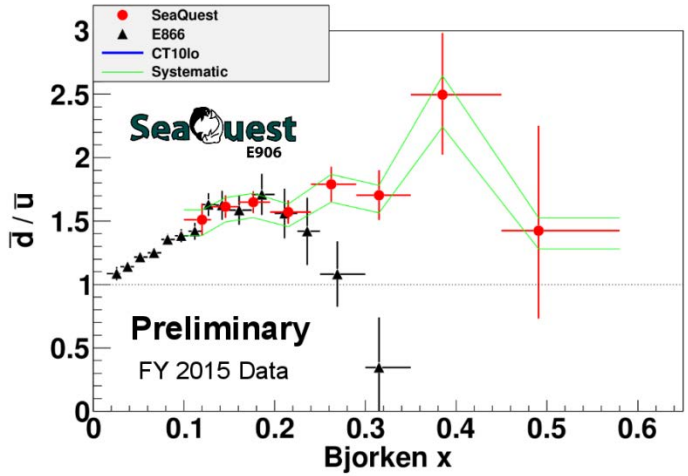
E-906 and future fixed-target Drell Yan

Wolfgang Lorenzon
University of Michigan

QCD-N 2016 Workshop, Trento, Italy
(15-July-2016)



COMPASS

E906 SeaQuest

Fermilab

J-PARC

This work is supported by

Current and Future D-Y Program at FNAL

Unpolarized Beam and Target w/ SeaQuest detector

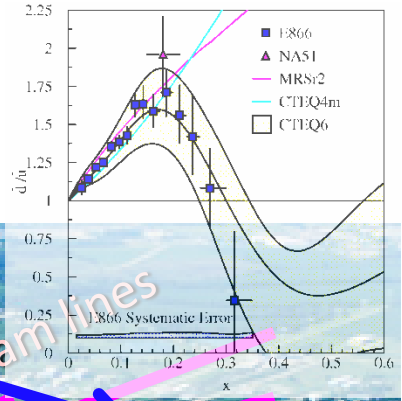
- **E-906**: 120 GeV p from Main Injector on LH_2,LD_2, C,Fe,W targets → **high-x Drell-Yan**
- Science run: March 2014 - July 2017
  - ➡ 2015 data set: preliminary results

Polarized Beam and/or Target w/ SeaQuest detector

→ development of **high-luminosity** facility for **polarized Drell-Yan**

- **E-1039**: SeaQuest w/ pol NH_3 target (2018-2019?)
  - ➡ probe sea quark distributions
- **E-1027**: pol p beam on (un)pol tgt (2020-2021?)
  - ➡ **Sivers sign change** (valence quark)

SeaQuest Experiment



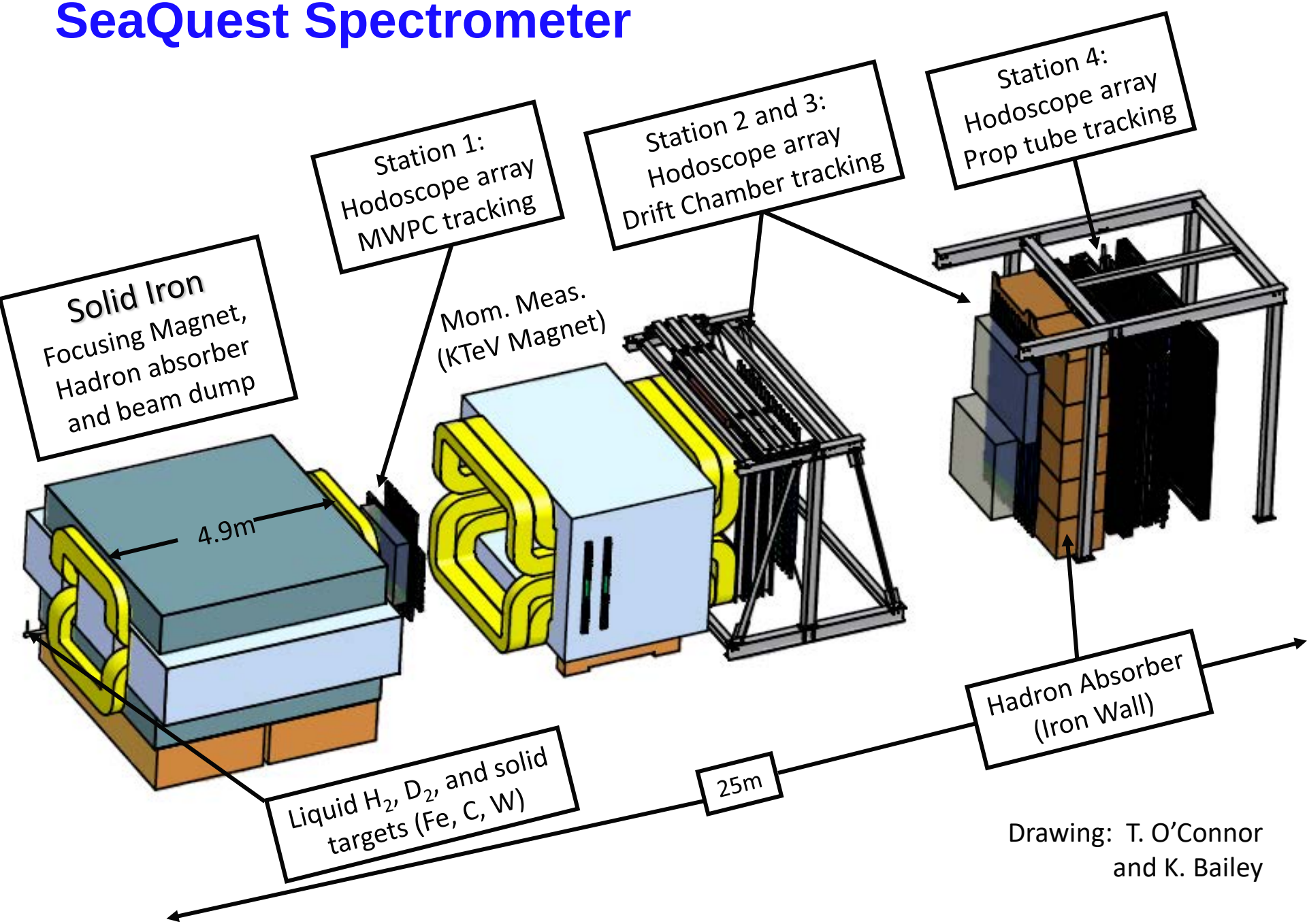
Fixed Target Beam lines

Tevatron 800 GeV

Main Injector
120 GeV

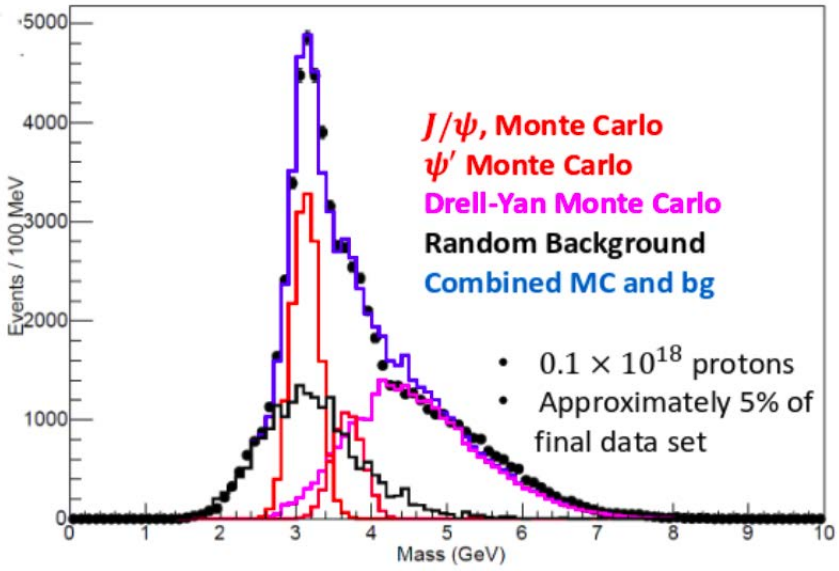
10% of available beam to SeaQuest / 90% to neutrino program

SeaQuest Spectrometer

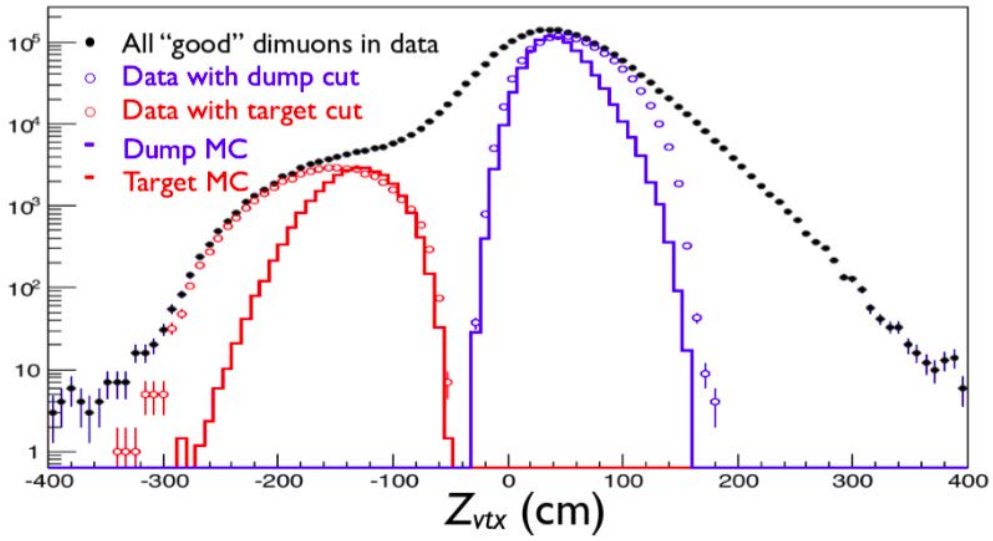


Drawing: T. O'Connor
and K. Bailey

Event Selection & Reconstruction

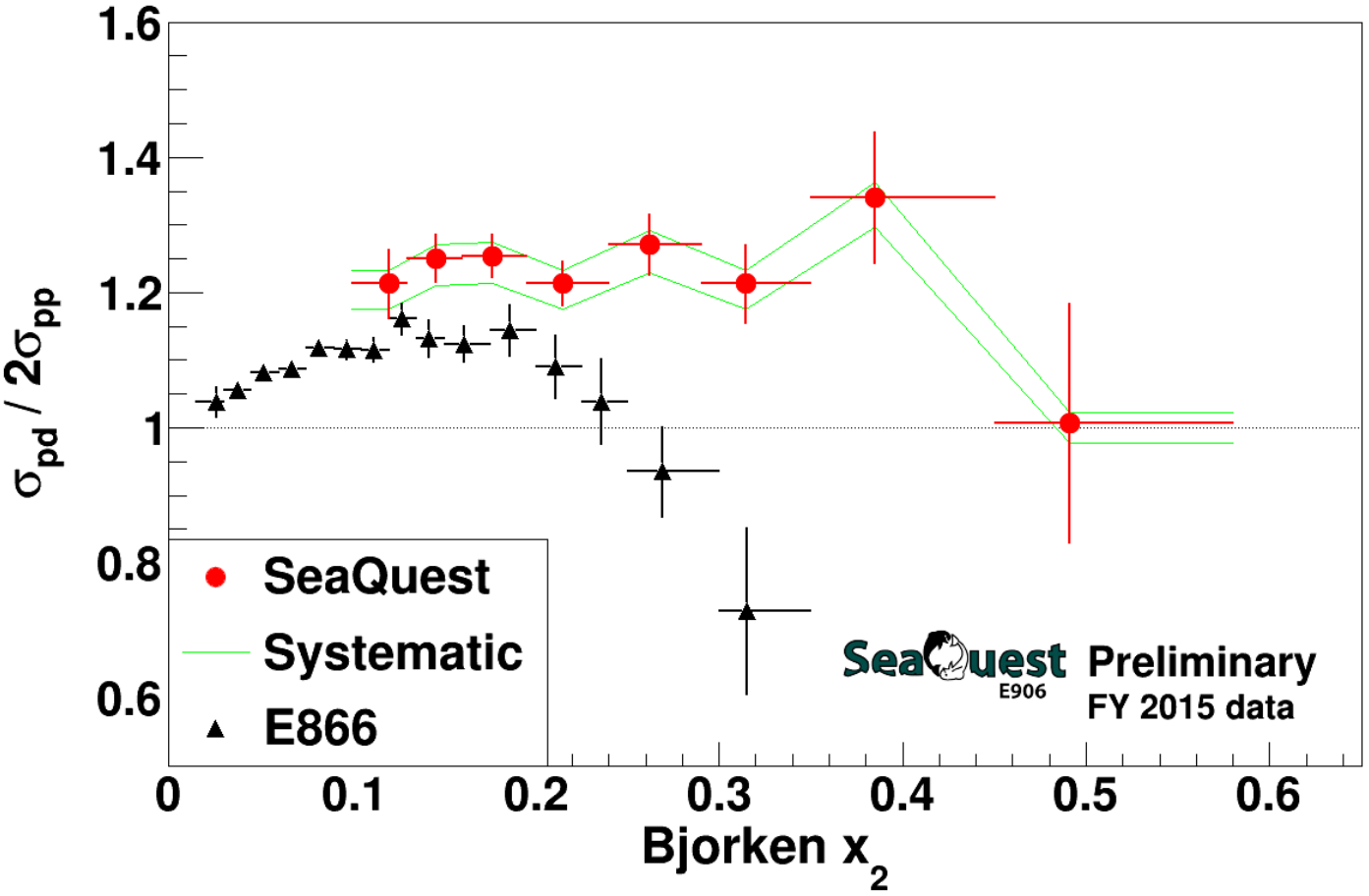


- Monte Carlo describe data well
- Resolution better than expected
  - $\sigma_M(J/\psi)$ ~180 MeV
  - σ_M(D-Y) ~220 MeV
  - J/ψ to ψ' separation
  - lower J/ψ mass cut (more Drell-Yan events)



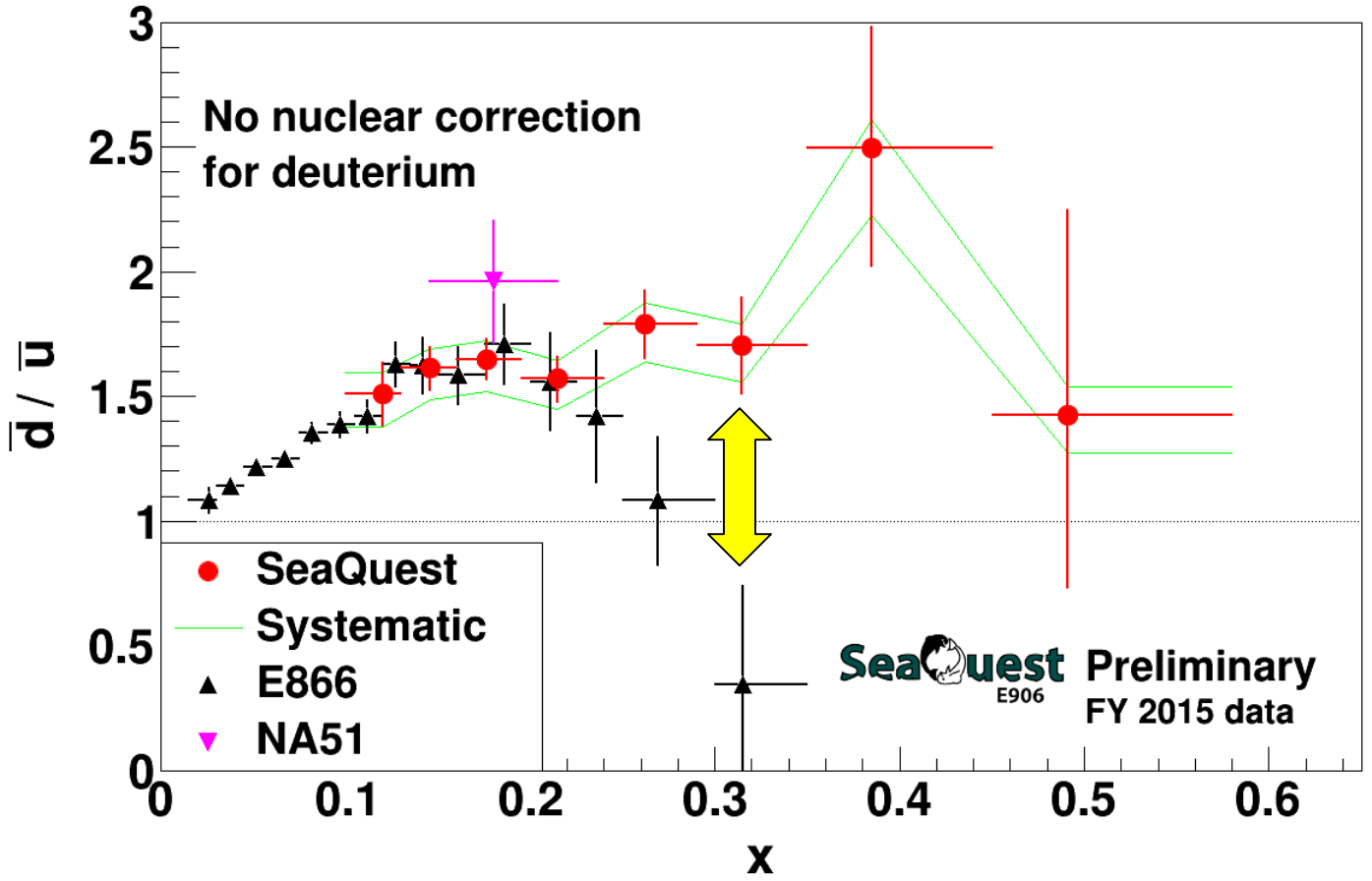
- good Target/Dump separation
- pointing resolution poor along beam axis
- dominated by random coincidences

SeaQuest Cross Section Ratio (2015 Data Set)



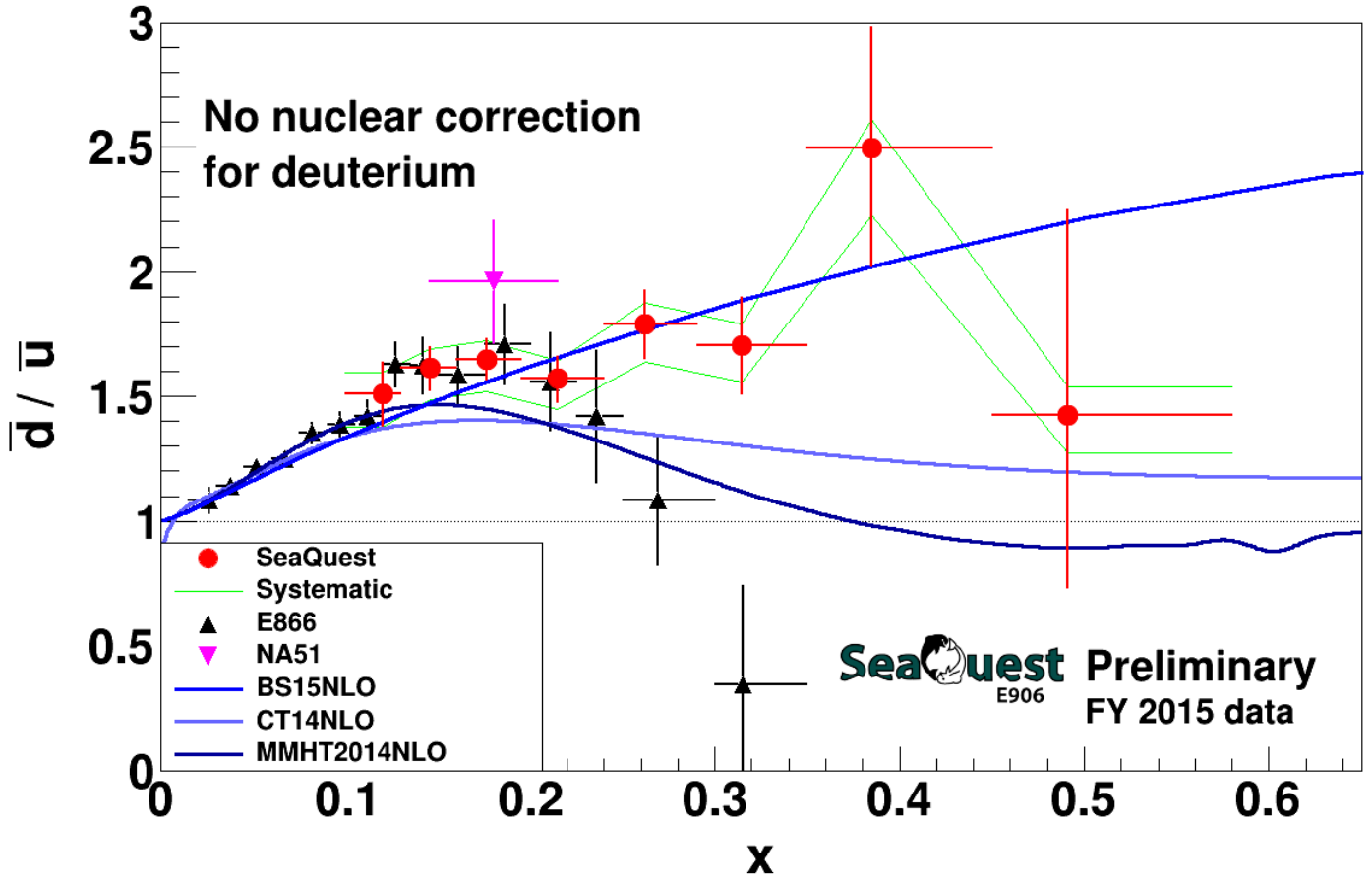
- different kinematics and Q^2 for E866 & SeaQuest data sets
- new chambers installed in March 2016: improve acceptance in high x_2 region
- 30% of anticipated data (~1.2×10^{18} pot)
- approved for 5×10^{18} pot

SeaQuest Leading Order extraction (2015 Data Set)



- E866 data is for $Q^2 = 54$ GeV^2 while SeaQuest data has $Q^2 \approx 29$ GeV^2
  - difference should be insignificant
- no nuclear correction for deuterium
  - expected larger at higher x, but still small compared to error bars
- is there disagreement at high x?

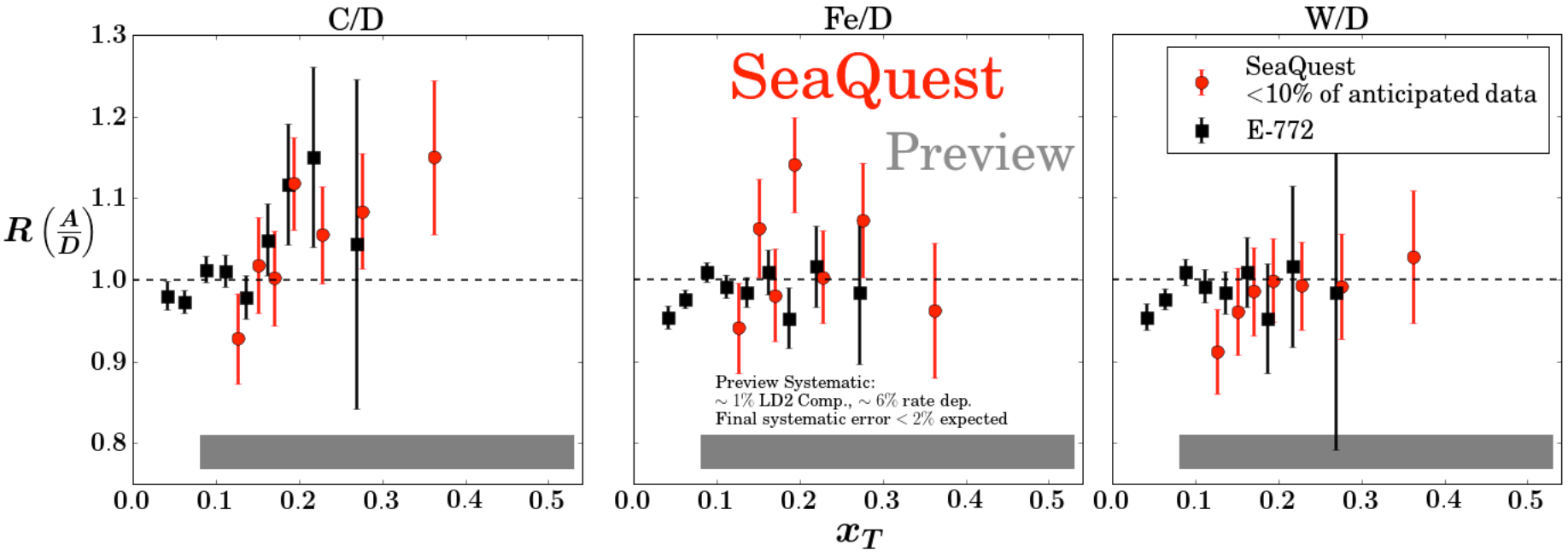
SeaQuest Leading Order extraction (2015 Data Set)



- BS15 (statistical model) calculated using parameters from NPA941(2015)307
- CT14 and MMHT2014 calculated with the LHAPDF library
- PDF scales taken as 29 GeV^2

SeaQuest Nuclear Dependence (Preview)

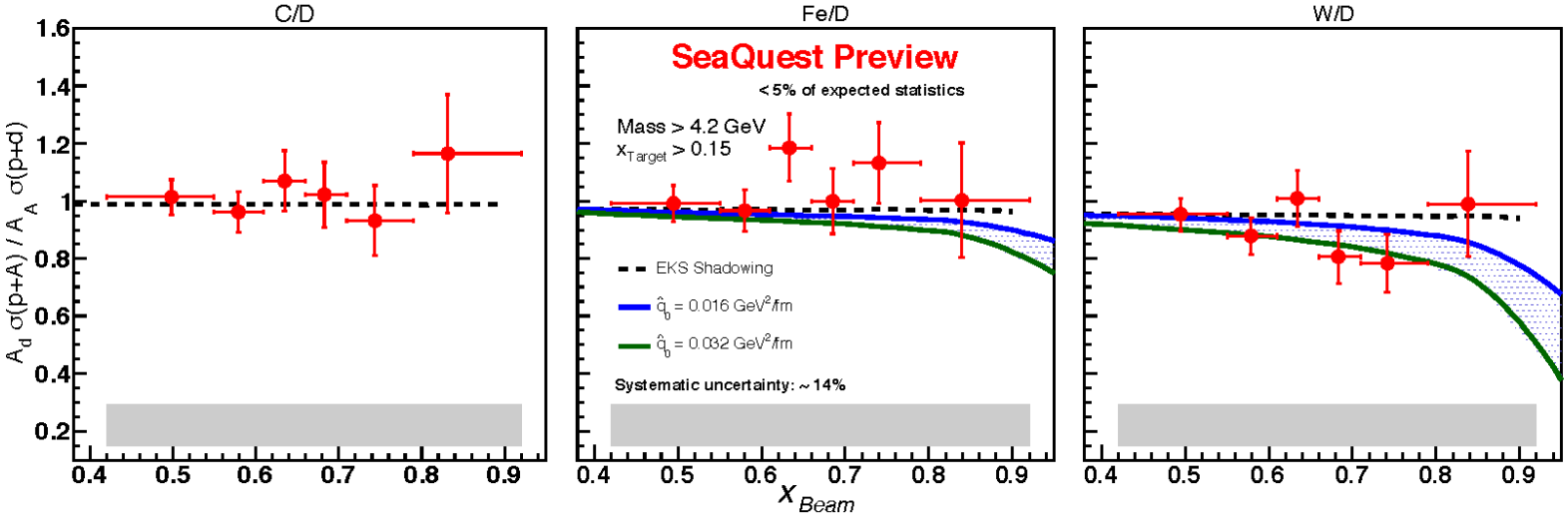
- no antiquark enhancement apparent
- 10% of anticipated statistical precision
- increased detector acceptance at large-x_T to come (new D1 chamber)

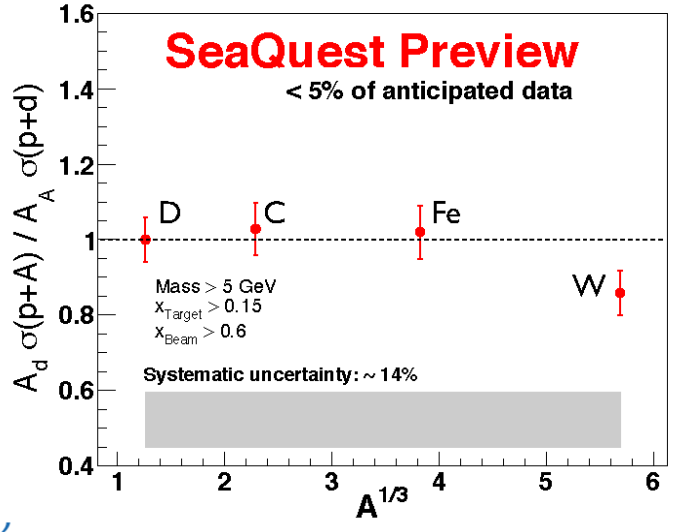


SeaQuest Quark Energy Loss (Preview)

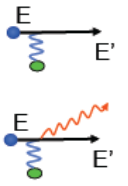
- Pre-interaction quark moves through cold nuclear matter and looses energy.
- Expect suppression of the per-nucleon cross section ratio to be significant at high x_{Beam} or x_F

R.B. Neufeld, I. Vitev and B. W. Zhang,PLB 704, 590 (2011)



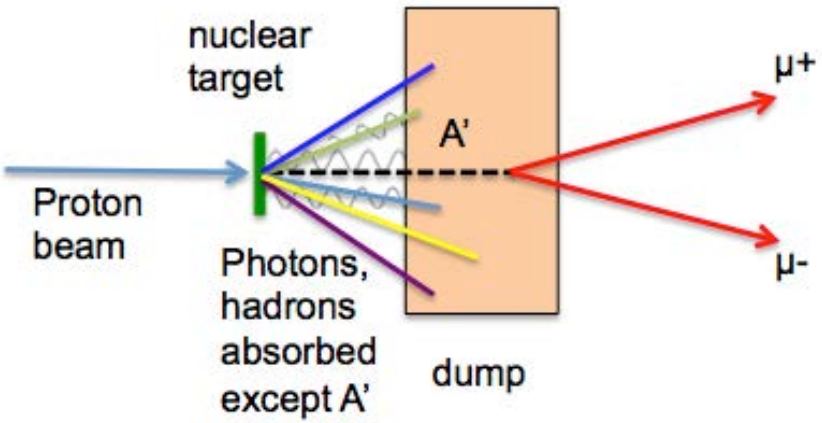


- Too early to make any conclusion on p+Fe as limited by the statistics
- A consistently negative slope beyond the shadowing strength is observed in p+W data.
- With 20x more statistics, we will be able to clearly distinguish between:
  - ➢ $-dE \propto A^{1/3}$ (or $\propto L$) → collisional
  - ➢ $-dE \propto A^{2/3}$ (or $\propto L^2$) → radiative



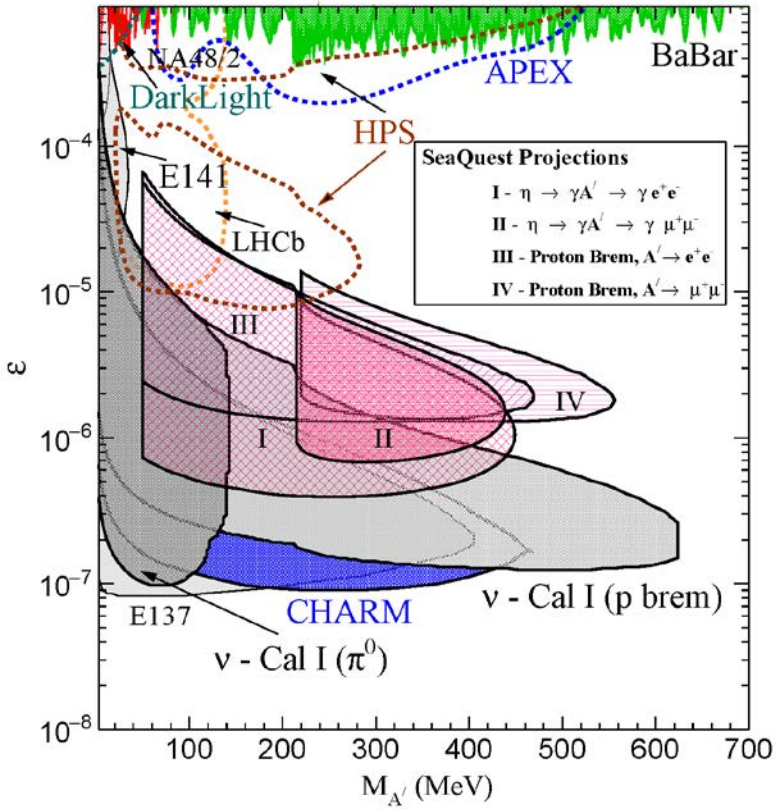
Search for Dark Photons at SeaQuest

- Classic Beam Dump Experiment



- Minimal impact on Drell-Yan program

  ➞ run parasitically during E906



$$l_o \approx \frac{0.8\,cm}{N_{eff}}\left(\frac{E_o}{10\,GeV}\right)\left(\frac{10^{-4}}{\varepsilon}\right)^2\left(\frac{100\,MeV}{m_{A'}}\right)^2$$

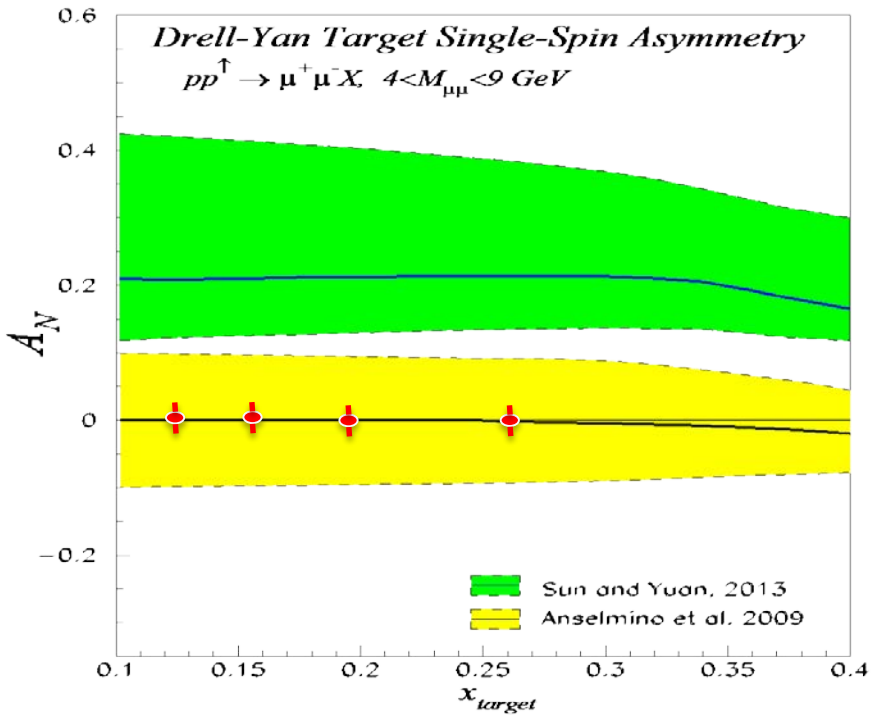
J. D. Bjorken et al, PRD **80** (2009) 075018

SeaQuest experimental parameters:

- ➞ E_0 = 5 - 110 GeV for Proton Bremsstrahlung
- ➞ N_{eff} = 2
- ➞ l_0 = 0.17m – 5.95m

Let's Add a Polarized Target (E-1039)

- Probe **Sea-quark Sivers Asymmetry** with a polarized proton target at SeaQuest
- Projected Statistical Precision with a Polarized Target at (E-1039)



Statistics shown for two calendar years of running:
- L = 7.2 *10^{42} /cm^2 ↔ POT = 2.8*10^{18}
- P = 85%

- existing SIDIS data poorly constrain sea-quark Sivers function (Anselmino)
- significant Sivers asymmetry expected from meson-cloud model (Sun & Yuan)
- **first Sea Quark Sivers Measurement**
- **determine sign and value of $\bar{u}$ Sivers distribution**

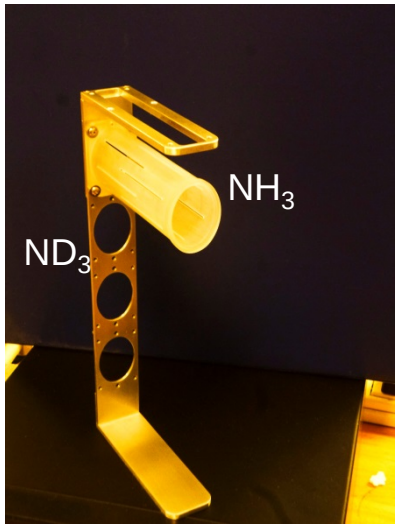
If $A_N \neq 0$, **major discovery**:
"Smoking Gun" evidence for $L_{\bar{u}} \neq 0$

Ref: Andi Klein (LANL)

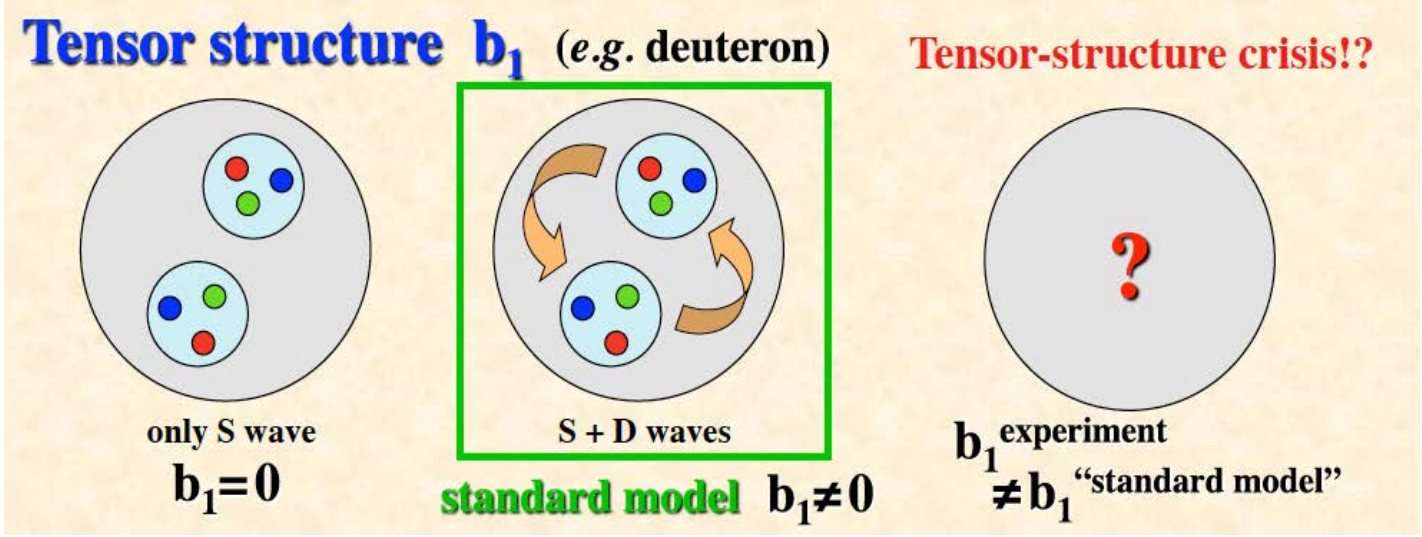
Further Plans with Polarized Targets (E-1039')

- Probe $\bar{d}$ **Sivers Asymmetry** with a polarized ND_3 target at SeaQuest
  - SeaQuest only place to measure d-bar (explore during E1039)
  - measure Sivers asymmetry for pp and pD and take ratio
    - requires measuring p and "n" in parallel to control systematic errors
    - microwave irradiates both targets at the same time
    - one cell NH_3, the other ND_3

Target holder



- Probe **Tensor** Polarization Deuteron (40% - 50%)

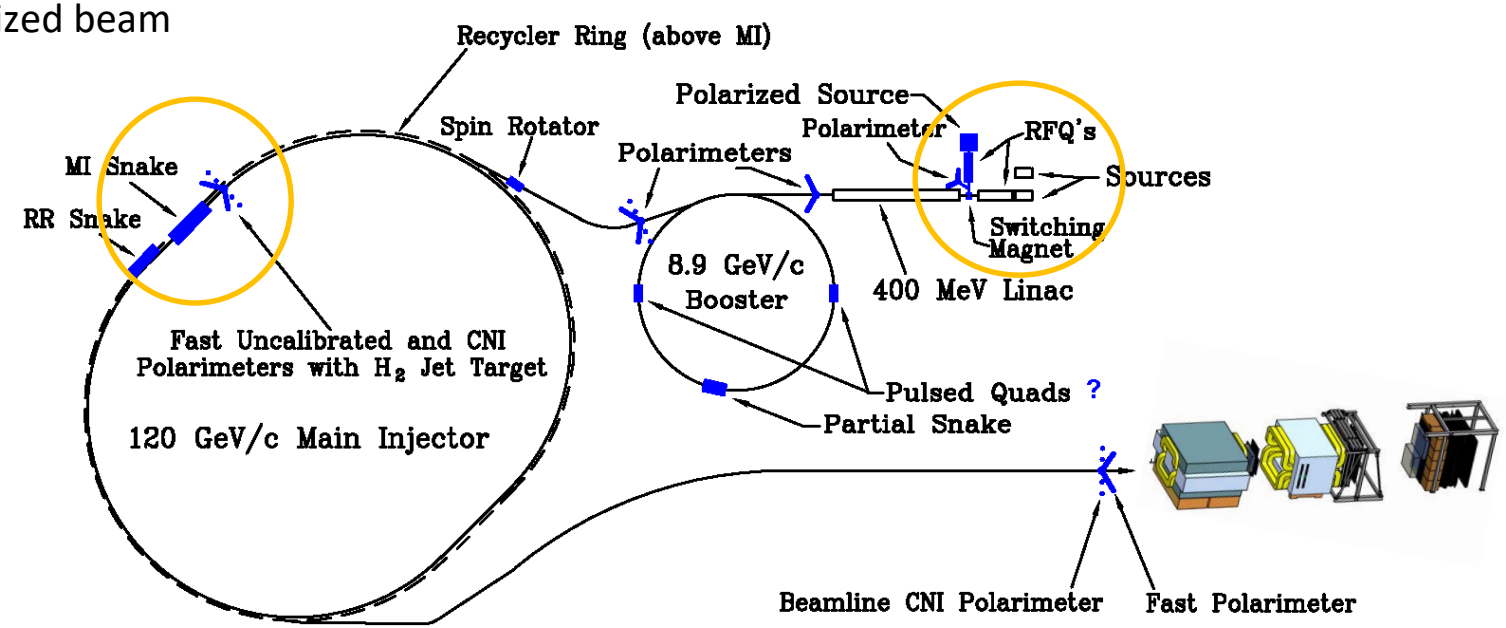


Ref: Andi Klein (LANL)

Let's Polarize the Beam at Fermilab (E-1027)

The Plan:

- Use fully understood SeaQuest Spectrometer
- Add polarized beam



- **Measure sign-change in Sivers Function:**
  - ⟶ QCD (and factorization) require sign change
  - ⟶ major milestone in hadronic physics (HP13)

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

- **Fermilab (best place for polarized DY):**
  - ⟶ very high luminosity, large x-coverage (primary beam, fixed target)
- **Cost Est.: $6M +$4M Contingency & Management = $10M** (in 2013)

(Un)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)	$\pi^- + p^\uparrow$	160 GeV $\sqrt{s}$ = 17	x_t = 0.1 – 0.3	2 x 10^{33}	0.14	P_t = 90% f = 0.22	1.1 x 10^{-3}	2015-2016, 2018
PANDA (GSI)	$\bar{p} + p^\uparrow$	15 GeV $\sqrt{s}$ = 5.5	x_t = 0.2 – 0.4	2 x 10^{32}	0.07	P_t = 90% f = 0.22	1.1 x 10^{-4}	>2018
PAX (GSI)	$p^\uparrow + \bar{p}$	collider $\sqrt{s}$ = 14	x_b = 0.1 – 0.9	2 x 10^{30}	0.06	P_b = 90%	2.3 x 10^{-5}	>2020?
NICA (JINR)	$p^\uparrow + p$	collider $\sqrt{s}$ = 26	x_b = 0.1 – 0.8	1 x 10^{31}	0.04	P_b = 70%	6.8 x 10^{-5}	>2020?
J-PARC (high-p beam line)	$\pi^- + p$	10-20 GeV $\sqrt{s}$ = 4.4-6.2	x_b = 0.2 – 0.97 x_t = 0.06 – 0.6	2 x 10^{31}	---	---	---	>2019? under discussion
fsPHENIX (RHIC)	$p^\uparrow + p^\uparrow$	$\sqrt{s}$ = 200 $\sqrt{s}$ = 510	x_b = 0.1 – 0.5 x_b = 0.05 – 0.6	8 x 10^{31} 6 x 10^{32}	0.08	P_b = 60% P_b = 50%	4.0 x 10^{-4} 2.1 x 10^{-3}	>2021
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 x 10^{35}	---	---	---	2012 - 2017
Pol tgt DY‡ (FNAL: E-1039)	$p + p^\uparrow$	120 GeV $\sqrt{s}$ = 15	x_t = 0.1 – 0.45	4.4 x 10^{35}	0 – 0.2*	P_t = 85% f = 0.176	0.15	>2018
Pol beam DY§ (FNAL: E-1027)	$p^\uparrow + p$	120 GeV $\sqrt{s}$ = 15	x_b = 0.35 – 0.9	2 x 10^{35}	0.04	P_b = 60%	1	>2020

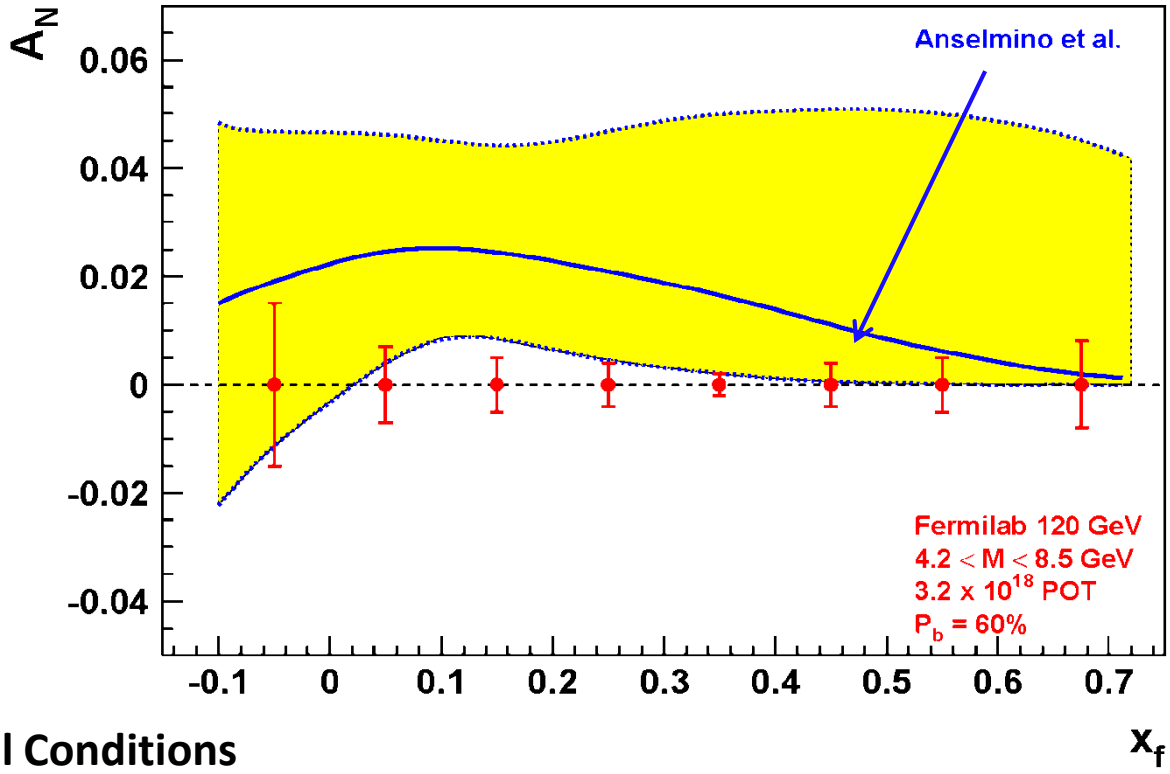
‡ *8 cm NH_3 target* / § *L= 1 x 10^{36} $cm^{-2}\ s^{-1}$ (LH_2 tgt limited)* / *L= 2 x 10^{35} $cm^{-2}\ s^{-1}$ (10% of MI beam limited)*

**not constrained by SIDIS data* / # rFOM = relative lumi * P^2 * f^2 wrt E-1027 (f=1 for pol p beams, f=0.22 for π^- beam on NH_3)

W. Lorenzon (U-Michigan) 7/2016

Expected Precision from E-1027 at Fermilab

- Probe **Valence-quark Sivers Asymmetry** with a polarized proton beam at SeaQuest



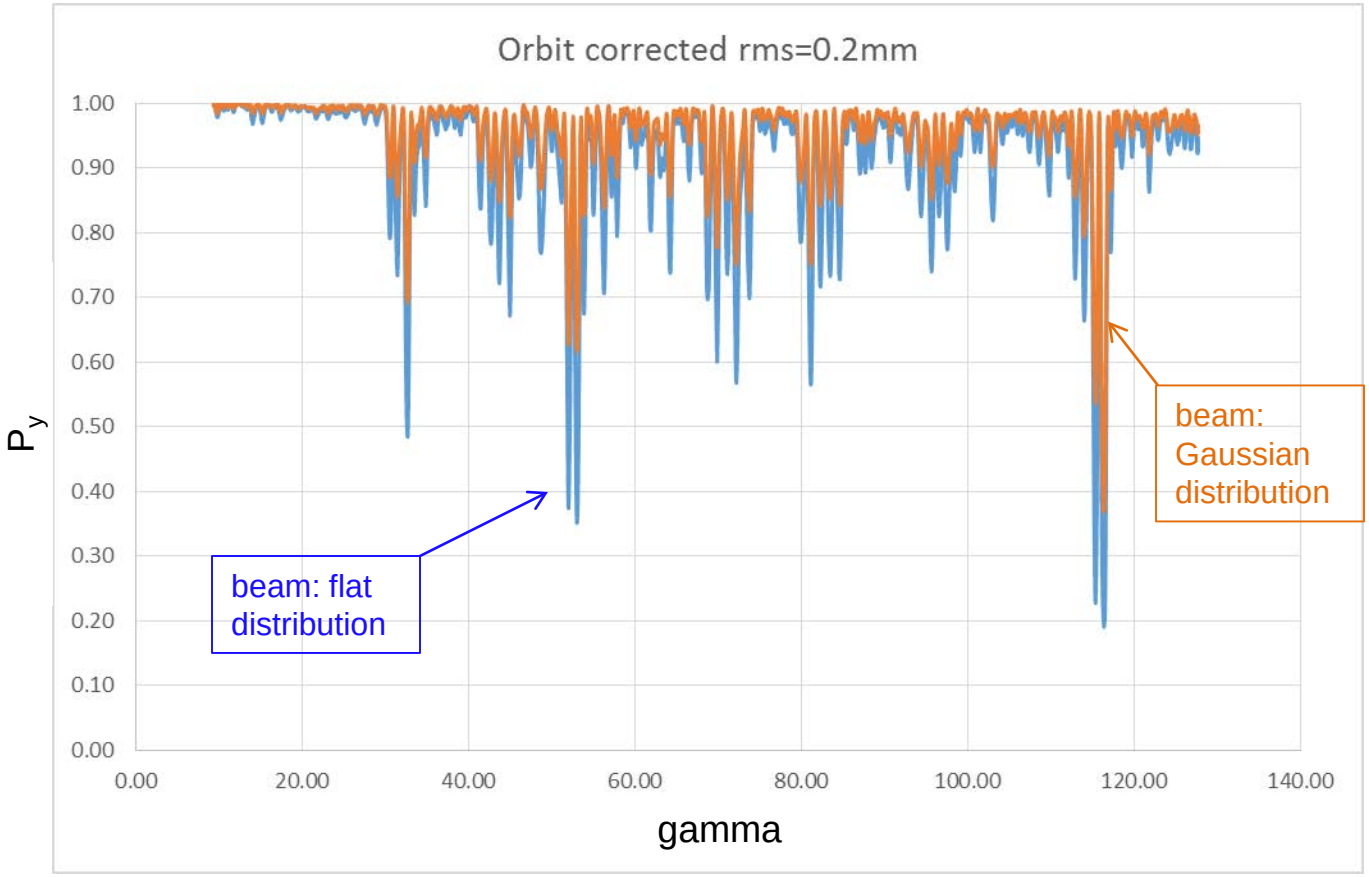
1.3 Mio DY events with no dilution

- **Experimental Conditions**
  - same as SeaQuest
  - luminosity: L_{av} = 2 x 10^{35} (10% of available beam time: I_{av} = 15 nA)
  - 3.2 X 10^{18} total protons for 5 x 10^5 min: (= 2 yrs at 50% efficiency) with P_b = 60%

Can measure not only sign, but also the size & probably shape of the Sivers function!

as well as TMD evolution!

Simulation of final polarization as function of Energy in MI



Point-like snake in correct location, actual ramp rate for acceleration.

Polarizations with magnet field error and misalignment (from magnet database and survey group), corrected (for SeaQuest running conditions)

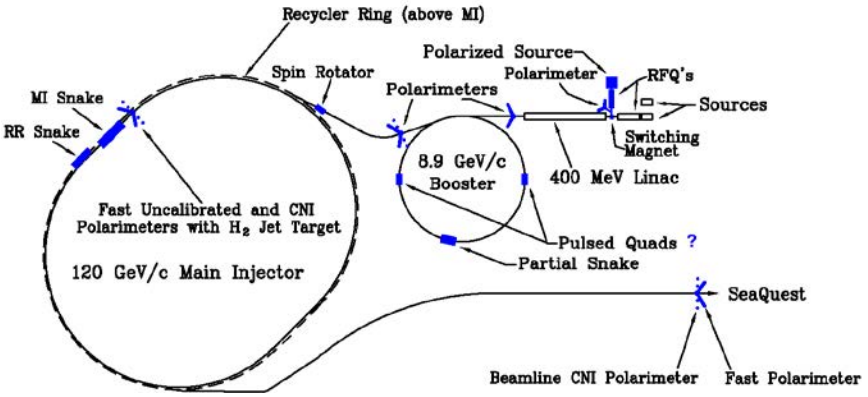
Final polarization: ~ 90%

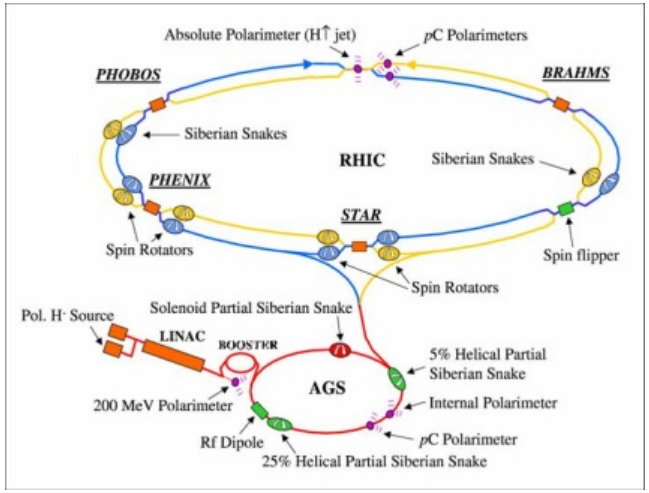
ε_{max} = 20 π mm.mrad in y plane and Δp =1.25*10^{-3} in longitudinal plane

Ref: Meiqin Xiao (FNAL)

Differences compared to RHIC

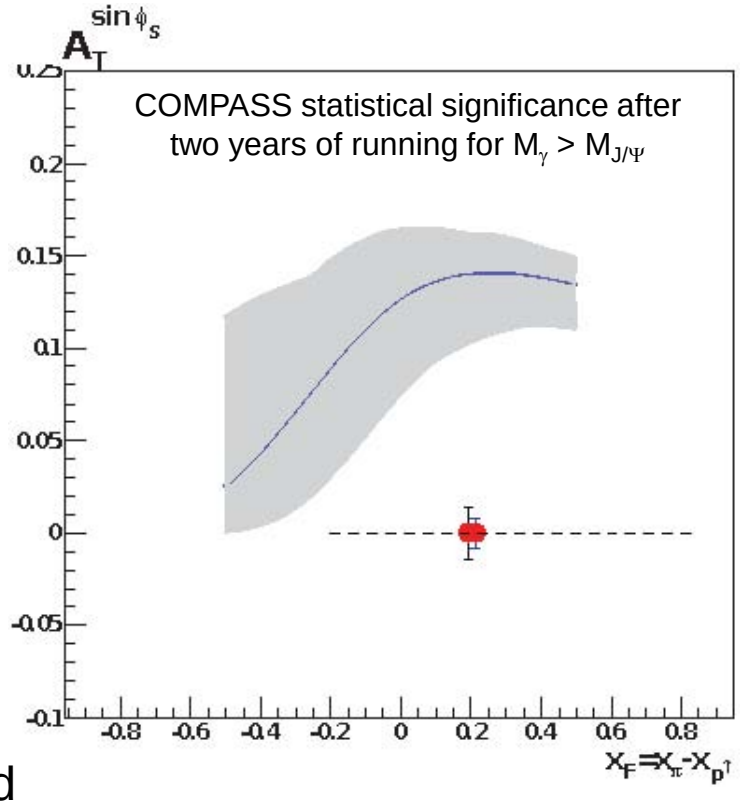
- **Most significant difference**:
  Ramp time of **Main Injector < 0.7 s**, at **RHIC 1-2 min**
  - ➡ **warm magnets** at MI vs. superconducting at RHIC
    - → pass through all depolarizing resonances much more quickly
- Beam remains in **MI ~2 s**, in **RHIC ~8 hours**
  - ➡ **extracted beam** vs. **storage ring**
  - ➡ much **less** time for **cumulative depolarization**
- **Disadvantage** compared to RHIC — no **institutional history** of accelerating polarized proton beams
  - ➡ Fermilab E704 had polarized beams through hyperon decays





COMPASS Projection & Plans

- COMPASS: 190 GeV π^- beam on transverse polarized H target (NH_3)
  - ➡ first year of polarized running completed
  - ➡ 2015 data ~120 days
  - ➡ Transverse target polarization ~80%
- estimated Statistics
  - ➡ DY events [$M(\mu^+\mu^-) > 4$ GeV/c^2): ~80,000
  - ➡ J/ψ events: ~2,000,000
- analysis on 2015 DY data underway
- **First physics results: SPIN 2016**
  - ➡ may be not yet full statistics
- 2018: second year of polarized DY scheduled



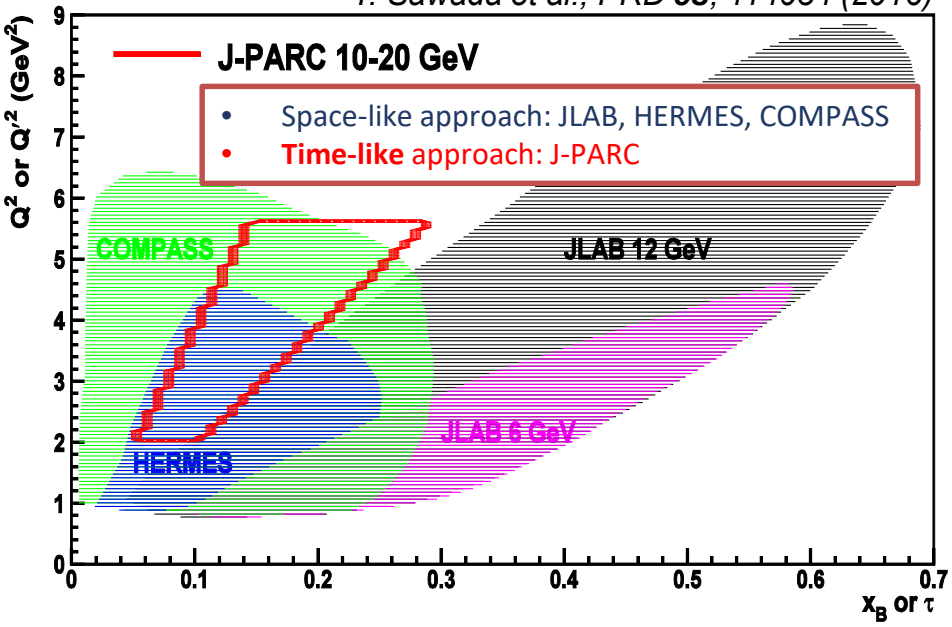
- COMPASS Beyond 2020 (under study: https://indico.cern.ch/event/502879/)
  - ➡ consider running with radio separated kaon/anti-proton beam for DY and spectroscopy
  - ➡ improve significantly our knowledge of pion and kaon PDFs
  - ➡ detailed study of the fundamental Lam-Tung relation violation
  - ➡ Gluon TMDs ?

Ref: M. Chiosso & Oleg Denisov (Torino)

J-PARC Projection & Plans

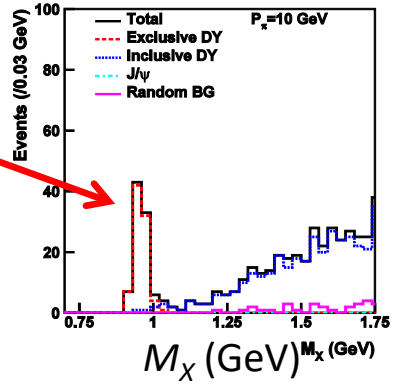
T. Sawada et al., PRD **93**, 114034 (2016)

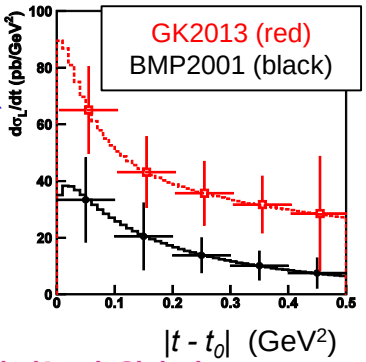
- Accessing GPD of nucleon via exclusive meson-induced Drell-Yan
  - ➡ Test of factorization of exclusive Drell-Yan process
  - ➡ Test of universality of GPD in space-like (DVMP) and time-like processes (D-Y).



- E50 experiment (Stage-1 approved by J-PARC) + μ-ID extension
  - ➡ **10-20 GeV π^-** beam on high momentum beam line at J-PARC
  - ➡ good missing mass resolution in exclusive D-Y events $(\pi^- p \to \mu^+ \mu^- n)$
  - ➡ Statistical accuracy adequate for discriminating between predictions from two current GPD models.

P_π = 10 GeV





GK2013: P. Kroll et al. Eur.Phys.J.C73, 2278 (2013)
BMP2001: E.R. Berger et al. Phys.Lett.B523, 265 (2001)

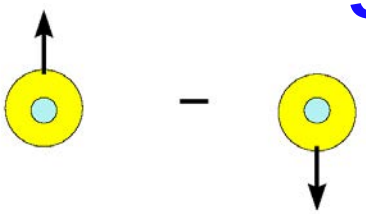
Ref: T. Sawada (Acad. Sinica)

Conclusions

- There is an exiting Drell-Yan program with polarized/unpolarized beams and targets underway
- Future opportunities look very promising
- We are eagerly awaiting results from COMPASS on the sign-change
- Hope to answer some of the questions:
  - → How much do the quarks and gluons contribute to the nucleon spin?
  - → Is there significant orbital angular momentum?
  - → Does TMD formalism work? Does Sivers function change sign?

Thank You

Sivers Function and Spin Crisis

$f_{1T}^{\perp}$ =  cannot exist w/o quark **OAM**

- describes transverse-momentum distribution of unpolarized quarks inside transversely polarized proton
- captures non-perturbative spin-orbit coupling effects inside a polarized proton

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

$\frac{1}{2}\Delta\Sigma \approx 25\%;\ \ \Delta G \approx 20\%$

$L \approx$ unmeasured

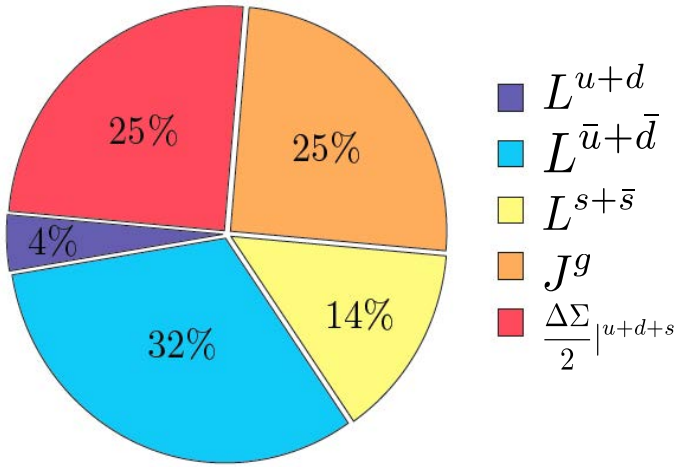
How measure quark OAM ?

- GPD: Generalized Parton Distribution
- TMD: Transverse Momentum Distribution

$$A_N = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} \stackrel{?}{\neq} 0$$

$$A_N^{DY} \propto \frac{u(x_b) \cdot f_{1T}^{\perp,\bar{u}}(x_t)}{u(x_b) \cdot \bar{u}(x_t)}$$

Lattice QCD:



$\Delta\Sigma_q \approx 25\%$

$2\ L_q \approx 50\%$ (4% (valence)+46% (sea))

$2\ J_g \approx 25\%$

K.-F. Liu *et al* arXiv:1203.6388