Looking forward in QCD

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Outline

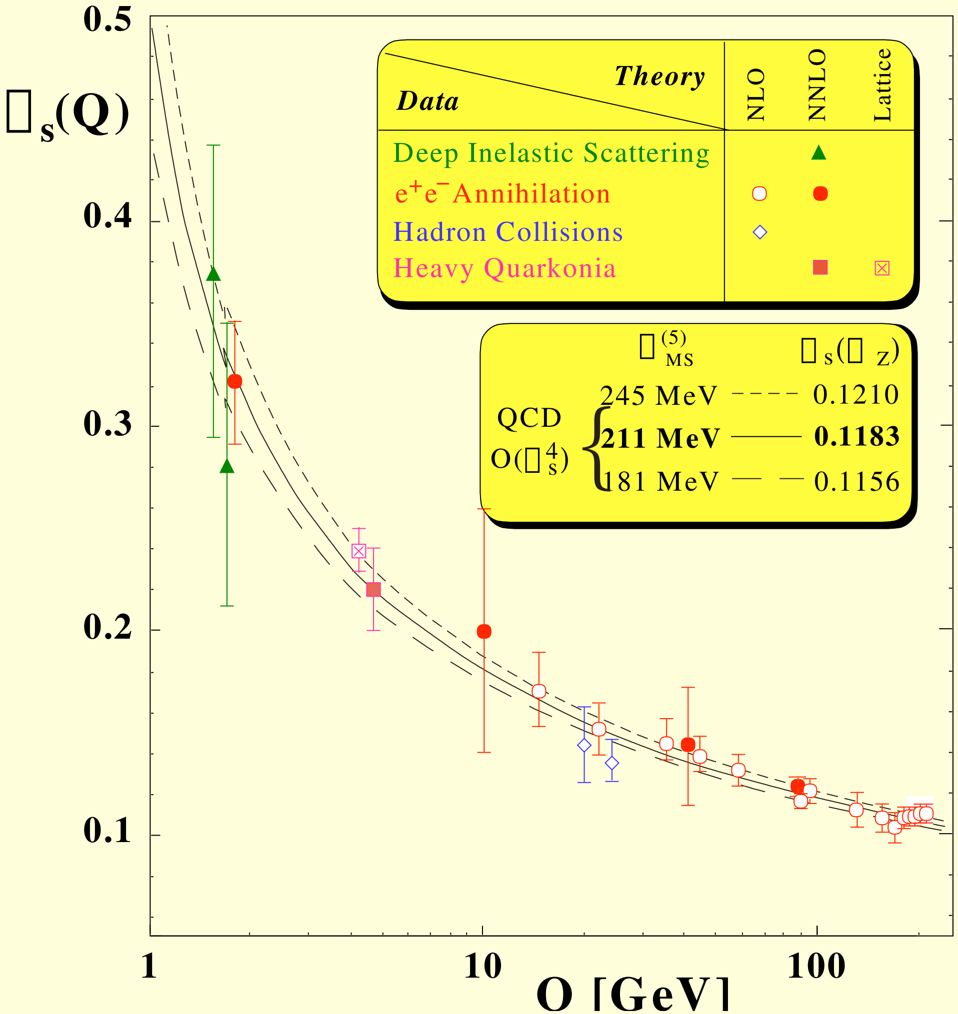
- Imaging a fast nucleon.
- Centrality trigger for pp collisions.
- Multijets - mapping of the correlations in nucleon
- Hard diffraction - probing nucleon periphery and color fluctuations

Why QCD is interesting

QCD is the only QFT realized in Nature which is potentially self consistent at all distances.*)

Interaction is strong at large distances - may provide confinement	$\Leftrightarrow$	Interaction is weak at small distances. No problems except probably at small x.

*)Amazing reversal of the paradigm of the 60's based on the Landau zero charge (increase of the strength of QFT interactions at short distances):
I.Pomeranchuk (~1956) - *``Our theory predicts infinities for the pion-nucleon interaction for small energies, but Nature seems not to know about this."*



Interaction at large distances is strong. However e.m. and weak interaction in this case are too weak to be relevant - solution should come from within QCD. In electroweak interactions situation is opposite - large interaction at short distances - need to modify the theory.

Strength of strong interaction $\alpha_s(Q)$ as a function of momentum transfer $Q \quad 1/distance$

⇒ *Detailed understanding of QCD will have lasting effect on the development of QFT.*

Role of High energy QCD:

- ☛ *Understanding the dynamics of strong gluon fields at small x: interesting by itself ; important for effective searches for new particles*

- ☛ *New unique probes of the nucleon structure*

- ☛ *Forward QCD dynamics is crucial for interpretation of the cosmic ray interactions near GZK cutoff*

Wish list (partially inspired by teaching/learning about applications of nuclear physics in medicine):

Want to be able to take CT scans of nucleon

in 3 D in quark and gluon light

at different momentum resolutions

instead of one dimensional scans - parton densities - which should continue especially at very small x.

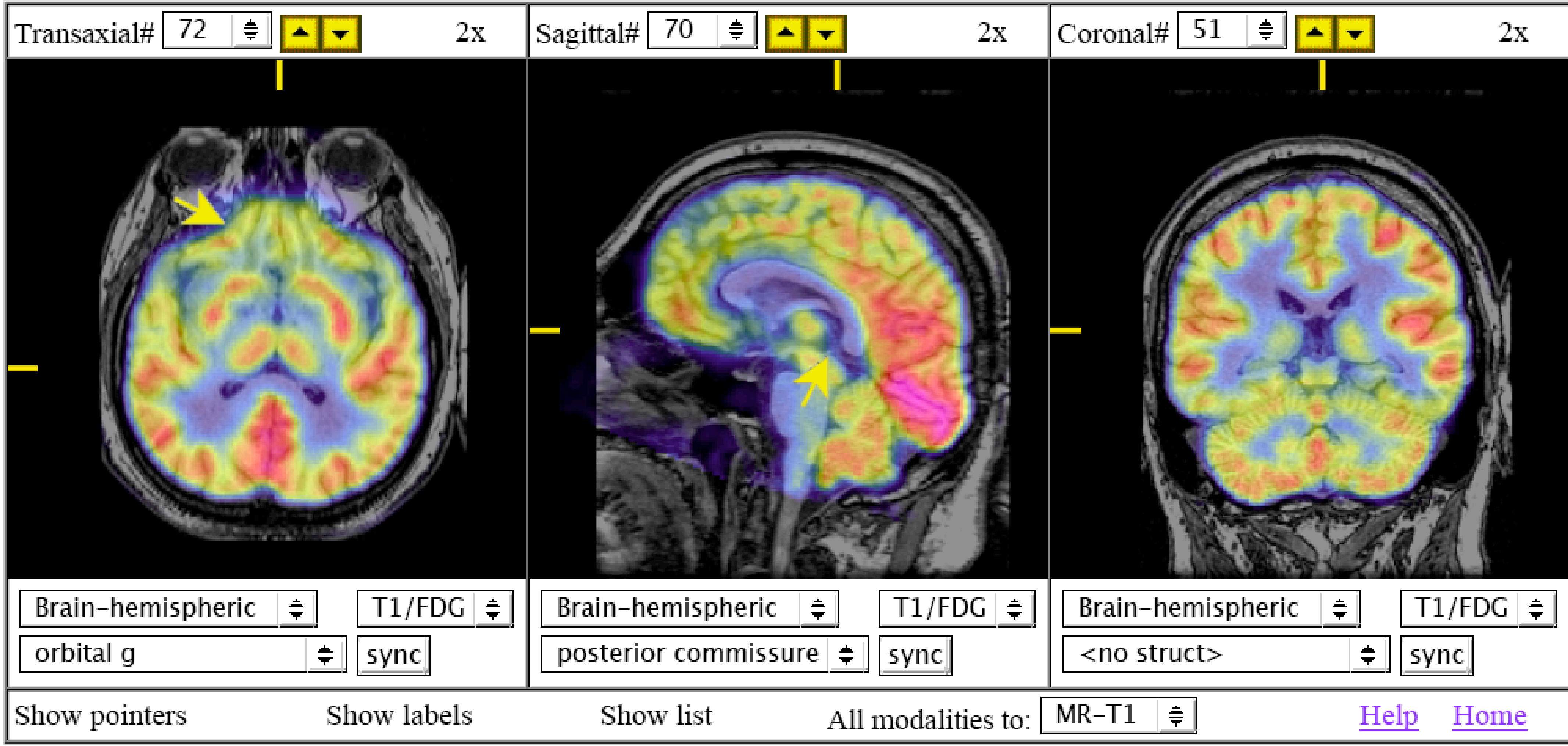
Learn how nucleon responds to various stimuli:

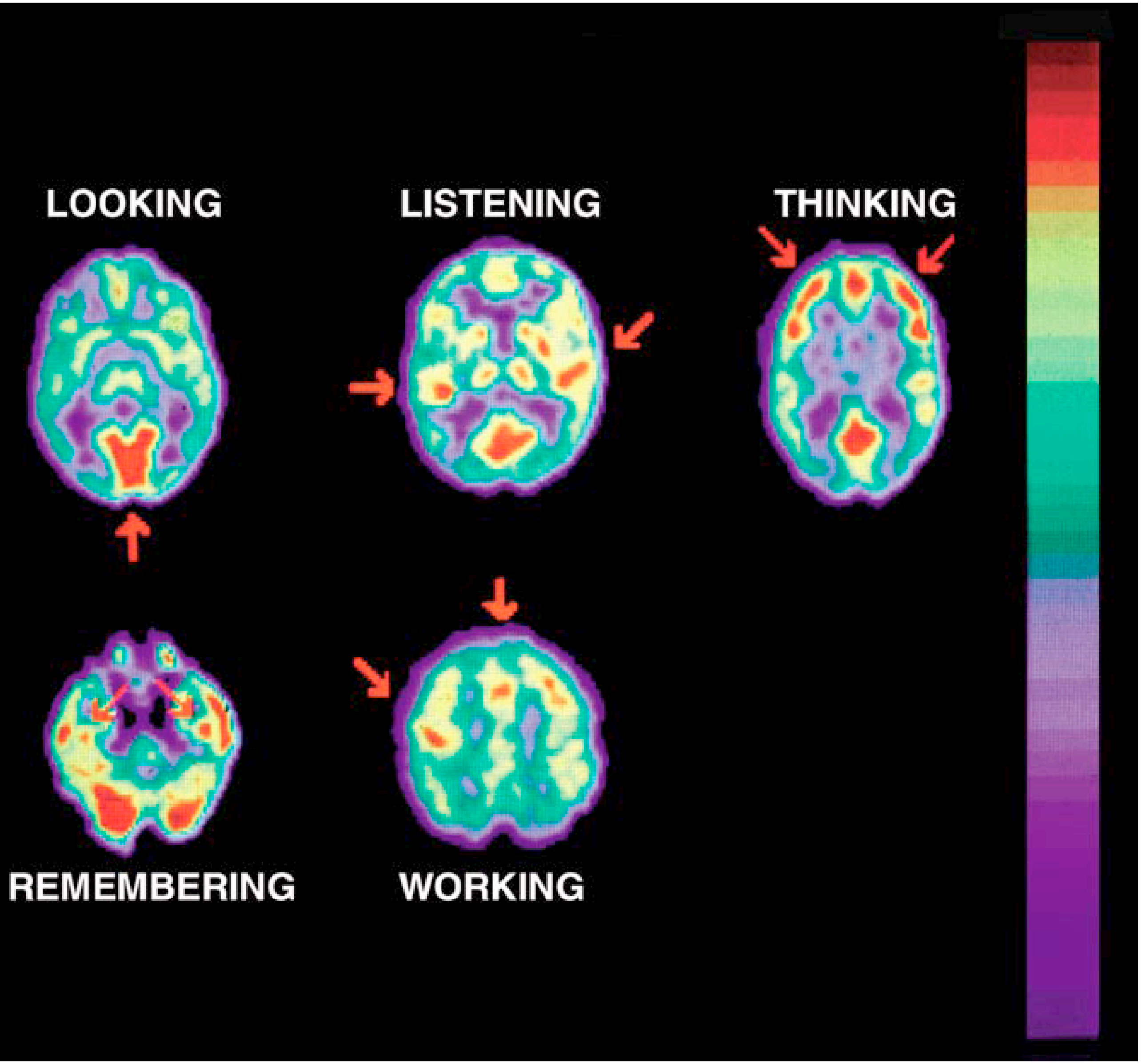
Correlations between partons

Correlations between longitudinal momenta of partons and transverse size of the nucleon.

We should learn to do at least as well as people who study brain!!!

Combined MRI & PET view of the 2D slices of a brain in different projections.



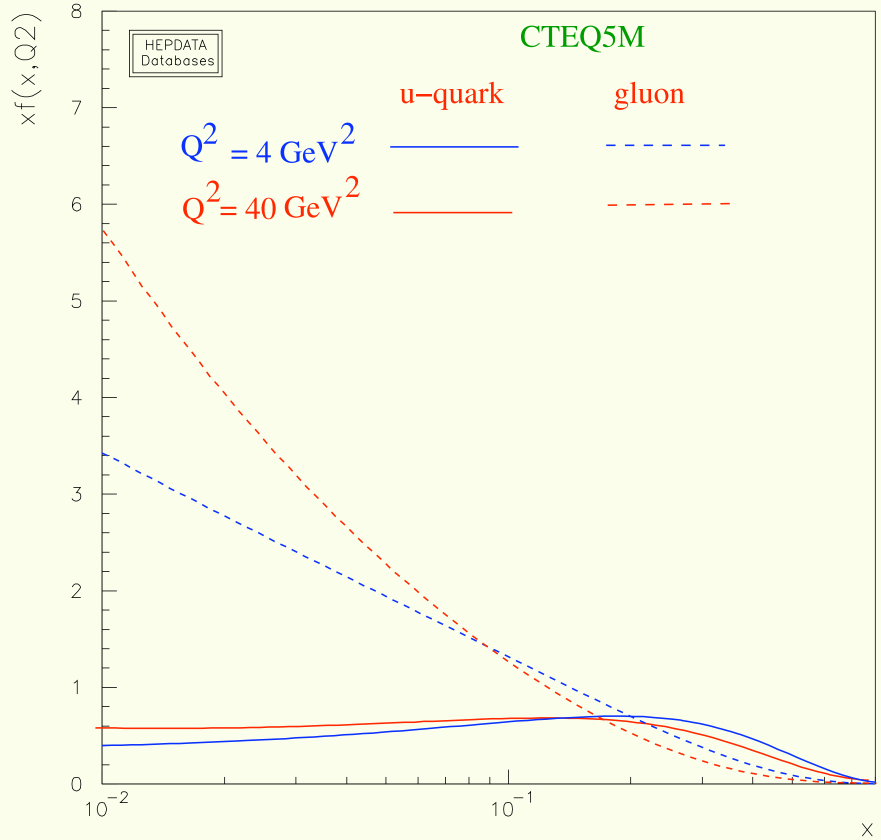


PET studies of glucose metabolism with FDG to map a human brain's activity in performing different tasks. Images are cross sections with the front of the brain at the top. Highest metabolic rates are in red, with lower values from yellow to blue. Arrows indicate the activated regions. Looking at a visual scene activated the visual cortex; listening to a mystery story with language and music activated the left and right auditory cortices; counting backward from 100 by sevens activated the frontal cortex; remembering a previously learned list of objects activated the hippocampus bilaterally; and touching the thumb to the fingers of the right hand activated the left motor cortex and supplementary motor system.

Key features of high energy QCD:

- Slow space-time evolution of the fast component of the high energy wave functions of colliding hadrons (Lorentz slow down)

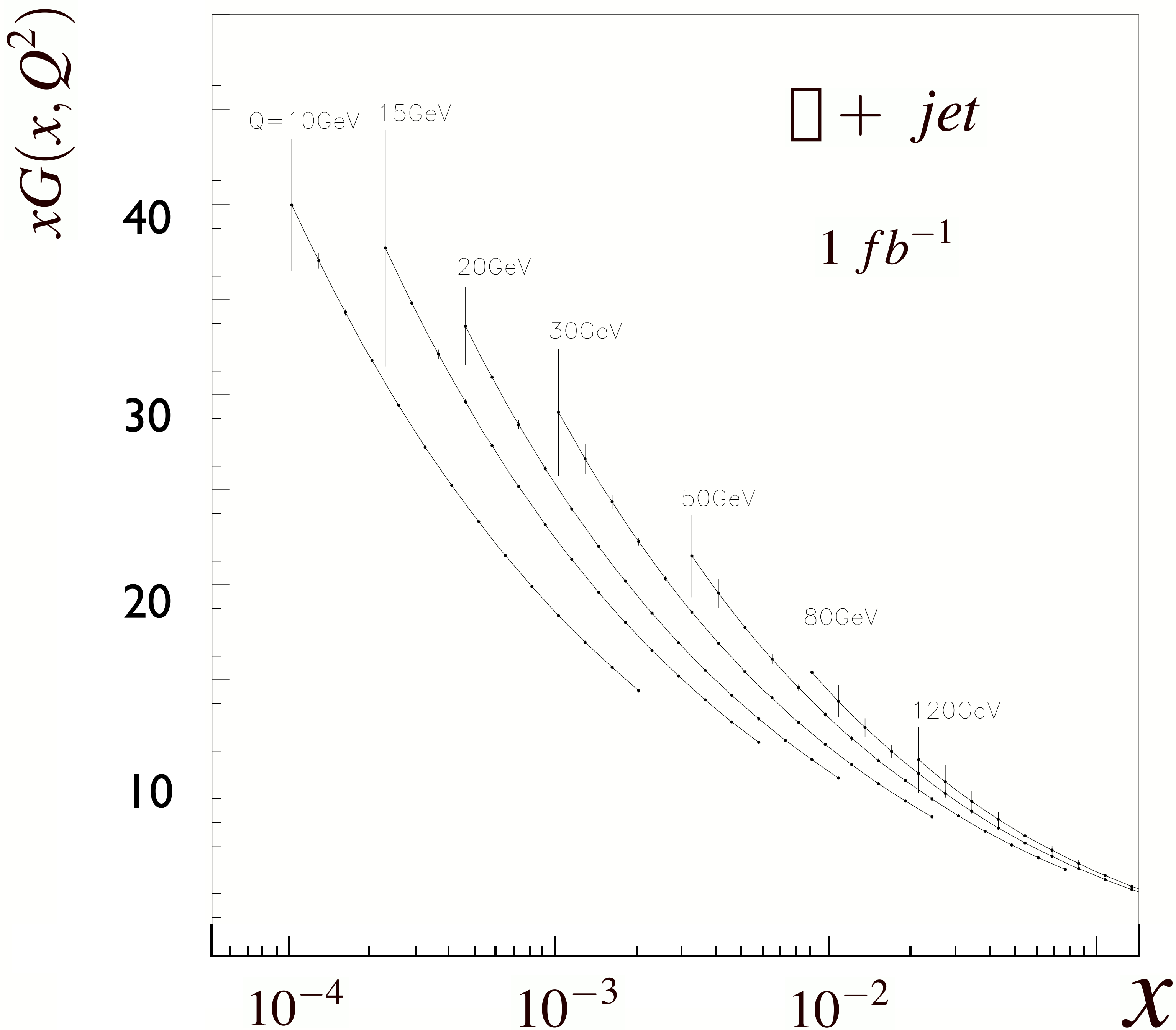
- Already at a rather modest resolution of the probe, Q~ 2 GeV, nucleon consists of not simply three quarks and few gluons but of tens of constituents and the number of constituents rapidly grows with energy.



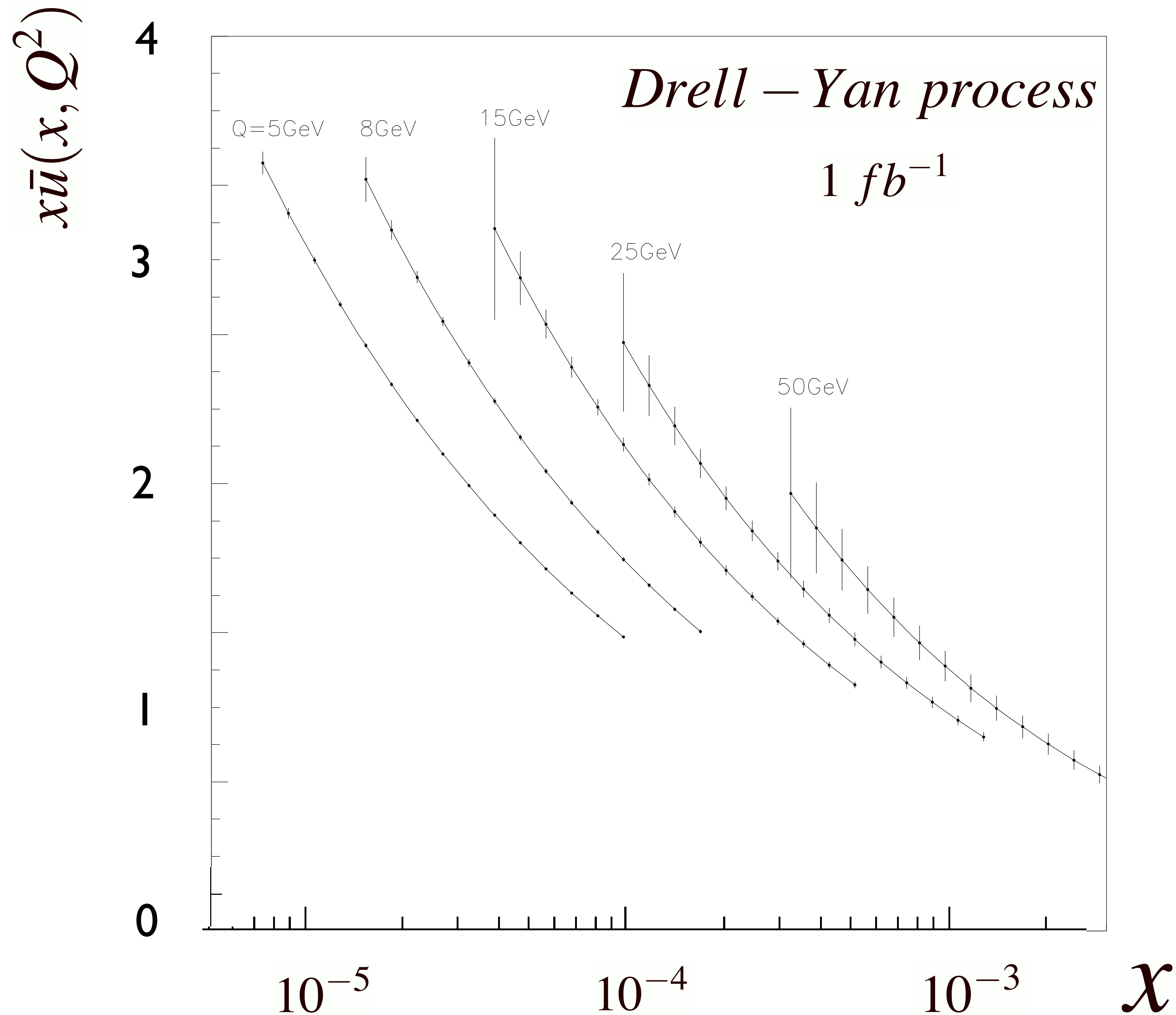
- Gluons carry ~50% of the nucleon momentum at the resolution scales as low as $Q^2 \sim m_N^2$ (nonperturbative dynamics). Speeds up generation of strong gluon fields at small x.

Warning: though single parton densities are generally reasonably well known the region of sufficiently small x where new physics is expected is not explored yet with a necessary number of cross checks even on the level of NLO QCD. In particular the gluon densities are directly measured for $x \geq 10^{-3}$ only. Accuracy of the LT approximation for small x is also needs further studies.

Kinematic of small x - medium x parton scattering at Tevatron resembles backscattering of a laser beam off a high energy electron beam. One needs very forward detector to measure the smallest x - there are several advanced tools - Zhang talk at the workshop. Counting rates even for processes like Drell-Yan and gamma-jet remain large close to the edge of the phase space.
A detector with a good acceptance at large rapidities would allow to extend HERA measurements at least by a factor of **twenty** both for gluons and quarks.

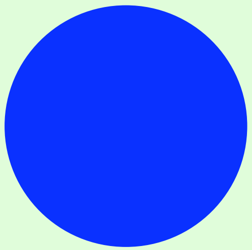


"recycled" Alvero et al 97 calculation for LHC

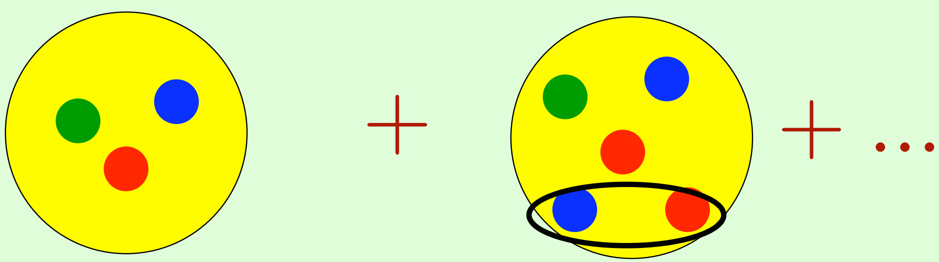


"recycled" Alvero et al 97 calculation for LHC

Image of nucleon at different resolutions, q. Rest frame.



resolution 1 fm, $q <$ 300 MeV/c

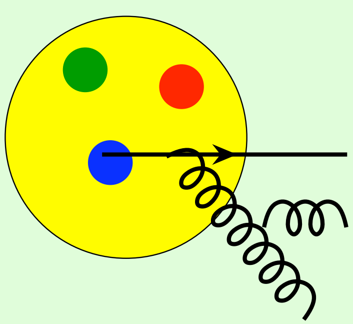


$q\bar{q}$ pair in □

resolution 1/3 fm

1000 > q > 300 MeV/c

Constituent quarks, pions (picture inspired by chiral QCD)



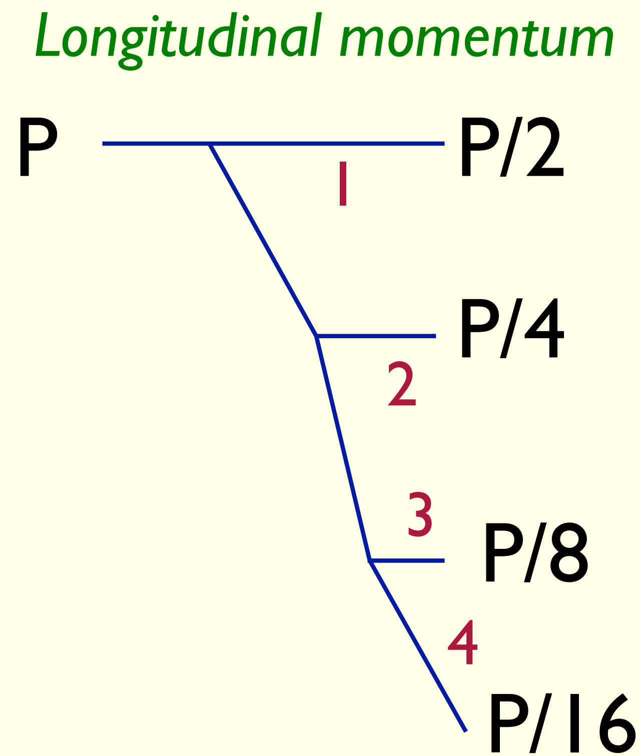
$q >$ 1000 MeV/c

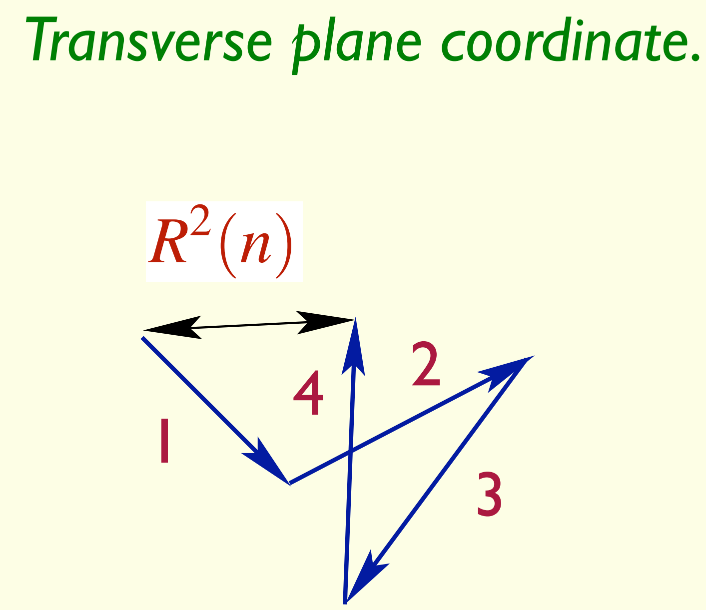
pQCD evolution

Image of nucleon at different resolutions, q. Fast frame.

Energy dependence of the transverse size of soft partons.

Decay of a fast parton





$R^2(n) \approx \frac{n}{k_{t0}^2}$ Random walk in b-space (Gribov 70). *(Drunken sailor walk)*

Length of the walk rapidity, y. The transverse size of the soft wee parton cloud should logarithmically grow with energy.

$$n \quad y \Longrightarrow R^2 = R_0^2 + cy \equiv R_0^2 + c' \ln s$$

Logarithmic increase of the t-slope of the elastic hadron-hadron scattering amplitude with energy:

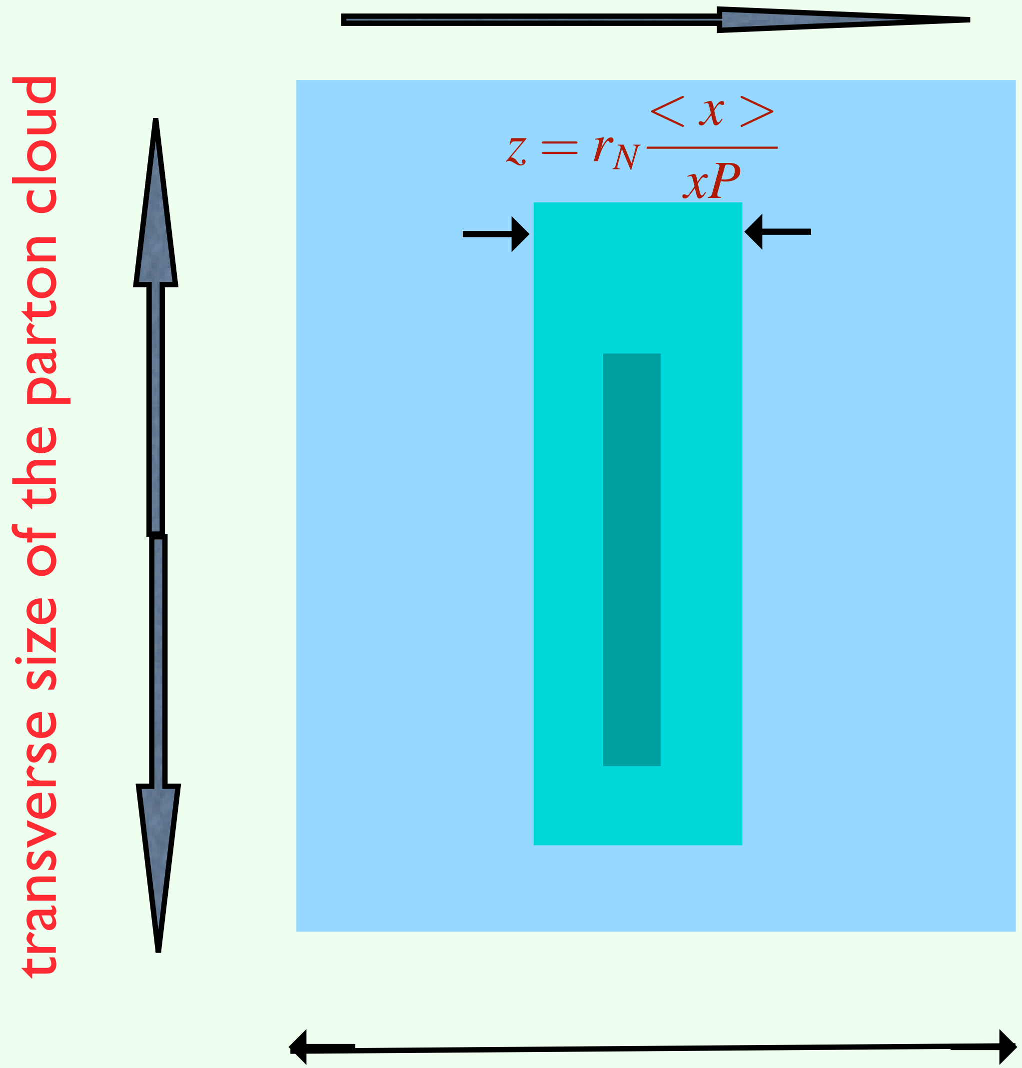
$$f(t) \quad \exp(Bt/2), \; B(s) = B_0 + 2\square' \ln(s/s_0)$$

$$\square' \quad 1/k_{t0}^2$$

Sagittal cut of the fast nucleon - low resolution scale

$$z = r_N \frac{<x>}{xP}$$

Momentum P in z direction



wee parton are spread over 1 fm even at high energies

Saggital Image at High resolution

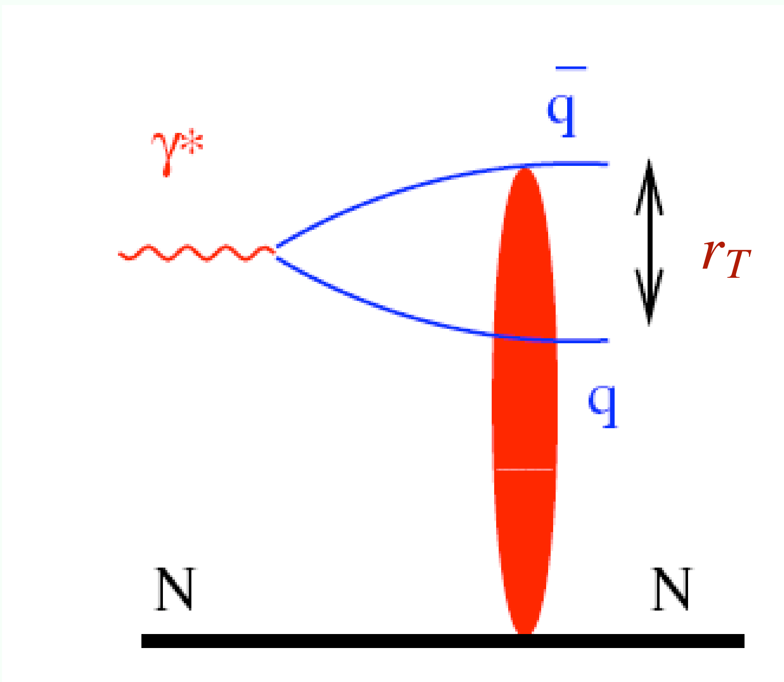
Gribov diffusion is much weaker as the transverse momenta in most of the decay ladder are much larger than the soft scale. Transverse size shrinks with increase of resolution scale!!! *No analogous effect in classical mechanics (brain images).*

Evidence: Π' for the process $\square + p \to J/\square + p$ is smaller than for soft processes by a factor of two.

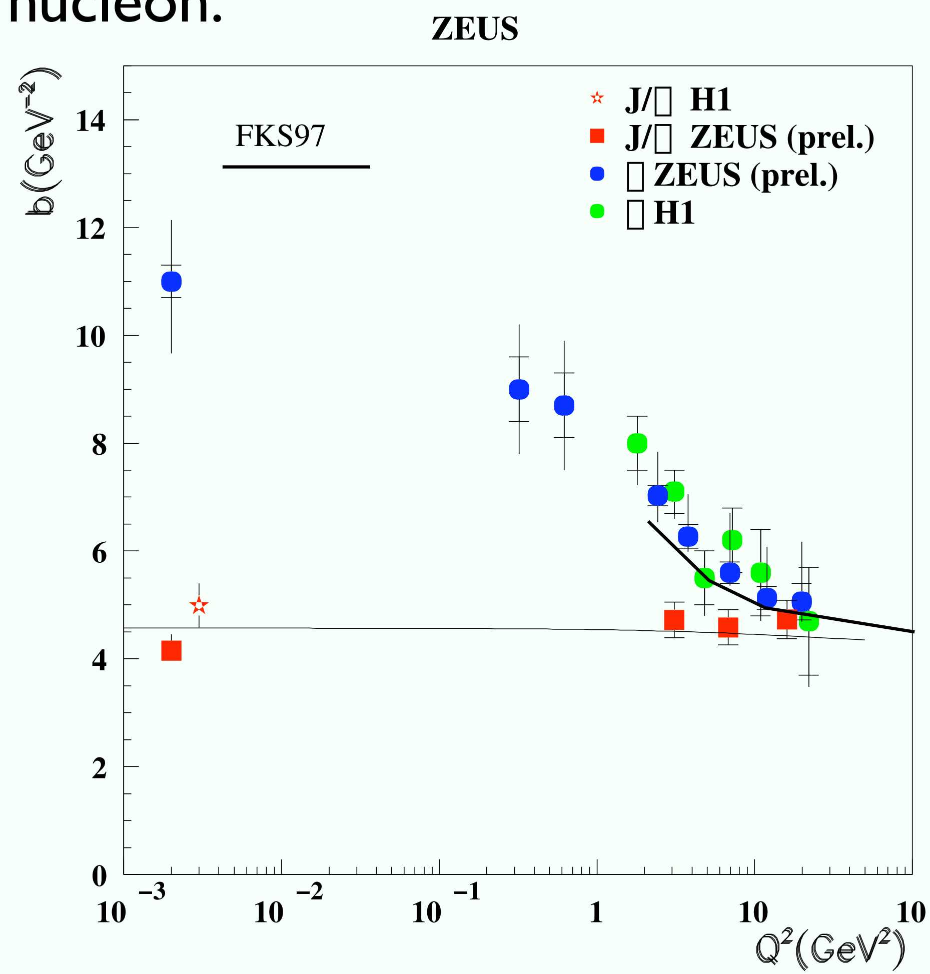
Confirms our prediction of 94 - BFGMS

Additional important effect: transverse distribution of x≥.05 gluons in the nucleon is significantly smaller than a naive guess based on the e.m. radius of the nucleus.

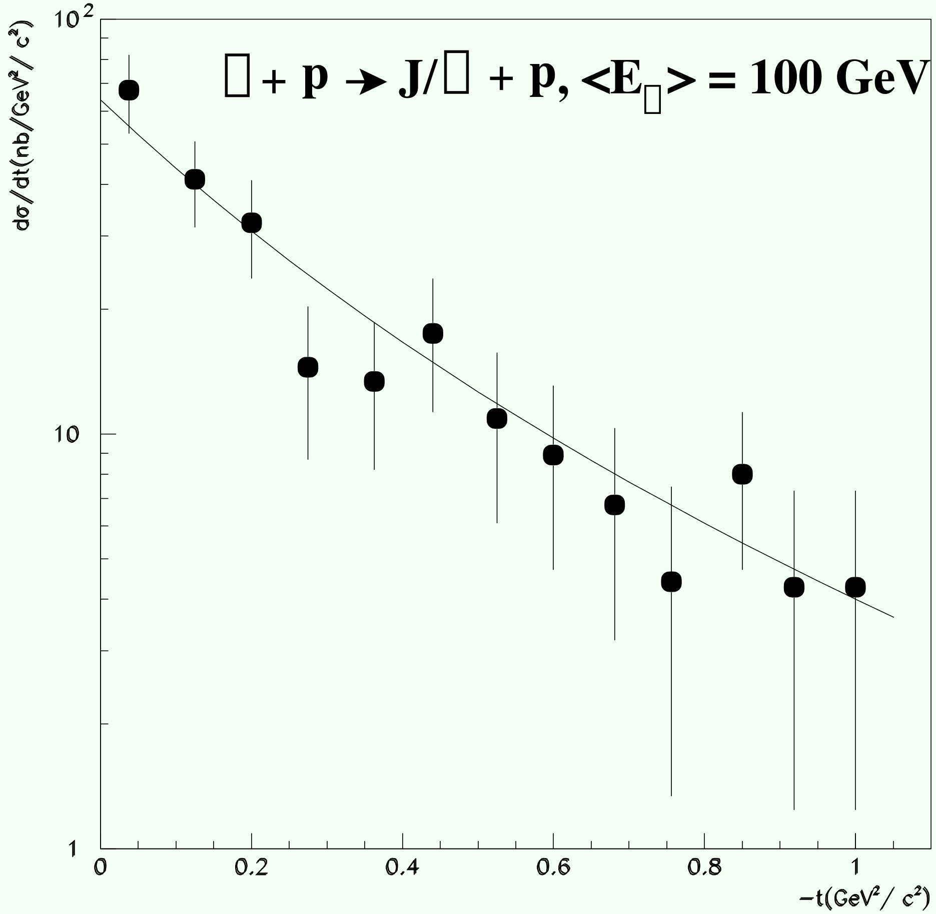
Transverse distribution of gluons can be extracted from the studies of exclusive vector meson electroproduction in DIS including J/psi photoproduction.
Theory: BFGMS 94,FKS96: process is dominated by the scattering of quark-antiquark pair in a small size configuration - t-dependence is predominantly due to the transverse spread of the gluons in the nucleon.



$$\frac{1}{Q}\left(\frac{1}{m_c}\right) \ll r_N$$



Convergence of the t-slopes of rho-meson production at large Q and J/psi photo(electro)production.



Data from: Binkley et al 82 (FNAL)

The curve corresponds to the two-gluon form factor of the nucleon

$$F_{2g}(t) = \frac{1}{(1 - t/m_{2g}^2)^2}$$ with $m_{2g}^2 = 1.1\ GeV^2,$

which is larger than e.m. dipole mass

$$m_{e.m.}^2 = 0.7\ GeV^2.$$ (FS02)

The difference is likely due to the chiral dynamics - lack of scattering off the pion field at x>0.05 (Weiss &MS 03)

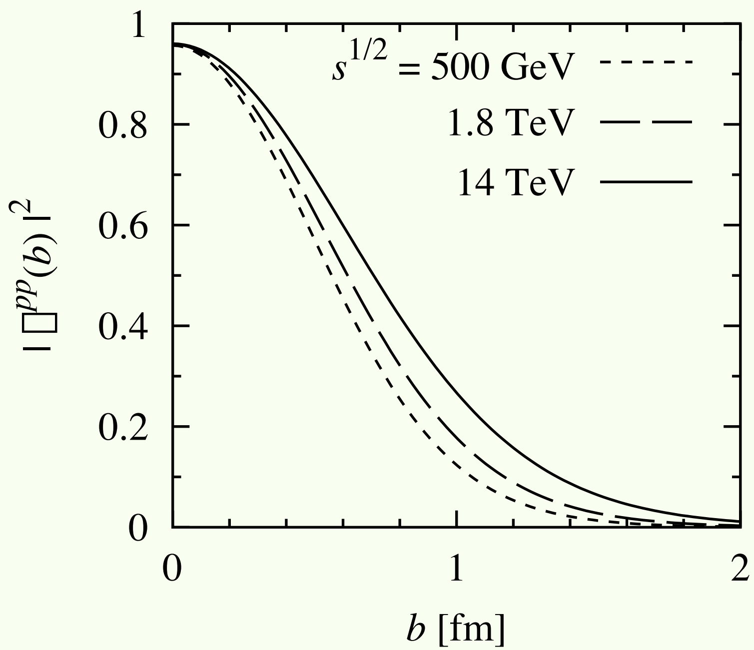
Large difference between impact parameters of soft interactions and hard interactions especially for x > 0.01.

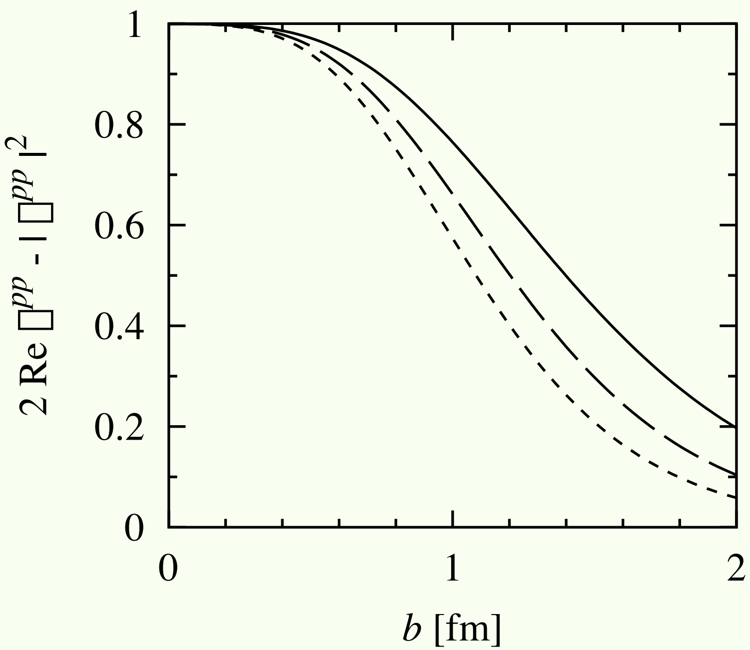
Implications: associated hadron production in dijet/new particle production; suppression of hard diffraction.

Impact parameter distribution in pp interaction

Study of the elastic scattering allows to determine how the strength of the interaction depends on the impact parameter, b:

$$\Gamma_h(s,b) = \frac{1}{2is}\frac{1}{(2\pi)^2}\int d^2\vec{q}\, e^{i\vec{q}\vec{b}} A_{hN}(s,t)$$





Calculation uses model of Islam et al

Probability of inel. interaction:

$$P(b) = 2\,Re\,\Gamma(b) - |\Gamma(b)|^2$$

$\Gamma(b) = 1 \equiv \sigma_{inel} = \sigma_{el}$ - black body limit.

Warning: relation between $\Gamma(s,b)$ and the scattering amplitude seems to indicate that elastic scattering occurs at small impact parameters. In fact this is the wave goes around the target which survived nearly complete absorption at small b. Relevant for suppression of hard diffraction at Tevatron.

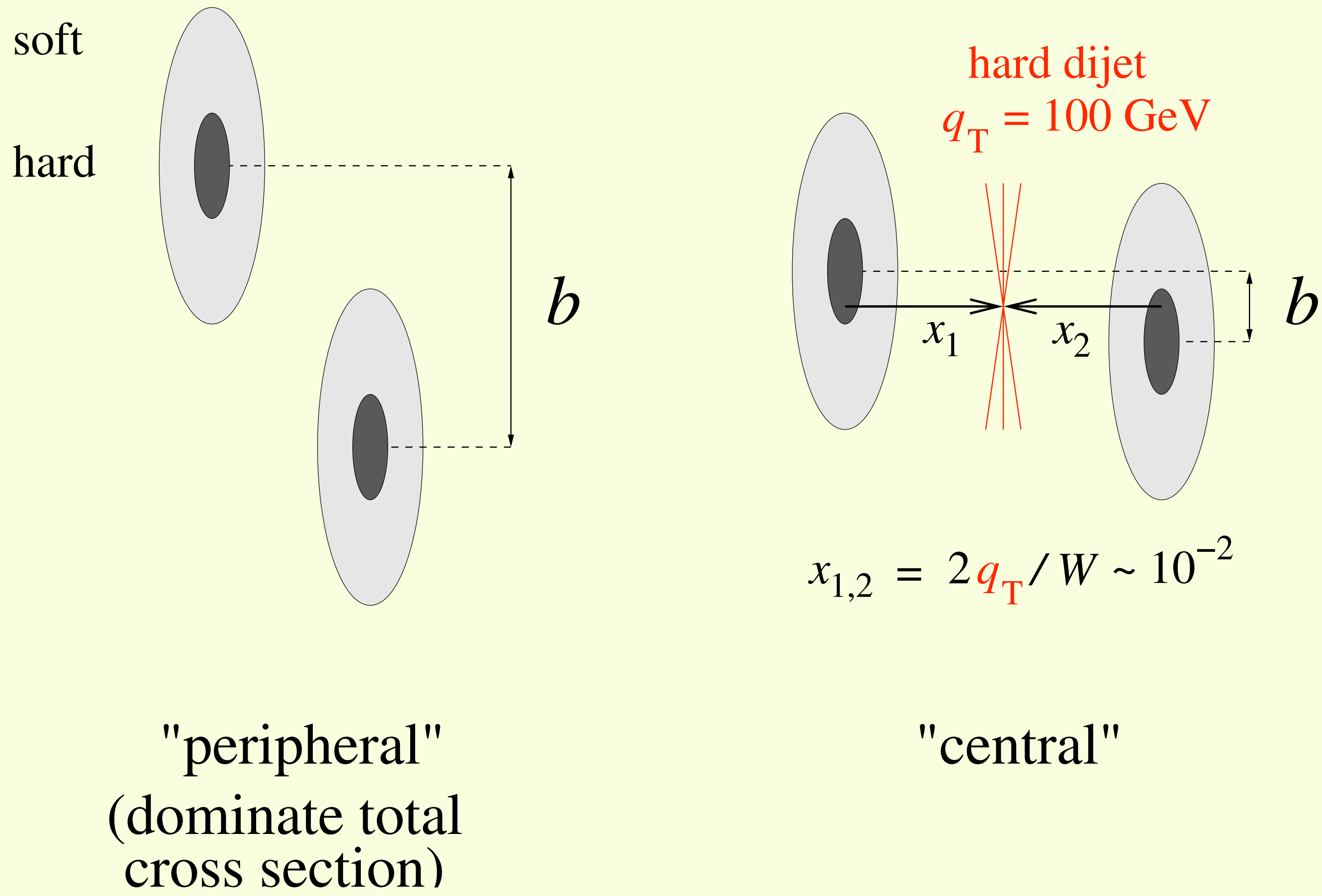
Answer is the same as using Eq. from the previous slide – complementarity principle: diffraction off the hole and absorptive disk of the same shape are the same.

Quiz: consider scattering of a deuteron off a large absorptive nucleus so that $\sigma_{inel}(pA) = \sigma_{el}(pA)$.

Select events where one nucleon went through the center (centrality trigger). What is probability that the second nucleon scatters elastically?

- ○ 100 %
- ○ 50 %
- ○ 0 %

Centrality of the collisions



Main idea: hard partons are more localized in transverse plane. Hence in events with hard interaction spectator partons experience much stronger gluon fields.

Transverse spatial distribution of hard partons in the nucleon

For gluons it is given by the Fourier transform of the two gluon form factor as

$$F_g(x, \rho; Q^2) \equiv \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i(\mathbf{\Delta}_\perp \boldsymbol{\rho})} F_g(x, t = -\mathbf{\Delta}^2_\perp; Q^2)$$

It is normalized to unit integral over the transverse plane, $\int d^2\rho \, F_g(x, \rho; Q^2) = 1.$

Using the dipole fit to the two-gluon form factor:

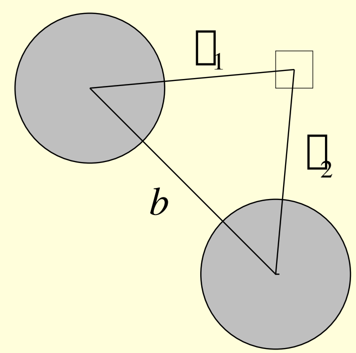
$$F_g(x, \rho) = \frac{m_g^2}{2\pi} \left(\frac{m_g \rho}{2}\right) K_1(m_g \rho), m_g = 1.1 GeV$$

The x dependence of the slope was modeled by fitting $m_g(x)$ to reproduce J/ψ data. The Q^2 dependence was accounted using LO DGLAP evolution at fixed ρ.

Impact parameter distribution for a hard multijet trigger.

For simplicity take $x_1 = x_2$ for colliding partons producing two jets with $x_1 x_2 = 4q_\perp^2/s$. Answer is not sensitive to a significant variation of x_i for fixed $q_\perp$.

The overlap integral of parton distributions in the transverse plane, defining the b–distribution for binary parton collisions producing a dijet follows from the figure:



Hence the distribution of the cross section for events with dijet trigger over the impact parameter b is given by

$$P_2(b) \equiv \int d^2\rho_1 \int d^2\rho_2 \, \delta^{(2)}(\boldsymbol{b} - \boldsymbol{\rho}_1 + \boldsymbol{\rho}_2) F_g(x_1, \rho_1) \, F_g(x_1, \rho_2),$$

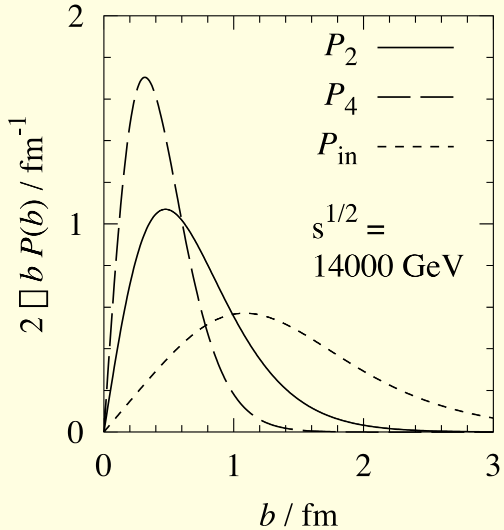
where $x_1 = 2q_\perp/\sqrt{s}$. Obviously $P_2(b)$ is automatically normalized to 1.

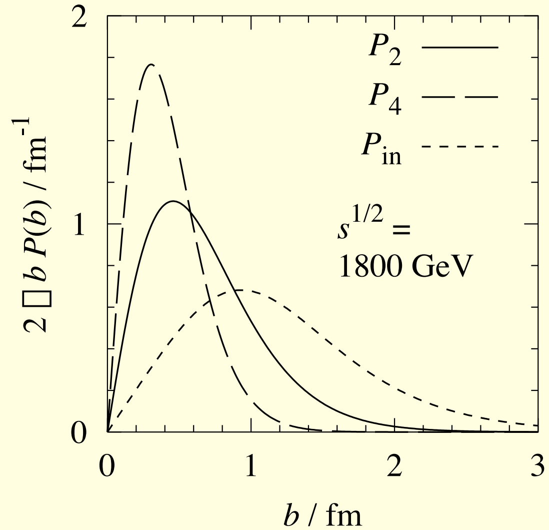
For a dipole parameterization:

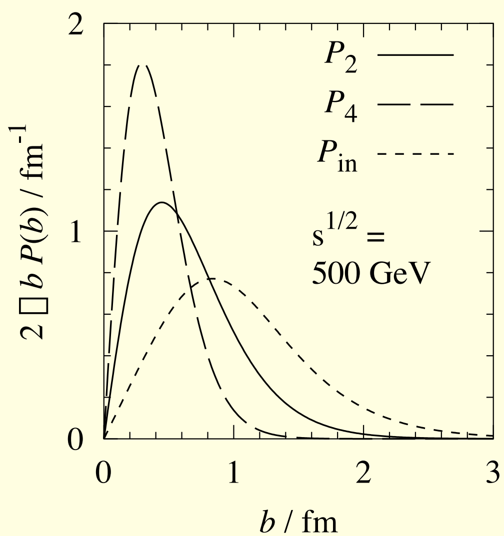
$$P_2(b) = \frac{m_g^2}{12\pi} \left(\frac{m_g b}{2}\right)^3 K_3(m_g b)$$

For two binary collisions producing four jets *assuming no correlation between gluons in the transverse plane*:

$$P_4(b) = \frac{P_2^2(b)}{\int d^2b \, P_2^2(b)}; P_4(b) = \frac{7\, m_g^2}{36\pi} \left(\frac{m_g b}{2}\right)^6 [K_3(m_g b)]^2 .$$







Difference between b-distributions for minimal bias and dijet, four jet events strongly increases with increase of incident energy. *Solid lines:* b–distributions for the dijet trigger, $P_2(b)$, with $q_\perp = 25\, GeV$, as obtained from the dipole–type gluon ρ–profile. *Long–dashed line:* b–distribution for double dijet events, $P_4(b)$. *Short–dashed line*: b–distribution for generic inelastic collisions.

Consider now event where via dijet trigger a central collision is selected. The fast spectator partons go through the stong gluon fields as well - up to large virtualities. They resolve the gluon fields with $x_2 \geq 4p_t^2/x_{spect}s$

To simplify the discussion, we consider instead of a parton in the ``projectile" the scattering of a small color--singlet dipole off the ``target" nucleon. This is in the spirit of the dipole picture of high--energy scattering of Mueller 94. For a small dipole interaction is weak:

$$\sigma_{inel}^{dipole-N}(x,d) = C\frac{\pi^2}{3}d^2\alpha_s(d^2)xG_N(x,\lambda/d^2), C = 1 \; for \; \bar{q}, \; C = 9/4 \; for \; gg \; dipole.$$

$\Rightarrow$ for fixes small size (virtuality) impact factor Γ reaches values close to one –breakdown of the pQCD description – as the incident energy increases.

Average p_t acquired by a spectator parton

$\Leftrightarrow$

Maximum p_t for which interaction remains nearly black times the geometrical factor to be at small impact parameter.

At Tevatron it leads to

$$< p_t^2 > \geq 2\ GeV^2\ for\ x \geq 0.05$$

$$< p_t^2 > \geq 1\ GeV^2\ for\ x \geq 0.004$$

Final state properties for central pp collisions

In the central (dijet triggered) pp collisions all leading partons will end up with large (few GeV/c) transverse momenta - similar to central pA collisions at RHIC.

$\longrightarrow$ Many similarities with expectations for spectra of leading hadrons inpA collisions Dumitru,Gerland, MS02.

Qualitative predictions for properties of the final states with dijet trigger

- The leading particle spectrum will be strongly suppressed compared to minimal bias events. The especially pronounced suppression for nucleons: for $z \geq 0.1$ the differential multiplicity of pions should exceed that of nucleons.

- The average transverse momenta of the leading particles $\geq 1\, GeV/c$.

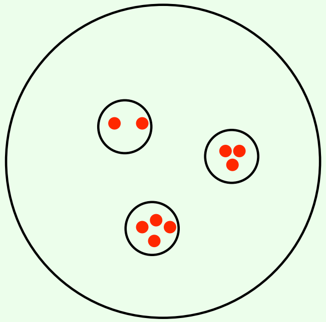
- A large fraction of the events will have no particles with $z \geq 0.02$-0.05. This suppression will occur simultaneously in both fragmentation regions, corresponding to the emergence of long--range rapidity correlations between the fragmentation regions.

- In the forward production of dimuons or dijets one expects a broadening of the distribution over transverse momenta (Gelis,Jalilian-Marian 2002), as well as a weaker dependence of the dimuon production cross section on the dimuon mass for masses of a few GeV (Frankfurt, MS2002).

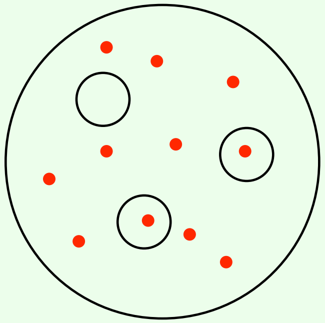
- At LHC we find much larger p_t broadening - will affect searches of the new particles. It would be difficult to establish direction of the jets unless $p_t(jet) \gg < p_t >_{BBL}$

- Forward cone of the primary proton - air interaction near ZGK cutoff will often resemble iron-air interactions.

Multi-jet production - study of parton correlations in nucleons

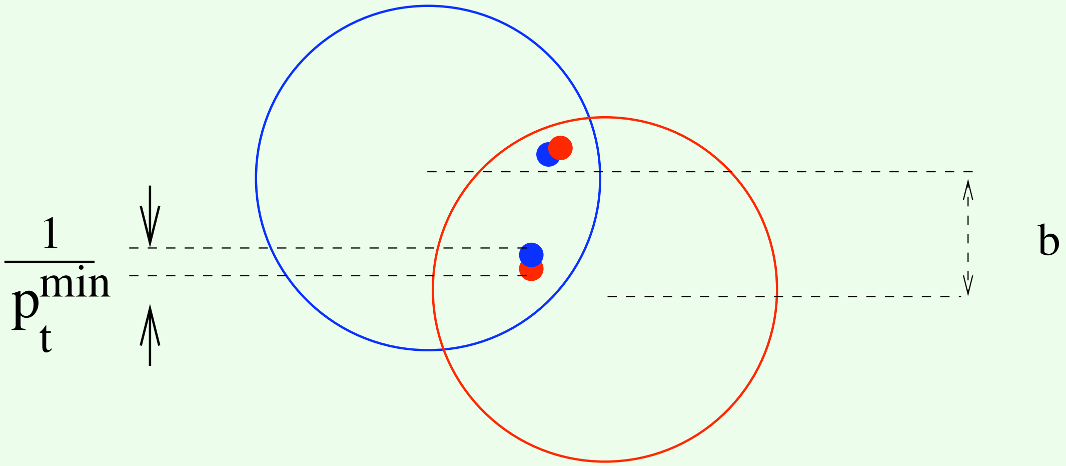


a)



b)

Where is the infinite number of primordial 'sea' partons in the infinite momentum state of the proton: inside the constituent quarks (a) or outside (b) ?



A view of double scattering in the transverse plane.

At high energies, two (three ...) pairs of partons can collide to produce multijet events which have distinctive kinematics from the process two partons → four partons.

Experimentally one measures the ratio

$$\square_{eff} = 14.5 \pm 1.7^{+\ 1.7}_{-\ 2.3}\ mb$$

$$\frac{\frac{d\square(p+\bar{p}\to jet_1+jet_2+jet_3+\square)}{d\square_{1,2,3,4}}}{\frac{d\square(p+\bar{p}\to jet_1+jet_2)}{d\square_{1,2}}+\frac{d\square(p+\bar{p}\to jet_3+\square)}{d\square_{1,2,3,4}}} = \frac{f(x_1,x_3)f(x_2,x_4)}{\square_{eff}f(x_1)f(x_2)f(x_3)f(x_4)}$$

where $f(x_1,x_3), f(x_2,x_4)$ longitudinal light-cone double parton densities and

$\square_{eff}$ is ``transverse correlation area".

CDF observed the effect in a restricted x-range: two balanced jets, and jet + photon and found $\square_{eff} = 14.5 \pm 1.7^{+\ 1.7}_{-\ 2.3}\ mb$ rather small - a naive expectation is $\square_{eff}$ ~ 60 mb indicating high degree of correlations between partons in the nucleon in the transverse plane. No dependence of $\square_{eff}$ on x_i was observed.

Possible sources of small $\sqcup_{eff}$ include:

☺ Small transverse area of the gluon field --accounts for 50 % of the enhancement $\sqcup_{eff}$ ~ 30mb (F&S & Weiss 03)

☺ Hot spots (QCD evolution) (A.Mueller)

☺ Constituent quarks - quark -gluon correlations (F&S&W)

A detector with acceptance over a large range of rapidities would allow to separate quark-gluon correlations at moderate x (constituent quarks) and effects due to the QCD evolution - which should dominate at small x. It would be possible also to compare quark-quark (very forward region), quark-gluon and gluon-gluon correlations as well as to study associated hadron production.

Searching for the ultimate color fluctuation in the nucleon wave function - 3 quark point like configurations

Fluctuations of interaction strength are likely to be correlated with quark content of the hadron. The smallest configurations are most likely the minimal Fock state ones.

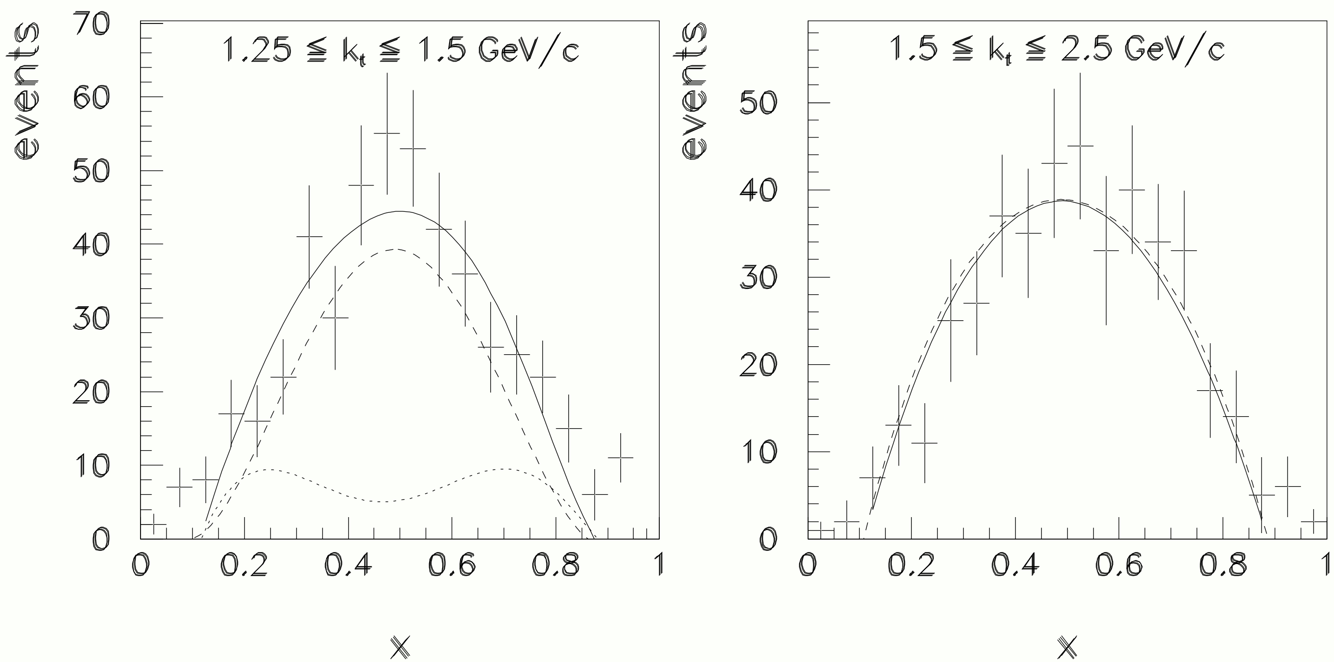
Important feature of QCD: QCD sum rules, form factors at large Q, chiral dynamics. Experimental evidence: Pion diffraction into two jets, inelastic coherent diffraction off nuclei.

☀ Very forward physics: $p\bar{p} \rightarrow$ "$jet_1 + jet_2 + jet_3$" $+ \bar{p}$ ☀

Measurement of the proton wave function in l3q> configuration with small transverse distance separation.

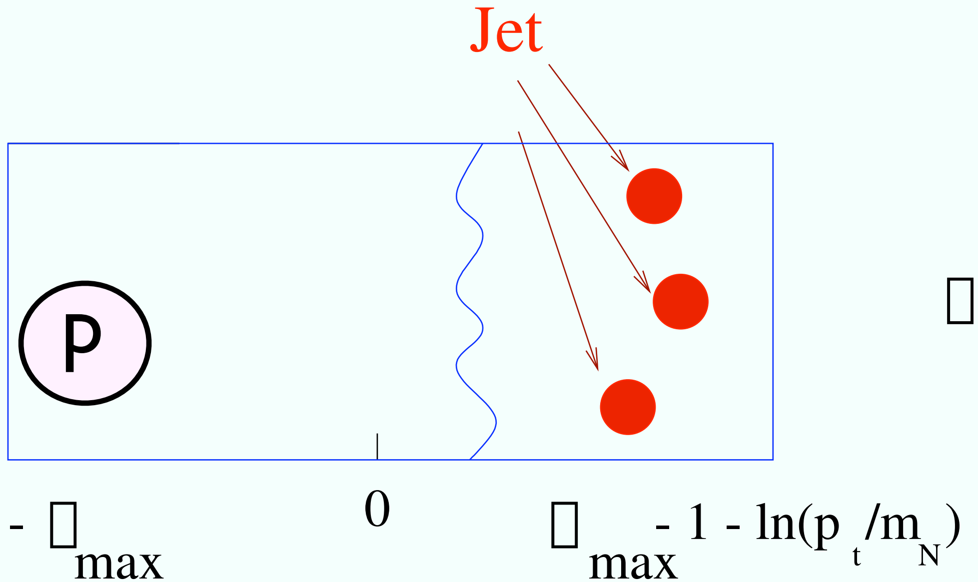
Extension of the study of $\square + N(A) \rightarrow \text{“}2\ high\ p_t\ jets'' + N(A)$

by FNAL 791 (2001), which confirmed Miller &F&S 93 prediction for the A-dependence, z-, p_t-dependence of the dijet coherent cross section.



Solid lines are the asymptotic (large pt) prediction:

$$\square(z) \quad \square^2_{\square}(z) \quad (1-z)^2 z^2$$



Lego plot for the coherent 3 jet production in proton-(anti)proton scattering

$$\frac{d\sigma(p\bar{p} \rightarrow (jet_1 + jet_2 + jet_3) + A)}{dt \prod_{i=1}^{3} dx_i d^2 p_{ti}} \quad \left[\alpha_s x G_N(x, p_t^2)\right]^2 \cdot$$

$$\cdot \frac{\psi_N^2(x_1, x_2, x_3)}{\prod_{i=1}^{3} p_i^4} \delta^2\left(\sum_{i=1}^{3} \vec{p}_{ti} - q_t\right) \delta\left(\sum_{i=1}^{3} x_i - 1\right) F_{2g}^2(t)$$

$where\ t = -q_t^2, x_A = M_{3\,jet}^2/2s, \psi_N$ nucleon 3 q wave function.

Advantages of the collider kinematics: it is easy to select coherent processes using zero angle neutron calorimeter. Energy dependence is very strong if there is no taming of gluon densities since

$$xG_N(x, Q^2 \sim 100\ GeV^2) \quad \frac{1}{\sqrt{x}} \quad \Longrightarrow \square_{3\ \ jet} \qquad s\ !!!$$

At TeV collider one can hope to distinguish three jet configurations with

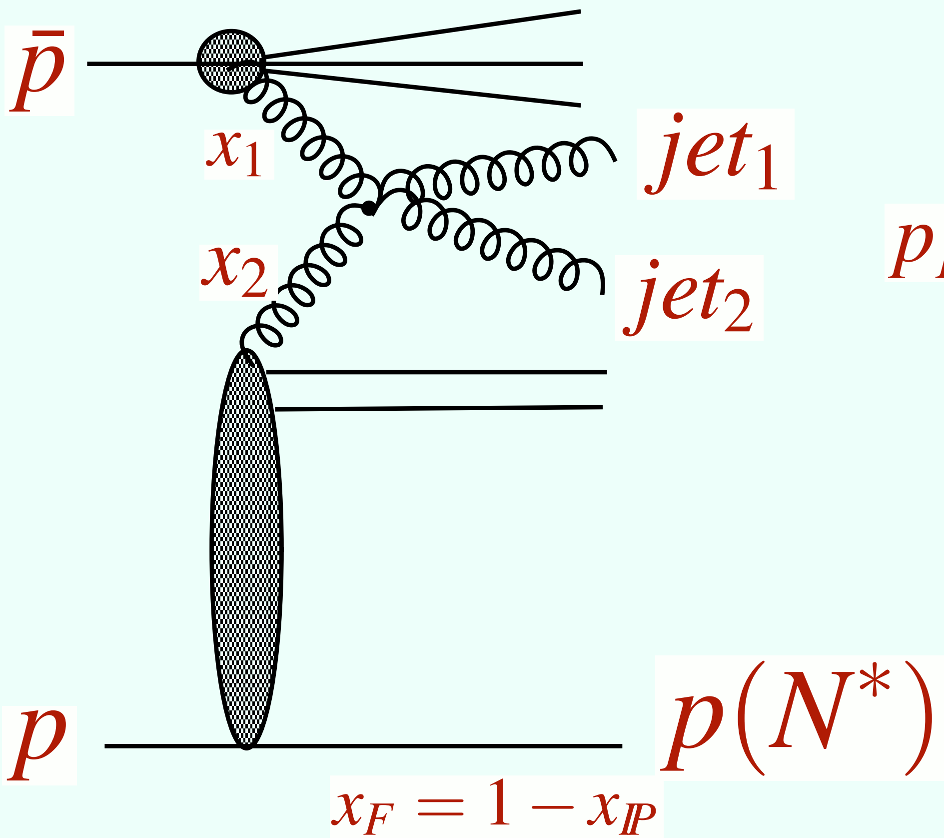
$p_t \geq\ 5\ GeV/c$ corresponding to $s = \frac{M^2_{3\ \ jet}}{s} = \frac{9p_t^2}{s} \sim\ 10^{-4}$

The magnitude of the cross section is $10^{\square 5}$ mb when integrated over $p_t \geq\ 5\ GeV/c$

Comments:

- If diquark-quark correlations are present in nucleons, one can look for 2 jet fragmentation.
- Interesting to search for exclusive channels at smaller p_t like $p \to p□^+□^-, □K^+, \ldots$ to find an effective trigger for interaction in point like configuration. Optimal way to do this would be via study of double diffraction in pp scattering looking for the channels rapidly growing with incident energy - as one expects for the scattering of two small dipoles.

Inclusive hard diffraction - *probing the edge of the nucleon and color fluctuations.*



$$p\bar{p} \longrightarrow \; jet_1 +_2 + X \; + \; \bar{p}$$

Kinematics is similar to the process extensively studied at HERA:

$\Box + p \to jet_1 + jet_2 + X + p$ and to some extent $\Box^* + p \longrightarrow X + p.$

(seminar of D.Sover on Friday)

What is the difference between the photon and with the proton cases?

Strong suppression in the proton case as one needs to require that soft partons did not lead to inelastic interaction:

$$P(b) = |1 - \square(b)|^2$$ -- favors large b

find a gluon in antiproton with $x = x_1 \geq 0.05$ at a transverse distance □

given by $F_g(x_1, \square)$ -- favors small □ and hence small b.

Hence **only peripheral collisions can contribute**. Net result is *a very strong suppression of hard diffraction as compared to calculations assuming the impulse approximation with the diffractive parton densities measured at HERA.*

The magnitude of the suppression is reasonably reproduced in this picture - see e.g. Martin, Khoze, Kaidalov, Ryskin papers.

⇒ Hard diffraction is a perfect way to scan the nucleon periphery. Complementary information from hard double diffraction.

- Sensitivity to the increase of the overall nucleon size with energy -larger suppression of hard diffraction at higher energies Observed at Tevatron.

- Possibility to probe correlation between strength of interaction and x & flavor of the parton in the diffracting nucleon.

  Breakdown of factorization for hard diffraction is not reduced to an overall renormalization factor as compared to HERA.

To explain qualitative expectations I have first to acknowledge that I cheated a bit.

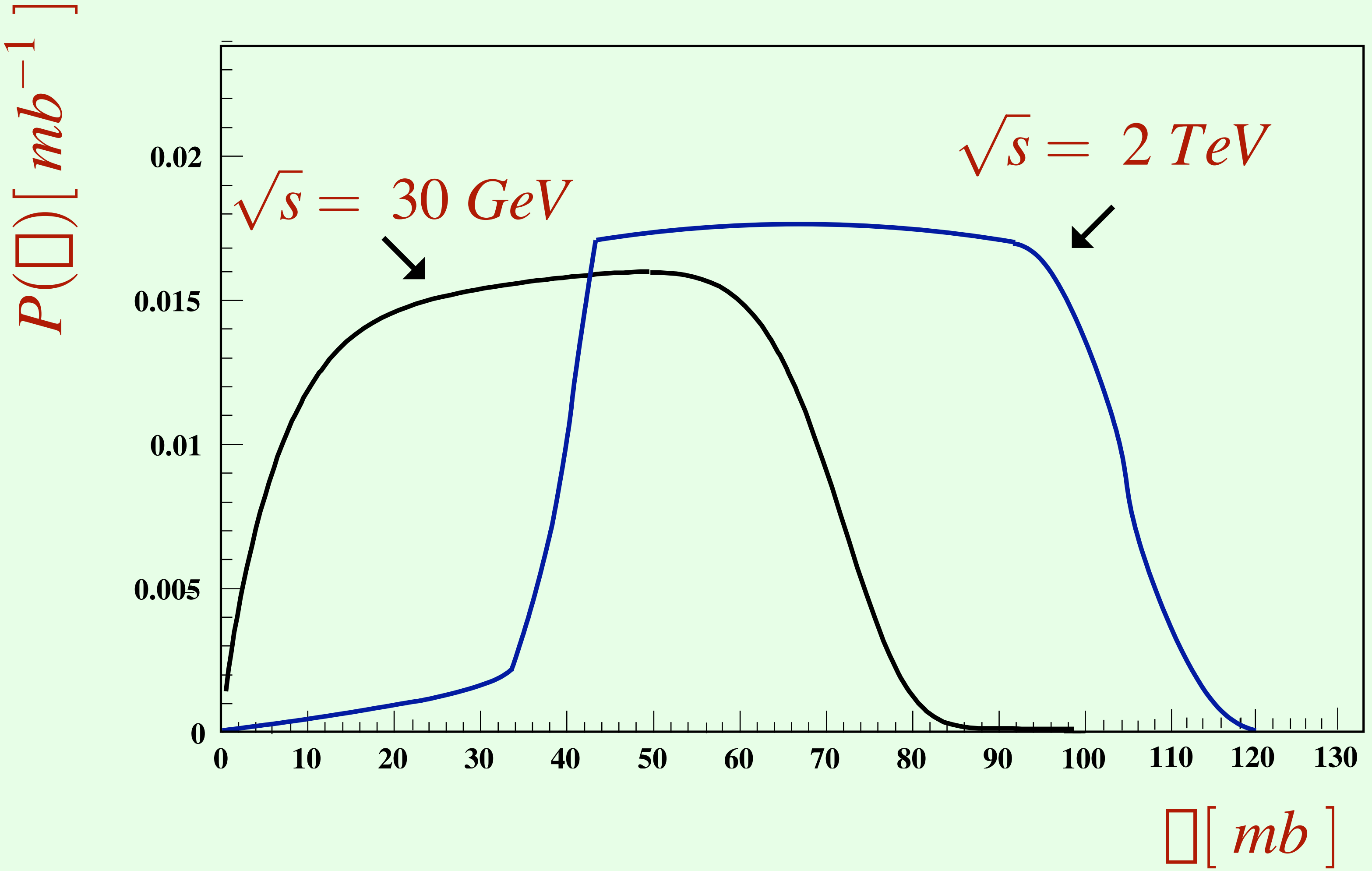
I did not discuss fluctuations of the strength of interaction of a fast nucleon (though I implicitly used it when discussing diffraction into three jets).

Due to a slow space-time evolution of the fast nucleon wave function one can treat the interaction as a superposition of interaction of configurations of different strength - Pomeranchuk & Feinberg, Good and Walker, Pumplin &Miettinen.

Convenient quantity - $P(\sigma)$ -probability that nucleon interacts with cross section σ

If there were no fluctuations of strength - there will be no inelastic diffraction at t=0:

$$\left.\frac{\frac{d\sigma(pp\to X+p)}{dt}}{\frac{d\sigma(pp\to p+p)}{dt}}\right|_{t=0} = \frac{\int(\sigma-\sigma_{tot})^2 P(\sigma)d\sigma}{\sigma_{tot}^2}$$



The 30 GeV curve is result of the analysis (Baym et al 93) of the FNAL diffractive pp and pd data which explains FNAL diffractive pA data (Frankfurt, Miller, MS 93-97). The 2TeV curve is my guess based on matching with fixed target data and collider diffractive data.

For small σ's absorption is smaller – hence

Small σ component of P(σ) is enhanced in the hard diffraction –

Hence we can address an old question –

Is the strength of the of interaction correlated with x, Is nucleon smaller when $x_1 \geq 0.3$ (0.5) parton is selected, etc.

Would show up in breakdown of factorization as a function of x_1

Conclusions: *Dedicated studies of QCD at Tevatron with a good acceptance in the very forward region would allow to obtain unique information on the QCD dynamics in the regime of strong gluon fields, observe new phenomena relevant for the understanding of the three dimensional structure of the nucleon.*

◈ ***Small x parton densities***

- Forward detector would allow to measure gluon and quark densities down to the region of $x \sim 10^{-5}$ where taming effects (deviations from DGLAP) become important.

- x-range will nicely complement & overlap with pp and Ultraperipheral Collision ranges at LHC range allowing tests of violation of pQCD factorization.

- Taming of the growth of the parton densities is likely to be manifested (already in the region of the onset of this black body regime) in drastic changes in the p_t broadening, dependence of the cross sections on virtualities, etc.

Tagging of central NN collisions

new window at high gluon fields & the process of nucleon fragmentation with clear connections to the cosmic ray physics near GZK.

Mapping of the proton wave function

- Multiparton correlations in nucleons (3D-picture)
- Measurement of three quark component of the nucleon wave function.
- Color fluctuations in nucleons: global effects & x-dependent effects