Directions
in
Hadron Physics (th)

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3DSPIN
MAPPING THE PROTON IN 3D
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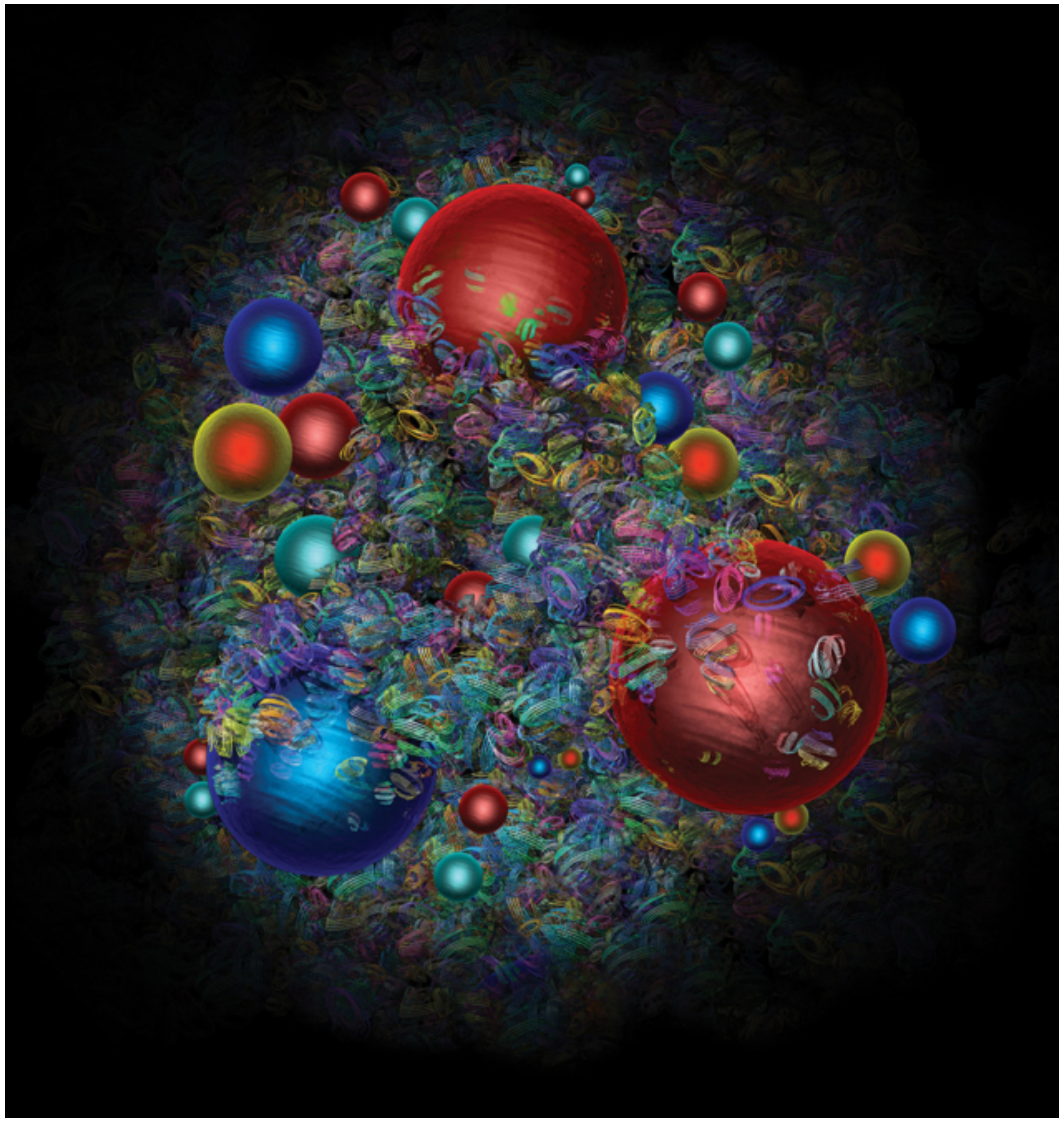
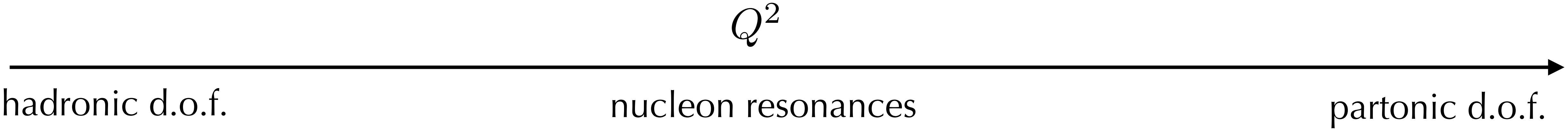
100 years of the discovery of the proton

``What proton is depends on how you look at it, or rather on how hard you hit it''

A. Cooper-Sarkar, CERN Courier, June, 2019





How can we explain the evolving picture of hadrons
from low to high Q^2?

The existence of hadrons, their properties and their binding into nuclei, do not appear in the Lagrangian of QCD

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}\left(i\gamma_\mu D^\mu - m\right)\psi - \frac{1}{2}\mathrm{Tr}\left\{G_{\mu\nu}G^{\mu\nu}\right\}$$

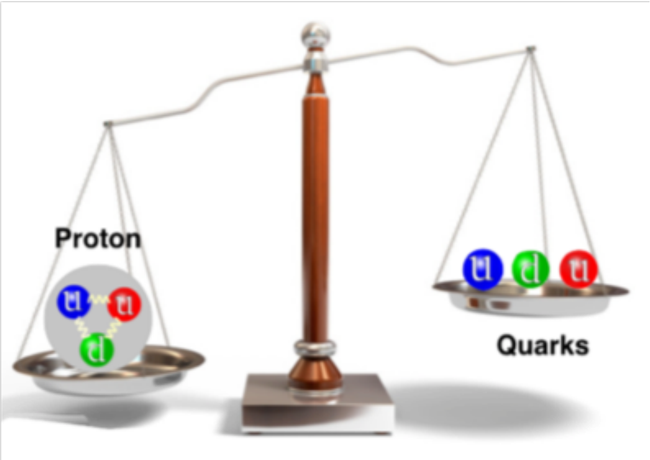
The Science questions:
The 2015 Long Range Plan for Nuclear Science

- How did visible matter come into being and how does it evolve?
- How does subatomic matter organise itself and what phenomena emerge?
- Are the fundamental interactions that are basic to the structure of matter fully understood?

Size

Spin

Mass



The Proton Charge Radius

Charge distribution

(up to relativistic corrections)

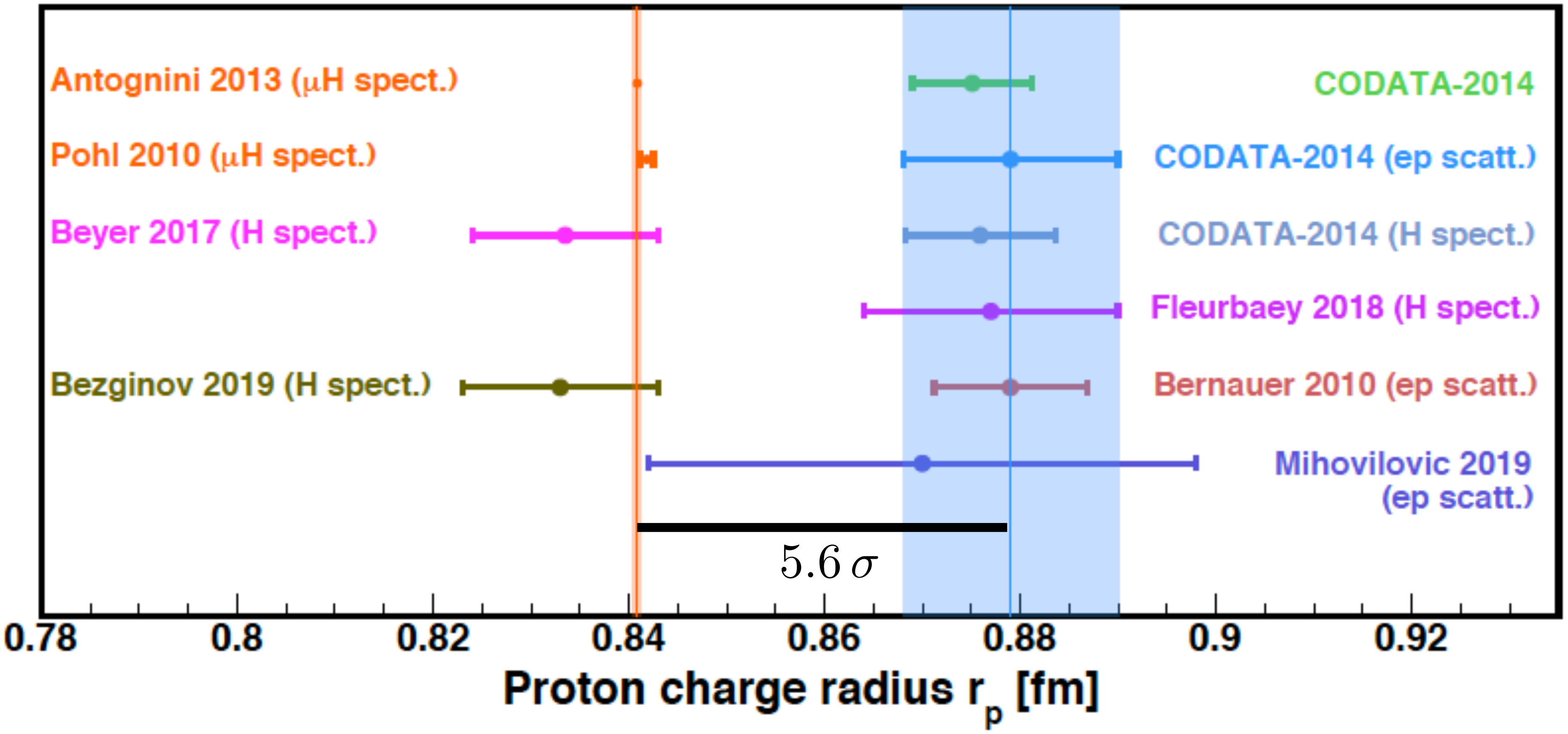
$$\rho_E(\vec{r}) = \int \frac{d^3q}{(2\pi)^3} e^{i\vec{q}\cdot\vec{r}} G_E(-\vec{q}^2)$$

Mean square radius:

$$\langle r^2 \rangle_E = \int d^3r\, r^2 \rho_E(\vec{r}) = 6\, \frac{\mathrm{d}G_E(0)}{\mathrm{d}Q^2}$$

Spectroscopy measurements: $V_C = -\frac{\alpha_{em}}{q^2} - 4\pi\alpha_{em} \frac{\mathrm{d}G_E(0)}{\mathrm{d}Q^2}$

Elastic electron scattering: $\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{\mathrm{d}\sigma_0}{\epsilon(1+\tau)} \left[\epsilon\, G_E(Q^2) + \tau\, G_M(Q^2)\right]$



Final PRad (JLab) result from ep scattering supports the smaller radius from spectroscopy

CODATA 2018 (all available data through 31 Dec. 2018): 0.8414 ± 0.019 fm

⟶ *Talks of N. Liyanage, R. Pohl*

The missing piece

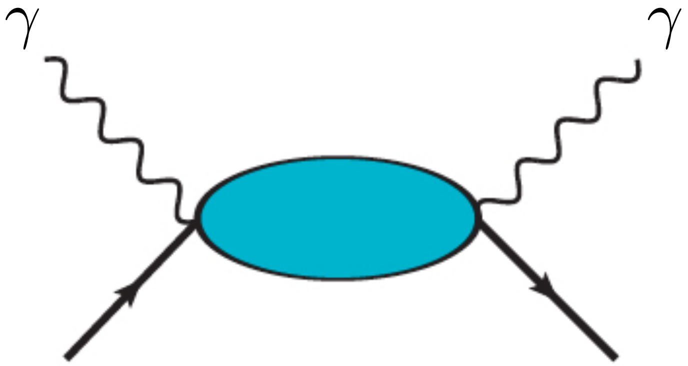
r_E (fm)	ep	μp
Spectroscopy	0.8758 ± 0.077	0.84087 ± 0.00039
Scattering	0.8770 ± 0.060	**???**

Measure radius with proton-muon scattering!

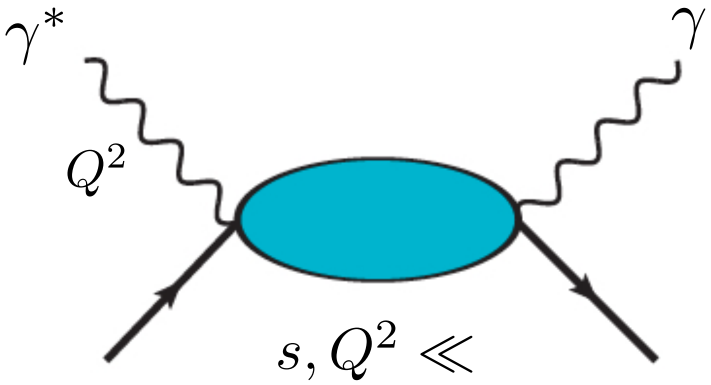
- MUSE at PSI
- ProRad at PRAE, Paris/Orsay
- ELPH, Tohoku U., Japan
- MAMI at Mainz
- COMPASS++ at CERN

Two-photon Physics

RCS polarizabilities



VCS generalized pol.



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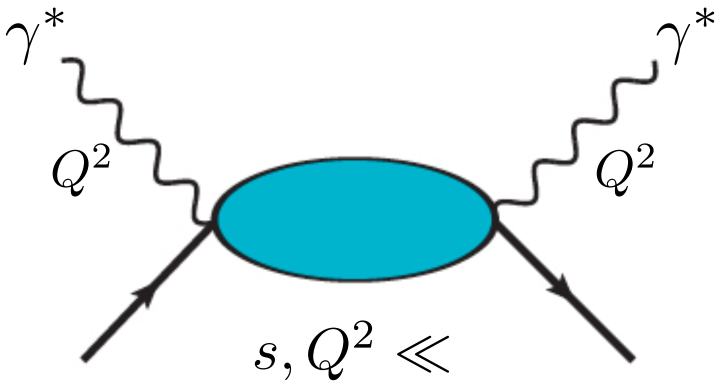
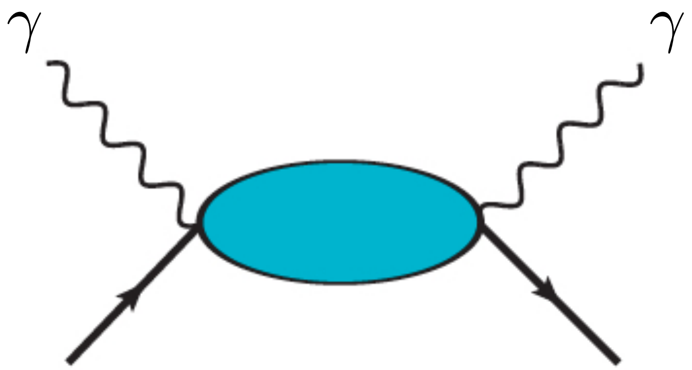


Compton scattering at threshold can be interpreted
as electron scattering by a target which is in constant electric and magnetic fields

Two-photon Physics

RCS polarizabilities



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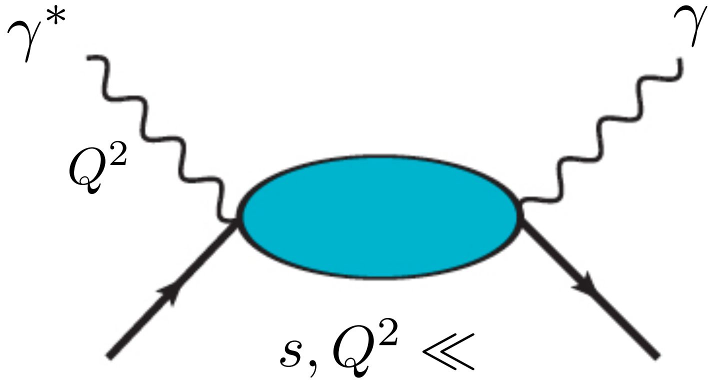
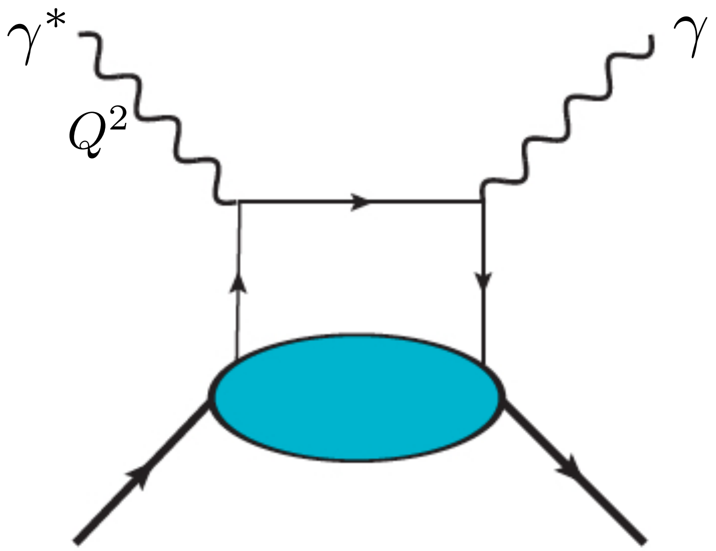


$s, Q^2 \ll$

$s, Q^2 \gg$

DVCS
generalized parton distributions



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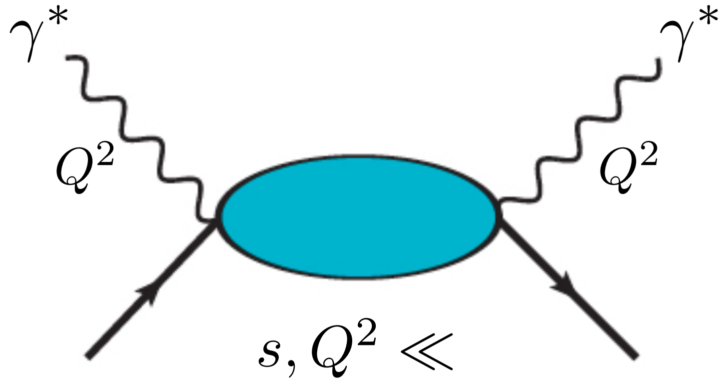

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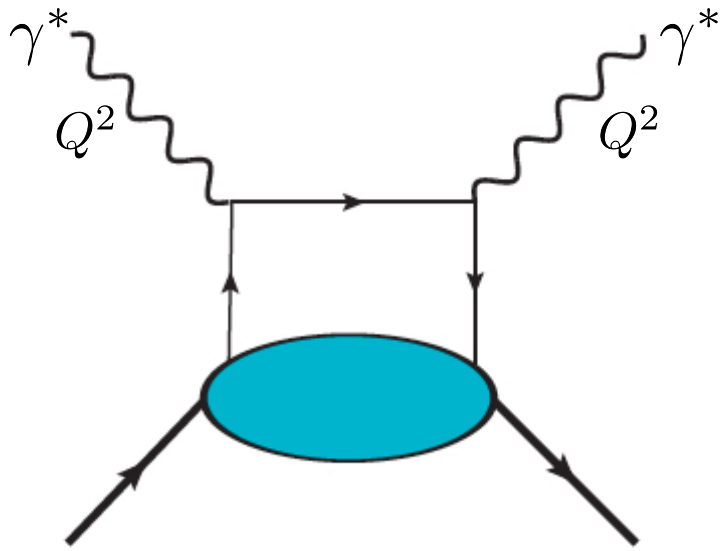
DIS
parton distributions



Real Compton Scattering at low energies

Measure of the strength of induced polarizations: 2 scalar polarizabilities + 4 spin polarizabilities

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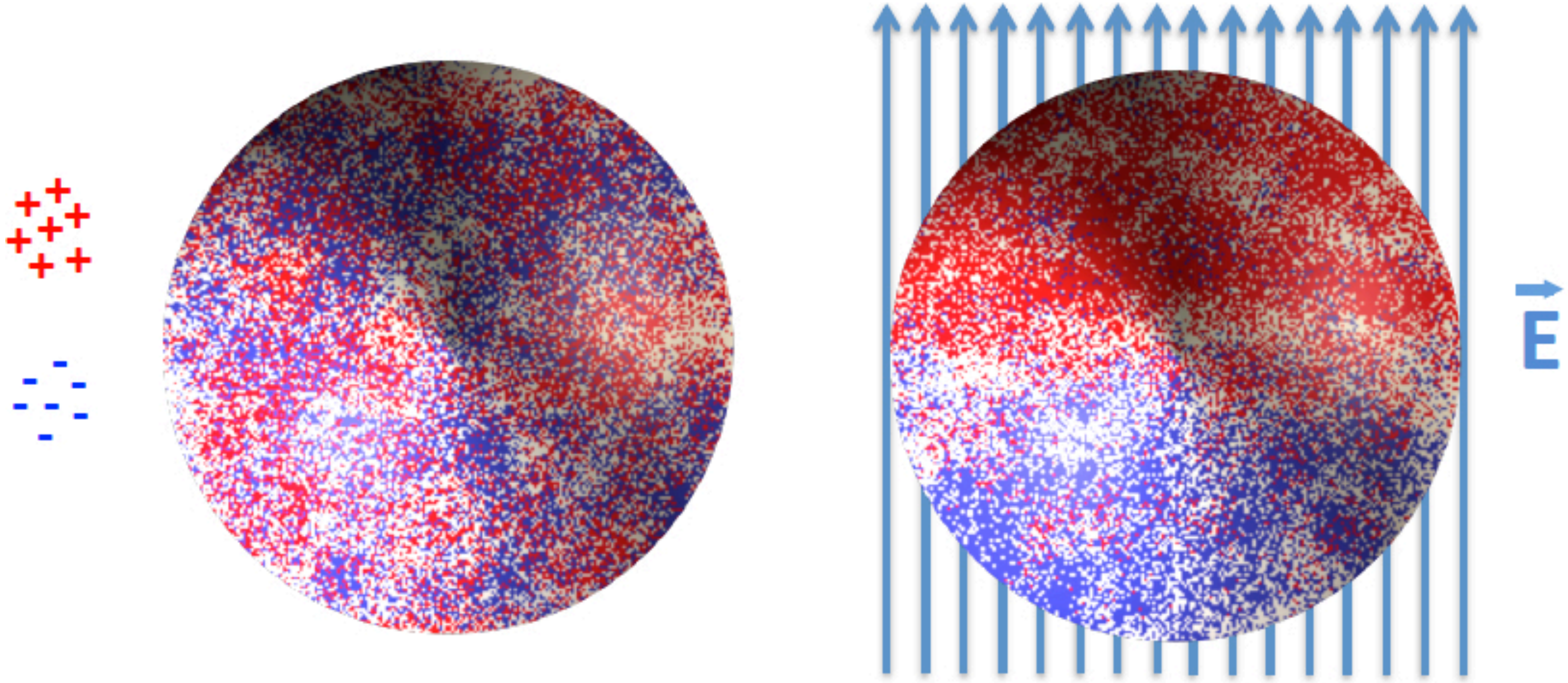

$$\vec{D}_E \sim \alpha_{\mathrm{E1}} \, \vec{E}$$

Unlike atoms,
it is not proportional to volume

$$V \sim \langle r_p \rangle^3 \approx 0.6 \, \mathrm{fm}^3$$

$$\alpha_{\mathrm{E1}} \approx 10^{-4} \, V_p$$

much ``stiffer'' than hydrogen!

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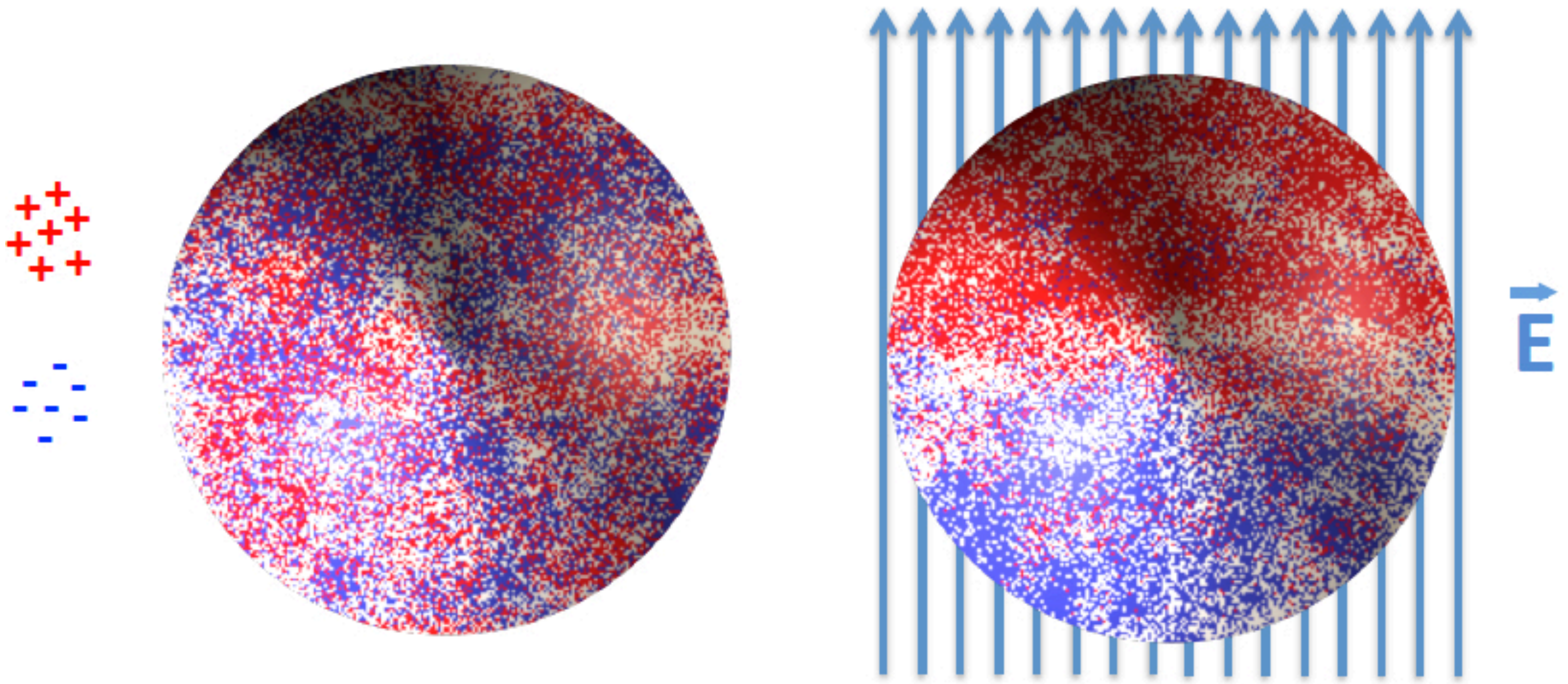
Measure of the strength of induced polarizations: 2 scalar polarizabilities + 4 spin polarizabilities



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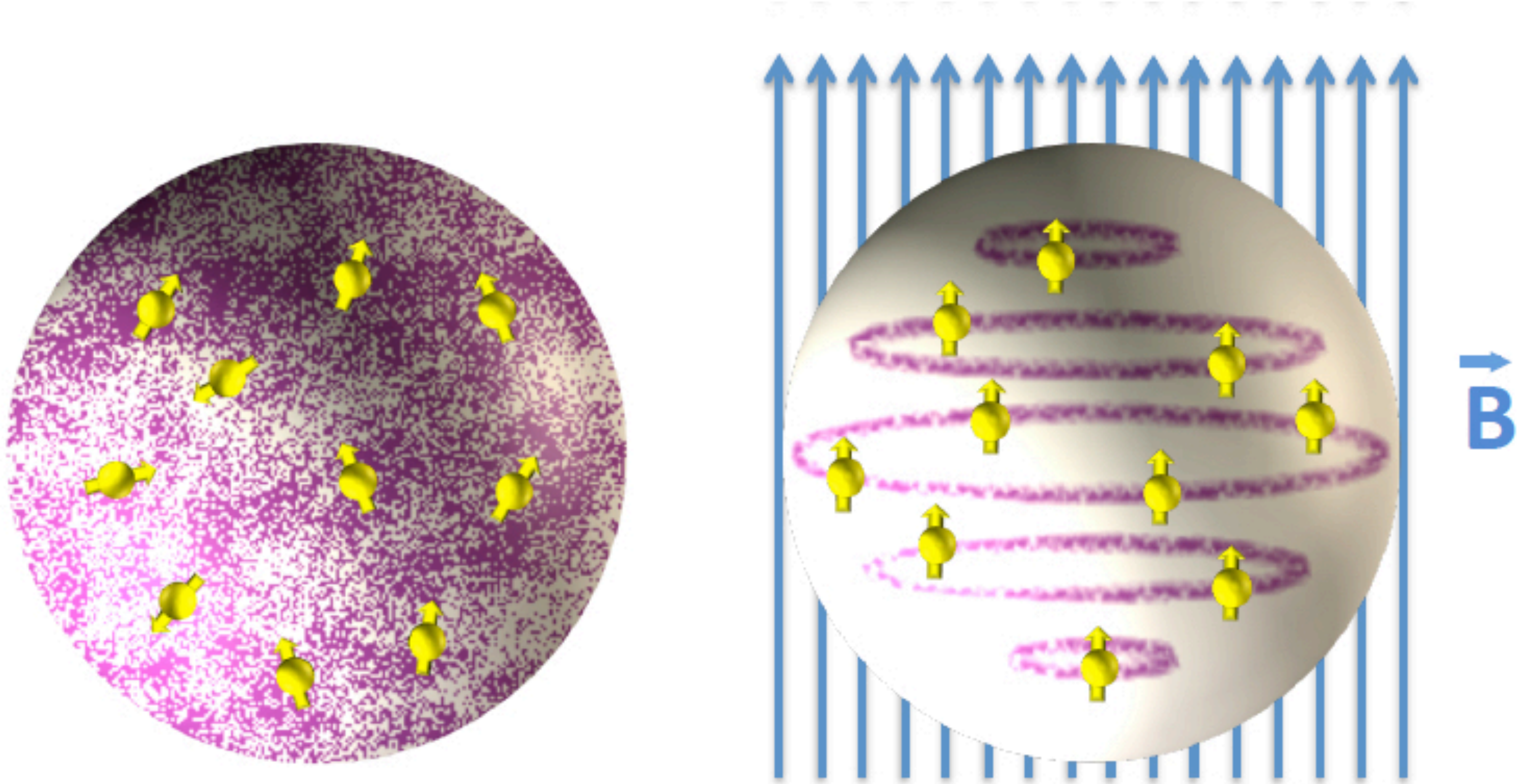

$$\vec{D}_M \sim \beta_{\mathrm{M1}}\,\vec{B}$$

$\beta^{\mathrm{para}}_{\mathrm{M1}} > 0$ proton spin aligns with external field

$\beta^{\mathrm{dia}}_{\mathrm{M1}} < 0$ induced current of pion cloud generates field opposite to the external one

Status of RCS scalar polarizabilities

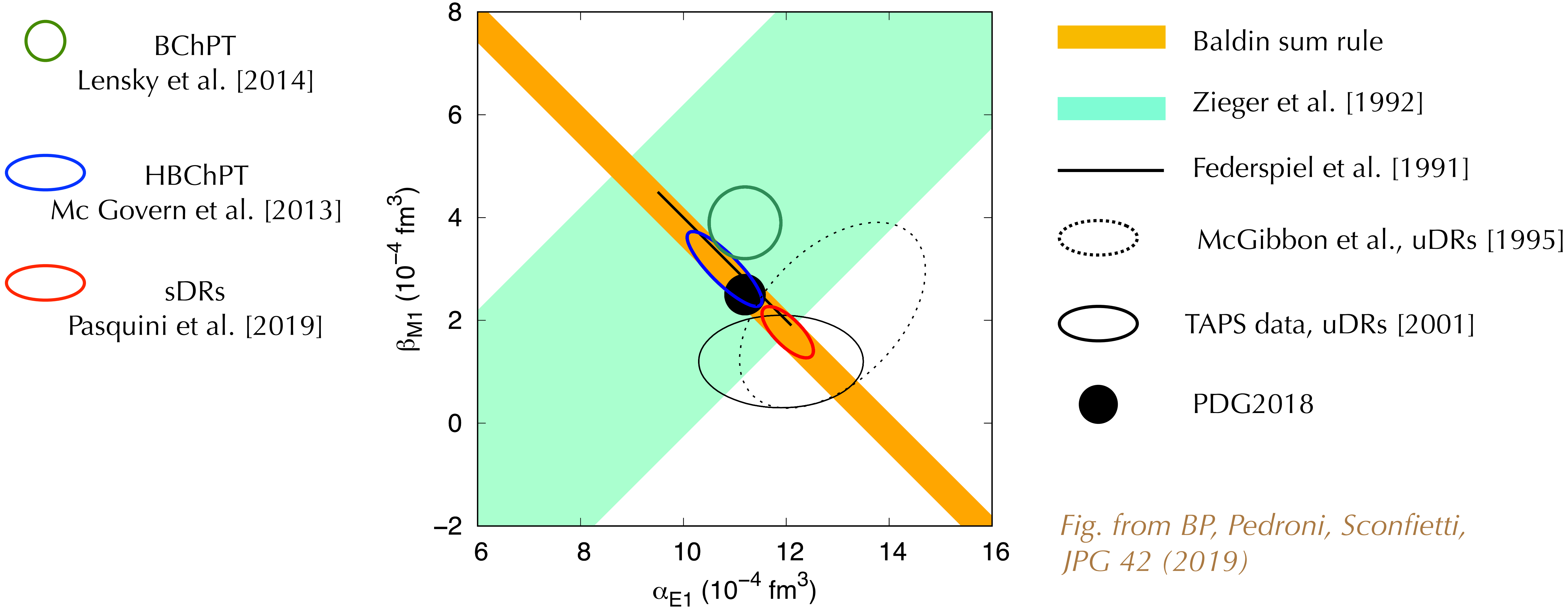

Fig. from BP, Pedroni, Sconfietti, JPG 42 (2019)

PDG2018: $\alpha_{\mathrm{E1}} = 11.2 \pm 0.4 \quad \beta_{\mathrm{M1}} = 2.5 \pm 0.4$

Baldin sum rule: $\alpha_{\mathrm{E1}} + \beta_{\mathrm{M1}} = 13.8 \pm 0.4$

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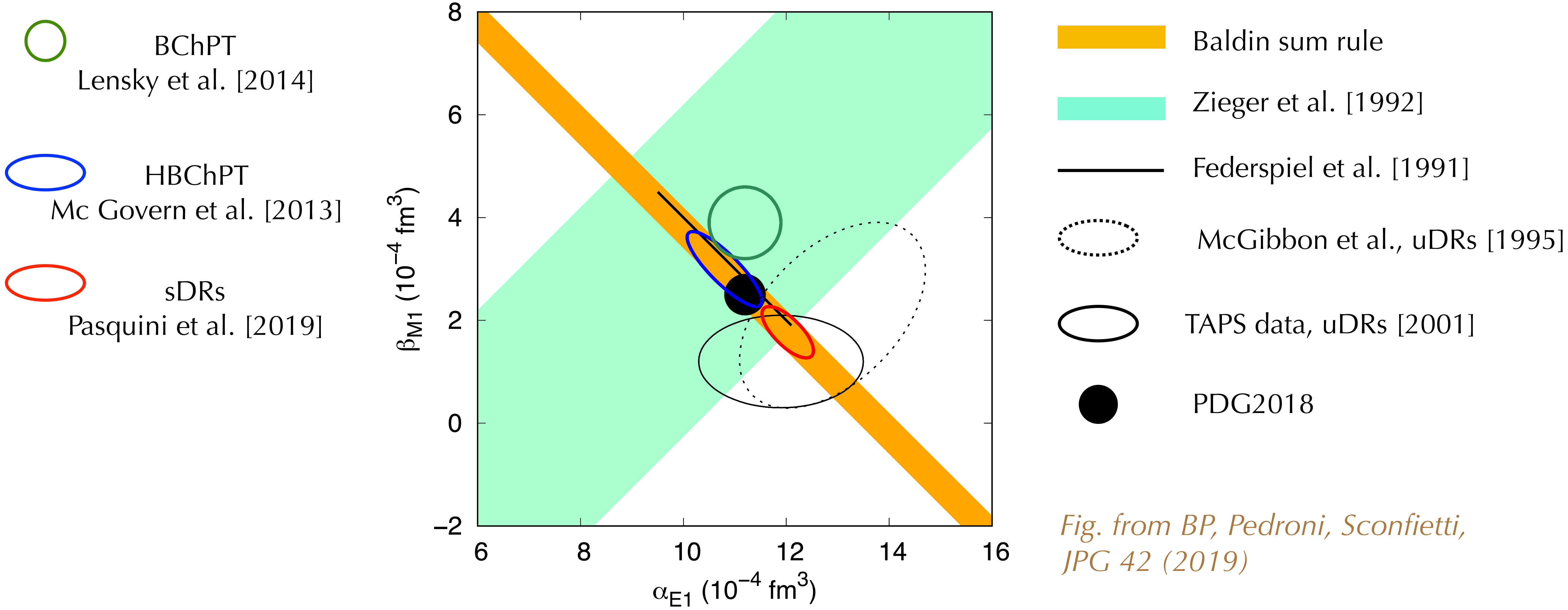

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Extractions obtained using different data sets and different theoretical models:

HBChPT

$$\alpha_{\rm E1} = 10.65 \pm 0.35\,(\text{stat.}) \pm 0.2\,(\text{Baldin}) \pm 0.3\,(\text{th.})$$

$$\beta_{\rm M1} = 3.15 \pm 0.35\,(\text{stat.}) \pm 0.2\,(\text{Baldin}) \pm 0.3\,(\text{th.})$$

Subtracted Dispersion Relations

$$\alpha_{\rm E1} = 12.03^{+0.48}_{-0.54}$$

$$\beta_{\rm M1} = 1.77^{+0.52}_{-0.54}$$

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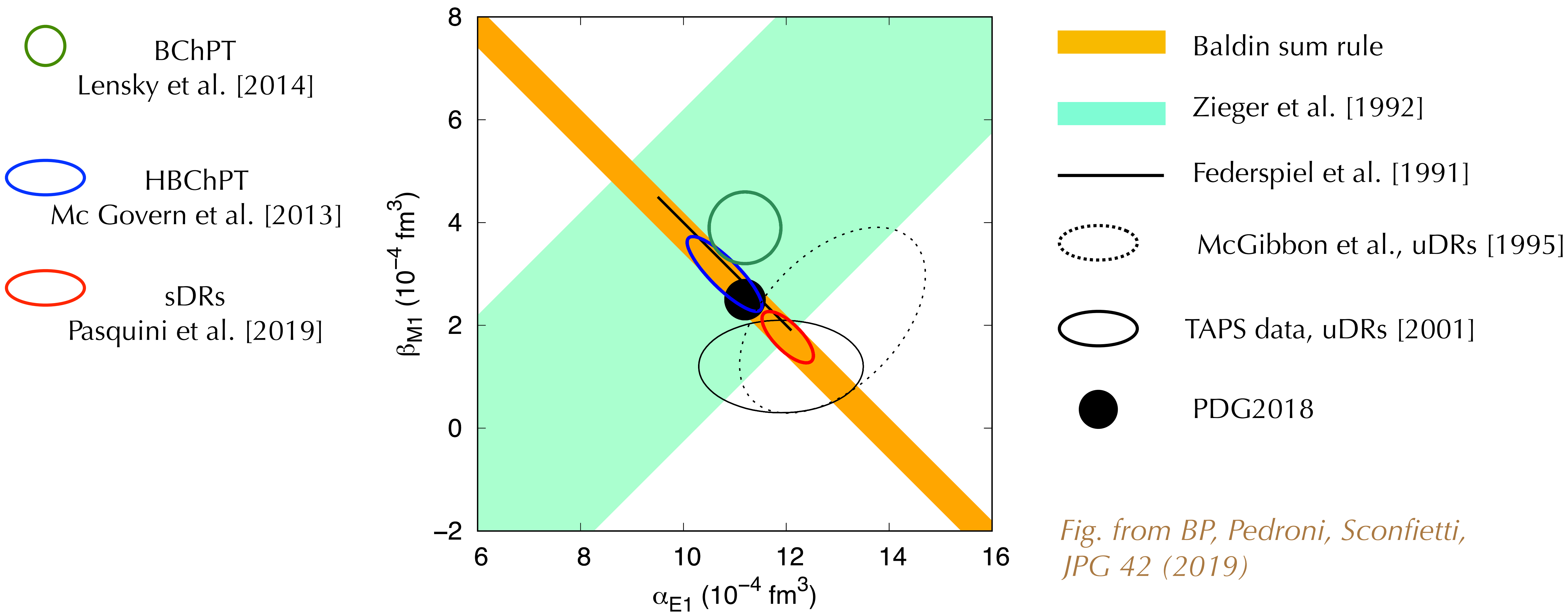

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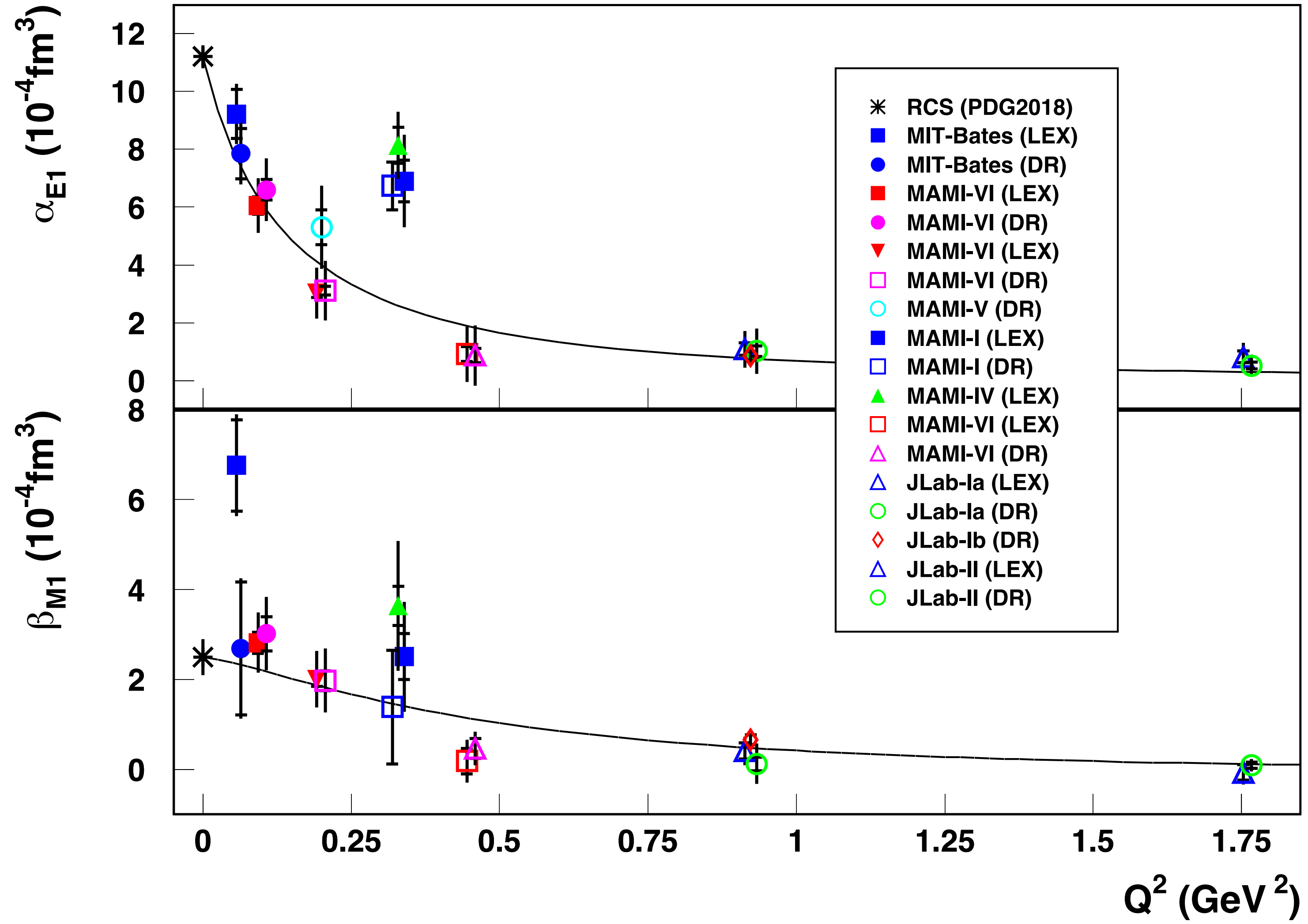
First extraction of spin pol. and very accurate data for scalar pol. from MAMI:

talks of P. Martel and E. Mornacchi

Status of VCS scalar polarizabilities

DR
fitted to data



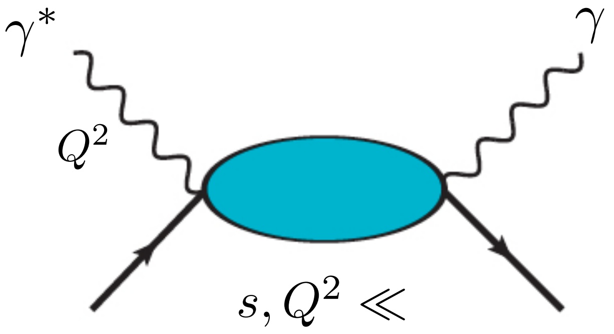


Fig. from Fonvieille, BP, Sparveris, arXiv:1910.11071

Two analysis methods: Low-Energy Expansion (LEX)
Dispersion Relations (DRs)

⇨

Model dependence:
spin GPs are taken from DR theory

New JLAB data under analysis: $0.3\,\mathrm{GeV}^2 \leq Q^2 \leq 0.75\,\mathrm{GeV}^2$

Plans to extract spin GPs directly from data under study
and
Efforts to reduce theoretical model dependence

Mean square polarizabilities radius

radius of induced electric and magnetic polarizations

(up to relativistic corrections)

$$\langle r^2 \rangle_{\mathrm{GP}} = -\frac{6}{\mathrm{GP}(0)} \frac{d}{dQ^2} \mathrm{GP}(Q^2)\Big|_{Q^2=0}$$

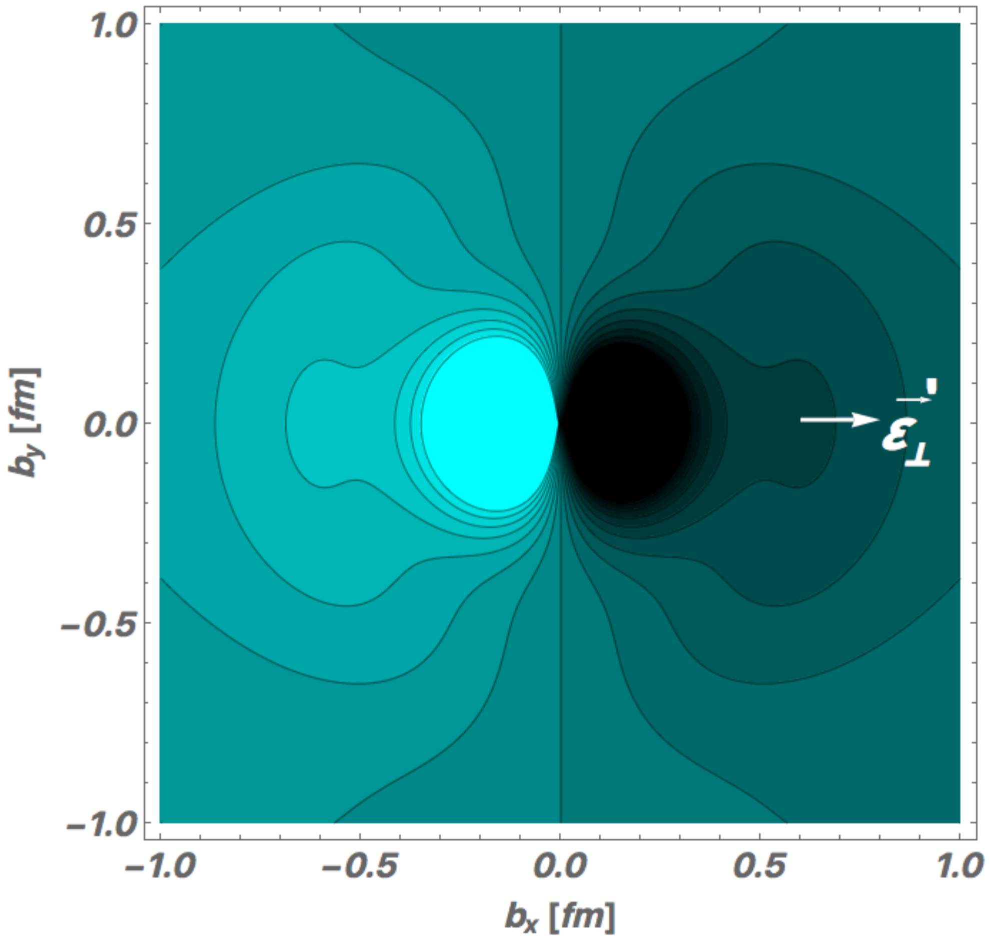
$\langle r^2 \rangle_{\mathrm{GP}}$ (fm^2)	resonance excitation	pion cloud	Total
α_{E1}	$0.60 \; {}^{+0.32}_{-0.26}$	$1.10 \; {}^{+0.04}_{-0.04}$	$1.70 \; {}^{+0.33}_{-0.24}$
β_{M1}	$2.67 \; {}^{+0.51}_{-0.37}$	$-3.91 \; {}^{+1.47}_{-2.00}$	$-1.24 \; {}^{+1.38}_{-1.86}$

- Square radius of electric GP much larger than square radius of charge distribution
- Dominance of long range effects of pion cloud

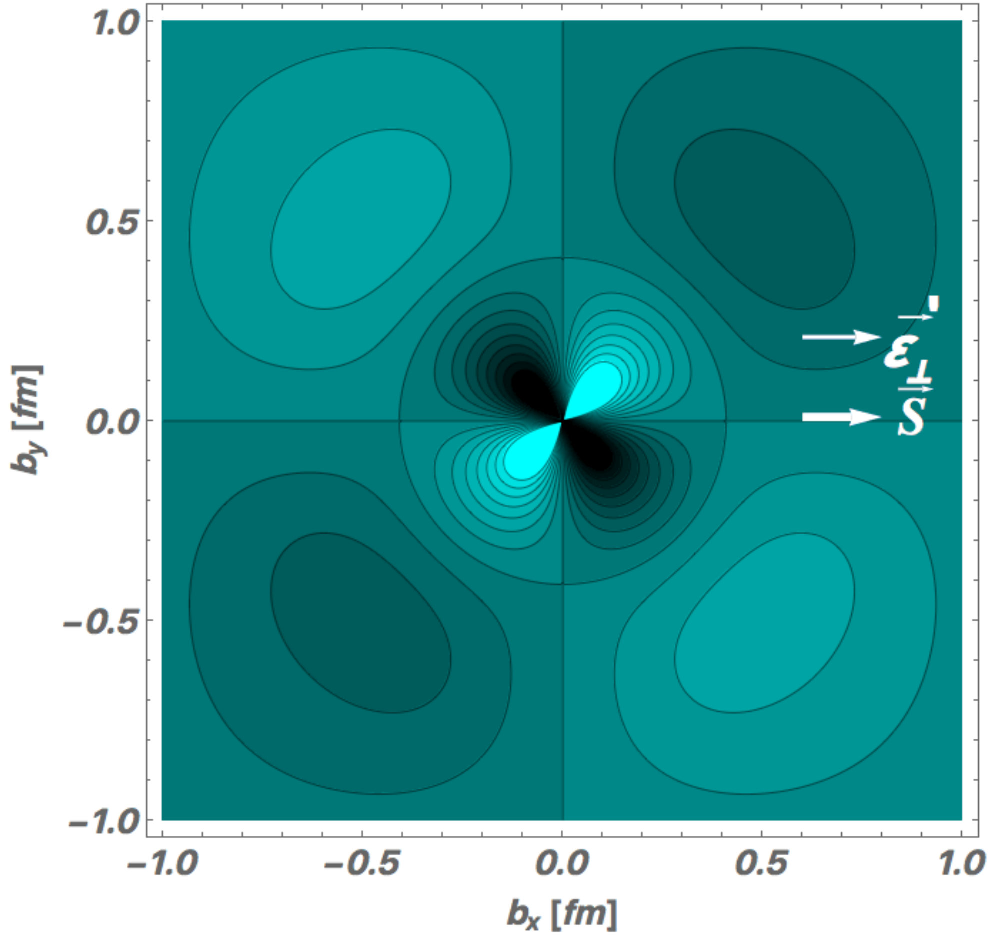
Fonvieille, BP, Sparveris, arXiv:1910.11071

Spatial density of induced polarizations

unpolarized proton target



transversely pol. proton target



light (dark) regions → larger (smaller) values

Light-front frame with fast moving proton in the longitudinal direction and $Q^2 = q_\perp^2$

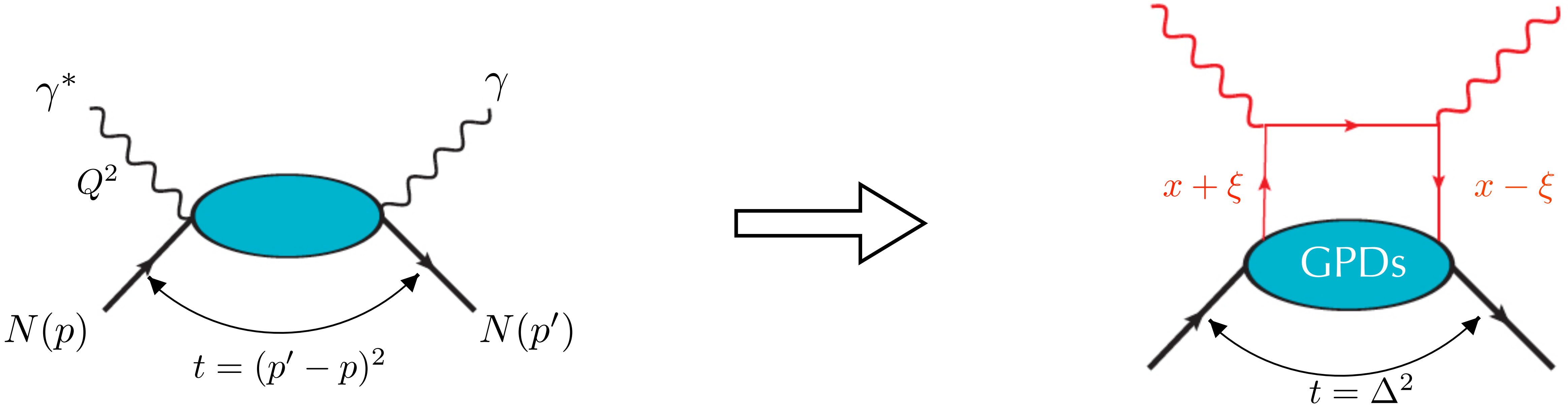
$\vec{q}_\perp \xleftrightarrow{\text{FT}} \vec{b}_\perp$

true probabilistic interpretation!

$\vec{E} \sim i q'^0 \vec{\epsilon}\,'_\perp$ quasi-static electric field → $\vec{P}$ induced polarization depending on scalar and spin GPs

Gorchtein, Lorcé, BP, Vanderhaeghen, PRL104 (2010) 112001

Partonic description: Deeply Virtual Compton Scattering



factorization for large Q^2, $|t| << Q^2$, s

$\mathcal{M}$ =[parton Ampl.] $\otimes$ [GPDs]

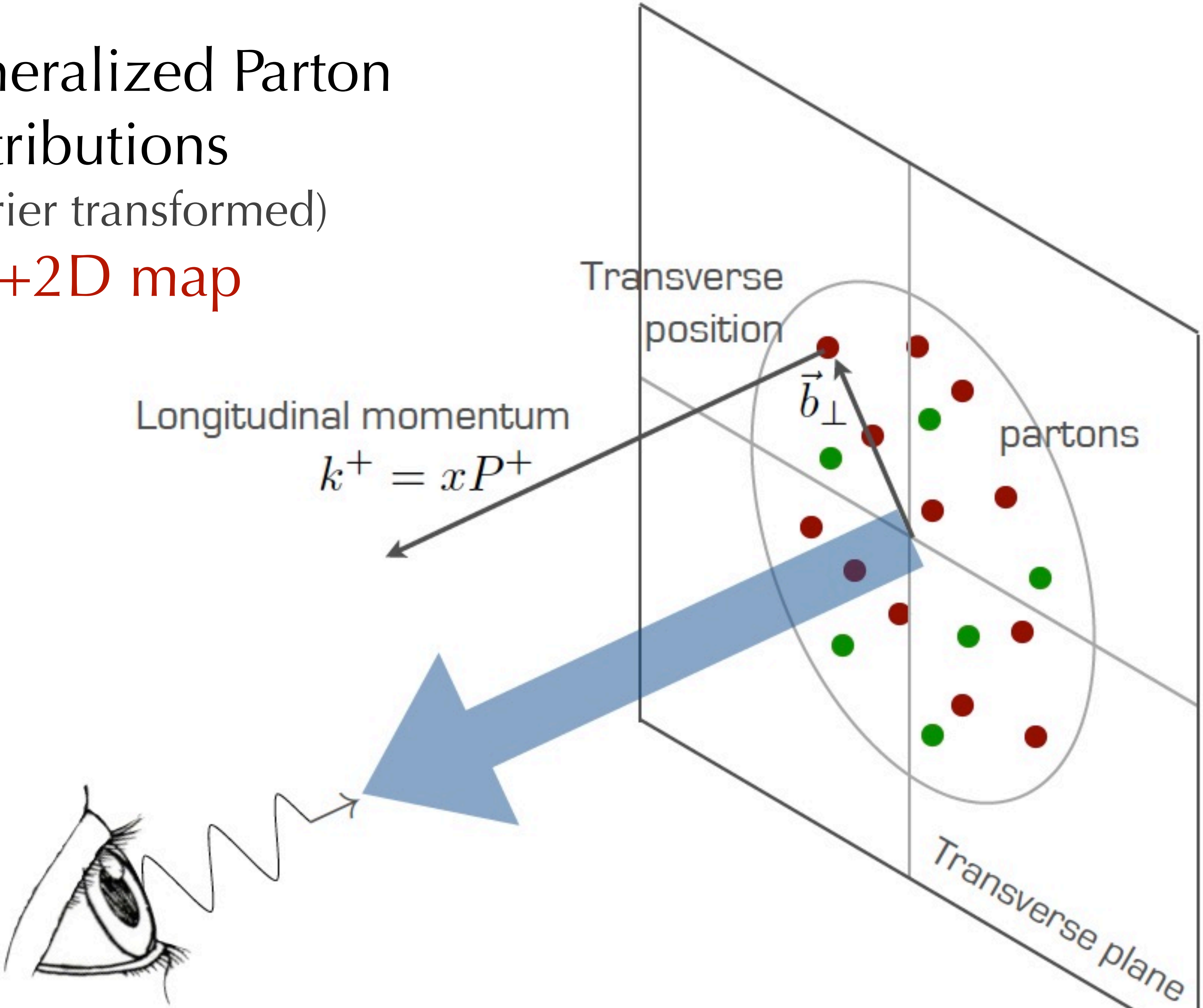
GPDs=GPDs (x,ξ,t)

- Transverse position size as function of x (2D+1D map)
- Form Factors of Energy Momentum Tensor ⟶ ``mechanical'' properties of the nucleon

Generalized Parton Distributions

(Fourier transformed)

1D+2D map



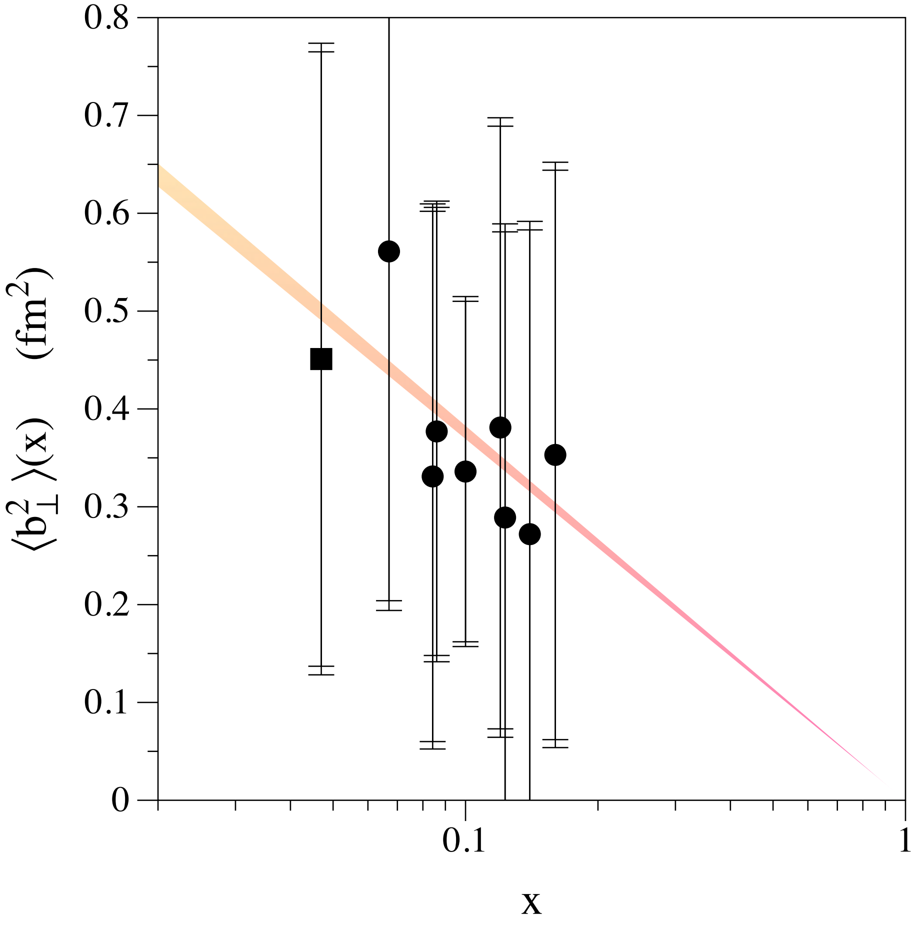
x-dependent transverse squared charge radius

$$H(x,0,\vec{b}_\perp) = \int_{-\infty}^{+\infty} \mathrm{d}^2\vec{\Delta}_\perp \, H(x,0,t)\, e^{-i\vec{\Delta}_\perp\cdot\vec{b}_\perp} \longrightarrow \langle \vec{b}_\perp^{\,2}(x)\rangle = \frac{\int \mathrm{d}^2\vec{b}_\perp \, \vec{b}_\perp^{\,2} \, H(x,0,b_\perp)}{\int \mathrm{d}^2\vec{b}_\perp H(x,0,b_\perp)}$$

$(t = -\vec{\Delta}_\perp^2)$ $\quad \xi = 0$ extrapolation from data

x-dependent transverse squared radius

CLAS and HERMES data



The errors are large,
but slowly we are getting some 3D information

Dupré et al., PRD95(2017)011501

x-dependent transverse squared charge radius

$$H(x,0,\vec{b}_\perp) = \int_{-\infty}^{+\infty} \mathrm{d}^2\vec{\Delta}_\perp \, H(x,0,t)\, e^{-i\vec{\Delta}_\perp\cdot\vec{b}_\perp} \longrightarrow \langle \vec{b}_\perp^{\,2}(x)\rangle = \frac{\int \mathrm{d}^2\vec{b}_\perp\, \vec{b}_\perp^{\,2}\, H(x,0,b_\perp)}{\int \mathrm{d}^2\vec{b}_\perp H(x,0,b_\perp)}$$

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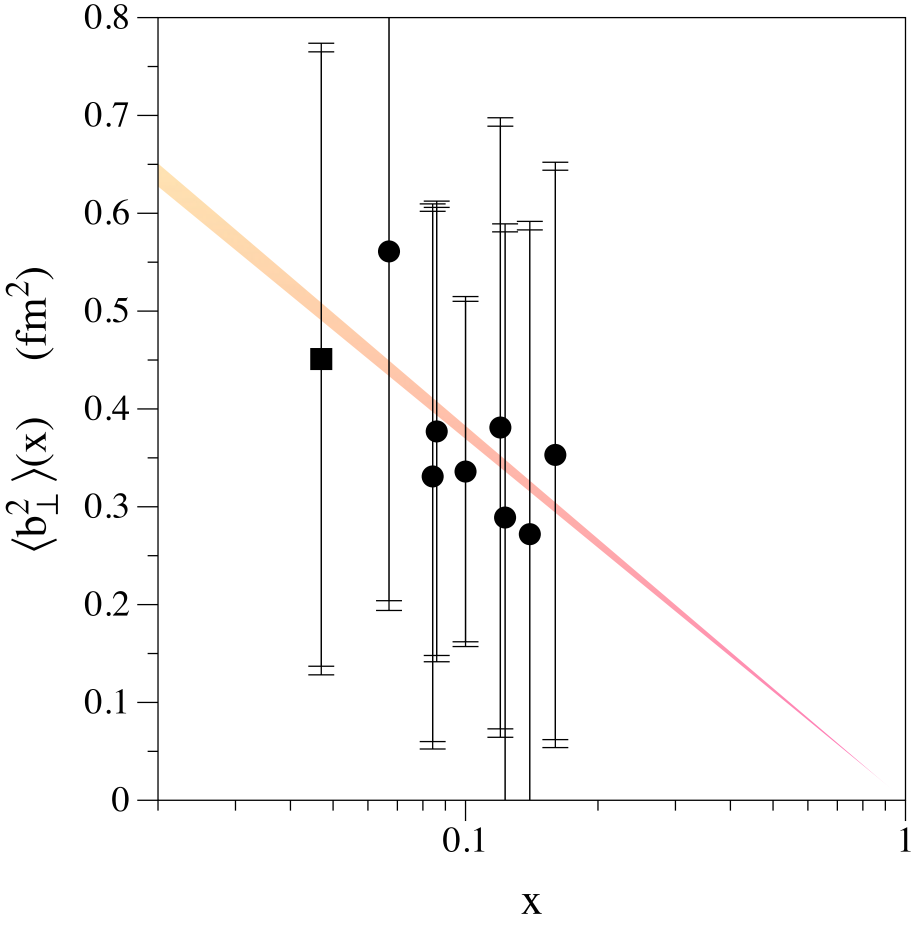
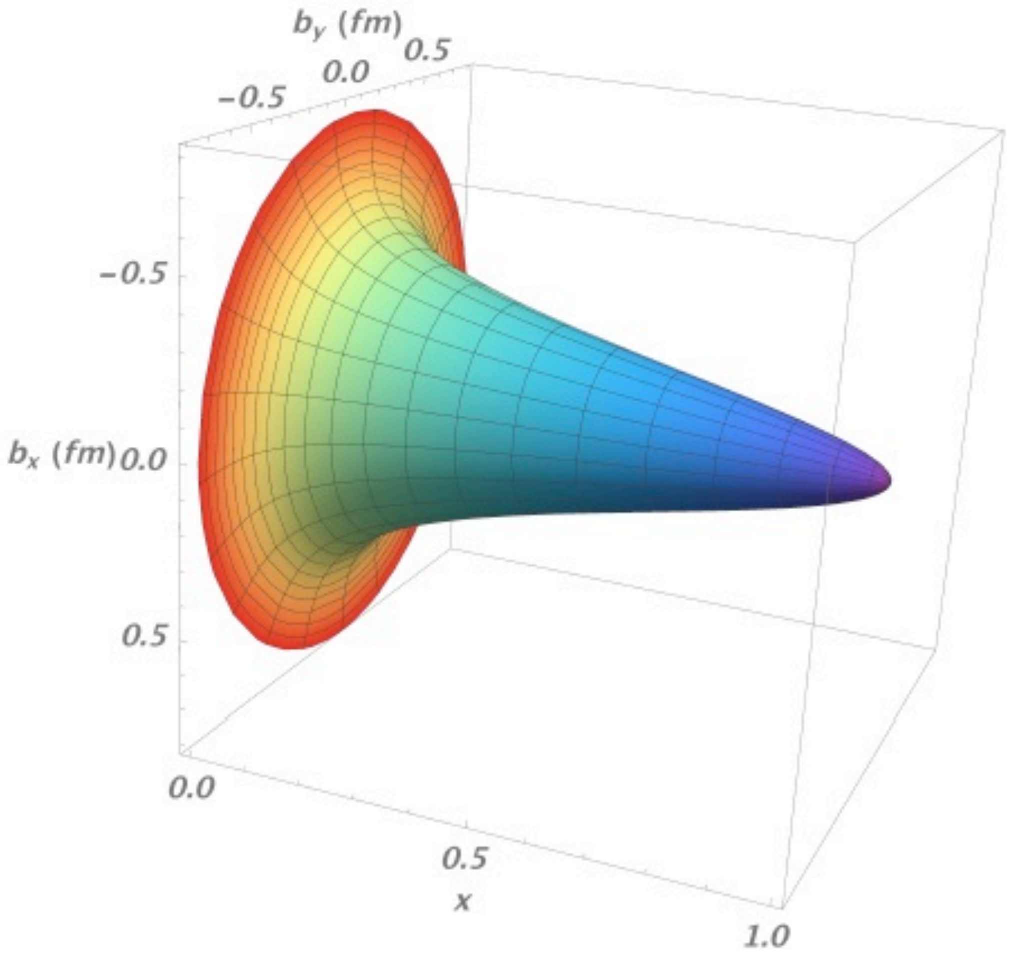


extrapolating
in the unmeasured
x-range

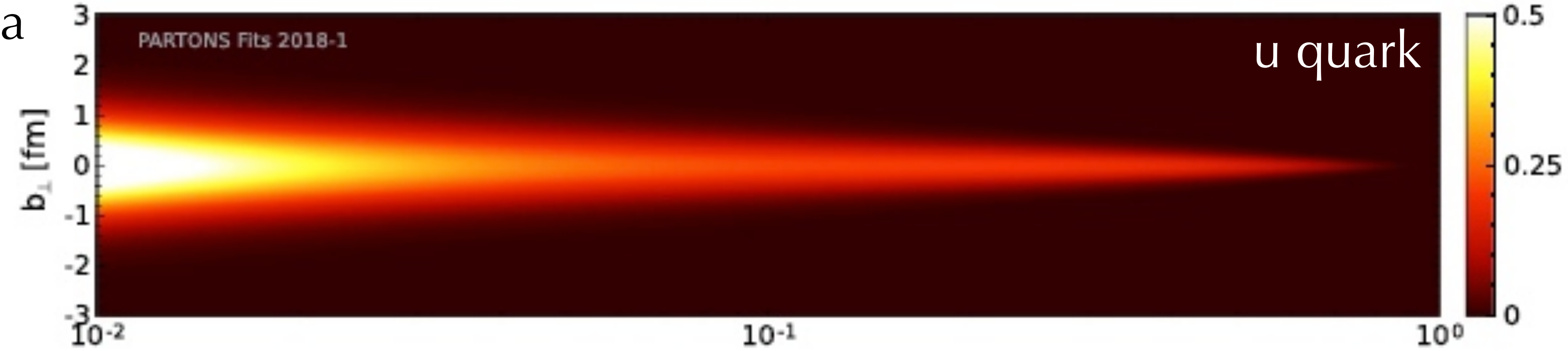


As x ⟶ 1, the active parton carries all the momentum
and represents the centre of momentum

Dupré et al., PRD95(2017)011501

New parametrization based on DRs: reduce problems related to the extrapolation to $\xi = 0$

CLAS and HERMES data

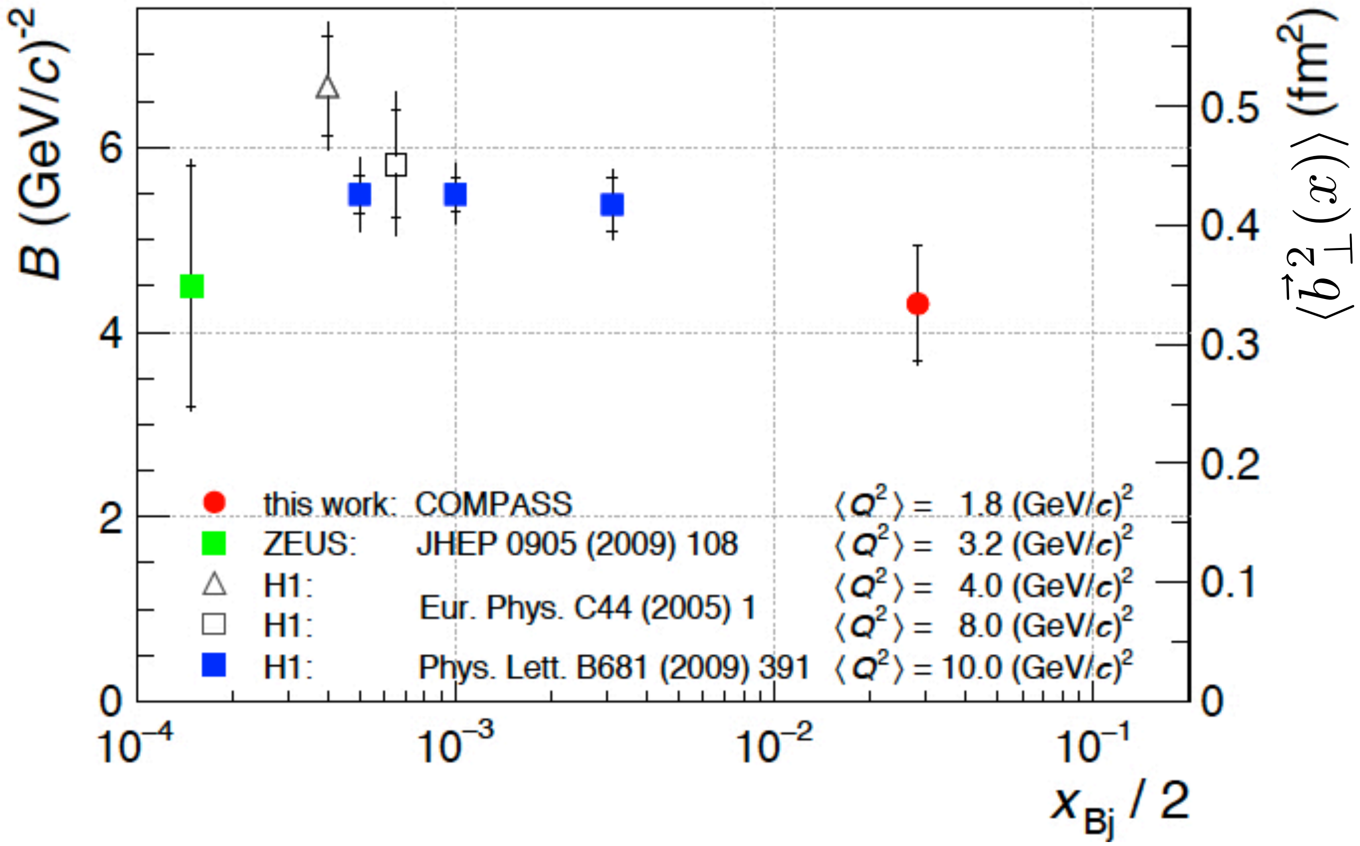


Moutarde et al., EPJC (2018)78

New results from COMPASS Coll.: arXiv:1802.02739

$$\frac{d\sigma}{dt} \approx e^{-B(x)|t|}$$

$$\langle \vec{b}_\perp^{\,2}(x) \rangle = 2\langle B(x) \rangle$$



Model dependence can not be avoided, but different fit methods and parametrizations can help to constraint the theoretical uncertainties

⟶ *Talk of D. Sokhan*

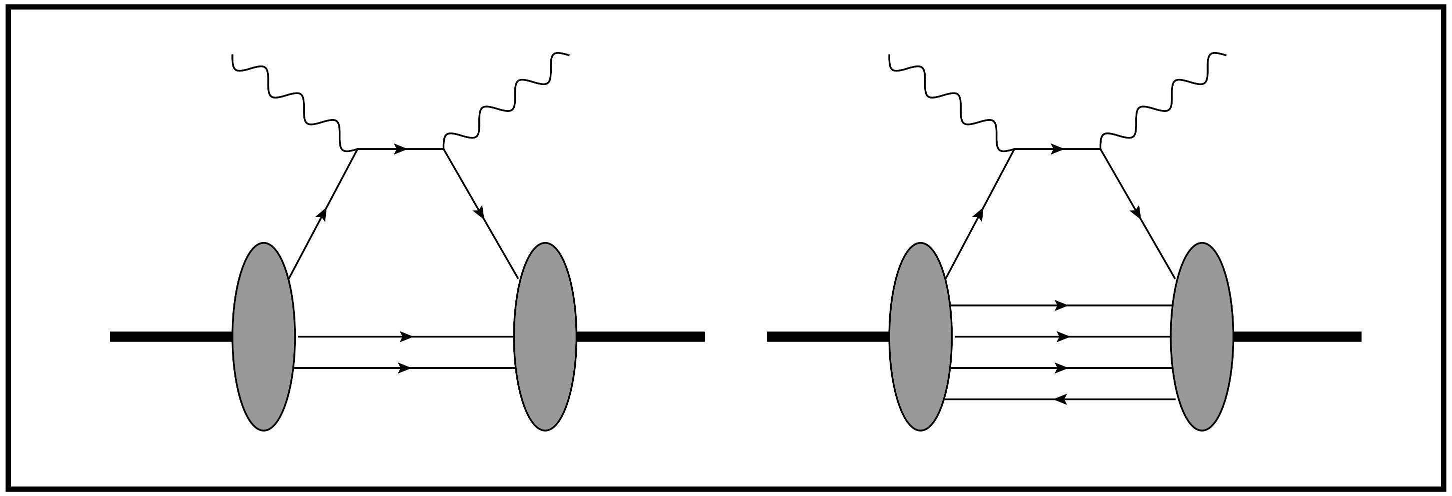
Probabilistic interpretation

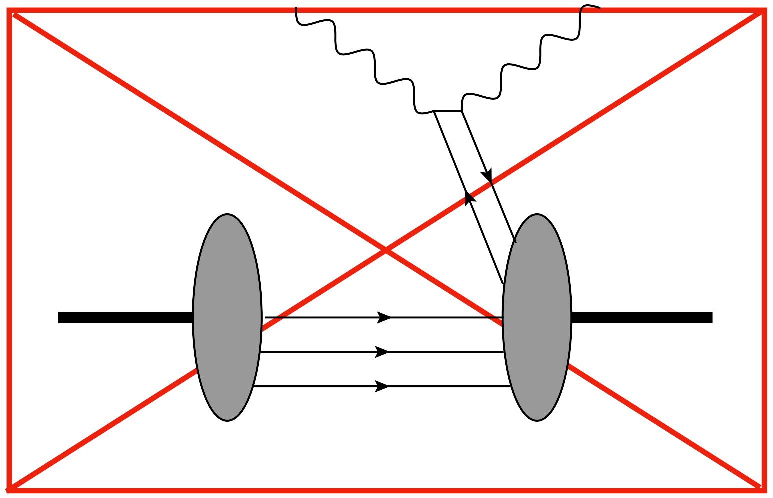
Drell-Yan frame: $\Delta^+ = 0 \quad \vec{\Delta}_\perp \neq 0$

✓ $\Delta^+ = 0 \longrightarrow$ no sensitivity to longitudinal Lorentz contraction

✓ $\vec{\Delta}_\perp \neq 0$: Transverse boosts $\longrightarrow$ no transverse Lorentz contraction

✓ Particle number is conserved in Drell-Yan frame $\Delta^+ = 0$





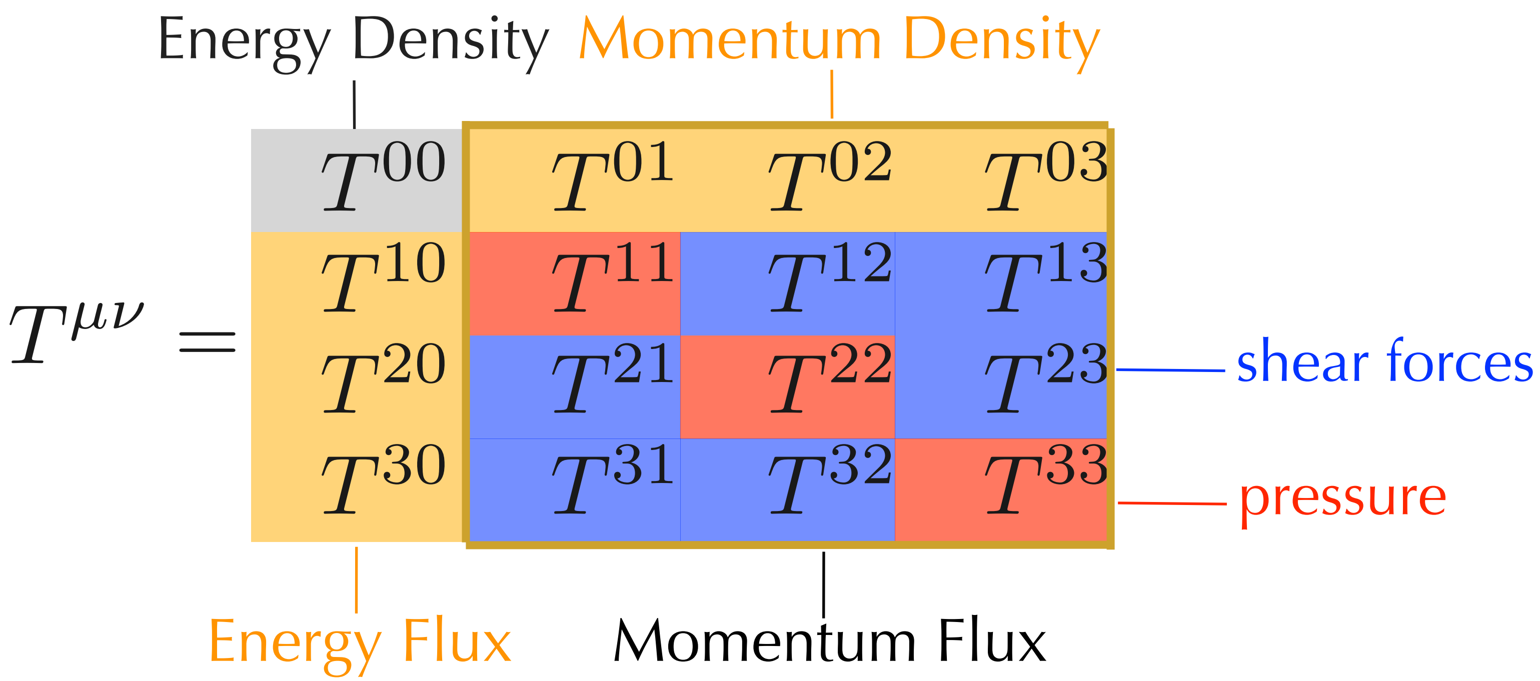
Relation with means square radius measured extracted from G_E

$$\langle b_\perp^2 \rangle_{\rm NR} = \int d^2 b_\perp^2 \, b_\perp^2 \, \rho_{\rm NR}(b) = -4G'_E(0) = \tfrac{2}{3}\langle r^2 \rangle_{\rm NR}$$

$$\langle b_\perp^2 \rangle_{\rm NR} = \langle b_\perp^2 \rangle + \tfrac{\kappa_N}{4M_N^2} = \langle b_\perp^2 \rangle + 0.02 \ \text{fm}^2$$

G.A. Miller, PRC99 (2019)

Form Factors of Energy Momentum Tensor



Energy Density

Momentum Density

$$T^{\mu\nu} = \begin{matrix} T^{00} & T^{01} & T^{02} & T^{03} \\ T^{10} & T^{11} & T^{12} & T^{13} \\ T^{20} & T^{21} & T^{22} & T^{23} \\ T^{30} & T^{31} & T^{32} & T^{33} \end{matrix}$$

shear forces

pressure

Energy Flux

Momentum Flux

$$\langle p| T^{Q,G}_{\mu\nu} |p'\rangle = \bar{u}(p') \left[M_2^{Q,G}(t) \frac{P_\mu P_\nu}{M_N} + J^{Q,G}(t) \frac{i(P_\mu \sigma_{\nu\rho} + P_\nu \sigma_{\mu\rho})\Delta^\rho}{2M_N} + d_1^{Q,G}(t) \frac{\Delta_\mu \Delta_\nu - g_{\mu\nu}\Delta^2}{5M_N} \pm \bar{c}(t) g_{\mu\nu} \right] u(p)$$

Relation with second-moments of GPDs:

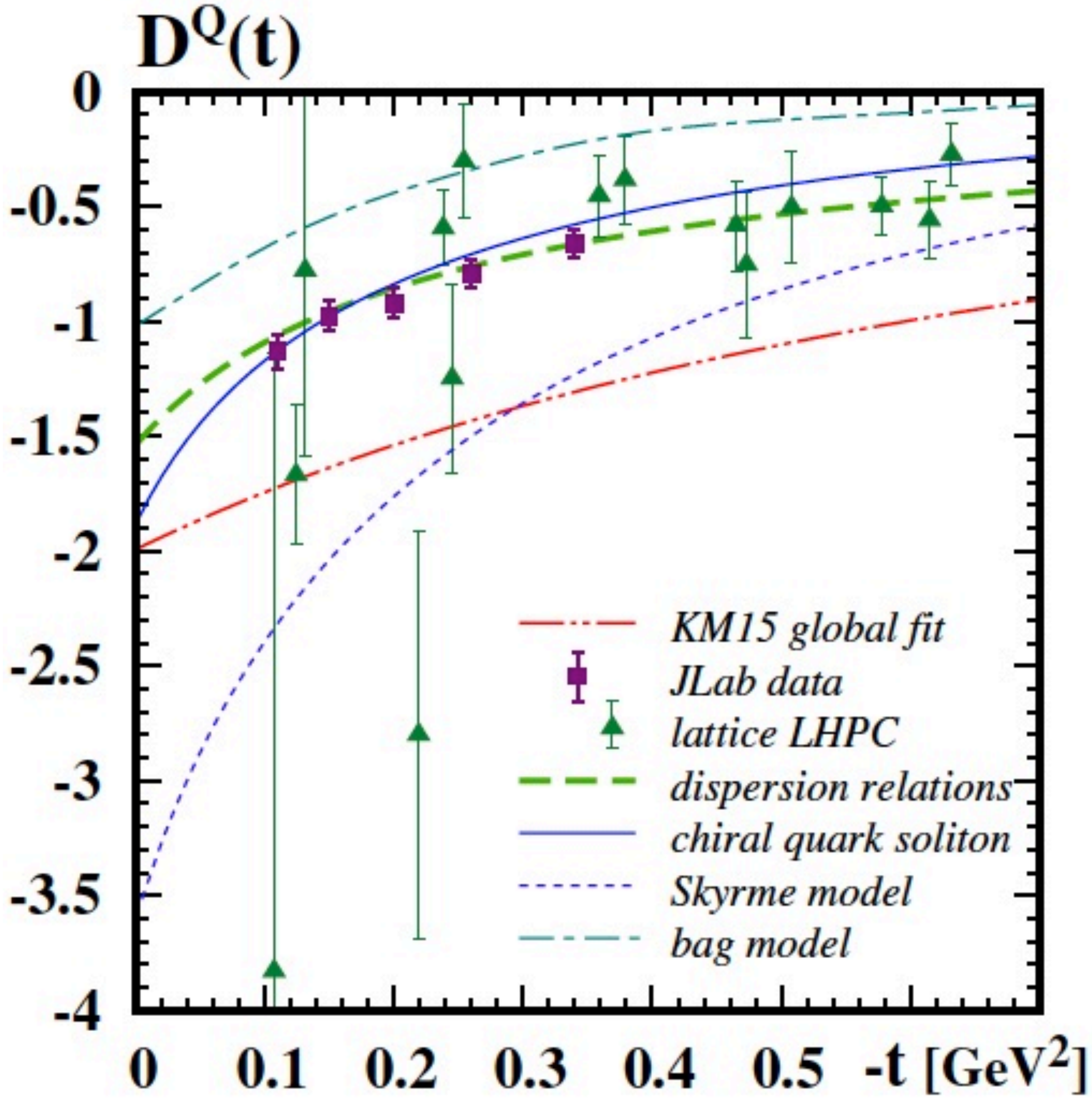
$$\sum_q \int \mathrm{d}x\, x\, H^q(x,\xi,t) = M_2^Q(t) + \frac{4}{5} d_1^Q(t)\xi^2$$

$$\sum_q \int \mathrm{d}x\, x\, E^q(x,\xi,t) = 2J^Q(t) - M_2^Q(t) - \frac{4}{5} d_1^Q(t)\xi^2$$

"Charges" of the EMT Form Factors at t=0

$M_2(0)$	nucleon momentum carried by parton
$J(0)$	angular momentum of partons
$d_1(0)$	D-term ("stability" of the nucleon)

D-term form factor



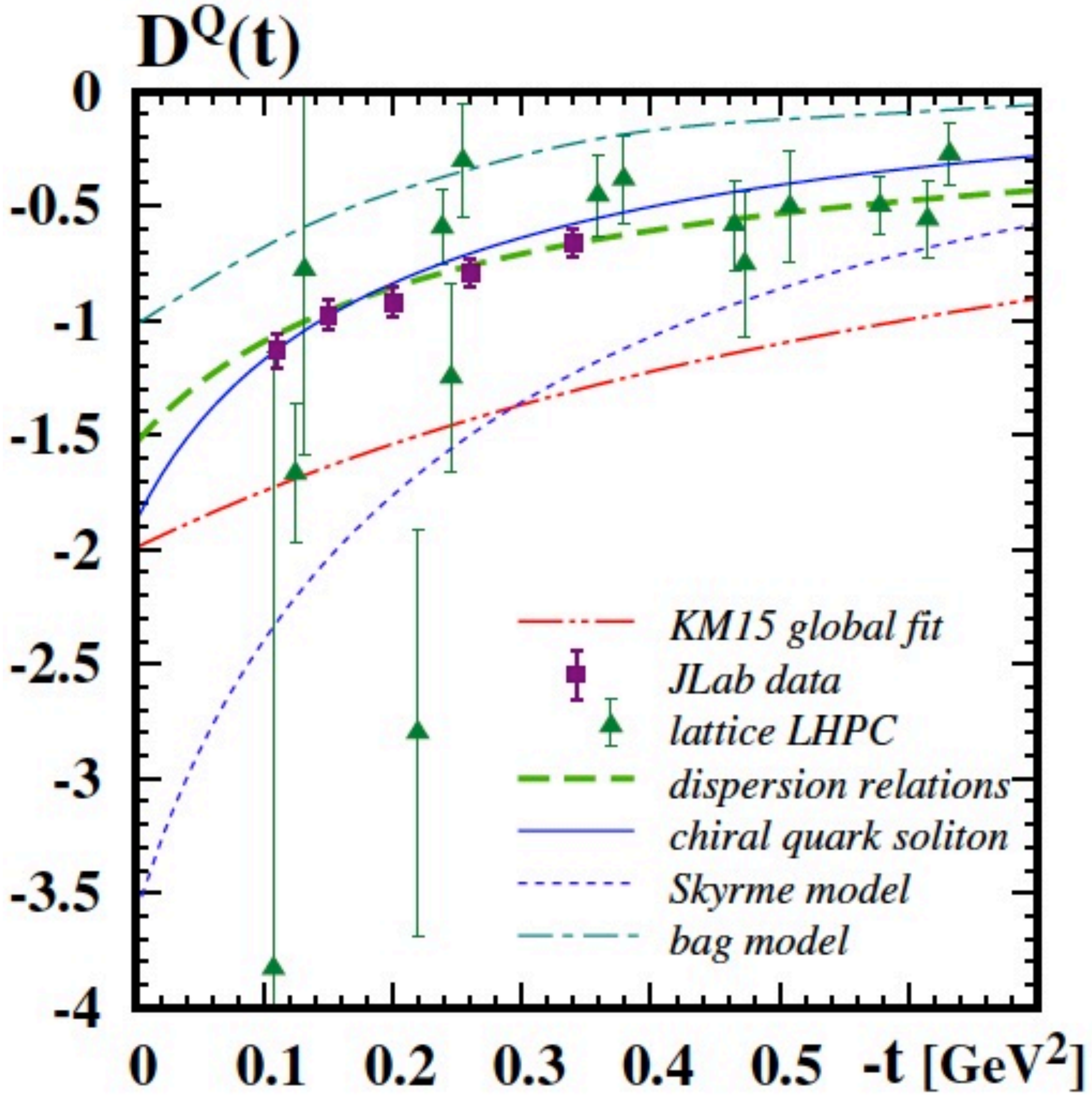
Polyakov and Schweitzer,
Int. J. Mod. Phys. A33 (2018) 1830025

Normal force distribution in the system:

$$\langle r^2\rangle_{\rm mech} = \frac{\int d^3r\, r^2[\frac{2}{3}s(r)+p(r)]}{\int d^3r\,[\frac{2}{3}s(r)+p(r)]} = \frac{6\,D(0)}{\int_{-\infty}^{0} dt D(t)}$$

$\langle r^2\rangle_{\rm mech} \approx 0.75\,\langle r^2\rangle_{\rm charge}$ Chiral quark soliton model

D-term form factor



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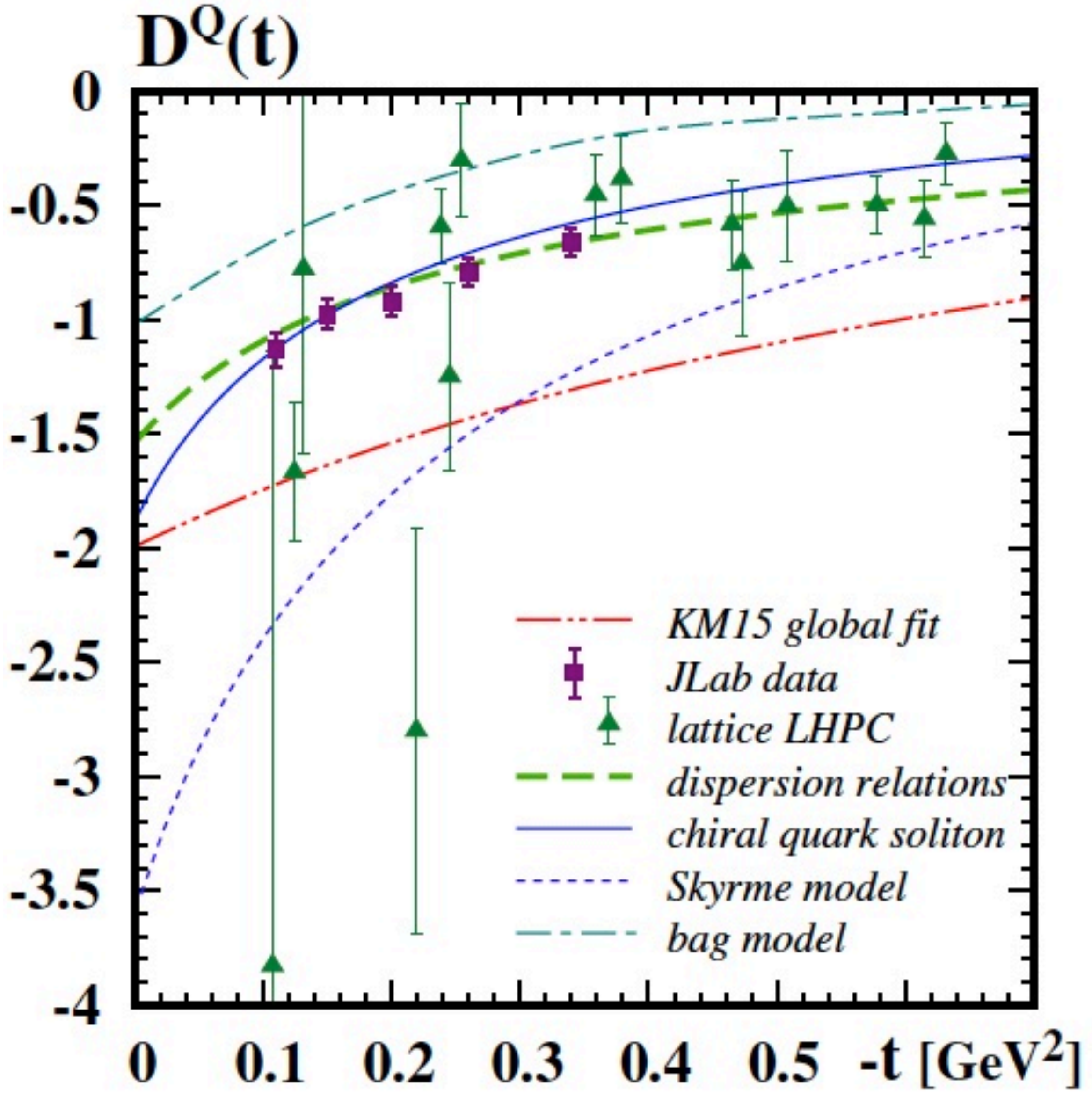

Polyakov and Schweitzer,
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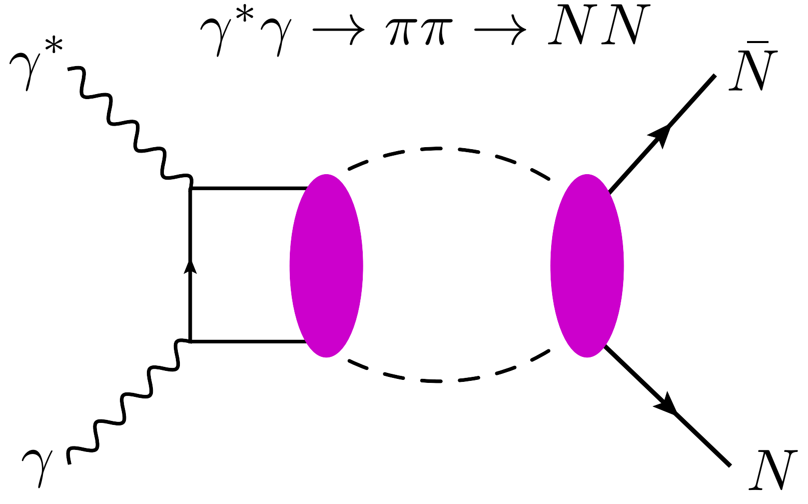
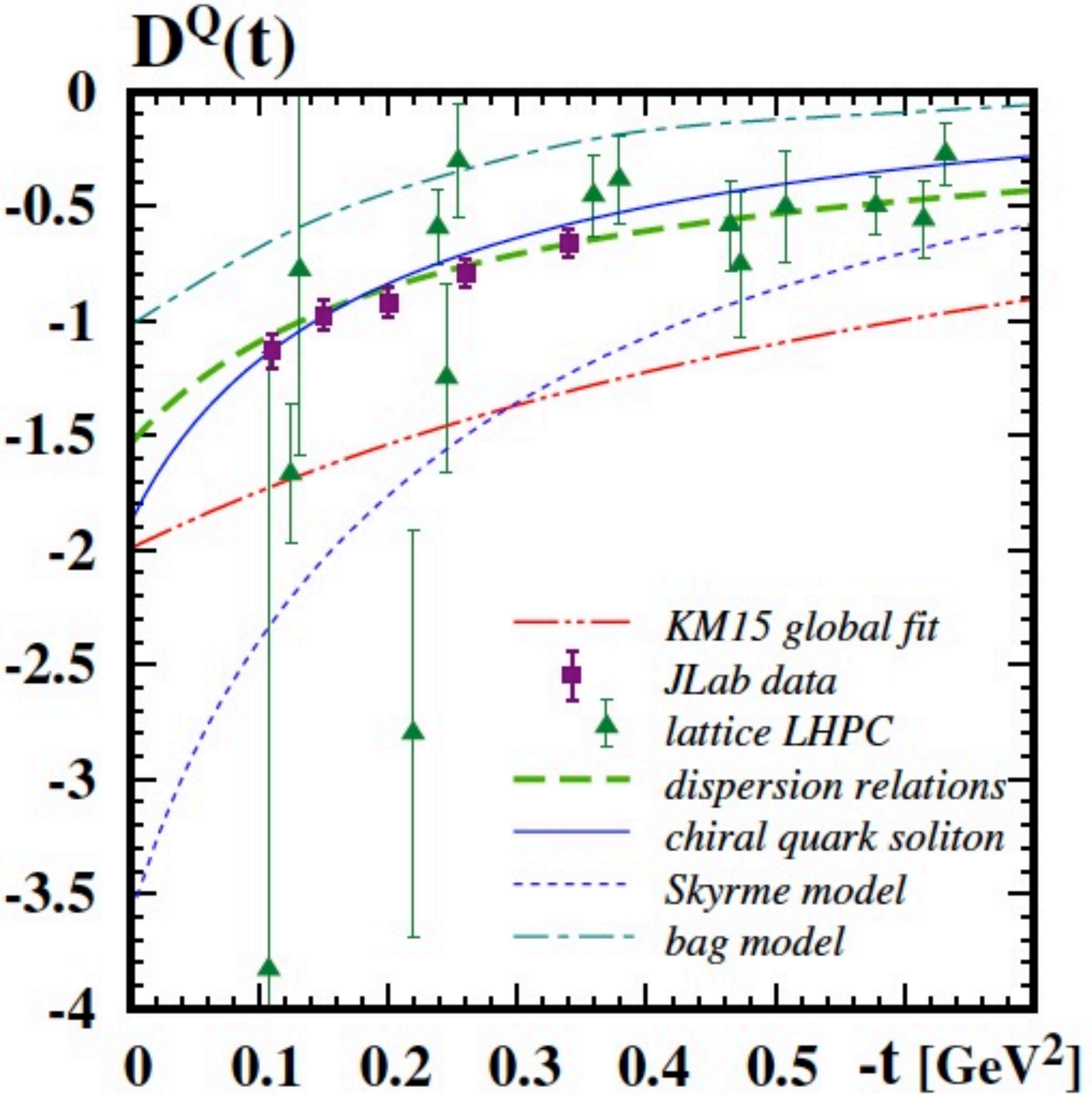
Dispersion Relations:
BP, Polyakov, Vanderhaeghen, PLB739(2014)133

D-term from t-channel dispersion relations

$\gamma^*\gamma \to \pi\pi \to N\bar{N}$



D-term form factor

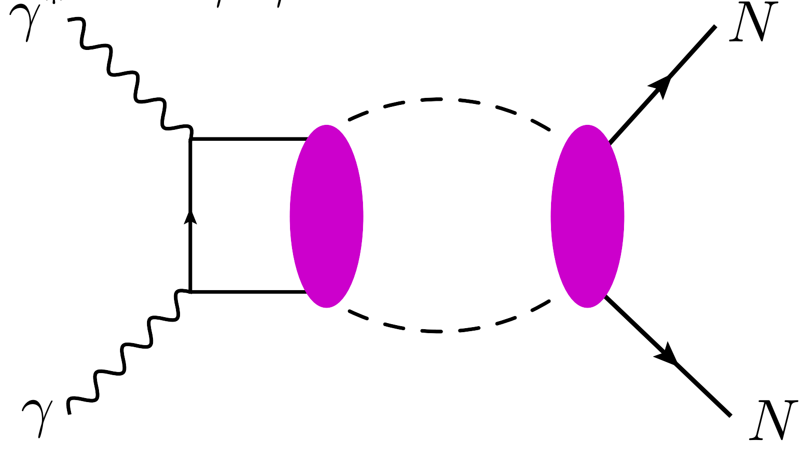


Polyakov and Schweitzer,
Int. J. Mod. Phys. A33 (2018) 1830025

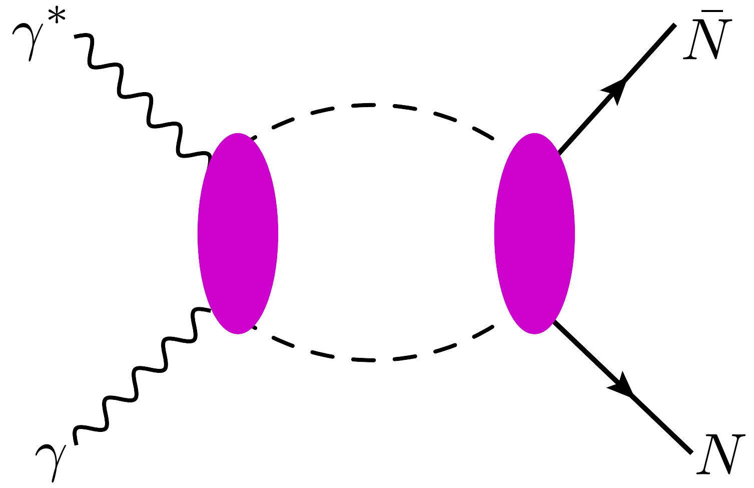
Dispersion Relations:
BP, Polyakov, Vanderhaeghen, PLB739(2014)133

D-term from t-channel dispersion relations

$\gamma^*\gamma \to \pi\pi \to N\bar{N}$



the same two-pion correlated state enters
the diamagnetic contribution to $\beta_{\mathrm{M1}}(Q^2)$ from DRs

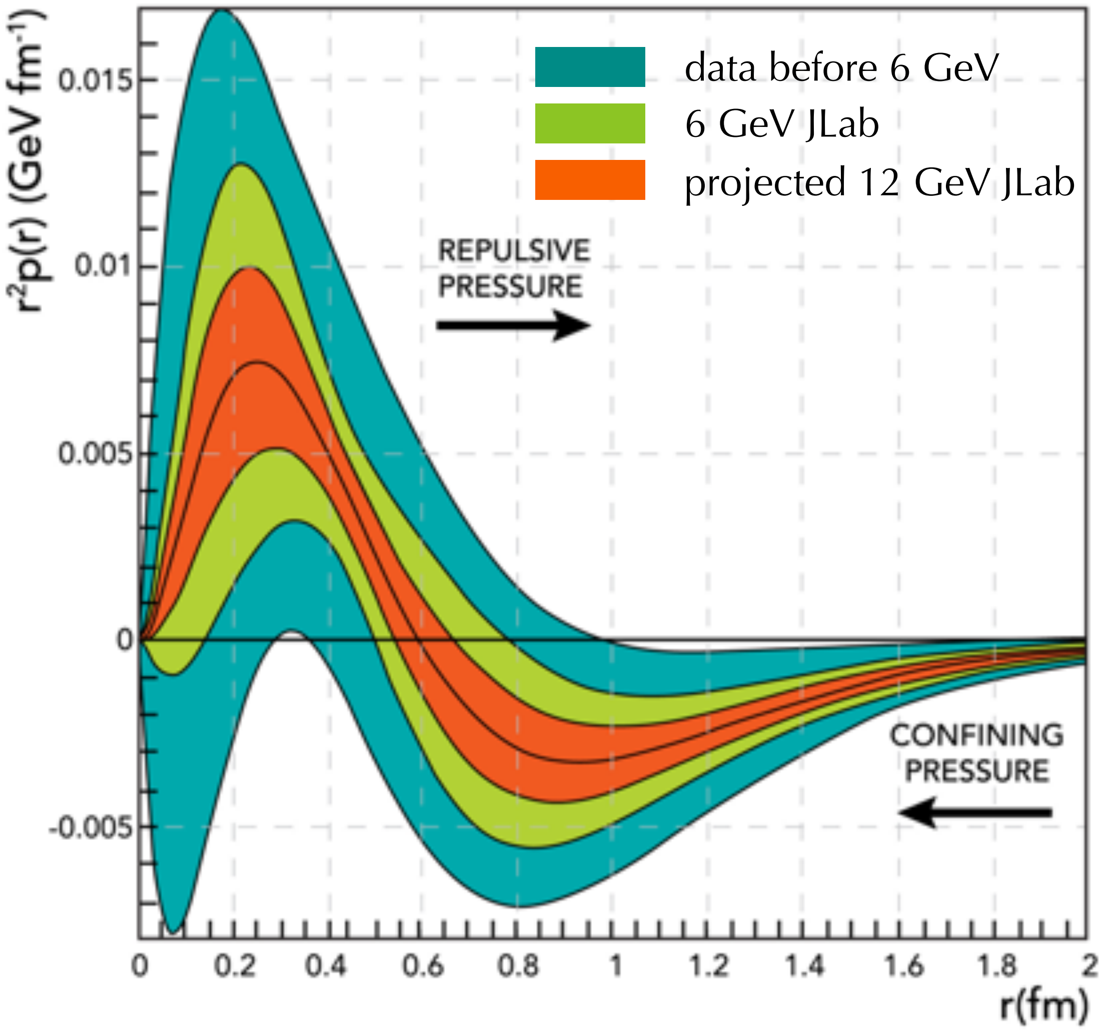


Efforts to develop unified framework connecting low and high Q^2 regimes

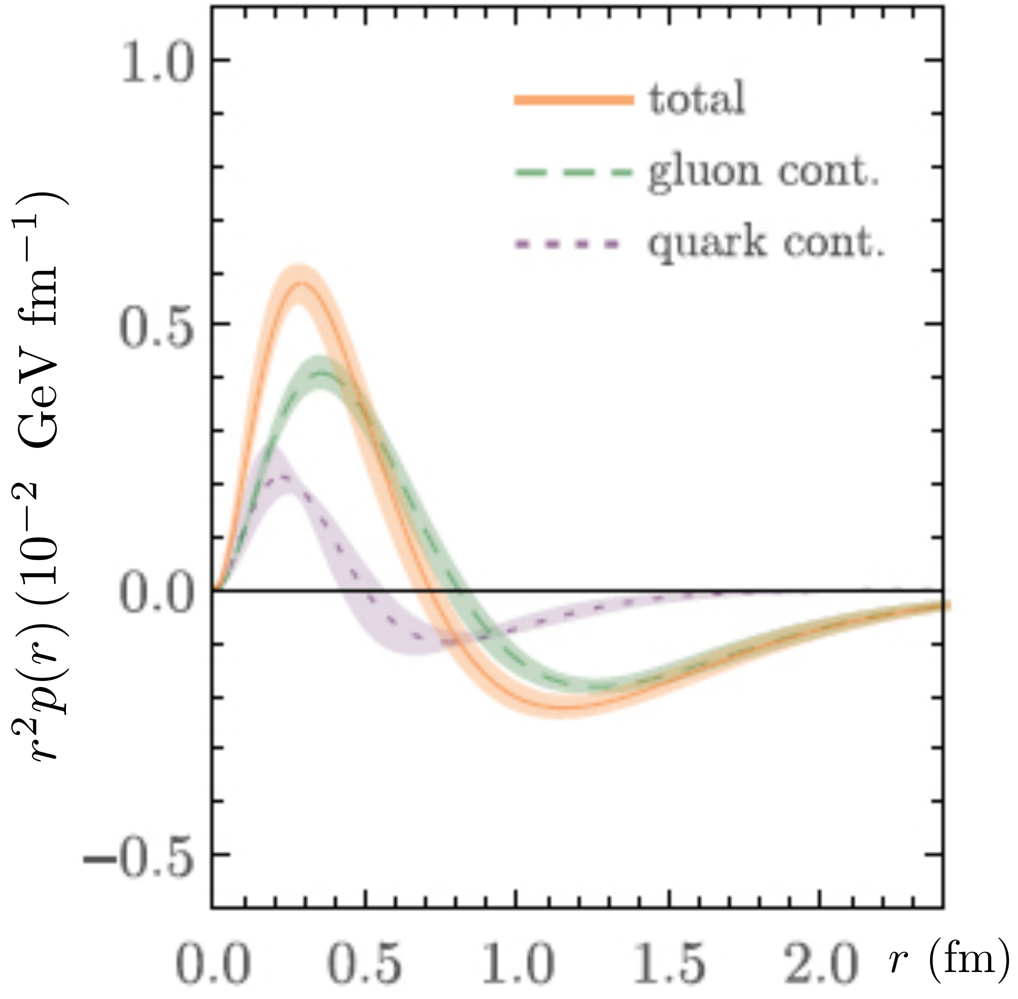
Belitsky, Mueller, Yao Ji, NPB878(2014)214; Eichmann, Fischer, PRD87 (2013)

Radial pressure distribution

$$\tilde{D}(r) \overset{\text{FT}}{\longleftrightarrow} D(t) \qquad r^2 p(r) = \frac{1}{3}\frac{d}{dr} r^2 \frac{d}{dr}\tilde{D}(r)$$



Girod, Elouadrhiri,Burkert, Nature 557 (2018) 7705

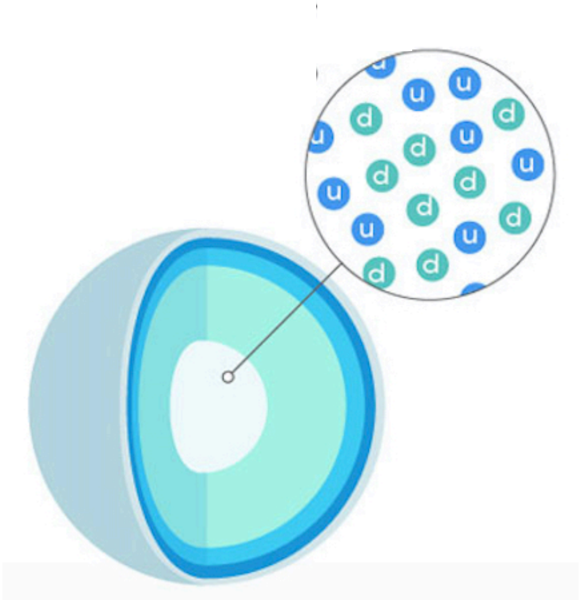


Shanahan, Detmold, PRL122 (2019) 072003

Necessary to verify model assumptions in the exp extraction with more data coming from JLab, COMPASS and the future EIC

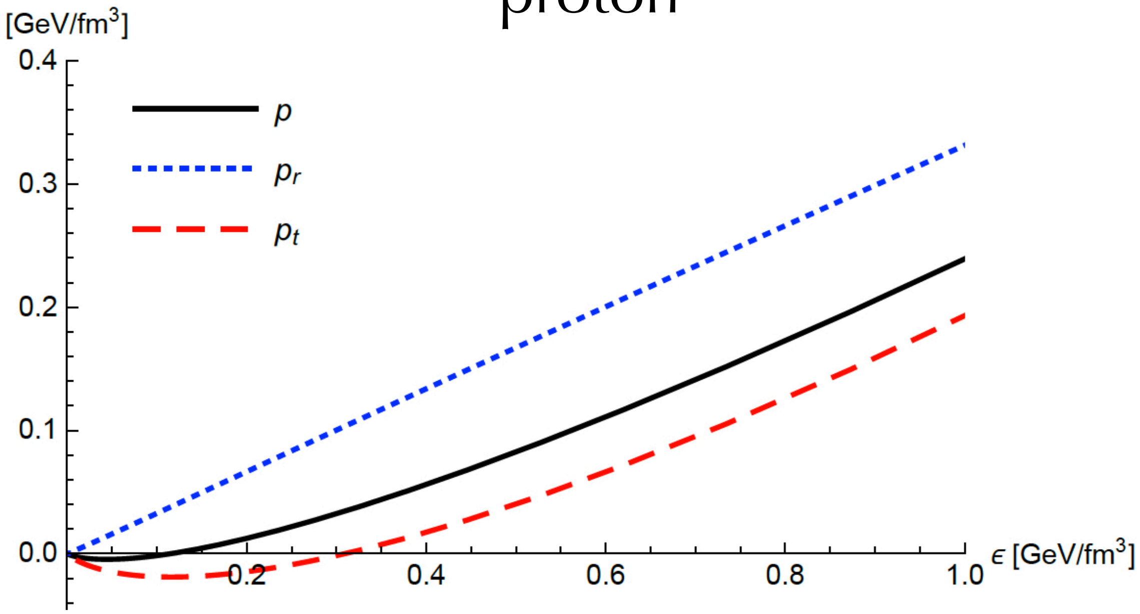
Kumericki, Nature 570 (2019) 7759

⟶ *Talks of Elouadrhiri, Shanahan, Trawinski*



The knowledge of pressure in hadronic matter can in principle allows us to make predictions on the behaviour of neutron stars

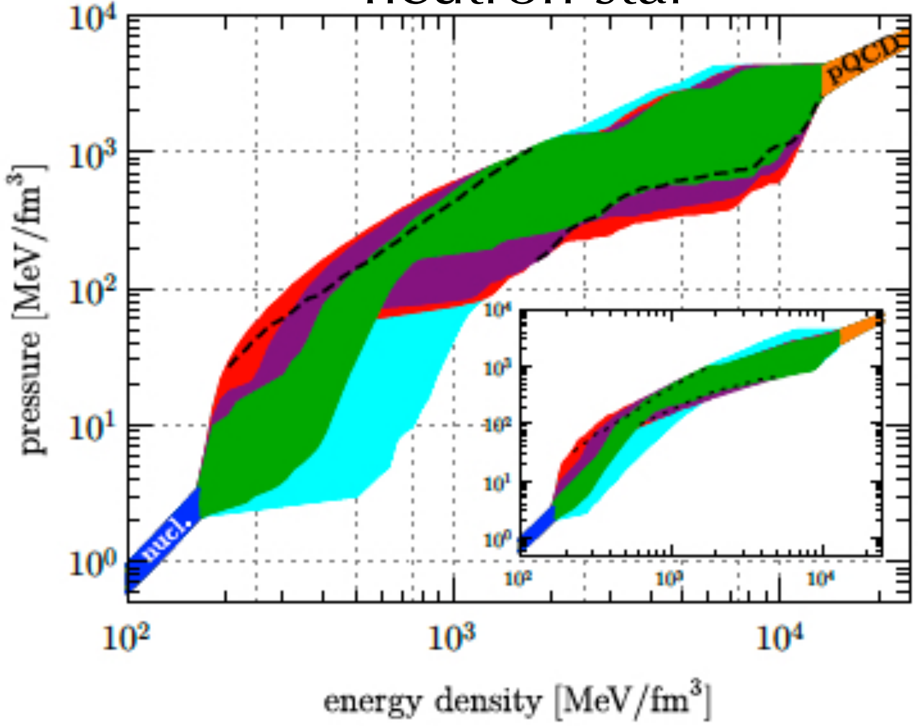
proton



Lorcè, Moutarde, Trawinski, EPJ C79 (2019) 89

Rajan, Liuti, Yagi, arXiv:1812.01479

neutron star



Annala et al., PRL120 (2018) 172703

Exciting results but need more solid underpinnings!

⟶ *Talk of J. Van den Brand*

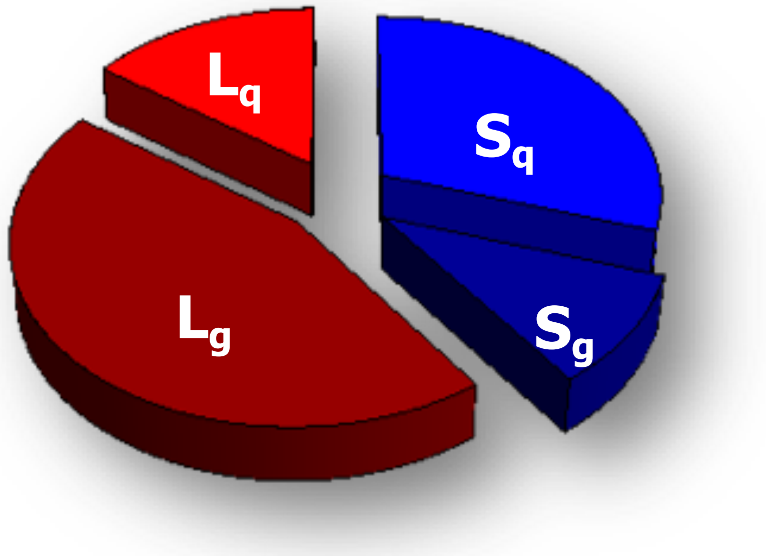
Angular Momentum Relation (Ji's Sum Rule)

X. Ji, PRL 78 (1997) 610

quark and gluon contribution to the nucleon spin

$$J^{q,g} = \frac{1}{2}\int_{-1}^{1} dx\, x\, \big(\underset{\substack{\big\downarrow \\ \text{at } \xi = 0 \text{ unpolarized PDF}}}{H^{q,g}(x,\xi,0)} + \underset{\substack{\big\downarrow \\ \text{not directly accessible}}}{E^{q,g}(x,\xi,0)}\big)$$

$$J^q = L^q + \overset{\frac{1}{2}\Delta\Sigma \text{ from DIS}}{\overset{\uparrow}{S^q}}$$



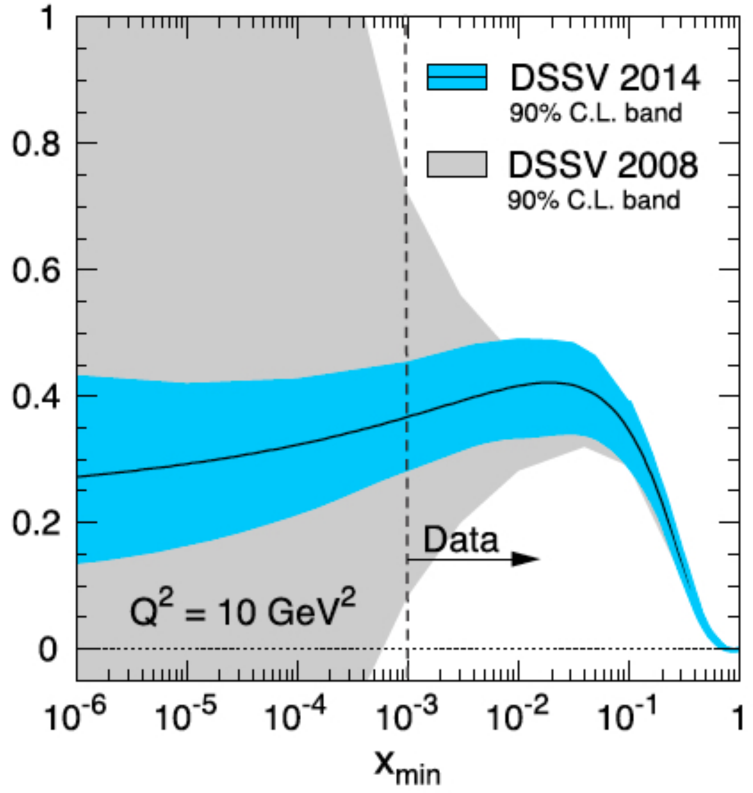
$$J^g = L^g + \overset{\frac{1}{2}\Delta g \text{ from DIS}}{\overset{\uparrow}{S^g}}$$

- Requires extrapolation at t=0
- Requires spanning x at fixed values of ξ ($\xi = 0$ is the most convenient)
- Does not have an interpretation as angular momentum density as a function of x

Spin contributions to proton angular momentum from data

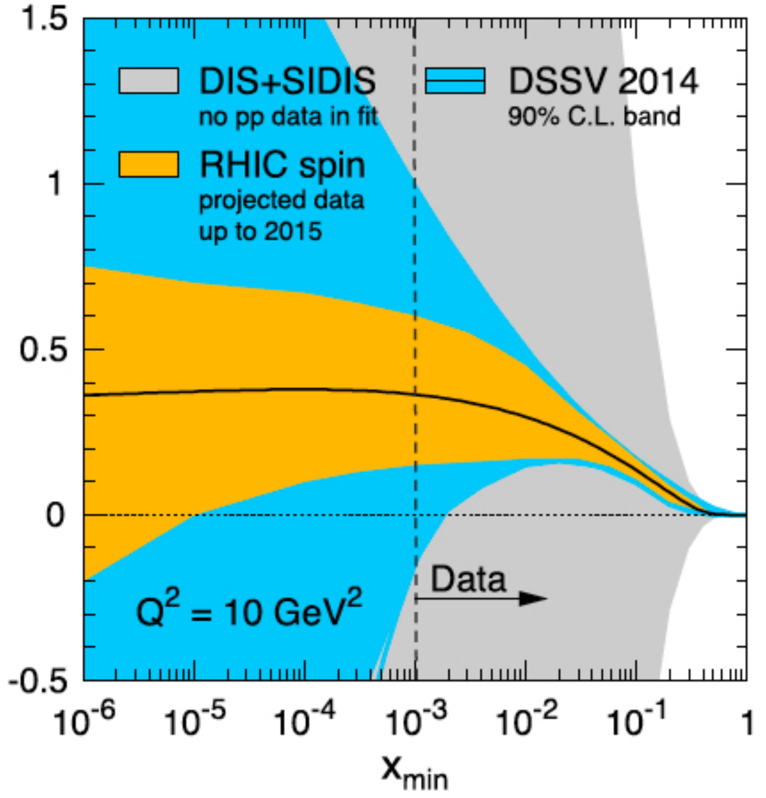
Quark spin

$$\int_{x_{min}}^{1} dx\, \Delta\Sigma(x, Q^2)$$



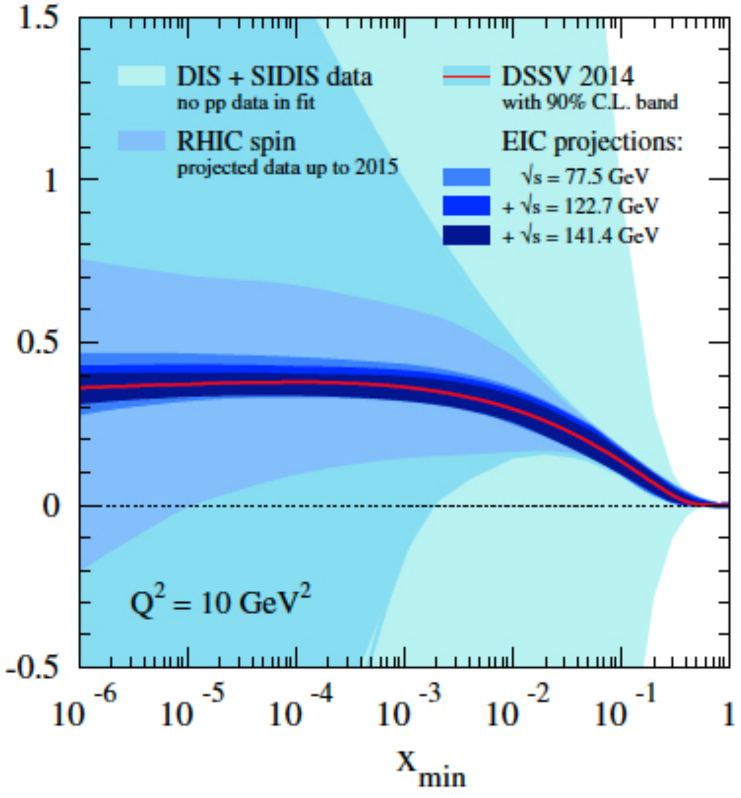
Gluon spin

$$\int_{x_{min}}^{1} dx\, \Delta g(x, Q^2)$$



Gluon spin with EIC

$$\int_{x_{min}}^{1} dx\, \Delta g(x, Q^2)$$



Aschenauer, Sassot and Stratmann, PRD92 (2015) 094030; Aschenauer et al. Rep.Prog.Phys. 82 (2019) 024301

We are constantly improving the knowledge of the contributions to the spin of the nucleon

However the details on the flavor and sea contributions are still sketchy

What about a direct measurement of orbital angular momentum?

⟶ *Talk of R. Fatemi*

Orbital angular momentum of the proton from GPDs

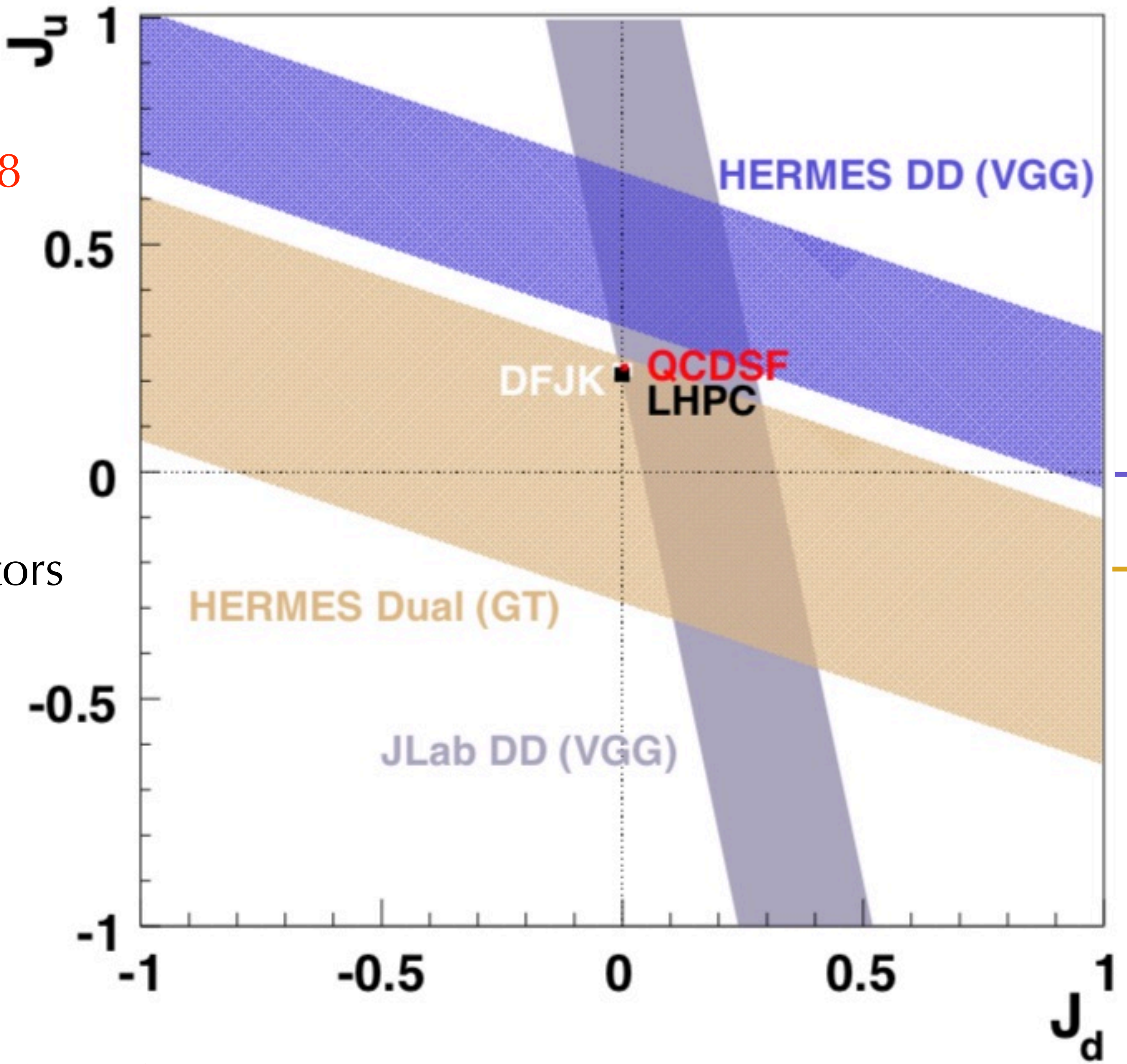
Lattice results

QCDSF: PoS (Lattice 2007) 158

LHPC: PRD77 (2008) 094502

GPDs extracted from form factors

DFJK, EPJC39 (2005) 1



extractions from HERMES data using two different models

JLab Hall A, Phys. Rev. Lett. 99 (2007) 242501

Hermes Coll., JHEP 06 (2008) 066

Problem of model dependent extractions

Orbital angular momentum of the proton from GPDs

Lattice results

QCDSF: PoS (Lattice 2007) 158

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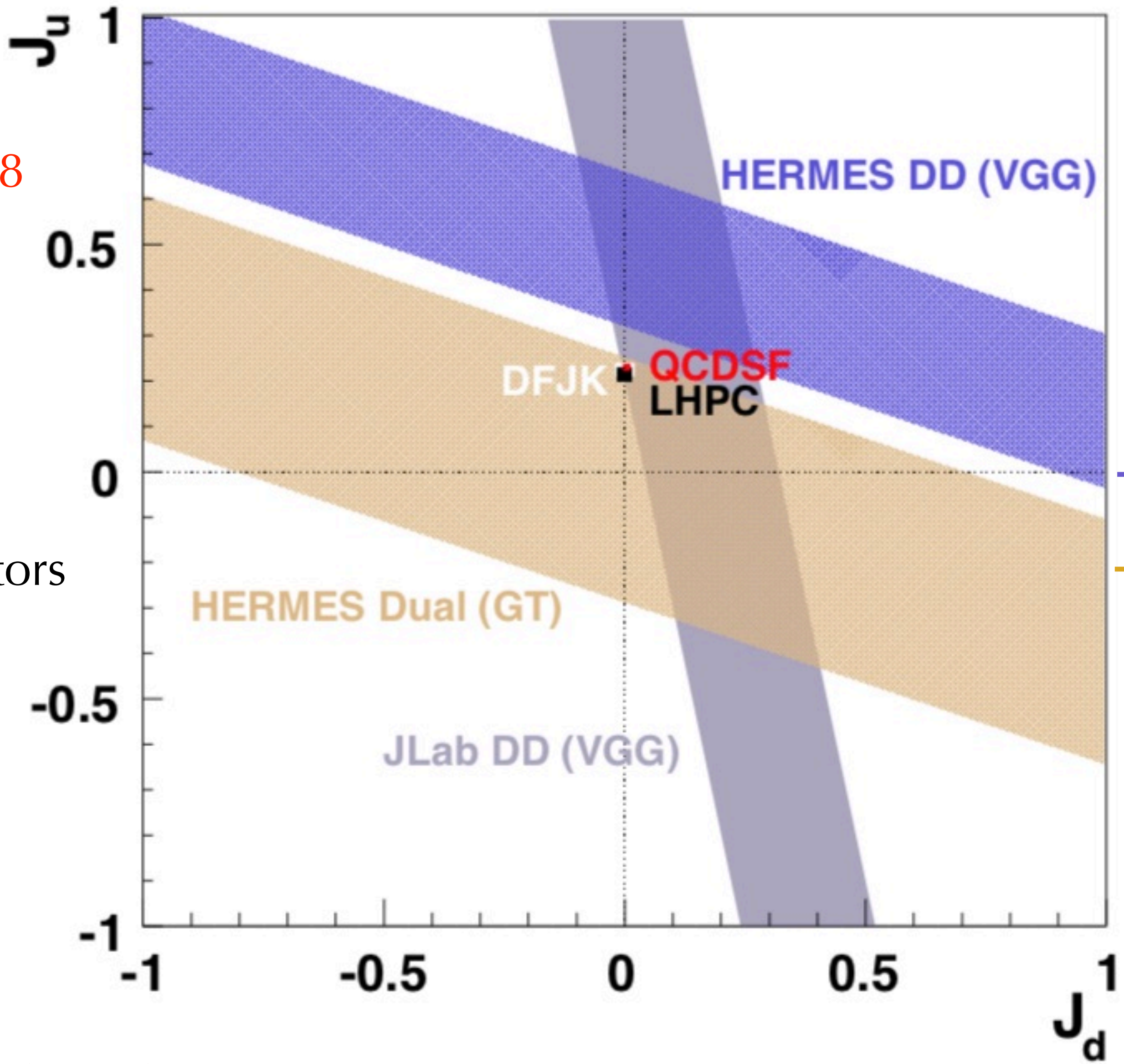

extractions from HERMES data using two different models

JLab Hall A, Phys. Rev. Lett. 99 (2007) 242501

Hermes Coll., JHEP 06 (2008) 066

Problem of model dependent extractions

Twist-3 GPDs?

$$L^q = -\int_{-1}^{1} \mathrm{d}x\, x\, G_2^q(x, \xi = 0, t = 0)$$

Very challenging! We can not address the individual twist-3 GPDs *[Aslan et al., PRD 98 (2018) 014038]*

Recent formalism: Kriesten et al., arXiv:1903.05742

Orbital angular momentum of the proton from Wigner functions

$$L_z^q = \int \mathrm{d}x\mathrm{d}^2\vec{k}_\perp\mathrm{d}^2\vec{b}_\perp(\vec{b}_\perp \times \vec{k}_\perp)\mathcal{W}^q_{LU}(x,\vec{b}_\perp,\vec{k}_\perp)$$

Lorcé, BP, PRD 84 (2011) 014015

Hatta, PLB 708 (2012) 186

Lorcé, BP, Xiong, Yuan, PRD 85 (2012) 114006

Orbital angular momentum of the proton from Wigner functions

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relation to GTMD: $L_z^q = -\int \mathrm{d}x\, \mathrm{d}^2\vec{k}_\perp \frac{\vec{k}_\perp^{\,2}}{M^2} F_{1,4}^q(x, \vec{k}_\perp^{\,2})\big|_{\Delta=0}$

Lorcé, BP, PRD 84 (2011) 014015

Hatta, PLB 708 (2012) 186

Lorcé, BP, Xiong, Yuan, PRD 85 (2012) 114006

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- intuitive definition of OAM
- mutually orthogonal components of quark position and momentum

  ⟶ no conflict with uncertainty principle
- the integrand L_z^q represents the OAM density
- same equation for both Jaffe-Manohar (staple-like link) and Ji (straight link) OAM
- equation holds also for gluon OAM
- it can be calculated in LQCD *Engelhardt, PRD95 (2017) 094505*

Lorcé, BP, PRD 84 (2011) 014015

Hatta, PLB 708 (2012) 186

Lorcé, BP, Xiong, Yuan, PRD 85 (2012) 114006

Orbital angular momentum of the proton from Wigner functions

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$$L_z^q = \int \mathrm{d}^2\vec{b}_\perp \vec{b}_\perp \times \langle \vec{k}_\perp^q \rangle \longrightarrow \langle \vec{k}_\perp(\vec{b}_\perp) \rangle = \int \mathrm{d}x\mathrm{d}\vec{k}_\perp\, \vec{k}_\perp\, \rho_{LU}^q(\vec{b}_\perp, \vec{k}_\perp, x)$$

Lorcé, BP, PRD 84 (2011) 014015

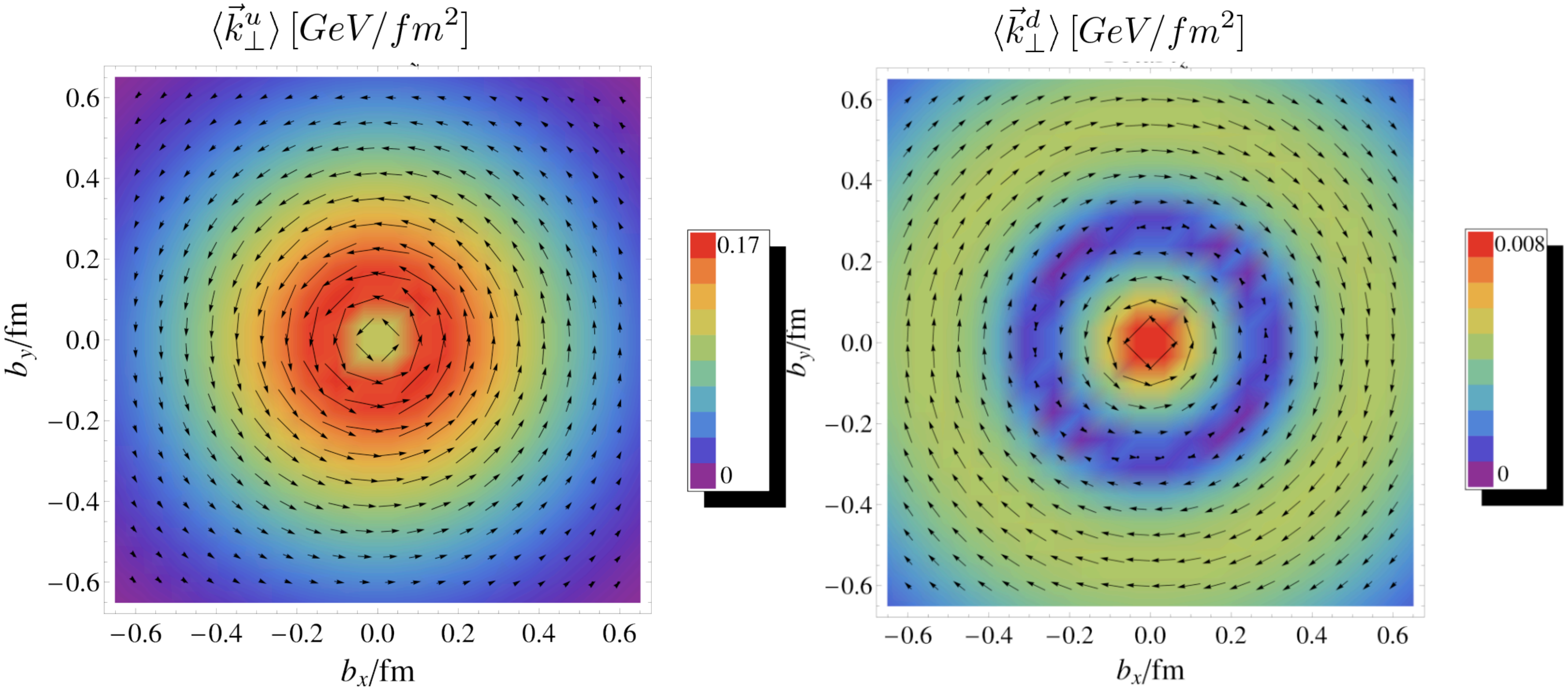
Hatta, PLB 708 (2012) 186

Lorcé, BP, Xiong, Yuan, PRD 85 (2012) 114006

Orbital angular momentum of the proton from Wigner functions

$$L_z^q = \int \mathrm{d}x\mathrm{d}^2\vec{k}_\perp \mathrm{d}^2\vec{b}_\perp (\vec{b}_\perp \times \vec{k}_\perp)\mathcal{W}^q_{LU}(x,\vec{b}_\perp,\vec{k}_\perp)$$

$$L_z^q = \int \mathrm{d}^2\vec{b}_\perp \vec{b}_\perp \times \langle \vec{k}^q_\perp \rangle \longrightarrow \langle \vec{k}_\perp(\vec{b}_\perp)\rangle = \int \mathrm{d}x\mathrm{d}\vec{k}_\perp \, \vec{k}_\perp \, \rho^q_{LU}(\vec{b}_\perp,\vec{k}_\perp,x)$$



Lorcé, BP, PRD 84 (2011) 014015

Hatta, PLB 708 (2012) 186

Lorcé, BP, Xiong, Yuan, PRD 85 (2012) 114006

Orbital angular momentum of the proton from Wigner functions

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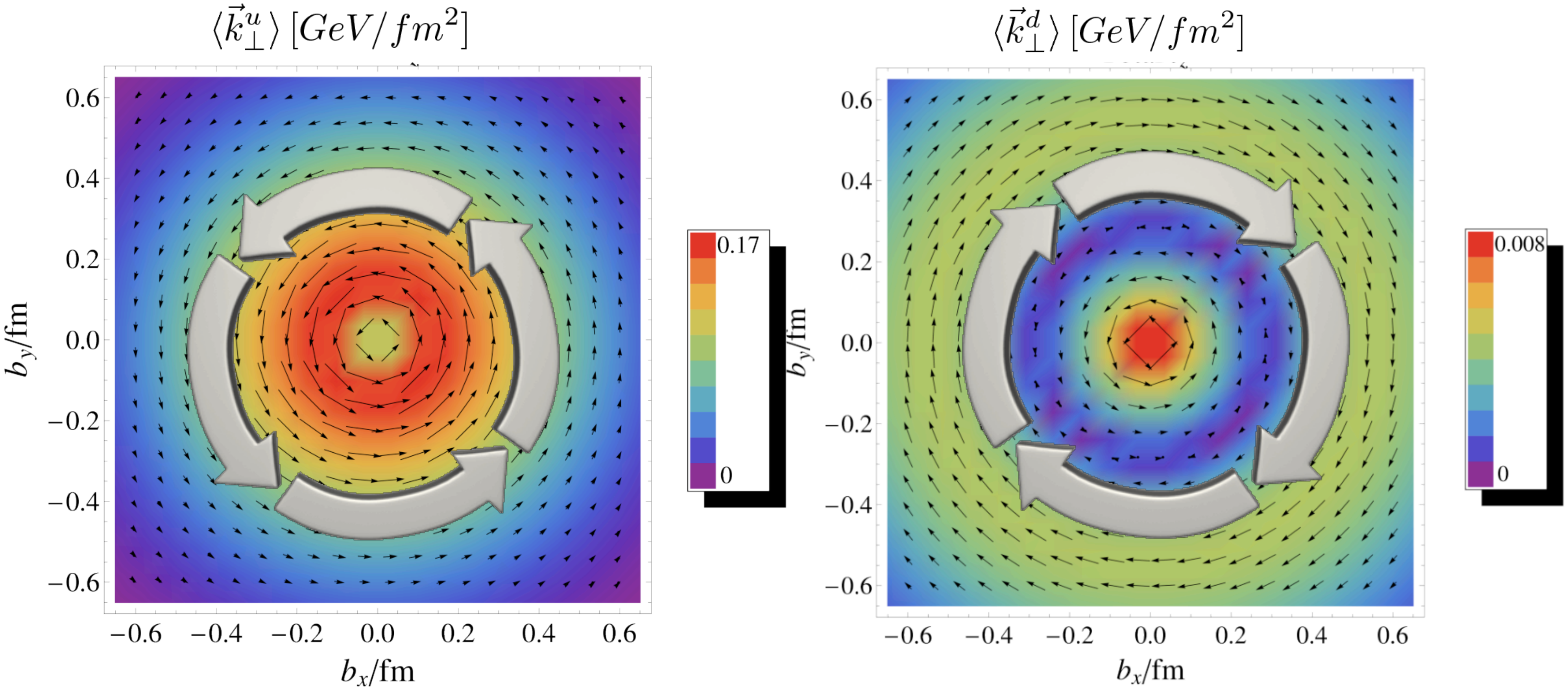


⟶ Proton spin

→ u-quark OAM

← d-quark OAM

Lorcé, BP, PRD 84 (2011) 014015

Hatta, PLB 708 (2012) 186

Lorcé, BP, Xiong, Yuan, PRD 85 (2012) 114006

Angular correlations

quark polarization

nucleon polarization

$\mathcal{W}_X$	U	L	T_x	T_y
U	$\langle 1 \rangle$	$\langle S_L^q \ell_L^q \rangle$	$\langle S_x^q \ell_x^q \rangle$	$\langle S_y^q \ell_y^q \rangle$
L	$\langle S_L \ell_L^q \rangle$	$\langle S_L S_L^q \rangle$	$\langle S_L \ell_L^q S_x^q \ell_x^q \rangle$	$\langle S_L \ell_L^q S_y^q \ell_y^q \rangle$
T_x	$\langle S_x \ell_x^q \rangle$	$\langle S_x \ell_x^q S_L^q \ell_L^q \rangle$	$\langle S_x S_x^q \rangle$	$\langle S_x \ell_x^q S_y^q \ell_y^q \rangle$
T_y	$\langle S_y \ell_y^q \rangle$	$\langle S_y \ell_y^q S_L^q \ell_L^q \rangle$	$\langle S_y \ell_y^q S_x^q \ell_x^q \rangle$	$\langle S_y S_y^q \rangle$

$\boxed{\xi = 0}$

$\int d^2\vec{k}_\perp$

$\int d^2\vec{b}_\perp$

GPD	U	L	T
U	H		$\mathcal{E}_T$
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	$H_T,\ \tilde{H}_T$

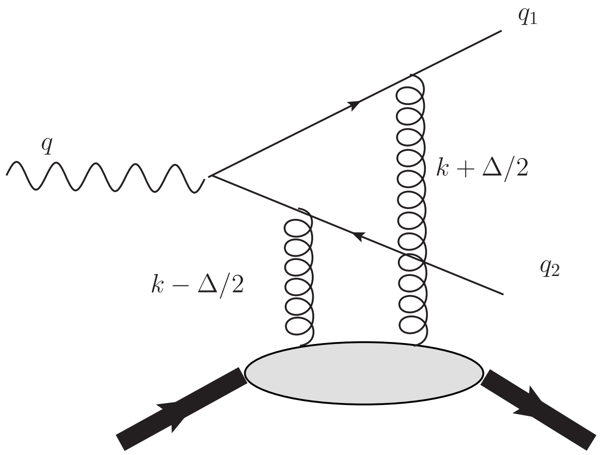
TMD	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

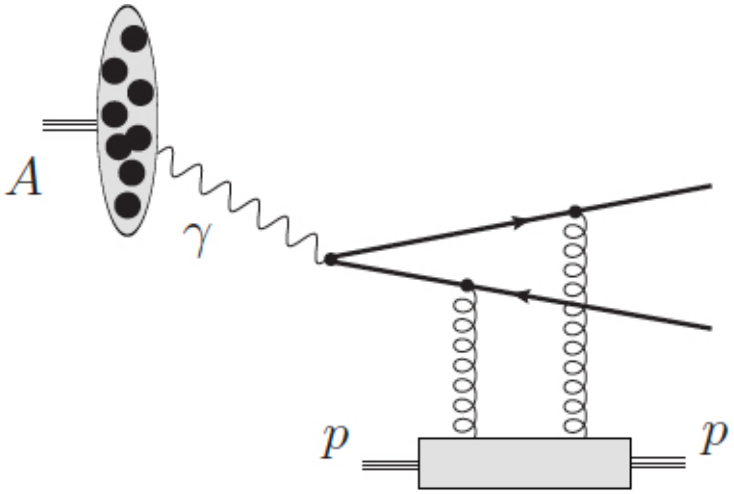
each distribution contains unique information

the distributions in **red** vanish if there is no quark orbital angular momentum

the distributions in **black** survive in the collinear limit

GTMDs from observables

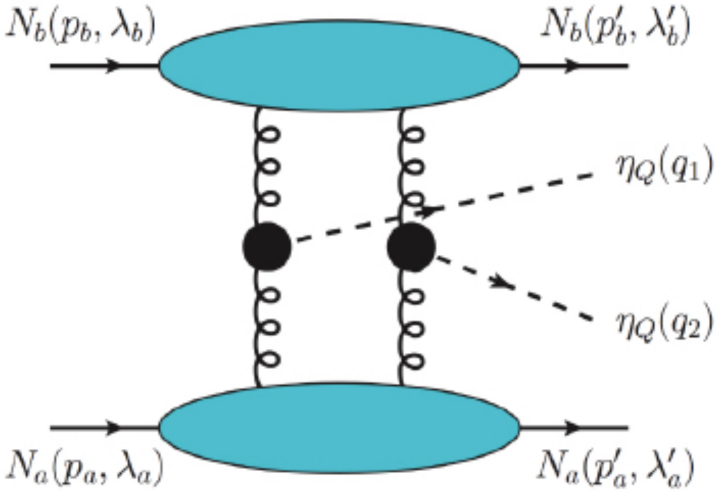




Exclusive dijet production in ep DIS and in pa UPC (gluon GTMDs)

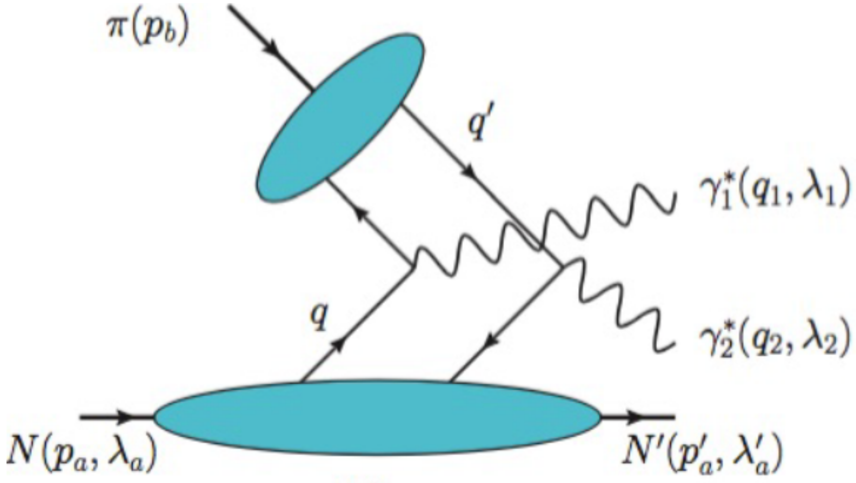
Hatta, Xiao, Yuan, PRL 116 (2016) 202301
Hatta, Nakagawa, Xiao, Yuan, Zhao, PRD 95 (2017) 114032

Ji, Yuan, Zhao, PRL 118 (2017) 192004
Hagiwara, et al., PRD 96 (2016) 034009



Exclusive double quarkonia production in nucleon-nucleon collisions (gluon GTMDs)

Bhattacharya, Metz, Ojha, Tsai, Zhou, arXiv:1802.10550
Boussarie, Hatta, Xiao, Yuan, arXiv: 1807.08697



Exclusive pion-nucleon double Drell-Yan (quark GTMDs)

Bhattacharya, Metz, Zhou, PLB 771 (2017) 396

Key information from Transverse Momentum Dependent PDFs

- Complete momentum spectrum of single particle
- Transverse momentum size as function of x (3D map)
- Spin-Spin and Spin-Orbit Correlations of partons
- Information on parton orbital angular momentum
  (no direct model-independent relation)
- Extractions from SIDIS require knowledge of Fragmentation Functions
- Test what we can calculate with QCD (perturbative and lattice)

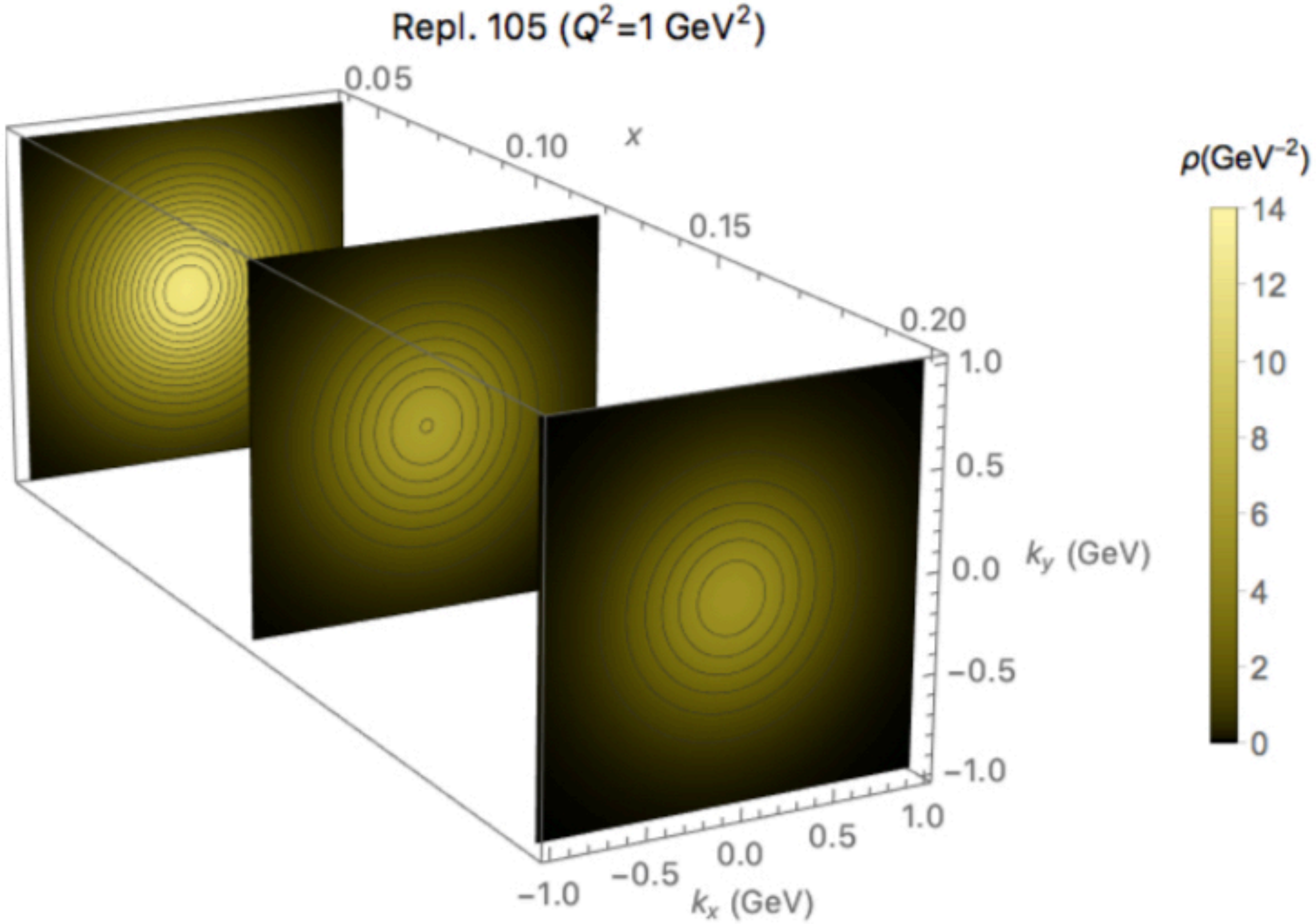
Talks of A. Prokudin, M. Chiosso, M. Engelhardt

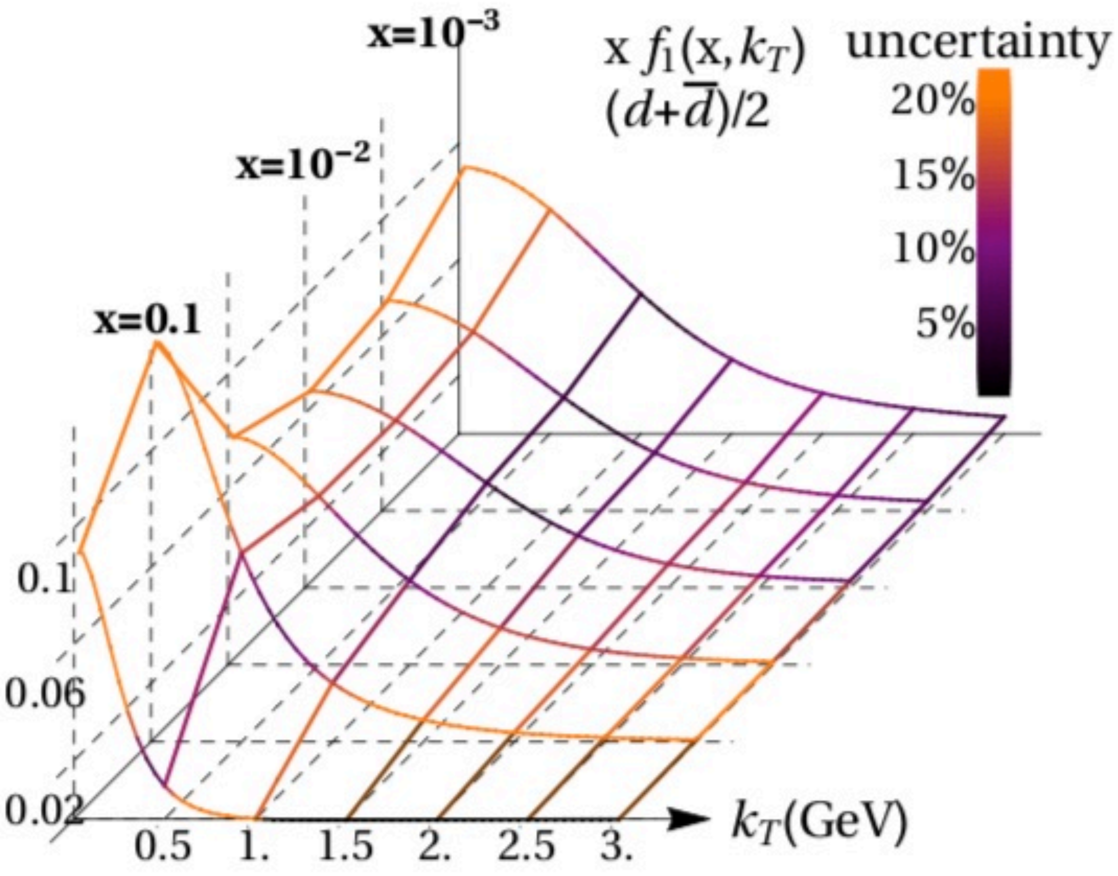
Quark unpolarized TMD extractions

	Framework	HERMES	COMPASS	DY	Z Production	N of points
KN 2006 **hep-ph/0506225**	NLL/NLO	✗	✗	✓	✓	98
Pavia 2013 **arXiv:1309.3507**	No evo	✓	✗	✗	✗	1538
Torino 2014 **arXiv:1312.6261**	No evo	✓ (separately)	✓ (separately)	✗	✗	576(H) 6284(C)
DEMS 2014 **arXiv:1407.3311**	NNLL/NLO	✗	✗	✓	✓	223
EIKV 2014 **arXiv:1401.5078**	NLL/LO	1(x,Q^2)bin	1(x,Q^2)bin	✓	✓	500
Pavia 2016 **arXiv:1703.10157**	NLL/LO	✓	✓	✓	✓	8059
SV 2017 **arXiv:1706.01473**	NNLL/NNLO	✗	✗	✓	✓	309
BSV 2019 **arXiv:1902.08474**	NNLL/NNLO	✗	✗	✓	✓	457

Quark unpolarized TMD extractions

$f_1(x, \vec{k}_\perp)$





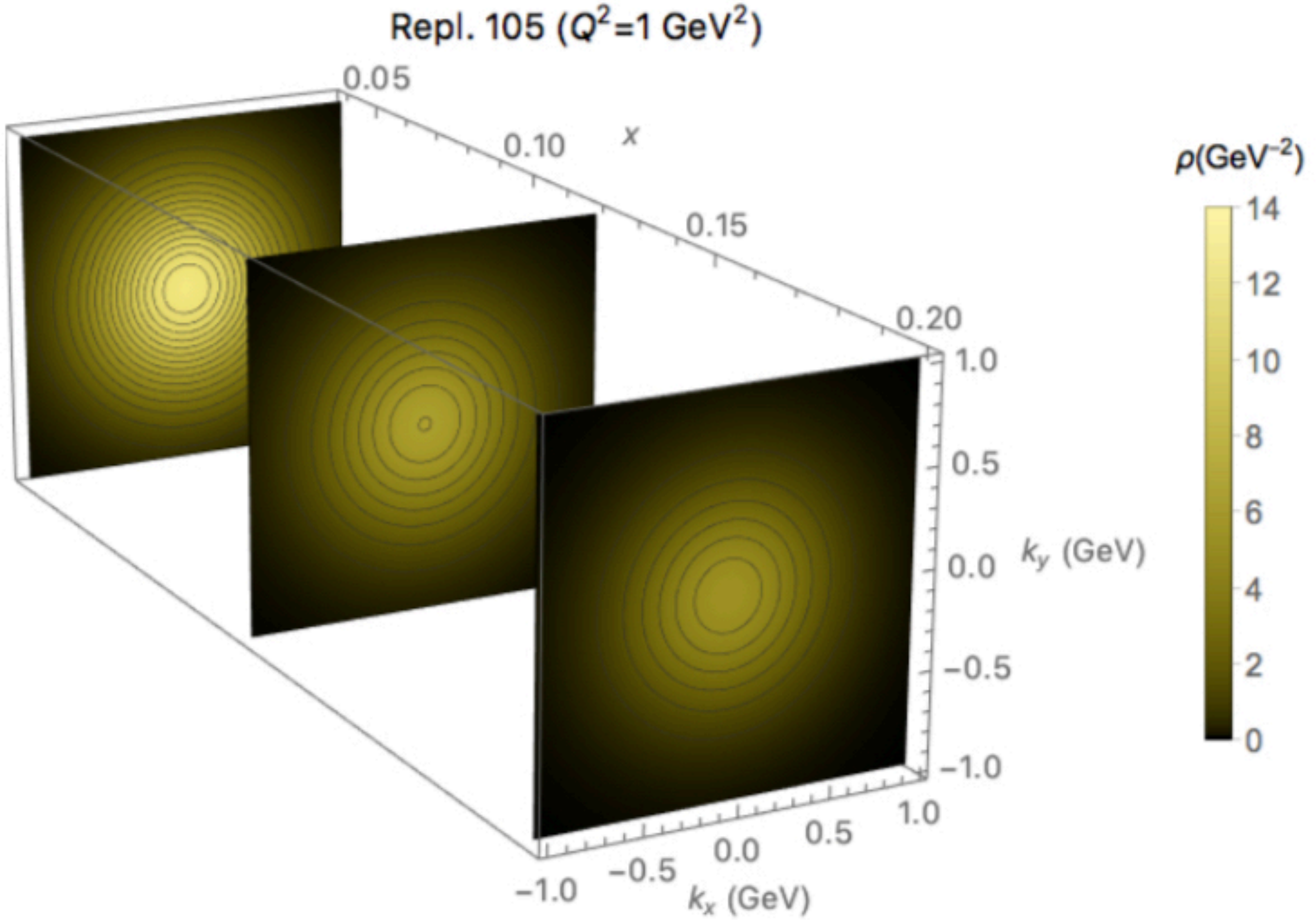
Bacchetta, Delcarro, Pisano, Radici, Signori,
JHEP 1706 (2017) 081

Bertone, Scimemi, Vladimirov,
JHEP 1906 (2019) 28

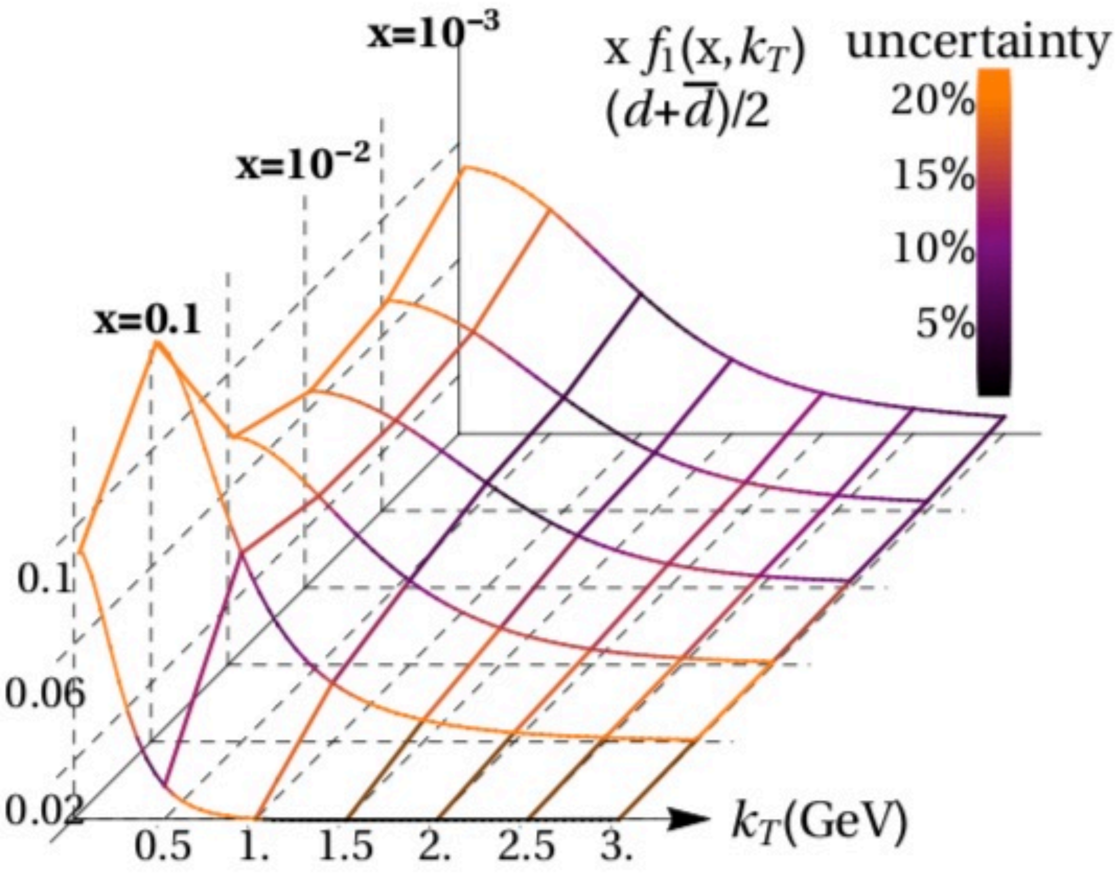
- Density in transverse-momentum space for unpolarized quark in unpolarized nucleon
  ⟶ monopole distribution, wider at smaller x_B
  ⟶ reconstructed from measured data

Quark unpolarized TMD extractions

$f_1(x, \vec{k}_\perp)$



Bacchetta, Delcarro, Pisano, Radici, Signori, JHEP 1706 (2017) 081



Bertone, Scimemi, Vladimirov, JHEP 1906 (2019) 28

Open issues:

- ☐ Flavor dependence and more flexible functional forms
- ☐ Different choices in implementation of TMD formalism
- ☐ More data needed to test the formalism
- ☐ Improvements on the knowledge of the fragmentation functions

Library and Plotting tools for collinear parton distributions

LHAPDF
lhapdf.hepforge.org

xFitter
www.xfitter.org

APFEL++
github.com/vbertone/apfelxx
apfel.mi.infn.it

Dedicated Softwares to study GPDs

PARTONS
partons.cea.fr

PARtonic
Tomography
Of
Nucleon
Software

GeParD

not yet public

Dedicated software to study and fit TMDs

arTeMiDe
teorica.fis.ucm.es/artemide

TMD lib and TMD Plotter
tmdlib.hepforge.org

NangaParbat
public soon

Efforts to combine different inputs to understand TMDs and GPDs in an unified framework

Proton mass decomposition

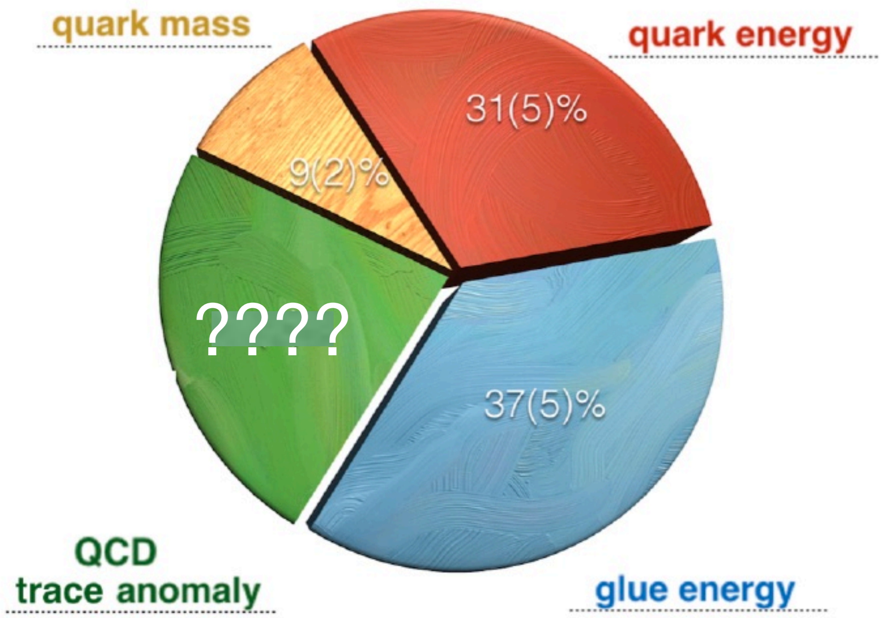
$$M = \underbrace{M_q + M_g}_{\text{quark/gluon kinetic energy}} + \overset{\text{quark mass}}{M_m} + \overset{\text{trace anomaly}}{M_a}$$

X. Ji, PRD 52 (1995) 271

$M_q + M_g$: related to <x>$_{q,g}$ ⟶ from DIS

M_m : quark condensate ⟶ πN sigma term

M_a : ???? possibly from exclusive production of heavy quarkonia at threshold ⟶ *talk of Y. Hatta*



Lattice QCD
Y.-B. Yang, et al., PRL 121 (2018)

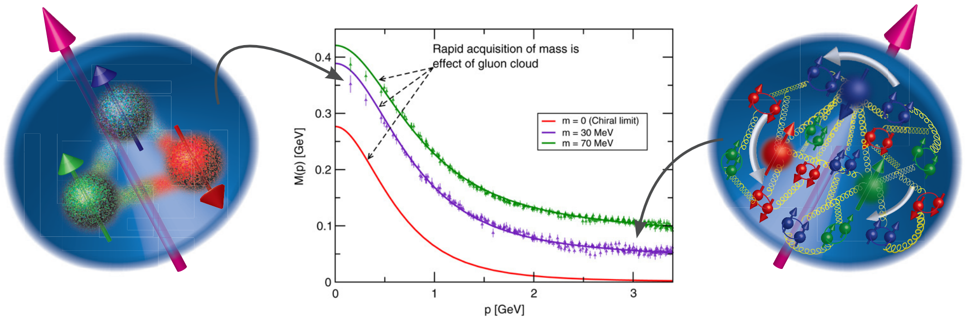
- different proton mass decompositions *[C. Roberts, C. Lorcé]*
- clearly identify observables directly linked to gluon anomaly and measurable at JLab and EIC

The Proton Mass

At the heart of most visible matter.

Temple University, March 28-29, 2016

Philadelphia, Pennsylvania



$$M_p = 2m_u^{\rm eff} + m_d^{\rm eff}$$

$$H_{\rm QCD} = H_q + H_m + H_g + H_a$$

Speakers

Stan Brodsky (S
Xiandong Ji (Ma
Dima Kharzeev
Keh-Fei Liu (Ur
David Richards
Craig Roberts (A
Martin Savage (U
Stepan Stepanya
George Sterman

Moderat

Alfred Mueller (

ECT*

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IN NUCLEAR PHYSICS AND RELATED AREAS
TRENTO, ITALY
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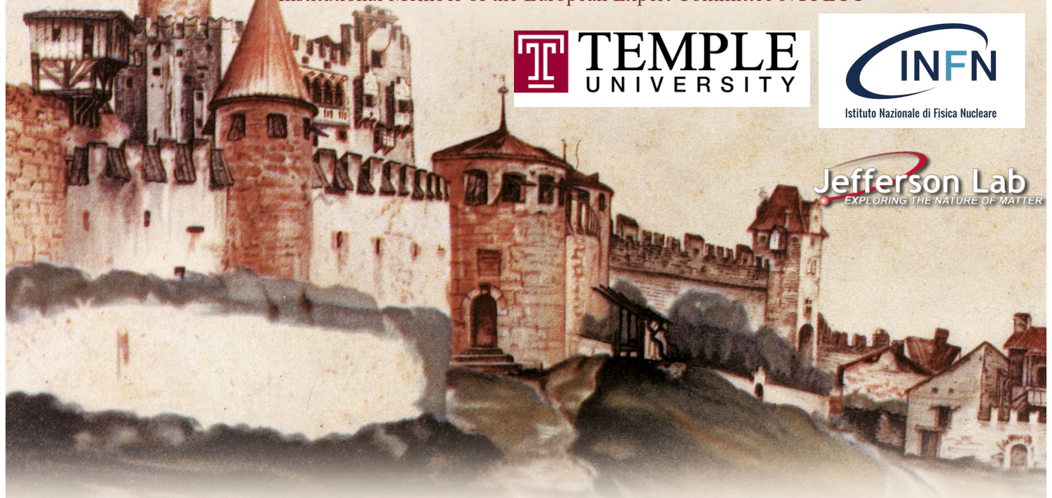

Castello di Trento ("Trint"), watercolor 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495). British Museum,

The Proton Mass: At the Heart of Most Visible Matter

Trento, April 3 - 7, 2017

Main Topics

aly contribution, ...

ical model approaches, ...

ar structure function, …

Chen Jian-Ping (*Jefferson Lab*),
ade Abhay (*Stony Brook University*),
Lin Huey-Wen (*Michigan State University*),
Amsterdam), Papavassiliou Joannis
berts Craig (*Argonne National Lab*),
titute of Technology), Dima Kharzeev

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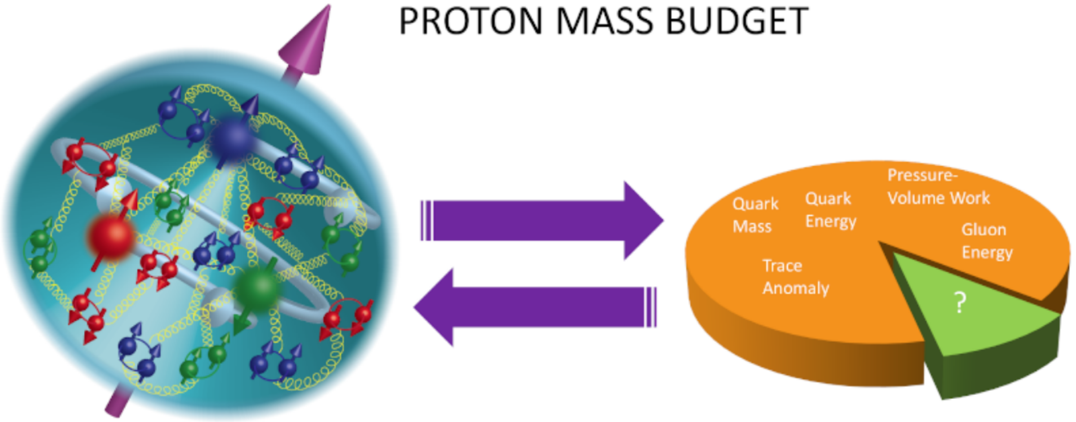
INT Workshop INT-20-77W

Origin of the Visible Universe: Unraveling the Proton Mass

May 4 - 8, 2020

PROTON MASS BUDGET

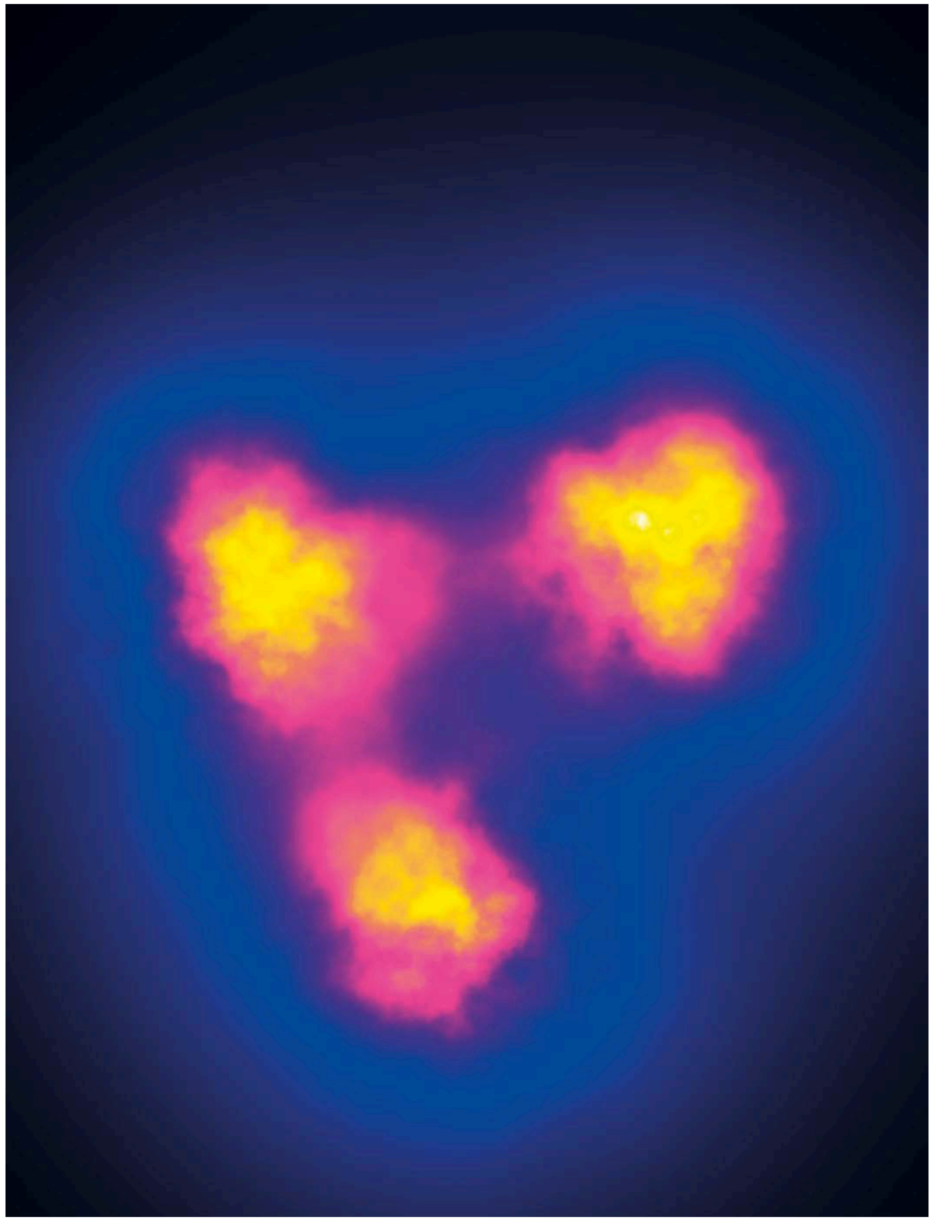


100 years from the discovery of the existence of the proton

100 years of evolving understanding of the proton

There is still much to learn about the proton…..

New challenges to interpret upcoming data from JLab12, COMPASS, MAMI, JPARC,EIC,..



CERN Courier cover, June 2019