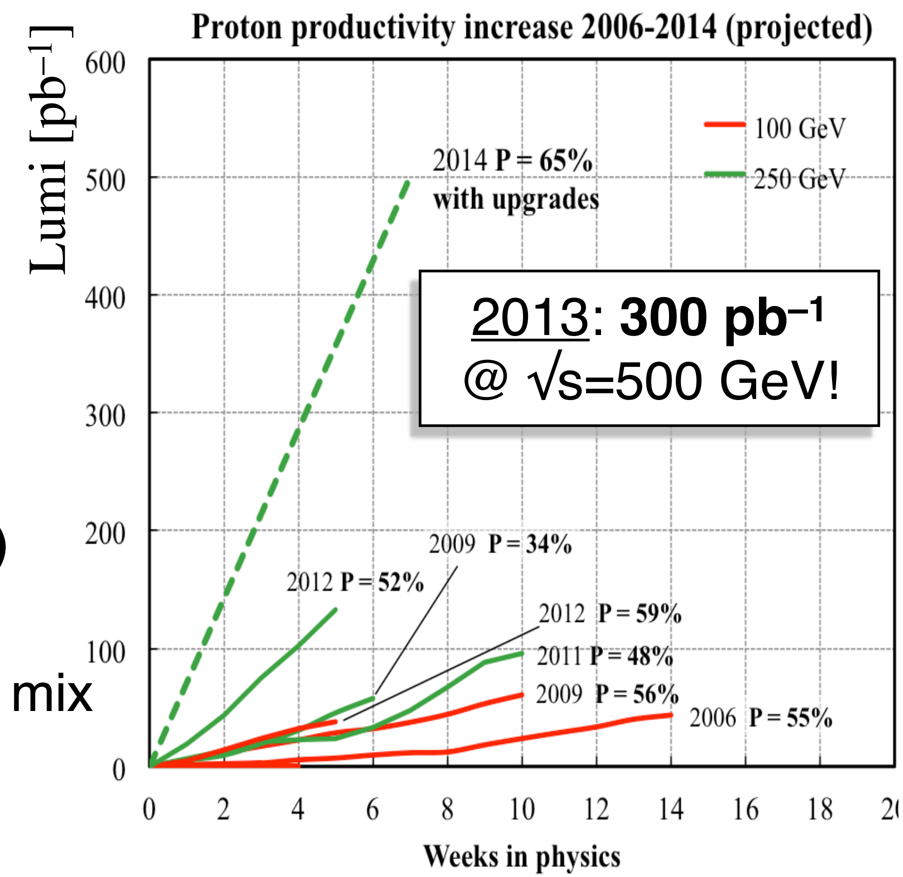
The Hadron Physics Landscape :
Next 10 Years

Jefferson Lab

The Facilities : Today

- **12 GeV** polarized e : first beam 2013, commission^{g} 2014, produc^{n} 2015
- Complementary capabilities in 4 Halls
  → **broad physics program**



STAR PHENIX

- Transv (T) & Longit (L) polarized p beams
  colliding at $\sqrt{s}$ = 200 GeV or 500 GeV
- L core : $A_{LL}^{\pi 0}$ (PHENIX) & A_{LL}^{jet} (STAR) → **Δg(x)**
  : $A_L^{W\pm}$ at $\sqrt{s}$ = 500 GeV → **Δqbar(x)**
- T core : A_N $^{\pi 0, \eta, jet, \ldots}$ → Sivers/Collins/Twist-3 mix

SeaQuest E906

- 120 GeV p from Main Injector on p,d,A targets → **high-x Drell-Yan**
- Production running declared Mar'14

COMPASS **COMPASS-II**

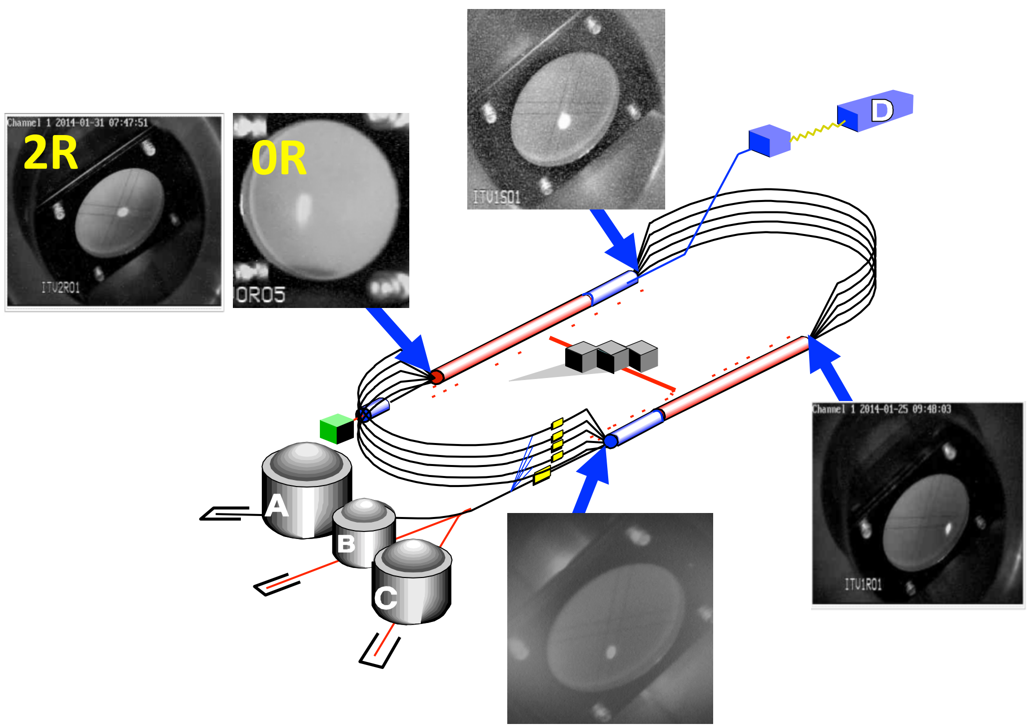
- 190 GeV π^- beam on T-polarized H target → **polarized Drell-Yan**
- First beam expected end of 2014

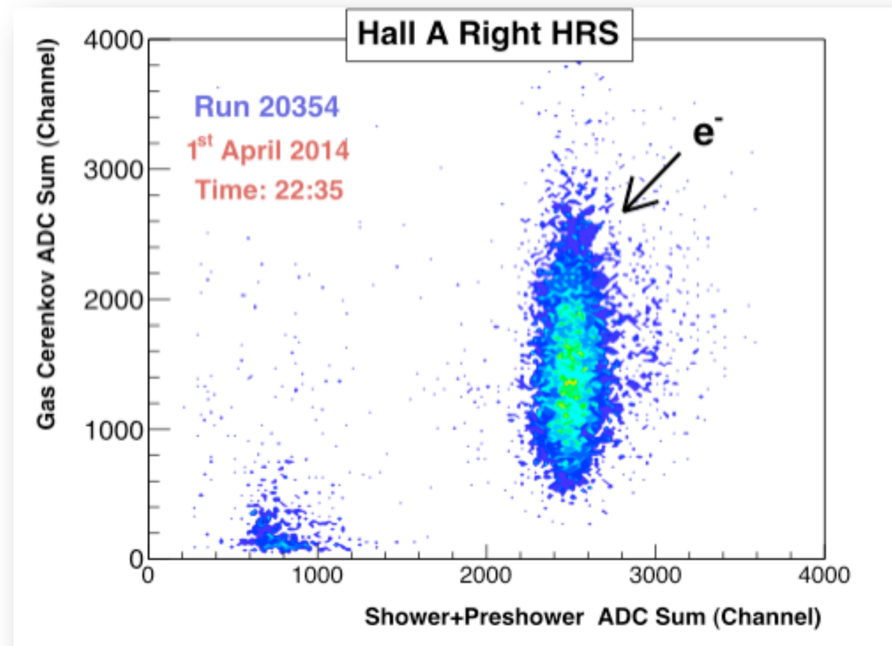
Beam Commissioning to Hall A

Jefferson Lab in Newport News hits major milestone in accelerator upgrade

April 30, 2014 | By Tamara Dietrich, tdietrich@dailypress.com | Daily Press

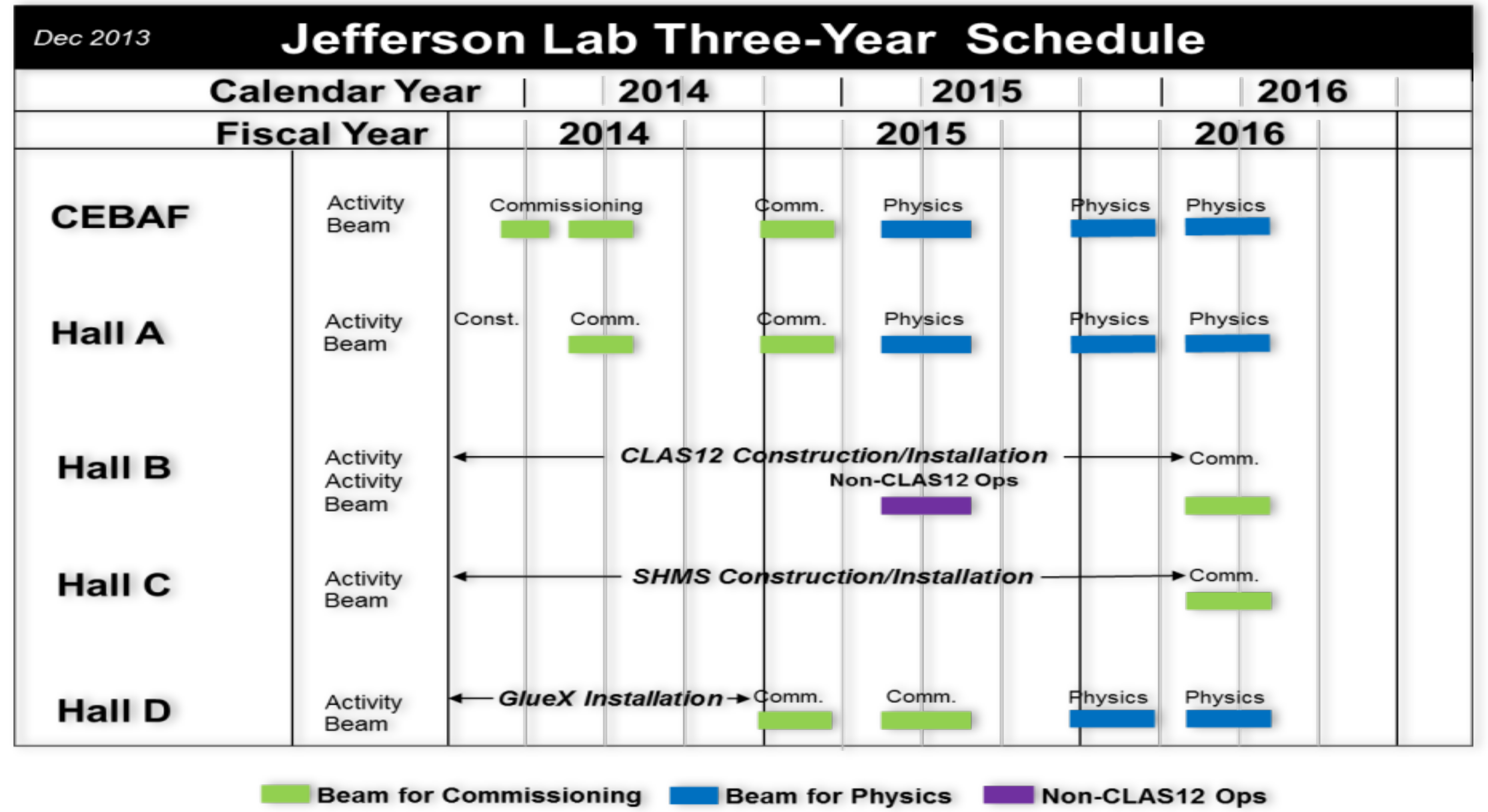
Jefferson Lab in Newport News has reached a "major milestone" in its drive to double the energy of its electron accelerator and become the only facility in the world capable of answering key questions about quarks, the building blocks of matter.





Beam on carbon target in Hall A ; E_{beam} = 6.1 GeV

12 GeV CEBAF: Three Year Schedule



Pushing to Physics

The Facilities : 2020+

we hope ...

Jefferson Lab

- **SOLID** detector in Hall A → large acceptance & high rate for **parity violation** (PVDIS) & **polarized SIDIS** programs

STAR PHENIX

Forward! Forward! → *higher η = higher x_{beam}, lower x_{target}*

- **STAR Forward Calorimeter System** = EMCal + HCal → forward **jets** & e/h separaton for **Drell-Yan**
- **fsPHENIX** = forward spectrom w EMCal, HCal, RICH, tracking → forward **jets** + **identified hadrons** and **Drell-Yan**

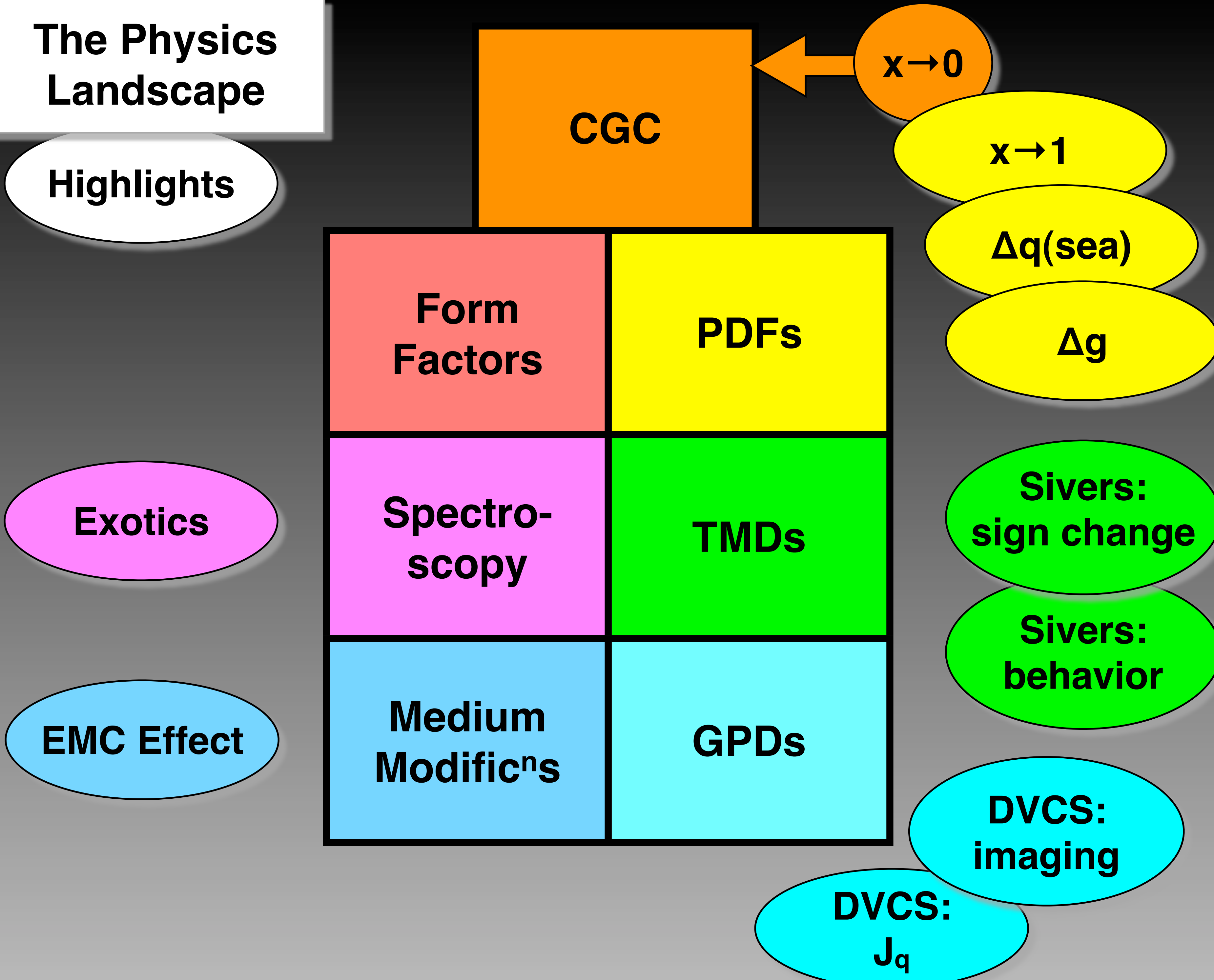
Fermilab

Polarized Beam and/or Target w SeaQuest detector

*A **high-luminosity** facility for **polarized Drell-Yan***

- **E-1027** MI p↑ beam w polarized source + 1 Siberian Snake
- **E-1039** SeaQuest with polarized p↑ target

The Physics Landscape



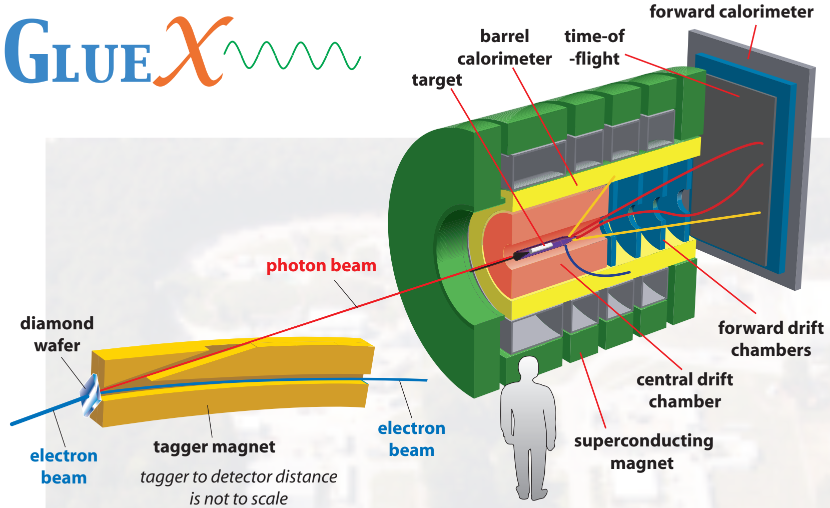
Spectroscopy

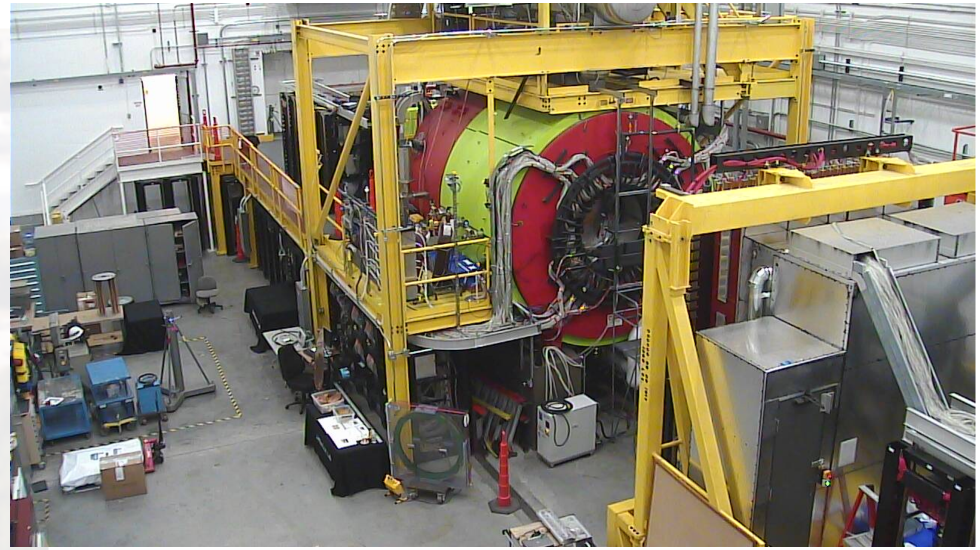
Low-x and the CGC

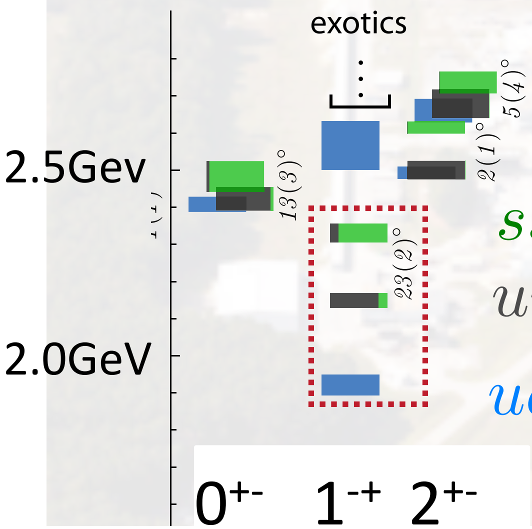
Medium Modifications : the EMC Effect

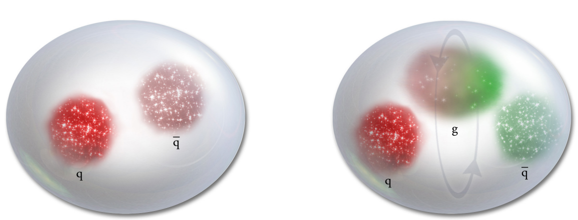
Form Factors

Installed & Ready for Beam in October





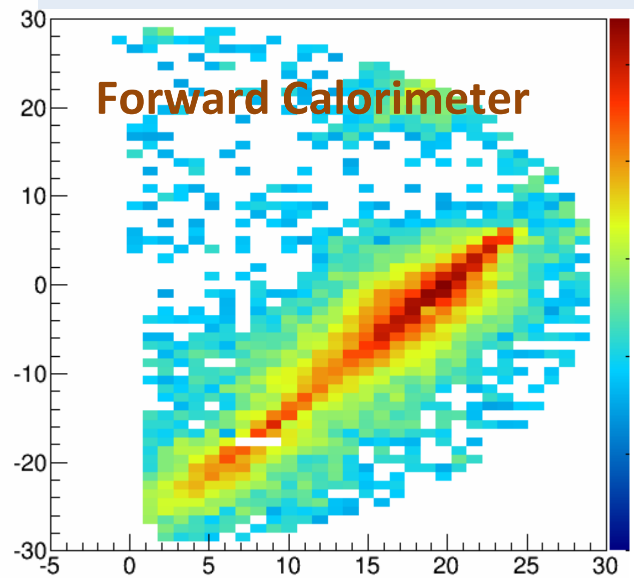


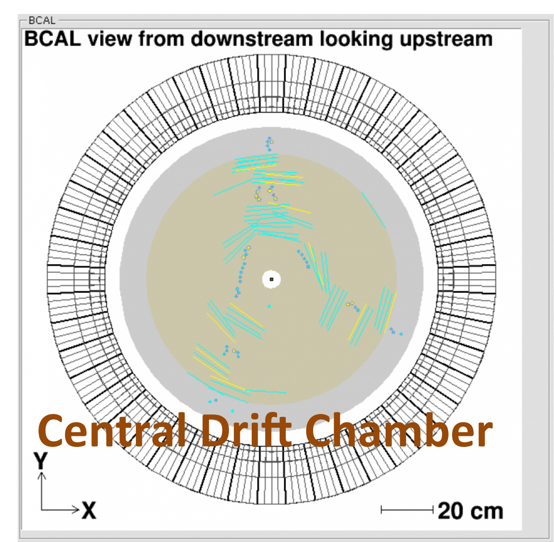


Exotic Quantum-number Hybrid Mesons

NSAC **milestone HP15 (2018)**

Cosmic Events for Commissioning and Alignment





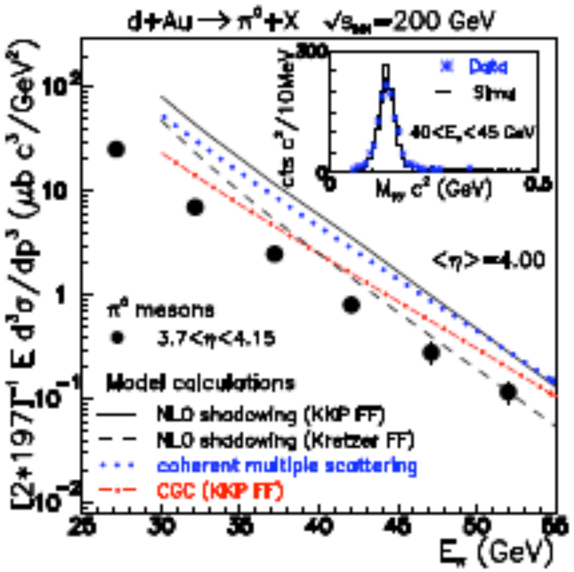
talk: Curtis Meyer

Solenoid on!

Low x & the Color Glass Condensate

Study pA → nucleus enhances gluon density → "effectively" lowers x

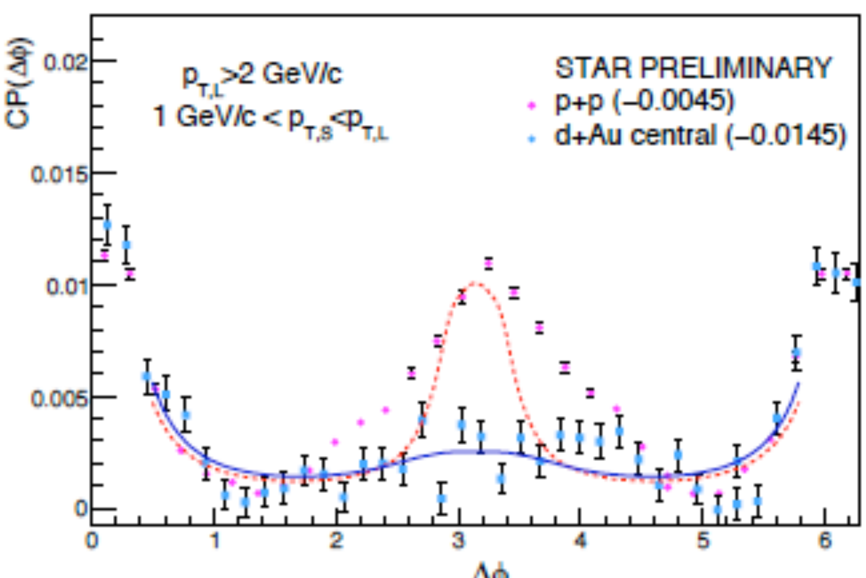
Forward rapidity → high-x quark (beam) vs low-x gluon (target)



STAR d+Au

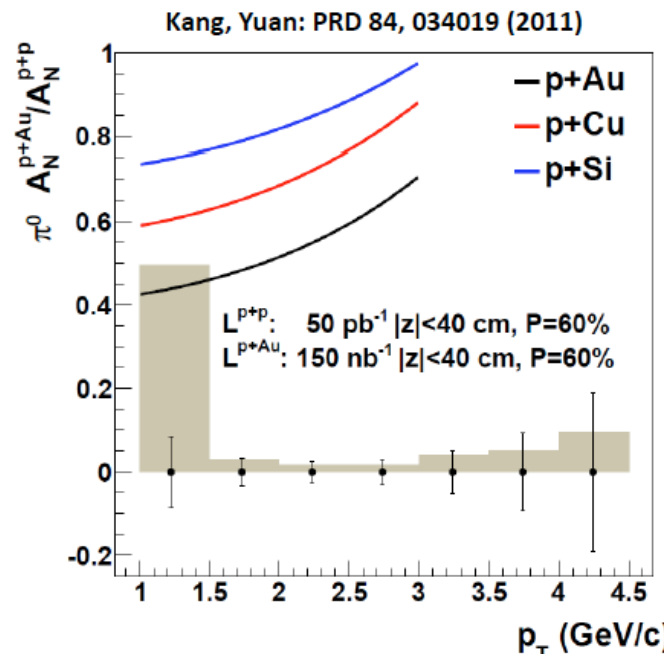
multiplicites
← drop

correlation
w recoiling
parton drops
↓



- mult. scat. of quark through saturated gluons?
- g recombination → CGC?

RHIC Future: p↑+A SSAs



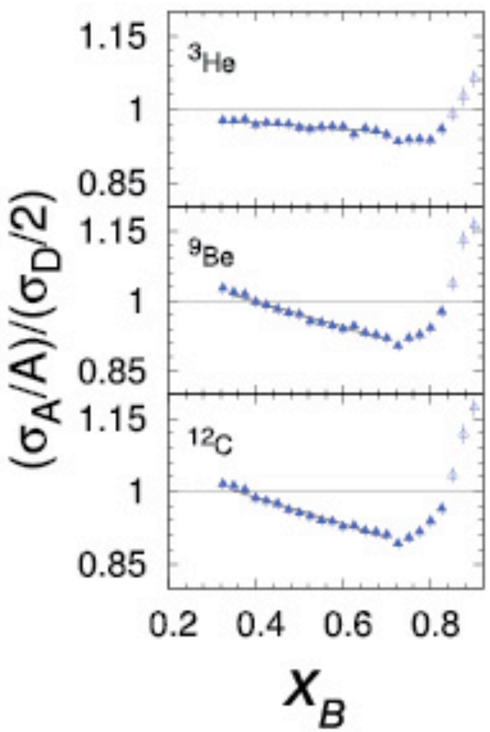
talk: John Lajoie

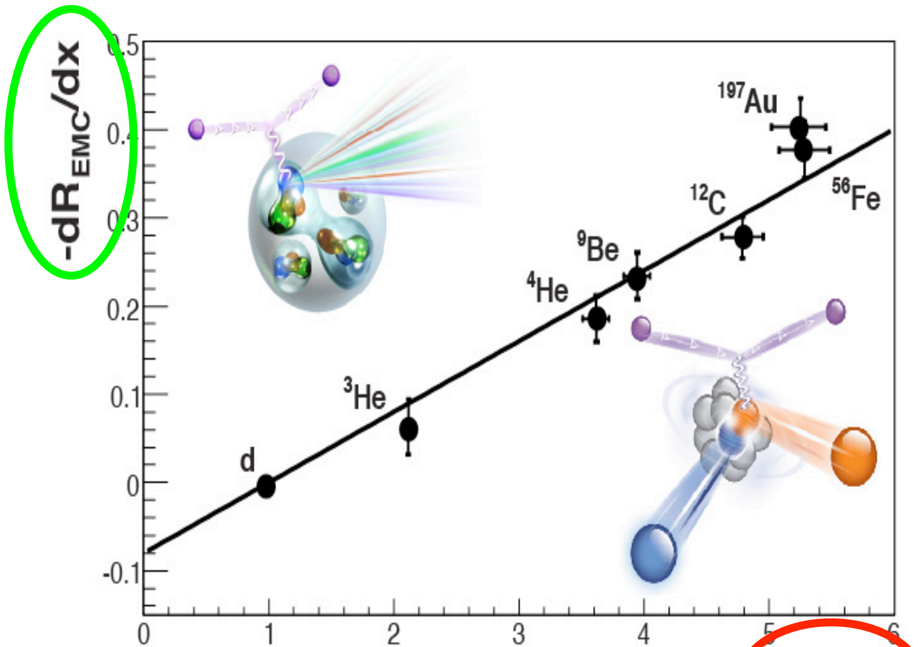
The EMC Effect & Short-Range Correlations

inclusive A(e,e′) at x > 1

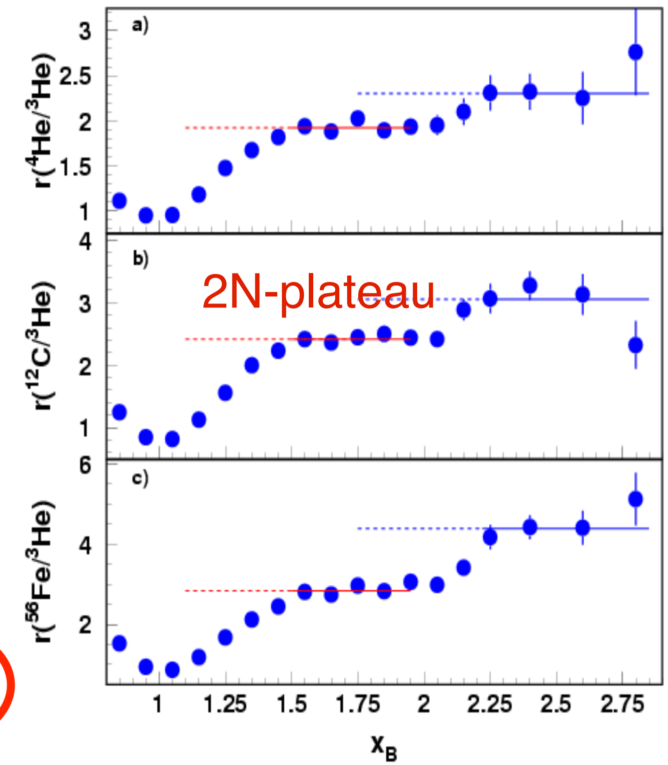
EMC Slopes
$0.35 \leq x_B \leq 0.7$

SRC Scaling factors
$1.5 \leq x_B \leq 2$





$$a_2(A/d) = \left(\frac{2}{A}\right)\frac{\sigma_A(\text{2N-plateau})}{\sigma_d(\text{2N-plateau})}$$



K. Egiyan et al, PRL96, 082501 (2006)

SRC: nucleons see strong repulsive core at short distances
EMC effect: quark momentum in nucleus is altered

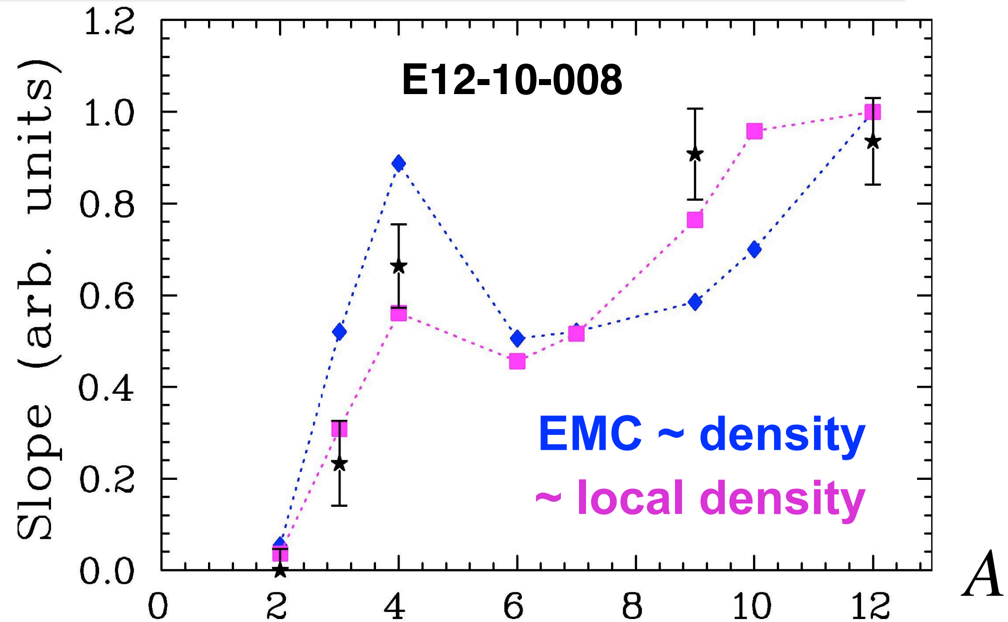
Weinstein *et al.*, PRL 106, 052301 (2011)

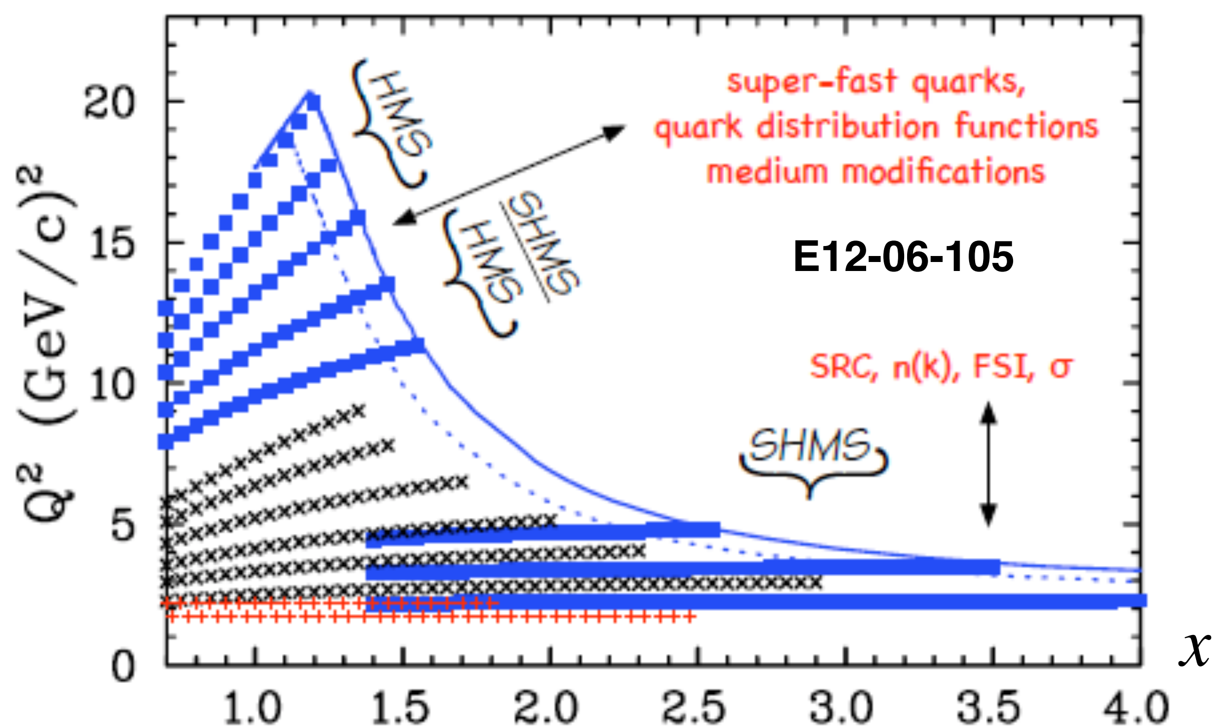
EMC & SRC: 5 approved expts to sort it out

Some features :

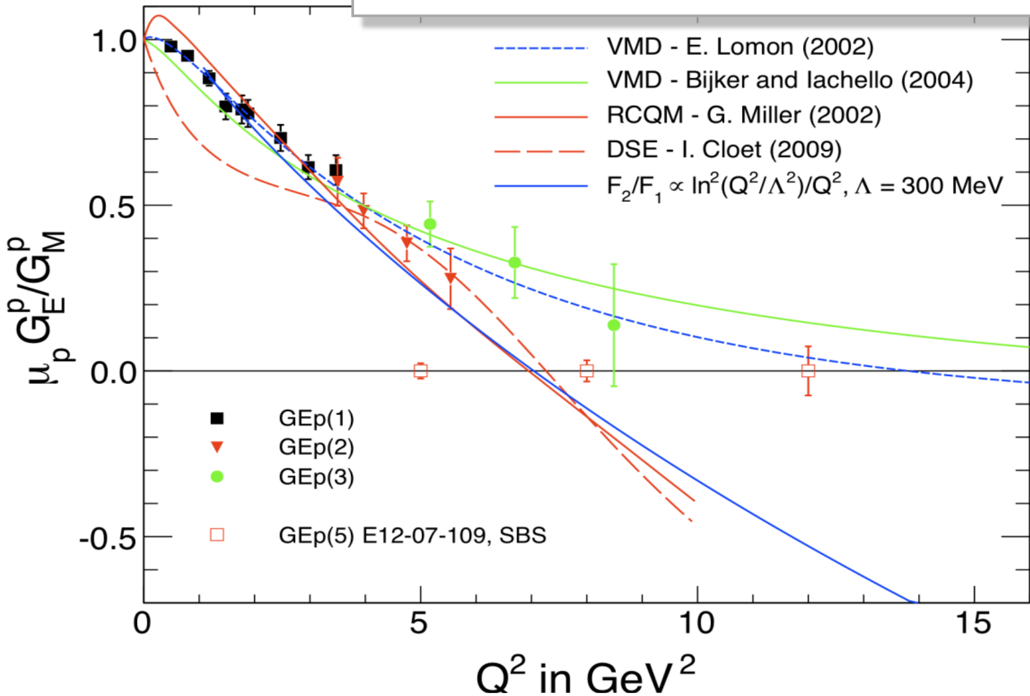
- exhaustive target scan to vary nuclear properties → e.g. **local density** :
  ^{1}H, ^{2}H, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li, ^{9}Be, ^{10}Be, ^{11}B, ^{12}C, ^{40}Ca, ^{48}Ca, Cu
- study **isospin dependence** of effects
- extensive kinematic scan → to **x > 3** seeking second **3N-plateau** & to $Q^2 \approx 20$

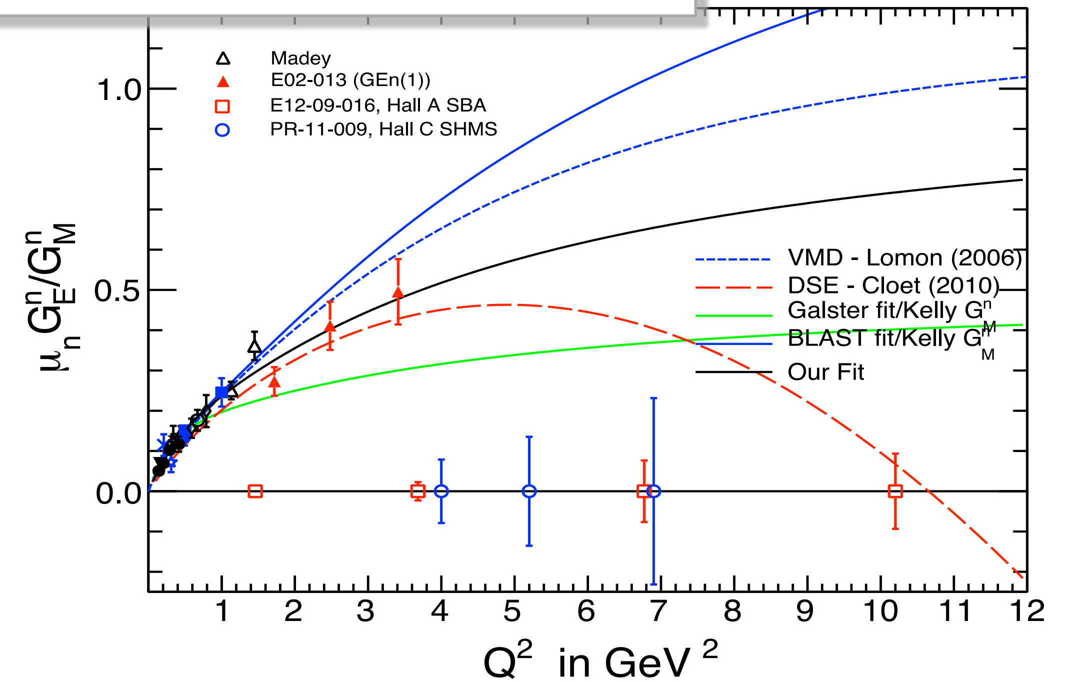
^{2}H, ^{3}He, ^{4}He, ^{6,7}Li, ^{9}Be, ^{10,11}B, ^{12}C, ^{40,48}Ca, Cu, Au

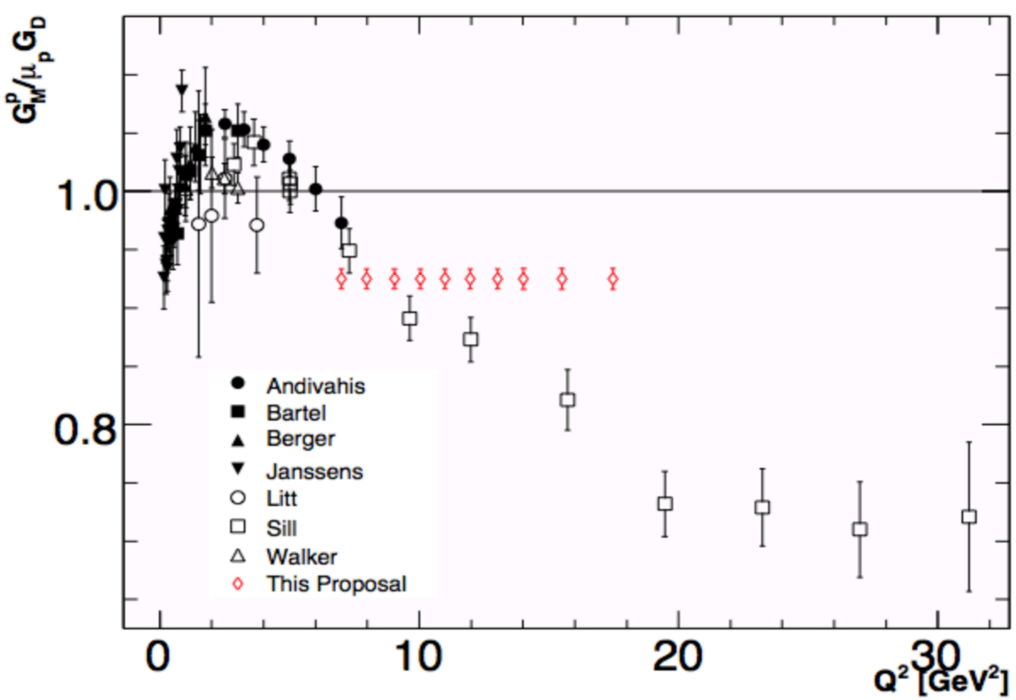


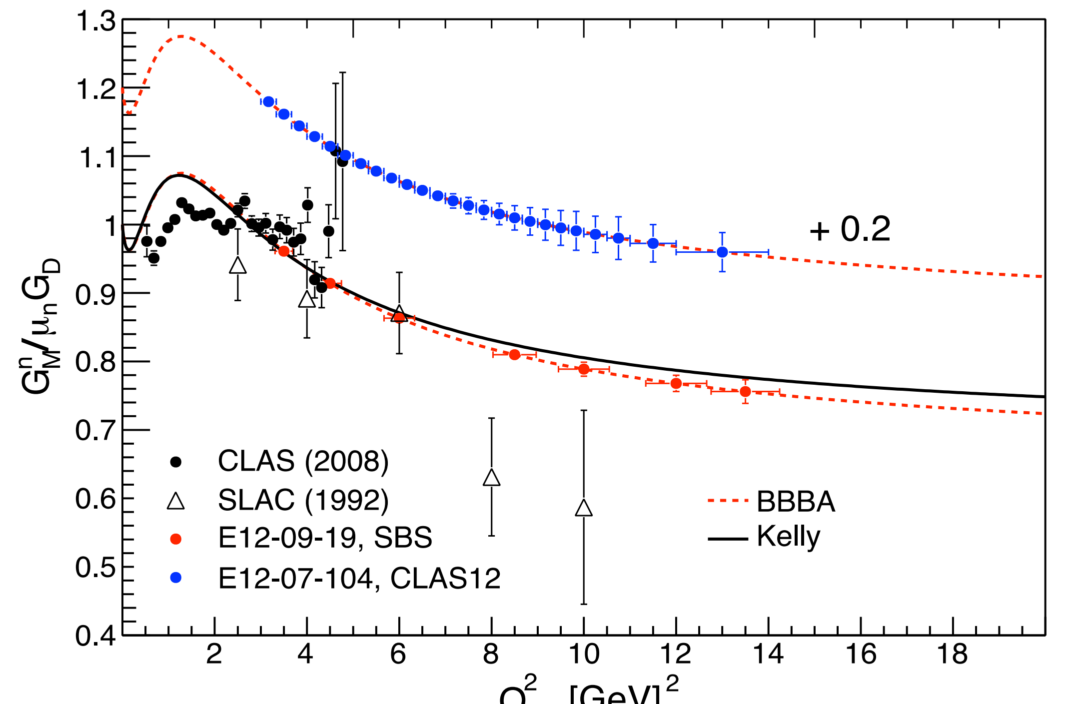


Nucleon Form Factors : 6 Approved Expts





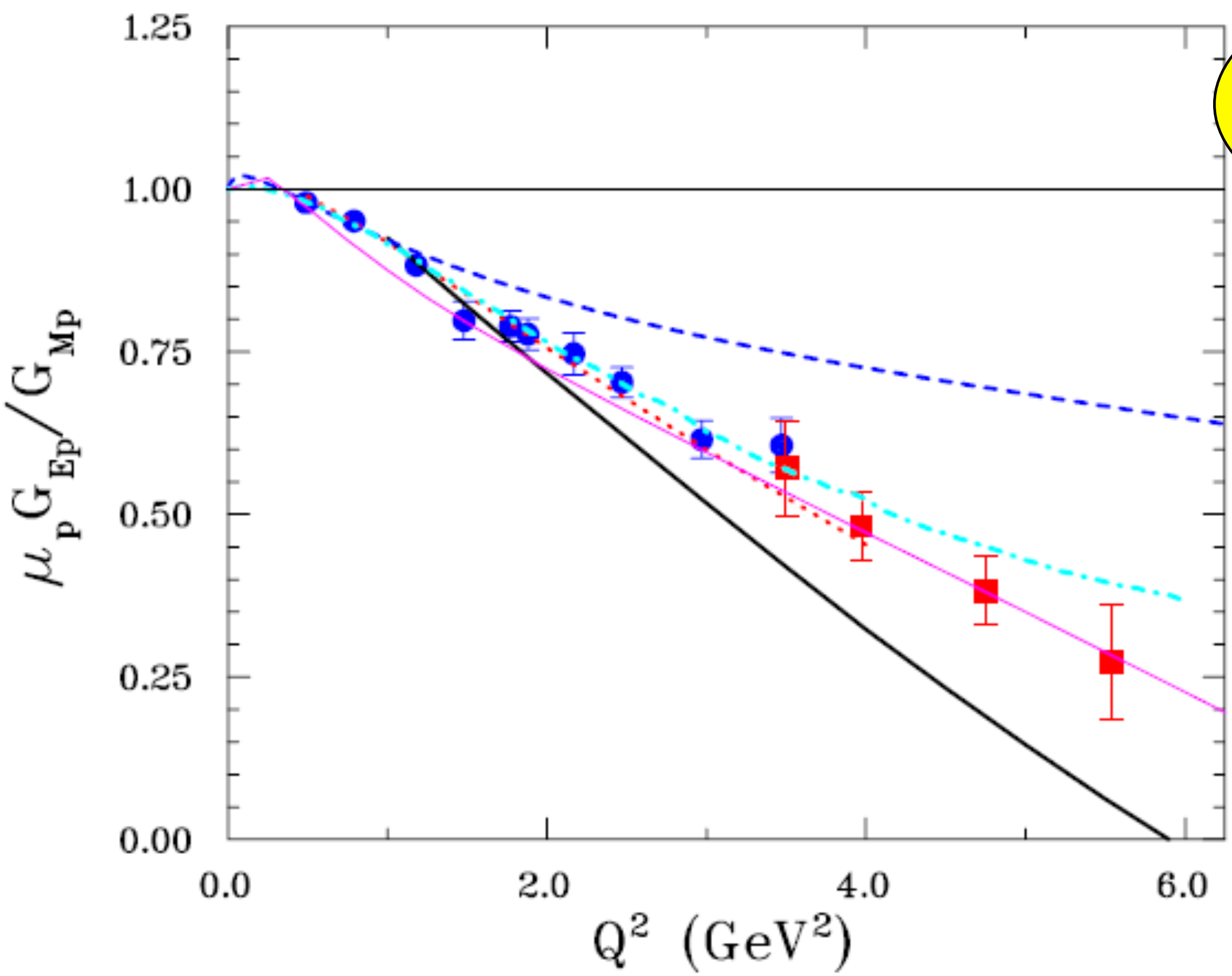




Quark Orbital Angular Momentum

Many calculations able to reproduce the falloff in G_E/G_M

- ***Descriptions differ in details, but nearly all were directly or indirectly related to quark angular momentum***



JLab-12: $Q^2 \rightarrow 12$ GeV^2

S. Boffi, et al.

F. Cardarelli, et al.

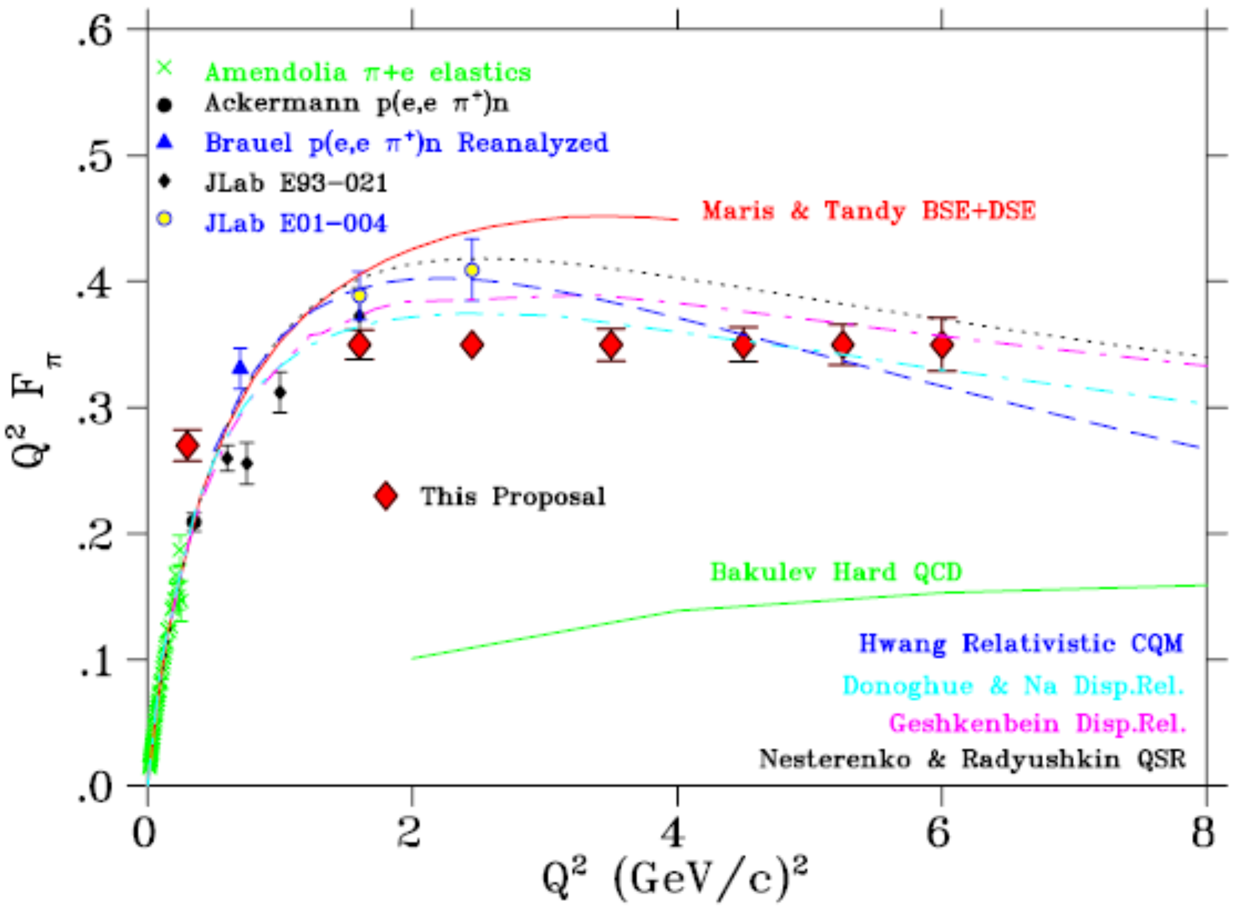
P. Chung, F. Coester

F. Gross, P. Agbakpe

G.A. Miller, M. Frank

C. Perdrisat, V. Punjabi, and M. Vanderhaeghen, PPNP 59 (2007)

Charged Pion Form Factor



Study transition from non-perturb. to perturb. regime

Expected at lower Q^2 than for nucleon

pQCD makes exact prediction for $Q^2 \rightarrow \infty$, benchmark for all nucleon structure models

Models from relativistic CQM to hard QCD calculations

E12-06-101: ***Hall C, 52 days, 2018 (fully comm. SHMS), rating: A (PAC 35)***

Parton Distribution Functions :

The Limit $x \to 1$ of $q(x)$ and $\Delta q(x)$

PDFs in the limit $x \to 1$

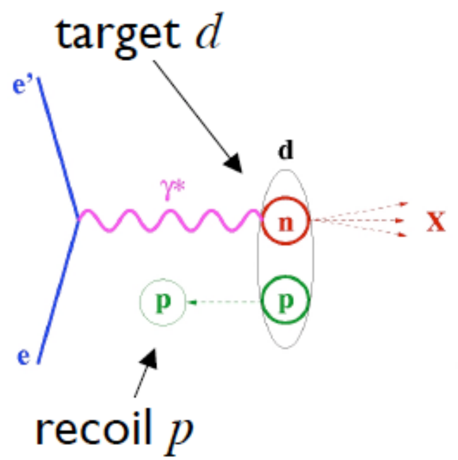
$x \to 1$ predictions	F_2^n/F_2^p	d/u	A_1^n	A_1^p
SU(6)	2/3	1/2	0	5/9
Diquark Model/Feynman	1/4	0	1	1
Quark Model/Isgur	1/4	0	1	1
Perturbative QCD	3/7	1/5	1	1
QCD Counting Rules	3/7	1/5	1	1

What happens at this bizarre limit?

d/u as $x \to 1$ plagued by **nuclear corrections** on D or 3He

2 clever strategies at 12 GeV!

BONUS: recoil detec$^{\mathbf{n}}$



slow backward p
($p < 100$ MeV)

→ neutron nearly on-shell

→ minimize rescattering

MARATHON: ^{3}He / ^{3}H

- extract n/p ratio from ratio of A=3 structure functions

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}}}{2F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}} - \mathcal{R}}$$

→ ratio of ^{3}He to ^{3}H EMC ratios cancels to ~1% for $x < 0.85$

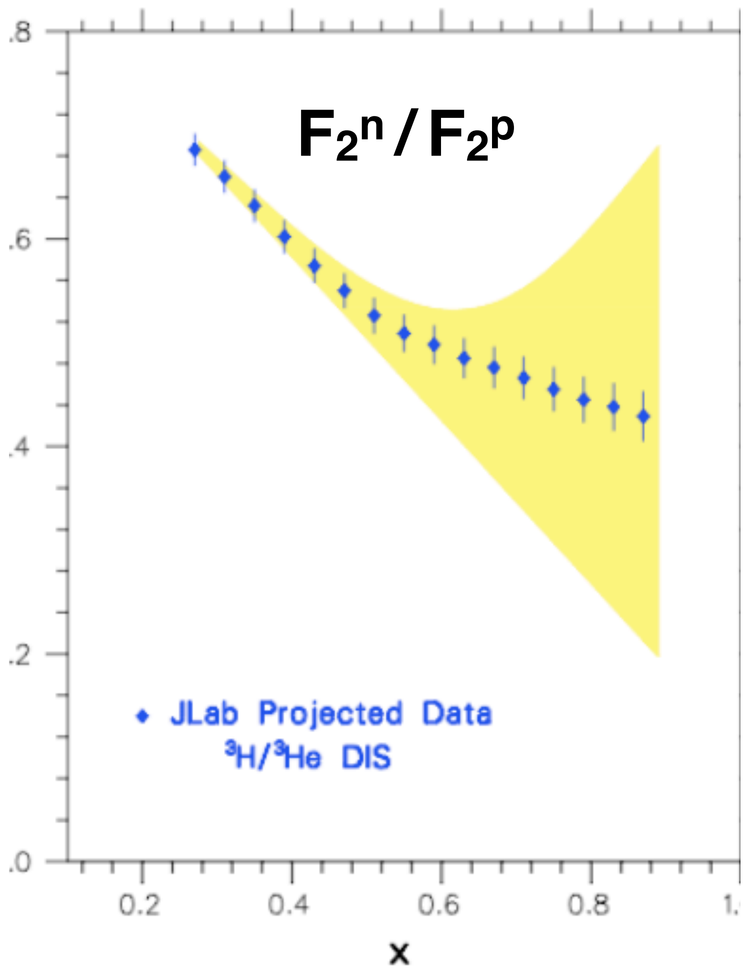
.C.R. Makins, QCD Town Mtg, Philadelphia, Sep 13, 2014

d/u (x → 1)

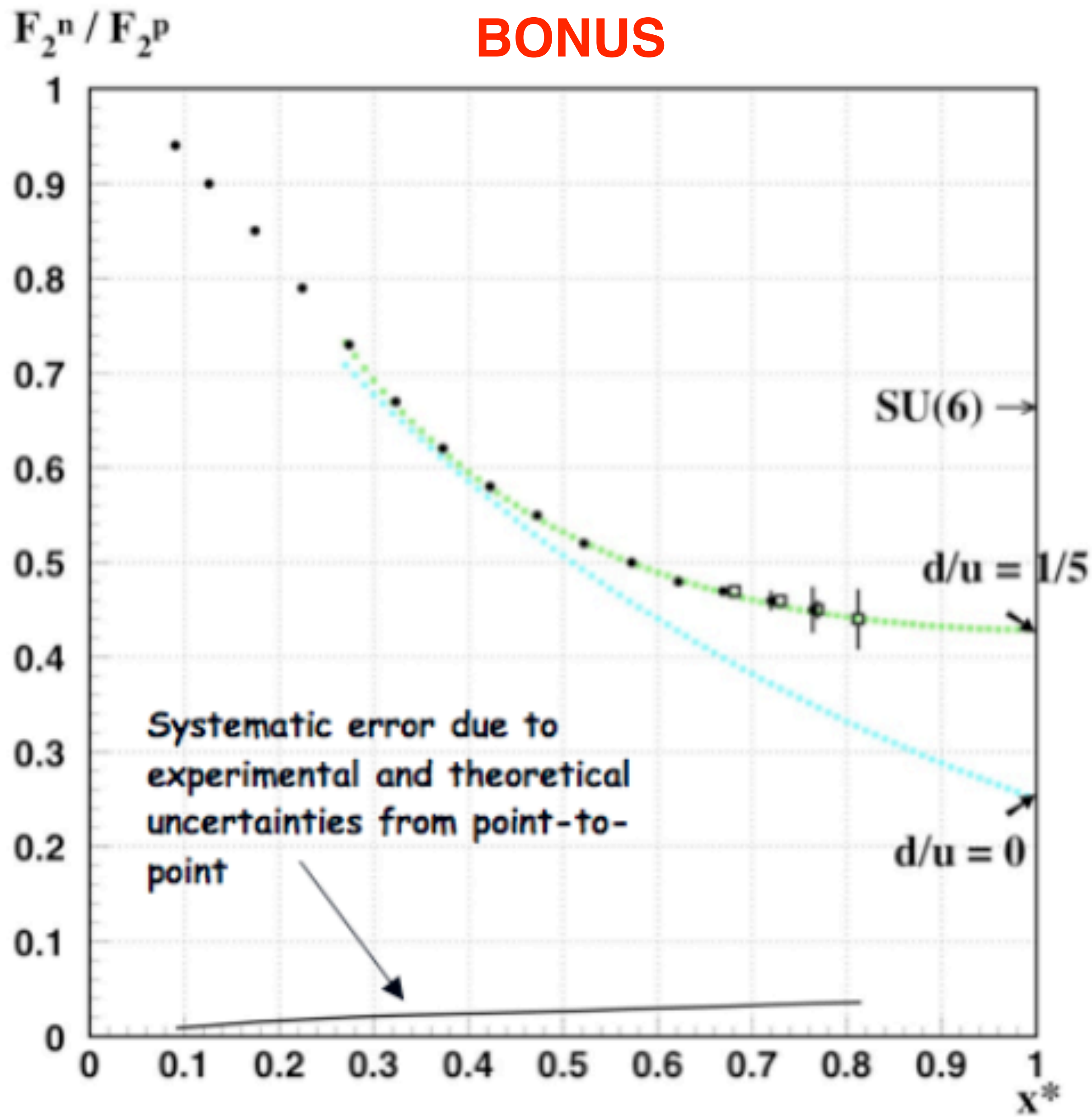
Yellow band = current theory uncertainty

Definitive results at last!

MARATHON



BONUS



NSAC milestone HP14 (2018) → unpolarized part

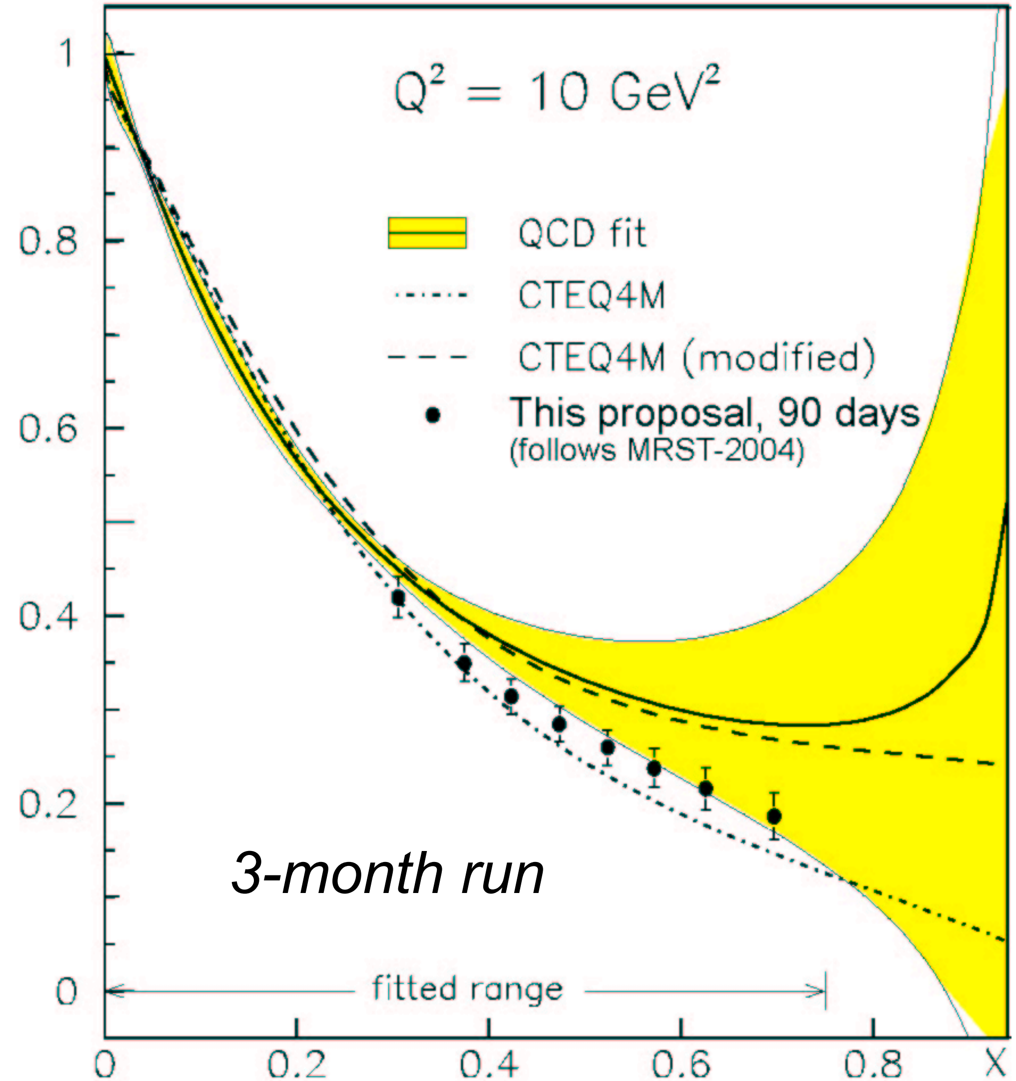
2020+ : PVDIS on the Proton → d/u(x→1) with SOLID

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[\mathbf{a}(x) + Y(y)\,\mathbf{b}(x)\right]$$

$$a^P(x) \approx \frac{u(x)+0.91d(x)}{u(x)+0.25d(x)}$$

Deuteron analysis has large nuclear corrections (Yellow)

A_{PV} for the **proton** has no nuclear corrections → complementary to BONUS & MARATHON



The challenge is to get statistical and systematic errors ~ 2%

Spin structure at large x

- Spin-dependent PDFs are even less well understood at large x than spin-averaged PDFs

- Predictions for $x \to 1$ behavior:

  → scalar diquark dominance

$$\frac{\Delta u}{u} \to 1\,, \quad \frac{\Delta d}{d} \to -\frac{1}{3} \qquad A_1^{p,n} \to 1$$

  → hard gluon exchange

$$\frac{\Delta u}{u} \to 1\,, \quad \frac{\Delta d}{d} \to 1 \qquad A_1^{p,n} \to 1$$

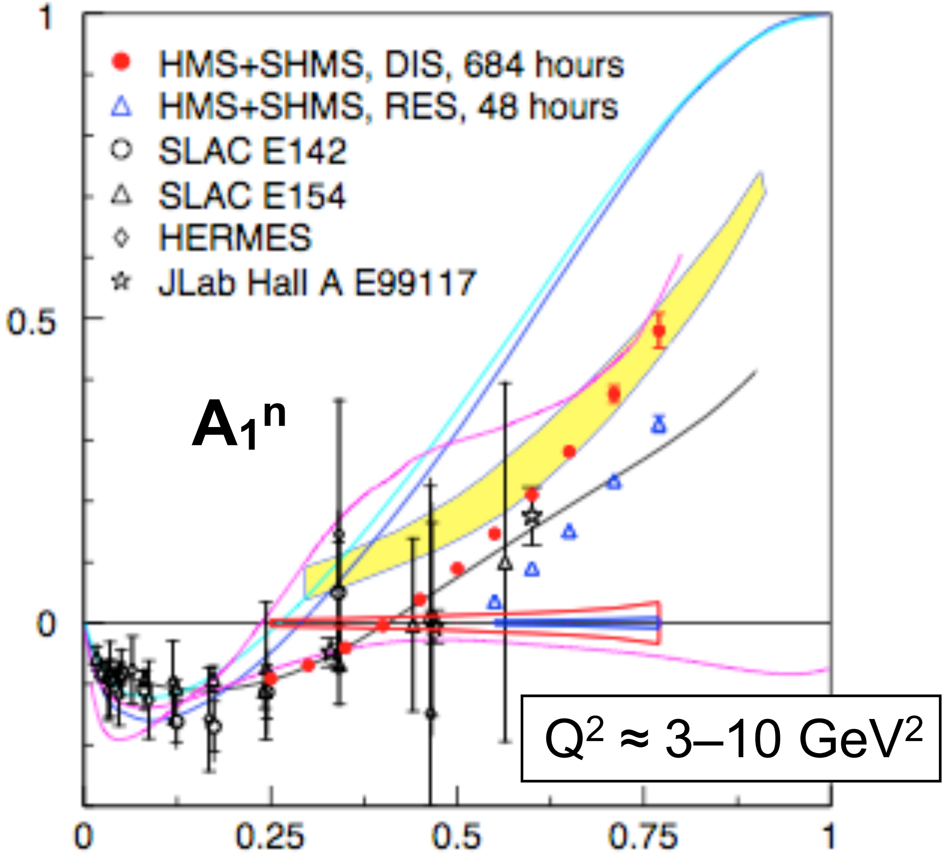
  → spin-flavor symmetry

$$\frac{\Delta u}{u} = \frac{2}{3}\,, \quad \frac{\Delta d}{d} = -\frac{1}{3} \qquad A_1^p = \frac{5}{9}\,, \quad A_1^n = 0$$

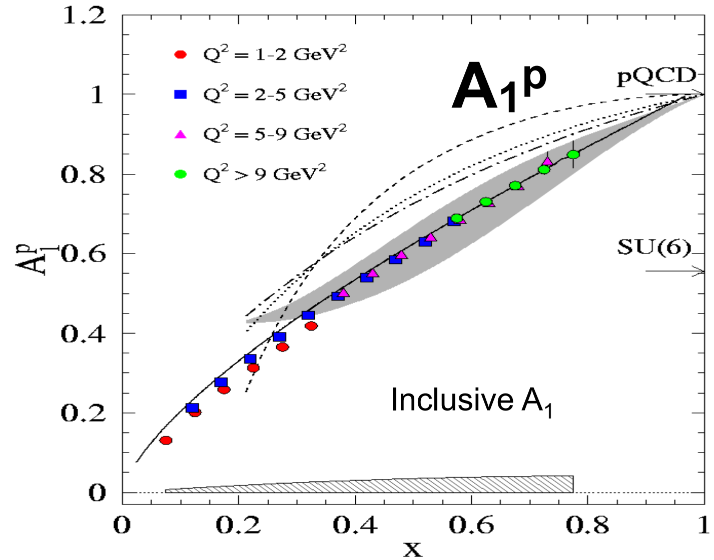
- Spin PDFs almost completely unconstrained for $x \gtrsim 0.6$

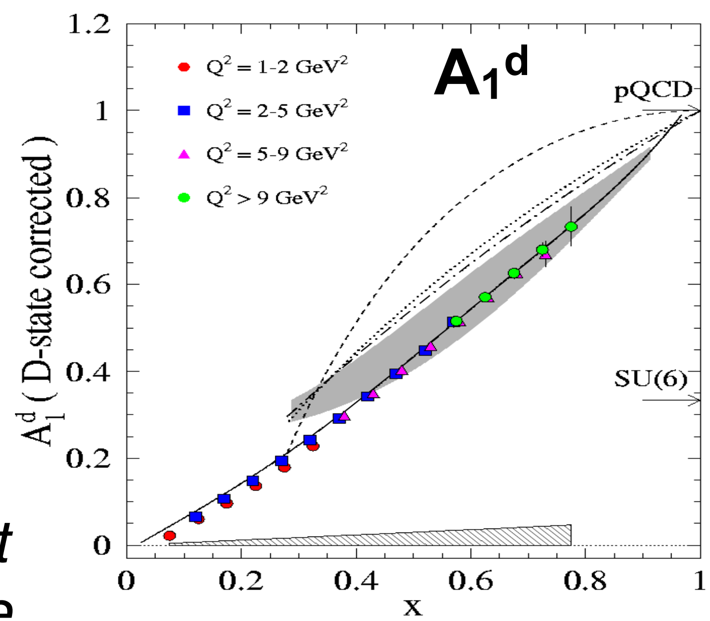
A_1 inclusive as $x \to 1$ from H, D, ^{3}He

^{3}He: **Hall C** E12-06-110



NH$_3$,ND$_3$: **CLAS** E12-06-109





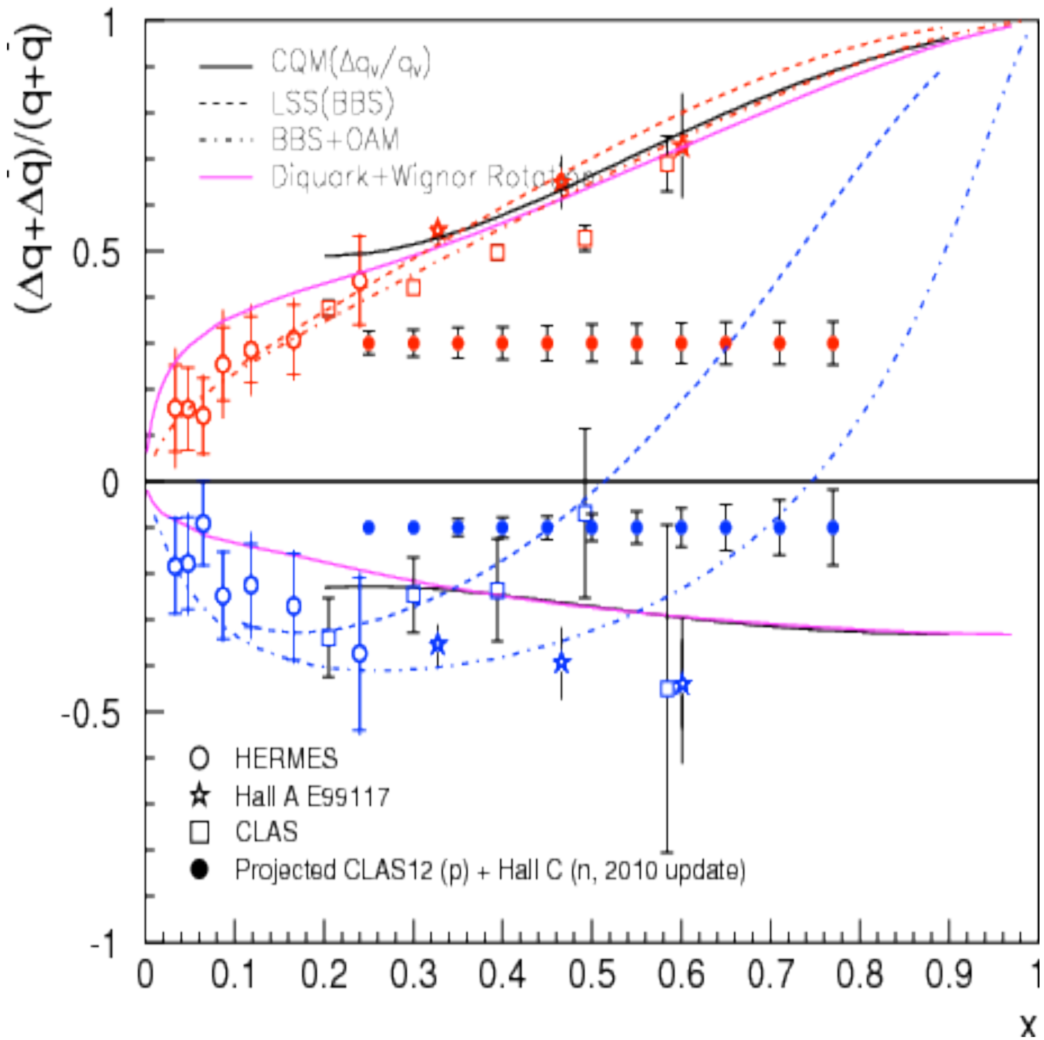
CLAS will measure SIDIS asymmetries too, concurrently with these

also **^{3}He**: **Hall A** E12-06-122

Reconstruct **$\Delta u/u$** & **$\Delta d/d$** *at high x from any two of these*

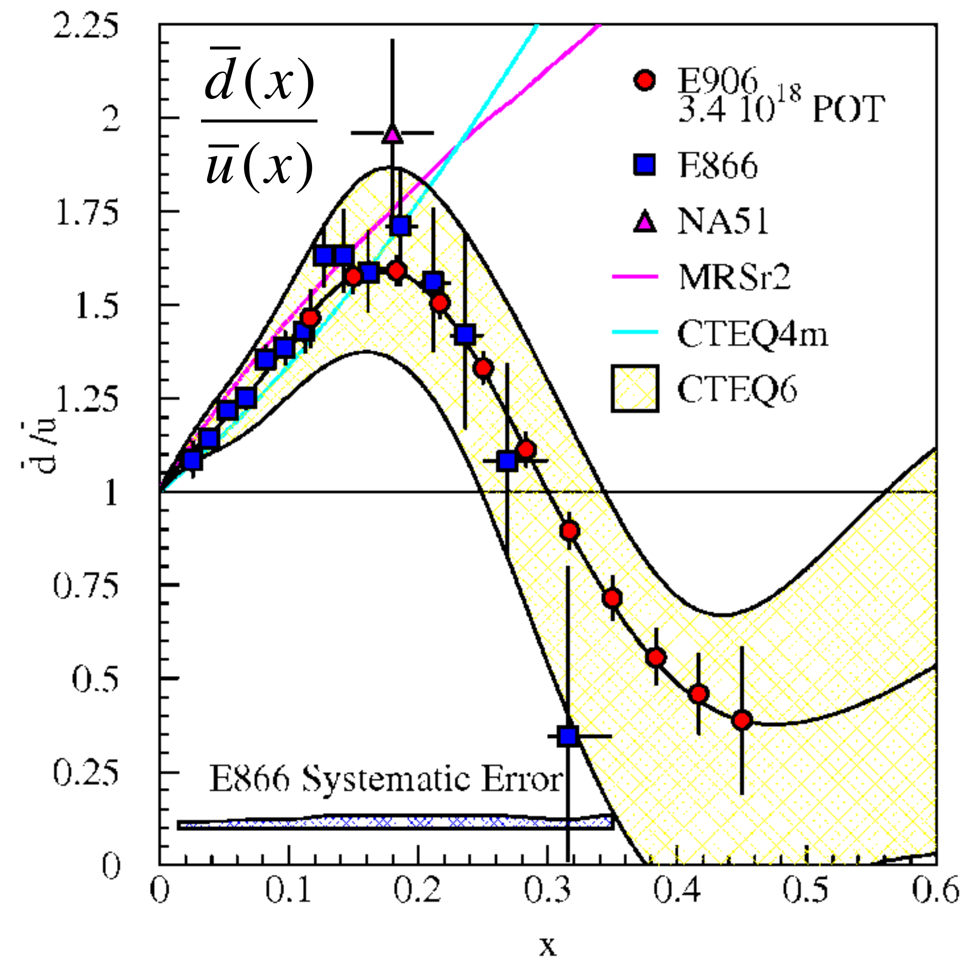
Valence Quark Polarizⁿ as x → 1

Combining A_1^n **Hall C** & A_1^p **CLAS**



Drell-Yan : Sea Quark PDFs as x → 1

SeaQuest at FNAL : 2 yr projecⁿ



Definitive valence quark polarizations at x > 0.6 →

NSAC milestone HP14 (2018) polarized part

Parton Distribution Functions :

Gluon and Antiquark Polarization

Longitudinal Data

	√s	L* (pb^{-1})
2006	200	7
2009	200	**25**
"	500	10
2011	500	12
2012	500	82
2013	500	**300**

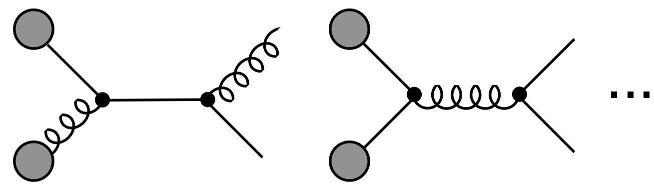
L* recorded at STAR

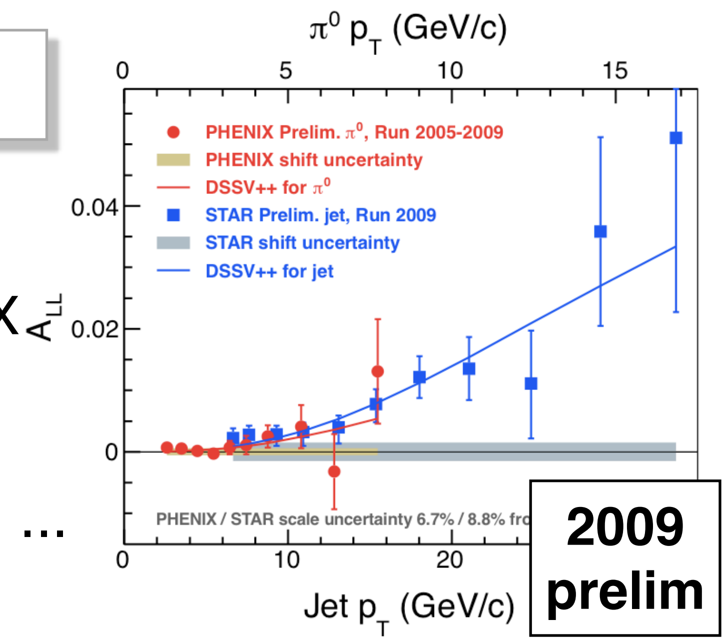
Δg at RHIC → 2020

(1) Δg workhorses:

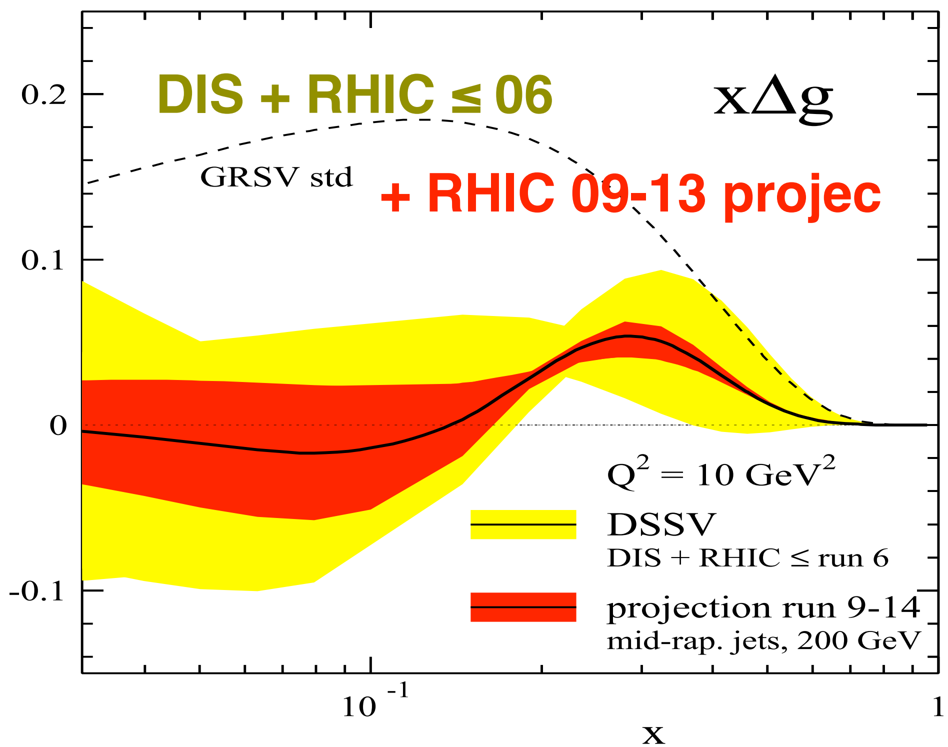
A_{LL} → π^0 + X @ PHENIX

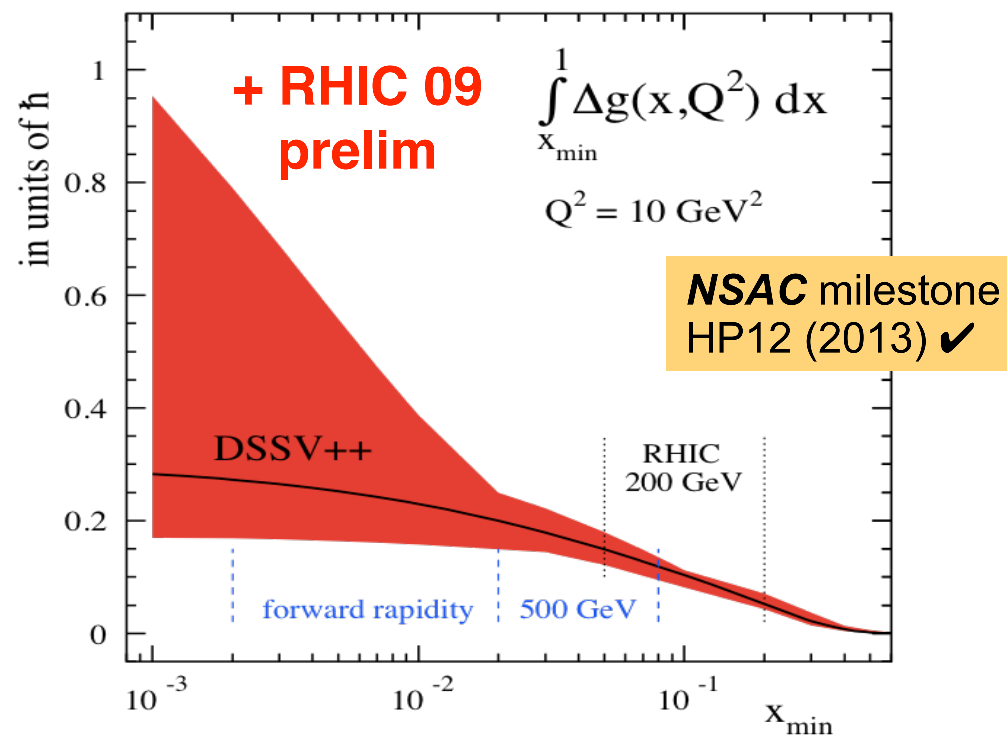
A_{LL} → jet + X @ STAR

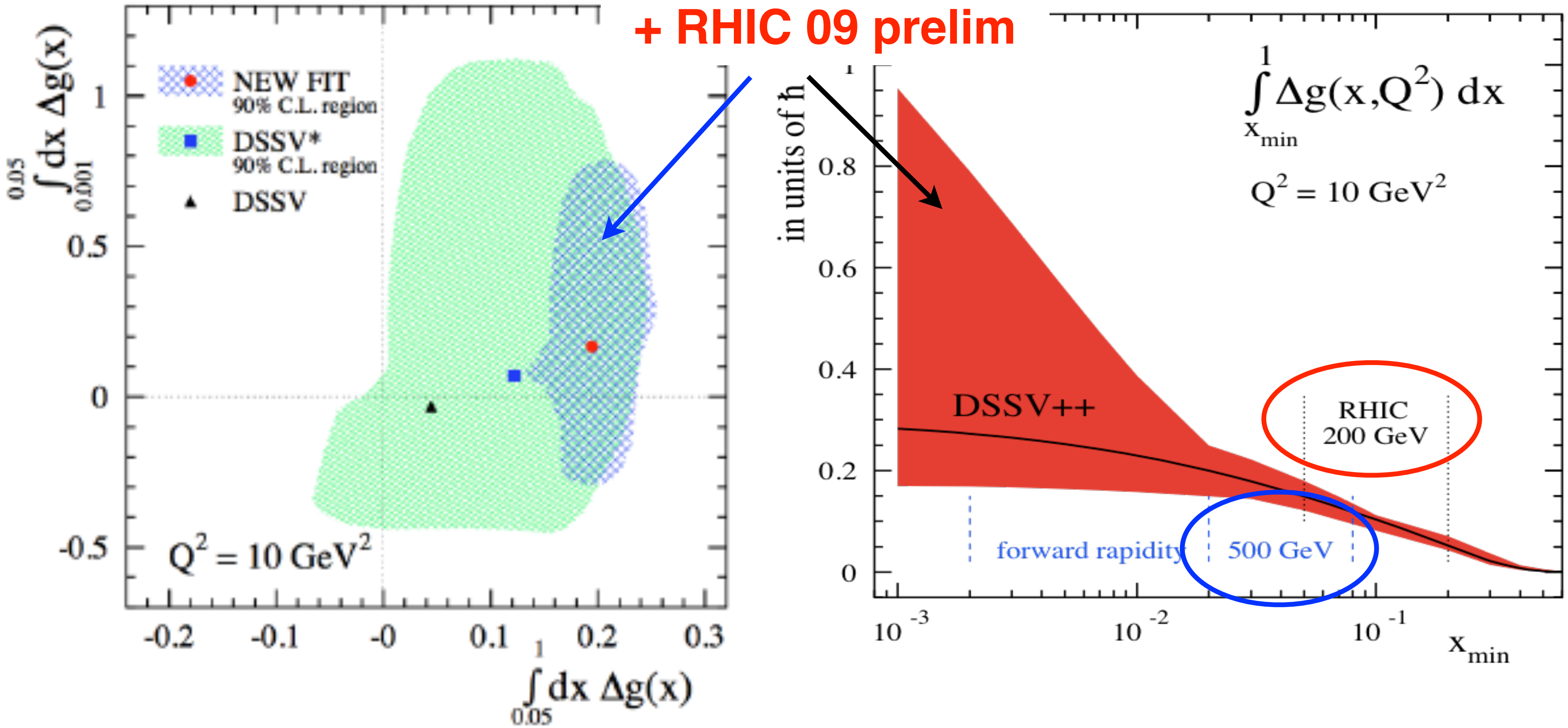




pQCD Fits :

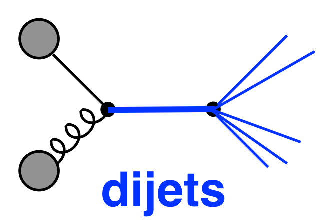


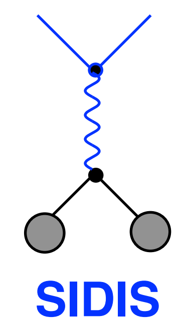




(2) reduce x_{min} from **0.05** → **0.02** via √s = 500 GeV &
new/near-term forward detectors (e.g. PHENIX MPC)

(3) constrain **x-dependence** of Δg(x) via **≈exclusive final states**
→ **dijets** at STAR & **di-π^0** at PHENIX
→ reconstruct initial-state **parton kinematics**





Δg 2020+

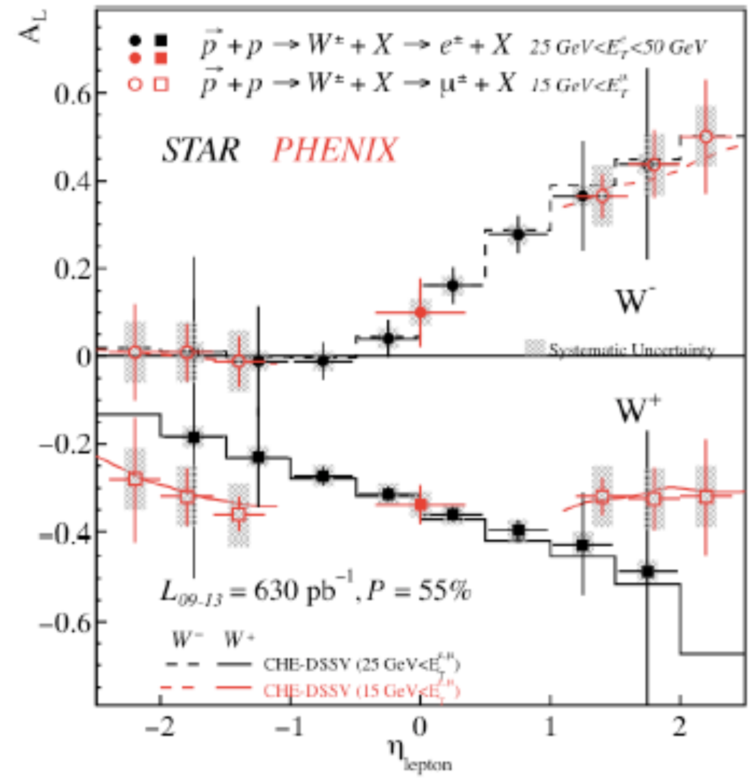
(4) forward upgrades : **reduce x_{min}** → **0.001**

Longitudinal Data

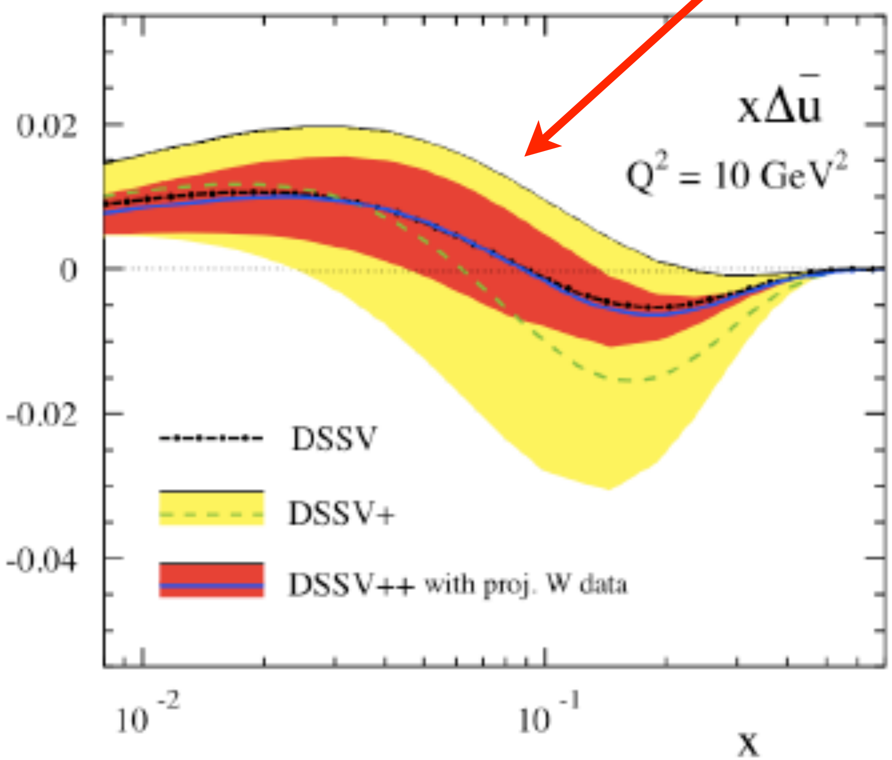
	$\sqrt{s}$	L* (pb^{-1})
2006	200	7
2009	200	**25**
"	500	10
2011	500	12
2012	500	82
2013	500	**300**

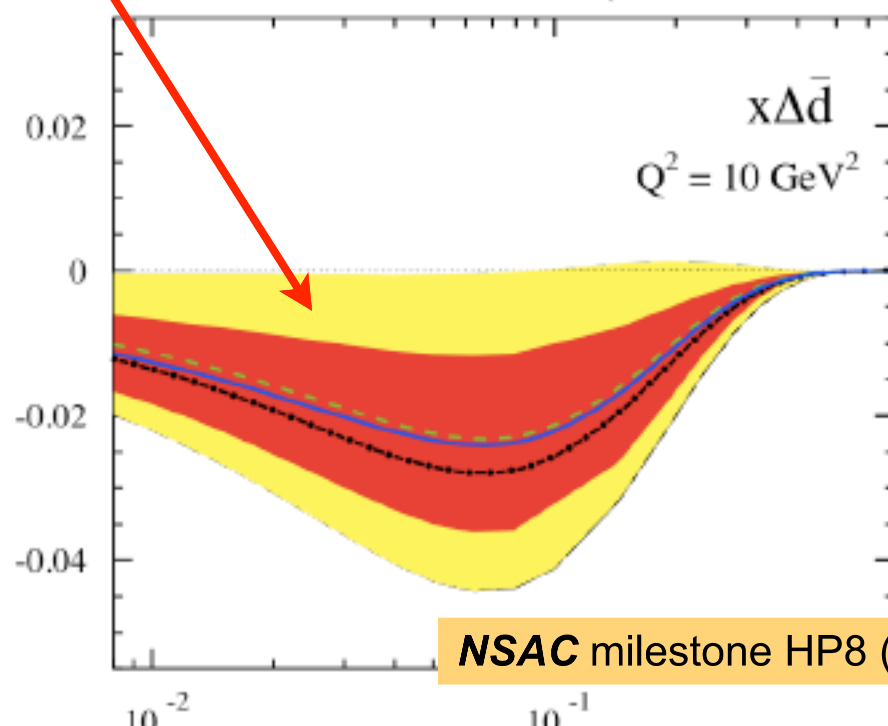
Δqbar at RHIC : $A_L(W^{\pm})$

simulated data matching **2012-13** lumi →



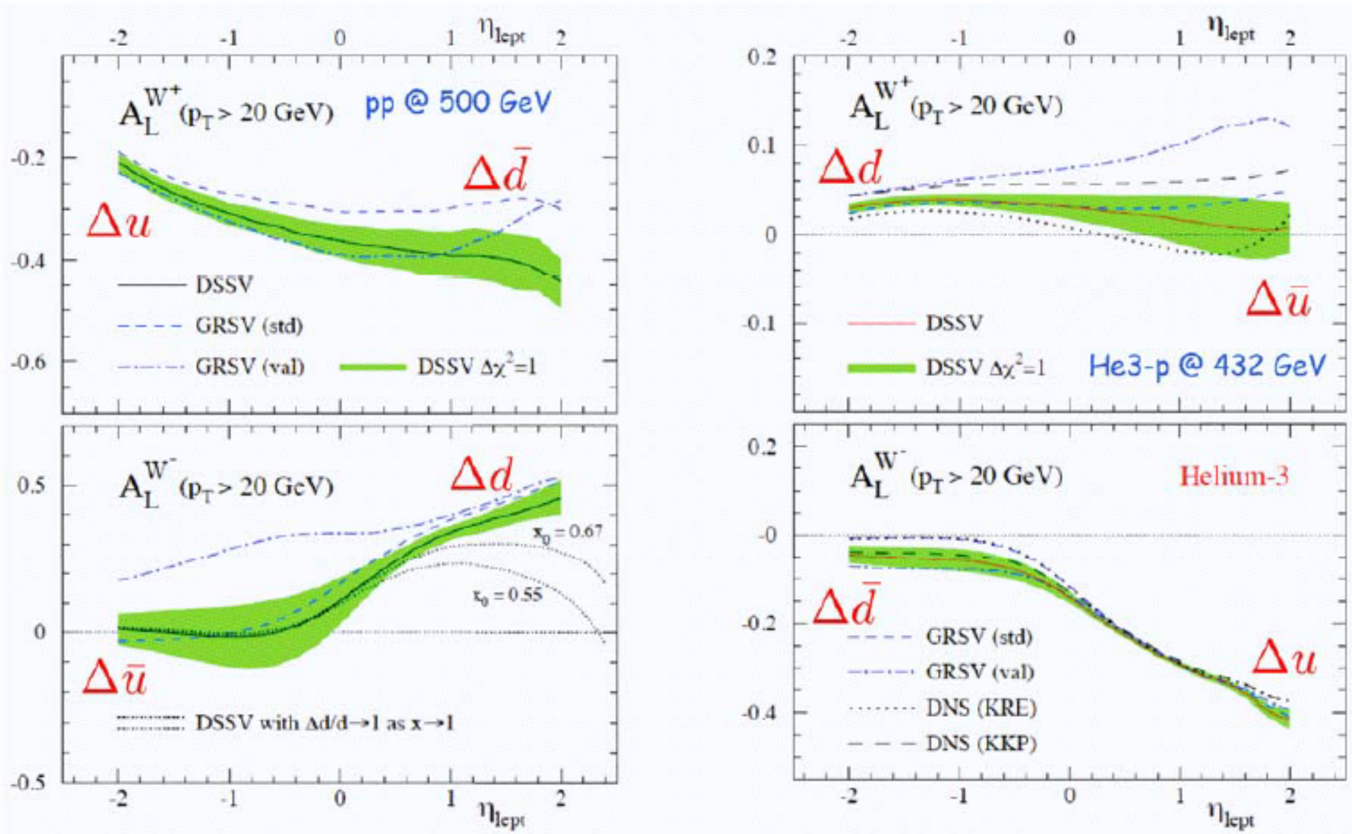
& **matching fits** :





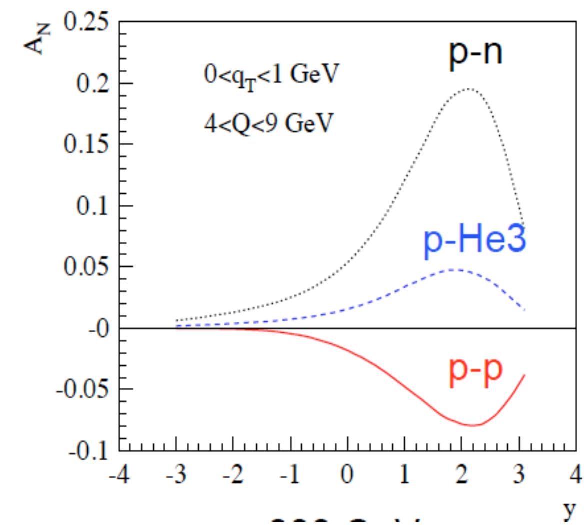
NSAC **milestone HP8 (2013) ✔**

Polarized ^{3}He at RHIC, beyond 2017



Goal: $^3He^{++}$ at 3E12 s^{-1} with 70% polarization

Tag proton spectator with Roman pots phase II



- Source R&D underway at MIT
- Important for EIC

Thanks to R. Milner

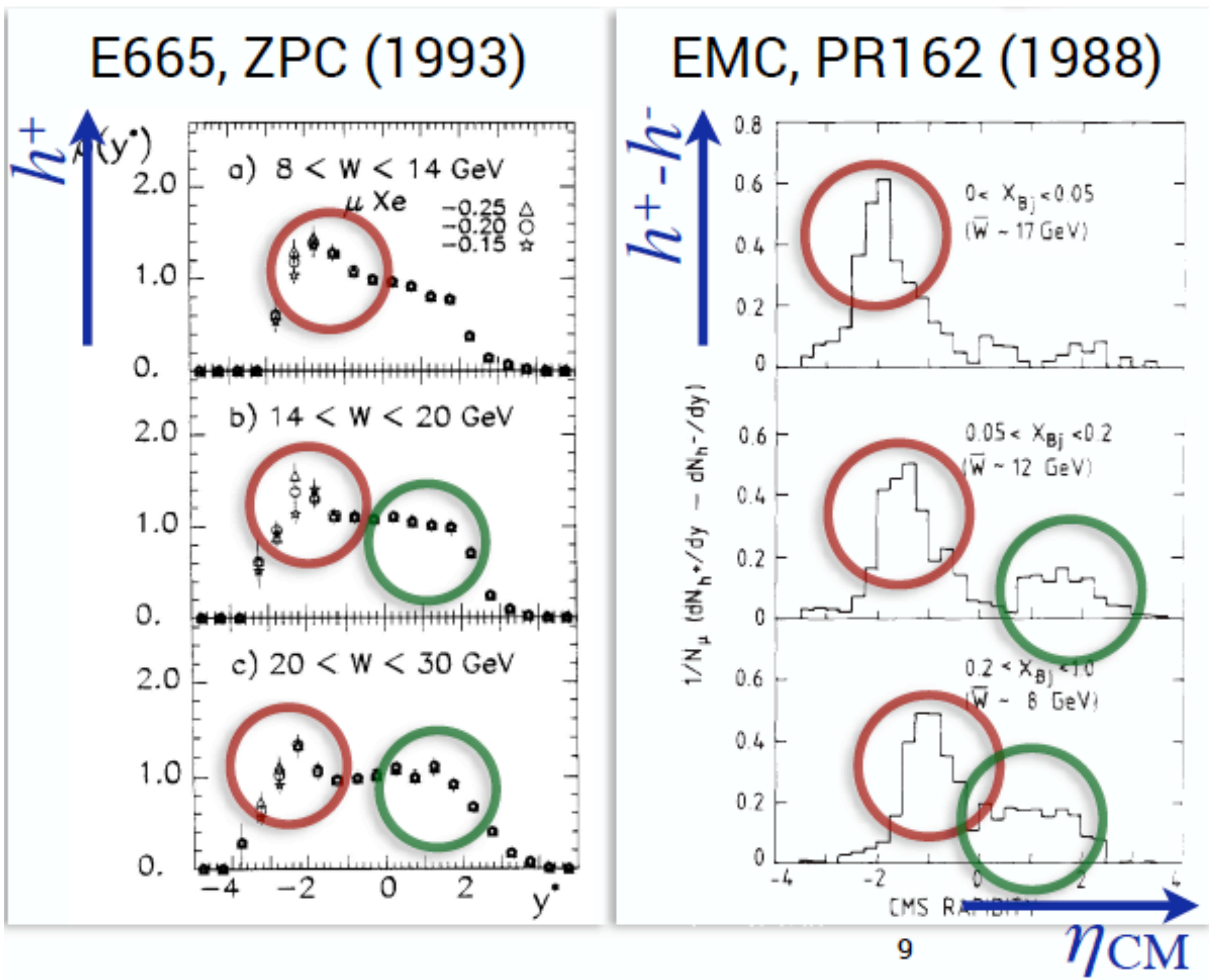
https://indico.bnl.gov/conferenceProgram.py?confid=405 for proceedings of September 2011 RBRC/BNL workshop *on Opportunities for Polarized He-3 in RHIC and EIC.*

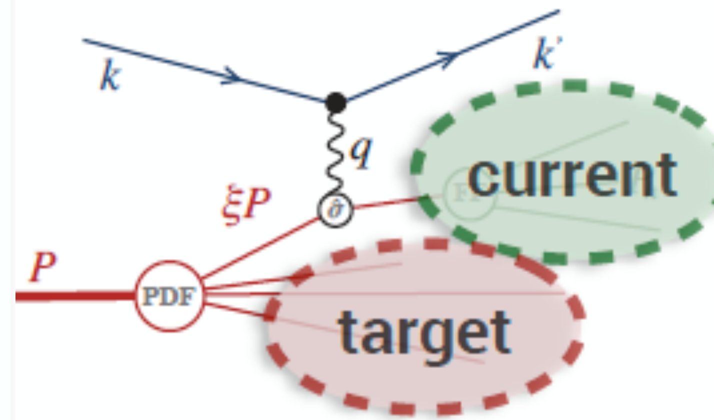
Analysis depends on **factorization** : e.g. at LO →

Δqbar at JLab : SIDIS

$$d\sigma^h \sim \sum_q e_q^2\, q(x) \cdot \hat{\sigma} \cdot D^{q\to h}(z)$$

... and knowledge of **fragmentation** functions (or fitted MC model thereof)





Caution required at modest energies

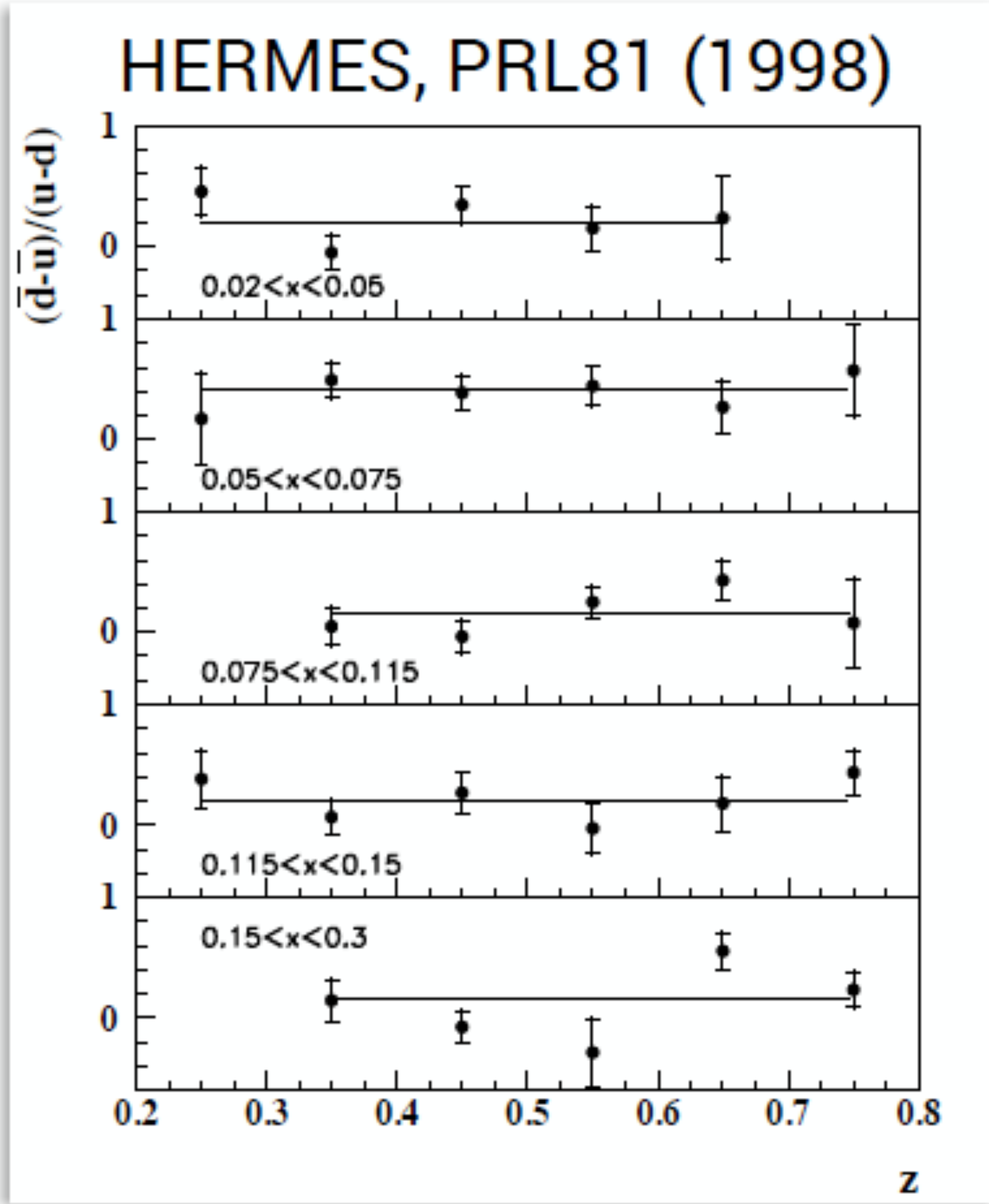
HERMES $3.1 < W < 7.2$

JLab $2.3 < W < 4.5$

not all that different ...

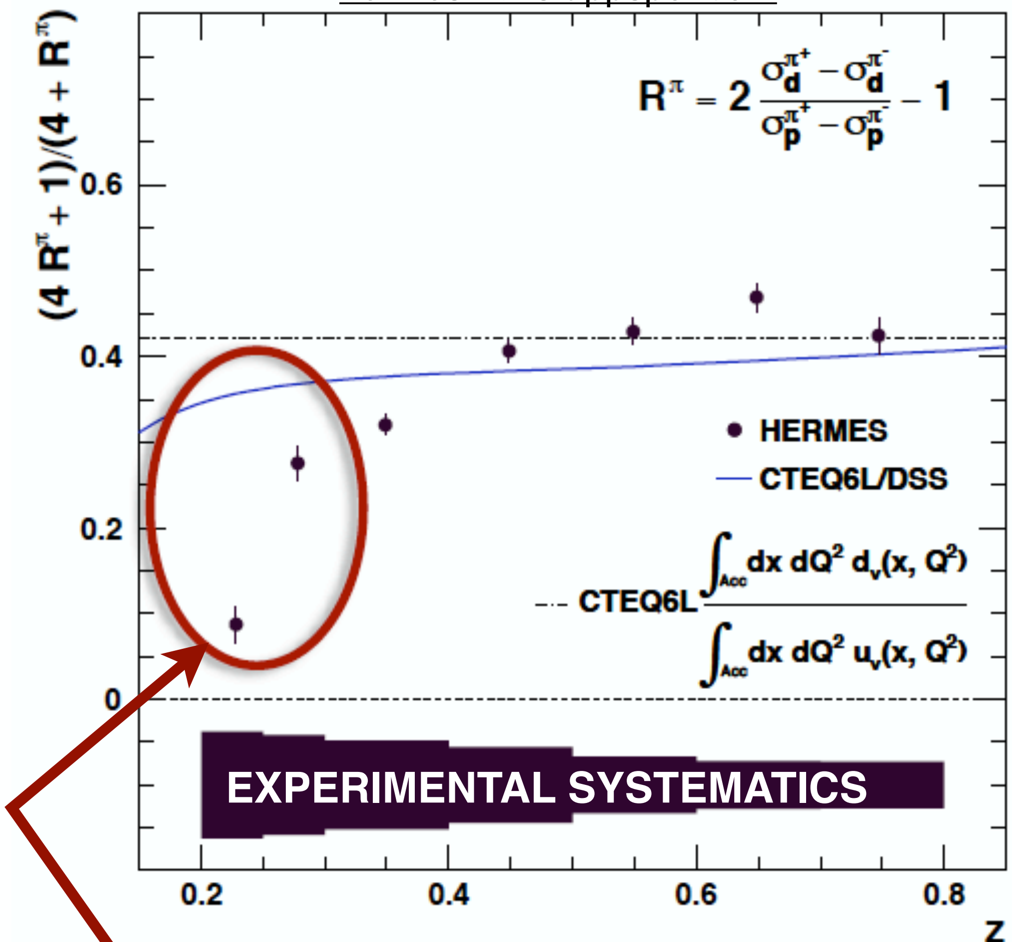
1st and last search for LO-factorizn edge

LO** extractions of **PDF(x)** combinations from $\pi^\pm$ **multiplicities



Final multiplicities (2013) all combined:

hermesmults.appspot.com

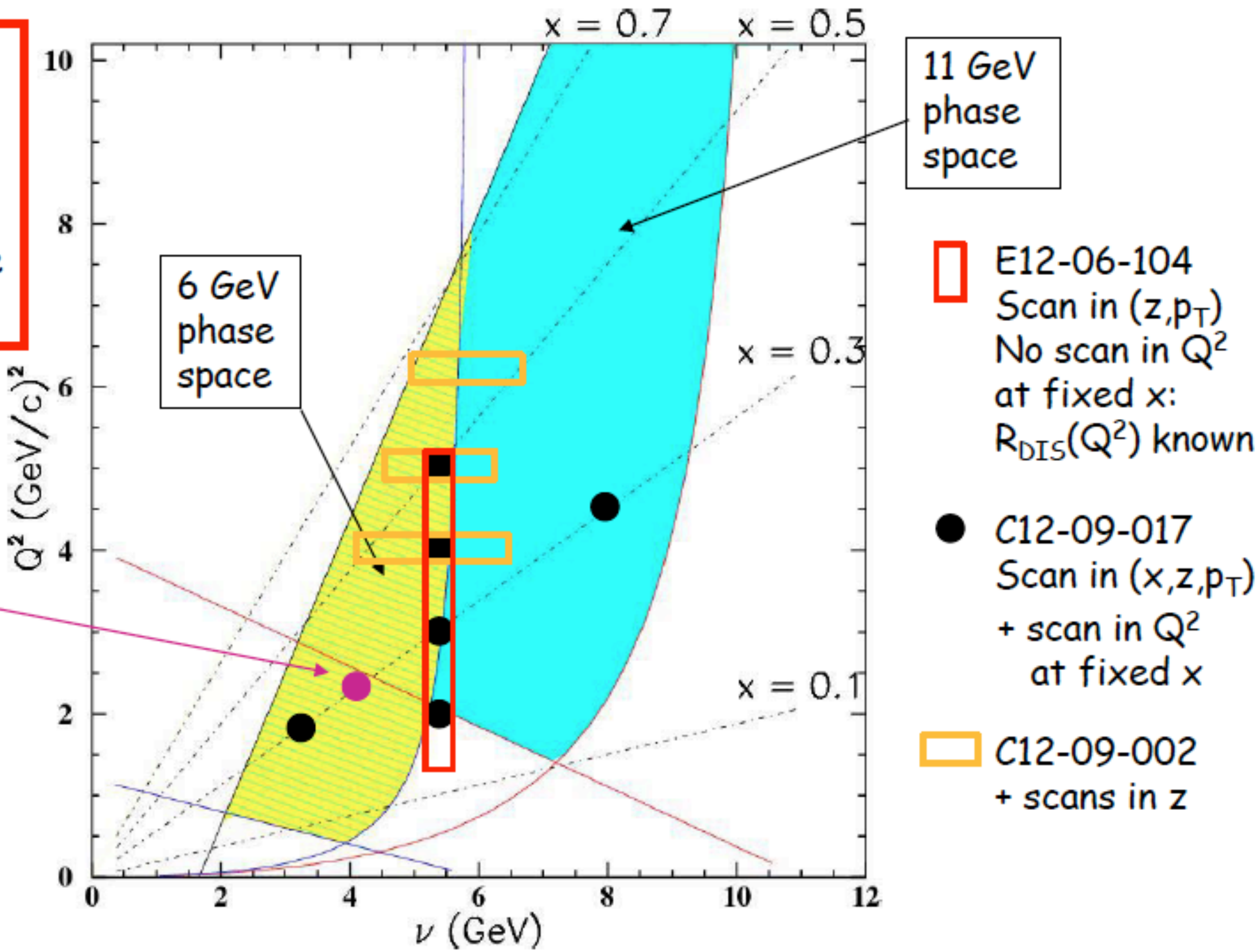


✔ only breaks down where it **MUST**

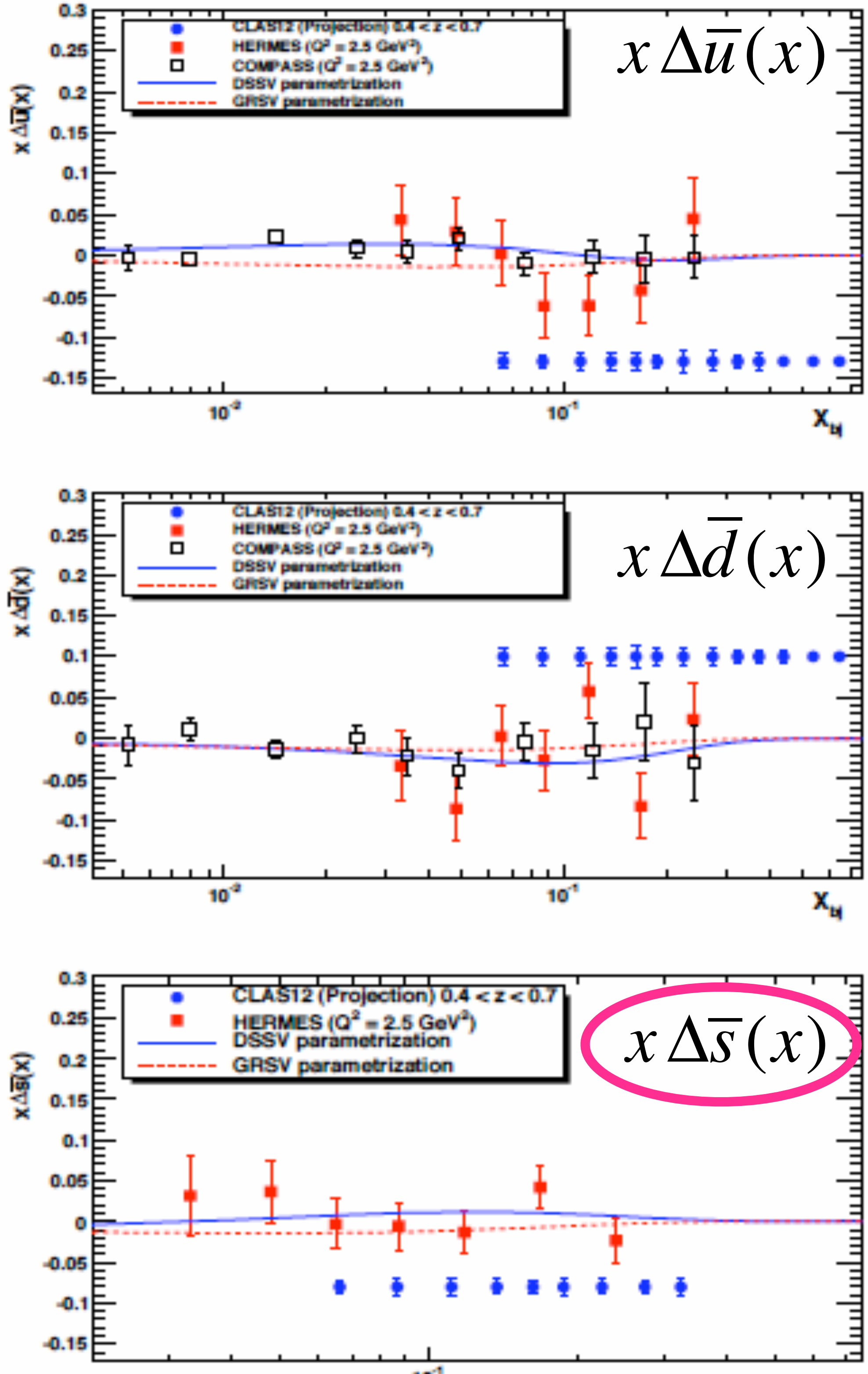
JLab SIDIS : Careful Strategy

(1) Make **high-precision scans** of $\sigma(x,z,p_T,Q^2)$ with **Hall C spectrometers**

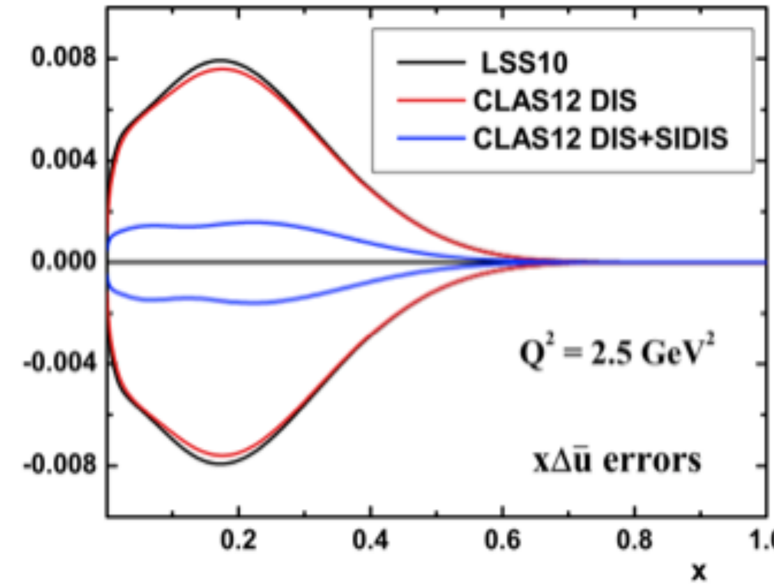
All together:
data base of precise SIDIS cross sections over nice range of x and Q^2!

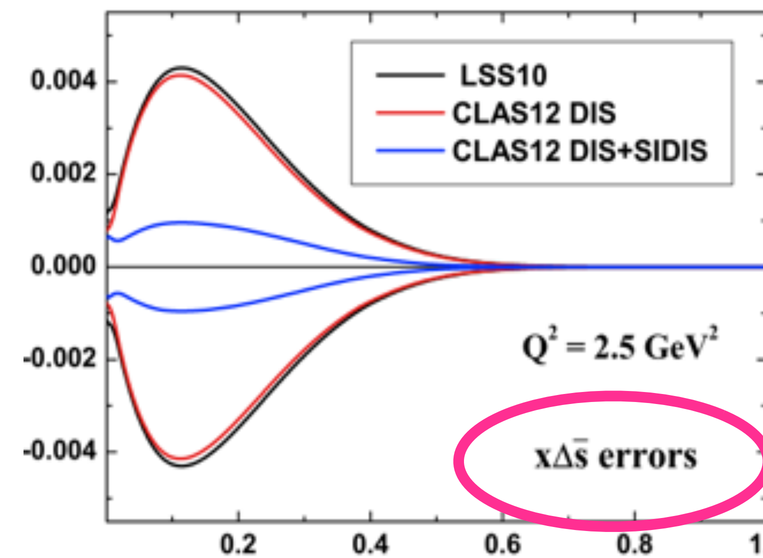


CLAS12 SIDIS: Δqbar Statistical Projections



Improved PDFs from NLO analyses





*CLAS12 RICH → Kaon ID

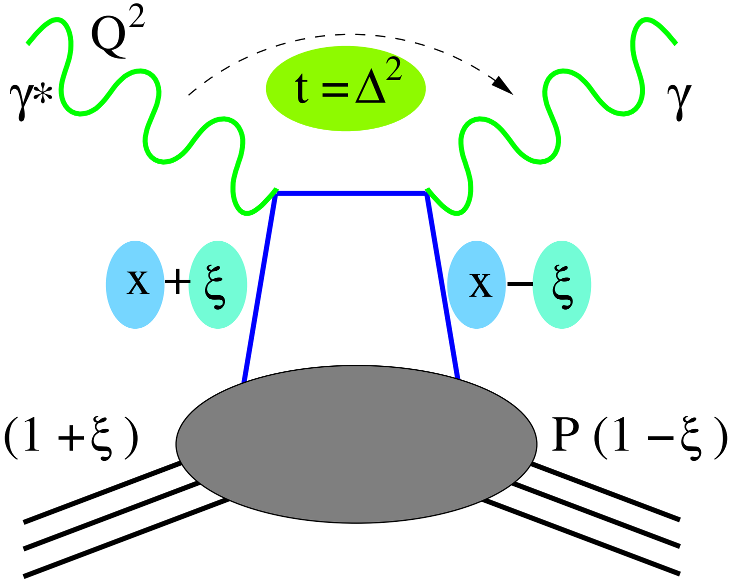
Generalized Parton Distributions:

Spatial Imaging of Partons
& their
Orbital Angular Momentum

hard exclusive processes →

Generalized Parton Distributions

DVCS

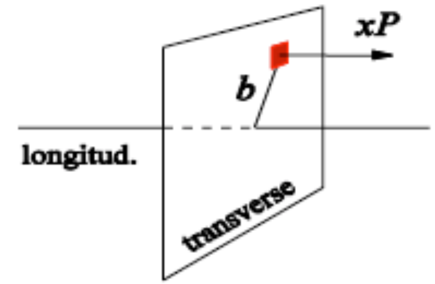


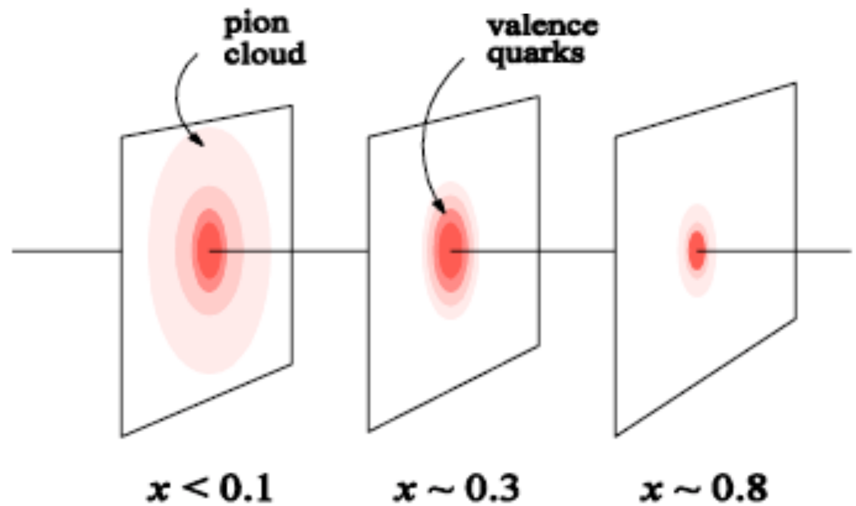
Four new distributions : GPDs

$$
\begin{aligned}
q \text{ helicity sum} &\rightarrow H(x, \xi, t) \\
&\rightarrow E(x, \xi, t) \\
q \text{ helicity diff} &\rightarrow \tilde{H}(x, \xi, t) \\
&\rightarrow \tilde{E}(x, \xi, t)
\end{aligned}
$$

Goal 1: Transverse Imaging of Nucleon

Fourier transform of t-dependence





Goal 2: Orbital Angular Momentum

Ji's Sum Rule for $J^q = \frac{1}{2}\Delta\Sigma + L^q$

$$J^q = \frac{1}{2}\int_{-1}^{1} x\,dx\,[H^q(x,\xi,t=0) + E^q(x,\xi,t=0)]$$

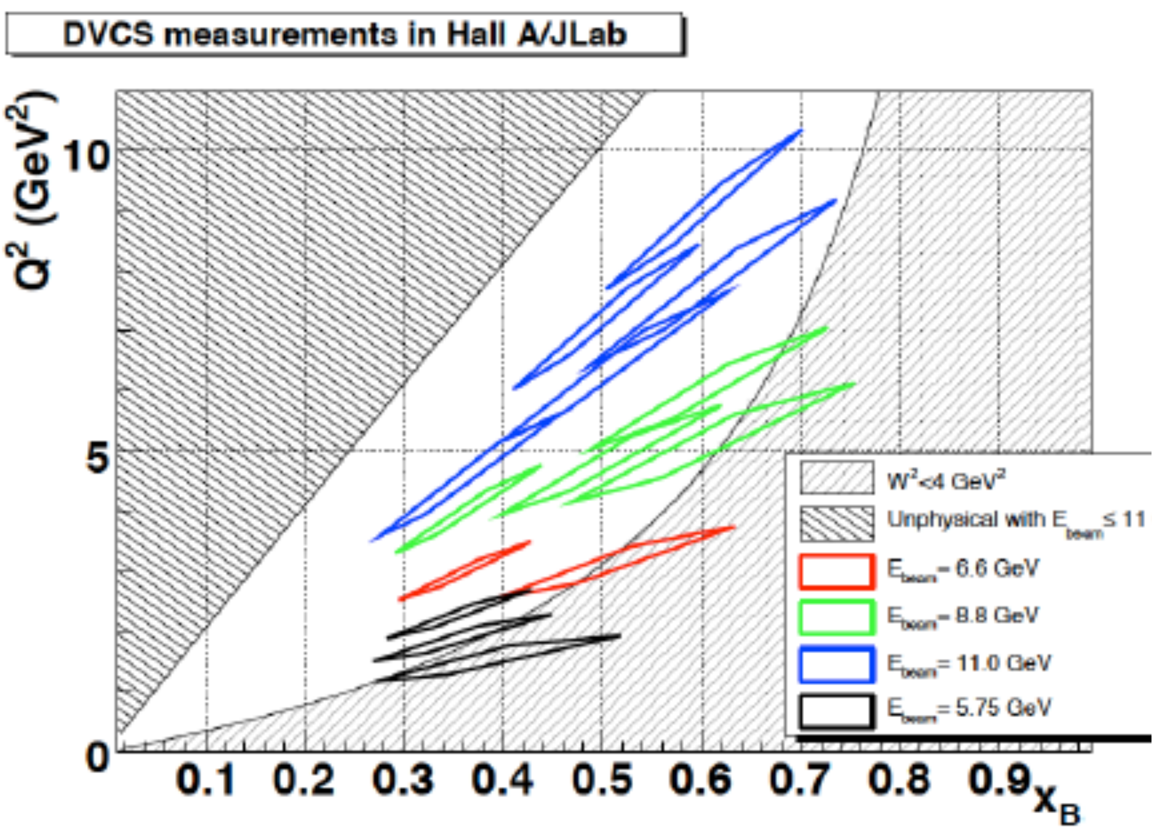
DVCS Strategy at JLab-12

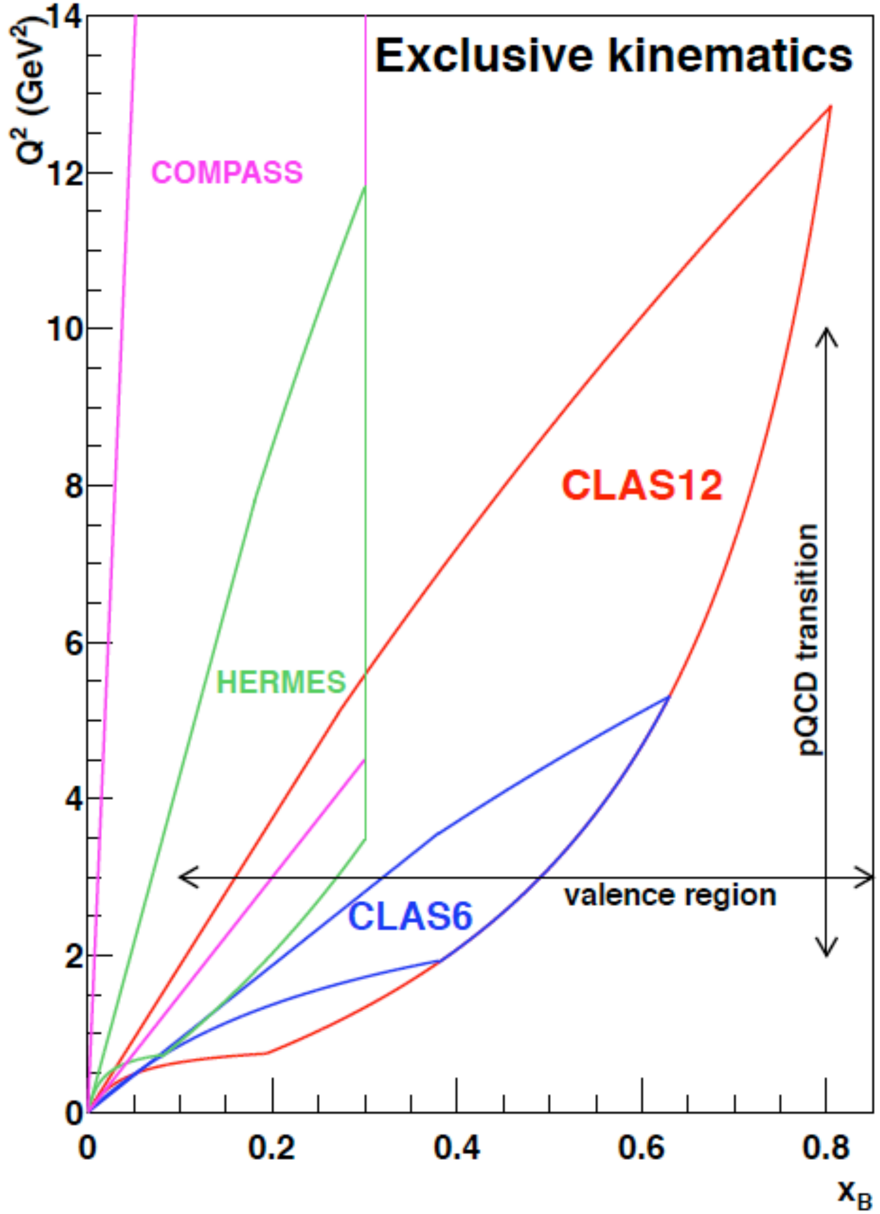
(2) Measure DVCS at **CLAS** in **broad kinematic range** with **polarized & unpol** observables

(1) Establish scaling of σ_{DVCS} in **Hall A**

E12-06-114 : unpol H target, Lpol beam

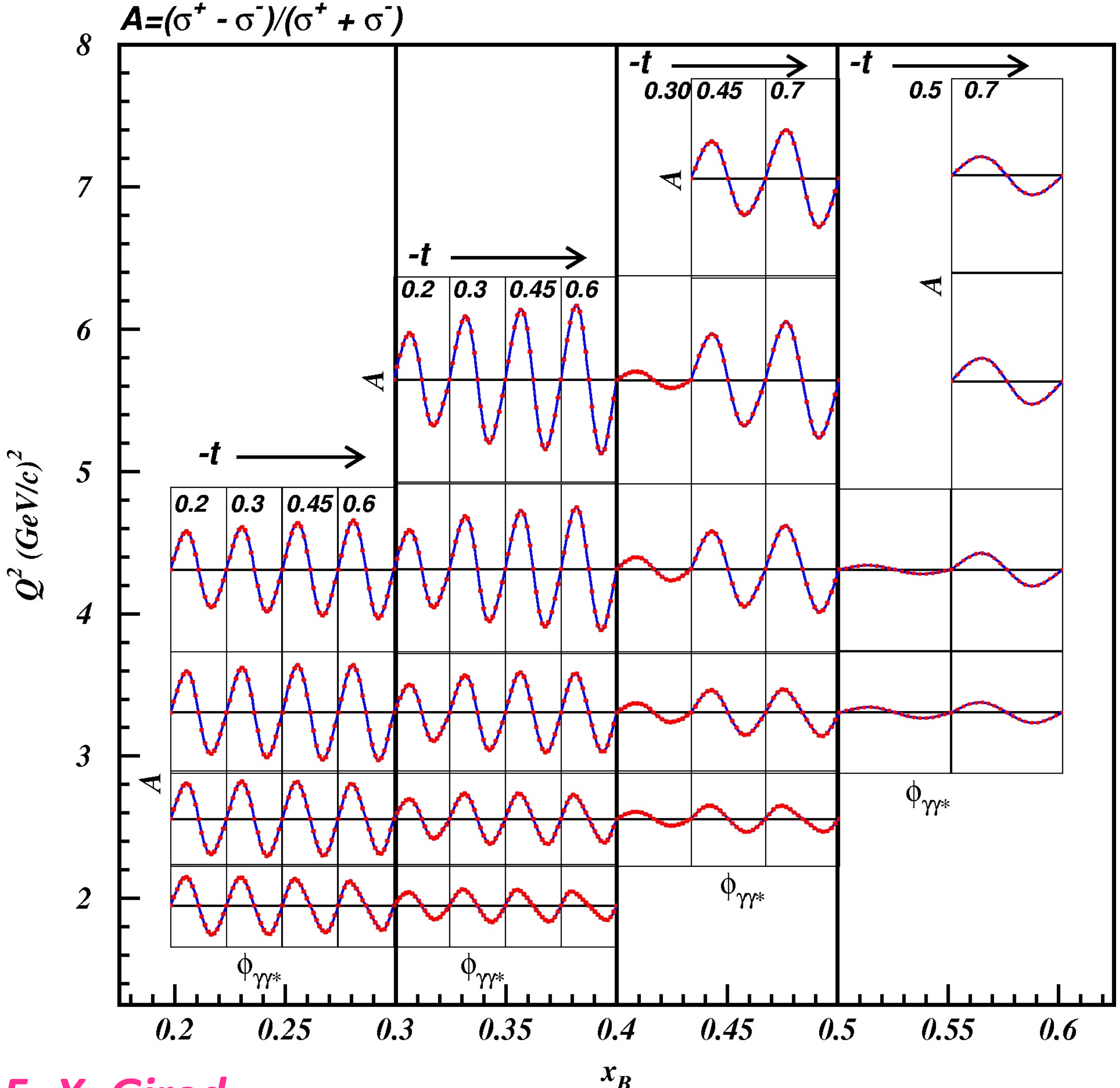
→ *runs **very early** ≈ 2014*





Proton BSA DVCS A_{LU} **CLAS E12-06-009**

80 days @ $\mathcal{L} = 10^{35}$ cm^{-2}s^{-1} with 85% polarized beam $\quad A_{LU} \propto F_1 \mathcal{H} + \xi G_M \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E}$



Projections for CLAS12

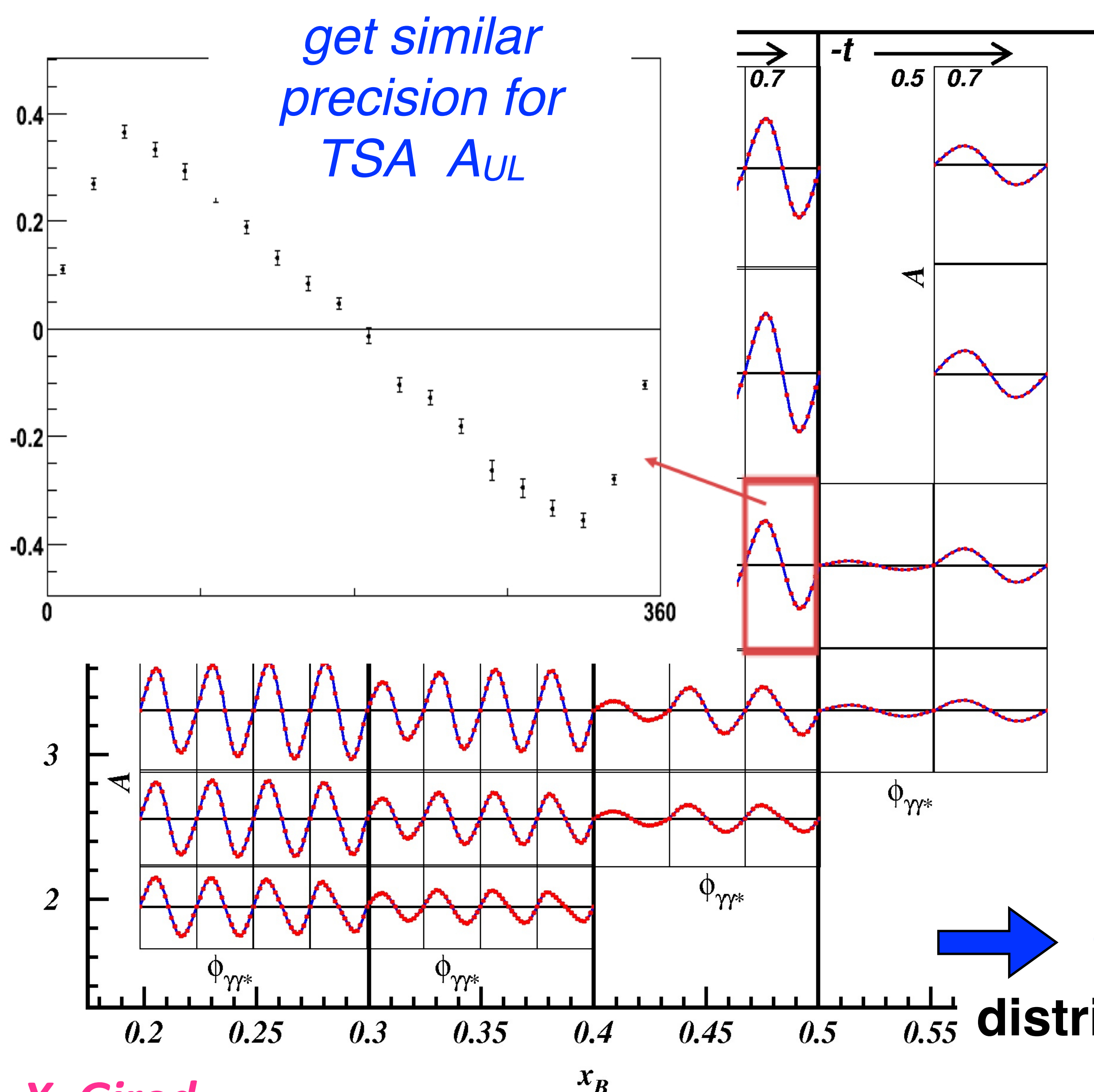
Statistical uncertainties :
from 1 % (low Q^2)
to 10 % (high Q^2)

Unprecedented statistics
over the full ϕ range
up to high $x = 0.6$

F.-X. Girod

Proton BSA DVCS A_{LU} **CLAS E12-06-009**

80 days @ $\mathcal{L} = 10^{35}$ cm^{-2}s^{-1} with 85% polarized beam $\quad A_{LU} \propto F_1\mathcal{H} + \xi G_M\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}$



Projections for CLAS12

Statistical uncertainties : from 1 % (low Q^2) to 10 % (high Q^2)

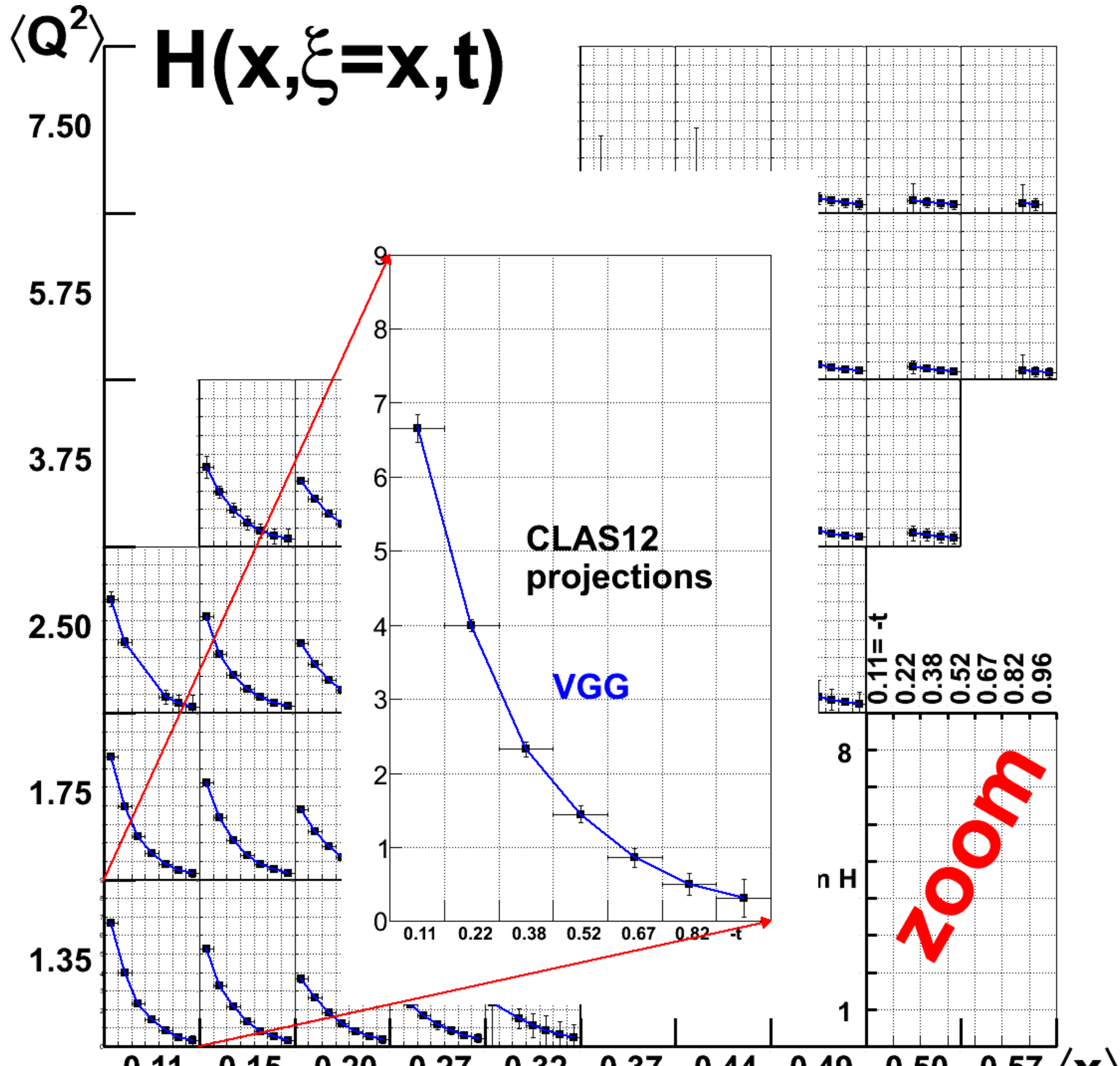
Unprecedented statistics over the full ϕ range up to high $x = 0.6$

Goal 1: spatial distributions of partons

F.-X. Girod

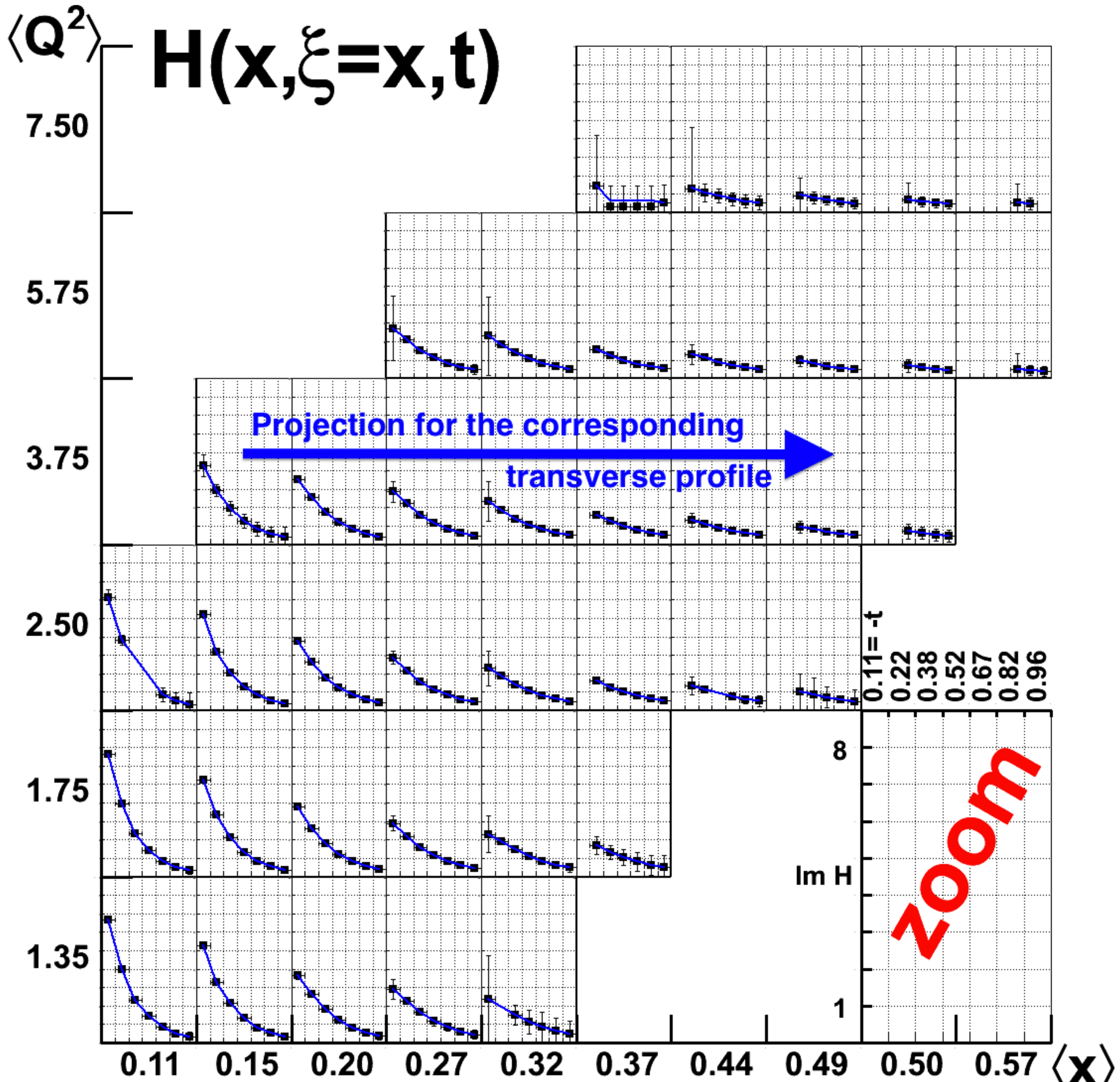
Projected impact on GPD extraction methods

Using simulated data based on VGG model. Input GPD H extracted with good accuracy



F.-X. Girod

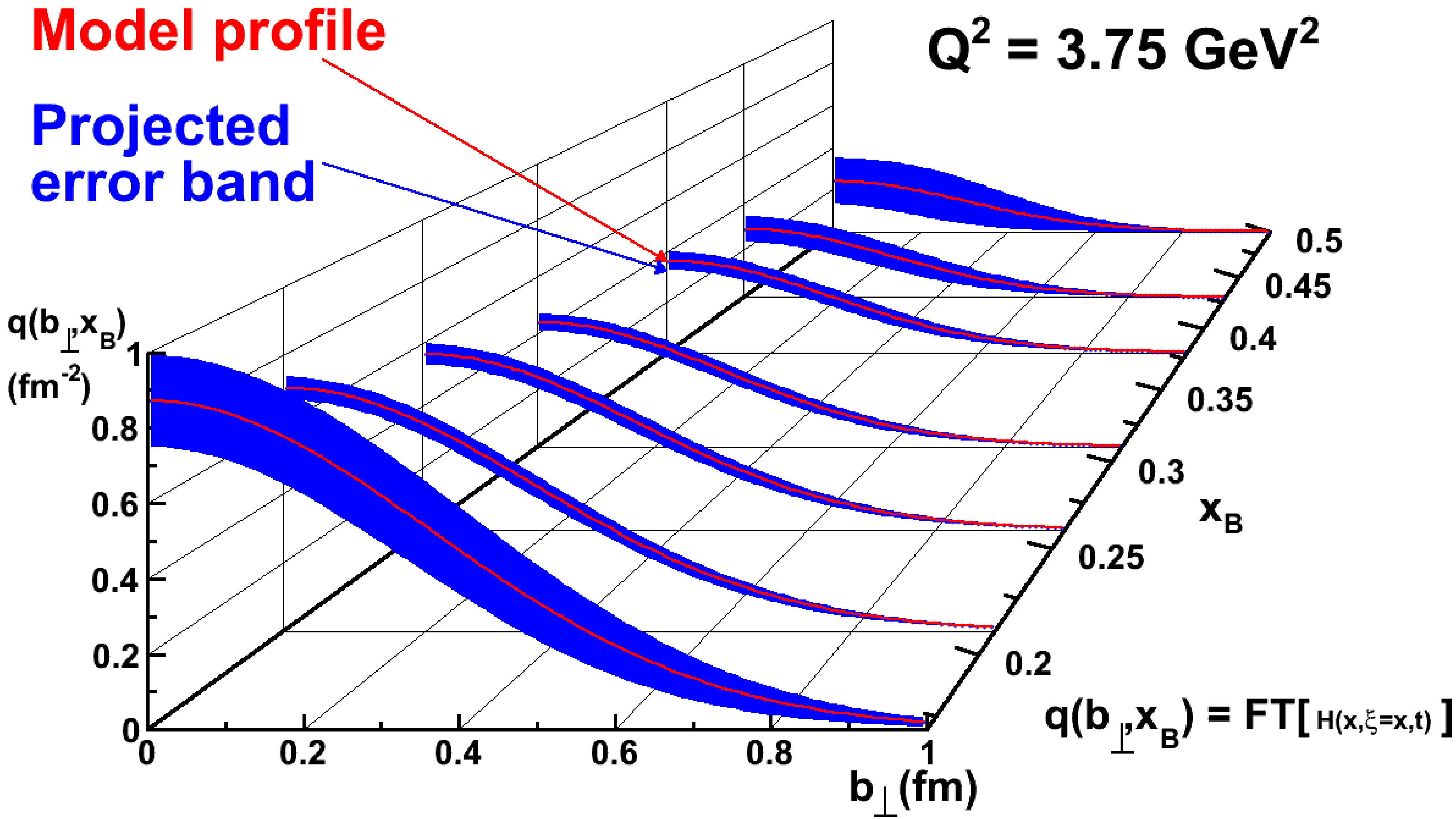
Projected impact on GPD extraction methods



Using simulated data based on VGG model. Input GPD H extracted with good accuracy

F.-X. Girod

Projection for the Nucleon transverse profile

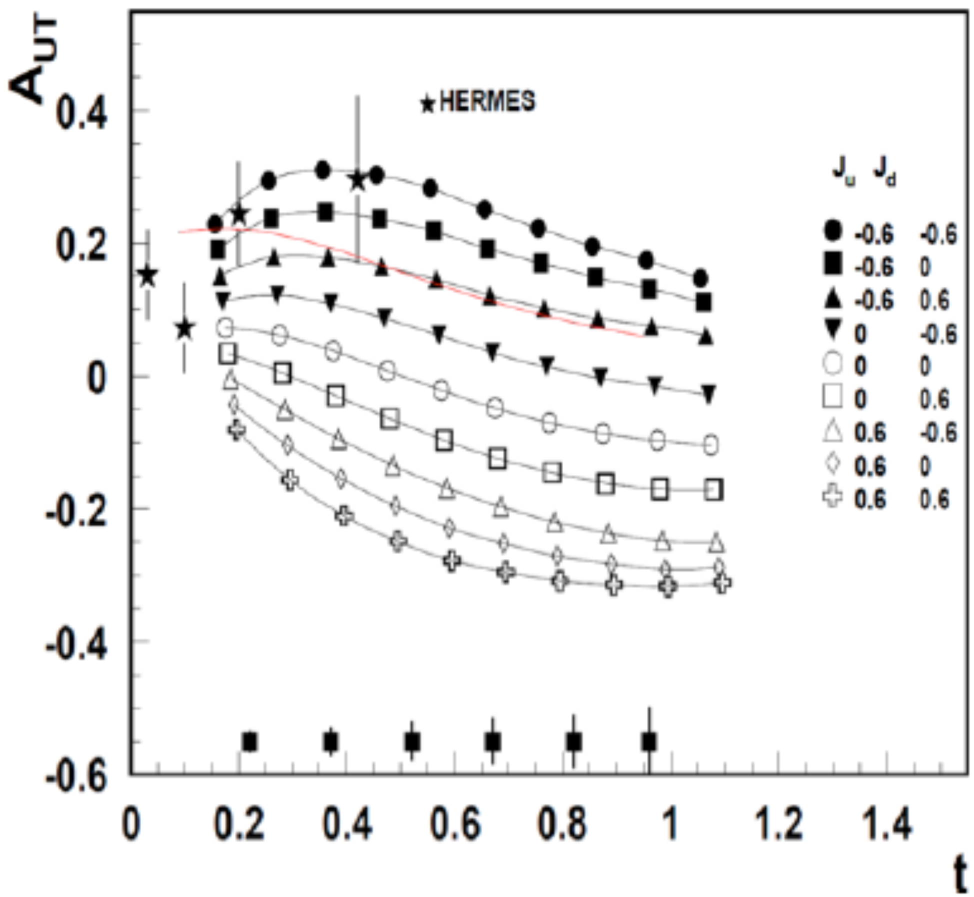


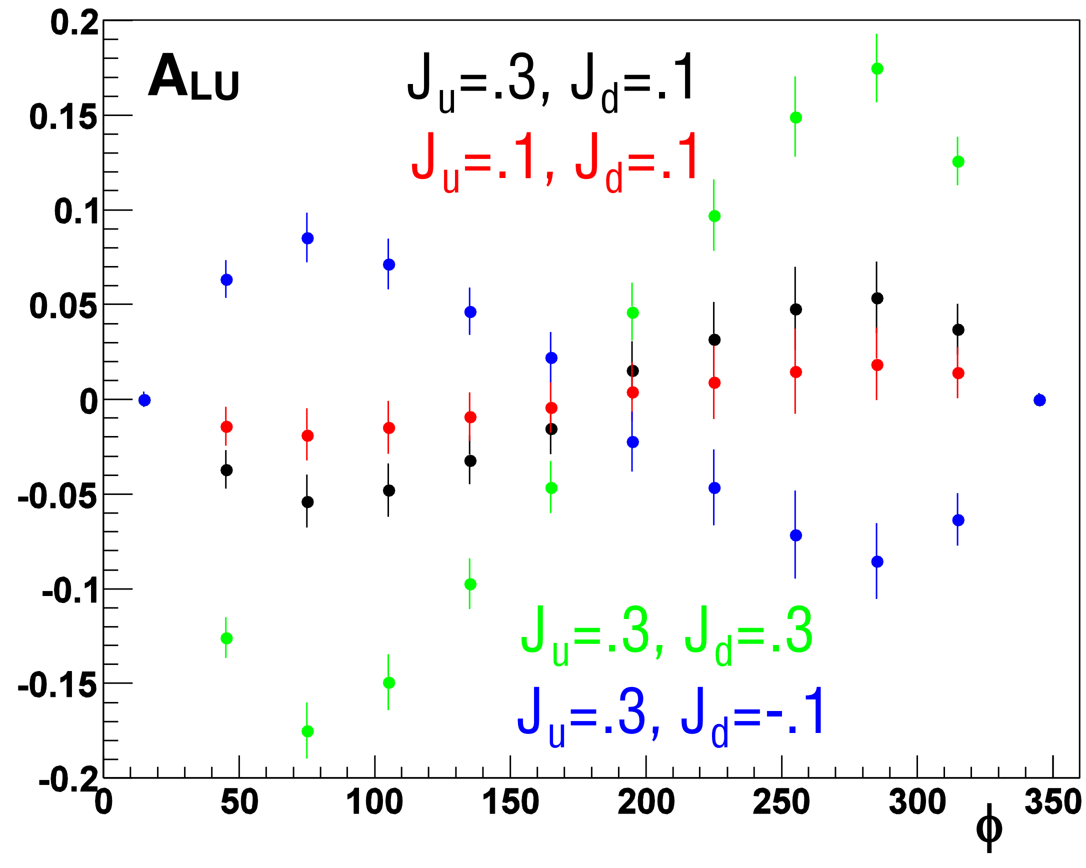
Precision tomography in the valence region

DVCS Goal 2: Access to L via GPD E

Model predictions (VGG) for different values of J_u & J_d

- C12-12-010: **CLAS** w **HD-Ice Transverse** target
- E12-11-003: **CLAS** w **Unpol Deuterium** target





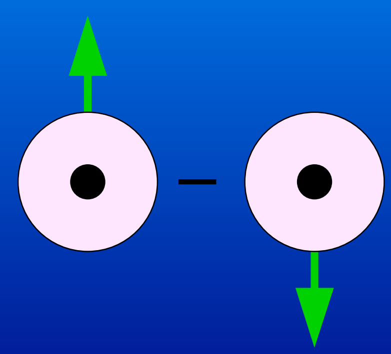
sensitivity to $\mathbf{J_u}$ excellent, $\mathbf{J_d}$ very good

$\mathbf{J_u}$, $\mathbf{J_d}$ sensitivity reversed

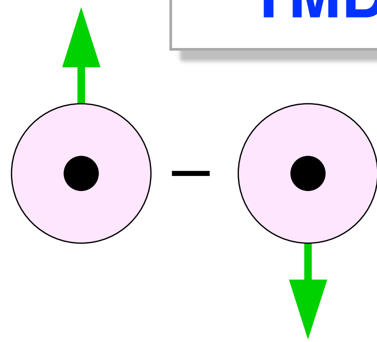
more flavors → <u>exclusive meson</u> program (more challenging)

TMDs : The Sivers Function

$$f_{1T}^{\perp}(x, k_T)$$

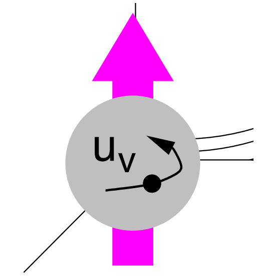


TMDs : The Sivers Distribution

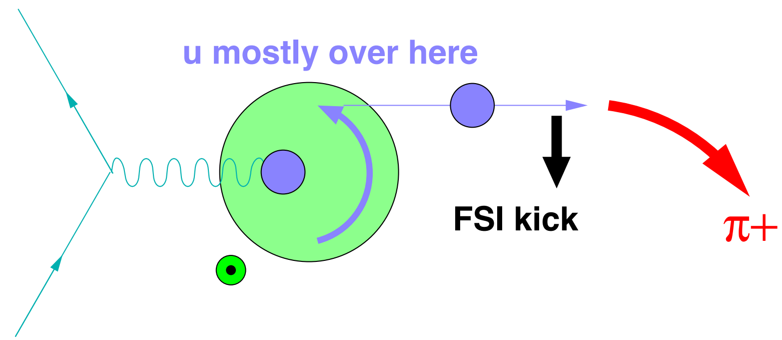
$$f_{1T}^{\perp}(x, k_T) = $$ 

Can't exist without quark **OAM**

(Orbital Angular Momentum)



but it is <u>not</u> L ... SSAs produced via some "lensing function", e.g. →

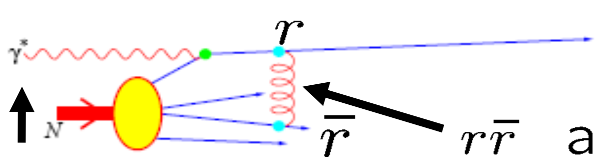


"Smoking gun" prediction of **TMD formalism**:

∴ **Goal #1** = observe the **Sivers Sign Change**

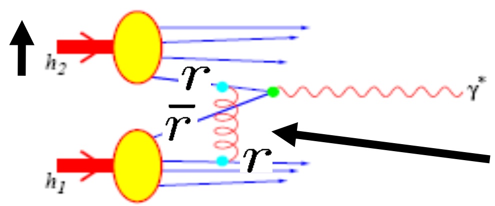
$$f_{1T}^{\perp}\Big|_{DIS} = -\, f_{1T}^{\perp}\Big|_{DY,W}$$

DIS



$r\bar{r}$ attractive

DY

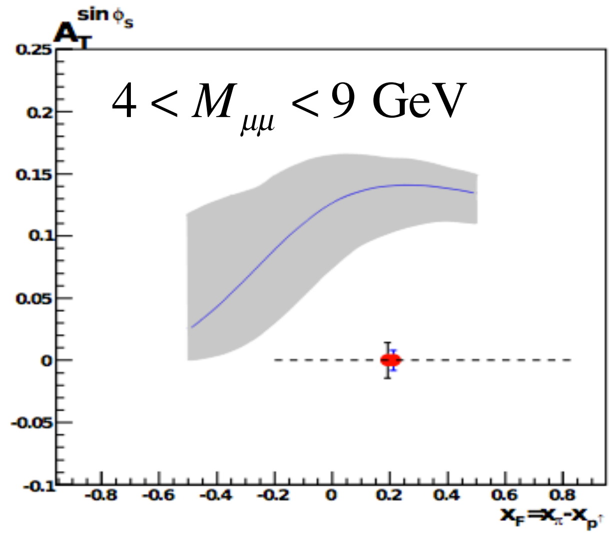


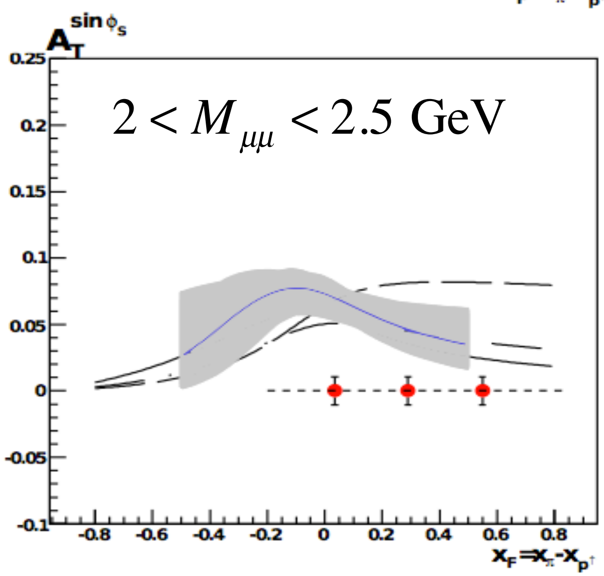
rr repulsive

- ***NSAC*** Milestone HP13 (**2015**) "Test unique QCD predictions for relations between single-transverse spin phenomena in p-p scattering and those observed in deep-inelastic scattering."
- COMPASS-II, RHIC-spin, polarized FNAL

The Sivers Sign Change < 2020

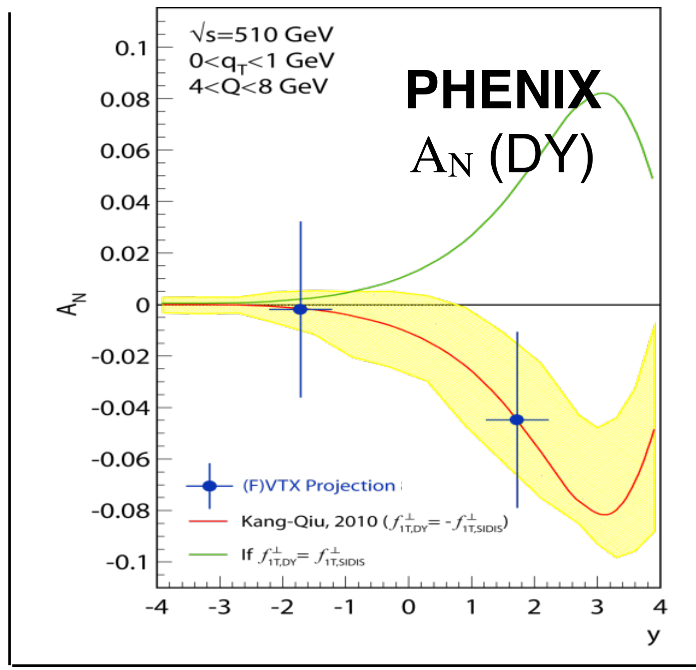
- **COMPASS-II** (2014)
  $\pi^- p\uparrow$ Drell-Yan

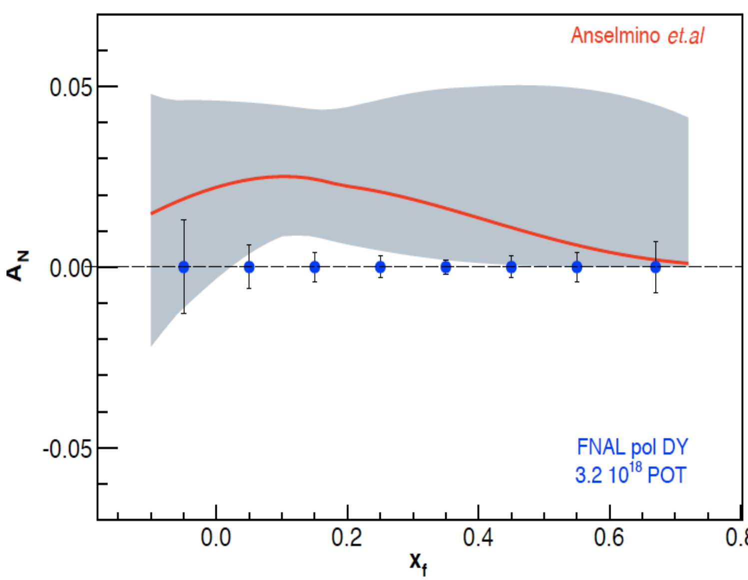


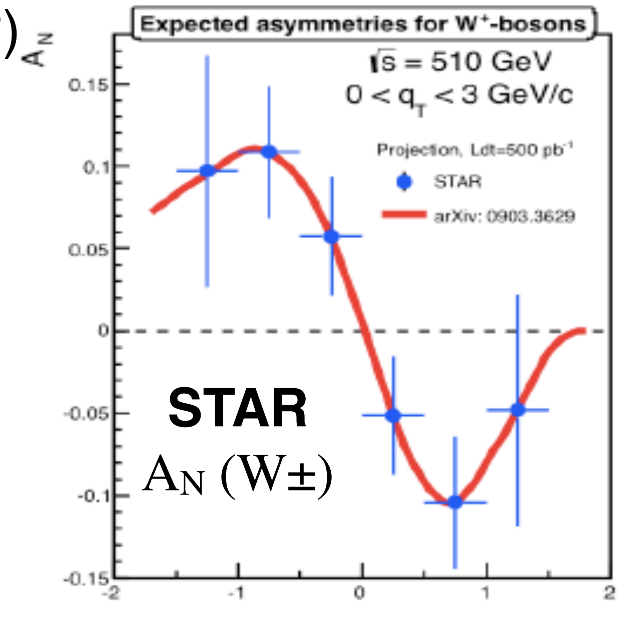


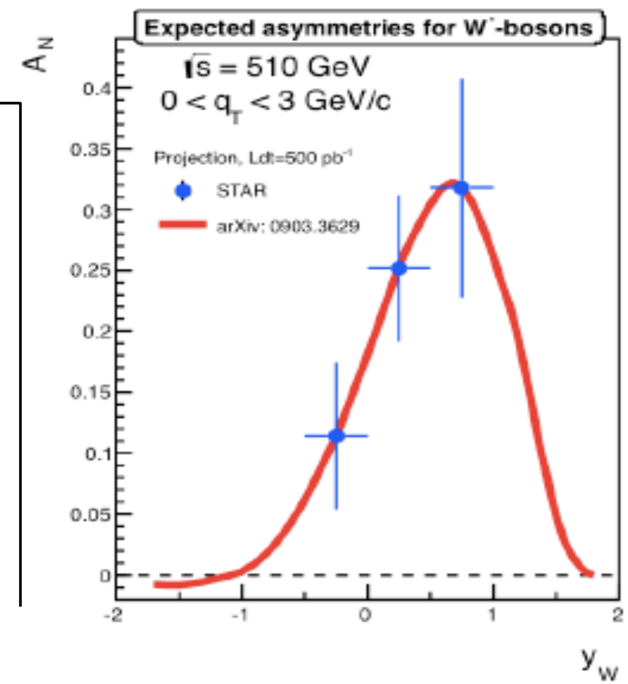
- **Beam-Polarized SeaQuest** (2017+)

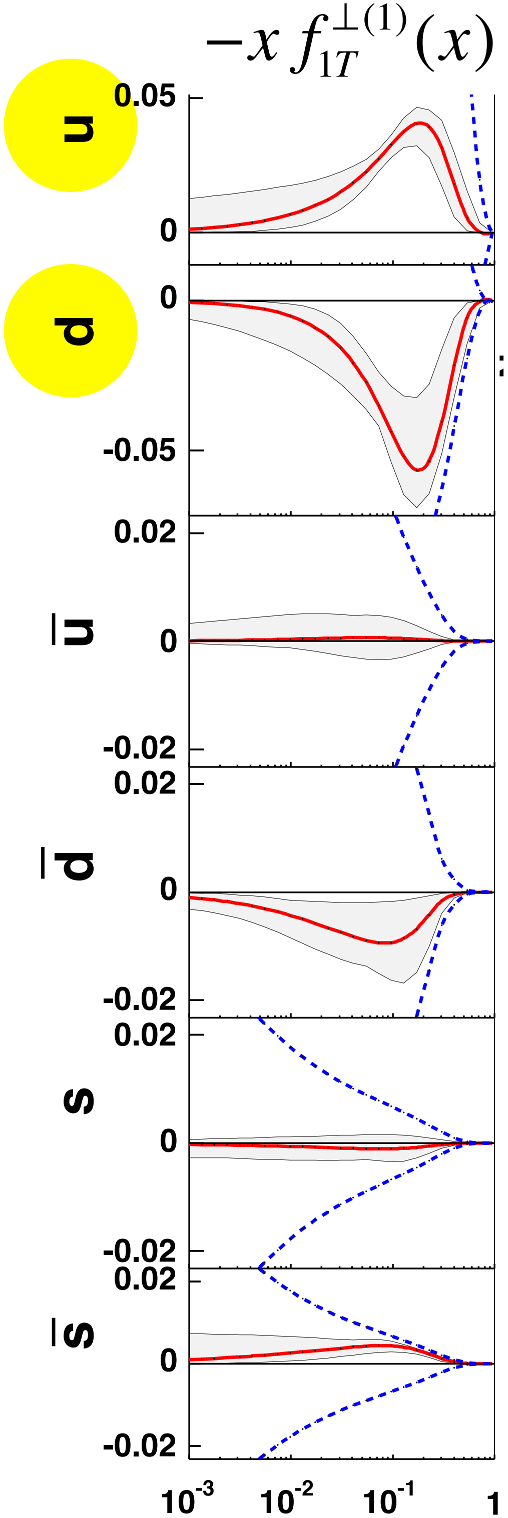
RHIC : **500 pb^{-1}** (2016?)











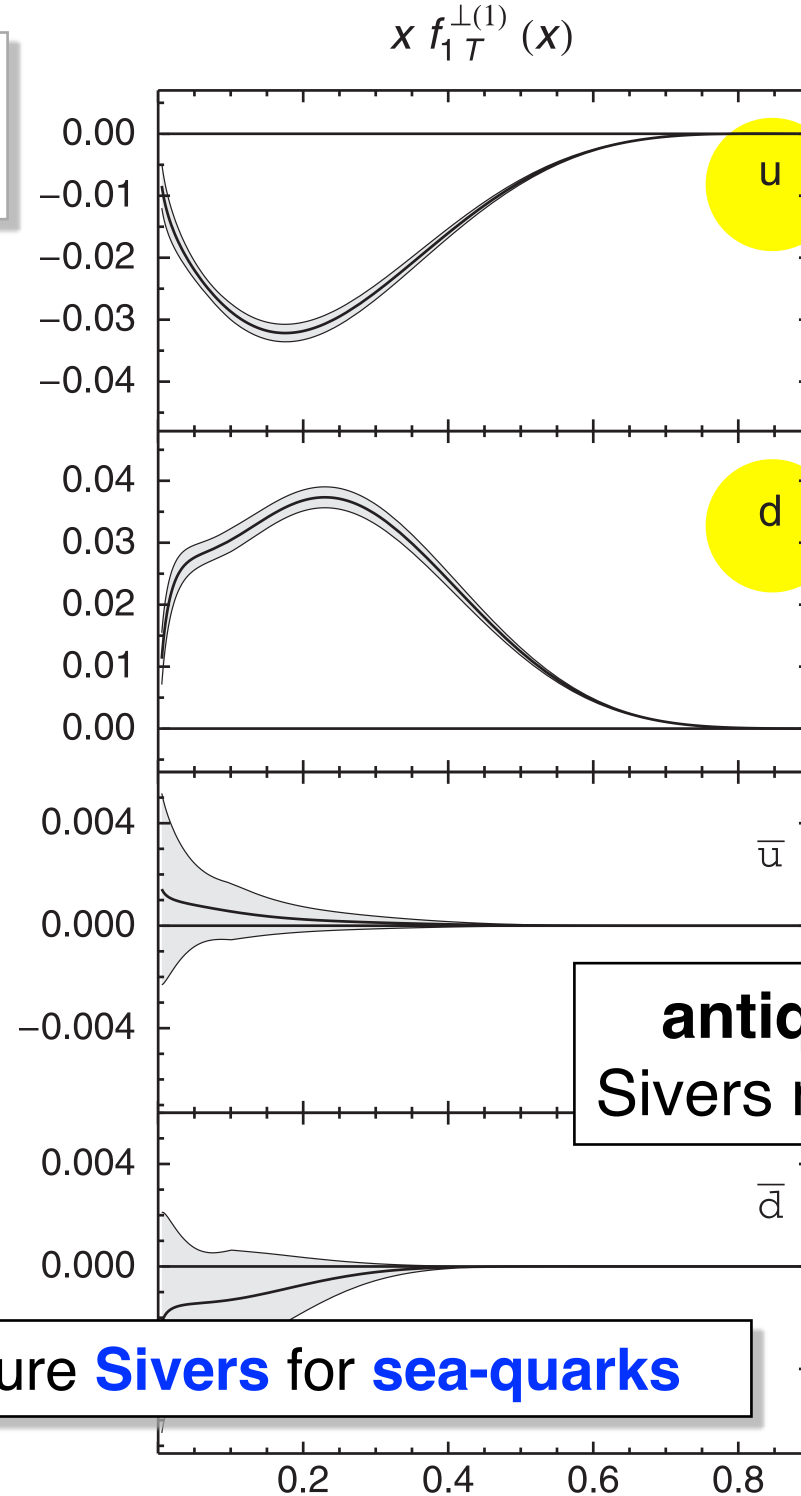
Global Fits to SIDIS data

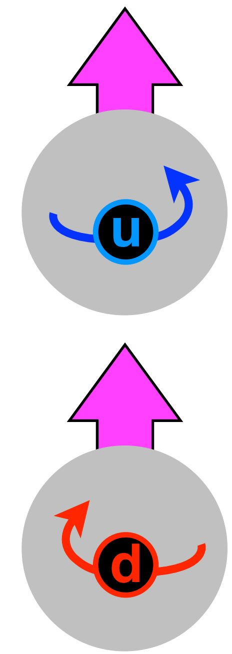
← *Anselmino et al, EPJA 39 (2009)*

final data

Bacchetta & Radici, PRL 107 (2011)

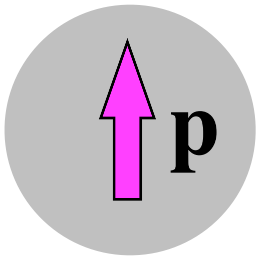
antiquark
orbital L ≠ 0
favoured





antiquark
Sivers now ≈ 0

Goal #2 = measure **Sivers** for **sea-quarks**



Meson Cloud on an Envelope → It <u>ORBITS</u>

Pions have $J^P = 0^-$ = **negative parity** ...

→ ***need <u>L = 1</u>*** to get proton's $J^P = ½^+$

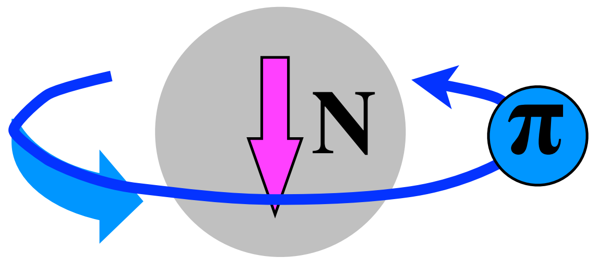
$|p\rangle = p + N\pi + \Delta\pi + \ldots$

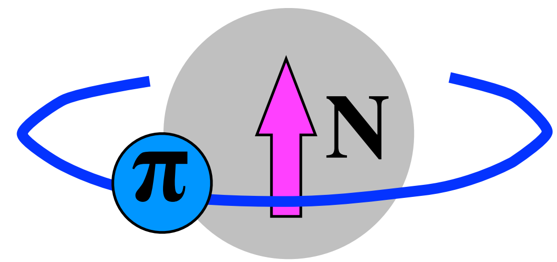
Nπ cloud:

2/3 $\mathbf{n\ \pi^+}$

1/3 $p\ \pi^0$

$\otimes$





2/3 $L_z = +1$

1/3 $L_z = 0$

Lattice support: K.F. Liu

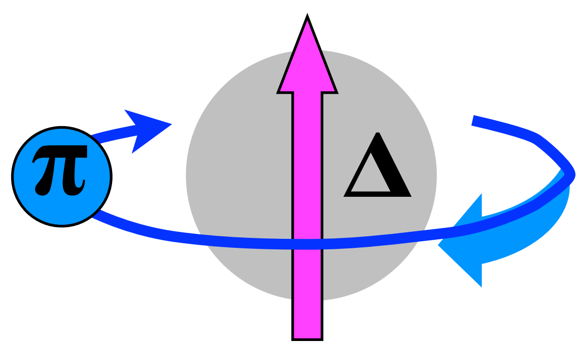
Δπ cloud:

1/2 $\Delta^{++}\ \pi^-$

1/3 $\Delta^+\ \pi^0$

1/6 $\Delta^0\ \pi^+$

$\otimes$



1/2 $L_z = -1$

1/3 $L_z = 0$

1/6 $L_z = +1$

L** is in the **SEA

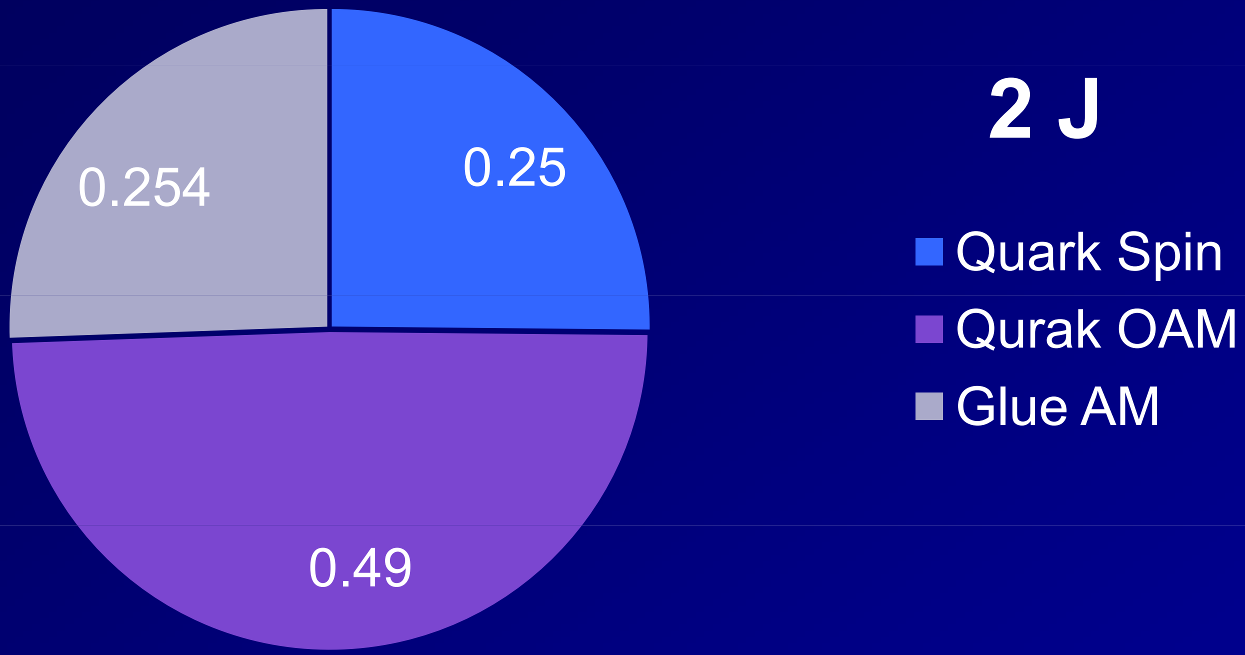
Dominant source of:

u,dbar-sea = $\mathbf{n\ \pi^+}$ with **L_z(pion) > 0**

d,ubar-sea = $\Delta^{++}\ \pi^-$ with **L_z(pion) < 0**

Quark Spin, Orbital Angular Momentum, and Gule Angular Momentum

KehFeh Liu,
INT Workshop, Feb 2012



New: add DI
Disconnected
Insertions
→ Pure Sea

The Sea is Orbiting!

$$\Delta q \approx 0.25;$$

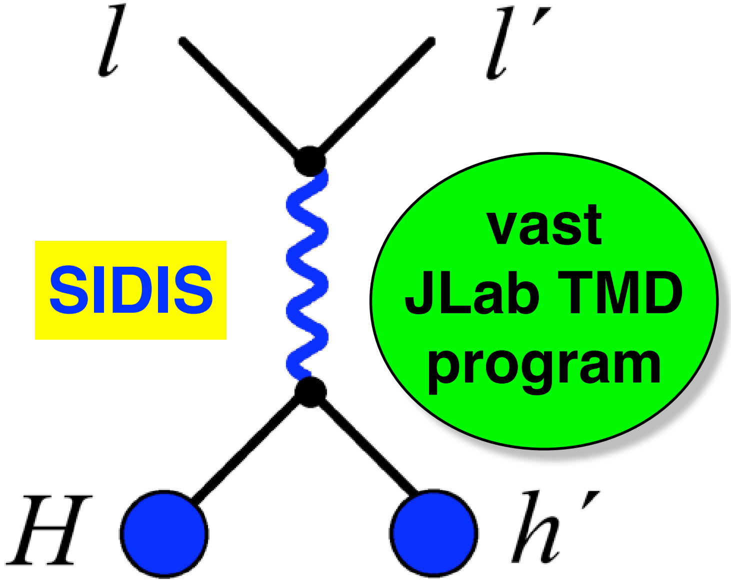
$$2\,L_q \approx 0.49\ (0.0(\mathrm{CI})\boxed{+0.49(\mathrm{DI})});$$

$$2\,\mathrm{J}_g \approx 0.25$$

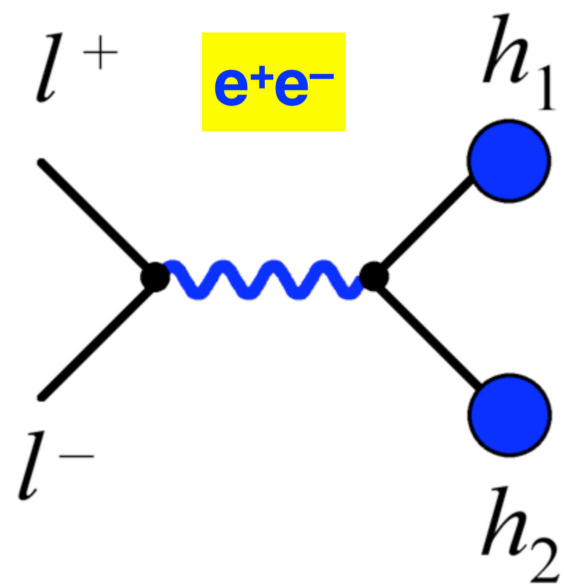
Leptons: clean, surgical tools

- *Disentangle* ***distribution*** *(f) and* ***fragmentation*** *(D) functions → measure* ***<u>all process</u>***
  - *Disentangle* ***quark flavours*** *q → measure as many* ***<u>hadron species</u>*** *H,h as possible*

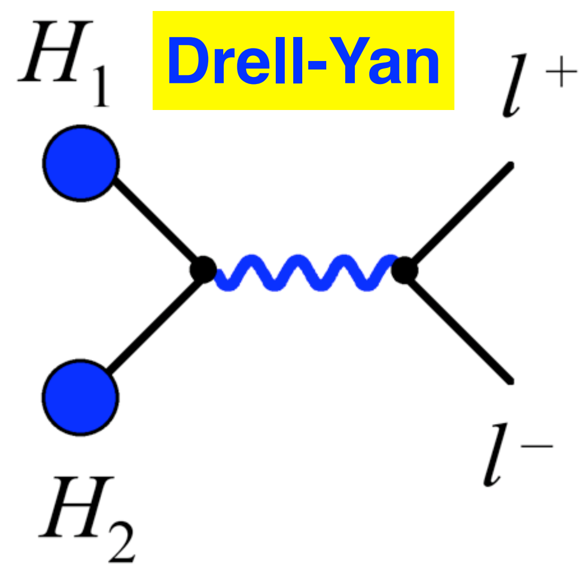
These are the **only** processes where TMD factorization is proven



$$\sum_q e_q^2 \; \mathbf{f}_{\mathbf{q}}^{(\mathbf{H})}(x) \; \mathbf{D}_{\mathbf{q}}^{\mathbf{h}'}(z)$$



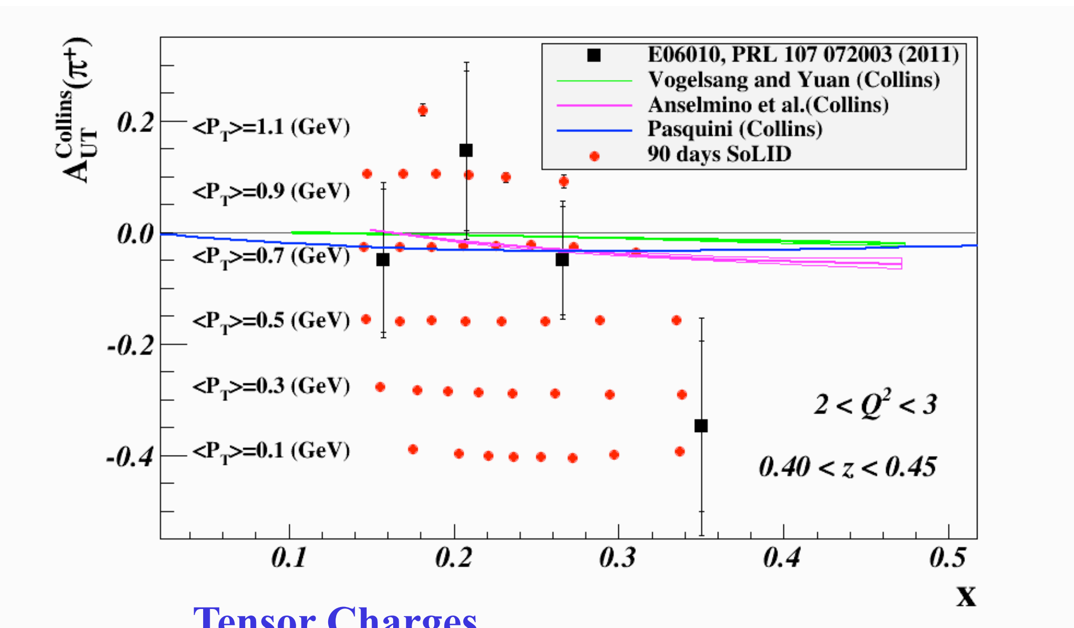
$$\sum_q e_q^2 \; \mathbf{D}_{\mathbf{q}}^{\mathbf{h_1}}(z_1) \; \mathbf{D}_{\bar{\mathbf{q}}}^{\mathbf{h_2}}(z_2)$$



$$\sum_q e_q^2 \; \mathbf{f}_{\mathbf{q}}^{(\mathbf{H_1})}(x_1) \; \mathbf{f}_{\bar{\mathbf{q}}}^{(\mathbf{H_2})}(x_2)$$

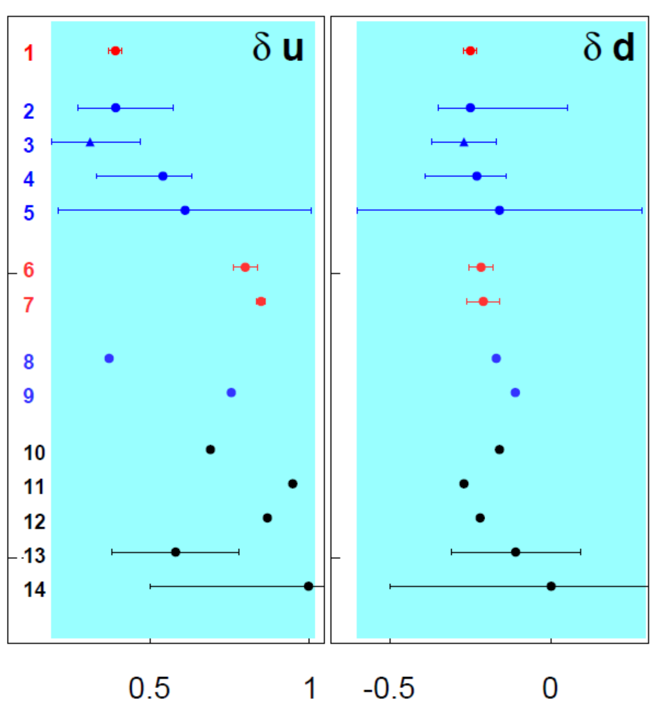
Nucleon Structure with SoLID-SIDIS

Collins Asymmetry *Total > 1400 points*



Semi-inclusive Deep Inelastic Scattering *program*:
Large Acceptance + High Luminosity
+ Polarized targets
→ **4-D** mapping of **Collins**, Sivers, and pretzelocity asymmetries,…
→ Tensor charge of quarks, **transversity** distributions, **TMDs**…
→Benchmark test of Lattice QCD, probe QCD Dynamics and quark orbital motion

Tensor Charges



SoLID projections

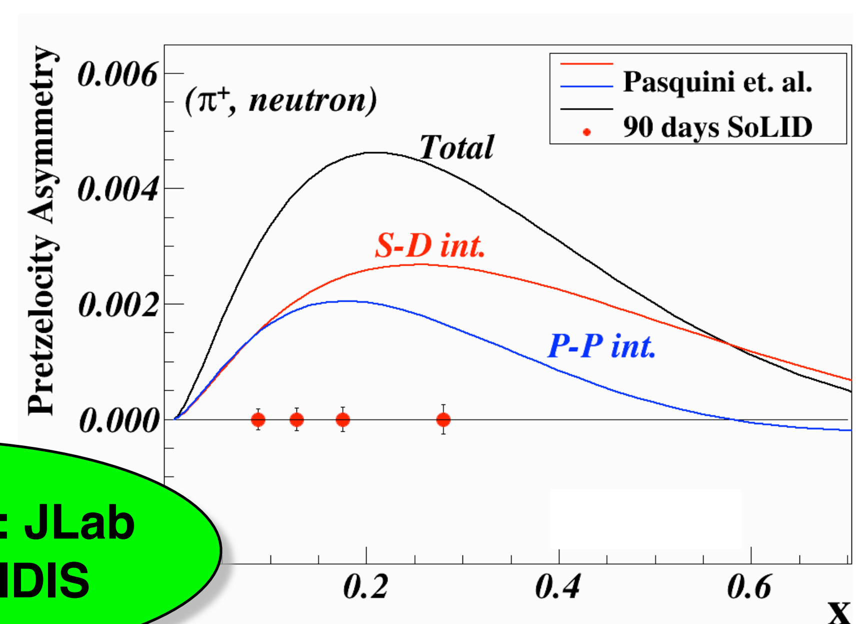
Extractions from existing data

LQCD

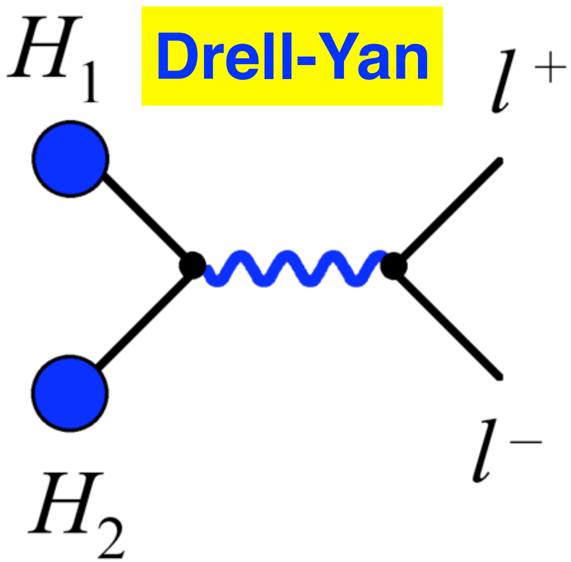
DSE

Models

Pretzelosity → information on OAM

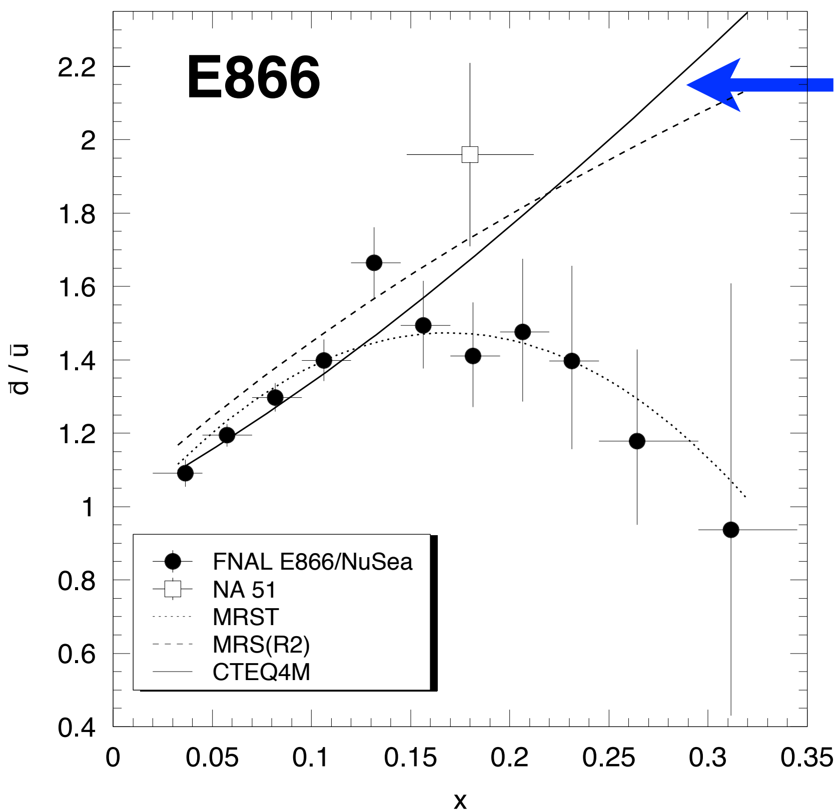


One example: JLab TMDs via SIDIS



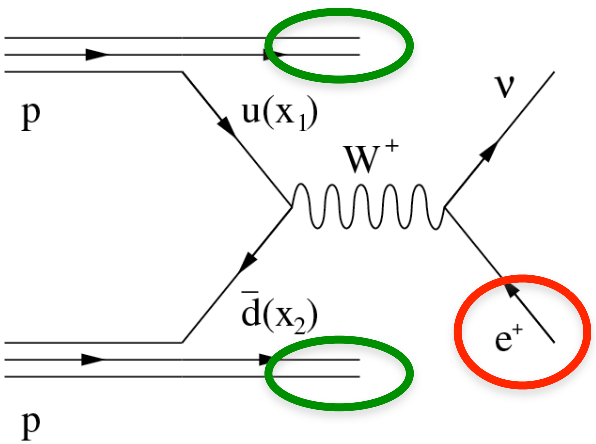
The Missing Spin Program: Drell-Yan

$$\sum_q e_q^2 \; \mathbf{f}_{\mathbf{q}}^{(\mathbf{H_1})}(x_1) \; \mathbf{f}_{\bar{\mathbf{q}}}^{(\mathbf{H_2})}(x_2)$$



- Clean access to **sea quarks** e.g. $\bar{d}(x)/\bar{u}(x)$ at E866/SeaQuest
- Crucial test of **TMD formalism** → **sign change** of T-odd functions

W reconstruction Strategy



Ingredients for the analysis

- Isolated electron
- neutrino (not measured directly)
- Hadronic recoil

W-reconstrucn achieved!

despite the ν!

- **Select events with the W-signature**
  - Isolated high P_T > 25 GeV electron
  - Hadronic recoil with total P_T > 18 GeV

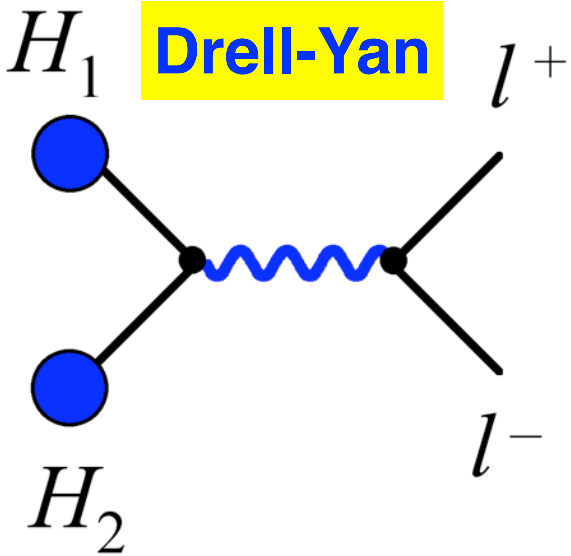
- **Neutrino transverse momentum is reconstructed from missing P_T**

$$\vec{P}_T^{\nu} \approx -\sum_{i \in \substack{\text{tracks} \\ \text{clusters}}} \vec{P}_T^{i}$$

- **Neutrino's longitudinal momentum is reconstructed from the decay kinematics**

$$M_W^2 = (E_e + E_\nu)^2 - (\vec{p}_e + \vec{p}_\nu)^2$$

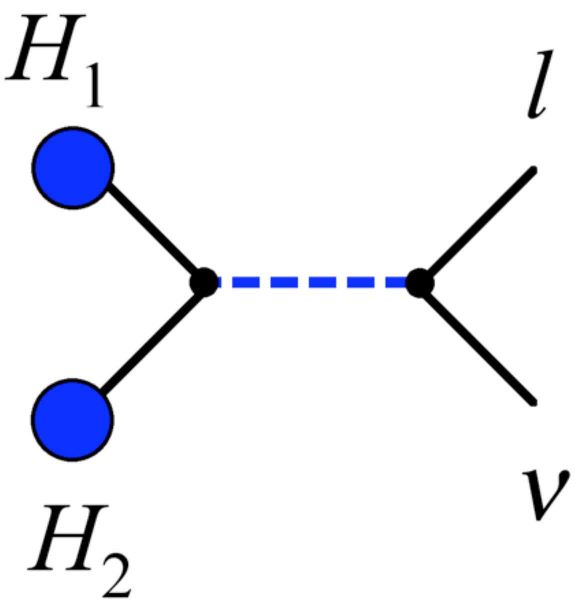
Drell-Yan



The Third Spin Program : Drell-Yan & W-production

$$\sum_q e_q^2 \; \mathbf{f}_{\mathbf{q}}^{(\mathbf{H_1})}(x_1) \; \mathbf{f}_{\bar{\mathbf{q}}}^{(\mathbf{H_2})}(x_2)$$

W production



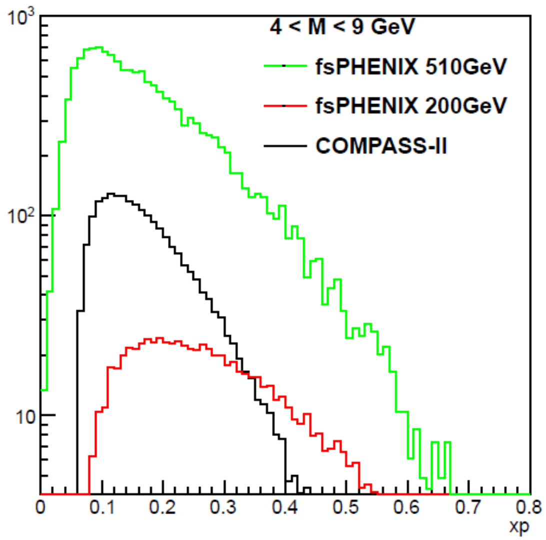
- Clean access to **sea quarks** e.g. $\Delta\bar{u}(x), \Delta\bar{d}(x)$ at RHIC
- Crucial test of **TMD formalism** → **sign change** of T-odd functions

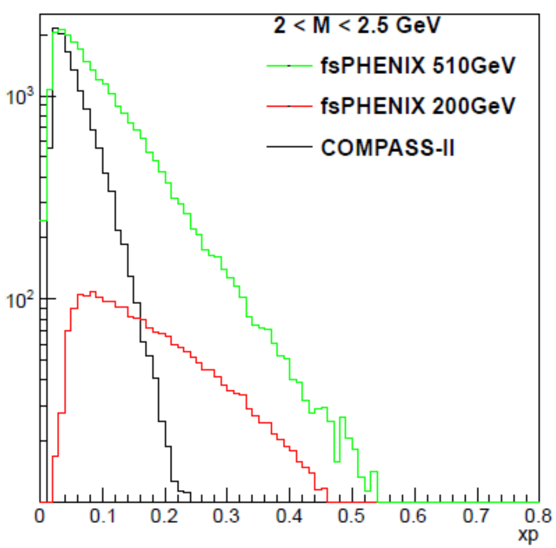
★ A **complete** spin program requires multiple hadron species → **nucleon & meson beams**

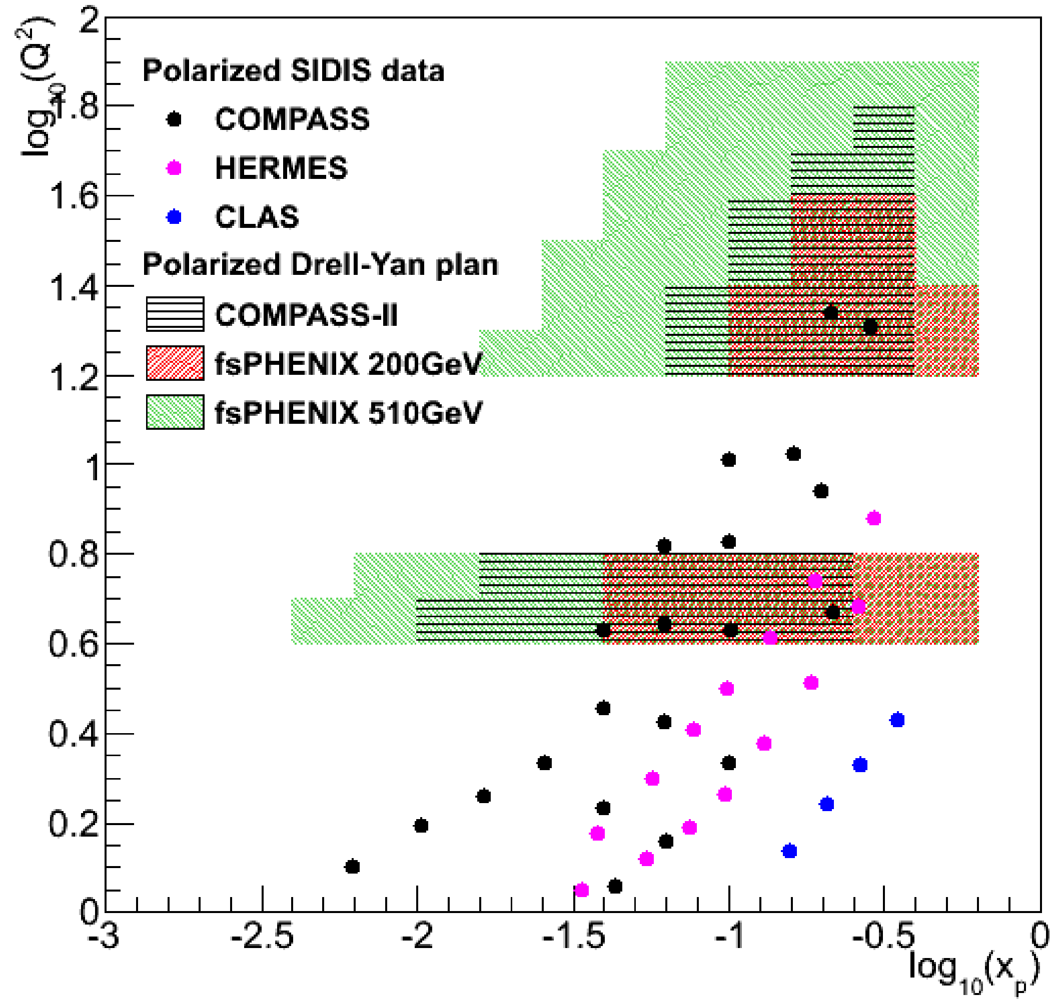
2020+

Drell-Yan : fsPHENIX and COMPASS-II

$$FoM = (1/\delta A_T^{\sin\phi_S})^2 = \frac{N}{2}P^2$$







Shaded regions deliniate $\delta A_T^{\sin\phi_S} < 0.1$

John Lojoie

COMPASS, E-1027, E-1039 (and Beyond)

	Beam Pol.	Target Pol.	Favored Quarks	Physics Goals			
				(Sivers Function)			L_{sea}
				sign change	size	shape	
COMPASS $\pi^- p^\uparrow \to \mu^+ \mu^- X$	✘	✔	valence	✔	✘	✘	✘
E-1027 $p^\uparrow p \to \mu^+ \mu^- X$	✔	✘	valence	✔	✔	✔	✘
E-1039 $p\, p^\uparrow \to \mu^+ \mu^- X$	✘	✔	sea	✘	✔	✔	✔
E-10XX $p^\uparrow p^\uparrow \to \mu^+ \mu^- X$ $\vec{p}\, \vec{p} \to \mu^+ \mu^- X$	✔	✔	sea & valence	Transversity, Helicity, Other TMDs …			

W. Lorenzon

Planned Polarized Drell-Yan Experiments

Experiment	Particles	Energy (GeV)	x_b or x_t	Luminosity ($cm^{-2}\,s^{-1}$)	$A_T^{\sin\phi_S}$	P_b or P_t (f)	rFOM#	Timeline
COMPASS (CERN)	$\pi^{\pm} + p^{\uparrow}$	160 GeV $\sqrt{s} = 17$	$x_t = 0.2 – 0.3$	2×10^{33}	0.14	P_t = 90% f = 0.22	1.1×10^{-3}	2014, 2018
PANDA (GSI)	$\bar{p} + p^{\uparrow}$	15 GeV $\sqrt{s} = 5.5$	$x_t = 0.2 – 0.4$	2×10^{32}	0.07	P_t = 90% f = 0.22	1.1×10^{-4}	>2018
PAX (GSI)	$p^{\uparrow} + \bar{p}$	collider $\sqrt{s} = 14$	$x_b = 0.1 – 0.9$	2×10^{30}	0.06	P_b = 90%	2.3×10^{-5}	>2020?
NICA (JINR)	$p^{\uparrow} + p$	collider $\sqrt{s} = 26$	$x_b = 0.1 – 0.8$	1×10^{31}	0.04	P_b = 70%	6.8×10^{-5}	>2018
PHENIX (RHIC)	$p^{\uparrow} + p^{\uparrow}$	collider $\sqrt{s} = 500$	$x_b = 0.05 – 0.1$	2×10^{32}	0.06	P_b = 60%	3.6×10^{-4}	>2018
SeaQuest (FNAL: E-906)	$p + p$	120 GeV $\sqrt{s} = 15$	$x_b = 0.35 – 0.9$ $x_t = 0.1 – 0.45$	3.4×10^{35}	---	---	---	2012 - 2015
Pol tgt DY‡ (FNAL: E-1039)	$p + p^{\uparrow}$	120 GeV $\sqrt{s} = 15$	$x_t = 0.1 – 0.45$	4.4×10^{35}	0 – 0.2*	P_t = 88% f = 0.176	0.15	2016
Pol beam DY§ (FNAL: E-1027)	$p^{\uparrow} + p$	120 GeV $\sqrt{s} = 15$	$x_b = 0.35 – 0.9$	2×10^{35}	0.04	P_b = 60%	1	2018

‡ *8 cm NH_3 target* § *L= 1×10^{36} $cm^{-2}\,s^{-1}$ (LH_2 tgt limited) / L= 2×10^{35} $cm^{-2}\,s^{-1}$ (10% of MI beam limited)*
**not constrained by SIDIS data* / # rFOM = relative lumi * P^2 * f^2 wrt E-1027 (f=1 for pol p beams)

W. Lorenzon (U-Michigan) 8/15/2014

Conclusions

- After the coming 5-10 years, the hadron physics landscape will have **changed**

- Nucleon **form factors** will be <u>done</u>
  ... meson form factors will likely remain a question

- The **valence-x** region — where spin effects are centered — will be rather thoroughly mapped
  ... low-x extrapolations will likely remain an issue,
  but can it ever be resolved?

- Parton **OAM** is a key issue & will be assaulted with a great deal of data, but is theory able to reliably interpret them?

- No more **milestones**! The coming decade of data will no doubt influence the next ones we should write.

Grateful thanks to the many people who contributed slides, and the countless people who made the plots!