relax

Parton Energy Loss in QCD Medium

Yuri L. Dokshitzer

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

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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,

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

Finite Medium

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

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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]

Expectation:

$$\hat{q}_{\rm HOT} \sim 10 - 30\, \hat{q}_{\rm COLD}$$

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music of the spheres

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Colour and Nuclei

Colour dynamics in pp, pA, AB

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So, *collisions* or *paricipants* ?

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

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

So, *collisions* or *paricipants* ?

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

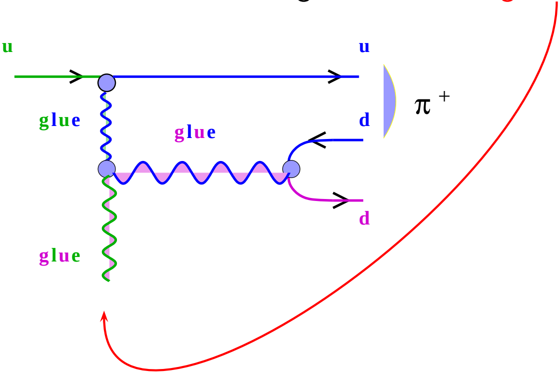
The QCD LPM effect gives a striking example to the contrary ...

colour in Quark scattering

Quark inelastic scattering scenario

colour in Quark scattering

Quark inelastic scattering scenario : one gluon exchange



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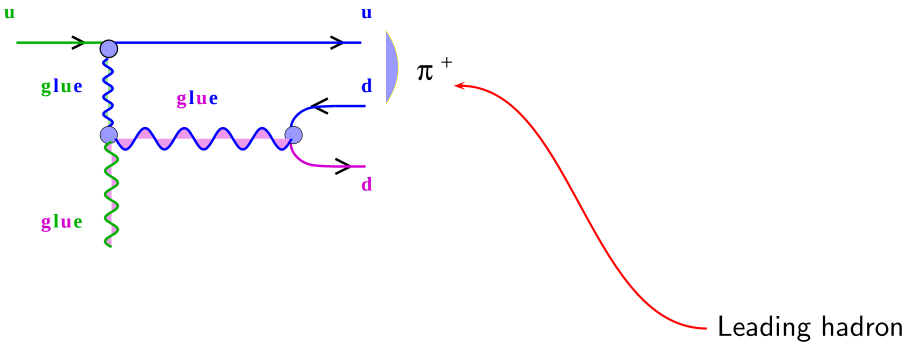

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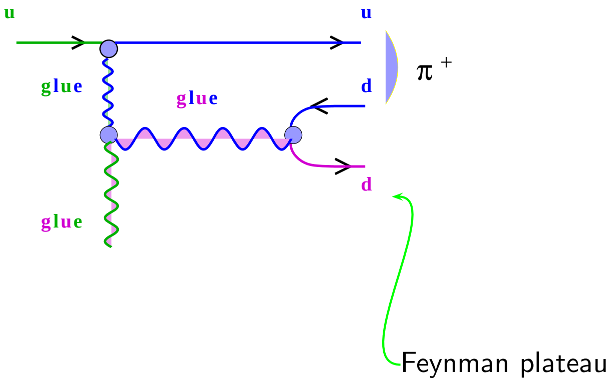

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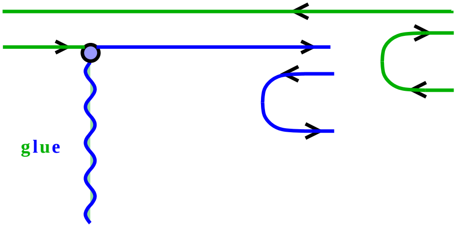
Meson inelastic scattering scenario: gluon exchange



= two "quark chains"

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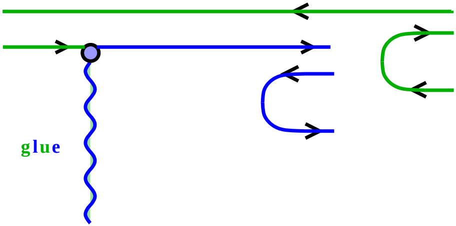

= two "quark chains"
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Painting the proton

Single scattering scenario

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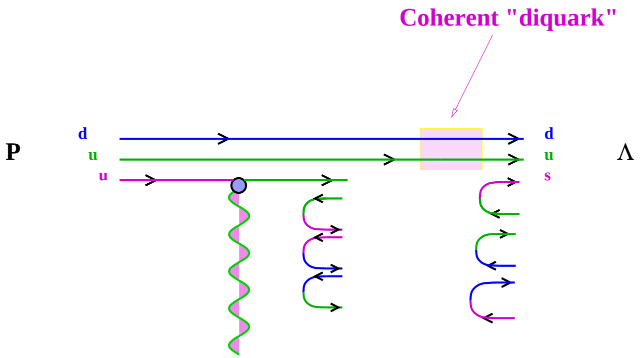

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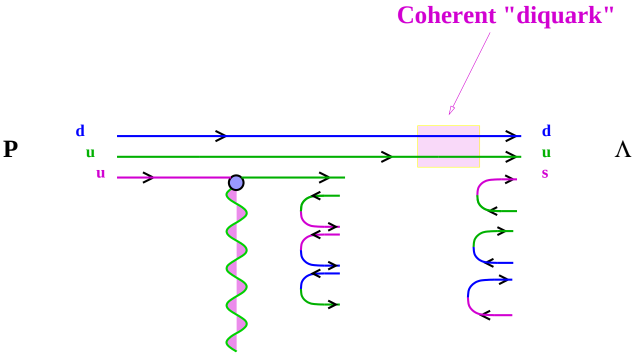

Coherence of the *diquark* ain't broken:

Painting the proton

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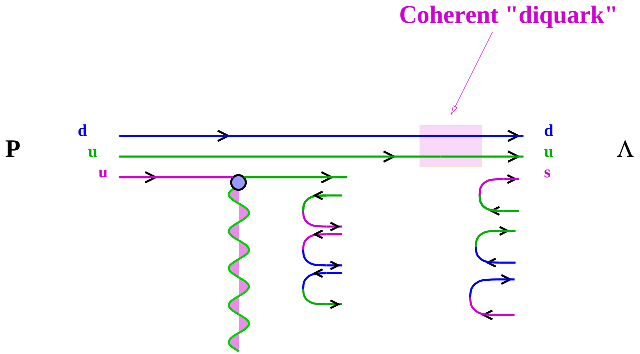

Coherence of the *diquark* ain't broken:

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

Repainting the Proton

Repainting the Proton

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

Re painting the Proton

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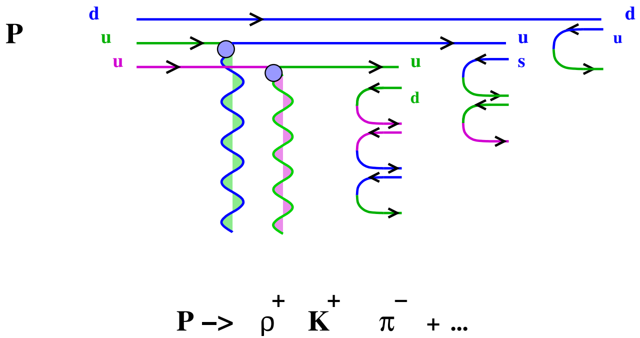

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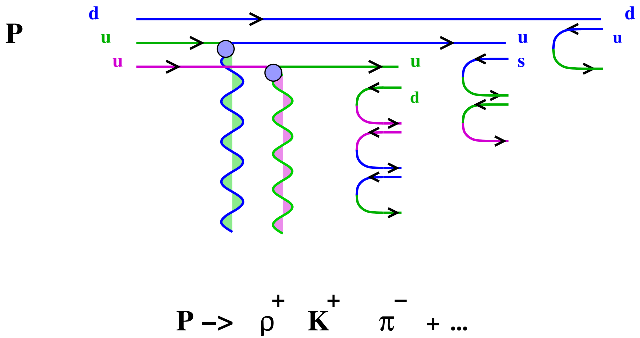

Proton is "*fragile*"

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

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

multiple Proton collisions

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Baryons disappear from the fragmentation region

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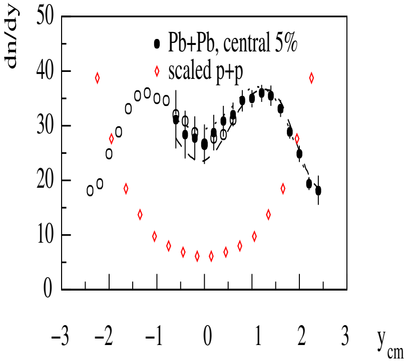
CERN $\sqrt{s} = 17$ GeV (NA49)

- in Pb Pb collisions



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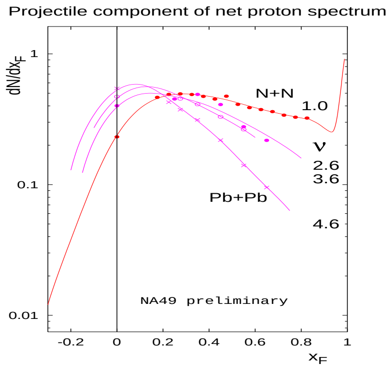

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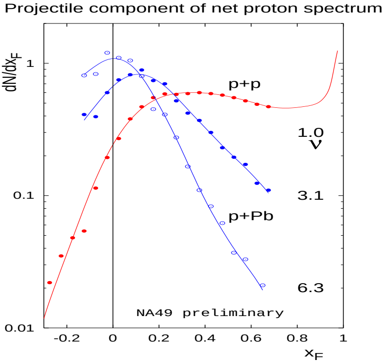

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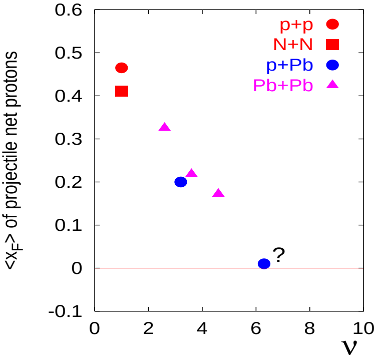

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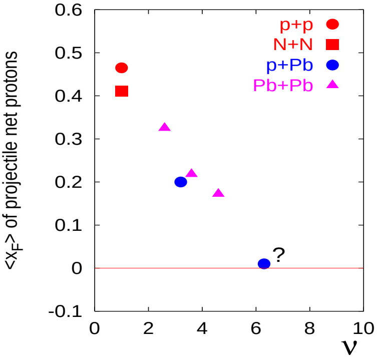

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Known as Proton Stopping.

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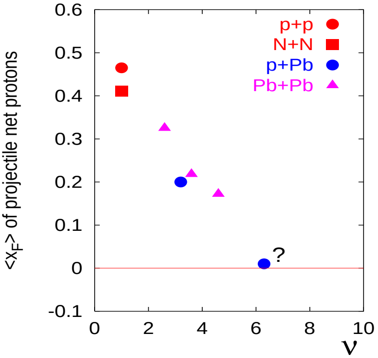

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multiple collisions and Hadron Multiplicity

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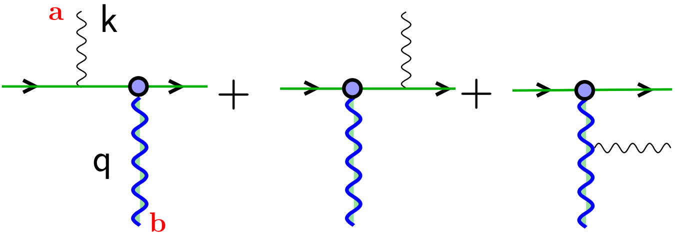
One gluon exchange: accompanying radiation



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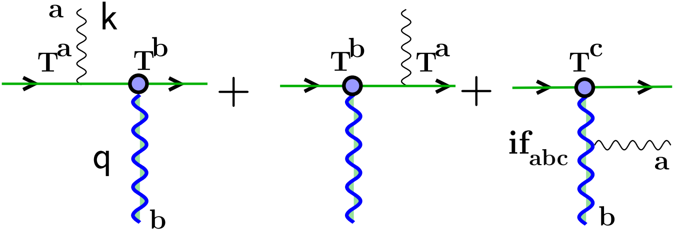

$$-\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2} \qquad +\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2} \qquad +\frac{\mathbf{q}_\perp - \mathbf{k}_\perp}{(\mathbf{q}_\perp - \mathbf{k}_\perp)^2}$$

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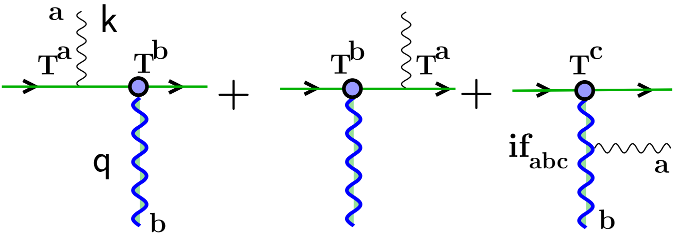

$$-\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2}\mathbf{T^b T^a}+\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2}\mathbf{T^a T^b}+\frac{\mathbf{q}_\perp-\mathbf{k}_\perp}{(\mathbf{q}_\perp-\mathbf{k}_\perp)^2}\, if_{abc}\mathbf{T^c}$$

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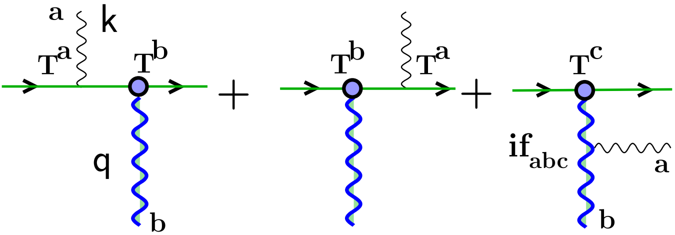

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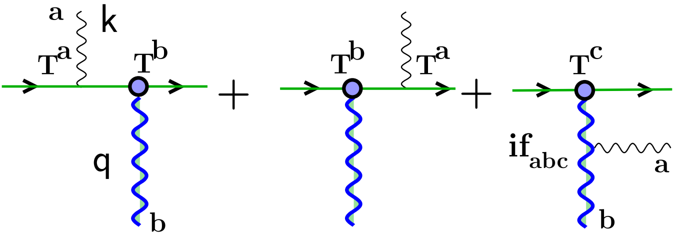

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- Accompanying gluon radiation spectrum :

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

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

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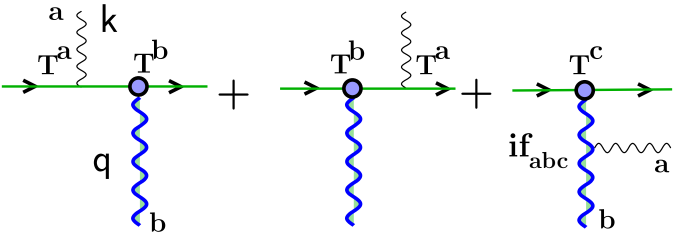

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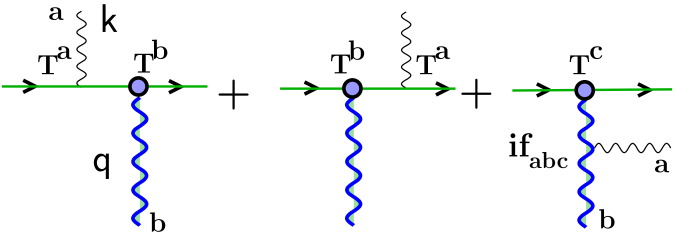
$\Longrightarrow$ scattering cross section of the projectile

multiple collisions and Hadron Multiplicity

One gluon exchange: accompanying radiation



$$-\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2}\mathbf{T}^b\mathbf{T}^a+\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2}\mathbf{T}^a\mathbf{T}^b+\frac{\mathbf{q}_\perp-\mathbf{k}_\perp}{(\mathbf{q}_\perp-\mathbf{k}_\perp)^2}\,if_{abc}\mathbf{T}^c = if_{abc}\mathbf{T}^c\cdot\left[\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2}+\frac{\mathbf{q}_\perp-\mathbf{k}_\perp}{(\mathbf{q}_\perp-\mathbf{k}_\perp)^2}\right]$$

- Particle density is *universal* — it does not depend on the projectile : $(if_{abc})^2 \to N_c \to$ one Pomeron. Conservation of Colour at work

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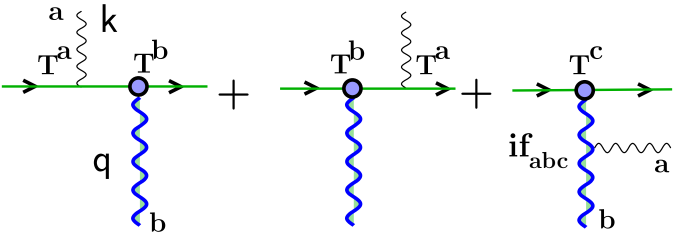

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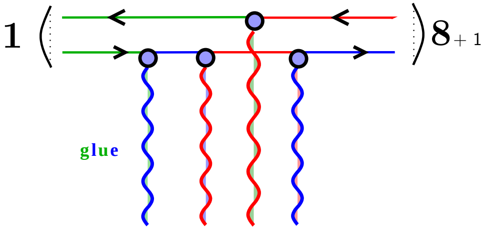
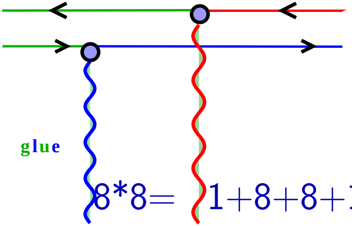
- Multiple scattering of a quark (meson) $\Longrightarrow$ N P*articipant scaling*

colour capacity



Multiple collisions of a (2-quark) pion

colour capacity



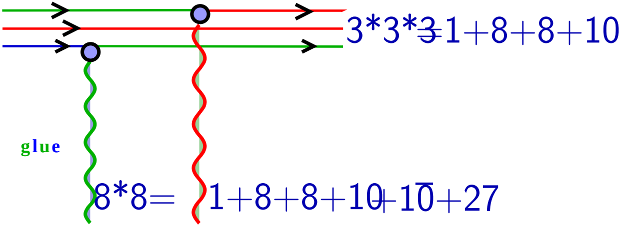
$3 * \bar{3} = 1 + 8$

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

Consider double scattering (two gluon exchange)

In meson scattering only two colour representations can be realized

colour capacity



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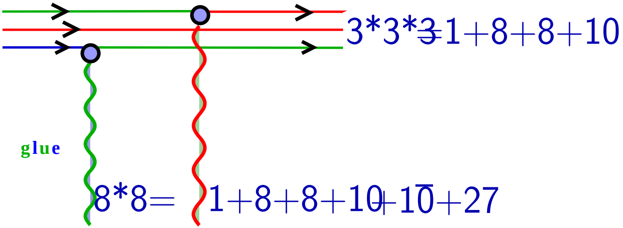
The (3-quark) proton is more *capacious*, but still . . .

colour capacity



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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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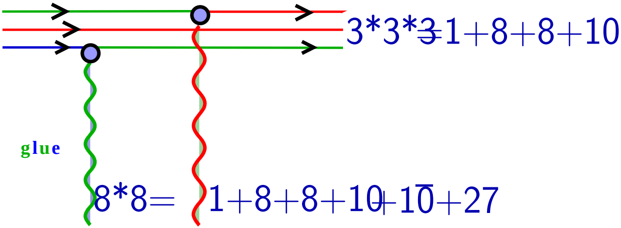

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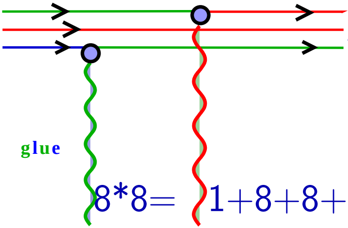

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Nowhere near 2 Pomerons

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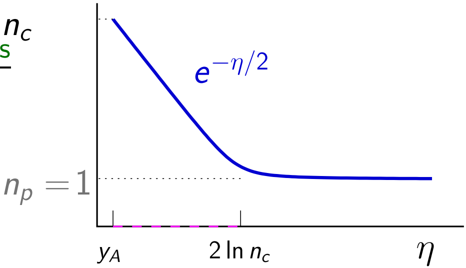
It is the factor $N_{coh.}^{-1}$ that describes the coherent LPM suppression.

LPM gluons

Rapidity distribution of LPM gluons



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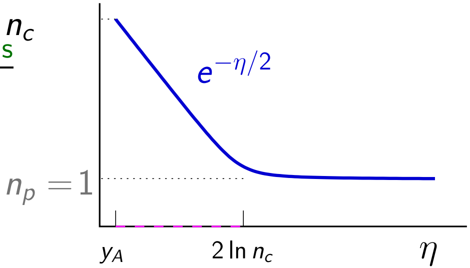

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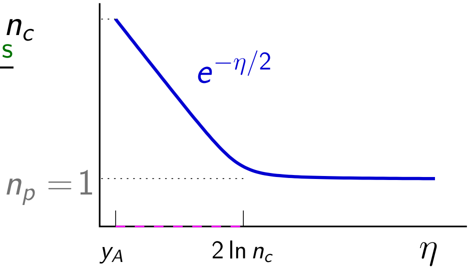

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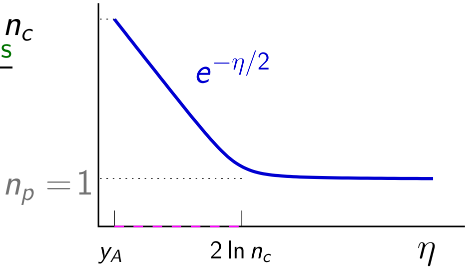

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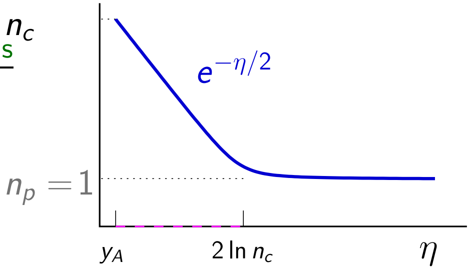

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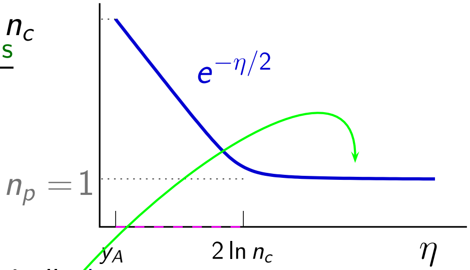

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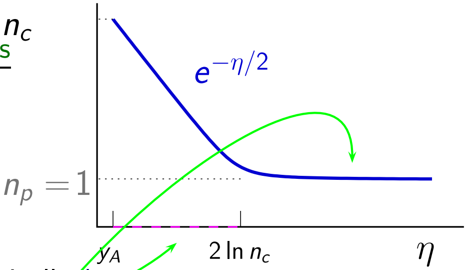

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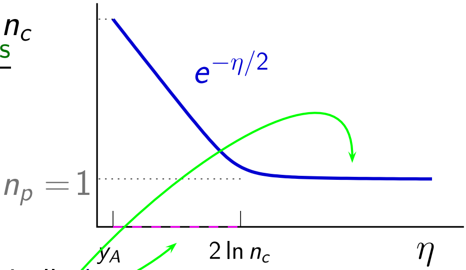

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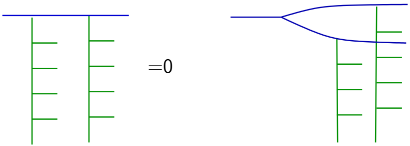

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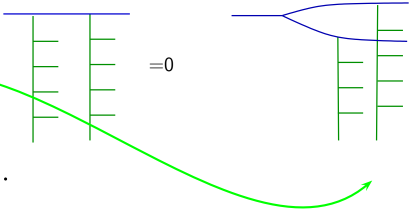

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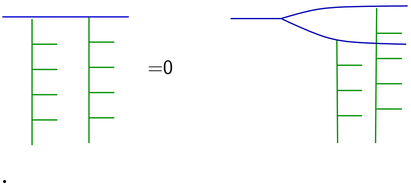

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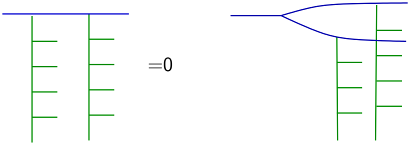

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Parton capacity of the projectile depends on the energy (x_h) and on the resolution — $k_{\perp h}$ of the observed final state hadron h.

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In the framework of the standard hadron (multi-Pomeron) picture (e.g., the successful Dual Parton Model of Capella & Kaidalov et al.) one includes final state interactions to explain spectacular heavy ion phenomena like J/ψ suppression, enhancement of strangeness, etc.

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Surprises to be expected. Mind your head.

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Jet Quenching

exhaustively covered by Urs in his last lecture

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A couple of hints

gluons in-between-jets

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The case of $2 \to 2$ hard parton scattering is more involved (4 emitters), especially so for *gluon–gluon* scattering.

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Here one encounters 6 (5 for $SU(3)$) colour channels that mix with each other under soft gluon radiation, and the classical picture of gluon (or dipole) multiplication is likely to fail.

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Puzzle of large angle Soft Gluon radiation

Soft anomalous dimension ,

$$\frac{\partial}{\partial \ln Q} M \propto \left\{ -N_c \ln\left(\frac{t\,u}{s^2}\right) \cdot \hat{\Gamma} \right\} \cdot M, \qquad \hat{\Gamma} V_i = E_i V_i .$$

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Three "ain't-so-simple" ones were found to satisfy the cubic equation:

$$\left[E_i - \frac{4}{3}\right]^3 - \frac{(1+3b^2)(1+3x^2)}{3}\left[E_i - \frac{4}{3}\right] - \frac{2(1-9b^2)(1-9x^2)}{27} = 0,$$

where

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Mark the *mysterious symmetry* w.r.t. to $x \to b$: interchanging internal (group rank) and external (scattering angle) variables of the problem ...

more hints

Some news concerning
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Have a look at the *simplest* element of the parton multiplication Hamiltonian (non-singlet anomalous dimension) in three loops, α_s^3

3rd loop non-singlet a.d.

$$P_{\rm ns}^{(2)+}(x) = 16 C_A C_F n_f \Bigg(\frac{1}{6} p_{\rm qq}(x) \Bigg[\frac{10}{3}\zeta_2 - \frac{209}{36} - 9\zeta_3 - \frac{167}{18}\mathrm{H}_0 + 2\mathrm{H}_0\zeta_2 - 7\mathrm{H}_0$$

$$+3\mathrm{H}_{1,0,0} - \mathrm{H}_3 \Bigg] + \frac{1}{3} p_{\rm qq}(-x) \Bigg[\frac{3}{2}\zeta_3 - \frac{5}{3}\zeta_2 - \mathrm{H}_{-2,0} - 2\mathrm{H}_{-1}\zeta_2 - \frac{10}{3}\mathrm{H}_{-1,0} - \mathrm{H}_-$$

$$+2\mathrm{H}_{-1,2} + \frac{1}{2}\mathrm{H}_0\zeta_2 + \frac{5}{3}\mathrm{H}_{0,0} + \mathrm{H}_{0,0,0} - \mathrm{H}_3 \Bigg] + (1-x)\Bigg[\frac{1}{6}\zeta_2 - \frac{257}{54} - \frac{43}{18}\mathrm{H}_0 -$$

$$-(1+x)\Bigg[\frac{2}{3}\mathrm{H}_{-1,0} + \frac{1}{2}\mathrm{H}_2 \Bigg] + \frac{1}{3}\zeta_2 + \mathrm{H}_0 + \frac{1}{6}\mathrm{H}_{0,0} + \delta(1-x)\Bigg[\frac{5}{4} - \frac{167}{54}\zeta_2 + \frac{1}{20}\zeta_2$$

$$+16\, C_A C_F{}^2 \Bigg(p_{\rm qq}(x) \Bigg[\frac{5}{6}\zeta_3 - \frac{69}{20}\zeta_2{}^2 - \mathrm{H}_{-3,0} - 3\mathrm{H}_{-2}\zeta_2 - 14\mathrm{H}_{-2,-1,0} + 3\mathrm{H}_{-2,0}$$

$$-4\mathrm{H}_{-2,2} - \frac{151}{48}\mathrm{H}_0 + \frac{41}{12}\mathrm{H}_0\zeta_2 - \frac{17}{2}\mathrm{H}_0\zeta_3 - \frac{13}{4}\mathrm{H}_{0,0} - 4\mathrm{H}_{0,0}\zeta_2 - \frac{23}{12}\mathrm{H}_{0,0,0} + 5\mathrm{H}$$

$$-24\mathrm{H}_1\zeta_3 - 16\mathrm{H}_{1,-2,0} + \frac{67}{9}\mathrm{H}_{1,0} - 2\mathrm{H}_{1,0}\zeta_2 + \frac{31}{3}\mathrm{H}_{1,0,0} + 11\mathrm{H}_{1,0,0,0} + 8\mathrm{H}_{1,1,0,0}$$

3rd loop, more

$$+\frac{67}{9}\mathrm{H}_2 - 2\mathrm{H}_2\zeta_2 + \frac{11}{3}\mathrm{H}_{2,0} + 5\mathrm{H}_{2,0,0} + \mathrm{H}_{3,0}\Big] + p_{\mathrm{qq}}(-x)\Big[\frac{1}{4}\zeta_2{}^2 - \frac{67}{9}\zeta_2 + \frac{31}{4}\zeta$$

$$-32\mathrm{H}_{-2}\zeta_2 - 4\mathrm{H}_{-2,-1,0} - \frac{31}{6}\mathrm{H}_{-2,0} + 21\mathrm{H}_{-2,0,0} + 30\mathrm{H}_{-2,2} - \frac{31}{3}\mathrm{H}_{-1}\zeta_2 - 42\mathrm{H}$$

$$-4\mathrm{H}_{-1,-2,0} + 56\mathrm{H}_{-1,-1}\zeta_2 - 36\mathrm{H}_{-1,-1,0,0} - 56\mathrm{H}_{-1,-1,2} - \frac{134}{9}\mathrm{H}_{-1,0} - 42\mathrm{H}_{-1}$$

$$+32\mathrm{H}_{-1,3} - \frac{31}{6}\mathrm{H}_{-1,0,0} + 17\mathrm{H}_{-1,0,0,0} + \frac{31}{3}\mathrm{H}_{-1,2} + 2\mathrm{H}_{-1,2,0} + \frac{13}{12}\mathrm{H}_0\zeta_2 + \frac{29}{2}\mathrm{H}$$

$$+13\mathrm{H}_{0,0}\zeta_2 + \frac{89}{12}\mathrm{H}_{0,0,0} - 5\mathrm{H}_{0,0,0,0} - 7\mathrm{H}_2\zeta_2 - \frac{31}{6}\mathrm{H}_3 - 10\mathrm{H}_4\Big] + (1-x)\Big[\frac{133}{36} +$$

$$-\frac{167}{4}\zeta_3 - 2\mathrm{H}_0\zeta_3 - 2\mathrm{H}_{-3,0} + \mathrm{H}_{-2}\zeta_2 + 2\mathrm{H}_{-2,-1,0} - 3\mathrm{H}_{-2,0,0} + \frac{77}{4}\mathrm{H}_{0,0,0} - \frac{20}{6}$$

$$+4\mathrm{H}_{1,0,0} + \frac{14}{3}\mathrm{H}_{1,0}\Big] + (1+x)\Big[\frac{43}{2}\zeta_2 - 3\zeta_2{}^2 + \frac{25}{2}\mathrm{H}_{-2,0} - 31\mathrm{H}_{-1}\zeta_2 - 14\mathrm{H}_{-1,-}$$

$$+24\mathrm{H}_{-1,2} + 23\mathrm{H}_{-1,0,0} + \frac{55}{2}\mathrm{H}_0\zeta_2 + 5\mathrm{H}_{0,0}\zeta_2 + \frac{1457}{48}\mathrm{H}_0 - \frac{1025}{36}\mathrm{H}_{0,0} - \frac{155}{6}\mathrm{H}_2$$

3rd loop, and more

$$+2\mathrm{H}_{2,0,0} - 3\mathrm{H}_4\Big] - 5\zeta_2 - \frac{1}{2}\zeta_2{}^2 + 50\zeta_3 - 2\mathrm{H}_{-3,0} - 7\mathrm{H}_{-2,0} - \mathrm{H}_0\zeta_3 - \frac{37}{2}\mathrm{H}_0\zeta_2$$

$$-2\mathrm{H}_{0,0}\zeta_2 + \frac{185}{6}\mathrm{H}_{0,0} - 22\mathrm{H}_{0,0,0} - 4\mathrm{H}_{0,0,0,0} + \frac{28}{3}\mathrm{H}_2 + 6\mathrm{H}_3 + \delta(1-x)\Big[\frac{151}{64} +$$

$$-\frac{247}{60}\zeta_2{}^2 + \frac{211}{12}\zeta_3 + \frac{15}{2}\zeta_5\Big]\Big) + 16\, C_A{}^2 C_F \Big(p_{\mathrm{qq}}(x)\Big[\frac{245}{48} - \frac{67}{18}\zeta_2 + \frac{12}{5}\zeta_2{}^2 + \frac{1}{2}$$

$$+\mathrm{H}_{-3,0} + 4\mathrm{H}_{-2,-1,0} - \frac{3}{2}\mathrm{H}_{-2,0} - \mathrm{H}_{-2,0,0} + 2\mathrm{H}_{-2,2} - \frac{31}{12}\mathrm{H}_0\zeta_2 + 4\mathrm{H}_0\zeta_3 + \frac{389}{72}$$

$$-\mathrm{H}_{0,0,0,0} + 9\mathrm{H}_1\zeta_3 + 6\mathrm{H}_{1,-2,0} - \mathrm{H}_{1,0}\zeta_2 - \frac{11}{4}\mathrm{H}_{1,0,0} - 3\mathrm{H}_{1,0,0,0} - 4\mathrm{H}_{1,1,0,0} + 4\mathrm{H}$$

$$+\frac{11}{12}\mathrm{H}_3 + \mathrm{H}_4\Big] + p_{\mathrm{qq}}(-x)\Big[\frac{67}{18}\zeta_2 - \zeta_2{}^2 - \frac{11}{4}\zeta_3 - \mathrm{H}_{-3,0} + 8\mathrm{H}_{-2}\zeta_2 + \frac{11}{6}\mathrm{H}_{-2,0}$$

$$-3\mathrm{H}_{-1,0,0,0} + \frac{11}{3}\mathrm{H}_{-1}\zeta_2 + 12\mathrm{H}_{-1}\zeta_3 - 16\mathrm{H}_{-1,-1}\zeta_2 + 8\mathrm{H}_{-1,-1,0,0} + 16\mathrm{H}_{-1,-1,2}$$

$$-8\mathrm{H}_{-2,2} + 11\mathrm{H}_{-1,0}\zeta_2 + \frac{11}{6}\mathrm{H}_{-1,0,0} - \frac{11}{3}\mathrm{H}_{-1,2} - 8\mathrm{H}_{-1,3} - \frac{3}{4}\mathrm{H}_0 - \frac{1}{6}\mathrm{H}_0\zeta_2 - 4$$

3rd loop, and again

$$-3\mathrm{H}_{0,0}\zeta_2 - \frac{31}{12}\mathrm{H}_{0,0,0} + \mathrm{H}_{0,0,0,0} + 2\mathrm{H}_2\zeta_2 + \frac{11}{6}\mathrm{H}_3 + 2\mathrm{H}_4\Big] + (1-x)\Big[\frac{1883}{108} - \frac{1}{2}$$

$$-\mathrm{H}_{-2,-1,0} + \frac{1}{2}\mathrm{H}_{-3,0} - \frac{1}{2}\mathrm{H}_{-2}\zeta_2 + \frac{1}{2}\mathrm{H}_{-2,0,0} + \frac{523}{36}\mathrm{H}_0 + \mathrm{H}_0\zeta_3 - \frac{13}{3}\mathrm{H}_{0,0} - \frac{5}{2}\mathrm{H}$$

$$-2\mathrm{H}_{1,0,0}\Big] + (1+x)\Big[8\mathrm{H}_{-1}\zeta_2 + 4\mathrm{H}_{-1,-1,0} + \frac{8}{3}\mathrm{H}_{-1,0} - 5\mathrm{H}_{-1,0,0} - 6\mathrm{H}_{-1,2} - \frac{13}{3}$$

$$-\frac{43}{4}\zeta_3 - \frac{5}{2}\mathrm{H}_{-2,0} - \frac{11}{2}\mathrm{H}_0\zeta_2 - \frac{1}{2}\mathrm{H}_2\zeta_2 - \frac{5}{4}\mathrm{H}_{0,0}\zeta_2 + 7\mathrm{H}_2 - \frac{1}{4}\mathrm{H}_{2,0,0} + 3\mathrm{H}_3 + \frac{3}{4}$$

$$+\frac{1}{4}{\zeta_2}^2 - \frac{8}{3}\zeta_2 + \frac{17}{2}\zeta_3 + \mathrm{H}_{-2,0} - \frac{19}{2}\mathrm{H}_0 + \frac{5}{2}\mathrm{H}_0\zeta_2 - \mathrm{H}_0\zeta_3 + \frac{13}{3}\mathrm{H}_{0,0} + \frac{5}{2}\mathrm{H}_{0,0,0}$$

$$-\delta(1-x)\Big[\frac{1657}{576} - \frac{281}{27}\zeta_2 + \frac{1}{8}{\zeta_2}^2 + \frac{97}{9}\zeta_3 - \frac{5}{2}\zeta_5\Big]\Big) + 16\,C_F n_f^2\Big(\frac{1}{18}p_{\mathrm{qq}}(x)\Big[\mathrm{H}_{0,}$$

$$+(1-x)\Big[\frac{13}{54} + \frac{1}{9}\mathrm{H}_0\Big] - \delta(1-x)\Big[\frac{17}{144} - \frac{5}{27}\zeta_2 + \frac{1}{9}\zeta_3\Big]\Big) + 16\,{C_F}^2 n_f\Big(\frac{1}{3}p_{\mathrm{qq}}(x)\Big[$$

3rd loop, and still some more

$$-\frac{55}{16}+\frac{5}{8}\mathrm{H}_0+\mathrm{H}_0\zeta_2+\frac{3}{2}\mathrm{H}_{0,0}-\mathrm{H}_{0,0,0}-\frac{10}{3}\mathrm{H}_{1,0}-\frac{10}{3}\mathrm{H}_2-2\mathrm{H}_{2,0}-2\mathrm{H}_3\Big]+\frac{2}{3}$$

$$-\frac{3}{2}\zeta_3+\mathrm{H}_{-2,0}+2\mathrm{H}_{-1}\zeta_2+\frac{10}{3}\mathrm{H}_{-1,0}+\mathrm{H}_{-1,0,0}-2\mathrm{H}_{-1,2}-\frac{1}{2}\mathrm{H}_0\zeta_2-\frac{5}{3}\mathrm{H}_{0,0}-$$

$$-(1-x)\left[\frac{10}{9}+\frac{19}{18}\mathrm{H}_{0,0}-\frac{4}{3}\mathrm{H}_1+\frac{2}{3}\mathrm{H}_{1,0}+\frac{4}{3}\mathrm{H}_2\right]+(1+x)\Big[\frac{4}{3}\mathrm{H}_{-1,0}-\frac{25}{24}\mathrm{H}_0+$$

$$+\frac{7}{9}\mathrm{H}_{0,0}+\frac{4}{3}\mathrm{H}_2-\delta(1-x)\left[\frac{23}{16}-\frac{5}{12}\zeta_2-\frac{29}{30}{\zeta_2}^2+\frac{17}{6}\zeta_3\right]\Big)+16\,{C_F}^3\Big(p_{\mathrm{qq}}(x)\Big[$$

$$+6\mathrm{H}_{-2}\zeta_2+12\mathrm{H}_{-2,-1,0}-6\mathrm{H}_{-2,0,0}-\frac{3}{16}\mathrm{H}_0-\frac{3}{2}\mathrm{H}_0\zeta_2+\mathrm{H}_0\zeta_3+\frac{13}{8}\mathrm{H}_{0,0}-2\mathrm{H}_0$$

$$+12\mathrm{H}_1\zeta_3+8\mathrm{H}_{1,-2,0}-6\mathrm{H}_{1,0,0}-4\mathrm{H}_{1,0,0,0}+4\mathrm{H}_{1,2,0}-3\mathrm{H}_{2,0}+2\mathrm{H}_{2,0,0}+4\mathrm{H}_{2,1}$$

$$+4\mathrm{H}_{3,0}+4\mathrm{H}_{3,1}+2\mathrm{H}_4\Big]+p_{\mathrm{qq}}(-x)\Big[\frac{7}{2}{\zeta_2}^2-\frac{9}{2}\zeta_3-6\mathrm{H}_{-3,0}+32\mathrm{H}_{-2}\zeta_2+8\mathrm{H}_{-2}$$

$$-26\mathrm{H}_{-2,0,0}-28\mathrm{H}_{-2,2}+6\mathrm{H}_{-1}\zeta_2+36\mathrm{H}_{-1}\zeta_3+8\mathrm{H}_{-1,-2,0}-48\mathrm{H}_{-1,-1}\zeta_2+40\mathrm{H}$$

3rd loop, and UFF

$$+48\mathrm{H}_{-1,-1,2} + 40\mathrm{H}_{-1,0}\zeta_2 + 3\mathrm{H}_{-1,0,0} - 22\mathrm{H}_{-1,0,0,0} - 6\mathrm{H}_{-1,2} - 4\mathrm{H}_{-1,2,0} - 32$$

$$-\frac{3}{2}\mathrm{H}_0\zeta_2 - 13\mathrm{H}_0\zeta_3 - 14\mathrm{H}_{0,0}\zeta_2 - \frac{9}{2}\mathrm{H}_{0,0,0} + 6\mathrm{H}_{0,0,0,0} + 6\mathrm{H}_2\zeta_2 + 3\mathrm{H}_3 + 2\mathrm{H}_{3,0}$$

$$+(1-x)\Big[2\mathrm{H}_{-3,0} - \frac{31}{8} + 4\mathrm{H}_{-2,0,0} + \mathrm{H}_{0,0}\zeta_2 - 3\mathrm{H}_{0,0,0,0} + 35\mathrm{H}_1 + 6\mathrm{H}_1\zeta_2 - \mathrm{H}_{1,}$$

$$+(1+x)\Big[\frac{37}{10}{\zeta_2}^2 - \frac{93}{4}\zeta_2 - \frac{81}{2}\zeta_3 - 15\mathrm{H}_{-2,0} + 30\mathrm{H}_{-1}\zeta_2 + 12\mathrm{H}_{-1,-1,0} - 2\mathrm{H}_{-1,0}$$

$$-24\mathrm{H}_{-1,2} - \frac{539}{16}\mathrm{H}_0 - 28\mathrm{H}_0\zeta_2 + \frac{191}{8}\mathrm{H}_{0,0} + 20\mathrm{H}_{0,0,0} + \frac{85}{4}\mathrm{H}_2 - 3\mathrm{H}_{2,0,0} - 2\mathrm{H}_3$$

$$-\mathrm{H}_4\Big] + 4\zeta_2 + 33\zeta_3 + 4\mathrm{H}_{-3,0} + 10\mathrm{H}_{-2,0} + \frac{67}{2}\mathrm{H}_0 + 6\mathrm{H}_0\zeta_3 + 19\mathrm{H}_0\zeta_2 - 25\mathrm{H}_{0,0}$$

$$-2\mathrm{H}_2 - \mathrm{H}_{2,0} - 4\mathrm{H}_3 + \delta(1-x)\left[\frac{29}{32} - 2\zeta_2\zeta_3 + \frac{9}{8}\zeta_2 + \frac{18}{5}{\zeta_2}^2 + \frac{17}{4}\zeta_3 - 15\zeta_5\right]\Bigg)$$

music of the spheres

2×2 anomalous dimension matrix occupies

1 st loop: $1/10$ page

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Moch, Vermaseren and Vogt

[waterfall of results launched
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not too encouraging a trend ...

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How to reduce complexity ?

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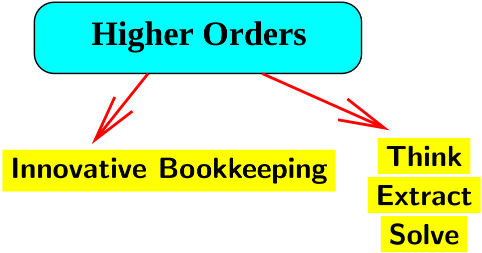
Guidelines



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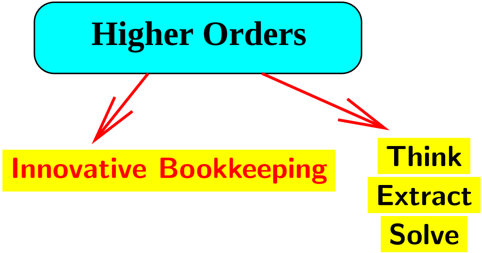

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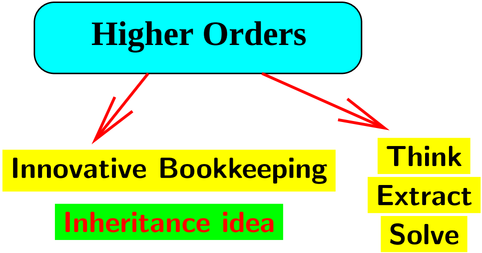

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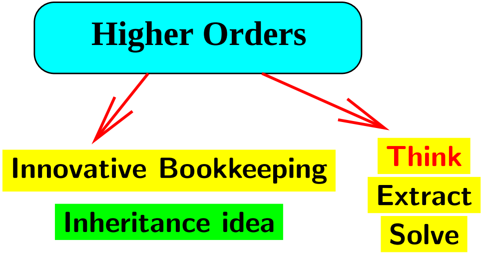

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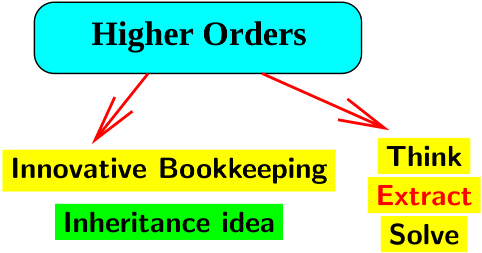

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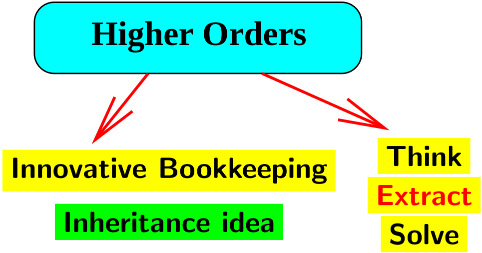

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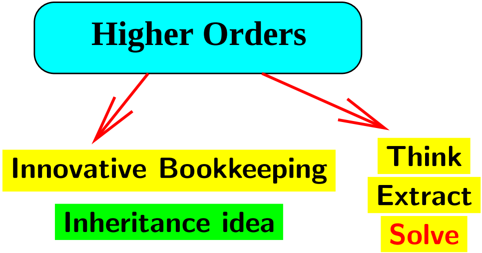

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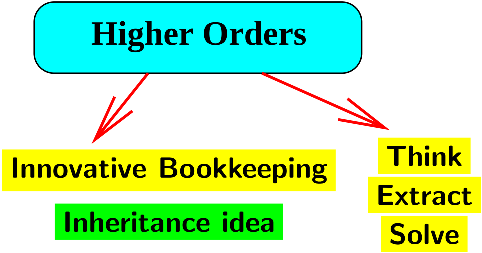
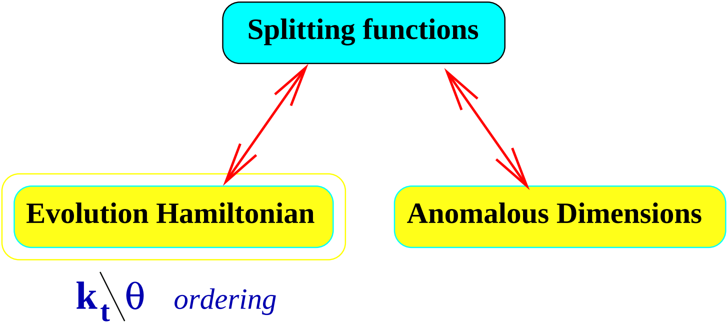


An essential part of gluon dynamics is Classical. (F.Low)
"Classical" does not mean "Simple".
However, it has a good chance to be Exactly Solvable.

➥ A playing ground for theoretical theory: SUSY, AdS/CFT, . . .

Innovative Bookkeeping

In the standard approach,



- parton splitting functions are equated with anomalous dimensions;
- they are different for DIS and e^+e^- evolution;
- "clever evolution variables" are different too

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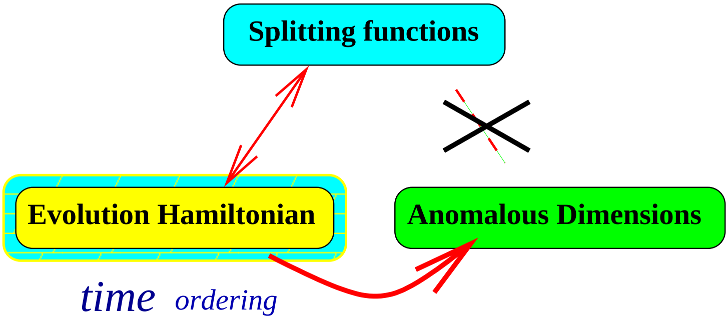
In the new approach,



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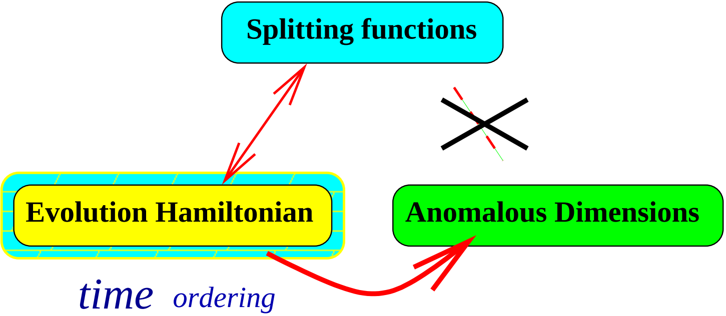

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old new evolution — Innovative Bookkeeping

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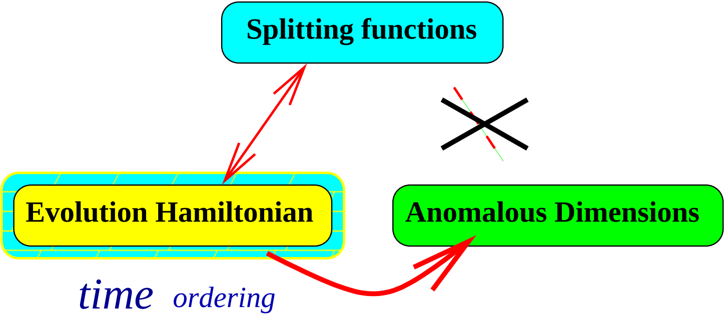

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inherited from previous loops !

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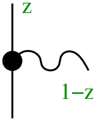
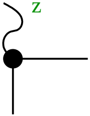
Recall an old hint from QCD ...

Relating parton splittings



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



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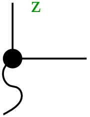

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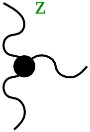

$$= N_c \cdot \frac{1+z^4+(1-z)^4}{z(1-z)}$$

Four "parton splitting functions"

$${}^{q[g]}_{q}(z)\,, \qquad {}^{g[q]}_{q}(z)\,, \qquad {}^{q[\bar{q}]}_{g}(z)\,, \qquad {}^{g[g]}_{g}(z)$$

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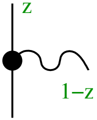

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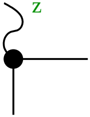

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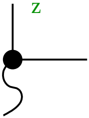

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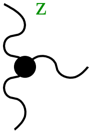

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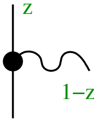

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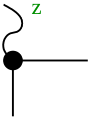

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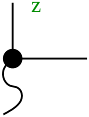

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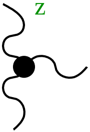

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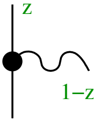

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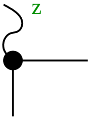

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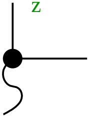

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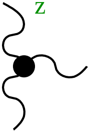

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Three (QED) "kernels" are inter-related; gluon self-interaction stays put :

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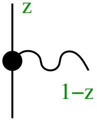

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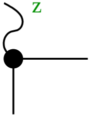

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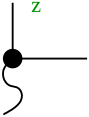

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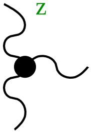

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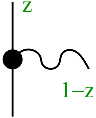

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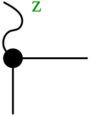

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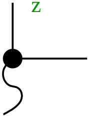

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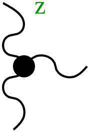

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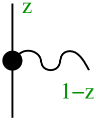

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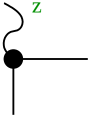

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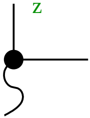

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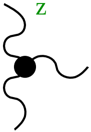

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✓ the Regge behaviour (large N_c)	Lipatov Faddeev & Korchemsky (1994)
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- ✗ Full integrability via AdS/CFT — Maldacena; Witten, Gubser, Klebanov, Polyakov (1998)

And here we arrive at the second — Divide and Conquer — issue

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$$\tilde{\gamma}_{q\to q(x)+g} = \frac{C_F\alpha_s}{\pi}\left[\frac{x}{1-x} + (1-x)\cdot\frac{1}{2}\right],$$

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Let us look at the rôles these animals play on the QCD stage

Gluenatomy

Clagons :

- ✗ Classical Field
- ✓ infrared singular, $d\omega/\omega$
- ✓ define the physical coupling
- ✓ responsible for
  - ➥ DL radiative effects,
  - ➥ reggeization,
  - ➥ QCD/Lund string (gluers)
- ✓ play the major rôle in evolution

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In addition,

- ✗ Tree multi-clagon (Parke–Taylor) amplitudes are *known exactly*
- ✗ It is clagons which dominate in all the *integrability cases*

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Matter content = 4 Majorana fermions, 6 scalars;
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$$\frac{\text{clever 2nd loop}}{\text{clever 1st loop}} < 2\% \qquad \left(\begin{array}{c} \text{Heavy quark fragmentation} \\ \text{D-r, Khoze \& Troyan , PRD 1996} \end{array} \right)$$

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Employ $\mathcal{N}=4$ SYM to simplify the major part of the QCD dynamics !

to conclude

- A steady progress in high order perturbative QCD calculations is worth accompanying by reflections upon the origin and the structure of higher loop correction effects
- Reformulation of parton cascades in terms of Gribov–Lipatov reciprocity respecting evolution equations (RREE)
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- The Low theorem should be part of theor.phys. curriculum, worldwide
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Phenomenologists tend to oppose the acceptance of unobservable matters and grand systems erected in speculative thinking;

[Center for advanced research in phenomenology]

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- strong colour fields at small coupling ! CGC, LPM, ...

A New Interesting Phenomenon in the Medium ...

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