Towards discoveries in semi/hard hadron physics

Color transparency in hard 2–>3 hadron induced processes and probing of nondiagonal GPD and perturbative Reggeons

Mark Strikman, 2024 , Amber workshop

Hadron physics - two focal points: structure of hadrons and dynamics of

strong interaction. Critical role played by processes for which factorization theorems hold.

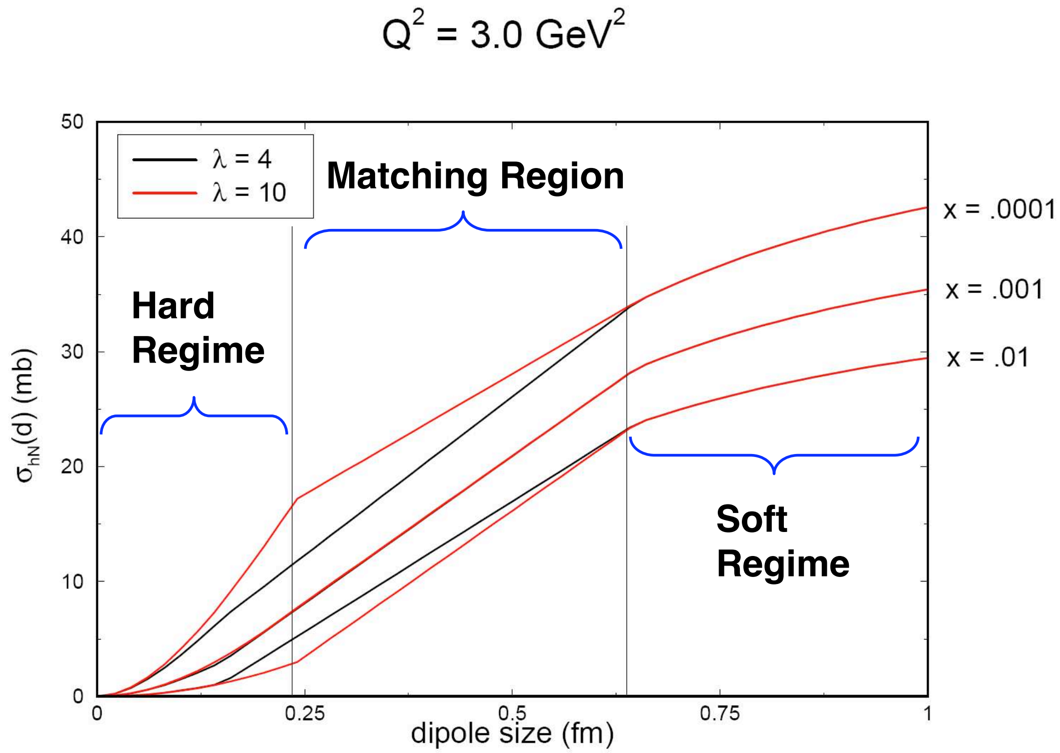
Theorems identify the processes for which separation between wave function and effects of initial /final state interaction holds: DIS, DY

Proof of factorization is based on use of closure —> one dimensional image of nucleon, pion,.

Not sufficient to understand parton structure of hadrons or final state o

for pp collision with production of two jets.

Analysis of Frankfurt et al.: Data on the DIS at HERA, exclusive vector meson production: data are consistent with pQCD expression for cross section for small $d \leq 0.3$ fm $q\bar{q}$ dipoles and smooth matching with soft physics at $d \geq 0.6$ fm:



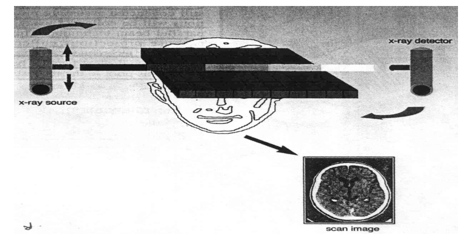
High energy scanning - step II - three D scan

The longitudinal fractions - x's and the transverse separations between the constituents in the projectile do not change during the interaction if energy of collisions is high enough.

Hence it should be possible to measure 3D distribution of partons in nucleon:

1D - momentum + 2D transverse coordinates - 2D slices at set of x values

~ CT computer tomography



Generalized parton distributions

x

1D - parton distribution

ρ- transverse coordinate

x

3D - generalized parton distribution

High energy CT = QCD factorization theorem for DIS exclusive meson processes

The prove is based (as for dijet production) on the CT property of QCD not on closure like the factorization theorem for inclusive DIS.

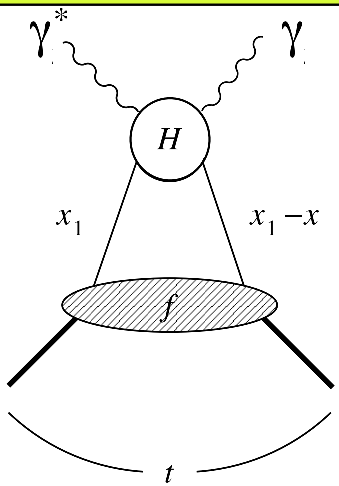
$\gamma^* + N \to \gamma + N(baryonic\, system)$ D.Muller 94 et al, Radyushkin 96, Ji 96, Collins &Freund 98

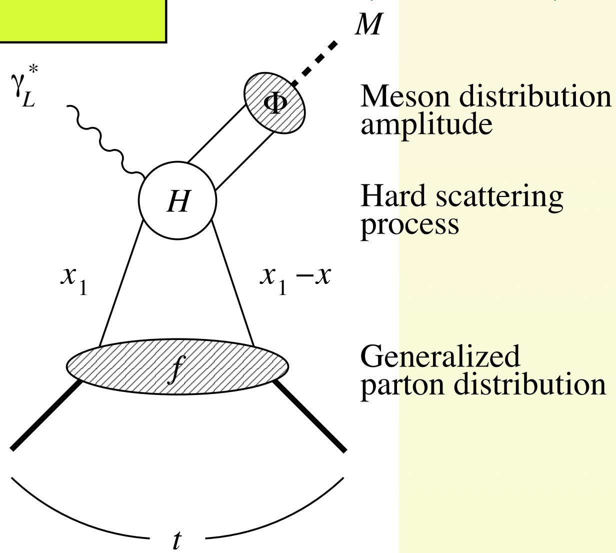
$\pi + T(A,N) \to jet_1 + jet_2 + T(A,N)$ Frankfurt, Miller, MS 93

$\gamma^*_L + N \to "meson"(mesons) + N(baryonic\, system)$ Brodsky,Frankfurt, Gunion,Mueller, MS 94 - vector mesons, small x

Collins, Frankfurt, MS 97 -

provide new effective tools for study of the 3D hadron structure, high energy color transparency and opacity and chiral dynamics





Baryo-baryonic

$\Longrightarrow$ **Need to trigger on small size configurations at high energies.**

Two ideas:

$\diamond$ Select special final states: diffraction of pion into two high transverse momentum jets - an analog of the positronium inelastic diffraction. Qualitatively - from the uncertainty relation $d \sim 1/p_t(jet)$

$\diamond$ $\diamond$ Select a small initial state - diffraction of longitudinally polarized virtual photon into mesons. Employs the decrease of the transverse separation between q and $\bar{q}$ in the wave function of γ_L^*, $d \propto 1/Q$.

For hadron & photon beam main requirement that squeezing is significant enough. Entering color transparency regime.

$$\pi + N(A) \rightarrow \text{“}2\ high\ p_t\ jets\text{''} + N(A)$$

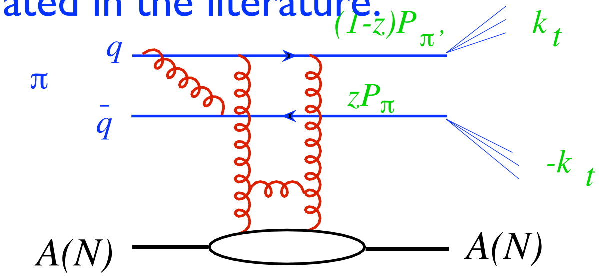
Mechanism:

Pion approaches the target in a frozen small size $q\bar{q}$ configuration and scatters elastically via interaction with $G_{target}(x, Q^2)$.

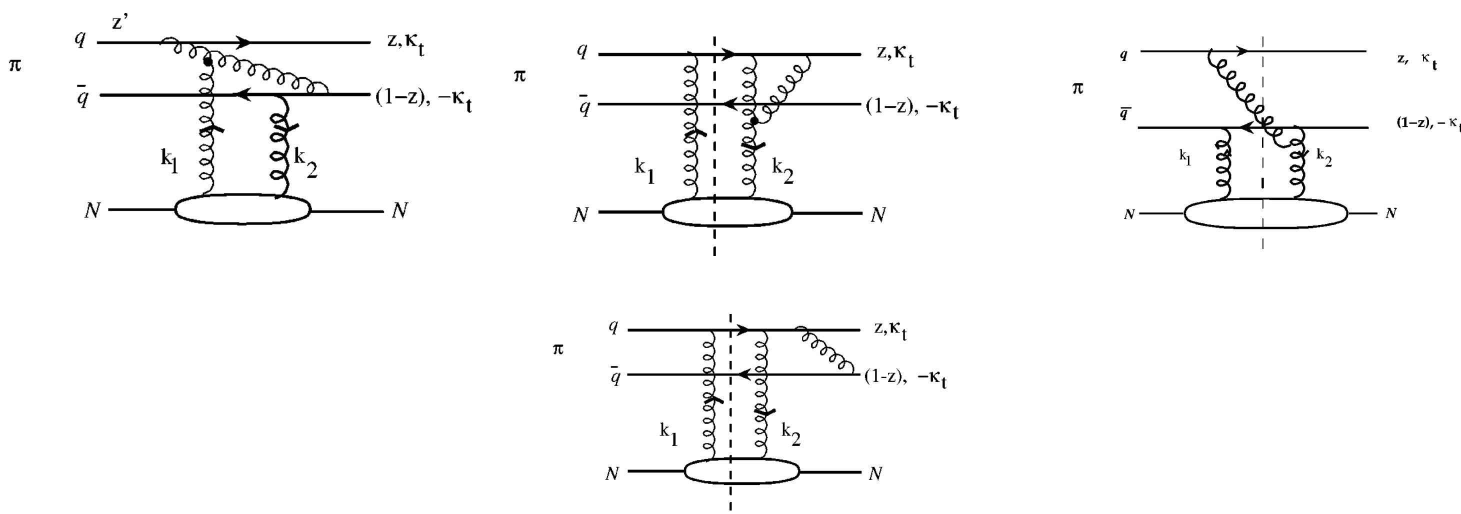
- First attempt of the theoretical analysis of πN process - Randa 80 - power law dependence of p_t of the jet (wrong power)
- First attempt of the theoretical analysis of πA process - Brodsky et al 81 - exponential suppression of p_t spectra, weak A dependence ($A^{1/3}$)
- pQCD analysis - Frankfurt, Miller, MS 93; elaborated arguments related to factorization 2003

Calculation accounts for energy-momentum conservation, gauge invariance, QCD evolution and asymptotic freedom.
This is nontrivial since these properties are often violated in the literature.

One of dominant diagrams



Examples of the Suppressed diagrams



A slightly simplified final answer is

$$A(\pi + N \to 2\, jets + N)(z, p_t, t = 0) \propto$$

$$\int d^2 d \psi_\pi^{q\bar{q}} \sigma_{q\bar{q}-N(A)}(d, s) \exp(i p_t d)$$

$$d = r_t^q - r_t^{\bar{q}},$$

$\psi_\pi^{q\bar{q}}(z, d) \propto z(1-z)_{d\to 0}$ is the quark-antiquark Fock component of the meson light cone wave function

$\Longrightarrow$ A-dependence: $A^{4/3}\left[\frac{G_A(x,k_t^2)}{AG_N(x,k_t^2)}\right]^2$, where $x = M^2_{dijet}/s$. $(A^{4/3} = A^2/R_A^2)$

$\Longrightarrow$ $\frac{d\sigma(z)}{dz} \propto \phi_\pi^2(z) \approx z^2(1-z)^2$ where $z = E_{jet_1}/E_\pi$.

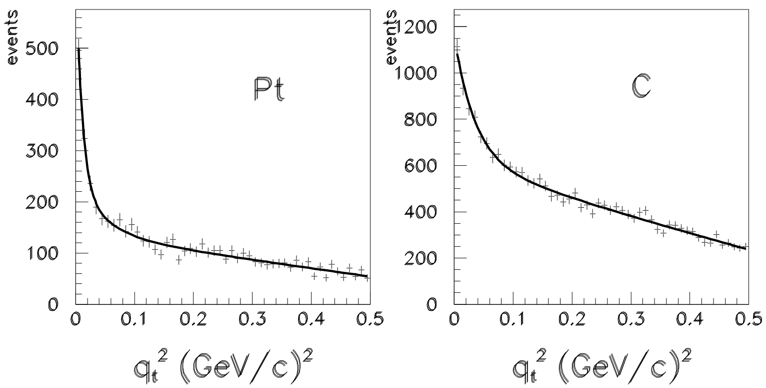
$\Longrightarrow$ k_t dependence: $\frac{d\sigma}{d^2k_t} \propto \frac{1}{k_t^n}, n \approx 8$ for $x \sim 0.02$

$\Longrightarrow$ Absolute cross section is also predicted

What is the naive expectation for the A-dependence of pion dissociation for heavy nuclei? Pion scatters off a black absorptive target. So at impact parameters $b < R_A$ interaction is purely inelastic, while at $b > R_A$ no interaction. Hence $\sigma_{inel} = \pi R_A^2$. How large is σ_{el}? Remember the Babinet's principle from electrodynamics: scattering off a screen and the complementary hole are equivalent. Hence $\sigma_{el} = \pi R_A^2$, while inelastic diffraction occurs only due to the scattering off the edge and hence $\propto A^{1/3}$

The E-791 (FNAL) data $E^{\pi}_{inc} = 500 GeV$ (D.Ashery et al, PRL 2000)

♡ Coherent peak is well resolved:



Number of events as a function of q_t^2, where $q_t = \Sigma_i p_t^i$ for the cut $\Sigma p_z \geq 0.9 p_\pi$.

$\heartsuit\heartsuit$ Observed A-dependence $A^{1.61\pm0.08}$ $[C\rightarrow Pt]$

FMS prediction $A^{1.54}$ $[C\rightarrow Pt]$ for large k_t & extra small enhancement for intermediate k_t.

For soft diffraction the Pt/C ratio is ~ 7 times smaller!!

(An early prediction Bertsch, Brodsky, Goldhaber, Gunion 81

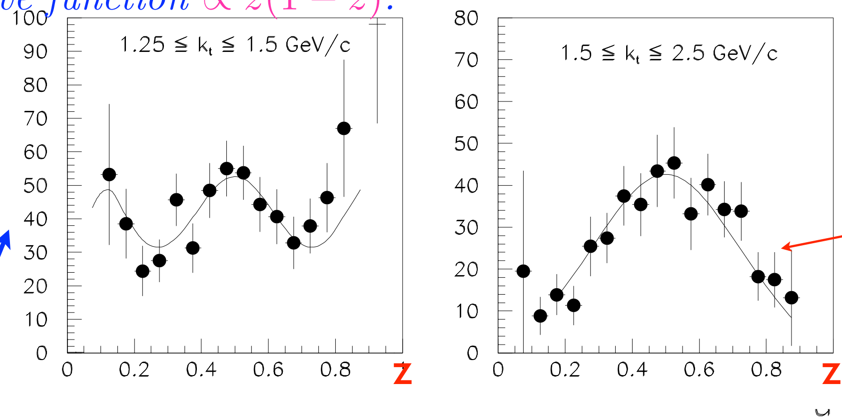
$\sigma(A)\propto A^{1/3}$)

In soft diffraction color fluctuations are also important leading to

$$\sigma_{soft\ diffr}(\pi + A \rightarrow X + A) \propto A^{.7}$$

Miller Frankfurt &S, 93

♡♡♡ *The z dependence is consistent with dominance of the asymptotic pion wave function $\propto z(1-z)$.*



prediction

(π wave funct)²

$$Q^2(\pi\ f.f.) \sim 4k_t^2(jet)$$

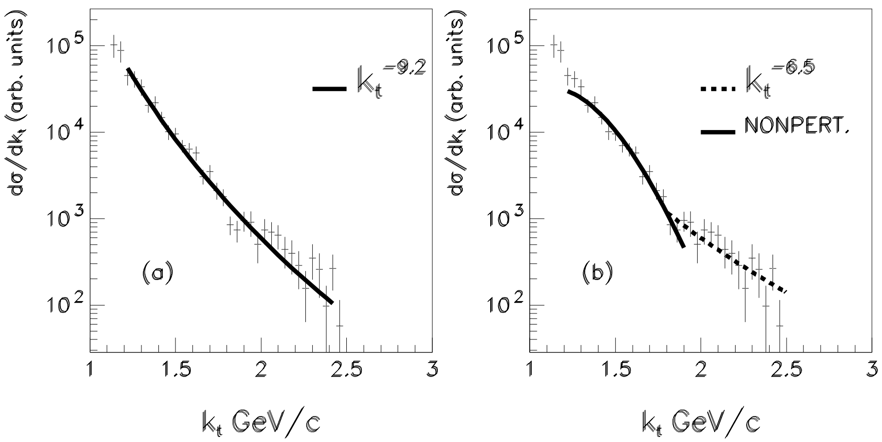
$$\Downarrow$$

strong squeezing in π form factor for Q^2=6 GeV²

Squeezing occurs already before the leading term (1-z)z dominates!!!

Caveats - - acceptance corrections for kt <1.5 GeV is large & definition jet is poor.

♡♡♡♡ k_t^{-n} *dependence of* $d\sigma/dk_t^2 \propto 1/k_t^{7.5}$ *for* $k_t \geq 1.7 GeV/c$ *close to the QCD prediction -* $n \sim 8.0$ *for the kinematics of E791*



$\Longrightarrow$ • *High-energy color transparency is* **directly** *observed.*

• *The pion* $q\bar{q}$ *wave function is* **directly** *measured.*

To do list theorist's. dream

- A-dependence aș a function of hardness: A1.6 vs A0.7
- t- dependence; - for t=0 measures color fluctuations in projectile
- Absolute total ross section

  Minimum - maximum oscillations pattern as a function of t

- Kaon - pion comparisons

For example, in the case pion and kaon induced exclusive dijet production

- $\frac{\sigma(K^- N)}{\sigma(\pi^- N)}$ = 0.7 for total cross section

  Squire of the kaon and pion wf in the origin $\left(\frac{f_K}{f_\pi}\right)^2 \sim 1.5$

  for exclusive dijet production

Important to develop a toolkit of hadron induced processes which which select small configurations and hence factorizable. Would allow to study GPDs of different hadrons

Natural candidate - large angle 2➔2 processes. One of the first applications of CT ideas was to use nuclei to test whether pp➔pp,... is dominated by point-like configurations (Brodsky & Mueller, 82).

Problem:

. Need to account for the evolution of wave package with distance.

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Problem:

the lab momenta of produced nucleons are of the order -t/2m - cannot treat configurations as frozen up to very large t

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Natural candidate - large angle $2\to2$ processes. One of the first applications of CT ideas was to use nuclei to test whether $pp\to pp$,... is dominated by point-like configurations (Brodsky & Mueller, 82).

Problem:

the lab momenta of produced nucleons are of the order $-t/2m$ - cannot treat configurations as frozen up to very large t

Freezing: ***Main challenge:*** $|qqq\rangle$ ($|q\bar{q}\rangle$) is not an eigenstate of the QCD Hamiltonian. So even if we find an elementary process in which interaction is dominated by small size configurations - they are not frozen. They evolve with time - expand after interaction to average configurations and contract before interaction from average configurations (FFLS88)

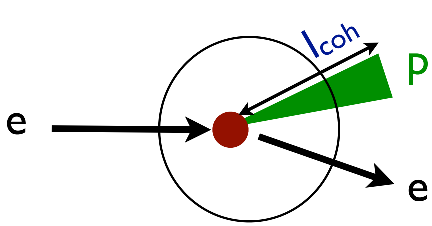
$$|\Psi_{PLC}(t)\rangle = \sum_{i=1}^{\infty} a_i \exp(iE_i t)\,|\Psi_i t)\rangle = \exp(iE_1 t) \sum_{i=1}^{\infty} a_i \exp\left(\frac{i(m_i^2 - m_1^2)t}{2P}\right) |\Psi_i t)\rangle$$

$$\boxed{\sigma^{PLC}(z) = \left(\sigma_{hard} + \frac{z}{l_{coh}}\left[\sigma - \sigma_{hard}\right]\right)\theta(l_{coh} - z) + \sigma\theta(z - l_{coh})}$$

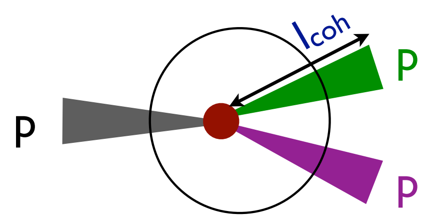
Quantum Diffusion model of expansion

$l_{coh}\sim$ (0.4- 0.8) fm E_h[GeV]

actually *<u>incoherence</u>* *length*



eA→ ep (A-1) at large Q

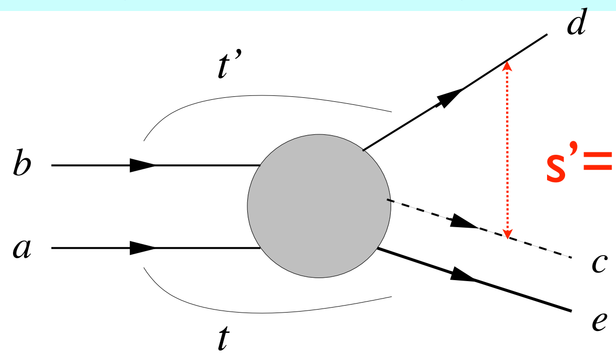


pA→ pp (A-1) at large t and intermediate energies

The same expression with the same parameters describes production of leading hadrons in DIS - U.Mozel et al

2 →3 branching processes: new direction in probing GPDs and CT

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 (MS94)



$s' = (p_d + p_c)^2$

Limit:

-t’ > few GeV^2, -t’/ s’ ~1/2

-t=const ~ 0

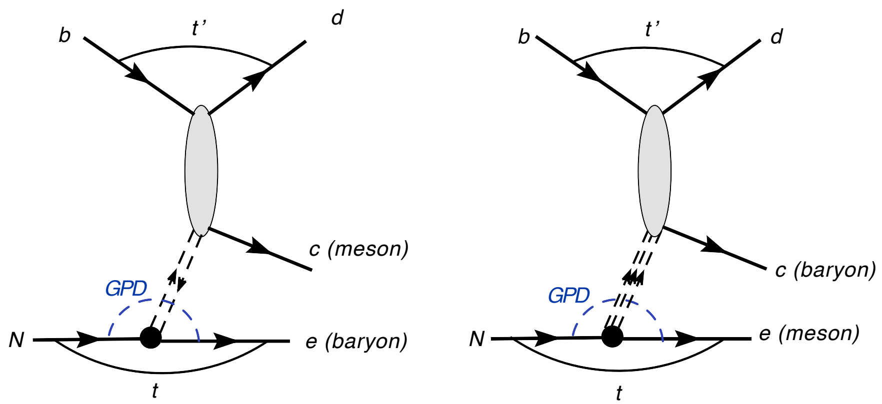
➡ s’/s<<1

2 →3 branching processes:

- test onset of CT for 2 →2 avoiding freezing effects
- measure transverse sizes of b, d,c
- measure cross sections of large angle pion - pion (kaon) scattering
- probe 5q in nucleon and 4q in mesons
- measure GPDs of nucleons, mesons and photons(!)

First two quantitative evaluations of pp—> pN pi, Kumano, MS, and Sudoh PRD 09; Kumano &MS Phys.Lett. 10

Factorization:



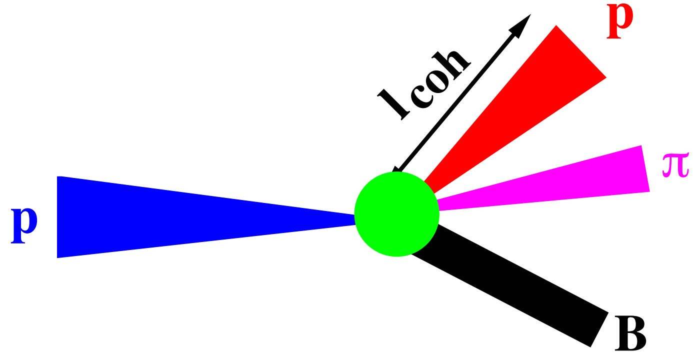
If the upper block is a hard (2 →2) process, "b", "d", "c" are in small size configurations as well as exchange system (qq, qqq). Can̄ use CT argument as in the proof of QCD factorization of meson exclusive production in DIS (Collins, LF, MS 97)

$$\Downarrow$$

$$\mathcal{M}_{NN\to N\pi B} = GPD(N \to B) \otimes \psi_b^i \otimes H \otimes \psi_d \otimes \psi_c$$

Minimal condition for factorization:

$$l_{coh} > r_N \sim 0.8 \text{ fm}$$



Time evolution of the 2 → 3 process

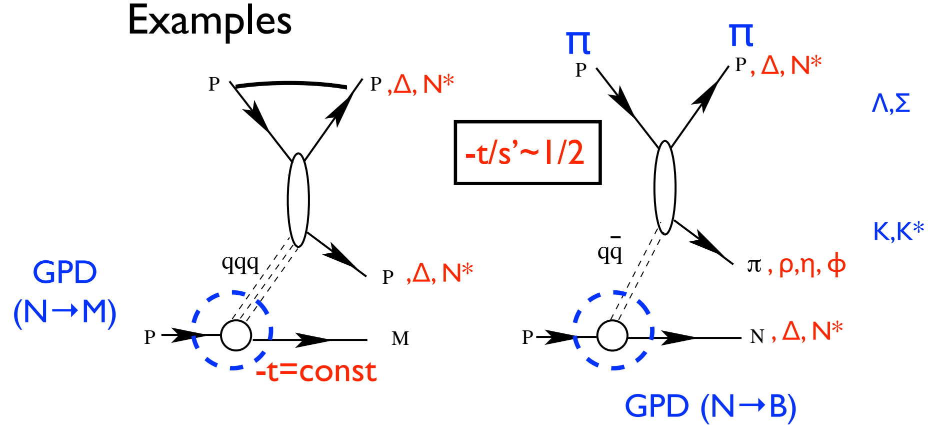
$$l_{coh} = (0.4 \div 0.6 \text{ fm}) \cdot p_h/(\text{GeV}/c)$$

$$p_c \geq 3 \div 4 \text{ GeV}/c, \quad p_d \geq 3 \div 4 \text{ GeV}/c$$

$$p_b \geq 6 \div 8 \, \text{GeV/c}$$

Much easier to reach the regime of freezing than in CT reactions with nuclei

Examples



$$\pi^- p \to \pi^- \pi^- \Delta^{++}, \quad \pi^- p \to \pi^- \pi^+ \Delta^0, \quad \pi^- p \to \pi^- \pi^0 p,$$

Advantage - CT for pions is observed, easier to squeeze pions. Measurements at small t - close to pion pole can normalize GPDs and determine elastic $\pi^- \pi^-$, $\pi^- \pi^+$, $\pi^- \pi^0$ cross sections

Similar for Kaon beams

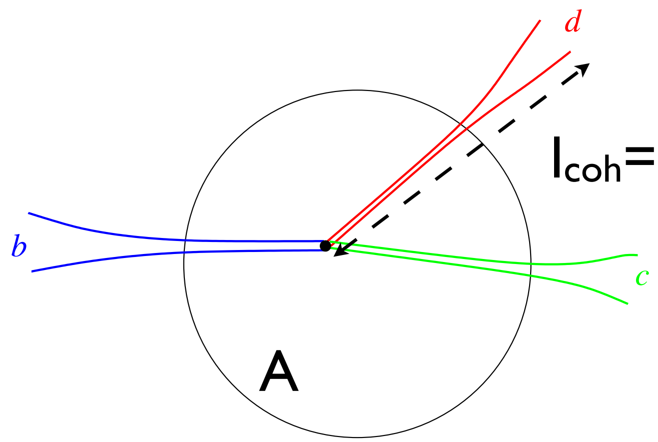
AMBER / COMPASS has veery good momentum resolution (hence good missing mass resolution) - so a recoil / veto detector may not be necessary

How to check that squeezing takes place and one can use GPD logic?

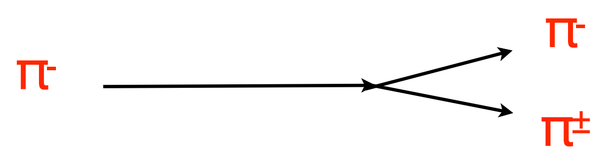
Use as example process $\pi^- A \to \pi^- \pi^\pm A^*$

- easier to squeeze
- COMPASS 190 GeV data on tape
- Early data from FNAL

$p_f(\pi) = p_i(\pi)/2$, vary $p_{ft}(\pi) = 1 - 2$ GeV/c; $p_{ft}(\pi^-) + p_{ft}(\pi^\pm) \sim 0$



l_{coh}=60 fm



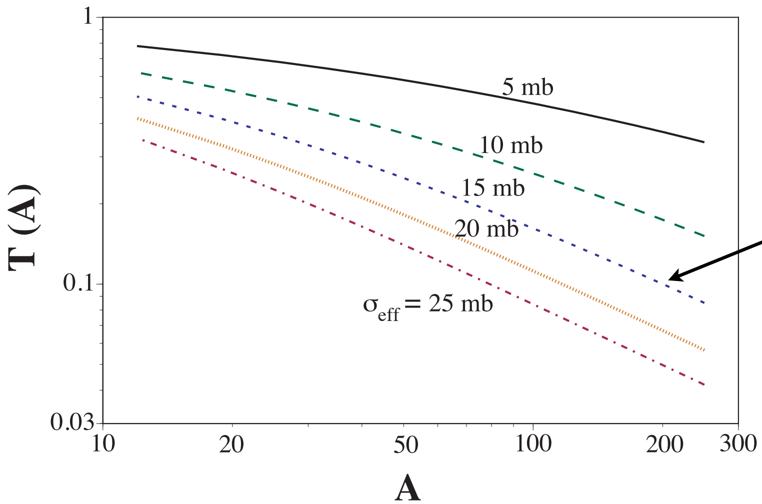
Branching (2→3) processes with nuclei - freezing is 100% effective for p_{inc} > 100 GeV/c - study of one effect only - CT due to squeezing of the size of fast hadrons

$$T_A = \frac{\frac{d\sigma(\pi^- A \to \pi^- \pi^+ A^*)}{d\Omega}}{Z\frac{d\sigma(\pi^- p \to \pi^- \pi^+ n)}{d\Omega}}$$

$$T_A(\vec{p}_b, \vec{p}_c, \vec{p}_d) = \frac{1}{A}\int d^3r \rho_A(\vec{r}) P_b(\vec{p}_b, \vec{r}) P_c(\vec{p}_c, \vec{r}) P_d(\vec{p}_d, \vec{r})$$

where $\vec{p}_b, \vec{p}_c, \vec{p}_d$ are three momenta of the incoming and outgoing particles b, c, d; ρ_A is the nuclear density normalized to $\int \rho_A(\vec{r}) d^3r = A$

$$P_j(\vec{p}_j, \vec{r}) = \exp\left(-\int_{\text{path}} dz\, \sigma_{\text{eff}}(\vec{p}_j, z)\rho_A(z)\right)$$



Large effect even if the pion radius is changed just by 30%

If there are two scales in pion (Gribov) - steps in $T(k_t^\pi)$ as a function of k_t^π

If squeezing is large enough can measure quark- antiquark size using dipole - nucleon cross section

If squeezing is large enough one can measure quark- antiquark size using dipole - nucleon cross section which I discussed before

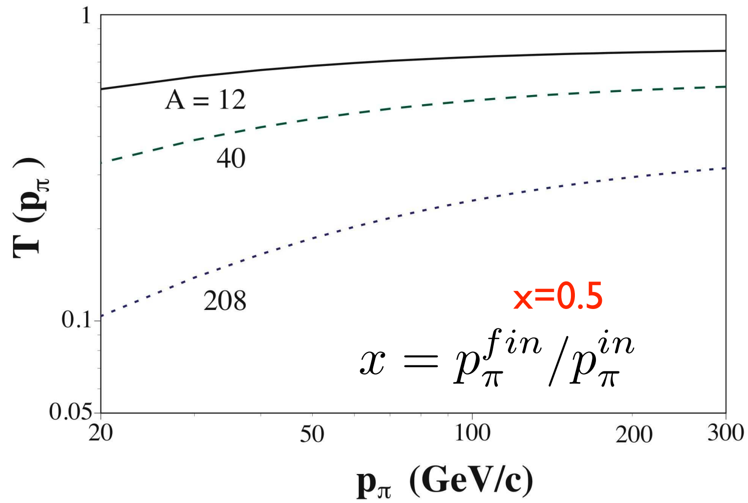
$$\sigma(d,x) = \frac{\pi^2}{3}\alpha_s(Q^2_{eff})d^2\left[xG_N(x,Q^2_{eff}) + \frac{2}{3}xS_N(x,Q^2_{eff})\right]$$

Defrosting point like configurations - energy dependence for fixed s',t'

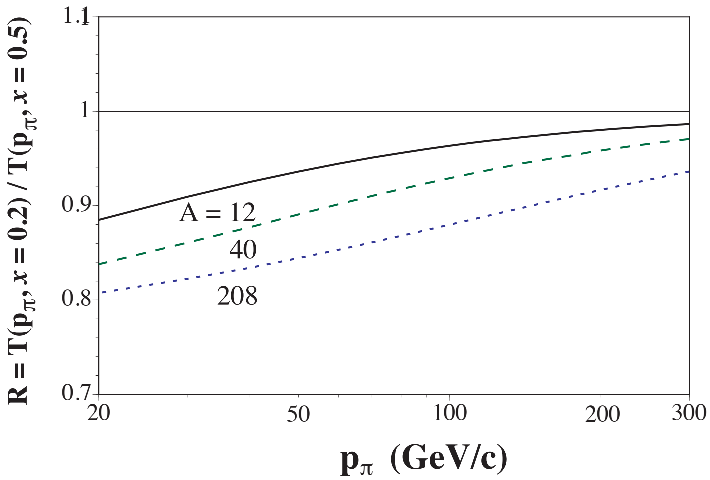
$$\sigma^{PLC}(z) = \left(\sigma_{hard} + \frac{z}{l_{coh}}\left[\sigma - \sigma_{hard}\right]\right)\theta(l_{coh} - z) + \sigma\theta(z - l_{coh})$$

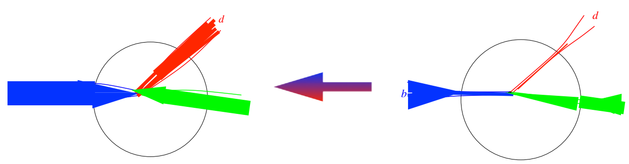
Quantum Diffusion model of expansion

Use $l_{coh} \sim 0.6$ fm E_h[GeV]   which describes well CT for pion electroproduction

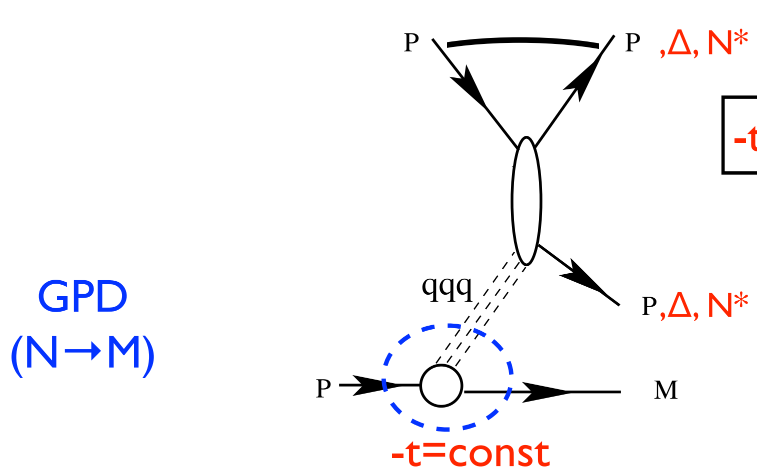


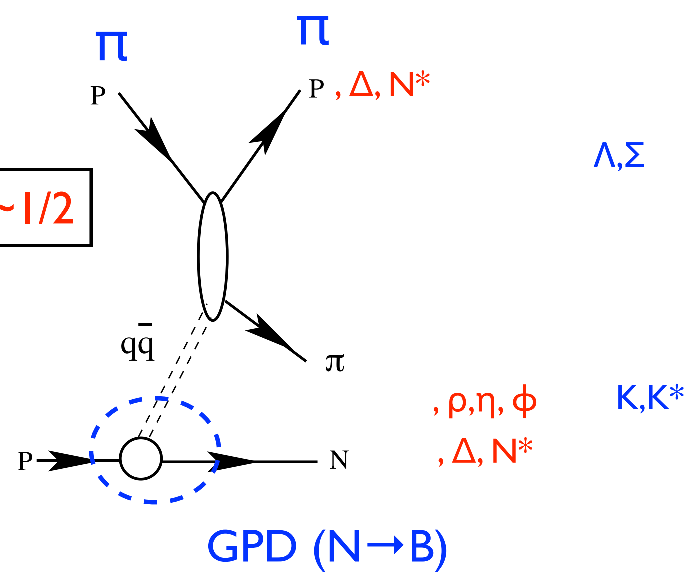
$$x = p_\pi^{fin}/p_\pi^{in}$$





Examples





$$pp \to pN + M(\pi, \eta, \pi\pi)$$

$$pp \to p\Delta + M(\pi, \eta, \pi\pi)$$

$$pp \to p\Lambda + K^+$$

$$\pi^- p \to p\pi + M$$

$$\pi^- p \to \pi^- \pi^- \Delta^{++},$$

COMPASS

$$\pi^- p \to \pi^- \pi^+ \Delta^0,$$

$$\pi^- p \to \pi^- \pi^0 p,$$

J-PARC if beams of pions with energies 20 -40 GeV are doable

$$\pi^- p \to \pi^- p + (\pi^0 \pi^0 \ - forward\ low\ p_t)$$

Study of Hidden/Intrinsic Strangeness & Charm in hadrons

$pp \to \Lambda_{sp}$ (any other strange baryon)+ $K^+(K^*)$ + p

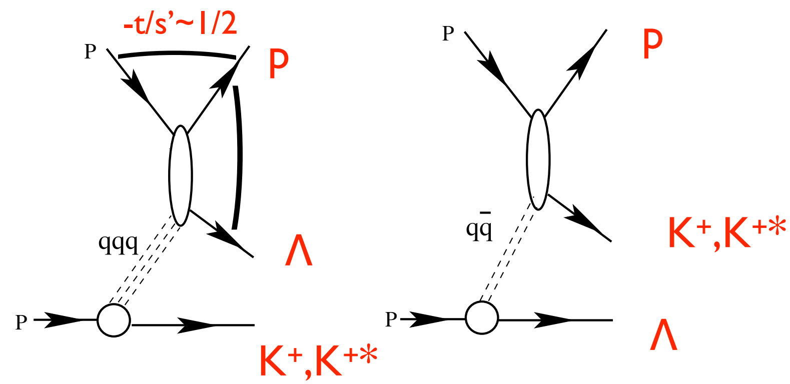
$pp \to K(K^*)_{sp} + \Lambda + p$

$pp \to \phi_{sp} + p + p$

BNL experiment: EVA has few candidate events

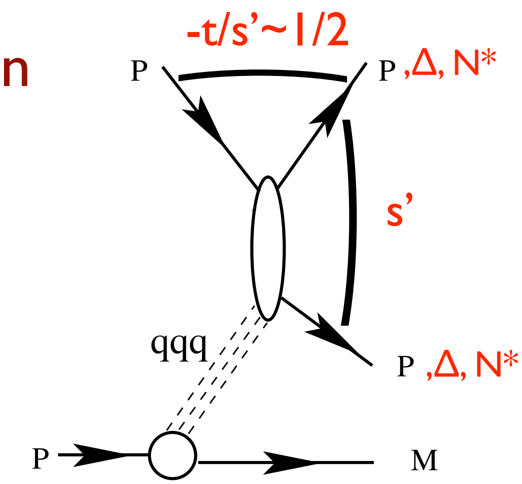
$pp \to \bar{D}_{sp} + \Lambda_c + p$

$\pi^+ p \to K^+_{sp} + \bar{K}^0 + p$



Study of the spin structure of the nucleon

use of polarized beams and/or targets



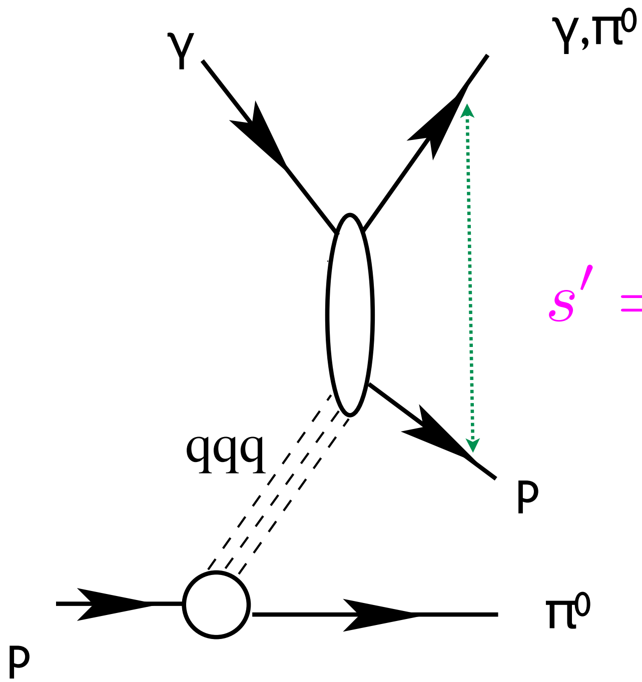
$\vec{p}\vec{p} \to \Lambda_{sp}$ (any other strange baryon)+ $K^{+}(K^{*})$ + p

$\vec{p}\vec{p} \to$ $K^{+}(K^{*})_{sp}$ $+\vec{\Lambda}$(any other strange baryon)+ p

$\vec{p}\vec{p} \to \Delta_{sp}$ (any other strange baryon)+ meson + p

study of the NΔ GPDs - more GPDs than for NN case - QCD chiral model - selection rules; single transverse spin asymmetries

Frankfurt, Pobilitsa, Polyakov, MS 98



$$s' = (1 - \alpha_\pi)s$$

Recent studies by Qiu et al, Szymanowski, Pire

$$\alpha_\pi = (E_\pi - p_\pi^{(3)})/m_p$$

Slow pion corresponds to large s' and hence allows large t for a large range of c.m. angles for E_γ ~10 GeV

Small probability of πN is to some extent compensates by smaller s' since $\sigma_{\gamma N \to \pi N} \propto (s'/s)^{-7}$

A-dependence - large longitudinal momenta of p &π^0 → CT effects significant for fixed α_π and with increase of proton p_t .

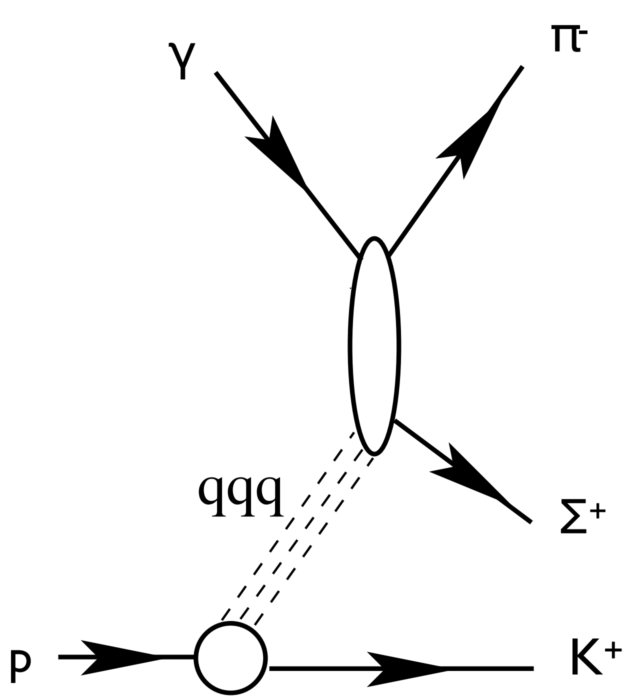
Very interesting channel: $\gamma + p \to \pi^0 + p + (\pi^0\pi^0), M_{\pi^0\pi^0} < 600\, MeV$

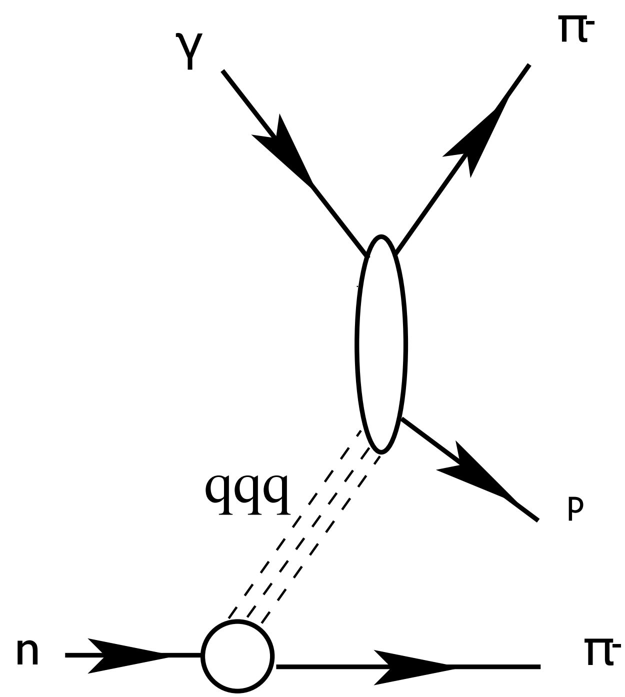
$\gamma + n \to \pi^- + p + (\pi^0\pi^0), M_{\pi^0\pi^0} < 600\, MeV$

σ's?

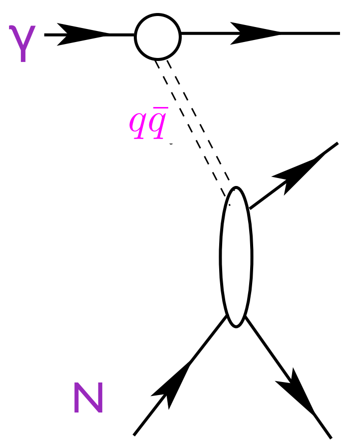
Remark: α_γ=0 simplifies using photon beam without tagging

Other interesting channels





Four quark component in real photon



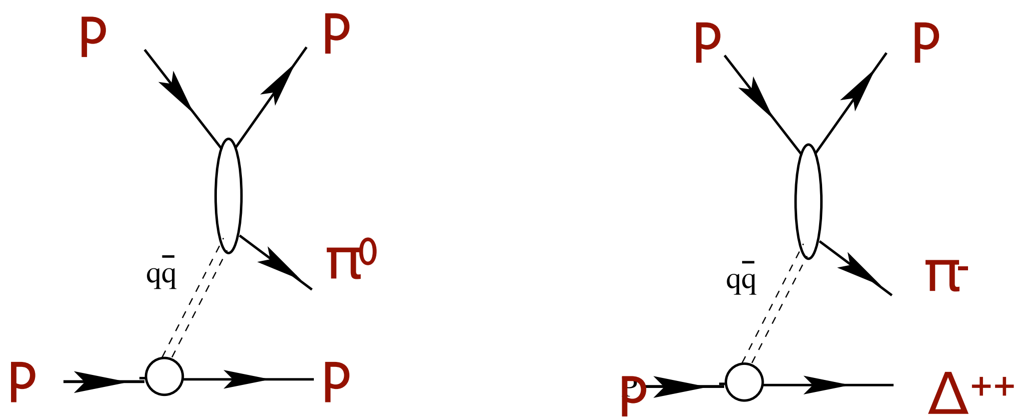
π(meson) with large longitudinal momentum and small p_t

meson with large longitudinal momentum and large k_t

Baryon with $p_t \sim -k_t$

A detailed theoretical study of the reactions $pp \rightarrow NN\pi$, $N\Delta\pi$ was recently completed. Factorization based on squeezing

Kumano, Strikman, and Sudoh 09



Strategy of the first numerical analysis:

- account for contributions of GPDs corresponding to
  $q\bar{q}$ pairs with S=1 and 0
- Approximate the ERBL configurations by the pion and ρ-meson poles
- Use experimental information about

$$\pi^- p \to \pi^- p,\ \pi^- p \to \rho^- p$$
$$\pi^+ p \to \pi^+ p,\ \pi^+ p \to \rho^+ p$$

much better data are necessary for beams of energies of the order 10 GeV - J-PARC!!!

$$d\sigma = \frac{S}{4\sqrt{(p_a \cdot p_b)^2 - m_N^4}} \overline{\sum}_{\lambda_a,\lambda_b} \sum_{\lambda_d,\lambda_e} |\mathcal{M}_{NNN\pi B}|^2$$

$$\times \frac{1}{2E_c}\frac{d^3p_c}{(2\pi)^3}\frac{1}{2E_d}\frac{d^3p_d}{(2\pi)^3}\frac{1}{2E_e}\frac{d^3p_e}{(2\pi)^3}(2\pi)^4\delta^4(p_a + p_b - p_c - p_d - p_e)$$

$$\frac{d\sigma}{d\alpha d^2 p_{BT} d\theta_{cm}} = f(\alpha, p_{BT})\phi(s', \theta_{cm})$$

$$\alpha \equiv \alpha_{spec} = (1-\xi)/(1+\xi)$$

$$s' = (1-\alpha)s$$

$$\phi(s', \theta_{cm}) \approx (s')^n \gamma(\theta_{cm})$$

$$\mathcal{M}_N^V = \int \frac{d\lambda}{2\pi} e^{i\lambda x} \left\langle N, p_e \left| \overline{\psi}(-\lambda n/2) \not{n} \psi(\lambda n/2) \right| N, p_a \right\rangle$$
$$= I_N \, \overline{\psi}_N(p_e) \big[H(x,\xi,t) \not{n} + E(x,\xi,t) \frac{i\sigma^{\alpha\beta} n_\alpha \Delta_\beta}{2m_N} \big] \psi_N(p_a)$$

$$I_N =< 1/2 || \widetilde{T} || 1/2 > \left\langle \tfrac{1}{2} M_N : 1m \middle| \tfrac{1}{2} M_N' \right\rangle / \sqrt{2}$$

$$\mathcal{M}_N^A = \int \frac{d\lambda}{2\pi} e^{i\lambda x} \left\langle N, p_e \left| \overline{\psi}(-\lambda n/2) \not{n} \gamma_5 \psi(\lambda n/2) \right| N, p_a \right\rangle$$
$$= I_N \, \overline{\psi}_N(p_e) \big[\widetilde{H}(x,\xi,t) \not{n} \gamma_5 + \widetilde{E}(x,\xi,t) \frac{n \cdot \Delta \gamma_5}{2m_N} \big] \psi_N(p_a)$$

N →Δ transitions

$$\mathcal{M}^V_{N\to\Delta} = \int \frac{d\lambda}{2\pi} e^{i\lambda x} \left\langle \Delta, p_e \left| \overline{\psi}(-\lambda n/2) \not{n} \psi(\lambda n/2) \right| N, p_a \right\rangle$$
$$= I_{\Delta N} \overline{\psi}^\mu_\Delta(p_e) \big[H_M(x,\xi,t) \mathcal{K}^M_{\mu\nu} n^\nu + H_E(x,\xi,t) \mathcal{K}^E_{\mu\nu} n^\nu$$
$$+ H_C(x,\xi,t) \mathcal{K}^C_{\mu\nu} n^\nu \big] \psi_N(p_a),$$

$$\mathcal{K}^M_{\mu\nu} = -i \frac{3(m_\Delta + m_N)}{2m_N[(m_\Delta + m_N)^2 - t]} \varepsilon_{\mu\nu\lambda\sigma} P^\lambda \Delta^\sigma,$$
$$\mathcal{K}^E_{\mu\nu} = -\mathcal{K}^M_{\mu\nu} - \frac{6(m_\Delta + m_N)}{m_N Z(t)} \varepsilon_{\mu\sigma\lambda\rho} P^\lambda \Delta^\rho \varepsilon^\sigma_{\nu\kappa\delta} P^\kappa \Delta^\delta \gamma^5,$$
$$\mathcal{K}^C_{\mu\nu} = -i \frac{3(m_\Delta + m_N)}{m_N Z(t)} \Delta_\mu (t P_\nu - \Delta \cdot P \Delta_\nu) \gamma^5,$$

where m_Δ is the Δ mass, and $Z(t)$ is defined by

$$Z(t) = [(m_\Delta + m_N)^2 - t][(m_\Delta - m_N)^2 - t].$$

$$
\begin{aligned}
\mathcal{M}^{A}_{N\to\Delta} &= \int \frac{d\lambda}{2\pi} e^{i\lambda x} \left\langle \Delta, p_e \left| \overline{\psi}(-\lambda n/2) \not{n} \gamma^5 \psi(\lambda n/2) \right| N, p_a \right\rangle \\
&= I_{\Delta N}\, \overline{\psi}^{\mu}_{\Delta}(p_e) \Big[\widetilde{H}_1(x,\xi,t) n_\mu + \widetilde{H}_2(x,\xi,t) \frac{\Delta_\mu (n\cdot\Delta)}{m_N^2} \\
&\qquad + \widetilde{H}_3(x,\xi,t) \frac{n_\mu \not{\Delta} - \Delta_\mu \not{n}}{m_N} \\
&\qquad + \widetilde{H}_4(x,\xi,t) \frac{P\cdot\Delta n_\mu - 2\Delta_\mu}{m_N^2} \Big] \psi_N(p_a)
\end{aligned}
$$

$$
\begin{aligned}
\phi_\pi(z) &= \sqrt{3} f_\pi z(1-z), \\
\phi_\rho(z) &= \sqrt{6} f_\rho z(1-z).
\end{aligned}
$$

$$\frac{d\sigma_{NN\to N\pi B}}{dt\,dt'} = \int_{y_{min}}^{y_{max}} dy \; \frac{s}{16\,(2\pi)^2\, m_N\, p_N}$$
$$\times \sqrt{\frac{(ys-t-m_N^2)^2-4m_N^2 t}{(s-2m_N^2)^2-4m_N^4}} \; \frac{d\sigma_{MN\pi N}(s'=ys,t')}{dt'}$$
$$\times \sum_{\lambda_a,\,\lambda_e} \frac{1}{[\phi_M(z)]^2} \left|\mathcal{M}_{N\to B}\right|^2$$

$$y \equiv \frac{s'}{s} = \frac{t + m_N^2 + 2(m_N E_N - E_B E_N + p_B p_N \cos\theta_e)}{s}$$

$$y_{min} = \frac{Q_0^2 + 2m_N^2 - t'}{s}, \quad -t' \geq Q_0^2$$

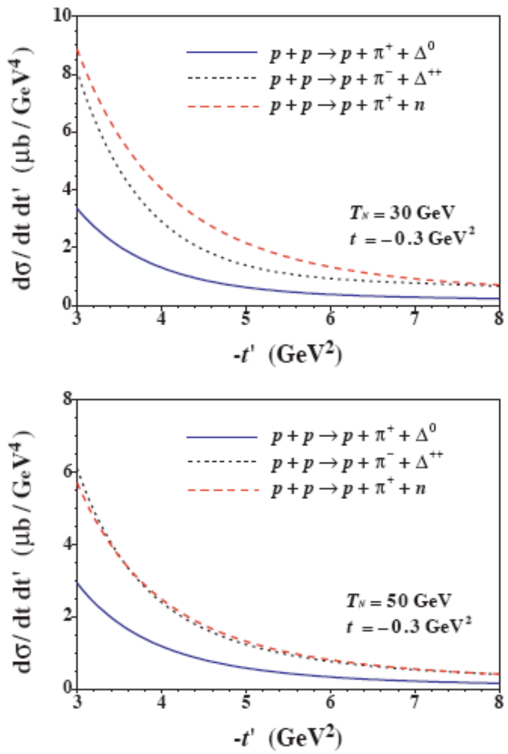


FIG. 11: Differential cross section as a function of t'. The incident proton-beam energy is 30 (50) GeV in the upper (lower) figure, and the momentum transfer is $t = -0.3$ GeV^2. The solid, dotted, and dashed curves indicate the cross sections for $p+p \to p+\pi^+ + \Delta^0$, $p+p \to p+\pi^- + \Delta^{++}$, and $p+p \to p+\pi^+ + n$, respectively.

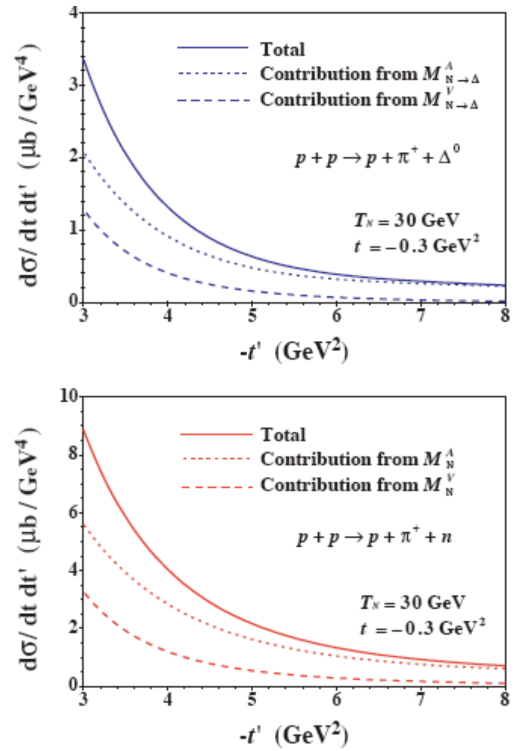


FIG. 12: Differential cross section as a function of t'. The incident proton-beam energy is 30 GeV, and the momentum transfer is $t = -0.3$ GeV^2. The upper (lower) figure indicates the cross section for the process $p+p \to p+\pi^+ + \Delta^0$ ($p+p \to p+\pi^+ + n$). The solid, dotted, and dashed curves indicate the cross sections for the total, axial-vector (π) contribution, vector (ρ) contribution, respectively.

Same cross section for antiproton projectiles!

Large enough cross sections to be measured with modern detectors

Strong dependence of σ on proton transverse polarization (similar to DIS case of pion production Frankfurt, Pobilitsa, Polyakov, MS)

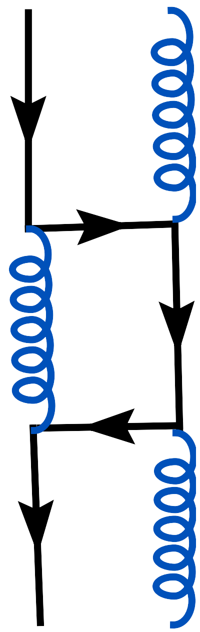
Yet another direction - QCD for non vacuum exchanges

— complementary to BFKL Pomeron

pQCD Reggeons

Quark exchanges in pQCD via two body processes

pQCD - quark exchange is reggeized (Fadin and Sherman 1976, Bogdan and Fadin and 2006)



Important property of quark regge trajectory in pQCD

$\alpha_q(t)$ - weak dependence on t

From Azimov displacement relation

For quark antiquark exchange: $A \propto s^{2\alpha_q(t)-1}$

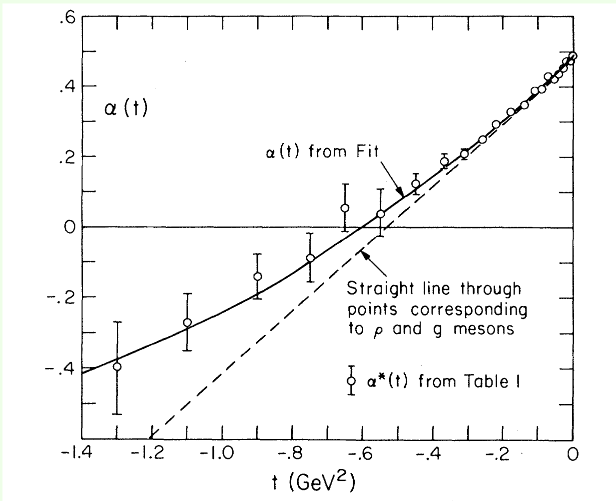
For three quark exchange: $A \propto s^{3\alpha_q(t)-2}$

$$\downarrow$$

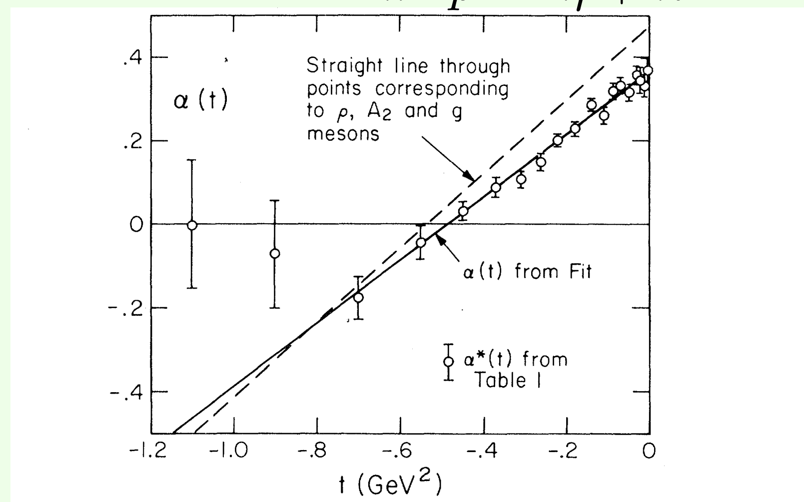
Relation between effective baryon and quark trajectories at large t

$$\boxed{\alpha_N(t)= 3\alpha_M(t)/2-0.5}$$

reaction $\pi^- p \to \pi^0 + n$



reaction $\pi^- p \to \eta + n$



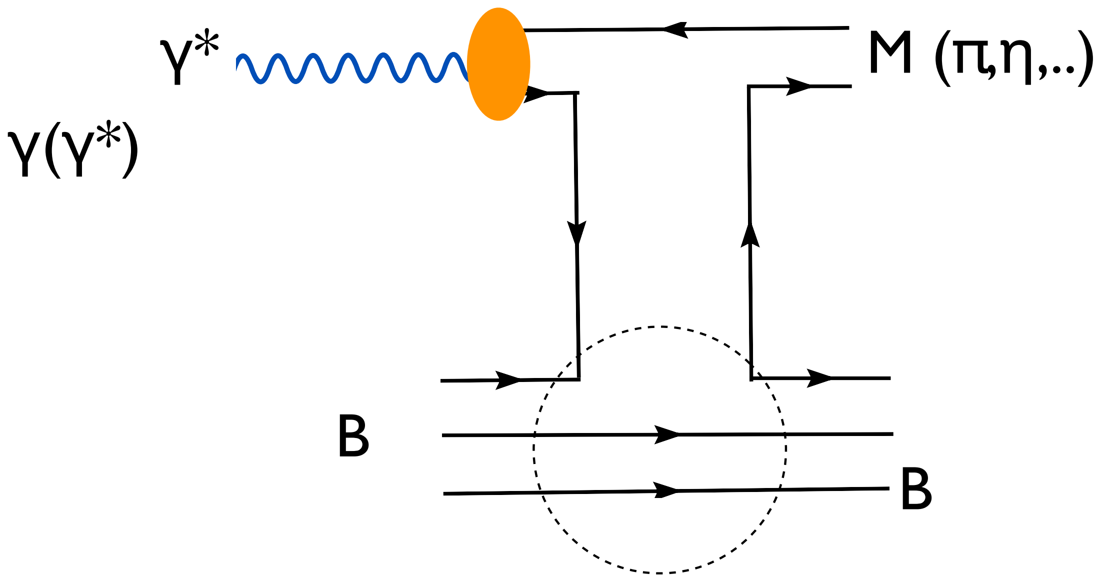
$\alpha_M(-t > 1 \text{ GeV}^2) = -(0.2 \div 0.4)$

↓

$\alpha_B(-t > 1 \text{ GeV}^2) = -(0.8 \div 1.1)$

$\alpha_q(-t > 1 \text{ GeV}^2) = (0.3 \div 0.4)$

as compared to nonreggeized case of 0.5 - reggeization effect is rather small



Energy range of meson beams of Amber is wide enough to study variation with energy of cross section for fixed t, At EIC Q dependence can be studies as well.

Conclusions

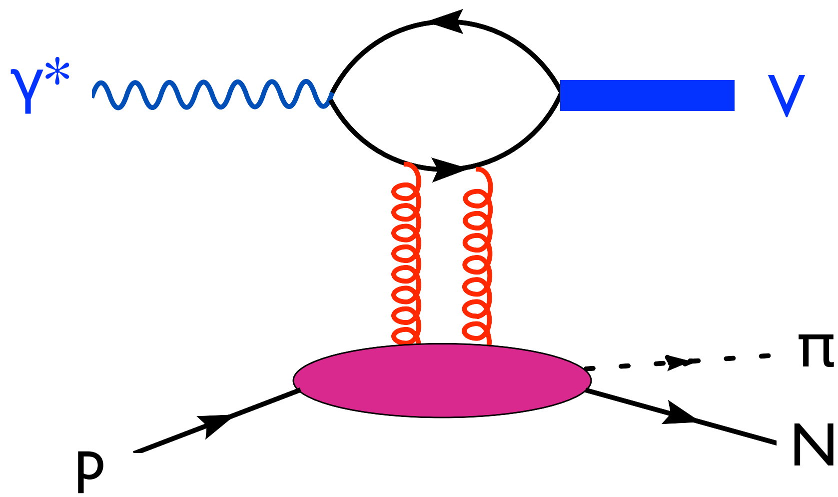
A broad program of hadronic physics studies hard / semihard reactions are feezible at Jparc, with Amber, PANDA, and in a long run at the EIC.

Discovery potential:

- high energy CT for hadronic processes
- Quantum diffusion for a multitude of hadrons
- 3D structure of hadrons - GPDs
- color fluctuations in hadrons

Backup

2→ 3 processes: γ^* +N → VM + gap + meson + baryon



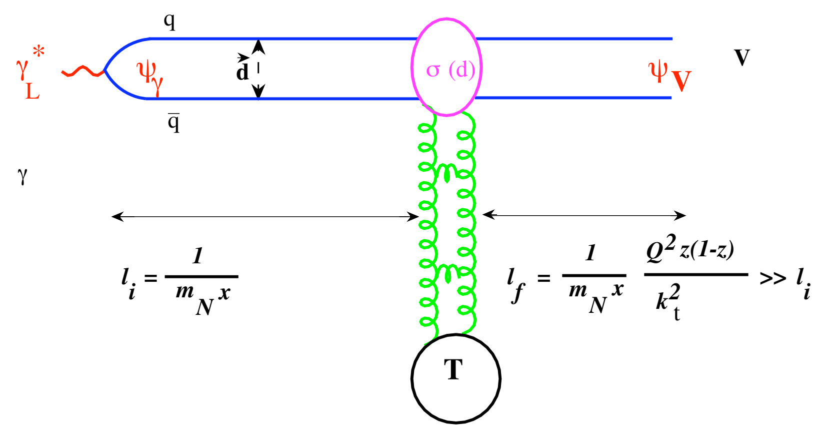
(also pions + $q\bar{q}$ exchange - dominate for x>0.1)

$$M_{\pi N} \sim M_{\pi} + M_N$$

detailed analysis of *chiral limit - low mass* $N\pi$- Polyakov and Stratmann 06

Vector meson diffractive production: Theory and HERA data

Space-time picture of Vector meson production at small x in the target rest frame



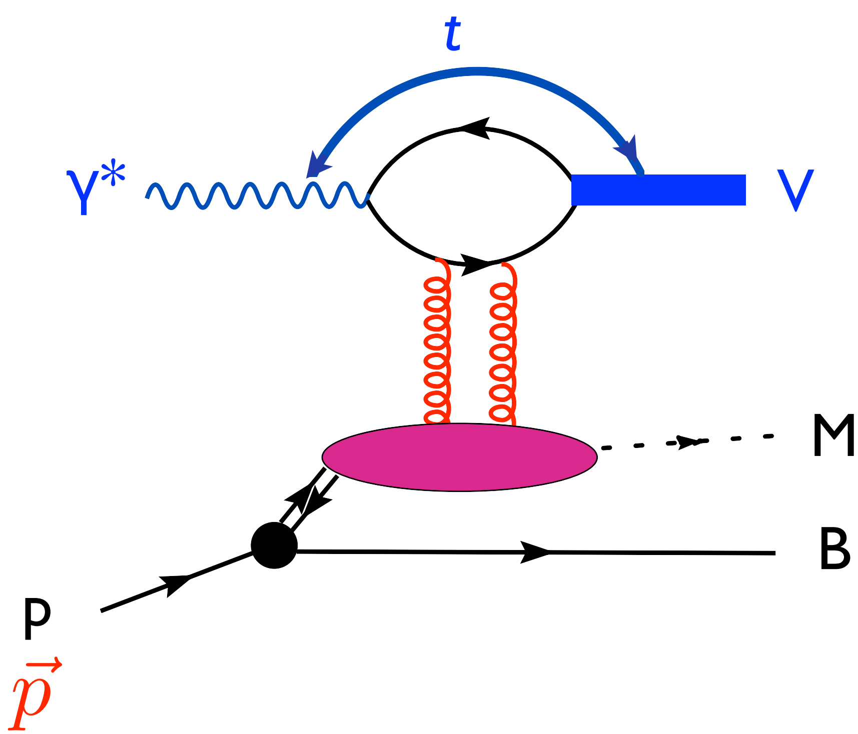
$\Rightarrow$ *Similar to the* $\pi + T \rightarrow 2jets + T$ *process,* $A(\gamma_L^* + p \rightarrow V + p)$ *at* $p_t = 0$ *is a convolution of the light-cone wave function of the photon* $\Psi_{\gamma^* \rightarrow |q\bar{q}\rangle}$*, the amplitude of elastic* $q\bar{q}$ *- target scattering,* $A(q\bar{q}T)$*, and the wave function of vector meson,* ψ_V*:* $A = \int d^2 d\psi^L_{\gamma*}(z,d)\sigma(d,s)\psi_V^{q\bar{q}}(z,d)$.

large t - color transparency limit

Abramowicz, F,S 95

Weiss , MS 03

Enberg, Pire, Szymanowski et al 02 &06



"π N" large t pion GPD

"ρ N" from ρ polarization - transversity GPD of nucleon

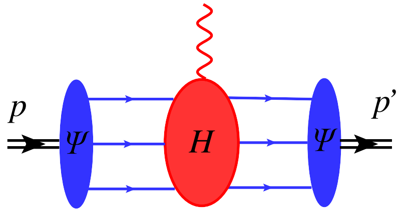
"K Λ" - probe strange quarks in nucleons specially for Stan

Evidence for CT in pion production at Jlab ⇒ -t > 3 GeV^2 sufficient

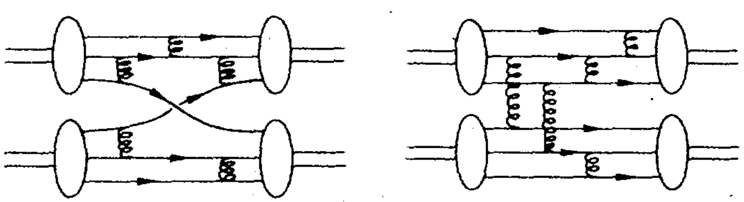
So far we do not understand the origin of **the most fundamental hadronic processes in pQCD -large angle two body reactions** (-t/s=const, s) π +p → π +p, p +p → p +p,... and even form factors

Early QCD approach (Brodsky - Farrar - Lepage)

Lowest order pQCD diagrams for form factors, two body processes involving **all constituents**



exchange of gluons between all three quarks



Typical pQCD diagrams for elastic pp scattering

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

Indicates dominance of minimal Fock components of small size:

$$\boxed{r^2_{transverse} \propto 1/Q^2}$$

Puzzle - power counting roughly works for many large angle processes- they do not look as soft physics - quark degrees of freedom are relevant.

TABLE V. The scaling between E755 and E838 has been measured for eight meson-baryon and 2 baryon-baryon interactions at $\theta_{c.m.} = 90°$. The nominal beam momentum was 5.9 GeV/c and 9.9 GeV/c for E838 and E755, respectively. There is also an overall systematic error of $\Delta n_{syst} = \pm 0.3$ from systematic errors of $\pm 13\%$ for E838 and $\pm 9\%$ for E755.

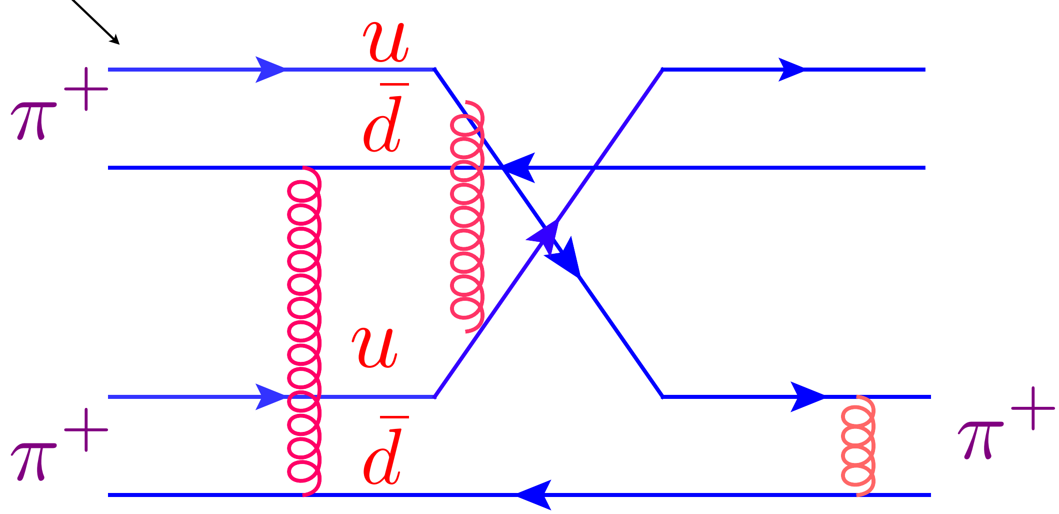
		Cross section			n-2
No.	Interaction	E838	E755		$(\frac{d\sigma}{dt} \sim 1/s^{n-2})$
1	$\pi^+ p \to p\pi^+$	132 ± 10	4.6 ± 0.3	n-2=8	6.7 ± 0.2
2	$\pi^- p \to p\pi^-$	73 ± 5	1.7 ± 0.2	n-2=8	7.5 ± 0.3
3	$K^+ p \to pK^+$	219 ± 30	3.4 ± 1.4	n-2=8	$8.3^{+0.6}_{-1.0}$
4	$K^- p \to pK^-$	18 ± 6	0.9 ± 0.9	n-2=8	≥ 3.9
5	$\pi^+ p \to p\rho^+$	214 ± 30	3.4 ± 0.7		8.3 ± 0.5
6	$\pi^- p \to p\rho^-$	99 ± 13	1.3 ± 0.6	n-2=8	8.7 ± 1.0
13	$\pi^+ p \to \pi^+\Delta^+$	45 ± 10	2.0 ± 0.6	n-2=8	6.2 ± 0.8
15	$\pi^- p \to \pi^+\Delta^-$	24 ± 5	≤ 0.12	n-2=8	≥ 10.1
17	$pp \to pp$	3300 ± 40	48 ± 5	n-2=10	9.1 ± 0.2
18	$\bar{p}p \to p\bar{p}$	75 ± 8	≤ 2.1	n-2=10	≥ 7.5

Reactions where quark exchanges are allowed have much larger cross sections

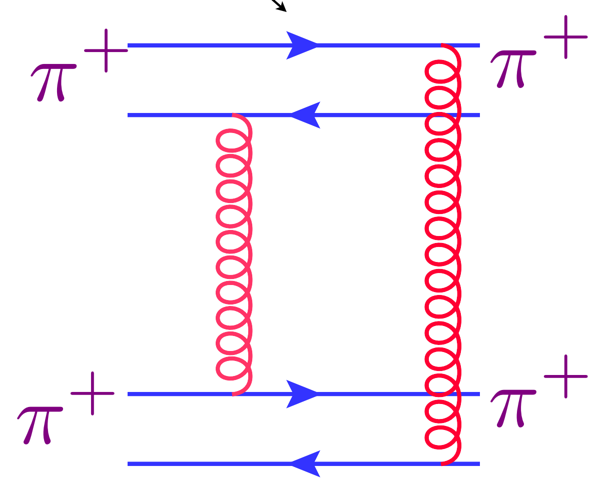
However absolute values of say form factors are too small, large angle Compton expectations contradict the data, etc

Do these regularities indicates dominance of minimal Fock components of small size?

Theory (A.Mueller et al 80-81) - competition between diagrams corresponding to the scattering in small size configurations and pinch contribution (Landshoff diagrams)



$$\frac{1}{s^6}$$



$\frac{1}{s^5}$ *+ Sudakov logarithm suppression of large size configurations* $\to 1/s^6$

??