The Abdus Salam International Centre for Theoretical Physics

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School on Strongly Coupled Physics Beyond the Standard Model

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Advanced Collider Physics - Jets and Boosted Jets

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Jets & Boosted Jets

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School on Strongly Coupled Physics Beyond the Standard Model

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Outline

Lecture I:

- Some motivation.
- Jets in QCD.

Lecture II:

- Splitting function.
- Substructure: Jet mass.
- Other jet shapes (angularity, planar flow), filtering. (depends on time)
- The template overlap method. (discussion?)

G. Sterman, QCD and Jets (Tasi 2004), hep-ph/0412013.
R. Ellis, QCD at TASI 94.
D. Soper, QCD TASI hep-ph/0011256.
G. Salam, Jetography (review) 0906.1833.
S. Catani, et. al (review) hep-ph/0005025.
L. Almeida et. al, 0807.0234.

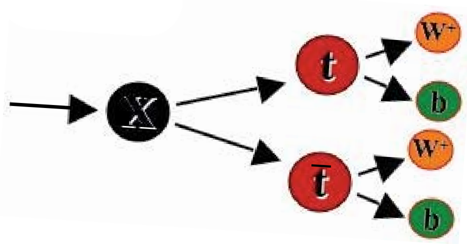
Lecture I:

Some motivation;

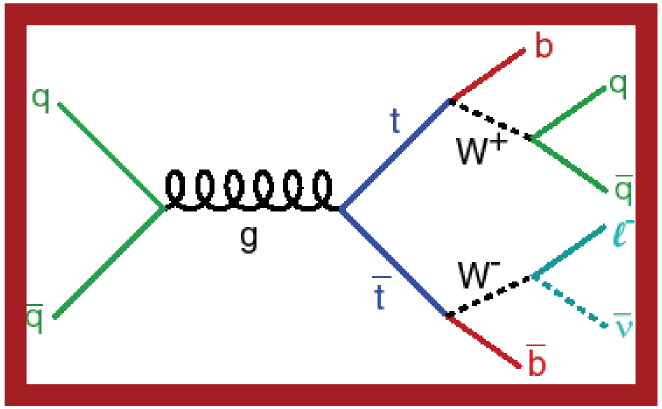
Jets in QCD.

Connection to this school's theme

What if we have a heavy resonance decaying dominantly to tops $H/W/Z$?



Conventional tops (mild boost),
reconstructed mostly as 4 jets events.



Question: Show that the opening angle is $\Delta\theta_{ij} \sim m_J/E_J$?

Connection to this school's theme

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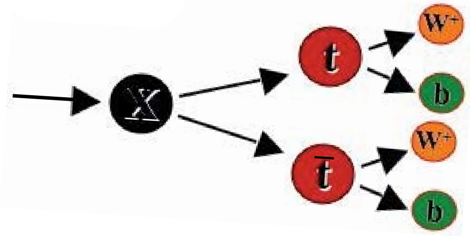
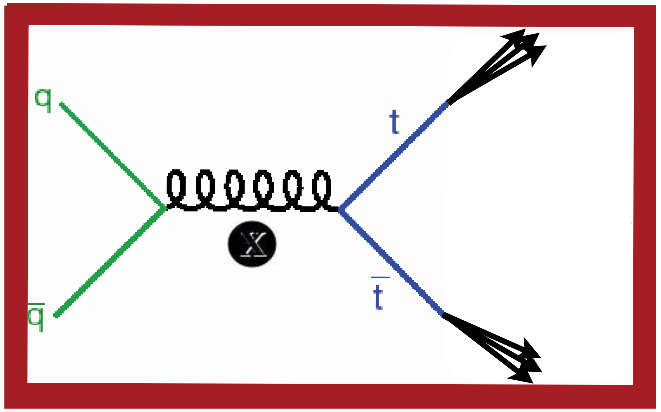
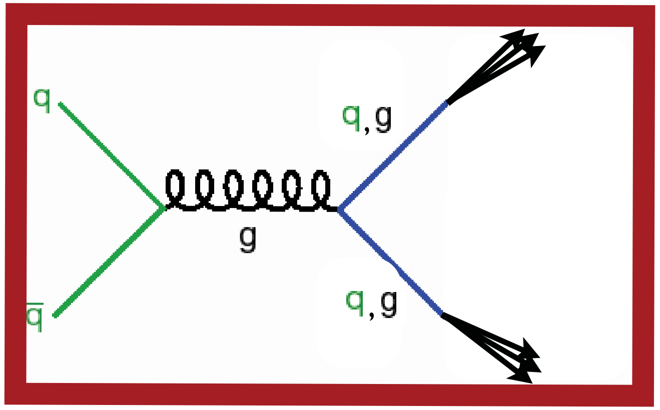


$$\Delta\theta_{ij} \sim m_J/E_J$$

Boosted tops appears as 2 jets, top jets.



Apart from mass, similar to ordinary 2-jet QCD process.



But what are jets??

Intuitive definition: spray of particles moving in the same direction.

More precise: Objects that describe differential energy flow that are sensitive to microscopic (perturbative) dynamics & insensitive to long distance (non-perturbative) physics.

Let us see an example.

Intro': $e^+e^- \rightarrow quarks$

$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

Far below the Z pole: $R = \dfrac{\sum_q \sigma(e^+e^- \rightarrow q\bar{q})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = 3\sum_q Q_q^2 \,.$

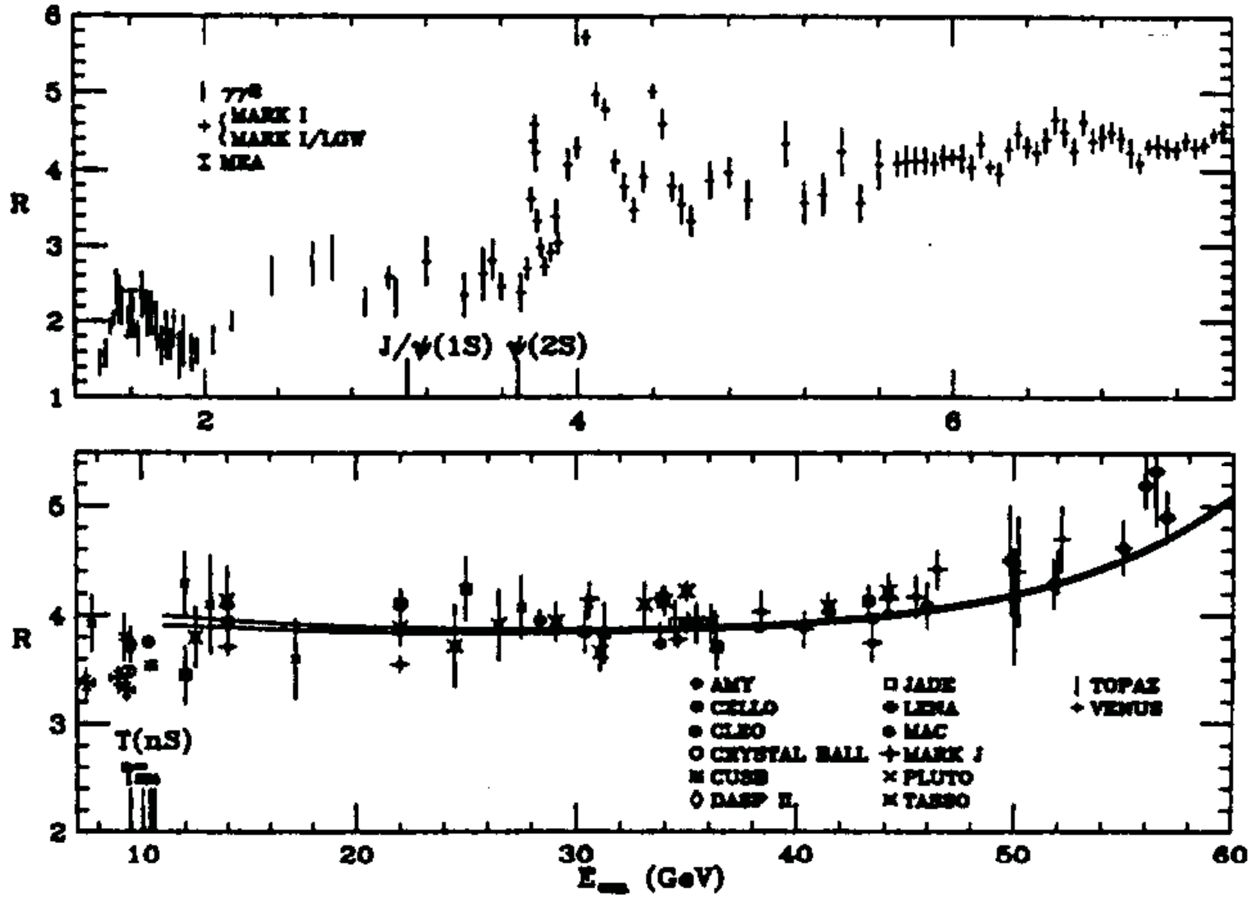
On the Z pole, the corresponding quantity is the ratio of the partial decay widths of the Z to hadrons and to muon pairs:

$$R_Z = \frac{\Gamma(Z \rightarrow \text{hadrons})}{\Gamma(Z \rightarrow \mu^+\mu^-)} = \frac{\sum_q \Gamma(Z \rightarrow q\bar{q})}{\Gamma(Z \rightarrow \mu^+\mu^-)} = \frac{3\sum_q (a_q^2 + v_q^2)}{a_\mu^2 + v_\mu^2} \,.$$

Intro': $e^+e^- \rightarrow quarks$

For the 3 light quarks: $R = 3\left[\left(\frac{2}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 + \left(-\frac{1}{3}\right)^2\right] = 2$

Adding $c, c+b$ yield $R = 10/3, 11/3$

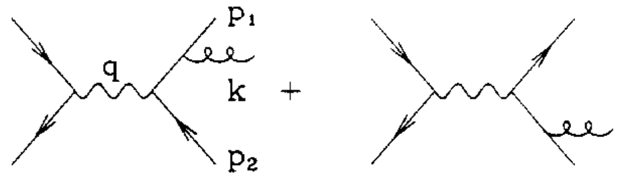


Results seem always higher??

Intro': $e^+e^- \to quarks$ @ NLO

Contribution from higher orders ...

$$e^+(q_1) + e^-(q_2) \to q(p_1) + \bar{q}(p_2) + g(k)$$



it is convenient to write the three-body phase space integration as

$$d\Phi_3 = \frac{s}{2^{10}\pi^5} d\alpha\, d\cos\beta\, d\gamma\, dx_1\, dx_2$$

where α, β, γ are Euler angles, and $x_1 = 2E_q/\sqrt{s}$ and $x_2 = 2E_{\bar{q}}/\sqrt{s}$ are the energy fractions of the final state quark and antiquark. The matrix element is obtained using the Feynman rules.

$$\sigma^{q\bar{q}g} = \sigma_0\, 3 \sum_q Q_q^2 \int dx_1 dx_2\, \frac{C_F \alpha_S}{2\pi} \frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)} \qquad \sigma_0 = \frac{4\pi\alpha^2}{3s} Q_f^2 \,.$$

$C_F = 4/3$

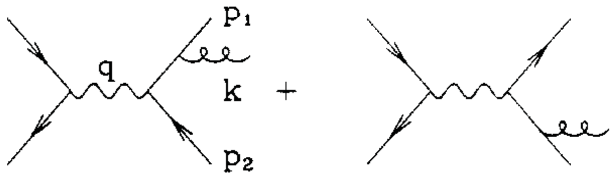
where the integration region is: $0 \le x_1, x_2 \le 1,\ x_1 + x_2 \ge 1.$

the integrals are divergent at $x_i = 1$.

Intro': $e^+e^- \rightarrow quarks$ @ NLO

Contribution from higher orders ...

$$e^+(q_1) + e^-(q_2) \rightarrow q(p_1) + \bar{q}(p_2) + g(k)$$



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$C_F = 4/3$

Question: are the x's Lorentz invariant?

Show that $s_{12} \equiv m_{12}^2 = (p_1 + p_2)^2 = s(1 - x_3)$

$e^+e^- \rightarrow quarks$: Soft & collinear singularities of QCD

Since $1 - x_1 = x_2 E_g (1 - \cos\theta_{2g})/\sqrt{s}$

and $1 - x_2 = x_1 E_g (1 - \cos\theta_{1g})/\sqrt{s}$, where E_g is the gluon energy

and θ_{ig} the angles between the gluon and the quarks,

$$\Downarrow$$

singularities come from regions

of phase space where the gluon is *collinear* with the quark or antiquark, $\theta_{ig} \rightarrow 0$,

or where the gluon is *soft*, $E_g \rightarrow 0$.

These singularities are not physical due to the IR hadronic scale of QCD. However, the corresponding IR dynamics cannot be described in perturbation theory.

$e^+e^- \to quarks$: regularization of the total Xsection

The above singularities actually don't really affect the total Xsec' if it's appropriately regularized (various ways). We use Dim' Reg', it affects both phase space & Dirac matrix trace factors.

$$\sigma^{q\bar{q}g}(\epsilon) \;=\; \sigma_0 \; 3\sum_q Q_q^2 \, H(\epsilon) \; \int dx_1 dx_2 \; \frac{2\alpha_S}{3\pi} \; \frac{x_1^2 + x_2^2 - \epsilon(2 - x_1 - x_2)}{(1-x_1)^{1+\epsilon}(1-x_2)^{1+\epsilon}}$$

with $\epsilon = \frac{1}{2}(4-d)$, and $H(\epsilon) = \dfrac{3(1-\epsilon)^2}{(3-2\epsilon)\Gamma(2-2\epsilon)} = 1 + O(\epsilon)$.

$$\sigma^{q\bar{q}g}(\epsilon) \;=\; \sigma_0 \; 3\sum_q Q_q^2 \, \frac{C_F \alpha_S}{2\pi} \; H(\epsilon) \; \left[\frac{2}{\epsilon^2} + \frac{3}{\epsilon} + \frac{19}{2} + O(\epsilon)\right] \; .$$

$e^+e^- \rightarrow quarks$: regularization of the total Xsection

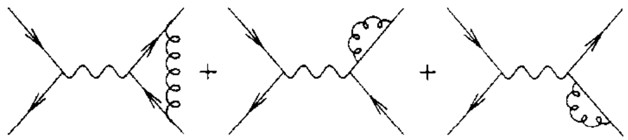
The virtual gluon contribution can be calculated in a similar fashion, with dimensional regularization again used to control the infra-red divergences in the loops. The result is

$$\sigma^{q\bar{q}(g)}(\epsilon) \;=\; \sigma_0\, 3 \sum_q Q_q^2\, \frac{C_F \alpha_S}{2\pi}\, H(\epsilon)\, \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} - 8 + O(\epsilon)\right] .$$

When the two contributions are added together, the poles exactly cancel and the result is *finite* in the limit $\epsilon \to 0$:

$$R \;=\; 3 \sum_q Q_q^2\, \left\{1 + \frac{\alpha_S}{\pi} + O(\alpha_S^2)\right\} .$$

Note that the next-to-leading order correction is positive, and with a value for α_S of about 0.15, can accommodate the experimental measurement at $\sqrt{s} = 34$ GeV. In contrast, the corresponding correction is negative for a scalar gluon.



Jets

The previous success, regarding the total rate, didn't tell us anything about the distribution of energy flow / hadrons in the final state & how to linked it with the partonic Xsec':

LO - $\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2 Q_f^2}{2s}(1+\cos^2\theta)$?? NLO - $\frac{1}{\sigma}\frac{d^2\sigma}{dx_1 dx_2} = C_F\frac{\alpha_S}{2\pi}\frac{x_1^2+x_2^2}{(1-x_1)(1-x_2)}$??

We expect the fragmented hadrons to roughly follow the parton direction, as seen in data from the 50s in cosmic ray & then latter on consistently in many exp'.

Then the soft/collinear gluons events would still have energy flow of 2 outgoing partons - "2 jets" topology.

On the other hand a well separated Xtra gluon emission is suppressed & look like an Xtra energy flow source - "3 jets"

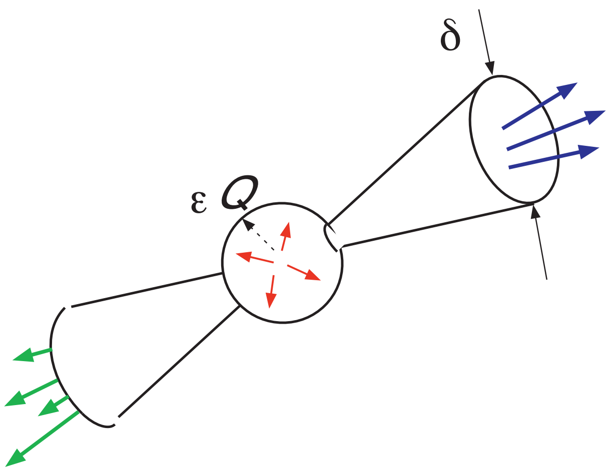
Cone Jets, IRC safety (Sterman-Weinberg, 77)

Need to find a definition of these object, calculable in perturbation theory & yield finite rates (IRC save).

SW: a final state is classified as two-jet-like if

all but a fraction ϵ of the total available energy is contained

in a pair of cones of half-angle δ.



Cone jets for e^+e^- annihilation.

Cone Jets, IRC safety (Sterman-Weinberg, 77)

two-jet cross section is then obtained by integrating the matrix elements

over the appropriate region of phase space determined by ϵ and δ.

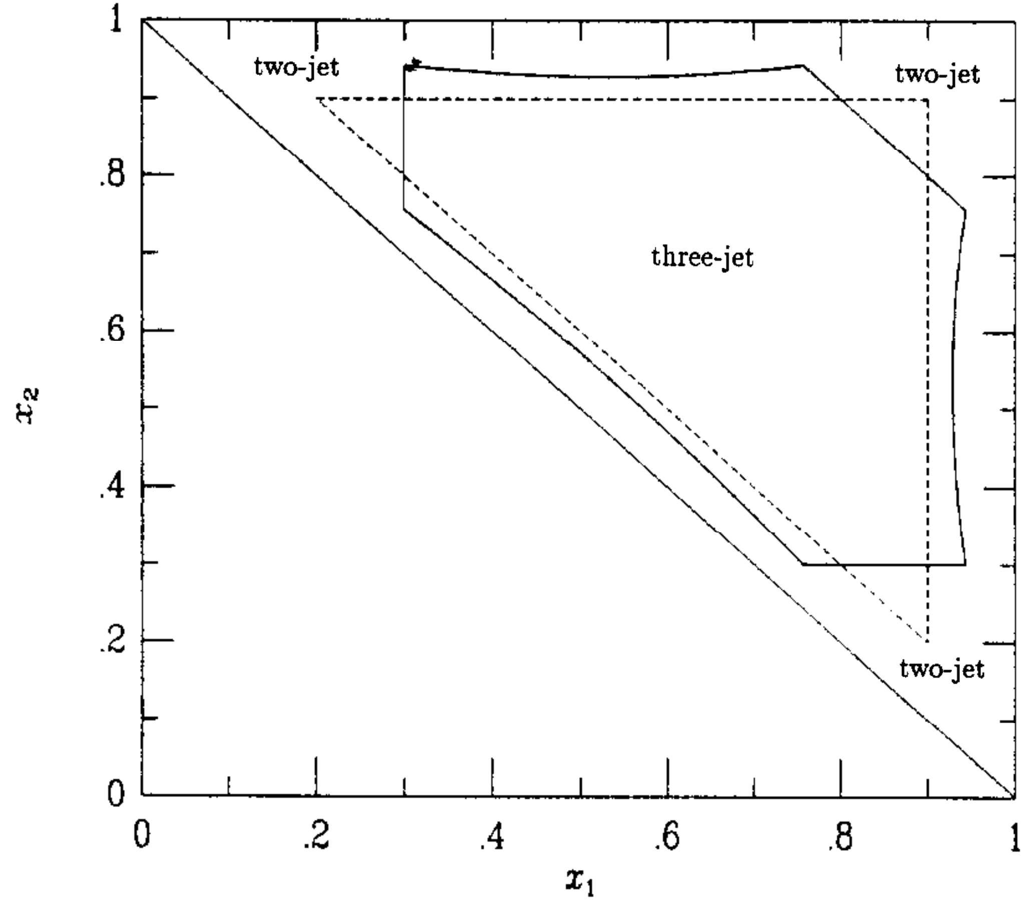
At lowest order, the two-jet and total cross sections obviously

coincide, for any values of the parameters.

At $O(\alpha_S)$, the two-jet cross section is obtained by integrating

over the appropriate range of x_1 and x_2.

Cone Jets, IRC safety (Sterman-Weinberg, 77)



Boundaries between the two- and three-jet regions in the (x_1, x_2) plane for (a) Sterman-Weinberg jets with $(\epsilon, \delta) = (0.3, 30°)$ (solid lines), and (b) JADE algorithm jets with $y = 0.1$ (dashed lines).

Cone Jets, IRC safety (Sterman-Weinberg, 77)

at this order $\sigma = \sigma_2 + \sigma_3$.

σ_3 can be performed in 4 dimensions, since the matrix

element singularities are outside the three-jet region at this order.

Defining the two and three-jet fractions by $f_i = \sigma_i/\sigma$ $(i = 2, 3)$

$$
\begin{aligned}
f_2 &= 1 - 8C_F \frac{\alpha_S}{2\pi} \left\{ \log\frac{1}{\delta} \left[\log\left(\frac{1}{2\epsilon} - 1\right) - \frac{3}{4} + 3\epsilon \right] \right. \\
&\quad \left. + \frac{\pi^2}{12} - \frac{7}{16} - \epsilon + \frac{3}{2}\epsilon^2 + O(\delta^2 \log\epsilon) \right\} , \\
f_3 &= 1 - f_2 .
\end{aligned}
$$

This is IRC safe, observables as well as derivatives, such as angular dist' etc ...

Cone Jets, IRC safety

This is IRC save, observables as well as derivatives, such as angular dist' etc ...

Notice that when the parameters ϵ and δ are small, the $O(\alpha_S)$ correction becomes logarithmically large. This is simply the vestige of the soft and collinear singularities. There are techniques for resumming terms involving $\alpha_S \log \delta$ to all orders in perturbation theory; when δ is small this should improve on the first order result.

It implies that the number of jets is not a physical parameter!
The intuitive connection between partons & jets holds only at LO.

At higher orders in perturbation theory, we can have events with more than three jets.

For example, the $O(\alpha_S^2)$ $q\bar{q}q\bar{q}$ and $q\bar{q}gg$ production processes can give rise to four jet events.

Cones in hadron colliders

Sterman-Weinberg cones give inefficient ‘tiling’ of the phase-space 4pi solid angle.

Similarly for hadronic machine one needs to use different E threshold and not COM.

And, also non trivial to implement in practice, “where to place the cone?” And, “how to deal with overlaps?”. Thus, alternatives were constructed.

One needs to find way to cluster partons (energy) in an IR safe manner.

Iterative Cones

To be fully specified, seeded iterative jet algorithms must deal with two issues:

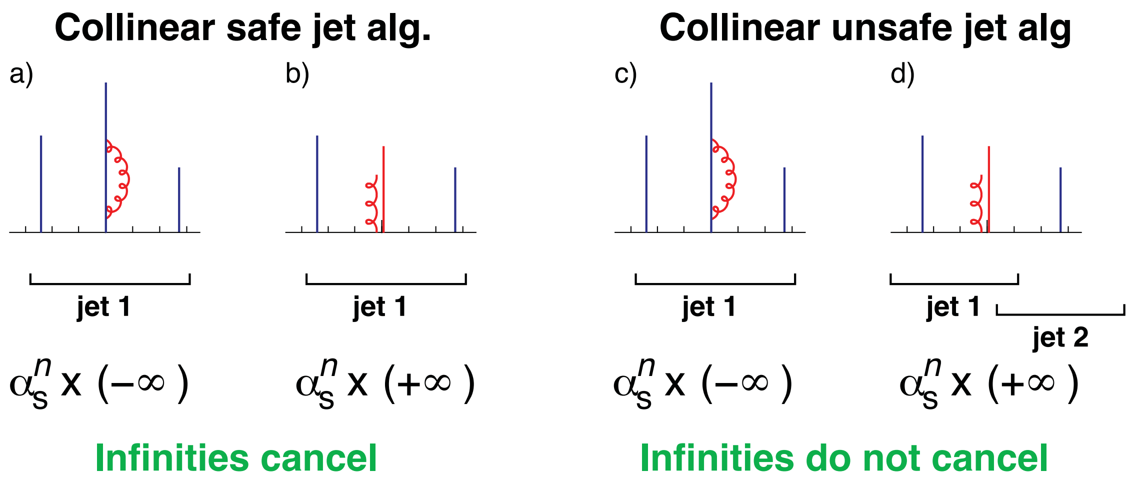
- What should one take as the seeds?
- What should one one do when the cones obtained by iterating two distinct seeds "overlap" (i.e. share particles)?

Overlapping cones: the progressive removal approach

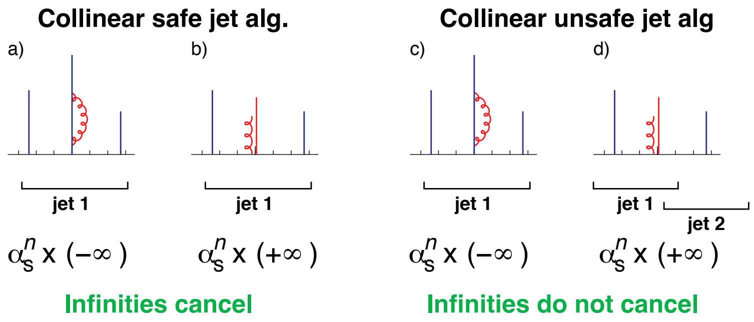
One approach is to take as one's first seed the particle (or calorimeter tower) with the largest transverse momentum. Once one has found the corresponding stable cone, one calls it a jet and removes from the event all particles contained in that jet. One then takes as a new seed the hardest particle/tower among those that remain, and uses that to find the next jet, repeating the procedure until no particles are left (above some optional threshold). This avoids any issue of overlapping cones. A possible name for such algorithms is iterative cone with progressive removal (IC-PR) of particles.

Overlapping cones: the progressive removal approach

IC-PR algorithms' use of the hardest particle in an event gives them the drawback that they are collinear unsafe: the splitting of the hardest particle (say p_1) into a nearly collinear pair (p_{1a}, p_{1b}) can have the consequence that another, less hard particle, p_2, pointing in a different direction and with $p_{t,1a}, p_{t,1b} < p_{t,2} < p_{t,1}$, suddenly becomes the hardest particle in the event, thus leading to a different final set of jets. We will return to



Overlapping cones: the progressive removal approach



The IC-PR case. IC-PR algorithms suffer from collinear unsafety, as illustrated in fig. 1. With a collinear safe jet algorithm, if configuration (a) (with an optional virtual loop also drawn in) leads to one jet, then the same configuration with one particle split collinearly, (b), also leads to a single jet. In perturbative QCD, after integrating over loop variables in (a) and the splitting angle in (b), both diagrams have infinite weights, but with opposite signs, so that the total weight for the 1-jet configuration is finite.

Diagrams (c) and (d) are similar, but for an IC-PR algorithm. In configuration (c), the central particle is hardest and provides the first seed. The stable cone obtained by iterating from this seed contains all the particles, and one obtains a single jet. In configuration (d), the fact that the central particle has split collinearly means that it is now the leftmost particle that is hardest and so provides the first seed. Iteration from that seed leads to a jet (jet 1) that does not contain the rightmost particle. That rightmost particle therefore remains, provides a new seed, and goes on to form a jet in its own right

. As we have discussed above, it is problematic for the result of the jet finding to depend on a collinear splitting. The formal perturbative QCD consequence of this here is that the infinities in diagrams (c) and (d) contribute separately to the 1-jet and 2-jet cross sections. Thus both the 1-jet and 2-jet cross sections are divergent.

Split and Merge

2.1.3 Overlapping cones: the split–merge approach

Another approach to the issue of the same particle appearing in many cones applies if one chooses, as a first stage, to find all the stable cones obtained by iterating from all particles or calorimeter towers (or those for example above some seed threshold $\sim 1-2\text{GeV}$).[5] One may then run a split–merge (SM) procedure, which merges a pair of cones if more than a fraction f of the softer cone's transverse momentum is in particles shared with the harder cone; otherwise the shared particles are assigned to the cone to which they are closer. A possible generic name for such algorithms is IC-SM. The exact behaviour of SM procedures

depends on the precise ordering of split and merge steps and a fairly widespread procedure is described in detail in [21]. It essentially works as follows, acting on an initial list of "protojets", which is just the full list of stable cones:

1. Take the protojet with the largest p_t (the 'hardest' protojet), label it a.
2. Find the next hardest protojet that shares particles with the a (i.e. overlaps), label it b. If no such protojet exists, then remove a from the list of protojets and add it to the list of final jets.

Split and Merge

3. Determine the total p_t of the particles shared between the two protojets, $p_{t,\text{shared}}$.
   - If $p_{t,\text{shared}}/p_{t,b} > f$, where f is a free parameter known as the overlap threshold, replace protojets a and b with a single merged protojet.
   - Otherwise "split" the protojets, for example assigning the shared particles just to the protojet whose axis is closer (in angle).
4. Then repeat from step 1 as long as there are protojets left.

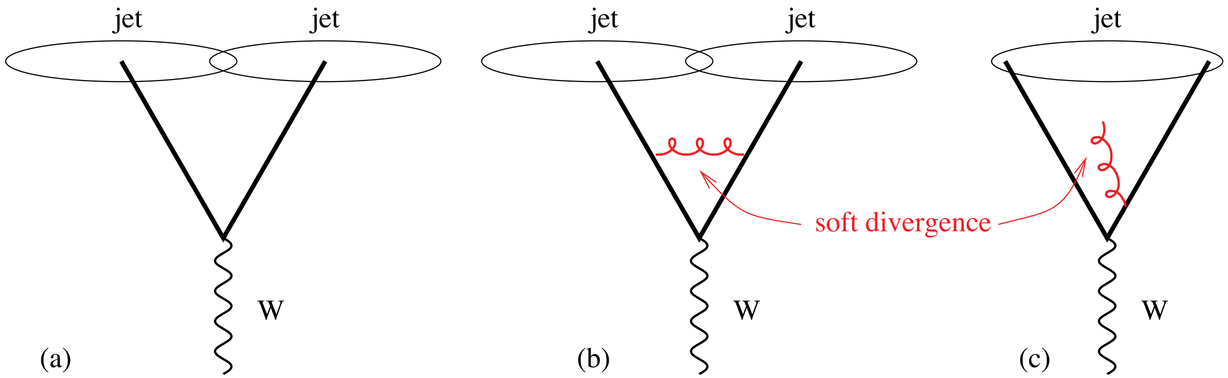


Figure 2: Configurations illustrating IR unsafety of IC-SM algorithms in events with a W and two hard partons. The addition of a soft gluon converts the event from having two jets to just one jet. In contrast to fig. 1, here the explicit angular structure is shown (rather than p_t as a function of rapidity).

Split and Merge, Seedless

SISCone: Salam and Soyez, “A practical Seedless Infrared-Safe Cone jet algorithm,” JHEP 0705 (2007)

A computational strategy for identifying all cones was outlined in ref. [21]: one takes all subsets of particles and establishes for each one whether it corresponds to a stable cone — i.e. one calculates its total momentum, draws a circle around the resulting axis, and if the points contained in the circle are exactly as those in the initial subset, then one has found a stable cone. This is guaranteed to find all stable cones.

The above seedless procedure was intended for fixed-order calculations, with a very limited number of particles. It becomes impractical for larger numbers of particles because there are $\mathcal{O}\left(2^N\right)$ possible subsets (think of an N-bit binary number where each bit corresponds to a particle, and the subset consists of all particles whose bit is turned on). Testing the stable-cone property takes $\mathcal{O}\left(N\right)$ time for each subset and so the total time is $\mathcal{O}\left(N2^N\right)$. This exponential-time behaviour made seedless cones impractical for use on events with realistic numbers of particles (the $N2^N$ approach would take about 10^{17} years to cluster 100 particles). However in 2007 a polynomial-time geometrically-based solution was found to the problem of identifying all stable cones [40]. The corresponding algorithm is known as SISCone and it is described in section 3.2. An explicit test of the IR safety of SISCone is shown in fig. 5.

Sequential recombination jet algorithms

Jade (Jade Collab' 88)

$$\min\,(p_i+p_j)^2 = \min\,2E_iE_j(1-\cos\theta_{ij}) > ys, \qquad i,j = q,\bar{q},g\;,$$

$$0 < x_1, x_2 < 1-y, \qquad x_1+x_2 > 1+y.$$

$$\begin{aligned} f_3 &= C_F\frac{\alpha_S}{2\pi}\left[(3-6y)\log\left(\frac{y}{1-2y}\right)+2\log^2\left(\frac{y}{1-y}\right)\right. \\ &\quad \left.+\frac{5}{2}-6y-\frac{9}{2}y^2+4\,\mathrm{Li}_2\left(\frac{y}{1-y}\right)-\frac{\pi^2}{3}\right]\,, \qquad (123) \\ f_2 &= 1-f_3\,, \end{aligned}$$

where Li_2 is the dilogarithm function,

$$\mathrm{Li}_2(x) = -\int_0^x dy\,\frac{\log y}{1-y}\,.$$

Jade

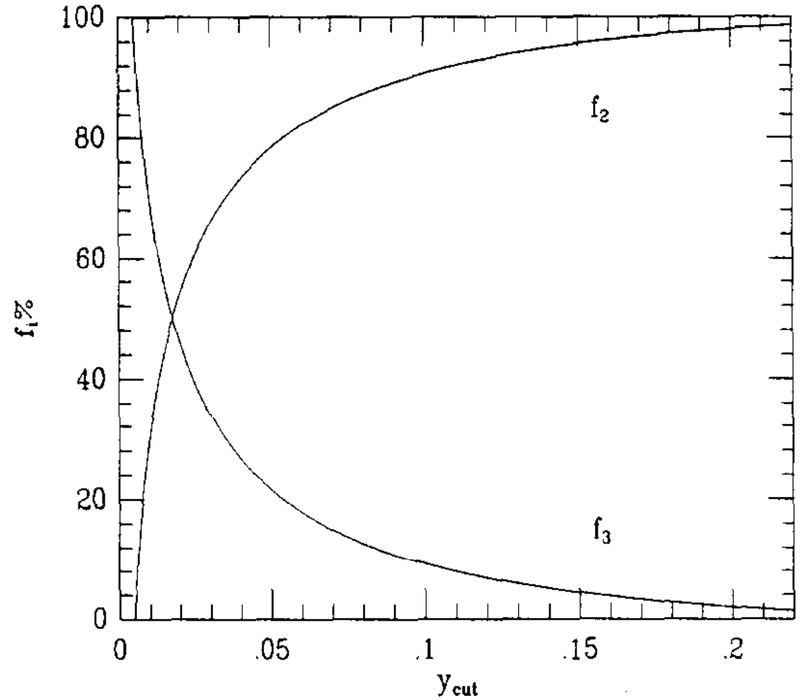


Figure 12: The values of f_3 and f_2 from Eq. (123)

Eq. (123) is valid for $y < \frac{1}{3}$. Fig. 12 shows the two and three jet ratios from Eq. 123 for $\alpha_S = 0.118$. The soft and collinear singularities again reappear as large logarithms in the limit $y \to 0$. Clearly the result in Eq. (123) only makes sense for y values large enough such that $f_2 \gg f_3$, so that the $O(\alpha_S)$ correction to f_2 is perturbatively small.

The k_t algorithm in e^+e^-

The e^+e^- k_t algorithm [27] is identical to the JADE algorithm except as concerns the distance measure, which is

$$y_{ij} = \frac{2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})}{Q^2}\,. \tag{4}$$

In the collinear limit, $\theta_{ij} \ll 1$, the numerator just reduces to $(\min(E_i, E_j)\theta_{ij})^2$ which is nothing but the squared transverse momentum of i relative to j (if i is the softer particle)

— this is the origin of the name k_t-algorithm.[8] The use of the minimal energy ensures that the distance between two soft, back-to-back particles is larger than that between a soft particle and a hard one that's nearby in angle.

Another way of thinking about eq. (4) is that the distance measure is essentially proportional to the squared inverse of the splitting probability for one parton k to go into two, i and j, in the limit where either i or j is soft and they are collinear to each other,

$$\frac{dP_{k\to ij}}{dE_i d\theta_{ij}} \sim \frac{\alpha_s}{\min(E_i, E_j)\theta_{ij}} \tag{5}$$

The k_t algorithm with incoming hadrons

$$d_{ij} = \min(p_{ti}^2, p_{tj}^2)\frac{\Delta R_{ij}^2}{R^2}\,, \qquad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2\,,$$

$$d_{iB} = p_{ti}^2\,,$$

1. Work out all the d_{ij} and d_{iB}
2. Find the minimum of the d_{ij} and d_{iB}.
3. If it is a d_{ij}, recombine i and j into a single new particle and return to step 1.
4. Otherwise, if it is a d_{iB}, declare i to be a [final-state] jet, and remove it from the list of particles. Return to step 1.
5. Stop when no particles remain.

The anti-k_t algorithm

One can generalise the k_t and Cambridge/Aachen distance measures as

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}\,, \qquad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2\,,$$
$$d_{iB} = p_{ti}^{2p}\,,$$

where p is a parameter that is 1 for the k_t algorithm, and 0 for C/A. It was observed in [33] that if one takes $p = -1$, dubbed the "anti-k_t" algorithm, then this favours clusterings that involve hard particles rather than clusterings that involve soft particles (k_t algorithm) or energy-independent clusterings (C/A). This ultimately means that the jets grow outwards around hard "seeds". However since the algorithm still involves a combination of energy and angle in its distance measure, this is a collinear-safe growth (a collinear branching automatically gets clustered right at the beginning of the sequence). The result is an IRC safe algorithm that gives circular hard jets, making it an attractive replacement for certain cone-type algorithms (notably IC-PR algorithms).

Summary lecture I

Jetty phenomena (spikes of energy flow) in QCD at high energies is due to asymptotic freedom & its non-abelian nature.

Use various prescriptions (jet algorithms) to obtain finite (IR safe) & perturbative differential description.

Resulting distributions (number of jets etc.) are prescription dependent, but within an algorithm short distance physics is transparent.

Assuming that confinement (hadronization) do not interfere much, it allows us to make contact with partonic calculation, with quarks/gluons final states.

Lecture II

Splitting function (LO)

Jet substructure:

Jet mass (signal & background)

Other shapes and filtering

Template function (maybe ...)

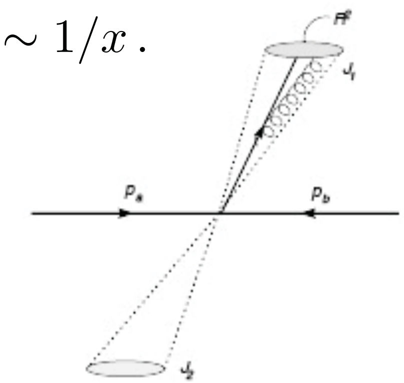
The Splitting Function (leading log, gluon emission)

In the limit where the emitted gluon is soft and collinear we find:

In QCD the probability for a parton j to emit a parton i with energy fraction x at angle θ is

$$d\sigma \propto \alpha_s P_{ij}(x) dx \frac{d\theta}{\theta}$$

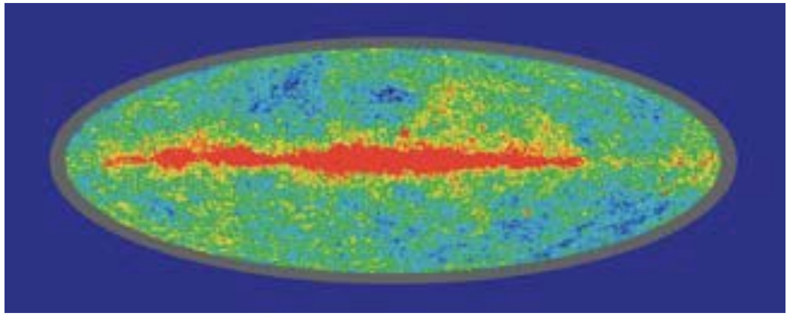
$P_{ij}(x)$ is the Altarelli-Parisi matrix $P_{ij} \sim 1/x$.

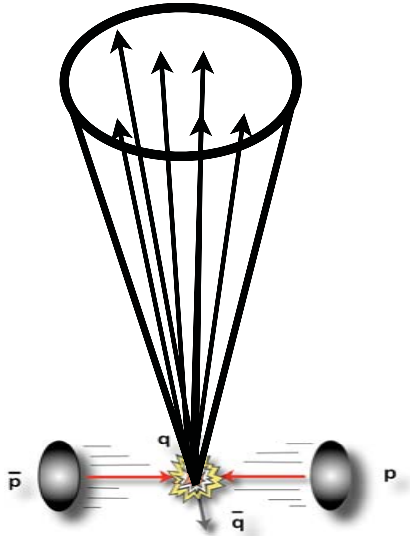


As discussed below, above limit seems (fortunately) to be valid for a search for massive boosted jets:

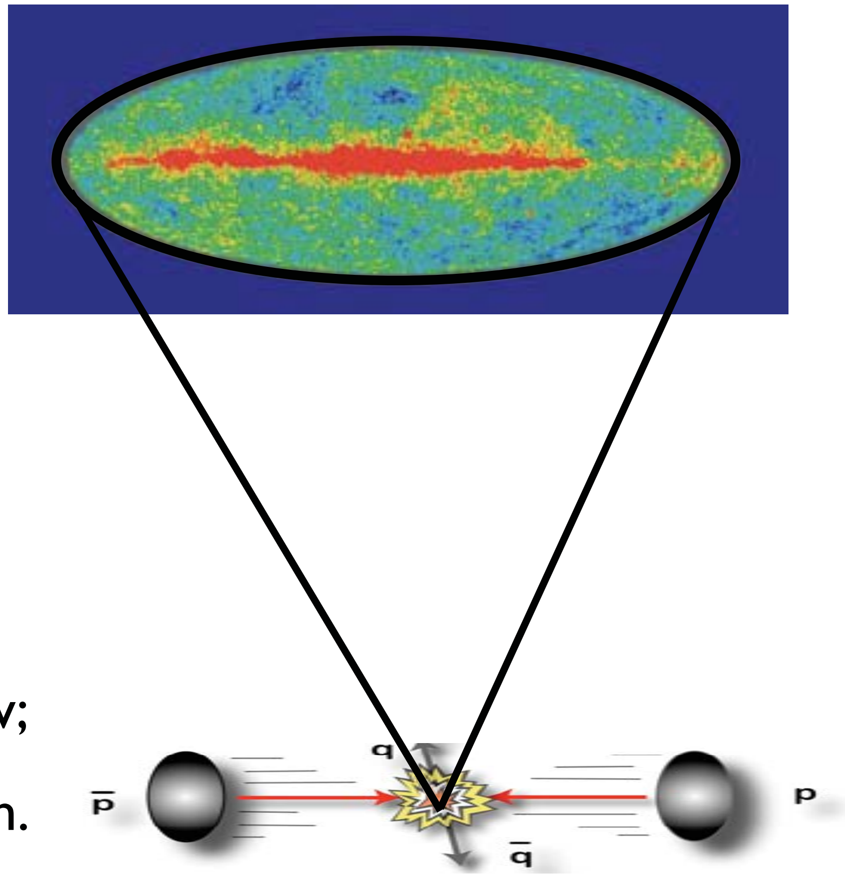
$$\Lambda_{\rm QCD} \ll m_{\rm peak} \ll m_J \ll P_T R \,, \quad R \ll 1$$

Understanding the inside of massive boosted jets





Jet substructure



(i) Mass;

(ii) Angularity (filtering) & planar flow;

(iii) Beyond shapes, template function.

Large mass => perturbative control (asymptotic freedom)

- Use simple perturbation theory to define & compute set of jet-shape variables.

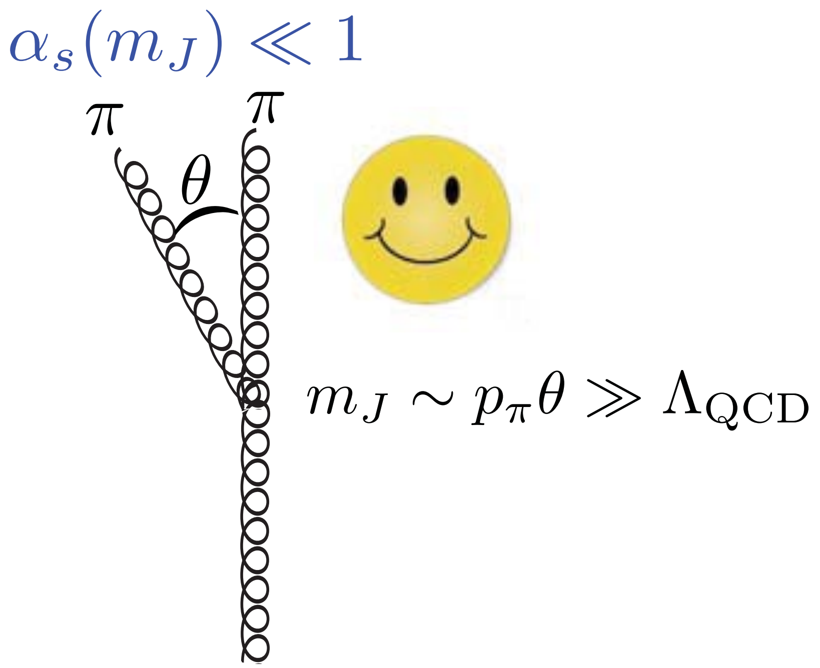
$$\alpha_s(m_J) \sim 1$$

π

$$m_J \sim m_\pi \sim \Lambda_{\rm QCD}$$

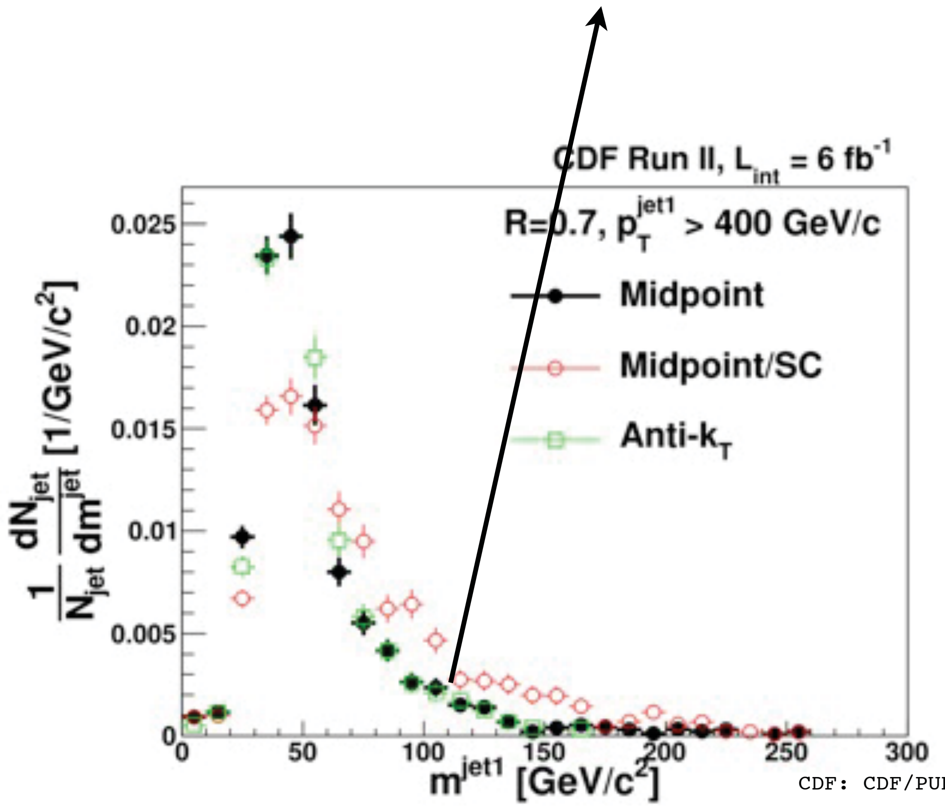
Large mass => perturbative control (asymptotic freedom)

- Use simple perturbation theory to define & compute set of jet-shape variables.



The big picture: Energy flow of massive narrow jets, QCD first

- Interested in narrow, massive energetic (boosted) jets: $m_{\rm peak} \ll m_J \ll P_T R\,, \quad R \ll 1$



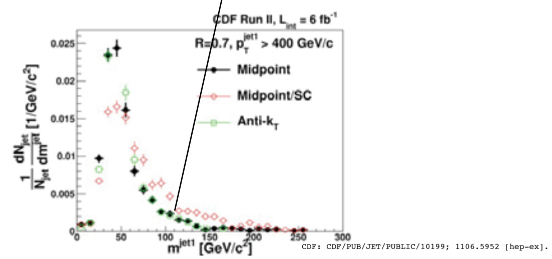
CDF: CDF/PUB/JET/PUBLIC/10199; 1106.5952 [hep-ex].

Jet substructure

Use splitting function to get some qualitative understanding:

2-body partonic IR-safe approx' for jet substructure.

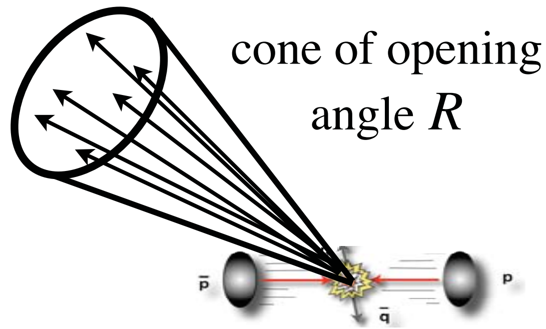
$m_{\text{peak}} \ll m_J \ll P_T R\,, \quad R \ll 1$



Since signal is EW mass boosted particles, obvious variable to distinguish between signal & QCD background is the jet mass.

Jet mass definition:

$$m_J^2 = (\textstyle\sum_{i \in R} P_i)^2, \quad Pi^2 = 0$$



cone of opening angle R

Jet mass from splitting function (leading log)

$$d\sigma \propto \alpha_s P_{ij}(x) dx \frac{d\theta}{\theta} \;\; \mathit{with} \quad P_{ij} \sim 1/x\,.$$

Given $m_J^2 \approx x E_J^2\,\theta^2 \Rightarrow \frac{d\sigma}{dm_J^2} \propto \alpha_s \frac{C_F}{m_J^2} \int_{\frac{m_J}{E_J}}^{R} \frac{d\theta}{\theta} \propto \alpha_s \frac{C_F}{m_J^2} \log\left(\frac{E^2 R^2}{m_J^2}\right)$

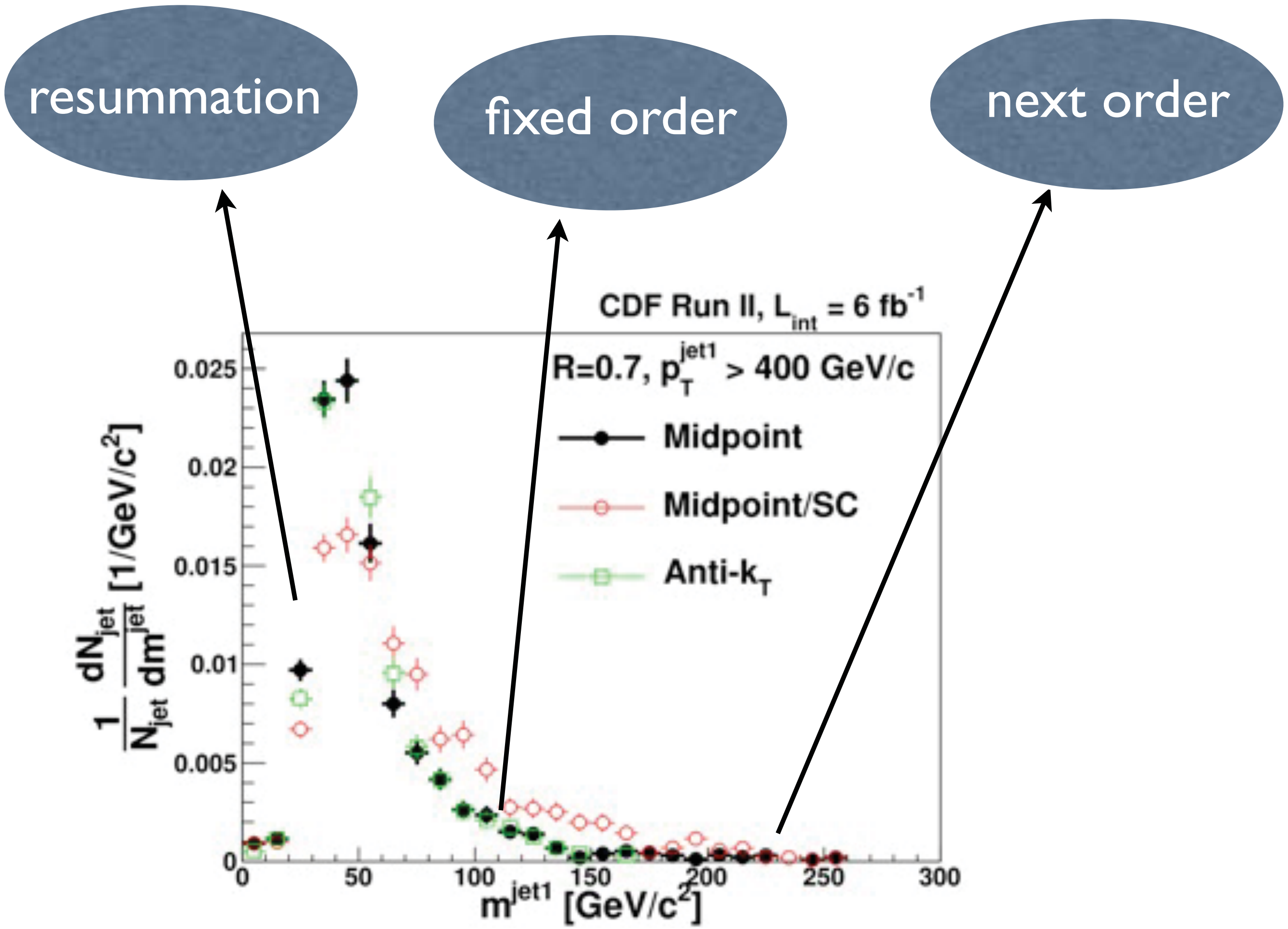
$C_F = 4/3$ for quarks, $C_A = 3$ for gluons.

As long as $\alpha_s(m_J^2) \ll \alpha_s(m_J^2)\log\left(\frac{p_T^2 R^2}{m_J^2}\right) \ll 1$

We can use fix order perturbation theory.

Questions: what are the relevant mass range for this approx' for jet of *E~1 TeV & R=0.4* ?
What is the average jet mass for these parameters?

Summary QCD jet mass



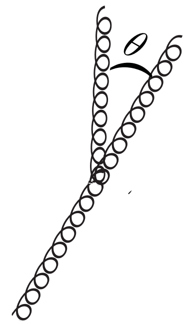
Questions: What is the shape of top jet mass distribution?

Jet substructure beyond mass

2-body partonic approximation actually tells us more:

Kinematics is trivial, for given mass & momenta: a single more variable, distribution extracted from splitting function.

angular distribution: $\frac{d^2\sigma}{dm_J^2 d\theta} \propto \frac{C_F}{m_J^2 \theta}$, and $\theta_{\min} = \frac{2m_J}{E_J}$



Questions: Show that the Higgs jet angular distribution is given by θ^{-3}, with the same min' angle.

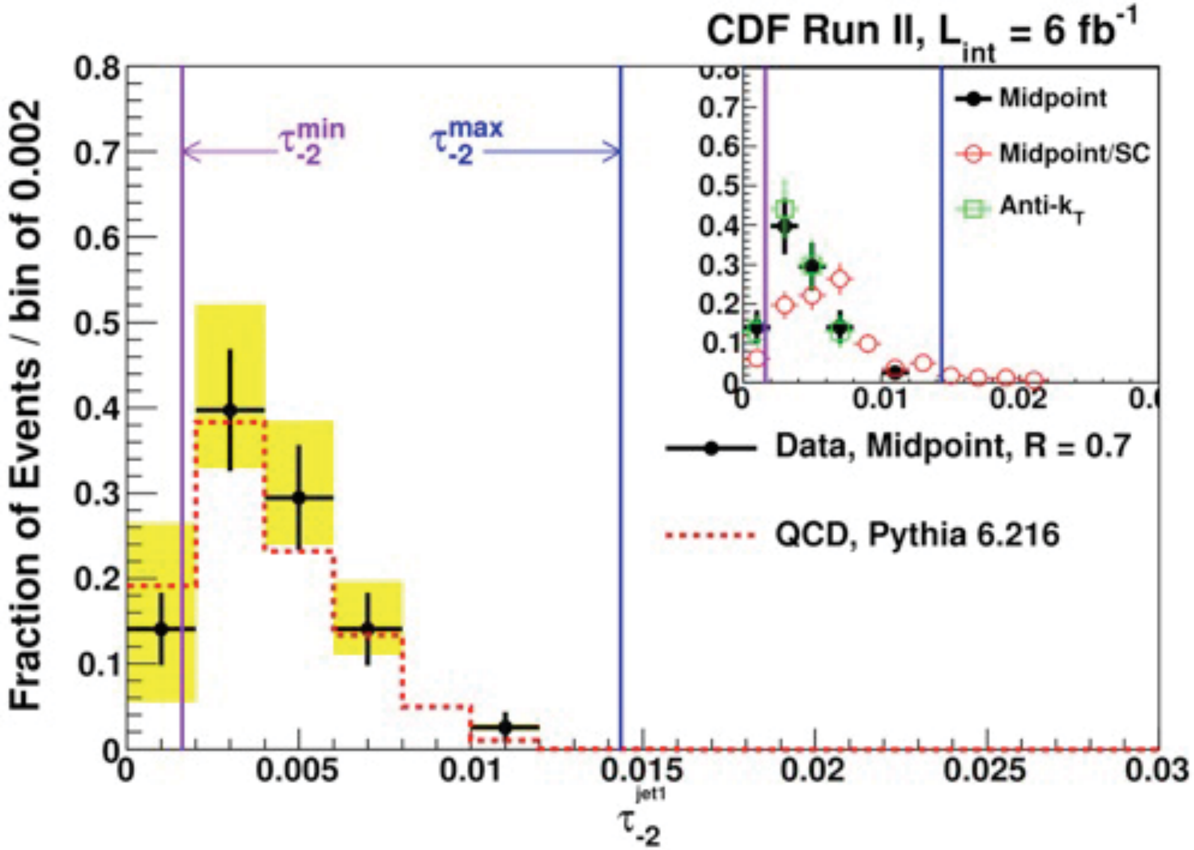
Testing with real data

Alon, Duchovni, GP & Sinervo, for the CDF, 10199, 10234, 1106.5952 [hep-ex];

Boosted jets' angular distribution, angularity τ_{-2}

$$\frac{d\sigma}{d\theta} \longrightarrow \frac{d\sigma}{d\tau_{-2}} \approx 1/\tau_{-2}\,, \quad \tau_{-2}^{\min} = \left(\frac{m_J}{2E_J}\right)^3 \qquad \left(\tau_{-2} \sim \sum_{i\in J} E_i\theta_i^4\right)$$

Almeida, Lee, GP, Sterman & Sung (10)



Questions: Derive the above angularity dist' (for large angles).

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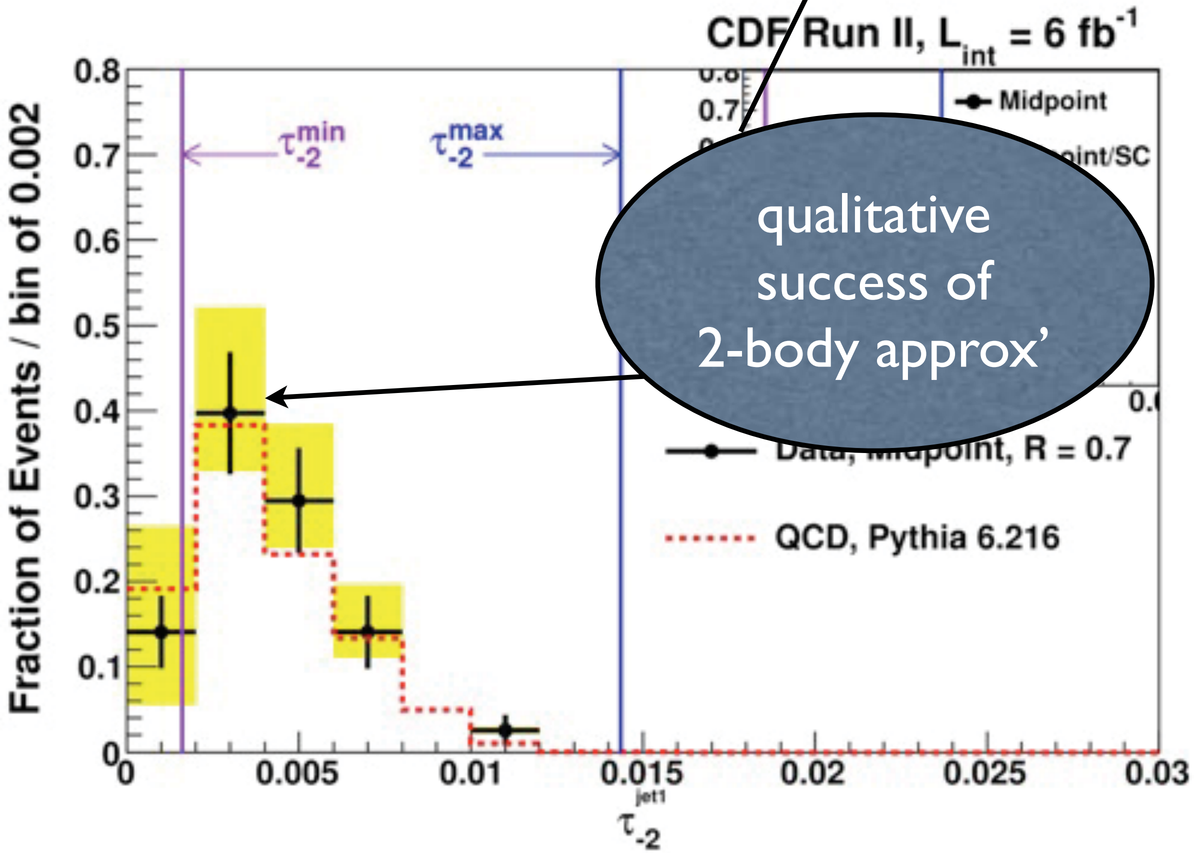


Questions: Derive the above angularity dist' (for large angles).

Summary

New era: colliders energy > electroweak (EW) scale.

Probing the mechanism of EW symmetry breaking.

New phenomena is kinematically allowed narrow ultra massive energetic jets.

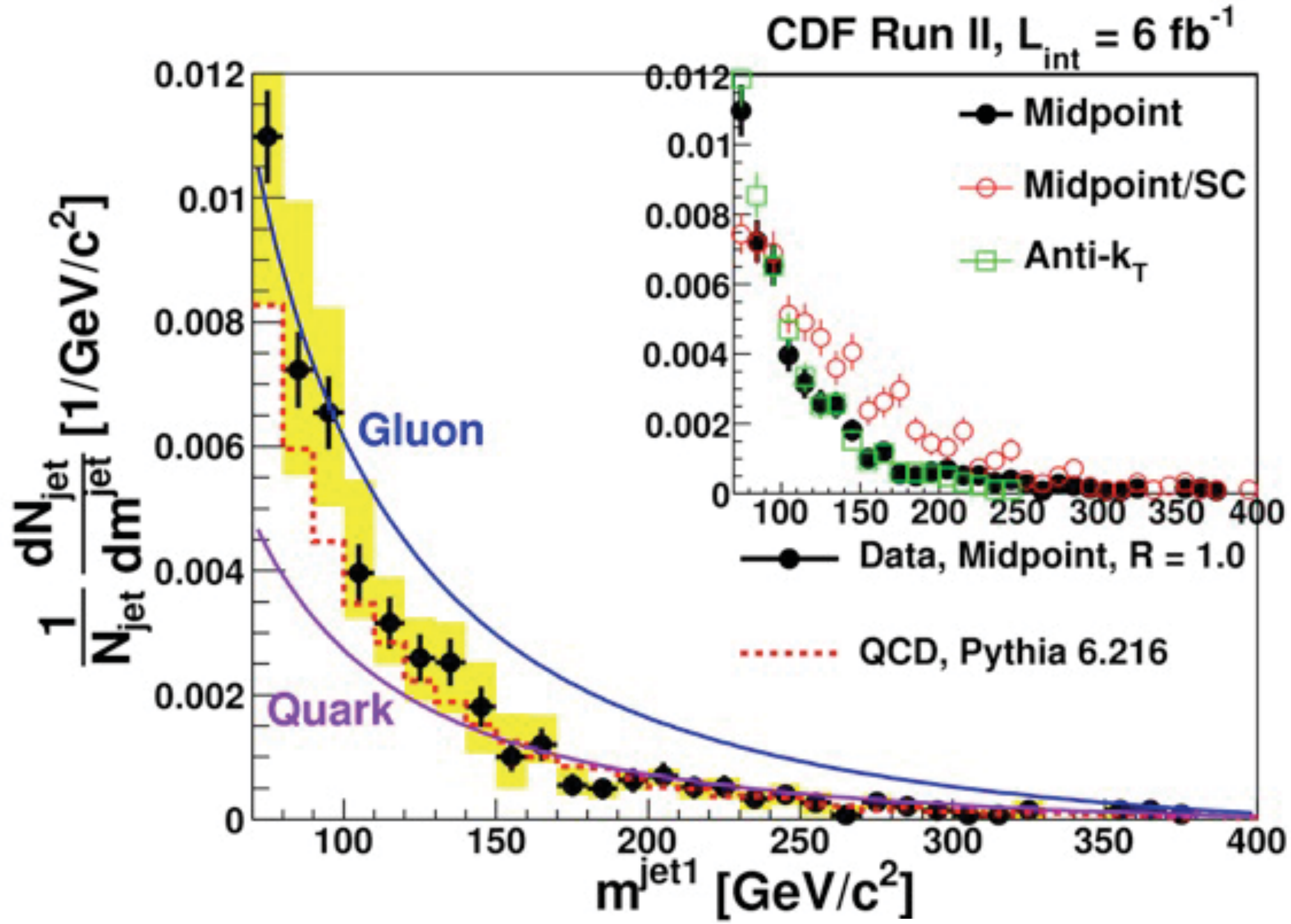
Might arise from new type of microscopic dynamics.

But maybe also from QCD => requires understanding.

Interesting: sometimes boosted kinematics is useful to control S/B even for softer physics, due to reduce in combinatorial background & reduce of noise.

Boosted jets mass distribution, $E_J > 400\,\mathrm{GeV}$

$$\frac{d\sigma}{dm_J^2} \propto \frac{C_F}{m_J^2} \log\left(\frac{E^2 R^2}{m_J^2}\right) \quad \text{(expect mostly quarks } C_F = 4/3\text{)}$$



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