QFT
QED, QCD
HEPP

- II

Yuri Dokshitzer

Baltic School 2021

Color Octet Gluons

Harald Fritzsch & Murray Gell-Mann

Proc. XVI Intern. Conf. on **H**igh **E**nergy **P**hysics,
Chicago, 1972, Vol. 2, p. 135.

Advantages of the Color Octet Gluon Picture

M.Gell-Mann, G. Fritzsch and H. Leutwyler

Received 1 October 1973

"It is pointed out that there are several advantages in abstracting properties of hadrons and their currents from a Yang-Mills gauge model based on colored quarks and color octet gluons."

Gauge invariance

$f \to Sf \qquad S = e^{ia}$ — unitary rotation of a fermion field

free Lagrangian ($\bar{f} f$) stays invariant:

no respect to the phase of the wave function

QCD Lagrangian (minimal, renormalisable, unique)

local non-respect: $a = a(x)$

$$\mathcal{L} = \frac{1}{2g^2}([D_\mu, D_\beta])^2 + \bar{f}(iD-m)f$$

1973

covariant derivative

$$D_\mu = \frac{\partial}{\partial x_\mu} - i A_\mu \qquad A_\mu \to A_\mu + \frac{\partial}{\partial x_\mu} a(x)$$

$a(x)$ - number field: $i[D,D] = \partial_\mu A_\beta - \partial_\beta A_\mu$ U(1), QED

$a(x)$ - matrix: $i[D,D] = \partial_\mu A_\beta - \partial_\beta A_\mu - i[A_\mu A_\beta]$ SU(3), QCD

Recall:

*In the crossing channel, the imaginary part of the loop amplitude is proportional to the cross section of pair production (unitarity). Thus, the "zero-charge" sign of the β-function inevitably follows from **positivity** of the decay cross section !*

1969

Khriplovich: *the **SU(2)** Yang–Mills gauge theory coupling **disrespects** this wisdom !*

Why and **how** then the Landau-Pomeranchuk argument failed in the non-Abelian gauge field theory ?

1977

Gribov:

physics of "anti-screening"
- statistical effect of "zero-fluctuations"

AUTOPSY OF ASYMPTOTIC FREEDOM

- To address a question starting from ***how*** or ***why*** we better talk ***physical degrees of freedom***; use the Hamiltonian language

- Then, we have gluons of ***two sorts***:

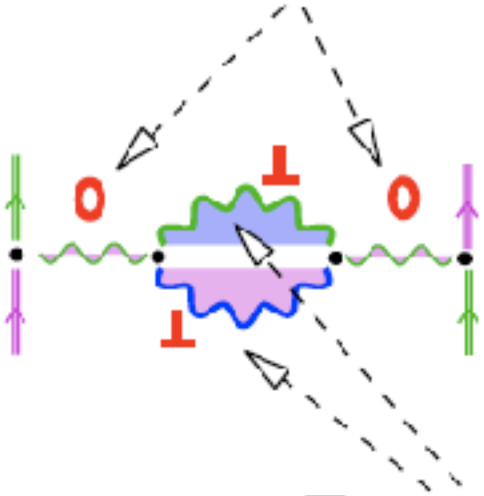
➡ two "physical" transversely polarized gluons and

➡ Coulomb gluon field - the mediator of the *instantaneous interaction* between colour charges.

autopsy of AF

Consider Coulomb interaction between two heavy colour charges

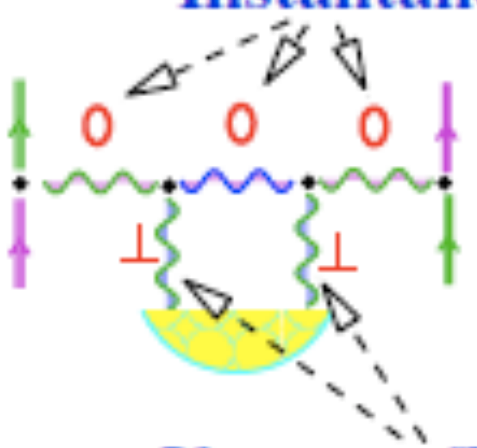
Instantaneous Coulomb interaction



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

Transverse gluons **(and quarks)** ⟷ ***screening***

Instantaneous Coulomb interaction



$$= +N_c * 4$$

Vacuum fluctuations of transverse fields ⟷ ***ANTI-screening***

Combine into the QCD β–function:

$$\beta(\alpha_s) = \frac{\mathrm{d}}{\mathrm{d}\ln Q^2} 4\pi\alpha_s^{-1}(Q^2) \;=\; \left[4 - \frac{1}{3}\right] * N_c - \frac{2}{3} * n_f$$

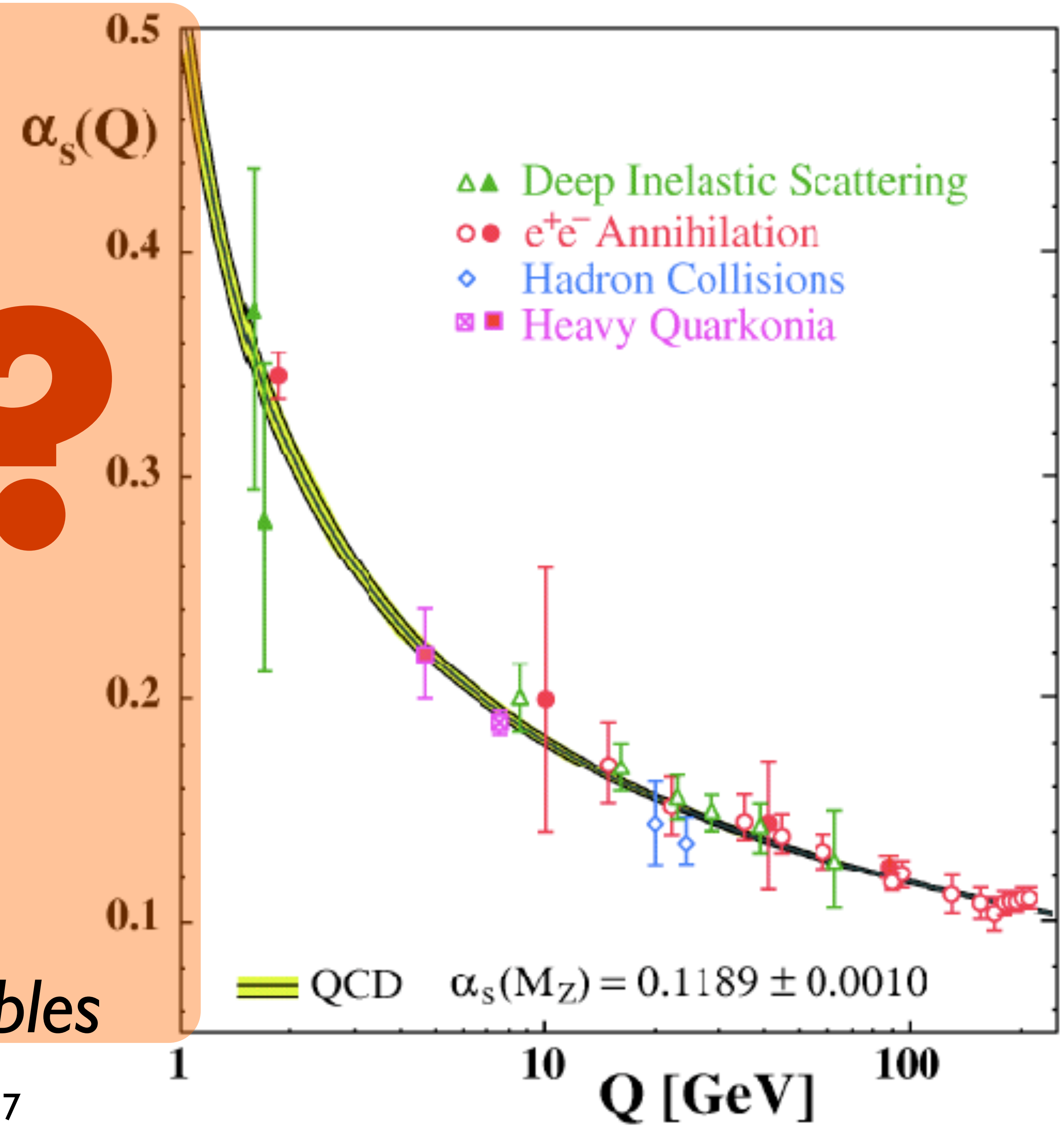
Running QCD coupling

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

- Λ_{QCD} - the fundamental scale at which coupling *blows up*
- Perturbative calculations are 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

Collinear-and-Infrared-Safe observables

?



Speaking of "***perturbative QCD***" can have two meanings :

{1} *In a strict sense of the word, perturbative (**PT**) approach implies representing an answer for a (calculable) quantity in terms of series in a (small) expansion parameter.*

{2} *In a broad sense, PT means applying the language of quarks and gluons to a problem, be it of perturbative (short-distance, small-coupling) or non- perturbative nature.*

The quark–gluon picture works well across the board.

Moreover, in many cases it seems to work ***too well***.

(Classical example - the story of baryon magnetic moments where the naive quark model counting works better than sophisticated dynamical approaches)

This is another worry: "*too good to be true*" *ain't good enough*.

Looking at multi-particle production in hard (small-distance driven) processes, one often wonders :

... " where is " confinement ?..

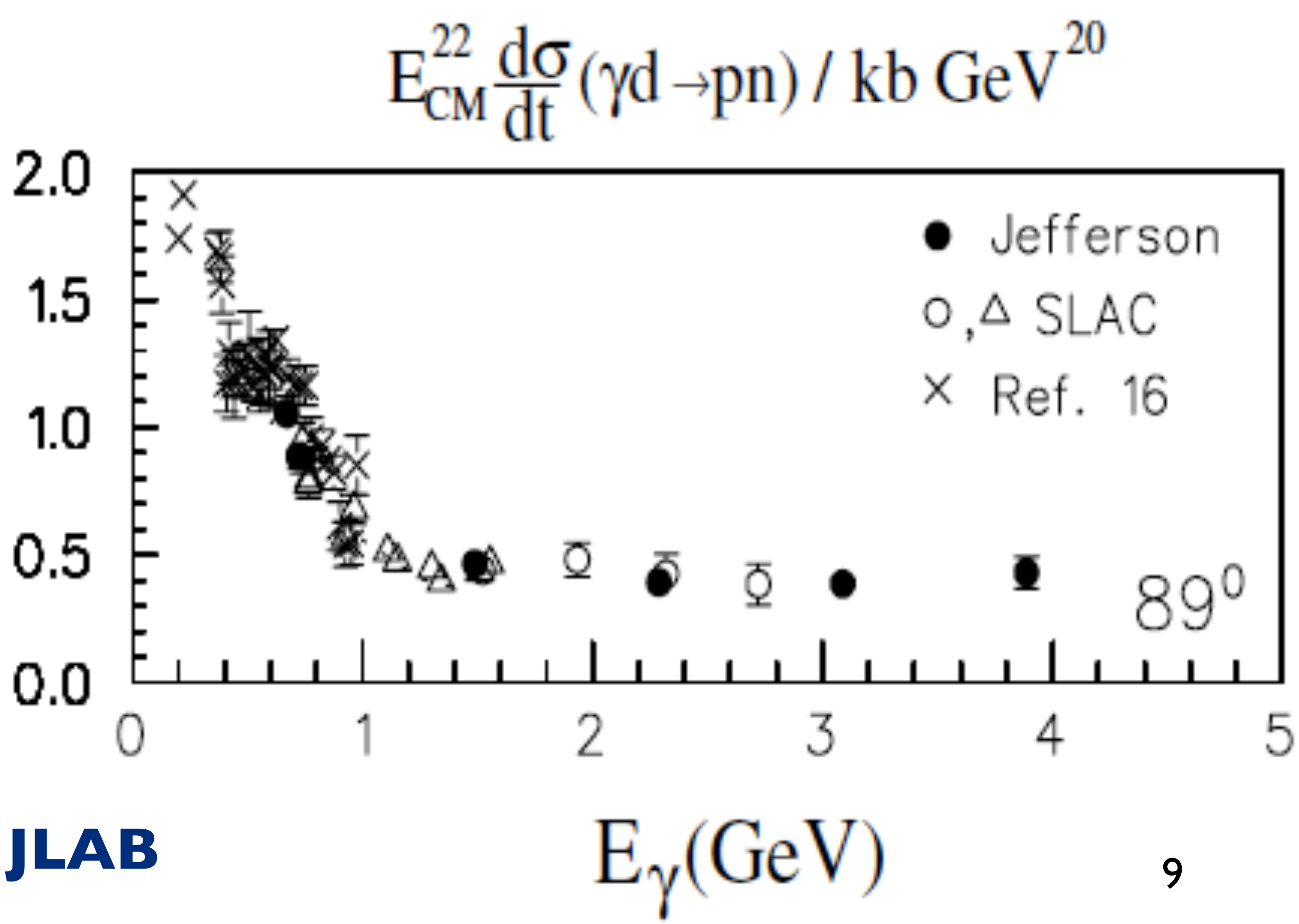
Dimensional counting (“quark counting rules”)

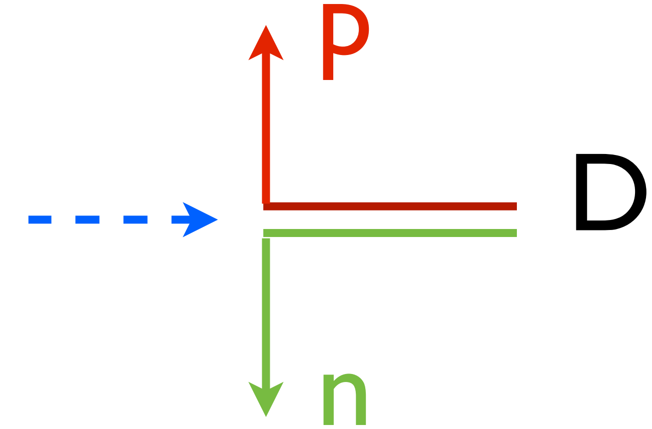
large angle scattering in the high energy / momentum transfer regime

$$\frac{d\sigma}{dt} = \frac{f(\Theta)}{s^{K-2}}; \qquad \frac{t}{s} = \text{const}$$

K *the number of participating elementary fields (quarks, leptons, intermediate bosons, etc)*

Example *: deuteron break-up by a photon,* $\gamma + D \longrightarrow p + n$





K = 1+6 + 6 = 13

it is very difficult to digest how the naive asymptotic regime settles that early !..

$$d\sigma \sim \alpha_s^{10} (q^2/N)$$

JLAB

Hard Processes

and
QCD partons

Hit hard to see what is it there *inside*

(a childish but productive idea)

Hit the Vacuum: ***e+e- annihilation into hadrons***,

Hit the Proton: ***deep inelastic lepton-hadron scattering*** (DIS),

Make two hadrons hit each another hard:

produce ***massive lepton pairs,***

heavy quarks and their bound states,

large transverse momentum jets and vector bosons

These are classical examples of ***hard processes***.

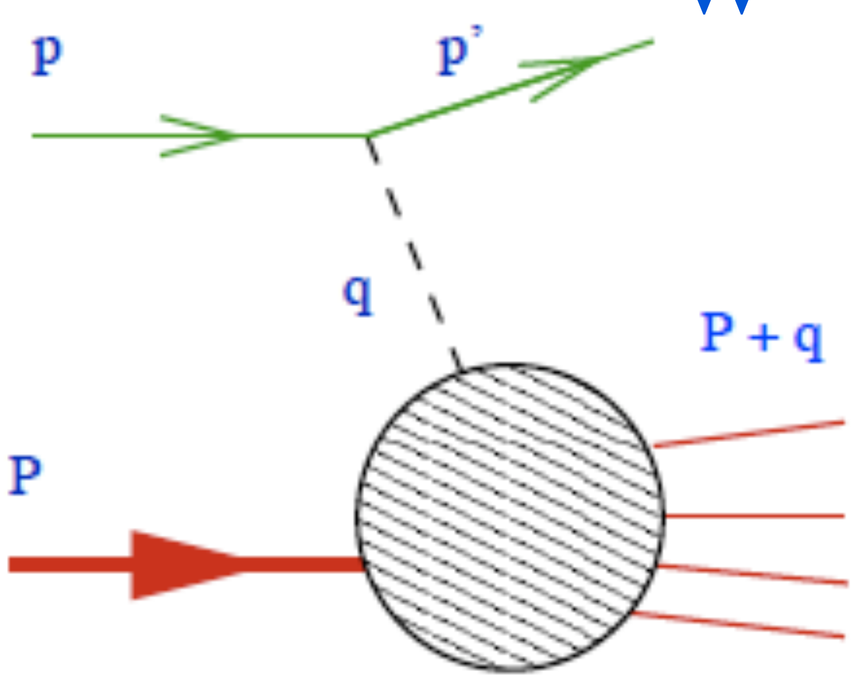
Momentum transfer = measure of "*hardness*"

Copious production of hadrons is typical for all these processes. On the other hand, at the microscopic level, multiple quark-gluon "production" is to be expected as a result of ***QCD bremsstrahlung*** - gluon radiation accompanying abrupt creation/scattering of colour partons.

Historically the 1st hard process - *Deep Inelastic* ***e-p*** *Scattering*

Bit of kinematics: invariant mass of final hadrons

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



Measure of inelasticity -

Bjorken variable $x = -\frac{q^2}{2(Pq)}$ $(0 \leq x \leq 1)$

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

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

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

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?)

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

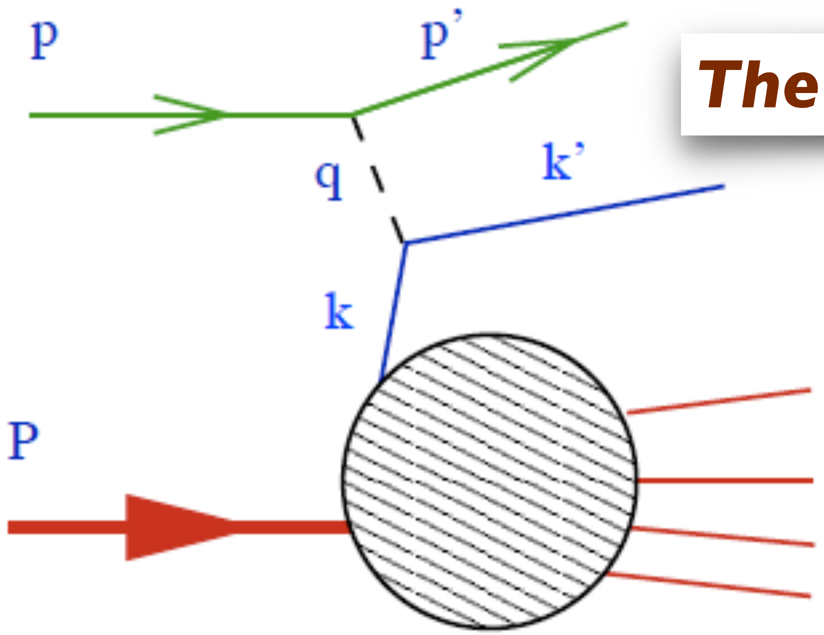
– excitation of one quark gets *redistributed* inside the proton via the confinement "*springs*" that bind quarks together and don't let them fly away.

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.

Conclusion: Proton is a *loosely bound* system



The idea of partons: equate inelastic electron-hadron scattering

with elastic electron-quark scattering !

Imagine that the quark-parton carries a finite fraction of the parent proton momentum $k \simeq z \cdot P \quad (k^2 \simeq 0)$

For the scattered quark,

$$(k')^2 = (zP + q)^2 \simeq 2(Pq) \cdot (z - x) \simeq 0$$

Meaning of the Bjorken variable : DIS selects a quark with momentum $x \cdot P$

$F^2_{\text{inelastic}}$ *- the probability of finding inside the proton a quark with a given momentum*

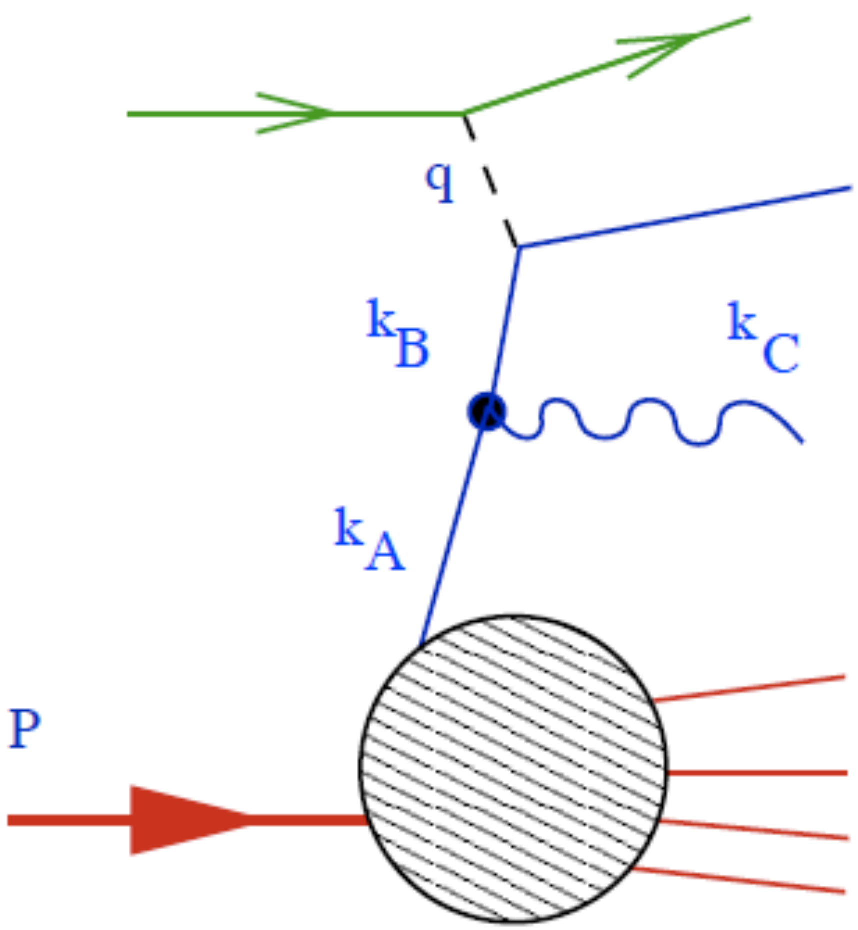
*The **Bjorken scaling** hypothesis - existence of the limiting distribution ("Bjorken limit")*

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

*However, it was realized, practically immediately after the **parton model** had appeared, that*

*the **Bjorken scaling** hypothesis cannot hold in **QFT** !*

Particle virtualities/transverse momenta in QFT are not limited; *as a result,* "partons" (quarks and gluons) may have transverse momenta up to $k_\perp^2 \ll Q^2 = |q^2|$



As a consequence, a number of particles involved turns out to be large in spite of the ***small coupling*** :

$$\int dw \propto \int^{Q^2} \frac{\alpha_s}{\pi} \frac{dk_\perp^2}{k_\perp^2} \sim \frac{\alpha_s}{\pi} \ln Q^2 = \mathcal{O}(1)$$

Such – "*collinear*" – enhancement is typical for QFTs with dimensionless coupling – "*logarithmic*" Field Theories

Physically, a QFT particle is surrounded by a virtual coat; its visible content depends on the resolution power of the probe

$$\lambda = \frac{1}{Q} = \frac{1}{\sqrt{-q^2}}$$

the Feynman–Bjorken picture of partons employed the classical (probabilistic) language: $\sigma_h = \sigma_q \otimes D_h^q$.

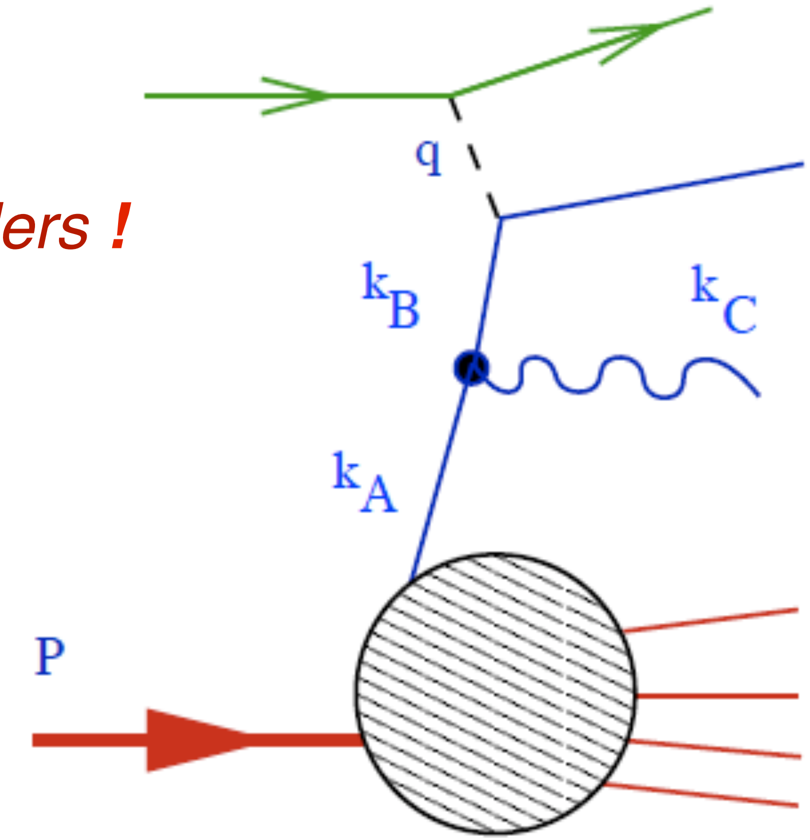
Is there any chance to rescue probabilistic interpretation of quark–gluon cascades, to speak of "QCD partons"?

QCD partons

Which are the ***most probable*** parton fluctuations?

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

LLA



Such contributions should - and can - be *resummed* in *all orders !*

Kinematics of the parton splitting A ⟶ B+C

$$k_B = z k_A\ ,\ k_C = (1 - z) k_A$$

Relation between virtualities of three participating partons :

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

Probability of the splitting process

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

To gain a large logarithmic enhancement, we have to have

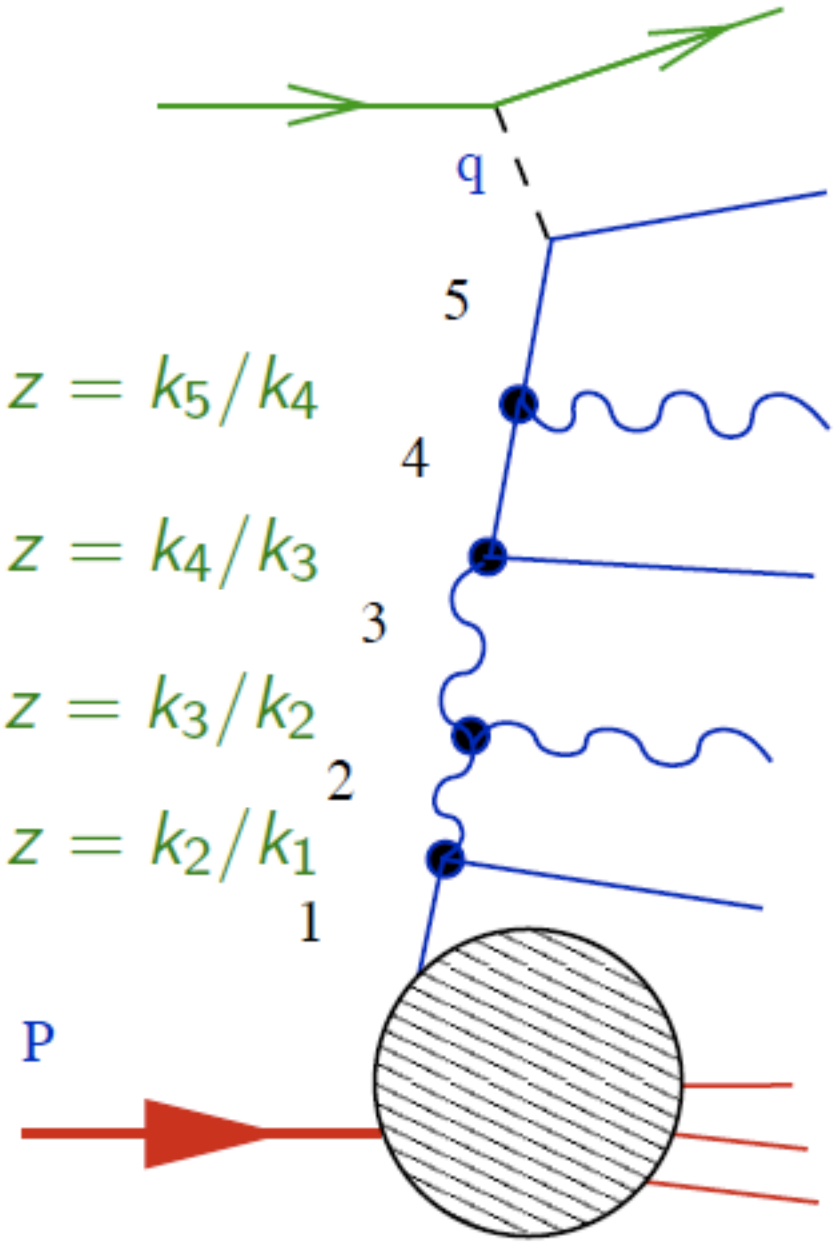
$$\frac{|k_B^2|}{z} \simeq \frac{k_\perp^2}{z(1-z)} \gg \frac{|k_A^2|}{1}$$

This inequality has a *transparent physical meaning* :

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

strongly ordered ***lifetimes*** of successive parton fluctuations

Evolution of a parton system becomes a *Markov chain* in a properly chosen "time", **~ ln Q²**



Evolution in the "*longitudinal*" momentum space is governed by

Four basic splitting processes **= parton Hamiltonian**

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

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

$g \to q(z) + \bar{q} \qquad \Phi_g^q(z) = T_R \cdot \left[z^2 + (1-z)^2 \right]$

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

We cannot predict, from the first principles, parton content (**B**) of a hadron (**h**).
However, perturbative QCD tells us how it changes with the momentum transfer $\mathbf{Q^2}$.

Equation for evolution of parton distributions reminds the *Schroedinger equation*

$$\frac{d}{d \ln Q^2} D_h^B(x, Q^2) = \frac{\alpha_s(Q^2)}{2\pi} \sum_{A=q,\bar{q},g} \int_x^1 \frac{dz}{z} \Phi_A^B(z) \cdot D_h^A\left(\frac{x}{z}, Q^2\right)$$

time derivative *wave function* *Hamiltonian* ***= Resummation Tool***

The logarithmic scaling violation pattern in DIS structure functions is well established and meticulously follows the QCD prediction based on the ***parton evolution picture***.

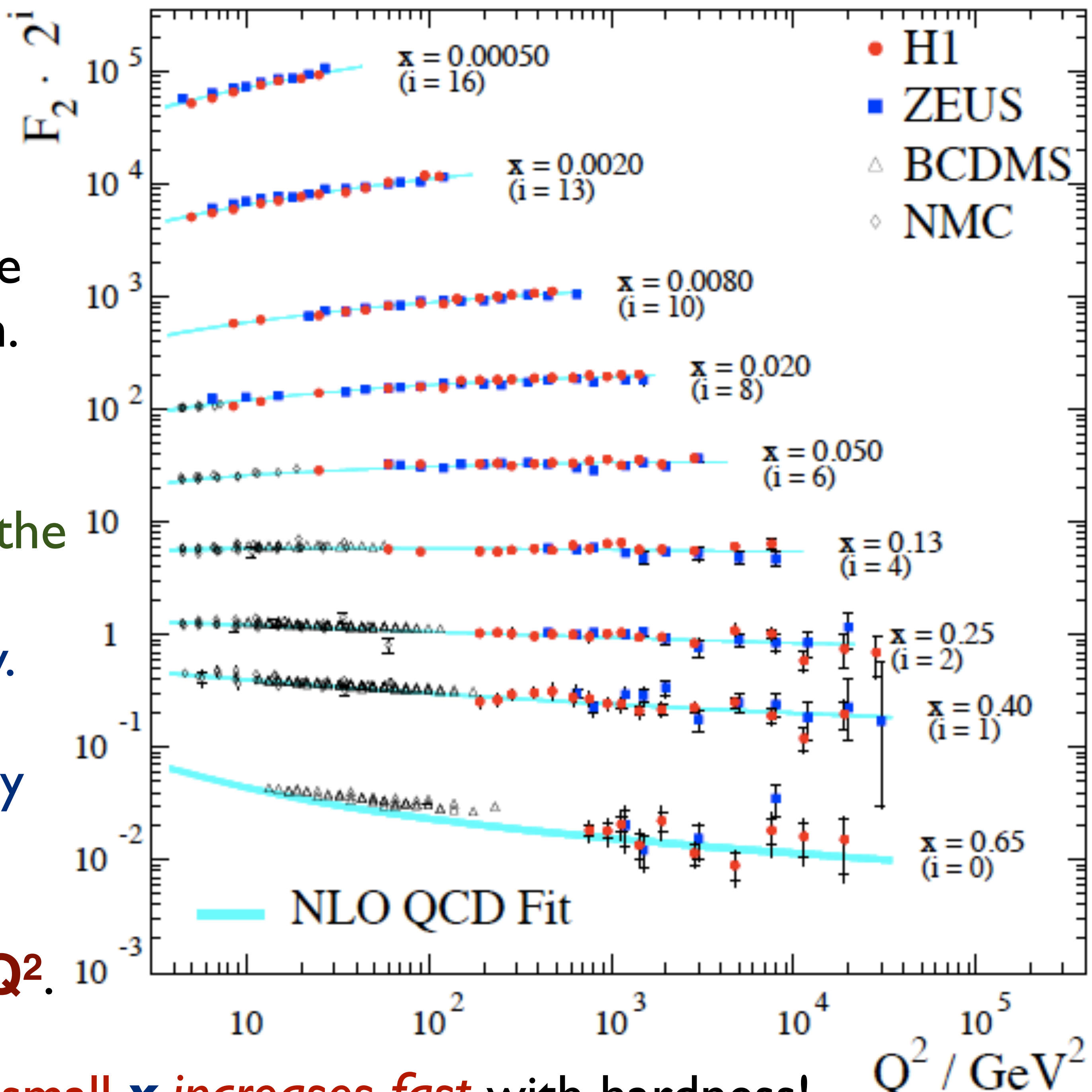
QCD quarks and gluons are not point-like particles (*as the orthodox parton model once assumed*). Each of them is surrounded by a proper field coat – a coherent virtual cloud –consisting of ***gluons*** and "sea" ***quark-antiquark pairs***.

A hard probe applied to such a dressed parton breaks coherence of the cloud.

Constituents of these field fluctuations emerge as particles accompanying the hard interaction.

The harder the hit, the larger an intensity of bremsstrahlung and, therefore, the fraction of the energy-momentum of the dressed parton that the bremsstrahlung quanta typically carry away.

Thus we should expect, e.g., that the probability that a hit "bare" core quark carries a ***large fraction*** **x ~1** of the energy of its dressed parent will *decrease* with increase of $\mathbf{Q^2}$.



At the same time, the density of partons with small ***x*** *increases fast* with hardness!

In **DIS** we look for a "***bare***" quark inside a target ***dressed*** one.

In **e+e−** hadron annihilation at large energy **$s = Q^2$** the chain of events is reversed. Here we produce instead a ***bare quark*** with energy **$Q/2$**, which then "***dresses up***".

In the process of restoring its proper field-coat our ***parton*** produces (*a controllable amount of*) ***bremsstrahlung radiation*** which leads to formation of a ***hadron jet***.

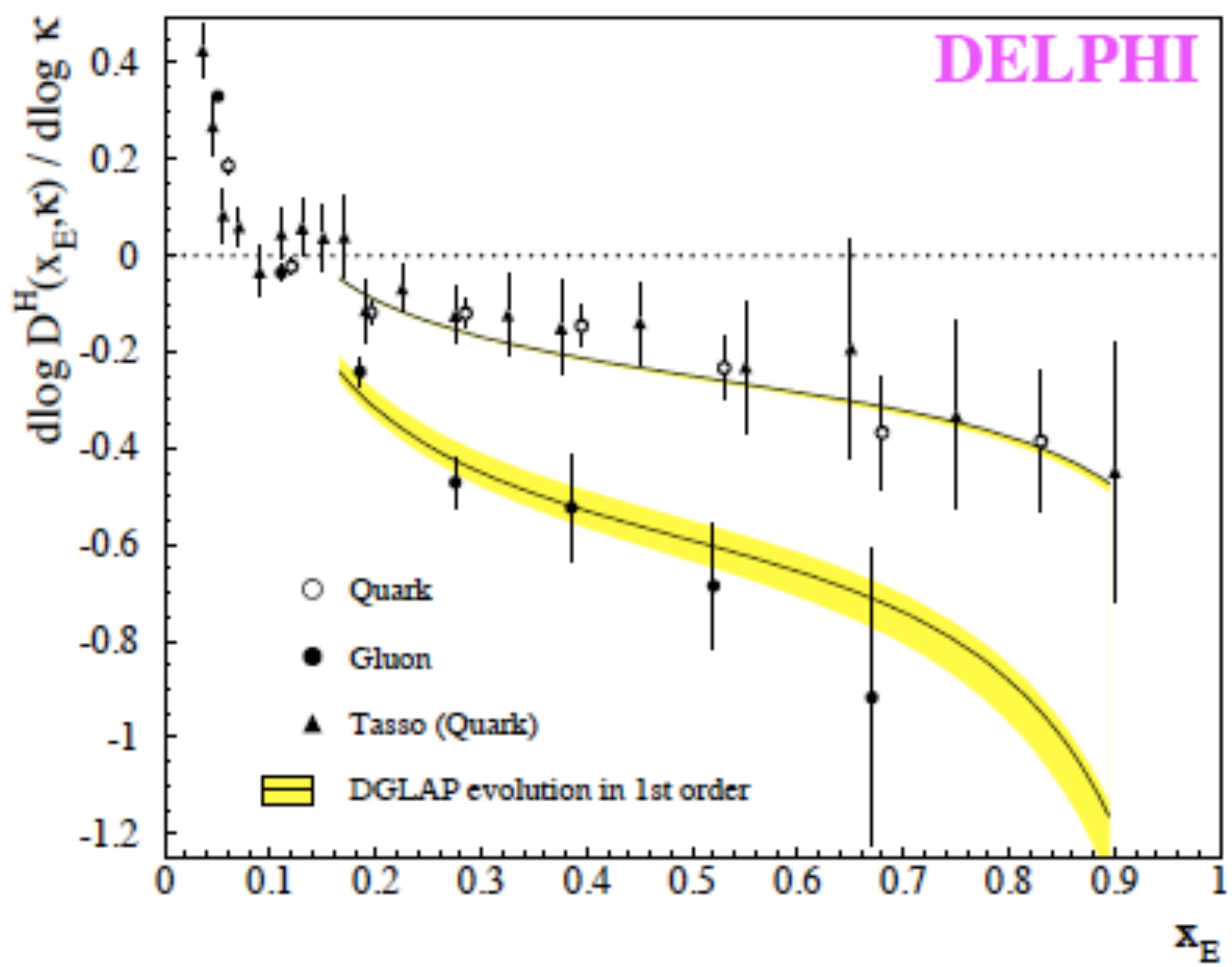
Having done so, in the end of the day it becomes a ***constituent*** of one of the hadrons that hit the detector. Typically, this is the leading hadron.

However, the fraction **x** of the initial energy **$Q/2$** that is left to the leader depends on the amount of accompanying radiation and, therefore, on **Q^2** (*the larger, the smaller*).

Scaling violation in quark and gluon fragmentation

Ratio of the** slopes **gives the ratio of the colour factors :

$$\frac{C_A}{C_F} = 2.23 \pm 0.09_{\text{stat.}} \pm 0.06_{\text{syst.}}$$

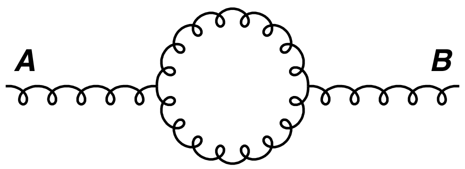


Absolute values of gluon and quark "colour charges" - quadratic Casimir operators

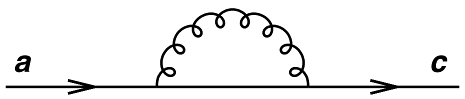
$$\sum_{a=1}^{N_c^2-1} T_R^a T_R^a = C_R \cdot \mathbf{I}$$

for any group representation ***R***

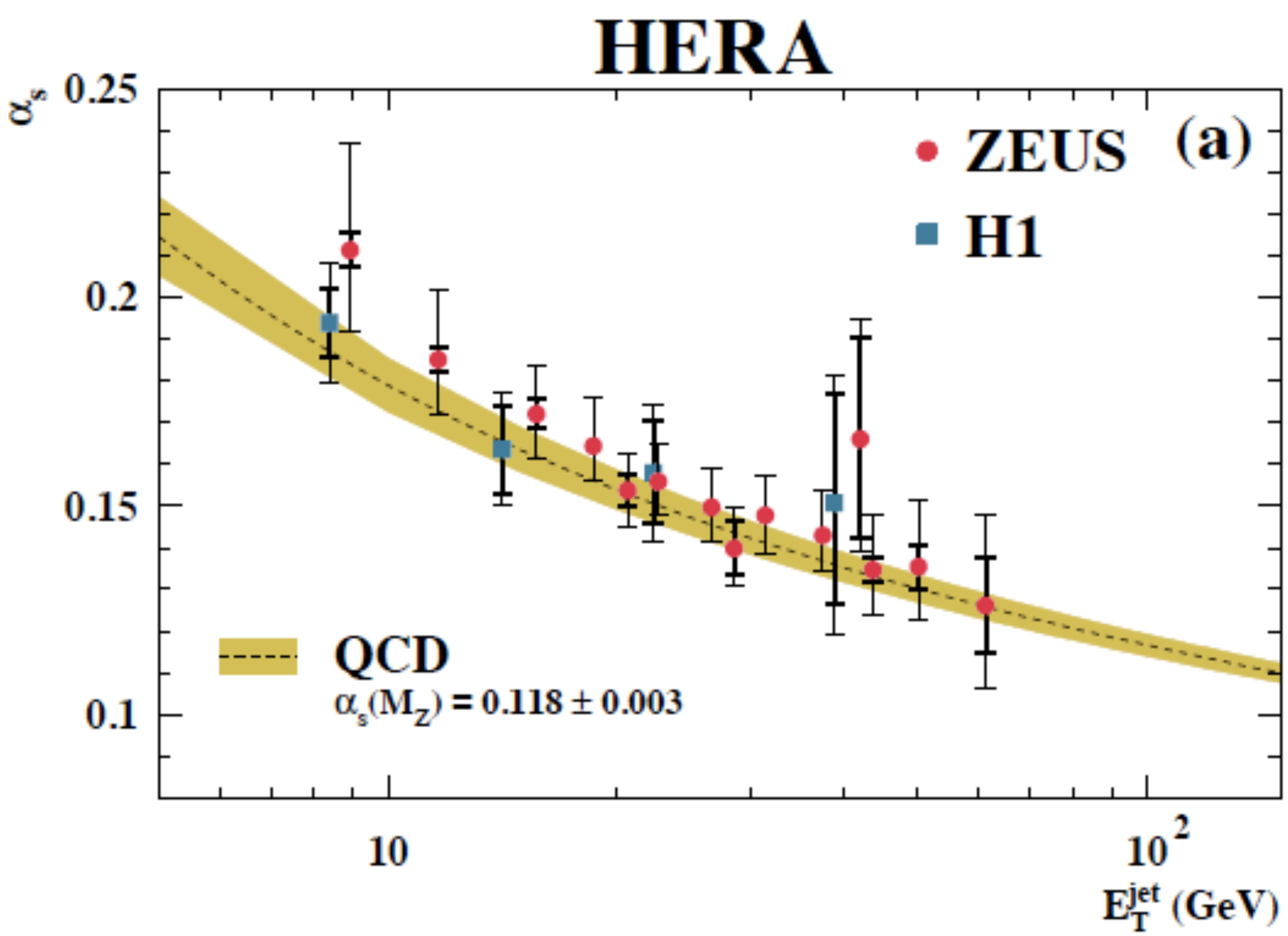
C_A - adjoint (gluon field)



C_F - fundamental (quarks)



4-jet angular correlations and jet shapes



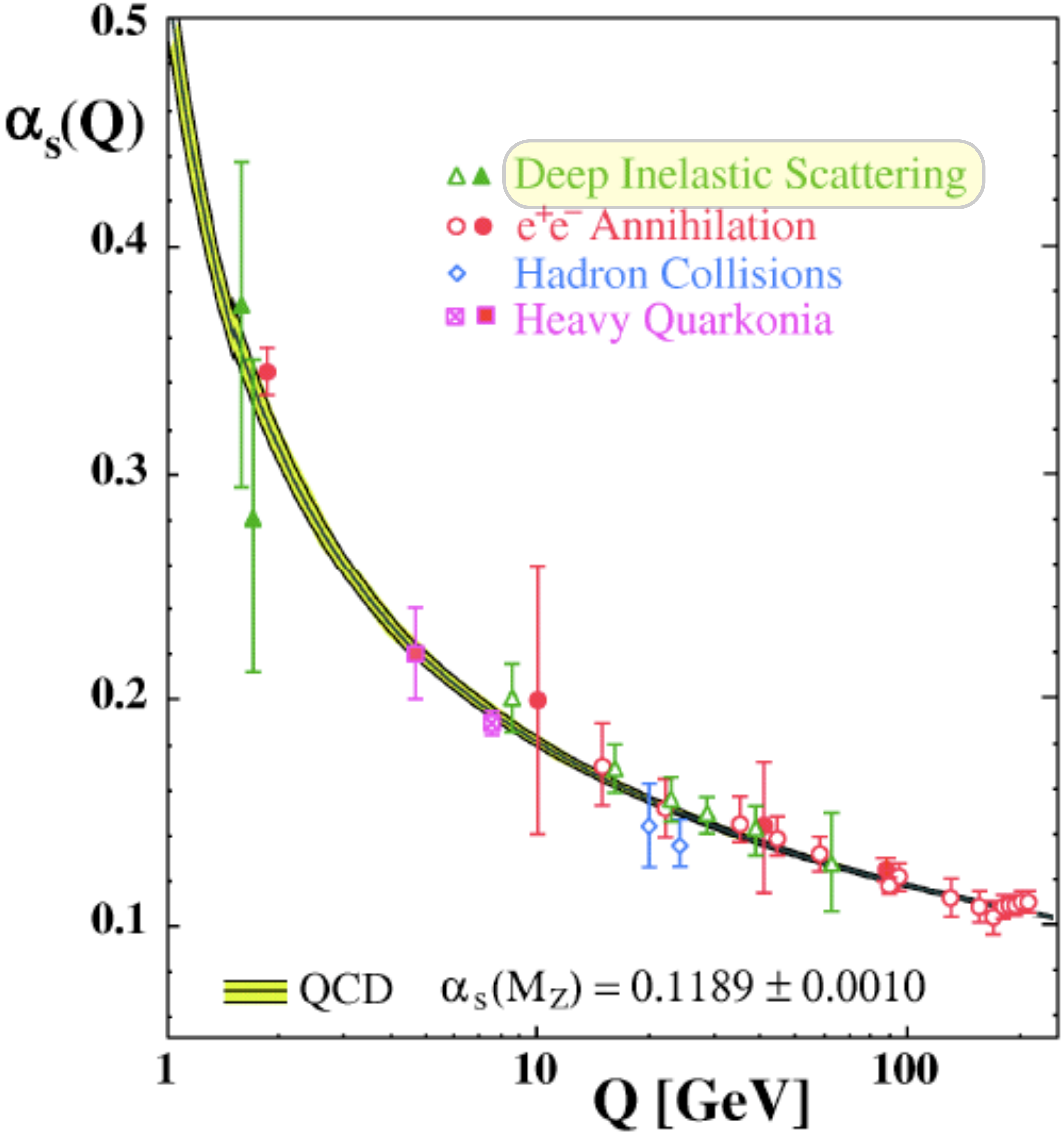
Results of α_s as a function of E_T^{jet} from HERA experiments H1 and ZEUS

$$C_A = 2.89 \pm 0.01 \text{ (stat.)} \pm 0.21 \text{ (syst.)}$$
$$C_F = 1.30 \pm 0.01 \text{ (stat.)} \pm 0.09 \text{ (syst.)}$$

$$C_A = N_c \qquad = 3.00$$

$$C_F = \frac{N_c^2 - 1}{2N_c} \qquad \approx 1.33$$

Summary of the QCD coupling measurements



Asymptotic Freedom

Indirect evidence that ***gluons are there***, and that they behave, has been obtained from the study of the ***scaling violation pattern***.

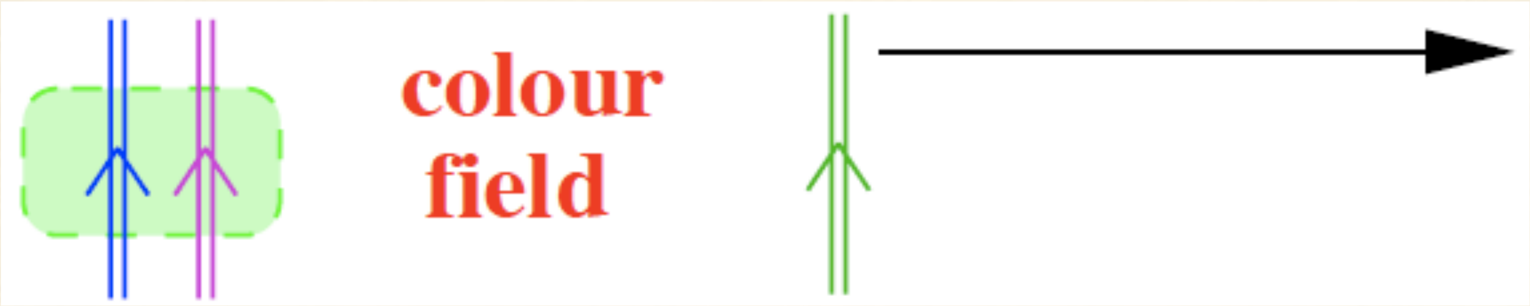
How do hadrons emerge

from an underlying quark-gluon ensemble ?

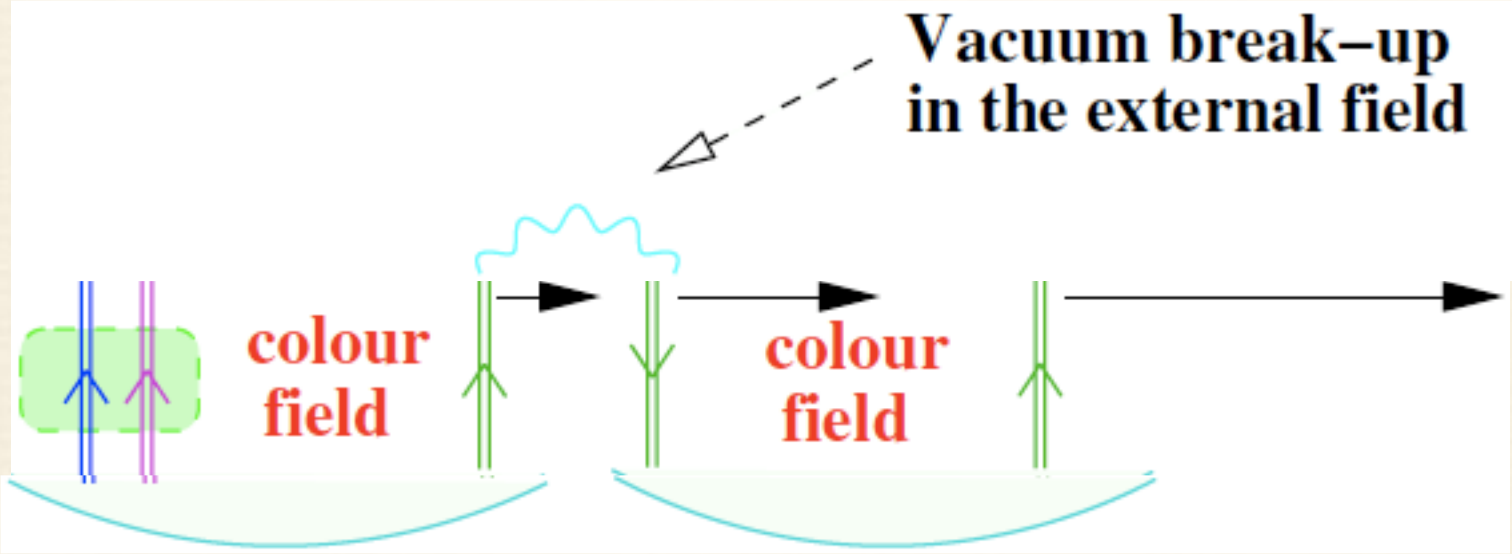
Is there correspondence between observable hadron and calculable quark-gluon production ?

Kogut–Susskind vacuum breaking picture

- In a DIS a *green* quark in the proton is hit by a virtual photon
- The quark leaves the stage and the colour field starts to build up



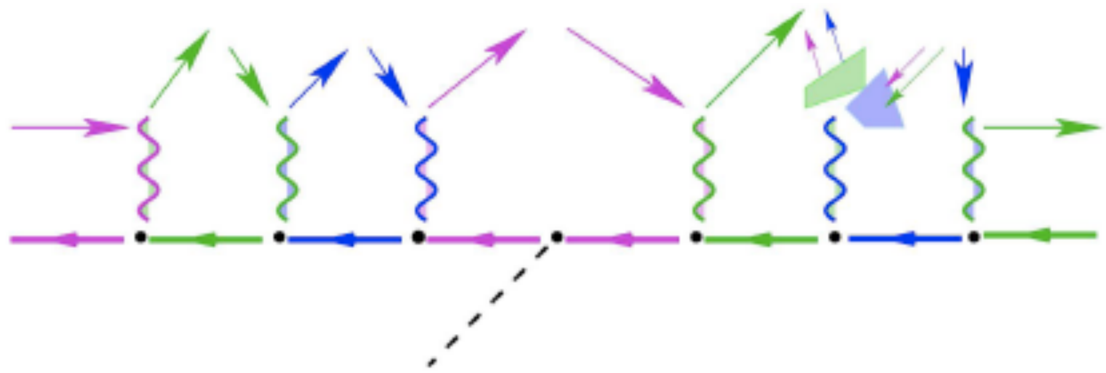
- A *green–anti-green* quark pair pops up from the vacuum, splitting the system into two globally blanched sub-systems.



FEYNMAN PLATEAU

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

Phenomenological realization of the Kogut–Susskind scenario



$\Longrightarrow$ a "String" of hadrons

The base of the Lund Model

The key features of the Lund hadronization model:

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

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

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.
The first indirect evidence in favour of *gluons* came from DIS where it was found that the electrically charged partons (quarks) carry, on aggregate, *less than 50%* of the proton's energy–momentum.

Now, we see a gluon emitted as a "real" particle.

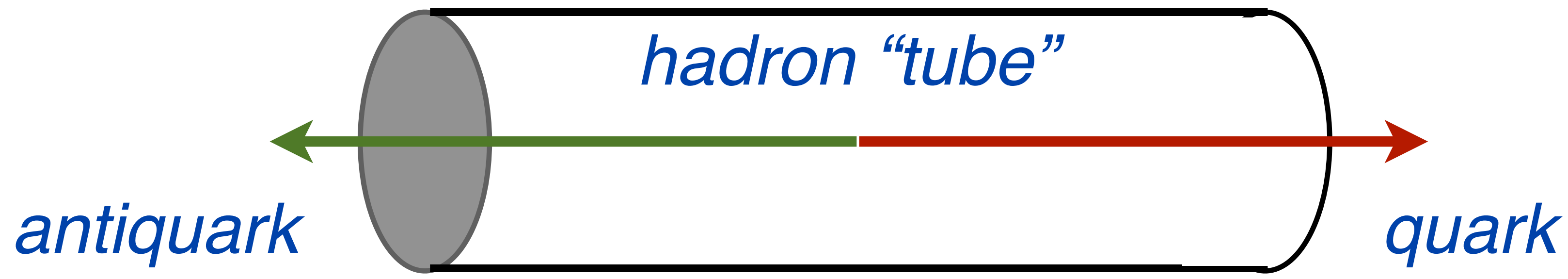
What sort of final hadronic state will it produce?

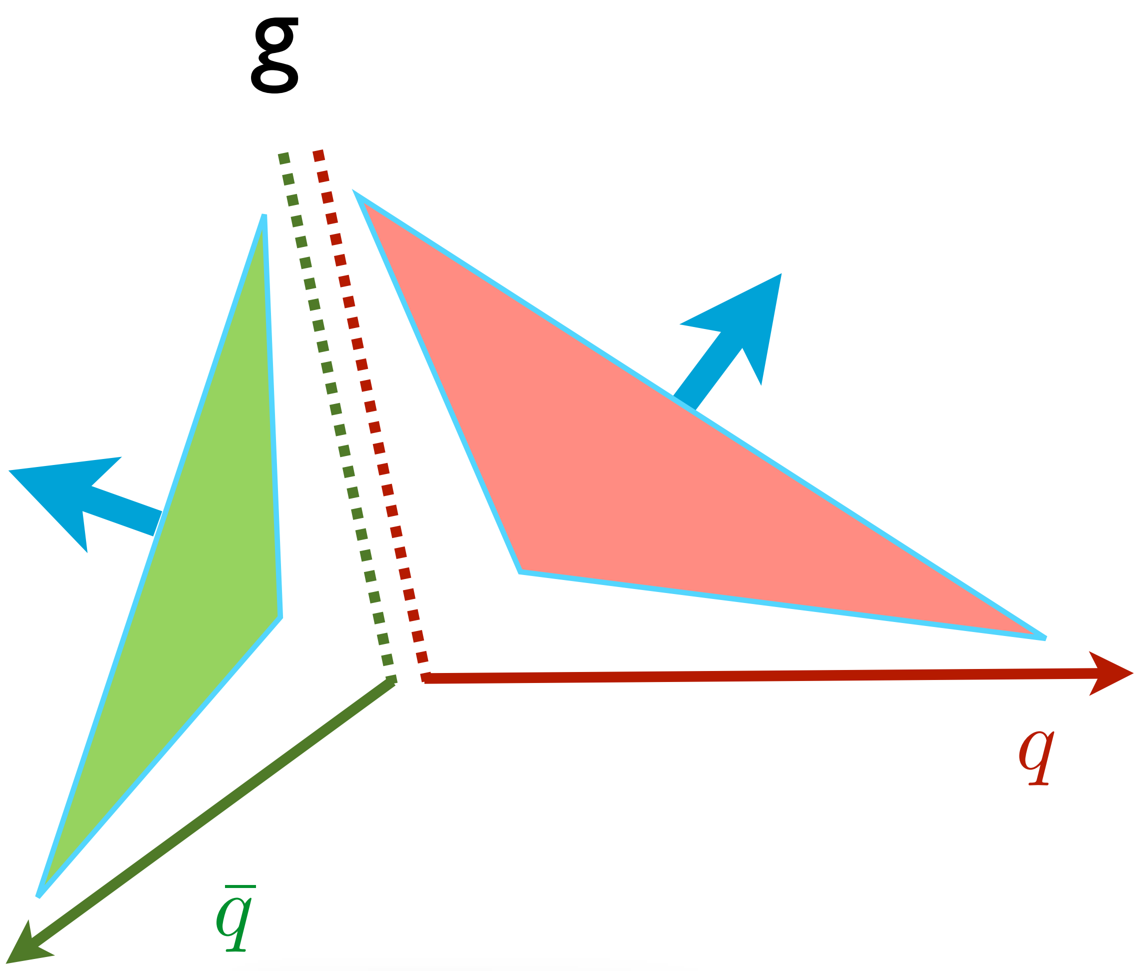
B.Andersson, G.Gustafson & C.Peterson, Lund Univ., Sweden (1977)

Gluon $\simeq$ quark-antiquark pair:
$3 \otimes \bar{3} = N_c^2 = 9 \quad \simeq \quad 8 = N_c^2 - 1.$
Relative mismatch : $\mathcal{O}(1/N_c^2) \ll 1$ (the large-N_c limit)

Lund model interpretation of a *gluon* —

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





Lund "String effect"

kinematical effect of a "boosted hotdog"

Lund's stress on ***topology*** of the dominant ***colour flow*** found support from **p**QCD

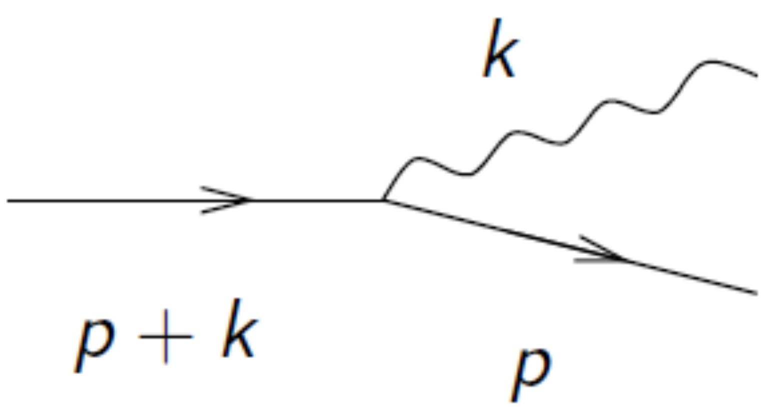
*The main message from various manifestations of "**QCD Radiophysics**"*

- *- the yield of final state **hadrons** is proportional*
- *to the Poynting vector of the underlying soft **gluon** field **!***

To answer the question as how do offspring partons influence the hadronic yield, one has to realize first ***what is the condition*** for a gluon to behave as an ***independent coloured object*** and thus as an ***additional source of new particles***.

It takes time to emit a gluon.

The formation time can be simply estimated as a ***lifetime*** of the virtual **(p + k)** quark state



Making use of the Heisenberg uncertainty principle, with account of the Lorentz contraction,

$$t_g^{\text{form}} \sim \frac{1}{M_{virt}} \cdot \frac{E}{M_{virt}} = \frac{E}{(p+k)^2} \approx \frac{E}{kE\Theta^2} \approx \frac{k}{k_\perp^2}$$

Comparing with the hadronization time, $t_g^{\text{hadr}} \approx kR^2$,

$$t_g^{\text{form}} \sim \frac{k}{k_\perp^2} \quad < \quad t_g^{hadr} \sim kR^2$$

the gluon's being is guaranteed *iff* its transverse momentum is large:

$$k_\perp > R^{-1} = \text{a few hundred MeV.}$$

"**Get-born-before-dying**" condition goes along with the ***coupling*** behaviour $\alpha_s(k_\perp^2)$

- $R^{-1} \ll k_\perp \ll k \sim \sqrt{Q^2}$

- the domain of ***quasi-collinear*** hard parton splittings leading to the scaling violation effects in DIS structure functions and jet fragmentation (inclusive particle distributions)

- $R^{-1} \ll k_\perp \sim k \ll \sqrt{Q^2}$

- ***large angle soft*** gluon emission responsible for drag effects in inter-jet multiplicity flows

- $R^{-1} \ll k_\perp \ll k \ll \sqrt{Q^2}$

- ***double-logarithmic*** (soft & collinear) gluon bremsstrahlung off quarks and gluons causing jet multiplicity grow with energy and determining QCD parton Form Factors

All these are legitimate, PT-controllable, QCD sub-processes.

Parton pairs with *small relative transverse momenta* lie beyond PT control.

Let us look at the gluons radiated at the ***lower edge*** of the PT phase space : $k_\perp \sim R^{-1}$.

An appearance of a "***gluer***" is a signal of switching on the ***real strong interaction*** :

$$\left(t^{\text{form}} \sim t^{\text{hadr}}\right)_{\text{gluer}}$$

Inclusive spectrum of **gluers** makes one think of the ***Feynman hadron plateau*** :

$$dN = \left[\int_{k_\perp \sim R^{-1}} \frac{dk_\perp^2}{k_\perp^2}\, 4C_F \frac{\alpha_s(k_\perp^2)}{4\pi}\right] \frac{dk}{k} = \text{const} \cdot \frac{dk}{k}$$

Qualitative space-time analysis of parton cascades accompanied by the example of the ***one-particle inclusive spectrum*** whose shape at small ***x*** was found to be ***insensitive, at the PT level, to large-distance phenomena*** gave rise to the idea of ***mathematical similarity*** between calculable parton and observable hadron distributions :

"Asymptotic Freedom and Local Parton–Hadron Duality" **(1984)**

The two ***fragmentation models*** that have survived the pressure of LEP scrutiny

— the **Lund string** (Andersson, Gustafson)
— the **HERWIG cluster** (Marchesini,Webber) do respect the locality and the LPHD :

Lund by construction (universal fragmentation of the colour tube)
HERWIG by virtue of finiteness of $\mathbf{M^2}$ of neighbouring partons.

For quite some time in the 80s, LUND and HERWIG seemed "orthogonal".

LUND was ignoring the ***PT parton multiplication*** until it got hard-pressured by LEP.

Good start : we learned how much of what we observe in jet physics can be explained merely by an accurate account of the momentum conservation and Lorentz kinematics.

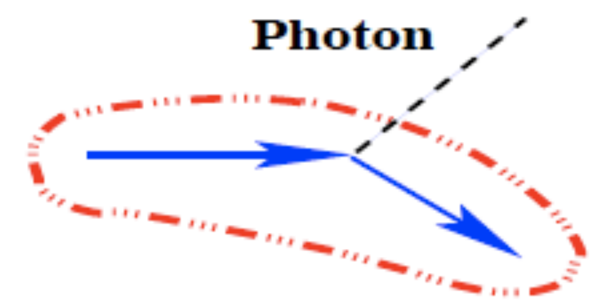
On the other hand, the HERWIG ideologues from the start put an emphasis on the **PT** cascades, having chosen the **PT–NP** separation parameter Q_0 as low as possible.

At the same time, HERWIG had to learn, after the LUND, how to embed important effects of ***colour topology*** upon large-angle particle production: the ***inter-jet phenomena***

Convergence : "The string effect and QCD coherence", Phys.Lett. 165B (1985) 147

Lund gluon

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

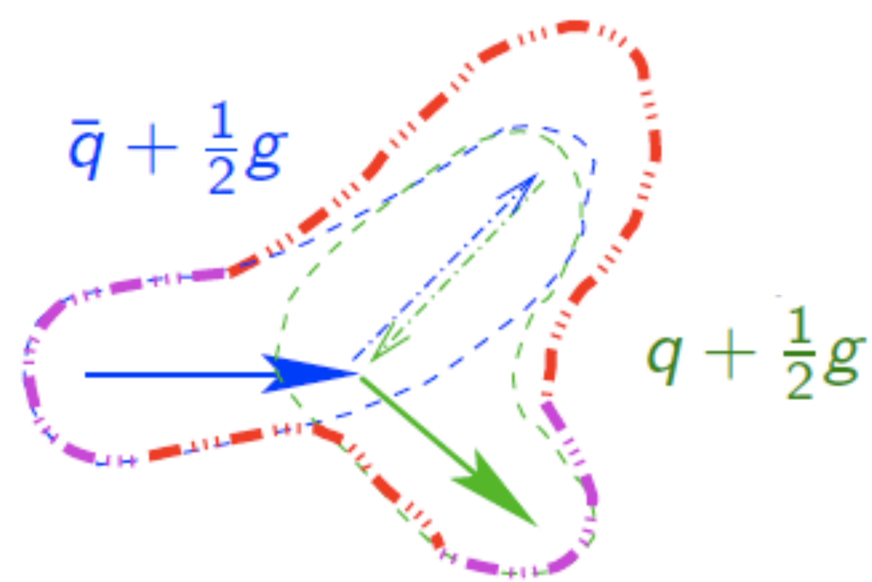


Now substitute a gluon for the photon in the same kinematics

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

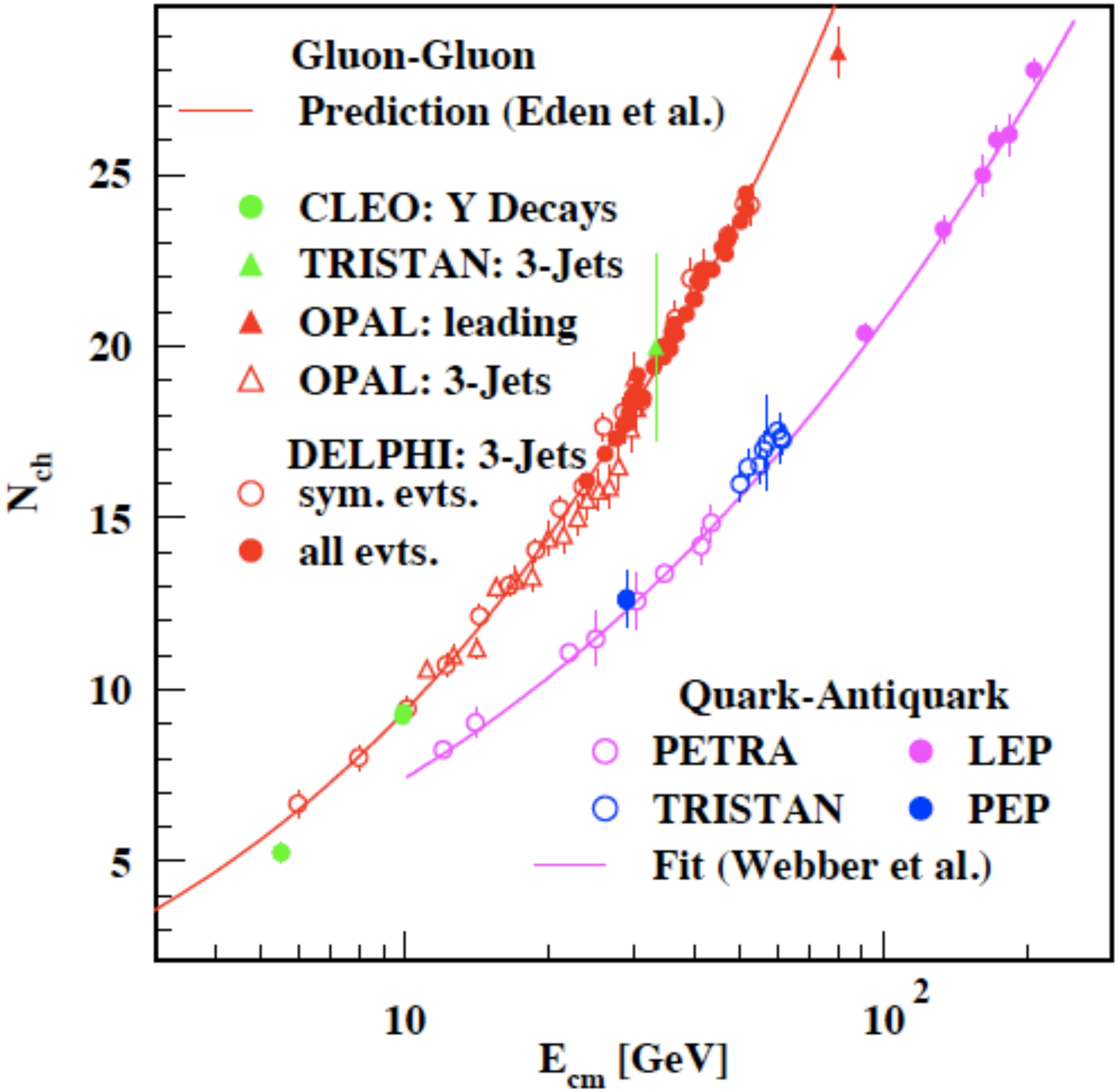
Lund: hadrons = the sum of two independent (properly boosted) colorless substrings

accuracy of such substitution - $1/N_c^2$



The first immediate consequence :

Double Multiplicity of hadrons
in fragmentation of the *gluon*



Look at experimental findings

Lessons :

- N increases *faster* than $\ln E$

($\Longrightarrow$ Feynman was wrong)

- $N_g/N_q < 2$

however

look at the ***energy derivative*** :

- $$\frac{dN_g}{dN_q} = \frac{N_c}{C_F} = \frac{2N_c^2}{N_c^2-1} = \frac{9}{4} \simeq 2$$

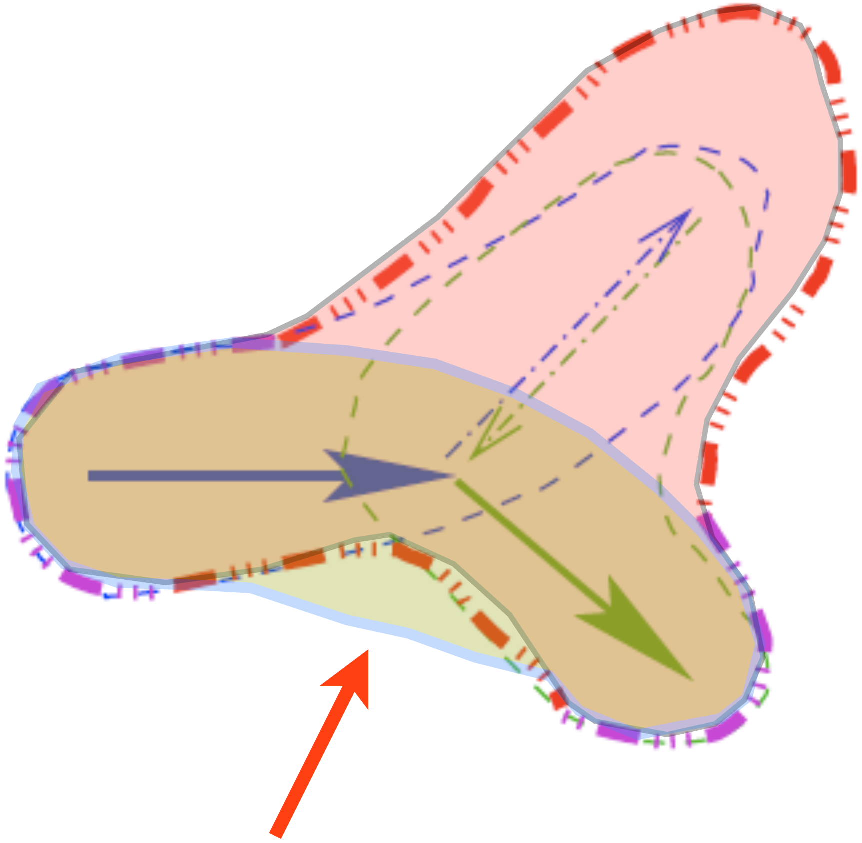
It is bremsstrahlung gluons who add to the hadron yield

Parton cascades respect QCD "colour counting"

Now return to a more subtle - and powerful - consequence of the Lund picture

QCD
Radiophysics

colour drag



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

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

Let's look into the *inter-quark valley* and compare the hadron yield with that in the $q\bar{q}\gamma$ event

The overlay results in a magnificent "*String effect*"

depletion of particle production in the $q\bar{q}$ valley

Destructive interference from the QCD point of view

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)

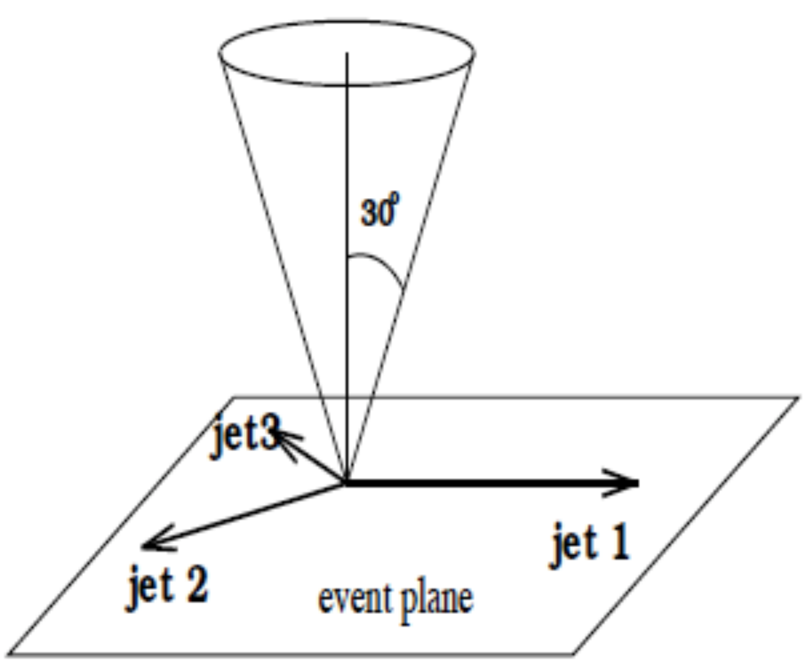
Multitude of the ratios of hadron flows between jets in various multi-jet processes gives example of non-trivial CIS (collinear-and-infrared-safe) QCD observable

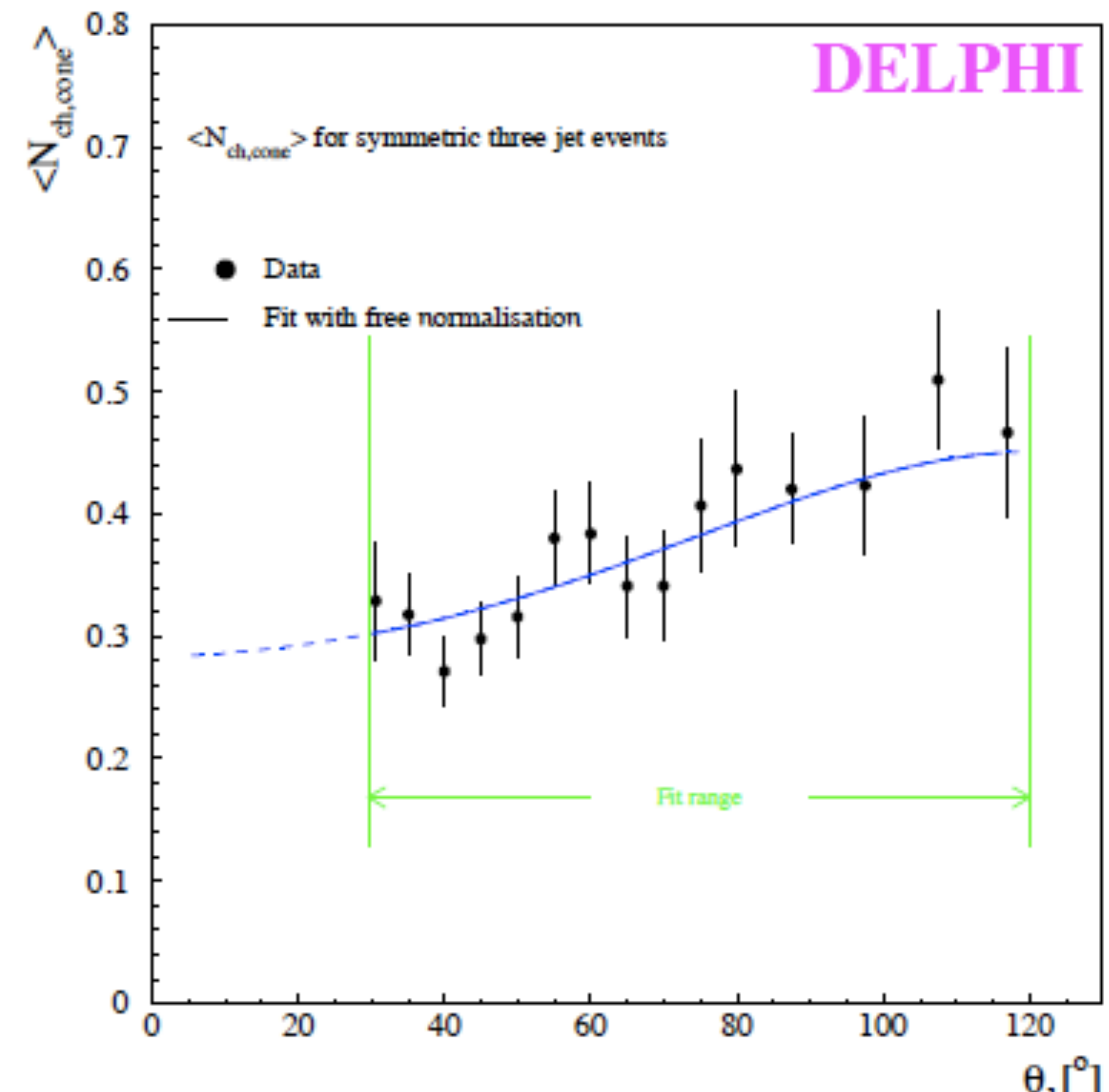
The classical *string effect* – the ratio of the multiplicity flow between a quark (antiquark) and a gluon to that in the quark valley in symmetric (“Mercedes”) three-jet e+e– annihilation events :

$$\frac{dN_{qg}^{(q\bar{q}g)}}{dN_{q\bar{q}}^{(q\bar{q}g)}} \simeq \frac{5N_c^2-1}{2N_c^2-4} \quad = \frac{22}{7} \simeq \pi$$

Emitting an energetic gluon off the initial quark pair depletes accompanying radiation in the *backward* direction: colour is *dragged out* of the quark valley. This destructive interference effect is *so strong* that the resulting multiplicity flow between quarks falls below that in the *least favourable* direction - *transversal* to the 3-jet event plane :

$$\frac{dN_{\perp}^{(q\bar{q}\gamma)}}{dN_{q\bar{q}}^{(q\bar{q}g)}} \simeq \frac{N_C+2C_F}{2(4C_F-N_c)} = \frac{17}{14}$$





The *colour field* that an ensemble of hard primary **partons** (parton antenna) develops, determines, on the “one-to-one” basis, the structure of final flows of **hadrons**.

The Poynting vector of the ***colour field*** gets “*translated*” into the ***hadron*** Poynting vector :

When viewed ***globally***, confinement is about “***renaming***” a flying-away **quark** into a flying-away **pion** rather than about forces “***pulling***” quarks together.

QCD coherence is crucial for multiplication of partons ***inside*** jets as well.

Destructive interference suppresses multiple production of *very small momentum* gluons.
It is particles with ***intermediate energies*** that happen to multiply most efficiently !

The energy spectrum of relatively soft secondary partons in jets develops a "***hump*** ".
The position, the width and the height of this hump evolve with $\mathbf{Q^2}$ in a predictable way.

This prediction was derived in 1984 in the so-called MLLA (Modified Leading Log Approximation).

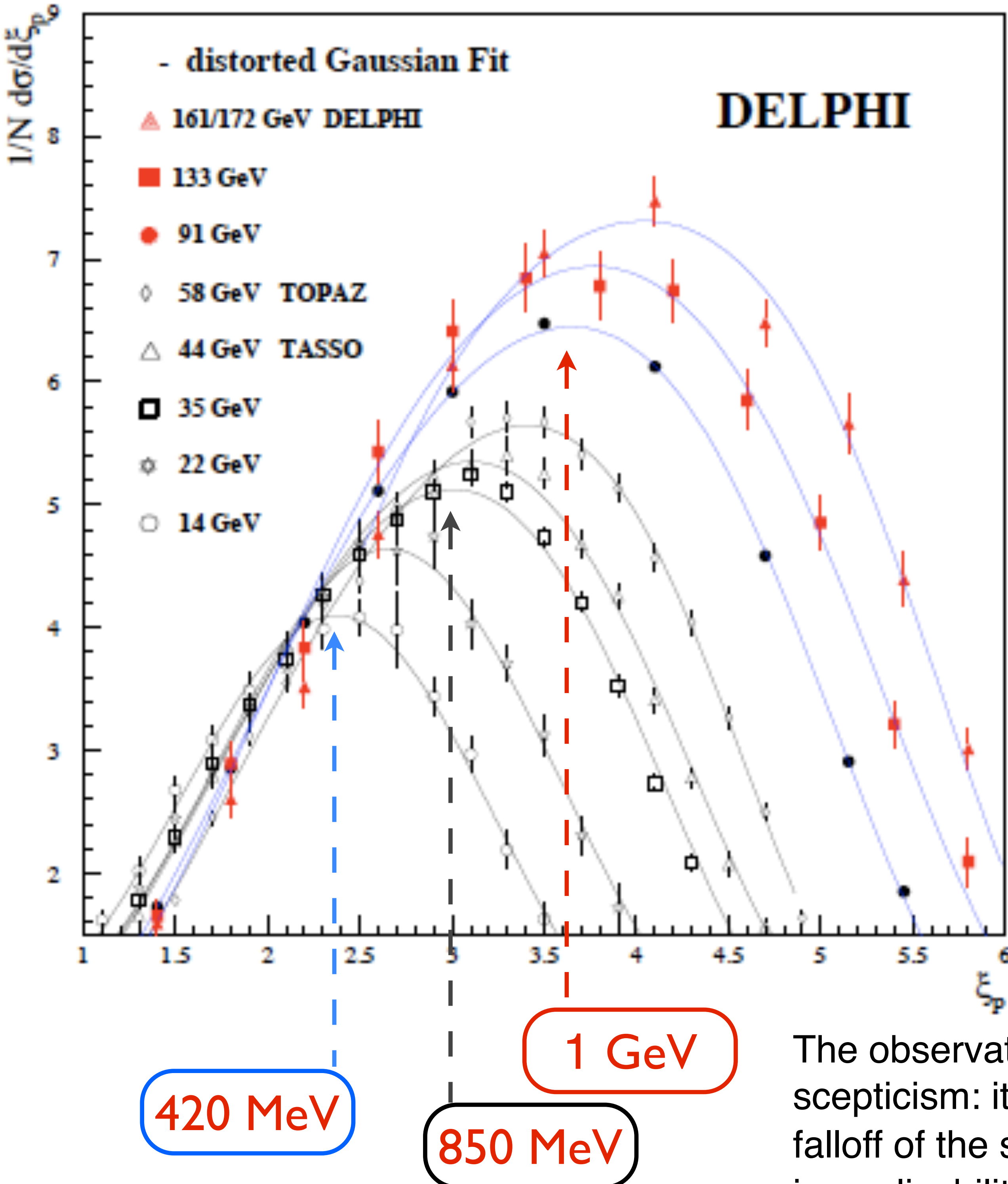
It took into account essential ingredients of parton multiplication in the next-to-leading order :

- parton ***splitting functions*** responsible for the energy balance in parton splitting
- the ***running coupling*** depending on the *relative transverse momentum* of the offspring
- the ***exact angular ordering.*** The latter - a consequence of ***soft gluon coherence***.

Moreover, in turned out that "**soft jet fragmentation**" can be predicted, in certain sense, ***from the first principles*** unlike **DIS** parton distributions where one always needs a **NP** input.

The shape of the inclusive spectrum of *all charged* ***hadrons*** (dominated by pions)
exhibits the same features as the MLLA **parton** spectrum

First scrutinized at LEP, the similarity of *parton* and *hadron* energy spectra has been verified at SLC and KEK $\mathbf{e^+e^-}$ machines, as well as at HERA and Tevatron (where jets originate not from quarks dug up from the vacuum by a virtual photon/Z^0 but from partons kicked out from initial hadron(s)).



LPHD IN-JET

The comparison of the spectra of all charged hadrons at various annihilation energies Q with the so-called "*distorted Gaussian*" fit which employs the first four moments (the mean, width, skewness and kurtosis) of the MLLA distribution around its maximum.

Shall we say : a (routine, interesting, wonderful) check of yet another QCD prediction?

Such a close similarity offers a ***deep puzzle***, even a worry, rather than a successful test

The observation of the parton-hadron similarity was initially met with a serious scepticism: it looked more natural to blame the ***finite hadron mass effects*** for falloff of the spectrum at large ξ (small momenta) rather than seriously believe in applicability of the PT consideration down to such ***disturbingly small scales***.

It is ***not the energy*** of the jet itself but ***the maximal parton transverse momentum*** inside it, $k_{\perp\max} \simeq E_{\rm jet} \sin \Theta_{\rm cone}$ that determines the ***hardness scale*** and thus the yield and the distribution of the accompanying radiation.

This means that by choosing a small opening angle one can study relatively small hardness scales **but in a cleaner environment** : due to the ***Lorentz boost effect***, eventually all particles that form a short small-Q^2 QCD "**hump**" are now ***relativistic*** and are concentrated ***at the tip of the jet !***

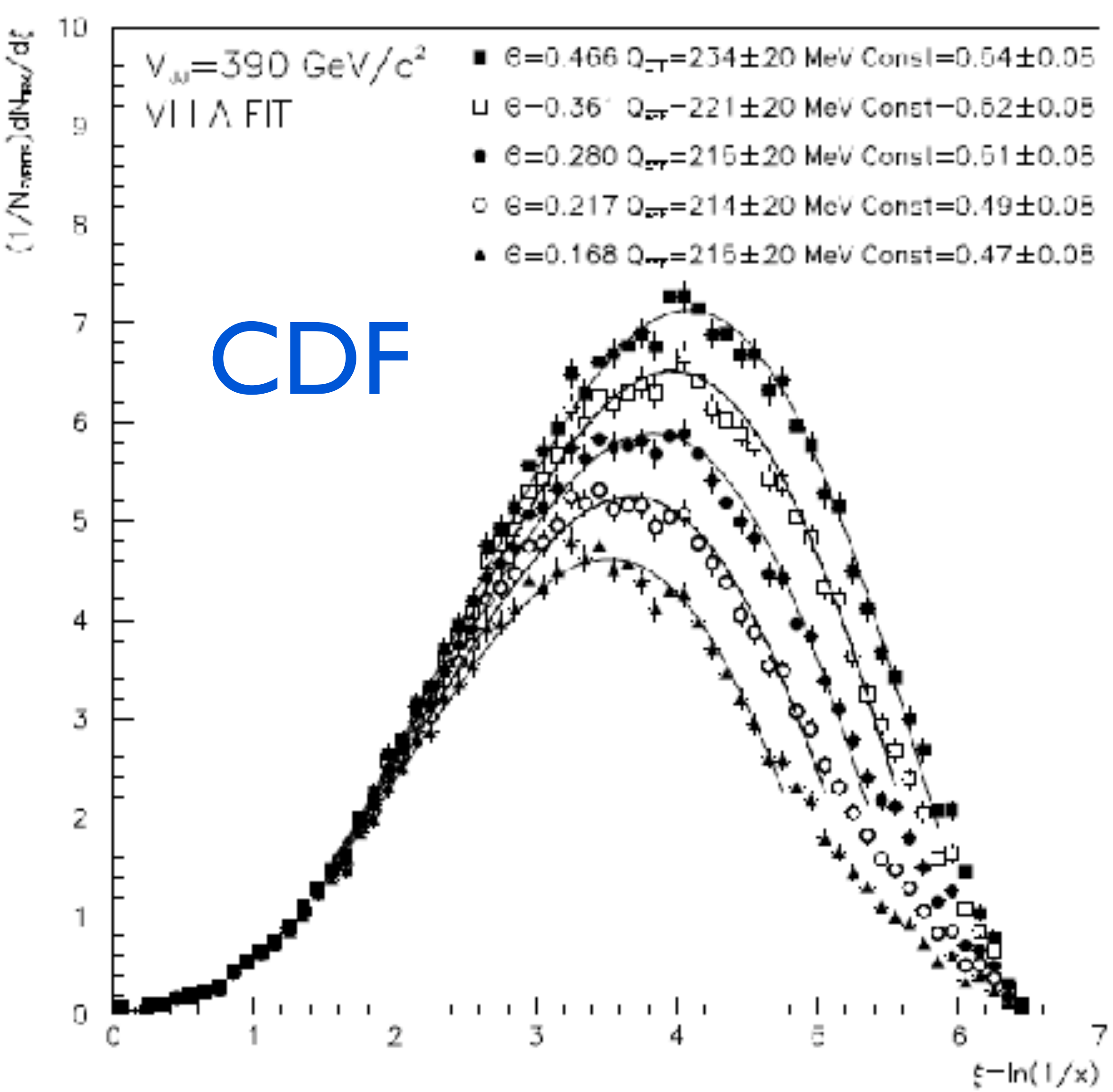
Selecting hadrons inside a cone **0.14** around a quark jet with E_{jet}**=100 GeV** one would see that very *dubious* **Q=14 GeV** curve but now with the maximum ***boosted*** from **0.45 GeV** to **6 GeV !**

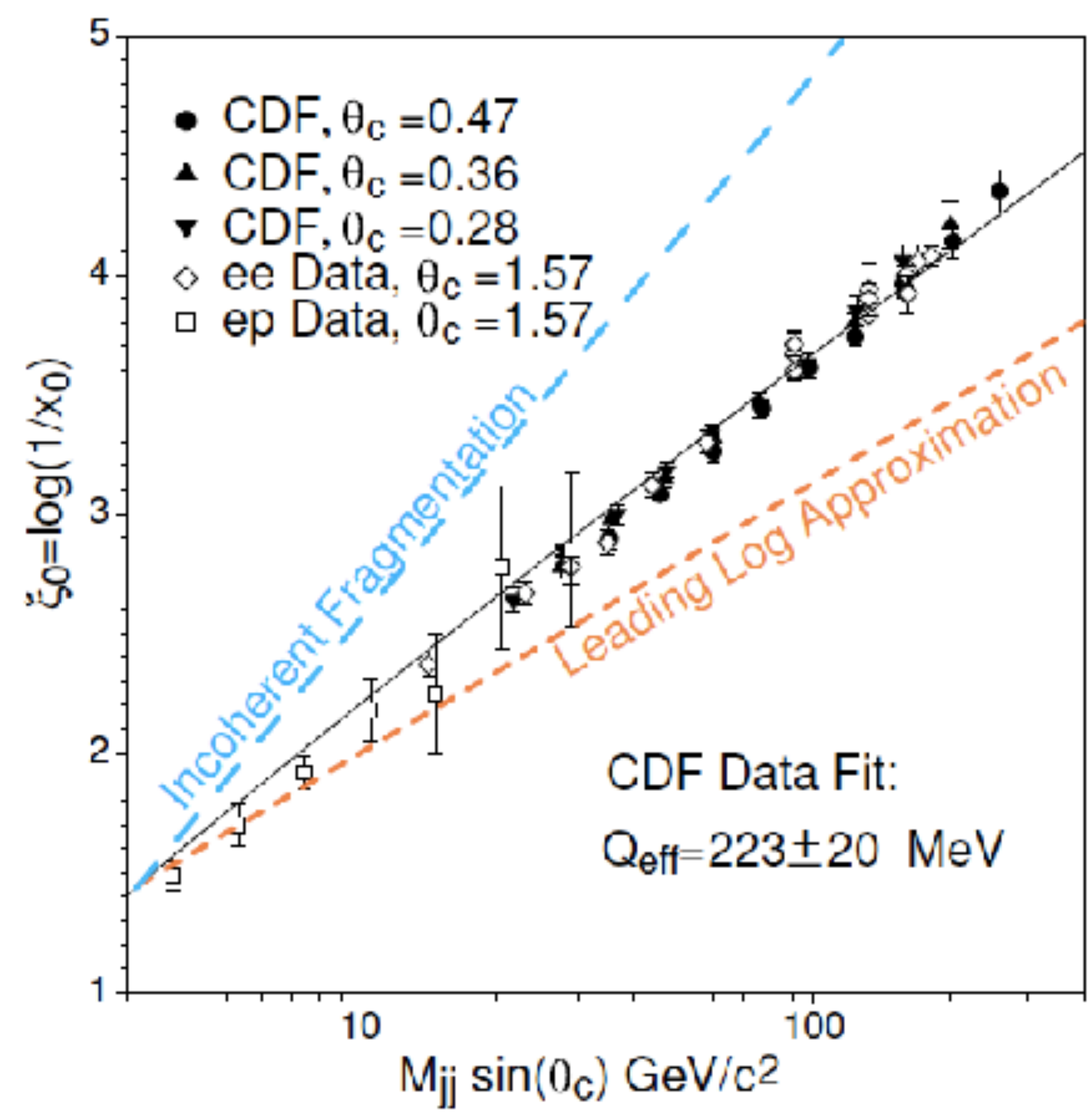
jets with restricted "opening angle"

Position of the Hump as a function of the ***hardness*** of the jet $Q = M_{jj} \sin \Theta_c$

is a ***parameter-free*** *pQCD prediction*

The plot combines e^+e^-, ***DIS*** and ***hh*** data **!**





punchline

The ***ratios*** of particle flows between jets (**intERjet** radiophysics),
and the ***shape*** of inclusive spectra of secondary particles (**intRAjet** cascades) are calculable (**C**ollinear-and-**I**nfrared-**S**afe) quantities.

Moreover, the perturbative QCD predictions actually describe flows of **hadrons** **!**

The strange thing is, these phenomena reveal themselves in present-day experiments via hadrons (pions) with extremely small momenta $k_\perp$, where we are expecting to hit the non-perturbative domain — large coupling $\alpha_s(k_\perp)$ — and potential ***failure*** of the *quark–gluon language* as such.

The fact that the underlying perturbative dynamics of colour is being impressed upon "miserable" pions with 100–300 MeV momenta, could not be a priori expected.

At the same time, it repeatedly 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.

"SOFT CONFINEMENT" **. . .**