Hadron interactions, color and QCD partons

4. Energetic quarks and gluons in QCD media

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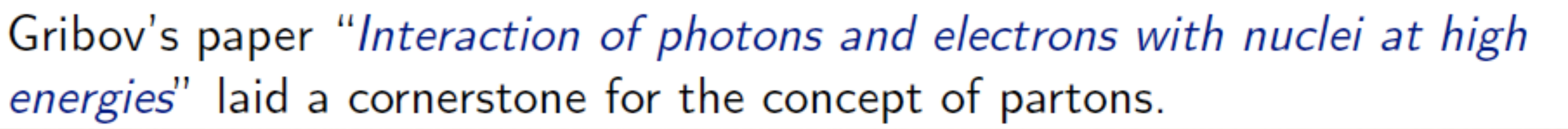
nucleus as a goal and as the means

For many years QCD ideas have been used to picture high-energy scattering in nuclear matter.

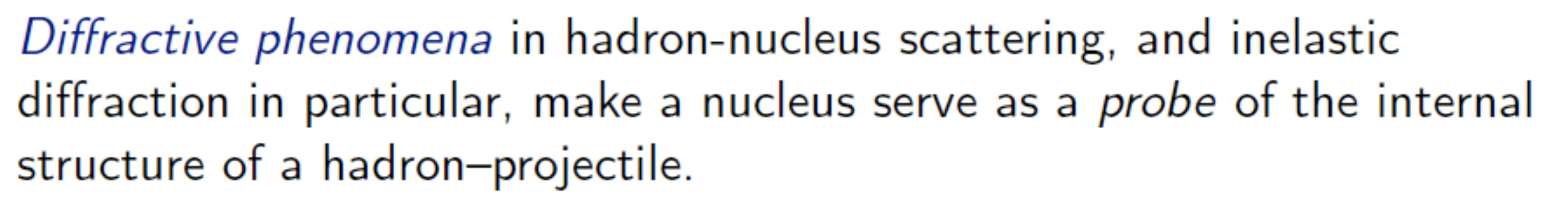
QCD-motivated constructions in nuclear physics included :

the small-distance core of the intra-nuclear potential,
modeling excitations of a nucleus with a “color tube”,
percolating strings, physics or chiral condensate, etc., etc.

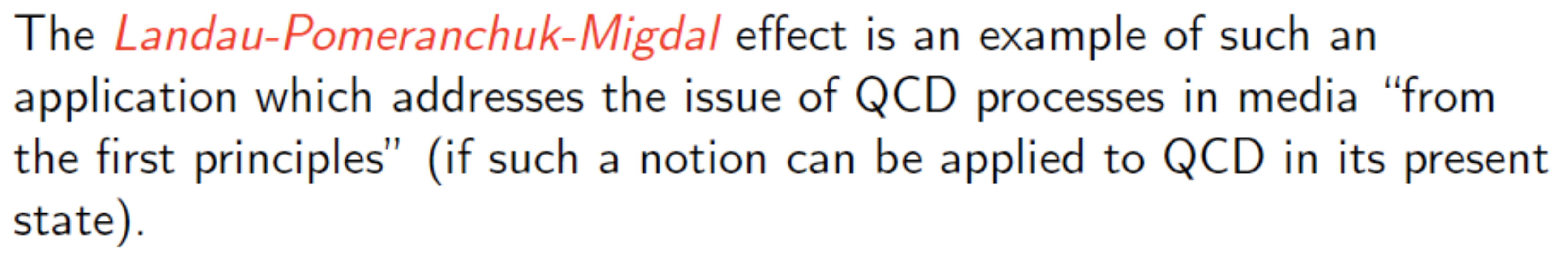
HEPP vs
HENP : ***Nucleus has always been a source of inspiration for High Energy Physics.***



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



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.



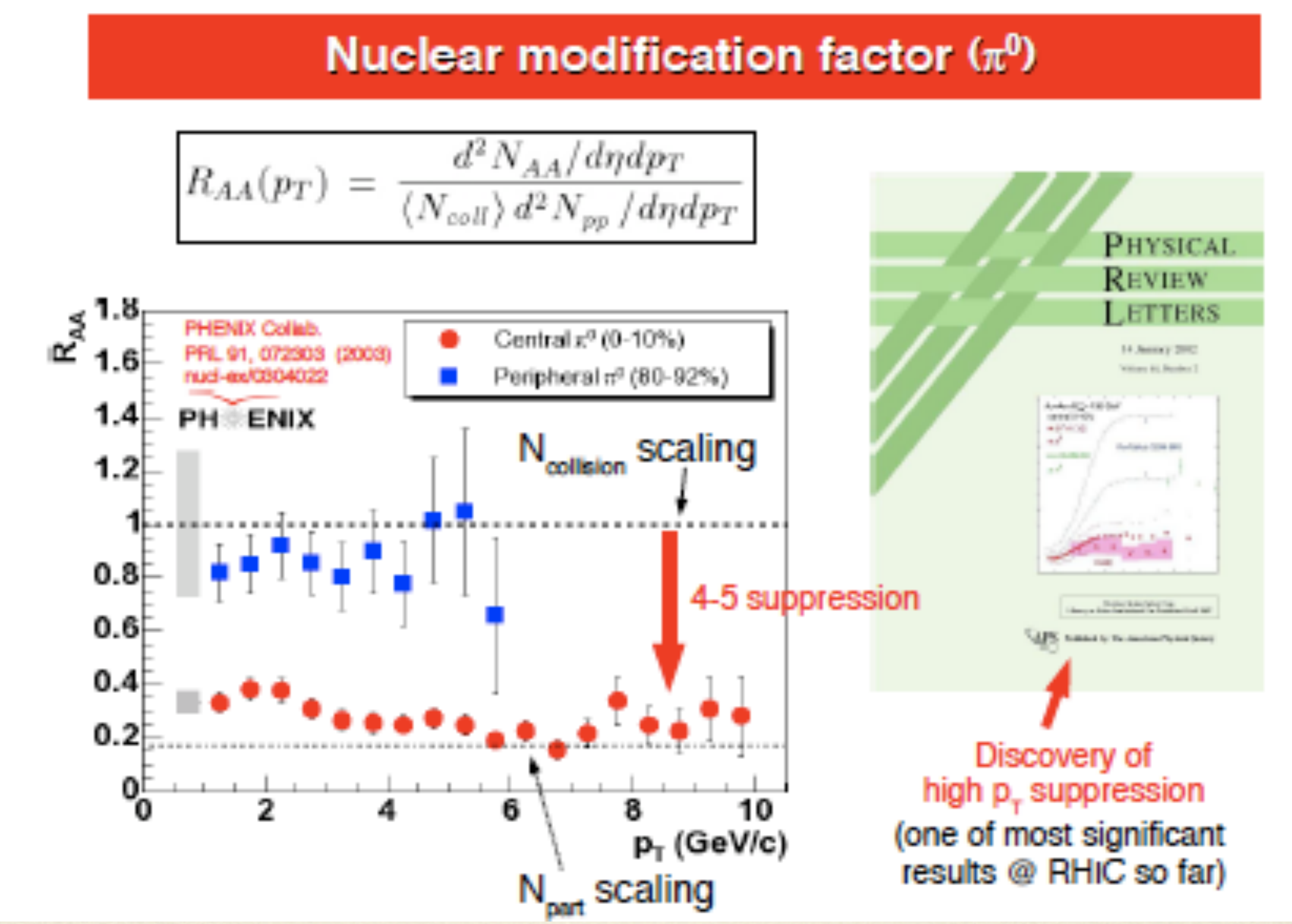
The *Landau-Pomeranchuk-Migdal* effect is an example of such an application which addresses the issue of QCD processes in media "from the first principles" (if such a notion can be applied to QCD in its present state).

plan

We will touch upon recent phenomenological findings and a tiny little bit of theory :

1. introductory puzzles
2. nucleus as partonometer
3. medium-induced gluon radiation (LMP suppression)
4. baryon stopping, strangeness suppression and nucleus as colorometer
5. “scaling quest”, LMP and the “old hadron physics”
6. confinement in HI environment

Most spectacular RHIC finding - quenching of large p_t hadrons



Nuclear modification factor (π^0)

$$R_{AA}(p_T) = \frac{d^2N_{AA}/d\eta dp_T}{\langle N_{coll}\rangle\, d^2N_{pp}/d\eta dp_T}$$

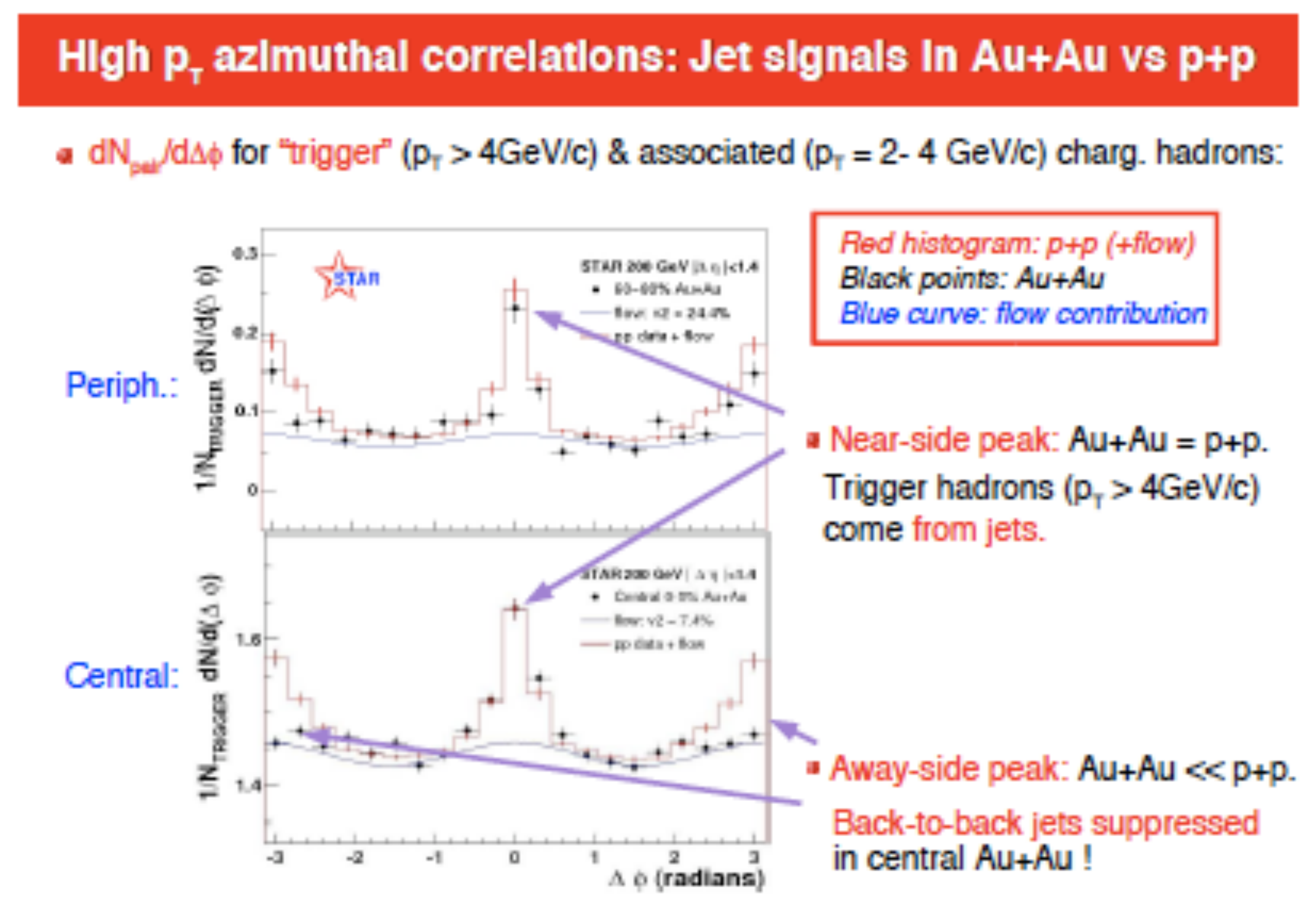
$N_{collision}$ scaling

4-5 suppression

N_{part} scaling

Discovery of high p_T suppression (one of most significant results @ RHIC so far)

back-to-back particle correlations in the medium



High p_T azimuthal correlations: Jet signals in Au+Au vs p+p

- $dN_{pair}/d\Delta\phi$ for "trigger" ($p_T > 4$GeV/c) & associated ($p_T = 2$- 4 GeV/c) charg. hadrons:

Red histogram: p+p (+flow)
Black points: Au+Au
Blue curve: flow contribution

Periph.:

Central:

- Near-side peak: Au+Au = p+p.

  Trigger hadrons ($p_T > 4$GeV/c) come from jets.

- Away-side peak: Au+Au << p+p.

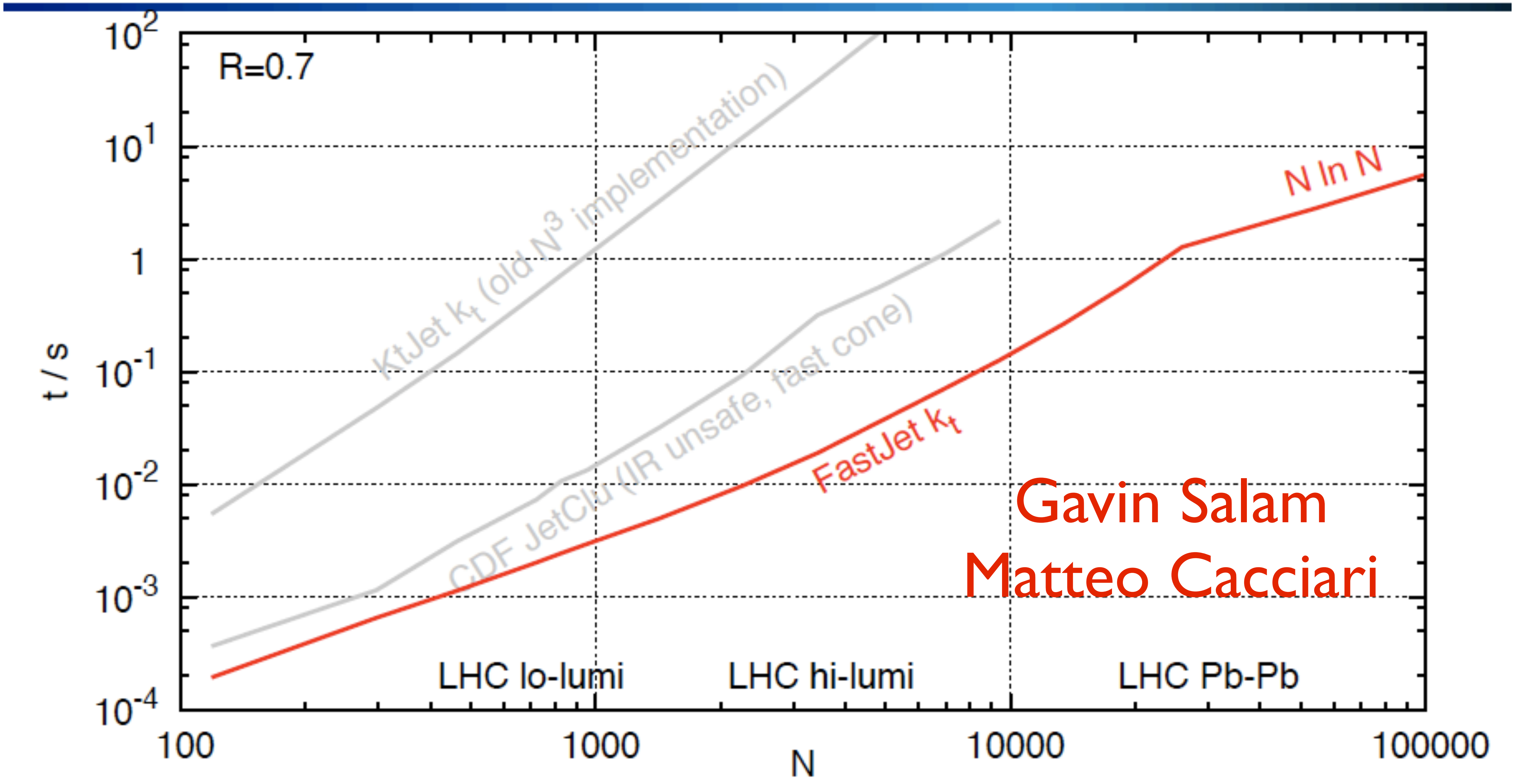
  Back-to-back jets suppressed in central Au+Au !

recoiling particles "backward jet" are washed away by medium

jet studies in HI collisions have recently become possible

Towards Jetography, G. Salam (p. 17)
└Snowmass
  └Speeding up k_t

k_t algorithm speed: old & new



Gavin Salam
Matteo Cacciari

Factorisation of momentum & geometry
→ **2–3 orders of magnitude gain in speed!**

Speed competitive with fast cone algorithms

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 ***Color Glass Condensate*** banner

one observes that the ***characteristic hardness scale*** grows invariably as

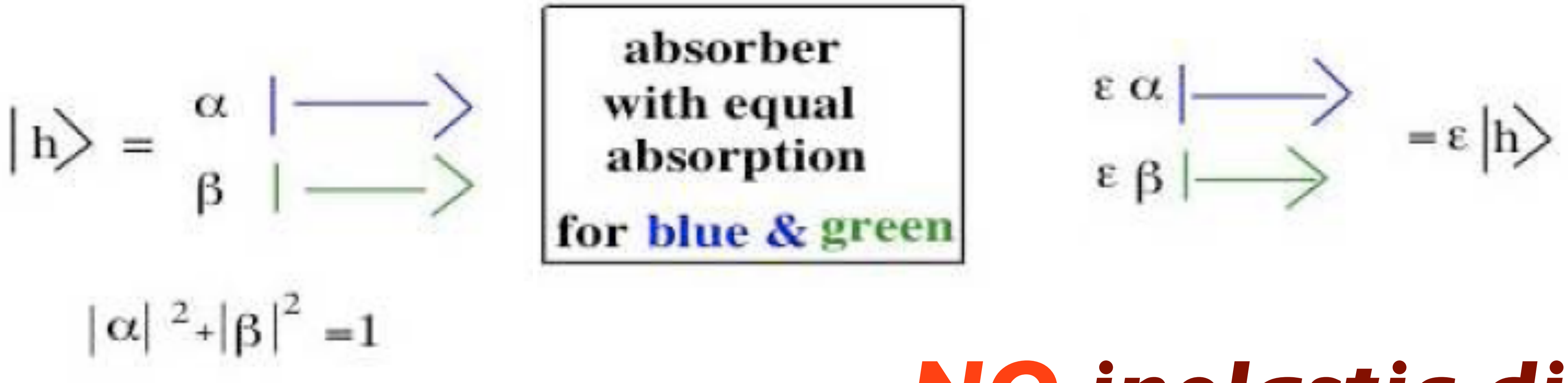
$$Q^2 \sim A^{1/3}$$

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

energy loss, jet broadening, jet quenching

What a hadron is ?

Hadron as a FT object is a *coherent sum* of various configurations.
At *high energies* they scatter independently (Feinberg & Pomeranchuk)



$|h\rangle = \alpha\,|\longrightarrow\rangle + \beta\,|\longrightarrow\rangle$

absorber with equal absorption for blue & green

$\varepsilon\alpha\,|\longrightarrow\rangle + \varepsilon\beta\,|\longrightarrow\rangle = \varepsilon\,|h\rangle$

$|\alpha|^2+|\beta|^2=1$

NO inelastic diffraction

$|h\rangle = \alpha\,|\longrightarrow\rangle + \beta\,|\longrightarrow\rangle$

absorber with different absorption for blue & green

$\varepsilon_1\alpha\,|\longrightarrow\rangle + \varepsilon_2\beta\,|\longrightarrow\rangle \neq \gamma\,|h\rangle$

now take an absorber that differentiates btw different configurations ...

inelastic diffraction

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

Fluctuations in scattering cross section

Proton does not have no definite size (neither content): it may interact with another proton with 20 mb cross section, and may with 100 mb ...

Which one you get depends on chance as well as on your measurement bias !

Define $P_h(\sigma)$ (*Good & Walker* 1960)
— the probability for a hadron h to interact with a given cross section:

$$\sigma_h{}^{\mathrm{tot}} = \langle\sigma\rangle_h \equiv \int d\sigma\, \sigma \cdot P_h(\sigma).$$

$\Rightarrow$ $P_h(\sigma)$ satisfies a number of constraints, based on information about *soft diffraction* off proton and nuclei.

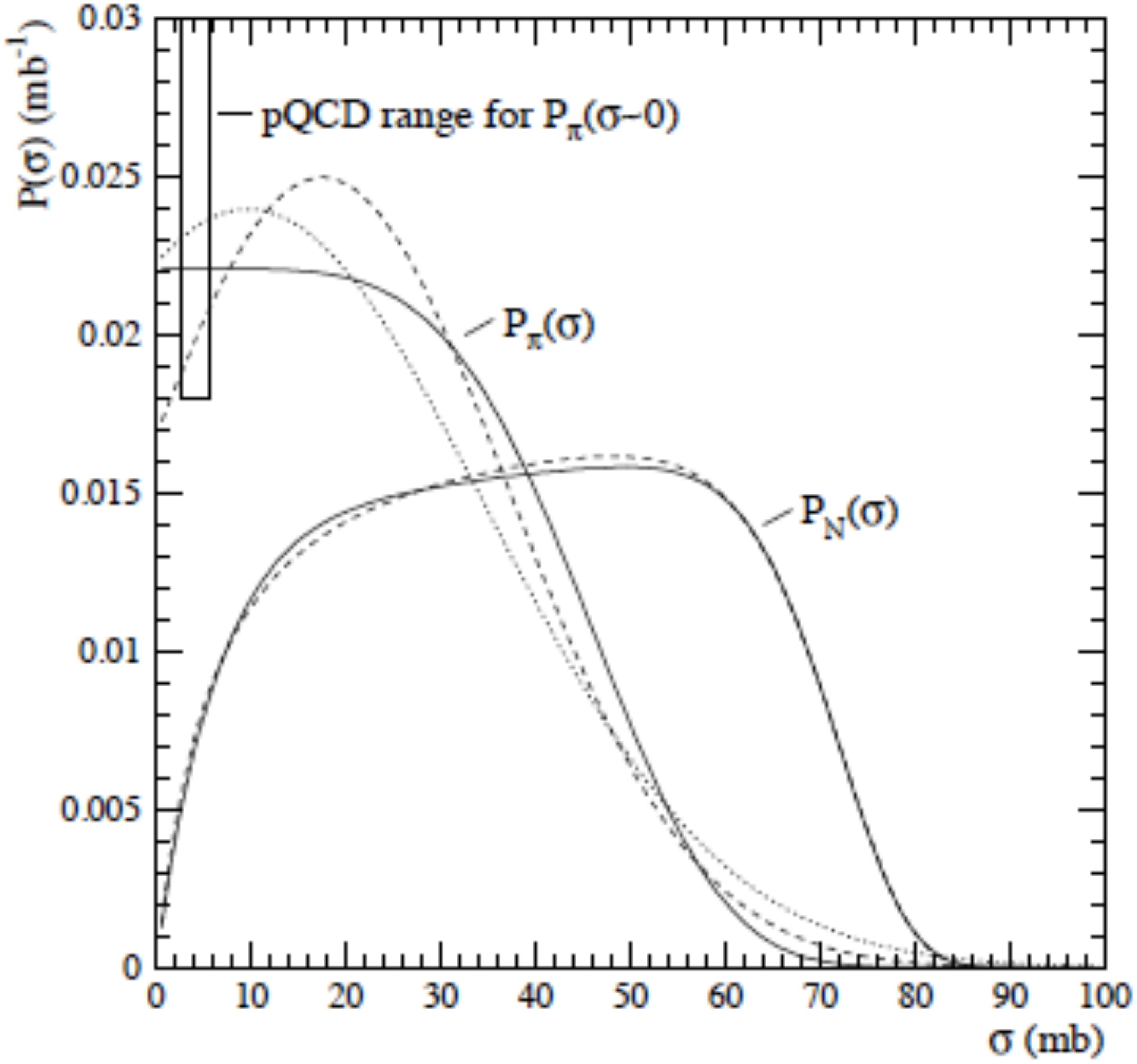
For example, (*Pumplin & Miettinen* 1978)

$$\left.\frac{\sigma(hA \to h^* A)}{\sigma(hA \to hA)}\right|_{t=0} = \frac{\langle\sigma^2\rangle_h}{\langle\sigma\rangle_h{}^2} - 1.$$

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

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

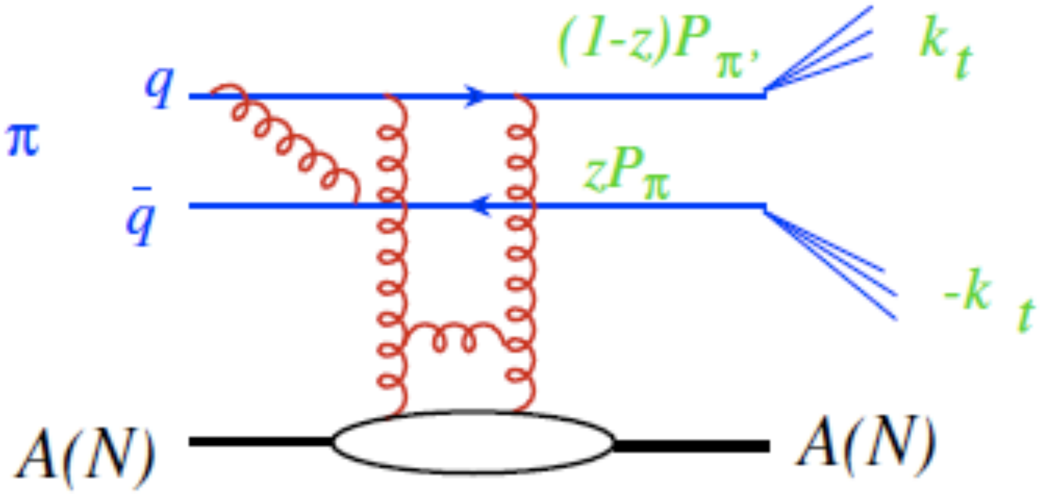
Very broad distributions!



small-size quark configurations - source of "color transparency"

Jets from Diffractive Dissociation of π

$$\pi + N(A) \rightarrow 2\ \text{high}\!-\!k_\perp\ \text{jets} + N(A)$$



π hits the target in a frozen small size $q\bar{q}$ configuration and scatters quasi-elastically via $G^2_{\text{target}}(x, Q^2)$.

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

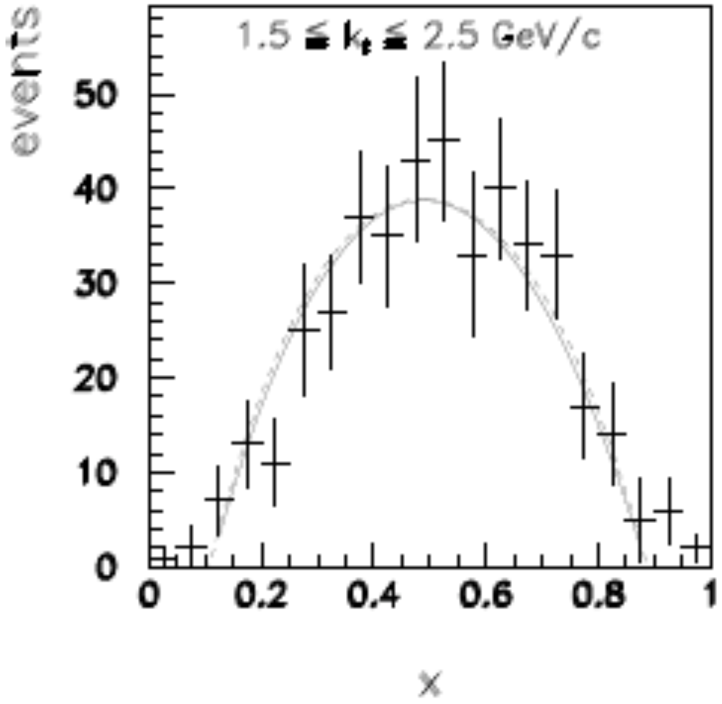
An early expectation (81):	$A^{1/3}$	Bertsch,Brodsky,Goldhaber,Gunion
QCD prediction (93):	$A^{1.54}$	Frankfurt, Miller, Strikman
Experiment (98-00): E-791 ($E^\pi = 500$ GeV)	$A^{1.61\pm0.08}$	

Direct observation of *colour transparency*

The **z-distribution** of jet momenta *is consistent* with the asymptotic pion wave function:

$$\sigma(z) \propto \phi^2_\pi(z)$$

$$\phi_\pi(z) \propto z(1-z)$$ (Brodsky & Lepage 1980)



nucleus as a “small-distance filter” !

Landau-Pomeranchuk-Migdal effect

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

The ***Landau-Pomeranchuk-Migdal*** effect is a rare example of such an application which addresses the issue of QCD processes in media **from the first principles**.

LPM is about radiation induced by multiple scattering of a projectile in a medium.

Landau and Pomeranchuk (1953) noticed that the energy spectrum of photons caused by multiple scattering of a relativistic charge in a medium is essentially different from the Bethe-Heitler pattern. A few years later a quantitative analysis of the problem was carried out by Arkady Migdal (1956).

Symbolically, the photon radiation intensity per unit length reads

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

in the photon energy range $\frac{\omega}{E} < \frac{E}{E_{LPM}}$

Here ***E*** is the energy of the projectile, and ***E***

Here ***E*** is the energy of the projectile, and $\boldsymbol{E_{LPM}}$ is the energy parameter of the problem, built up of the quantities characterizing the medium : the mean free path of the electron λ

a typical momentum transfer in a single scattering μ

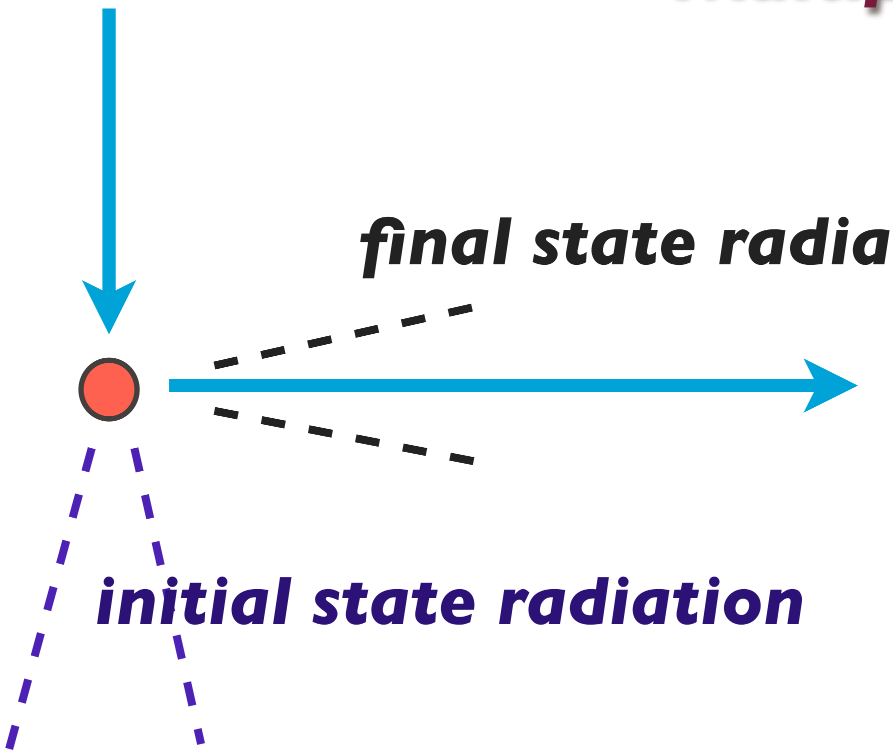
(~ *the inverse radius of the scattering potential*)

$$E_{\mathrm{LPM}} = \lambda\mu^2$$

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

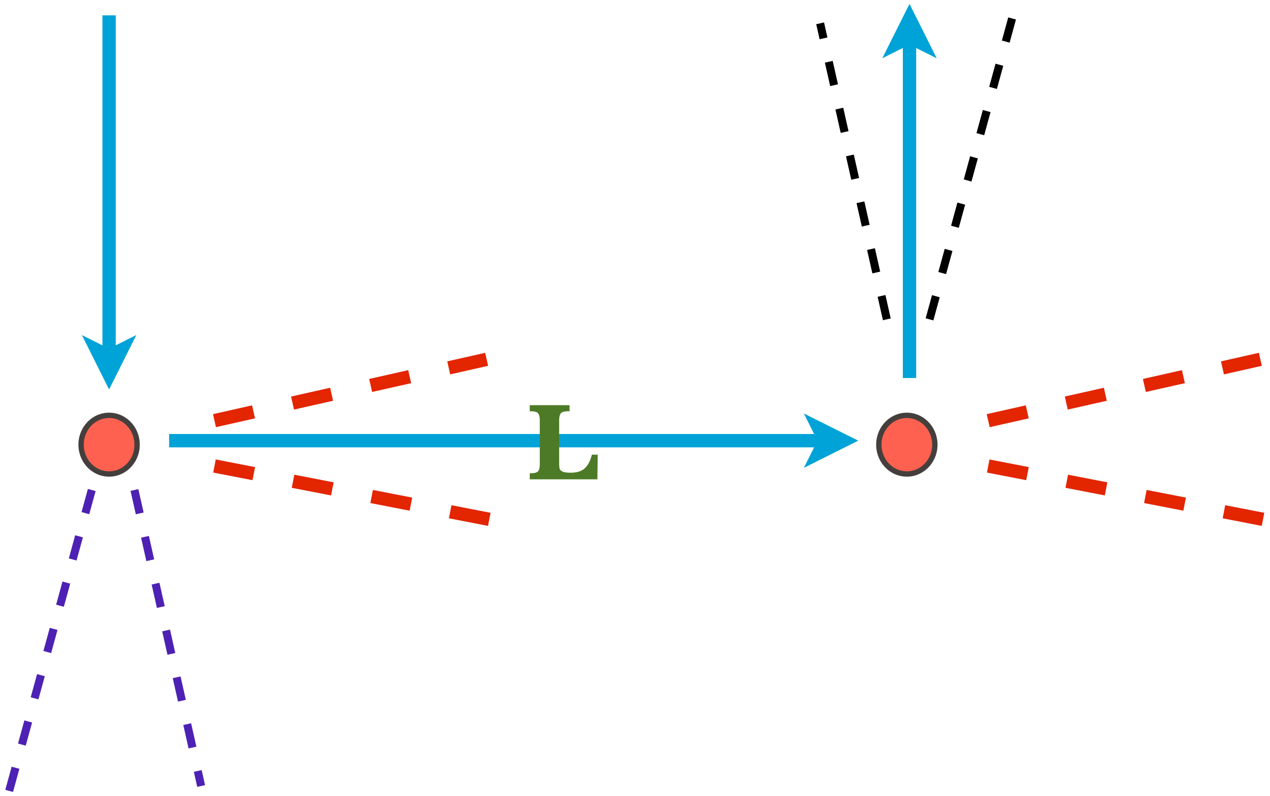
To be compared with the B-H independent radiation regime $\omega\frac{dI}{d\omega\,dz} \propto \frac{\alpha}{\lambda}$

Multiple scattering and radiation formation time



final state radiation *(regeneration of the Coulomb disc)*

initial state radiation *(shaking-off the Coulomb field)*



$$\mathbf{t}_{\rm form} = \frac{\omega}{\mathbf{k}_\perp^2} < \mathbf{L}$$

4 bremsstrahlung cones

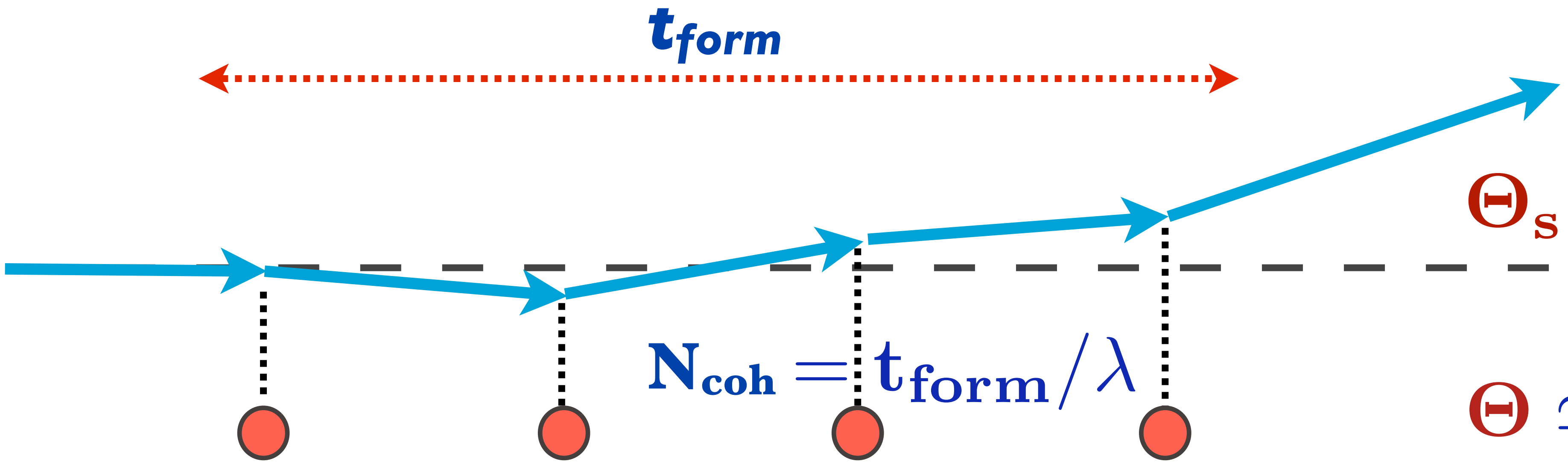
however if

$$\mathbf{t}_{\rm form} = \frac{\omega}{\mathbf{k}_\perp^2} > \mathbf{L}$$

2 bremsstrahlung cones

multiple scatterings not necessarily cause additional radiation

Within the time interval ***t_{form}***, photon radiation amplitudes interfere



$$\mathbf{\Theta_s \sim \sqrt{N_{coh}} \cdot \frac{\mu}{E}}$$

$$\mathbf{\Theta \simeq \frac{k_\perp}{\omega} = \frac{1}{\sqrt{\omega\lambda \cdot N_{coh}}}}$$

One photon emission per ***N_{coh}*** scattering centers

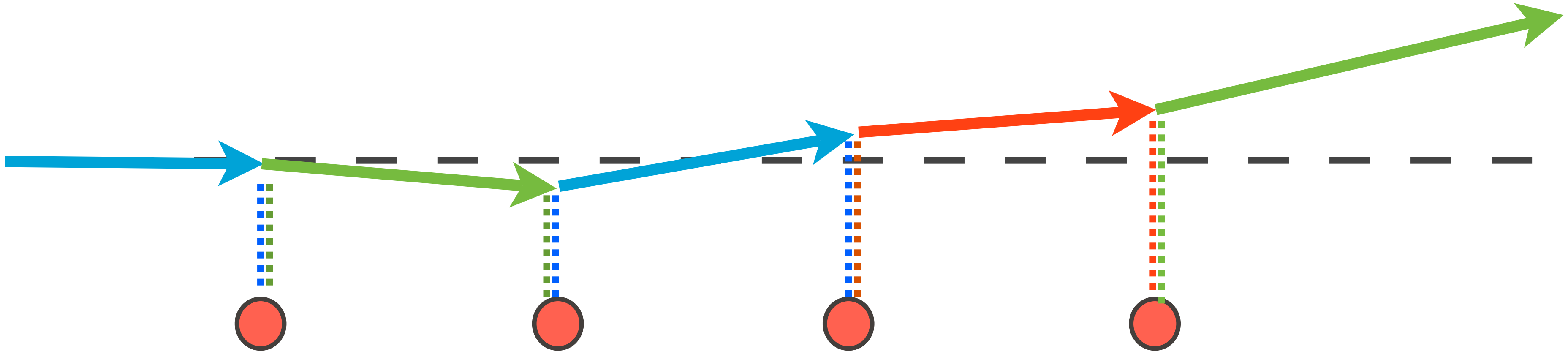
$$\mathbf{N_{coh} = \sqrt{E^2/\omega\, E_{LPM}}}$$

$$\omega\frac{dI}{d\omega\, dz} \propto \frac{\alpha}{\lambda} \cdot \sqrt{\frac{\omega}{E^2} E_{LPM}} = \omega \frac{\mathbf{dI}}{\mathbf{d\omega\, dz}}^{\mathbf{(BH)}} \cdot \frac{\mathbf{1}}{\mathbf{N_{coh}}}$$

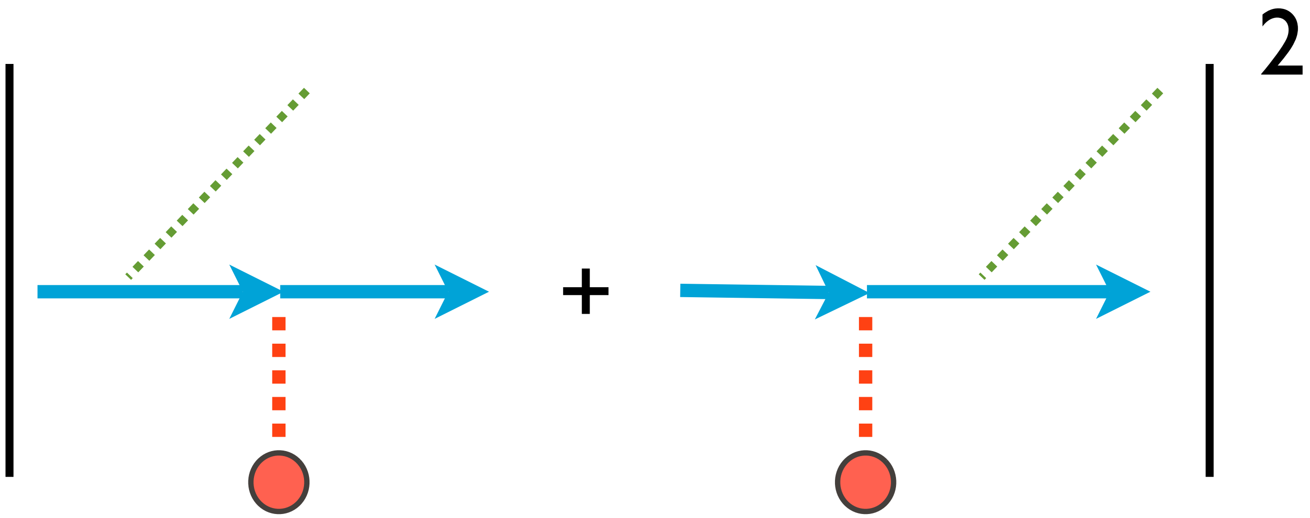
QCD scattering - multiple gluon exchange - "rotates" quark color.

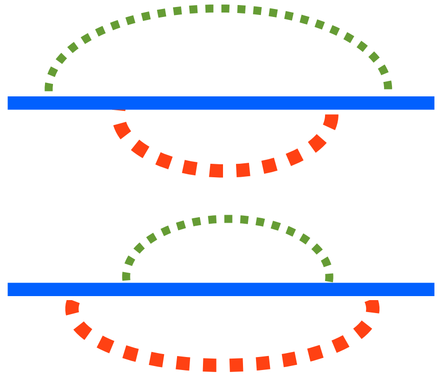
Expect finite answer in the limit

$$\mathbf{E \to \infty \; (\Theta_s \to 0)}$$



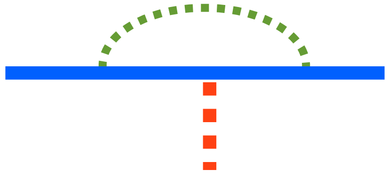
However, the first QCD analysis showed: *multiple quark scattering does not allow for interference !?*





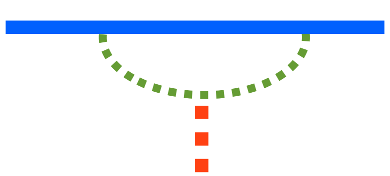
$$C_F = \frac{N_c^2-1}{2N_c} \sim \frac{\mathbf{N_c}}{\mathbf{2}}$$

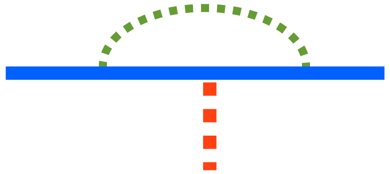
interference is colour-suppressed !



$$-\frac{\mathbf{1}}{\mathbf{2N_c}}$$

Looks ***as if*** quark, having radiated a virtual gluon, has lost its ability to interact - lost its color charge.
In certain sense, it has indeed ... The "color charge" is carried by ***gluon***





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

It is **yet-to-be-formed** ***gluon*** that re-scatters in the medium !

$$\mathbf{k_\perp^2} = \mathbf{N_{coh}} \cdot \mu^2 = \omega/(\lambda \mathbf{N_{coh}}) \quad \Longrightarrow \quad \mathbf{N_{coh}} = \sqrt{\omega/\mathbf{E_{LPM}}}$$

$$\omega \frac{\mathbf{dI}}{\mathbf{d\omega\, dz}} = \omega \frac{\mathbf{dI}}{\mathbf{d\omega\, dz}}^{\mathbf{(BH)}} \cdot \frac{\mathbf{1}}{\mathbf{N_{coh}}} = \frac{\alpha_s}{\lambda}\sqrt{\frac{E_{LPM}}{\omega}}$$

over-singular spectrum
at small gluon energies

Curiously, the **energy losses** have the same energy dependence in QCD & QED.

Very unfortunately, the issue of ***medium induced radiation effects*** often goes under the banner of ***“mean energy losses”*** - the quantity that never enters ...

Finite size medium

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

The only (NP) parameter of the problem, characterizing the medium — ***transport coefficient***

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

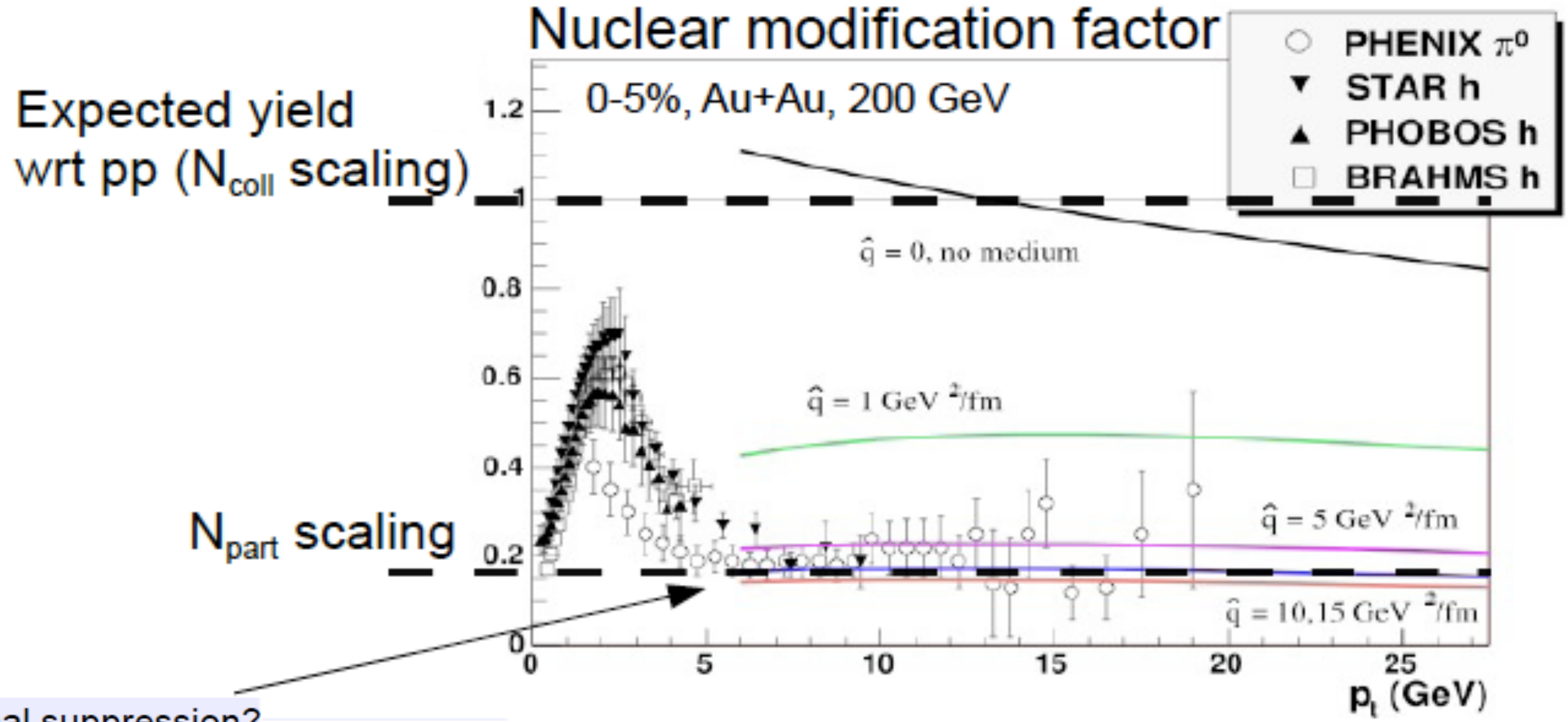
(The “*average squared momentum transfer*” for the quasi-Coulomb scattering is *log-divergent*.
The upper limit is determined by the *characteristic transverse distance* btw ***q & g*** .)

Hence, for large enough ***L~A^{1/3}*** the problem stays ***under perturbative control !***

Handle on **q** in “cold nuclei” — medium effects in Drell-Yan pair production, DIS on nuclei, etc.

To find in experiment a large **q** — to discover a new “***hot*** ” state of quark–gluon matter... (**?**)

particle/jet quenching



Maximal suppression?

$$N_{coll} \times \frac{S}{V} \approx N_{part}/2$$

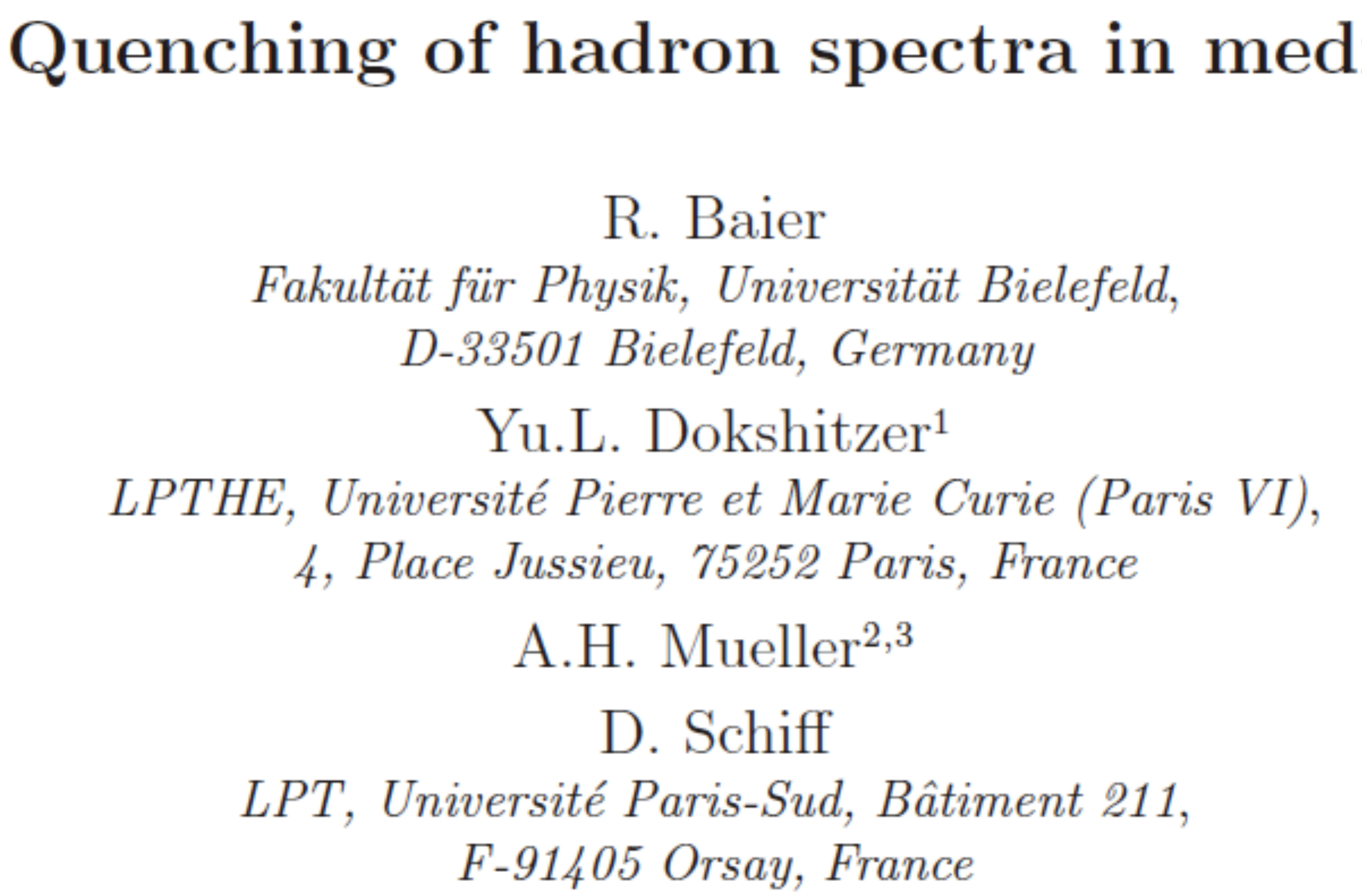
The medium is "***black***": Leading spectra are suppressed by up to a factor of **5-6** wrt collision weighted **pp** reference

Loizides (PHOBOS) ISMD-2009

proved to be a final state effect (photons are not quenched)

Phenomenon closely linked
with medium induced radiation :

JET QUENCHING



Quenching of hadron spectra in media

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arXiv:hep-ph/0106347v1

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

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

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

QCD quenching

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

exact expression includes
infrared integration region

N - multiplicity of medium induced gluons with energies larger than ω

Checking Infrared sensitivity of the quenching factor

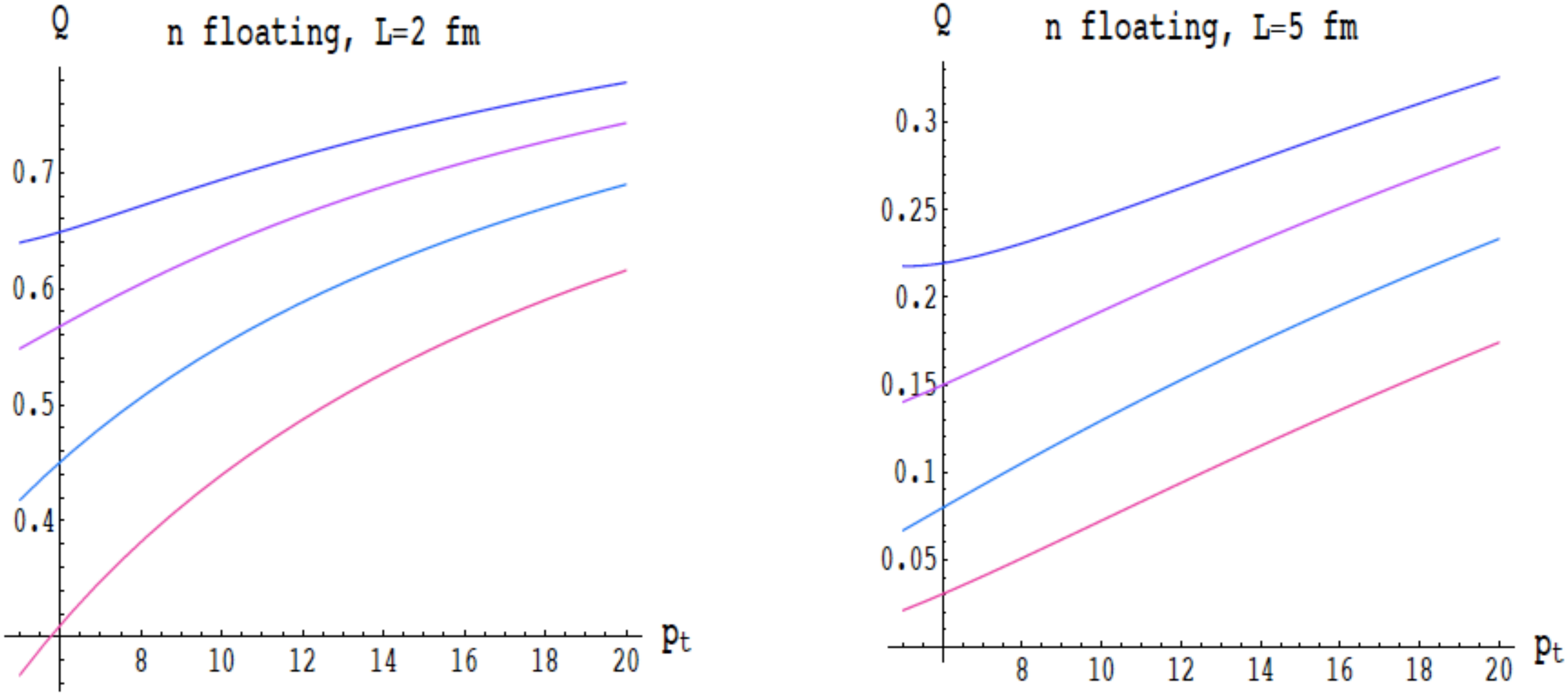


Figure 3: "Infrared" dependence of the quenching factor for hot medium. The curves (from bottom to top) correspond to the gluon energy cuts 0, 100, 300 and 500 MeV.

news : bad and good

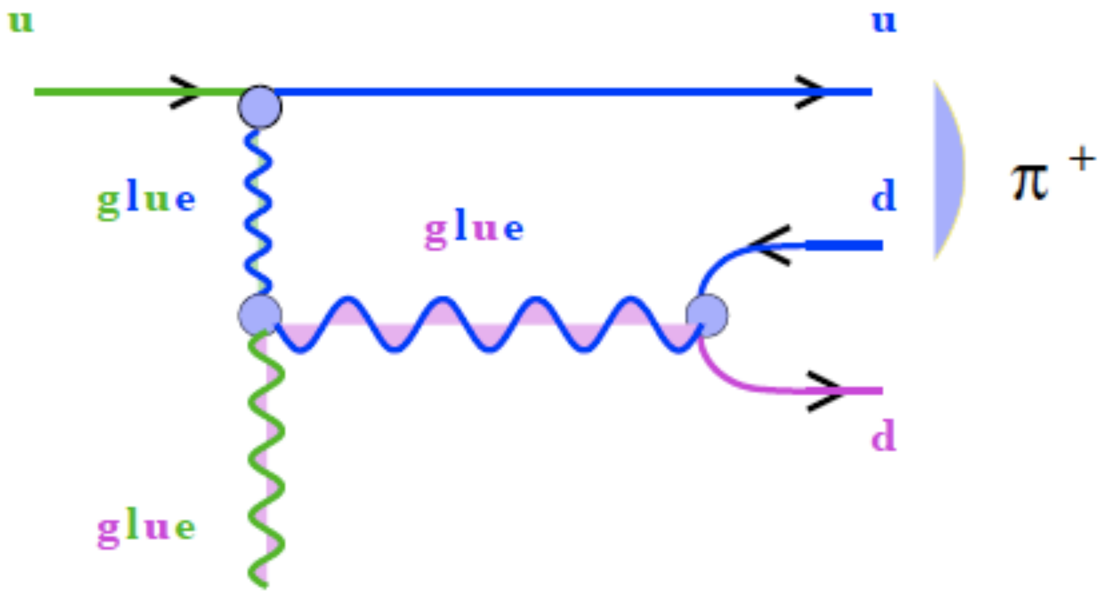
Factor 4 uncertainty in the prediction of the quenching factor - the price we pay for our ignorance of spectral properties of gluons with momenta < 0.5 GeV

This is what makes the LHC Heavy Ion program of high p_t jet studies so exciting from the QCD viewpoint.

Strengthened by the recent breakthrough development of QCD motivated **fast** jet finding algorithms :

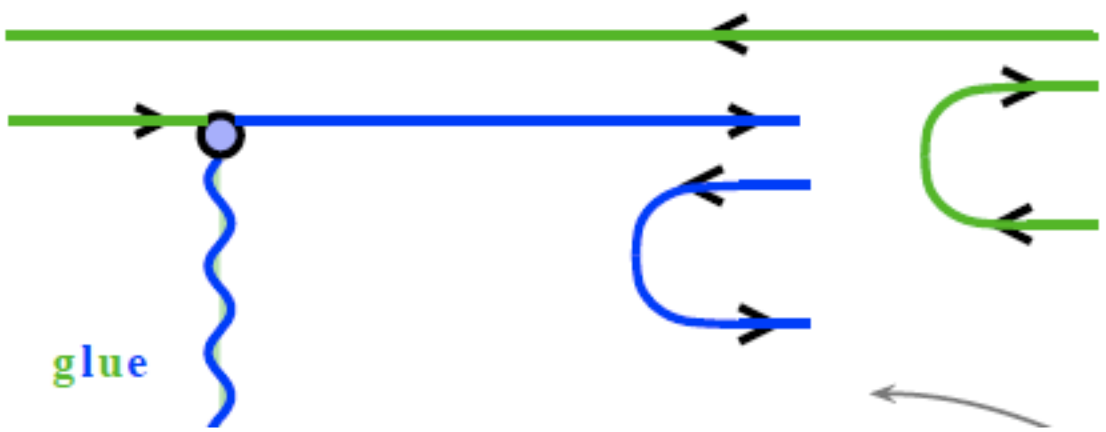
Gavin Salam, Matteo Cacciari, Gregory Soyez, et al

color in hadron scattering



leading hadron

meson scattering



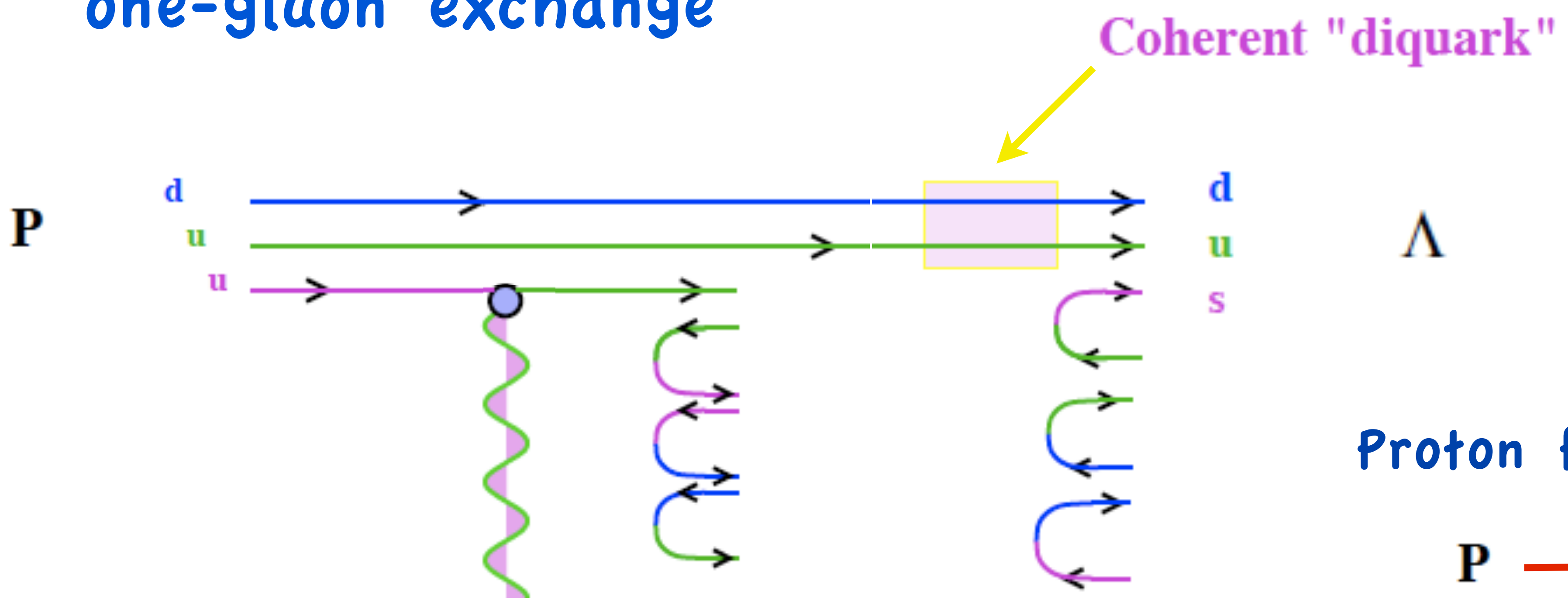
two “quark chains”

Feynman plateau

= s-channel image of the Pomeron

painting the Proton

one-gluon exchange

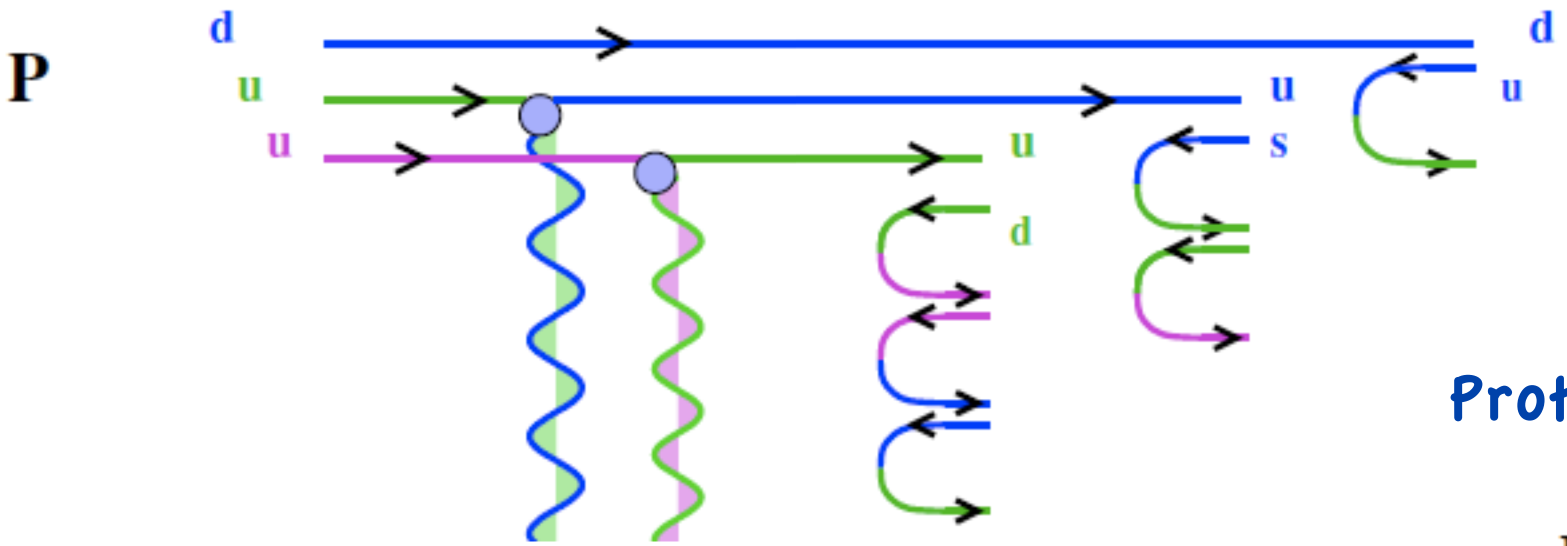


leading baryon

Proton fragmentation :

$P \rightarrow \Lambda \pi^{+} + \ldots$

double scattering



all three leading
quarks fragment
independently

Proton “decay” :

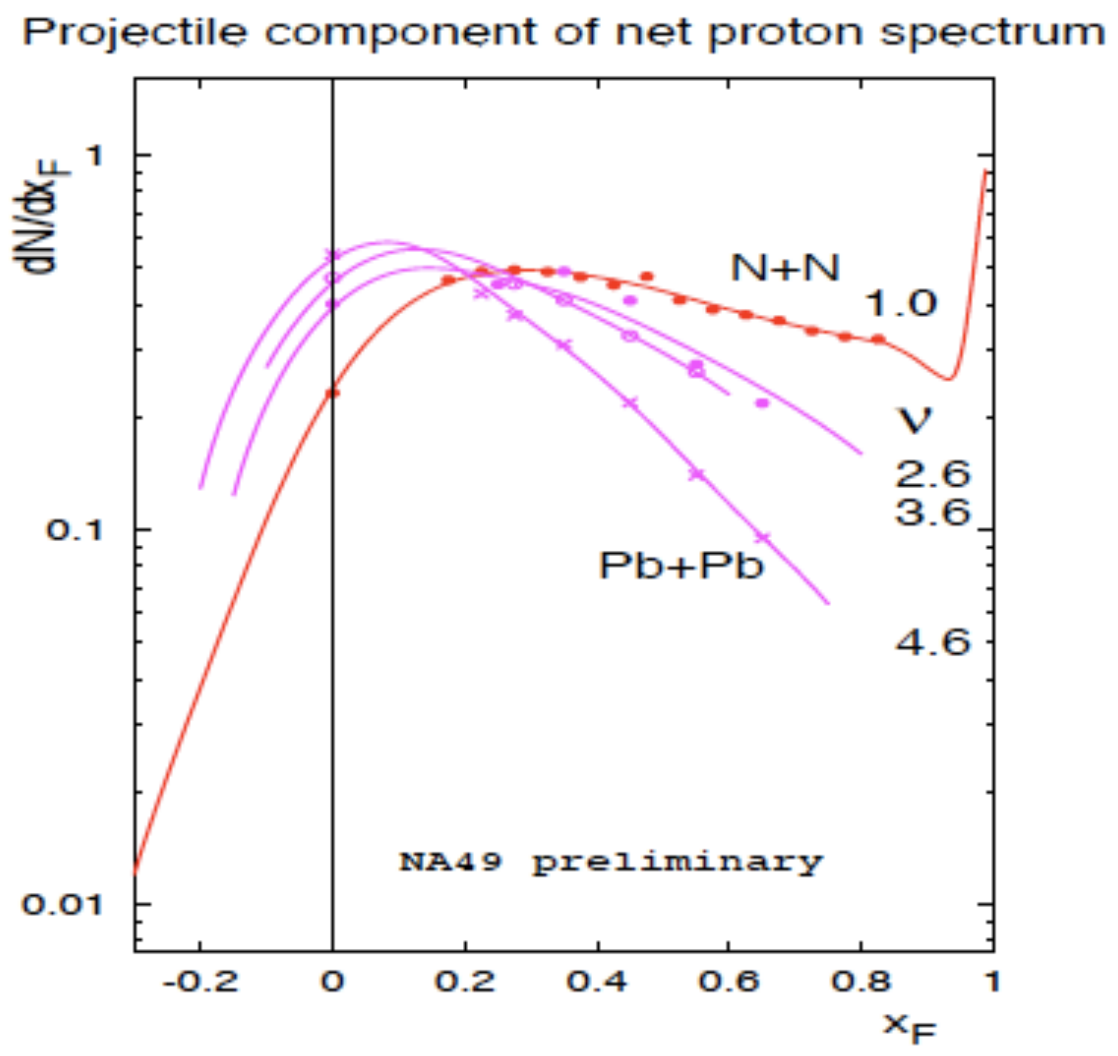
$P \rightarrow \rho^{+} K^{+} \pi^{-} + \ldots$

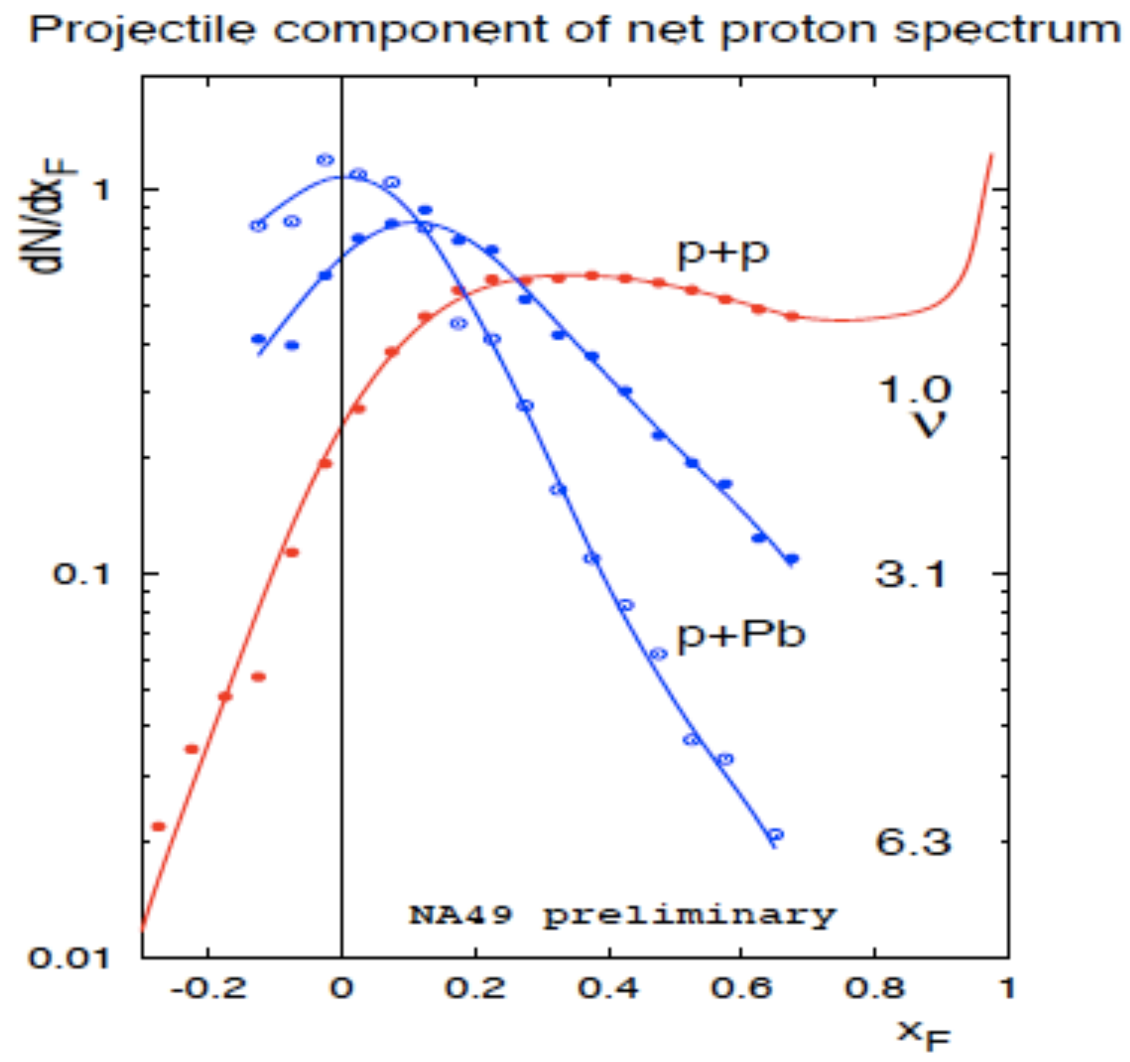
Baryons disappear from the fragmentation region

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

[strengthened by RHIC (Au+Au, 100 GeV)]

importantly : the same phenomenon in pA



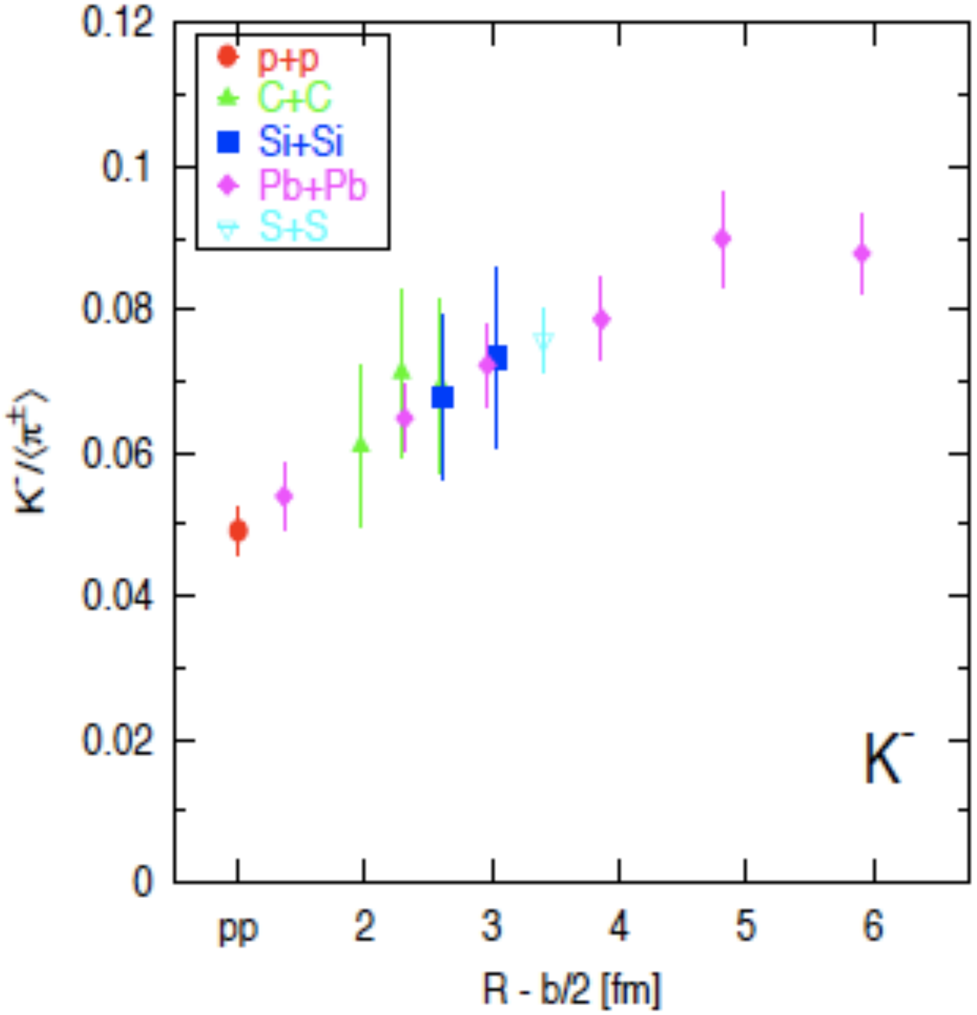


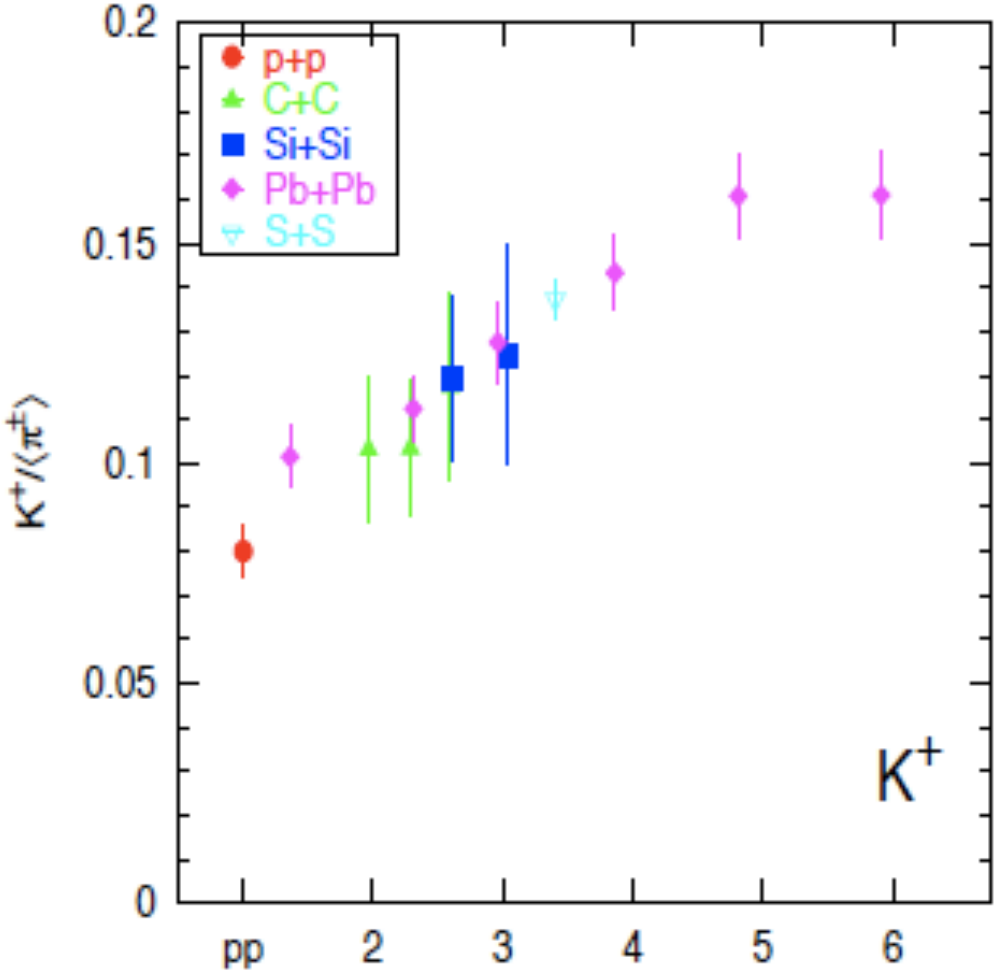
so-called "baryon stopping" develops with *the number of collisions*

not a sign of a "new state of matter" but rather of fragility of the proton

strangeness puzzle

The usual suppression of strange particle production is lifted off in multiple collisions





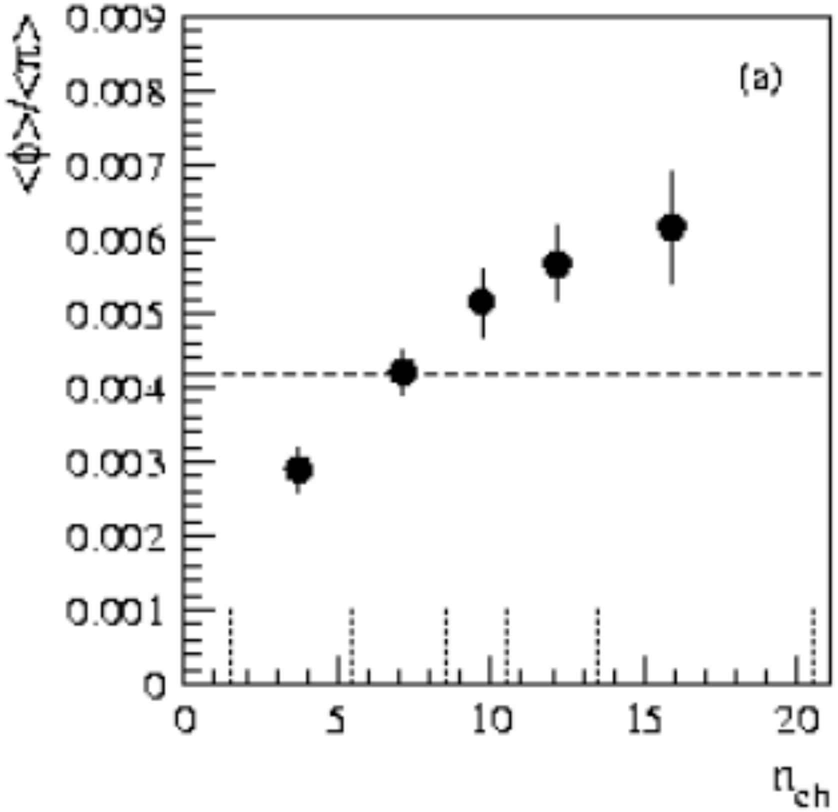
The same pattern for the production of strange baryons.

The fact that it has nothing to do with "QGP" :

seen in pA collisions

and even in pp collisions !

*relative yield of ϕ mesons in **pp** as a function of final state multiplicity (a trigger for multiple collisions)*



scaling quest

Imagine a target hit by a relativistic projectile (be it a hadron or a heavy 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***" ?

How to compare a quantity one measures in **AA** (or **pA**) collisions,
with the one ***simply rescaled*** from an elementary **pp** interaction ?

It is in this harmlessly looking "*simply rescaled*" where the devil resides.

Should an observable in **AA** interactions scale
with the number of ***participating nucleons*** (which may be as large as $\mathbf{n_p = 2A}$)
or instead as the number of ***elementary nucleon–nucleon collisions***, $\mathbf{n_c \sim A^{4/3}}$ ***?***

HARD phenomena are commonly expected to ***scale*** as $\mathbf{n_c}$, ***SOFT*** — as $\mathbf{n_p}$.

though strange this may seem, but

the QCD LPM effect provides a striking counter-example ...

LPM effect in *hA* scattering

recall : 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:

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

having combined the two estimates, we arrived at

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

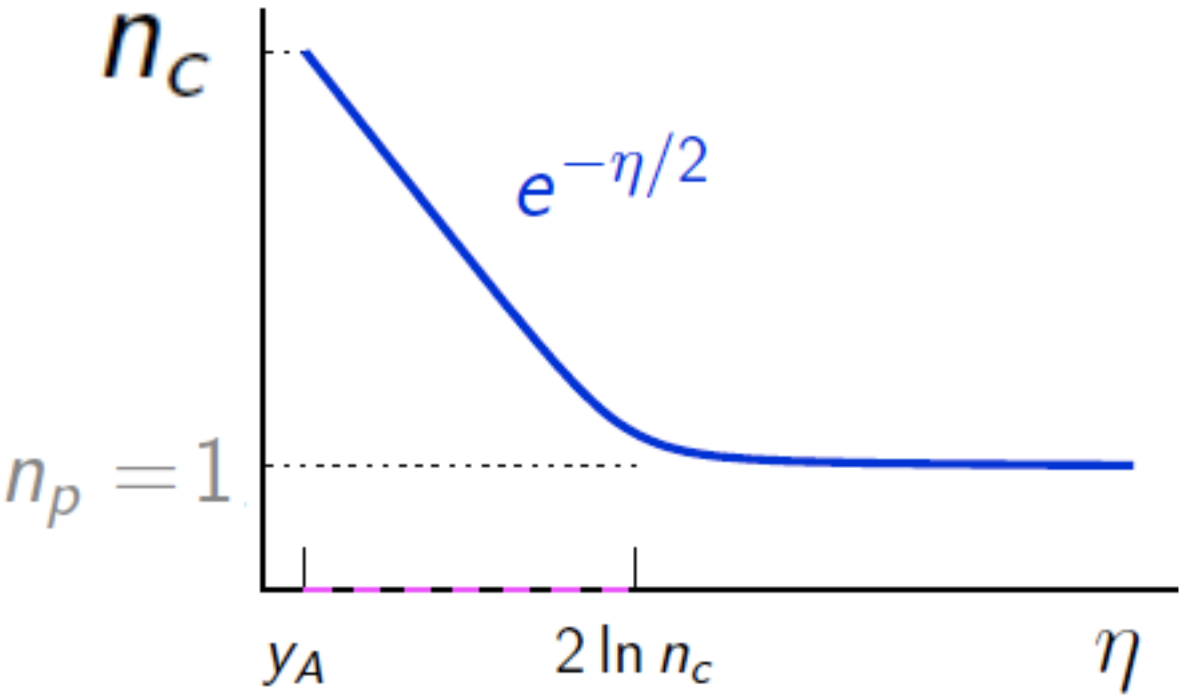
The *more energetic* gluons have
larger transverse momenta

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

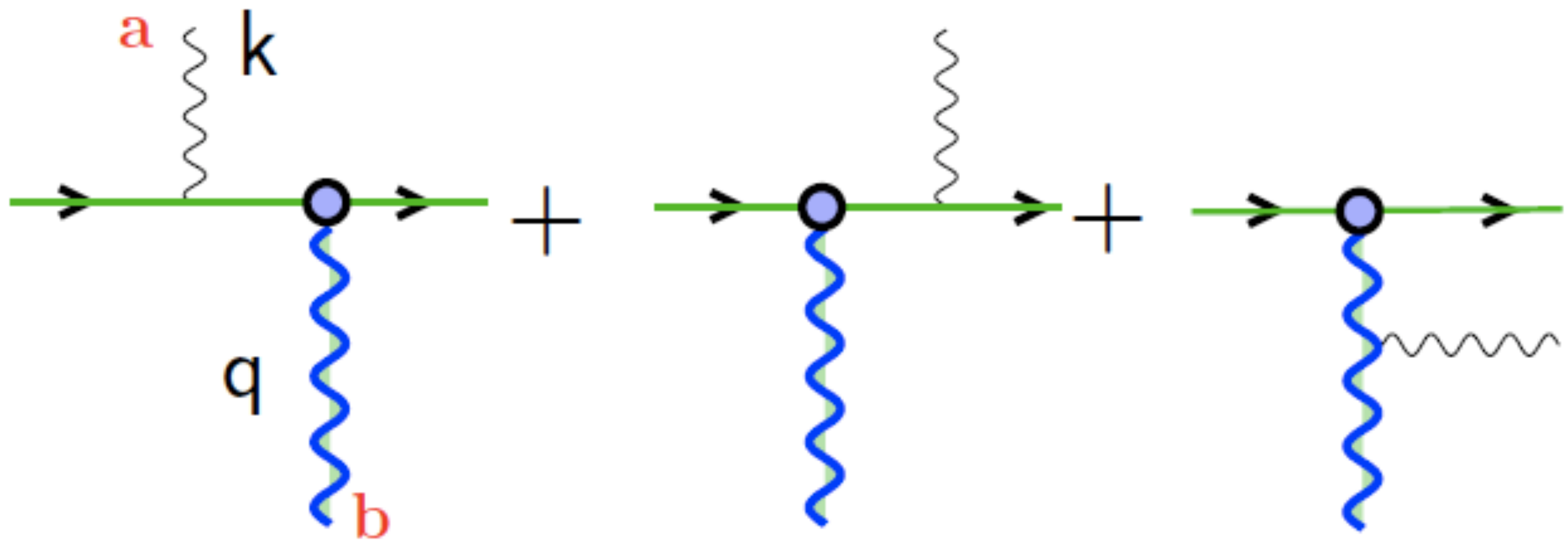
while the *less hard* radiation
obeys the *collisional scaling* pattern

! ?

Here comes confusing part ...



multiple collisions and Hadron Multiplicity



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

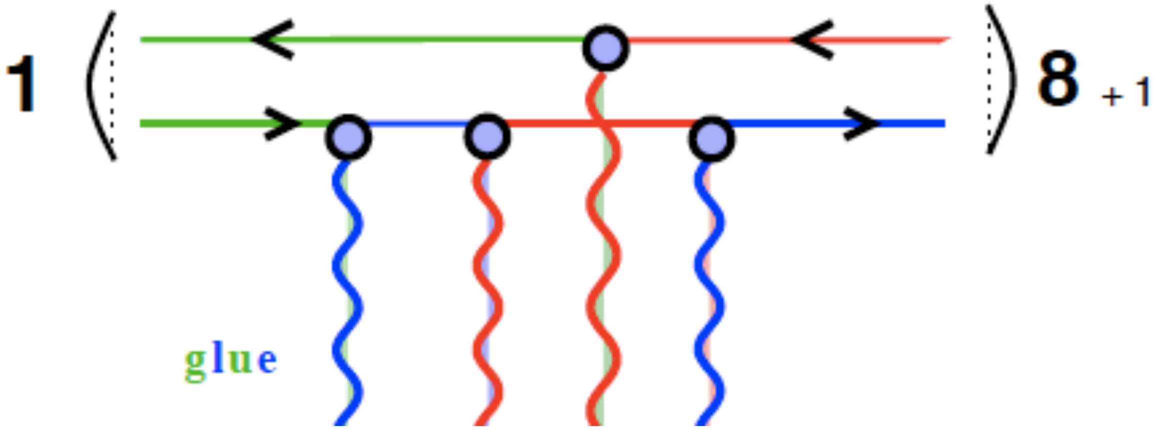
Accompanying gluon radiation depends
on the t-channel color exchange
but not on the nature of colliding objects !

- 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

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

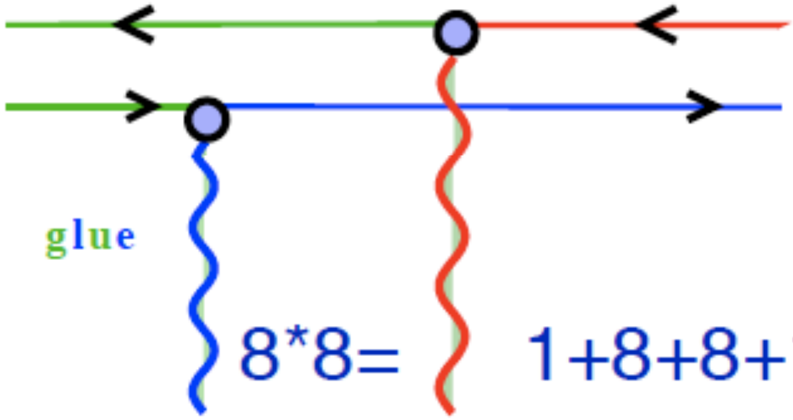
color capacity

Imagine ***multiple scattering*** in the QCD medium of a (2-quark) ***pion***



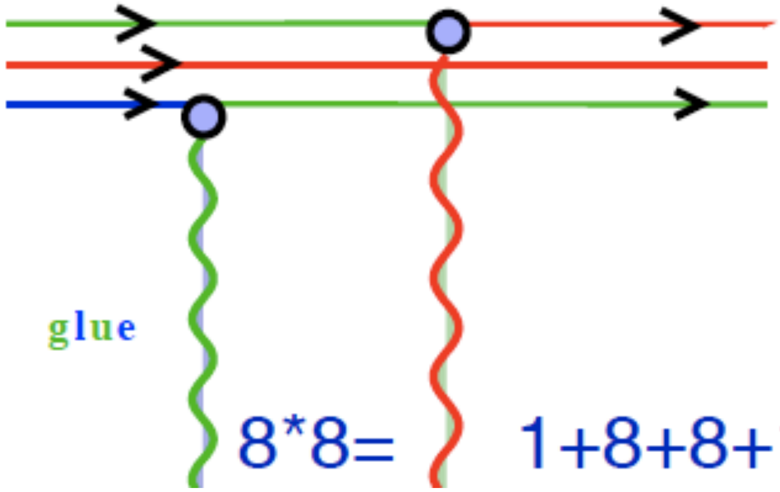
Many scatterings *BUT*
only ***one Pomeron !?***

Consider double scattering (two gluon exchange)



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

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



$3*3*3=1+8+8+10$

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

In meson scattering only ***two colour representations*** can be realized ...

The proton is more “capacious” *BUT* still ...

if we took a free average over gluon colours,

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

would get a ***double density*** of hadrons = ***two Pomerons***

cannot be realized on a ***valence-built proton*** : $\frac{1}{27}\cdot 0+\frac{8+8}{27}\cdot 3+\frac{10}{27}\cdot 6=4$ ***= 1.33 P*** **?**

time for climax

How to produce many final state hadrons in scattering in a medium?

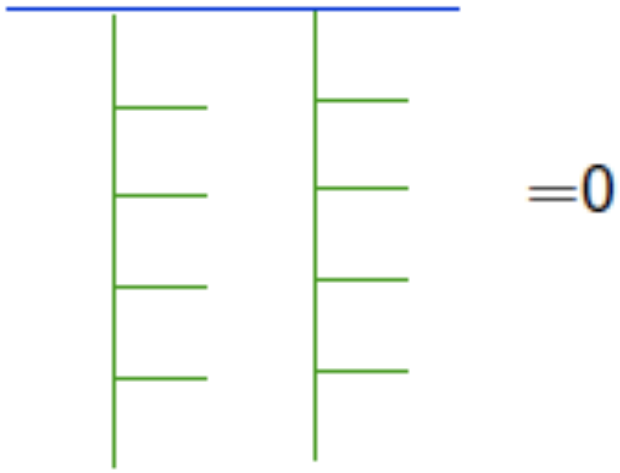
Color coherence, breathing projectiles and relativistic Gribov-Regge theory

Coherent picture of hadron accompaniment applies to the ***bulk of multiplicity*** (small transverse momentum hadrons) and implies relatively "***compact*** " projectiles (on the *penetrator* side).

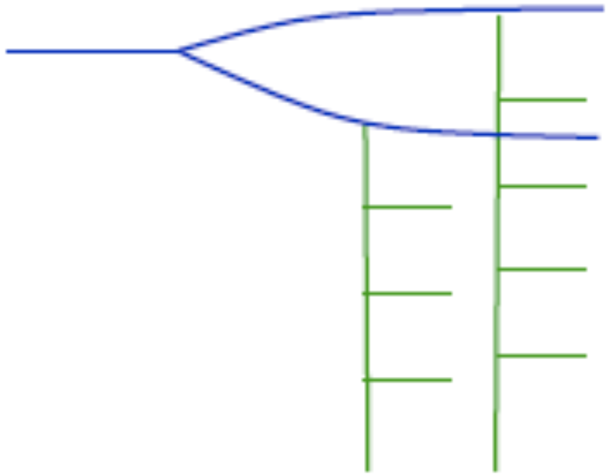
This destructive ***color coherence*** invalidates the ***multi-Pomeron exchange*** picture **!**

To have **N** **Pomerons** produce (up to) **N** times enhanced density of the hadron plateau, one must be able to find **N** *independent* (incoherent) *partons* inside the projectile.

Recall the good old *Amati-Fubini-Stanghellini puzzle* (heritage of the good old Gribov-Regge theory) :



Successive scatterings of a parton ***DO NOT*** produce ***branch points*** in the complex **J** plane (Reggeon loops).



The ***Mandelstam construction*** generates "*Reggeon cuts* ", with Pomerons attached to separate — ***coexisting*** — partons.

Confinement in Multiple Collisions

Medium induced radiation should lead to

- softening of particle spectra in a jet muddling thru medium,
- increase of (soft) particle multiplicity due to particles with
- specific relation btw energy and emission angle

Systematic jet studies in HI collisions have just started (thanks to fast jet finders) !

In the framework of the standard hadron (multi-Pomeron) picture 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 to "***non-independent fragmentation*** "
— **cross-talking** Pomerons, **overlapping** strings, "string **ropes**", . . . you name it

From the point of view of the color dynamics, in **pA** and **AA** environments we face an intrinsically new, unanswered question : After the pancakes separate, at each impact parameter we have the ***color field strength*** that corresponds to **~ $A^{1/3}$ / fm^2** strings...

How does the vacuum break up in such a – *stronger than usual* – ***color field*** ?

LEP has left the question unanswered ...
because it had never been asked ...

A stronger field might mean smaller distances, therefore -
larger momentum scales in hadronization, therefore -
larger strangeness yield - and many more unexplored "gifts" **...**