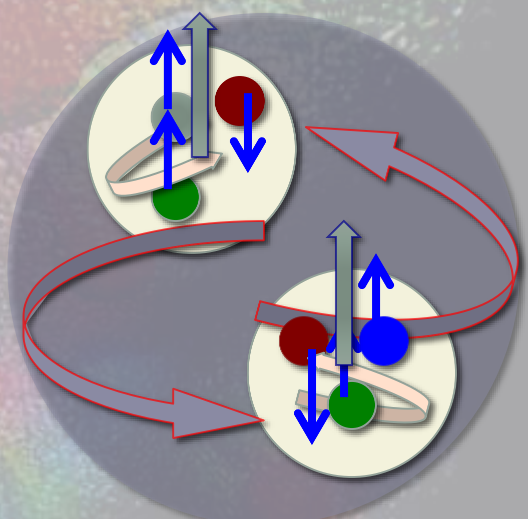
MECHANICAL PROPERTIES OF THE NUCLEON FROM EXCLUSIVE REACTIONS

INSTITUTE OF NUCLEAR PHYSICS, U. OF WASHINGTON
PROBING NUCLEONS AND NUCLEI, OCTOBER 2019

Simonetta Liuti
University of Virginia



Diversion on tensor charge and the Strumia effect…

PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees Search Press

Beyond-Standard-Model Tensor Interaction and Hadron Phenomenology

Aurore Courtoy, Stefan Baeßler, Martín González–Alonso, and Simonetta Liuti

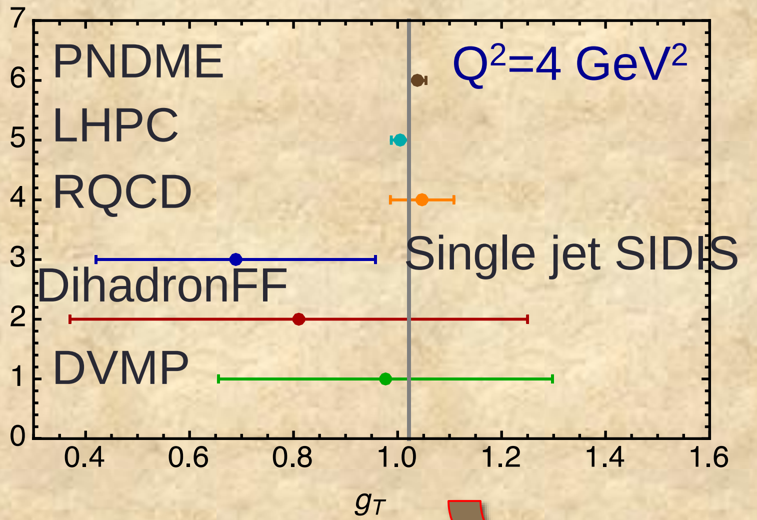
Phys. Rev. Lett. **115**, 162001 – Published 15 October 2015

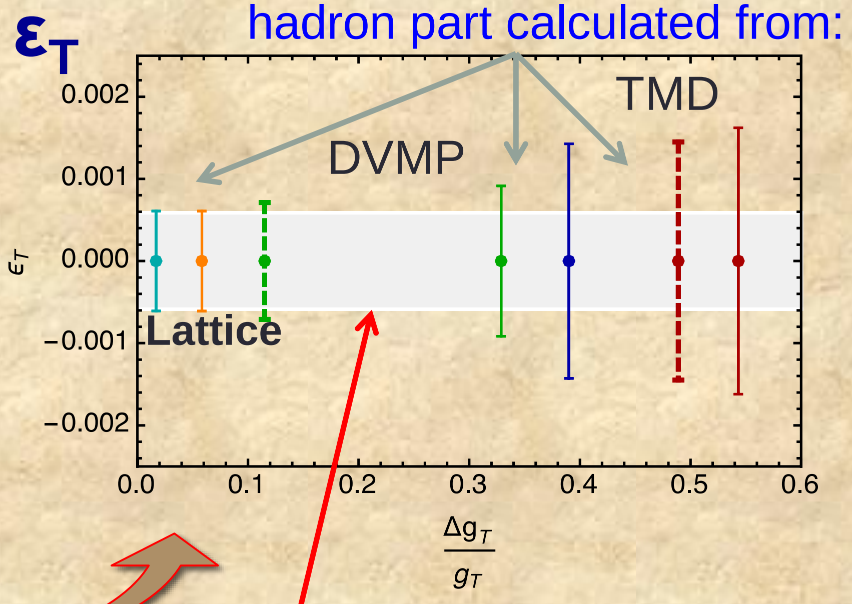
Setting the record straight:

<u>First</u> evaluation of the impact of the experimental tensor charge (g_T) on the extraction of BSM type elementary tensor interactions (ε_T)

It should have been quoted in INT talk on Week 2!!

Impact on BSM searches…





From EW processes $|\varepsilon_T\, g_T| < 6.4\times10^{-4}$

Pattie et al, PRC88 (2013)

A. Courtoy, S.Baessler, M. Gonzalez-Alonso, S.L, arXiv:1503.06814

Outline

- **Physics goals**

quarks and gluons **imaging**, **origin of mass, spin**, **nuclear structure**

- **Theory**

Energy Momentum Tensor (EMT) and Generalized Parton Distributions (GPDs): probing the mechanical properties of the proton

- **Method**

Femtography. Fourier transforms, merging information from lattice, models/parametrizations

- **Disentangling quark and gluon OAM**

twist-3 GPDs (Brandon Kriesten, Thursday),
k_T dependence (GTMDs) from lattice (Abha Rajan, Friday)

- **A concerted effort**

Center for Nuclear Femtography at Jefferson Lab

CENTER *for* NUCLEAR FEMTOGRAPHY

  - organizing a variety of approaches /setting benchmarks
  - extraction from experiments at EIC ➔ ***beyond standard analyses/computational methods/phen. approaches***

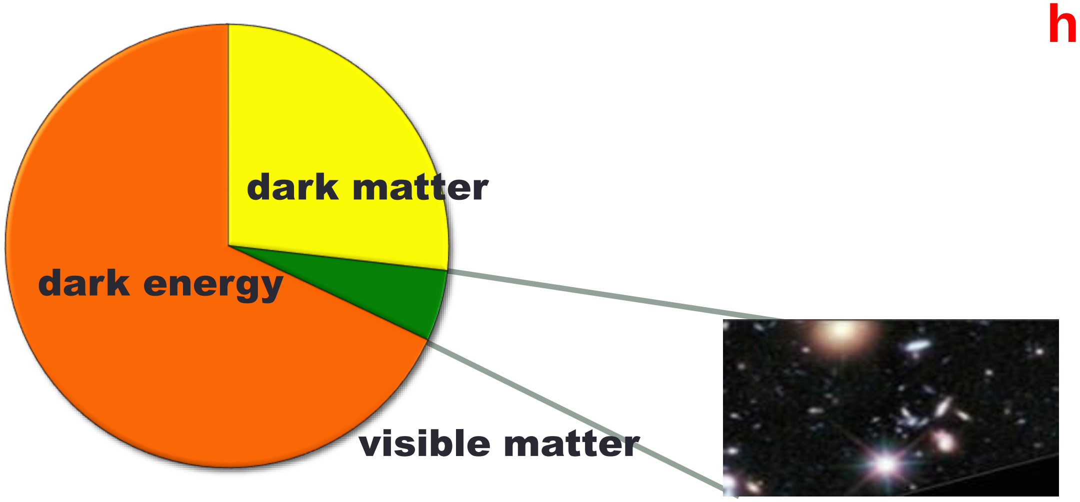
- **Conclusions and Outlook**

1. PHYSICS GOALS

GPDs and Deeply Virtual Exclusive Experiments

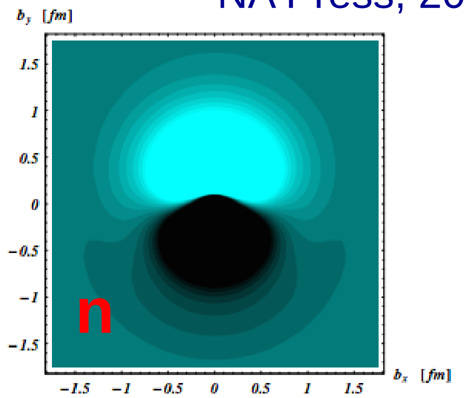
A new paradigm that will allow us to both penetrate and visualize the deep structure of visible matter … to answer questions that we couldn't even afford asking before

what is the origin of mass and spin?



what is the spatial structure of hadrons?

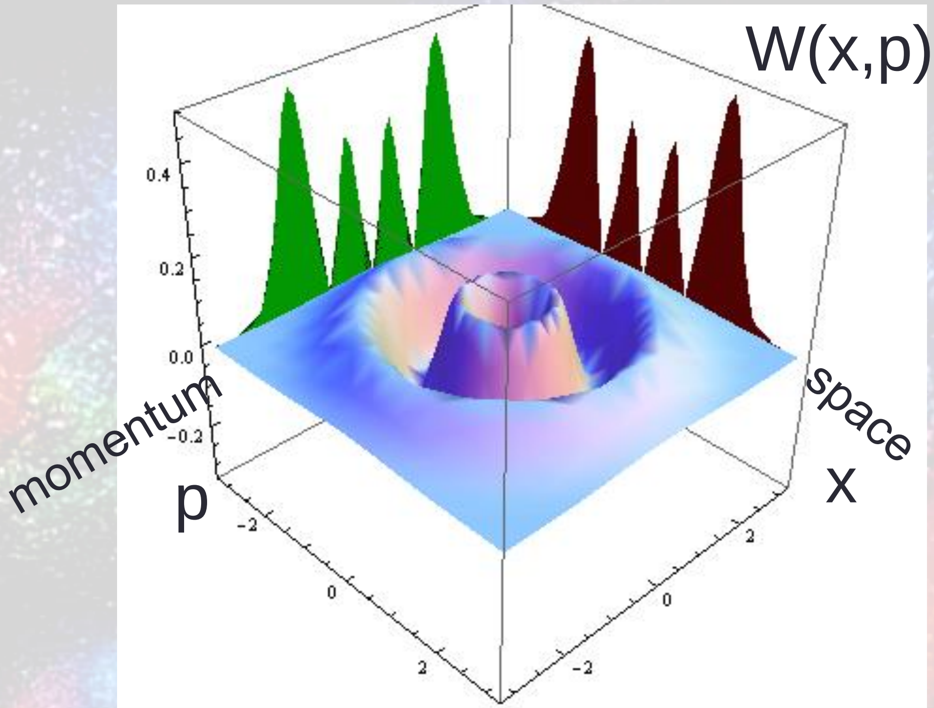
NA Press, 2013



what is the distribution of forces/pressure inside the nucleon?

M. Burkardt
Ph. Haegler, M. Diehl
C.Carlson,
M.Vanderheaghen

GPDs connect to complex phase space distributions (Wigner)



…To observe, evaluate and interpret Wigner distributions requires stepping up data analyses from the standard methods → developing new numerical/analytic/quantum computing methods

2. THEORY: EMT AND GPDS

How does the proton get its mass and spin?

$$\mathcal{L}_{QCD} = \overline{\psi}\left(i\gamma_\mu D^\mu - m\right)\psi - \frac{1}{4}F_{a,\mu\nu}F_a^{\mu\nu}$$

Invariance of L $_{QCD}$ under **translations** and **rotations**

Energy Momentum Tensor

from **translation** inv. ➡

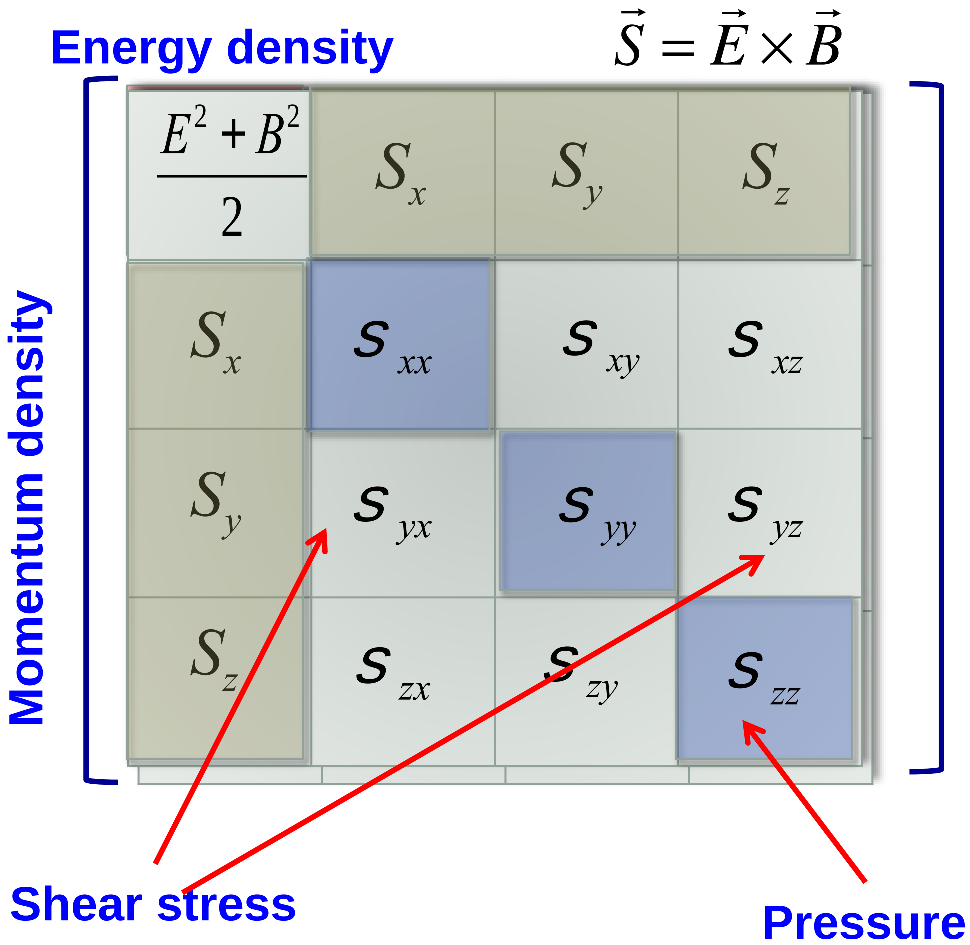
$$T^{\mu\nu}_{QCD} = \frac{1}{4}\,\overline{\psi}\,\gamma^{(\mu}D^{\nu)}\psi + Tr\left\{F^{\mu\alpha}F^{\nu}_{\alpha} - \frac{1}{2}g^{\mu\nu}F^2\right\}$$

Angular Momentum Tensor

from **rotation** inv. ➡

$$M^{\mu\nu\lambda}_{QCD} = x^\nu T^{\mu\lambda}_{QCD} - x^\lambda T^{\mu\nu}_{QCD}$$

QCD Energy Momentum Tensor and Angular Momentum



Angular Momentum density

$$M^{mnl} = x^n T^{ml} - x^l T^{mn}$$

Conserved quantities

Momentum

$$P^\mu = \int d^3\mathbf{x}\, T^{o\mu}$$

Angular Momentum

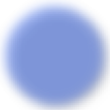
$$M^{\mu\nu} = \int d^3\mathbf{x}\, M^{o\mu\nu}$$

$$= \int d^3\mathbf{x} \left[x^\mu T^{o\nu} - x^\nu T^{o\mu} \right]$$

EMT matrix elements

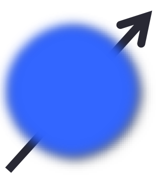
$$t = (p - p')^2 = \Delta^2$$

S=0



$$\langle p' \mid T^{\mu\nu} \mid p \rangle = 2\left[A(t)P^{\mu\nu} + C(t)(\Delta^2 g^{\mu\nu} - \Delta^{\mu\nu})\right] + \widetilde{C}(t)g^{\mu\nu}$$

S=1/2



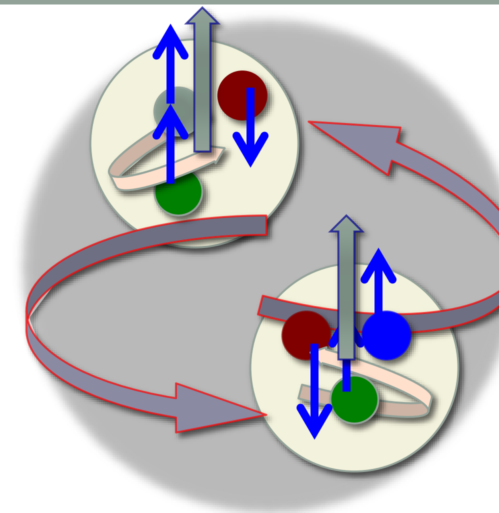
$$\langle p', \Lambda \mid T^{\mu\nu} \mid p, \Lambda \rangle = A(t)\bar{U}(p',\Lambda')[\gamma^\mu P^\nu + \gamma^\nu P^\mu]U(p,\Lambda) + B(t)\bar{U}(p',\Lambda')i\,\frac{\sigma^{\mu(\nu}\Delta^{\nu)}}{2M}U(p,\Lambda)$$
$$+C(t)[\Delta^2 g^{\mu\nu} - \Delta^{\mu\nu}]\bar{U}(p',\Lambda')U(p,\Lambda) + \widetilde{C}(t)g^{\mu\nu}\bar{U}(p',\Lambda')U(p,\Lambda)$$

forward

off-forward

q and g not separately conserved

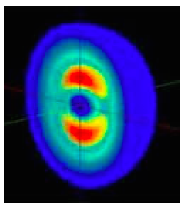
Energy Momentum Tensor in a spin 1 system



Angular momentum sum rule for spin one hadronic systems

Swadhin K. Taneja,[1,*] Kunal Kathuria,[2,†] Simonetta Liuti,[2,‡] and Gary R. Goldstein[3,§]

PRD86(2012)

S=1 

$$
\begin{aligned}
\langle p',\Lambda'|T^{\mu\nu}|p,\Lambda\rangle = &-\frac{1}{2}P^\mu P^\nu(\epsilon'^*\epsilon)\mathcal{G}_1(t) - \frac{1}{4}P^\mu P^\nu \frac{(\epsilon P)(\epsilon'^* P)}{M^2}\mathcal{G}_2(t) \\
&-\frac{1}{2}\left[\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2\right](\epsilon'^*\epsilon)\mathcal{G}_3(t) - \frac{1}{4}\left[\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2\right]\frac{(\epsilon P)(\epsilon'^* P)}{M^2}\mathcal{G}_4(t) \\
&+\frac{1}{4}\left[\left(\epsilon'^{*\mu}(\epsilon P)+\epsilon^\mu(\epsilon'^* P)\right)P^\nu + \mu\leftrightarrow\nu\right]\mathcal{G}_5(t) \\
&+\frac{1}{4}\left[\left(\epsilon'^{*\mu}(\epsilon P)-\epsilon^\mu(\epsilon'^* P)\right)\Delta^\nu + \mu\leftrightarrow\nu + 2g_{\mu\nu}(\epsilon P)(\epsilon'^* P) - (\epsilon'^{*\mu}\epsilon^\nu+\epsilon'^{*\nu}\epsilon^\mu)\Delta^2\right]\mathcal{G}_6(t) \\
&+\frac{1}{2}\left[\epsilon^{*\prime\mu}\epsilon^\nu + \epsilon'^{*\nu}\epsilon^\mu\right]\mathcal{G}_7(t) + g^{\mu\nu}(\epsilon'^*\epsilon)M^2\mathcal{G}_8(t)
\end{aligned}
$$

Energy Momentum Tensor relations (spin ½)

Momentum

$$\langle p'|\int d^3x\, T^{0i}_{q,g}\,|p\rangle = p^i\langle p'|p\rangle = A^{q,g}p^i\int d^3x\, 2p^0 \quad \Rightarrow \quad A^q + A^g = 1$$

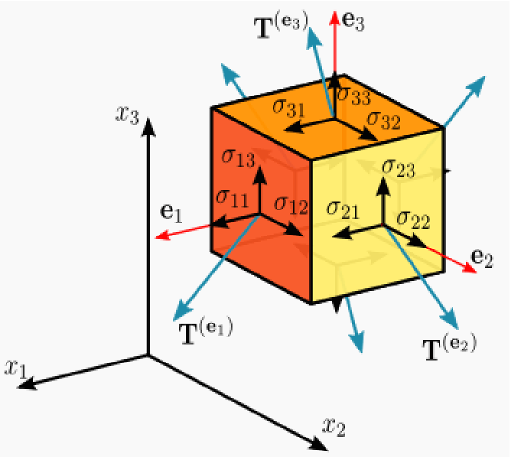
Angular Momentum

$$\langle p'|\int d^3x\left(x_1 T^{02}_{q,g} - x_2 T^{01}_{q,g}\right)|p\rangle = (A+B)^{q,g}\int d^3x\, p^0 \quad \Rightarrow \quad \frac{1}{2}\left(A^{q,g} + B^{q,g}\right) = J_z^{q,g}$$

Stress Tensor

(Donoghue et al., PLB 2001, Polyakov Shuvaev (2002) 0207153)
Goeke, Polyakov and Schweitzer(2002), Polyakov Schweitzer (20

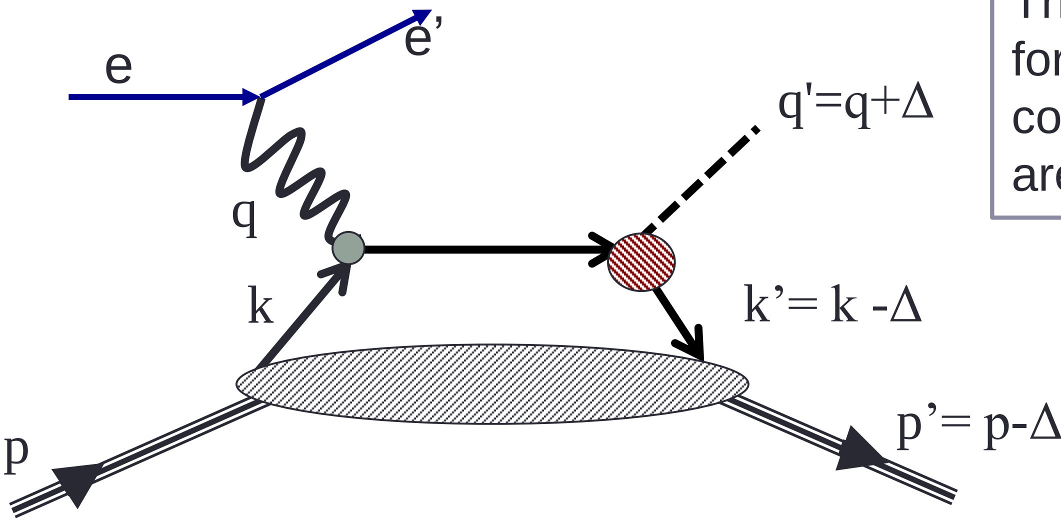
$$T_{ij}(\vec{r}) = \frac{1}{M}\int \frac{d^3\Delta}{(2\pi)^3}\, e^{i\vec{q}\cdot\vec{r}}\left(\Delta_i\Delta_j - \Delta^2\delta_{ij}\right)C(t)$$



C defines the stresses (forces) inside the nucleon

GPDs and the Energy Momentum Tensor

Jaffe Manohar (1990) and Ji (1997) both saw that there was an off-forward part in the EMTmatrix element



The observables for the off-forward correlation function are the GPDs

$$\langle P-\Delta, \Lambda' \mid \bar{q}(0)\gamma^{+}\mathcal{W}(0,z)q(z^{-}) \mid P, \Lambda\rangle_{\mathbf{z}_T=0}$$

Ji went one step forward and noticed that for the quark and gluon operators defining angular momentum as

MOMENTS

The EMT off-forward matrix elements coincide with the ones for a specific correlation function at $z^{-}=0$

$$M^{+12} = \psi^{\dagger}\sigma^{12}\psi + \psi^{\dagger}\left[\vec{x}\times(-i\vec{D})\right]^{3}\psi + \left[\vec{x}\times(\vec{E}\times\vec{B})\right]^{3}$$

quark field

gluon field

Local operators: OPE&Mellin Moments (X. Ji, 1998)

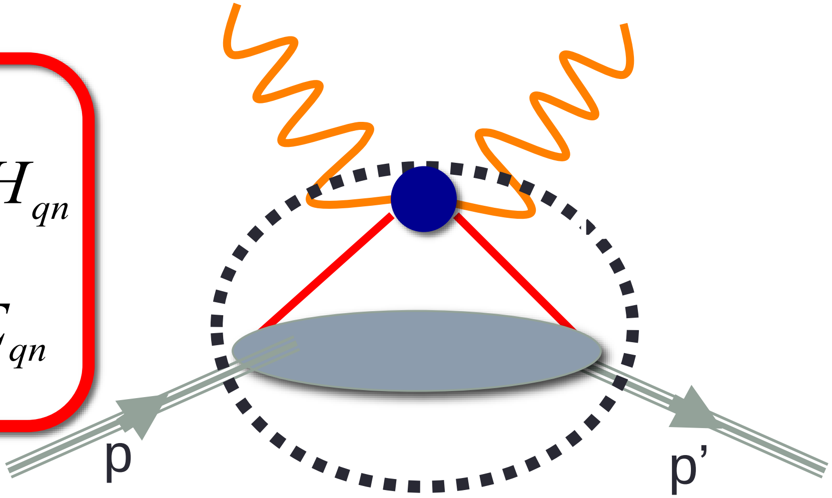
$$n_{\mu_1}\ldots n_{\mu_n}\langle P'|O_q^{\mu_1\cdots\mu_n}|P\rangle = \overline{U}(P')\,\not{n}\,U(P)H_{qn}(\xi,t) + \overline{U}(P')\frac{\sigma^{\mu\alpha}n_\mu i\Delta_\alpha}{2M}U(P)E_{qn}(\xi,t)$$

helicity conserving helicity flip

Mellin Moments

$$\int_{-1}^{1} dx\, x^{n-1} H_q(x,\xi,t) = H_{qn}$$

$$\int_{-1}^{1} dx\, x^{n-1} E_q(x,\xi,t) = E_{qn}$$



2^{nd} Mellin moments

From OPE ⟷ From EMT

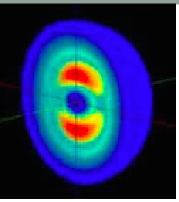
Nucleon

$$\int dx\, x H(x,\xi,t) = A_{20}(t) + \xi^2 C_{20}(t) \equiv A(t) + \xi^2 C(t)$$

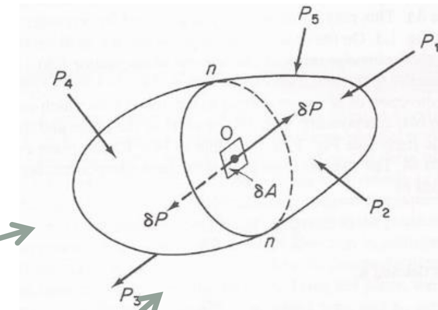
$$\int dx\, x E(x,\xi,t) = B_{20}(t) - \xi^2 C_{20}(t) \equiv B(t) - \xi^2 C(t)$$

← D-term

GPDs are the key to interpret the mechanical properties of the proton



Deuteron



From OPE ⟺ From EMT

$$2\int dx\, x[H_1(x,\xi,t) - \frac{1}{3}H_5(x,\xi,t)] = \mathcal{G}_1(t) + \boxed{\xi^2\mathcal{G}_3(t)}$$ Momentum

$$2\int dx\, x H_2(x,\xi,t) = \mathcal{G}_5(t)$$ Angular Momentum

$$2\int dx\, x H_3(x,\xi,t) = \mathcal{G}_2(t) + \boxed{\xi^2\mathcal{G}_4(t)}$$ Quadrupole

$$-4\int dx\, x H_4(x,\xi,t) = \xi\mathcal{G}_6(t)$$ T-odd

$$\int dx\, x H_5(x,\xi,t) = -\frac{t}{8M_D^2}\mathcal{G}_6(t) + \frac{1}{2}\mathcal{G}_7(t)$$ Connected to b_1 SR

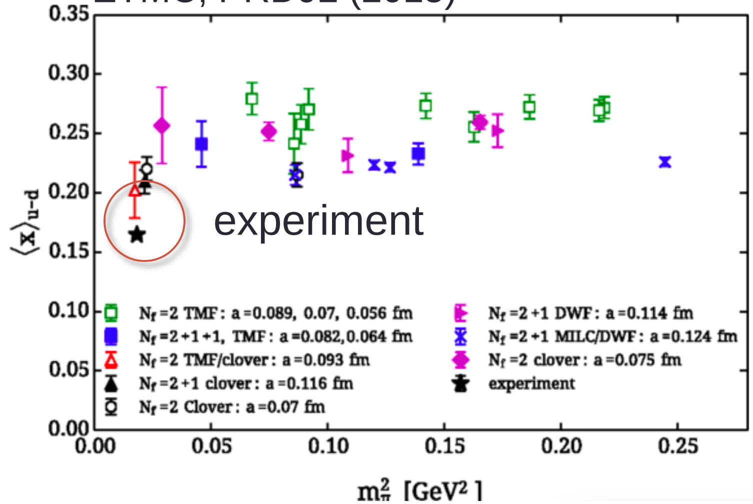
Double flip D-term dependent on polarization

Connecting with observables: work in progress with W. Cosyn and A. Freese

Momentum/energy, angular momentum and pressure

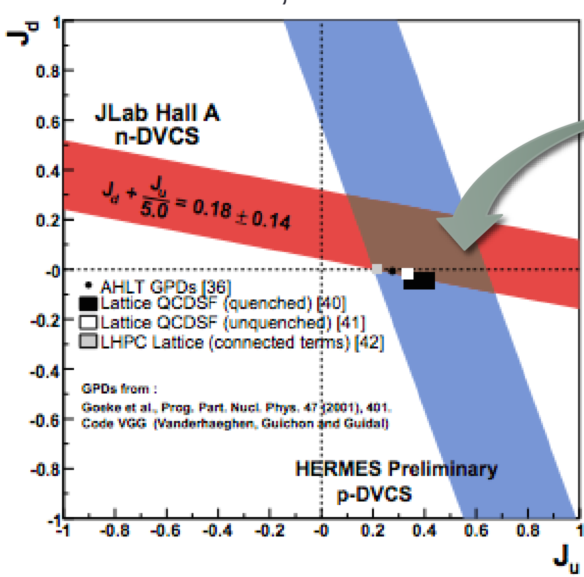
A^{u-d}_{20}

ETMC, PRD92 (2015)

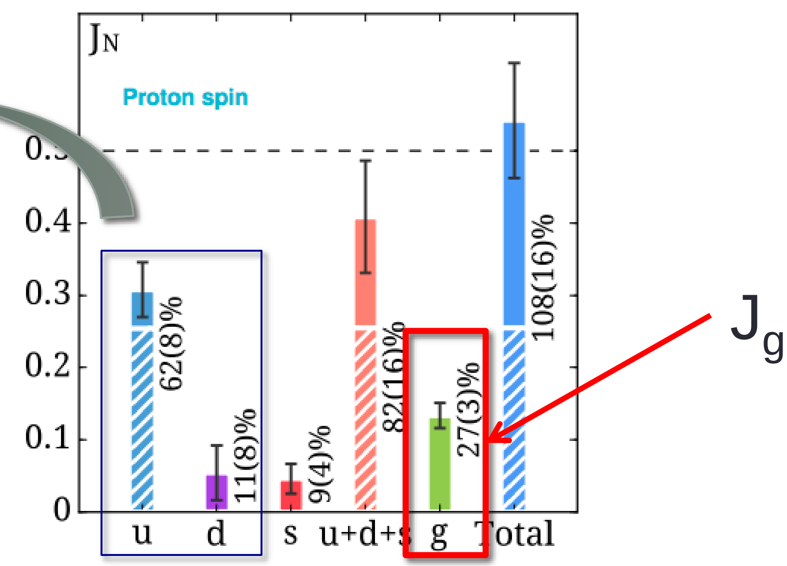


$A_{20}+B_{20}$

Jlab Hall A, Mazouz et al. PRL (2007)



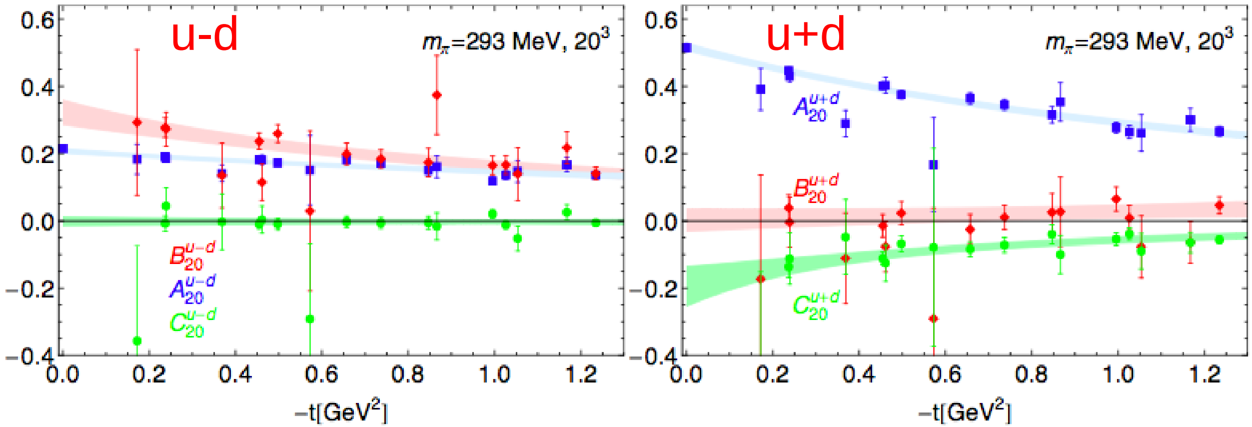
C. Alexandrou et al., PRL119(2017)

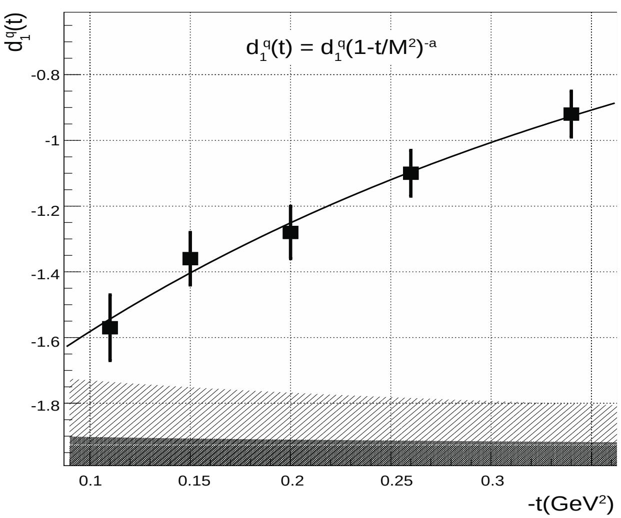


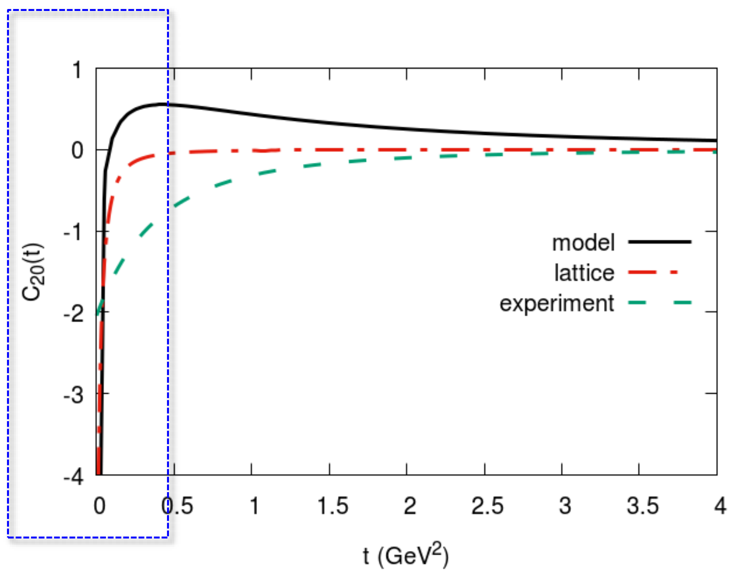
consistent with χQCD Coll., Deka et al. PRD(2015)

C_{20}

Ph. Haegler, JoP: **295** (2011) 012009







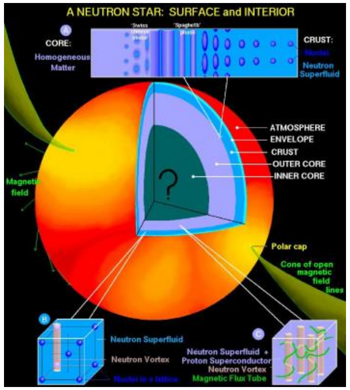
Jlab Hall B, Burkert Elouadrhiri, Girod, Nature (2018)

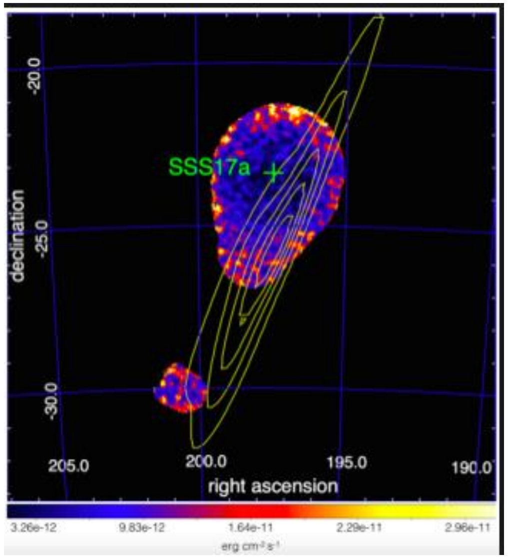
Neutron stars as a laboratory for testing QCD…

- Comparing the QCD EMT with the Equation of State of neutron stars, after event GW178017 (see W. Van de Brandt's talk at SPIN 2018)

- GW178017 is the observation of GWs and EM waves (gamma burst) from a binary neutron star merger

- *Candidate nuclear matter Equations Of State (EOS) must now also satisfy the GW170817 constraints on the Tidal Deformation of compact stars*
  V.Paschalidis et al., PRD, arXiv:1712.00451





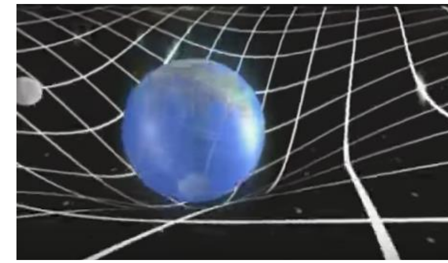
In GR, EMT is the source of the gravitational field

Action ➔Einstein Equations

$$S = \int \sqrt{-g}\left[\frac{1}{16\pi G}\mathcal{R} - \mathcal{L}_m\right] d^4x$$

Ricci scalar ➔curvature

Flat space



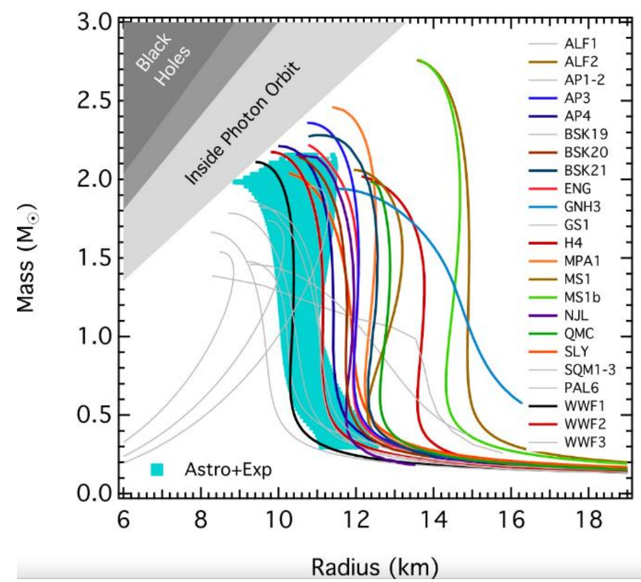
$$T_{\mu\nu} = \frac{\delta \mathcal{L}_m}{\delta g^{\mu\nu}} + g_{\mu\nu}\mathcal{L}_m$$

TOV Equations

$$\frac{dp}{dr} = -\frac{G(\epsilon(r) + 4\pi r^3 p(r)/c^2)(p(r)/c^2 + \rho)}{r(r - 2G\,\epsilon(r)/c^2)}$$

EoS p(r)-ρ(r) relation

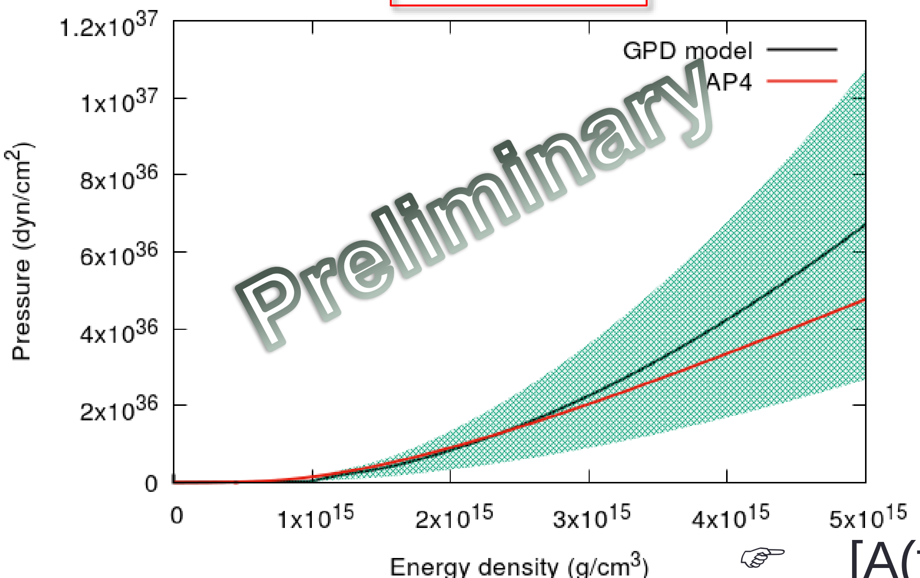
Mass - Radius



Constraints on the Equation of State of Neutron Stars from High Energy Deeply Virtual Exclusive Experiments

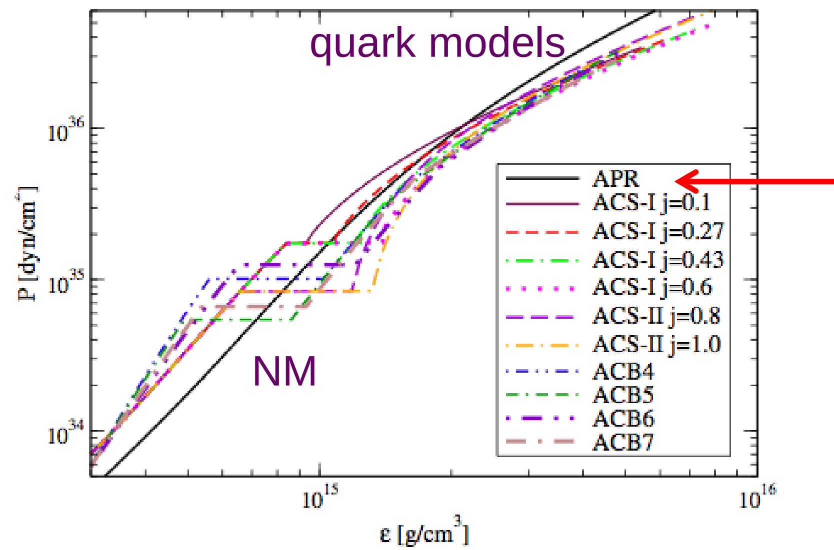
☞ $[tC(t)=tC_{20}]$

Equation of state



☞ $[A(t)=A_{20}]$

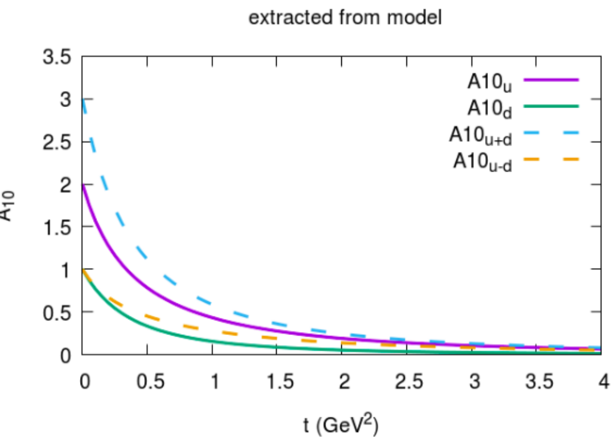
V.Paschalidis et al., PRD, arXiv:1712.00451



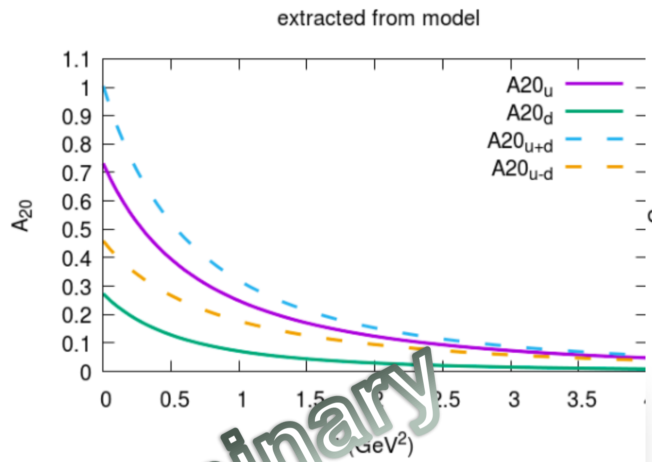
APR=Ahmed Pandharipande Ravenall

SL, A. Rajan, K. Yagi, in preparation

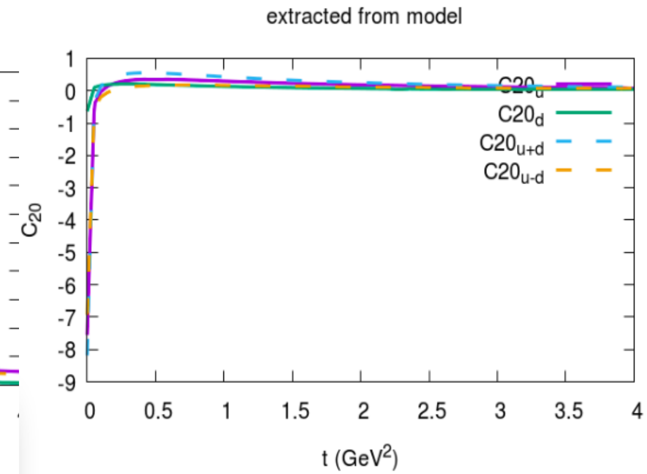
Quarks



$A_{10}(t)$



$A_{20}(t)$



$C_{20}(t)$

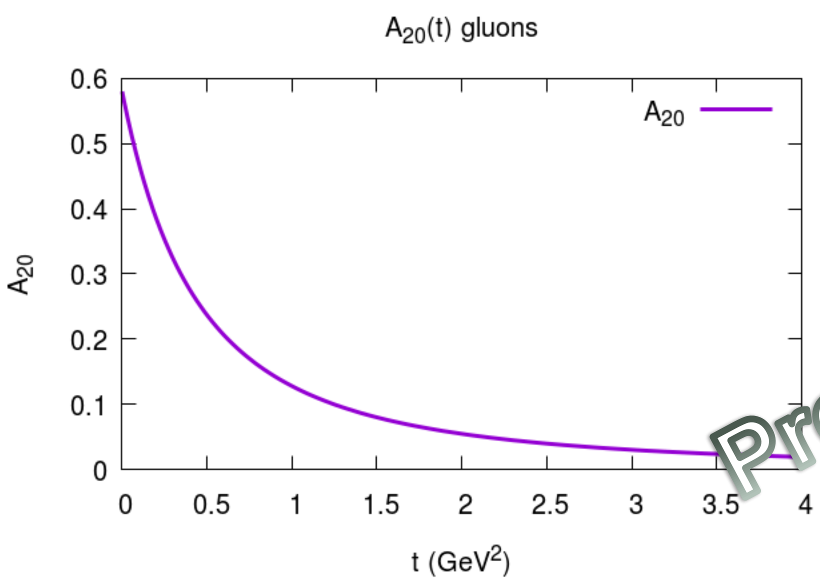
Preliminary

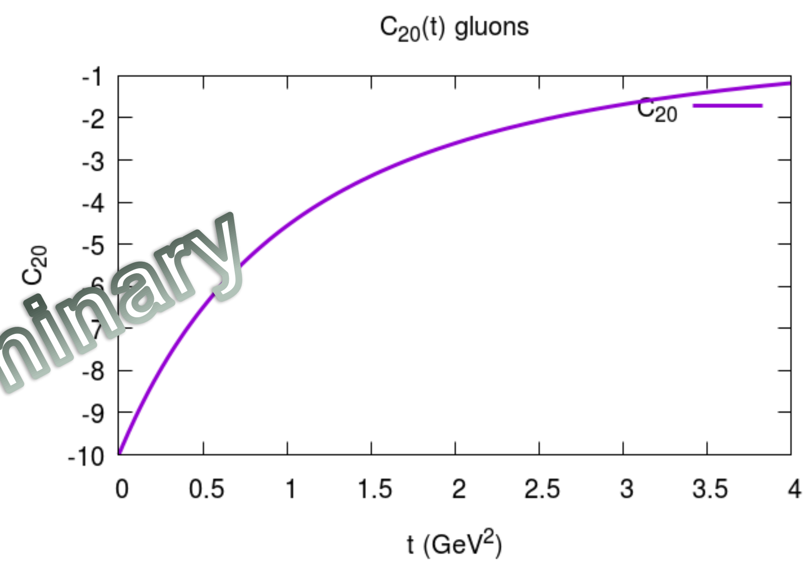
☞ $[A_{10}(t)] = \rho(r)$

☞ $[A_{20}(t)] = \varepsilon(r)$

☞ $[tC_{20}(t)] = p(r)$

Gluons





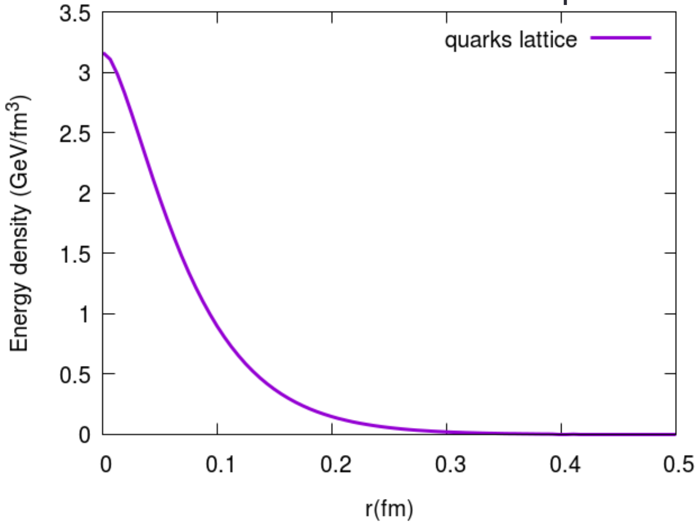
$A^g_{20}(t)$ $C^g_{20}(t)$

☞ $[A^g_{20}(t)] = \varepsilon_g$

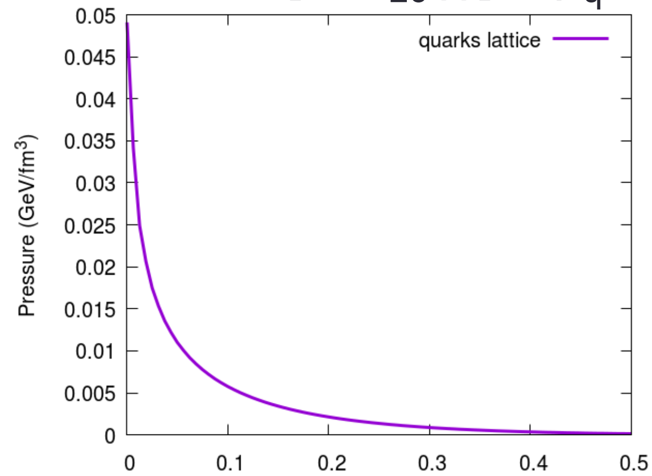
☞ $[tC^g_{20}(t)] = p_g$

Quarks

☞ $[A^q_{20}(t)] = \varepsilon_q$

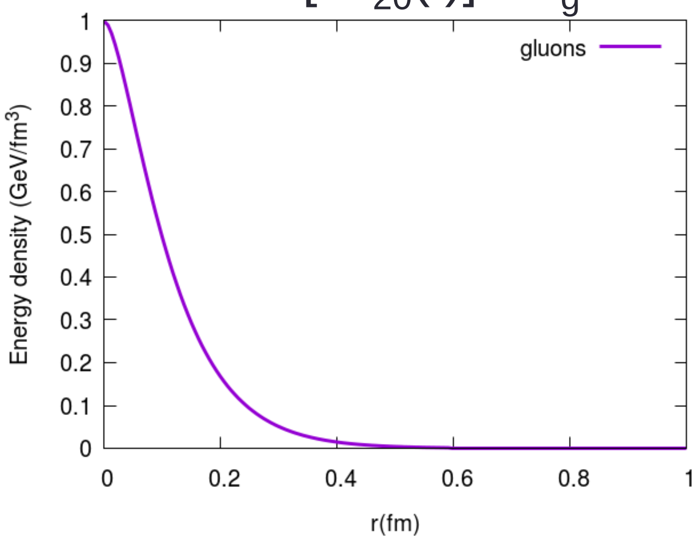


☞ $[t\ C^q_{20}(t)] = p_q$

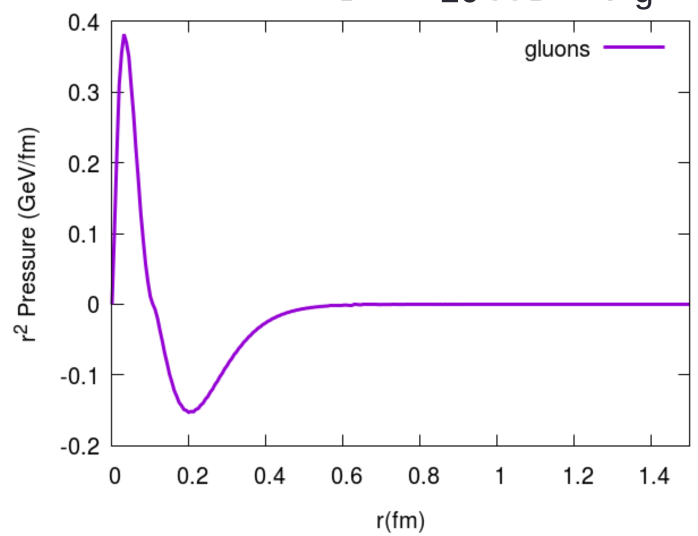


Gluons

☞ $[A^g_{20}(t)] = \varepsilon_g$

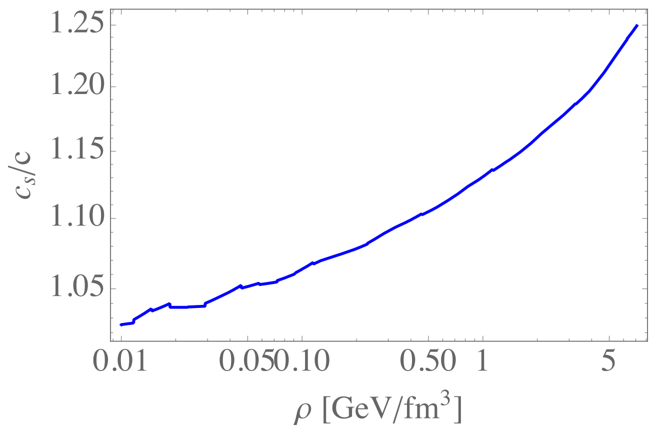


☞ $[t\ C^g_{20}(t)] = p_g$

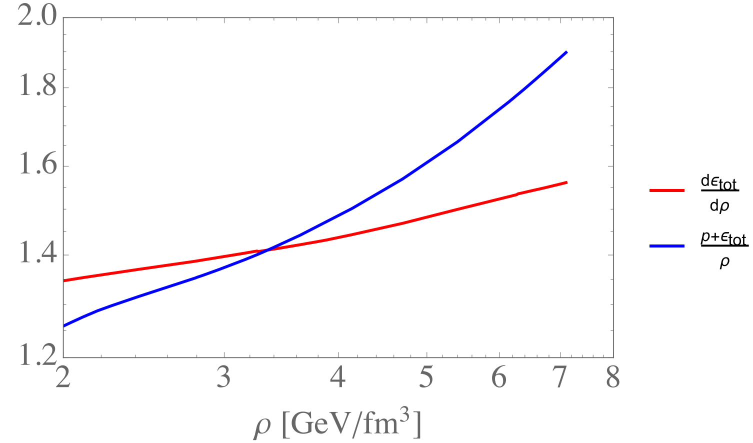


Consistency checks: causality, 1^{st} law of thermodynamics (energy conservation)

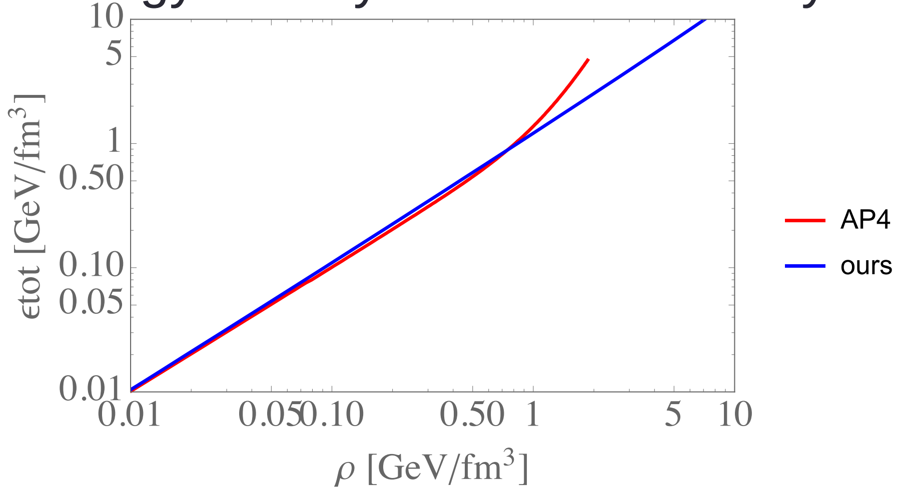
causality



1^{st} law



Energy density vs number density



GW/neutron stars data have us raising questions on some outstanding problems in a new perspective

- Is the GR EMT the QCD EMT?

For internal consistency of the theory GR EMT is symmetric, how do we deal with anti-symmetric terms

Bakker, Leader &Trueman (2004), Lorce (2017)

- Mass energy density in QCD

X.Ji (1995), K.F. Liu χQCD (2014), Lorce (2017), Hatta (2018)

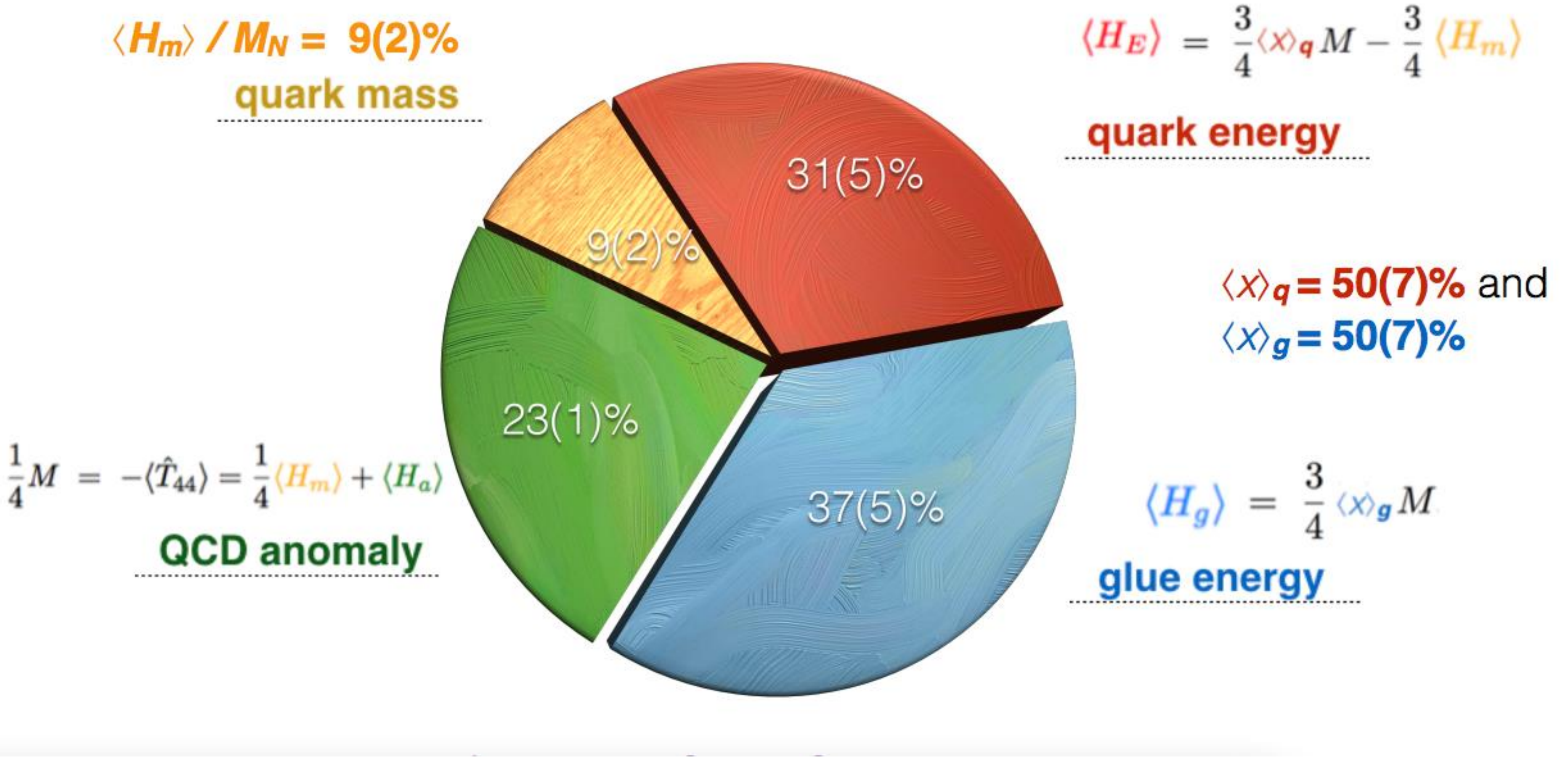
- Role of gluons

W. Detmold and P.Shanahan (2018), M. Constantinou (2018)

- Interpretation of forces

M. Burkardt

The nucleon mass in Lattice QCD



Y. Yang et al., χQCD Coll

A closer look at mass

$$H_{QCD} = \langle T^{00} \rangle = H_q + H_g + H_m + H_a$$

$$H_q = \langle \bar{\psi}(-i\,\mathbf{D}\cdot\gamma)\psi \rangle$$ quark energy

$$H_g = \left\langle \frac{1}{2}(E^2 + B^2) \right\rangle$$ gluon field energy

$$H_m = \left\langle m\,\bar{\psi}\left(1 + \frac{1}{4}\gamma_m\right)\psi \right\rangle$$

$$H_a = \left\langle \frac{1}{4}\beta(g)(E^2 - B^2) \right\rangle$$

quark mass anomaly

trace anomaly

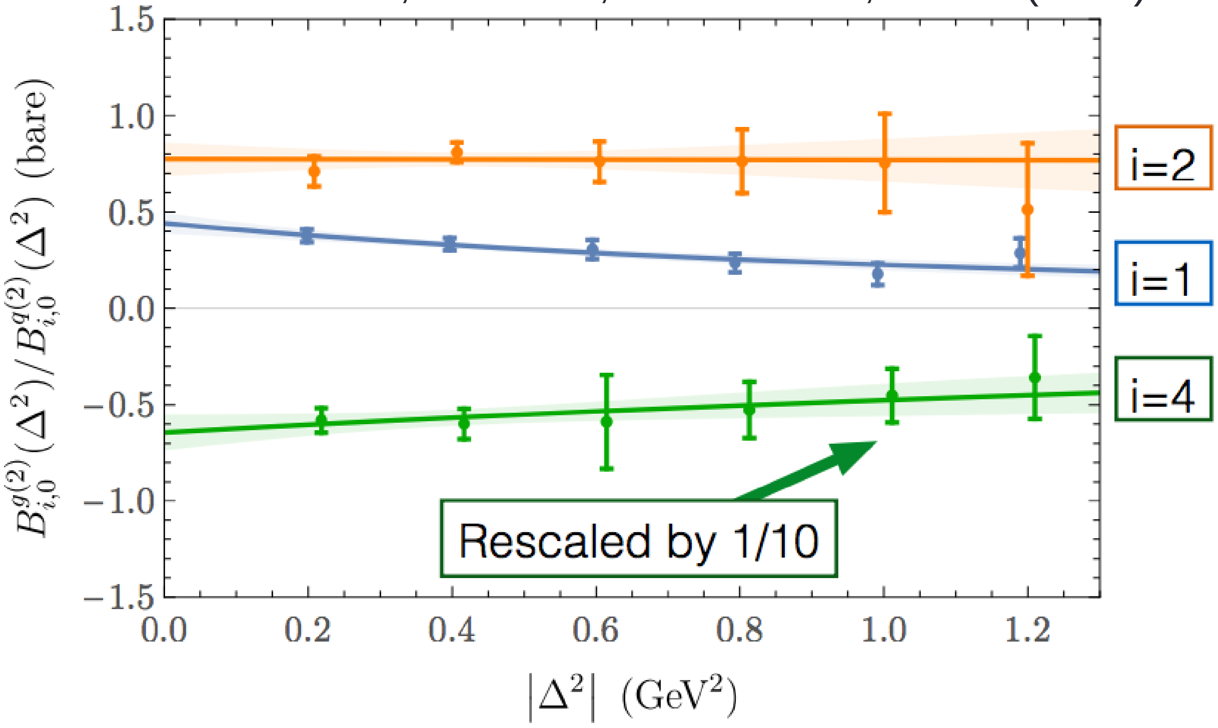
gluon anomaly

X. Ji (1995)

Deuteron

Ratio of Gluons/Quarks

W. Detmold, D.Pefkou, P. Shanahan, PRD95(2017)



$$\frac{B_1^{g(2)}}{B_1^{q(2)}}, \frac{B_2^{g(2)}}{B_2^{q(2)}}, \frac{B_4^{g(2)}}{B_4^{q(2)}}$$

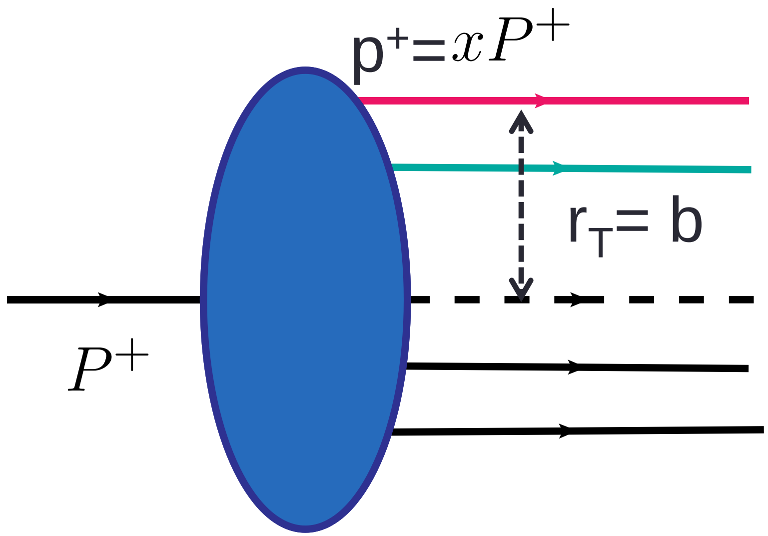
experimentally… an open field…

3. FEMTOGRAPHY

Facing the next challenge….images at the femtoscale

five orders of magnitude below

The Proton Relativistic Wave Function: Poincaré Invariance



Center of P⁺

$$\vec{R}_T = \frac{1}{P^+}\sum_i (x_i P^+)\vec{r}^{\,i}_T$$

- P^+ plays the role of mass
- “The subgroup of the Poincaré group that leaves the surface z^+=const invariant, is isomorphic to the Galilean group in 2D”
- We can disentangle the transverse components from the longitudinal components in boosts

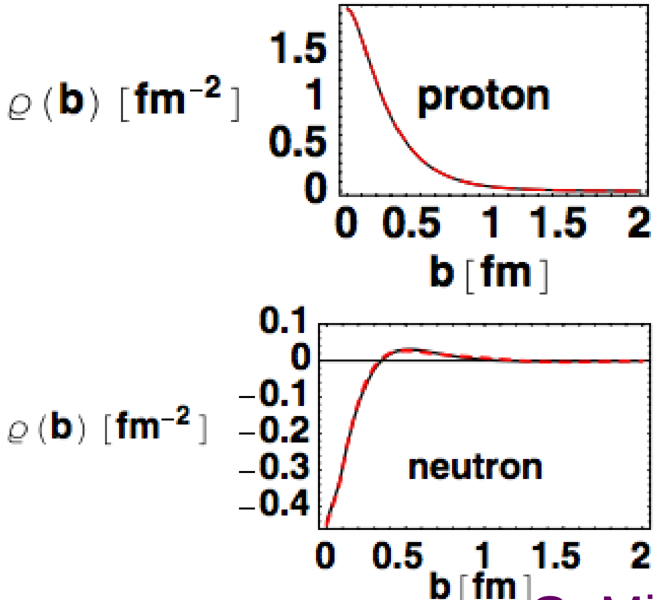
Implication

We can map out faithfully the spatial quark distributions in the transverse plane (no modeling/approximation)

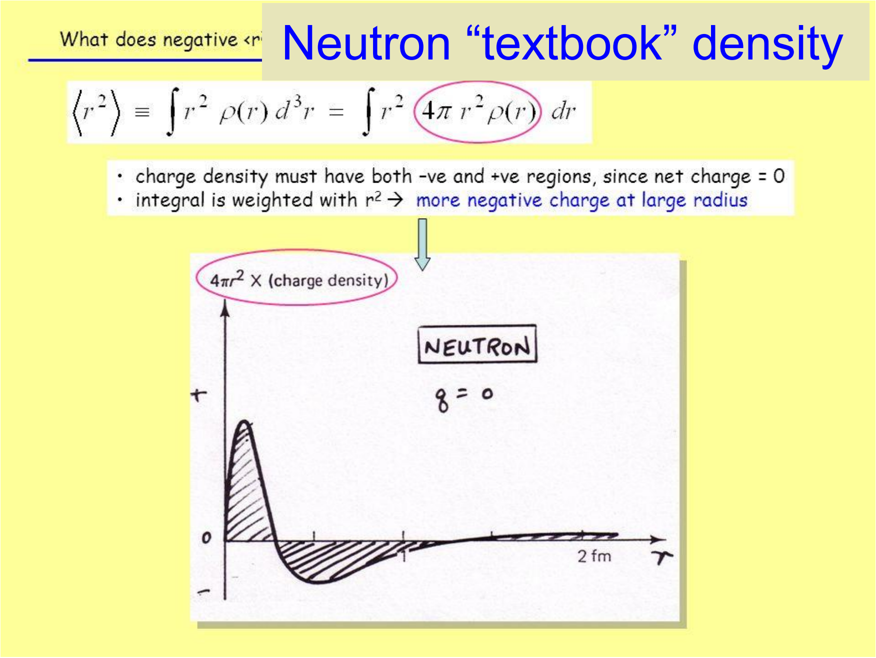
$$q(x,\vec{b}) = \frac{dn}{dx\,d^2\vec{b}}$$

Soper (1977), Burkardt (2001)

Already a surprise: re-evaluation of nucleon charge distribution

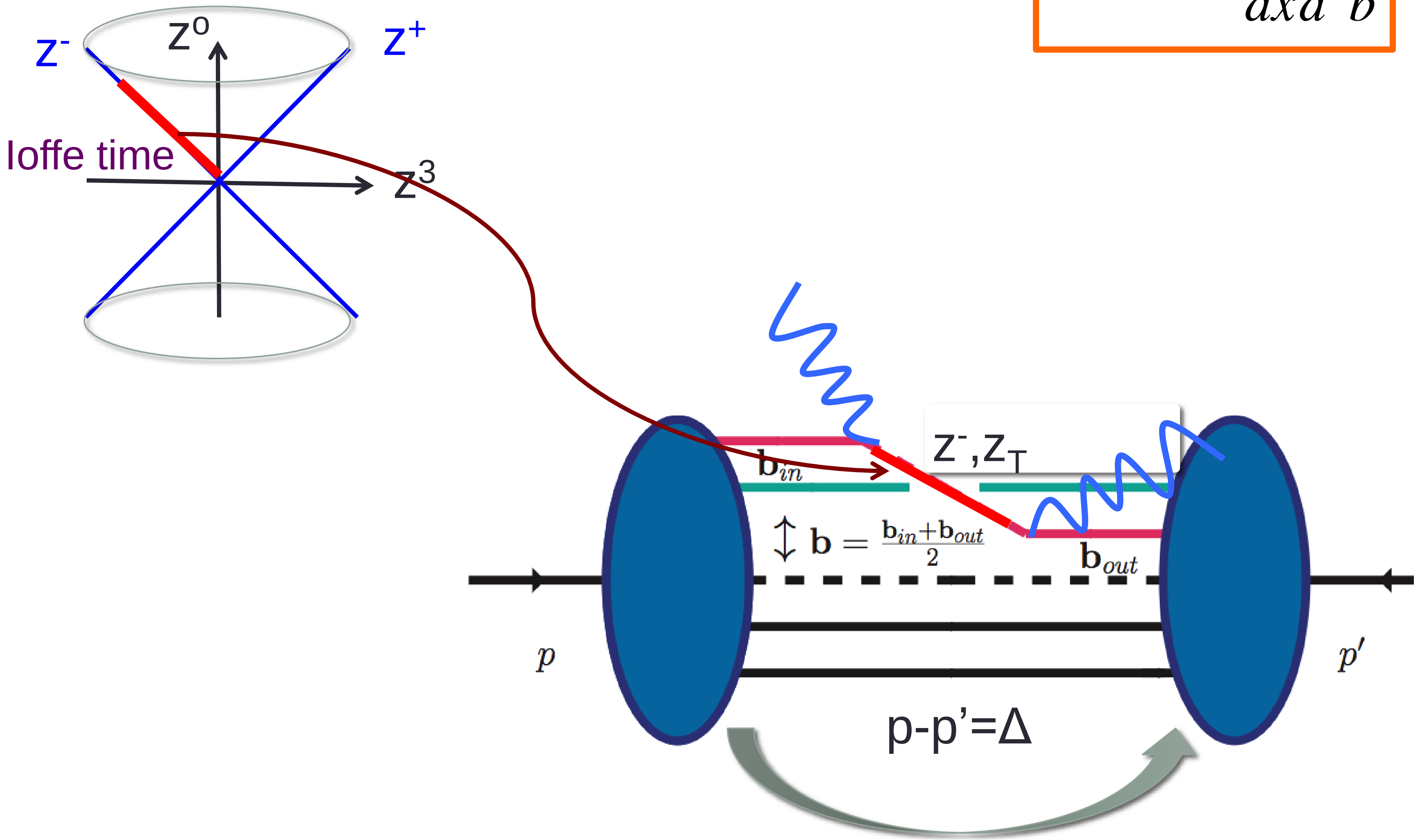


G. Miller(2007)



Two distinct distance scales

$$q(x,\vec{b}) = \frac{dn}{dx\,d^2\vec{b}}$$



GPDs involve two types of distance

$$H^q(x,0,\Delta) = \int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle P-\Delta,\Lambda' \mid \bar{q}(0)\gamma^+ q(z^-) \mid P,\Lambda\rangle_{\mathbf{z}_T=0}$$

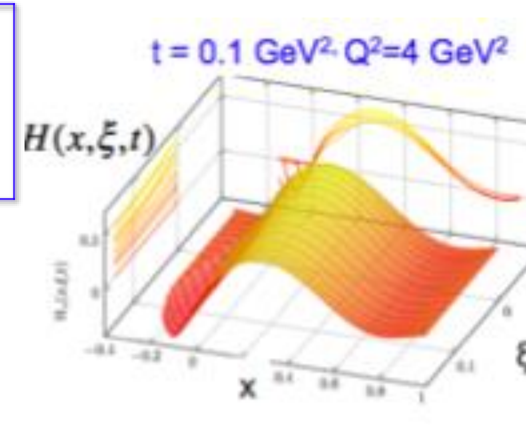
x distribution ➡ **Fourier transform** of **non-diagonal** density distribution in **z^-**

Δ distribution ➡ **Fourier transform** of **diagonal** density distribution in **b**

$$\bar{q}_+^\dagger(0,b)q_+(z^-,b) \rightarrow \rho(0,b;z^-,b)$$

Ioffe time reconstruction

A. Rajan, SL (LC Meeting, 2018)



Reconstructed

3. OAM AND OTHER GENERALIZED WANDZURA WILCZEK RELATIONS

Abha Rajan, Friday

Based on

PHYSICAL REVIEW D **94**, 034041 (2016)

Parton transverse momentum and orbital angular momentum distributions

Abha Rajan,[1,*] Aurore Courtoy,[2,†] Michael Engelhardt,[3,‡] and Simonetta Liuti[4,§]
[1]Physics Department, University of Virginia, 382 McCormick Road, Charlottesville, Virginia 22904, USA
[2]Catedrática CONACyT, Departamento de Física, Centro de Investigación y de Estudios Avanzados,
Apartado Postal 14-740, 07000 México D.F., México
[3]... of Physics, New Mexico State University, Box 30001 MSC 3D,
[4]Physics Depa...

The quark ... integral of a W... and momentu... forward Com... explicit link t... transverse m... determinatio... orbital angul... polarized tar...

DOI: 10.110...

PRD2018

Lorentz Invariance and QCD Equation of Motion Relations for Generalized Parton Distributions and the Dynamical Origin of Proton Orbital Angular Momentum

Abha Rajan,[1,*] Michael Engelhardt,[2,†] and Simonetta Liuti[3,‡]
[1] University of Virginia - Physics Department, 382 McCormick Rd., Charlottesville, Virginia 22904 - USA
[2] New Mexico State University - Department of Physics, Box 30001 MSC 3D, Las Cruces NM, 88003 - USA
[3] University of Virginia - Physics Department, 382 McCormick Rd., Charlottesville, Virginia 22904 - USA and Laboratori Nazionali di Frascati, INFN, Frascati, Italy.

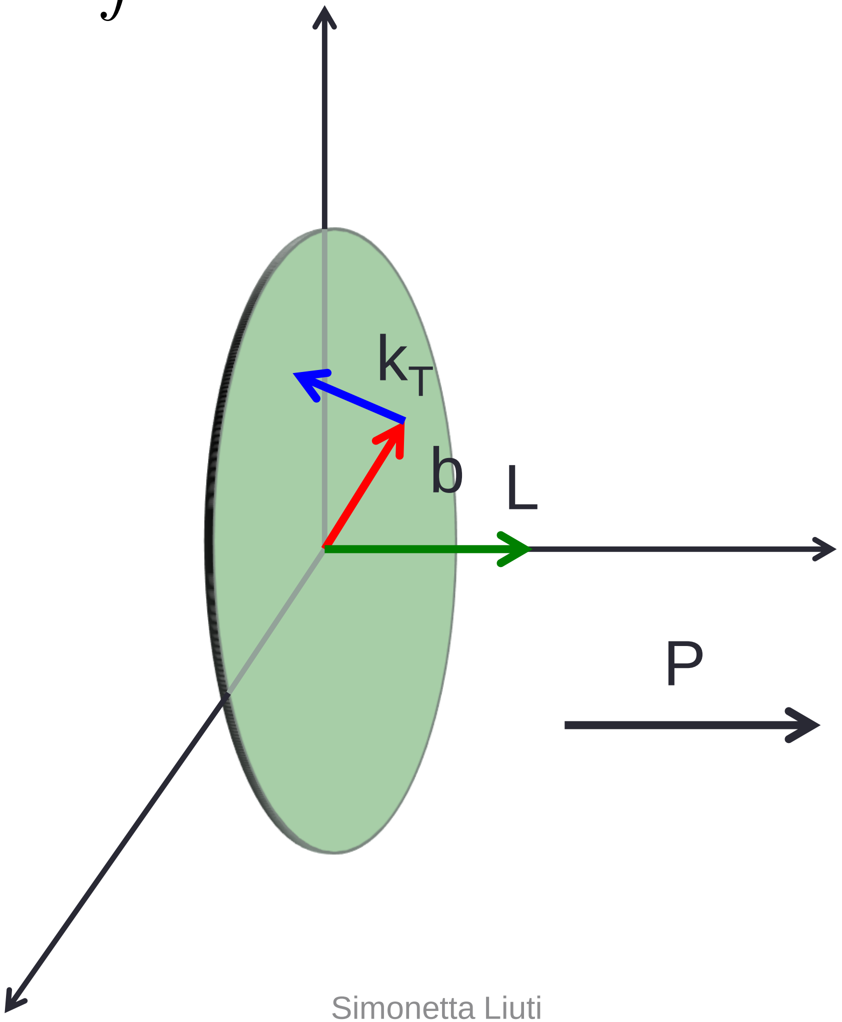
We derive new Lorentz Invariance and Equation of Motion Relations between twist-three Generalized Parton Distributions (GPDs) and moments in the parton transverse momentum, k_T, of twist-two Generalized Transverse Momentum-Dependent Distributions (GTMDs), as a function of the parton longitudinal momentum fraction x. Although GTMDs in principle define the observables for partonic orbital motion, experiments that can unambiguously detect them appear remote at present. The relations presented here provide a solution to this impasse in that, e.g., the orbital angular momentum density is connected to directly measurable twist-three GPDs. Out of 16 possible Equation of Motion relations that can be written in the T-even sector, we focus on three helicity configurations that can be detected analyzing specific spin asymmetries: two correspond to longitudinal proton polarization and are associated with quark orbital angular momentum and spin-orbit correlations; the third, obtained for transverse proton polarization, is a generalization of the relation obeyed by the g_2 structure function. We also exhibit an additional relation connecting the off-forward extension of the Sivers function to an off-forward Qiu-Sterman term.

arXiv:1709.05770

Definition: Wigner Distributions

$$L_q^{\mathcal{U}} = \int dx \int d^2\mathbf{k}_T \int d^2\mathbf{b}\,(\mathbf{b}\times\mathbf{k}_T)_z\,\mathcal{W}^{\mathcal{U}}(x,\mathbf{k}_T,\mathbf{b})$$

Hatta Burkardt
Lorce, Pasquini,
Xiong, Yuan
Mukherjee,
Courtoy,
Engelhardt, Rajan,
SL



Possible Observable for L_q

$$\frac{1}{M}\int d^2k_T\, k_T^2\, F_{14}(x,0,k_T^2,0,0) = \langle b_T \times k_T \rangle_3(x)$$

$L_q(x)$

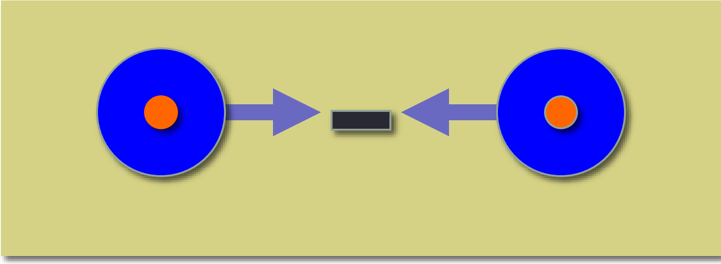
k_T moment of a GTMD
(Lorce and Pasquini)

$\xi=0$
$k_T \bullet \Delta_T=0$
$\Delta_T^2=0$

CAN IT BE MEASURED?

Is there any observable that we can identify OAM with?

A New Relation



A. Rajan, A. Courtoy, M. Engelhardt, S.L., PRD (2016) arXiv:1601.06117
A. Rajan, M. Engelhardt, S.L., PRD (2018) arXiv:1709.05770

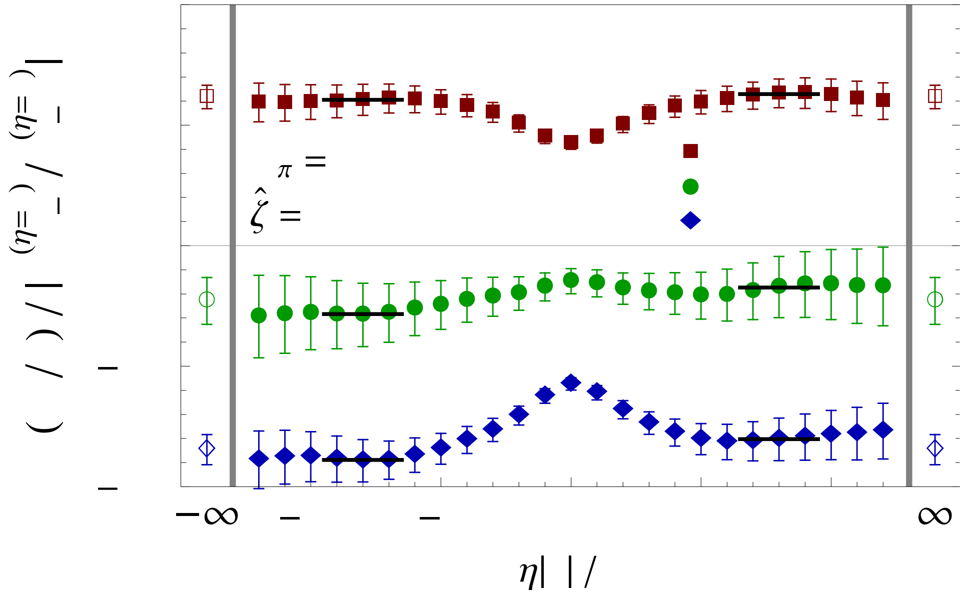
$$\frac{1}{M}\int d^2k_T\, k_T^2\, F_{14}(x,0,k_T^2,0,0) = -\int_x^1 dy\, \left[\widetilde{E}_{2T} + H + E\right]$$

OAM: twist 2 GTMD

twist-3 GPD

Generalized Lorentz Invariance Relation (LIR)

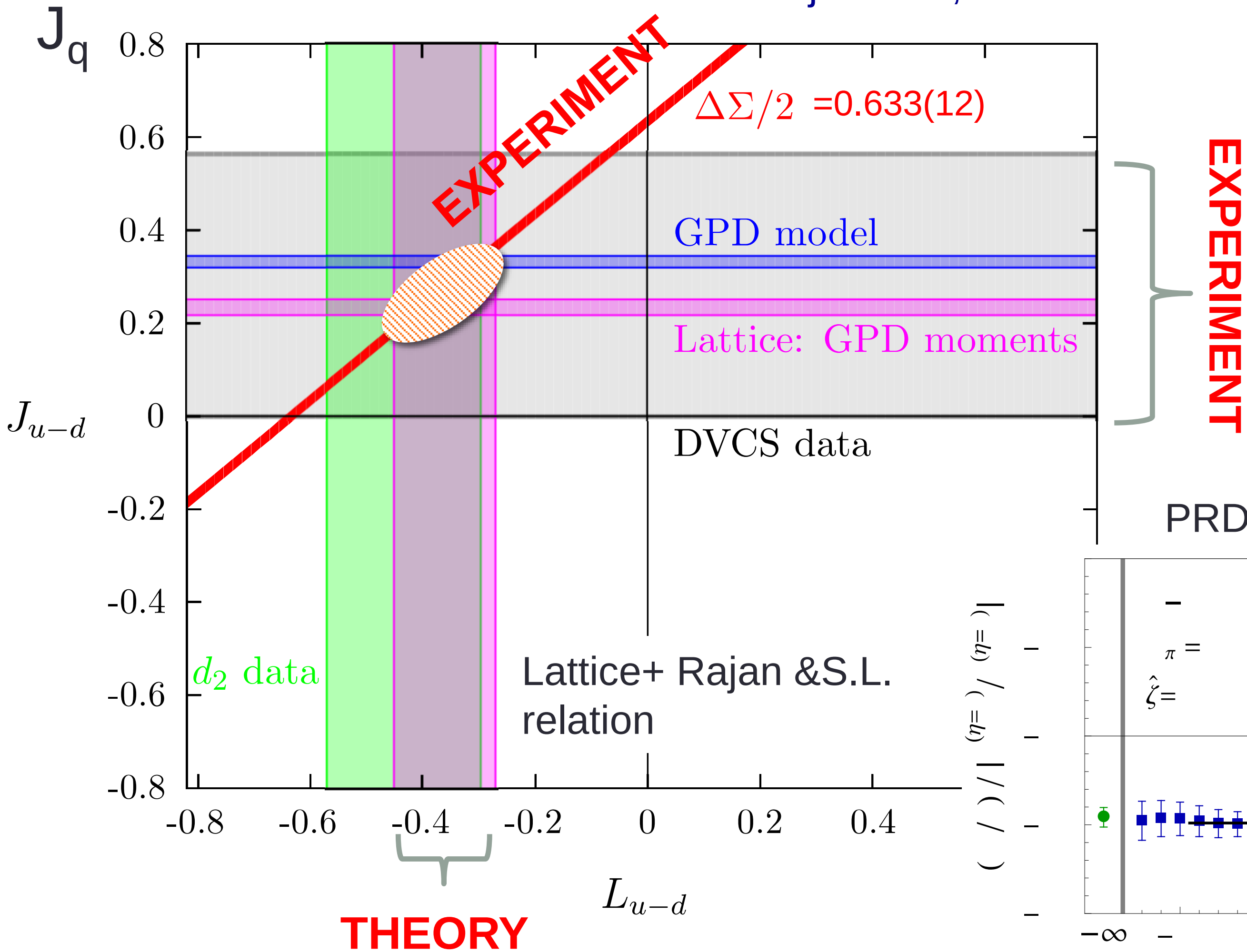
M. Engelhardt, PRD (2017)



Quark sector :

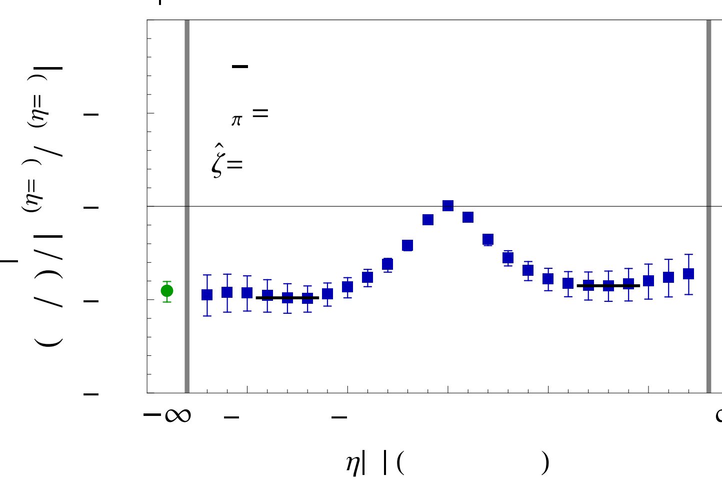
$$J_q = L_q + \frac{1}{2}\Delta\Sigma_q$$

A. Rajan et al, PRD (2016) arXiv:1601.06117
A. Rajan et al, arXiv:1709.05770



Mazouz et al. PRL (2007)

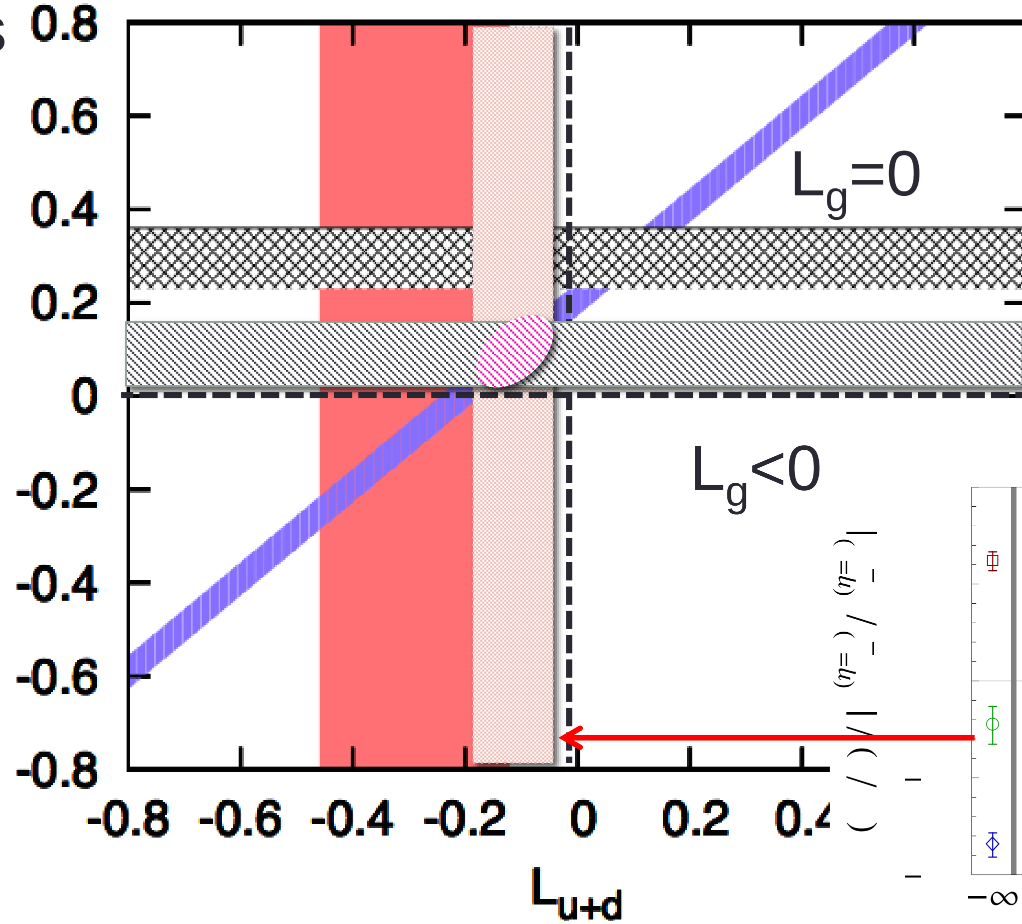
M. Engelhardt
PRD, arXiv:1701.01536



EIC ➔ Adding gluons: Present data consistent with L_g<0

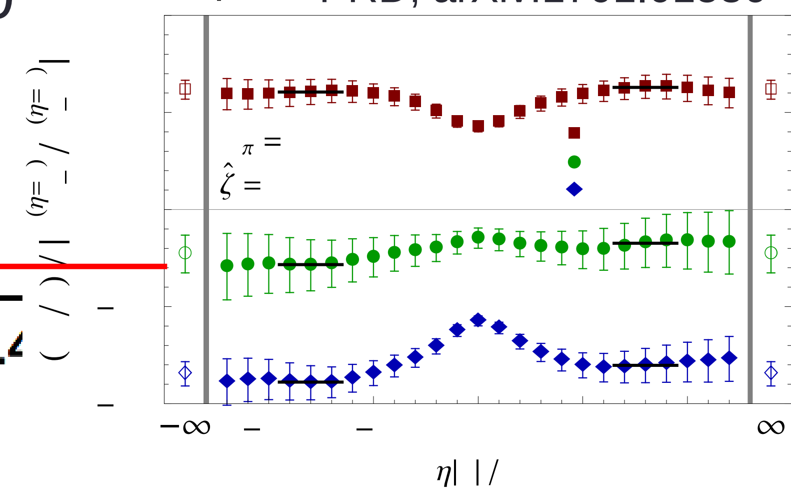
$$\frac{1}{2} - (\Delta G + L_g^{JM}) = L_q^{JM} + \frac{1}{2}\Delta\Sigma_q$$

Gluons



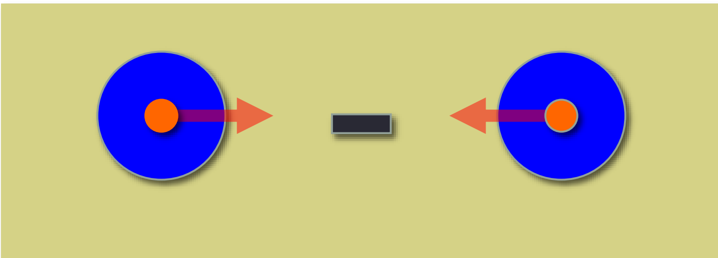
Using the "estimated" measured value of ΔG

M. Engelhardt,
PRD, arXiv:1701.01536



Other correlations: quark and gluon spin-orbit

A. Rajan et al, arXiv:1709.05770, PRD



Beam Target Spin Correlation: longitudinally polarized quark density in an unpolarized proton

chiral odd magnetic moment

Chiral symmetry breaking test!

$$\frac{1}{2}\int dx\, x\widetilde{H} + \frac{m_q}{2M}\kappa_T^q = \int dx\, x(2\widetilde{H}'_{2T} + E'_{2T} + \widetilde{H}) + \frac{1}{2}e_q$$

$(J \times S)$ $- J_T \times S_T$ $L_z S_z$ $S_z S_z$

$J_z S_z$

Interpretation of gauge link

$M_2(v^-)$

$$\int dx \int d^2k_T\, \mathcal{M}^{i,S}_{\Lambda'\Lambda} = \quad i\epsilon^{ij} g v^- \frac{1}{2P^+} \int_0^1 ds\, \langle p',\Lambda'|\bar{\psi}(0)\gamma^+ U(0,sv) F^{+j}(sv) U(sv,0)\psi(0)|p,\Lambda\rangle$$

$$\int dx \int d^2k_T\, \mathcal{M}^{i,A}_{\Lambda'\Lambda} = \quad -g v^- \frac{1}{2P^+} \int_0^1 ds\, \langle p',\Lambda'|\bar{\psi}(0)\gamma^+\gamma^5 U(0,sv) F^{+i}(sv) U(sv,0)\psi(0)|p,\Lambda\rangle$$

Force acting on quark

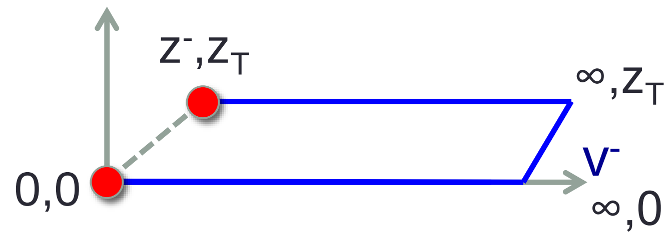
Non zero only for staple link

$M_3(v^-=0)$

$$\int dx\, x \int d^2k_T\, \mathcal{M}^{i,S}_{\Lambda'\Lambda} = \frac{ig}{4(P^+)^2} \langle p',\Lambda'|\bar{\psi}(0)\gamma^+\gamma^5 F^{+i}(0)\psi(0)|p,\Lambda\rangle$$

$$\int dx\, x \int d^2k_T\, \mathcal{M}^{i,A}_{\Lambda'\Lambda} = \frac{g}{4(P^+)^2} \epsilon^{ij} \langle p',\Lambda'|\bar{\psi}(0)\gamma^+ F^{+j}(0)\psi(0)|p,\Lambda\rangle$$

A more profound understanding of quark-gluon-quark correlations



Two types

- Difference between JM and Ji (LIR violating term)

$$L^{JM}(x) - L^{Ji}(x) = \mathcal{M}_{F_{14}} - \mathcal{M}_{F_{14}}|_{y=0} = -\int_x^1 dy\, \mathcal{A}_{F_{14}}(y).$$

- Genuine twist 3 term (Generalized Qiu Sterman)

$$\int d^2k_T\, \frac{k_T^2}{M^2}\, F_{14}^{JM} - \int d^2k_T\, \frac{k_T^2}{M^2}\, F_{14}^{Ji} = T_F(x, x, \Delta)$$

An experimental measurement of twist 3 GPDs is sensitive to OAM but it cannot disentangle the difference between JM and Ji decompositions

Relations between gauge links derivatives

$$\frac{d}{dv^-}\mathcal{M}^{i,S(n=2)}_{\Lambda\Lambda'}\bigg|_{v^-=0} = i(2P^+)\mathcal{M}^{i,A(n=3)}_{\Lambda\Lambda'}$$

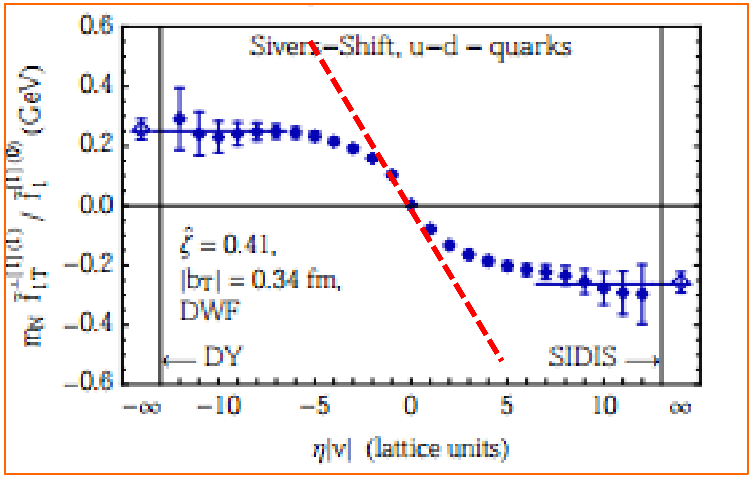
$$\frac{d}{dv^-}\mathcal{M}^{i,A(n=2)}_{\Lambda\Lambda'}\bigg|_{v^-=0} = -i(2P^+)\mathcal{M}^{i,S(n=3)}_{\Lambda}$$

Proton transverse spin configuration

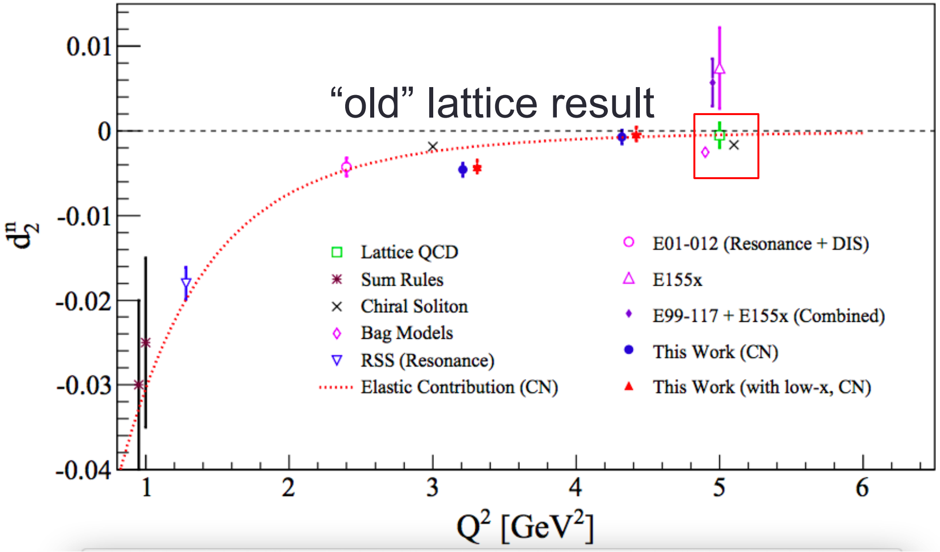
n=2

n=3

Slope of Sivers function in staple length



Genuine twist three d_2



Work in progress: W. Armstrong, F. Aslan, M. Burkardt, M. Engelhardt, SL

4. A NEW EFFORT

Brandon Kriesten, Thursday

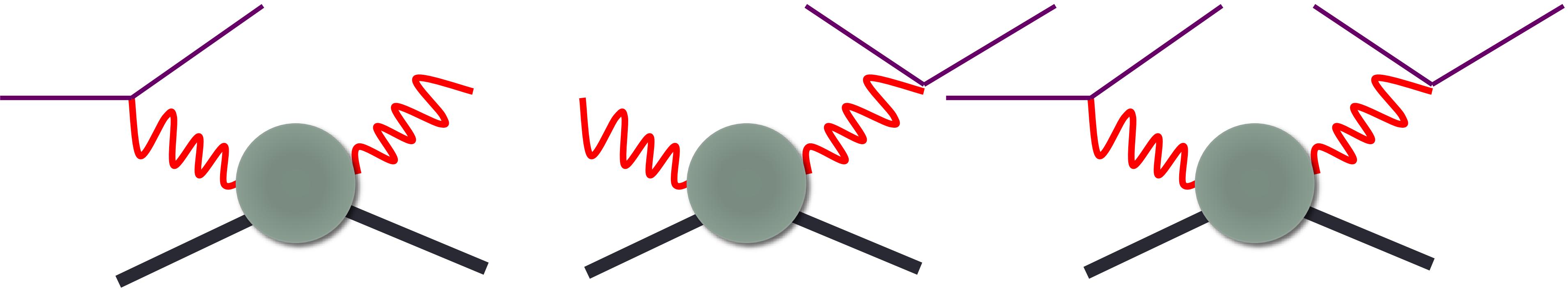
Multi-process, multi-variable analysis

- ✓ Deeply Virtual Compton Scattering
- ✓ Deeply Virtual Meson Production
- ✓ Timelike Compton Scattering
- ✓ Double DVCS
- ✓ DVCS, TCS with Recoil Polarization
- ✓ Exclusive DY

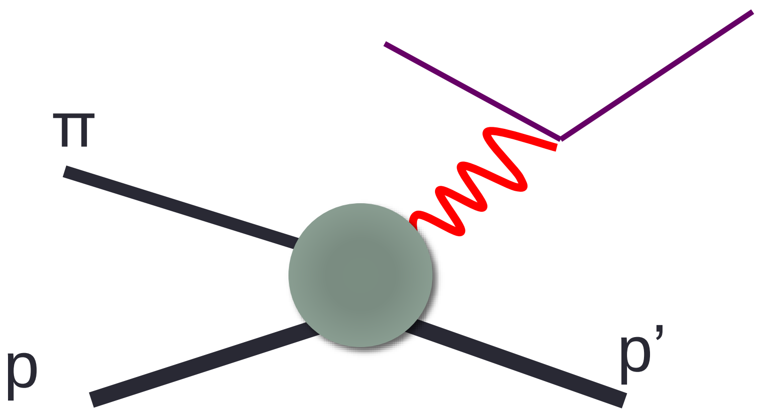
Universality

(BTW…NEED EIC TO CARRY OUT THIS PROGRAM)

All the channels



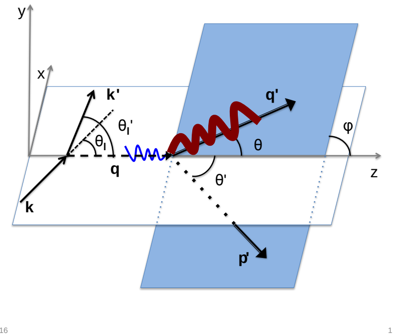
DVCS TCS DDVCS



...

Exclusive pion induced DY **(EDY)**, T. Sawada et al., PRD93 (2016)
accessible at LHC SPIN ➔ **P. Di Nezza's talk**

DVCS



Helicity Amplitude Composition of Deeply Virtual Compton Scattering Processes and Bethe-Heitler Interference

Brandon Kriesten,[*] Simonetta Liuti,[†] Liliet Calero Diaz,[‡] Dustin Keller,[§] Brandon Kriesten,[*] Andrew Meyer,[¶] and Abha Rajan[**]

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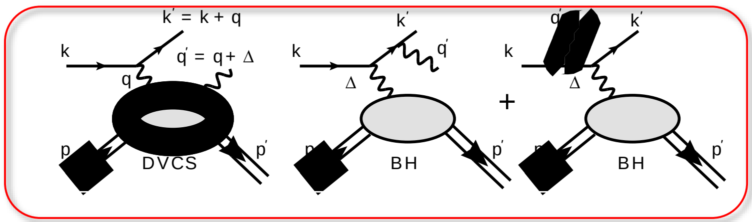
Gary R. Goldstein[††]

Department of Physics and Astronomy, Tufts University, Medford, MA 02155 USA.

J. Osvaldo Gonzalez-Hernandez[‡‡]

INFN, Torino



$$\frac{d^5\sigma_{DVCS}}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} = \frac{\alpha^3}{16\pi^2(s-M^2)^2\sqrt{1+\gamma^2}}|T_{DVCS}|^2$$

twist two GPDs

twist three GPDs

$$= \frac{\Gamma}{Q^2(1-\epsilon)}\Big\{ F_{UU,T} + \epsilon F_{UU,L} + \epsilon\cos 2\phi F_{UU}^{\cos 2\phi}$$

$$+ \sqrt{\epsilon(\epsilon+1)}\left[\cos\phi F_{UU}^{\cos\phi} + \sin\phi F_{UU}^{\sin\phi}\right]$$

$$+ \lambda_e \sqrt{2\epsilon(1-\epsilon)}\sin\phi F_{LU}^{\sin\phi}$$

$$+ S_L \left[F_{UL} + \sqrt{\epsilon(\epsilon+1)}\sin\phi F_{UL}^{\sin\phi} + \epsilon\sin 2\phi F_{UL}^{\sin 2\phi}\right]$$

$$+ \lambda_e \sqrt{1-\epsilon^2} F_{LL} + 2\lambda_e \sqrt{\epsilon(1-\epsilon)}\cos\phi F_{LL}^{\cos\phi}$$

$$+ |S_T| \Big[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right)$$

$$\epsilon\sin(\phi+\phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S) F_{UT}^{\sin(3\phi-\phi_S)}$$

$$+\sqrt{2\epsilon(1+\epsilon)}\left(\sin\phi_S F_{UT}^{\sin\phi_S} + \sin(2\phi-\phi_S) F_{UT}^{\sin(2\phi-\phi_S)}\right)\Big]$$

$$+ \lambda_e |S_L| \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}$$

$$+\sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{LT}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

GPD Content

$t << Q^2$ $\xi < 1$

(with Brandon Kriesten et al., in preparation)

twist 2

$$F_{UU,T} = 4\Big[(1-\xi^2)\left(|\,\mathcal{H}\,|^2 + |\,\tilde{\mathcal{H}}\,|^2\right) + \frac{t_o - t}{2M^2}\left(|\,\mathcal{E}\,|^2 + \xi^2\,|\,\tilde{\mathcal{E}}\,|^2\right) - \frac{2\xi^2}{1-\xi^2}\,\Re\mathrm{e}\left(\mathcal{H}\mathcal{E}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{E}}^*\right)\Big]$$

$$F_{LL} = 2\left[2(1-\xi^2)\;|\,\mathcal{H}\widetilde{\mathcal{H}}\,| + 4\xi\,\frac{t_o - t}{2M^2}\;|\,\mathcal{E}\widetilde{\mathcal{E}}\,| + \frac{2\xi^2}{1-\xi^2}\,\Re\mathrm{e}\left(\mathcal{H}\widetilde{\mathcal{E}} + \widetilde{\mathcal{H}}\mathcal{E}\right)\right]$$

spin-orbit

twist 3

twist 2

$$F_{UU}^{\cos\phi} = -2\,(1-\xi^2)\,\Re\mathrm{e}\Big[\left(2\widetilde{\mathcal{H}}_{2T} + \mathcal{E}_{2T} + 2\widetilde{\mathcal{H}}'_{2T} + \mathcal{E}'_{2T}\right)\left(\mathcal{H} - \frac{\xi^2}{1-\xi^2}\mathcal{E}\right)$$

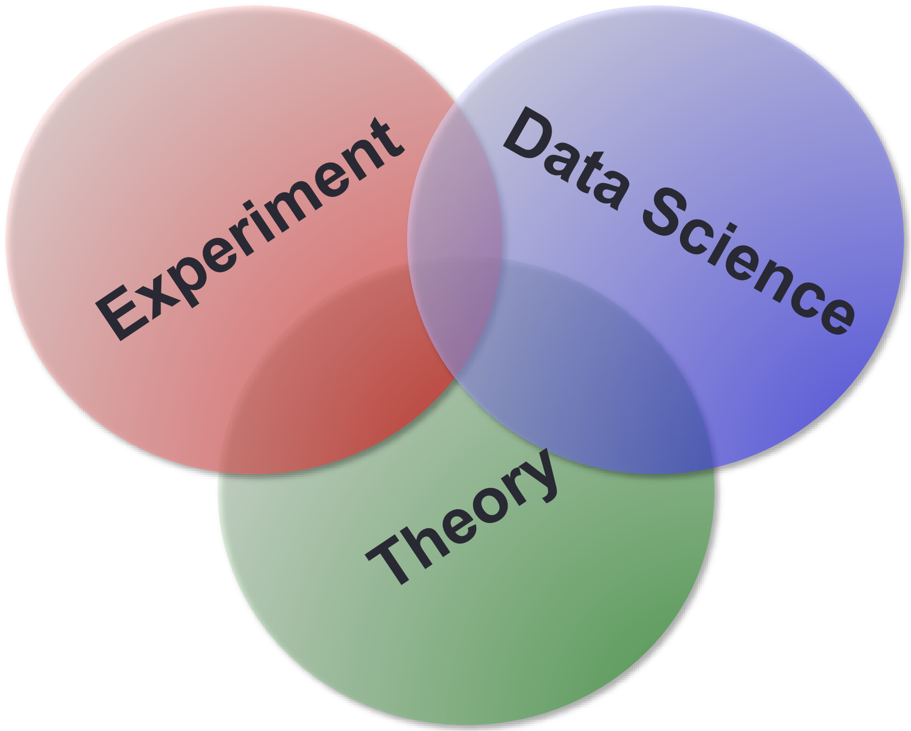
Because we are able to describe it as a GPD, OAM can be disentangled from data

A. Rajan et al, PRD (2016) arXiv:1601.06117
A. Rajan et al, arXiv:1709.05770

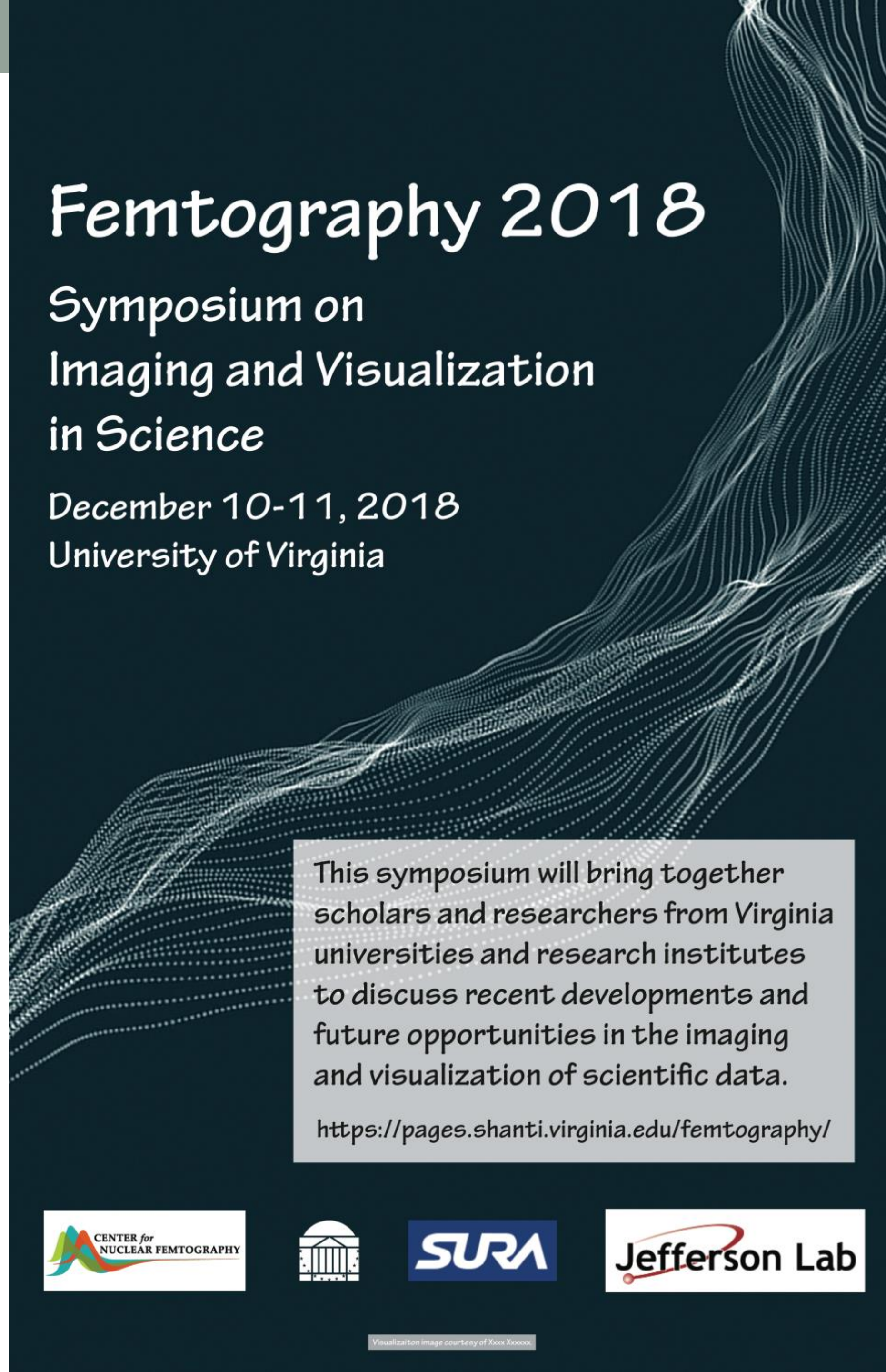
How do we detect all this?

- Need to handle unprecedentedly large and varied volumes of data from different sources
- The analyses requirements call for an evolution of the standard physics methodologies.
- Infusion of Data Science methods into the physics analysis workflow provides that evolution.
- **No centralized hub!**
- White paper with benchmarks is needed!

Venue: Center for Femtography at Jefferson Lab



Announcing Uva Symposium on Imaging and Visualization December 10-11, 2018


Femtography 2018
Symposium on
Imaging and Visualization
in Science
December 10-11, 2018
University of Virginia
This symposium will bring together scholars and researchers from Virginia universities and research institutes to discuss recent developments and future opportunities in the imaging and visualization of scientific data.
https://pages.shanti.virginia.edu/femtography/
CENTER for NUCLEAR FEMTOGRAPHY
SURA
Jefferson Lab