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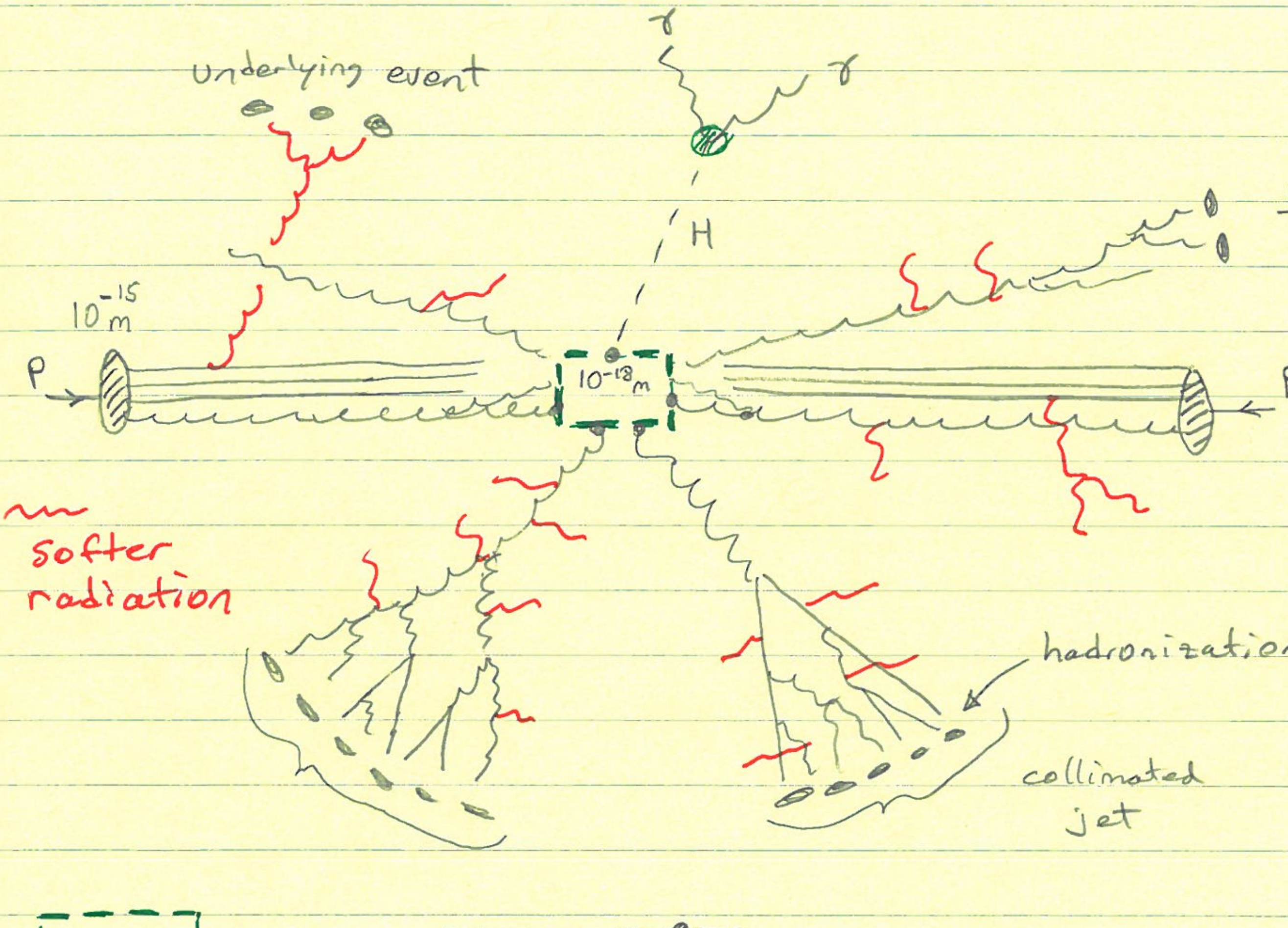
Vienna Lectures: Intro to Collider Physics and Effective Field Theory Methods

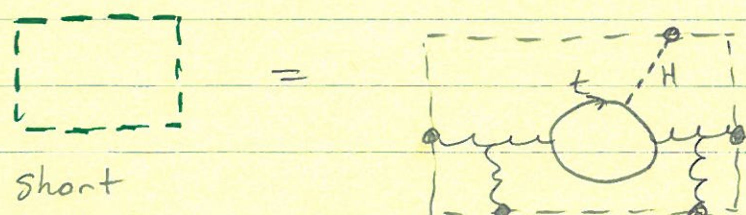
June 2016

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

LHC collision of two protons



[all scales in between also probed]

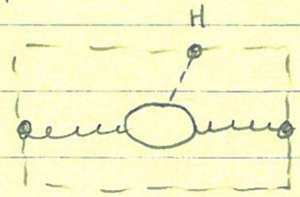


short distance process

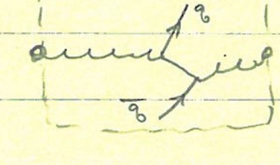
$gg \to H + gg$

($pp \to H + 2$ jets)

or



$gg \to H$ ($pp \to H + 0$-jets)



$gg \to q\bar{q}, \ldots$ $pp \to 2$ jets

$> 10^5$ more likely

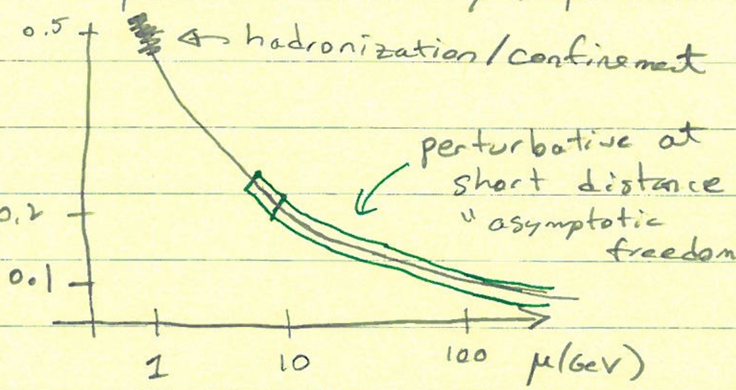
QCD $\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \sum_i \bar{\Psi}_i (i\not{D} - m_i)\Psi_i$

$iD^\mu = i\partial^\mu + g T^a A^{\mu a}$

In QCD the <u>energy scale</u> "μ" of a process is very important

$\alpha_s = \frac{g^2}{4\pi} = \alpha_s(\mu)$

↑ strong coupling



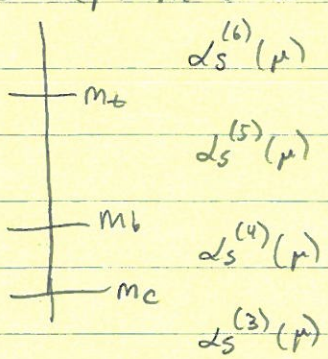
need to know "μ" values to find appropriate coupling to use for different parts of the collision

<u>Concept: Renormalization & Decoupling</u>

- parameters g in QFT (EFT) must be defined by a renormalization scheme ($\overline{MS}$, ...). [O too in EFT]
- schemes depend on cutoff/ren. scale "μ"

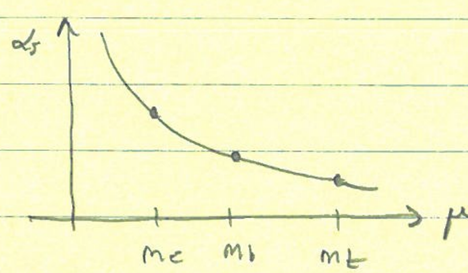
eg. $\alpha_s^{(n_f)}(\mu)$ in QCD

$$\mu \frac{d}{d\mu} \alpha_s^{(n_f)}(\mu) = -\frac{\beta_0^{(n_f)}}{2\pi}\left[\alpha_s^{(n_f)}(\mu)\right]^2 + \cdots$$



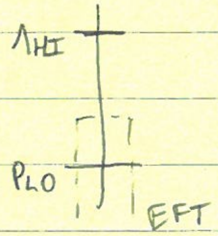
$$\beta_0^{(n_f)} = 11 - \frac{2}{3} n_f$$

Hmwk

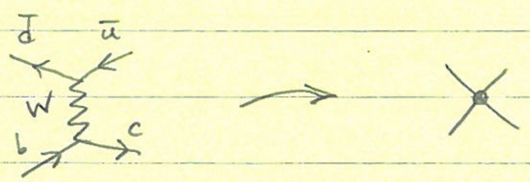


Effects from heavy (or offshell) particles are suppressed/decouple

$p_{LO} \ll \Lambda_{HI}$



eg



$\frac{(\bar{\Psi}\cdots\Psi)(\bar{\Psi}\cdots\Psi)}{m_W^2}$ $m_W^2 \gg p_i^2$

eg. SM as EFT $\qquad \mathcal{L} = \mathcal{L}^{(0)}_{SM} + \mathcal{L}^{(1)} + \mathcal{L}^{(2)} + \cdots$

$\qquad\qquad\qquad\qquad\qquad\qquad \uparrow \qquad\quad \sim \frac{\mathcal{O}^{(\text{dim}5)}}{\Lambda_{new}} \qquad \sim \frac{\mathcal{O}^{(\text{dim}6)}}{\Lambda_{new}^2}$

Λ_{new}

$\Lambda_{weak} \ll \Lambda_{new}$ $\qquad$ dim ≤ 4 $\qquad\qquad$ Hmwk

SM $\quad t, H, W, Z$

here power counting of EFT $\Leftrightarrow$ dim $\mathcal{O}$ [not always]

eg. $\mathcal{L}^{(2)} = \frac{C_B}{\Lambda_{new}^2} \underbrace{H^\dagger H \, B_{\mu\nu} B^{\mu\nu}}_{\text{operator}}$ $\qquad$ gives $H \to \gamma\gamma$ from "new" physics

coupling $\qquad$ Higgs $\qquad$ $U(1)_Y$

[ignoring flavor & counting Baryon # conserving Ops: $\quad 1 \ \mathcal{L}^{(1)}, \ 59 \ \mathcal{L}^{(2)}$]

Factorization $\to$ very successful!

key tool to calculate cross sections for collisions is ability to <u>independently</u> consider different parts of process

$$d\sigma \sim \begin{pmatrix}\text{Prob. for} \\ \text{gluons taken} \\ \text{from protons}\end{pmatrix} \boxed{\begin{pmatrix}\hat\sigma(gg\to H), \\ \hat\sigma(gg \to Hg), \ldots\end{pmatrix}} \begin{pmatrix}\text{Prob for gluons} \\ \text{to produce} \\ \text{jets}\end{pmatrix}$$

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

$$\sigma = \int dx_1 \, dx_2 \, \underbrace{f_g(x_1,\mu)} \, f_g(x_2,\mu) \, \boxed{\underbrace{\hat\sigma_{gg\to H+any}(x_1,x_2,\mu,M_H)}_{\text{short distance}}} * (1)$$

$\boxed{\text{Universal}}$ parton dist'n function

= Prob of finding g in proton with momentum fraction x_1 [prob. density]

(1) $= \sum_i (\text{Prob})(i)$ $\quad$ We sum over everything that can happen (with final state quarks & gluons) so are not sensitive to dynamics of jet formation

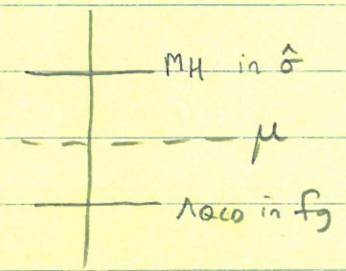
[• need to be inclusive to avoid sensitivity to low energy scales & hadronization process

Practical Limits on $\sum_i$ → cuts on jets to control bkgnds
→ enhance signal by $\geq N$ jets (SUSY)

Still sum over dynamics inside the jet & characterize it by a few variables: jet momentum $p_J^\mu = \sum_{i \in J} p_i^\mu$
angular size R

<u>What is μ in f_g's & $\hat{\sigma}$?</u>

• scale dividing the long & short dist. physics



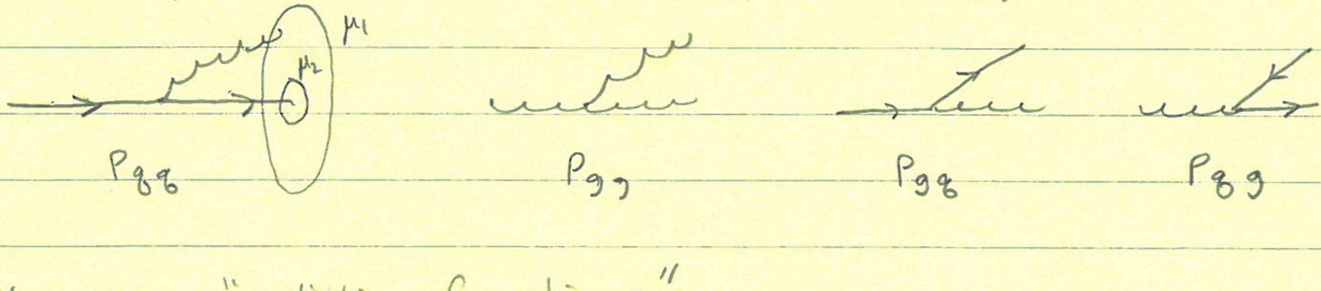
• Dependence tying them together is logarithmic

$$\ln\left(\frac{m_H}{\Lambda_{QCD}}\right) = \underbrace{\ln\left(\frac{m_H}{\mu}\right)}_{\text{in } \hat{\sigma}} + \underbrace{\ln\left(\frac{\mu}{\Lambda_{QCD}}\right)}_{\text{in } f_g\text{'s}}$$

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

$$\mu \frac{d}{d\mu} f_i(x,\mu) = \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z}\right) f_j(z,\mu) \qquad \text{DGLAP eqtns}$$

dist'n changes due to evolution by splitting



P_{ij} are "splitting functions"

$$P_{gg}(z) = \frac{\alpha_s(\mu) C_A}{\pi}\left[\frac{x}{(1-x)_+} + \frac{(1-x)}{x} + x(1-x)\right] + \mathcal{O}(\alpha_s^2)$$

$C_A = 3$

just like $\alpha_s(\mu)$ their evolution is important

Also $\mu \frac{d}{d\mu} \sigma = 0$, dependence of $\hat{\sigma}$ cancels $f_g f_g$

f_g wants $\mu \simeq 1\,\mathrm{GeV} \gtrsim \Lambda_{QCD}$

$\hat{\sigma}$ wants $\mu \simeq m_H$!

Solution :

$$f_g(x,\mu) = \int_x^1 \frac{dz}{z}\, U_{gi}\!\left(\frac{x}{z},\mu,\mu_0\right) f_g(z,\mu_0)$$

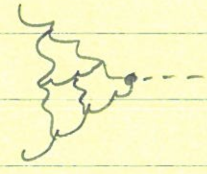
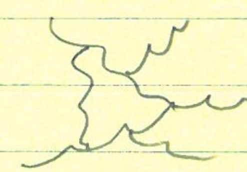
$$\sigma = \int dx_1\, dx_2\, \frac{dz_1}{z_1} \frac{dz_2}{z_2}\, f_i(z_1,\mu_0)\, f_j(z_2,\mu_0)\, U_{ig}\!\left(\frac{x_1}{z_1},\mu,\mu_0\right) U_{jg}\!\left(\frac{x_2}{z_2},\mu,\mu_0\right)$$
$$\times\ \hat{\sigma}_{gg\to H+any}(x_1,x_2,\mu,m_H)$$

take $\mu_0 \simeq 1\,\mathrm{GeV}$ $\qquad$ $f_i(z,\mu_0)$ non-pert input (fit)

$\mu \simeq m_H$

U_{gi} sums ∞ series of logarithms $\alpha_s(\mu) \ln\left(\frac{\mu}{\mu_0}\right)$
which encode dynamics btwn two scales
"renormalization group"

Activities in Collider Physics

- $\boxed{}$ higher order α_s^n, loops  & legs 
- Parton Shower Monte Carlo for jets
- PDF's $f_i(x,\mu)$, global fits
- Factorization (validity, more specific final states)
- Resummation finding U_{gi}'s at higher order & other cases

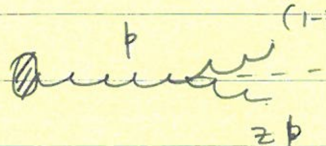
$$\sum_{i=0} c_i\, \alpha_s^i \ln^{2i}\left(\frac{\mu}{\mu_0}\right) \quad \text{double logs can appear}$$

- Observables

Jets

final state quarks & gluons observed as <u>jets</u>, why?

enhancement from collinear $\theta \to 0$ & soft $E \to 0$ singularities

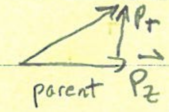


$$\propto \frac{\alpha_s C_A}{\pi} \underbrace{\frac{dE}{E}\frac{d\theta}{\theta}}_{\frac{dz}{1-z}\frac{dk_T}{k_T}}$$

<u>soft</u> & <u>collinear</u> ∞ $E \to 0, \theta \to 0$

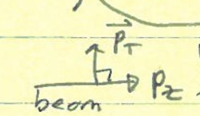
$E = (1-z)p$
$k_T = E \sin\theta$

for only collinear : $\propto \frac{dk_T}{k_T}\, dz\, P_{gg}(z)$



gluons & quark like to split in collimated manner

- inclusive inside jet (IR div. cancels) [but cf. jet substructure ]
- angular cutoff R for size of jets & cutoff on amount of energy outside the N-jets } One log each

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

any remaining jets $p_T < 30 \text{ GeV} \equiv p_T^{cut}$
"1-jet event"

eg. H + 0-jets (used in Higgs discovery, ... σ! Higgs coupling)

~~discovery~~

only jets with $p_T \leq 30$ GeV

$$\sigma \sim \sigma_{incl} \left(1 - 2\frac{\alpha_s(\mu) C_A}{\pi} \ln^2\left(\frac{p_T^{cut}}{m_H}\right) + \dots \right)$$ "jet veto"

LL : $\sim 1 + \alpha_s L^2 + \alpha_s^2 L^4 + \dots$ exponentiate

$$\exp\left(-\frac{2\alpha_s C_A}{\pi} \ln^2\left(\frac{p_T^{cut}}{m_H}\right) + \text{running coupling terms} \right)$$

example of <u>Sudakov Form</u> Factor from restricting radiation

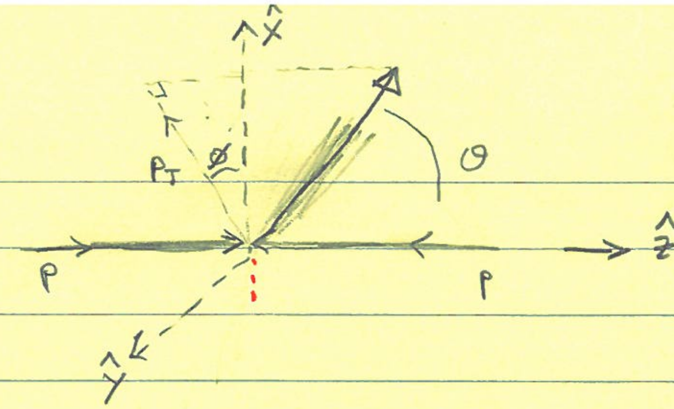
<u>IR safety test</u>

invariant under $p_i \to p_j + p_k$

$p_i \,//\, p_j$ or $p_j \to 0$

"Extra Notes"

Hadron Collider Variables



Know proton collision CM frame

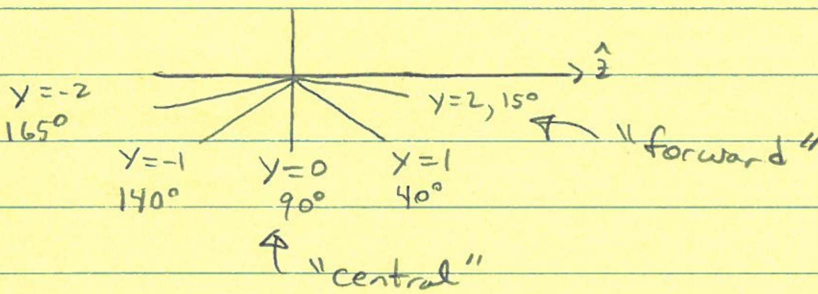
don't know gluon collision CM frame $\int dx_1 \int dx_2$

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

- $\{p_x, p_y\} \Leftrightarrow \{p_T, \phi\}$

- for $\{E, p_z\}$ use $\{m, y\}$ $\qquad p^2 = m^2$

rapidity $\quad y = \frac{1}{2} \ln\left(\frac{E+p_z}{E-p_z}\right) \overset{m=0}{=} \ln \cot \frac{\theta}{2}$



$E = \sqrt{m^2 + p_T^2} \cosh y$

$p_z = \sqrt{m^2 + p_T^2} \sinh y$

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

angular size $\quad \Delta R = \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$

Roughly: Jet Radius R is $(\Delta R)^{jet} \lesssim R$ 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)

$$d_{ij} = \min(p_{Ti}^{2r}, p_{Tj}^{2r}) \frac{\Delta R_{ij}^2}{R^2} = \text{distance}(i,j)$$

$$d_{iB} = p_{Ti}^{2r} = \text{distance}(i, \text{beam})$$

Find $\min(\{d_{ij}\}, \{d_{iB}\})$ L = all particles

$i,j \in L$ ↓ join i & j into new particle in L, repeat

↘ discard i (into beam), repeat

$r=1$ k_T algorithm, clusters soft particles first (jet regions not circular)

$r=0$ Cambridge/Aachen, geometric

$r=-1$ Anti-k_T, clusters harder collinear particles first (circular regions) (default ATLAS & CMS)

Above R is true definition of jet radius parameter & is close to "rough" definition for anti-k_T