Diffraction - mapping transverse structure of strong interactions

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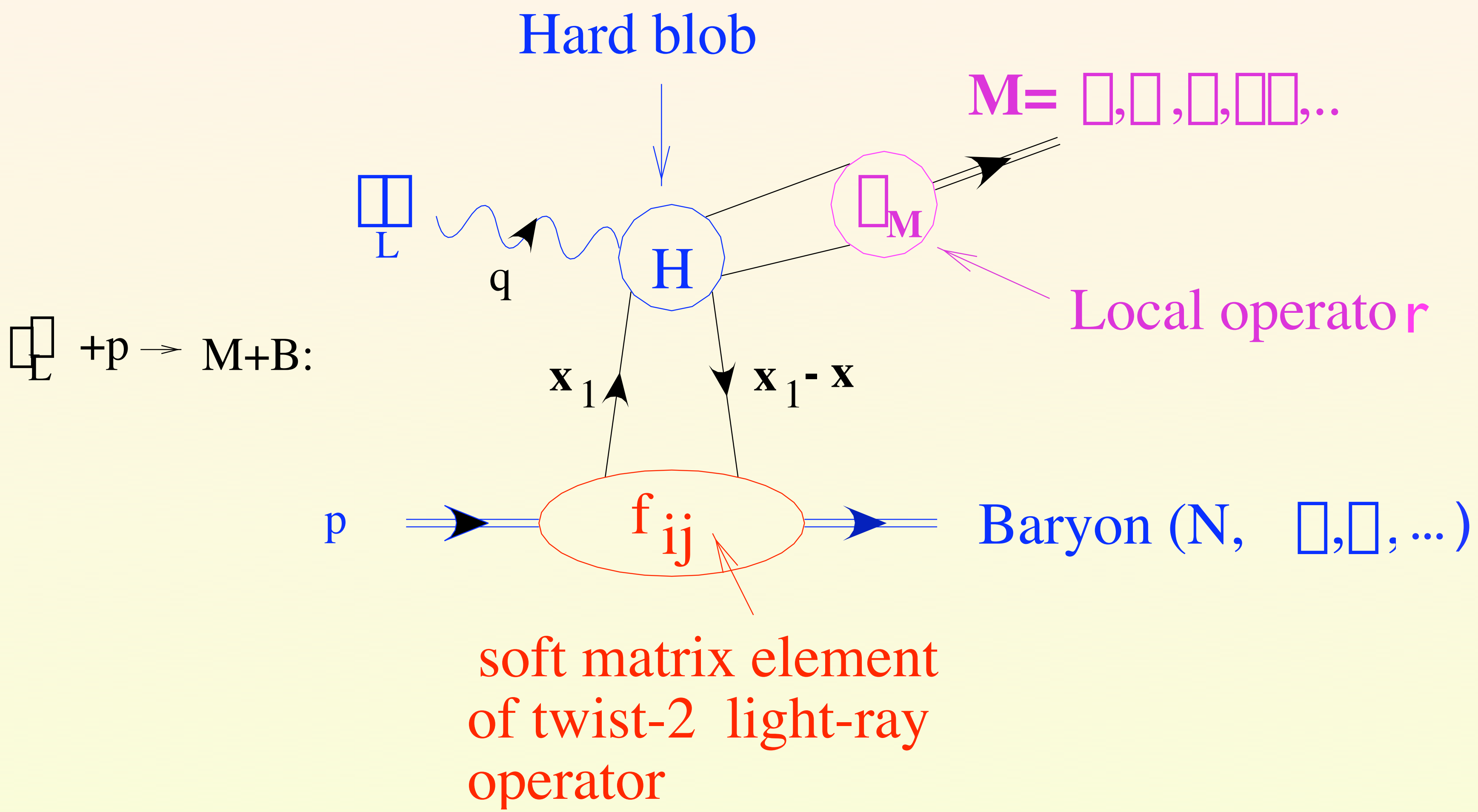
So far major successes of QCD in describing high energy hadron hadron collisions were for **hard inclusive processes** - collision of two partons. *Sufficient to know only longitudinal single parton densities.*

Knowledge of the transverse spread of partons which depends on x is necessary to build a realistic description of the global structure of the final states in pp collisions.

Progress in the recent years was due to the study of hard diffraction at HERA and related studies at Tevatron,

QCD factorization theorem for DIS exclusive processes

(Brodsky,Frankfurt, Gunion,Mueller, MS 94 - vector mesons,small x; general case Collins, Frankfurt, MS 97)



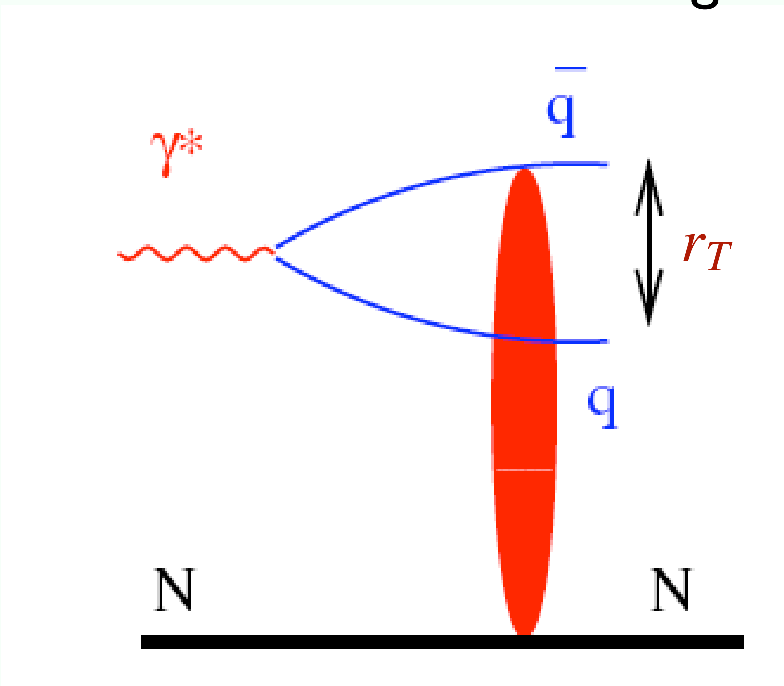
Extensive data on VM production from HERA support dominance of the pQCD dynamics. Numerical calculations including transverse size of the wave function of vector meson explain key elements of high Q^2 data. The most important ones are:

- Energy dependence of J/ψ production; absolute cross section of $J/\psi,$ production.

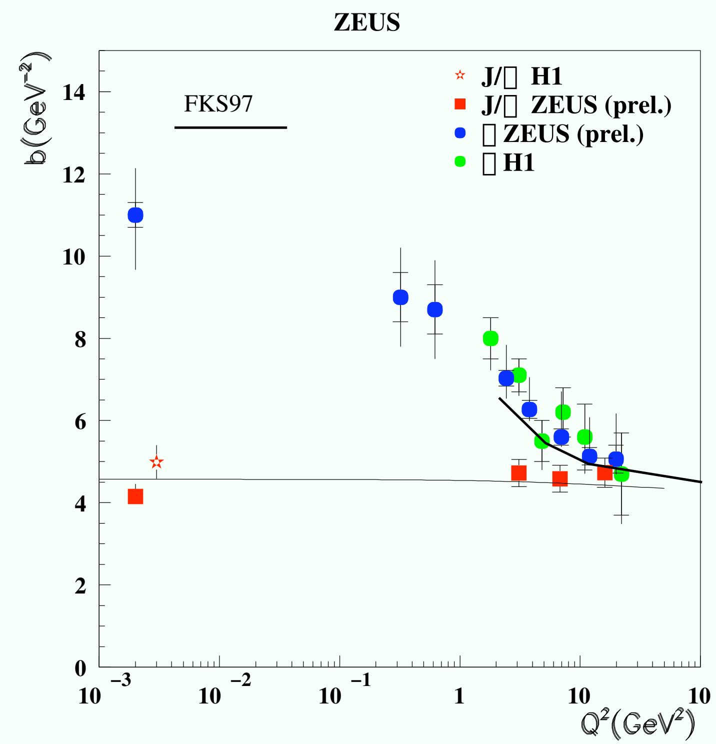
- Absolute cross section and energy dependence of ρ−meson production at $Q^2 \geq 20\ GeV^2$. Explanation of the data at lower Q^2 is more sensitive to the higher twist effects, and uncertainties of the low Q^2 gluon densities.

- Universal t-slope: 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 - two gluon nucleon form factor, $F_g(x,t)$. $d\sigma/dt \quad F_g^2(x,t)$.

  Onset of universal regime FKS[Frankfurt,Koepf, MS] 97.



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



Convergence of the t-slopes, B ($\frac{d\sigma}{dt} = A\exp(Bt)$), of ρ-meson electroproduction to the slope of J/psi photo(electro)production.

⇒ Transverse distribution of gluons can be extracted from $\gamma + p \to J/\psi + N$

$$F_g(x,t) = 1/(1-t/m_g(x)^2)^2, m_g^2(x=0.05) \sim 1 GeV^2, m_g^2(x=0.001) \sim 0.6 GeV^2.$$

For x=0.05 it is much harder than e.m. form factor (dynamical origin - chiral dynamics) $\Rightarrow$ more narrow transverse distribution of gluons than a naive expectation. (Frankfurt, MS , Weiss -02-03)

The gluon transverse distribution is given by the Fourier transform of the two gluon form factor as

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

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

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

with x-dependent m_g fitted to reproduce the slope of J/ψ photoproduction.

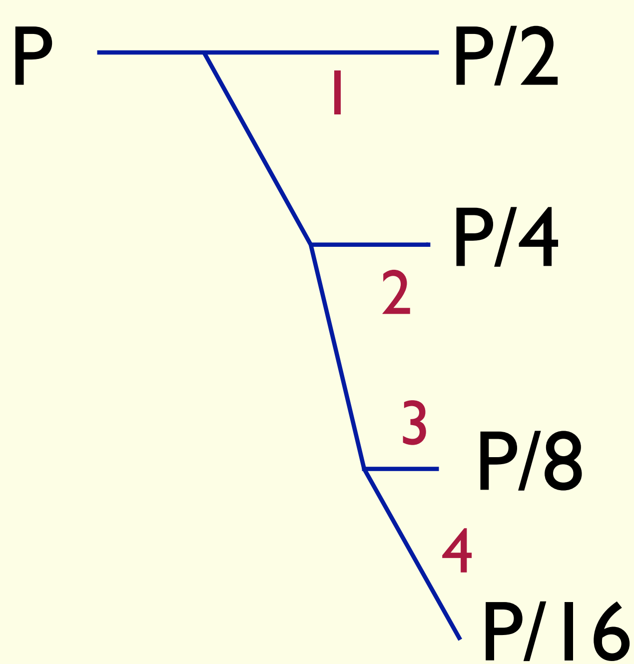
The Q^2 dependence was accounted using LO DGLAP evolution at fixed ρ .

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

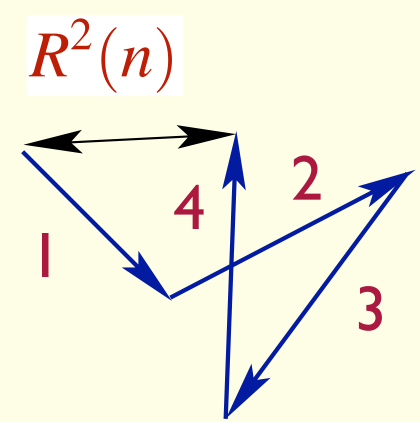
Energy dependence of the transverse size of soft partons.

Decay of a fast parton

Longitudinal momentum



Transverse plane coordinate.



$R^2(n) \approx \dfrac{n}{k_{t0}^2}$ 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:

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

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

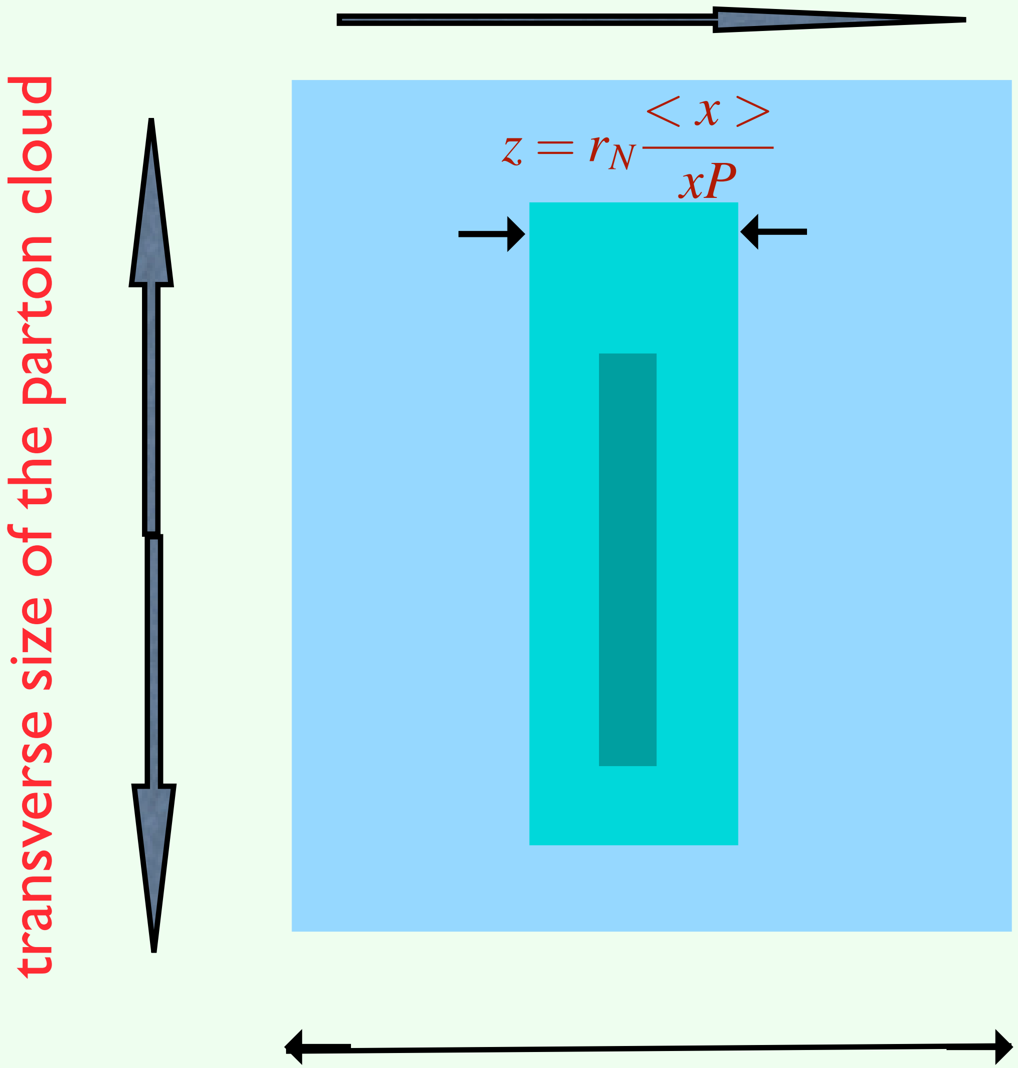
Increase is slowed down by increase of parton densities at small transverse distances from the center.

$\Longrightarrow$ Radius of strong interaction increases with energy. At LHC energies, (transverse size)^2 of a nucleon in the rest frame of another nucleon is four times larger than at rest!!!

Sagittal cut of the fast nucleon - low resolution scale

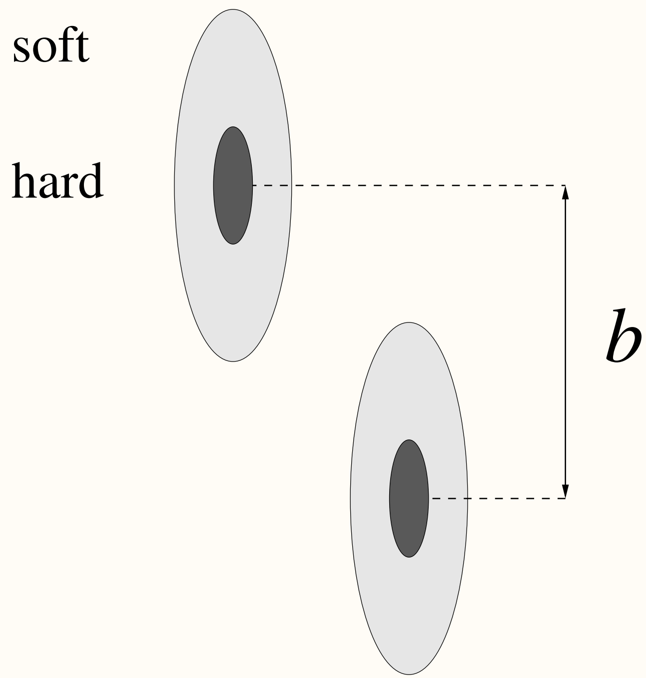
$$z = r_N \frac{< x >}{xP}$$

Momentum P in z direction

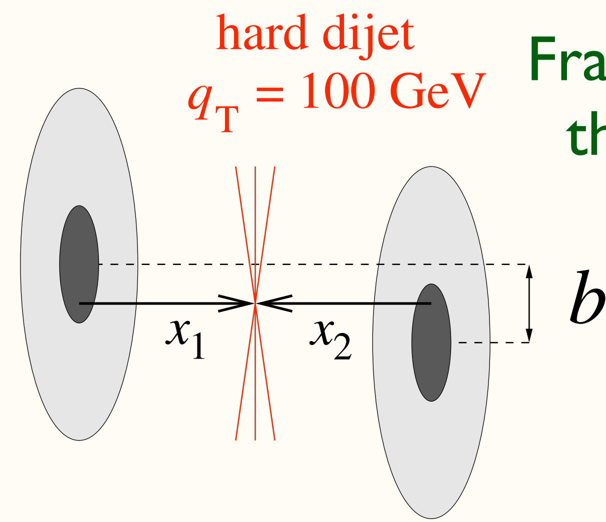


wee parton are spread over 1 fm even at high energies

Implication - hard processes correspond to collisions where nucleons overlap stronger & more partons hit each other - use hard collision trigger to study central collisions.



"peripheral"
(dominate total cross section)



$$x_{1,2} = 2q_T / W \sim 10^{-2}$$

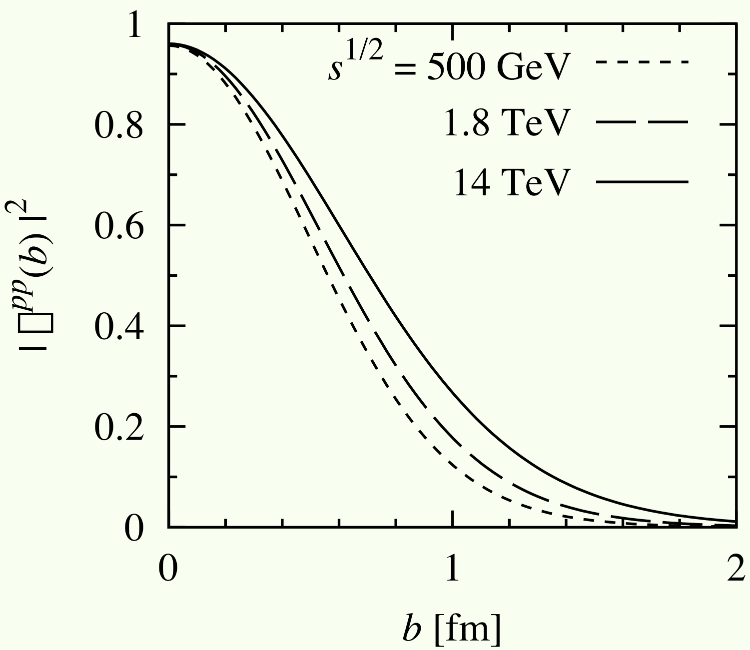
"central"

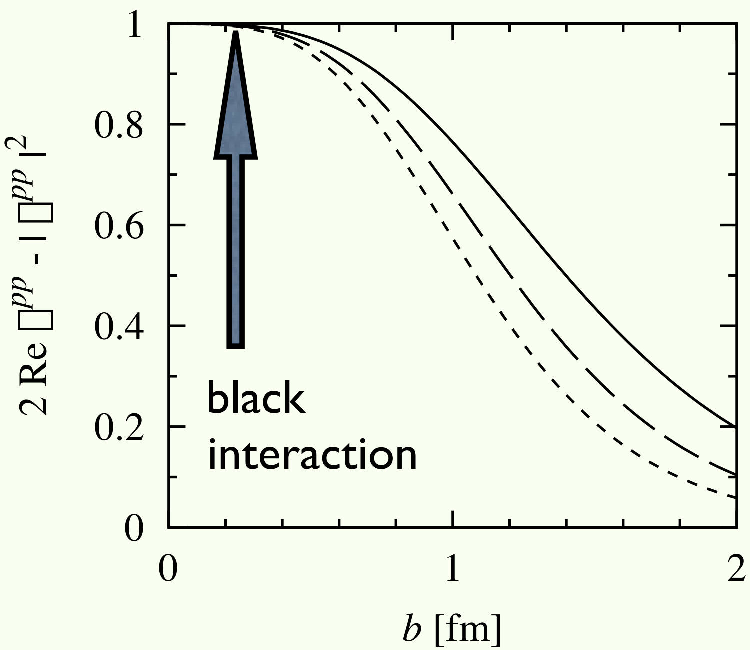
Frankfurt's talk in the afternoon.

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 – Babinet principle: diffraction off the hole and absorptive disk of the same shape are the same.

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

Important feature of QCD: hadrons can exist in small size containing minimal possible number of quarks - three in a nucleon (minimal Fock space configurations).

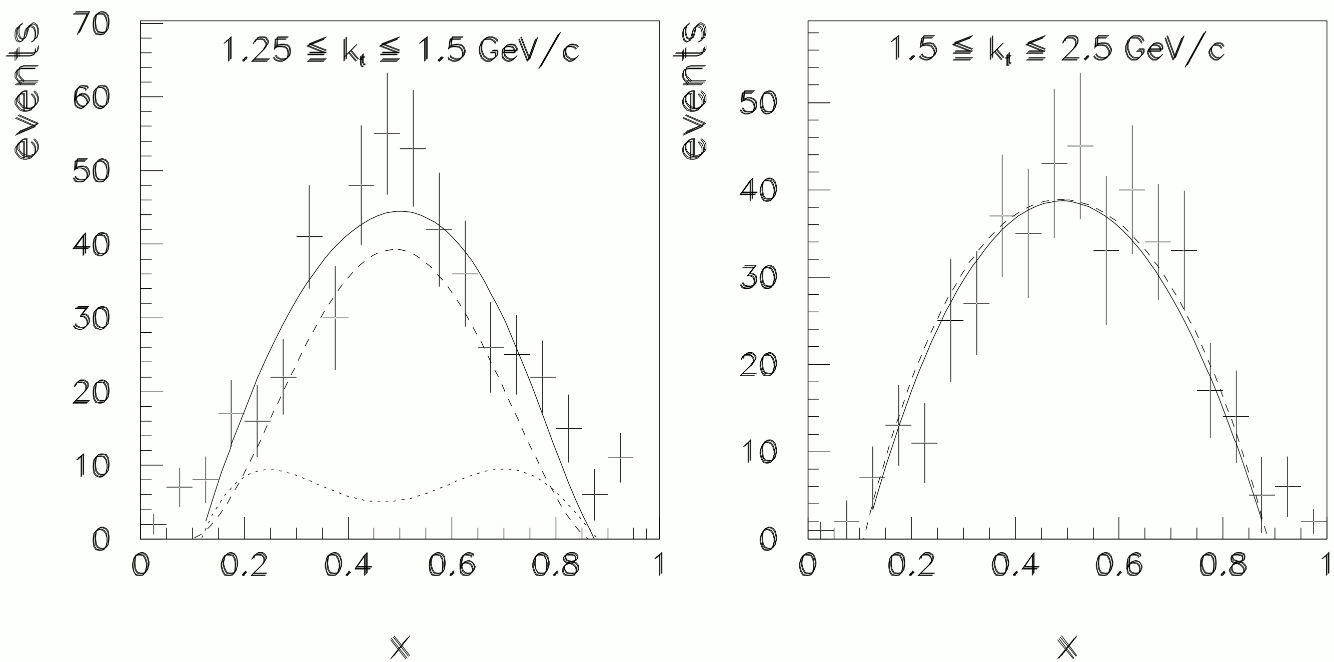
Experimental evidence: Pion diffraction into two jets.

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

Measurement of the proton wave function in |3q> configuration with small transverse distance separation- *important for nucleon decays in GUTS.*

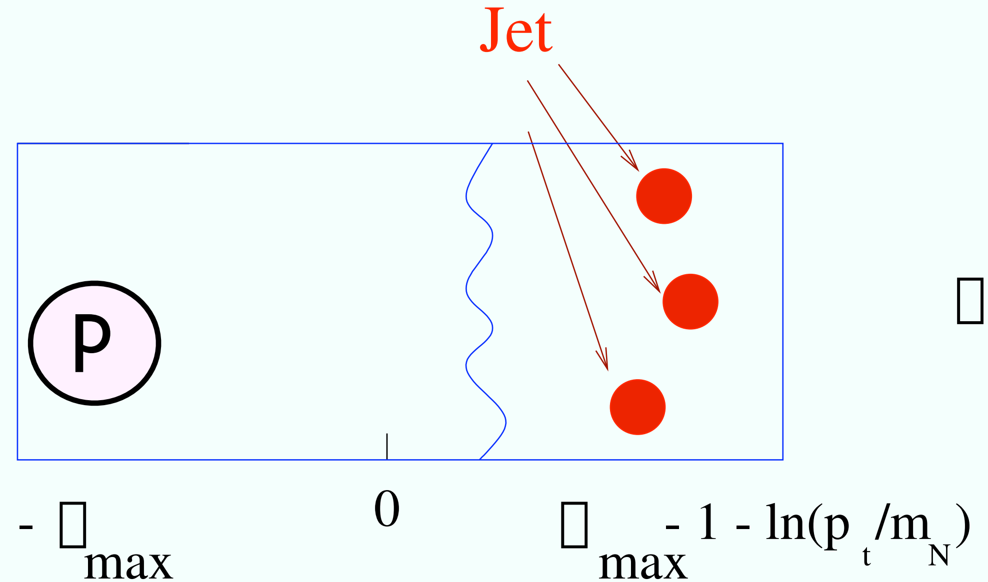
Extension of the study of $\square + N(A) \rightarrow$ “$2\ high\ p_t\ jets$” $+ N(A)$

by FNAL 791 (2001), which confirmed QCD prediction of Miller &F&S 93 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

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

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

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

Advantages of the collider kinematics: it is easy to select coherent processes using very forward proton detector (TOTEM) . Energy dependence is very strong if there is no taming of gluon densities since

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

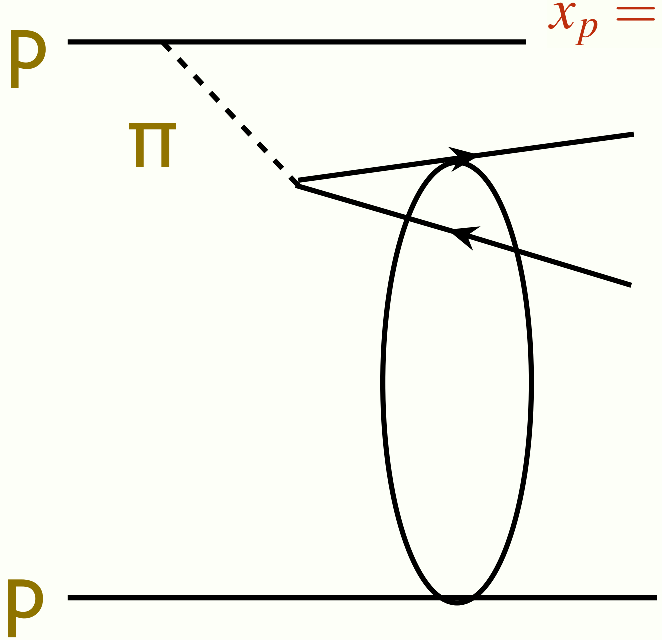
At LHC one can hope to separate three jet final state with $p_t \geq 5-8\ GeV/c.$

Main problem - acceptance for jets $y_{jet}(p_t = 10\ GeV/c) \sim 6.$

Probes very small x: $x = \frac{M^2_{3\,jet}}{2s} = \frac{9p_t^2}{2s} \sim 10^{-5}_{|p_t=10\ GeV/c}$

The magnitude of the cross section is 10□5 mb when integrated over $p_t \geq 10GeV/c.$

Much better acceptance for the process similar to the pion dissociation into two jets: $pp \rightarrow p + p + two\ jets.$



$x_p = 1 - x_\pi$

$x_{jet_1} = x_\pi z \sim 0.02$

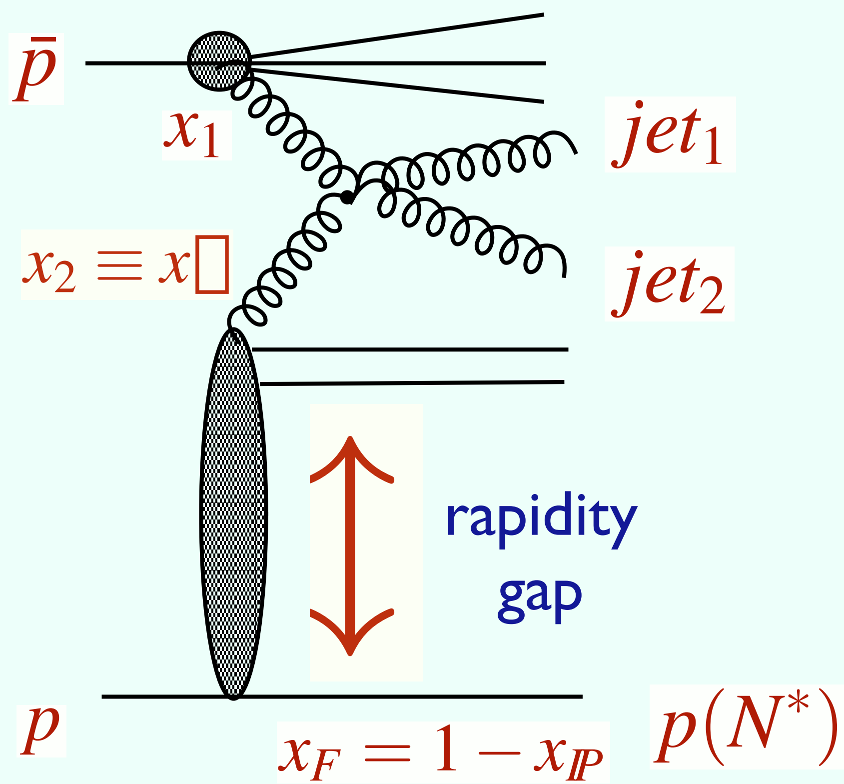
$x_{jet_2} = x_\pi (1-z) \sim 0.02$

$$x_p = (1 - x_{I\!P})$$

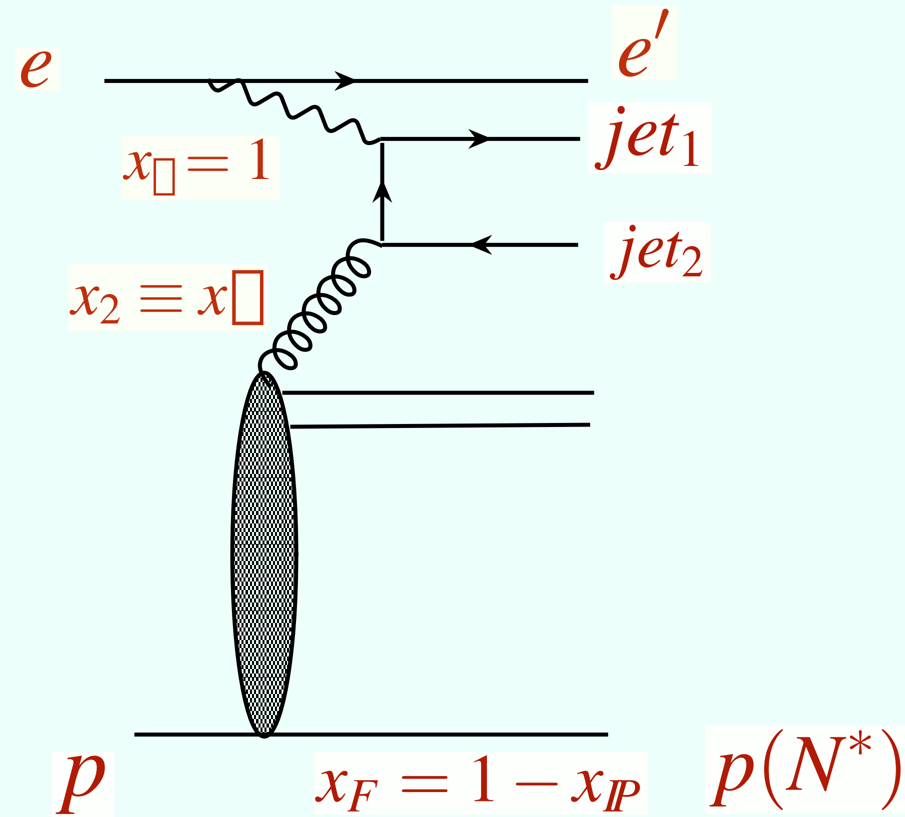
$$x_{I\!P} = \frac{p_t^2}{z(1-z)x_\pi s} \sim 10^{-4}$$

Inclusive hard diffraction - *probing nucleon periphery and color fluctuations.*

$p\bar{p} \rightarrow jet_1 + jet_2 + X + p$



$e + p \rightarrow e + jet_1 + jet_2 + X + p$



Process was first suggested by Ingelman and Schlein as a way to study dynamics of diffraction. For DIS one can introduce fraction / diffractive structure function which satisfy QCD factorization theorem for fixed $x_{I\!P}, p_N^T$

First observed at CERN collider by Schlein (UA-8) and extensively studied at HERA and Tevatron.

Key experimental observations

HERA

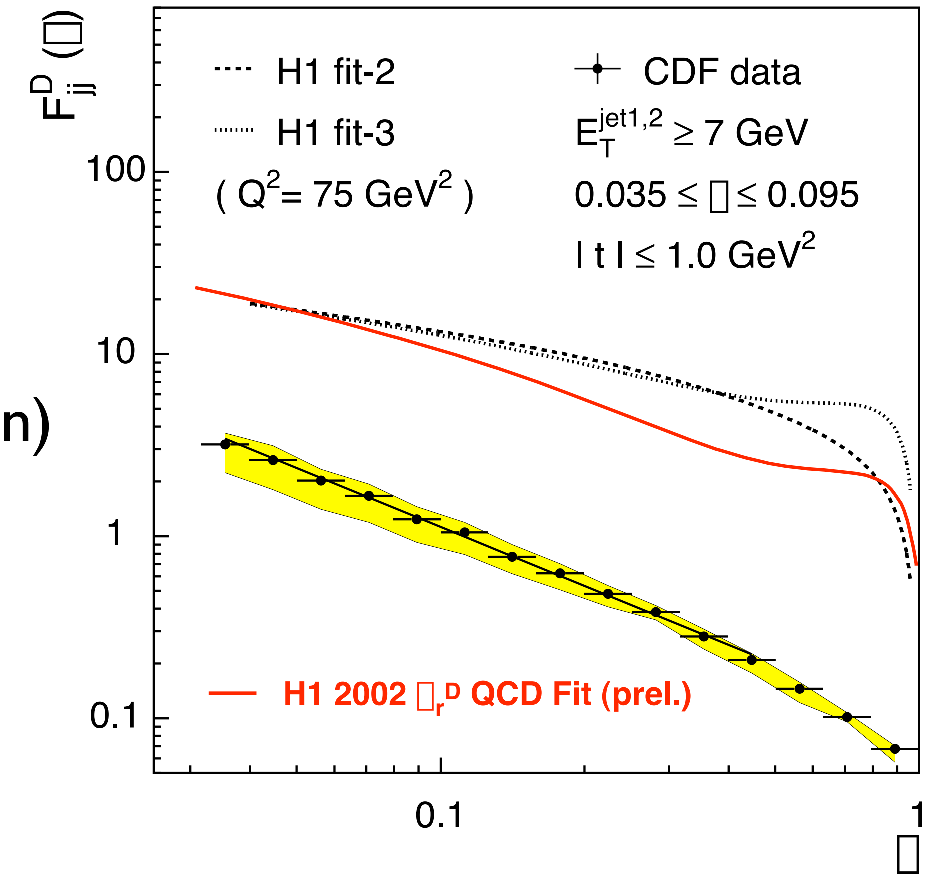
- QCD factorization works
- Gluon diffractive pdf >> Quark diffractive pdf

Tevatron

- Approximate factorization in x_I

(x of parton in the proton which breaks down)

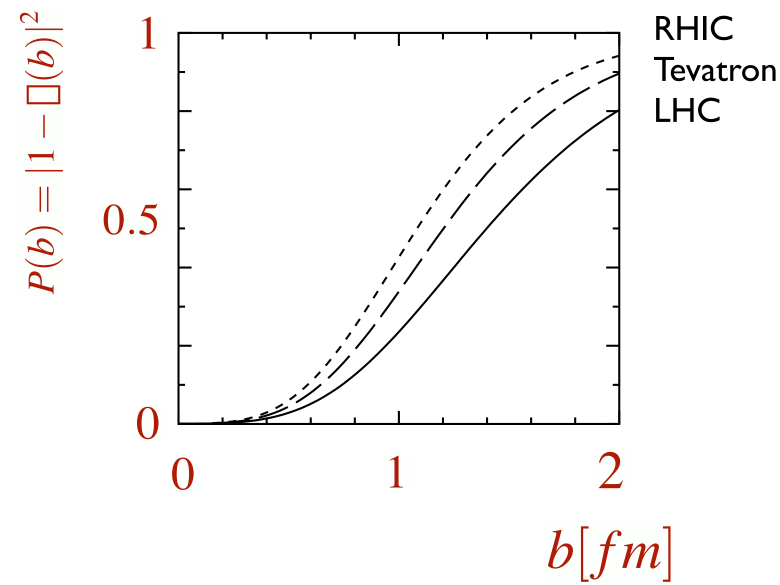
- A factor 5-10 overall suppression as compared to the QCD factorization.



What is the difference between γ and p projectiles?

Strong suppression in the proton case is due to the requirement that soft partons do not lead to inelastic interaction:

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

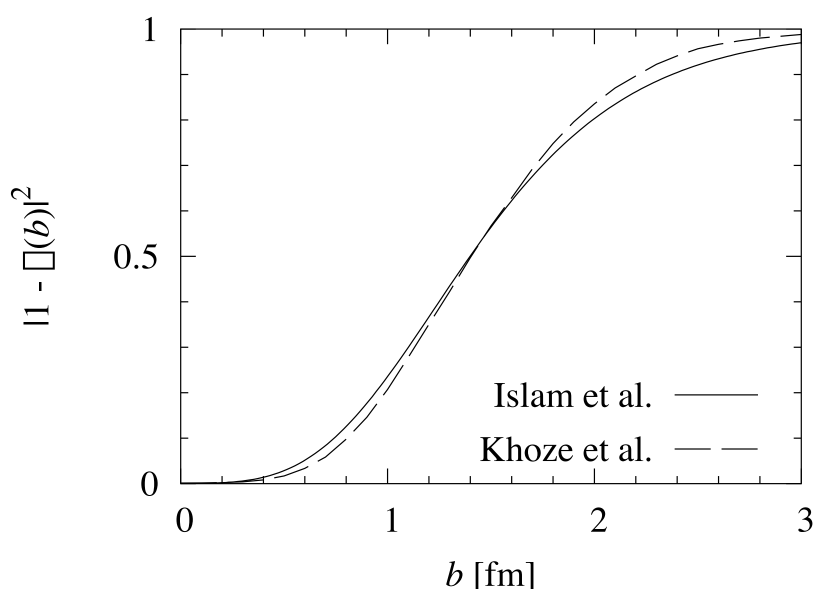


find a gluon in antiproton with $x = x_1 \geq 0.05$

at a transverse distance $\Box$ given by $F_g(x_1, \Box)$

and parton in diffractive pdf at transverse distance $\Box' \approx \vec{b} - \Box$

-- favors small $\Box'$ & $\Box$ 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 -a factor 5 -10.*

Consistent with the FNAL data - a more detailed comparison requires better HERA diffractive data and detailed modeling of x_1 range of the FNAL data.

This simple model accounts for geometry of high energy collisions and does not have free parameters. Numerical results are similar in several respects to that obtained in A Martin, V Khoze, A Kaidalov, M Ryskin papers.

$\Longrightarrow$ Hard diffraction is a good way to scan the nucleon periphery.

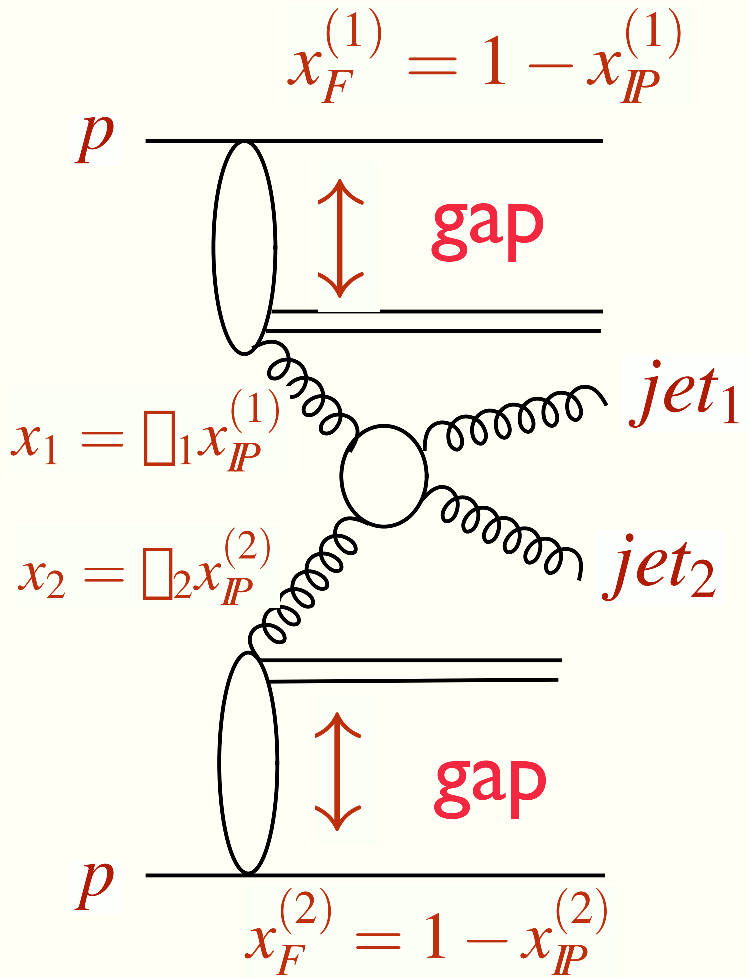
- Sensitivity to the increase of the overall nucleon size with energy -larger suppression of hard diffraction at higher energies Observed at Tevatron.

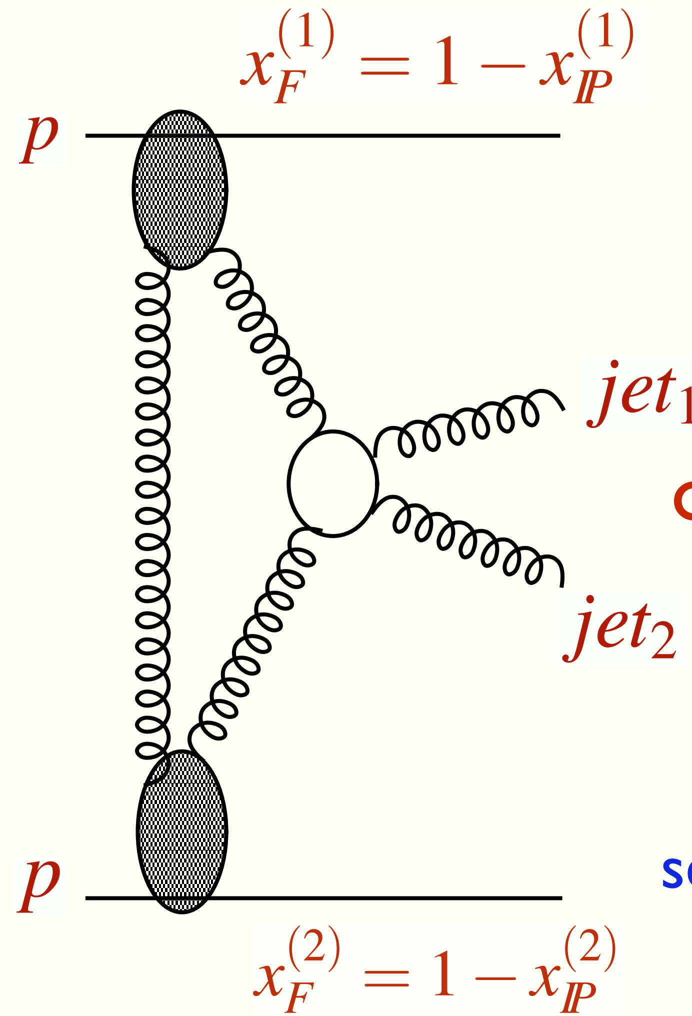
- Possibility to probe correlation between strength of interaction and x_1 & flavor of the parton in the diffracting nucleon.

  Breakdown of QCD factorization for hard diffraction is not just by an overall renormalization factor as compared to HERA diffractive pdf's.

- Look for breakdown of the Regge factorization that is the same x dependence of diffractive pdf's at different $x_{I\!P}$

Complementary information from hard double diffraction.





or Higgs, χ_c

see A.Martin talk

Erarchy of gap survival probabilities, P, (suppression due to soft interactions)

$$P(pp \to p + X + 2\ jets) \sim 0.05 - 0.1 > P(pp \to pp + 2 jets + X) \sim 0.1$$
$$> P(pp \to pp + Higgs) \sim 0.04$$

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

- *Hard exclusive diffraction*

  - ***Mapping of the three quark component of proton wave function & quark-antiquark component of pion wave function.***

  - ***Probing gluon fields at very small x***

Hard single inclusive & double diffraction (inclusive and exclusive)

- ☛ ***Measuring parton structure of the vacuum exchange /Pomeron at very small x.***

- ☛ ***Mapping transition from black limit at small b to transparency at large b.***