CLAS12 SIDIS longitudinal target results

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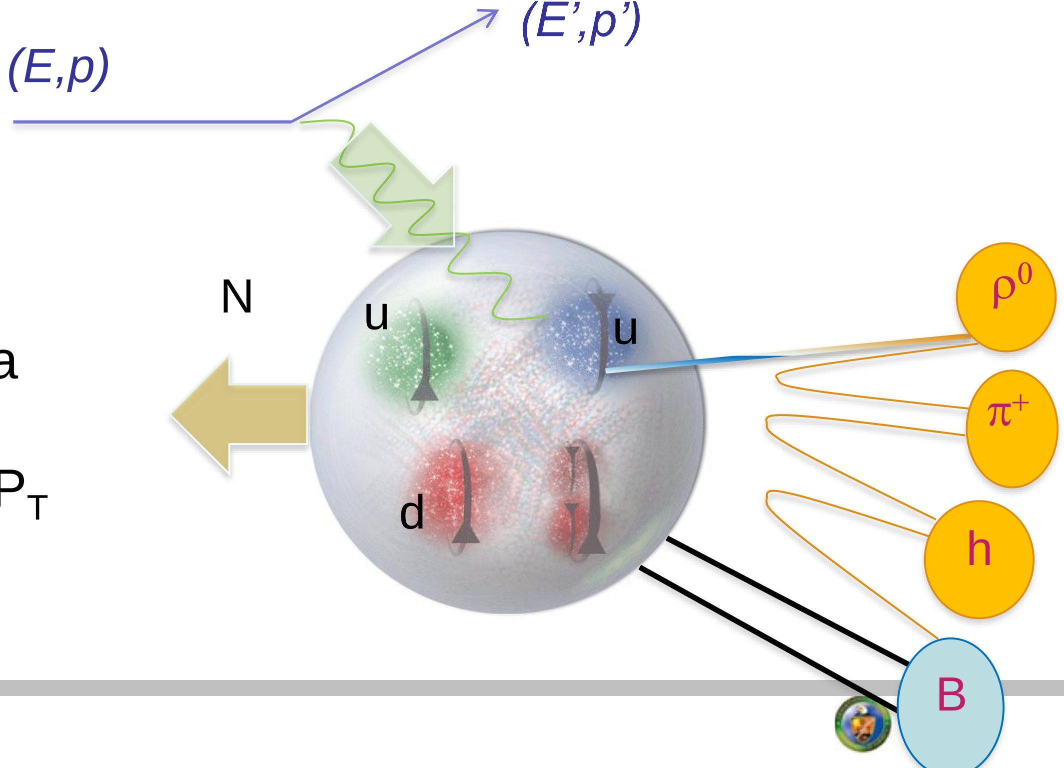


Introduction

– Dilution from nitrogen and carbon runs

– Comparison with proton data

– Comparison with MC

– Double spin asymmetry vs P_T

Summary

Longitudinally polarized target: SIDIS x-sections

Lepton helicity→ "+1" along the beam

Semi-Inclusive:

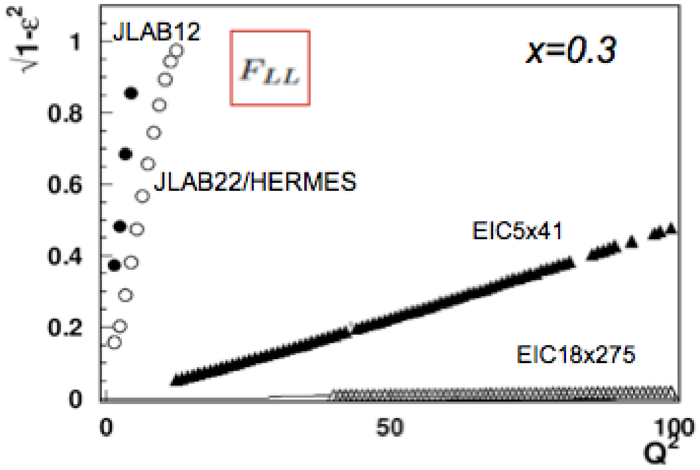
$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

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

Proton helicity→ "+1" opposite to the beam

Depolarization factor D(y)

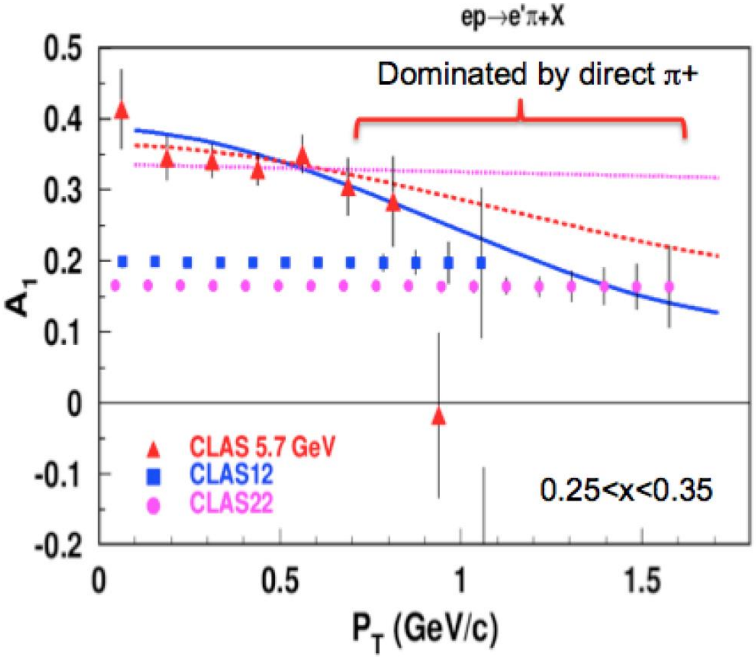
- Formula defined with respect to photon direction (cos θ adds correction)
- $F_{UU,L}$ vs z,P_T practically unknown (dedicated studies proposed for JLab PAC)

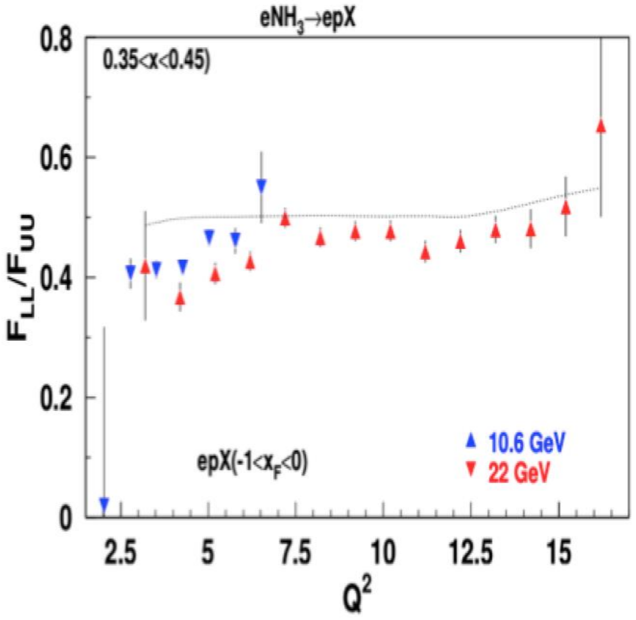


understanding g1(x,k_T)

From JLAB-22 GeV upgrade document (ArXiv:2306.09360)

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 , $h_{1T}^\perp$

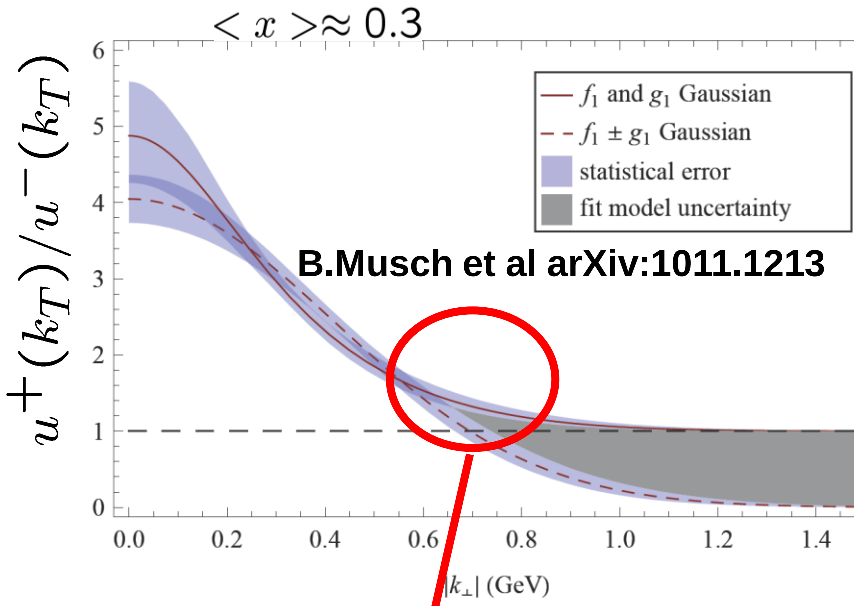




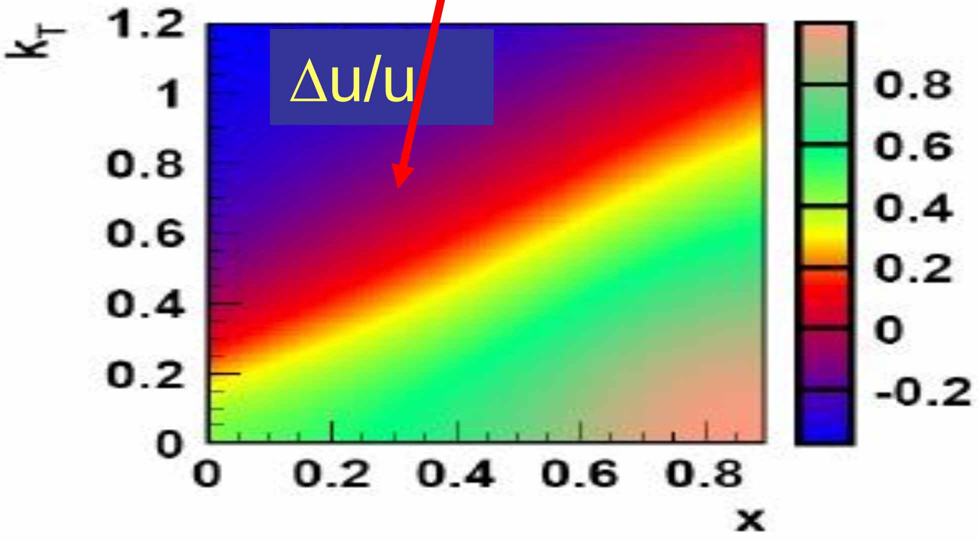
Critical capability to measure the double spin asymmetry in multidimensional bins

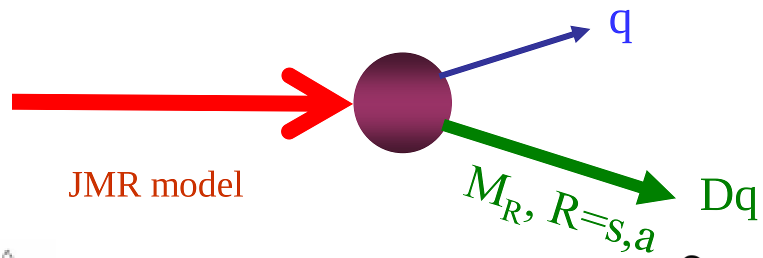
- P_T-dependence → access the k_T-dependence of helicity distributions, $g_1(x,k_T)$
- Q^2-dependence → understand systematics, prove the observable is under control

Quark distributions at large k_T: lattice



B.Musch et al arXiv:1011.1213





JMR model

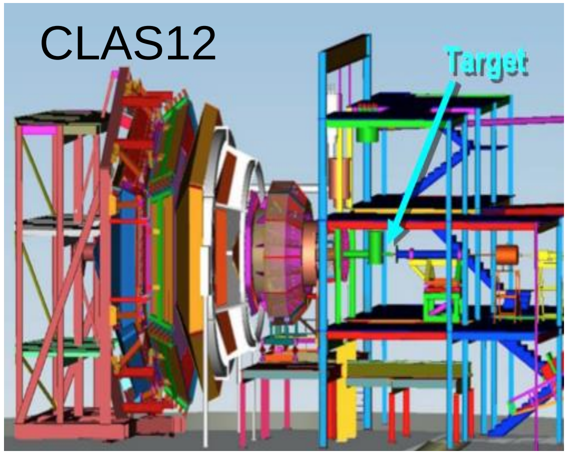
$$u^+(x,\mathbf{k}_T^2) \propto \frac{(xM+m)^2}{(\mathbf{k}_T^2+\lambda_R^2)^{2\alpha}},$$

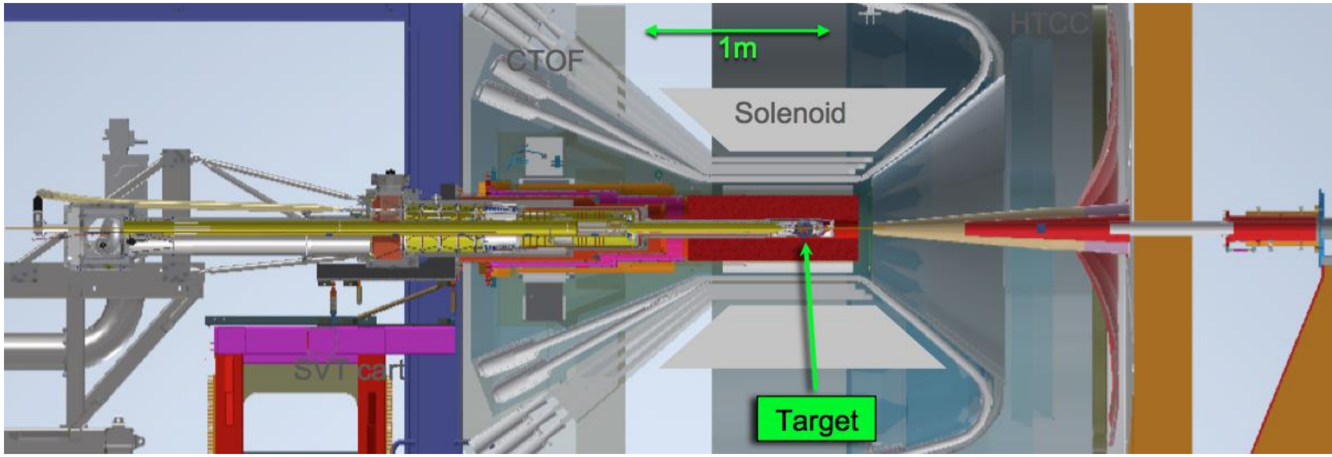
$$u^-(x,\mathbf{k}_T^2) \propto \frac{\boxed{\mathbf{k}_T^2}}{(\mathbf{k}_T^2+\lambda_R^2)^{2\alpha}},$$

Sign change of Δu/u consistent between lattice and diquark model

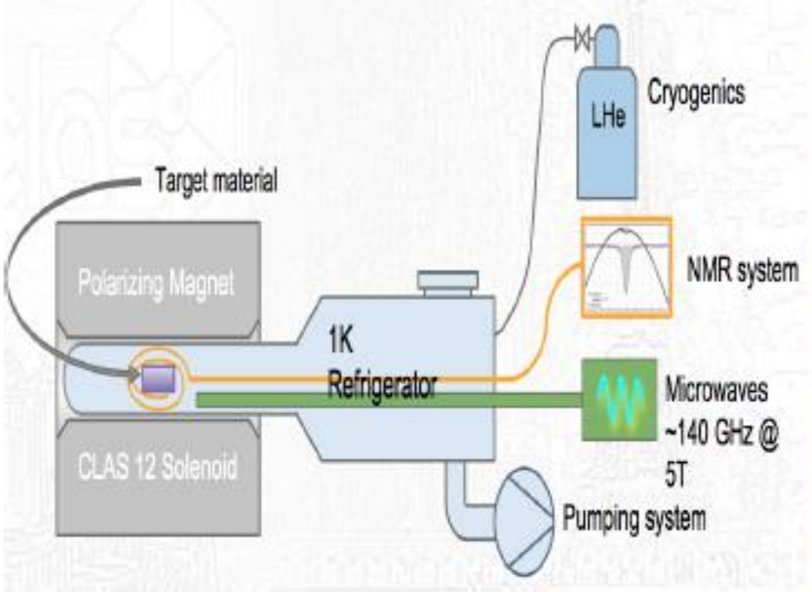
$$\frac{1}{2}(q^+ + q^-) \equiv \quad q(x) \quad \equiv f_1^q$$
$$\frac{1}{2}(q^+ - q^-) \equiv \Delta q(x) \equiv g_1^q$$

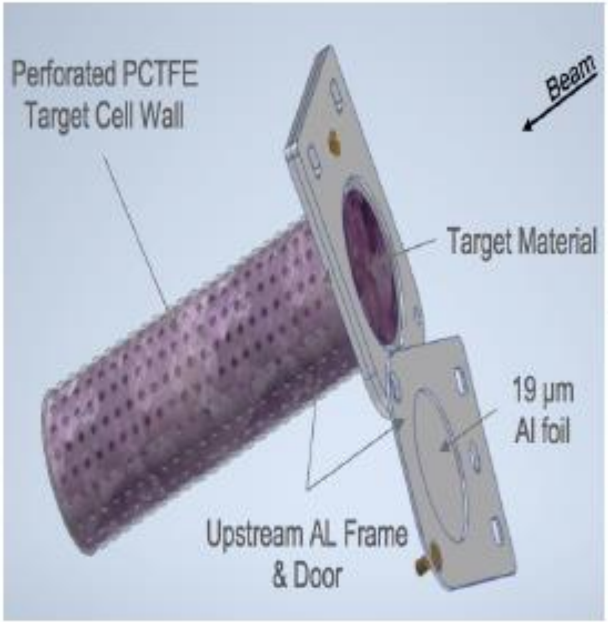
CLAS12 RGC experiment with longitudinally polarized target

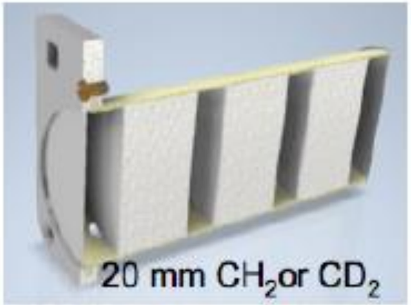


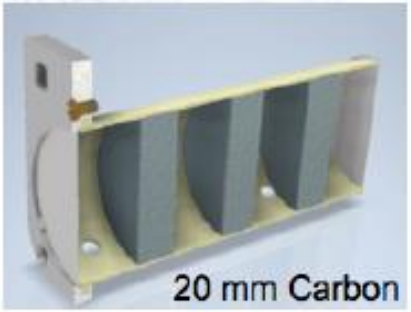


E12-06-109, E12-06-119, E12-07-107, E12-09-009









A Dynamic Nuclear Polarized

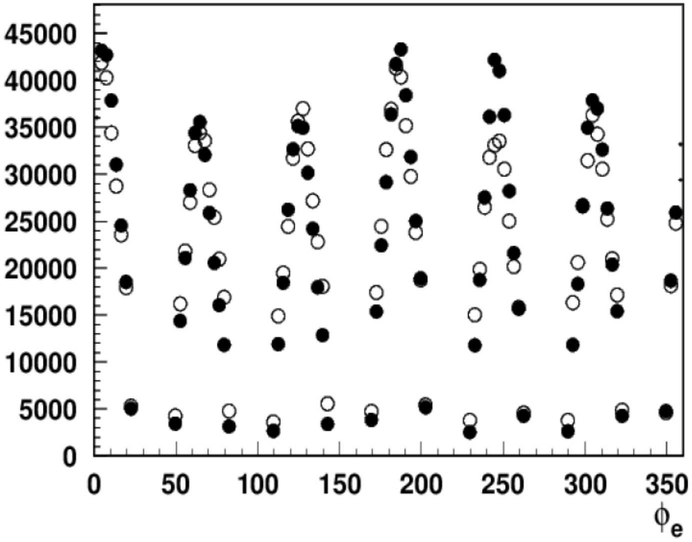
Kinematics

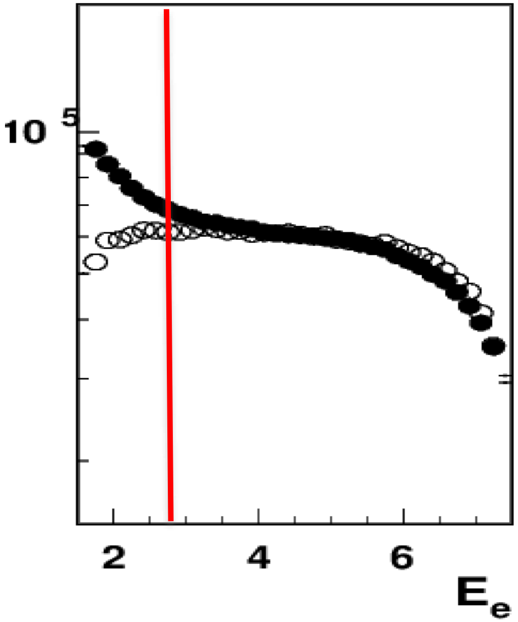
MC files generated with PEPSI generator, reconstructed after GEANT4 simulation

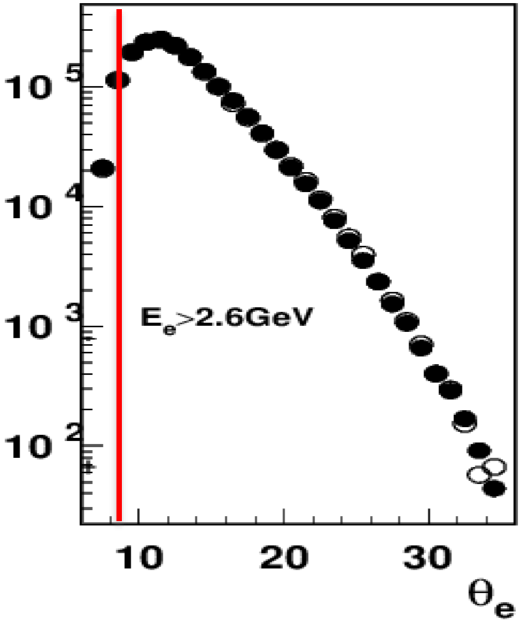
Use preliminary data from RGC experiment

The same cuts applied to MC and data Ee>2.6 (remove photoproduction), 35>θ>8

Remove acceptance edges

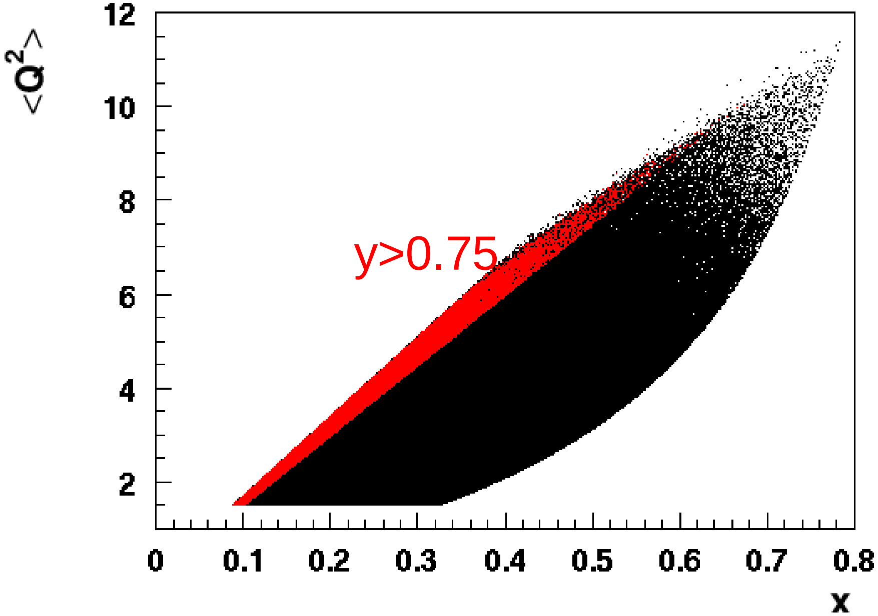


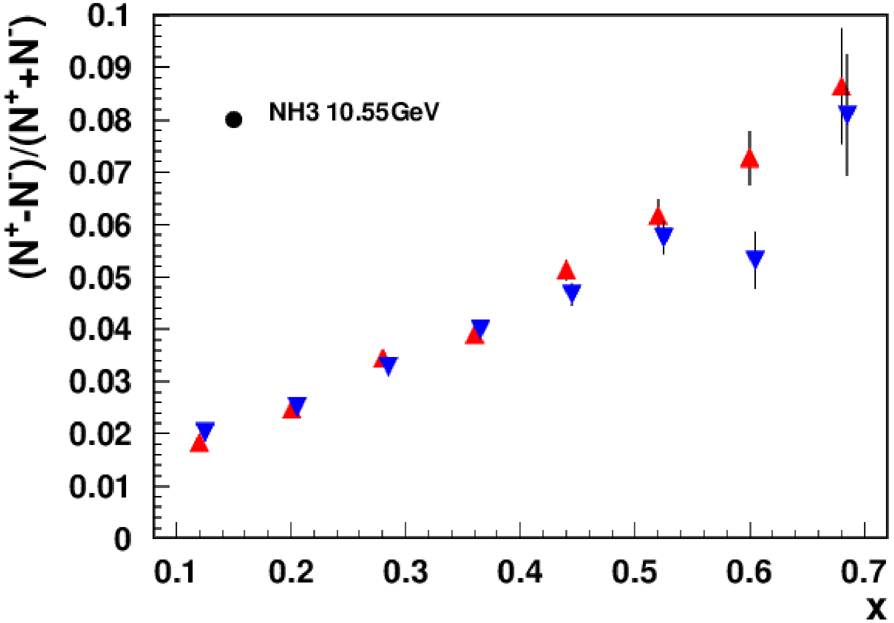


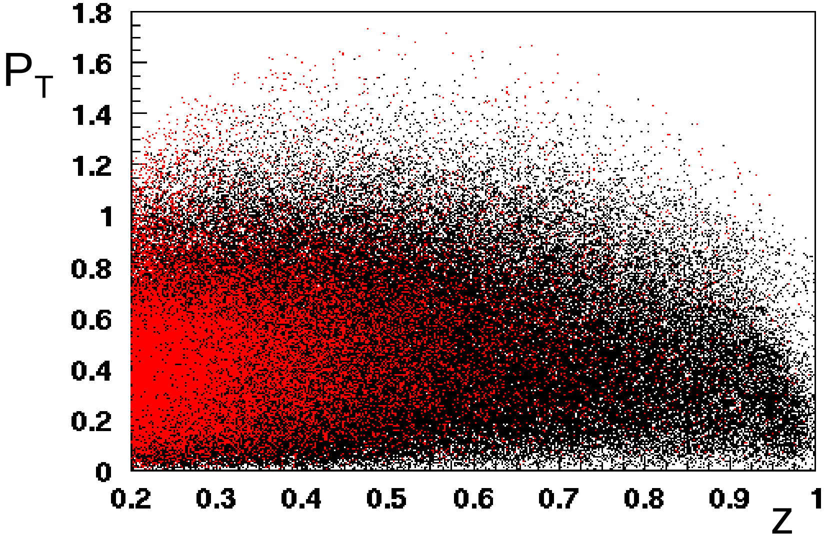


Within fiducial region MC and data are consistent

Double spin asymmetry from RGC NH3







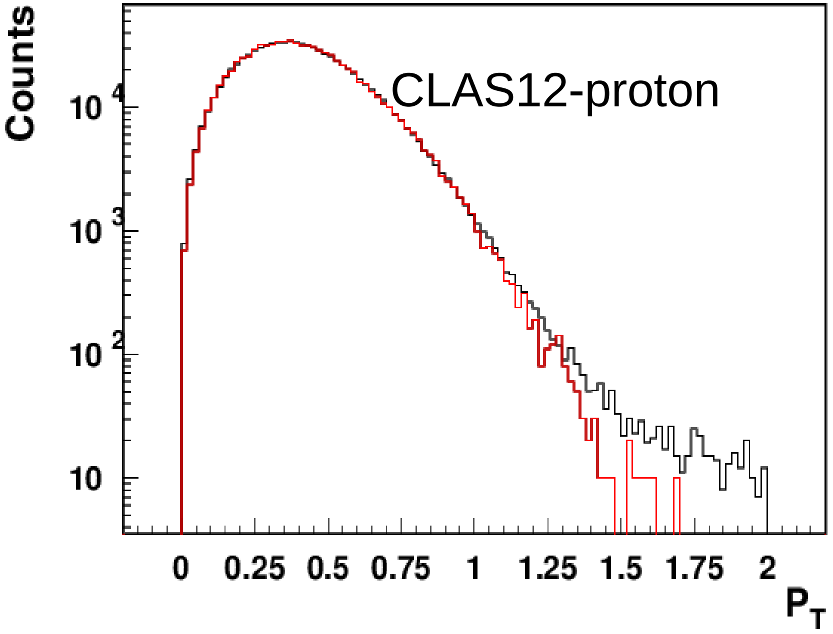
W>2,Q2>1,y<0.75,0.8>z>0.3

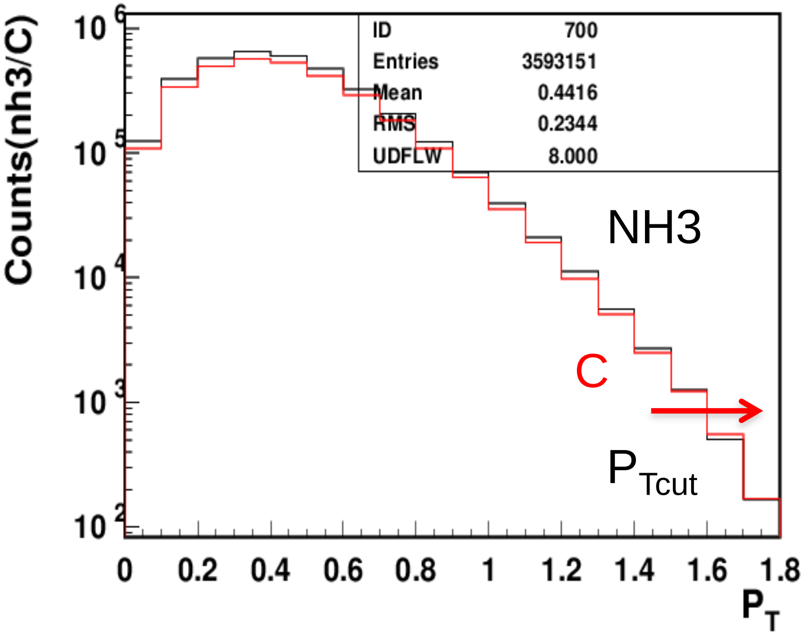
$N^+ \rightarrow \lambda S_{||}=1$

$N^- \rightarrow \lambda S_{||}=-1$

Double spinasymmetry extracted for 2 target polarization states Strong Negative pol→red, positive→blue So far <10% of data, calibrations in progress.

Extracting the proton from NH_3

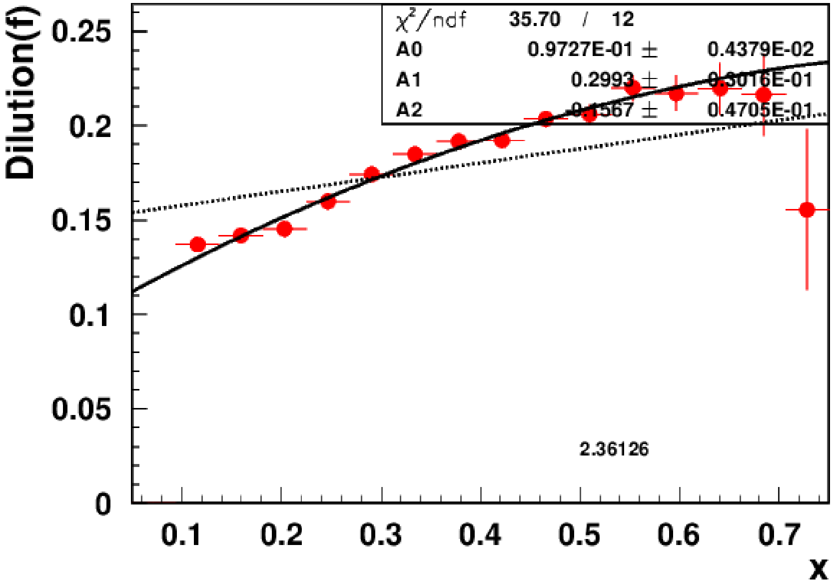




- Nuclear background can be different for different processes
- P_T above 1.5 are mainly from nuclear background, and can be used to normalize the nuclear part to get polarized protons→ NH_3-N

Procedure for normalization: move cut in P_T and normalize NH3 and C counts

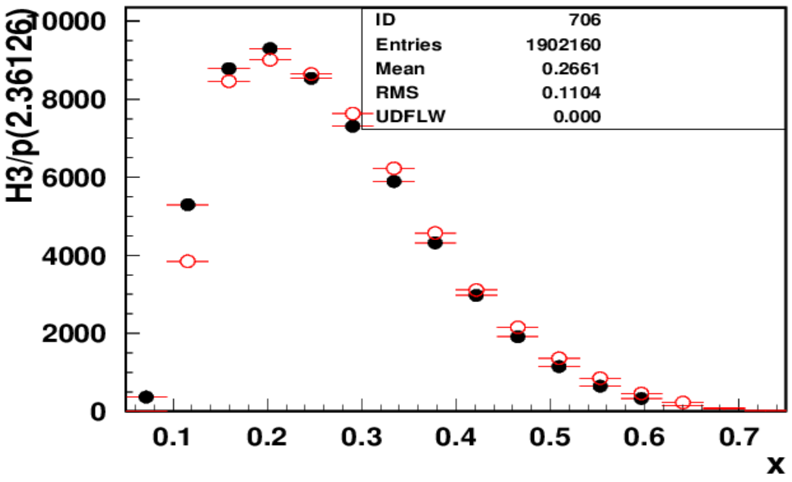
DSA from NH3: understanding dilution

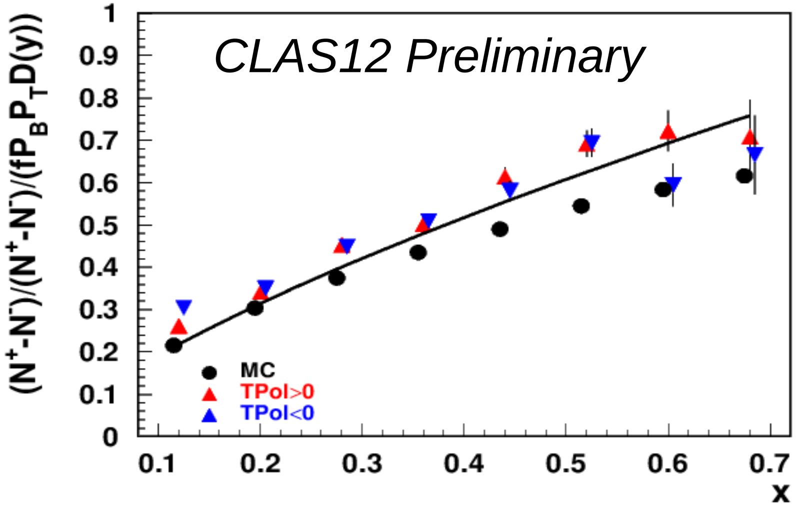


Asymmetry may scaled up/down additional 10%, with variation of polarization and dilution product

Beam pol 82%
Negative pol(blue). 70-77%
positive polarization(red) 82-90%

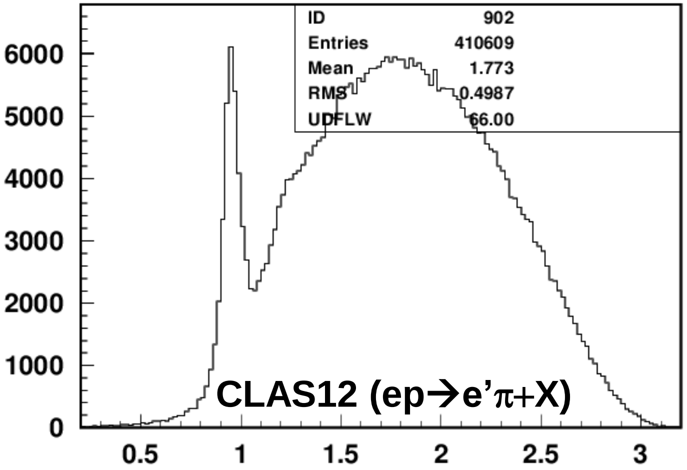
Scale uncertainty ~10% from f*D(y)*Tpol

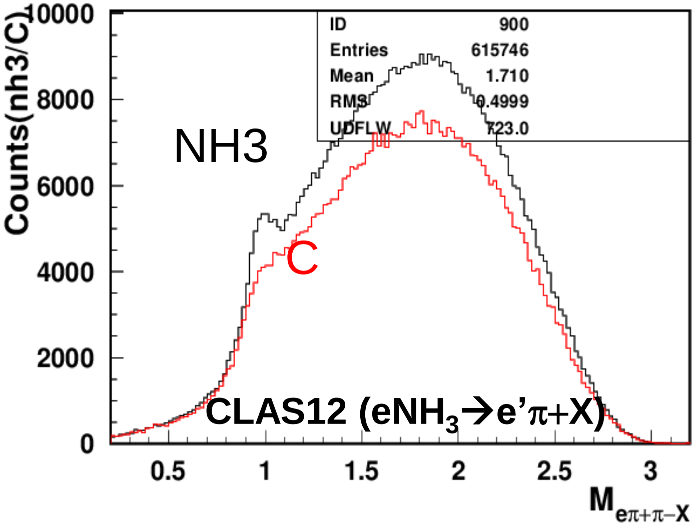


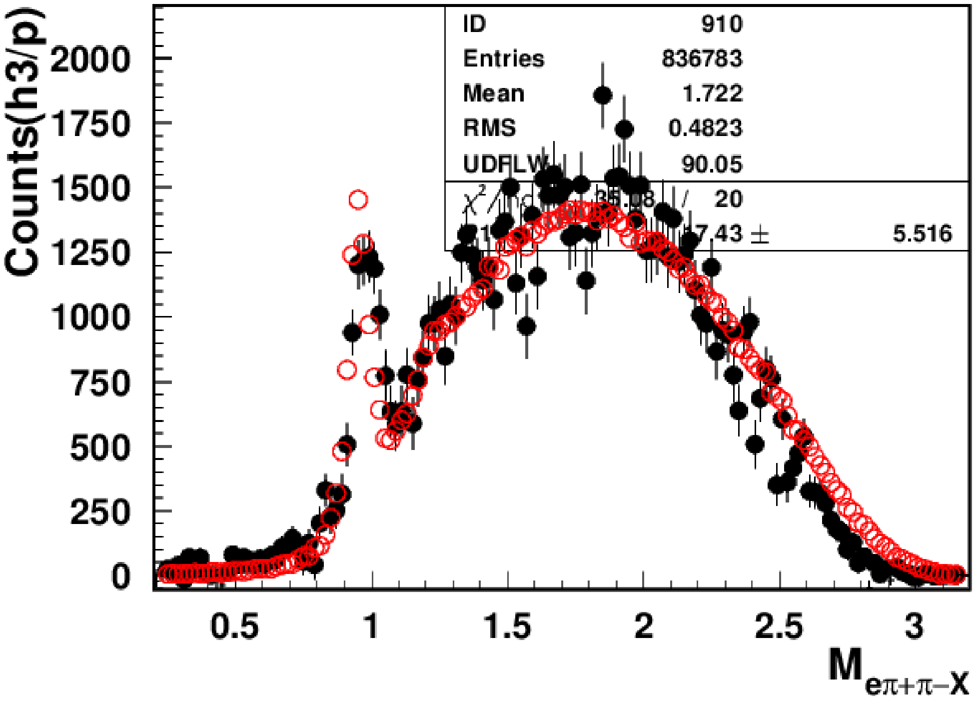


average kinematics identical in data/mc (black circles)

NH3-C vs proton in RGA



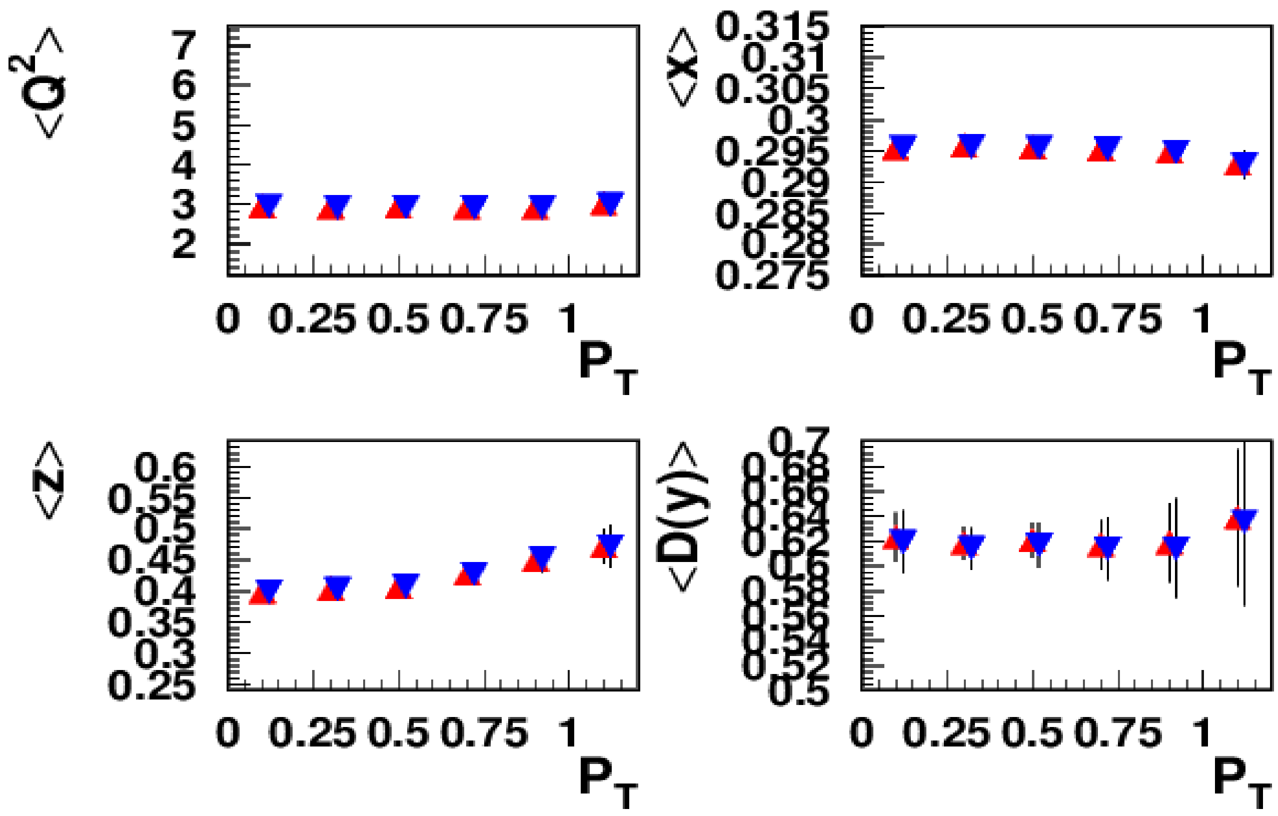




After subtraction hydrogen from NH_3 and p (CLAS12 RGA) look similar (with some shifts, also slightly better resolutions in RGA)

A_1 P_T-dependence

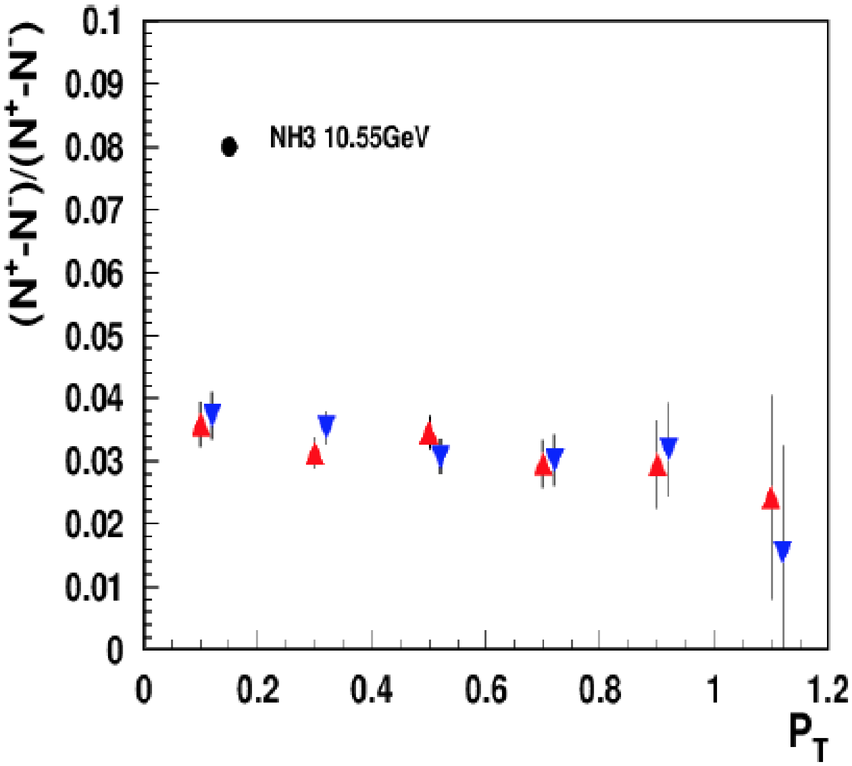
0.25<x<0.35

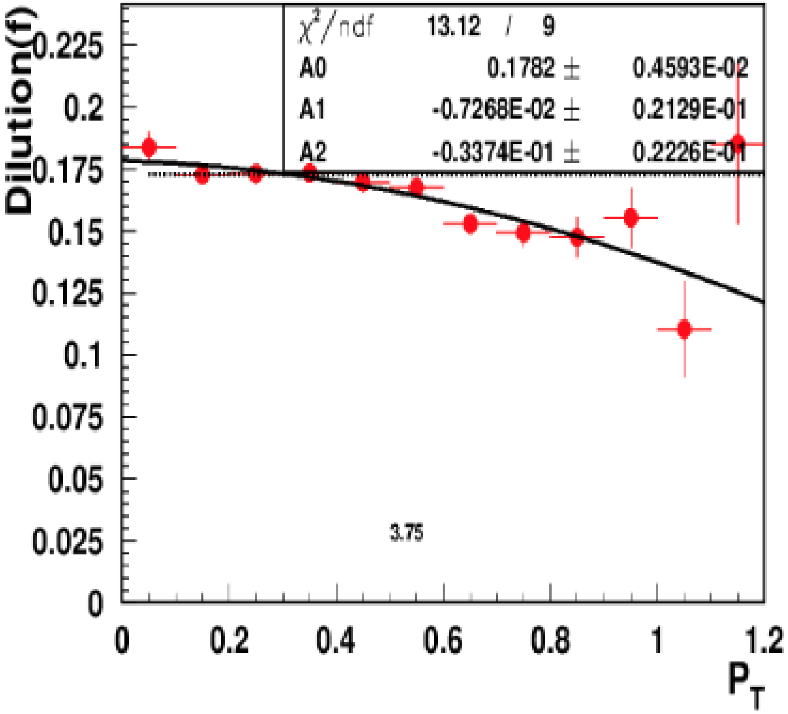


Small bins in x needed to minimize the correlations from kinematics

A_1 P_T-dependence

0.25<x<0.35, 0.2<z<0.8 (MX>1.5)

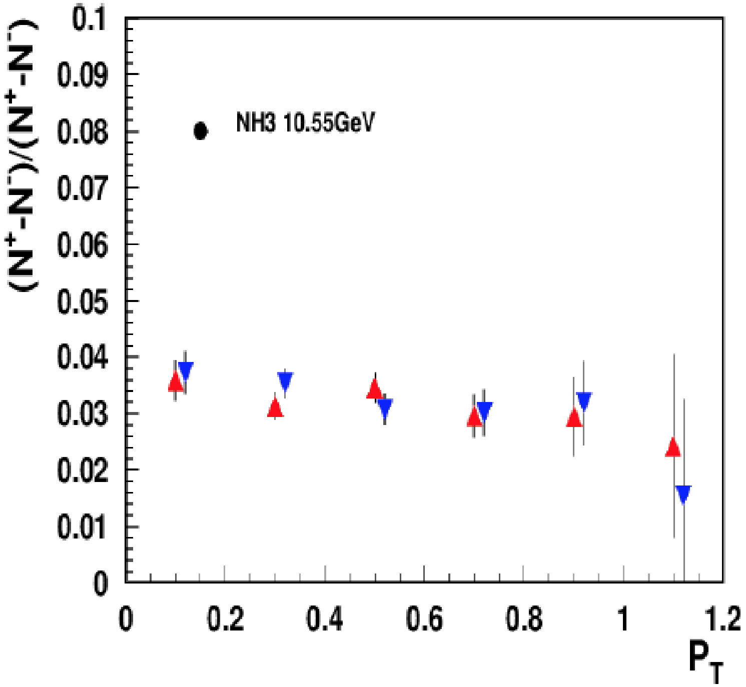


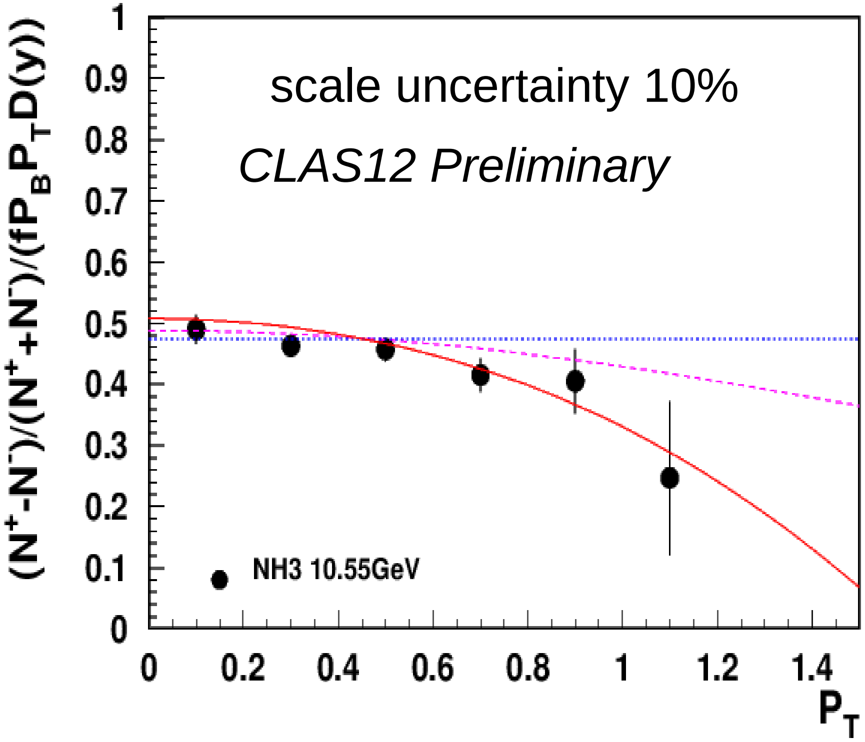


Apply dilution factor to get the DSA on the polarized hydrogen

A_1 P_T-dependence

0.25<x<0.35, 0.2<z<0.8 (MX>1.5)





With more statistics can

- check with finer bins in P_T,
- extract the the same for dihadron sample

- Red curve predictions from Lattice accounting different widths in $g_1(x,k_T)$ and $f_1(x,k_T)$

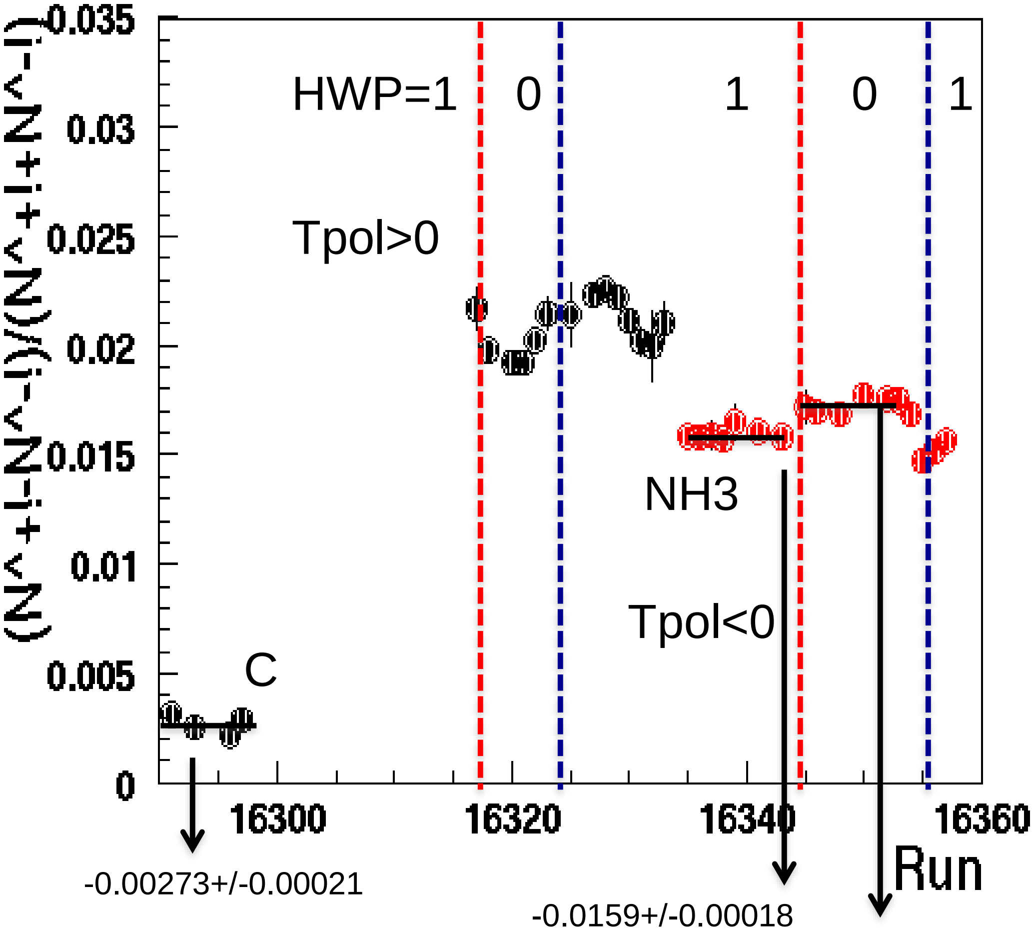
SUMMARY

- The P_T-dependence of A_1 is studied using the CLAS12 Run group C (RGC) polarized NH3 data
- Dilution factor extracted with normalization of N/C at large P_T, with negligible counts from hydrogen (minor dependence on the P_{Tcut})
- x-dependence of A_1 consistent with world SIDIS data
- Preliminary extraction of A_1 vs P_T demonstrates the study is feasible, indicate some reduction of A_1 at large P_T (possible factors include: increasing $F_{UU,L}$,VM contributions at small P_T, nuclear effects,…)

- TODO list:
- finalize the value and systematics of the product *f**D(y)*Tpol
- development of the nuclear MC for multidimensional description of *f*

Support slides….

Double spin asymmetry from RGC NH_3



-0.00273+/-0.00021

-0.0159+/-0.00018

-0.0173+/-0.00015

More positive lepton helicity $\lambda=1$ for HWP=1

With Tpol>0 the proton helicity $\Lambda=-1$ $A_1 \sim \Lambda\lambda$

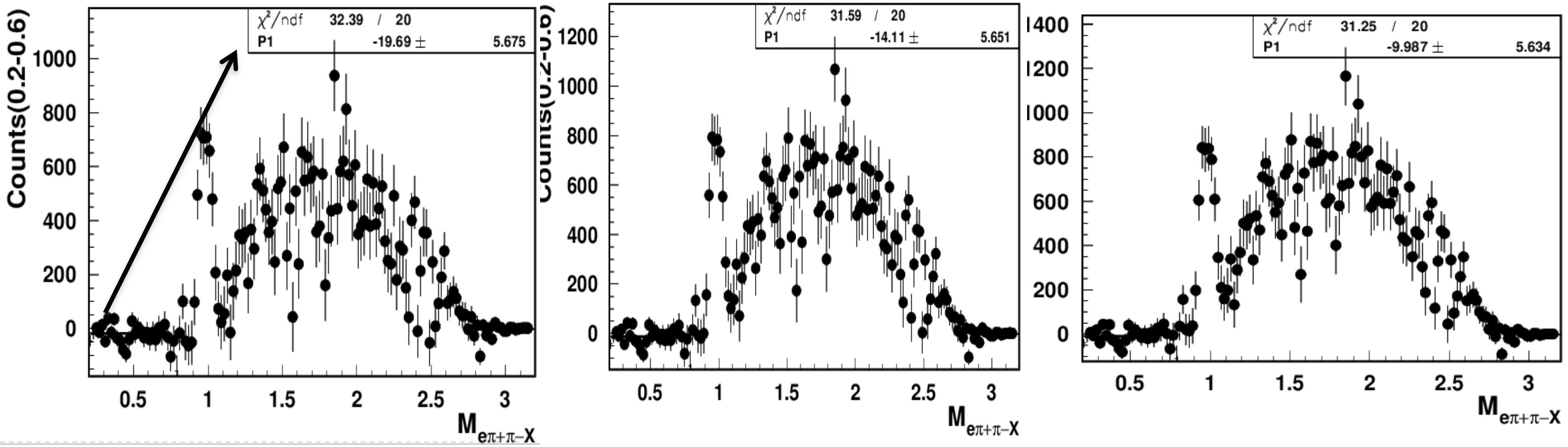
HWP changes visible in DSA charge asymmetry (always positive) to large extent should cancel out in sum

Later on was monitored to stay at much lower levels

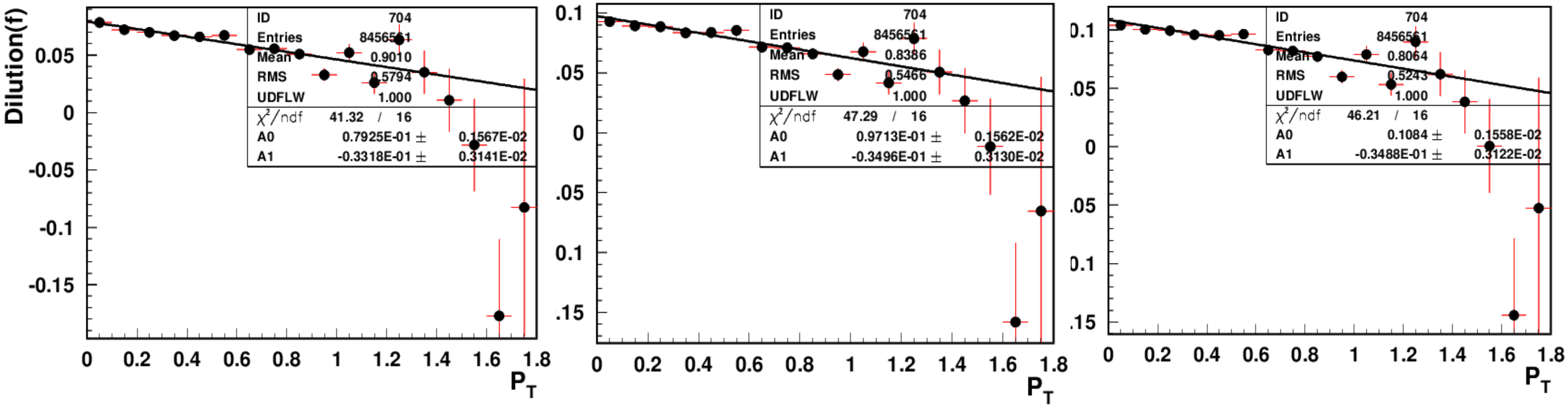
$N^+ \rightarrow \lambda S_{||}=1$

$N^- \rightarrow \lambda S_{||}=-1$

Dilution factor: moving P_T cut

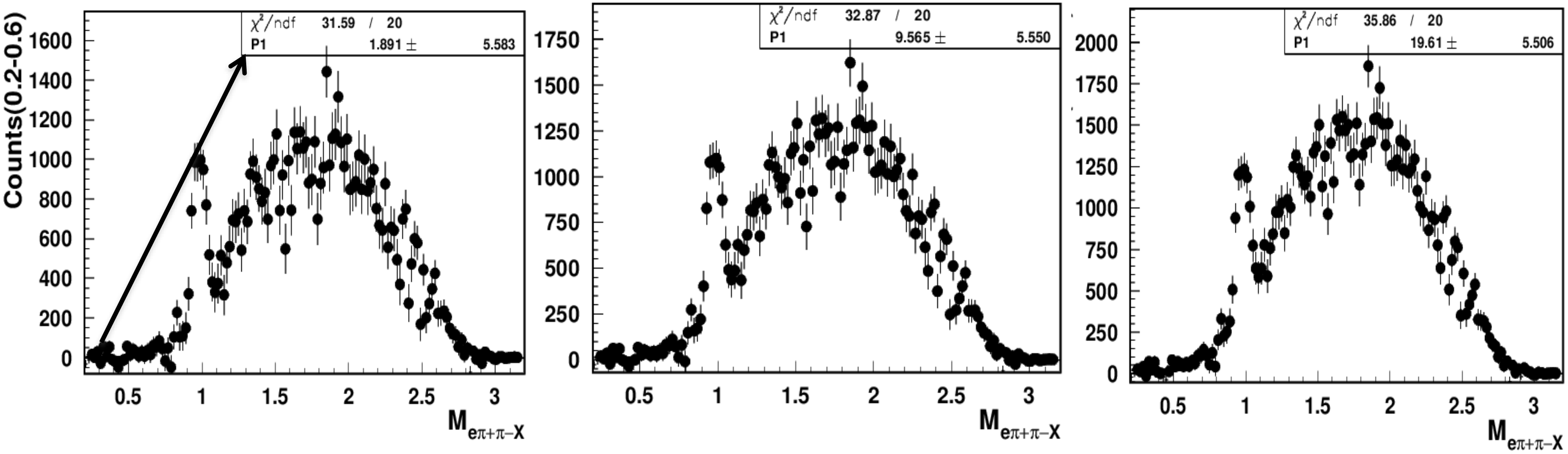


Increase P_T, fit the M_X in the range (0.2:0.6), where no hydrogen counts expected



gradient stays roughly the same, while the value depends on the carbon subtraction

Dilution factor



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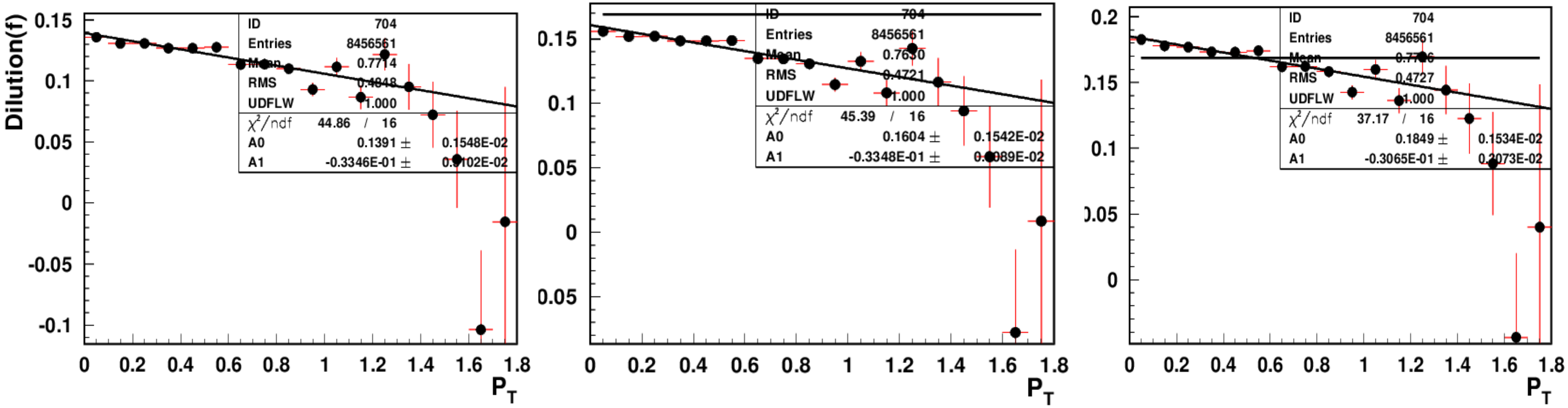

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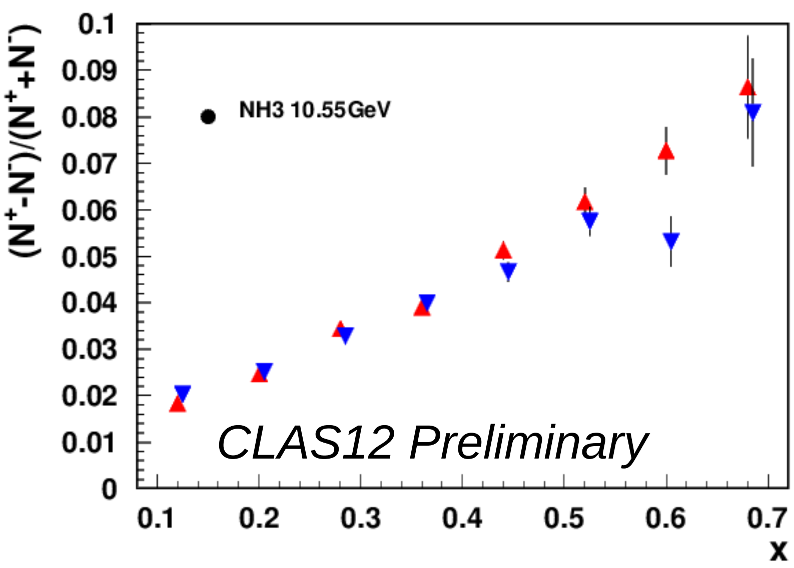
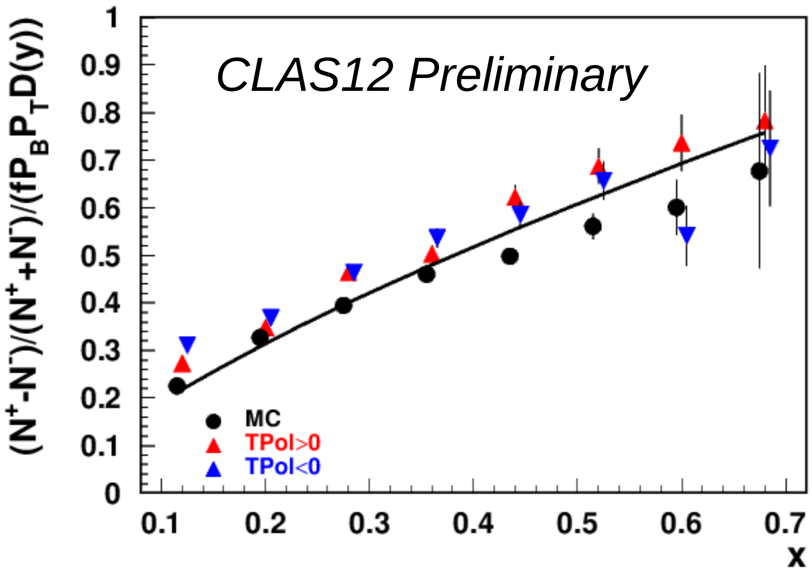
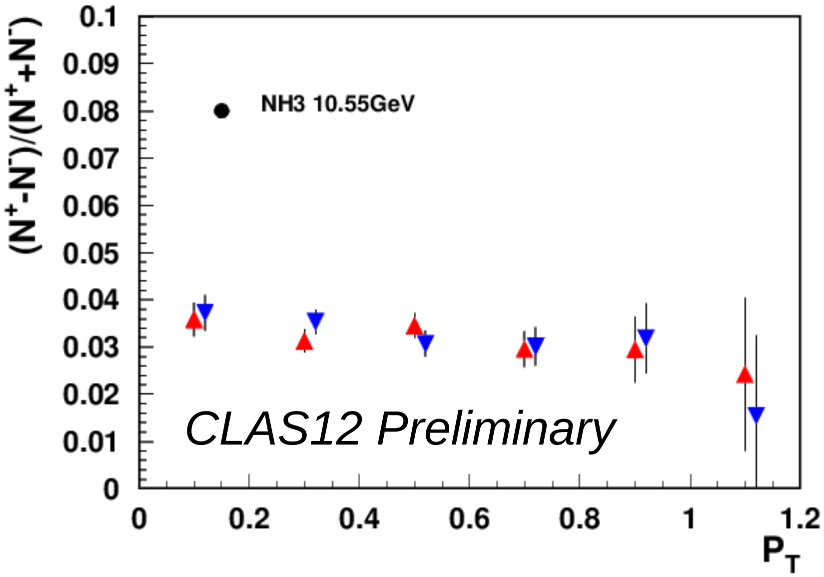
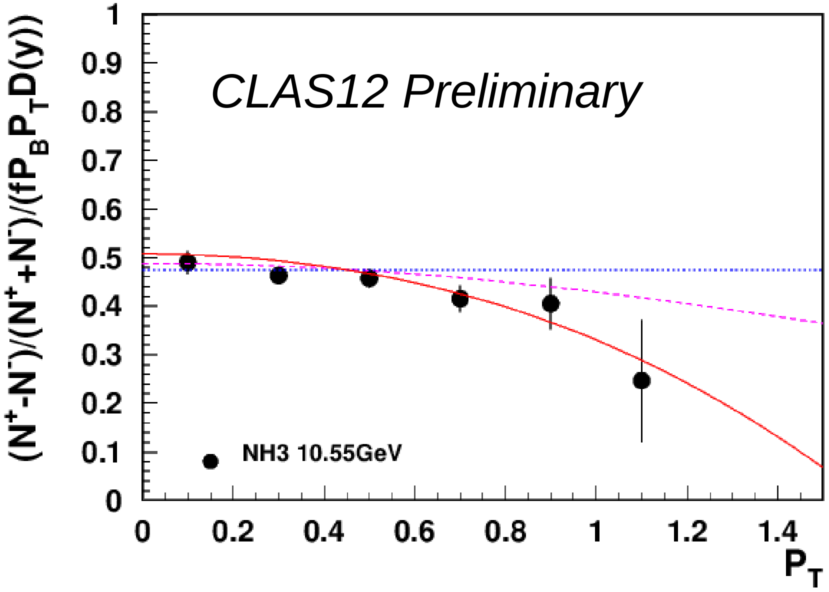
Double spin asymmetry: final plots

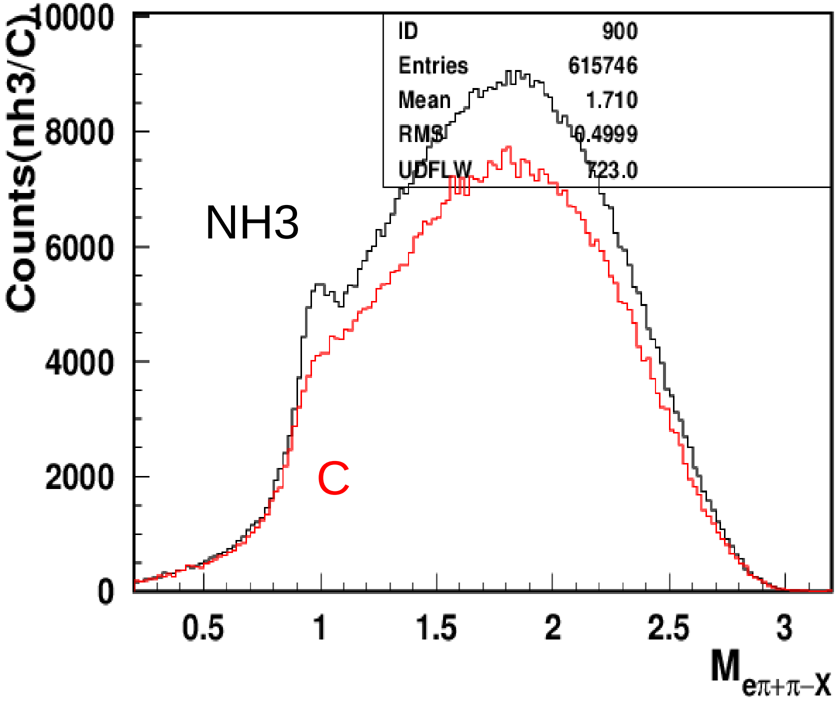


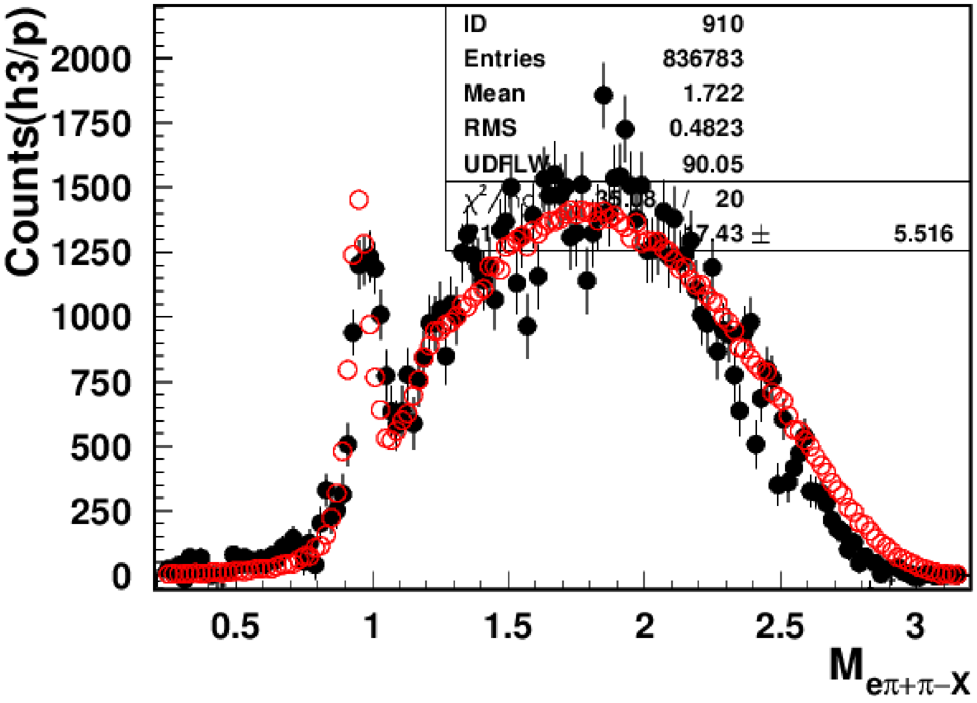




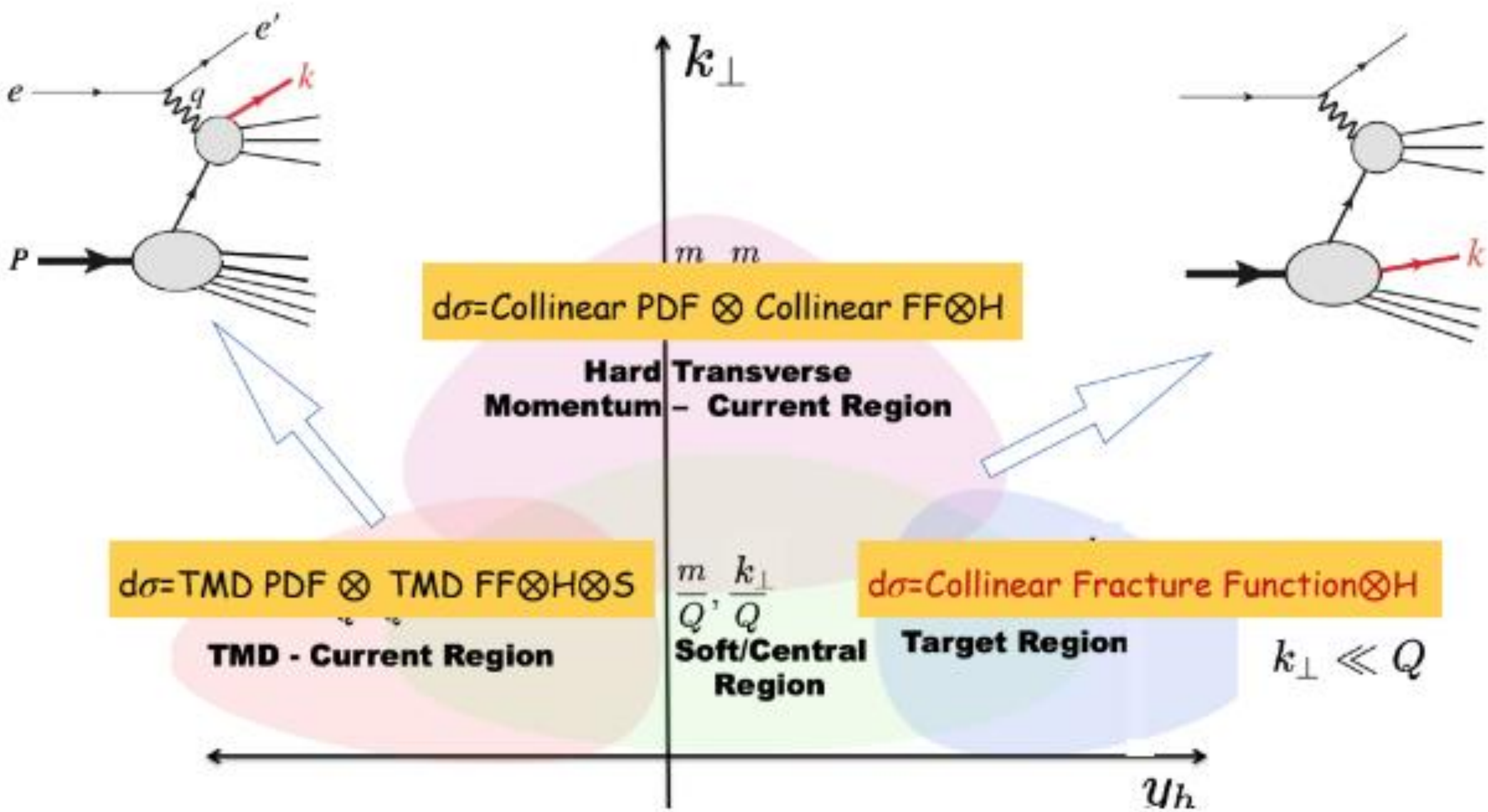


NH3-C vs proton in RGA





After subtraction hydrogen from NH3 and p from RGA look similar (with some shifts, also slightly better resolutions in RGA)



dσ=Collinear PDF ⊗ Collinear FF⊗H

dσ=TMD PDF ⊗ TMD FF⊗H⊗S

dσ=Collinear Fracture Function⊗H

[Figure from M. Boglione *et al JHEP* 10 (2019) 122]

Sensitivity of d-quark structure to ^{3}He: Simulation

Statistics for 30 days
Bin:
$< x >= 0.425$
$< Q^2 >= 5.0$
$< z >= 0.44.$

$$f_1^{q/N}(x,k_T) = f_1^{q/N}(x)\,\frac{e^{-k_T^2/\langle k_T^2\rangle_q}}{\pi\langle k_T^2\rangle_q},$$

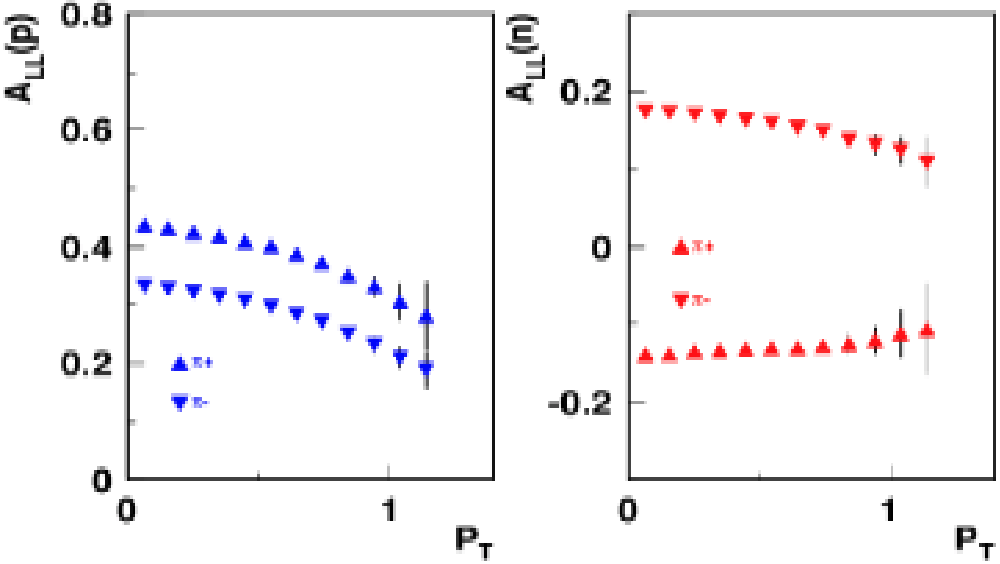
$$g_1^{q/N}(x,k_T) = g_1^{q/N}(x)\,\frac{e^{-k_T^2/\langle k_T^2\rangle_{\Delta q}}}{\pi\langle k_T^2\rangle_{\Delta q}},$$

$$F_{LL}^N = x\sum_q e_q^2 g_1^q(x,Q^2) D^q(z,Q^2)\ P_{\Delta q}$$

Using:
LO GRV for PDF x,Q^2

LO DSS for $D_1(z,Q^2)$
$<p_T^2>=0.16$
$< k_T^2>$u/d=0.25

$< k_T^2>\Delta u=0.22$
$< k_T^2>\Delta d=0.22$



Note: for proton $\pi+$ (triangle up) $\pi-$ (triangle down) A_LLs have the same sign for proton and opposite signs for neutron

Sensitivity of d-quark structure to ^{3}He

Assuming LO parton model, k_T distributions are Gaussian, in the valence region, and known widths for unpolarized distributions known, the double spin asymmetries vs k_T-widths of Δu and Δd depend on a linear combination of π+ and π- A_{LL}-asymmetries.

$$P_{\Delta d} = -\frac{e^{\frac{P_T^2}{\langle k_T^2\rangle_{\Delta d} z^2 + \langle p_T^2\rangle}}}{\pi(\langle k_T^2\rangle_{\Delta d} z^2 + \langle p_T^2\rangle)}$$

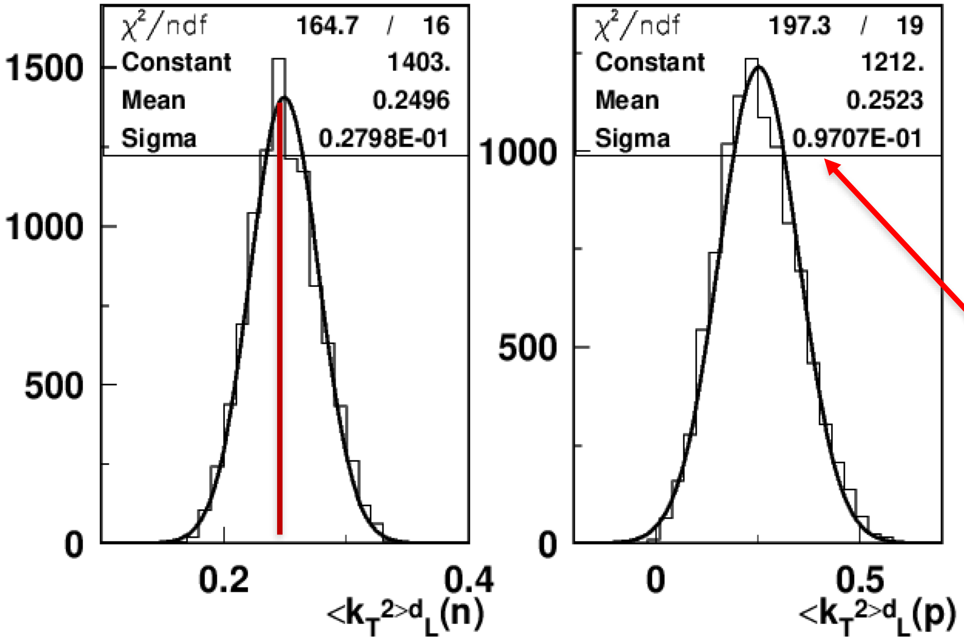
$$P_{\Delta u} = -\frac{e^{\frac{P_T^2}{\langle k_T^2\rangle_{\Delta u} z^2 + \langle p_T^2\rangle}}}{\pi(\langle k_T^2\rangle_{\Delta u} z^2 + \langle p_T^2\rangle)}$$

$$P_{\Delta u} = \theta A_{LL,n}^{\pi+} + \epsilon A_{LL,n}^{\pi-}$$

$$P_{\Delta d} = \mu A_{LL,n}^{\pi+} + \nu A_{LL,n}^{\pi-}$$

Uncertainties accounted:

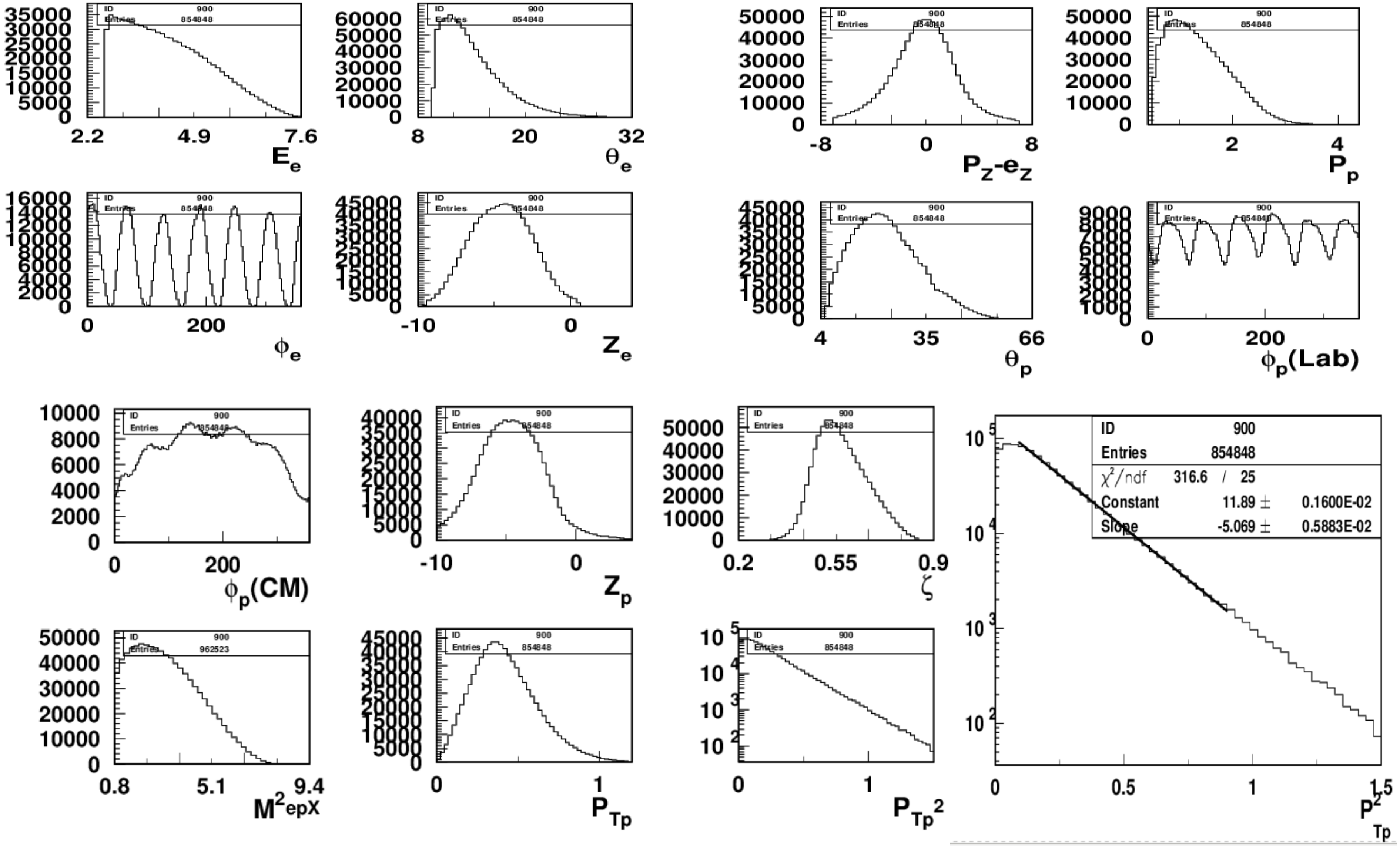
- unpolarized widths for u and d known within 20%
- Δd/Δu at large x known within 20%



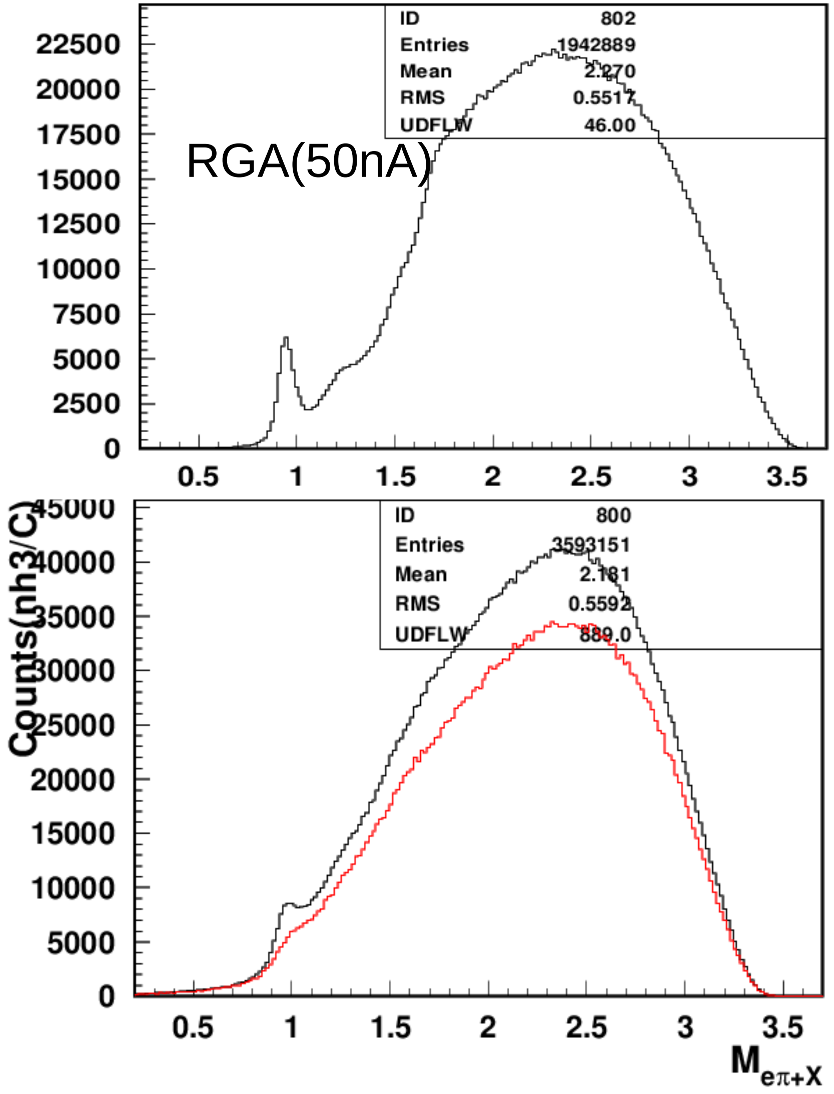
The k_T-dependent width of polarized d-quarks has significantly smaller uncertainty from neutron data due to order of magnitude large and canceling contributions in proton

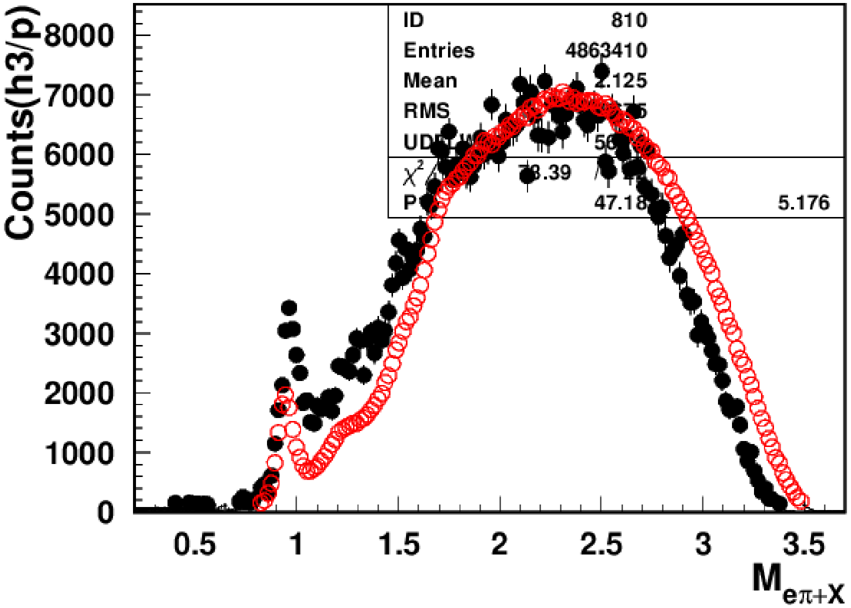
(input widths Δu→0.22, Δ→0.25
u→0.3, d→0.33)

Target SSA in ep→e’ pπ+X (RGC)



NH3-C vs proton in RGA





Agreement worse for single pions

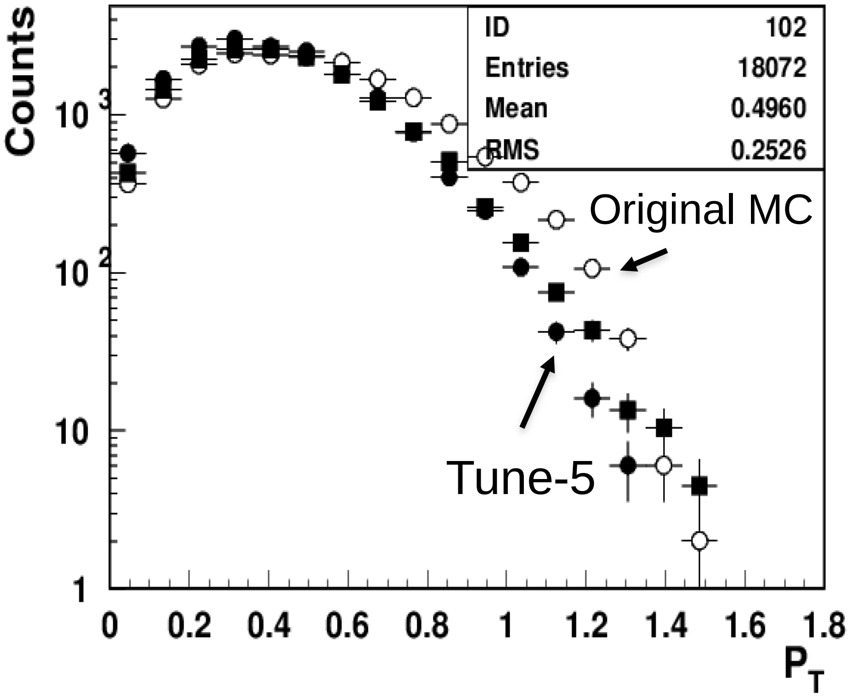
After subtraction hydrogen from NH3 and p from RGA look similar (with some bigger shifts, also slightly better resolutions in RGA)
To be checked for cuts

Adding nuclear background

- Comparing nuclear MC (A. Alaoui/L. El Fassi) with RGC carbon

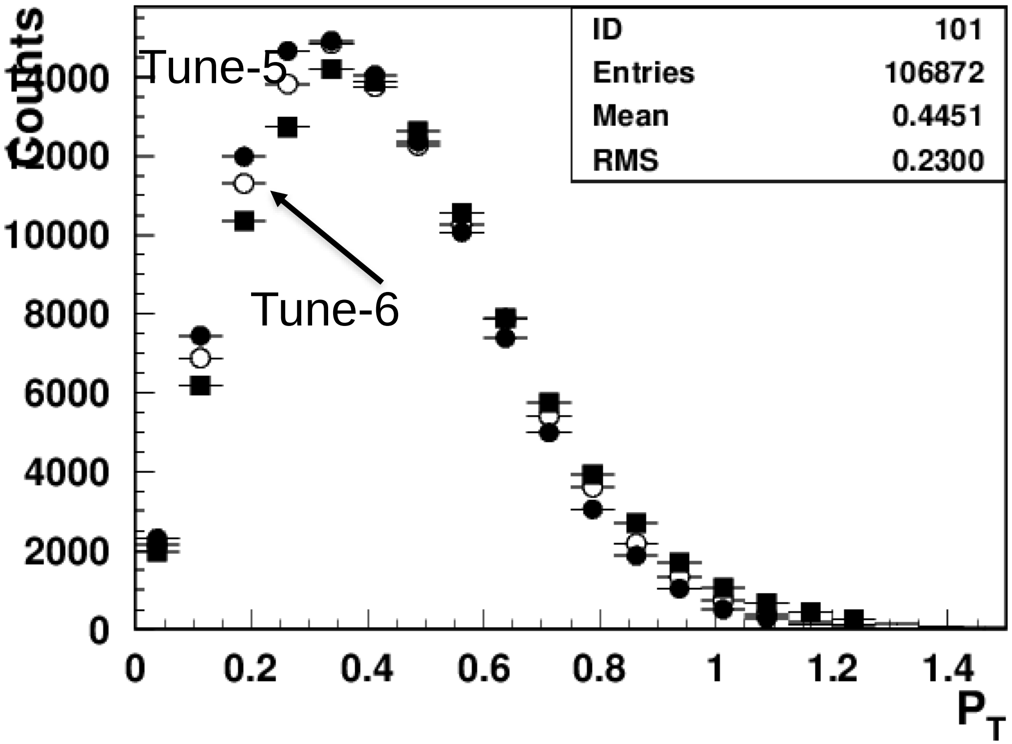
Squares RGC carbon run#16128

e'π+X


Original MC

Tune-5

e'π+X

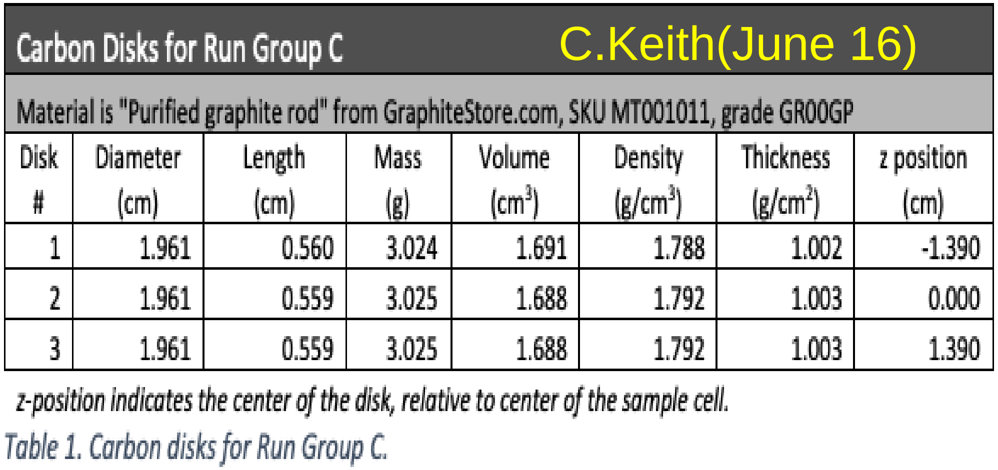

Tune-5

Tune-6

Nuclear MC (PYTHIA based) has been tuned in several iterations to get closer to RGC carbon data (main changes: use the same input as for clasdis with enhanced VM fractions)
Will need accounting of radiative corrections for fine tuning

Vertex studies with carbon: data vs MC

Filled circles RGC carbon run#16128 (line MC)



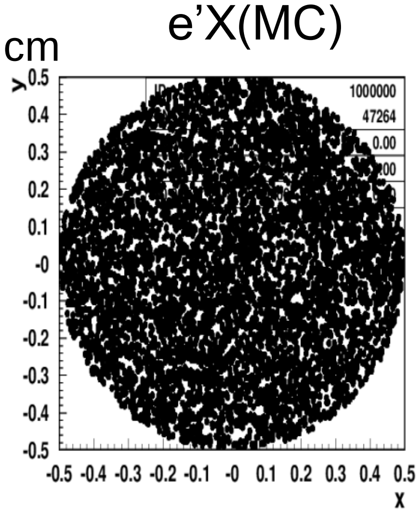
Carbon Disks for Run Group C C.Keith(June 16)

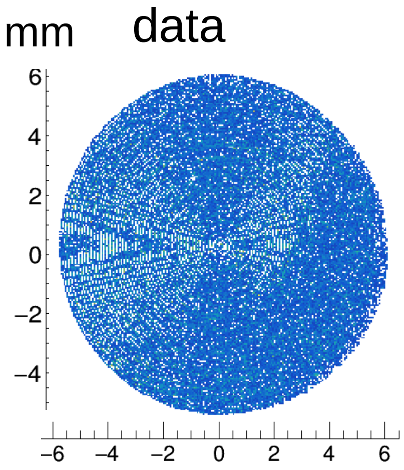
Material is "Purified graphite rod" from GraphiteStore.com, SKU MT001011, grade GR00GP

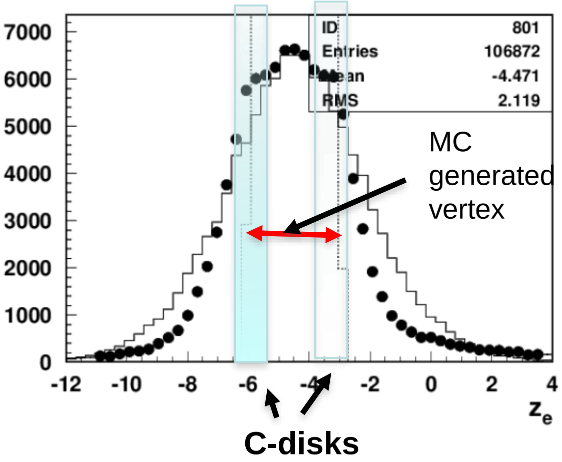
Disk #	Diameter (cm)	Length (cm)	Mass (g)	Volume (cm^3)	Density (g/cm^3)	Thickness (g/cm^2)	z position (cm)
1	1.961	0.560	3.024	1.691	1.788	1.002	-1.390
2	1.961	0.559	3.025	1.688	1.792	1.003	0.000
3	1.961	0.559	3.025	1.688	1.792	1.003	1.390

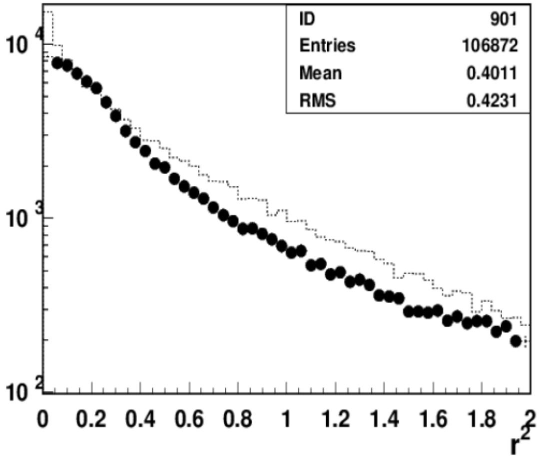
z-position indicates the center of the disk, relative to center of the sample cell.

Table 1. Carbon disks for Run Group C.

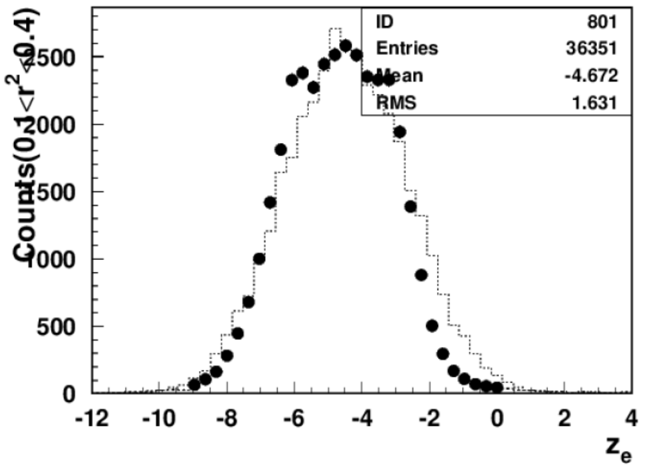








Removing edges improves agreement



MC seem to be wider.
For the same range in transverse space the z-vertex distributions look compatible.

B2B correlations with long. Pol. Target

N/q	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^h, \hat{t}_1^\perp$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^h, \hat{t}_{1L}^\perp$
T	$\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$	$\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp h}$

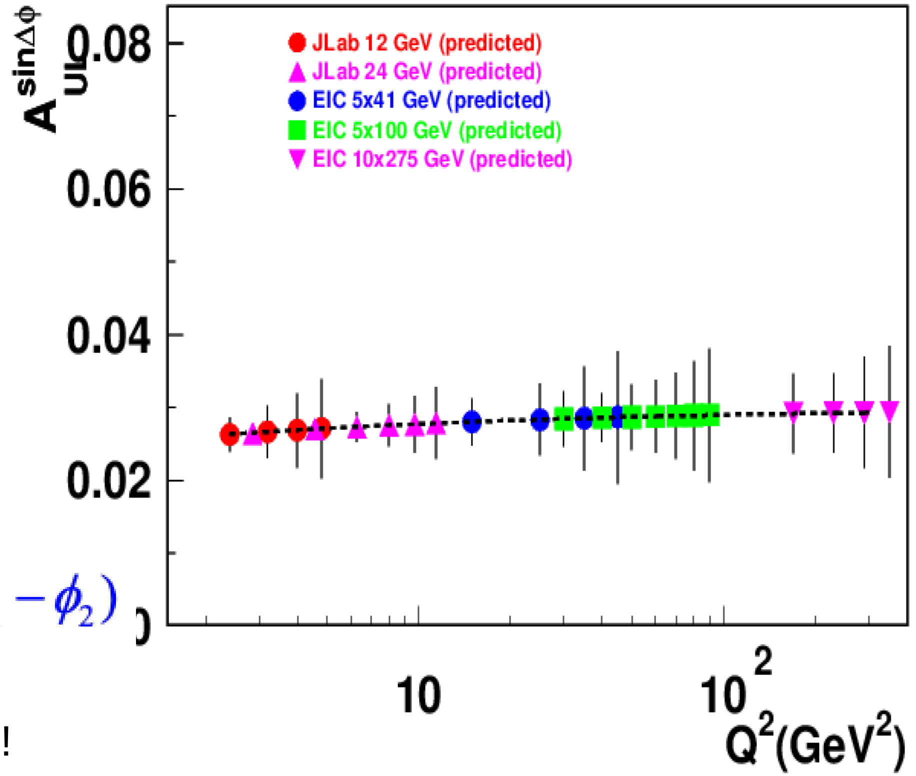
A. Kotzinian, arXiv:1107.2292

$$\sigma_{UU} = F_0^{\hat{u}\cdot D_1}$$

$$\sigma_{UL} = -\frac{P_{T1}P_{T2}}{m_2 m_N} F_{k1}^{\hat{u}_{1L}^{\perp h}\cdot D_1} \sin(\phi_1 - \phi_2)$$

No depolarization, like Sivers!

Lumi: JLab 10^{35}, EIC4x51/5x100/10x275 0.044,0.6,1x10^{34})
y>0.05,100 days



CL AS12 proposals

NH3/ND3

E12-09-009

E12-07-107

E12-09-007A

^{3}He

C12-20-002

^{7}LiD

E12-14-001

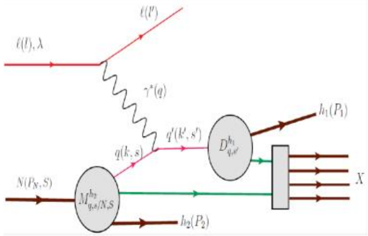
- Target SSA can be measured in the full Q^2 range, combining different facilities
- Advantages: Higher Lumi for JLab, less suppression at high Q^2 for EIC
- JLab24 will be crucial to bridge the studies of FFs between JLab12 and EIC in the valence region

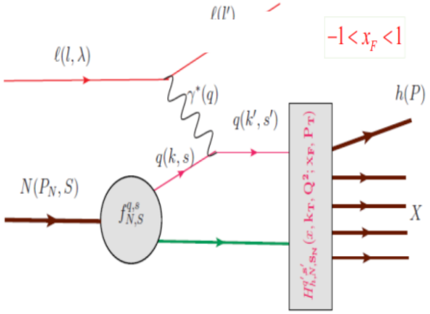
MC simulations: Why LUND works?

- A single-hadron MC with the SIDIS cross-section where widths of k_T-distributions of pions are extracted from the data is not reproducing well the data.
- LUND fragmentation based MCs were successfully used worldwide from JLab to LHC, showing good agreement with data.

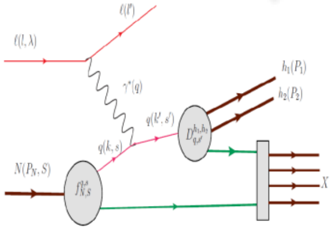
So why the LUND-MCs are so successful in description of hard scattering processes, and SIDIS in the first place?

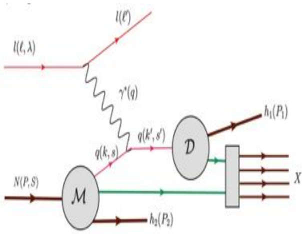
- The hadronization into different hadrons, in particular Vector Mesons is accounted (full kinematics)
- Accessible phase space properly accounted
- The correlations between hadrons, as well a as target and current fragments accounted
- ….





subsamples

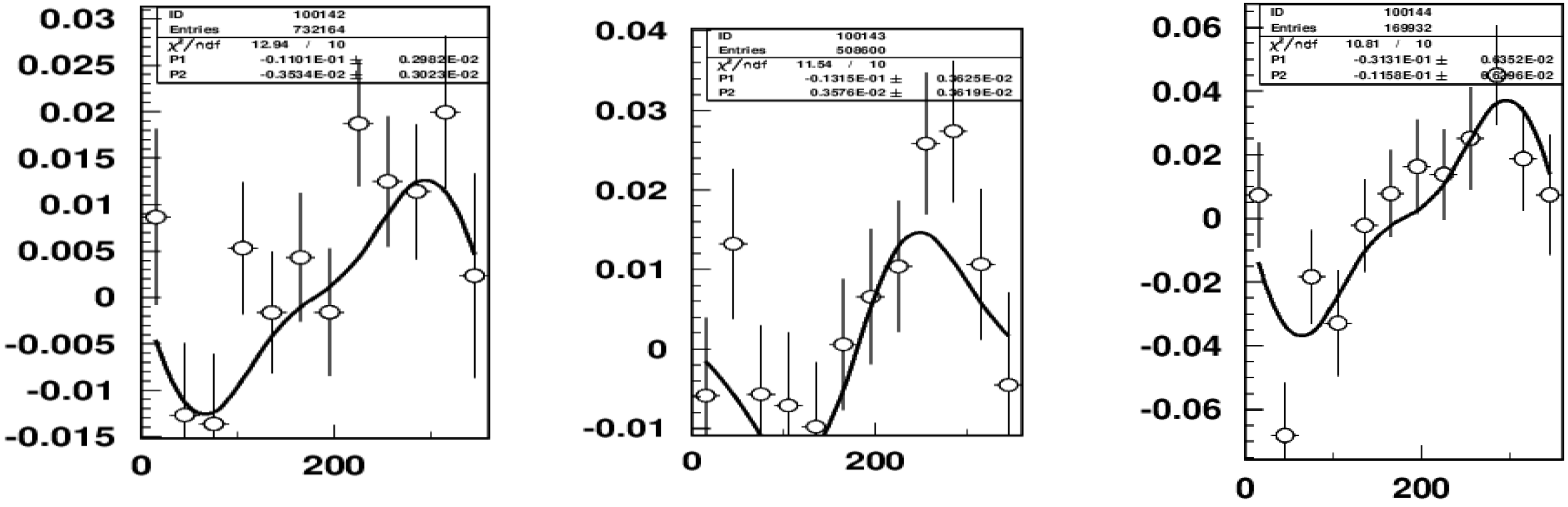


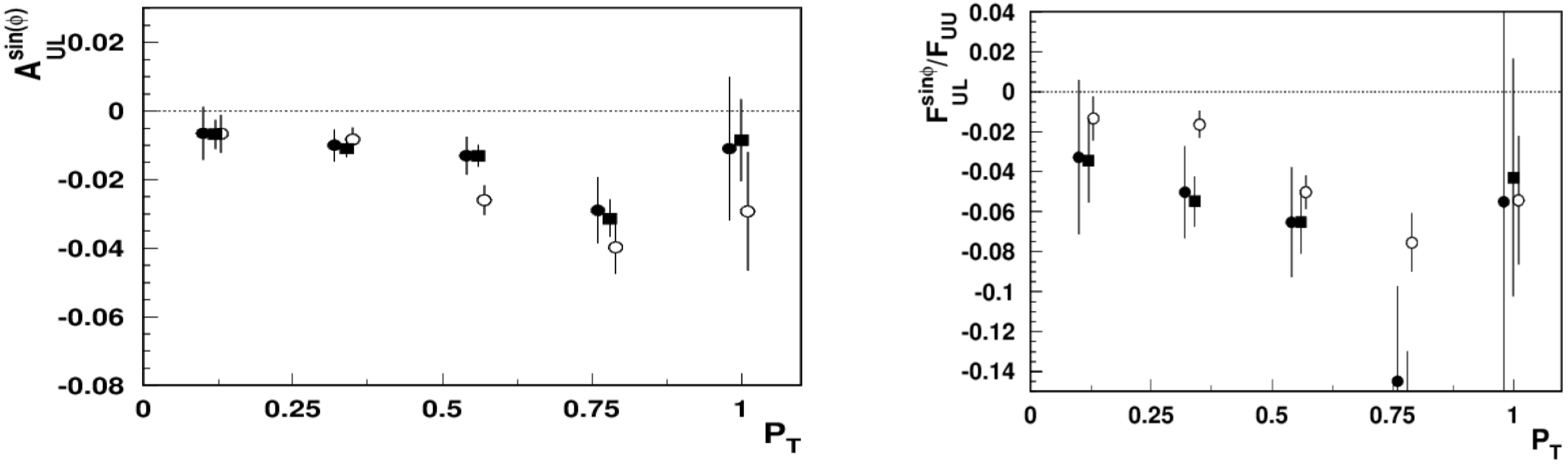


To understand the measurements we should be able to simulate, at least the basic features we are trying to study (P_T and Q^2,-dependences in particular)

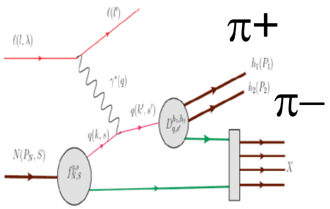
The studies of correlated hadron pairs in SIDIS may be a key for proper interpretation !!!

Target SSA in ep→e’ pπ+X

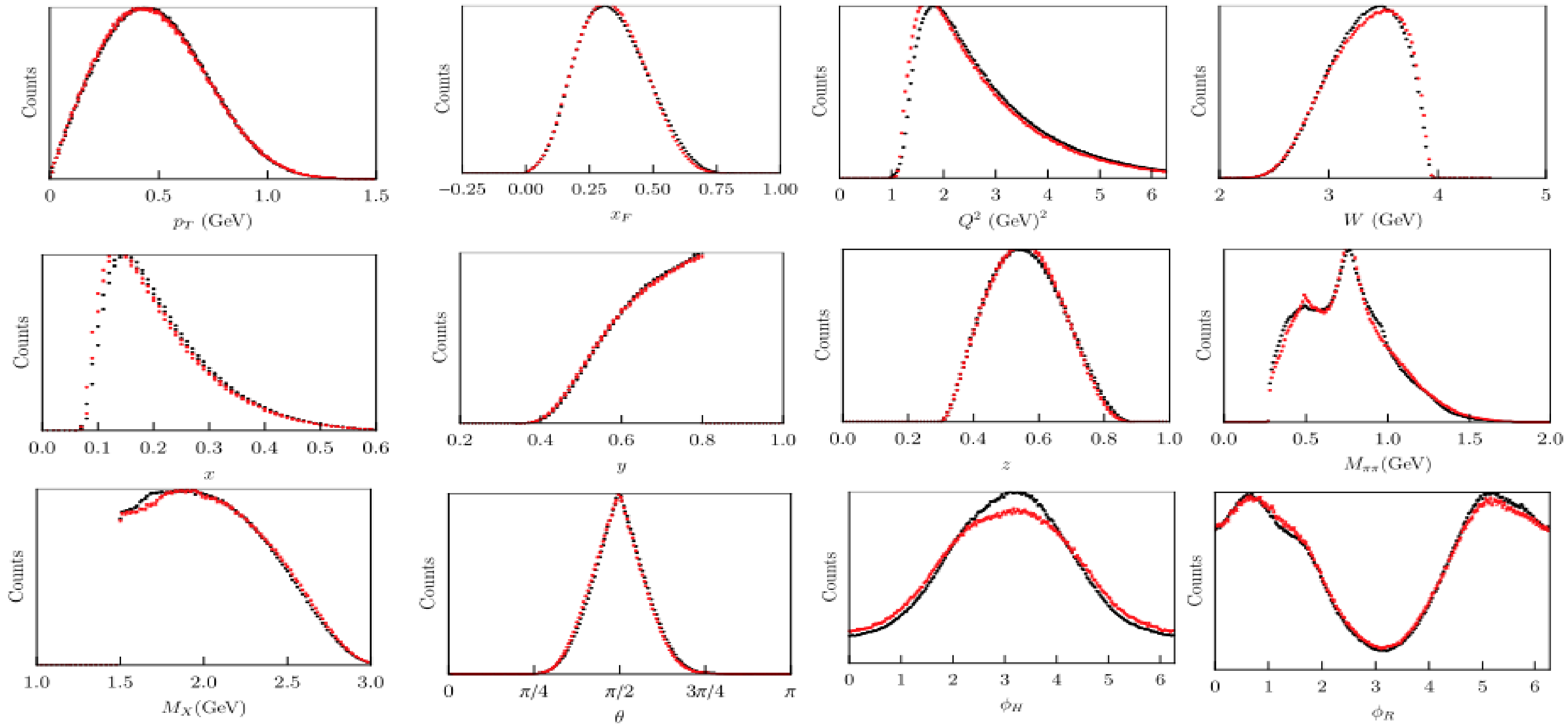




SIDIS ehhX: CLAS12 data vs MC



CLAS12 dihadron production ep→ehhX



CLAS12 MC, based on the PEPSI(LEPTO) simulation with most parameters ”default” is in a good agreement with CLAS12 measurements for all relevant distributions

Sensitivity of d-quark structure to ^{3}He: Simulation

Statistics for 30 days
Bin:
$< x >= 0.425$
$< Q^2 >= 5.0$
$< z >= 0.44.$

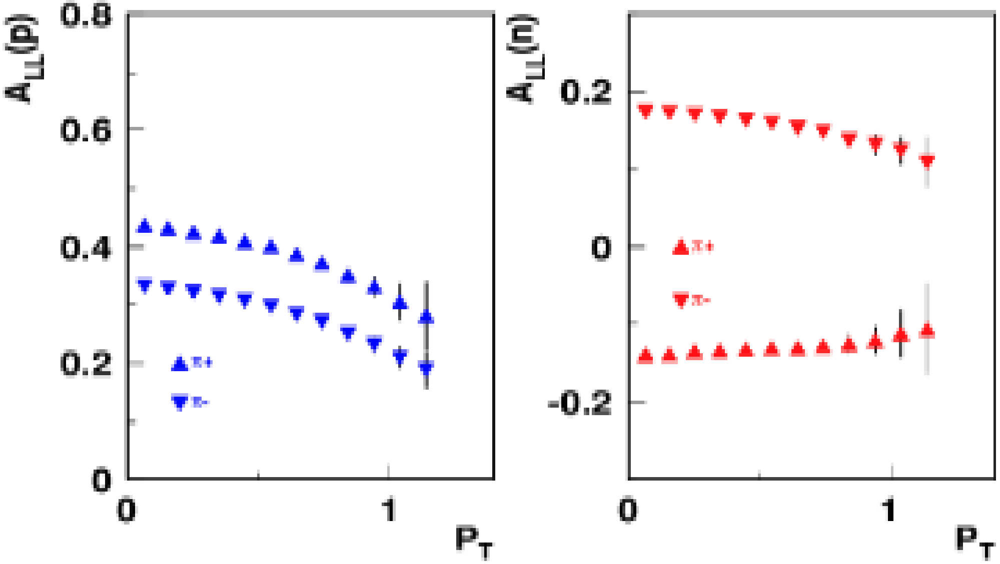
$$f_1^{q/N}(x,k_T) = f_1^{q/N}(x)\,\frac{e^{-k_T^2/\langle k_T^2\rangle_q}}{\pi\langle k_T^2\rangle_q},$$

$$g_1^{q/N}(x,k_T) = g_1^{q/N}(x)\,\frac{e^{-k_T^2/\langle k_T^2\rangle_{\Delta q}}}{\pi\langle k_T^2\rangle_{\Delta q}},$$

$$F_{LL}^N = x\sum_q e_q^2 g_1^q(x,Q^2) D^q(z,Q^2)\ P_{\Delta q}$$

Using:
LO GRV for PDF x,Q^2

LO DSS for $D_1(z,Q^2)$
$\langle p_T^2\rangle=0.16$
$\langle k_T^2\rangle u=0.3$
$\langle k_T^2\rangle u=0.33$
$\langle k_T^2\rangle \Delta u=0.22$
$\langle k_T^2\rangle \Delta d=0.25$



Note: for proton π+ (triangle up) π– (triangle down) A_LLs have the same sign for proton and opposite signs for neutron

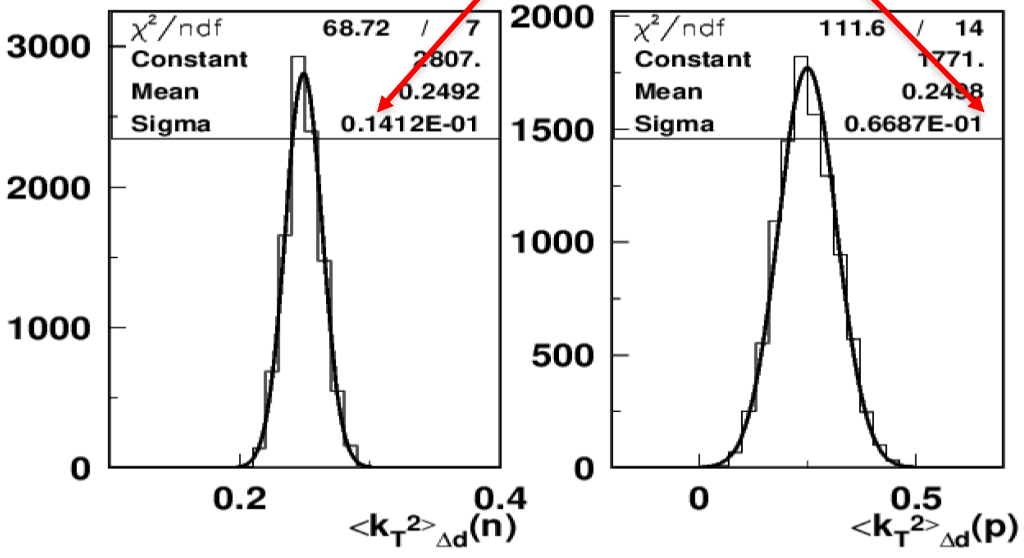
Polarized quark structure from proton and ^{3}He

The k_T-dependent width of polarized d-quarks has significantly smaller uncertainty from neutron data due to order of magnitude large and canceling contributions in proton (input values for u→0.22, d→0.25)

$$P_{\Delta d} = -\frac{e^{\frac{P_T^2}{\langle k_T^2\rangle_{\Delta d} z^2 + \langle p_T^2\rangle}}}{\pi(\langle k_T^2\rangle_{\Delta d} z^2 + \langle p_T^2\rangle)}$$

$$P_{\Delta u} = -\frac{e^{\frac{P_T^2}{\langle k_T^2\rangle_{\Delta u} z^2 + \langle p_T^2\rangle}}}{\pi(\langle k_T^2\rangle_{\Delta u} z^2 + \langle p_T^2\rangle)}$$

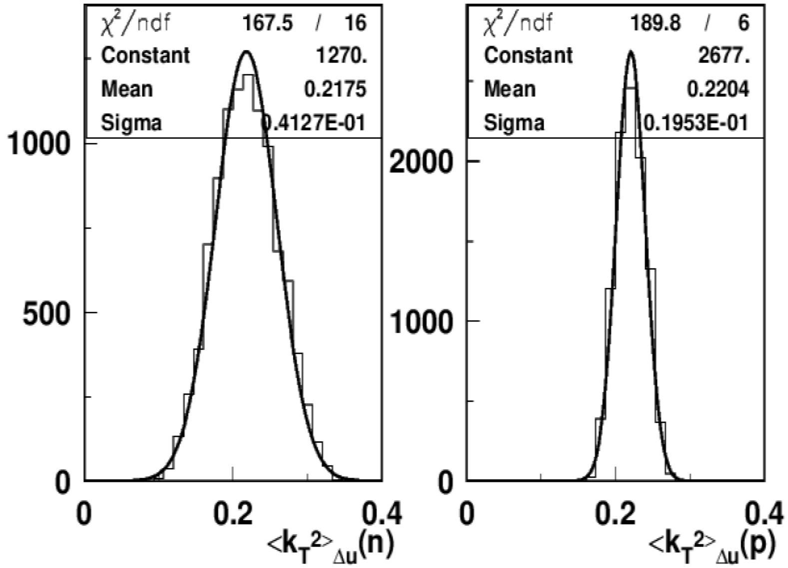
- unpolarized widths for u and d known within 10%
- ☐ Δd/Δu at large x known within 20%
- 1sigma spread of ALLs



neutron

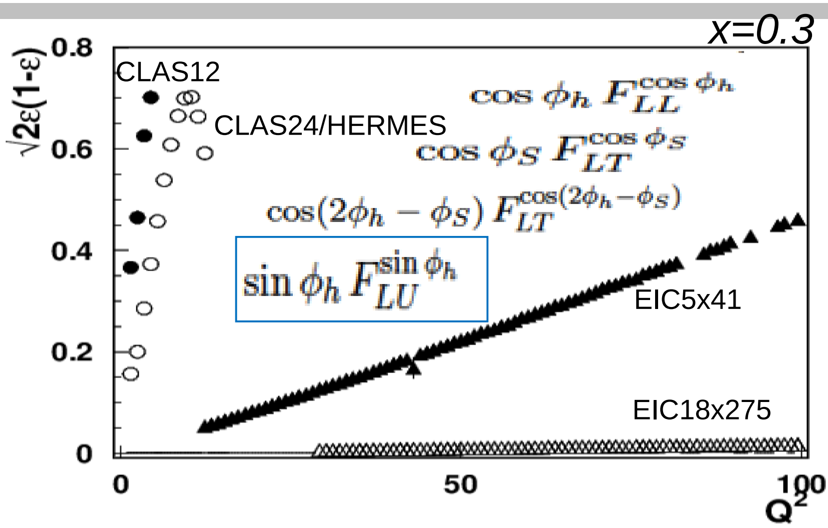
proton

Decent extraction for u-quarks



Extractions of TMDs (both Δd and Δu) can be performed within model assumptions

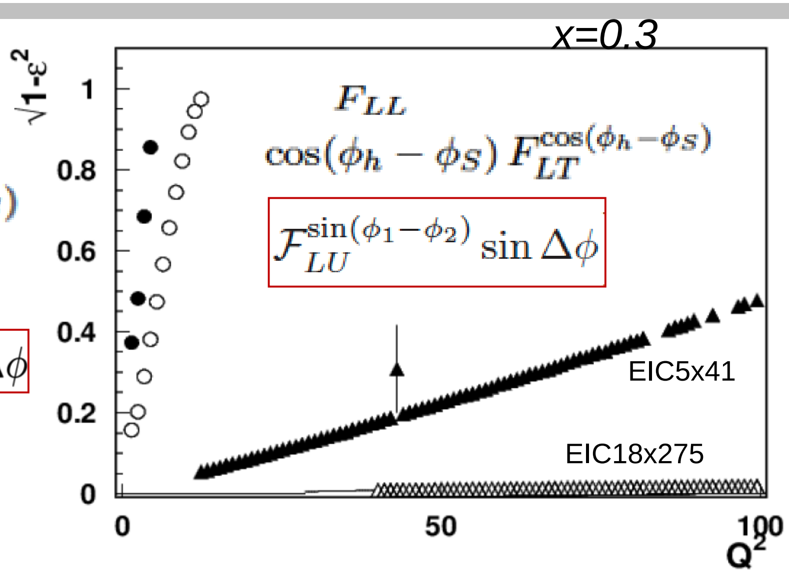
SIDIS: Kinematic factors at large x

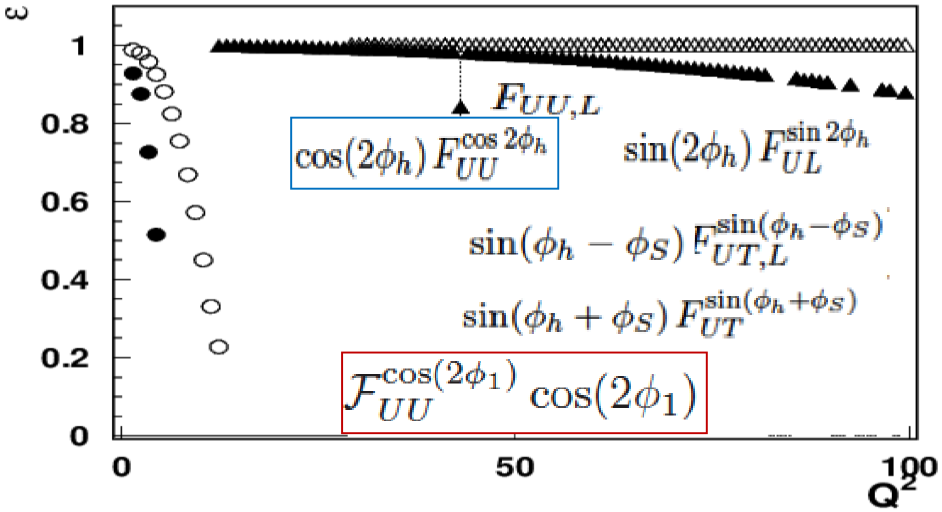


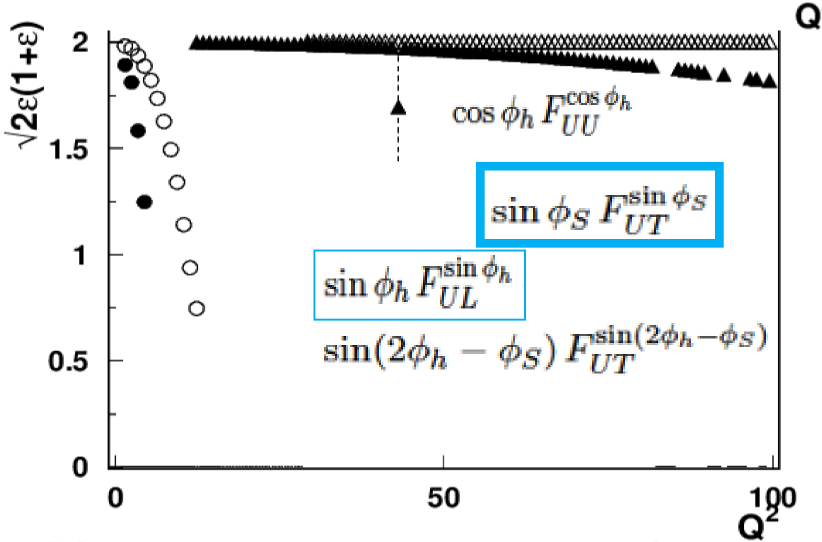
$F_{UU,T}$

$F_{UT,T}^{\sin(\phi_h-\phi_S)}$

$\mathcal{F}_{UL}^{\sin(\phi_1-\phi_2)}\sin\Delta\phi$





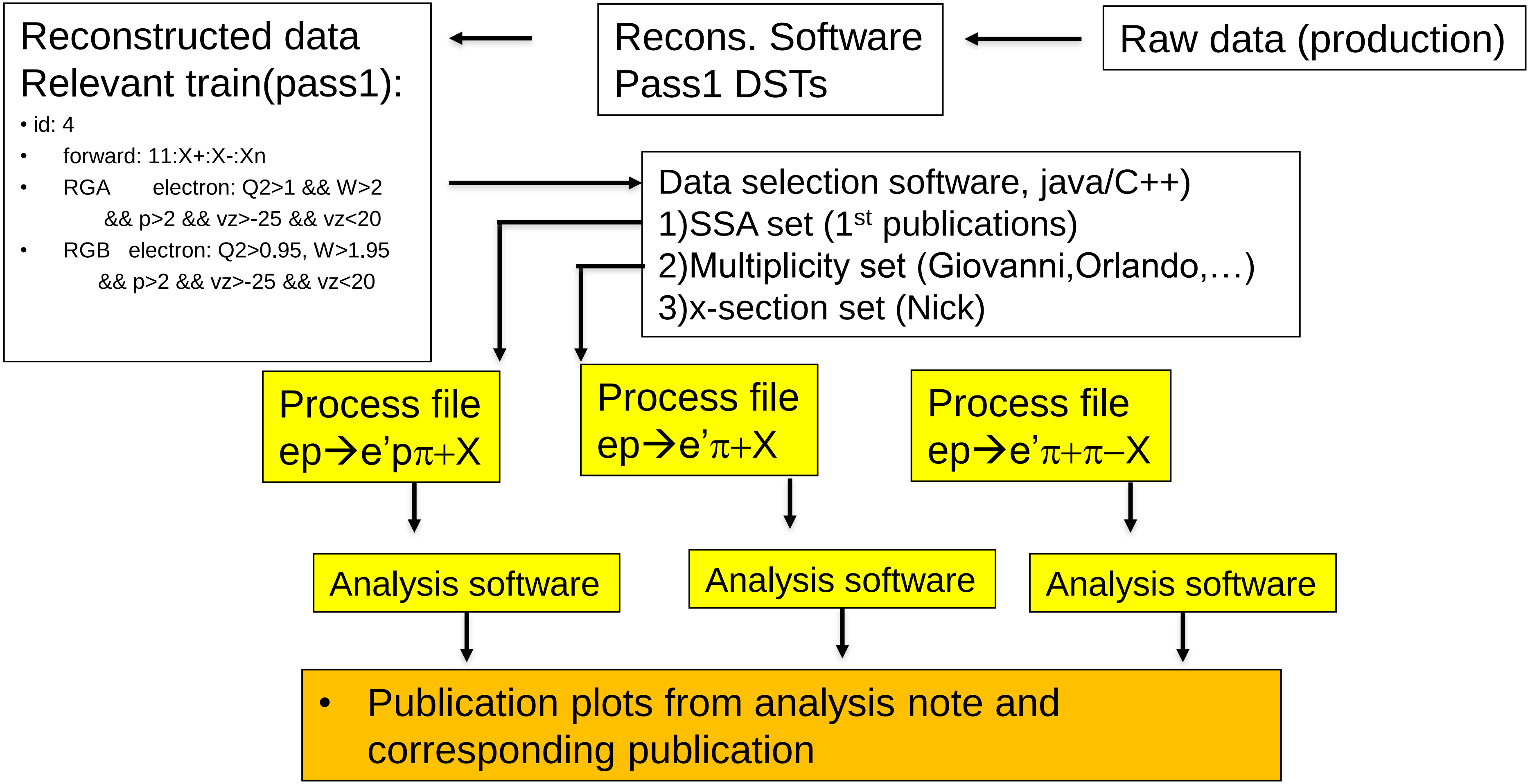


- At large x fixed target experiments are sensitive to all Structure Functions
- For EIC, observables surviving the $\varepsilon \rightarrow 1$ limit (F_{UU}, F_{UL}, Transversely pol. F_{UT})

CLAS12 data preservation

https://clasweb.jlab.org/wiki/index.php/Hall-B_Task_Forces_2020#Data_Preservation

Layers of data abstraction hierarchy



Raw data (production)

Recons. Software
Pass1 DSTs

Reconstructed data
Relevant train(pass1):

- id: 4
- forward: 11:X+:X-:Xn
- RGA electron: Q2>1 && W>2 && p>2 && vz>-25 && vz<20
- RGB electron: Q2>0.95, W>1.95 && p>2 && vz>-25 && vz<20

Data selection software, java/C++)
1)SSA set (1st publications)
2)Multiplicity set (Giovanni,Orlando,…)
3)x-section set (Nick)

Process file
ep→e’pπ+X

Process file
ep→e’π+X

Process file
ep→e’π+π–X

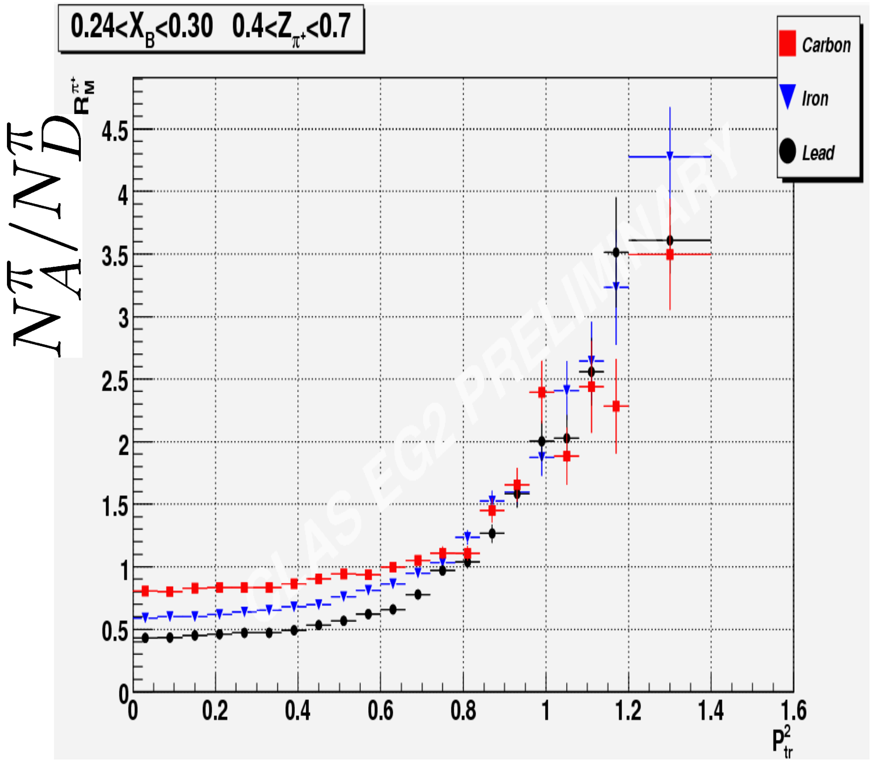
Analysis software

Analysis software

Analysis software

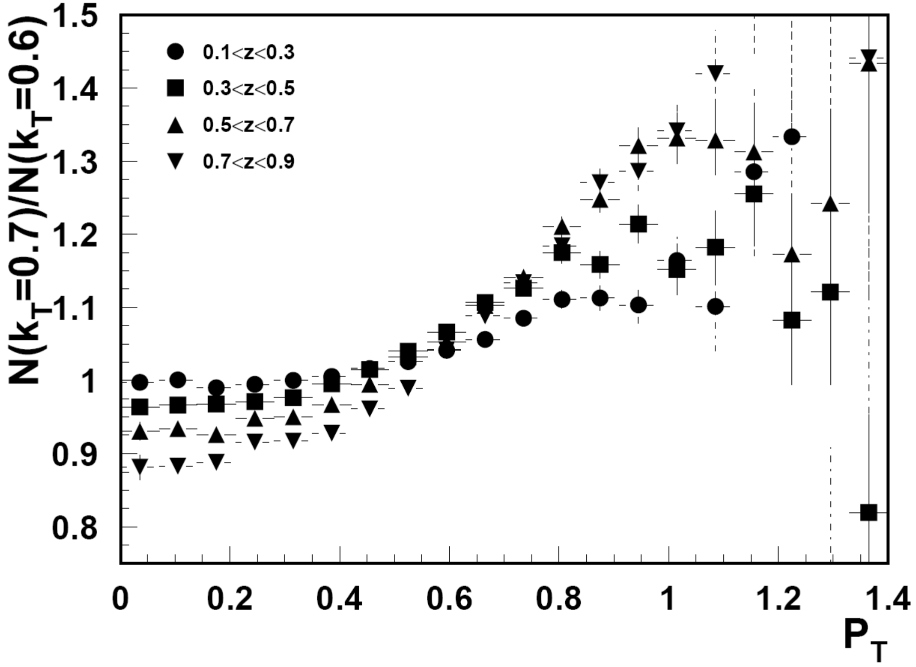
- Publication plots from analysis note and corresponding publication

Quark distributions at large k_T



bigger effect at large z

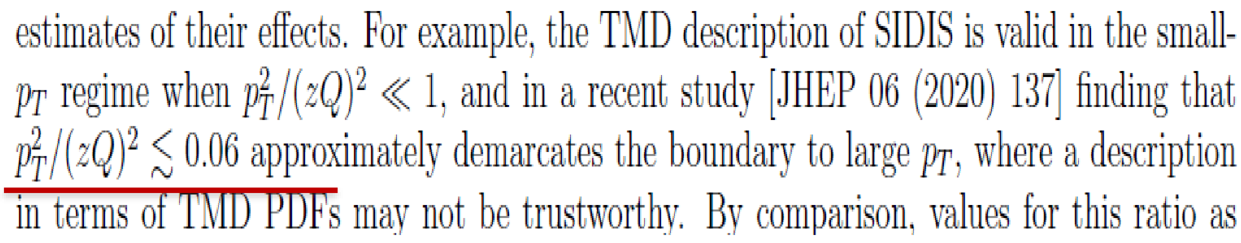
$$P_T = p_\perp + z\,k_T$$



Higher probability to find a hadron at large P_T in nuclei

k_T-distributions may be wider in nuclei?

Current theory limitations (q_T/Q)



estimates of their effects. For example, the TMD description of SIDIS is valid in the small-p_T regime when $p_T^2/(zQ)^2 \ll 1$, and in a recent study [JHEP 06 (2020) 137] finding that $p_T^2/(zQ)^2 \lesssim 0.06$ approximately demarcates the boundary to large p_T, where a description in terms of TMD PDFs may not be trustworthy. By comparison, values for this ratio as

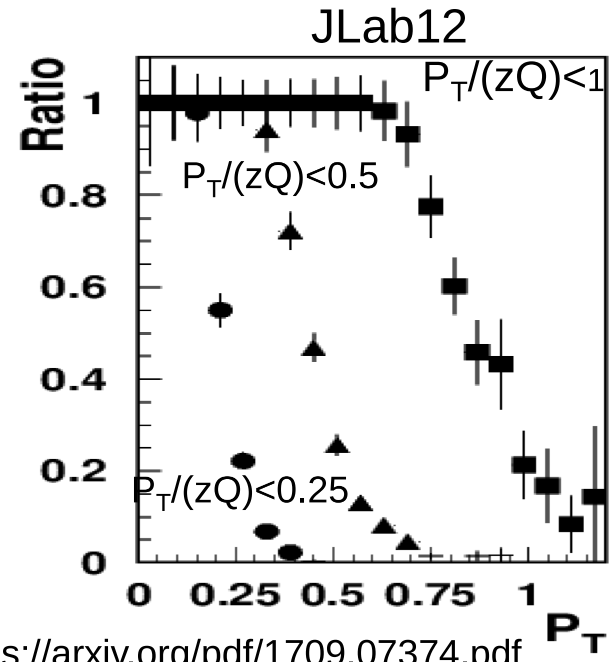
The q_T=P_T/z theory "trustworthy" cut:

1)Suppresses moderate Q^2 and large P_T (sensitive to k_T), where all kind of azimuthal modulations are most significant

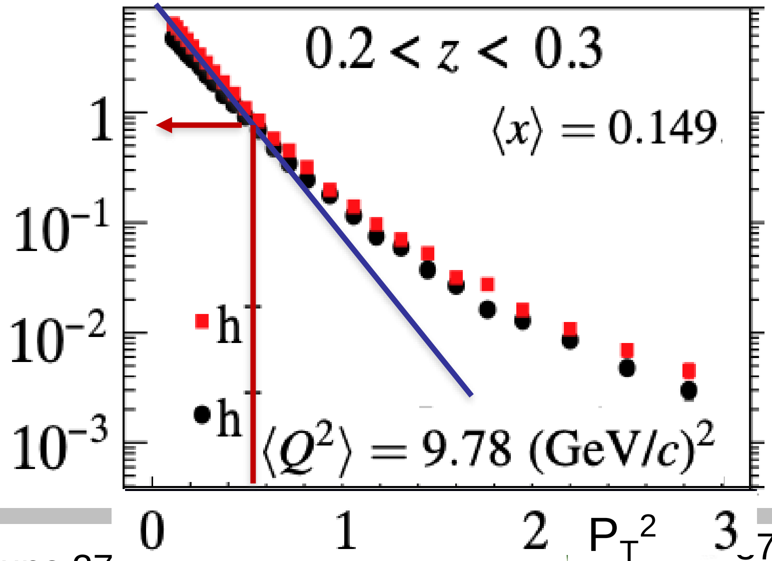
2)Enhances large z region (ex. Exclusive Events) in TMD and low z in FO calculations

3) Cuts not only most of the JLab data, but practically all accessible in polarized SIDIS large P_T samples , including ones from HERMES COMPASS, and even EIC.

Details available from https://indico.jlab.org/event/439/
JLab/HERMES/COMPASS/EIC talks



https://arxiv.org/pdf/1709.07374.pdf



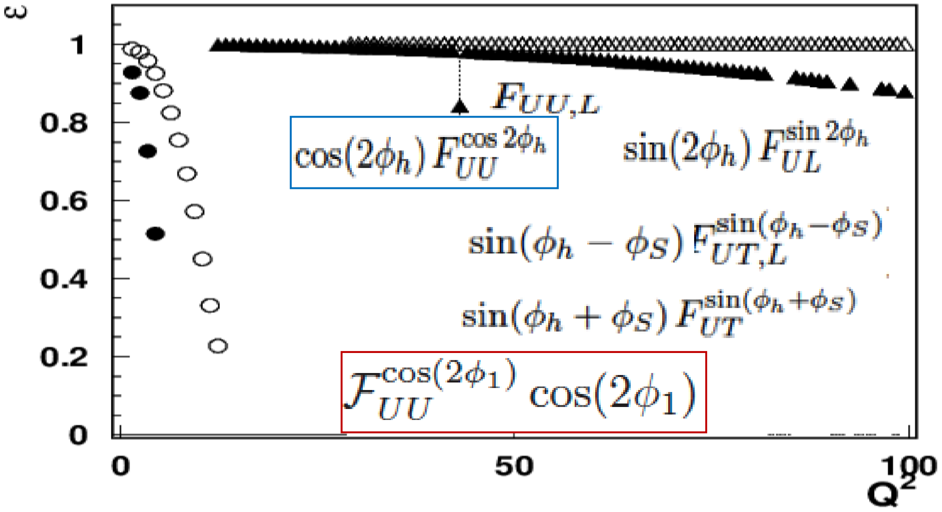
Complementarity between JLab and EIC

$F_{UU,T}$ Multiplicities, evolution of unpolarized SFs

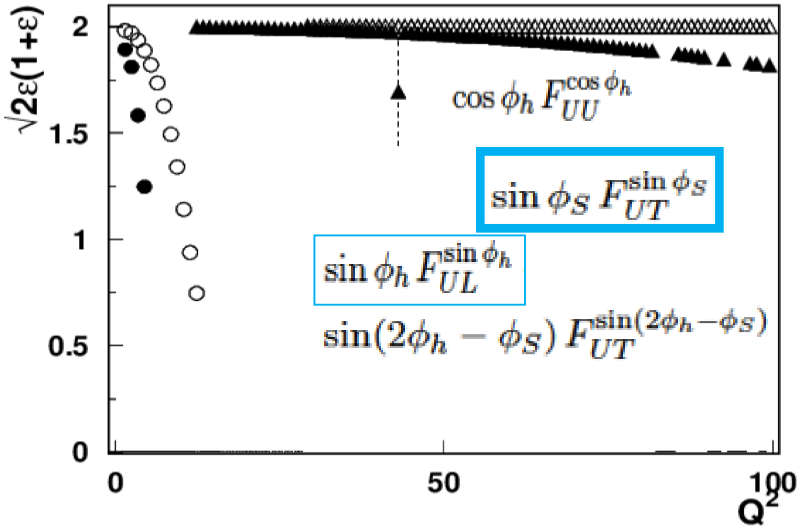
$F_{UT,T}^{\sin(\phi_h-\phi_S)}$ Sivers and Collins SSAs (Transverse target)

$\mathcal{F}_{UL}^{\sin(\phi_1-\phi_2)} \sin\Delta\phi$ Longitudinally polarized Target spin asymmetries in correlations of CFR and TFR (single and dihadron)

Observables with no ε-dependence or not suppressed at low ***y*** provide complementarity set



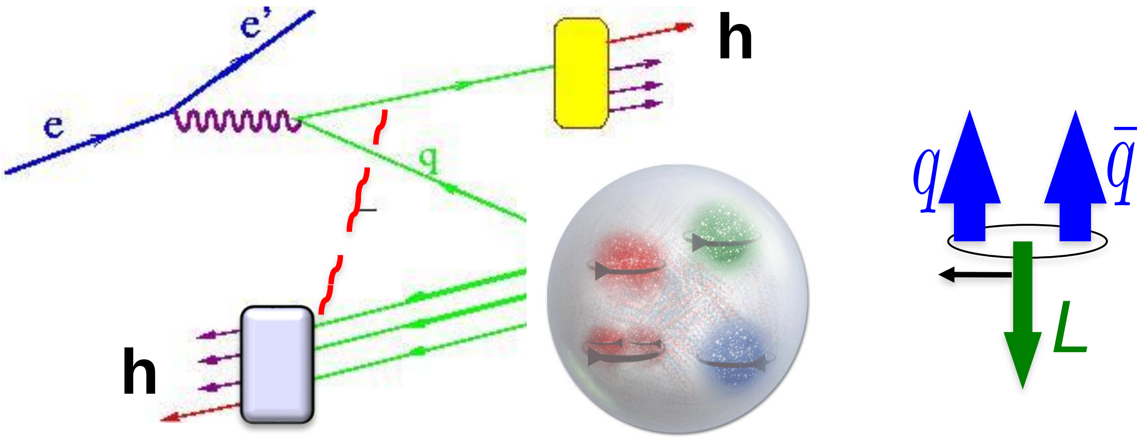
x=0.3



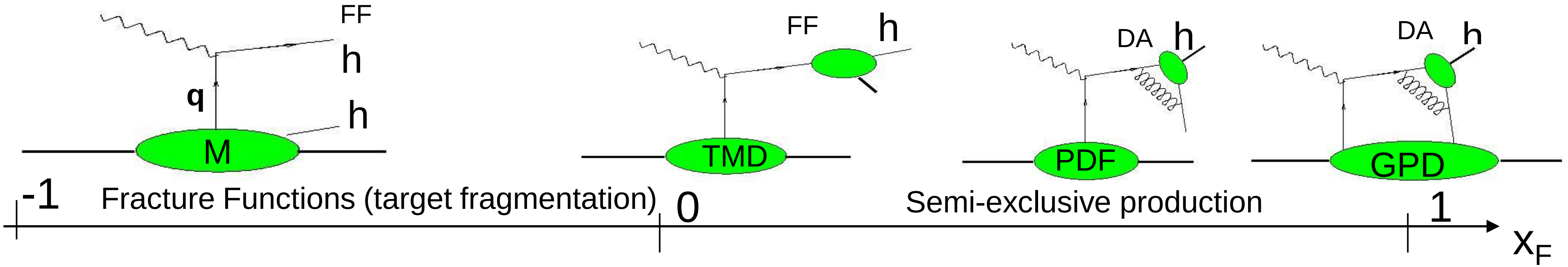
Hadron production in hard scattering in SIDIS

x_F – fractional momentum in the CM frame

x_F>0 (current fragmentation)



x_F<0 (target fragmentation)



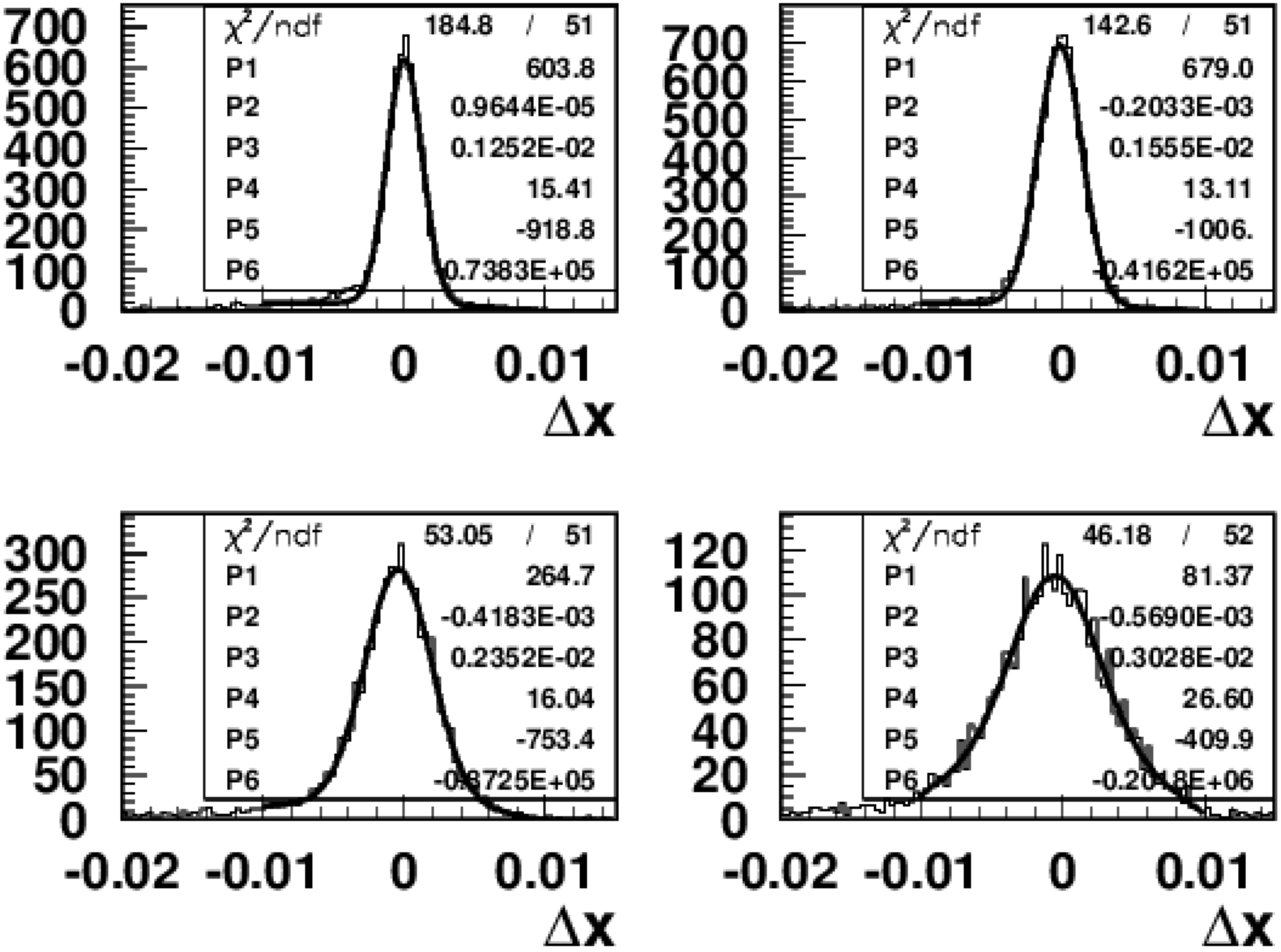
Fracture Functions (target fragmentation)

Semi-exclusive production

Different non-perturbative objects may be involved in description, depending on kinematical conditions, introducing different dependence on Q^2

Resolutions in x

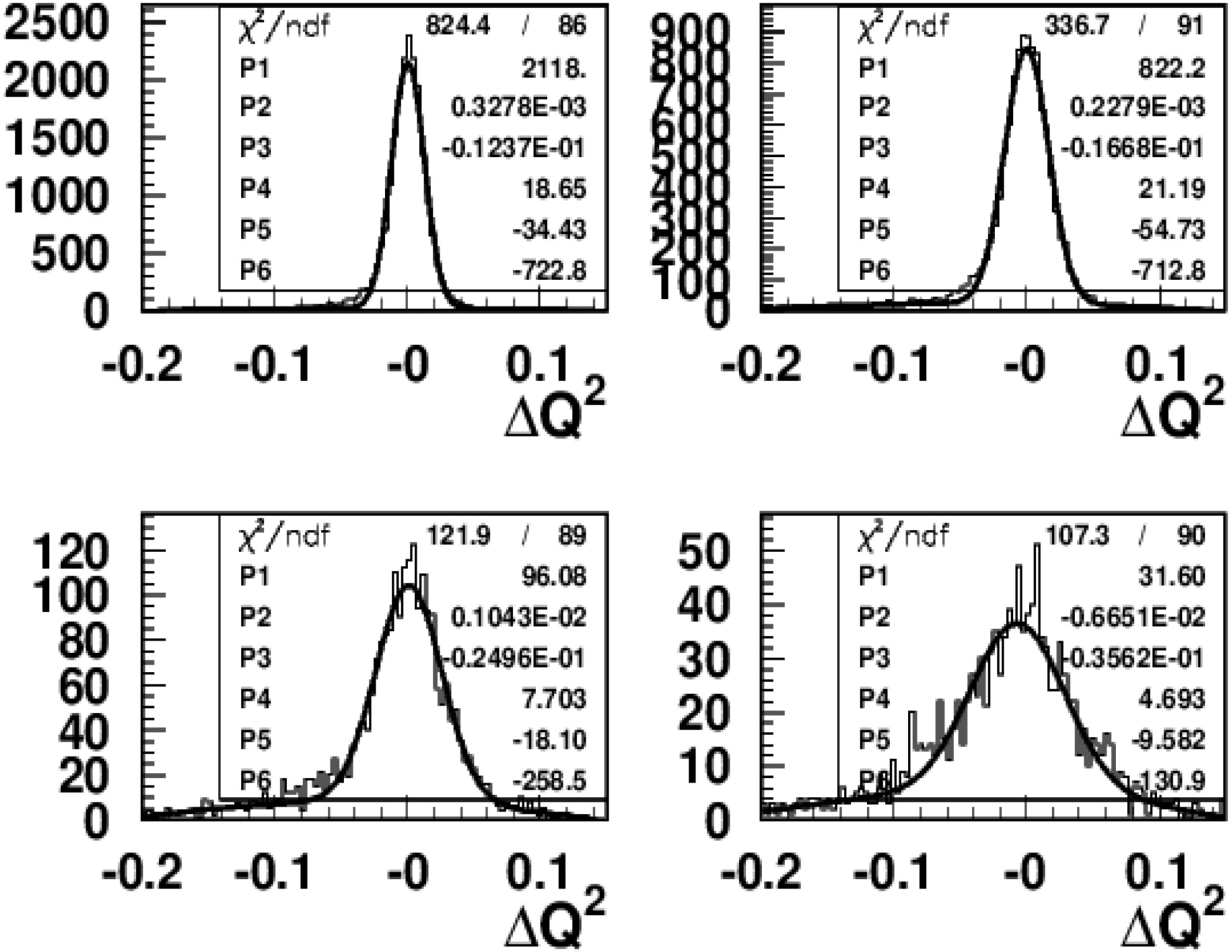
X-bins
0.0540
0.0590
0.0644
0.0704
0.0768
0.0839
0.0917
0.1001
0.1093
0.1194
0.1304
0.1424
0.1555
0.1699
0.1855
0.2026
0.2213
0.2417
0.2639
0.2882
0.3148
0.3438
0.3755
0.4101
0.4479
0.4891
0.5342
0.5834
0.6372
0.6959
0.7600



Bins ~4sigma

1.000
1.0814
1.1694
1.2646
1.3675
1.4788
1.5991
1.7292
1.8700
2.0222
2.1867
2.3647
2.5571
2.7652
2.9903
3.2336
3.4968
3.7814
4.0891
4.4219
4.7818
5.1709
5.5917
6.0468
6.5389
7.0711
7.6465
8.2688
8.9418
9.6695
10.4564
11.3074
12.2276
13.2227
14.2988
15.4625
16.7209
18.0816

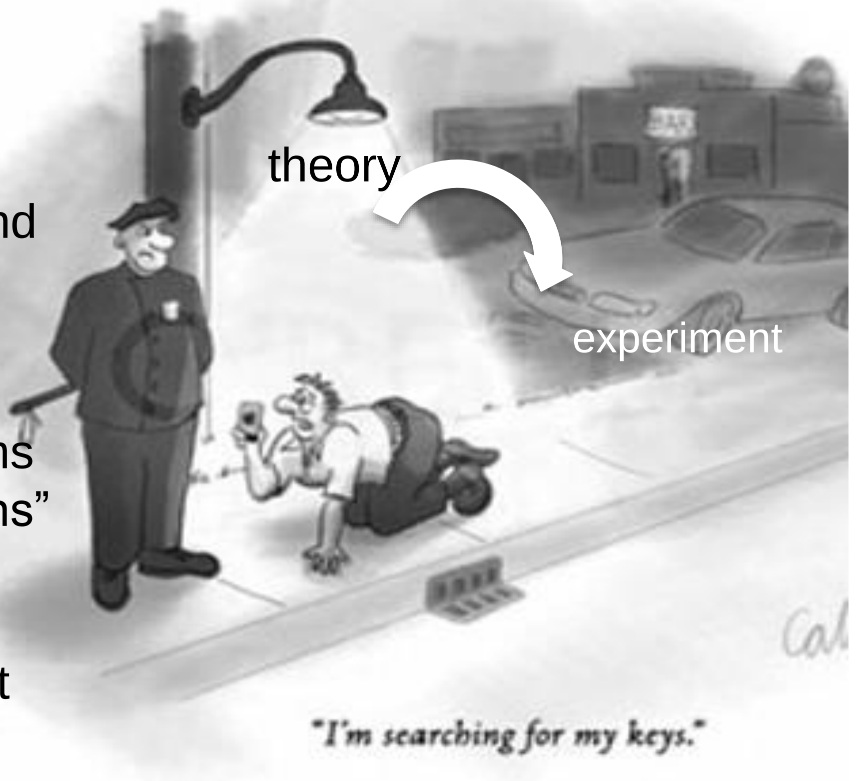
Resolutions in Q^2



Bins ~5sigma

Nucleon structure, TMDs and SSAs

- Large effects observed at relatively large x, relatively large P_T and relatively low Q^2
- Theoretical framework works better, and is "trustworthy" at higher Q^2 and lower P_T
- TMD Fragmentation functions poorly known and understood, systematics not controlled well
- Higher twist SSAs are significant, indicating strong quark-gluon correlations, issues theory has, may become a key to resolve the problems
- Real experiments have "phase space limitations" due to finite energies, introducing correlations between kinematical variables
- Impact of radiative corrections with full account of azimuthal moments in the polarized x-sections still in development



"I'm searching for my keys."

The main goal of SIDIS measurements is the study of non-perturbative QCD, through spin-orbit correlations, where they are significant enough to be measurable

Understanding of the limitations of the current TMD framework with all its assumptions and approximations, is important for predictions, and projections for future experiments