Vienna Lectures: Intro to Collider Physics and Effective Field Theory Methods

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http://www2.lns.mit.edu/~iains/register EFTx

LHC collision of two protons

- Underlying event
- Forward jet
- Softer radiation
- Hadronization ($10^{-15}$ m)
- Collimated jet

Short distance process

$gg \rightarrow H + gg$  
$gg \rightarrow H + 2\text{jets}$  
$(pp \rightarrow H + 0\text{-jets})$

$gg \rightarrow 8\bar{8},..$  
$pp \rightarrow 2\text{jets}$  
$>10^5$ more likely
In QCD the energy scale \( \mu \) of a process is very important.

\[
\Delta s = \frac{g^2}{4\pi} = \Delta s(\mu)
\]

A strong coupling needs to know \( \mu \) values to find appropriate coupling to use for different parts of the collision.

Concept: Renormalization & Decoupling

- Parameters \( g \) in QFT (EFT) must be defined by a renormalization scheme (\( \overline{MS} \), ...).

- Schemes depend on cutoff/ren. scale \( \mu \).

\[
\Delta s_{(n)}(\mu) \text{ in QCD}
\]

\[
\mu \frac{d}{d\mu} \Delta s_{(n)}(\mu) = -\frac{\beta_{(n)}}{2\pi} \left[ \Delta s_{(n)}(\mu) \right]^2 + ...
\]

\[
\beta_{(n)} = \frac{11 - \frac{2}{3} n_f}{\beta_0}
\]

\[
\Delta s_{(3)}(\mu) \quad \text{Hmwrk}
\]

Effects from heavy (or offshell) particles are suppressed/decouple.

\[
P_{lo} \ll \Lambda_H
\]

\[
\Lambda_H \quad \text{eg} \quad \begin{array}{c}
\overline{u} \\
\overline{d} \\
\end{array}
\quad \rightarrow \quad \begin{array}{c}
\overline{c} \\
\overline{s} \\
\end{array}
\quad \rightarrow \quad \begin{array}{c}
\overline{c} \\
\overline{s} \\
\end{array}
\quad \begin{array}{c}
\Phi \rightarrow \Phi \Phi \\
\Phi \rightarrow \Phi \Phi \\
\end{array}
\quad \frac{m_\phi^2}{m_\phi^2} \quad m_\phi \gg P_{lo}^2
\]

EFT
eg. $SM \mathrel{\overset{\sim}{\leftrightarrow}} EFT \quad \mathcal{L} = \mathcal{L}_S^{(0)} + \mathcal{L}_S^{(1)} + \mathcal{L}_S^{(2)} + \cdots$

- $\Lambda_{\text{New}}$
- $\Lambda_{\text{New}} \ll \Lambda_{\text{Weak}}$
- $\Lambda_{\text{New}} \ll \Lambda_{\text{Weak}}$

Here power counting of $EFT \ll \dim \mathcal{O}$ \[ \text{not always} \]

eg. $\mathcal{O}^{(2)} \equiv \frac{C_2}{\Lambda_{\text{New}}} H^+H B_{\mu \nu}B^{\mu \nu}$ give $H \to 3\gamma$ from "new" physics

ignoring flavor & counting Baryon & conserving Ops : $1 \times (1), 59 \times (2)$

\[ \text{Factorization } \rightarrow \text{very successful!} \]

key tool to calculate cross sections for collisions is ability to independently consider different parts of process
do $\sim$ (Prob. for gluons taken from protons)
\[
\begin{bmatrix}
\delta (gg \rightarrow H) \\
\delta (gg \rightarrow Hg)
\end{bmatrix}
\]
\[
\text{(Prob for gluons to produce jets)}
\]

eg. $pp \rightarrow H + \text{anything} \leftarrow [0+1+2+\cdots \text{sets}]$

\[
\sigma = \int dx_1dx_2f_g(x_1, \mu)f_g(x_2, \mu) \left\{ \delta (gg \rightarrow H + \text{any} (X_1, X_2, \mu, MH)) \times (1) \right\}
\]

universal parton distn function

= Prob of finding $g$ in proton
with momentum fraction $x_1$ [parton density]

$\delta (1) = \sum_i \text{Prob}(i)$

we sum over everything that can happen
(with final state quarks & gluons) so are not sensitive to dynamics of jet formation
need to be inclusive to avoid sensitivity to low energy scales & hadronization process.

Practical limits on $\hat{s}$, $t$ cuts on jets to control bkgs:

$\rightarrow$ enhance signal by $\geq N$ jets (RUSR).

Still sum over dynamics inside the jet & characterize it by a few variables: jet momentum $p_T^j = \sum_i p_T^i$, angular size $R$.

What is $\mu$ in $f_g$'s $\hat{s}$?

- Scale dividing the long & short dist. physics.

- Dependence tying them together is logarithmic:

$$\ln \left( \frac{M_H}{\Lambda_{\text{scale}}} \right) = \ln \left( \frac{\mu}{\Lambda_{\text{scale}}} \right)$$

in $\hat{s}$

in $f_g$'s

$f_g(x, \mu)$: depending on scale $\mu$, where we probe the gluon the dist'n changes

$$\mu \frac{d}{d\mu} f_i(x, \mu) = \int \frac{dz}{z} P_{ij}(x) f_j \left( \frac{z}{x}, \mu \right)$$

dist'n changes due to evolution by splitting

$P_{gg}$

$P_{gq}$

$P_{qg}$

$P_{gg}$

$P_{qq}$

$P_{qg}$

$P_{gq}$

$P_{ij}$ are "splitting functions":

$$P_{gg}(z) = \frac{d\sigma(p \rightarrow p)}{d\mu} C_A \left[ \frac{x}{1-x} + \frac{(1-x)}{x} + x(1-x) \right] + O(x^2)$$

$CA = 3$

Just like $d\sigma(p)$, their evolution is important.
Also \( \mu \frac{d}{dt} \sigma = 0 \), dependence of \( \sigma \) cancels \( f_g f_g \)

\( f_g \) wants \( \mu \geq 1 \text{GeV} \geq \Lambda_{QCD} \)

\( \sigma \) wants \( \mu = M_H \)

Solution:

\[
f_g(x, \mu) = \int \frac{dz}{z} U_g i(\frac{x}{z}, \mu, \mu_0) f_g(z, \mu_0)
\]

\[
\sigma = \int \frac{dx_1 dx_2 dz_1 dz_2}{z_1 z_2} f_i(\frac{z_1}{\mu_0}) f_j(\frac{z_2}{\mu_0}) U_{ij}(\frac{x_1}{z_1}, \mu, \mu_0) U_{ij}(\frac{x_2}{z_2}, \mu, \mu_0)
\]

\[
\times \delta_{g g} \Rightarrow H_{igg}(x_1, x_2, \mu, M_H)
\]

\( \mu_0 \gg 1 \text{GeV} \)

\( f_i(z, \mu_0) \) non-pert input (fit)

\( \mu \geq M_H \)

Ugi sums \( \infty \) series of logarithms \( ds(\mu) \ln(\frac{\mu}{\mu_0}) \)

which encode dynamics between two scales

"renormalization group"

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Activities in Collider Physics

- Higher order \( ds \), loops

- Parton Shower Monte Carlo for jets

- PDF's \( f_i(x, \mu) \), global fits

- Factorization (validity, more specific final states)

- Resummation finding Ugi's at higher order & other cases

\[
\sum_{i=0}^{\infty} c_i \ln^2(\frac{\mu}{\mu_0})
\]

Double logs can appear

- Observables
Jets

final state quarks & gluons observed as jets, why?

enhancement from collinear $q \rightarrow 0 \&$ soft $E \rightarrow 0$ singularities

$\begin{align*}
\frac{\partial \sigma}{\partial \vec{q}} &= e^2 \int \frac{dE}{E} \frac{d\Omega}{\Omega} \\
&= (1-\epsilon)_p \\
&= \frac{2}{1-\epsilon} \frac{d\vec{k}_T}{k_T} \\
\end{align*}$

for only $\frac{d\vec{k}_T}{k_T} \frac{d\vec{q}}{\vec{q}} \sim g(\epsilon)$

gluons & quarks like to split in collimated manner

• inclusive inside jet [but cf. jet substructure]

• angular cutoff $R$ for size of jets & cutoff on amount of energy outside the $N$-jets

eg. 1 jet of $R=0.5$ with $p_T \geq 30$ GeV (beam $p_T$)

any remaining jets $p_T < 30$ GeV = $p_T^{cut}$

"1-jet event"

eg. H + 0-jets (used in Higgs discovery, $\sigma^2$ discovery)

only jets with $p_T \leq 30$ GeV

$\sigma \sim \sigma_{inc} \left(1 - \frac{2\Delta s(\mu)}{\pi} \ln^2 \left(\frac{p_T^{cut}}{\mu H}\right) + \ldots\right)$ "jet veto"

LL : $\sim 1 + \Delta S^2 + \Delta L^2 + \ldots$ exponentiate

$\exp \left(-\frac{2\Delta s(\mu)}{\pi} \ln^2 \left(\frac{p_T^{cut}}{\mu H}\right) + \text{running coupling terms}\right)$

example of

Sudakov Form

Factor from

IR safety test

invariant under $p_T \rightarrow p_T + p_k$

$p_T/p_\perp$ or $p_T \neq 0$
Hadron Collider Variables

Know proton collision CM frame

don't know gluon collision CM frame \( \int dx_1 \int dx_2 \)

Use variables that are boost invariant along \( \hat{z} \)

- \( \Sigma P_x, P_y \rightarrow \Sigma P_T, \phi \)

- for \( \Sigma E, P_z \) use \( \Sigma m, y \)

Rapidity \( y = \frac{1}{2} \ln \left( \frac{E + P_z}{E - P_z} \right) \) \( m = 0 \)

\[ E = \sqrt{m^2 + P_T^2} \text{ cosh} y \]
\[ P_T^2 = \sqrt{m^2 + P_T^2} \text{ sinh} y \]

\( \Delta y = y_1 - y_2 \) is \( \hat{z} \) boost invariant

Angular size \( \Delta R = \sqrt{(\Delta y)^2 + (\Delta \phi)^2} \)

Roughly: Jet Radius \( R \) is \( (\Delta R)^{jet} = R \) where \( (\Delta R)^{jet} \) means with respect to the jet axis rather than beam axis.
"Extra Notes"

Jet Algorithms  "How precisely do we define a jet?"

Which particles do we group?  IR safety

Recombination Algorithms  (now most popular)

Consider set of particles  (hadrons, partons, calorimeter cells)

\[ d_{ij} = \min \left( \frac{p_{Tj}^2}{p_{Tj}^2}, \frac{p_{Ti}^2}{p_{Ti}^2} \right) \frac{\Delta R_{ij}^2}{R^2} = \text{distance (i,j)} \]

\[ d_{i0} = \frac{p_{Ti}^2}{R^2} = \text{distance (i, beam)} \]

Find \( \min \left( \sum d_{i,j}^2, \sum d_{i,0}^2 \right) \)  \( L = \text{all particles} \)

\[ \text{join } i,j \text{ into new particle in } L \text{, repeat} \]

\[ \text{discord } i \text{ (into beam), repeat} \]

\( R = 1 \)  \( \text{kt algorithm, clusters soft particles first (jet regions)} \)

\( R = 0 \)  \( \text{Cambridge/Aachen, geometric} \)

\( R = -1 \)  \( \text{Anti-kt, clusters harder collinear particles first (circum regions)} \)

\( \text{(default ATLAS & CMS)} \)

Above \( R \) is true definition of jet radius parameter & is close to "rough" definition for anti-kt