15+5

Multi-dimensional Imaging of Nucleons, Nuclei, and Mesons at the EIC

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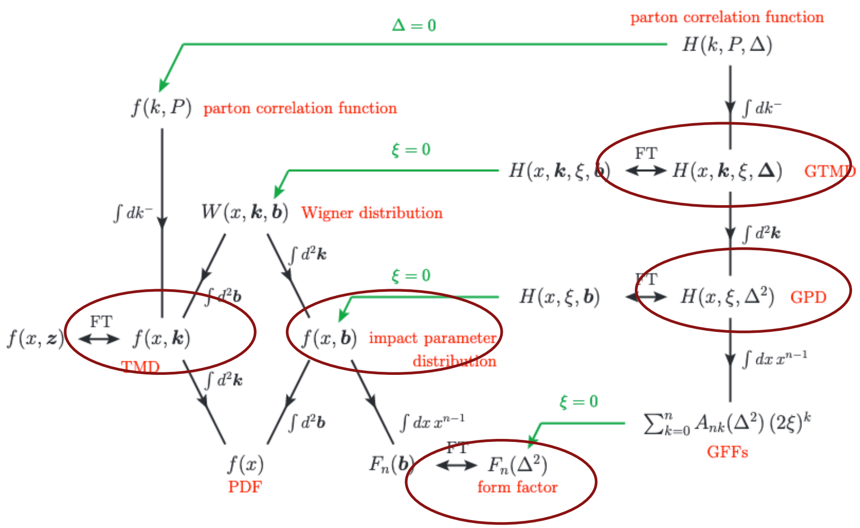
Duke UNIVERSITY
Jefferson Lab

Overview

- Summarizes an impressive amount of work on
  - Nucleon and Meson Form Factors
  - Generalized Parton Distribution Functions (GPDs) from exclusive processes
  - Transverse Momentum Dependent Distribution Functions (TMDs) from Semi Inclusive Processes
  - Accessing to Wigner functions
  - Using light, polarized nuclei $(d,\ ^3He,\ ^4He)$ as neutron targets, investigate nuclear effects and exploit the possibility of tensor polarized targets

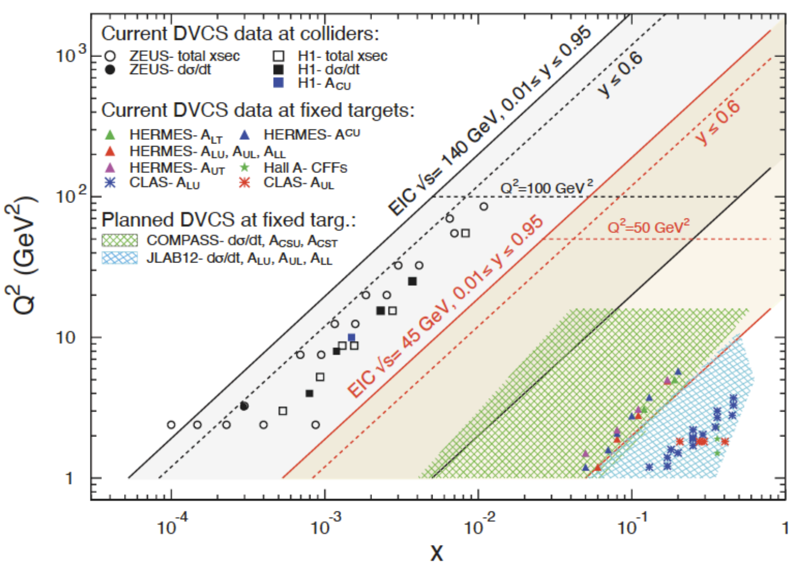


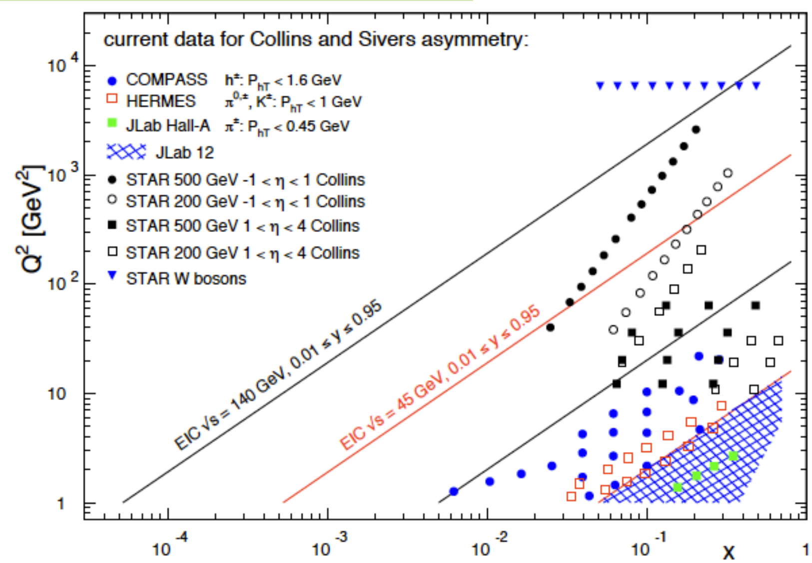
Diehl,2003

Coverage

- Common theme on EIC impact
  - Extended kinematic coverage and precision, along with polarization and possible beam charge degrees of freedom allow multi-pronged approach →needed to extract multidimensional objects
  - TMD factorization is valid

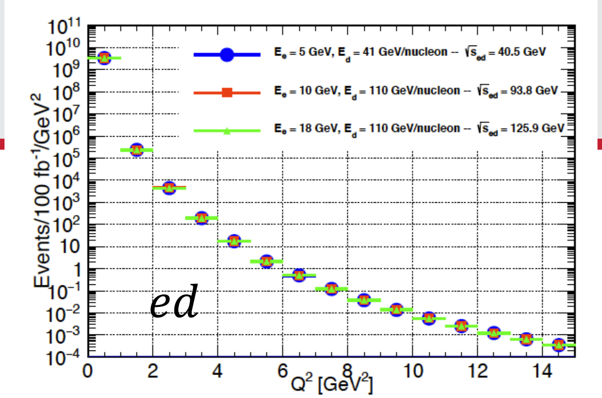
Large Q^2 lever arm: probe evolution, disentangle contributions to σ

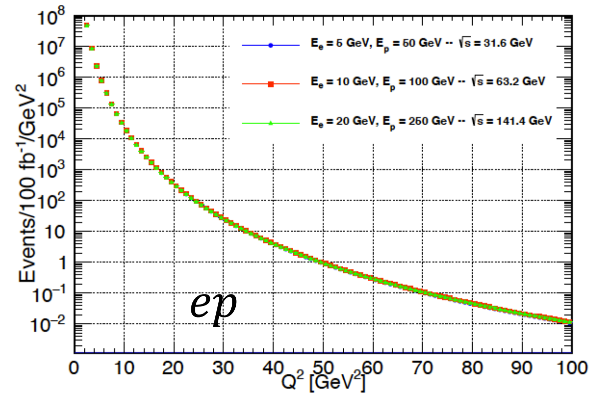




Coverage to low x: access sea and gluon distributions

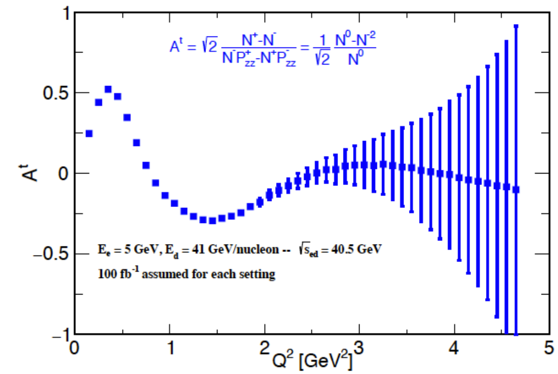
Nucleon





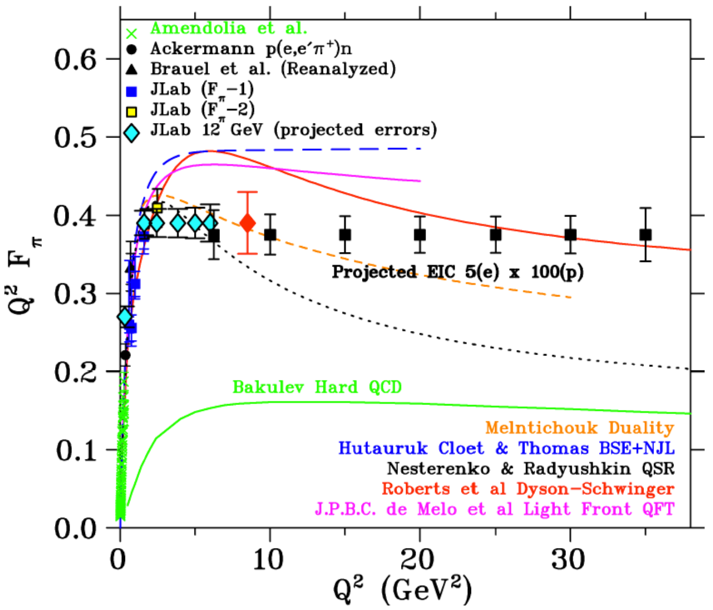
- Magnetic form factors up to the highest Q^2
- Nucleon FF up to ~45 GeV^2
- Deuteron up to ~5 GeV^2

- Tensor polarized up to $\approx 2.5\ GeV^2$



Meson Form Factors

- Interplay between emergent hadronic mass and Higgs-mass mechanism → π determined due to QCD, $K\ \frac{1}{3}$ from Higgs
- From factors $e + p \rightarrow e' + n + \pi$, at low $-t$ scattering off pion cloud (also can get $\frac{\sigma_L}{\sigma_T}$ from π^{-}/π^{+} ratios)
- K form factor from $e + p \rightarrow e' + \Sigma^{0}/\Lambda + K^{+}$
  - Still under investigation if scattering from K cloud dominates at same kinematics a and how σ_L/σ_T can be verified (probably from Σ^0/Λ)
  - Possibility for first quality F_K measurement at $Q^2 > 0.2$

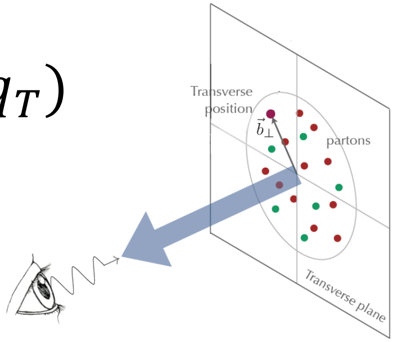


Using $20 fb^{-1}, 5\times100$

Generalized Parton Distribution Functions

- Four chiral even $(H, E, \widetilde{H}, \tilde{E})$, four chiral odd (q_T)
- Depend on x, Q^2, ξ, t
- Can be related to impact parameter

$$q(x, \vec{b}\,) = \int \frac{d^2\vec{q}}{4\pi^2} e^{i\vec{b}\cdot\vec{q}} \mathrm{H}^{\mathrm{q}}(\mathrm{x}, \xi = 0, t = -\vec{q}^2, \mu^2)$$



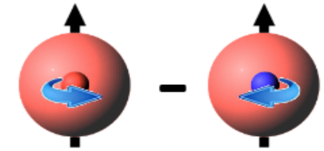
Energy Momentum Tensor Form Factors

- Need complete set of observables including spin and beam-charge asymmetries to meaningfuly constrain EMT factors including d −term

$$\mathbf{H}^q(x, \xi, t) \xrightarrow{t \to 0} q(x) \text{ or } f_1(x)$$

"Elusive"

$$\mathbf{E}^q(x, \xi, t) \longleftrightarrow f_{1T}(x, k_T)$$



Sivers: quark k_T & nucleon transv. spin

$$2J^q = \lim_{t \to 0} \int x \left(\mathbf{H}^q(x, \xi, t) + \mathbf{E}^q(x, \xi, t) \right) dx$$

mass & energy distribution

$$\int_{-1}^{1} dx \, x \, H^a(x, \xi, t) = A^a(t) + \xi^2 d_1^a(t)$$

$$\int_{-1}^{1} dx \, x \, E^a(x, \xi, t) = 2J^a(t) - A^a(t) - \xi^2 d_1^a(t)$$

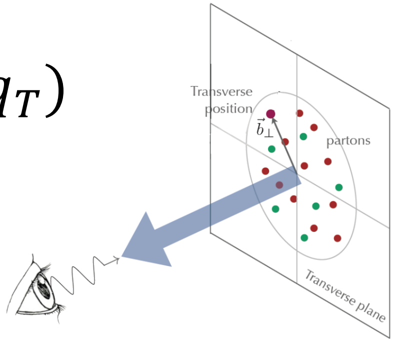
Angular momentum distribution

Force & Pressure distribution

M. Polyakov, P. Schweitzer, Int.J.Mod.Phys. A33 (2018)

Slide from N d'Hose

Generalized Parton Distribution Functions



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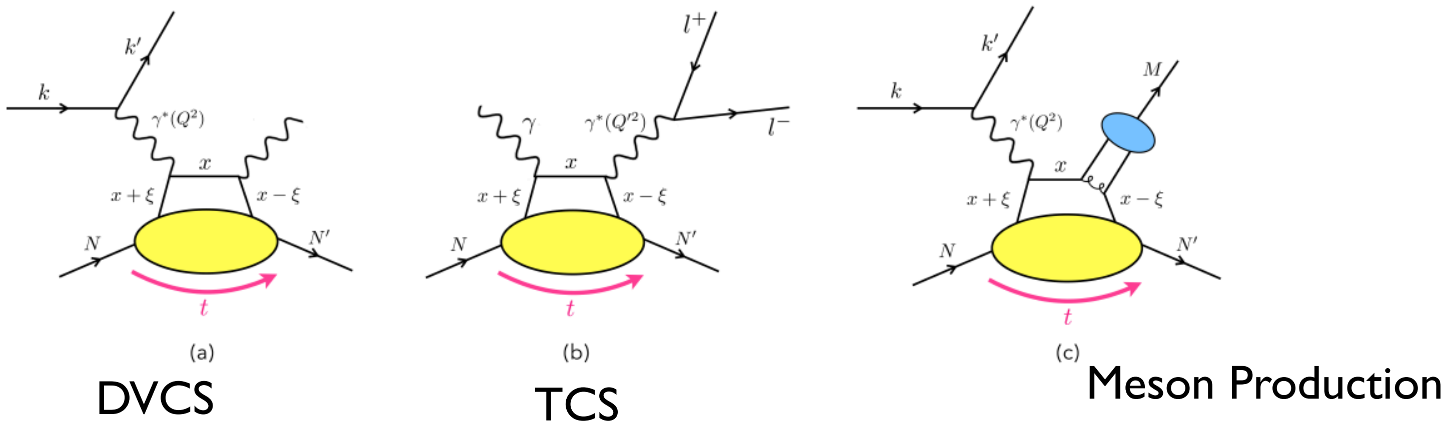
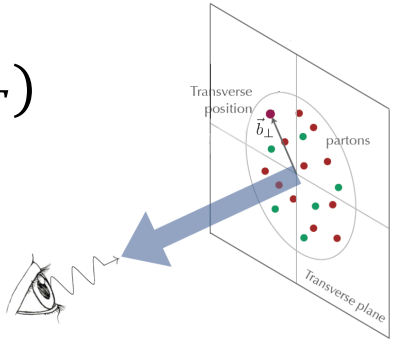
- Accessed in exclusive processes



Generalized Parton Distribution Functions



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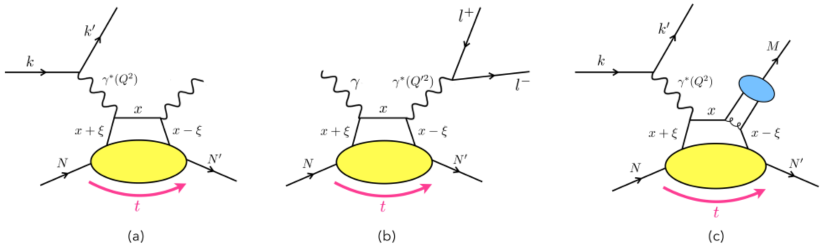
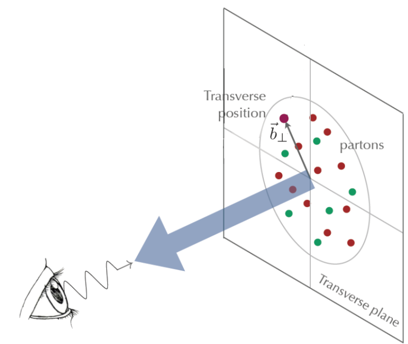


- Meson production channels at the EIC
  - Heavy: access to gluons
  - Vector : similar to DVCS but allows quark flavor separation
  - Light pseudoscalar: access to parity odd and chiral odd GPDs → connection to transversity

Generalized Parton Distribution Functions



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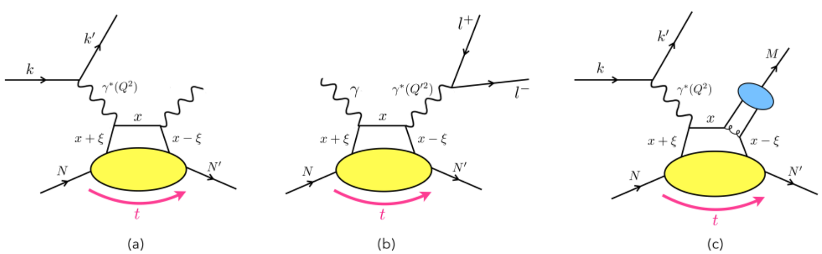
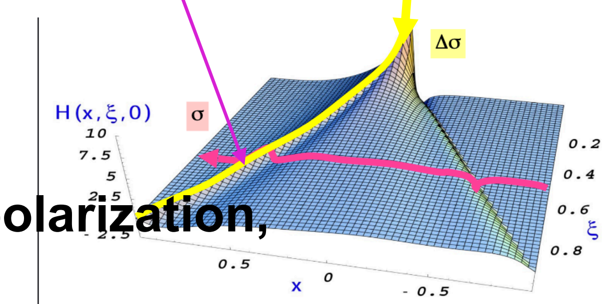


$$T_{\mathrm{DVCS}} \sim \int_{-1}^{1} \mathrm{d}x \frac{\mathrm{GPD}(x,\xi,t)}{x \pm \xi - i\epsilon} + \mathcal{O}\left(\frac{t}{Q^2}\right)$$
$$\sim \mathrm{PV}\int_{-1}^{1} \mathrm{d}x \frac{\mathrm{GPD}(x,\xi,t)}{x \pm \xi} \pm i\pi\,\mathrm{GPD}(\mp\xi,\xi,t) + \mathcal{O}\left(\frac{t}{Q^2}\right)$$

- Measured amplitudes contain complex convolutions of GPDs
- Cross section also contains contributions from competing processes and interferences

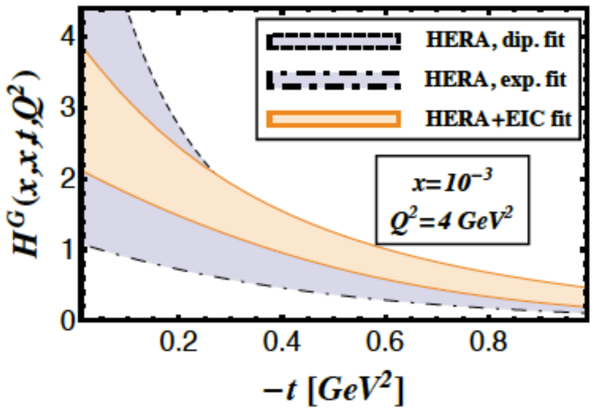
→Need many degrees of freedom and long kinematic lever arms to disentangle GPDs from measured cross-section



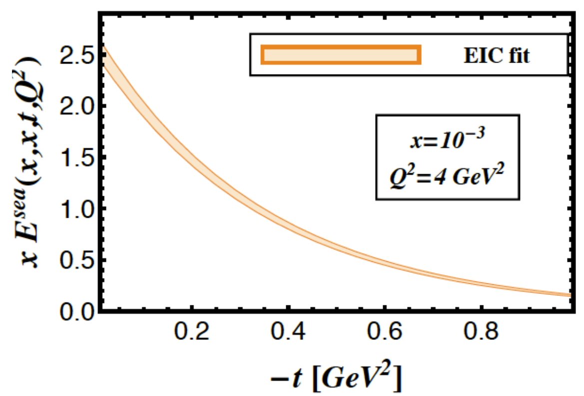
- **Flexibility of EIC ideal with wide coverage in Q^2, t, polarization, possibly beam charge** **+ high precision**
- **Everything can be measured at the same experiment**

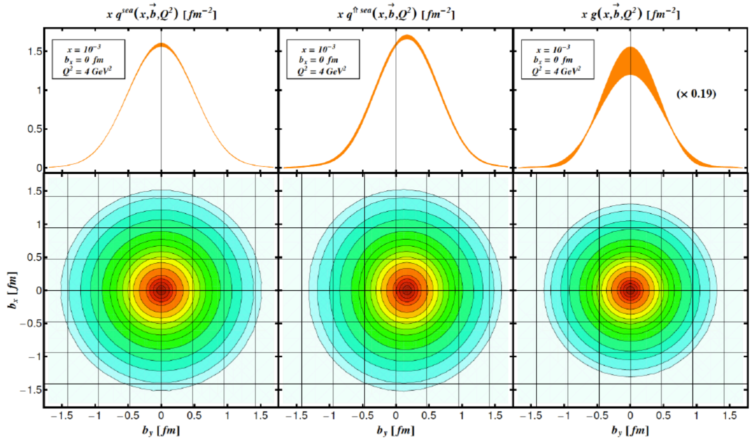
EIC kinematic lever arm

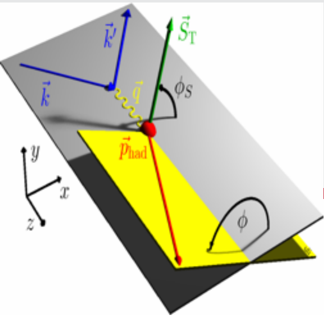
- EIC impact on sea quarks
- Extraction of E needs polarized beams
  →no constraints from Hera data
  →E crucial in ingredient in Ji sum rule



- EIC with good forward acceptance will cover a large lever arm in t →needed for spatial imaging

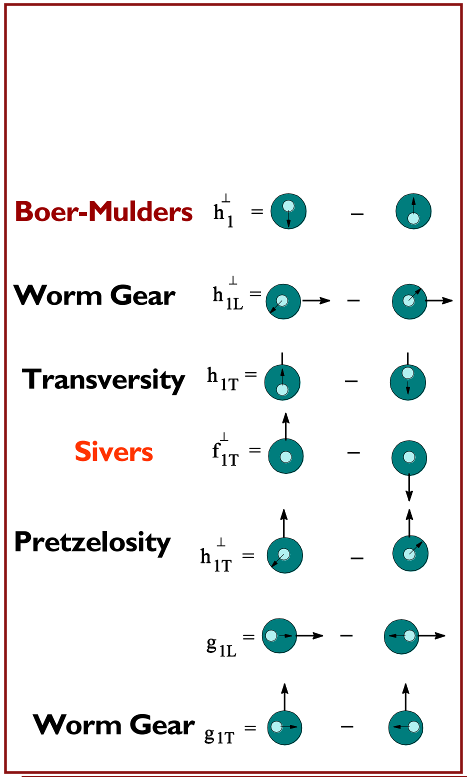






TMD PDFs from SIDIS

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$



$$d^6\sigma = \frac{4\pi\alpha^2 sx}{Q^4}\times$$

$$\{[1+(1-y)^2]\sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z,P_{h\perp}^2)$$
$$+(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Unpolarized

$$-|S_L|(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$
$$+|S_T|(1-y)\frac{P_{h\perp}}{zM_h}\sin(\phi_h^l+\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_1^q(x) H_1^{\perp q}(z,P_{h\perp}^2)$$
$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{zM_N}\sin(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z,P_{h\perp}^2)$$
$$+|S_T|(1-y)\frac{P_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_{1T}^{\perp(2)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$
$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_{q,\bar{q}} e_q^2 g_1^q(x) D_1^q(z,P_{h\perp}^2)$$

Polarized target

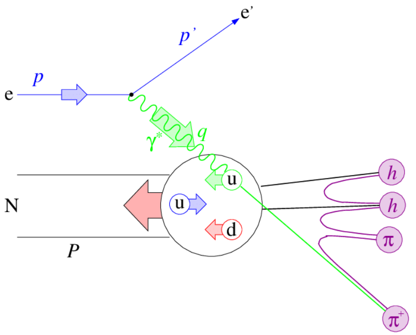
$$+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{P_{h\perp}}{zM_N}\cos(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 g_{1T}^{(1)q}(x) D_1^q(z,P_{h\perp}^2)\}$$

Polarzied beam and target

S_L and S_T: Target Polarizations; λe: Beam Polarization

x: momentum fraction carried by struck quark, z: fractional energy of hadron

Evolution of TMDs



$$F_{UT}^{\sin(\phi-\phi_s)} = \sum_q e_q^2 |C_V(Q)|^2 [R(Q,\mu_0) \otimes f_{1T,q}^{\perp}(x;\mu_0) \otimes D_{1,q}(z;\mu_0)](p_T),$$

Evolution Kernel

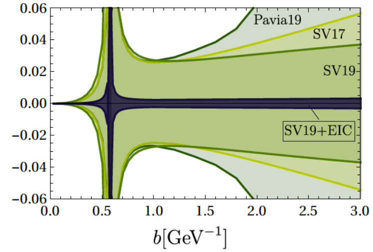
TMD PDF

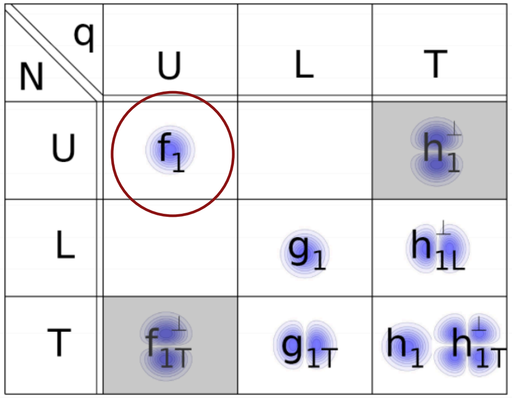
TMD FF

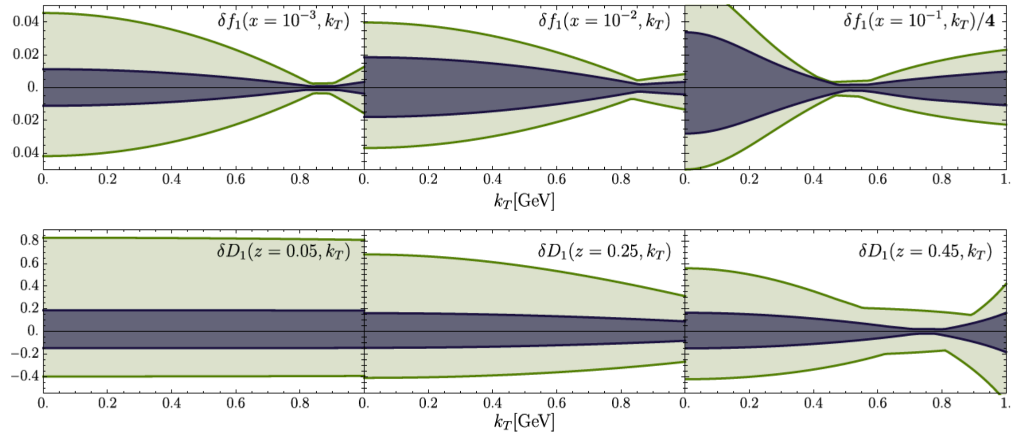
- Need larger lever arm in Q^2, x, k_T to determine evolution kernel, TMDs
- EIC will have large Q^2, x coverage → pin down evolution kernel, TMDs@low x
- Large p_T coverage → larger b coverage, where TMDs are unconstrained
- TMD factorization on more solid ground at EIC then at other high precision facilities (small $\frac{p_T}{Q} < \approx 1\ GeV$)

Impact of EIC on TMD measurements

- Results from SV19 refit with EIC pseudodata ($10\ fb^{-1}$), results from Pavia19 consistent
- As expected, biggest reduction in kernel→independent of TMD
- TMD PDF and FF uncert reduction mostly at low x, low z

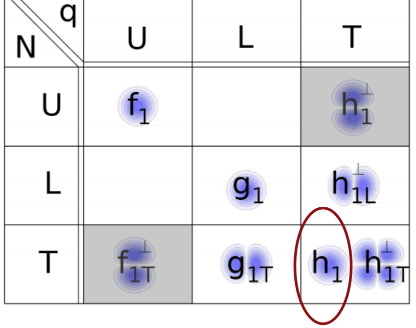




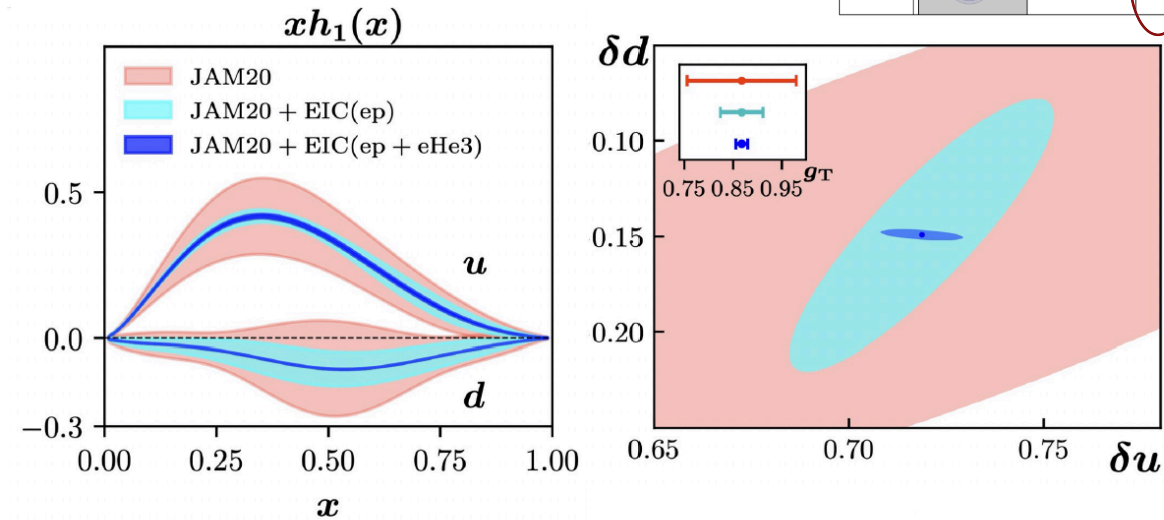


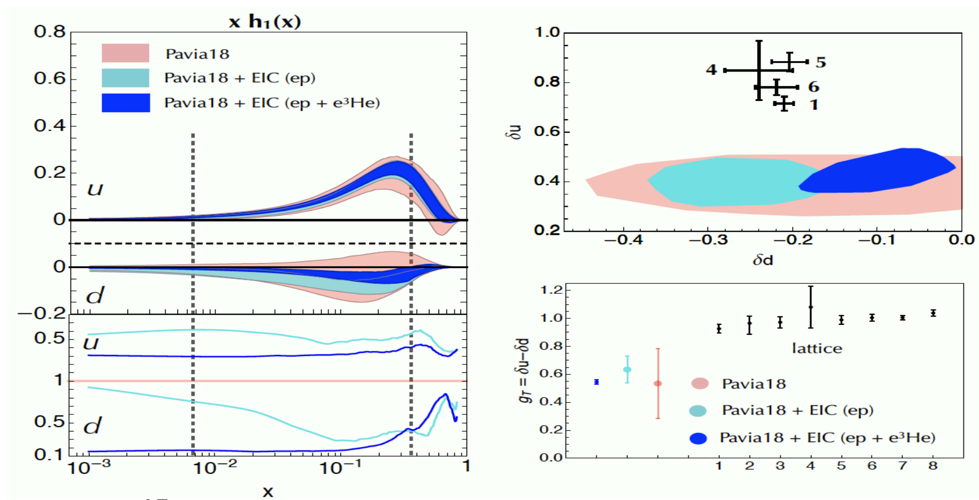
TMD PDF f^u(top) and FF D^{π^+} (bottom)

Impact on Transversity and Tensor charge



- Chiral-odd transversity $h(x)$ can be accessed single and di-hadron measurements (complementary)
- $\int h(x)dx \propto g_T$(tensor charge)→can be compared to lattice, needed to estimate coupling to certain new physics interactions

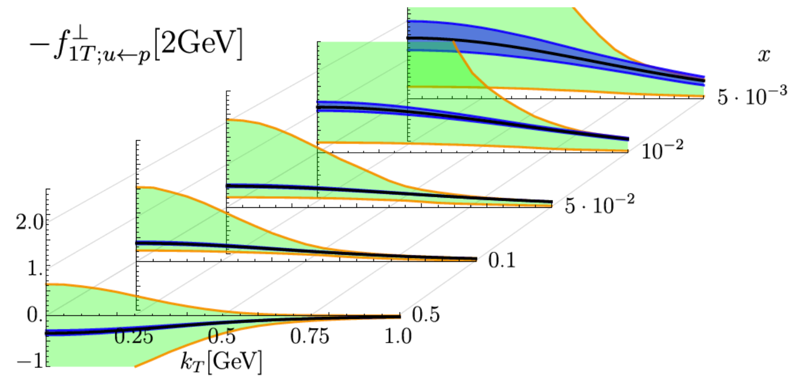


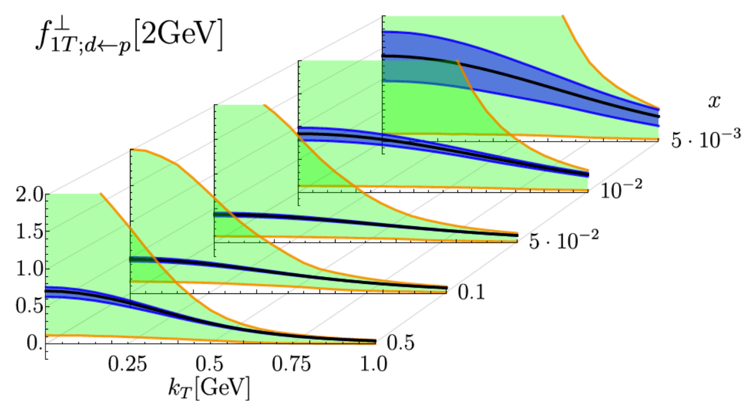


Constrains on T-odd Sivers

N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

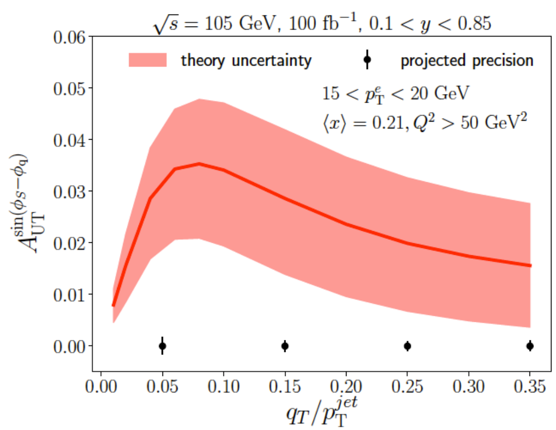
- Sivers function is one of the “original” TMDs
- T-odd, vanishes if there is no OAM
- Modified universality
- Can be precisely determined in single spin asymmetries
- Impact of EIC data will be enormous
- Impact on $f_d^{\perp}$ from He^3 data in particular noteworthy



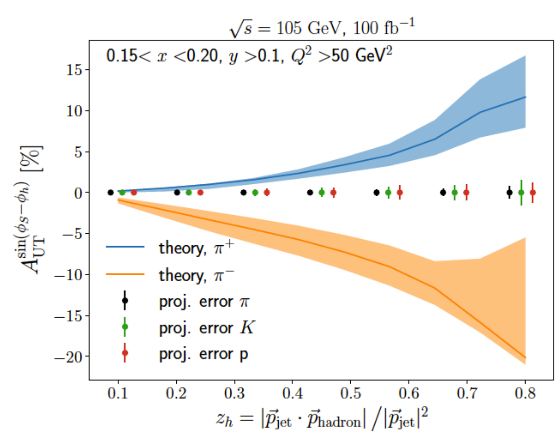


Accessing TMD PDFs and FFs with Jets

- Jets can be used as proxy for outgoing parton
  →Decouple PDF and Fragmentation function (FF)
  →breaks convolution of transverse momenta
- Enables to
  - measure TMD w/o FF contribution
  - FF w/o TMD contribution



Sivers asymmetry



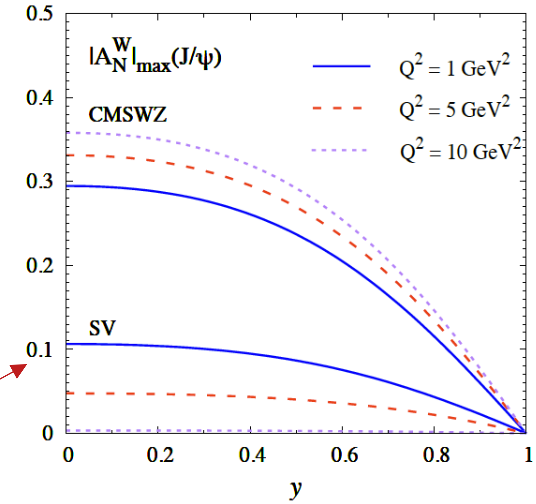
Collins asymmetry

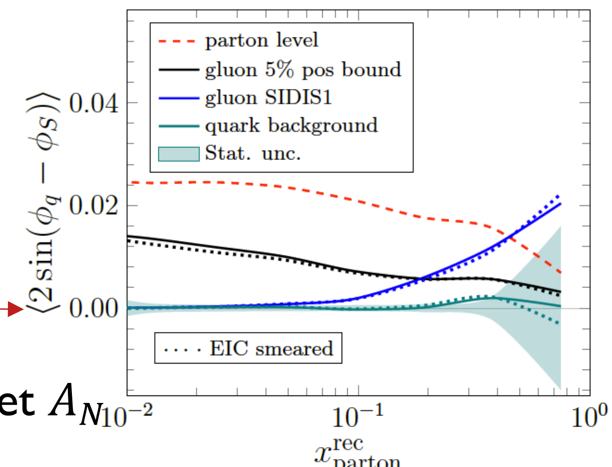
Phys.Rev.D 102 (2020) 7, 074015

Access to Gluon TMDs with dijets

- Gluon TMDs structure more involved than quark sector
  - 8 TMDs, two types: Weizsacker-Williams (WW) and dipole
  - SIDIS unique for WW type
  - Very little known about unpolarized and polarized gluon TMDs
  - Heavy quarkonium ideal channel, but relation of asymmetries to gluon TMDs model dependent
  - Open heavy quark (e.g. D meson pairs) also good, but large uncertainties
    →dijet/dihedron most promising
- Example: Gluon Sivers via dijet asymmetries

$J/\Psi\ A_N$

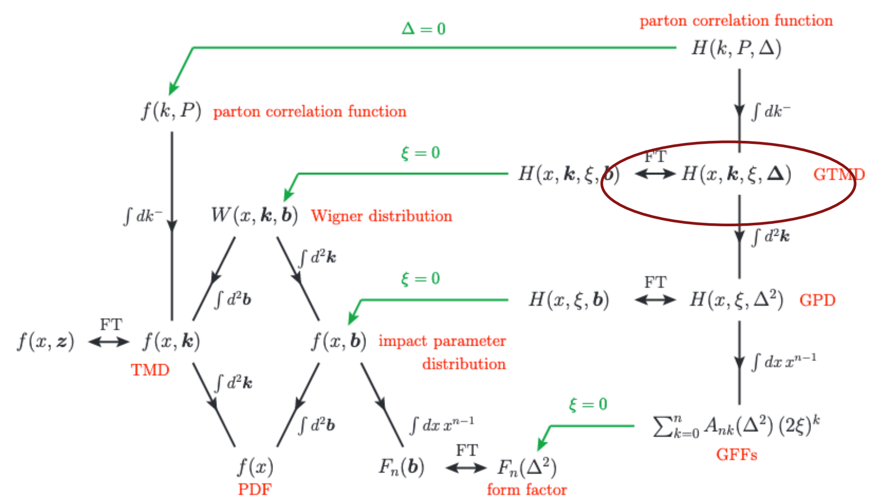




Dijet A_N

$10\ fb^{-1}, 18{\times}275$

Wigner/GTMDs



- GTMDs ≠ TMDs +GPDs➔encode additional correlations between k_T and b_T
- Can e.g. extract orbital angular momentum in intuitive way

$$L^z_{q,g} = \int dx \int d^2\mathbf{k}_\perp d^2\mathbf{b}_\perp (\mathbf{b}_\perp \times \mathbf{k}_\perp)^z W^{q,g}_{LU}(x, \mathbf{k}_\perp, \mathbf{b}_\perp, \mathcal{W}).$$

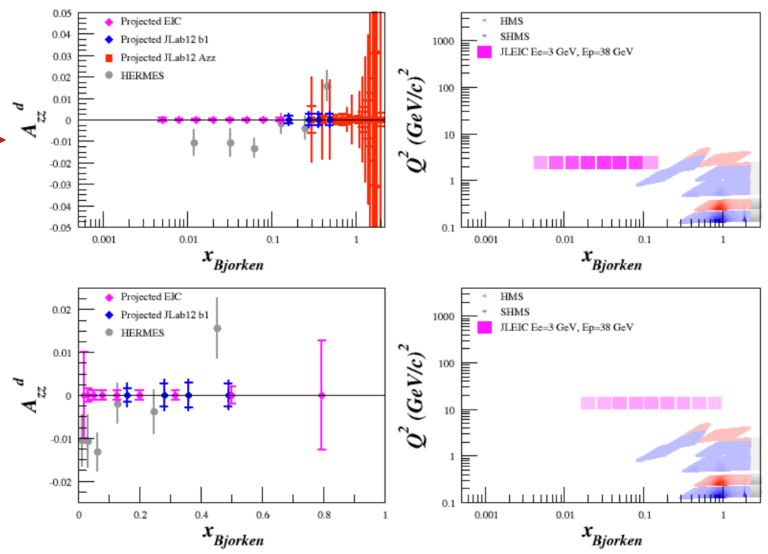
Gluon GTMD at small x from diffractive dijets →two momentum vectors, sum and difference of jet momenta: Measure azimuthal modulations between both→related to $b_\perp$, $k_\perp$ correlation

- Asymmetries of ≈ a few percent expected
- More processes? (also to access quark GTMD, currently only in πN scattering)

Light Nuclei

- Coherent DVCS
  - Possible due to EIC ability to detect recoiling nucleon (much easier in collider)
  - Nuclear tomography, e.g. EMC effect
  - EMT of nucleus, e.g. “d term” → pressure &forces inside the nucleon

  - Deuteron, 3He, 4He complimentary in binding energies and spin complexity. (D: spin 1: more complex structure 3He spin ½: same as proton, structure the same 4He, spin 0 Simpler)
- Tensor polarized deuteron
  - 4 additional structure functions b_{1-4}
  - b_1 has partonic interpretation and is explicitly dependent on surrounding nucleon
  - In quasi elastic regime sensitive to S/D components of deuteron wavefunction
  - Asymmetries significant with spectator tagging

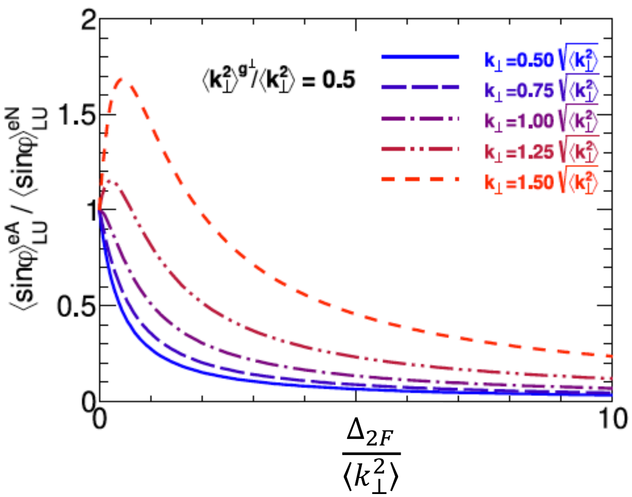


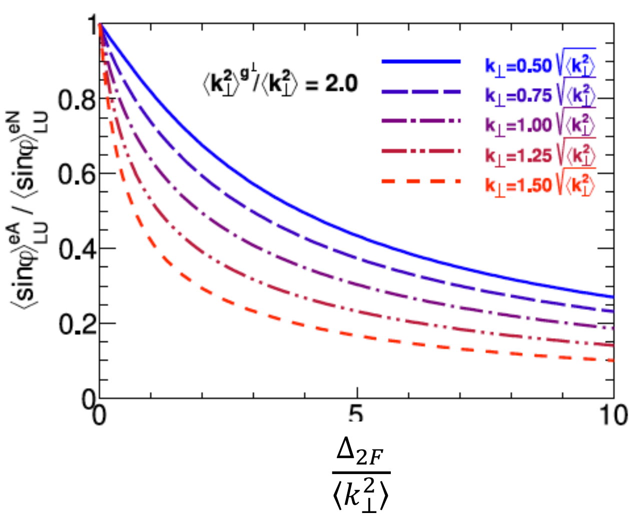
$1 fb^{-1}$@3×38

Medium Modification of Azimuthal Asymmetries

- In gaussian approximation
  $f_1^A(x, k_\perp) \approx \frac{A}{\pi\alpha} \mathrm{f}_1^{\mathrm{N}}(\mathrm{x}) \mathrm{e}^{\frac{-\vec{\mathrm{k}}_\perp^2}{\alpha}}$, with $\alpha = \langle k_\perp^2 \rangle + \Delta_{2F}$
  Quark transport parameter Δ_{2F} related to gluon density (due to interaction with gluons)
- Jets are sensitive to TMD PDF k_T only

$$\frac{\langle \sin\phi \rangle_{LU}^{eA}}{\langle \sin\phi \rangle_{LU}^{eN}} \approx \frac{\langle k_\perp^2 \rangle_A}{\langle k_\perp^2 \rangle} \left(\frac{\langle k_\perp^2 \rangle^{g^\perp}}{\langle k_\perp^2 \rangle_A^{g^\perp}} \right)^2 \exp\left[\left(\frac{1}{\langle k_\perp^2 \rangle_A} - \frac{1}{\langle k_\perp^2 \rangle} - \frac{1}{\langle k_\perp^2 \rangle_A^{g^\perp}} + \frac{1}{\langle k_\perp^2 \rangle^{g^\perp}} \right) \vec{k}_\perp^2 \right].$$



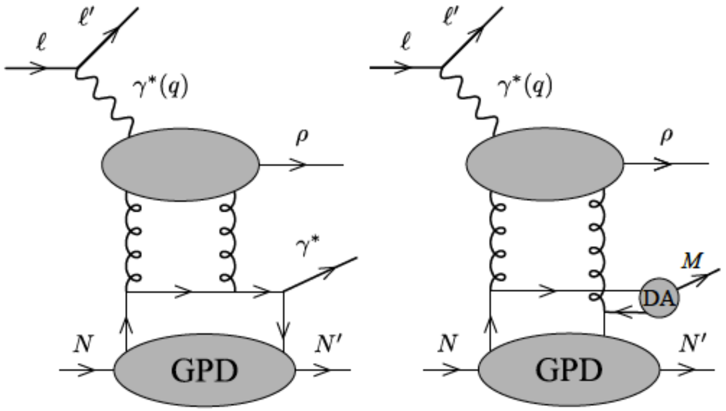


Summary

- Thank you all for your contributions!

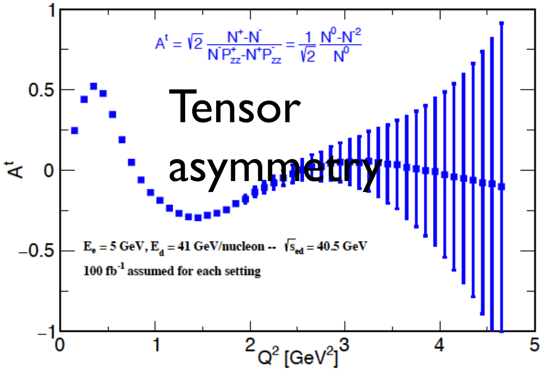
Backup

Diffractive DVCS and photoproduction of $\gamma\gamma$ / $\gamma\rho$



- New processes to be explored
- Diffractive DVCS and meson production
  - Diffractive processes make up large part of the x-section
  - Covers different regime in ξ, decorrelates from x
- Photoproduction of $\gamma\gamma$ and $\gamma\rho$ probe different kinematics in ξ
- Chiral odd GPDs can be accessed using decay distribution of ρ
  - Connection to transversity

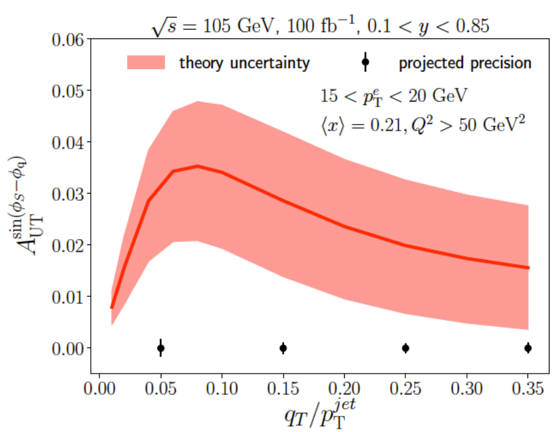
Tensor polarized up to ≈ 2.5 GeV

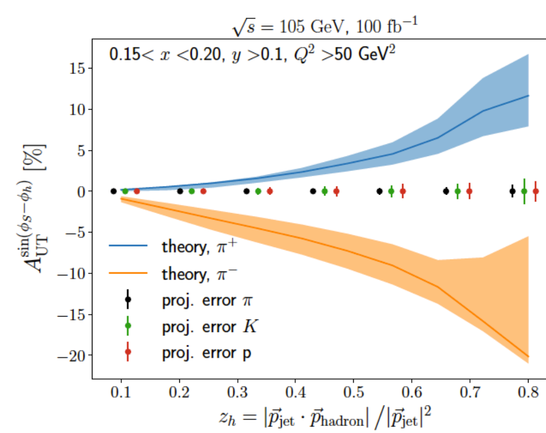


Di-hadron and jets

Quark transport parameter Δ_{2F} related to gluon density (interaction with gluons)

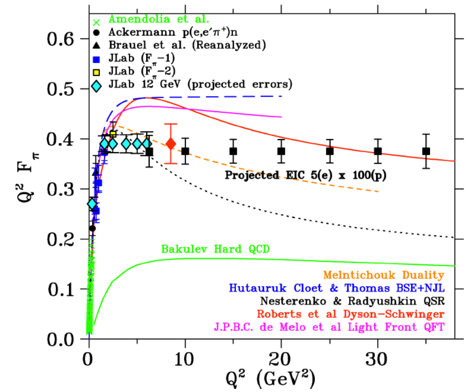
$$d^2\ell_\perp e^{-(\vec{k}_\perp-\vec{\ell}_\perp)^2/\Delta_{2F}} f_q^N(x,\ell_\perp),$$





Meson form factors

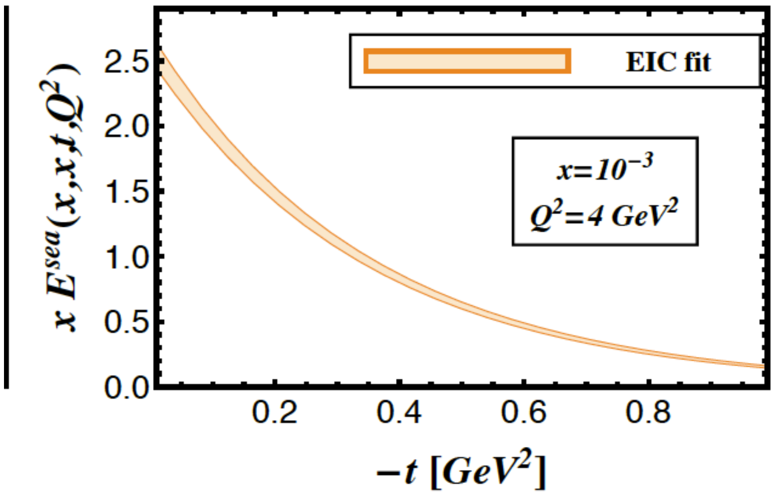
- Elucidating in vis a vis mass generation (see also discussion about mass generation in 7.1) (kaon 1/3 higgs, pion almost 100% QCD)
- (how is F extracted again?)
- Kaon cloud unclear, to be verified by Jlab →sigma0/lambda ratio to ge \sigma_L/sigma_T

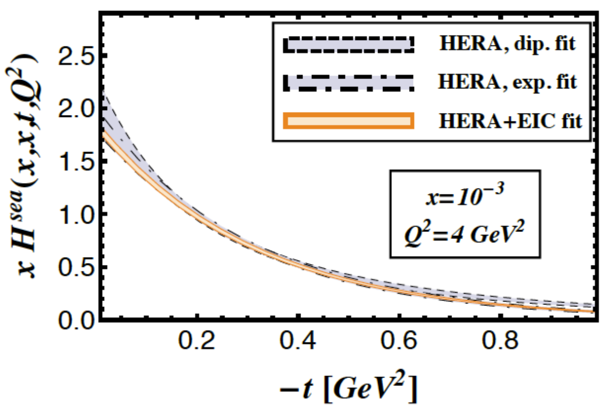


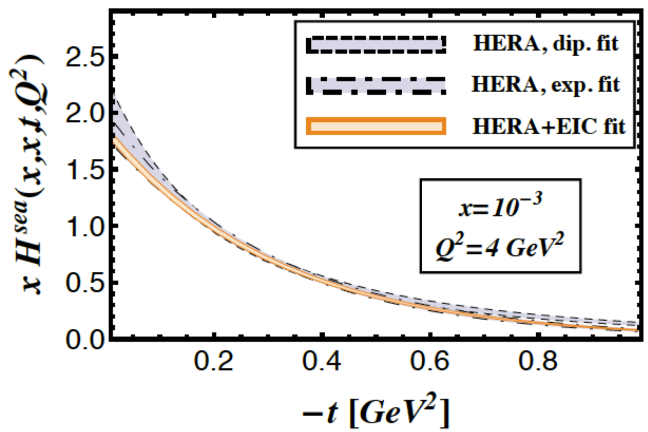
- f

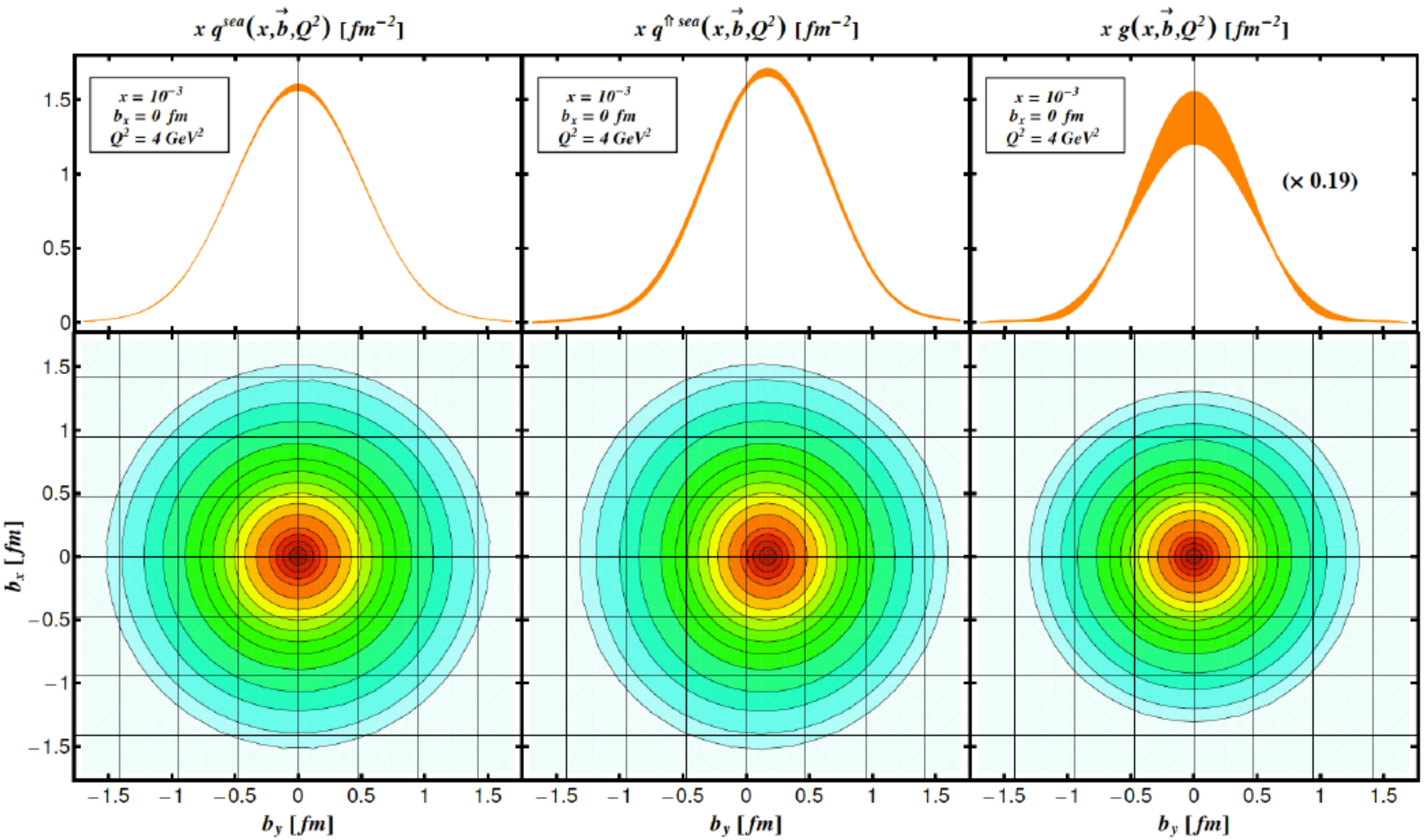
GPD

- GPDs are related to CFF which in general contain convolutions
- Impact picture is FT of t dependence
- →large kinematic coverage essential









$x\,q^{sea}(x,\vec{b},Q^2)$ [fm^{-2}]
$x\,q^{\Uparrow sea}(x,\vec{b},Q^2)$ [fm^{-2}]
$x\,g(x,\vec{b},Q^2)$ [fm^{-2}]
$x = 10^{-3}$
$b_x = 0$ fm
$Q^2 = 4$ GeV^2
(× 0.19)
b_x [fm]
b_y [fm]

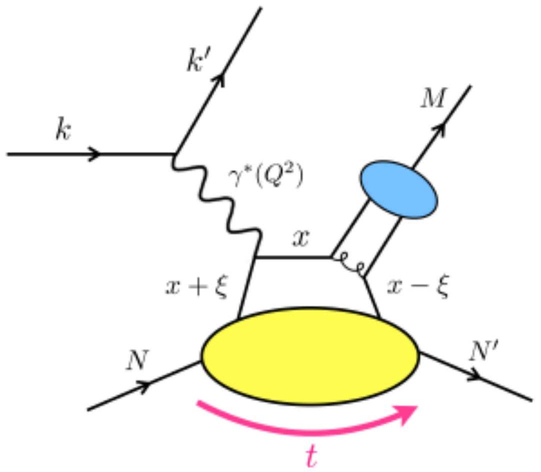
TMD

$$F_{UT}^{\sin(\phi-\phi_s)} = \sum_q e_q^2 |C_V(Q)|^2 \int \frac{d^2b}{(2\pi)^2} e^{i(bp_T)/z} R(Q,b,\mu_0) f_{1T,q}^{\perp}(x,b;\mu_0) D_{1,q}(z,b;\mu_0)$$

- EMT → D term (with positron beam)

GPD measurements in meson production

- Heavy: access to gluons
- Vector : similar to DVCS but allows quark flavor separation
- Light pseudoscalar: access to parity odd and chiral odd GPDs, connection to transversity



(c)

- ”Golden channels”… :.?
- TMDs,
  - Precision in x,kT
  - Evolution (← strong suite of the EIC)
- Collins/Sivers →Tensor charge
- Gluon TMDs →di-hadrons, jets, heavy quarks
- Di-hadron
- Jets
- Wigner

Light nuclei

- Coherent DVCS by detecting recoling nucleon
- Deuterium →tensor polarization
- Medium Modification azimuthal modulation
-

Outline

- Imaging in position space and GPDs
- TMDs
- Wigner functions
- Nuclei

Imaging in Position Space

- Form factor
  - → probe magnetic form factors to highest Q2 (I guess at low Q2 one loses sensitivity anyways…)
  - At $\epsilon \approx 1$(unlike fixed target) → I guess that means no G_E?
  - Q2> 1.0 (acceptance for Q2 < 1.0 not there for electron), proton will need far forward detectors for low Q2
  - No double spin asymmetries (too small)
  - Adding positron beam will help with studying two-photon processes

  - e-d possible up to $Q^2 = 5$ GeV^2
  - Tensor polarization measureents up to 2.5GeV2

- Nuclei
    - Tensor polarization possible at EIC?

GPDs

- [306][309],[310]
- See pub in [306]
- Form factor of EMT