Hadron interactions, color and QCD partons

1. Asymptotic freedom, DIS and the QCD parton picture

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This week we will discuss some selected topics :

1. Asymptotic freedom, QCD partons and their dynamics ("*evolution*")

2. Jets, "soft gluons", QCD coherence effects and parton-hadron duality

3. Non-perturbative effects in jets ("*probing confinement*")

4. Partons in QCD media and HI physics

5. Exploring SUSY for simplifying QCD

introduction lecture : plan

- QCD : **status quo**
- Asymptotic Freedom : **WHY ?..**
- Hard QCD processes and **partons**
- Leading logarithms and **“fluctuation time”**
- DIS and **“parton evolution”**

Our field has emerged as a result of the digression:

natural philosophy > physics > quantum physics > particle physics.

Our predecessors specified : **elementary particle physics > high energy physics**.

In the past 40 years, with an advent of Quantum Chromodynamics, we have witnessed the final step after which QCD has acquired its today's split personality:

high energy physics > soft physics + hard physics.

Both "**hard**" and "**soft**" are hard subjects, and the softer - the harder.

high energy HI physics is about to play a special role in linking them !

Thanks to the **Asymptotic Freedom**, one can control, by means of good old perturbation theory, how do quarks and gluons behave at small space-time intervals.

Perturbative QCD (**pQCD**) controls the relevant cross sections and, to a lesser extent, the structure of final states produced in ***hard interactions***.

However, whatever the hardness of the process, it is ***hadrons***, not ***quarks and gluons***, that hit the detectors...

For this reason alone, the applicability of the pQCD approach, even to ***hard processes***, is far from being obvious. One has to rely on plausible arguments (completeness, duality) and look for observables less vulnerable towards our ignorance about confinement.

To give an example, we cannot deduce from the first principles quark and gluon ("parton") distributions inside hadrons (PDF, or structure functions).

However, the rate of their Q^2-dependence (***scaling violation***) stays under pQCD jurisdiction : it is predictable and gives an example of a so-called ***Collinear-and-Infrared-Safe*** (CIS) observable.

Speaking about the final state structure, we cannot predict, say, the kaon multiplicity or the pion energy spectrum. However, one can decide to be not too picky and concentrate on ***global characteristics*** of the final states rather than on the yield of specific hadrons.

Being sufficiently inclusive with respect to final hadron species, one can rely on a picture of the ***energy-momentum flow*** in hard collisions supplied by pQCD - the jet pattern.

Until recently QCD studies were concentrated on small-distance phenomena, observables and characteristics that are as insensitive as possible to large-distance confinement physics.

This is the realm of "**hard processes**" in which a large momentum transfer Q^2, either time-like $\mathbf{Q^2 > 1\ GeV^2}$, or space-like $\mathbf{Q^2 < -1\ GeV^2}$, is applied to hadrons in order to probe their small-distance quark-gluon structure.

There are well elaborated procedures for counting jets (CIS jet finding algorithms) and for quantifying the internal structure of jets (CIS jet shape variables).

They allow the study of the gross features of the final states while staying away from the physics of hadronization.

Along these lines one visualizes ***asymptotic freedom***, checks out ***gluon spin*** and ***color***, predicts and verifies ***scaling violation pattern*** in hard cross sections, etc.

These checks have constituted the basic QCD tests of the first two decades since 1973.

The epoch of "QCD checks" is over.

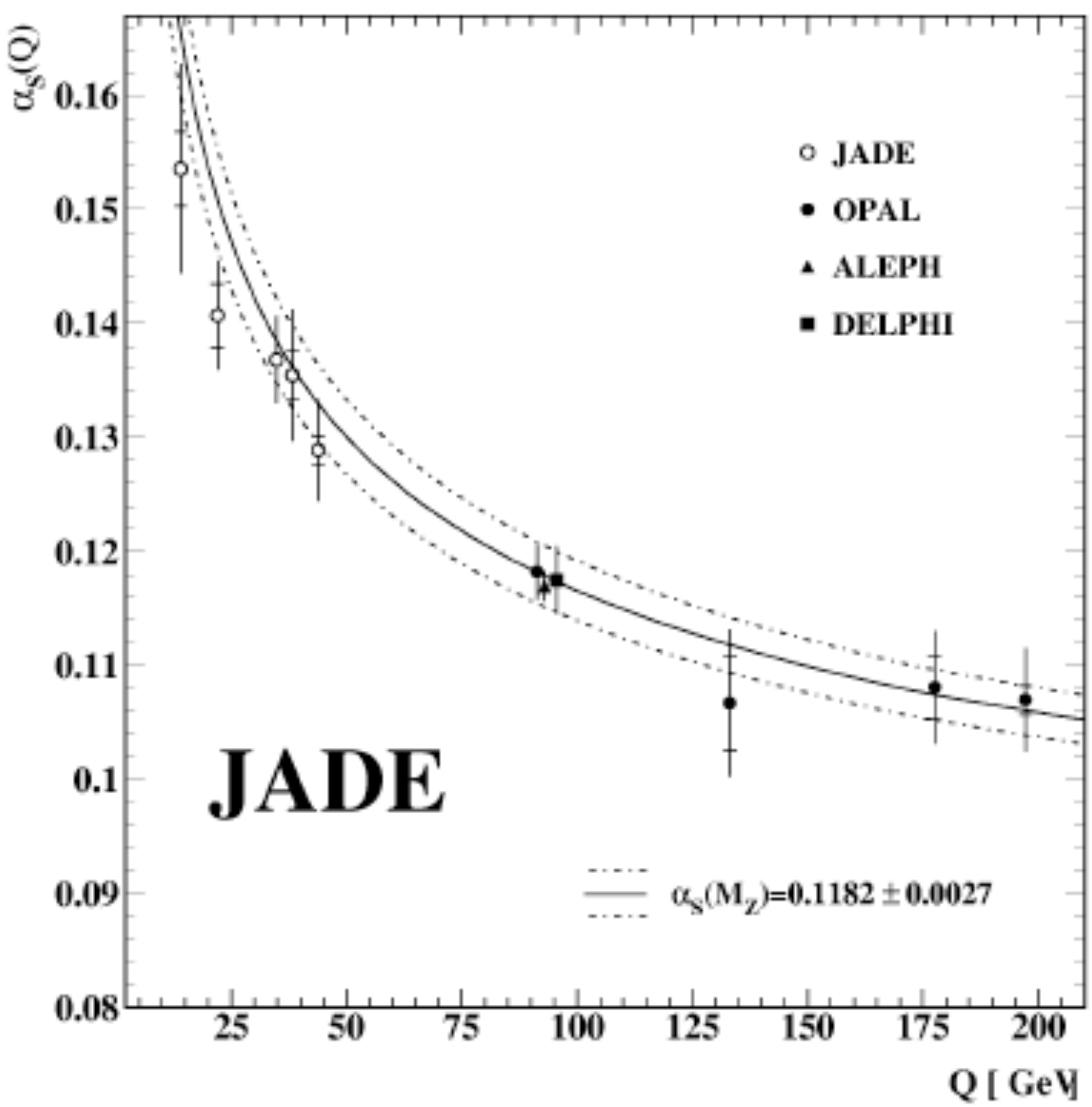
Now we rather need to try to ***probe*** genuine confinement effects in hard processes to ***learn*** about hadrons and strong interactions ...

Among most accurate QCD checks :

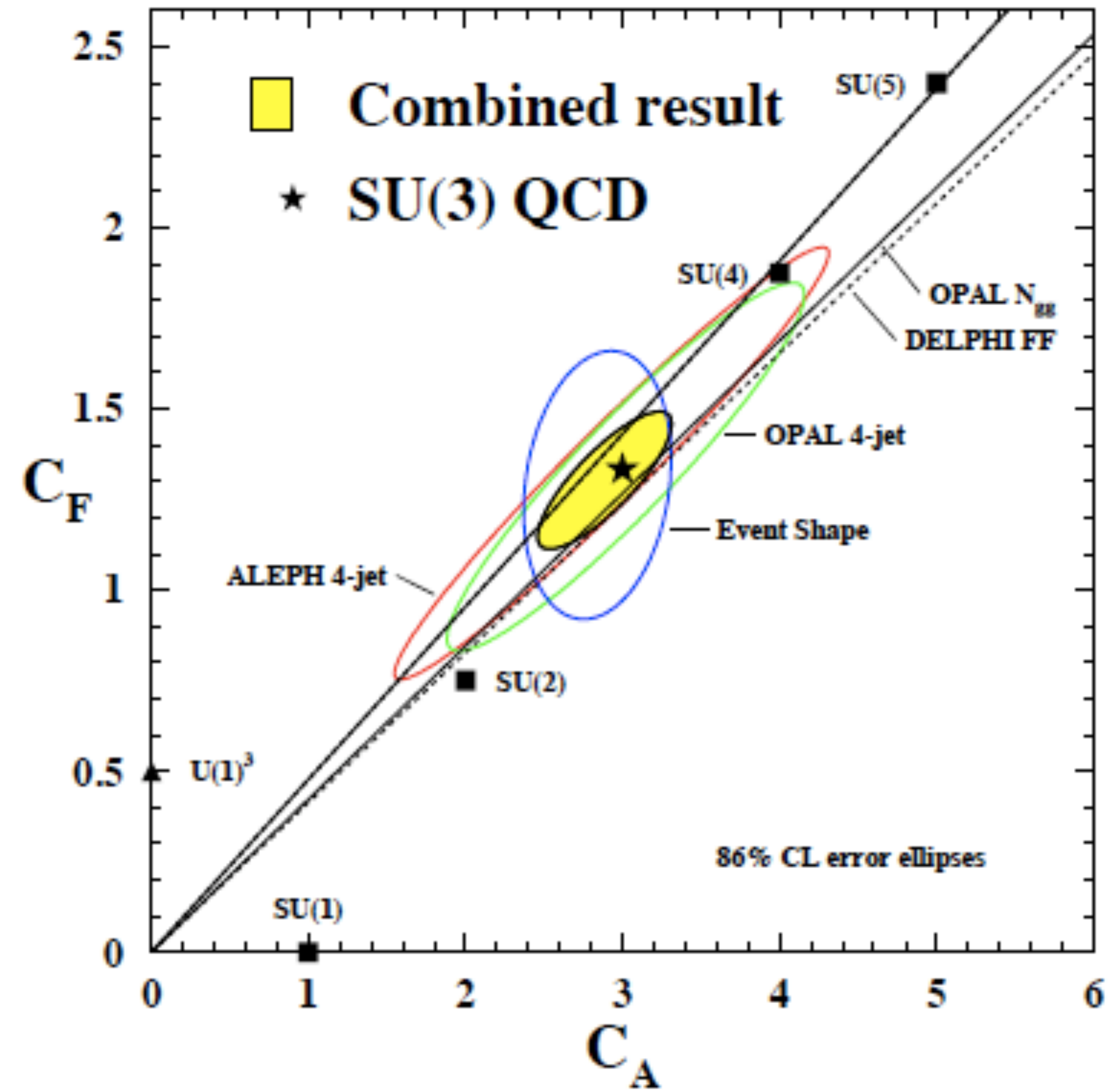
4-jet event production

e^+e^- experiments (LEP)

Running of the QCD coupling

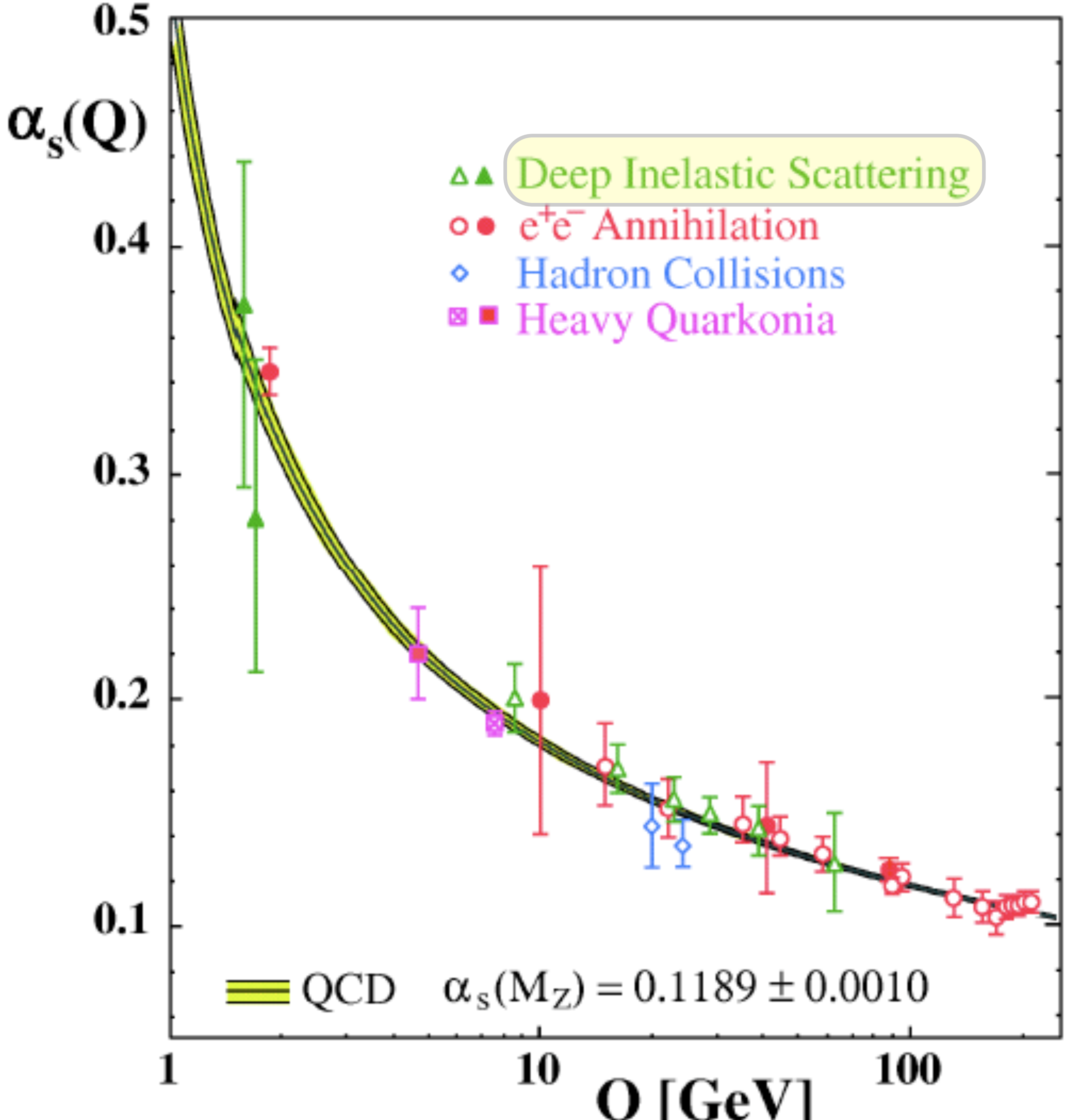


Nature of the QCD gauge group



JADE experiment - the smaller brother or prototype of the OPAL (LEP)

Summary of the QCD coupling measurements (2008)



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 ?..***

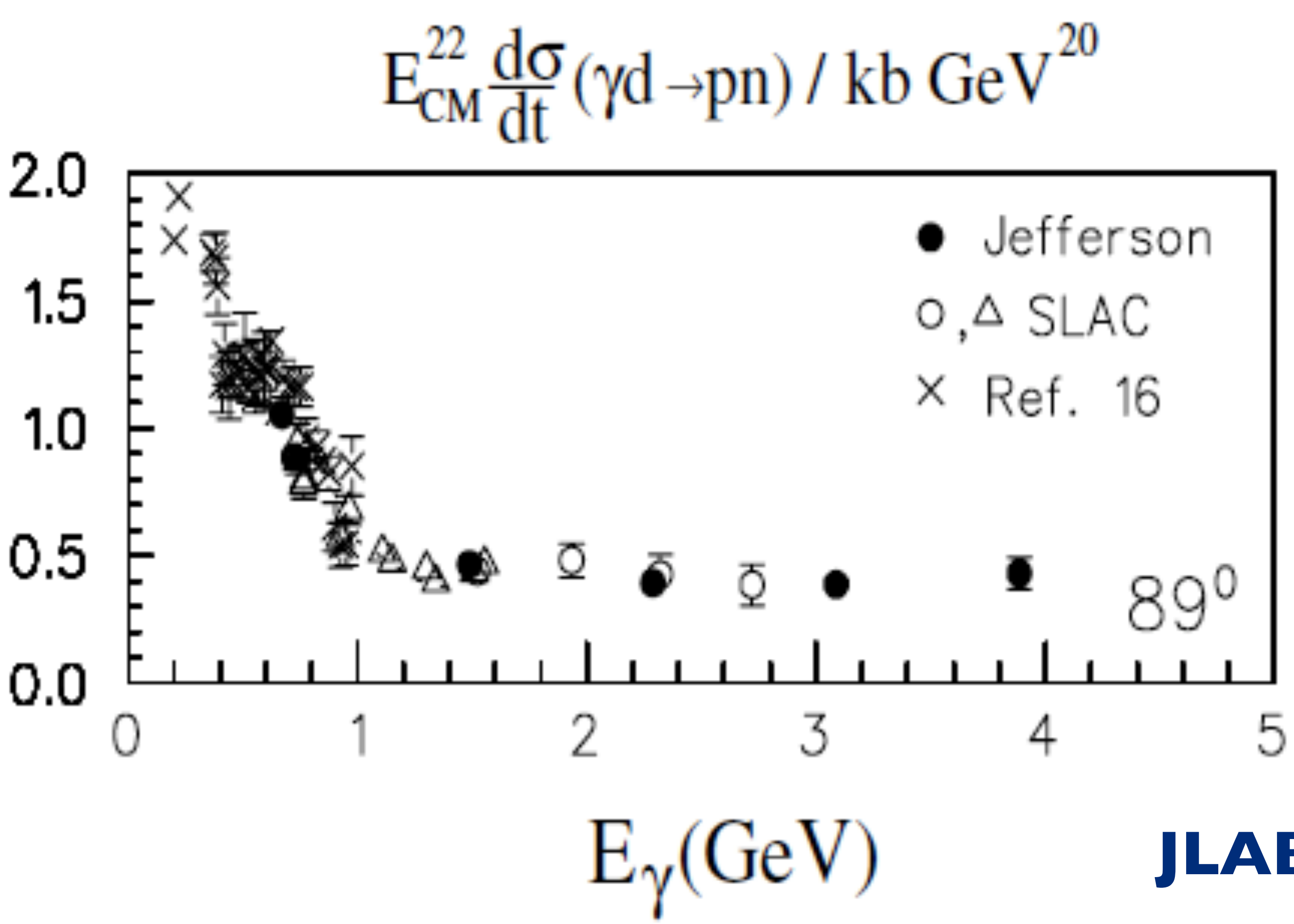
Dimensional counting *("quark counting rules")*

large angle scattering in the high energy / momentum transfer regime

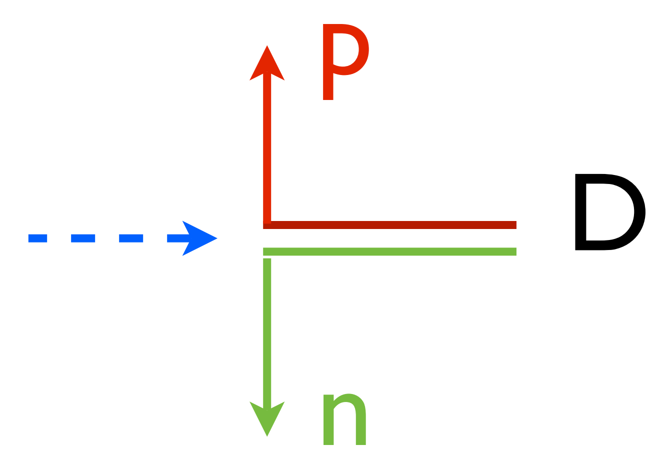
$$\boxed{\frac{d\sigma}{dt} = \frac{f(\Theta)}{s^{K-2}}; \qquad \frac{t}{s} = \text{const}}$$

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

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



JLAB



K* = *1+6* + *6* = *13

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

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

SU(3) symmetry of the hadron spectrum has led to the picture of ***three Quarks***.

Necessity to bind them has led to the notion of ***Gluons***

- *flavor-blind* strong interaction carriers.

A brief ***pre-history***

and ***autopsy***

of ***Asymptotic Freedom***

a brief history of Asymptotic Freedom

1955

The polarization of **QED** vacuum makes the coupling run with virtuality $\alpha \to \alpha(\mathbf{k^2})$

Initial calculation of the fermion loop produced *a wrong sign* - a ***QCD**-ish* β-function

This ***error*** was not a ***mistake*** : it was worth making***!***

mistake:	smth. done wrongly, or smth. that should not have been done.

Longman Dictionary of Contemporary English

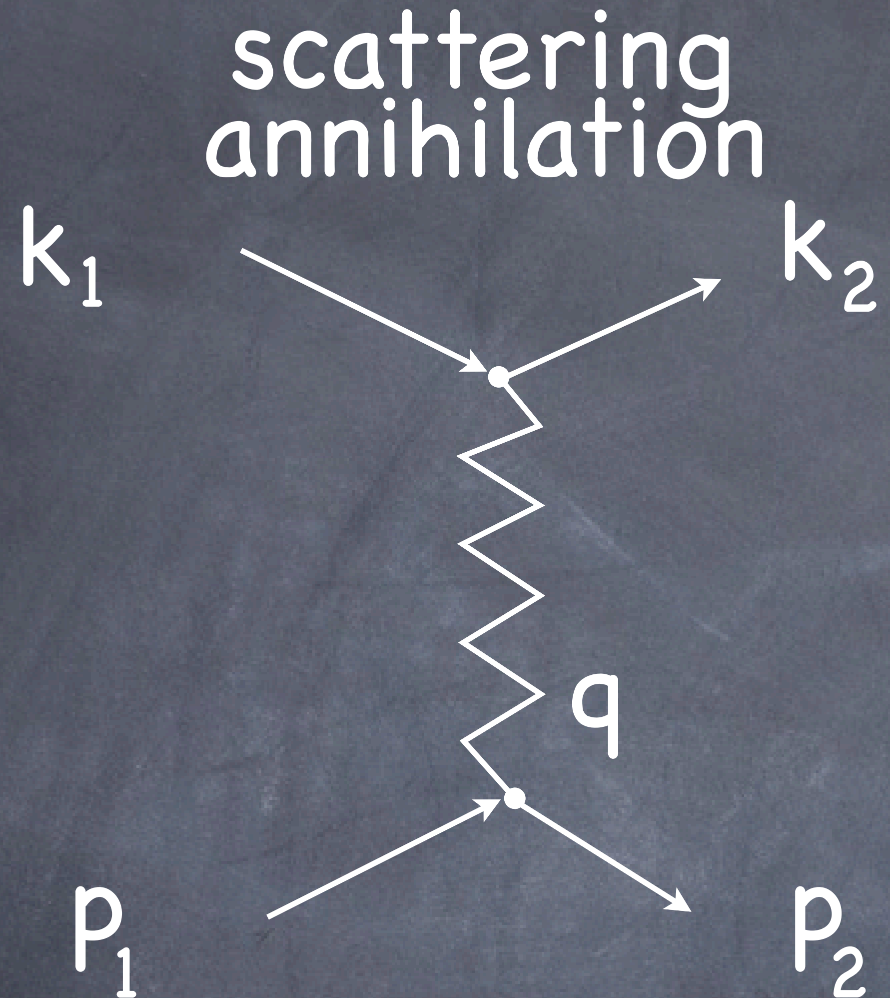
The time spanned *before B.Ioffe and A.Galanin have pointed at the error* proved to be enough for *L.Landau* and *I.Pomeranchuk* to develop and enthusiastically discuss with their pupils a beautiful physical picture of what we know now under the name of "***asymptotic freedom***".

"***Moscow Zero***": vanishing of the physical interaction (*renormalized coupling*) in the limit of a *point-like bare interaction* $\Lambda_{\rm UV} \to \infty$. "*...**nullification** of the theory is tacitly accepted even by theoretical physicists who profess to dispute it.*" (Landau)

Looked as a general, inevitable property of a QFT... (*Pomeranchuk*, 1955-58)

1958 Dyson : " *the correct meson theory will not be found in the next hundred years*"

1960 Landau : " *the Hamiltonian method for strong interactions is dead and must be buried, although of course with deserved honour* "



relativistic crossing

$s=(p_1+k_1)^2$ invariant energy

$t=(p_1-p_2)^2$ momentum transfer

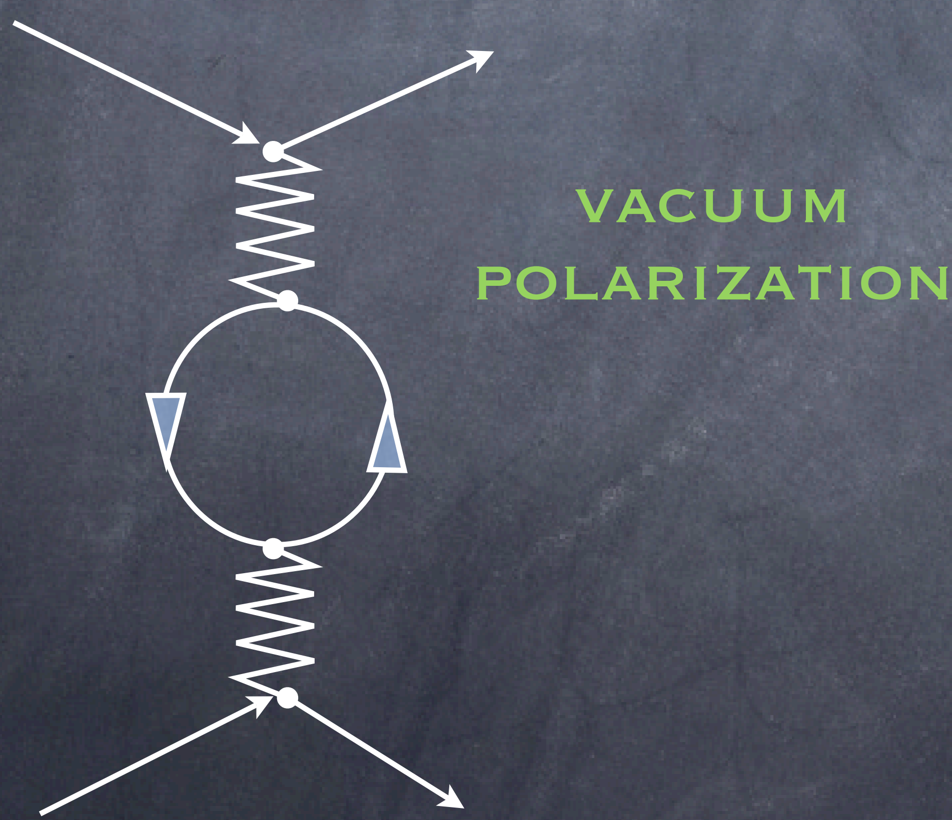
one and the same amplitude as a function of its *invariants* A(s,t) describes three physically different processes related by *crossing*

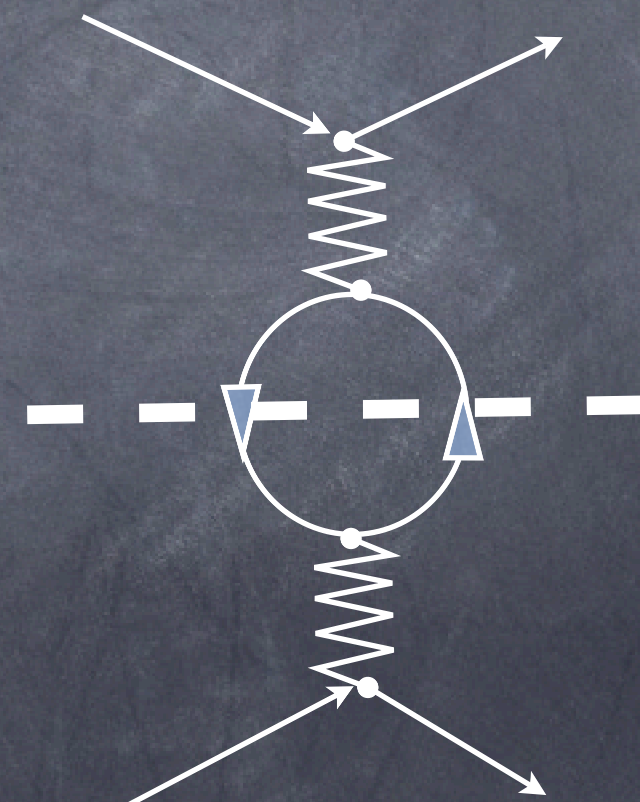
A(s,t) is an **analytic function** of energy s (causality) and of the momentum transfer t (crossing) whose **singularities** are determined by the unitarity as any symmetry,

the **crossing symmetry** has many a powerful, and sometimes dramatic, consequences

in particular, it is *crossing* and *unitarity* that made one think that the "*asymptotically free*" behavior of the effective coupling (*QCD*) is **impossible**

Indeed, as any QFT amplitude, the ***vacuum polarization*** *loop is analytic in* $\boldsymbol{k^2}$.





$\mathrm{Im}\, A = BB^* > 0$

*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

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

*" Same-sign **charges** repulse; same-sign **currents** attract (gluon magnetic moment)..."*

This sort of qualitative incantations do not explain how does YM QFT manage to overpass the unitarity **+** *crossing Landau-Pomeranchuk argument ...*

Why then - and **how** - did this argument fail in the non-Abelian gauge field theory ?

1977

V.Gribov : *physics of "anti-screening" - statistical effect of "zero-fluctuations"*

AUTOPSY OF ASYMPTOTIC FREEDOM

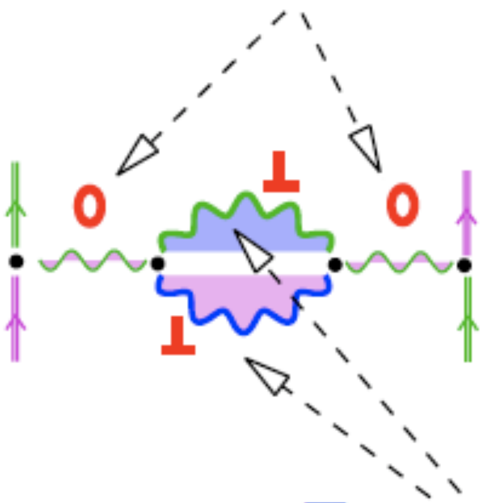
- To address a question starting from *what* or *why* we better talk *physical degrees of freedom*; use the Hamiltonian language
- Then, we have gluons of *two sorts*:

➡ two "physical" transversely polarized gluons and

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

Consider Coulomb interaction between two heavy colour charges

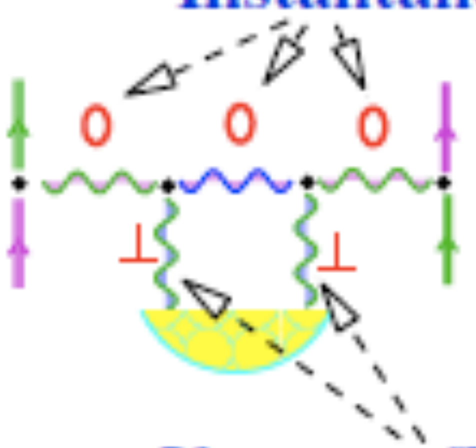
Instantaneous Coulomb interaction



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

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

Instantaneous Coulomb interaction



$$= +N_c * 4$$

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

Combine into the QCD β–function:

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

Hard Processes

and QCD partons

High-energy ***e+e- annihilation into hadrons***,

deep inelastic lepton-hadron scattering (DIS),

production in hadron-hadron collisions of

massive lepton pairs,

heavy quarks and their bound states,

large transverse momentum jets and vector bosons

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

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.

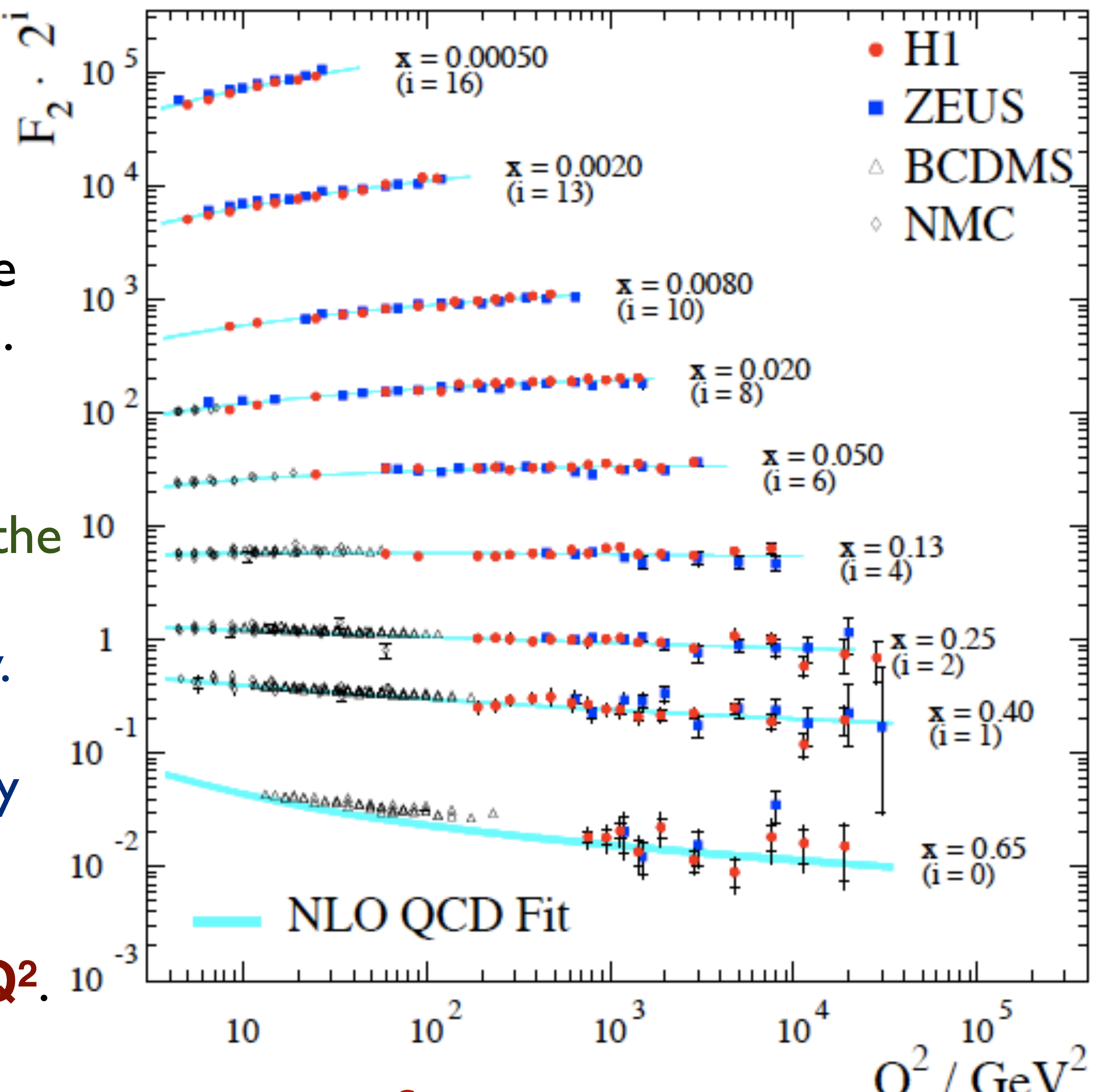
Is there any correspondence between observable hadron and calculable quark-gluon production ?

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

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 **Q^2**.

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

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

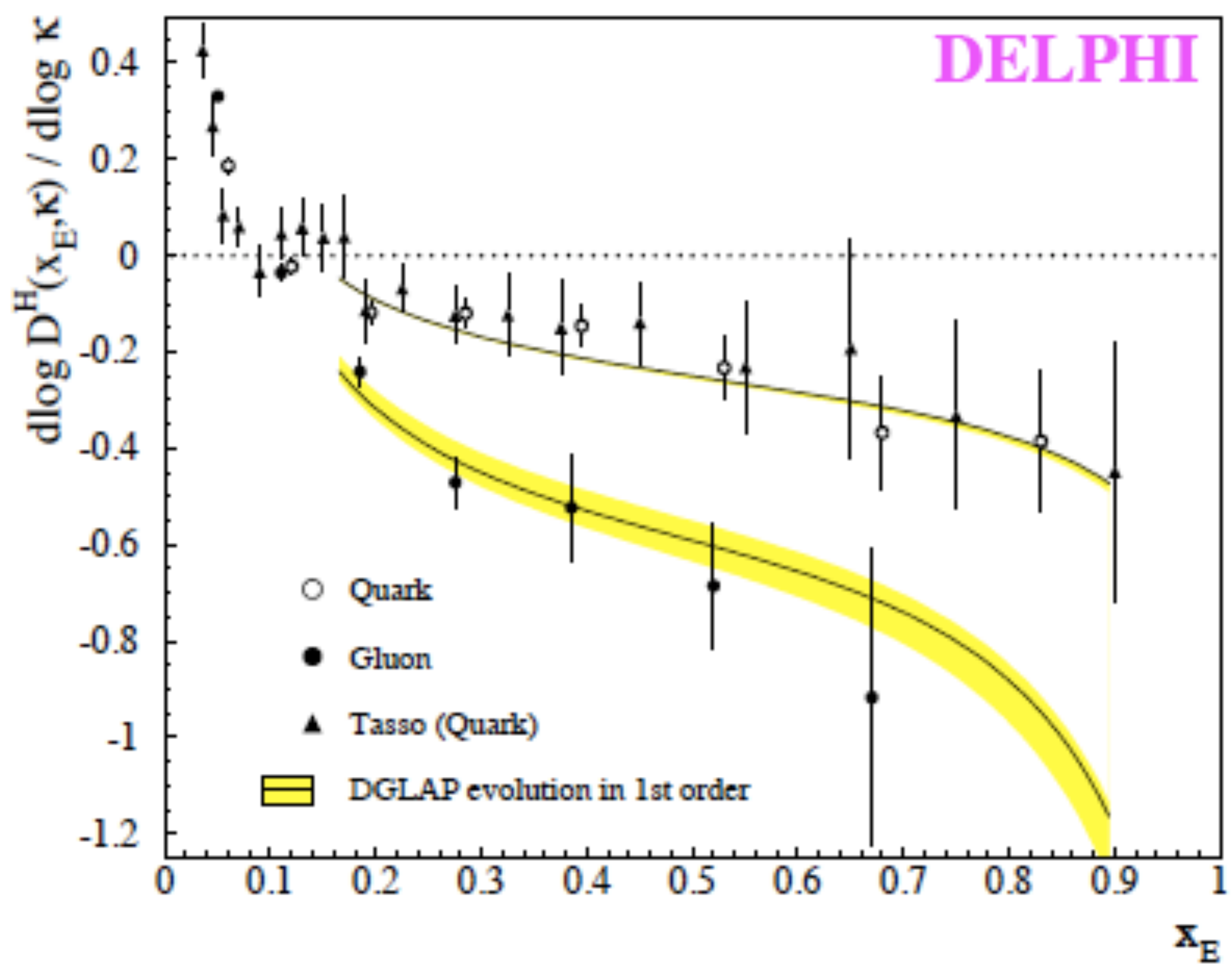
In **DIS** we look for a "***bare***" quark inside a target ***dressed*** one.

In **e+e−** hadron annihilation at large energy $\mathbf{s = Q^2}$ 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 $\mathbf{Q^2}$ (*the larger, the smaller*).



Scaling violation in quark and gluon fragmentation

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

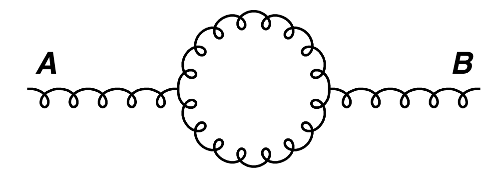
$$\frac{C_A}{C_F} = 2.23 \pm 0.09_{\text{stat.}} \pm 0.06_{\text{syst.}}$$

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

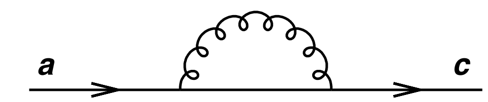
$$\sum_{a=1}^{N_c^2-1} T_R^a T_R^a = C_R \cdot \mathbf{I}$$

for any group representation R

C_A - adjoint (gluon field)

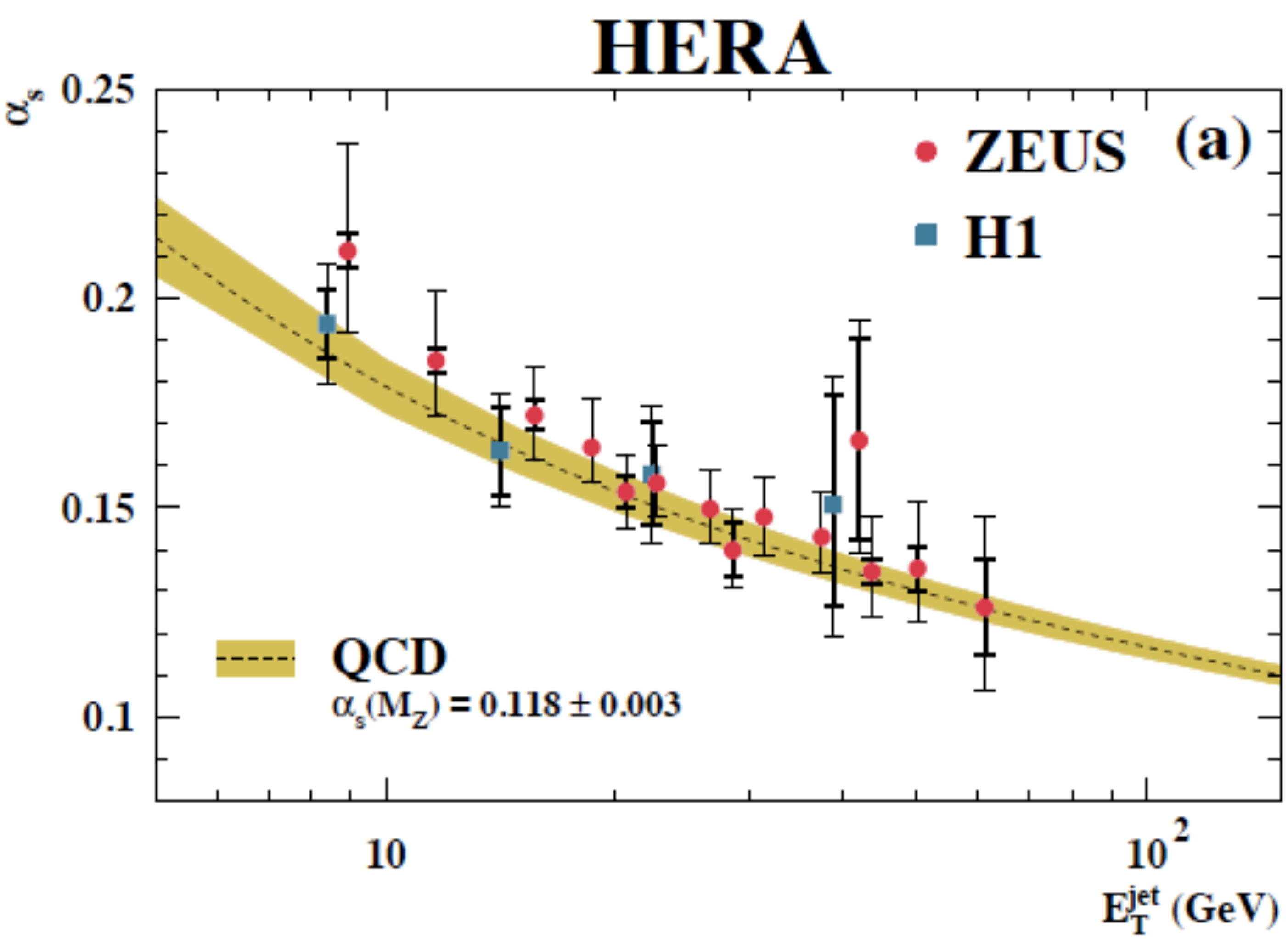


C_F - fundamental (quarks)



were recently extracted from

4-jet angular correlations and jet shapes



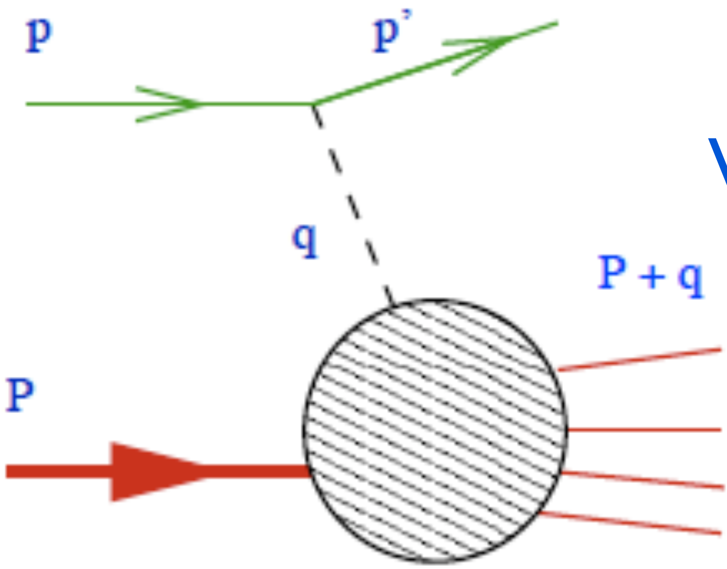
Results of α_s as a function of E_T^{jet} from HERA experiments H1 and ZEUS

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

$$C_A = N_c \qquad = 3.00$$

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

In fact, the same rules (*and the same formulae*) apply to the *scaling violation pattern* in **e+e− fragmentation functions** (*time-like parton evolution*) as to that in the DIS **parton distributions** (*space-like evolution*).



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 $\boxed{x = -\frac{q^2}{2(Pq)}}$ $(0 \le x \le 1)$

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

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

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?)

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

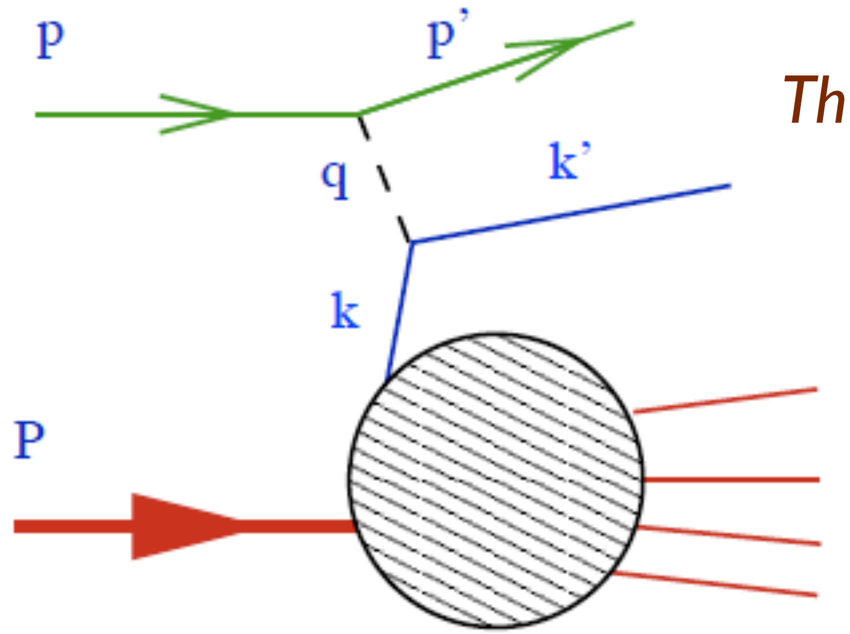
– excitation of one quark gets *redistributed* inside the proton via the confinement "*springs*" that bind quarks together and don't let them fly away.

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 : $\boxed{\text{DIS selects a quark with momentum } x \cdot P}$

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

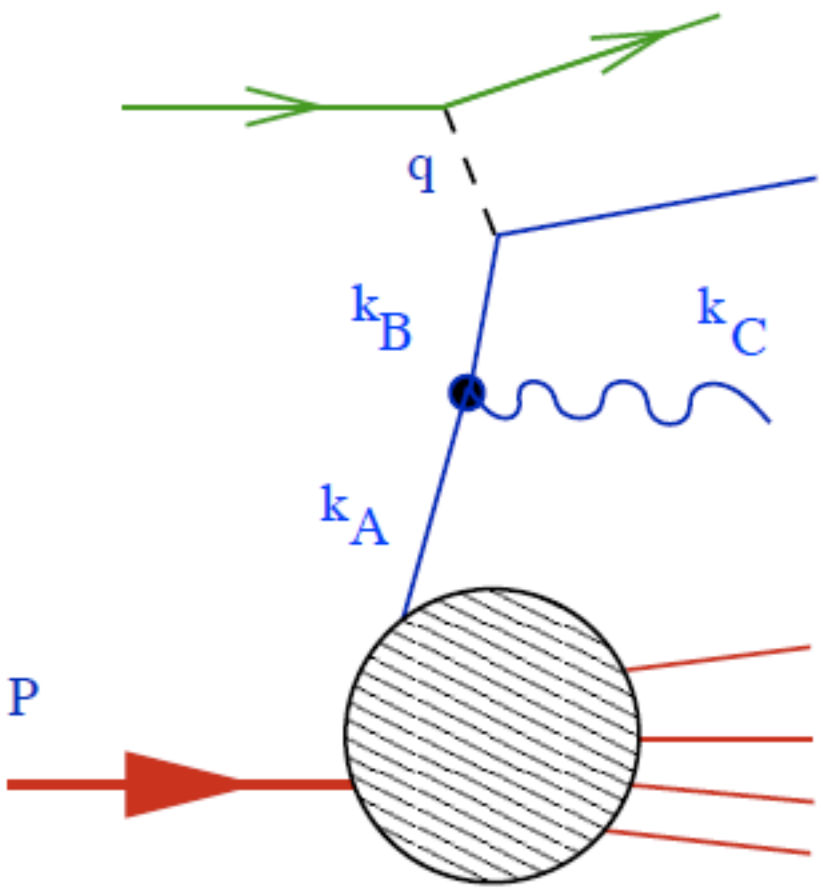
The ***Bjorken scaling*** *hypothesis - existence of the limiting distribution ("Bjorken limit")*

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

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"?

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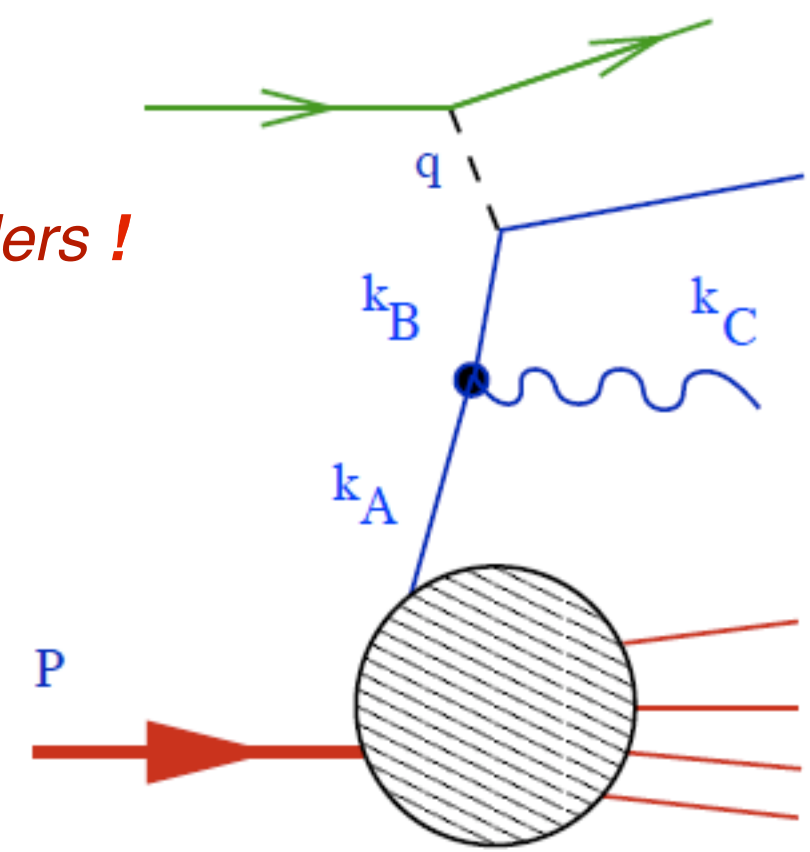
Which are the ***most probable*** parton fluctuations?

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



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

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

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

Relation between virtualities of three participating partons :

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

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

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

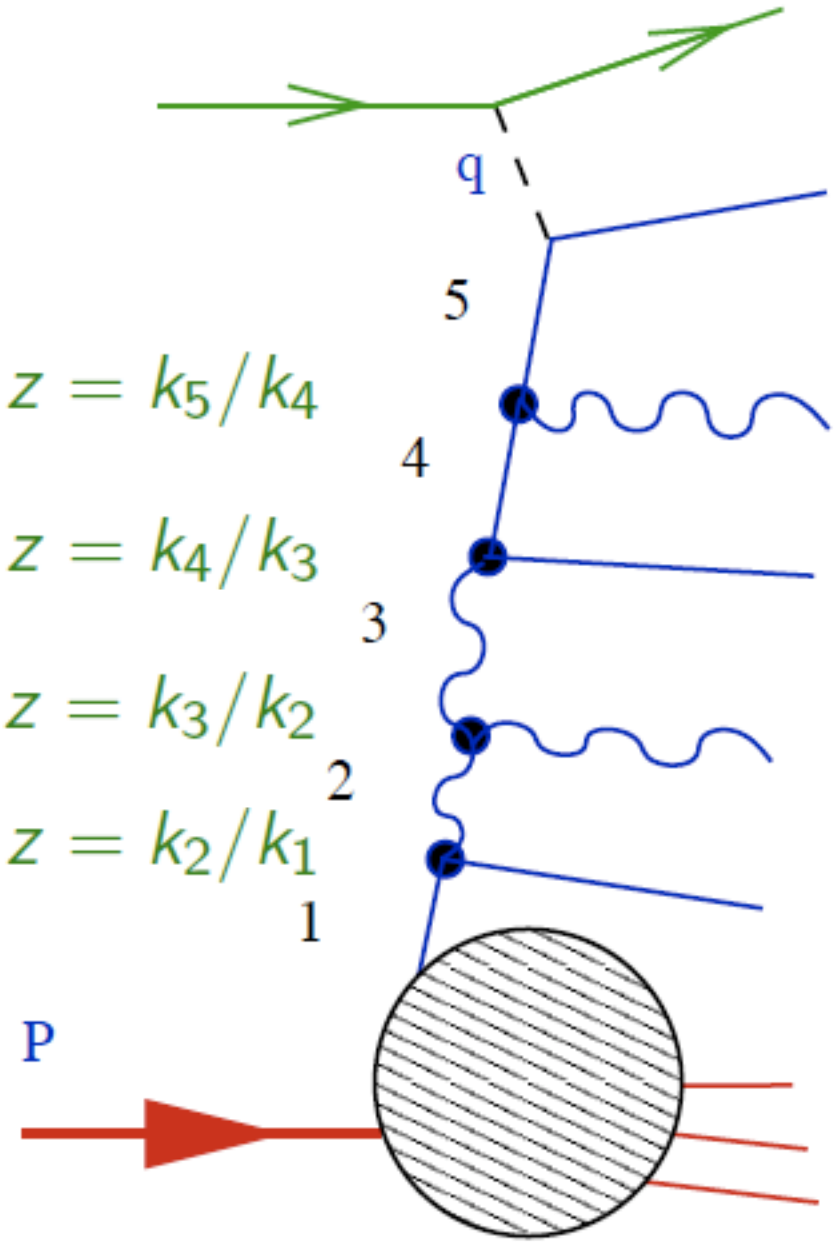
This inequality has a *transparent physical meaning* :

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

strongly ordered
lifetimes
of successive parton fluctuations

Evolution of a parton system becomes a *Markov chain* in a properly chosen “time”, **~ ln Q^2**

DGLAP



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

Four basic splitting processes **= parton Hamiltonian**

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

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

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

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

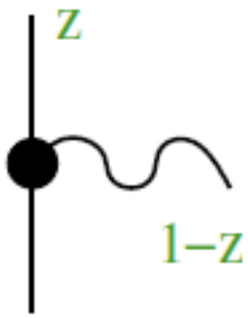
We cannot predict, from the first principles, parton content (**B**) of a hadron (**h**).
However, perturbative QCD tells us how it changes with the momentum transfer **Q^2**.

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

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

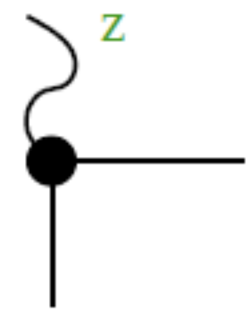
time derivative *wave function* *Hamiltonian* ***= Resummation Tool***

Apparent and *Hidden* symmetries of **parton dynamics**

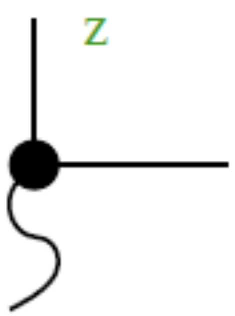


$$= C_F \cdot \boxed{\frac{1+z^2}{1-z}}$$

QED



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



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

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

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

Three (QED) "kernels" are inter-related; gluon self-interaction stays put

- The story continues, however : All four are related !

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

Colour factors *were excluded from the game …*

Super-Symmetric partner of QCD

+ *infinite number of hidden invariants ! ..*

$C_F = T_R = C_A$ ($= N_C$)