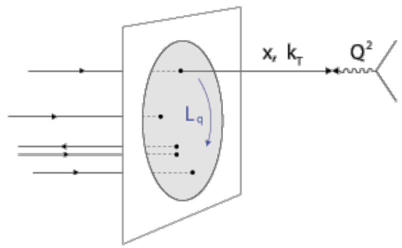
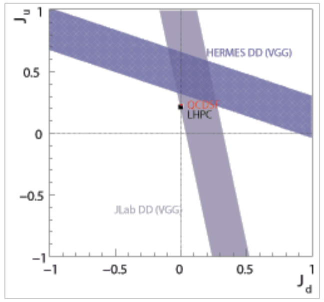
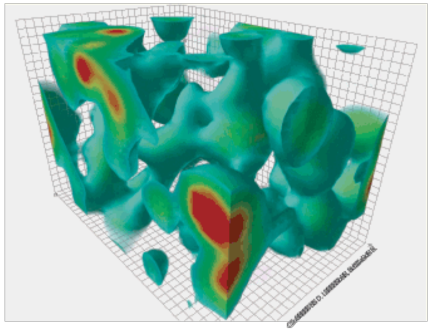
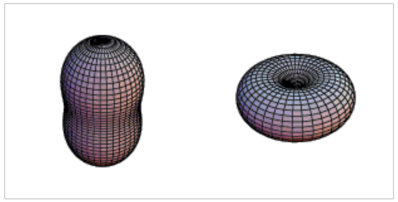








VM production and GPDs : polarization, angular momentum, ...

Marc Vanderhaeghen
Johannes Gutenberg Universität, Mainz

INT Workshop "Orbital Angular Momentum in QCD"

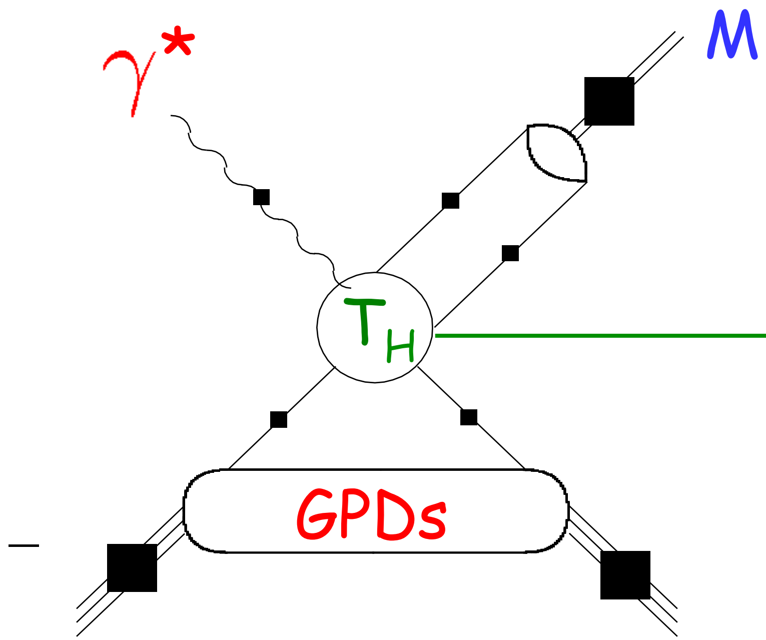
Seattle, February 6 - 17, 2012

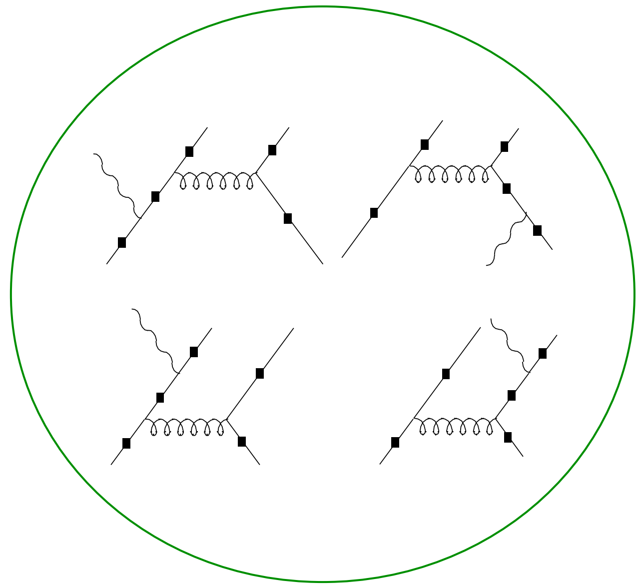
Outline

- Vector meson production in the GPD framework
- Modeling the GPD E and its connection to J_q
- Observables
- $N \rightarrow \Delta$ DVCS

Vector meson production in the GPD framework

Hard electroproduction of mesons ($\rho^{0,\pm}$, ω, φ, π, ...)





Factorization theorem shown for longitudinal photon

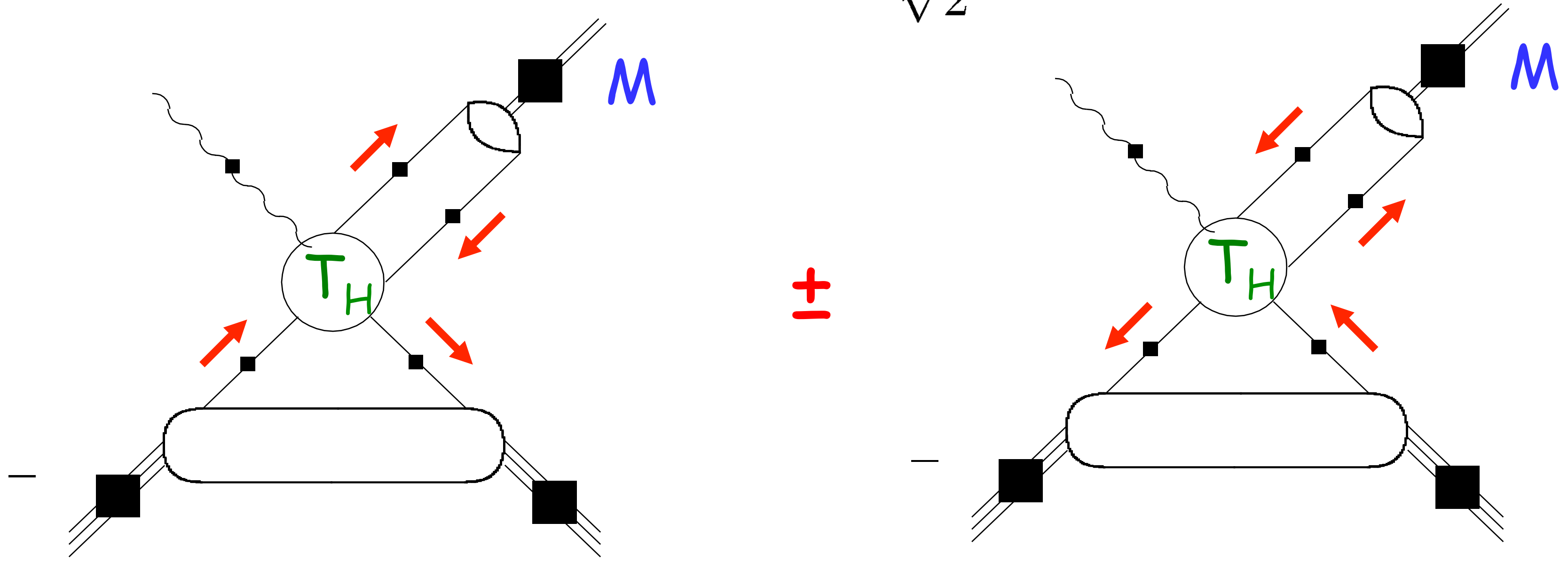
hard scattering amplitude

Collins, Frankfurt, Strikman (1997)

Meson acts as helicity filter

longitudinally pol. Vector meson $|\rho_L\rangle = \frac{1}{\sqrt{2}}|\uparrow\downarrow + \downarrow\uparrow\rangle$

PseudoScalar meson $|\pi\rangle = \frac{1}{\sqrt{2}}|\uparrow\downarrow - \downarrow\uparrow\rangle$



➡ Vector meson : accesses unpolarized GPDs H and E

➡ PseudoScalar meson : accesses polarized GPDs $\tilde{H}$ and $\tilde{E}$

Hard electroproduction of vector mesons ($\rho^{0,\pm}$, ω , φ)

- amplitude for longitudinally polarized vector meson

$$\mathcal{M}^{L}_{V_L} = -ie\,\frac{4}{9}\,\frac{1}{Q}\left[\int_0^1 dz\,\frac{\Phi_{V_L}(z)}{z}\right]\frac{1}{2}\,(4\pi\alpha_s)$$
$$\times \left\{A_{V_L N}\,\bar{N}(p')\,\gamma\cdot n\,N(p) + B_{V_L N}\,\bar{N}(p')\,i\sigma^{\kappa\lambda}\frac{n_\kappa\Delta_\lambda}{2\,m_N}\,N(p)\right\}$$

- leading (1 gluon exchange) amplitude depends on α_s goes as 1/Q

- dependence on meson distribution amplitude Φ_V

$$\Phi_{V_L}(z) = f_V\,6\,z\,(1-z)$$
$$\text{with}\quad f_\rho = 0.216\ \text{GeV},\quad f_\omega = 0.195\ \text{GeV},\quad \text{from}\quad V \to e^+e^-$$

Mankiewicz, Piller, Weigl (1998) Vdh, Guichon, Guidal (1998)

Flavor decomposition of GPDs H and E

ρ^0

$$A_{\rho^0_L\, p} = \int_{-1}^{1} dx \; \frac{1}{\sqrt{2}} \left(e_u \; H^u \; - \; e_d \; H^d \right) \; \left\{ \frac{1}{x - \xi + i\epsilon} + \frac{1}{x + \xi - i\epsilon} \right\}$$

$$B_{\rho^0_L\, p} = \int_{-1}^{1} dx \; \frac{1}{\sqrt{2}} \left(e_u \; E^u \; - \; e_d \; E^d \right) \; \left\{ \frac{1}{x - \xi + i\epsilon} + \frac{1}{x + \xi - i\epsilon} \right\}$$

$\rho^\pm$

$$A_{\rho^+_L\, n} = - \int_{-1}^{1} dx \; \left(H^u \; - \; H^d \right) \; \left\{ \frac{e_u}{x - \xi + i\epsilon} + \frac{e_d}{x + \xi - i\epsilon} \right\}$$

$$B_{\rho^+_L\, n} = - \int_{-1}^{1} dx \; \left(E^u \; - \; E^d \right) \; \left\{ \frac{e_u}{x - \xi + i\epsilon} + \frac{e_d}{x + \xi - i\epsilon} \right\}$$

ω

$$A_{\omega_L\, p} = \int_{-1}^{1} dx \; \frac{1}{\sqrt{2}} \left(e_u \; H^u \; + \; e_d \; H^d \right) \; \left\{ \frac{1}{x - \xi + i\epsilon} + \frac{1}{x + \xi - i\epsilon} \right\}$$

$$B_{\omega_L\, p} = \int_{-1}^{1} dx \; \frac{1}{\sqrt{2}} \left(e_u \; E^u \; + \; e_d \; E^d \right) \; \left\{ \frac{1}{x - \xi + i\epsilon} + \frac{1}{x + \xi - i\epsilon} \right\}$$

Modeling the GPD E
and
its connection to J_q

GPDs : t dependence (small -t)

$$F_1^q(t) = \int_{-1}^{1} dx\, H^q(x,\xi,t) \qquad F_2^q(t) = \int_{-1}^{1} dx\, E^q(x,\xi,t)$$

evaluate for ξ = 0 : model $H^q(x,0,t)$ and $E^q(x,0,t)$

small -t (-t < 1 GeV^2) : Regge model Goeke, Polyakov, Vdh (2001)

- t = 0 : $H^q(x,0,0) + H^q(-x,0,0) = q_v(x) \sim \frac{1}{x^{\alpha(0)}}$ $\quad \alpha(0) \simeq 0.5$
- t ≠ 0 : $H^q(x,0,t) + H^q(-x,0,t) \sim \frac{1}{x^{\alpha(t)}}$ $\quad \alpha(t) = \alpha(0) + \alpha' t$

Regge trajectory $\alpha' \simeq 0.9\ \mathrm{GeV}^{-2}$

$$\boxed{F_1^q(t) = \int_0^1 dx\, q_v(x) \frac{1}{x^{\alpha_1' t}} \qquad F_2^q(t) = \int_0^1 dx\, \kappa_q\, q_v(x) \frac{1}{x^{\alpha_2' t}}}$$

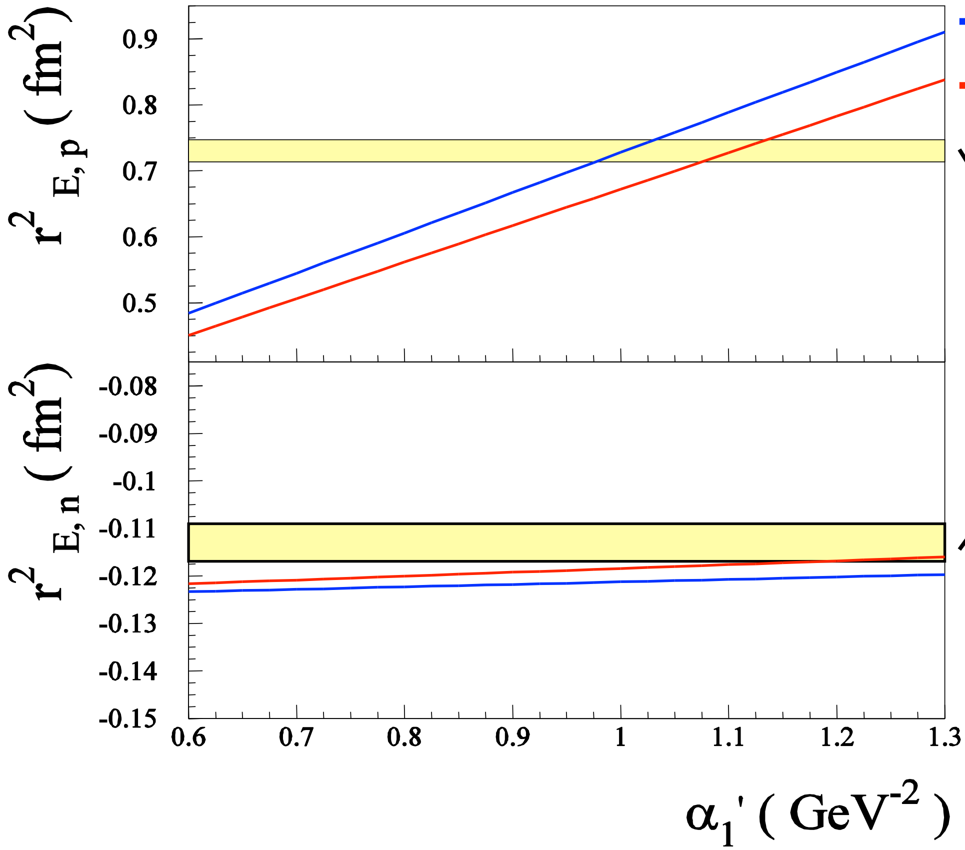
regge slopes : $\alpha_1^{'}$, $\alpha_2^{'}$ determined from rms radii

valence model for E

proton & neutron charge radii

$$r^2_{E,p} = r^2_{1,p} + \frac{3}{2}\frac{\kappa_p}{M_N^2} \qquad r^2_{1,p} = -6\,\alpha_1' \int_0^1 dx \left\{ e_u\, u_v(x) + e_d\, d_v(x) \right\} \ln x$$

$$r^2_{E,n} = r^2_{1,n} + \frac{3}{2}\frac{\kappa_n}{M_N^2} \qquad r^2_{1,n} = -6\,\alpha_1' \int_0^1 dx \left\{ e_u\, d_v(x) + e_d\, u_v(x) \right\} \ln x$$



Regge model

modified Regge model

experiment

consistent with slopes of meson Regge trajectories (~ 0.9 GeV^{-2})

Regge slope

GPDs : t dependence (large -t)

modified Regge parametrization : Guidal, Polyakov, Radyushkin, Vdh (2005)

$$
\begin{aligned}
H^q(x,0,t) &= q_v(x)\, x^{-\alpha_1'\,(1-x)\,t} \\
E^q(x,0,t) &= \frac{\kappa_q}{N_q}\,(1-x)^{\eta_q}\, q_v(x)\, x^{-\alpha_2'\,(1-x)\,t}
\end{aligned}
$$

- Input : forward parton distributions at μ^2 = 1 GeV^2 (MRST2002 NNLO)
- Drell-Yan-West relation : exp(- α´ t) -> exp(- α´ (1 - x) t) Burkardt (2001)
- parameters :

  regge slopes : α_1', α_2' determined from rms radii

  η_u , η_d determined from F_2 / F_1 at large -t
- future constraints : moments from lattice QCD

connection large Q^2 of FF <-> large x of GPD

$$I = \int_0^1 dx (1-x)^\nu \, e^{\alpha' Q^2 (1-x) \ln x} = \int_0^1 dx e^{\nu \ln(1-x) + \alpha' Q^2 (1-x) \ln x}$$

$$= \int_0^1 dx \, e^{f(x, Q^2)}$$

at large Q^2 : integral dominated by maximum of $f(x,Q^2)$, remainder region is exp. suppressed (method of steepest descent)

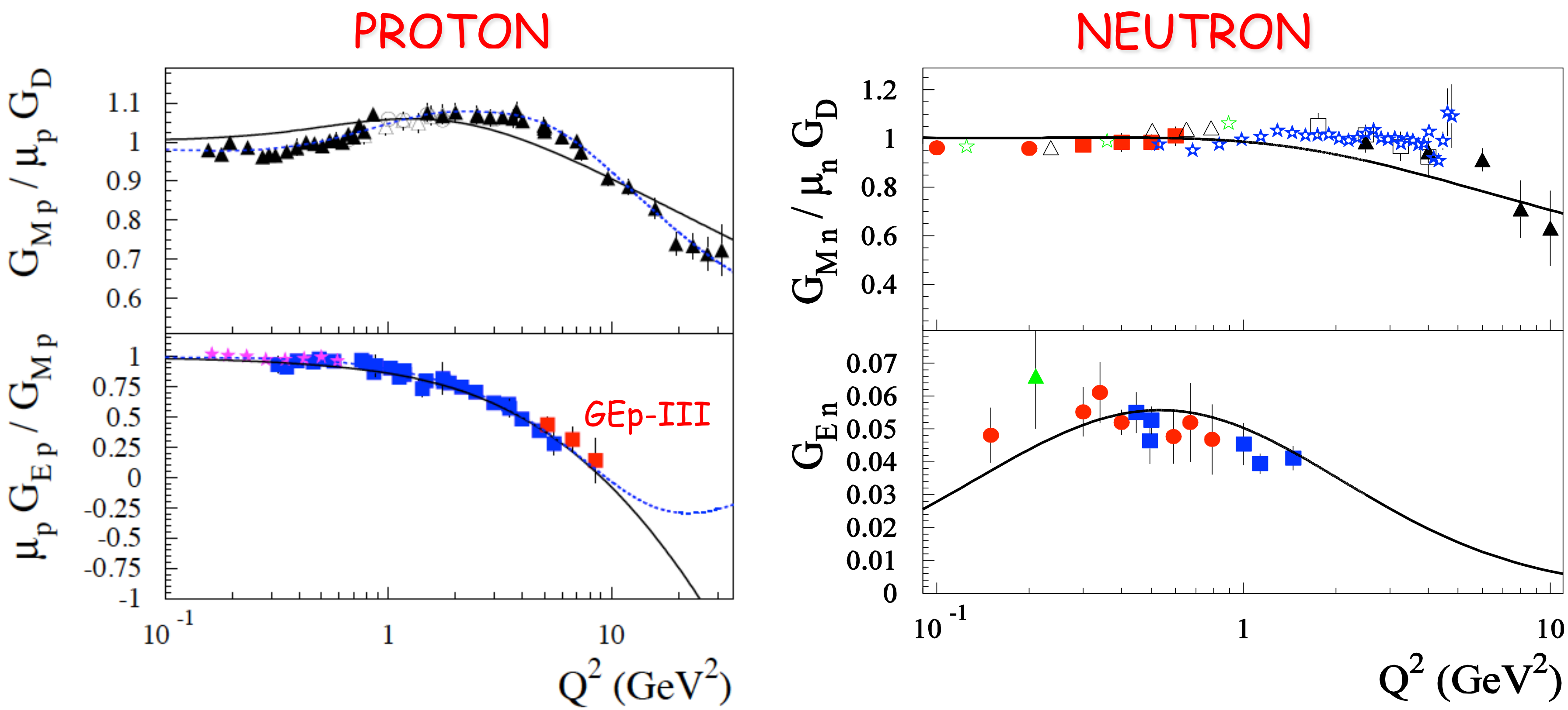
$f(x,Q^2)$ reaches maximum for : $x = x_0 \simeq 1 - \dfrac{\nu}{\alpha' Q^2}$

"Drell-Yan-West" relation for PDF/GPD :

at large Q^2 : I is dominated by its behavior around x -> 1

$$\boxed{I \simeq e^{f(x_0, Q^2)} \left(\frac{2}{f''(x_0, Q^2)} \right)^{1/2} \frac{\sqrt{\pi}}{2} \sim \left(\frac{1}{\alpha' Q^2} \right)^{(\nu+1)/2}}$$

Nucleon electromagnetic form factors



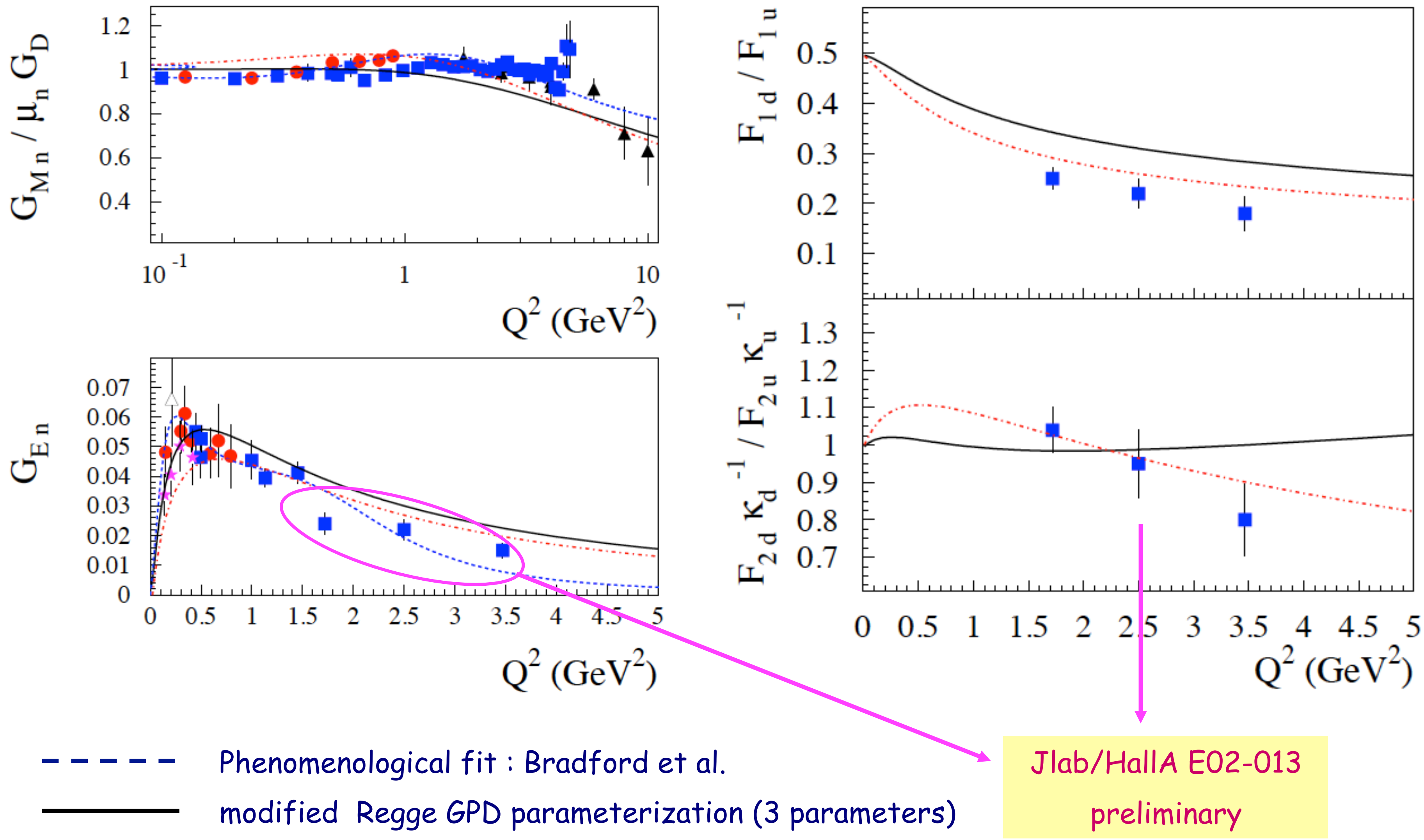
→ modified Regge GPD parameterization

3-parameter fit
- 1 : Regge slope -> proton Dirac (Pauli) radius
- 2, 3 : large x behavior of GPD E^u, E^d -> large Q^2 behavior of F2p, F2n

Guidal, Polyakov, Radyushkin, Vdh (2005)

also Diehl, Feldmann, Jakob, Kroll (2005)

neutron e.m. form factors

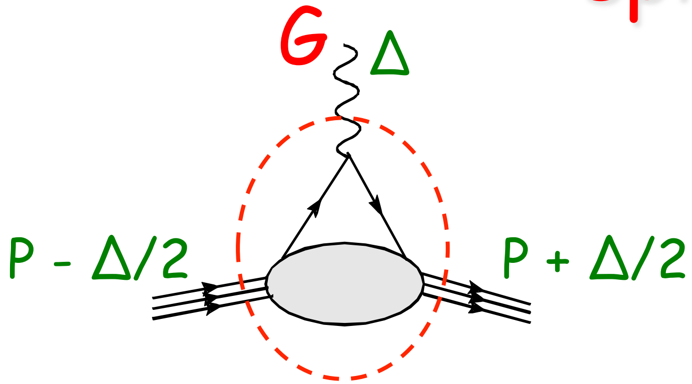


Phenomenological fit : Bradford et al.

modified Regge GPD parameterization (3 parameters)

modified Regge GPD parameterization (6 parameters)

Energy momentum form factors / spin of nucleon



nucleon in external classical gravitational field

⇨ G couples to energy-momentum tensor

$$(\mu,\nu) \equiv \frac{1}{2}(\mu\nu + \nu\mu)$$

$$\langle N \,|\, T^{\mu\nu}(0) \,|\, N\rangle$$
$$= \bar{N}\left\{ A(t)\,\gamma^{(\mu}P^{\nu)} + B(t)\,P^{(\mu}i\sigma^{\nu)\alpha}\frac{\Delta_\alpha}{2\,M} + C(t)\,\left(\Delta^\mu\Delta^\nu - \Delta^2 g^{\mu\nu}\right)\frac{1}{M}\right\} N$$

➡ link to GPDs :

X. Ji (1997)

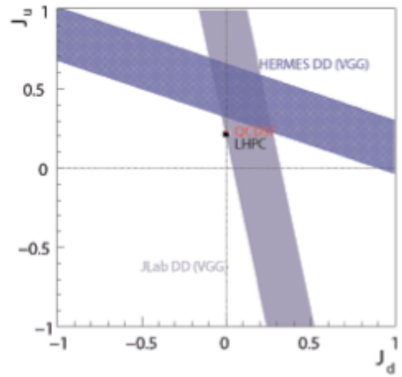
$$\int_{-1}^{1} dx\, x\, H(x,\xi,t) \;=\; A(t) + 4\,\xi^2\, C(t)$$

$$\int_{-1}^{1} dx\, x\, E(x,\xi,t) \;=\; B(t) - 4\,\xi^2\, C(t)$$

➡ SPIN "relation"

$$\boxed{\int_{-1}^{1} dx\, x\left\{ H^q(x,\xi,0) + E^q(x,\xi,0)\right\} = A(0) + B(0) = 2\,J^q}$$

quark contribution to proton spin



$$2\,J^q = \int_{-1}^{1} dx\, x \left\{ H^q(x,0,0) + E^q(x,0,0) \right\}$$

X. Ji (1997)

$$\boxed{2\,J^q = M_2^q + \int_{-1}^{1} dx\, x\, E^q(x,0,0)}$$ with $M_2^q = \int_0^1 dx\, x\, [q(x) + \bar{q}(x)]$

parametrizations for E^q : $E^q(x,0,0) = \kappa_q / N_q\,(1-x)^{\eta_q}\, q_v(x)$

PROTON	M_2^q	$2\,J^q$ GPD valence model	$2\,J^q$ Lattice (LHPC) (4 GeV²)
u	0.37	0.58	≈ 0.47
d	0.20	-0.06	≈ 0.00
s	0.04	0.04	
u + d + s	**0.61**	**0.56**	

GPD model (μ^2 = 2 GeV²)

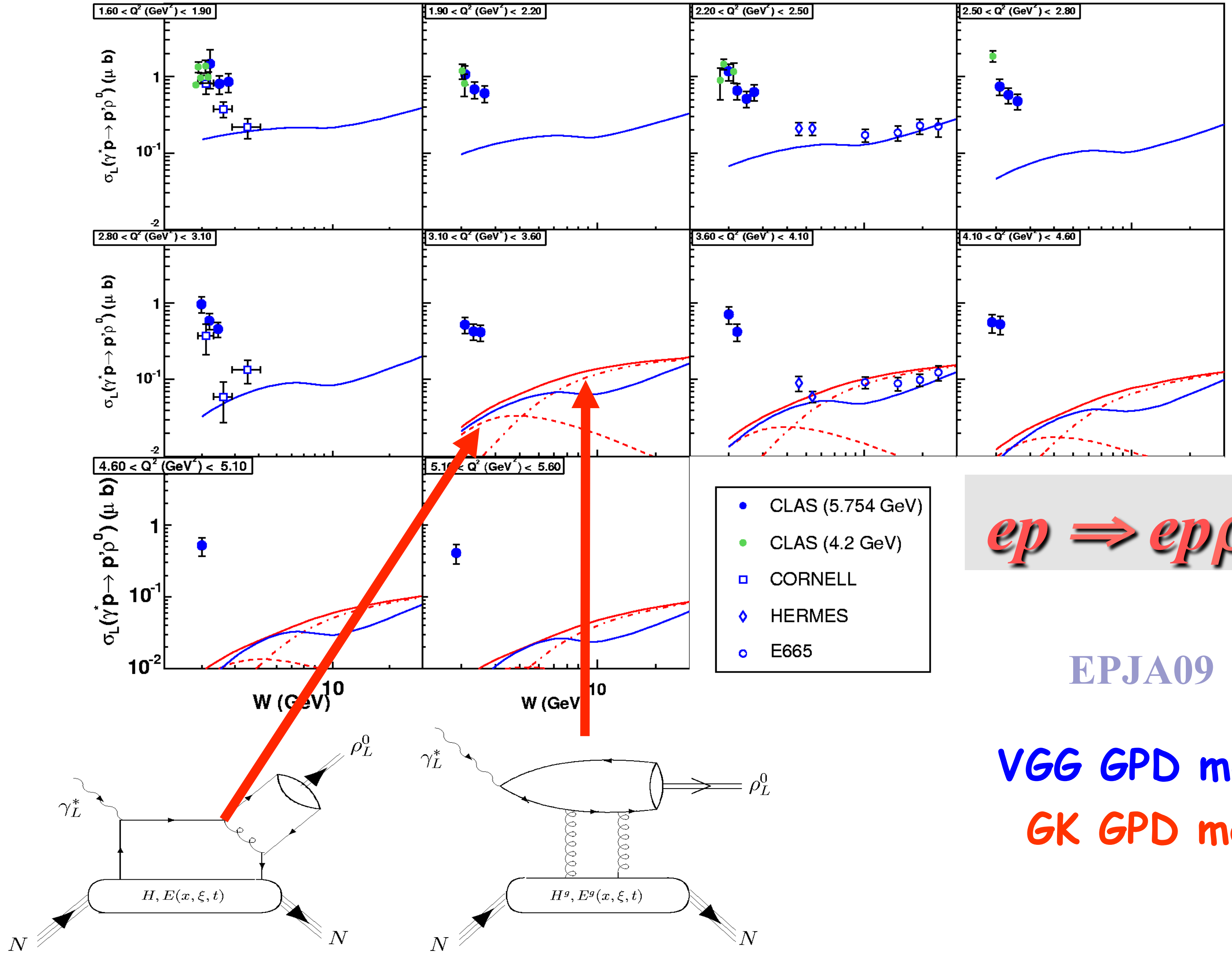
Goeke, Polyakov, Vdh (2001)

lattice : full QCD,

no disconnected diagrams so far

Observables

Hard electroproduction of ρ^0 : cross sections

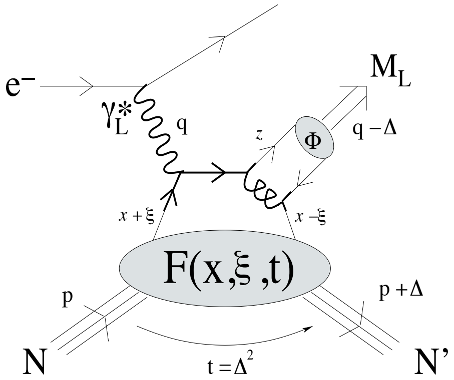


$ep \Rightarrow ep\rho^0$

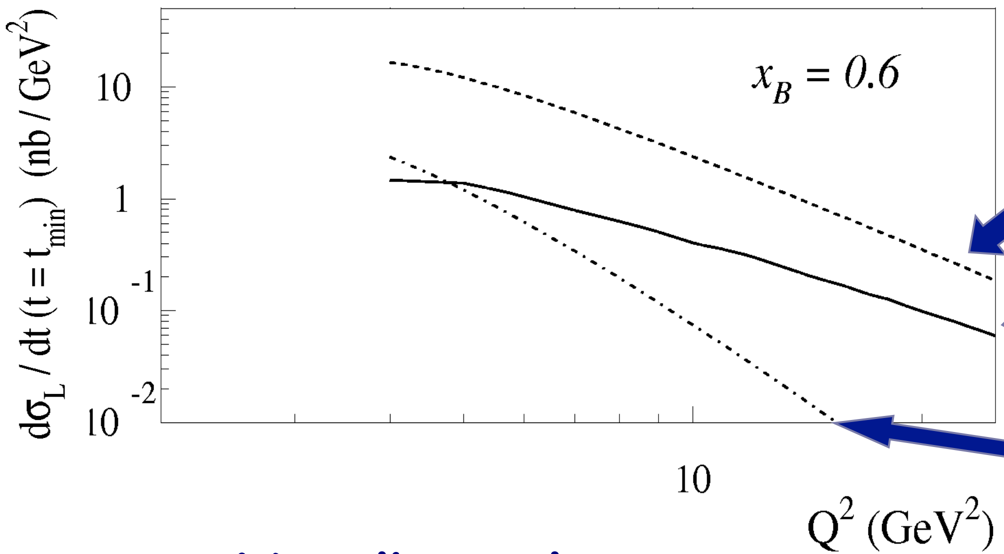
EPJA09

VGG GPD model

GK GPD model



Interpretation in terms of GPDs ?

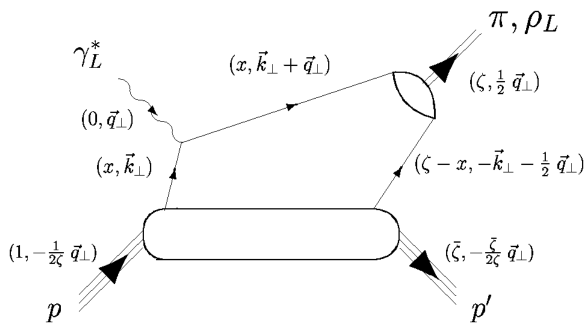


LO (w/o kperp effect)

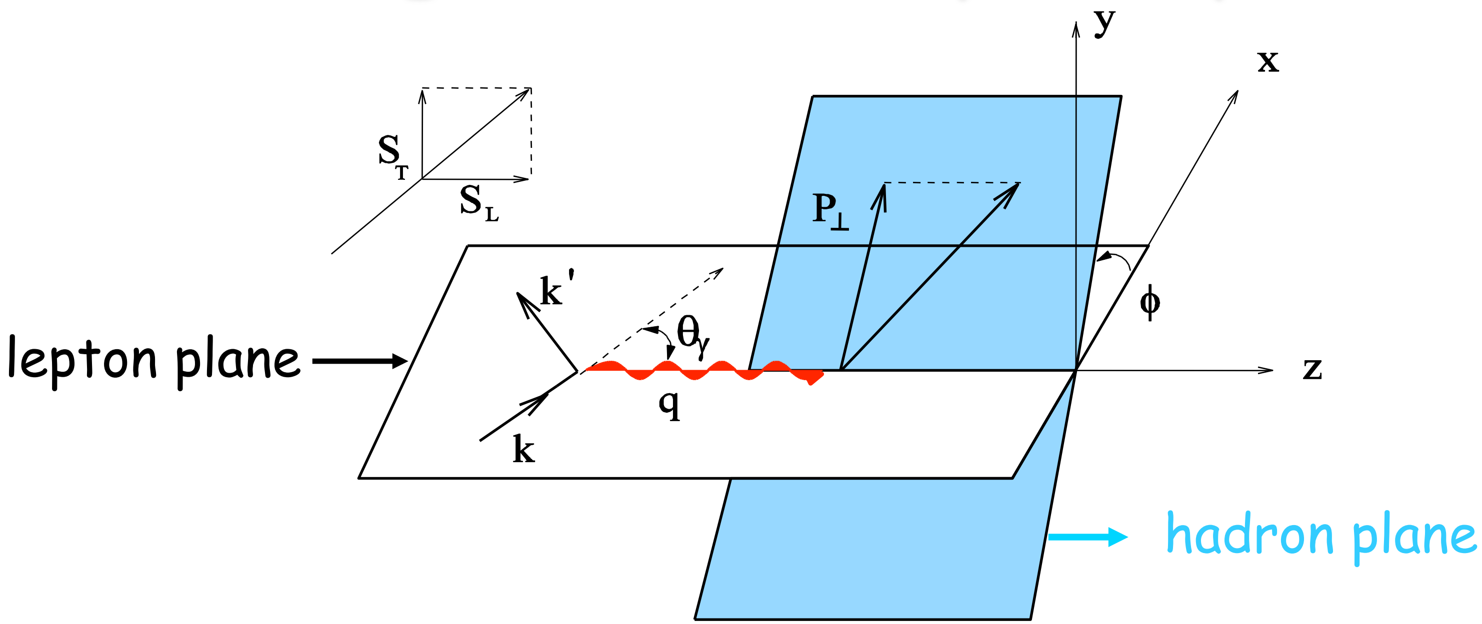
with kperp effect

Soft overlap

Handbag diagram calculation requires large correction factors



Hard electroproduction of mesons : target normal spin asymmetry



in leading order (in Q) ➡ 2 observables $\sigma = \sigma_L + P_n \, \sigma_L^n$

➡ Asymmetry : $\boxed{\mathcal{A} = \dfrac{2\,\sigma_L^n}{\pi\,\sigma_L}}$

P_n: Target polarization normal to hadron plane

Hard electroprod. of vector mesons : target normal spin asymmetry

$$\mathcal{A}_{V_L N} = -\frac{2\,|\Delta_\perp|}{\pi} \times \frac{\mathrm{Im}(AB^*)\,/\,m_N}{|A|^2\,(1-\xi^2) - |B|^2\,\left(\xi^2 + t/(4m_N^2)\right) - \mathrm{Re}(AB^*)\,2\,\xi^2}$$

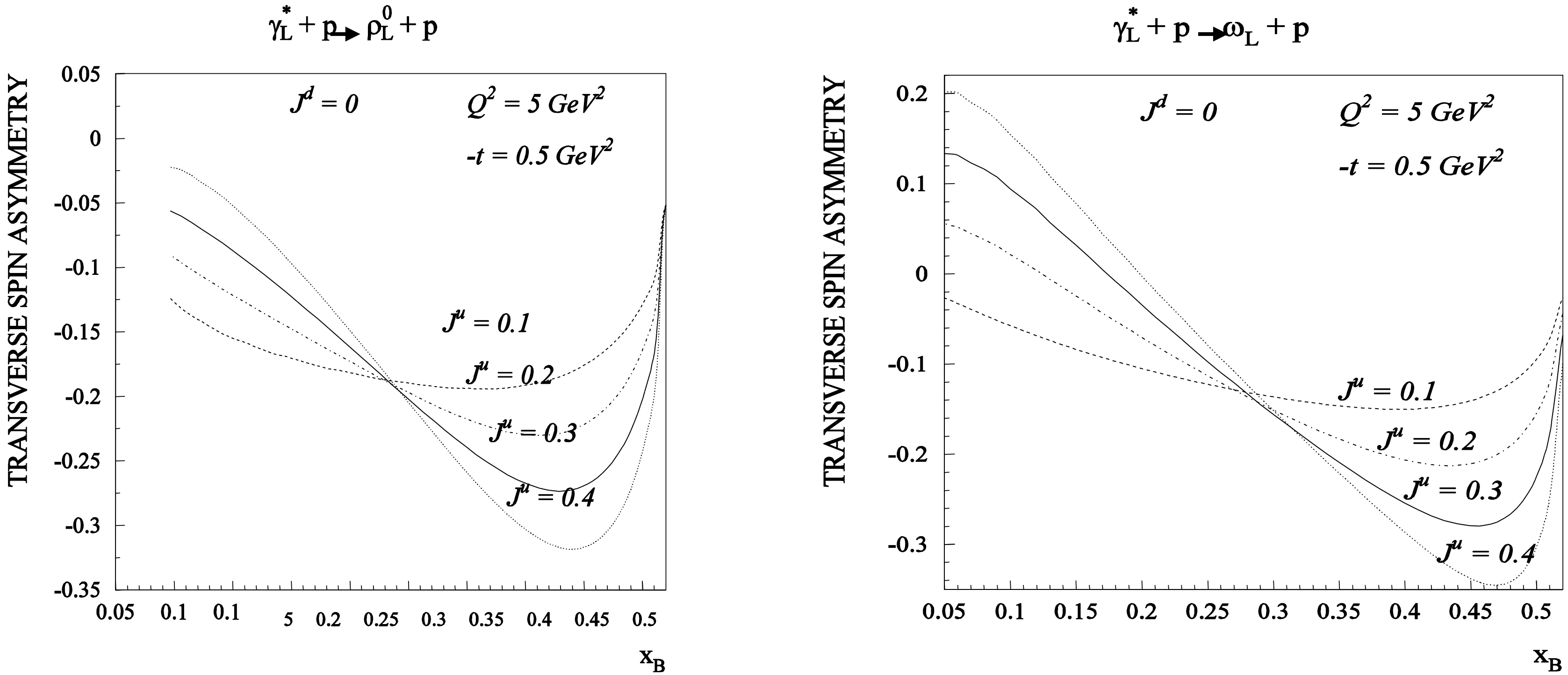
- A $\longrightarrow$ GPD H B $\longrightarrow$ GPD E
- linear dependence on GPD E $\longleftrightarrow$ unpolarized cross section
- ratio : less sensitive to NLO and higher twist effects
- sensitivity to J^u and J^d

measure of TOTAL angular momentum contribution to proton spin

Goeke, Polyakov, Vdh (2001)

Hard electroprod. of vector mesons : target normal spin asymmetry

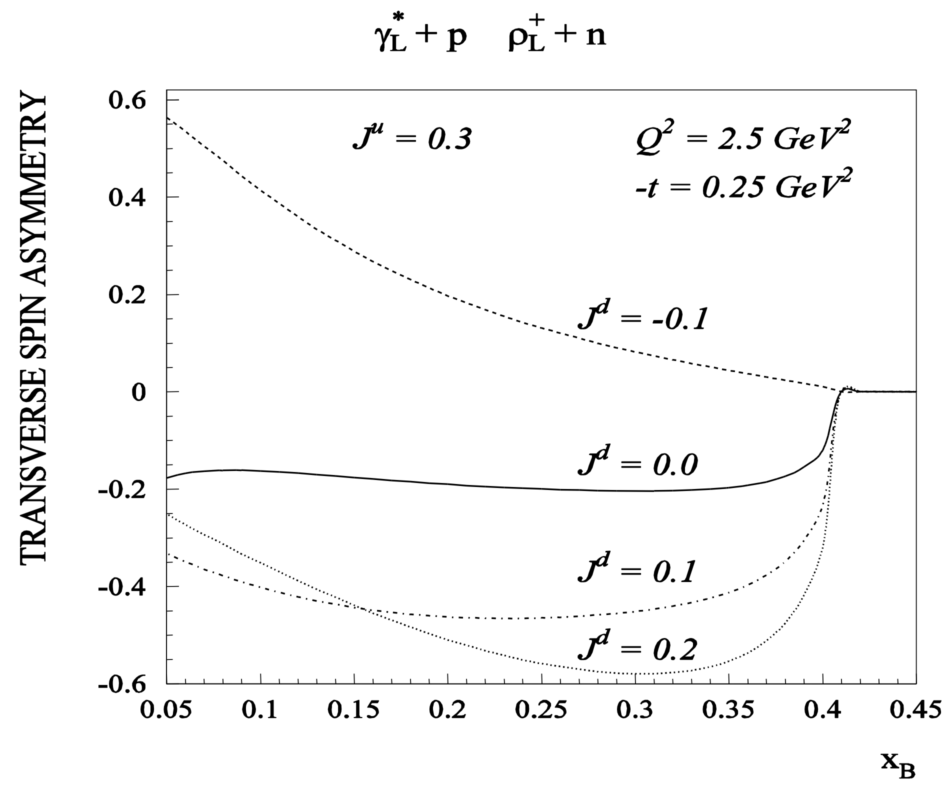
target polarized normal to hadronic plane



ρ^0_L sensitive to (2 J^u + J^d)

ω_L sensitive to (2 J^u - J^d)

Hard electroprod. of vector mesons : target normal spin asymmetry



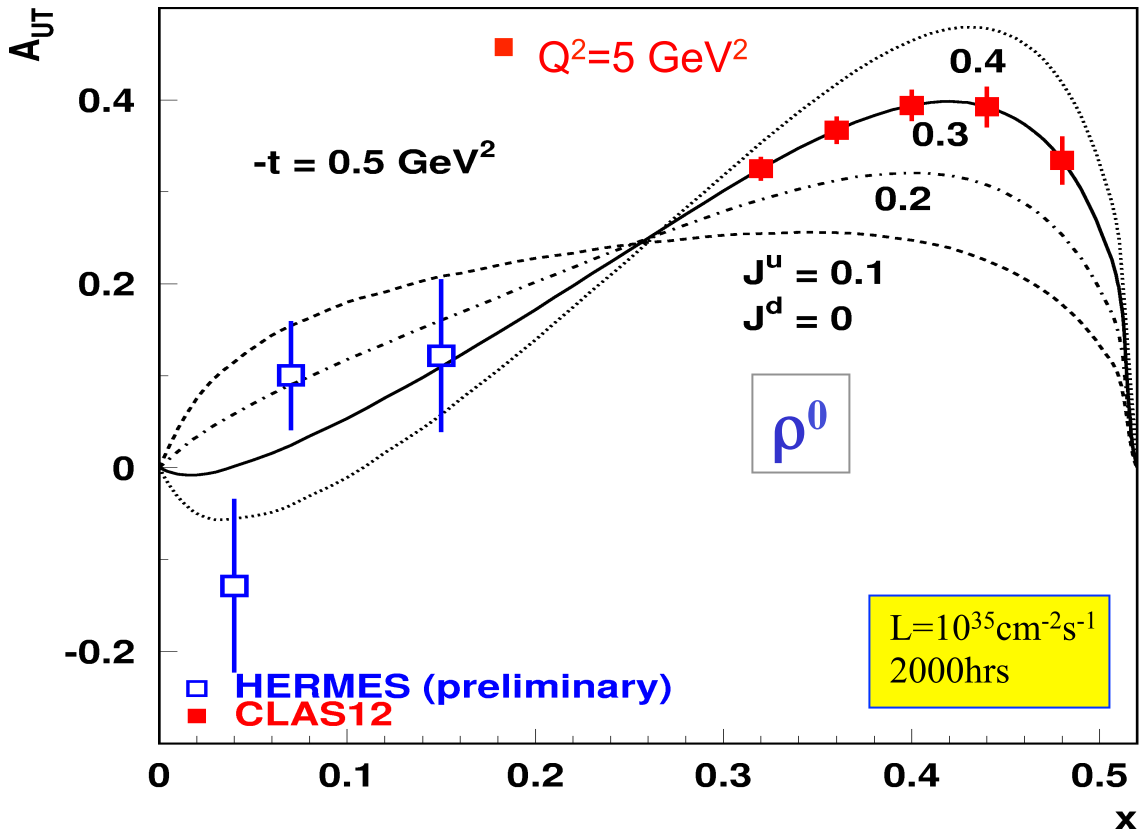
ρ^+_L sensitive to (J^u - J^d)

exclusive ρ^0 prod. with transverse target

$$A_{UT} = -\frac{2\Delta\,(\mathrm{Im}(AB^*))/\pi}{|A|^2(1-\xi^2) - |B|^2(\xi^2+t/4m^2) - \mathrm{Re}(AB^*)2\xi^2}$$

ρ^0

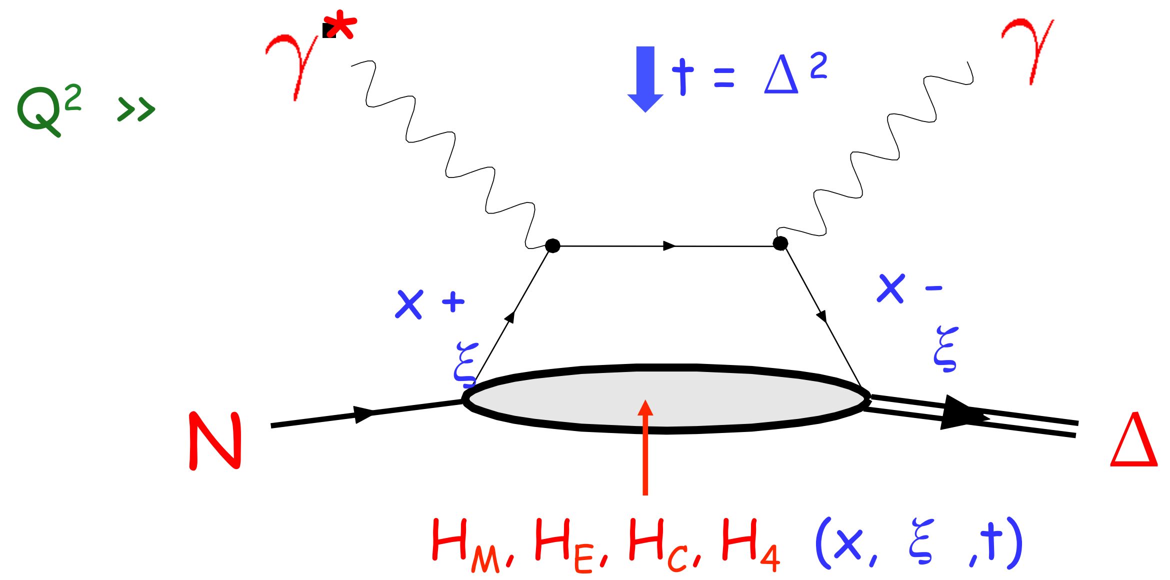
$A \sim (2H^u + H^d)$
$B \sim (2E^u + E^d)$



Asymmetry depends linearly on the GPD E, which enters Ji's sum rule.

N -> Δ DVCS

$N \to \Delta$ DVCS and GPDs



low –t process :
-t << Q^2

$$\int_{-1}^{1} dx\, H_M(x,\xi,t) = 2\, G_M^*(t)$$
$$\int_{-1}^{1} dx\, H_E(x,\xi,t) = 2\, G_E^*(t)$$
$$\int_{-1}^{1} dx\, H_C(x,\xi,t) = 2\, G_C^*(t)$$
$$\int_{-1}^{1} dx\, H_4(x,\xi,t) = 0$$

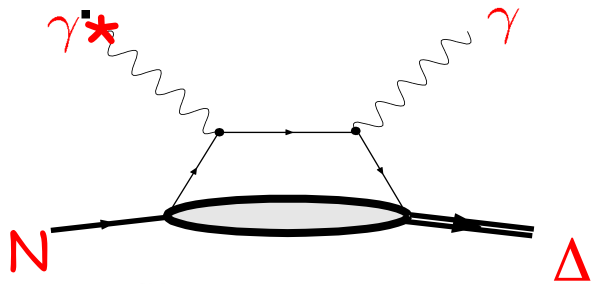
Jones-Scadron

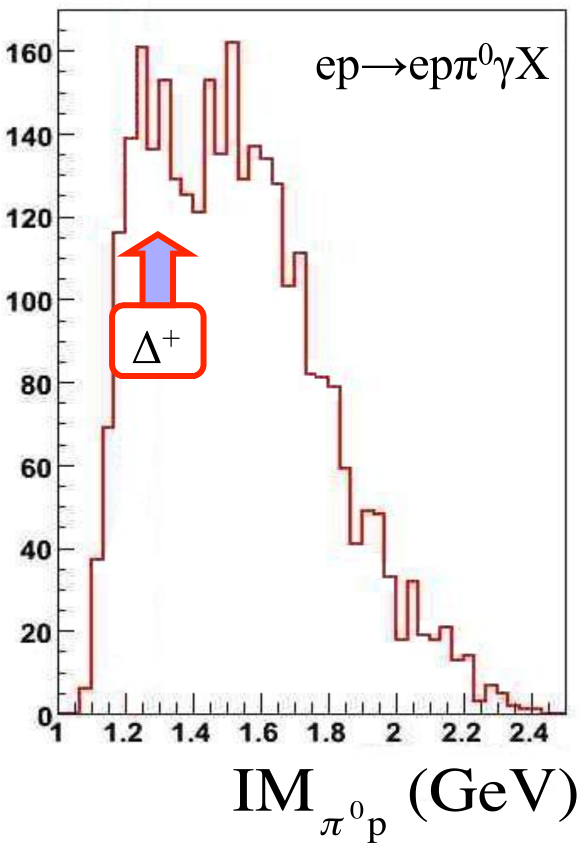
$N \to \Delta$ form factors

N -> Δ DVCS events in CLAS

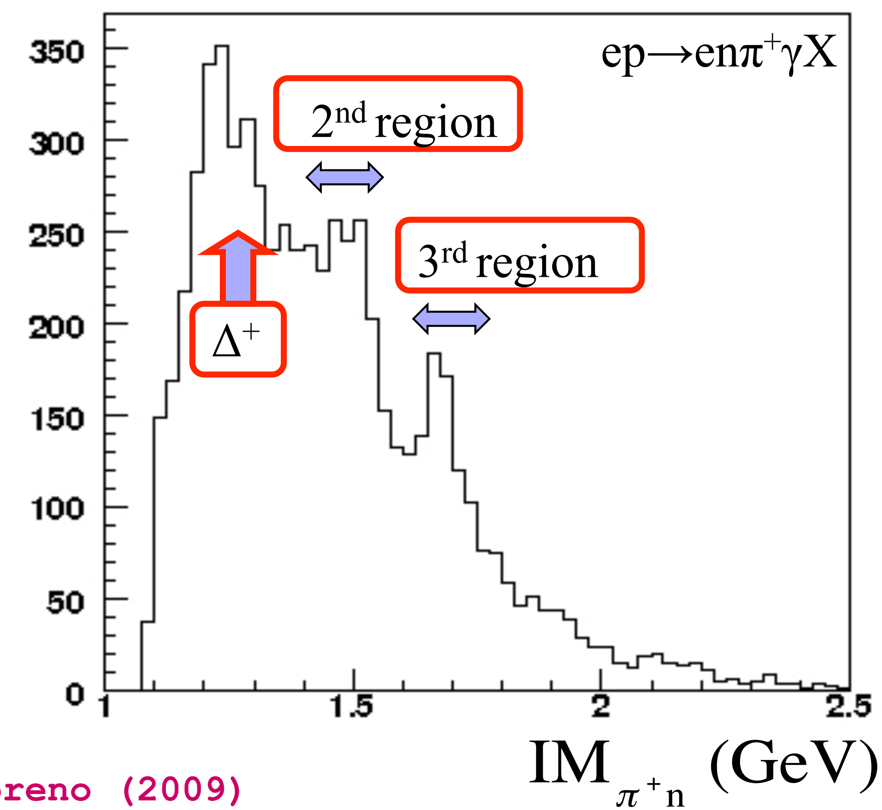
W > 2 GeV

$Q^2 \approx 2.5\ GeV^2$





Moreno (2009)



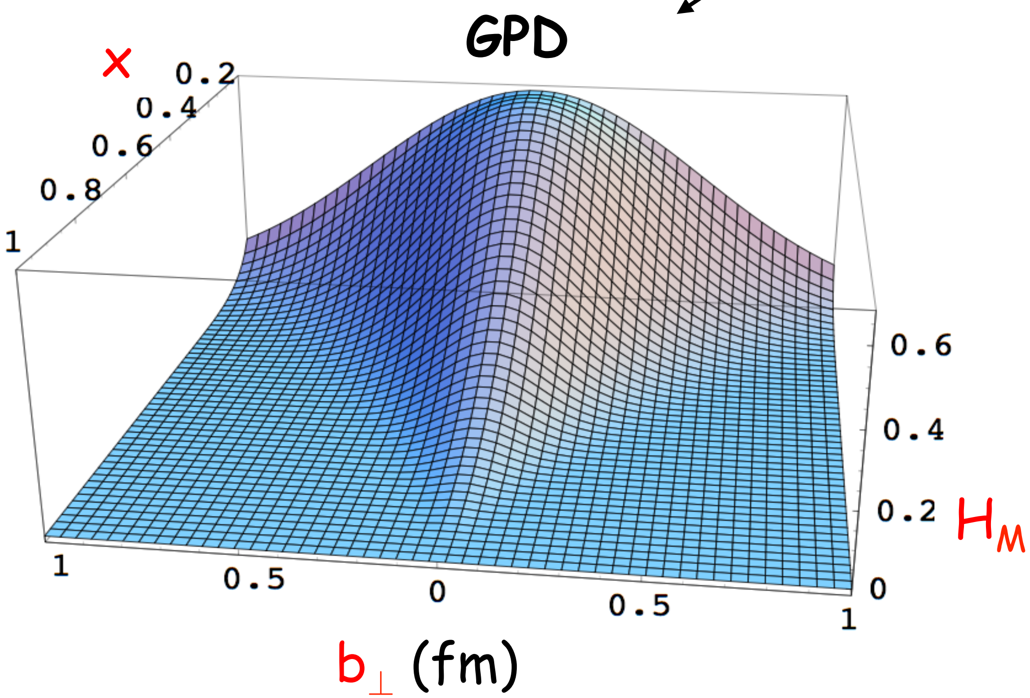
$N \to \Delta$ magnetic dipole GPD and FF

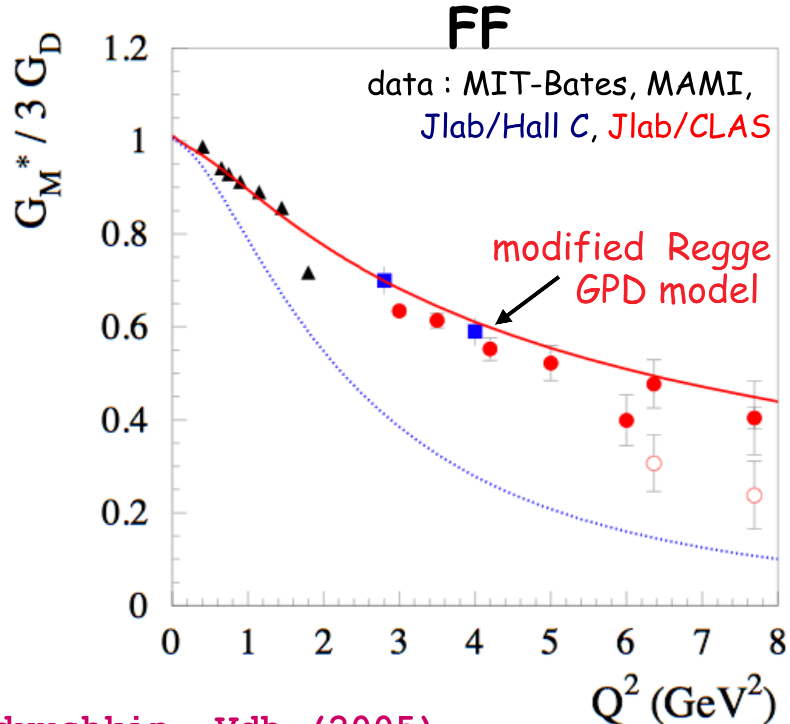
large N_c : $G^*_M(0) = \kappa_V / \sqrt{2} = 2.62$

large N_c limit

EXP : $G^*_M(0) = 3.02$

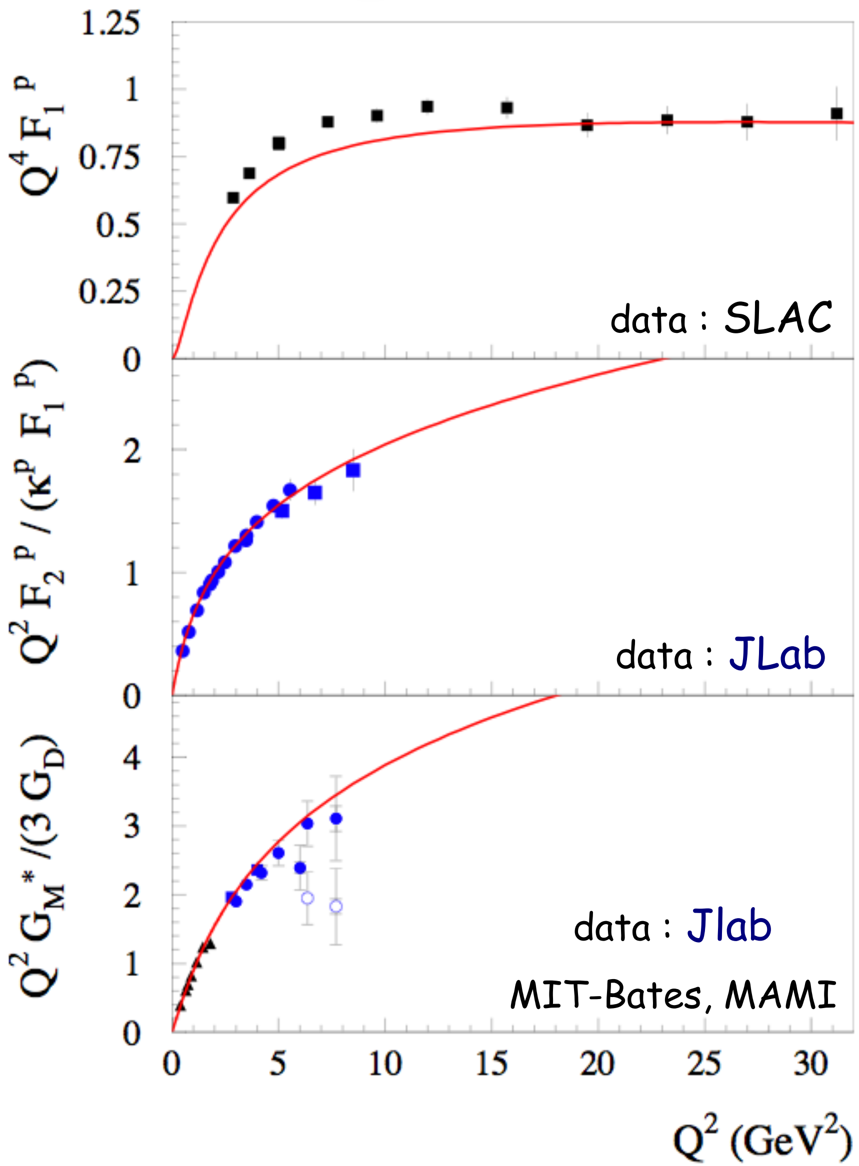
$$G^*_M(t) = \frac{G^*_M(0)}{\kappa_V} \int_{-1}^{+1} dx \left\{ E^u(x,\xi,t) - E^d(x,\xi,t) \right\} = \frac{G^*_M(0)}{\kappa_V} \left\{ F_2^p(t) - F_2^n(t) \right\}$$



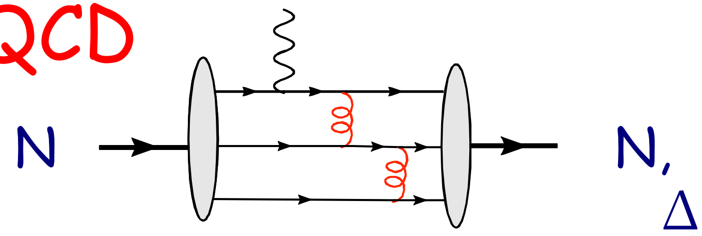


Guidal, Polyakov, Radyushkin, Vdh (2005)

scaling behavior of N and N -> Δ FF



PQCD



+ collinear quarks

$F_1{}^p \sim 1/Q^4$

$F_2{}^p / F_1{}^p \sim 1/Q^2$

$G_M{}^* \sim 1/Q^4$

GPD —— modified Regge GPD model

Guidal, Polyakov, Radyushkin, Vdh (2005)

Challenges / outlook

- Physics of light vector meson production

  in the valence region : remains to be understood

  (u-quark dominance, meson exchanges, higher twist, … ?)

  for gluons : large correction factors needed

- Transverse target spin asymmetry seems a promising observable to minimize higher order/ higher twist corrections

  Linear dependence on GPD E (J_q)

- N -> Δ DVCS : quark GPDs in excited state,

  test of dynamical relations (large N_c)

  relation with GPD E_q