Jet substructure

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Background material with help from Zoltan Nagy and Michael Spannowsky

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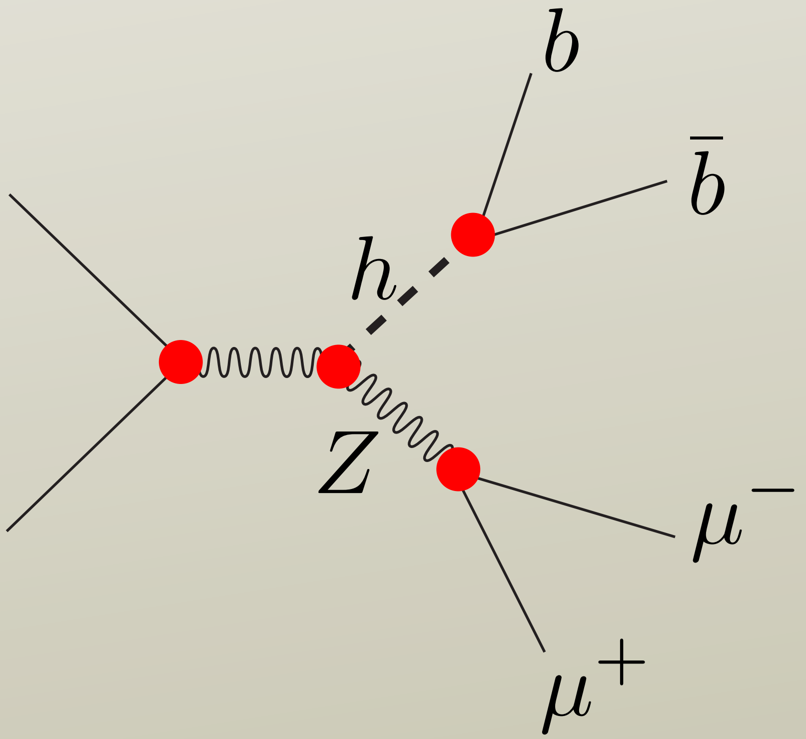
- There are several methods that use jet substructure to find signals of interest in LHC data.
- This talk is about some of the techniques that these methods use.
- It is also about the structure in nature that these methods try to take advantage of.

Signals and backgrounds at the LHC

Signal events

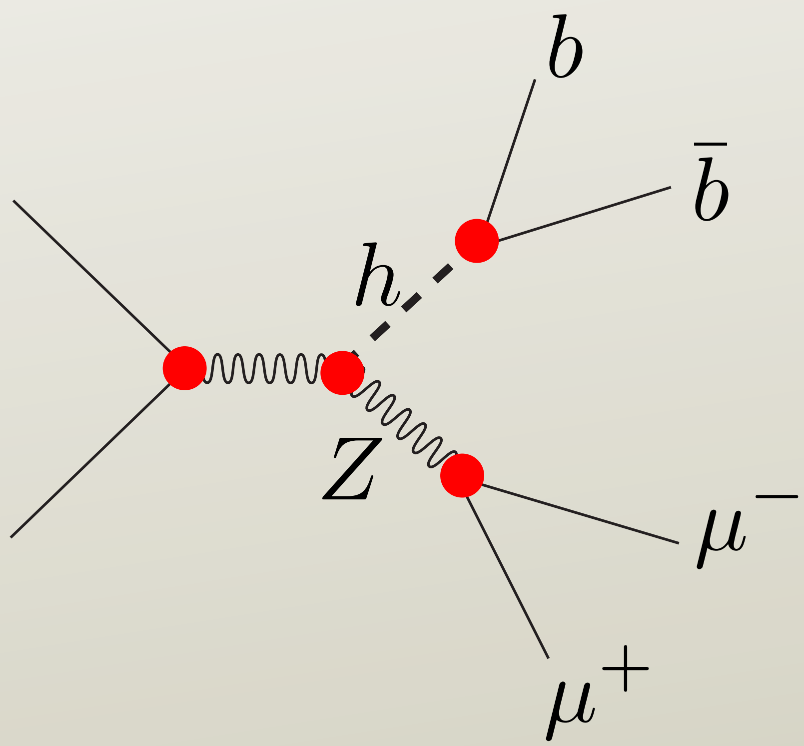
- I take a signal event to be one in which one or more new heavy particles is created and decays.
- Sometimes there is a chain of decays.
- Also, top quarks could be part of both signal and background events for some signals.

A Higgs boson signal event

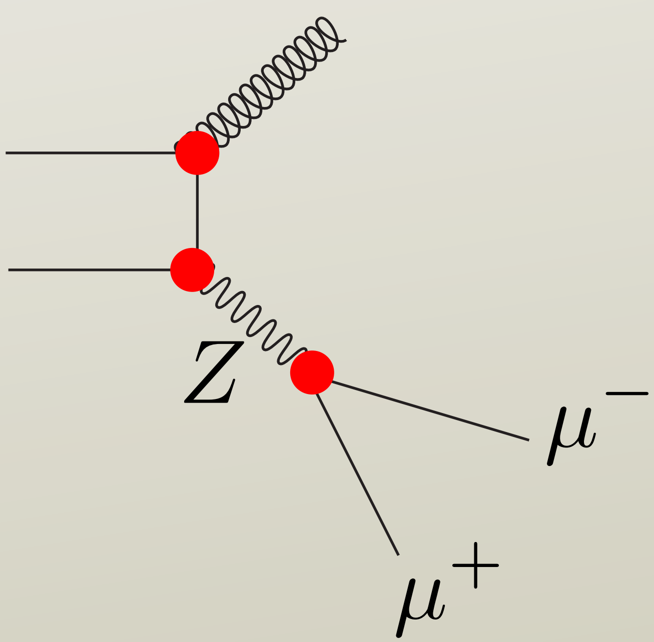


Background events

- There are always background events that can look like the signal events.



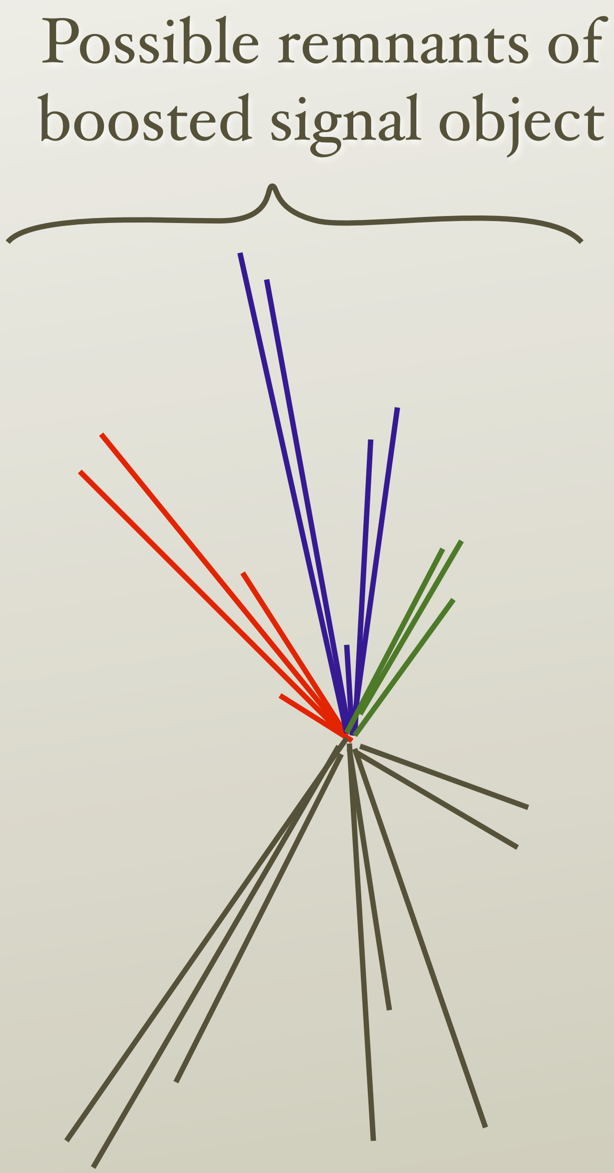
We want to find this.



In a background of this.

Signal and background with jets

- Both signal and background events have jets.
- There are several techniques for separating signal from background using the structure of the jets.
- This is especially effective for highly boosted heavy objects.

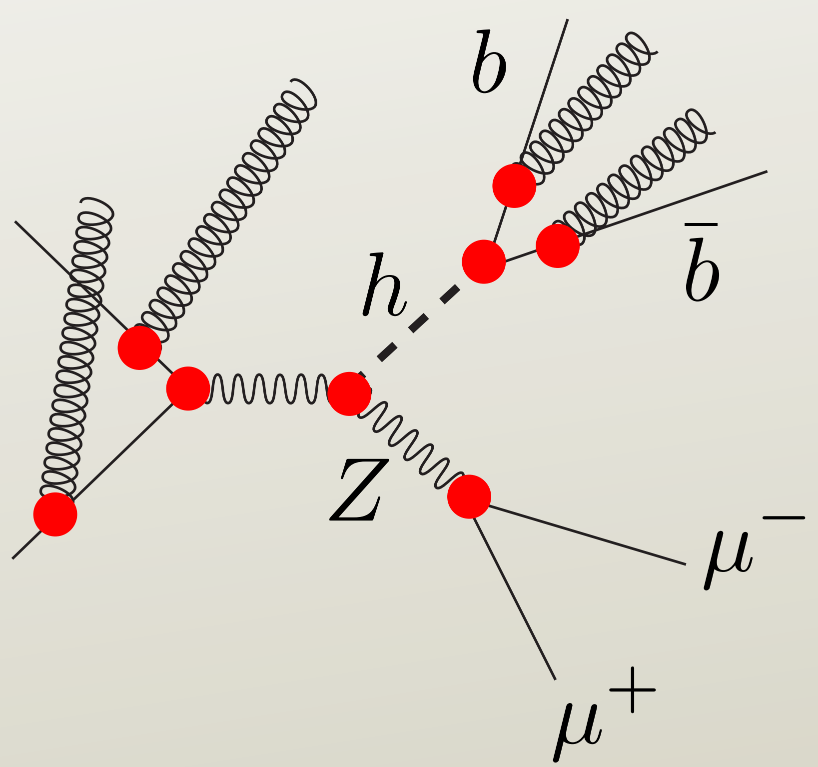


What gauge field theory has to say

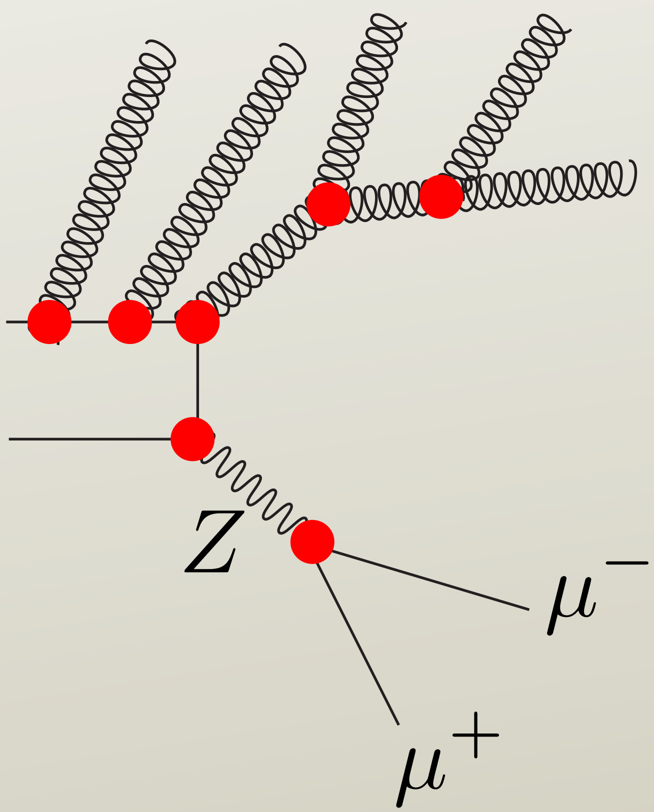
- One can use field theory to understand the characteristics of background events and the characteristics of signal events (with heavy particle decays).
- Schemes for selecting signal events depend on using the similarities and differences in signal and background events.
- I will try to outline the characteristics that can be used.

Initial state radiation

- One immediate similarity is that both signal and background events have initial state radiation.



A Higgs signal event



A similar background event

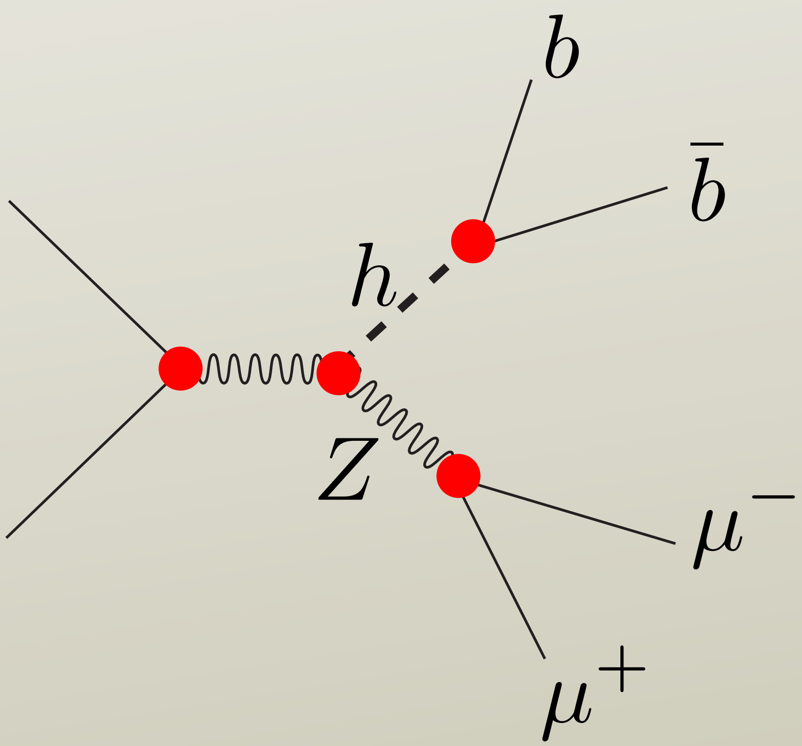
- This makes the signal/background separation difficult.

- More on this later.

Start with event selection

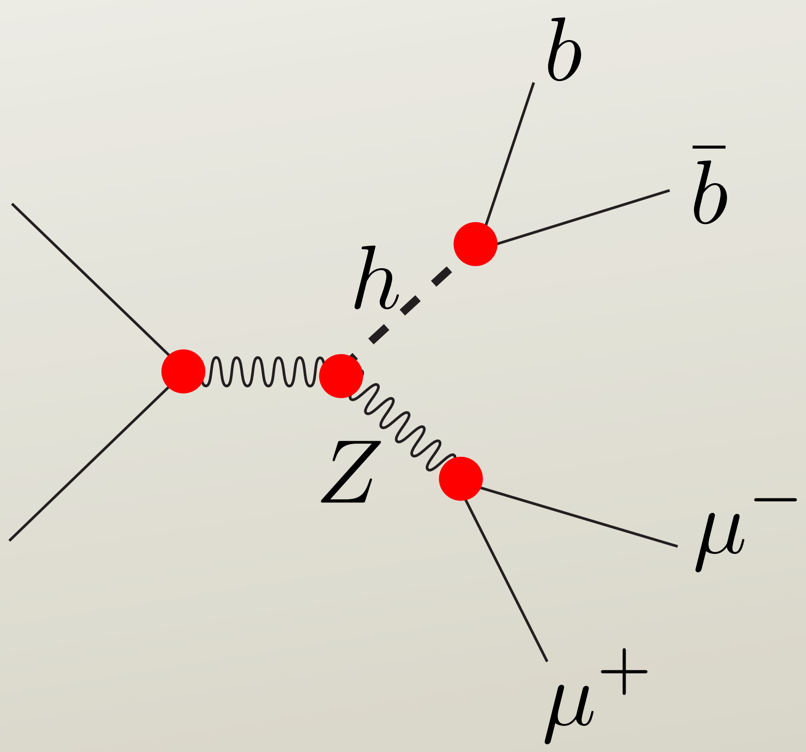
- Electron or muon pair near the Z mass.
- Large P_T of the lepton pair and of recoiling jet (>200 GeV).
- Large P_T implies that the possible Higgs decay products are easier to isolate: they are part of a (rather fat) jet.

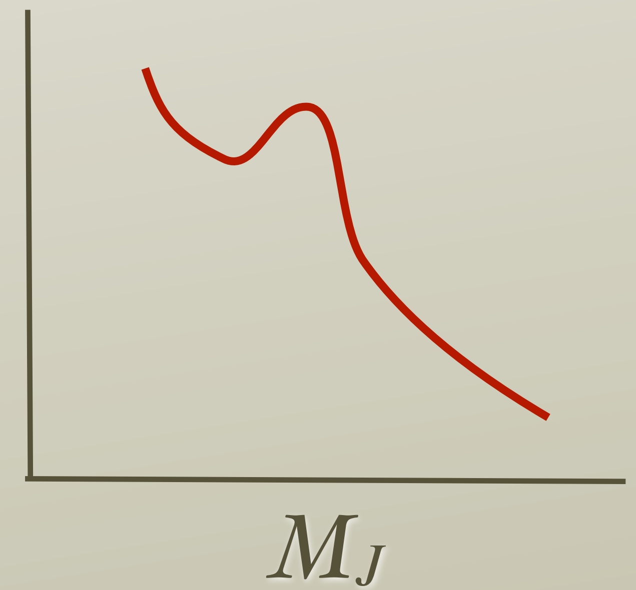
Butterworth, Davison, Rubin, and Salam (2008)

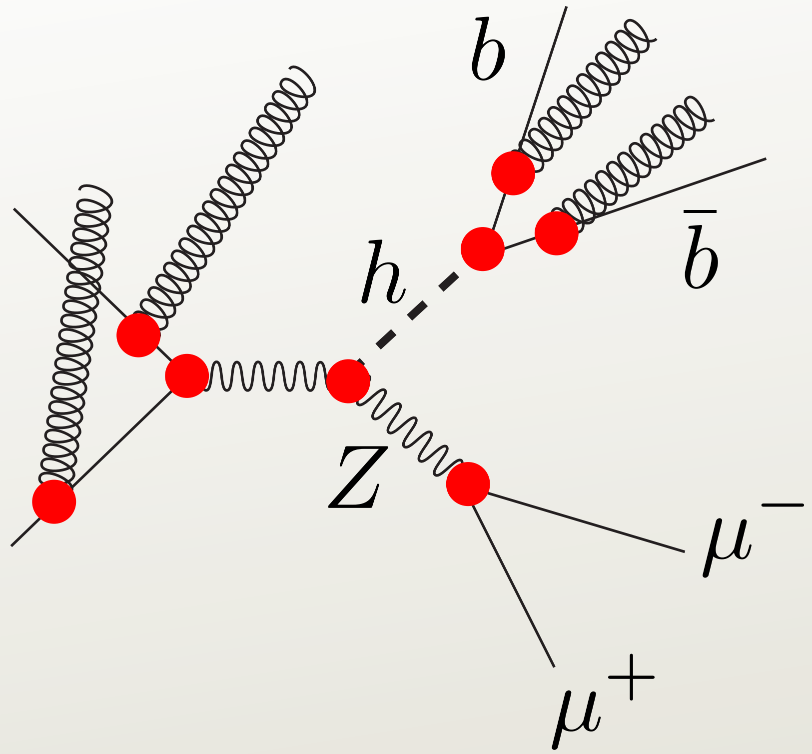


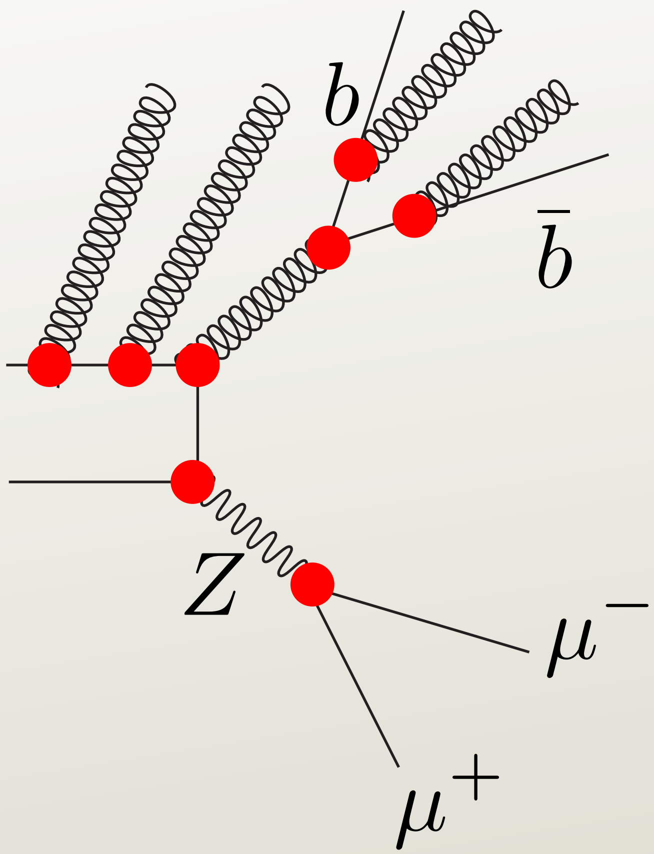
Define the fat jet

- Look for a high P_T jet using the Cambridge-Aachen (angle) algorithm with R=1.2.
- We might hope that the distribution of the mass of the fat jet shows a bump at the Higgs mass.

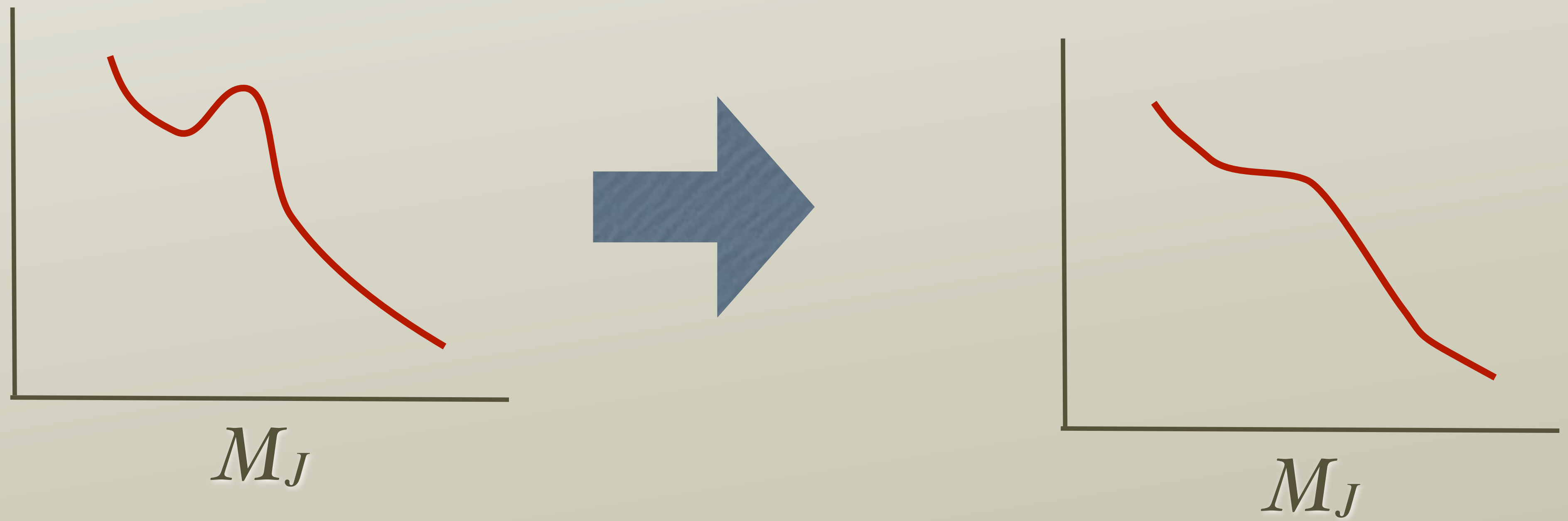






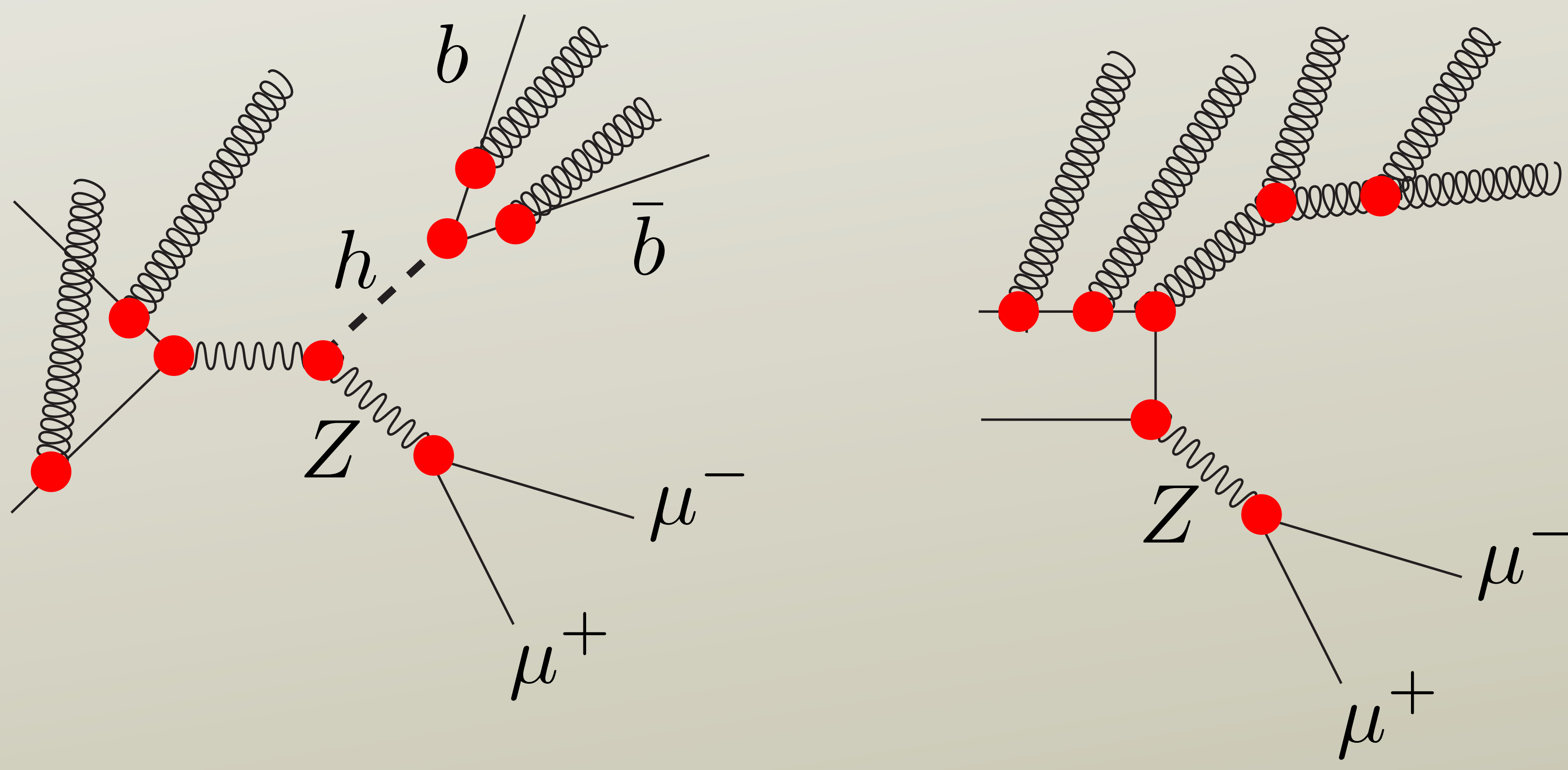


- Since QCD is operating, the mass bump gets smeared out.



Subjet analysis

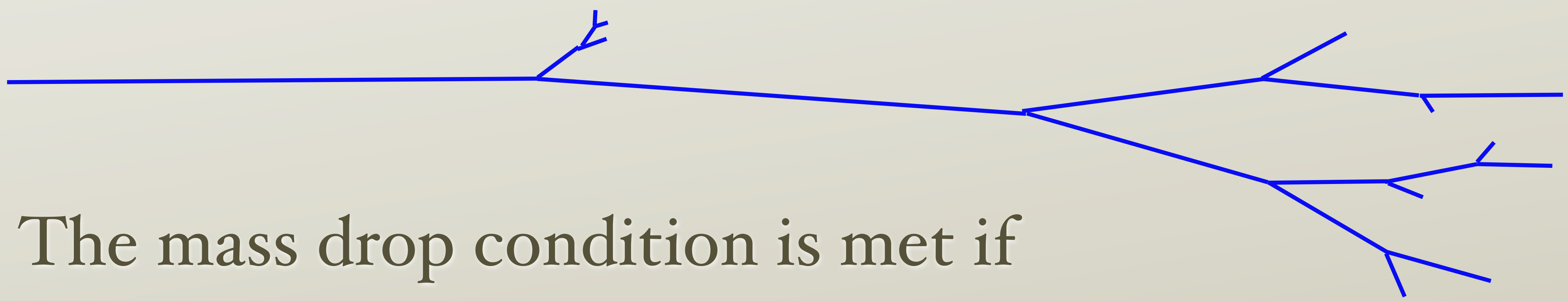
- We would like to take apart the fat jet in order to get rid of the contaminating initial state radiation.



Butterworth, Davison, Rubin, and Salam (2008)

Jet mass drop and filtering

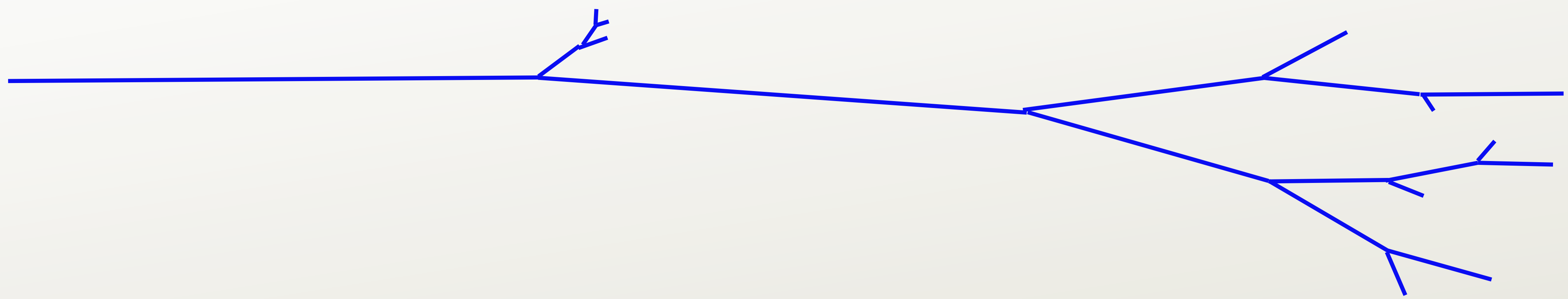
- Step I: mass drop.
  - Examine the C-A splitting tree, starting at the trunk.



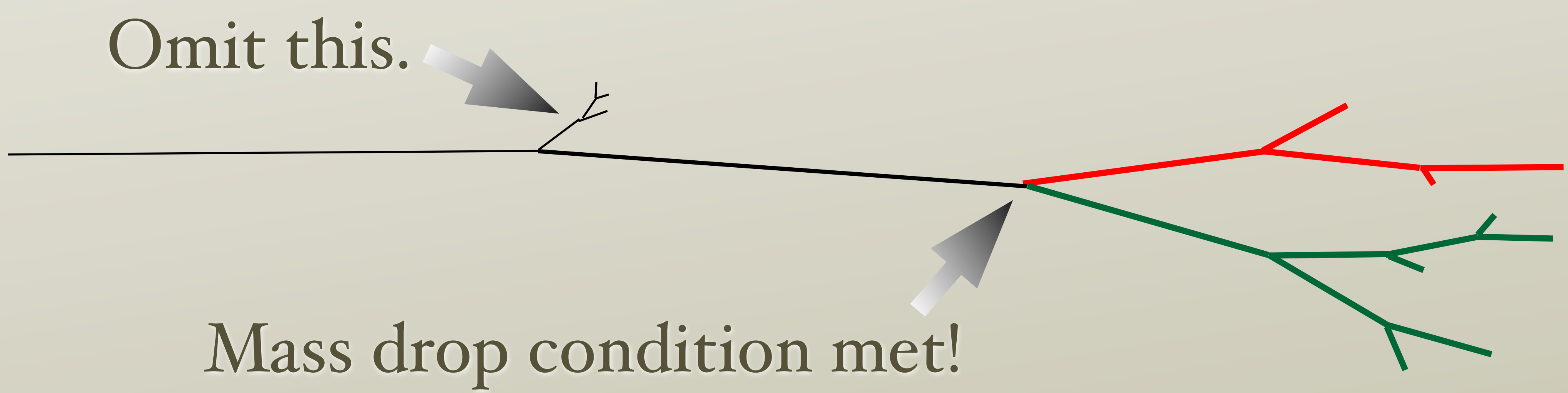
  - The mass drop condition is met if

$$\max(M_i, M_j) < 0.67\, M_{\{i,j\}}$$

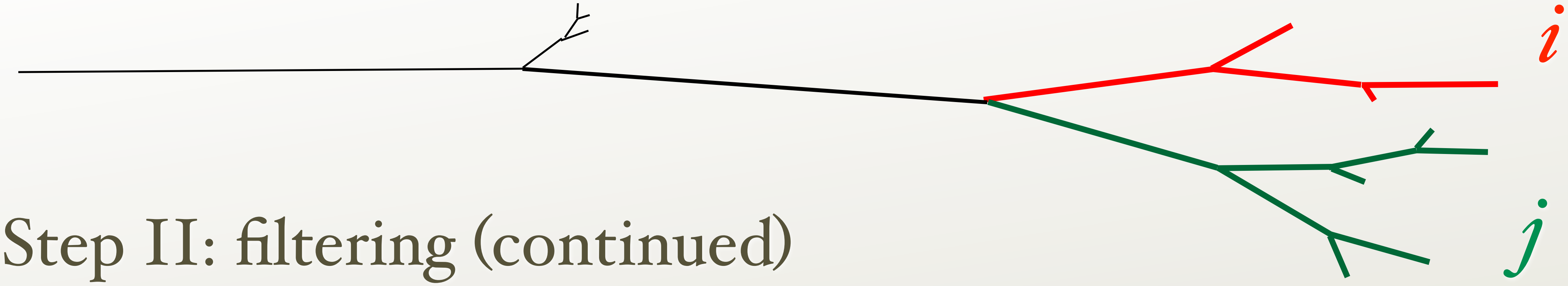
$$\min(p_{T,i}^2, p_{T,j}^2)[(y_i - y_j)^2 + (\phi_i - \phi_j)^2] > 0.09\, M_{\{i,j\}}^2$$



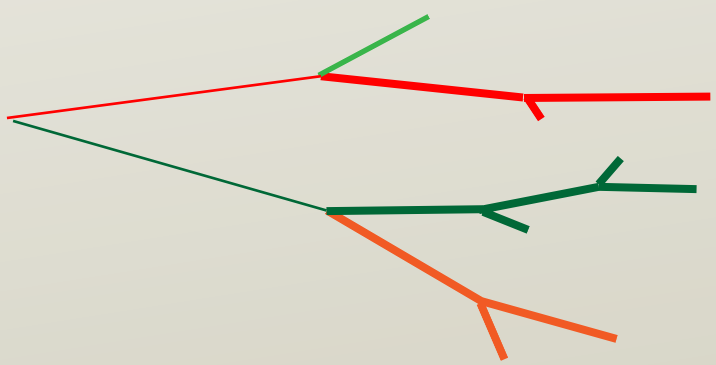
- If mass drop condition isn't met, omit smaller p_T daughter and keep looking.
- If it is never met, remove the event from your sample.



- Step II: filtering the prospective *b*-jets, *i* and *j*.
  - Are both prospective *b*-jets tagged as containing *b*-quarks?
  - If i and j are not *b*-tagged, reject the event.

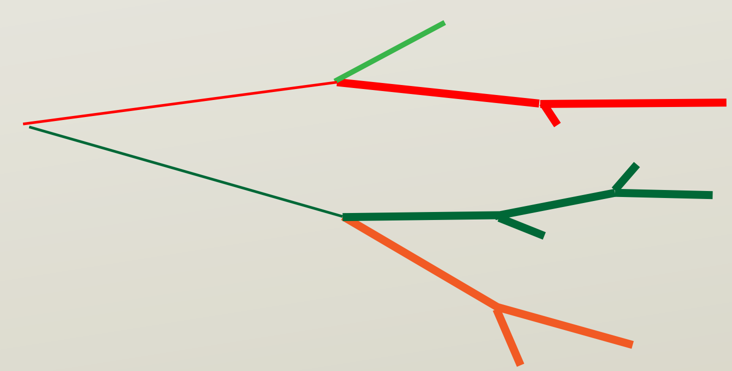


- Step II: filtering (continued)
  - Apply the C-A algorithm with to protojets *i* and *j* with
    $$R = \min\left(\frac{1}{2}[(y_i - y_j)^2 + (\phi_i - \phi_j)^2]^{1/2}, 0.3\right)$$



  - Are the two highest p_T subjets thus found tagged as containing b-quarks?
  - If not, throw out the event.

- Step II: filtering (continued some more)
  - Throw out all but the three highest p_T subjets thus found.
  - What remains is the filtered jet.



- Measure the mass of this filtered jet.

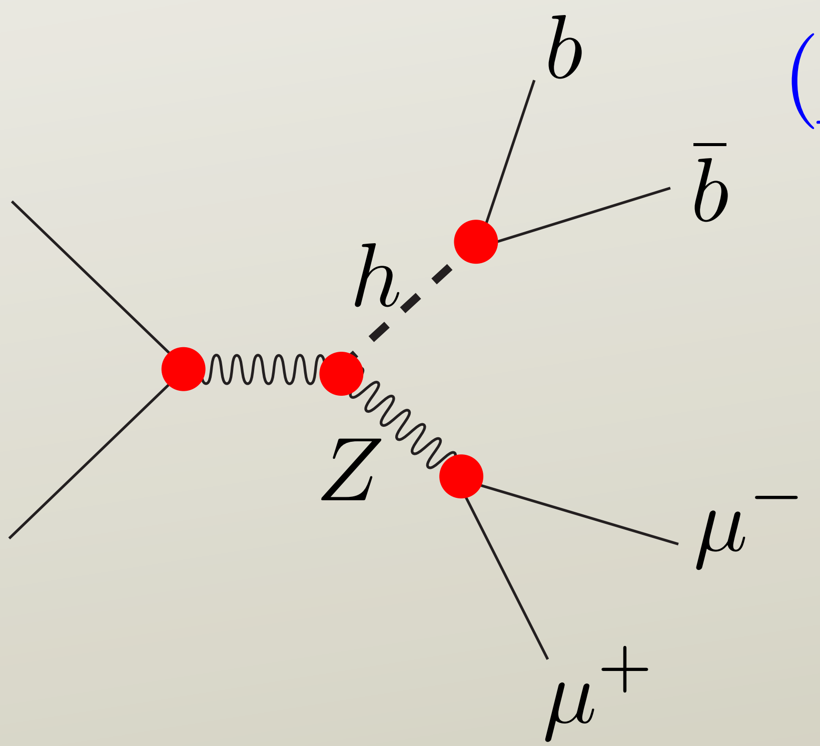
Other methods

- There are other algorithms for subjet analysis.
- Some are looking for something specific, as in the BDRS method above and the Johns Hopkins and HEP top quark taggers.
- Others are more generic, as in pruning and trimming.

Features of gauge field theory that we are looking for

Mass bumps

- One key feature of signal events is that the decay products of a heavy particle have a fixed mass.

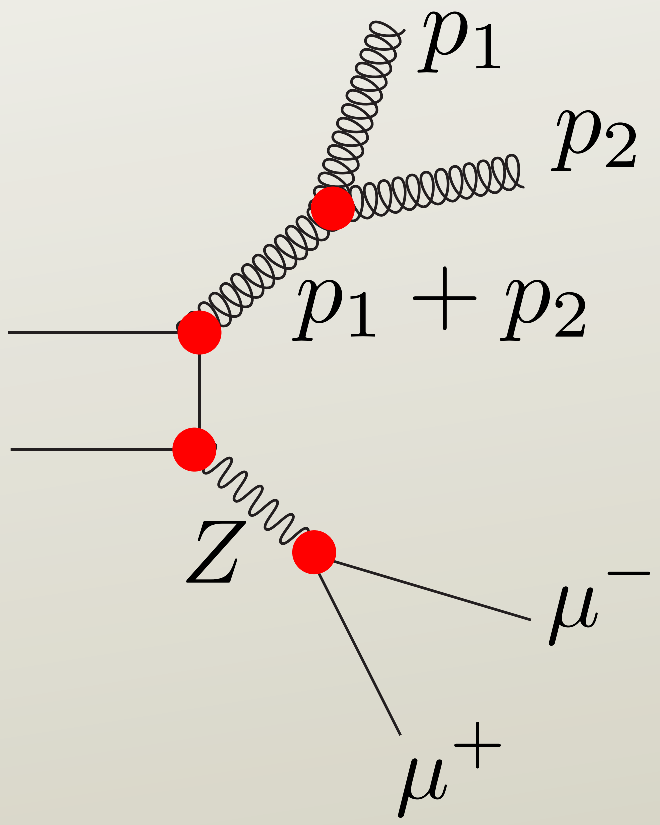


$$(p_b + p_{\bar{b}})^2 = M_h^2$$

- The theoretical uncertainty of this is $M_h \Gamma_h$.
- The practical uncertainty is much larger.

Mass in QCD splittings

- QCD splittings have a very different distribution as a function mass.



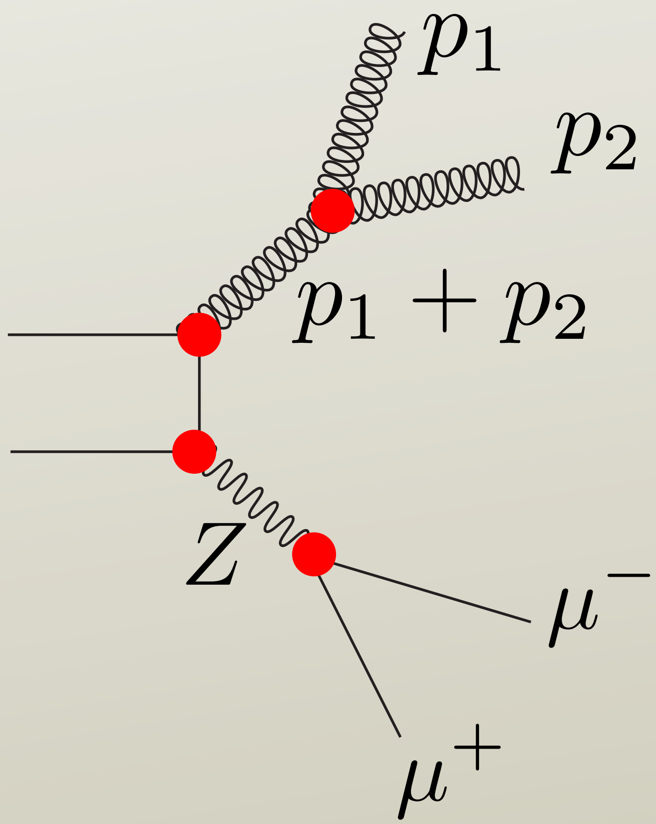
- I will use a scaled virtuality as a "hardness variable":

$$v = \frac{(p_1 + p_2)^2}{(p_1 + p_2) \cdot Q_0}$$

- Q_0 is the momentum of the outgoing partons in the hard process.

QCD tree graph results

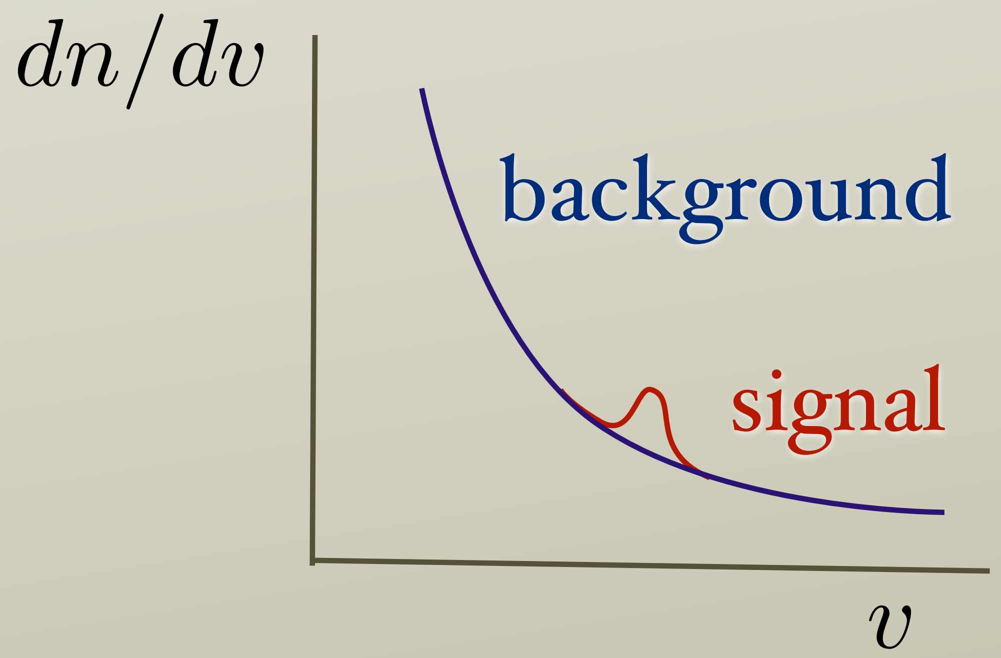
$$v = \frac{(p_1 + p_2)^2}{(p_1 + p_2) \cdot Q_0}$$



- Differential probability is

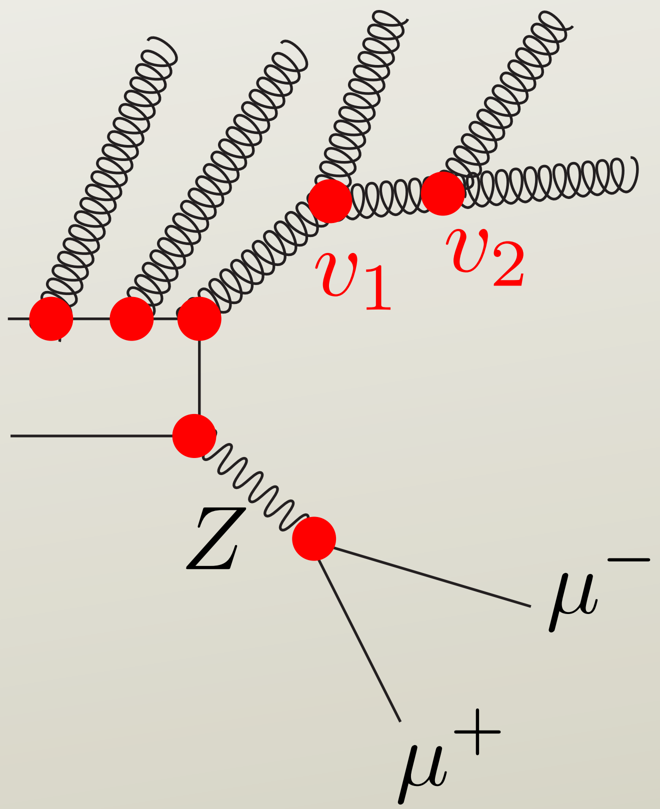
$$dn \approx \frac{dv}{v}\, C\, \alpha_s \log(\tilde{v}/v)$$

- The log (and $\tilde{v}$) comes from $\int dz$.



Nested splittings

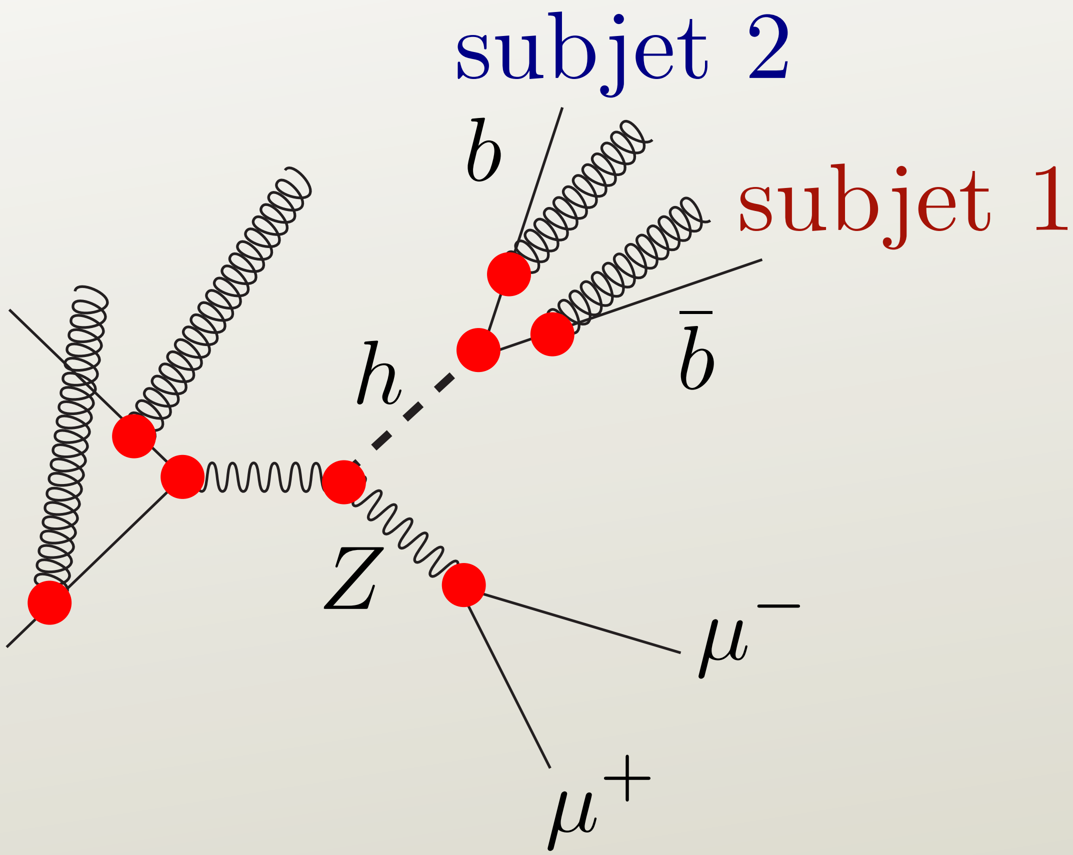
- The same structure can be (approximately) iterated.

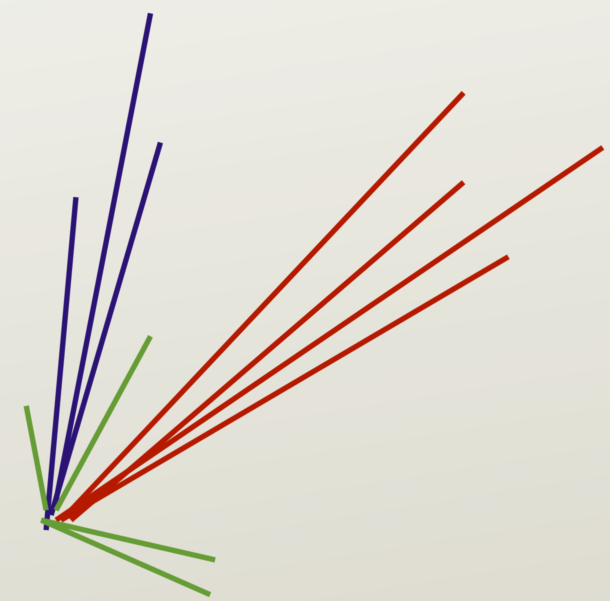


- $v_2 < v_1$.
- Set $v_2 = 0$ in splitting 1.

$$dn \approx \frac{dv_1}{v_1}\, C_1\, \alpha_s \log(\tilde{v}_1/v_1)$$
$$\times \frac{dv_2}{v_2}\, C_2\, \alpha_s \log(\tilde{v}_2/v_2)$$
$$\times\, \theta(v_2 < v_1)$$

An application of this

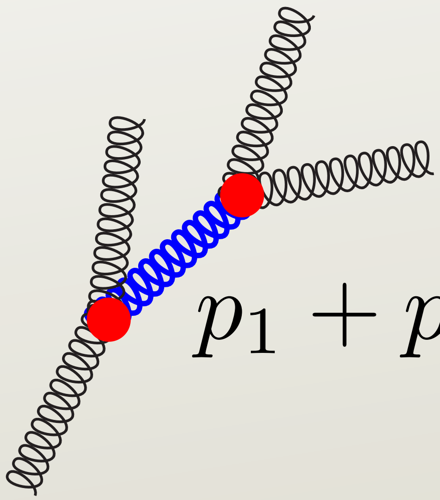




- A Higgs boson will likely decay to two low mass subjets, plus soft gluons.
- Try to find the low mass subjets.
- A "mass drop" condition can be part of this.
  (Butterworth, Davison, Rubin & Salam.)
- Measure the mass of subjet pair.

Sudakov factor

- A better approximation for dn includes a Sudakov factor.



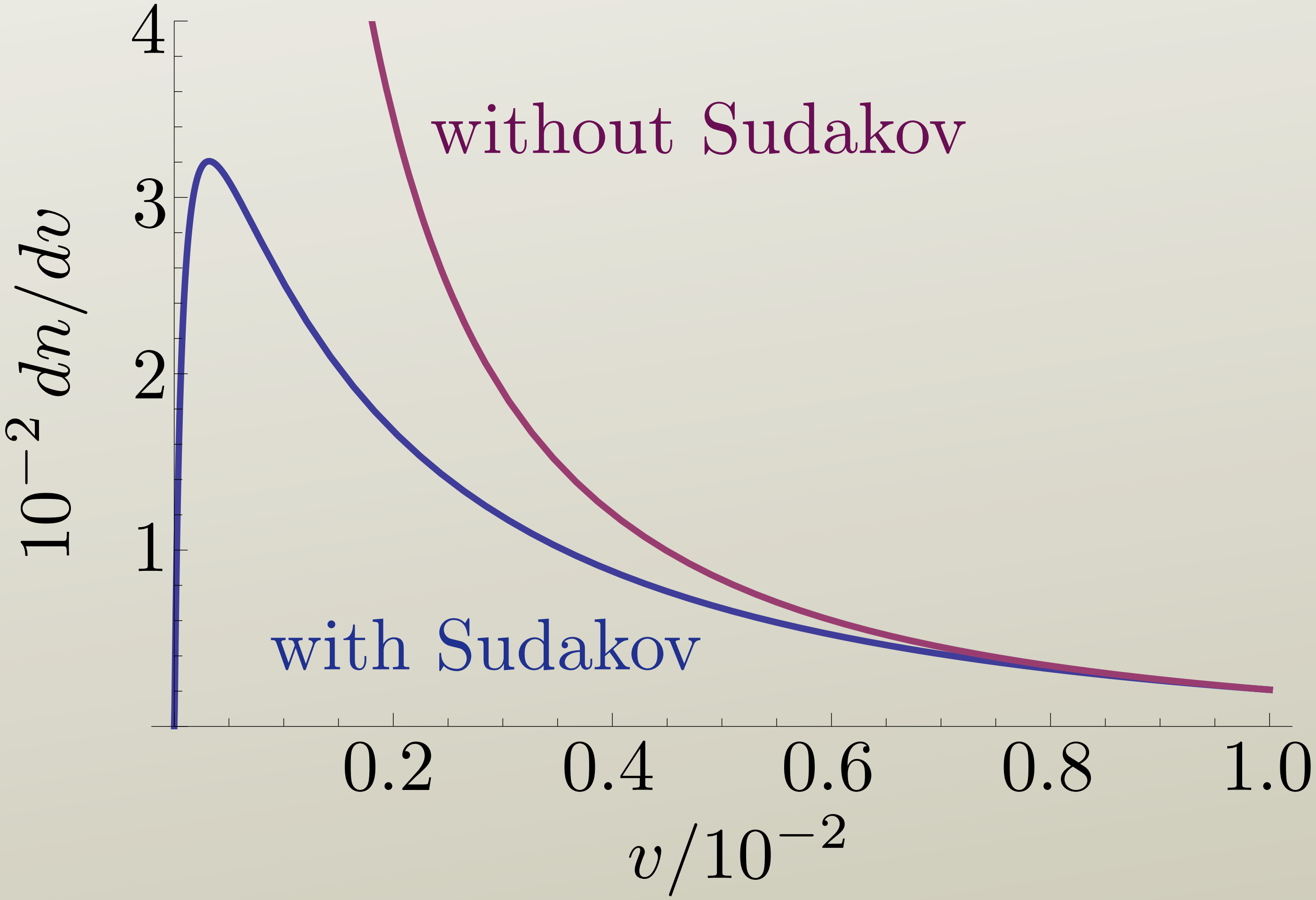
$$dn \approx \frac{dv}{v}\; C\,\alpha_s \log(\tilde{v}/v)$$
$$\exp\left(-\int_v^{v_1} \frac{d\bar{v}}{\bar{v}}\; C\,\alpha_s \log(\tilde{v}/\bar{v})\right)$$

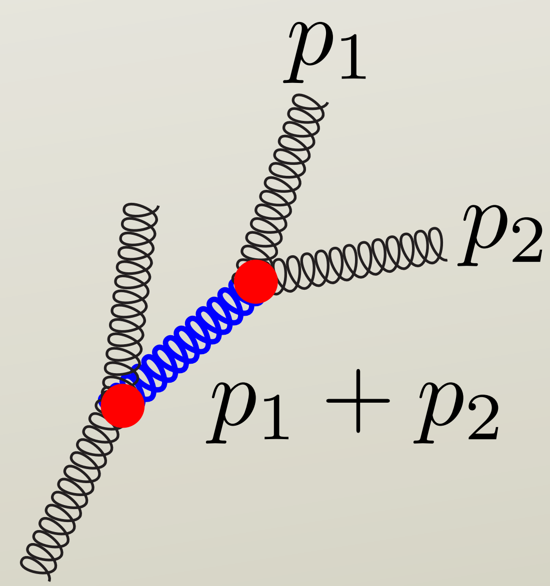
- We think of a renormalization group approach with a running resolution scale.

- The Sudakov factor accounts for virtual graphs and unresolved real parton emissions.

Example of effect of Sudakov

$$dn \approx \frac{dv}{v}\; C\,\alpha_s \log(v/\tilde{v}) \exp\left(- \int_v^{v_1} \frac{d\bar{v}}{\bar{v}}\; C\,\alpha_s \log(\bar{v}/\tilde{v}) \right)$$





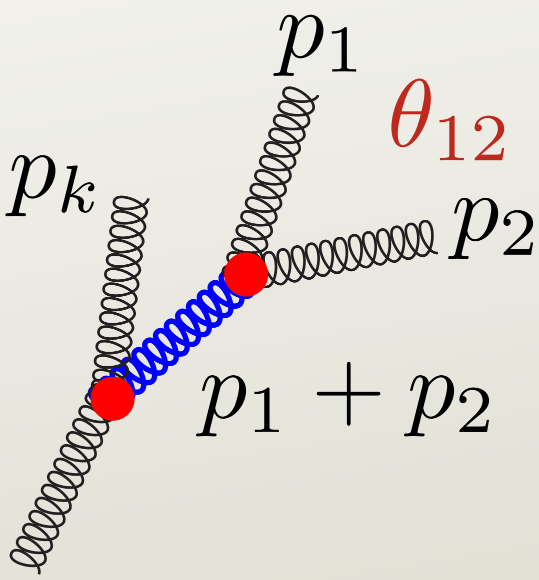
Example with

$C\alpha_s = 0.3$

$\tilde{v} = 0.02$

$v_1 = 0.01$

Distribution in angles



- For a given v, what is the distribution in the angle θ_{12} between $\vec{p}_1$ and $\vec{p}_2$?

- Kinematically,

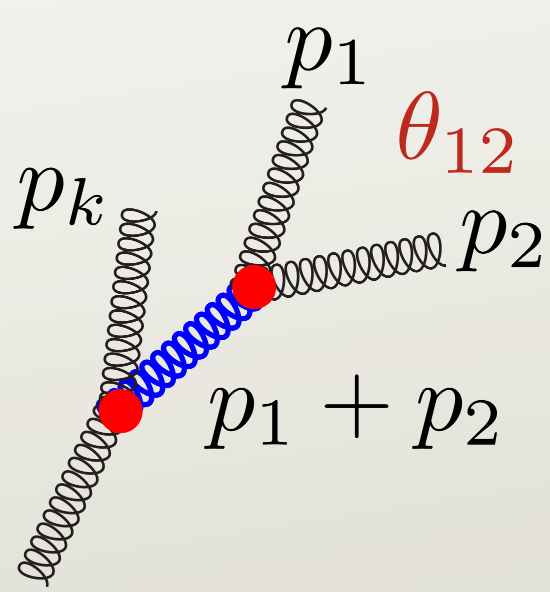
$$\theta_{12}^2 > v \, \frac{4Q_0^2}{(p_1 + p_2) \cdot Q_0}$$

- For larger, but not too large, θ_{12},

$$v = \frac{(p_1 + p_2)^2}{(p_1 + p_2) \cdot Q_0}$$

$$dn \propto \frac{d\theta_{12}^2}{\theta_{12}^2}$$

Large angles



- Large θ_{12} corresponds to $|\vec{p}_1| \ll |\vec{p}_2|$.
- (Or gluon 2 could be the soft one.)
- For emission of soft gluon 1, interference with emission from parton k is important.
- Parton k is the color connected partner.

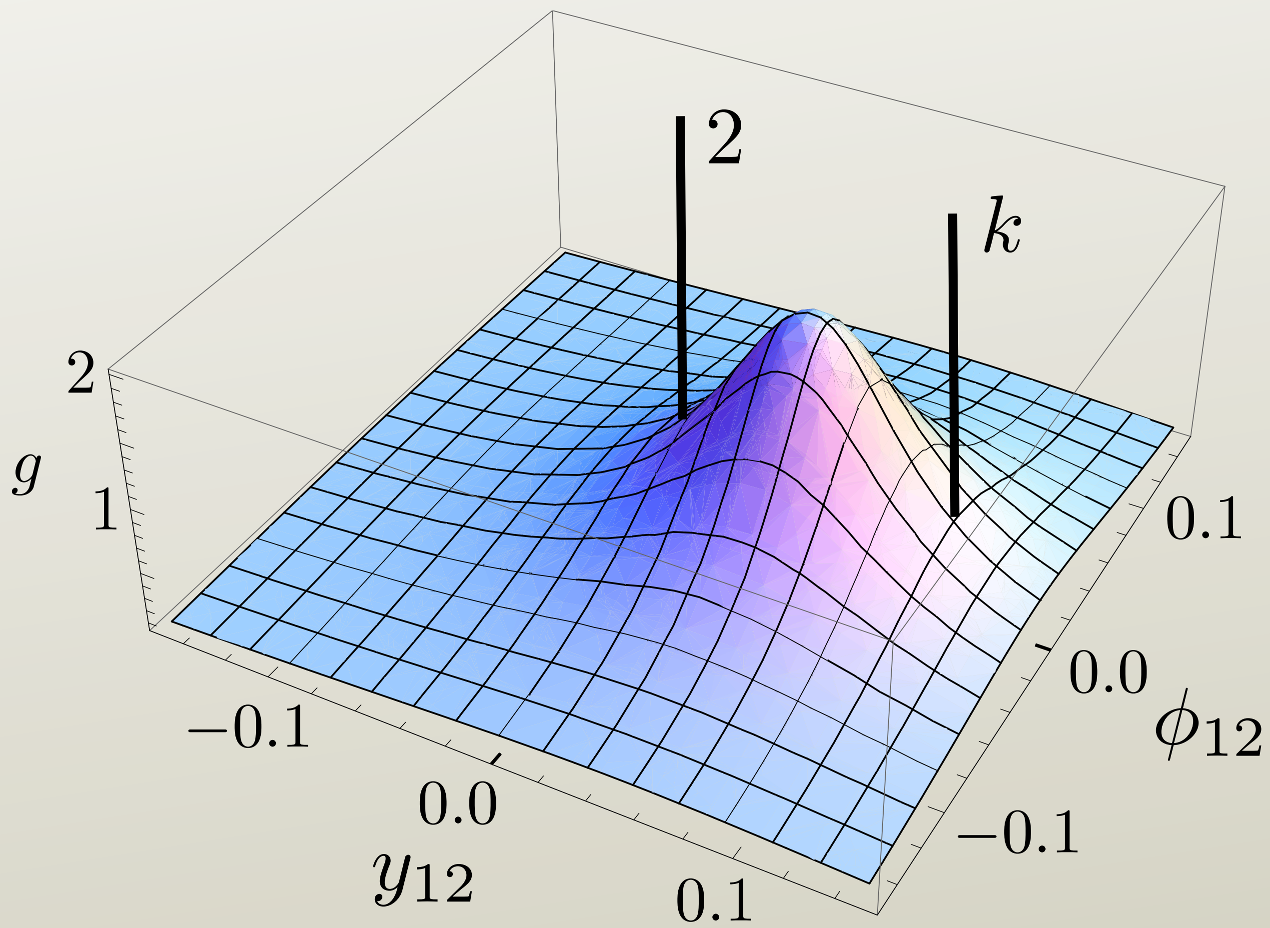
- With interference,

$$dn \propto \frac{d\theta_{12}^2}{\theta_{12}^2} g(\theta_{12}^2) \qquad g(\theta_{12}^2) = \frac{\theta_{2k}^2}{\theta_{12}^2 + \theta_{1k}^2}$$

Effect of the angle factor

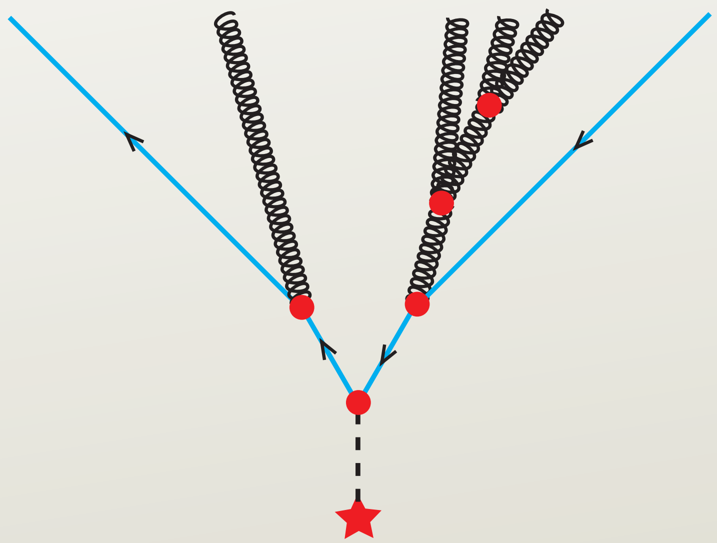
$$dn \propto \frac{d\theta_{12}^2}{\theta_{12}^2} g(\theta_{12}^2)$$

$$g(\theta_{12}^2) = \frac{\theta_{2k}^2}{\theta_{12}^2 + \theta_{1k}^2}$$

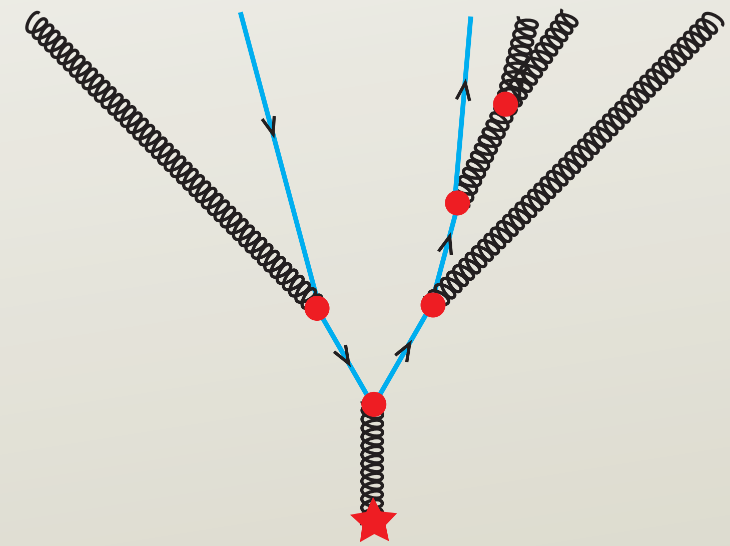


- Emission with $\theta_{12} \gg \theta_{2k}$ is suppressed.
- Emission between partons 2 and k is enhanced.

An application of this



After $H \to b + \bar{b}$
Soft gluons between b and $\bar{b}$



After $g \to b + \bar{b}$
Soft gluons away from b and $\bar{b}$

- *Cf.* "pull" (Gallicchio & Schwartz).

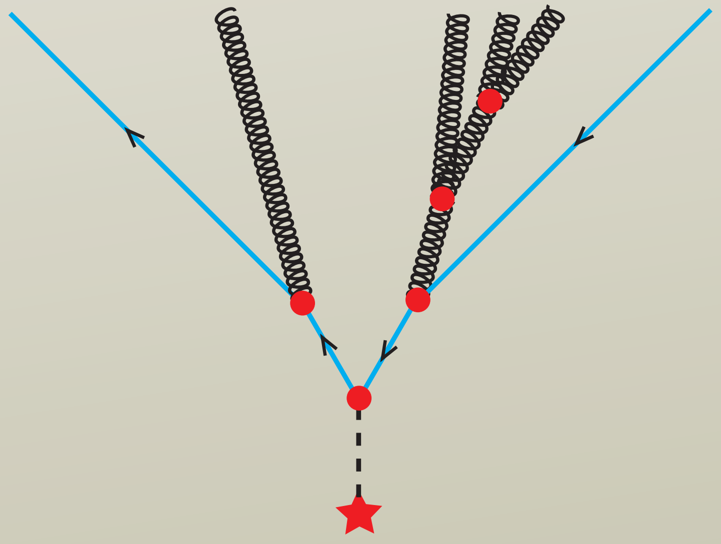
Gluons want to be soft

- Large angles $\Longrightarrow$ small z:

$$z(1-z) = \frac{v}{\theta^2} \frac{Q_0^2}{(p_1+p_2)\cdot Q_0}$$

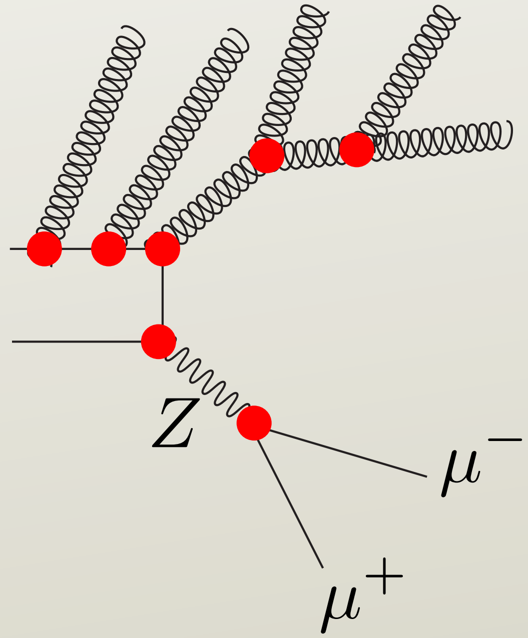
- So we expect lots of soft gluon radiation.

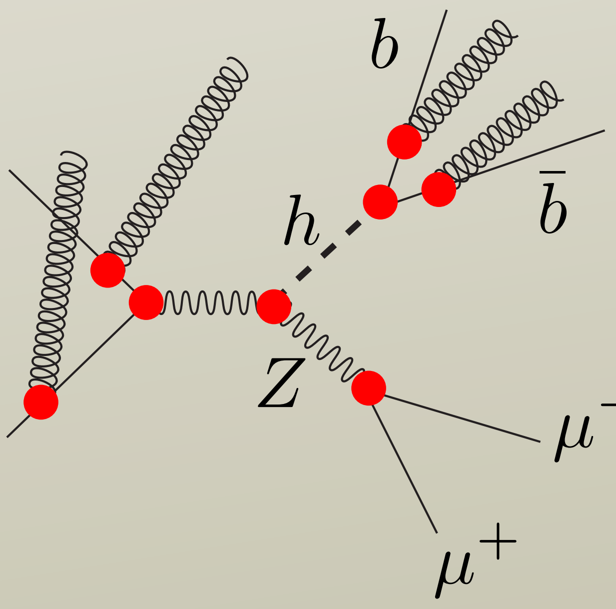
- However, soft gluon radiation is limited by "angular ordering" from $g(\theta)$.



More soft gluons come from initial state radiation

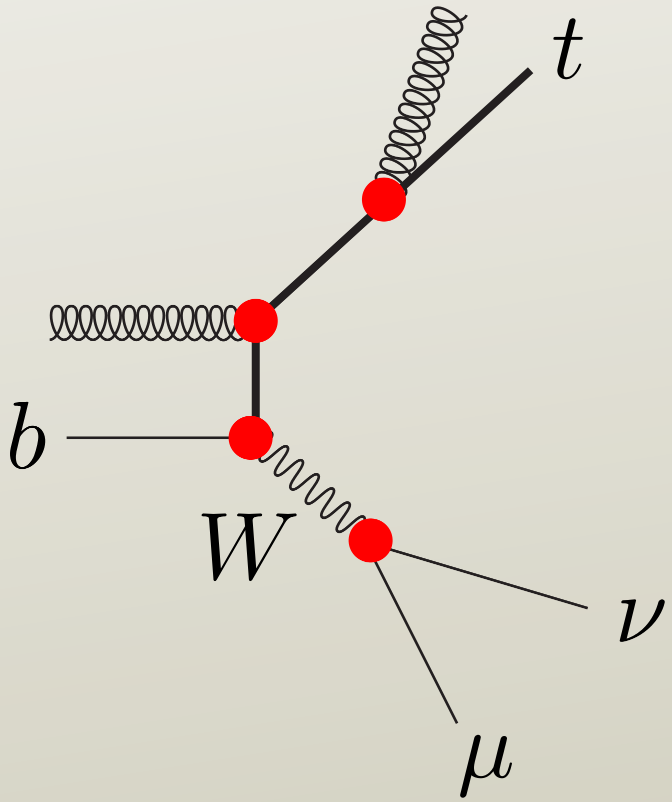
- There is initial state radiation in both signal and background events.
- It can come at central rapidities.
- It is largely rather low transverse momentum.





Heavy particles with color

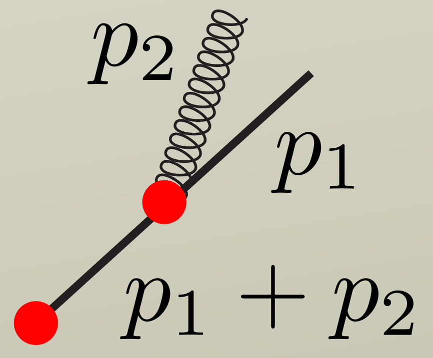
- A heavy particle with color will radiate gluons.
- There is singularity in $|\mathcal{M}|^2$.



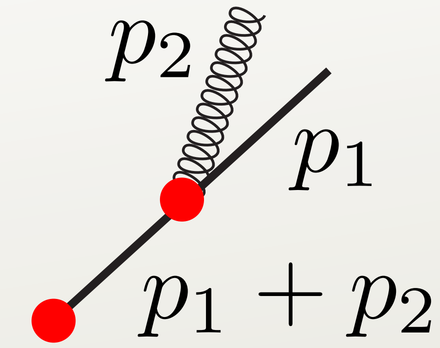
$$dn \propto \frac{dv}{v}\ \alpha_s \log(\theta_{\min}/\theta_{\max})$$

where the hardness v is now

$$v = \frac{(p_1 + p_2)^2 - M^2}{(p_1 + p_2) \cdot Q_0}$$



- The collinear singularity is cut off:

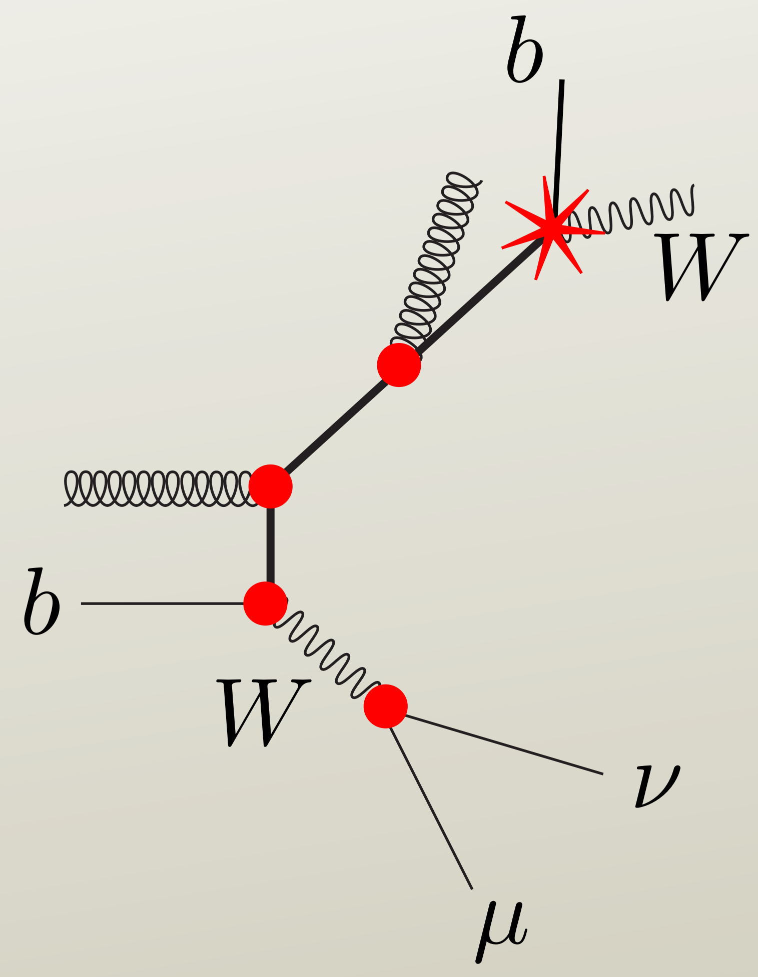


$$\theta^2_{\min} \sim \min\left(\frac{M^2 Q_0^2}{((p_1+p_2)\cdot Q_0)^2}, v\,\frac{4Q_0^2}{(p_1+p_2)\cdot Q_0}\right)$$

- There are no emissions that take longer than the particle lifetime:

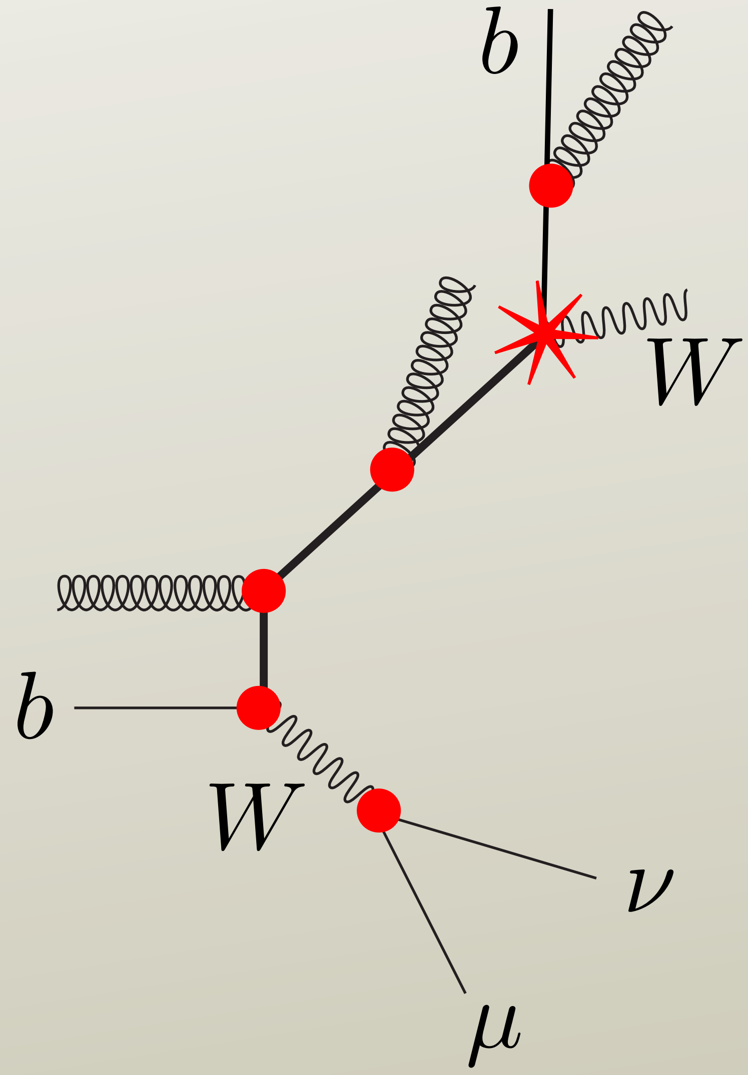
$$v > \frac{M\Gamma}{(p_1+p_2)\cdot Q_0}$$

Heavy particles decay



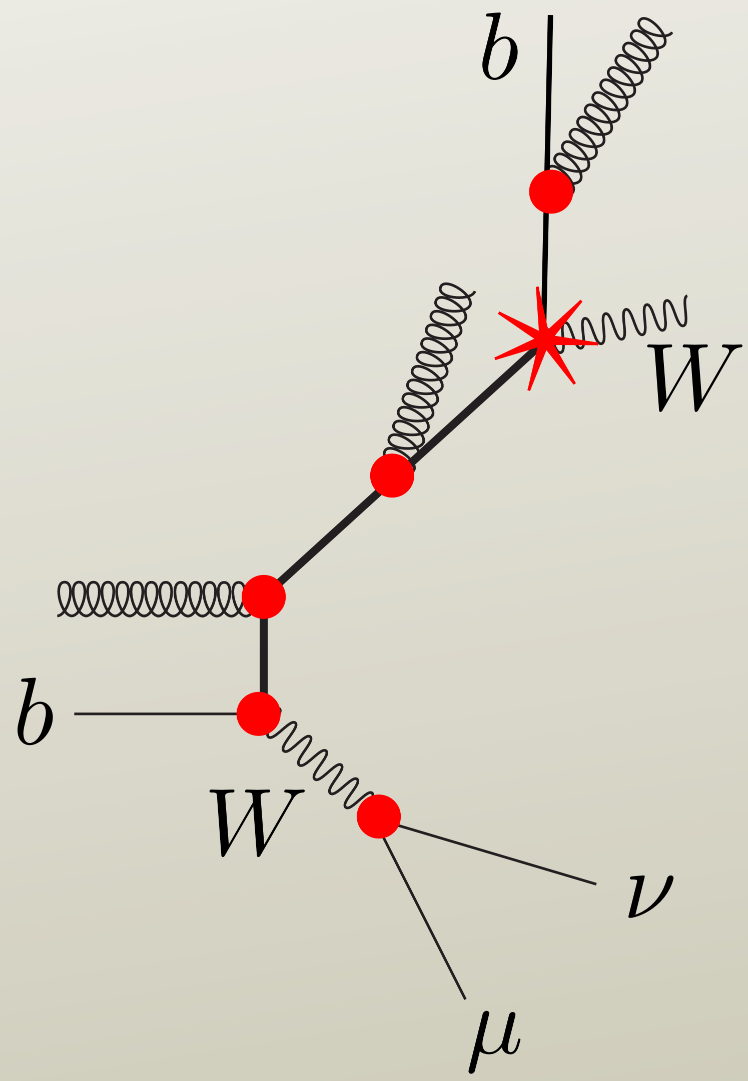
Daughters radiate

- In $t \to b + W$, a lot of energy is released.
- Color charge is accelerated.
- Gluons are radiated.
- The first radiation is from a color dipole of
  - The final state b-quark;
  - The "initial state" t-quark;

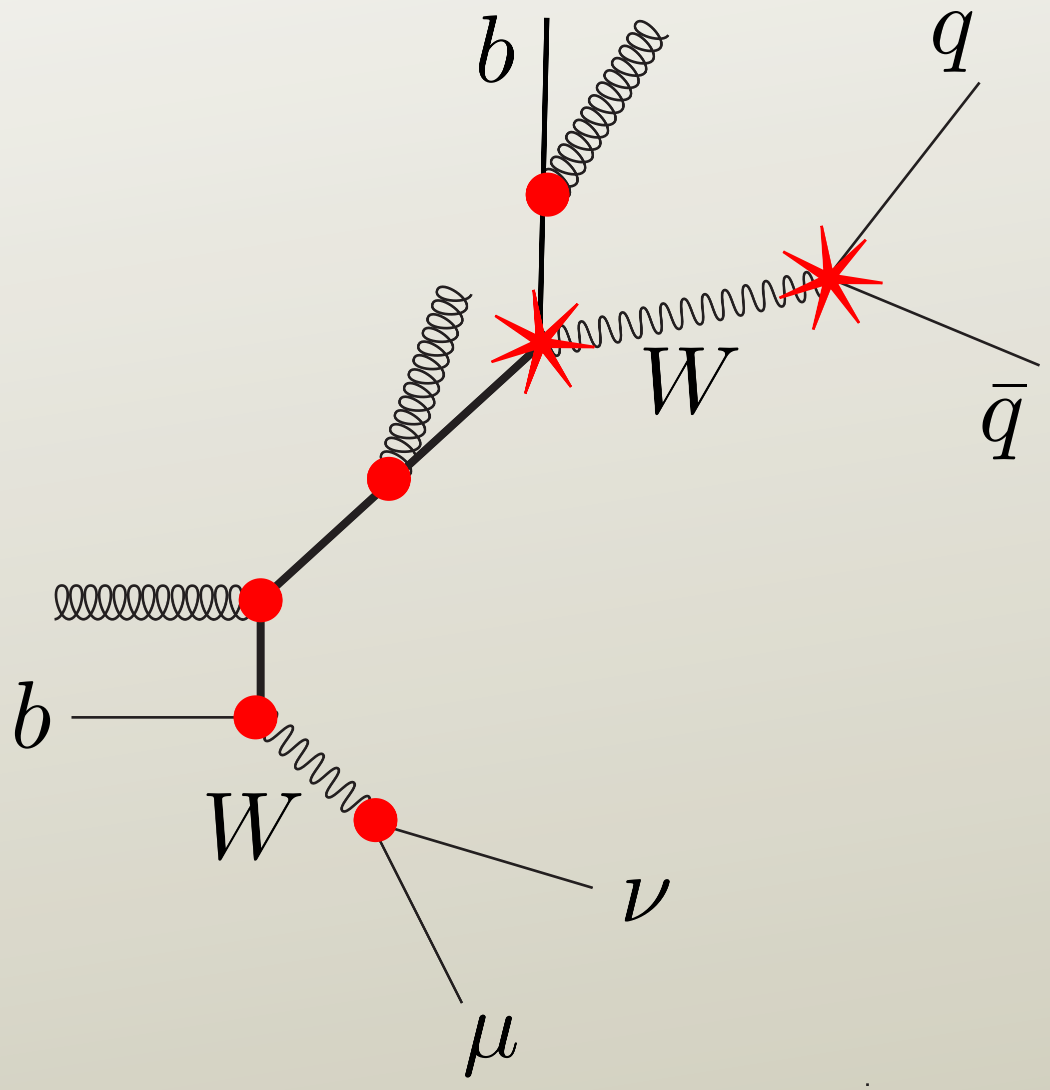


Where does the radiation go?

- The first radiation is from a color dipole of
  - The final state b-quark;
  - The "initial state" t-quark;
- Direction of g is likely collinear with the b.
- Direction of g is likely within angle $M/|\vec{P}_t|$ of the top.
- If the top is highly boosted, this is a narrow cone.

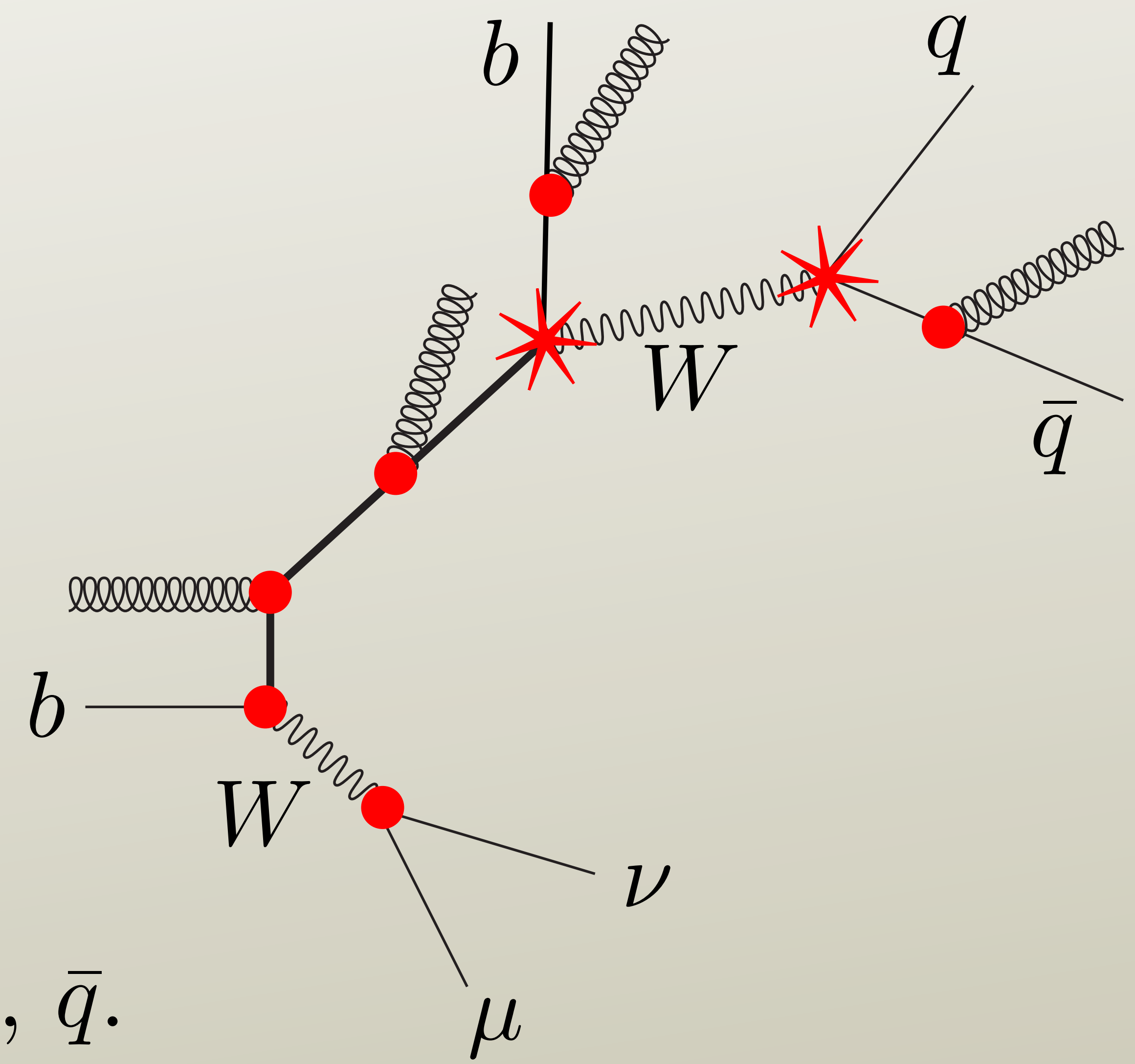


Heavy particles decay



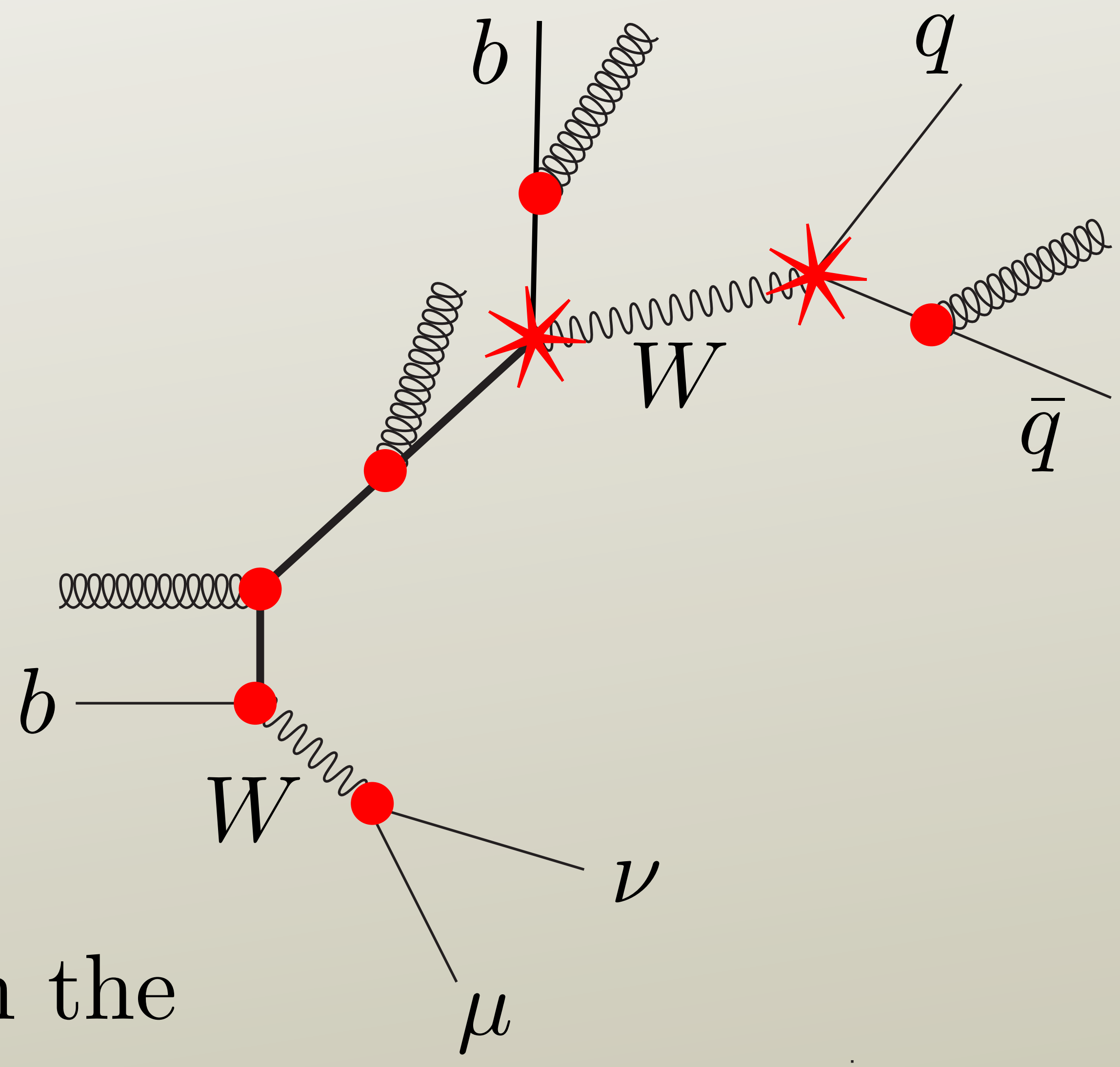
Daughters radiate

- In $W \to q + \bar{q}$, a lot of energy is released.
- Color charge is accelerated.
- Gluons are radiated.
- The first radiation is from a color dipole of
  - The final state quark, q;
  - The final state anti-quark, $\bar{q}$.



Where does the radiation go?

- The first radiation is from a color dipole of
  - The final state quark, q;
  - The final state anti-quark, $\bar{q}$.
- Direction of g is likely collinear with the q or $\bar{q}$.
- In any case, it is likely between the q and $\bar{q}$.



Comments

- Since we know something abut where the collinear or soft radiation goes in a heavy particle decay, sequential heavy particle decays should have good signatures.

- We do have the problem of contamination from initial state radiation.

- Having highly boosted heavy objects helps with this.