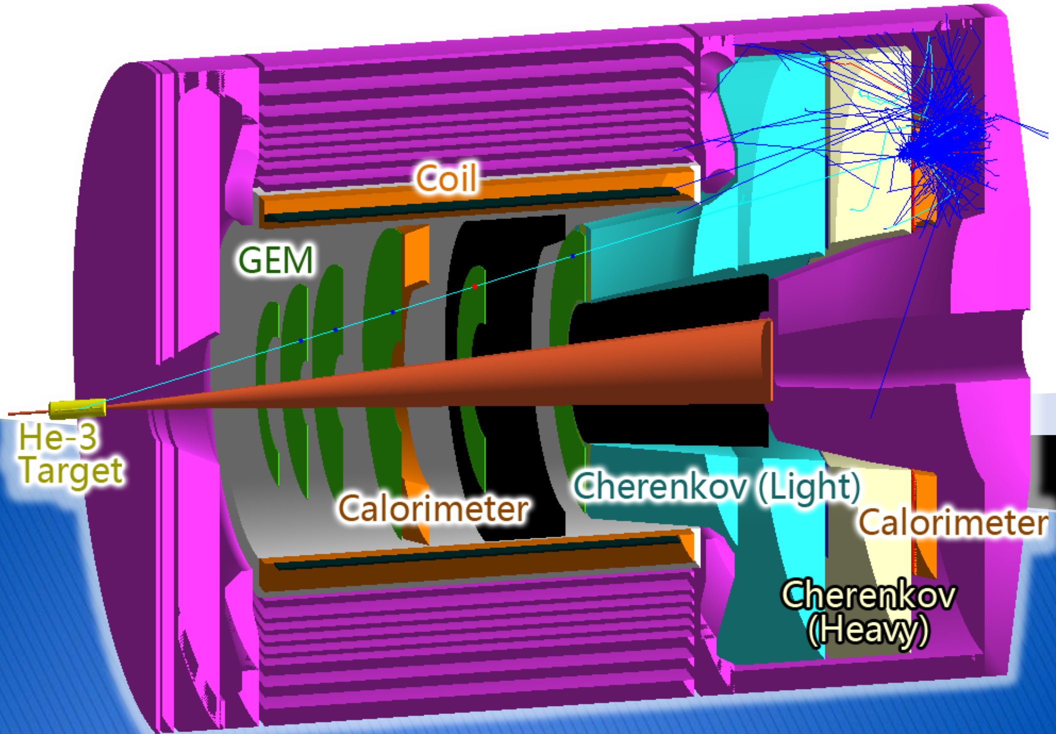
E12-10-006, E12-11-007, PR12-11-108

SIDIS Charged-Pion Production with SoLID and Pol. Targets

Jin Huang, MIT

for the Hall A SoLID SIDIS collaboration



Jefferson Lab

12 GeV Upgrade
Future Science at Jefferson Lab

Experiments/Proposals

E12-10-006 (PAC35): Transversely pol. ^{3}He, Collins, Sivers, Pretzelosity
E12-11-007 (PAC37): Longitudinally pol. ^{3}He, Worm-gear TMDs
PR12-11-108 (PAC38): Transversely pol. Proton

Collaboration

ANL, Peking U., CalState-LA, CIAE, W&M, Duke, FIU, Hampton, Huangshan U., Huazhong U.S.T., IMP CAS, Cagliari U. and INFN, INFN-Catania, INFN-Bari and U. of Bari, INFN-Frascati, INFN-Pavia, Torino U. and INFN, JLab, JSI (Slovenia), Lanzhou U, LBNL, Longwood U, LANL, MIT, Miss. State, New Mexico, ODU, Penn State at Berks, Rutgers, Seoul Nat. U., St. Mary's, Syracuse, Shandong U, Tel aviv, Temple, Tsinghua U, UConn, Glasgow, UIUC, Kentucky, Maryland, UMass, New Hampshire, USTC, UVa

and the Hall A Collaboration

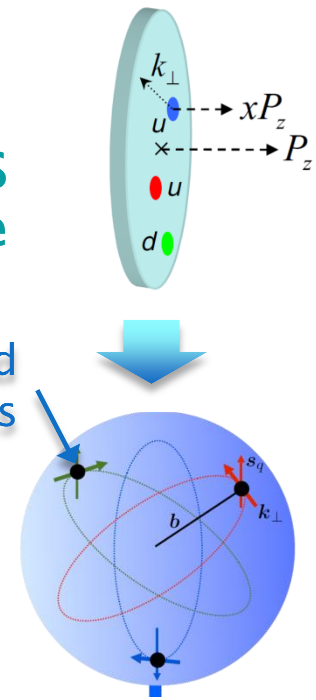
Strong theory support, Over 180 collaborators, 50 institutions, 8 countries, strong overlap with PVDIS Collaboration

Transverse Momentum Dependent (TMD) Parton Distributions

- TMD PDFs link
  - Intrinsic motion of partons
  - Parton spin
  - Spin of the nucleon
- Multi-Dimension structure
  - Probes orbital motion of quarks
- A new phase of study, fast developing field
  - Great advance in theories (factorization, models, Lattice
  - Not sys. studied until recent years
    - Semi-Inclusive DIS (SIDIS): HERMES, COMPASS, Jlab-6GeV, ...
    - p-p(p_bar) process : FNAL, BNL, ...

in DIS
Nucleon -> Plate

Transverse motion preserved
Imaging the dynamics



Leading-Twist TMD PDFs

Nucleon Spin

Quark Spin

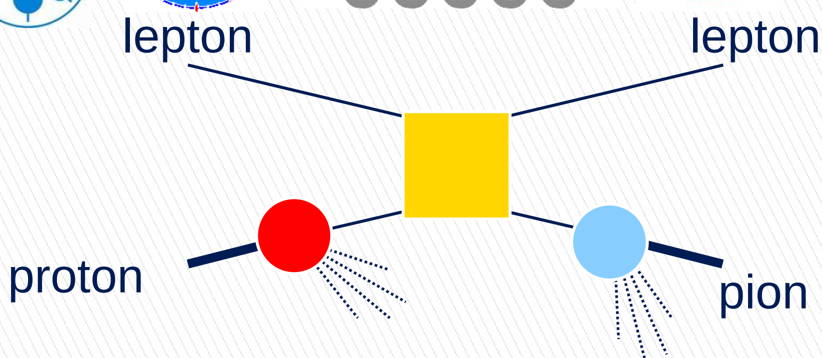
Nucleon Polarization	Quark polarization		
	Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	$f_1 =$		$h_1^{\perp} = \; - $ **Boer-Mulders**
L		$g_1 = \; - $ **Helicity**	$h_{1L}^{\perp} = \; - $ **Long-Transversity**
T	$f_{1T}^{\perp} = \; - $ **Sivers**	$g_{1T} = \; - $ **Trans-Helicity**	$h_1 = \; - $ **Transversity** $h_{1T}^{\perp} = \; - $ **Pretzelosity**

Leading-Twist TMD PDFs

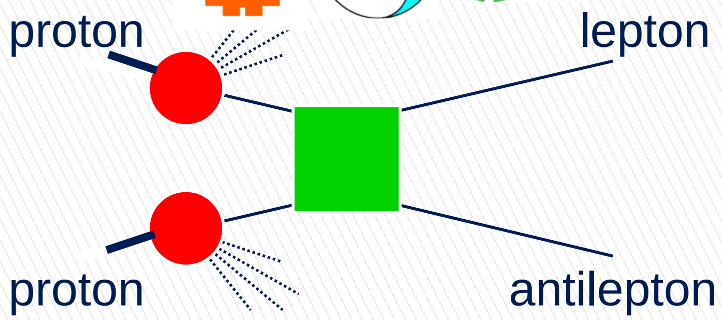
Nucleon Spin
Quark Spin

Nucleon Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
U	$f_1 =$		$h_1^{\perp} = \; - \;$ Boer-Mulders
L		$g_1 = \; - \;$ Helicity	$h_{1L}^{\perp} = \; - \;$ Long-Transversity
T	$f_{1T}^{\perp} = \; - \;$ Sivers	$g_{1T} = \; - \;$ Trans-Helicity	$h_1 = \; - \;$ Transversity $h_{1T}^{\perp} = \; - \;$ Pretzelosity

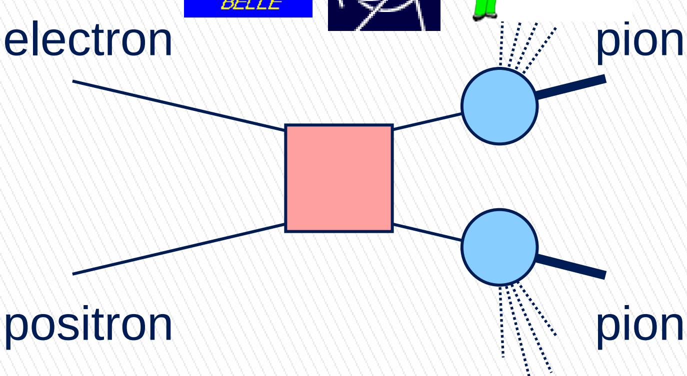
Access TMDs through Hard Processes



SIDIS



Drell-Yan



$e^{-}e^{+}$ to pions

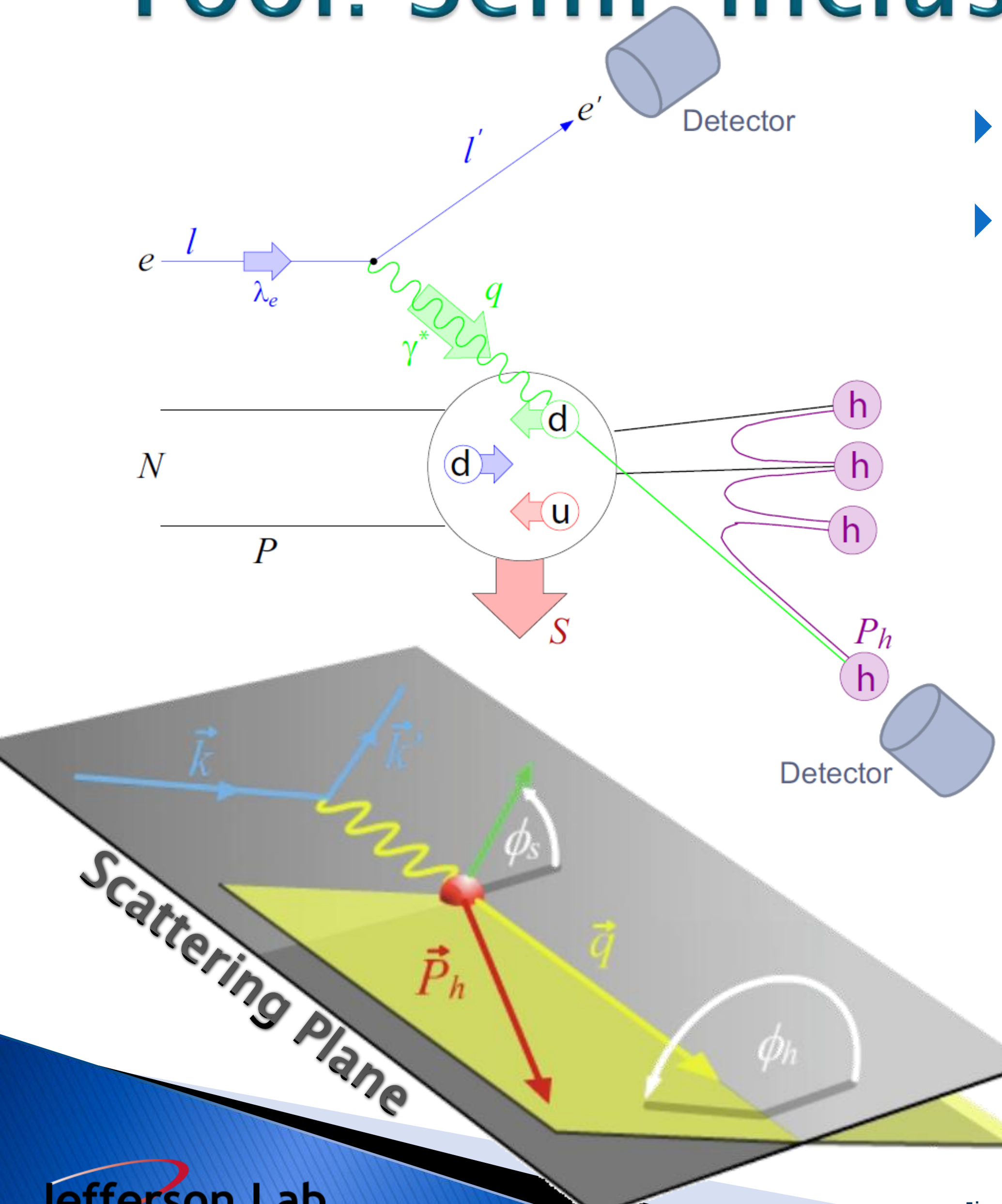
- Partonic scattering amplitude
- Fragmentation amplitude
- Distribution amplitude

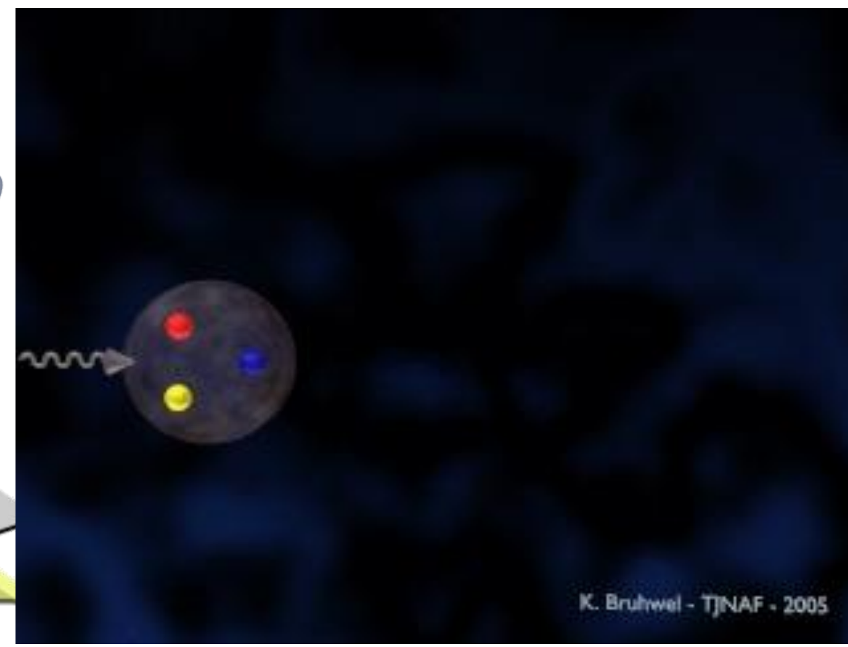
$$f_{1T}^{\perp q}(SIDIS) = -f_{1T}^{\perp q}(DY)$$

$$h_1^{\perp}(\mathrm{SIDIS}) = -h_1^{\perp}(\mathrm{DY})$$

Tool: Semi-inclusive DIS (SIDIS)

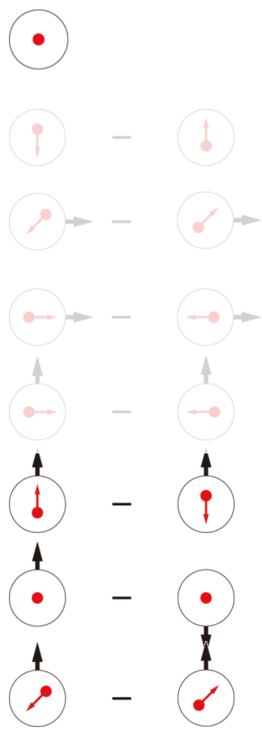
- Gold mine for TMDs
- Access all eight leading-twist TMDs through spin-comb. & azimuthal-modulations





SIDIS is Gold Mine for TMD

- $f_1 =$
- Boer-Mulder $h_1^{\perp} =$
- Worm Gear $h_{1L}^{\perp} =$
- Helicity $g_1 =$
- Worm Gear $g_{1T} =$
- Transversity $h_{1T} =$
- Sivers $f_{1T}^{\perp} =$
- Pretzelosity $h_{1T}^{\perp} =$



$$\frac{d\sigma}{dxdyd\phi_S dzd\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\cdot$$

$$\{F_{UU,T} +$$

$$+\varepsilon\cos(2\phi_h)\cdot F_{UU}^{\cos(2\phi_h)} + \ldots$$

$$+S_L[\varepsilon\sin(2\phi_h)\cdot F_{UL}^{\sin(2\phi_h)} + \ldots]$$

$$+S_L\lambda_e[\sqrt{1-\varepsilon^2}\cdot F_{LL} + \ldots]$$

$$+S_T\lambda_e[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\cdot F_{LT}^{\cos(\phi_h-\phi_S)} + \ldots]$$

$$+S_T[\varepsilon\sin(\phi_h+\phi_S)\cdot F_{UT}^{\sin(\phi_h+\phi_S)}$$

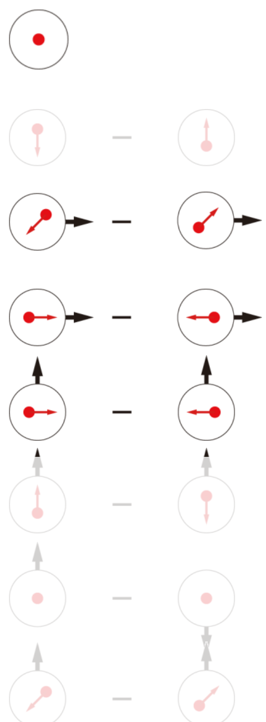
$$+\sin(\phi_h-\phi_S)\cdot(F_{UT}^{\sin(\phi_h-\phi_S)} + \ldots)$$

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

S_L, S_T: Target Polarization; λ_e: Beam Polarization

SIDIS is Gold Mine for TMD

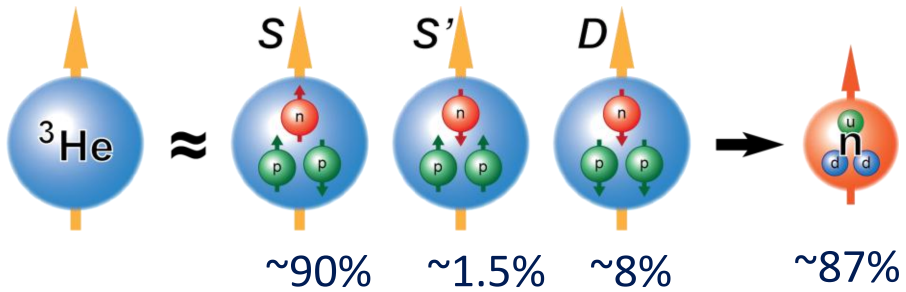
$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\cdot$$



	$f_1 =$	$\{F_{UU,T} +$
Boer-Mulder	$h_1^{\perp} =$	$+\varepsilon\cos(2\phi_h)\cdot F_{UU}^{\cos(2\phi_h)} + \ldots$
Worm Gear	$h_{1L}^{\perp} =$	$+S_L[\varepsilon\sin(2\phi_h)\cdot F_{UL}^{\sin(2\phi_h)} + \ldots]$
Helicity	$g_1 =$	$+S_L\lambda_e[\sqrt{1-\varepsilon^2}\cdot F_{LL} + \ldots]$
Worm Gear	$g_{1T} =$	$+S_T\lambda_e[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\cdot F_{LT}^{\cos(\phi_h-\phi_S)} + \ldots]$
Transversity	$h_{1T} =$	$+S_T[\varepsilon\sin(\phi_h+\phi_S)\cdot F_{UT}^{\sin(\phi_h+\phi_S)}$
Sivers	$f_{1T}^{\perp} =$	$+\sin(\phi_h-\phi_S)\cdot(F_{UT}^{\sin(\phi_h-\phi_S)} + \ldots)$
Pretzelosity	$h_{1T}^{\perp} =$	$+\varepsilon\sin(3\phi_h-\phi_S)\cdot F_{UT}^{\sin(3\phi_h-\phi_S)} + \ldots]\}$

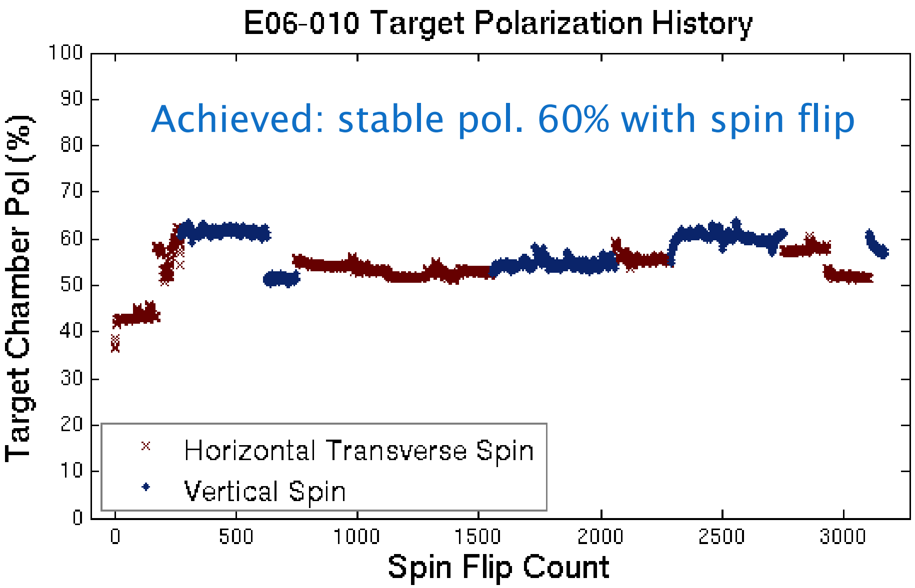
S_L, S_T: Target Polarization; λ_e: Beam Polarization

Polarized ^{3}He Target



Effective pol. neutron target

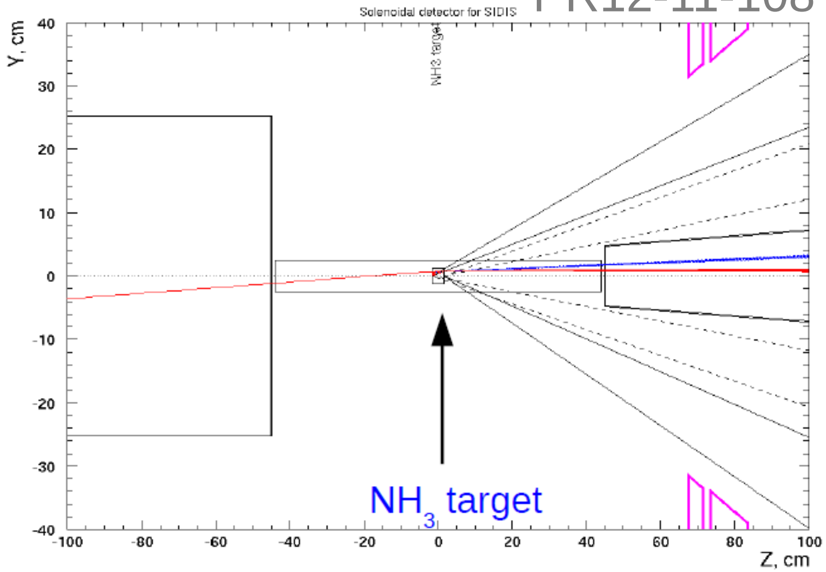
- High 10^{36} N/cm^2/s polarized luminosity
- Achieved performance:
  - High polarization > 60% achieved
  - Supports both long. & trans. spin
  - Frequent spin flip
- Advantages over pol. deuteron targets for n



Polarized NH_3 Target

- Existing target
  - 3 cm NH_3 target, in 5T field
  - Dynamic nuclear polarization/NMR polarimetry
  - Optimized for long. setting
- New
  - New magnet design (proposed) 28º opening (L/T)
  - AFP spin flip (R&D planned)
- Beam line design
  - beam line experience of Hall A g2p/GEP-II
  - Simulated in GEANT
  - 100nA beam, $10^{35}/cm^2/s$

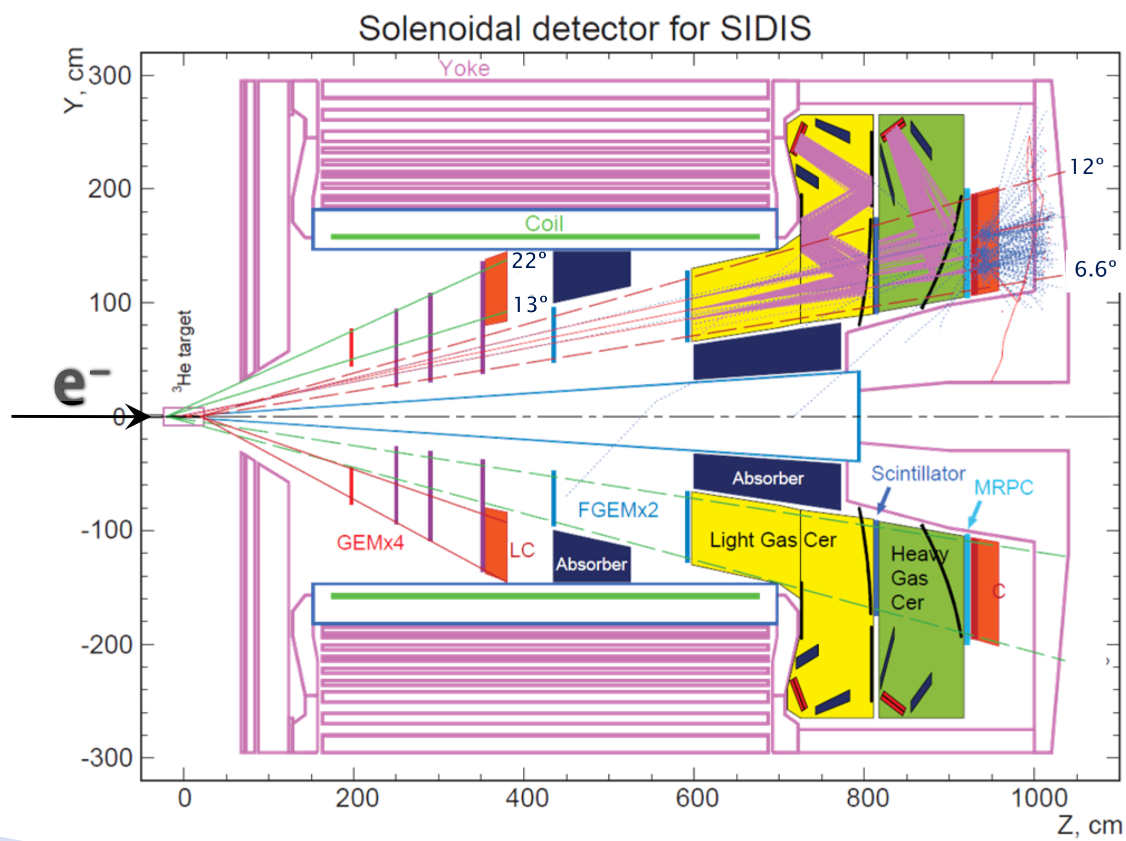
Beamline simulation
PR12-11-108



The SoLID Spectrometer

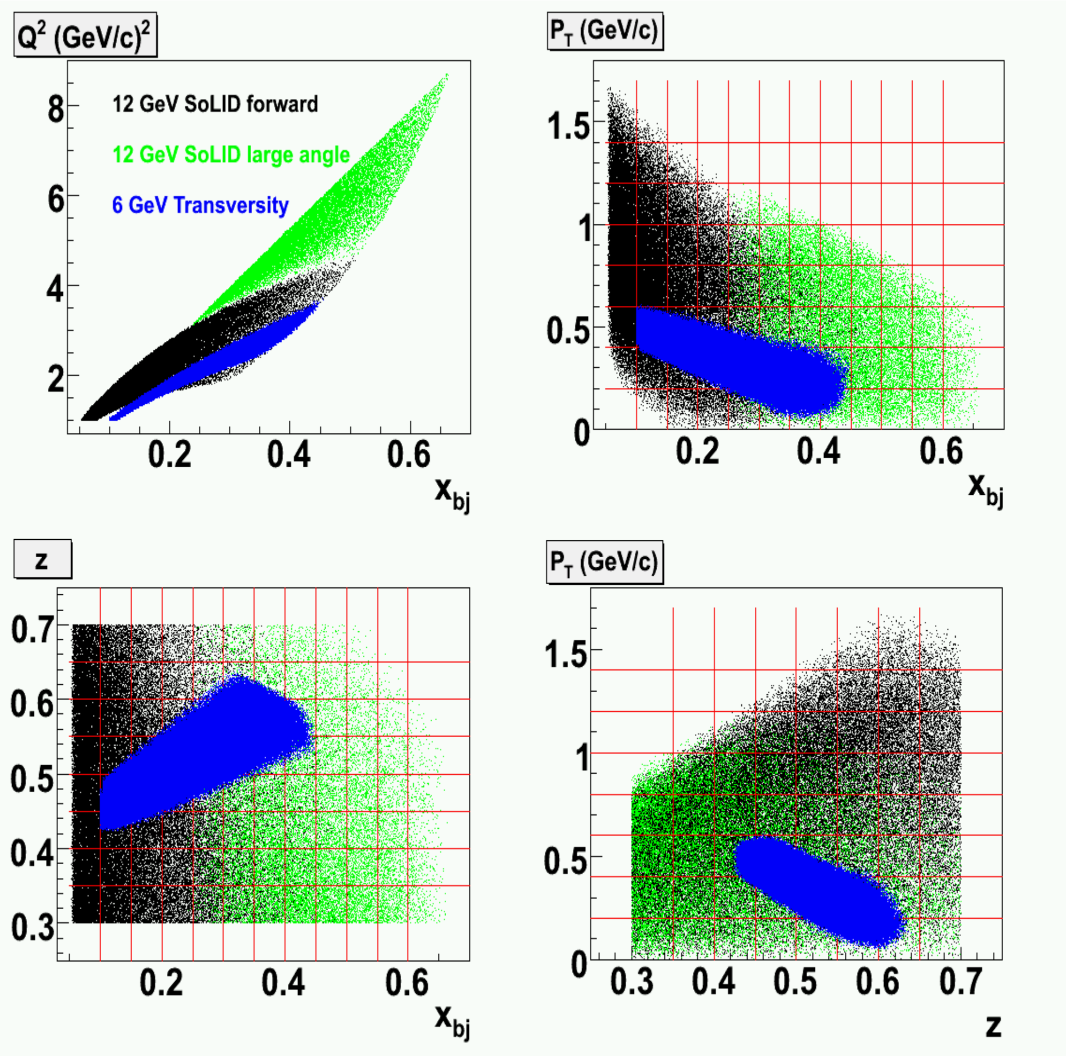
- High Luminosity
- Large acceptance: enable 4D-mapping
- Full azimuthal angular coverage: small systematics
- Largely share hardware with PVDIS

- GEM: high rate tracking
- LC: In field calorimeter
- Cerenkov: PID
- MRPC: TOF, PID @ low p
- C: Calorimeter



Phase space coverage

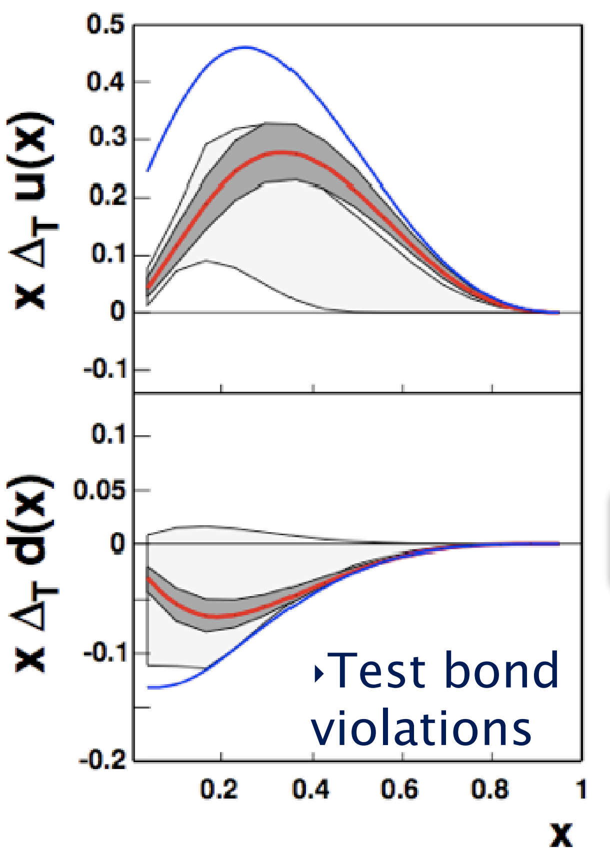
- Natural Extension of E06-010
- Much wider phase space
  - Also data at low and high z value to access target frag. and exclusive channels.
- Both transverse and longitudinal polarized target. 6/7 polarized leading twist TMDs Studied



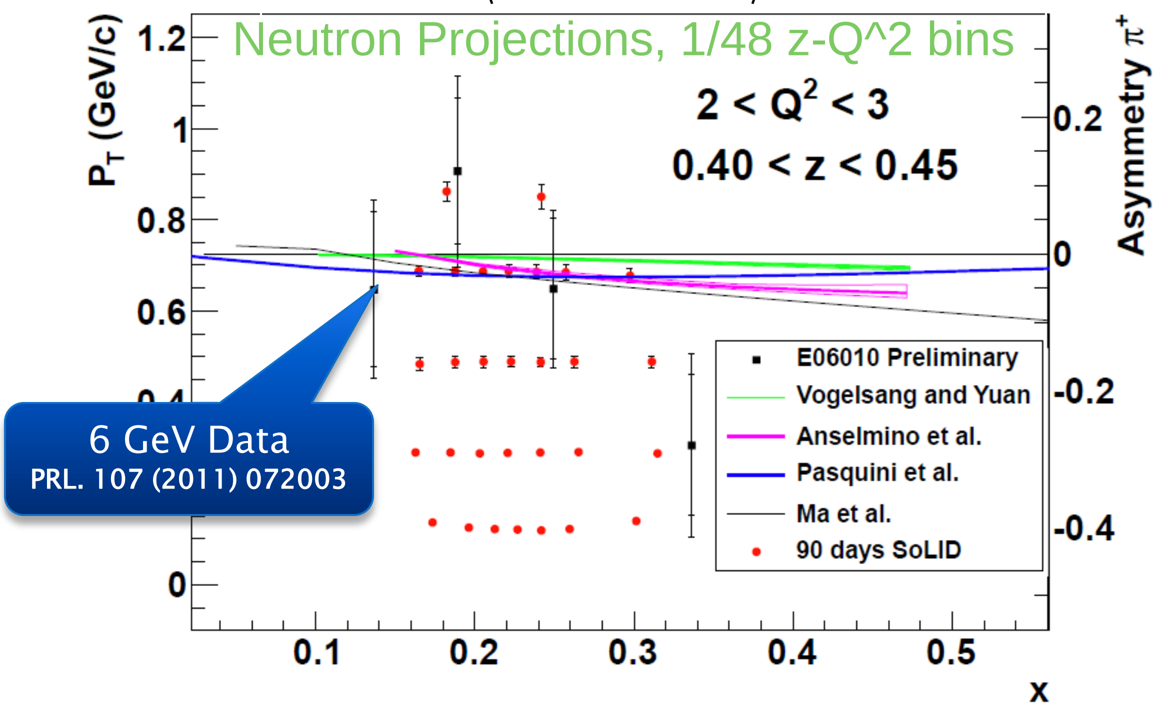
Transversity

h_{1T} =

- The third PDFs in addition to f_1 and g_{1L}
- 10% quark tensor charge from both SSA data
  - Fundamental property, benchmark test of Lattice QCD

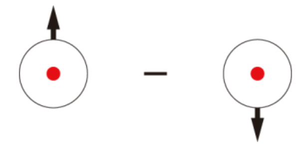


$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_s) \rangle \propto h_{1T} \otimes H_1^{\perp}$$

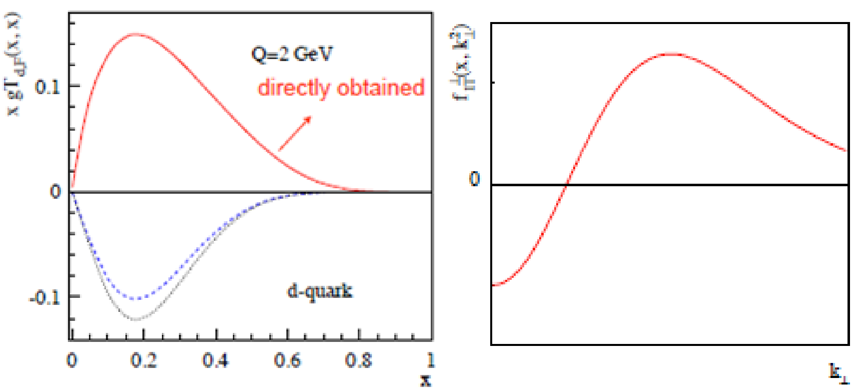


Sivers Function

$f_{1T}^{\perp}$ =



- Correlation between nucleon spin with quark angular momentum
- Important test for factorization $f_{1T}^{\perp q}\Big|_{SIDIS} = -f_{1T}^{\perp q}\Big|_{D-Y}$
- Different sign with twist-3 quark-gluon corr. dis. at high P_T?
  - See Dr. Qiu's talk
- T-odd final state interaction -> Target SSA

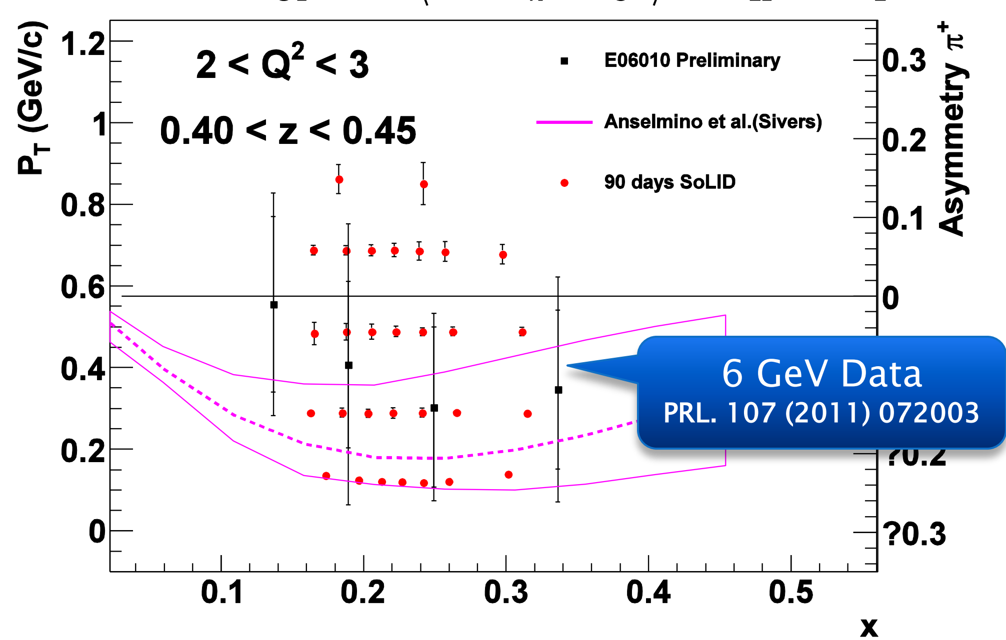


Zhongbo Kang, RBRC/BNL

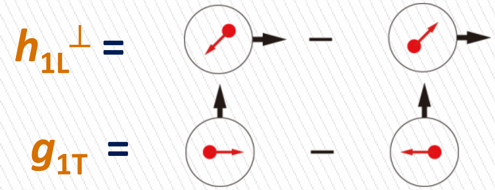
$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\text{SIDIS}}$$

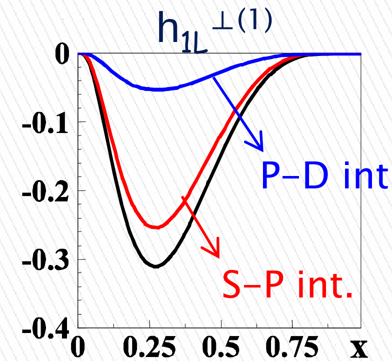
Neutron Projection , 1/48 z-Q^2 bins

$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_s) \rangle \propto f_{1T}^{\perp} \otimes D_1$$



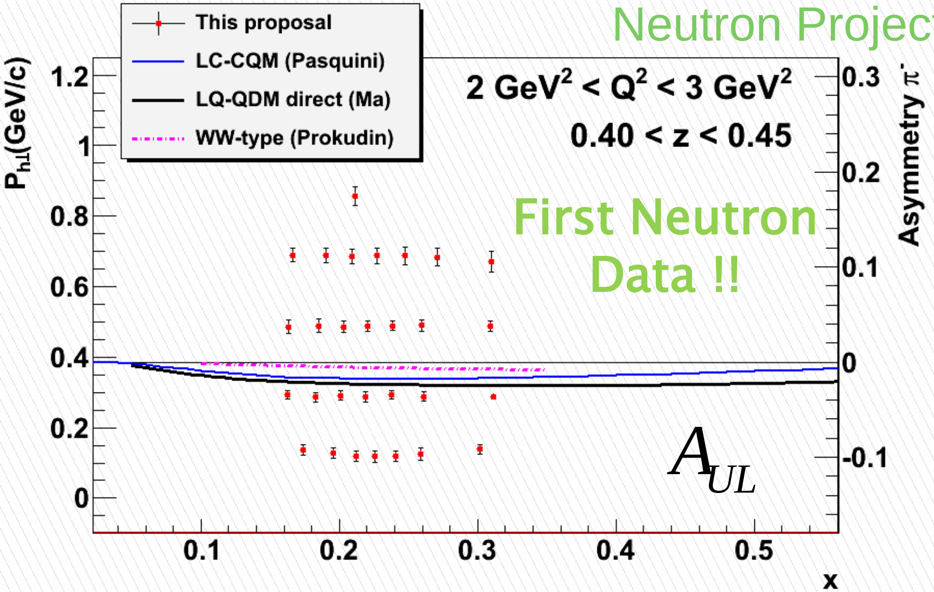
Worm-gear functions

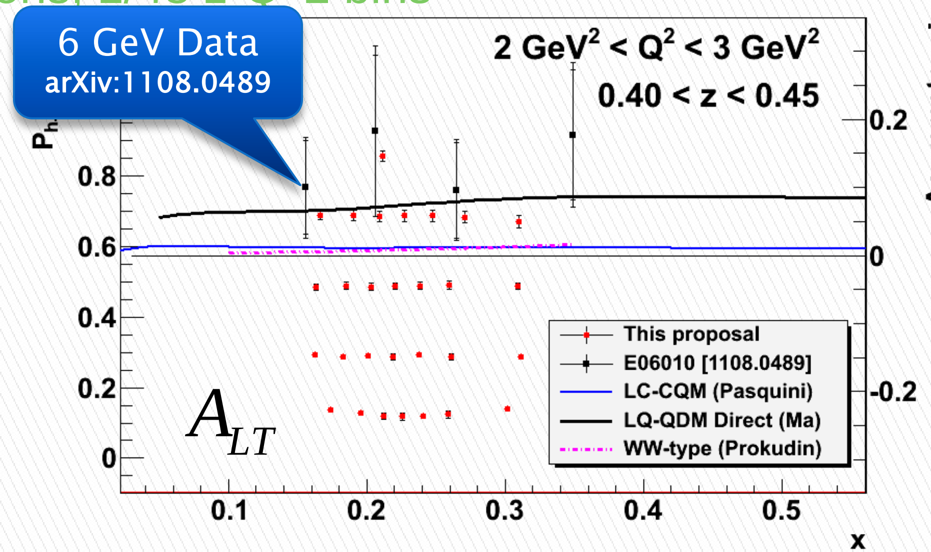




- Dominated by real part of interference between L=0 (S) and L=1 (P) states
- No GPD correspondence
- Lattice QCD -> Moments of worm-gear TMDs
- Model Calculations -> $h_{1L}^{\perp} =? -g_{1T}$
- Connections with Collinear PDFs through WW approx. and LIR.

Neutron Projections, 1/48 z-Q^2 bins



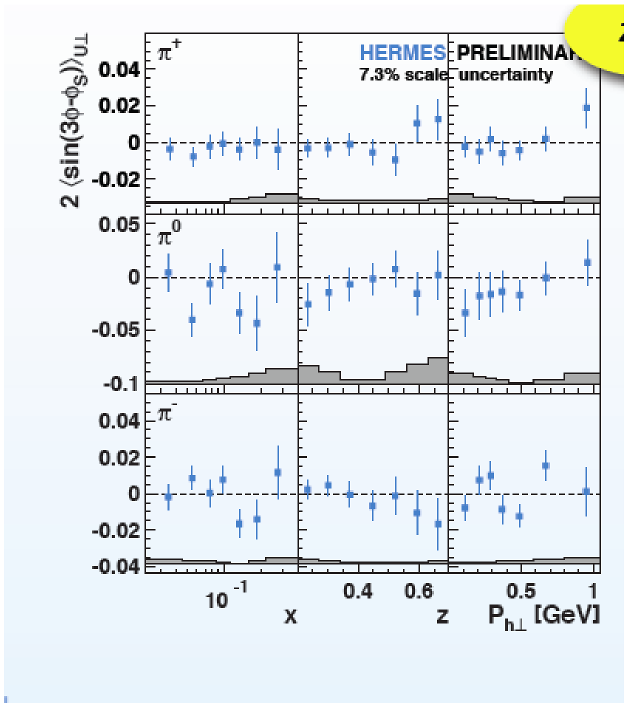


$$A_{UL} \sim h_{1L}^{\perp}(x) \otimes H^{\perp}{}_{1}(z)$$

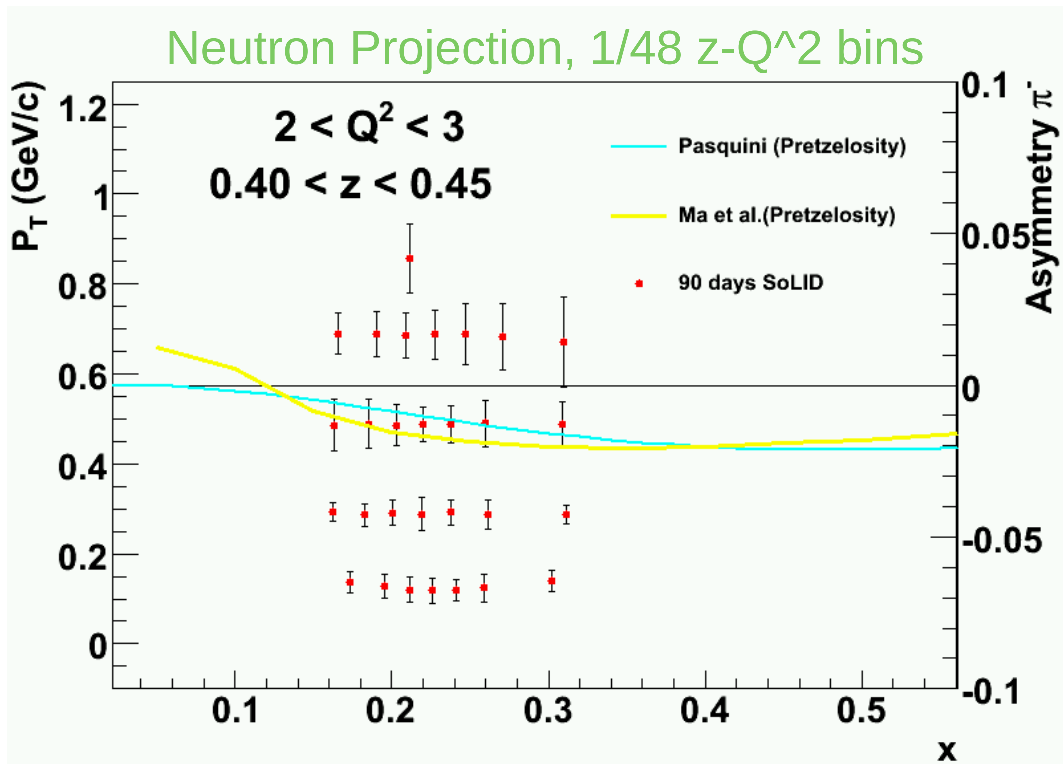
$$A_{LT} \sim g_{1T}(x) \otimes D_1(z)$$

Pretzlosity: $h_{1T}^{\perp}$ =

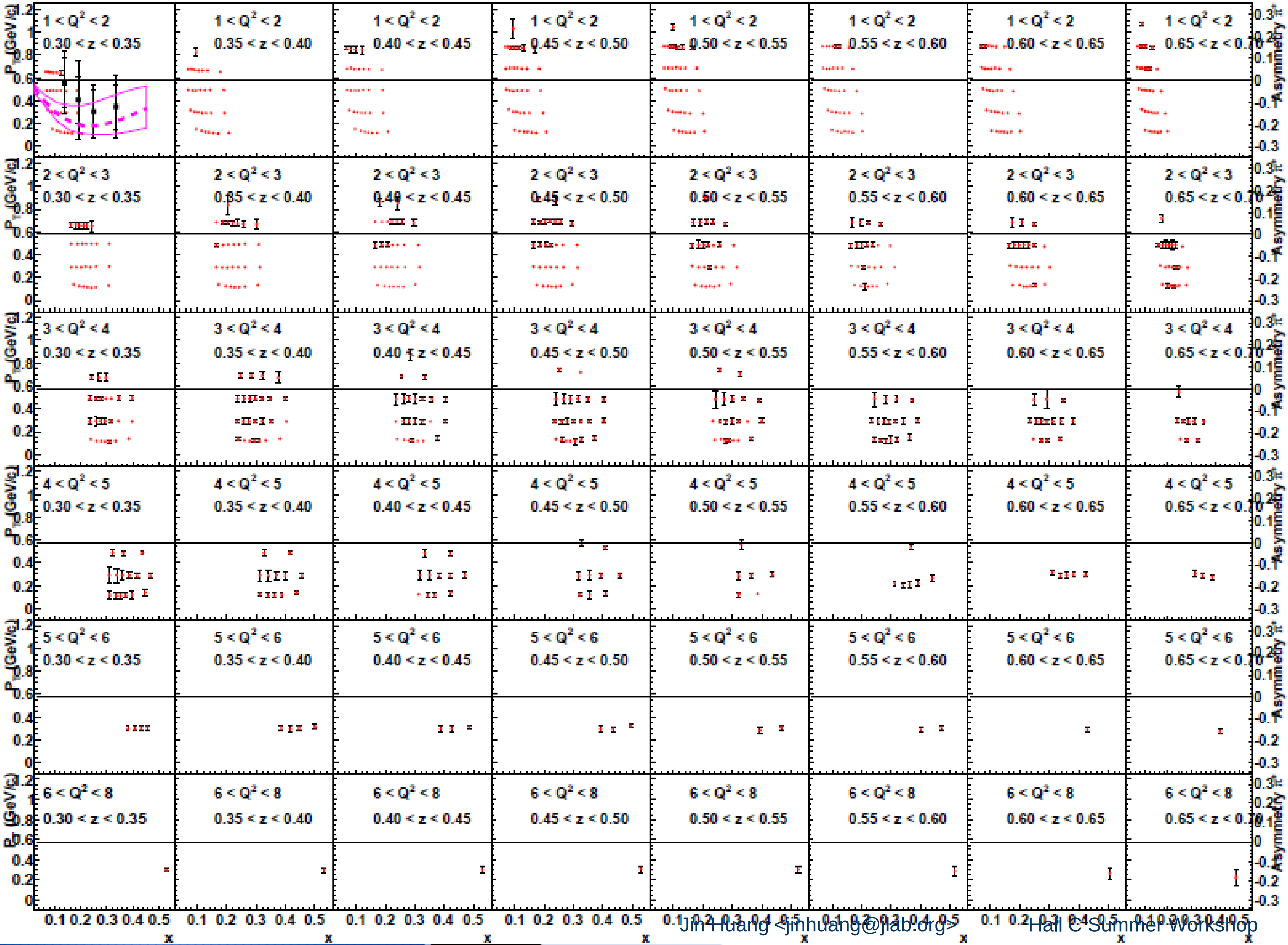
- Relativistic effect of quark
  PRD 78, 114024 (2008)
- (in models) direct measurement of OAM
  PRD 58, 096008 (1998)
- Expect first non-zero Pretzelosity asymmetries



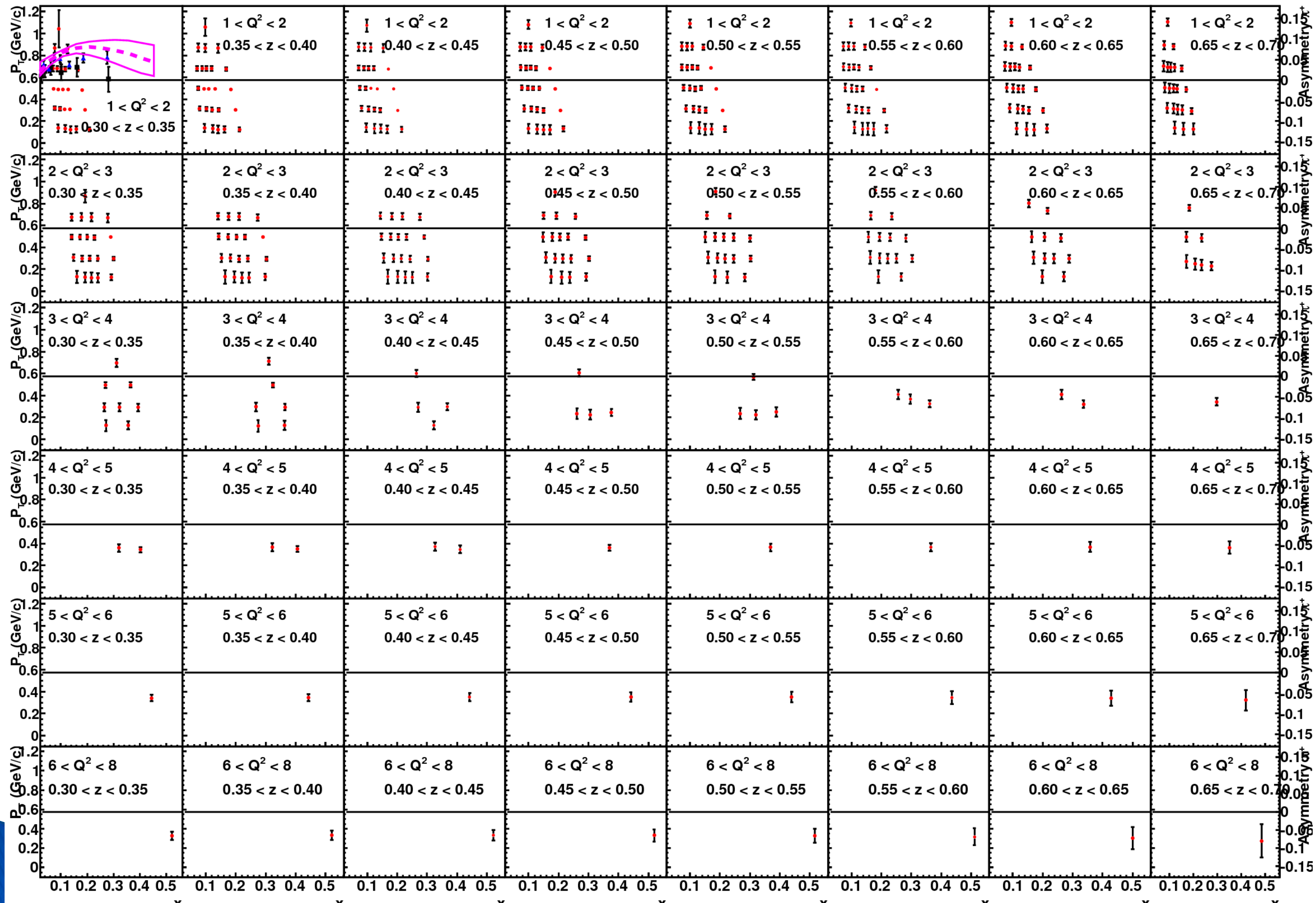
M. Diefenthaler, EINN 2009



Map asymmetries in a 4-D (x, z, Q^2, P_T): Neutron



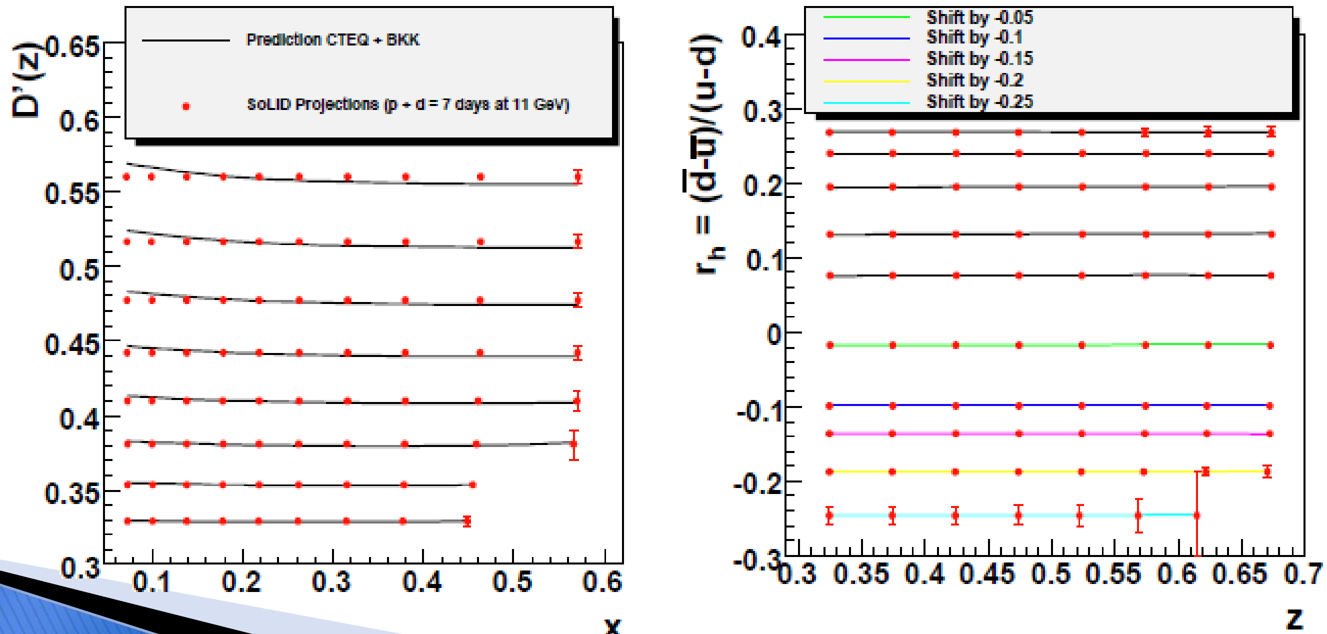
Proton 4-D Projection



SIDIS Factorization Test at 11 GeV

- Proton/deuteron/^{3}He unpolarized data in a large phase space coverage.
- Understand SIDIS process (Factorization , P_T dependence)
  - Complementary to Hall B & C R_{SIDIS}, P_T dependence studies.
- Understand the Nuclear effect in the light nuclei.

E12-10-006 dedicated unpolarized data

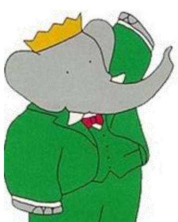


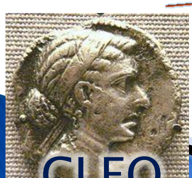
Responsibilities

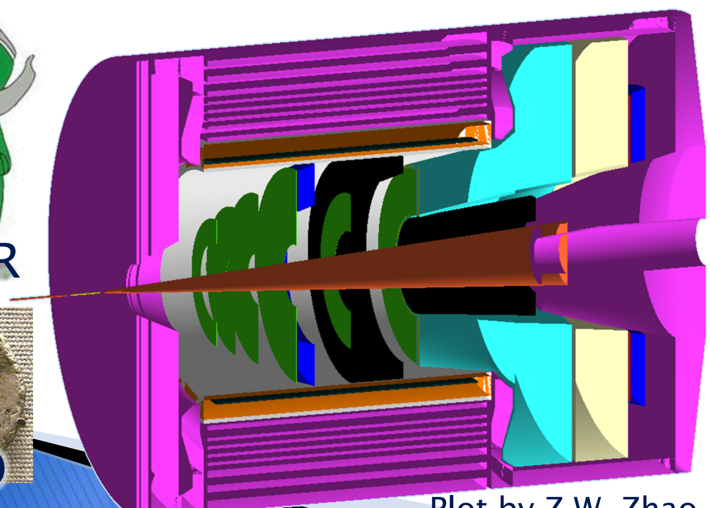
- **International collaboration** (8 countries, 50+ institutes and 190+ collaborators)
  - Rapid Growth in US-China Collaboration (2 grants from NSFC)
- **Joint effort** with PVDIS-SoLID (shared detector/DAQ).
- Complete study of **magnet** options (pursuing CLEO now)
- **Pipeline DAQ** (Hall D standard)
- **GEM Tracker** (Chinese Hadron Collaboration with Jlab/UVA/INFN) +**Tracking** (Caltech + U. Mass + Syracuse + JLab)
- **MRPC TOF** (Chinese Hadron Collaboration, successful in RHIC-STAR)
- Detailed conceptual design of **Gas Cerenkov** (Duke + Temple)
- Two proposed technologies: Shashlyk/SciFi for **E&M Cal** (Duke+ UVA + MIT + Los Alamos)

Recent Progress I:
Magnet Choices and Simulation Framework

- Possible choices of magnets
  - BABAR, CLEO, CDF, ZEUS, Hall D, New design
  - Field and acceptance studied for the first four
- GEMC based simulation framework
  - Allow for quantitative decisions on magnet acceptance
  - Rates/background studies

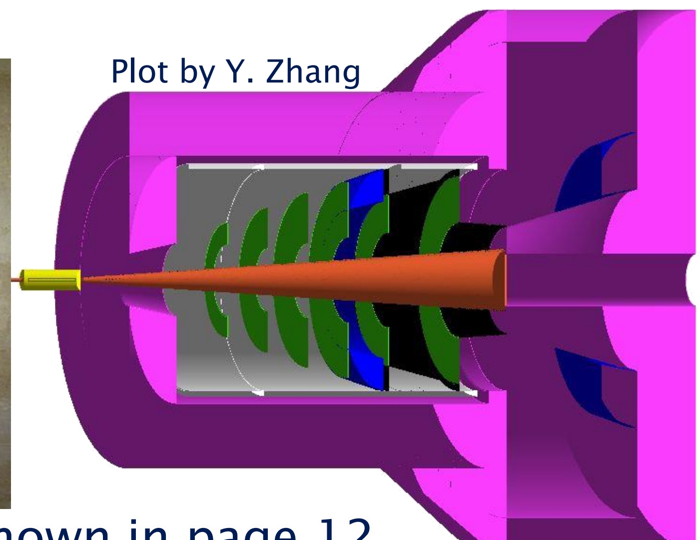






Plot by Z.W. Zhao

Plot by Y. Zhang

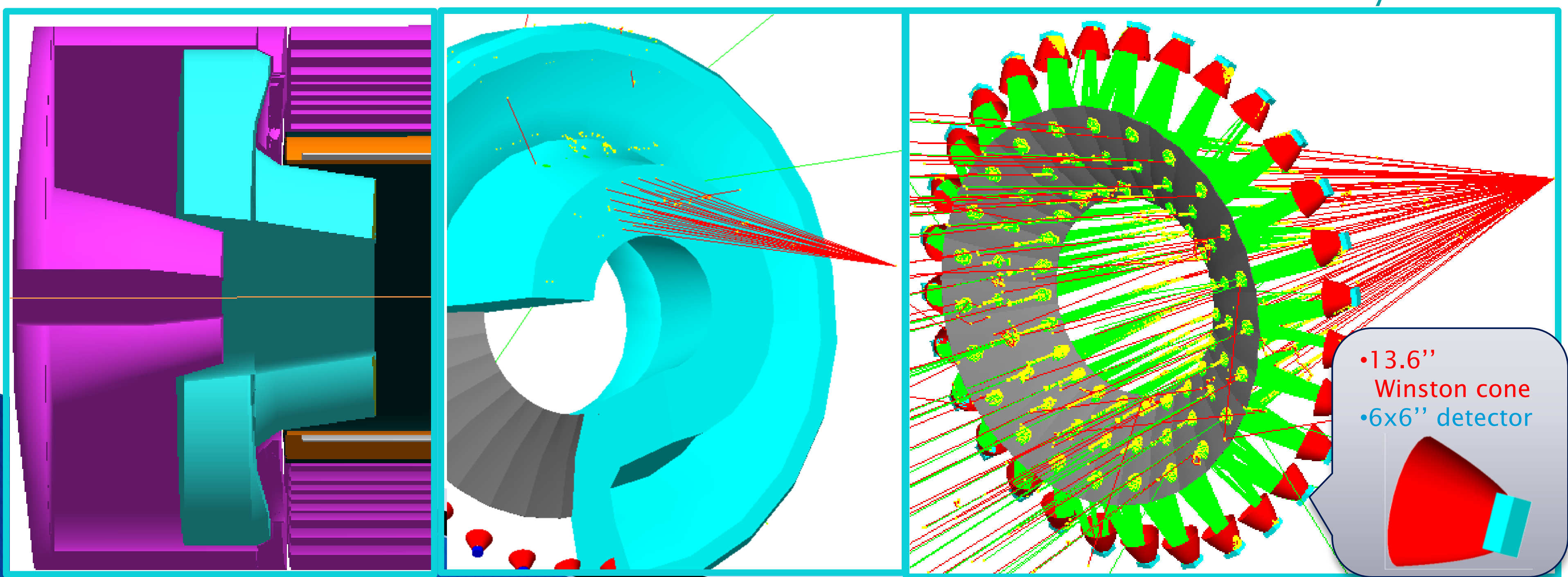


CDF shown in page 12

Recent Progress II: Cerenkov Detector Design

- Good progress with optics design
  - Near perfect optics eff. achieved with Winston cone + 6x6'' det.
- Viable photo detectors
  - Field-resistive PMTs or GEM-CsI detectors, Test on-goning
- Next stage is R&D and prototyping.

Plots by S. Malace



Other Major Progress

- GEM
  - R&D Efforts from UVa/INFN/JLab are combined with the GEM R&D for the Super-BigBite & EIC
  - Two major Grand support from China
- EM calorimeters
  - Choices of Shashlik & SciFi (Pb or Fe) studied
  - The Shashlik design is more favored
- MRPC
  - Onsite test in November
- DAQ system
  - Follows the Hall D path
- Web: http://hallaweb.jlab.org/12GeV/SoLID/

Summary

- SIDIS is a powerful tool to study Parton dynamics in the amplitude level (TMDs)
  - Tensor Charge, Spin-OAM correlation, flavor dependence, etc.

- SoLID is an ideal device to study SIDIS
  - High luminosity, large acceptance and full azimuthal coverage
  - Will provide ultimate precision (4-D) of SSA/DSA, at high-x (valence), low Q^2 region, which is crucial input to global analysis.
  - Test SIDIS factorization, P_T dependence at JLab12 (complementary to SIDIS programs in Hall B/C)

- Integrated Effort in SoLID R&D with PVDIS
  - Steady progress
  - In preparation for the Director Review.