Inclusive Quasi-real Photoproduction Measurements at HERMES

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on behalf of the HERMES Collaboration

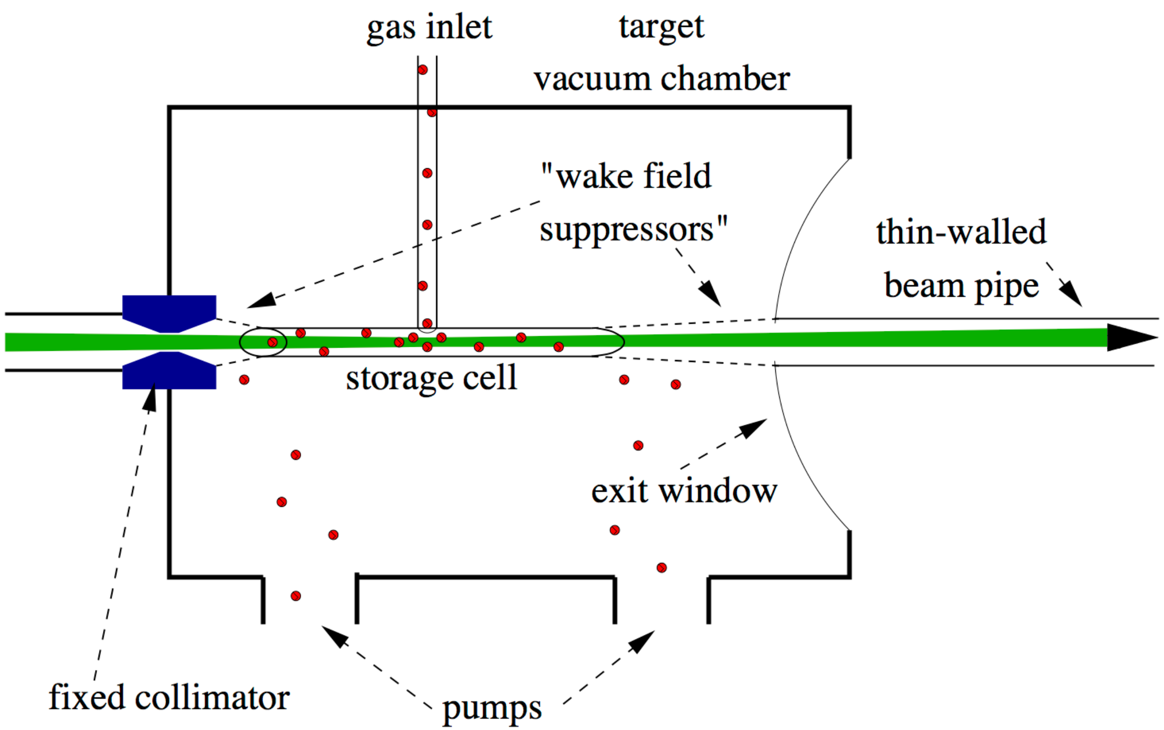
- Azimuthal Asymmetries from Transversely Polarized Protons
- Transverse Lambda Polarization from Nuclear Targets
- Bose-Einstein Correlations from Nuclear Targets

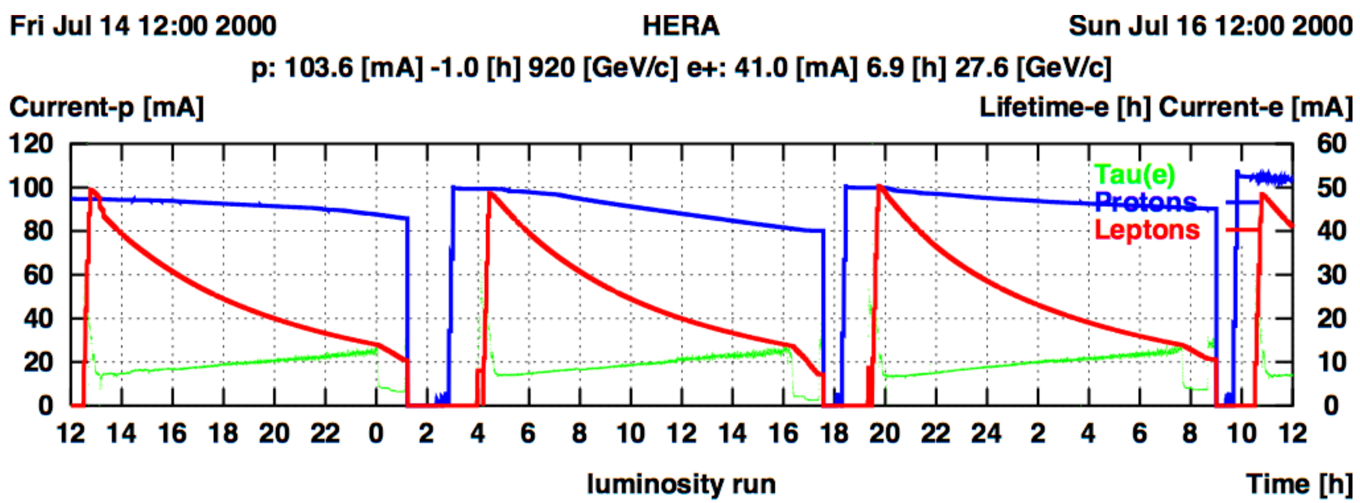
The HERMES Experiment

- Experiment located at DESY in Hamburg, Germany
- Members Institutions from: Armenia, Belgium, Canada, China, Germany, Italy, Japan, Netherlands, Poland, Russia, UK, and USA
- Run/target History:
  - 1995: Commissioning/ Polarized ^{3}He
  - 1996/97: Polarized ^{1}H, Unpolarized ^{1}H, ^{2}H, ^{3}He, ^{14}N
  - 1998/99: Polarized ^{2}H, +RICH and Charm Upgrades
  - 2000: Polarized ^{2}H, Unpolarized ^{1}H, ^{2}H, ^{4}He, ^{20}Ne, ^{84}Kr
  - 2002-05: Polarized ^{1}H, Unpolarized ^{1}H, ^{2}H, ^{84}Kr, $^{(130)}Xe$
  - 2006-07: Unpolarized ^{1}H, ^{2}H
- Positron and electron beams of 27.5 GeV, average current 30 mA, average polarization 50%

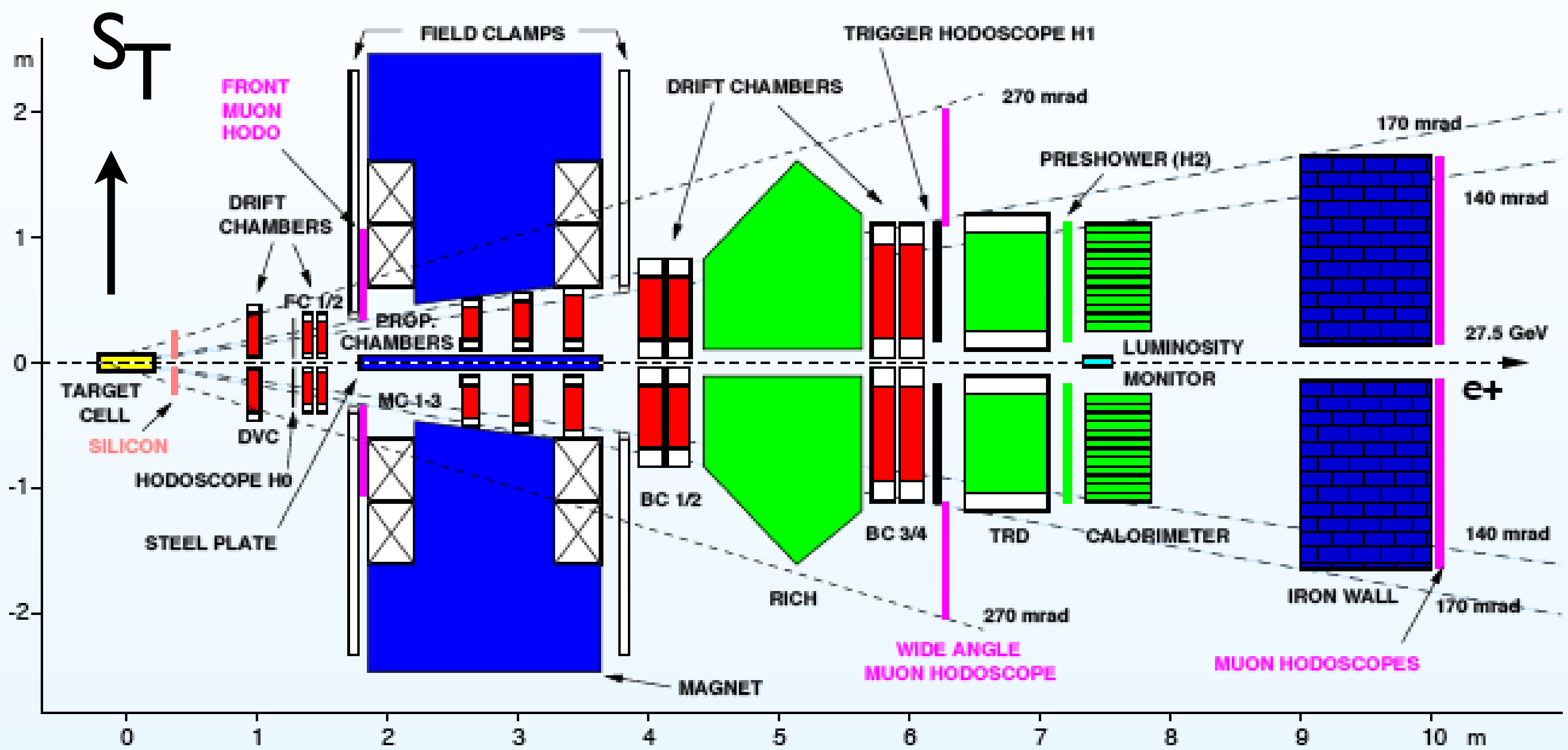
The HERMES Internal Gas Target

- Average Target Thickness $10^{13} - 10^{15}$ atoms/cm^2
- High Density End-of-Fill Running





The HERMES Spectrometer



- large momentum and angle acceptance: $\theta_{\text{hor.}} \leqslant 175\,\mathrm{mrad}$, $40\,\mathrm{mrad} \leqslant \theta_{\text{vert.}} \leqslant 140\,\mathrm{mrad}$
- good momentum resolution: $\Delta p/p = 0{,}7 - 1{,}3\%$
- and angle resolution: $\Delta\theta \leqslant 0{,}6\,\mathrm{mrad}$
- very clean lepton-hadron separation, hadron identification with RICH

Transverse Single Spin Asymmetries (SSA)

- Left-right cross section asymmetries have been measured for high-energy inclusive hadron-nucleon, nucleus reactions for three decades, over a CM energy range from 5 - 500 GeV
- Asymmetries generally increase with P_T and Feynman x_F
- In the last decade, transverse SSAs have been measured from semi-inclusive DIS at HERMES, COMPASS and Jefferson Lab
- Theoretical approaches now routinely based on transverse momentum dependent (TMD) parton distribution and fragmentation functions, e.g., Sivers and Collins.
- Another approach is to introduce higher-twist multiparton correlations.

Relevant Scales

- These approaches have different domains of validity, but some regions in common, roughly delineated by three relevant scales: Λ_{QCD}, P_T, and Q.

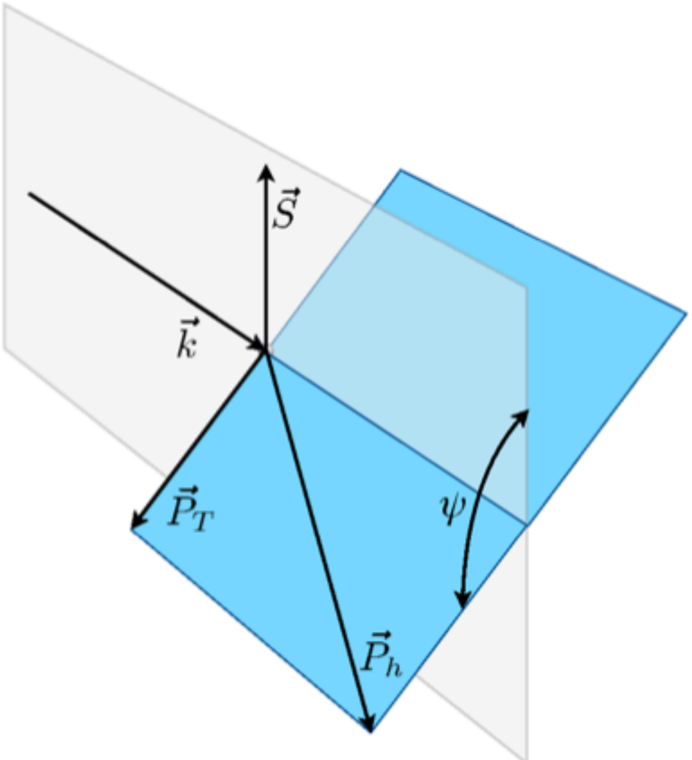
  1. Theory makes no reliable prediction for $\Lambda_{QCD} \approx P_T \approx Q$
  2. If P_T is large and largest scale, one expects a $1/P_T$ power suppression
  3. For $Q^2 > P_T^2$ and $Q^2 \gg \Lambda_{QCD}$, TMD approach gives significant SSA
  4. $Q^2 \gg P_T^2 \gg \Lambda_{QCD}$, higher twist and TMD approaches are equivalent.

- Inclusive Electroproduction SSAs allow one to compare high and low Q^2 asymmetries for the same P_T

HERMES Data Selection

- "Unpolarized" electrons incident on transversely polarized H target
- Average target polarization perpendicular to beam of 0.713±0.063, reversed in 1-3 minute intervals
- Selected events had to contain at least one charged hadron with momentum between 2 and 15 GeV; scattered electron not required but can be present
- Significant corrections were made for trigger efficiencies for low momentum hadrons
- RICH detector used to determine hadron ID
- Kinematic variable are relative to electron beam: P_T, x_F , and azimuthal angle ψ

Azimuthal Angle Definition

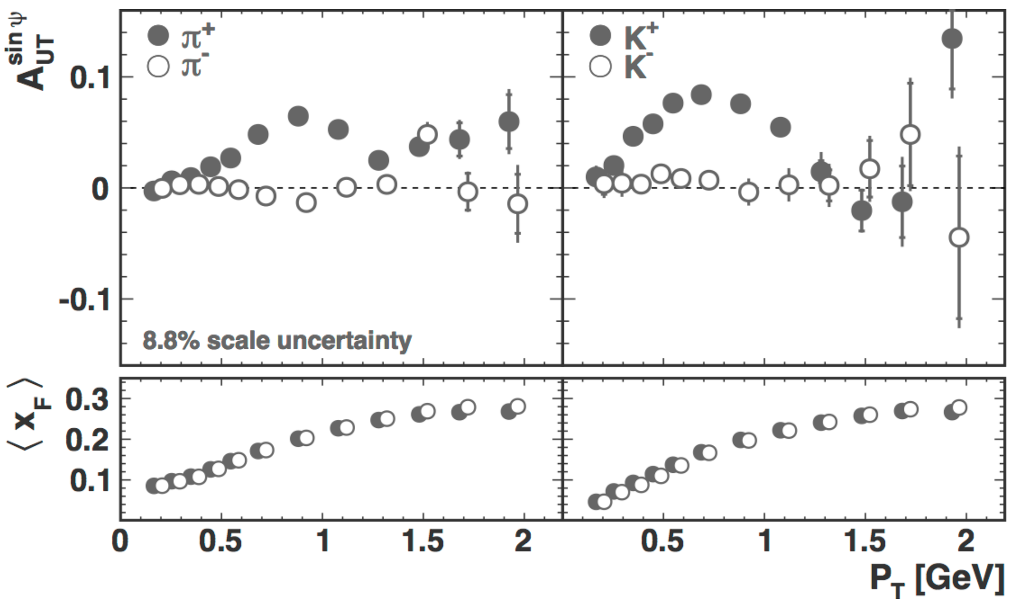


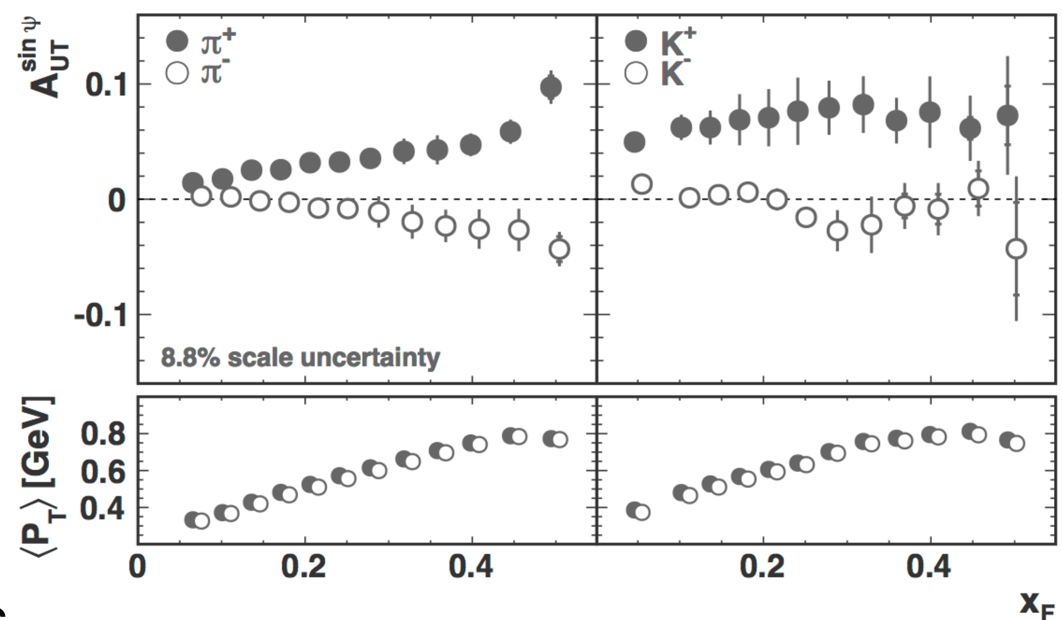
- Cross section in terms of SSA $A_{UT}^{\sin\psi}$

$$d\sigma = d\sigma_{UU}[1 + S_T A_{UT}^{\sin\psi} \sin\psi]$$

- Left-right asymmetry $A_N = -\frac{2}{\pi} A_{UT}^{\sin\psi}$

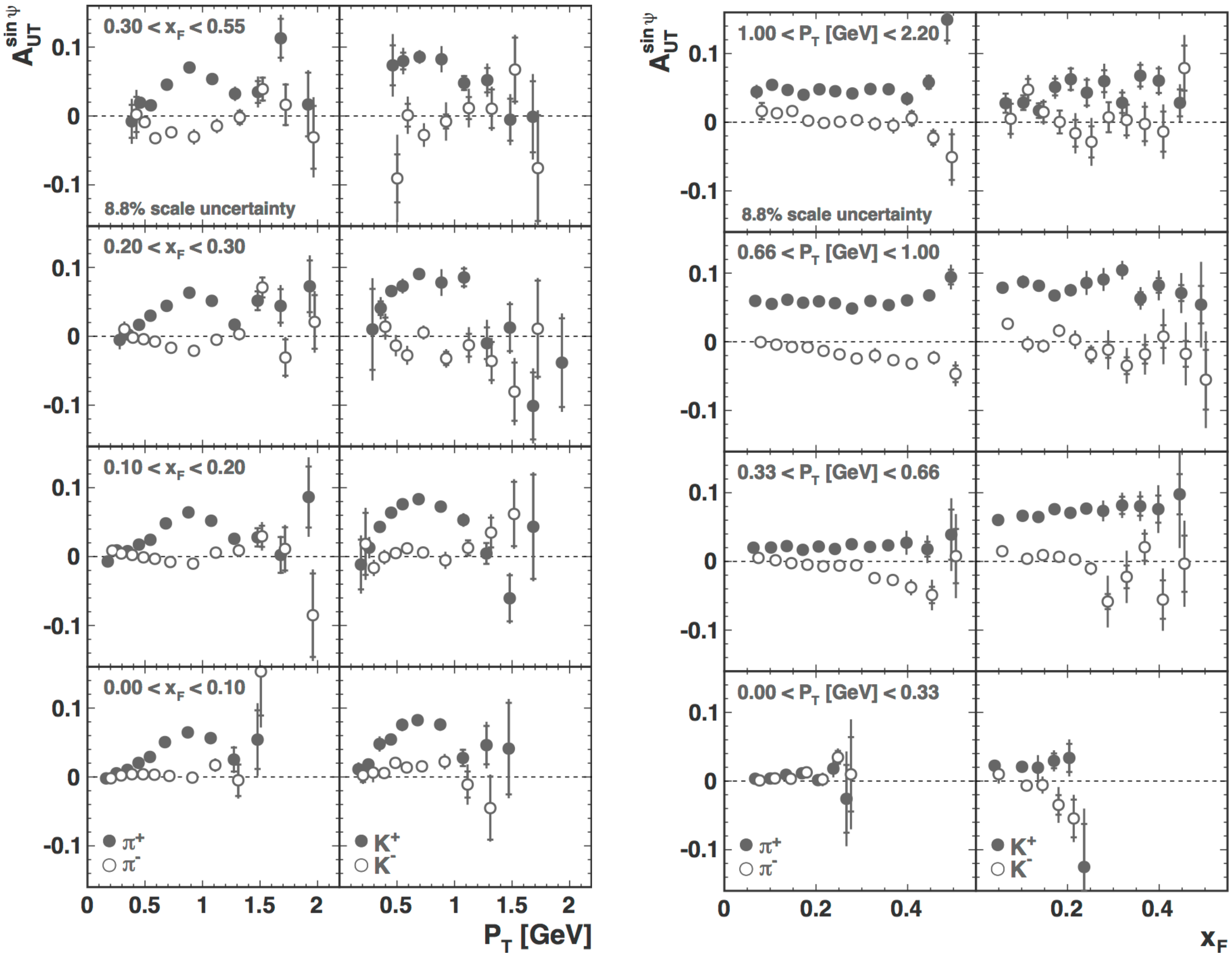
P_T and X_F Dependences for integrated data





- Strong kinematic correlation!
- Similar to hadron asymmetries

Separated P_T and X_F Asymmetries



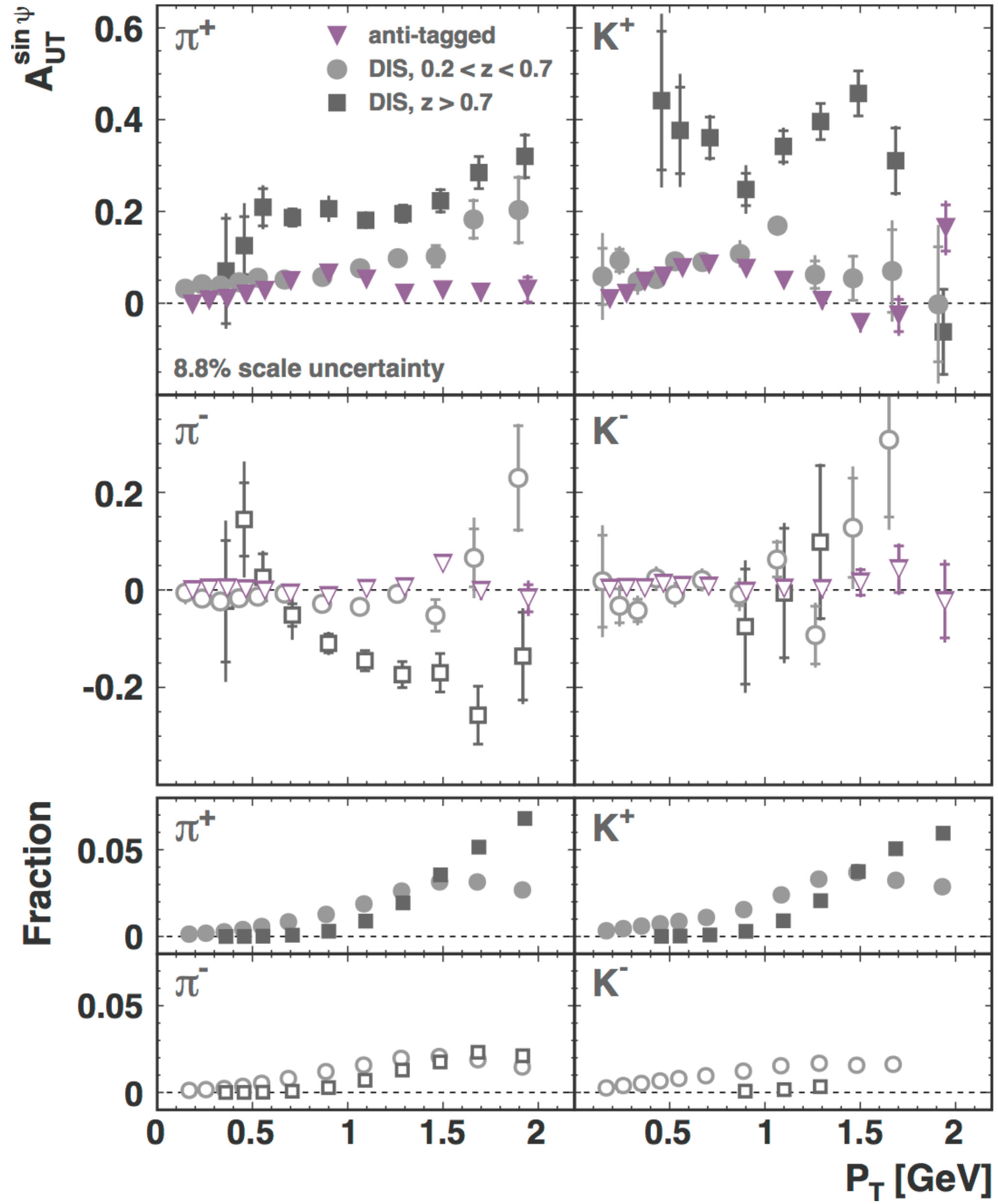
P_T Distributions with/without Electrons - Definitions

- Now place requirements on electron

1. "Anti-tagged" = No electron, Q^2 nearly 0, (90% of inclusive yield)
2. Tagged, DIS with $0.2 < z < 0.7$, "standard" SIDIS
3. Tagged, DIS with $z > 0.7$. SIDIS with "high" P_T and exclusive

P_T Distributions with/without Electrons - Results

- Anti-tagged ≈ Inclusive, P_T is only large scale, $Q^2 \approx 0$
- Midrange z SIDIS, Q^2 large, SSA larger than inclusive for positive hadrons
- Large z SIDIS, Q^2 large, P_T large, larger asymmetries
- Exclusive mesons at high z, favored fragmentation of negative pions from struck down quarks?
- See A. Airapetian et al., Phys. Lett. B 728 (2014) 183-190, for more details



Hadron-production of Transversely Polarized Λ Hyperons in Nuclei

- Many observations of Λ transverse polarization in inclusive hadron-nucleon, hadron-nucleus, nucleus-nucleus reactions starting from 300 GeV p-Be collisions reported by Bunce et al. in 1976.

- Roughly independent of beam energy, increases with p_T, dependence on Feynman x_F depends on beam hadron type.

- Mild decrease of polarization in heavier nuclei

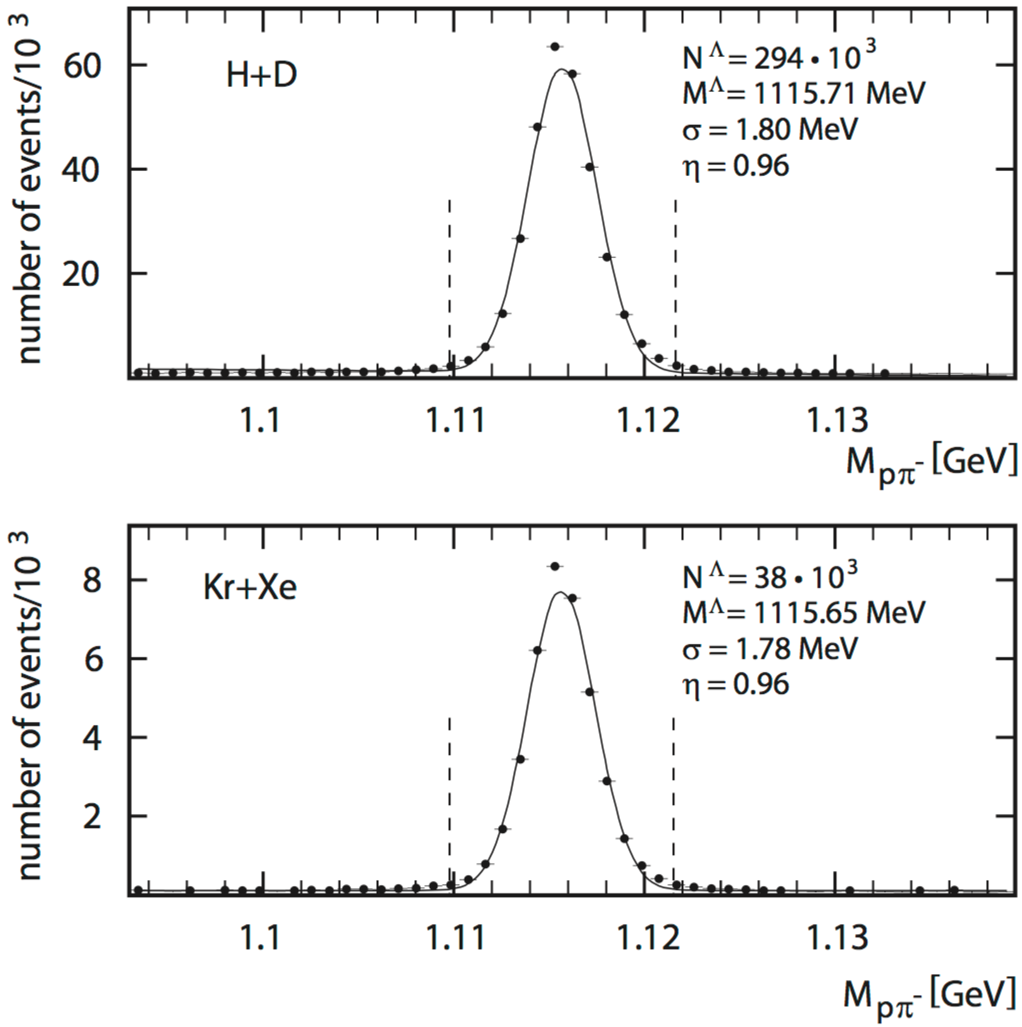
- No generally accepted theoretical explanation! Recent developments based on twist-3 factorization of transverse-momentum-dependent parton densities and fragmentation.

Photo-production of Transversely Polarized Λ Hyperons in Nuclei

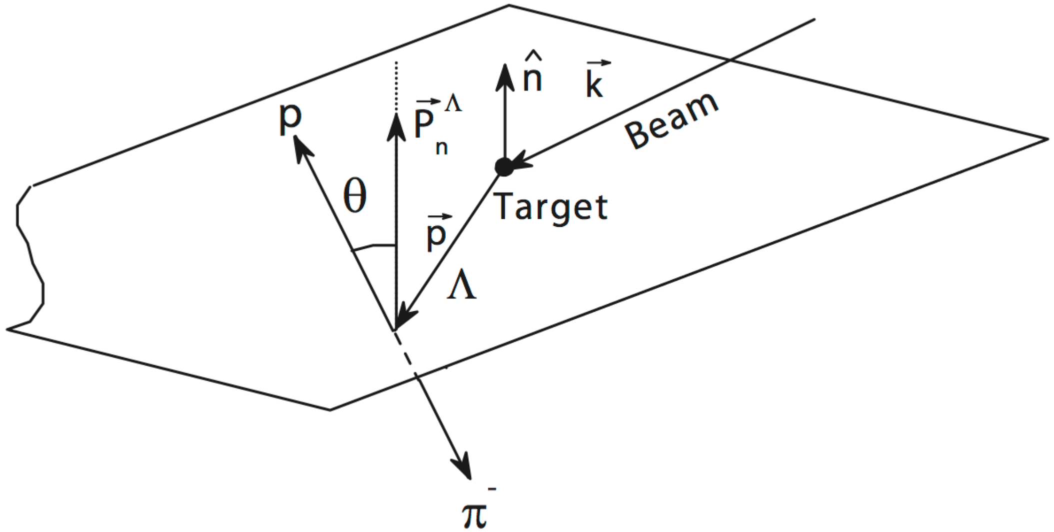
- First observations of transverse polarization of Λ seen at CERN (25-70 GeV) and SLAC (20 GeV), but small statistics
- Recent report by HERMES of transverse polarization in Λ and anti-Λ from hydrogen using quasi-real (untagged) photo-production with energies ranging from 6 to 26 GeV (average energy of 16 GeV)
- Present work explores nuclear dependence of transverse Λ polarization in H, D, He, Kr and Xe targets
- For more details, see A. Airapetian et al., Phys. Rev. D 90 (2014) 072007.

HERMES Event Selection

- No scattered electron required in trigger
- Events with at least two oppositely charged hadrons selected
- RICH detector used to assure that positive hadron was not a pion.
- Both hadron tracks required to be in the same spectrometer half.
- Decay vertex required to be downstream of internal gas target



Lambda Polarization



- Parity-violating weak decay allows polarization determination:

$$\frac{dN}{d\Omega} = \frac{dN_0}{d\Omega}(1 + \alpha P_n^{\Lambda} \cos\theta)$$

- For perfect 4π acceptance: $P_n^{\Lambda} = \frac{3}{\alpha}\langle\cos\theta\rangle$

- For perfect top/bottom symmetric acceptance: $P_n^{\Lambda} = \frac{\langle\cos\theta\rangle}{\alpha\langle\cos^2\theta\rangle}$

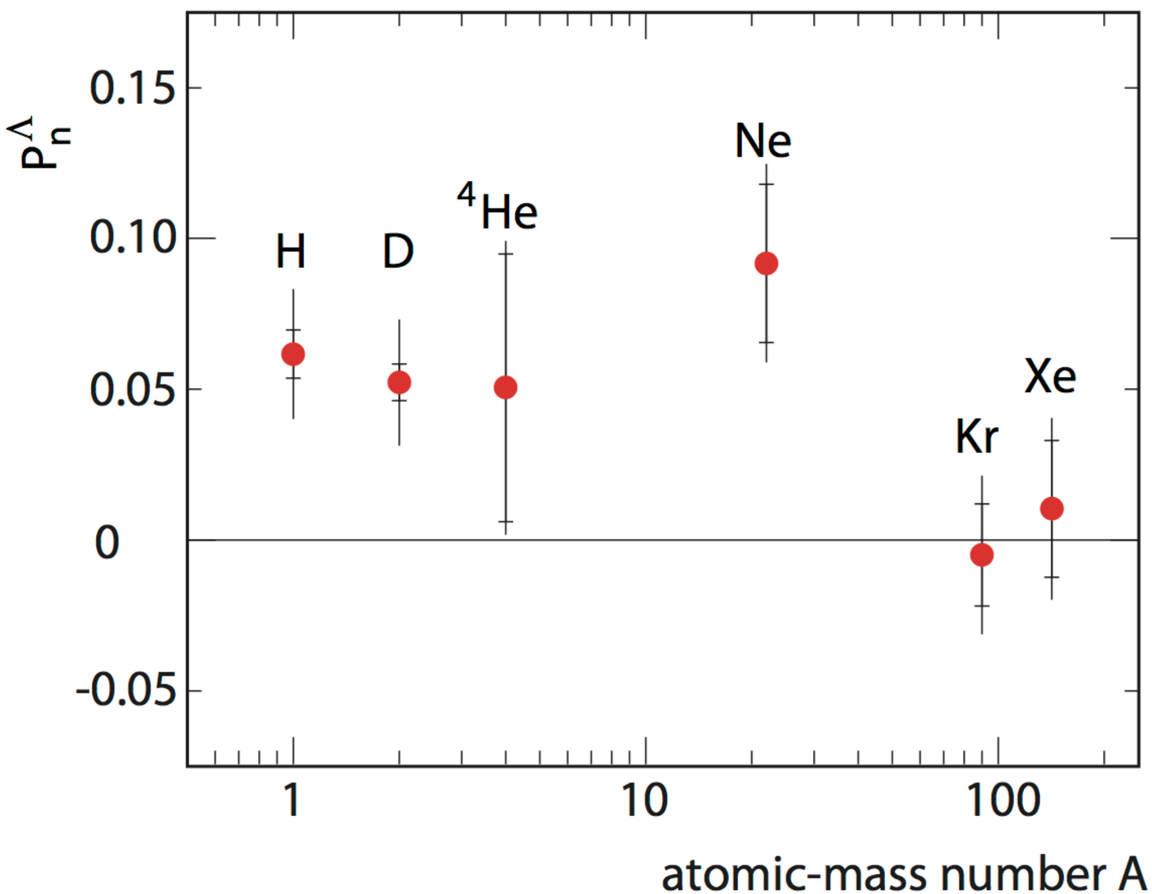
Lambda Kinematics

- For untagged photo-production the 4-momentum of the photon is not known on an event-by-event basis, hence x_F cannot be calculated.
- Instead "light-cone momentum fraction" ζ is used to provide information on forward/backward production in γ-N CM frame

$$\zeta = \frac{E^{\Lambda} + p_L}{E_e + p_e}$$

- "Forward" production for $\zeta > 0.25$; "Backward" production for $\zeta < 0.25$
- Unknown possible contribution from decay of heavy hyperons, such as, Σ^0, $\Sigma(1385)$ and Ξ

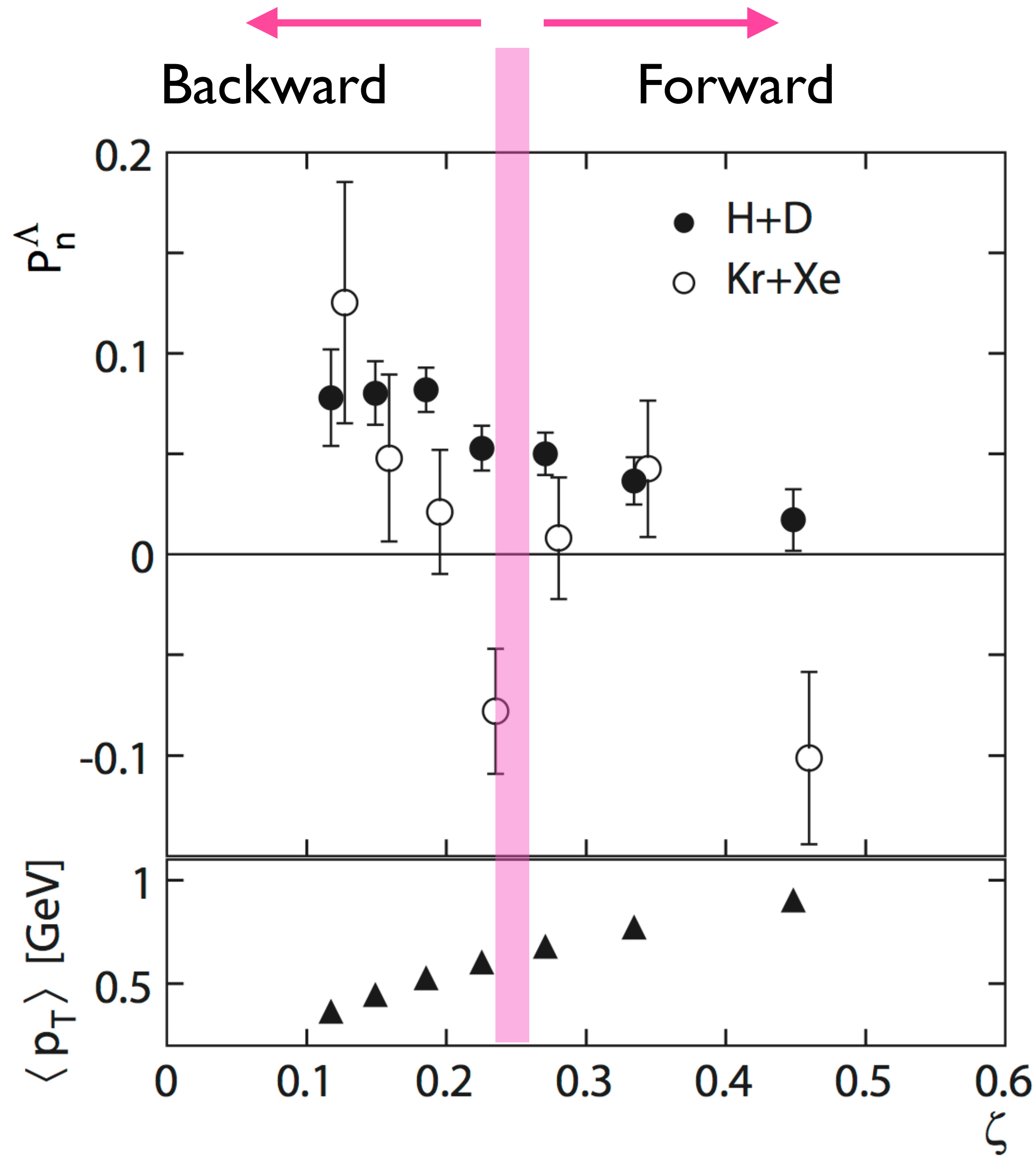
Nuclear Dependence of Λ Polarization



- Positive polarization in light nuclei
- Polarization in heavy nuclei consistent with zero

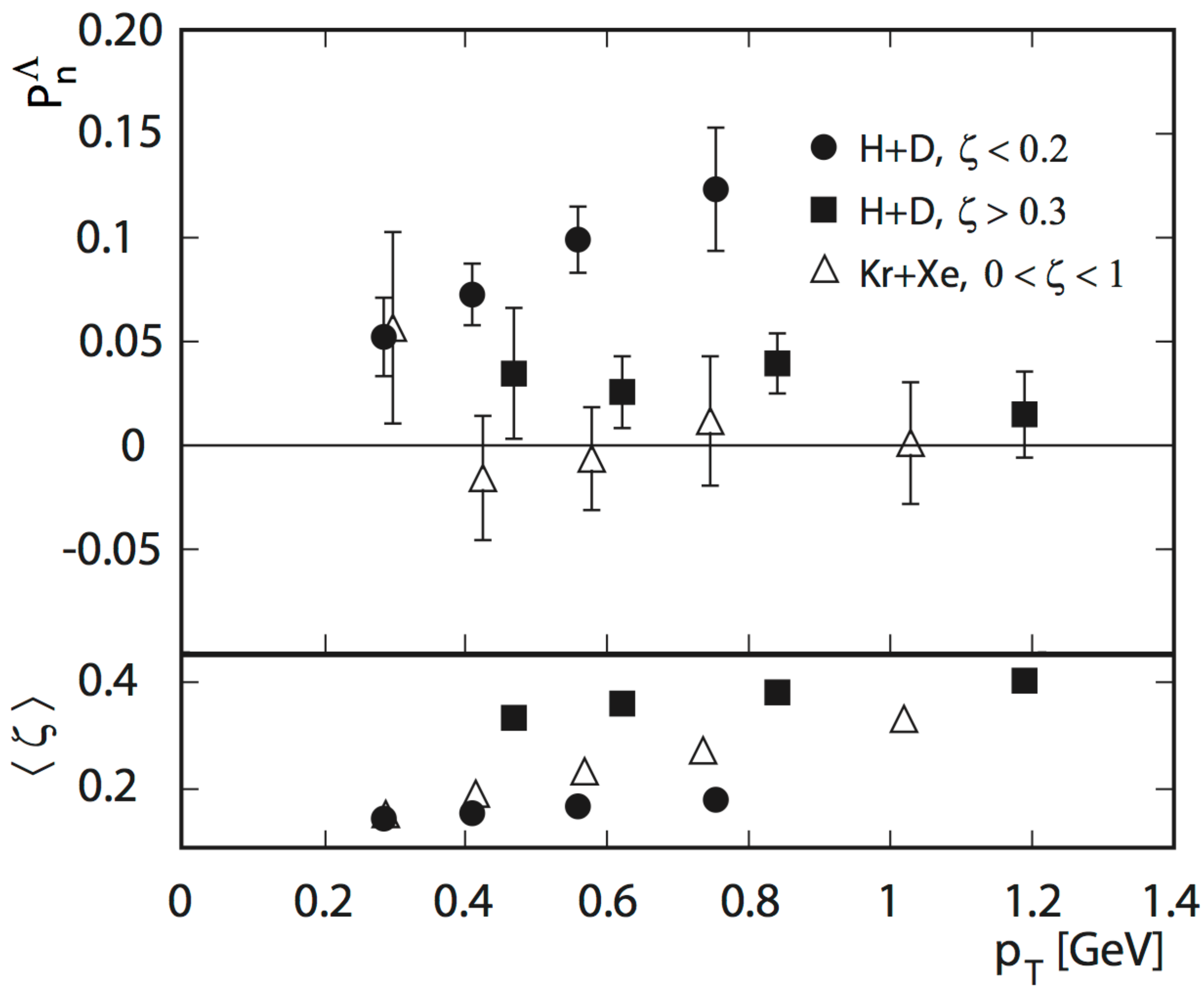
"Forward/Backward" Dependence

- Stronger polarization in "backward" region ($\zeta < 0.2$)
- No strong dependence in heavy nuclei
- p_T correlated with ζ



Polarization Dependence on p_T

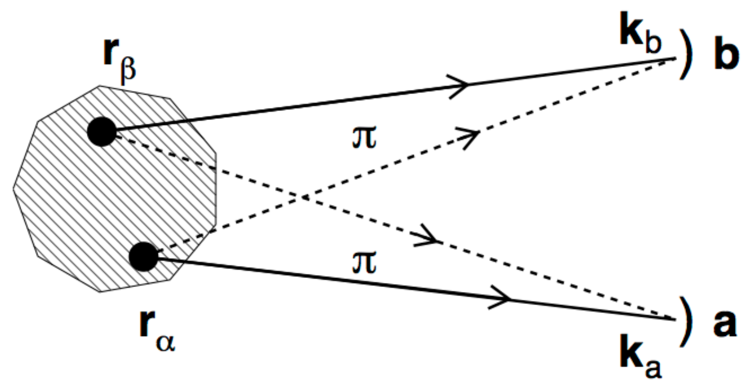
- In backward region, linear increase with p_T for H+D
- Little dependence in forward direction for H+D
- Heavy nuclei remain consistent with zero for all p_T



Uses of Bose-Einstein Correlations

- Hanbury Brown and Twiss first used correlations of photons to measure stellar radii (1956).
- Goldhaber et al. look at correlations in pions from proton-antiproton annihilation (1959).
- Widely used in heavy ion collisions to study spatial and time distributions of decaying “hot” distribution
- Less commonly studied in high energy e+e- annihilation and lepton induced DIS at CERN, HERA, Fermilab, and recently Jefferson Lab
- Uniquely able to study spatial distribution of hadron production in a high energy reaction
- Here we report results of study of nuclear dependence; see arXiv: 1505.03102 for more details

Basics of BEC



- The two emitted pions are indistinguishable, hence their wave function $\Psi_{2\pi}$ must be symmetric under interchange.

- For plane waves, one finds

$$|\Psi_{2\pi}|^2 = 1 + \cos\left[(\mathbf{k_a} - \mathbf{k_b}) \cdot (\mathbf{r}_\alpha - \mathbf{r}_\beta)\right]$$

- the projection of spatial distance along direction of momentum difference

- One can generalize to point sources with continuous space-time distributions and find a two-particle correlation function $R(p_1,p_2)$

BEC Correlation Function R

- The correlation function R is defined in terms of the two particle probability density $D(p_1, p_2)$ for bosons with 4-momenta p_1 and p_2 divided by the product of the single particle probability densities $D(p_1)$ and $D(p_2)$:

$$R(p_1, p_2) = \frac{D(p_1, p_2)}{D(p_1) \cdot D(p_2)}$$

- In principle this is a function of 6 variables for on-shell particles; in particular, in heavy-ion analyses one could expect an exponential decay in time, with a spheroidal distribution in space.

- The single particle probability distributions are in principle quite difficult to measure exactly since one must integrate over all of the un-observed particle's momentum, matched to the experimental acceptance for the measured two-particle distribution. This might explain some of the observed variation between different experiments.

Goldhaber Parameterization of R

- Most analyses from annihilation and DIS use the Goldhaber parametrization based on the Lorentz-invariant T^2 :

$$T^2 = -(p_1 - p_2)^2 = S - 4m_\pi^2$$

$$R(T) = 1 + \lambda \cdot e^{-T^2 r_G^2}$$

- The source distribution size is characterized by r_G
- The incoherence of the sources (chaoticity) is parameterized by λ, where λ=0 would be for a perfectly coherent source and λ=1 for a perfectly incoherent source.
- Calculation of these parameters from first principles is challenging! Within any model or theory, all production and interaction effects (e.g. in the final state) must be included.

Nuclear Effects in BEC

- Experimentally, one can ask whether there is a dependence in the BEC parameters as a function of nuclear size; both parameters could be affected by re-interactions or changes in the fundamental production process within the nuclear environment.

- Earlier measurements by BBCN measured correlations in Ne and found no significant difference from that on the proton

- HERMES has been able to collect data for correlation studies on targets of ^{1}H, ^{2}H, $^{3,4}He$, N, Ne, Kr and Xe

HERMES Data Analysis

- Semi-inclusive DIS (not quasi-real photo-production) with $Q^2 > 1$ GeV^2 and $W^2 > 10$ GeV^2
- Two charged hadrons with momenta between 2 and 15 GeV required, in addition to the scattered electron
- No hadron ID is used (!) RICH analysis difficult for particles with very similar momenta and positions in detector; these events show the strongest correlation.
- Monte-Carlo simulations tuned to HERMES data predict that the relative proportion of hadron types π/K/p is 78%/12%/10%
- Also predicts 55% of like-sign pairs and 66% of unlike sign pairs are truly pions. Approximately 2% of like-sign pairs are kaon pairs
- Non-identical hadron pairs have no BEC so they “dilute” the effect

Construction of Experimental Correlation Function

- In actual experiment, we cannot reliably determine the denominator in the correlation function, so a reference distributions which lacks BEC is determined from the data.

$$R(p_1, p_2) = D(p_1, p_2)/D_r(p_1, p_2)$$

- Two different reference distributions were used for the HERMES analysis:

   1. Method of event mixing (MEM)

   2. Method of unlike-sign pairs (MUS)

- To further reduce systematic biases, a double ratio is used, based on the experimental simulation:

   1. R^{MEM} = (like/mixed)^{exp} / (like/mixed)^{MC}

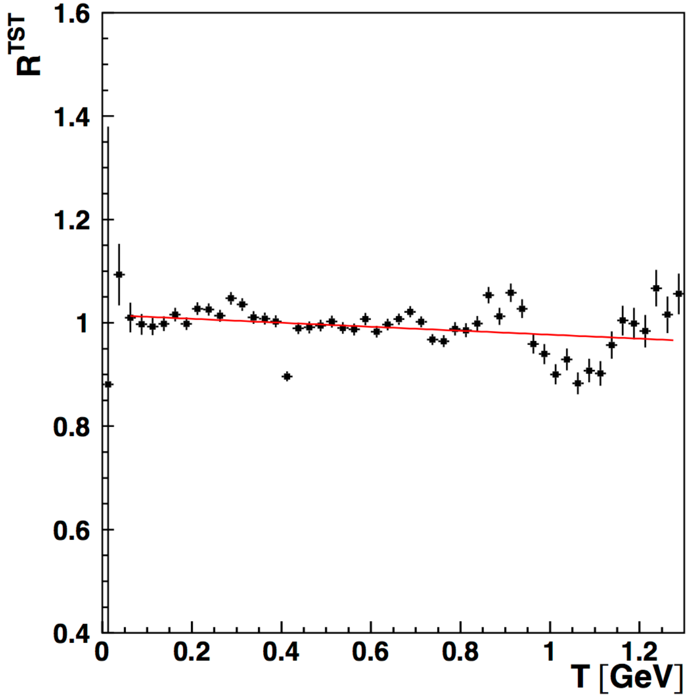
   1. R^{MUS} = (like/unlike)^{exp} / (like/unlike)^{MC}

Tests of Simulation and Method

- Following standard practice, a modified Goldhaber parameterization is used to account for normalization effect and long-range correlations affected by the spectrometer; this introduces 2 additional free parameters to the fit.

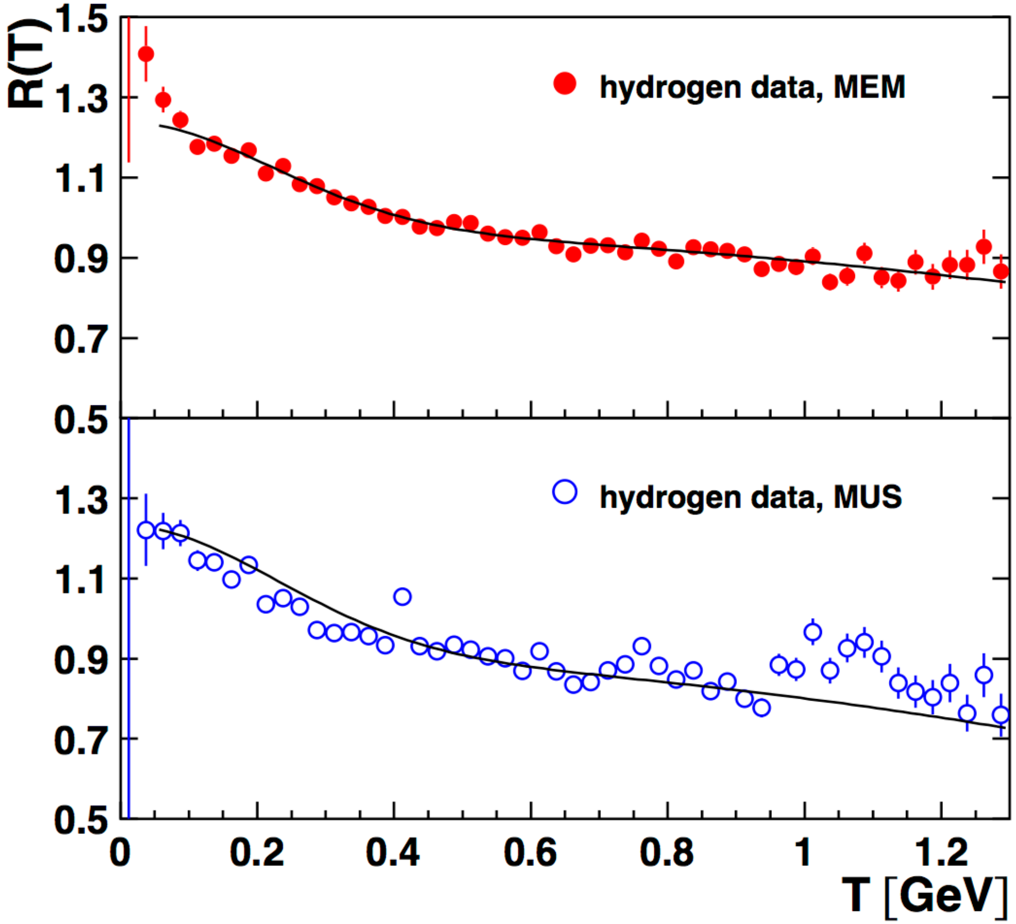
$$R(T) = \gamma \cdot [1 + \lambda \cdot e^{-T^2 r_G^2}] \cdot (1 + \delta \cdot T^2)$$

- We construct a test correlation function to look for biases in the method: R^{TST} = (unlike/mixed)^{exp} / (unlike/mixed)^{MC} and fit with the modified Goldhaber parameterization



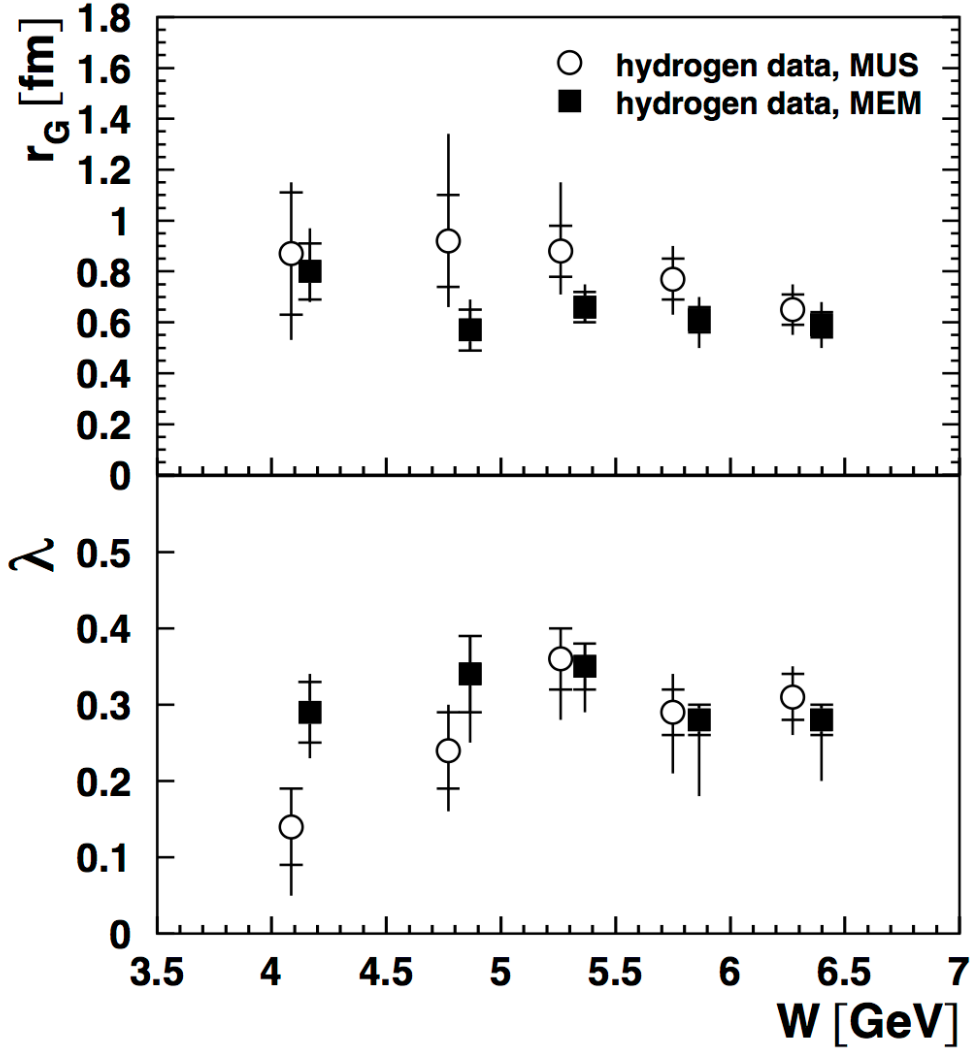
Using 0.05 < T < 1.30 GeV yields
$\lambda = 0.000 \pm 0.003$ and $r_G = 0.0 \pm 1.4$ fm

Double Ratio Correlations for Hydrogen



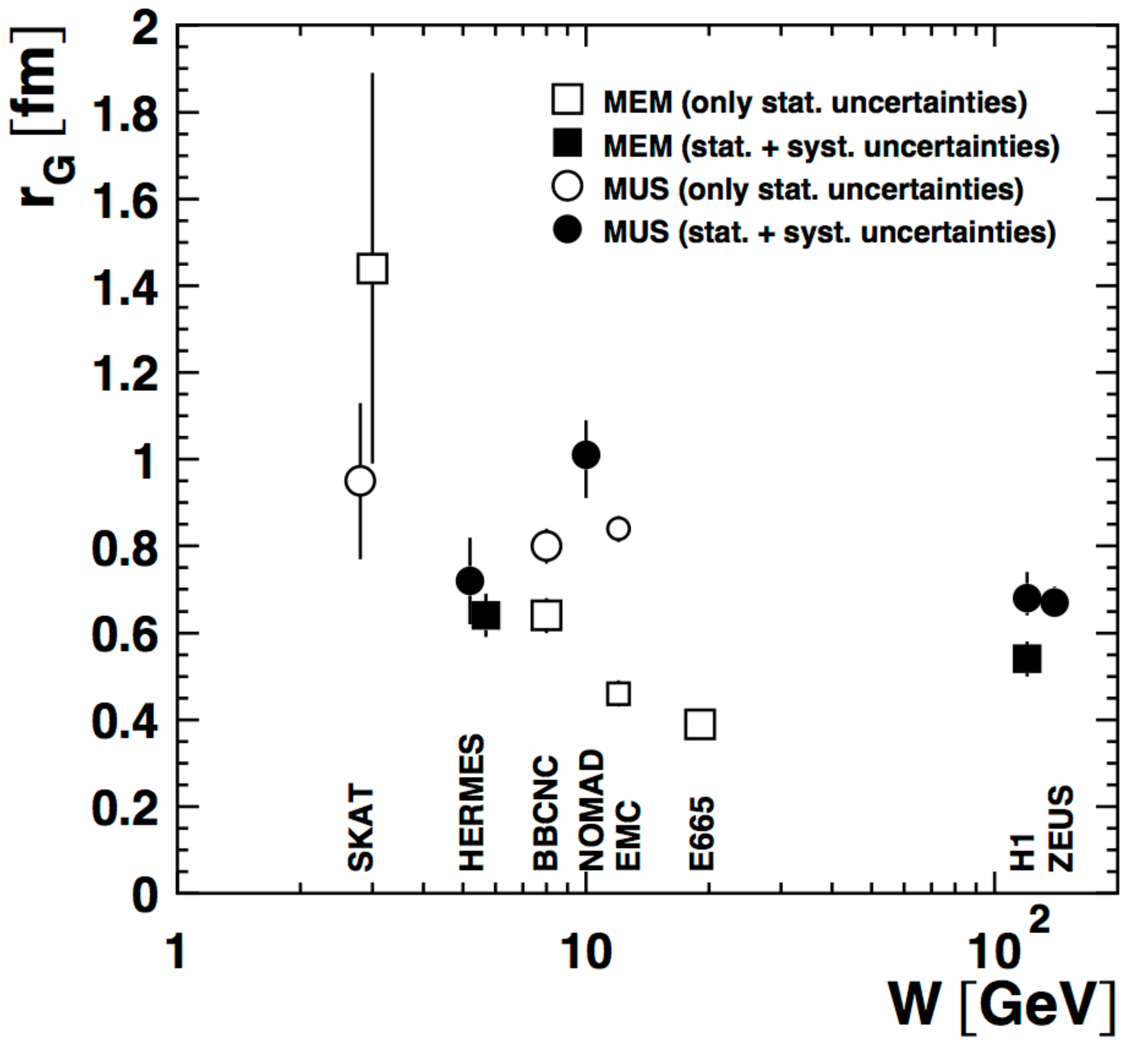
- Fits are performed for 0.05 GeV < T < 1.30 GeV

W dependence of HERMES parameters

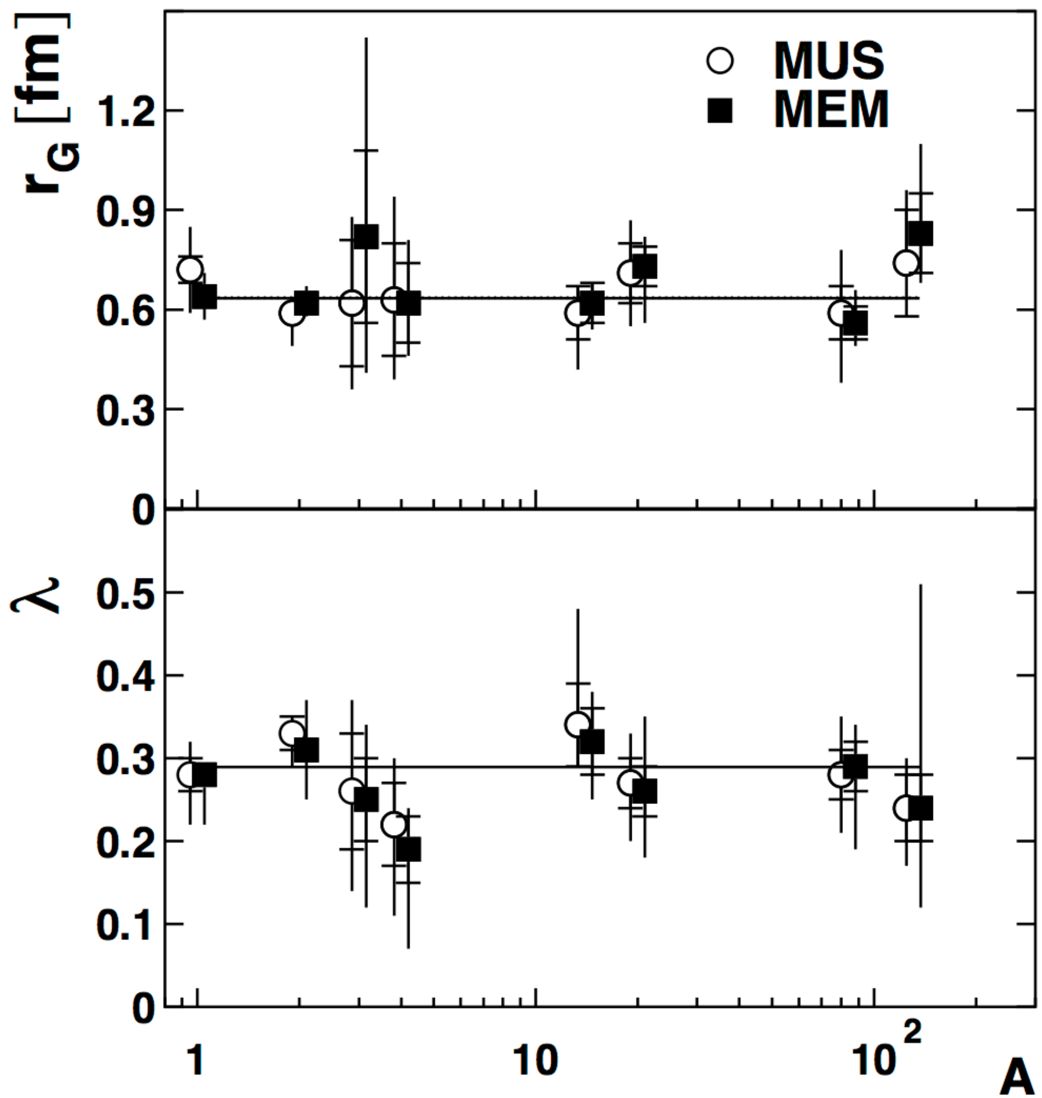


- Statistical and systematic added in quadrature

Comparison of Hydrogen Results to Earlier Measurements



Dependence on Target Mass



- Horizontal lines are average value

Summary

- A_UT from quasi-real photo-production provides information on low Q^2 asymmetries and “tagging” can connect different kinematic scale regimes for one data set
- Transverse Lambda polarization from low Q^2 photons is largest in backward production and appears to decrease to zero for large nuclei
- Within precision of measurement, no nuclear dependence is seen in BEC correlations measured at HERMES over a broad range of nuclei

Back-up Slides

Electroproduction of hadrons with a Transverse Target

HERMES switched from longitudinal to **transverse** target polarization from 2002 to 2005

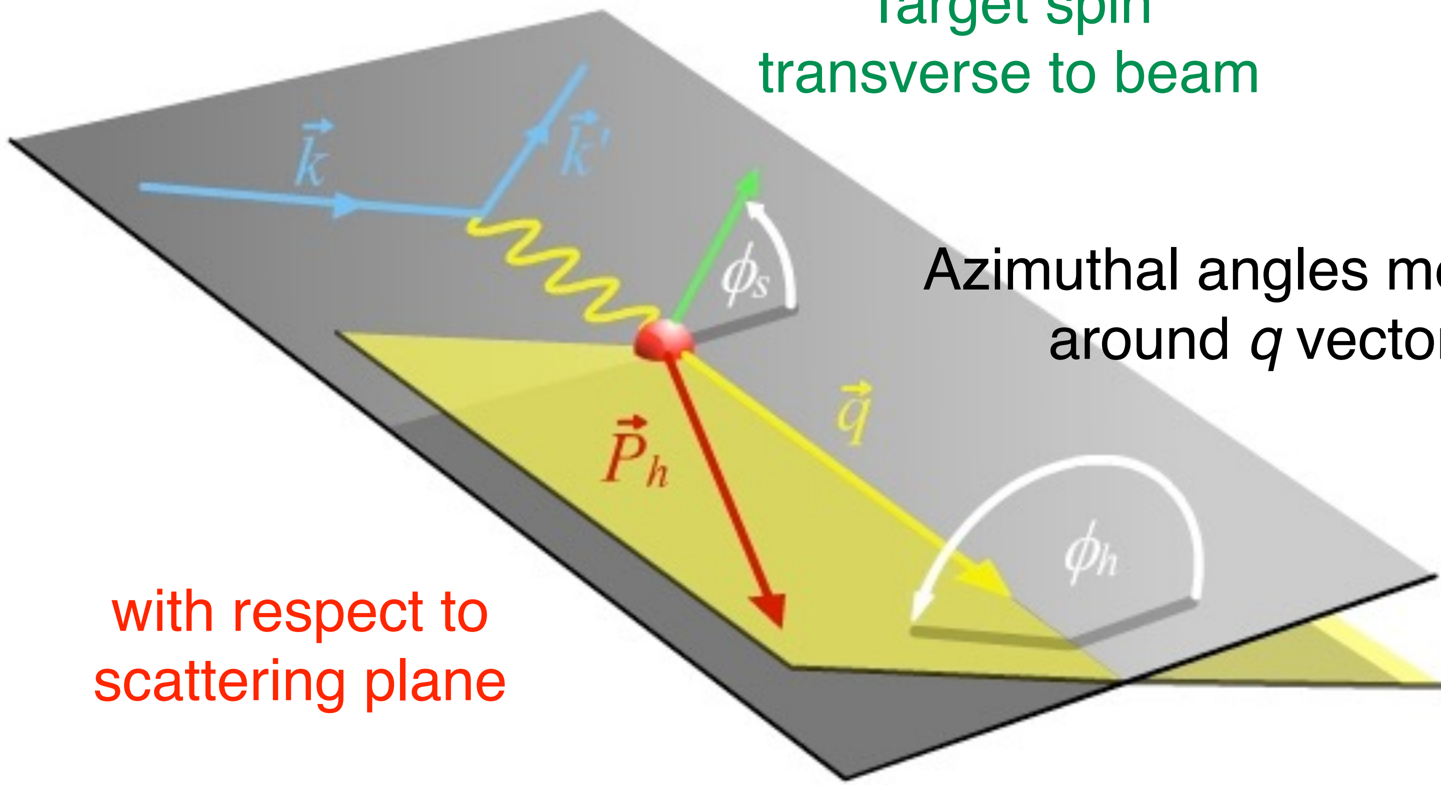
Measure dependence of hadron production on **two azimuthal angles**

Electron beam defines scattering plane

Target spin transverse to beam

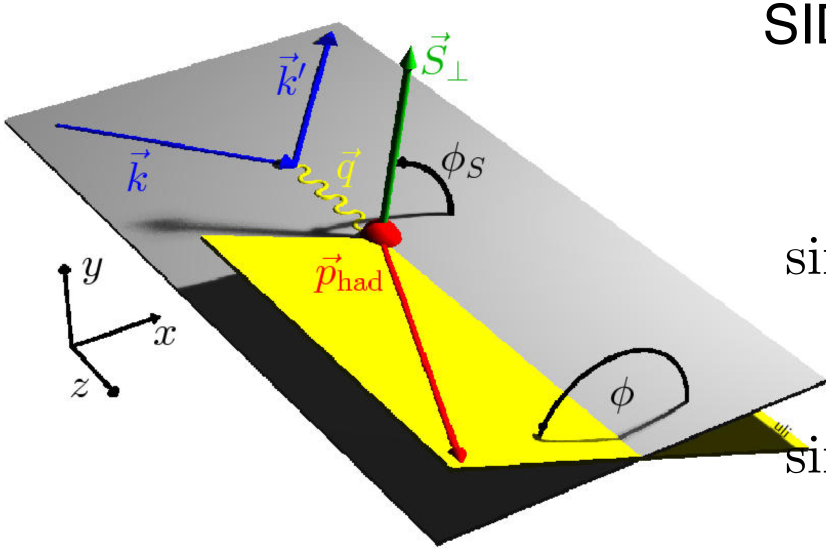
Azimuthal angles measured around *q* vector ...

with respect to scattering plane

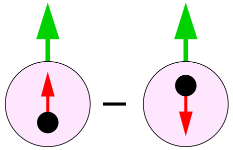
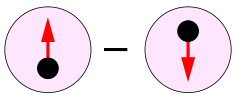


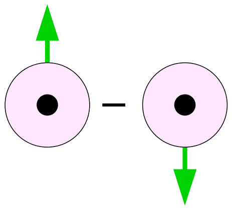
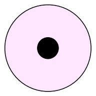
ϕ_S **= target spin orientation** ϕ_h **= pion ("hadron")direction**

Electroproduction of hadrons with a Transverse Target

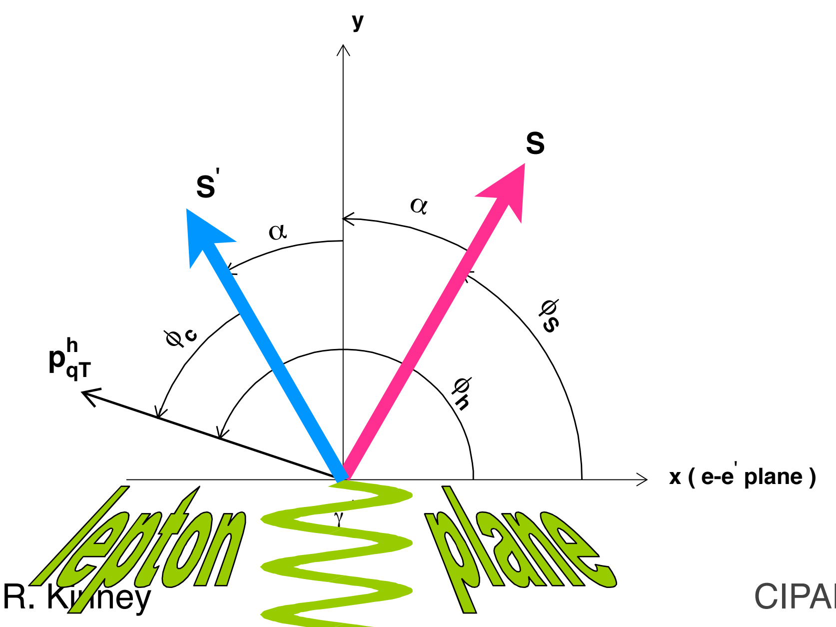


SIDIS xsec with *transverse target* polarization has ***two*** similar terms:

$\sin(\phi_h^l + \phi_S^l) \Rightarrow h_1$ =  $\otimes H_1^\perp$ = 

$\sin(\phi_h^l - \phi_S^l) \Rightarrow f_{1T}^\perp$ =  $\otimes D_1$ = 

separate Sivers and Collins mechanisms



- $(\phi_h^l - \phi_S^l)$ = angle of hadron relative to **initial** quark spin
- $(\phi_h^l + \phi_S^l) = \pi + (\phi_h^l - \phi_S^{l'})$ = hadron relative to **final** quark spin

Table of Nuclear Lambda Results

	H	D	^{4}He	Ne	Kr	Xe
P_n^Λ	0.062	0.052	0.051	0.092	-0.005	0.010
δP_n^Λ(stat)	0.008	0.006	0.044	0.026	0.017	0.023
$N^\Lambda/10^3$	108.5	185.9	3.4	10.2	24.2	13.7
η	0.96	0.96	0.96	0.96	0.96	0.97
ΔM^Λ [MeV]	0.02	0.05	0.09	0.11	0.04	0.00
σ [MeV]	1.79	1.82	1.96	1.89	1.77	1.79
$\langle p_T \rangle$ [GeV]	0.63	0.63	0.67	0.68	0.64	0.64
$\langle \zeta \rangle$	0.25	0.25	0.27	0.27	0.25	0.25

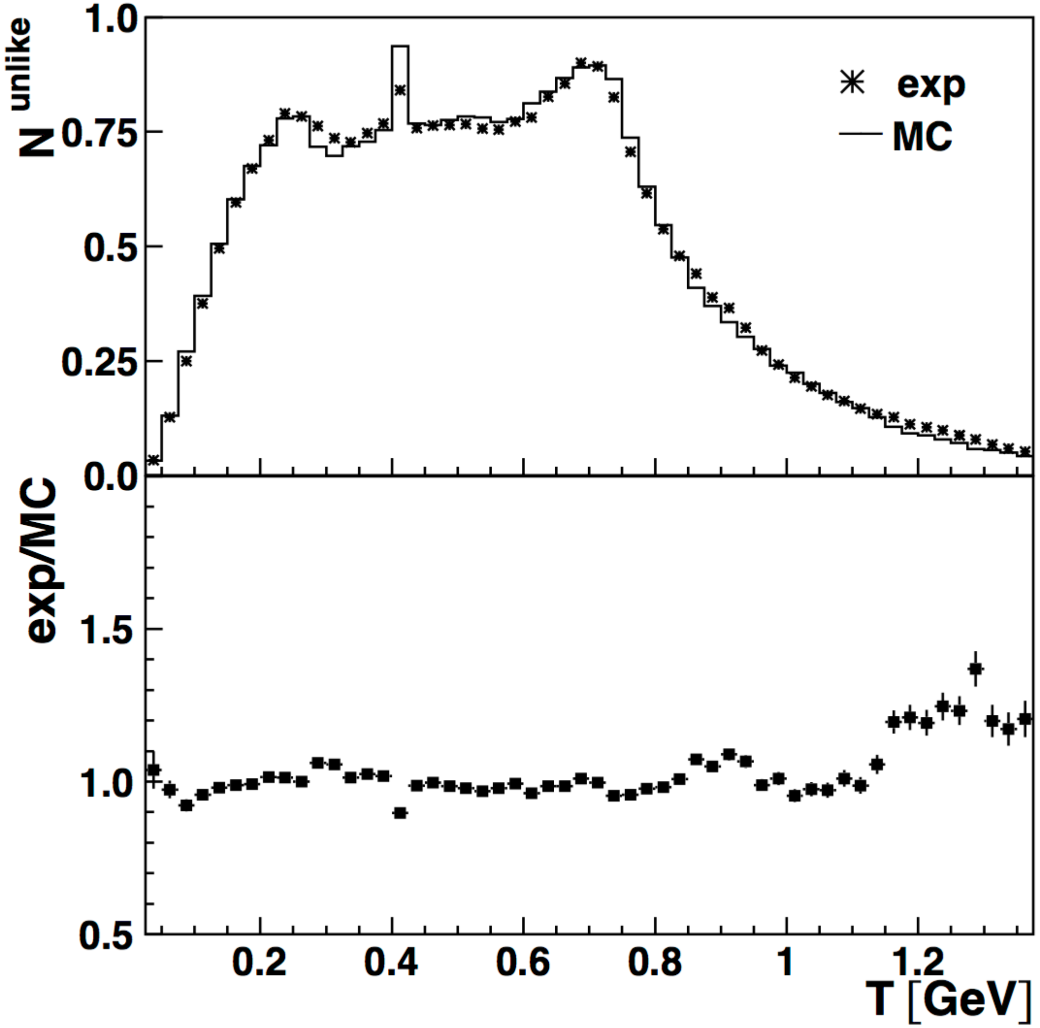
- Systematic uncertainty in polarization is 0.02 for all targets

BEC Pair Statistics

Table 1. Number of DIS events with more than one detected hadron, N_{ev}, the number of like-sign hadron pairs, N^{like}, and of unlike-sign hadron pairs, N^{unlike}, that meet the kinematic requirements for each target.

Nucleus	N_{ev}	N^{like}	N^{unlike}
^{1}H	1145046	478946	958185
^{2}H	1297356	680143	1178797
^{3}He	34391	15295	29165
^{4}He	79776	30539	59244
N	92968	41112	78402
Ne	175594	75898	146145
Kr	211456	91391	172946
Xe	106274	46130	87125

Simulation of Unlike-sign Pair Distributions



BEC Hydrogen Fit Parameters

Table 2. Results for the Goldhaber parametrization fitted to the HERMES hydrogen data, both for the mixed-event method (MEM) and the method of unlike-sign pairs (MUS).

Method	Goldhaber parameters
MEM	$r_G = 0.64 \pm 0.03(\text{stat})^{+0.04}_{-0.04}(\text{sys})$ fm $\lambda = 0.28 \pm 0.01(\text{stat})^{+0.00}_{-0.05}(\text{sys})$
MUS	$r_G = 0.72 \pm 0.04(\text{stat})^{+0.09}_{-0.09}(\text{sys})$ fm $\lambda = 0.28 \pm 0.02(\text{stat})^{+0.02}_{-0.04}(\text{sys})$

A dependence Average Fit

Table 3. Fit of a constant to the Goldhaber parameters as a function of the target atomic mass A. Results are given for both the mixed-event method (MEM) and the method of unlike-sign pairs (MUS).

Method	Value	χ^2/NDF
MEM	$r_G = 0.634 \pm 0.017$ fm $\lambda = 0.289 \pm 0.006$	1.5 2.1
MUS	$r_G = 0.636 \pm 0.021$ fm $\lambda = 0.289 \pm 0.011$	1.2 1.4