Jets: QCD and Beyond

DESY, QCD@LHC 2013

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An integral feature of LHC Physics,

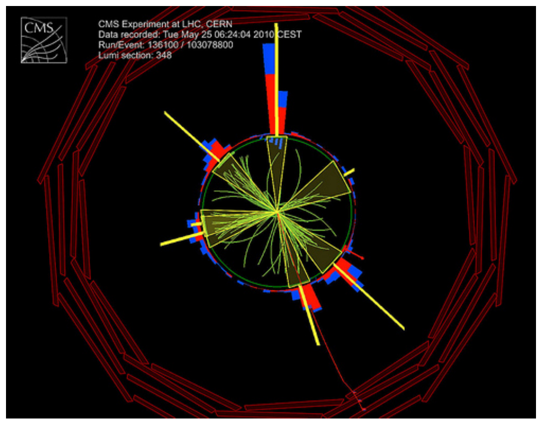
represented widely at the workshop in many talks.
See esp. review of Tevatron/LHC; A. Ruiz-Martinez.

This seminar is mostly background material. (Wish there were time for jets in nuclei!)
Some talk and pictures, but also a some slides of quantum field theory, but self-contained.

1. What Are Jets in Particle Physics?
2. The Jet, a Brief Biography
3. What Are They Good For?
4. Why and When Are There Jets in Quantum Field Theory?
5. Infrared Safety, Energy Flow and the Classical-Quantum Connection
6. Beyond QCD: Finding Jets, Boosted decays and Electroweak Radiation

1. What Are Particle Jets?

- **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.**



- **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, but see HL LHC).**

- **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.**

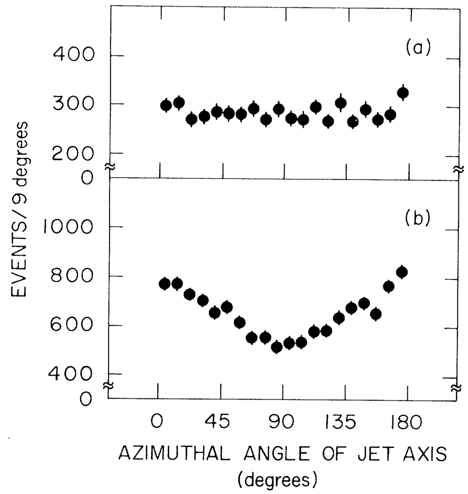
- **For confining theories, the process of hadronization should also not require large momentum transfers. This is ensured in QCD by the presence of 'light' quarks, with masses below $\Lambda_{\rm QCD}$.**

2. Particle 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)

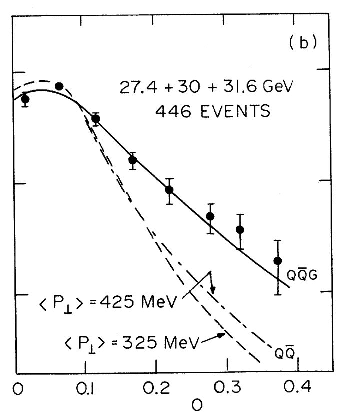
- **The era of high energy physics**
  - **Parton model for DIS – what happens to partons in the final state? In pair production . . .**

– **Answer: SLAC 1975: angular distribution for energy flow follows Born expression for spin-1/2 quarks** **(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)**



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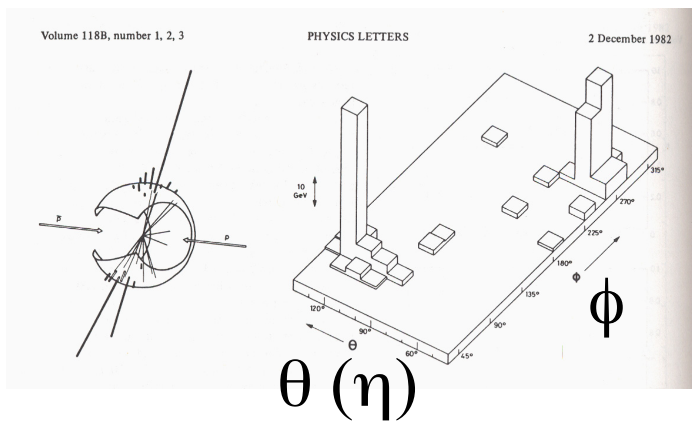
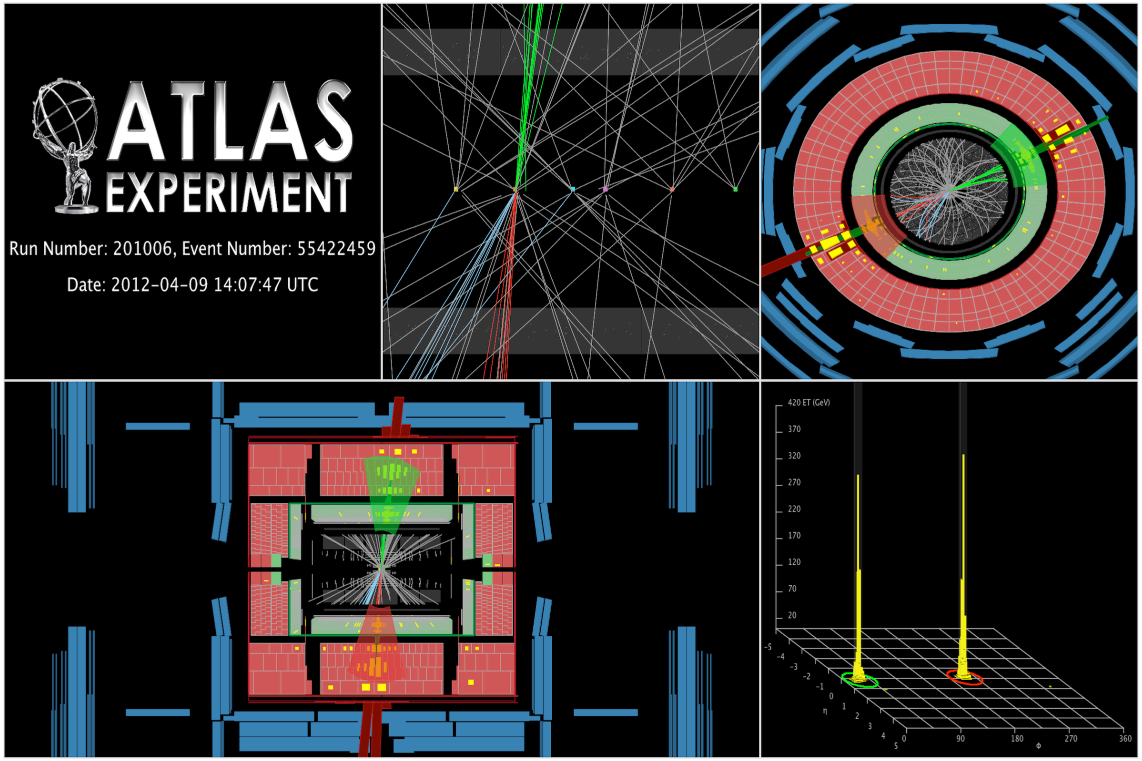
– 80's: Direct and indirect 'sightings' of scattered parton jets at Fermilab and the ISR, often in the context of single-particle spectra. Overall, however, an unsettled period until the SPS large angular coverage makes possible (UA1) 'lego plots' in terms of energy flow, and leads to the unequivocal 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 $\rightarrow$ 8, heading towards 14 GeV .**

One of the big guys . . .



3. What are Jets Good For?

For example: tests of the standard model. Quark compositeness tests of the "Rutherford-like" scattering of quarks by gluon exchange.

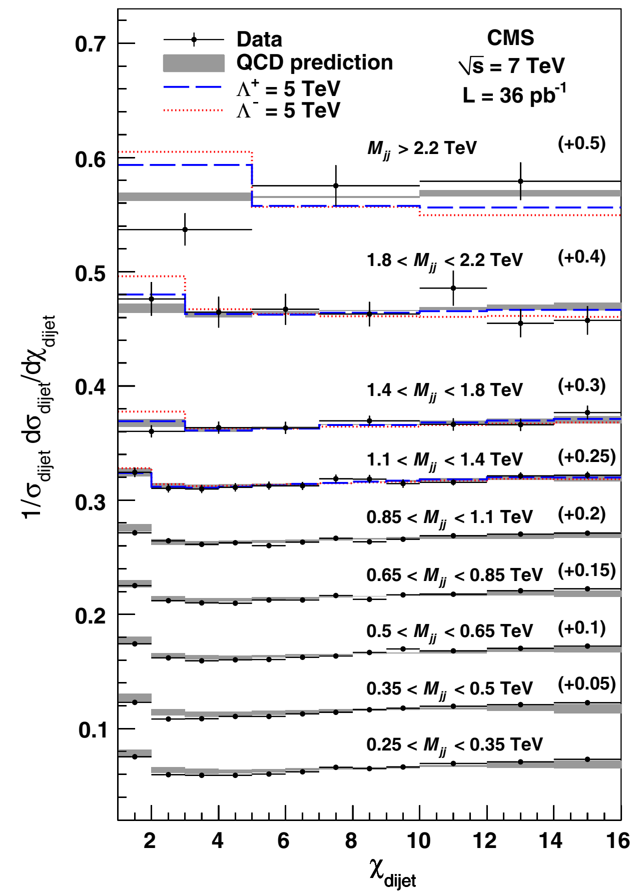
Measurement of Dijet Angular Distributions and Search for Quark Compositeness in pp Collisions at $\sqrt{s} = 7$ TeV

V. Khachatryan *et al.*[*]
(CMS Collaboration)

(Received 10 February 2011; published 18 May 2011)

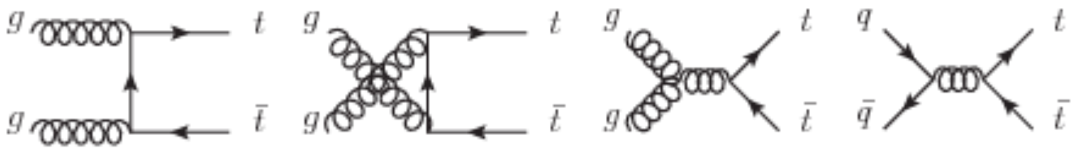
Dijet angular distributions are measured over a wide range of dijet invariant masses in pp collisions at $\sqrt{s} = 7$ TeV, at the CERN LHC. The event sample, recorded with the CMS detector, corresponds to an integrated luminosity of 36 pb^{-1}. The data are found to be in good agreement with the predictions of perturbative QCD, and yield no evidence of quark compositeness. With a modified frequentist approach, a lower limit on the contact interaction scale for left-handed quarks of $\Lambda^+ = 5.6$ TeV ($\Lambda^- = 6.7$ TeV) for destructive (constructive) interference is obtained at the 95% confidence level.

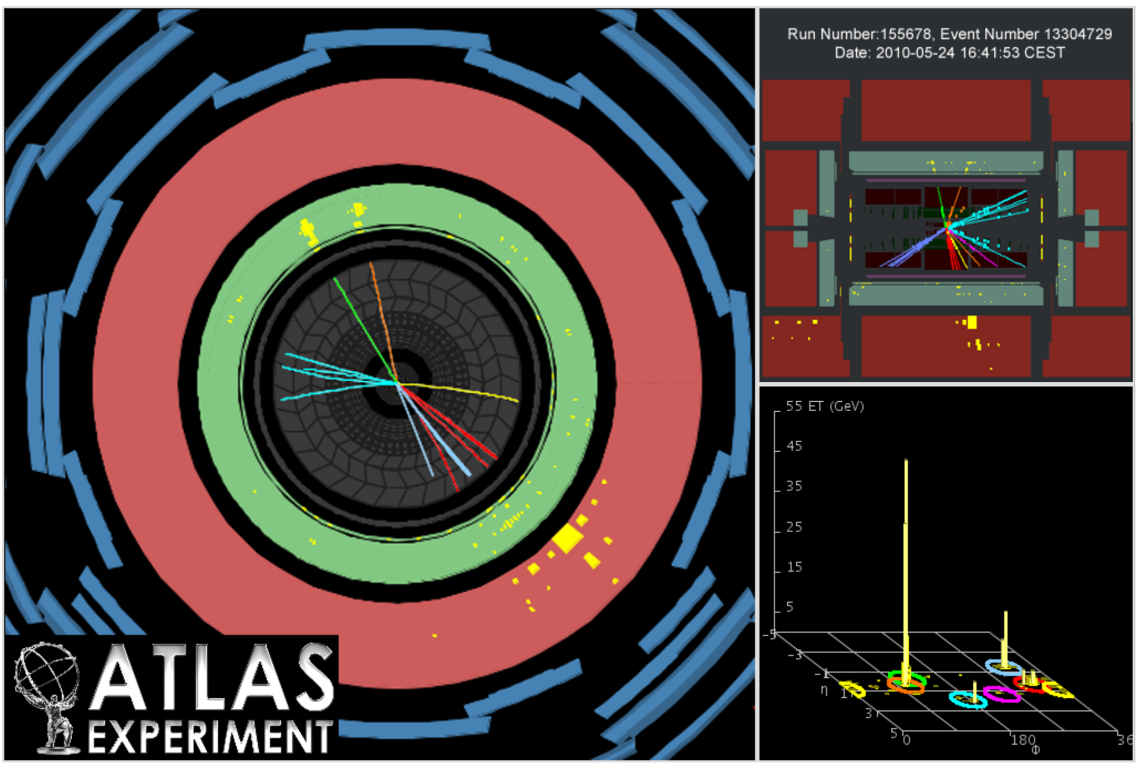
DOI: 10.1103/PhysRevLett.106.201804 PACS numbers: 13.85.Rm, 12.38.Bx, 12.38.Qk, 12.60.Rc



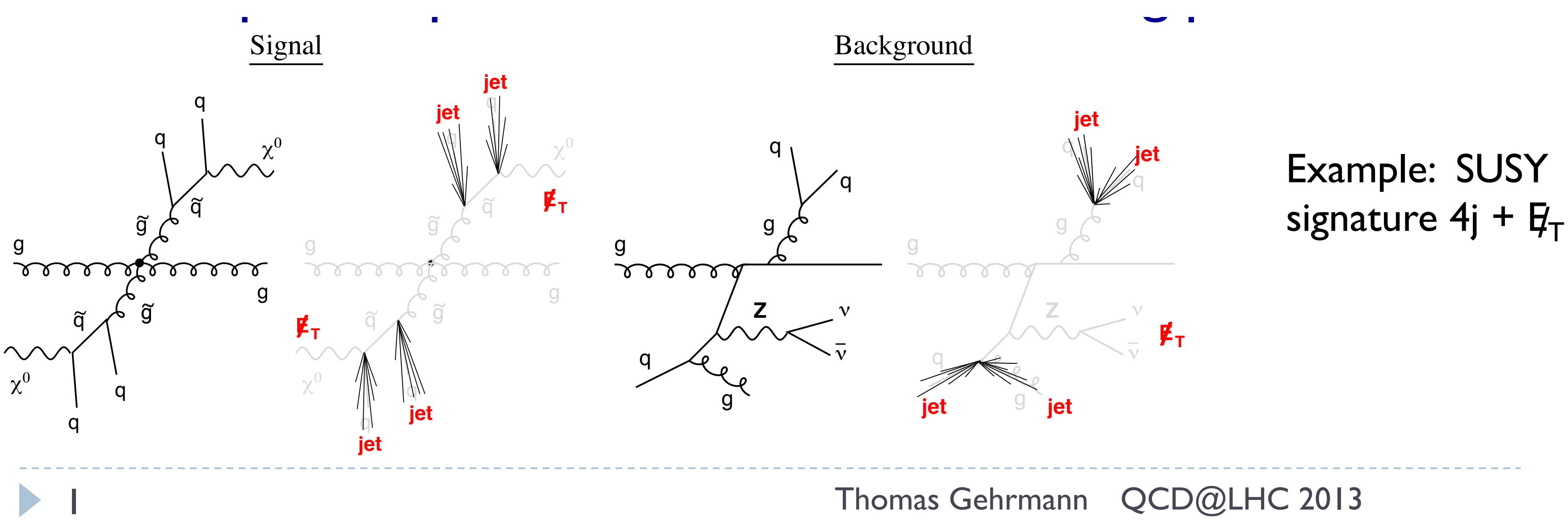
Observing the decay, and hence production of heavy particles

(from Schilling 1206,4484):





Backgrounds and signals. Here in supersymmetry searches



Jets appear whenever a short-lived state, whether QCD, electroweak, or new physics, decays to strongly-interacting matter.

4. Why and When Are There Jets?

- **Jet cross sections:**

$$d\sigma(a+b\to\{p_i\})/dQ$$

$$= \int dx_a dx_b \; H(x_a p_a, x_b p_b, Q)_{ab\to c_1\dots c_{N_{\rm jets}}+X}$$

$$\times f_{a/A}(x_a p_A)\, f_{b'/B}(x_b p_B)$$

$$\times d\left[\prod_{i=1}^{N_{\rm jets}} J_{c_i}(p_i)\; S_{a'b'\to c_1\dots c_{N_{\rm jets}}}(p_{\rm soft})\right]$$

- **Why this structure? In particular, why IR finite, factorized jets? And why are jets "autonomous", independent of the rest of the diagram? Let's address these in turn – partly with quantum mechanical, partly with classical reasoning.**

- **The Universality of Long-distance behavior:**

- **All perturbation theory follows from Schrödinger equation for mixing of (free particle) states,**

$$i\hbar \frac{\partial}{\partial t}|\psi(t) >= \left(H^{(0)} + V\right)|\psi(t) >$$

Usually with free-state "IN" boundary condition :

$$|\psi(t=-\infty) >= |m_0 >= |p_1^{\mathrm{IN}}, p_2^{\mathrm{IN}}\rangle$$

- **Notation :** $V_{ji} = \langle m_j|V|m_i\rangle$ **(vertices)**

- **Theories differ in their list of particles and their (hermitian)** V**s.**

- Solutions to the Schrödinger equation are sums of ordered time integrals. "Old-fashioned perturbation theory."

$$\langle m_n | m_0 \rangle = \sum_{\tau \text{ orders}} \int_{-\infty}^{\infty} d\tau_n \ldots \int_{-\infty}^{\tau_2} d\tau_1$$
$$\times \prod_{\text{loops } i} \int \frac{d^3\ell_i}{(2\pi)^3} \prod_{\text{lines } j} \frac{1}{2E_j} \times \prod_{\text{vertices } a} iV_{a \to a+1}$$
$$\times \exp\left[i \sum_{\text{states } m} \left(\sum_{j \text{ in } m} E(\vec{p}_j) \right) (\tau_m - \tau_{m-1}) \right]$$

- At vertex m, time τ_m, V switches state $m-1$ to state m, and in particle physics, each state is a collection of particles, all with "on-shell" energies, $E_j = \sqrt{\vec{P}_j^{\,2} + m_j^2}$.
- Time integrals extend to infinity, but usually oscillations damp them and answers are finite. Long-time, "infrared" divergences (logs) come about when phases vanish and the t integrals diverge.

- **When does this happen?** **Here's the phase:**

$$\exp\left[\, i \sum_{\text{states}\, m} \left(\sum_{j\,\text{in}\, m} E(\vec{p}_j) \right) (\tau_m - \tau_{m-1}) \right] =$$

$$\exp\left[\, i \sum_{\text{vertices}\, m} \left(\sum_{j\,\text{in}\, m} E(\vec{p}_j) \;-\; \sum_{j\,\text{in}\, m-1} E(\vec{p}_j) \right)\, \tau_m \right]$$

- **Divergences for $\tau_i \to \infty$ requires two things:**

i) (RHS) the phase must vanish $\leftrightarrow$ "degenerate states"

$$\sum_{j\,\in m} E(\vec{p}_j) = \sum_{j\,\in m+1} E(\vec{p}_j)\,, \quad \text{and}$$

ii) (LHS) it must also be stationary in loop momenta ℓ_i:

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

where the β_js are normal 4-velocities:

$$\beta_j = \pm\partial E_j / \partial \ell_i\,.$$

- **Condition of stationary phase:**

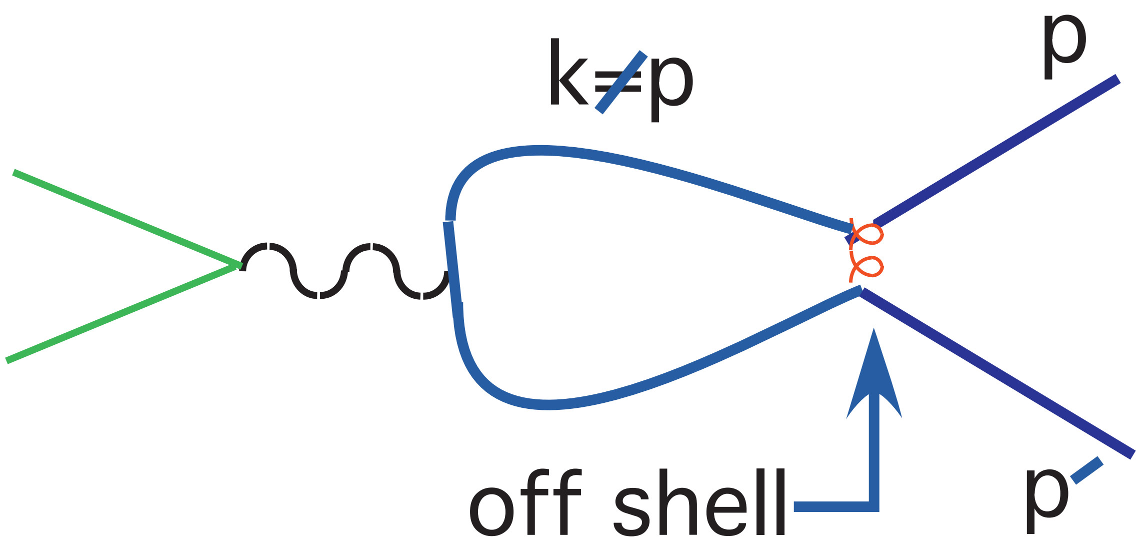
$$\sum_{\text{states } m} \sum_{j \text{ in } m} (\pm\beta_j^\mu)(\tau_{m+1} - \tau_m) = 0$$

- $\beta^\mu \Delta t = x^\mu$ **is a classical translation. For IR divergences, there must be free, classical propagation as $t \to \infty$!**

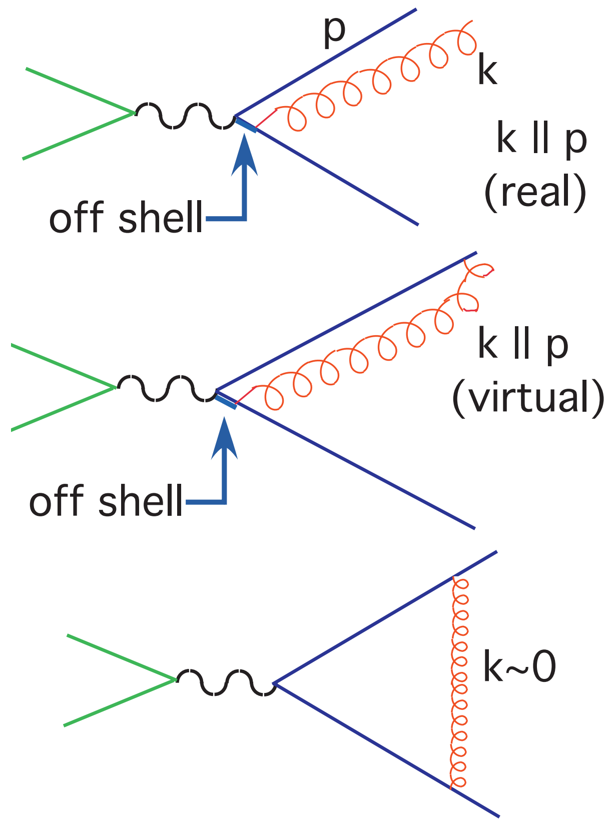
- **If all fast partons emerge from the same point in space-time, they can only rescatter with collinear partons. In essence, this is the answer to "when are there jets?" It requires strong localization in both amplitudes and their complex conjugates.**

- **Let's illustrate the role of classical propagation.**

- **Example: degenerate states that cannot give long-time divergences:**

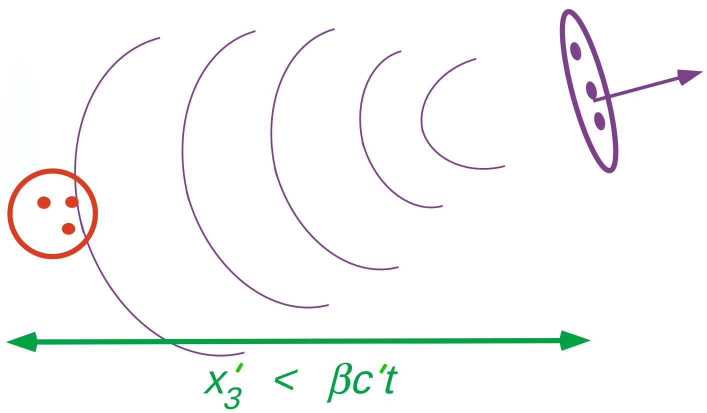


- **For particles emerging from a local scattering, (only) collinear (or soft) lines can give long-time behavior. Example:**



- **This generalizes to any order, and any field theory.**

- **The physical basis of autonomy for jets in gauge theories:** **classical field of a scattered source ("quark")**



$$\Delta \equiv x_3' - \beta c t'$$

x' frame **x frame**

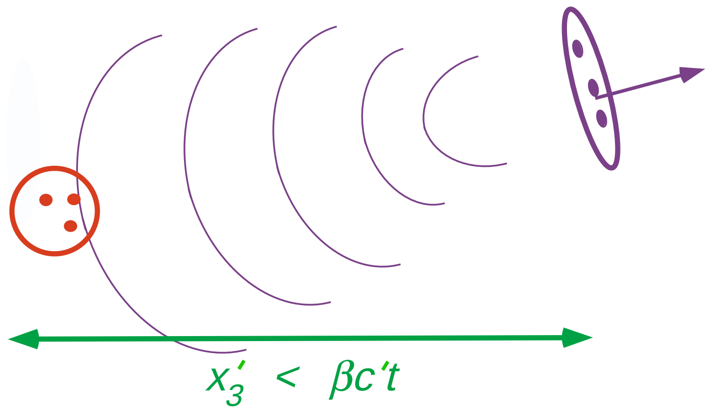
(everything else) **(jet)**

- **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.

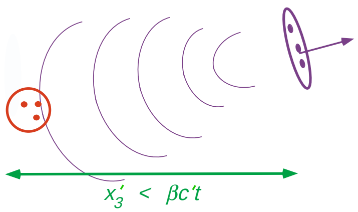


- **Let's say our quark moves in the x_3' direction (as seen by the recoiling system, "everything else").**

Coordinate Lorentz transformation to the rest frame of the quark:

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

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



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

- **The "gluon field" A^μ is uncontracted, but is mostly a total derivative as seen in the x' frame:**

$$A^\mu = q\frac{\partial}{\partial x'_\mu}\ \ln\left(\Delta(t', x_3')\right) + \mathcal{O}(1-\beta) \sim A^-$$

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

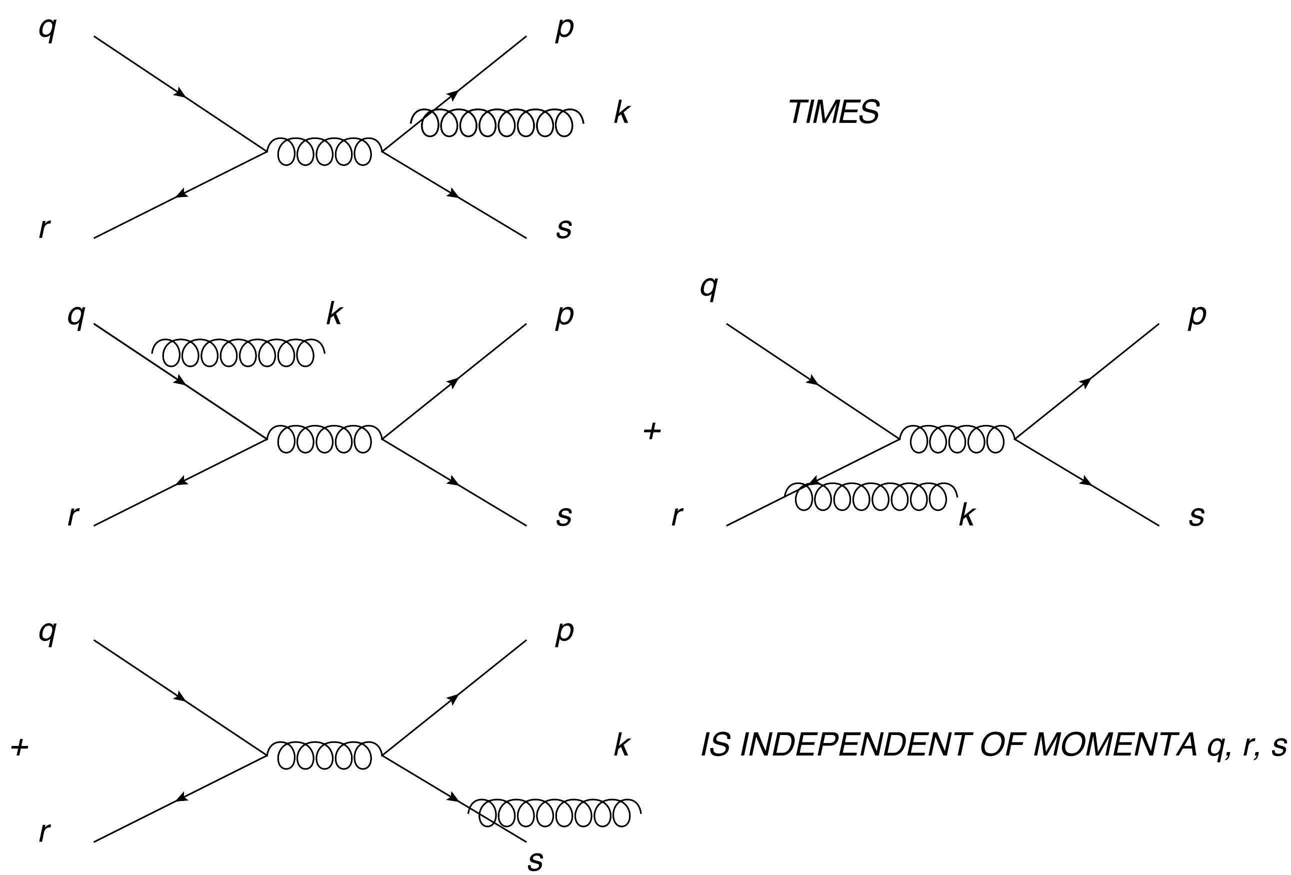
- The electric, $\vec{\mathrm{E}}$ field of the receeding particle is highly contracted, and does not overlap with the recoiling system once the source leaves the vicinity.

- The residual "drag" forces 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 "jet autonomy", i.e. factorization.

- **How it works in the QCD: for k collinear to p, with q, r and s the rest of the collision system, all diagrams contribute, but:**



- **Thus, gauge invariance is the key to the factorization of jets in QCD. The jet only knows the rest of the world as a source of unphysically-polarized gluons.**

5. Infrared Safety, Energy Flow and the Classical-Quantum Connection

- Pause and reflect: amplitudes for the production of parallel-moving particles are greatly enhanced. Each such set is a jet.
- Massless lines can split, so the number of particles in the jet is indefinite, and the amplitudes are truly divergent.
- For massive lines, once $m \ll E$, amplitudes are enhanced, if not divergent.
- But how to get predictions from divergent amplitudes? And anyway, in QCD, $t \to \infty$ surely invalidates perturbation theory.
- We want to use the jets, because that's where the action is, but we can't follow them to infinity, and that's the problem.
- We want to strike a balance, and here's the analogy that comes to our rescue.

- **QED: exclusive cross sections typically have "infrared divergent" corrections**

$$\delta\sigma_{\mathrm{ee}\to\mathrm{ee}}\left(Q, m_e, m_\gamma = 0, \alpha_{\mathrm{EM}}\right) \sim \alpha_{\mathrm{EM}}\, \beta_{AB}(Q/m_e)\, \ln \frac{m_\gamma}{Q}$$

- **Energy resolution ϵQ (Bloch-Nordsieck)**
  $\to$ IR finiteness (sum over $E_\gamma \leq \epsilon Q$)

$$\delta\overline{\sigma}_{\mathrm{ee}\to\mathrm{ee}+X(\epsilon)}\left(Q, m_e, \epsilon Q, \alpha_{\mathrm{EM}}\right) \sim \alpha_{\mathrm{EM}}\, \beta_{AB}(Q/m_e)\, \ln \epsilon$$

- **Correction is small if $\alpha_{\mathrm{EM}} \ln(1/\epsilon)$ is small**

- **Impossibility of observing arbitrarily soft γ**
  $\leftrightarrow$ **radiation of accelerated charges in the classical limit**

- **Could something like this happen:**

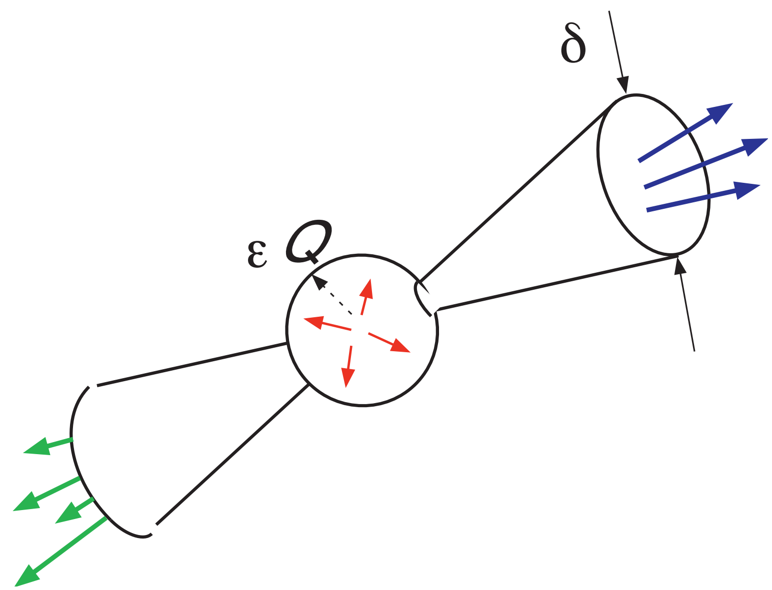
  - **for QED with $m_e = 0$?**

  - **for QCD with $m_q = 0$?**

  - **Can we find observables that have no factors $\ln(m/Q)$, only at worst $(m/Q)\ln(m/Q)$?**

– ϵ not enough ... but an extra *angular* resolution works

– Impossibility of resolving collinear massless particles



- Now trade high-energy for zero-mass limit

- Perfect for QCD: asymptotic freedom $\rightarrow$ $\alpha_s(Q)$ decreases with Q, but it works in any theory, including electroweak at very high energies $\gg M_W$, M_Z.

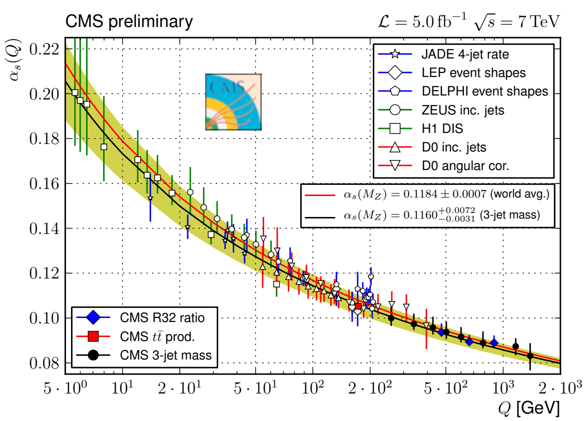
- New class of observables: Jet Cross sections

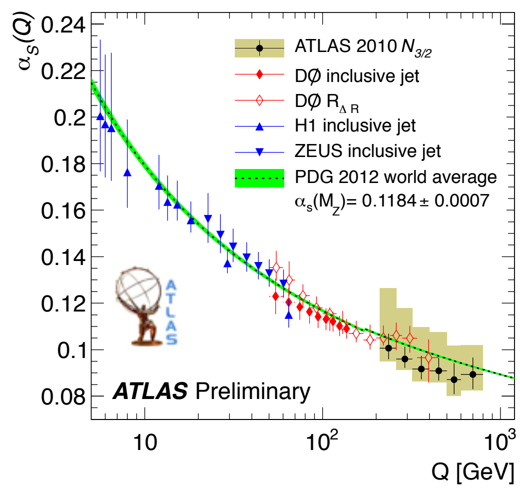
$$\sigma\left(Q/\mu, \alpha_s(\mu)\right) = \sigma\left(1, \alpha_s(Q)\right)$$

- **Determination of α_s from an infrared safe cross section**

$$\hat{\sigma}(\alpha_s) = \sum_{n=0}^{n_{\max}} C_n(\mu)\alpha_s^n(\mu) + \Delta \;\rightarrow$$
$$\alpha_s(\mu) = f(\sigma(\mu), C_n(\mu), \Delta)$$

- **And here's what it looks like now:**





(K. Kousouris , QCD@LHC 2013)

- **Freedom from arbitrarily long-time dependence is called Infrared safety**

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

- **Any observable based on the flow of energy is infrared safe since it is unaffected by collinear rearrangements and soft radiation.**

- **Energy flow has a long history in gauge theory:**

ON THE TRANSFER OF ENERGY IN THE ELECTROMAGNETIC FIELD.

[*Phil. Trans.* **175**, 1884, pp. 343–361.]

[*Received* December 17, 1883. *Read* January 10, 1884.]

A space containing electric currents may be regarded as a field where energy is transformed at certain points into the electric and magnetic kinds by means of batteries, dynamos, thermoelectric actions, and so on, while in other parts of the field this energy is again transformed into heat, work done by electromagnetic forces, or any form of energy yielded by currents.

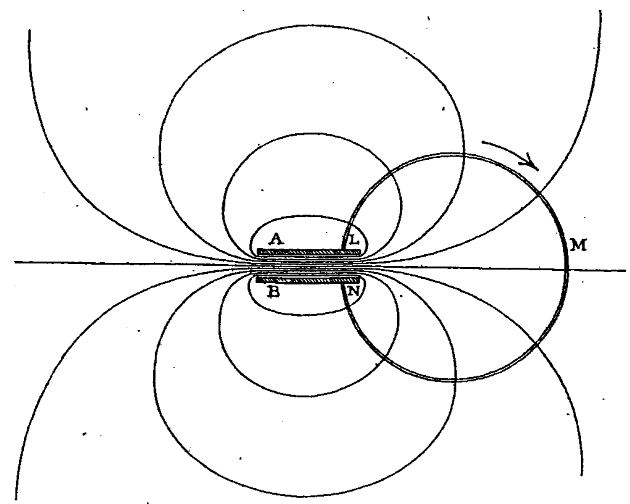
On interpreting the expression it is found that it implies that the energy flows as stated before, that is, perpendicularly to the plane containing the lines of electric and magnetic force, that the amount crossing unit area per second of this plane is equal to the product

$$\frac{\text{electromotive intensity} \times \text{magnetic intensity} \times \text{sine included angle}}{4\pi},$$

while the direction of flow is given by the three quantities, electromotive intensity, magnetic intensity, flow of energy, being in right-handed order.

(2) *Discharge of a condenser through a wire.*

We shall first consider the case of the slow discharge of a simple condenser consisting of two charged parallel plates when connected by a wire of very great resistance, as in this case we can form an approximate idea of the actual path of the energy.



- **Radiation from the discharge of a condenser: the Drell-Yan process of its day.**

- **Lowest order QCD and QED quantum bremsstrahlung share the same angular and frequency distribution as classica l radiation**

$$\frac{d\sigma}{d\omega d\cos\theta} \propto \frac{1}{\omega}\frac{1}{1-\cos^2\theta}$$

- **At lowest order, QCD "subjets" will follow this essentially classical distribution. Between jets, the analog needs an examination of the "soft" function, "S", sensitive to color coherence.**

6. Finding Jets, Boosting Jets and the Electroweak Content

- Most recent analyses use IR safe clustering algorithms to identify jets. They go like this . . .
  - Starts with measurements in calorimeter "towers" p_i
  - For each precluster i in the list, define (relative to beams)

$$d_i = p_{T,i}^{2a} \qquad 1 \geq a \geq -1\,.$$

$$a = 1 \text{ ``}k_T\text{''}\,,\ a = 0 \text{ ``}CA\text{''}\,,\ a = -1 \text{ ``anti}-k_T\text{''}$$

  - For each pair (i, j) of preclusters $(i \neq j)$, define

$$d_{ij} = \min\left(p_{T,i}^{2a}, p_{T,j}^{2a}\right) \frac{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}{R^2}$$

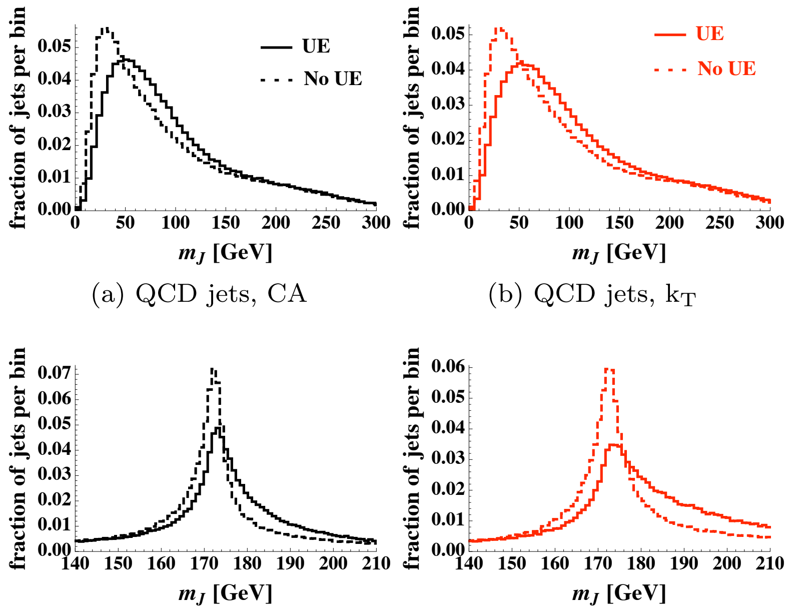
  - Find $d_{\min}$ among all d_i, d_{ij}
  - if $d_{\min}$ is a d_i: identify as "jet"
  - if $d_{\min}$ is a d_{ij}: combine into new precluster $p_{ij} = p_i + p_j$
  - Repeat (leaving out "jets")
  - End result: list of "jets" (most with small d_i)

- **In fact, the jets found in this way need not be the products of a single quark or gluon emerging from a short-distance scattering.**

- **This is the essence of quantum mechanical nature of particle scattering. Saying a jet comes from a scattered gluon or quark is always a "best description" corresponding to a most likely quantum history. Corrections due to coherent quantum histories are higher orders in α_s, and those due to incoherent histories generally decrease as powers of $p_{\rm jet}$.**

- **In fact, the energy deposited in any region of the detector will rarely be from only one source. For example . . .**

- **They may be “contaminated” by “random” radiation from a single hadronic collision (“underlying event”), via multiple parton scatterings.**



(a) QCD jets, CA

(b) QCD jets, k_T

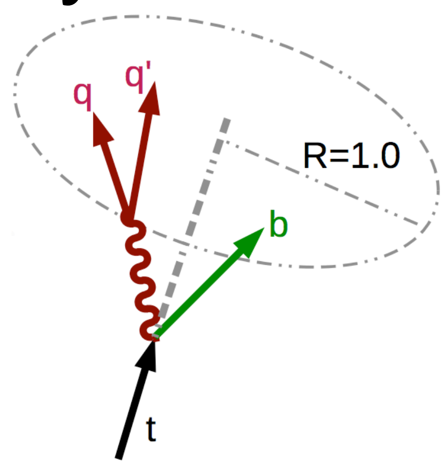
(c) top jets, CA

(d) top jets, k_T

FIG. 21: Distribution in m_J with and without underlying event for QCD and top jets, using the CA and k_T algorithms. The jets have p_T between 500 and 700 GeV, and D = 1.0. The samples are described further in Appendix A.

(S.D. Ellis, J.K. Vermillian, J. Walsh, 0912.003)

- **They may be "diluted" by radiation from totally separate collisions ("pile-up"). For a high-luminosity LHC this will become even more of a problem.**
- **They may also not be made of radiation at all in the usual sense – they may be the decay products of a heavy, but highly boosted particle – a top quark, for example, but perhaps a new particle, or highly boosted Standard Model particles from the decay of a very heavy resonance.**



Event with a fully-contained top jet:

(C. Pollard, talk at "Boost 2013")

- Using the "clustering history", we may be able to distinguish decays from QCD (and from each other).

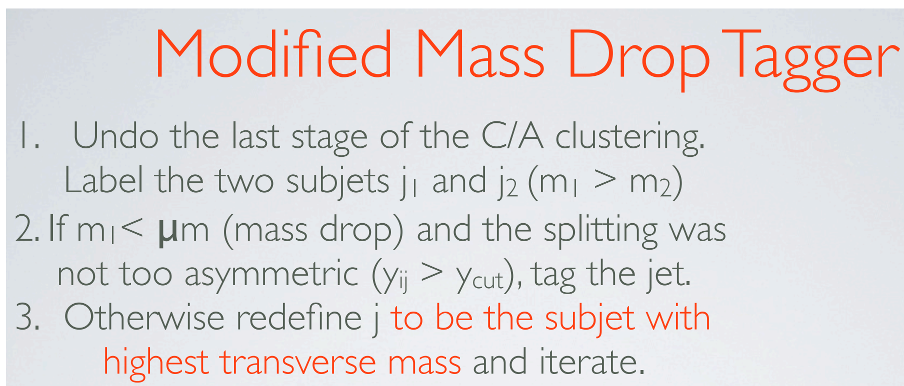
- Beyond decays, comparing E and θ-dependence from a source at low angles
QCD bremsstrahlung:

$$\frac{d\sigma(E,\theta)}{dE d\theta} = C\,\frac{1}{E\theta}$$

- with other source that are independent might look like:

$$\frac{d\sigma(E,R)}{dE d\theta} \sim C'\,\frac{e^{E/E_0}}{E}$$

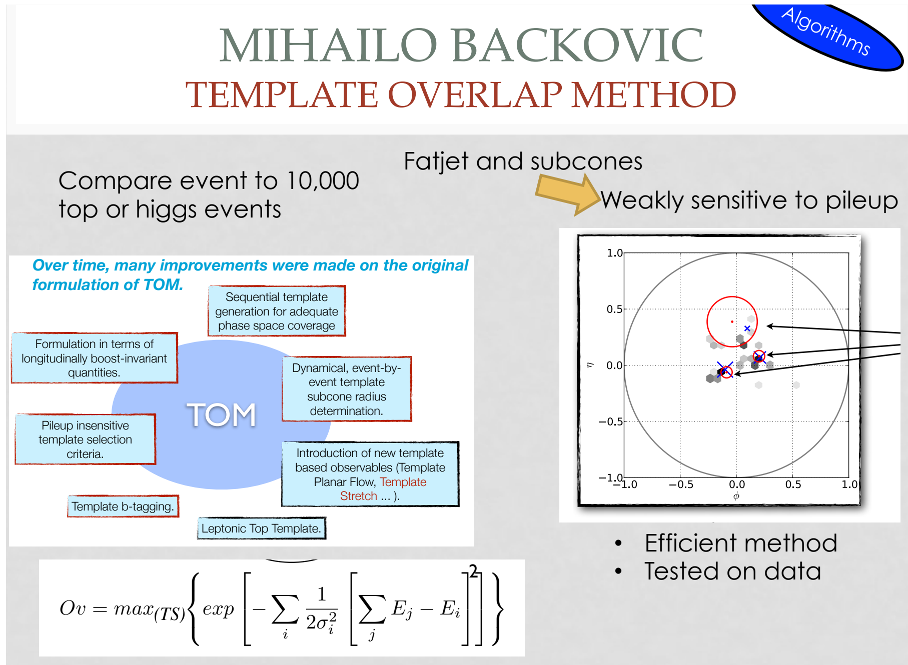
- Can optimize bremsstrahlung at the expense of incoherent radiation by a judicious choice of R.
- All of this depends on the relative incoherence of the radiation we wish to discard.
- More generally, recent work has concentrated on these possibilities, leading to a new generation of jet analysis tools.
- Much work devoted to taking jets apart: “mass drop”,



(Marzanni, talk at “Boost 2013”)

- The “modification” here reflects a field in dynamic progress.

- **One can also look for matching to "templates" based on a top (or other) hypothesis:**



(M. Schwartz summary talk at Boost 2013)

- **and “pruning” (roughly, removing soft radiation to suppress QCD background) and “trimming” (roughly, removing uncorrelated radiation to reveal the interesting part)**

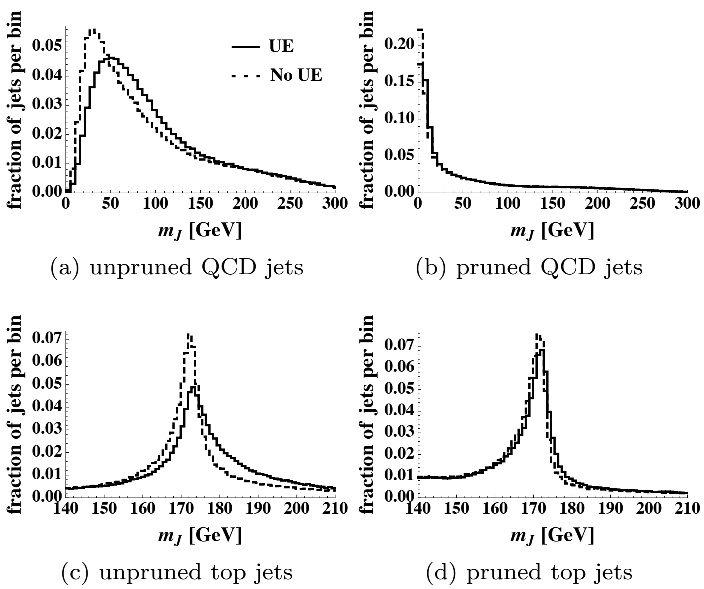


FIG. 25: Distributions in m_J with and without underlying event, for QCD and top jets, using the CA algorithm, with and without pruning. The jets have p_T between 500 and 700 GeV, and D = 1.0.

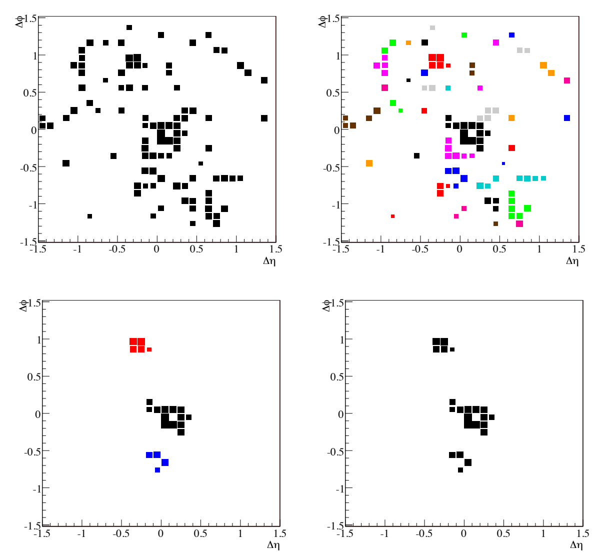


Figure 5: Step by step illustration of the jet trimming procedure. Proceeding from left to right, top to bottom, we show a jet as initially clustered (using anti-k_T with $R_0 = 1.5$), the constituent k_T subjets with $R_{\text{sub}} = 0.2$, the subjets surviving the $p_{Ti} < f_{\text{cut}} \cdot p_T$ cut (where $f_{\text{cut}} = 0.03$), and the final trimmed jet. To make the figure easier to read, the area of each cell is proportional to the log of the cell's p_T.

(S.D. Ellis, J.K. Vermillian, J. Walsh, 0912.0033)

(D. Krohn, J. Thaler, L.T. Wang 0912.1342)

- **At very high energy, they may include, or even result from, radiation with massive quanta, such as W and Z bosons. Indeed, the size of electroweak corrections is approaching tens of percent for some cross sections. These are generally negative, suggesting they will be compensated in part by electroweak radiation at comparable rates. For very high energy they might even be part of virtual "jets."**

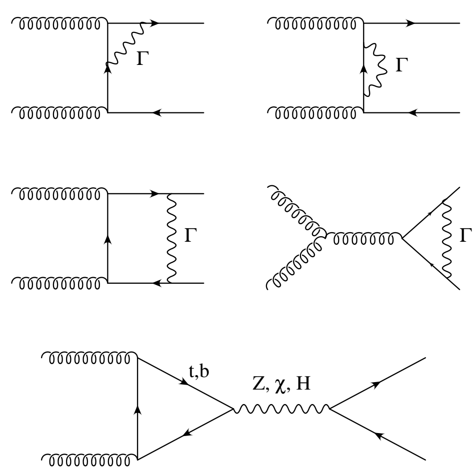


Figure 3: Sample diagrams for the virtual corrections. Γ stands for all contributions from gauge boson, Goldstone boson and Higgs exchange.

(J.H. Kühn, A. Scharf, P. Uwer 1305.5773)

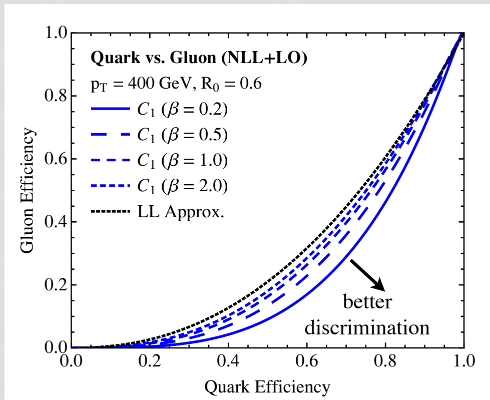
- **Aims also include separation (statistical) of quark and gluon jets, and real progress has been made, for instance . . .**

Introduce n-point correlation functions

$$\mathrm{ECF}(2,\beta) = \sum_{i<j\in J} p_{Ti}\, p_{Tj} (R_{ij})^{\beta}$$

$$\mathrm{ECF}(3,\beta) = \sum_{i<j<k\in J} p_{Ti}\, p_{Tj}\, p_{Tk} \left(R_{ij} R_{ik} R_{jk}\right)^{\beta}$$

Analytic calculations imply smaller β is better
For quark/gluon discrimination



(A. Larkoski, talk at Boost 2013

In summary:

- Jets are messengers of quantum fluctuations at short distances, capable of bridging the twenty orders of magnitude between the shortest distances probed at the LHC and the size of its detectors.
- Their presence reflects universal behavior in perturbative quantum processes.
- They are integral to high energy QCD, but are not restricted to it.
- They carry information not only in their energies and directions, but also in their internal structure, about which we still have much to learn.