Parton Energy Loss in QCD Medium

Yuri L. Dokshitzer

LPTHE, University Paris VI & VII
PNPI, St. Petersburg
CERN TH

Les Houches
March 25 – April 5, 2008

Piercing the Wall

The wall of our ignorance is still stone solid.

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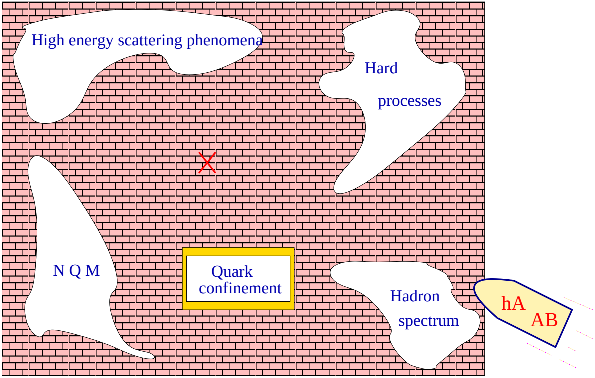

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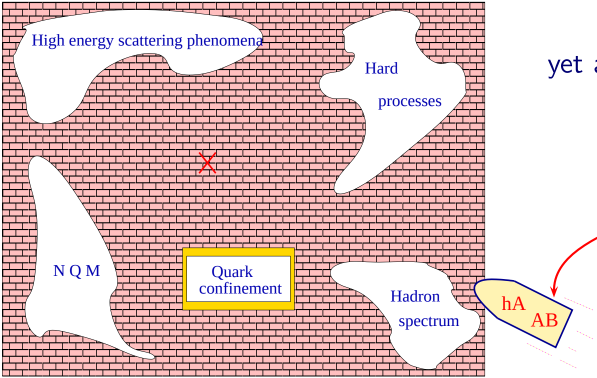

yet another brick in the wall

The Hope :

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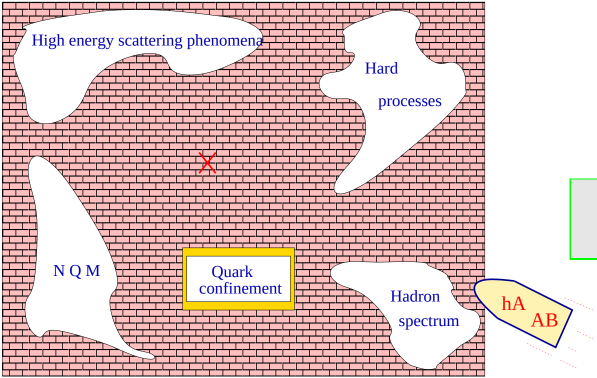

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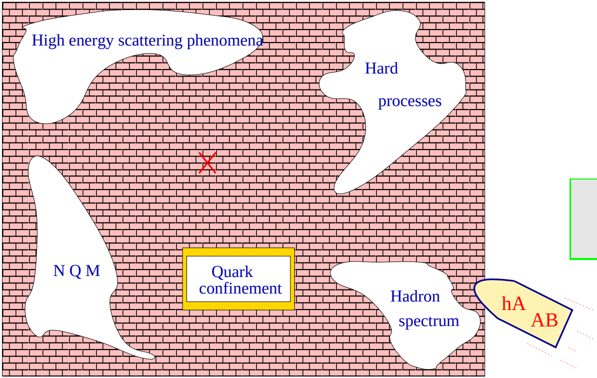

The Hope :

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again . . .

Asymptotic Freedom

and

QCD Partons

Running coupling

The strong coupling, α_s, *runs:*

$$Q^2 \frac{\partial \alpha_s}{\partial Q^2} = \beta(\alpha_s), \qquad \beta(\alpha_s) = -\alpha_s^2 (b_0 + b_1 \alpha_s + b_2 \alpha_s^2 + \ldots),$$

$$b_0 = \frac{11 N_c - 2 n_f}{12\pi}, \quad b_1 = \frac{17 N_c^2 - 5 N_c n_f - 3 C_F n_f}{24\pi^2}; \qquad \left(C_F = \frac{N_c^2 - 1}{2 N_c} \right)$$

Note sign: Asymptotic Freedom, due to gluon to self-interaction

- At high scales Q, coupling is weak
  ➠quarks and gluons are almost free, their interactions stay under the perturbation theory control
- At low scales, coupling becomes (catastrophically) large
  ➠quarks and gluons interact strongly — they are confined into hadrons. Perturbation theory should fail.

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Asymptotic Freedom : *WHY* ?

- It seems natural to expect the effective interaction strength to *decrease* at large distances.
- Moreover, it was long thought to be *inevitable* as corresponding to the physics of 'screening'.
- The fact that the vacuum fluctuations have to screen the external charge, in QFT follows from the first principles: unitarity and crossing symmetry (= Lorentz invariance + causality).

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So, why does this most general argument fail in non-Abelian QFT ?

Autopsy of Asymptotic Freedom

To address questions starting from *what* or *why* we better talk physical degrees of freedom; use the *Hamiltonian language*. Then, we have gluons of two sorts: 'physical' transverse gluons and the Coulomb gluon field — mediator of the instantaneous interaction between colour charges.

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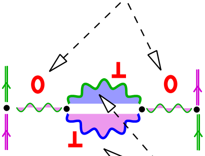

$$= -N_c * \frac{1}{3} \quad -n_f * \frac{2}{3}$$

Transverse gluons **(and quarks)**

screening

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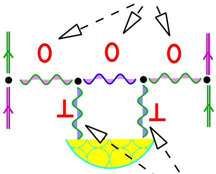

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Vacuum fluctuations of transverse fields

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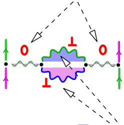

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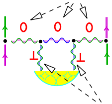

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Vacuum fluctuations of transverse fields

Combine into the QCD β–function:

$$\beta(\alpha_s) = \frac{\mathrm{d}}{\mathrm{d}\ln Q^2} 4\pi\alpha_s^{-1}(Q^2)$$

$$= \left[4 - \frac{1}{3}\right] * N_c - \frac{2}{3} * n_f$$

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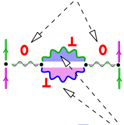

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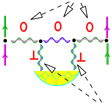

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The origin of *antiscreening* — deepening of the ground state under the 2nd order perturbation in NQM:

$$\Delta E_0 = \sum_n \frac{|\langle 0|\delta V|n\rangle|^2}{E_0 - E_n} < 0.$$

Running coupling (cont.)

Solve $Q^2 \frac{\partial \alpha_s}{\partial Q^2} = -b_0 \alpha_s^2 \quad \Rightarrow \quad \alpha_s(Q^2) = \frac{\alpha_s(Q_0^2)}{1 + b_0 \alpha_s(Q_0^2) \ln \frac{Q^2}{Q_0^2}} = \frac{1}{b_0 \ln \frac{Q^2}{\Lambda^2}}$

- Λ (aka Λ_{QCD}) — the fundamental QCD scale, at which coupling blows up.
- Perturbative calculations valid for large scales $Q \gg \Lambda$.
- Not an obvious statement: we deal with hadrons in nature, while applying QCD to quarks and gluons ...
- "Animalistic" Ideology : some observables are *more equal* than the other

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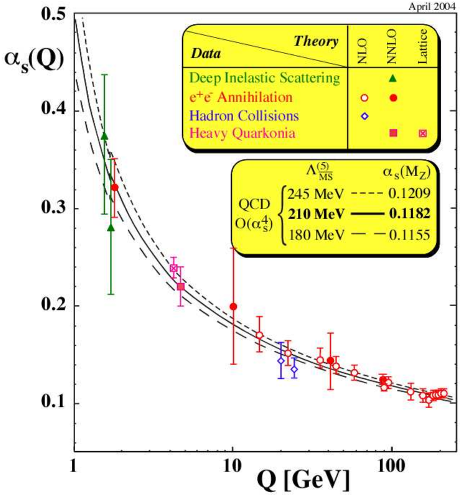

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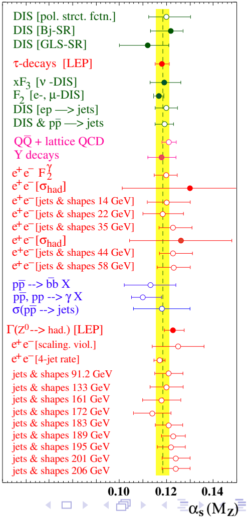

Hard QCD interactions

Hit hard to see what is it there *inside* (a childish but productive idea)

Hard QCD interactions

Hit hard to see what is it there *inside*

Heat the *Vacuum*

- e^+e^- annihilation into hadrons : $e^+e^- \to q\bar{q} \to$ hadrons.

Hard QCD interactions

Hit hard to see what is it there *inside*

Hit the *proton* (with an electromagnetic/electroweak probe)

- e^+e^- annihilation into hadrons : $e^+e^- \to q\bar{q} \to$ hadrons.
- Deep Inelastic lepton-hadron Scattering (DIS) : $e^-p \to e^- + X$.

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    - ➥ lepton pairs ($\mu^+\mu^-$, the Drell-Yan process),
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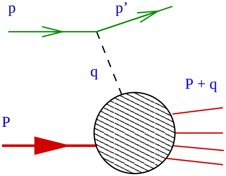
Momentum transfer = measure of "*hardness*"

Deep Inelastic lepton-proton Scattering



Bit of kinematics: invariant mass of final hadrons

$$W^2 - M_P^2 = (P+q)^2 - M_P^2$$
$$= 2(Pq)\left(1 - \frac{-q^2}{2(Pq)}\right) \equiv 2(Pq)\cdot(1-x)$$

$$\frac{d\sigma_{\text{elastic}}}{dq^2} = \left(\frac{d\sigma}{dq^2}\right)_{\text{point}} \cdot F^2_{\text{elastic}}(q^2)$$

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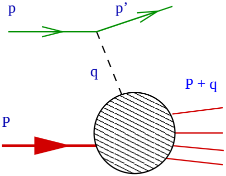

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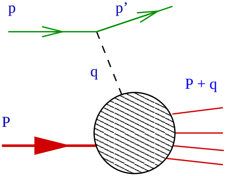

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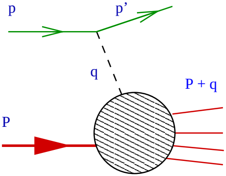

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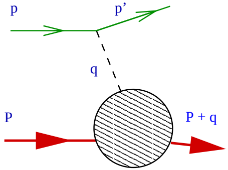

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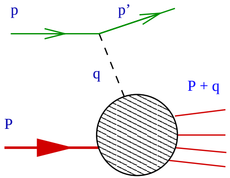

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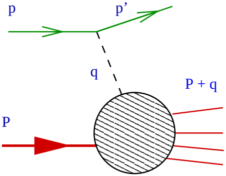

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$$\frac{d\sigma_{\text{elastic}}}{dq^2} = \left(\frac{d\sigma}{dq^2}\right)_{\text{point}} \cdot F^2_{\text{elastic}}(q^2)$$
$$\frac{d\sigma_{\text{inelastic}}}{dq^2} = \left(\frac{d\sigma}{dq^2}\right)_{\text{point}} \cdot F^2_{\text{inelastic}}(q^2, x) \cdot dx$$

What to expect for *elastic* and *inelastic* proton Form Factors $F^2(q^2)$?

Free quarks

Two plausible and one crazy scenarios for the $|q^2| \to \infty$ (Bjorken) limit

1). Smooth electric charge distribution: (classical picture)

$$F^2_{\text{elastic}}(q^2) \sim F^2_{\text{inelastic}}(q^2) \ll 1$$

– external probe penetrates the proton as knife thru butter.

2). Tightly bound point charges inside the proton: (quarks?)

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– excitation of one quark gets *redistributed* inside the proton via the confinement "*springs*" that bind quarks together and don't let them fly away.

3). Now look at this: (Mother Nature)

$$F^2_{\text{elastic}}(q^2) \ll 1; \quad F^2_{\text{inelastic}}(q^2) \sim 1$$

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Bjorken scaling: Partons

Conclusion: Proton is a *loosely bound* system (of 3 quarks + glue + $\cdots$)

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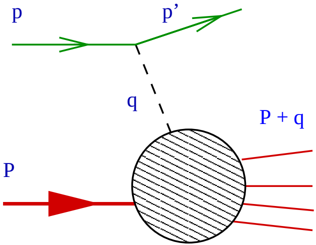

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Inelastic electron–proton scattering

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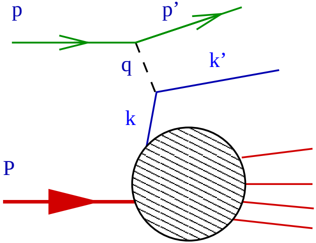

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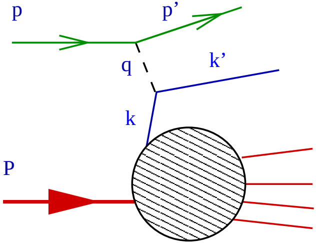

Let the parton carry a finite fraction of the proton momentum $k \simeq z \cdot P \quad (k^2 \simeq 0)$

$$\begin{aligned} (k')^2 &= (zP+q)^2 \\ &\simeq 2(Pq)\cdot(z-x) \simeq 0\,. \end{aligned}$$

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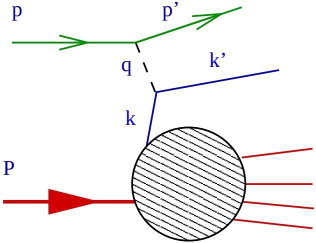

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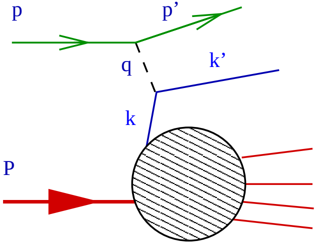

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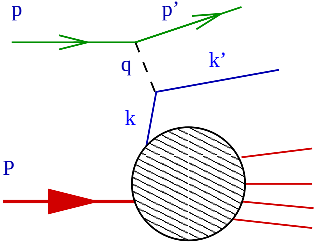

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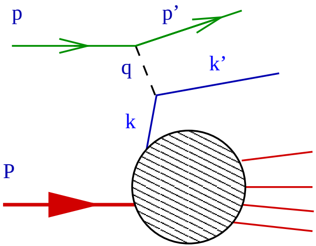
Existence of the *limiting* distribution

$$F^2_{\text{inelastic}}(q^2, x) = D_P^q(x)\,; \qquad |q^2| \to \infty,\ x = \text{const}$$

constitutes the *Bjorken scaling hypothesis*.

Violation of scaling is inevitable in QFT



Particle virtualities/transverse momenta in QFT are not limited. In particular, in a DIS process, "partons" (quarks and gluons) may have transverse momenta up to

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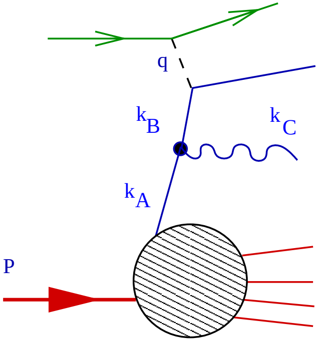

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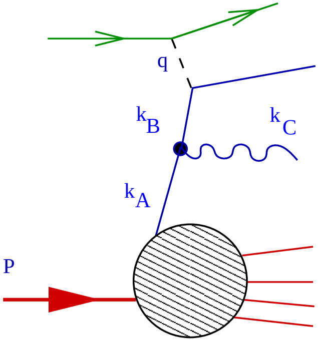

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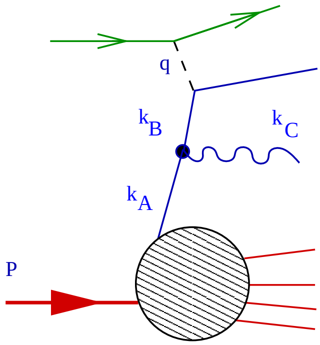

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Physically, a QFT particle is surrounded by a *virtual coat*; its visible content depends on the *resolution power* of the probe $\lambda = \frac{1}{Q} = \frac{1}{\sqrt{-q^2}}$

Partons in QFT?

Thus we learned that in QCD the probability to find a parton q inside the target h must depend on the resolution, Q^2

$$D_h^q = D_h^q(x, \ln Q^2)\,.$$

Moreover, the Feynman–Bjorken picture of partons employed the classical (probabilistic) language:

$$\sigma_h = \sigma_q \otimes D_h^q\,.$$

However, as we see, quarks and gluons multiply willingly, $w = \mathcal{O}(1)$.

Is there any chance to rescue probabilistic interpretation of quark–gluon cascades, to speak of "QCD partons"?

The question may sound silly, since in QFT the number of Feynman graphs grows as $(n!)^2$ with the number n of participating particles . . .

However, which are the *most probable* parton fluctuations?

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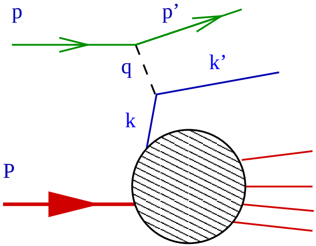
$$(\alpha_s)^n \implies (\alpha_s \cdot \ln Q^2)^n$$

Long-living partons fluctuations



Kinematics of the parton splitting $A \to B + C$

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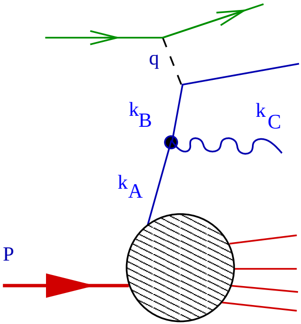

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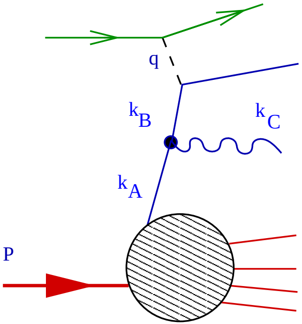

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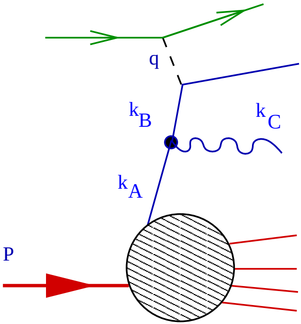

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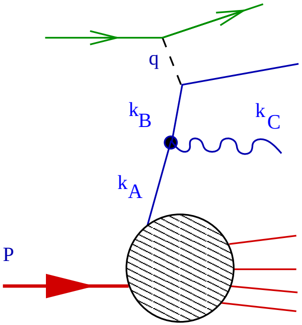

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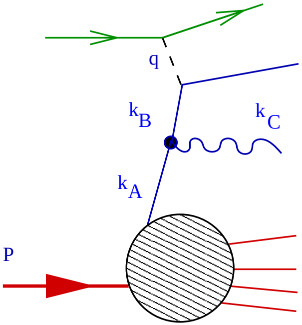

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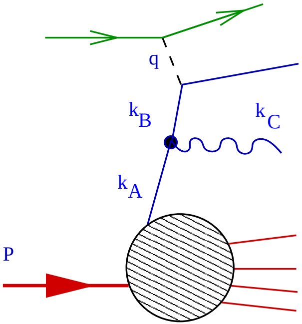

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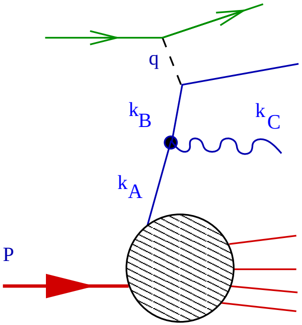

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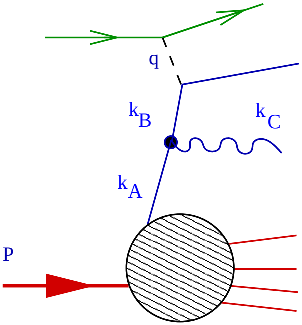

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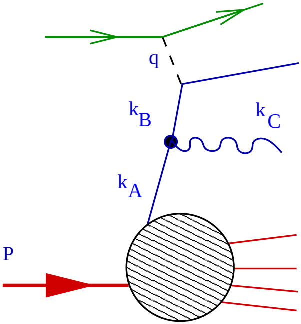
This inequality has a transparent physical meaning:

$$\frac{z \cdot E_A}{|k_B^2|} \ll \frac{E_A}{|k_A^2|}$$

Long-living partons fluctuations



Kinematics of the parton splitting $A \to B + C$

$$k_B \simeq z k_A\,, \quad k_C \simeq (1-z) k_A$$

$$\frac{|k_B^2|}{z} = \frac{|k_A^2|}{1} + \frac{k_C^2}{1-z} + \frac{k_\perp^2}{z(1-z)}$$

Probability of the splitting process :

$$dw \propto \frac{\alpha_s}{\pi} \frac{dk_\perp^2\, k_\perp^2}{(k_B^2)^2} \propto \frac{\alpha_s}{\pi} \frac{dk_\perp^2}{k_\perp^2}\,,$$

$$\frac{|k_B^2|}{z} \simeq \frac{k_\perp^2}{z(1-z)} \gg \frac{|k_A^2|}{1} \left(\text{as well as } \frac{k_C^2}{1-z} \right).$$

This inequality has a transparent physical meaning:

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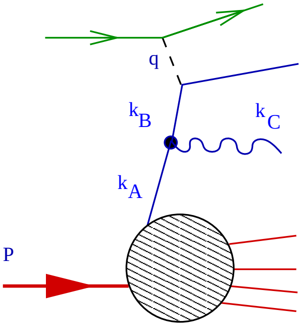

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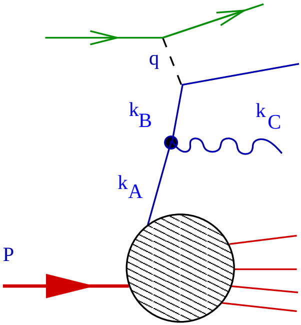
This inequality has a transparent physical meaning:

$$t_B \equiv \frac{E_B}{|k_B^2|} = \frac{z \cdot E_A}{|k_B^2|} \ll \frac{E_A}{|k_A^2|} \equiv t_A$$

Long-living partons fluctuations



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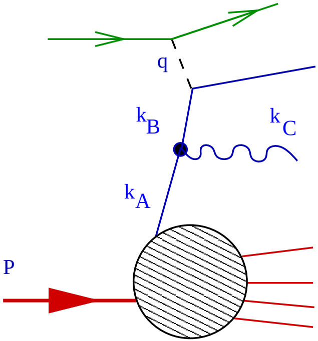
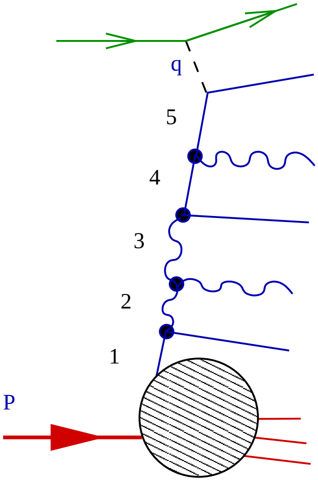
strongly ordered *lifetimes* of successive parton fluctuations !

quark–gluon cascades



So long as probability of one extra parton emission is large, one has to consider and treat *arbitrary number* of parton splittings

quark–gluon cascades



$$\frac{P}{\mu^2} \gg t_1 \gg t_2 \gg t_3 \gg t_4 \gg t_5 \gg \frac{P}{Q^2}$$

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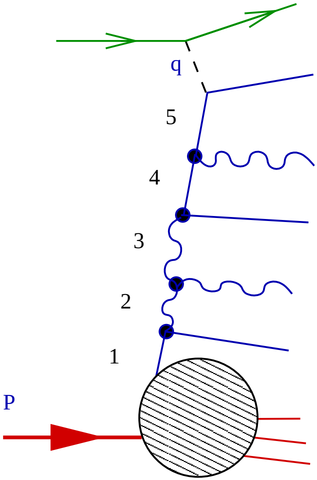

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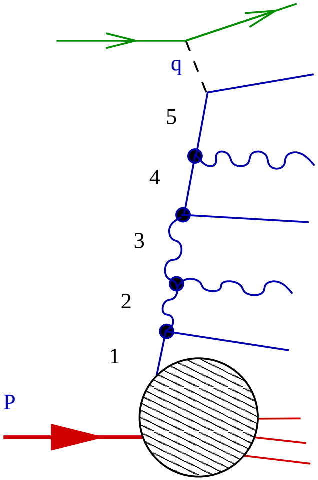
Four basic splitting processes :

quark–gluon cascades



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$q \rightarrow q(z) + g$ $\qquad z = k_5/k_4$

$$\Phi_q^q(z) = C_F \cdot \frac{1+z^2}{1-z},$$

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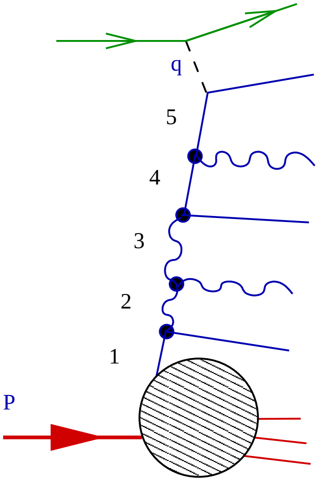

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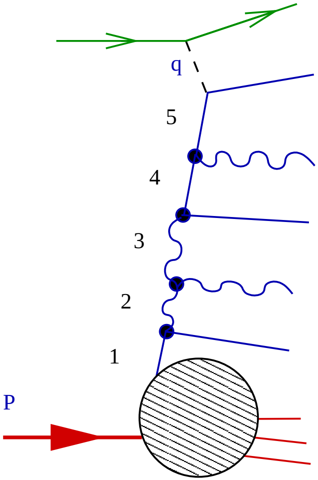

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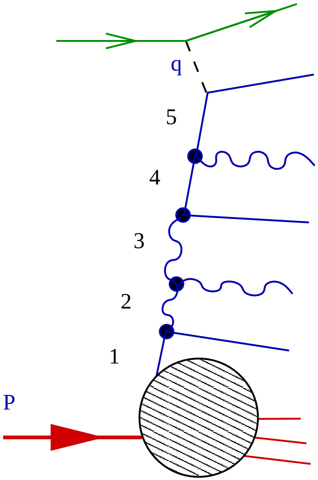

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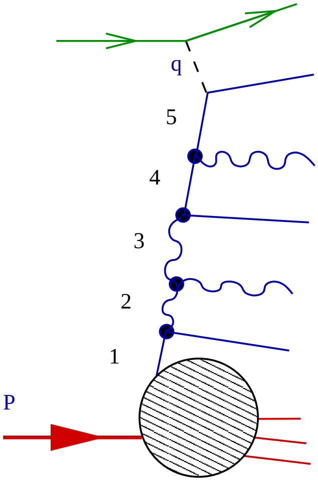

$$\mu^2 \ll k_{1\perp}^2 \ll k_{2\perp}^2 \ll k_{3\perp}^2 \ll k_{4\perp}^2 \ll k_{5\perp}^2 \ll Q^2$$

Four basic splitting processes :

“Hamiltonian” for parton cascades

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Logarithmic “evolution time” $\quad d\xi = \frac{\alpha_s}{2\pi} \frac{dk_\perp^2}{k_\perp^2}$

Relating parton splittings

Nowadays we cannot predict, from the first principles, parton content (B) of a hadron (h). However, perturbative QCD tells us how it *changes* with the resolution of the DIS process – momentum transfer Q^2.

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"wave function"

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"time derivative"

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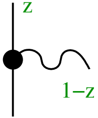
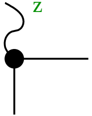
Parton Dynamics turned out to be extremely simple.

Have a deeper look at parton splitting probabilities
– our evolution Hamiltonian –
to fully appreciate the power of the probabilistic
interpretation of parton cascades

Apparent and Hidden symmetries



$$= C_F \cdot \frac{1+z^2}{1-z}$$



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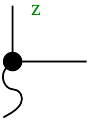
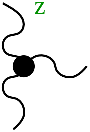


$$= T_R \cdot \left[\, z^2 + (1-z)^2 \,\right]$$

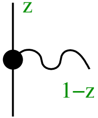


$$= N_c \cdot \frac{1+z^4+(1-z)^4}{z(1-z)}$$

Four "parton splitting functions"

$${}^{q[g]}_{q}(z)\,, \qquad {}^{g[q]}_{q}(z)\,, \qquad {}^{q[\bar{q}]}_{g}(z)\,, \qquad {}^{g[g]}_{g}(z)$$

Apparent and Hidden symmetries



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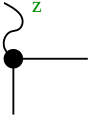

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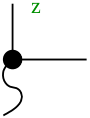

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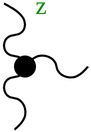
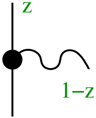


$$= N_c \cdot \frac{1+z^4+(1-z)^4}{z(1-z)}$$

- Exchange the decay products : $z \to 1-z$

${}^{q[g]}_{q}(z) \quad {}^{g[q]}_{q}(z)$ $\qquad$ ${}^{q[\bar{q}]}_{g}(z)$ $\qquad$ ${}^{g[g]}_{g}(z)$

Apparent and Hidden symmetries



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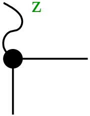

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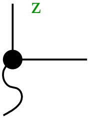

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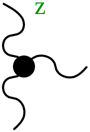

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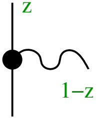
- Exchange the decay products : $z \longrightarrow 1-z$
- Exchange the parent and the offspring : $z \longrightarrow 1/z$

${}^{q[g]}_{q}(z)$ ${}^{g[q]}_{q}(z)\,,\quad {}^{q[\bar{q}]}_{g}(z)$ ${}^{g[g]}_{g}(z)$

Apparent and Hidden symmetries



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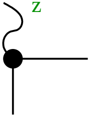

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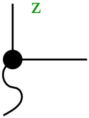

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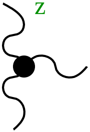

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- Exchange the decay products : $z \to 1-z$
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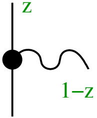
Three (QED) “kernels” are inter-related; gluon self-interaction stays put :

$$\boxed{\, {}^{q[g]}_{q}(z)\,, \quad {}^{g[q]}_{q}(z)\,, \quad {}^{q[\bar{q}]}_{g}(z) \,} \; ; \qquad \boxed{\, {}^{g[g]}_{g}(z) \,}$$

Apparent and Hidden symmetries



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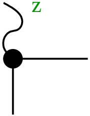

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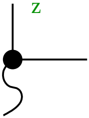

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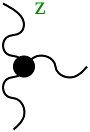

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- Exchange the decay products : $z \to 1-z$
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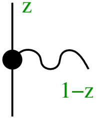
- The story continues, however :

All four are related !

$$w_q(z) = \boxed{\, {}^{q[g]}_{q}(z) + {}^{g[q]}_{q}(z) \;=\; {}^{q[\bar q]}_{g}(z) + {}^{g[g]}_{g}(z) \,} = w_g(z)$$

Apparent and Hidden symmetries



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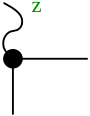

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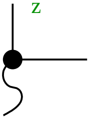

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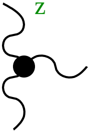

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All four are related !

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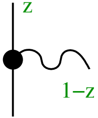

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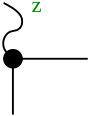

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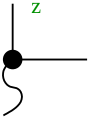
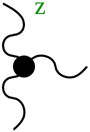


$$= T_R \cdot \left[\, z^2 + (1-z)^2 \,\right]$$



$$= N_c \cdot \frac{1+z^4+(1-z)^4}{z(1-z)}$$

- Exchange the decay products : $z \to 1-z$
- Exchange the parent and the offspring : $z \to 1/z$
- The story continues, however : Super-Symmetry

All four are related ! (*over-constrained* system [+ conformal symm. etc])

$$w_q(z) \;=\; \boxed{\boxed{{}^{q[g]}_{q}(z) + {}^{g[q]}_{q}(z) \;=\; {}^{q[\bar{q}]}_{g}(z)} + \boxed{{}^{g[g]}_{g}(z)}} \;=\; w_g(z)$$

Résumé

Collinear (mass) and soft (infrared) singularities make multi-parton configurations *probable*, in spite of the smallness of the coupling constant α_s, thus forcing us to analyze internal structure of small-distance Hard QCD Processes in *all orders* in perturbation theory. (Ain't easy.)

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Feynman-Bjorken Partons

Quarks inside proton.

They are point-like.

Bjorken scaling.

Probabilistic picture.

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Feynman-Bjorken Partons	QCD Partons
Quarks inside proton.	YES.
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Probabilistic picture.	YES. And a rich one in that.

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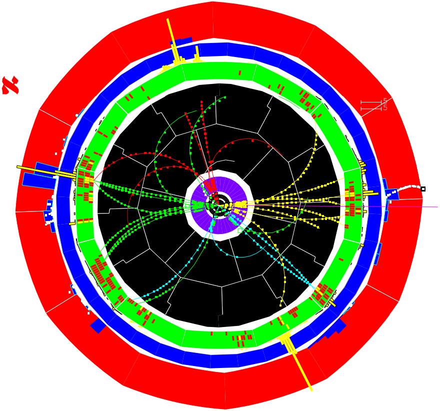
"How do we see and study QCD partons in nature?"

Hadron Jets

and

QCD Radiophysics

Quarks → jets of hadrons



Aleph Higgs event:

- Claim: it corresponds to $ZH \to q\bar{q}b\bar{b}$.
- But actually just bunches ('jets') of hadrons.

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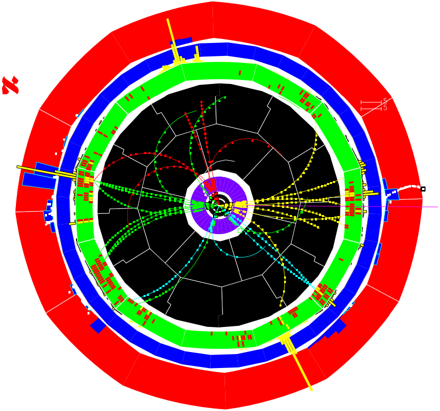

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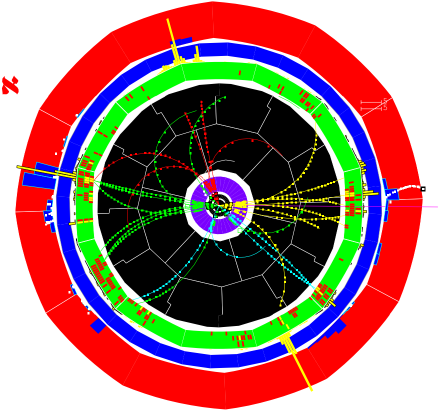

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Need understanding of QCD

Jet as a 'string' of hadrons

Existence of Jets was envisaged from "parton models" in the late 1960's.

Kogut–Susskind vacuum breaking picture :

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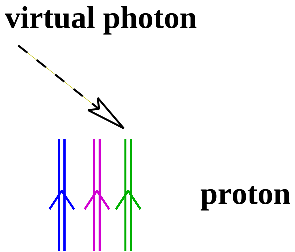

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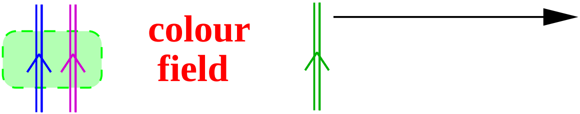

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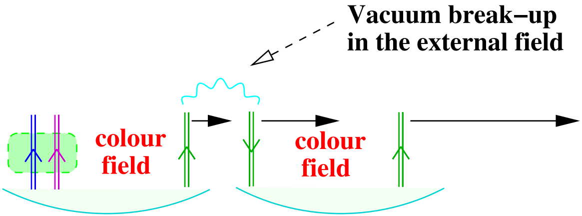

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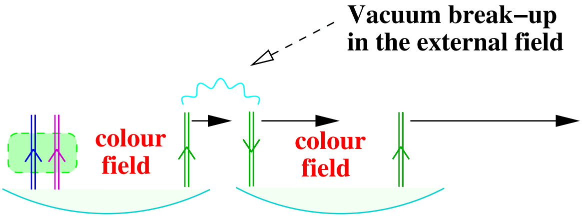
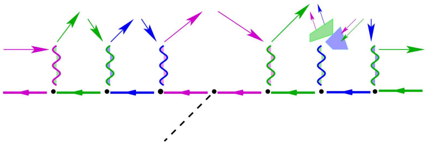


Repeating, one gets the "Feynman Plateau" :

"One" hadron per $\frac{\Delta\omega}{\omega}$; Hadron multiplicity $\propto \ln Q$.

Lund wisdom

Phenomenological realization of the Kogut–Susskind scenario



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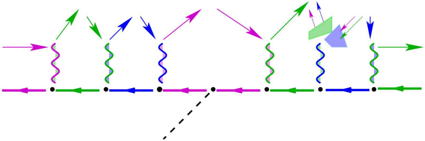

⟹ a "String" of hadrons

The base of the Lund Model

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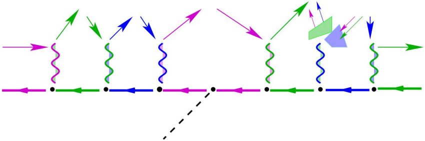

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The base of the Lund Model

The key features of the Lund hadronization model:

- Uniformity in *rapidity*: $dN_h = \text{const} \times \frac{d\omega_h}{\omega_h}$
- Limited $k_\perp$ of hadrons
- Quark combinatorics at work:
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  - *mesons* vs. *baryons*

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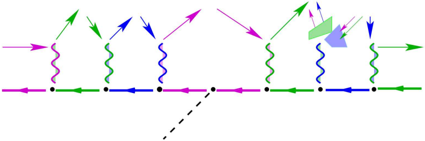

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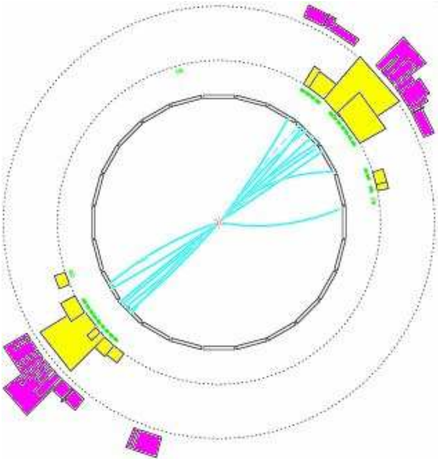
The crucial step: Stress on the *rôle of colour* in multiple hadroproduction

$q\bar{q} \longrightarrow$ hadrons



Near 'perfect' 2-jet event

2 well-collimated jets of particles.

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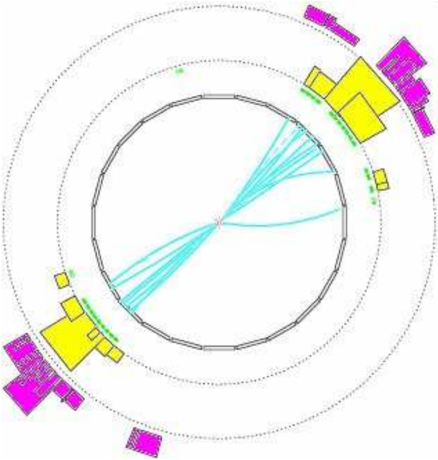

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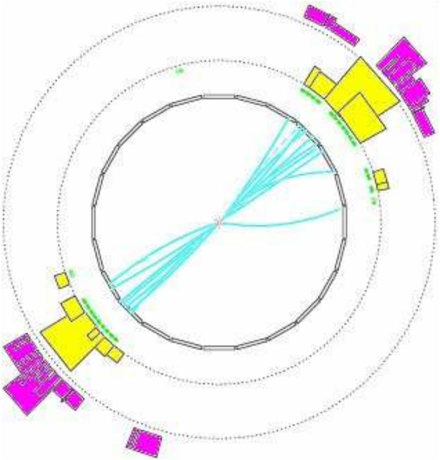

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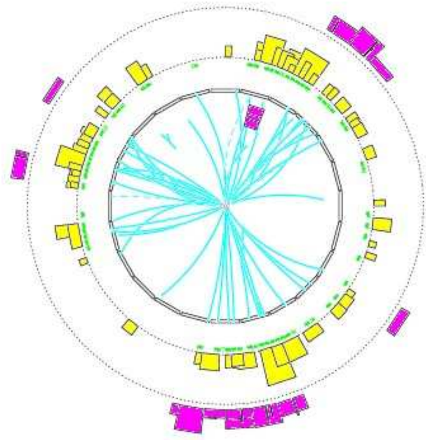
Moreover,

In 10% of e^+e^- annihilation events
— striking fluctuations !

Third jet



By eye, can make out 3-jet structure.

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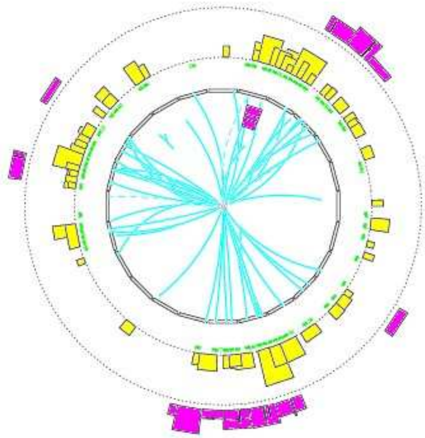

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No surprise : (Kogut & Susskind, 1974)

Hard gluon bremsstrahlung off the $q\bar{q}$ pair *may be expected* to give rise to 3-jet events . . .

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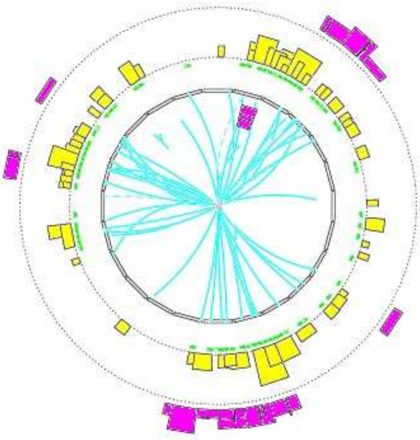

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The first QCD analysis was done by J.Ellis, M.Gaillard & G.Ross (1976)

- Planar events with large $k_\perp$;
- How to measure gluon spin ;
- Gluon jet – softer, more populated.

Gluon $\longrightarrow$ hadrons

QCD possesses $N_c^2 - 1$ gauge fields — vector gluons g.

At large distances, they are supposed to "glue" quarks together.

At small distances (space-time intervals) g is as legitimate a parton as q is.

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B.Andersson, G.Gustafson & C.Peterson, Lund Univ., Sweden (1977)

Gluon $\simeq$ quark-antiquark pair:
$3 \otimes \overline{3} = N_c^2 = 9 \quad \simeq \quad 8 = N_c^2 - 1.$
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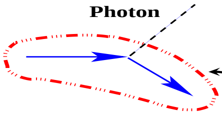
Lund model interpretation of a *gluon* —

Gluon – a "*kink*" on the "string" (colour tube)
that connects the quark with the antiquark

Colour “drag”

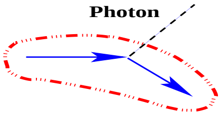
Look at hadrons produced in a $q\bar{q}$+photon e^+e^- annihilation event.

Colour "drag"



Look at hadrons produced in a $q\bar{q}$+photon e^+e^- annihilation event.
The hot-dog of hadrons that was "*cylindric*" in the cms, is now *lopsided* [boosted string]

Colour "drag"



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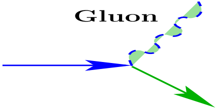

Now substitute a gluon for the photon in the same kinematics.

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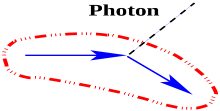

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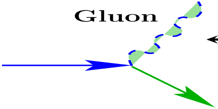

The gluon carries "double" colour charge; quark pair is *repainted* into octet colour state.

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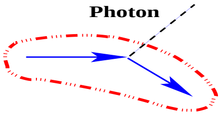

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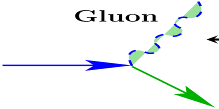

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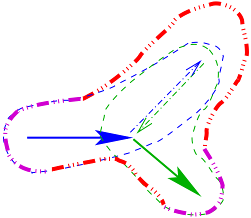

Lund: hadrons = the sum of two independent (properly boosted) colorless substrings, made of

$$q + \tfrac{1}{2}g \quad \text{and} \quad \bar{q} + \tfrac{1}{2}g \,.$$

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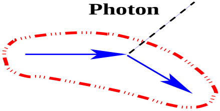

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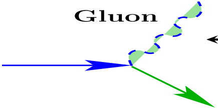

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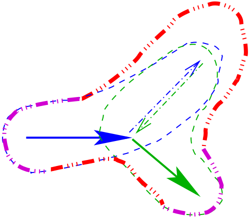
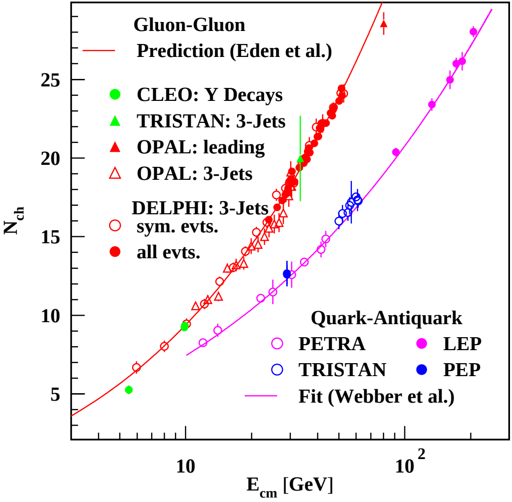


The first immediate consequence :

Double Multiplicity of hadrons
in fragmentation of the *gluon*

Comparing hadron multiplicities



Look at experimental findings

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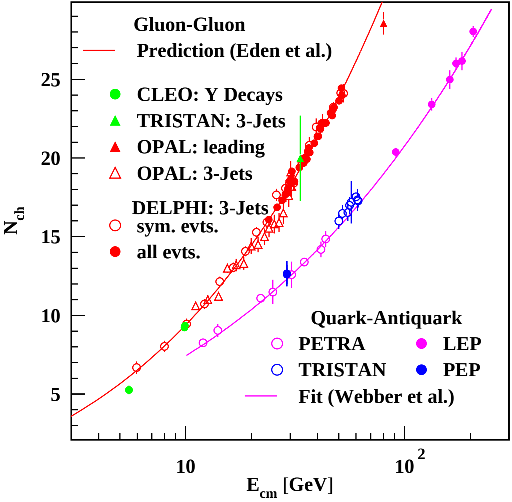

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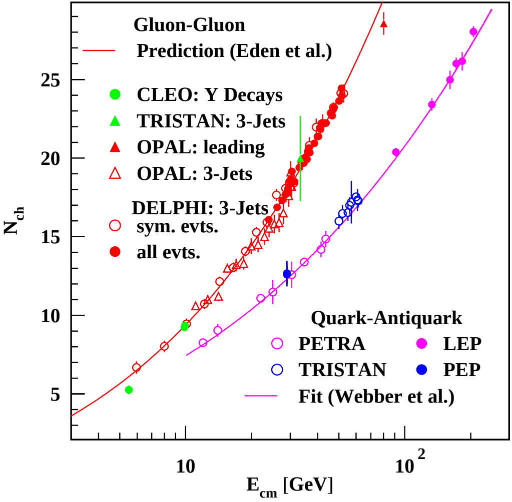

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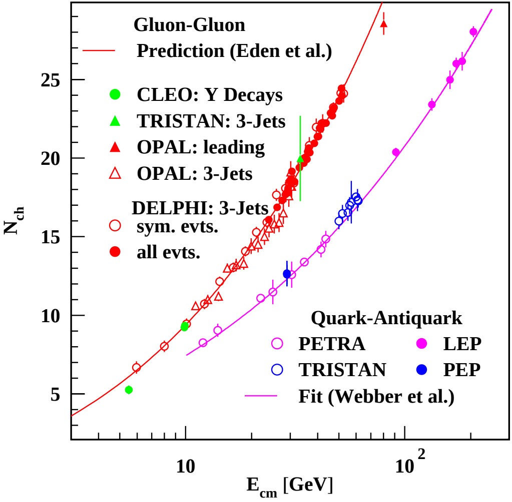

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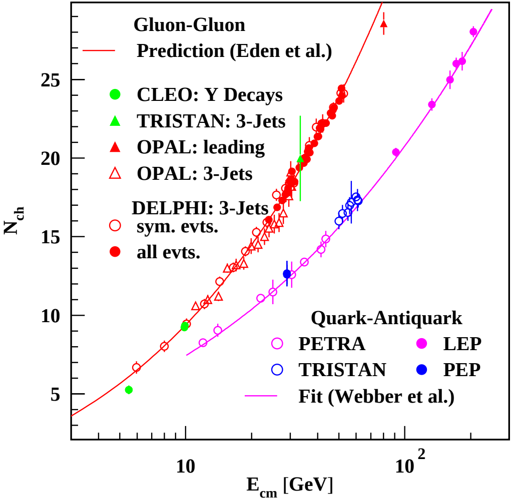

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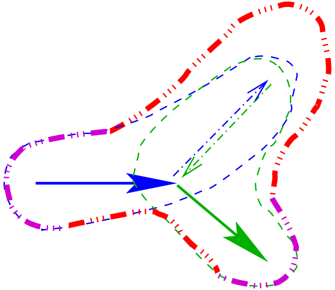
Now let's look at a more subtle consequence of Lund wisdom

Inter-Jet QCD coherence



Lund: final hadrons are given by the sum of two independent substrings made of

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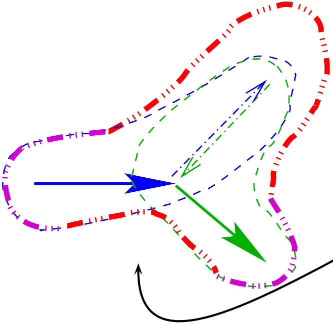

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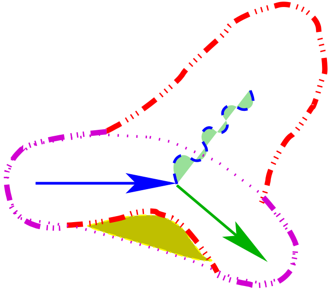

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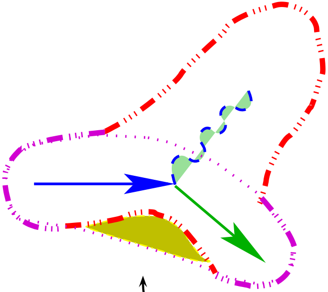

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Destructive interference
from the QCD point of view

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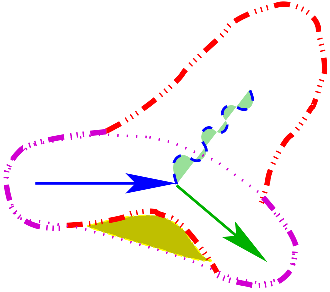

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QCD prediction :

$$\frac{dN_{q\bar{q}}^{(q\bar{q}\gamma)}}{dN_{q\bar{q}}^{(q\bar{q}g)}} \simeq \frac{2(N_c^2-1)}{N_c^2-2} = \frac{16}{7}$$

(experiment: 2.3 ± 0.2)

Ratios of hadron flows between jets in various multi-jet processes — example of non-trivial CIS (collinear-and-infrared-safe) QCD observable

Quantum Mechanics strikes back

Rediscovery of the *quantum-mechanical nature* of gluon radiation played the major rôle in understanding the *internal structure* of jets as well.

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Recall an amazing historical example: Cosmic ray physics (mid 50's); conversion of high energy photons into e^+e^- pairs in the emulsion

Chudakov effect

Charged particle leaves a track of ionized atoms in photo-emulsion.

electron track 

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Photon converts into *two* electric charges : $\gamma \to e^+e^-$.

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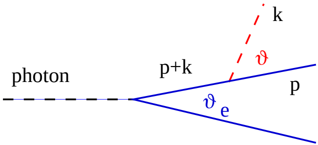
(size of the e^+e^- dipole) is

$\rho_\perp \simeq c\,t \cdot \vartheta_e$



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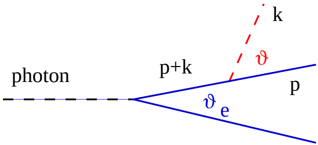

The photon is emitted after the time (lifetime of the virtual $p+k$ state)

$$t \simeq \frac{(p+k)_0}{(p+k)^2} \simeq \frac{p_0}{2p_0k_0(1-\cos\vartheta)} \simeq \frac{1}{k_0\vartheta^2} \simeq \frac{1}{k_\perp}\cdot\frac{1}{\vartheta} = \lambda_\perp \cdot \frac{1}{\vartheta}$$

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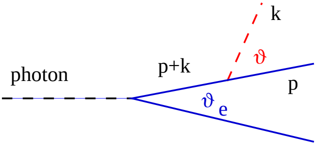
$\vartheta < \vartheta_e$ – independent radiation off e^- & e^+



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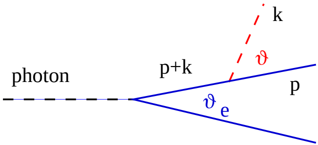

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$\vartheta > \vartheta_e$ – no emission ! $(\rho_\perp < \lambda_\perp)$

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intRA-jet coherence

Angular Ordering is *more restrictive* than the fluctuation time ordering:
$\vartheta \leq \vartheta_e$ versus $\vartheta \leq \vartheta_e \cdot \sqrt{\frac{p_0}{k_0}}$ that follows from (DGLAP)

$$t_\gamma = \frac{p_0}{p_\perp^2} \simeq \frac{1}{p_0 {\vartheta_e}^2} < \frac{1}{k_0 \vartheta^2} \simeq \frac{k_0}{k_\perp^2} = t_e$$

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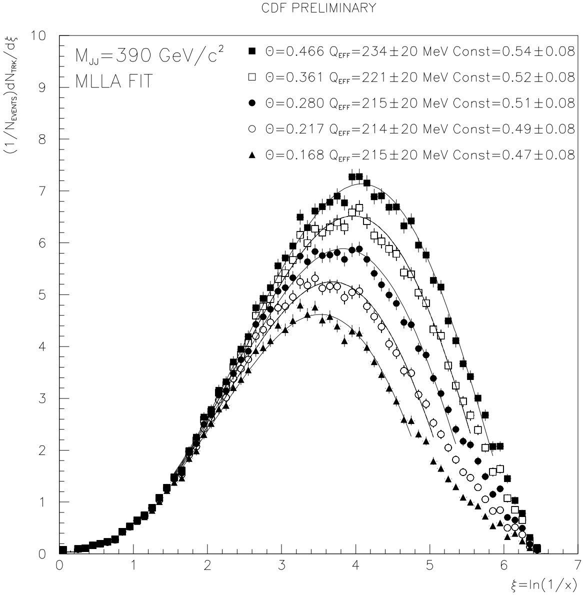
while the softest particles (that seem to be the easiest to produce) should not multiply at all !

Hump-backed plateau



First confronted with theory in $e^+e^- \to h+X$.

CDF (Tevatron)

$pp \to 2$ jets

Charged hadron yield as a function of $\ln(1/x)$ for different values of jet hardness, versus (MLLA) QCD prediction.

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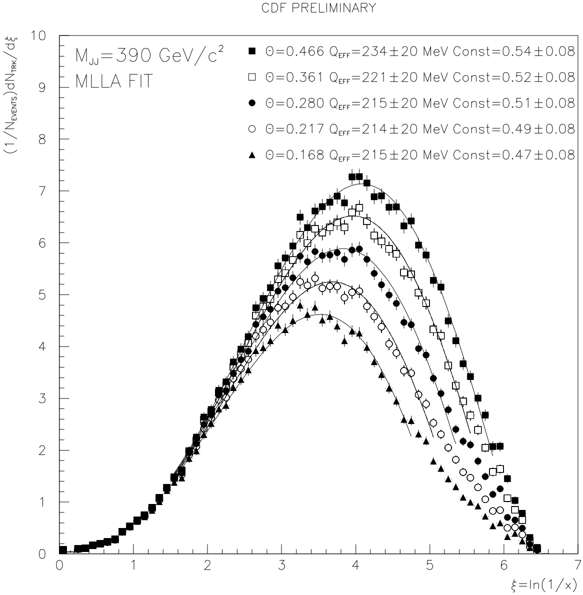

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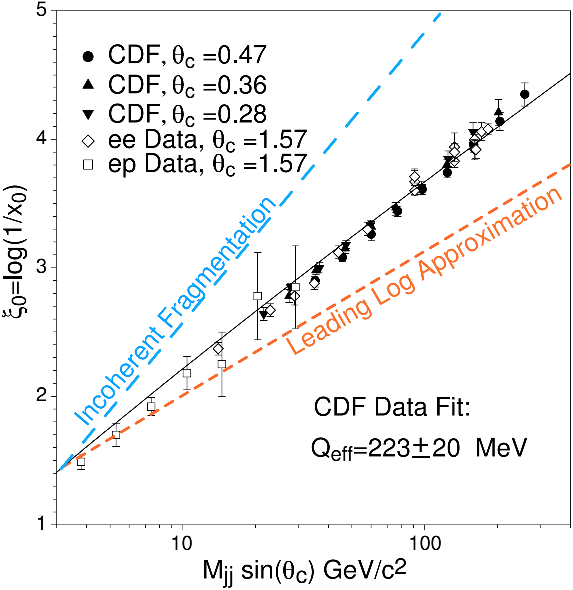
One free parameter – overall normalization (the number of final π's per extra gluon)

Hump (continued)



Position of the Hump as a function of

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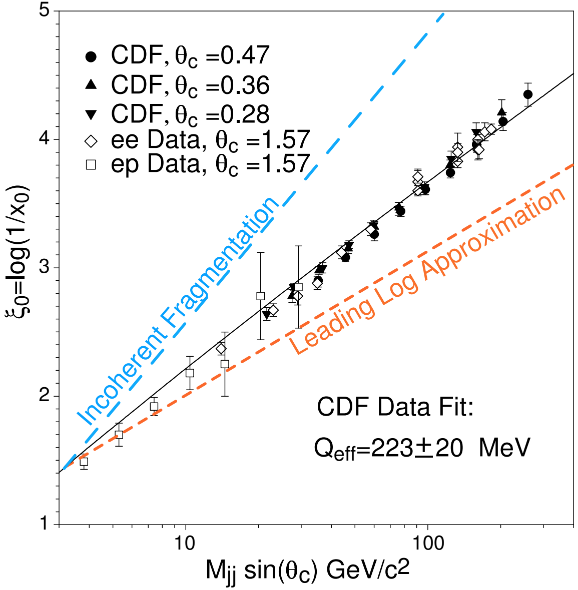

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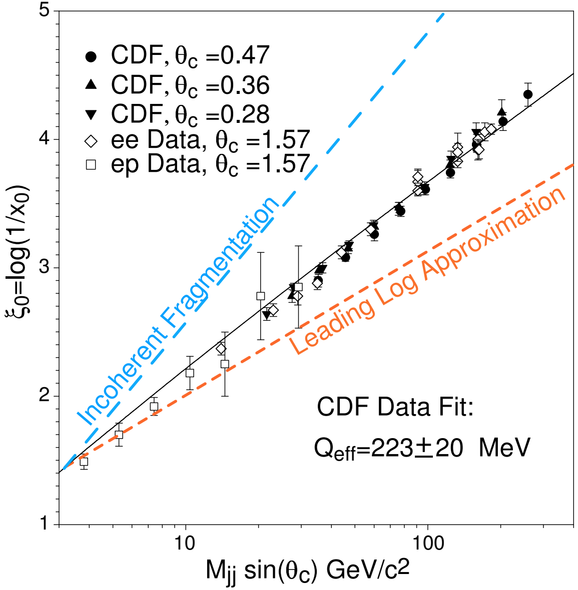

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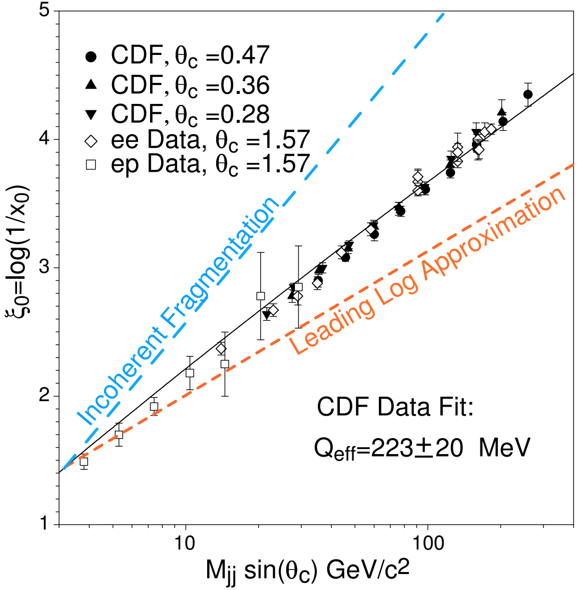

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Mark Universality:
same behaviour seen in e^+e^-, DIS (ep), hadron–hadron coll.

Soft Confinement

So, the *ratios* of particle flows between jets (intERjet radiophysics), as well as the *shape* of the inclusive energy spectra of secondary particles (intRAjet cascades) turn out to be formally calculable (CIS) quantities. Moreover, these perturbative QCD predictions actually work.

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At the same time, it sends us a powerful message: confinement – transformation of quarks and gluons into hadrons – has a *non-violent* nature: there is no visible reshuffling of energy–momentum at the hadronization stage. Known under the name of the *Local Parton-Hadron Duality hypothesis* (LPHD), explaining this phenomenon remains *a challenge* for the future quantitative theory of colour confinement.

LPHD gift

Both Inter-Jet and Intra-Jet phenomena fully reveal colour coherence in QCD parton multiplication. Their solid imprint upon the *angular* and *energy* spectra of *relatively soft hadrons* are sending us a powerful message (— a free lunch that we have not found enzymes yet to devour)

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- ☛ what is it,
- ☛ *what do we know* about it,
- ☛ and, more importantly, *what we don't*

BRIGHT IDEA

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Explore collisions with, and of, nuclei to study non-perturbative — large — colour fields

EXTRAS

Soft gluons

We spoke about the *Collinear* enhancement in $1 \to 2$ parton splittings.

Radiation of gluons is enhanced even stronger :

$$dw[A \to A + g(z)] \propto C_A \cdot dz \left[\frac{2(1-z)}{z} + \mathcal{O}(z) \right]$$

We are facing an additional *Soft* (infra-red) enhancement which is characteristic for small-energy *vector* fields (photons, gluons), $z \ll 1$.

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Ain't any "catastrophe" but a simple consequence of the fact that any charged particle is always surrounded by a long-range Coulomb field which gets *shaken off* when the charge is accelerated.
As a result,

$$w_A \sim C_A \frac{\alpha_s}{\pi} \ln^2 Q^2 . \qquad [\text{parton multiplicities, form factors, etc.}]$$

Soft gluons

We spoke about the *Collinear* enhancement in $1 \to 2$ parton splittings. Radiation of gluons is enhanced even stronger :

$$dw[A \to A + g(z)] \propto C_A \cdot dz \left[\frac{2(1-z)}{z} + \mathcal{O}(z) \right]$$

We are facing an additional *Soft* (infra-red) enhancement which is characteristic for small-energy *vector* fields (photons, gluons), $z \ll 1$.

Divergence of the total emission probability at $z \to 0$ is known (from the good old QED times) under the catchy name of "Infra-Red catastrophe".

An important remark :

soft gluon radiation has a *classical nature* (celebrated F.Low theorem).

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This statement has rather *dramatic consequences* which still remain to be properly digested by the theoretical community . . .