Neutron spin structure studies at EIC

Alessio Del Dotto, (INFN LNF, Italy)

Evaristo Cisbani (INFN Roma1)

contributions from

Leonid Kaptari (Bogoliubov Lab. Theor. Phys),

Emanuele Pace (Tor Vergara Univ. & INFN Roma 2),

Sergio Scopetta (Perugia Univ. & INFN Perugia),

Giovanni Salmè (INFN Roma)

Outline

- Formalism (DIS / SIDIS)
- ^{3}He as effective polarized n target
- Experimental status (g_1^n, A_n, TMD …)
- Approved “upcoming” experiments
- EIC features
- SiDIS off ^{3}He and information on the neutron structure:
  - Recent theoretical developments in SiDIS studies including the final state interaction through a distorted spin dependent spectral function
  - “spectator” SiDIS measurements → tagging D or pp
- Conclusions

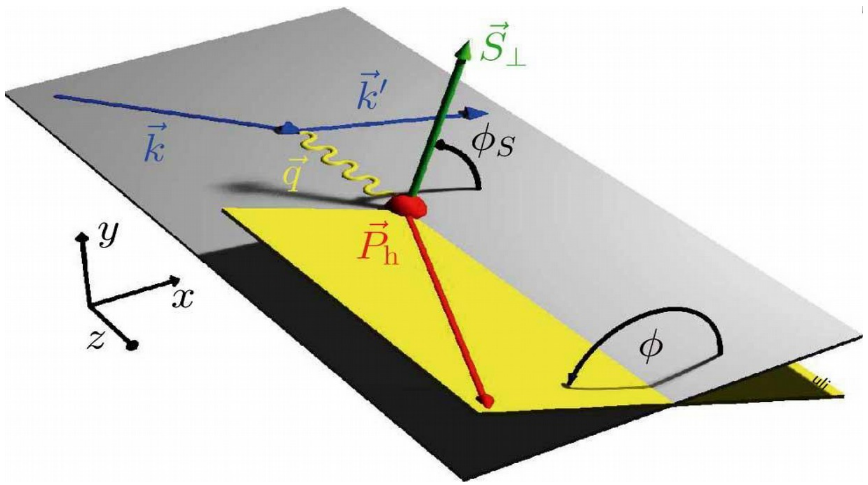
(Spin) Neutron structure

Goal: To study the inner structure of the neutron and its spin degrees of freedom (mainly by DIS and related)

The free neutron decays in about 1000 s and has no net charge → need an "effective" polarized neutron target

- SIDIS on transversely polarized target

$$A_{UT} \equiv \frac{1}{|S_T|} \frac{d\sigma(\phi, \phi_S) - d\sigma(\phi, \phi_S + \pi)}{d\sigma(\phi, \phi_S) + d\sigma(\phi, \phi_S + \pi)}$$



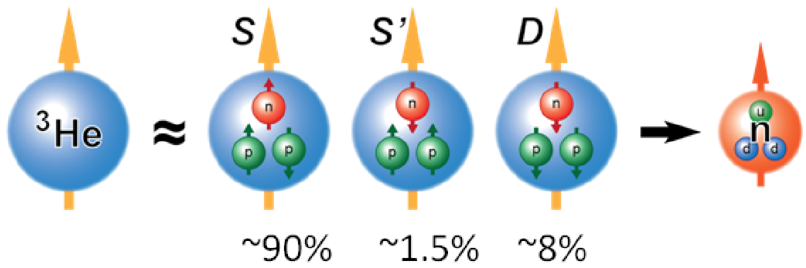
$$\sigma_{SiDIS} \sim TMD(x, p_T^2, Q^2) \otimes \sigma_{\gamma^* q} \otimes FF(z, k_T^2, Q^2)$$

- **TMD**: probability density to strike a quark with ***x*** fraction of longitudinal momentum and transverse momentum $\boldsymbol{p_T}$
- **FF**: probability density of the struck quark, with transverse momentum $\boldsymbol{k_T}$ to fragment in an hadron carrying a fraction ***z*** of the parton momentum

^{3}He polarized target

The key quantity to calculate the effective polarizations is the ^{3}He spectral function S(E,p) … it appears in DIS, SIDIS, DVCS, ...

$$^3\vec{He} \simeq \vec{n}$$



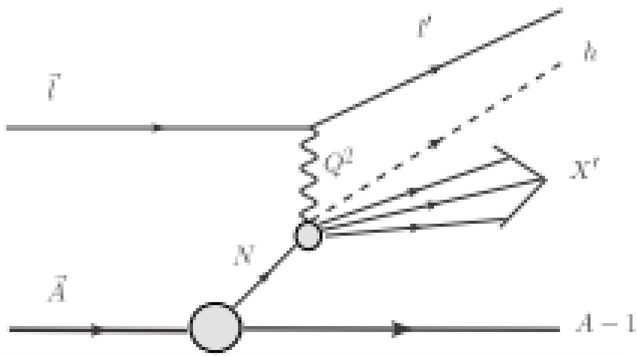
The two photons are mostly in a s=0 wave.

Main idea:

- The virtual photon interacts with a single nucleon. The FSI's among the hadron, the nucleon and the (fully interacting) spectator nuclear system is disregarded
- The internal structure of the bound nucleon is the same as the free one

(Ciofi degli Atti et al .,PRC48(1993)R968)

---> applied to DiS, first naive extension to SiDIS



$$A_n \simeq \frac{1}{p_n f_n}(A_3^{exp} - 2p_p f_p A_p^{exp})$$

Effective polarizations:

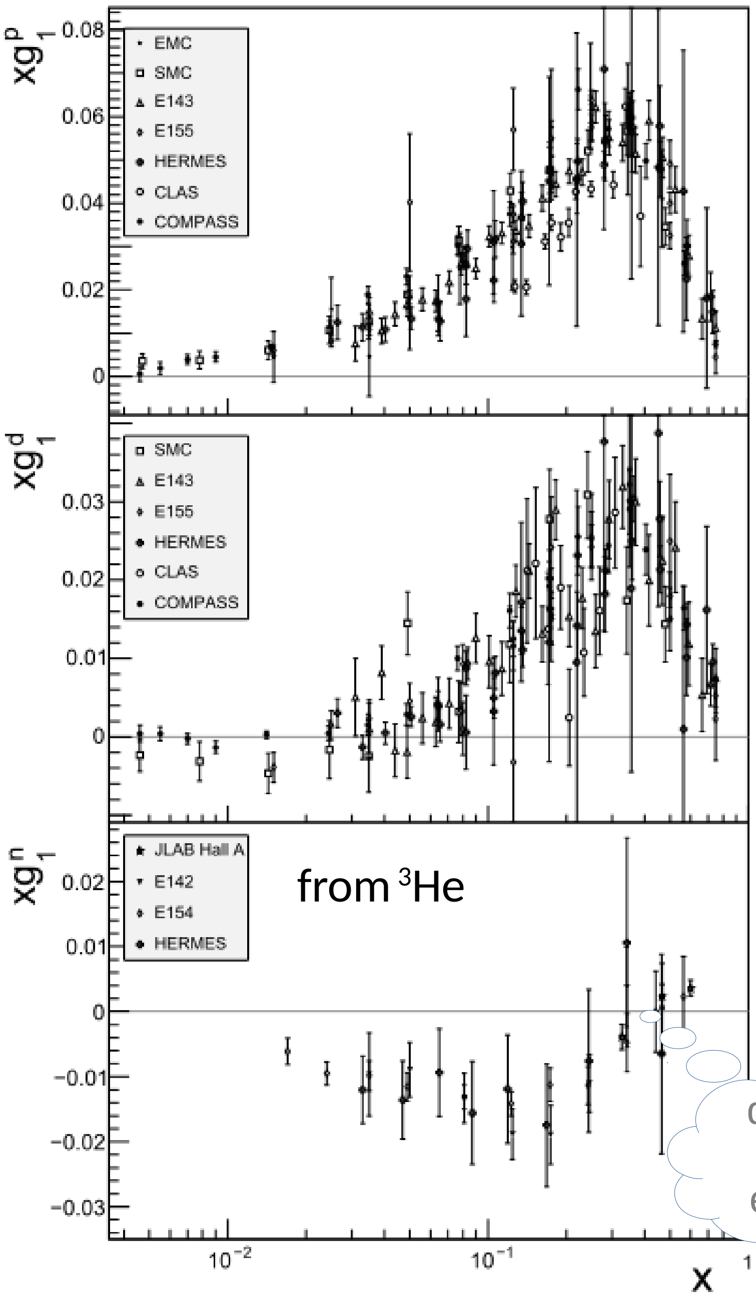
$$p_p = -0.023 \qquad p_n = 0.878$$

Dilution factor:

$$f_{p(n)} \simeq 0.2$$

Neutron Spin Structure Function from polarized DIS

arXiv:1209.2803-2013



di-quark dofs effects?

Both x<0.04 and >0.4 need neutron data!
Most of the existing data at very small x taken at $Q^2<1$

Large space for experimental improvements:

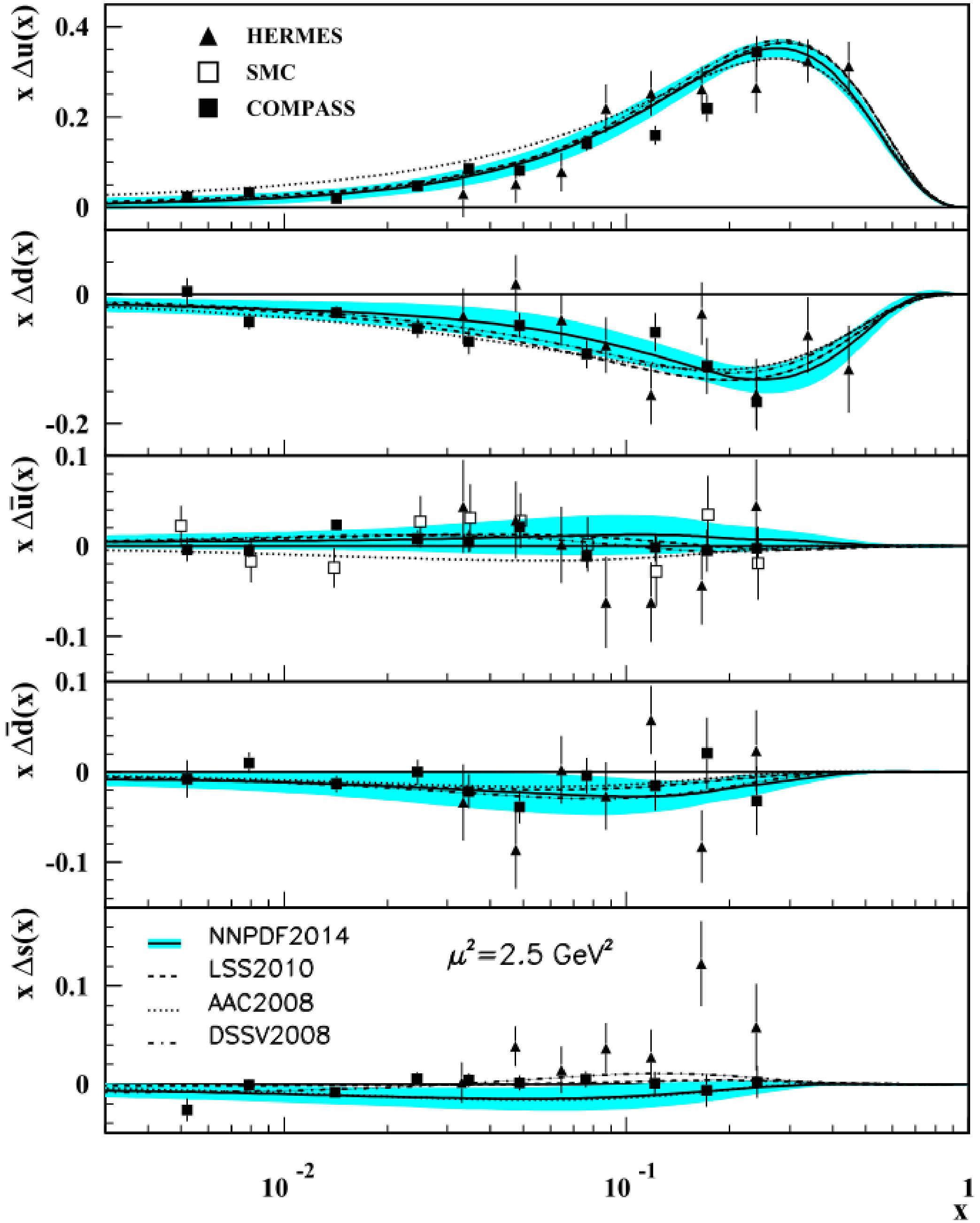
- Bjorken sum rule (a «direct» check of QCD) (more accuracy with new data)
- $g_1^p+g_1^n$ and $g_1^p-g_1^n$ at small x is related for DGLAP evolution

Need well established «baseline» to understand Higher Twist effects e.g. g_2

Both D (previous talk) and 3He targets needed to extract consistent data on neutron from non trivial nuclear effects

Nucleon spin & flavor decomposition

Polarized parton densities from PDG-2017



Extend, improve

decomposition requires data

from SIDIS π^+/π^- , K^+/K^-

(need good PID), and

different targets p,D,^{3}He

Both D and ^{3}He targets needed:

- D: treatment of nuclear effects somehow simpler, but difference of similar terms to extract n (g_1^d-g_1^p)
- ^{3}He: n effective polarization but nuclear effects more complicated

FSI in ^{3}He **distorted** spectral function

L. Kaptari, A.DD., E. Pace, G. Salmè,S. Scopetta., PRC 89 (2014)
A.DD., E. Pace, G. Salmè, S. Scopetta, PRC95 (2017)

Progresses have been done!

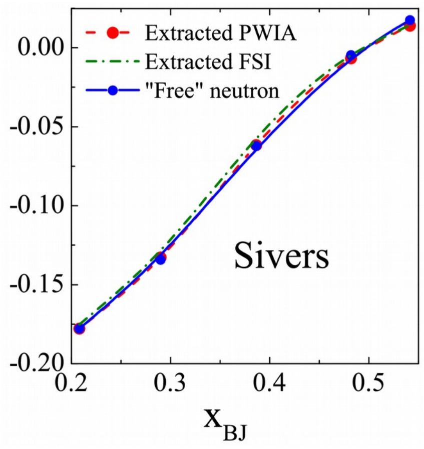
1) PWIA: $\langle p_n \rangle = 0.876$, $\langle p_p \rangle = -0.0237$, $\theta_e = 30^o$, $\theta_\pi = 14^o$

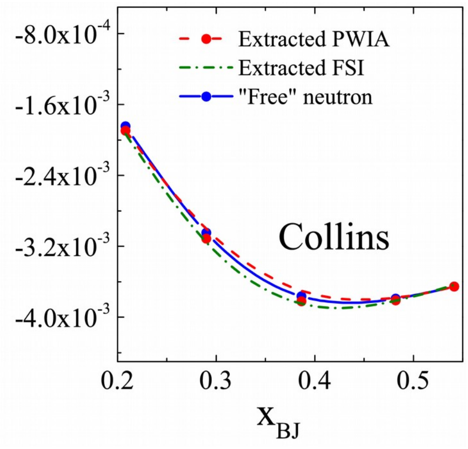
E_{beam}, GeV	x_{Bj}	ν GeV	p_π GeV/c	$f_n(x,z)$	$\langle p_n \rangle f_n$	$f_p(x,z)$	$\langle p_p \rangle f_p$
8.8	0.21	7.55	3.40	0.304	0.266	0.348	-8.410^{-3}
8.8	0.29	7.15	3.19	0.286	0.251	0.357	-8.510^{-3}
8.8	0.48	6.36	2.77	0.257	0.225	0.372	-8.910^{-3}
11	0.21	9.68	4.29	0.302	0.265	0.349	-8.310^{-3}
11	0.29	9.28	4.11	0.285	0.25	0.357	-8.510^{-3}

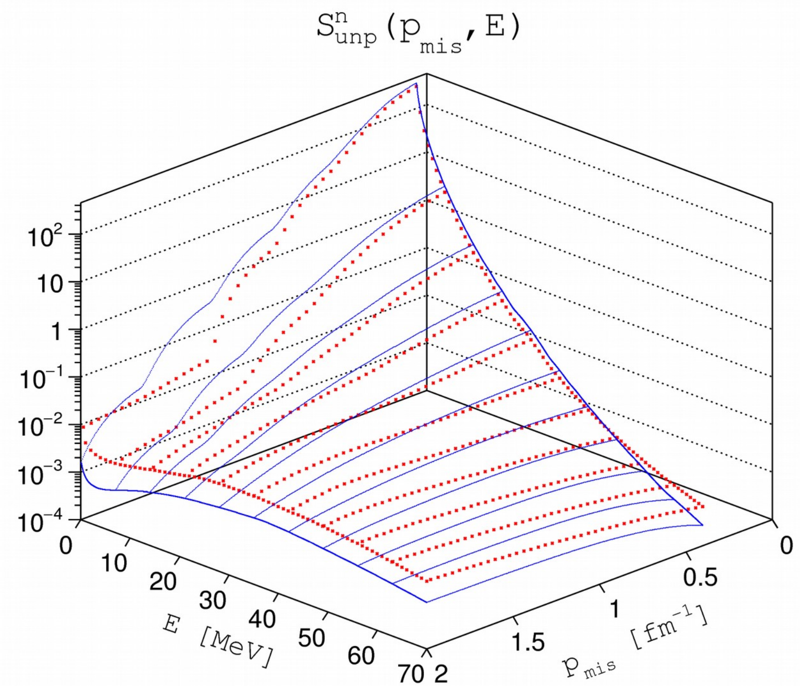
2) FSI: $\langle p_n \rangle = 0.756$, $\langle p_p \rangle = -0.0265$, $\langle N_n \rangle = 0.85$, $\langle N_p \rangle = 0.87$, $\langle \sigma_{eff.} \rangle = 71\ mb$

E_{beam}, GeV	x_{Bj}	ν GeV	p_π GeV/c	$f_n(x,z)$	$\langle p_n \rangle f_n$	$f_p(x,z)$	$\langle p_p \rangle f_p$
8.8	0.21	7.55	3.40	0.353	0.267	0.405	-1.110^{-2}
8.8	0.29	7.15	3.19	0.332	0.251	0.415	-1.110^{-2}
8.8	0.48	6.36	2.77	0.298	0.225	0.432	-1.210^{-2}
11	0.21	9.68	4.29	0.351	0.266	0.405	-1.10^{-2}
11	0.29	9.28	4.11	0.331	0.250	0.415	-1.110^{-2}

$$A_n \simeq \frac{1}{p_n^{FSI}\ f_n^{FSI}}\left(A_3^{exp} - 2p_p^{FSI} f_p^{FSI} A_p^{exp}\right) \simeq \frac{1}{p_n\ f_n}\left(A_3^{exp} - 2p_p f_p A_p^{exp}\right)$$





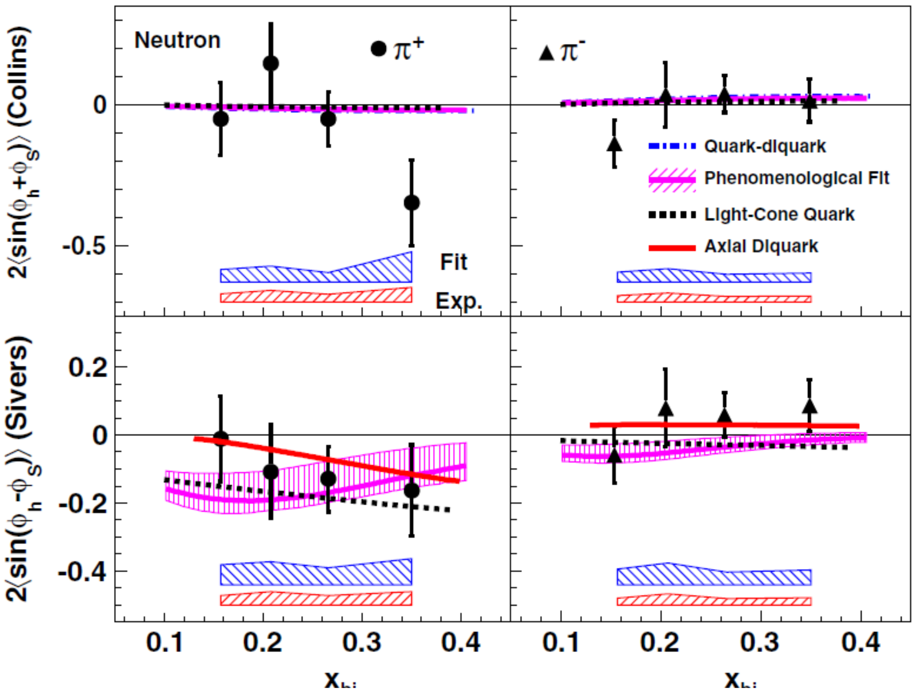


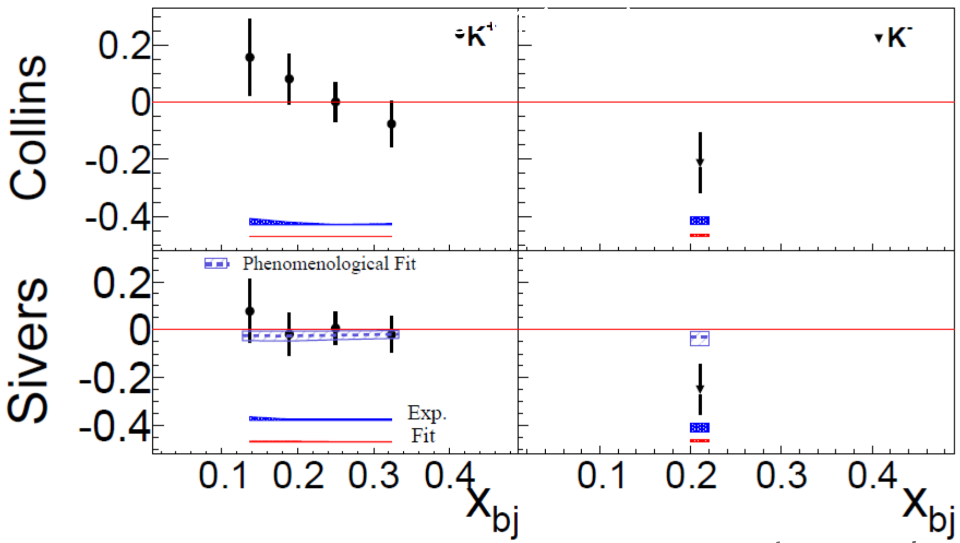
- **The usual extraction is safe in the valence region and for the Jlab kinematics**
- **At very low x (EIC) the FSI grows up, better to have an experimental measurement (spectator SIDIS, exclusive measurements, cross sections ...)**

Existing data on ^{3}He

$$e + {}^3He^{\uparrow} \rightarrow e' + \pi(K)^{\pm} + X$$

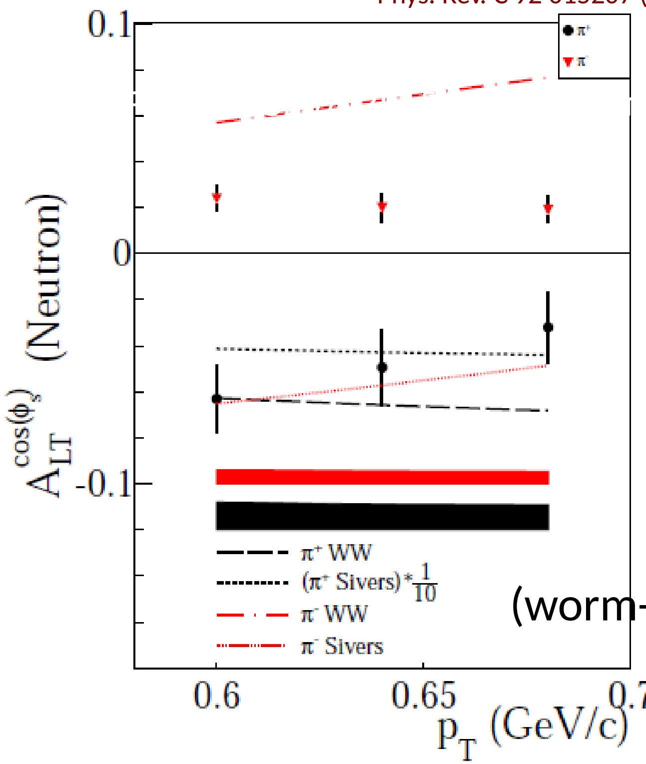
Qian et al. PRL 107, 072003 (2011)





$$\vec{e} + {}^3He^{\uparrow} \rightarrow h + X$$

Phys. Rev. C 92 015207 (2015)



(worm-gear)

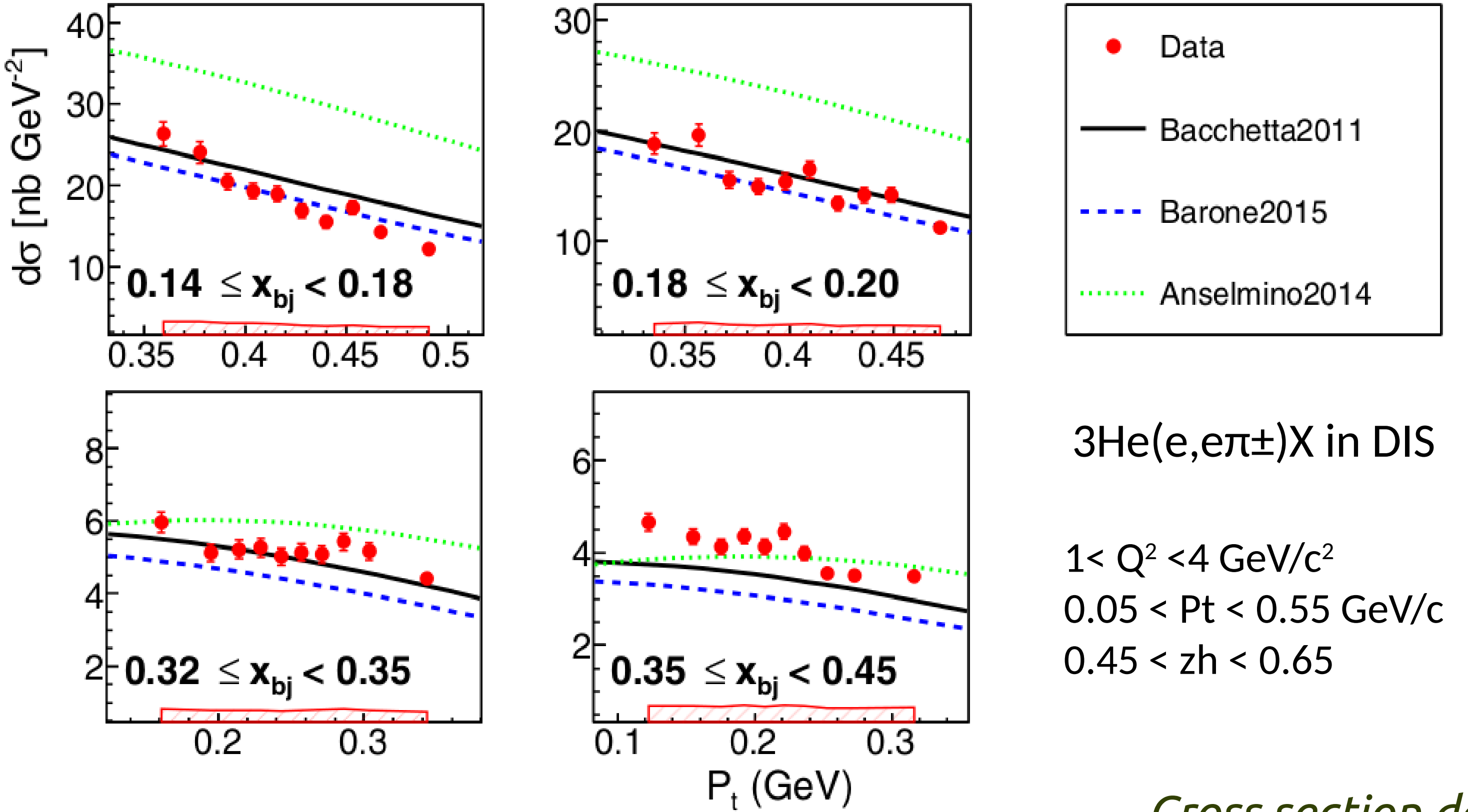
Rather evident LT asymmetries, with opposite signs, but very limited data →
not clean picture, need further exp. data at broad phase space and with higher precision

Negative Sievers for π^+ (d opposite to u)?

K and π^- Asymmetries negligible (not fully consistent with p and D existing data)

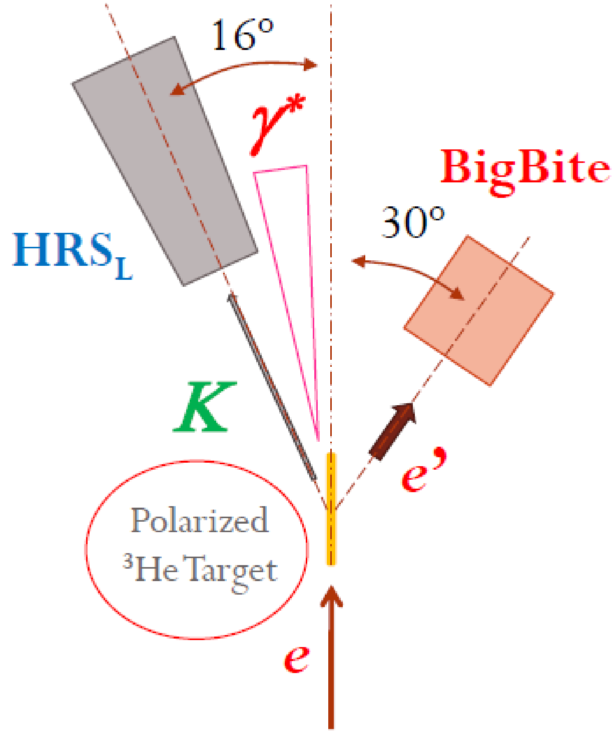
^{3}He Cross section data in (unpolarized) SiDIS

PHYSICAL REVIEW C 95, 035209 (2017)



3He(e,eπ±)X in DIS

$1 < Q^2 < 4$ GeV/c^2
$0.05 < Pt < 0.55$ GeV/c
$0.45 < zh < 0.65$



«Simple» model (at lower twist) reproduce reasonably well the main features of the data; no large higher-twists contribution in explored Q2 range

Estimated $\langle k_T^2 \rangle$ width smaller than from global analyses of other data (model based!)

Cross section data (also polarized!) valuable to quantitative estimate of:

- *transverse quark motion*
- *FSI in light nuclei*
- *...*

Expected better accuracy in EIC hermetic 4pi detectors respect to fixed target, limited acceptance, experiments

“Standard” SIDIS cross sections

First measurement of unpolarized SIDIS cross section off ^{3}He (X. Yan et al, PRC 95, 035209 (2017))

- For a similar analysis on polarized data the expected error is of order 15%

A.DD., L.P. Kaptari, E. Pace, G. Salmè, S. Scopetta, PRC 96, 065203 (2017)

- A look back at the light cone distributions:
  - The relative difference around the peak > 15%
  - The relative difference in the mean polarizations is of the order of 15%

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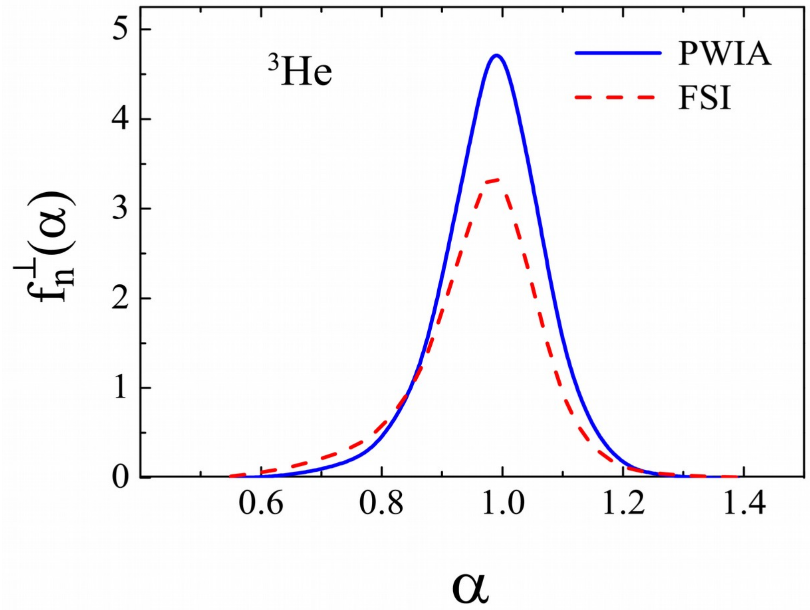


Even if the spectral function is convoluted with TMDs (and structure function) the analysis can still provide valuable information with an expected accuracy on sigma at the level of 10%! (at least considering the current available data).

Near future experiments by ^{3}He/^{3}H @ JLab

DIS - Structure Functions in ^3H and ^3He nuclei — Running

MARATHON Collaboration E12-10-103, G. Petratos et al. : Measurement of F_{2n}/F_{2p}, d/u ratios and A=3 EMC effect in deep inelastic electron scattering off the Tritium and Helium mirror nuclei

$hallaweb.jlab.org/12GeV/$

Cates G. et al., E12-09-018, JLAB approved experiment : Measurement of Semi-Inclusive Pion and Kaon Electroproduction on a Transversely Polarized ^{3}He Target — SBS ~2022

$hallaweb.jlab.org/collab/PAC/PAC38/E12-09-018-SIDIS.pdf$

SIDIS regime on polarized ^{3}He , e.g. — SoLID >2022

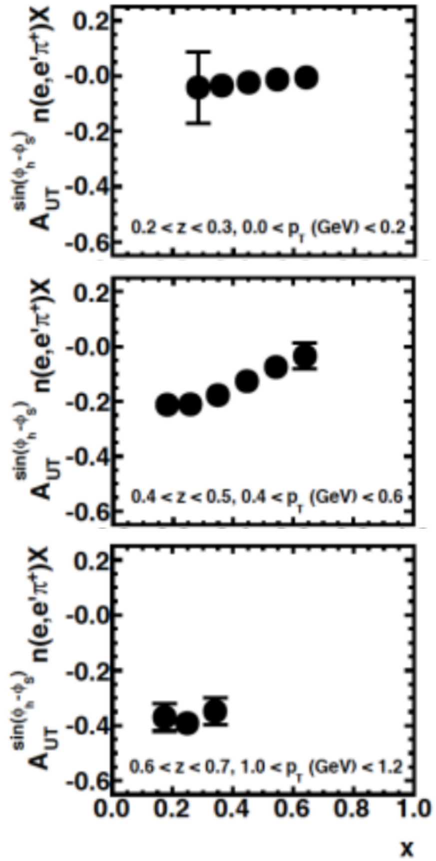
Hall A, $http://hallaweb.jlab.org/12GeV/$

H. Gao et al., PR12-09-014 : Target Single-Spin Asymmetry in Semi-Inclusive Deep-Inelastic $(e, e'\pi^{\pm})$ Reaction on a Transversely Polarized ^{3}He Target

J.P. Chen et al., PR12-11-007: Asymmetries in Semi-Inclusive Deep-Inelastic $(e, e'\pi^{\pm})$ Reactions on a Longitudinally Polarized ^{3}He Target at 8.8 and 11 GeV

$www.jlab.org/\ jinhuang/12GeV/12GeV\,LongitudinalHe3.pdf$

SBS SIDIS SSA

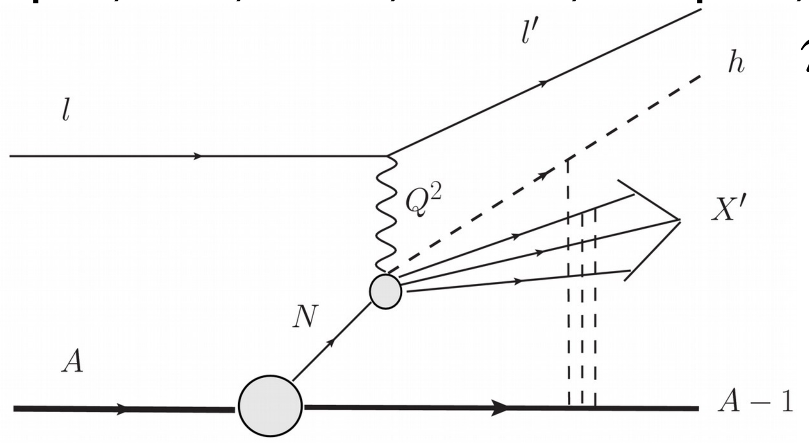


1<Q2<10 GeV^2,
0<pT<1.2 GeV
0.2<z<0.7
0.1<x<0.7

Precise multidimensional 3He (polarized) (SI)DIS data at large x (an moderate Q2) in the coming decades
…. together with experiments on H/D based targets

Spectator SiDIS

L. Kaptari, A.DD., E. Pace, G. Salmè,S. Scopetta., PRC 89 (2014)



A-1 = D, pp, ...

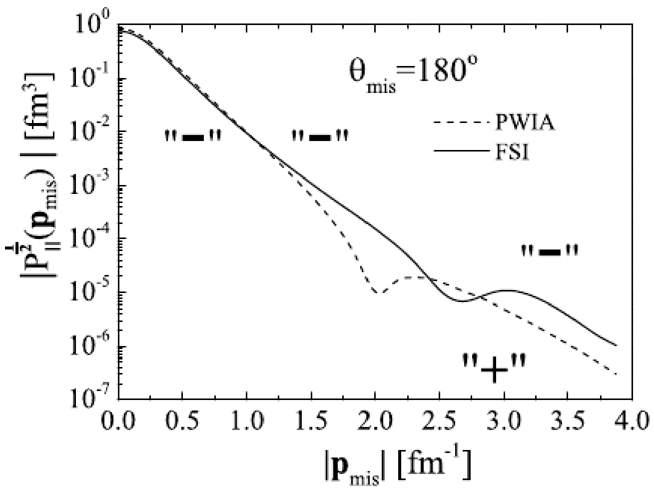
Deuteron in the final state → g1p

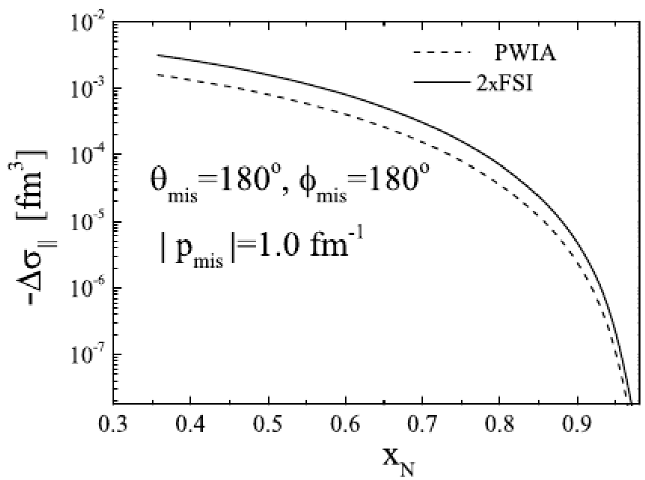
pp in the final state → g1n

$$\frac{\Delta\sigma^{\hat{\mathbf{S}}_A}}{d\varphi_e\, dx\, dy\, d\mathbf{P}_D} \equiv \frac{d\sigma^{\hat{\mathbf{S}}_A}(h_e=1) - d\sigma^{\hat{\mathbf{S}}_A}(h_e=-1)}{d\varphi_e\, dx\, dy\, d\mathbf{P}_D} =$$

$$\approx 4\frac{\alpha_{em}^2}{Q^2 z_N \mathcal{E}}\frac{m_N}{E_N}\, g_1^p\left(\frac{x}{z}\right)\mathcal{P}_{||}^{\frac{1}{2}}(\mathbf{p}_{mis})\mathcal{E}(2-y)\left[1-\frac{|\mathbf{p}_{mis}|}{m_N}\right] \qquad \textit{Bjorken limit}$$

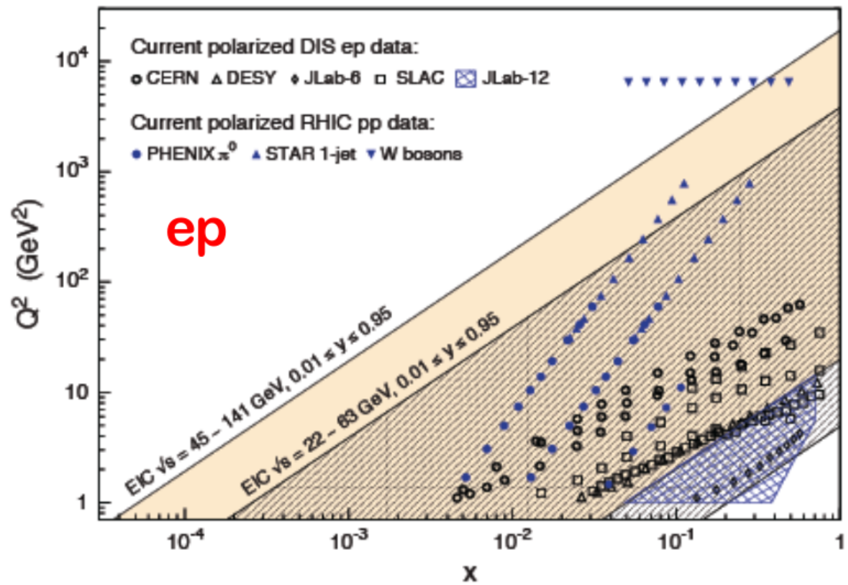
- Measuring g_1^p and doing a comparison with g_1^p from a proton target → test of the model for the FSI in different kinematical regions
- g_1^p, study of EMC effect (high x), shadowing and anti-shadowing effects (low x)
- g_1^n of bound nucleons direct measurement

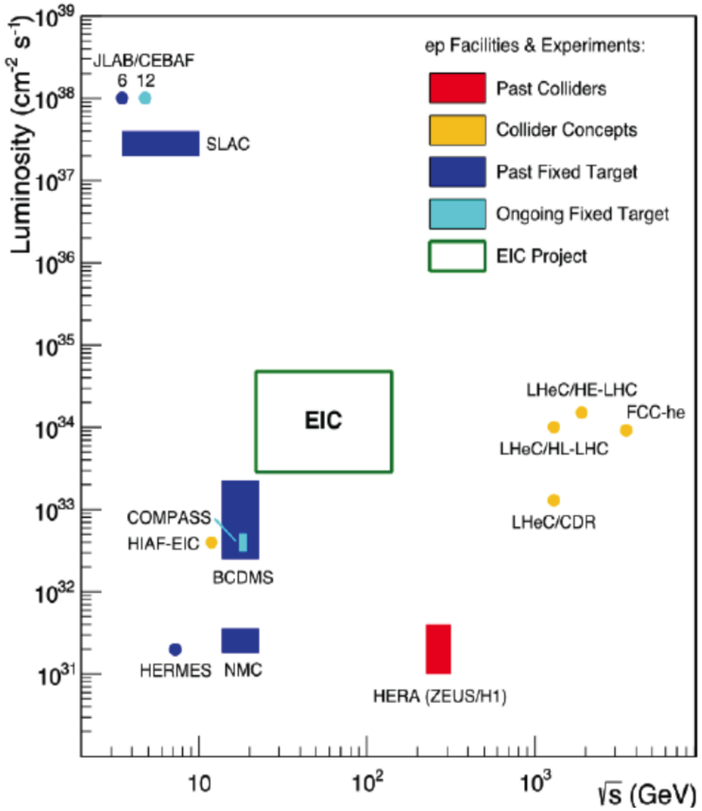


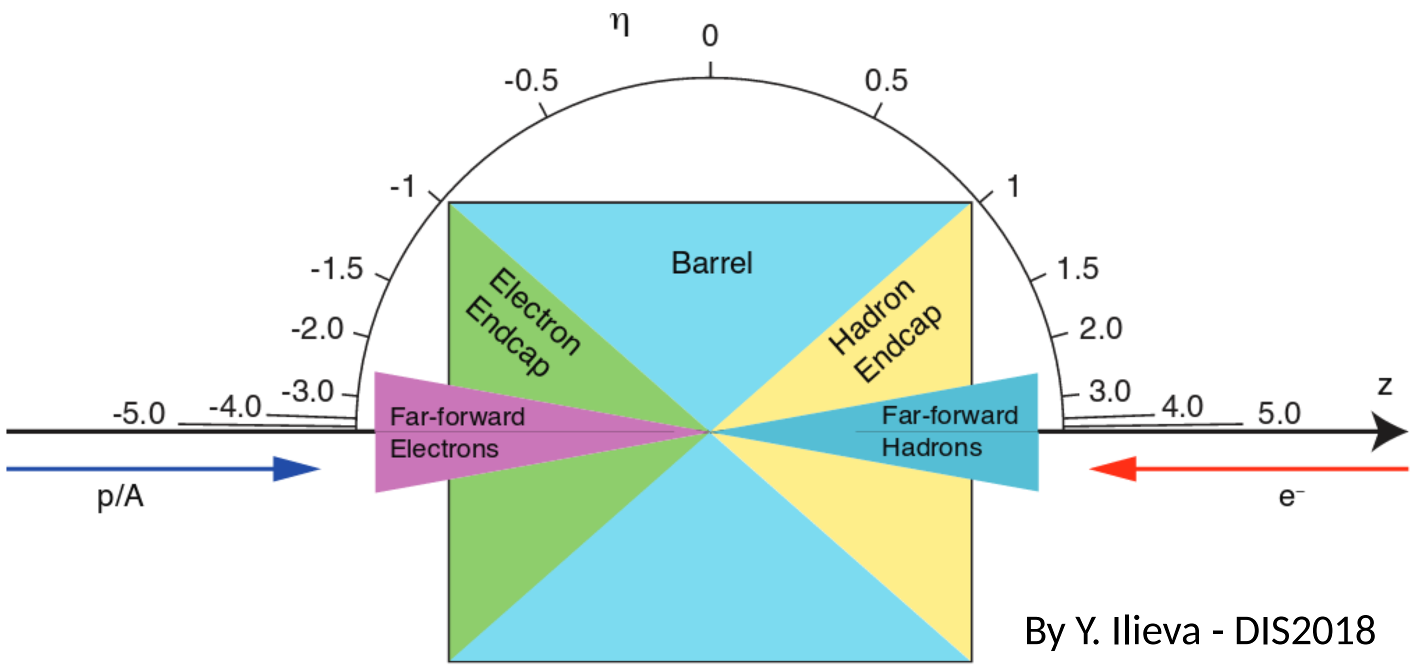


EIC main features for n structure studies

- D, ^{3}He polarized ions
- Luminosity
- Extended x and Q^2 space
- 4 pi hermetic detectors



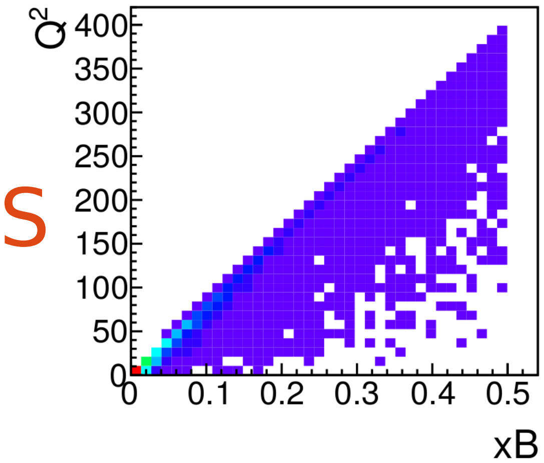


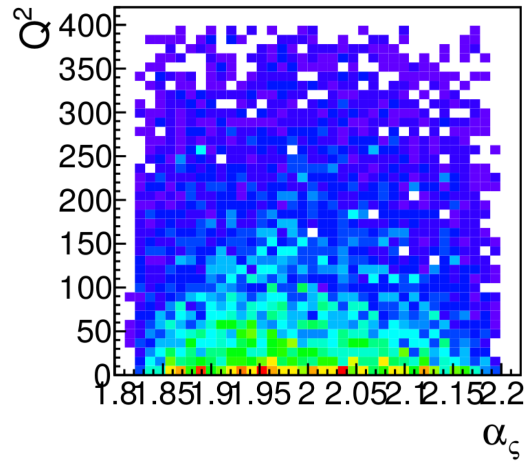


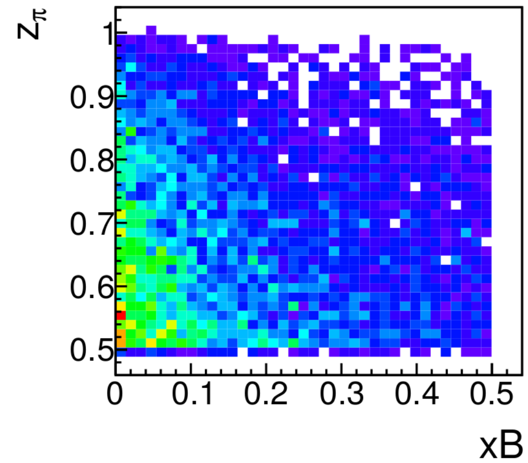
By Y. Ilieva - DIS2018

Electron Ion Collider: Detector Requirements and R&D Handbook (A. Kiselev and Th. Ullrich, Eds.), in preparation

^{3}He spectator SIDiS phase space







e + ^{3}He $\rightarrow$ e' + π + ς + X

t=$(p_{^3He}-p_\varsigma)^2 \rightarrow \approx m_N^2$

ς=D or pp, N=p or n

Beam Momenta:

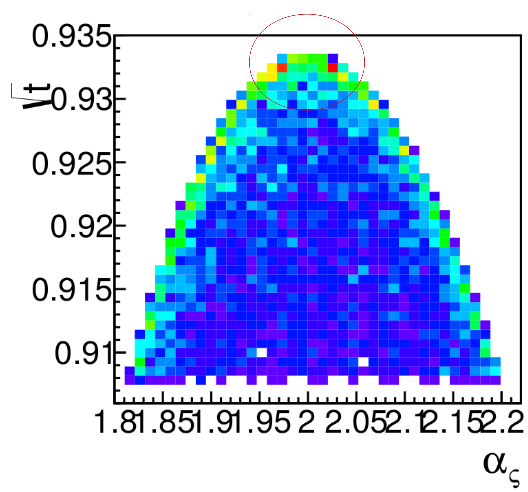
e = 10 GeV (+z)

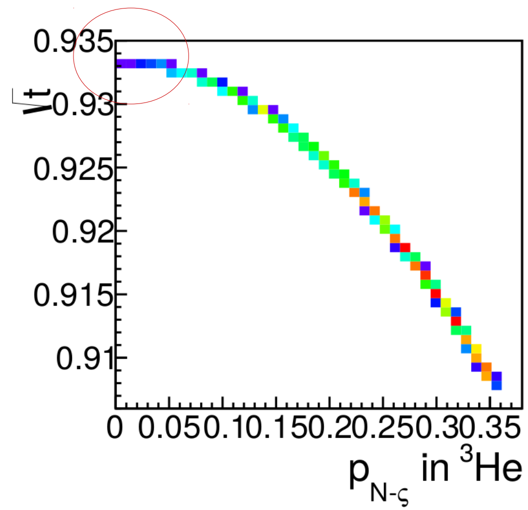
3He = 60 GeV (-z)

DIS: Q2>1

Base Unit is GeV

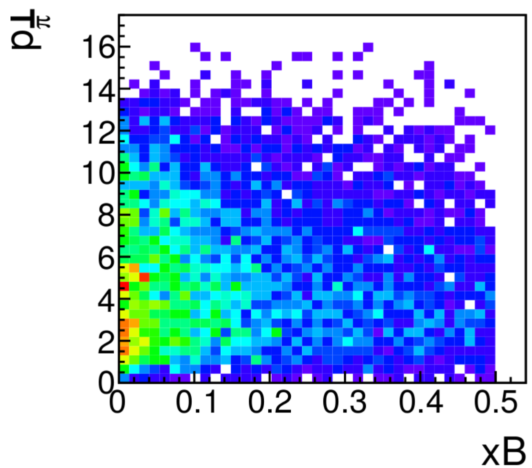
Angles in degrees

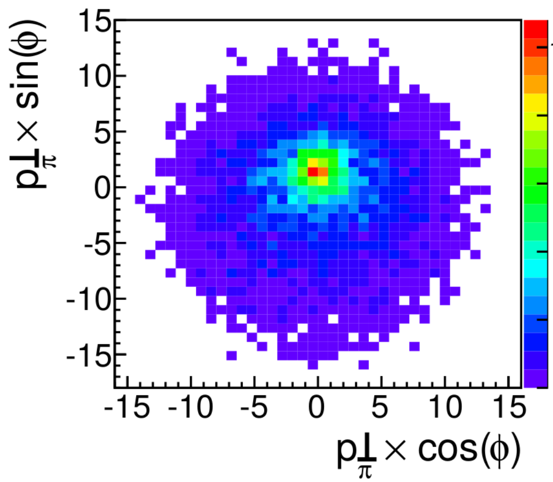


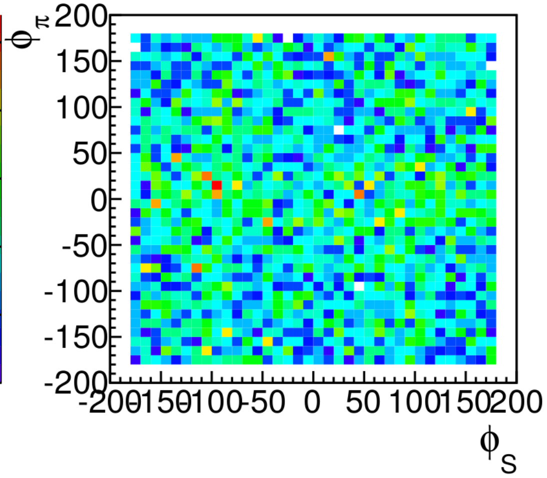


Light-cone momentum fraction of the spectators

$$\alpha_\zeta = \frac{A(p_\zeta \cdot q)}{P_A \cdot q}$$



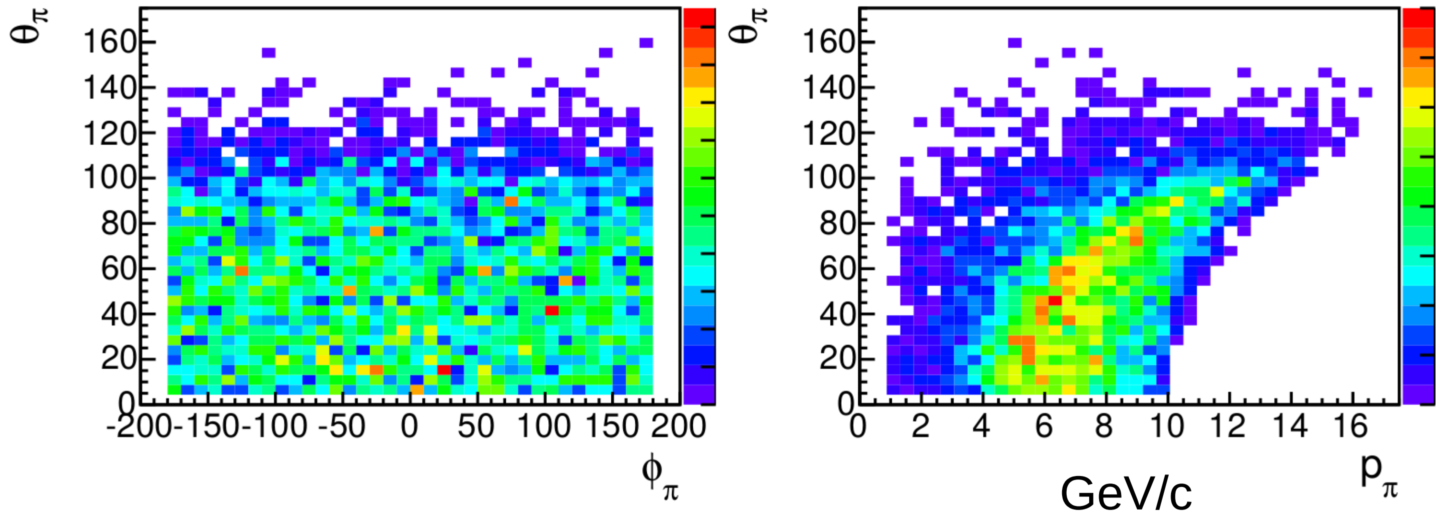




(polarized) spectator (SI)DiS, possible measurements

$$e +^3 He \rightarrow$$

Detected hadron from struck nucleon



spectator DIS

$$e' + \varsigma + X$$

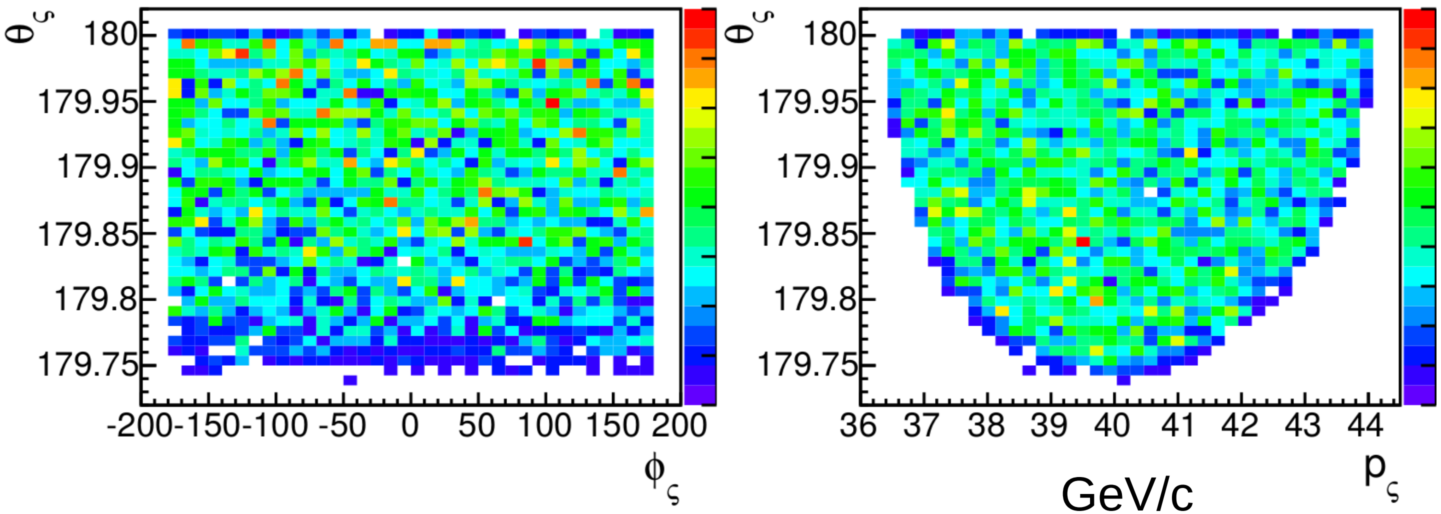
(Semi-)exclusive

$$e' + \varsigma + \pi(\text{or} K\ldots) + X$$

$$\varsigma = \text{D or pp}$$

$$X = \text{undetected}$$

Spectator hadron



$$p_\varsigma \simeq 2/3 p_{^3He}$$

Spectator at small angle!
Far forward ...

D and p (pp) have different rigidity!

Angles in degrees

Concluding remarks

Experimental nucleon (spin) structure functions intrinsically involved with nuclear effects:

- To "clearly" get rid of nuclear effects need to pursue different approaches:
  D …. previous talk
  ^{3}He … not only for "n" but also for ^{3}He itself (e.g. EMC effect …)

- Theoretical approaches are under refinement and extension for FSI and other low x effects (anti-shadowing …)

- To measure (polarized) cross section (other than asymmetries) may open interesting scenario in understanding the nuclear effects (need good luminosity monitor and detector performances)

- Spectator technique (almost exclusive DIS) seems experimentally applicable to ^{3}He as long as the D spectator tagging is too; this may represent a valuable step forward in EIC

- ^{3}He polarimetry is probably not trivial in a collider and need a careful R&D

Hadron Asymmetry for 3He polarimetry ?

- Polarimetry of ^{3}He ion beam is not trivial
- Precise data on An ^{3}He(pi) cou be a potential tool

Phys.Rev C89 042201 (2014)