(Semi)Exclusive meson production at EIC energies

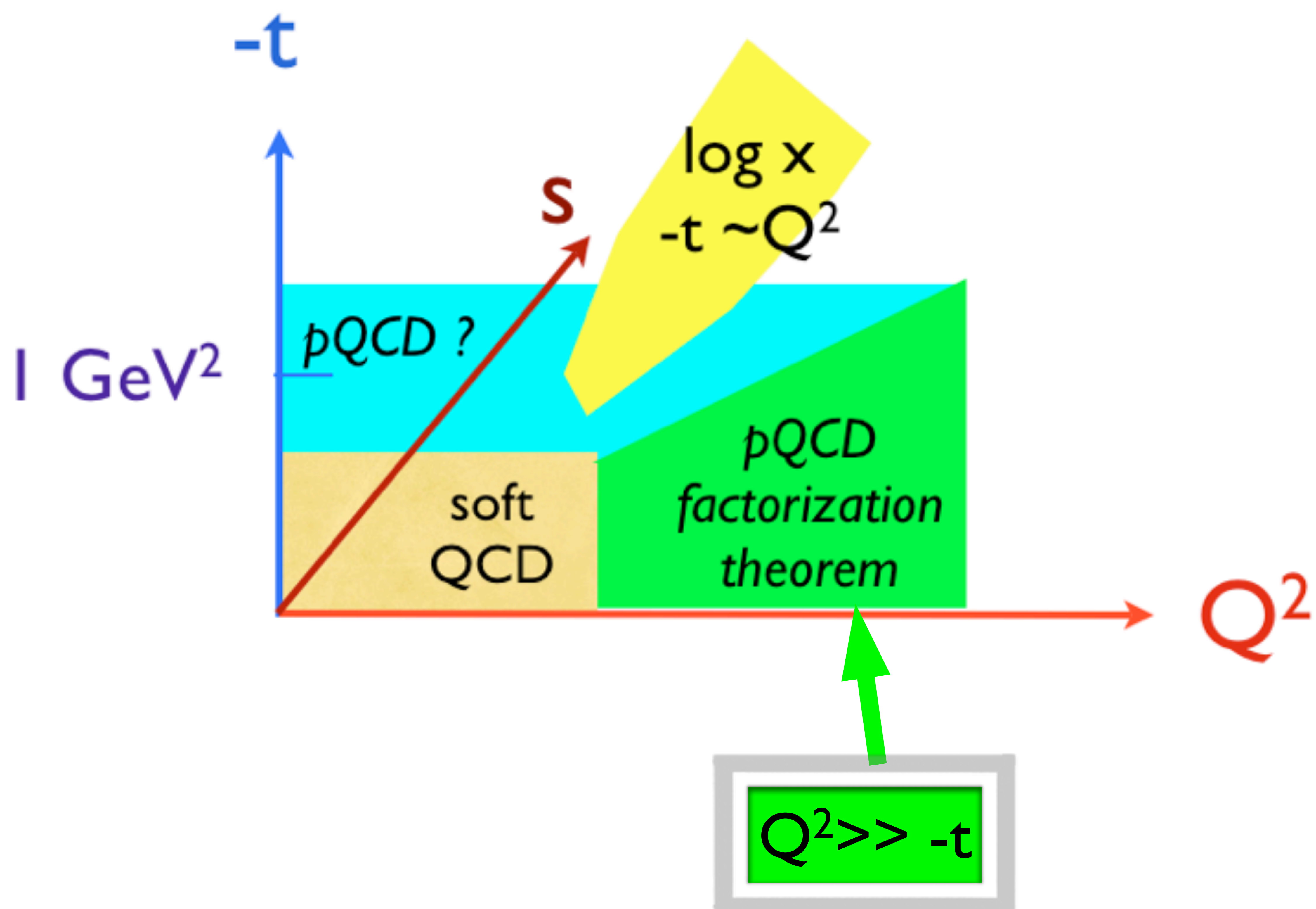
Mark Strikman

Jlab exclusive workshop, 5/19/10

Outline

- Introduction - what was (not) learned in 15 years of studies
- Meson production - does squeezing takes place?
- Rapidity gap processes with J/ψ and VM at large pt and DGLAP
- α'_{IP} for J/ψ production: pQCD and nonpQCD mechanisms
- From 2 → 2 to 2 →3 hard processes

3D (Q^2, t ,s) *landscape of exclusive processes at EIC*



Three interesting high energy regimes

- x=const, $Q^2 \to \infty$, t=const << Q^2
- $-t \sim Q^2$, $s \to \infty$
- $-t > Q^2 \sim$ GeV^2, $s \to \infty$

Studies of the diffraction at HERA stimulated derivation of new QCD factorization theorems. In difference from derivation in the inclusive case which used closure, main ingredient of the proofs is color transparency property of QCD.

Exclusive processes

$$\gamma^* + N \rightarrow \gamma + N(baryonic\, system)$$

D.Muller 94 et al, Radyushkin 96, Ji 96, Collins &Freund 98

$$\pi + T(A,N) \rightarrow jet_1 + jet_2 + T(A,N)$$

Frankfurt, Miller, MS 93 & 03

$$\gamma_L^* + N \rightarrow "meson"(mesons) + N(baryonic\, system)$$

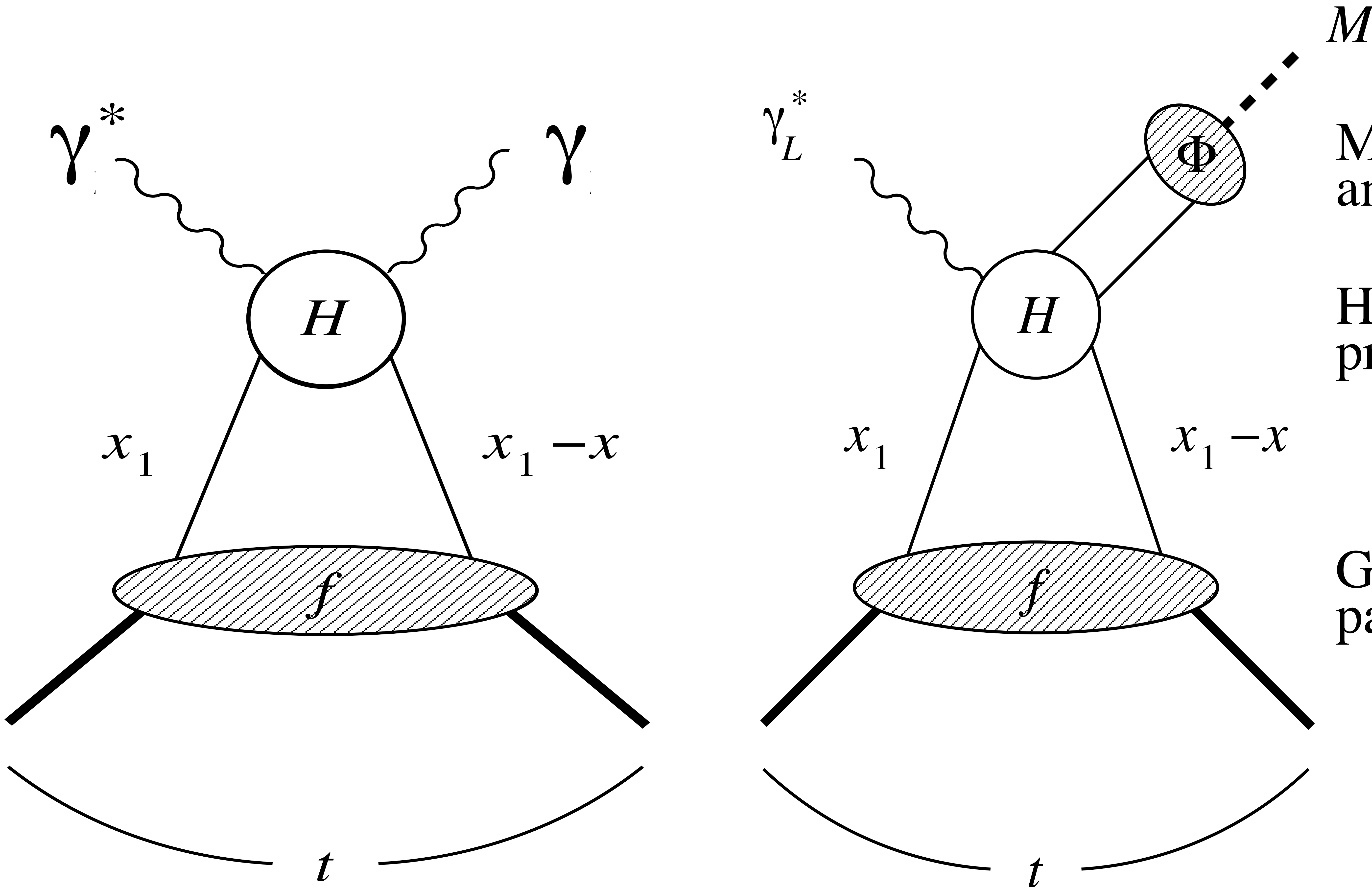
Brodsky,Frankfurt, Gunion,Mueller, MS 94- vector mesons, small x

Collins, Frankfurt, MS 97 - general case

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

Fragmentation processes including diffraction

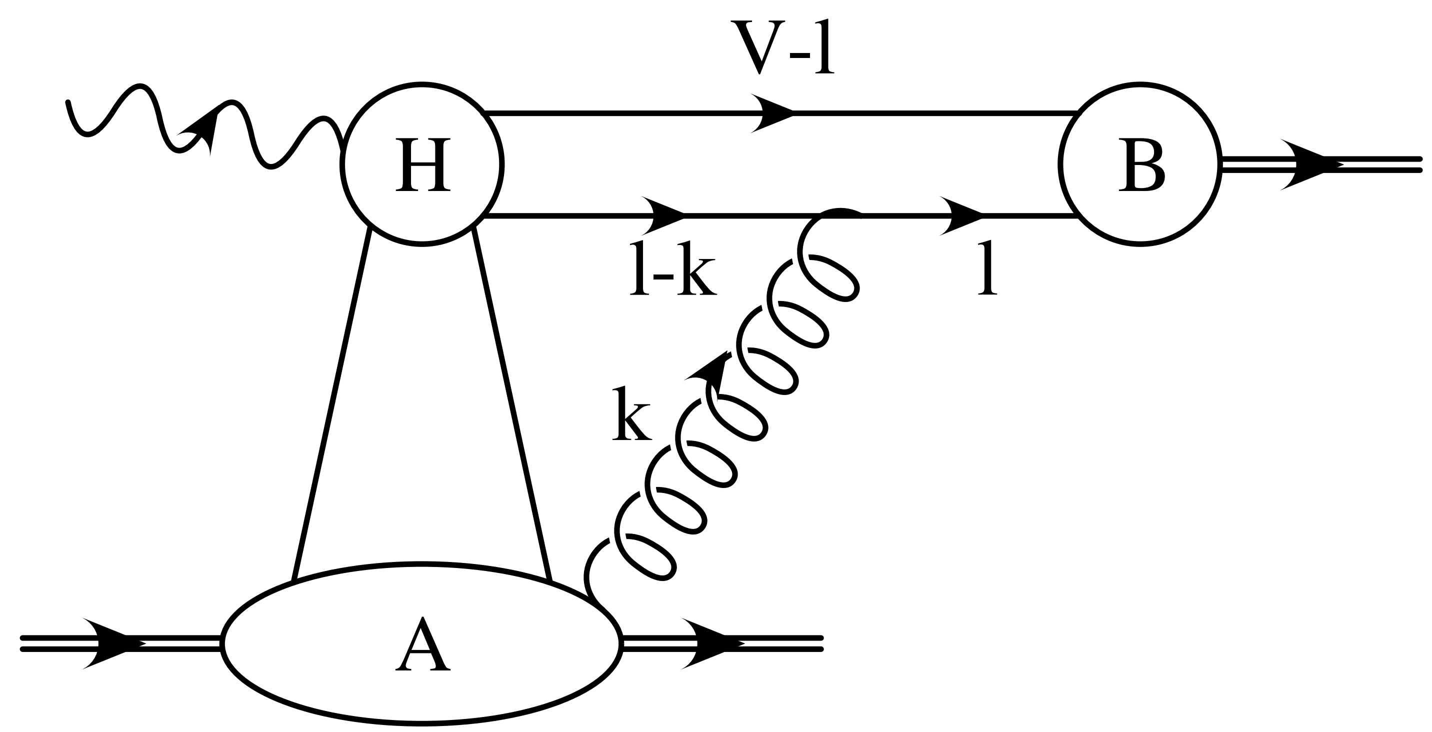
Proof in QCD - Collins 98



t-dependence only from GPD's

For large enough x (x>0.1?) the configuration in the nucleon which is likely to give the dominant contribution is when virtual photon hits a highly localized $q\bar{q}$ pair. So the minimal Fock component in N which contributes is $4q\bar{q}$.

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

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

To squeeze, or not to squeeze: this is the question.

Factorization and link to CT are best seen in the Breit frame

Before the interaction

N

$\Rightarrow$ (p,p)

γ^*

O (0, q)

After photon absorption: for $m^2_{\text{meson system}}$= const, m^2_{baryon}=const, x=const, $Q^2 \to \infty$

Meson system	Baryon system
$\Leftarrow$ fast left movers	fast right movers $\Rightarrow$

No soft interactions between left and right movers is possible provided the meson system has a small size. Insured by the choice of γ^*_L. Note that large Q^2 is not enough - need large W!

For γ^*_T nonperturbative contribution is suppressed only by ln Q^2 similar to $F_{2N}(x,Q^2)$

Signature differences between VM production with γ^*_T and γ^*_L are

- larger t-slope for " γ^*_T
- increase of σ_L/σ_T with W at mixed Q^2

Difficult measurements - H1 sees some evidence for a larger σ_T t-slope, ZEUS does not.

Fixed target data - moderate Q - higher twist effects are definitely important .
However squeezing is taking place at least starting at $Q^2 \sim 3$ GeV^2

Measurements of CT for pion and rho production at Jlab - pion case will be discussed in W. Cosey talk. Some evidence also from HERMES

How big are HT effects?

Summary of conclusions of FKS[Frankfurt,Koepf, MS] 95, 97 for VM production

Structure of the answer: $\sigma_L \propto \frac{Q^2}{(Q^2+M^2)^4}$

$$A_L \propto Q \int dz d^2k_t \psi_V(z,k_t) \left(\frac{1}{Q^2+M^2_{q\bar{q}}}\right)^2$$

extra power - from scattering operator = Laplacian applied to ψ_L

$$M^2_{q\bar{q}} = \frac{m_q^2+k_t^2}{z(1-z)}$$

mass^2 of the intermediate quark- antiquark state

- ≥ 1 GeV^2 for light mesons & for J/ψ a factor of 1.5 larger than $m^2_{J/\psi}$

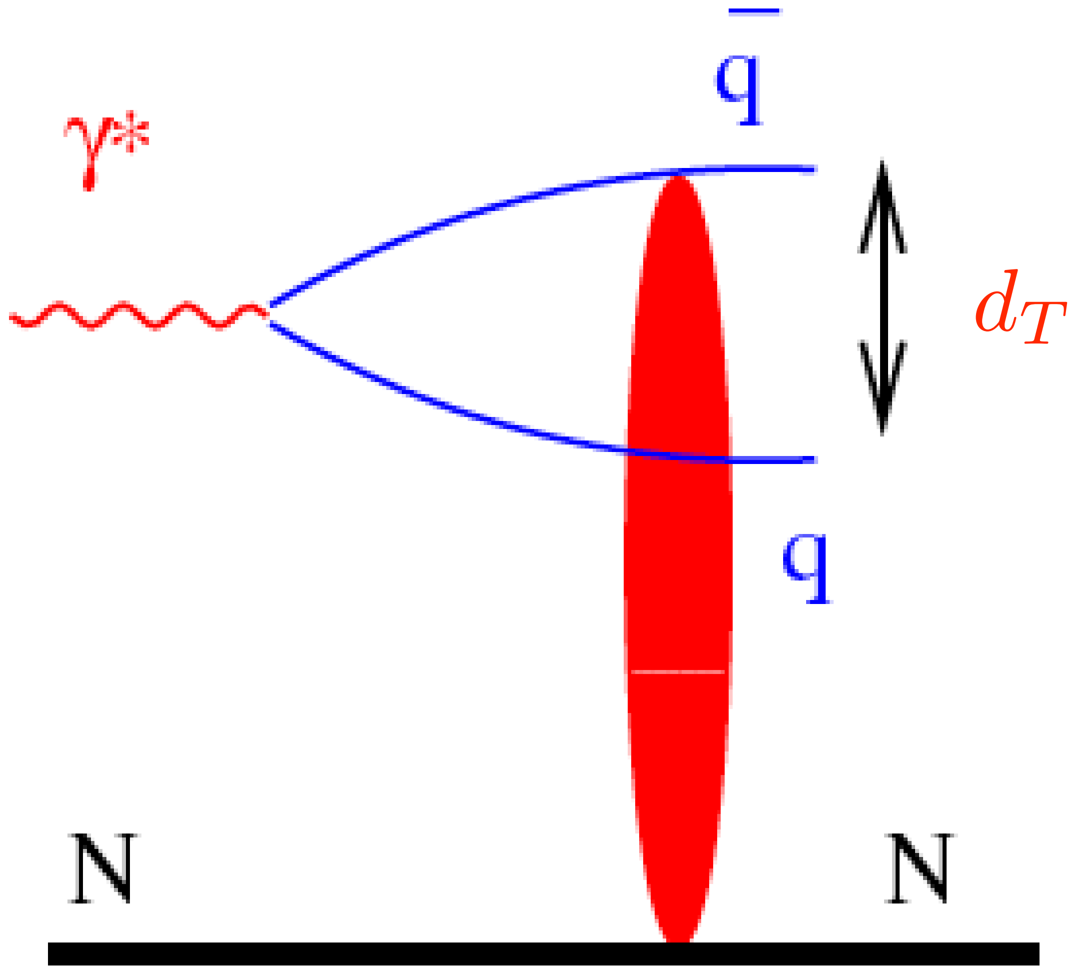
LT≡ $M^2_{q\bar{q}} \ll Q^2$

Fermi motion of quarks

$$\left(\frac{1}{Q^2+M^2}\right)^4 = \frac{1}{Q^8}(1-4M^2/Q^2+10M^4/Q^4+....)$$

- HT are large up to $Q^2 \sim 20$ GeV^2
- HT $1/Q^4$ are large up to $Q^2 \sim 5$ GeV^2
- Transverse momenta rapidly increase with Q^2 - squeezing is effective !!

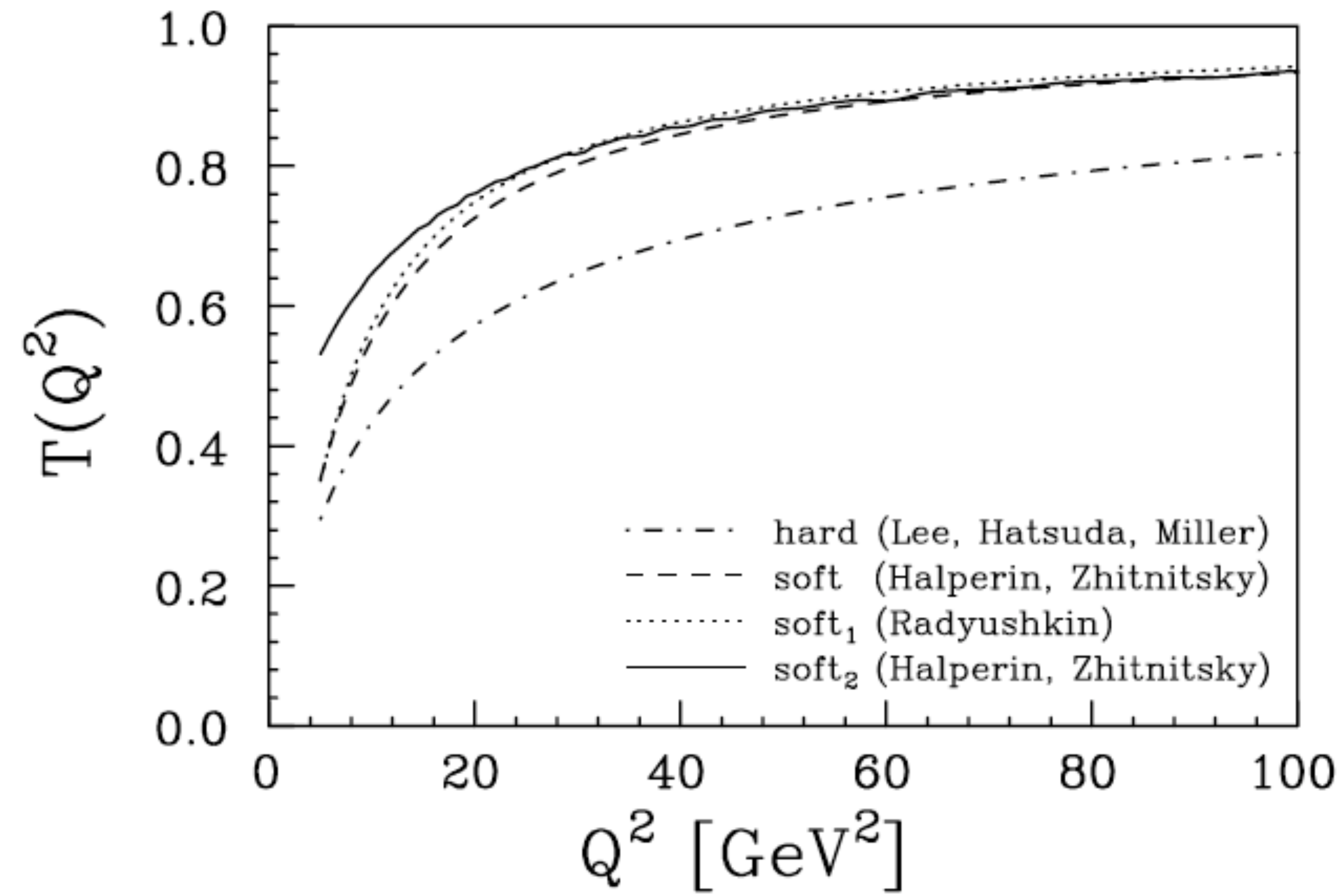
Warning - HT increase with increase of -t

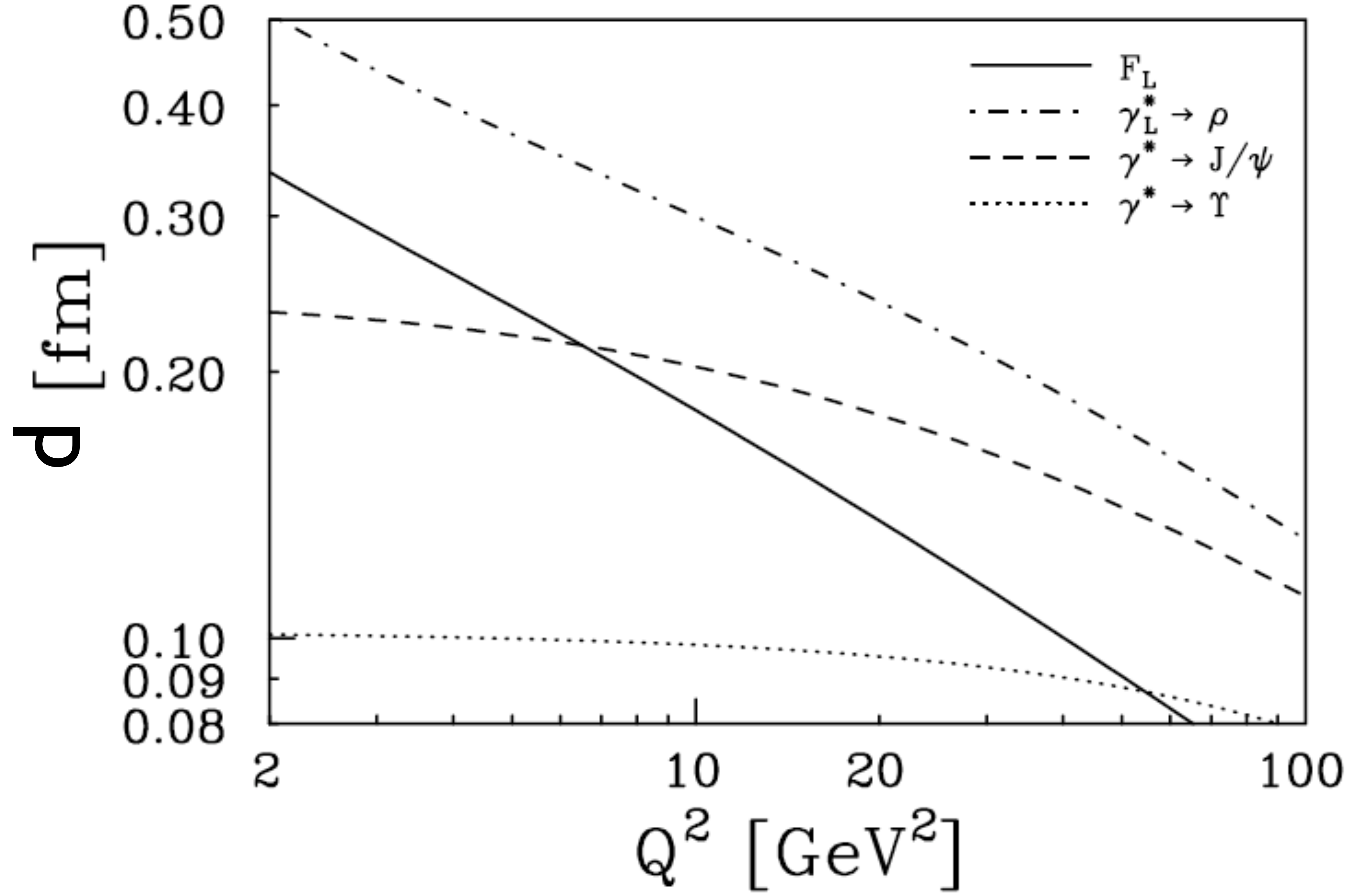


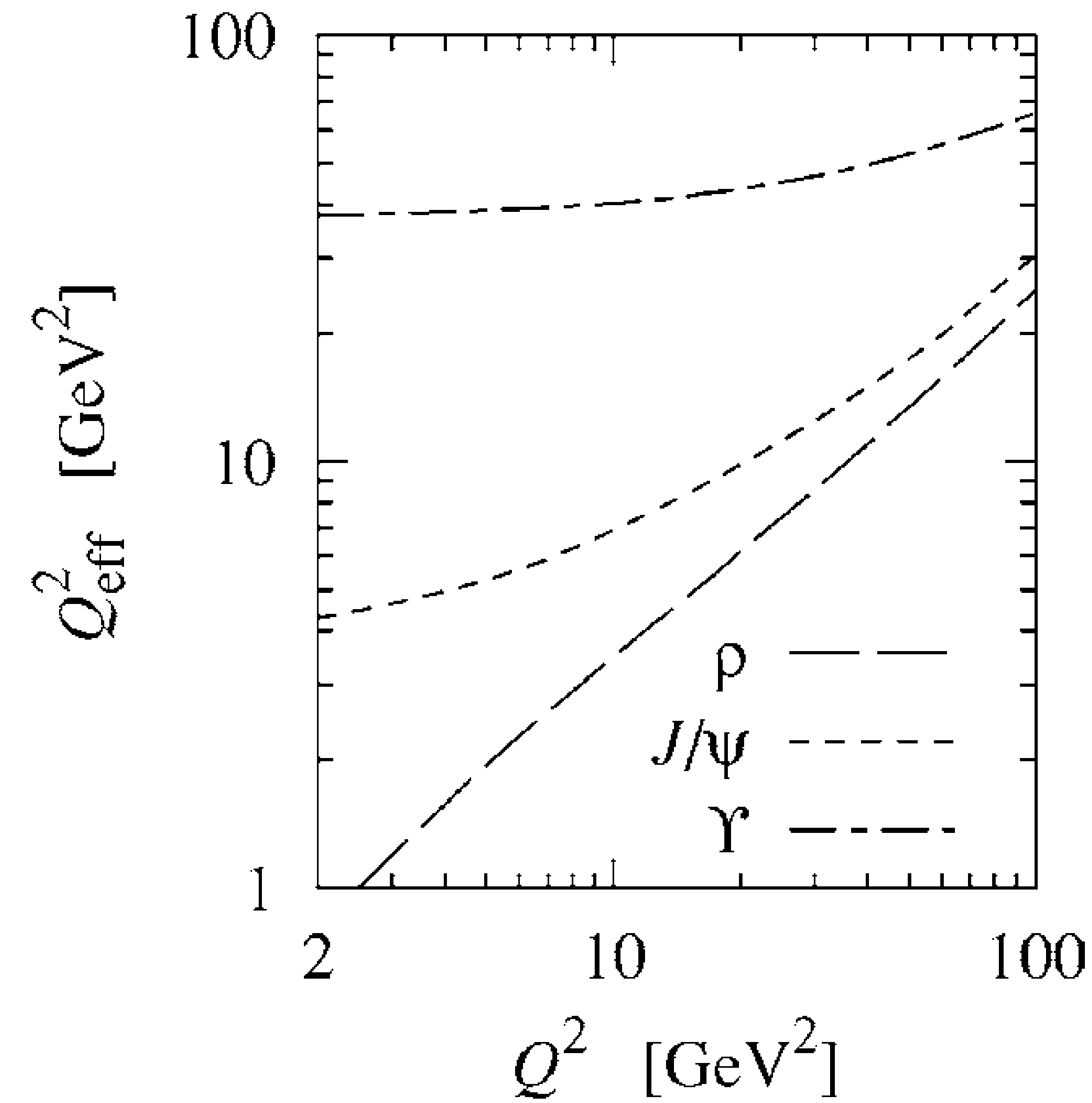
$$d_T \propto \frac{1}{Q}\left(\frac{1}{m_c}\right) \ll r_N$$

FKS95

$$T(Q^2) \propto \frac{\left|\int d^2b\,dz\,\Psi_{\gamma_L^*}(z,\mathbf{d})\sigma(q\bar{q}-N)\phi_V(z,\mathbf{d})\right|^2}{\left|\int d^2b\,dz\,\Psi_{\gamma_L^*}(z,\mathbf{d})\sigma(q\bar{q}-N)\phi_V(z,0)\right|^2}$$





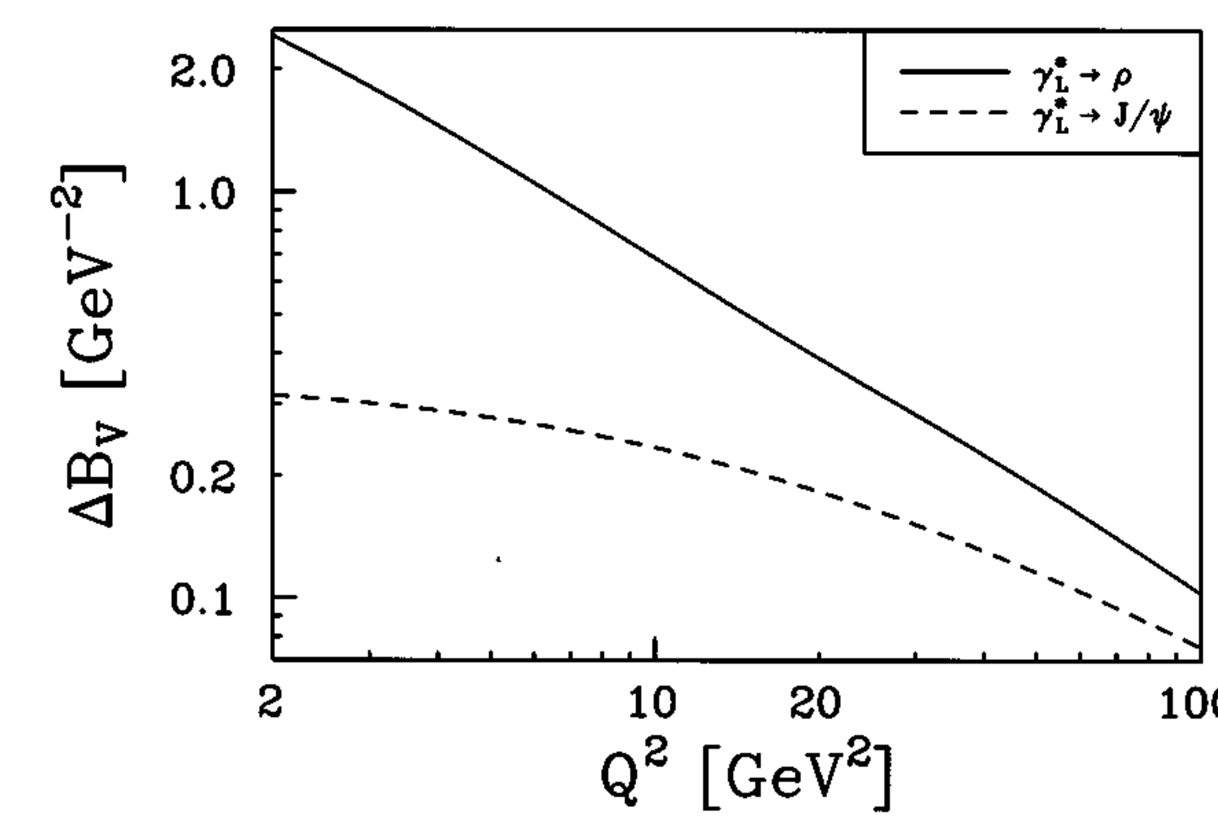


Large NLO effects:
$Q^2_{eff} << Q^2$

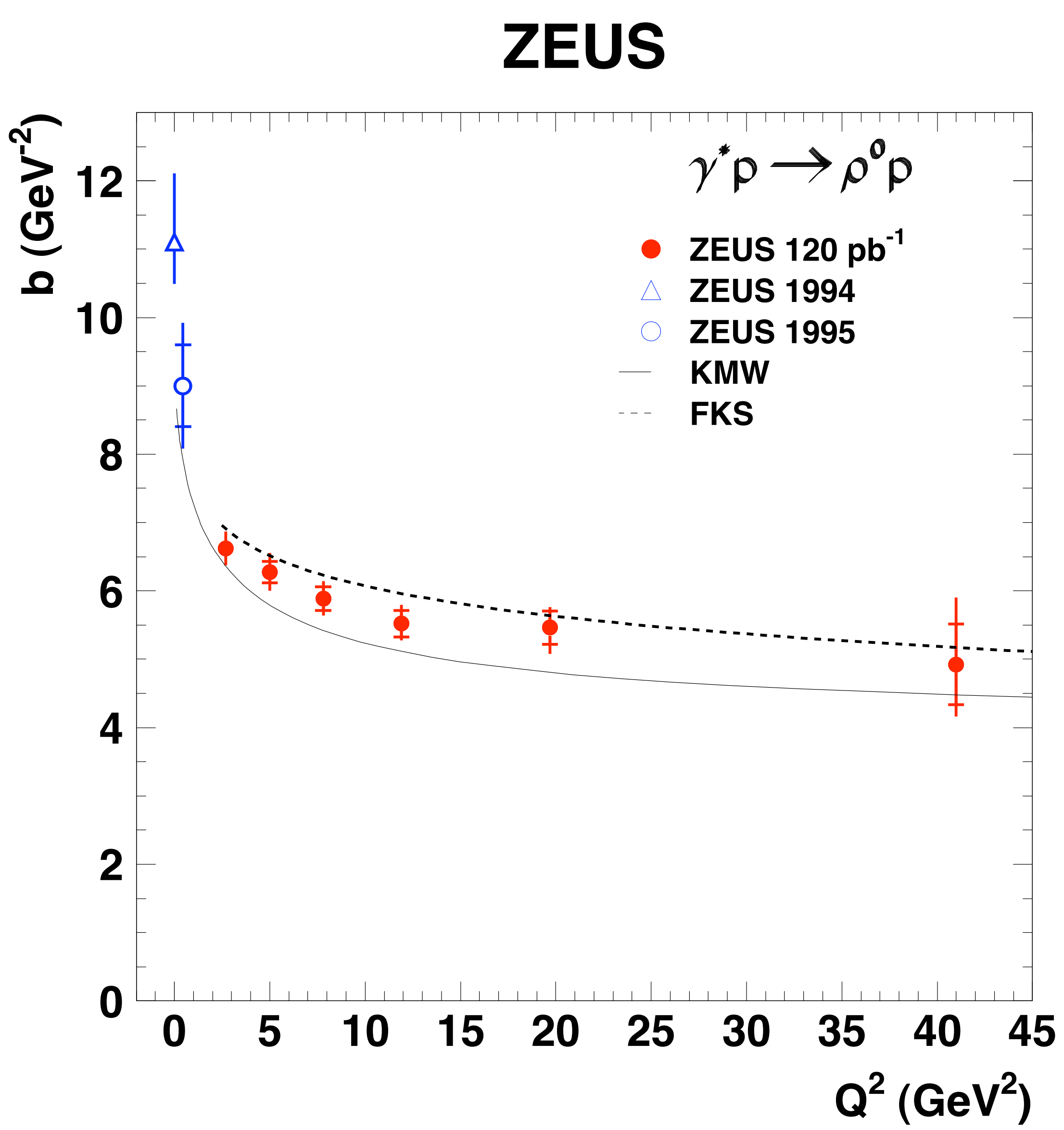
Predictions:

- A rather slow convergence of the t-slopes B of ρ and J/ψ at large Q
- Weak Q dependence of B(J/ψ)
- Fast increase of σ(γ*→ρ) only at large Q

$$\frac{d\sigma}{dt} \propto \exp(Bt)$$



Implications for color transparency studies with nuclei



$$\frac{B(Q^2) - B_{2g}}{B(Q^2=0) - B_{2g}} \sim \frac{R^2(dipole)}{R^2_\rho}$$

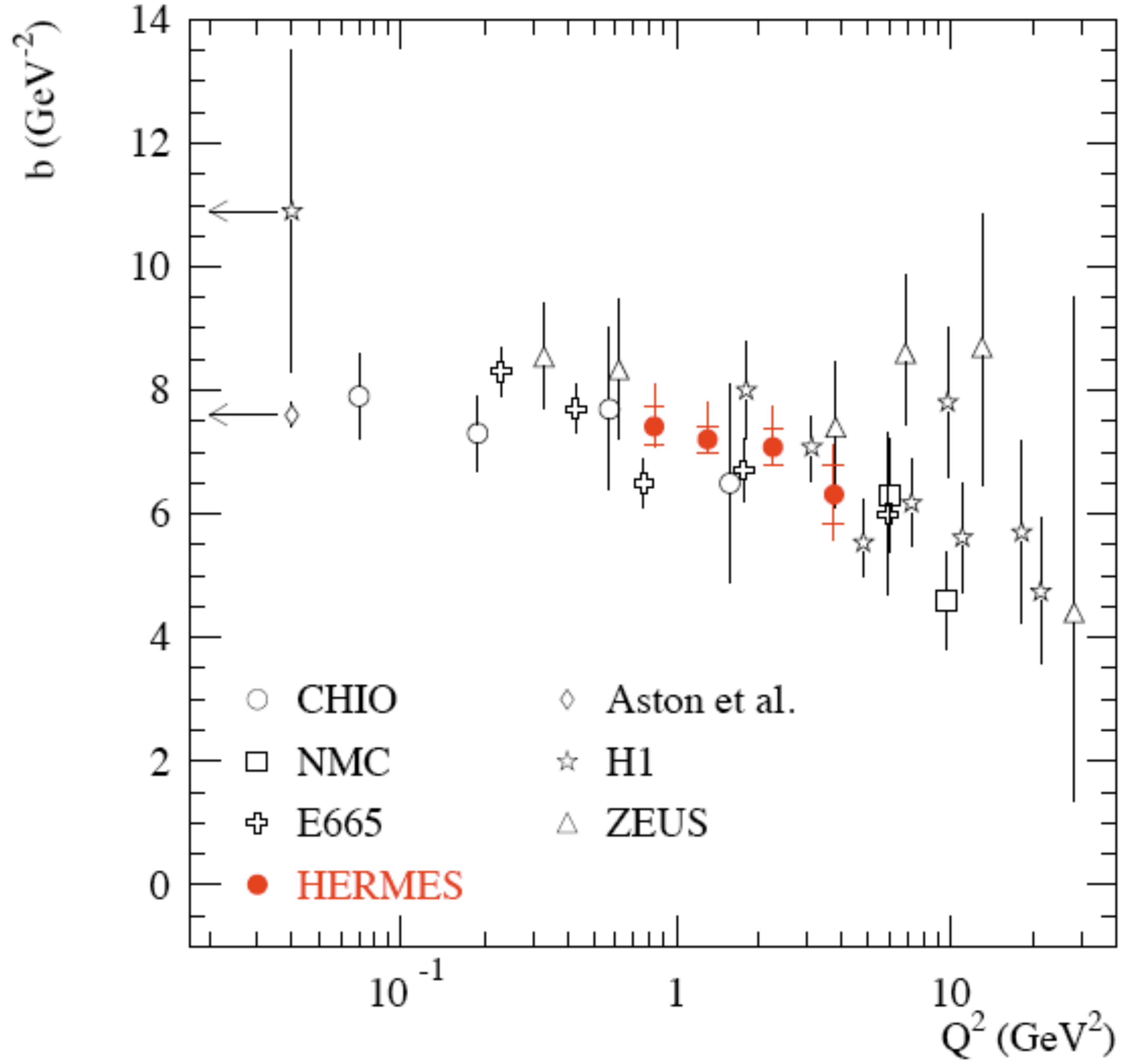
$$\frac{R^2(dipole)(Q^2 \geq 3\mathrm{GeV}^2)}{R^2_\rho} \leq 1/2 \div 1/3$$

Convergence of B for ρ-meson electroproduction to the slope of J/ψ photo(electro)production - **direct proof of squeezing.**

Expect significant CT effects for meson production for $Q^2 \geq 3\mathrm{GeV}^2$

Consistent with Jlab 6, at collider - possible shift to higher Q^2 due on set of black regime and nuclear shadowing

Where transition from soft to hard dynamics occurs?
Is there a significant squeezing for Q^2=2 GeV^2?



Small change of the slope for Q^2=2 GeV^2 as compared to Q^2=0 GeV^2? HERMES: $\Delta B < 1$ GeV^2

$r^2(Q^2=2\ \mathrm{GeV}^2)/\ r^2(Q^2=0\ \mathrm{GeV}^2) \geq 2/3$

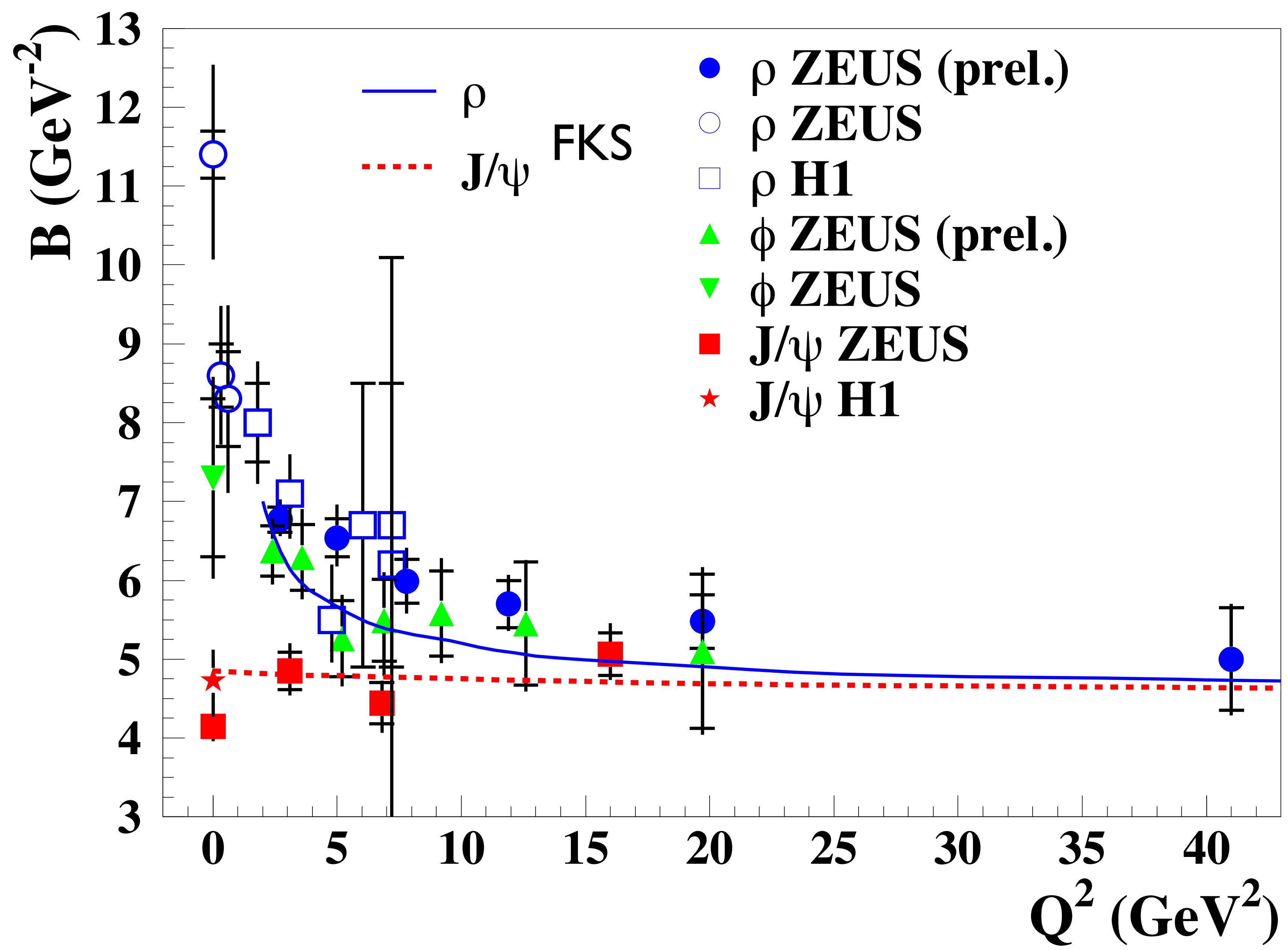
Extraction of information on GPDs from data at $Q^2 \leq 2 \div 3$ GeV^2 is problematic

Need CT data for π & ρ production at $Q^2 = 2 \div 4$ GeV^2 , $q_0 \sim 10 \div 20$ GeV HERMES? Easy for collider kinematics of EIC

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,

Onset of universal regime FKS 97.

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



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

Issue: precision.

Upsilon - the smallest hadron - are HT corrections large for photoproduction?

FMS - Frankfurt, McDermott, Strikman 98 dipole approximation - HT a factor of two suppression; large effect of real part and skewedness. $Q^2_{eff} \sim 40$ GeV^2

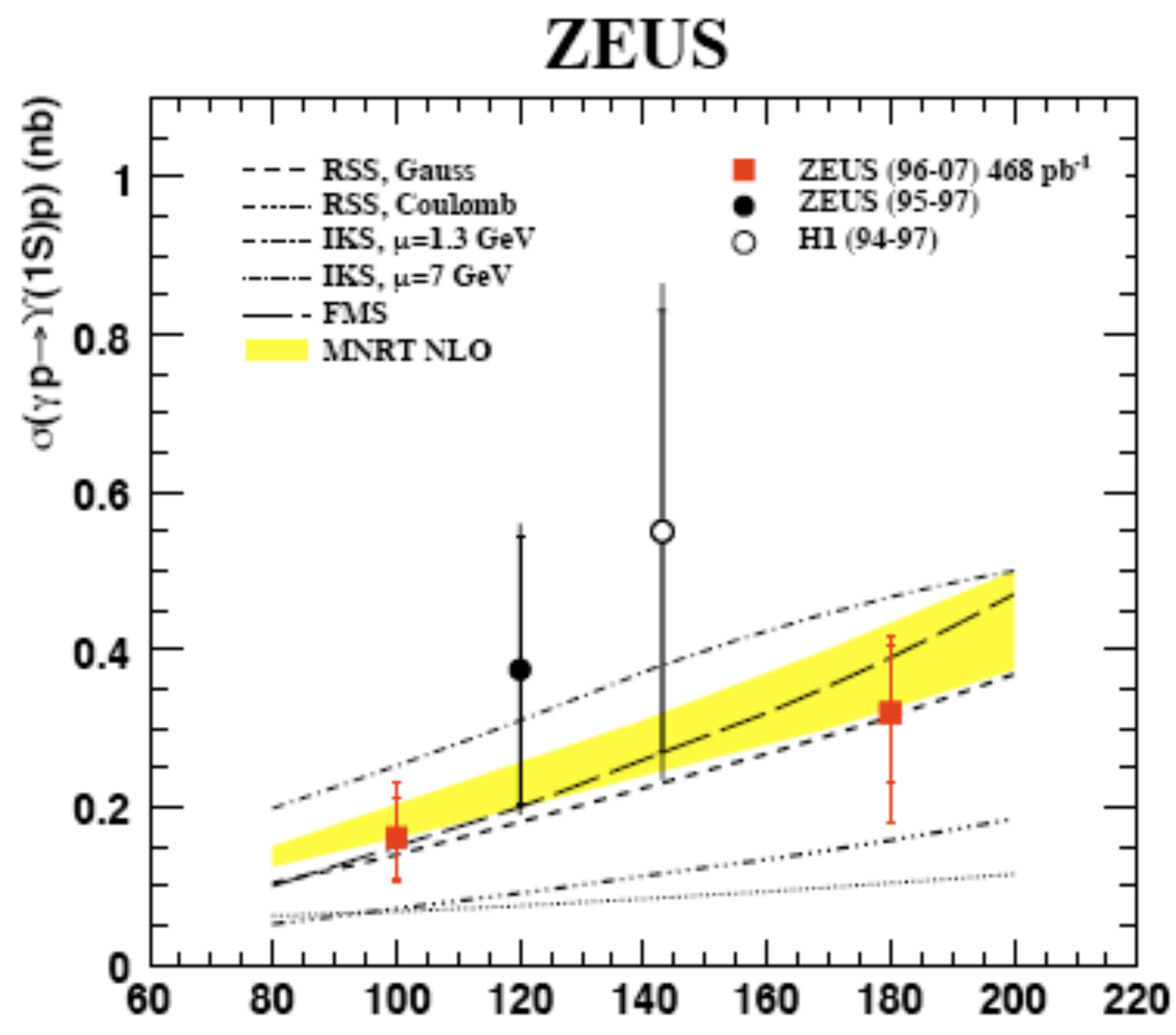
NLO calculations:

Ivanov, Krasnikov, Szymanowski 05 Strong dependence of NLO result on μ_R.

Data described for a very small μ_R

Martin et al 08 much smaller sensitivity?

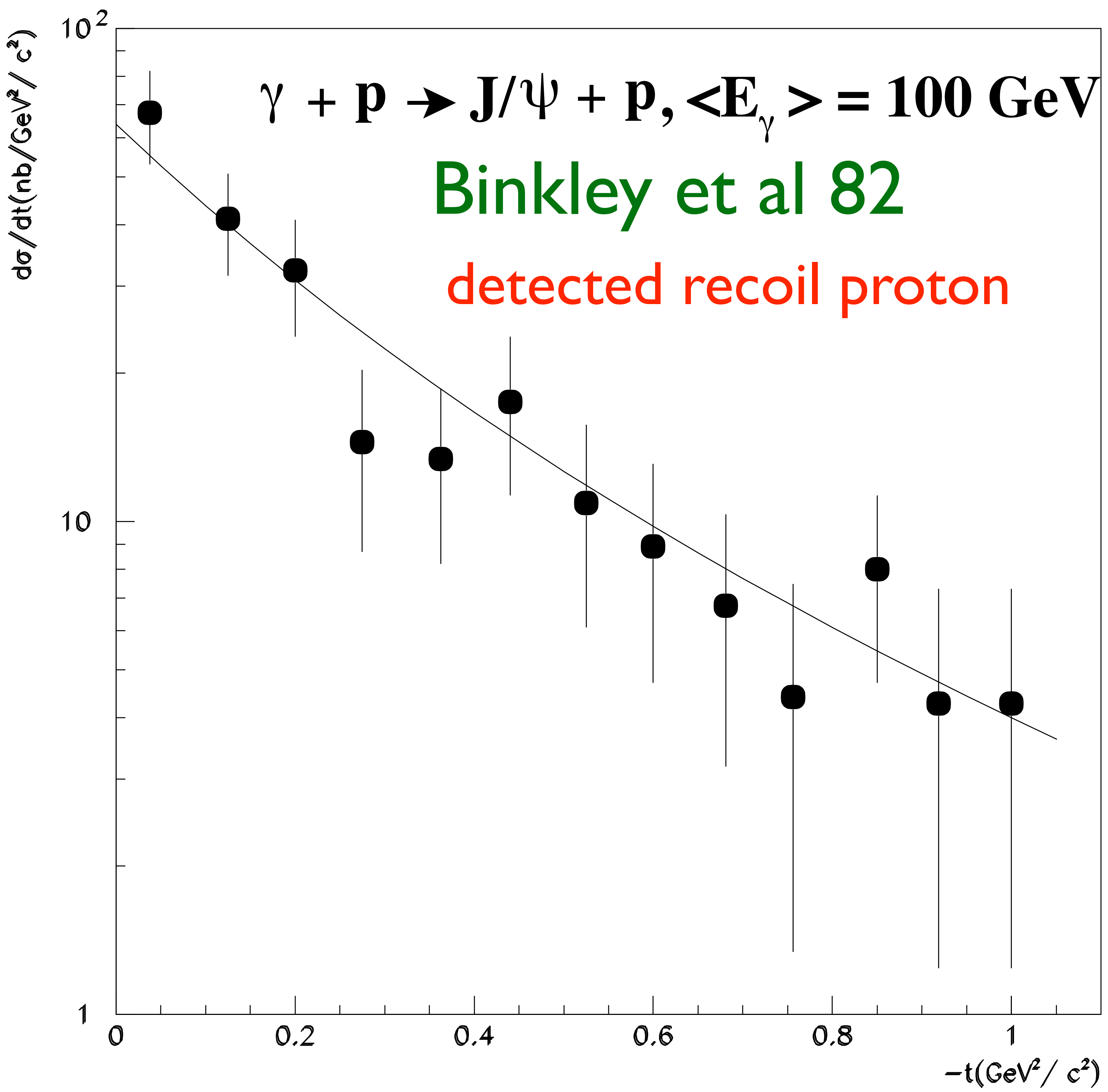
open questions - energy conservation and related issues with gauge invariance. treatment of the meson wave function



Transverse gluon spread

Enters into calculation of the gap survival probability in the double Pomeron exclusive Higgs production in a very sensitive way. Relevant for new particle searches.

☛ *Important to understand gluon GPD transverse shape as a function of x dependence*



Theoretical analysis of J/ψ photoproduction at corres $100\ GeV \geq E_\gamma \geq 10\ GeV$ n factor of the nucleon for

$$0.03 \leq x \leq 0.2,\ Q_0^2 \sim\ 3\ GeV^2, -t \leq 2\ GeV^2$$

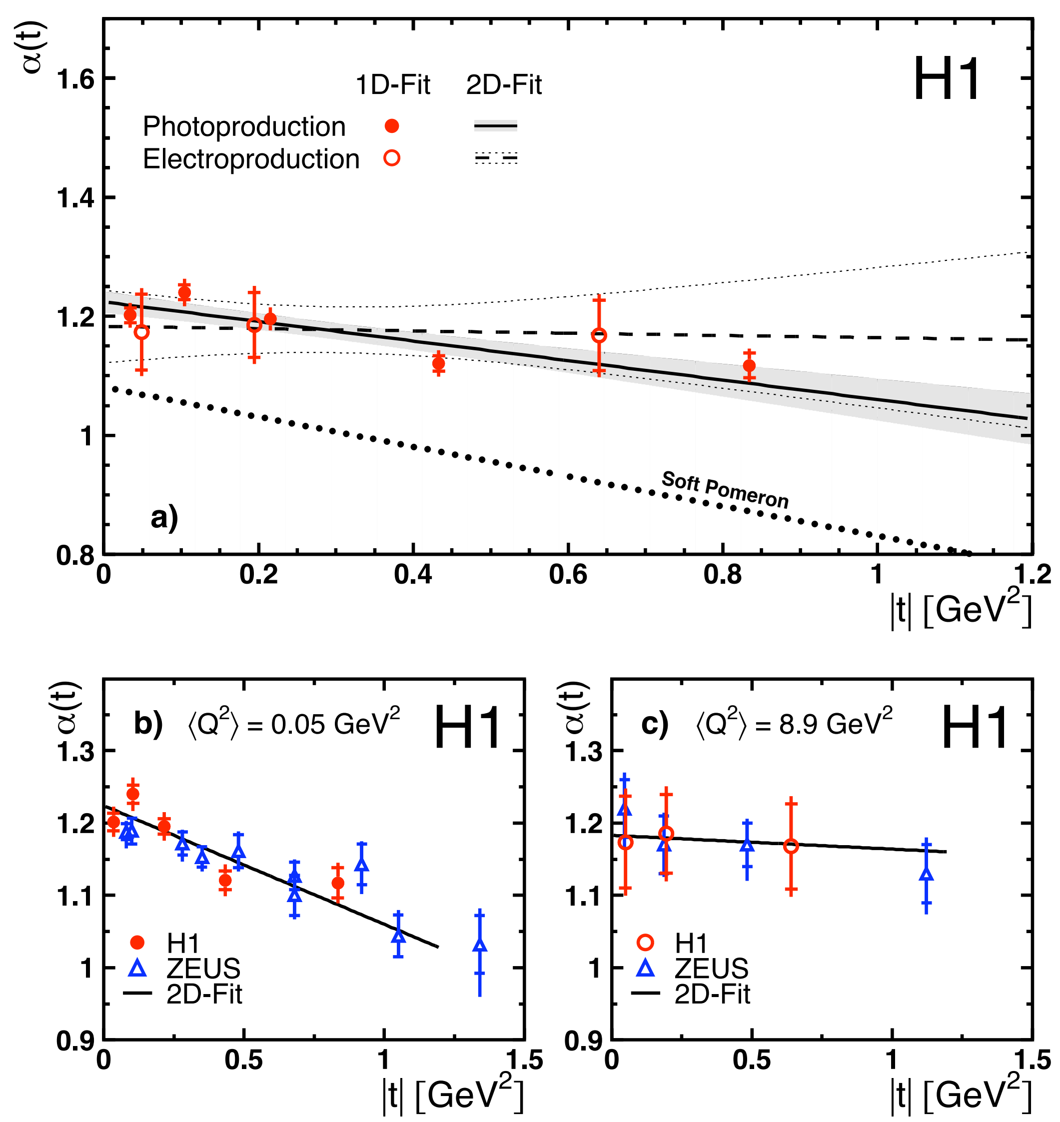
$$F_g(x, Q^2, t) = (1 - t/m_g^2)^{-2}.\ m_g^2 = 1.1\ GeV^2$$

which is larger than e.m. dipole mass

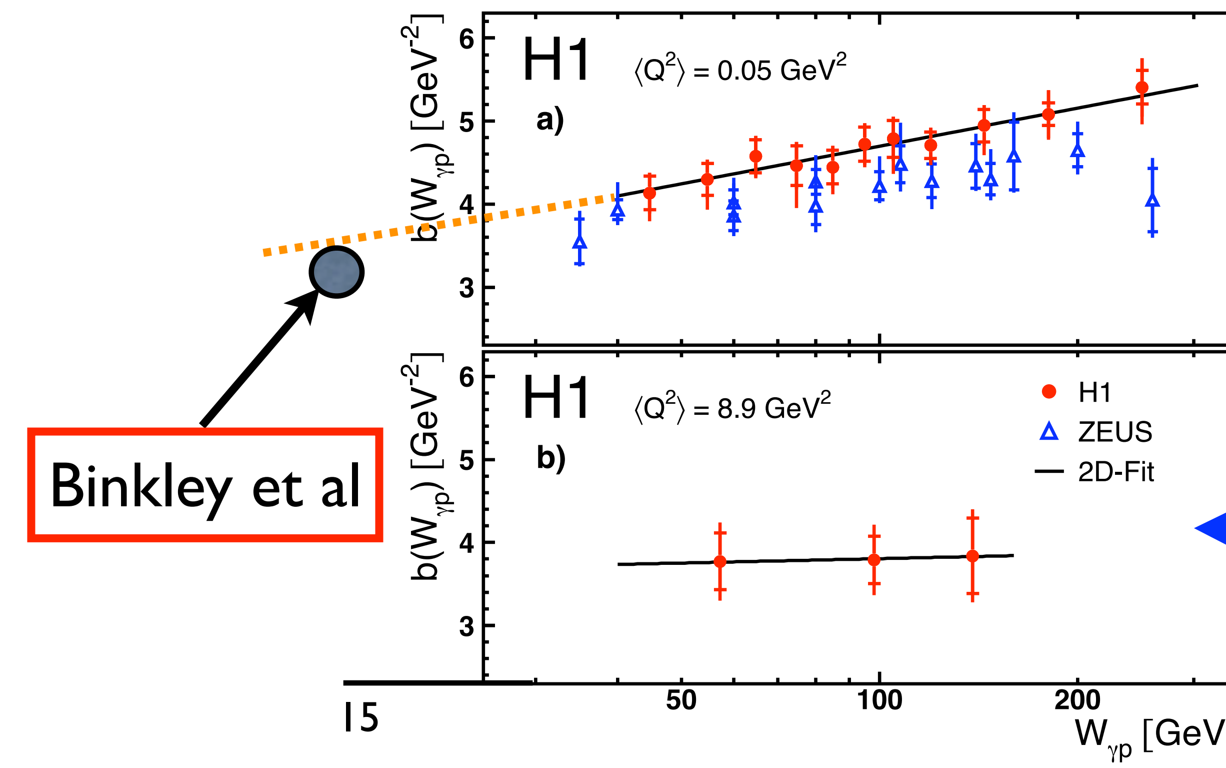
$$m_{e.m.}^2 = 0.7\ GeV^2.$$ (FS02)

Significant contribution to the difference isdue to the chiral dynamics - lack of scattering off the pion field at x>0.05 (Weiss &MS 03)

J/ψ elastic photo and electro production



The effective trajectory $\alpha(t)$ as a function of $|t|$ in the range $40 < W_{\gamma p} < 305$ GeV



$$B = B_0 + 2\alpha' ln(x_0/x)$$

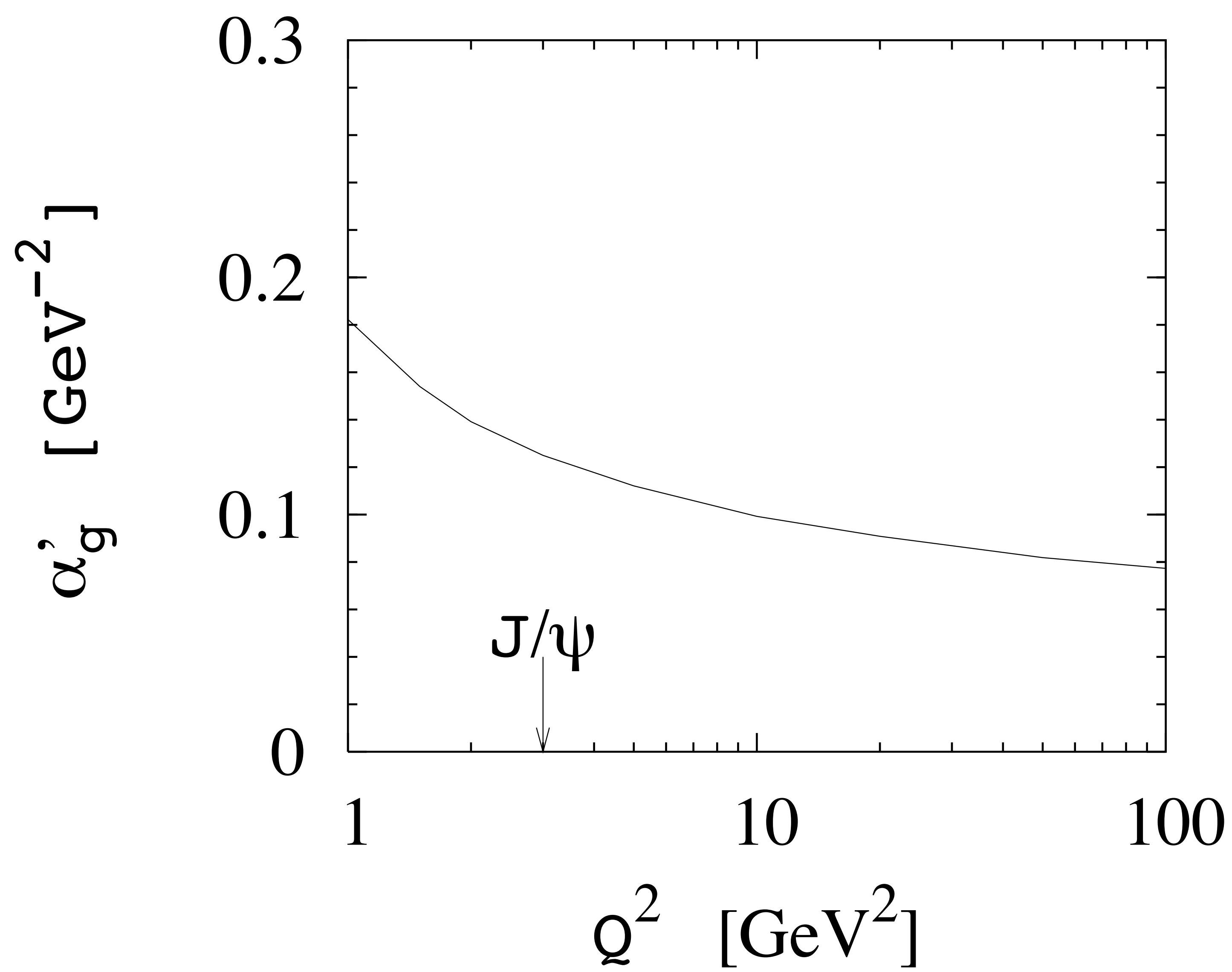
α' consistent with zero!!!

t-slope, b, for J/ψ especially at Q^2=9 GeV^2 is systematically lower than for DVCS and for ρ - production

Experimental problems - poor resolution in t for -t < 0.1 GeV^2(large difference for these t for dipole end exp fits), proton is practically never detected while veto relies on soft Regge model - while dynamics changes with increase of -t where inelastic dominates.

Can we reliably extract variation with x of the ρ- dependence of gluon GPDs from J/psi data?

☻ DGLAP evolution of α' is slow between photo an electro production do explain the drop



Frankfurt, MS, Weiss 03

☹ Fluctuations in the transverse size is due to HT in the J/psi wave function: on the amplitude level 10 -20 % of large size configurations for real photon case - can lead to drop of α´ between Q^2=0 and 10 GeV^2 (McDermott & F&S) of the order 0.05 GeV^{-2}

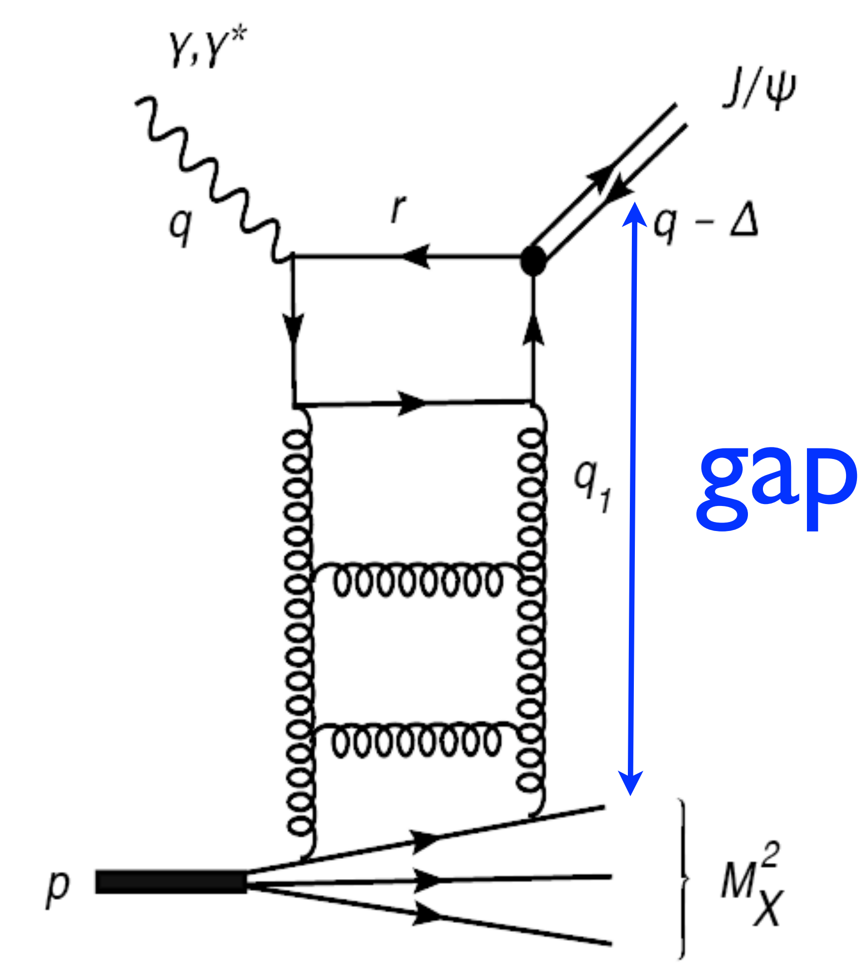
☞ DGLAP is modified at -t comparable to Q^2 Blok, Frankfurt, MS, 10

New effect - DGLAP at large t

CFS factorization theorem derived in the limit $-t \ll Q^2$

For $-t \sim Q^2$, in the double log approximation essentially no energy dependence of the ladder - hence α_{IP} is close to one - effectively looks as presence of α' of the order of 0.07 GeV^{-2}- but effect does not reflect increase of the transverse distribution of partons !!! (Blok, FS, 10)

Consider process for $-t \le Q^2 + M_V^2$



Elementary reaction - scattering of a hadron (γ, γ*) off a parton of the target at large $t=(p_\gamma-p_V)^2$

FS 89 (large t pp→p +gap + jet), FS95

Mueller & Tung 91

Forshaw & Ryskin 95

$$x_J = \frac{-t}{-t + M_X^2 - m_N^2}$$

Larger cross section than exclusive which has the same s - dependence

$$\frac{d\sigma_{\gamma+p\to V+X}}{dt dx_J} = \frac{d\sigma_{\gamma+quark\to V+quark}}{dt}\left[\frac{81}{16}g_p(x_J,t)+\sum_i(q_p^i(x_J,t)+\bar{q}_p^i(x_J,t))\right]$$

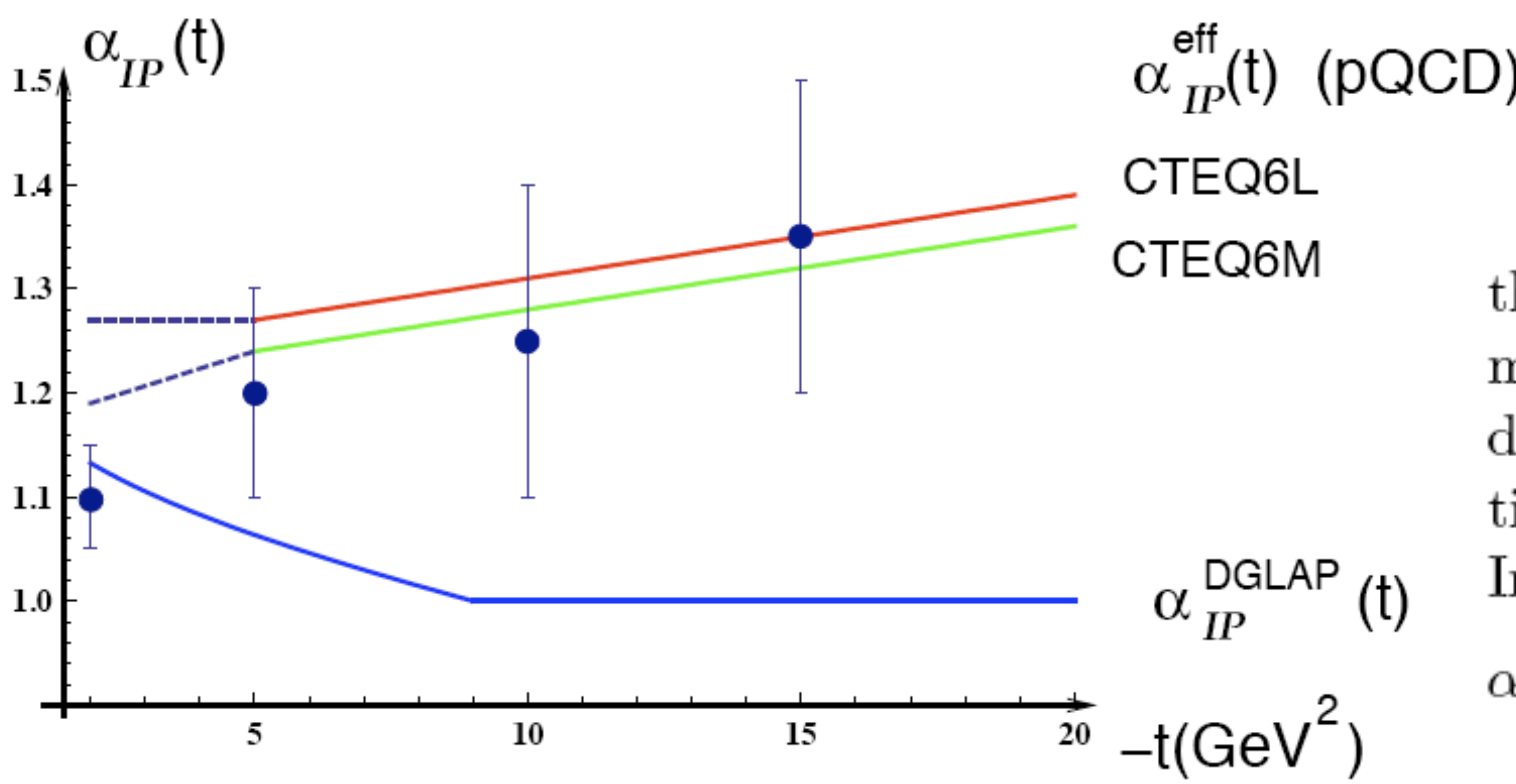
For $-t \leq Q^2 + M_V^2$

$$\frac{d\sigma}{dt dx_J} = \Phi(t,Q^2,M_V^2)^2\frac{(4N_c^2 I_1(u))^2}{\pi u^2}G(x_J,t).$$

Here

$$u = \sqrt{16N_c\log(x/x_J)\chi'},\ \chi' = \frac{1}{b}\log(\frac{\log((Q^2+M_V^2)/\Lambda^2)}{\log(-t+Q_0^2)/\Lambda^2}),$$

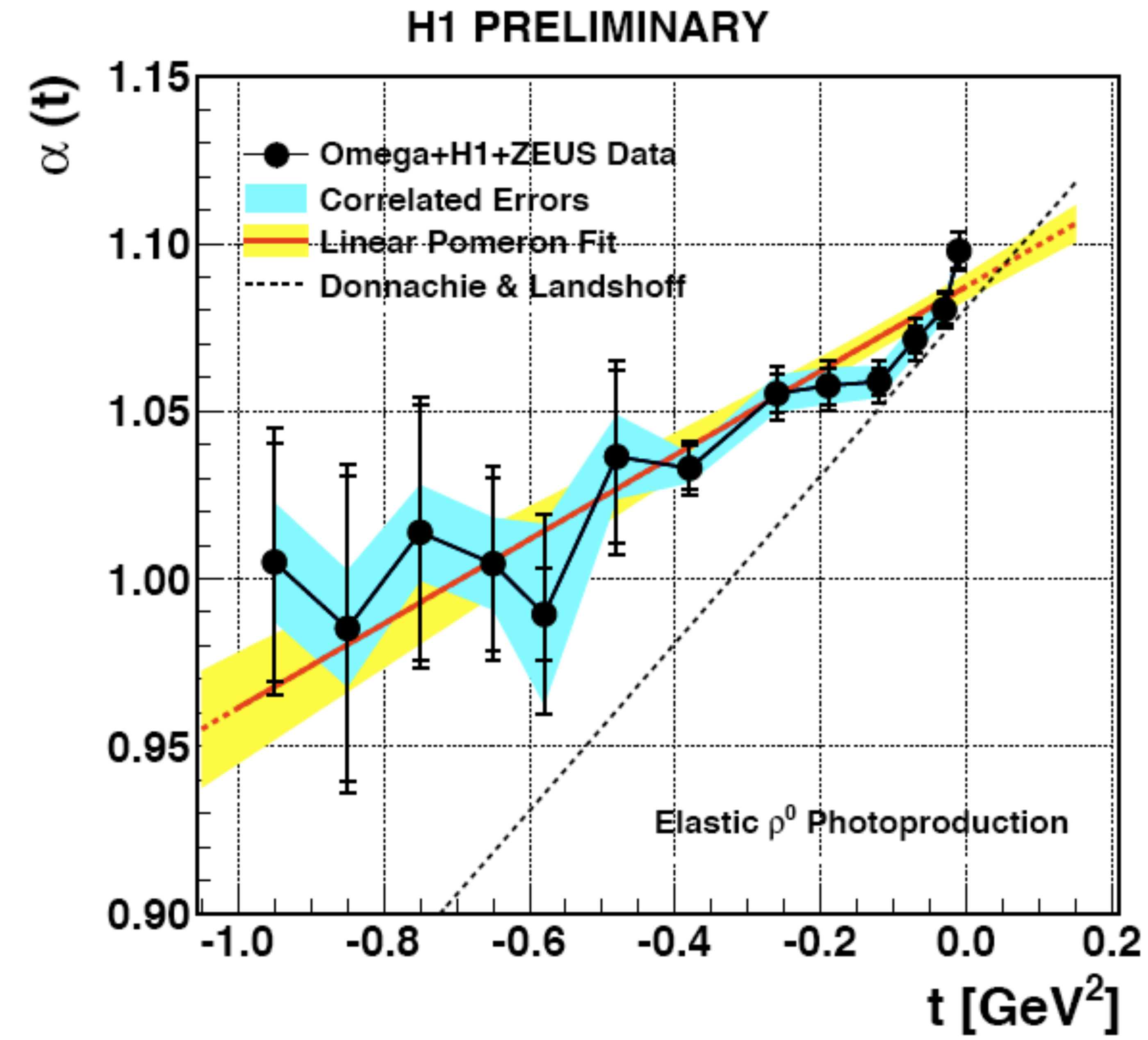
$$x_J = -t/(M_X^2 - m_p^2 - t), x \sim 3(Q^2+M_V^2)/(2s),\ b = 11 - 2/3N_f, N_c = 3, s = W_{\gamma p}^2$$



The comparison between the experimental data and theoretical prediction for the HID cross section at HERA for the "effective Pomeron" $\alpha_P^{\mathrm{eff}}(t)$, i.e. (1/2) logarithmic derivative of the cross section $d\sigma/dt$, obtained after integrating between the energy dependent cuts, as given in the text. The dashed curve means large theoretical uncertainties in the corresponding kinematic region. The values are given at for $W_{\gamma p} = 150$ GeV. In the same figure we depict also "true (DGLAP) "Pomeron", i.e. logarithmic derivative $\alpha_P(t)^{\mathrm{DGLAP}} = 0.5\frac{d(d\sigma/)dtdx_J))}{dlog(x/x_J)}$ at this energy. $\Lambda_{\mathrm{QCD}} = 300$ MeV.

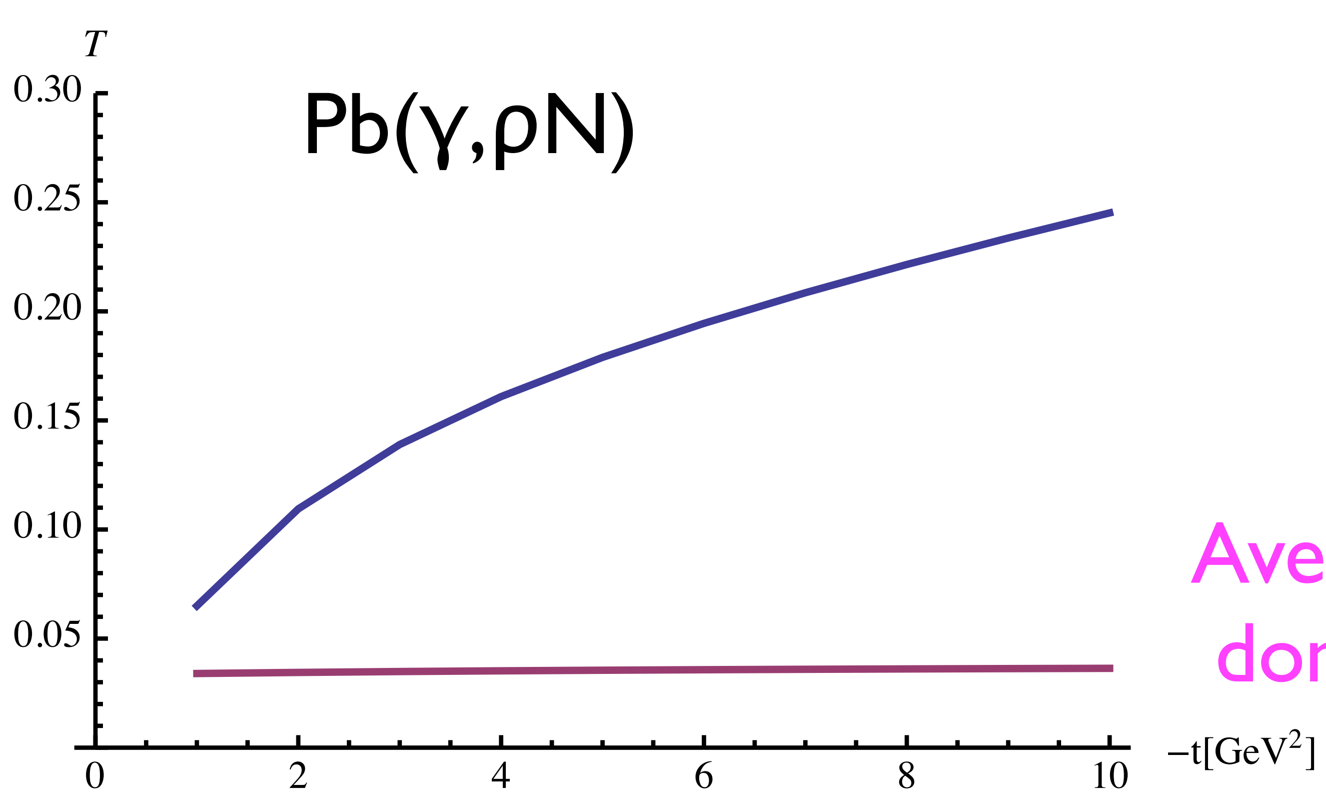
Note that in this calculation the scale governing the J/ψ production was taken to be M_V^2. More realistic estimate (at least for exclusive photoproduction is 3 GeV^2)

Maybe relevant for the explanation of the pattern observed in photoproduction of ρ-mesons. No diffusion if -t is larger than the soft scale.



Test of squeezing: $\gamma + A \rightarrow \rho + p + (A-1)^*$ $(p_t(\rho) + p_t(N) \leq k_F)$

Transparency ratio: $T = \sigma(\gamma + A \rightarrow \rho + p + (A-1)^*) / Z\sigma(\gamma + p \rightarrow \rho + p) >>$ Glauber value



CT (optimistic)

Average configuration dominance

Early squeezing - graduate shift of <σ> for dominant configurations

Negligible effect from proton squeezing - fast expansion

Early scaling in DIS → mechanism of inelastic diffraction is likely to change at $-t \sim 1\ \mathrm{GeV}^2$. Hence subtraction of inelastic contribution done via MC at HERA for these t is especially problematic.

☛ *Need a design of the detector with proton detection up to large t*

Slow convergence of the Fourier transform of $F_{2g}(t)$ for dipole fit. For $b=0$

$$fract \equiv \frac{\int_0^{-t_{max}} F_{2g}(t)dt}{\int_0^{\infty} F_{2g}(t)dt} = \frac{1}{1 - t_{max}/M_{2g}^2} \Rightarrow fract(-t_{max} = 1\mathrm{GeV}^2) = 1/2$$

☛ To probe small b large Q^2 are necessary - otherwise factorization in the form given by CFS is broken

$$\frac{d\sigma_{\gamma+p\to V+X}}{dt dx_J} = \frac{d\sigma_{\gamma+quark\to V+quark}}{dt}\left[\frac{81}{16}g_p(x_J,t)+\sum_i(q_p^i(x_J,t)+\bar{q}_p^i(x_J,t))\right]$$

- - t ~ 1÷ 2 GeV^2 + strong enhancement of interactions with gluons - unique way to excite gluonic modes in nucleon at x_J ~ 0.2. Novel baryon I=1/2 spectroscopy if gluons are not strongly coupled to valence quarks - in any case - a new tool - price - good forward detector not only for protons and neutrons but also for mesons. Interesting effects in the case of polarized proton are possible - need further analysis.

- Can also check chiral dynamics in near threshold πN production, Polyakov et al

Exclusive channels with nonvacuum exchange in t -channel

$\gamma_L^* + N \to \pi N(\Delta), K - Hyperon, \rho^{\pm} N(\Delta),$

Medium energy EIC is optimal - at higher W cross sections are too small, doable with current detector design

T.Horn 2d talk

Presence of many channels allows to perform many cross checks

eA option is an advantage - can check how fast squeezing sets in (guess - starting at Q^2= 4GeV^2)

$\gamma_L^* + A \to \pi A'$

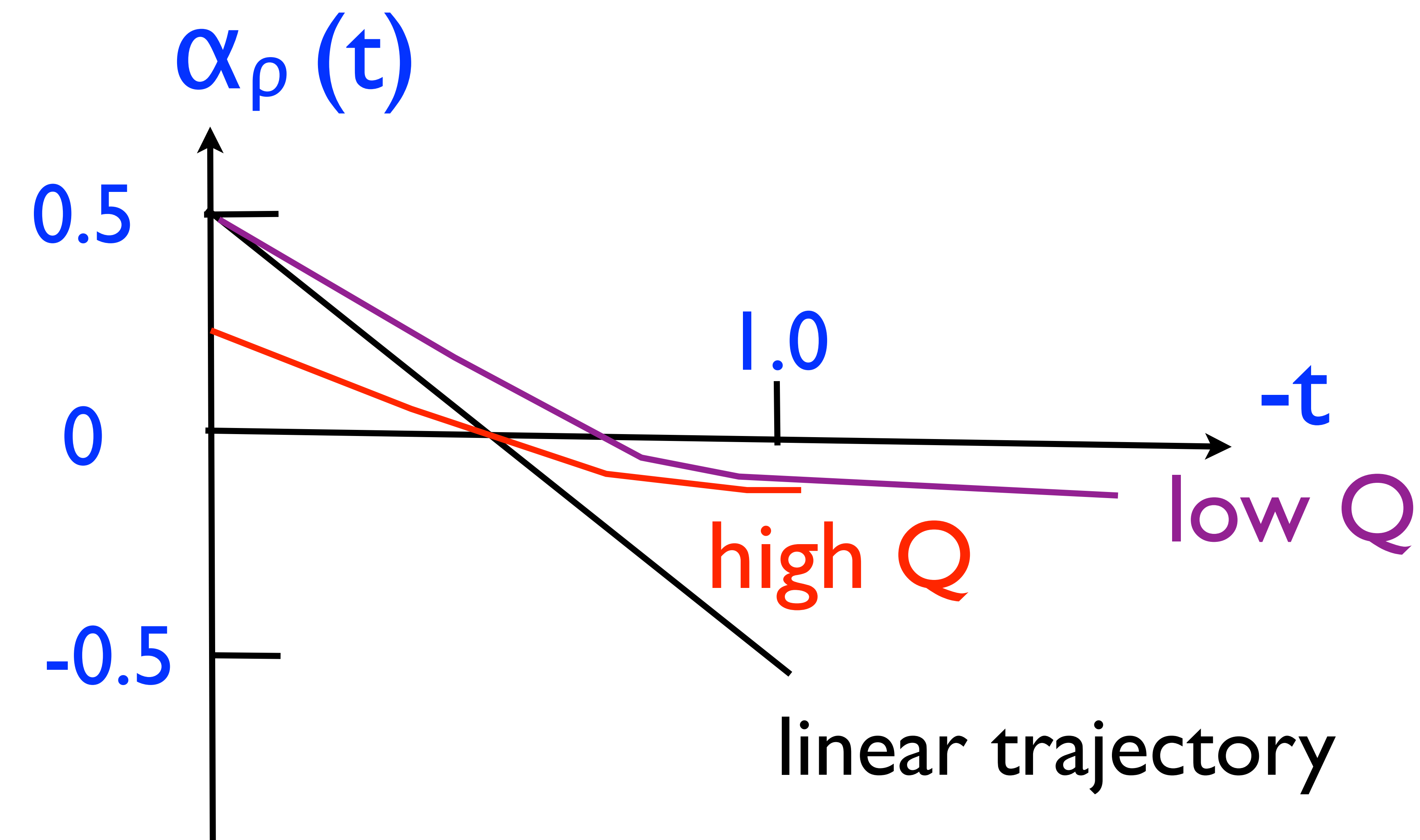
main advantage vs Jlab - frozen approximation is good ⇒ much larger CT for same Q

Energy and t dependence - $\alpha^{pert}_R(t)$

My guess - $\alpha^{pert}_R(t)$ closer to nonreggeized two quark exchange: $\alpha^{pert}_R(t) \sim 0$

$\alpha_R(pert)$ ($-t > 1$ GeV^2) ~ -0.2,

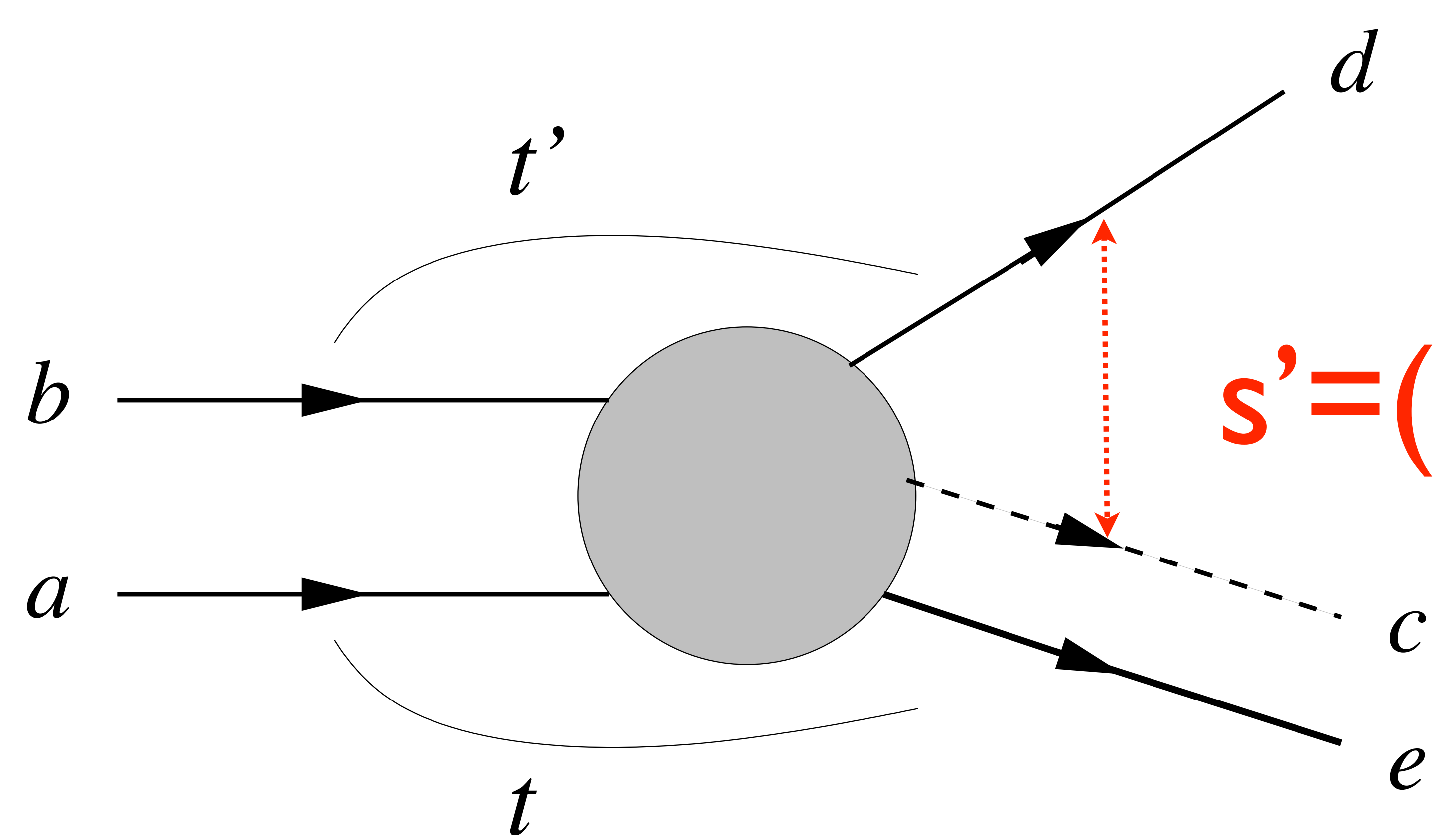
$\alpha'_R(pert) << \alpha'_R(nonperturb)$



Interesting physics in broad range of Q.

☀ New type of hard hadronic processes - *branching exclusive processes* of large c.m. angle scattering on a "cluster" in a target/projectile (MS94)

to study both CT of 2 → 2 and hadron GPDs



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

Limit:

$-t' >$ few GeV^2, $-t'/s' \sim 1/2$

$-t = \text{const} \sim 0$

➡ $s'/s = y < 1$,

$t_{min} = [m_a^2 - m_b^2/(1-y)]y$

Two recent papers: Kumano, MS, and Sudoh PRD 09;
Kumano &MS arXiv:0909.1299, Phys.Lett. 2010

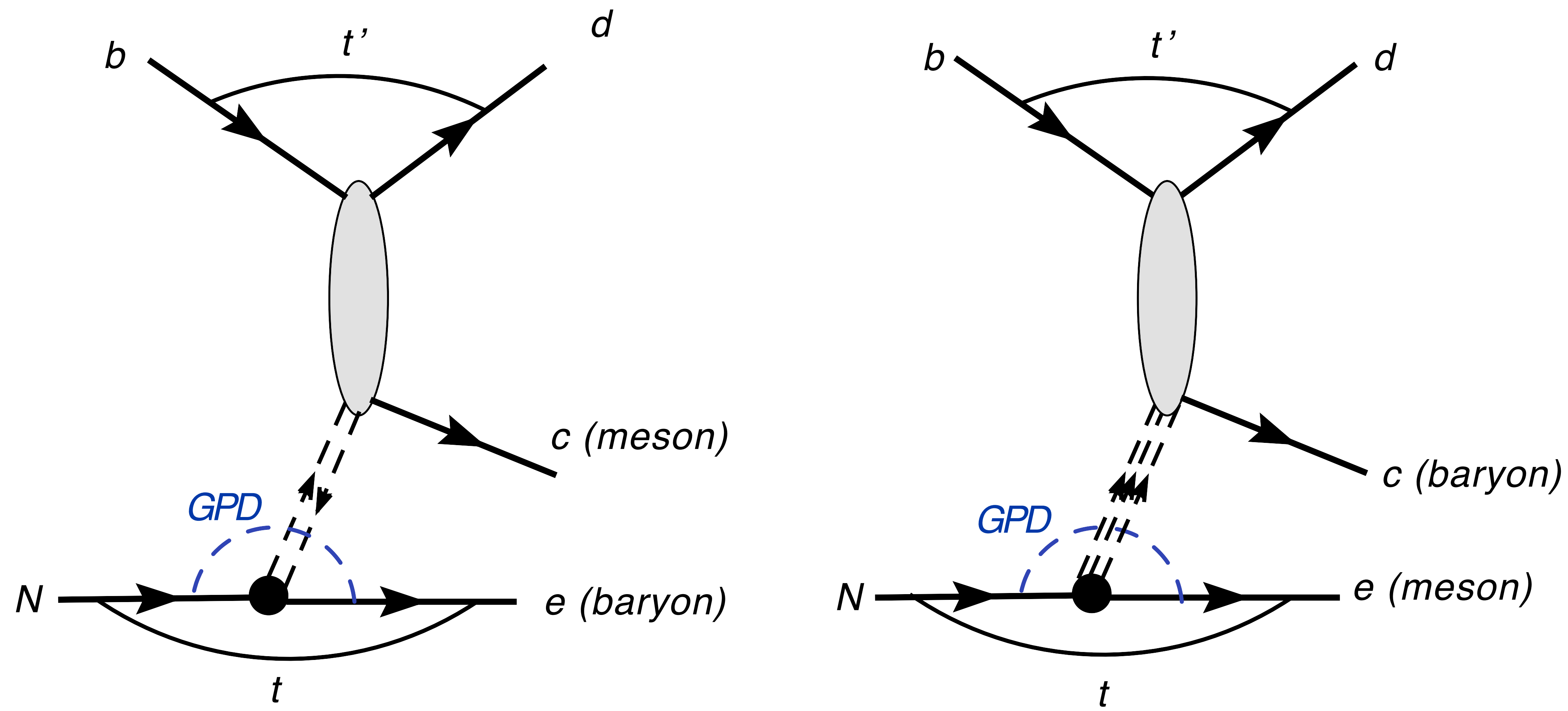
$2 \to 3$ branching processes:

- test onset of CT for $2 \to 2$ avoiding diffusion effects

For example at what s',t process $\gamma\pi \to \pi\pi$ is due to scattering in small configurations, when point -like component of photon starts to dominate.

- measure transverse sizes of b, d,c
- measure cross sections of large angle (γ)pion - pion (kaon) scattering
- probe 5q in nucleon and 4q in mesons
- measure GPDs of nucleons, photons, and mesons(!)
- measure pattern of freezing of space evolution of small size configurations

Factorization:



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

⇓

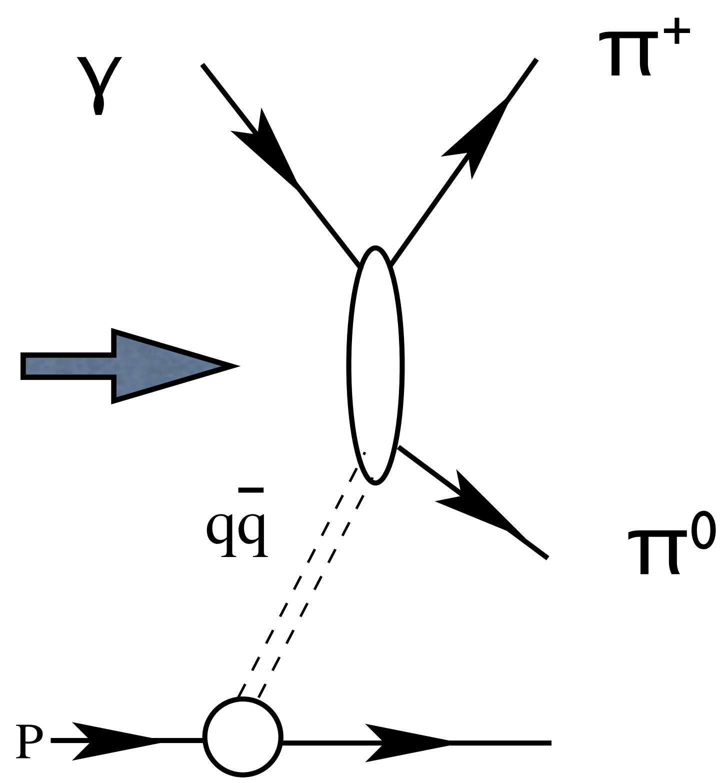
$$\mathcal{M}_{NN\to N\pi B} = GPD(N \to B) \otimes \psi_b^i \otimes H \otimes \psi_d \otimes \psi_c$$

For e p collider possible processes

$\gamma\ (\gamma^*) + p \rightarrow \underbrace{\pi^+ \pi^0}\ n$

current fragmentation

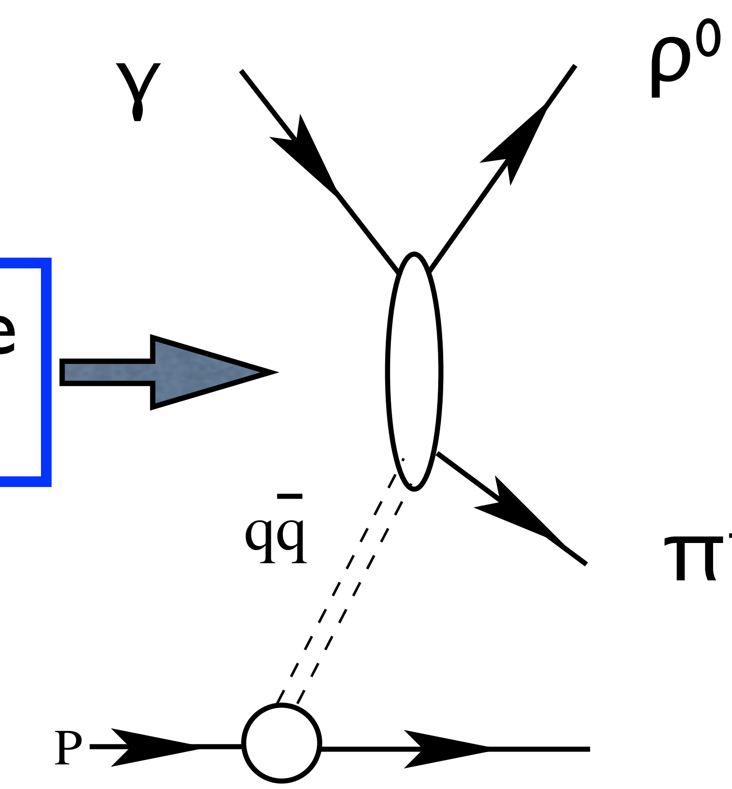
quark exchange in t -channel



$\gamma\ (\gamma^*) + p \rightarrow \rho^0\ \underbrace{\pi^+ n}$

nucleon fragmentation

vacuum exchange in t -channel



For e A collider examples of possible processes

$\gamma^* + A \rightarrow \underbrace{\pi^+ \pi^0}\ A^*$

current fragmentation

$\gamma^* + A \rightarrow \rho^0\ \underbrace{\pi^+ A^*}$

nuclear fragmentation

rapidity interval between π^+ and A regulates formation time and hence CT!!!

Study of Hidden/Intrinsic Strangeness & Charm in hadrons

$\gamma p \rightarrow M + \Lambda_{sp}$ (any other strange baryon)+ $K^+(K^*)$

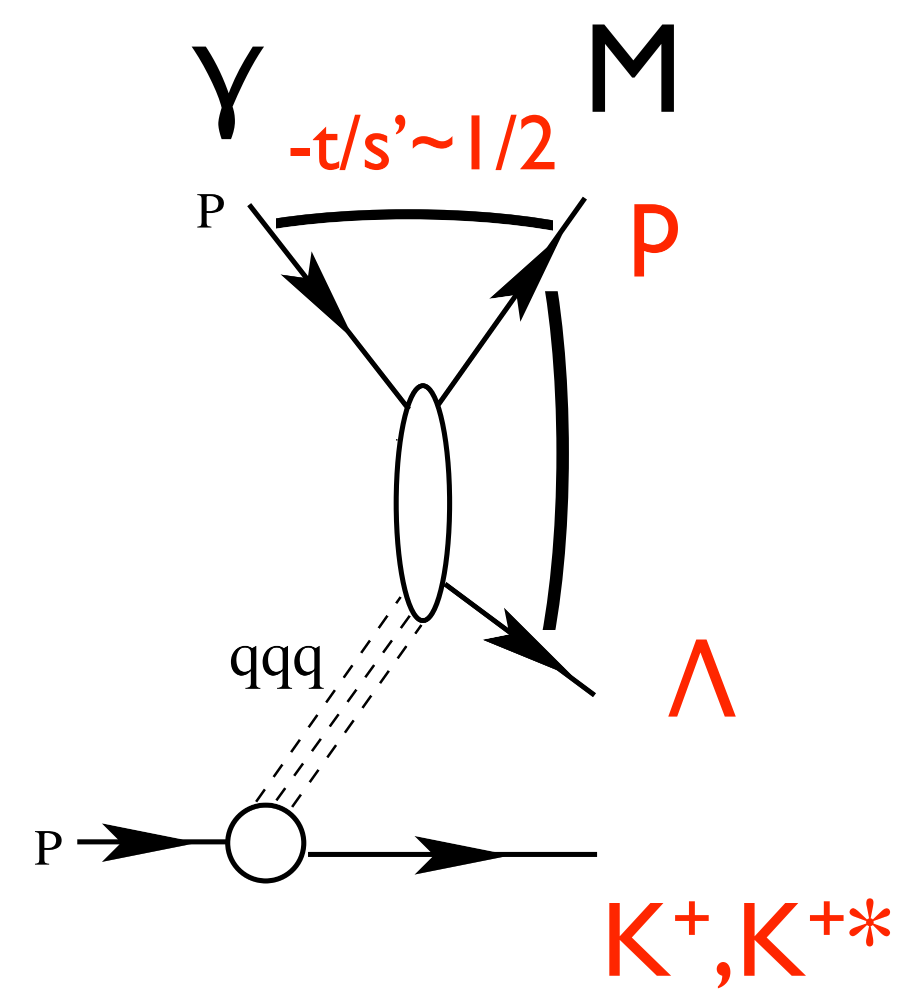
$\gamma p \rightarrow K(K^*)_{sp} + \Lambda + p$

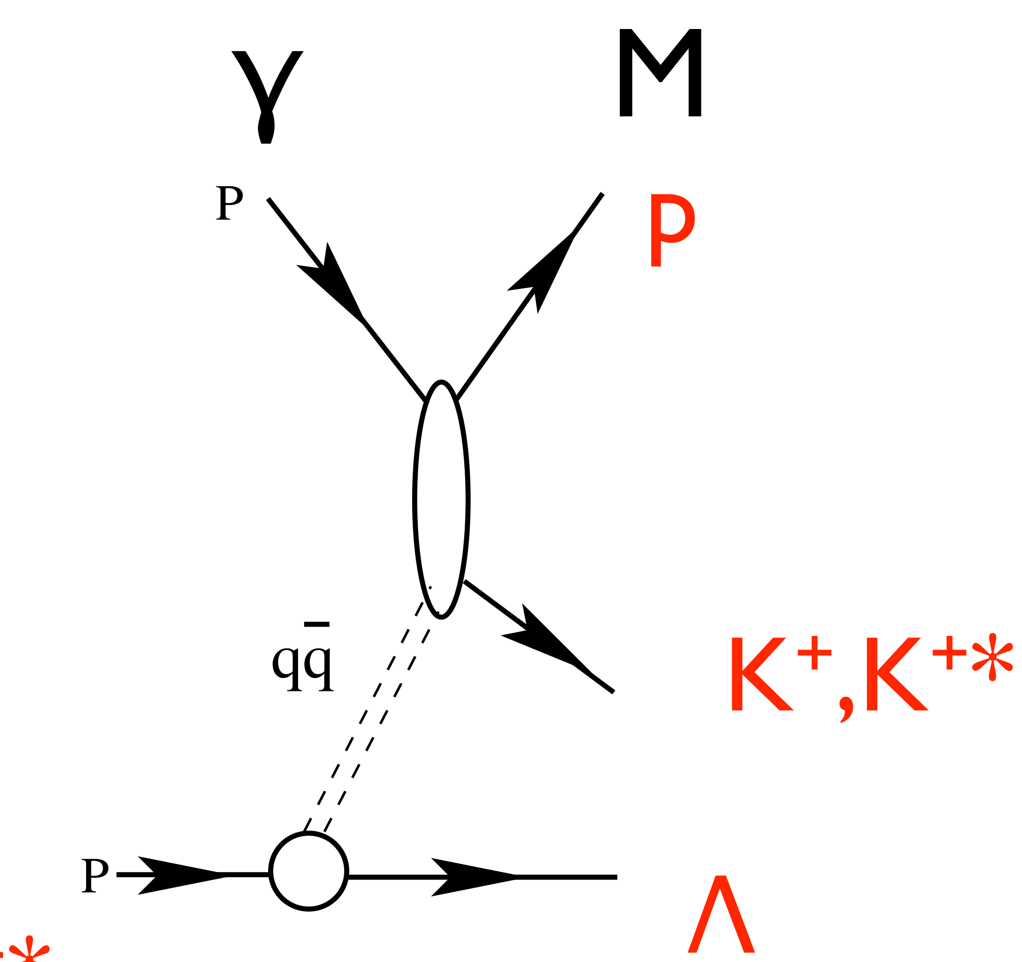
$pp \rightarrow \varphi_{sp} + p + p$

BNL experiment: EVA has few candidate events

$\gamma p \rightarrow \bar{D}_{sp} + \Lambda_c + M$

$\gamma p \rightarrow M + \bar{D}_{sp} + \Lambda_c$



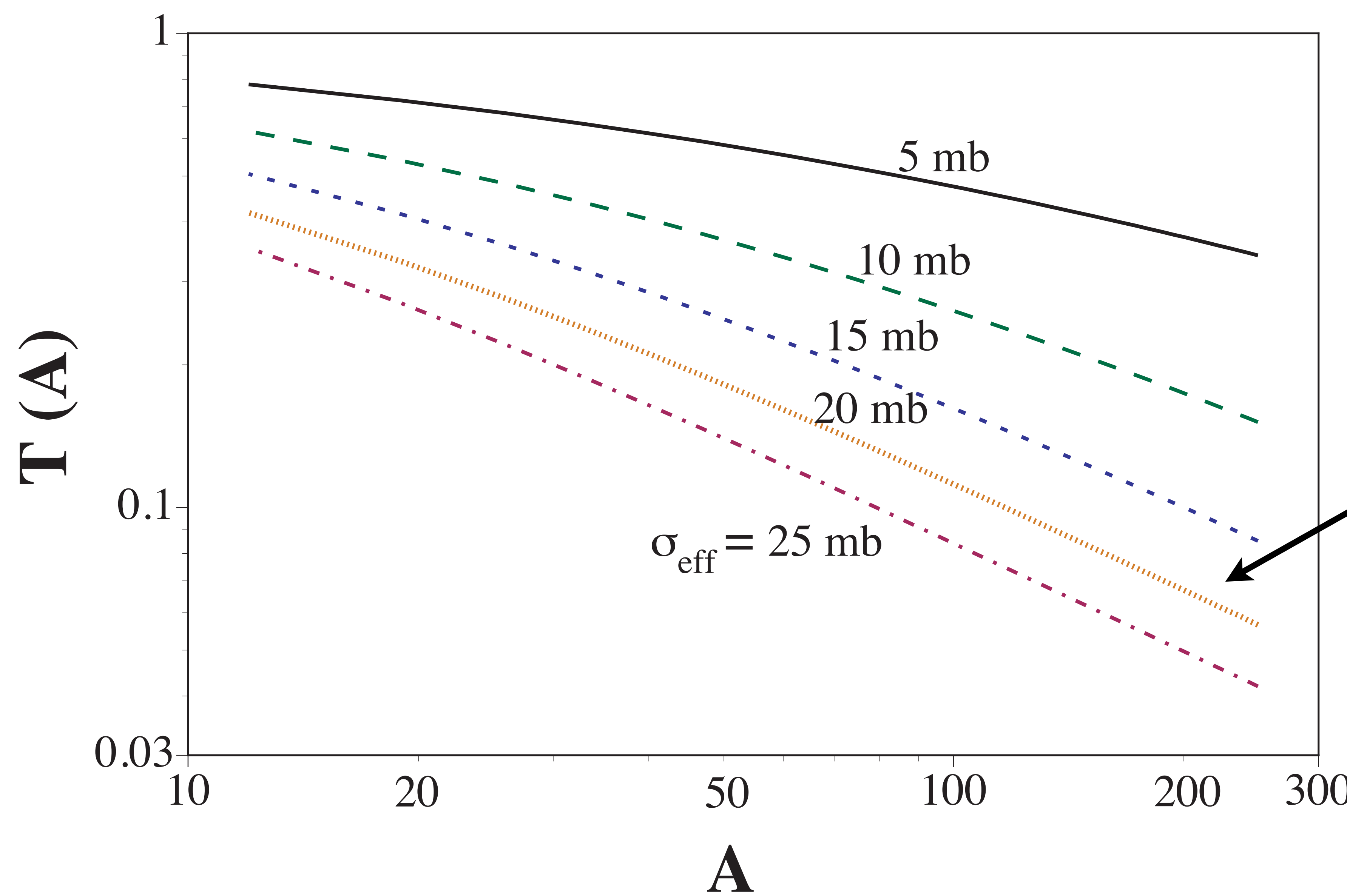


$$T_A = \frac{\frac{d\sigma(\gamma A \to \pi^- \pi^0 A^*)}{d\Omega}}{Z \frac{d\sigma(\gamma n \to \pi^- \pi^0 p)}{d\Omega}}$$

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

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 $\int \rho_A(\vec{r}) d^3 r = A$

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



Large effect even if the pion radius is changed just by 20%

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

Discussed 2 $\rightarrow$3 processes will allow

- to discover the pattern of interplay of large and small transverse distance effects (soft and hard physics) in wide range of the processes including elastic scattering, large angle two body processes
- measure a variety of GPDs including GPDs of photon
- compare wave function of different mesons
- map the space-time evolution of small wave packets at distances $1 < z < 6$ fm
- test the role of chiral degrees of freedom in hard interactions

Conclusions

- HERA left plenty of open questions related to the dynamics of exclusive VM production and characteristics of GPDs - especially the gluon GPD which dominates at small x.

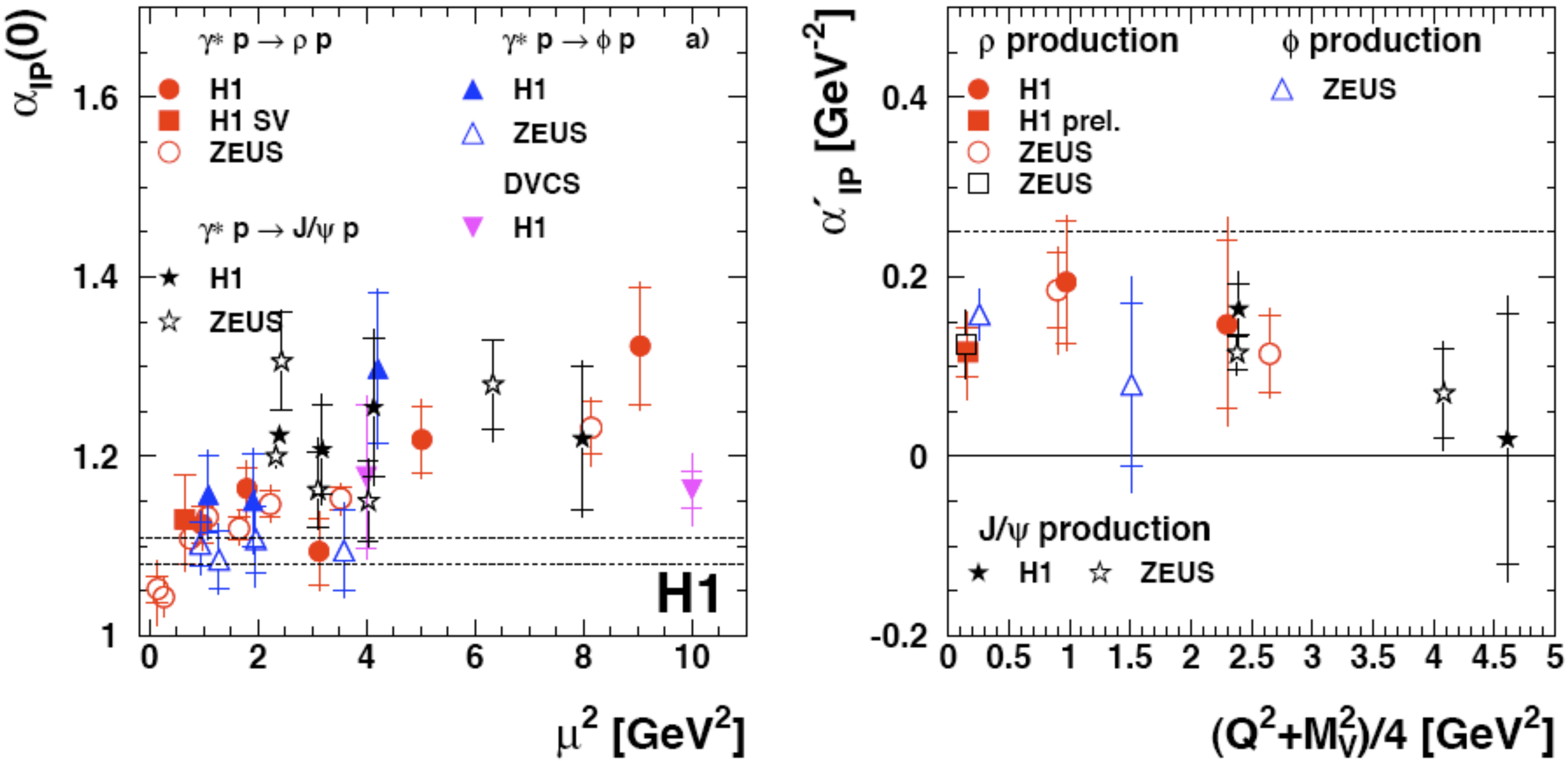
- QCD factorization theorem for exclusive processes imposes a condition on t which could be probed at given Q for the purposes of studying GPDs

- Rapidity gap processes provide tests of elastic hard scattering in QCD at large t and also serve as a new tool for studying $N \rightarrow N^*$ form factors involving gluons

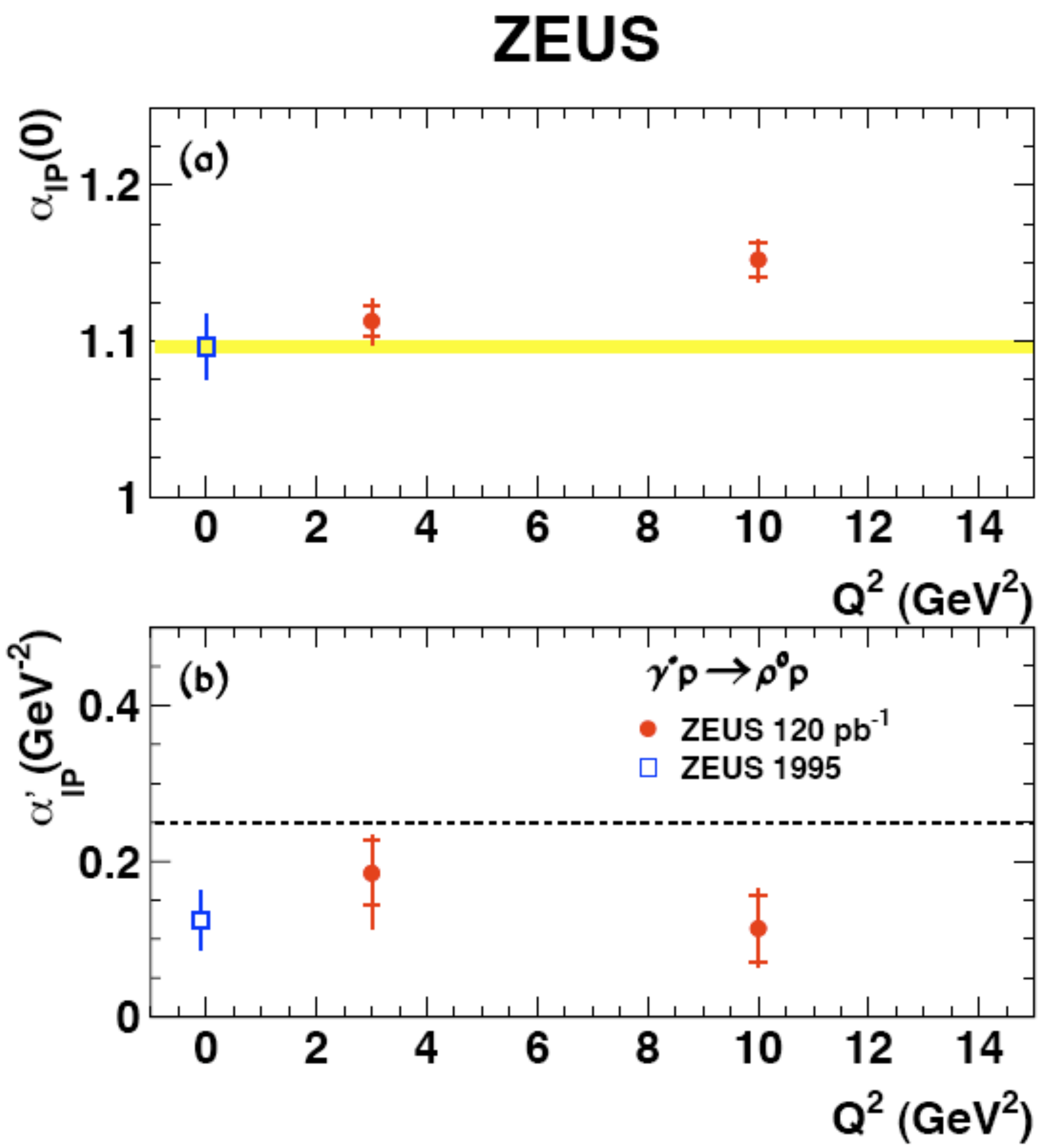
- Many novel processes in QCD not yet explored which will reveal QCD high energy dynamics and hadron structure on multiparton level

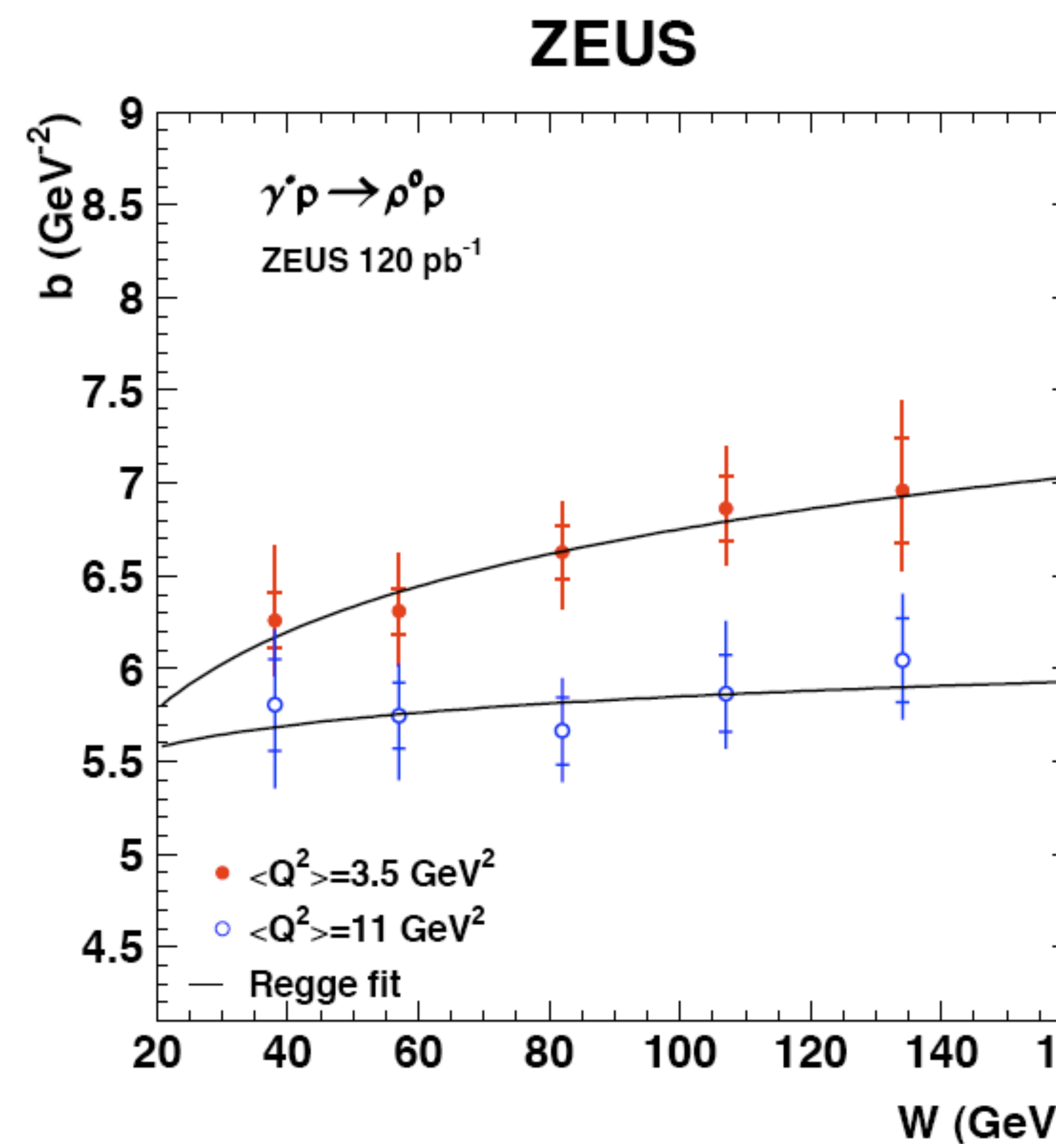
- Key for a successful experimental research in this field is a sufficiently hermetic detector in the nucleon fragmentation region.

Supplementary slides



$\mu^2 = (Q^2 + M_V^2)/4$ for VM production and $\mu^2 = Q^2$ for DVCS





$$B = B_0 + 2\alpha'_{I\!P} \ln(x_0/x)$$

Figure 23: *The parameters of the effective Pomeron trajectory in exclusive ρ^0 electroproduction, (a) $\alpha_{I\!P}(0)$ and (b) $\alpha'_{I\!P}$, as a function of Q^2. The inner error bars indicate the statistical uncertainty, the outer error bars represent the statistical and systematic uncertainty added in quadrature. The band in (a) and the dashed line in (b) are at the values of the parameters of the soft Pomeron [19, 20].*

Strength of the gluon field should depend on the size of the quark configurations - for small configurations the field is strongly screened - gluon density much smaller than average.

Do we know anything about such fluctuations?

Yes - MS + LF + C.Weiss, D.Treliani PRL 08

Consider $\gamma_L^* + p \to V + X$ for Q^2 > few GeV^2

In this limit the QCD factorization theorem (BFGMS03, CFS07) for these processes is applicable

Expand initial proton state in a set of partonic states characterized by the number of partons and their transverse positions, summarily labeled as $|n\rangle$

$$|p\rangle = \sum_n a_n |n\rangle$$

Each configuration n has a definite gluon density $G(x, Q^2| n)$ given by the expectation valu the twist--2 gluon operator in the state $|n\rangle$

$$G(x,Q^2) \;\; = \;\; \sum_n |a_n|^2 G(x,Q^2|n) \; \equiv \; \langle G \rangle$$

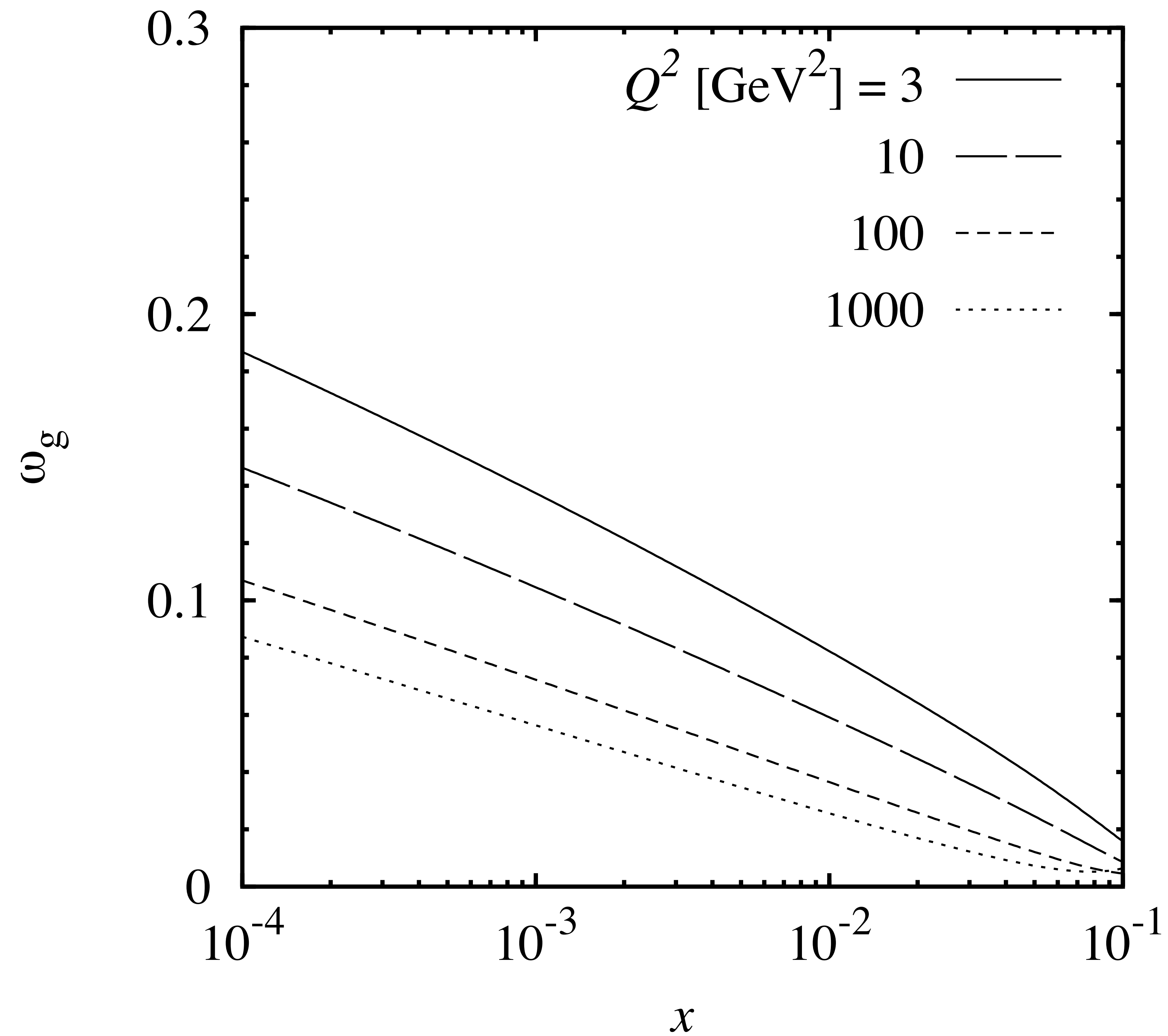
Making use of the completeness of partonic states, we find that the elastic($X = p$) and total diffractive (X arbitrary) cross sections are proportional to

$$(d\sigma_{\rm el}/dt)_{t=0} \quad \propto \quad \left[\sum_n |a_n|^2 G(x,Q^2|n)\right]^2 \equiv \langle G\rangle^2,$$

$$(d\sigma_{\rm diff}/dt)_{t=0} \quad \propto \quad \sum_n |a_n|^2 \left[G(x,Q^2|n)\right]^2 \equiv \langle G^2\rangle.$$

Hence cross section of inelastic diffraction is $\sigma_{\rm inel} = \sigma_{\rm diff} - \sigma_{\rm el}$

$$\Rightarrow \quad \boxed{\omega_g \equiv \frac{\langle G^2\rangle - \langle G\rangle^2}{\langle G\rangle^2} = \frac{d\sigma_{\gamma^*+p\to VM+X}}{dt} \Big/ \frac{d\sigma_{\gamma^*+p\to VM+p}}{dt}\Bigg|_{t=0}.}$$



The dispersion of fluctuations of the gluon density, ω_g, as a function of x for several values of Q^2, as obtained from the scaling model we developed which connects fluctuations of σ and fluctuations of color. We naturally reproduce the observed magnitude of the ratio measured experimentally at HERA.