Probing the nucleon structure with SIDIS at Jefferson Lab.

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INFN – Frascati

(for the CLAS collaboration)
Physics Motivation

Describe the complex nucleon structure in terms of partonic degrees of freedom of QCD

- Our knowledge on the universal parton distribution functions (PDFs) and fragmentation functions (FFs), which connect the partonic dynamics to the observed hadrons, has been improved in recent years,
- As a probability density to find a parton (quark or gluon) inside a hadron with the parton carrying the hadron’s longitudinal momentum fraction $x$, the PDFs have provided us information about the partonic structure of a hadron.
- Partonic structure of hadrons has been investigated beyond the PDFs by exploring the parton’s motion and its spatial distribution in the direction perpendicular to the parent hadron’s momentum.
The nucleon parton model and TMDs

In the collinear approximation:

\[ \mathbf{p} = x \mathbf{P} \]

Parton transverse momentum

\[ \mathbf{p} = x \mathbf{P} + \mathbf{p}_T \]

DIS distribution functions

\[ f_1(x), g_1(x), h_1(x) \]

more complex dist. functions

\[ f_1(x, \mathbf{p}_T), g_1(x, \mathbf{p}_T), h_1(x, \mathbf{p}_T) \]

Transverse Momentum Distributions (TMDs) of partons describe the distribution of quarks and gluons in a nucleon with respect to \( x \) and the intrinsic transverse momentum \( p_T \) carried by the quarks.

<table>
<thead>
<tr>
<th>Quark</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nucleon</td>
<td>U</td>
<td>f1</td>
<td>h1 ( \perp )</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>g1</td>
<td>h_{1L} ( \rightarrow )</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>f_{1T} ( \perp )</td>
<td>g_{1T} ( \rightarrow )</td>
</tr>
</tbody>
</table>
The nucleon parton model and TMDs

In the collinear approximation:

- TMDs are universal objects, i.e. the same functions can be found in SIDIS, $e^+e^-$, DY, etc.

Parton transverse momentum

\[ \vec{p} = x\vec{P} + \vec{p}_T \]

Transverse Momentum Distributions (TMDs) of partons describe the distribution of quarks and gluons in a nucleon with respect to $x$ and the intrinsic transverse momentum $p_T$ carried by the quarks.

After quark transverse momentum ($p_T$) integration only $f_1, g_1$ and $h_1$ survive.

<table>
<thead>
<tr>
<th></th>
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<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>nuc</td>
<td>$f_1$</td>
<td>$g_1$</td>
<td>$h_{1L}$</td>
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<td>leon</td>
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<tr>
<td>T</td>
<td>$f_{1T}$</td>
<td>$g_{1T}$</td>
<td>$h_{1T}$</td>
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</tbody>
</table>
The Spin Structure of the Proton

- From NLO-QCD analysis of DIS measurements
  \[ \Delta \Sigma \approx 0.2 \]
  \[ \Delta G = 1.0 \pm 1.2 \rightarrow \text{probably small?} \]
- Quark polarization \( \Delta q(x) \)
  \[ \rightarrow \text{first 5-flavor separation from HERMES} \]
- Transversity \( \delta q(x) \)
  \[ \rightarrow \text{a new window on quark spin} \]
  \[ \rightarrow \text{azimuthal asymmetries from HERMES and JLab} \]
  \[ \rightarrow \text{future: flavor decomposition} \]
- Gluon polarization \( \Delta G(x) \)
  \[ \rightarrow \text{RHIC-spin and COMPASS started providing answers!} \]
- Orbital angular momentum \( L \)
  \[ \rightarrow \text{how to determine?} \]
  \[ \rightarrow \text{GPD's and TMD's} \]

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \]

We want to solve this puzzle! \[ \rightarrow \]
need large range in \( x \) and \( Q^2 \) and high luminosity for precision!
TMD measurements with CLAS at JLab

TMDs are studied at JLab through SIDIS on nucleons (and nuclei) with different experimental equipments
- measuring transverse momentum of final state hadrons in SIDIS gives access to the transverse momentum distributions (TMDs) of partons
- spin asymmetries measurements give us access to different TMDs, providing information on how quarks are confined in hadrons

(here we will concentrate on CLAS detector and linearly polarized target results)

**CLAS @ Hall B**
- large acceptance spectrometer with good resolution
- luminosity $\approx 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- asymmetry measurements over a broad kinematical range
- polarized electron beam
- polarized solid NH3 and ND3 targets
JLab Accelerator CEBAF

- Continuous Electron Beam
- Energy 0.8-5.7 GeV
- 200μA, polarization 85%
- Simultaneous delivery to 3Halls

CLAS

06/09/2012
Hall B: Cebaf Large Acceptance Spectrometer

- **Beam**
  - Liquid D$_2$ (H$_2$) target + start counter; e minitorus
  - Drift chambers: argon/CO$_2$ gas, 35,000 cells

- **Torus magnet**
  - 6 superconducting coils

- **Electromagnetic calorimeters**
  - Lead/scintillator, 1296 photomultipliers

- **Time-of-flight counters**
  - Plastic scintillators, 684 photomultipliers

- **Gas Cherenkov counters**
  - e/$\pi$ separation, 216 PMTs

- **CLAS is designed to measure exclusive reactions with multi-particle final states**

- **Broad angular coverage** (8° - 140° in LAB frame)
- **Charged particle momentum resolution** ~0.5% forward dir
SIDIS kinematical plane and observables

\[ Q^2 = (k - k')^2 \]
\[ y = \frac{\nu}{E} \]
\[ x = \frac{Q^2}{2M\nu} \]
\[ z = \frac{E_h}{\nu} \]

\[ \nu = E - E' \]

\( Q^2 \) = momentum transfer
\( x \) = momentum fraction of the proton carried by the quark
\( z \) = quark energy carried by the hadron
\( P_{h\perp} \) = transverse momentum of the hadron to the virtual photon direction
\( \phi_h \) = angle between hadron and lepton plane
\[
\frac{d\sigma}{dy \, d\psi \, dz \, d\phi_h \, dP_{h\perp}^2} = \\
\frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} \\
+ \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin \phi_h F_{LU}^{\sin \phi_h} \\
+ S_{||} \left[ \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_h F_{UL}^{\sin \phi_h} + \varepsilon \sin(2\phi_h) F_{UL}^{\sin 2\phi_h} \right] \\
+ S_{||} \lambda_e \left[ \sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_h F_{LL}^{\cos \phi_h} \right] \\
+ |S_{\perp}| \left[ \sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \\
+ \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} \\
+ \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_S F_{UT}^{\sin \phi_S} + \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \right] \\
+ |S_{\perp}| \lambda_e \left[ \sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_S F_{LT}^{\cos \phi_S} \\
+ \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \right] \right\},
\]

Bacchetta et al., JHEP 0702:093,2007
\[
\frac{d\sigma}{y \, d\psi \, d\phi_h \, dP_{h\perp}^2} = \frac{\alpha^2}{x y Q^2} \left( \frac{y^2}{2(1 - \varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2 \varepsilon(1 + \varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} \right. \\
+ \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2 \varepsilon(1 - \varepsilon)} \sin \phi_h F_{LU}^{\sin \phi_h} \\
+ S_\parallel \left[ \sqrt{2 \varepsilon(1 + \varepsilon)} \sin \phi_h F_{UL}^{\sin \phi_h} + \varepsilon \sin(2\phi_h) F_{UL}^{\sin 2\phi_h} \right] \\
+ S_\parallel \lambda_e \left[ \sqrt{1 - \varepsilon^2} F_{LL} + \sqrt{2 \varepsilon(1 - \varepsilon)} \cos \phi_h F_{LL}^{\cos \phi_h} \right] \\
+ |S_\perp| \left[ \sin(\phi_h - \phi_S)(F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)}) \right. \\
+ \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} \\
+ \sqrt{2 \varepsilon(1 + \varepsilon)} \sin \phi_S F_{UT}^{\sin \phi_S} + \sqrt{2 \varepsilon(1 + \varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \right] \\
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+ \sqrt{2 \varepsilon(1 - \varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \right\}.
\]

18 structure functions

Leading Twist

Bacchetta et al., JHEP 0702:093, 2007

06/09/2012
SIDIS cross section

\[ \frac{d\sigma}{y d^3z d\phi_h dP_{h\perp}^2} = \alpha^2 \frac{\gamma^2}{2x(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} \right. \\
+ \varepsilon \cos(2\phi_h) F_{UU}^{\cos2\phi_h} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin\phi_h F_{LU}^{\sin\phi_h} \\
+ S_{||} \left[ \sqrt{2\varepsilon(1+\varepsilon)} \sin\phi_h F_{UL}^{\sin\phi_h} + \varepsilon \sin(2\phi_h) F_{UL}^{\sin2\phi_h} \right] \\
+ S_{||}\lambda_e \left[ \sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} \cos\phi_h F_{LL}^{\cos\phi_h} \right] \left[ \sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \right. \\
+ \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} \\
+ \sqrt{2\varepsilon(1+\varepsilon)} \sin\phi_h F_{UT}^{\sin\phi_S} + \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \right] \\
+ S_{||}\lambda_e \left[ \sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)} \cos\phi_S F_{LT}^{\cos\phi_S} \right. \\
+ \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \right\} , \]

where each structure function now depends also on transverse hadron momentum \( P_{h\perp} \)

Bacchetta et al., JHEP 0702:093,2007
\[
\frac{d\sigma}{dy \, d\psi \, dz \, d\phi_h \, dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \left\{ F_{UU,T} + \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin \phi_h F_{LU}^{\sin \phi_h} \right. \\
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+ \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h+\phi_S)} - \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h-\phi_S)} \\
+ \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_S F_{UT}^{\sin \phi_S} + \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin 2\phi_h-\phi_S} \left[ \right] \\
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+ \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h-\phi_S)} \right\}.
\]

18 structure functions

Structure functions decomposition

\[ F \propto DF \otimes FF \]

where each structure function now depends also on transverse hadron momentum \( P_{h\perp} \)

Bacchetta et al., JHEP 0702:093,2007
Double spin asymmetry

\[ e p \rightarrow e' \pi X \]

\[ A_{LL} = \frac{1}{fD(y)P_B P_t} \frac{N^+ - N^-}{N^+ + N^-} \propto \frac{g_1(x, P_T)}{f_1(x, P_T)} \]

Avakian et al. PRL105 (2010)

Calculations using gaussian ansatz

\[ f_1(x, k_T) = f_1(x) e^{-\frac{k_T^2}{\langle k_T^2 \rangle_f}} \]

\[ g_1(x, k_T) = g_1(x) e^{-\frac{k_T^2}{\langle k_T^2 \rangle_g}} \]

\[ \frac{\langle k_T^2 \rangle_g}{\langle k_T^2 \rangle_f} = 1.0 \]

\[ \frac{\langle k_T^2 \rangle_g}{\langle k_T^2 \rangle_f} = 0.68 \]

\[ \frac{\langle k_T^2 \rangle_g}{\langle k_T^2 \rangle_f} = 0.4 \]
Double spin asymmetry

\[ e p \rightarrow e' \pi X \]

\[ A_{LL} = \frac{1}{fD(y)P_B P_t} \frac{N^+ - N^-}{N^+ + N^-} \propto \frac{g_1(x, P_T)}{f_1(x, P_T)} \]

Calculations using gaussian ansatz

\[ <k_T^2>_g / <k_T^2>_f \]

new CLAS results
Double spin asymmetry

\[ e p \rightarrow e' \pi X \]

\[ A_{LL} = \frac{1}{fD(y)P_B P_t} \frac{N^+ - N^-}{N^+ + N^-} \propto \frac{g_1(x, P_T)}{f_1(x, P_T)} \]

Avakian et al. PRL105 (2010)

new CLAS results
Target single spin asymmetry

\[ \sigma_{UL} \propto F_{UL}^{\sin^2 \phi} \sin 2\phi + F_{UL}^{\sin \phi} \sin \phi \]

higher twist

HT terms are important at JLab

Collins FF of transverse polarized quark in unpol. hadron

correlation between transverse spin of quarks and longitudinal spin of nucleon

Avakian et al. PRL105 (2010)
• $A_{UL} \sin 2\phi$ (leading twist) is small suggesting that the Collins $\pi^+$ and $\pi^-$ FF are nearly equal and opposite

\[ F_{UL} \sin 2\phi \propto h_{1L}^\perp \otimes H_1^\perp \]
Dihadron analysis

factorization:

\[ \sigma_{SIDIS}^{hh} \propto \sum_f \sigma \otimes \text{pdf}_f(x) \otimes \text{frag}_{f \to hh}(z) \]

In the dihadron channel, different FFs appear but it also brings a very useful advantage:

in single hadron production, the observables are convolution of TMDs

\[ F_{LU}^{\sin 2\varphi} \propto h_{1L}^{\perp} \otimes H_{1}^{\perp} \]

in double hadron production, observables are product of TMDs
CLAS dihadron beam spin asymmetries

\[ P_h = P_1 + P_2 \]

\[ R = (P_1 - P_2)/2 \]

\[ F_{LU}^{\sin \phi_R} \propto h_L^q H_1^{<q} \]

\[ A_{LU} = \frac{1}{P_{beam}} \frac{N^+ - N^-}{N^+ + N^-} \]

\[ \vec{e} \vec{p} \rightarrow e' \pi^+ \pi^- X \]

\[ p0 \sin(\phi_R) + p1\sin(2\phi_R) \]

**PRELIMINARY**
6 GeV CEBAF

End physics program @ 6 GeV in 2012

20 cryomodules

06/09/2012
12 GeV CEBAF

Add 5 cryomodules

20 cryomodules

Add arc

20 cryomodules

Add 5 cryomodules

Upgrade magnets and power supplies

06/09/2012 QCD12
12 GeV CEBAF

End physics program @ 6 GeV in 2012

Upgrade magnets and power supplies

6 GeV CEBAF

CHL-2

Upgrade magnets and power supplies

12 GeV CEBAF

Add 5 cryomodules

20 cryomodules

Add arc

20 cryomodules

Add 5 cryomodules

Beam Power: 1MW
Beam Current: 90 µA
Max Pass energy: 2.2 GeV
Max Energy Hall A-C: 10.9 GeV
Max Energy Hall D: 12 GeV

May 2013
Accelerator Commissioning starts

October 2013
Hall Commissioning starts

06/09/2012
QCD12
Hall B - CLAS12 Highlights

Key Features:
1 torus & 1 solenoid magnet

new detectors: Cerenkovs, calorimeters, drift chambers, silicon vertex tracker

re-use some existing detector
Hall B - CLAS12 Highlights

Key Features:
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Drift Chamber Region 1 (Idaho State U)
Key Features:
- 1 torus & 1 solenoid magnet
- new detectors: Cerenkovs, calorimeters, drift chambers, silicon vertex tracker
- re-use some existing detector

Drift Chamber Region 1 (Idaho State U)
Drift Chamber Region 2 (Old Dominion U)
Hall B - CLAS12 Highlights

Key Features:
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Drift Chamber Region 1 (Idaho State U)
Drift Chamber Region 2 (Old Dominion U)
Drift Chamber Region 3 (Jefferson Lab)

06/09/2012 QCD12
Hall B - CLAS12 Highlights

Key Features:
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re-use some

PCAL
(JLab/Ohio/W&M/NSU/JMU)

Drift Chamber Region 1
(Idaho State U)

Drift Chamber Region 2
(Old Dominion U)

Drift Chamber Region 3
(Jefferson Lab)

06/09/2012

QCD12
Hall B - CLAS12 Highlights

Key Features:
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new detectors: Cerenkovs, calorimeters, drift chambers, silicon vertex tracker
re-use some existing detector
PCAL (JLab/Ohio/W&M/NSU/JMU)

Drift Chamber Region 1 (Idaho State U)
Drift Chamber Region 2 (Old Dominion U)
Drift Chamber Region 3 (Jefferson Lab)

Silicon Vertex Tracker (JLab/FNAL/UNH)
**PID in CLAS12**

- TOF scintillators
- Low Threshold Cerenkov
- High Threshold Cerenkov

RICH detector to replace LTCC - good PID of kaons over the whole kinematics range

<table>
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<th>GeV/c</th>
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<th>3</th>
<th>4</th>
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<td>$K/p$</td>
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<td>LTCC</td>
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</tr>
</tbody>
</table>

- Kaon ID necessary for TMD flavor separation
- Rejection factor >1000 because of relative $\pi/K$ production rate

**Graph:**

- First RICH prototype test at CERN in summer 2011 with pion beam

- Cherenkov rings for pions with 10 GeV/c momentum, measured with 8 H8500
- A new prototype is under construction and will be tested in summer 2012

06/09/2012
### Physics program with CLAS12

<table>
<thead>
<tr>
<th>Proposal</th>
<th>Contact Person</th>
<th>Physics</th>
<th>Energy (GeV)</th>
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<td>Gothe, Mokeev</td>
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<td>Long. Spin Str.</td>
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<td>Assume polarized experiments run 50% of time w/ reversed field</td>
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<td>007/008 need 26d reversed field</td>
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<td>PR-09-007(a)</td>
<td>Hafidi</td>
<td>Partonic SIDIS</td>
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<td>PR-09-008</td>
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### Physics program with CLAS12

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<th>Proposal</th>
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<th>Energy (GeV)</th>
<th>PAC days</th>
<th>Parallel Running</th>
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<td>Gothe, Mokeev</td>
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Experiments for the first 5 years of data taking already approved

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</table>
Conclusions

• TMDs are needed to understand nucleon spin
• They provide a deep insight into the nucleon structure
• Study of TMDs is one of the main items in the JLab physics program
• The 6GeV generation of experiments have shown evidence of sizeable effects due to TMDs but also open questions
• Azimuthal moments can be extracted in multidimensional analysis with high statistics.
• A new 12GeV generation of experiments is in preparation at JLab with higher luminosity and improved detectors to test fundamental properties of TMDs.
BACKUP SLIDES
CLAS asymmetries – $A_{LU}$

Aghasyan et al PLB704 (2011)
• CLAS data for $A_{LU}\pi^0$
• Unpolarized liquid hydrogen target
• Beam energy of 5.776 GeV
• $Q^2>1;\ 0.4<z<0.7$

For the first time $A_{LU}$ two dimensional mapping for $0.4<z<0.7$