relax
Parton Energy Loss in QCD Medium

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

\[ k_\perp^2 \sim \mu^2 \cdot N_{\text{coh}} = \mu^2 \cdot \frac{t}{\lambda}; \]

Gluon formation time:

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

Equating the two expressions for \( t \),

\[ k_\perp^2 \sim \sqrt{\frac{\omega \mu^2}{\lambda}}; \quad t = \frac{\lambda k_\perp^2}{\mu^2}; \quad N_{\text{coh}} = \frac{\omega}{\lambda \mu^2}. \]

Thus,

\[ \frac{\omega \, dl}{d\omega \, dz} \propto \frac{\alpha_s}{\lambda} \cdot \frac{1}{N_{\text{coh}}} = \frac{\alpha_s}{\lambda} \sqrt{\frac{E_{\text{LPM}}}{\omega}}. \]

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\[ c \, t < L \quad \Rightarrow \quad \omega < \omega_{\text{max}} = \frac{\mu^2}{\lambda} \frac{L^2}{\lambda}. \]
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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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\[ \hat{q}_{\text{HOT}} \sim 10 - 30 \hat{q}_{\text{COLD}} \]
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or a he-e-e-eavy ion
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Imagine a target hit by a relativistic projectile.

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How to compare a quantity one measures in $AA$ (or $pA$) collisions, with the one *simply rescaled* from an elementary $pp$ interaction?
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It is in this harmlessly looking “simply rescaled” where the devil resides.
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It is in this harmlessly looking “\textit{simply rescaled}” where the devil resides.

Should a given observable in \textit{AA} interactions scale with the number of \textit{participating nucleons} (which may be as large as \(n_p = 2A\)) or instead as the number of \textit{elementary nucleon–nucleon collisions}, \(n_c \propto A^{4/3}\)?
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Colour dynamics in \(pp, pA, AB\)
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So, *collisions* or *participants*?
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So, collisions or participants?

*Hard interactions* are commonly expected to scale as $n_c$, *soft* — as $n_p$. 
Colour dynamics in $pp$, $pA$, $AB$

So, *collisions* or *participants*?

*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 ...
Quark inelastic scattering scenario
Quark inelastic scattering scenario: one gluon exchange

\( \pi^+ \)
Quark inelastic scattering scenario: one gluon exchange
Quark inelastic scattering scenario: one gluon exchange

Feynman plateau
Meson inelastic scattering scenario: gluon exchange

= two “quark chains”
Meson inelastic scattering scenario: gluon exchange

= two “quark chains” known as the Pomeron
Painting the proton

Single scattering scenario
Painting the proton

Single scattering scenario

Coherent "diquark"
Painting the proton

Single scattering scenario

Coherence of the \textit{diquark} ain’t broken:
Single scattering scenario

Coherence of the diquark ain’t broken:

$\rightarrow$ a Leading Baryon: $B(1) \rightarrow B(2/3) + M(1/3) + \ldots$
Kick it *twice* to break the coherence of the valence quarks
Kick it *twice* to break the *coherence* of the *valence quarks*

\[ P \rightarrow \rho^+ K^+ \pi^- + \ldots \]
Kick it *twice* to break the coherence of the valence quarks

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
Baryons disappear from the fragmentation region
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CERN $\sqrt{s} = 17$ GeV (NA49)

- in Pb Pb collisions
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- in Pb Pb collisions
- in p Pb collisions
Baryons disappear from the fragmentation region

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

- in Pb Pb collisions
- in p Pb collisions
- $\langle x_F \rangle$ of net protons

$\nu$ — number of collisions
Baryons disappear from the fragmentation region

\[ \text{CERN } \sqrt{s} = 17 \text{ GeV (NA49)} \]

- in Pb Pb collisions
- in p Pb collisions
- \( \langle x_F \rangle \) of net protons

Known as Proton Stopping.
Baryons disappear from the fragmentation region

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

- in Pb Pb collisions
- in p Pb collisions
- $<x_F>$ of net protons

Known as Proton Stopping. Better be called Proton Decay
multiple collisions and Hadron Multiplicity
One gluon exchange: \( a \) \( k \) \( b \)

accompanying radiation
One gluon exchange: accompanying radiation

\[ \frac{k_\perp}{k^2_a} + \frac{k_\perp}{k^2_b} + \frac{q_\perp - k_\perp}{(q_\perp - k_\perp)^2} \]
One gluon exchange: accompanying radiation

\[ k^a \rightarrow b^a T^a \rightarrow T^b \rightarrow \]  
\[ q^a \rightarrow b^a T^a \rightarrow T^b \rightarrow \]  
\[ k^a \rightarrow b^a T^a \rightarrow T^b \rightarrow \]  
\[ q^a \rightarrow b^a T^a \rightarrow T^b \rightarrow \]  

\[ \frac{k_{\perp}}{k_{\perp}^2} T^b T^a + \frac{k_{\perp}}{k_{\perp}^2} T^a T^b + \frac{q_{\perp} - k_{\perp}}{(q_{\perp} - k_{\perp})^2} i f_{abc} T^c \]
One gluon exchange:  accompanying radiation

\[
\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2} T^a T^b + \frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2} T^a T^b + \frac{\mathbf{q}_\perp - \mathbf{k}_\perp}{(\mathbf{q}_\perp - \mathbf{k}_\perp)^2} \text{if}_{abc} T^c = \text{if}_{abc} 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]
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multiple collisions and Hadron Multiplicity

One gluon exchange: accompanying radiation

\[ a \quad \xrightarrow{k} \quad b \]
\[ T^a \quad \xrightarrow{T^b} \quad T^b \quad \xrightarrow{q} \quad T^a \quad \xrightarrow{T_c} \quad \text{if}_{abc} \]

\[ \frac{-k^2}{k^2} T^b T^a + \frac{k^2}{k^2} T^a T^b + \frac{q - k}{(q - k)^2} \text{if}_{abc} T_c = \text{if}_{abc} T_c \cdot \left[ \frac{k^2}{k^2} + \frac{q - k}{(q - k)^2} \right] \]

Accompanying gluon radiation spectrum:

✓ \[ d\omega/\omega \quad \Rightarrow \quad \text{rapidity plateau} \]
✓ \[ k^2 < q^2 \quad \Rightarrow \quad \text{finite transverse momenta} \]
One gluon exchange: accompanying radiation

\[ T^a \rightarrow k \rightarrow T^b \]

\[ q \rightarrow b \]

\[ T^b \rightarrow T^a \rightarrow T^c \]

\[ if_{abc} \rightarrow a \rightarrow b \]

\[ -\frac{k_{\perp}}{k_{\perp}^2} T^b T^a + \frac{k_{\perp}}{k_{\perp}^2} T^a T^b + \frac{q_{\perp} - k_{\perp}}{(q_{\perp} - k_{\perp})^2} \]

\[ if_{abc} T^c = if_{abc} T^c \left[ \frac{k_{\perp}}{k_{\perp}^2} + \frac{q_{\perp} - k_{\perp}}{(q_{\perp} - k_{\perp})^2} \right] \]

\[ \implies \text{scattering cross section of the projectile} \]
multiple collisions and Hadron Multiplicity

One gluon exchange: accompanying radiation

Particle density is universal — it does not depend on the projectile:

\((if_{abc})^2 \rightarrow N_c \rightarrow \text{one Pomeron.}\) Conservation of Colour at work
One gluon exchange: accompanying radiation

\[ a \xrightarrow{k} a + b \xrightarrow{\text{radiation}} + c \xrightarrow{\text{radiation}} \]

\[ T^a \xrightarrow{k} T^b + T^b \xrightarrow{\text{radiation}} + T^c \xrightarrow{\text{radiation}} a \]

\[-\frac{k_{\perp}}{k_{\perp}^2} T^b T^a + \frac{k_{\perp}}{k_{\perp}^2} T^a T^b + \frac{q_{\perp} - k_{\perp}}{(q_{\perp} - k_{\perp})^2} if_{abc} T^c = if_{abc} T^c \cdot \left[ \frac{k_{\perp}}{k_{\perp}^2} + \frac{q_{\perp} - k_{\perp}}{(q_{\perp} - k_{\perp})^2} \right] \]

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

- Multiple scattering of a quark (meson) \( \implies N \text{ Participant scaling} \)
Multiple collisions of a (2-quark) pion
Consider double scattering (two gluon exchange) in meson scattering only two colour representations can be realized.
Consider double scattering (two gluon exchange)
The (3-quark) proton is more *capacious*, but still . . .
Consider double scattering (two gluon exchange)
The (3-quark) proton is more *capacious*, but still . . .

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

\[
\frac{1}{64} \cdot 0 + \frac{8 + 8}{64} \cdot 3 + \frac{10 + 10}{64} \cdot 6 + \frac{27}{64} \cdot 8 = 6 = 2 \cdot N_c \quad \Rightarrow \quad \text{Double density of hadrons} \\
= 2 \text{ Pomerons}
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\]

Cannot be realized on a *valence-built* proton:

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\frac{1}{27} \cdot 0 + \frac{8 + 8}{27} \cdot 3 + \frac{10}{27} \cdot 6 = 4
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\text{Double density of hadrons} = 2 \text{ Pomerons}
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\]

Nowhere near 2 Pomerons
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 ??**
Successive collisions of a projectile with a *limited colour capacity* do not produce much of additional hadron yield ....

Where are then multiple Pomerons ??

Look at the by-product of the Landau–Pomeranchuk–Migdal physics ...
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}}, \quad \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)
Inclusive spectrum of medium-induced gluon radiation:

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The number of collisions of the projectile, \( n_c = L/\lambda \)
Inclusive spectrum of medium-induced gluon radiation:

\[ \frac{\omega}{d\omega} \sim \frac{\alpha_s}{\pi} \cdot \left[ \frac{L}{\lambda} \right] \cdot \frac{\sqrt{\mu^2 \lambda}}{\omega}, \quad \mu^2 \lambda < \omega < \mu^2 \lambda \left[ \frac{L}{\lambda} \right]^2 \]

The coherent suppression factor
Inclusive spectrum of medium-induced gluon radiation:

$$\frac{\omega \, d n}{d \omega} \approx \frac{\alpha_s}{\pi} \cdot \left[ \frac{L}{\lambda} \right] \cdot \sqrt{\frac{\mu^2 \lambda}{\omega}}, \quad \mu^2 \lambda < \omega < \mu^2 \lambda \left[ \frac{L}{\lambda} \right]^2$$

$N_{coh.} > 1$ scattering centres that fall inside the formation length of the gluon act as a single scatterer.

$$N_{coh.} \approx \frac{\ell_{coh.}}{\lambda} \approx \frac{1}{\lambda} \cdot \frac{\omega}{k_{\perp}^2}.$$
LPM effect in $hA$ scattering

Inclusive spectrum of medium-induced gluon radiation:

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

$N_{coh.} > 1$ scattering centres that fall *inside the formation length* of the gluon act as a single scatterer. At the same time, the gluon is subject to *Brownian motion* in the transverse momentum plane:

$$k^2_\perp \simeq N_{coh.} \cdot \mu^2, \quad N_{coh.} \simeq \frac{\ell_{coh.}}{\lambda} \simeq \frac{1}{\lambda} \cdot \frac{\omega}{k^2_\perp}.$$
Inclusive spectrum of medium-induced gluon radiation:

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k^2_\perp \approx N_{\text{coh.}} \cdot \mu^2, \quad N_{\text{coh.}} \approx \frac{\ell_{\text{coh.}}}{\lambda} \approx \frac{1}{\lambda} \cdot \frac{\omega}{k^2_\perp}.
\]

Combining the two estimates results in

\[
N_{\text{coh.}} \approx \sqrt{\frac{\omega}{\mu^2 \lambda}} \quad \text{and} \quad k^2_\perp \approx \sqrt{\frac{\mu^2}{\lambda}} \cdot \omega.
\]
Inclusive spectrum of medium-induced gluon radiation:

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

\(N_{coh.} > 1\) scattering centres that fall *inside the formation length* of the gluon act as a single scatterer. At the same time, the gluon is subject to *Brownian motion* in the transverse momentum plane:

\[
k^2_\perp \simeq N_{coh.} \cdot \mu^2, \quad N_{coh.} \simeq \frac{\ell_{coh.}}{\lambda} \simeq \frac{1}{\lambda} \cdot \frac{\omega}{k^2_\perp}.
\]

Combining the two estimates results in

\[
N_{coh.} \simeq \sqrt{\frac{\omega}{\mu^2 \lambda}} \quad \text{and} \quad k^2_\perp \simeq \sqrt{\frac{\mu^2}{\lambda} \cdot \omega}.
\]

It is the factor \(N_{coh.}^{-1}\) that describes the coherent LPM suppression.
Rapidity distribution of LPM gluons

\[ n_p = 1 \]

\[ n_c \]

\[ e^{-\eta/2} \]

[Diagram showing the distribution]
Rapidity distribution of LPM gluons

Here comes confusing part ...
Rapidity distribution of LPM gluons

\[ k_{\perp}^2 \approx \sqrt{\frac{\mu^2}{\lambda}} \cdot \omega \]

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The *more energetic* gluons have typically *larger transverse momenta*. 
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Many successive collisions ... but only one Pomeron. The destructive LPM coherence invalidates the multi-Pomeron exchange picture?! Does it indeed?
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To have $n_c$ Pomerons attached, one must compare $n_c$ with the number of \textit{independent} (incoherent, resolved) \textit{partons} inside the projectile:

$$C(x_h, Q_{\text{res}}) = \int_{x_h}^{1} \frac{dx}{x} \left[ xG_{\text{proj}}(x, Q_{\text{res}}^2) \right], \quad x_{\text{proj}} = 1.$$
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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 $h$. 


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 $J/\psi$ suppression, enhancement of strangeness, etc.
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After the pancakes separate, at each impact parameter we have a dense colour field whose strength corresponds to $n_p/fm^2 \propto A^{1/3}$ “strings”.

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- **softening** of particle spectra in a jet muddling thru medium,
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⇒

Jet Quenching
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$\implies$

Jet Quenching

exhaustively covered by Urs in his last lecture
Isn’t QCD actually *simpler* than it looks?
Isn’t QCD actually \textit{simpler} than it looks?

\begin{center}
A couple of hints
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2- and 3-prong colour antennae are sort of “trivial”: coherence being taken care of, the answers turned out to be essentially additive.

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

The difficult quest of sorting out large angle gluon radiation in all orders in $(\alpha_s \log Q)^n$ was set up and solved by George Sterman and collaborators. 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,

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

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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

$$x = \frac{1}{N_c}, \quad b \equiv \frac{\ln(t/s) - \ln(u/s)}{\ln(t/s) + \ln(u/s)}.$$
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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 . . .
Some news concerning apparent complexity/hidden simplicity of gluon dynamics
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Have a look at the *simplest* element of the parton multiplication Hamiltonian (non-singlet anomalous dimension) in three loops, $\alpha_s^3$
\[ P_{(2)^+}^{(2)}(x) = 16 C_A C_F n_f \left( \frac{1}{6} p_{qq}(x) \left[ \frac{10}{3} \zeta_2 - \frac{209}{36} - 9 \zeta_3 - \frac{167}{18} H_0 + 2 H_0 \zeta_2 - 7 H_0 \right. \right. \]
\[ + 3 H_{1,0,0} - H_3 \left. \right] + \frac{1}{3} p_{qq}(-x) \left[ \frac{3}{2} \zeta_3 - \frac{5}{3} \zeta_2 - H_{-2,0} - 2 H_{-1} \zeta_2 - \frac{10}{3} H_{-1,0} - H_{-1,2} \right. \]
\[ + \frac{1}{2} H_0 \zeta_2 + \frac{5}{3} H_{0,0} + H_{0,0,0} - H_3 \left. \right] + (1 - x) \left[ \frac{1}{6} \zeta_2 - \frac{257}{54} - \frac{43}{18} H_0 - \frac{2}{3} \right. \]
\[ - (1 + x) \left[ \frac{2}{3} H_{-1,0} + \frac{1}{2} H_2 \right] + \frac{1}{3} \zeta_2 + H_0 + \frac{1}{6} H_{0,0} + \delta(1 - x) \left[ \frac{5}{4} - \frac{167}{54} \zeta_2 + \frac{1}{20} \zeta_2 \right. \]
\[ + 16 C_A C_F^2 \left( p_{qq}(x) \left[ \frac{5}{6} \zeta_3 - \frac{69}{20} \zeta_2^2 - H_{-3,0} - 3 H_{-2} \zeta_2 - 14 H_{-2,-1,0} + 3 H_{-2,0} \right. \right. \]
\[ - 4 H_{-2,2} - \frac{151}{48} H_0 + \frac{41}{12} H_0 \zeta_2 - \frac{17}{2} H_0 \zeta_3 - \frac{13}{4} H_{0,0} - 4 H_{0,0} \zeta_2 - \frac{23}{12} \right. \]
\[ H_{0,0,0} + 5 H_{0,0,0} \left. \right] - 24 H_{1} \zeta_3 - 16 H_{1,-2,0} + \frac{67}{9} H_{1,0} - 2 H_{1,0} \zeta_2 + \frac{31}{3} H_{1,0,0} + 11 H_{1,0,0,0} + 8 H_{1,1,0,0} \]
\[
+ \frac{67}{9} H_2 - 2H_2 \zeta_2 + \frac{11}{3} H_{2,0} + 5H_{2,0,0} + H_{3,0} \Bigg] + p_{qq}(-x) \left[ \frac{1}{4} \zeta_2^2 - \frac{67}{9} \zeta_2 + \frac{31}{4} \zeta_3 \right.

- 32H_{-2} \zeta_2 - 4H_{-2,-1,0} - \frac{31}{6} H_{-2,0} + 21H_{-2,0,0} + 30H_{-2,2} - \frac{31}{3} H_{-1} \zeta_2 - 42H_{-1,-1} \zeta_2

- 4H_{-1,-2,0} + 56H_{-1,-1} \zeta_2 - 36H_{-1,-1,0,0} - 56H_{-1,-1,2} - \frac{134}{9} H_{-1,0} - 42H_{-1,1}

+ 32H_{-1,3} - \frac{31}{6} H_{-1,0,0} + 17H_{-1,0,0,0} + \frac{31}{3} H_{-1,2} + 2H_{-2,0,0} + \frac{13}{12} H_0 \zeta_2 + \frac{29}{2} H_0 \zeta_3

+ 13H_{0,0} \zeta_2 + \frac{89}{12} H_{0,0,0} - 5H_{0,0,0,0} - 7H_2 \zeta_2 - \frac{31}{6} H_3 - 10H_4 \Bigg] + (1-x) \left[ \frac{133}{36} + \frac{167}{4} \zeta_3 - 2H_0 \zeta_3 - 2H_{-3,0} + H_{-2} \zeta_2 + 2H_{-2,-1,0} - 3H_{-2,0,0} + \frac{77}{4} H_{0,0,0} - \frac{209}{6}

+ 4H_{1,0,0} + \frac{14}{3} H_{1,0} \Bigg] + (1+x) \left[ \frac{43}{2} \zeta_2 - 3 \zeta_2^2 + \frac{25}{2} H_{-2,0} - 31H_{-1} \zeta_2 - 14H_{-1,-1}

+ 24H_{-1,2} + 23H_{-1,0,0} + \frac{55}{2} H_0 \zeta_2 + 5H_{0,0} \zeta_2 + \frac{1457}{48} H_0 - \frac{1025}{36} H_{0,0} - \frac{155}{6} H_2 \right]
\]
\[ +2H_{2,0,0} - 3H_4 \] - 5\zeta_2 - \frac{1}{2}\zeta_2^2 + 50\zeta_3 - 2H_{-3,0} - 7H_{-2,0} - H_0\zeta_3 - \frac{37}{2}H_0\zeta_2 + \\
-2H_{0,0}\zeta_2 + \frac{185}{6}H_{0,0} - 22H_{0,0,0} - 4H_{0,0,0,0} + \frac{28}{3}H_2 + 6H_3 + \delta(1-x) \left[ \frac{151}{64} + \right. \\
-\frac{247}{60}\zeta_2^2 + \frac{211}{12}\zeta_3 + \frac{15}{2}\zeta_5 \right] + 16 C_A^2 C_F \left( p_{qq}(x) \left[ \frac{245}{48} - \frac{67}{18}\zeta_2 + \frac{12}{5}\zeta_2^2 + \frac{1}{2}\zeta_3 \right] + H_{-3,0} + 4H_{-2,-1,0} - \frac{3}{2}H_{-2,0} - H_{-2,0,0} + 2H_{-2,2} - \frac{31}{12}H_0\zeta_2 + 4H_0\zeta_3 + \frac{389}{72}H_4 \right) \\
+ H_{0,0,0,0} + 9H_{1}\zeta_3 + 6H_{1,-2,0} - H_{1,0}\zeta_2 - \frac{11}{4}H_{1,0,0} - 3H_{1,0,0,0} - 4H_{1,1,0,0} + 4H_{1,0}\zeta_3 + \\
\frac{11}{12}H_3 + H_4 \right] + p_{qq}(-x) \left[ \frac{67}{18}\zeta_2 - \zeta_2^2 - \frac{11}{4}\zeta_3 - H_{-3,0} + 8H_{-2}\zeta_2 + \frac{11}{6}H_{-2,0} \right. \\
- 3H_{-1,0,0,0} + \frac{11}{3}H_{-1}\zeta_2 + 12H_{-1}\zeta_3 - 16H_{-1,-1}\zeta_2 + 8H_{-1,-1,0,0} + 16H_{-1,-1,2} \\
- 8H_{-2,2} + 11H_{-1,0}\zeta_2 + \frac{11}{6}H_{-1,0,0} - \frac{11}{3}H_{-1,2} - 8H_{-1,3} - \frac{3}{4}H_0 - \frac{1}{6}H_0\zeta_2 - \frac{1}{4}H_0\zeta_3 - \frac{37}{2}H_0\zeta_2 \]
−3H_{0,0}\zeta_2 - \frac{31}{12}H_{0,0,0} + H_{0,0,0,0} + 2H_2\zeta_2 + \frac{11}{6}H_3 + 2H_4 \right) + (1-x) \left[ \frac{1883}{108} - \frac{1}{2} \right]
\left[ -H_{-2,-1,0} + \frac{1}{2}H_{-3,0} - \frac{1}{2}H_{-2}\zeta_2 + \frac{1}{2}H_{-2,0,0} + \frac{523}{36}H_0 + H_0\zeta_3 - \frac{13}{3}H_{0,0} - \frac{5}{2}H_{-2,0,0} - 2H_{1,0,0} \right] + (1+x) \left[ 8H_{-1}\zeta_2 + 4H_{-1,-1,0} + \frac{8}{3}H_{-1,0} - 5H_{-1,0,0} - 6H_{-1,2} - \frac{13}{3} \right]
\left[ -\frac{43}{4}\zeta_3 - \frac{5}{2}H_{-2,0} - \frac{11}{2}H_0\zeta_2 + \frac{1}{2}H_2\zeta_2 - \frac{5}{4}H_{0,0}\zeta_2 + 7H_2 - \frac{1}{4}H_{2,0,0} + 3H_3 + \frac{3}{4} \right]
\left[ \frac{1}{4}\zeta_2^2 - \frac{8}{3}\zeta_2 + \frac{17}{2}\zeta_3 + H_{-2,0} - \frac{19}{2}H_0 + \frac{5}{2}H_0\zeta_2 - H_0\zeta_3 + \frac{13}{3}H_{0,0} + \frac{5}{2}H_{0,0,0} \right]
\left[ -\delta(1-x) \left[ \frac{1657}{576} - \frac{281}{27}\zeta_2 + \frac{18}{2}\zeta_2^2 + \frac{97}{9}\zeta_3 - \frac{5}{2}\zeta_5 \right] \right) + 16C_Fn_f^2 \left( \frac{1}{18}\rho_{qq}(x) \left[ H_{0,0} + \right] \right)
\left( \frac{13}{54} + \frac{1}{9}H_0 \right] - \delta(1-x) \left[ \frac{17}{144} - \frac{5}{27}\zeta_2 + \frac{1}{9}\zeta_3 \right) \right] + 16C_F^2n_f \left( \frac{1}{3}\rho_{qq}(x) \left[ + \right]
\left( \frac{13}{54} + \frac{1}{9}H_0 \right] - \delta(1-x) \left[ \frac{17}{144} - \frac{5}{27}\zeta_2 + \frac{1}{9}\zeta_3 \right) \right] + 16C_F^2n_f \left( \frac{1}{3}\rho_{qq}(x) \left[ + \right]
$$\begin{align*}
&\frac{-55}{16} + \frac{5}{8} H_0 + H_0 \zeta_2 + \frac{3}{2} H_{0,0} - H_{0,0,0} - \frac{10}{3} H_{1,0} - \frac{10}{3} H_2 - 2H_{2,0} - 2H_3 \right) + \frac{2}{3} \\
&\frac{-3}{2} \zeta_3 + H_{-2,0} + 2H_{-1} \zeta_2 + \frac{10}{3} H_{-1,0} + H_{-1,0,0} - 2H_{-1,2} - \frac{1}{2} H_0 \zeta_2 - \frac{5}{3} H_{0,0} - \\
&-(1-x) \left[ \frac{10}{9} + \frac{19}{18} H_{0,0} - \frac{4}{3} H_1 + \frac{2}{3} H_{1,0} + \frac{4}{3} H_2 \right] + (1+x) \left[ \frac{4}{3} H_{-1,0} - \frac{25}{24} H_0 + \\
&+\frac{7}{9} H_{0,0} + \frac{4}{3} H_2 - \delta(1-x) \left[ \frac{23}{16} - \frac{5}{12} \zeta_3 - \frac{29}{30} \zeta_2^2 + \frac{17}{6} \zeta_3 \right] \right) + 16 C_F^3 \left( p_{qq}(x) \left[ \\
&+6H_{-2} \zeta_2 + 12H_{-2,-1,0} - 6H_{-2,0,0} - \frac{3}{16} H_0 - \frac{3}{2} H_0 \zeta_2 + H_0 \zeta_3 + \frac{13}{8} H_{0,0} - 2H_0 \\
&+12H_{1} \zeta_3 + 8H_{1,-2,0} - 6H_{1,0,0} - 4H_{1,0,0,0} + 4H_{1,2,0} - 3H_2,0 + 2H_{2,0,0} + 4H_{2,1} \\
&+4H_{3,0} + 4H_{3,1} + 2H_4 \right] + p_{qq}(-x) \left[ \frac{7}{2} \zeta_2^2 - \frac{9}{2} \zeta_3 - 6H_{-3,0} + 32H_{-2} \zeta_2 + 8H_{-2} \\
&-26H_{-2,0,0} - 28H_{-2,2} + 6H_{-1} \zeta_2 + 36H_{-1} \zeta_3 + 8H_{-1,-2,0} - 48H_{-1,-1} \zeta_2 + 40 \right] \right] \right).
\end{align*}$$
2 × 2 anomalous dimension matrix occupies

1st loop: 1/10 page
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3rd loop: 100 pages (200 K asci)

Moch, Vermaseren and Vogt

[ waterfall of results launched
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$$V \sim \begin{cases} 10^{\frac{N(N-1)}{2}} - 1 \\ 10^{2^{N-1}} - 2 \end{cases}$$
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\end{array} \right. \]

not too encouraging a trend …
How to reduce complexity?
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**Guidelines**

- Higher Orders
- Innovative Bookkeeping
- Think
- Extract
- Solve
How to reduce complexity?

**Guidelines**

- ✓ exploit internal properties:
  - Drell–Levy–Yan relation
  - Gribov–Lipatov reciprocity

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**Solve**
High order QCD Dynamics made simple?

Fighting complexity

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Higher Orders

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- Inheritance idea

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An essential part of gluon dynamics is Classical.

(F.Low)
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→ A playing ground for theoretical theory: SUSY, AdS/CFT, ...
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.
In the new approach,

- Splitting functions are disconnected from the anomalous dimensions;
- The evolution kernel is identical for space- and time-like cascades (Gribov–Lipatov reciprocity relation true in all orders);
- Unique evolution variable — parton fluctuation time.

\textit{time ordering}
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The origin of the GL reciprocity violation is essentially kinematical: inherited from previous loops!
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Hypothesis of the new RR evolution kernel $\mathcal{P}$

D-r, Marchesini & Salam (2005)

was verified at 3 loops for the nonsinglet channel, $(\gamma^{(T)} - \gamma^{(S)}) = OK$

Mitov, Moch & Vogt (2006)
Reducing complexity

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In the moment space, the GL symmetry, $x \rightarrow 1/x \Leftrightarrow N \rightarrow -(N + 1)$, translates into dependence on the conformal Casimir $J^2 = N(N + 1)$.

By means of the large $N$ expansion,

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- 2loop quark transversity
- 2loop linearly polarized gluon
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Extra QCD checks:

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Also true for SUSYs,

- in 4 loops in $\lambda \phi^4$,
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- AdS/CFT ($\mathcal{N} = 4$ SYM $\alpha \gg 1$)
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Moreover, the most resent result: in $\mathcal{N} = 4$, GLR holds for twist 3, in $3 + 4$ loops \cite{Matteo Beccaria et. al (2007)}.
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What is so special about $\mathcal{N} = 4$ SYM?
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What is so special about $\mathcal{N}=4$ SYM ?

This QFT has a good chance to be solvable — “integrable”. Dynamics can be fully integrated if the system possesses a sufficient (infinite!) number of conservation laws, — integrals of motion.
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Recall an old hint from QCD ...
Relating parton splittings

\[ z \]

\[ 1 - z \]

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

\[ z \]

\[ = T_R \cdot [z^2 + (1 - z)^2] \]

\[ z \]

\[ = C_F \cdot \frac{1 + (1 - z)^2}{z} \]

\[ z \]

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

Four “parton splitting functions”

\[ q[g](z), \quad g[q](z), \quad q[\bar{q}](z), \quad g[g](z) \]
Relating parton splittings

\[ z(1-z) = C_F \cdot \frac{1 + z^2}{1 - z} \]

\[ z = T_R \cdot [z^2 + (1-z)^2] \]

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

- Exchange the decay products: \( z \rightarrow 1 - z \)
Relating parton splittings

\[
\begin{align*}
\frac{1 - z}{z} &= C_F \cdot \frac{1 + z^2}{1 - z} \\
\frac{z}{1 - z} &= C_F \cdot \frac{1 + (1 - z)^2}{z} \\
\frac{z^2}{1 - z} &= T_R \cdot \left[ z^2 + (1 - z)^2 \right] \\
\frac{1 + z^4 + (1 - z)^4}{z(1 - z)} &= N_c \cdot 
\end{align*}
\]

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- Exchange the parent and the offspring: \( z \rightarrow \frac{1}{z} \) (GLR)
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- Exchange the decay products: \( z \rightarrow 1 - z \)
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Three (QED) “kernels” are inter-related; gluon self-interaction stays put:

- \( q[g](Z) \)
- \( g[q](Z) \)
- \( q[\bar{q}](Z) \)
- \( g[g](Z) \)
Relating parton splittings

\[
\begin{align*}
\frac{1}{1-z} &= C_F \cdot \frac{1 + z^2}{1 - z}, \\
\frac{z}{1-z} &= C_F \cdot \frac{1 + (1-z)^2}{z}, \\
\frac{z}{z} &= T_R \cdot \left[ z^2 + (1-z)^2 \right], \\
\frac{z}{z} &= N_c \cdot \frac{1 + z^4 + (1-z)^4}{z(1-z)}.
\end{align*}
\]

- Exchange the decay products: \( z \to 1 - z \)
- Exchange the parent and the offspring: \( z \to 1/z \) (GLR)
- The story continues, however:

All four are related!

\[
w_q(z) = \begin{array}{c}
q[g]_q(z) + g[q]_q(z) = q[\bar{q}]_g(z) + g[g]_g(z)
\end{array} = w_g(z)
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\[ z \rightarrow 1 - z \]

\[ z \rightarrow \frac{1}{z} \quad \text{(GLR)} \]

The story continues, however:

\[ C_F = T_R = N_c : \text{Super-Symmetry} \]

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\[ \equiv \text{infinite number of conservation laws} ! \]

\[ w_q(z) = \frac{q[g](z)}{q} + \frac{g[q](z)}{q} = \frac{q[\bar{q}](z)}{g} + \frac{g[g](z)}{g} = w_g(z) \]
The integrability feature manifests itself already in certain sectors of QCD, in specific problems where one can identify QCD with SUSY-QCD:

✓ the Regge behaviour (large $N_c$)  
Lipatov  
Faddeev & Korchemsky (1994)

✓ baryon wave function  
Braun, Derkachov, Korchemsky, Manashov; Belitsky (1999)

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The higher the symmetry, the deeper integrability.
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The higher the symmetry, the deeper integrability. $\mathcal{N} = 4$ — the extreme:

- ✗ Conformal theory $\beta(\alpha) \equiv 0$
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- ✗ All order expansion for $\alpha_{\text{phys}}$

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**WHY and WHAT FOR?**
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And here we arrive at the second — Divide and Conquer — issue
Recall the diagonal first loop anomalous dimensions:

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

\[
\tilde{\gamma}_{g \rightarrow g(x)+g} = \frac{C_A \alpha_s}{\pi} \left[ \frac{x}{1-x} + (1-x) \cdot (x + x^{-1}) \right].
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Classical and quantum contributions respect the GL relation, individually:

\[-xf(1/x) = f(x)\]
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Let us look at the rôles these animals play on the QCD stage
Clagons:

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

Quagons:

- Quantum d.o.f.s (constituents)
- infrared irrelevant, $d\omega \cdot \omega$
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- responsible for conservation of
  - $P$-parity,
  - $C$-parity,
  - colour
- minor rôle
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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; everyone in the adjoint representation.
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\[
\frac{d}{d \ln \mu^2} \left( \frac{\alpha(\mu^2)}{4\pi} \right)^{-1}_{QCD} = -\frac{11}{3} \cdot C_A + n_f \cdot T_R \cdot \int_0^1 dx \ [x^2 + (1 - x)^2]
\]
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Matter content = 4 Majorana fermions, 6 scalars;
everyone in the **adjoint** representation.

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\frac{d}{d \ln \mu^2} \left( \frac{\alpha(\mu^2)}{4\pi} \right)^{-1}_{\text{QCD}} = -\frac{11}{3} \cdot C_A + n_f \cdot T_R \cdot \int_0^1 dx \, 2 \left[ x^2 + (1-x)^2 \right]
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Now, \( \mathcal{N}=4 \) SUSY :

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\( \beta(\alpha) \equiv 0 \) in all orders !  \( \implies \)  \( \gamma \Rightarrow \frac{x}{1-x} \) + no quagons !

\( \ldots \) makes one think of a \textit{classical nature} (!!!) of the SYM-4 dynamics
$\mathcal{N} = 4$ SYM has already demonstrated viability of the *inheritance* idea.
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\[
\text{clever 2nd loop} < 2\% \quad \text{(Heavy quark fragmentation)} \\
\text{clever 1st loop} \quad \text{(D-r, Khoze & Troyan, PRD 1996)}
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Employ $\mathcal{N}=4$ SYM to simplify the major part of the QCD dynamics!
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)
- reduces complexity by (at least) an order of magnitude
- improves perturbative series (less singular, better “convergent”)
- links interesting phenomena in the DIS and $e^+e^-$ annihilation channels

The Low theorem should be part of theor.phys. curriculum, worldwide

Complete solution of the $\mathcal{N}=4$ SYM QFT should provide us with a one-line-all-orders description of the major part of QCD dynamics.
to conclude

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What is phenomenology?

**Google:**
Phenomenologists tend to oppose the acceptance of unobservable matters and grand systems erected in speculative thinking;

[Center for advanced research in phenomenology]

**Wikipedia:**
Phenomenology is a current in philosophy that takes intuitive experience of phenomena (what presents itself to us in conscious experience) as its starting point and tries to extract the essential features of experiences and the essence of what we experience.

[early 20th century philosophers: Husserl, Merleau-Ponty, Heidegger]
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- strong colour fields at small coupling! CGC, LPM, ...
A New Interesting Phenomenon in the Medium ...
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