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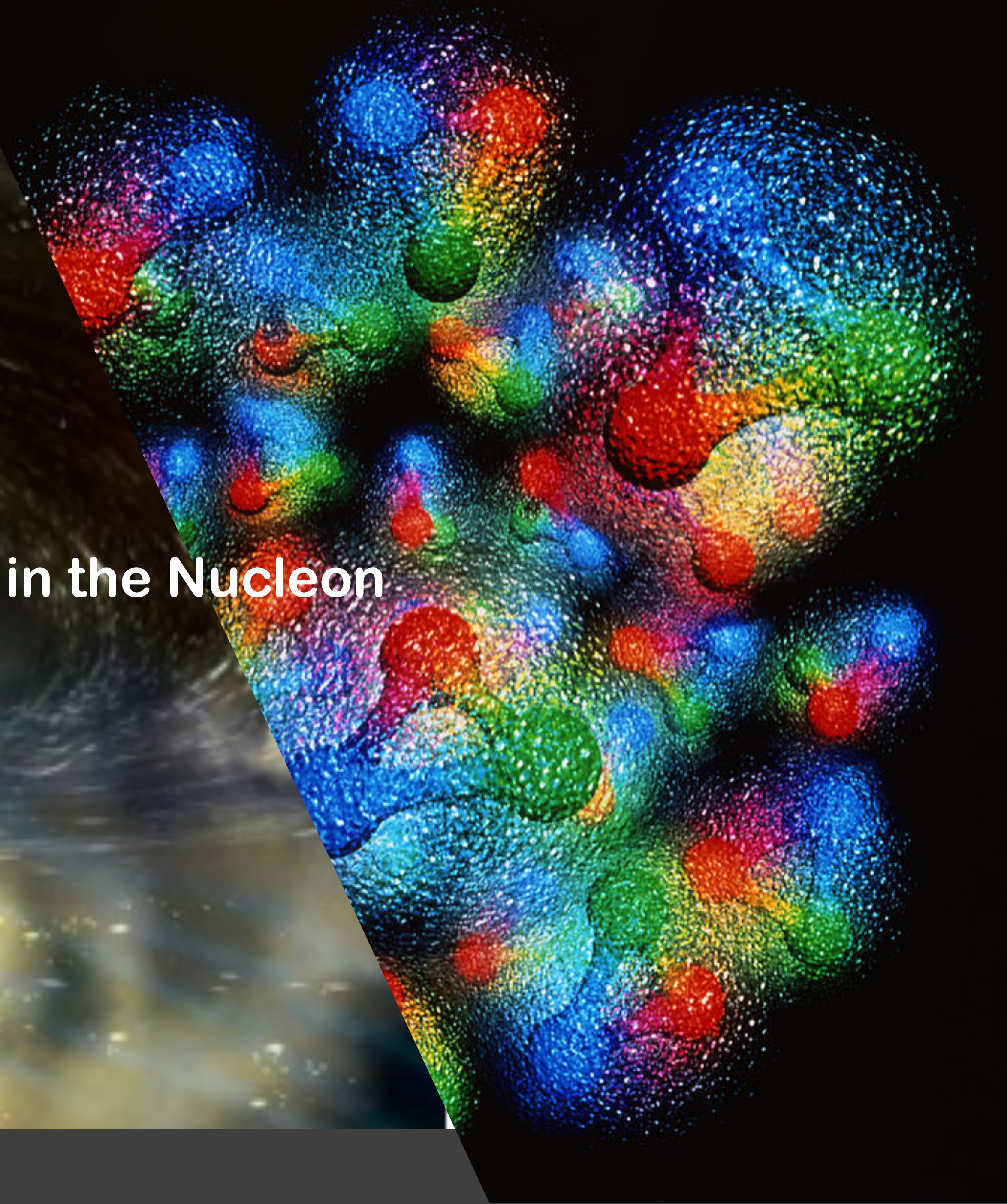
Capturing the Image of Quarks and Gluons in the Nucleon with the JLab to LHC Large Data Array

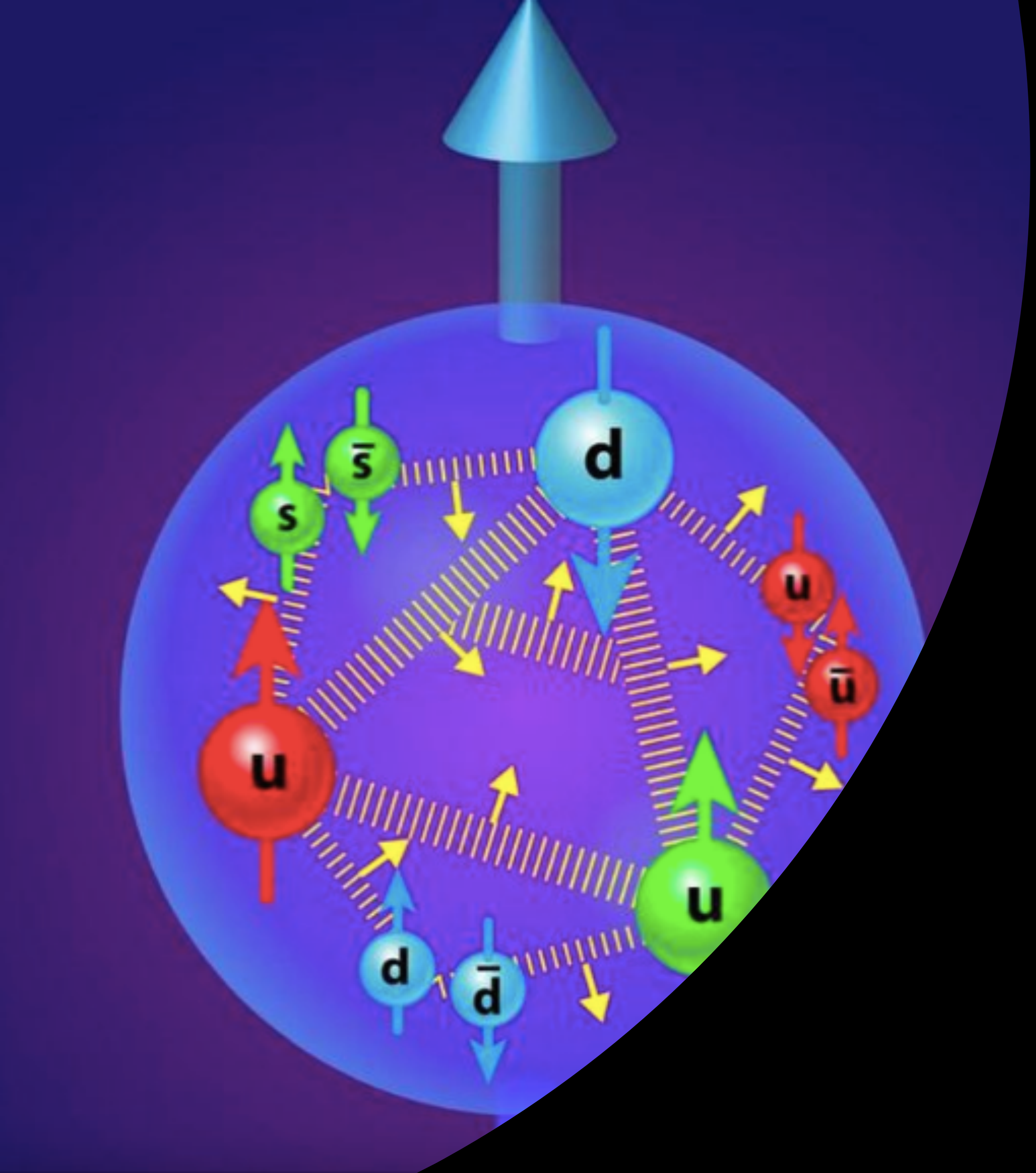
Snowmass EF06

August 19, 2020

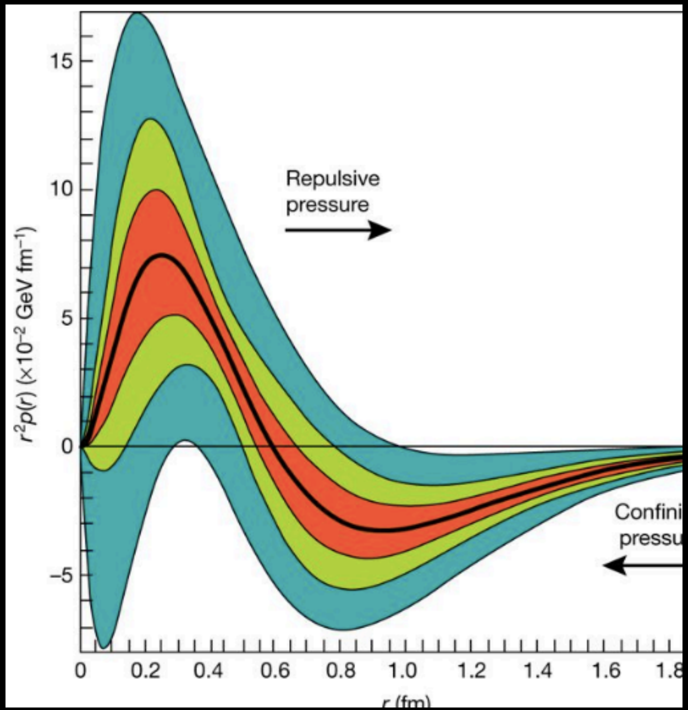


GPDs and Deeply Virtual Exclusive Experiments

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



How does the proton/neutron get its mass and spin and how do we test this dynamics?



“The average peak pressure near the center is about 10^{35} pascals, which exceeds the pressure estimated for the most densely packed known objects in the Universe, neutron stars”

Burkert, Elouadrhiri, Girod, Nature 557, 396 (2018)

How do we measure pressure and forces inside the proton?

The QCD Energy Momentum Tensor

Momentum density

Mass

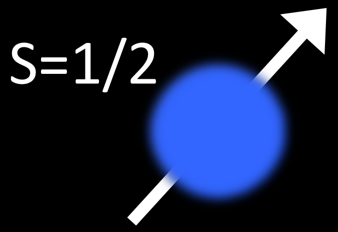
$$\begin{bmatrix} \frac{E^2+B^2}{2} & S_x & S_y & S_z \\ S_x & \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ S_y & \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ S_z & \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix}$$

Momentum density

Shear stress

Pressure

$\vec{S} = \vec{E} \times \vec{B}$



(X. Ji, 1997)

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

off-forward

q and g not separately conserved

$$P = \frac{p + p'}{2}$$
$$\Delta = p' - p = q - q'$$
$$t = (p - p')^2 = \Delta^2$$

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Direct calculation of EMT form factors

Donoghue et al. PLB529 (2002),

C. Corianò et al. PRD(2018),

A. Freese , QCD Evolution 2019

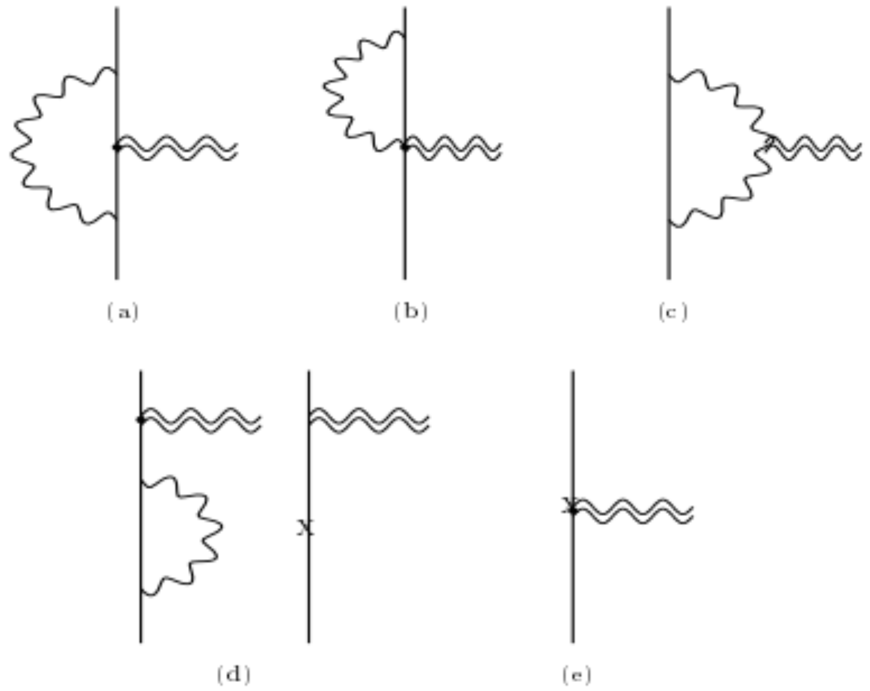
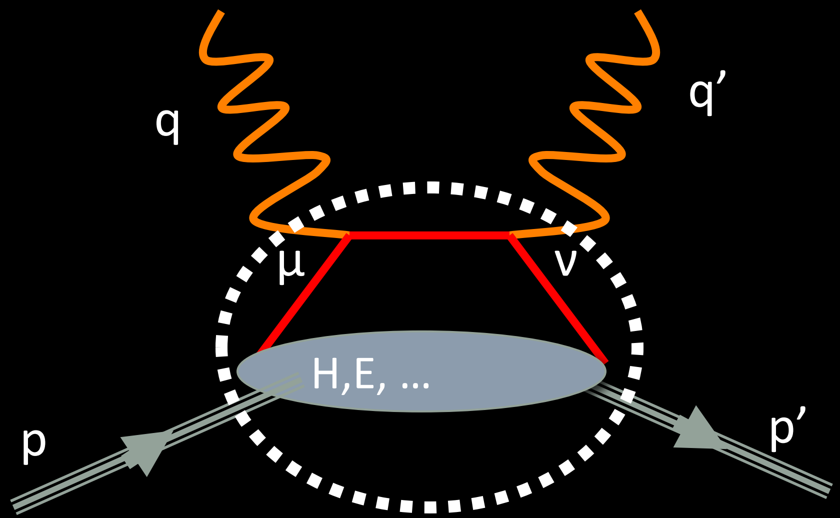
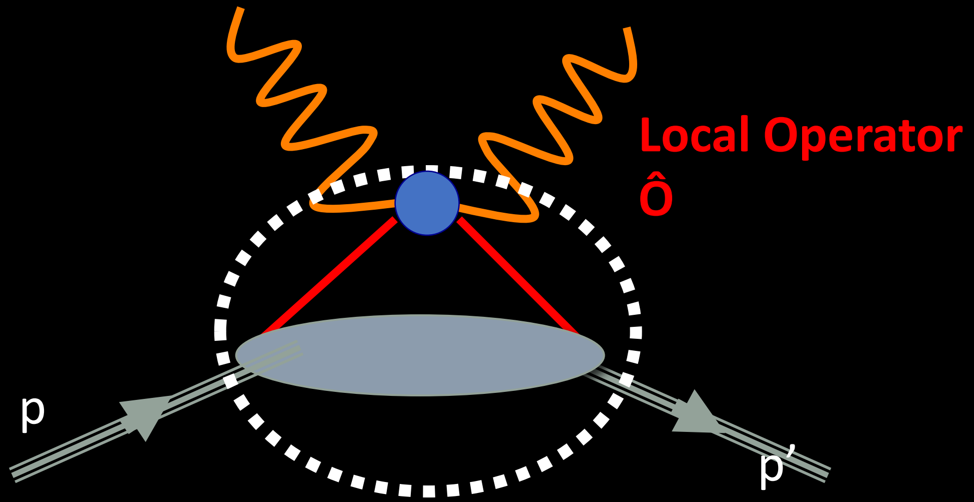


Figure 2: Feynman diagrams for spin 1/2 radiative corrections to $T_{\mu\nu}$.

EMT matrix elements from Generalized Parton Distributions Moments (X.Ji,1997)



GPD

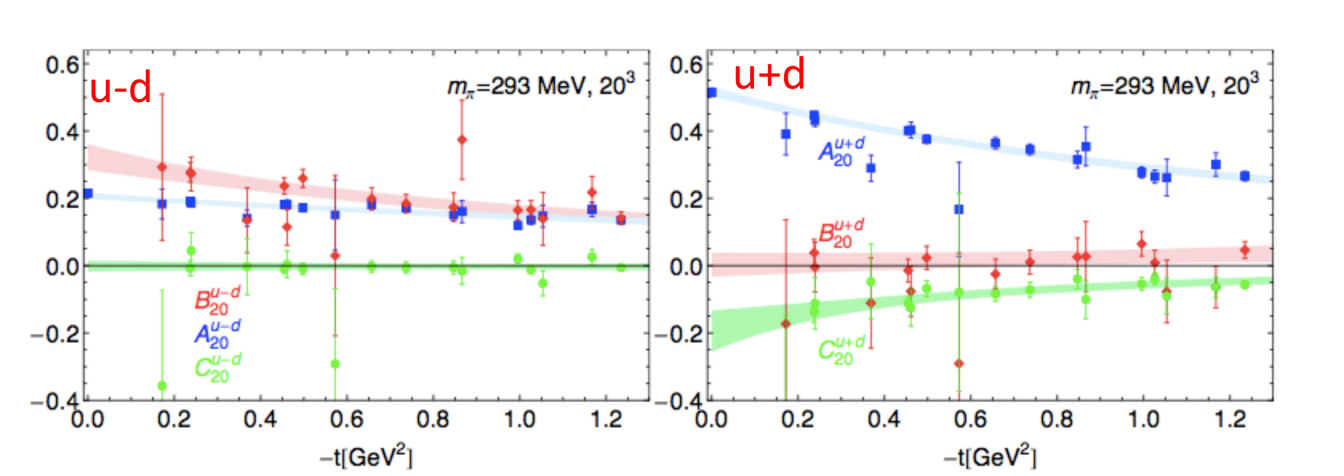


GPD Moments → EMT Form Factors

- Large momentum transfer $Q^2 >> M^2$ ➔ “deep”
- Large Invariant Mass $W^2 >> M^2$ ➔ equivalent to an “inelastic” process

Physical interpretation of EMT form factors

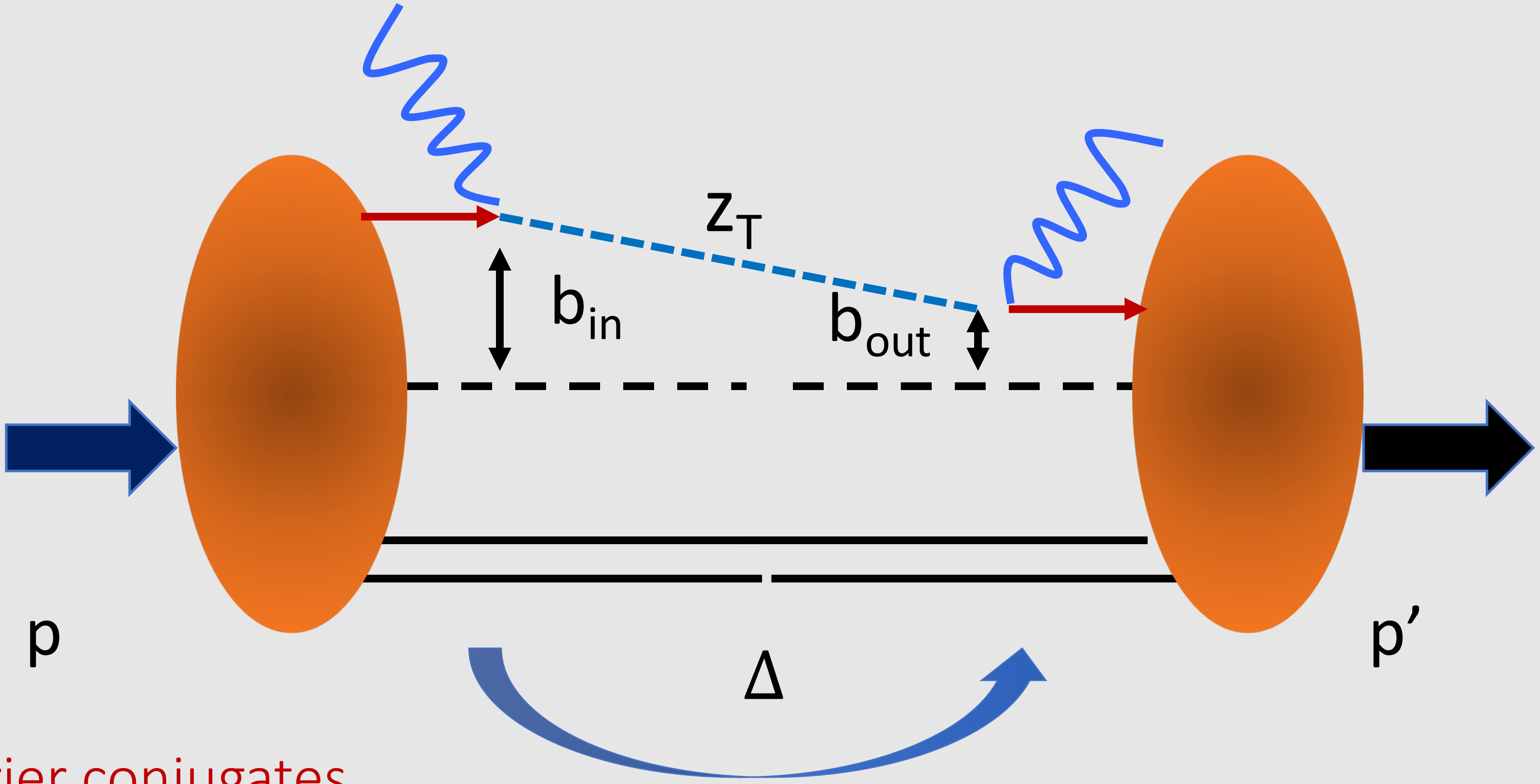
$$\frac{1}{2}\left(A_q + B_q\right) = J_q = \frac{1}{2}\left(A_{20} + B_{20}\right)$$	$$J_q^i = \int d^3r\epsilon^{ijk}r_jT_{0k}$$ Angular Momentum
$$A_q = \langle x_q \rangle = A_{20}$$	Momentum
$$C_q = \text{Internal Forces} = C_{20}$$	$$\int d^3r\left(r^ir^j - \delta^{ij}r^2\right)T_{ij}$$ Pressure



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

More recent results in review paper
Huey Wen Lin et al., arXiv 2006.08636

Accessing transverse distances through Fourier transformation



Two types of Fourier conjugates

$$b = \frac{b_{in} + b_{out}}{2}$$

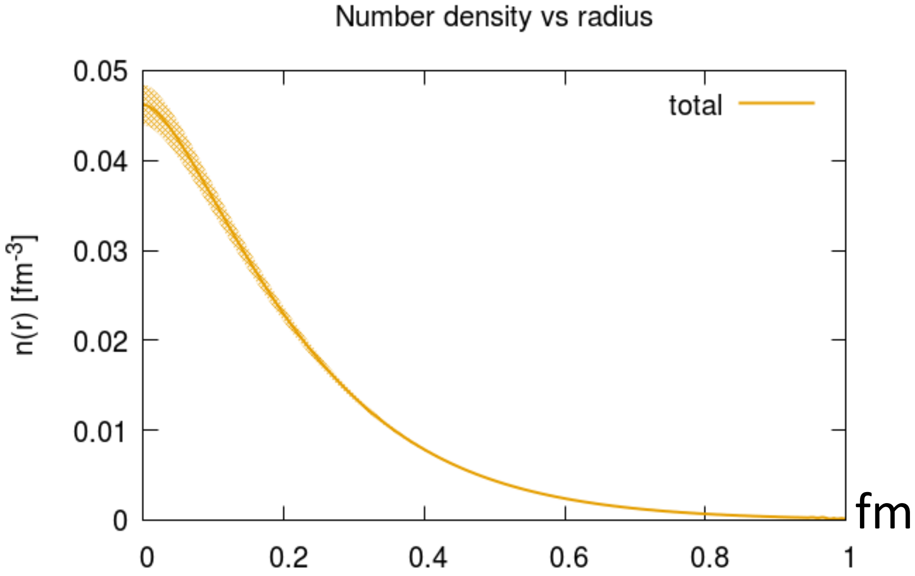
$$\Delta = p - p'$$

$$z_T = b_{in} - b_{out}$$

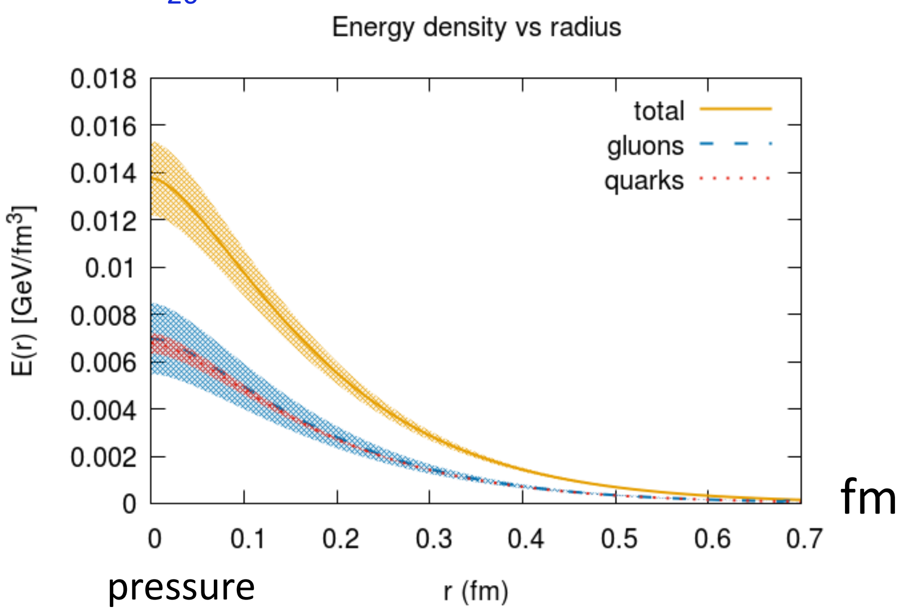
k_T

Related to Ioffe "time"

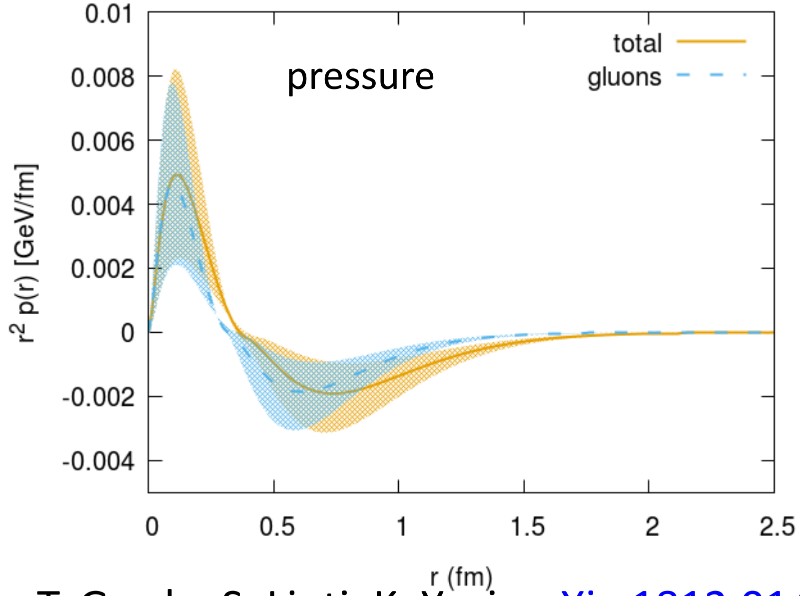
A_{10}



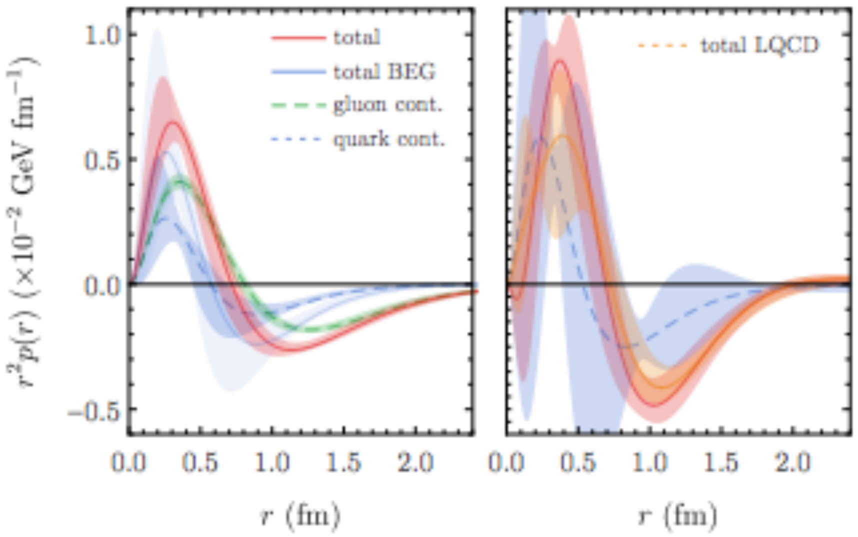
A_{20}



C_{20}



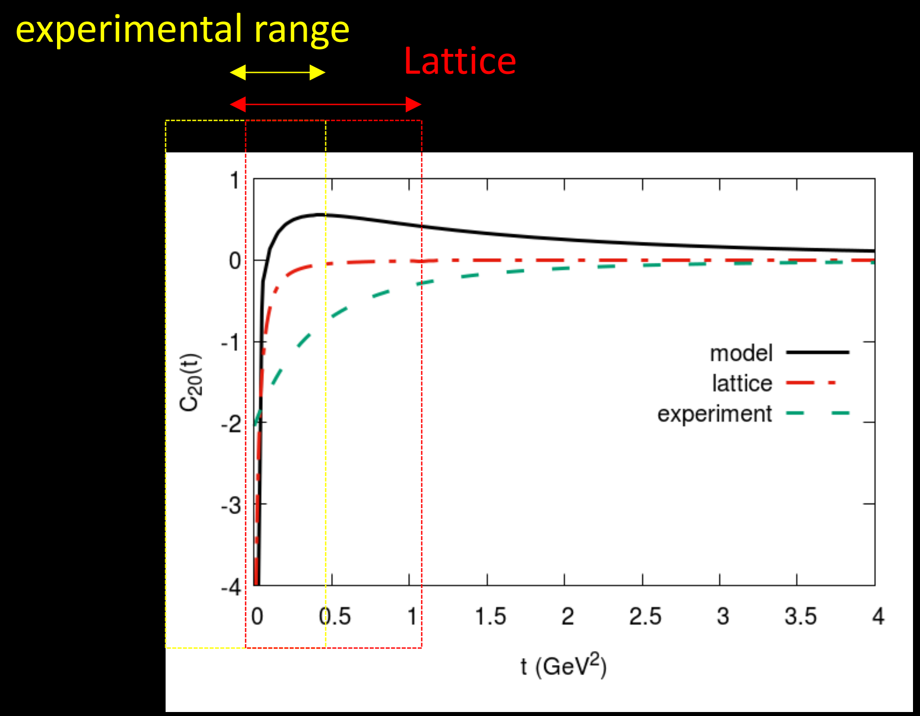
pressure



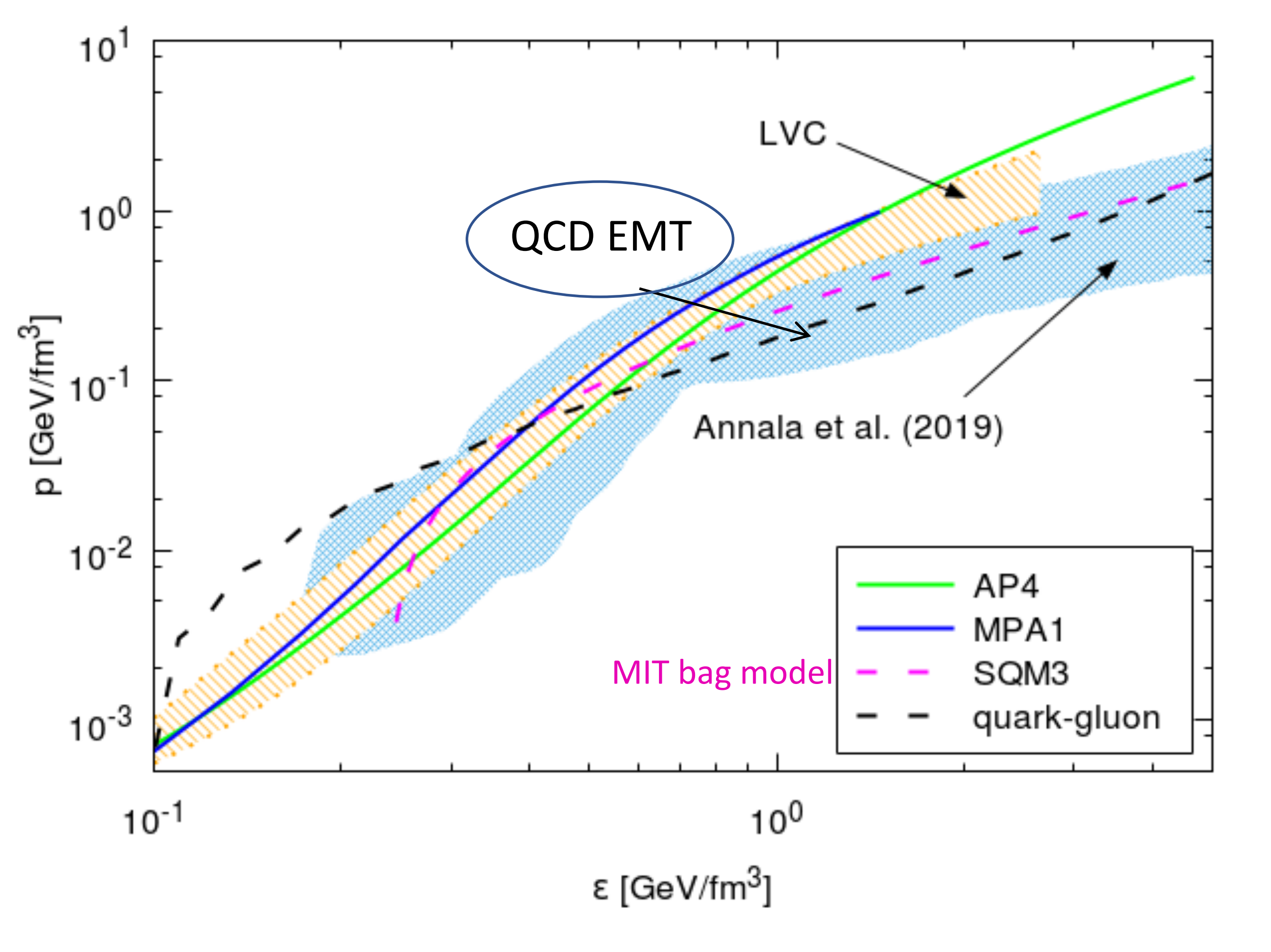
A. Rajan, T. Gorda, S. Liuti, K. Yagi, arXiv:1812.01479

Detmold, Shahanan, Phys.Rev.Lett. 122 (2019)

C_{20}


experimental range
Lattice
1
0
-1
-2
-3
-4
$C_{20}(t)$
0
0.5
1
1.5
2
2.5
3
3.5
4
t (GeV^2)
model
lattice
experiment

The Jlab extraction of the pressure measurement helps us understand the EoS of neutron stars

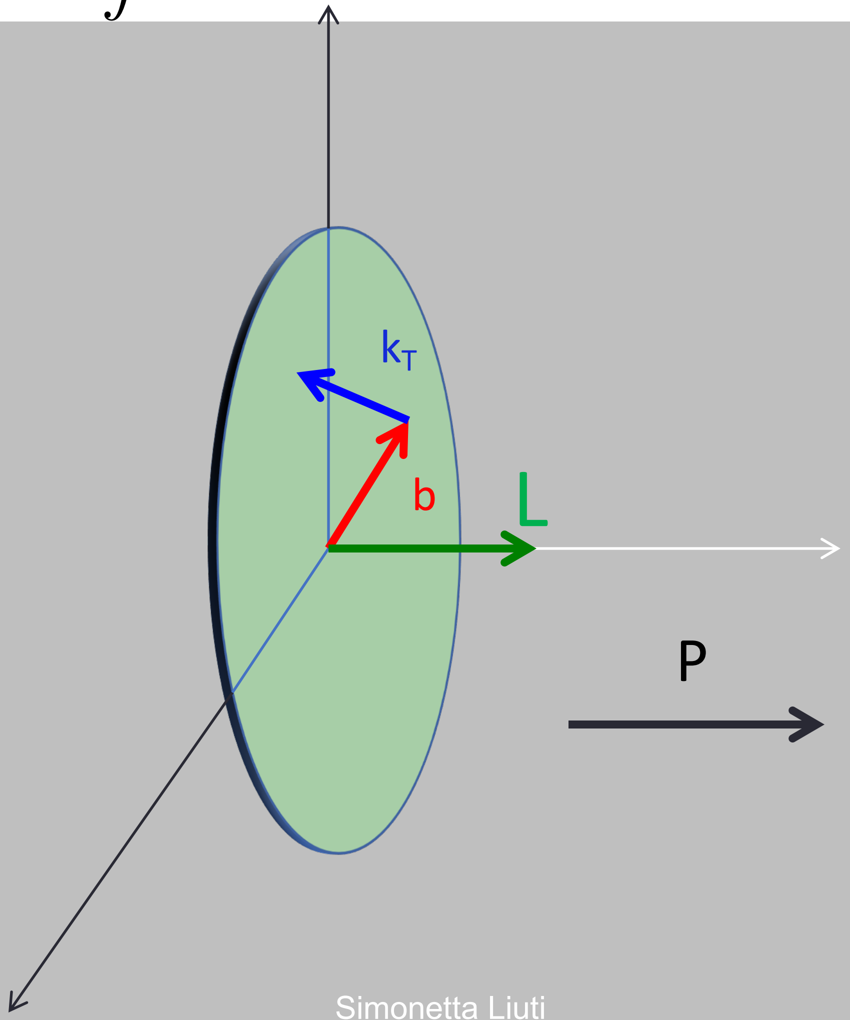


A. Rajan, T. Gorda, SL, K. Yagi, submitted for publication

Orbital angular momentum definition through Wigner Distributions

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

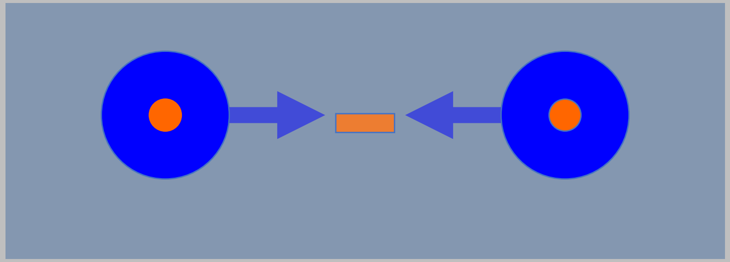
Hatta
Burkardt
Lorce, Pasquini,
Ji, Xiong, Yuan
Mukherjee,
Courtoy, Engelhardt, Rajan, SL



Angular Momentum Sum Rule

A. Rajan, A. Courtoy, M. Engelhardt, S.L., PRD (2016)
A. Rajan, M. Engelhardt, S.L., PRD (2018)

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



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

Twist – 3 GPD

$$\tilde{E}_{2T} = -\int_x^1 \frac{dy}{y}(H+E) + \left[\frac{\tilde{H}}{x} - \int_x^1 \frac{dy}{y^2}\tilde{H}\right] + \left[\frac{1}{x}\mathcal{M}_{F_{14}} - \int_x^1 \frac{dy}{y^2}\mathcal{M}_{F_{14}}\right]$$

New! From DVCS

DVCS (Ji,‘97)

Polarized ep
$g_1(x)$

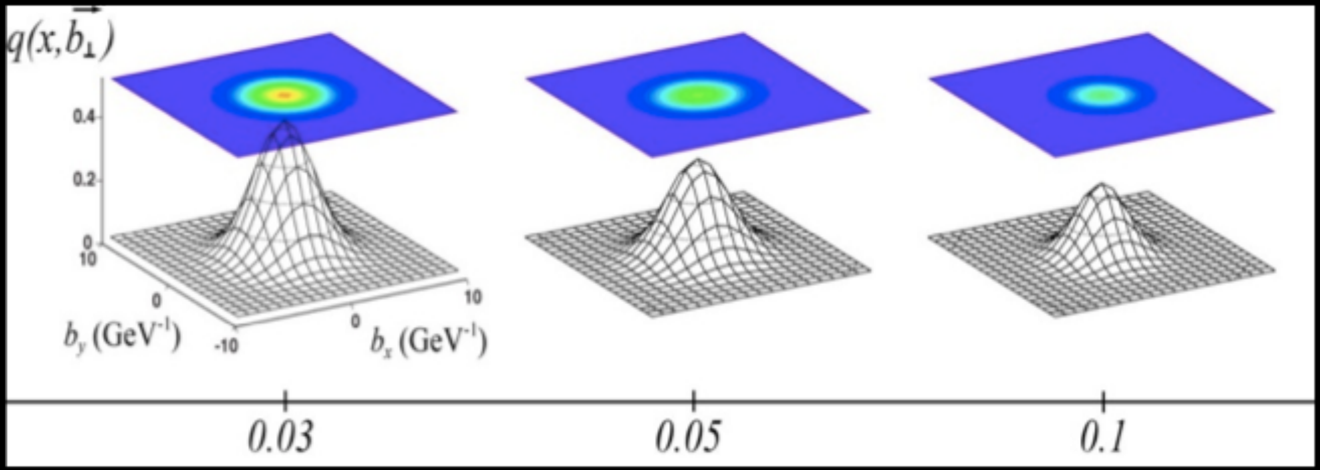
Burkardt
Hatta

Color force/gauge link

Integrated in x

L = J - S + 0

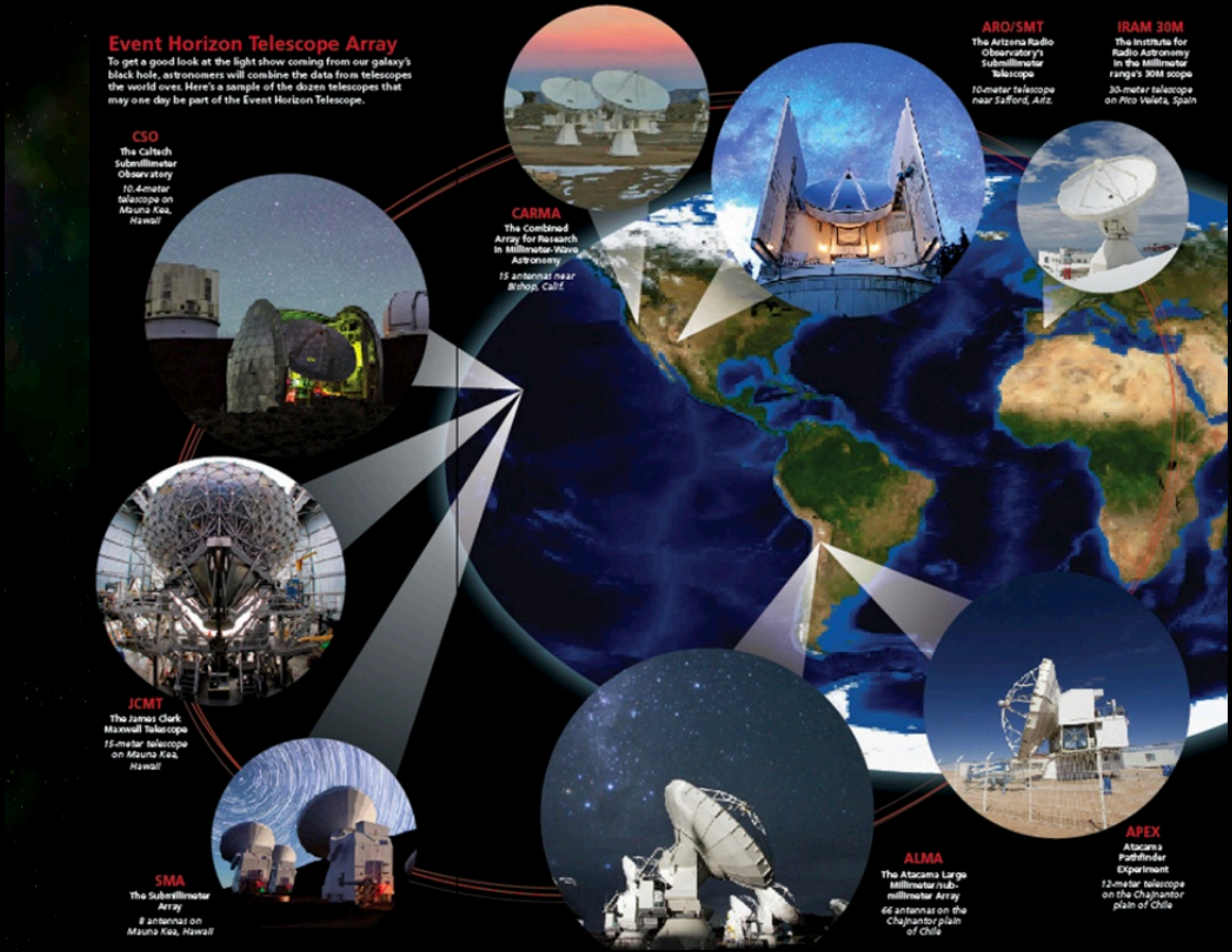
Measuring the Nucleon Gravitomagnetic Form Factors



graph from M. Defurne

A multi-step, multi-prong process that compares to imaging a black hole

Images courtesy of Kent Yagi, UVA



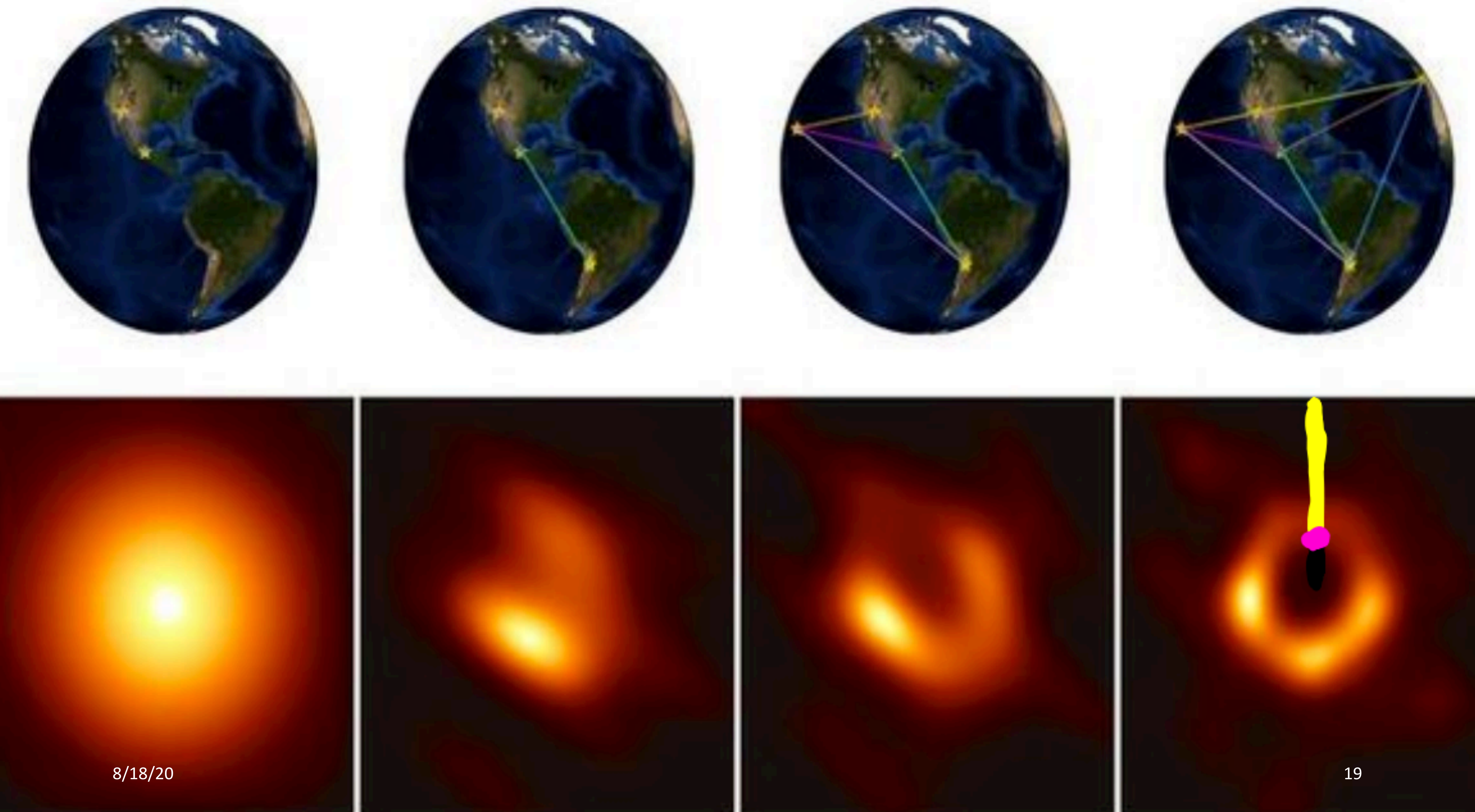
Event Horizon Telescope (EHT)

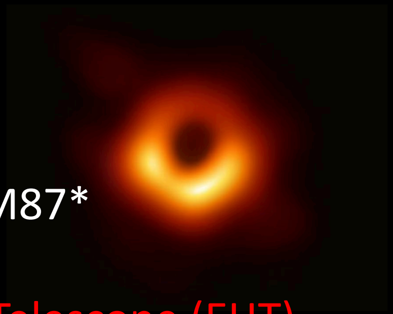
In a nutshell…..

$$Telescope\ size = \frac{wavelength}{dimension} \Rightarrow Size\ of\ Earth = \frac{wavelength}{40\ \mu\ arcsec} \Rightarrow wavelength = 1mm$$

- Detector: a network of telescopes (EHT)
- Imaging technique: Very Long Baseline Interferometry (VLBI)
- Computational processing/simulation/validation of the derived image

S. Doeleman et al., APJL Focus issue, 2019
https://iopscience.iop.org/journal/2041-8205/page/Focus_on_EHT





Event Horizon Telescope (EHT)

- ✓ Main idea: Very Long Baseline Interferometry (VLBI), an array of smaller telescopes synchronized to focus on the same object and act as a giant telescope
- ✓ Precision: large aperture (many telescopes widely spaced) and high frequency radio waves
- ✓ Data Management: 5 petabytes physically transported to a central location. Data from all eight sites were combined to create a composite set of images, revealing for the first time M87*'s event horizon.

It took nearly two decades to achieve !

Jefferson Lab@12 GeV

- ✓ Main idea: use DVCS, TCS, DVMP… and related processes as probes
- ✓ Precision: high luminosity in a wide kinematic range is key!
- ✓ Data Management: unprecedented amount of data need new AI based techniques to handle the image making

In the course of 10 years, first proton image!

Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
Hadron spectra as probes of QCD	0	2	1	3	0	**6**
Transverse structure of the hadrons	6	3	3	1	0	**13**
Longitudinal structure of the hadrons	2	3	7	0	0	**12**
3D structure of the hadrons	5	9	6	0	0	**20**
Hadrons and cold nuclear matter	8	5	7	0	1	**21**
Low-energy tests of the Standard Model and Fundamental Symmetries	3	1	0	1	2	**7**
Total	**24**	**23**	**24**	**5**	**3**	**79**

Center for Femtography (CNF)

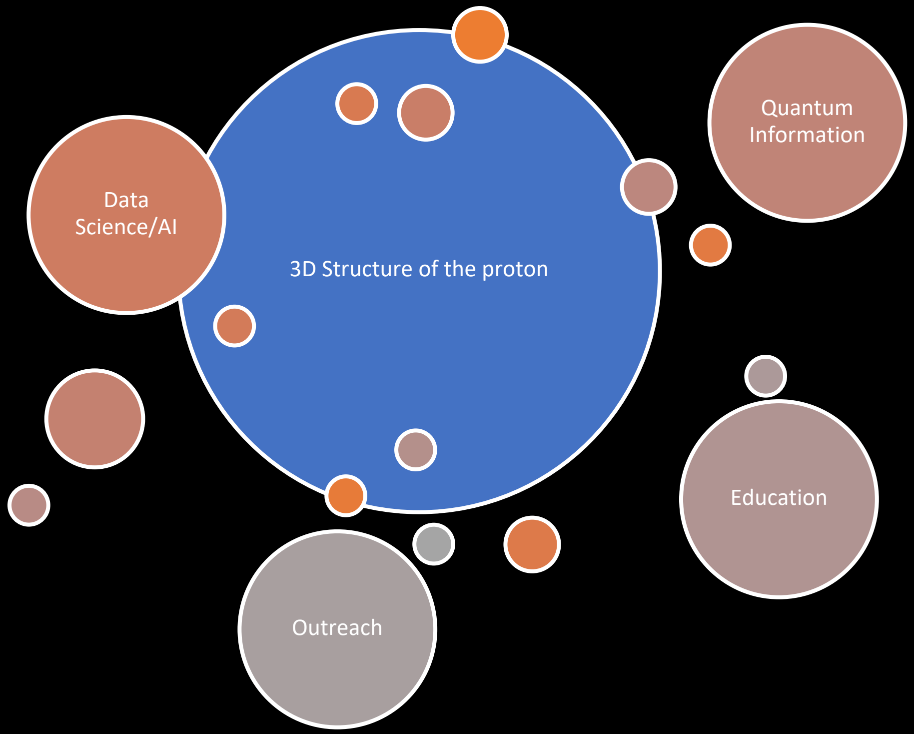
CENTER *for*
NUCLEAR FEMTOGRAPHY

SURA

- December 2018 -- Founded at UVA meeting
- Summer 2019 -- Pilot projects started funded by SURA
- Summer 2020 -- Xiangdong Ji is appointed director

CNF Talks series starts on September 2nd and will continue every Wednesday at 11am, please join our discussions!
(Newly designed website will have all information)

sl4y@virginia.edu



- CNF has funded multiple projects on Femtography
- Covering different areas
  - Experimental data
  - ML & AI
  - Inverse problems
  - Lattice calculations
  - …
- Total funding exceeding $0.5M per year
- Now it is time to organize different efforts into a larger collaboration, involving people outside VA.

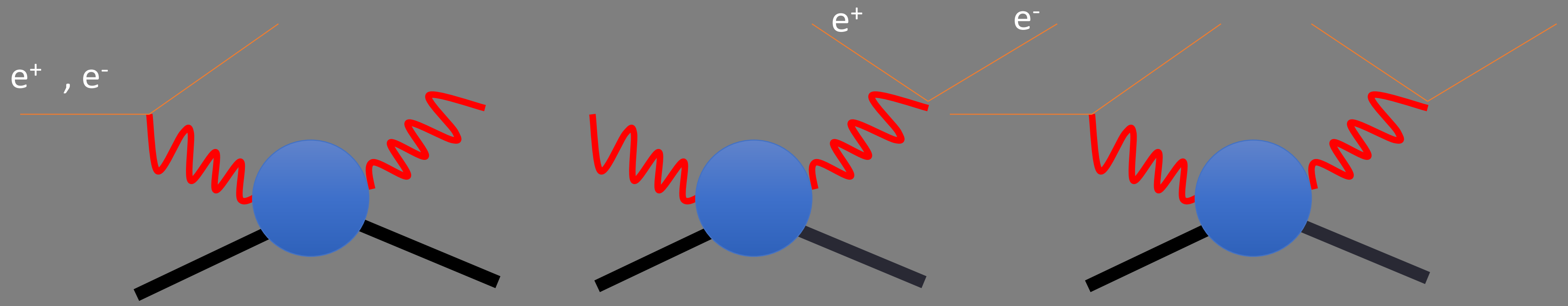
Courtesy of X. Ji

Coordinated directions

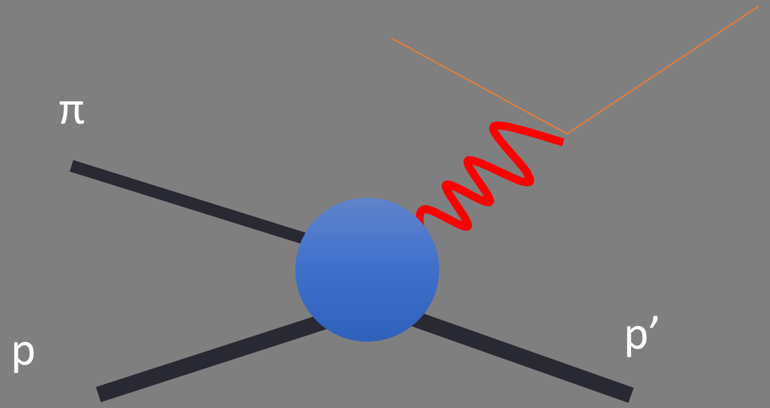
1. GPD related experimental data base (+form factors)
2. GPD models and parametrizations
3. QCD scale evolution to NLO or NNLO
4. Lattice QCD calculations on GPDs
5. GPD fitting (inverse problem), ML and AI technique.
6. GPD data base, 3D Femtography, outreach.

Courtesy of X. Ji

Harnessing/coordinating information from all channels

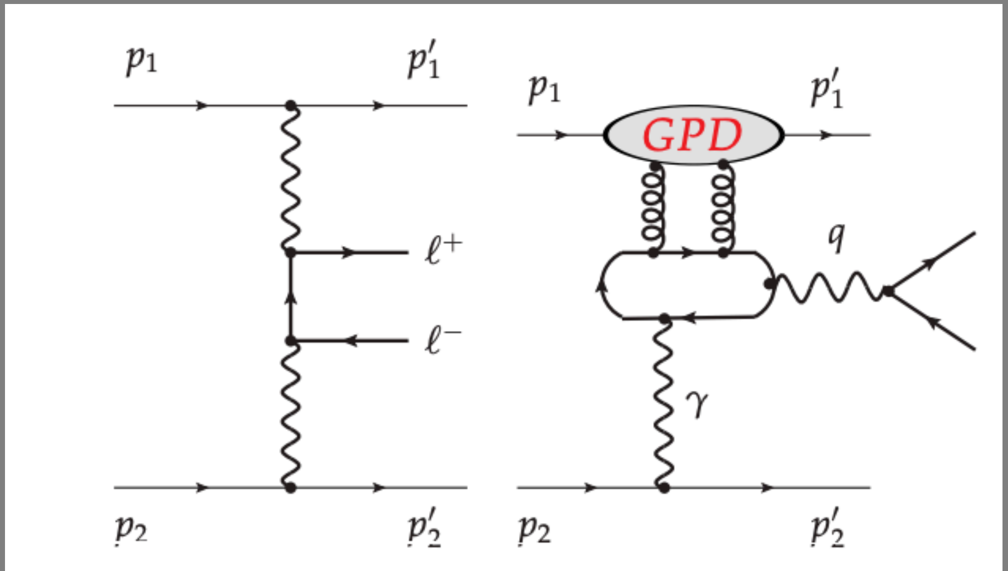


DVCS, DVMP   TCS   DDVCS

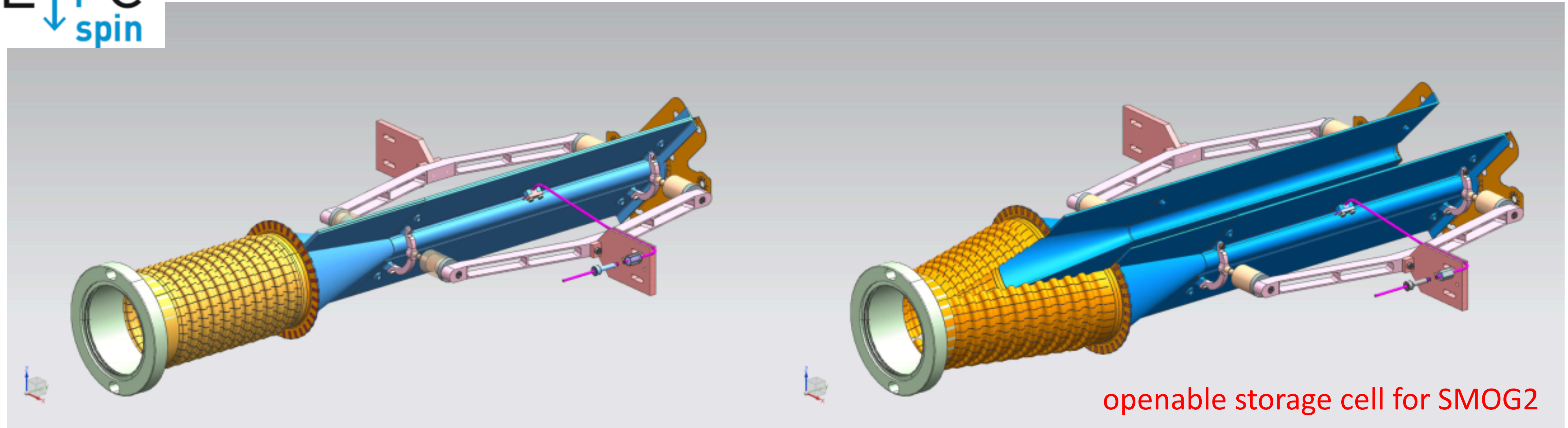


Exclusive pion induced DY (EDY)

Sawada et al., PRD93 (2016)



(a) BH (b) TCS with gluon GPDs



Unpolarized

LHCb experiment pioneered fixed-target physics with LHC beams, thanks to the SMOG internal gas target

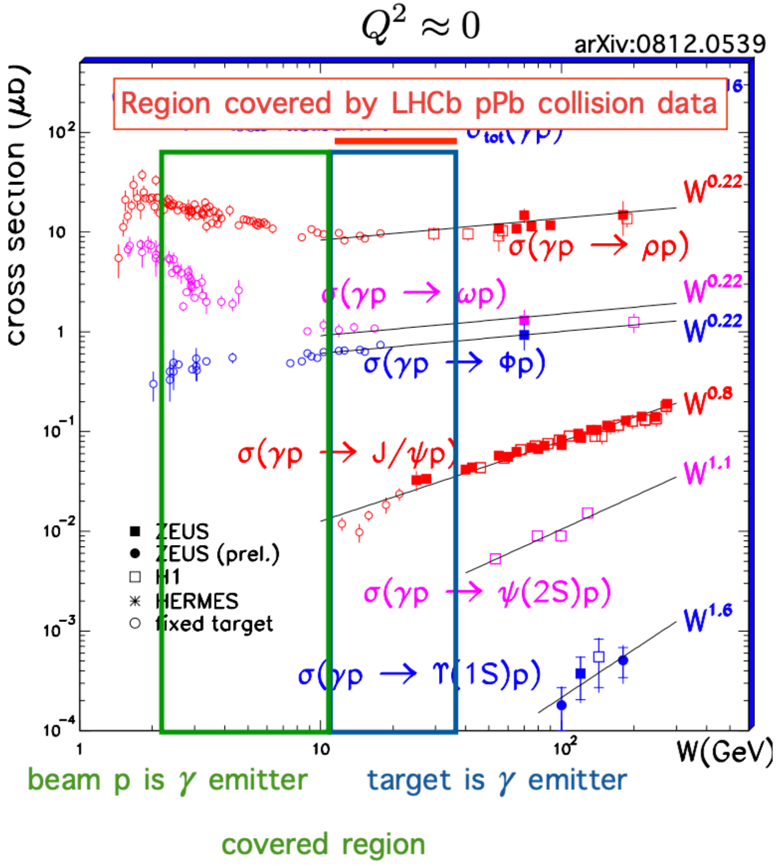
Polarized

The LHCSpin Project

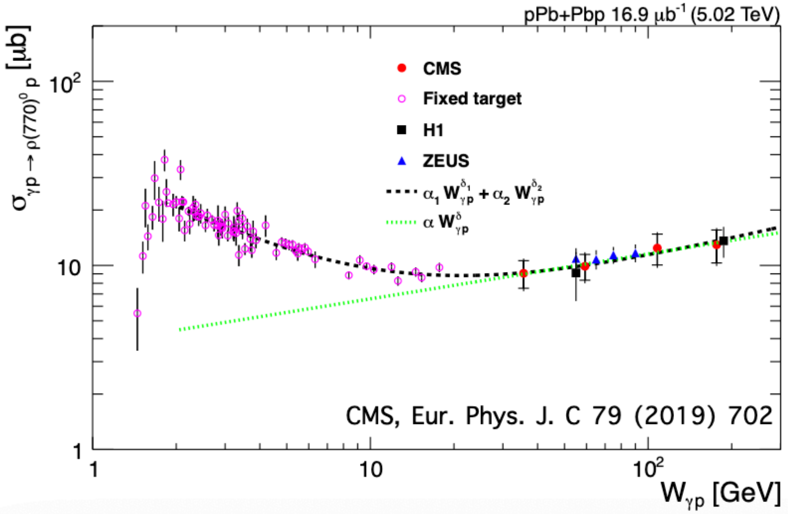
C.A. Aidala, A. Bacchetta, M. Boglione, G. Bozzi, V. Carassiti, M. Chiosso, R. Cimino, G. Ciullo, M. Contalbrigo, U. D'Alesio, P. Di Nezza, R. Engels, K. Grigoryev, D. Keller, P. Lenisa, S. Liuti, A. Metz, P.J. Mulders, F. Murgia, A. Nass, D. Panzieri, L.L. Pappalardo, B. Pasquini, C. Pisano, M. Radici, F. Rathmann, D. Reggiani, M. Schlegel, S. Scopetta, E. Steffens, A. Vasilyev

Feasibility study (unpolarized target)

Exclusive ρ^0 production

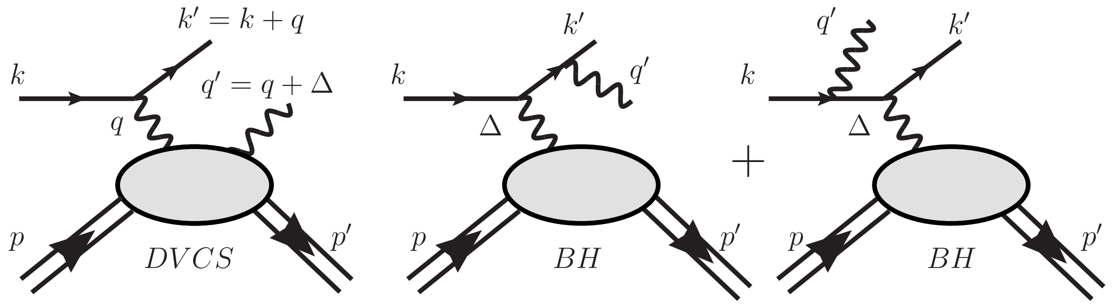


- Measure nuclear ratios
- Compare to pPb collision data
- Theorists contacted for solid theory interpretation
- Measured recently by CMS



courtesy P. Di Nezza

We need a robust framework for the cross section, where kinematic limits are under control (beyond "harmonics" model)

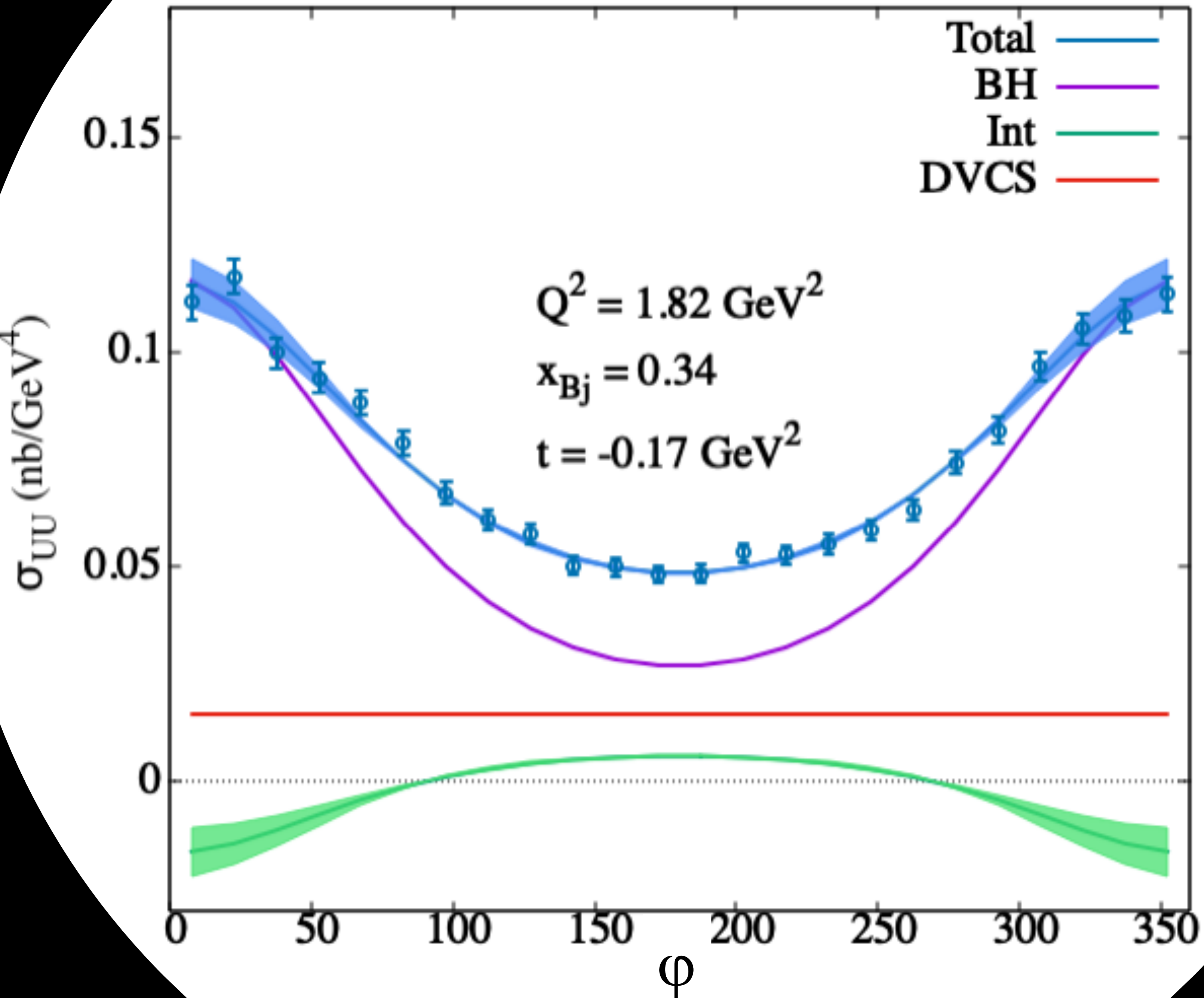


B. Kriesten et al, *Phys.Rev. D* 101 (2020)

B. Kriesten and S. Liuti, arXiv 2004.08890

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

$$T(k,p,k',q',p') = T_{DVCS}(k,p,k',q',p') + T_{BH}(k,p,k',q',p'),$$



Total
BH
Int
DVCS
Q² = 1.82 GeV²
x_Bj = 0.34
t = -0.17 GeV²
σ_UU (nb/GeV⁴)
0.15
0.1
0.05
0
0
50
100
150
200
250
300
350
φ

DVCS

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

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

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

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

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

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

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

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

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

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

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

twist two GPDs

twist three GPDs

U

L

T

BH

$$\frac{d^5\sigma^{BH}_{unpol}}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} \equiv \frac{\Gamma}{t}F^{BH}_{UU} = \frac{\Gamma}{t}\left[A(y,x_{Bj},t,Q^2,\phi)\left(F_1^2+\tau F_2^2\right)+B(y,x_{Bj},t,Q^2,\phi)\tau G_M^2(t)\right]$$

$$A = \frac{16\,M^2}{t(k\,q')(k'\,q')}\left[4\tau\left((k\,P)^2+(k'\,P)^2\right)-(\tau+1)\left((k\,\Delta)^2+(k'\,\Delta)^2\right)\right]$$

$$B = \frac{32\,M^2}{t(k\,q')(k'\,q')}\left[(k\,\Delta)^2+(k'\,\Delta)^2\right],$$

…compared to BKM, NPB (2001)

$$|\mathcal{T}_{\mathrm{BH}}|^2 = \frac{e^6}{x_{\mathrm{B}}^2 y^2 (1+\epsilon^2)^2 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \times \left\{ c_0^{\mathrm{BH}} + \sum_{n=1}^{2} c_n^{\mathrm{BH}} \cos(n\phi) + s_1^{\mathrm{BH}} \sin(\phi) \right\},$$

$$\begin{aligned} c_{0,\mathrm{unp}}^{\mathrm{BH}} = {} & 8K^2 \left\{ (2+3\epsilon^2) \frac{Q^2}{\Delta^2} \left(F_1^2 - \frac{\Delta^2}{4M^2} F_2^2 \right) + 2x_{\mathrm{B}}^2 (F_1+F_2)^2 \right\} \\ & + (2-y)^2 \left\{ (2+\epsilon^2) \left[\frac{4x_{\mathrm{B}}^2 M^2}{\Delta^2} \left(1 + \frac{\Delta^2}{Q^2} \right)^2 \right. \right. \\ & \left. + 4(1-x_{\mathrm{B}}) \left(1 + x_{\mathrm{B}} \frac{\Delta^2}{Q^2} \right) \right] \left(F_1^2 - \frac{\Delta^2}{4M^2} F_2^2 \right) \\ & + 4x_{\mathrm{B}}^2 \left[x_{\mathrm{B}} + \left(1 - x_{\mathrm{B}} + \frac{\epsilon^2}{2} \right) \left(1 - \frac{\Delta^2}{Q^2} \right)^2 \right. \\ & \left. \left. - x_{\mathrm{B}}(1-2x_{\mathrm{B}}) \frac{\Delta^4}{Q^4} \right] (F_1+F_2)^2 \right\} \\ & + 8(1+\epsilon^2) \left(1 - y - \frac{\epsilon^2 y^2}{4} \right) \\ & \times \left\{ 2\epsilon^2 \left(1 - \frac{\Delta^2}{4M^2} \right) \left(F_1^2 - \frac{\Delta^2}{4M^2} F_2^2 \right) - x_{\mathrm{B}}^2 \left(1 - \frac{\Delta^2}{Q^2} \right)^2 (F_1+F_2)^2 \right\}, \end{aligned}$$
(

$$\begin{aligned} c_{1,\mathrm{unp}}^{\mathrm{BH}} = {} & 8K(2-y) \left\{ \left(\frac{4x_{\mathrm{B}}^2 M^2}{\Delta^2} - 2x_{\mathrm{B}} - \epsilon^2 \right) \left(F_1^2 - \frac{\Delta^2}{4M^2} F_2^2 \right) \right. \\ & \left. + 2x_{\mathrm{B}}^2 \left(1 - (1-2x_{\mathrm{B}}) \frac{\Delta^2}{Q^2} \right) (F_1+F_2)^2 \right\}, \end{aligned}$$
(

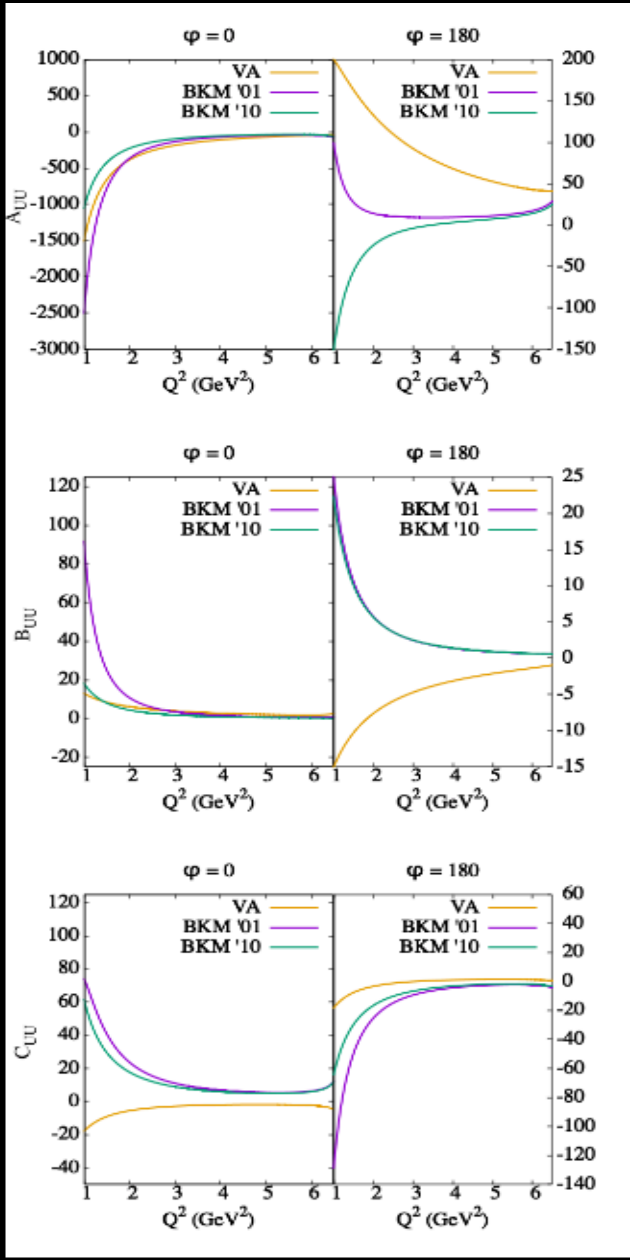
$$c_{2,\mathrm{unp}}^{\mathrm{BH}} = 8x_{\mathrm{B}}^2 K^2 \left\{ \frac{4M^2}{\Delta^2} \left(F_1^2 - \frac{\Delta^2}{4M^2} F_2^2 \right) + 2(F_1+F_2)^2 \right\}.$$
(

BH-DVCS interference

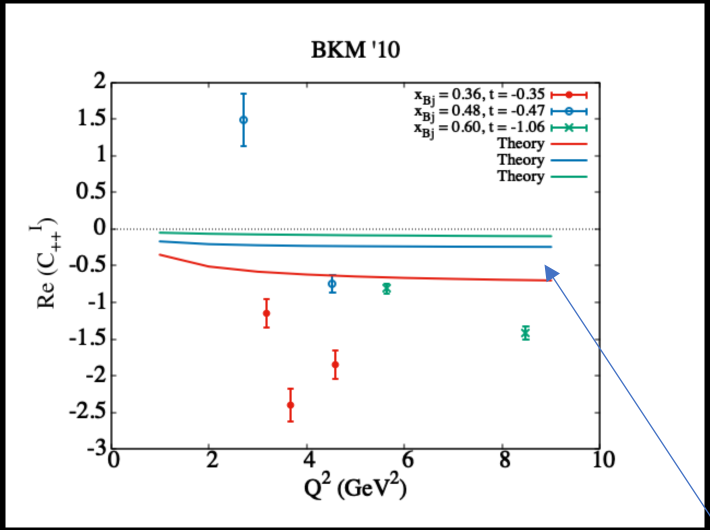
$$F_{UU}^{\mathcal{I}} = F_{UU}^{\mathcal{I},tw2} + \frac{K}{\sqrt{Q^2}} F_{UU}^{\mathcal{I},tw3}$$

$$F_{UU}^{\mathcal{I},tw2} = A_{UU}^{\mathcal{I}} \Re e \left(F_1 \mathcal{H} + \tau F_2 \mathcal{E}\right) + B_{UU}^{\mathcal{I}} G_M \Re e \left(\mathcal{H} + \mathcal{E}\right) + C_{UU}^{\mathcal{I}} G_M \Re e \widetilde{\mathcal{H}}$$

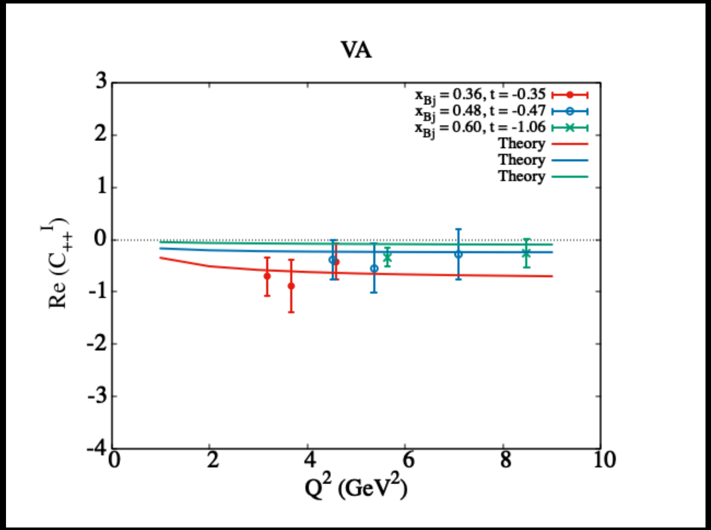
Impact on Q^2 dependence



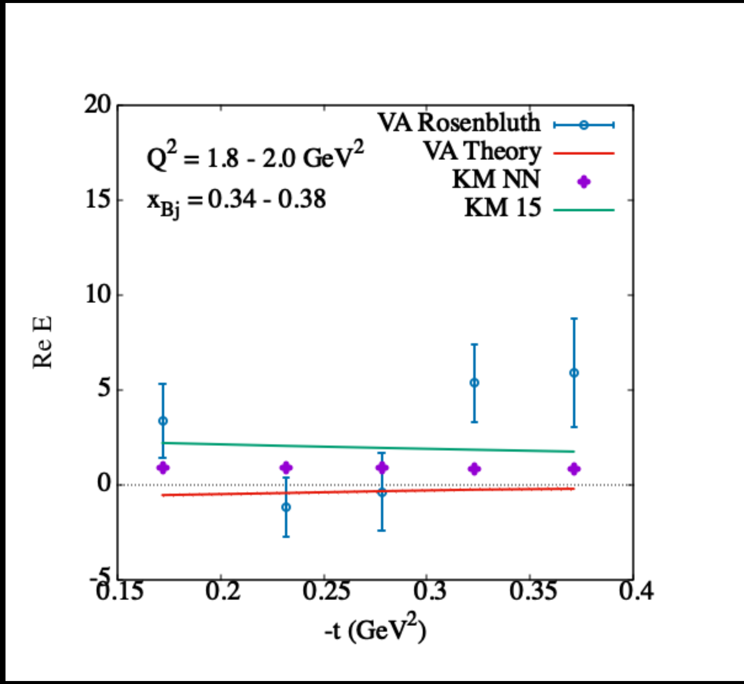
Re H

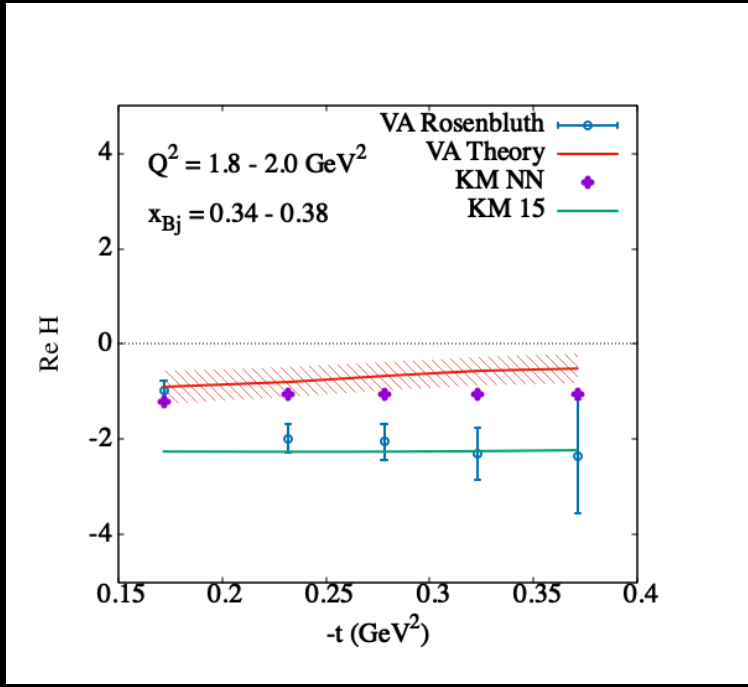


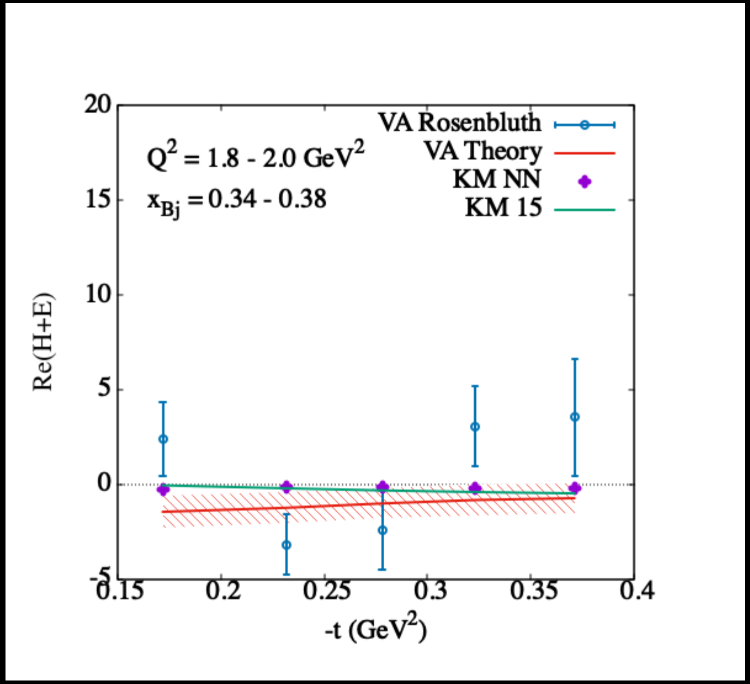
Re H

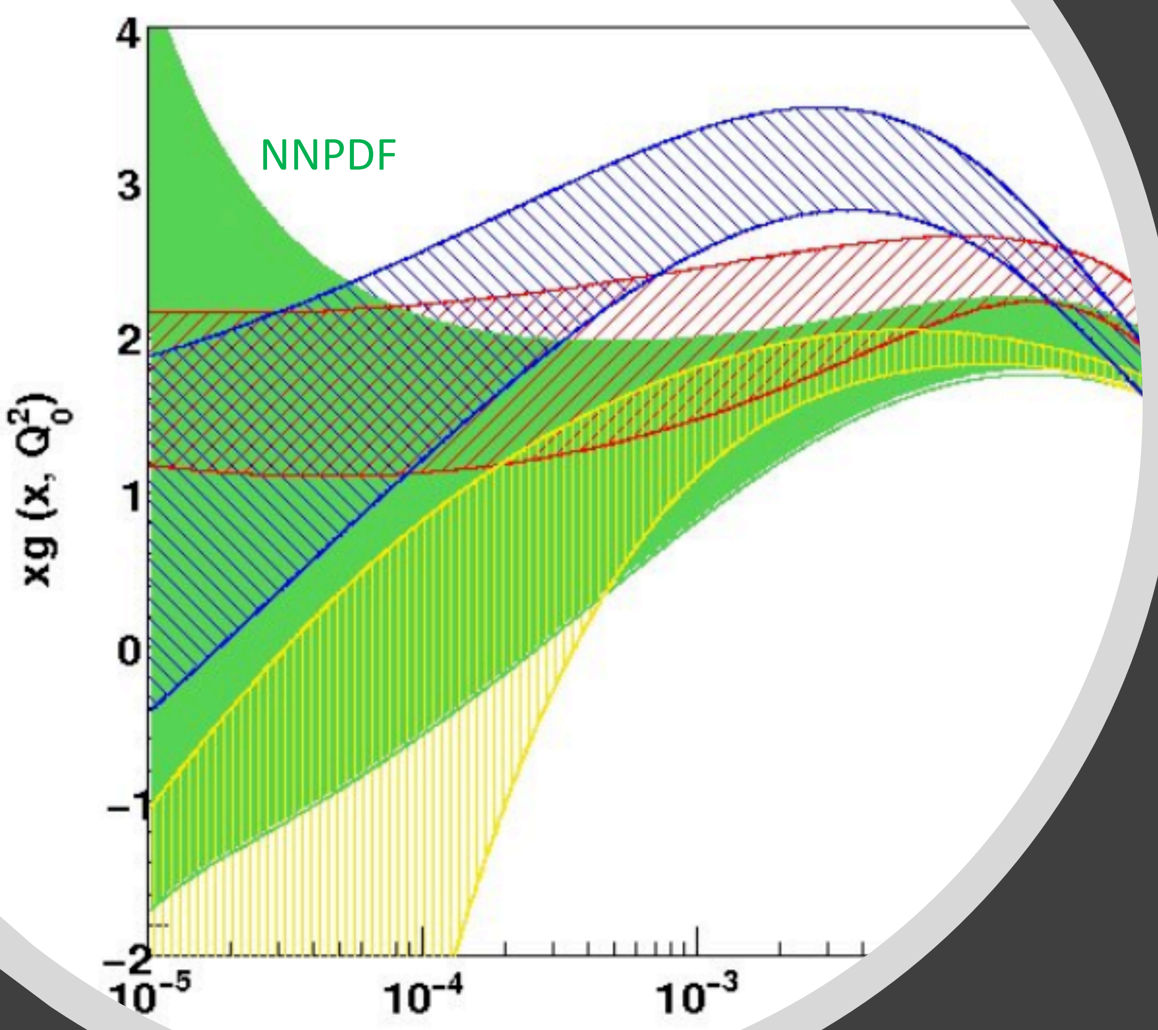


pQCD Evolution


VA Rosenbluth
VA Theory
KM NN
KM 15
$Q^2 = 1.8 - 2.0\ GeV^2$
$x_{Bj} = 0.34 - 0.38$
Re E
-t (GeV^2)


VA Rosenbluth
VA Theory
KM NN
KM 15
$Q^2 = 1.8 - 2.0\ GeV^2$
$x_{Bj} = 0.34 - 0.38$
Re H
-t (GeV^2)


VA Rosenbluth
VA Theory
KM NN
KM 15
$Q^2 = 1.8 - 2.0\ GeV^2$
$x_{Bj} = 0.34 - 0.38$
Re(H+E)
-t (GeV^2)



Extracting information from data with standard methods is painstakingly slow: can we use ML/AI?

Brandon Kriesten (UVA), Jake Grigsby (UVA), Pete Alonzi (DS, UVA), Matthias Burkardt (NMSU), Joshua Hoskins (Mary Washington U.), SL

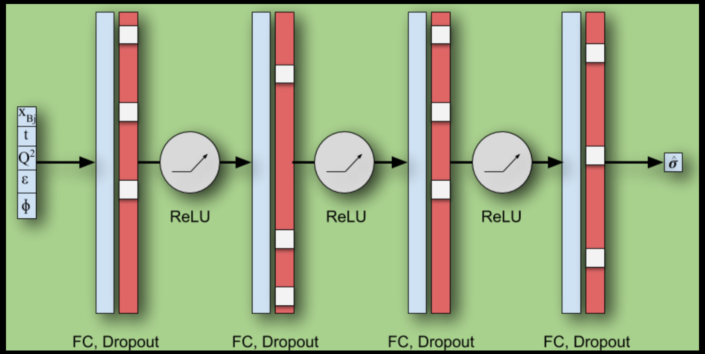
UVA Strategy: supervised learning algorithm augmented by unsupervised (UMAP) method

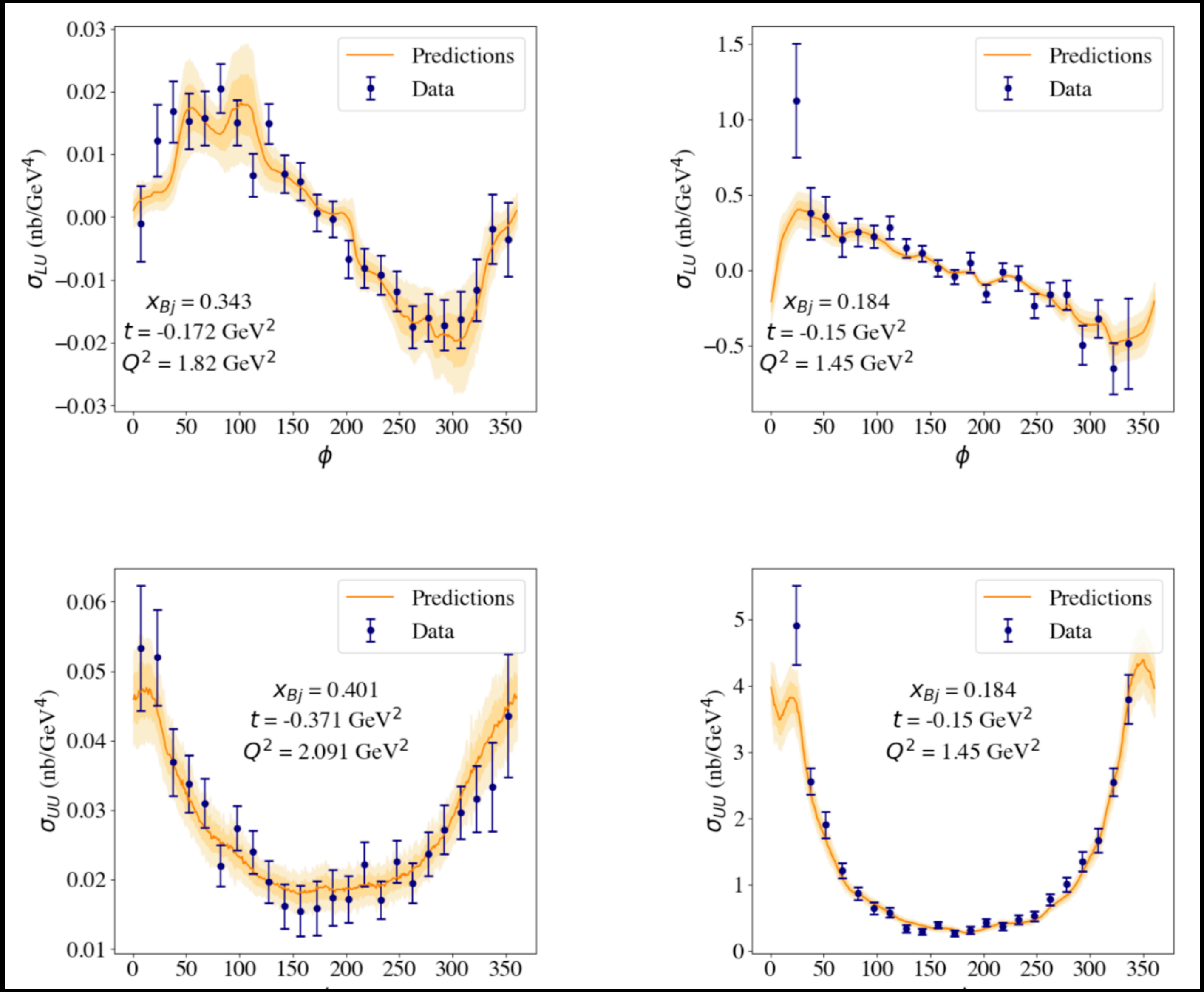
- Using Deep Neural Networks for regression

  - The model is a multilayered perceptron (MLP) with 4 hidden layers, each followed by a rectified inear unit (ReLU) activation function

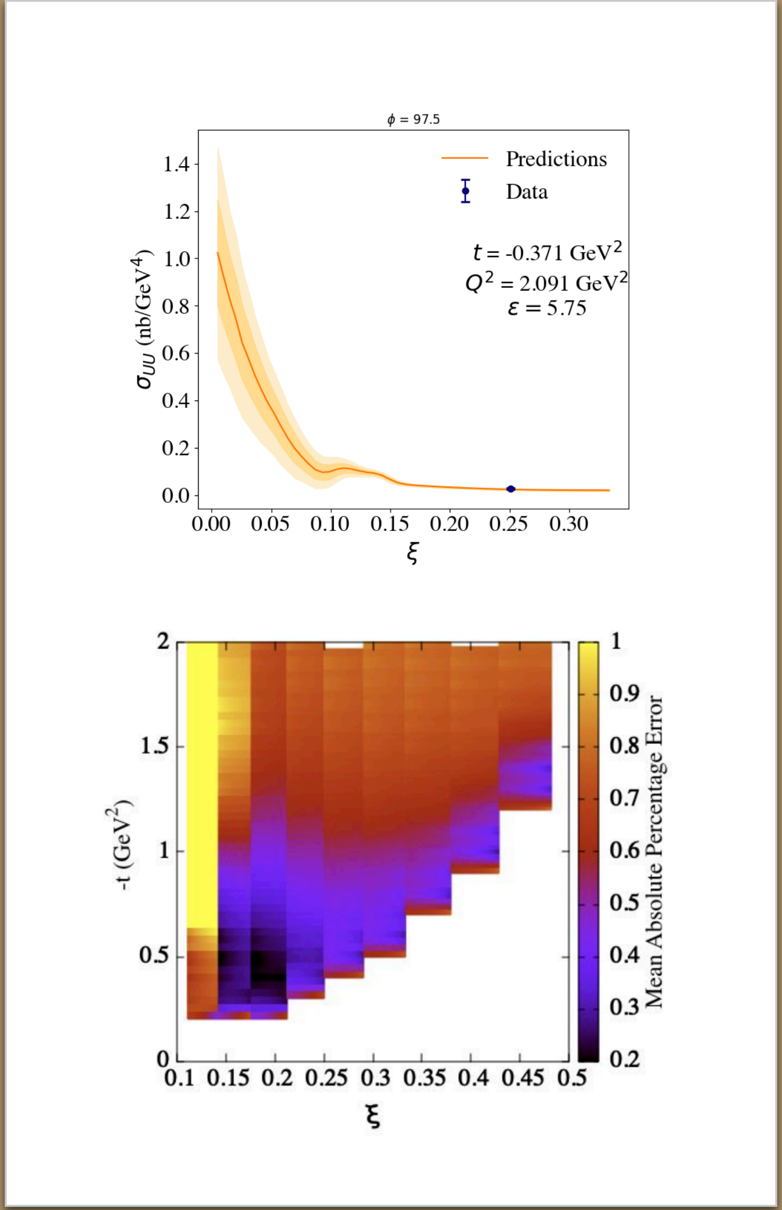
  - Once the model is trained, we can use it to make predictions about the value of the cross section in a given kinematic region. The cross section at a point (x_{Bj}, t, Q^2, E, ϕ) is computed by a forward pass of the network. This operation is parallelizable and can run efficiently on a GPU

  - **We estimate the model's uncertainty by performing many forward passes per prediction point, with Dropout turned on.**





Learning the $\boldsymbol{\varphi}$ dependence



Estimating Uncertainty

(complementary to PARTON, next talk!)

- We are not restricted to kinematic bins that have already been measured - the model learns to extrapolate between existing bins.
- We can sweep through regions where data do not exist, and use the model's uncertainty estimate to advise our use of its predictions
- This creates a distribution of predictions, and we use the mean and standard deviation of that distribution to estimate uncertainty
- (Gal &

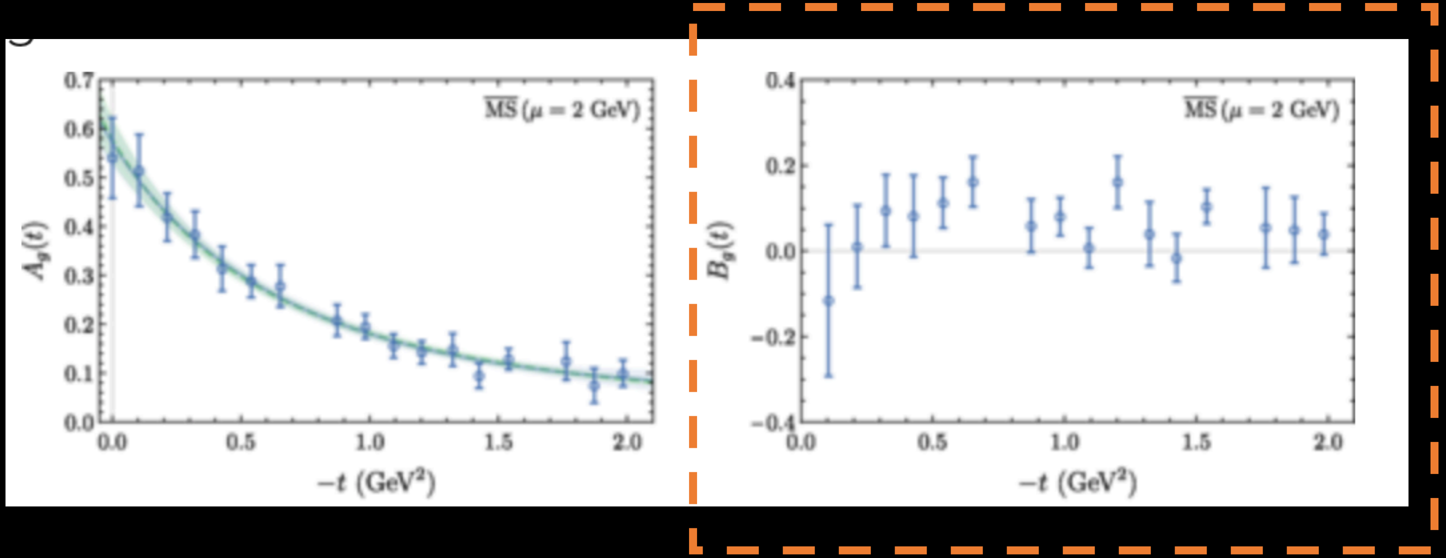
This model will be open-sourced

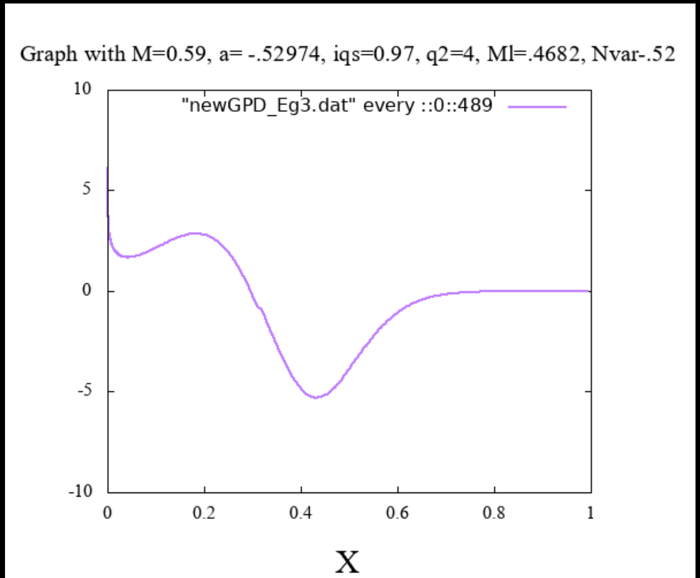
Moving Towards EIC, LHCSpin

Gluon GPDs $J_g + \Sigma_q J_q = \frac{1}{2}$ H_g, E_g

Accessed through PQCD evolution and J/ψ production

Parametrizations/models merging information from lattice QCD





UVA “state of the art results” (B. Kriesten, P. Velie. E. Yeats, F. Yepez)

What I left out

- Nuclei: ^{4}He and deuteron GPDs
- π^0 electroproduction as a means to access the tensor charge and transversity GPDs

CONCLUSIONS

Immense discovery potential as we uncover the mechanical properties the of the proton and observe its spatial images through deeply virtual exclusive experiments

To observe, evaluate and interpret GPDs and Wigner distributions at the subatomic level requires stepping up data analyses from the standard methods

developing new numerical/analytic/quantum computing methods

Center for Nuclear Femtography is a natural entry in the Snowmass Agenda!