



The 8th International Workshop on the Physics of Excited Nucleons

# NSTAR 2011

MAY 17-20, 2011  
JEFFERSON LAB † NEWPORT NEWS VA

**TOPICS**

- \* New results on pseudoscalar and vector meson production
- \* "Complete" experimental determinations of meson-production amplitudes
- \* Reaction models, PWA and resonance parameters
- \* Baryon resonance structure and quark models
- \* Baryon resonances in  $N_c$  expansion
- \* Baryon structure at short and long distances
- \* Dynamical models and coupled channel analysis
- \* Dyson-Schwinger approaches to baryon resonances
- \* Baryon resonances in lattice QCD
- \* Baryon resonances in holographic QCD
- \* Chiral symmetry and baryon resonances
- \* Laboratory reports and future projects

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<http://conferences.jlab.org/nstar2011/>

Jefferson Lab

# Transverse quark densities

Marc Vanderhaeghen  
Johannes Gutenberg Universität, Mainz

JLab, May 17-20, 2011



# Outline

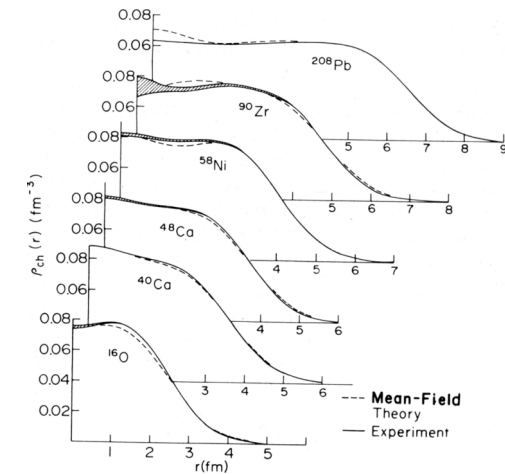
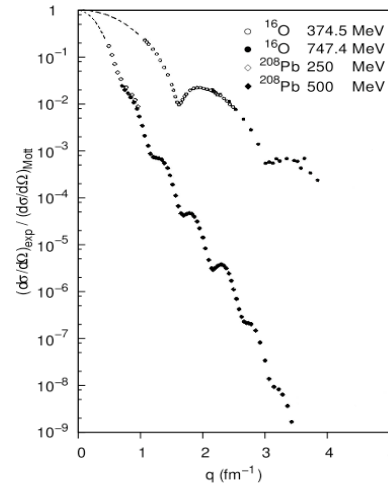
## ➔ What do we know about the transverse structure (imaging) of hadrons ?

- Light-front charge densities  $\leftrightarrow$  elastic nucleon **Form Factors**
- Shape of hadrons  $\leftrightarrow$  higher **e.m. moments** of transverse charge densities (systems of spin 1 or higher)
- Electromagnetic structure of the  **$\Delta(1232)$  resonance**  
transverse charge densities from recent lattice results
- Baryon resonance structure / **transition charge densities**  
 $\leftrightarrow$   $N \rightarrow N^*$  **Transition Form Factors**

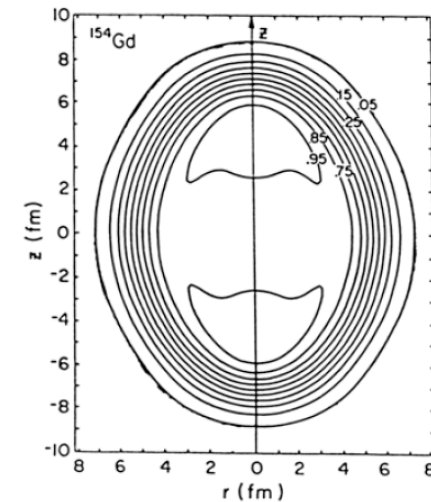
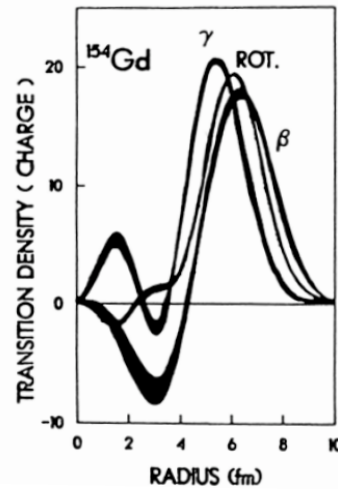
$\Delta(1232)$ ,  $P_{11}(1440)$ ,  $S_{11}(1535)$ ,  $D_{13}(1520)$ ,...

# size and shape of non-relativistic many-body systems

**Sizes** of nuclei  
as revealed through  
**elastic** electron scattering



**Shapes** of deformed nuclei  
as revealed through  
**inelastic** electron scattering



perspective on "Shape of Hadrons" : Alexandrou, Papanicolas, Vdh (2011)

# size of proton : electric charge radius



Lamb shift in muonic H (PSI)

Pohl et al.  
Nature 466 (2010) 213

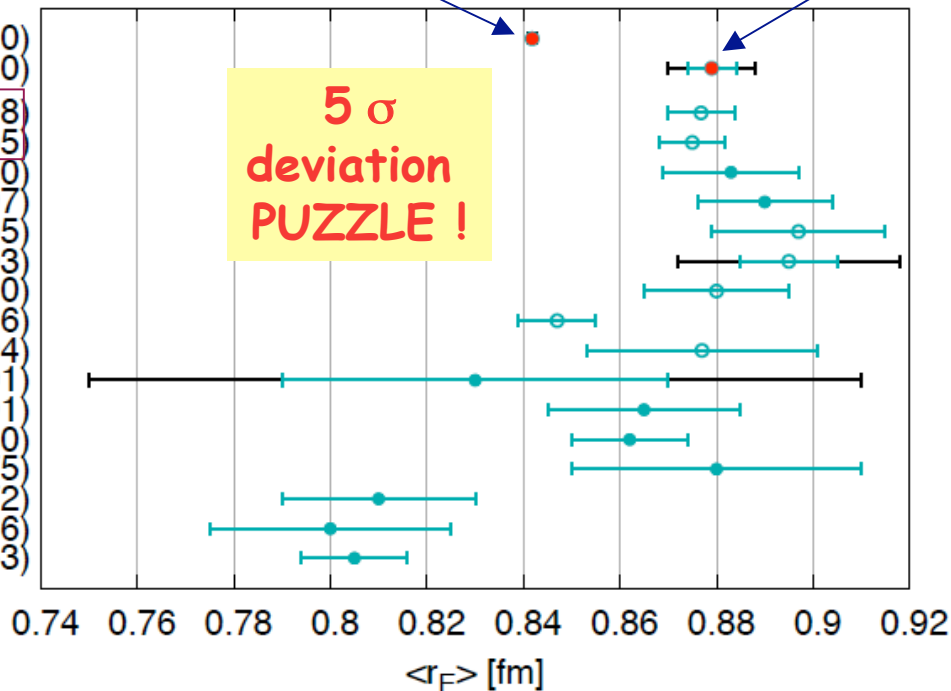
$$\langle r_E \rangle = 0,84184(67) \text{ fm}$$

ep-scattering (MAMI)

Bernauer et al.  
PRL 105 (2010) 242001

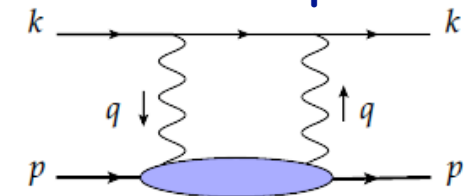
$$\langle r_E \rangle = 0,879(8) \text{ fm}$$

- Pohl et al. (2010)
- Bernauer et al. (2010)
- CODATA 06 (2008)
- CODATA 02 (2005)
- Melnikov et al. (2000)
- Udem et al. (1997)
- Blunden et al. (2005)
- Sick et al. (2003)
- Rosenfelder et al. (2000)
- Mergell et al. (1996)
- Wong et al. (1994)
- Eschrich et al. (2001)
- McCord et al. (1991)
- Simon et al. (1980)
- Borkowski et al. (1975)
- Akimov et al. (1972)
- Frerejacque et al. (1966)
- Hand et al. (1963)



corrections to Lamb shift are **300  $\mu\text{eV}$**  below expectation

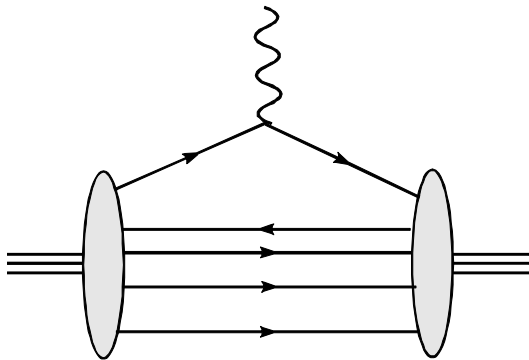
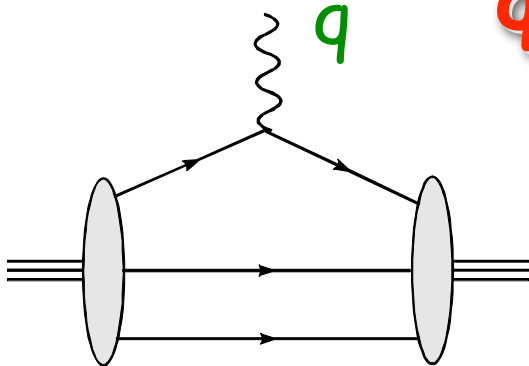
proton structure corrections have been reevaluated/updated



$$\Delta E = (- 36.9 \pm 2.4) \mu\text{eV}$$

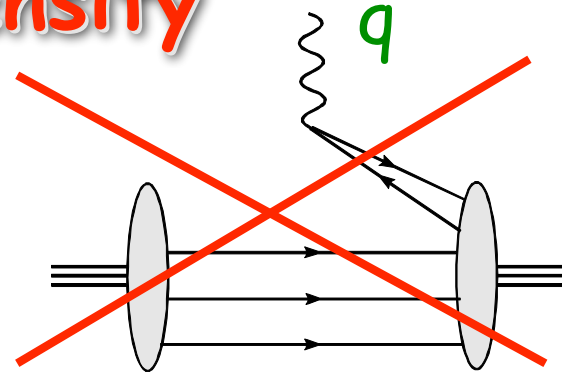
Carlson, Vdh (2011)

# interpretation of Form Factor as quark density



overlap of wave function  
Fock components with  
same number of quarks

interpretation as  
probability/charge density



overlap of wave function Fock  
components with different  
number of constituents

NO probability/charge  
density interpretation

absent in a LIGHT-FRONT frame !

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

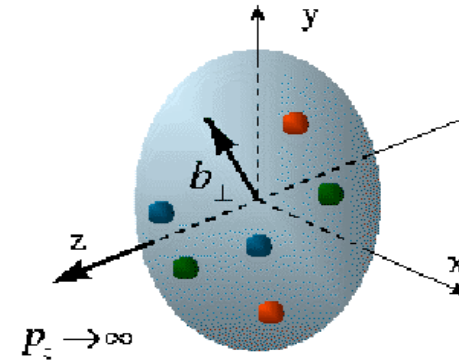
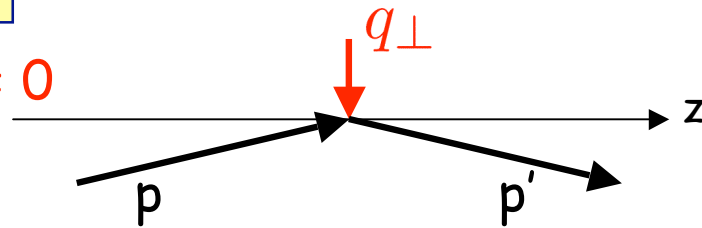
# quark transverse charge densities in nucleon (I)

light-front



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

$$Q^2 \equiv \vec{q}_\perp^2$$

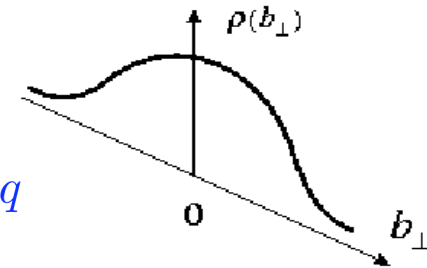


photon only couples to forward moving quarks



quark charge density operator

$$J^+ \equiv J^0 + J^3 = \bar{q}\gamma^+q = 2q_+^\dagger q_+, \quad \text{with} \quad q_+ \equiv \frac{1}{4}\gamma^-\gamma^+q$$



★ longitudinally polarized nucleon

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

Miller  
(2007)

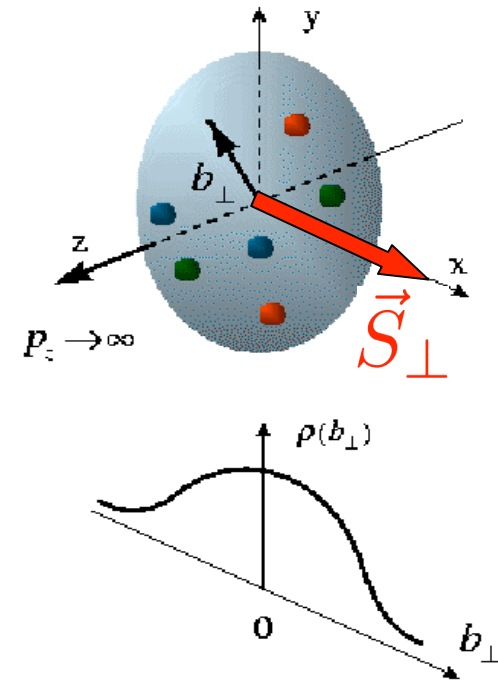
# quark transverse charge densities in nucleon (II)

## ★ transversely polarized nucleon

transverse spin  $\vec{S}_\perp = \cos \phi_S \hat{e}_x + \sin \phi_S \hat{e}_y$

e.g. along x-axis :  $\phi_S = 0$

$\vec{b} = b (\cos \phi_b \hat{e}_x + \sin \phi_b \hat{e}_y)$

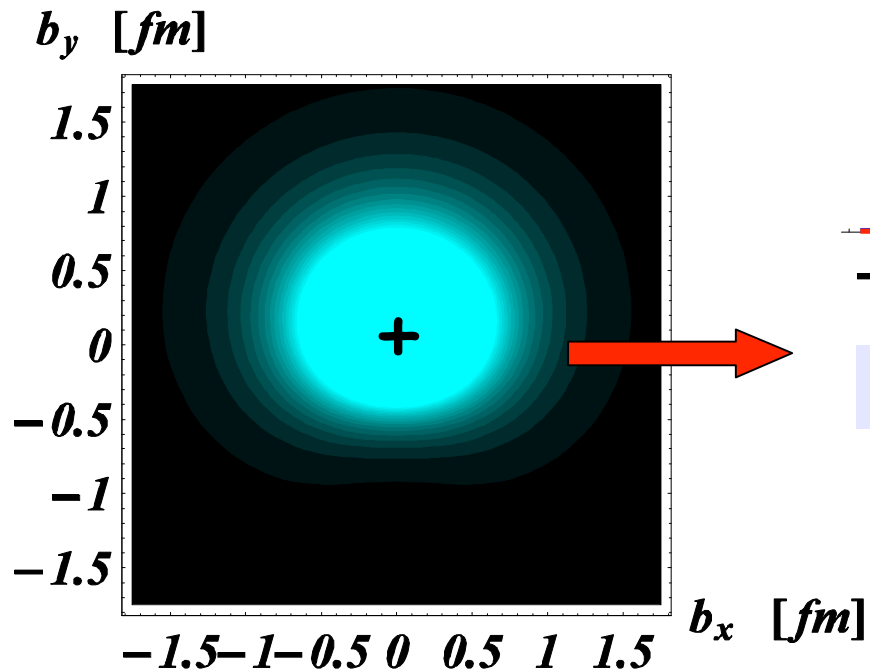
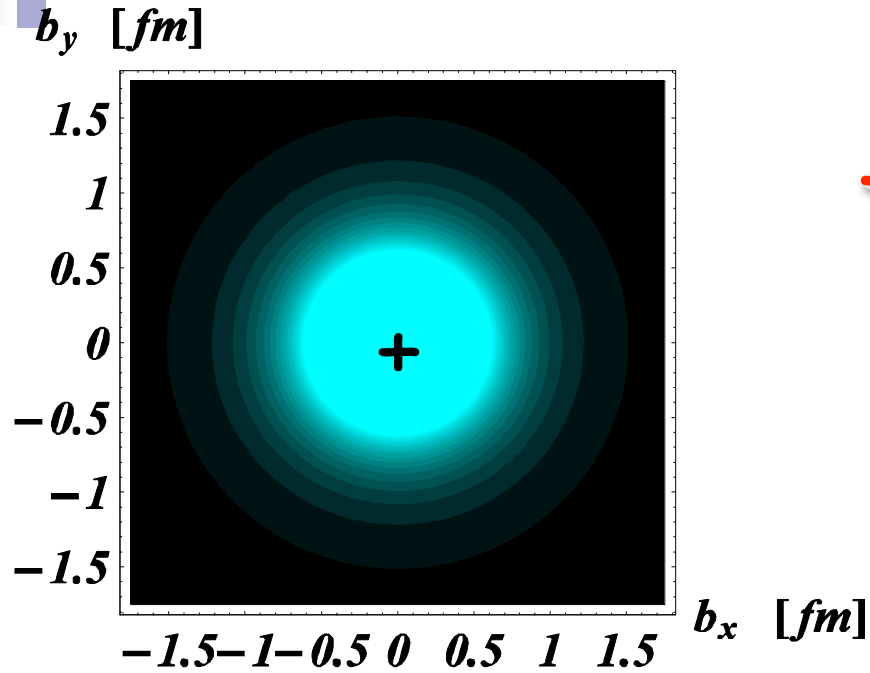


$$\begin{aligned} \rho_T^N(\vec{b}) &\equiv \int \frac{d^2 \vec{q}_\perp}{(2\pi)^2} e^{-i \vec{q}_\perp \cdot \vec{b}} \frac{1}{2P^+} \langle P^+, \frac{\vec{q}_\perp}{2}, s_\perp = +\frac{1}{2} | J^+(0) | P^+, -\frac{\vec{q}_\perp}{2}, s_\perp = +\frac{1}{2} \rangle \\ &= \rho_0^N(b) + \sin(\phi_b -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

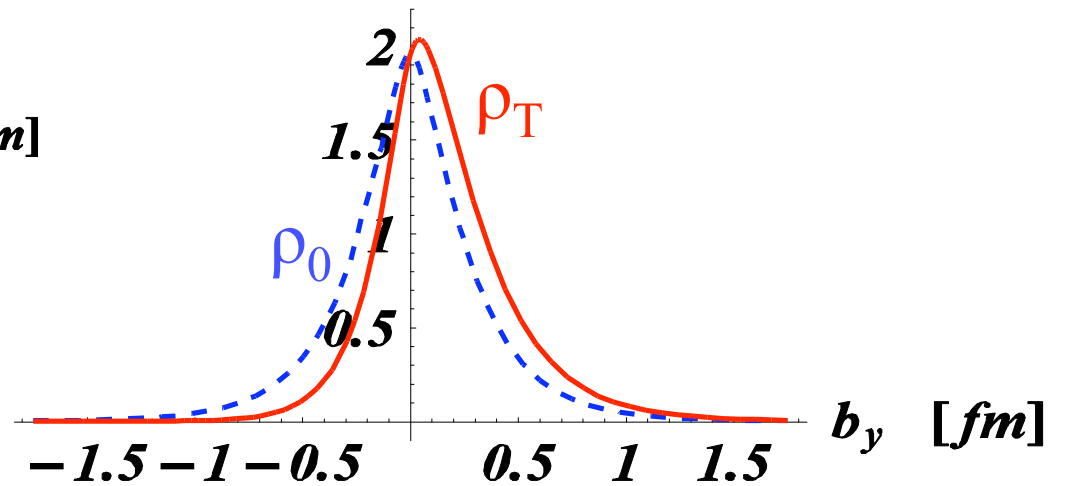
dipole field pattern

Carlson, Vdh (2007)

# empirical quark transverse densities in proton



$\rho_0^P, \rho_T^P$  [ $1/fm^2$ ]



induced EDM :  $d_y = F_{2p}(0) \cdot e / (2 M_N)$

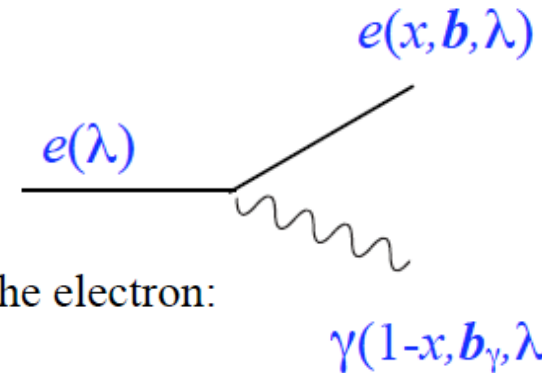
data : Arrington, Melnitchouk, Tjon (2007)

densities : Miller (2007); Carlson, Vdh (2007)



# transverse densities of $e\gamma$ Fock state in electron

Hoyer, Kurki (2009)



The wave functions give the densities of the  $|e\gamma\rangle$  Fock state of the electron:

$$\rho_0(x, \mathbf{b}) = \frac{\alpha m^2}{2\pi^2} \left[ \frac{1+x^2}{1-x} K_1^2(mb) + (1-x) K_0^2(mb) \right]$$

LC Wavefunction :

Brodsky, Drell (1980)

$$\rho_x(x, \mathbf{b}) = \rho_0(x, \mathbf{b}) + \frac{\alpha m^2}{\pi^2} x \sin(\phi_b) K_0(mb) K_1(mb)$$

from which the Pauli form factor is obtained (exact at order  $\alpha$ )

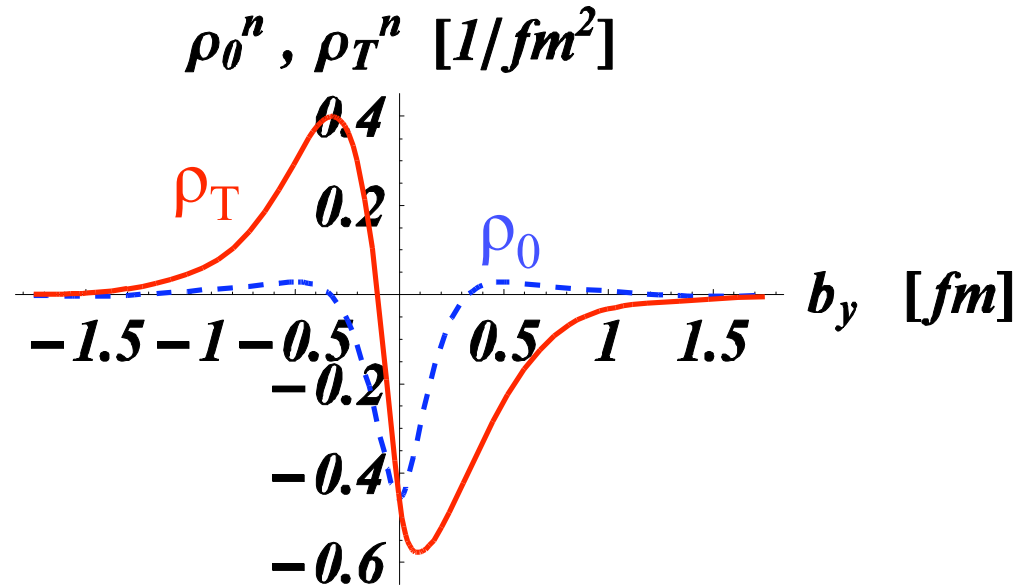
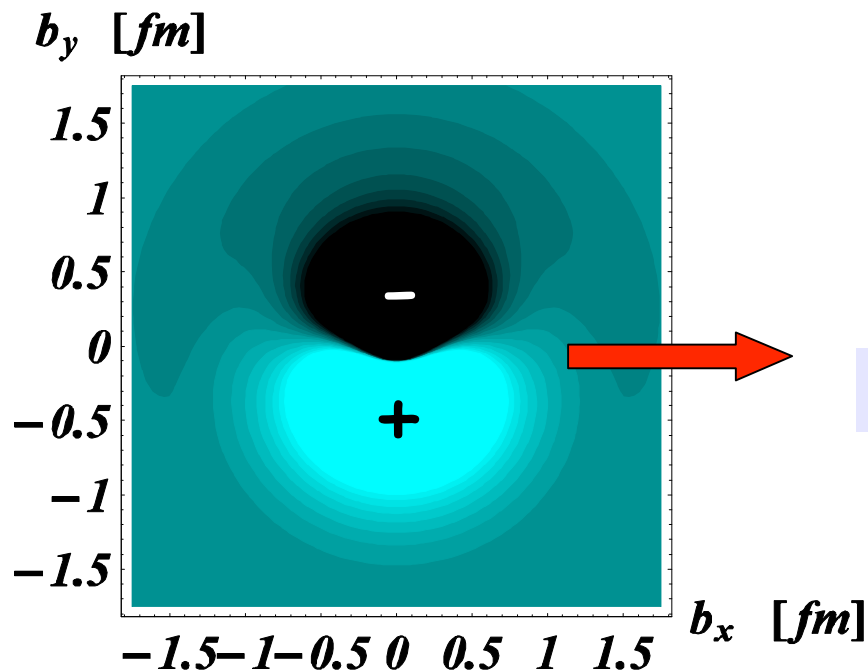
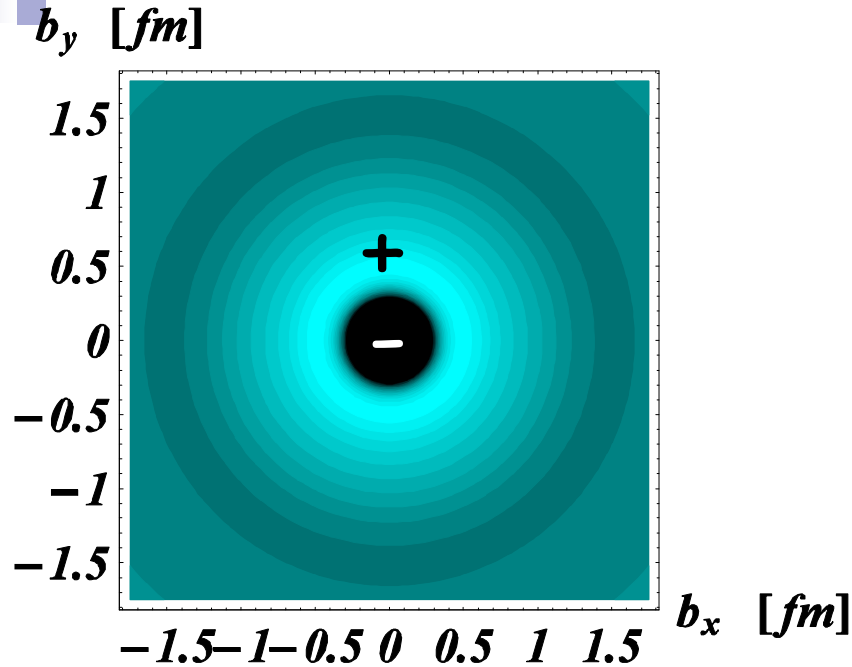
$$F_2(Q^2) = \frac{4\alpha m^3}{\pi Q} \int_0^1 dx x \int_0^\infty db b J_1(bQ) K_0(mb) K_1(mb)$$

x- and b-dependence factorizes

$$= \frac{2\alpha m^2}{\pi} \frac{1}{Q\sqrt{Q^2+4m^2}} \log \left[ \frac{1}{2m} \left( \sqrt{Q^2+4m^2} + Q \right) \right]$$

Exact expression from loop integral

# empirical quark transverse densities in neutron



induced EDM :  $d_y = F_{2n}(0) \cdot e / (2 M_N)$

data: Bradford, Bodek, Budd, Arrington (2006)

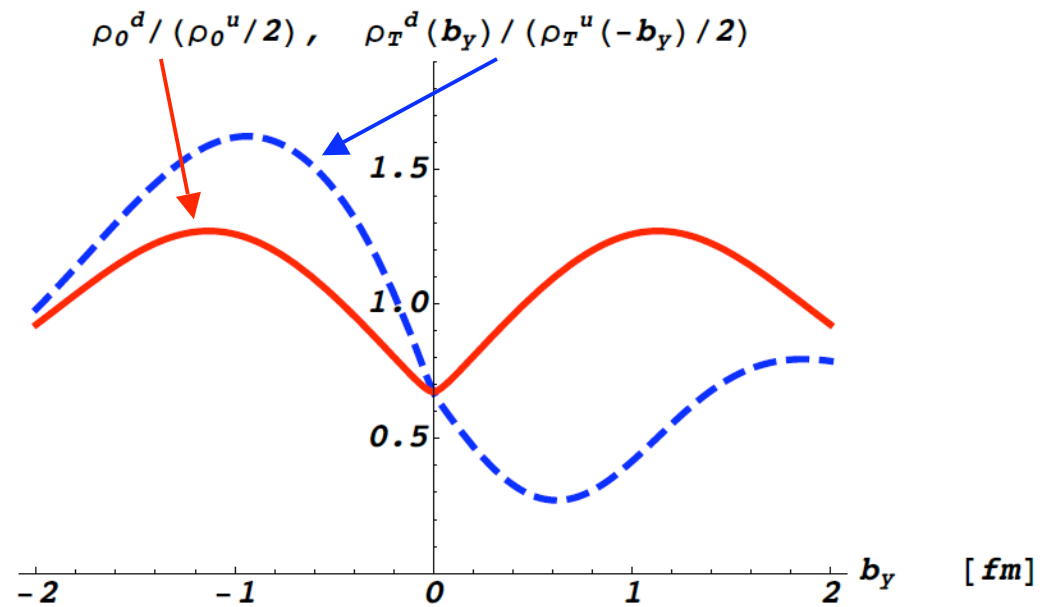
densities : Miller (2007); Carlson, Vdh (2007)

# d/u quark spatial distributions

2D spatial distr. :

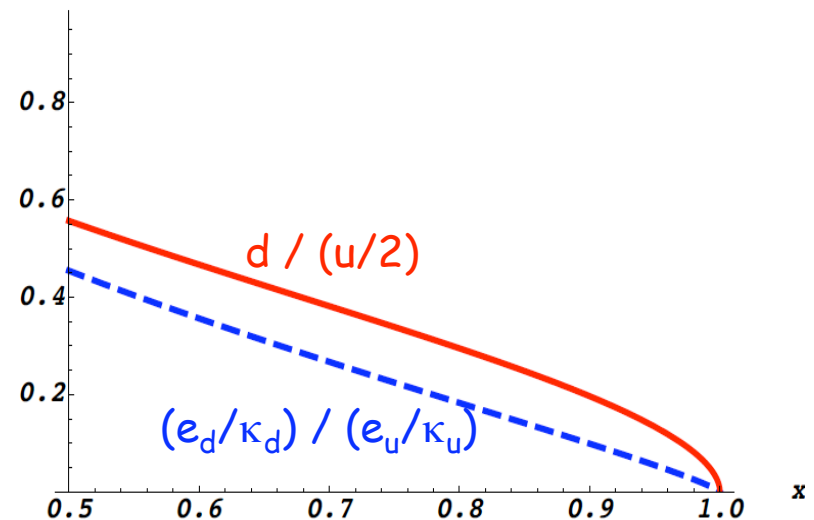
d-quark distr. spread out further in proton compared to u-quark distr.

Opposite behavior for neutron

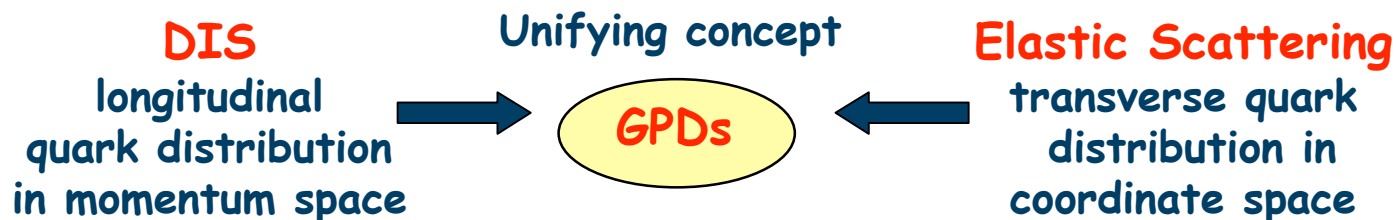


# d/u quark momentum distributions

transverse spatial and longitudinal momentum distribution can be combined in a 3D picture of nucleon, described through a GPD

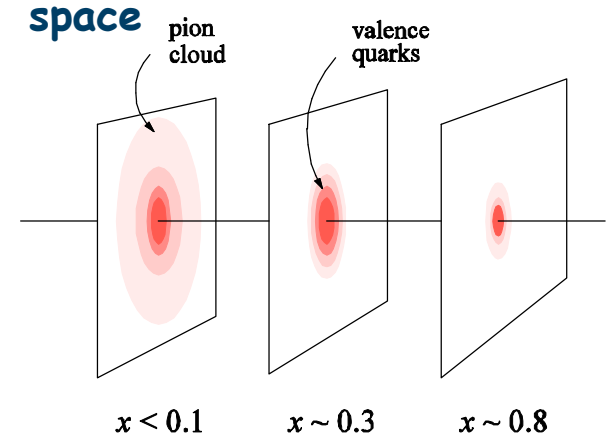
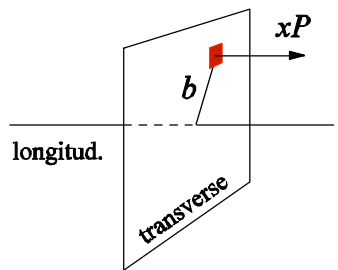
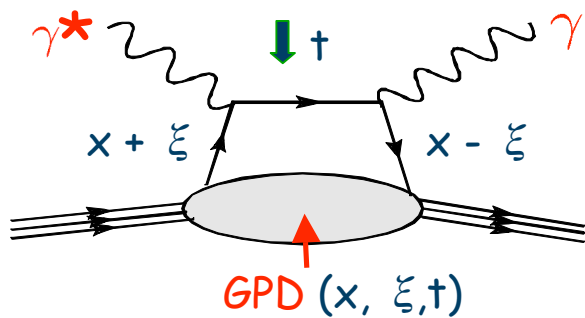


# Generalized Parton Distributions (GPDs) : 3D picture of nucleon



fully-correlated quark distributions in **both** coordinate and momentum space

$Q^2 \gg 1 \text{ GeV}^2$



Burkardt (2000, 2003), Belitsky, Ji, Yuan (2004)

figure courtesy Weiss

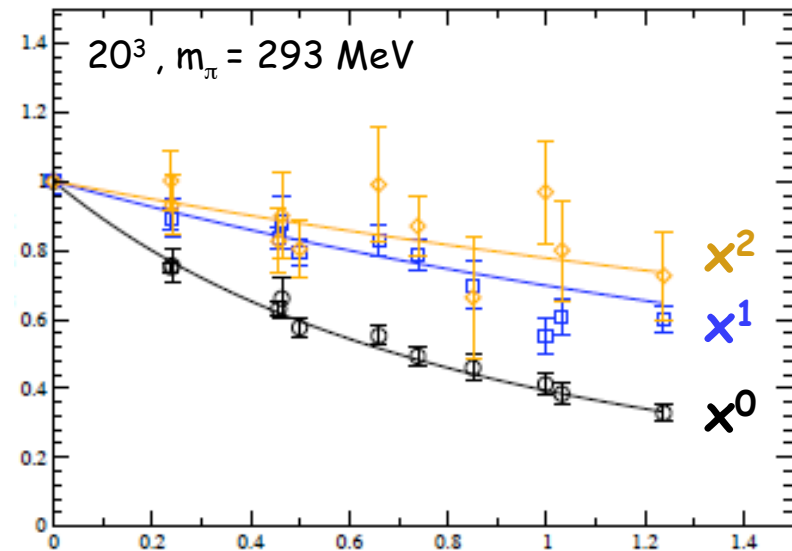
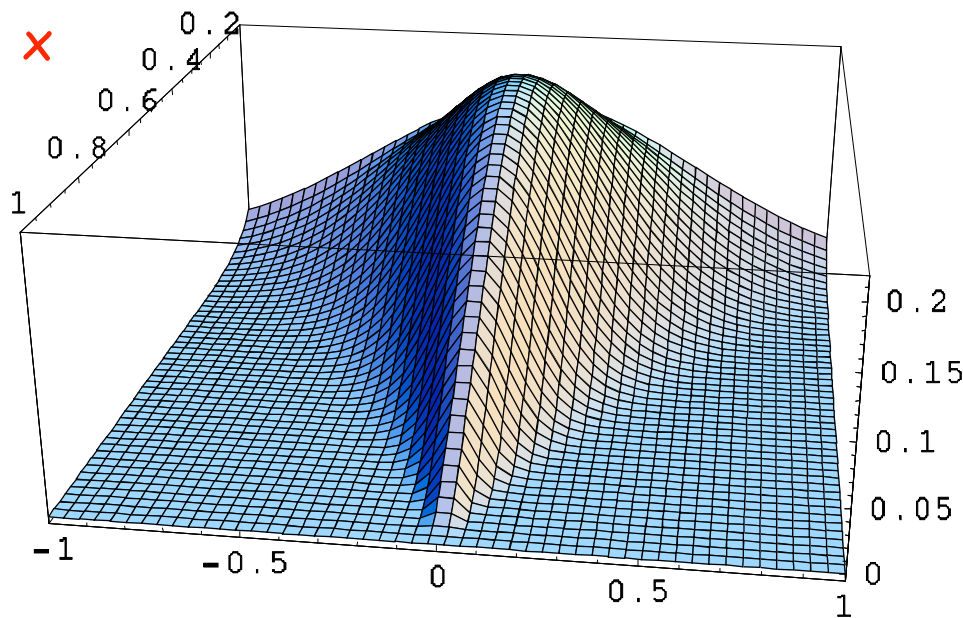
# GPDs : transverse image of nucleon

GPDs : quark distributions w.r.t.  
longitudinal momentum  $x$  and  
transverse position  $b_{\perp}$

lattice QCD : moments of GPDs

$$H^u(x, b_{\perp})$$

$x^n$  moment of  $H^{u-d}$



$b_{\perp}$  (fm)

Fourier transform

$-t$  ( $\text{GeV}^2$ )

Guidal, Polyakov, Radyushkin, Vdh (2005),

Diehl, Feldmann, Jakob, Kroll (2005)

LHPC Coll.



# Spin-1 transverse densities

# transversely polarized deuteron

$$Q_{s_{\perp}}^d \equiv e \int d^2\vec{b} (b_x^2 - b_y^2) \rho_{T s_{\perp}}^d(\vec{b})$$

$$Q_1^d = -\frac{1}{2} Q_0^d = \frac{1}{2} \{ [G_M(0) - 2] + [G_Q(0) + 1] \} \left( \frac{e}{M_d^2} \right)$$

experiment :

$$G_M(0) = 1.71$$

$$G_Q(0) = 25.84(3)$$

$$s_{\perp} = +1$$

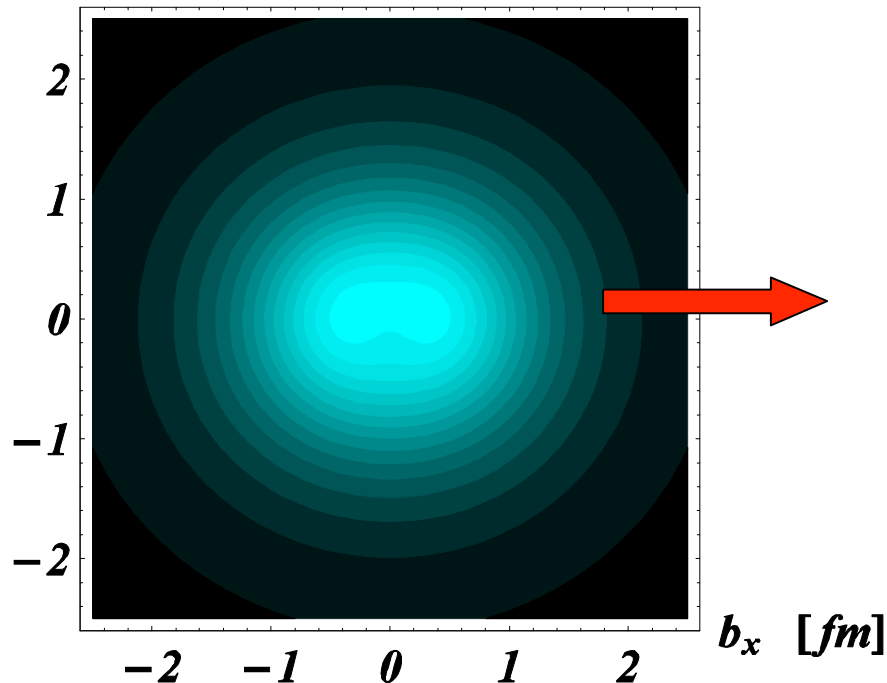
Carlson, Vdh  
(2008)

$$s_{\perp} = 0$$

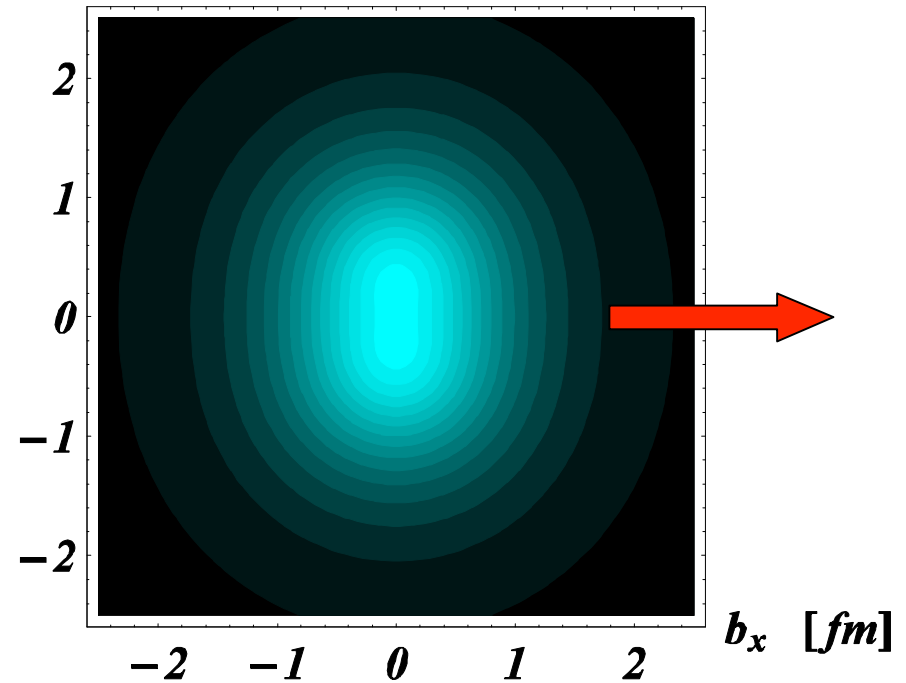
$$Q_1^d > 0$$

$$Q_0^d < 0$$

$b_y$  [fm]



$b_y$  [fm]



# E.M. moments of W bosons

for spin-1 point particle

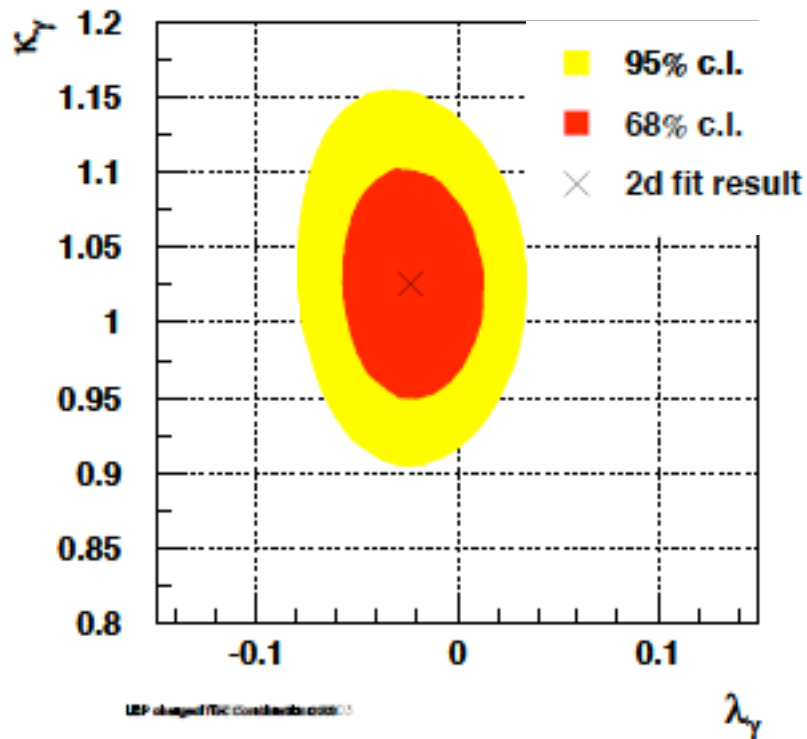
$$G_M(0) = 2 \text{ and } G_Q(0) = -1$$

$$\mu = \frac{e}{2M_W} \{2 + (\kappa - 1) + \lambda\}$$

$$Q = -\frac{e}{M_W^2} \{1 + (\kappa - 1) - \lambda\}$$

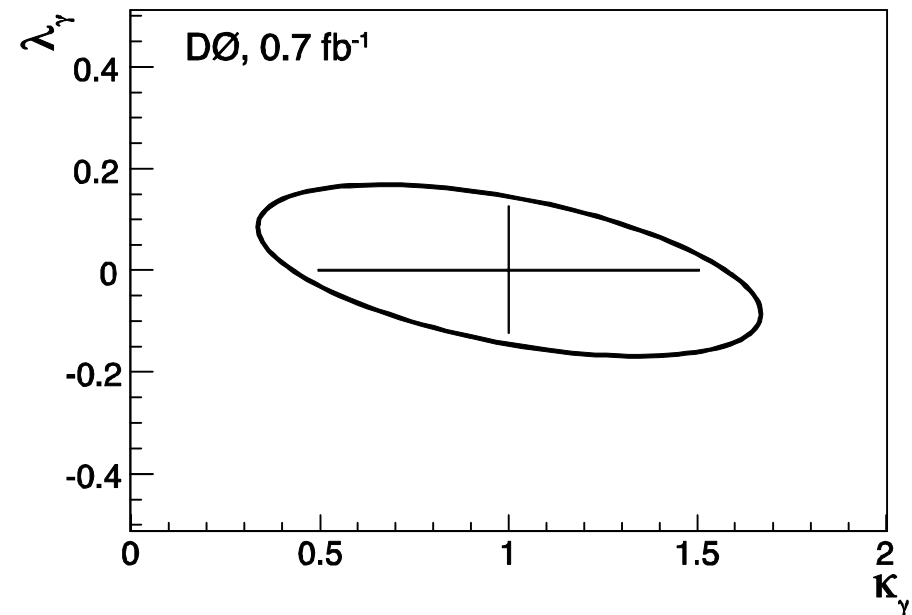
LEP Electroweak working group

hep-ex/0612034



DØ Collaboration

PRL100, 241805 (2008)





# natural values for e.m. moments of point particle with spin $j$

Lorcé (2008)

$$G_{E0}(0) = 1$$

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

$$G_{E2}(0) = -j(2j - 1)$$

$$G_{M3}(0) = -\frac{1}{3}j(2j - 1)(2j - 2)$$

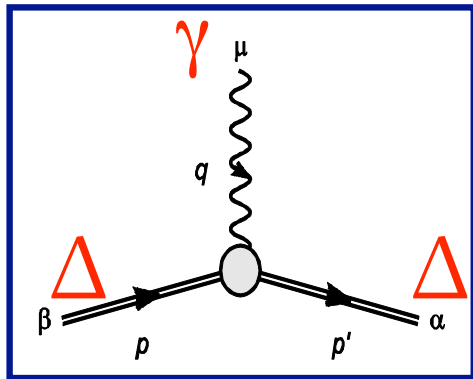
$j$	$G_{E0}(0)$	$G_{M1}(0)$	$G_{E2}(0)$	$G_{M3}(0)$	$G_{E4}(0)$	$G_{M5}(0)$	$G_{E6}(0)$
0	1	0	0	0	0	0	0
1/2	1	1	0	0	0	0	0
1	1	2	-1	0	0	0	0
3/2	1	3	-3	-1	0	0	0
2	1	4	-6	-4	1	0	0
5/2	1	5	-10	-10	5	1	0
3	1	6	-15	-20	15	6	-1
...							

 transverse charge densities depend only on anomalous values  
 of e.m. moments  reflect internal structure

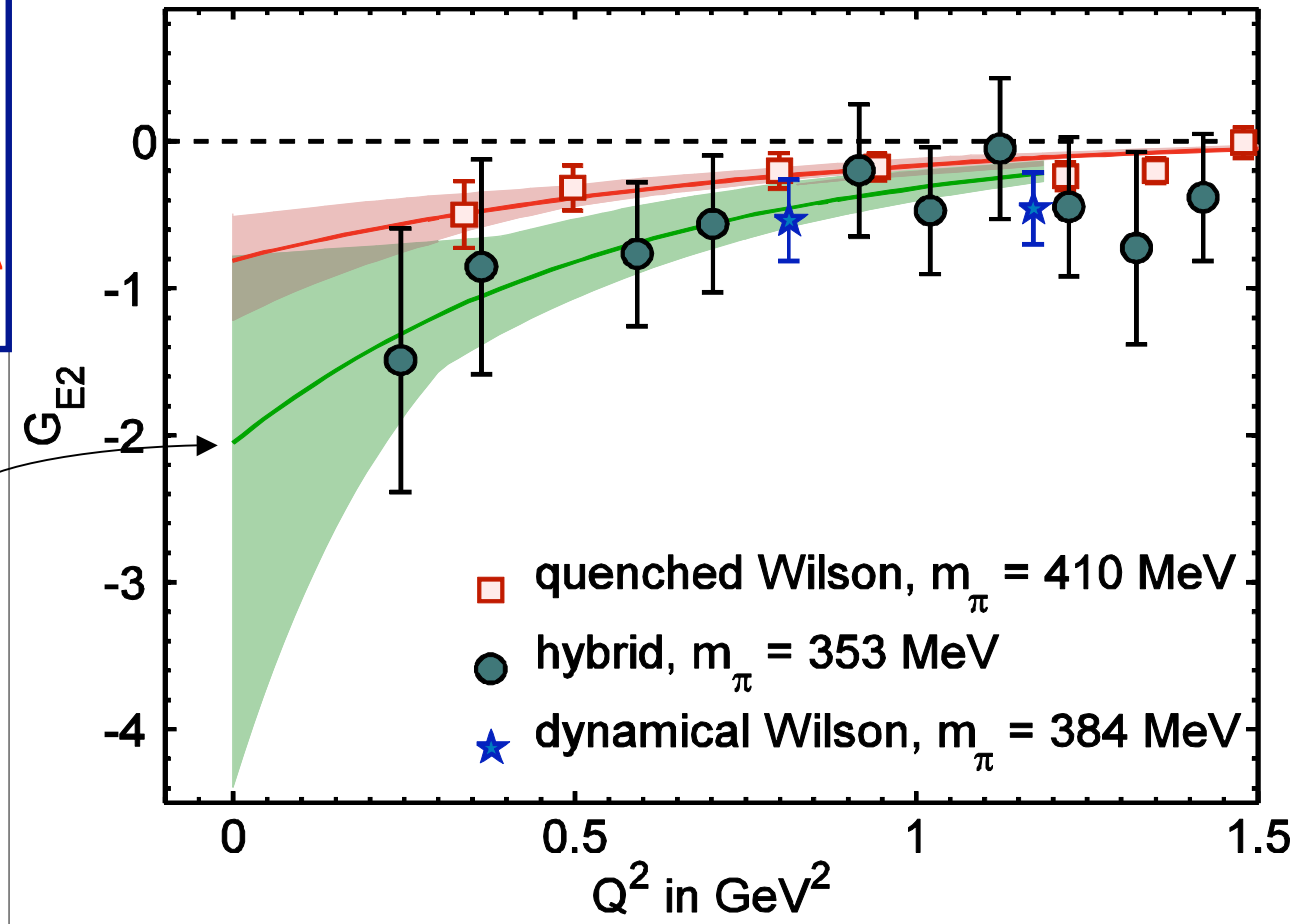


# Spin-3/2 transverse densities

# Hadron shape : e.m. $\Delta$ to $\Delta$ transition



$C0$  ,  $M1$  ,  
 $C2$  ,  $M3$   
 transitions



lattice analysis :

# quark transverse charge densities in $\Delta(1232)$

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

$$Q_{s_{\perp}}^{\Delta} \equiv e \int d^2 \vec{b} (b_x^2 - b_y^2) \rho_{T s_{\perp}}^{\Delta}(\vec{b})$$

$$Q_{\frac{3}{2}}^{\Delta} = -Q_{\frac{1}{2}}^{\Delta} = \frac{1}{2} \{2 [G_{M1}(0) - 3e_{\Delta}] + [G_{E2}(0) + 3e_{\Delta}]\} \left( \frac{e}{M_{\Delta}^2} \right) \quad s_{\perp} = +3/2$$

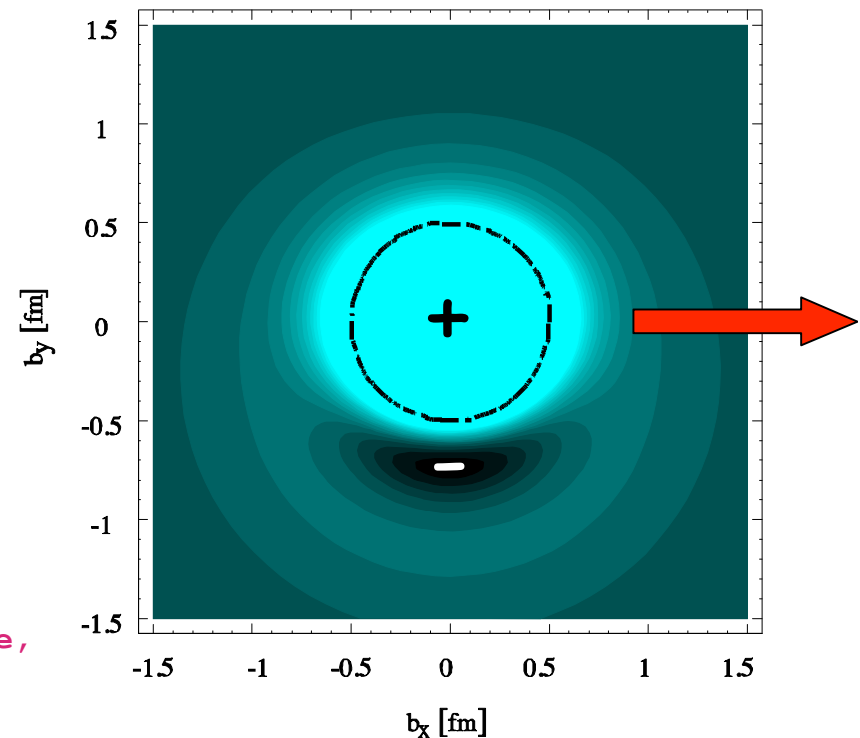
for spin-3/2 point particle

$$G_{M1}(0) = 3e_{\Delta} \quad \text{and} \quad G_{E2}(0) = -3e_{\Delta}$$

transverse charge densities  
depend only on anomalous  
values of e.m. moments  
-> reflect internal structure

lattice analysis :

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



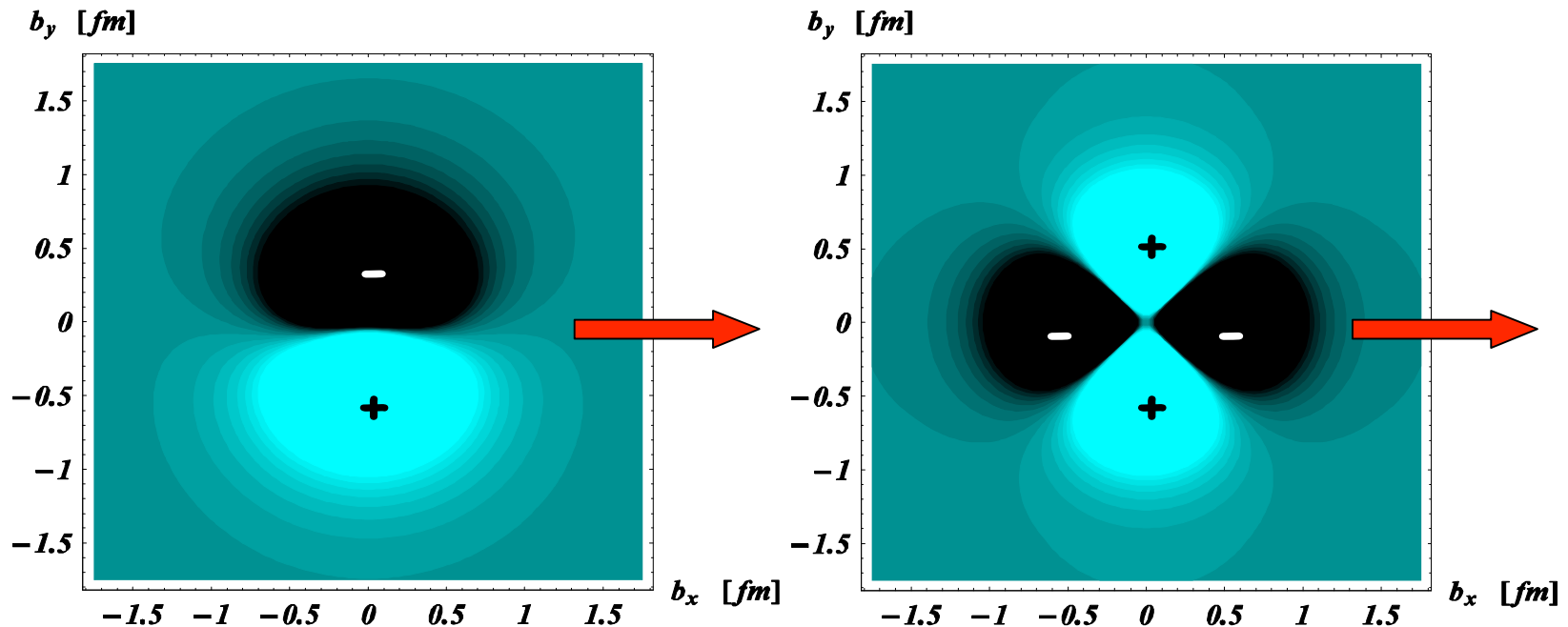


# Transverse charge densities for

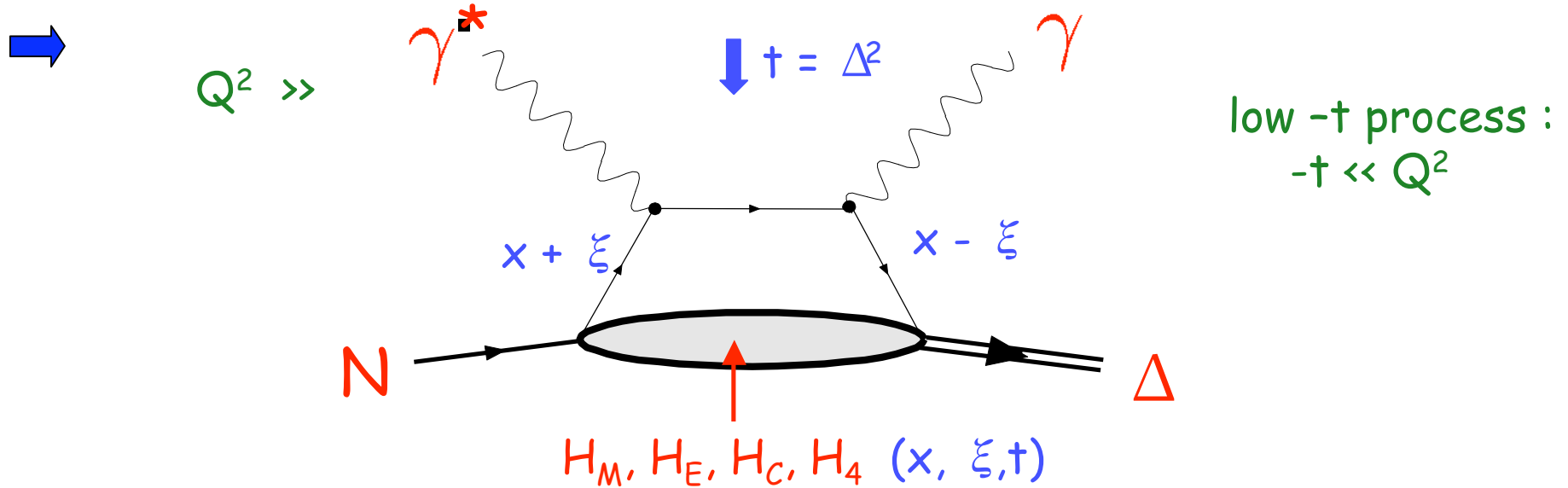
$N \rightarrow \Delta(1232), P_{11}(1440),$   
 $S_{11}(1535), D_{13}(1520), \dots$

# N $\rightarrow$ $\Delta(1232)$ transition densities in transverse spin state

$$\begin{aligned} \rho_T^{N\Delta}(\vec{b}) &\equiv \int \frac{d^2\vec{q}_\perp}{(2\pi)^2} e^{-i\vec{q}_\perp \cdot \vec{b}} \frac{1}{2P^+} \langle P^+, \frac{\vec{q}_\perp}{2}, s_\perp^\Delta = +\frac{1}{2} | J^+(0) | P^+, -\frac{\vec{q}_\perp}{2}, s_\perp^N = +\frac{1}{2} \rangle \\ &= \int_0^\infty \frac{dQ}{2\pi} \frac{Q}{2} \left\{ J_0(bQ) G_{+\frac{1}{2}+\frac{1}{2}}^+ \rightarrow \text{monopole} \right. \\ &\quad \left. - \sin(\phi_b - \phi_S) J_1(bQ) \left[ \sqrt{3} G_{+\frac{3}{2}+\frac{1}{2}}^+ + G_{+\frac{1}{2}-\frac{1}{2}}^+ \right] \rightarrow \text{dipole} \right. \\ &\quad \left. - \cos 2(\phi_b - \phi_S) J_2(bQ) \sqrt{3} G_{+\frac{3}{2}-\frac{1}{2}}^+ \right\} \rightarrow \text{quadrupole} \end{aligned}$$



# $N \rightarrow \Delta$ DVCS and GPDs



$\int_{-1}^1 dx H_M(x, \xi, t) = 2G_M^*(t)$

$\int_{-1}^1 dx H_E(x, \xi, t) = 2G_E^*(t)$

$\int_{-1}^1 dx H_C(x, \xi, t) = 2G_C^*(t)$

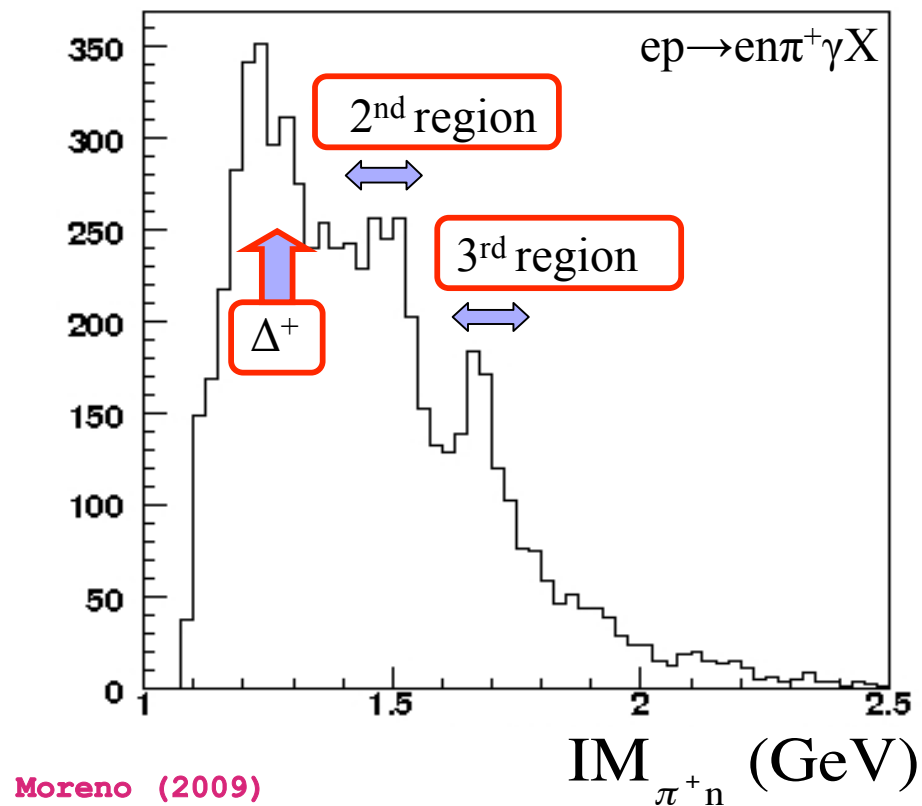
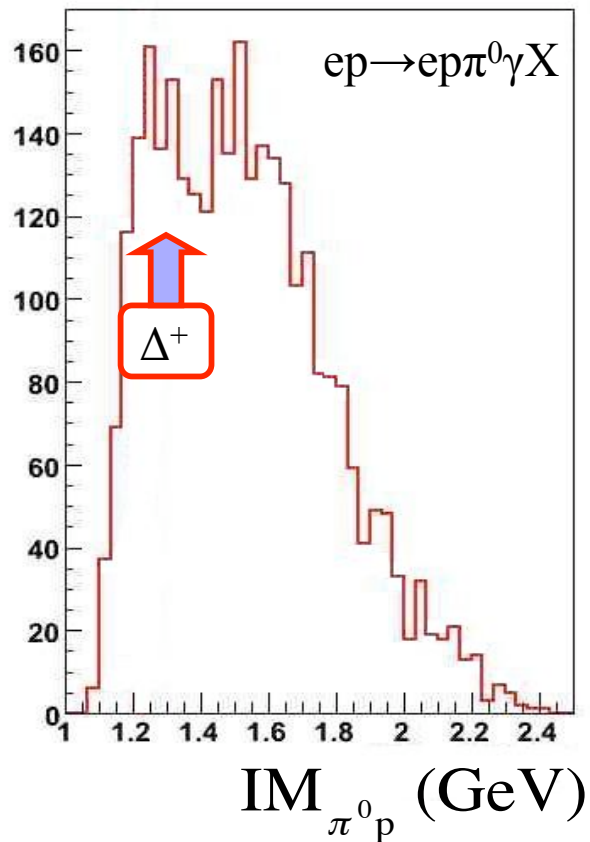
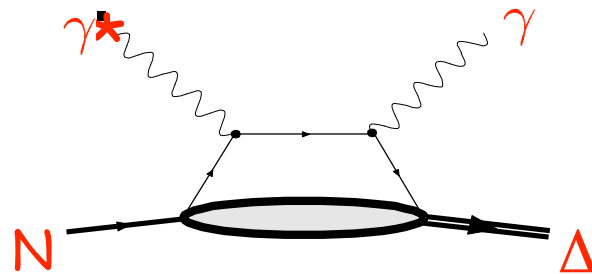
$\int_{-1}^1 dx H_4(x, \xi, t) = 0$

} Jones-Scadron  
N  $\rightarrow$   $\Delta$  form factors

# $N \rightarrow \Delta$ DVCS events in CLAS

$W > 2 \text{ GeV}$

$Q^2 \approx 2.5 \text{ GeV}^2$



Moreno (2009)



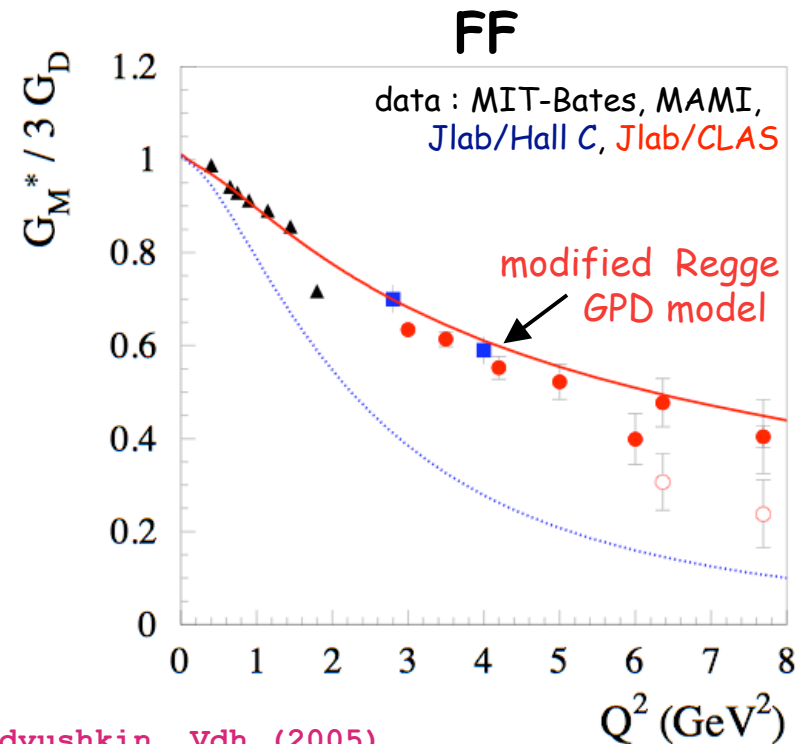
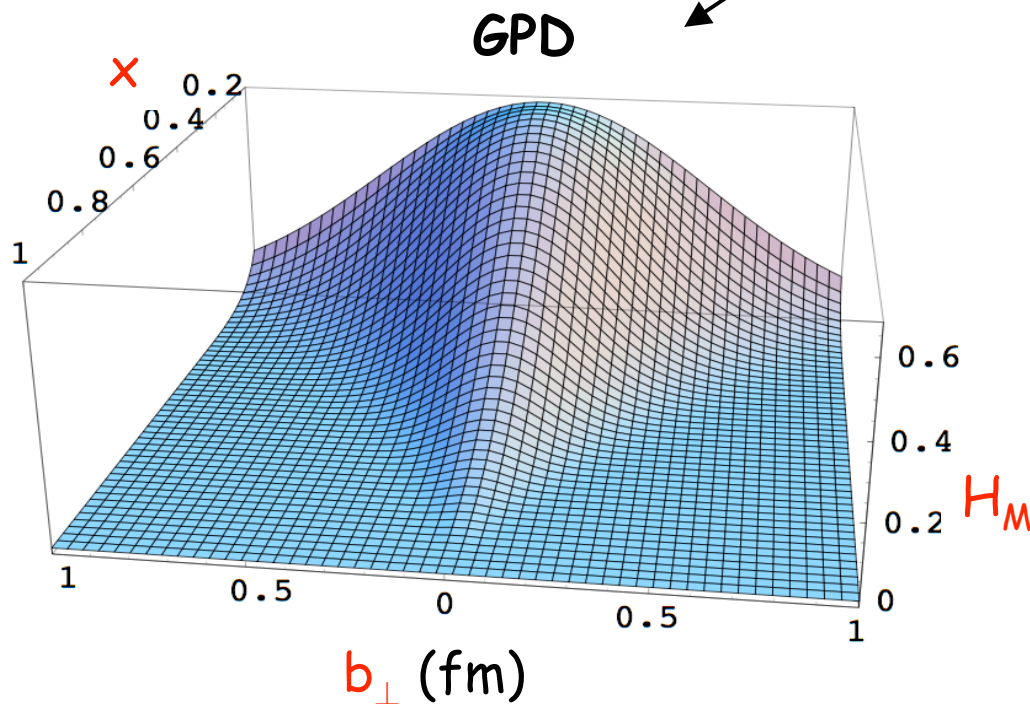
# N → Δ magnetic dipole GPD and FF

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

EXP :  $G_M^*(0) = 3.02$

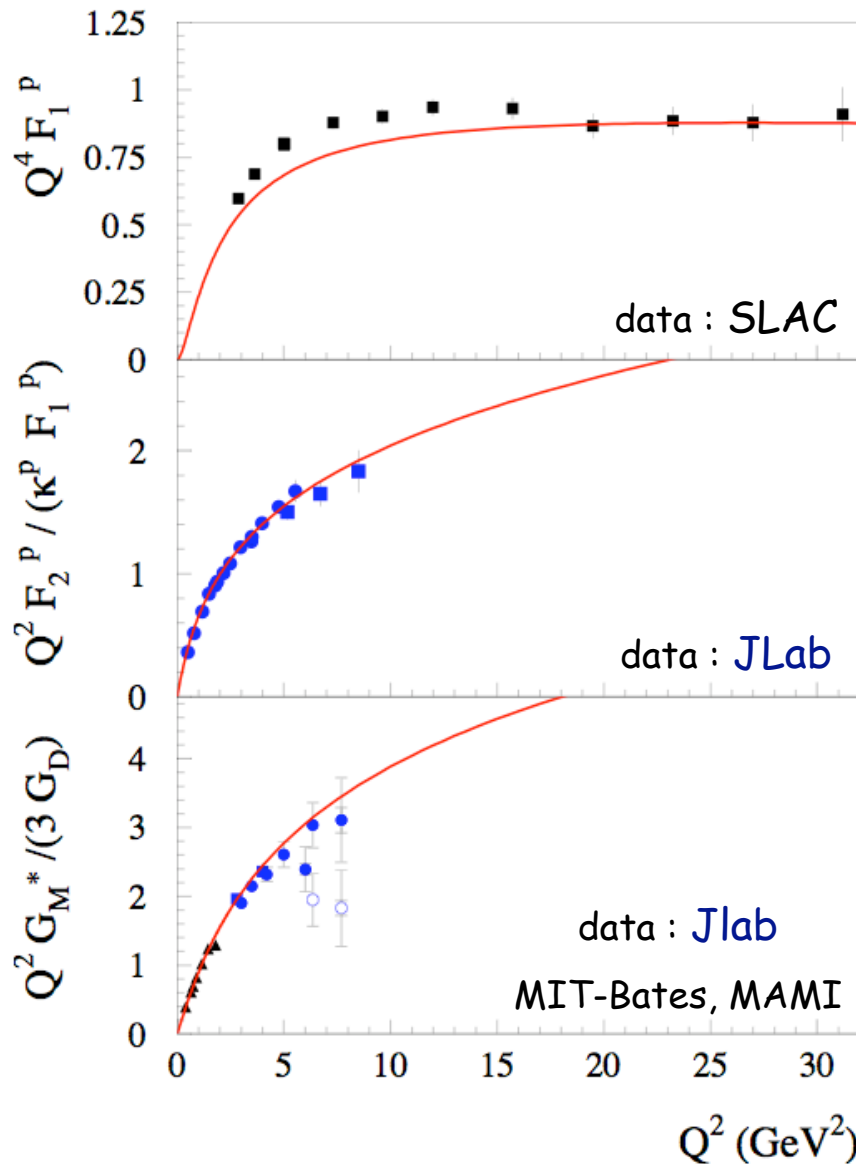
large  $N_c$  limit

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

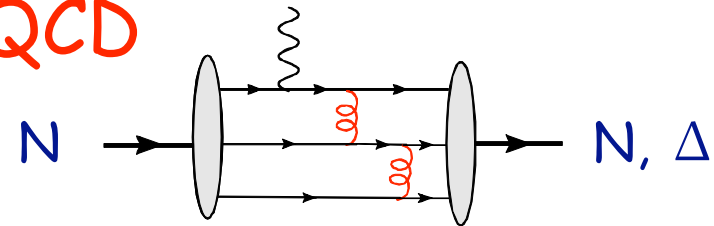


Guidal, Polyakov, Radyushkin, Vdh (2005)

# scaling behavior of N and N $\rightarrow$ $\Delta$ 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)

# N → Δ : E2 and C2 FFs

→ large  $N_c$  limit of QCD :

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

Buchmann, Hester, Lebed (2002)

EXP :  $r_n^2 = -0.113(3) \text{ fm}^2$

large  $N_c$  :  $Q_{p \rightarrow \Delta^+} = -0.080 \text{ fm}^2$

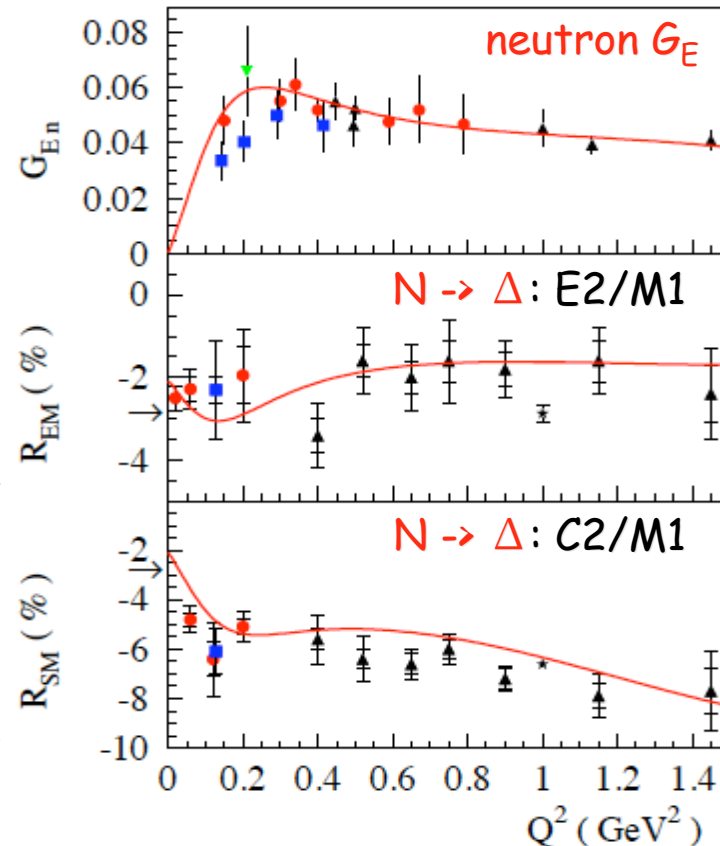
EXP :  $Q_{p \rightarrow \Delta^+} = -0.085(3) \text{ fm}^2$

→ finite (low)  $Q^2$  :

$$G_E^*(Q^2) \simeq \frac{1}{\sqrt{2}} \frac{(M_\Delta^2 - M_N^2)}{2} \frac{G_E^n(Q^2)}{Q^2}$$

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

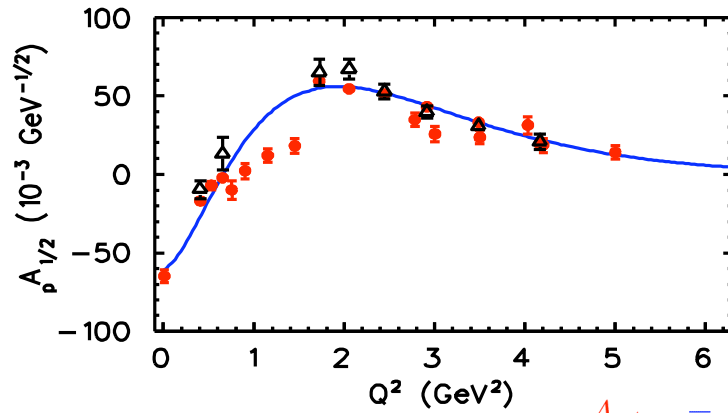
Pascalutsa, Vdh (2006)



$G_{En}$  fit: Bradford, Bodek, Budd, Arrington (2006)

E2, C2 data: MAMI, NIKHEF, MIT-Bates, JLab

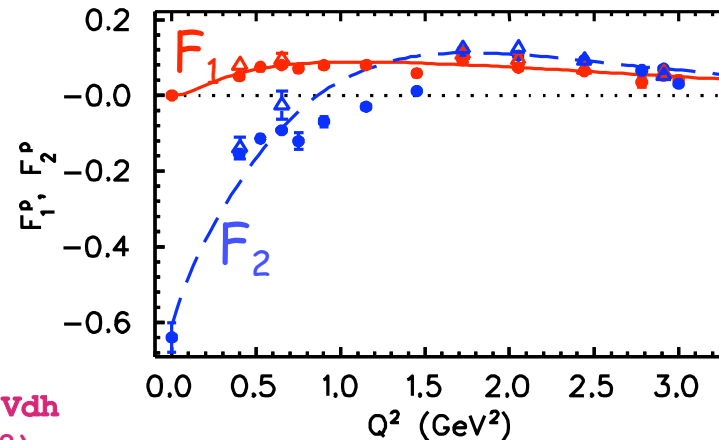
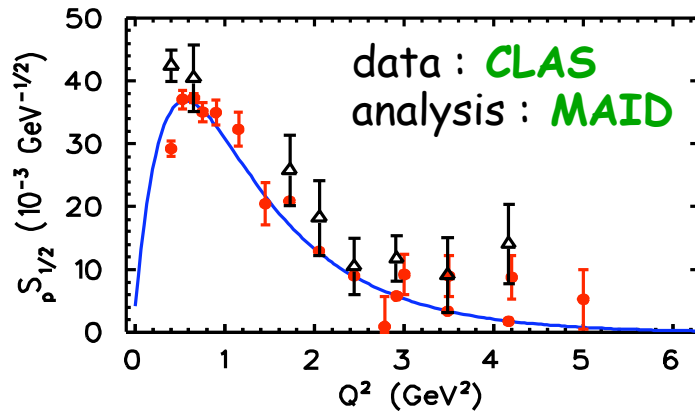
# empirical transition FFs for p → P<sub>11</sub>(1440) excitation



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

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

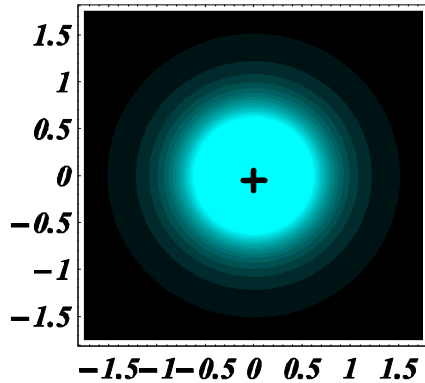
$$S_{1/2} = e \frac{Q_-}{\sqrt{2K} (4M_N M^*)^{1/2}} \left( \frac{Q_+ + Q_-}{2M^*} \right) \frac{(M^* + M_N)}{Q^2} \left\{ F_1^{NN^*} - \frac{Q^2}{(M^* + M_N)^2} F_2^{NN^*} \right\}$$



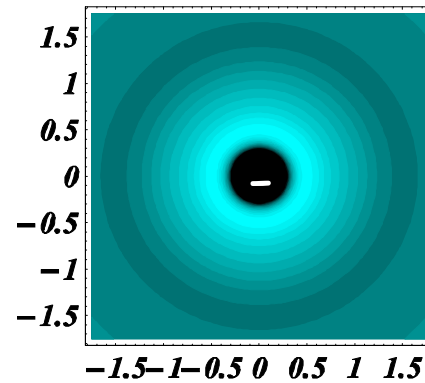
Tiator, Vdh  
(2008)

# empirical transverse transition densities

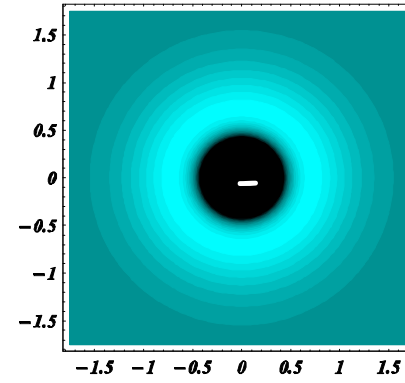
p



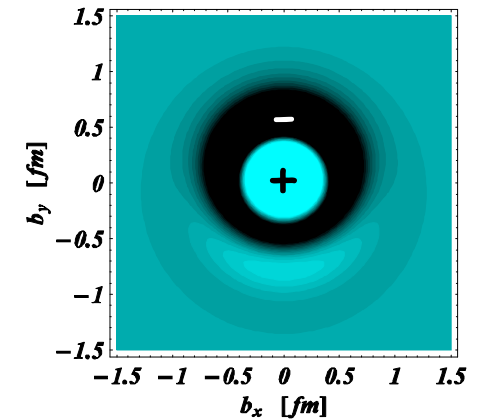
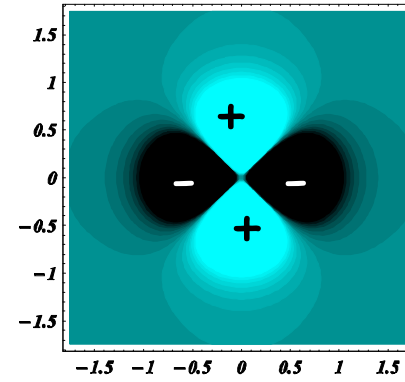
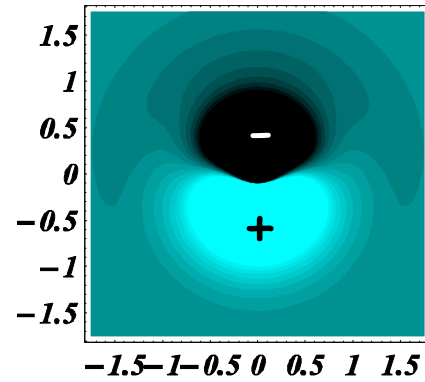
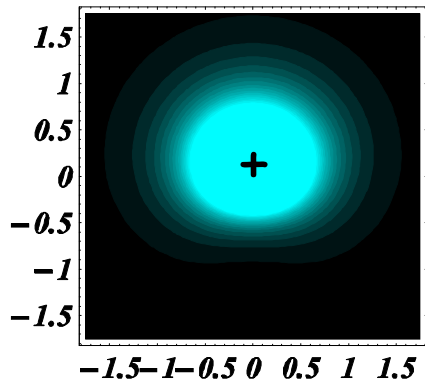
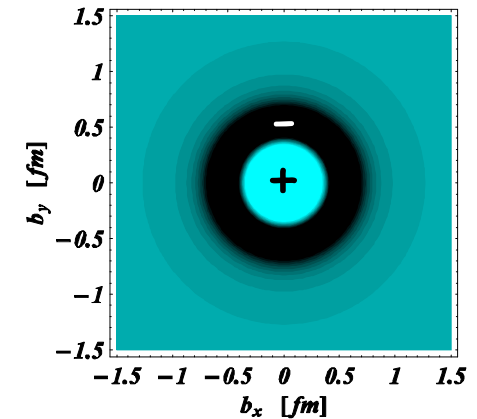
n



p  $\rightarrow$   $\Delta^+$  (1232)



p  $\rightarrow$   $N^*$  (1440)

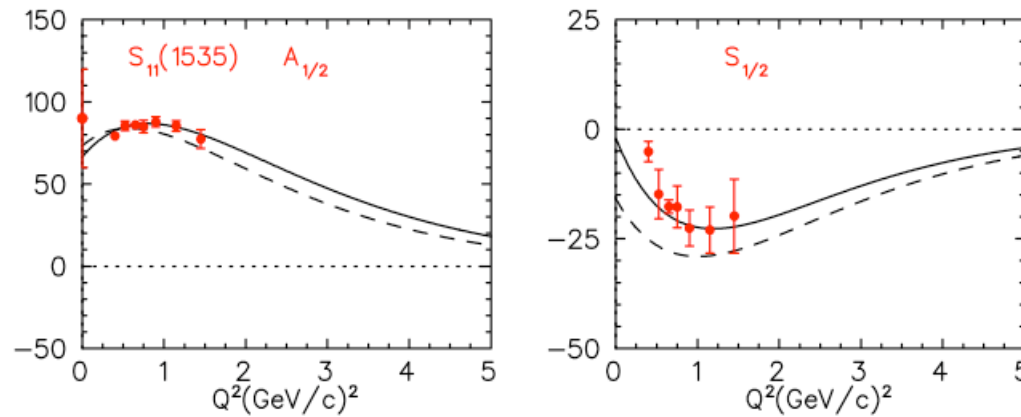


Carlson, Vdh (2007)

quadrupole  
pattern

Tiator, Vdh (2008)

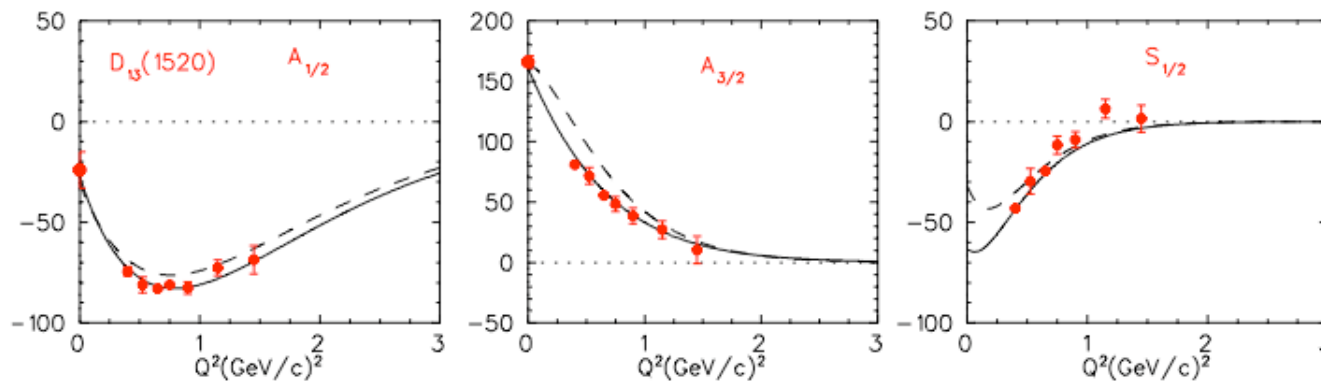
# empirical transition FFs for $p \rightarrow S_{11}(1535), D_{13}(1520)$ excitations

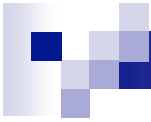


data : CLAS

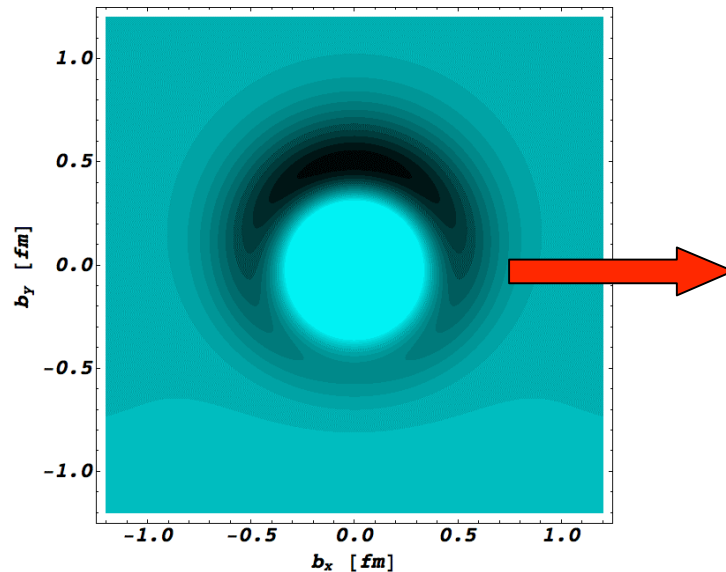
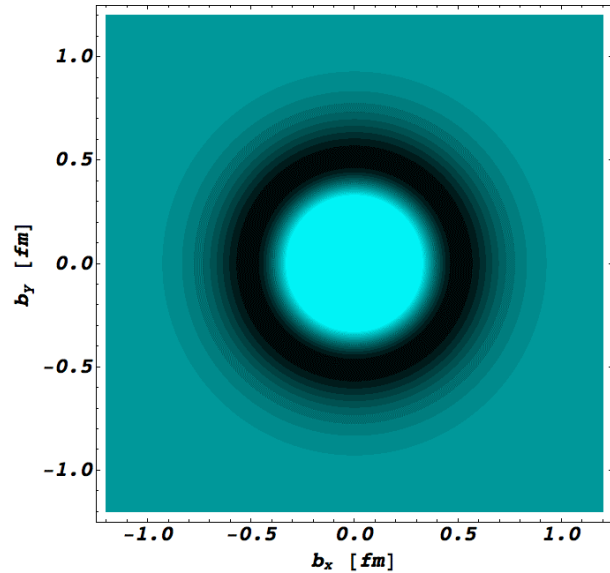
analysis : MAID

— 2007  
 - - - 2003



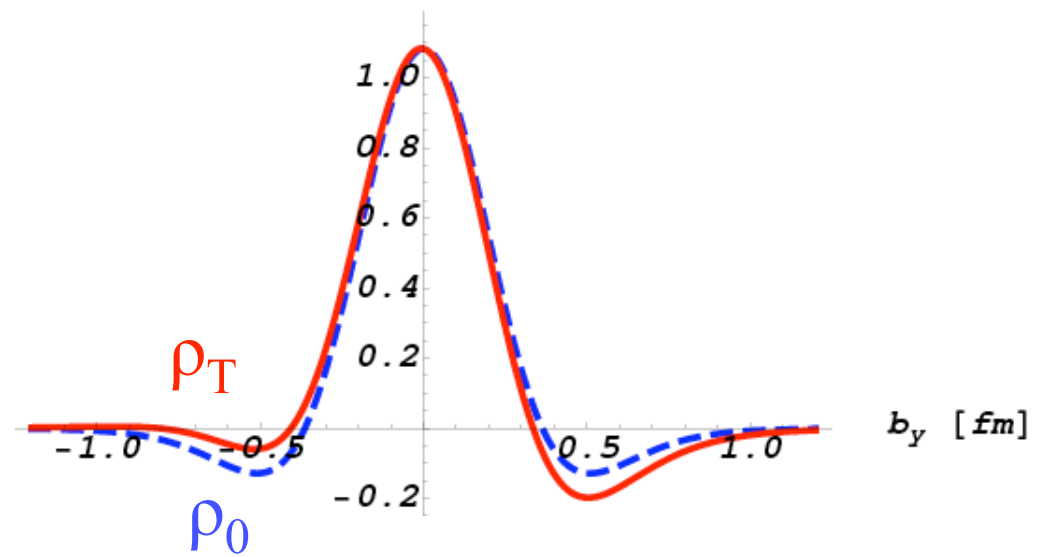


# empirical transverse transition densities for $p \rightarrow S_{11}(1535)$ excitation



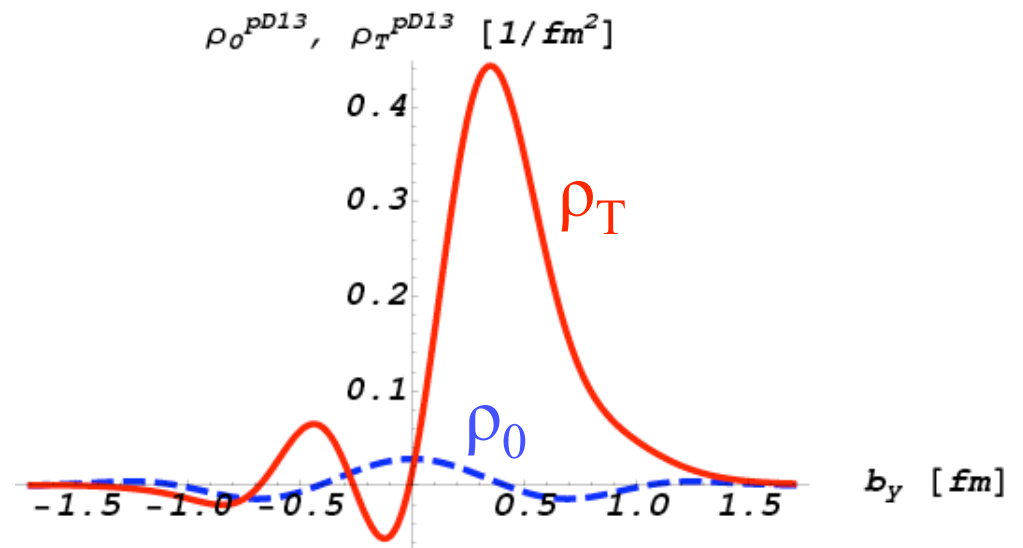
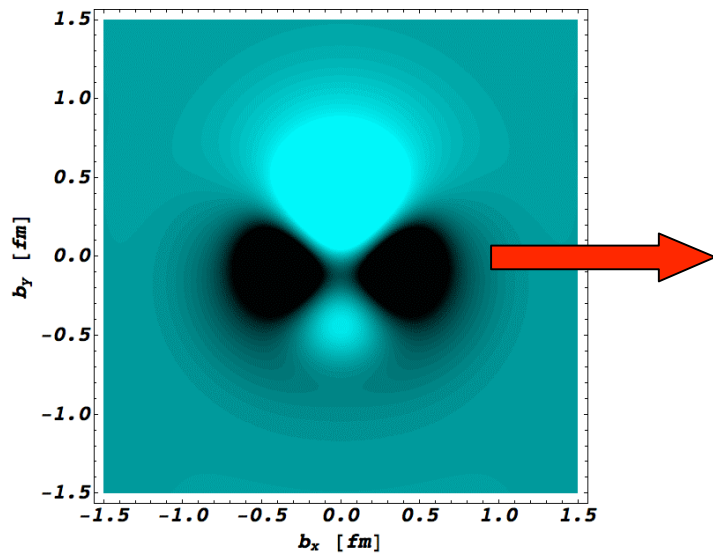
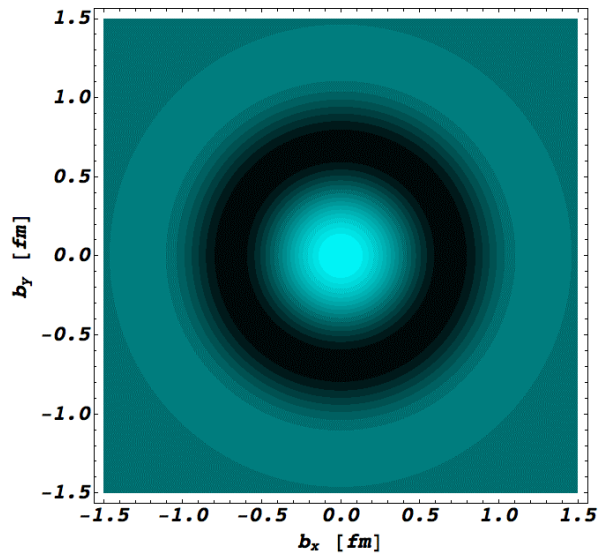
transition  $s_{\perp} = +1/2 \rightarrow s_{\perp} = -1/2$

$\rho_0^{pS11}, \rho_T^{pS11}$  [ $1/\text{fm}^2$ ]



Tiator, Vdh

# empirical transverse transition densities for $p \rightarrow D_{13}(1520)$ excitation



transition  $s_{\perp} = +1/2 \rightarrow s_{\perp} = -1/2$

Tiator, Vdh





# Summary

## Light-front charge densities provide a 2D transverse imaging of hadrons

- elastic nucleon form factors : empirical transverse charge densities reveal **different spatial distributions** of u / d quarks
- Shape of hadrons can be understood within relativistic quantum field theory from higher **e.m. moments** of transverse charge densities as **deviations** from their "natural" values
- electromagnetic structure of the  **$\Delta(1232)$  resonance**  
**Lattice QCD results** allows to access transverse charge densities, pointing to a **prolate  $\Delta$  deformation** when viewed from the light-front
- **$N \rightarrow N^*$**  transition form factors allow to map out the nucleon-resonance **transition charge densities**

$\Delta(1232)$ ,  $P_{11}(1440)$ ,  $S_{11}(1535)$ ,  $D_{13}(1520)$ ,...