Parton Energy Loss in QCD Medium

Yuri L. Dokshitzer

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

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Quantum Mechanics strikes back

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

Chudakov effect

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

electron track

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

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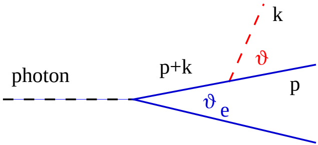
Transverse distance between two charges
(size of the e^+e^- dipole) is

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



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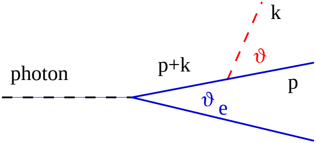

The photon is emitted after the time (lifetime of the virtual $p+k$ state)

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

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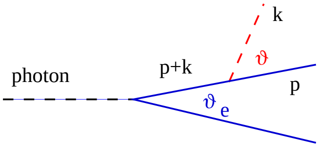
$\vartheta < \vartheta_e$ – independent radiation off e^- & e^+



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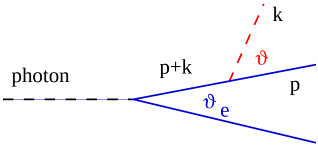

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$\vartheta > \vartheta_e$ – no emission ! $\quad (\rho_\perp < \lambda_\perp)$

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intRA-jet coherence

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

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

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

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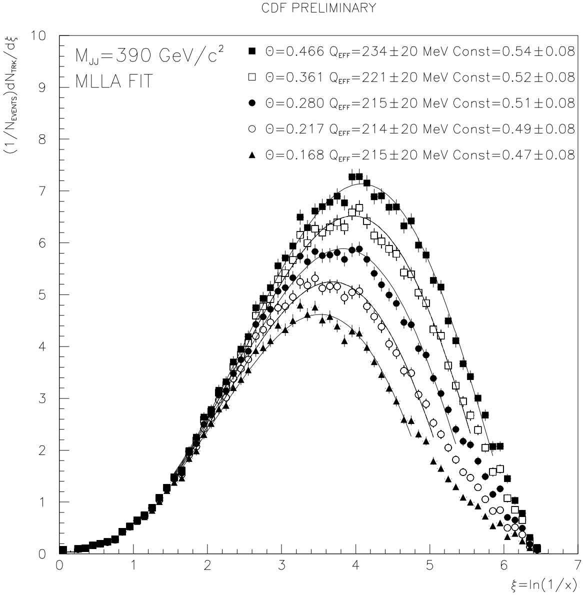
while the softest particles (that seem to be the easiest to produce) should not multiply at all !

Hump-backed plateau



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

CDF (Tevatron)

$pp \rightarrow 2$ jets

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

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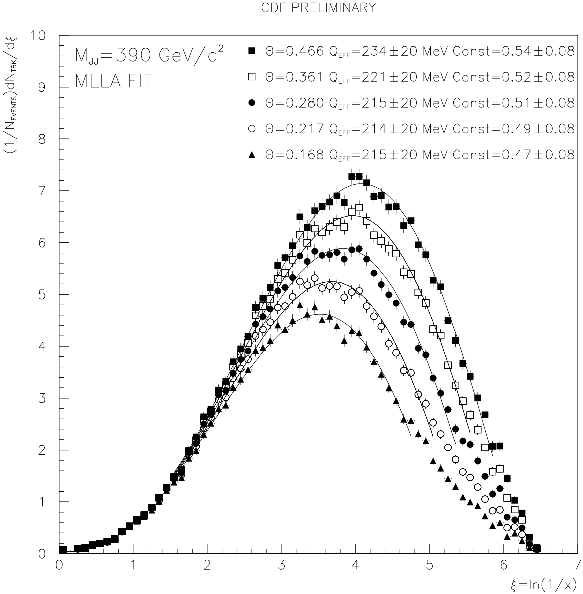

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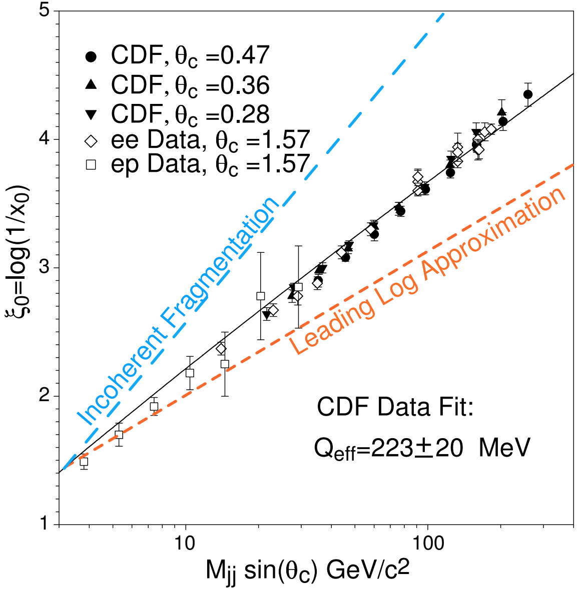
One free parameter – overall normalization (the number of final π's per extra gluon)

Hump (continued)



Position of the Hump as a function of

$Q = M_{jj} \sin \Theta_c$

(hardness of the jet)

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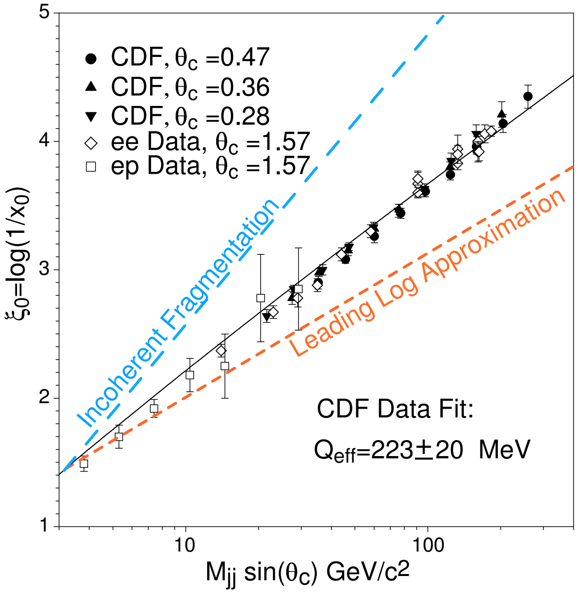

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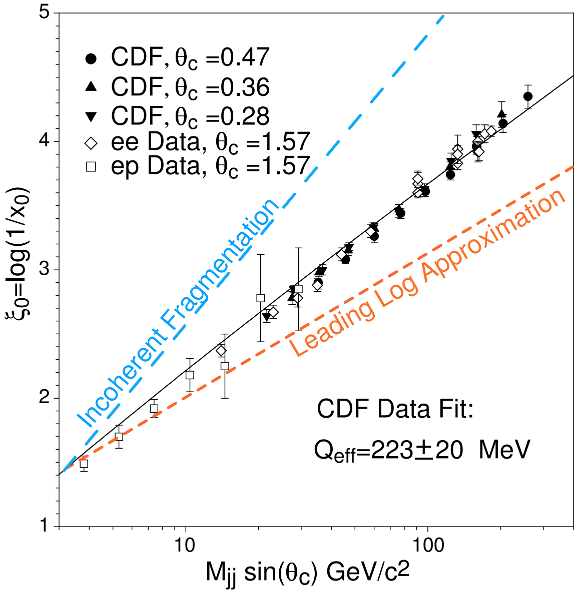

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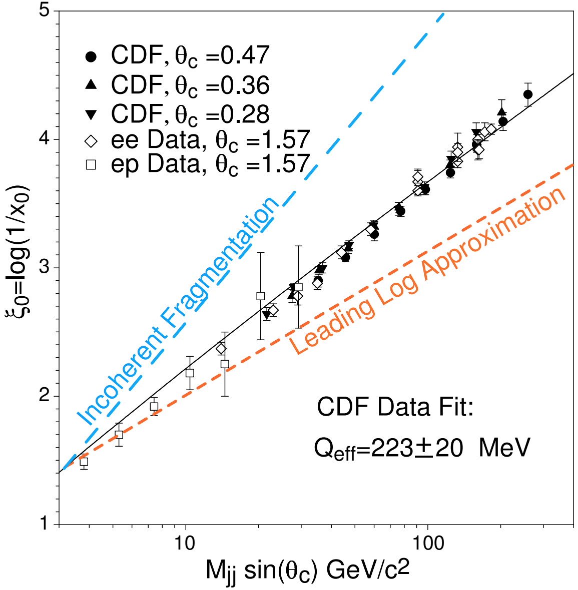

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Mark Universality:

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

Soft Confinement

So, the *ratios* of particle flows between jets (intERjet radiophysics), as well as the *shape* of the inclusive energy spectra of secondary particles (intRAjet cascades) turn out to be formally calculable (CIS) quantities.
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We should rather feel *puzzled* than satisfied.

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LPHD gift

Both Inter-Jet and Intra-Jet phenomena fully reveal colour coherence in QCD parton multiplication. Their solid imprint upon the *angular* and *energy* spectra of *relatively soft hadrons* are sending us a powerful message

(— a free lunch that we have not found enzymes yet to devour)

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For the time being, we are *exploiting* this gift: *hadron flow* practitioners developing smart tools for triggering on new physics, *colour glass* brewers, *small-x BFKL* lovers, — no-one would hesitate to put gluons and hadrons into (more or less) one-to-one correspondence.

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

Heritage or Handicap?

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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*.

alarm

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all our “default” knowledge

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INFRARED alarm

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Covariant derivative

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

The Coulomb field "propagator"

Gribov Copies

Covariant derivative

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

The Coulomb field "propagator" (*Abelian*)

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

Gribov Copies

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

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Estimate of *non-linearity* :

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

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Estimate of *non-linearity* :

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

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

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

Gribov Confinement: setting up the Problem

- The question of interest is
  The confinement in the real world (with 2 very light u and d quarks), rather than **a** confinement.
- No mechanism for binding massless *bosons* (gluons) seems to exist in Quantum Field Theory (QFT), while the Pauli exclusion principle may provide means for binding together massless *fermions* (light quarks).
- The problem of ultraviolet regularization may be more than a technical trick in a QFT with apparently infrared-unstable dynamics: the ultraviolet and infrared regimes of the theory may be closely linked.
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To understand and describe a physical process in a *confining theory*, it is necessary to take into consideration the response of the vacuum, which leads to essential modifications of the quark and gluon Green functions.

Vacuum instability and supercritical binding

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

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

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Supercritical binding by over-charged nuclei

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

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

- Classically, the electron "*falls onto the centre*".
- Quantum-mechanically, it also "*falls*", but into the Dirac sea.
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$$A_Z \implies A_{Z-1} + e^+ \,, \qquad \text{for } Z > Z_{\text{crit.}}$$

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

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

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

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

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

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

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Phasis Publishing House, Moscow (2002)

www.prospero.hu/gribov.html

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Heavy Ions, Small distances and Jets

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Those exploring Confinement hide behind *bars* (e.g. $48 \times (24)^3$)

(Asymptotic) Freedom lovers wander around, wondering . . .

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Specifications:

- 3.83 km circumference
- 2 independent rings:
  - 120 bunches/ring
  - 106 ns crossing time
- **A + A collisions @ $\sqrt{s}$ = 200 GeV**
- Luminosity: $2 \cdot 10^{26}$ cm^{-2} s^{-1} (~1.4 kHz)
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4 experiments:

BRAHMS, PHENIX, PHOBOS, STAR

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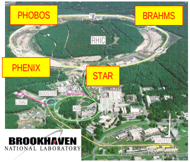

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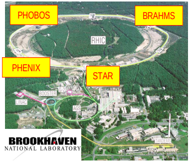

small distances are *mysteriously* emerging in multiple scattering environment:

- Landau-Pomeranchuk-Midgal medium-induced radiation
- CGC $Q^2 \propto A^{1/3}$

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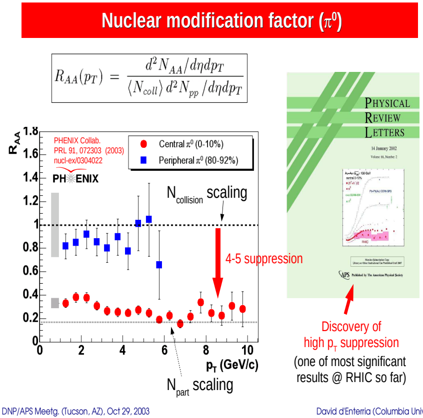

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- CGC $Q^2 \propto A^{1/3}$

Large P_T pion yield gets strongly *suppressed* in central collisions,

Heavy Ions, Small distances and Jets

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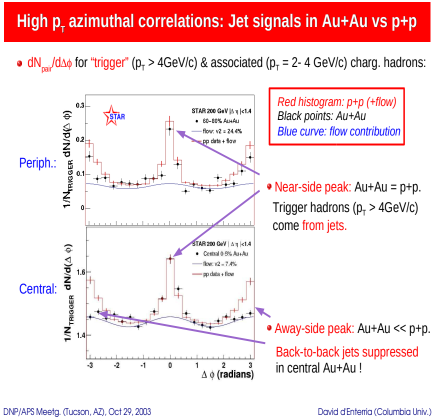

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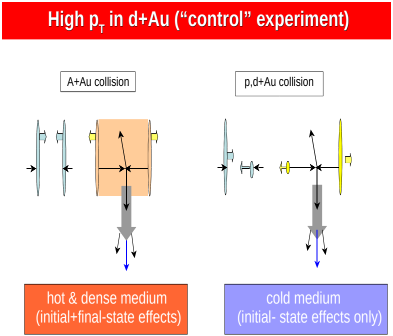

BUT :

in $d + A$ scattering

NOT ANYMORE

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QCD in the Medium

search for Clarity out of Mess

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Lecture II

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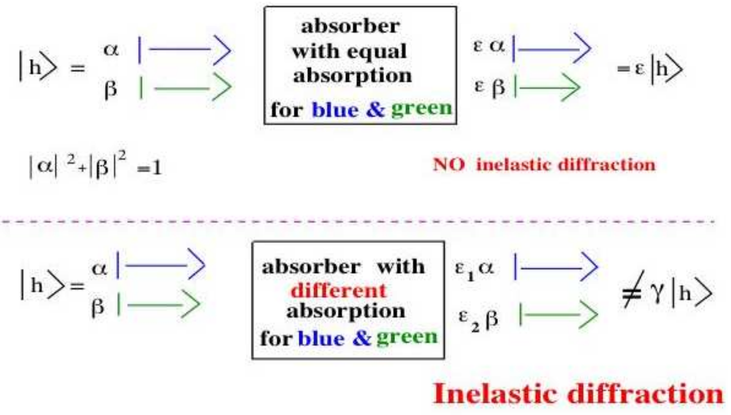

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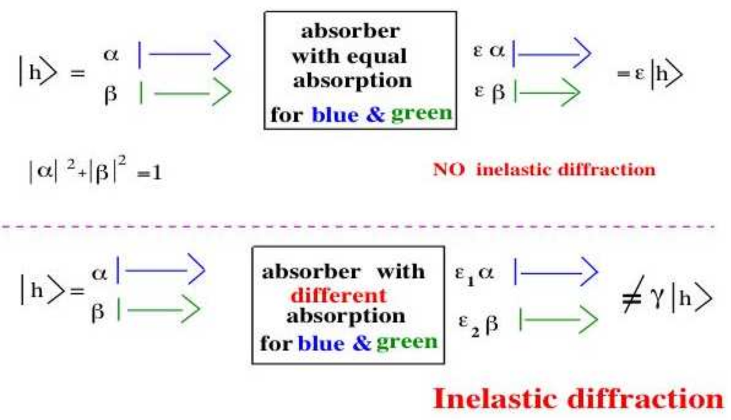

$h \to h^*$ as means of probing *internal structure* of the hadron projectile

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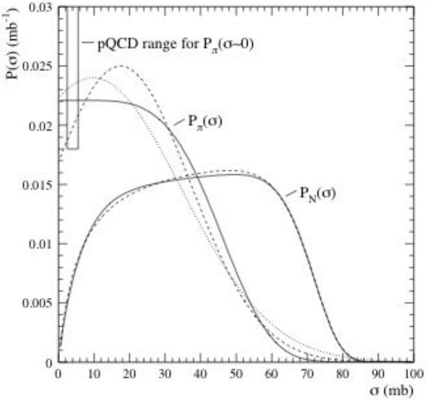
$\Rightarrow$ The pQCD regime for small σ's: (*Baym et al.* 1993)

$$P_h(\sigma) \propto \sigma^{n_q - 2}.$$

Very broad distributions!



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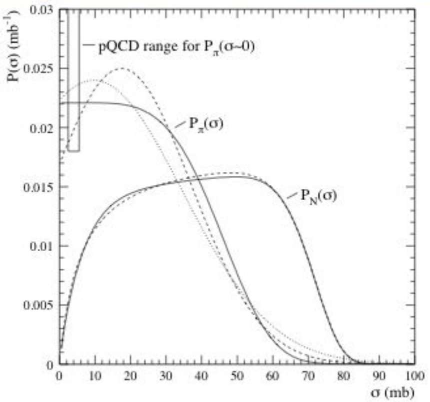

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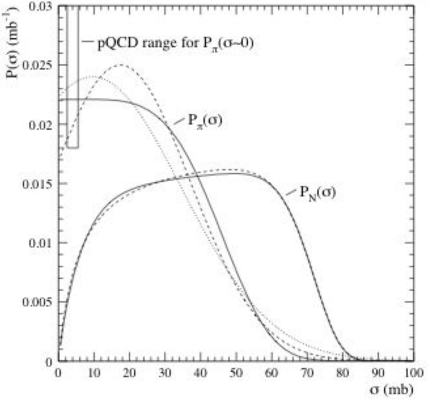

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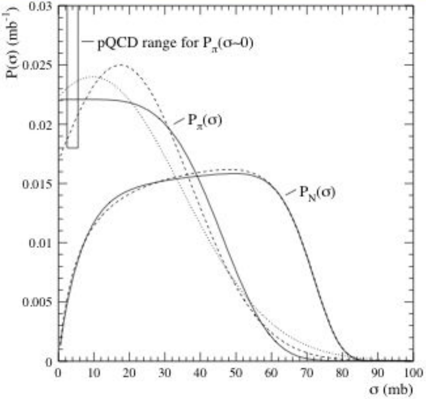

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Presence of *weakly interacting* configurations in hadrons (*penetrators*)

$\Longrightarrow$

Configurations with interaction strength *larger than average* (*perpetrators*)

Jets from Diffractive Dissociation of π

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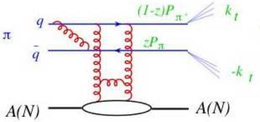

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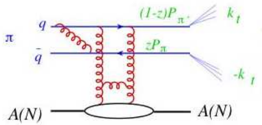

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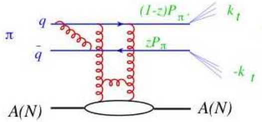

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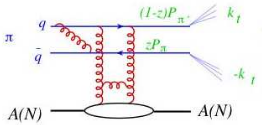

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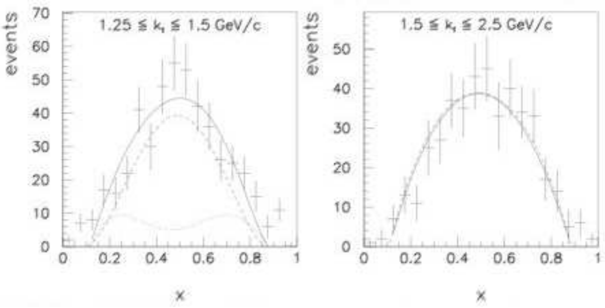
A-dependence of the diffractive jet production cross section $\sigma(A)$

An early expectation (81):	$A^{1/3}$
QCD prediction (93):	$A^{1.54}$
Experiment (98-00): E-791 ($E^\pi = 500$ GeV)	$A^{1.61\pm0.08}$

Direct observation of *colour transparency*

♡ The z-distribution of jet momenta



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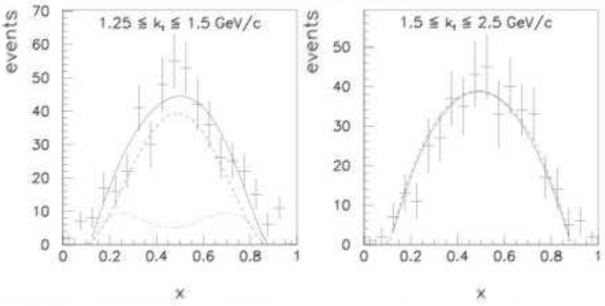

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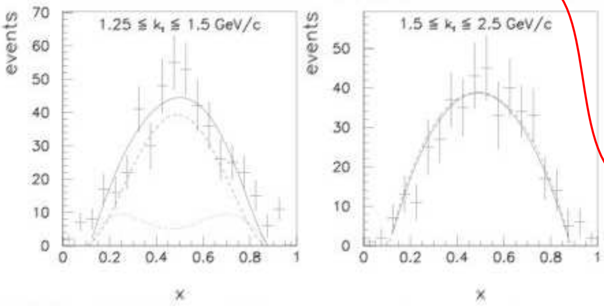

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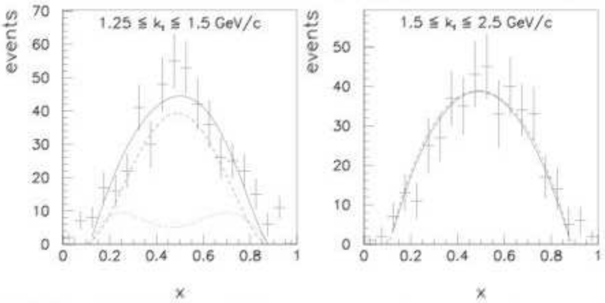

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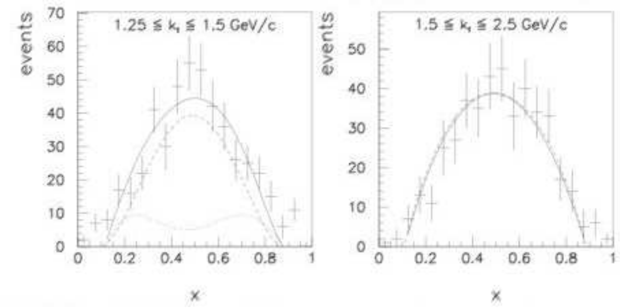

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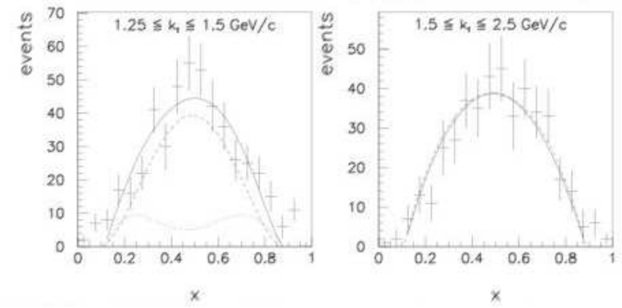

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Next step: $p + A \to 3\ jets + A$ (RHIC) & $p + \bar{p} \to 3\ jets + \bar{p}$ (Tevatron)

LPM effect

is about radiation induced by multiple scattering of a projectile in a medium. In 1953 Landau and Pomeranchuk noticed that the energy spectrum of photons caused by multiple scattering of a relativistic charge in a medium is essentially different from the Bethe-Heitler pattern. Symbolically, the photon radiation intensity per unit length reads

$$\omega \frac{dI}{d\omega\, dz} \propto \frac{\alpha}{\lambda} \cdot \sqrt{\frac{\omega}{E^2} E_{LPM}}\,; \qquad \frac{\omega}{E} < \frac{E}{E_{LPM}}\,. \tag{1}$$

Here E is the energy of the projectile, and E_{LPM} is the energy parameter of the problem, built up of the quantities characterising the medium. These are: the mean free path of the electron, λ, and a typical momentum transfer in a single scattering, μ (of the order of the inverse radius of the scattering potential):

$$E_{LPM} = \lambda\, \mu^2\,. \tag{2}$$

In QED the parameter E_{LPM} is in a ball-park of 10^4 GeV. Such an enormously large value explains why it took four decades to experimentally verify the LPM phenomenon (SLAC 1995).

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LPM spectrum

The LPM spectrum should be compared with the Bethe-Heitler formula

$$\omega \frac{dI}{d\omega\, dz} \propto \frac{\alpha}{\lambda}\,, \tag{3}$$

— independent photon emission at each successive scattering act.

Contrary to (3), the LPM spectrum (1) is free from an "infrared catastrophe": small photon frequencies are relatively suppressed, so that the energy distribution is proportional to $d\omega/\sqrt{\omega}$. Integrating (1) over photon energy ($\omega < E$ in the $E \to \infty$ limit), one deduces the radiative energy loss per unit length to be proportional to $\sqrt{E}$,

$$-\frac{dE}{dz} \propto \frac{\alpha}{\lambda}\sqrt{E\, E_{LPM}}\,. \tag{4}$$

QCD LPM on the back of envelope

"Brownian kicks" of the to-be-radiated gluon:

$$k_\perp^2 \simeq \mu^2 \cdot N_{coh} = \mu^2 \cdot \frac{t}{\lambda};$$

Gluon formation time:

$$t = \frac{\omega}{k_\perp^2}.$$

Equating the two expressions for t,

$$k_\perp^2 \simeq \sqrt{\frac{\omega\,\mu^2}{\lambda}}; \qquad t = \frac{\lambda\,k_\perp^2}{\mu^2}; \qquad N_{coh} = \frac{\omega}{\lambda\,\mu^2}.$$

Thus,

$$\frac{\omega\, dI}{d\omega\, dz} \propto \frac{\alpha_s}{\lambda} \cdot \frac{1}{N_{coh}} = \frac{\alpha_s}{\lambda}\sqrt{\frac{E_{LPM}}{\omega}}$$

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$$c\,t < L \implies \omega < \omega_{\max} = \frac{\mu^2}{\lambda}\,L^2$$

QCD LPM on the back of envelope

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transport coefficient

The only (non-perturbative) parameter of the problem, characterising the medium — transport coefficient

$$\hat{q} = \frac{\mu^2}{\lambda}$$

Hence, for L large enough stays under perturbative control !

To extract from experiment a *large* $\hat{q}$ — to observe a new "hot" state of quark–gluon matter as compared to a "cold" nucleus.

Handle on $\hat{q}$ in cold nuclei — for example, medium effects in Drell-Yan pair production, DIS on nuclei [François Arleo]

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music of the spheres

Imagine a target hit by a relativistic projectile.

music of the spheres

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A fast nucleon

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Colour and Nuclei

Colour dynamics in pp, pA, AB

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Hard interactions are commonly expected to scale as n_c, *soft* — as n_p.

Colour dynamics in *pp*, *pA*, *AB*

So, *collisions* or *paricipants* ?

Hard interactions are commonly expected to scale as n_c, *soft* — as n_p.

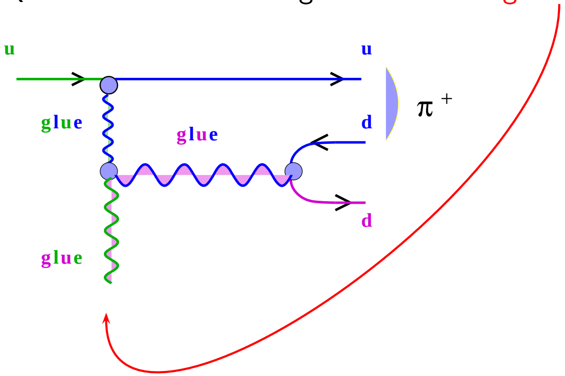
The QCD LPM effect gives a striking example to the contrary …

colour in Quark scattering

Quark inelastic scattering scenario

colour in Quark scattering

Quark inelastic scattering scenario : one gluon exchange



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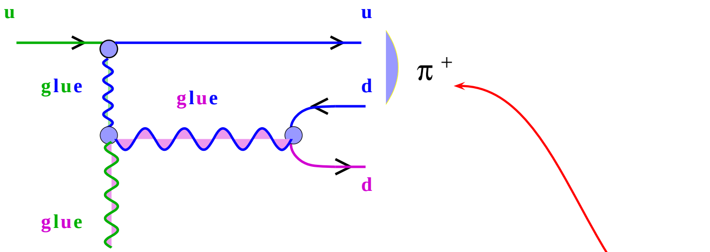

Leading hadron

colour in Quark scattering

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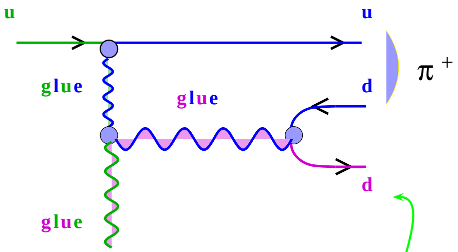
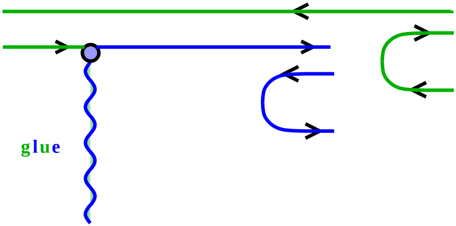


Feynman plateau

colour in Quark scattering

Meson inelastic scattering scenario: gluon exchange



= two "quark chains"

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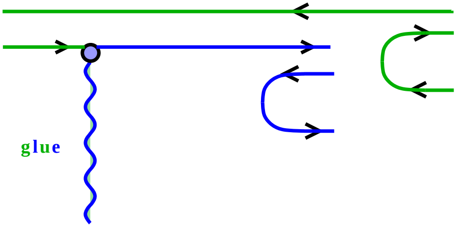

= two "quark chains"
known as the Pomeron

Painting the proton

Single scattering scenario

Painting the proton

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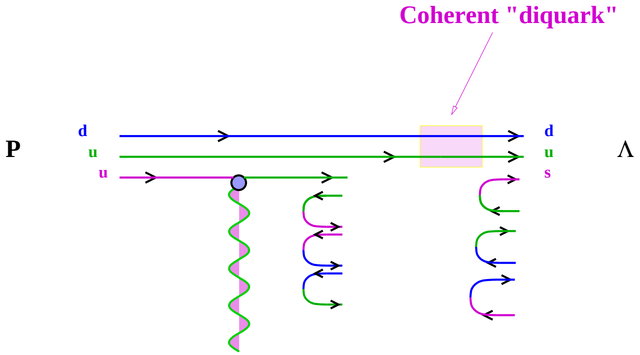

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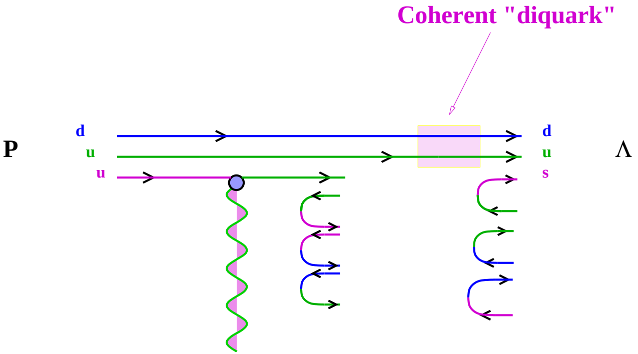

Coherence of the *diquark* ain't broken:

Painting the proton

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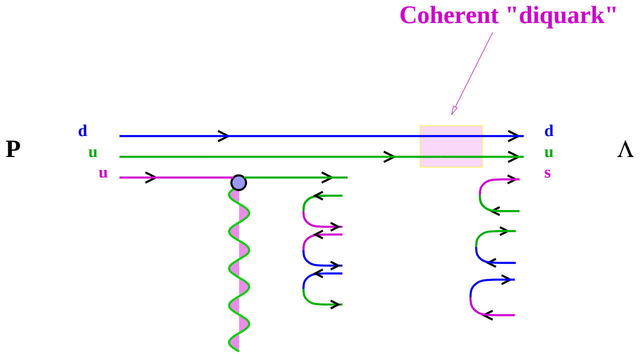

Coherence of the *diquark* ain't broken:

$\Longrightarrow$ a Leading Baryon: $B(1) \rightarrow B(2/3) + M(1/3) + \ldots$

Repainting the Proton

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Kick it *twice* to break the coherence of the valence quarks

Re painting the Proton

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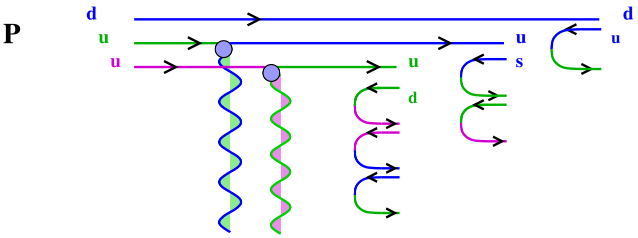

P –> ρ^{+} K^{+} π^{-} + ...

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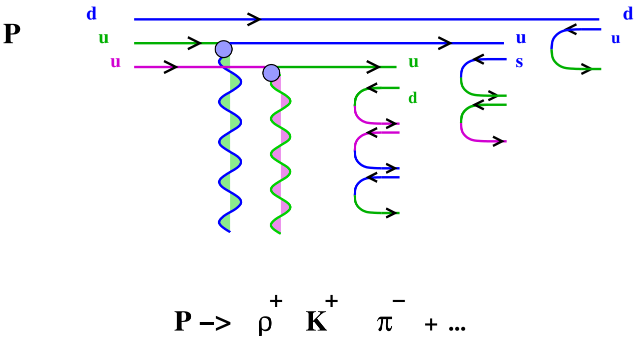

Proton is "*fragile*"

Expect the baryon quantum number *to sink* into the sea :

$$B(1) \to M(1/3) + M(1/3) + M(1/3) + \ldots + B(0)$$

multiple Proton collisions

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Baryons disappear from the fragmentation region

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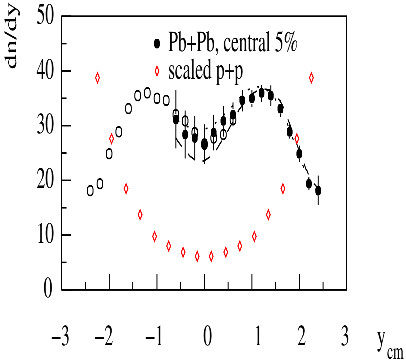
CERN $\sqrt{s} = 17$ GeV (NA49)

- in Pb Pb collisions



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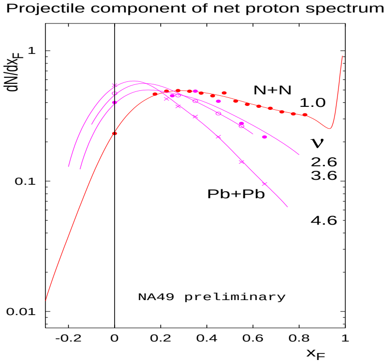

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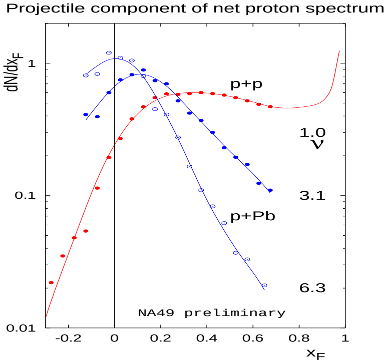

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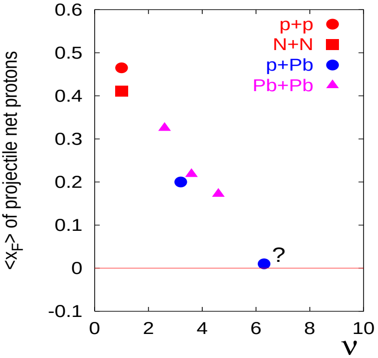

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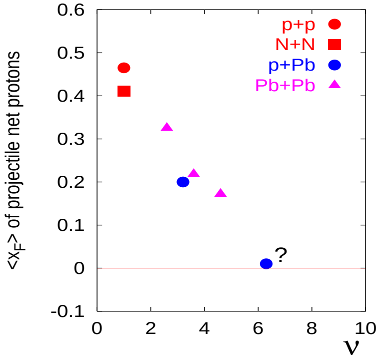

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Known as Proton Stopping.

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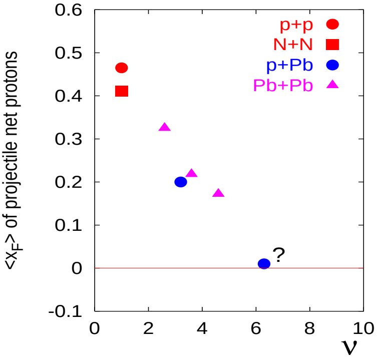

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multiple collisions and Hadron Multiplicity

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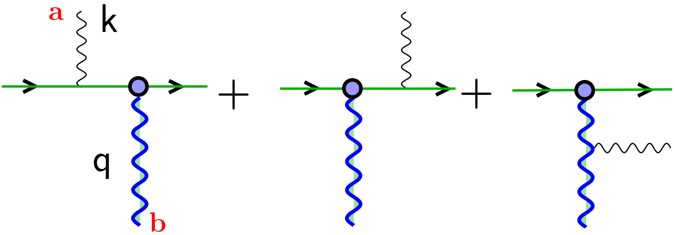
One gluon exchange: accompanying radiation



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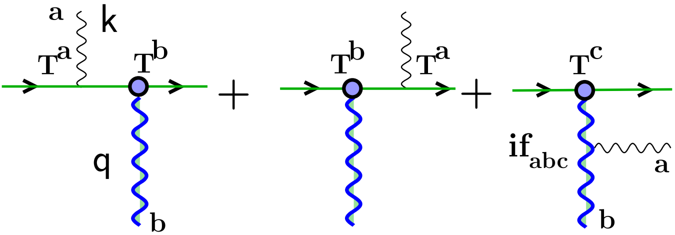

$$-\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2} \qquad +\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2} \qquad +\frac{\mathbf{q}_\perp - \mathbf{k}_\perp}{(\mathbf{q}_\perp - \mathbf{k}_\perp)^2}$$

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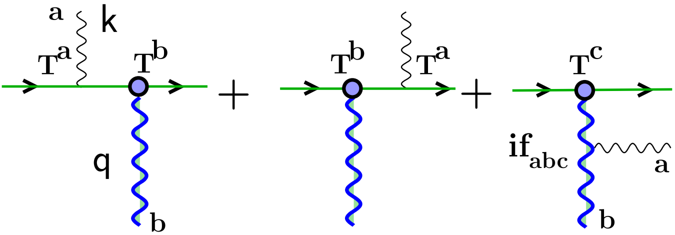

$$-\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2}\mathbf{T}^b\mathbf{T}^a+\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2}\mathbf{T}^a\mathbf{T}^b+\frac{\mathbf{q}_\perp-\mathbf{k}_\perp}{(\mathbf{q}_\perp-\mathbf{k}_\perp)^2}\, if_{abc}\mathbf{T}^c$$

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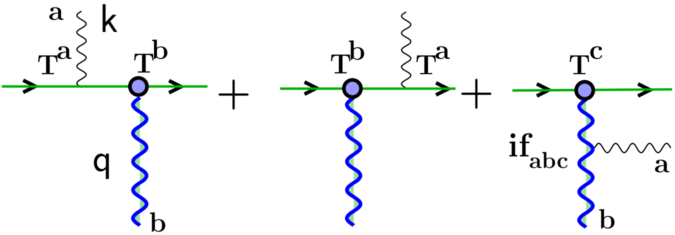

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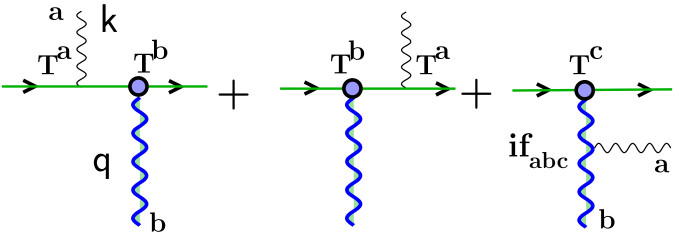

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- Accompanying gluon radiation spectrum :

✓ $d\omega/\omega \implies$ rapidity plateau ;

✓ $k_\perp < q_\perp \implies$ finite transverse momenta.

multiple collisions and Hadron Multiplicity

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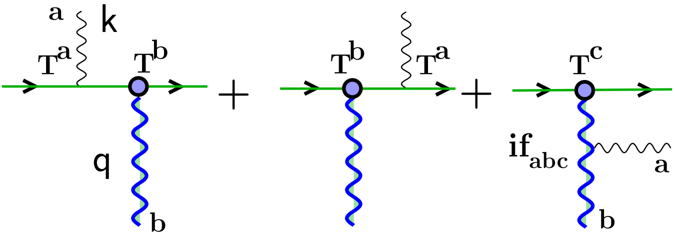

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$\Longrightarrow$ scattering cross section of the projectile

multiple collisions and Hadron Multiplicity

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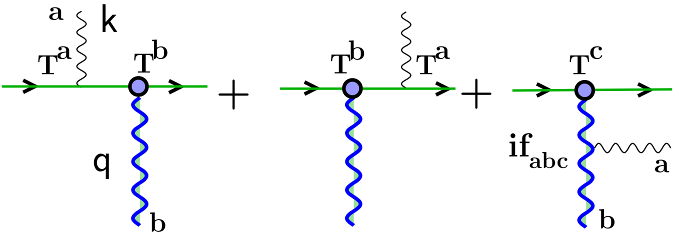

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  $(if_{abc})^2 \to N_c \to$ one Pomeron. Conservation of Colour at work

multiple collisions and Hadron Multiplicity

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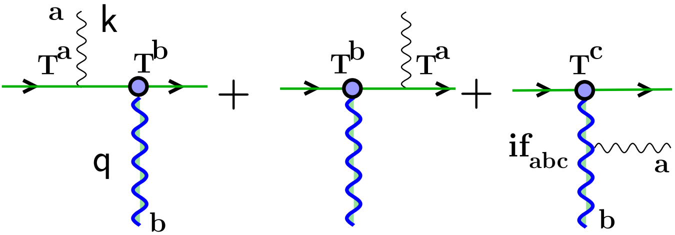

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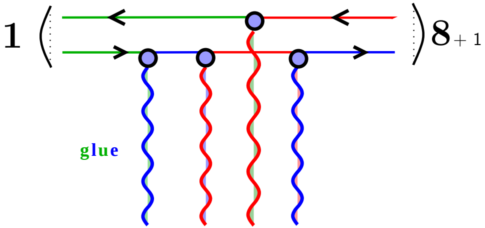
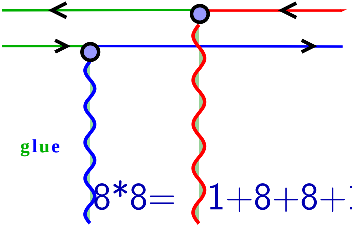
- Multiple scattering of a quark (meson) $\Longrightarrow$ N *Participant scaling*

colour capacity



Multiple collisions of a (2-quark) pion

colour capacity



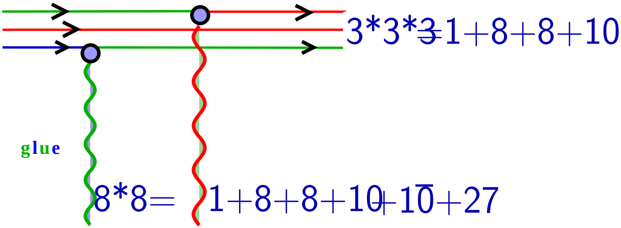
$3 * \bar{3} = 1 + 8$

$8 * 8 = 1 + 8 + 8 + 10 + \overline{10} + 27$

Consider double scattering (two gluon exchange)

In meson scattering only two colour representations can be realized

colour capacity



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The (3-quark) proton is more *capacious*, but still . . .

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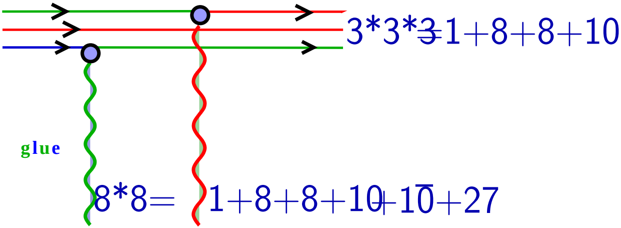

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Calculate the average colour charge of the two-gluon system:

$$\frac{1}{64}\cdot 0+\frac{8+8}{64}\cdot 3+\frac{10+\overline{10}}{64}\cdot 6+\frac{27}{64}\cdot 8=6=2\cdot N_c \Longrightarrow$$

Double density of hadrons
=2 Pomerons

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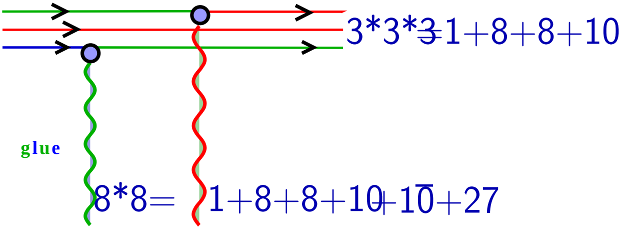

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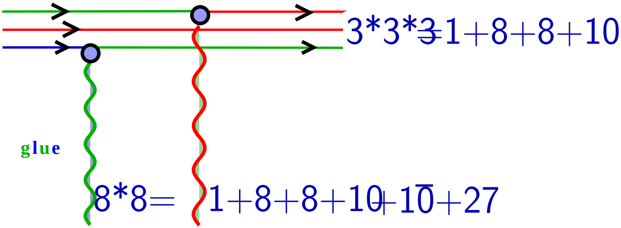

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Nowhere near 2 Pomerons

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Successive collisions of a projectile with a *limited colour capacity* do not produce much of additional hadron yield ....

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Where are then multiple Pomerons ??

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Look at the by-product of the Landau–Pomeranchuk–Migdal physics ...

LPM effect in hA scattering

Inclusive spectrum of medium-induced gluon radiation:

$$\frac{\omega\, dn}{d\omega} \simeq \frac{\alpha_s}{\pi} \cdot \left[\frac{L}{\lambda}\right] \cdot \sqrt{\frac{\mu^2 \lambda}{\omega}}, \qquad \mu^2\lambda < \omega < \mu^2\lambda \left[\frac{L}{\lambda}\right]^2$$

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Bethe-Heitler spectrum (independent radiation off each scattering centre)

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The number of collisions of the projectile, $n_c = L/\lambda$

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The coherent suppression factor

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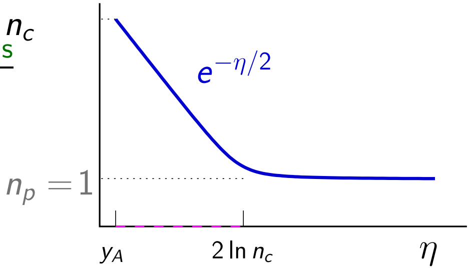
It is the factor $N_{coh.}^{-1}$ that describes the coherent LPM suppression.

LPM gluons

Rapidity distribution of LPM gluons



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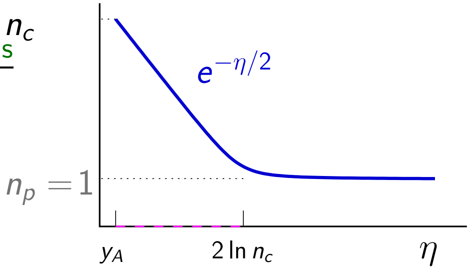

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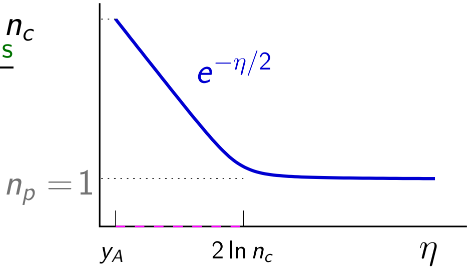

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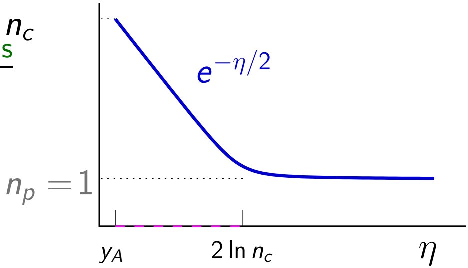

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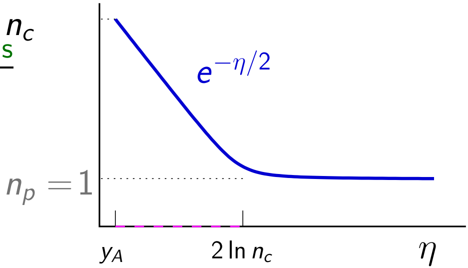

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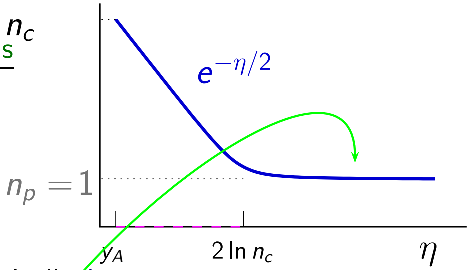

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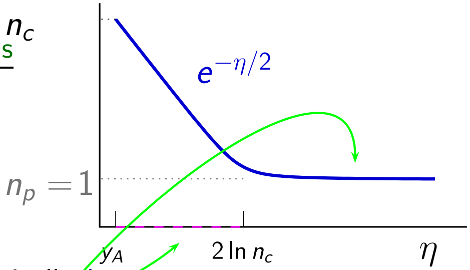

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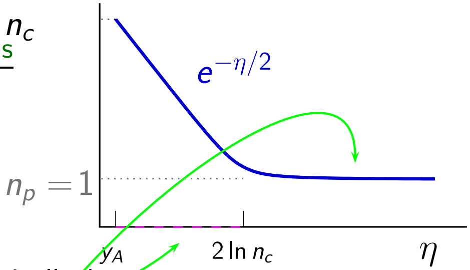

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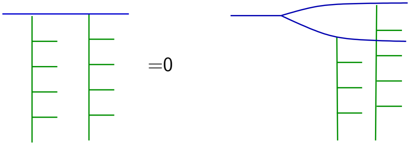

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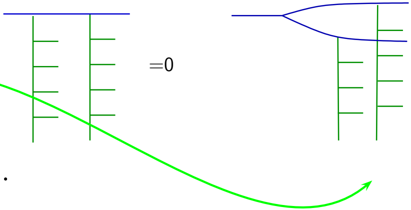

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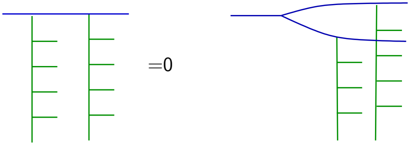

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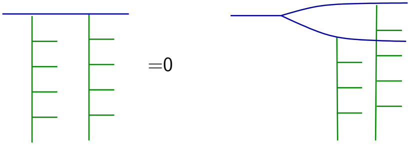

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Parton capacity of the projectile depends on the energy (x_h) and on the resolution — $k_{\perp h}$ of the observed final state hadron h.

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Surprises to be expected. Mind your head.

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Medium induced radiation should lead to

$$\Longrightarrow$$

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