TMD Study with SIDIS on Tensor Polarized Deuteron

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SoLID Collaboration Meeting
Winter 2023

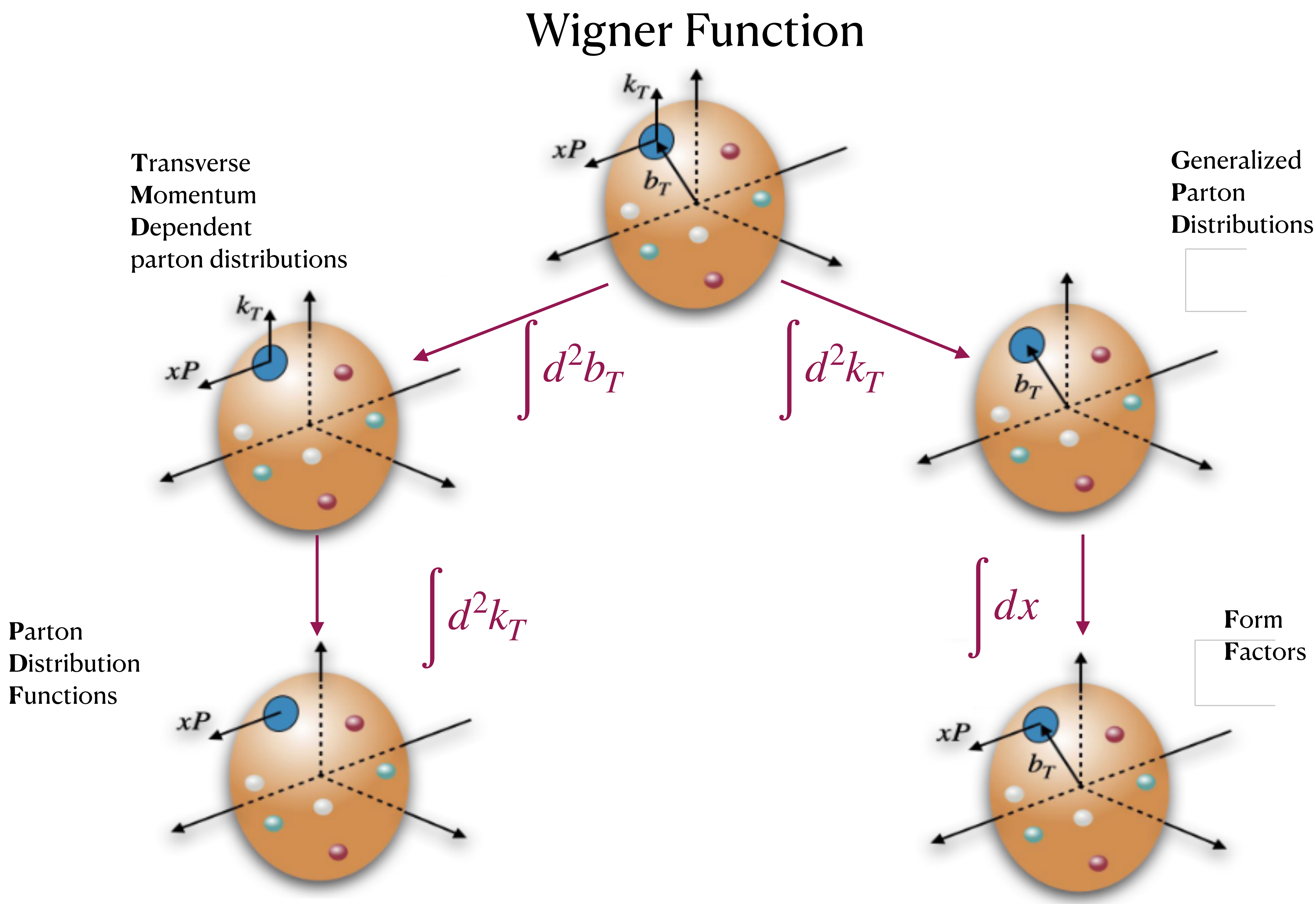
University of New Hampshire

UNIVERSITÀ DI PAVIA

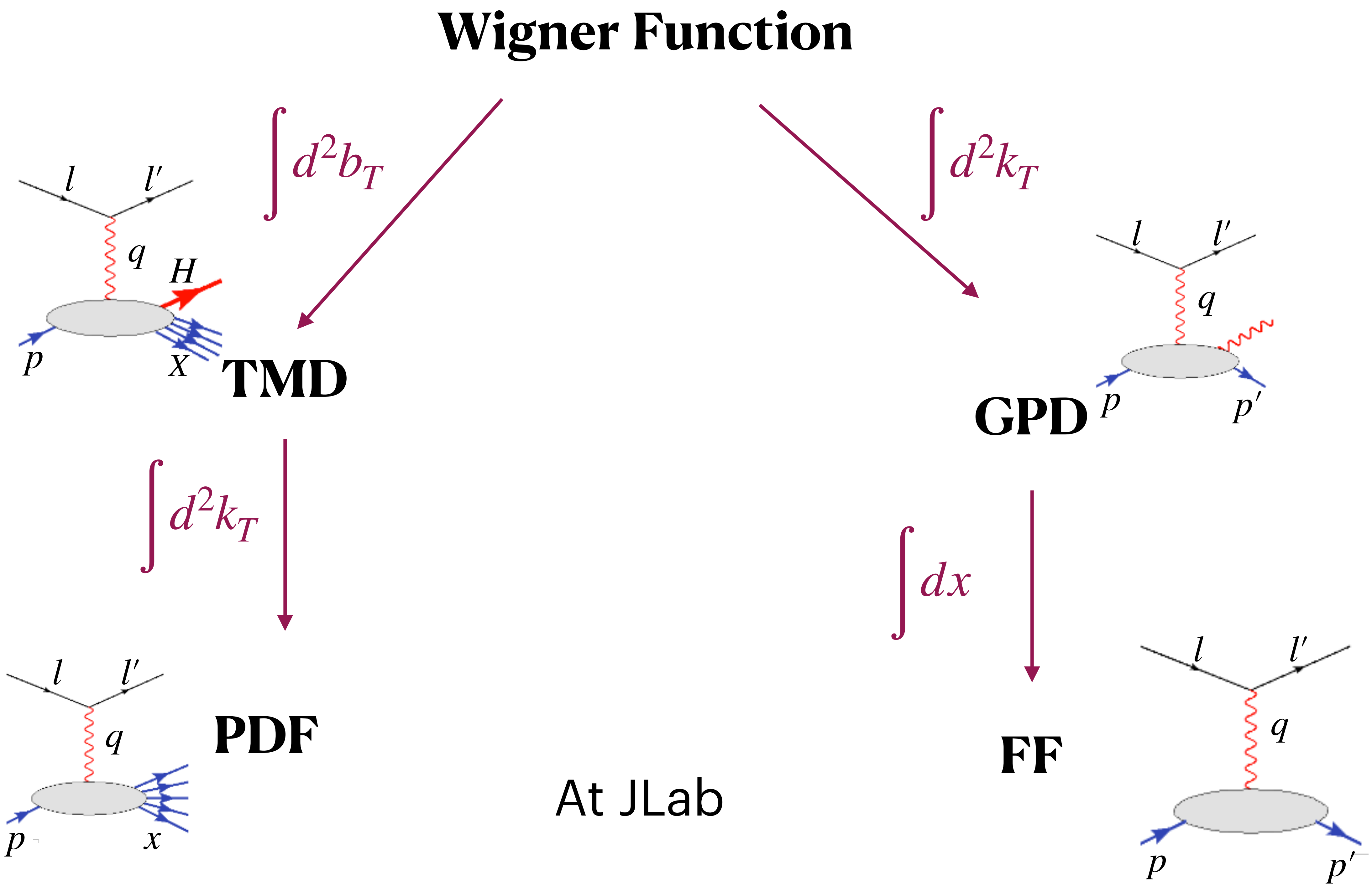
UNIVERSITY of VIRGINIA

Jefferson Lab

Unified View of Nucleon Structure

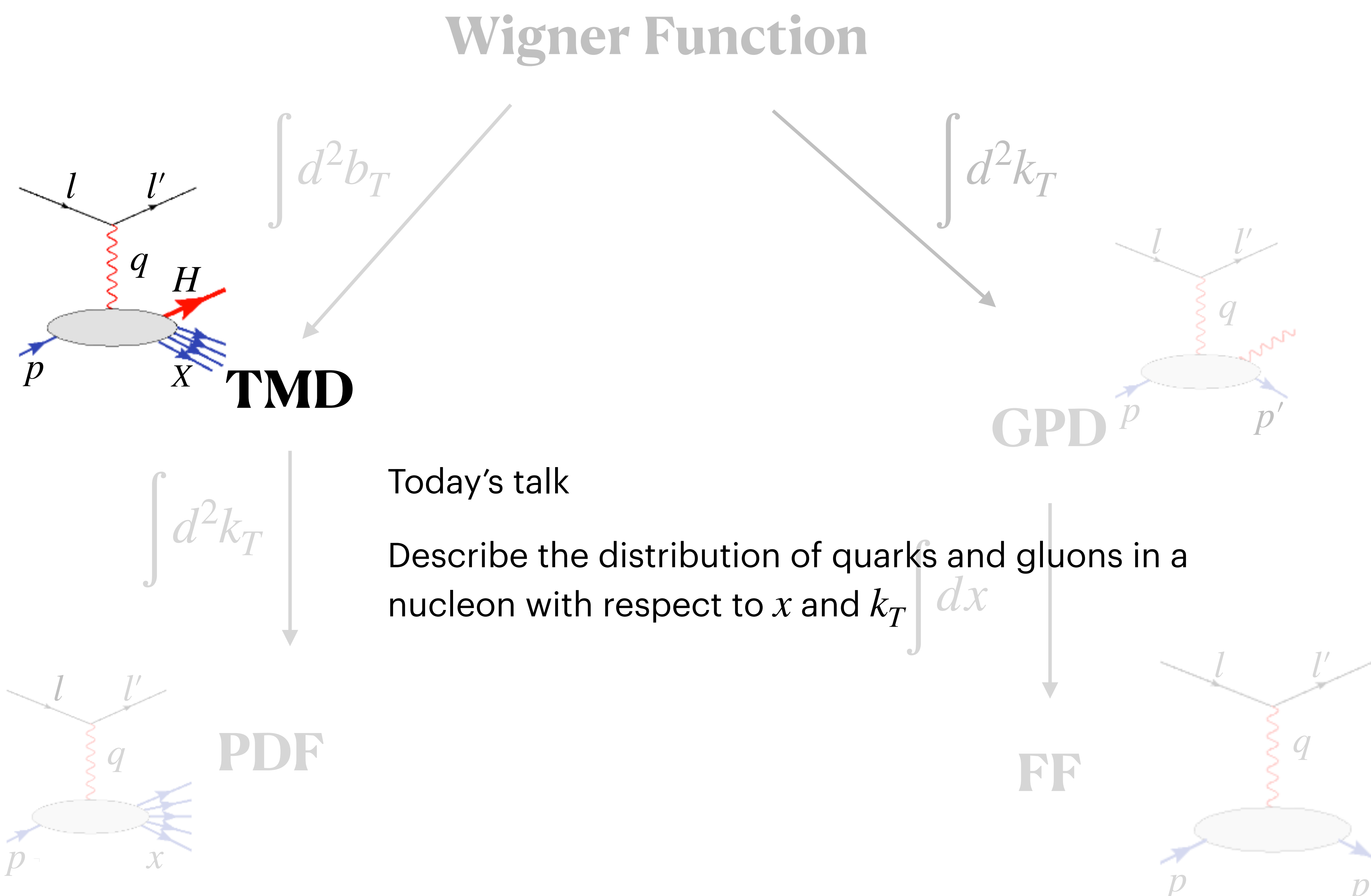


Unified View of Nucleon Structure



At JLab

Unified View of Nucleon Structure

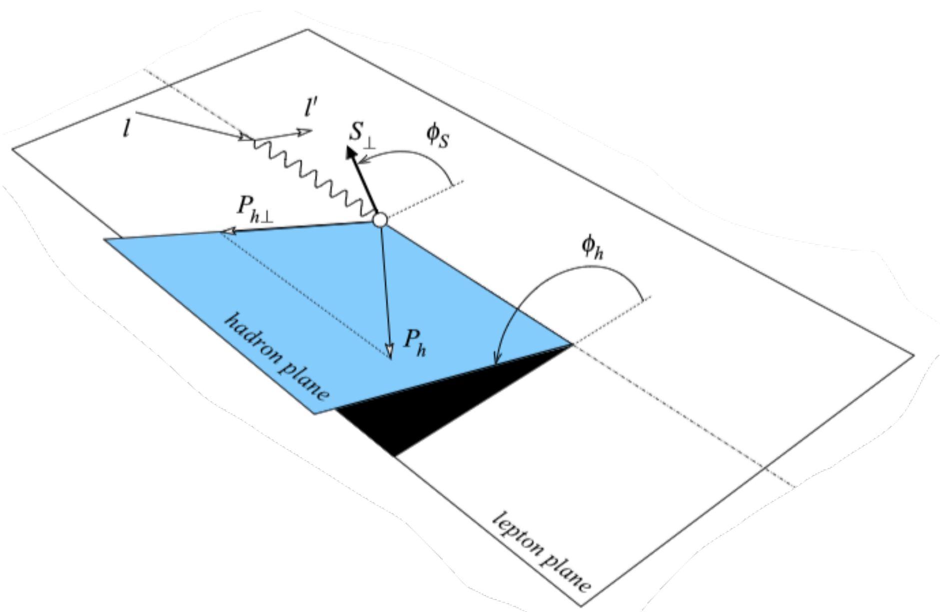


Today's talk

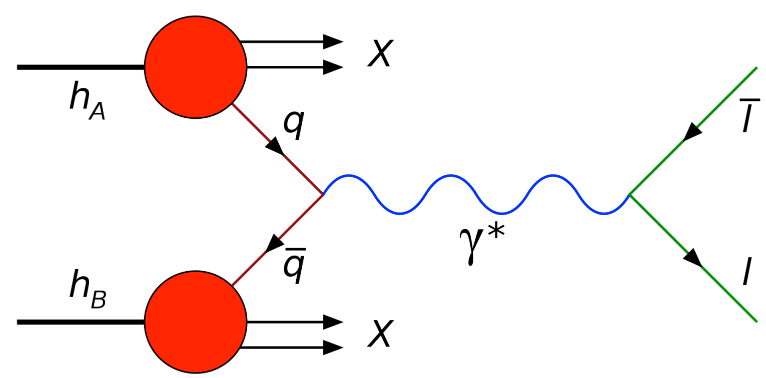
Describe the distribution of quarks and gluons in a nucleon with respect to x and k_T

Accessing TMDs

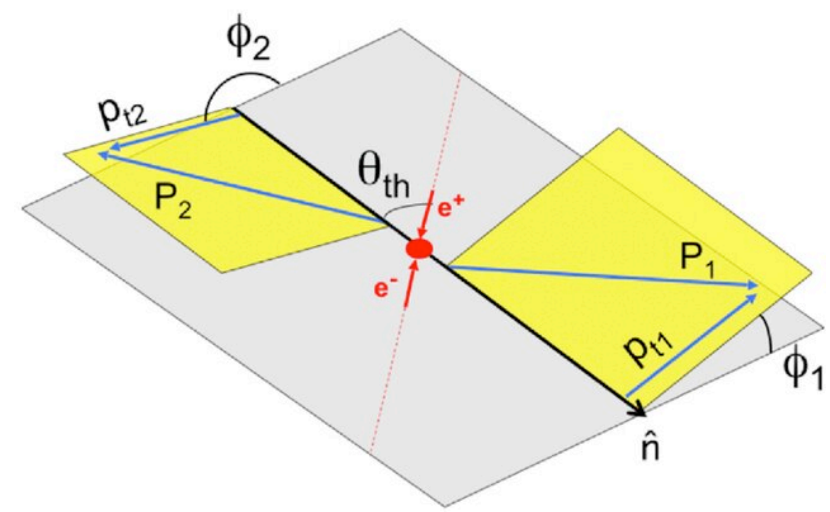
SIDIS
JLab, HERMES, COMPASS



Drell-Yan
COMPASS, Fermilab, RHIC



$e^- + e^+ \rightarrow h_1 + h_2 + X$
Belle, BarBar



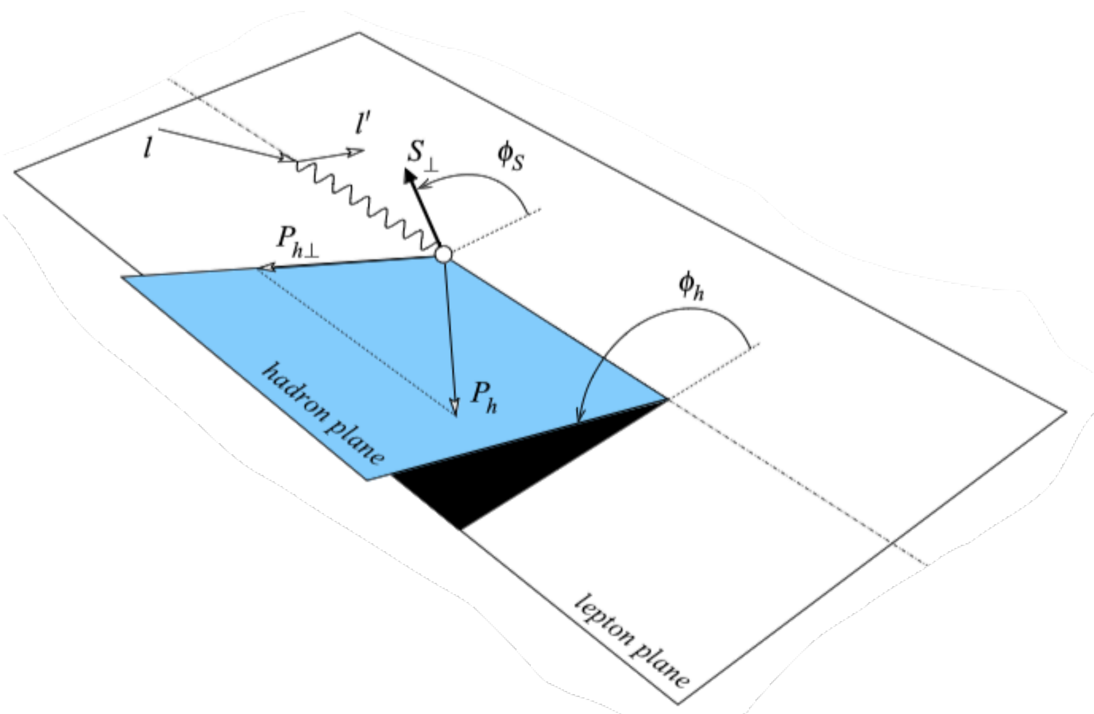
★TMD factorization needs two observed momenta.

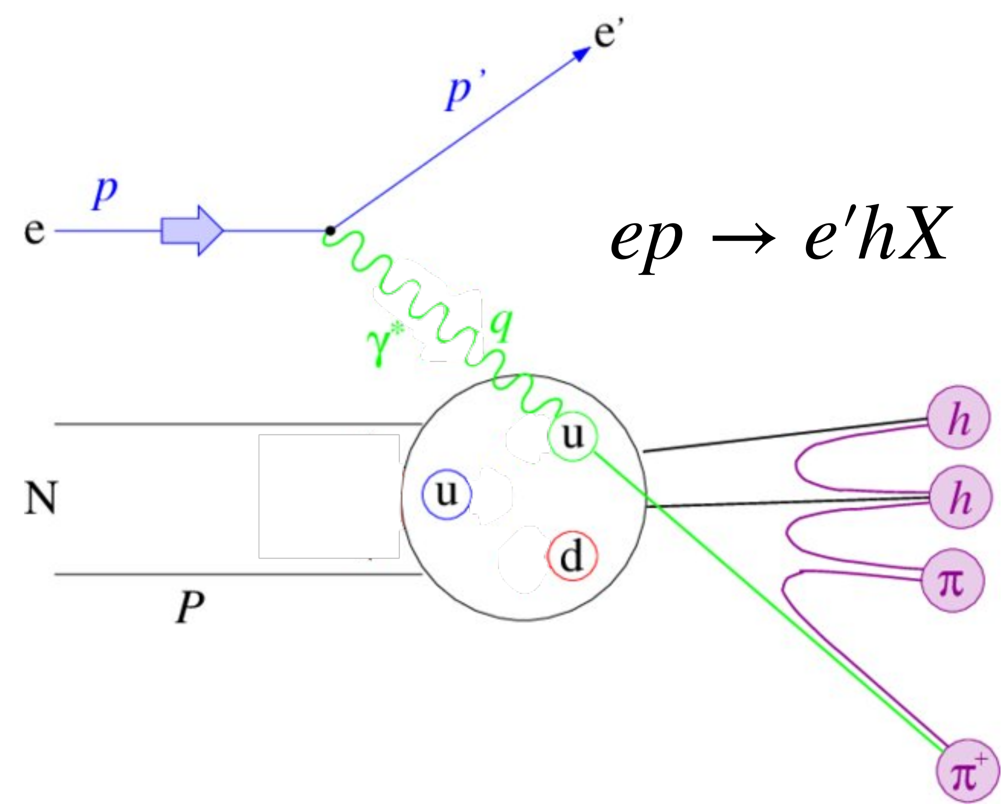
★Sensitive to:

- parton model with gluons and sea quarks
- partons have transverse momentum and angular momentum
- full decomposition of the nucleon spin

Accessing TMDs at JLab

SIDIS





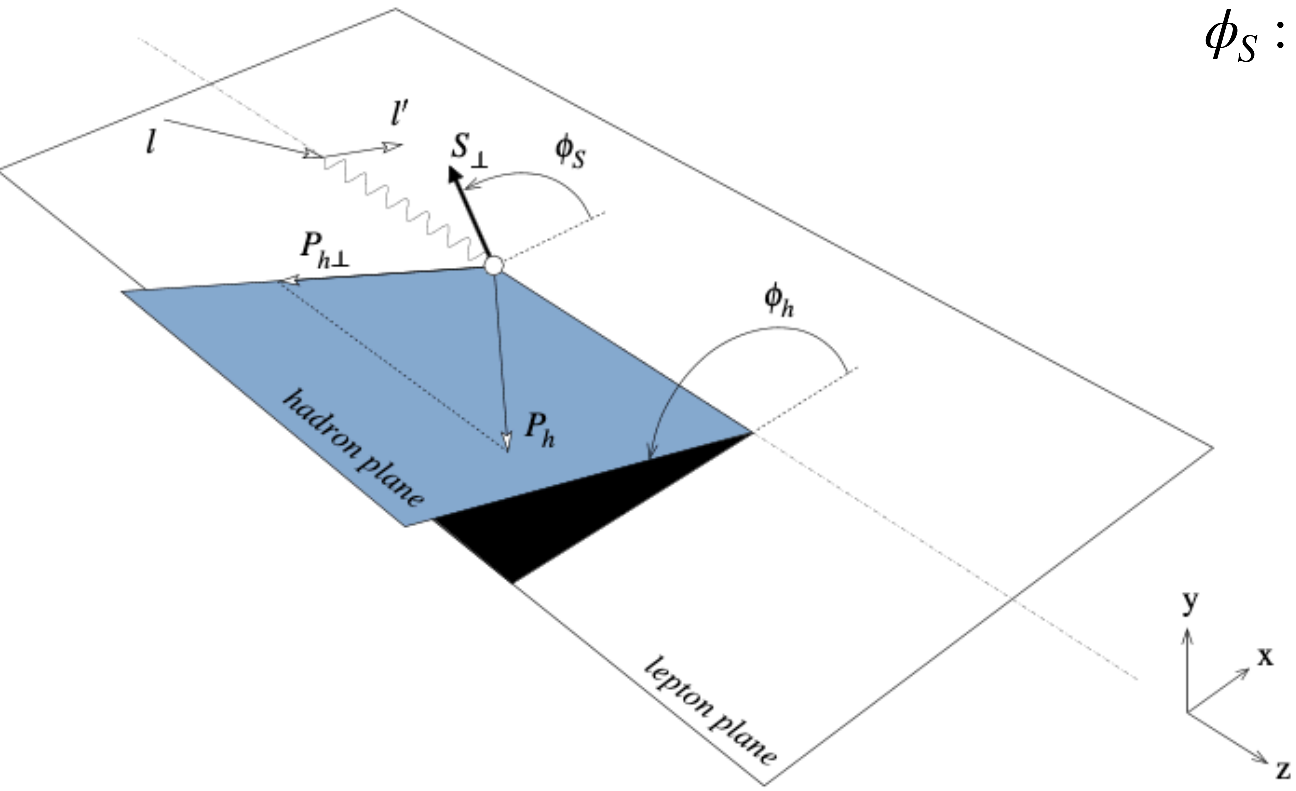
$$ep \rightarrow e'hX$$

$$x \;\; Q^2 \;\; \phi_s \;\; z \;\; P_{h\perp} \;\; \phi_h$$

multi-dimensional observables

TMDs are NOT direct physical observables!

SIDIS Kinematics



ϕ_h : Angle between lepton and hadron planes

ϕ_S : Angle between lepton plane and nucleon spin

Momentum transfer: $Q^2 = -(l - l')^2$

Center-of-mass energy: $s = (P + l)^2$

Invariant mass: $W^2 = (P + q)^2$

Missing mass: $W'^2 = (P + q - P_h)^2$

Fraction of the energy lost in the nucleon rest frame: $y = \dfrac{P \cdot q}{P \cdot l}$

$$x = \frac{Q^2}{2P \cdot q} \qquad z = \frac{P_h \cdot P}{P \cdot q}$$

$$\gamma = \frac{2Mx}{Q} \qquad \varepsilon = \frac{1 - y - \frac{1}{4}\gamma^2 y^2}{1 - y + \frac{1}{2}y^2 + \frac{1}{4}\gamma^2 y^2}$$

$$\cos\phi_h = \frac{\hat{\mathbf{q}} \times \mathbf{l}}{|\hat{\mathbf{q}} \times \mathbf{l}|} \cdot \frac{\hat{\mathbf{q}} \times \mathbf{P}_h}{|\hat{\mathbf{q}} \times \mathbf{P}_h|}$$

$$\sin\phi_h = \frac{(\mathbf{l} \times \mathbf{P}_h) \cdot \hat{\mathbf{q}}}{|\hat{\mathbf{q}} \times \mathbf{l}||\hat{\mathbf{q}} \times \mathbf{P}_h|}$$

Trento Conventions
Phys. Rev. D70, 117504 (2004)

SIDIS differential cross section

λ_e Electron helicity

$S_{||}$ Longitudinally polarized nucleon

$S_\perp$ Perpendicular polarized nucleon

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

In OPE approximation: cross section decomposed in a model independent way into 18 structure function F related to the various azimuthal modulations

arXiv:hep-ph/0611265v2

Spin 1/2

SIDIS differential cross section at leading twist

$$\frac{d\sigma}{dxdydzd\phi_s d\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{uu,T} + \varepsilon cos(2\phi_h)F_{UU}^{cos2\phi_h} +$$

$$S_{||}\varepsilon sin(2\phi_h)F_{UL}^{sin2\phi_h} +$$

$$S_{||}\lambda_\varepsilon\sqrt{1-\varepsilon^2}F_{LL} +$$

$$S_\perp\Big[sin(\phi_h-\phi_s)F_{UT}^{sin(\phi_h-\phi_s)} + \varepsilon sin(\phi_h+\phi_s)F_{UT}^{sin(\phi_h+\phi_s)} + \varepsilon sin(3\phi_h-\phi_s)F_{UT}^{sin(3\phi_h-\phi_s)}\Big] +$$

$$S_\perp\lambda_e\sqrt{1-\varepsilon^2}cos(\phi_h-\phi_s)F_{LT}^{cos(\phi_h-\phi_s)}\Big\}$$

Spin 1/2

Structure functions in terms of TMDs

$$F_{UU,T} = \mathcal{C}\left[f_1 D_1\right]$$

$$F_{UU}^{\cos 2\phi_h} = \mathcal{C}\left[-\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)-\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{M M_h} h_1^{\perp} H_1^{\perp}\right]$$

$$F_{UL}^{\sin 2\phi_h} = \mathcal{C}\left[-\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)-\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{M M_h} h_{1L}^{\perp} H_1^{\perp}\right]$$

$$F_{LL} = \mathcal{C}\left[g_{1L} D_1\right]$$

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

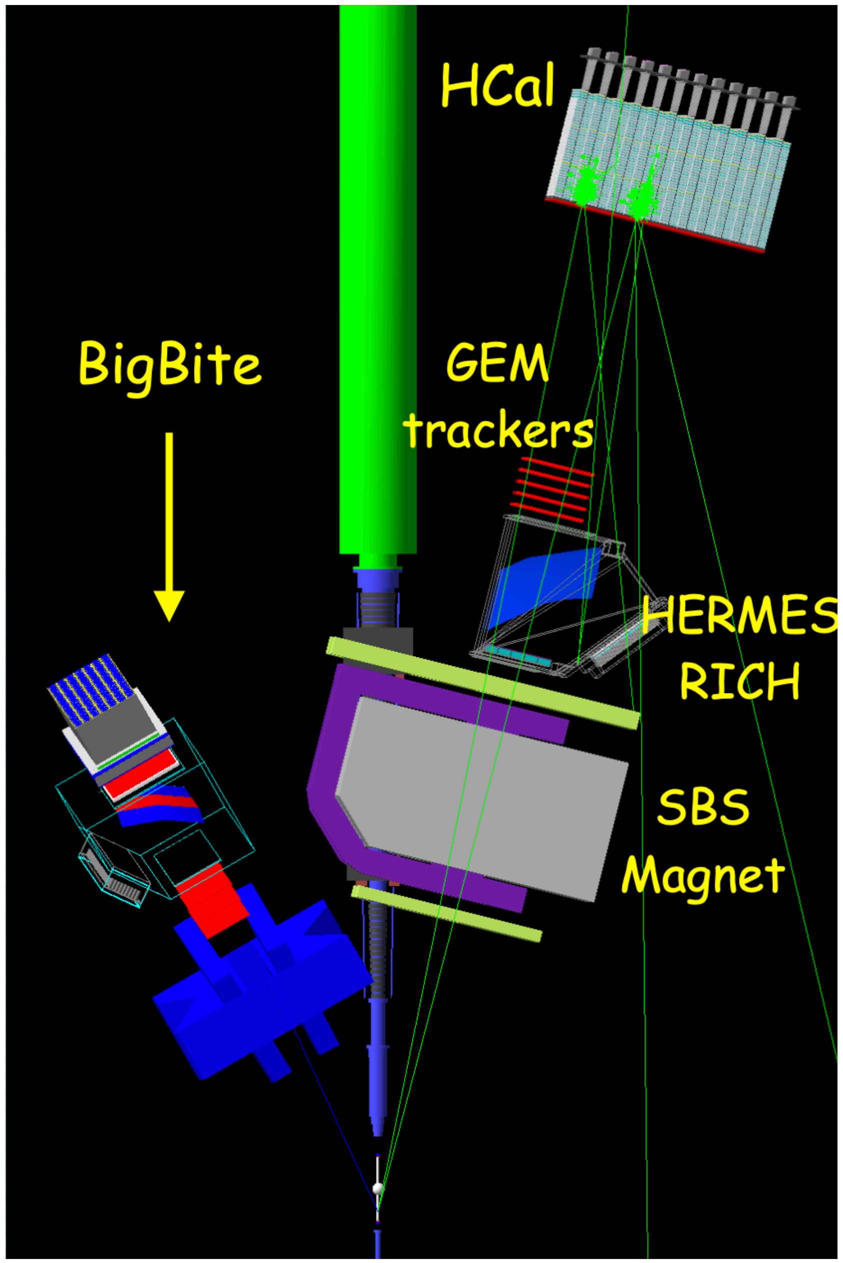
$$F_{UT}^{\sin(\phi_h+\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h} h_1 H_1^{\perp}\right]$$

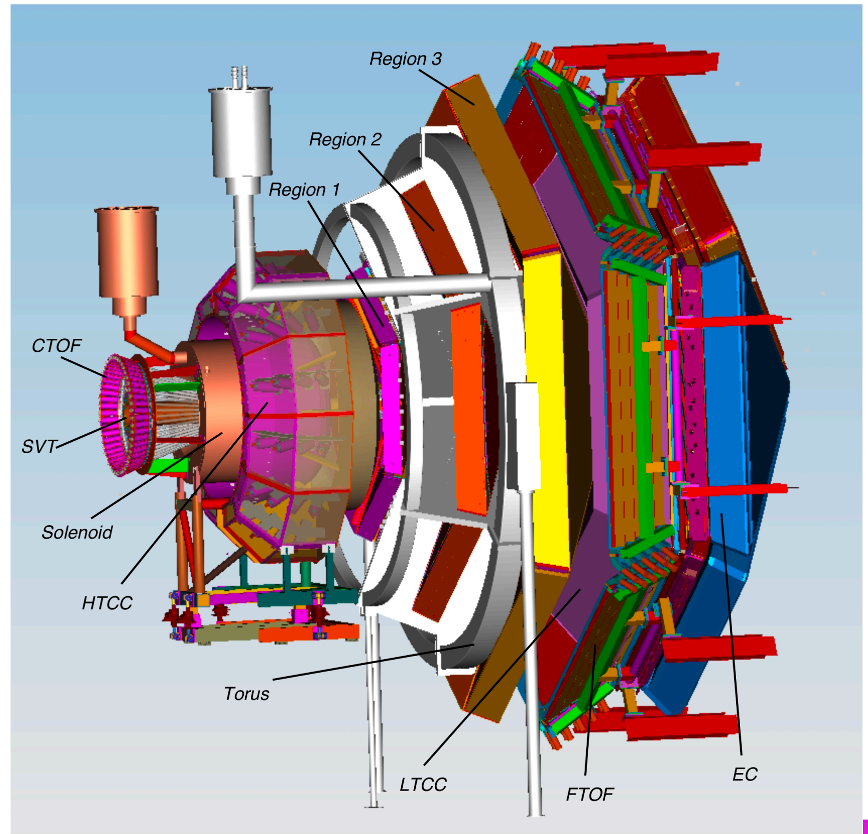
$$F_{UT}^{\sin(3\phi_h-\phi_S)} = \mathcal{C}\left[\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)\left(\boldsymbol{p}_T\cdot\boldsymbol{k}_T\right)+\boldsymbol{p}_T^2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)-4\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)^2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)}{2M^2 M_h} h_{1T}^{\perp} H_1^{\perp}\right]$$

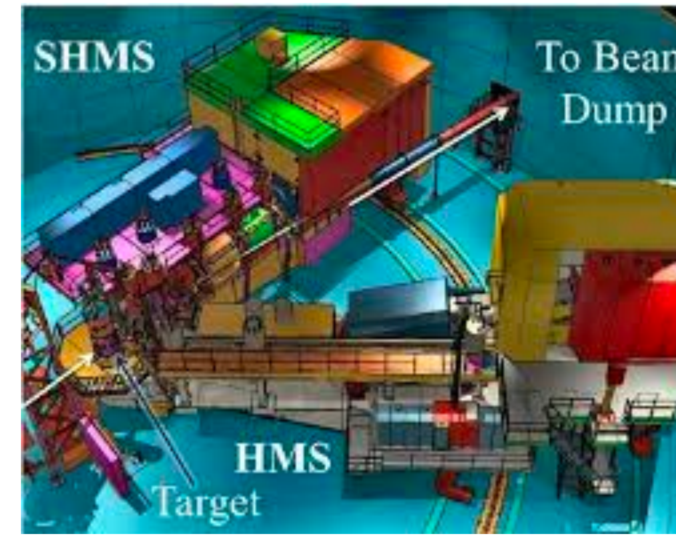
$$F_{LT}^{\cos(\phi_h-\phi_S)} = \mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M} g_{1T} D_1\right]$$

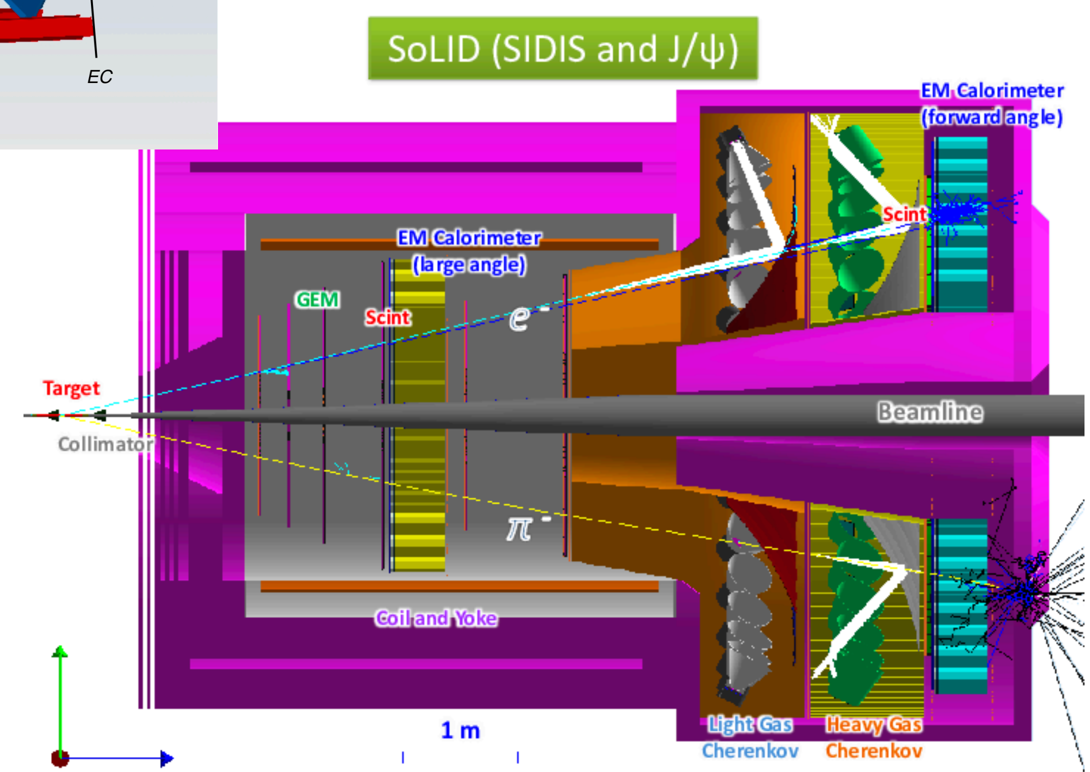
Spin 1/2

Many experiments at JLab







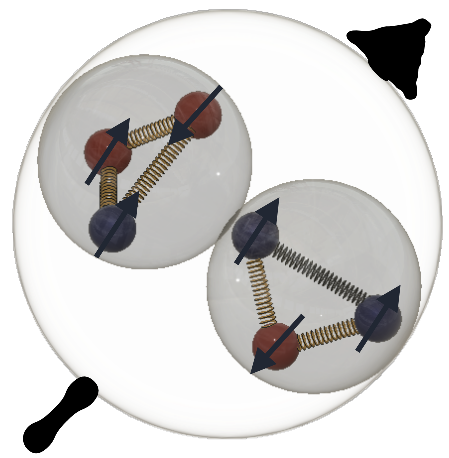


- Hall A
- Hall B
- Hall C

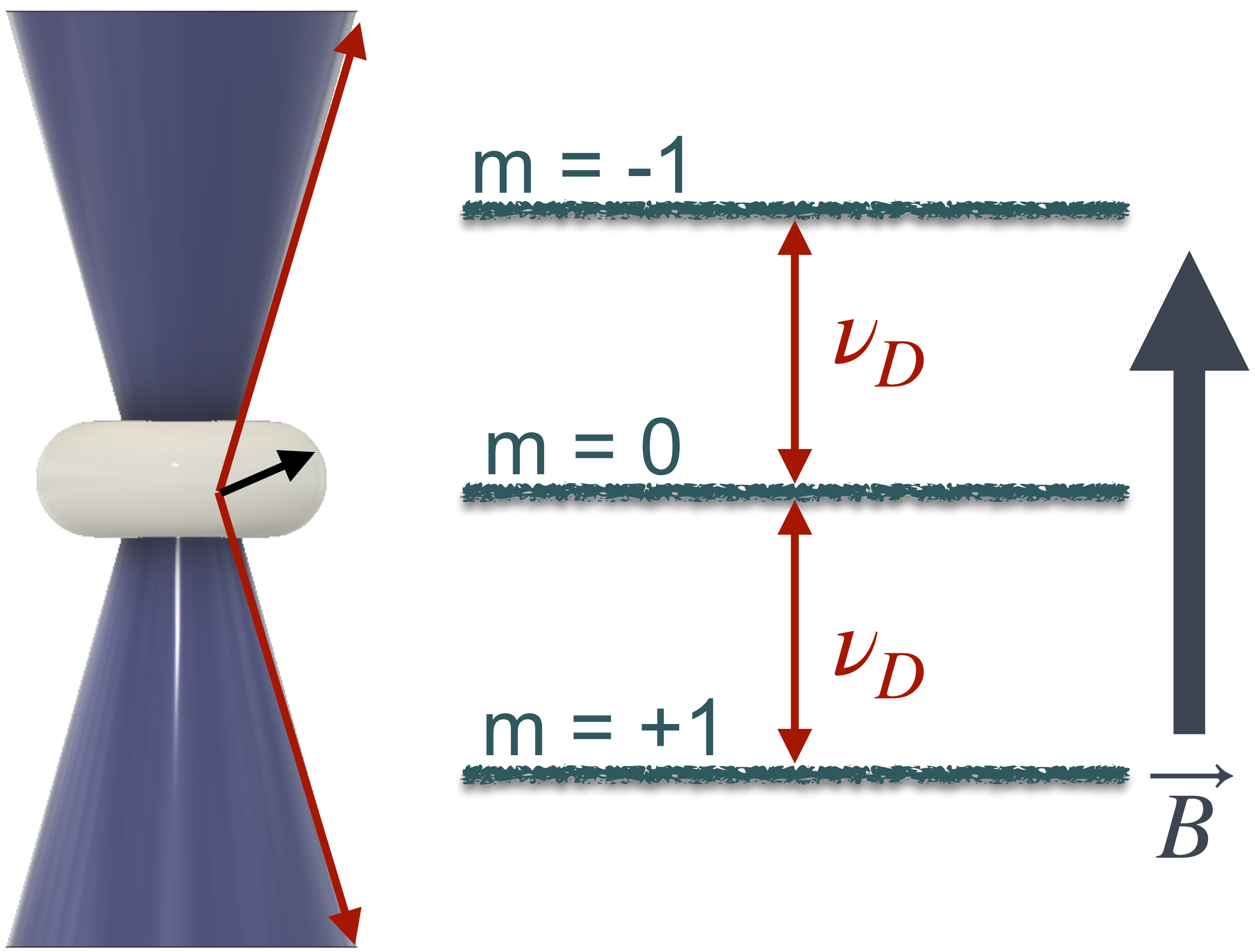
Spin 1/2

Beyond the scope of this talk

What about Spin 1?



Spin 1: Polarization



No quadrupole interaction

$\nu_D = \frac{\mu_D B}{h}$: Larmor frequency

$\nu_D = 6.54 MHz/T$

Spin-1 System

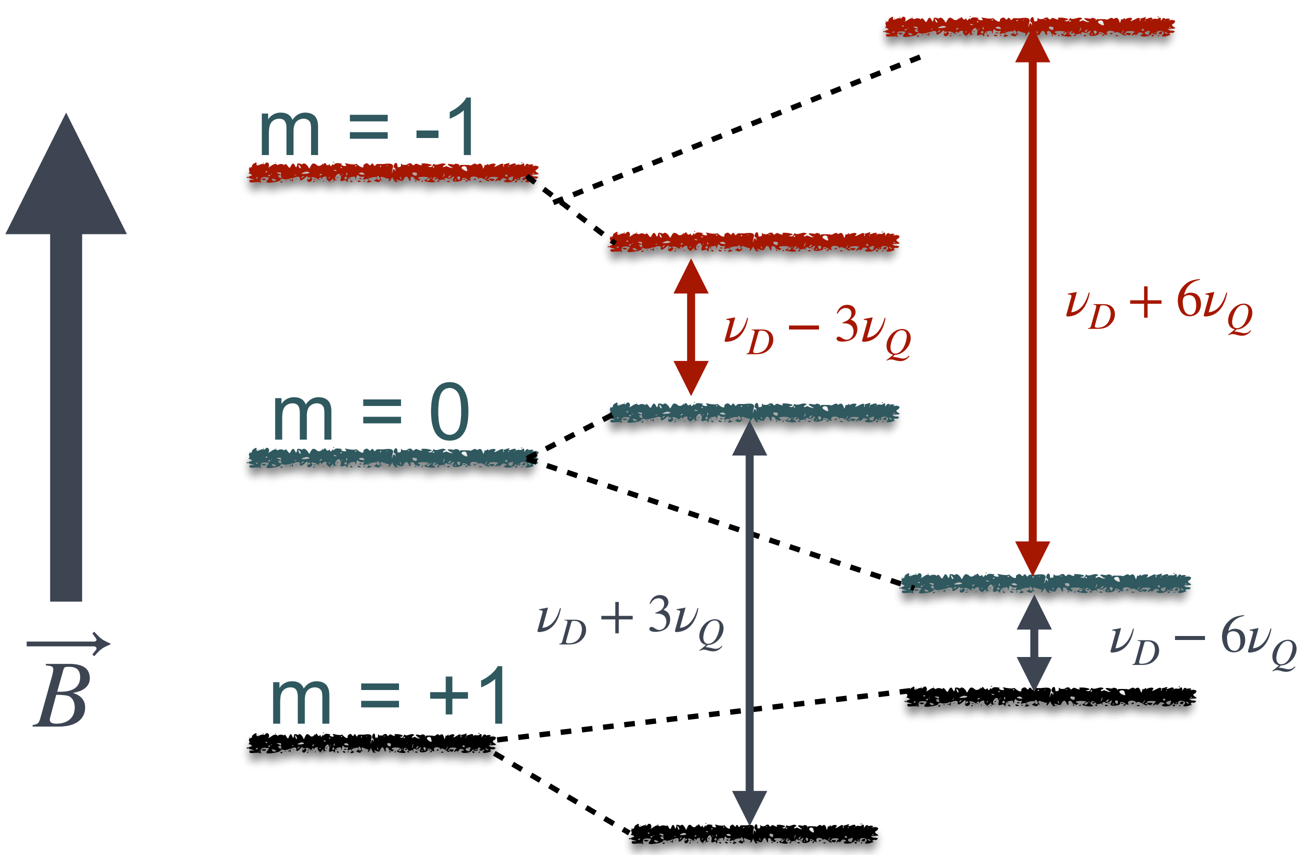
- In a magnetic field → 3 sub-levels (+1, 0, 1) due to Zeeman interaction.
- Two energy transitions I_+ (+1→0) and $I\_$ (0 → -1).

Spin 1: Polarization

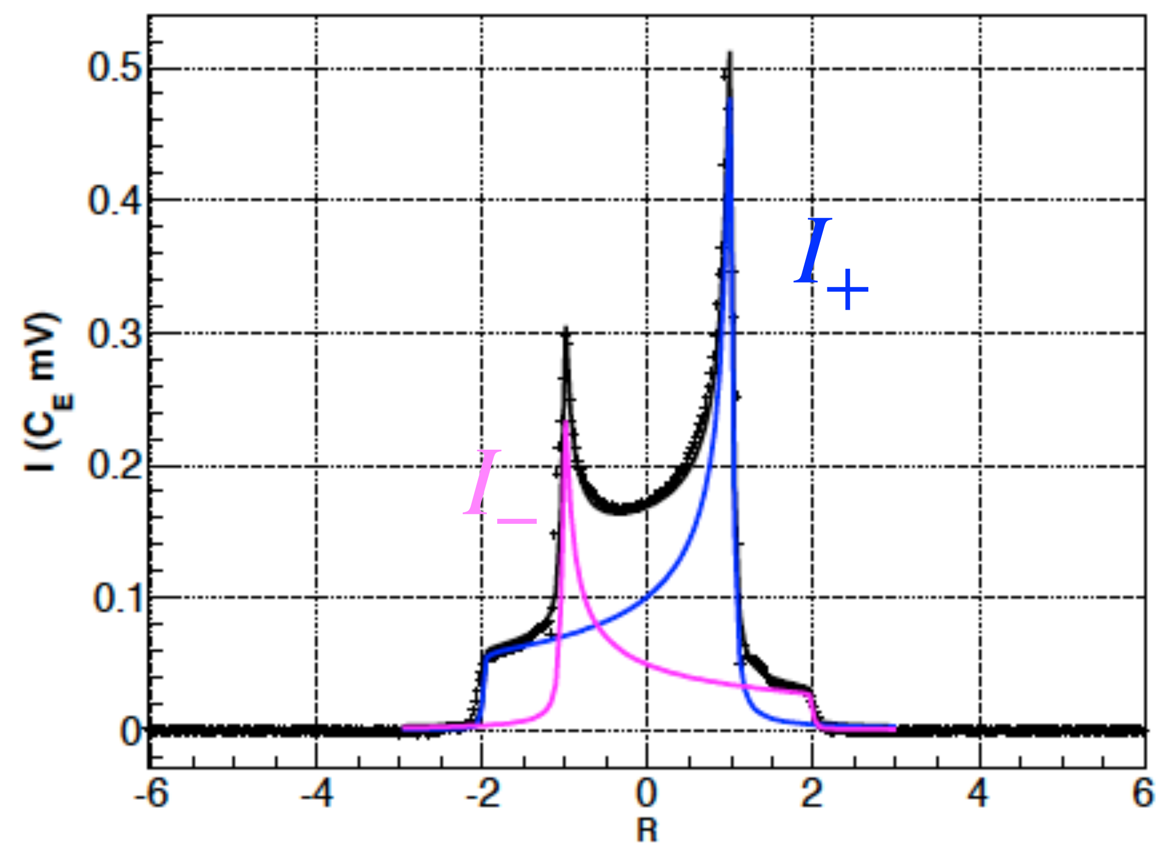
$$E_m = -h\nu_D m + h\nu_Q(cos^2\theta - 1)(3m^2 - 2)$$

eQ : Electric Quadrupole interaction shifts energy levels
eq : Electric field gradient
θ : angle between *eq* and *B*

$\nu_Q = \frac{e^2qQ}{8h}$: Quadrupole Frequency $\rightarrow \nu_Q = 335.6kHz$



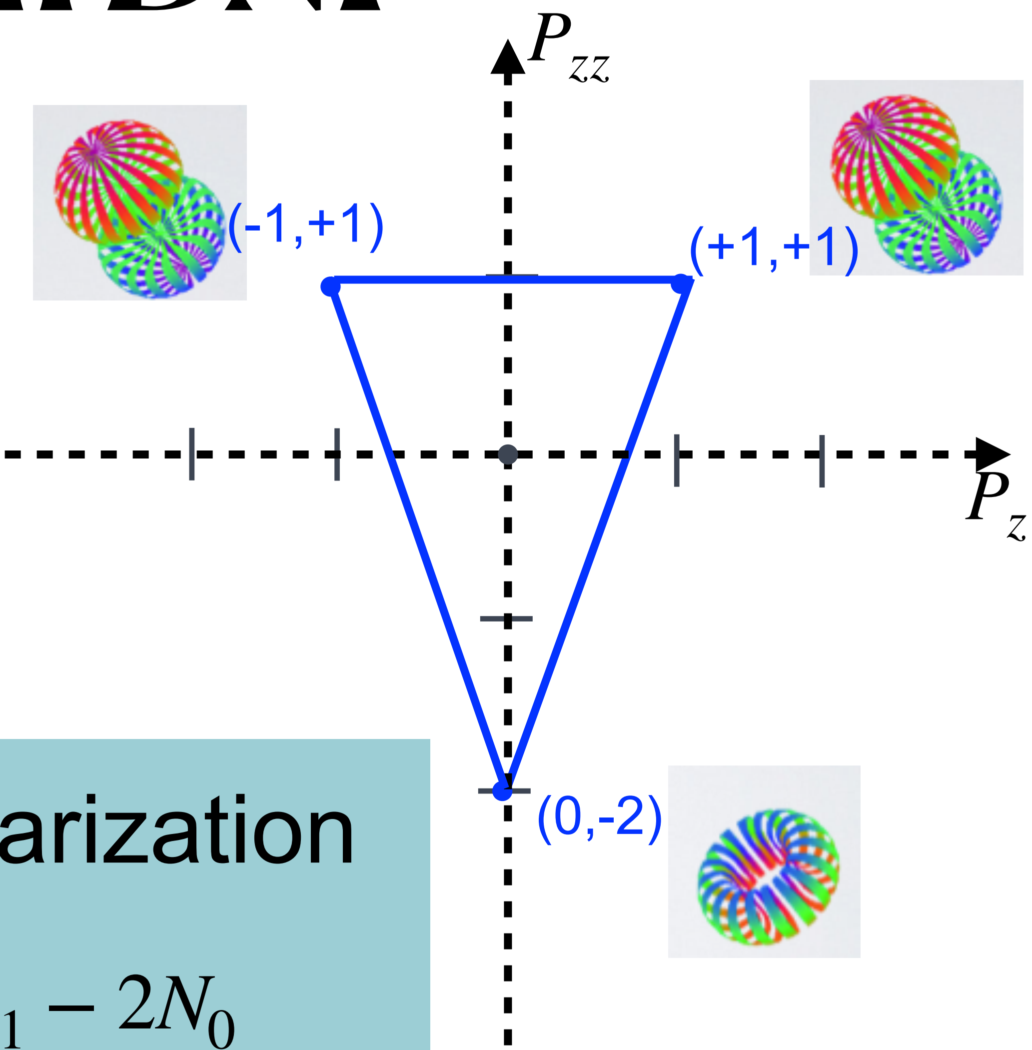
Deuteron NMR Line-shape.



$$R = \frac{\nu - \nu_D}{3\nu_Q}$$

Eur. Phys. J. A53 (2017)

Enhancing with DNP

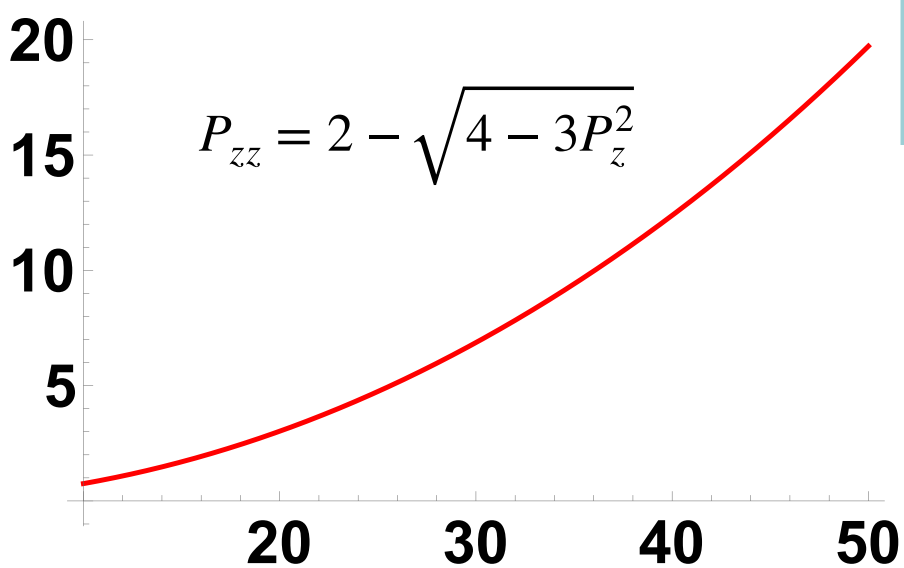


Vector Polarization

$$P_z = N_{+1} - N_{-1}$$
$$-1 < P_z < +1$$

Tensor Polarization

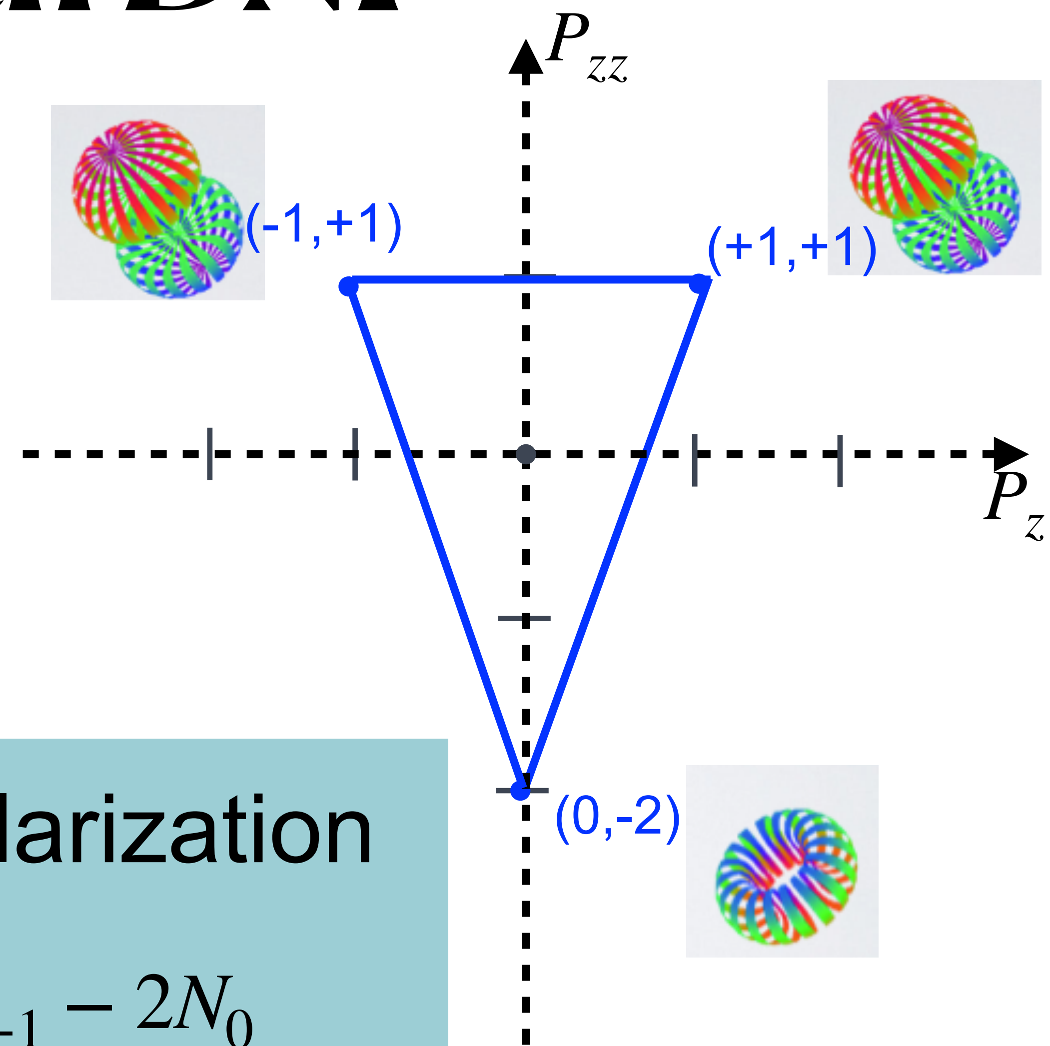
$$P_{zz} = N_{+1} + N_{-1} - 2N_0$$
$$-2 < P_{zz} < +1$$



Normalization:

$$N_{+1} + N_{-1} + N_0 = 1$$

Enhancing with DNP



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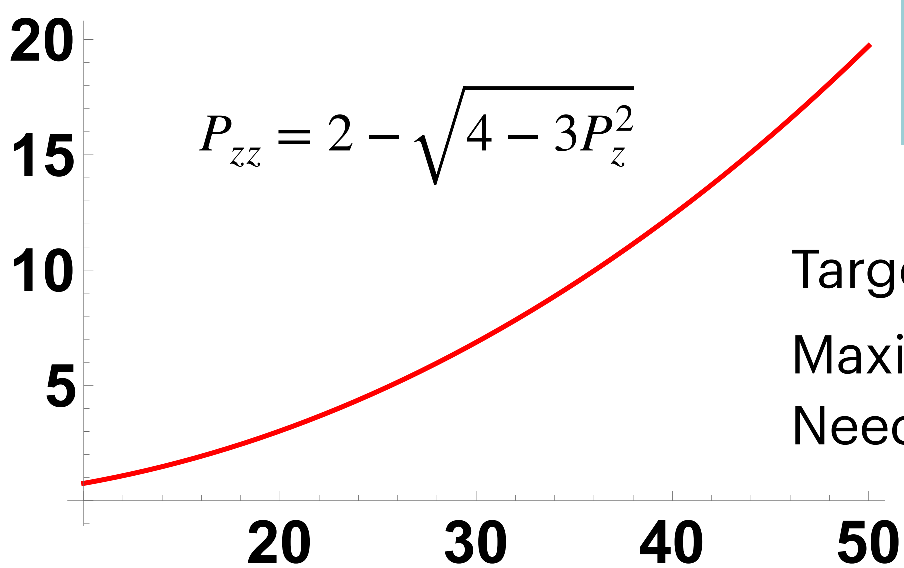


Target material ND_3

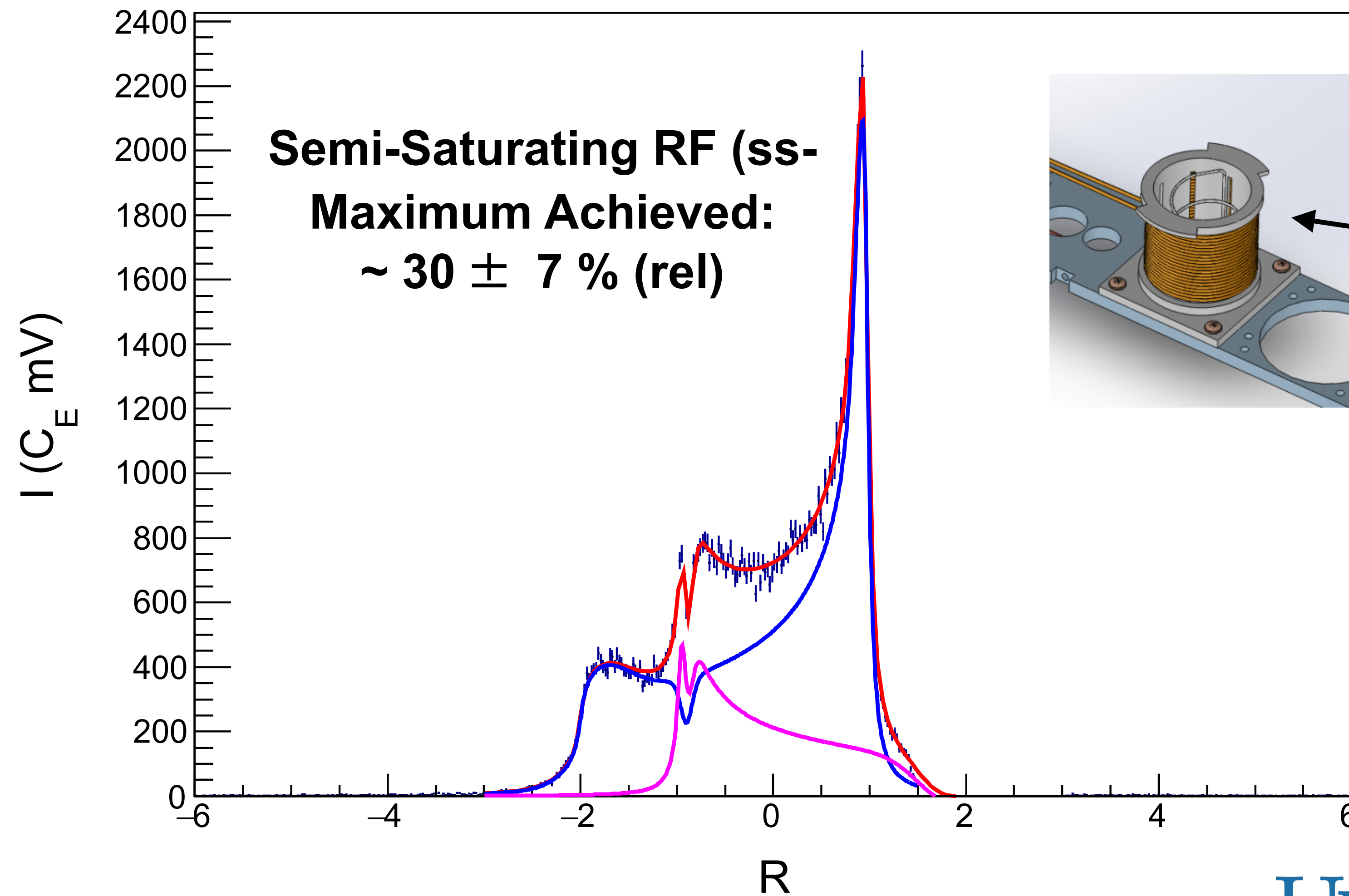
Maximum P_{zz} ~ 10% with DNP

Needed target development

Normalization:

$$N_{+1} + N_{-1} + N_0 = 1$$

Enhancing P_{zz} : DNP + ssRF



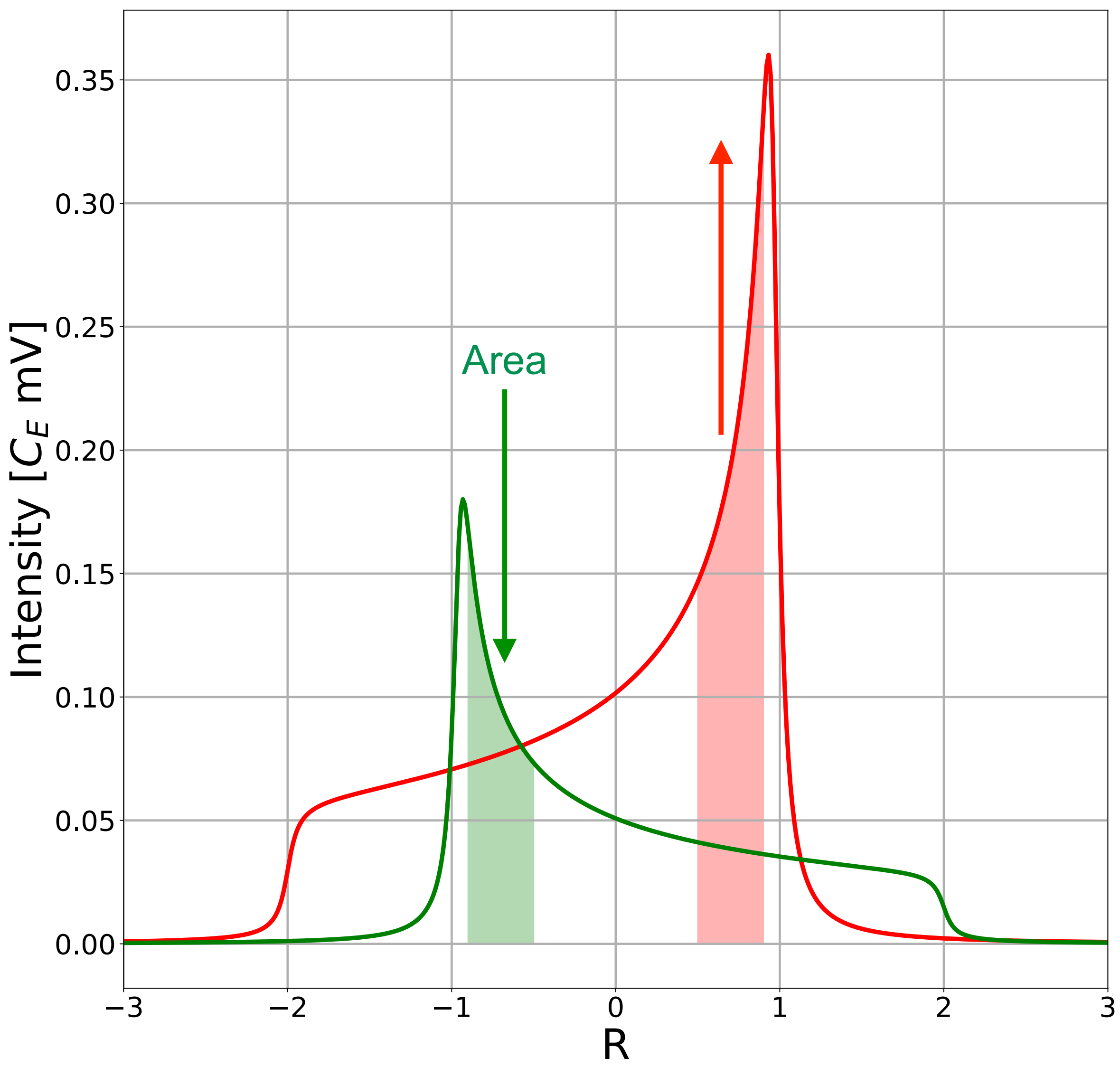
Target cup

ssRF + AFP: ~32 ± 8.5 % (rel)

University of Virginia

D. Keller Eur. Phys. J. A53 (2017)

Measuring tensor polarization



1. Differential binning
2. Spin temperature consistency

$$P_z = C(I_+ + I_-)$$
$$P_{zz} = C(I_+ - I_-)$$

3. Rate response

$$A_{lost} = \frac{1}{2} A_{gained}$$

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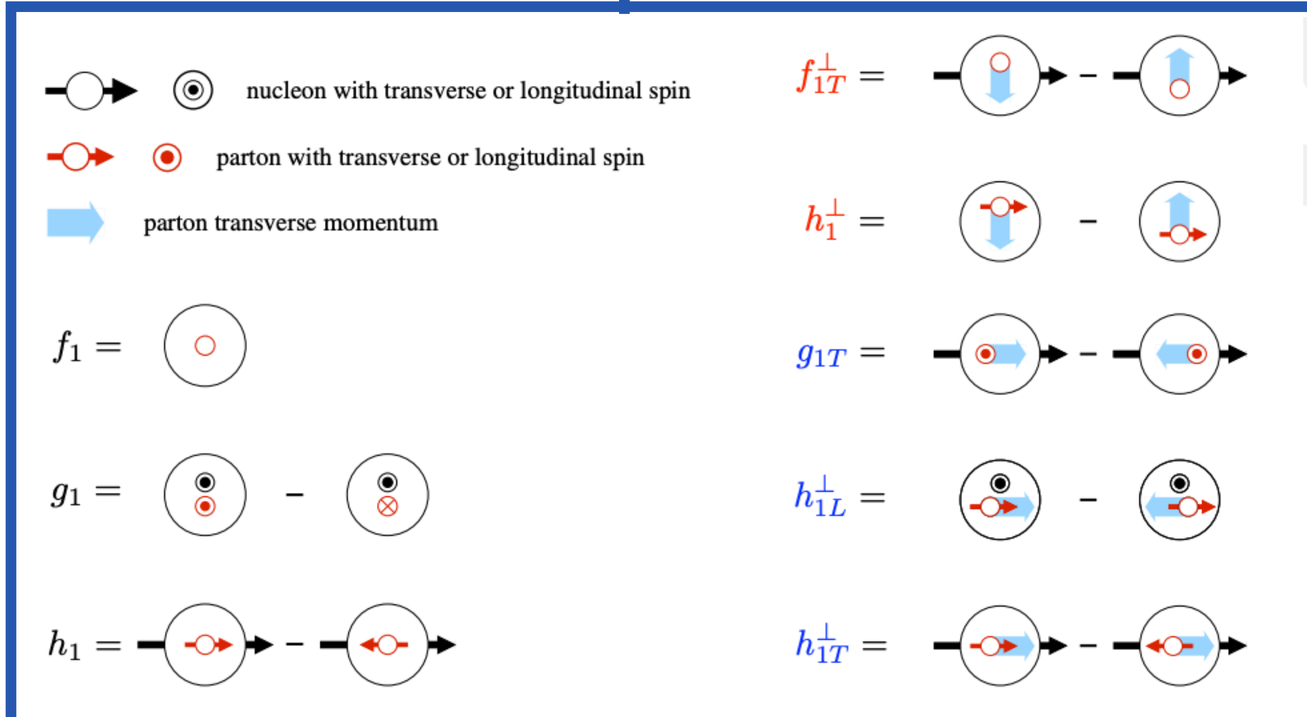
NIM 1050, 168177, (2023)

Leading twist distribution functions

Quark / Hadron	U (γ^+) T-even	U (γ^+) T-odd	L ($\gamma^+\gamma_5$) T-even	L ($\gamma^+\gamma_5$) T-odd	T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$) T-even	T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$) T-odd
U	f_1					$[h_1^\perp]$
L			g_{1L}		$[h_{1L}^\perp]$	
T		$f_{1T}^\perp$	g_{1T}		$[h_1], [h_{1T}^\perp]$	
LL	f_{1LL}					$[h_{1LL}^\perp]$
LT	f_{1LT}			g_{1LT}		$[h_{1LT}], [h_{1LT}^\perp]$
TT	f_{1TT}			g_{1TT}		$[h_{1TT}], [h_{1TT}^\perp]$

Spin 1/2



After integrating over the transverse momentum:

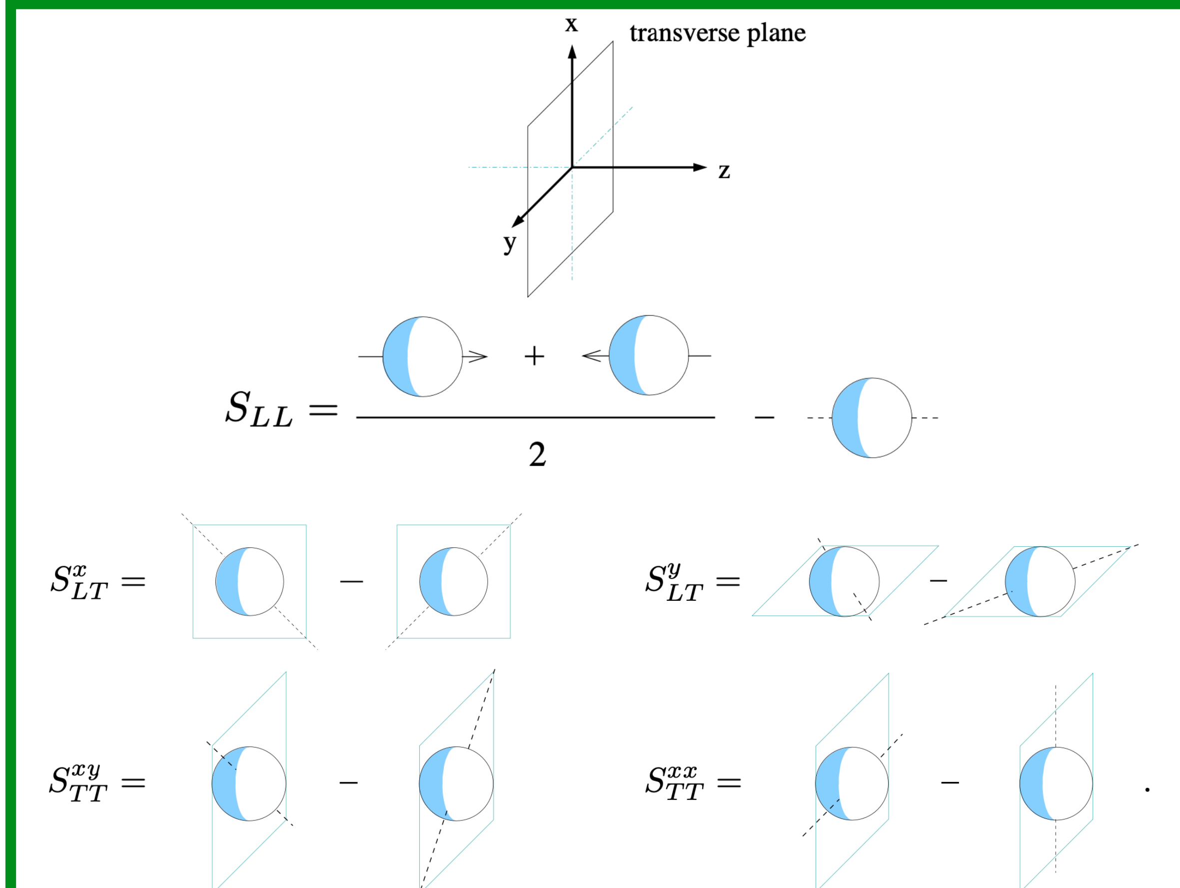
Quark / Hadron	U (γ^+) T-even	U (γ^+) T-odd	L ($\gamma^+\gamma_5$) T-even	L ($\gamma^+\gamma_5$) T-odd	T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$) T-even	T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$) T-odd
U	f_1					
L			$g_{1L}(g_1)$			
T					$[h_1]$	
LL	$f_{1LL}(b_1)$					
LT						*1
TT						

Phys. Rev. D 62 (2000)

Leading twist distribution functions

Hadron \ Quark	U (γ^+) T-even	U (γ^+) T-odd	L ($\gamma^+\gamma_5$) T-even	L ($\gamma^+\gamma_5$) T-odd	T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$) T-even	T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$) T-odd
U	f_1					$[h_1^\perp]$
L			g_{1L}		$[h_{1L}^\perp]$	
T		$f_{1T}^\perp$	g_{1T}		$[h_1], [h_{1T}^\perp]$	
LL	f_{1LL}					$[h_{1LL}^\perp]$
LT	f_{1LT}			g_{1LT}		$[h_{1LT}], [h_{1LT}^\perp]$
TT	f_{1TT}			g_{1TT}		$[h_{1TT}], [h_{1TT}^\perp]$

Spin 1



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Hadron \ Quark	U (γ^+) T-even	U (γ^+) T-odd	L ($\gamma^+\gamma_5$) T-even	L ($\gamma^+\gamma_5$) T-odd	T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$) T-even	T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$) T-odd
U	f_1					
L			$g_{1L}\,(g_1)$			
T					$[h_1]$	
LL	$f_{1LL}\,(b_1)$					
LT						*1
TT						

Phys. Rev. D 62 (2000)

Leading twist distribution functions

Quark / Hadron	U (γ^+)		L ($\gamma^+\gamma_5$)		T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$)	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	f_1					$[h_1^\perp]$
L			g_{1L}		$[h_{1L}^\perp]$	
T		$f_{1T}^\perp$	g_{1T}		$[h_1], [h_{1T}^\perp]$	
LL	f_{1LL}					$[h_{1LL}^\perp]$
LT	f_{1LT}			g_{1LT}		$[h_{1LT}], [h_{1LT}^\perp]$
TT	f_{1TT}			g_{1TT}		$[h_{1TT}], [h_{1TT}^\perp]$

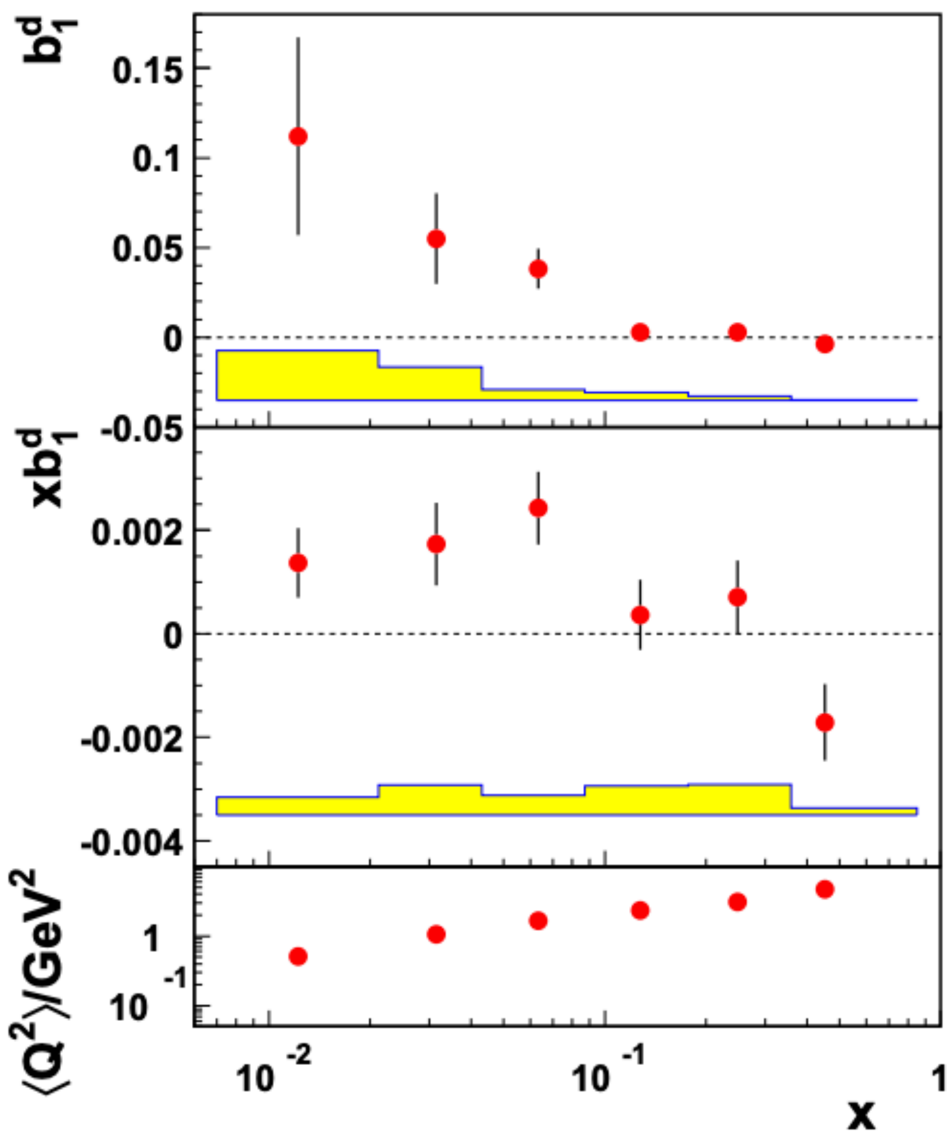
Quark / Hadron	U (γ^+)		L ($\gamma^+\gamma_5$)		T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$)	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	f_1					
L			$g_{1L}(g_1)$			
T					$[h_1]$	
LL	$f_{1LL}(b_1)$					
LT						*1
TT						

Spin 1

- Only b1 has been measured by Hermes Phys.Rev.Lett. 95 (2005).
- A new measurement of b1 will be done at JLab (E12-13-011).

SIDIS spin 1 measurements open the door to a complete new set of observables that can tell us about color degrees of freedom and beyond standard hadron physics.

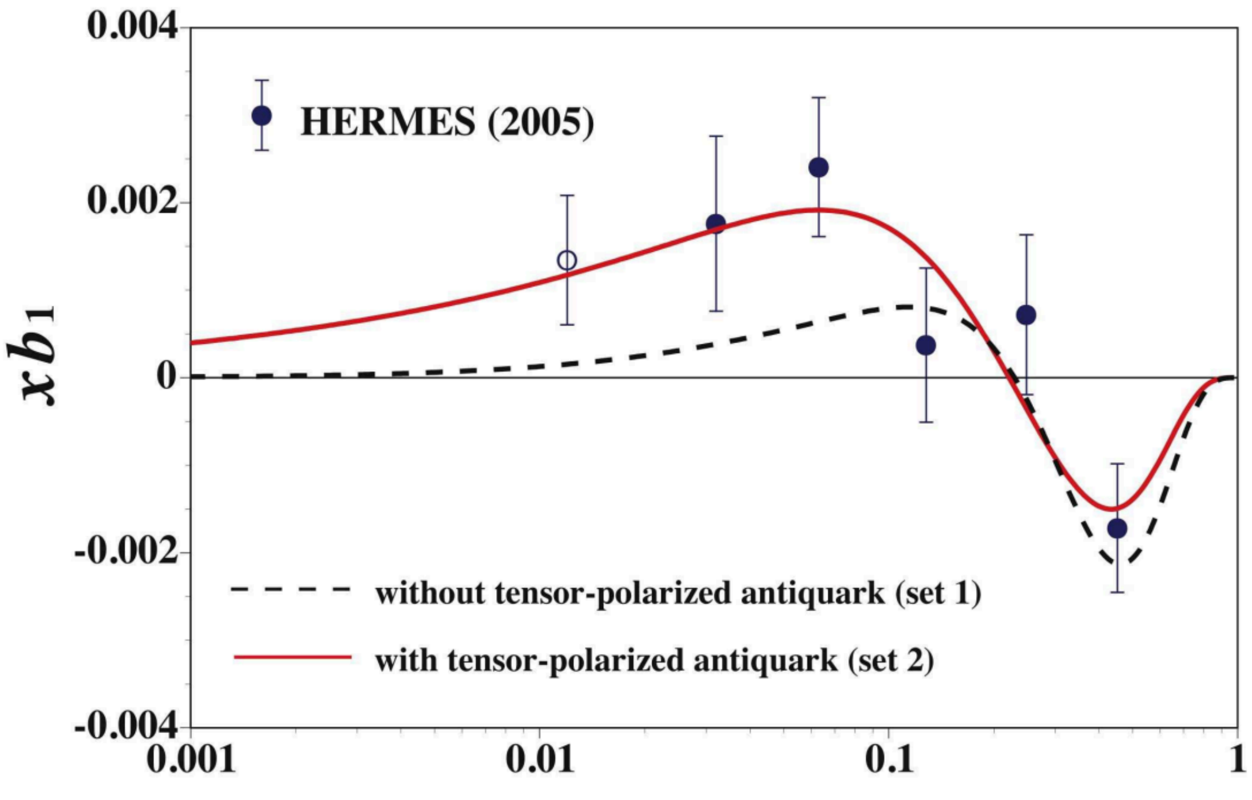
Hermes Experiment: First Measurement of b_1



- $0.5\ \text{GeV}^2 < Q^2 < 5\ \text{GeV}^2$
- $0.01 < x < 0.45\ \text{GeV}^2$
- Positrons in the momentum range of 2.5 GeV to 27 GeV
- The average target vector Pz and tensor Pzz polarizations are typically more than 80%
- Polarized gas target (integrated luminosity 42 pb^{-1})
- *The rise of b_1 for decreasing values of x can be interpreted to originate from the same mechanism that leads to nuclear shadowing in unpolarized scattering.*

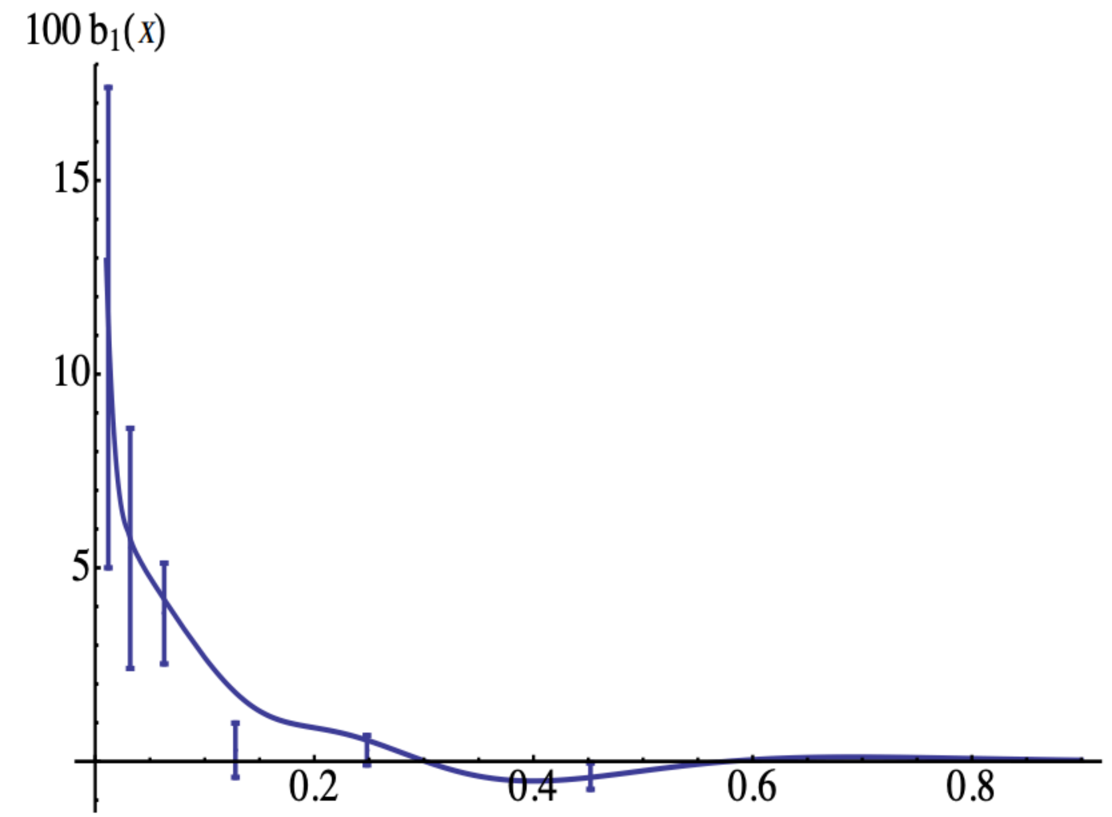
Phys.Rev.Lett. 95 (2005)

Theory predictions of b_1



We found that a significant antiquark tensor polarization exists if the overall tensor polarization vanishes for the valence quarks although such a result could depend on the assumed functional form. ***Further experimental measurements are needed for b_1 such as at JLab*** *as well as Drell-Yan measurements with tensor-polarized deuteron at hadron facilities, J-PARC and GSI-FAIR.*

Phys. Rev. D 82, 017501 (2010)

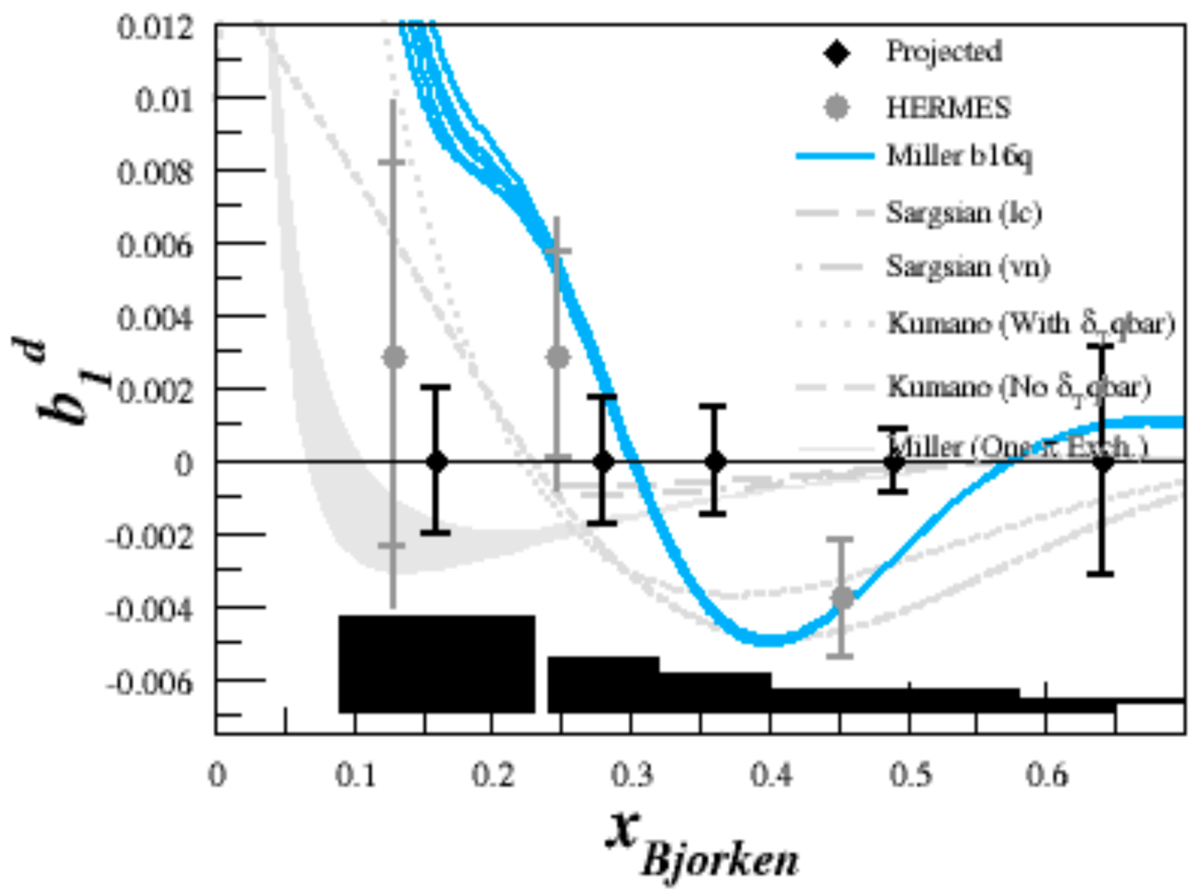


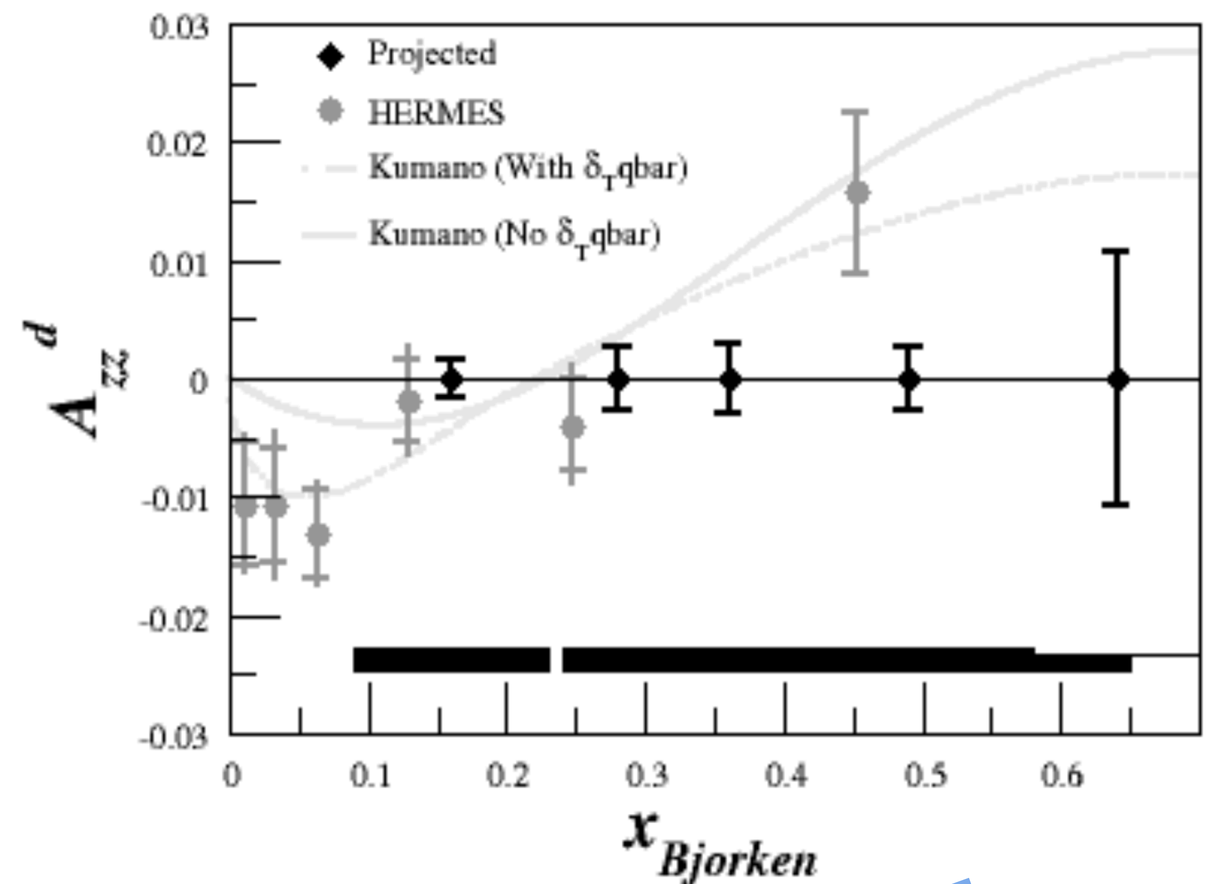
Hidden-color model: six-quark configurations (with ~ 0.15% probability to exist in the deuteron) proposed and found to give substantial contributions for values of x > 0.2.

Phys. Rev. C 89, 045203 (2014)

b_1 at JLab

K. Slifer, J. P. Chen, N. Kalantarians, D. Keller, E. Long, O. Rondon, N. Santiesteban, P. Solvignon





- Solid tensor polarized ND3 target
- A⁻ physics rating
- 30 Days at Hall C

See E. Long's talk

What can we really measure with a Spin 1 target?

Previous work…

- Leading twist: A. Bacchetta (thesis) arXiv:hep-ph/0212025
- Leading twist: Phys. Rev. D 62 (2000)
- Phys. Rev. C 102, 065204 (2020)
- Up to twist 4: Phys. Rev. D 103 (2021)

Explicit cross-sections weren't completely estimated for all processes. A theory effort is currently being done.

Longitudinally polarized target

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

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

vector

$$+\,S_{\parallel}\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]$$

$$+\,S_{\parallel}\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]$$

tensor

$$+\,T_{\parallel\parallel}\Big[F_{U(LL),T} + \varepsilon F_{U(LL),L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{U(LL)}^{\cos\phi_h}$$

$$+\,\varepsilon\cos(2\phi_h)\,F_{U(LL)}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{L(LL)}^{\sin\phi_h}\Big]\Big\}.$$

Courtesy of A. Bacchetta (private communication) 2023.

Tensor-polarized structure functions

To be published

$$F_{U(LL),T} = \mathcal{C}\left[f_{1LL} D_1\right],$$

$$F_{U(LL),L} = 0,$$

$$F_{U(LL)}^{\cos\phi_h} = \frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x h_{LL}\, H_1^{\perp} + \frac{M_h}{M} f_{1LL}\frac{\tilde{D}^{\perp}}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x f_{LL}^{\perp} D_1 + \frac{M_h}{M} h_{1LL}^{\perp}\frac{\tilde{H}}{z}\right)\right],$$

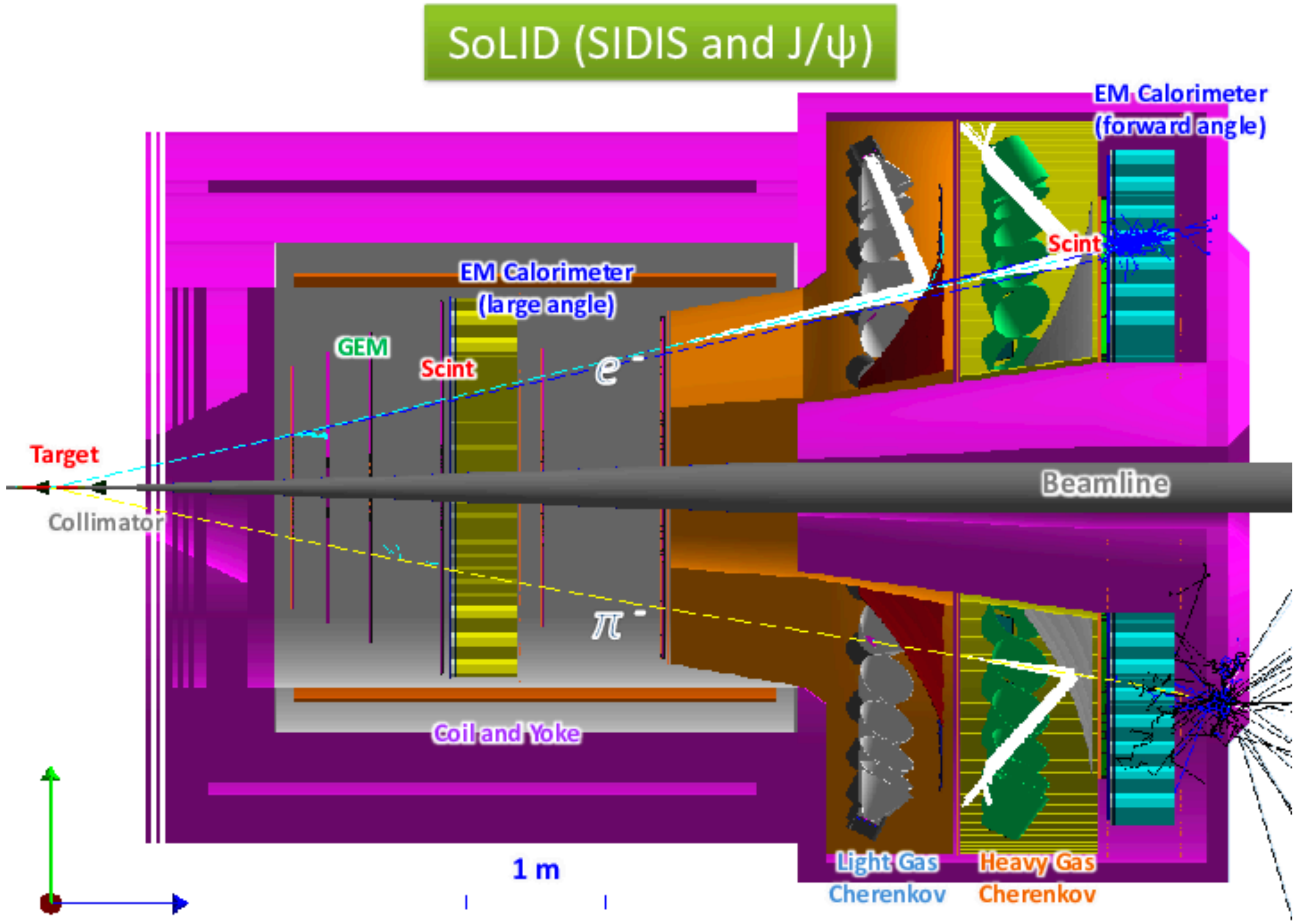
$$F_{U(LL)}^{\cos 2\phi_h} = \mathcal{C}\left[-\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right) - \boldsymbol{k}_T\cdot\boldsymbol{p}_T}{M M_h} h_{1LL}^{\perp} H_1^{\perp}\right],$$

$$F_{L(LL)}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x e_{LL}\, H_1^{\perp} + \frac{M_h}{M} f_{1LL}\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x g_{LL}^{\perp} D_1 + \frac{M_h}{M} h_{1LL}^{\perp}\frac{\tilde{E}}{z}\right)\right].$$

Spin-1 leading twist

Courtesy of A. Bacchetta (private communication) 2023.

Spin 1 TMDs in SoLID



There are not predictions of the expected measurements.
Crude estimate: Scale the unpolarized asymmetries by 10%

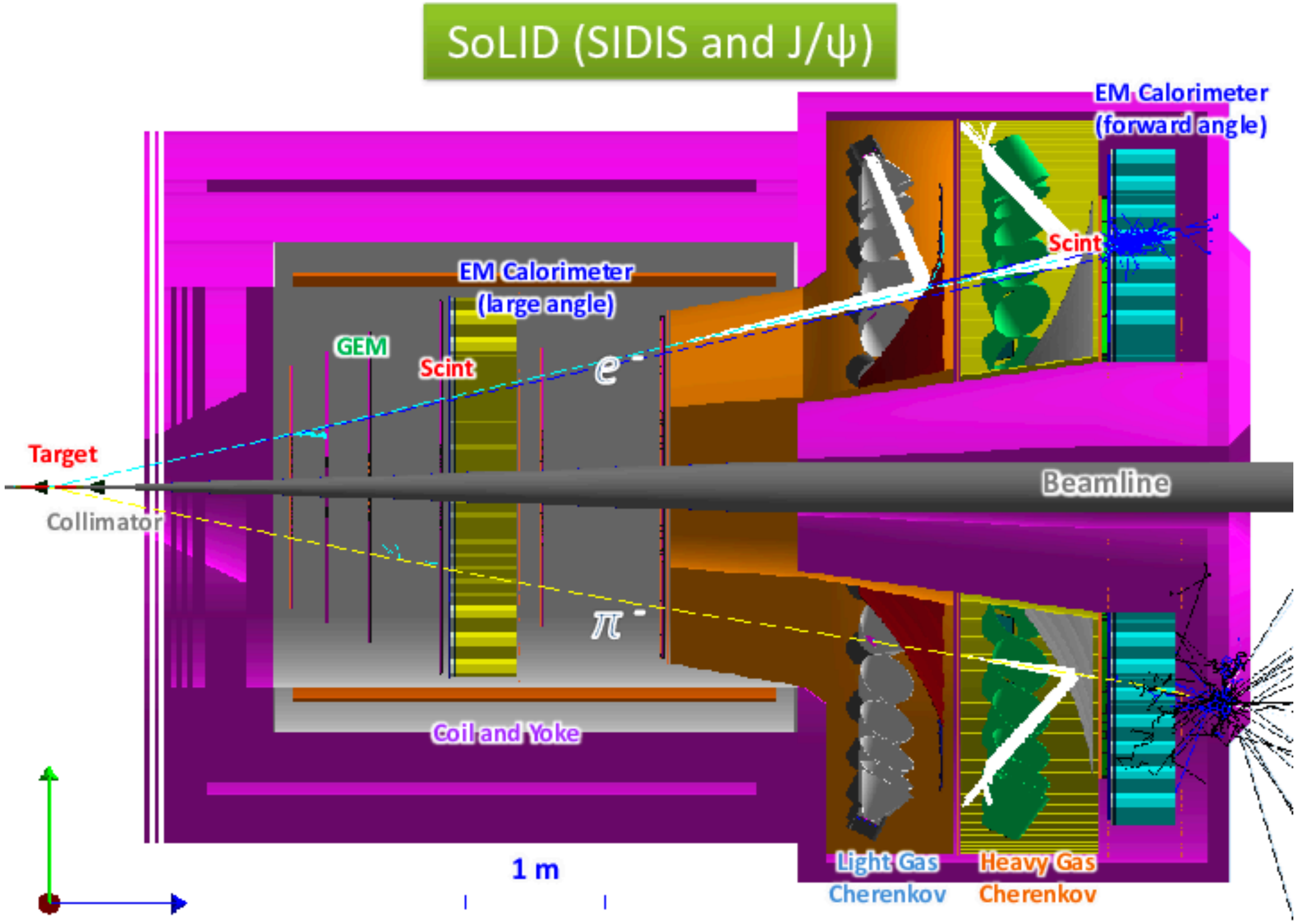
Spin 1 TMDs in SoLID

$0.3 < z < 0.7$

$Q^2 > 1.0$ GeV^2

$W > 2.3$ GeV

$W' > 1.6$ GeV



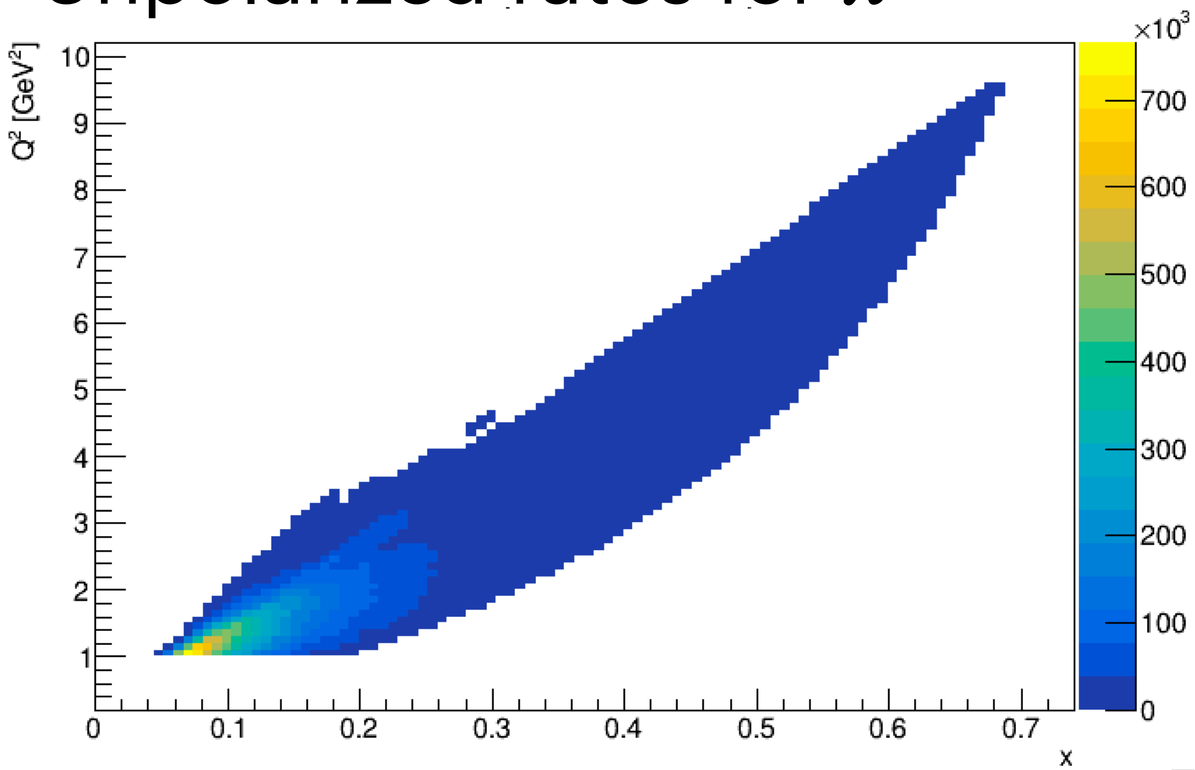
Assuming:

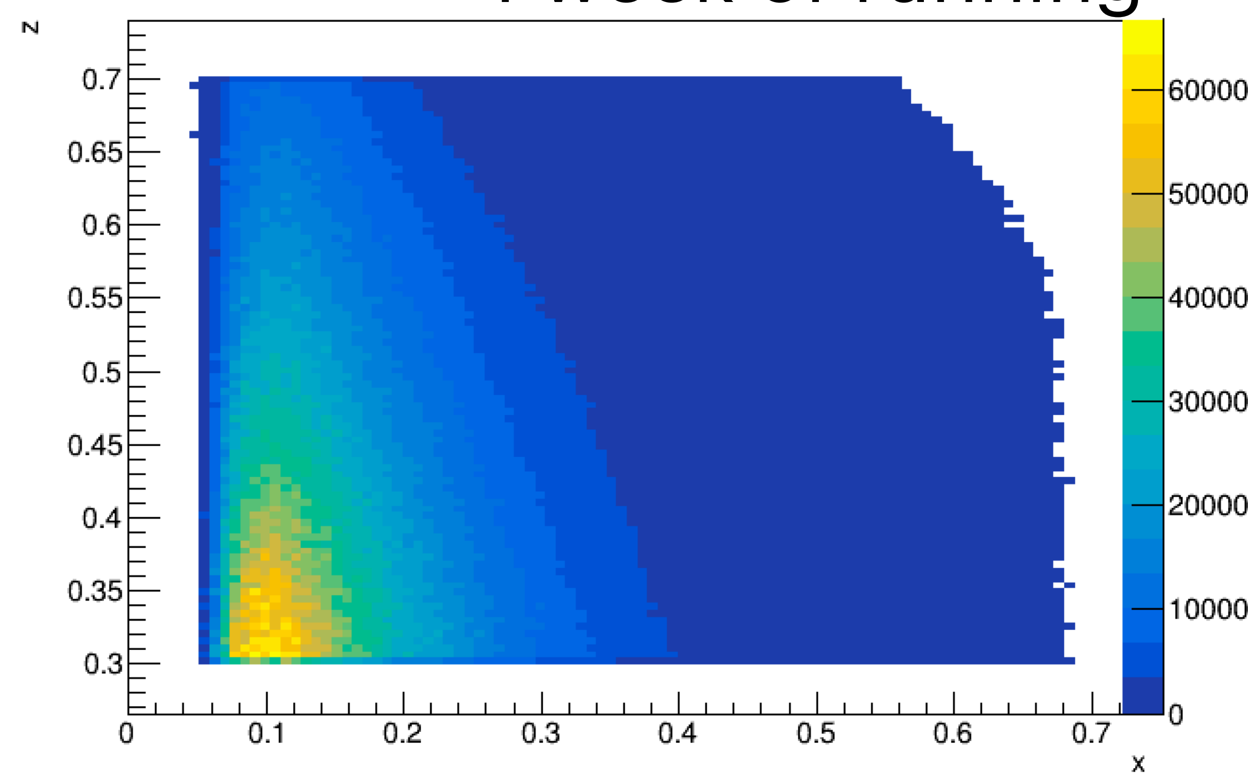
- ★ Luminosity 10^{35} cm^2/s
- ★ Pure D-> 1n + 1p

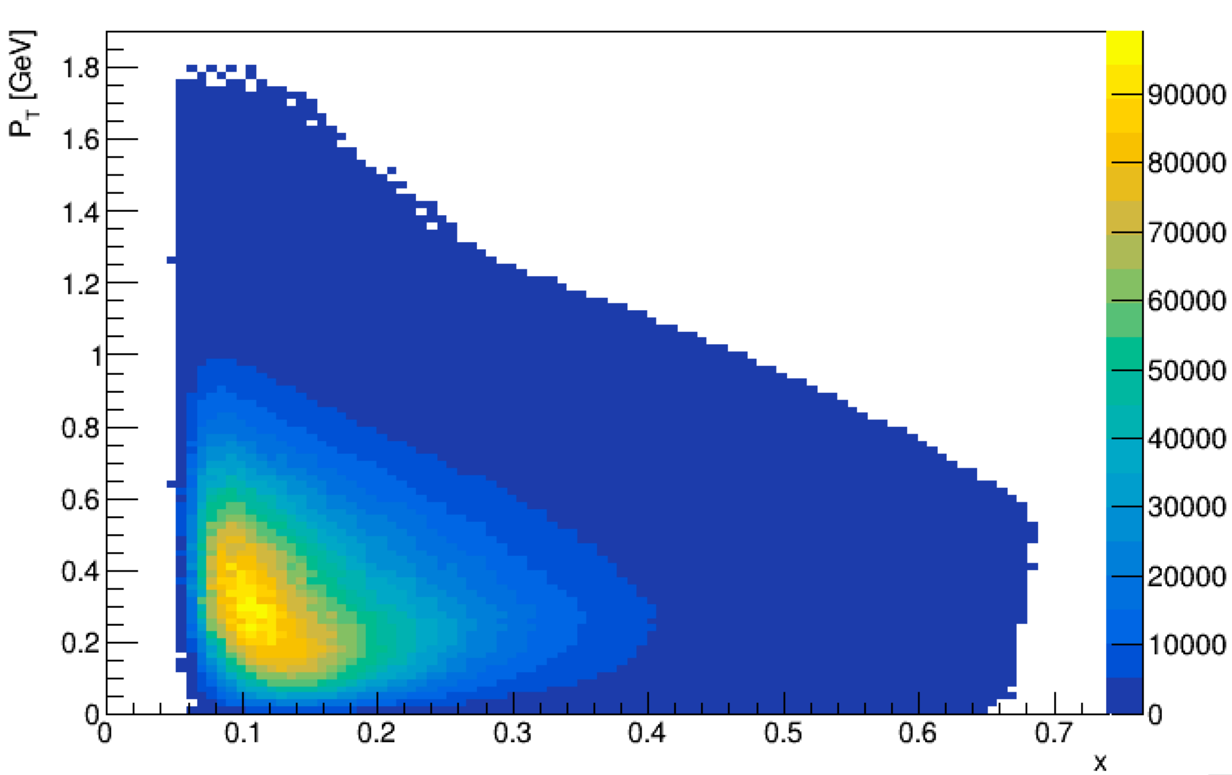
SoLID coverage

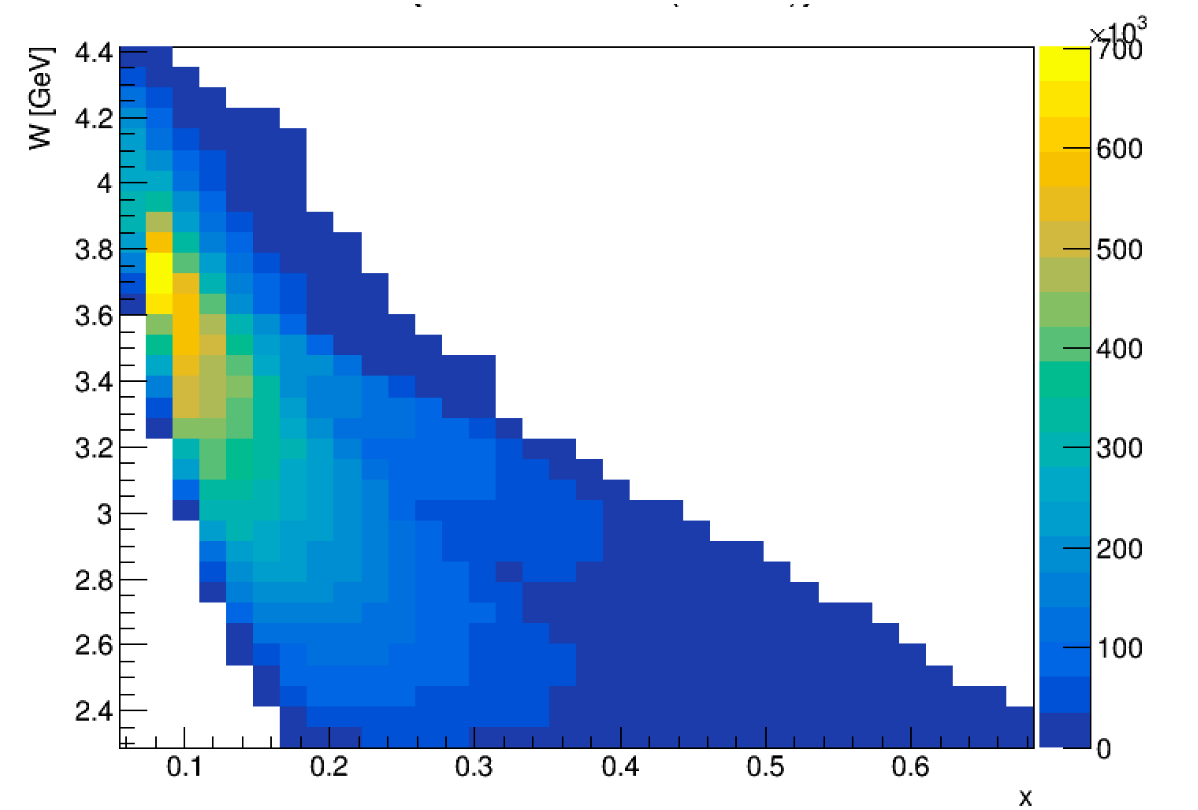
Unpolarized rates for π^-

1 week of running







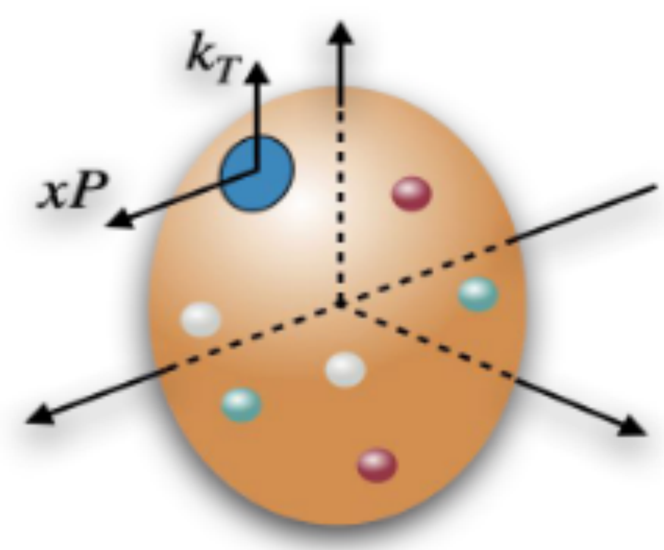


Next Steps

- No predictions: Use Hall B data (Run group C ~ 12% tensor polarization) to estimate the rates and possible sensitivity to structure functions shape/structure.
- Exploratory measurement: Propose a run in the short term (probably around the time of the already approved tensor experiments) to map the longitudinal distributions with better precision.
- Continue target development and plan for all possible configurations of polarization.
- Formalize a plan to measure the distributions with the SoLID detector.

Summary

- SIDIS spin 1 measurements open the door to a complete new set of observables that can tell us about color degrees of freedom and beyond standard hadron physics.
- Theory efforts are being made to provide full cross-section estimates.
- SoLID will be the best playground to perform measurements with higher luminosity and full azimuthal coverage.



Thank you!