High-energy hadron physics at future facilities

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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.*

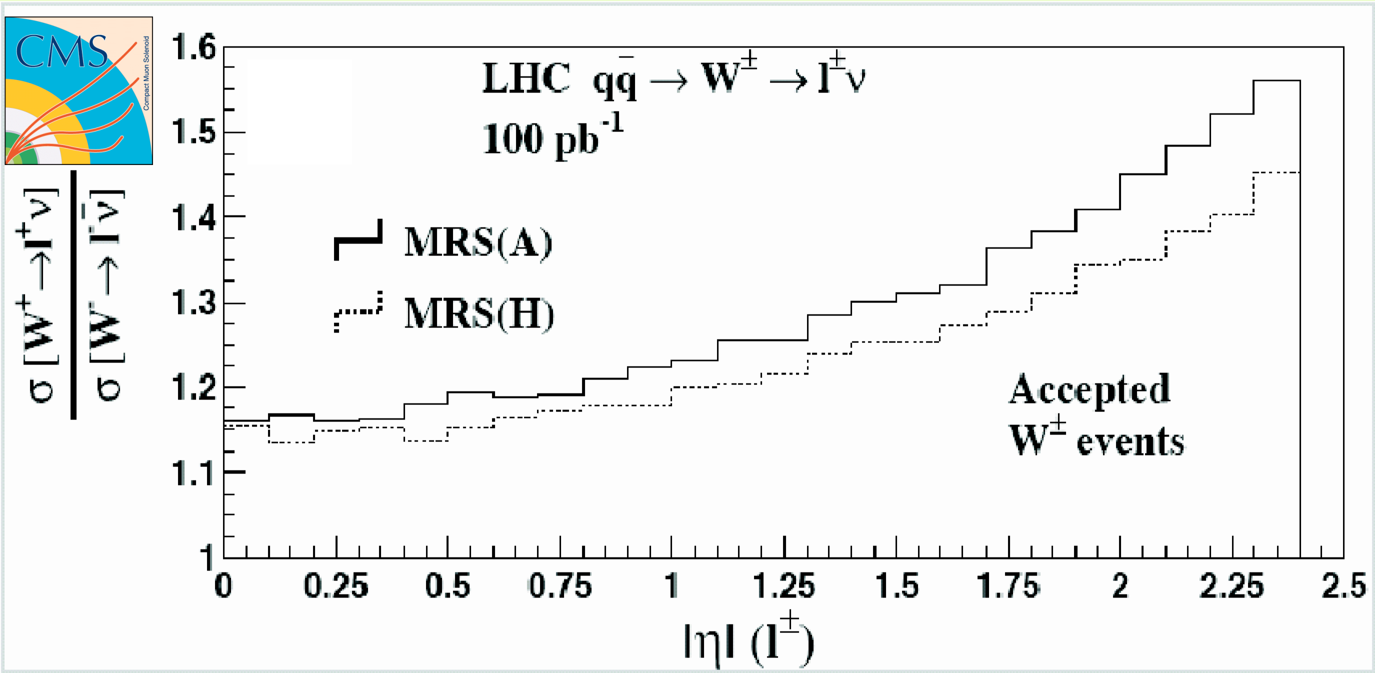
Knowledge of

- ☛ *the transverse spread of partons*
- ☛ *longitudinal and transverse correlations of partons*

which **depend on flavor, x polarization of the parton,** is necessary for

- ◈ understanding microscopic structure of nucleon bound state.
- ◈ building a realistic description of the global structure of the final states in pp collisions at collider energies

I will not discuss perspectives of parton distribution studies at RHIC and EIC. Just few words about LHC - first runs of LHC starting next year will dramatically change the field of parton density studies. Example: CMS study for very modest lumi:



$2 \cdot 10^6$ W$\to\mu\nu$ produced for **$|\eta|<2.4$**
➠ high precision measurements of **d/u at x≤ 0.1**

For many clean hard lepton channels (Z-boson,...) acceptance and high counting rates for x< 0.5

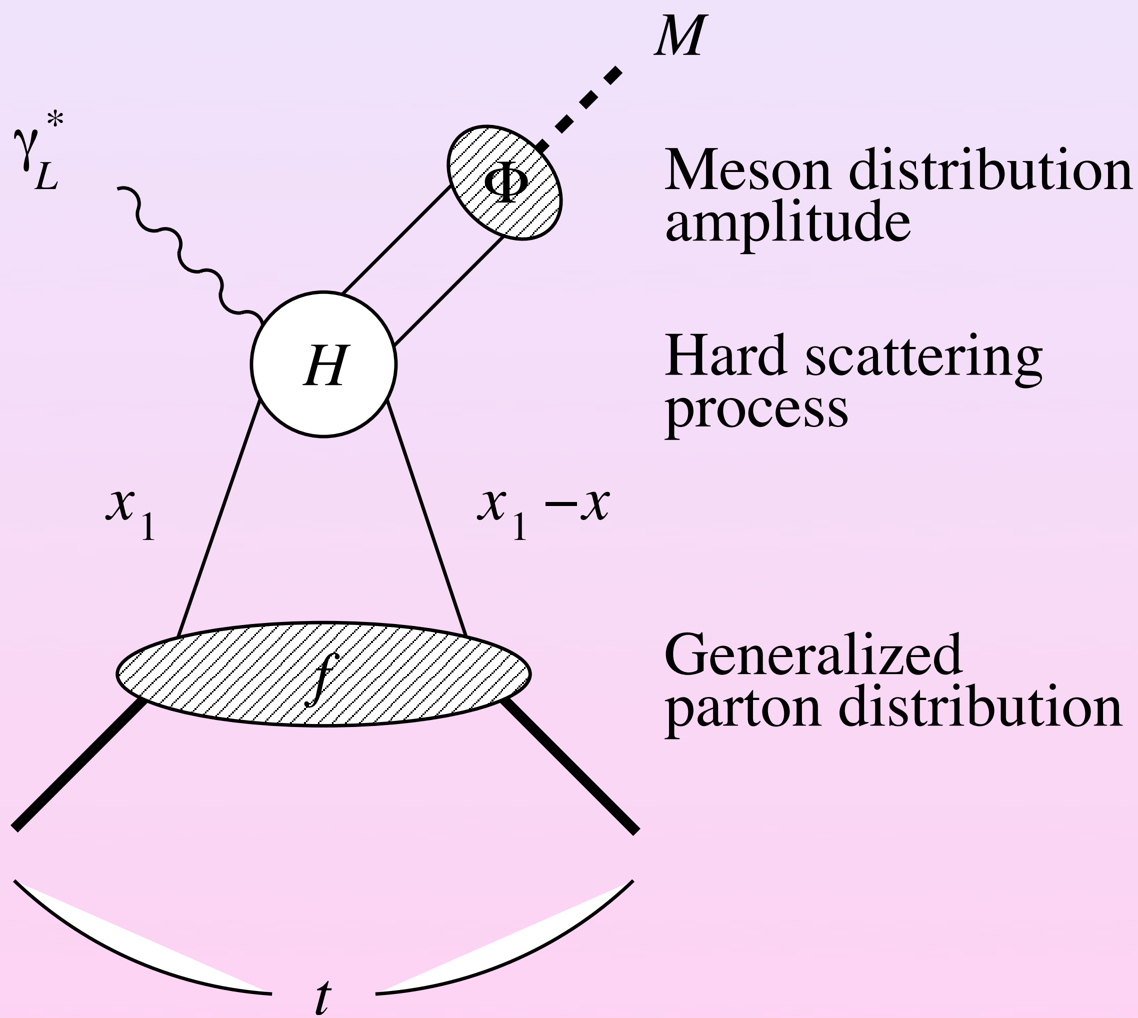
Also, will not discuss LHC potential for study of small x dynamics

3 dimensional single parton distribution in nucleon

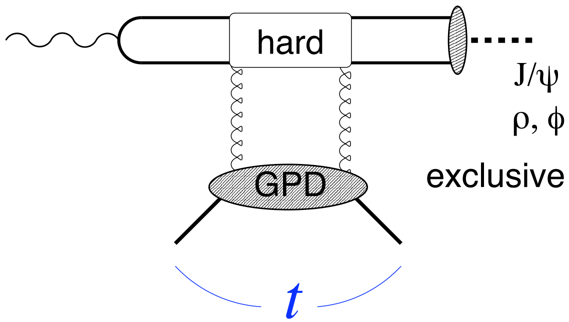
1D - parton distribution

3D - generalized parton distribution

QCD factorization theorem for DIS exclusive meson production processes (Brodsky,Frankfurt, Gunion,Mueller, MS 94 - vector mesons, small x; general case Collins, Frankfurt, MS 97)



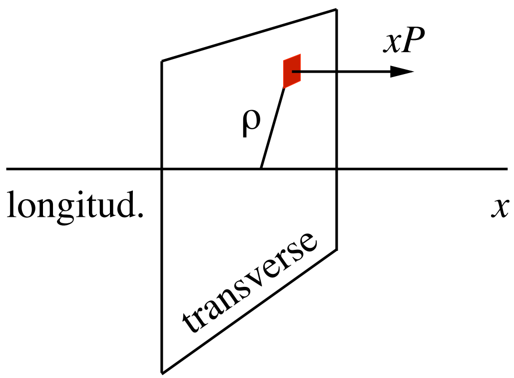
- Transverse spatial distribution of gluons



$$G(x, Q^2_{\mathrm{eff}}; t) \; = \; G(x, Q^2_{\mathrm{eff}}) \; \times \; F_g(x, Q^2_{\mathrm{eff}}; t)$$

generalized gluon dist'n

two–gluon formfactor



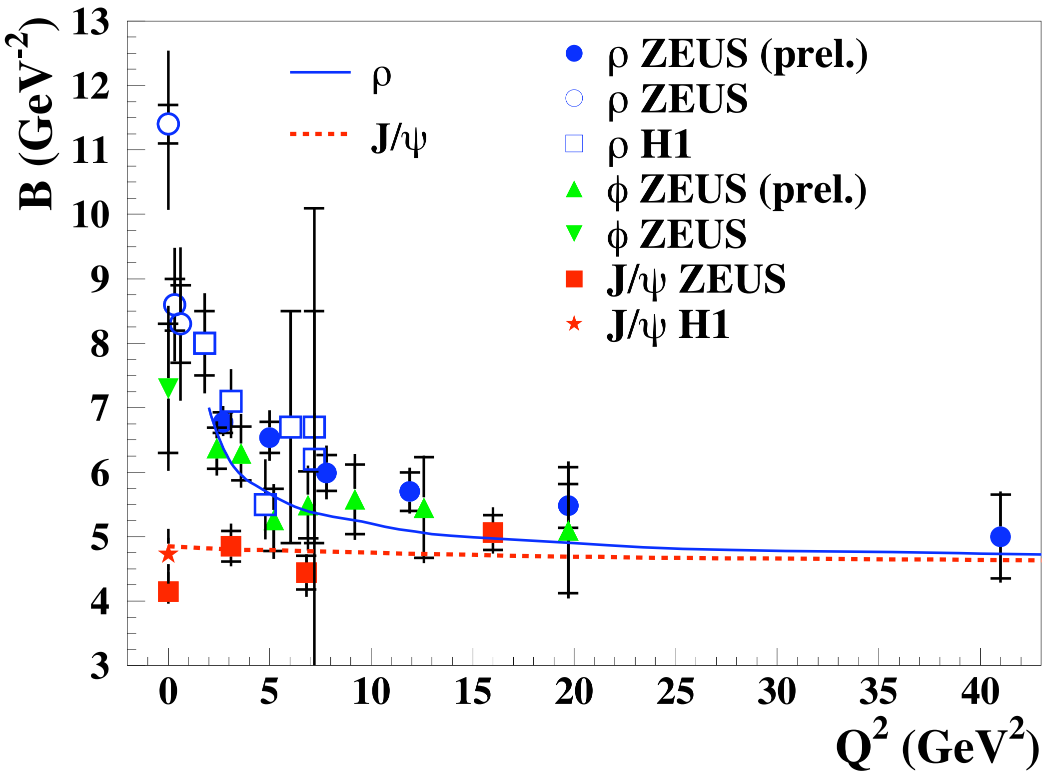
$$F_g(x, t) \; = \; \int d^2\rho \, e^{-i\vec{\Delta}_\perp \cdot \vec{\rho}} \; \boxed{F_g(x, \boldsymbol{\rho})}$$

transverse spatial distribution of gluons

$$\langle \rho^2 \rangle_g \; = \; 4 \, \frac{\partial}{\partial t} \, F_g(x, t)$$

gluonic transverse size of nucleon, x–dependent!

– Can be extracted from t–dependence of $\frac{d\sigma}{dt}(\gamma^* p \to V p)$

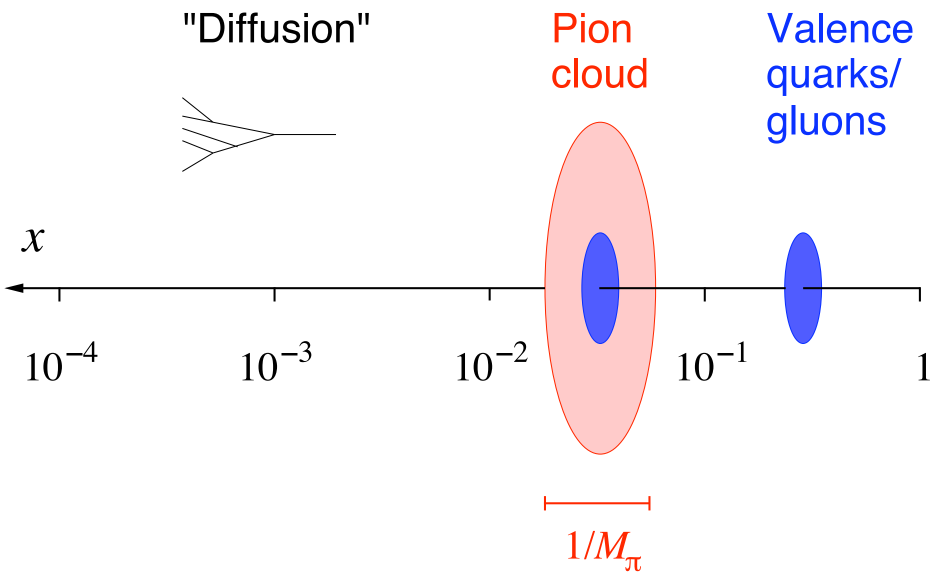


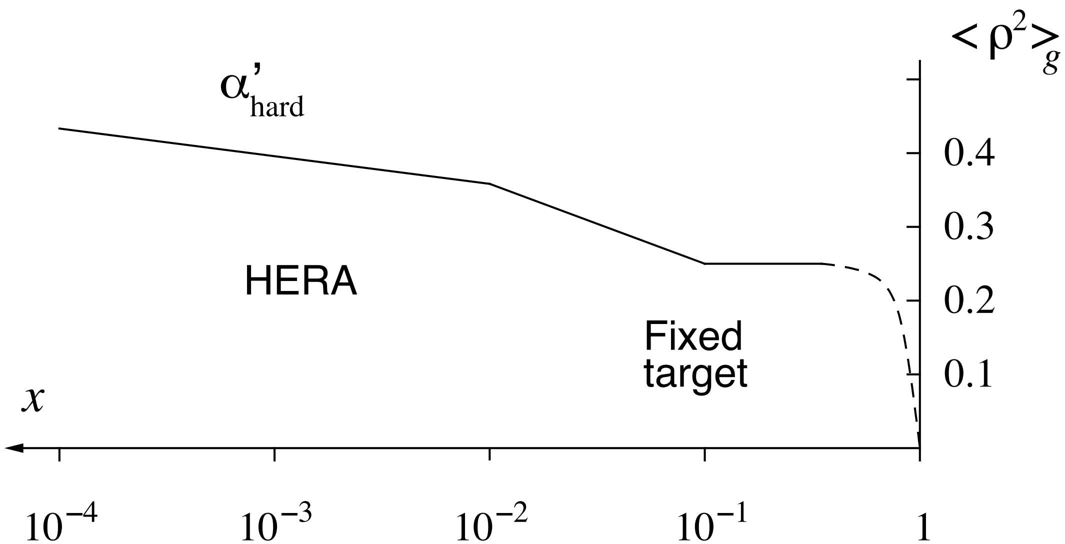
curves - FKS97 prediction

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

⇒ Transverse distribution of gluons can be extracted from $\gamma + N \rightarrow J/\psi\ (\Upsilon) + N$ --- HERA; future: COMPASS, ultraperipheral collisions at LHC (AA, pA), RHICII, EIC

• Gluonic transverse size: x–dependence





Gluon transverse size decreases with increase of x

Pion cloud contributes for $x<M_\pi/M_N$ [MS &C.Weiss 03]

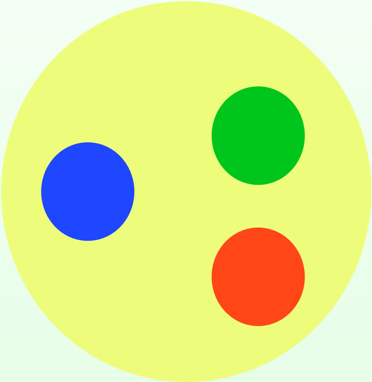
– Transverse size at large x <u>much smaller</u> than proton radius in soft interactions:

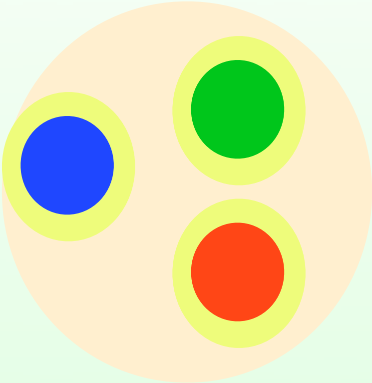
$$\langle\rho^2\rangle(x > 10^{-2}) \ll R^2_{\text{soft}}$$

$\Downarrow$

Two scale picture of pp collisions at LHC

Correlations between partons in nucleons



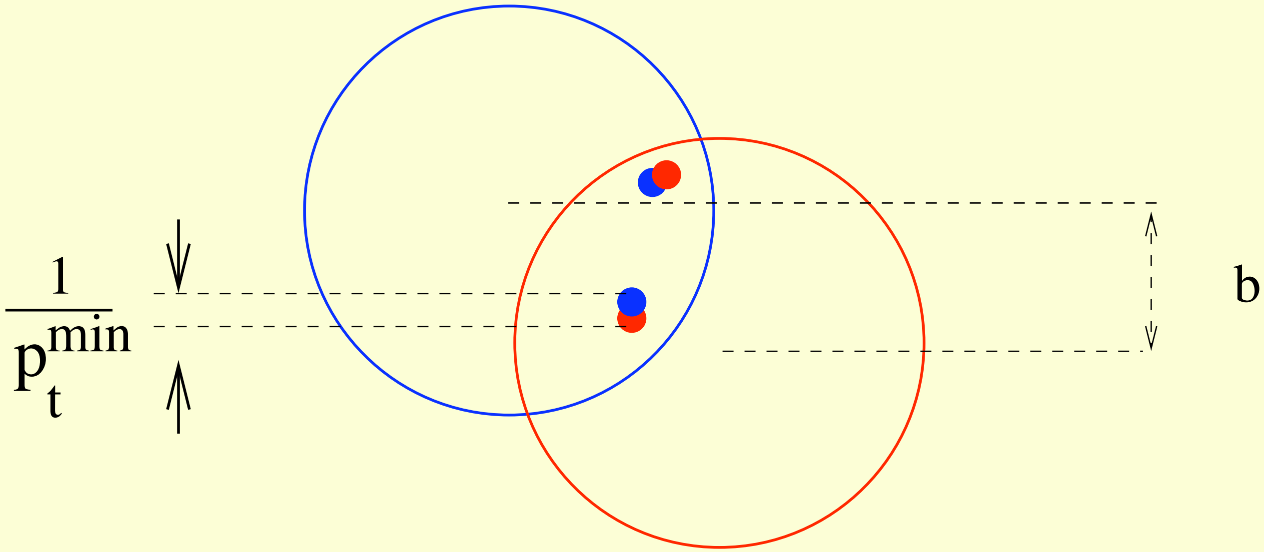


MIT bag model:
no correlation between
quarks and gluons

Instanton liquid chiral model:
strong correlation between
quarks and gluons

Multi-jet production - study of parton correlations in nucleons

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.



A view of double scattering in the transverse plane

Experimentally one measures the ratios like

$$\frac{\frac{d\sigma(p+\bar{p}\to jet_1+jet_2+jet_3+\gamma)}{d\Omega_{1,2,3,4}}}{\frac{d\sigma(p+\bar{p}\to jet_1+jet_2)}{d\Omega_{1,2}}\cdot\frac{d\sigma(p+\bar{p}\to jet_3+\gamma)}{d\Omega_{3,4}}}=\frac{f(x_1,x_3)f(x_2,x_4)}{\sigma_{eff}f(x_1)f(x_2)f(x_3)f(x_4)}$$

where $f(x_1,x_3)$, $f(x_2,x_4)$ longitudinal light-cone double parton densities and σ_{eff} is ``transverse correlation area".

If partons are not correlated in transverse plane, σ_{eff} can be expressed through GPDs - $F_{q(g)}(x,\rho)$.

Taking transverse distribution as in e.m. form factors leads to σ_{eff} =60 mb

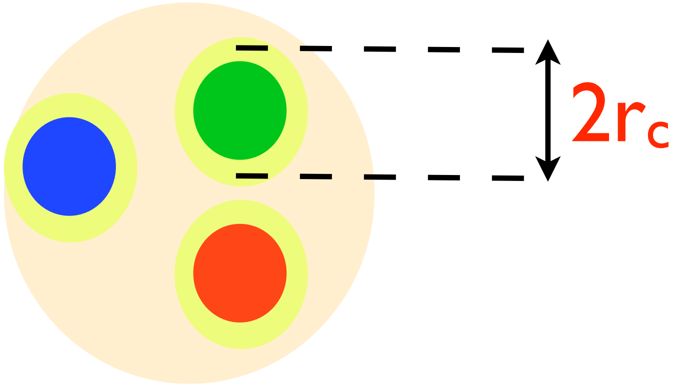
Our analysis of HERA data indicates more localized gluon transverse distributions ➠ σ_{eff} =34 mb

CDF observed the effect in a restricted x-range: two balanced jets, and jet + photon and found $\sigma_{eff}=14.5\pm1.7^{+\,1.7}_{-\,2.3}\,mb$ indicating high degree of correlations between partons in the nucleon in the transverse plane.

Need to check this tantalizing indication of correlations in the nucleon wave function, dependence on the channel - correlations of quarks, quarks- gluons,.... .

Possibilities: RHIC II including spin, new analyses at Tevatron.

Theory: possible dynamical mechanism - in the instanton liquid model of QCD vacuum there are strong gluon fields localized near valence quarks of the nucleon in the volume of radius $r_c \sim r_N/3$.



This leads to the enhancement factor: $\frac{8}{9} + \frac{1}{9}\frac{r_N^2}{r_c^2} \sim 2$ of necessary magnitude.

Other direction- study of the correlation between x of the parton and overall transverse size of configuration.

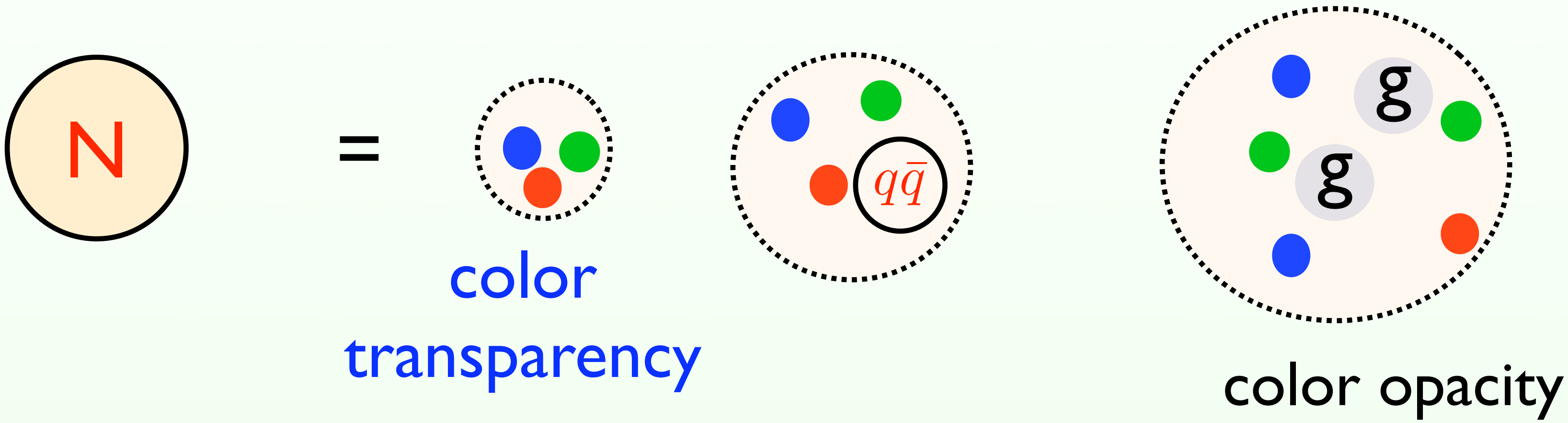
General idea - larger the transverse size, more multiple soft and hard interactions, leading to increase of the associated hadron multiplicity.

Examples:

- Compare size of configurations with u/d quark at given x: associated hadron production in events with W^+ and W^- — LHC & RHICII

- Dependence of size on helicity of quark: $\lambda q = \lambda_N$ vs $\lambda_q = -\lambda_N$ — RHICII

Color fluctuations in hadrons

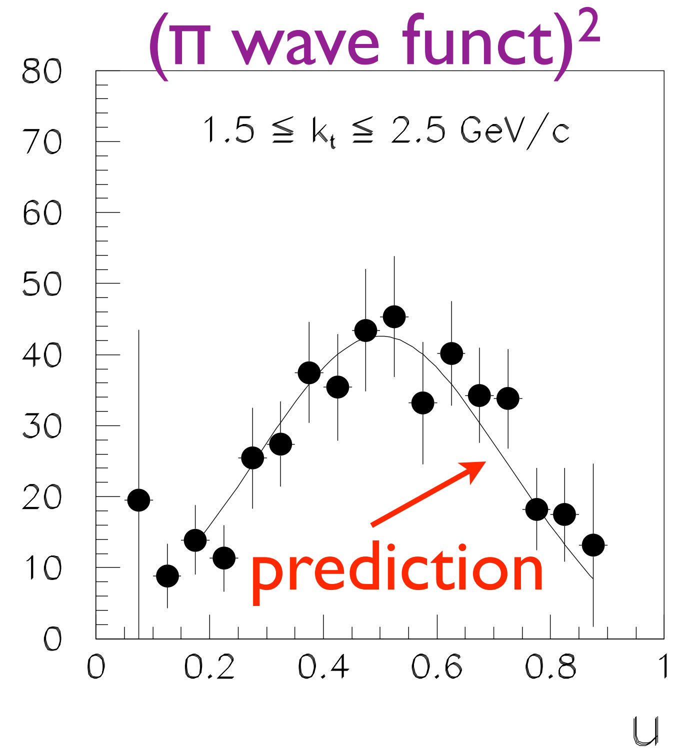


Focus on color transparency (CT) phenomena which select "point-like" (small size) configurations in the projectile which weakly interaction with media.

For nucleon point-like 3q configurations are responsible for nucleon decay in GUT, for form factors at $Q^2 \to \infty$

At high energies weakness of interaction of point-like configurations with nucleons - is routinely used for explanation of DIS phenomena at HERA.

First experimental observation of high energy CT for pion interaction (Ashery 2000): $\pi + A \to$ "jet"+"jet" $+A$. Confirmed predictions of pQCD (Frankfurt ,Miller, MS93) for *A-dependence, distribution over energy fraction, u carried by one jet, dependence on p_t(jet), etc*



Overall, presence of small $\bar{q}q$ configurations in $\pi,\rho,\ldots$ mesons is now well established

CT - Intermediate energies

Main issues

☛ At what Q^2 / t particular processes select point-like configurations - for example interplay of end point and LT contributions in the e.m. form factors,....

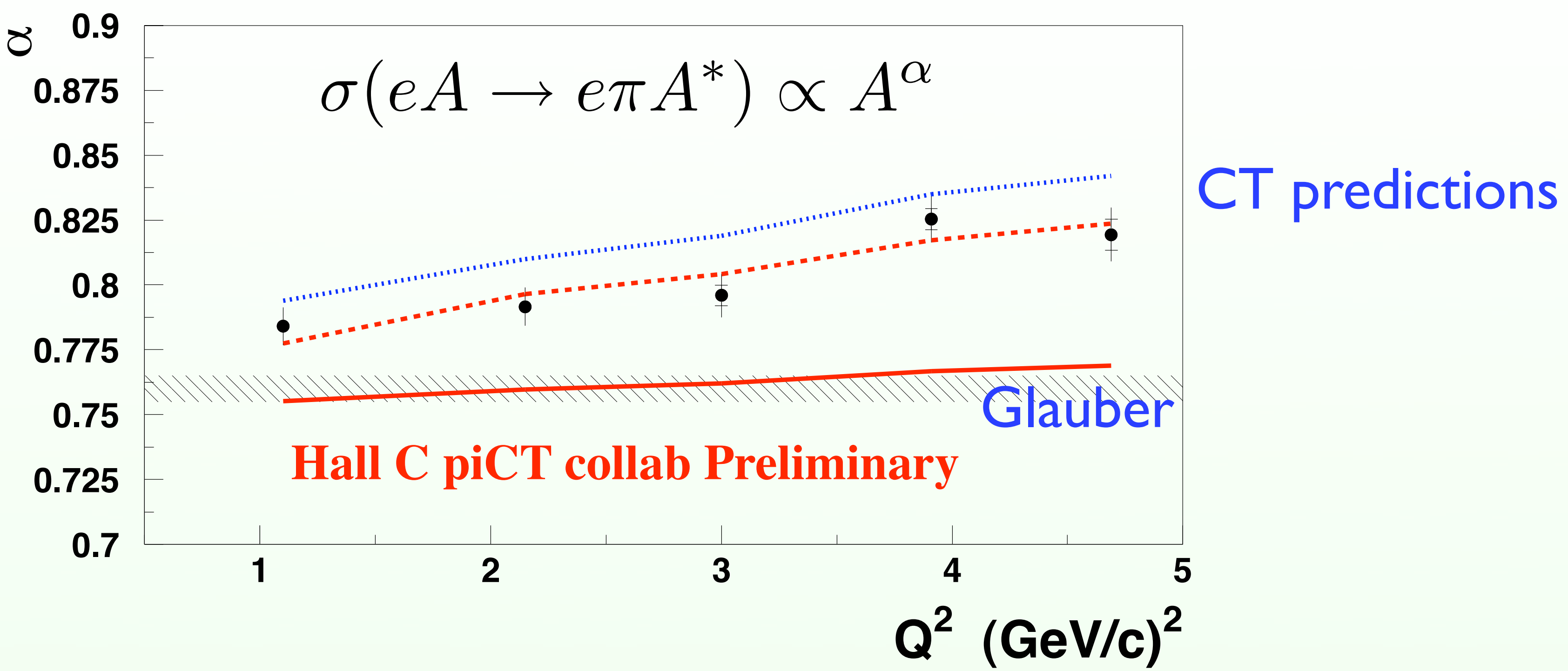
☛ If the point-like configuration is formed - how long it will remain smaller than average configuration

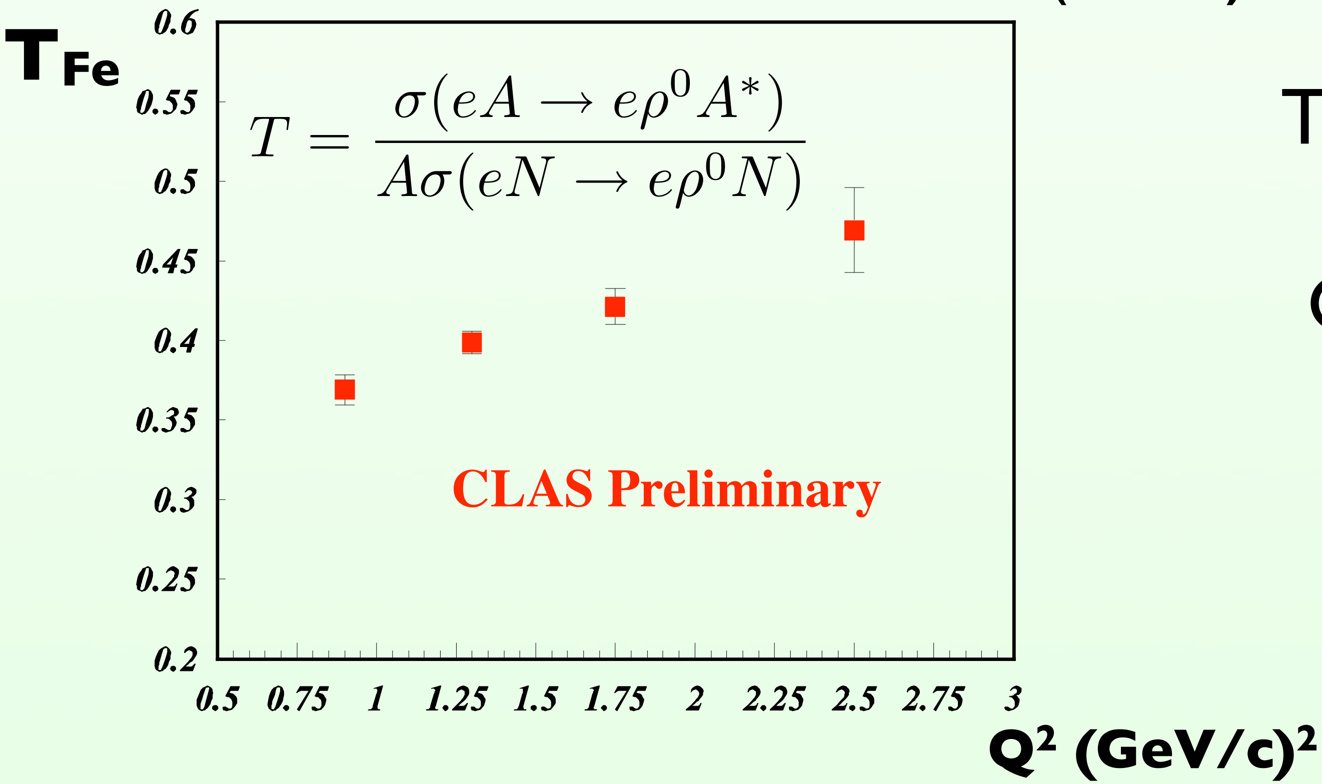
$l_{coh} = (0.3 \div 0.4 \ \mathrm{fm}) \ p_h \ [\mathrm{GeV}]$ Farrar et al , Miller and Jennings

$l_{coh}(\pi) \sim l_{coh}(N)$ due to similarity of the Regge slopes for meson and baryon trajectories

Recent progress on the experimental end - two Jlab experiments, plus supporting results from HERMES experiment

Side remark: this $l_{coh}(\pi)$ much smaller than used in heavy ion MC





The Jlab data seem to be consistent with CT predictions with coherence length $l_{coh} = 0.3\ p_h$ [GeV]

Main challenge is to investigate CT for the case of the hadronic projectile - processes

$\pi + p \to \pi + p + (A-1)$, $p + A \to p + p + (A-1)$,...

which were originally suggested by Mueller and Brodsky in 82 as a way to understand the origin of one of **the most fundamental hadronic processes in pQCD -large angle two body reactions** (-t/s=const, s $\to \infty$)

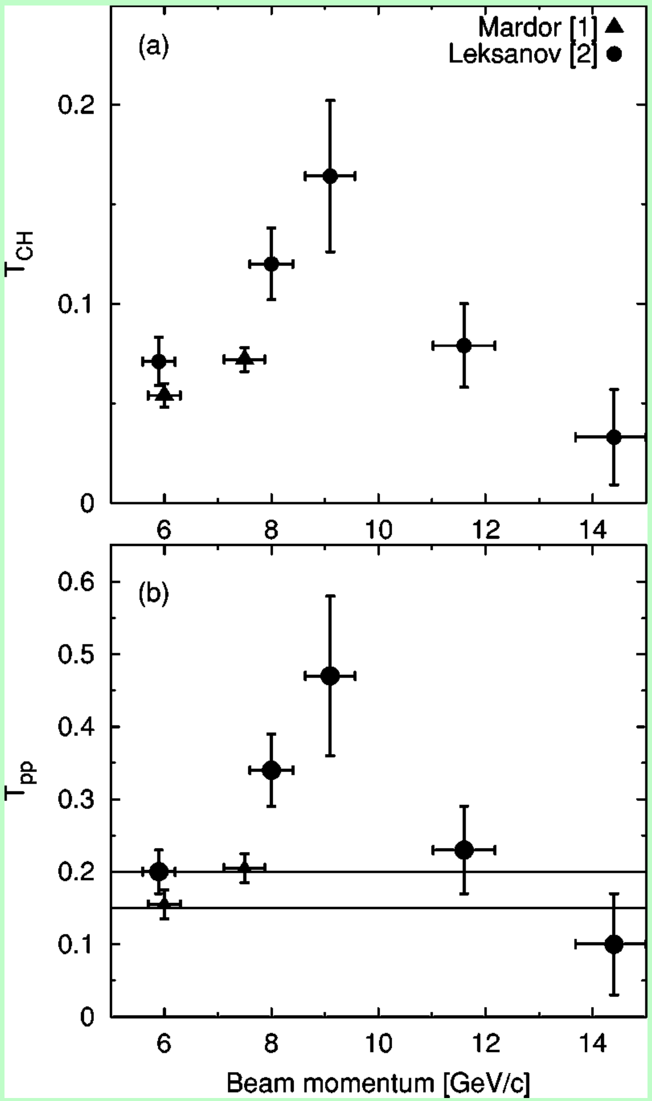
$\pi + p \to \pi + p$, $p + p \to p + p$,... (all together 20 reactions studied were studied at BNL)

Summary: reactions are dominated by quark exchanges with

$$\frac{d\sigma}{d\theta_{c.m.}} = f(\theta_{c.m.}) s^{(-\sum n_{q_i} - \sum n_{q_f} + 2)}$$

Indicates dominance of minimal Fock components of small size

Long story of the studies of p+A → pp (A-1) at BNL by EVA exp.



Nuclear transparency T_{CH} as a function of beam momentum (experiment used CH target)

Nuclear transparency T_{pp} as a function of beam momentum (defined so $T_{pp}=1$ - corresponds to the impulse approximation). Errors shown are statistical which dominate for these measurements

- ✦ Eikonal approximation calculation with proper normalization of the wave function agrees well the 5.9 GeV data.

- ✦ Significant effect for $p = 9$ GeV where $l_{coh} = 2.7$ fm (assuming $l_{coh} = 0.3\ p_h$ as for pions) is sufficient to suppress expansion effects. Magnitude of the enhancement expected in CT models is consistent with the data.

- ✦ Glauber level transparency for 11.5 -14.2 GeV a problem for all models as it is observed in a wide energy range $24\ GeV^2 \leq s' \leq 30\ GeV^2$. **Challenge for QCD theory !!!**

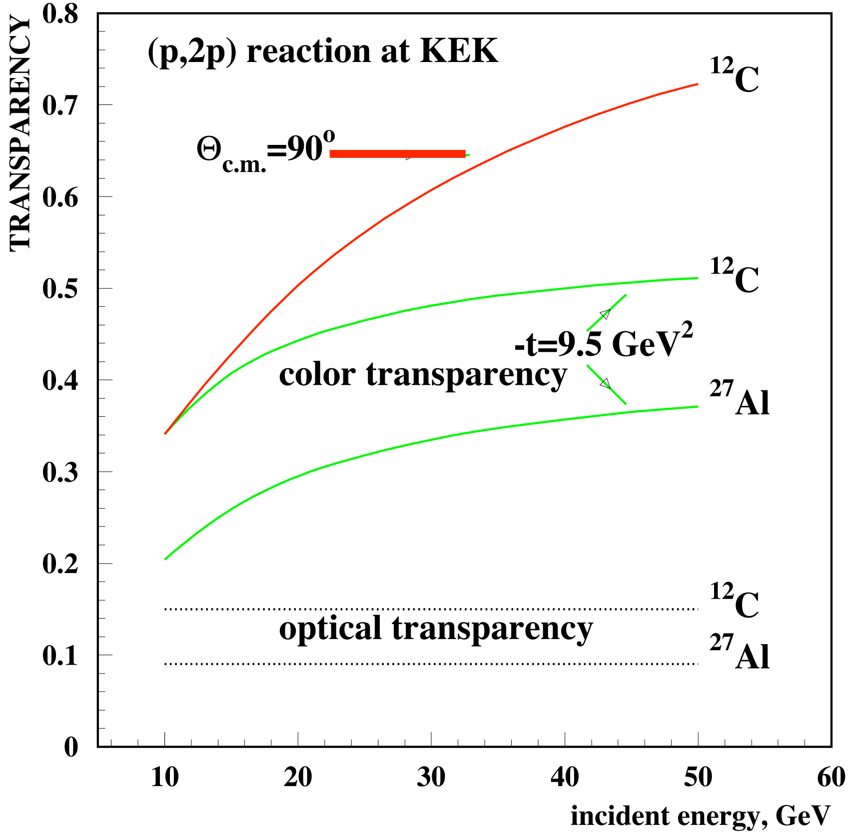
Critical to perform new studies of CT phenomenon in hadronic reactions at energies above 10 GeV where expansion effects are moderate. WIll complement the program of CT in eA scattering at Jlab at 12 GeV.

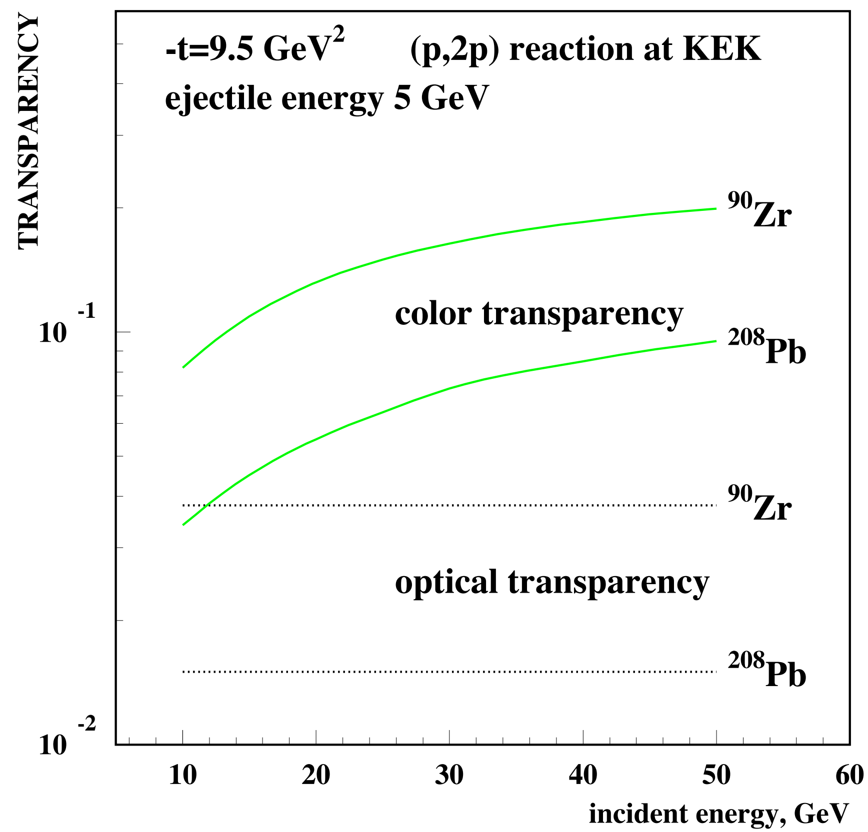
J-PARC & GSI

Advantages - progress in electronics leading to a possibility to work at higher luminosity, wider range of hadron beams including antiprotons at GSI, possibility of polarized beams

☛ (p,2p) at the range of 10-20 GeV for all angles including those close to $\theta_{c.m.} \sim 90^0$

☛ E_p>20 GeV rates for $\theta_{c.m.} \sim 90^0$ are probably too low. Different strategy - T (E_p) for large but fixed t. In this case l_{coh} for initial and the fastest of two final nucleons is very large. Only the slow nucleon has time to expand leading to transparency very similar to the one in A(e,e'p). (Zhalov &MS 89)





Energy dependence of the nuclear transparency calculated in the quantum diffusion model with l_{coh} = 0.4 fm p_N[GeV] ~ as compared to the expectations of the Glauber model.

☛ Study channels where gluon exchanges are not allowed

$$p + A \to \Delta^0 + p + (A-1)$$

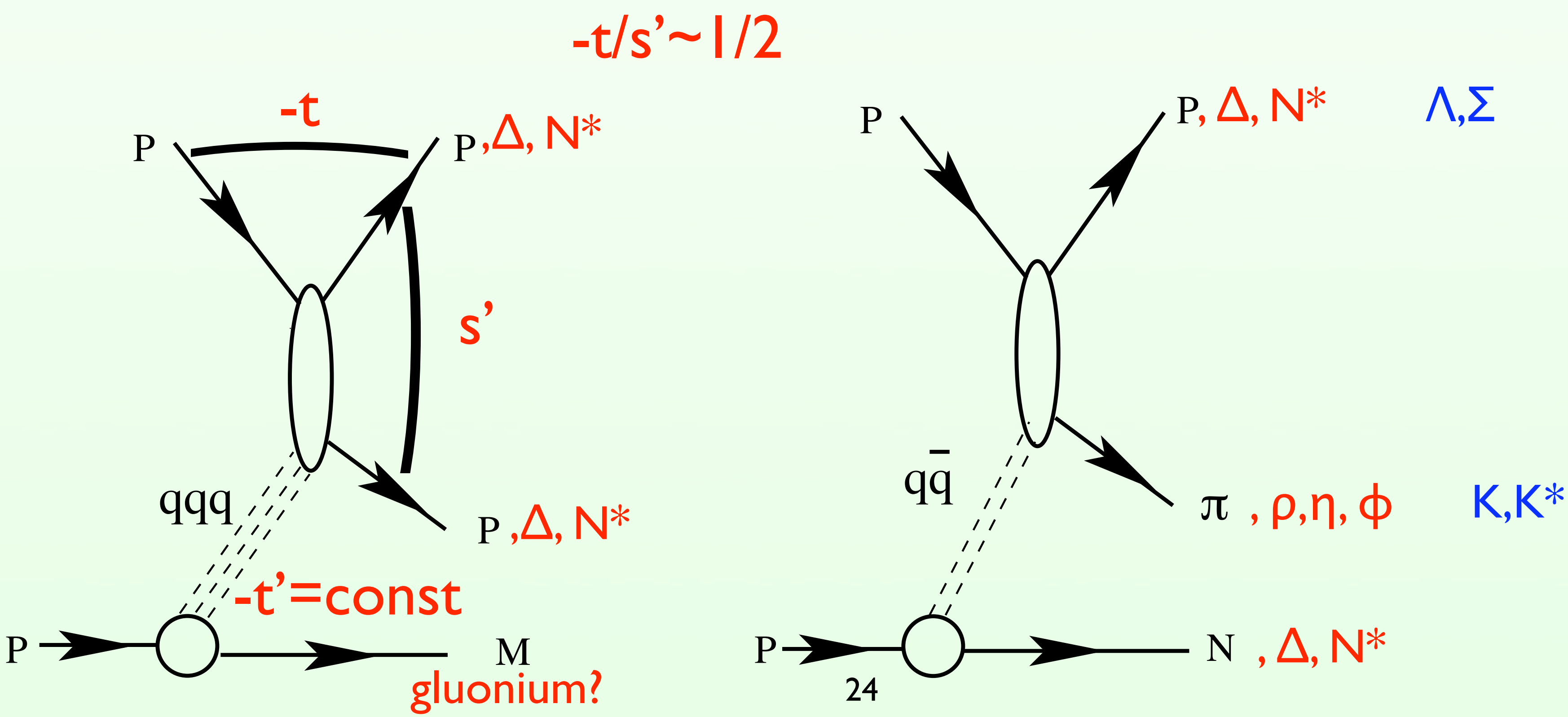
☛ Polarized proton - comparison of T for helicity conserving and helicity flip amplitudes, study of the origin of the Krish effect using polarized proton beam and polarized target like ^{7}Li

☛ Special twist for antiprotons:

$$\bar{p} + A \to \pi^+ + \pi^- + (A-1)$$

Detectors which can study CT are well suited also to study generalized parton distributions using hadronic projectiles complementing the studies with lepton projectiles. *Will be especially beneficial to study in parallel with 12 GeV program at Jlab (GPD studies is the main trust of Jlab program)*

Idea is to consider new type of hard hadronic processes - ***branching exclusive processes*** of large c.m.angle scattering on a "cluster" in a target/projectile (MS95)

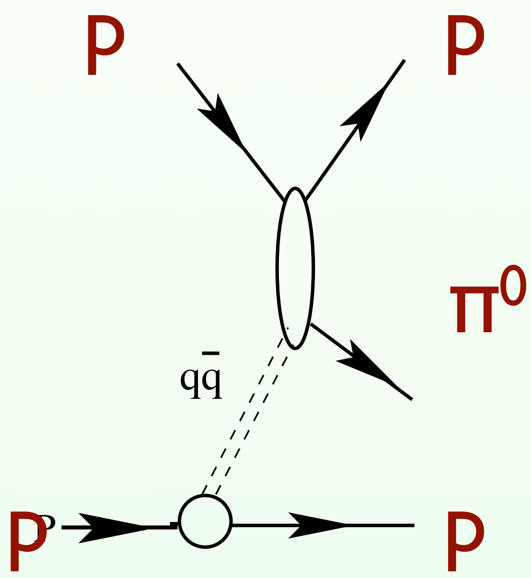


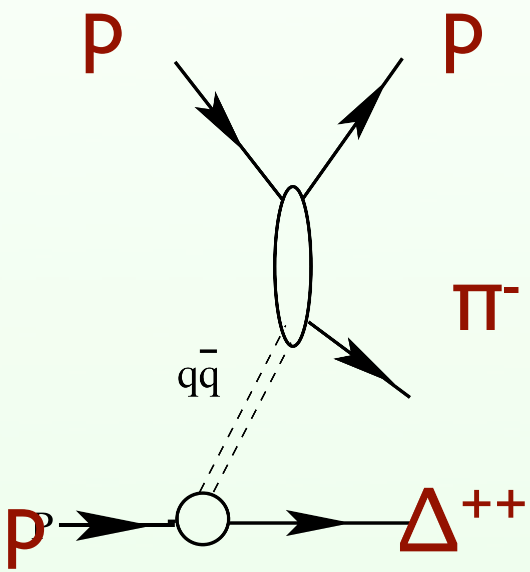
Scaling relations between hadron and electron projectiles for the same momentum of spectator in the proton rest frame

$$\frac{\dfrac{d\sigma(p+p\to p+p+\pi^0)}{d\alpha_{\pi^0}\, d^2p_t/\alpha_{\pi^0}}}{\dfrac{d\sigma(e+N\to e+N+\pi^0)}{d\alpha_{\pi^0}\, d^2p_t/\alpha_{\pi^0}}} \approx \frac{\sigma(p+p\to p+p)}{\sigma(eN\to eN)},$$

$$\frac{\dfrac{d\sigma^{pp\to p+\pi+B}}{d\alpha_B\, d^2p_{tB}\, d\theta_{c.m.}(p\pi)}}{\dfrac{d\sigma^{p\pi\to p+\pi}}{d\theta_{c.m.}}(s_{p\pi})} = \frac{\dfrac{d\sigma^{\gamma_L^*+p\to\pi+B}(Q^2)}{d\alpha_B\, d^2p_t}}{\sigma^{\gamma_L^*+\pi\to\pi}(Q^2)}$$

A detailed theoretical study of the reactions $pp \rightarrow NN\pi$, $N\Delta\pi$ is now under way Kumano, et al





Conclusions I:

Dedicated studies at hadron colliders with a good acceptance in the forward region would allow to observe new phenomena relevant for the understanding of the three dimensional structure of the nucleon

◈ *Mapping of the proton wave function*

- ☛ **Multiparton correlations in nucleons (3D-picture)**
- ☛ **Color fluctuations in nucleons: global effects & x-dependent effects**
- ☞ **Measurement of three quark component of the nucleon wave function in p + p (A)→ "3 jets" + p (A) - a challenging process for experimental studies (analog of π→"2 jets")**

Conclusions II:

Fixed target experiments

- ☛ **Hard exclusive and branching processes with beams of energies 10 - 50 GeV off a proton (neutron) would provide unique opportunities to study fine details of the quark-gluon structure of hadrons including studies of various GPDs with a nice complementarity to the 12 GeV Jlab program, and possible links to experiments at RHIC and LHC.**

- ☛ **Hard exclusive processes with nuclei - unique tools for probing both dynamics of elementary reactions (including origin of large spin effects in the polarized pp scattering) and space time evolution of wave packages which are small in the initial moment.**