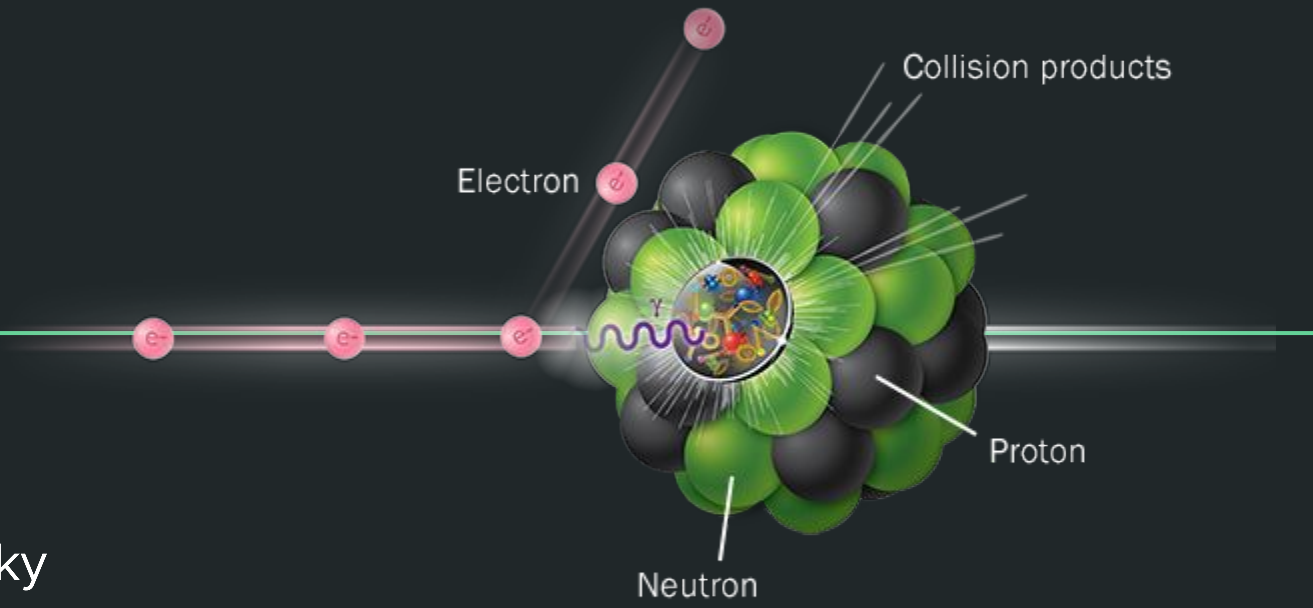
Experimental Measurements at the EIC



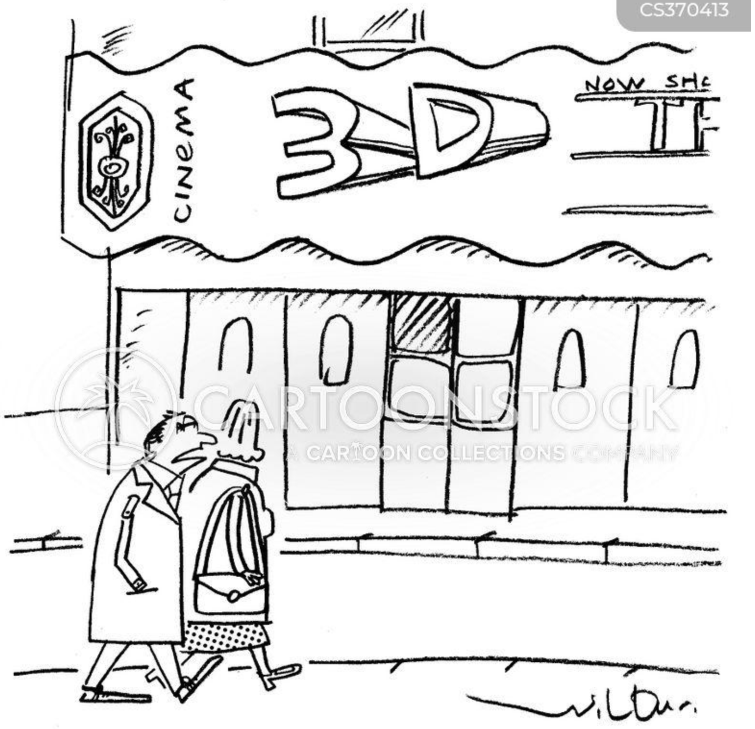
Renee Fatemi
University of Kentucky

Lecture IV

There is so much more to the proton!

We spent a lot of time talking about helicity distributions in Lectures I & II because they gave us a nice platform to investigate how to detect, reconstruct and analyse inclusive and semi-inclusive DIS events.

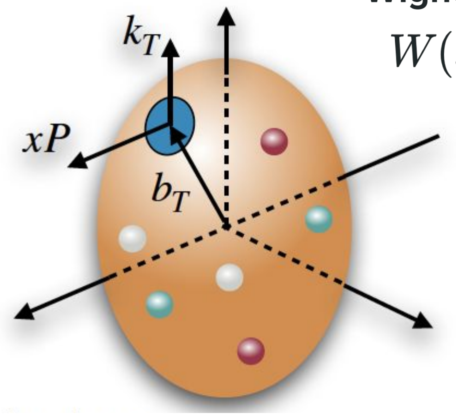
With those tools in our toolbox, let's take a step back and think about the many dimensions of the proton.



SADLY THE CHARACTERS ARE STILL ONE-DIMENSIONAL.

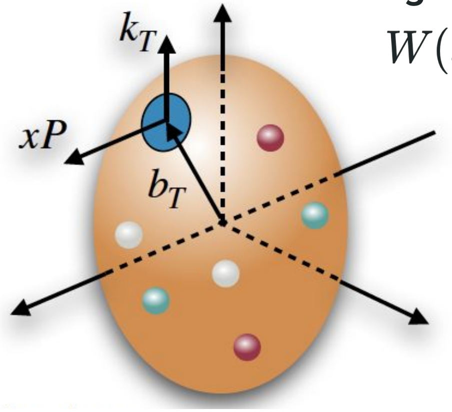
Wigner Functions

$$W(x,\, k_T\,, b_T)$$



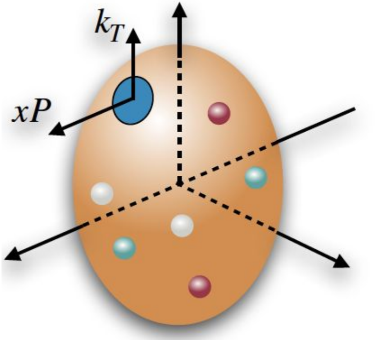
Wigner Functions

$W(x,\ k_T\ , b_T)$



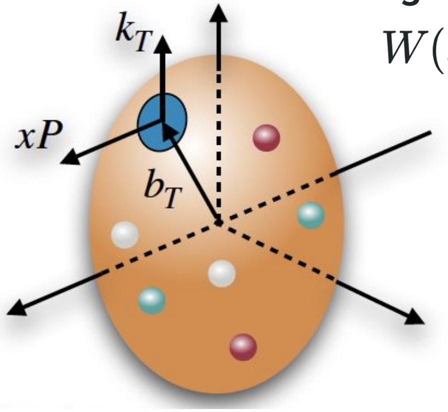
Transverse Momentum Distributions

$f(x, k_T)$



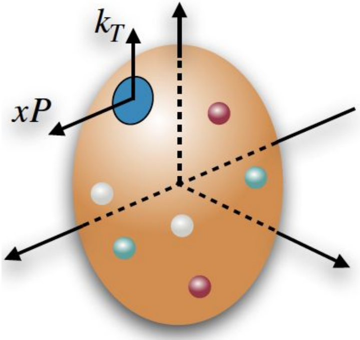
Wigner Functions

$W(x,\, k_T\,, b_T)$



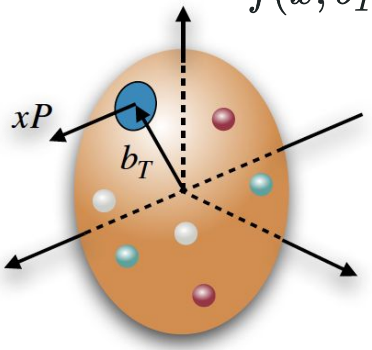
TMDs

$f(x, k_T)$



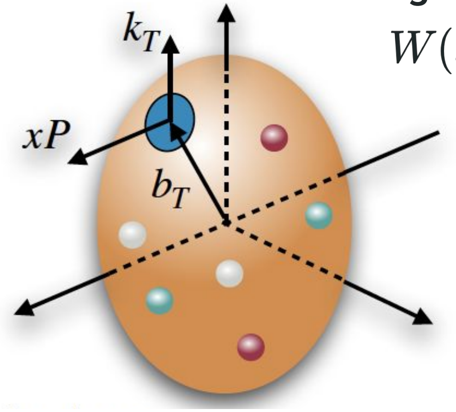
Fourier Transform of
Generalized Parton Distributions

$f(x, b_T)$



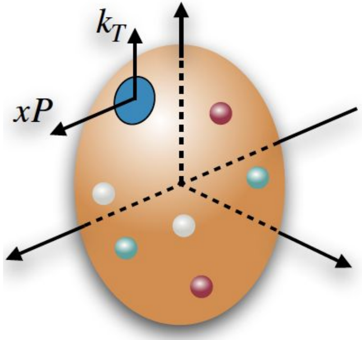
Wigner Functions

$W(x,\ k_T\ ,b_T)$



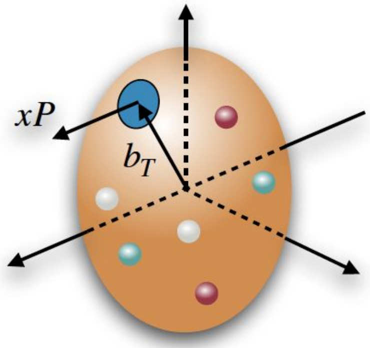
TMDs

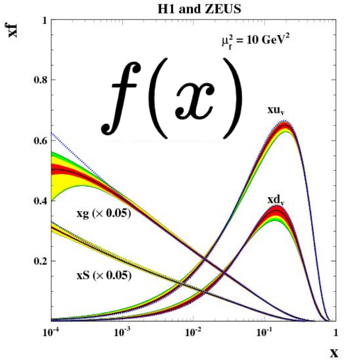
$f(x, k_T)$



Fourier Transform of **GPDs**

$f(x, b_T)$





Can we measure a Wigner Function?

- Five years ago this question would have been met with silence.

- In 2016 **Hatta, Xiao and Yuan** proposed using diffractive dijet production at the EIC to probe the fourier transform of the gluon Wigner distribution.

- Requires reconstruction of dijet, with a rapidity gap, ie no activity between the jet and the hadron beam.

- Sensitive to k_T via the dijet relative $P_T = \frac{(P_{t1} - P_{T2})}{2}$

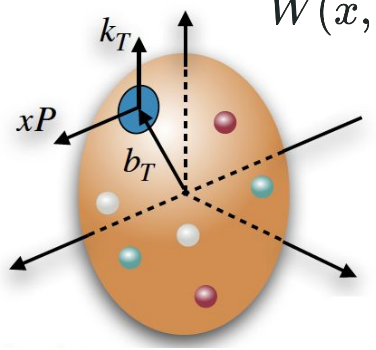
- Sensitive to b_T via the proton transverse recoil:

$$\Delta x_T = -(P_{T1} + P_{T2})$$

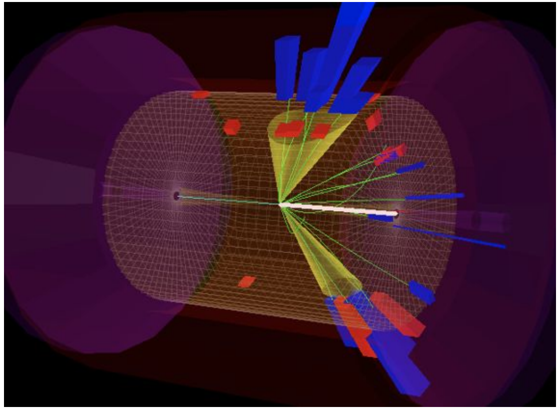
- Azimuthal correlations between P_T and Δx are sensitive to correlations between k_T and b_T in the Wigner distribution.

Wigner Functions

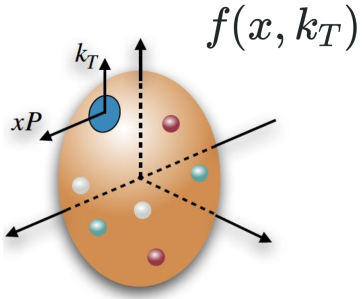
$$W(x, k_T, b_T)$$



Theory is rapidly evolving - promising new experimental channels are being developed.

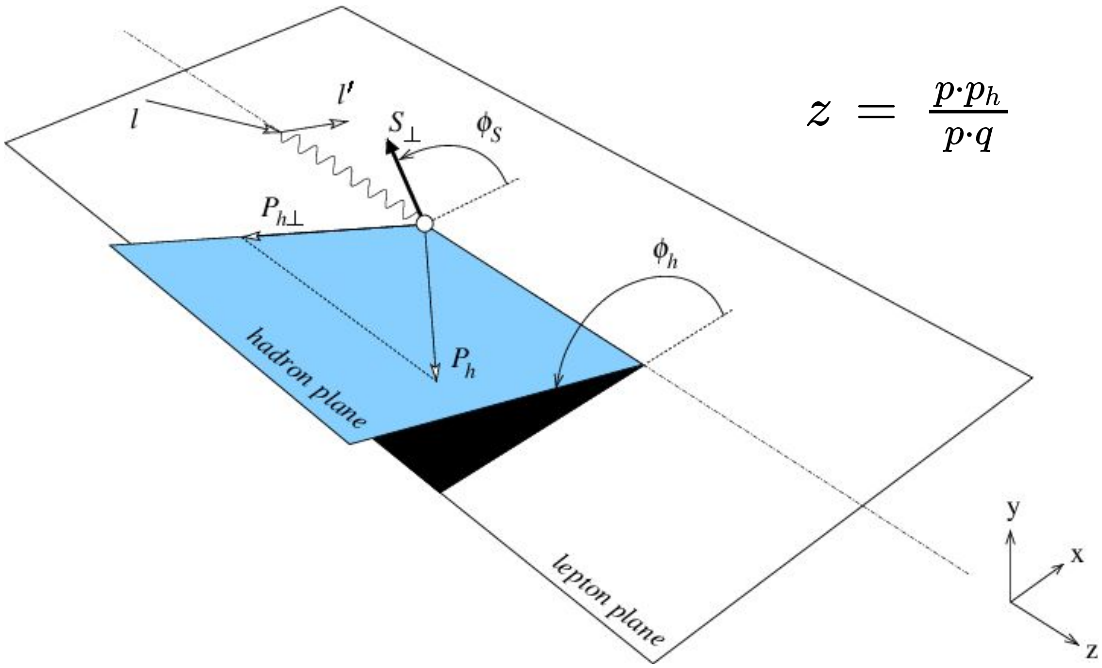


TMD parton distribution functions

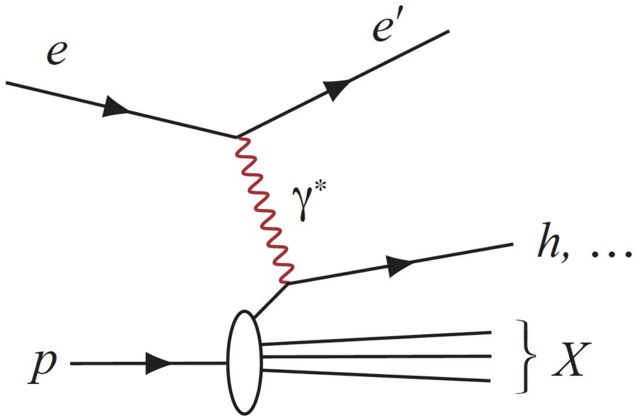


		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1(x,k_T^2)$		$h_1^\perp(x,k_T^2)$ - Boer-Mulders
	L		$g_1(x,k_T^2)$ - Helicity	$h_{1L}^\perp(x,k_T^2)$ - Long-Transversity
	T	$f_1^\perp(x,k_T^2)$ - Sivers	$g_{1T}(x,k_T^2)$ - Trans-Helicity	$h_1(x,k_T^2)$ - Transversity $h_{1T}^\perp(x,k_T^2)$ - Pretzelosity

TMDs require SIDIS



$$z = \frac{p \cdot p_h}{p \cdot q}$$



In addition to to standard DIS kinematic variables it is necessary to measure:

- $P_{h\perp}$ the transverse momentum of the reconstructed hadron
- ϕ_h the angle between the hadron and scattering plane
- ϕ_S the angle between the nucleon spin and the scattering plane.

Lepton-Hadron Cross-section

$F_{XY,Z}$

- X is polarization of electron beam WRT to γ^*
- Y is the polarization of proton beam WRT γ^*
- Z is the polarization of the virtual photon

$$
\begin{aligned}
\frac{d^6\sigma}{dx\,dy\,dz\,d\phi\,d\phi_S\,dP_{h\perp}^2} = {} & \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\epsilon F_{UU,L} \\
& +\sqrt{2\epsilon(1+\epsilon)}\cos\phi\, F_{UU}^{\cos\phi}+\epsilon\cos(2\phi)\, F_{UU}^{\cos(2\phi)}+\lambda_e\sqrt{2\epsilon(1-\epsilon)}\sin\phi\, F_{LU}^{\sin\phi} \\
& +S_L\left[\sqrt{2\epsilon(1+\epsilon)}\sin\phi\, F_{UL}^{\sin\phi}+\epsilon\sin(2\phi)\, F_{UL}^{\sin(2\phi)}\right] \\
& +S_L\lambda_e\left[\sqrt{1-\epsilon^2}\, F_{LL}+\sqrt{2\epsilon(1-\epsilon)}\cos\phi\, F_{LL}^{\cos\phi}\right] \\
& +|S_T|\Big[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)}+\epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right) \\
& +\epsilon\sin(\phi+\phi_S)\, F_{UT}^{\sin(\phi+\phi_S)}+\epsilon\sin(3\phi-\phi_S)\, F_{UT}^{\sin(3\phi-\phi_S)} \\
& +\sqrt{2\epsilon(1+\epsilon)}\sin\phi_S\, F_{UT}^{\sin\phi_S}+\sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)\, F_{UT}^{\sin(2\phi-\phi_S)}\Big] \\
& +|S_T|\lambda_e\Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)\, F_{LT}^{\cos(\phi-\phi_S)}+\sqrt{2\epsilon(1-\epsilon)}\cos\phi_S\, F_{LT}^{\cos\phi_S} \\
& +\sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)\, F_{LT}^{\cos(2\phi-\phi_S)}\Big]\Big\}.
\end{aligned}
$$

Lepton-Hadron Cross-section

$F_{XY,Z}$

- X is polarization of electron beam WRT to $\boldsymbol{\gamma}^*$
- Y is the polarization of proton beam WRT $\boldsymbol{\gamma}^*$
- Z is the polarization of the virtual photon

$$\frac{d^6\sigma}{dx\,dy\,dz\,d\phi\,d\phi_S\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\epsilon F_{UU,L}$$

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

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

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

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

Transversity and Collins FF

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

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

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

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

$$F_{UT}^{\sin(\phi+\phi_S)} = \mathcal{C}\left[-\frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M_h}\,\delta q\, H_1^\perp\right]$$

and

$$F_{UT,T}^{\sin(\phi-\phi_S)} = \mathcal{C}\left[-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M}\, f_{1T}^\perp\, D_1\right]$$

Lepton-Hadron Cross-section

$F_{XY,Z}$

- X is polarization of electron beam WRT to γ^*
- Y is the polarization of proton beam WRT γ^*
- Z is the polarization of the virtual photon

$$\frac{d^6\sigma}{dx\,dy\,dz\,d\phi\,d\phi_S\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\epsilon F_{UU,L}$$
$$+\sqrt{2\epsilon(1+\epsilon)}\cos\phi\, F_{UU}^{\cos\phi}+\epsilon\cos(2\phi)\, F_{UU}^{\cos(2\phi)}+\lambda_e\sqrt{2\epsilon(1-\epsilon)}\sin\phi\, F_{LU}^{\sin\phi}$$
$$+S_L\left[\sqrt{2\epsilon(1+\epsilon)}\sin\phi\, F_{UL}^{\sin\phi}+\epsilon\sin(2\phi)\, F_{UL}^{\sin(2\phi)}\right]$$
$$+S_L\lambda_e\left[\sqrt{1-\epsilon^2}\,F_{LL}+\sqrt{2\epsilon(1-\epsilon)}\cos\phi\, F_{LL}^{\cos\phi}\right]$$
$$+|S_T|\Big[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)}+\epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right)$$
$$+\epsilon\sin(\phi+\phi_S)\, F_{UT}^{\sin(\phi+\phi_S)}+\epsilon\sin(3\phi-\phi_S)\, F_{UT}^{\sin(3\phi-\phi_S)}$$
$$+\sqrt{2\epsilon(1+\epsilon)}\sin\phi_S\, F_{UT}^{\sin\phi_S}+\sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)\, F_{UT}^{\sin(2\phi-\phi_S)}\Big]$$
$$+|S_T|\lambda_e\Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)\, F_{LT}^{\cos(\phi-\phi_S)}+\sqrt{2\epsilon(1-\epsilon)}\cos\phi_S\, F_{LT}^{\cos\phi_S}$$
$$+\sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)\, F_{LT}^{\cos(2\phi-\phi_S)}\Big]\Big\}.$$

$$F_{UT}^{\sin(\phi+\phi_S)} = \mathcal{C}\left[-\frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M_h}\,\delta q\, H_1^{\perp}\right]$$

and

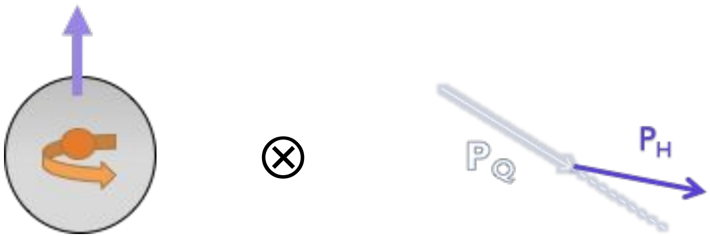
$$F_{UT,T}^{\sin(\phi-\phi_S)} = \mathcal{C}\left[-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M}\, f_{1T}^{\perp}\, D_1\right]$$

Sivers and spin independent FF

TMD extraction requires global analysis of both PDF and FF!!

Sivers ⊗ FF

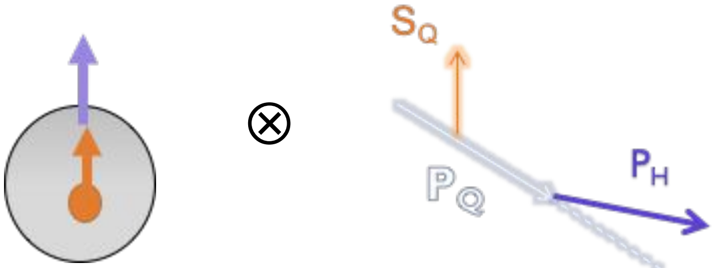
$$F_{UT,T}^{\sin(\phi-\phi_S)} = \mathcal{C}\left[-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M} f_{1T}^{\perp} D_1 \right]$$



Transversity ⊗ Collins

$$F_{UT}^{\sin(\phi+\phi_S)} = \mathcal{C}\left[-\frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M_h} \delta q\, H_1^{\perp} \right]$$

$$A_{UT}^{\sin(\phi_h+\phi_s)}(x,y,z,P_T) = \frac{2(1-y)}{1+(1-y)^2}\,\frac{F_{UT}^{\sin(\phi_h+\phi_s)}}{F_{UU}}\,.$$



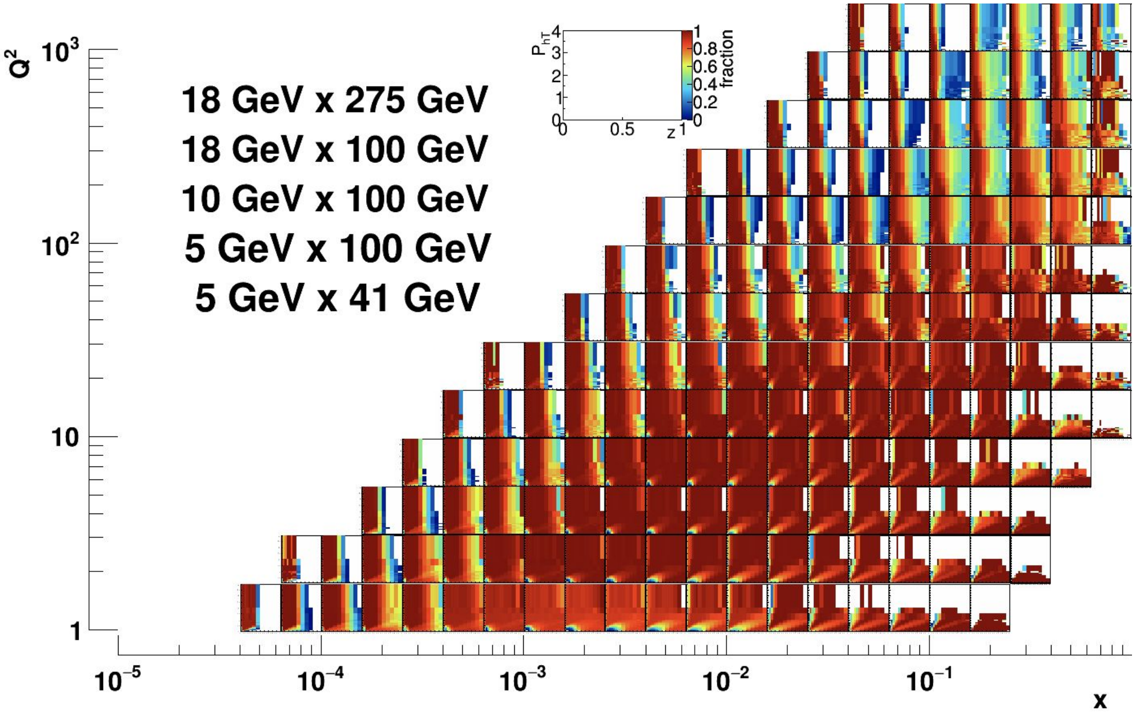
TMDs at the EIC

Yellow Report : 2103.05419

Hadron acceptance fractions as a function of z and $P_{h\perp}$

Low acceptance at intermediate x and high Q2 is do to limit PID capabilities.

This region is important because ***TMD evolution is not fully prescribed by theory. There is a non-perturbative component that must be measured experimentally***.



Affinity for TMD Factorization

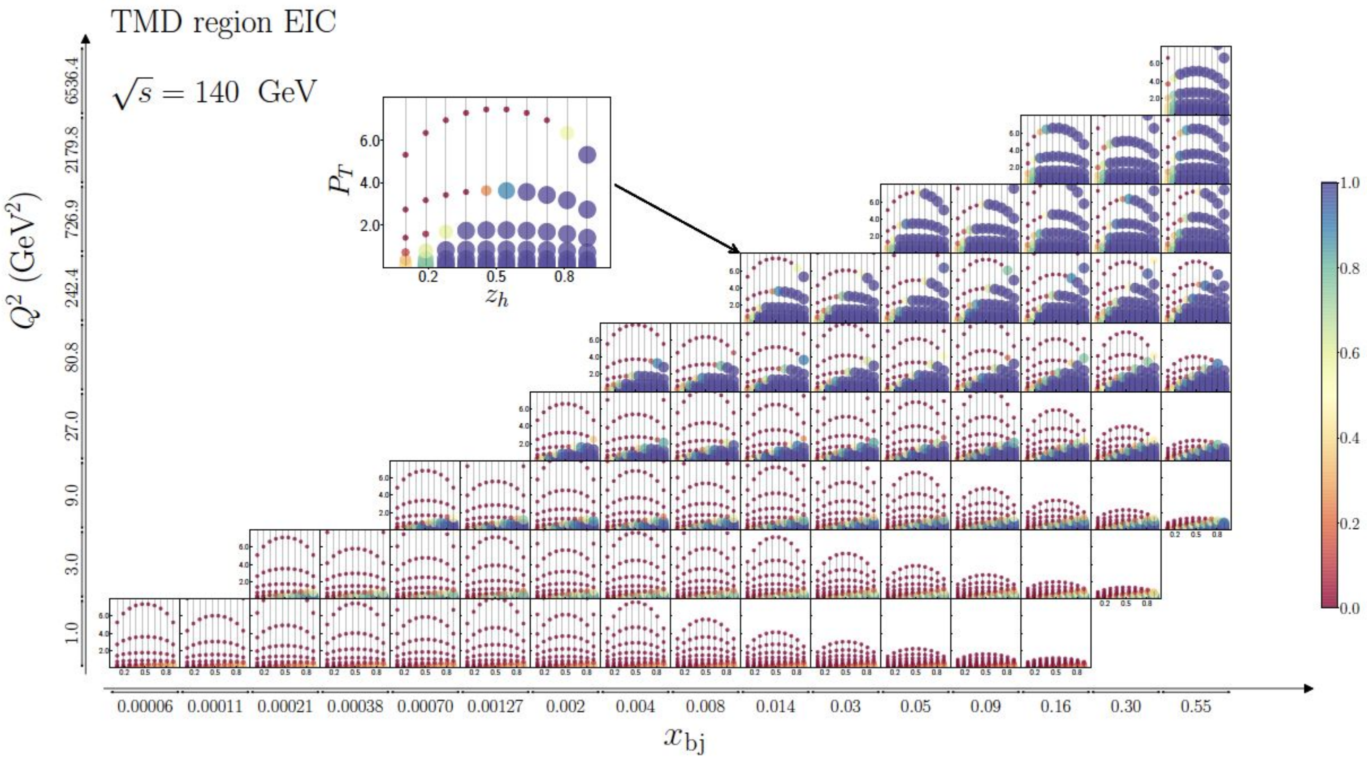
Yellow Report : 2103.05419

x-Q^2 plane for future EIC measurement at √s = 140 GeV.

Dot represent affinity for factorization.

$$\frac{P_T}{zQ} < 0.25$$

The sea of red at low Q^2 excludes many previous measurements.



Affinity for TMD Factorization

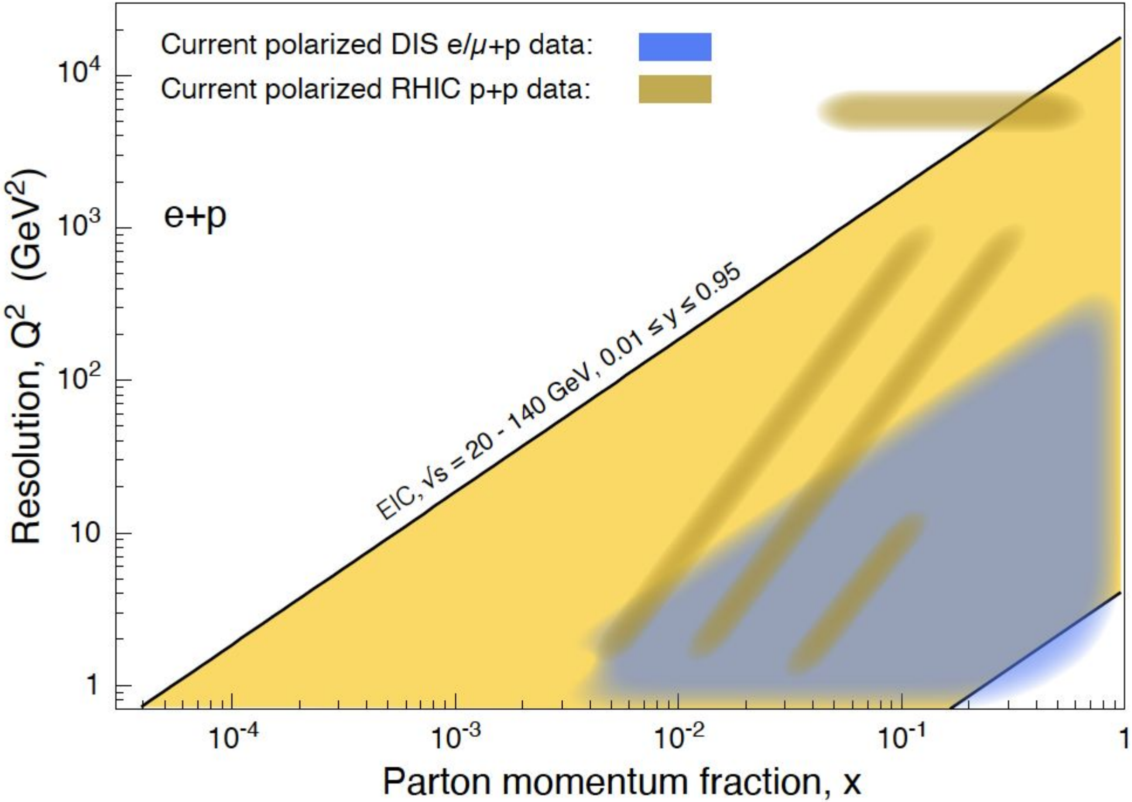
Yellow Report : 2103.05419

x-Q^2 plane for future EIC measurement at √s = 140 GeV.

Dots represent affinity for factorization.

$$\frac{P_T}{zQ} < 0.25$$

The sea of red at low Q^2 excludes many previous measurements.



Yellow Report : 2103.05419

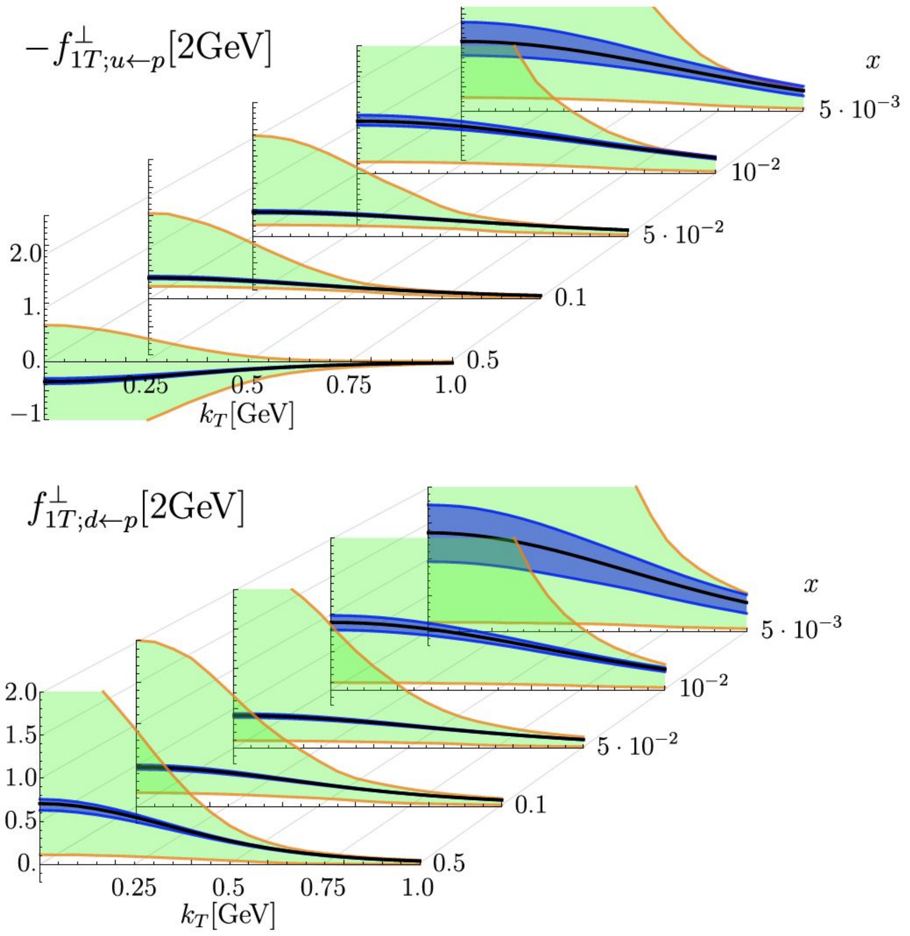
EIC impact on u/d Sivers

Current (green) and EIC (blue) constraints on the up and down Sivers functions.

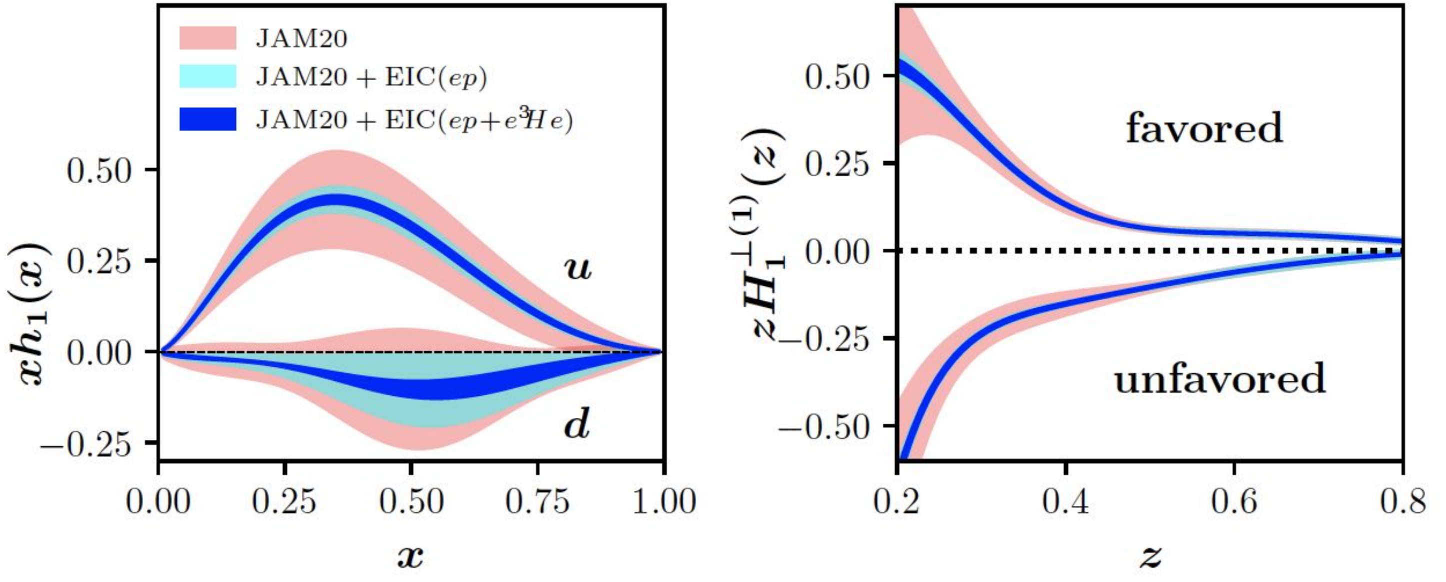
The size of the error bars is due to the limited subset of existing data that satisfies factorization conditions.

Uncertainties can be reduced by more than an order of magnitude for all flavors.

The wide range of hadron pT facilitates the mapping in kT



EIC Impact on Transversity and Collins Functions

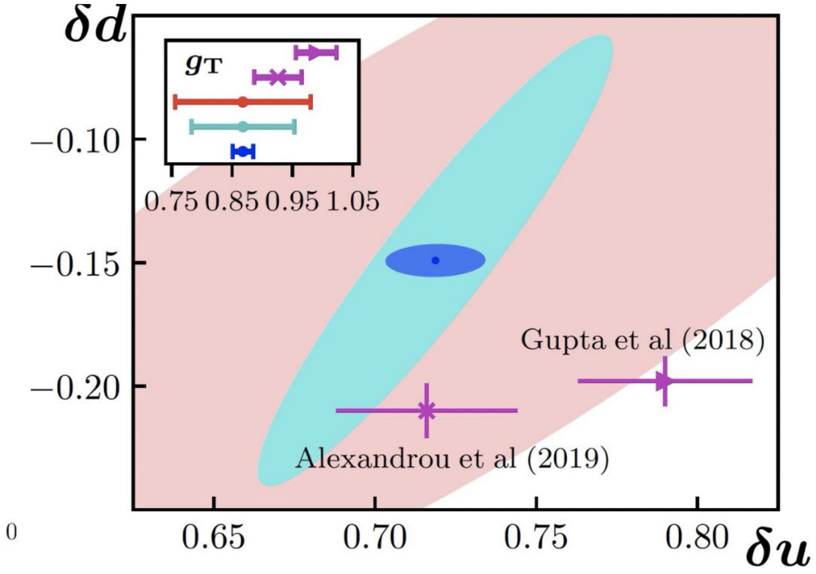


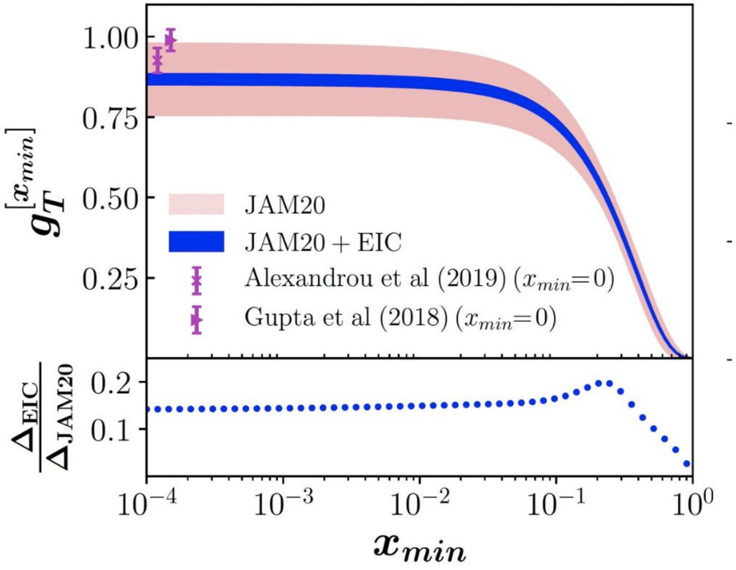
L. Gamberg, Z. Kang, D. Pitonyak, A. Prokudin, N. Sato Phys.Lett.B 816 (2021)
JAM20: Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato, Phys.Rev.D 102 (2020)

EIC constraints on tensor charge

$$\delta q\left(Q^2\right) \equiv \int_0^1 dx\,\left(h_1^q(x,Q^2) - h_1^{\bar{q}}(x,Q^2)\right)$$

$$g_T = \delta u - \delta d$$





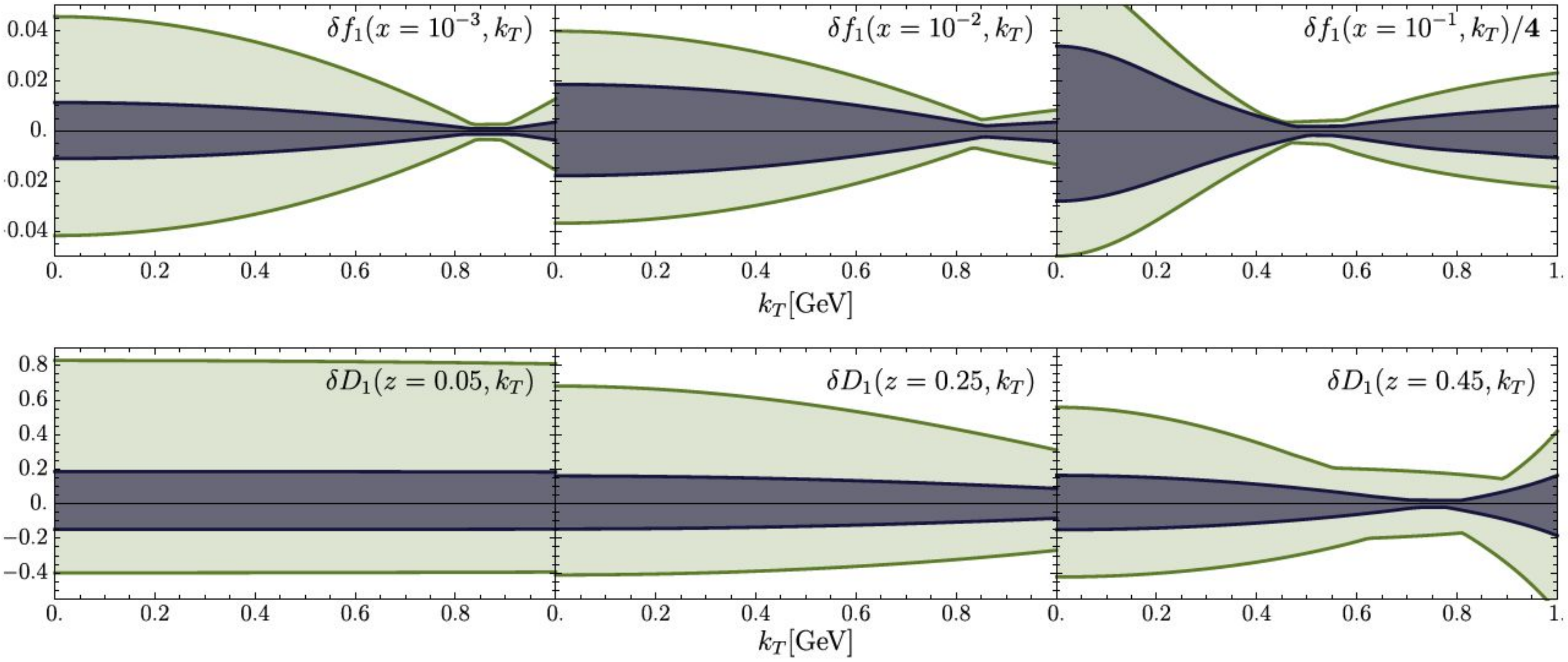
L. Gamberg, Z. Kang, D. Pitonyak, A. Prokudin, N. Sato Phys.Lett.B 816 (2021)

JAM20: Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato, Phys.Rev.D 102 (2020)

Yellow Report : 2103.05419

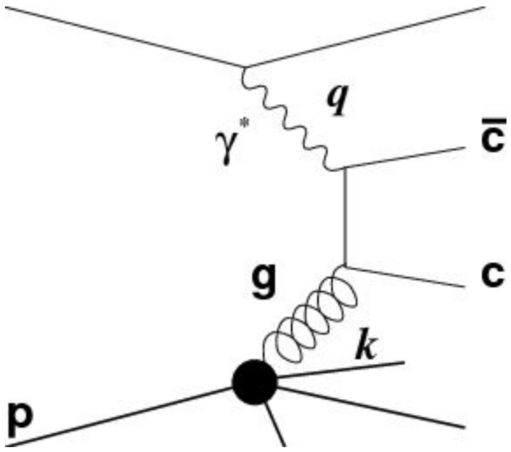
EIC impact on Unpolarized TMD PDFs and FF

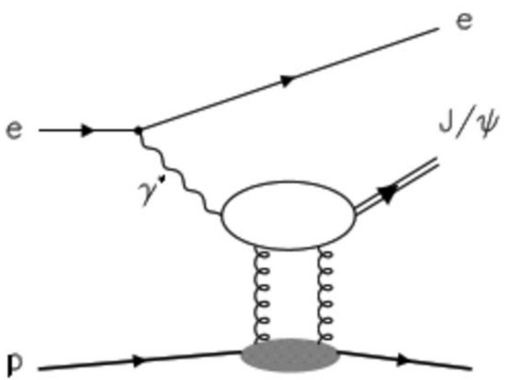
Impact on unpolarized up quark TMD PDF and unpolarized u-pi TMD FF/

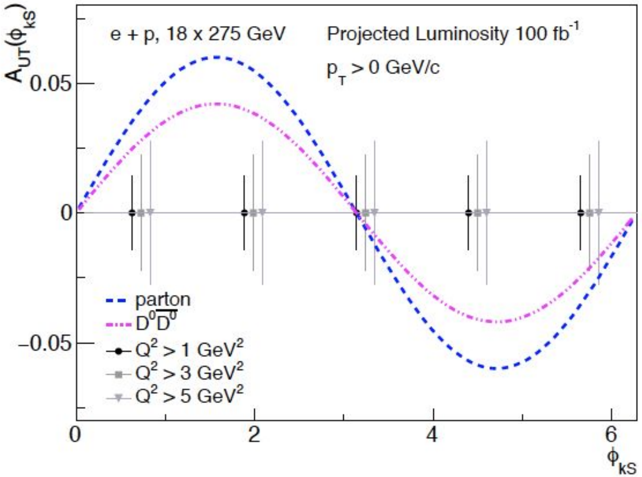


Gluon TMDs at the EIC

- Gluon TMDs are nearly unconstrained
- Can access at an EIC via
  - Quarkonium production
  - Open charm production
  - Charm jet production

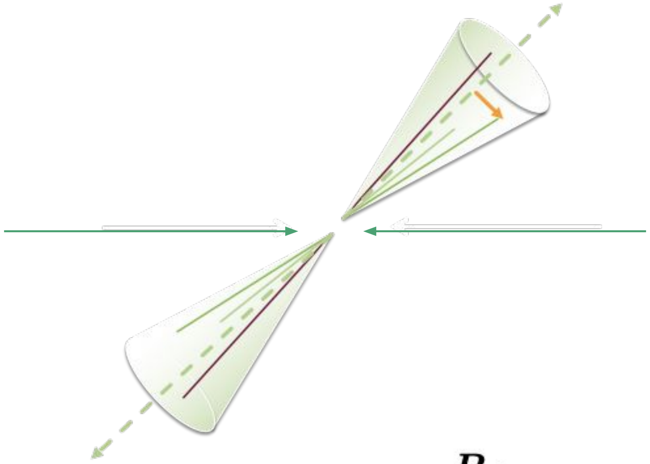




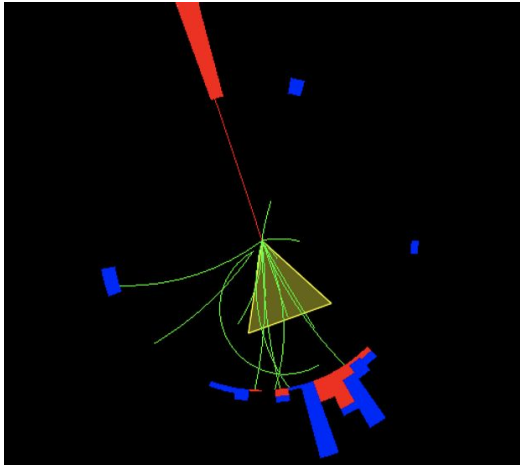


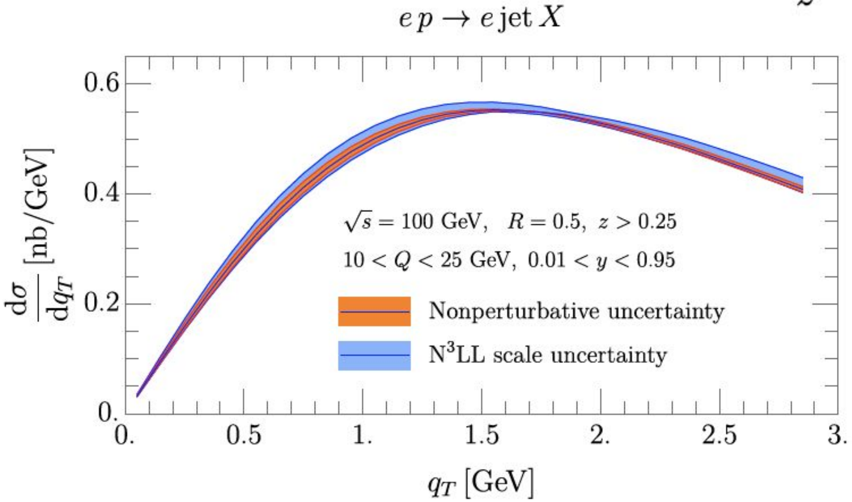
Using Jets to access TMDs

- Jets are classic collider tools
- Natural to extend to an EIC
- Jet qT measurement probes TMD PDFs and is independent of TMD FF
- Hadron in jet measurements are sensitive to transversity + Collins



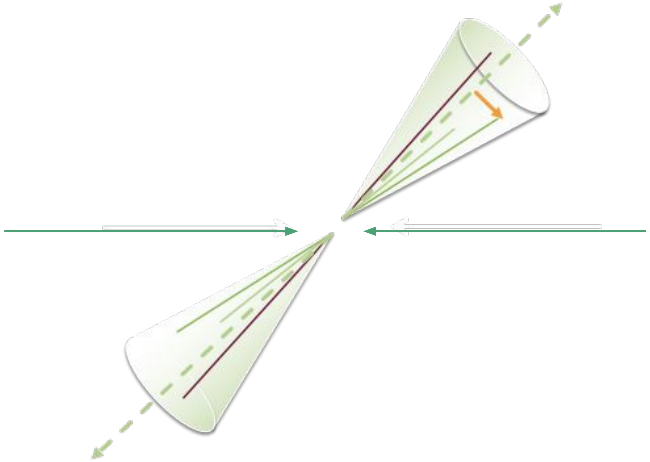
$$\boldsymbol{q} = \frac{\boldsymbol{P}_J}{z} + \boldsymbol{q}_{\rm in} \,,$$

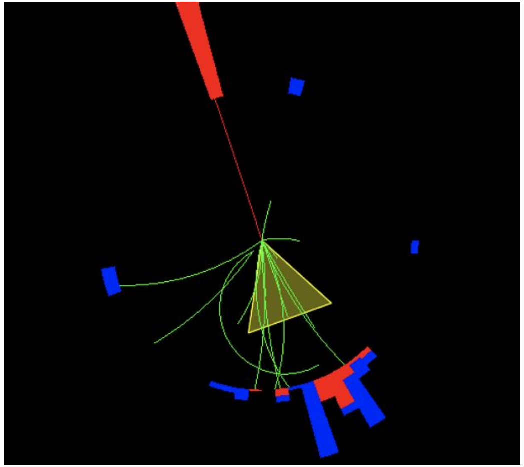




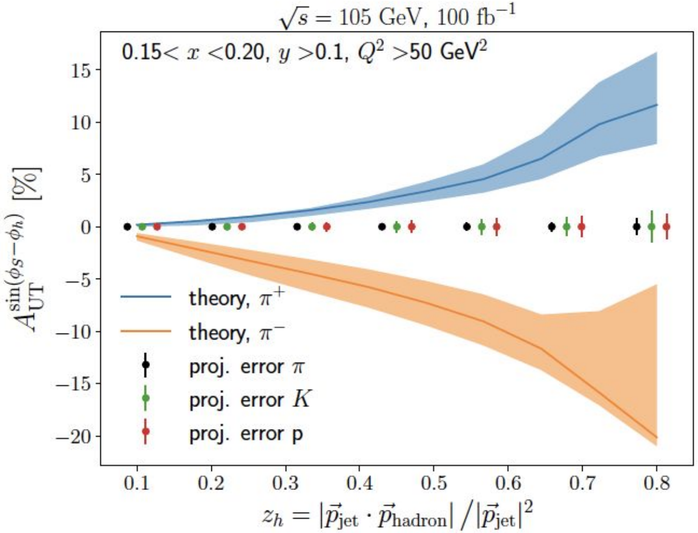
Using Jets to access TMDs

- Jets are classic collider tools
- Natural to extend to an EIC
- Jet qT measurement probes TMD PDFs and is independent of TMD FF
- Hadron in jet measurements are sensitive to transversity + Collins





Bands are current uncertainty on transversity and Collins functions. Points are projected statistical errors.

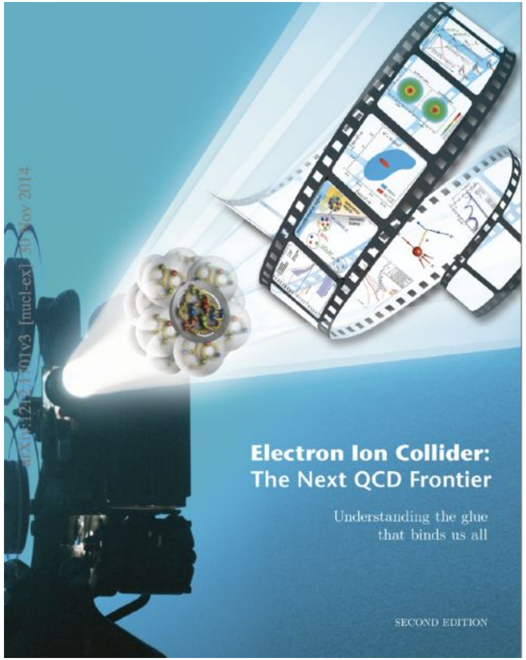


There is so much more!

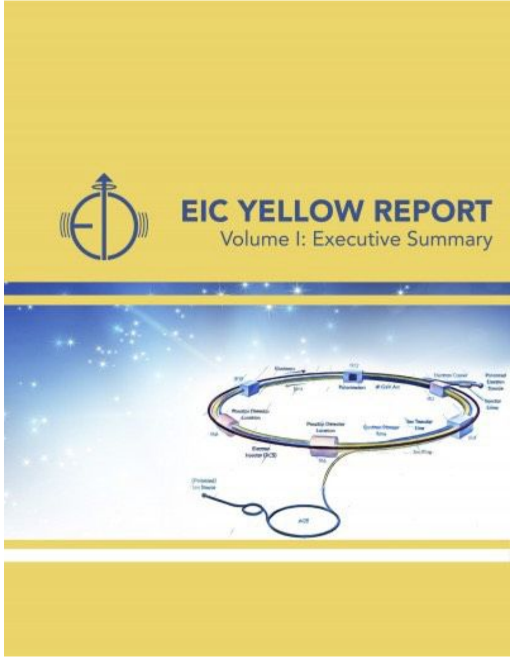
I encourage you to take a look at the EIC White & Yellow papers.

Many more topics to study:
- Origin of Proton Mass
- GPDs vis DVCS
- Nuclear PDFs
- Gluon Saturation
- Charged Lepton Flavor Violation

Thank you!



arXiv:1212:1701



arXiv:2103.05419