Electroweak Corrections at LHC Energies

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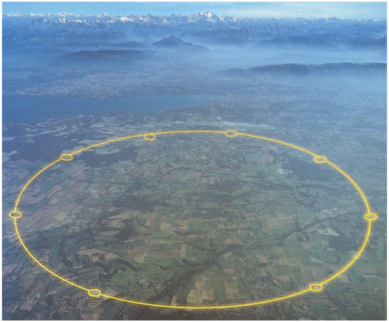
Outline

1. Introduction
2. Resummation
3. Factorization
4. LHC Processes
5. Conclusions

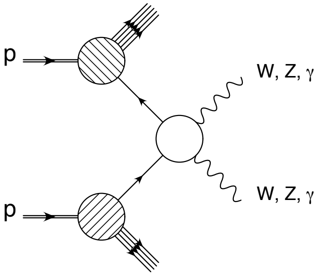
Large Hadron Collider (LHC, Big Bang Collider)

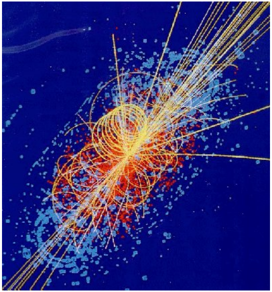
- proton - proton collider
- $E_{\mathrm{cm}} = 14$ TeV
- increased luminosity and energy over the Tevatron
- Finding the Higgs, SUSY, extra dimensions, black holes, . . .
- 2009?



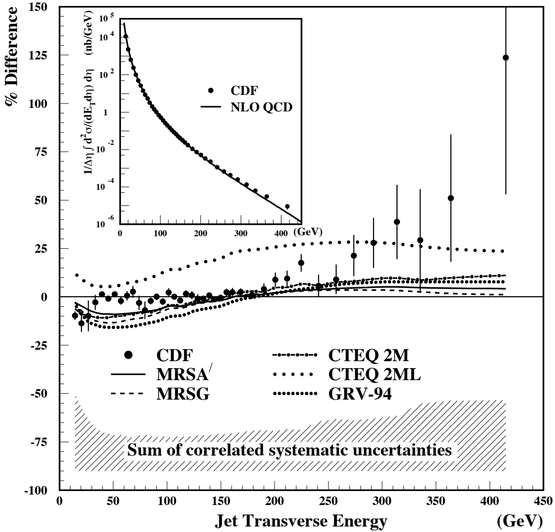
proton-proton collisions

- strong interaction dynamics complicates computation
- asymptotic freedom allows for perturbative calculation of parton-parton collisions.
- look at parton-parton subprocesses, and turn into cross-sections using parton distribution functions





Pitfalls



% Difference
CDF
NLO QCD
(GeV)
CDF
MRSA'
MRSG
CTEQ 2M
CTEQ 2ML
GRV-94
Sum of correlated systematic uncertainties
Jet Transverse Energy
(GeV)

Parton Processes

Typical LHC processes being studied such as jet production, t-quark pair production, squark pair production proceed via energetic partonic processes

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

with $Q \sim \sqrt{s}$ of order (few) TeV.

Final state invariant masses are much smaller than Q.
[dijet production]

Describe these using SCET. Work in the regime

$$s \sim -t \sim -u \sim Q^2$$

(Hard Scattering)

Include ($Q \sim$ TeV)

- QCD and EW radiative corrections
- Higgs Radiative corrections due to g_t
- Mass effects due to m_t, m_H, M_W and M_Z
- Neglect m^2/Q^2.

Include all m_H/M_Z, etc. dependence, but drop m_H/Q and m_Z/Q terms.

Only need to drop power corrections in the loops — easy to include at tree-level. Effects sub 1% for $\sqrt{\hat{s}} > 1$ TeV.

Terminology:

Electroweak corrections: excluding QCD
Depend on α and $\alpha/\sin^2\theta_W$, with $\alpha_s \to 0$

Purely QCD effects computed before by different methods.

Automatically include mixed $\alpha\alpha_s$ terms

Numerical Values

To get 1% accuracy, need:

- One loop high scale QCD matching
- One loop low scale QCD + EW matching
- Two loop QCD running (cusp + non-cusp)
- One loop EW running (cusp + non cusp)

One loop QCD running (20-50) >

One loop EW running (1.2-1.5) >

One loop QCD low-scale matching for *t*-quark (1.30)>

2 loop QCD cusp (1.12) >

2 loop QCD non-cusp, 1 loop low scale matching, 1 loop high scale matching, Higgs corrections (1.02-1.05)

3 loop QCD cusp 0.1%

Previous Work

Lots of papers:

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

This talk based on

J. Chiu, F. Golf, R. Kelley, A.M, PRL 100 (2008) 021802

J. Chiu, F. Golf, R. Kelley, A.M, PRD 77 (2008) 053004

J. Chiu, R. Kelley, A.M, PRD 78 (2008) 073006

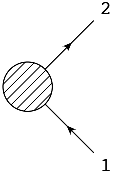
J. Chiu, A. Fuhrer, A. Hoang, R. Kelley, A.M, PRD 79 (2009) 053007

J. Chiu, A. Fuhrer, R. Kelley, A.M, in preparation

Sudakov Form Factor

Sufficient to compute *n*-particle hard scattering to the required accuracy

Consider the scattering of a fermion by an external current $\bar{\psi}\gamma^\mu\psi$



$$Q^2 = -q^2 = 2p_1 \cdot p_2$$

$$F_E(Q^2/M^2)\ [\bar{u}(p_2)\gamma^\mu u(p_1)] = \langle p_2|\bar{\psi}\gamma^\mu\psi|p_1\rangle$$

Contains $\alpha \log^2(Q^2/M^2)$ — Sudakov double logarithms

Structure of Terms

$$\mathcal{S} = \begin{pmatrix} 1 & & & & \\ \alpha L^2 & \alpha L & \alpha & & \\ \alpha^2 L^4 & \alpha^2 L^3 & \alpha^2 L^2 & \alpha^2 L & \alpha^2 \\ \alpha^3 L^6 & & \ldots & & \\ \vdots & & & & \end{pmatrix}$$

In the leading-log regime $L \sim 1/\alpha$, the various terms are of order

$$\mathcal{S} = \begin{pmatrix} 1 & & & & \\ \frac{1}{\alpha} & 1 & \alpha & & \\ \frac{1}{\alpha^2} & \frac{1}{\alpha} & 1 & \alpha & \alpha^2 \\ \frac{1}{\alpha^3} & & \ldots & & \\ \vdots & & & & \end{pmatrix}.$$

Infrared Evolution Equation

Collins formula for the Sudakov form factor

$$\log F_E(Q^2) = \log F_0(M) + \int_{M^2}^{Q^2} \frac{\mathrm{d}\mu^2}{\mu^2} \left[\zeta(\mu) + \xi(M) + \int_{M^2}^{\mu^2} \frac{\mathrm{d}\mu'^2}{\mu'^2} \Gamma(\mu') \right]$$

F_0, ζ, ξ and Γ are functions only of α at the relevant scale.

Γ is the cusp anomalous dimension.

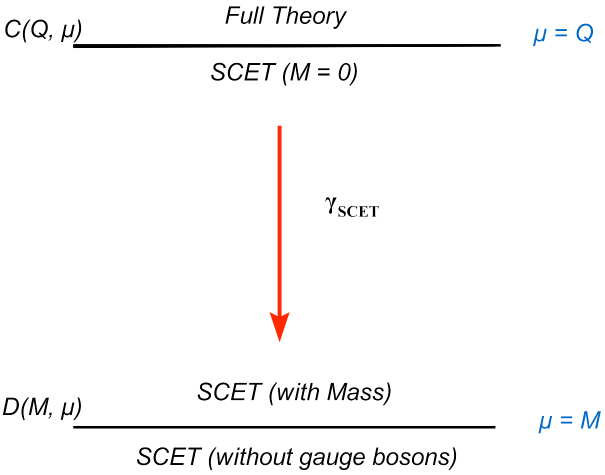
ξ integral can be done to give

$$\xi\left(\alpha\left(M\right)\right) \log Q^2/M^2$$

Used by the Karlsruhe group for electroweak corrections.
Compare with fixed order computation.

Kuhn, Jantzen, Penin, Smirnov

Outline of SCET Calculation



SCET Formula

$$\log F_E(Q^2) = C(\alpha(Q)) + \int_Q^M \frac{\mathrm{d}\mu}{\mu}\left[A(\alpha(\mu))\log\frac{\mu^2}{Q^2} + B(\alpha(\mu))\right] + D_0(\alpha(M)) + D_1(\alpha(M))\log\frac{Q^2}{M^2}$$

- C: matching at Q — high scale matching
- $A\log\mu^2/Q^2 + B$: SCET anomalous dimension
- $D_0 + D_1\log Q^2/M^2$: matching at M — low scale matching
- There is a $\log Q$ in the matching at M
- Equivalent to Infrared Evolution Equation

Resummation: Exponentiated Form

Exponentiated form:

$$\log \mathcal{S} = \begin{pmatrix} \alpha L^2 & \alpha L & \alpha & & \\ \alpha^2 L^3 & \alpha^2 L^2 & \alpha^2 L & \alpha^2 & \\ \alpha^3 L^4 & \alpha^3 L^3 & \alpha^3 L^2 & \alpha^3 L & \alpha^3 \\ \alpha^4 L^5 & & \ldots & & \\ \vdots & & & & \end{pmatrix}$$

In the leading-log regime $\alpha L \sim 1$:

$$\log \mathcal{S} = \begin{pmatrix} \frac{1}{\alpha} & 1 & \alpha & & \\ \frac{1}{\alpha} & 1 & \alpha & \alpha^2 & \\ \frac{1}{\alpha} & 1 & \alpha & \alpha^2 & \alpha^3 \\ \frac{1}{\alpha} & & \ldots & & \\ \vdots & & & & \end{pmatrix}.$$

Resummation: Exponentiated Form

$$\log \mathcal{S} = \frac{1}{\alpha} f_0 + f_1 + \alpha f_2 + \ldots = \frac{1}{\alpha}\left[f_0 + \alpha f_1 + \alpha^2 f_2 + \ldots\right]$$

so that f_1 and f_2 are corrections to $\log A$. However,

$$\mathcal{S} = \exp\left[\frac{1}{\alpha} f_0 + f_1 + \alpha f_2 + \ldots\right] = e^{\frac{1}{\alpha} f_0} \times e^{f_1} \times e^{\alpha f_2} \times \ldots$$

Must include the LL and NLL series. The NLL series is *not* a correction.

LL: one-loop cusp
NLL: two-loop cusp, one-loop non-cusp, one-loop D_1
NNLL: three-loop cusp, two-loop non-cusp and D_1, one-loop C and D_0

Literature: One-loop LL, NLL, etc.

Resummation: Electroweak

$\alpha L^2 \sim 1$ (same counting that Beneke used)

$$\mathcal{S} = \begin{pmatrix} 1 & & & & \\ 1 & \alpha^{1/2} & \alpha & & \\ 1 & \alpha^{1/2} & \alpha & \alpha^{3/2} & \alpha^2 \\ 1 & & & \ldots & \\ & & \vdots & & \end{pmatrix}$$

and in exponentiated form

$$\log \mathcal{S} = \begin{pmatrix} 1 & \alpha^{1/2} & \alpha & & \\ \alpha^{1/2} & \alpha & \alpha^{3/2} & \alpha^2 & \\ \alpha & \alpha^{3/2} & \alpha^2 & \alpha^{5/2} & \alpha^3 \\ \alpha^{3/2} & & & \ldots & \\ \vdots & & & & \end{pmatrix}.$$

Resummation: Electroweak

Need two loop terms and the mixed $\alpha_{EW}\alpha_s$ terms which are summed by the RGE.

Can get the required two-loop electroweak from the one-loop running.

Explicitly checked with the two-loop results of the Karlsruhe group.

Normal RGE: Sum all logs, but not constants
(n terms at α^n)

SCET RGE: Sum all logs, but not constants and single log
($2n - 1$ terms at α^n).

Standard Nomenclature

$$
\begin{aligned}
F_E(Q) = \quad & 1 && \text{LO} \\
+ \quad & \alpha^1 \left(L^2 + L^1 + L^0 \right) && \text{NLO} \\
+ \quad & \alpha^2 \left(L^4 + L^3 + L^2 + L^1 + L^0 \right) && \text{NNLO} \\
+ \quad & \alpha^3 \left(L^6 + L^5 + L^4 + L^3 + L^2 + L^1 + L^0 \right) && \text{N}^3\text{LO}
\end{aligned}
$$

The α^n term has powers of L up to L^{2n}. $2n+1$ terms at order n

- The αL^2 is called LL_{FO}, αL is called NLL_{FO}, αL is called $NNLL_{FO}$
- $\alpha^2 L^4$ is called LL_{FO}, $\alpha^2 L^3$ is called NLL_{FO}, $\alpha^2 L^2$ is called $NNLL_{FO}$

Toy Theory

Consider a $SU(2)$ gauge theory (completely) spontaneously broken by a Higgs in the fundamental representation.

All gauge bosons have a common mass M.

Infrared structure perturbative and regulated by M

Write group theory in terms of C_F, C_A — only makes sense for $SU(2)$ Otherwise $SU(N) \to SU(N-1)$ and some gauge bosons remain massless.

Fermions have a mass m

Large scale Q, with $Q \gg M$, $Q \gg m$, and neglect M^2/Q^2 and m^2/Q^2 power corrections.

Can easily get the desired standard model results from this computation by bookeeping.

Notation

$$\begin{aligned} \mathsf{L}_Q &= \log \frac{Q^2}{\mu^2} \\ \mathsf{L}_M &= \log \frac{M^2}{\mu^2} \\ \mathsf{L}_{Q/M} &= \log \frac{Q^2}{M^2} = \mathsf{L}_Q - \mathsf{L}_M \end{aligned}$$

Sudakov Form Factor at One Loop

$$F_E(Q^2) = 1 + \frac{\alpha\, C_F}{4\pi}\left[-\mathsf{L}^2_{Q/M} + 3\mathsf{L}_{Q/M} - \frac{7}{2} - \frac{2\pi^2}{3}\right]$$

High Scale Matching:

$$C(Q,\mu) = 1 + \frac{\alpha\, C_F}{4\pi}\left[-\mathsf{L}^2_{Q} + 3\mathsf{L}_{Q} + \frac{\pi^2}{6} - 8\right]$$

Running:

$$\gamma(\mu) = \frac{\alpha\, C_F}{4\pi}\left[4\mathsf{L}_Q - 6\right]$$

Low Scale Matching:

$$D(Q,M,\mu) = 1 + \frac{\alpha\, C_F}{4\pi}\left[2\mathsf{L}_M\mathsf{L}_Q - \mathsf{L}^2_M - 3\mathsf{L}_M + \frac{9}{2} - \frac{5\pi^2}{6}\right]$$

Factorization of Scales

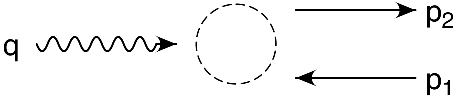
EFT has factored the Q and M dependence.

The Q dependence goes into the matching condition, plus the single-log D_1 term in the low-scale matching in the EFT.

The M dependence is in the EFT computation.

Breit Frame

Work in the Breit frame where the two particles are back to back,



and move in the directions given by the null vectors

$$n^\mu = (1, \mathbf{n}), \quad \bar{n}^\mu = (1, -\mathbf{n})$$

and define

$$p^+ = n \cdot p, \quad p^- = \bar{n} \cdot p, \quad p^\mu = \frac{1}{2} n^\mu (\bar{n} \cdot p) + \frac{1}{2} \bar{n}^\mu (n \cdot p) + p_\perp^\mu$$

EFT Modes

EFT has n-collinear $\bar{n}$-collinear, and soft mass modes:

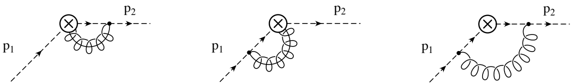
$$\begin{array}{rcccc} & & p^- & p^+ & p_\perp \\ n\text{-collinear} & : & Q & Q^2/M & M \\ \bar{n}\text{-collinear} & : & Q^2/M & Q & M \\ \text{mass} & : & M & M & M \end{array}$$

Introduce fields $\xi_{n,p}$, $\xi_{\bar{n},p}$, $A_{n,p}$, $A_{\bar{n},p}$, A. Collinear gauge invariance requires fields in the combination

$$\left[W_n^\dagger \xi_n\right]$$

W_n is a collinear Wilson line in the $\bar{n}$ direction, and contains A_n.

Graphs in SCET



The EFT amplitude factors into three pieces.
The n-collinear diagram: ($f_\epsilon = (4\pi)^{-\epsilon}\,\mu^{2\epsilon} e^{\epsilon\gamma_E}$)

$$I_n = -2ig^2 C_F f_\epsilon \int \frac{\mathrm{d}^d k}{(2\pi)^d} \frac{1}{[-\bar{n}\cdot k]} \frac{\bar{n}\cdot(p_2 - k)}{\left[(p_2-k)^2\right]} \frac{1}{k^2 - M^2}$$

Integrate over k^+ by contours

$$I_n = -2\frac{C_F\alpha}{4\pi}\mu^{2\epsilon} e^{\epsilon\gamma_E}\Gamma(\epsilon)\int_0^1 dz \frac{1-z}{z}\left[M^2(1-z) - p_2^2 z(1-z)\right]^{-\epsilon}$$

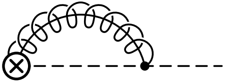
For $z \to 0$ this integral diverges for $M \neq 0$, even if $p_2^2 \neq 0$.
If $M = 0$, $z^{-\epsilon}$ from the $p_2^2 \neq 0$ term regulates the integral.

Δ Regulator

$$\frac{1}{(p_i+k)^2-m_i^2} \rightarrow \frac{1}{(p_i+k)^2-m_i^2-\Delta_i}$$

This regulator can be implemented at the level of the Lagrangian, since it corresponds to a shift in the particle mass. The on-shell condition remains $p_i^2=m_i^2$. [The regulator cancels in the amplitude unlike the real vs virtual cancellation between different processes]

In the n_i-collinear sector:



particle i has propagator

$$\frac{\bar{n}_i \cdot (p_i+k)}{(p_i+k)^2-m_i^2-\Delta_i}$$

Δ Regulator

Don't need to regulate the collinear Wilson lines.

For the soft lines:

$$p_i^\mu = \frac{1}{2}\left(\bar{n}_i \cdot p_i\right) n_i^\mu$$

$$\frac{1}{(p_i+k)^2 - m_i^2 - \Delta_i} \to \frac{1}{2p_i \cdot k - \Delta_i} = \frac{1}{(\bar{n}_i \cdot p_i)(n_i \cdot k) - \Delta_i}$$

so

$$\frac{1}{n_i \cdot k} \to \frac{1}{n_i \cdot k - \delta_i}, \qquad \delta_i = \frac{\Delta_i}{\bar{n}_i \cdot p_i}$$

is the regulator for soft graphs.

For the soft diagram, one finds

$$
\begin{aligned}
I_s &= -2ig^2 C_F f_\epsilon \int \frac{\mathrm{d}^d k}{(2\pi)^d} \frac{1}{k^2 - M^2} \frac{1}{-n\cdot k - \delta_2} \frac{1}{-\bar{n}\cdot k - \delta_1} \\
&= \frac{\alpha C_F}{4\pi}\left[-\frac{2}{\epsilon^2} + \frac{2}{\epsilon}\log\frac{\delta_1\delta_2}{\mu^2} + \mathsf{L}_M^2 - 2\mathsf{L}_M \log\frac{\delta_1\delta_2}{\mu^2} + \frac{\pi^2}{6}\right]
\end{aligned}
$$

Depends on $\delta_1\delta_2$

Zero Bin Subtractions

Need them

Stewart, AM

Lee and Sterman, Collins, Sterman, Idilbi and Mehen

There is a double counting because the $p \to 0$ collinear integral overlaps the soft integral.
The collinear graph for particle 2 is:

$$
\begin{aligned}
I_n - I_{n\varnothing} \quad = \quad & \frac{\alpha C_F}{4\pi}\left[\frac{2}{\epsilon^2} - \frac{2}{\epsilon}\log\frac{\Delta_2}{\mu^2} + \frac{2}{\epsilon} - 2\left(1 - \log\frac{\Delta_2}{\mu^2}\right)\mathsf{L}_M \right. \\
& \left. - \mathsf{L}_M^2 - \frac{\pi^2}{2} + 2\right]
\end{aligned}
$$

Depends only on M and Δ_2 — does not depend on particle 1: $W_n^\dagger \xi_n$

Total Result

The sum of all three graphs gives the correct Sudakov form-factor.

Cancellation of regulator:

$$
\begin{aligned}
\text{soft} &= \left(\frac{2}{\epsilon} - 2\mathsf{L}_M\right) \log \frac{\delta_1 \delta_2}{\mu^2} \\
I_n - I_{n\varnothing} &= -\left(\frac{2}{\epsilon} - 2\mathsf{L}_M\right) \log \frac{\Delta_2}{\mu^2} \\
I_{\bar{n}} - I_{\bar{n}\varnothing} &= -\left(\frac{2}{\epsilon} - 2\mathsf{L}_M\right) \log \frac{\Delta_1}{\mu^2} \\
\text{total} &= \left(\frac{2}{\epsilon} - 2\mathsf{L}_M\right) \log \frac{\delta_1 \delta_2 \mu^2}{\Delta_1 \Delta_2} \\
&= \left(\frac{2}{\epsilon} - 2\mathsf{L}_M\right) \log \frac{\mu^2}{Q^2}
\end{aligned}
$$

Color Operators

General amplitude has different gauge structures $q\bar{q} \to q\bar{q}$:

$$\bar{q}_4\, q_3\, \bar{q}_2\, q_1 \qquad\qquad \bar{q}_4\, T^A q_3\, \bar{q}_2\, T^A q_1 \quad \text{(drop } \gamma \text{ structure)}$$

Can abbreviate it as

$$c_1\, 1 \otimes 1 + c_8 T^A \otimes T^A$$

Color operators such as $\mathbf{T}_1 \cdot \mathbf{T}_2$ for gluon exchange between 1 and 2

$$\begin{aligned} \mathbf{T}_1 \cdot \mathbf{T}_2 (1 \otimes 1) &= C_F 1 \otimes 1 \\ \mathbf{T}_1 \cdot \mathbf{T}_3 (1 \otimes 1) &= (T^A \otimes T^A) \end{aligned}$$

and so on. So write the amplitude as an operator in color space.

Factorization

Look at the one-loop computation with r external legs. The collinear part has the form

$$\sum_i \mathbf{T}_i \cdot \mathbf{T}_i \left[A \log \frac{\Delta_i}{\mu^2} + b_i(m_i) \right]$$

A independent of properties of i, b_i depends on masses, spin, etc. The soft part has the form

$$\sum_{\langle ij \rangle} \mathbf{T}_i \cdot \mathbf{T}_j \left[C(n_i \cdot n_j) \log \delta_i \delta_j + D(n_i \cdot n_j) \right]$$

where C and D do not depend on the particle properties, but can depend on directions.

Factorization

Can show that cancellation of the δ dependence allows one to write this in the form (linear in L):

$$\sum_i \mathbf{1} C_F \left[K_i \log(\bar{n}_i \cdot p_i) + B_i(m_i) \right] + \sum_{\langle ij \rangle} \mathbf{T}_i \cdot \mathbf{T}_j \; S_{ij}(n_i \cdot n_j)$$

L 1 1

A sum of one-particle collinear terms and a pairwise soft function. True for the finite and infinite parts, i.e. the anomalous dimension and low-scale matching.

K is proportional to the cusp anomalous dimension

Knowing the Sudakov form factor gives both pieces, so can compute an arbitrary process with *any* number of external particles.

$$
\begin{aligned}
\mathsf{L}_M &= \log \frac{M^2}{\mu^2} \\
\mathsf{L}_p &= \log \frac{\bar{n}\cdot p}{\mu}
\end{aligned}
$$

$$
S(n_i, n_j) = \left(-\frac{2}{\epsilon} + 2\mathsf{L}_M\right) \log \frac{n_i \cdot n_j - i0^+}{2}
$$

$[W^\dagger \xi]$	γ	D
ψ	$4\mathsf{L}_p - 3$	$2\mathsf{L}_M\mathsf{L}_p - \frac{1}{2}\mathsf{L}_M^2 - \frac{3}{2}\mathsf{L}_M - \frac{5\pi^2}{12} + \frac{9}{4} + f_F(m/M)$
ϕ	$4\mathsf{L}_p - 4$	$2\mathsf{L}_M\mathsf{L}_p - \frac{1}{2}\mathsf{L}_M^2 - 2\mathsf{L}_M - \frac{5\pi^2}{12} + \frac{7}{4} + +f_S(m/M)$

Gauge bosons and Higgs messy because of wavefunction contribution.

$$
W_T \propto C_A = 2 \qquad W_L \propto C_F = \frac{3}{4}
$$

All Orders

Can prove that

$$\log \mathbf{A} \;=\; \sum_i \mathbf{1}\left[K_i \log(\bar{n}_i \cdot p_i) + B_i(m_i)\right] \;+\; \mathbf{S}(\{\mathbf{T}_i, n_i\})$$

L   1   1

Still linear in L to all orders. The collinear functions are still determined by the Sudakov form factor. Soft need not be a sum on pairs.

The soft function **S** is a matrix that is order 1, so any matrix ordering contributions do not affect the L terms since the collinear part is proportional to **1**.

S can depend on the conformal ratios if $r \geq 4$ (see Neubert's talk):

$$\frac{(n_i \cdot n_j)(n_k \cdot n_l)}{(n_i \cdot n_k)(n_j \cdot n_l)}$$

Two Loops

Important result of Aybat, Dixon, Sterman; Dixon, Magnea, Sterman and Dixon

$$\text{two loop soft anom dim} = \frac{K^{(2)}}{K^{(1)}} \times \text{one loop soft anom dim}$$

Factorization properties combined with the color structure imply that one can use the sum on pairs formula to two-loop order. Chiu et al.

Can now compute all standard model processes (at the parton level) at high energy to better than 1% accuracy.

[See Iain Stewart's talk for convolution with beam function and pdfs]

Structure of Gauge Amplitudes

UV/IR correspondence:

IR structure of massless gauge theory amplitudes in perturbation theory = UV structure of the amplitudes

UV structure of massless gauge theory amplitudes = UV structure of massive gauge theory amplitudes.

For massless case using the full theory, IR regulated by $1/\epsilon$

For massive case by L_M.

The constraints on the structure follow from factorization.

Standard Model

Results for the standard model for quarks and leptons have been computed: J. Chiu, R. Kelley, A.M, PRD 78 (2008) 073006

Extended the results all standard model processes — finished the computations for external Higgs fields or gauge bosons.

Can compute longitudinal gauge bosons using the Goldstone boson equivalence theorem.
[See talk by R. Kelley at SCET09.]

Scattering

The intermediate gauge boson is off-shell by Q^2, and can be shrunk to a point.

Study 4-particle operators in the effective theory.

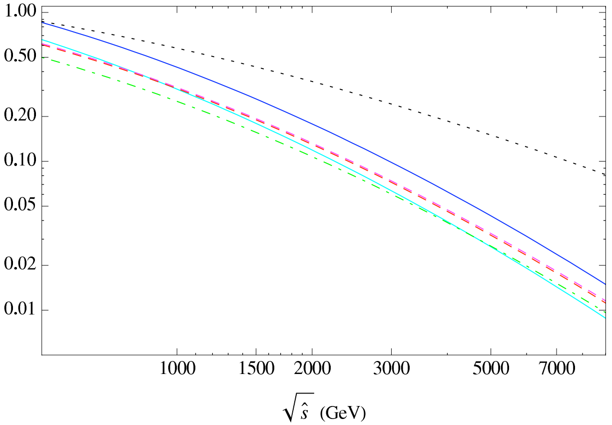
Hard part of the calculation (pun intended) is the one-loop matching.

Results

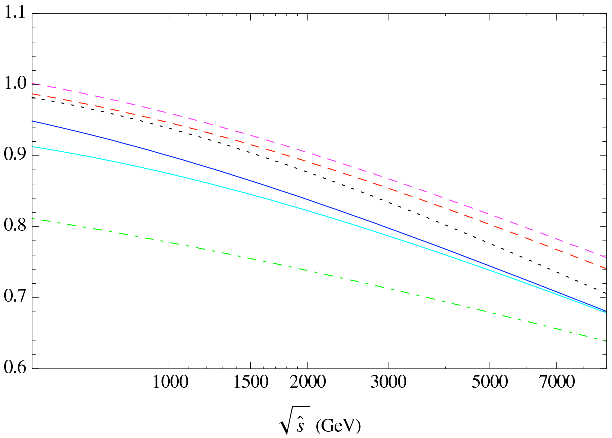
Apply the above methods to scattering in the standard model. There are 80 amplitudes to compute — different flavors and chiralities.

Show plots of results. Experimentally, one gets the dijet mass distribution, with dijet invariant mass $M = \sqrt{\hat{s}}$, and jet transverse energy E_T given by

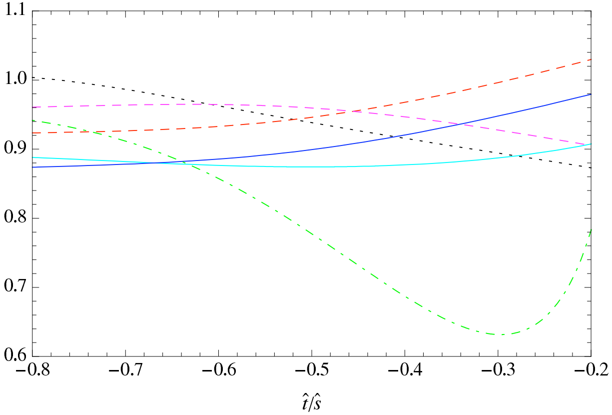
$$\begin{aligned} 2E_T &= \sqrt{\hat{s}} \sin\theta \\ -\frac{\hat{t}}{\hat{s}} &= \sin^2(\theta/2) \end{aligned}$$



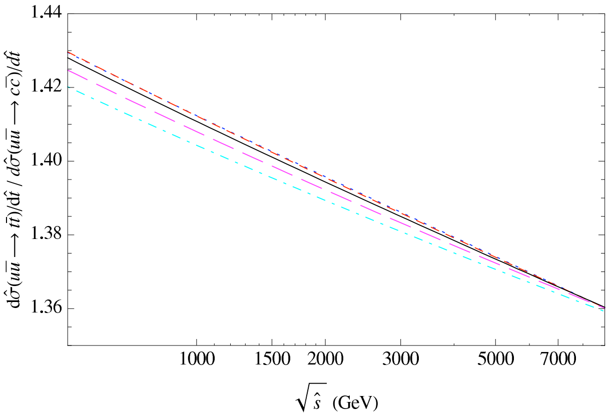
Rates for $u\bar{u} \to \mu^+\mu^-$ (dotted black), $u\bar{u} \to u\bar{u}$ (solid cyan), $u\bar{u} \to c\bar{c}$ (dashed red), $u\bar{u} \to t\bar{t}$ (solid blue), $u\bar{u} \to d\bar{d}$ (dot-dashed green) and $u\bar{u} \to b\bar{b}$ (dashed magenta) as a function of $\sqrt{\hat{s}}$ in GeV at $\theta = 90^\circ$, normalized to their tree-level values without any radiative corrections. Note the logarithmic scale.



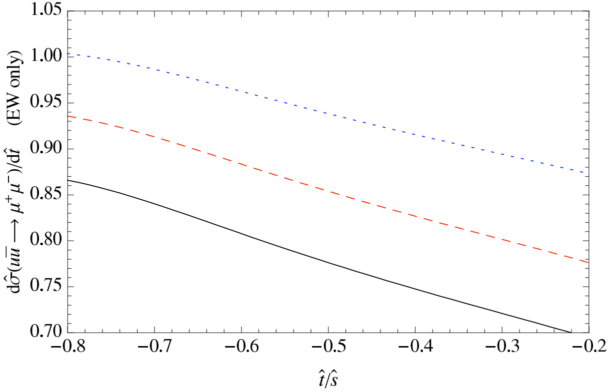
Electroweak corrections to $u\bar{u} \to \mu^+\mu^-$ (dotted black), $u\bar{u} \to u\bar{u}$ (solid cyan), $u\bar{u} \to c\bar{c}$ (dashed red), $u\bar{u} \to t\bar{t}$ (solid blue), $u\bar{u} \to d\bar{d}$ (dot-dashed green) and $u\bar{u} \to b\bar{b}$ (dashed magenta) as a function of $\sqrt{\hat{s}}$ in GeV at $\theta = 90°$. The large corrections for $u\bar{u} \to d\bar{d}$ arise from the t-channel W exchange graph.



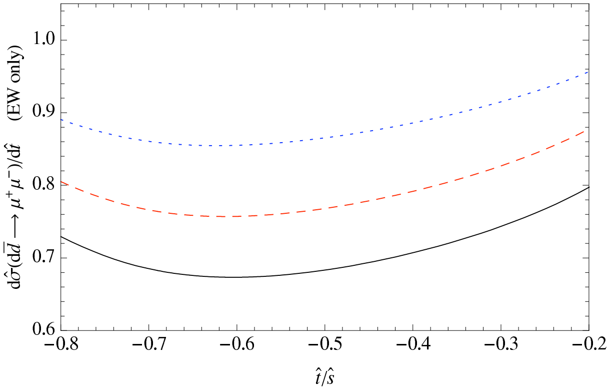
Electroweak corrections to $u\bar{u} \to \mu^+\mu^-$ (dotted black), $u\bar{u} \to u\bar{u}$ (solid cyan), $u\bar{u} \to c\bar{c}$ (dashed red), $u\bar{u} \to t\bar{t}$ (solid blue), $u\bar{u} \to d\bar{d}$ (dot-dashed green) and $u\bar{u} \to b\bar{b}$ (dashed magenta) as a function of $\hat{t}/\hat{s}$ for $\sqrt{\hat{s}} = 1$ TeV. The large corrections for $u\bar{u} \to d\bar{d}$ arise from the t-channel W exchange graph.



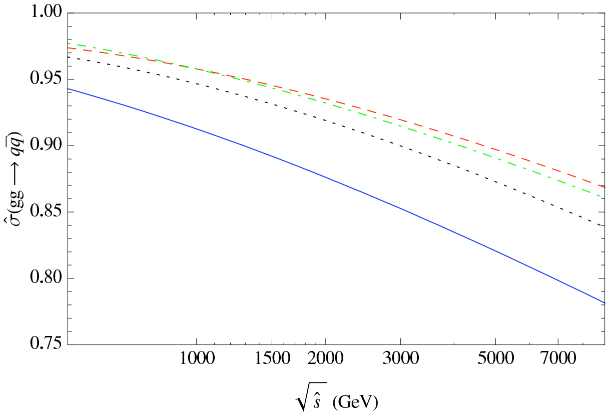
The ratio $(u\bar{u} \to t\bar{t})/(u\bar{u} \to c\bar{c})$ at $\hat{t} = -0.2\hat{s}$, (dotted blue), $\hat{t} = -0.35\hat{s}$ (dashed red), $\hat{t} = -0.5\hat{s}$ (solid black), $\hat{t} = -0.65\hat{s}$ (long-dashed magenta) and $\hat{t} = -0.8\hat{s}$ (dot-dashed cyan) as a function of $\sqrt{\hat{s}}$ in GeV.



Electroweak corrections to $u\bar{u} \to \mu^+\mu^-$ at $\sqrt{\hat{s}} = 1$ TeV, (dotted blue), $\sqrt{\hat{s}} = 2.5$ TeV (dashed red) and $\sqrt{\hat{s}} = 5$ TeV (solid black) as a function of $-\hat{t}/\hat{s}$.

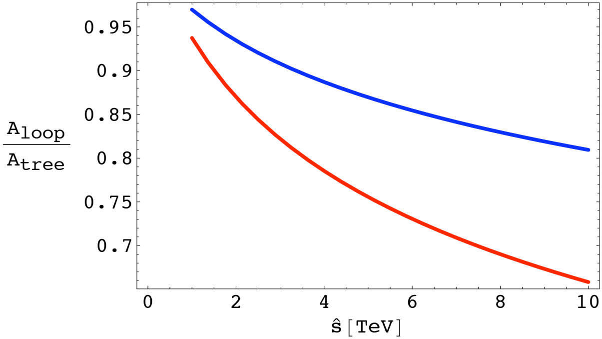


Electroweak corrections to $d\bar{d} \to \mu^+\mu^-$ at $\sqrt{\hat{s}} = 1$ TeV, (dotted blue), $\sqrt{\hat{s}} = 2.5$ TeV (long-dashed red) and $\sqrt{\hat{s}} = 5$ TeV (solid black) as a function of $\hat{t}/\hat{s}$.



Electroweak corrections to $gg \to u\bar{u}, c\bar{c}$ (dotted black), $gg \to d\bar{d}, s\bar{s}$ (dashed red), $gg \to t\bar{t}$ (solid blue) and $gg \to b\bar{b}$ (dot-dashed green) as a function of $\sqrt{\hat{s}}$ in GeV.

WW Production



$u\bar{u} \longrightarrow W_T W_T$

$u\bar{u} \longrightarrow W_L W_L$

Conclusions

- Understand the factorization structure of ampitudes
- Compute electroweak corrections in a systematic way. Much simpler than a direct computation.
- Include dependence on M_W, M_Z and m_t in a spontaneously broken gauge theory including gauge mixing.
- Include Higgs corrections.
- Can be extended to other electroweak processes such as squark production
- Purely electroweak corrections are important for LHC cross-sections.