Jets and Infrared Safety
"The Story and Stories of Jets at Acceleraors"

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1. **Seeing the Unseen at Accelerators**
2. **From Short to Long Distances in Quantum Field Theory:**
   What we can't compute and what we can: IR Safety and Energy Flow
3. **A Brief Biography of Particle Jets**
4. **Looking forward**
5. **Conclusion**

1. Seeing the Unseen at Colliders

(First, a few comments on the Triumph of the Standard Model at Accelerators)

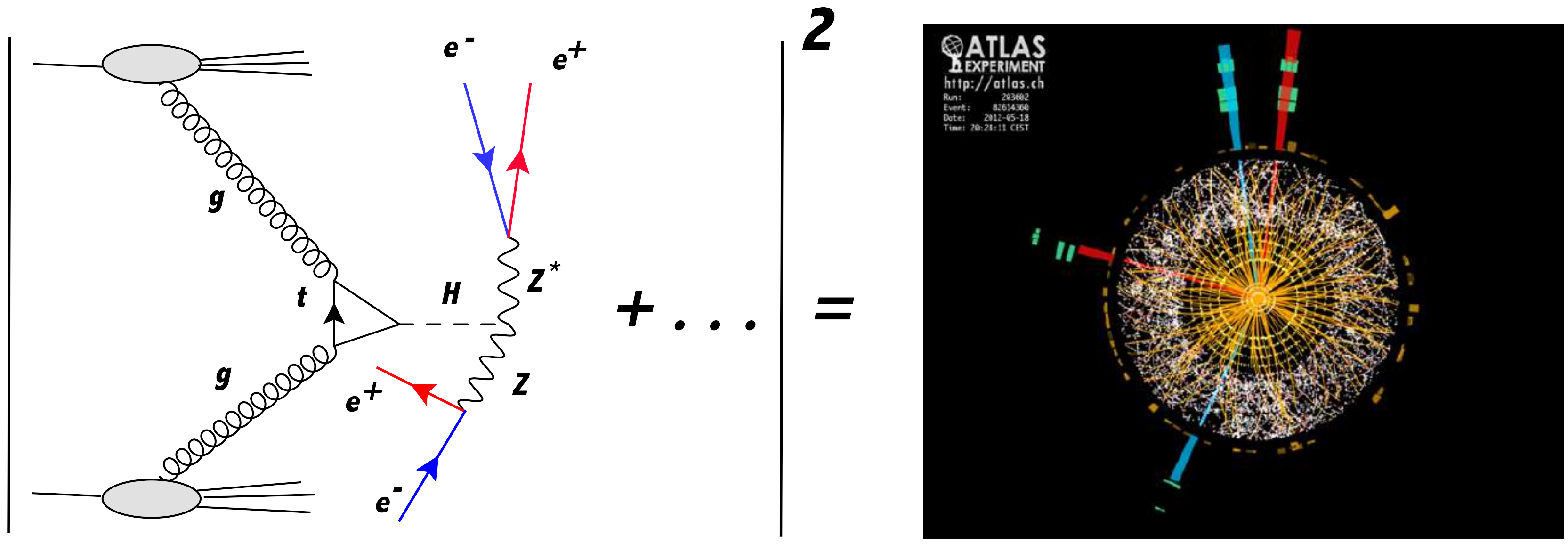
- High energy accelerators offer the most direct window to short-lived quantum processes.

- The strategy of probing matter at short distances has resulted in the identification/discovery of the gauge and matter fields of the Standard Model (visible matter in the universe).

- Accelerator programs, however complex and costly, remain experiments following the scientific canon. They are capable of design, replication and variation in response to the demands of nature and the imagination.

- I will review a little of how quantum field theory is applied in accelerator experiments, how jets emerge in final states, and what they tell us.

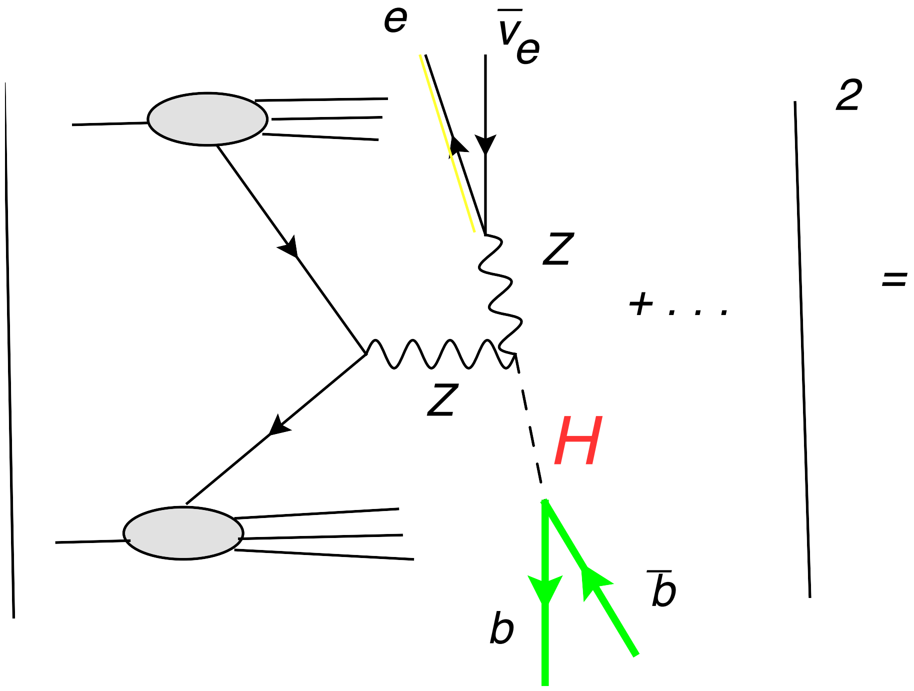
We can sum it up with a picture worth a thousand words:

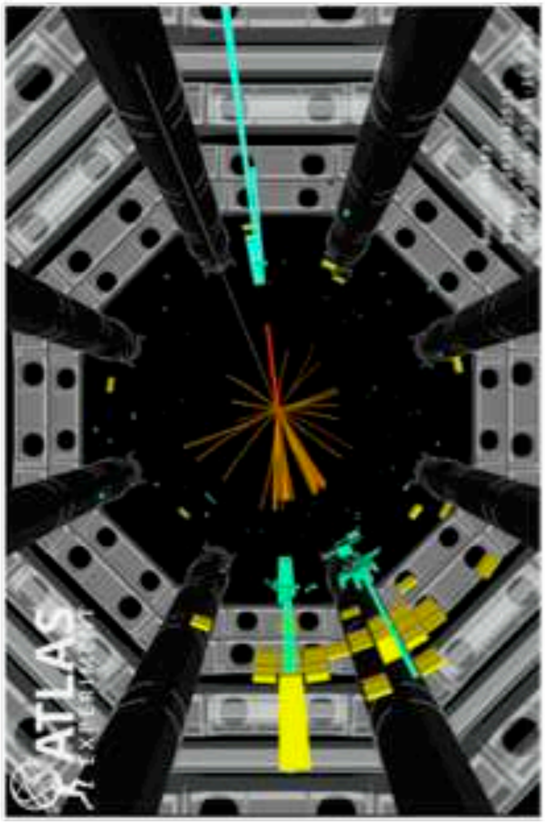


From $SU(3)$ color through the Higgs into $SU(2)_L \times U(1)$.

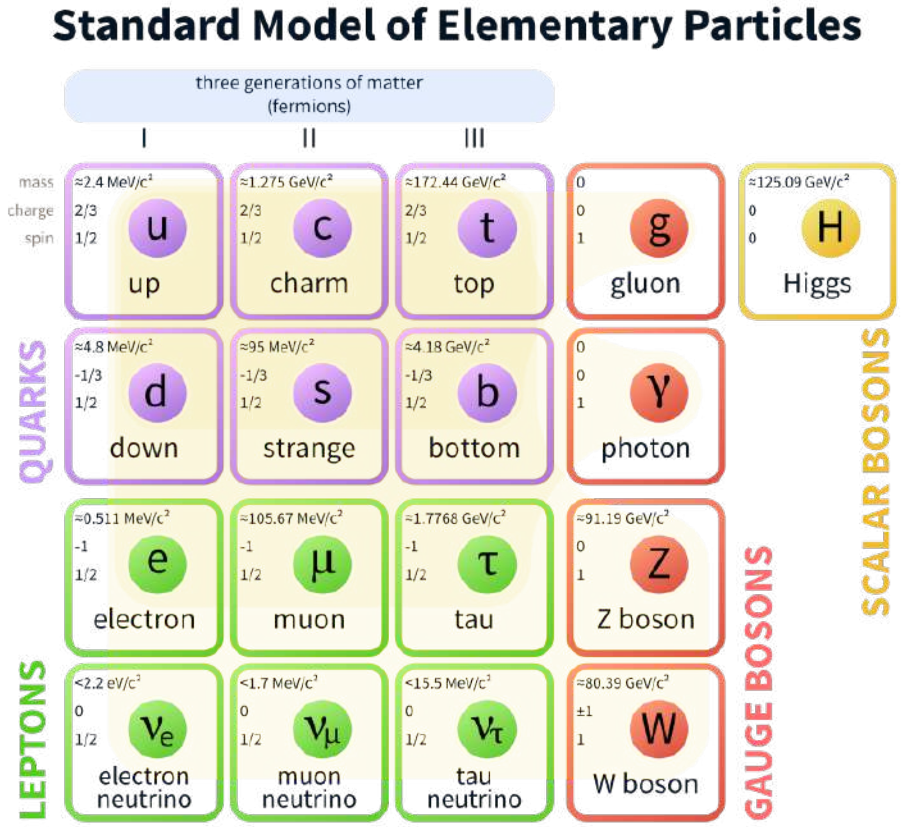
Every observed final state is the result of a quantum-mechanical set of stories, and so far the stories supplied by the Standard Model, built on an unbroken $SU(3)$ color gauge theory (very much like the original Yang-Mills Lagrangian) and a spontaneously-broken $SU(2)_L \times U(1)$, account for essentially all observations at accelerators and in nature.

Not long after, $Z + H \to b\bar{b}$ as revealed in boosted dijet decays:





THE PARTICLE CONTENT OF THE STANDARD MODEL: OBSERVED AND INFERRED



The six quarks in the upper left-hand corner are not seen in isolation, although five have lifetimes long enough to be "seen". The original three were inferred as an alphabet for bound states in the "quark model (Gell Mann & Zweig) from the mid-1960s.

The quarks and gluons provide Quantum Chromodynamics (QCD), the strong interactions of the Standard Model.

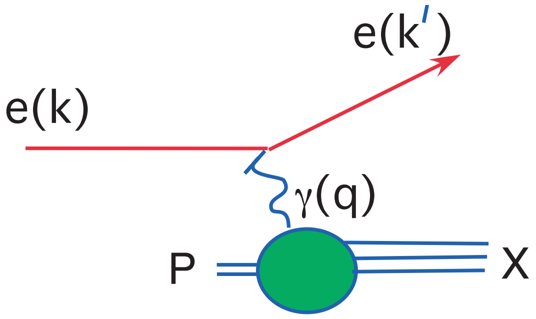
- A long story short: QCD reconciled the irreconcilable.

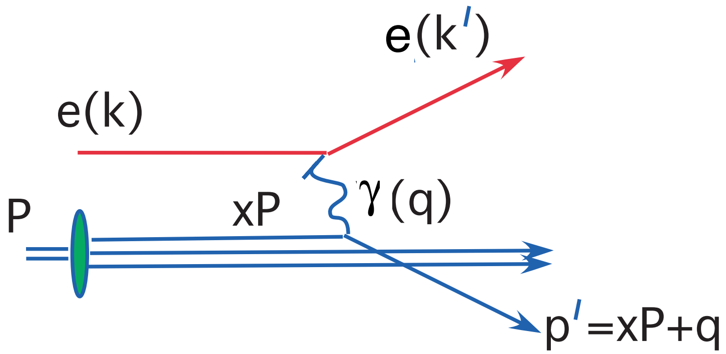
  Here was the problem . . .

  1. Quarks and gluons explain spectroscopy, but aren't seen directly – confinement.

  2. In highly ("deep") inelastic, electron-proton scattering, the inclusive cross section was found to well-approximated by lowest-order elastic scattering of point-like (spin-1/2) particles (="partons" = quarks here) a result called "scaling":

$$\left.\frac{d\sigma_{e+p}(Q,P\cdot q)}{dQ^2}\right|_{\text{inclusive}} \simeq F\left(x=\frac{Q^2}{2p\cdot q}\right)\left.\frac{d\sigma^{\text{free}}_{e+\text{spin}\,\frac{1}{2}}(Q,xP)}{dQ^2}\right|_{\text{elastic}}$$





- If the "spin-$\frac{1}{2}$" is a quark, how can a confined quark scatter freely?

- **In 1973, this paradoxical combination of confined bound states at long distances and nearly free behavior at short distances was explained by asymptotic freedom: In QCD, the force between quarks behaves at short distances like**

$$\text{force}(r) \sim \frac{\alpha_s(r)}{r^2}, \qquad \alpha_s(r^2) = \frac{4\pi}{\ln\left(\frac{1}{r^2\Lambda^2}\right)}$$

where $\Lambda \sim 0.2$ GeV. For distances much less than $1/(0.2\,GeV) \sim 10^{-13}$ cm the force weakens. These are the distances that began to be probed in deep inelastic scattering experiments at SLAC in the 1970s.

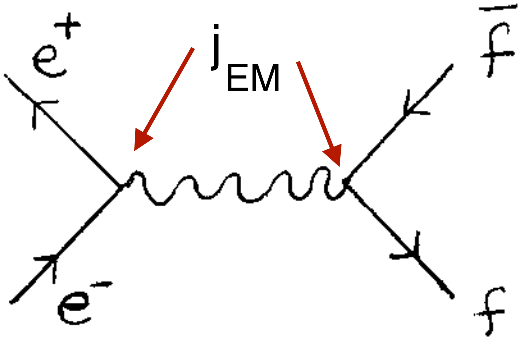
- **The short explanation of DIS: Over the times $ct \leq \hbar/0.2GeV$ it takes the electron to scatter from a quark-parton, the quark really does seem free. Later, the quark radiates, and is eventually confined, but by then it's too late to change the probability for an event that has already happened.**

- **The function $F(x)$ is interpreted as the probability to find quark of momentum xP in a target of total momentum P – a parton distribution.**

- **To explore further, SLAC used the quantum mechanical credo:**

  anything that can happen, will happen.

- **Quarks have electric charge, so if they are there to be produced, they will be. This can happen when colliding electron-positron pairs annihilate to a virtual photon, which ungratefully decays to just anything with charge:**



- **But of course, because of confinement, it's not really that. But more generally, we believe that a virtual photon decays through a local operator:** $j_{\mathrm{em}}(x)$ **.**

- **This enables translating measurements into correlation functions . . . In fact, the cross section for electron-positron annihilation probes the vacuum with an electromagnetic current.**

- **On the one hand, all final states are familiar hadrons, with nothing special about them to tell the tale of QCD, $|N\rangle = |\text{pions, protons}\ldots\rangle$,**

$$\sigma_{\mathrm{e^+e^-\to\ hadrons}}(Q) \quad = \quad \sigma_0 \sum_N |\langle N|j^\mu_{\mathrm{em}}(0)|0\rangle|^2\,\delta^4(Q-p_N)$$

- **On the other hand, $\sum_N |N\rangle\langle N| = 1$, and using translation invariance this gives**

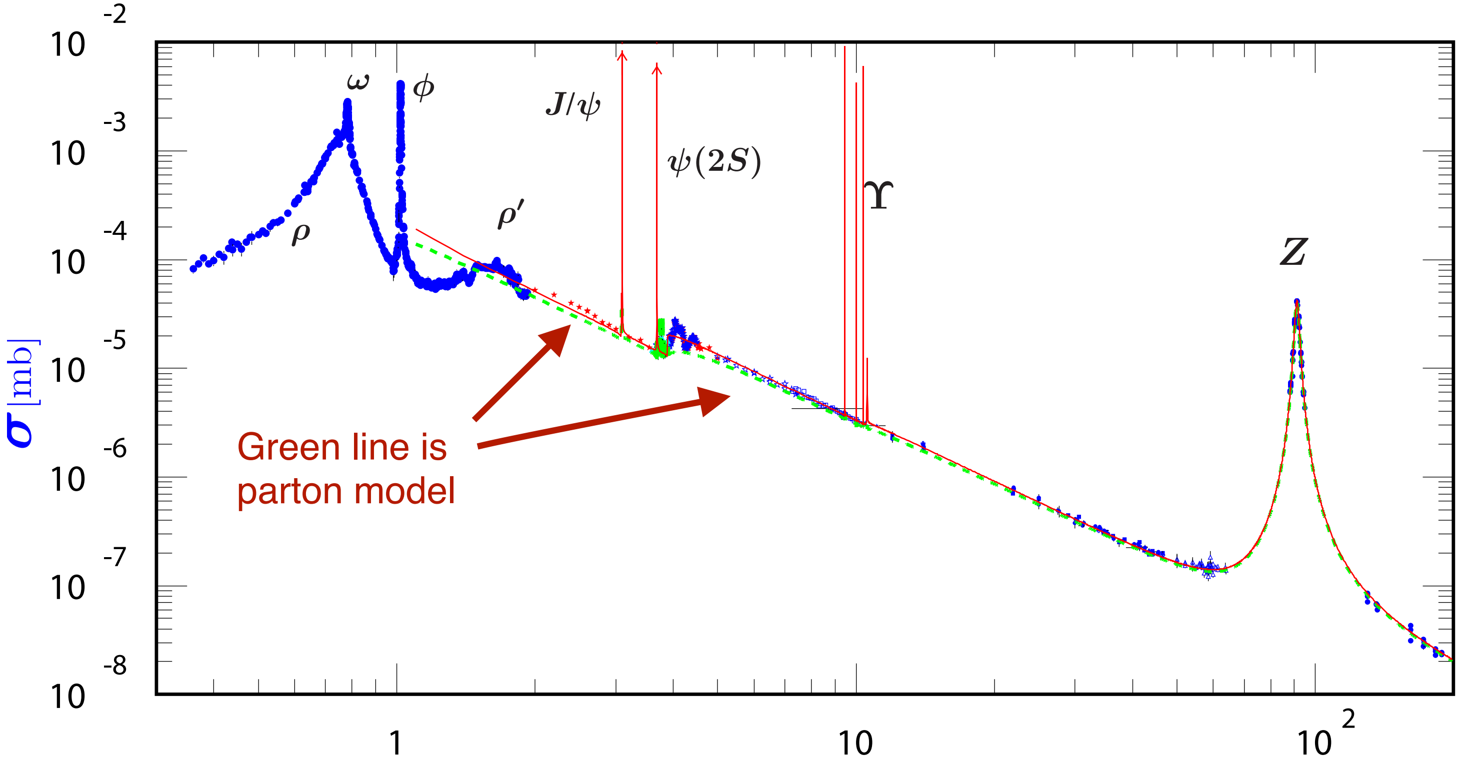
$$\sigma_{\mathrm{e^+e^-\to\ hadrons}}(Q) \quad = \quad \sigma_0 \int d^4x\, e^{-iQ\cdot x}\ \langle 0|j^\mu_{\mathrm{em}}(0)\ j^\mu_{\mathrm{em}}(x)|0\rangle$$

- **We are probing the vacuum at short distances, imposed by the Fourier transform as $Q\to\infty$. The currents are only a distance $1/Q$ apart.**

- **Asymptotic freedom suggests a "free" result: QCD at lowest order ("quark-parton model") at cm. energy Q**

$$\sigma^{tot}_{e^+e^-\to\mathrm{hadrons}} \quad = \quad \frac{4\pi\alpha^2_{\mathrm{EM}}}{3Q^2}\sum_i f_i^2 \qquad (f_i = 2/3 \text{ or } -1/3)$$

- This works for σ_{tot} to quite a good approximation! (with calculable corrections)



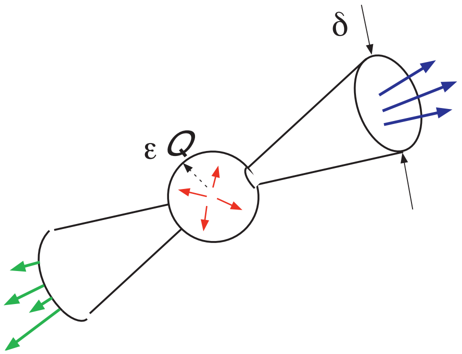
- So the “free” theory again describes the inclusive sum over confined (nonperturbative) bound states – another “paradox”.

- **Is there an imprint on these states of their origin? Yes. What to look for? The spin of the quarks is imprinted in their angular distribution:**

$$\frac{d\sigma_i(Q)}{d\cos\theta} = \frac{\pi\alpha_{\mathrm{EM}}^2}{2Q^2}\, f_i^2\left(1+\cos^2\theta\right)$$

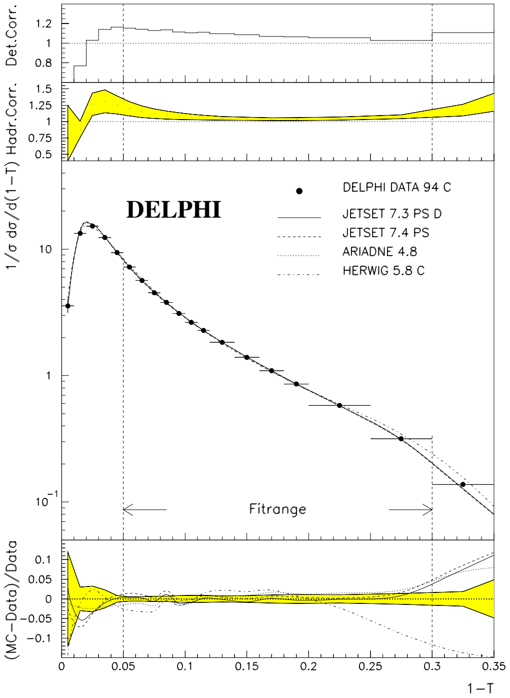
- **It's not quarks, but we can look for a back to back flow of energy by finding an axis that maximizes the projection of particle momenta ("thrust")**

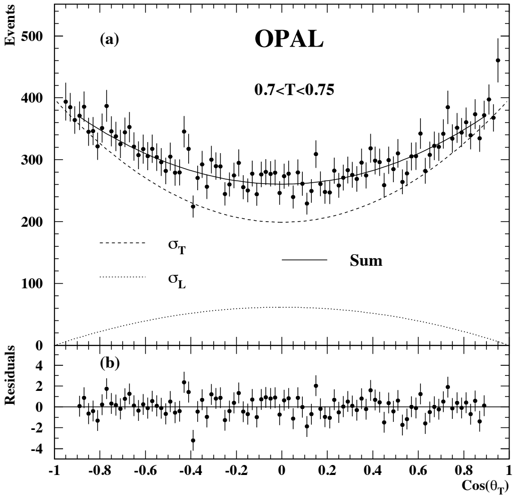
$$\frac{d\sigma_{\mathrm{e^+e^-}\to\ \mathrm{hadrons}}(Q)}{dT} \propto \sum_N \left|\langle 0|j^\mu_{\mathrm{em}}(0)|N\rangle\right|^2 \delta^4(Q-p_N)\ \delta\left(T - \frac{1}{Q}\max_{\hat{\mathrm{n}}}\sum_{i\in N}|\vec{p}_i\cdot\hat{\mathrm{n}}|\right)$$

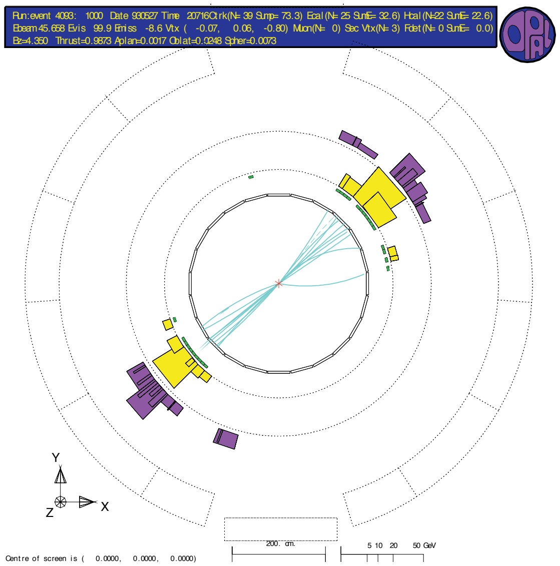


- **When the particles all line up, $T \to 1$ (neglecting masses). So what happens in real life?**

- **Here's what was found (from a little later, at LEP):**







- **Thrust is peaked near unity and the axis follows the $1 + \cos^2\theta$ distribution – reflecting the production of spin $\frac{1}{2}$ particles – back-to-back. All this despite confinement. Quarks have been replaced by "jets" of hadrons. What could be better? But what's going on? How can we understand persistence of short-distance structure into the final state, evolving over many many orders of magnitude in time? An answer is the goal of the rest of the talk.**

2. From Short to Long Distances in Quantum Field Theory
(What we can't compute yet, and what we can)

- At the short distances accessible to accelerators, we can expand around the free field theory. The transitions between states provide stories that provide predictions.

- Perturbation theory really just follows from Schrödinger's equation, by mixing free particle states (more on this later),

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

Usually with free-state "IN" boundary condition :

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

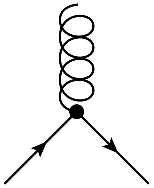
- Notation : $V_{ji} = \langle m_j|V|m_i\rangle$ (vertices)

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

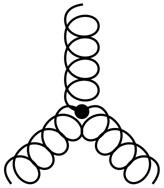
For QCD, the Lagrange density

$$
\begin{aligned}
\mathcal{L}_{\mathrm{QCD}} &= \overline{\psi}_i(i\gamma^\mu\partial_\mu - m)\psi_i - \tfrac{1}{4}F_a^{\mu\nu}F^a_{\mu\nu} - g_{\mathrm{s}}\,\overline{\psi}_i\lambda^a_{ij}\psi_j\,\gamma^\mu A^a_\mu \\
F_a^{\mu\nu} &= \partial^\mu A_a^\nu - \partial^\nu A_a^\mu - 2g_{\mathrm{s}}\,f_{abc}A_b^\mu A_c^\nu
\end{aligned}
$$

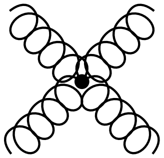
And vertices



$g_{\mathrm{s}}\,\bar{\psi}_i\lambda^a_{ij}\psi_j\gamma^\mu A^a_\mu$ quark-gluon vertex



$g_{\mathrm{s}}\,(\partial^\mu A_a^\nu - \partial^\nu A_a^\mu)f_{abc}A^b_\mu A^c_\nu$ 3-gluon vertex

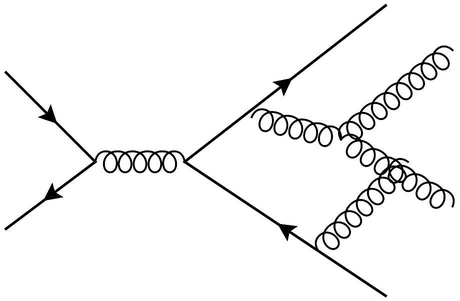


$g_{\mathrm{s}}^2\,f_{abc}A_b^\mu A_c^\nu\,f_{ade}A^d_\mu A^e_\nu$ 4-gluon vertex

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

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

- **Each term in this expansion corresponds to a “time-ordered” diagram**



Each diagram contains an enormous among of information.

- **And, the amplitudes can fail to converge when:**

$1.\quad \tau_i \to \tau_j$ **or** $2.\quad \tau_i \to \infty$.

- **1. Coinciding times in . . .**

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

- The **“Ultraviolet=UV”** problem from $\tau_i \to \tau_j$ is solved by renormalization, and results in scaling each term in V by an appropriate coupling constant $g(\mu)$, with

$$(\tau_i - \tau_j)_{\min} = 1/\mu.$$

In 4 dimensions only Yang-Mills theories have the property of asymptotic freedom,

$$g(\mu) \sim 1/\ln(\mu).$$

- The couplings of the Standard Model are either asymptotically free, or are small enough to not change much over experimentally-accessible energies.

- This makes an expansion in powers of $\alpha_s(\mu) = g^2(\mu)/4\pi$ plausible.

- Once we do the expansion using renormalization, the form of an "ideal cross section" would be the following:

- one with only a single kinematic scale, to which we can set μ:

$$\begin{aligned} Q^2\ \hat{\sigma}_{\rm SD}(Q^2,\mu^2,\alpha_s(\mu)) &= \sum_n c_n(Q^2/\mu^2)\ {\alpha_s}^n(\mu) + \mathcal{O}\left(\frac{1}{Q^p}\right) \\ &= \sum_n c_n(1)\ {\alpha_s}^n(Q) + \mathcal{O}\left(\frac{1}{Q^p}\right) \end{aligned}$$

- The key is to find quantities that are observable, and for which the coefficients are well-behaved, and do not depend on scales μ for which the coupling is too large.

- Such quantities are commonly called "infrared safe"

- For proton accelerators or hadronic final states, the problem is that there are rather few examples. And the reason is . . .

- 2. Large times in . . .

$$\langle m_n | m_0 \rangle \;=\; \sum_{\tau\ \mathrm{orders}} \int_{-\infty}^{\infty} d\tau_n \ldots \int_{-\infty}^{\tau_2} d\tau_1 \prod_i \int \frac{d^3\ell_i}{(2\pi)^3} \prod_j \frac{1}{2E_j} \times \prod_a iV_{a\to a+1}$$

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

- Divergences from $\tau_i \to \infty$ are "Infrared=IR". In some sense, their "solution" is jets.

- 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?** **Two ways of writing the phase (state m begins at time τ_m):**

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

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

i) (RHS) the phase must vanish ↔ "degenerate states"

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

ii) (LHS) the phase must be stationary in the sum over states:

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

where the β_js are normal 4-velocities:

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

- Condition of stationary phase for any loop l_i that passes through the particles of a set of degenerate states S_i. (Landau Equations)

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

- $\beta^\mu \Delta\tau = x^\mu$ is a classical translation. For IR divergences, there must be free, classical propagation as $t \to \infty$. Easy to satisfy if all the β_j's are equal.

- This is what we get for high energy, as all velocities approach c.

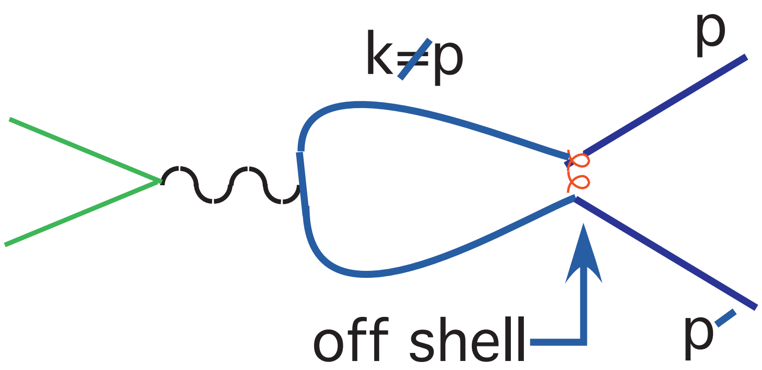
- Whenever fast partons (quarks or gluons) emerge from the same point in space-time,

  they will rescatter over long times with collinear partons.

  And note, all these states describe the same flow of energy. This is where infrared divergences come from.

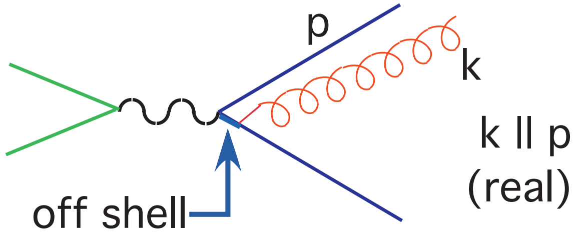
- Let's illustrate the role of classical propagation.

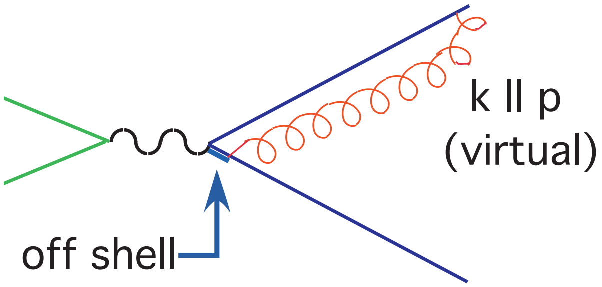
- Example: degenerate states that cannot give long-time divergences:

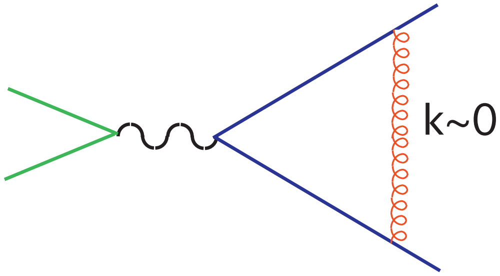


- This makes identifying enhancements a lot simpler!

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







- **This generalizes to any order, and any field theory, but gauge theories alone have soft $(k \to 0)$ divergences. Jets are associated with classical stories of collinear particles interacting to large times.**

- **These are what we can't compute in perturbation theory (as physical processes).**

- **But** for e^+e^- annihilation, if we include all the states that can result from these collinear rescatterings, the $\tau \to \infty$ divergences are guaranteed to cancel, because the total probability for something to happen has to be one (unitarity).

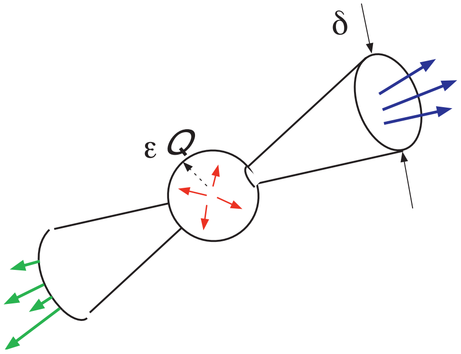
- If we calculate detailed final states (how many quarks, how many gluons) we get totally unphysical answers, but if we sum over all possibilities so as to preserve energy flow, perturbation theory can give good answers.

- For example, you can use the optical theorem to show that the total cross section is IR safe (Appelquist, Georgi (1973))

- Once again, a sufficiently inclusive process that is nonperturbative at long distances can be described by the lowest order in the perturbative coupling, with calculable corrections.

- The same applies to jet cross sections if they are designed to respect the flow of energy.
- These are what we can compute.

  (technically, all these singularities can be derived from rotationally non-invariant – but still hermitian – truncations of the QFT hamiltonian. see Soft-Collinear Effective Theory.)



- The smaller (larger) the “resolutions” ϵ and δ, the more (less) sensitivity to long times. We follow the story only to times like $1/Q\delta$.

ENERGY FLOW IS THE ORGANIZING PRINCIPLE OF THE CLASSICAL STORIES

(GS (1975); GS and S. Weinberg (1977))

3. A Brief Biolgraphy of Particle Jets

- **Prehistory: the 1950's – 1960's**
  - **First observations of high-energy collisions from cosmic rays**
  - **Particle jets in cosmic rays . . . (the word is coined)**

    "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))

- **1960's - 70's. The era of high energy physics begins**

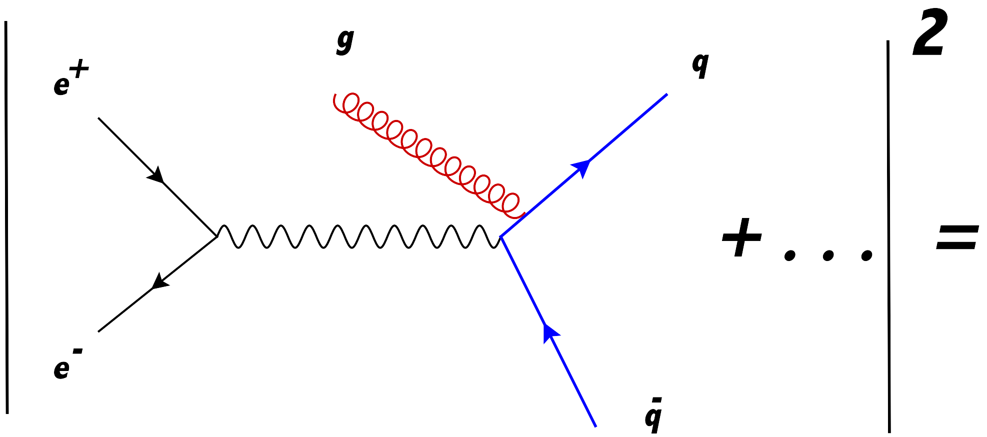
  Once asymptotic freedom explained scaling (Feynman, Bjorken)

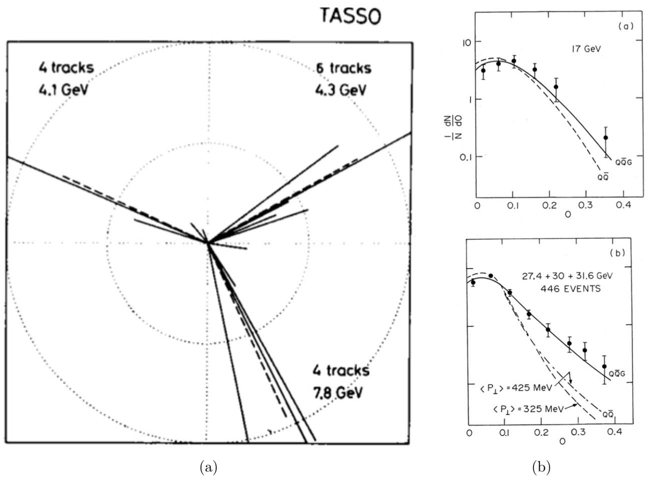
$$\sigma^{\rm incl}_{e\,{\rm proton}}\left(Q,x=\frac{Q^2}{2p\cdot q}\right)\to\sigma^{\rm excl}_{e\,{\rm parton}}(Q)\times F_{\rm proton}(x)\,, \qquad (1)$$

  - **this is when the question arose: what happens to partons in the final state?**

    (Feynman, Bjorken & Paschos, Drell, Levy & Yan, 1969)
  - **Do "the hadrons 'remember' the directions along which the bare constituents were emitted? . . . "the observation of such 'jets' in colliding beam processes would be most spectacular." (Bjorken & Brodsky, 1969) Or does confinement forbid it?**

- **1975 - 1980. the first quark and gluon jets**
  - As we've seen: in electron-positron annihilation to hadrons, the angular distribution for energy flow follows the lowest-order ("Born") cross section for the creation of spin-1/2 pairs of quarks and antiquarks (As first seen by Hanson *et al*, at SLAC in 1975)
  - And then (Ellis, Gaillard, Ross (1976) Ellis, Karliner (1979)): hints of three gluons in Upsilon decay, and then unequivocal gluon jets at Petra (1979) (S.L. Wu (1984))



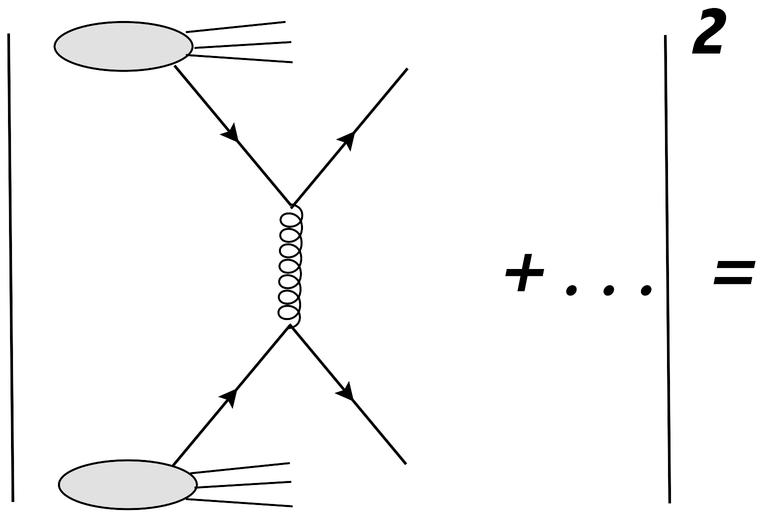


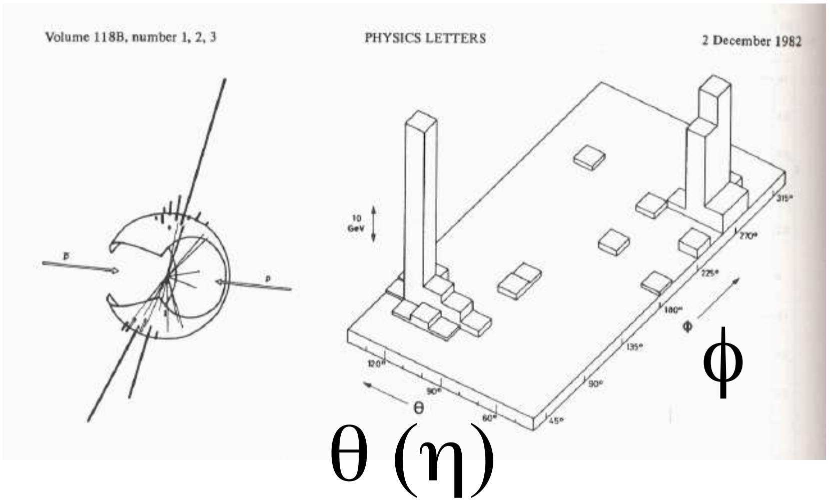
(a) (b)

(On the right, O is oblateness, which measures the spread of energy in a plane.)

  - Confirmed color as a dynamical charge.

- **1980's Jets resolved at hadron colliders**
  - **direct and indirect 'sightings' of scattered parton jets: Fermilab, the ISR,, dots (UA2) 'lego plots' in terms of energy flow, and unequivocal observation.**

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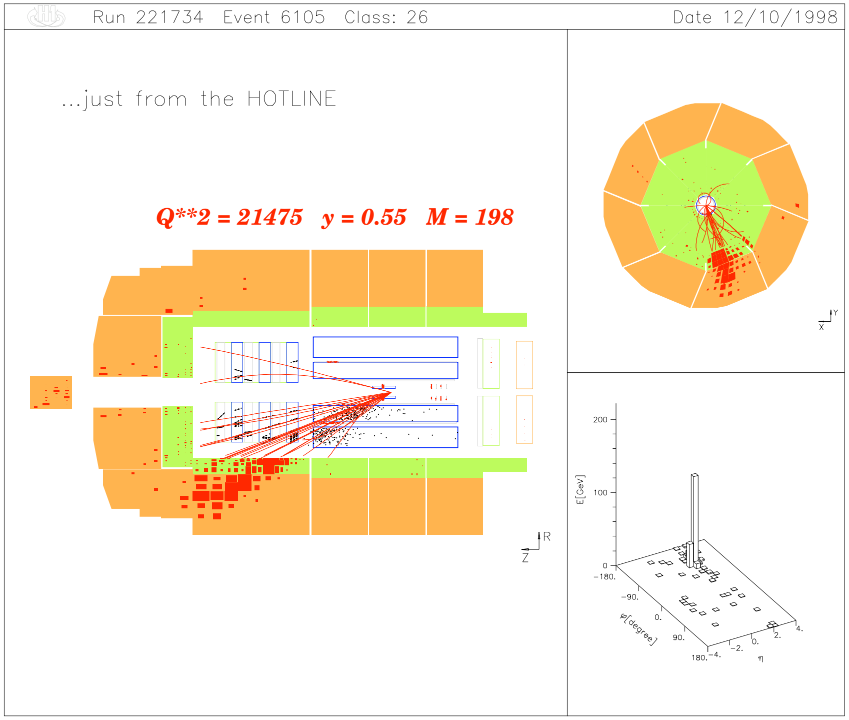
2 December 1982

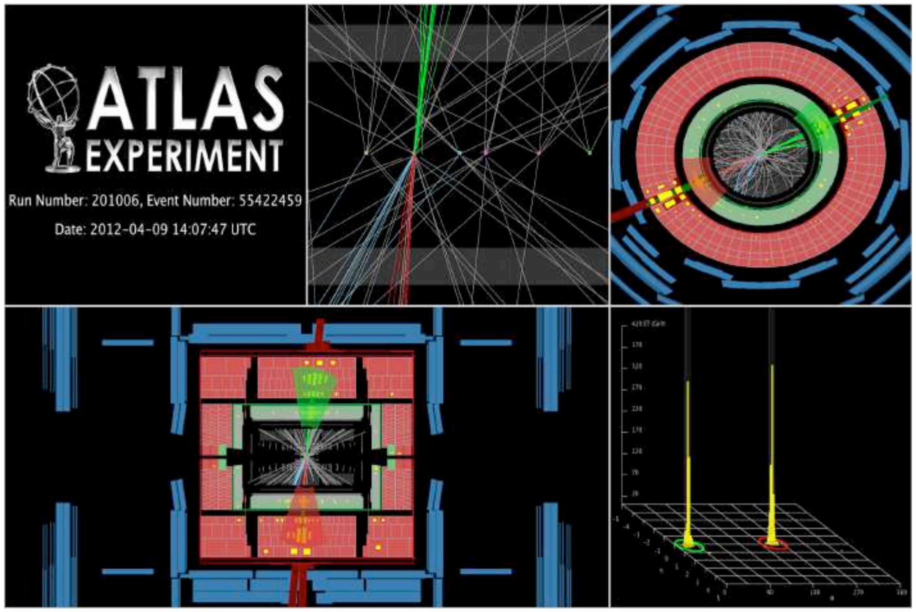
- **Essential behavior captured by extension of parton model (Horgan, Jacob 1981).**

- **1990's – 2005. The great Standard Model machines: HERA, the Tevatron Run I, and LEP I and II provided jet cross sections over multiple orders of magnitude. The scattered quark appears.**



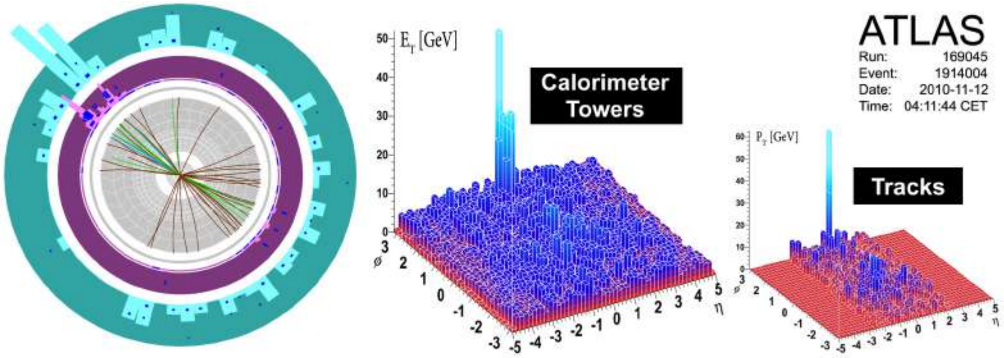
- **And now a new era of jets at the anticipated limits of the SM, ushered in by Tevatron and at the LHC: 2 $\to$ 7 $\to$ 8 $\to$ 13 TeV . A factor of 10^3 since the first sighting at SLAC.**

- **Events at the scale $\delta x \sim \frac{\hbar}{1\ \mathrm{TeV}} \sim 2 \times 10^{-19}$ meters . . . observed about 10 meters away.**



In brief, in their other life: shining from the inside, jets are a probe of new phases of strongly-interacting matter in nuclear collisions at RHIC and the LHC,

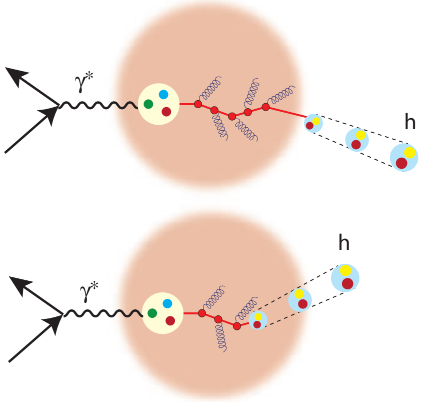
(Bjorken (1983) . . .)



(From 1011.6182)

And of “cold nuclei” in electron-ion collisions,

(A. Arccadi *et al.*, Electron-ion Collider White Paper (1212.1701))



4. The Theory of Jets at Colliders (∼ a review of week 1)

- What we do: For e^+e^- collisions, we compute jet cross sections directly in perturbative QCD as though the final state consisted of quarks and gluons

- Because they depend only on (relatively) short distances (no times of stationary phase!)

- Much recent interest is in formalized energy flow – introduce an "energy flow operator" in terms of the energy-momentum tensor $T_{\mu\nu}$:

$$\mathcal{E}(\hat{n})\,|N\rangle \;=\; \lim_{r\to\infty} \int_0^\infty \frac{dt}{(2\pi)^2}\, r^2\, \hat{n}_i\, T_{0i}(t,r)$$

which gives:

$$\mathcal{E}(\hat{n})\,|N\rangle \;=\; \sum_{i=1}^{N} \delta^2(\hat{n}-\hat{n}_i)\, E_i\, |N\rangle$$

In terms of which thrust, for example is given by:

$$\frac{d\sigma_{\mathrm{e^+e^-\to\ hadrons}}(Q)}{dT} \;=\; \sigma_0 \sum_N |\langle 0|j^\mu_{\mathrm{em}}(0)|N\rangle|^2\, \delta^4(Q-p_N)\ \delta\left(T - \frac{1}{Q}\max_{\hat{\mathrm{n}}} \sum_{i\in N} |\vec{p}_i\cdot\hat{\mathrm{n}}|\right)$$

$$= \sigma_0 \int d^4y\, e^{iq\cdot y} \langle 0|\, j^\mu_{\mathrm{em}}(y)\, \delta\left(T - \frac{1}{Q}\,\mathcal{E}(\hat{n})\ \cos|\hat{n}\cdot\hat{n}_t|\right)\, j_{\mathrm{em},\mu}(0)|0\rangle$$

- **More generally, study "EEC"s = "energy-energy correlations" in** $\mathrm{e^+e^-}$

$$\langle \mathcal{E}(n_1)\mathcal{E}(n+\Delta n)\rangle \;=\; \sigma_0 \int d^4y\, e^{iq\cdot y} \int d^2\hat{n}\, \langle 0|\, j^{\mu}_{\mathrm{em}}(y)\, \mathcal{E}(\hat{n})\mathcal{E}(\hat{n}+\Delta n)\; j_{\mathrm{em},\mu}(0)|0\rangle$$

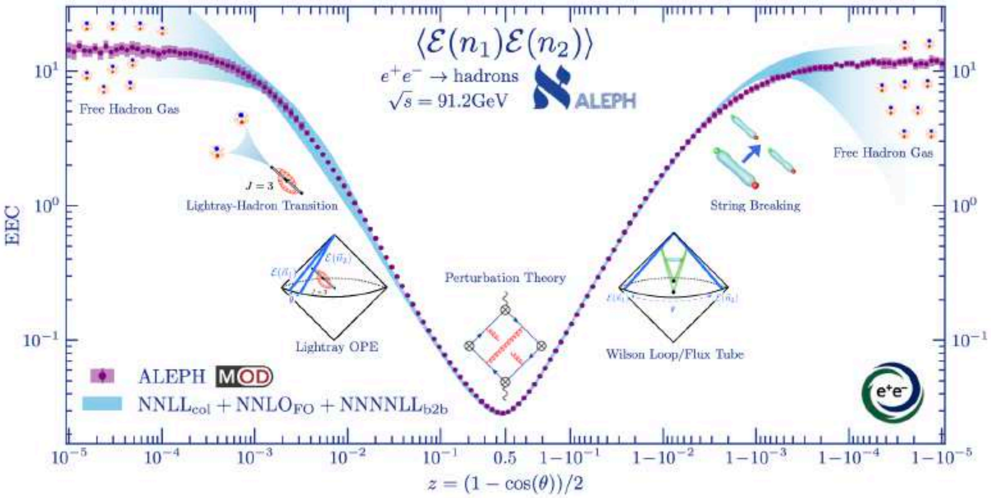


FIG. 4: The energy correlator from partons to hadrons: A measurement of the EEC using archival data from the ALEPH tracker. Statistical error bars are shown as vertical lines and systematic error bars as purple boxes. ALEPH data is compared with state-of-the-art theoretical predictions, shown in light blue. Our re-analysis greatly extends both the precision, and angular range of the measurement, enabling a complete view of the dynamics of QCD.

from: Bossi et al. 2511,00149. See also I. Moult, Loopfest 2026

- **At the edges, small and wide angles, a view of the perturbative-nonperturbative transition. Benchmarks for a future theory of hadronization.**

- **Colliding electrons with hadrons involves the scattering of “pre-existing” quarks and gluons from hadrons, whose interactions extend back to nucleosythesis, requiring:**

  Factorization: Following the New Stories into the Final State: Before the collision, a lot of stories inside the proton, but the probability for each is the same in every proton!

  The essence of predictions for the Standard Model and proposed theories:

$$Q^2\sigma_{\rm phys}(Q,m,f) \;=\; C(Q/\mu,\alpha_s(\mu),f) \otimes f_{\rm LD}(\mu,m) \;+\; \mathcal{O}\left(\frac{1}{Q^p}\right)$$

  $\mu =$ factorization scale; $m=$ IR scale **(m *may* be perturbative)**

  “First this and then that” multiplication of probabilities – the essence of factorization. It requires a “sufficiently” inclusive cross section, much as in the calculation of jets in e^+e^- annihilation.

- **Newly-minted jets and possible “new physics” are in C; $f_{\rm LD}$ “universal”**

- Again, the factorized cross section:

$$Q^2\sigma_{\rm phys}(Q,m,f) \;=\; C(Q/\mu,\alpha_s(\mu),f) \otimes f_{\rm LD}(\mu,m) \;+\; \mathcal{O}\left(\frac{1}{Q^p}\right)$$

- What we do:
  - Compute σ and $f_{\rm LD}$ in an IR-regulated variant of QCD, where we can prove the factorization explicitly, then extract C, assuming it is the same in true QCD as in its IR-regulated version.
  - Then compare the formula with physical parton distributions to a suite of data and do a "global fit" for the $f(x,\mu)$ for different quarks and the gluon.
- What we get: absolute predictions for the creation of jets and heavy particles from QCD, and for new degrees of freedom in BSM hypotheses.
  - The process is a "bootstrap", resulting in feedback between parton distributions, predictions and measurements.
- Here is where precision is sought. New observables – like EECs – can reveal the time-evolution of partons on their way to forming hadrons - the transition to strong coupling.

5. Conclusion

- **The EIC will be a jet factory**
- **Many of these jets will be at relatively low energy – perhaps an advantage for the study of hadronization in vacuum and in cold nuclear matter.**
- **Let’s see what Felix tells us!**