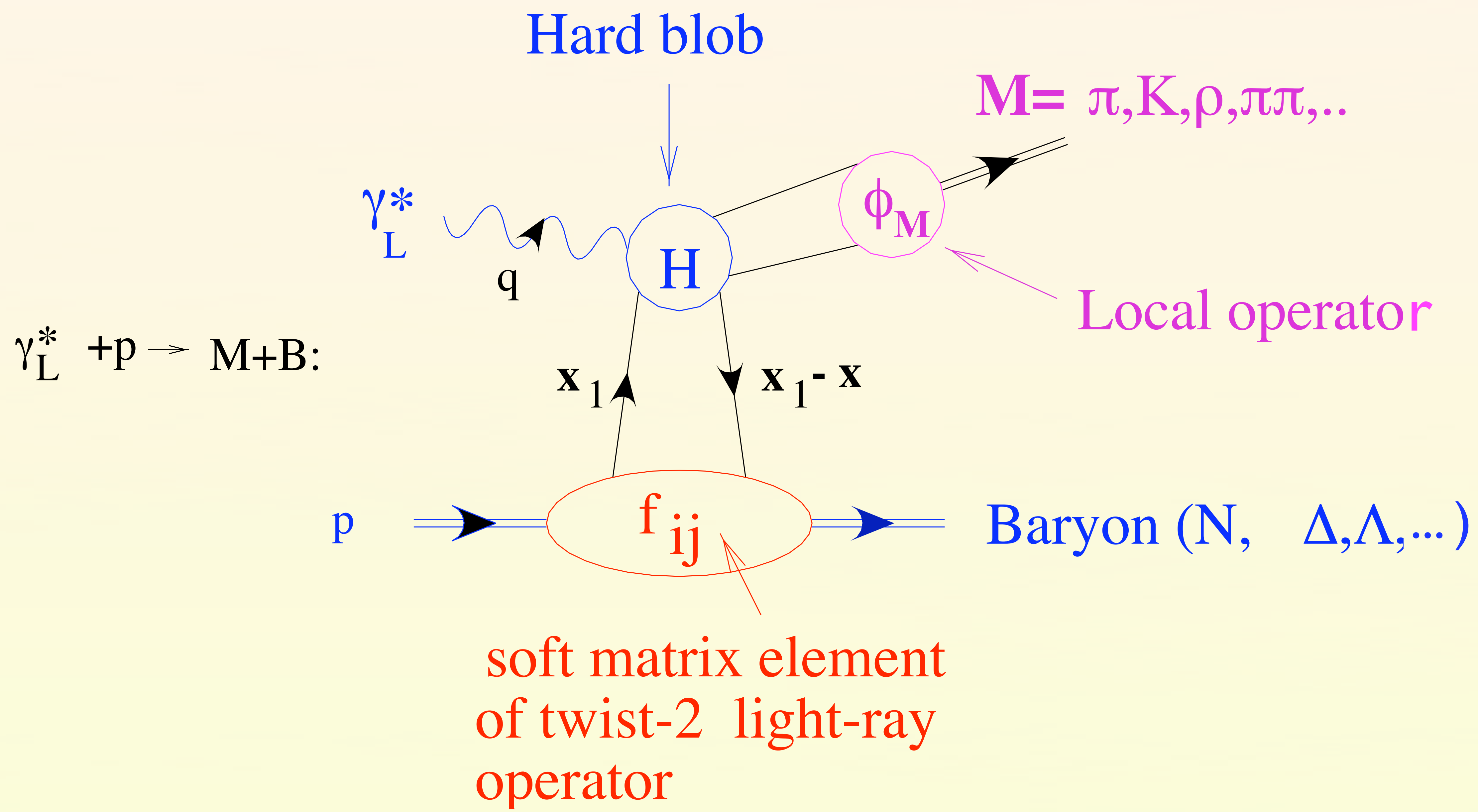
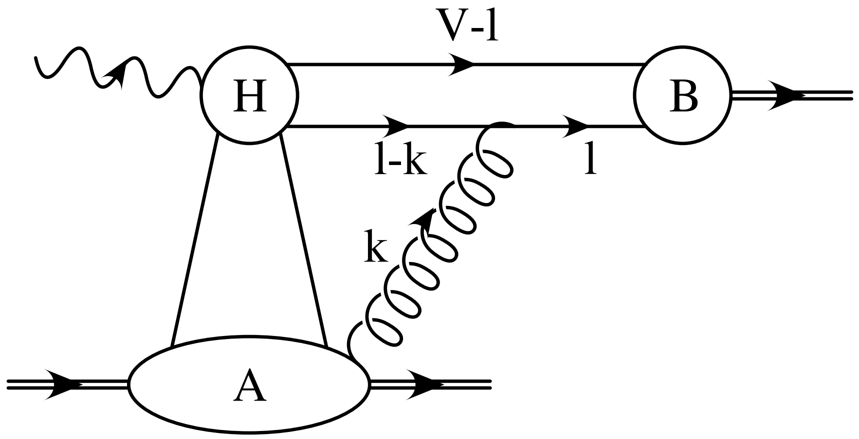
QCD factorization theorem for DIS exclusive processes

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



Diagrams like:



where an extra gluon is exchanged between the hard blocks are suppressed by a factor $\frac{1}{Q^2}$. —Very lengthy proof - CFS

we also presented a simpler proof not so rigorous but more intuitive

Qualitatively - due to color screening/transparency - small transverse size of γ_L^* selects small size (point-like) configurations in meson.

NO FACTORIZATION WITHOUT COLOR TRANSPARENCY

Vector meson diffractive production: Theory and HERA data

$$A(\gamma_L^* + p \to V + p) \ at \ p_t = 0$$

is a convolution of the light-cone wave function of the photon $\Psi_{\gamma^* \to |q\bar{q}\rangle}$, *the amplitude of elastic* $q\bar{q}$ *- target scattering,* $A(q\bar{q}T)$, *and the wave function of vector meson,* ψ_V: $A = \int d^2 d \psi^L_{\gamma *}(z,d) \sigma(d,s) \psi_V^{q\bar{q}}(z,d)$.

In the kinematics relevant for Jlab

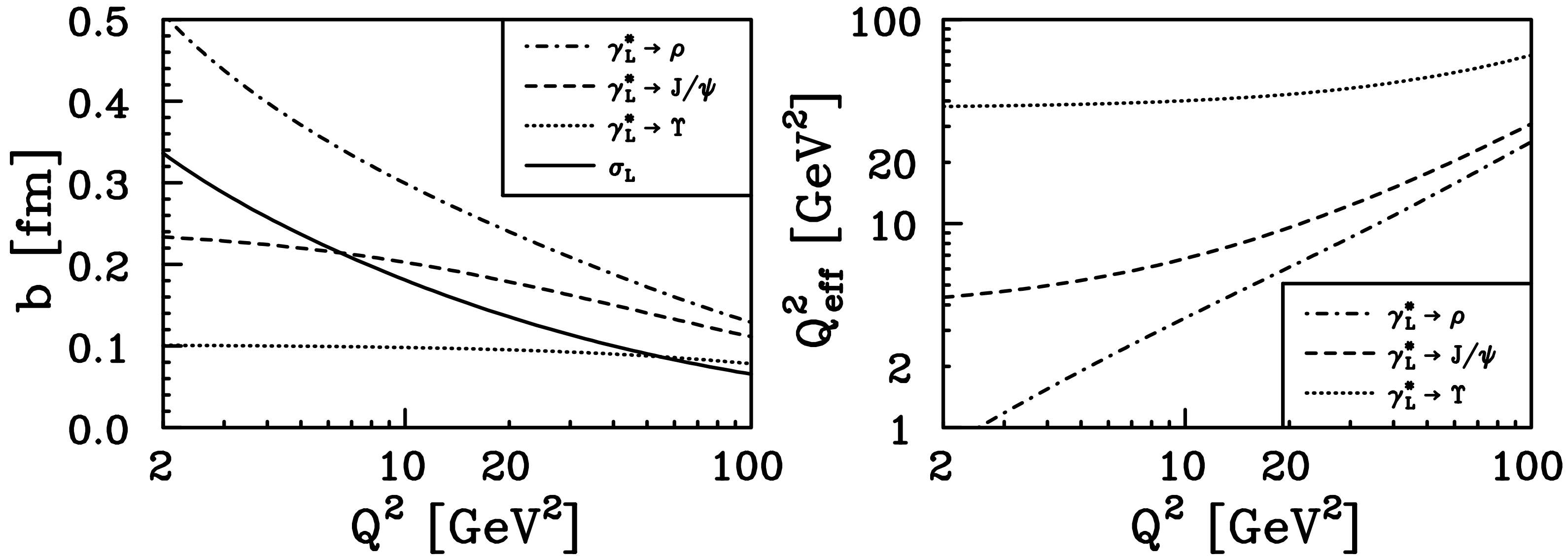
$$\sigma(q\bar{q}N) = \frac{\pi}{3} d^2 \alpha_s(Q^2_{eff}) \left[x_N G_N(x_N, Q^2_{eff}) + 2/3 x_N S_N(x_N, Q^2_{eff})\right]$$

Since at larger x pdf's are smaller, σ is smaller. Maybe easier to satisfy conditions of factorization theorem.

In the convolution integral a narrow - $b \propto \frac{1}{Q}$ - $\Psi^{L}_{\gamma^*}(b)$ is convoluted with a broad wave function of a light vector meson

$\Rightarrow$ average distance are smaller in σ_L are smaller than in VM production

$\Rightarrow$ Effective Q^2 is smaller for VM production than for σ_L



Hence next to leading order leading twist corrections are significant and one can try to model them by changing $Q^2 \rightarrow Q^2_{eff}$ in the parton densities.

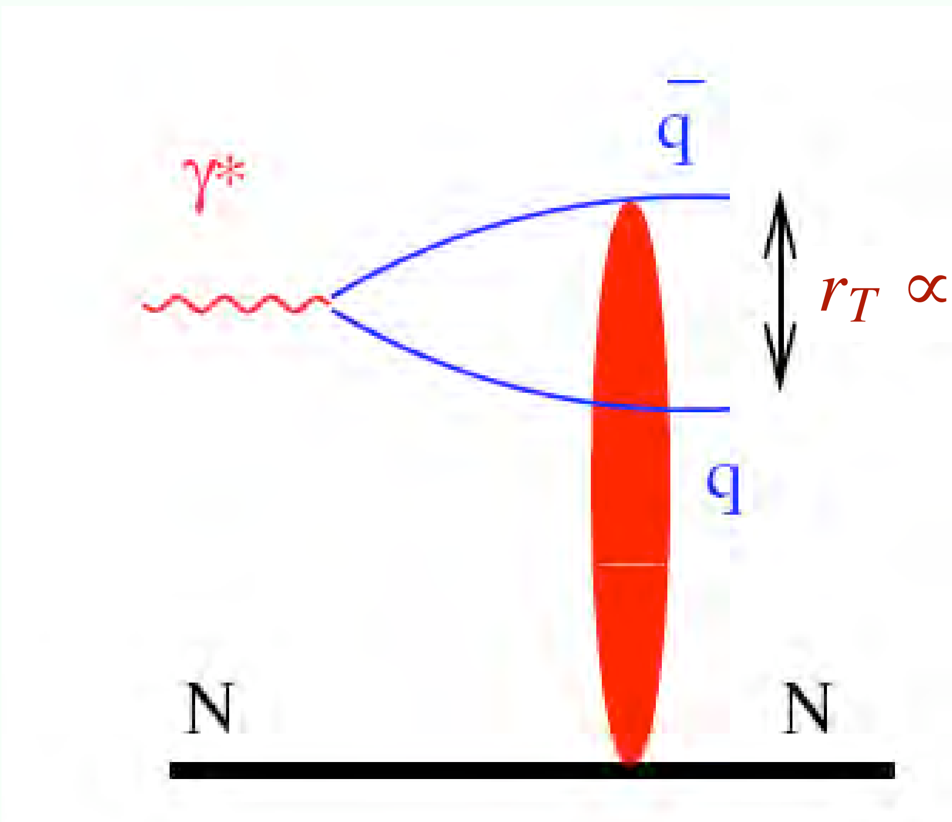
Extensive data on VM production from HERA support dominance of the pQCD dynamics. Numerical calculations including finite transverse size effects explain key elements of high Q^2 data. The most important ones are:

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

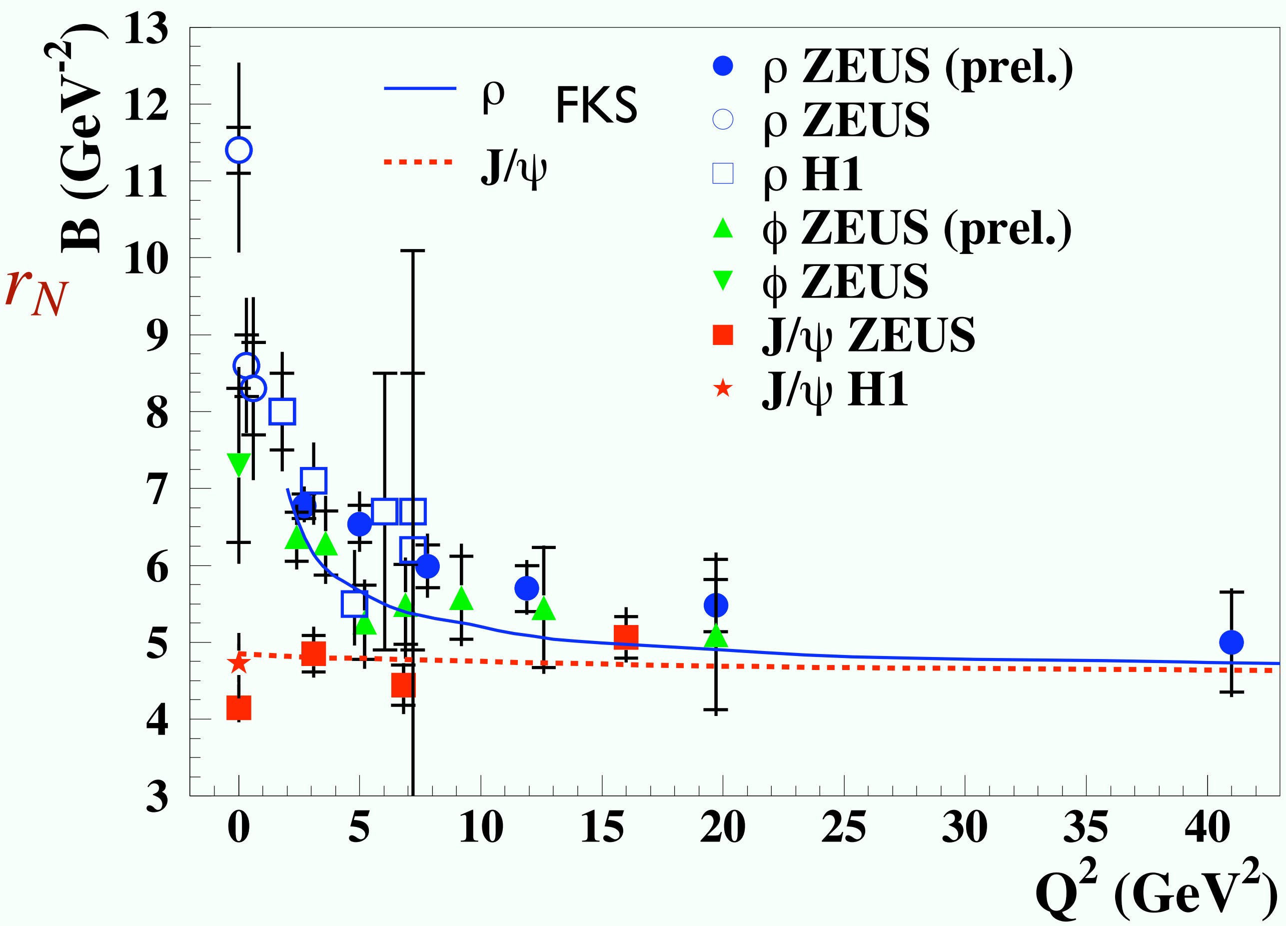
- Absolute cross section and energy dependence of ρ−meson production at $Q^2 \geq 20\ GeV^2$. Explanation of the data at lower Q^2 is more sensitive to the higher twist effects, and uncertainties of the low Q^2 gluon densities.

- 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, $F_g(x,t)$. $d\sigma/dt \propto F_g^2(x,t)$.

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



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



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

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

B slope data for ρ-meson production support importance of HT effects up to $Q^2 \sim 10\ GeV^2$

Similar situation for the absolute cross sections. One can see this from the structure of energy denominators:

$$\frac{1}{Q^2 + M^2} \rightarrow \frac{1}{Q^2}\Big|_{LT}$$

$M^2 > M_V^2$ mass^2 in the intermediate state

$$\frac{1}{Q^6} \rightarrow \frac{Q^2}{(Q^2 + M^2)^4}$$

For $M^2 = 1\ GeV^2$ and $Q^2 = 5\ GeV^2$ reduction of σ by factor > 2

- Presence of small size $q\bar{q}$ Fock componentss in light mesons is unambigously established
- At transverse separations $d \lesssim 0.3$ fm pQCD reasonably describes "small $q\bar{q}$ - dipole"- nucleon interaction for $10^{-4} < x < 10^{-2}$
- Color transparency is established for the interaction of small dipoles with nucleons and with nuclei (for $x \sim 10^{-2}$)

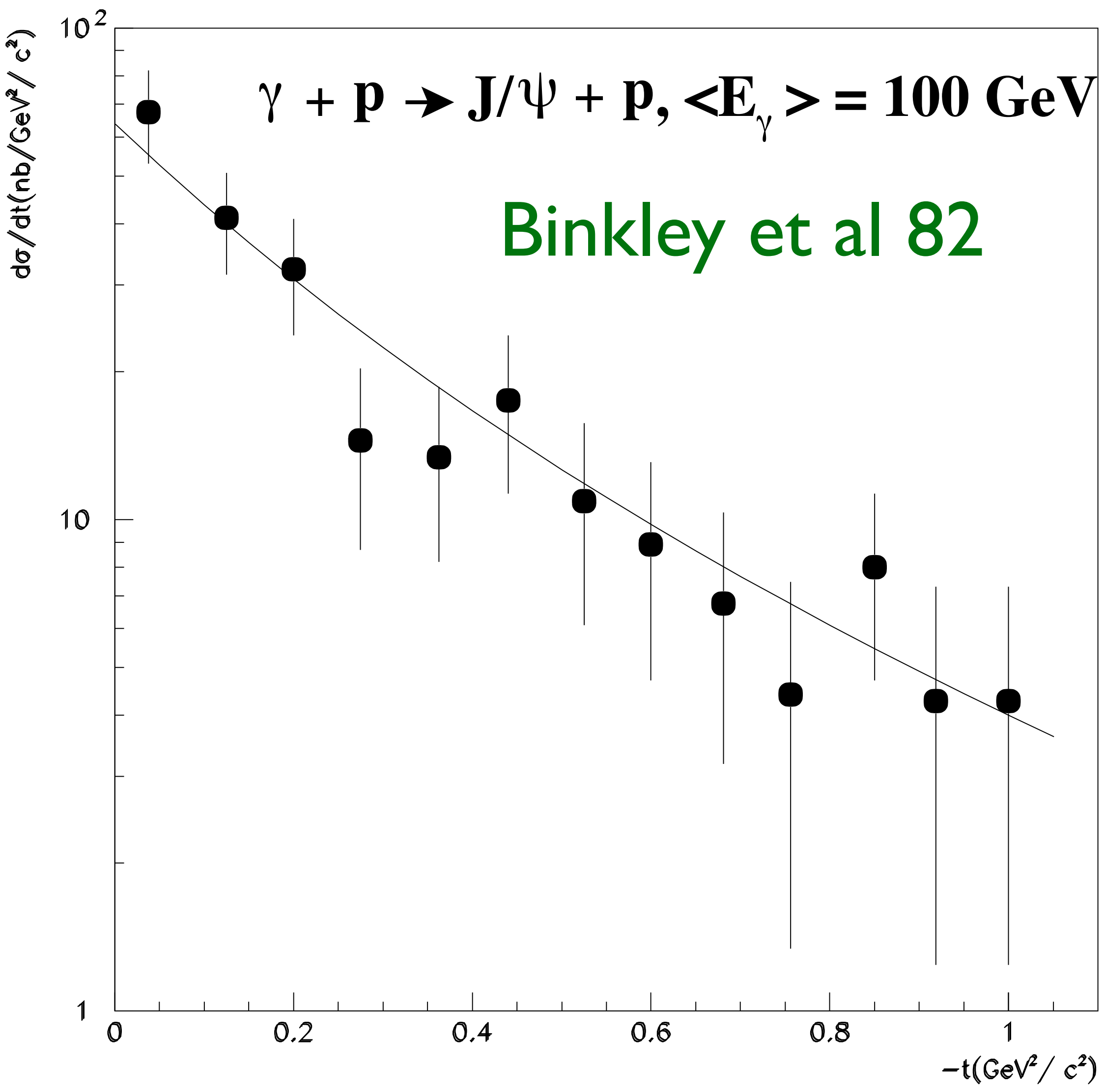
No difference in squeezing for σ_L and σ_T - Sudakov f.f. start at low Q?

Goal 1 - determination of transverse distribution of gluons for x~ 0.3

Convergence of the t-slope of ρ-meson electroproduction to the slope of J/ψ photo(electro) production.

⇒ Transverse distribution of gluons can be extracted from

$$\gamma + p \to J/\psi + N$$



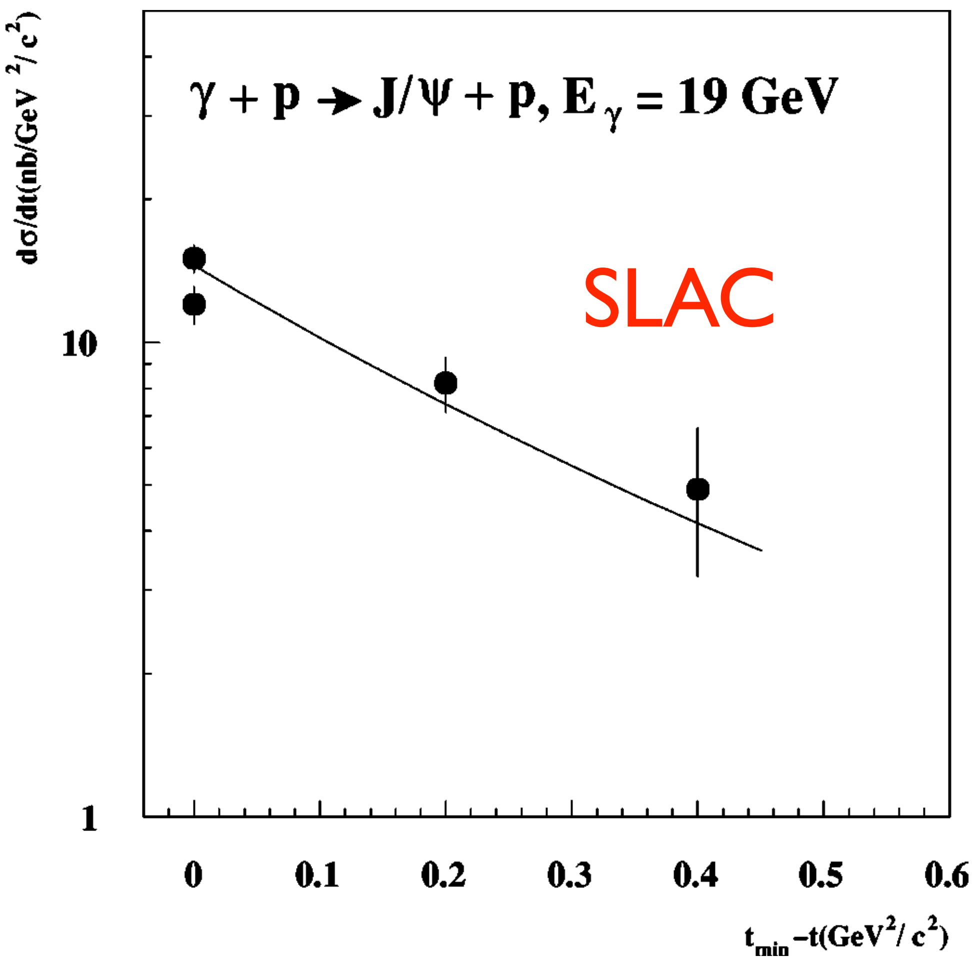
Theoretical analysis of J/ψ photoproduction at $100\ GeV \geq E_\gamma \geq 10\ GeV$ corresponds to the two-gluon form factor of the nucleon for $0.03 \leq x \leq 0.2,\ Q_0^2 \sim\ 3\ GeV^2, -t \leq 2\ GeV^2$

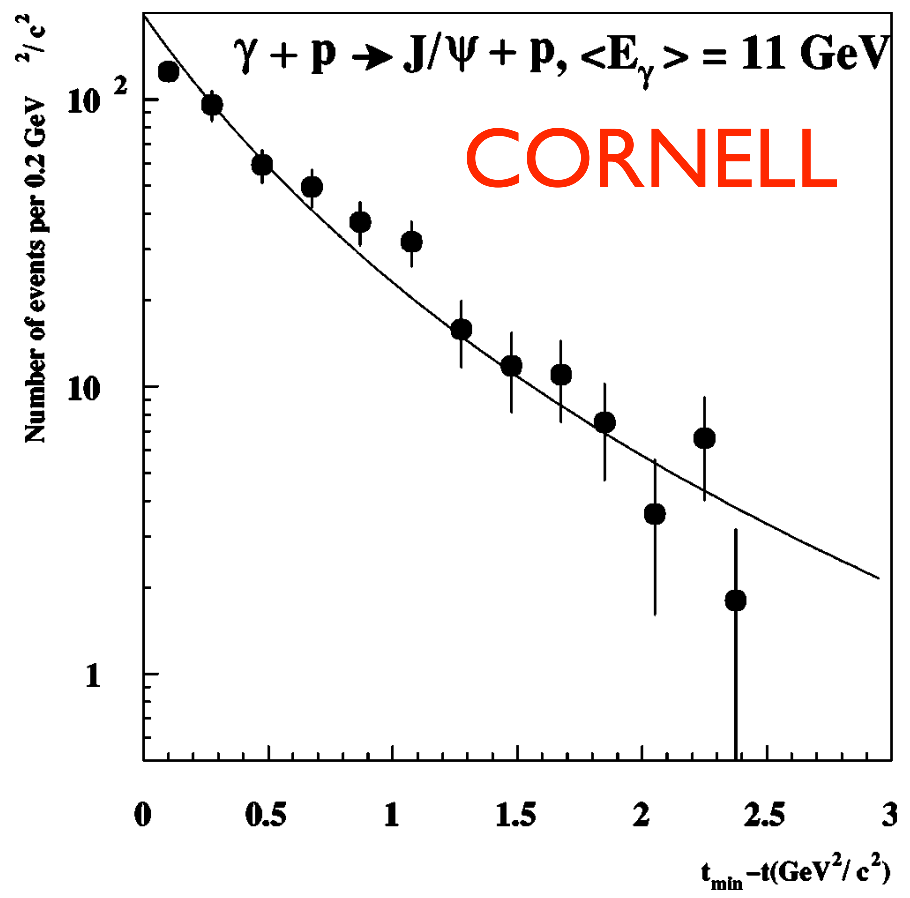
$$F_g(x, Q^2, t) = (1 - t/m_g^2)^{-2}.\ m_g^2 = 1.1\ GeV^2$$

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)

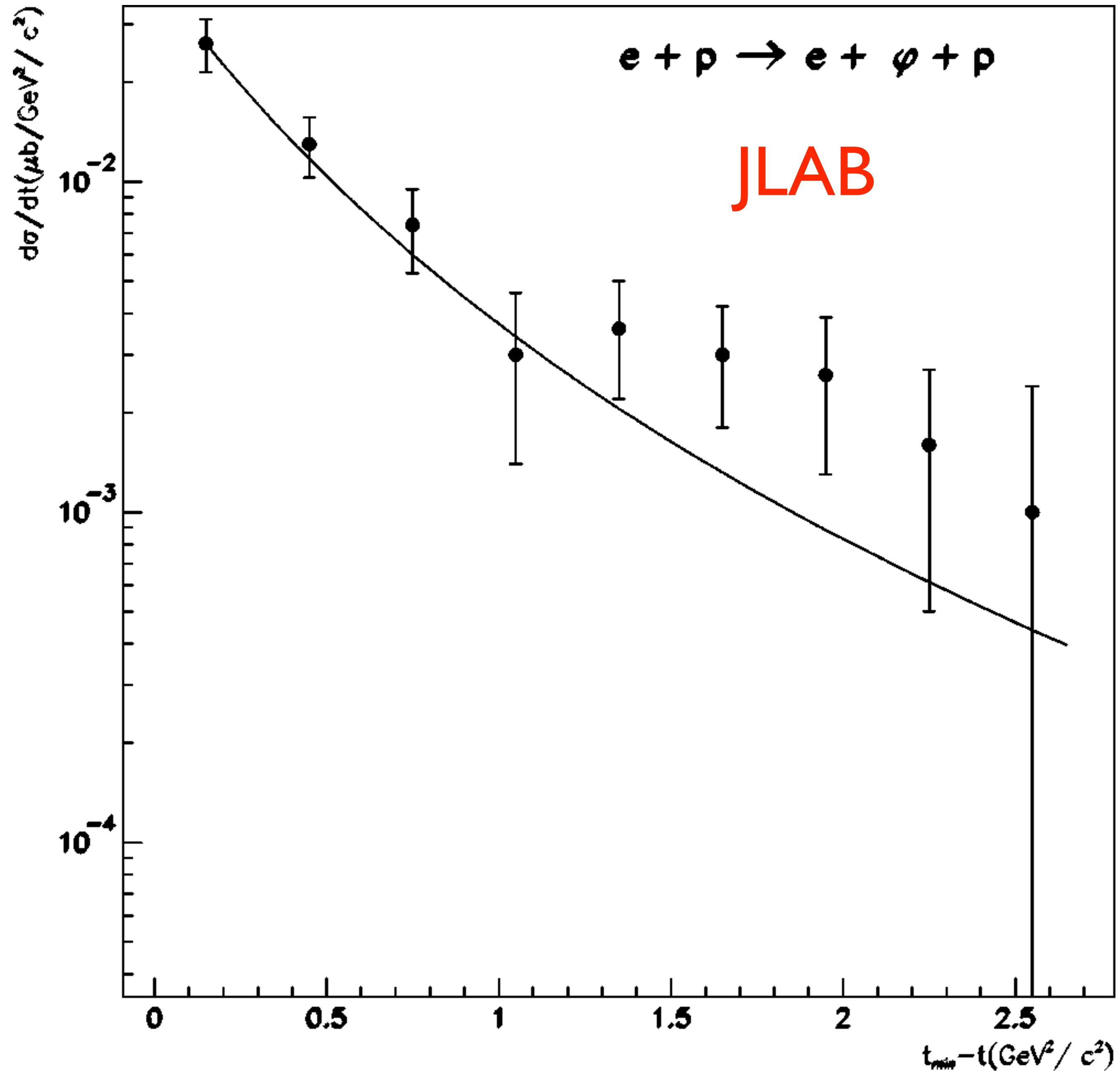




$$-t_{min} = 0.41 \ \ \mathrm{GeV}^2$$

Curves are the same dipole fit as at E=100 GeV. At higher energies slope changes.

Jlab data suggest that for intermediate energies squeezing for φ maybe strong enough



$$\langle W \rangle = 2.3 \ \text{GeV}, \langle Q^2 \rangle = 1 \ \text{GeV}^2.$$

Goal II - comparing wave functions of different mesons and different baryons

Though transverse size remains not negligible for Q^2=5 GeV^2, transverse size is reduced to < 0.4 fm

➡ separation into three blocks and onset of CT is possible (easier because the cross sections are smaller, but expansion effects are larger)

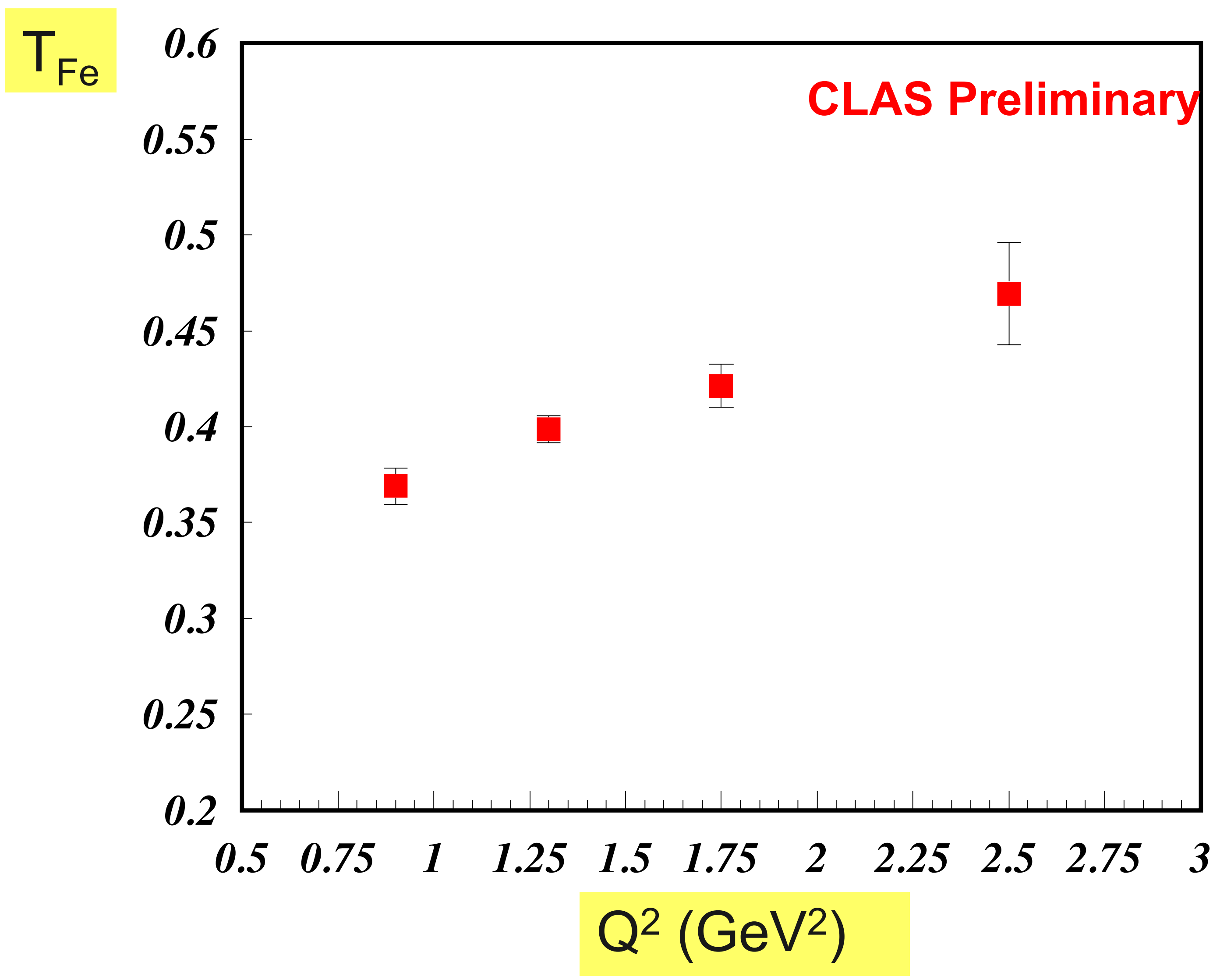
$$l_{coh} \sim 2p_M/\Delta m_M^2 \sim \frac{1}{xM_N} Q^2/\Delta m_M^2$$

where $\Delta m_M^2 \leq 1$ GeV^2 is the characteristic light-cone energy denominator for a meson M. The condition $l_{coh} \gg r_N$ is satisfied for $x \leq 0.2$ already for $Q^2 \geq 5$ GeV^2.

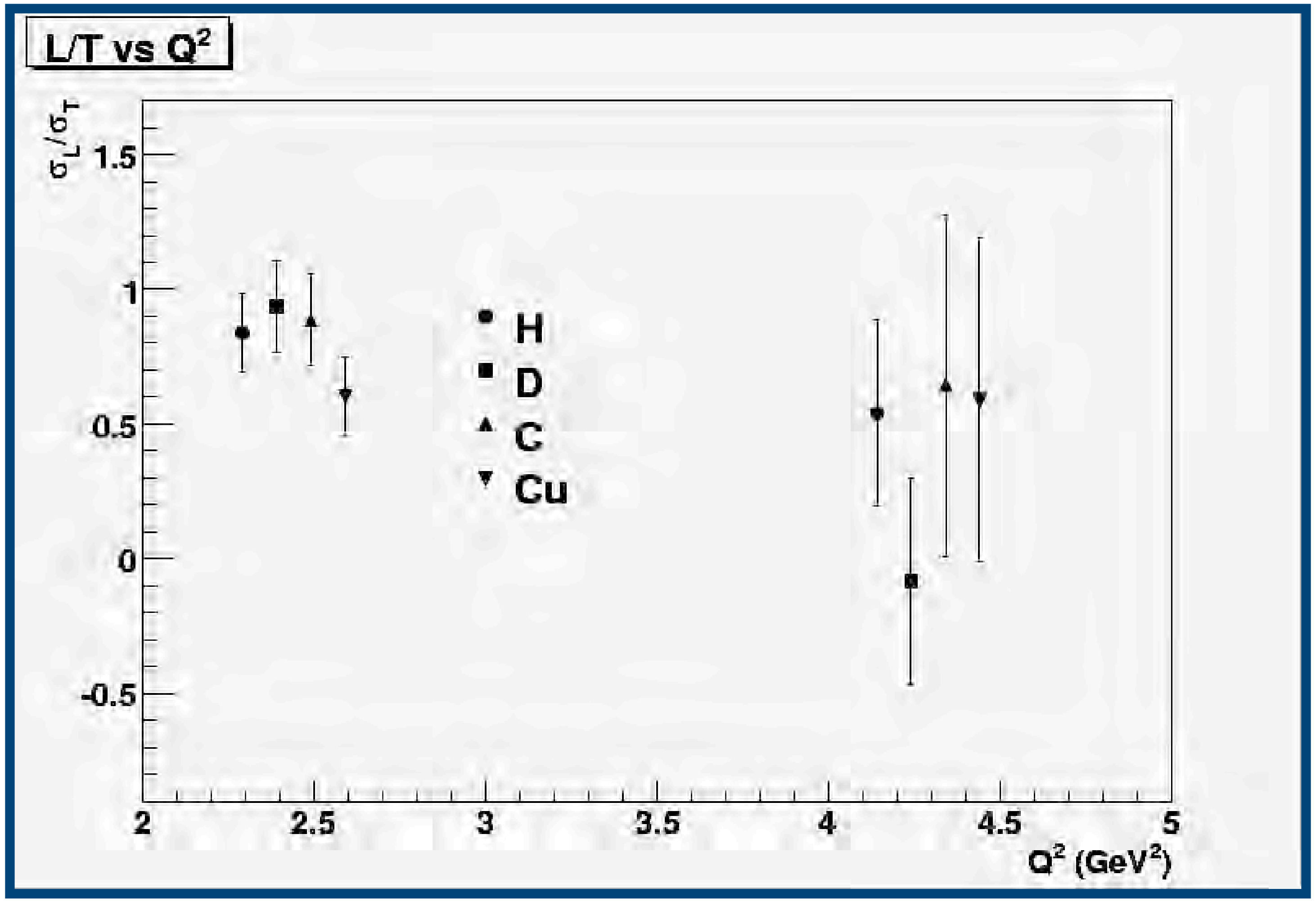
Encouraging evidence from two Jlab experiments

Preliminary Results from CLAS EG2 data

T_A vs. Q^2 corrected with acceptance, radiative and absorption effects

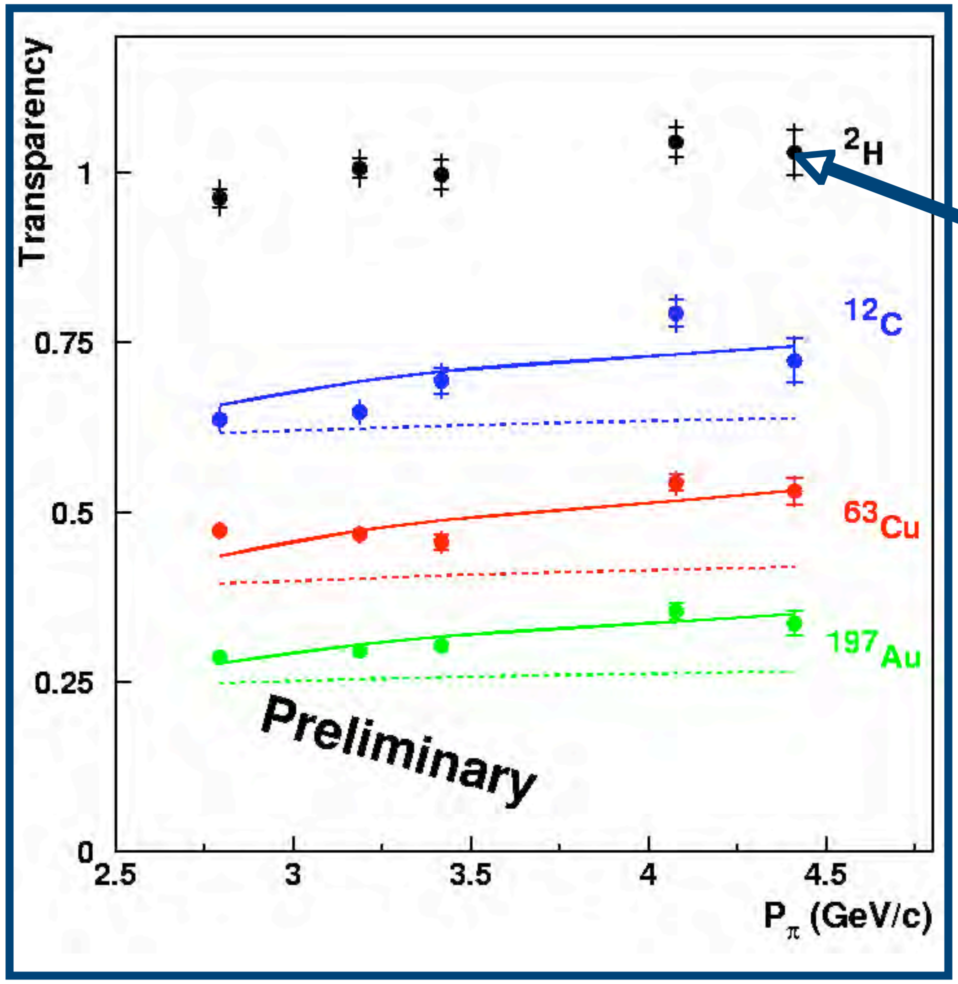


Preliminary results from L/T separation at Q^2 =2.1 & 4.0$(GeV/c)^2$ on all targets suggests that data is consistent with the quasi-free approximation.



No evidence for increase of σ_L/σ_T with Q

`P_π' Dependence of Transparency



$$T = \frac{(\text{Data/Simulation})_A}{(\text{Data/Simulation})_p}$$

Inner error bar are statistical uncertainties outer error bar are the quadrature sum of statistical and pt. to pt. systematic uncertainties.

Al data from the dummy target is not shown

Solid/Dashed lines are predictions with and without CT
A. Larson, G. Miller and M. Strikman, nuc-th/0604022

A precocious factorization into three blocks

overlapping integral between photon and meson wave functions, hard blob and gpd.

⇒ precocious scaling of ratios at fixed x, t as a function of Q^2:

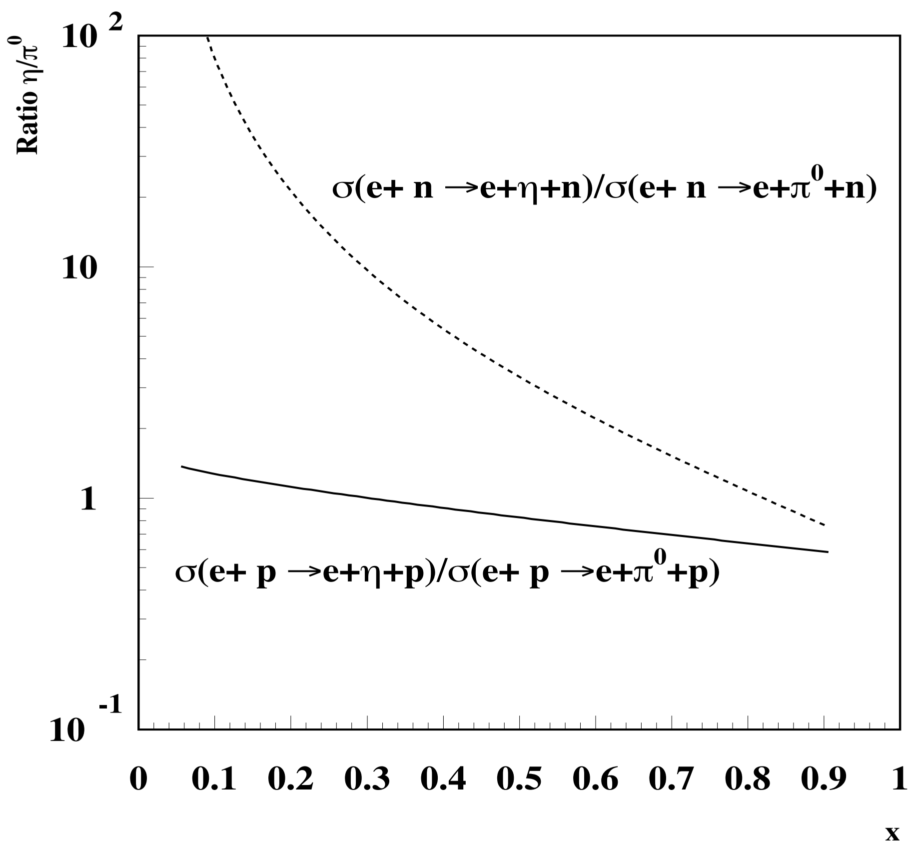
Eides & FS 98

- ☛ spin asymmetries
- ☛ ratios of different meson channels
- ☛ ratios of different baryon channels - nondiagonal bariobarionic gpds

Examples:

$$\frac{\sigma(\gamma_L + p \to \rho^+ n)}{\sigma(\gamma_L + n \to \rho^- + p)} \to 4$$

at large x



U(1) Anomaly changes ratios

$\Rightarrow \quad \eta : \eta' = 1 : 0.87$ (QCD) vs $1 : 2$ (naive $SU(3)$)

Comparing wave functions of kaon and pions Δ-isobars and nucleons

The hard exclusive processes allow to address such questions as

- How different are the wave functions of pions and kaon?

- Can one use the $N_c \gg 1$ limit to connect the wave functions of nucleons and isobar states? Can one observe difference between Δ's and nucleons due to singlet diquark effects in nucleons which are absent for Δ

$SU_{fl}(3)$ relations

$$\frac{\sigma(\gamma_L + p \to K^+ + \Lambda)}{\sigma(\gamma_L + p \to \pi^+ + n)}$$

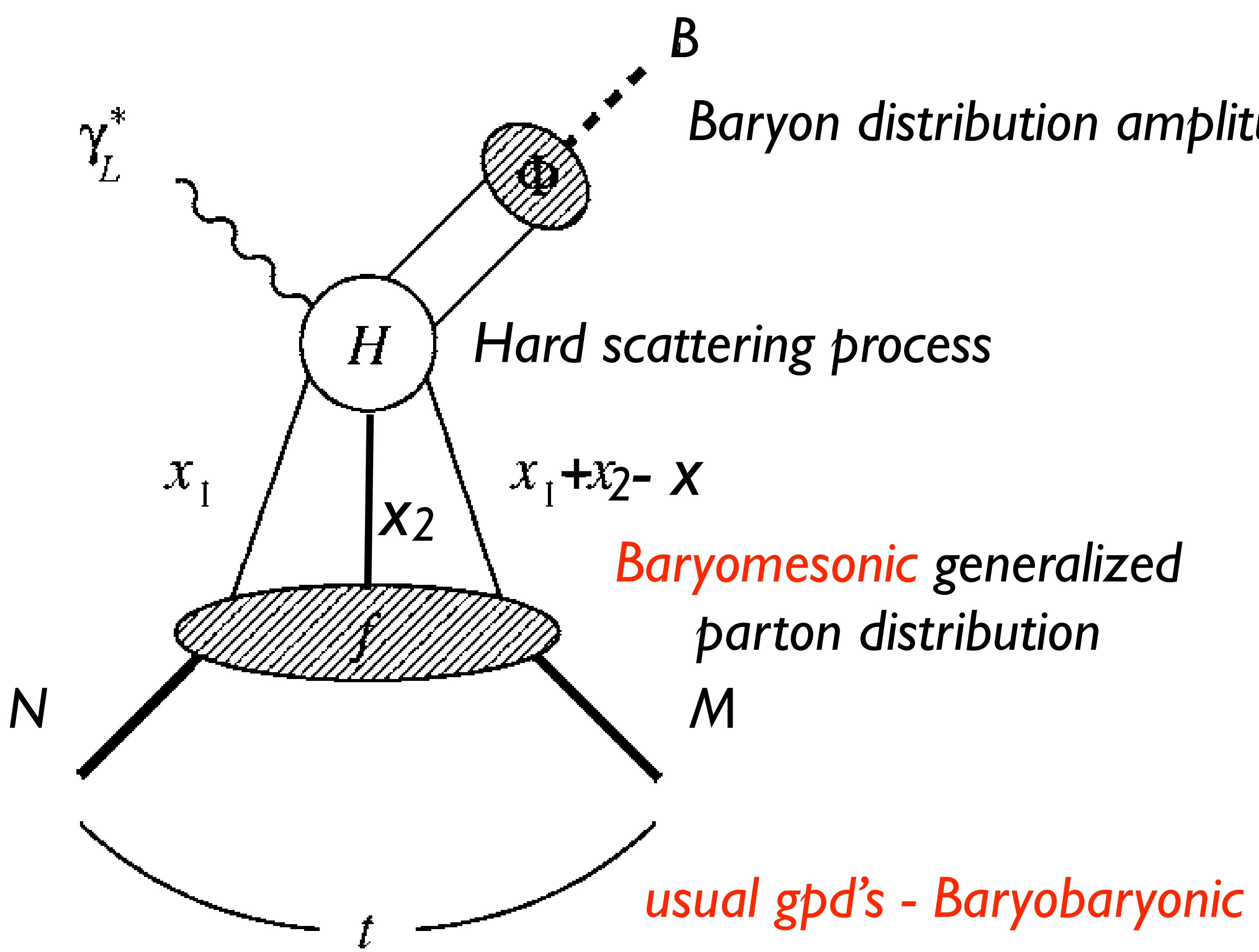
$$\approx \frac{f_K^2}{6\ f_\pi^2} \frac{[3(2\Delta u_s - \Delta d_s - \Delta s_s) - (2\Delta u_v - \Delta d_v - \Delta s_v)]^2}{[3(\Delta u_s - \Delta d_s) - (\Delta u_v - \Delta d_v)]^2}$$

$$|M(\gamma_L^* p \to \pi^+ \Delta^0)|^2 = \frac{1}{2}|M(\gamma_L^* p \to \pi^+ n)|^2$$

$$|M(\gamma_L^* p \to \pi^- \Delta^{++})|^2 = \frac{3}{2}|M(\gamma_L^* n \to \pi^- p)|^2$$

The proof of the factorization for the meson exclusive production (Collins, Frankfurt and MS) is essentially based on the observation that the cancellation of the soft gluon interactions is intimately related to the fact that the meson arises from a small size quark-antiquark pair generated by the hard scattering. Thus the pair starts as a small-size configuration and only substantially later grows to a normal hadronic size, to a meson. Similarly, the factorization theorem should be valid for the production of leading baryon

Frankfurt, Polyakov, MS 2000



For large enough x (x>0.3?) the configuration in the nucleon which is likely to give the dominant contribution is when virtual photon hits a highly localized three quarks. So the minimal Fock component in N which contributes is 4q$\bar{q}$ which is quite different from the reaction with leading meson.

$$\int \prod_{i=1}^{3} dz_i^- \exp[i\sum_{i=1}^{3} x_i\,(p\cdot z_i)]\cdot \langle M(p-\Delta)|\varepsilon_{abc}\,\psi^a_{j_1}(z_1)\,\psi^b_{j_2}(z_2)\,\psi^c_{j_3}(z_3)|N(p)\rangle\Big|_{z_i^+=z_i^\perp=0} =$$

$$= \delta(1-\zeta-x_1-x_2-x_3)\,F_{j_1j_2j_3}(x_1,x_2,x_3,\zeta,t)\,,$$ Mesobaryonic GPDs

Production of a fast baryon and recoiling mesonic system.

In the Bjorken limit the light cone fraction of the slow meson satisfies condition:

$$\alpha_M = \frac{p_{M-}}{p_{N-}} = \frac{E_h - p_{3M}}{E_N - p_{N3}} = \frac{E_M - p_{3M}}{m_N} = 1 - x$$

If the color transparency suppresses the final state interaction between the fast moving nucleon and the residual meson state early enough it would be natural to expect an early onset of the factorization of the cross section to a function which depends on α_{M}, p_t and the cross section of the electron-nucleon elastic scattering:

$$\frac{d\sigma(e + N \to e + N + M)}{d\alpha_M d^2 p_t / \alpha_M} = f_M(\alpha_M, p_t)(1 - \alpha_M)\sigma(eN \to eN),$$

hence the cross section drops strongly with Q^2 - will be possible to study at Jlab 12 GeV machine.