Story of QCD partons: old, recent, new

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Asymptotic Freedom

and

QCD Partons

Running coupling

The strong coupling, α_s, *runs:*

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

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

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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- Moreover, it was long thought to be *inevitable* as corresponding to the physics of 'screening'.
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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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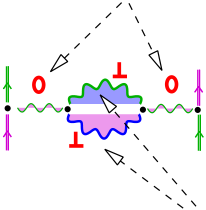
Instantaneous Coulomb interaction



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

Transverse gluons **(and quarks)**

screening

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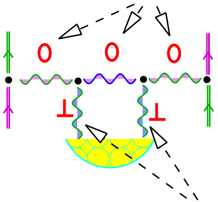

$$= +N_c * 4$$

Vacuum fluctuations of transverse fields

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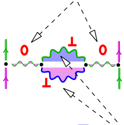

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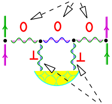

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Vacuum fluctuations of transverse fields

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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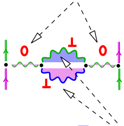

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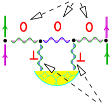

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The origin of *antiscreening* — deepening of the ground state under the 2nd order perturbation in NQM:

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

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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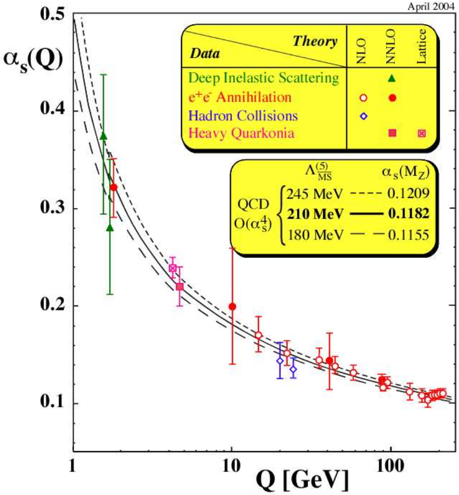

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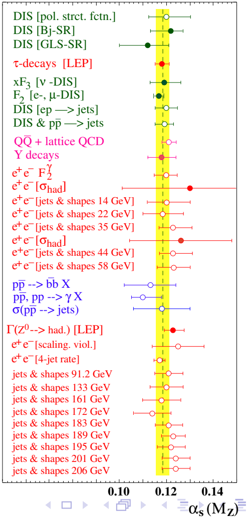

Hard QCD interactions

$\boxed{\text{Hit hard to see what is it there } \textit{inside}}$ (a childish but productive idea)

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Heat the *Vacuum*

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

Hard QCD interactions

$\boxed{\text{Hit hard to see what is it there } \textit{inside}}$

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

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- Deep Inelastic lepton-hadron Scattering (DIS) : $e^-p \to e^- + X$.

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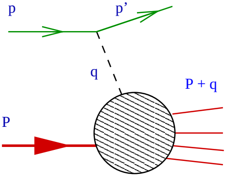
$\boxed{\text{Momentum transfer} = \text{measure of ``}\textit{hardness}\text{''}}$

Deep Inelastic lepton-proton Scattering



Bit of kinematics: invariant mass of final hadrons

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

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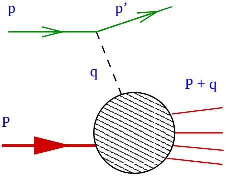

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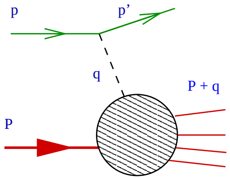

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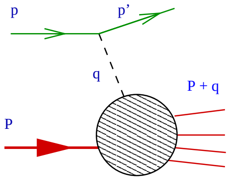

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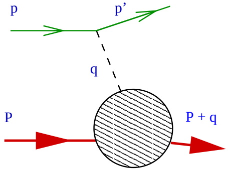

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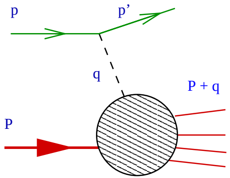

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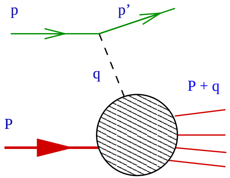

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What to expect for *elastic* and *inelastic* proton Form Factors $F^2(q^2)$?

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?)

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

– 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)

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

– there *are* points (quarks) inside proton, *but* the hit quark behaves as a *free* particle that flies away without caring about confinement.

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Bjorken scaling: Partons

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

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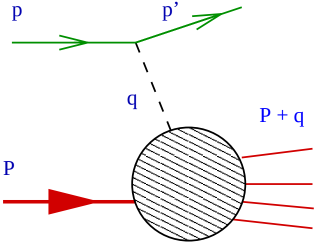

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Inelastic electron–proton scattering

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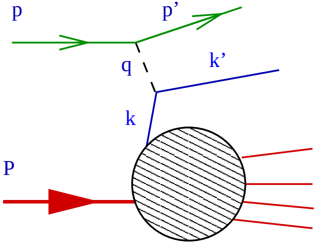

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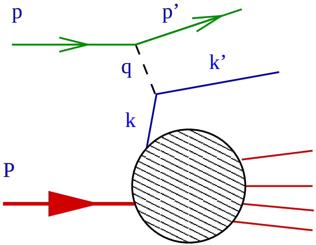

Let the parton carry a finite fraction of the proton momentum $k \simeq z \cdot P \quad (k^2 \simeq 0)$

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

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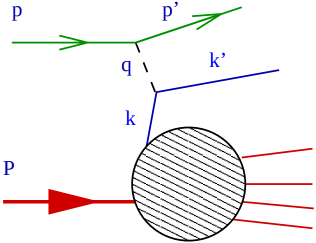

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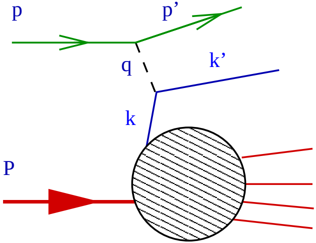

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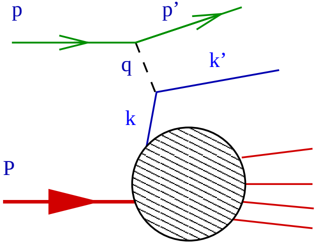

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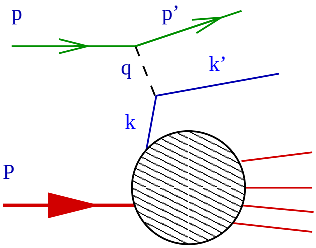
Existence of the *limiting* distribution

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

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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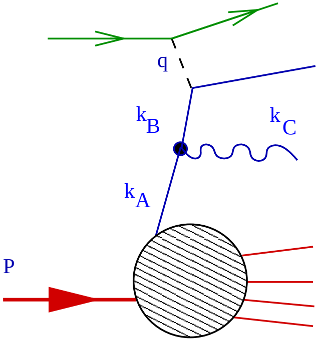

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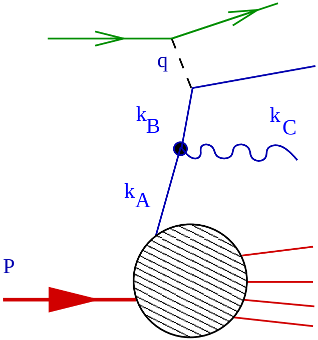

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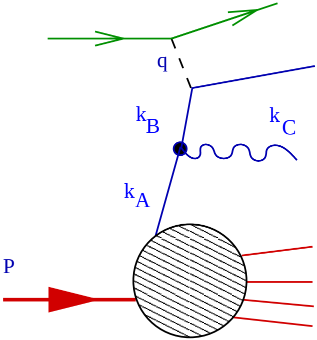

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Physically, a QFT particle is surrounded by a *virtual coat*; its visible content depends on the *resolution power* of the probe $\lambda = \frac{1}{Q} = \frac{1}{\sqrt{-q^2}}$

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 . . .

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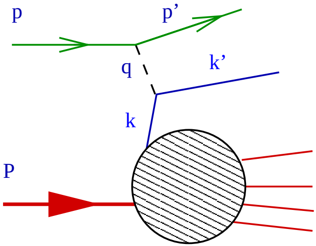
Long-living partons fluctuations



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

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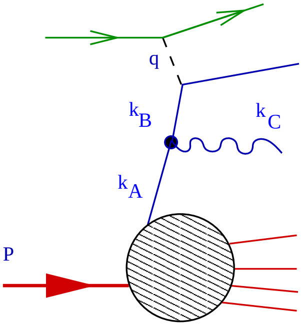

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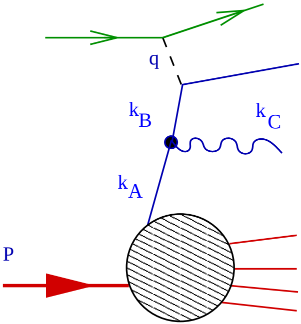

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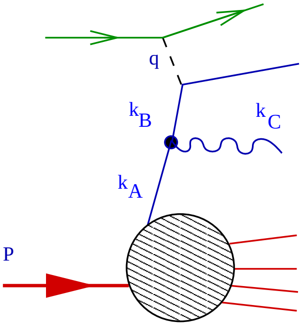

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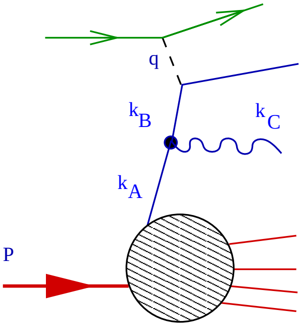

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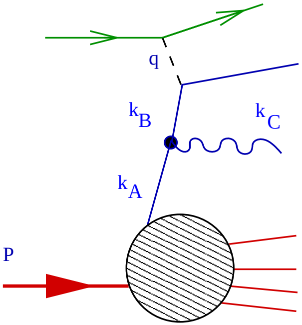

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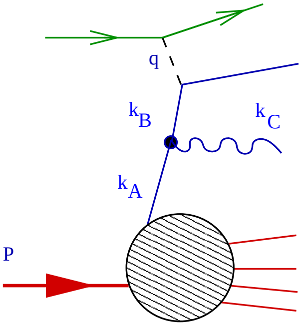

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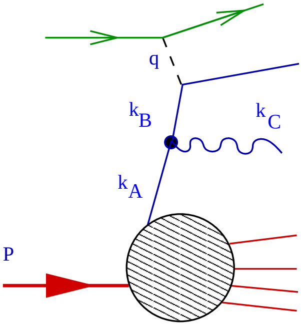

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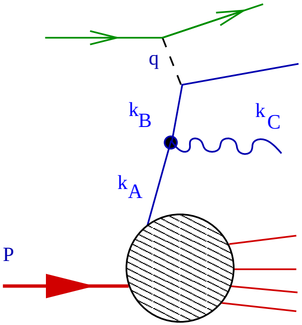

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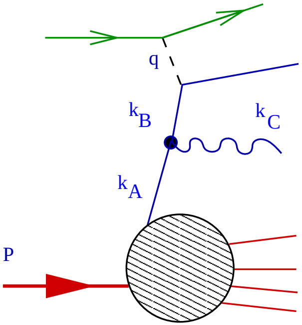

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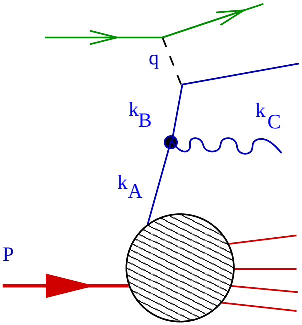

Kinematics of the parton splitting $A \to B + C$

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

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

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:

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

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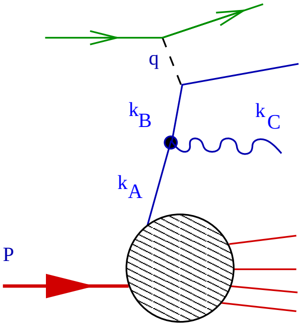

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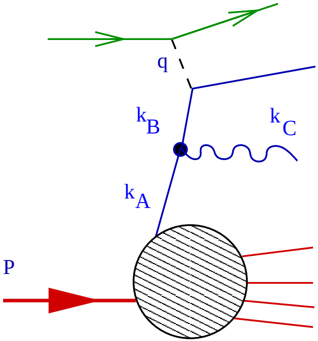
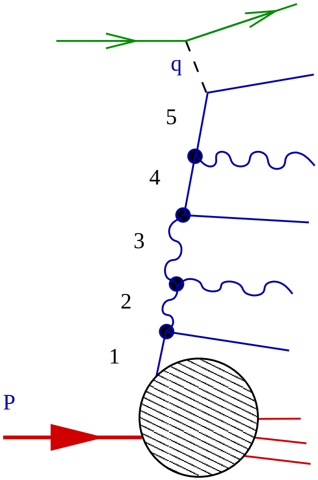
$\boxed{\text{strongly ordered } \textit{lifetimes} \text{ of successive parton fluctuations !}}$

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



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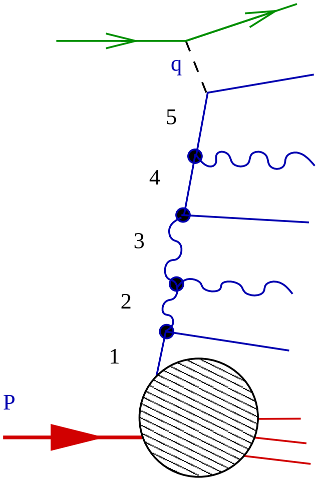

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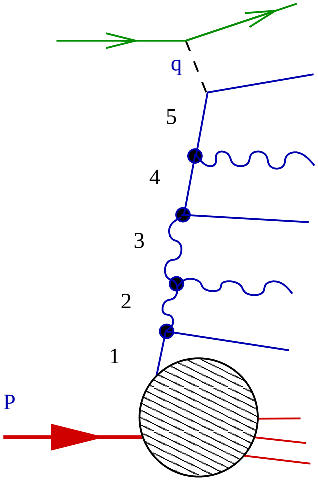

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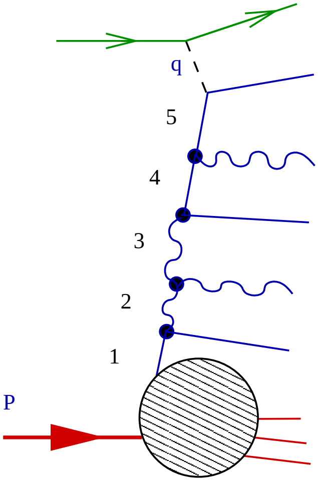

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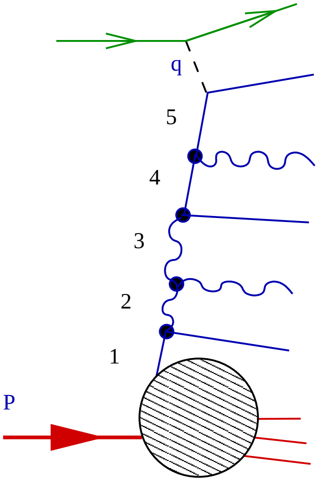

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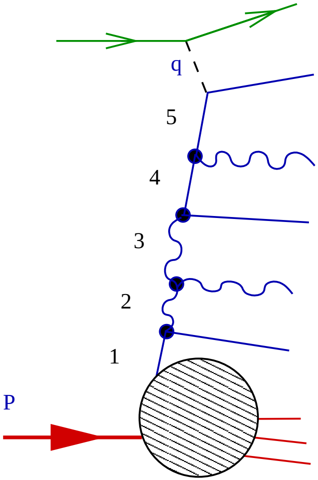

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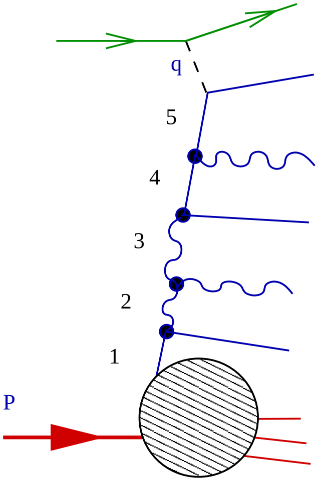

$$\mu^2 \ll k_{1\perp}^2 \ll k_{2\perp}^2 \ll k_{3\perp}^2 \ll k_{4\perp}^2 \ll k_{5\perp}^2 \ll Q^2$$

Four basic splitting processes :

"Hamiltonian" for parton cascades

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

Evolution

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.

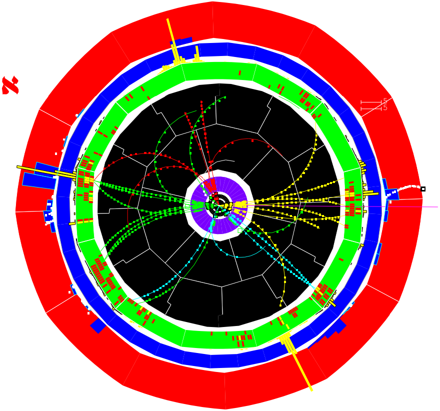
Hidden symmetries of the QCD evolution
may eventually allow one to "exactly solve"
the major part of parton dynamics

Hadron Jets

and

QCD Radiophysics

Quarks $\longrightarrow$ jets of hadrons



Aleph Higgs event:

- Claim: it corresponds to $ZH \to q\bar{q}b\bar{b}$.
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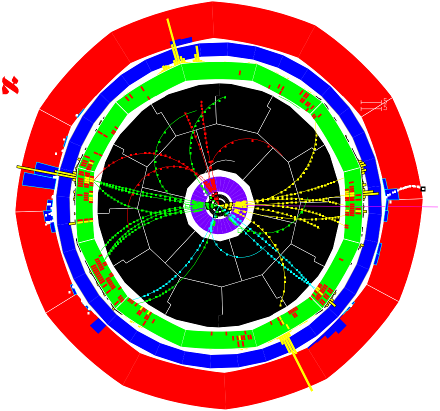

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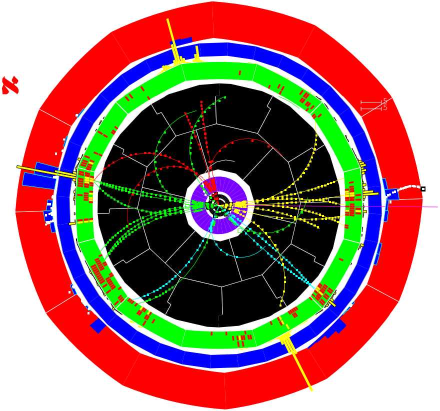

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Need understanding of QCD

Jet as a 'string' of hadrons

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Kogut–Susskind vacuum breaking picture :

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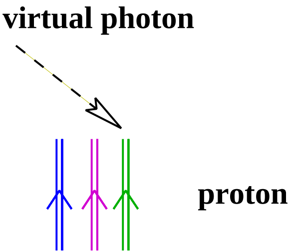

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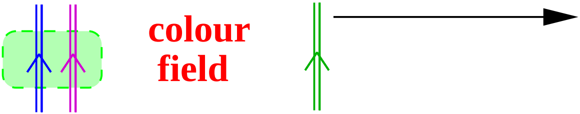

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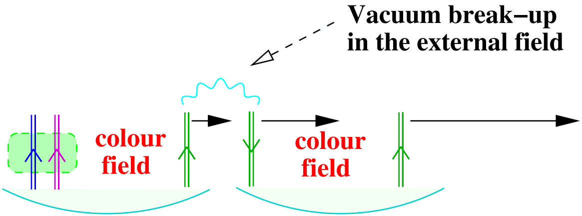

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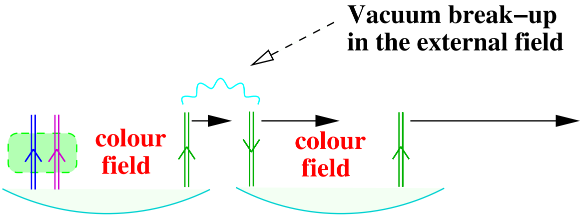
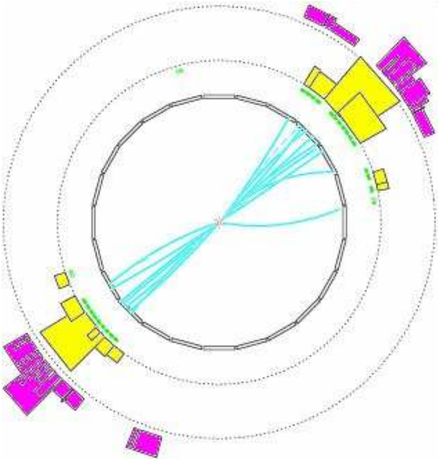


Repeating, one gets the "Feynman Plateau" :

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

$q\bar{q} \longrightarrow$ hadrons



Near 'perfect' 2-jet event

2 well-collimated jets of particles.

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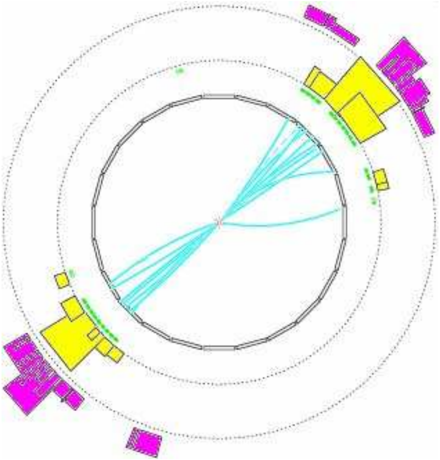

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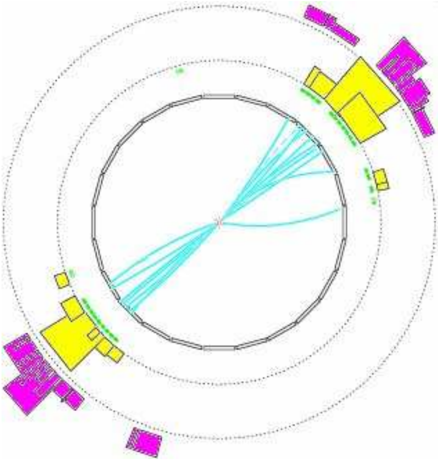

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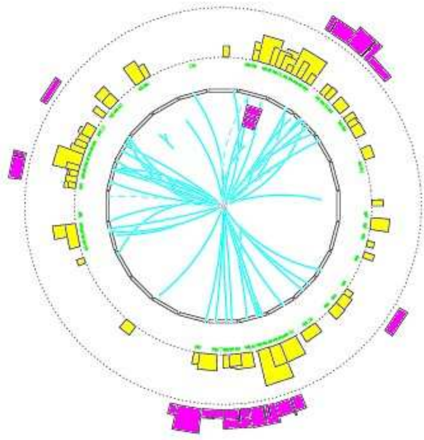
Moreover,

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

Third jet



By eye, can make out 3-jet structure.

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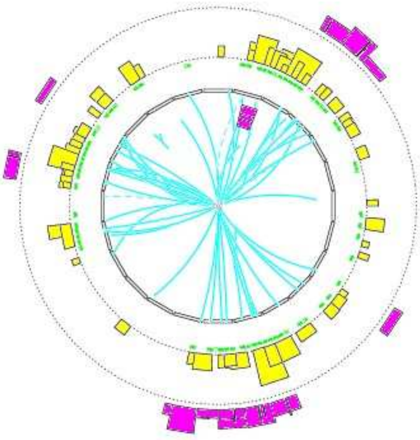

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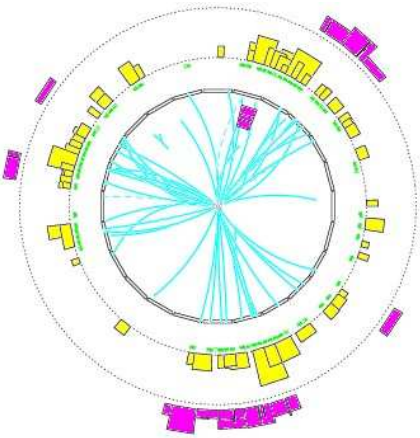

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The first QCD analysis was done by J.Ellis, M.Gaillard & G.Ross (1976)

- 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.

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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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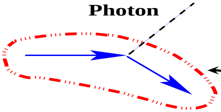
Lund model interpretation of a *gluon* —

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]

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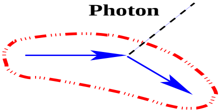

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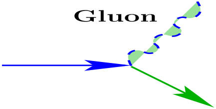

Now substitute a gluon for the photon in the same kinematics.

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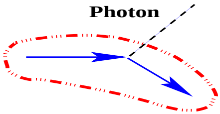

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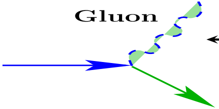

The gluon carries “double” colour charge; quark pair is *repainted* into octet colour state.

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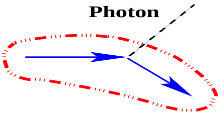

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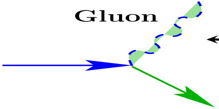

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Lund: hadrons = the sum of two independent (properly boosted) colorless substrings, made of

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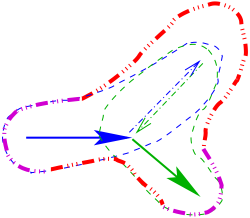
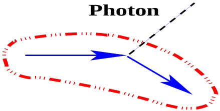
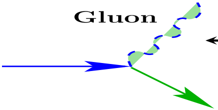


Colour "drag"



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



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

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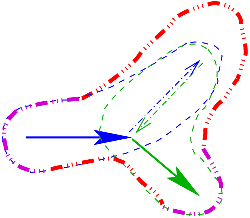
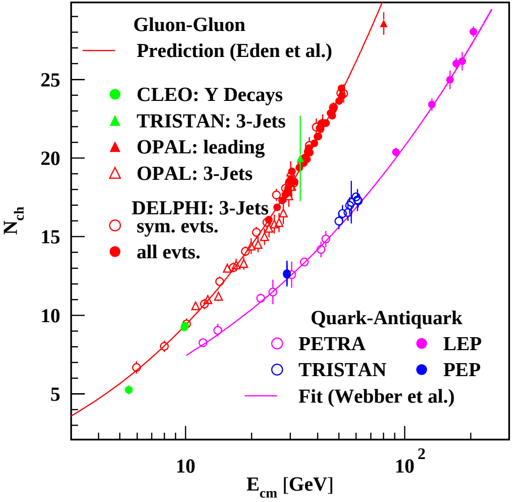


The first immediate consequence :

Double Multiplicity of hadrons
in fragmentation of the *gluon*

Comparing hadron multiplicities



Look at experimental findings

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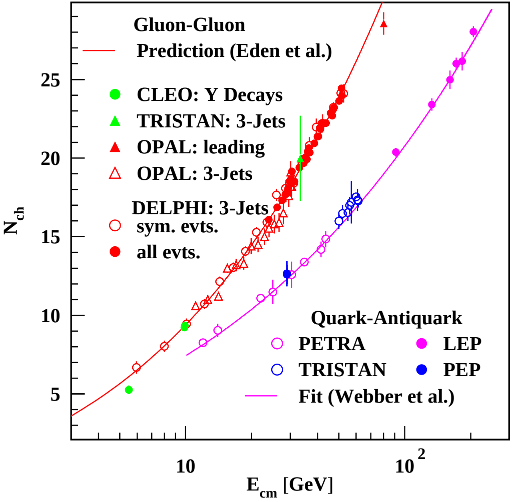

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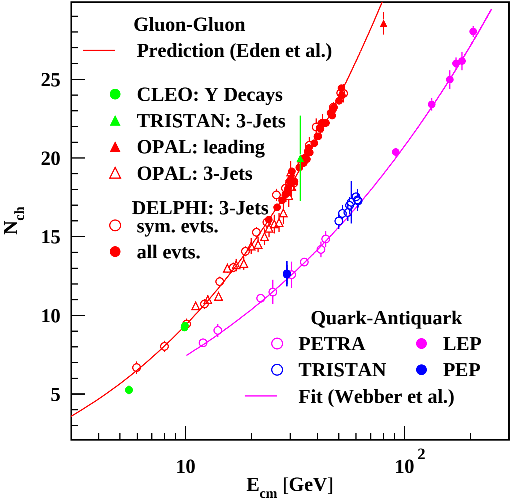

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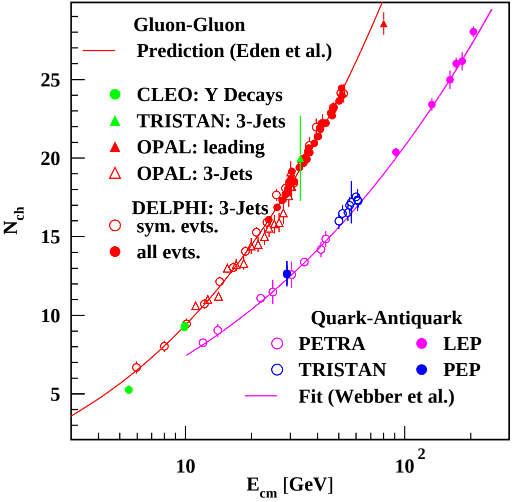

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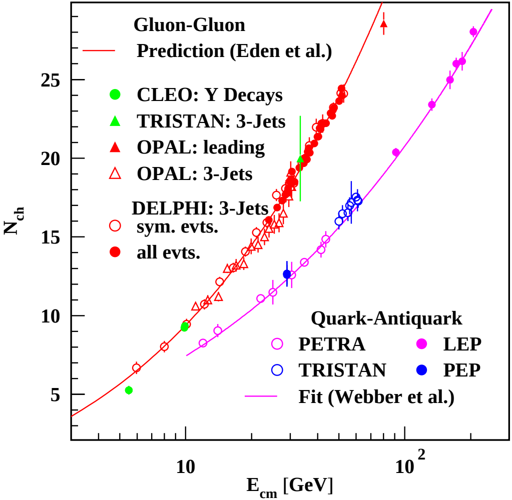

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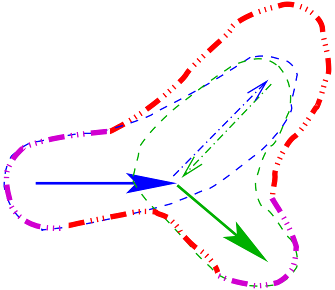
Now let's look at a more subtle consequence of Lund wisdom

Inter-Jet QCD coherence



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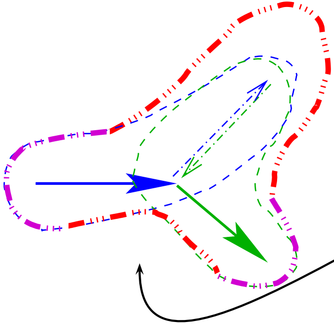

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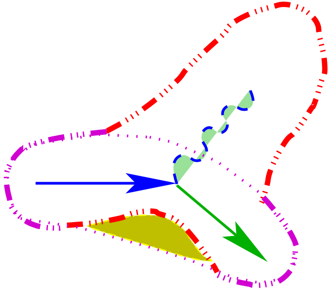

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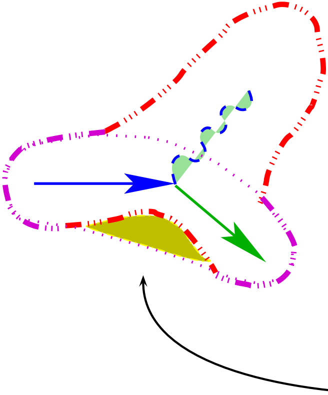

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Destructive interference
from the QCD point of view

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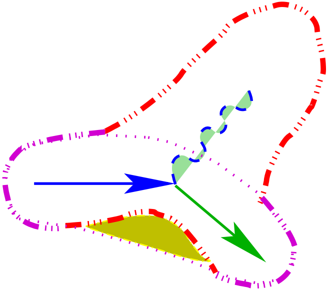

QCD prediction :

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

(experiment: 2.3 ± 0.2)

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from the QCD point of view

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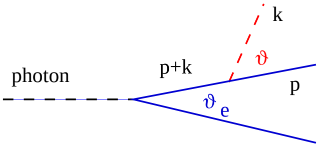
(size of the e^+e^- dipole) is

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



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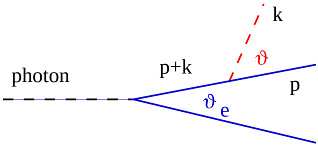

The photon is emitted after the time (lifetime of the virtual $p+k$ state)

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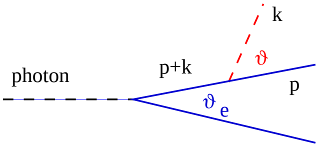
$\vartheta < \vartheta_e$ – independent radiation off e^- & e^+



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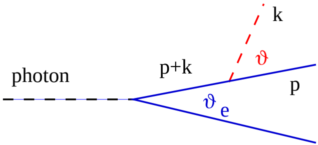

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$\vartheta > \vartheta_e$ – no emission ! $(\rho_\perp < \lambda_\perp)$

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intRA-jet coherence

Angular Ordering is *more restrictive* than the fluctuation time ordering:
$\vartheta \le \vartheta_e$ versus $\vartheta \le \vartheta_e \cdot \sqrt{\frac{p_0}{k_0}}$ 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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Significant difference when $k_0/p_0 = x \ll 1$ (soft radiation).

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$$(\ln k)_{\max} = \left(\frac{1}{2} - c \cdot \sqrt{\alpha_s(Q)} + \ldots\right) \cdot \ln Q\,, \qquad k_{\max} \simeq Q^{0.35}$$

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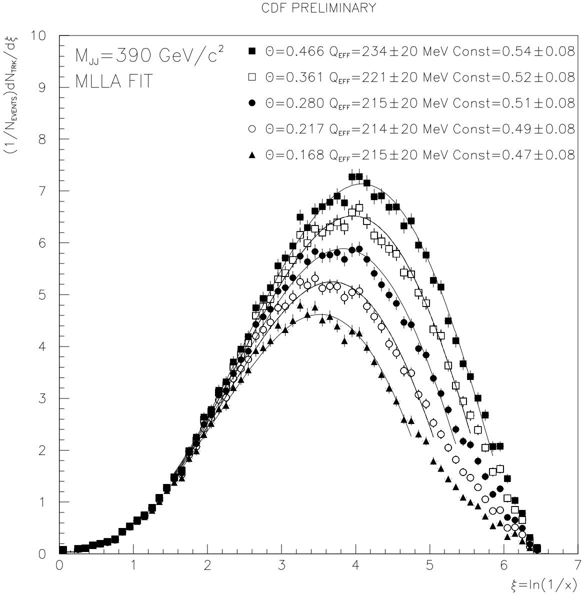
while the softest particles (that seem to be the easiest to produce) should not multiply at all !

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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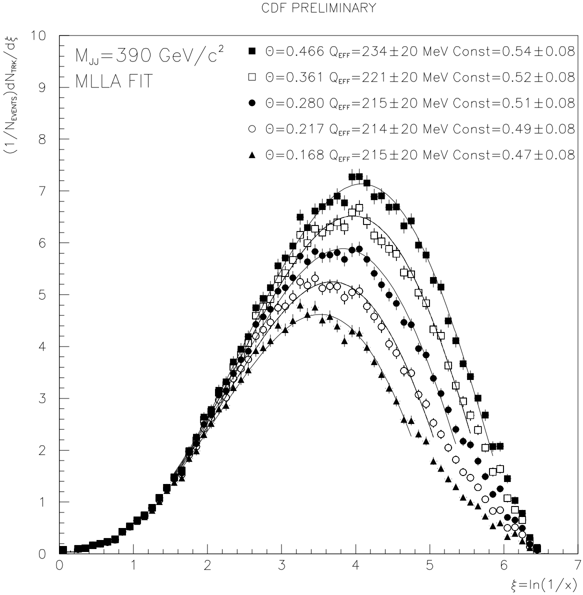

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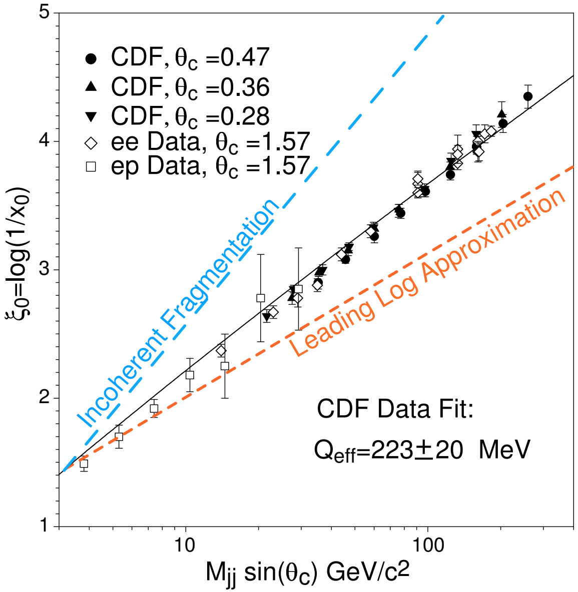
One free parameter – overall normalization (the number of final π's per extra gluon)

Hump (continued)



Position of the Hump as a function of

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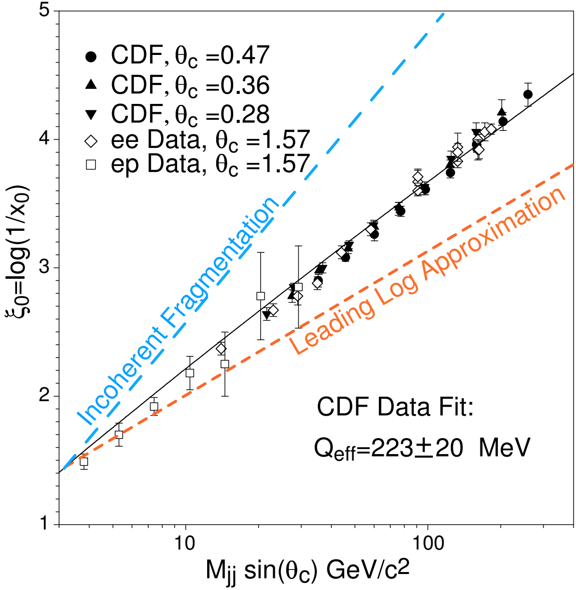

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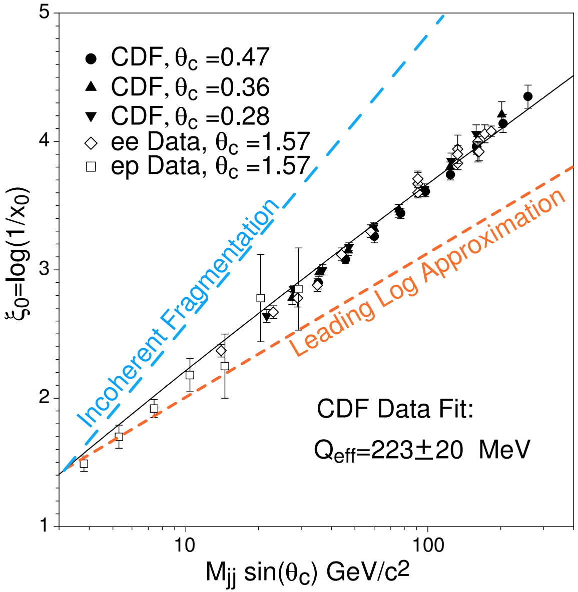

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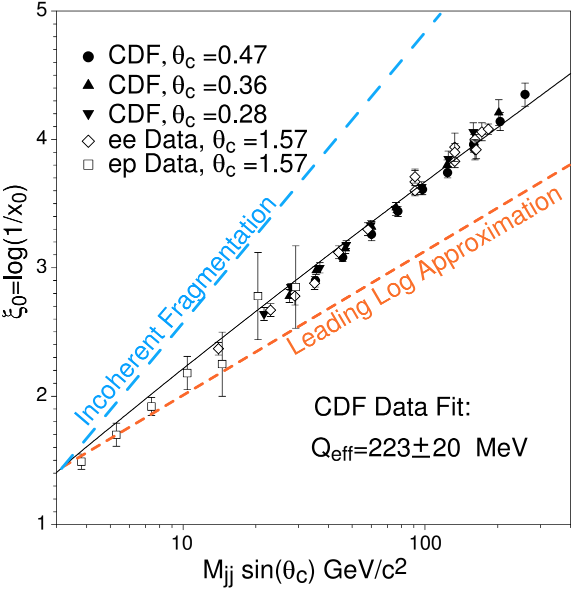

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Mark Universality:
same behaviour seen in e^+e^-, DIS (ep), hadron–hadron coll.

Soft Confinement

So, the *ratios* of particle flows between jets (intERjet radiophysics),
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We should rather feel *puzzled* than satisfied.

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Screwing Non-Perturbative QCD

with

Perturbative Tools

Event Shape observables

There is a specific (though not too narrow a) class of QCD observables that taught us a thing or two about genuine non-perturbative effects in multiple production of hadrons in hard processes. Among them — the so called *event shapes* which measure global properties of final states (jet profiles) in an inclusive manner.

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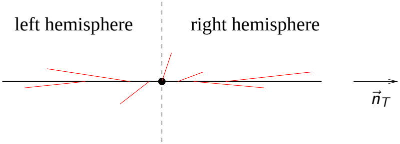

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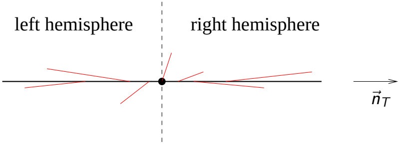

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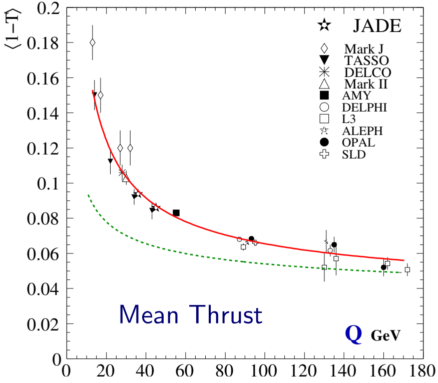
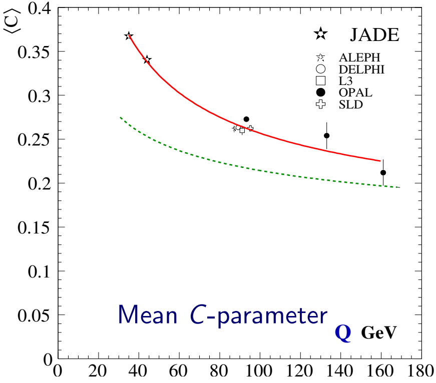
They are formally calculable in pQCD (being collinear and infrared safe) but possess large non-perturbative $1/Q$–suppressed corrections.

$1/Q$ Confinement effects in mean shapes





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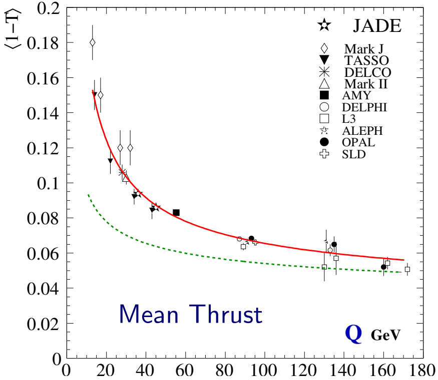

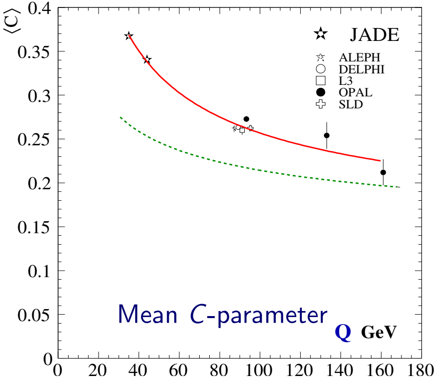

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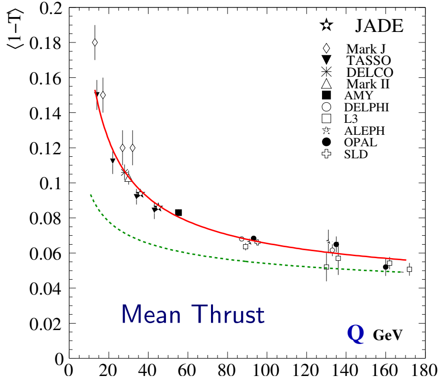

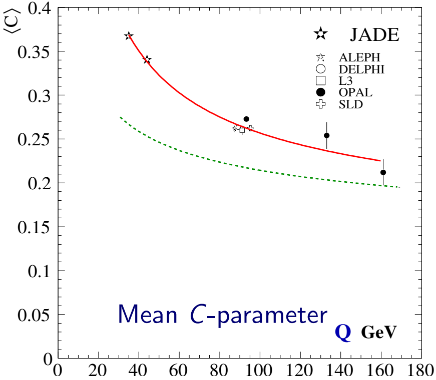

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"p" QCD
theory
8 years old
and
running

$$\left\{ \frac{4}{1} \Longrightarrow \frac{3\pi}{2} \right.$$

Non-perturbative Games

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Let's have a brief NP look at these

NP power corrections

This "industry-standard" way of fitting event-shape power corrections exploits the idea that the power correction is driven by the NP modification of the QCD coupling in the InfraRed:

$$\delta\mathcal{V}_p = \frac{2C_F}{\pi}\int_0^{\mu_I}\frac{dm}{m}\cdot\left(\frac{m}{Q}\right)^p\cdot\left(\alpha_s(m^2)-\alpha_s^{PT}(m^2)\right)\cdot c_{\mathcal{V}}$$

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Thus, one has to compare next-to-leading PT + NP predictions to data, fitting for $\alpha_s(Q^2)$ and α_0 (IR-average coupling), in a hope to see that both α_s and α_0 will turn out to be *independent of the observable*.

This Universality Hypothesis is the key ingredient of the game: the new NP parameter α_0 must inherit the *universal nature* of the QCD coupling itself.

The *power-corrections-to-event-shapes* business underwent quite an evolution. Its dramatic element was laregly due to impatience of experimenters who were too fast to feast on theoretical predictions before those could possibly reach a "*well-done*" cooking status.

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NP effects in means and distributions

This is as far as event shape *mean values* $\langle \mathcal{V} \rangle$ go, plus similar – and consistent – results from (theoretical and experimental) DIS jet studies.

The same technology is applicable to event shape *distributions*, $dN/d\mathcal{V}$. Here the genuine NP physics manifests itself, basically, in *shifting* the PT spectra, in $\mathcal{V}$ variable, by an amount propotional to $1/Q$ (D & Webber 1997)

Distributions turned out to be an important addition to the menu.

- Firstly, functions are more informative and revealing than numbers.
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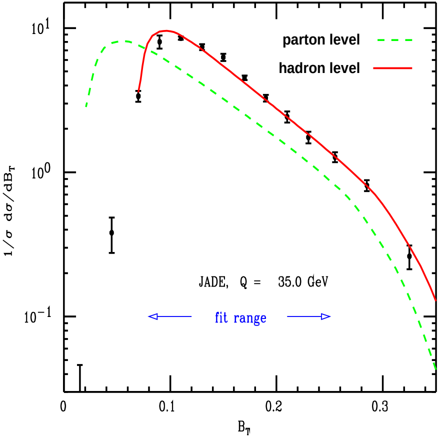

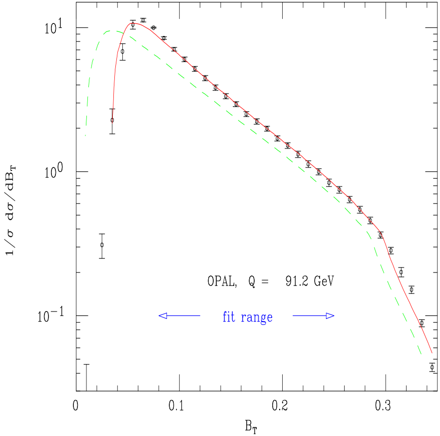

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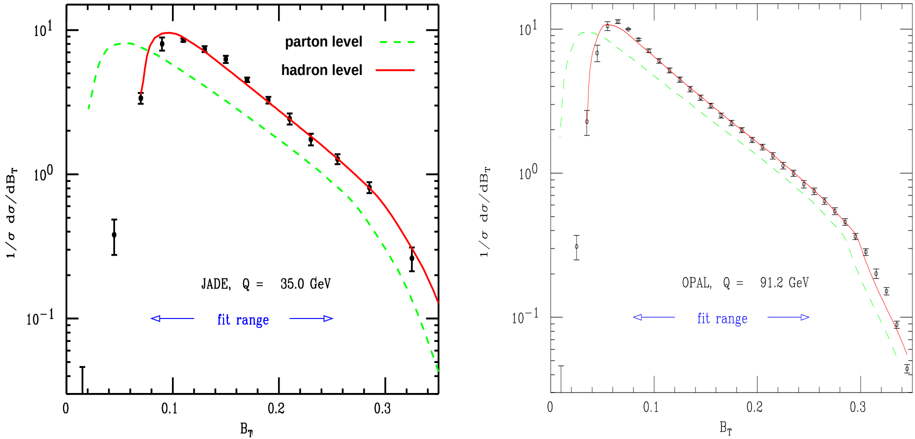

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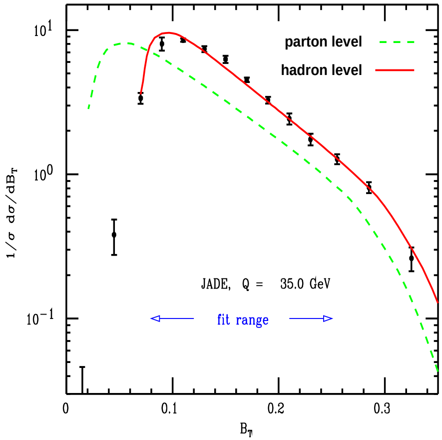

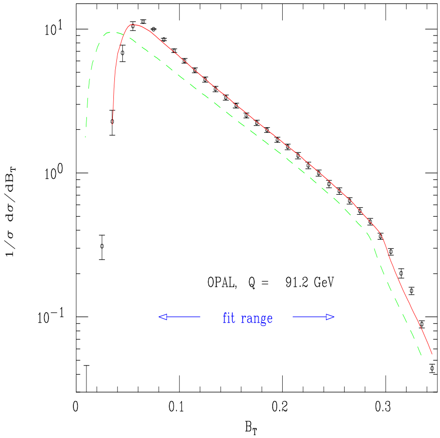

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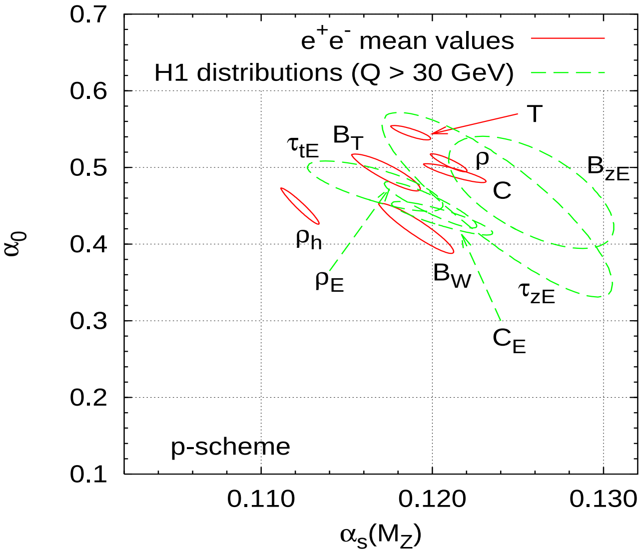
E.g., squeezing at the hadron-level (**!!**), *uncovered by the JADE gang*

Phenomenology of the QCD coupling



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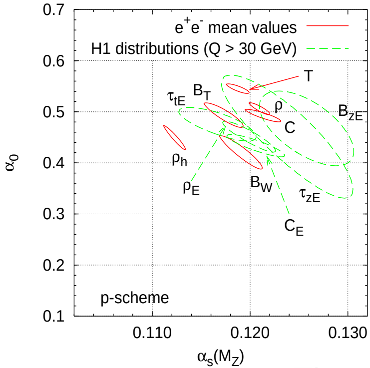

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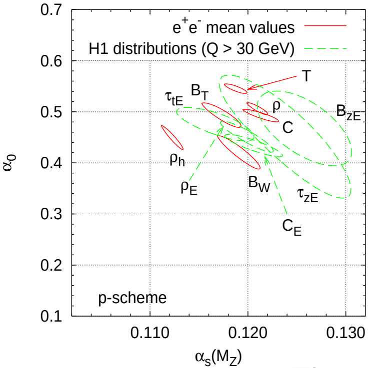

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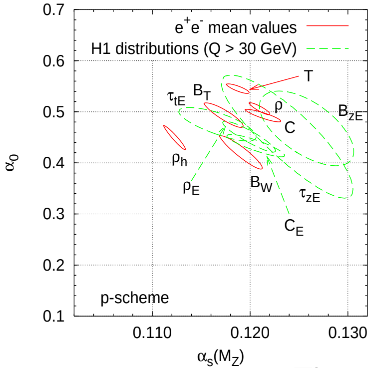

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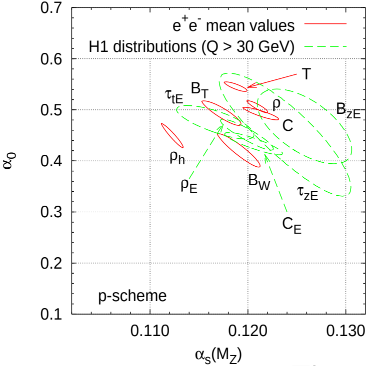

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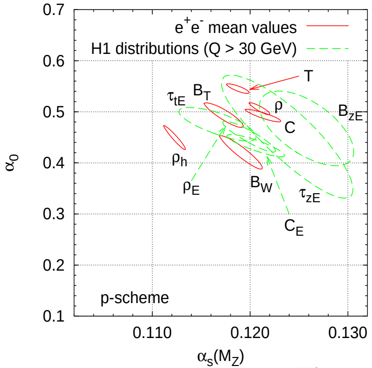

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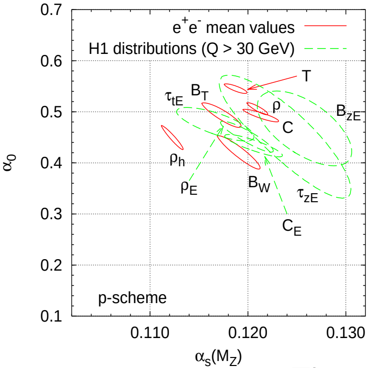

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Phenomenologists tend to oppose the acceptance of unobservable matters and grand systems erected in speculative thinking;

[Center for advanced research in phenomenology]

WIKIPEDIA:

Phenomenology is a current in philosophy that takes intuitive experience of phenomena (what presents itself to us in conscious experience) as its starting point and tries to extract the essential features of experiences and the essence of what we experience.

[early 20th century philosophers: Husserl, Merleau-Ponty, Heidegger]

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Plenty of New Interesting Phenomena in the Medium ...

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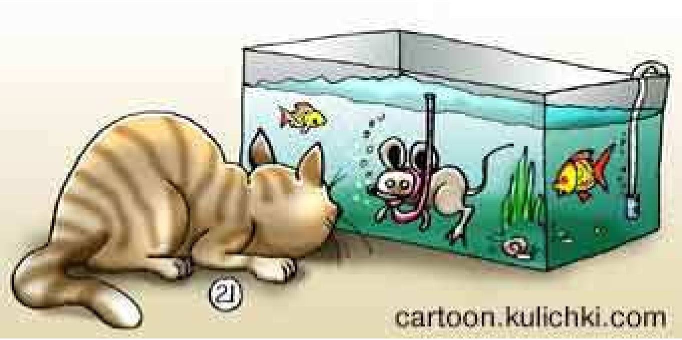

A RECENT IDEA

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Employ $\mathcal{N}=4$ Super-Symmetrical Yang–Mills QFT
to simplify QCD !

EXTRAS

Coulomb instability and Hadronization

What happens with the Coulomb field when the sources move apart?

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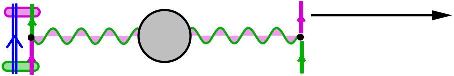

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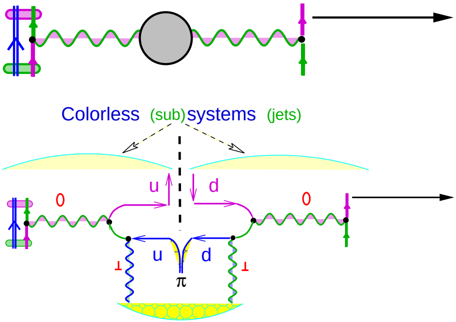

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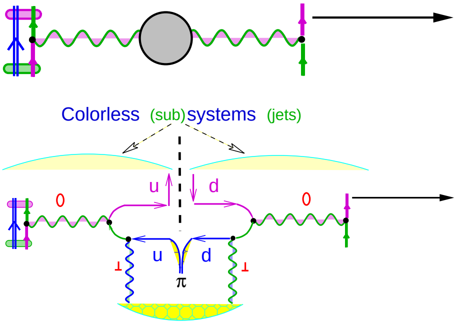

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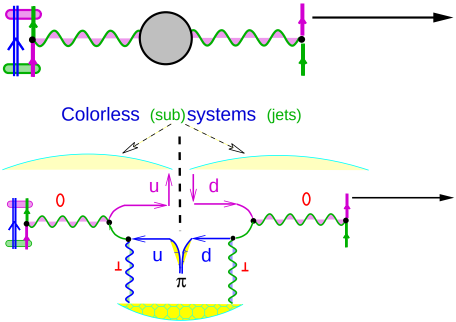

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$$\boxed{\frac{\alpha}{\pi} > \frac{\alpha_{\text{crit}}}{\pi} = C_F^{-1}\left[1-\sqrt{\frac{2}{3}}\right] \simeq 0.137}$$

$$\left(C_F = \frac{N_c^2-1}{2N_c} = \frac{4}{3}\right)$$

Heritage or Handicap?

An amazing success of the relativistic theory of electron and photon fields — quantum electrodynamics (QED) — has produced a long-lasting negative impact: it taught the generations of physicists that came into the business in/after the 70's to "*not to worry*".

Indeed, today one takes a lot of things for granted:

- One rarely questions whether the alternative roads to constructing QFT — secondary quantization, functional integral and the Feynman diagram approach — really lead to the same quantum theory of interacting fields
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One was taught to look upon the problems that arise with field-theoretical description of point-like objects and their interactions at very small distances (ultraviolet divergences) as purely technical: *renormalize it and forget it*.

Gribov Copies

Covariant derivative

$$\mathbf{D}\left[\mathbf{A}_{\perp}\right]\cdot \;=\; \nabla\cdot + i g_s \left[\mathbf{A}_{\perp}\,\cdot\right]$$

The Coulomb field "propagator"

Gribov Copies

Covariant derivative

$$\mathbf{D}\left[\mathbf{A}_{\perp}\right] . = \nabla . + ig_s \left[\mathbf{A}_{\perp} .\right]$$

The Coulomb field “propagator” (*Abelian*)

$$G(\mathbf{x}-\mathbf{y}) = - \quad \frac{1}{\nabla^2}$$

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averageover transverse vacuum fields $\mathbf{A}_\perp$

Gribov Copies

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Estimate of *non-linearity* :

$$g_s\mathbf{A}_\perp/\,\nabla \;\sim\; g_s\cdot|\mathbf{A}_\perp|\,L$$

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Estimate of *non-linearity* :

$$g_s\mathbf{A}_{\perp}/\,\nabla \;\sim\; g_s\cdot|\mathbf{A}_{\perp}|\,L \;\sim\; 1$$

Appearance of *Zero Modes* of the operator $\mathbf{D}[\mathbf{A}_{\perp}]\cdot\nabla$ signals

- a failure of extracting physical d.o.f. (gauge fixing);
- *Gribov horizon* C_0 (gauge fixing condition has multiple solutions);
- *Fundamental Domain* in the functional integral over gluon fields

Gribov Confinement: setting up the Problem

- The question of interest is
  The confinement in the real world (with 2 very light *u* and *d* quarks), rather than **a** confinement.
- No mechanism for binding massless *bosons* (gluons) seems to exist in Quantum Field Theory (QFT), while the Pauli exclusion principle may provide means for binding together massless *fermions* (light quarks).
- The problem of ultraviolet regularization may be more than a technical trick in a QFT with apparently infrared-unstable dynamics: the ultraviolet and infrared regimes of the theory may be closely linked.
- The Feynman diagram technique has to be reconsidered in QCD if one goes beyond trivial perturbative correction effects.
  Feynman's famous $i\epsilon$ prescription was designed for (and applies only to) the theories with *stable perturbative vacua*.

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To understand and describe a physical process in a *confining theory*, it is necessary to take into consideration the response of the vacuum, which leads to essential modifications of the quark and gluon Green functions.

Vacuum instability and supercritical binding

QED: physical objets — *electrons and photons* — are in one-to-one correspondence with the fundamental fields that one puts into the local Lagrangian of the theory.

QCD: the Vacuum changes the bare fields *beyond recognition*.

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Supercritical binding by over-charged nuclei

The expression for Dirac energy levels of an electron in an external static field created by the point-like electric charge Z contains
$\epsilon \propto \sqrt{1-(\alpha_{\mathrm{e.m.}}Z)^2}$.

For $Z > 137$ the energy becomes *complex*. This means instability.

- Classically, the electron *"falls onto the centre"*.
- Quantum-mechanically, it also *"falls"*, but into the Dirac sea.
- In QFT the instability develops when the energy ϵ of an empty atomic electron level drops, with increase of Z, below $-m_e c^2$.

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Thus, the ion becomes *unstable* and gets rid of an excessive electric charge by emitting a positron (Pomeranchuk & Smorodinsky 1945)

Binding “massless” fermions

In the QCD context, the increase of the running quark-gluon coupling at large distances replaces the large Z of the QED problem.

Gribov generalised the problem of supercritical binding in the field of an infinitely heavy source to the case of two massless fermions interacting via *Coulomb-like exchange*. He found that in this case the supercritical phenomenon develops much earlier.

Namely, a *pair of light fermions* develops supercritical behaviour if the coupling hits a definite critical value

$$\frac{\alpha}{\pi} > \frac{\alpha_{\rm crit}}{\pi} = 1 - \sqrt{\frac{2}{3}}\,.$$

With account of the QCD colour Casimir operator, the value of the coupling above which restructuring of the perturbative vacuum leads to *chiral symmetry breaking* and, likely, to *confinement*, translates into

$$\boxed{\frac{\alpha_{\rm crit}}{\pi} = C_F^{-1}\left[1-\sqrt{\frac{2}{3}}\right] \simeq 0.137} \qquad \left(C_F = \frac{N_c^2-1}{2N_c}\right) = \frac{4}{3}$$

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Gluon sector

In the analysis of the quark Green function, behaviour of α_s was implied.

An open problem: To construct and to analyse an equation for the gluon similar to that for the quark Green function. From this analysis a consistent picture of the coupling $g(q)$ rising above g_{crit} in the IR momentum region should emerge.

Difficulty: To learn to separate the running coupling effects from an unphysical gauge dependent phase that are both present in the gluon Green function.

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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,

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

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