Jets

Boston Jet Physics Workshop

Jan. 12, 2011

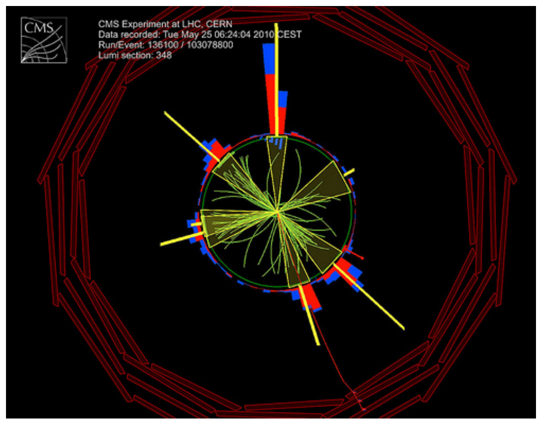
George Sterman, Stony Brook

Some general considerations to set the stage.

1. What Are Jets and What Are They Good For?
2. Jets, a Brief Biography
3. Factorization and Infrared Safety – Why Are There Jets?
4. The SCET Connection
5. Interjet and Intrajet
6. Random Thoughts and Preliminary Conclusions

1. What Are Jets and What Are They Good For?

- **An observable jet is any subset of particles $\{q_j\}$ with $(\Sigma_i\, q_i)^2 \ll (\Sigma_i\, E_i)^2$ and such that this set of lines is separated in direction – not embedded among other particles of similar energy. Or could it be?**



- **Jets are a signature of large momentum transfer through local interactions, as such direct evidence of short-distance physics. There is no other known production mechanism for jets in particle collisions; statistical fluctuations seem far too small (power laws vs. exponentials).**

- A set of jets results from the action of a composite local operator: $\mathcal{O}_N \sim \Pi_{a=1}^{N} \phi_a(0)$, with each jet representing the elementary quanta excited by field ϕ_a.
- But in cross sections the elementary quanta never emerge alone, we always sample complex 'out-states' X. Still, in many cases,

$$\sigma_{\mathcal{O}} \sim \sum_X |\langle p_1, p_2 | \mathcal{O}_N(0) | X \rangle|^2$$

is dominated by jet-like states, one for each field ϕ_a in $\mathcal{O}_N$.
- When is this 'natural'? Generally speaking, for any theory where 'weak coupling' describes the evolution of the quanta produced by the local interaction over times much longer than the inverse of the relative momenta in question. Conversely, however, it may not be natural for a theory with strong coupling over time scales comparable to these momenta.

- **For confining theories, the process of hadronization should also not require large momentum transfers. This is ensured in QCD by the presence of 'light' quarks, with masses below $\Lambda_{\rm QCD}$.**

- **For an epoch of weak coupling, the distributions of jets reflect the short-distance operators of the theory. In hadron colliders, these operators always include those of QCD ('background'), but potentially also those due to interactions or particles in the completion or transcendence of the Standard Model.**

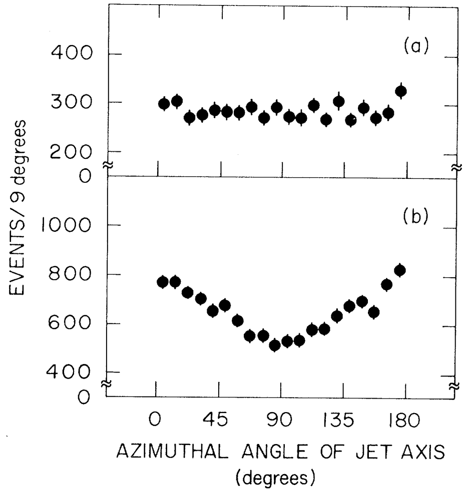
- **The actual final states may include more than the minimal numbers of jets, but if these are due to QCD or other Standard Model interactions, these are calculable corrections.**

2. Jets, a Brief Biography

- **Prehistory: the 1950's**
  - First theory of high-energy collisions; cosmic ray 'jets'
  - Particle jets in cosmic rays . . .
  - "The average transverse momentum resulting from our measurements is p_T=0.5 BeV/c for pions . . . Table 1 gives a summary of jet events observed to date . . ."
    – B. Edwards et al, Phil. Mag. 3, 237 (1957)

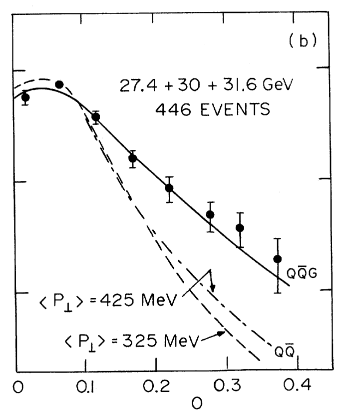
- **The era of high energy physics**
  - Parton model for DIS – what happens to partons in the final state? In pair production . . .

– **Answer: SLAC 1975: angular distribution for energy flow follows Born expression** (Hansen *et al*, 1975)



$$d\sigma/d\Omega \sim 1 + \alpha\cos^2\theta + P^2\alpha\sin^2\theta\cos 2\phi$$

– **Hints of three gluons in Upsilon decay, and unequivocal gluon jet at Petra** (MARK-J Collaboration, 1979 reproduced in Kramer and Ali, 2010)



,

– **80's: Direct and indirect 'sightings' of scattered parton jets at Fermilab and the ISR, often in the context of single-particle spectra. Overall, however, an unsettled period until the SPS large angular coverage makes possible 'lego plots' in terms of energy flow, and leads to the unequivocal observation of high-p_T jet pairs that represent scattered partons .**

– **90's: The Standard Model machines: HERA, the Tevatron Run I LEP I and II jet cross sections over multiple orders of magnitude.**

– **And now . . . The new era of jets at the limits of the SM, ushered in by Tevatron Run II, and now the LHC 7 heading towards 14 GeV (Following talks by Apanasevich, Huston).**

3. Factorization and Infrared Safety

- **Factorization structure and proofs:**
  - (1) Short distance incoherent with long distance dynamics;
  - (2) mutual incoherence when $v_{\rm rel} = c$.
  - For large $Q \sim \sqrt{s}$: long-distance logs from

$$d\sigma(Q, a+b \to N_{\rm jets})/dQ$$

$$= \int dx_a dx_b \; H(x_a p_a, x_b p_b, Q)_{a'b' \to c_1 \dots c_{N_{\rm jets}}}$$
$$\times \mathcal{P}_{a'/a}(x_a p, X_a)\, \mathcal{P}_{b'/b}(x_b p, X_b)$$
$$\otimes_{\rm soft} \prod_{i=1}^{N_{\rm jets}} J_{c_i}(X_i) \;\; \otimes_{\rm soft} S_{a'b' \to c_1 \dots c_{N_{\rm jets}}}(X_{\rm soft})$$

– A story with only these pieces:

* Evolved incoming partons $\mathcal{P}_{a'/a}$, $\mathcal{P}_{b'/b}$ collide at H (leaving "remnants" $X_{a,b}$)

* to produce outgoing jets J_{c_i},

* and coherent soft emission S,

* and H the 'coefficient' function of the operator $\mathcal{O}$ for the jets.

* For the right observables, holds to any fixed α_s^n, all $\ln^a \mu/Q$.

- Why this structure? Why IR finite, factorized jets and soft?

- **IR finiteness:** **Perturbative amplitudes are a sum of ordered time integrals.** **At τ_m, an interaction produces state m.**

$$\Gamma = \sum_{\tau \text{ orders}} \int_{-\infty}^{\infty} d\tau_n \ldots \int_{-\infty}^{\tau_2} d\tau_1$$
$$\times \prod_{\text{loops } i} \int \frac{d^3\ell_i}{(2\pi)^3} \prod_{\text{lines } j} \frac{1}{2E_j} \times \ (\text{spin factors})$$
$$\times \exp\left[i \sum_{\text{states } m} \left(\sum_{j \text{ in } m} E(\vec{p}_j) \right) (\tau_m - \tau_{m-1}) \right]$$

- $\tau_i \to \infty$ **give divergences, but long times require stationary phase**

$$\frac{\partial}{\partial \ell_{i\mu}} \left[\text{phase} \right] = \sum_{\text{states } m} \ \sum_{j \text{ in } m} (\pm \beta_j^{\mu})(\tau_{m+1} - \tau_m) = 0$$

- $\beta_j = \pm \partial E_j / \partial \ell_i$ **for j in loop i is four-velocity**

– **Again, the condition of stationary phase is:**

$$\sum_{\text{states } m} \sum_{j \text{ in } m} (\pm\beta_j^\mu)(\tau_{m+1} - \tau_m) = 0$$

– **The distance travelled around any loop is zero.**

– **Long times $\leftrightarrow$ free classical propagation**

* **Coleman-Norton interpretation of Landau equations.**

* **Fragments and outgoing jets can never rescatter with finite momentum transfer.**

- **Cancellation of Final State Divergences.**
  - **The phase:**

$$\text{phase} = \sum_{\text{states}\, m} \; \sum_{j\, \text{in}\, m} E_j(\vec{p}_j)\,(\tau_{m+1} - \tau_m)$$

  - **At stationary phase**

$$\text{phase} = \sum_{\text{jets}\, i} E_i^{(\text{total})} \times (\,\text{time elapsed}\,) \rightarrow \infty$$

  - **The phase is unchanged by IR emission, CO rearrangement.**

  - **If we also assign the same weight to all jet states states at a specific point stationary phase, the cross section becomes approximately a simple sum over all long time FS interactions in the neighborhood of that point.**

  - **The phases then cancel in the weighted sums**

$$\sigma = \left(\sum \Gamma\right)^{\dagger} \left(\sum \Gamma\right)$$

– **Freedom from arbitrarily long-time dependence**
$\leftrightarrow$ **Infrared safety**

– **The scale for the longest times sampled is set by parameters imposed on the final state, like final state jet masses.**

– **The role of energy flow emerges naturally, since it is unaffected by collinear rearrangements and soft radiation.**

– **But how do the soft fields of each jet affect the other? If fields from one jet influence the dynamics of others universality is lost (not it itself a bad thing, but a challenge).**

Soft fields in hadron-hadron scattering

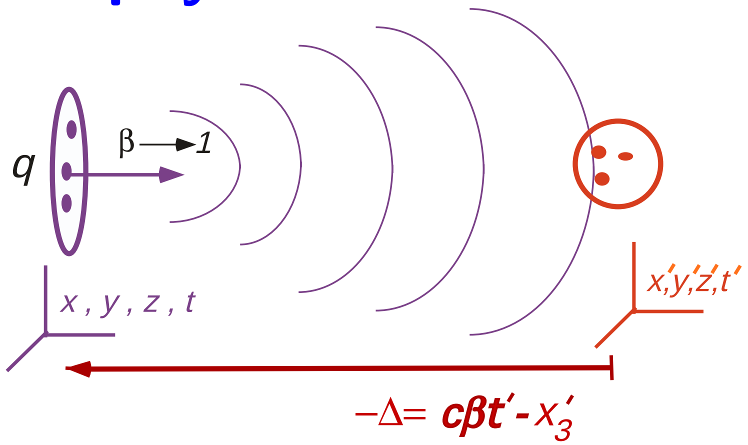
- Example: 'collinear factorization' for hadron-hadron scattering for a hard, inclusive process with momentum transfer M to produce final state $F + X$:

$$d\sigma_{\mathrm{H_1H_2}}(p_1, p_2, M) = \sum_{a,b} \int_0^1 d\xi_a \, d\xi_b d\hat{\sigma}_{ab\to F+X} \left(\xi_a p_1, \xi_b p_2, M, \mu\right) \times \phi_{a/H_1}(\xi_a, \mu) \, \phi_{b/H_2}(\xi_b, \mu)$$

- Factorization proofs: justifying the "universality" of the parton distributions.

- The same arguments allow us to define and analyze jets with calculable ambiguities (fragmentation functions).

- **The physical basis: classical fields**



$$\Delta \equiv x'_3 - \beta c t'$$

- **Why a classical picture isn't far-fetched . . .**

The correspondence principle is the key to IR divergences.

An accelerated charge must produce classical radiation,

and an infinite numbers of soft gluons are required to make a classical field.

Transformation of a scalar field:

$$\phi(x) = \frac{q}{(x_T^2 + x_3^2)^{1/2}} = \phi'(x') = \frac{q}{(x_T^2 + \gamma^2\Delta^2)^{1/2}}$$

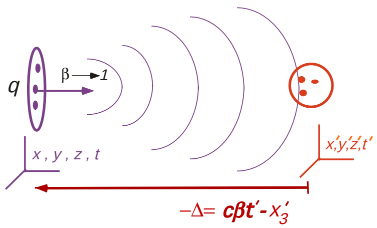
From the Lorentz transformation:

$$x_3 = \gamma(\beta c t' - x_3') \equiv -\gamma\Delta.$$

Closest approach is at $\Delta = 0$, i.e. $t' = \frac{1}{\beta c} x_3'$.

The scalar field transforms "like a ruler": At any fixed $\Delta \neq 0$, the field decreases like $1/\gamma = \sqrt{1-\beta^2}$.

Why? Because when the source sees a distance x_3, the observer sees a much larger distance.



field	x frame	x' frame
scalar	$\frac{q}{\lvert\vec{x}\rvert}$	$\frac{q}{(x_T^2+\gamma^2\Delta^2)^{1/2}}$
gauge (0)	$A^0(x) = \frac{q}{\lvert\vec{x}\rvert}$	$A'^0(x') = \frac{-q\gamma}{(x_T^2+\gamma^2\Delta^2)^{1/2}} \sim \gamma^0$
field strength	$E_3(x) = \frac{q}{\lvert\vec{x}\rvert^2}$	$\frac{E_3'(x')-q\gamma\Delta}{(x_T^2+\gamma^2\Delta^2)^{3/2}} \sim \frac{1}{\gamma^2}$

- **The “gluon field” A^μ is enhanced, yet is a total derivative:**

$$A^\mu = q\frac{\partial}{\partial x'_\mu}\ \ln\left(\Delta(t', x'_3)\right) + \mathcal{O}(1-\beta) \sim A^-$$

- **The “large” part of A^μ can be removed by a gauge transformation!**

- The electric, $\vec{\mathrm{E}}$ field of the incident particle does not overlap the "target" until the moment of the scattering.

- "Advanced" effects are corrections to the total derivative:

$$1 - \beta \sim \frac{1}{2} \left[\sqrt{1 - \beta^2}\right]^2 \sim \frac{m^2}{2E^2}$$

- Power-suppressed! These are corrections to factorization.

- At the same time, a gauge transformation also induces a phase on charged fields:

$$q(x) \Rightarrow q(x)\, e^{i \ln(\Delta)}$$

Cancelled if the fields are well-localized $\Leftrightarrow$ σ inclusive

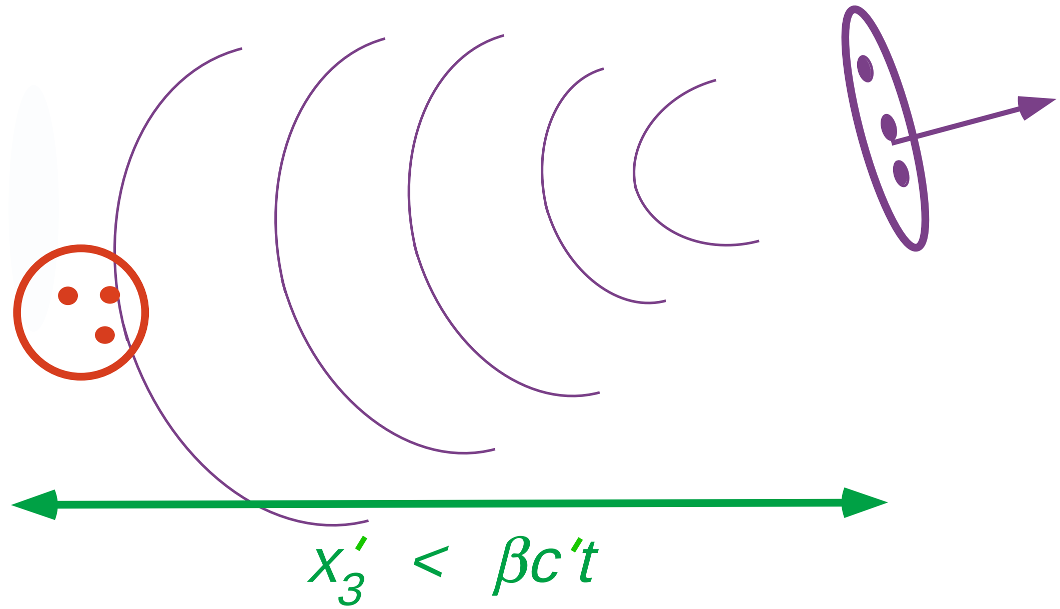
- **Initial-state interactions decouple from hard scattering**

- **Summarized by multiplicative factors: the parton distributions.**

  $\Rightarrow$ Cross section for inclusive hard scattering is IR safe, with power-suppressed corrections.

- **But what about cross sections where we observe specific particles or jets in the final state? Single hadrons, dihadron correlations, jet masses, shapes, subjets etc?**
  Talks by: Li, Sinervo, Loch, Hu, Bose.

- **Much of the same reasoning holds:**



- **For single-particle inclusive and jet fragmentation . . .**

  Interactions after the scattering happen too late to affect large momentum transfer, creation of heavy particle, etc.

  The fragmentation of partons to jets is too slow to know details of the hard scattering: factorization of fragmentation functions.

4. The SCET Connection

- Soft-collinear effective theory is the language of much recent work on jets. At this workshop, talks by Neubert, Ovanesyan, Stewart, Dunn, Walsh, Vermilion, Waalewijn.

- Comments growing out of discussions with Leo Almeida, Chris Lee, Ilmo Sung, Jon Walsh:

- SCET "builds in" many of the features just described into its Lagrangian(s), so that equivalent factorization theorems result.

- Where SCET overlaps with previous work, differences are often due to choices in how to solve equivalent evolution equations.

5. Short Distances, Intrajet and Interjet

- Our 'general' jet cross section:

$$d\sigma(Q, a+b \to N_{\rm jets})/dQ \;=\; \int dx_a dx_b \; H(x_a p_a, x_b p_b, Q)_{a'b' \to c_1 \dots c_{N_{\rm jets}}}$$
$$\times \mathcal{P}_{a'/a}(x_a p, X_a)\, \mathcal{P}_{b'/b}(x_b p, X_b)$$
$$\otimes_{\rm soft} \prod_{i=1}^{N_{\rm jets}} J_{c_i}(X_i) \;\; \otimes_{\rm soft} S_{a'b' \to c_1 \dots c_{N_{\rm jets}}}(X_{\rm soft})$$

- How to recognise BSM $H(x_a p_a, x_b p_b, Q)_{a'b' \to c_1 \dots c_{N_{\rm jets}}}$?
  How to organize QCD corrections to complex processes? Sapeta on K factors.

- How to recognize and define N jets? Talks by Kim and van Tilberg.

- The subject of much recent thought as implications for the LHC are spun out . . .

- **Telling gluon from quark jets will help. Talks by Gallicchio, Dunn.**

- **Some of the c_i may be boosted heavy SM particles, giving nonstandard jets. Talks by Tweedie, Perez, A. Martin, Shao, Han.**

- **But also: the possibility that one or more of the jets is initiated by a particle not in SM $\Rightarrow$ novel jet evolution.**

- **Soft radiation, $S_{a'b' \to c_1 \dots c_{N_{\text{jets}}}}(X_{\text{soft}})$ encodes color flow. (Hass and Dolen on $t\bar{t}$.)**

- **Any theoretical analysis requires a strategy for observation/recognition. (B. Martin in Spartyjets.)**

6. Random Thoughts and Preliminary Conclusions

- **The life story of a jet:**
  1. **the production of the initiating parton**
  2. **perturbative radiation / evolution**
  3. **hadronization**
- **Generally unwanted guests**
  1. **coherent radiation between jets**
  2. **incoherent radiation from pile-up**
  3. **somewhat coherent radiation from multiple interactions**
- **There are many limitations of current pQCD theory – reliance on inclusive observables limits, and there is plenty of room for improvement here.**
- **Color coherent radiation: generally described in terms of anomalous dimension matrices, but these change dimension with scale. An effective theory approach may be natural.**

- **In a 'medium', perturbative evolution may (and evidently is) by affected by collisions and external fields.**
- **For BSM, the ideal is to group all radiation from the initiating new particle, effectively produced on-shell. This can involve both combination, but also more recently subtraction (jet 'horticulture').**
- **In QCD, there is no 'correct' jet energy or mass; jet algorithms are driven by parameter choices, and varying parameters leads to changes in jet multiplicity. In principle, the numbers of jets are computable for any choice of parameters.**
- **Jet substructure feeds into and from higher-jet cross sections.**
- **Clearly, these viewpoints speak to each other: how to strike the right balance depends on what is being looked for.**
- **Progress will hopefully grow out of workshops like these, and reflection 'at home'.**