Ground and Excited Nucleon Structure in 3D

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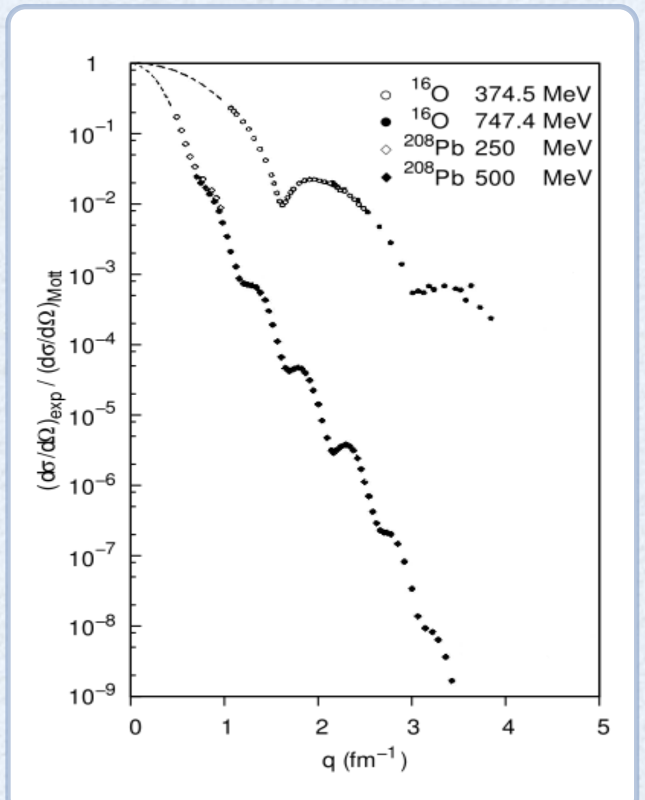
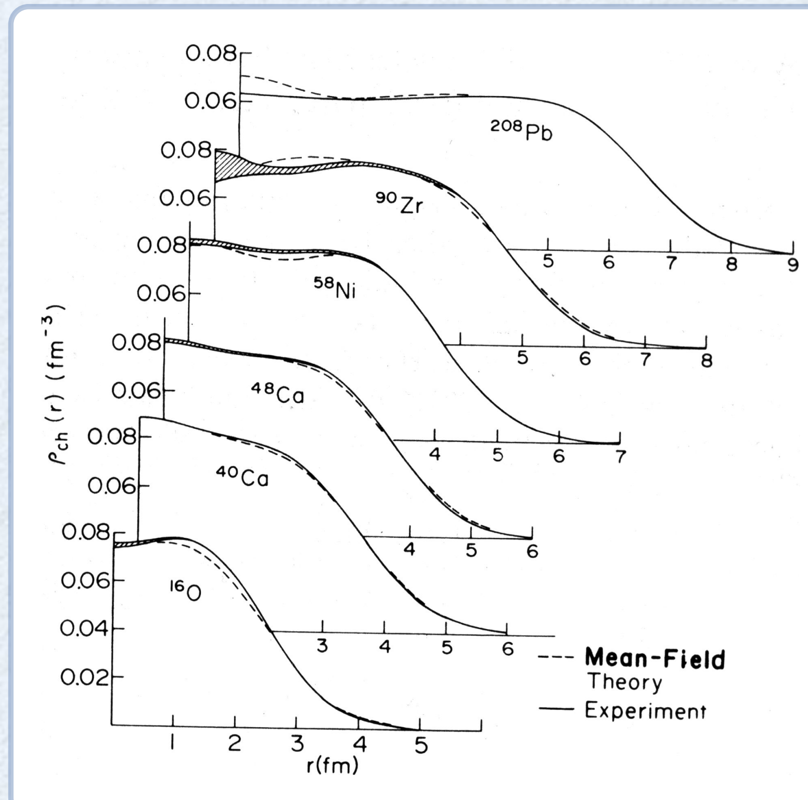
Imaging of atomic nuclei

sizes of nuclei:

as revealed through

elastic electron scattering



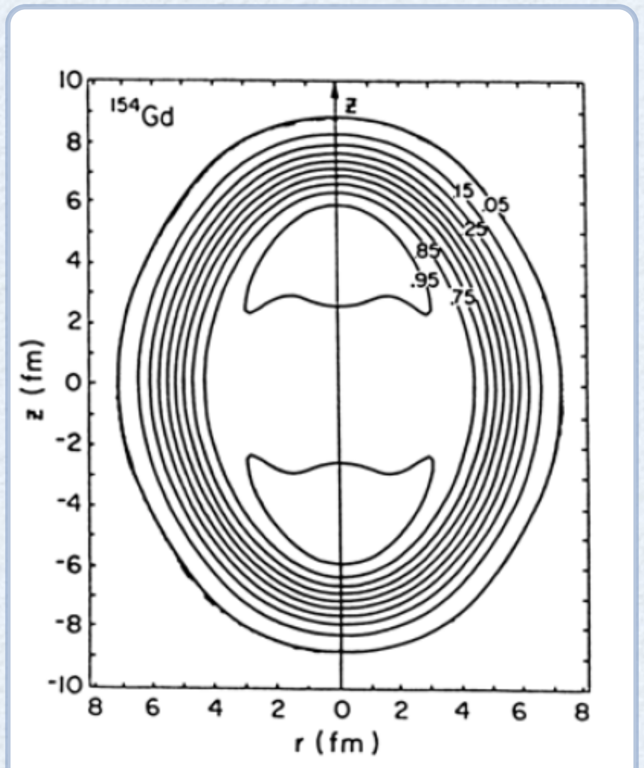


shapes of nuclei:

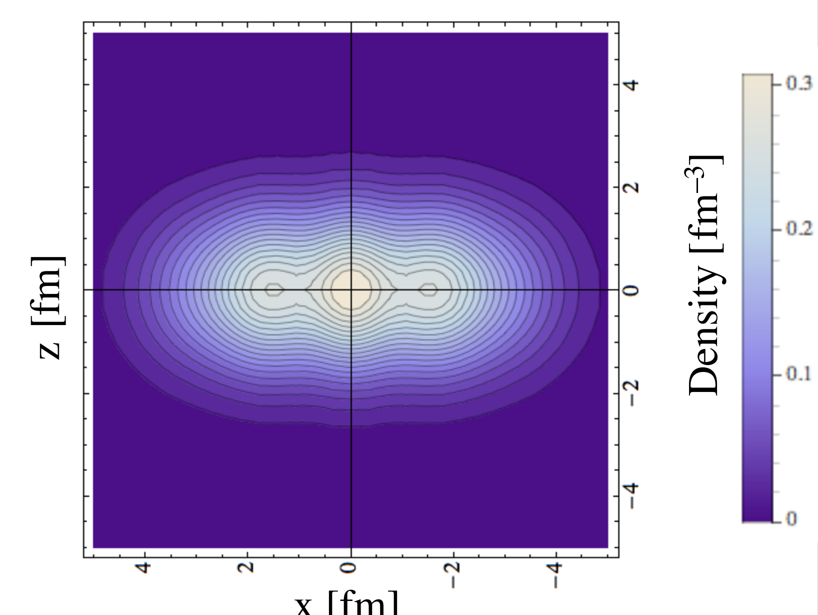
as revealed through

inelastic electron scattering

deformations, coherent states

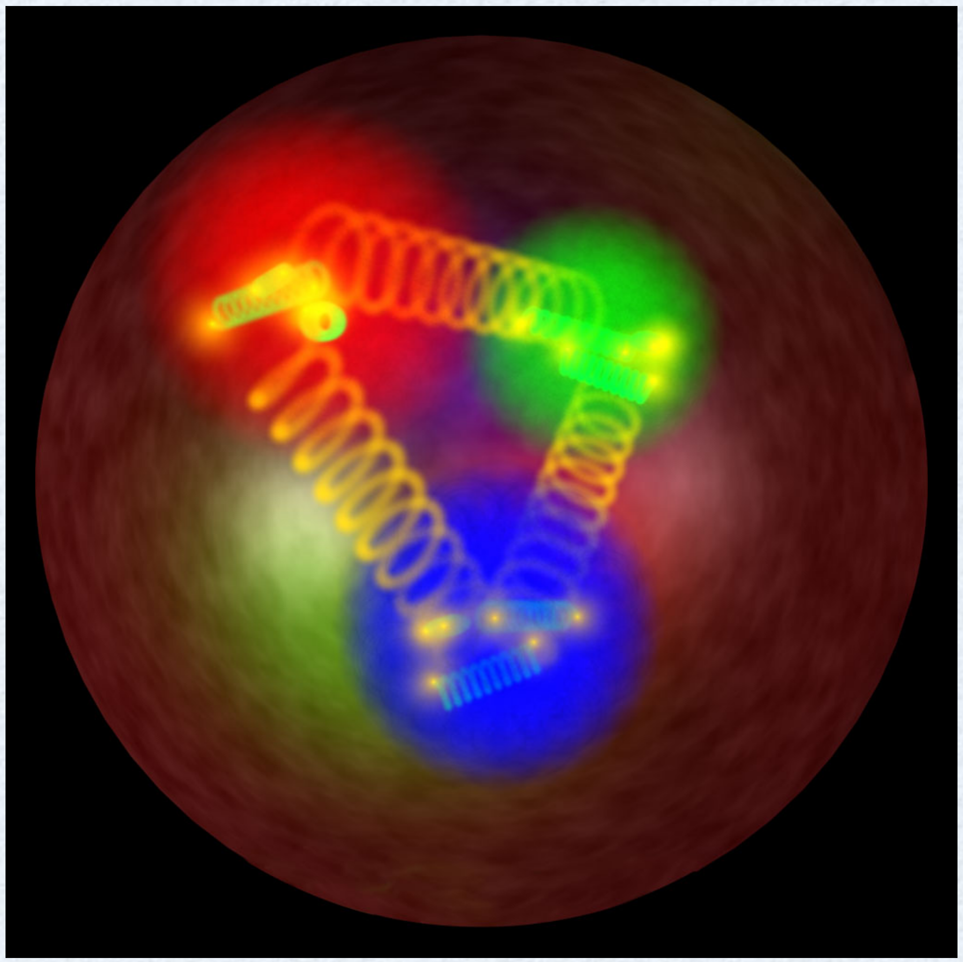


Hoyle state in ^{12}C

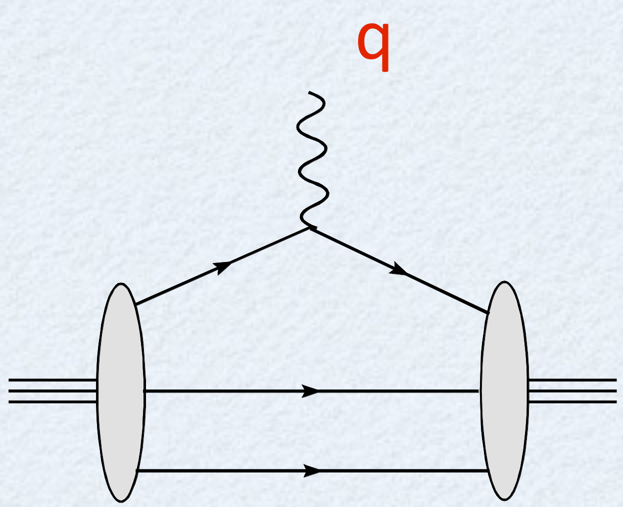


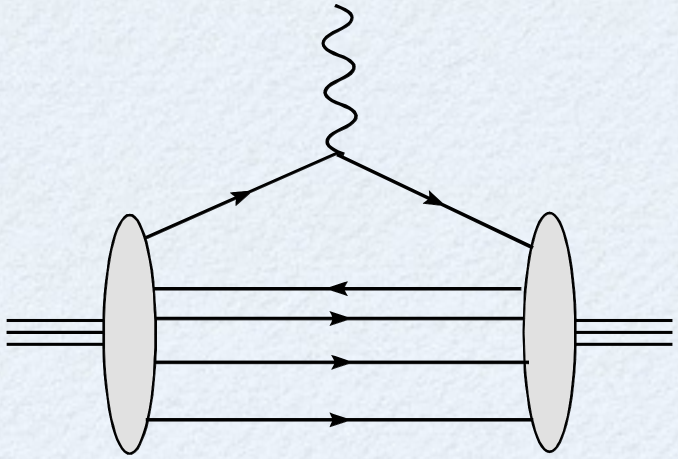
Draayer et al.

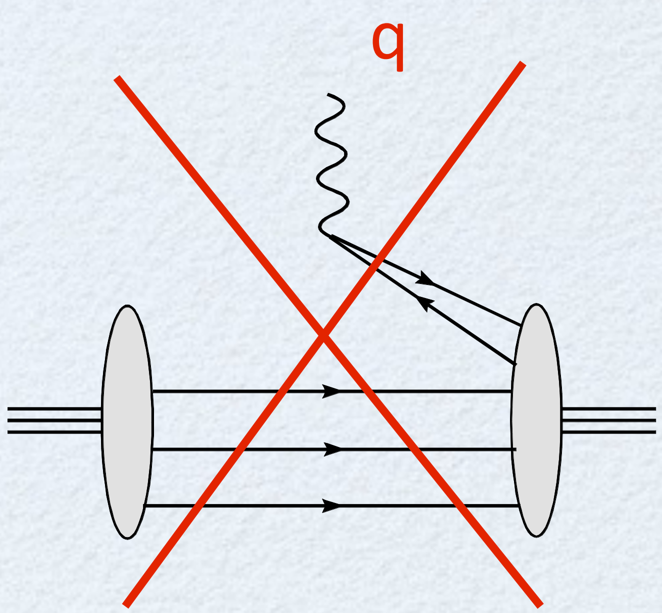
Imaging of protons, neutrons, and nucleon resonances



Interpretation of form factor as quark density







overlap of wave function
Fock components
with different number of quarks

NO probability / charge density
interpretation

absent in a light-front frame!

$$q^+ = q^0 + q^3 = 0$$

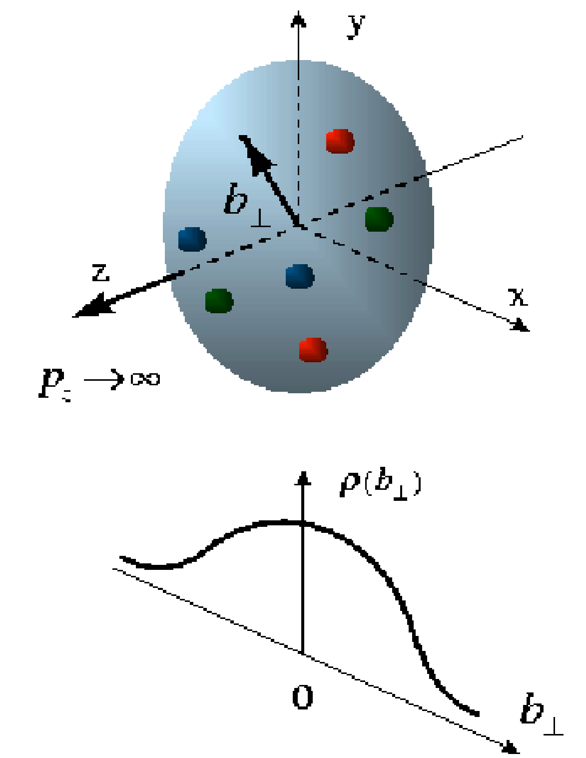
overlap of wave function
Fock components
with same number of quarks

quark transverse charge densities in nucleon

➡ longitudinally polarized nucleon

$$\rho_0^N(\vec{b}) \equiv \int \frac{d^2\vec{q}_\perp}{(2\pi)^2} e^{-i\vec{q}_\perp\cdot\vec{b}} \frac{1}{2P^+} \langle P^+, \frac{\vec{q}_\perp}{2}, \lambda | J^+(0) | P^+, -\frac{\vec{q}_\perp}{2}, \lambda \rangle$$
$$= \int_0^\infty \frac{dQ}{2\pi} Q J_0(bQ) F_1(Q^2)$$

Soper (1997)   Burkardt (2000)   Miller (2007)

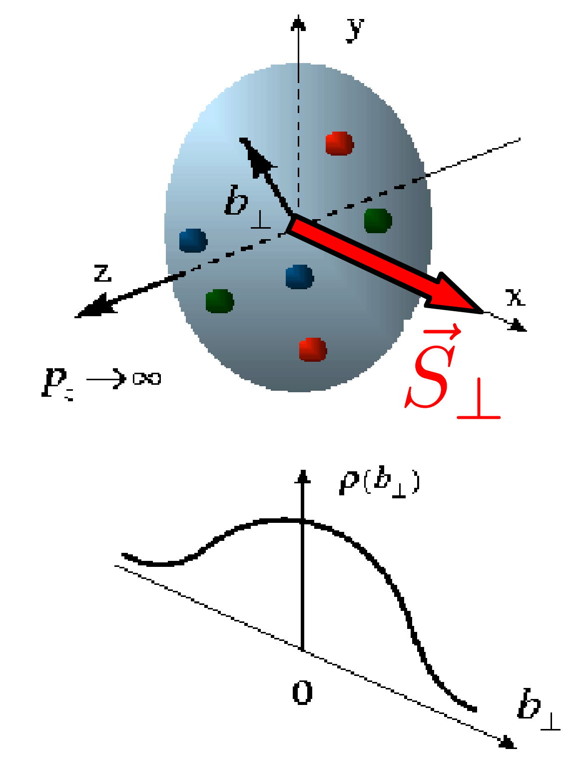


➡ transversely polarized nucleon

$$\rho_T^N(\vec{b}) \equiv \int \frac{d^2\vec{q}_\perp}{(2\pi)^2} e^{-i\vec{q}_\perp\cdot\vec{b}} \frac{1}{2P^+} \langle P^+, \frac{\vec{q}_\perp}{2}, s_\perp = +\frac{1}{2} | J^+(0) | P^+, -\frac{\vec{q}_\perp}{2}, s_\perp = +\frac{1}{2} \rangle$$
$$= \rho_0^N(b) + \sin(\phi_b - \phi_S) \int_0^\infty \frac{dQ}{2\pi} \frac{Q^2}{2M} J_1(bQ) F_2(Q^2)$$

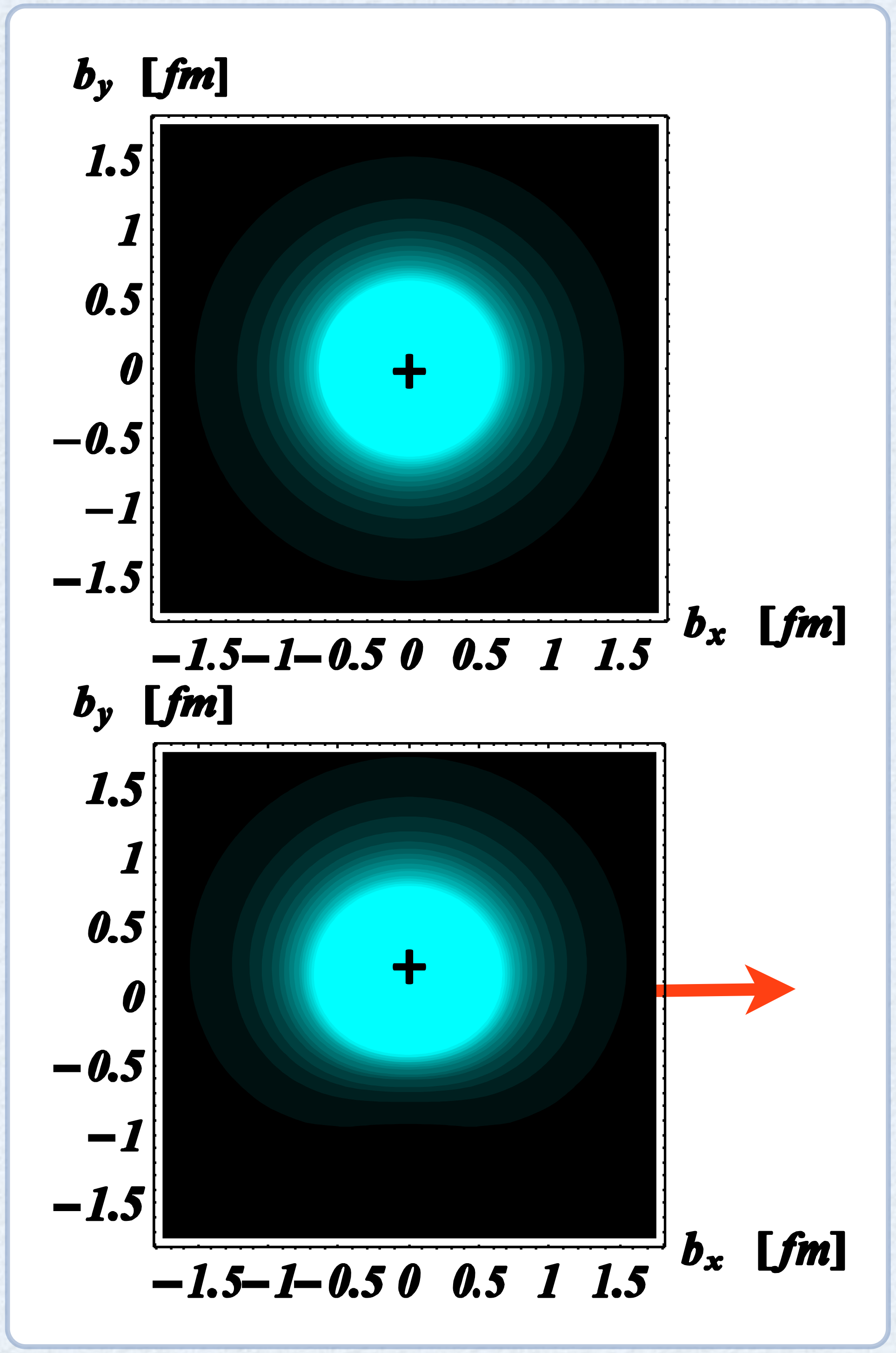
dipole field pattern

Carlson, Vdh (2007)

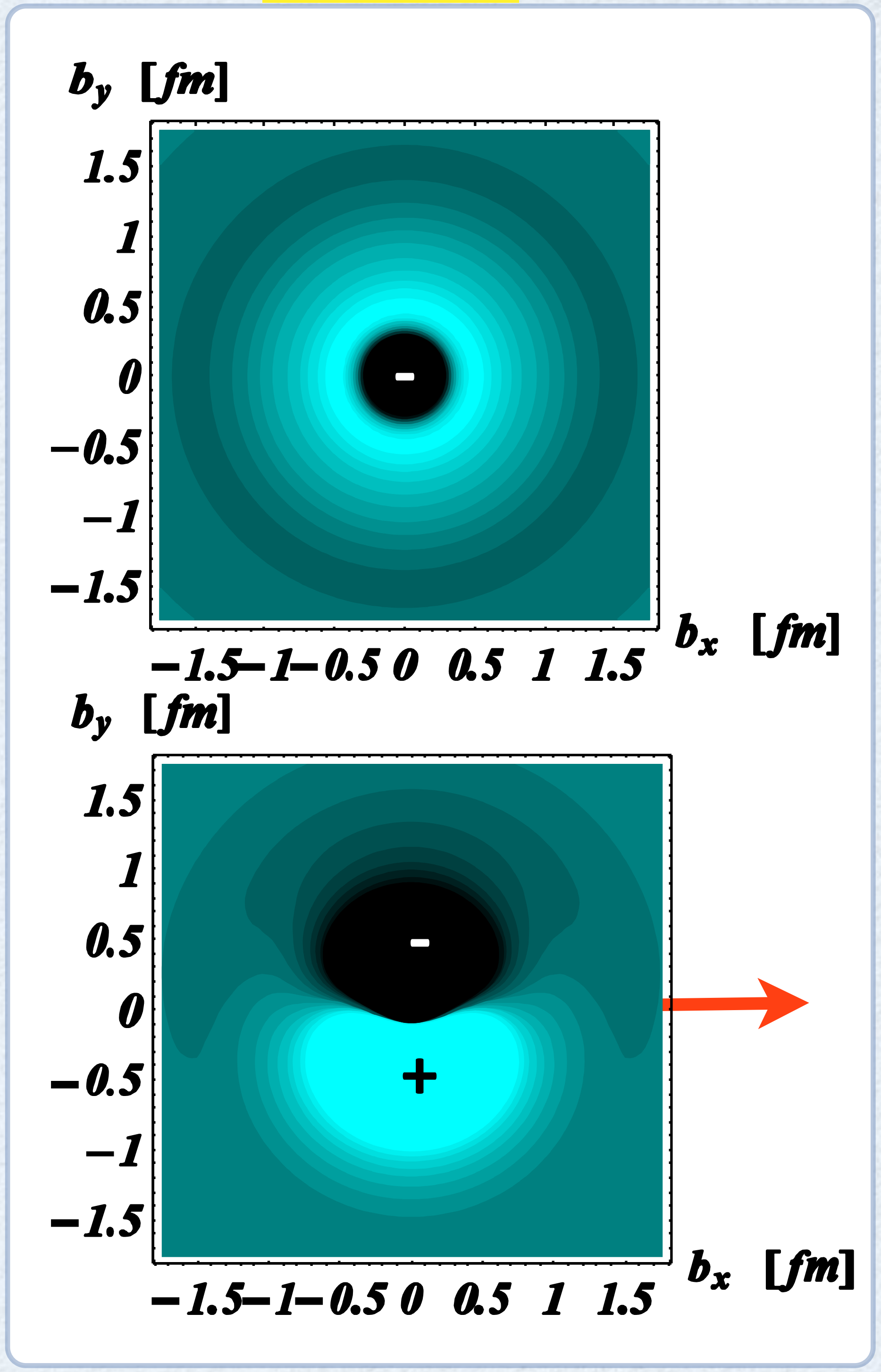


spatial imaging of nucleons

proton



neutron

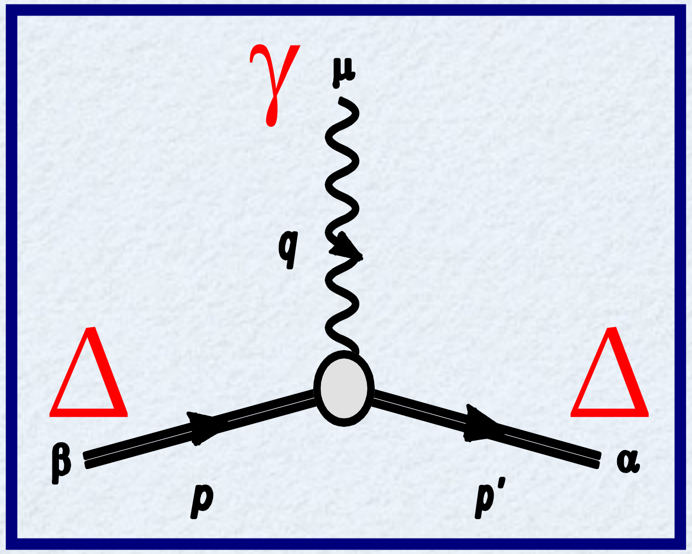


induced electric dipole moment:

$$d_y = \kappa \frac{e}{2M}$$

Miller (2007) Carlson, Vdh (2007)

Δ(1232) electromagnetic transitions



$$\langle \Delta(p',\lambda') \,|\, J^\mu(0) \,|\, \Delta(p,\lambda) \rangle$$
$$= -\bar{u}_\alpha(p',\lambda') \left\{ \left[F_1^*(Q^2) g^{\alpha\beta} + F_3^*(Q^2) \frac{q^\alpha q^\beta}{(2M)^2} \right] \gamma^\mu + \left[F_2^*(Q^2) g^{\alpha\beta} + F_4^*(Q^2) \frac{q^\alpha q^\beta}{(2M)^2} \right] \frac{i\sigma^{\mu\nu} q_\nu}{2M} \right\} u_\beta(p,\lambda)$$

4 multipole form factors

multipole moments

Electric charge FF:	$G_{E0}(Q^2)$	$e_\Delta = G_{E0}(0)$
Magnetic dipole FF:	$G_{M1}(Q^2)$	$\mu_\Delta = \frac{e_\Delta}{2M} G_{M1}(0)$
Electric quadrupole FF:	$G_{E2}(Q^2)$	$Q_\Delta = \frac{e_\Delta}{M^2} G_{E2}(0)$
Magnetic octuple FF:	$G_{M3}(Q^2)$	$O_\Delta = \frac{e_\Delta}{2M^3} G_{M3}(0)$

Quark charge densities in Δ(1232)

$$\rho^{\Delta}_{T s_\perp = \frac{3}{2}}(\vec{b}) \equiv \int \frac{d^2\vec{q}_\perp}{(2\pi)^2} e^{-i\,\vec{q}_\perp\cdot\vec{b}} \frac{1}{2P^+} \langle P^+, \frac{\vec{q}_\perp}{2}, s^\Delta_\perp = \frac{3}{2} \,|\, J^+(0) \,|\, P^+, -\frac{\vec{q}_\perp}{2}, s^\Delta_\perp = \frac{3}{2} \rangle$$

$$= \int_0^\infty \frac{dQ}{2\pi} Q \left\{ J_0(b\,Q)\, \frac{1}{4}\left(A_{\frac{3}{2}\,\frac{3}{2}} + 3A_{\frac{1}{2}\,\frac{1}{2}}\right) \longrightarrow G_{E0}(0) + \mathcal{O}(Q^2) \right.$$

$$- \sin(\phi_b - \phi_S)\, J_1(b\,Q) \frac{1}{4}\left(2\sqrt{3}A_{\frac{3}{2}\,\frac{1}{2}} + 3A_{\frac{1}{2}\,-\frac{1}{2}}\right) \longrightarrow \frac{Q}{2M}\{3G_{E0}(0) - G_{M1}(0) + \mathcal{O}(Q^2)\}$$

$$- \cos 2(\phi_b - \phi_S)\, J_2(b\,Q) \frac{\sqrt{3}}{2} A_{\frac{3}{2}\,-\frac{1}{2}} \longrightarrow \frac{Q^2}{8M^2}\{3G_{E0}(0) - 2G_{M1}(0) - G_{E2}(0) + \mathcal{O}(Q^2)\}$$

$$\left. + \sin 3(\phi_b - \phi_S)\, J_3(b\,Q) \frac{1}{4} A_{\frac{3}{2}\,-\frac{3}{2}} \right\} \longrightarrow \frac{Q^3}{32M^3}\{G_{E0}(0) - G_{M1}(0) - G_{E2}(0) + G_{M3}(0) + \mathcal{O}(Q^2)\}$$

Quadrupole moment:

$$Q^{\Delta}_{s_\perp} \equiv e \int d^2\vec{b}\,(b_x^2 - b_y^2)\, \rho^{\Delta}_{T\,s_\perp}(\vec{b})$$

$$Q^{\Delta}_{\frac{3}{2}} = -Q^{\Delta}_{\frac{1}{2}} = \frac{1}{2}\{2\,[G_{M1}(0) - 3e_\Delta] + [G_{E2}(0) + 3e_\Delta]\}\left(\frac{e}{M^2}\right)$$

for spin 3/2 point particle: transverse density = δ-function

leads to “natural values” of multipole moments

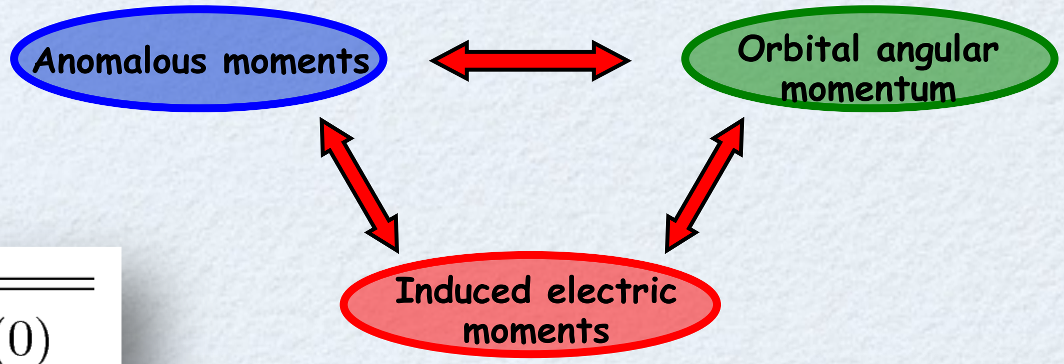
$$G_{E0}(0) = e_\Delta \quad G_{M1}(0) = 3e_\Delta, \quad G_{E2}(0) = -3e_\Delta, \quad G_{M3}(0) = -e_\Delta$$

Alexandrou, Korzec, Koutsou, Leontiou, Lorcé, Negele, Pascalutsa, Tsapalis, Vdh(2008)

Natural values of hadron e.m. moments

Transverse charge densities depend only on anomalous values of e.m. moments ⇒ determine hadron internal structure

Spin j : $2j+1$ multipoles



j	$G_{E0}(0)$ (e)	$G_{M1}(0)$ $(e/2M)$	$G_{E2}(0)$ (e/M^2)	$G_{M3}(0)$ $(e/2M^3)$	$G_{E4}(0)$ (e/M^4)	$G_{M5}(0)$ $(e/2M^5)$	
0	1						
1/2	1	1					Standard Model
1	1	2	-1				
3/2	1	3	-3	-1			Supergravity
2	1	4	-6	-4	1		
⋮							
j	C^0_{2j}	C^1_{2j}	$-C^2_{2j}$	$-C^3_{2j}$	C^4_{2j}	C^5_{2j}	

Charge normalization

Universal g=2 factor

$$G_{M1}(0) = 2j$$

Structureless particle

↓

No OAM

↓

No distortions

↓

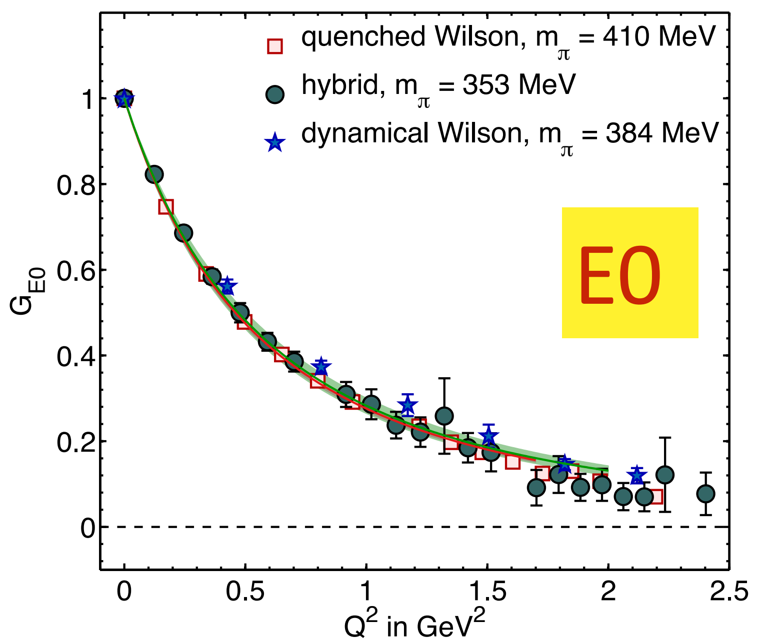
No anomalous moments

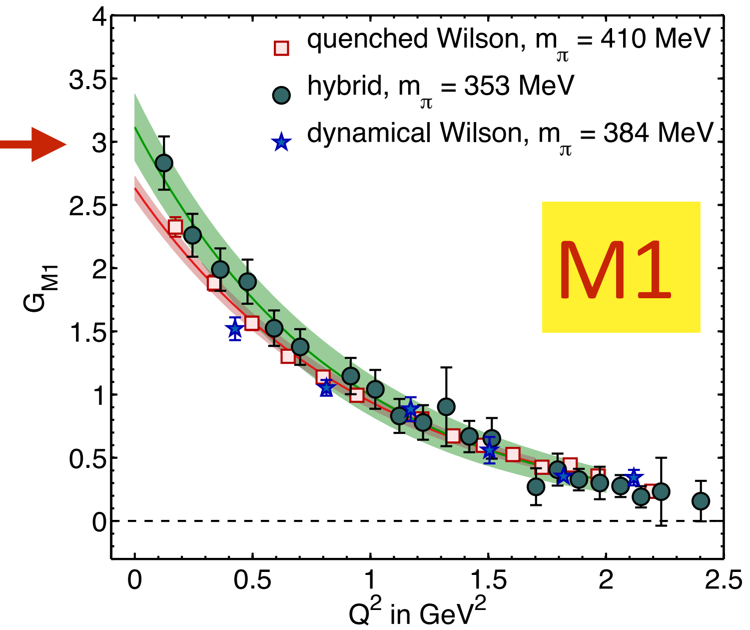
↓

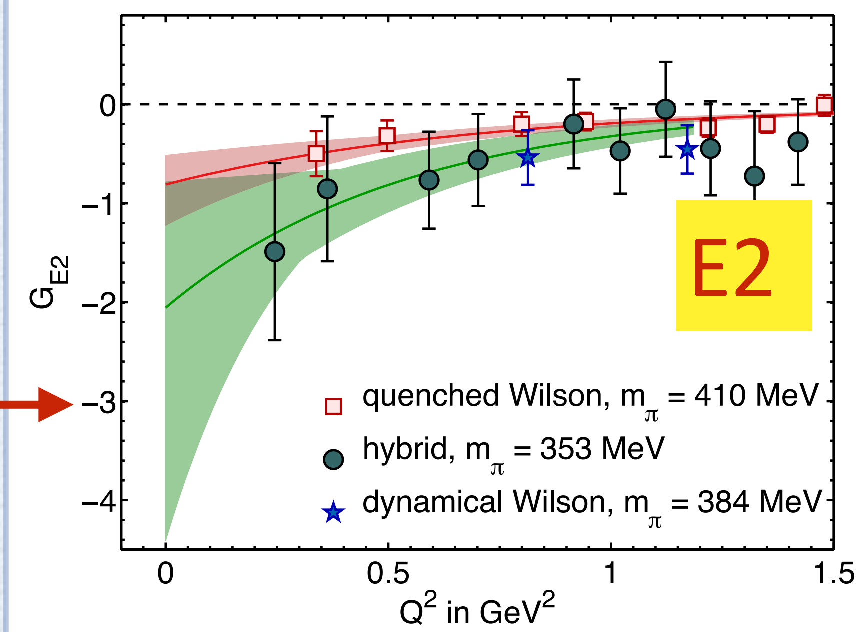
Natural EM moments

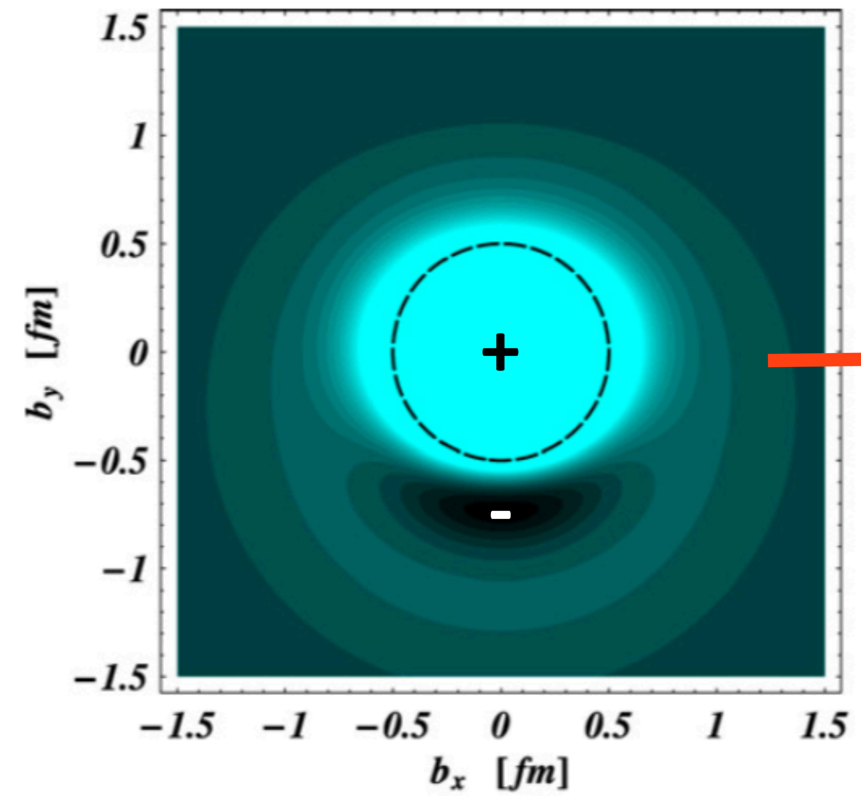
Lorcé (2008)

Quark charge densities in $\Delta^+(1232)$: lattice QCD







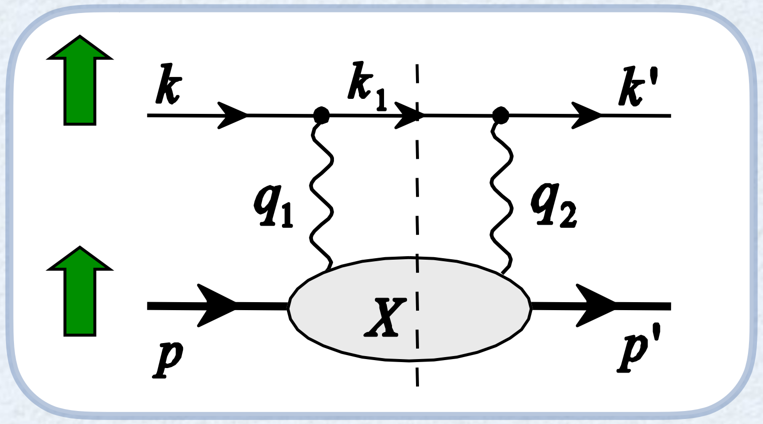


Alexandrou et al.(2008)

$s_\perp = 3/2$

Access Δ e.m. form factors in experiment: normal spin asymmetries

- Beam or target normal spin asymmetries:



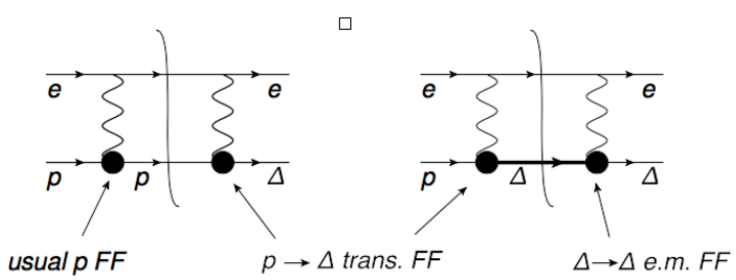
directly proportional to Im part of TPE

target: $A_n \sim \alpha_{em} \sim 10^{-2}$

beam: $B_n \sim \alpha_{em} \frac{m_e}{E_e} \sim 10^{-6} - 10^{-5}$

- B_n for ep -> eΔ accesses Δ e.m. FFs

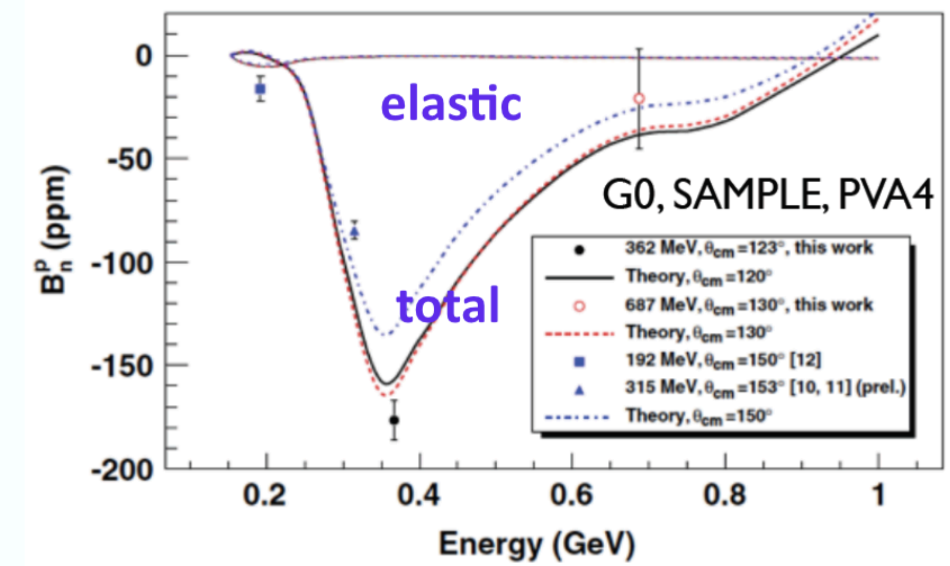
Carlson, Pasquini, Pauk, Vdh (2017)

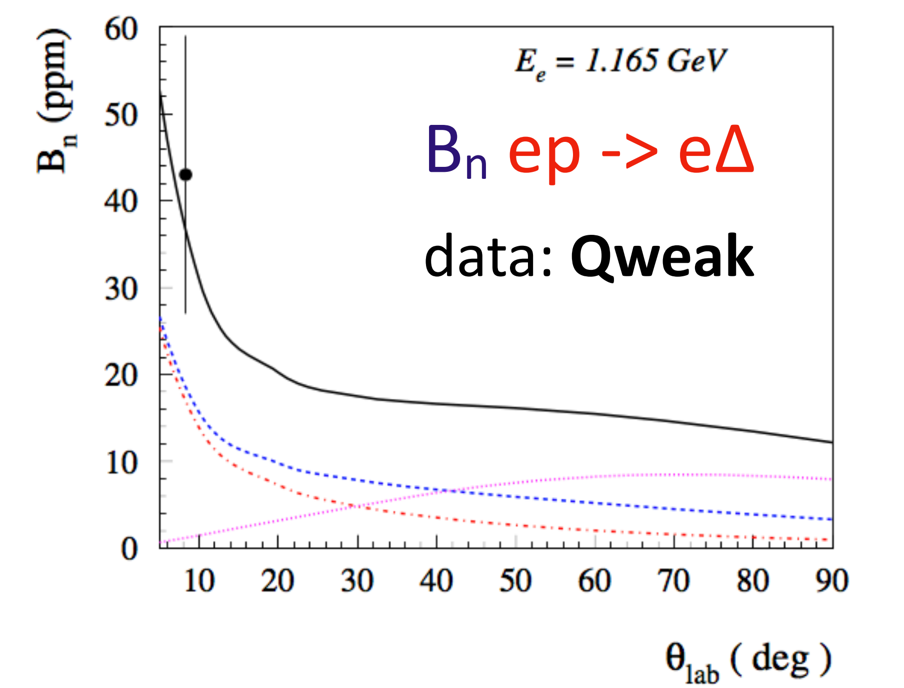


Results for QWeak kinematics

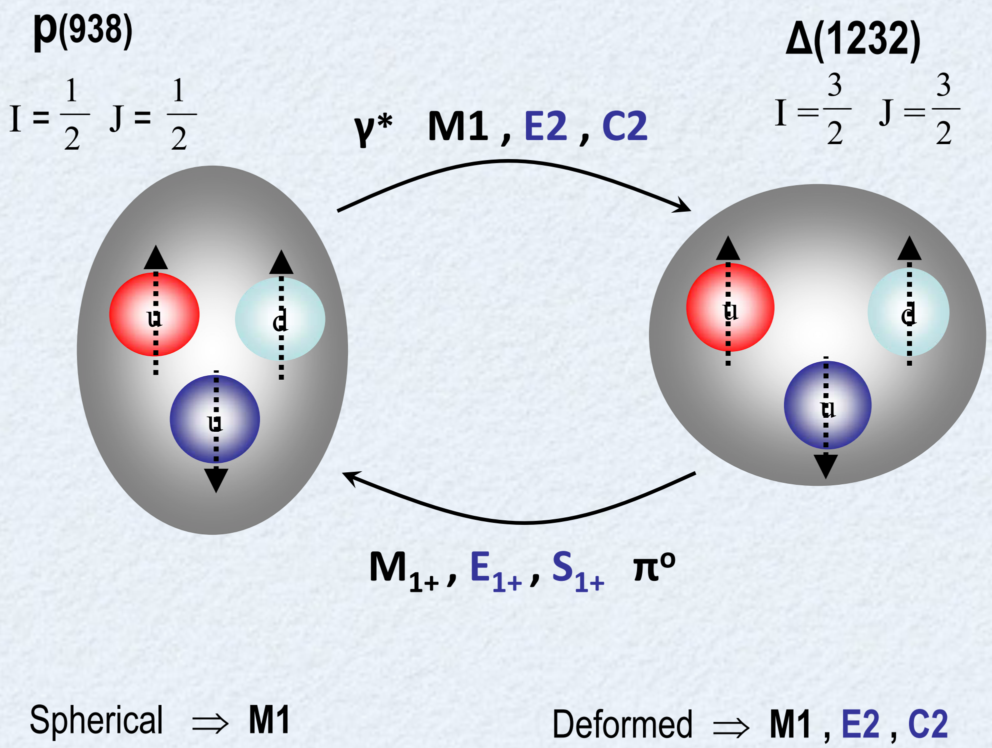
- Nucleon = dash-dot red line
- Δ = dashed blue line
- $S_{11} + D_{13}$ = dotted purple line
- Total = solid black line

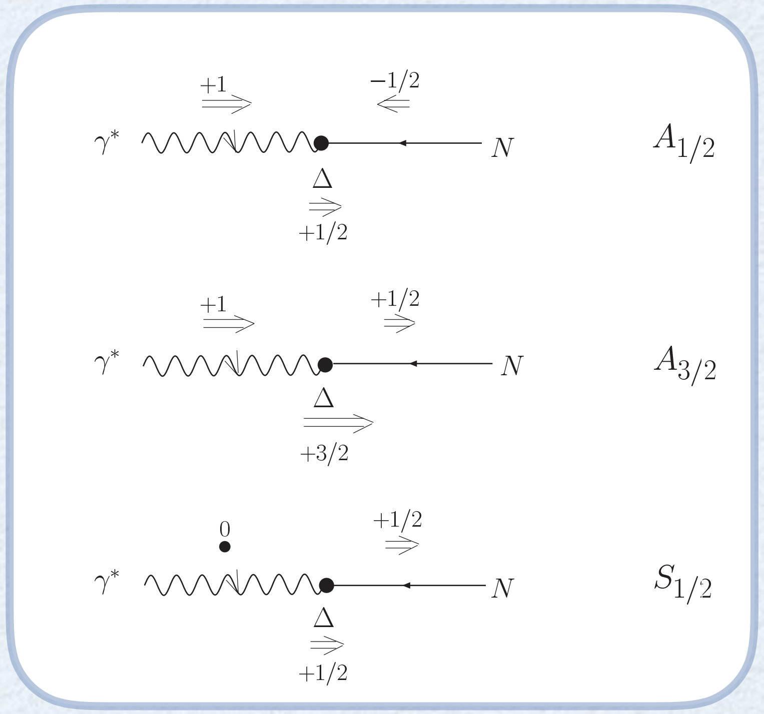
B_n ep -> ep Phys.Rev.Lett. 107 (2011) 022501





N → Δ(1232) e.m. transition densities





- experiment measures multipoles

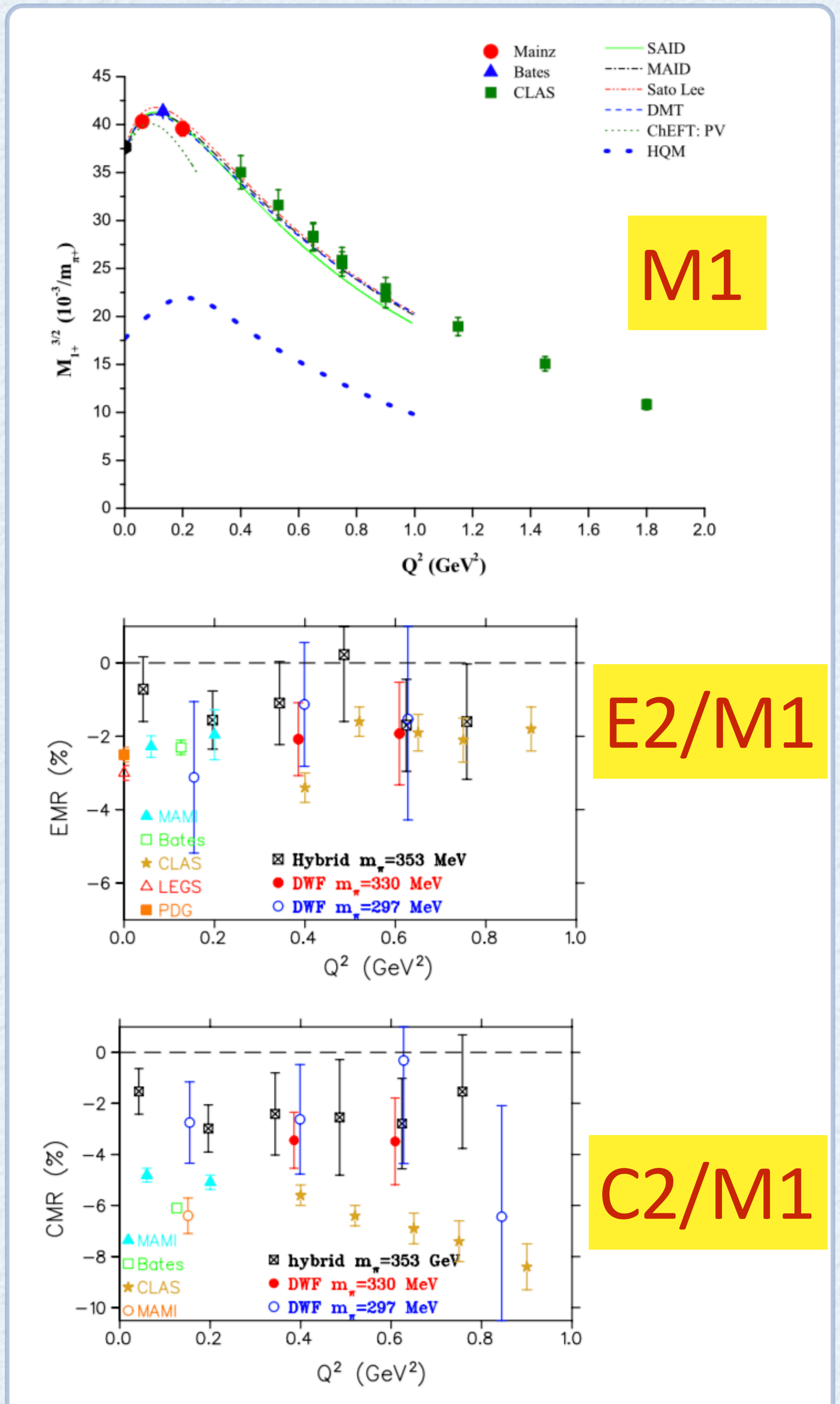
$$\bar{M}_{1+}^{(3/2)}(Q^2) \equiv \sqrt{\frac{2}{3}}\, a_\Delta \, \mathrm{Im} M_{1+}^{(3/2)}(Q^2, W = M_\Delta)$$

- theory calculates helicity amplitudes

$$\begin{aligned}
A_{3/2} &\equiv -\frac{e}{\sqrt{2q_\Delta}} \frac{1}{(4M_N M_\Delta)^{1/2}} \langle \Delta(\vec{0}, +3/2) \,|\, \mathbf{J}\cdot\epsilon_{\lambda=+1} \,|\, N(-\vec{q}, +1/2) \rangle \\
A_{1/2} &\equiv -\frac{e}{\sqrt{2q_\Delta}} \frac{1}{(4M_N M_\Delta)^{1/2}} \langle \Delta(\vec{0}, +1/2) \,|\, \mathbf{J}\cdot\epsilon_{\lambda=+1} \,|\, N(-\vec{q}, -1/2) \rangle \\
S_{1/2} &\equiv \frac{e}{\sqrt{2q_\Delta}} \frac{1}{(4M_N M_\Delta)^{1/2}} \langle \Delta(\vec{0}, +1/2) \,|\, J^0 \,|\, N(-\vec{q}, +1/2) \rangle .
\end{aligned}$$

$$\begin{aligned}
A_{3/2} &= -\frac{\sqrt{3}}{2} \left\{ \bar{M}_{1+}^{(3/2)} - \bar{E}_{1+}^{(3/2)} \right\} \\
A_{1/2} &= -\frac{1}{2} \left\{ \bar{M}_{1+}^{(3/2)} + 3\, \bar{E}_{1+}^{(3/2)} \right\} \\
S_{1/2} &= -\sqrt{2}\, \bar{S}_{1+}^{(3/2)}
\end{aligned}$$

N → Δ(1232) e.m. multipoles



Alexandrou,Papanicolas,Vdh(RMP 2012)

large N_c limit of QCD: N and **Δ**(1232) degenerate

Quadrupole moment related to neutron rms radius

$$Q_{p\to\Delta^+} = \frac{1}{\sqrt{2}}\, r_n^2\, \frac{N_c}{N_c+3}\sqrt{\frac{N_c+5}{N_c-1}}$$

Buchmann,Hester, Lebed(2002)

Exp.:	r_n^2	$= -0.113(3)\ \text{fm}^2$
large N_c :	$Q_{p\to\Delta^+}$	$= -0.080\ \text{fm}^2$
Exp.:	$Q_{p\to\Delta^+}$	$= -0.085(3)\ \text{fm}^2$

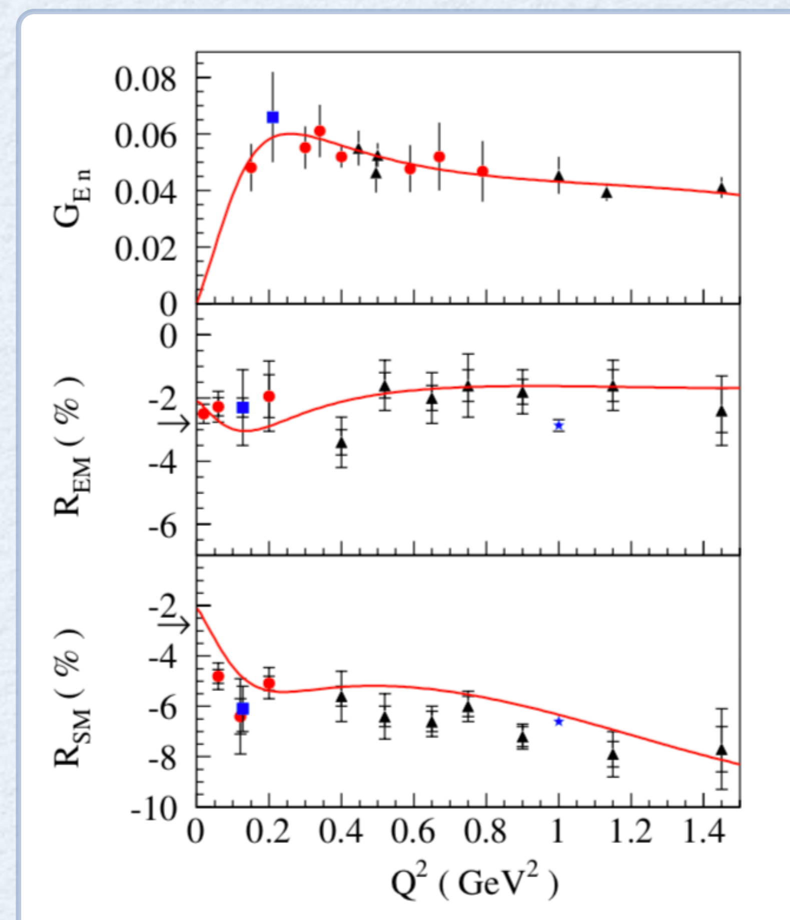
very good agreement !

low Q^2 relations

$$G_E^*(Q^2) = \left(\frac{M_N}{M_\Delta}\right)^{3/2} \frac{M_\Delta^2 - M_N^2}{2\sqrt{2}\,Q^2}\, G_{En}(Q^2)$$

$$G_C^*(Q^2) = \frac{4M_\Delta^2}{M_\Delta^2 - M_N^2}\, G_E^*(Q^2)$$

Pascalutsa, Vdh(2007)



$\mathbf{N} \rightarrow \mathbf{\Delta}(1232)$ transition densities

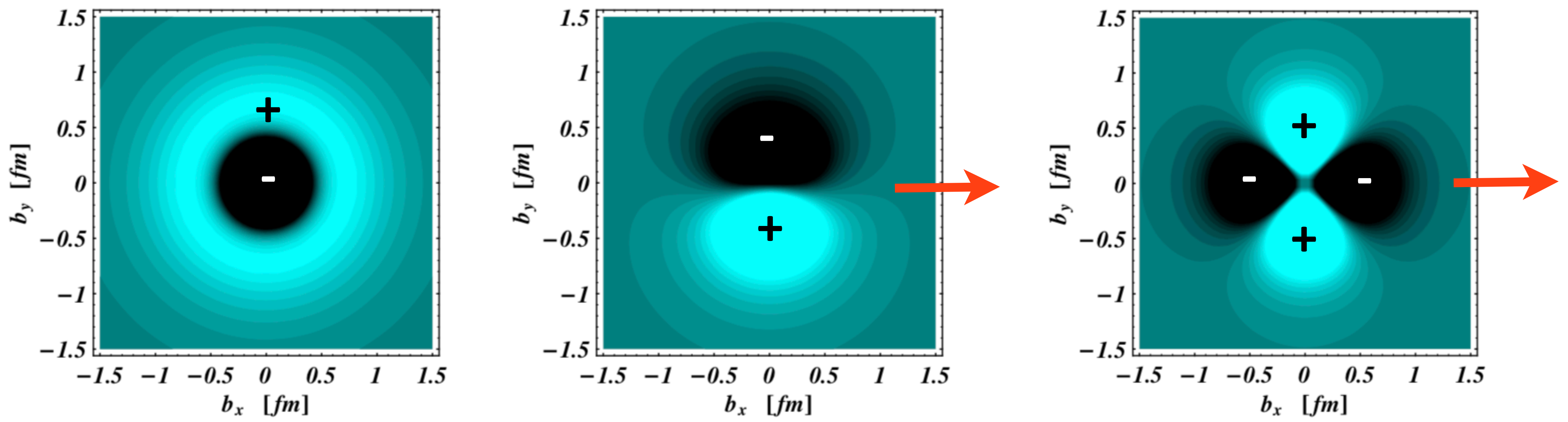
$$\rho_T^{N\Delta}(\vec{b}) \equiv \int \frac{d^2\vec{q}_\perp}{(2\pi)^2} e^{-i\,\vec{q}_\perp\cdot\vec{b}} \frac{1}{2P^+} \langle P^+, \frac{\vec{q}_\perp}{2}, s_\perp^\Delta = +\frac{1}{2} \,|\, J^+(0) \,|\, P^+, -\frac{\vec{q}_\perp}{2}, s_\perp^N = +\frac{1}{2} \rangle$$

$$= \int_0^\infty \frac{dQ}{2\pi}\frac{Q}{2} \left\{ J_0(b\,Q)\, G^+_{+\frac{1}{2}\,+\frac{1}{2}} \right. \quad \longrightarrow \text{monopole}$$

$$- \sin(\phi_b - \phi_S)\, J_1(b\,Q) \left[\sqrt{3} G^+_{+\frac{3}{2}\,+\frac{1}{2}} + G^+_{+\frac{1}{2}\,-\frac{1}{2}} \right] \quad \longrightarrow \text{dipole}$$

$$\left. - \cos 2(\phi_b - \phi_S)\, J_2(b\,Q) \sqrt{3}\, G^+_{+\frac{3}{2}\,-\frac{1}{2}} \right\} \quad \longrightarrow \text{quadrupole}$$

ρ_0 P -> Δ^+ ρ_T quadrupole term



Carlson, Vdh(2007)

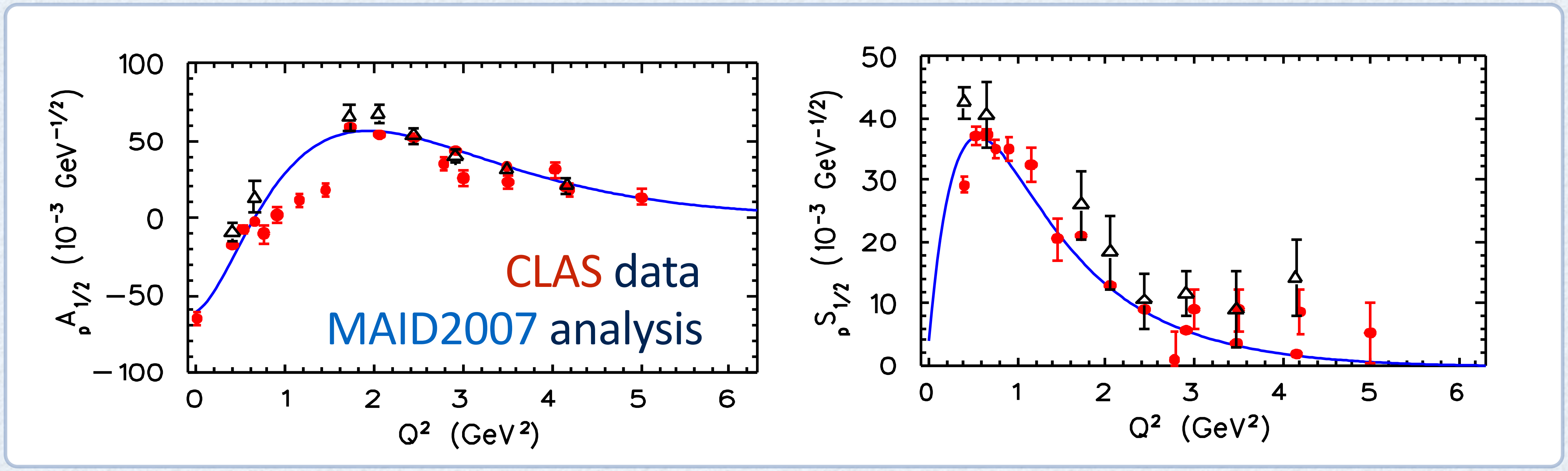
$N \rightarrow P_{11}(1440)$ transition densities

$$\langle N^*(p',\lambda') \,|\, J^\mu(0) \,|\, N(p,\lambda)\rangle = \bar{u}(p',\lambda') \left\{ F_1^{NN^*}(Q^2) \left(\gamma^\mu - \gamma \cdot q \, \frac{q^\mu}{q^2} \right) + F_2^{NN^*}(Q^2) \frac{i\sigma^{\mu\nu} q_\nu}{(M^* + M_N)} \right\} u(p,\lambda)$$

helicity amplitudes

$$A_{1/2} = e \, \frac{Q_-}{\sqrt{K}\,(4 M_N M^*)^{1/2}} \left\{ F_1^{NN^*} + F_2^{NN^*} \right\}$$

$$S_{1/2} = e \, \frac{Q_-}{\sqrt{2K}\,(4 M_N M^*)^{1/2}} \left(\frac{Q_+ Q_-}{2M^*} \right) \frac{(M^* + M_N)}{Q^2} \left\{ F_1^{NN^*} - \frac{Q^2}{(M^* + M_N)^2} F_2^{NN^*} \right\}$$

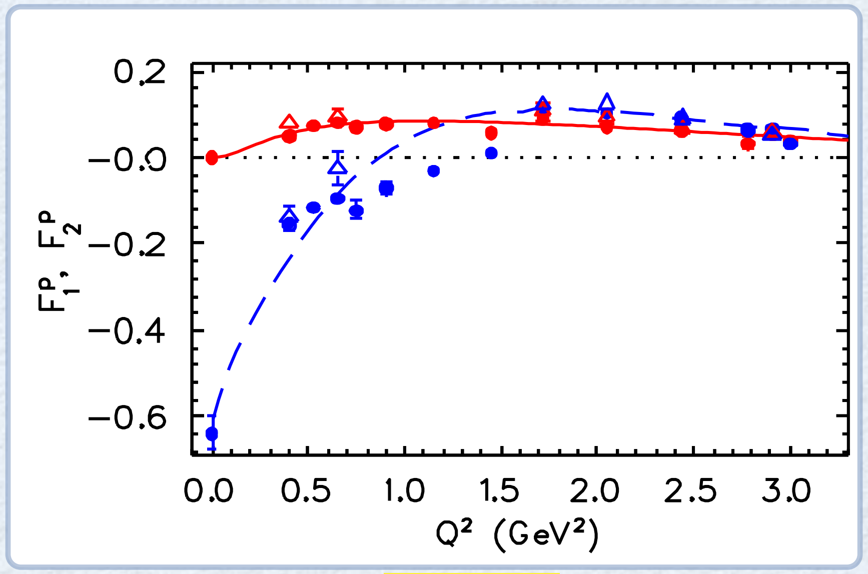


Tiator, Vdh(2008)

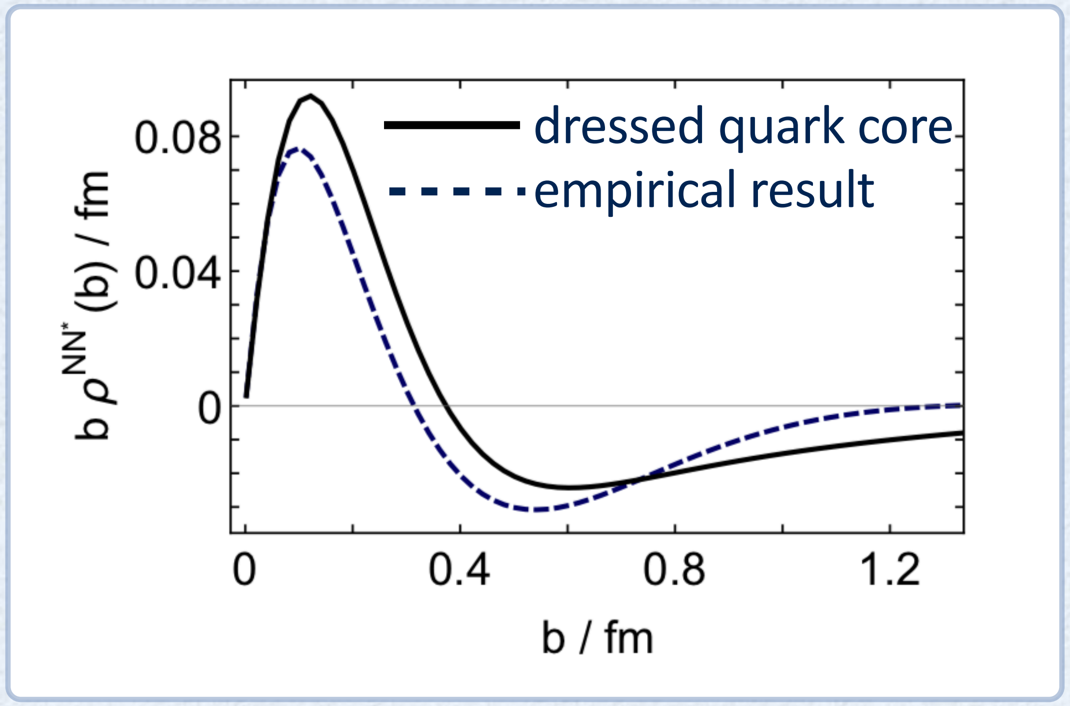
N → P₁₁(1440) transition densities

$$\rho_0^{NN^*}(\vec{b}) = \int_0^\infty \frac{dQ}{2\pi} Q\, J_0(b\,Q) F_1^{NN^*}(Q^2)$$

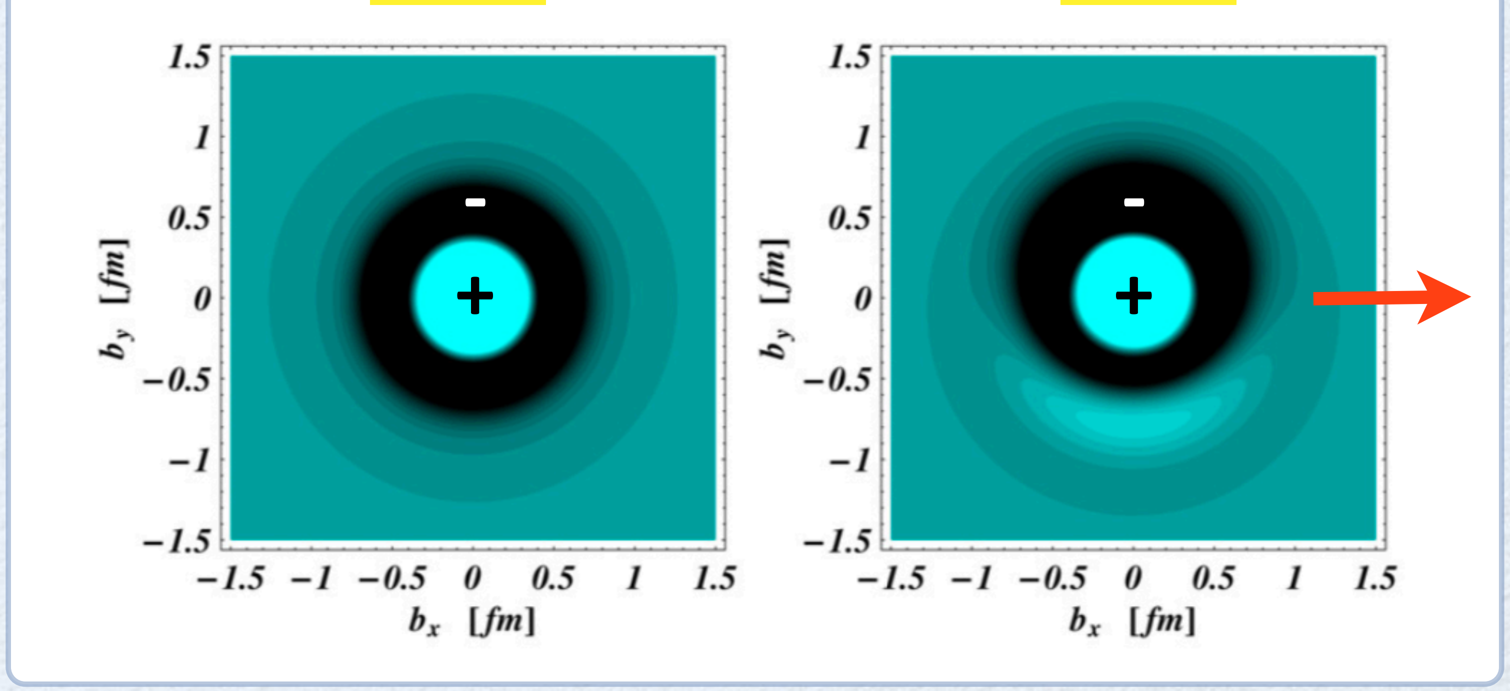
$$\rho_T^{NN^*}(\vec{b}) = \rho_0^{NN^*}(b) + \sin(\phi_b - \phi_S) \int_0^\infty \frac{dQ}{2\pi} \frac{Q^2}{(M^* + M_N)} J_1(b\,Q) F_2^{NN^*}(Q^2)$$



DSE: dressed quark core calculation



ρ_0 ρ_T

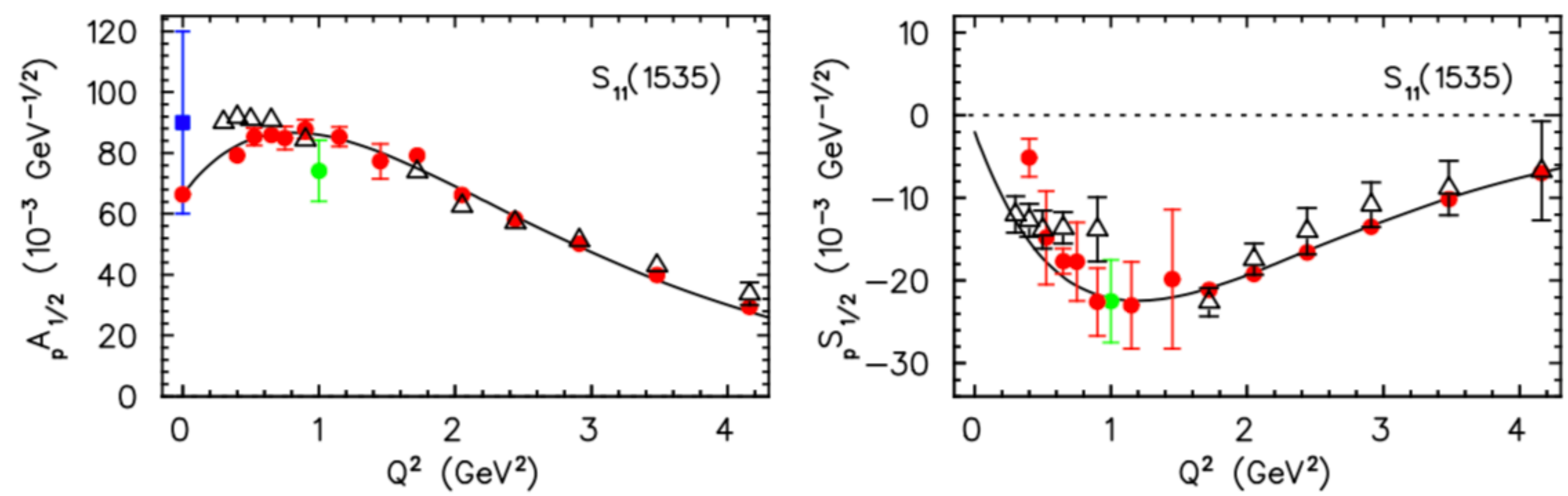


Roberts, Segovia et al.(2016,2018)

Tiator, Vdh(2008)

At large distances: u-quark core screened by mesonic tail (MB FSI)

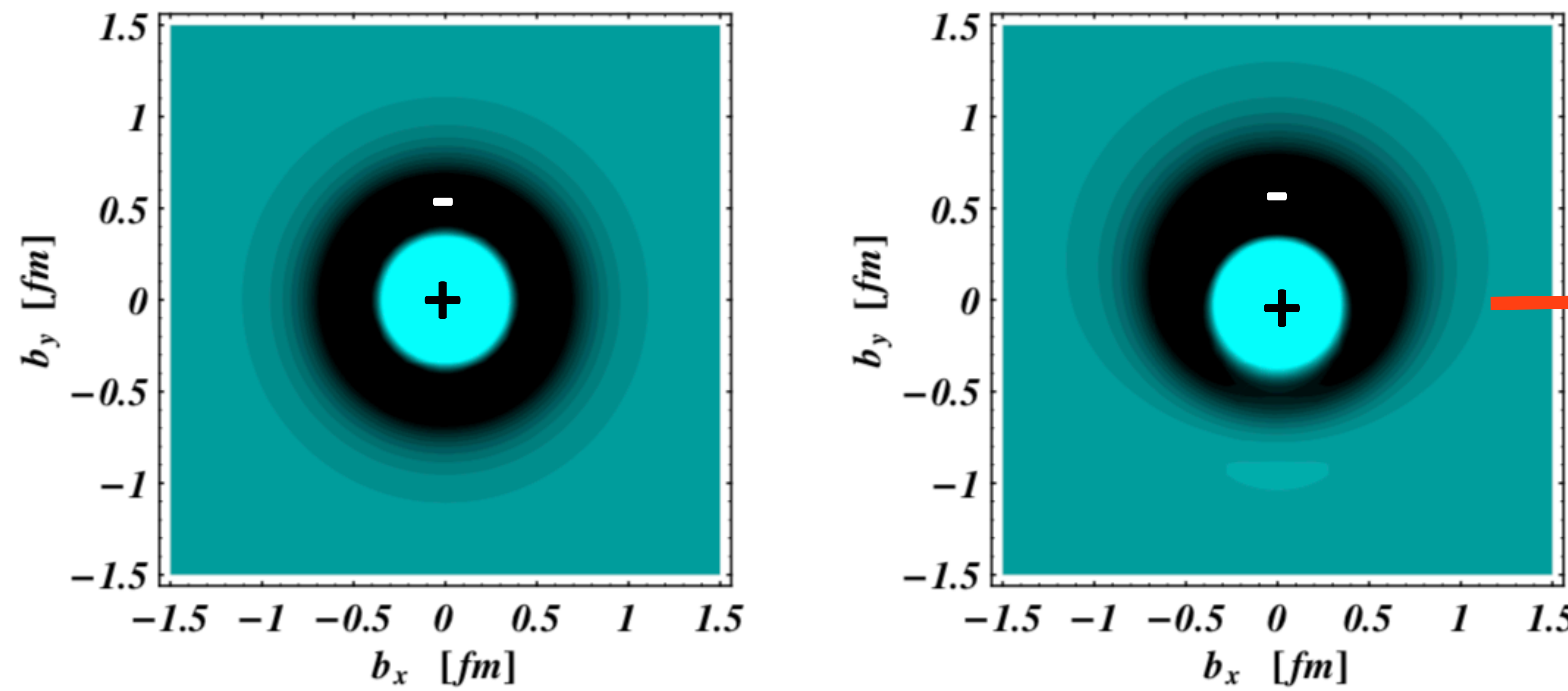
N → S11(1535) transition densities



CLAS data

MAID2007 analysis

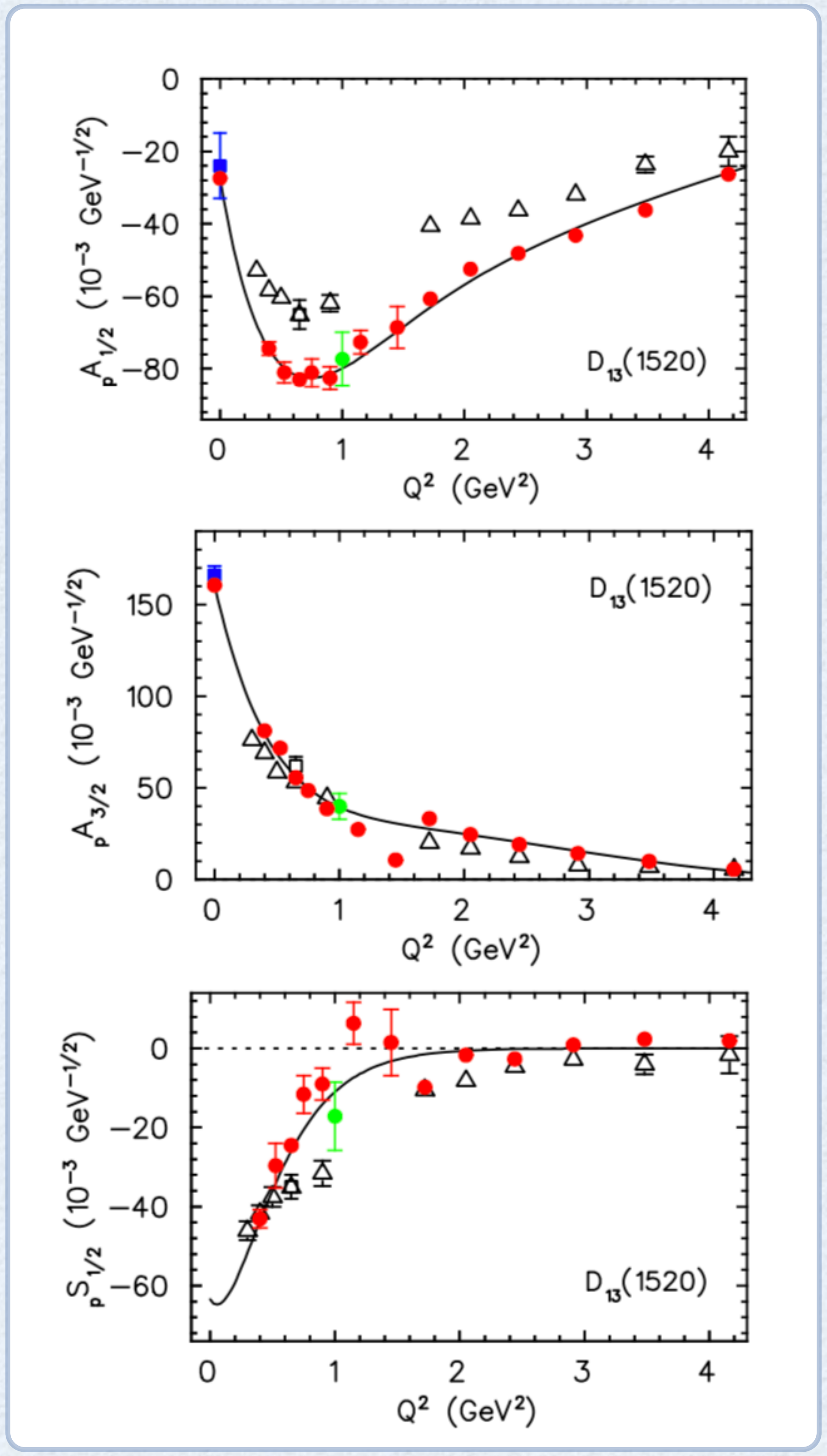
ρ_0 ρ_T



$s_\perp = -s'_\perp = +1/2$

Tiator, Vdh(2011)

$N \rightarrow D_{13}(1520)$ transition densities

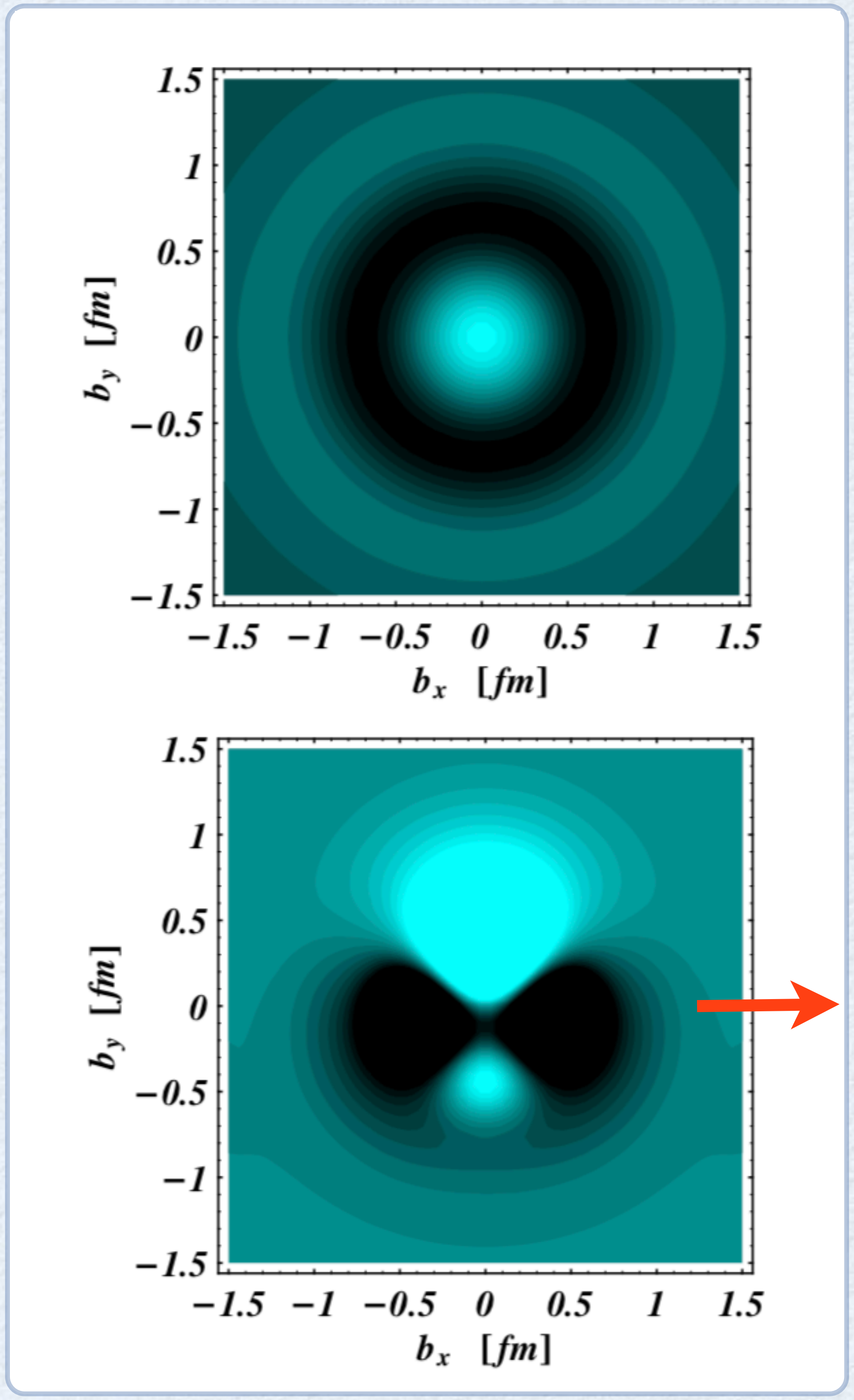


ρ_0

$\lambda = \lambda' = +1/2$

ρ_T

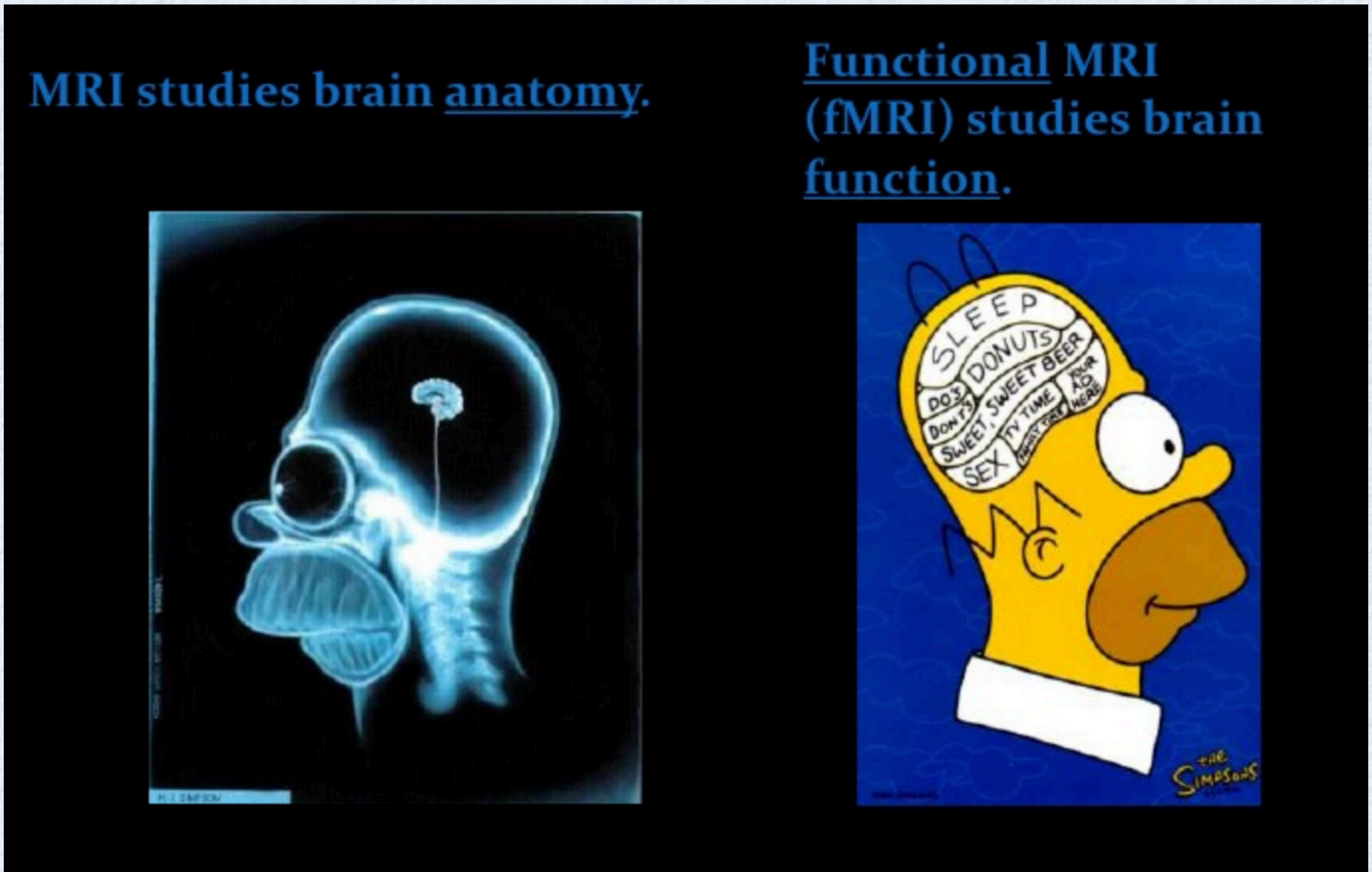
$s_\perp = -s'_\perp = +1/2$



Tiator, Vdh(2011)

large quadrupole

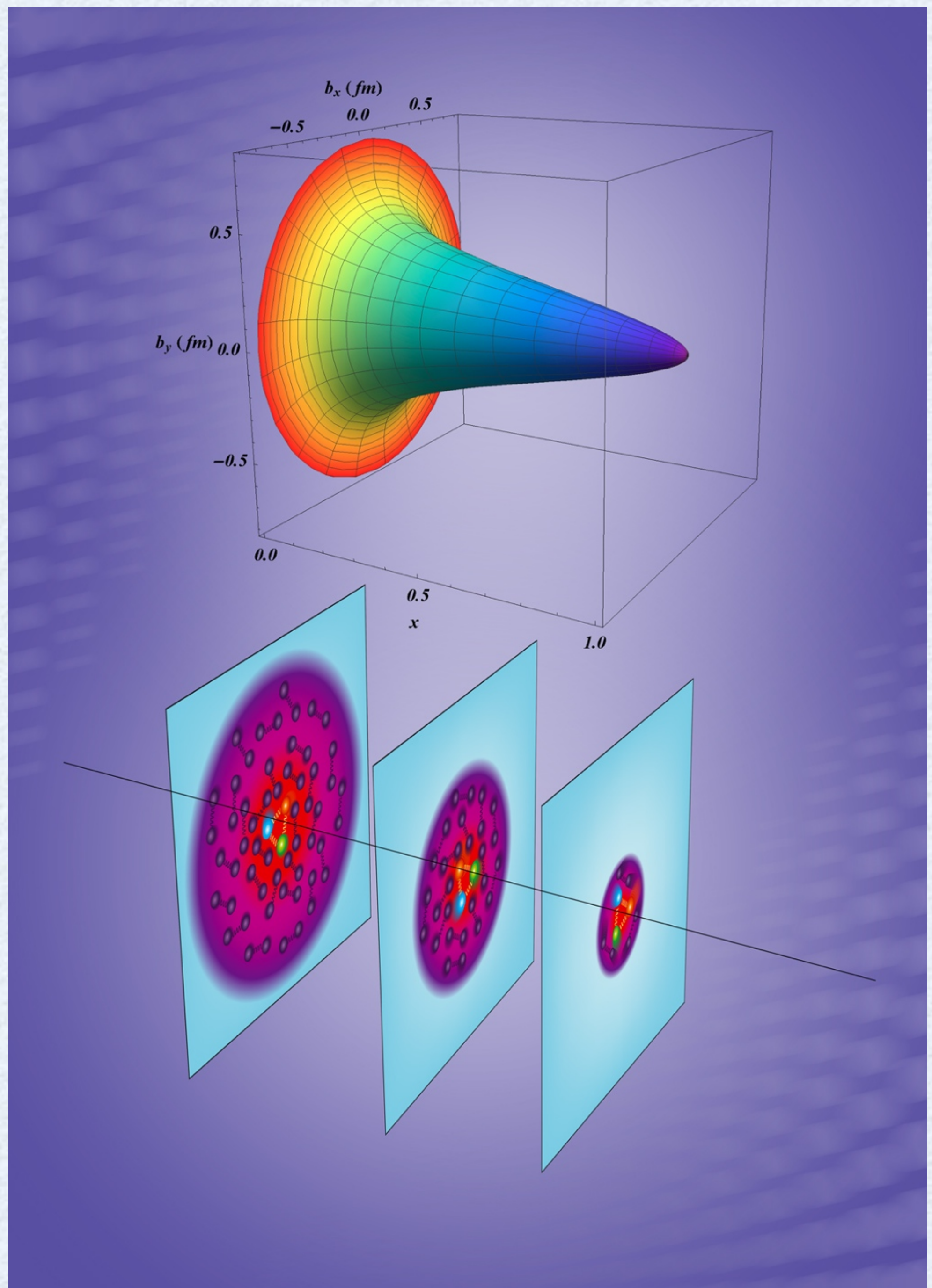
Structure vs dynamics:
Quark spatial vs momentum distributions



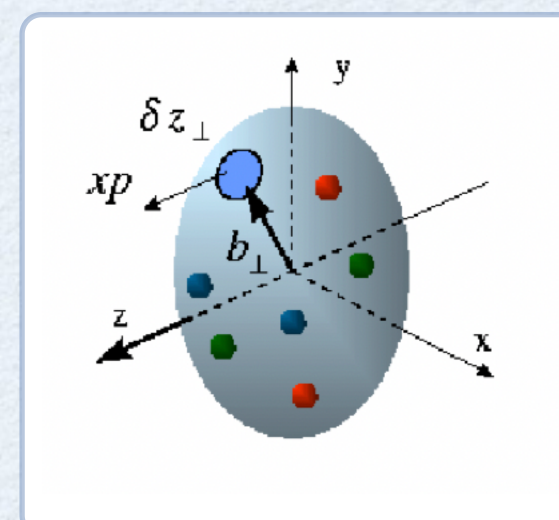
Correlations in transverse position/longitudinal momentum

elastic scattering → **GPDs** ← **DIS**

quark distributions in **transverse position space**



quark distributions in **longitudinal momentum**



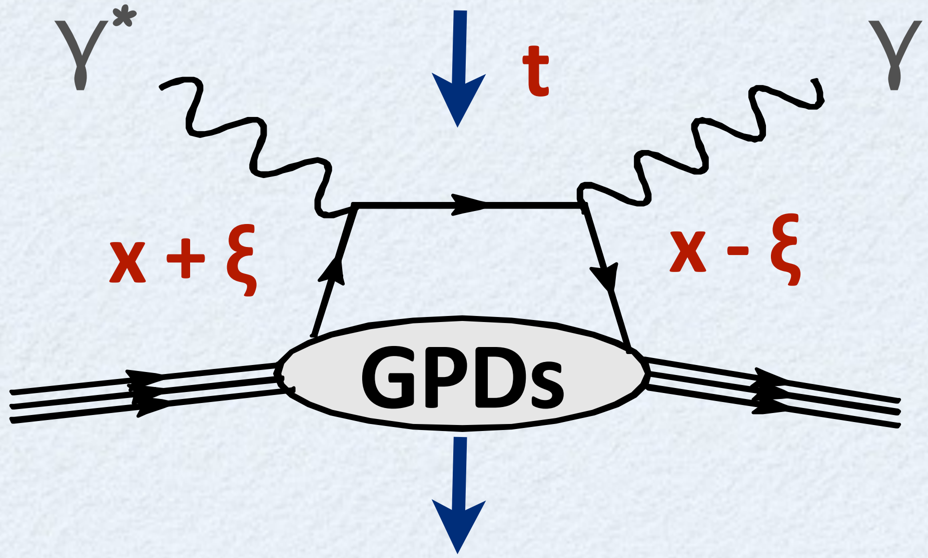
proton 3D imaging

Burkardt(2000, 2003)

Belitsky, Ji, Yuan (2004)

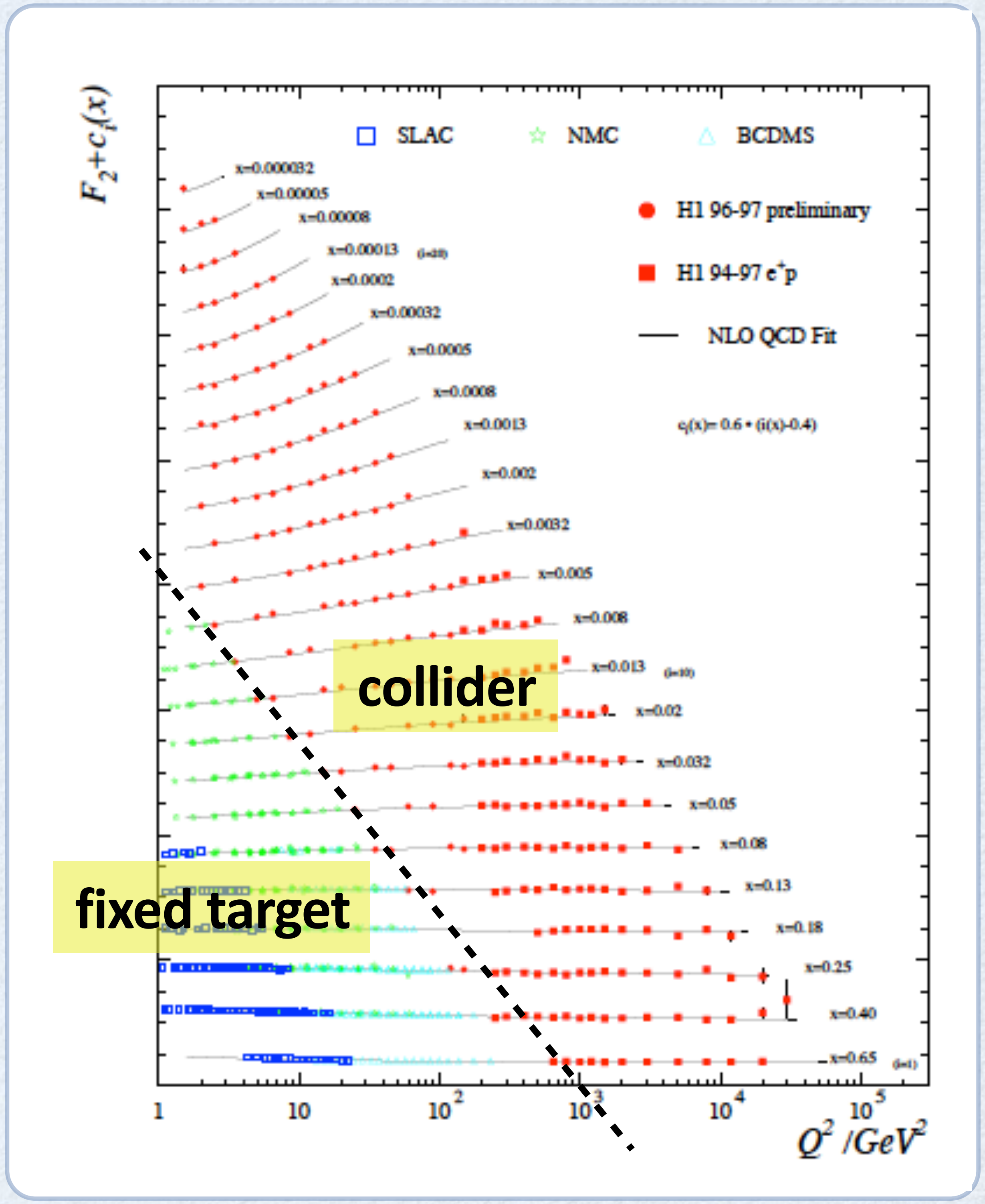
DVCS: tool to access GPDs

$Q^2 >> 1$ GeV^2



GPD(x, ξ, t)

world data on proton F_2



- at large Q^2: **QCD factorization theorem**

  Müller et al (1994)

  Ji (1995) Radyushkin (1996)

  Collins, Frankfurt, Strikman (1996)

  at twist-2: **4 quark helicity conserving GPDs**

- key: Q^2 leverage needed to test **QCD scaling**

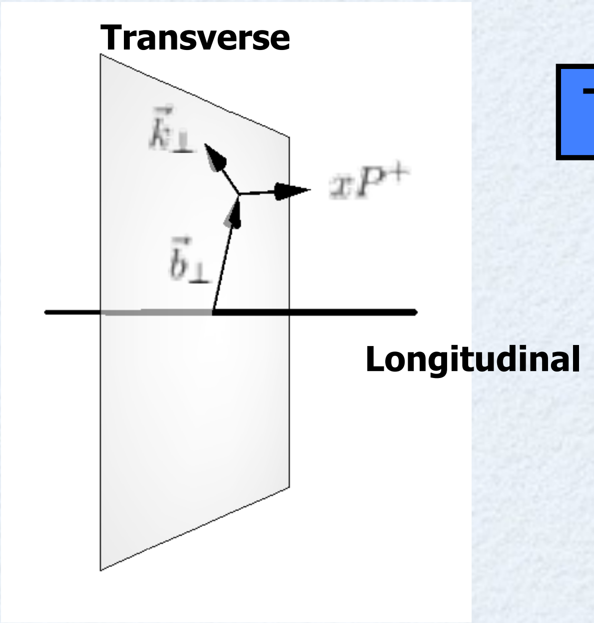
GTMDs

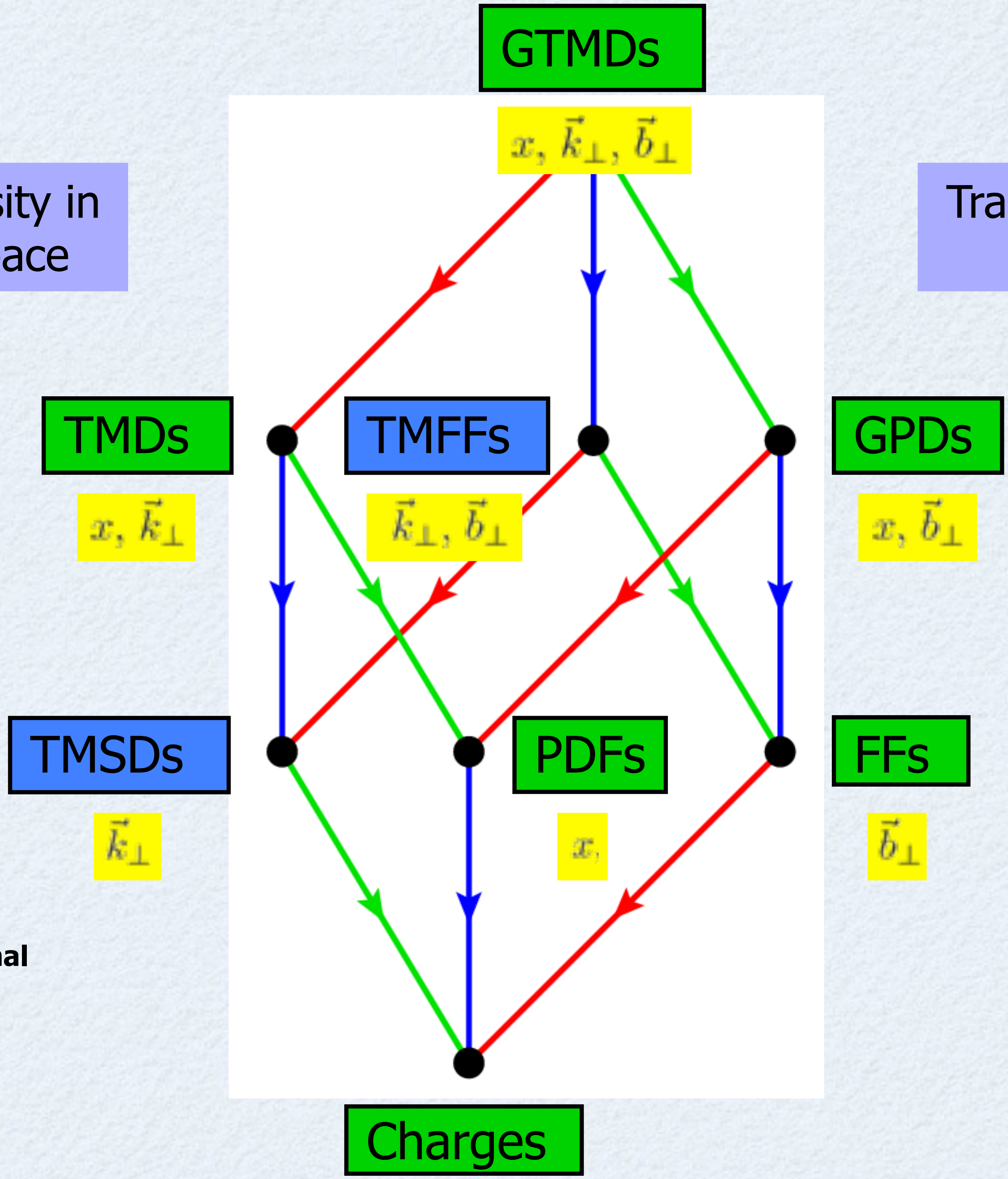
Momentum space $\vec{k}_\perp \leftrightarrow \vec{z}_\perp$, $\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$ **Position space**

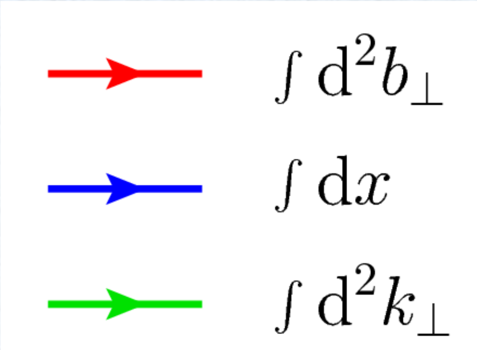
Transverse density in momentum space

Transverse density in position space

Lorcé (2011)







GPDs: known limits

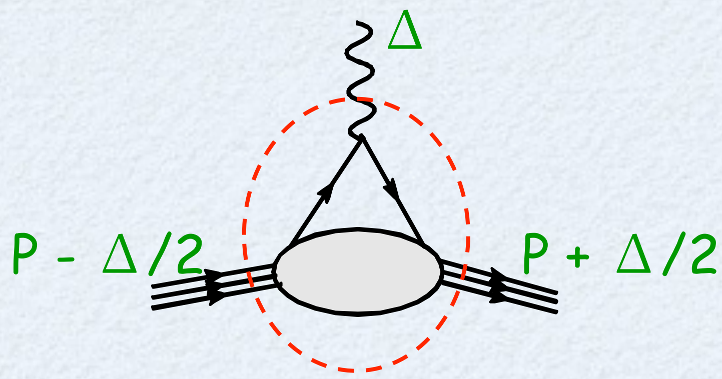
- in forward kinematics (ξ=0, t = 0) : **PDF limit**

$$H^q(x, \xi = 0, t = 0) = q(x)$$

$$\tilde{H}^q(x, \xi = 0, t = 0) = \Delta q(x)$$

$E, \tilde{E}^q$ do not appear in forward kinematics (DIS) ➡ **new information**

- first moments of GPDs : **elastic form factor limit**



t = Δ²

$$\int_{-1}^{+1} dx H^q(x, \xi, t) = F_1^q(t)$$ → Dirac FF

$$\int_{-1}^{+1} dx E^q(x, \xi, t) = F_2^q(t)$$ → Pauli FF

$$\int_{-1}^{+1} dx \tilde{H}^q(x, \xi, t) = G_A^q(t)$$ → axial FF

$$\int_{-1}^{+1} dx \tilde{E}^q(x, \xi, t) = G_P^q(t)$$ → pseudoscalar FF

GPDs: moments, total angular momentum

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

→ form factors of energy-momentum tensor

Polyakov, Weiss (1999)

Polyakov (2003)

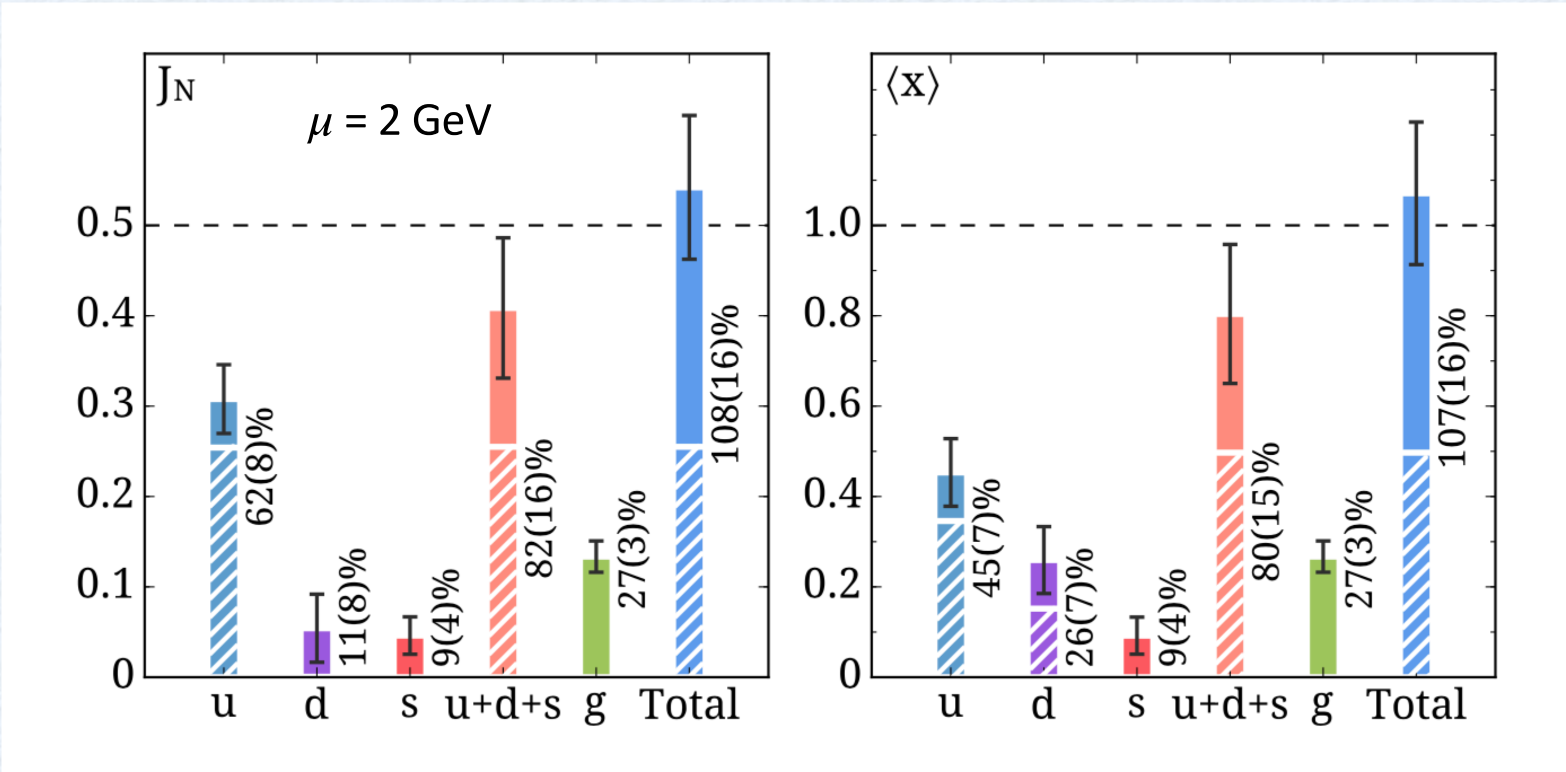
Goeke, Schweitzer et al. (2007)

Ji's angular momentum sum rule

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

lattice QCD calculations at the physical point

Alexandrou et al. (2017)



d, s-quarks carry very small total J in proton, u-quark carries around 60%, gluons around 30%

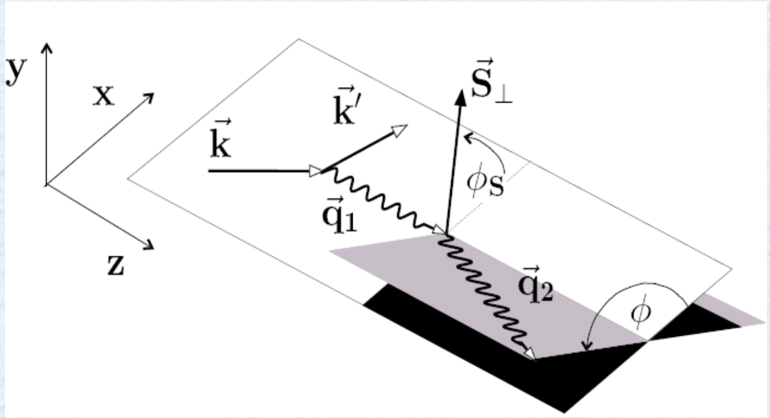
Sharing of momentum and total angular momentum between quarks and gluons identical in proton !

DVCS observables: path towards accessing GPDs

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

$\xi \sim x_B/(2-x_B)$

$k = t/4M^2$



Polarized beam, unpolarized target:

$\Delta\sigma_{LU} \sim \sin\phi\ \{F_1 H + \xi(F_1+F_2)\widetilde{H} + kF_2 E\}d\phi$ ⇒ $H(\xi,t)$

Unpolarized beam, longitudinal target:

$\Delta\sigma_{UL} \sim \sin\phi\ \{F_1\widetilde{H} + \xi(F_1+F_2)(H + \xi/(1+\xi)E)\}d\phi$ ⇒ $\widetilde{H}(\xi,t)$

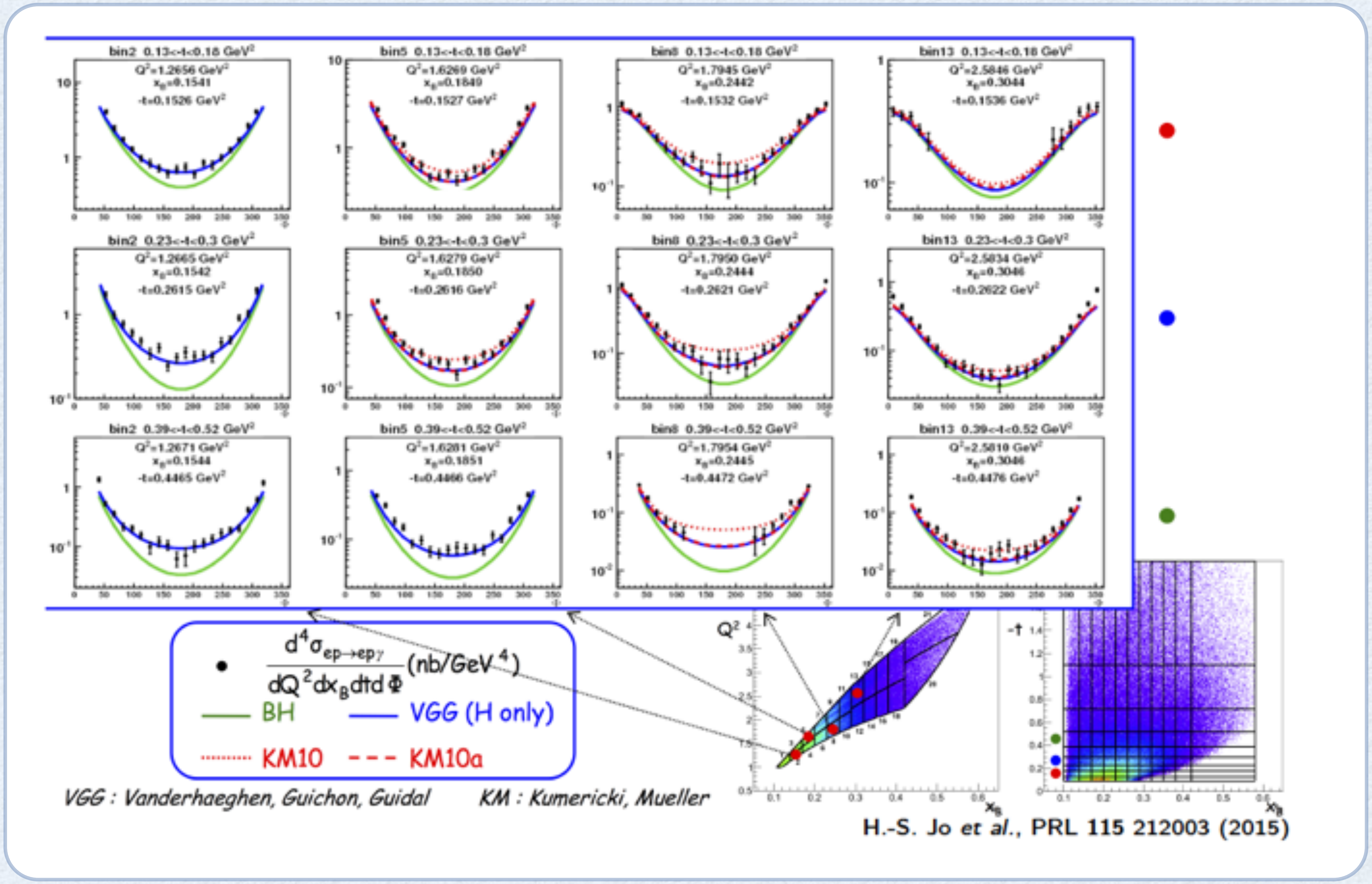
Unpolarized beam, transverse target:

$\Delta\sigma_{UT} \sim \cos\phi\sin(\phi_s-\phi)\{k(F_2 H - F_1 E)\}d\phi$ ⇒ $E(\xi,t)$

Unpolarized total cross section:

Separates h.t. contributions to DVCS ⇒ $\mathcal{Re}(T^{DVCS})$

DVCS unpolarized cross sections



➡ CFF fit extractions from data: Guidal(2008,...) Guidal, Moutarde(2009,...)

Kumericki, Mueller, Passek-Kumericki(2008,...)

Goldstein, Hernandez, Liuti(2011,…)

e.g. review: Kumericki, Liuti, Moutarde: EPJA52 (2016), no.6, 157

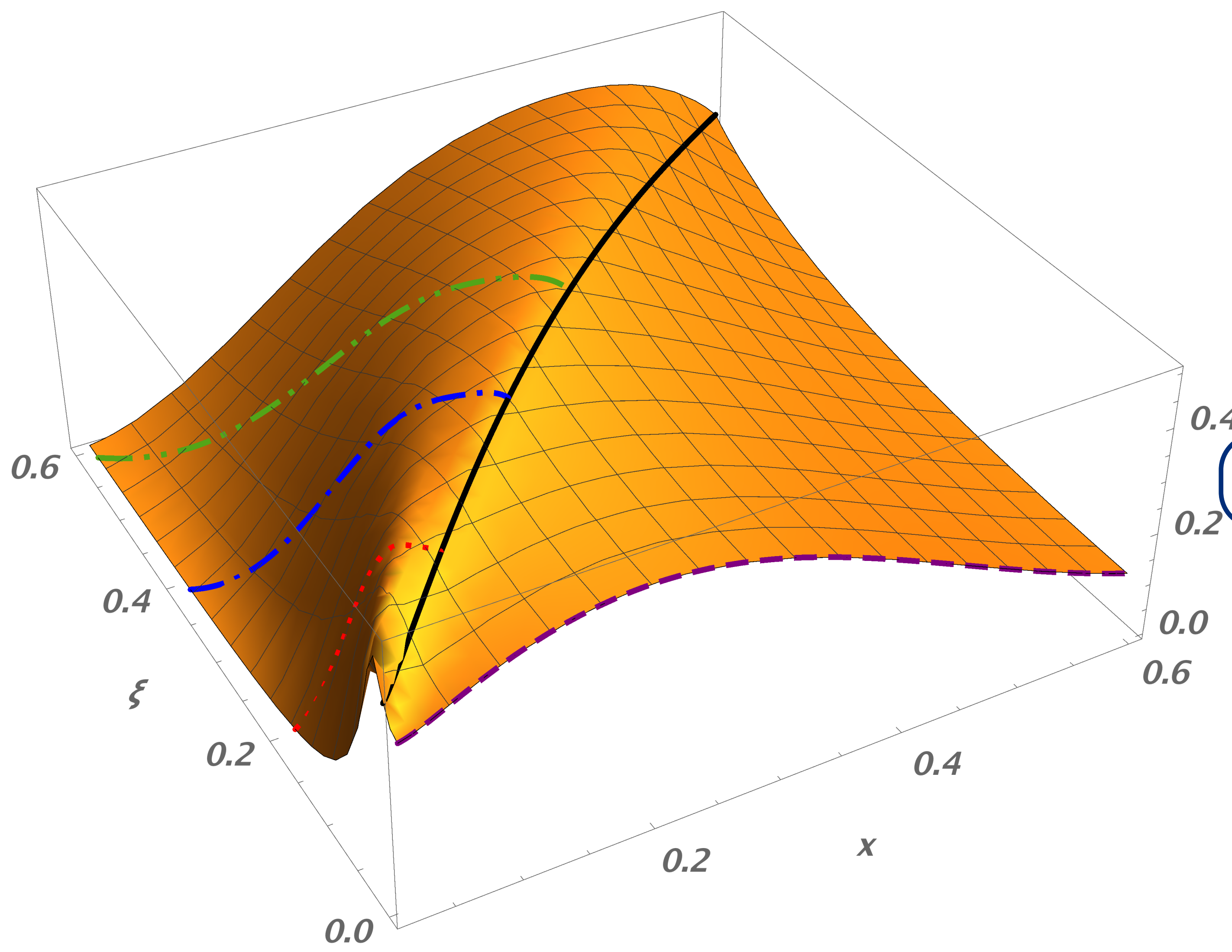
GPD H_+

$$H_+(x,\xi,t) \equiv H(x,\xi,t) - H(-x,\xi,t)$$

DIS: ξ=0 limit
momentum distribution x $q_+(x)$

DVCS: CFF
$\mathcal{H}_{Im}(x,0) = H_+(x,x,0)$
accesses GPD for x = ξ
DD model with $b_v = 1$, $b_v = 5$

DDVCS: e p -> e p $l^+ l^-$
$BSA \sim H_+(x,\xi,0)$
accesses GPD for x < ξ

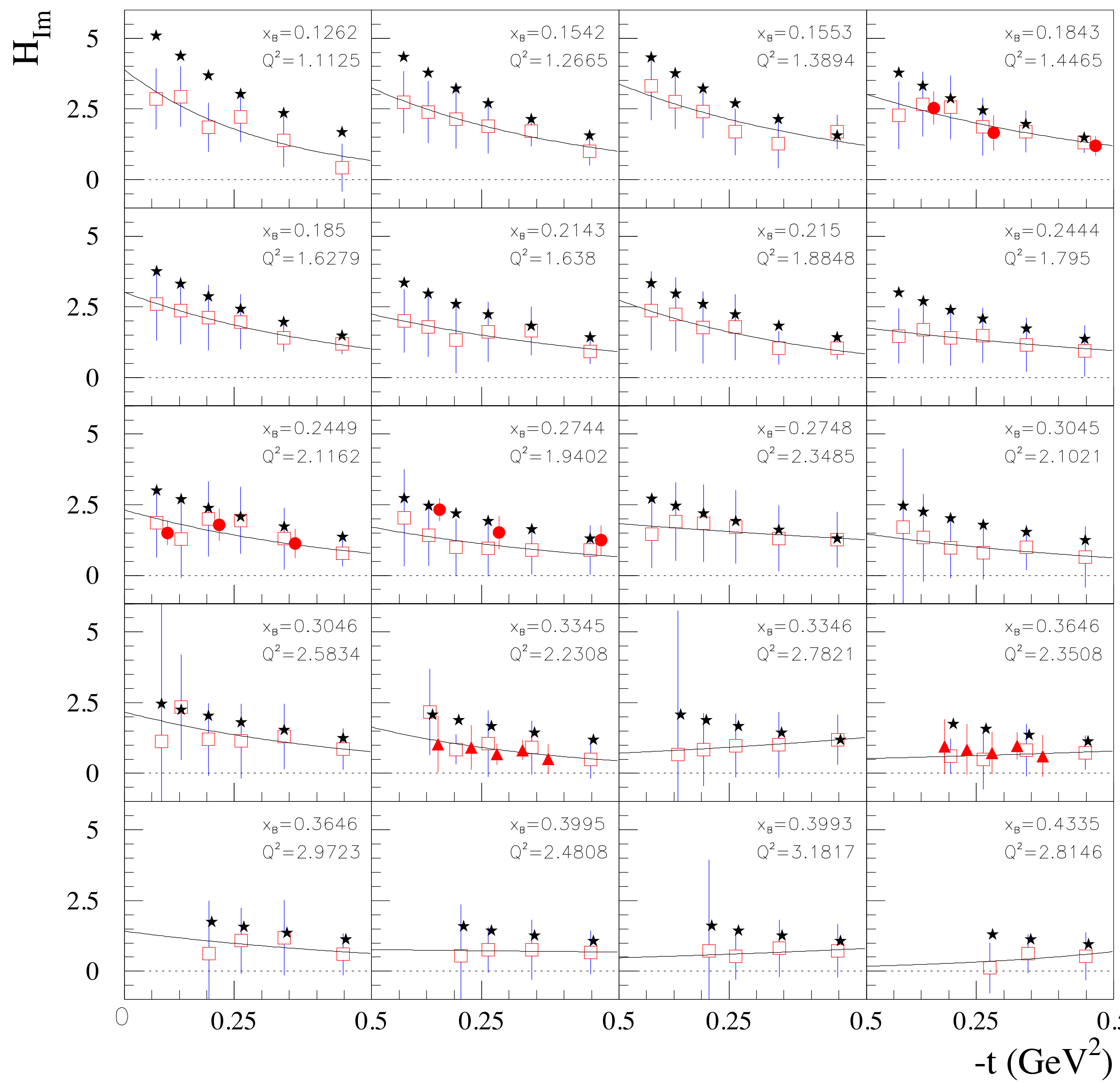


DVCS process accesses Compton Form Factors

$$\mathcal{H}_{Re}(\xi,t) \equiv \mathcal{P}\int_0^1 dx \left\{\frac{1}{x-\xi} + \frac{1}{x+\xi}\right\} H_+(x,\xi,t)$$

$$\mathcal{H}_{Im}(\xi,t) \equiv H_+(\xi,\xi,t)$$

global analysis of JLab 6 GeV data



$$\mathcal{H}_{Im}(\xi, t)$$

red solid circles:

CLAS: σ, A_{LU}, A_{UL}, A_{LL}

red open squares:

CLAS: σ, A_{LU}

red triangles:

Hall A: σ, A_{LU}

black stars

VGG model values

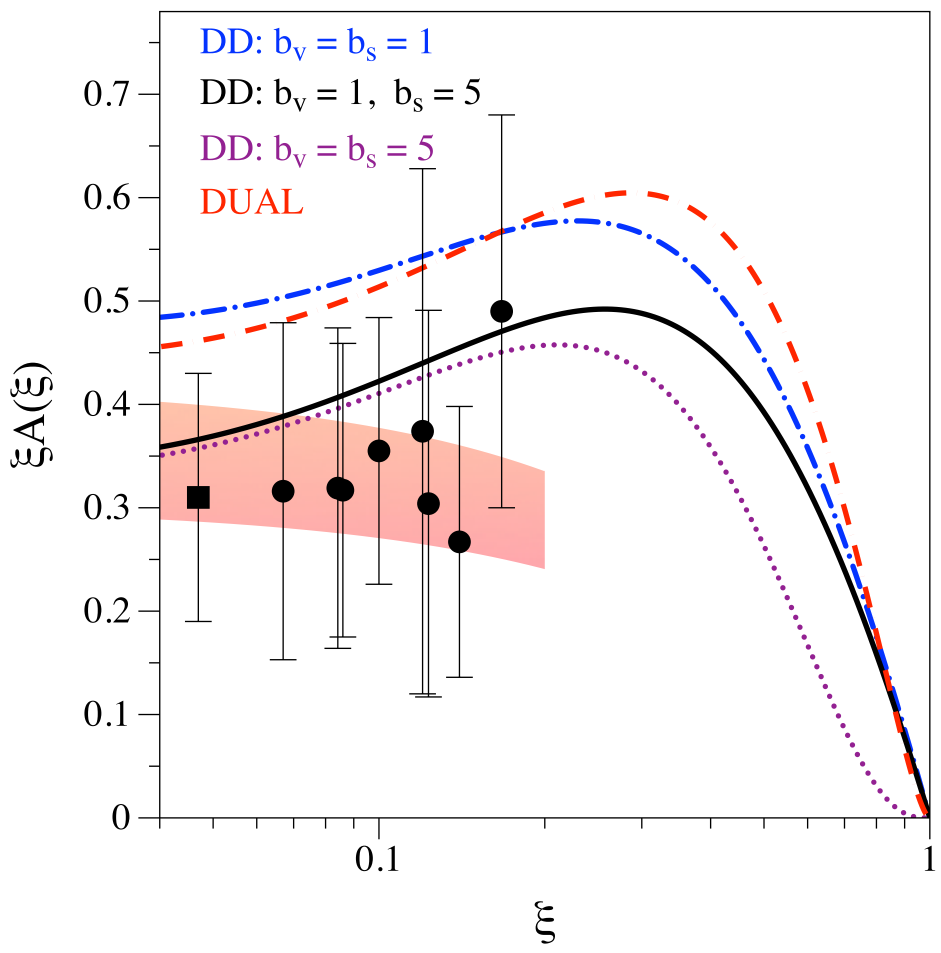
Dupré, Guidal, Vdh (2017)

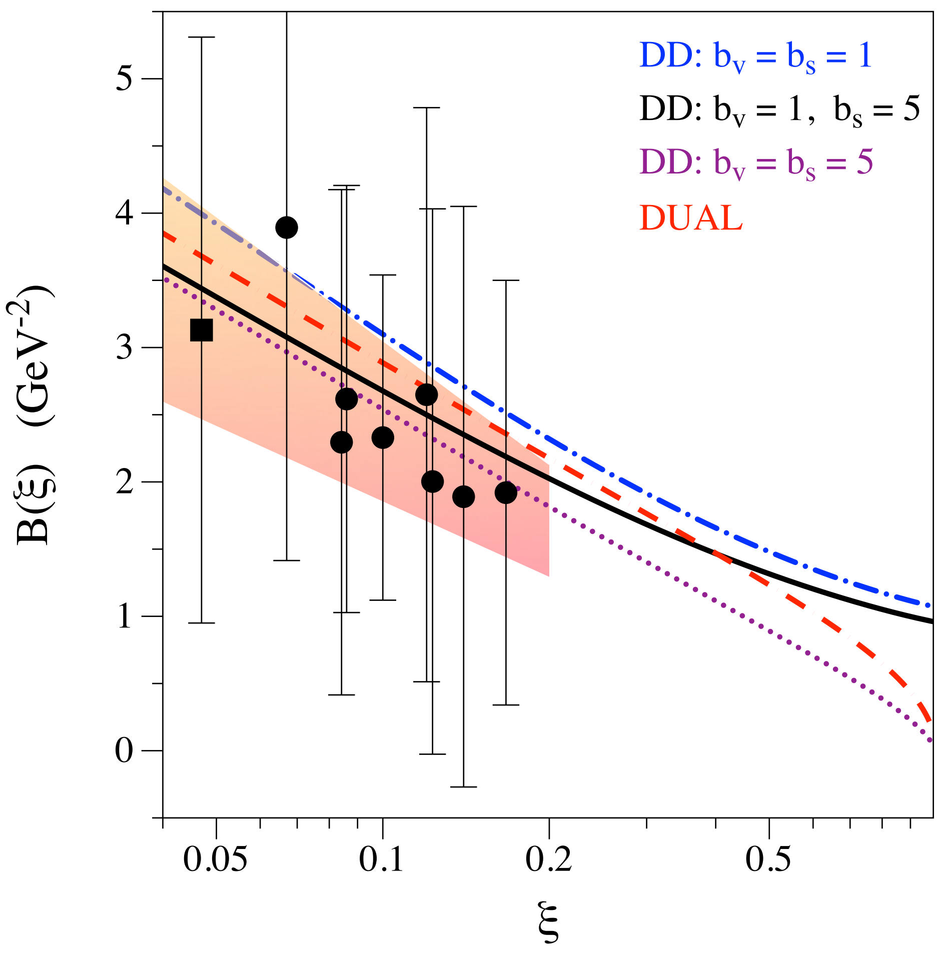
CFF $\mathcal{H}_{\mathrm{Im}}$:

$$\mathcal{H}_{Im}(\xi, t) = A(\xi)e^{B(\xi)t}$$

black circles: CFF fit of JLab data — **Dupré, Guidal, Vdh(2017)**

black squares: CFF fit of HERMES data — **Guidal, Moutarde(2009)**





$$A(\xi) = a_A(1-\xi)/\xi$$

red bands:

1- parameter

fits of data

$$B(\xi) = a_B \ln(1/\xi)$$

3D imaging

$$\rho^q(x, \mathbf{b}_\perp) = \int \frac{d^2\mathbf{\Delta}_\perp}{(2\pi)^2} e^{-i\mathbf{b}_\perp\cdot\mathbf{\Delta}_\perp} H_-^q(x, \xi = 0, -\mathbf{\Delta}_\perp{}^2)$$

Burkardt(2000)

number density of quarks (q) with longitudinal momentum x at a transverse distance $\mathbf{b}_\perp$ in proton

non-singlet (valence quark) GPDs: $H_-^q(x,0,t) \equiv H^q(x,0,t) + H^q(-x,0,t)$

x-dependent radius

$$\langle b_\perp^2\rangle^q(x) \equiv \frac{\int d^2\mathbf{b}_\perp \mathbf{b}_\perp^2 \rho^q(x,\mathbf{b}_\perp)}{\int d^2\mathbf{b}_\perp \rho^q(x,\mathbf{b}_\perp)} = -4\frac{\partial}{\partial\mathbf{\Delta}_\perp^2} \ln H_-^q(x,0,-\mathbf{\Delta}_\perp{}^2)\Big|_{\mathbf{\Delta}_\perp=0}$$

$$H_-^q(x,0,t) = q_v(x)e^{B_0(x)t} \longrightarrow \langle b_\perp^2\rangle^q(x) = 4B_0(x)$$

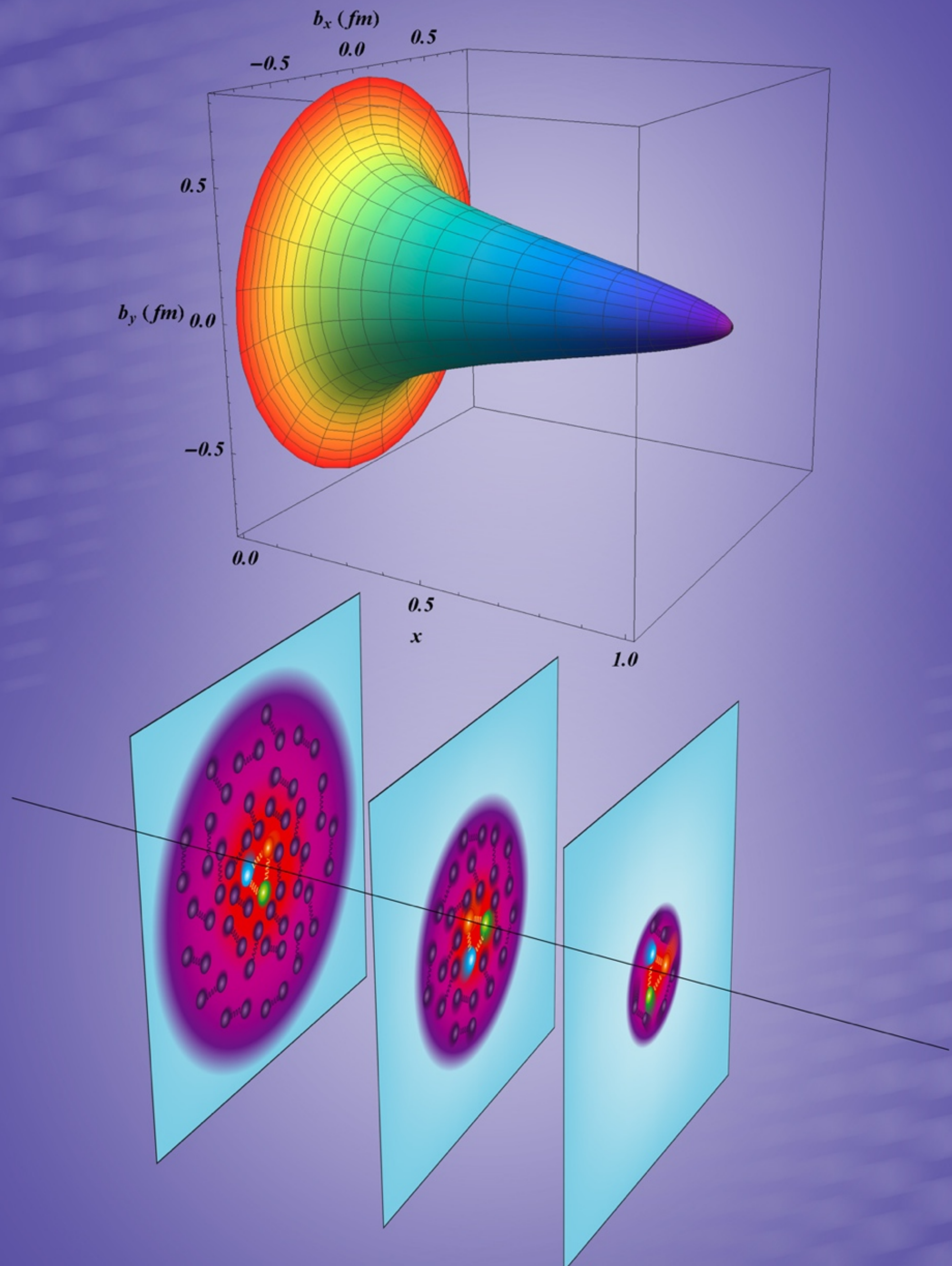
x-independent radius

$$\langle b_\perp^2\rangle^q = \frac{1}{N_q}\int_0^1 dx\, q_v(x)\, \langle b_\perp^2\rangle^q(x)$$

$N_u=2$, $N_d=1$

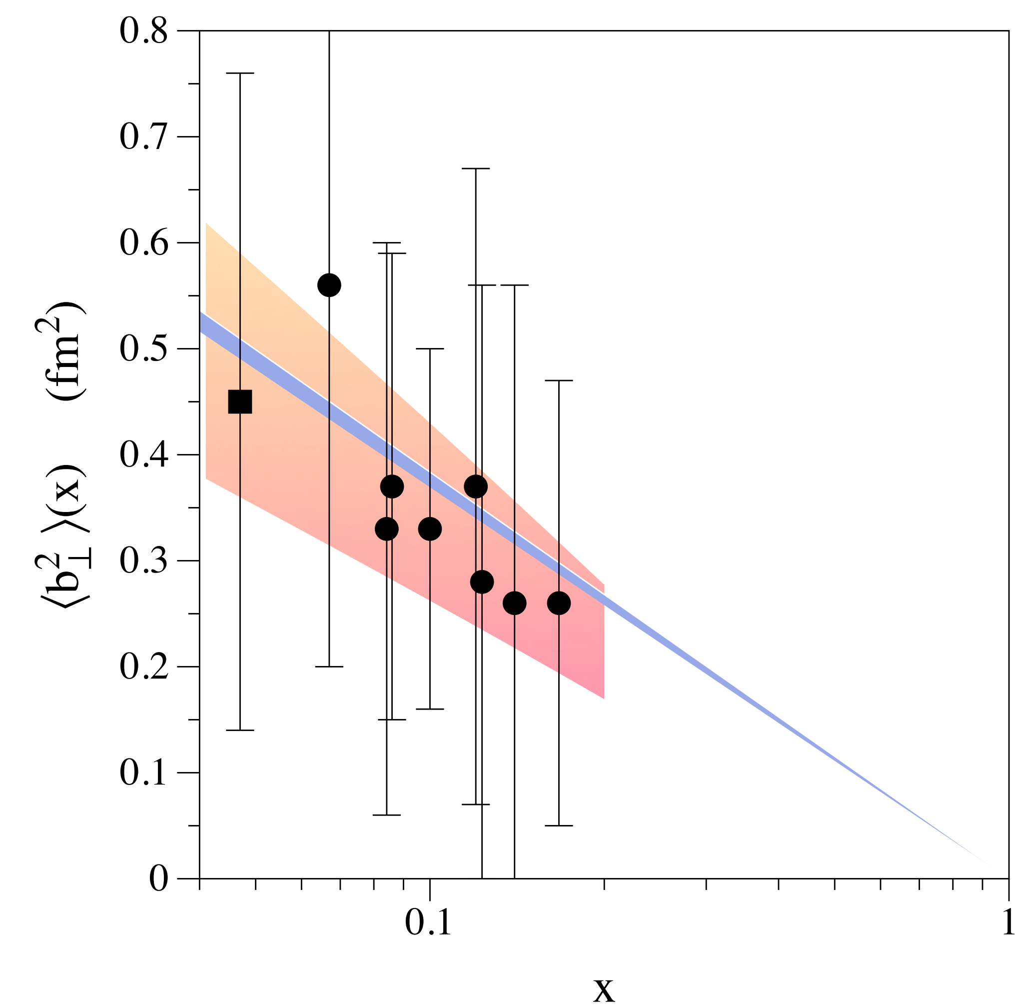
$$\langle b_\perp^2\rangle = 2e_u\langle b_\perp^2\rangle^u + e_d\langle b_\perp^2\rangle^d = 2/3\langle r_1^2\rangle = 0.43 \pm 0.01\ \text{fm}^2$$

Bernauer(2014)



3D imaging of proton

black circles: CFF fit of JLab data



narrow band: $B_0(x) = a_{B_0} \ln(1/x)$

a_{B_0} fixed from elastic scattering

Dupré, Guidal, Niccolai, Vdh(2017)

CFF $\mathcal{H}_{\rm Re}$: dispersion relation formalism

Anikin, Teryaev(2007) Diehl, Ivanov(2007) Polyakov, Vdh(2008)

Kumericki-Passek,Mueller,Passek (2008) Goldstein,Liuti(2009) Guidal,Moutarde,Vdh (2013)

➡ once-subtracted fixed-t dispersion relation

$$\mathcal{H}_{Re}(\xi,t) = -\Delta(t) + \mathcal{P}\int_0^1 dx\, H_+(x,x,t)\left[\frac{1}{x-\xi}+\frac{1}{x+\xi}\right]$$

ξ-independent subtraction function

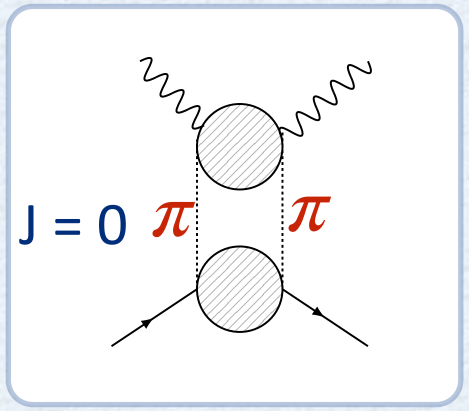
known from CFF $\mathcal{H}_{Im}(x,t)$

$$\Delta(t) \equiv \frac{2}{N_f}\int_{-1}^{1} dz\, \frac{D(z,t)}{1-z}$$

D-term

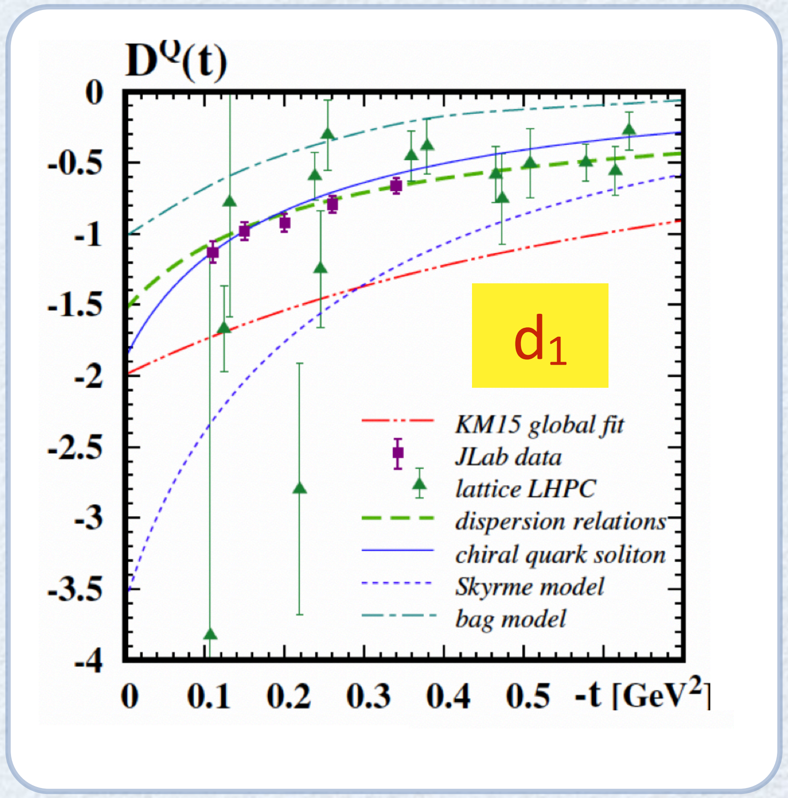
Polyakov, Weiss (1999)

$$D(z,t) = (1-z^2)\sum_{\substack{n=1 \\ n\ odd}}^{\infty} d_n(t)\, C_n^{3/2}(z)$$



dispersive estimate

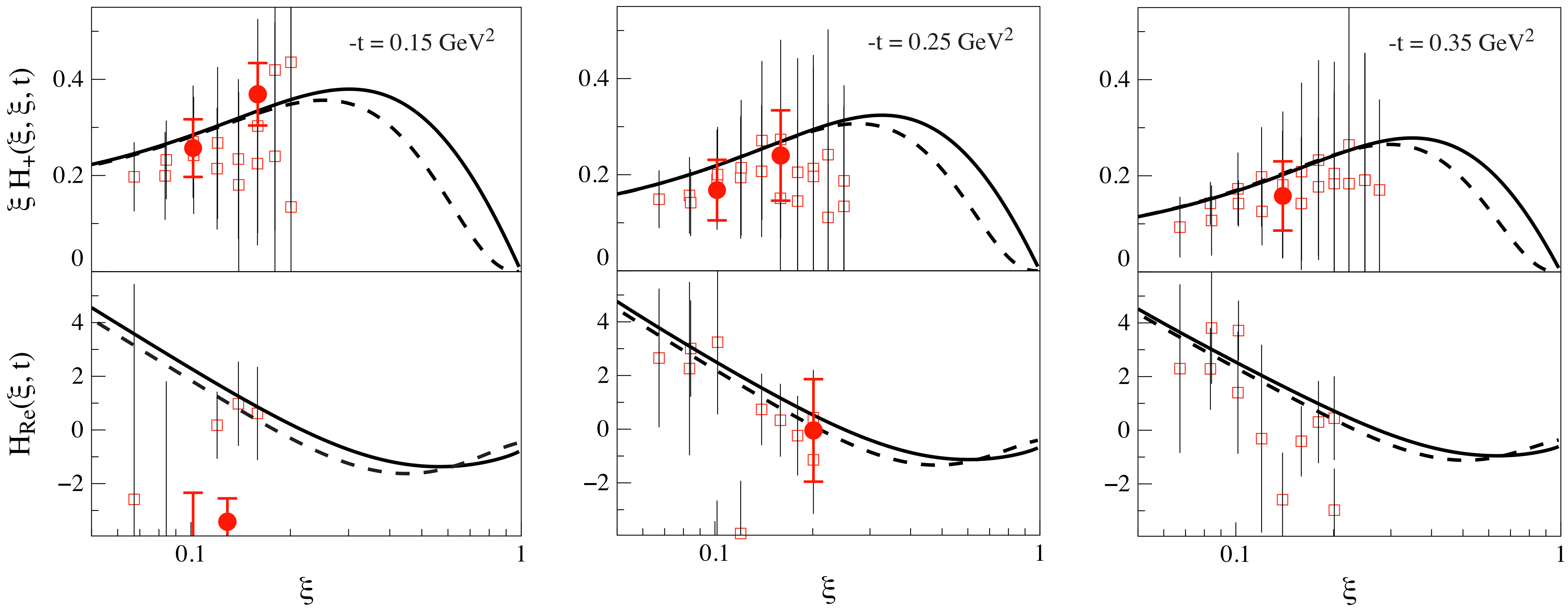
Pasquini, Polyakov, Vdh(2014)



Burkert, Elouadrhiri, Girod (2018)

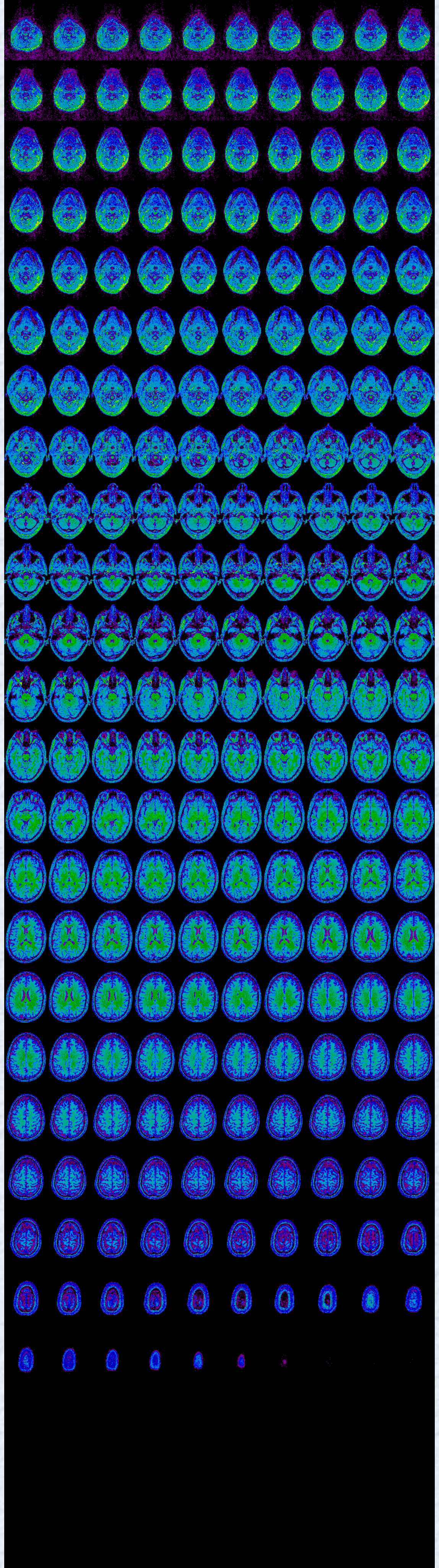
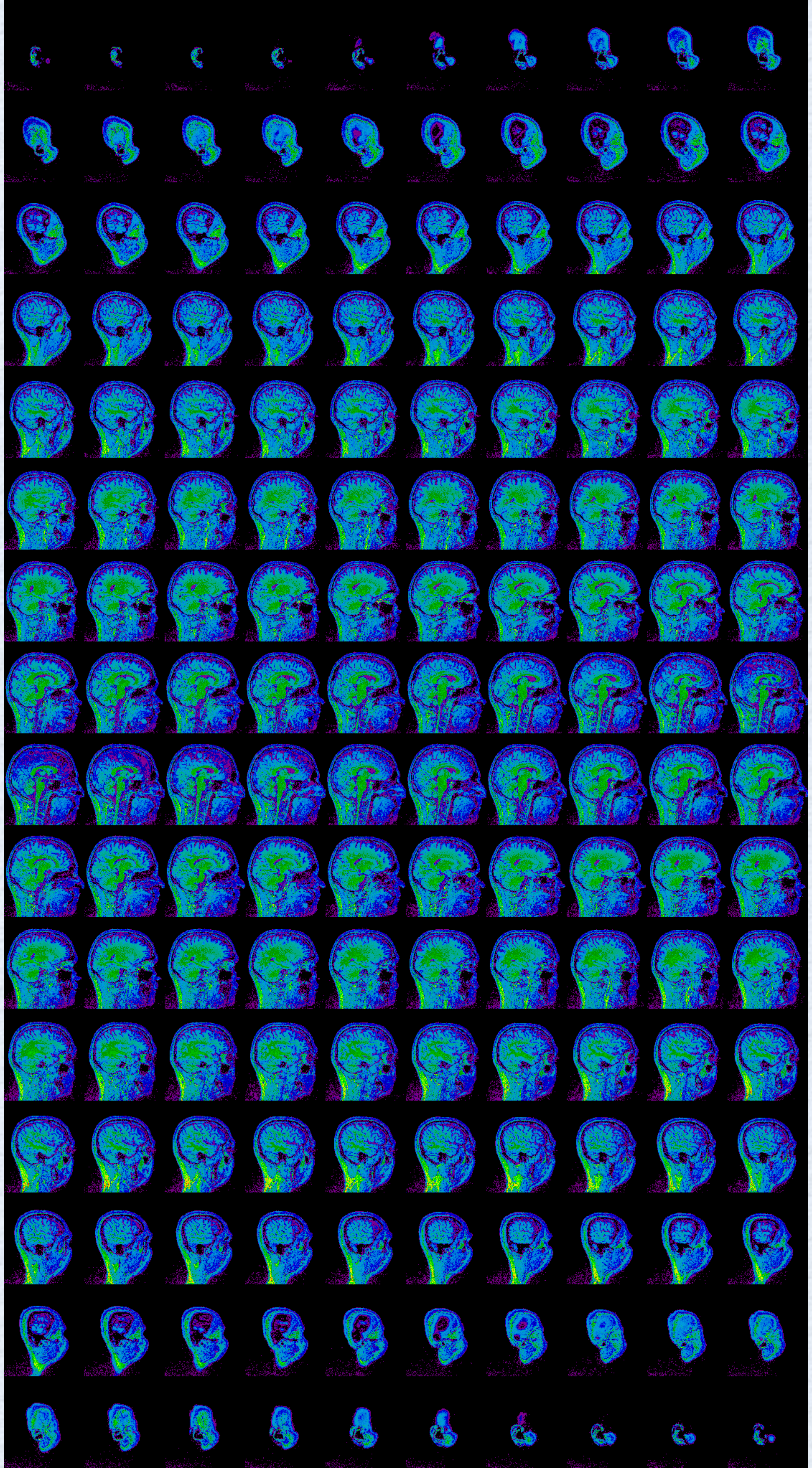
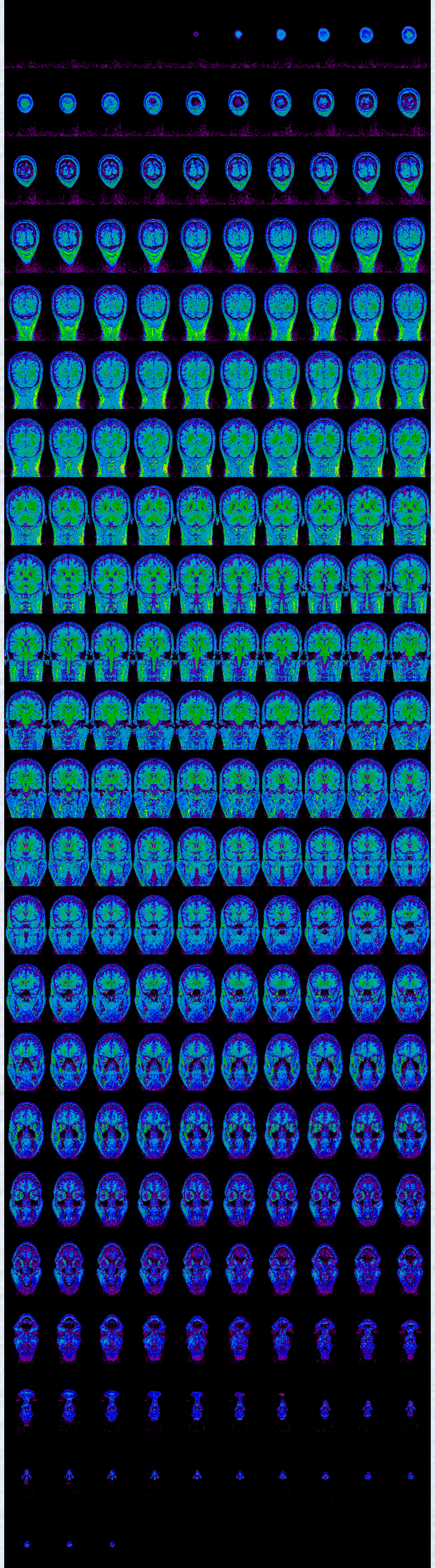
experimental strategy for CFF $\mathcal{H}_{Re}$: direct extraction vs dispersion formalism

red solid circles: CLAS: σ, A_{LU}, A_{UL}, A_{LL} red open squares: CLAS: σ, A_{LU}



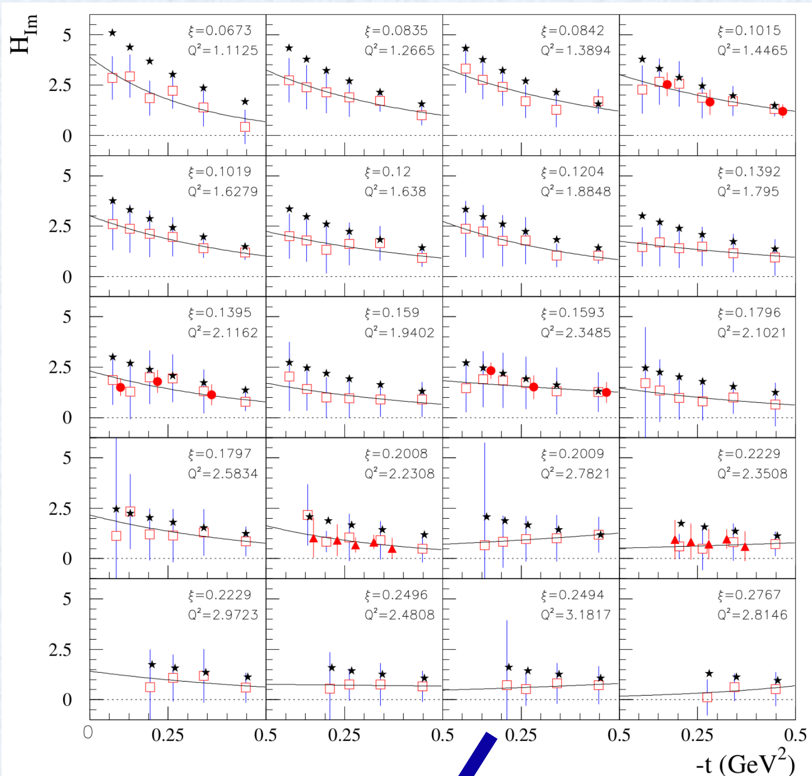
Curves for Δ(t) = 0; Δ(t) < 0 would shift H_{Re} curves up !

Dupré, Guidal, Niccolai, Vdh (2017)

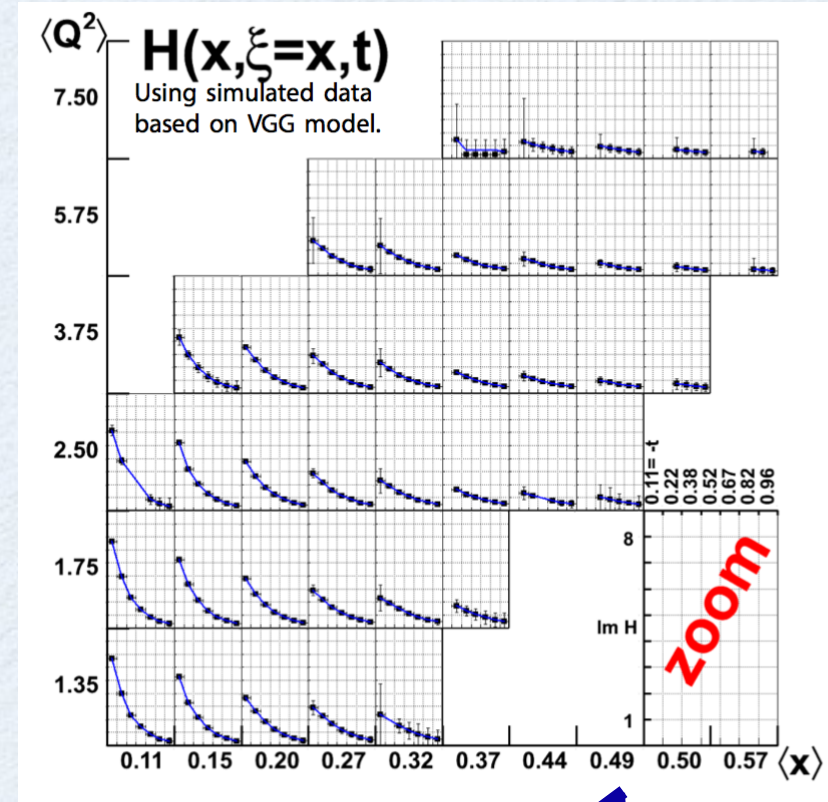




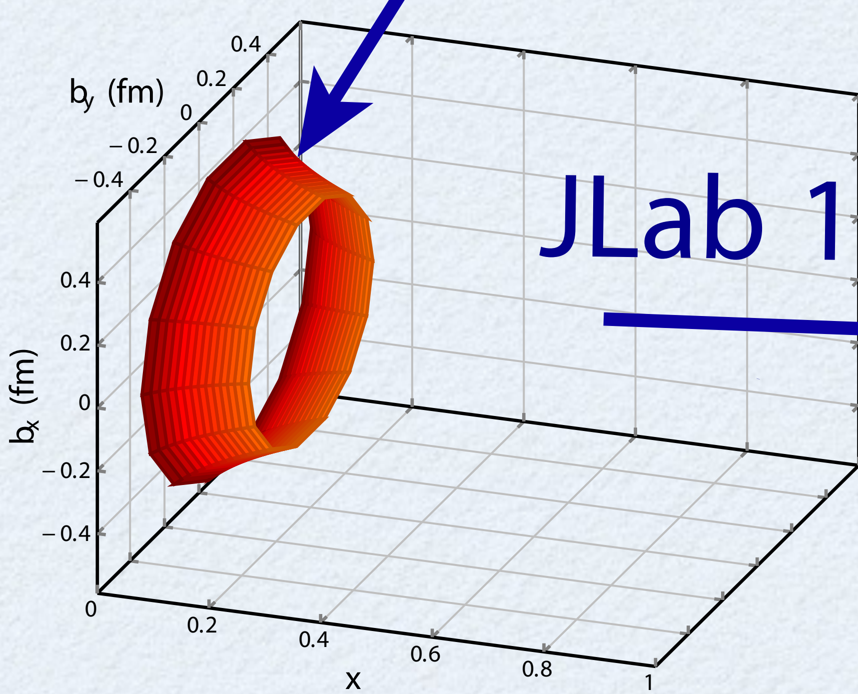
Projections for CFFs at JLab 12 GeV

Düpré-Guidal-Vanderhaeghen-PRD **95** 011501 (R) (2017)

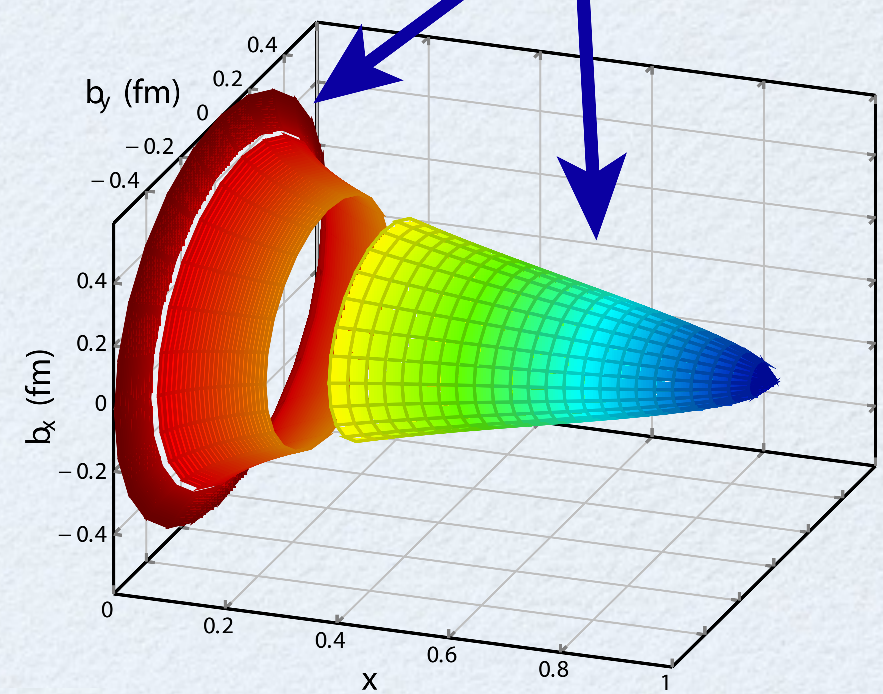


CLAS12 projections E12-06-119 with DVCS A_{UL} and A_{LU}

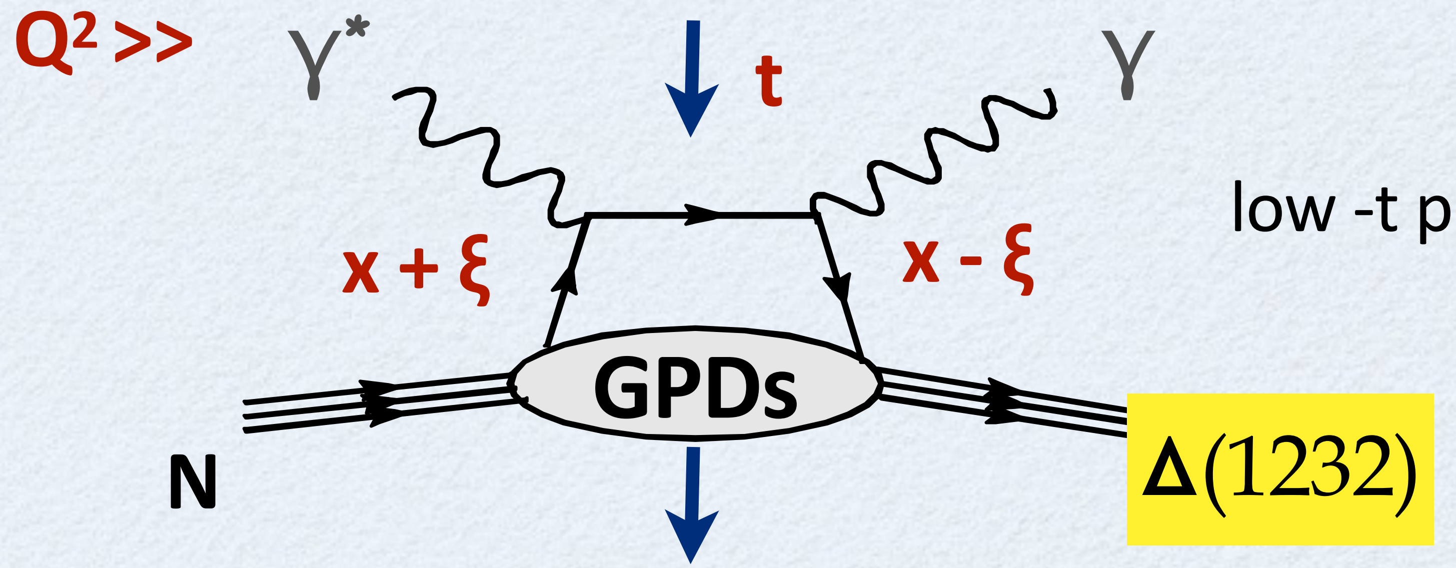




JLab 12 GeV



N → Δ(1232) DVCS and GPDs



low -t process: $-t \ll Q^2$

8 twist-2 **GPDs(x, ξ, t)**: 4 unpolarized, 4 polarized

➡ unpolarized GPDs: H_M, H_E, H_C, H_4 **Frankfurt, Polyakov, Strikman, Vdh (2000)**

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

Jones-Scadron e.m. FFs for N -> Δ

Similar relations for polarized GPDs

N → Δ(1232) magnetic dipole GPD

large N_c :

$$H_M(x,\xi,t) = 2\frac{G_M^*(0)}{\kappa_V}\{E^u(x,\xi,t) - E^d(x,\xi,t)\}$$

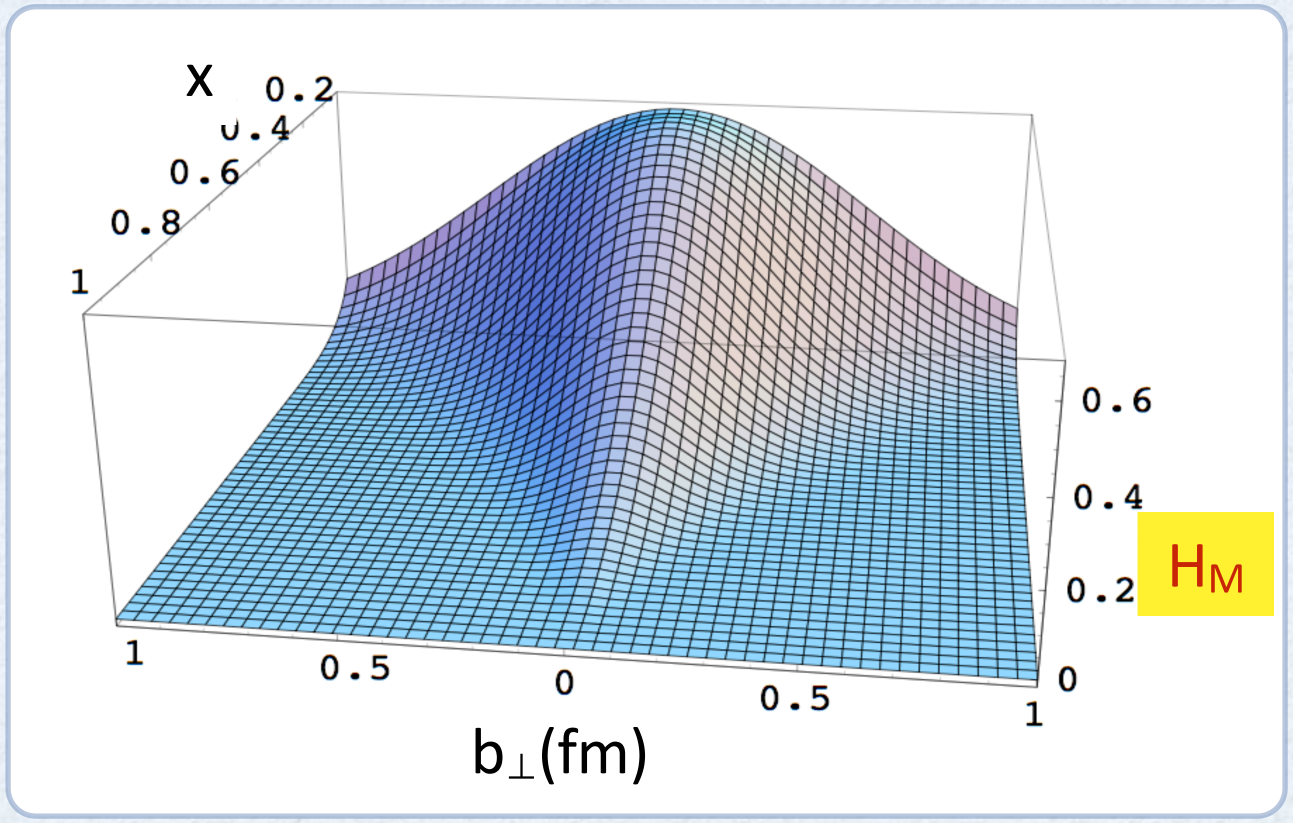
Frankfurt, Polyakov, Strikman, Vdh (2000)

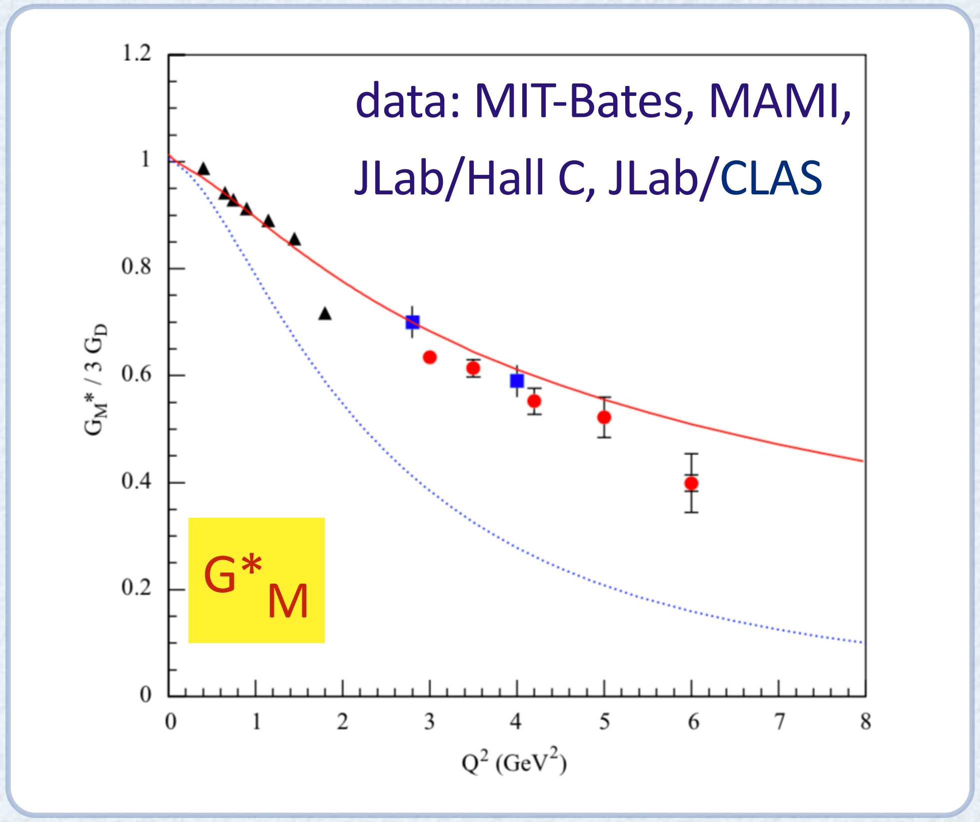
$$G_M^*(t) = \frac{G_M^*(0)}{\kappa_V}\int_{-1}^{+1}\{E^u(x,\xi,t) - E^d(x,\xi,t)\} = \frac{G_M^*(0)}{\kappa_V}\{F_2^p(t) - F_2^n(t)\}$$

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

exp : $G_M^*(0) \simeq 3.02$

large N_c + nucleon Regge GPD model





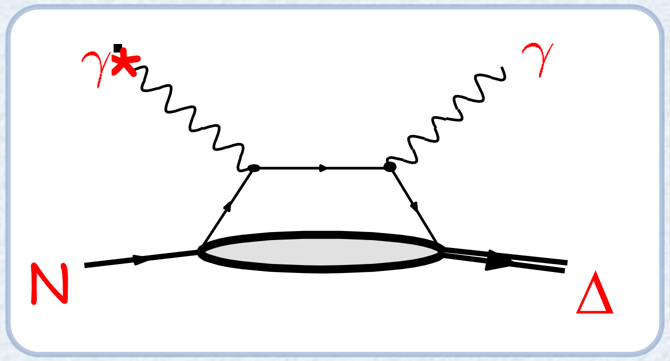
Guidal, Polyakov, Radyushkin, Vdh (2005)

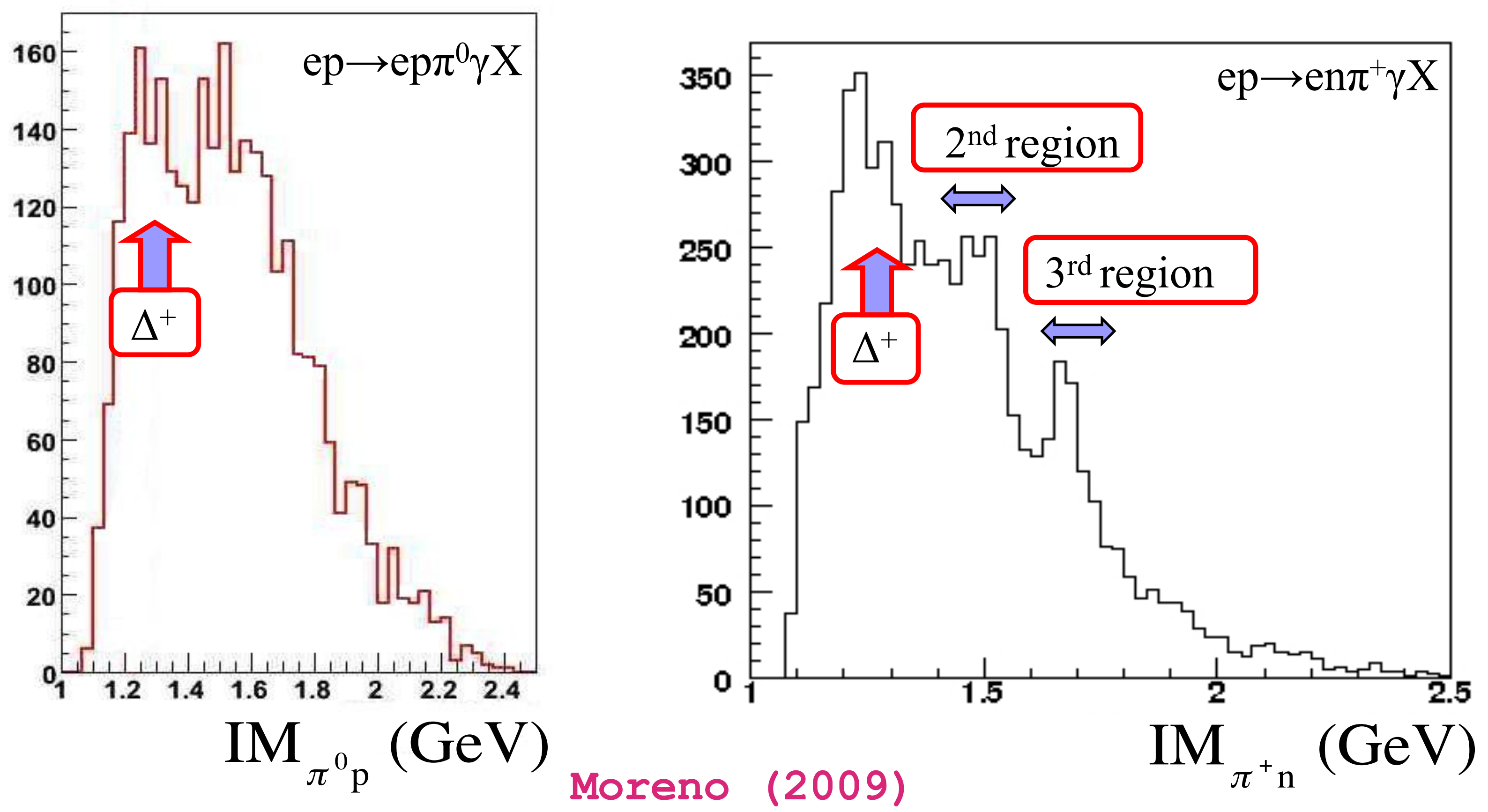
$N \to \Delta, N^*$ DVCS: experiment

events seen in CLAS6

W > 2 GeV

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





unique opportunity for CLAS12

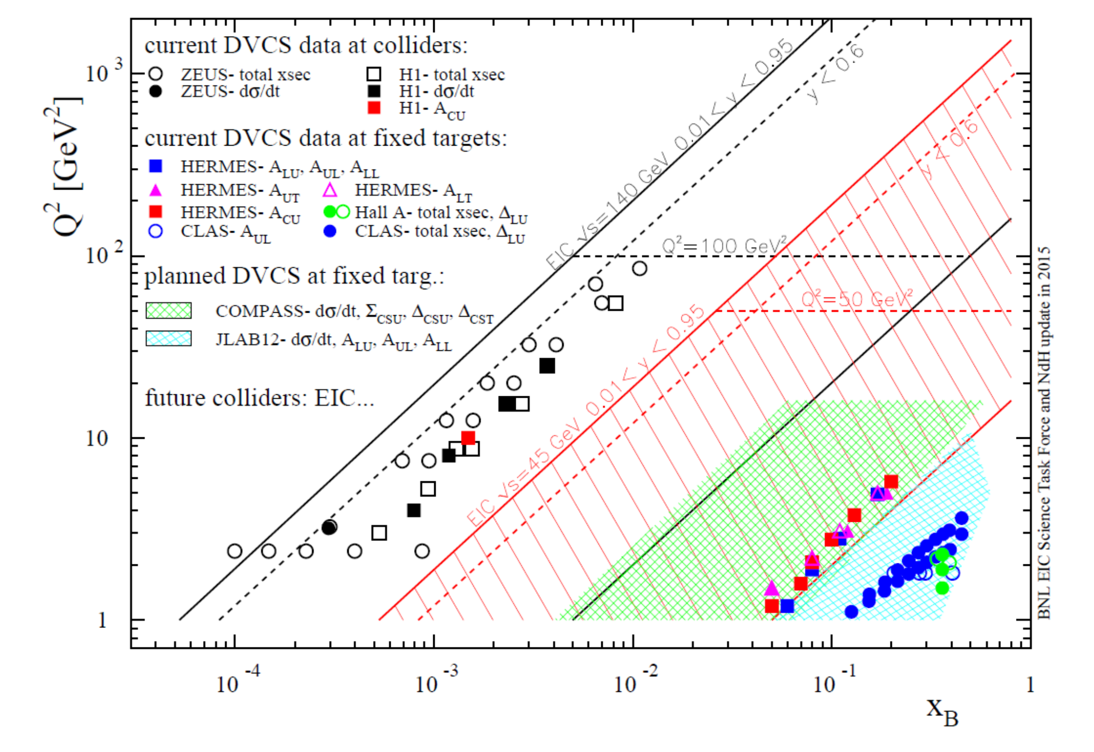
Outlook

- elastic / transition FFs have allowed to get a first glimpse at the spatial distributions of quarks in nucleons

- GPDs allow for a proton imaging in longitudinal momentum and transverse position: established for nucleon, new opportunities on quark structure in nucleon resonance excitations

- global analysis of JLab 6 GeV data have shown a proof of principle of such 3D imaging (tools available: fitters, neural network, dispersive techniques)

- systematic 3D imaging is in reach: COMPASS, JLab 12 GeV,...EIC



imaging and visualisation at the femtoscale just started