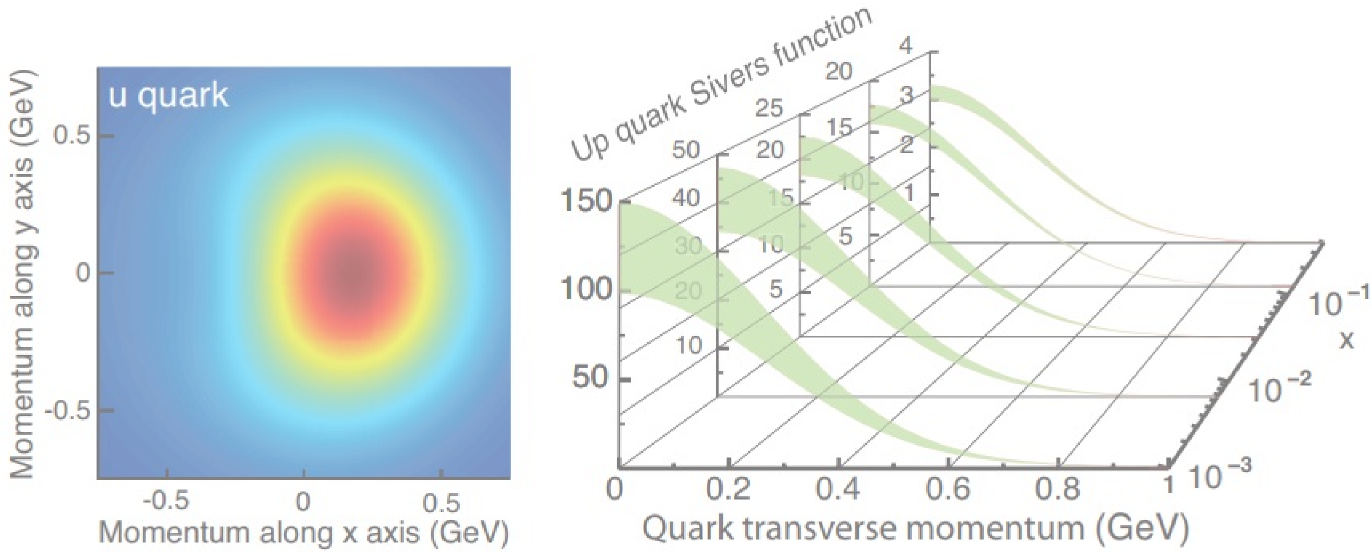

3D Structure of the Nucleon, p_T 2

Transverse Momentum Distributions

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Physics 290E
5 April 2017

The big questions

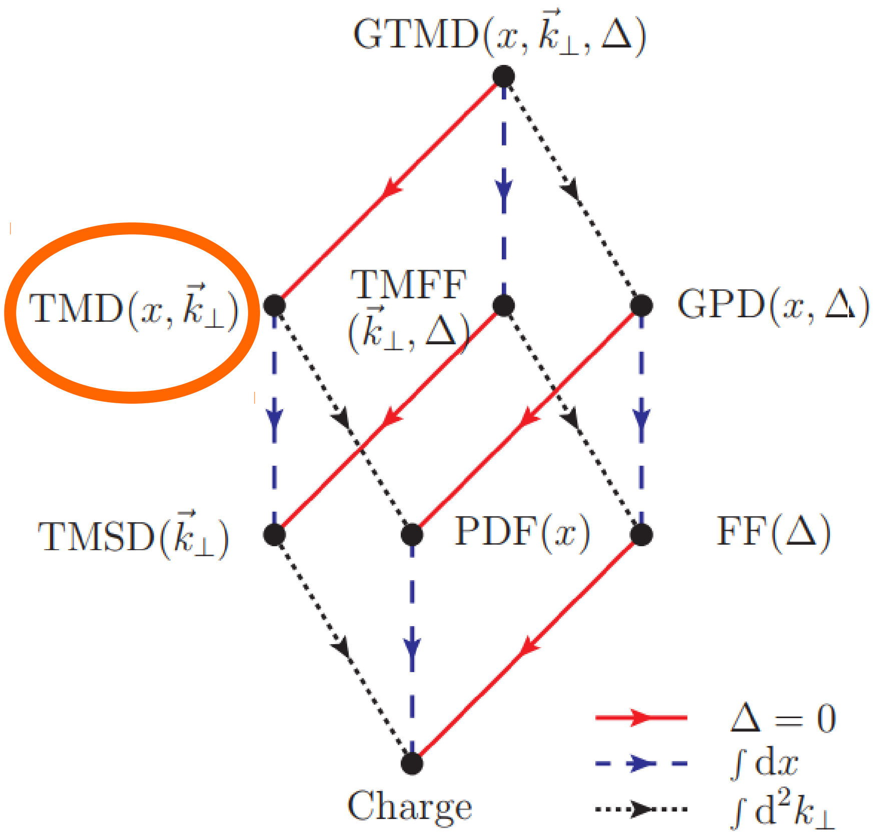
- What are TMDs?
- Why are they useful?
- How can they be measured?
- Status of existing measurements
- Prospects for future measurements

Background: Wigner distributions

- Holy grail: To measure/calculate the complete nucleon wavefunction $\psi(\mathbf{r}_g, \mathbf{r}_u, \mathbf{r}_{\bar{u}}, \mathbf{r}_d, \mathbf{r}_{\bar{d}}, \text{spins}, \ldots)$
  - 3D (position <u>or</u> momentum), complex-valued
- ψ is mathematically equivalent to the Wigner "quasiprobability" distribution $W(\mathbf{r}_g, \mathbf{p}_g, \mathbf{r}_u, \mathbf{p}_u, \ldots)$
  - 6D (position <u>and</u> momentum), <u>real</u>-valued
  - Not a true probability distribution (due to uncertainty principle), but similar in nature
- ψ/W encode *all* information on nucleon structure
- Unfortunately, we can't measure them directly
  - Only lower-dimensional projections

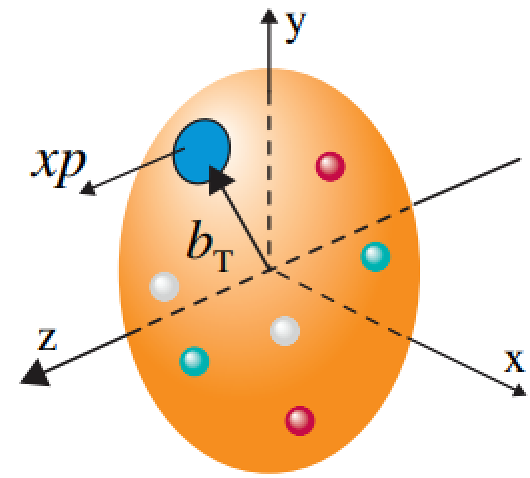
Nucleon structure "family tree"

- Integrate 6D *W* over longitudinal coordinate *z* to get 5D "GTMD"
  - Generalized TMD
  - Infinite-momentum frame: *z* is irrelevant
- Integrate GTMD over transverse coords, get 3D TMD
- Can further integrate TMD over transverse momenta to get familiar 1D PDF



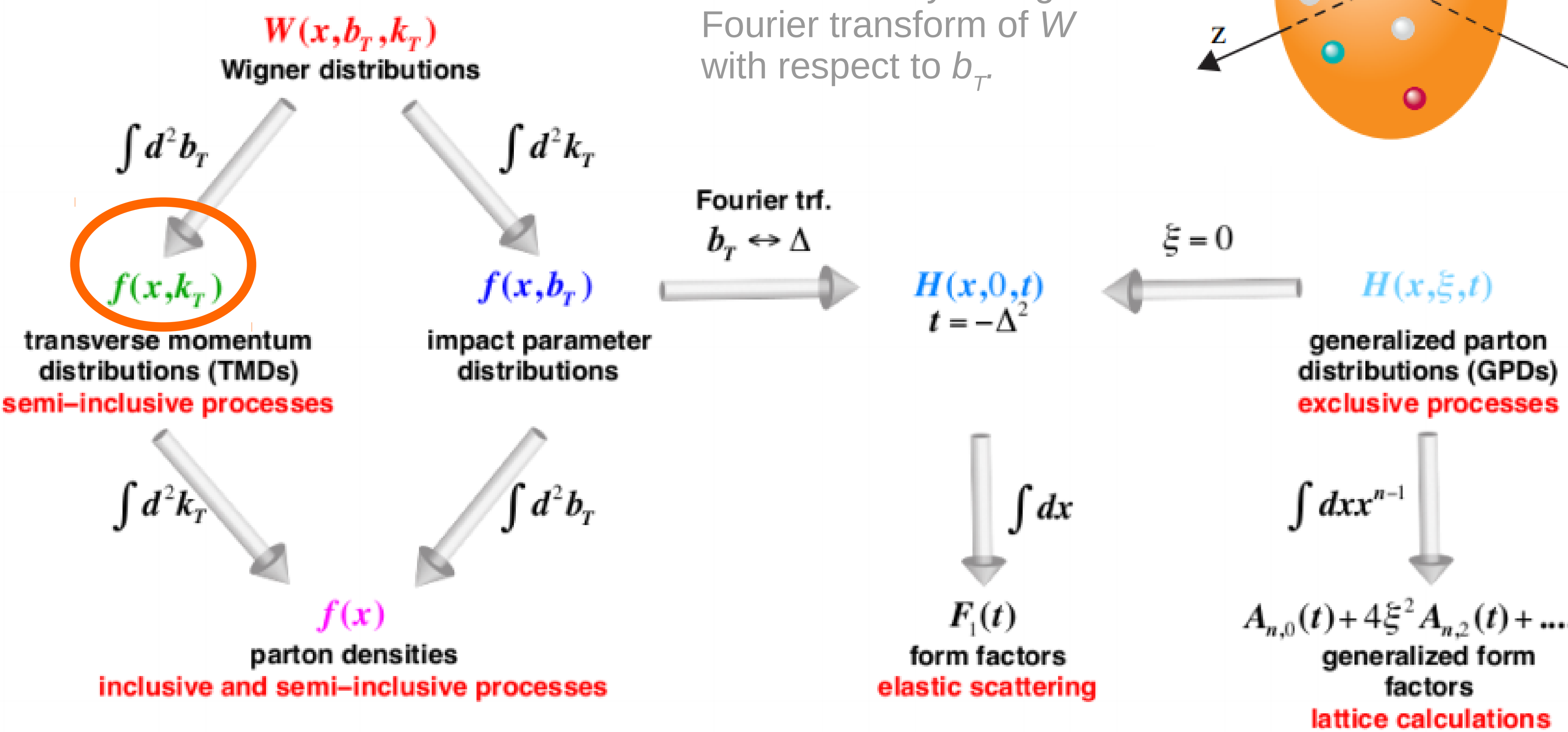
For the pedantic: GTMD is actually Fourier transform of (*z*-integrated) *W*. Δ is "conjugate momenta" of transverse coordinates $\mathbf{b}_T$ *(not the same as transverse momenta* $\boldsymbol{k}_T$*!)*

Family tree, again



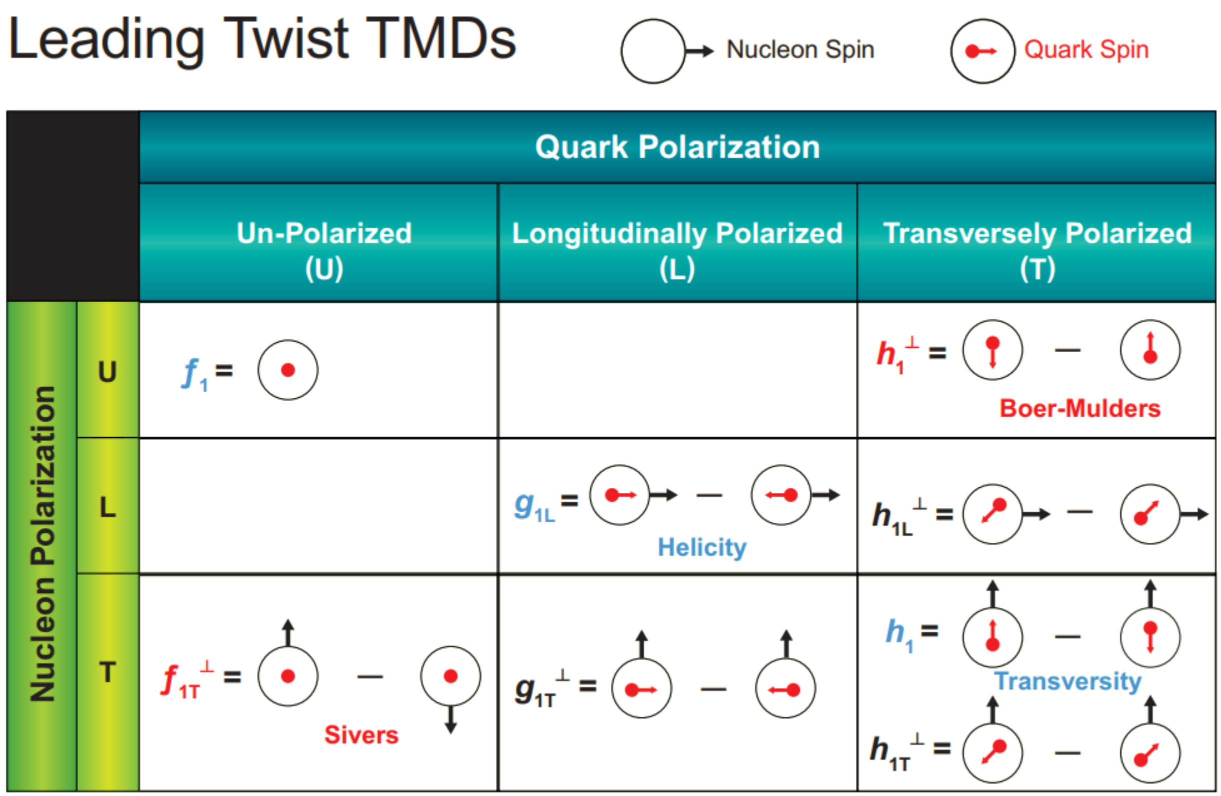
GTMDs not shown; can be obtained by taking Fourier transform of *W* with respect to b_T.

(z-integrated)



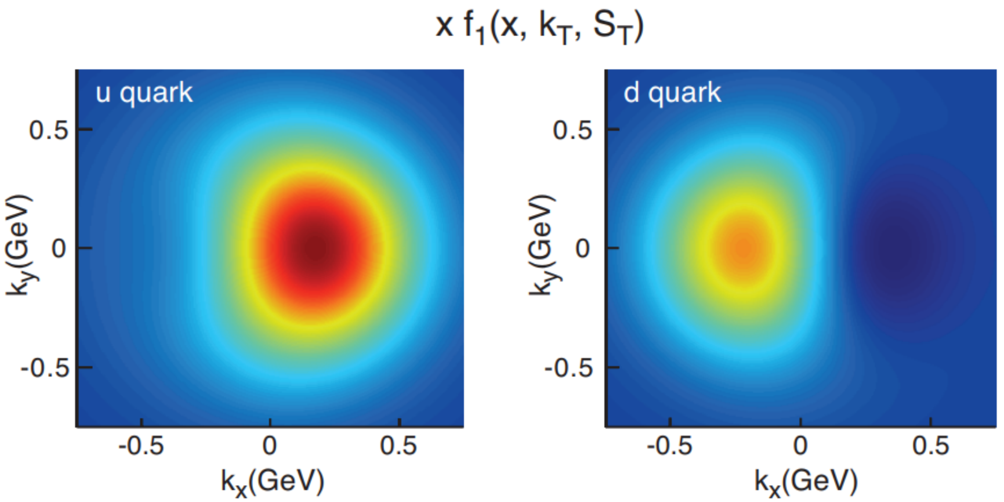
Eight different TMDs

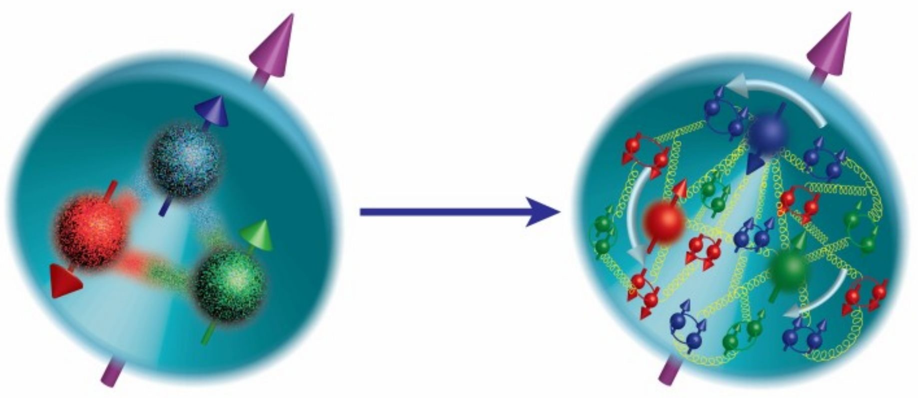
- Nucleon can be un-, longitudinally, or transversely polarized
- Likewise, our scattering process/measurement can be sensitive to different initial polarizations of the scattered parton
- Altogether, 8 TMDs per quark species, another 8 for gluons:



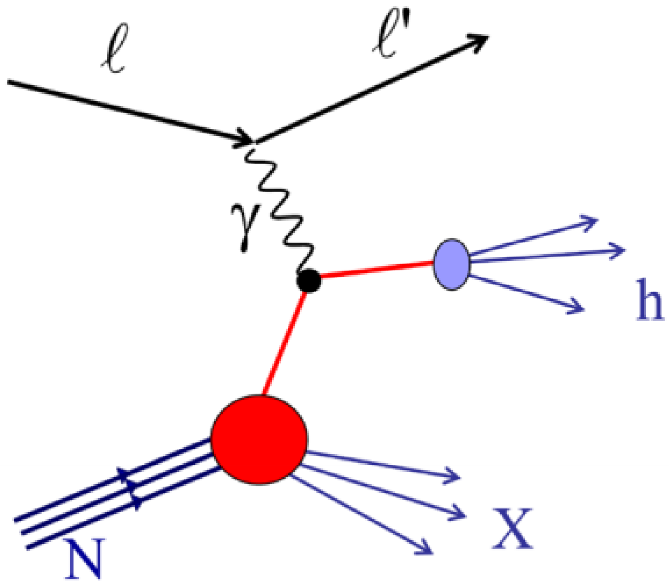
Why study TMDs?

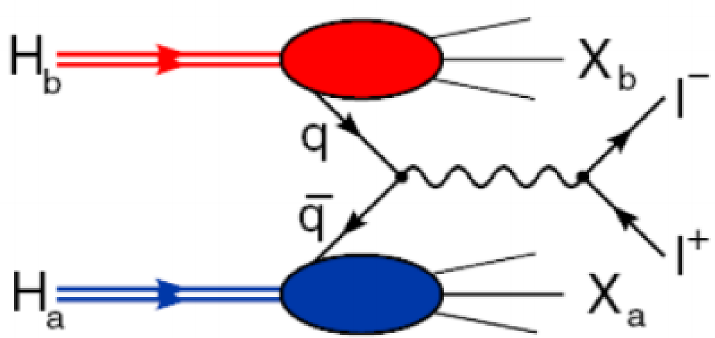
- Tomography: 3D imaging of nucleon in momentum space
  - Complimentary to GPDs: 3D in position space
- Orbital angular momentum's role in nucleon spin
  - k_T correlated w/ nucleon spin
- Correlation of parton spin with orbital ang. mom.
  - Contribution of sea quark, gluon polarization to nucleon spin
- Another handle on nucleon flavor structure





How to measure TMDs?





- Ordinary inclusive DIS won't work
  - Only measure outgoing lepton: not enough info
- Option 1: Semi-inclusive deep inelastic scattering (**SIDIS**)
  - Measure lepton + one outgoing hadron
- Option 2: Drell-Yan
  - E.g., $\pi p \rightarrow l^+ l^- X X'$
- Need polarized beam/target to disentangle the 8 TMDs
- Today's focus is SIDIS

SIDIS kinematics

$$Q^2 = (k-k')^2 = 4E_eE'_e\sin^2\left(\frac{\theta_e}{2}\right), \text{ Momentum transfer}$$

$$x = \frac{Q^2}{2M\nu}, \text{ quark momentum fraction}$$

$$\nu = \frac{P\cdot q}{M} = E_e - E'_e, \text{ N rest frame } E_{loss}$$

$$y = \frac{P\cdot q}{P\cdot k} = \frac{\nu}{E_e}$$

$$W^2 = (P+q)^2 = M^2 + Q^2\frac{1-x}{x}, \gamma^* N \text{ invariant mass}$$

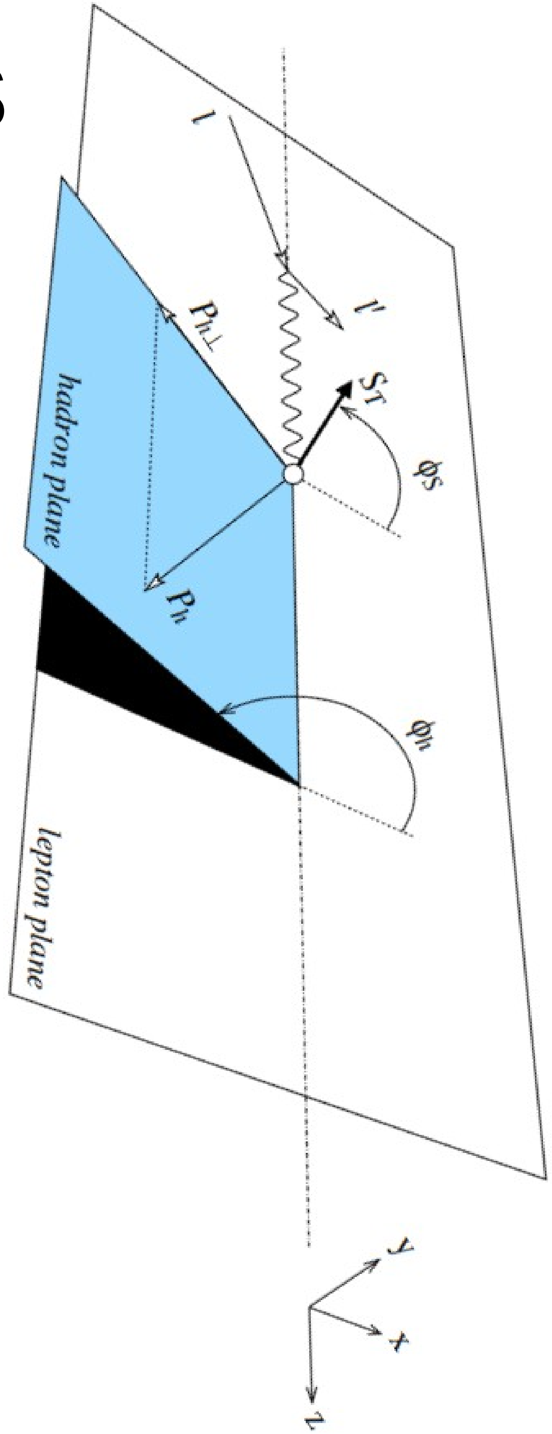
$$z = \frac{P\cdot P_h}{P\cdot q} = E_h/\nu, \text{ Hadron energy fraction}$$

$$p_T^h = \left|\mathbf{p}_h - \left(\frac{\mathbf{p}_h\cdot\mathbf{q}}{|\mathbf{q}|^2}\right)\mathbf{q}\right|, \text{ Hadron transverse momentum}$$

$$\phi_h = \text{ Angle between lepton and hadron planes}$$

$$\phi_S = \text{ Angle between lepton plane and nucleon spin}$$

$$W'^2 = M_X^2 = (P+q-P_h)^2, \text{ Missing mass}$$



SIDIS cross section

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon\,F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

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

unpol target

$\longrightarrow$ pol target

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

$\uparrow$ pol target

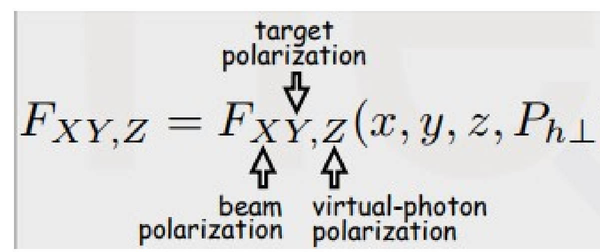
$$+\,|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

$$+\,\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

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

$$+\,|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

$$+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$



18 structure functions

SIDIS cross section

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

$h_1^\perp H_1^\perp$

$h_{1L}^\perp H_1^\perp$

$f_{1T}^\perp D_1$

$h_{1T}^\perp H_1^\perp$

$h_1 H_1^\perp$

$g_{1T} D_1$

14 independent azimuthal modulations

amplitudes of the modulations
→ TMD PDFs

SIDIS cross section

$$F_{UU,T} \sim f_1 \otimes D_1$$

$$F_{UU}^{\cos 2\phi_h} \sim h_1^\perp \otimes H_1^\perp$$

$$F_{UL}^{\sin 2\phi_h} \sim h_{1L}^\perp \otimes H_1^\perp$$

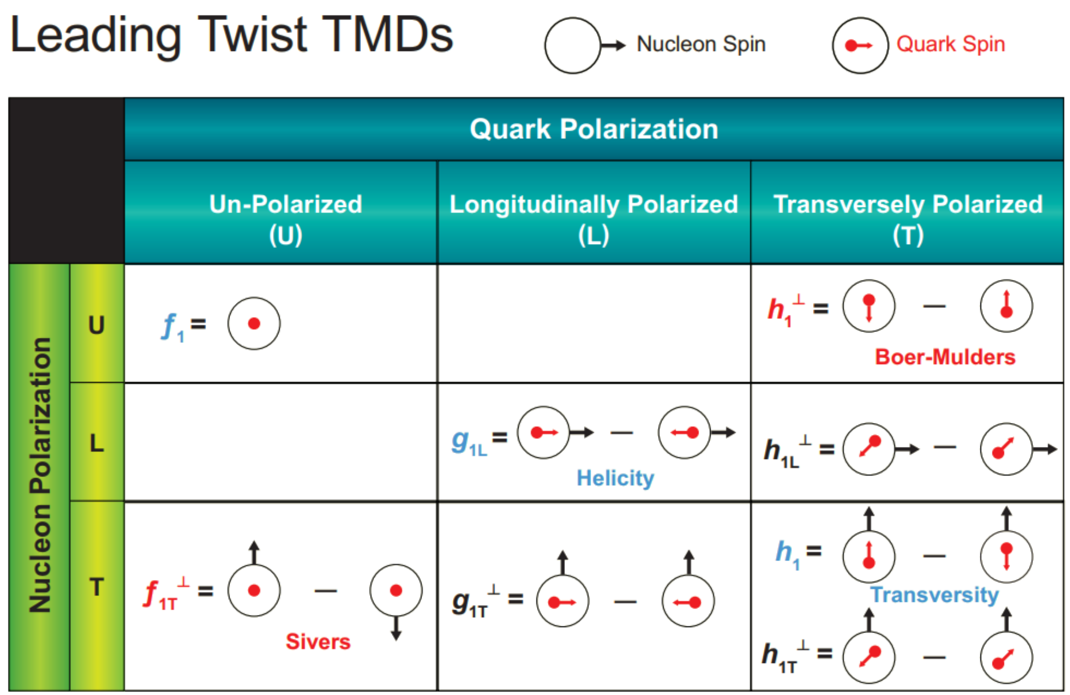
$$F_{LL} \sim g_1 \otimes D_1$$

$$F_{UT}^{\sin(\phi_h - \phi_S)} \sim f_{1T}^\perp \otimes D_1$$

$$F_{UT}^{\sin(\phi_h + \phi_S)} \sim h_1 \otimes H_1^\perp$$

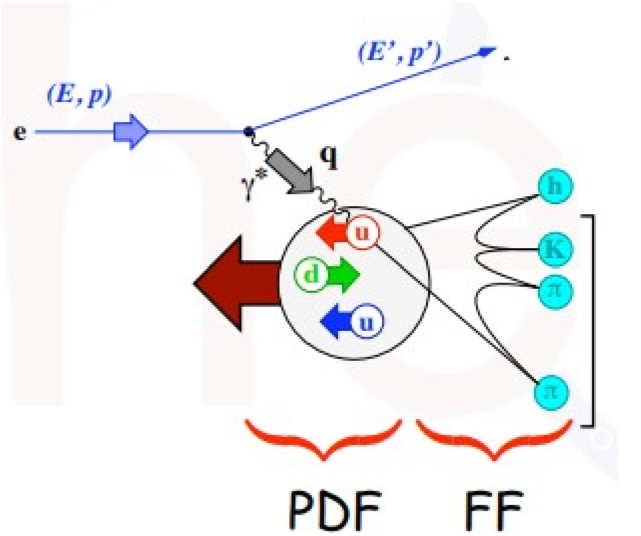
$$F_{UT}^{\sin(3\phi_h - \phi_S)} \sim h_{1T}^\perp \otimes H_1^\perp$$

$$F_{LT}^{\cos(\phi_h - \phi_S)} \sim g_{1T} \otimes D_1$$



$$F_{XY,Z} = F_{XY,Z}(x, y, z, P_{h\perp})$$

target polarization (X), beam polarization (Y), virtual-photon polarization (Z)



$$D_1(z, Q^2, p_\perp^2) = \text{Unpolarized TMD FF}$$

$$H_1^\perp(z, Q^2, p_\perp^2) = \text{Collins TMD FF}$$

TMD extraction

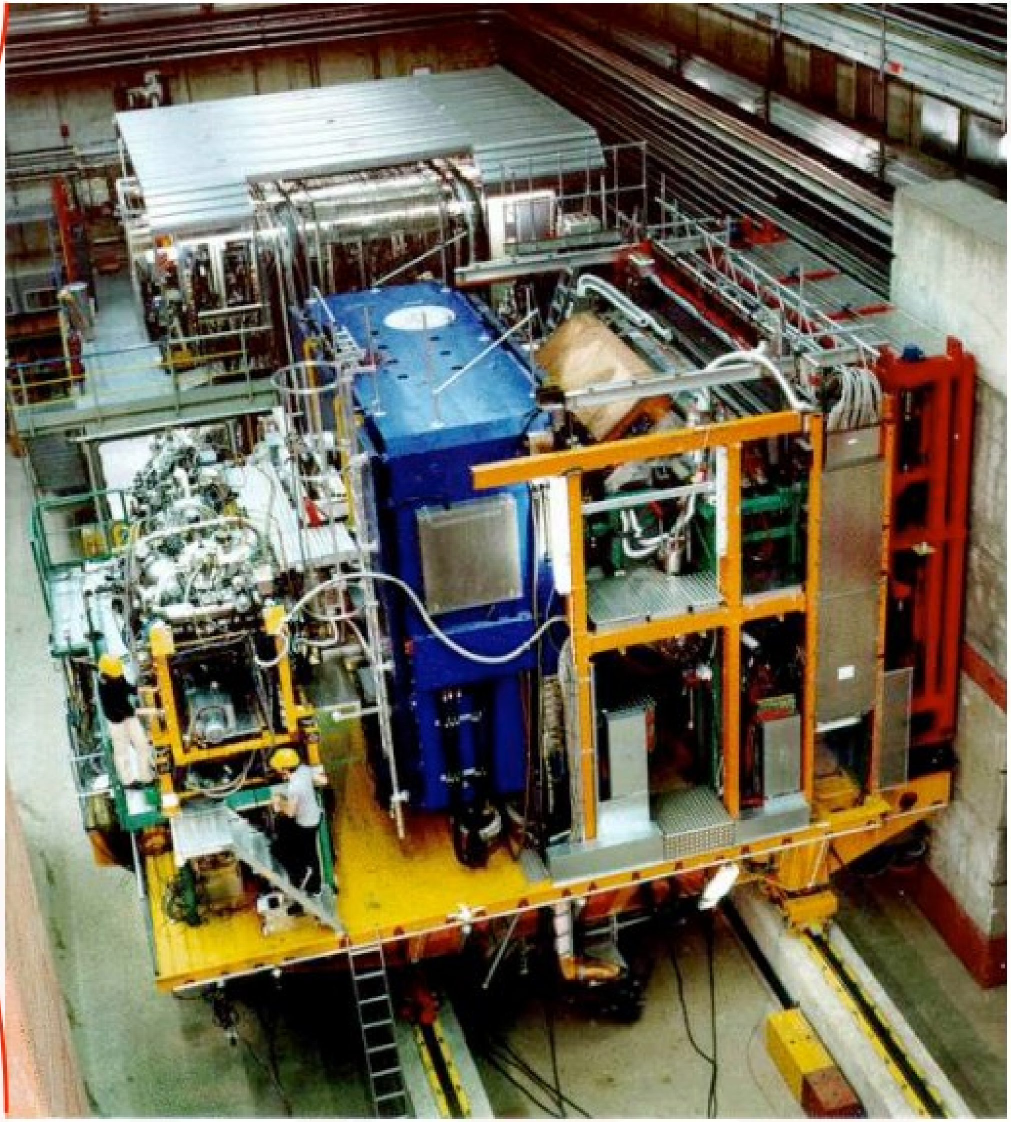
- For SIDIS, key is to measure azimuthal modulation
  - Angle between outgoing hadron $\mathbf{p_T}$ and nucleon spin
- Different "harmonics" associated with different structure functions, e.g., $F_{UU}^{\cos(2\varphi)}$
- Each *F* is in turn a convolution of a TMD with a FF (previous slide)
- Take data at various energies and polarizations → disentangle and extract the TMDs
  - All 8 extractable with sufficient luminosity and kinematic reach (future electron-ion collider?)

Experimental landscape

- Modern (incomplete) TMD information from:
  - HERMES @ DESY (1995-2007)
  - COMPASS @ CERN-SPS (2002-present, SIDIS 2012)
  - 6GeV CEBAF @ Jlab (~2004 – 2012, all three halls)
- Under construction:
  - 12 GeV CEBAF
- The future: Electron-ion collider (all 8 TMDs!)
  - Either MEIC @ JLab or eRHIC @ BNL
  - Needed to extend to higher Q^2, lower x → Probe sea quark and gluon TMDs

HERMES @ DESY

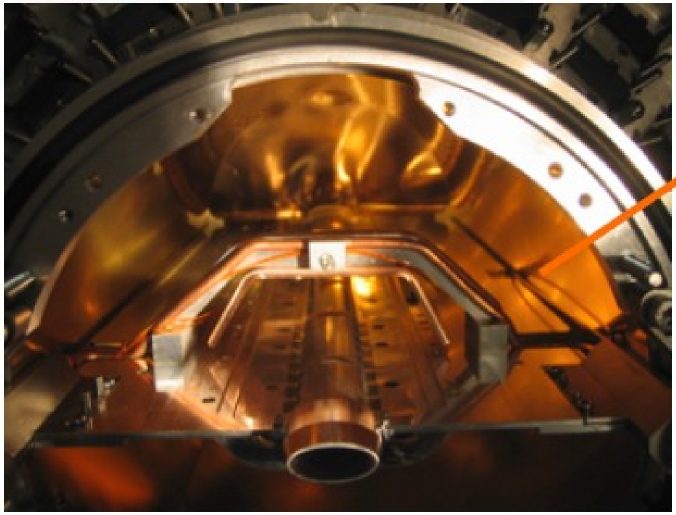
- 27.6 GeV HERA e^+/e^- beam

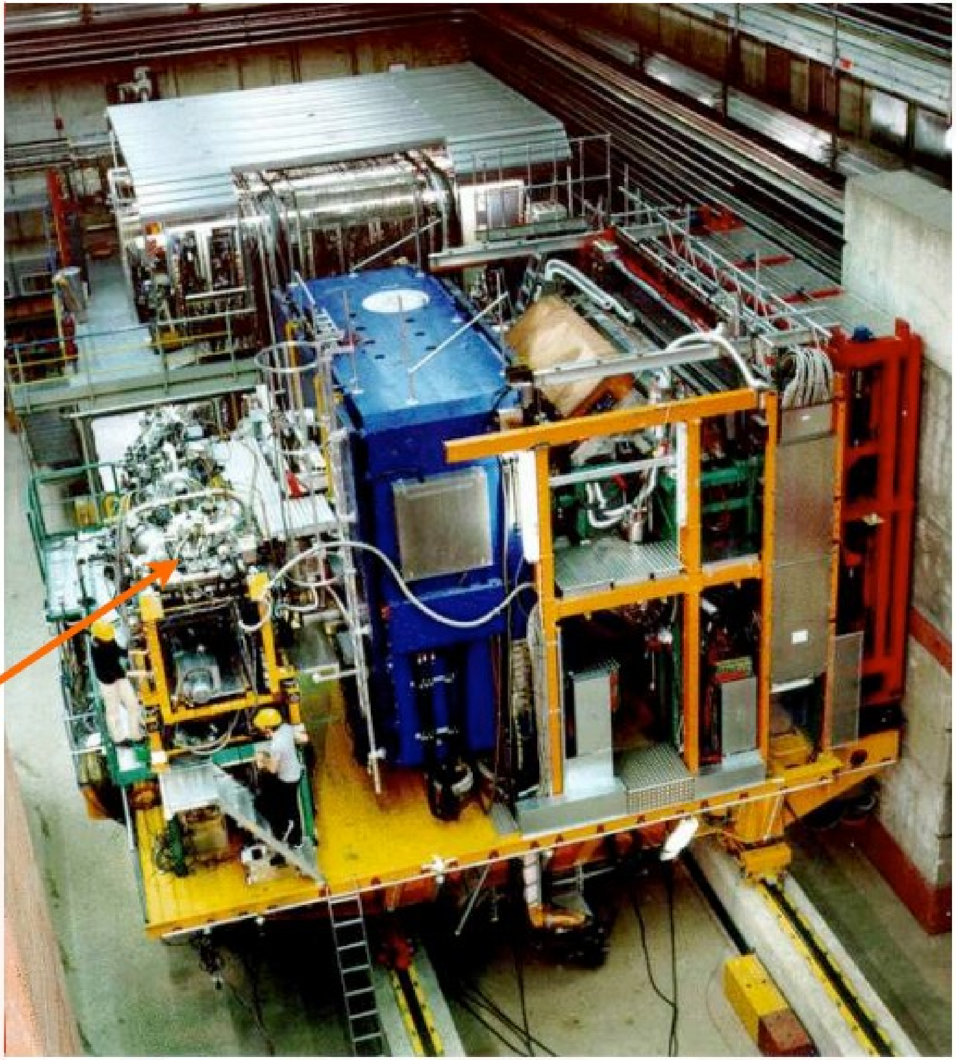


- longitudinally polarized

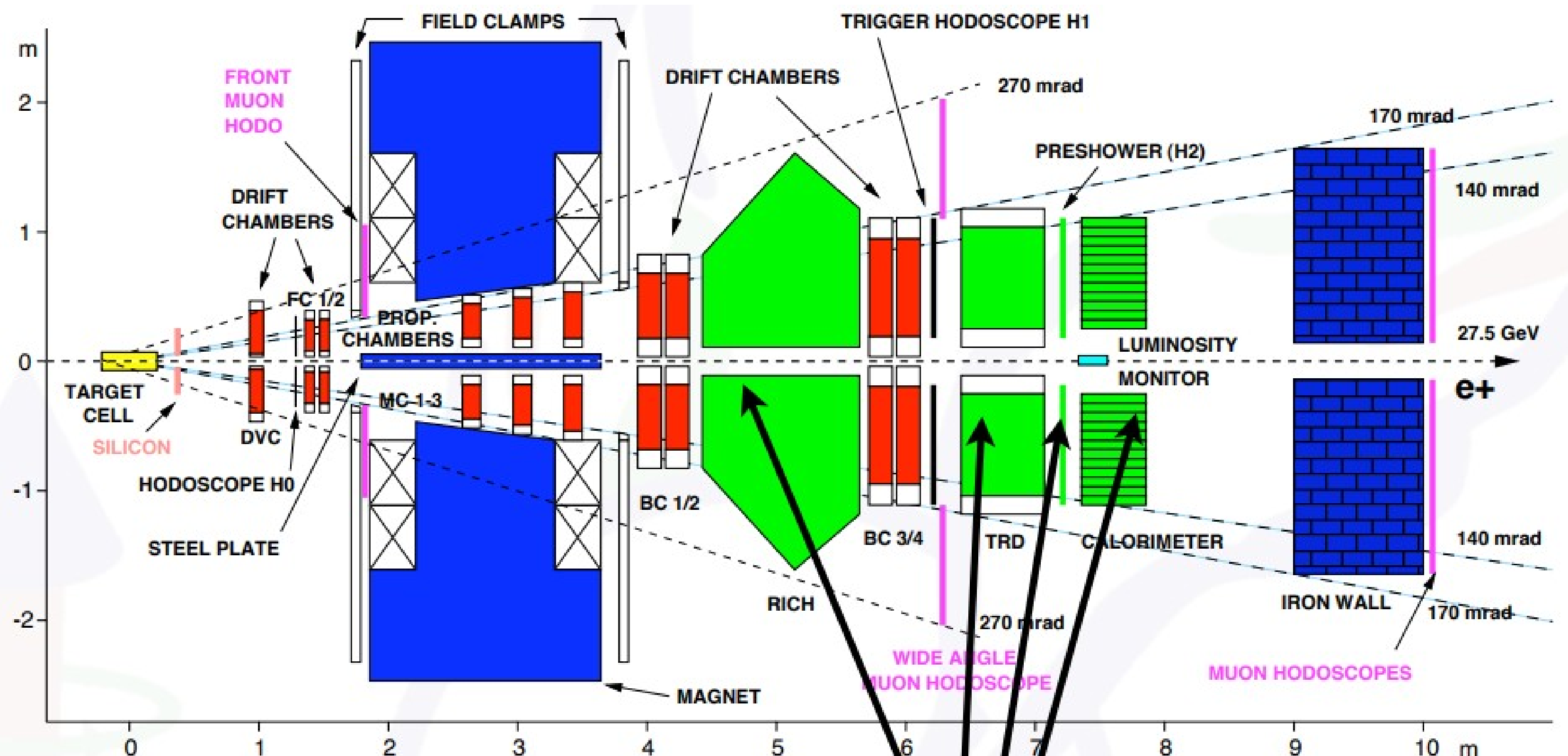
HERMES @ DESY

- pure gas targets
- internal to lepton ring
- unpolarized (^{1}H ... Xe)
- long. polarized: ^{1}H, ^{2}H, ^{3}He
- transversely polarized: ^{1}H





HERMES @ DESY



- pure gas targets internal to HERA 27.6 GeV lepton ring
- unpolarized (^{1}H ... Xe)
- long. polarized: ^{1}H, ^{2}H, ^{3}He
- transversely polarized: ^{1}H

Particle ID detectors allow for
- lepton/hadron separation
- RICH: pion/kaon/proton discrimination 2GeV<p<15GeV

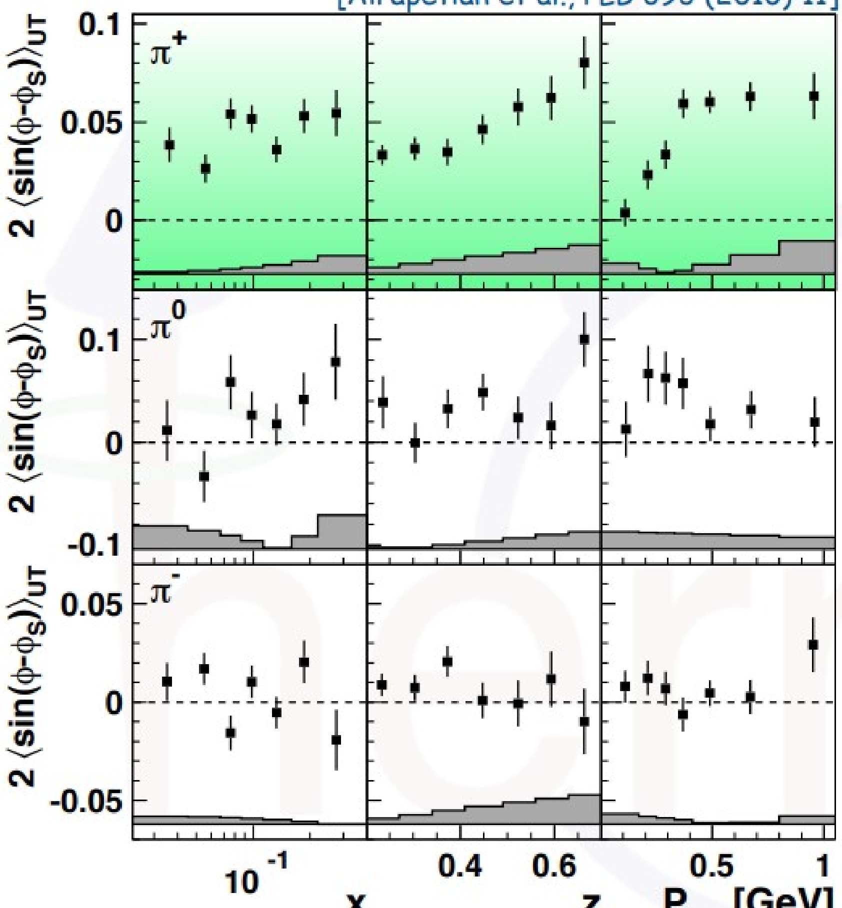
HERMES: Example data

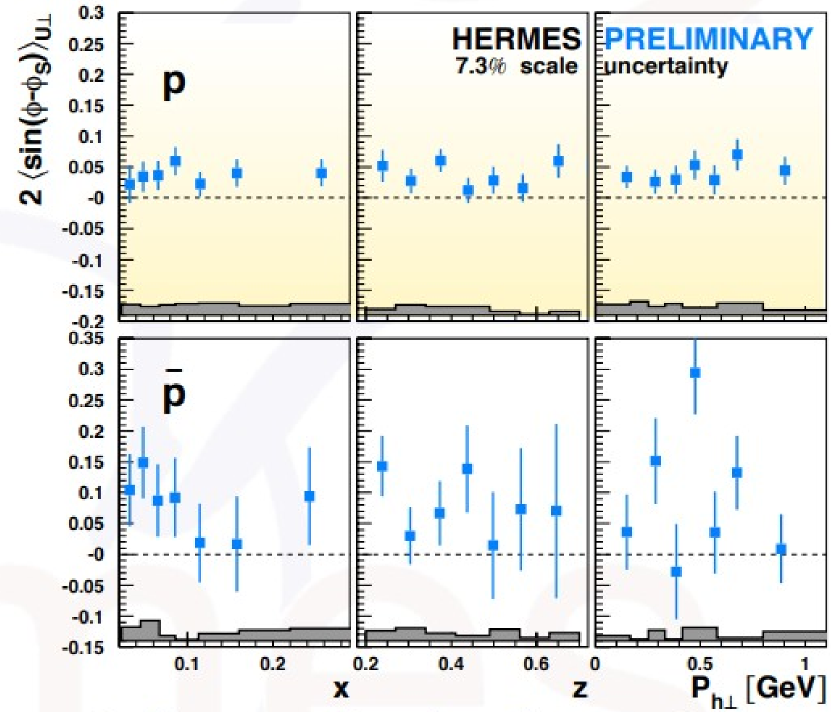
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Sivers amplitudes for baryons

$$2\langle \sin(\phi-\phi_S)\rangle_{\mathrm{UT}} = -\frac{\sum_q e_q^2 f_{1\mathrm{T}}^{\perp,q}(x,p_T^2) \otimes_{\mathcal{W}} D_1^q(z,k_T^2)}{\sum_q e_q^2 f_1^q(x,p_T^2)\otimes D_1^q(z,k_T^2)}$$

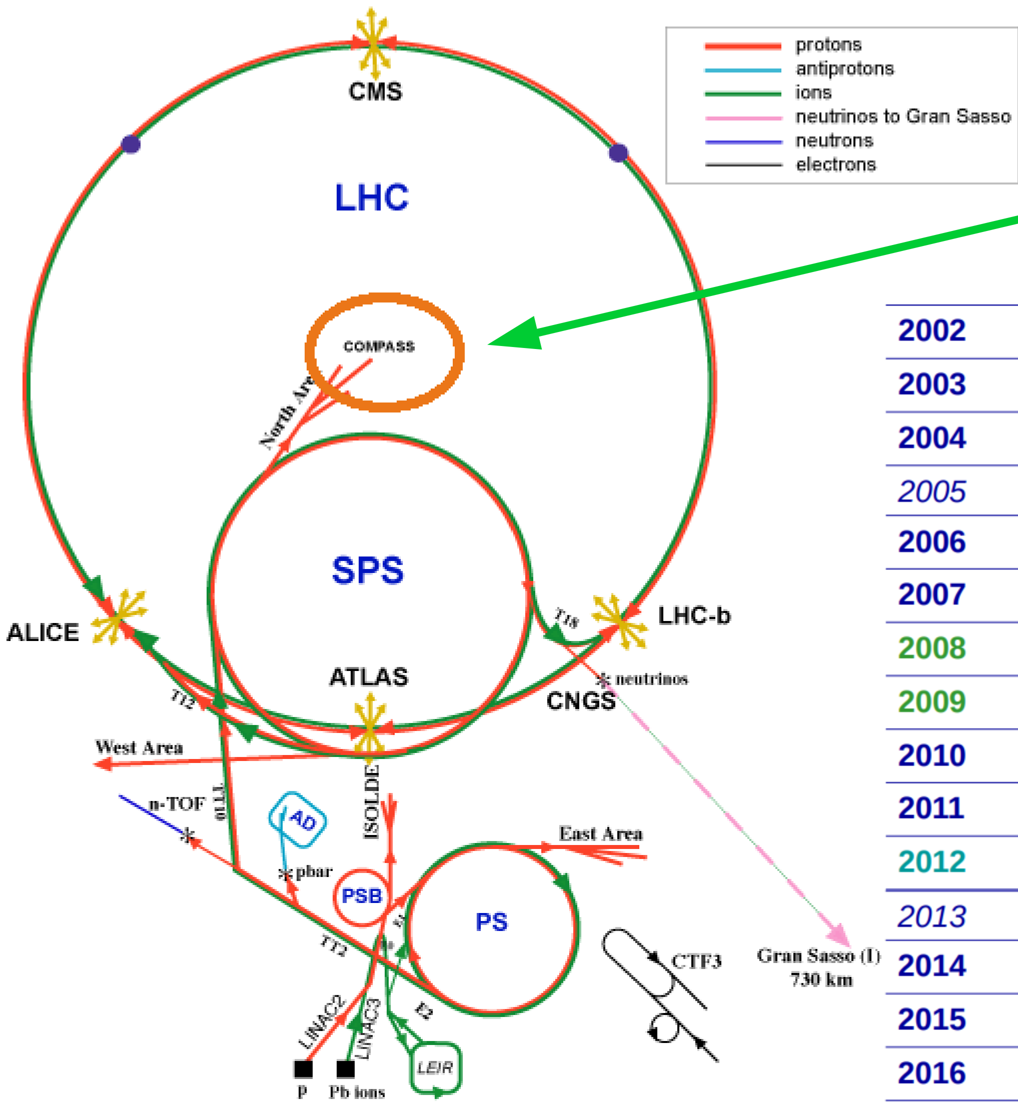
[Airapetian et al., PLB 693 (2010) 11]





similar amplitudes for positive pions and protons ☛ u-quark dominance (and not a FF effect)?

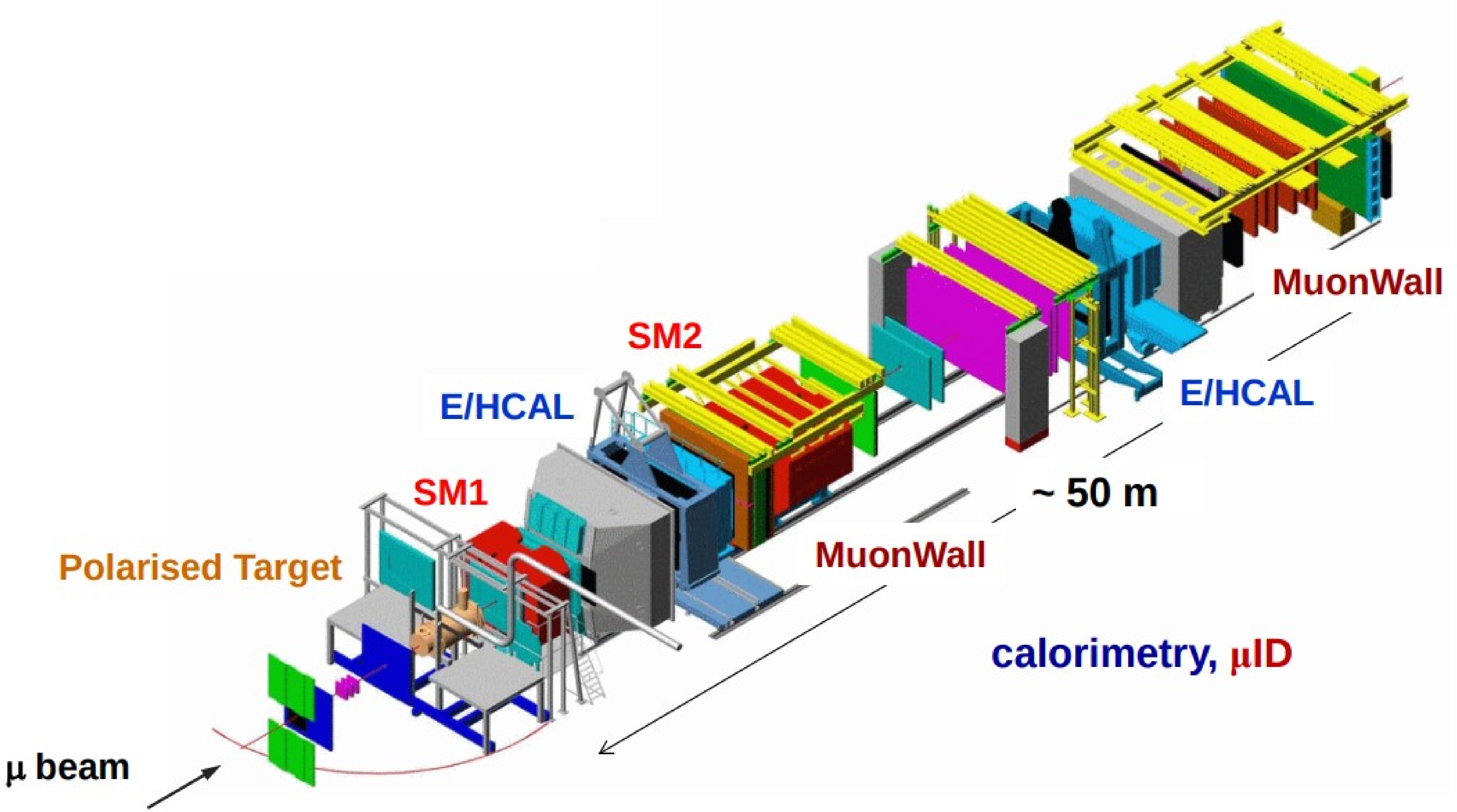
COMPASS @ CERN



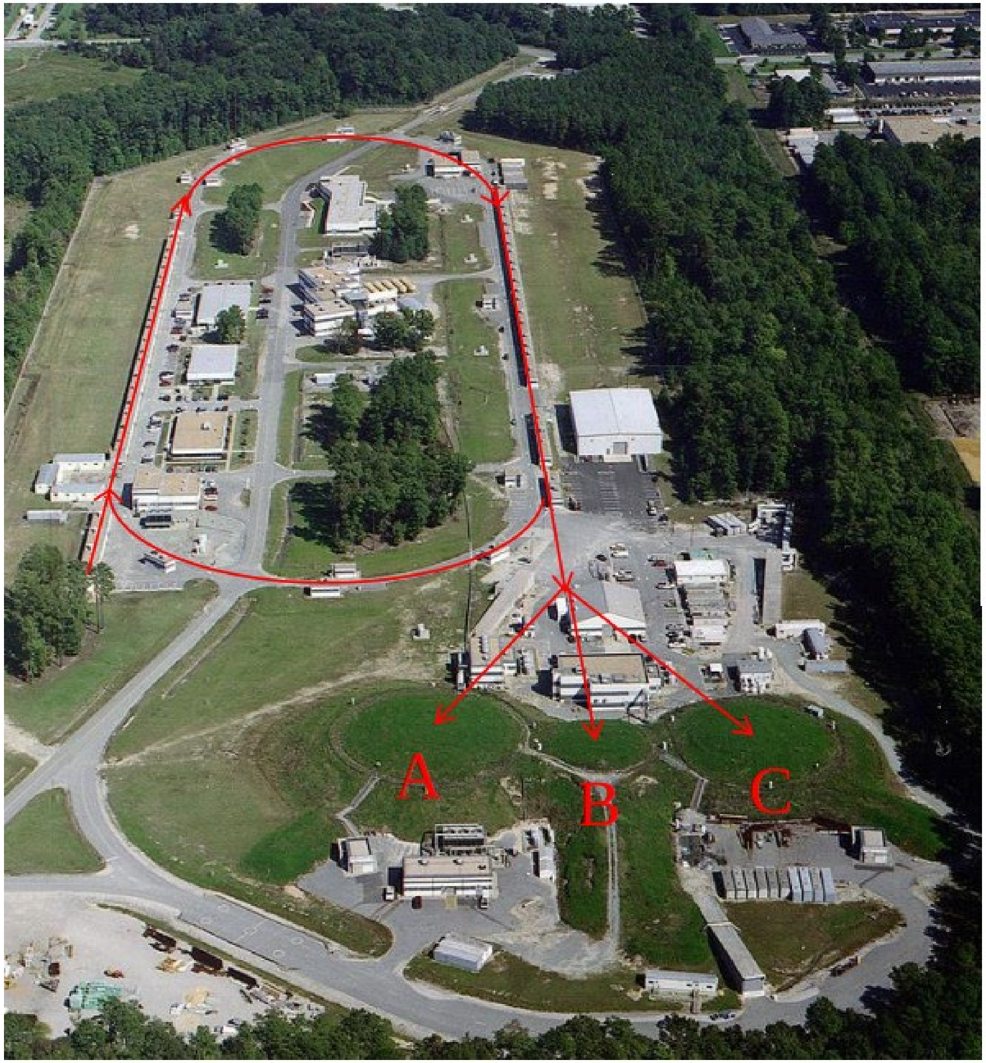
Unpolarized muons/mesons on fixed target (proton or deuteron, possibly polarized)

2002	**nucleon structure with**	**160 GeV μ**	L&T	**polarised deuteron target**
2003	**nucleon structure with**	**160 GeV μ**	L&T	**polarised deuteron target**
2004	**nucleon structure with**	**160 GeV μ**	L&T	**polarised deuteron target**
2005	*CERN accelerators shut down*			
2006	**nucleon structure with**	**160 GeV μ**	L	**polarised deuteron target**
2007	**nucleon structure with**	**160 GeV μ**	**L&T**	**polarised proton target**
2008	***hadron spectroscopy***			
2009	***hadron spectroscopy***			
2010	**nucleon structure with**	**160 GeV μ**	**T**	**polarised proton target**
2011	**nucleon structure with**	**190 GeV μ**	**L**	**polarised proton target**
2012	**Primakoff & DVCS / SIDIS test**			
2013	*CERN accelerators shut down*			
2014	Test beam Drell-Yan process with π beam and T polarised proton target			
2015	**Drell-Yan process with π beam and T polarised proton target**			
2016	**DVCS / SIDIS with μ beam and unpolarised proton target**			
2017	**DVCS / SIDIS with μ beam and unpolarised proton target**			
2018	**Drell-Yan process with π beam and T polarised proton target**			

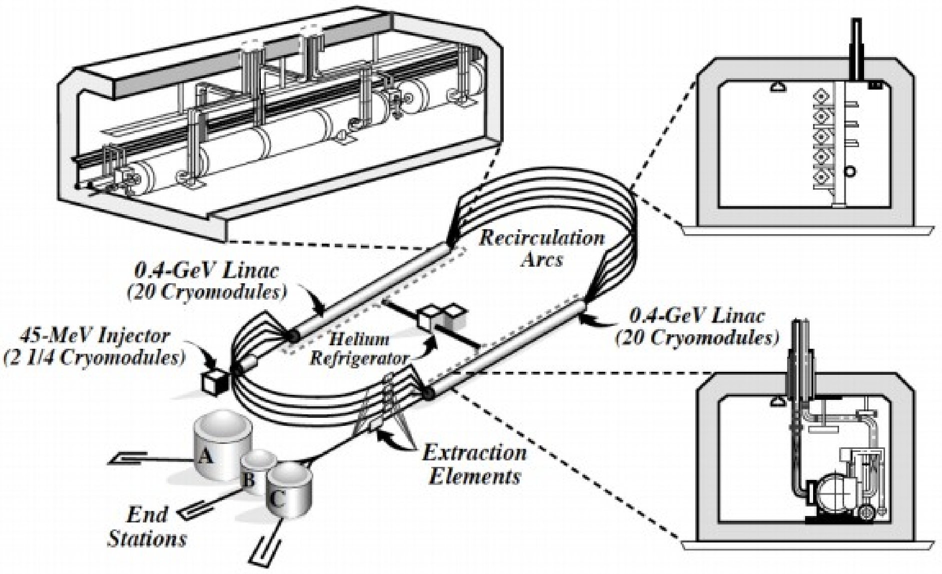
COMPASS @ CERN



CEBAF @ JLab

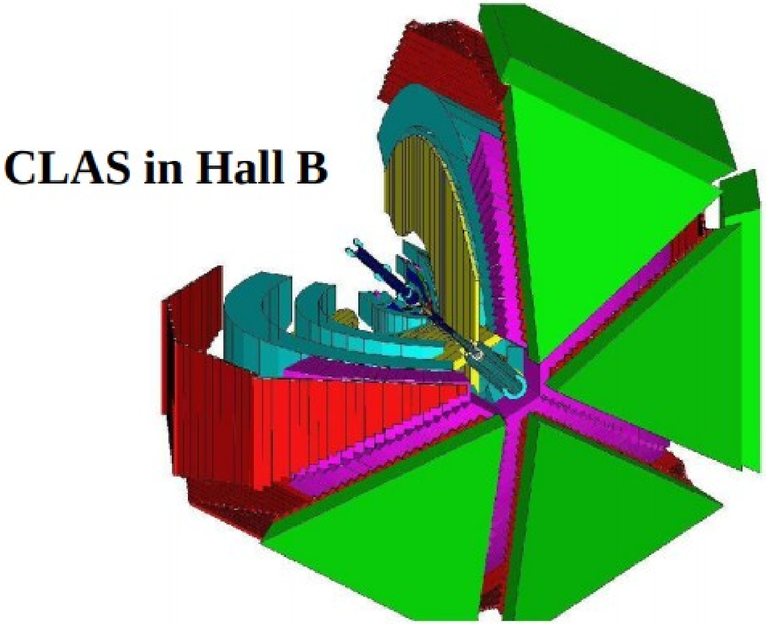


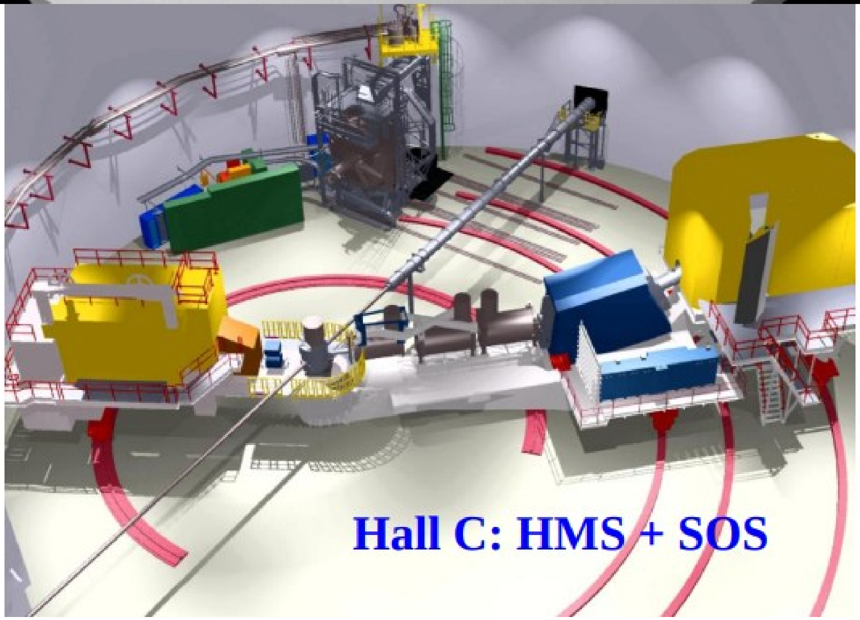
JLab Aerial View



- Superconducting RF electron linacs with up to 5X recirculation
- CW ("100%" duty factor) operation (2 ns bunch period, ~0.3 ps bunch length)
- Polarized source: up to 85-90% polarization
- Three experimental Halls
- Energy up to 6 GeV (upgrade will increase to 11(12) GeV to Halls A/B/C (D))
- Current (up to 180 μA CW)

CEBAF @ JLab

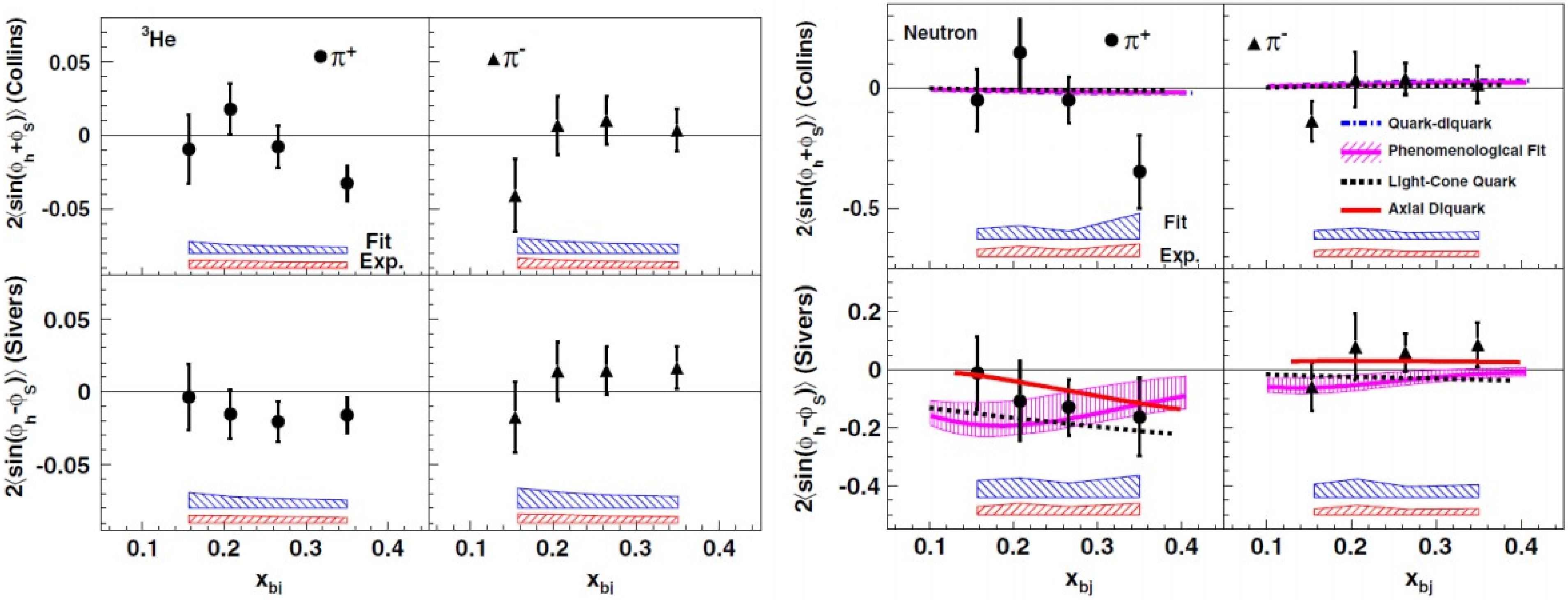




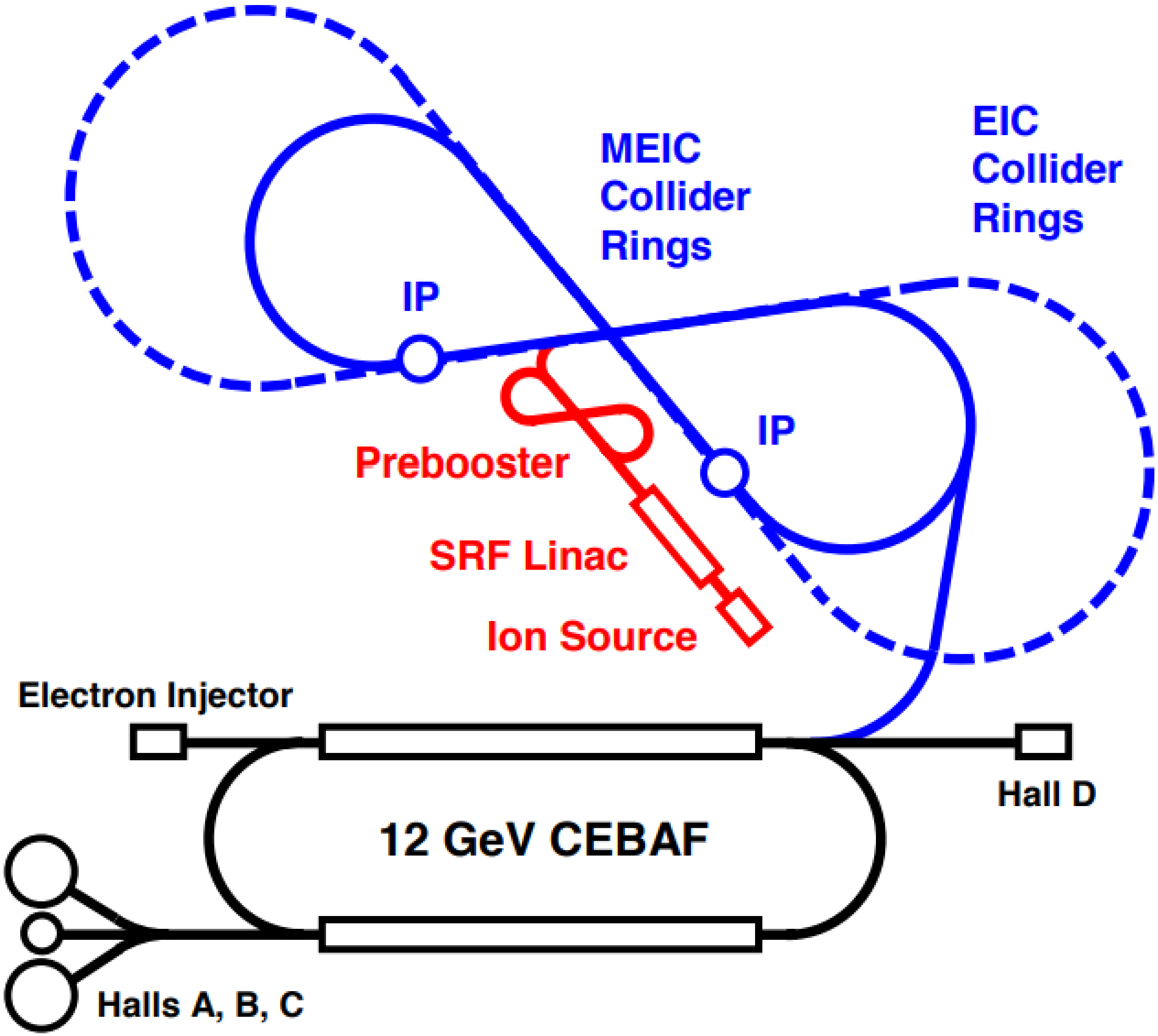
- **Hall A**: High resolution (dp/p ~ 10^{-4}) spectrometers, small acceptance for targeted measurements w/ well-controlled systematics, well-defined kinematics at high luminosities. ***NIM A 522, 294 (2004)***
- **Hall B**: Large acceptance, moderate resolution/luminosity for measurement of multi-particle final states with broad kinematic coverage: ***NIM A 503, 513 (2003)***
- **Hall C**: High momentum spectromer and Short Orbit Spectrometer—well-controlled acceptance for precise cross section measurements: ***PRC 78, 045202 (2008)***

CEBAF: Example data

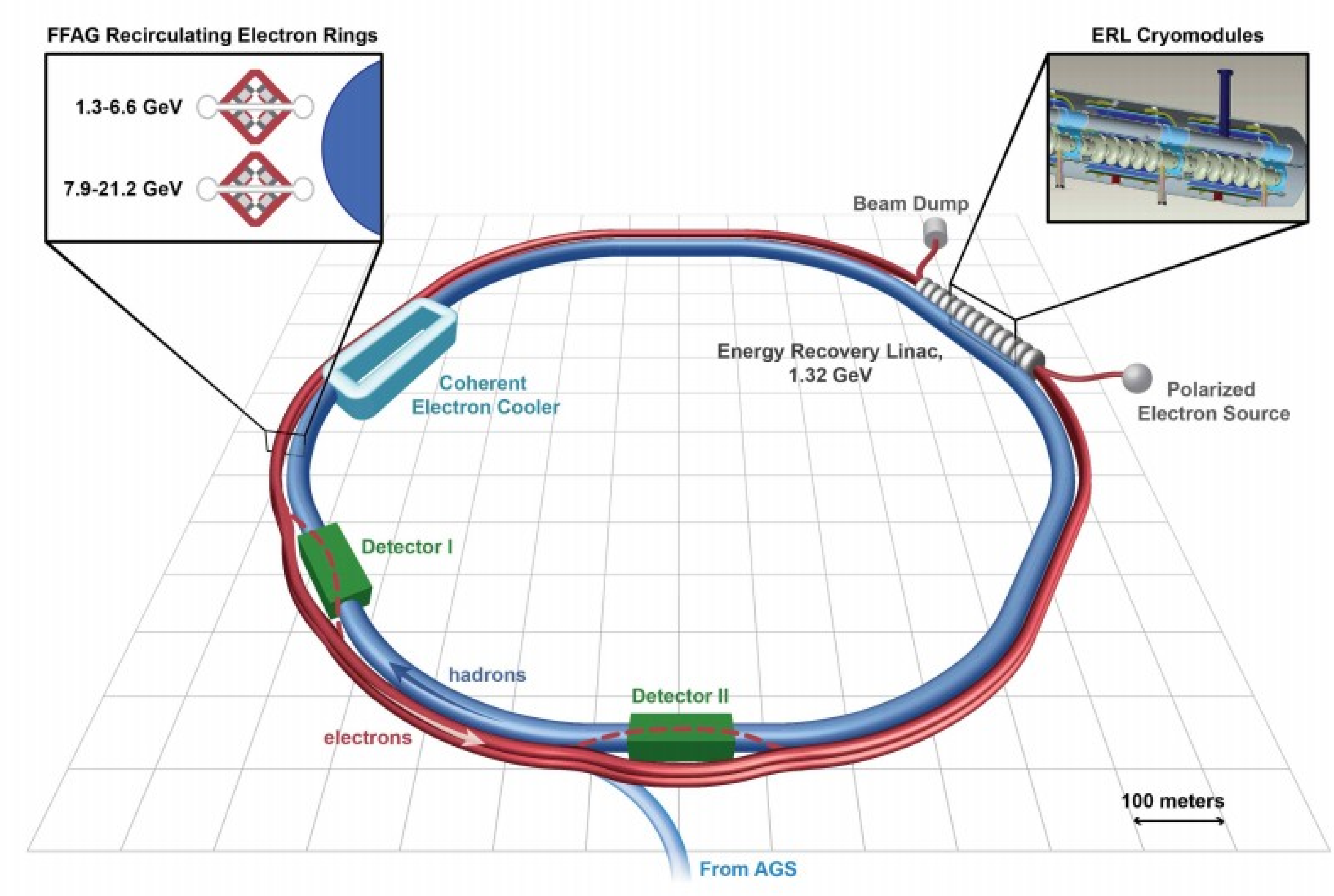
Collins and Sivers effects: *PRL 107, 072003 (2011)*



The future? MEIC @ JLab



The future? eRHIC @ BNL



Conclusions

- TMDs…
  - ...complement the 3D structure revealed by GPDs
  - ...provide unique insight into orbital angular momentum and spin-orbit coupling of partons
  - ...have been partially measured, but current fixed-target experiments are limited in reach
  - ...can be measured, at proposed EIC, to unprecedented precision, in all 8 forms, for all valence and sea quarks/gluons

References

- EIC whitepaper (very readable!): https://arxiv.org/abs/1212.1701
- HERMES: http://www-hermes.desy.de/notes/pub/TALK/gunar.3dpdfatlhc.pdf
- COMPASS: http://wwwcompass.cern.ch/compass/publications/talks/t2017/Bradamante_JLab2017.pdf
- CEBAF: https://www.jlab.org/conferences/qcd-evolution2015/talks/thursday/puckett.pdf
- Theory (Alessandro Bacchetta):
  - Slides: https://www.jlab.org/div_dept/theory/talks/bacchetta08_eic.pdf
  - Notes: https://www2.pv.infn.it/~bacchett/teaching/Bacchetta_Trento2012.pdf