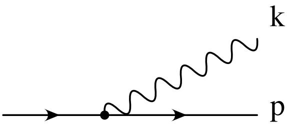
$$Q \sim 1 \text{ TeV}, \quad M_{W,Z} \sim 0.1 \text{ TeV}, \quad m_{\text{proton}} \sim 0.001 \text{ TeV}$$

Hierarchy of scales:

$$Q^2 \gg M_{W,Z}^2 \gg \Lambda_{\text{QCD}}^2$$

M_Z at a few TeV as important as m_b at LEP

Infrared Singularities in Radiation



The intermediate propagator is

$$\frac{1}{(p+k)^2 - m^2} = \frac{1}{2p\cdot k + k^2} = \frac{1}{2E_p\,\omega_k - 2\,|\mathbf{p}|\,|\mathbf{k}|\cos\theta + M^2}$$

For massless particles, $E_p = |\mathbf{p}|$ and $\omega_k = |\mathbf{k}|$

$$2E\omega\,(1-\cos\theta)$$

singularities as $\omega \to 0$ (soft) and $\theta \to 0$ (collinear). Leads to Sudakov double-logarithms cut-off by gauge boson mass M.

Inclusive vs. Exclusive Processes

Exclusive processes such as electron scattering at high energy are infrared divergent. Here the divergence is cutoff by M, so get $\log^2 Q^2/M^2$ for each order in perturbation theory.

Two powers of a log for each order in perturbation theory

Sterman-Weinberg jets — $\log\delta$ and $\log\epsilon$ from cone angle and energy resolution.

Inclusive rates have no log, e.g.

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

Sudakov Double Logarithms

There are no electroweak singlet targets or beams, so all processes behave like the exclusive case and have double logs.

M. Ciafaloni, P. Ciafaloni and D. Comelli, PRL 84 (2000) 4810

Even if one sums over final states

Typical form of the radiative corrections:

$$\frac{\alpha}{4\pi \sin^2\theta_W} \log^2 \frac{s}{M_{W,Z}^2} \sim 0.15$$

for $\sqrt{s} \sim 4$ TeV.

$\log^2 \sim 50$

QCD vs EW

QCD vs EW:

$$\frac{\alpha_s}{\alpha_W} \sim 3.7 \qquad \frac{\alpha_s}{4\pi} \sim 0.01 \qquad \frac{\alpha_W}{4\pi} \sim 0.003$$

QCD corrections are sensitive to IR cuts

$$\log^2 \frac{Q^2}{p_T^2}$$

QCD radiative corrections much larger than 1%.

EW corrections insensitive to IR cuts — but when $Q^2 \gg M_Z^2$, M_Z plays the role of the IR cut, and the corrections start growing.

Previous Work

M. Ciafaloni, P. Ciafaloni and D. Comelli

V. S. Fadin, L. N. Lipatov, A. D. Martin and M. Melles

B. Jantzen, J. H. Kuhn, A. A. Penin and V. A. Smirnov

M. Beccaria, F. M. Renard and C. Verzegnassi

A. Denner and S. Pozzorini

M. Hori, H. Kawamura and J. Kodaira

W. Beenakker and A. Werthenbach

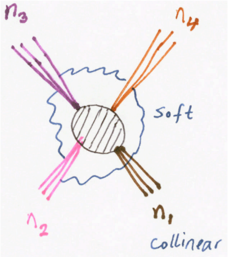
Work done with Chiu, Golf, Fuhrer, Kelley

Phys. Rev. Lett. **100** (2008) 021802 [arXiv:0709.2377]
Phys. Rev. D **77** (2008) 053004 [arXiv:0712.0396]
Phys. Rev. D **78** (2008) 073006 [arXiv:0806.1240]
Phys. Rev. D **80** (2009) 094013 [arXiv:0909.0012]
Phys. Rev. D **81** (2010) 014023 [arXiv:0909.0947
Phys. Rev. D **81** (2010) 093005 [arXiv:1003.0025

Use soft-collinear effective theory (SCET)

Bauer, Fleming, Luke, Pirjol, Stewart

SCET Result



EW corrections using SCET known for ALL hard scattering processes.

A universal collinear function for each external particle that depends on the particle energy and is independent of the process.

A soft-function that has the same form as for QCD,

$$-\frac{\alpha_i}{\pi}\, T_i \cdot T_j \, \log \frac{-n_i \cdot n_j}{2}$$

EW SCET

Only change — $\alpha_s \to \alpha_i$ and T_i are now EW generators.

Reproduces all the previous results obtained over the last 20 years by very difficult computations.

Reason we can do this is by neglecting power corrections of order

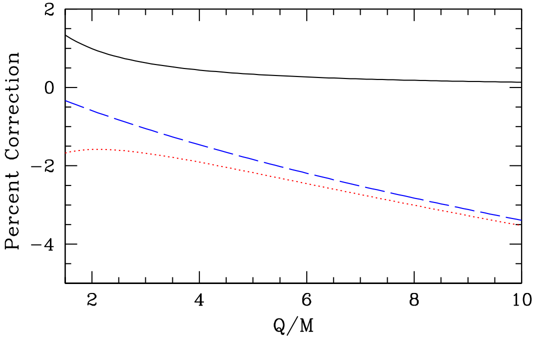
$$\frac{M_Z^2}{Q^2} \qquad \left(\frac{M_Z^2}{Q^2}\right)^2 \qquad \cdots$$

Results valid when $Q^2 \gg M_Z^2$

But that is precisely the region where the corrections are relevant.

Numerics

Non-SCET contributions are $\sim$ 1% in amplitude, $\sim$ 2% in rate.



Plot of the one-loop power corrections to the Sudakov form factor (solid black), the EFT one-loop correction (dotted red), and their sum, which is the total one-loop correction (dashed blue) as a percentage of the total form factor. The gauge coupling constant has been chosen to be the standard model $SU(2)_W$ value.

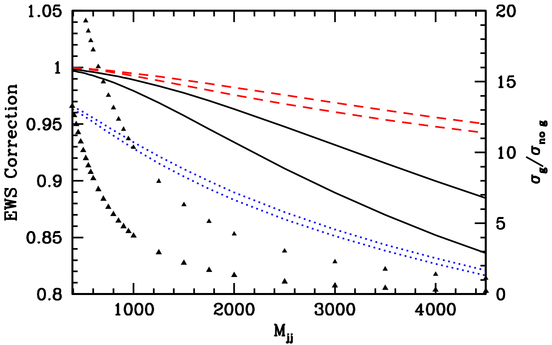
$t\bar{t}$

M. Trott, AM, PLB 711 (2012) 313

Bin [GeV]	$\mathcal{R}_t$		$\mathcal{R}_b$		$\mathcal{R}_c$	
[50, 3000]	–	–	0.99	0.99	0.99	0.99
[350, 3000]	0.97	0.97	–	–	–	–
[50, 250]	–	–	0.99	0.99	0.99	0.99
[250, 500]	–	–	1.00	1.00	1.00	1.00
[350, 500]	0.98	0.98	–	–	–	–
[500, 750]	0.97	0.97	0.99	0.99	0.99	0.99
[750, 1000]	0.95	0.95	0.98	0.98	0.98	0.98
[1000, 1500]	0.94	0.94	0.97	0.97	0.96	0.96
[1500, 2000]	0.92	0.92	0.95	0.95	0.95	0.95
[2000, 2500]	0.90	0.91	0.93	0.94	0.93	0.93
[2500, 3000]	0.88	0.89	0.92	0.93	0.92	0.92
[3000, 3500]	0.87	0.88	0.90	0.91	0.91	0.91

The EWS corrections for heavy quark production at the LHC. The left (right) columns are for $\sqrt{s} = 7\,(14)\,\mathrm{TeV}$.

$t\bar{t}$



EWS correction (left axis) to the LHC dijet spectrum as a function of dijet invariant mass (solid black). Also shown are the corrections to dijet processes involving external gluons (red dashed), and no external gluons (blue dotted). The black triangles are the ratio of cross sections (right axis) with and without external gluons. The lower and upper curves are $\sqrt{s} = 7\,\mathrm{TeV}$ and 14 TeV, respectively.

Conclusions

EW effects not included.

Largest source of uncertainty in theoretical predictions

Needs to be implemented in the Monte-Carlo, to implement phase-space cuts.