NUCLEON SPIN STRUCTURE – FUTURE EXPERIMENTS

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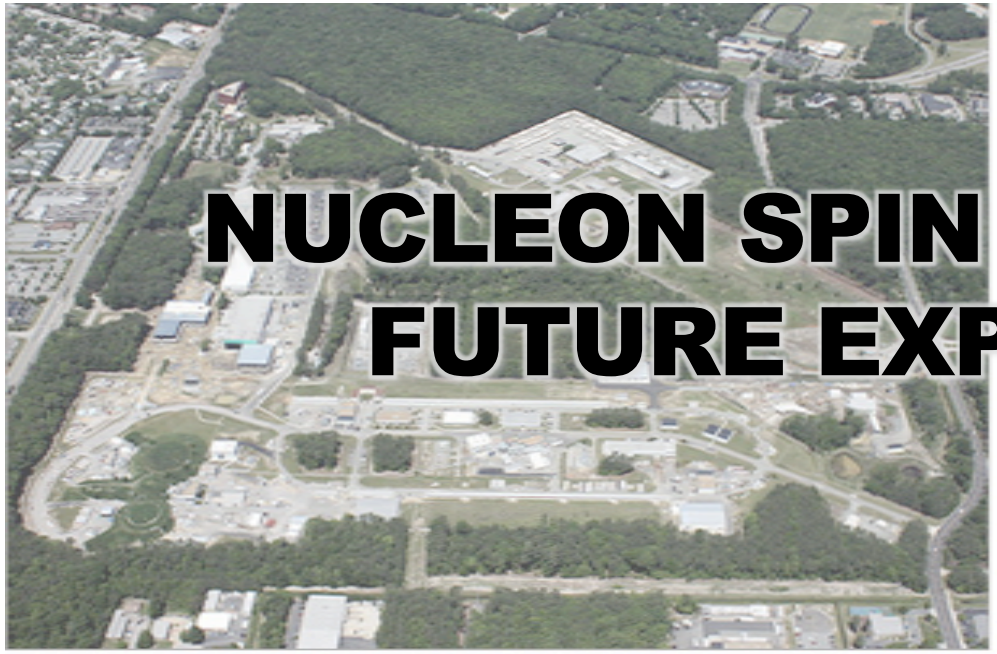
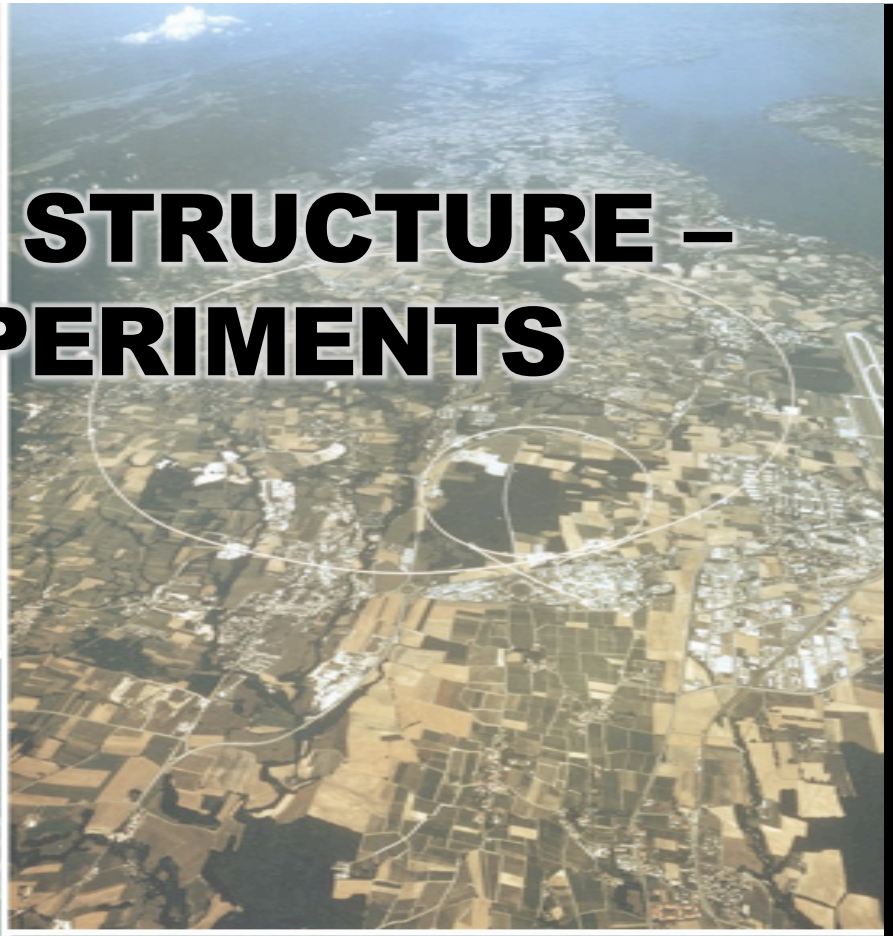
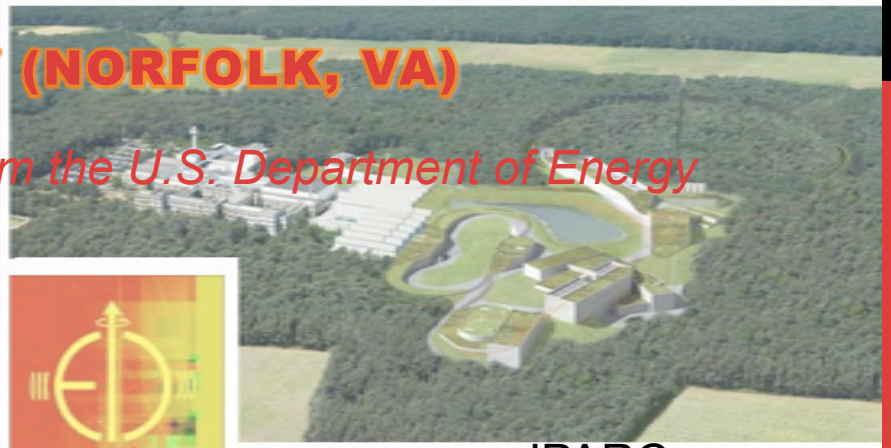
Supported by Grant DE-FG02-96ER40960 from the U.S. Department of Energy







…+ JPARC, …

OUTLINE

Where are we now?

What do we hope to learn in the (not-too distant) future?

What experiments are "on the books"?

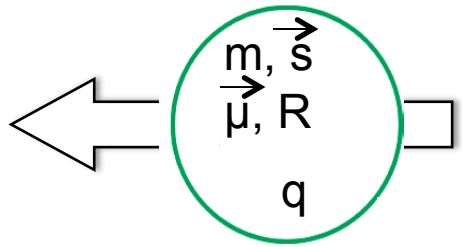
- Ongoing Program at RHIC and COMPASS
- Jefferson Lab at 12 GeV (2014…)
- [Apologies to JPARC, FAIR, FNAL,…]
- The more distant future: EIC

Conclusion and Outlook

INTRODUCTION

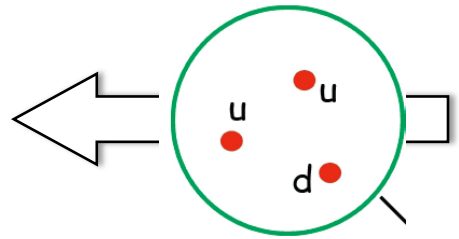
The Nucleon – pre 1960s

Static properties



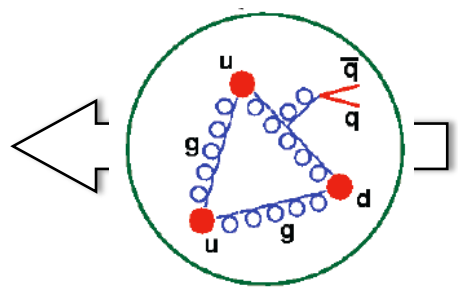
The Nucleon at moderate resolution…

Valence quark distributions



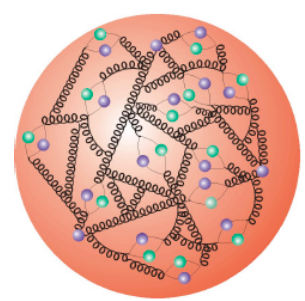
…a closer look…

Gluons and sea quarks



… and at very high resolution

"wee partons" at small momentum fraction x



INTRODUCTION

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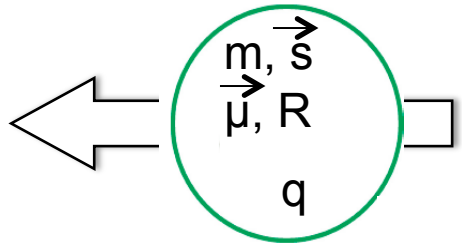

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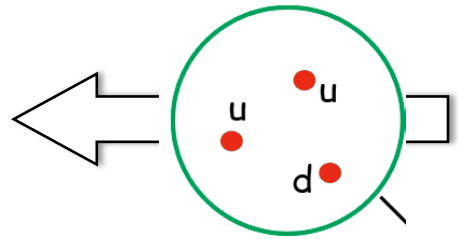

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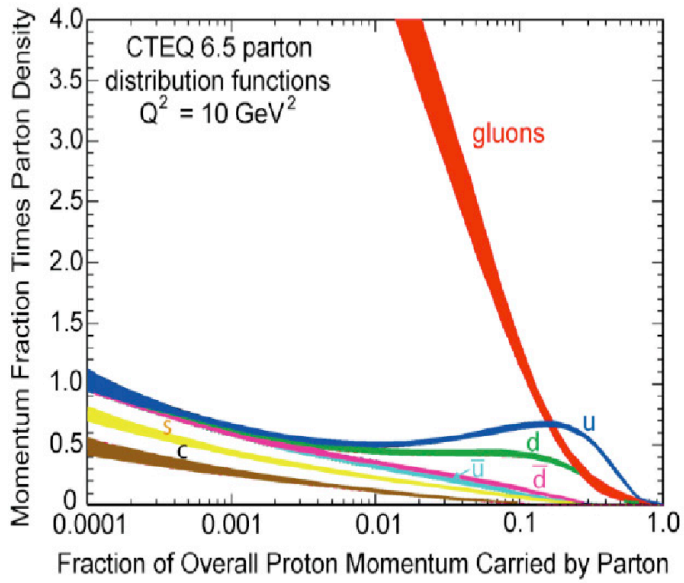
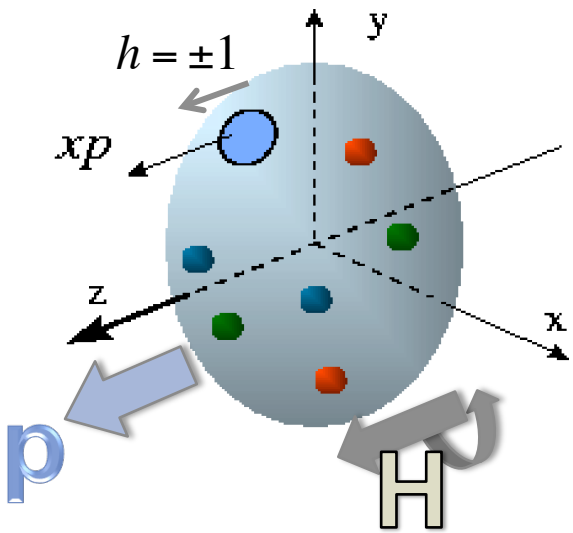


LONGITUDINAL SPIN STRUCTURE

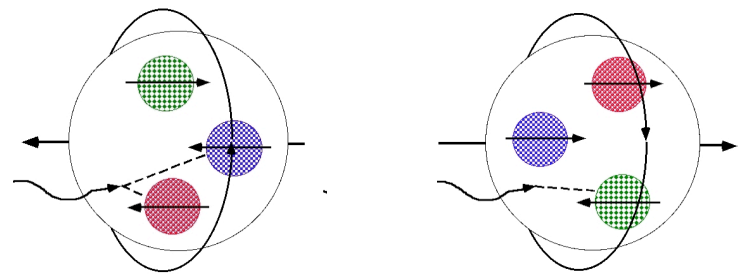
What would we LIKE to observe?

$$g_1(x) = \tfrac{1}{2}\sum_i e_i^2 \Delta q_i(x)$$



$$q(x, h \cdot H; Q^2)$$

Traditional "1-D" Parton Distributions (PDFs)
(inclusive, integrated over many variables)

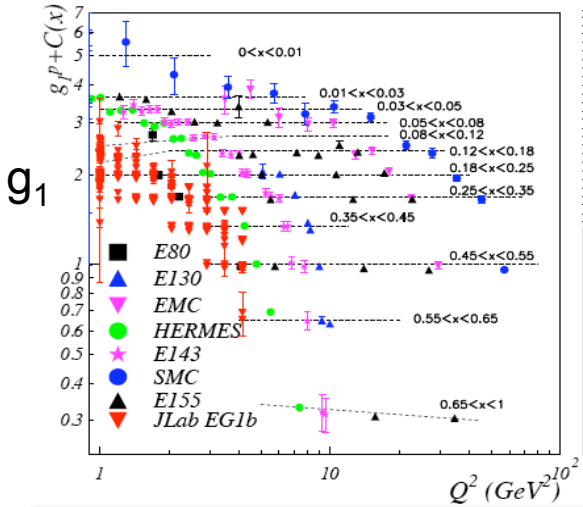


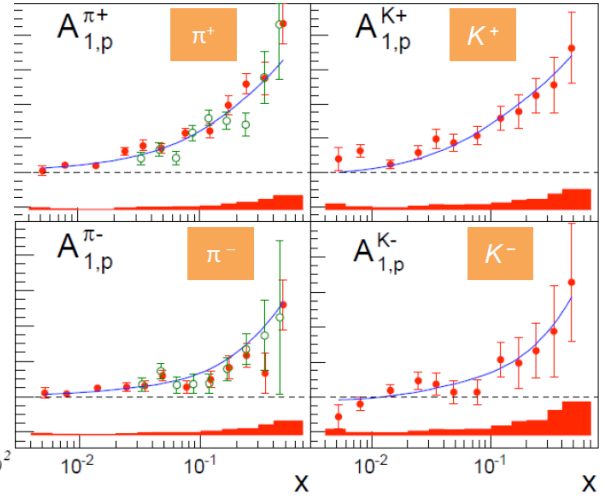
$$\Delta q = q\downarrow\Uparrow - q\uparrow\Uparrow \quad \sim \quad \langle P,s|\bar{q}\gamma^{\mu}\gamma^{5}q|P,s\rangle$$

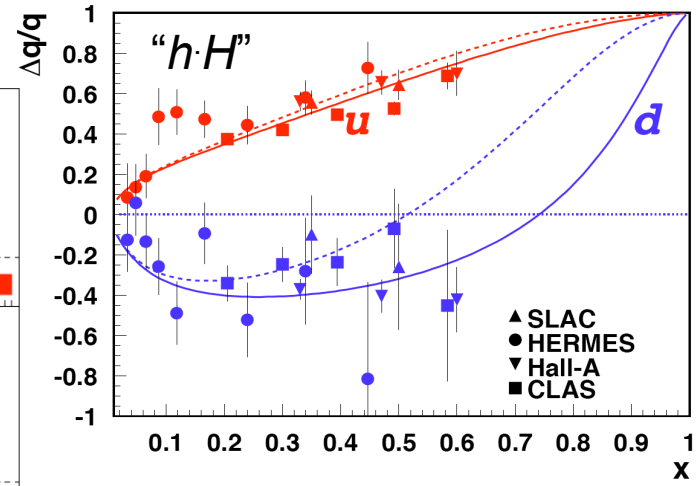
Integrated over all momentum fractions *x*: Total fraction of nucleon spin carried by quark helicities
Remaining contributions must come from quark orbital angular momentum and gluons:

$$\frac{1}{2} = S_p = \frac{1}{2}\sum_q \overbrace{\int_0^1 \Delta q(x)dx}^{\Delta\Sigma} + L_q + J_G$$

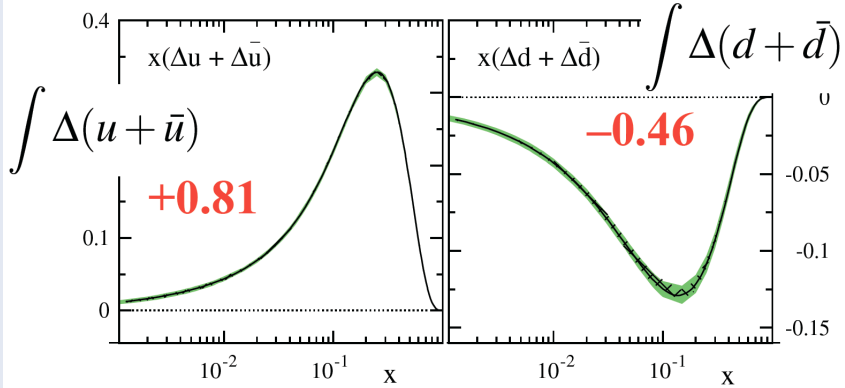
PRESENT SITUATION

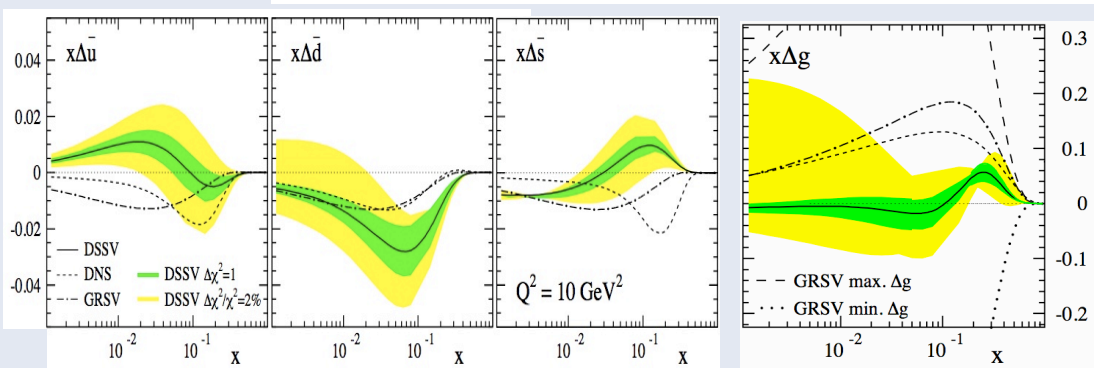




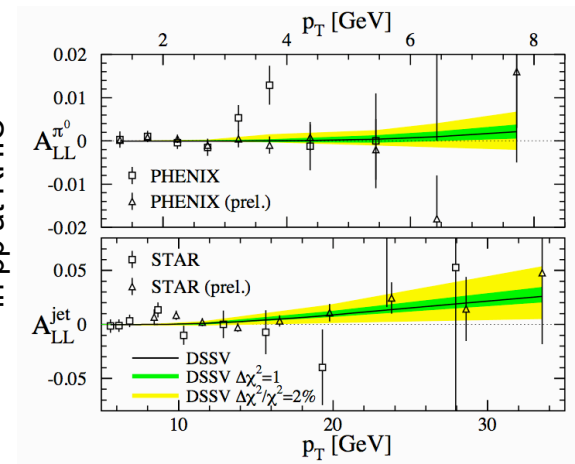


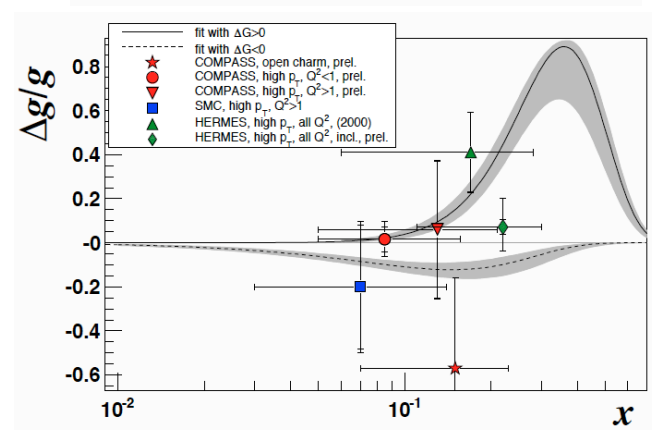
DSSV: PRL 101, 072001 (2008)





Asymmetries in pp at RHIC



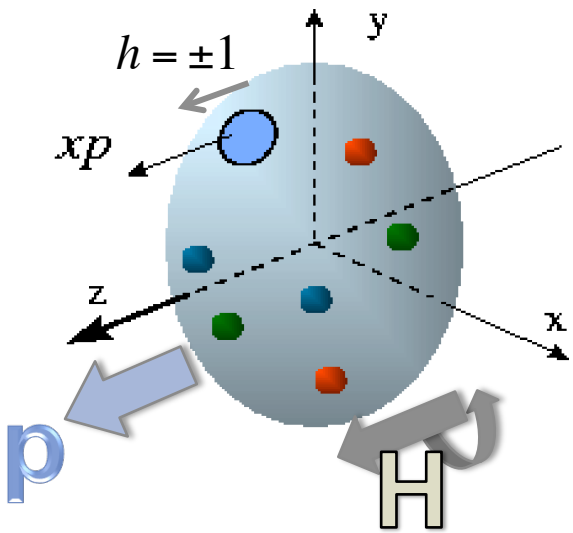


WHAT'S MISSING?

- **$\Delta u/u$ and $\Delta d/d$ at high *x* still poorly constrained**
- **What is happening with the strange sea polarization? >0? =0? <0? Zero crossing? (Tension DIS – SIDIS)**
- **Is the sea polarization isospin-symmetric? (note: we already know $\bar{u} \neq \bar{d}$)**
- **Gluon helicity distribution at large *x* and a small *x*? What is the integral ΔG?**
- **What happens at really small x << 0.01?**
- **… and where is the rest of the nucleon spin? (only 30-40% explained by quark helicities)**
  Orbital angular momentum of quarks, total angular momentum carried by gluons…

BEYOND THE 1-D PICTURE

What would we LIKE to observe?

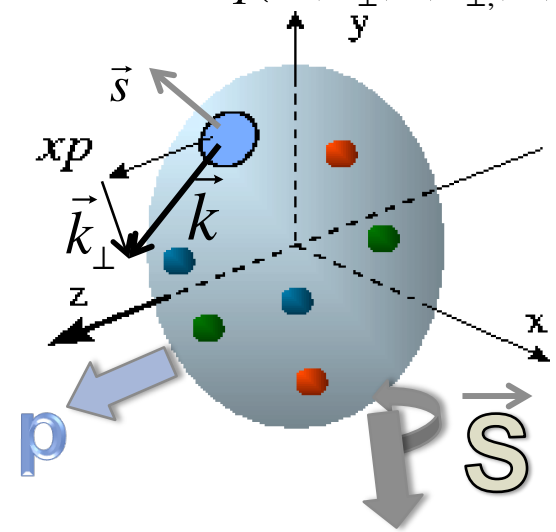


$$q(x, h \cdot H; Q^2)$$

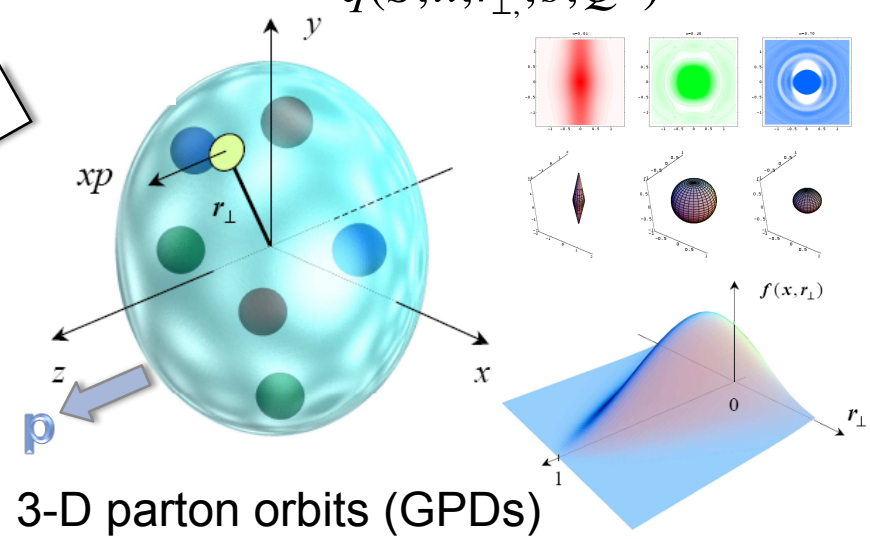
Traditional "1-D" Parton Distributions (PDFs)
(inclusive, integrated over many variables)

3-D Picture of parton flavor, spin and momentum (TMDs)

$$q(H, \vec{S}_\perp, x, \vec{k}_\perp, h, \vec{s}_\perp; Q^2)$$



$$q(\vec{S}, x, \vec{r}_\perp, \vec{s}; Q^2)$$



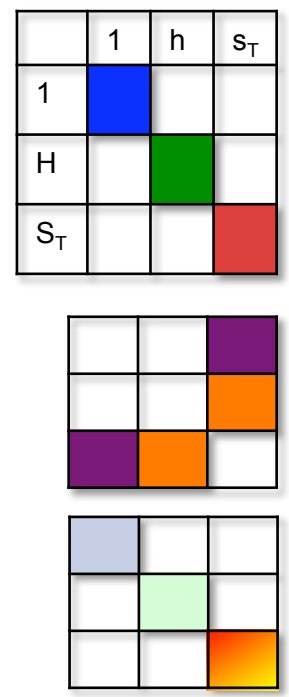
3-D parton orbits (GPDs)

BEYOND INCLUSIVE:

What CAN we observe?

Example: TMDs

- Have 2 pseudoscalars (h, H), 2 vectors $(\hat{z}, \vec{k}_\perp)$ and 2 axial vectors $(\vec{S}_\perp, \vec{s}_\perp)$
- Observables depend on x (and Q^2) and must be scalars!
- 3 possibilities without $\vec{k}_\perp$:
  - 1 (ordinary PDFs ⇒ unpolarized structure function F_1)
  - $H \cdot h$ (helicity PDFs ⇒ spin structure function g_1)
  - $\vec{S}_\perp \cdot \vec{s}_\perp$ (transversity PDFs/structure function h_1)
- 4 possibilities linear in $\vec{k}_\perp$:
  - $H\left(\vec{k}_\perp \cdot \vec{s}_\perp\right)$, $h\left(\vec{k}_\perp \cdot \vec{S}_\perp\right)$ ("Worm gear" PDFs g_{1T}, $h_{1L}{}^\perp$)
  - $\vec{S}_\perp \cdot \left(\vec{k}_\perp \times \hat{z}\right)$, $\vec{s}_\perp \cdot \left(\vec{k}_\perp \times \hat{z}\right)$ (Sivers, Boer-Mulders PDFs $f_{1T}{}^\perp$, $h_1{}^\perp$)
- Further possibilities quadratic in $\vec{k}_\perp$:
  - "Pretzelosity" $h_{1T}{}^\perp \left(\vec{k}_\perp \cdot \vec{S}_\perp\right) \cdot \left(\vec{k}_\perp \cdot \vec{s}_\perp\right) - \frac{1}{2}\left(\vec{S}_\perp \cdot \vec{s}_\perp\right)\vec{k}_\perp^2$
  - $(k_\perp)^2$ moments of the first three!

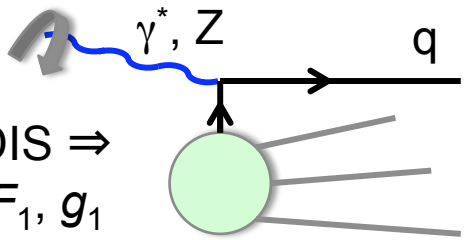


Preferably all sorted by quark flavor and for gluons, as well!

TOWARDS A COMPLETE PICTURE:

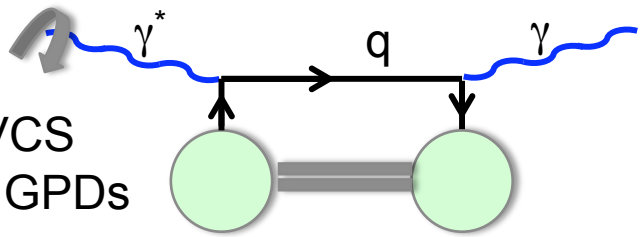
HOW can we access it?

Electroweak Probe to “see” partons…



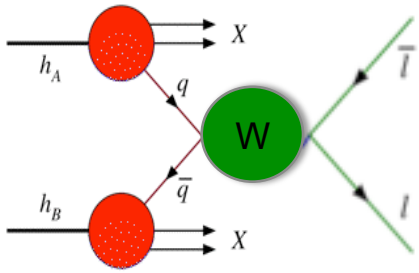
DIS ⇒
F_1, g_1

(1D only, no flavor tagging)

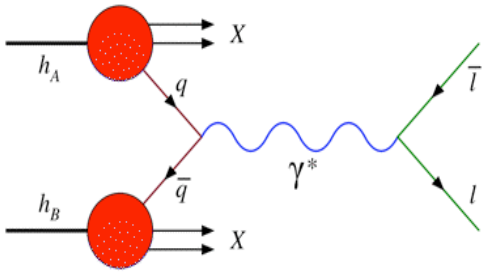


DVCS
⇒ GPDs

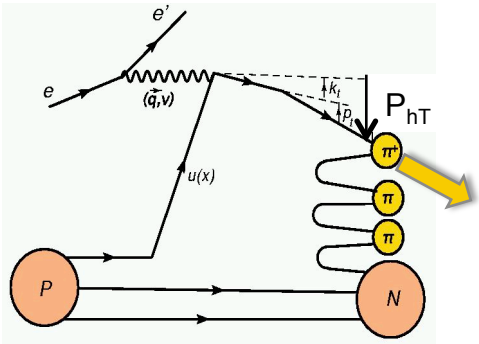
W production



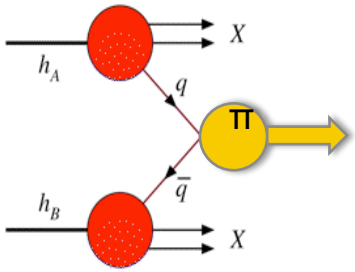
…+ extra hadrons to access all observables:



Drell-Yan

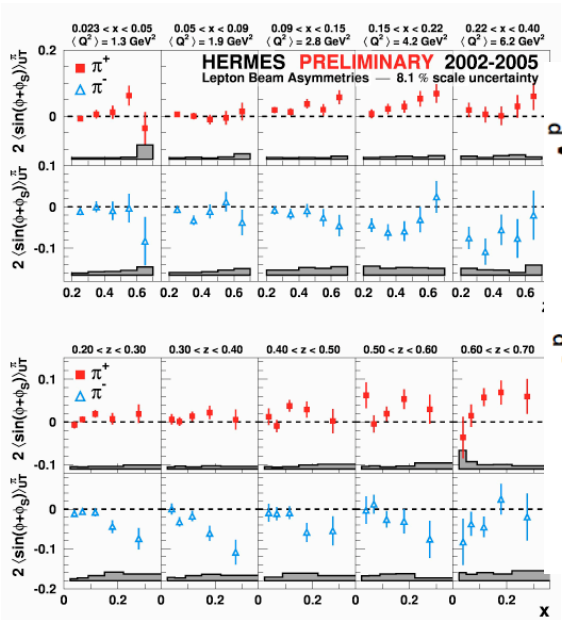


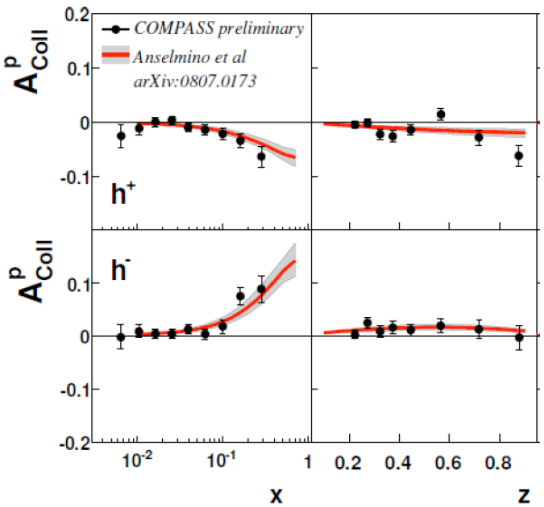
SIDIS

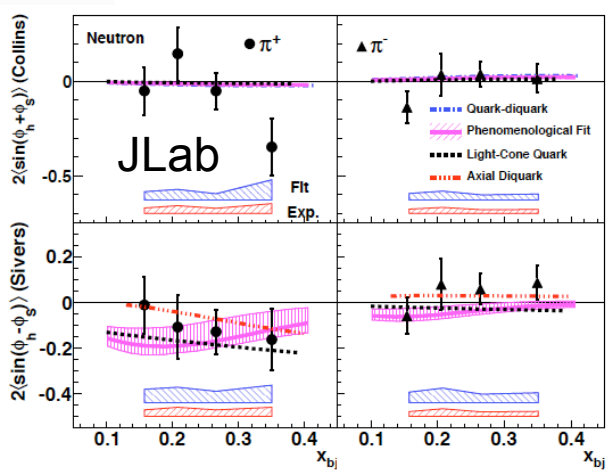


Hadron Production

THE PRESENT SITUATION - TMDS

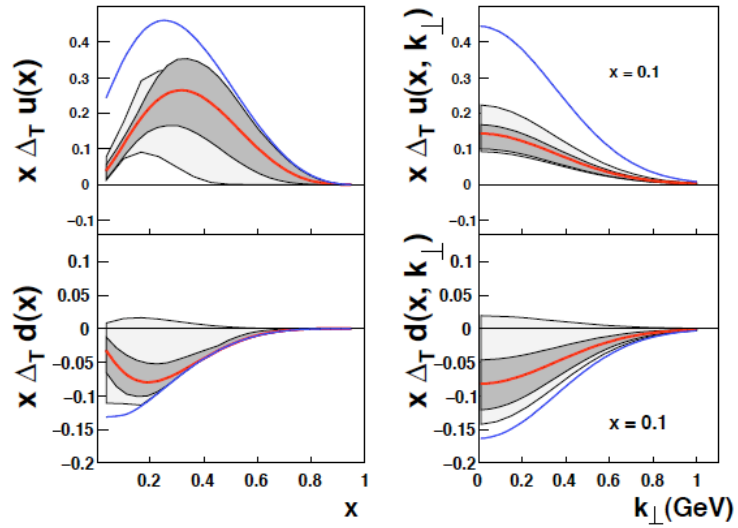




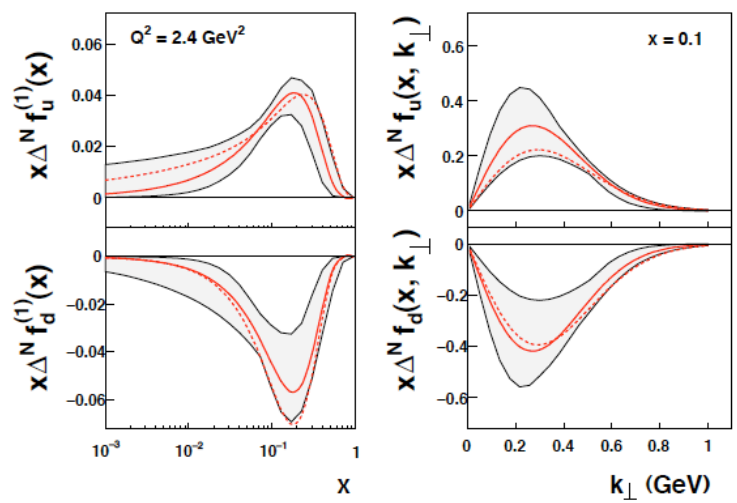


A full program to measure 8 TMDs has just begun…

Fit by Anselmino et al.



Transversity



Sivers Functions

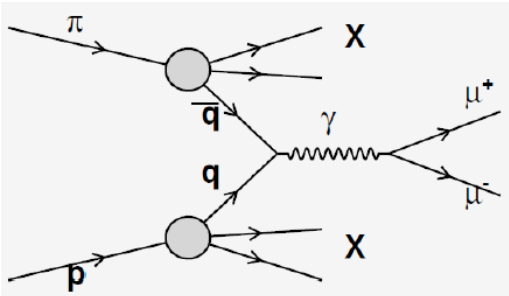
WHAT'S MISSING?

- Tensor charge of the nucleon (analog to vector and axial charges)
- Full mapping of all 11 TMD PDFs as a function of quark flavor in the valence region
- Test of universality
- Test of prediction that time-odd TMDs (e.g., Sivers asymmetry) change sign in Drell-Yan processes
- TMDs of sea quarks and gluons
- Towards a "wave function" of the nucleon including angular orbital momentum
  (Wigner distribution? Lattice comparison?)

THE FUTURE PROGRAM WITH COMPASS

- **More statistics on TMDs (Data 2010 on transverse p)**
- **More statistics on A_{1p} (inclusive and tagged) (Data 2011)**

- **COMPASS-II: Focus on transverse structure of the nucleon**
- **GPDs: towards orbital angular momentum**
- **Drell-Yan: Measure TMDs like Sivers, Boer-Mulders, "worm-gear", "pretzelocity"**



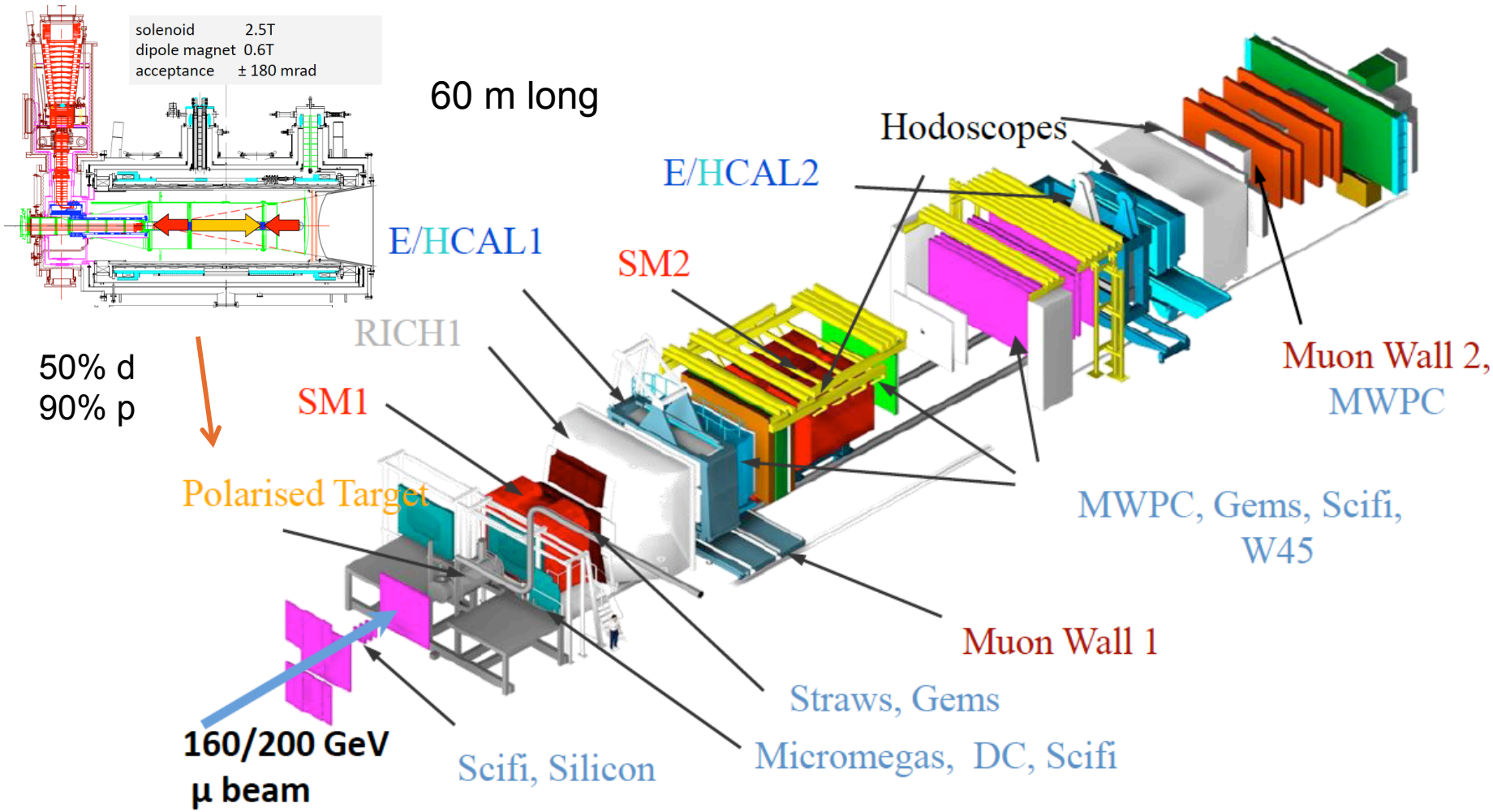
- **First two are T-odd: Should reverse sign in Drell-Yan => test!**

$$f_{1T}^{\perp}\Big|_{DY} = -f_{1T}^{\perp}\Big|_{DIS} \quad \text{and} \quad h_1^{\perp}\Big|_{DY} = -h_1^{\perp}\Big|_{DIS}$$

Sivers Boer-Mulders

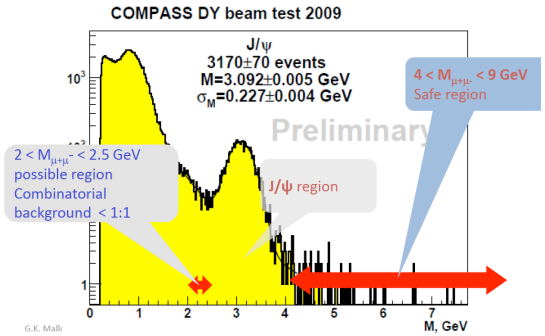
THE COMPASS SPECTROMETER

…will be upgraded for COMPASS II

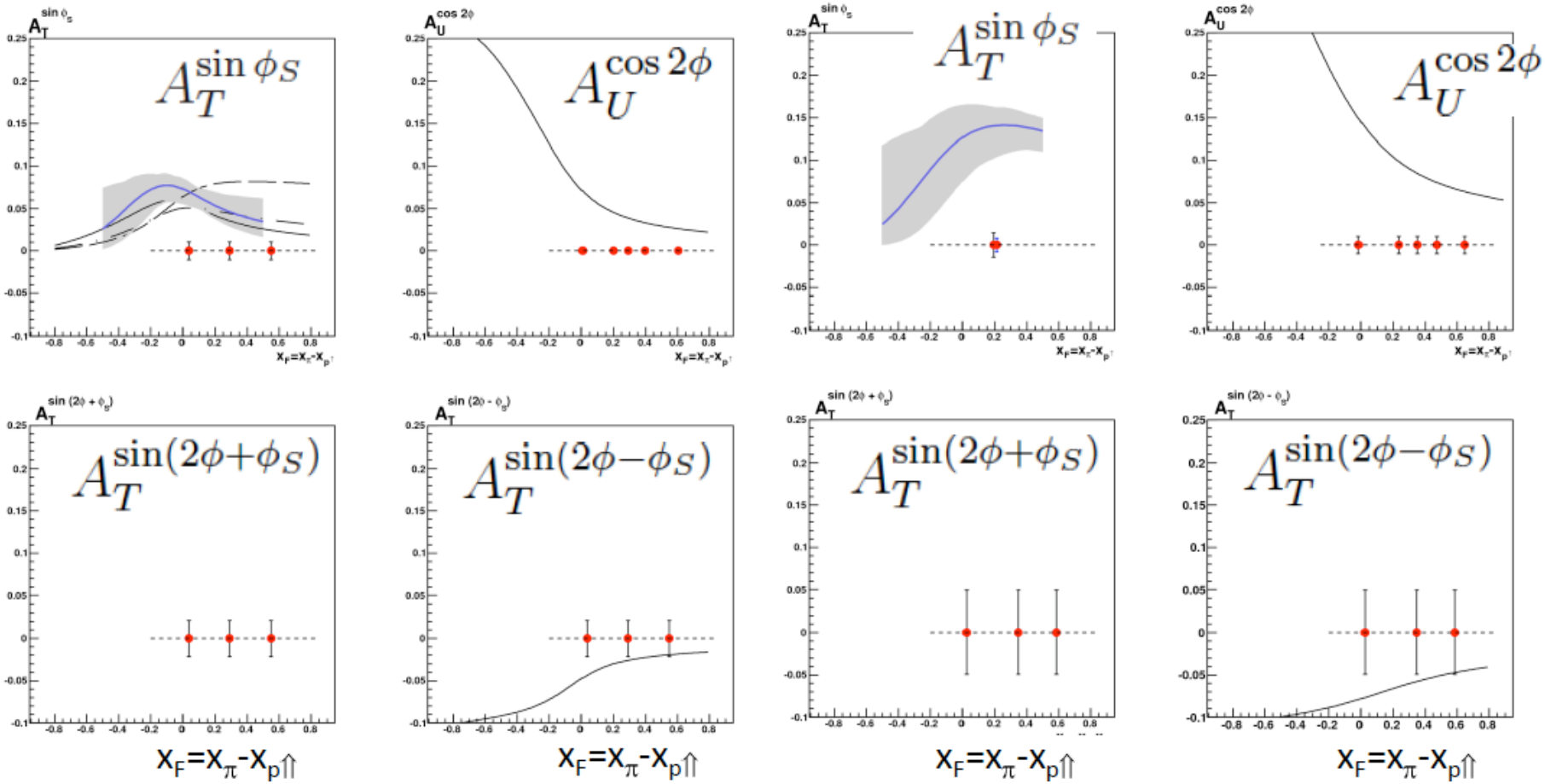


Polarization ≈ 75% from weak pion decay

DRELL-YAN (2014?)



$2.0 \leq M_{\mu\mu} \leq 2.5\ \mathrm{GeV/c^2}$ $\qquad$ $4. \leq M_{\mu\mu} \leq 9.\ \mathrm{GeV/c^2}$



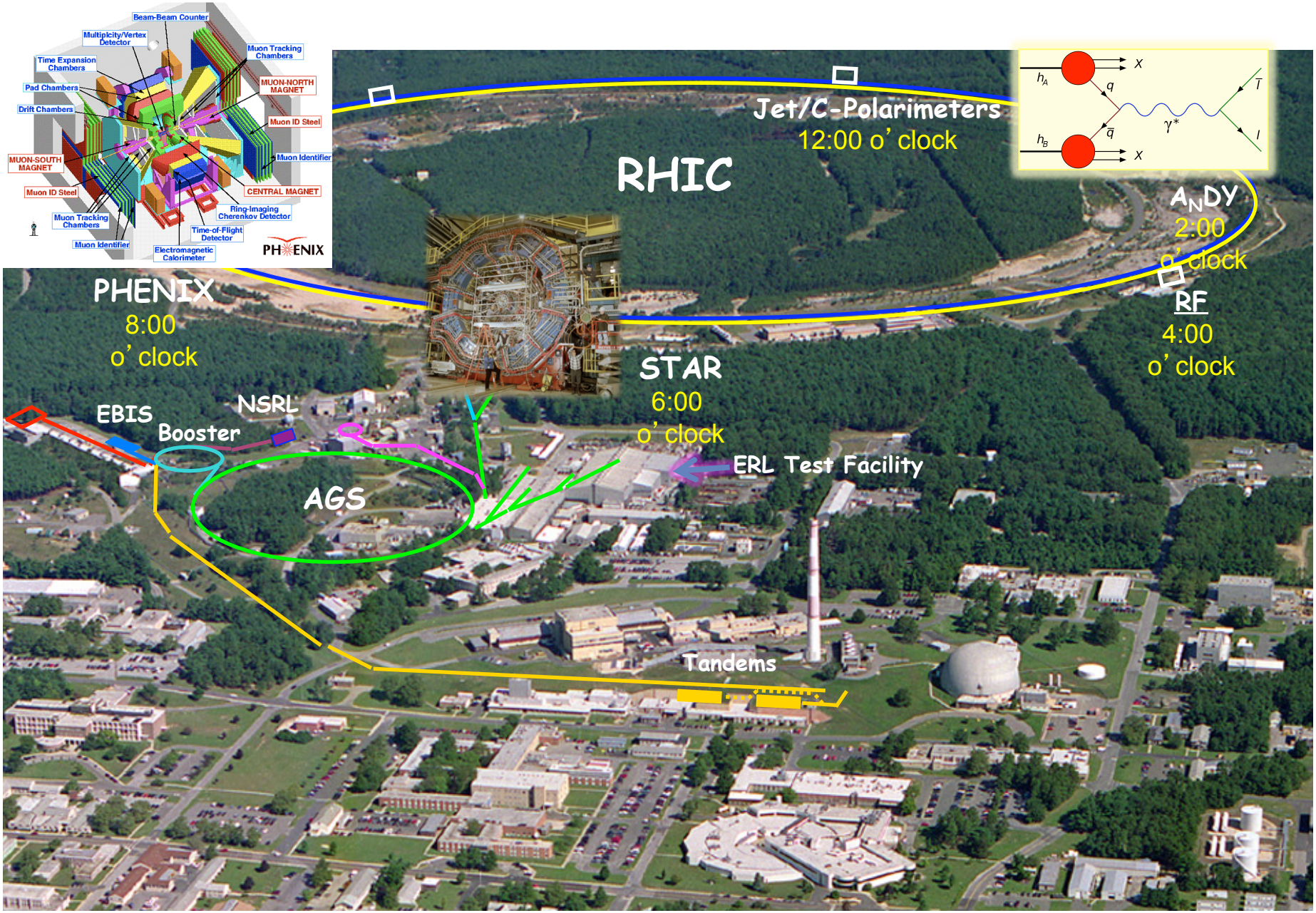
PP PROGRAM AT RHIC (ca. 2012 – 2015)

RHIC: expected to increase Pol. (50% -> 65%), lumi (x3 ?)

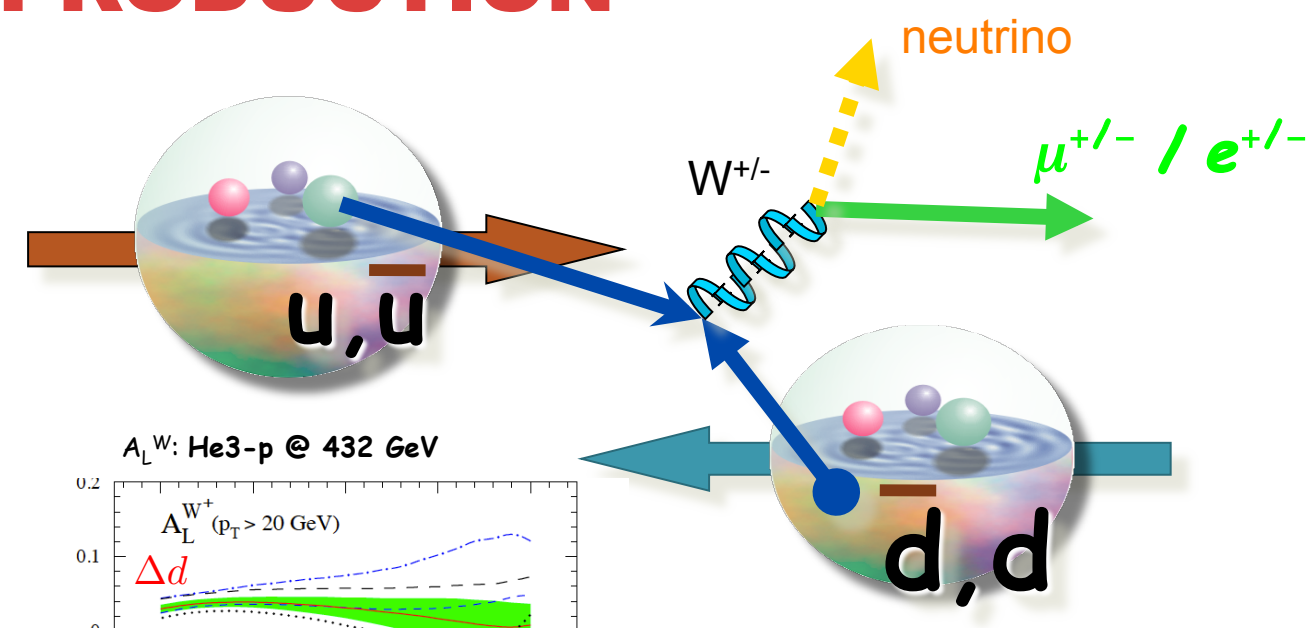
STAR + PHENIX upgrades complete for 2012

- **Extend *x*-range for measurements of ΔG:**
  - Asymmetric final state (π, η, γ, jets, …)
  - Higher CM energy
- **(Anti)quark polarization through W production**
- **pp collisions with single transverse spin -> TMDs, FFs (jet, dijet, dihadron production); universality?**
- **Polarized Drell-Yan**

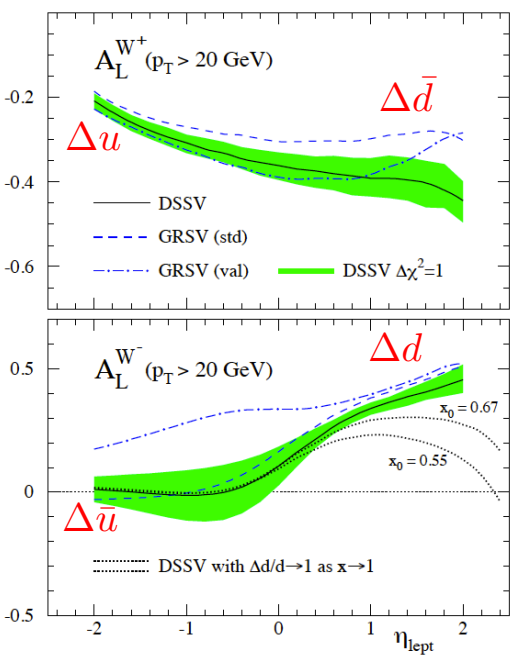
AnDY: test bed for Drell-Yan experiment to measure SSAs


Beam-Beam Counter
Multiplicity/Vertex Detector
Time Expansion Chambers
Pad Chambers
Drift Chambers
Muon Tracking Chambers
MUON-NORTH MAGNET
Muon ID Steel
Muon Identifier
MUON-SOUTH MAGNET
Muon ID Steel
CENTRAL MAGNET
Ring-Imaging Cherenkov Detector
Muon Tracking Chambers
Time-of-Flight Detector
Muon Identifier
Electromagnetic Calorimeter
PHENIX
PHENIX
8:00
o' clock
RHIC
Jet/C-Polarimeters
12:00 o' clock
A_N DY
2:00
o' clock
RF
4:00
o' clock
STAR
6:00
o' clock
EBIS
Booster
NSRL
AGS
ERL Test Facility
Tandems

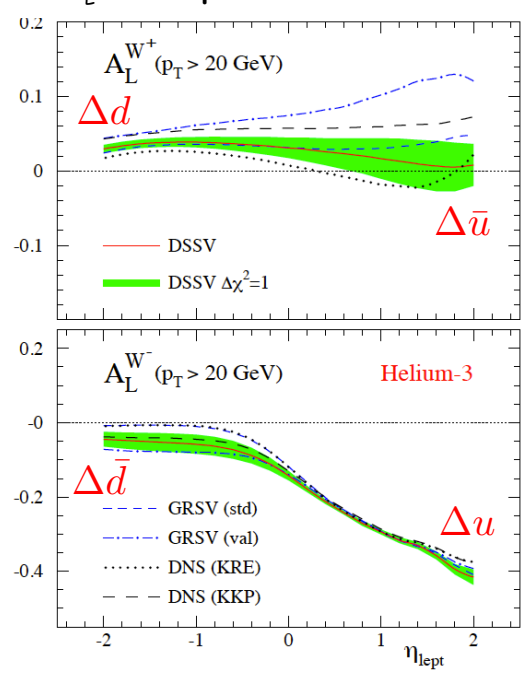
FLAVOR SEPARATION USING W PRODUCTION



A_L^W: pp @ 500 GeV



A_L^W: He3-p @ 432 GeV

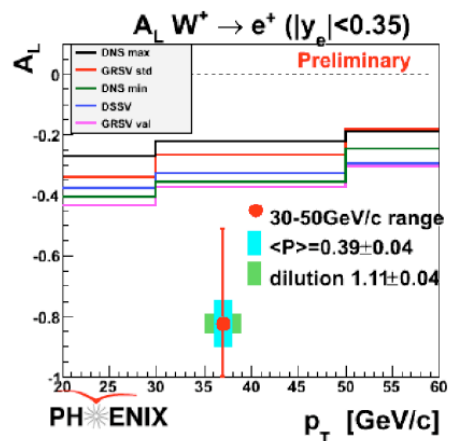


Since W production is maximally parity violating → W's couple only to one parton helicity
large Δu and Δd *result in* large asymmetries.

EXPECTED RESULTS

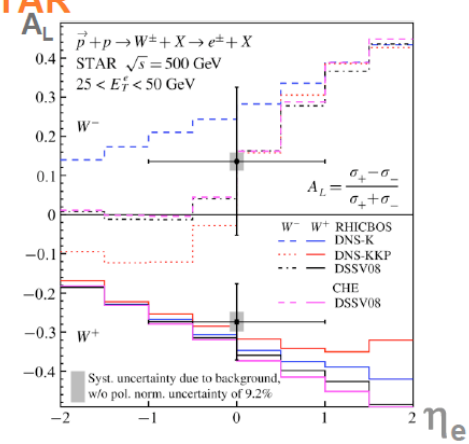
Present Situation:

PHENIX



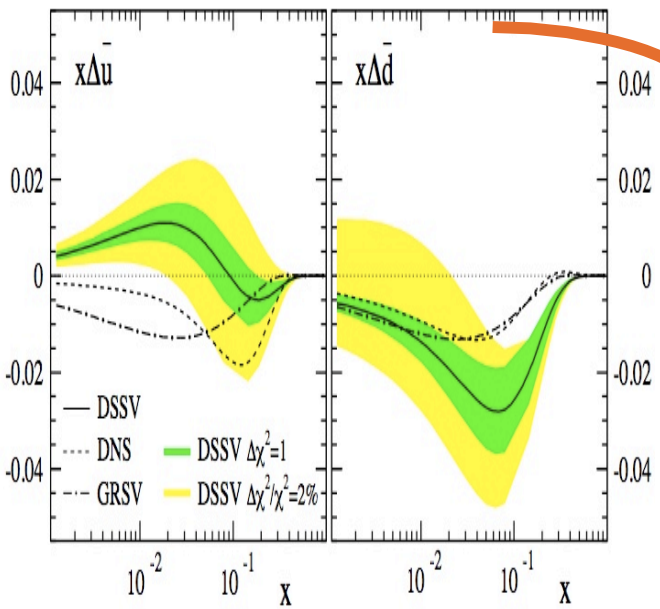
J. Haggerty ICHEP2010

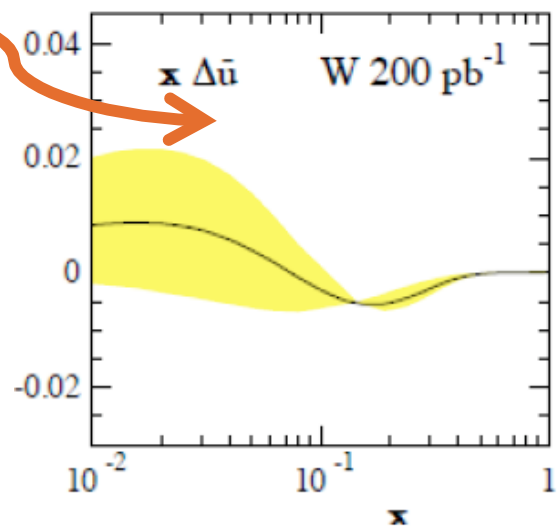
STAR

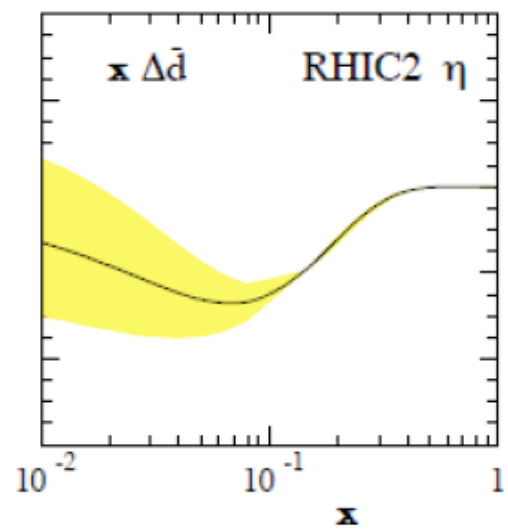


Phys.Rev.Lett. 106 (2011) 062002

Goal

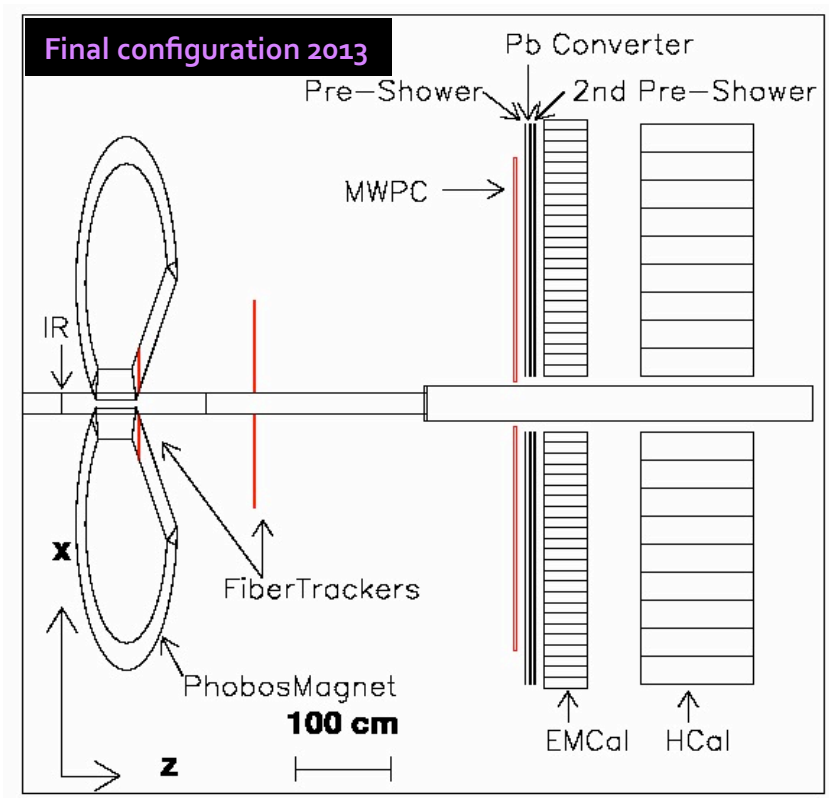


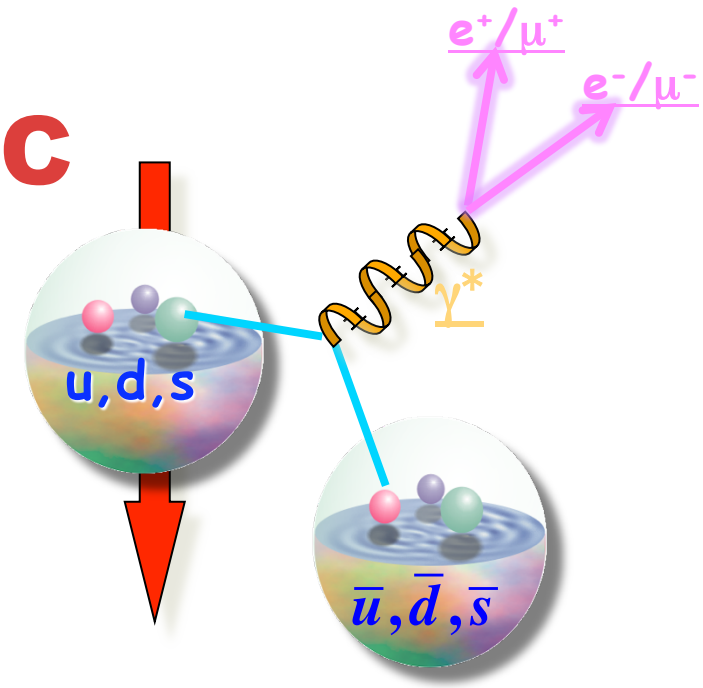




DRELL YAN AT RHIC

A_NDY @ IP-2





- Idea: have DY feasibility test at IP-2
  - staged measurements over 3 years
  - re-use as much detector equipment as possible to finish till summer 2014
- Measurement:
  - why IP-2
    - ✓ transverse polarization
    - ✓ measure parallel to $\sqrt{s}$ = 500 GeV W-program
  - η > 3, M>4 GeV $0.1<x_f<0.3$
  - → optimizes Signal / Background & DY rate
  - → measure δA_N^{DY} ~0.015 for $\int L$~100 pb^{-1}
- Proposal approved June 2011 BNL PAC

JEFFERSON LAB

CLOSE-OUT 6 GeV

- **Finish analysis on CLAS eg1-DVCS (SSAs + DSAs in $\pi^{+/0/-}$ production with longitudinally polarized H and D targets) and EG4 (SSFs at low Q^2)**
- **g_{2p} at low Q^2 (Hall A)**
- **Test electron run on HD-ICE**

12 GEV PROGRAM (6.6, 8.8 and 11 GeV in Halls A/B/C)

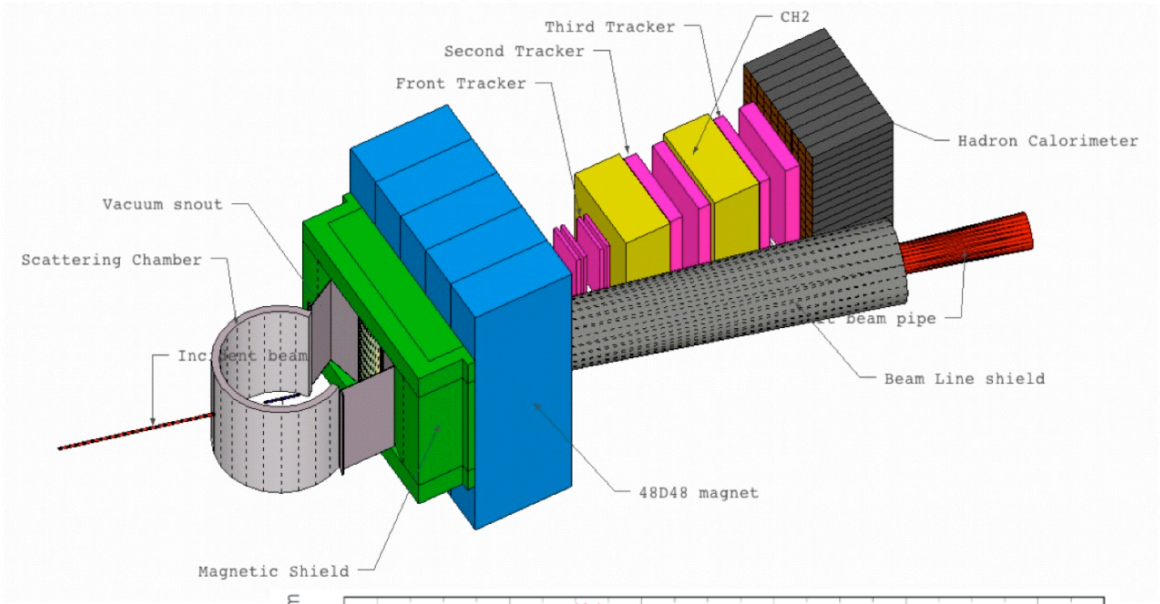
- **Inclusive SSFs on p, d, n (^{3}He) in all 3 Halls**
- **Tagged SSFs and TMDs on p, d, n (^{3}He) in all 3 Halls (including Kaons)**

GOAL: Complete map of all PDFs in the valence region $x > 0.1$

NEW CAPABILITIES – HALL A

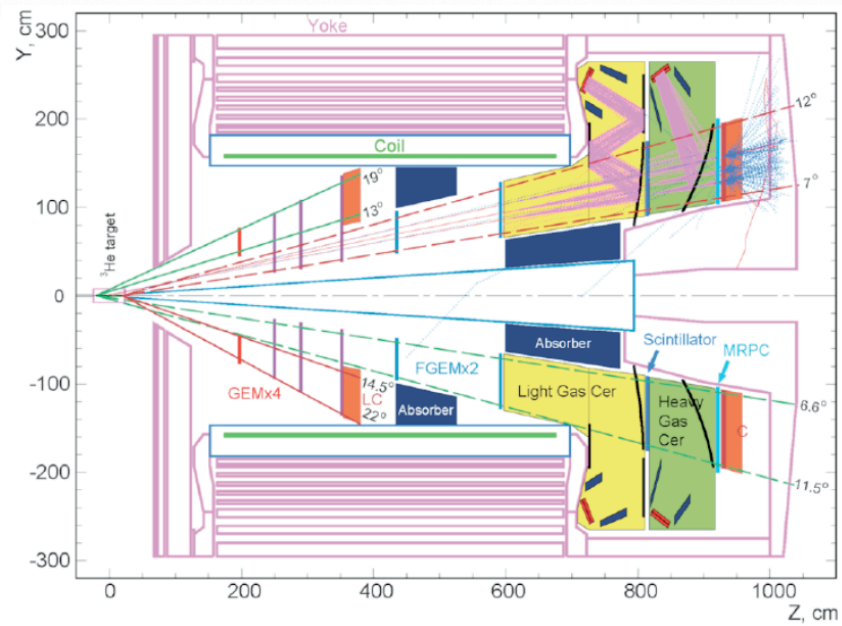
Super Big Byte

- (Moderately) large acceptance
- Full PID (K and π)
- Well-matched to high-luminosity ^{3}He target

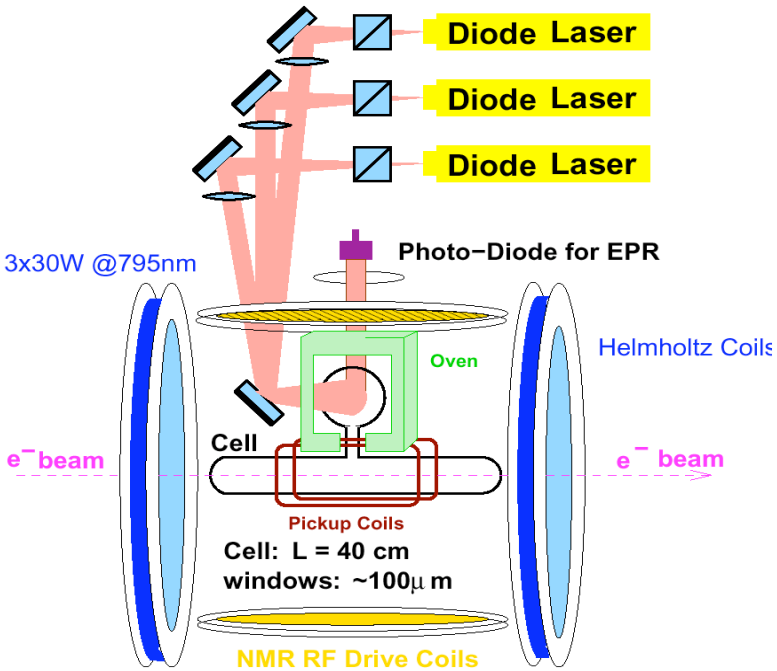


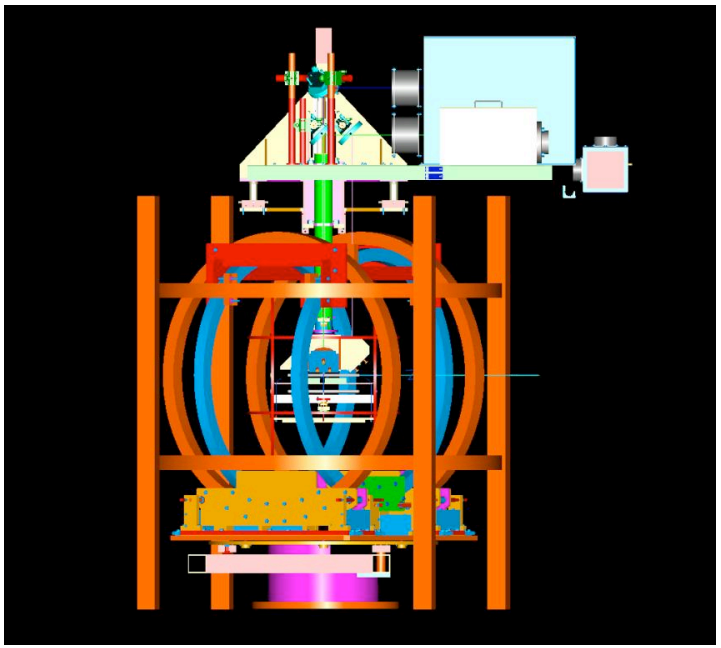
SoLID

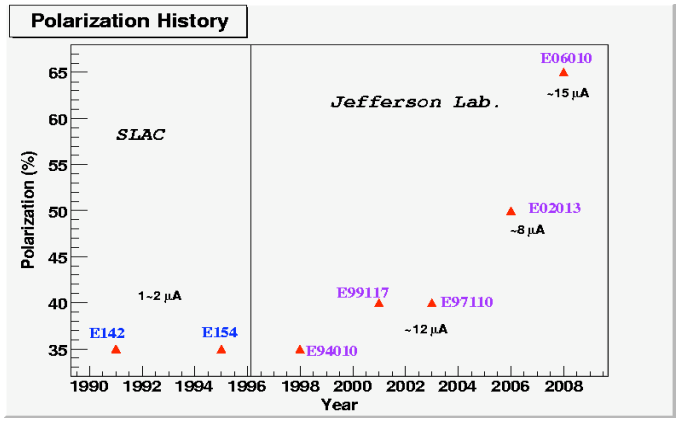
- Large acceptance (2π)
- Kinematic coverage out to moderately large P_T
- Capable of quite high luminosity (10^{36} cm^{-2}s^{-1})
- Requires major new funds

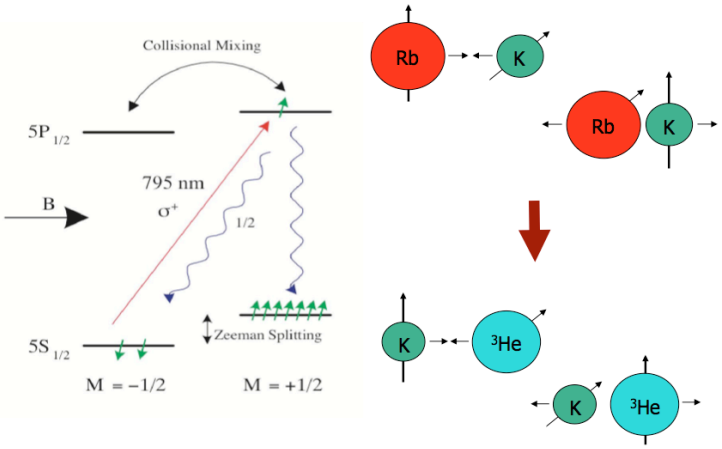


POLARIZED 3HE TARGETS (APPROX. POL. NEUTRON)









NEW CAPABILITIES – HALL B

CLAS12
(see next slide)

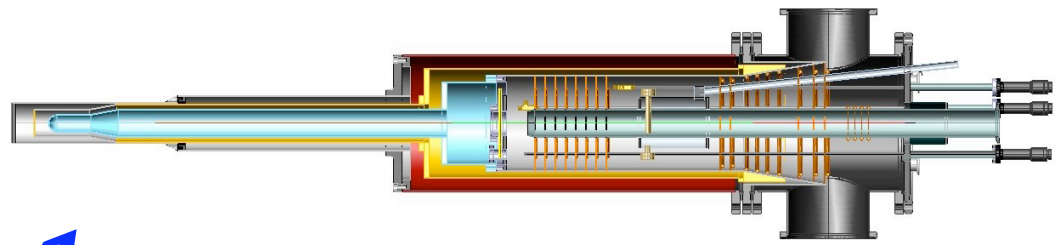
- VERY large acceptance
- Full PID (K and π)
  (K ID requires major new funds for RICH)
- Moderately high luminosity (10^{35} $cm^{-2}s^{-1}$)
  (matched to NH_3, ND_3)

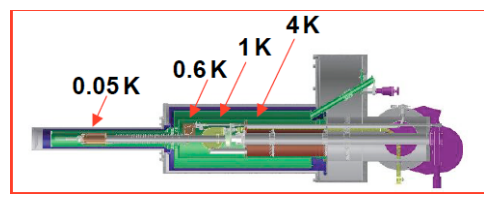
Polarized Targets

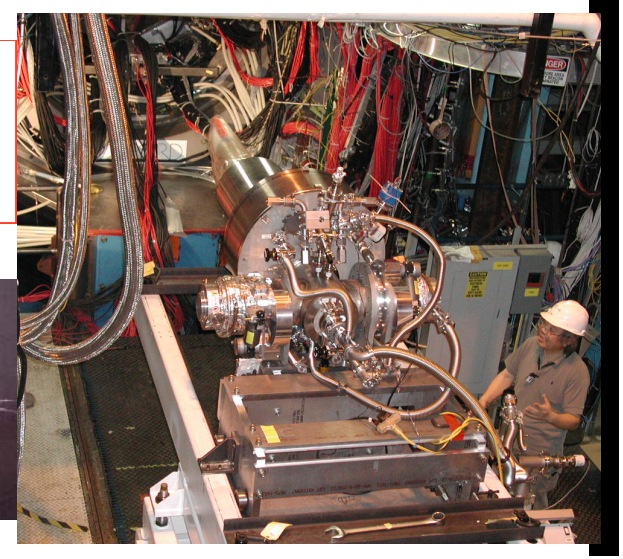
- Standard DNP longitudinal NH_3, ND_3 targets
  (funded by NSF MRI, under construction)
- HD-Ice target
  (suitability for e^- beam remains to be demonstrated)

Future longitudinally polarized target for CLAS12 (11 GeV program at Jefferson Lab)

- Horizontal ^{4}He evaporation cryostat
- 5 T B-field provided by central detector







CLAS12

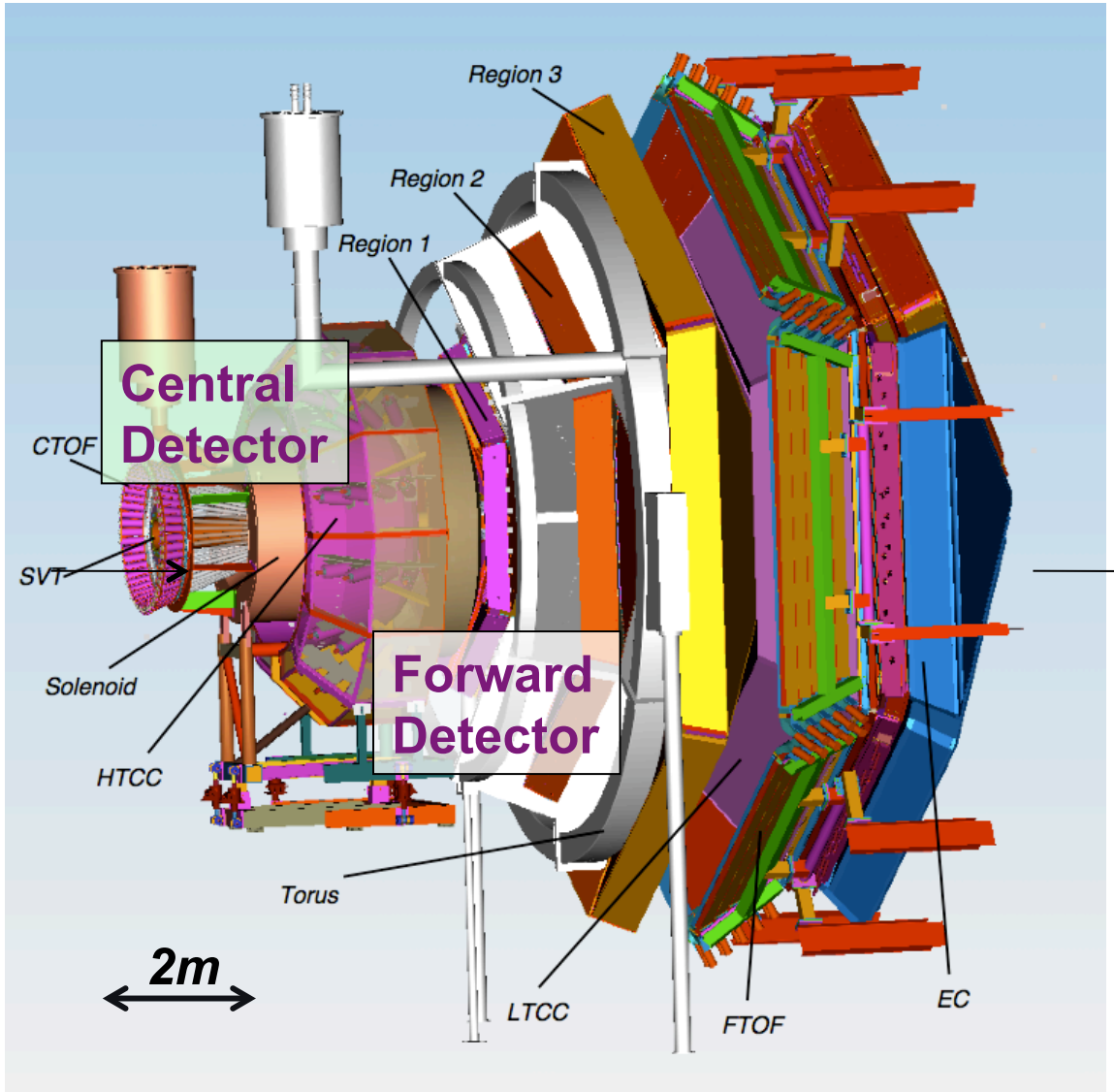
Under construction; expected to begin data taking in 2015 with upgraded 11 GeV beam

Base equipment

- **Forward Detector**
  - TORUS magnet
  - Forward vertex tracker
  - HT Cherenkov Counter
  - Drift chamber system
  - LT Cherenkov Counter
  - Forward ToF System
  - Preshower calorimeter
  - E.M. calorimeter
- **Central Detector**
  - SOLENOID magnet
  - Barrel Silicon Tracker
  - Central Time-of-Flight

Proposed equipment

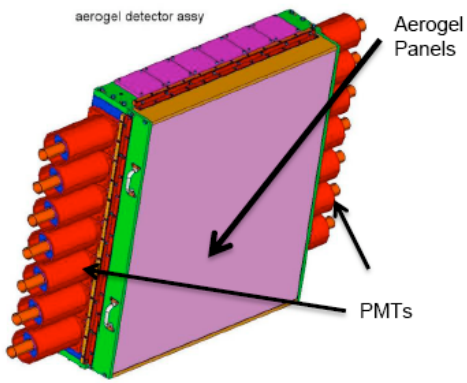
- Micromegas (CD & FD)
- RICH counter (FD)
- Neutron detector (CD)
- Small angle tagger (FD)

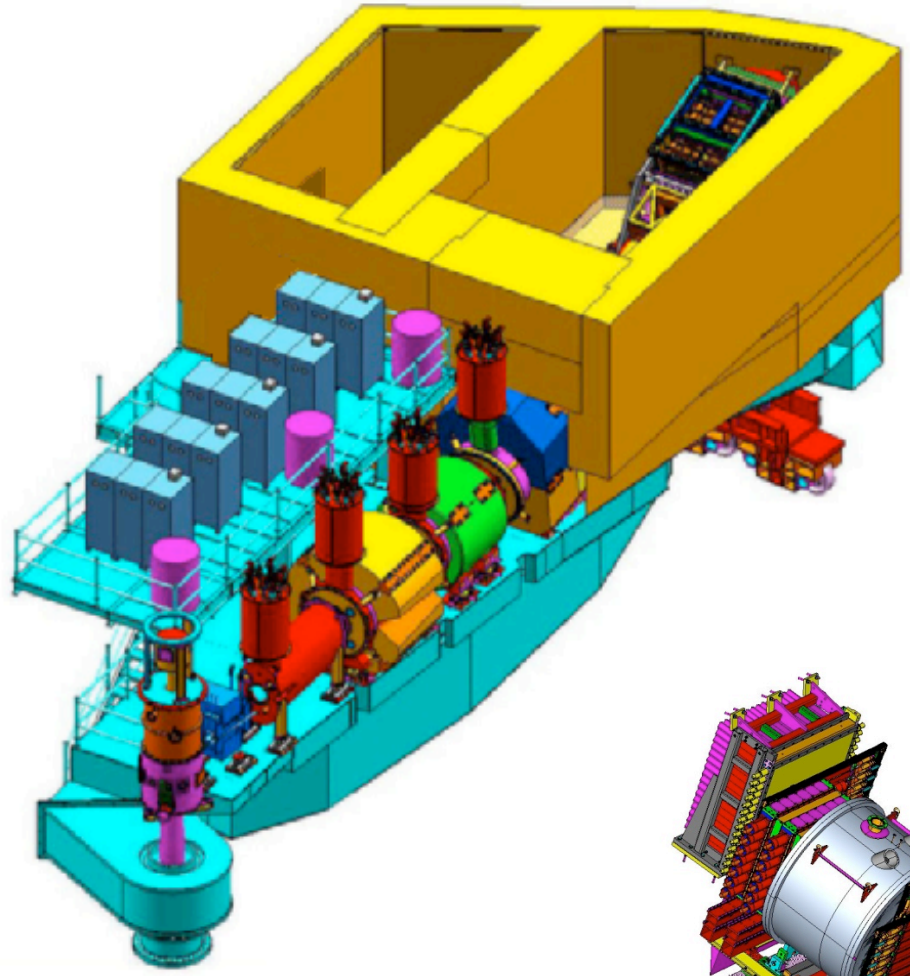


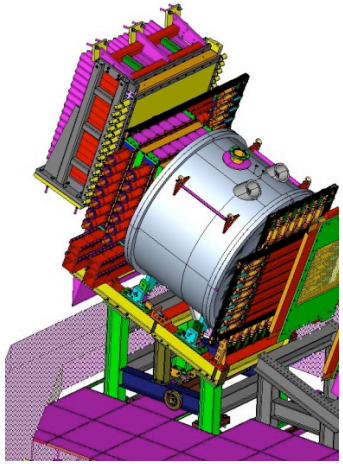
NEW CAPABILITIES – HALL C

Super HMS

- High momentum capability and resolution
- Full PID
- High luminosity polarized ^{3}He target (as in Hall A)

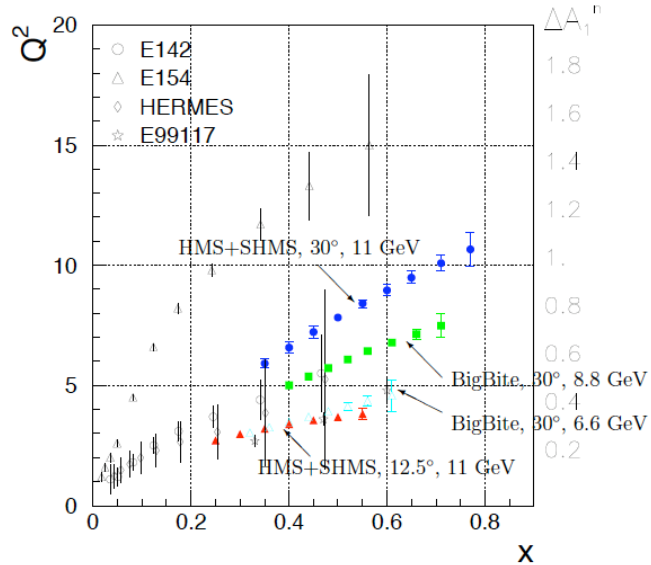




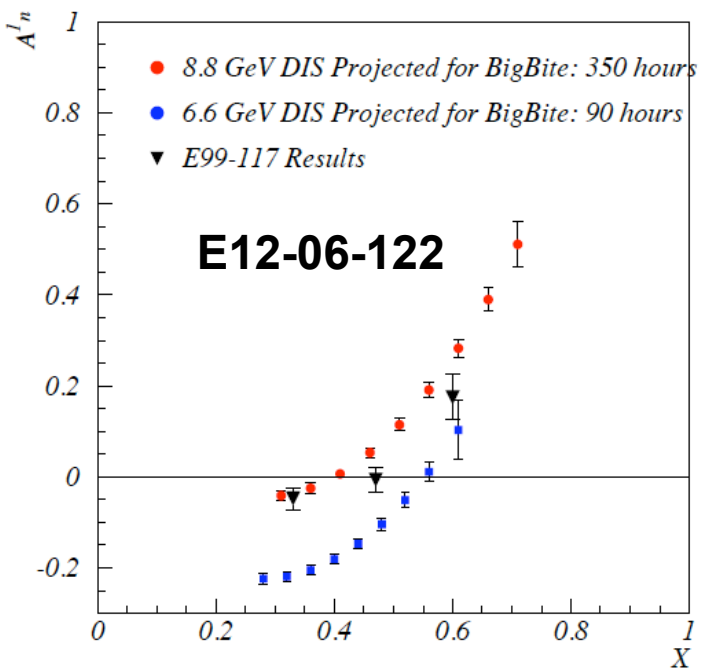


INCLUSIVE SSF – HALLS A/C

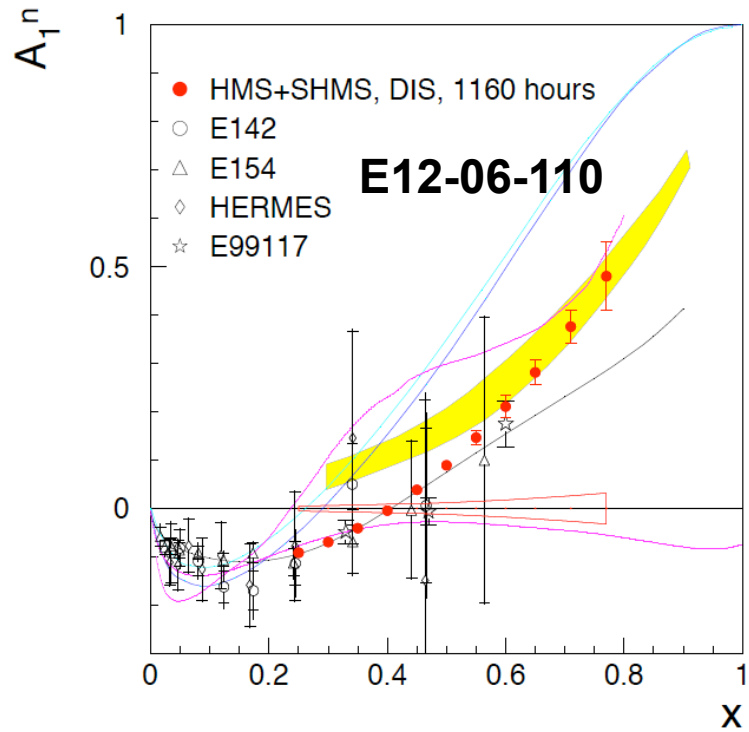
^{3}He -> A_{1n}, g_{1n}
Important constraint on Δd at large *x*



Hall A – BigByte

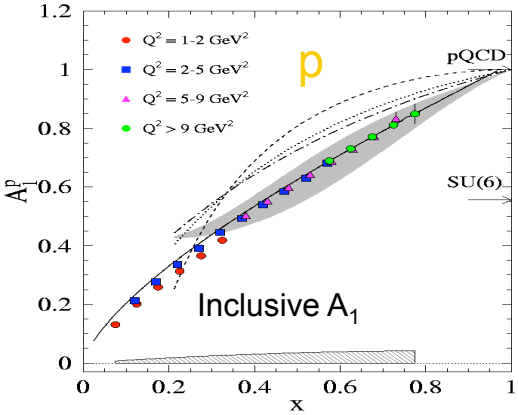


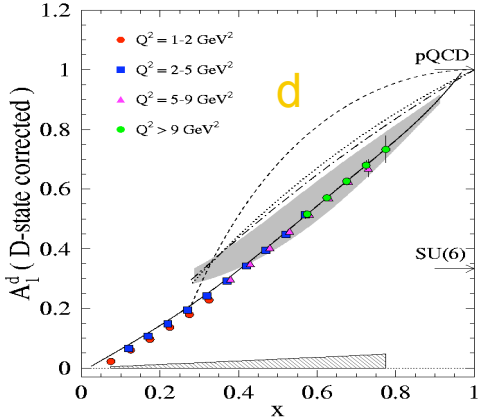
Hall C – SHMS+HMS



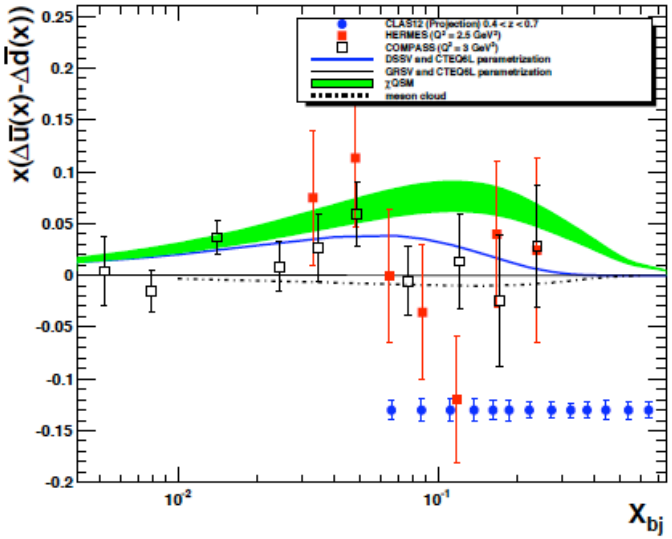
…+ g_{2n}

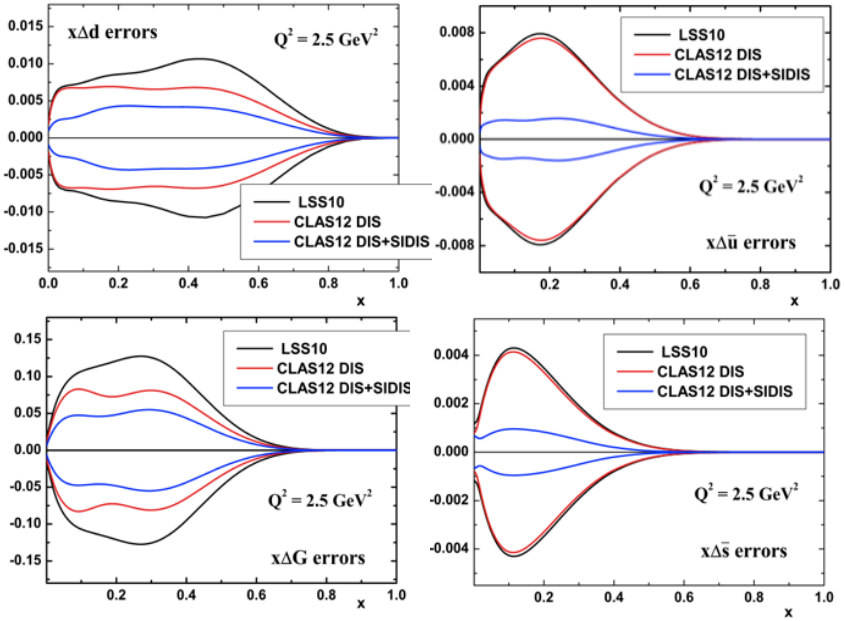
INCLUSIVE + TAGGED SSF – HALL B



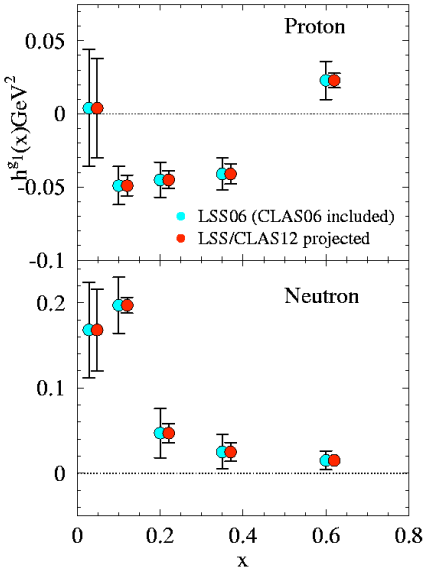


SIDIS A_1

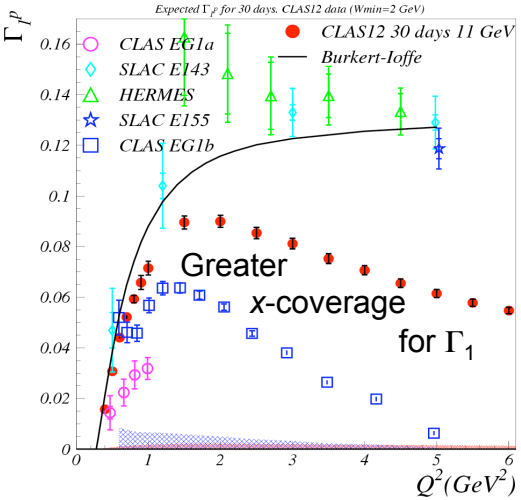




Improved PDFs from NLO analyses



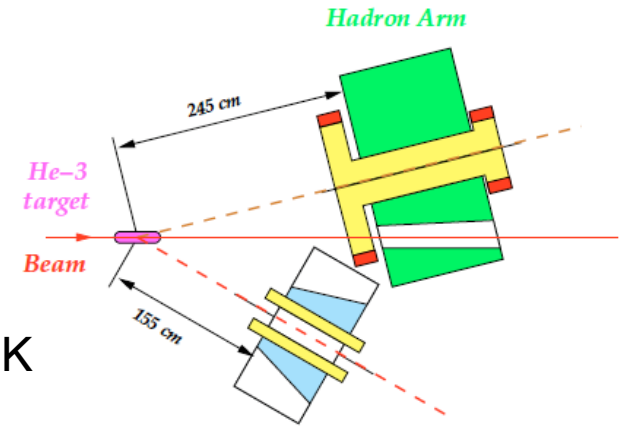
Better determination of Higher Twist vs. *x*



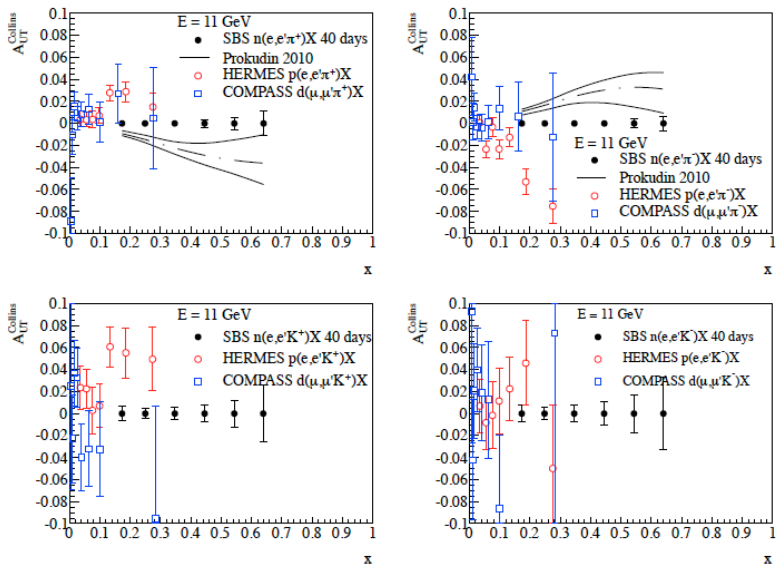
Improved coverage to evaluate moments

TMDS – HALL A

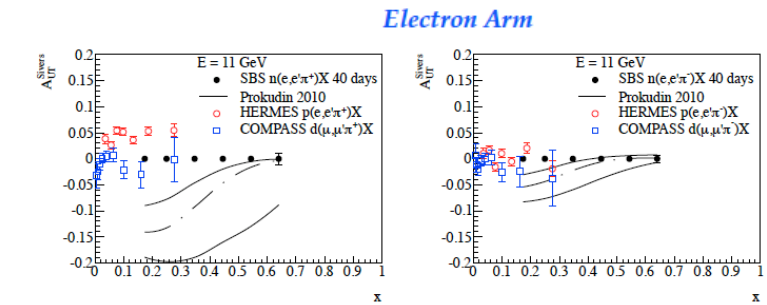
First generation: Use transverse ^{3}He target with Bigbite and Super Bigbite to measure Sivers, Collins (transversity), “worm-gear” and “pretzelosity” SSAs for π and K

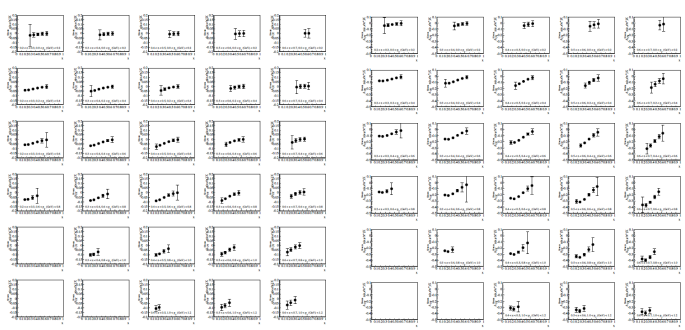


Collins



Sivers





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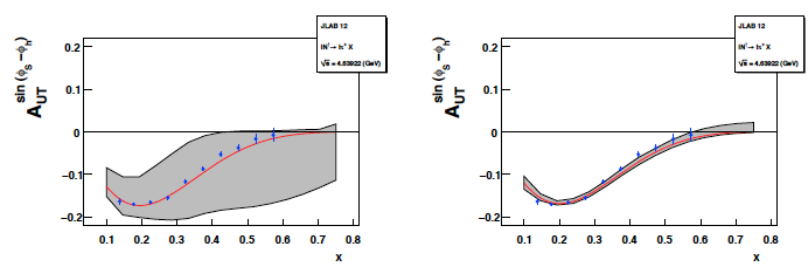


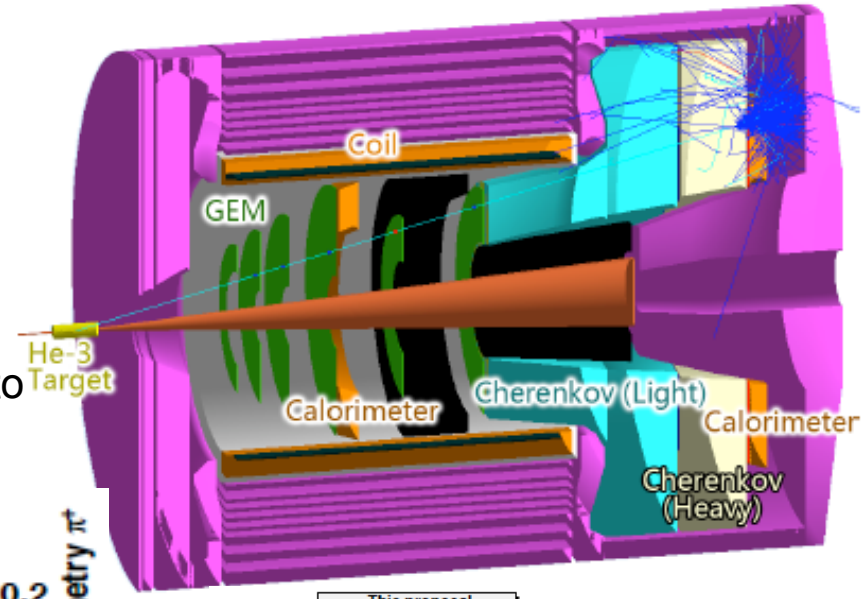
P12-09-018

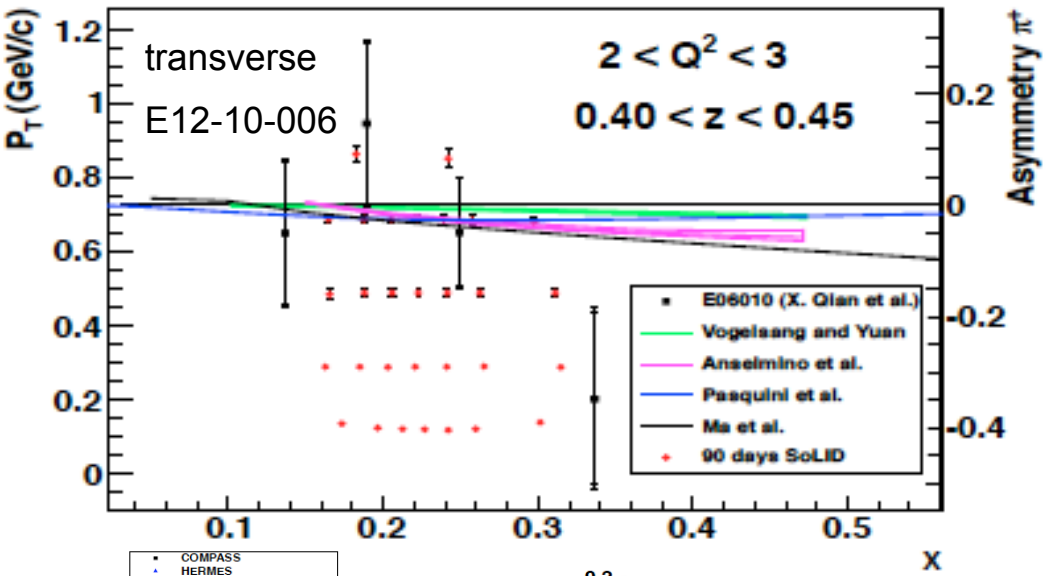
(a) A. Prokudin, 2010 best fit.

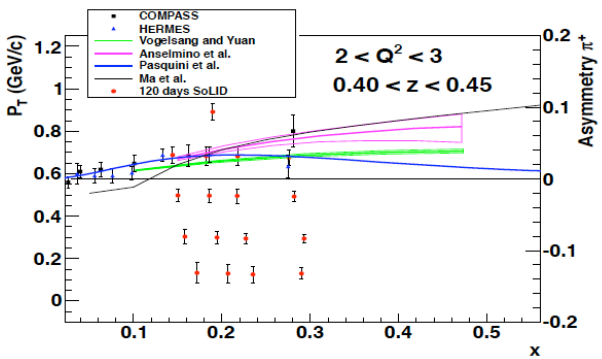
(b) Projected uncertainty band, *20* days $n(e,e'\pi^+)X$ at $E = 11$ GeV.

TMDS – HALL A

Later on: Use longitudinal and transverse ^{3}He target (and perhaps transverse p) with SoLID to measure all SSAs (TMDs) for π



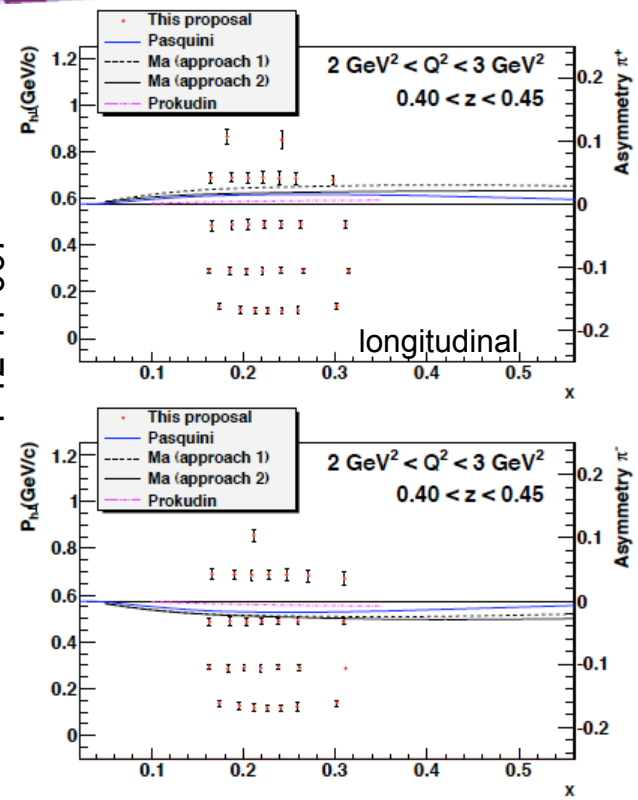




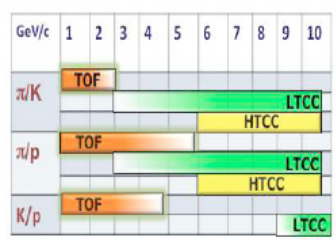
Proton

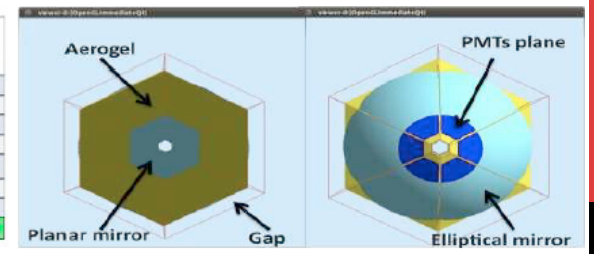
P12-11-108

P12-11-007



TMDS – CLAS12



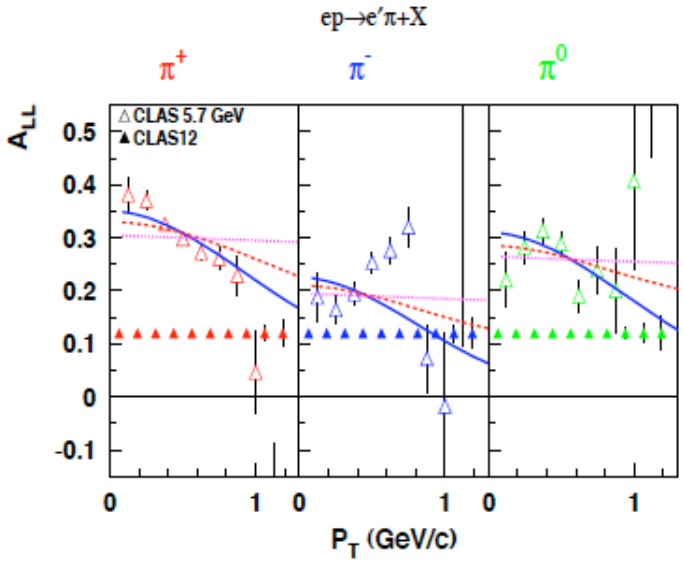


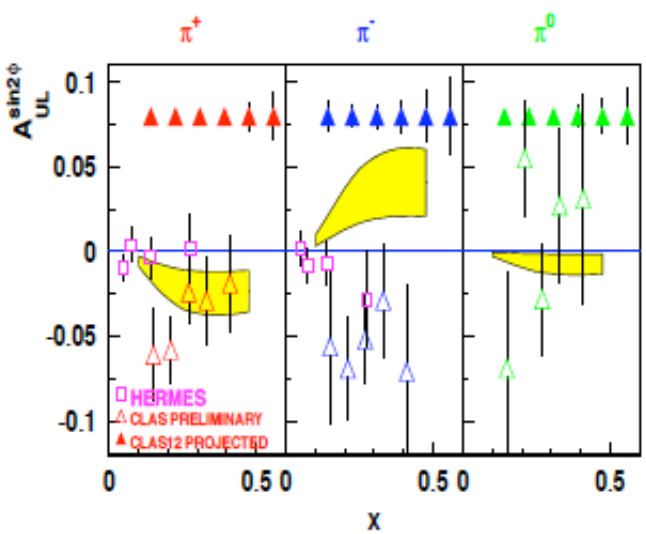
Comprehensive Program with **Longitudinal** and **Transverse** H, D targest

	Experiment	Quantity	Physics	Target	particle species	Kinematics	beam request	run group
Worm gear, HT	E12-07-107	$A_{UL}^{\sin\varphi}$ $A_{UL}^{\sin 2\varphi}$		NH_3 ND_3	π^+, π^-, π^0	x= 0.1-0.7 P_T=0.1-1.2	30 days 50 days	
Flavor tagging (Δq); pT dep.	E12-09-007b	$\Delta u, \Delta d, \Delta s$ $\Delta u, \Delta d, \Delta s$	$x(\Delta u-\Delta d)$	NH_3 ND_3	π^+, π^-, π^0 K^+, K^-, K^0_s	x=0.1-0.7	30 days 50 days	**170 days**
Kaons Worm gear	E12-09-009	A_1 $A_{UL}^{\sin\varphi}$ $A_{UL}^{\sin 2\varphi}$		NH_3 ND_3	π^+, π^-, π^0 K^+, K^-, K^0_s	Q^2= 1 - 9 x=0.1-0.7 P_T= 0.1-1.2	30 days 50 days	
Two-Hadron (Deferred)	PR12-11-109b	A_{UL}	h_L	NH_3 ND_3	$\pi\pi$, KK	x=0.05-0.6	30 days 50 days	
Transversity, Sivers, Worm Gear, Pretzelosity	PR12-11-111	SIDIS A_{UT}	Sivers, Transversity Pretzelosity	HD	π^+,π^-,π^0 K^+, K^-, K^0_s	Q^2=1-10GeV^2 x=0.1-0.7 P_T=0.2-1.5	100 days	**100 days**

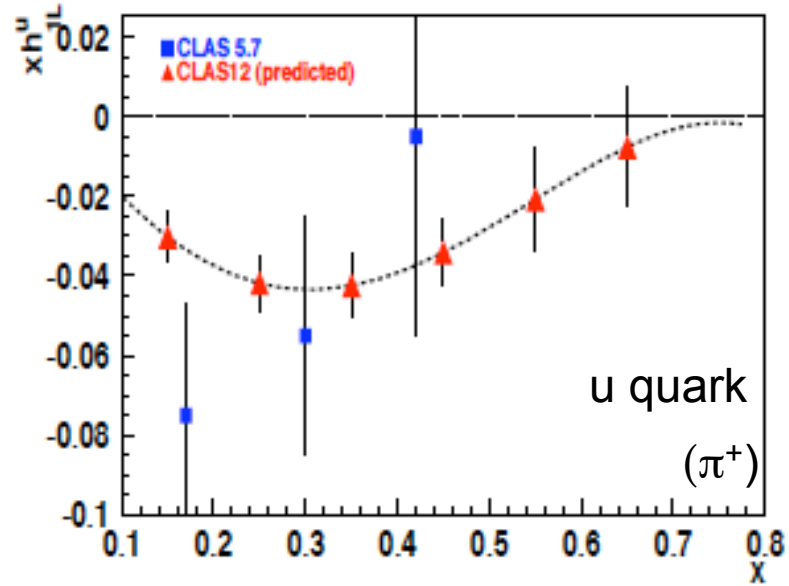
TMDS – CLAS12 (LONG. POL. P,D)

A_1 p_T distr.

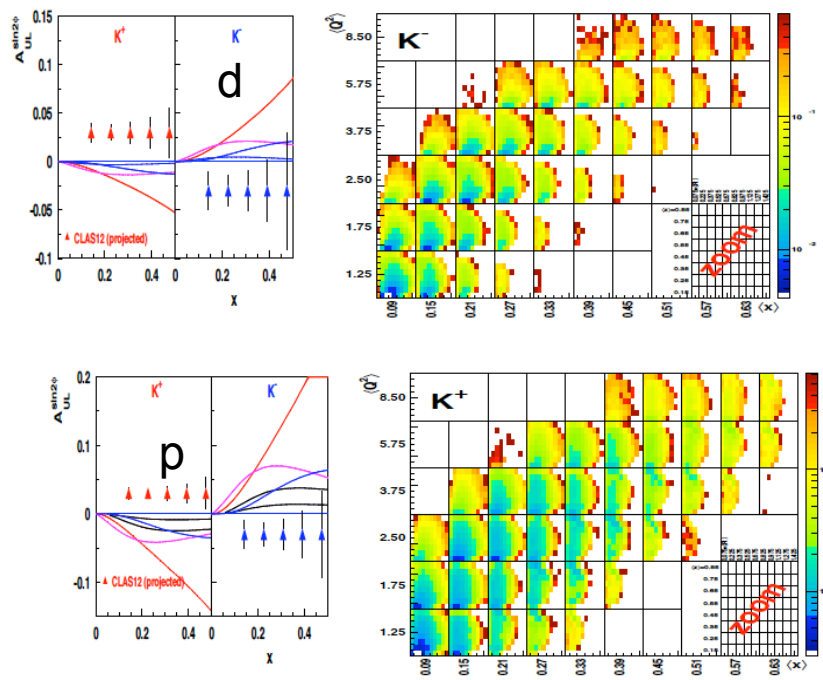




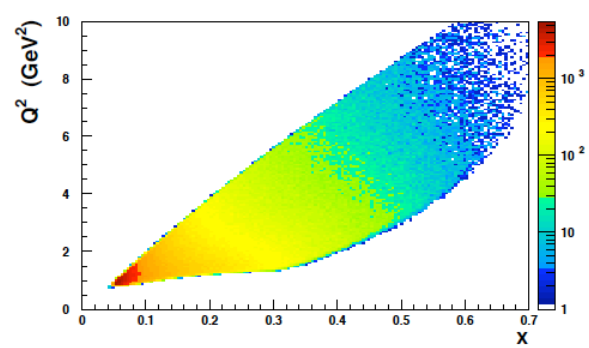
…+sinϕ
(Higher Twist)



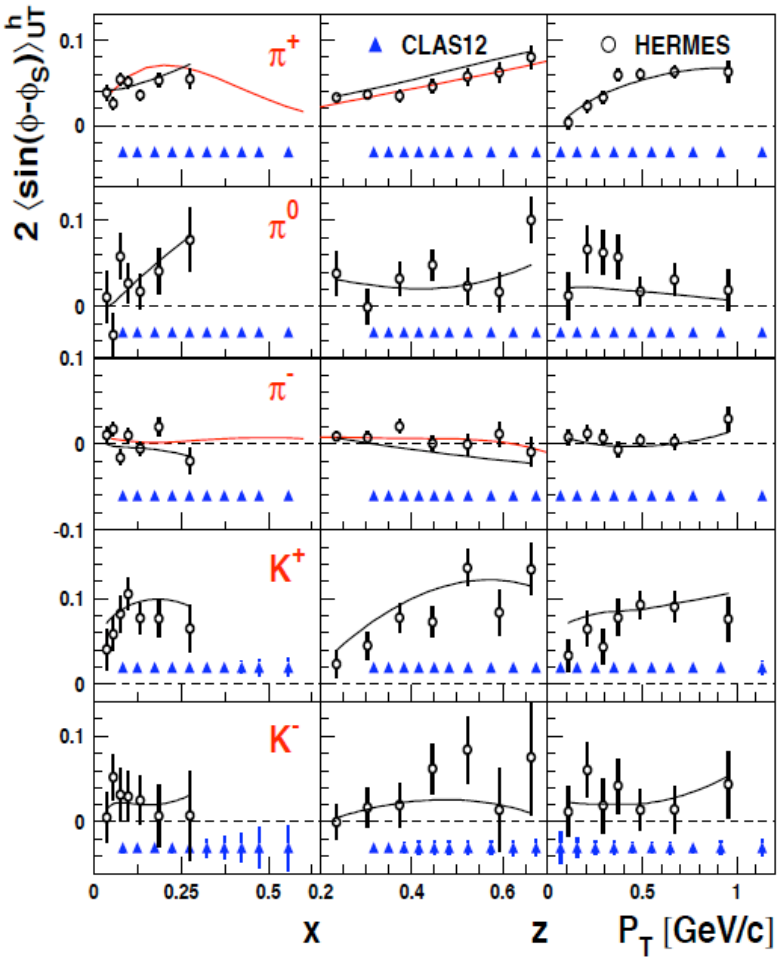
Worm Gear



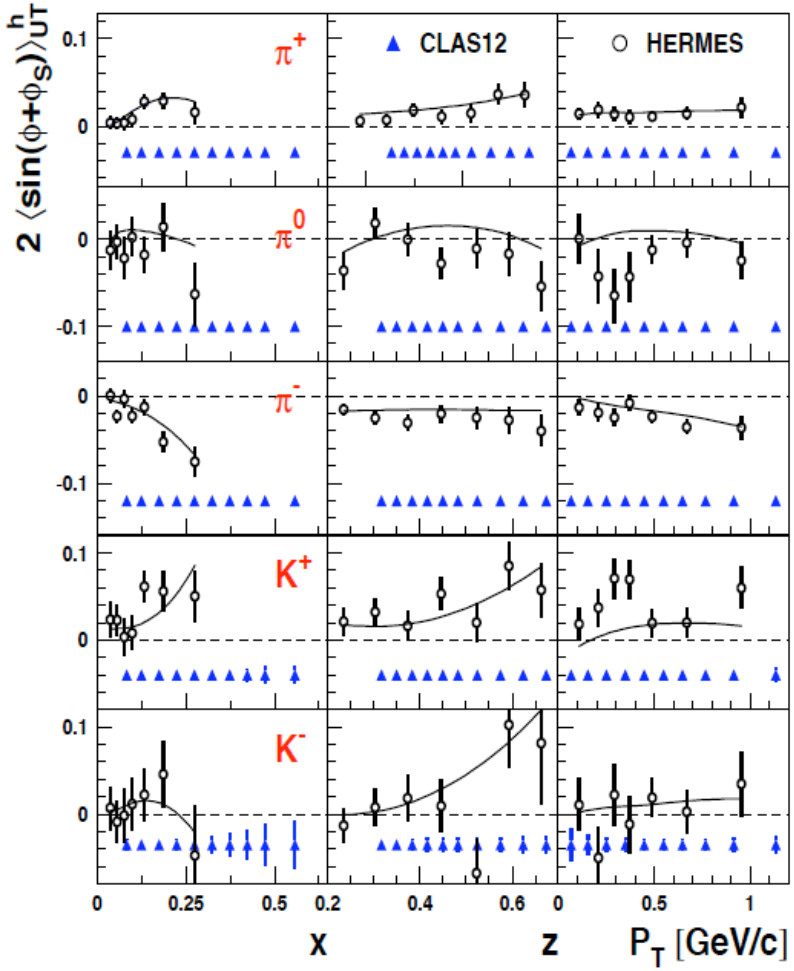
TMDS – CLAS12 TRANSVERSE HD-ICE (?)



Sivers

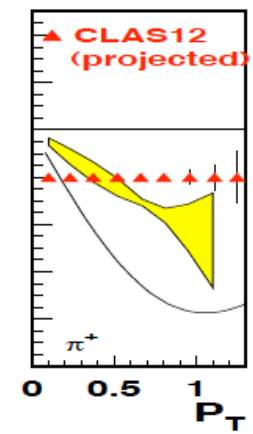


Collins

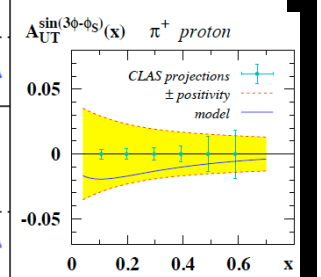


+

worm gear,



pretzelosity



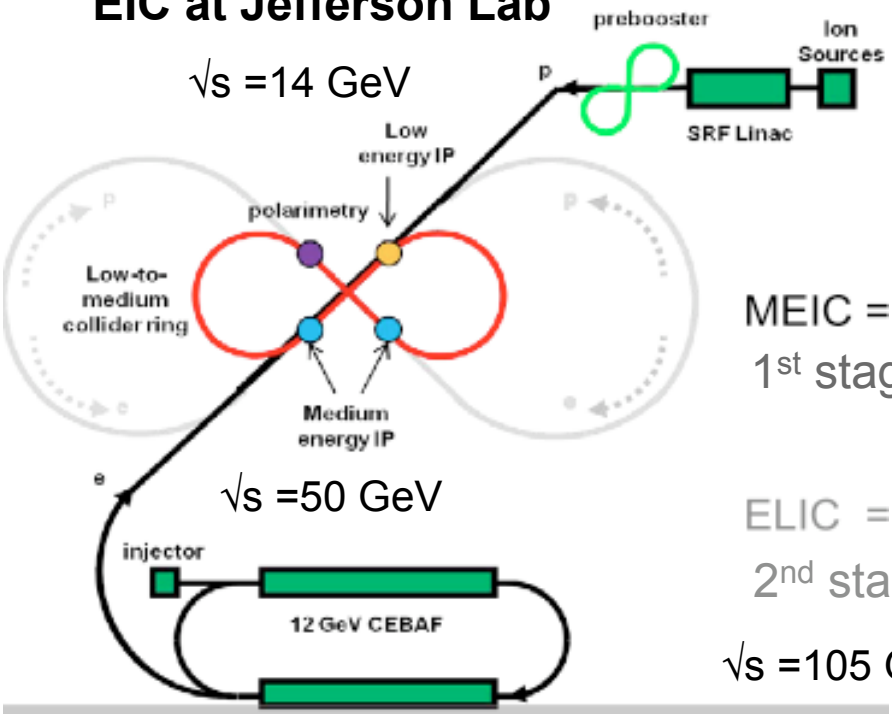
THE FUTURE: EIC OPTIONS

(2025?)

Both: About 10^{34} cm^{-2} s^{-1} (e-nucleon) per interaction point (IP) ~ to E_p

EIC at Jefferson Lab

√s =14 GeV



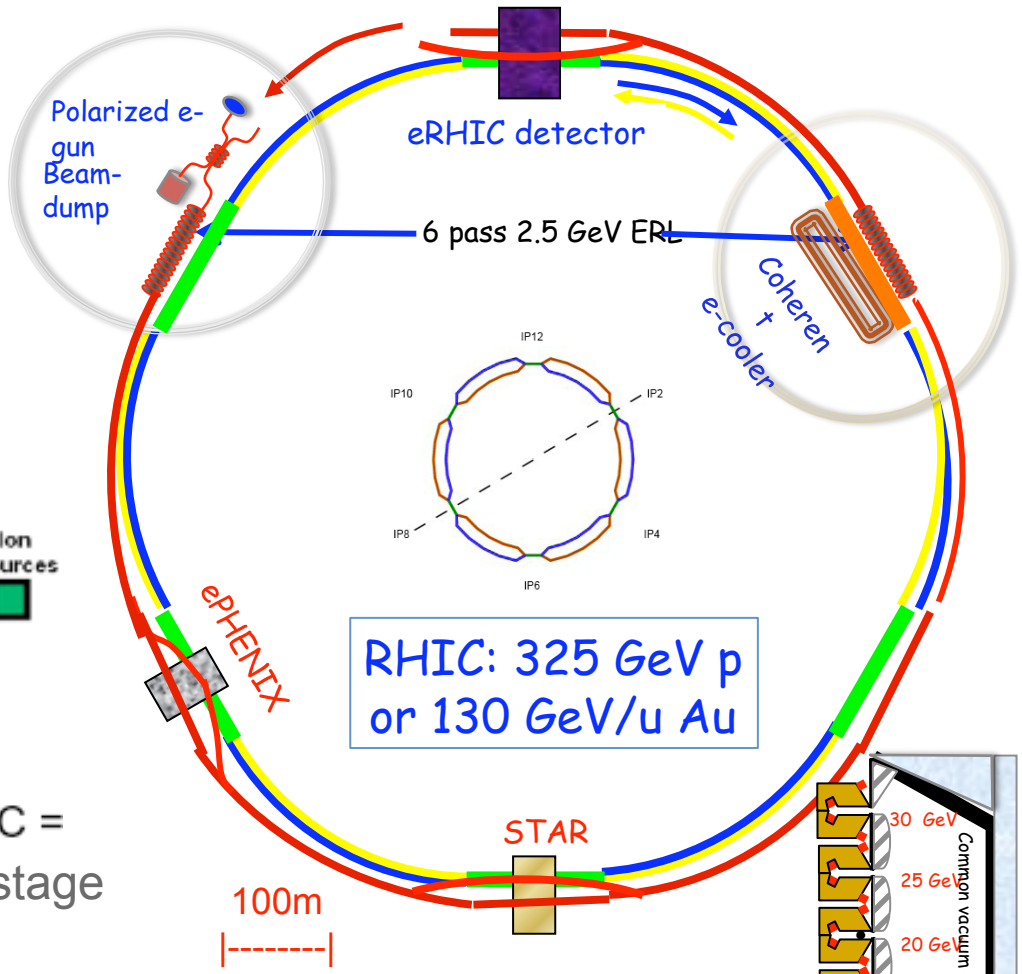
√s =50 GeV

MEIC = 1st stage

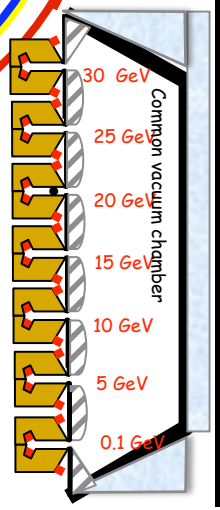
ELIC = 2nd stage

√s =105 GeV

eRHIC



√s =140 GeV

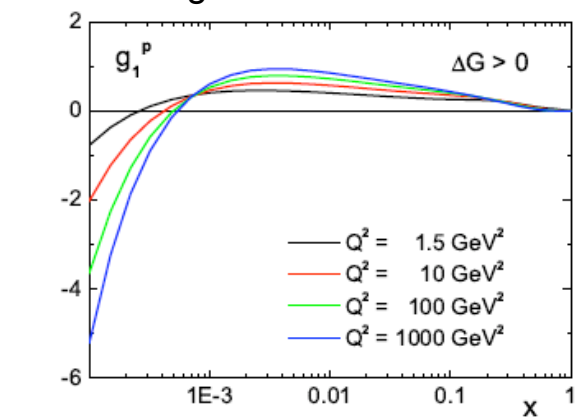


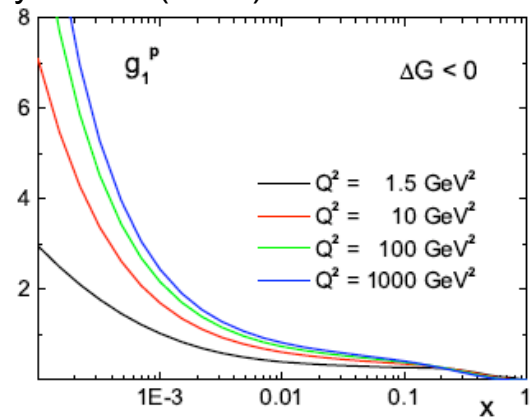
EIC: SSF EXAMPLE

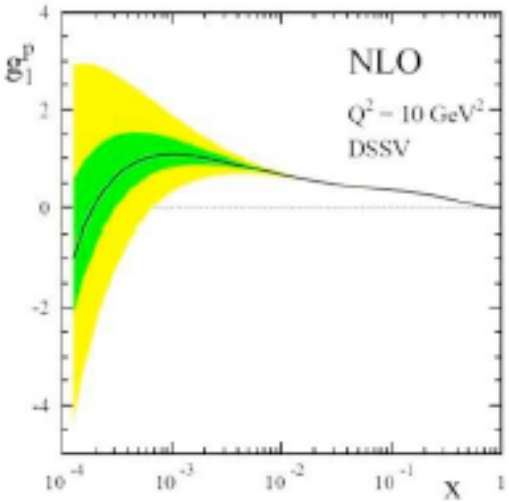
Pin down Δq and especially ΔG to the lowest *x* possible

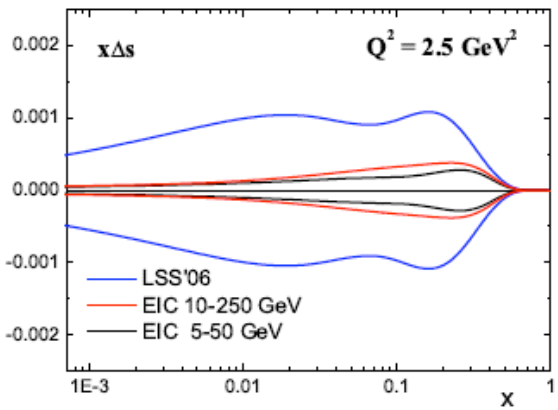
From INT 2010
arx1108p1713v1

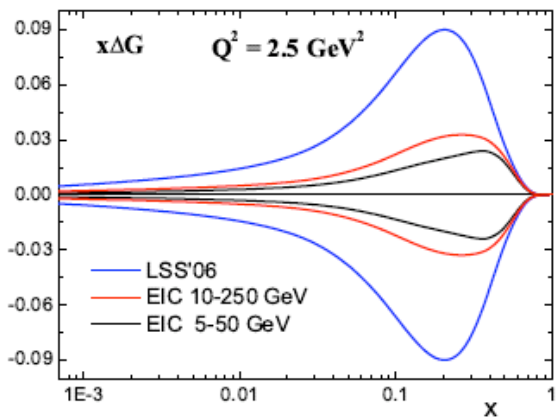
Progress in Particle and Nuclear Physics 63 (2009) 150

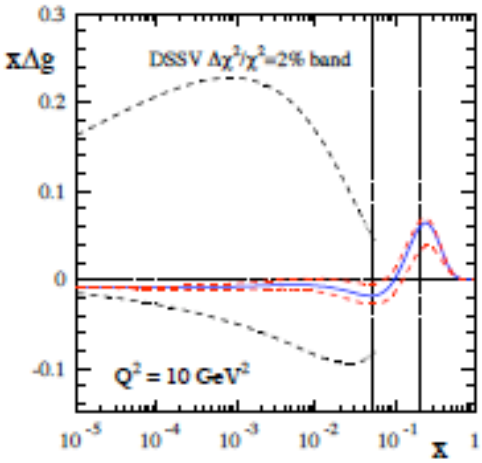




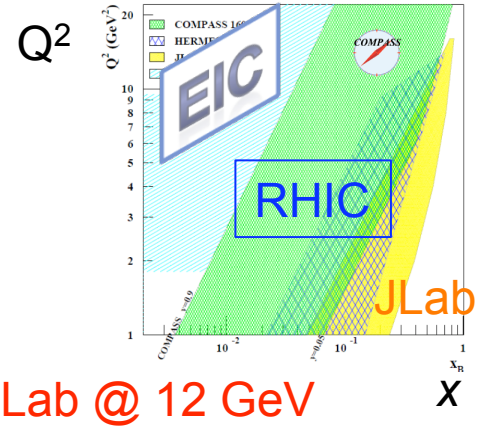








SUMMARY: COMPLETING THE PICTURE



- $\Delta u/u$ and $\Delta d/d$ at high *x* still poorly constrained JLab @ 12 GeV
- What is happening with the strange sea polarization? >0? =0? <0? Zero crossing? (Tension DIS – SIDIS) COMPASS, JLab
- Is the sea polarization isospin-symmetric? JLab high x; RHIC W, COMPASS
- Gluon helicity distribution at large *x* and a small *x*? What is the integral ΔG? JLab + COMPASS (NLO), RHIC, COMPASS
- What happens at really small x << 0.01?
- Tensor charge of the nucleon ALL
- Full mapping of all TMD PDFs as a function of quark flavor in the valence region JLab @ 12 GeV
- Test of universality RHIC
- Test of prediction that time-odd TMDs (e.g., Sivers asymmetry) change sign in Drell-Yan processes RHIC, COMPASS, FAIR, JPARC…
- TMDs of sea quarks and gluons

EIC

EIC