QCD HISTORIES

With a few personal perspectives

Philadelphia
April 6, 2003

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YITP, Stony Brook

- **The Context of QCD**
- **Quantum Chromodynamics**
- **How to Study a Theory with Confinement?**
- **Jets from QCD**
- **Factorization**
- **High Energy QCD Today**

Thanks to the APS

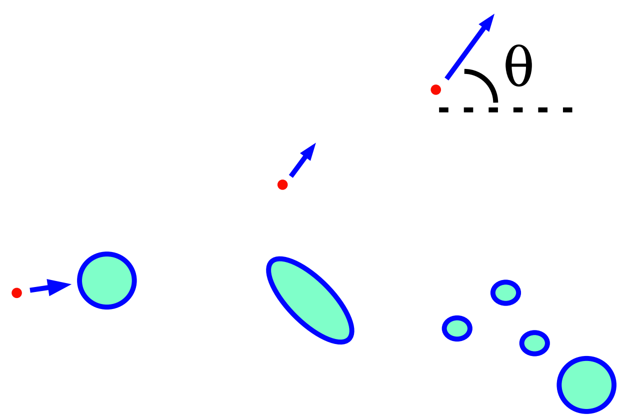
Congratulations to Al

THE CONTEXT OF QCD

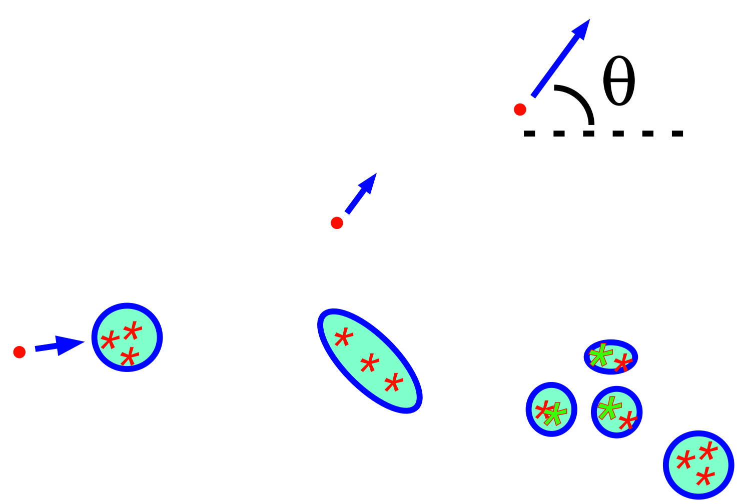
- **From** $p,\ n \Rightarrow$

  p n N(1440) N(1520) N(1535) N(1650) N(1675) N(1680) N(1700) N(1710) N(1720) N(1900) N(1990) N(2000) N(2080) N(2090) N(2100) N(2190) N(2200) N(2220) N(2250) N(2600) N(2700) N(3000 Region) Δ(1232) Δ(1600) Δ(1620) Δ(1700) Δ(1750) Δ(1900) Δ(1905) Δ(1910) Δ(1920) Δ(1930) Δ(1940) Δ(1950) Δ(2000) Δ(2150) Δ(2200) Δ(2300) Δ(2350) Δ(2390) Δ(2400) Δ(2420) Δ(2750) Δ(2950) Δ(3000 Region)

- **Composite yet irreducible? bootstrap → strings**



- **Composites of indivisibles? quark model**



- **Yet are the ⋆⋆'s "real"? Confinement**

- **Shadow of QED . . .**

$$\frac{g_e - 2}{2} = 1159.6521869 \pm 0.0000041 \times 10^{-6}$$

- **Nature makes its choice:**

  – **current algebra: $\star\star$'s provide currents**
  Yang & Mills:

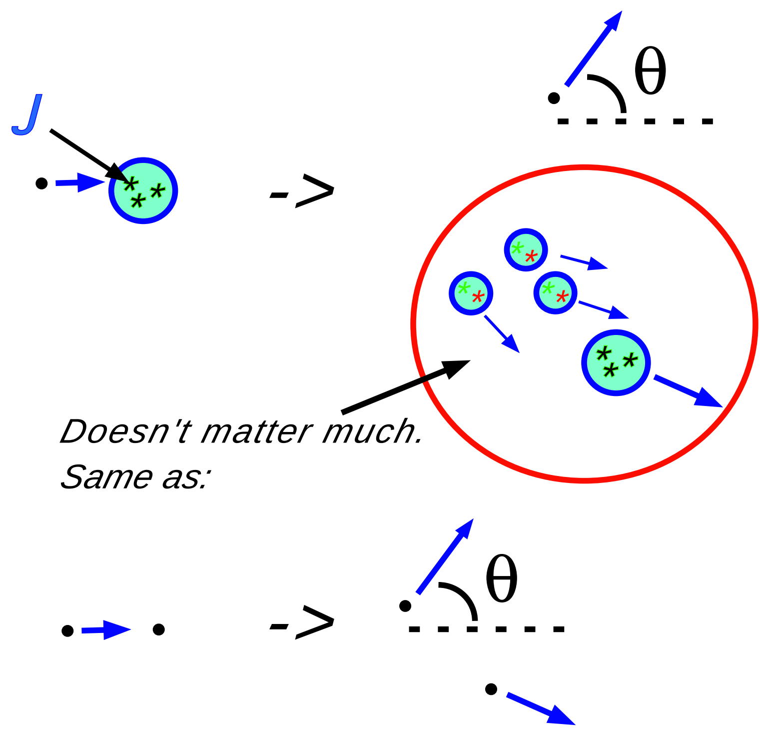
  currents $\rightarrow$ vector fields $\rightarrow$ forces

  "This is a very profound idea, perhaps the most profound idea in theoretical physics since the invention of Dirac theory."
  – J.J. Sakurai, Ann. Phys. 11, 1 (1960)

  – **dipole-like form factors:**
  $\star\star$ small & strongly coupled

- **Surprise: scaling in deep inelastic scattering**

  ep inelastic scattering **Electron sees ⋆⋆'s as spin-1/2 point particles**



- **The "strong" force seems weak,**
  almost irrelevant to the electron that scatters
- **The "quark-parton" model**
  - **Ignore ⋆⋆ interactions**
  - $\sigma = \sigma_{\mathrm{EM}} \times$ **(probability to a find parton)**

Progress with Correlations

- **pre-1975 inclusive analysis in field theory**
  - **EM Current (J) correlators**
  - **For any field theory with coupling $\alpha_s(\mu)$**

- **Deep-inelastic ep scattering, energy transfer $E = x(Q^2/2m_p)$, momentum transfer Q:**

$$\int dx\ x^{N-1}\sigma_{\rm ep}(x,Q) \sim \int dx\ x^{N-1}\ \langle p|J(Q)\ J(-Q)|p\rangle$$

$$= C_N(Q^2/\mu,\alpha_s(\mu))\ \langle p|O_N(0)|p\rangle_\mu$$

  - $O_N(0)$**: local operators**
  - μ**: scale of the coupling**
  - **Wilson, Brandt-Preparata, Frishman, Christ-Hasslacher-Mueller**

- **Evolution:**

$$\frac{d}{d\mu}\sigma_{\rm ep}(x,Q) = 0$$

  implies

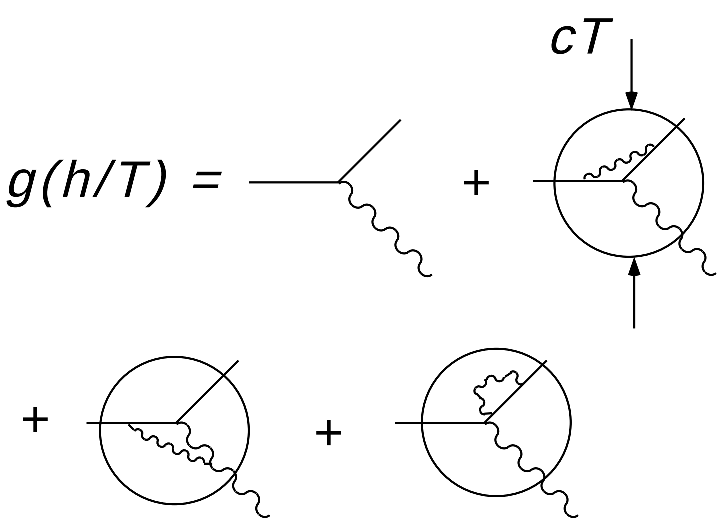
$$Q\frac{d}{dQ}\ \ln C_N(Q^2/\mu,\alpha_s(Q)) = \gamma^{(1)}\,\alpha_s(\mu) + \dots$$

- **Quantified the paradox: scaling $\to \alpha_s(Q)$ small, strong interactions "weak" in DIS**

QUANTUM CHROMODYNAMICS

$$\mathcal{L} = \sum_q \bar{q}\,(i\partial\!\!\!/ - gA\!\!\!/ + m_q\,)\,q - \frac{1}{4}\,F^2_{\mu\nu}[A]$$

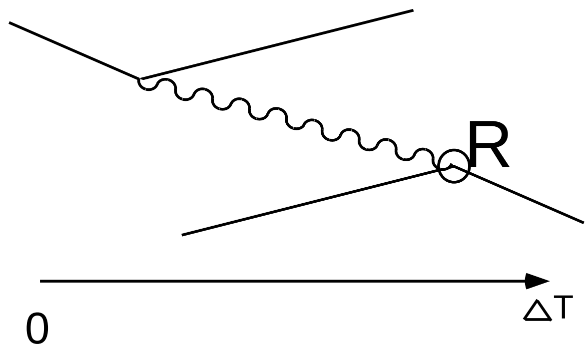
- **The Y-M theory of quarks (q) and gluons (A)**
- **Just the right sets of currents**
- **Just the right kind of forces:**
- **Compute the T (time) -dependence of:**

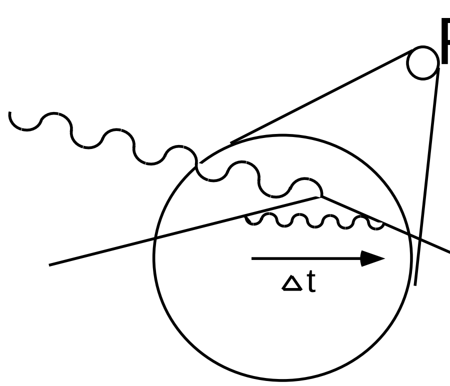


$$\alpha_s(Q) = 4\pi/b_0 \ln(Q^2/\Lambda^2_{\rm QCD})$$

- **Asymptotic freedom → scaling**
- **Gross-Wilczek, Politzer (1972)**
  - **Near a ⋆ (quark), force is weak**
- **Infrared strong coupling → quark confinement?**
  - **Far from a ⋆, force is strong**

- By the time a struck $\star$ gets far enough to feel a strong force, the electron is long gone. Then, $\star$'s reassemble into hadrons
- **1977: A physical picture for evolution**





- **Dokshitzer, Gribov-Lipatov, Altarelli-Parisi**
- **Asymptotic freedom is a big deal:**

$$\frac{\text{Asymptotic Freedom}}{\text{QCD}} = \frac{\text{Elliptical Orbits}}{\text{Newtonian Gravity}}$$

- **A beginning, not an end. For Newtonian gravity, the three-body problem. For QCD . . .**

HOW TO STUDY A THEORY WITH CONFINEMENT?

- **The goal**

$$\frac{\text{Nuclear Physics}}{\text{QCD}} = \frac{\text{Chemistry}}{\text{QED}}$$

- **But can we study the particles that**
  - **Give the currents (quarks)?**
  - **Give the forces (gluons)?**
  - **Expand in number of gluons?**
    Perturbation Theory
- **In QCD they're confined:**
  observed hadrons are bound states
- **Bound-state scattering:**
  Complexity & strong forces
- **Does this make sense at all?**
- **More analogies: atoms before observation of radioactivity & molecules before the explanation of Brownian motion**

Learning to calculate with the new theory

Correlation functions *vs.* the S-matrix

- **Correlation functions at short distances: PT-friendly**

$$\langle 0|J(x)\ J(0)|0\rangle = C\left(x\mu, \alpha_s(\mu)\right) = C\left(1, \alpha_s(x)\right)$$

  – e^+e^- **annihilation cross section, inclusive DIS**

- **The S-matrix, even at high energy: pretty hopeless in PT**

$$\langle B\ \text{out}|A\ \text{in}\rangle = f\left(Q/\mu, m/\mu, \alpha_s(\mu)\right) = f\left(1, m/Q, \alpha_s(Q)\right) = f\left(Q/m, 1, \alpha_s(m)\right)$$

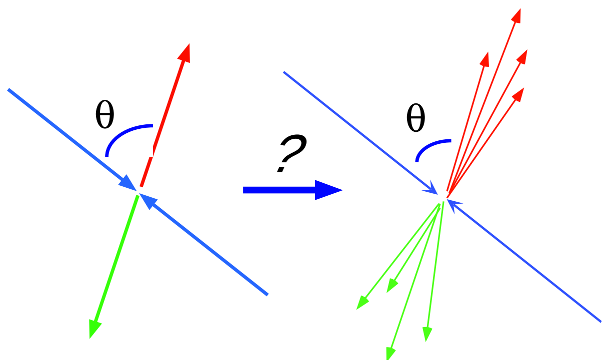
  – m – **mass scales:** m_π, m_p, m_q, $m_G = 0$ **. . .**

  – **Still, it's only the** *ratio* m/Q **that causes the problem**

- **Were we doomed to compute only correlations of currents?**
- **Were we *forbidden* to look inside the final state?**
- **Or, could it be possible to "see" quarks and gluons?**

Structure of final states: Cosmic rays to quark pairs

- **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)
  - **". . . We now come back to the subject of nucleon-nucleon interactions to discuss the distribution of pions in high energy jets."**
    – J.J. Sakurai, op. cit.
  - **Limited transverse momentum in secondaries of hadron collisions**
  - **What about quarks produced in e^+e^- annihilation?**



- **Extension of the parton model: q/e scattering to $\mathrm{e^+e^-} \rightarrow \mathrm{q\bar{q}}$. Conjecture p_T-cutoff.**
  - **A *prediction* for the angular distribution:** $1 + \cos^2\theta$
  - **"Because of our cutoff $k_{\rm max} \ll |q|$ . . . The distribution of secondaries in the colliding ring frame will look like two jets . . . "**
    – S.D. Drell, D.J. Levy and T.-M. Yan, Phys. Rev. D1
  - ***Here* was a question to ask of QCD. Would the final state look like this?**
  - **It did:**
    – G. Hansen et al, Phys. Rev. Lett. 35, 1609 (1975)

JETS FROM QCD

- **How I came to study e^+e^- final states**
  - **Thesis in the echos of the old and stirrings of the new:**
  - **complex analysis of scattering amplitudes (A. Dragt)**
  - **perturbative form factors in a Yukawa model (J. Sucher and C.H. Woo)**

- **Discussions at Urbana with S.J. Chang, J. Sullivan**

- **At the time of the J/Ψ ...**

- **Could $\sigma^{tot}_{e^+e^-}$ increase with Q? (No)**

- **Out of which came ...**

An abstract question; an abstract answer

- **QED: exclusive cross sections typically infrared divergent**

$$\sigma_{AB}\,(Q, m_e, m_\gamma = 0, \alpha_{\rm EM}) \sim \alpha_{\rm EM}\, \beta_{AB}(Q/m_e)\, \ln \frac{m_\gamma}{Q}$$

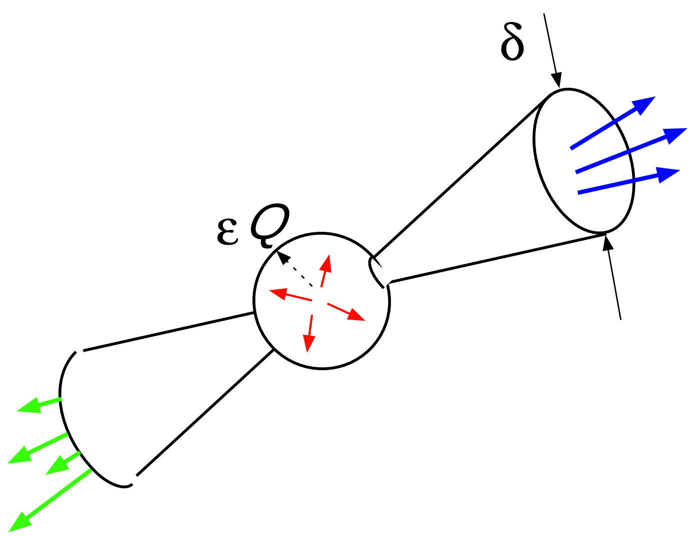
- **Energy resolution ϵQ (Bloch-Nordsieck) $\rightarrow$ IR finiteness (sum over $E_\gamma \le \epsilon Q$)**

$$\overline{\sigma}_{AB}\,(Q, m_e, \epsilon Q, \alpha_{\rm EM}) \sim \alpha_{\rm EM}\, \beta_{AB}(Q/m_e)\, \ln \frac{1}{\epsilon}$$

- **Impossibility of observing arbitrarily soft γ**

- **Could something like this happen:**
  - **For QED with $m_e = 0$?**
  - **For QCD with $m_q = 0$?**
  - **Kinoshita, Lee-Nauenberg**

- **It turns out that:**
  - ϵ **not enough . . .**
    but an extra *angular* resolution works
  - **Impossibility of resolving collinear massless particles**



- **No large ratios Q/m Infrared Safety**
- **Trade high-energy for zero-mass limit**
- **Perfect for QCD:**
  asymptotic freedom $\rightarrow \alpha_s(Q)$ decreases with Q
- **New class of observables: Jet Cross sections**

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

- **No need for a transverse momentum cutoff**
  - **IR finiteness $\rightarrow$ high-p_T suppressed by $\alpha_s(p_T)$**

- **How to identify Jet-like Cross Sections?**
- **"We define two states [to be] "jet-related" if they differ by the emission or absorption of a number of zero energy particles, or by the transformation of one set of parallel moving particles into another . . ."**
  - **GS ILL-(Th)-75-32 (preprint)**

- **How this idea become known . . . thanks to Jim Carrazone, Tom Appelquist, Joe Sucher, Tom Kinoshita, and its independent inventor, Steven Weinberg**
- **GS and S. Weinberg, Phys. Rev. Lett. 1977**
  - **Zero-mass limit as a diagonistic for pertubative calculability**

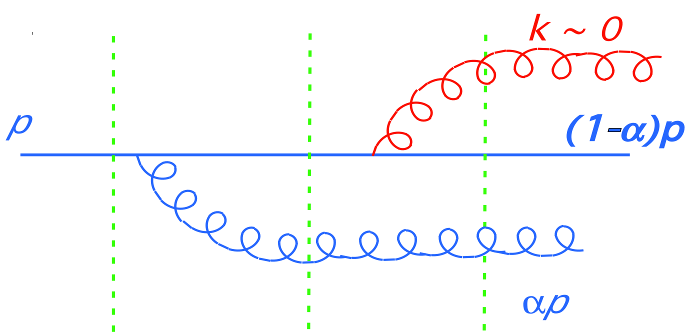
- **Jet cross sections; event shapes; jet calculus, jets in decay, gluon jets . . .**

What is Infrared Safety?

- Infrared Safety: "quantities . . . predictable. . . if: (a) they are finite in QCD perturbation theory and the perturbation series is sufficiently convergent, and (b) non-perturbative effects are not obviously dominant."
  - A. de Rújula, J. Ellis, E.G. Florates and M.K. Gaillard, Nucl. Phys. B138 (1978) 387
- Update as:
  QCD perturbation theory gives self-consistent predictions for a quantity C when C:
  - is dominated by short-distance dynamics in the infrared-regulated theory;
  - remains finite when the regulation is taken away.
- Parton-hadron duality: supplement by identification of parton & hadron multiplicities
  - Dokshitzer,Dyakanov,Khoze,Mueller,Troyan 1977 . . .

General Viewpoints

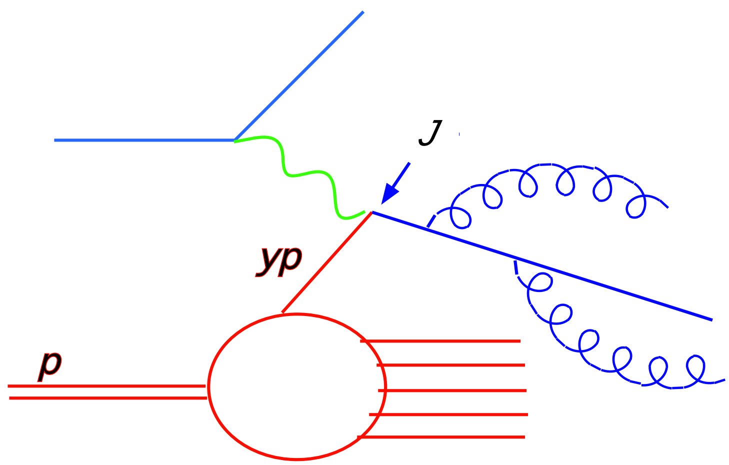
- Long distance behavior
  $\leftrightarrow$ free propagation in massless theory
- Jet substructure is long-distance dominated because particles can propagate freely between interactions



- Sum over states $\rightarrow$ total jet probability
- Short-distance dominated

FACTORIZATION

- **Generalize to incoming hadrons (as for cosmic rays)**
- **In DIS: "conditional" jet – supplies quark with momentum fraction y:**

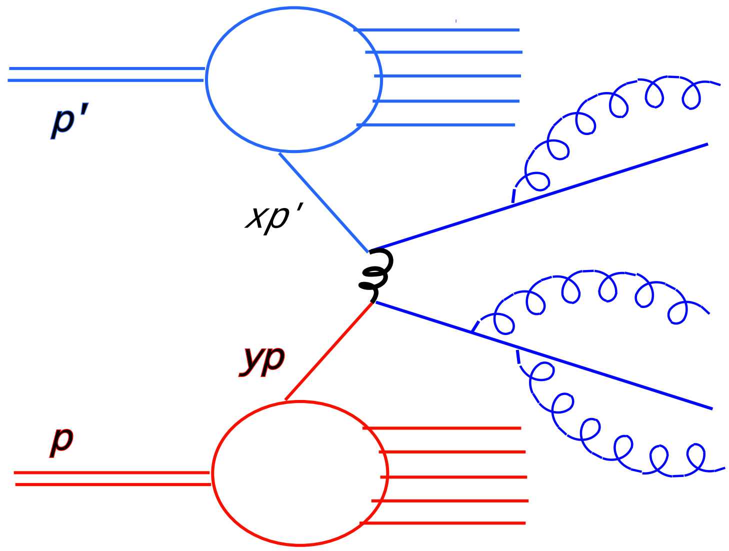


- **Factorization:**

$$W_N(q,p) \;=\; \sum_{a=\mathcal{Q},\bar{\mathcal{Q}},\mathcal{G}} \int_x^1 dy\, C_a\left(\frac{q^2}{\mu^2}, \frac{x}{y}, \alpha_s(\mu)\right)\; f_{a/N}(y,\mu)\,.$$

  – **Mueller (1974,1978), Politzer (1977) then Amati et al, Efremov-Radyushkin, R.K. Ellis et al., Libby, GS (all 1978) then Collins-GS (1981); Collins-Soper-GS (1985,88), Bodwin (1985); now Bauer et al (2002)**

– **And for hadron-hadron scattering: jets again**



What changed QCD from curious to obvious

- **Petra: gluon jet (1979)**
- **Lattice QCD verification of coexistence of confinement with asymptotic freedom (Creutz (1979))**
- **UA1, UA2: very high-p_T quark-quark scattering (1982)**

And Fundamental Advances in Theory

- **J.C. Collins & D.E. Soper on Resummation (1981,2)**

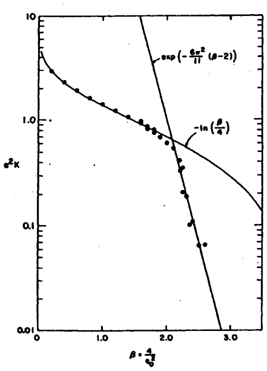


FIG. 6. The cutoff squared times the string tension as a function of β. The solid lines are the strong- and weak-coupling limits.

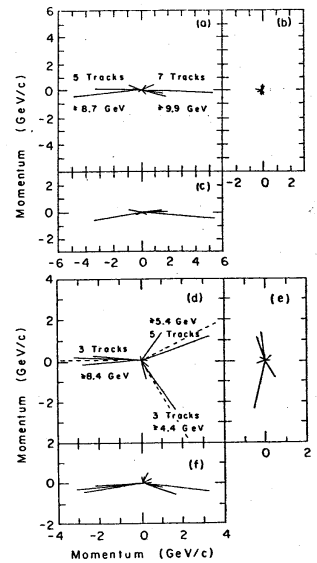


Fig. 6. Momentum space representation of a two-jet event (a)–(c) and a three-jet event (d)–(f) in each of three projections. (a), (d) $\hat{n}_2$–$\hat{n}_3$ plane; (b), (e) $\hat{n}_1$–$\hat{n}_2$ plane; (c), (f) $\hat{n}_1$–$\hat{n}_3$ plane.

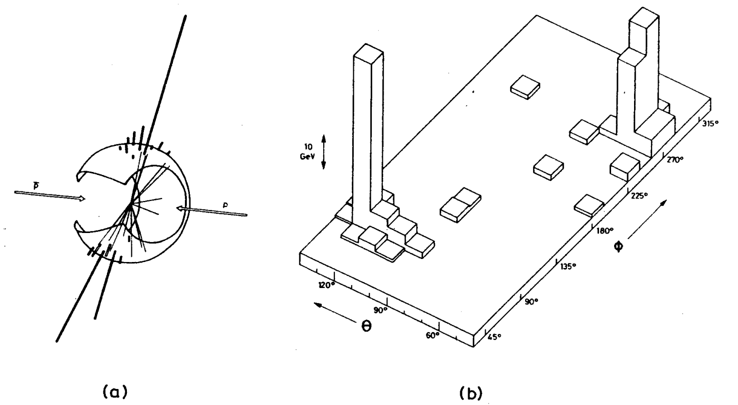


Fig. 4. Configuration of the event with the largest value of ΣE_T, 127 GeV (M = 140 GeV): (a) charged tracks pointing to the inner face of the central calorimeter are shown together with cell energies (indicated by heavy lines with lengths proportional to cell energies). (b) the cell energy distribution as a function of polar angle θ and azimuth ϕ.

HIGH ENERGY QCD TODAY

- All scales in all accelerator experiments
- Heavy quarks physics, effective field theories (factorization^{++})
- Colliding heavy ions, finite T and B
- Instantons & classical fields
- Hadronic structure (spin, etc.)

- Original issues remain: weak to strong QCD
  - fine jet substructure
  - footprints of color flow (new physics searches)
  - confinement for moving quanta
  - theory of hadronization

- Tradition: energy flow in gauge theories
  - Slow discharge of a condensor (Poynting)
  - Fast neutralization of a color dipole (LEP)

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.

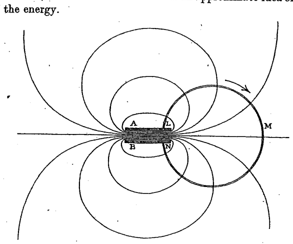
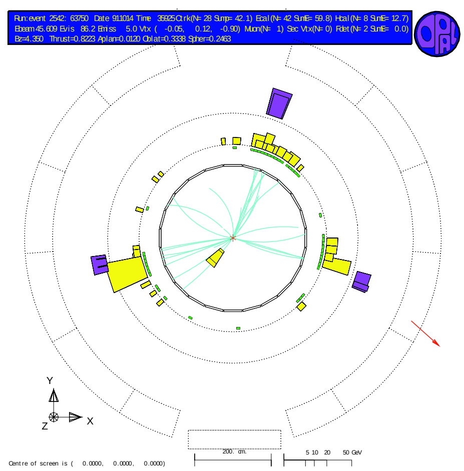


Fig. 2.



Thanks (My Own Good Luck)

- Recognition of my unpublished work
- Inspiration from Al Mueller
- The C.N. Yang Institute at Stony Brook
- Collaborators (70's): Steven Weinberg, Stephen Libby, Rob Ore, Bill Crutchfield
- John Collins and Dave Soper
- Wu-Ki Tung & the CTEQ Collaboration (how I learned about experiment)
- Postdocs/collaborators at the YITP
  - Jianwei Qiu
  - Gregory Korchemsky
  - Harry Contopanagos,
  - Werner Vogelsang
  - Andrei Belitsky
  - Maria Elena Tejeda-Yeomans
- My terrific students (Ashoke Sen . . . Carola Berger & Tibor Kucs)

We only have to ask the next right questions