Как продираться сквозь ядро/КГП. Пол-ответа

Yuri Dokshitzer

&

Воробьёвский Семинар

27.01.2022

plan

Medium induced gluon radiation

Jet Quenching

+ ***Hadroproduction in collisions of/with Heavy Ions***

with a stress on the physics of colour

the collisions/participants dilemma and "colour capacity"

"baryon stopping"

confinement in HI environment

Historically, the nucleus has always been a primary source of inspiration for High Energy Particle (HEP) physics.

Gribov's paper "*Interaction of photons and electrons with nuclei at high energies*" laid a cornerstone for the concept of partons.

Rigorous applications of QCD to scattering in media are scarce, in the first place because of the complexity of the problems involved.

Diffractive phenomena in hadron-nucleus scattering, and inelastic diffraction in particular, make a nucleus serve as a *probe* of the internal structure of a hadron–projectile.

The *Landau-Pomeranchuk-Migdal* effect is an example of such an application which addresses the issue of QCD processes in media "from the first principles" (if such a notion can be applied to QCD in its present state).

nucleus as "hardener"

It is becoming more and more clear that ***small distances*** naturally emerge in the ***multiple scattering environment***.

Treating phenomena that look a priori soft, such as

inelastic diffraction off nuclei,

medium ***induced radiation*** of gluons,

physics gathered under the ***Colour Glass Condensate*** banner

one observes that the characteristic hardness scale grows invariably as $Q^2 \sim A^{1/3}$

A priori soft minimum bias hadron interaction processes become "hard"*ish*

Example of such "hardening" -

medium induced gluon radiation, the LPM effect,
jet broadening and jet quenching

В аннотации я уже побрюзжал на предмет ***потерь энергии***.

Энергия не кошелёк, её нельзя потерять. Ею можно только поделиться: на соударения (***collisional losses***), либо на сопровождающее излучение (***radiative losses***). Поговорим про второй сюжет. Поэтому - *пол-ответа*.

Перед тем как приступить к делу, ещё одна брюзжалка - про

средние величины vs. ***типичные/характерные.***

Что можно гасить?

свет, известь, конкурента,... Говорят, можно гасить и струи.

О КХД-струях в среде, про "**jet quenching**" и пр., говорят и пишут в терминах ***средних потерь энергии***, ***среднего*** (добавленного) ***поперечного импульса*** и т.п.

В этой связи нелишне будет напомнить про

Deceiving *"means"*

mean energy loss

mean squared transverse momentum, etc

St. Petersburg paradox (D. Bernoulli)

(1738, Commentarii Academiae Scientiarum Imperialis Petropolitanae)

Toss a coin. 1 head=$2; 2 successive heads=$4,.. 3 heads=$8, etc
tail = game over

Average win: $\frac{1}{2}\left(\frac{1}{2}\cdot\$2+\frac{1}{4}\cdot\$4+\ldots\right)=\$\cdot\infty$ **(??)**

Mathematically correct. **Physically - irrelevant!**

"*after 29 rounds...not enough money in the Kingdom of France*"

playing against a Banker with *limited resources*:

Banker	Bankroll	Game value
Millionaire	$1,050,000	$20
Jeff Bezos (Jan. 2021)	$179,000,000,000	$37
World GDP (2020)	$83.8 trillion	$46

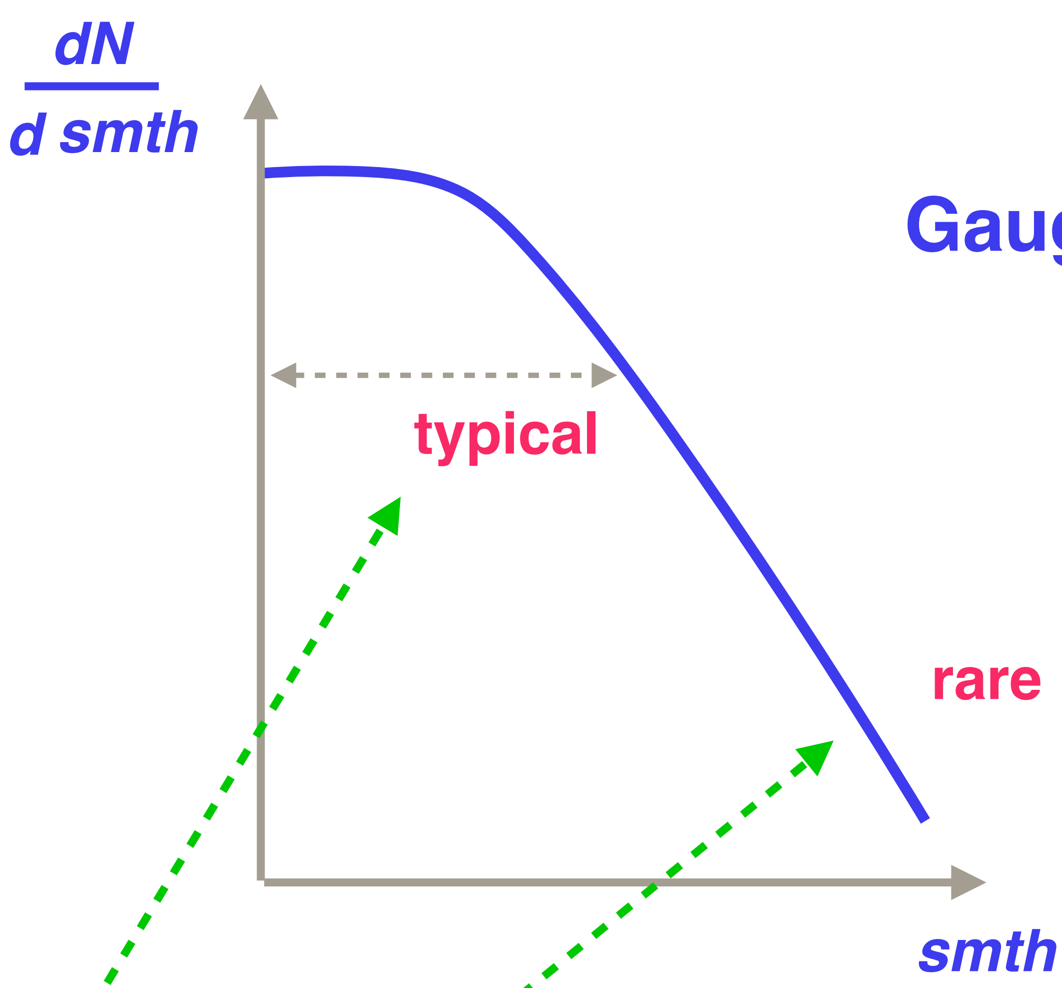
Similar deceptions often show up in HEP!

QCD is about *radiation*

Dimensionless coupling (renormalizable dynamics)

$$dw \propto \frac{dk_\perp^2}{k_\perp^2}, \quad k_\perp^2 \ll Q^2$$

q *and* ***g*** *transverse momenta*



Gauge symmetry (vector gluon field)

$$dw \propto \frac{d\omega}{\omega}, \quad \omega \ll E$$

g*luon energy*

Broad distributions of everything

Here is *essential Physics* while

it is here the *Means* are usually sitting!

Speedy Recall

of the basics

# of induced radiation physics

Landau-Pomeranchuk-Migdal effect is about radiation induced by multiple scattering of a charged particle traversing the medium.

In 1953 Landau and Pomeranchuk noticed that the energy spectrum of photons caused by multiple scattering of a relativistic charge is essentially different from the Bethe-Heitler pattern.

Symbolically, the photon radiation intensity per unit length reads

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

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

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

The LPM spectrum should be compared with the Bethe-Heitler formula — independent photon emission at each successive scattering act. $\omega \frac{dI}{d\omega\, dz} \propto \frac{\alpha}{\lambda}$

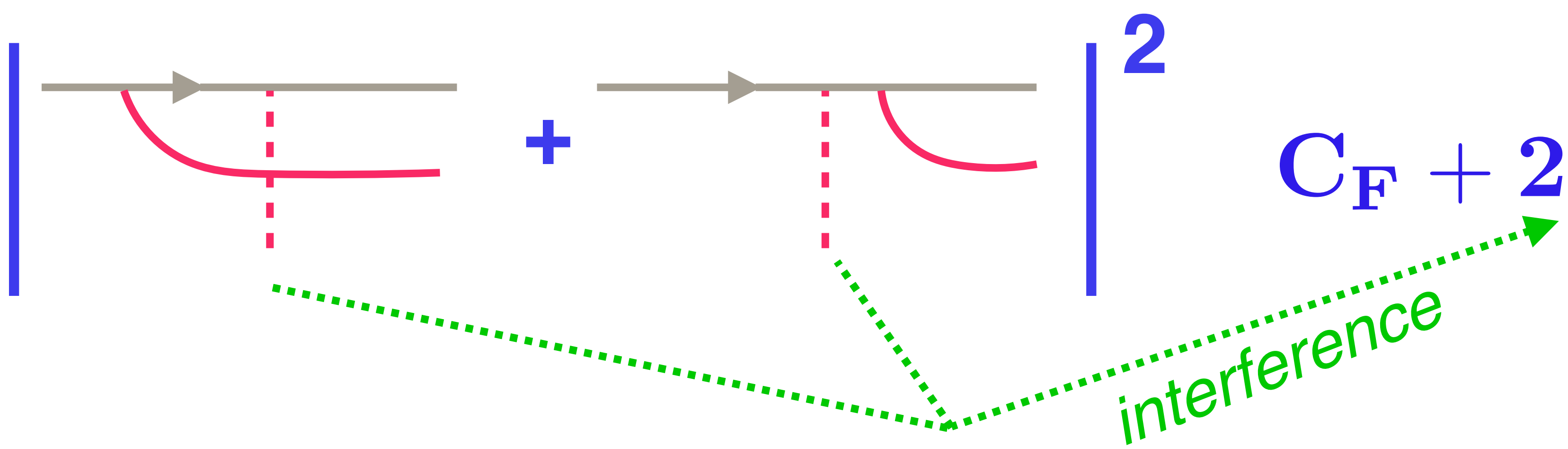
Contrary to B-H, the LPM spectrum is free from an “infrared catastrophe”: small photon frequencies are suppressed, so that the energy distribution is proportional to $d\omega/\sqrt{\omega}$

Integrating over photon energy one deduces the radiative energy loss per unit length :

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

LPM in QCD

Я вляпался в эту задачку в начале 90-тых. Случайно, увидев как мои коллеги-приятели Dominique Schiff (Orsay) & Rolf Baier (Bielefeld) штудируют препринт Guylasy & Wong. В нём утверждалось, что никакого ЛПМ эффекта в КХД нет, так как глюонные интерференции отсутствуют. Точнее, подавлены по цвету как $1/N_c^2$.



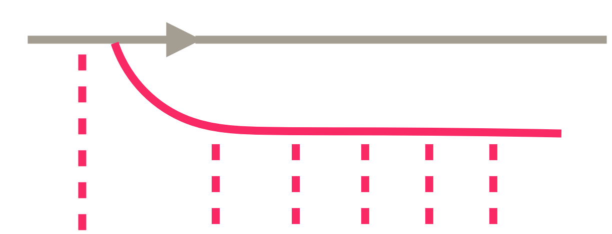
$$\mathbf{C_F} + \mathbf{2}\cdot\left(-\frac{\mathbf{1}}{\mathbf{2N_c}}\right) + \mathbf{C_F}$$

$$\mathbf{C_F} = \frac{\mathbf{N_c^2 - 1}}{\mathbf{2N_c}}$$

Было ясно, что это неправда. Потому что. Неясно было только, почему...

В приложении к картинке многократного рассеяния дело выглядело так, как будто кварк, однажды испустив глюон, отказывался наотрез взаимодействовать со средой. Как будто лишился своего цвета.

В некотором смысле это правда: свою "***цветовую силу***" кварк теряет. Только она не испаряется, а передаётся излучённому им **глюону**.



Собака зарылась в многократном перерассеянии средой глюона, который ещё не излучился, а только собирается "выйти в волновую зону"!

Справедливость восторжествовала.

ЛПМ-эффект вернулся.   Только встав с ног на голову...

Вместо ЛПМ-подавления мягких фотонов, $\omega\, dn^{\gamma}/d\omega \propto \sqrt{\omega}$

когерентность КХД-излучения привела, наоборот, к его ***усилению:***

$$\omega \frac{dn^{\rm glue}}{d\omega} \propto \frac{1}{\sqrt{\omega}}$$

Потом было много чего:

"Великий и ужасный" Al Mueller (Columbia Univ.) стал проверять наш результат, так как не мог поверить, что это может быть правдой.

Убедившись, присоединился к команде. В результате, случилось: исправление ашипок, обобщение на конечный размер мишени, связь с "уширением струй" с среде (*jet broadening*). Усилиями R. Baier'a результаты приложились к простым моделям расширяющейся среды (в мыслях о КГП).

К тем же результатам про индуцированное излучение глюонов пришёл Бронислав (Слава) Захаров, применивший элегантный метод, основанный на функциональном интеграле.

Последним (для меня) штрихом эпопей случился "*jet quenching*".

Математика всего этого весьма зубодробительная, но ответ, как это часто бывает с хорошей физикой, можно убедительно объяснить на пальцах.

LPM на пальцах

Inclusive spectrum of medium-induced gluon radiation:

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

$N_{coh.} > 1$ 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:

$$k_\perp^2 \simeq N_{coh.} \cdot \mu^2 \,, \qquad N_{coh.} \simeq \frac{\ell_{coh.}}{\lambda} \simeq \frac{1}{\lambda} \cdot \frac{\omega}{k_\perp^2}.$$

Combining the two estimates results in

$$N_{coh.} \simeq \sqrt{\frac{\omega}{\mu^2\lambda}} \quad \text{and} \quad k_\perp^2 \simeq \sqrt{\frac{\mu^2}{\lambda} \cdot \omega}\,.$$

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

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

total coherence:
1 B-H per brick

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

$$\hat{q} = \frac{\mu^2}{\lambda} = \rho \int^{[B^{-2}]} dQ^2\, Q^2 \frac{d\sigma}{dQ^2}, \qquad \mu^2 \ll Q^2 \ll B^{-2} = \mu^2 \frac{L}{\lambda}$$

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:

$$\hat{q}_{\mathrm{HOT}} \sim 10 \text{—} 30\, \hat{q}_{\mathrm{COLD}}$$

$$\hat{q}^{(R)} = \rho \int dq^2\, q^2\, \frac{d\sigma^{(R)}}{dq^2} \, .$$

Here ρ is the density of scattering centres, and $d\sigma^{(R)}$ is the single scattering cross section for a projectile parton in the colour representation R, with C_R the corresponding colour factor ($C_F = (N_c^2 - 1)/2N_c = 4/3$, $C_A = N_c = 3$ for quark and gluon, respectively).

In "cold" nuclear matter $\hat{q}$ can be calculated perturbatively and related to the gluon density $[xG(x, Q^2)]$ of the nucleus at a low momentum scale $Q^2 \simeq \hat{q}\, L$ and small but not too small x,

$$\hat{q}_{\rm cold} \;\simeq\; 0.009\,{\rm GeV}^3 \;\simeq\; 0.045\,\frac{{\rm GeV}^2}{\rm fm}$$

In the case of heavy ion collisions, the scattered hard parton traverses a medium that is expected to have an energy density much higher than that of nuclear matter, and the corresponding transport coefficient $\hat{q}_{\rm hot}$ can be much larger. If hot matter is formed in the final state, a perturbative estimate for the QGP with $T = 250$ MeV gives [11]

$$\hat{q}_{\rm hot} \;\simeq\; 0.2\,{\rm GeV}^3 \;\simeq\; 1\,\frac{{\rm GeV}^2}{\rm fm}.$$

Imagine a target hit by a relativistic projectile :

a fast nucleon

or a he-e-e-eavy ion

To be able to state that ***new physics*** manifests itself we better understand what would have to be expected if the physics were "***old***" ?

A difficult question is that of the ***scaling :***

Collisions or Participants ?

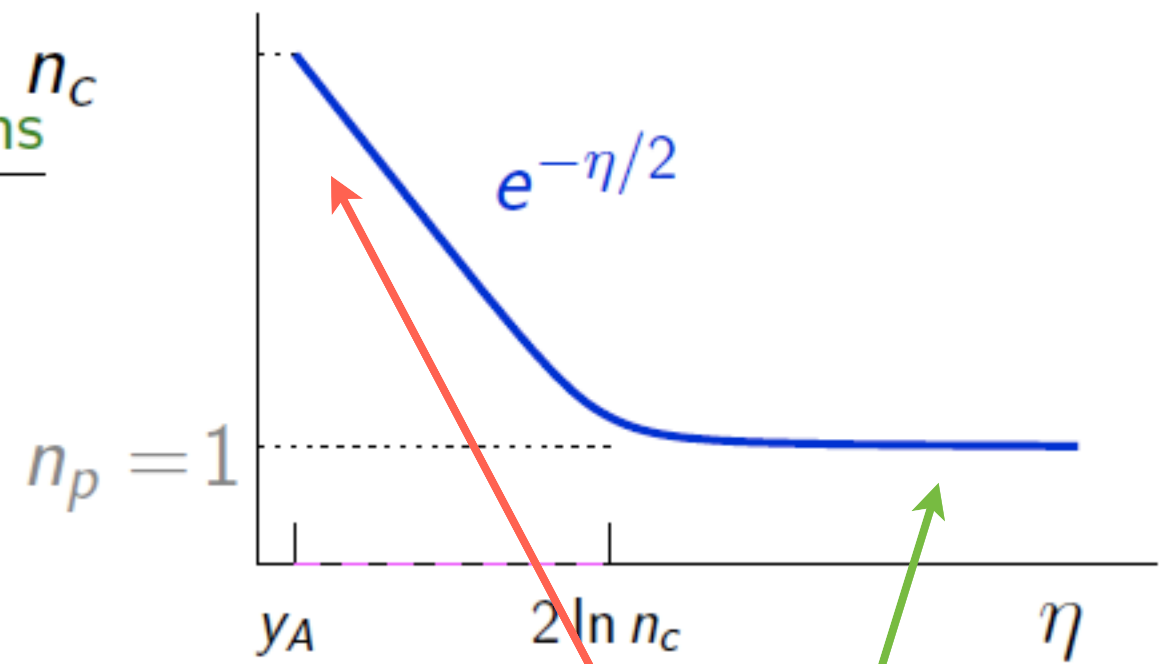
Hard interactions are commonly expected to scale as **nc**, ***soft*** — as **np**.

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

Recall

$$k_\perp^2 \simeq \sqrt{\frac{\mu^2}{\lambda} \cdot \omega}$$

Rapidity distribution of LPM gluons



Here comes confusing part ...

radiation corresponding to ***larger hardness scales*** follows the ***participant scaling***

while the ***less hard*** radiation (smaller k_t and energies) obeys the ***collisional scaling*** pattern

... in a striking contradiction with the general qualitative expectations !

Quenching

Quenching of hadron spectra in media

R. Baier
Fakultät für Physik, Universität Bielefeld,
D-33501 Bielefeld, Germany
Yu.L. Dokshitzer[1]
LPTHE, Université Pierre et Marie Curie (Paris VI),
4, Place Jussieu, 75252 Paris, France
A.H. Mueller[2,3]
D. Schiff
LPT, Université Paris-Sud, Bâtiment 211,
F-91405 Orsay, France

arXiv:hep-ph/0106347v1

$$\frac{d\sigma^{\text{medium}}(p_\perp)}{dp_\perp^2} \simeq \frac{d\sigma^{\text{vacuum}}(p_\perp + S(p_\perp))}{dp_\perp^2}$$

$$S(p_\perp) \simeq \sqrt{\frac{2\pi\,\alpha^2\,\omega_c p_\perp}{n}}\,.$$

$$\omega_c = \frac{\hat{q}}{2}L^2$$

To find the inclusive particle spectrum, one has to convolute the production cross section of the parton with energy $p_\perp + \epsilon$ with the distribution $D(\epsilon)$ in the parton energy loss ϵ

$$\frac{d\sigma^{\text{medium}}(p_\perp)}{dp_\perp^2} = \int d\epsilon\, D(\epsilon)\, \frac{d\sigma^{\text{vacuum}}(p_\perp + \epsilon)}{dp_\perp^2}$$

The quenching effect is customarily modelled by the substitution

$$\frac{d\sigma^{\text{medium}}(p_\perp)}{dp_\perp^2} = \frac{d\sigma^{\text{vacuum}}(p_\perp + S)}{dp_\perp^2}.$$

The *shift* parameter S is usually taken equal to the *mean* medium induced energy loss

$$S = \Delta E \equiv \int d\epsilon\, \epsilon\, D(\epsilon) \propto \alpha_s L^2 .$$

emerges as a result of the Taylor expansion based on the $\epsilon \ll p_\perp$ approximation:

$$\int d\epsilon\, D(\epsilon) \cdot \frac{d\sigma(p_\perp + \epsilon)}{dp_\perp^2} = \int d\epsilon\, D(\epsilon) \cdot \frac{d\sigma(p_\perp)}{dp_\perp^2} + \int d\epsilon\, \epsilon\, D(\epsilon) \cdot \frac{d}{dp_\perp} \frac{d\sigma(p_\perp)}{dp_\perp^2} + \dots$$

$$\simeq \frac{d\sigma}{dp_\perp^2} + \Delta E \cdot \frac{d}{dp_\perp}\left(\frac{d\sigma}{dp_\perp^2}\right) \simeq \frac{d\sigma(p_\perp + \Delta E)}{dp_\perp^2}.$$

Such an approximation misses, however, one essential point, namely that the vacuum distribution is a sharply falling function of $p_\perp$. This causes a strong bias which leads to an additional suppression of real gluon radiation. As a result, the *typical* energy carried by accompanying gluons turns out to be much smaller than the *mean*

In reality, the high-pt spectrum ***falls much faster*** than canonical . For many reasons:

$$\frac{d\sigma}{dp_\perp^2} \propto \quad \alpha_s^2(p_\perp^2)\,\frac{1}{p_\perp^4}\left[D\left(x = \frac{2p_\perp}{\sqrt{s}}; \ln p_\perp^2\right)\right]^2 \left(1 + c\,\exp\left\{-\frac{p_\perp^2}{\mu^2}\right\}\right)_{\text{Cronin}}$$

② ③ ② ①

$$\left[\bar{D}(x_F \to 1; \ln p_\perp^2)\right]$$

Final state **pt**-dependent form factor suppression to be added.

Depends on *what is measured :* a **single particle** or a **jet**. - ***How defined*** ?

Actually,
$$\frac{d\sigma^{\text{vacuum}}(p_\perp)}{dp_\perp^2} \propto \frac{1}{p_\perp^n}, \qquad n = n(p_\perp) \equiv -\frac{d}{d\ln p_\perp}\ln\frac{d\sigma^{\text{vacuum}}(p_\perp)}{dp_\perp^2}$$

$$n \simeq 10$$

$$\frac{d\sigma^{\text{vacuum}}(p_\perp)}{dp_\perp^2} = \text{const}\cdot(1.71 + p_\perp\,[\text{GeV}])^{-12.44}$$

PHENIX

Steepness of the **Vacuum** spectrum biases **Medium**-Induced radiation in

$$\frac{d\sigma^{\text{medium}}(p_\perp)}{dp_\perp^2} = \int d\epsilon\, D(\epsilon)\,\frac{d\sigma^{\text{vacuum}}(p_\perp+\epsilon)}{dp_\perp^2}$$

characteristic gluon frequency $\omega_c = \frac{\hat{q}}{2} L^2$

the inclusive energy spectrum of medium induced soft gluon radiation ($\omega \ll p_\perp$)

$$\frac{dI(\omega)}{d\omega} = \frac{\alpha}{\omega} \ln \left| \cos\left[(1+i)\sqrt{\frac{\omega_c}{2\omega}}\right]\right| = \frac{\alpha}{2\omega} \ln\left[\cosh^2\sqrt{\frac{\omega_c}{2\omega}} - \sin^2\sqrt{\frac{\omega_c}{2\omega}}\right]; \qquad \alpha \equiv \frac{2\alpha_s C_R}{\pi}.$$

This distribution peaks at small gluon energies,

$$\omega \frac{dI(\omega)}{d\omega} = \alpha \left\{\sqrt{\frac{\omega_c}{2\omega}} - \ln 2\right\} \cdot \left[1 + \mathcal{O}\left(\exp\left\{-\sqrt{\frac{2\omega_c}{\omega}}\right\}\right)\right], \qquad \omega < \omega_c\,,$$

while for energies above the characteristic scale it is small and falling fast with ω:

$$\omega \frac{dI(\omega)}{d\omega} \simeq \frac{\alpha}{12}\left(\frac{\omega_c}{\omega}\right)^2, \qquad \omega > \omega_c\,.$$

Derivation of parton energy loss distribution is straightforward. Qualitatively,

$$\epsilon D(\epsilon) \simeq \alpha \sqrt{\frac{\omega_c}{2\epsilon}} \exp\left\{-\frac{\pi\alpha^2\omega_c}{2\epsilon}\right\}$$

Fixing aggregate energy is taken care of by Mellin trick:

$$D(\epsilon) = \int_C \frac{d\nu}{2\pi i}\, \tilde{D}(\nu)\, e^{\nu\epsilon},$$
$$\tilde{D}(\nu) = \exp\left[-\int_0^\infty d\omega\, \frac{dI(\omega)}{d\omega}\left(1-e^{-\nu\omega}\right)\right].$$

Integrating by parts, an elegant formula emerges involving multiplicity of gluons with energy larger than a given ω:

$$\tilde{D}(\nu) = \exp\left[-\nu\int_0^\infty d\omega\, e^{-\nu\omega}\, N(\omega)\right] = \exp\left[-\int_0^\infty dz\, e^{-z}\, N\left(\frac{z}{\nu}\right)\right].$$

Approximating

$$\frac{d\sigma^{\text{vacuum}}(p_\perp+\epsilon)/dp_\perp^2}{d\sigma^{\text{vacuum}}(p_\perp)/dp_\perp^2} \simeq \left(\frac{p_\perp}{p_\perp+\epsilon}\right)^n \simeq \exp\left(-\frac{n\epsilon}{p_\perp}\right)$$

the convolution yields

$$Q(p_\perp) = \int d\epsilon\, D(\epsilon)\cdot\left(\frac{d\sigma^{\text{vacuum}}(p_\perp+\epsilon)/dp_\perp^2}{d\sigma^{\text{vacuum}}(p_\perp)/dp_\perp^2}\right)$$
$$= \tilde{D}\left(\frac{n}{p_\perp}\right) = \exp\left\{-\int_0^\infty dz\, e^{-z}\, N\left(\frac{p_\perp}{n}z\right)\right\}$$

In the essential integration region $\omega \sim 1/\nu \sim p_\perp/n \ll \omega_c,$

soft approximation applies, and

$$\tilde{D}(\nu) \simeq \exp\left\{-\alpha\left(\sqrt{2\pi\nu\omega_c} - \ln 2 \ln(\nu\omega_c) - 1.84146\right)\right\}$$

Representing the quenching factor as

$$Q(p_\perp) = \tilde{D}\left(\frac{n}{p_\perp}\right) = \exp\left\{-\frac{n}{p_\perp}\cdot S(p_\perp)\right\}$$

$$S(p_\perp) \simeq \sqrt{\frac{2\pi\,\alpha^2\,\omega_c p_\perp}{n}}.$$

A more accurate expression for multiplicity of medium induced gluons, including hard gluon corrections,

$$N(\omega) \simeq \alpha\left\{\sqrt{\frac{2\omega_c}{p_\perp}}\left[\frac{1}{\sqrt{x}} - 2 + \sqrt{x}\right] + \ln 2\left[\ln x + 1 - x\right]\right\}, \qquad x = \frac{\omega}{p_\perp}.$$

And for the shift function, correspondingly,

$$S(p_\perp) = p_\perp \int_0^1 dx\, N(x\,p_\perp)\, e^{-nx}$$

$$\approx \alpha\omega_c\cdot\left\{\sqrt{2\pi\frac{p_\perp}{n\,\omega_c}}\left(1 - \frac{2}{\sqrt{\pi\,n}} + \frac{1}{2n}\right) - \frac{p_\perp}{n\,\omega_c}\ln 2\left[\ln n + \gamma_E - 1 + \frac{1}{n}\right]\right\}$$

mean and typical

Mean energy loss

$$\Delta E \propto \alpha_s \sqrt{\omega_c \, \omega_{\max}} \,, \qquad \omega_{\max} = \min\{\, \omega_c \,,\; E \,\}$$

can be applied as shift only for very large transverse momenta, $p_\perp \gtrsim n\omega_c$, where quenching itself is vanishingly weak:

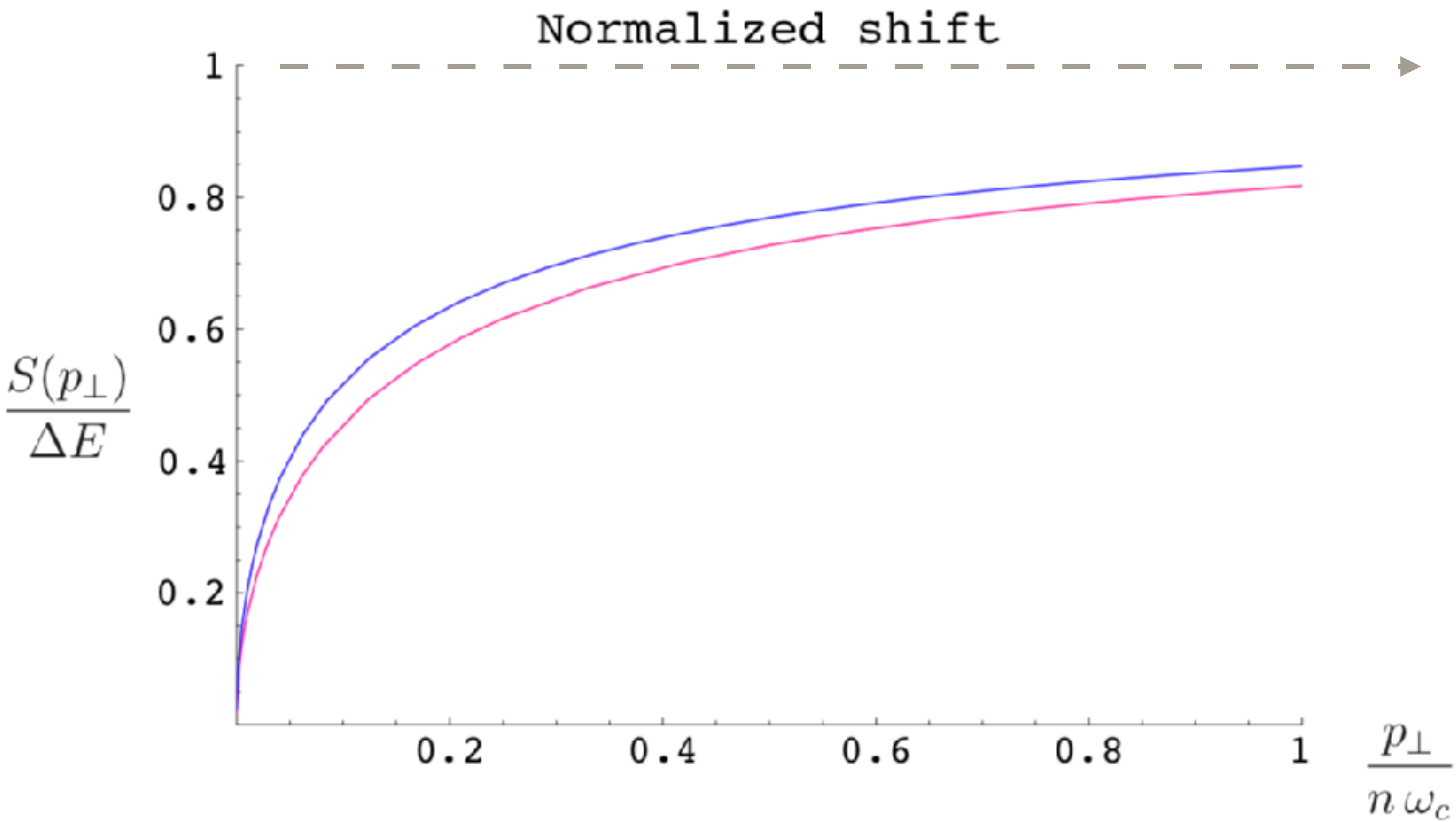
$$-\ln Q(p_\perp) = \frac{n}{p_\perp} \cdot \Delta E \;\propto\; \alpha_s \cdot \frac{n\omega_c}{p_\perp} < \alpha_s \,.$$

Instead, typical values of aggregate gluon energy that dominates the answer are

$$\langle \epsilon \rangle \;\simeq\; \sqrt{\frac{\pi \alpha^2 \omega_c \, p_\perp}{2\, n}} \qquad \text{for} \qquad p_\perp < \frac{\pi}{2} \alpha^2 \, n \, \omega_c \,,$$

$$\langle \epsilon \rangle \;\simeq\; \frac{p_\perp}{n} \qquad \text{for} \qquad p_\perp > \frac{\pi}{2} \alpha^2 \, n \, \omega_c \,,$$

Shift normalized by BDMPS energy loss $\Delta E = \frac{\pi}{4} \alpha \omega_c$



Shift $S(p_\perp)$ as a function of $X \equiv \frac{p_\perp}{n\omega_c}$ for $n = 4$ (lower curve) and $n = 10$ (upper curve)

Expression for Shift is formally Infrared Safe (integrals converge).

$$S(p_\perp) = \int_0^\infty d\omega\, N(\omega)\, \exp\left\{-\frac{n\,\omega}{p_\perp}\right\}$$

However, the answer remains *very sensitive* to small momenta (confinement region)

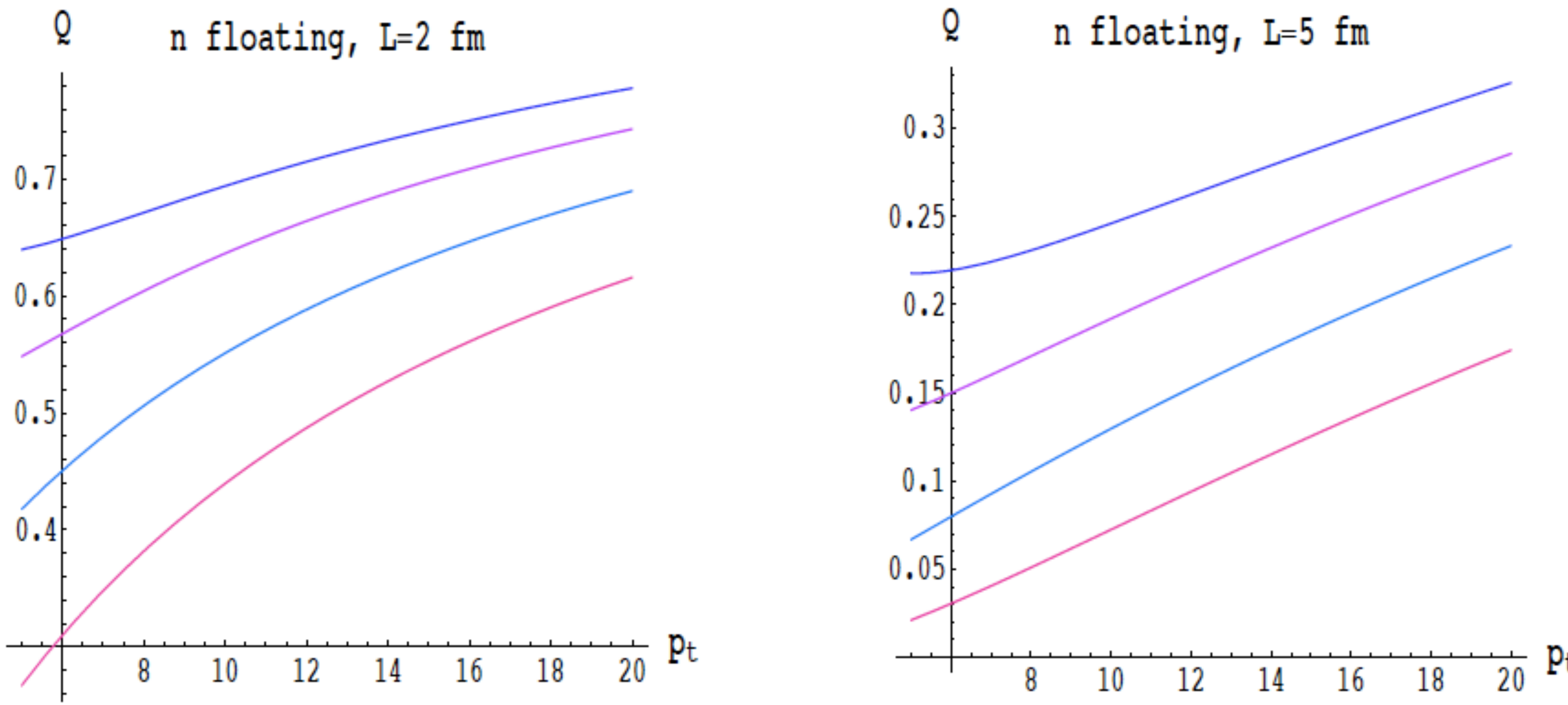
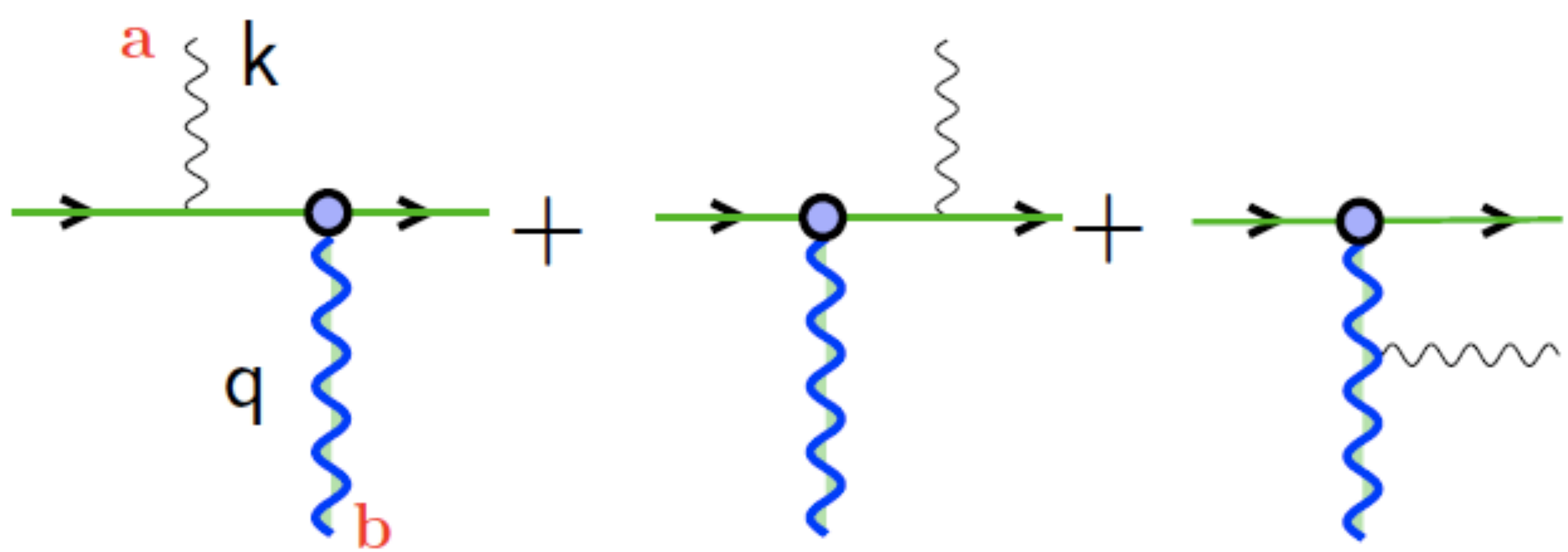


Figure 3: "Infrared" dependence of the quenching factor for hot medium. The curves (from bottom to top) correspond to the gluon energy cuts 0, 100, 300 and 500 MeV.

Hadroproduction

and Colour

multiple collisions and Hadron Multiplicity

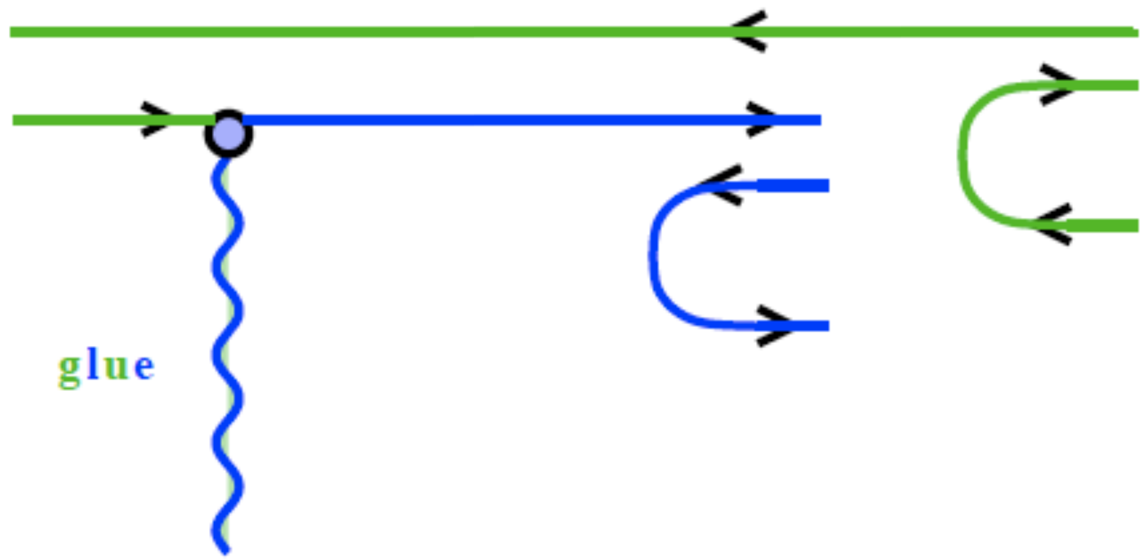


$$-\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2}\mathbf{T}^b\mathbf{T}^a+\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2}\mathbf{T}^a\mathbf{T}^b+\frac{\mathbf{q}_\perp-\mathbf{k}_\perp}{(\mathbf{q}_\perp-\mathbf{k}_\perp)^2}\,if_{abc}\mathbf{T}^c \;=\; if_{abc}\mathbf{T}^c\cdot\left[\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2}+\frac{\mathbf{q}_\perp-\mathbf{k}_\perp}{(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

Accompanying radiation depends on the
t-channel colour exchange
but not on the nature of colliding objects !

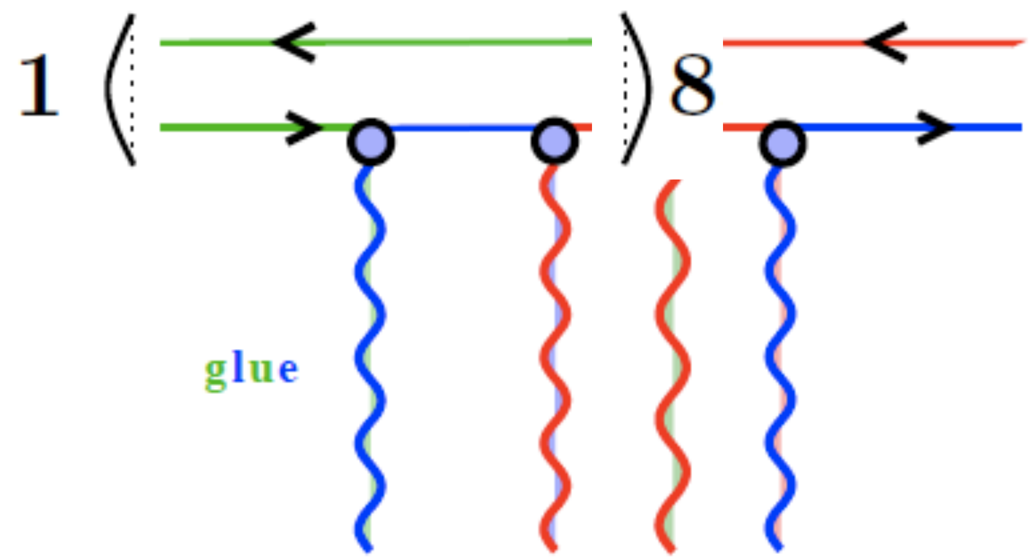
Such an universality - in the language of the Gribov-Regge theory
of high energy hadron interactions - is known under the name of ***Pomeron***

pion scattering



= two "quark chains"
known as the Pomeron

color-wise:



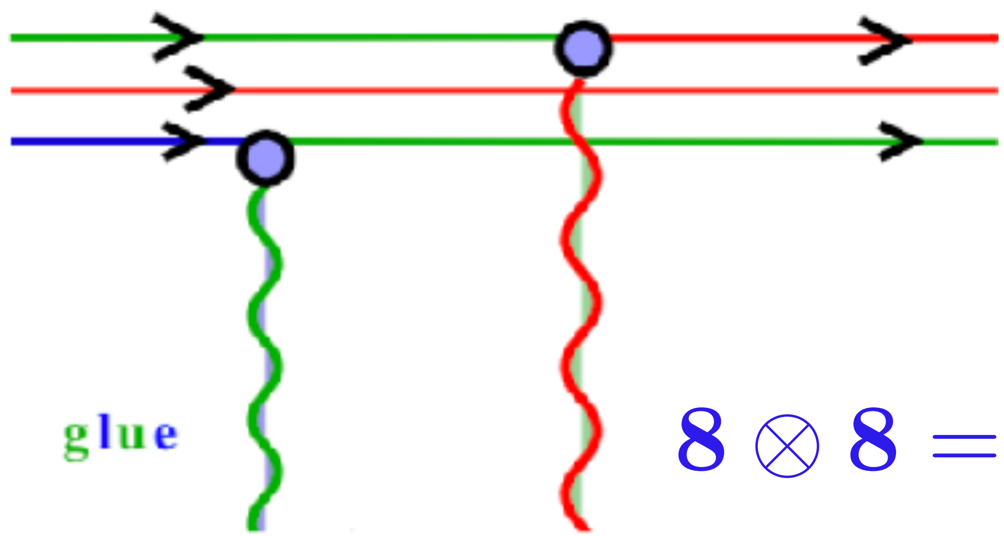
Successive collisions of a projectile ***with limited color capacity***
do not produce an additional hadron yield ....

Where are then multiple Pomerons ??

proton scattering

Consider double scattering (two gluon exchange)

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



$$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{1} + \mathbf{8}_a + \mathbf{8}_s + \mathbf{10}$$

$$\mathbf{8} \otimes \mathbf{8} = \mathbf{1} + \mathbf{8}_a + \mathbf{8}_s + \mathbf{10} + \overline{\mathbf{10}} + \mathbf{27}$$

missing

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

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

Double density of hadrons

=2 Pomerons

Cannot be realized on a *valence-built* proton

$$\frac{1}{27} \cdot 0 + \frac{8+8}{27} \cdot 3 + \frac{10}{27} \cdot 6 = 4$$

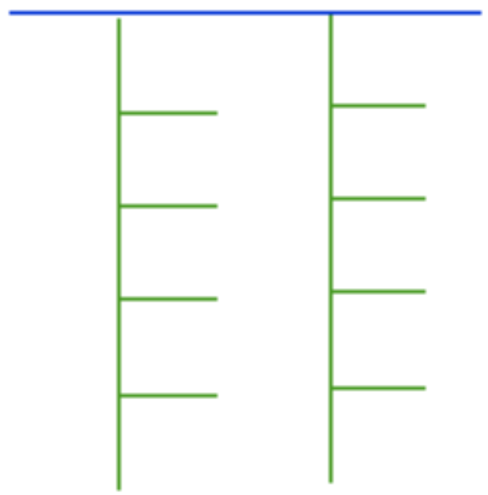
?

nowhere near two Pomerons...

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

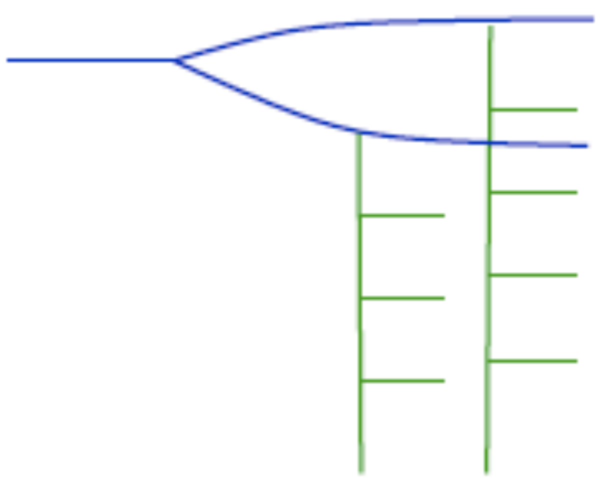
Where are then multiple Pomerons ??

Recall the good old “*Amati–Fubini–Stanghellini puzzle*”.



$=0$

Successive scattering of a particle DOES NOT produce ***branch points*** in the complex J plane (Reggeon loops).



It is the non-planar ***Mandelstam construction*** that generates “Reggeon ***cuts***”, with Reggeon “***ladders***” attached to separate — ***coexisting*** — partons.

From QCD point of view, the projectile hadron has to have enough ***colour capacity*** in order to be able to “*fully absorb* ” many gluons in a multiple scattering off nucleus

colour capacity

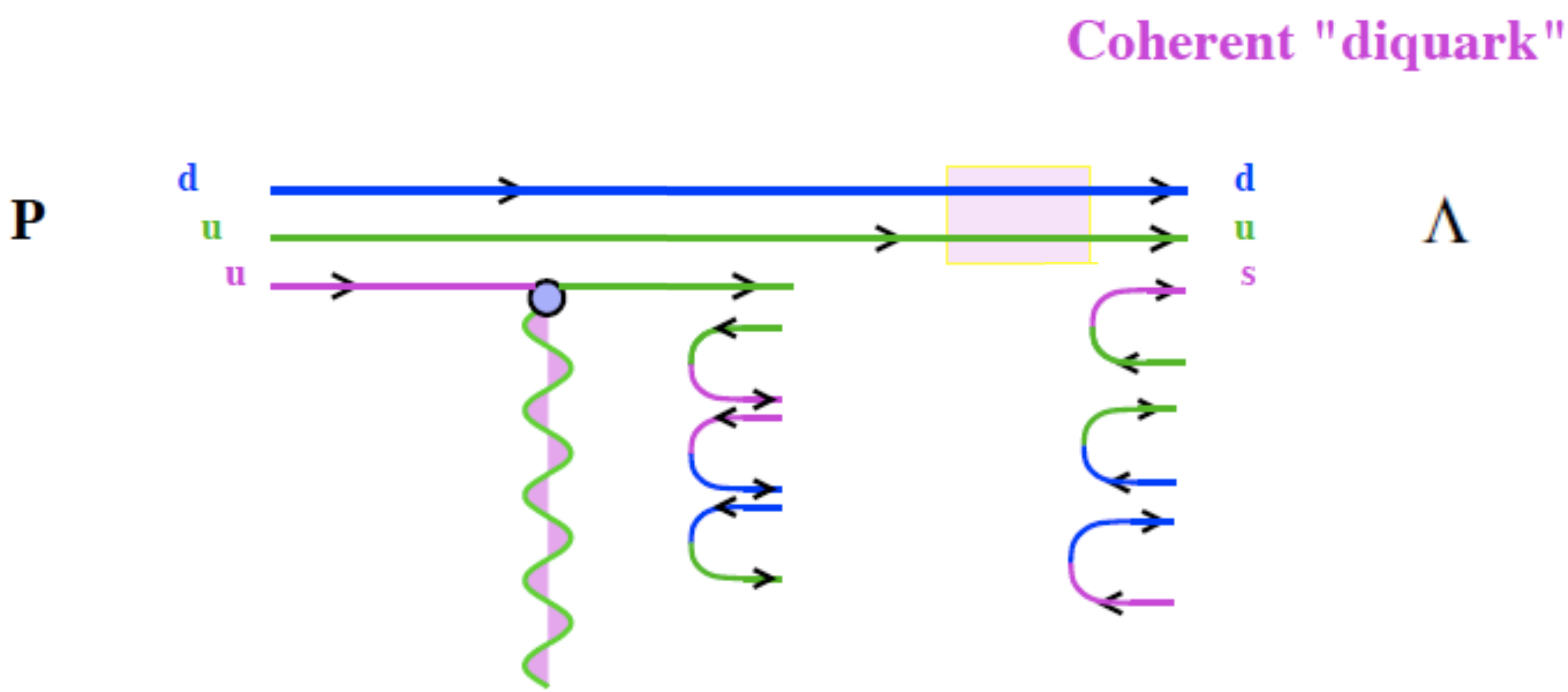
To have n_c Pomerons attached, one must compare n_c with the number of *independent* (incoherent, resolved) *partons* inside the projectile :

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

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.

STOPPING

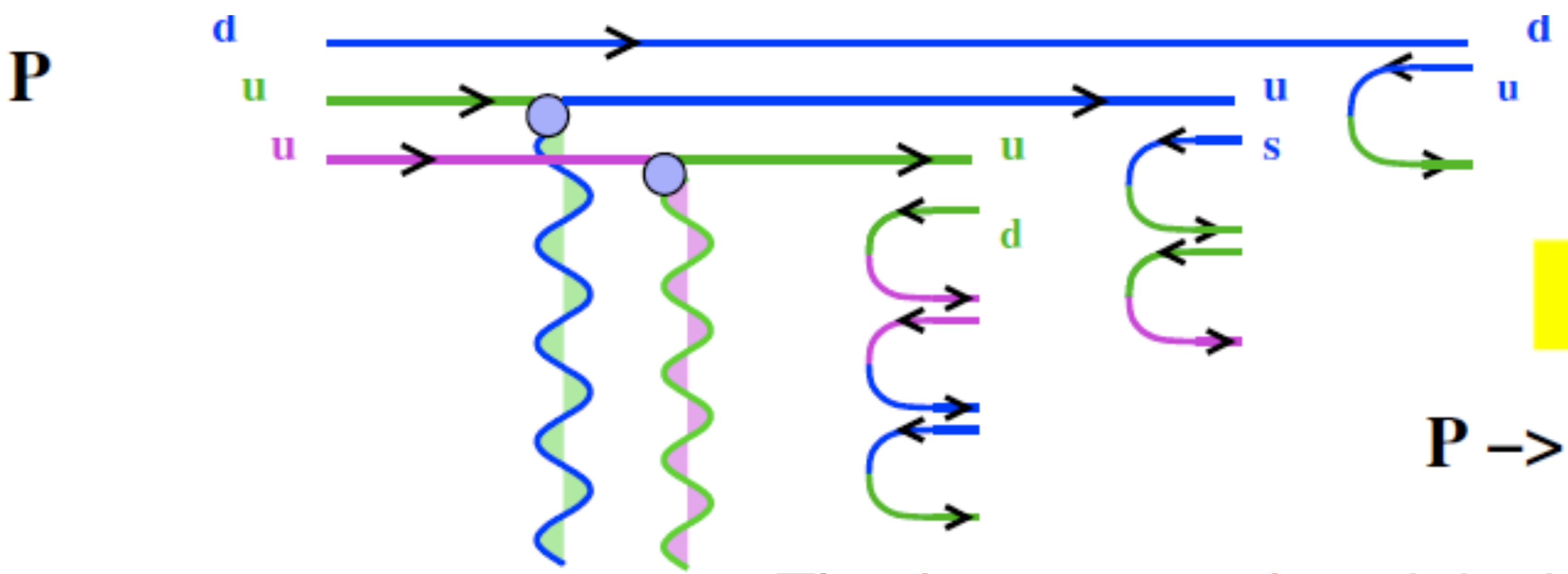
Single scattering scenario



Coherence of the *diquark* ain't broken:

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

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



Proton is "*fragile*"

$P \rightarrow \rho^{+} \; K^{+} \; \pi^{-} + \ldots$

How deep ?

The *baryon number* sinks in the vacuum ...

In "old terms" one can employ a *baryon Regge trajectory* tools.

In the QCD framework, it is important to keep in mind the key feature of colour dynamics of quarks : *the colour is linked to the baryon number !*

Baryon number currents floating in the vacuum get aligned in a colour field. Understanding the structure of colour field, should explain the depth of **B** sinking.

How to see baryon number transfer ("*stopping*") in **pp** collisions **?**
Look for fluctuations with higher particle multiplicity on one side

At LHC energies, the projectile **p** (on the higher multiplicity side) sinks into the sea not because of *lack of energy* but due to its "***decay***" = BN transfer.

baryon stopping in AA and pA

We know proton to be *fragile*.

It suffices to kick it with a photon (*with 1GeV virtuality*) and it is blown to pieces (***DIS***).

If nuclear environment does shift minimum bias phenomena to harder end,
we should expect manifestation of proton fragility in scattering of - and off - nuclei.

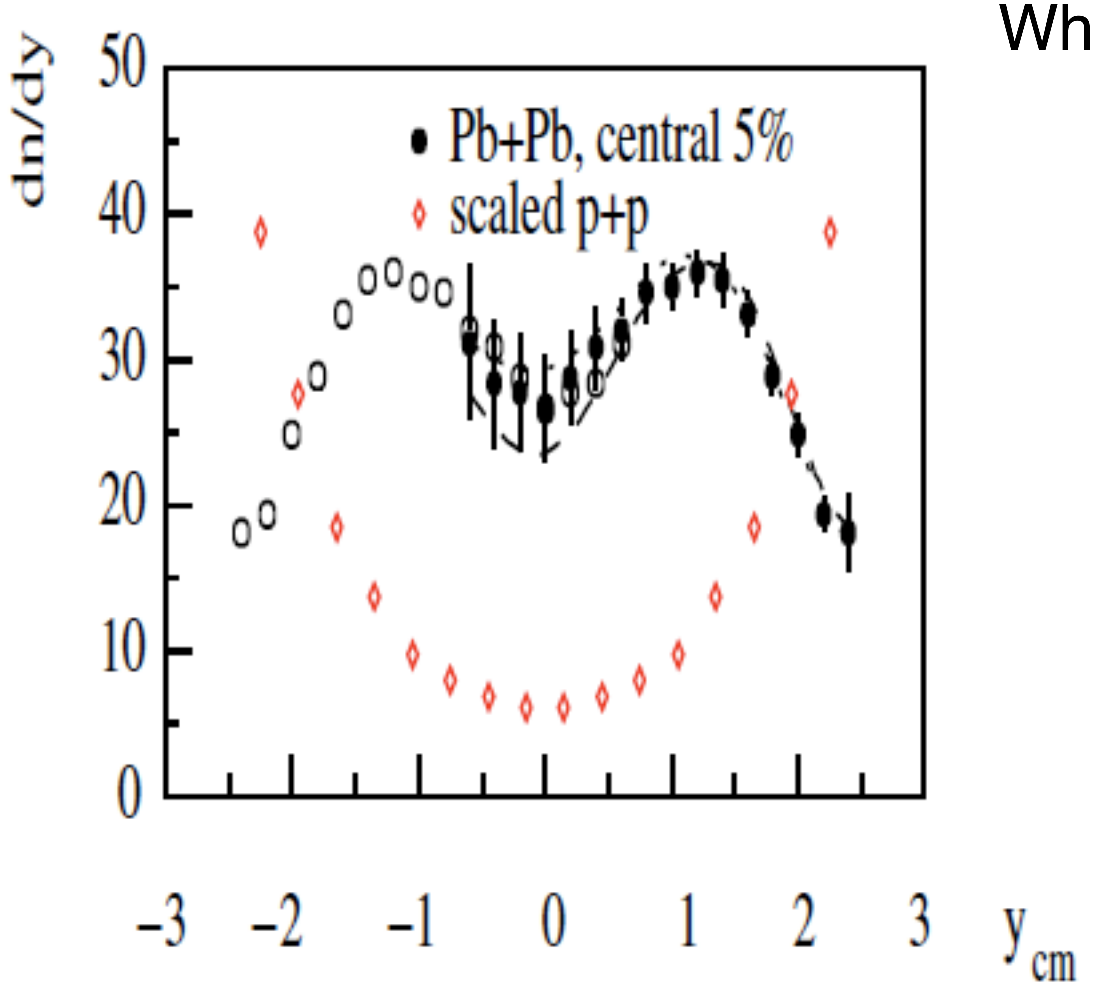
And indeed, this is the case.

The corresponding phenomenon is well know under an unfortunate name of ***proton stopping***.

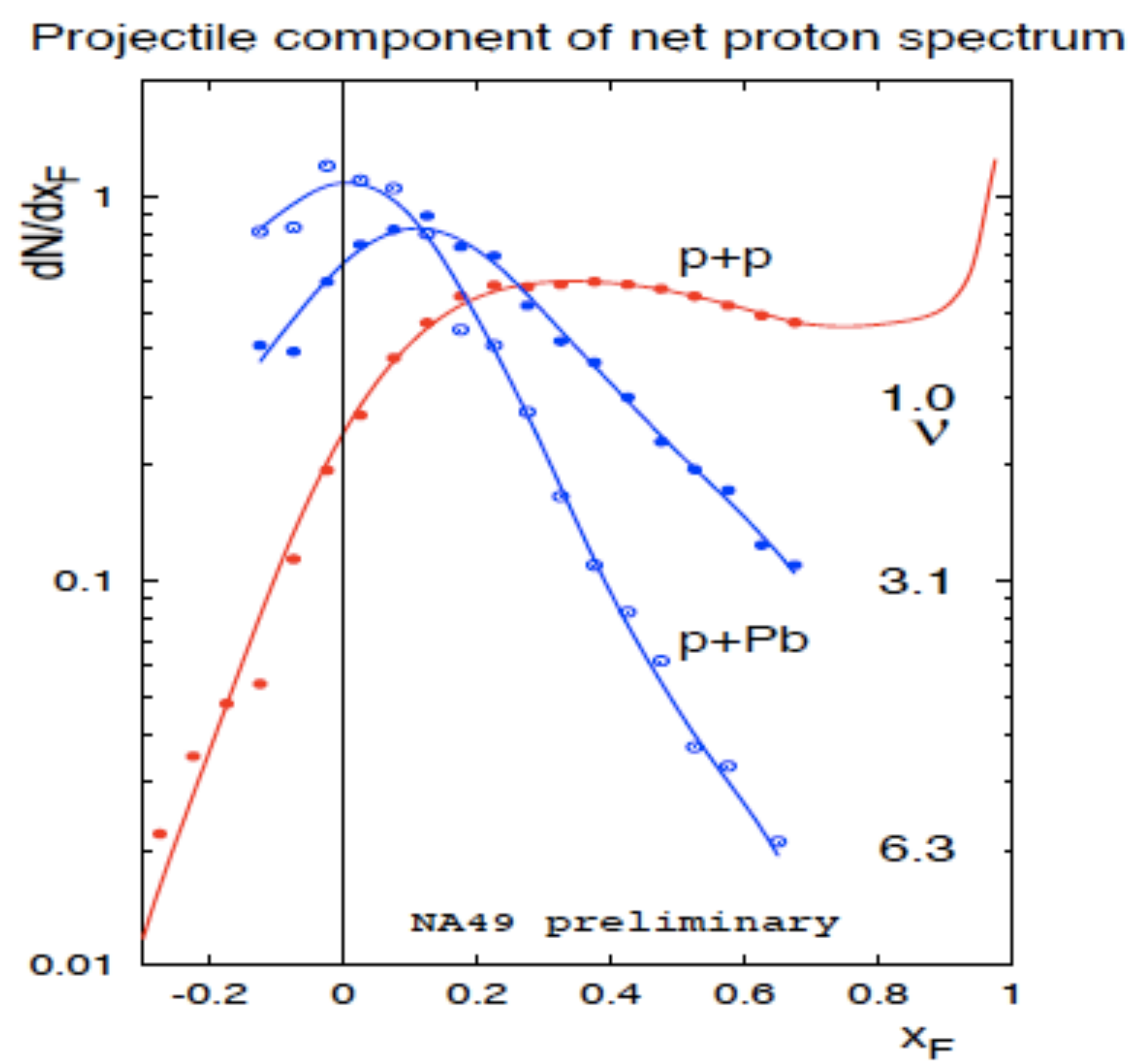
Even more importantly, the same happens in **pA**

What matters is the **number of collisions** ! (forget QGP)

PbPb



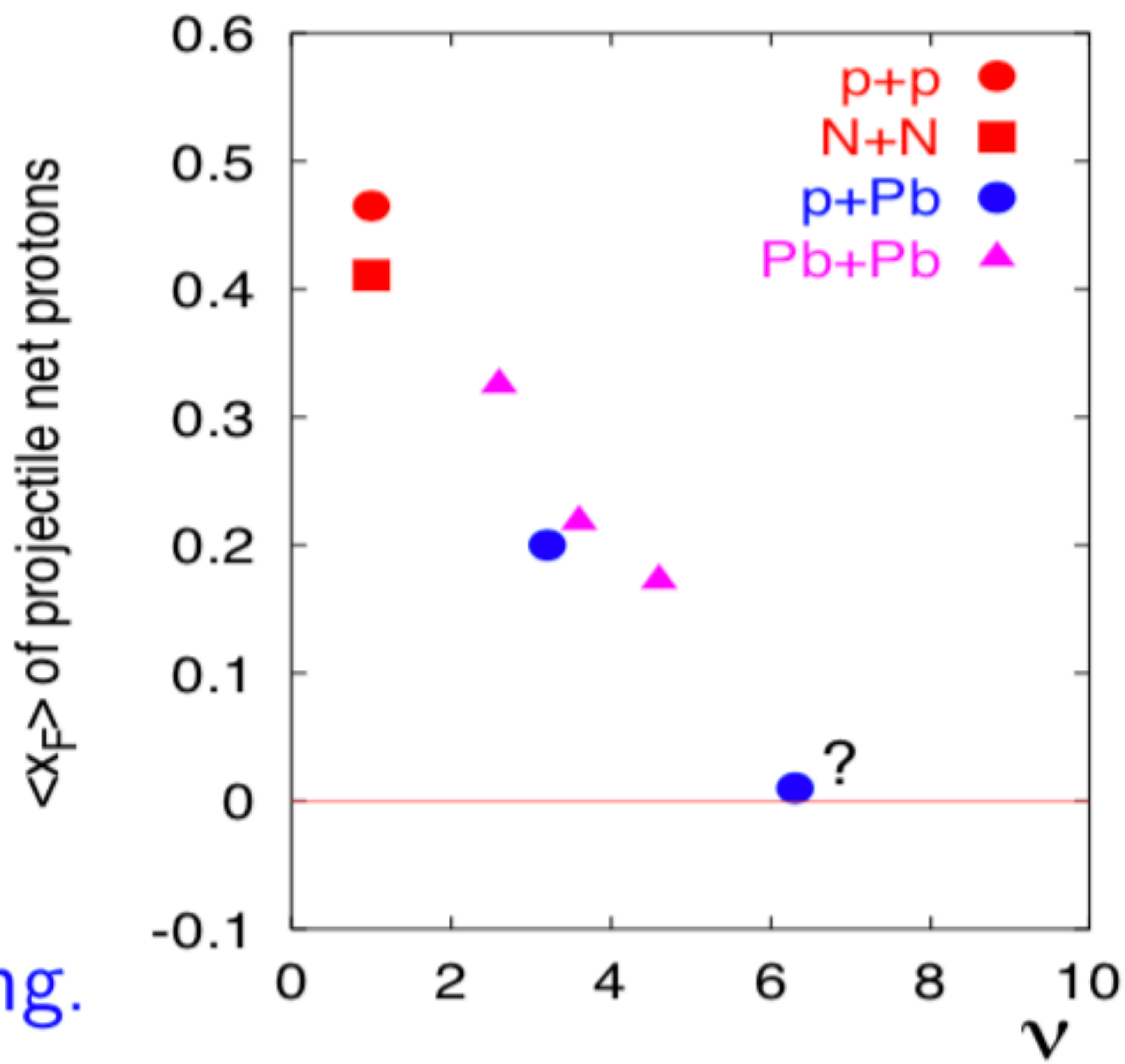
CERN $\sqrt{s} = 17$ GeV (NA49)



Baryons disappear from the fragmentation region

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

- $< x_F >$ of net protons



Known as Proton Stopping.

Better be called Proton Decay

ν — number of collisions

Confinement in Multiple Collisions

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.

"***Final state interaction***" is a synonym for "**non-independent fragmentation**"
— *cross-talking Pomerons, overlapping strings, "string ropes", . . .*

From the point of view of the color dynamics, in pA and AA environments we face an ***intrinsically new,*** ***unexplored question :***

After the pancakes separate, at each impact parameter we have a dense color field whose strength corresponds to $n_p/\mathrm{fm}^2 \propto A^{1/3}$ "***strings***".

How does the vacuum break up in such - *stronger than usual* - color fields ?

LEP has left the question unanswered

Strength of the color field → lifting off strangeness suppression

Geometry of the field → collective hadron flow effects

Practical advices to HENP experimenters:

- listen to theorists — they are not (necessarily) fools
- don’t trust theorists — they build their reputation on plausible ideas
  you - on truthful finding the facts of Nature.
- publish s.v.p. your results not waiting for
  a theoretical prediction/explanation paper to appears.
- you are not checking theory of strong hadron interactions
  which does not exist.
- such theory will be learnt and eventually built
  based on your results.