Colour Dynamics and Hadronization.

FRAGMENTATION

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Journée des Jets
LPNHE
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- Hard interactions and Jets
- Hadroproduction and Colour
- Gluons in and beyond(?) PT QCD
- Gluers
  - Gluers and Feynman plateau in hard and soft processes
  - Gluers and colour blanching
- LPHD and QCD Radiophysics
  - inside jets
  - in-between jets
- Things we learned and things we haven't yet
- α_s in and beyond(?) PT QCD
- How to demystify the Kogut–Susskind hadronization picture?

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Hard QCD interactions

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

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Heat the *Vacuum*

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

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

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

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production of a quark/gluon = "jet" of hadrons

Jet as a ‘string’ of hadrons

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Kogut–Susskind vacuum breaking picture :

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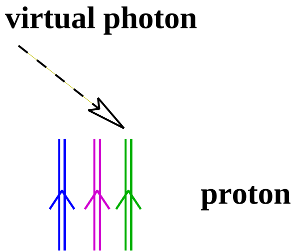

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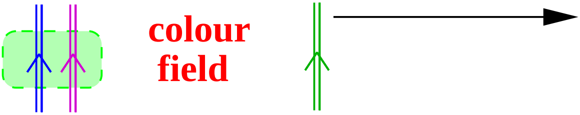

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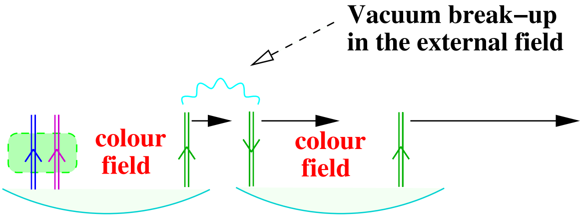

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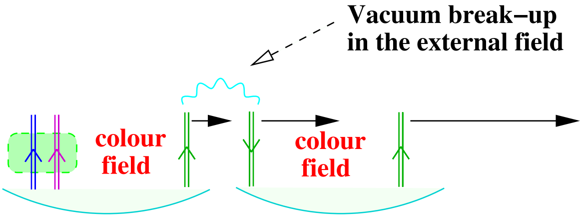
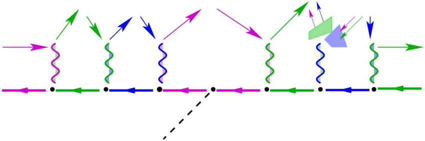


Repeating, one gets the “Feynman Plateau” :

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

Lund wisdom

Phenomenological realization of the Kogut–Susskind scenario



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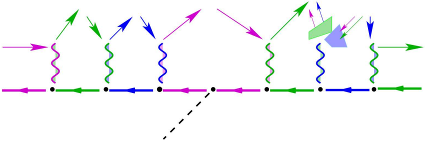

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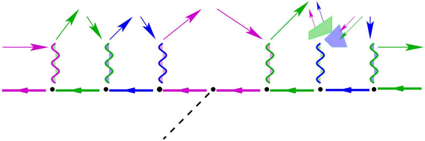

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The key features of the Lund hadronization model:

- Uniformity in *rapidity*: $dN_h = \text{const} \times \frac{d\omega_h}{\omega_h}$
- Limited $k_\perp$ of hadrons
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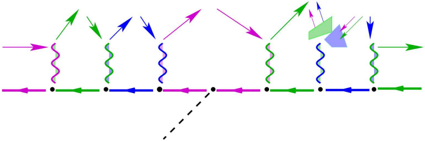

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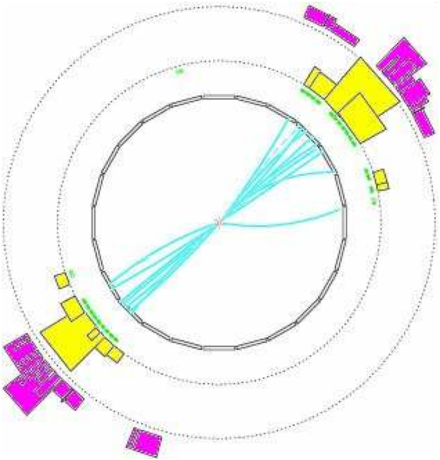
The crucial step: Stress on the *rôle of colour* in multiple hadroproduction

$q\bar{q} \longrightarrow$ hadrons



Near 'perfect' 2-jet event

2 well-collimated jets of particles.

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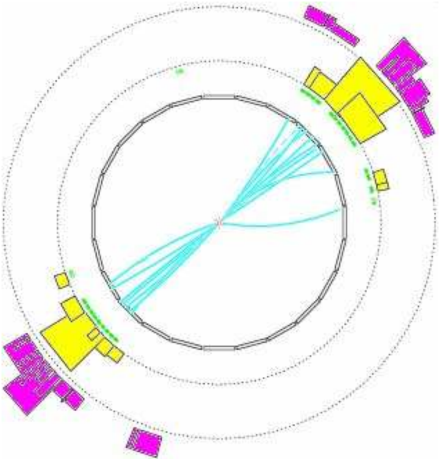

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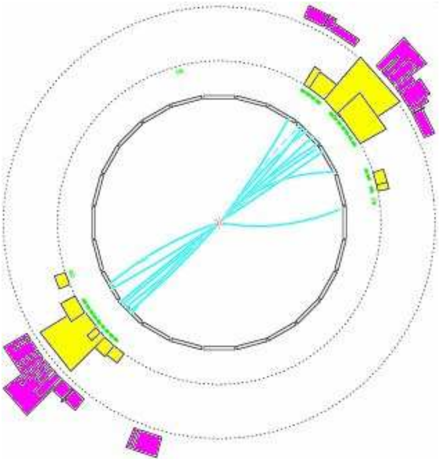

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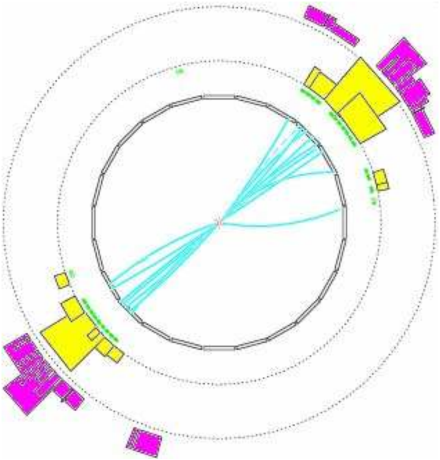

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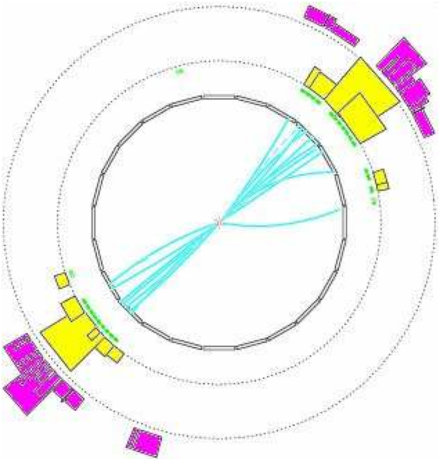

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Parton multiplication

In spite of the smallness of the PT coupling α_s, in hard processes quarks and gluons multiply willingly, giving rise to parton cascades populating QCD jets: $dw = \alpha_s \cdot \Phi(z) dz \cdot dk_\perp^2 / k_\perp^2$

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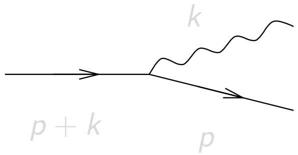
Parton Formation Time

To answer the question as how do offspring partons influence the hadronic yield, one has to realise 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 some time to emit a gluon. This time (so called *formation time*) can be simply estimated as a lifetime of a virtual $(p + k)$ quark state



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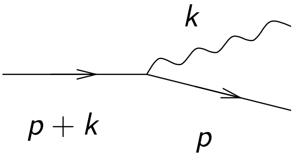

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In all cases $k_\perp^2 \ll Q^2$ — the domain of the MC cascade generation (scientific name: collinear factorization)

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Inclusive spectrum of gluers = Feynman plateau

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

NP Radiation and Feynman plateau

Parton pairs with small relative transverse momenta lie beyond the PT. Nevertheless, 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 in a system of colour charges:

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

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Rapidity plateau in *hh* interaction

Hadron plateau in "minimum bias" hadron–hadron collisions.

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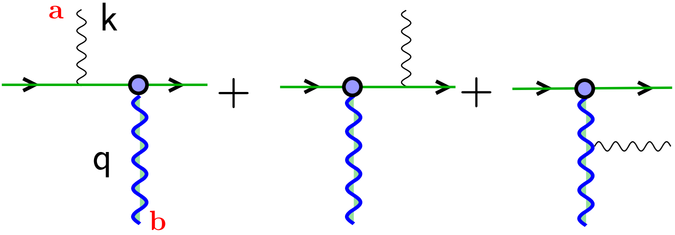

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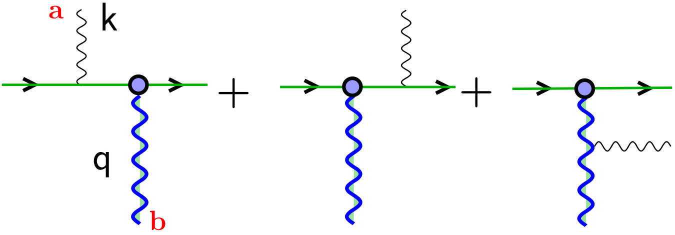

$$-\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2} \qquad +\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2} \qquad +\frac{\mathbf{q}_\perp - \mathbf{k}_\perp}{(\mathbf{q}_\perp - \mathbf{k}_\perp)^2}$$

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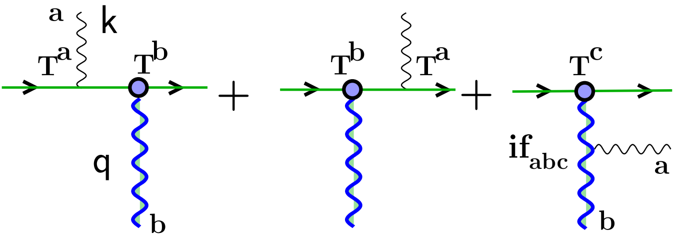

$$-\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2}\mathbf{T}^b\mathbf{T}^a+\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2}\mathbf{T}^a\mathbf{T}^b+\frac{\mathbf{q}_\perp-\mathbf{k}_\perp}{(\mathbf{q}_\perp-\mathbf{k}_\perp)^2}\,if_{abc}\mathbf{T}^c$$

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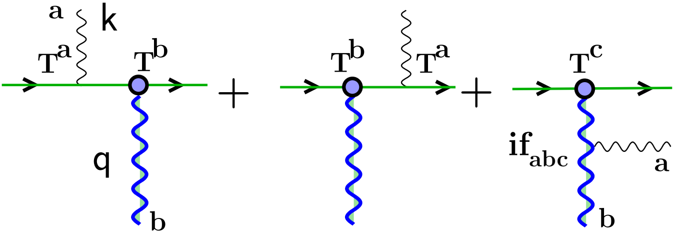

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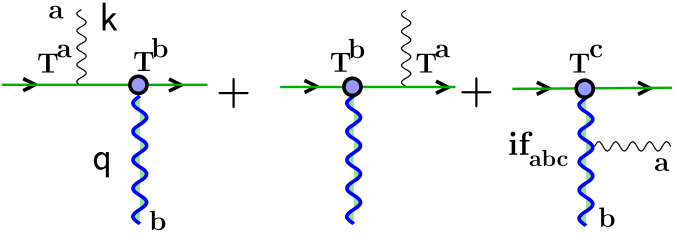

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- Accompanying gluon radiation spectrum :
  - ✓ $d\omega/\omega \Longrightarrow$ rapidity plateau ;
  - ✓ $k_\perp < q_\perp \Longrightarrow$ finite transverse momenta.

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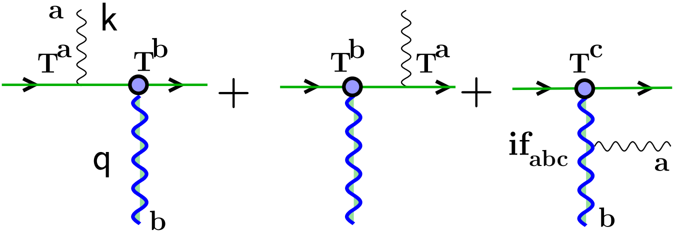

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$\Longrightarrow$ scattering cross section of the projectile

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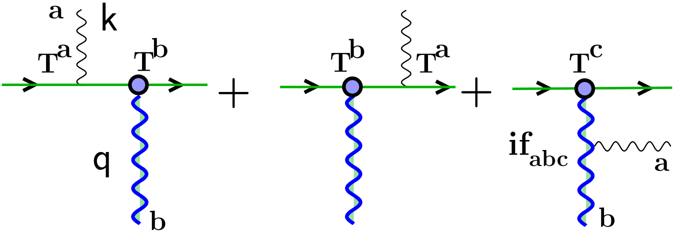

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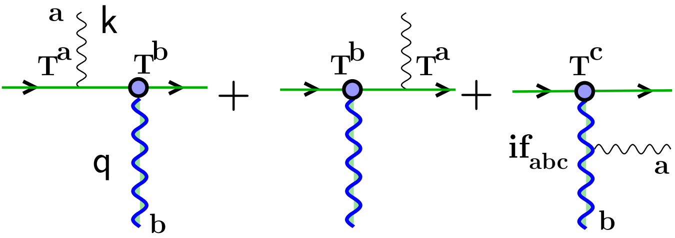

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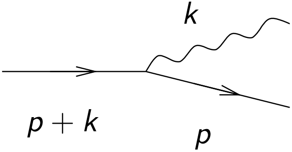
- Multiple scattering of a quark (meson) $\Longrightarrow$ N P*articipant scaling*

Gluers and Colour Blanching

How will an additional PT gluon contribute to the hadron yield?



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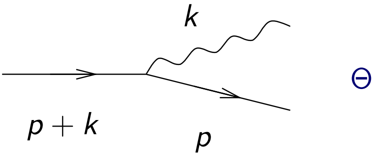

Look at the time when the secondary gluon (with emission angle $\Theta \simeq k_\perp / k$) and its parent will separate in the transverse plane at a critical confinement distance: $t^{\text{separ}} \cdot c\Theta \simeq \Delta\rho_\perp \sim R$.

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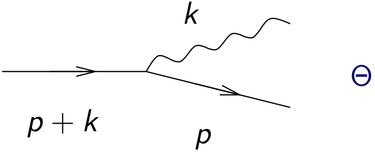

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We expect strong interaction to enter the stage at this moment:

- vacuum break-up,
- production of a hadron (or a few),
- colour blanching of separating objects a'la Kogut–Susskind

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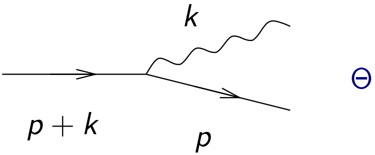

t^{separ} falls right in-between the formation and hadronization times:

$$\begin{aligned} t^{\text{form}} &\approx k/k_\perp^2 \,, \\ t^{\text{separ}} &\approx R/\Theta = t^{\text{form}} * (k_\perp R) \,, \\ t^{\text{hadr}} &\approx kR^2 \;= t^{\text{form}} * (k_\perp R)^2 \,. \end{aligned}$$

At this very time a *gluer* is formed with $k_{\text{gluer}} \sim (R\Theta)^{-1}$:

$$\left(t^{\text{form}} \sim t^{\text{separ}} \sim t^{\text{hadr}}\right)_{\text{gluer}} \approx R/\Theta = (t^{separ})_{qg} \,,$$

which ensures separation of partons as globally blanched sub-jets.

two important messages

1. The first (the softest) hadron that appears in the system due to the gluon radiation is *quite energetic*: $\omega_h \sim k_{\rm gluer} \sim (R\Theta)^{-1} \gg R^{-1}$.
This is the effect of the "Lorentz boost" of the qg system, *provided* it is the development of the colour field that is responsible indeed for the hadron production! (anti-Field–Feynman picture)

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LPHD

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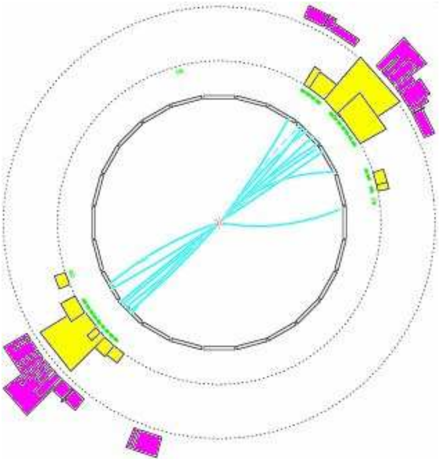
In fact, both Fragmentation Models (that survived) — the Lund string (Andersson, Gustafson et.al) and the HERWIG cluster (Marchesini, Webber) — do respect the locality:

- Lund by construction (universal fragmentation of the colour tube)
- HERWIG by virtue of finiteness of $\langle M^2 \rangle$ of neighbouring PT-partons.

$q\bar{q} \longrightarrow$ hadrons



Near 'perfect' 2-jet event

2 well-collimated jets of particles.

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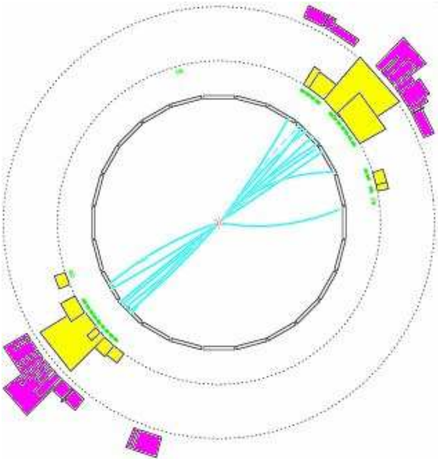

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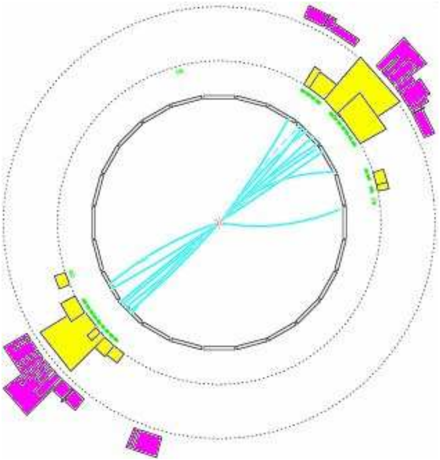

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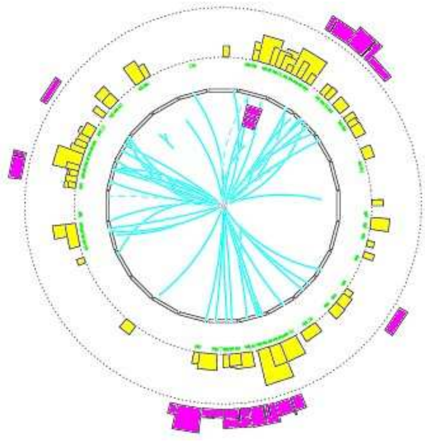
Moreover,

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

Third jet



By eye, can make out 3-jet structure.

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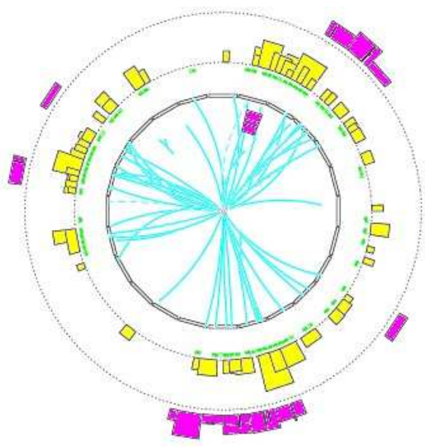

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No surprise : (Kogut & Susskind, 1974)

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

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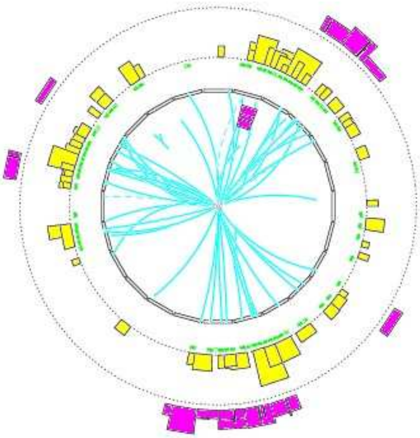

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The first QCD analysis was done by J.Ellis, M.Gaillard & G.Ross (1976)

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

Gluon $\longrightarrow$ hadrons

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

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

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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)

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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

Gluon as a kink

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

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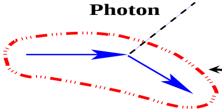

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The hot-dog of hadrons that was "*cylindric*" in the cms, is now *lopsided* [boosted string]

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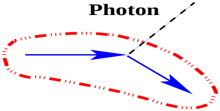

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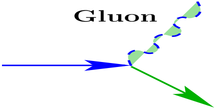

Now substitute a gluon for the photon in the same kinematics.

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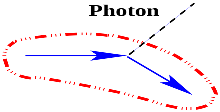

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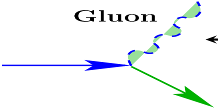

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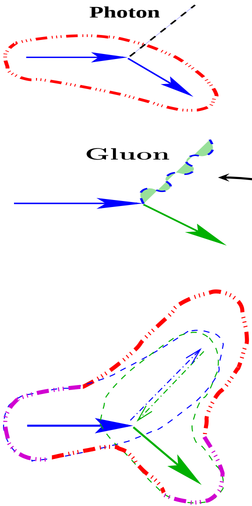

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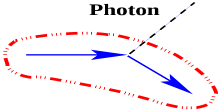
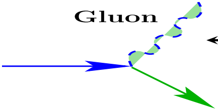
Lund: hadrons = the sum of two independent (properly boosted) colorless substrings, made of

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

Gluon as a kink



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.

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

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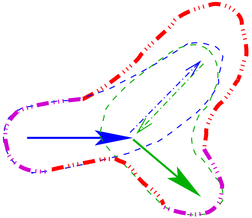
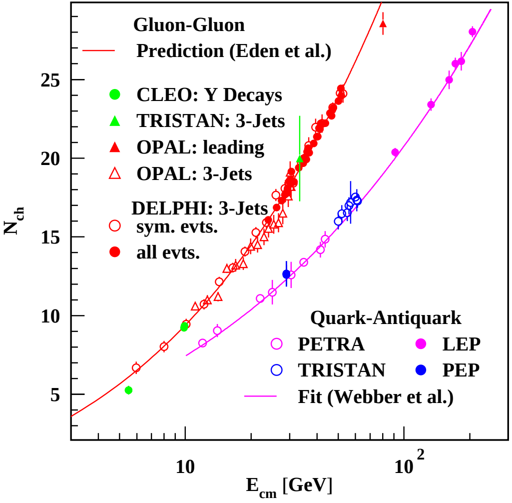


The first immediate consequence :

Double Multiplicity of hadrons in fragmentation of the *gluon*

Comparing hadron multiplicities

Look at experimental findings



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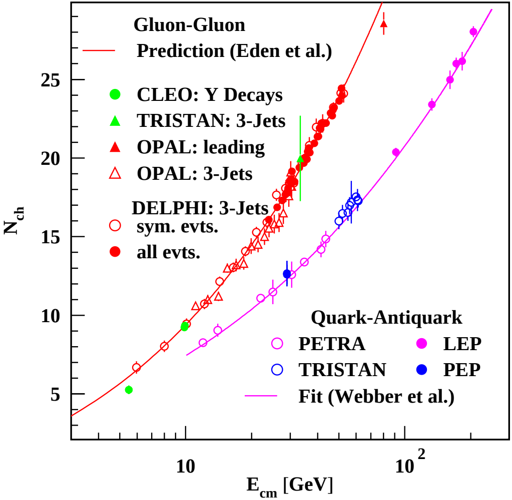

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- N increases *faster* than $\ln E$ ($\Longrightarrow$ Feynman was wrong)

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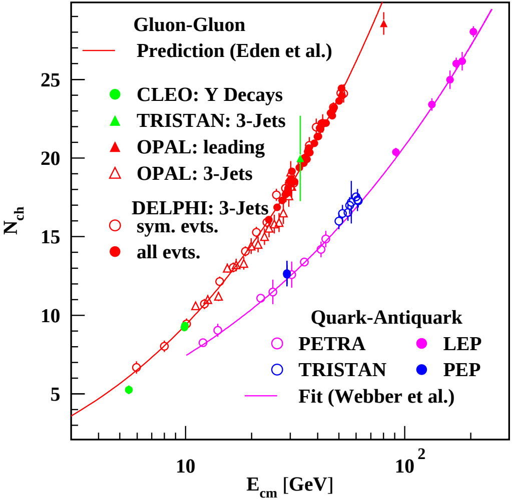

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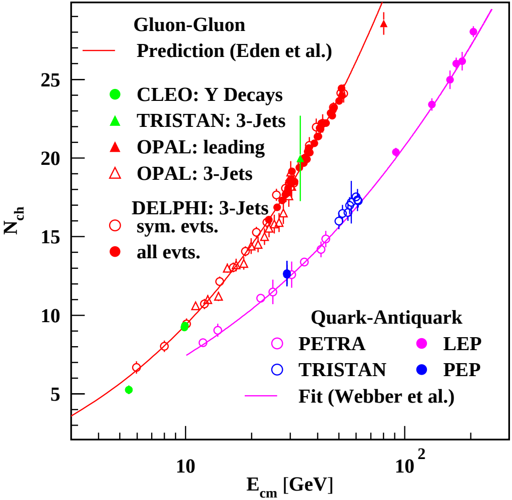

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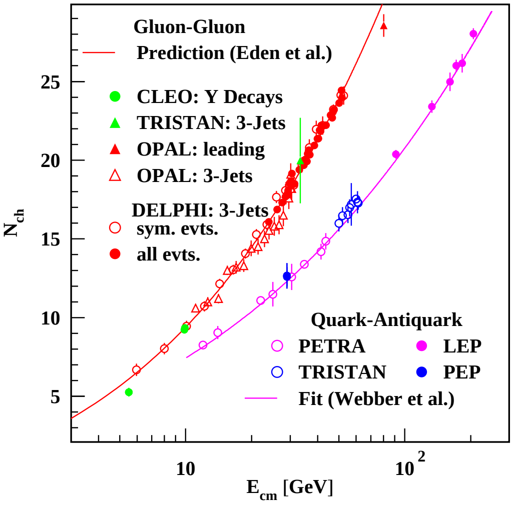

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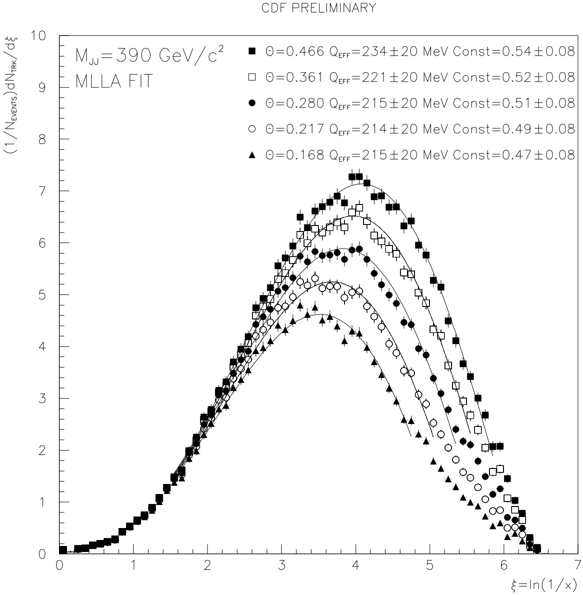
Which are the particles that multiply most efficiently inside the jet?

Hump-backed plateau



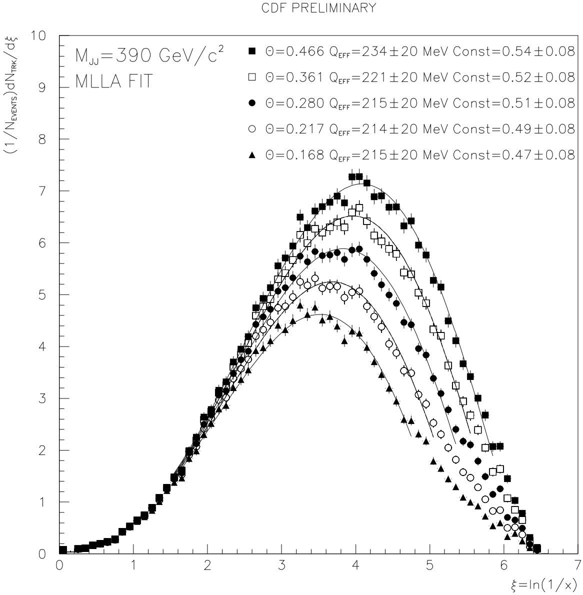
First confronted with theory in $e^+e^- \to h+X$.

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.

Hump-backed plateau



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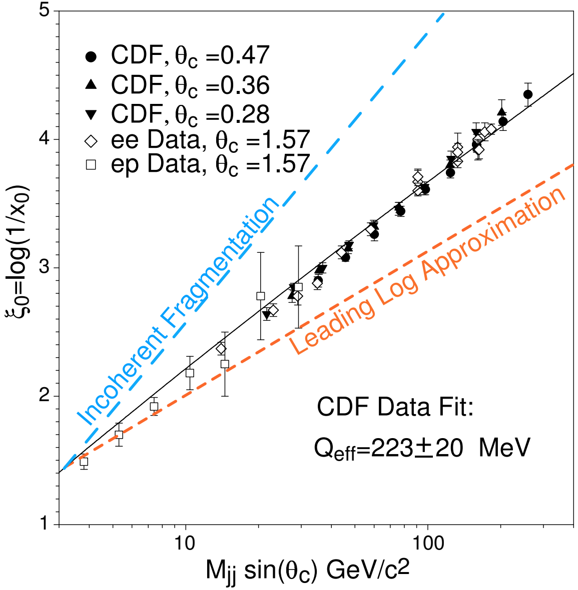
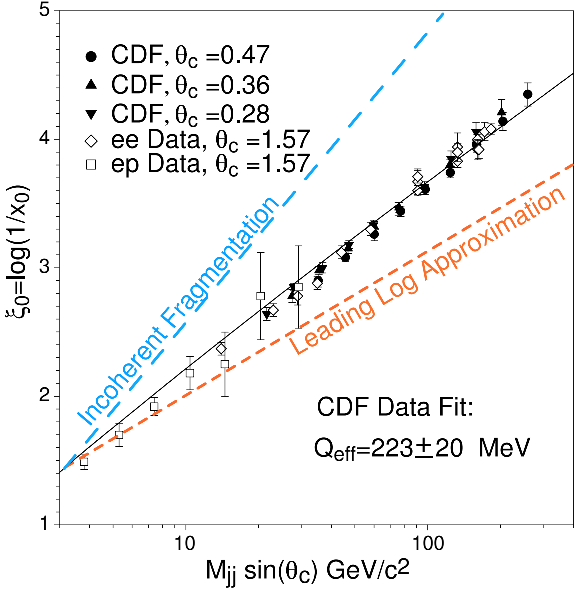
One free parameter – overall normalization (the number of final π's per extra gluon)

Hump (continued)



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

Hump (continued)



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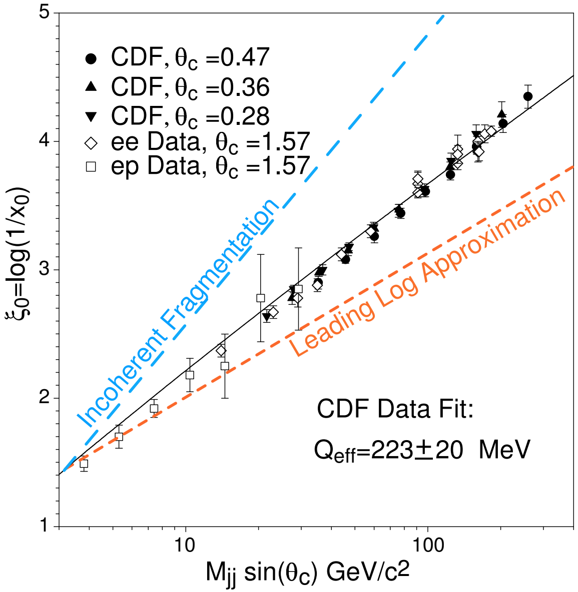

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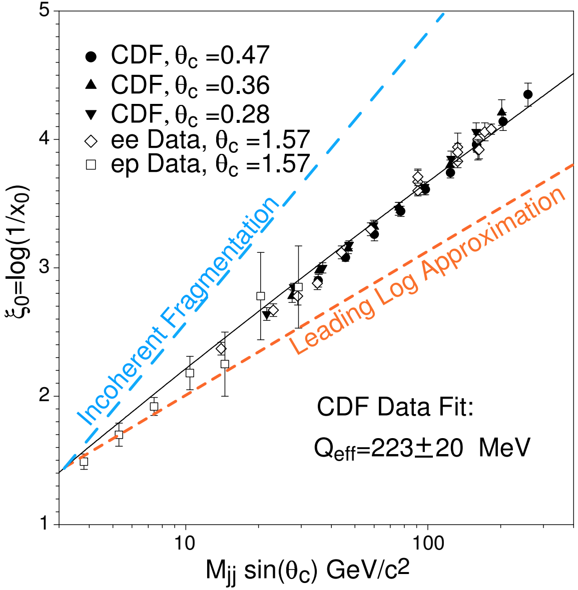

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Mark Universality: same behaviour seen in e^+e^-, DIS (ep), hadron–hadron coll.

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

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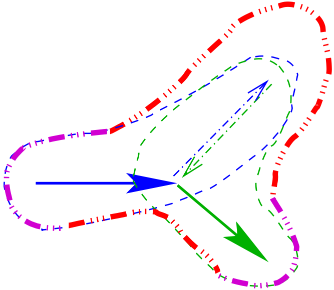

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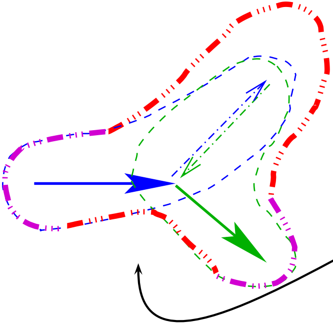

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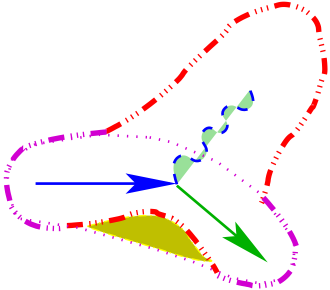

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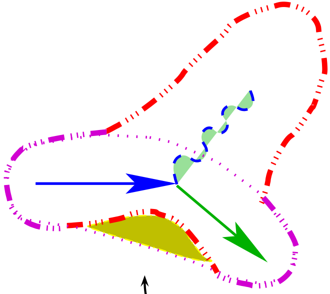

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Destructive interference
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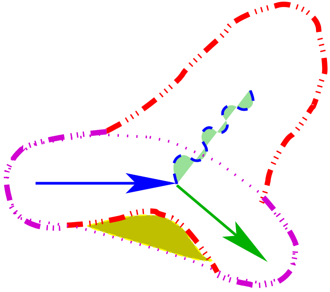

QCD prediction :

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

(experiment: 2.3 ± 0.2)

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Destructive interference
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

QCD Coupling in the NP-domain?

Recall the equation:

Inclusive spectrum of gluers = Feynman hadron plateau

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

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A first timid step in this direction was made in the 1990's.

Event Shape observables

There is a specific (though not too narrow a) class of QCD observables that taught us couple of things 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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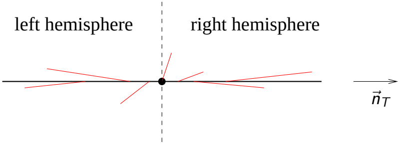

C-param. $$C = \frac{3}{2}\frac{\sum_{i,j} |\vec{p}_i||\vec{p}_j| \sin^2\theta_{ij}}{\left(\sum_i |\vec{p}_i|\right)^2}\,,$$

jet-mass $$\rho = \frac{\left(\sum_{i\in\text{hemisphere}} p_i\right)^2}{\left(\sum_i E_i\right)^2}\,,$$

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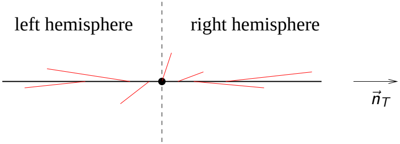

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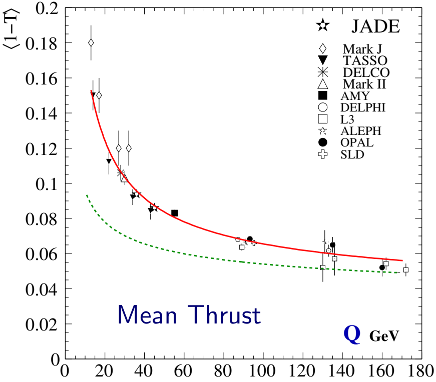
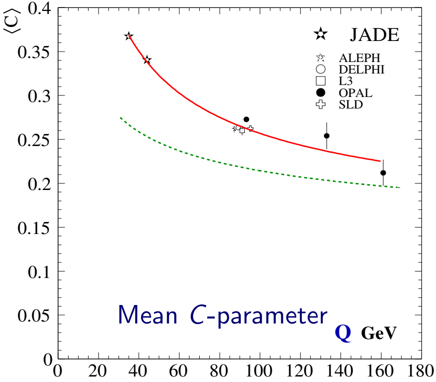
They are formally calculable in pQCD (being collinear and infrared safe) but possess large non-perturbative $1/Q$–suppressed corrections.

$1/Q$ Confinement effects in mean shapes





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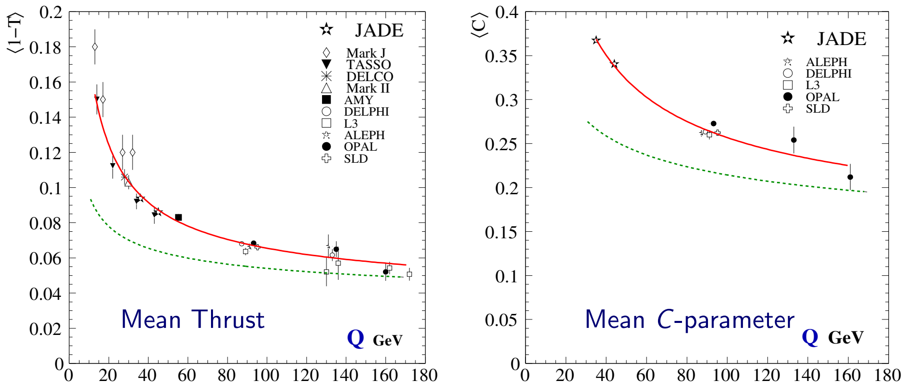

$$\langle 1-T\rangle_{\text{hadron}} \approx \langle 1-T\rangle_{\text{parton}} + 1\ \text{GeV}/Q$$

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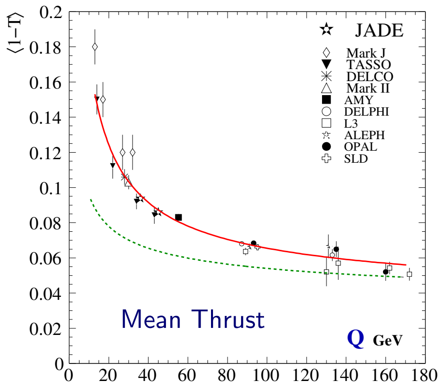

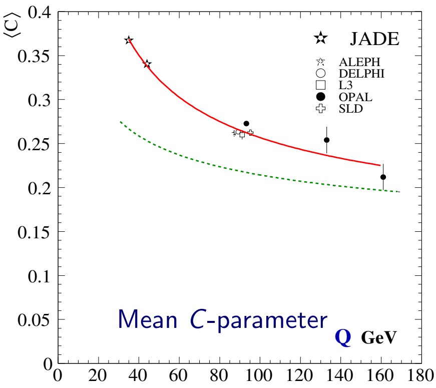

"p" QCD *theory*

12 years old and still running

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

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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- PT controlled observable dependent coefficient $c_{\mathcal{V}}$;
- *linear* damping, $p=1$, for the vast majority of event shapes;
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with α_0 the *first moment* of the coupling in the InfraRed:

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to be fitted simultaneously

Universality hypothesis

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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.

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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.
- Secondly, it was the studies of *event shape distributions* that allowed theorists to better understand what the hell they've been doing, thanks to pedagogical lessons theorists were taught by *those impatient* colleagues experimenters (P. Movilla Fernandez, JADE 1998)

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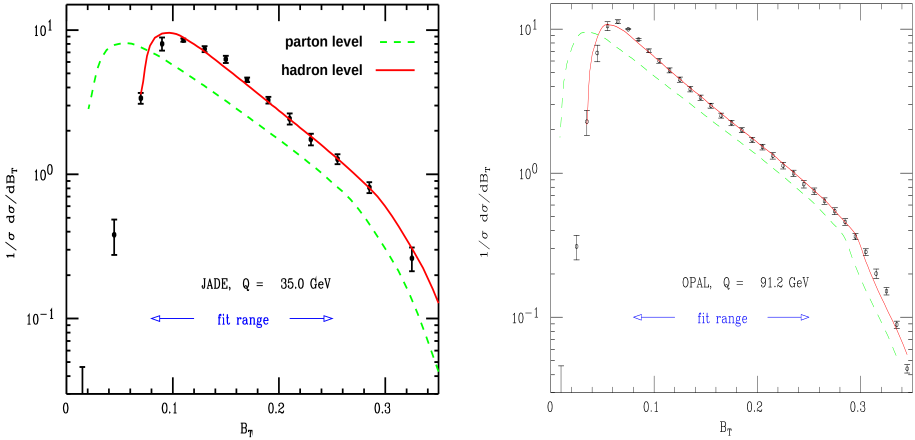

The *Jet Broadening* distribution has a rich structure exhibiting $\frac{\ln B}{Q}$ and $\frac{\ln Q}{Q}$ non-perturbative corrections.

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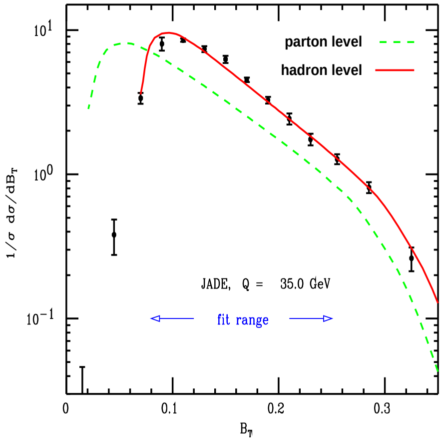

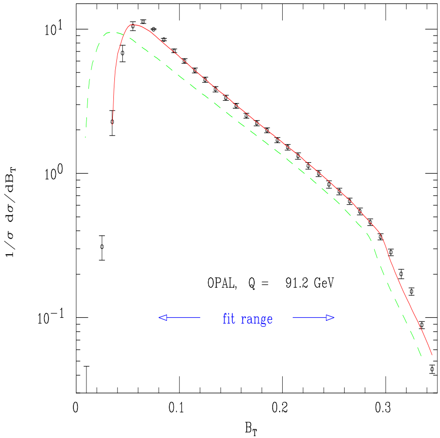

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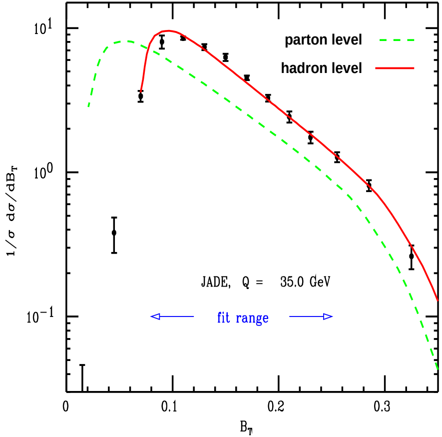

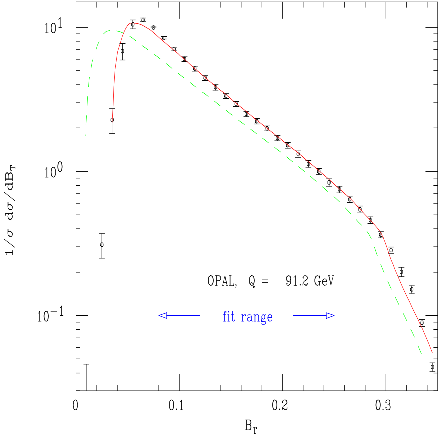

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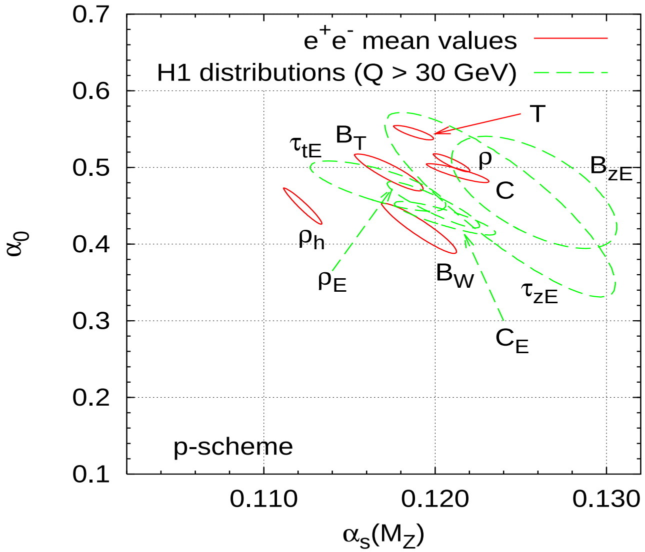
E.g., squeezing at the hadron-level *(!!), uncovered by the JADE gang*

Phenomenology of the QCD coupling



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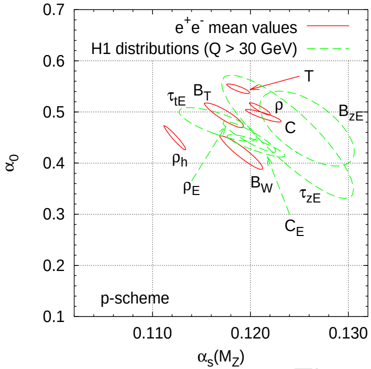

Theory + Phenomenology of $1/Q$ effects in event shape observables, both in e^+e^- annihilation and Deep Inelastic Scattering systematically points at the *average* value of the infrared coupling

$$\alpha_0 \equiv \frac{1}{2\text{ GeV}} \int_0^{2\text{ GeV}} dk\, \alpha_s(k^2) \sim 0.5$$

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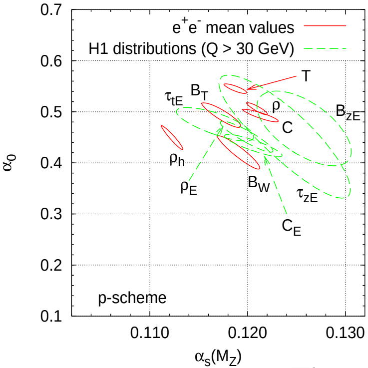

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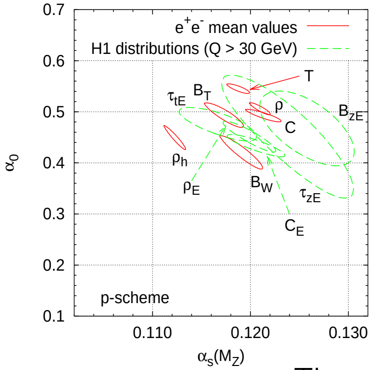

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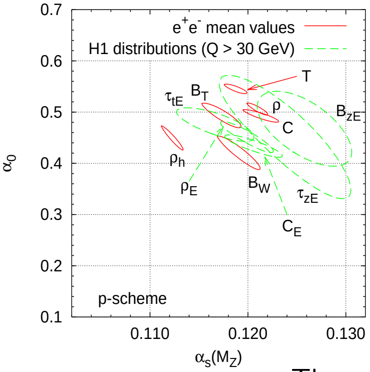

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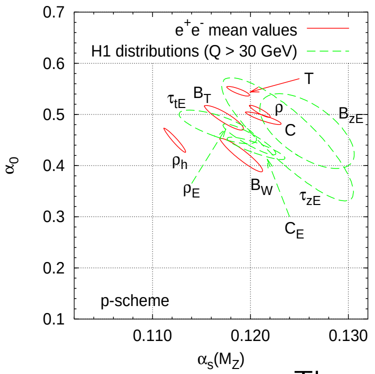

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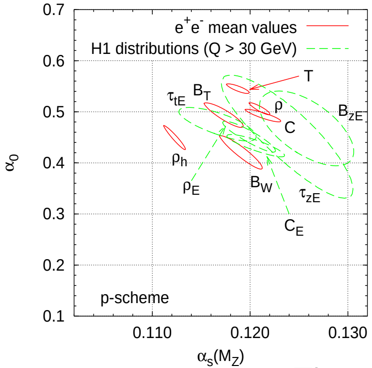

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Interestingly enough, the core of the potential solution of the problem of quantitative understanding of the physics of hadronization lies in a deeper penetration in the origin of the Asymptotic Freedom in non-Abelian QFT.

Asymptotic Freedom : *WHY* ?

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

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

Autopsy of Asymptotic Freedom

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

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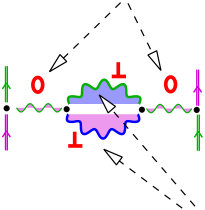

$$= -N_c * \frac{1}{3} \quad -n_f * \frac{2}{3}$$

Transverse gluons **(and quarks)**

↑

screening

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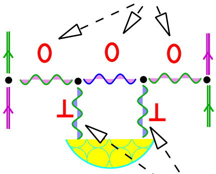
ANTI screening

Instantaneous Coulomb interaction



$$= +N_c * 4$$

Vacuum fluctuations of transverse fields

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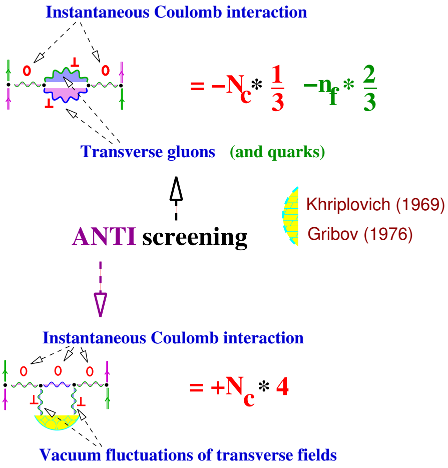

Combine into the QCD β–function:

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

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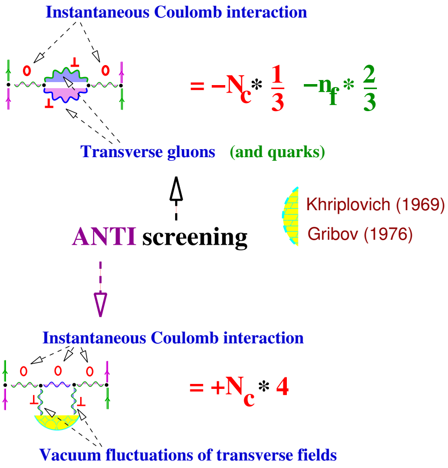

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The origin of *antiscreening* — deepening of the ground state under the 2nd order perturbation in NQM:

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

Coulomb instability and Hadronization

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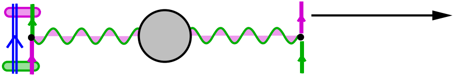

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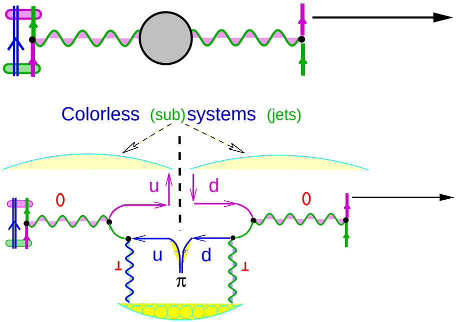

Bearing in mind that virtual quarks live in the background of gluons (zero fluctuations of $A_\perp$ gluon fields) what we look for is a mechanism for binding (negative energy) *vacuum quarks* into *colorless hadrons* (positive energy physical states of the theory)

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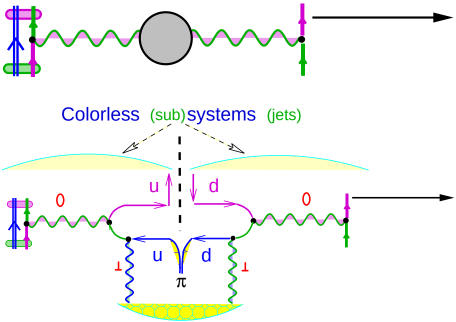

Bearing in mind that virtual quarks live in the background of gluons (zero fluctuations of $A_\perp$ gluon fields) what we look for is a mechanism for binding (negative energy) *vacuum quarks* into *colorless hadrons* (positive energy physical states of the theory)

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Coulomb instability and Hadronization

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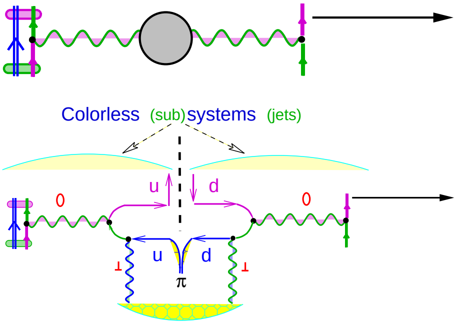

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$$\frac{\alpha}{\pi} > \frac{\alpha_{\text{crit}}}{\pi} = C_F^{-1}\left[1-\sqrt{\frac{2}{3}}\right] \simeq 0.137 \qquad \left(C_F = \frac{N_c^2-1}{2N_c} = \frac{4}{3}\right)$$

Gribov Copies

Covariant derivative

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

The Coulomb field “propagator”

Gribov Copies

Covariant derivative

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The Coulomb field "propagator" *(Abelian)*

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

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average over transverse vacuum fields $\mathbf{A}_\perp$

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

= the ghost rising from dead

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listen to Matteo Cacciari, attentively

EXTRAS

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:

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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 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.
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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.*

A known QFT example of such a violent response of the vacuum — screening of super-charged ions *with* $Z > 137$.

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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
$\epsilon \propto \sqrt{1-(\alpha_{\text{e.m.}} Z)^2}$.

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

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