Lecture 3: An Introduction to Jets

Last time, we made a profound assertition, that the process

$$pp \to 1\ 2\ 3 \cdots n$$

could be decomposed into a partonic cross section

$$\sum_{ij} ij \to \underbrace{1\ 2 \cdots}_{\text{few}} \times Br(1 \to \_\_) \\ \times Br(2 \to \_\_) \\ \vdots$$

We derived the NWA approximation, and stated its assumptions.

We asserted PDFs, but they are more delicate.

Crucial to this factorization is an assumption about measurements.

$$f(\text{hadrons}) \simeq f(\text{partons from the hard process})$$

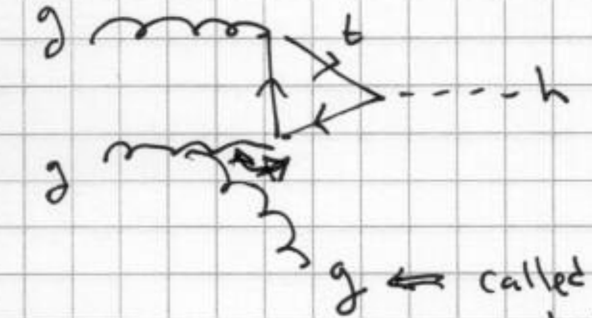
First, hadrons $\Leftrightarrow$ partons implies insensitivity to non-perturbative hadronization effects

Second, "all partons" vs. "partons from hard process" implies insensitivity to non-perturbative "underlying event" (what happens to the beam remnants)

Insensitivity to hadronization and UE has to be checked observable by observable. We will assume that's the case for these lectures.

Now, there is a <u>perturbative</u> phenomenon in QCD that is calculable and has a big impact on collider physics: initial- and final-state radiation.

Let's look at higher-order corrections to Higgs boson production



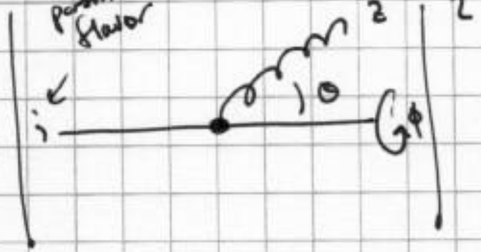
⇐ called ISR, since radiated from initial state

★ in the amplitude, you have a propagator $\frac{1}{q^2}$

Implies propagator "wants" to be on-shell. Want some kind of analog of NWA.

$\Longrightarrow$ soft-collinear limit. (puts intermediate gluon close to on-shell)

I won't prove it here, but you can show that.



$$\simeq \frac{2\alpha_s}{\pi}\,\underset{\substack{\uparrow\\ \text{color}\\ \text{factor}}}{C_i}\;\underset{\substack{\uparrow\\ \text{soft}\\ \text{singularity}}}{\frac{dz}{z}}\;\underset{\substack{\nwarrow\\ \text{collinear}\\ \text{singularity}}}{\frac{d\theta}{\theta}}\;\overset{\substack{\text{assuming}\\ \text{unpolarized}\\ \swarrow}}{\frac{d\phi}{2\pi}}$$

for gluon emission

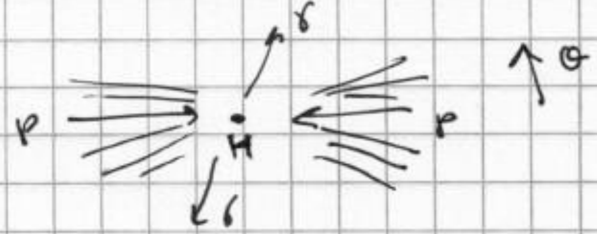
quarks $C_F = 4/3$

gluons $C_A = 3$

z = momentum fraction

θ = opening angle.

Preference for initial-state radiation to go in direction of initial state!



What is angular distribution of ISR, approximately?

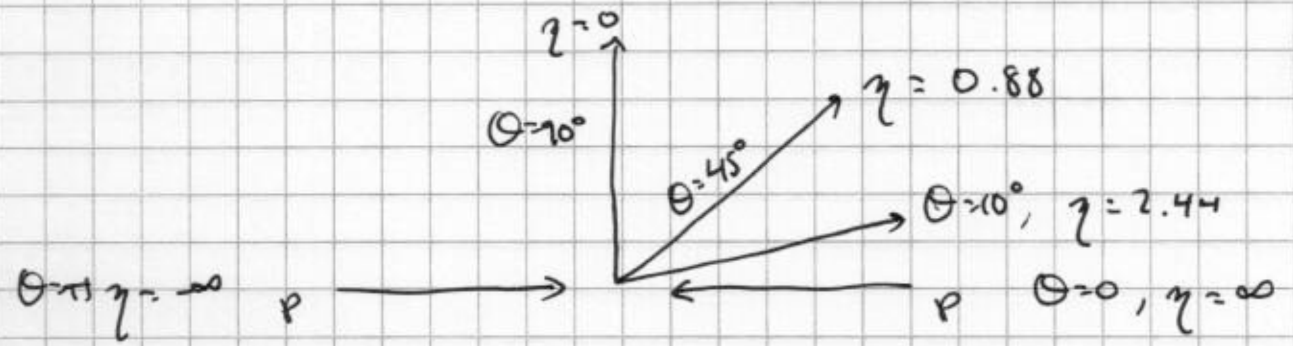
$\frac{d\theta}{\theta}$ near $\theta = 0$ $\quad$ $\frac{d\theta}{\pi - \theta}$ near $\theta = \pi$

$\Longrightarrow \frac{d\theta}{\sin\theta}$ strongly peaked in forward directions.

This peaking behavior of ISR (and other effects) is quite annoying to deal with, so we usually do a change of variables.

$$\eta = -\log \tan\frac{\theta}{2}$$

$$|d\eta| = \left|\frac{d\theta}{\sin\theta}\right| \Leftarrow \text{good exercise!}$$



ATLAS/CMS detectors have some sensitivity out to $\eta=5$.

η = "pseudorapidity"

Convenient, since massless QCD emissions have roughly uniform distribution in (η, ϕ) plane.

(For massive particles, better to use true rapidity

$$y = \frac{1}{2}\log\frac{E+p_z}{E-p_z}.)$$

This is why in proton-proton collisions we don't use

$$(E, p_x, p_y, p_z)$$

but rather use

$$(p_T, y, \phi, m)$$

Conversion is straight forward

$$E = \sqrt{p_T^2 + m^2} \cosh y$$
$$p_x = p_T \cos\phi$$
$$p_y = p_T \sin\phi$$
$$p_z = \sqrt{p_T^2 + m^2} \sinh y$$

p_T invariant to boosts along beam axis

Δy invariant to boosts along beam axis

But reason for y (or η) is distribution of radiation from QCD. being roughly flat.

(convenient for jet calibration)

Something that's confusing is that Feynman diagrams are good approximations to *inclusive* cross sections.

$\simeq \sigma_{\text{Higgs plus anything}}$.

↑ even if it isn't in the diagram!

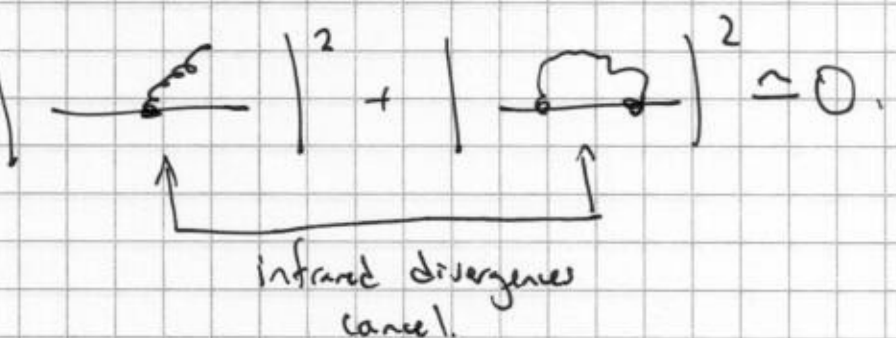
Why?

ISR scales like $\alpha_s \frac{d\theta}{\theta}$, so no real suppression.

↑ perturbative ↑ singular.

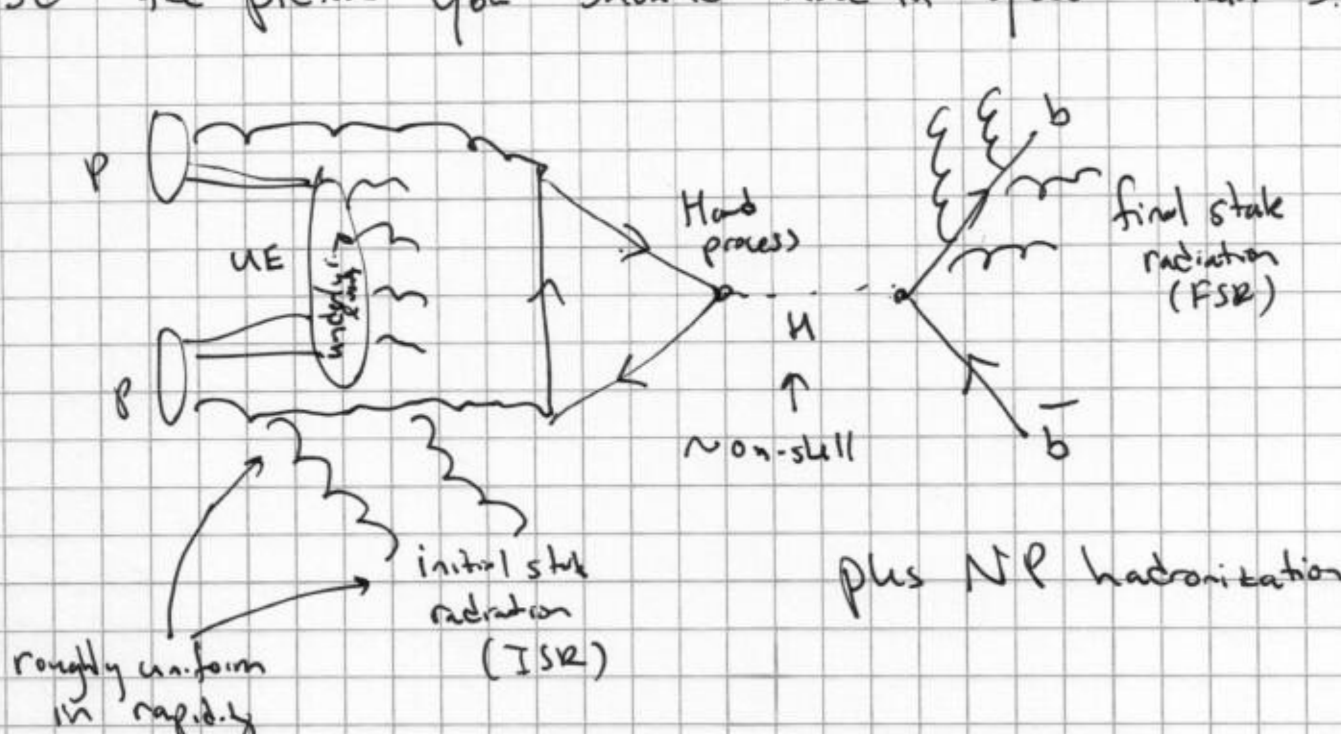
If you say "Higgs plus nothing else", you are sensitive to singular behavior.

If you say "Higgs plus anything else", you get cancelation



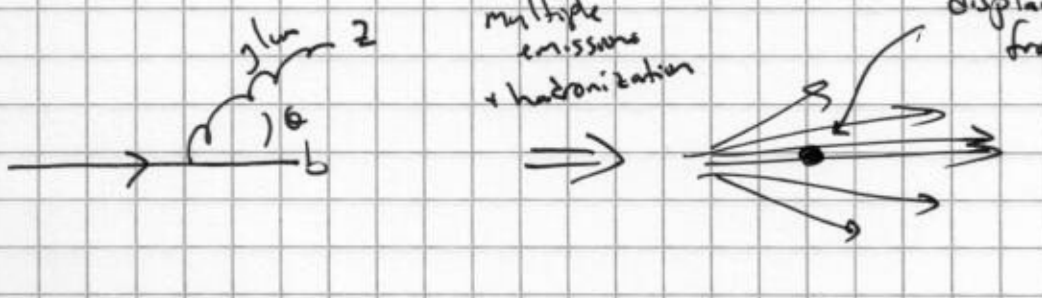
infrared divergences cancel.

So the picture you should have in your brain is.



plus NP hadronization

The same QCD singular structure shows up in final-state radiation. Preference for quarks and gluons to radiate soft-collinear gluons.



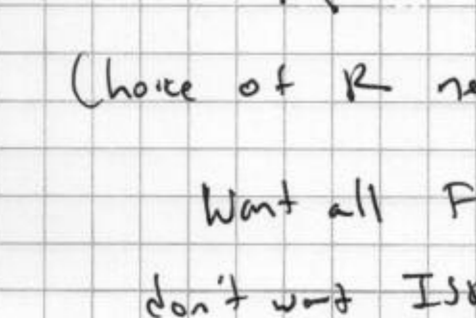
This is why jet algorithms are needed for collider data analysis, to "reverse" FSR showering.

Jet Algorithms (Very briefly)

Proxy for short-distance quarks / gluons constructed from long-distance hadrons.

Want an algorithm that is quasi-inclusive over soft-collinear gluon emissions

Jet definitions are fundamentally ambiguous, but typical algorithms (like anti-k_t) collect all radiation with some radius R (in η-ϕ or y-ϕ plane) into a jet.



$$\underset{\substack{\uparrow\\ \text{just B-hadron}}}{m_B} \neq \underset{\substack{\uparrow\\ \text{includes gluon radiation}}}{m_{b\text{-jet}}}$$

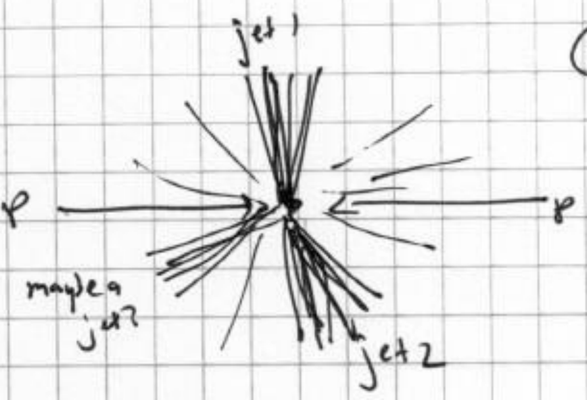
Choice of R needs to balance

Want all FSR $\Rightarrow \uparrow R$

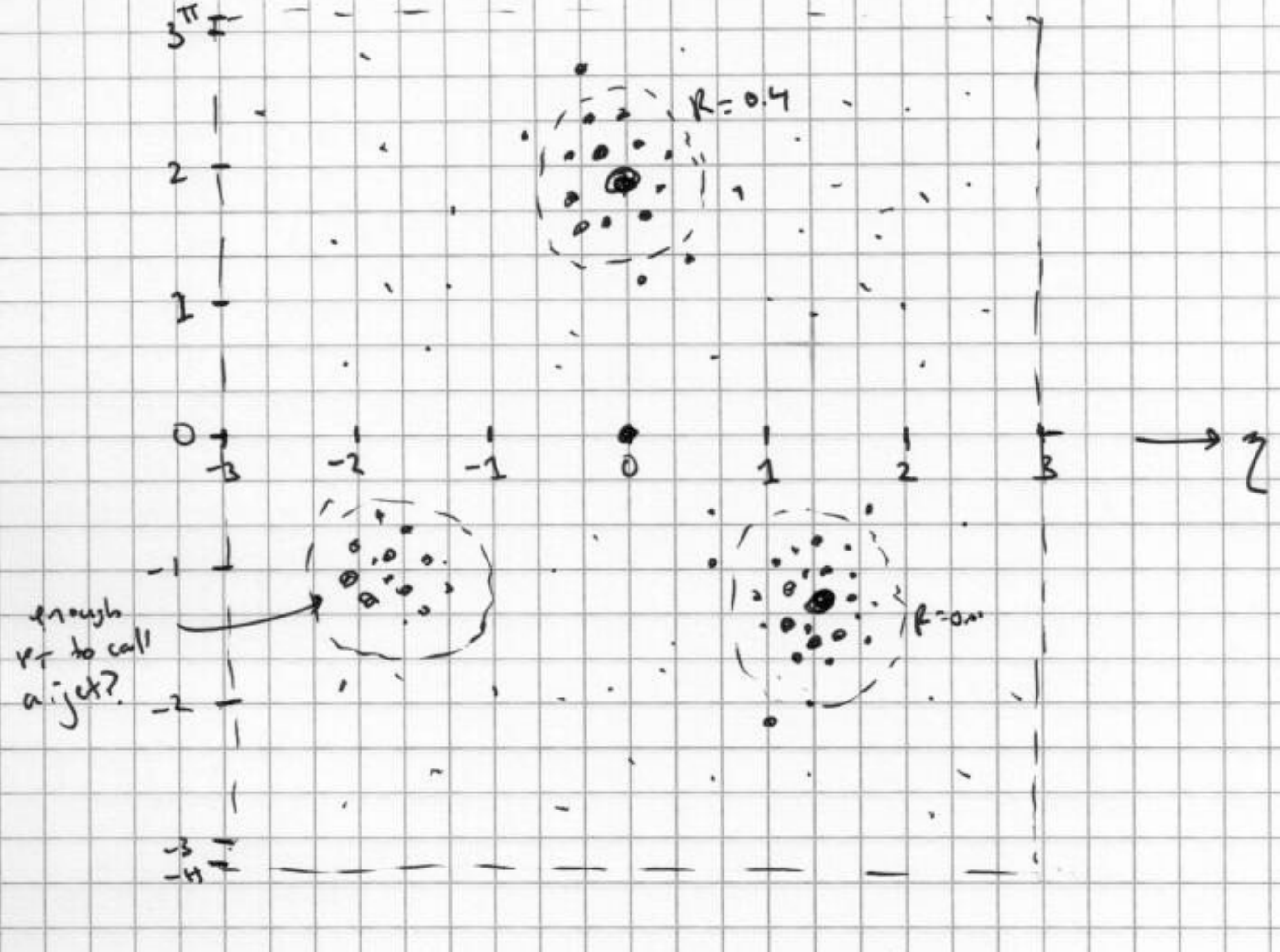
don't want ISR/UE $\Rightarrow \downarrow R$

$R \simeq 0.4$ typical at LHC, $m_{jet} \simeq 10\%\ p_{T\,jet}$

An example dijet event:



In lego plot form.



Uniform haze from ISR/UE/pileup.

Many different algorithms to map

$$\Big\{ \underset{\underset{\sim\text{massless}}{\uparrow}}{p_{\text{hadrons}}} \Big\} \Rightarrow \Big\{ \underset{\underset{\text{massive!}}{\uparrow}}{p_{\text{jet}}} \Big\}$$

Some concluding thoughts. 3 things I want you to remember.

① Have to think about observables. Even though I didn't spend much time discussing it, what you measure matters. There is no "theory of observables" (yet), so you have to think case by case.

② Factorization is crucial for making predictions. Can't predict "everything". Have to choose observables that respect PDFs, etc. otherwise no first-principles predictions (yet).

③ You see (quasi-)stable particles in your detector, not Standard Model particles. Good observables on hadrons $\Rightarrow$ good proxies for standard model states.

The Frontiers of Collider~~s~~ Physics

Always progress translating BSM scenarios into collider observables, but these don't break master formula. Cool "kinks" in Φ_n to exploit.

BSM scenarios with (quasi-) long-lived particles require new reconstruction techniques. Complicated interplay between QFT amplitudes and detector effects.

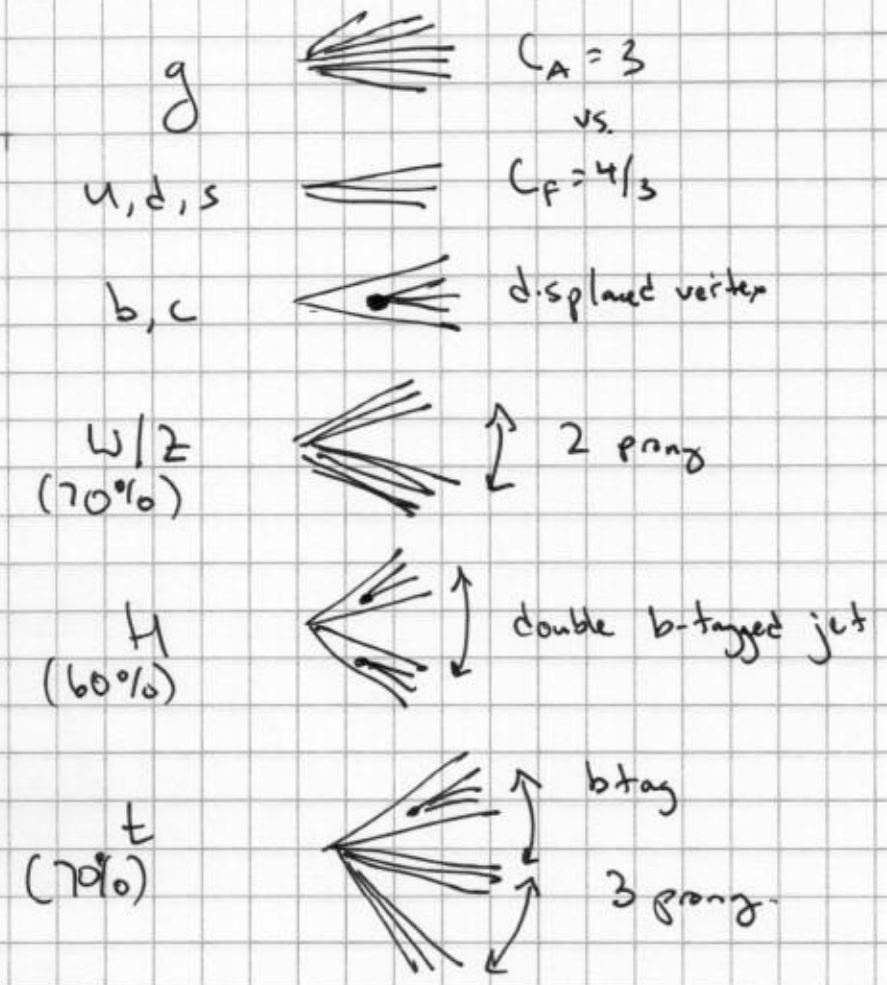
Jet substructure has become an important tool for BSM searches. If you have energetic enough cascade decays, can reconstruct heavy objects (W/Z/H, top, BSM) as single jet.

(In fact, at high enough energies everything is a jet, because of electroweak radiation.)

Some of this progress is happening via machine learning algorithms.

Jet Categories

Using observables to statistically separate jet types.



Without clever observables, these are indistinguishable

Jet substructure algorithms yield fantastic tagging performance.

Beyond the Master Formula?

$$\sigma_{\mathcal{M}} = \frac{1}{2E_{cm}^2} \sum_{n=2}^{\infty} \int d\Phi_n \left| \mathcal{M}_{AB \to 12 \cdots n} \right|^2 f_{\mathcal{M}}(\Phi_n)$$

Are there things you can do with colliders that don't fall into this framework?

(Hard to imagine anything else, but worth thinking about it.)

What is the "Space of measurements"?

e.g. infrared-collinear safe, but other classifications? (e.g. Sudakov safe?)

Bottom Line: Collider physics is a rich field, both in and beyond the standard model!