Opportunities with fixed-target Drell-Yan

Wolfgang Lorenzon
University of Michigan

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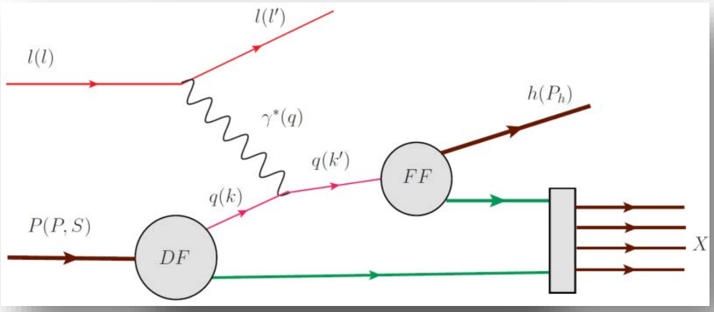
This work is supported by

Complementarity between SIDIS and Drell Yan

- SIDIS and Drell-Yan have similar physics reach:
  - ➞ tools to probe quark and antiquark structure of nucleon
  - ➞ electromagnetic probes

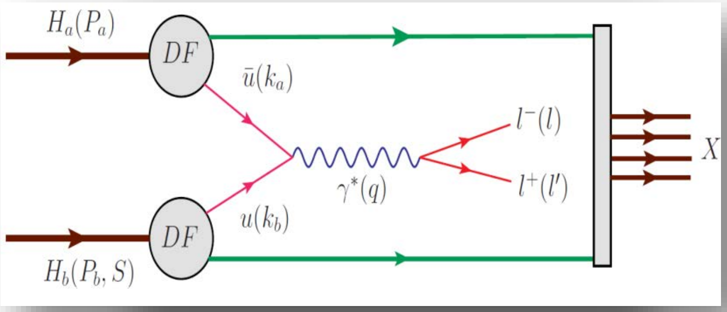
SIDIS (spacelike)



Quintessential probe of hadron structure:

- ➞ relatively simple to measure and calculate
- ➞ charge-weighted flavor sensitivity
- ➞ QCD final state effects
- ➞ fragmentation process
- ➞ **no quark-antiquark selectivity**

Drell-Yan (timelike) virtual photon



credit: A. Kotzinian

Cleanest probe to study hadron structure:

- ➞ no QCD final state effects
- ➞ no fragmentation process
- ➞ production of two TMD parton distribution functions
- ➞ **ability to select sea quark distribution**
- ➞ hadron beam: σ(DY) / σ(nuclear) ≈ 10^{-7}

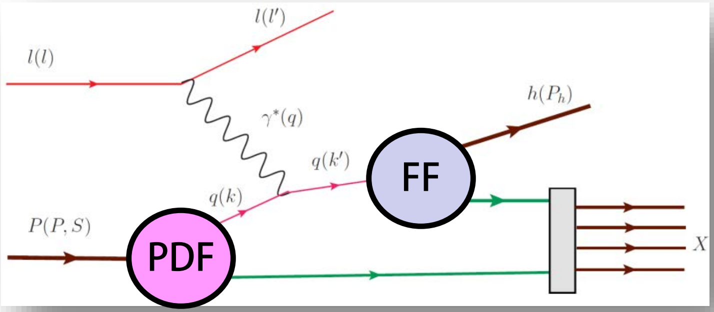
Factorization and Universality (SIDIS - DY)

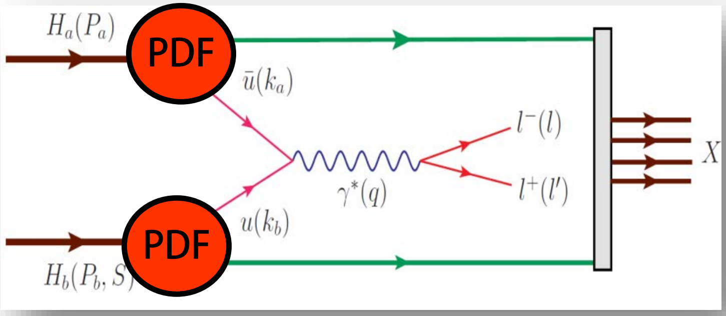
SIDIS

$\text{PDF} \otimes \text{FF}$

DY

$\text{PDF} \otimes \text{PDF}$





credit: A. Kotzinian

Probe Universality

are TMD PDFs in SIDIS identical to TMD PDFs in DY?

Test using unpolarized experiments, transverse SSA and DSA

LO SIDIS and single polarized DY cross sections

SIDIS

$$\frac{d\sigma^{LO}_{SIDIS}}{dx\,dy\,dz\,dp_T^2\,d\varphi_h\,d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]$$

$$\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\Bigg\{\; 1+\cos 2\phi_h\left(\varepsilon A_{UU}^{\cos 2\phi_h}\right)$$

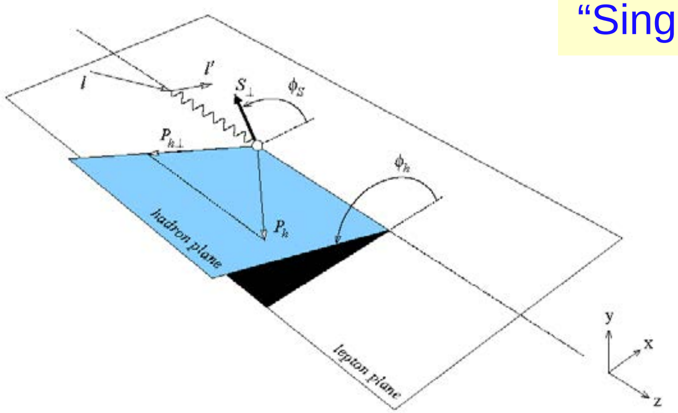
$$+\; S_T\begin{bmatrix}\sin(\phi_h-\phi_S)\left(A_{UT}^{\sin(\phi_h-\phi_S)}\right)\\ +\sin(\phi_h+\phi_S)\left(\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\right)\\ +\sin(3\phi_h-\phi_S)\left(\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\right)\end{bmatrix}$$

DY

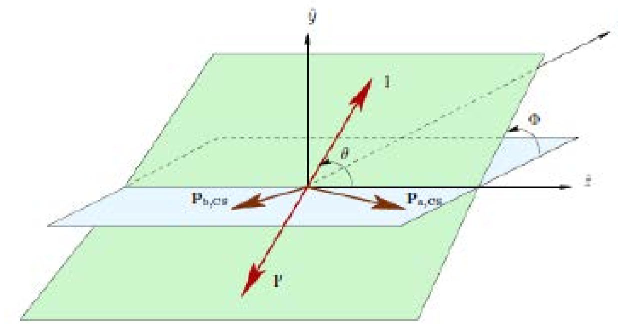
$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2}F_U^1\Bigg\{\; 1+\cos^2\theta+\sin^2\theta\cos 2\varphi_{CS}A_U^{\cos 2\varphi_{CS}}$$

$$+\; S_T\begin{bmatrix}\left(1+\cos^2\theta\right)\sin\varphi_S A_T^{\sin\varphi_S}\\ +\sin^2\theta\begin{pmatrix}\sin(2\varphi_{CS}+\varphi_S)A_T^{\sin(2\varphi_{CS}+\varphi_S)}\\ +\sin(2\varphi_{CS}-\varphi_S)A_T^{\sin(2\varphi_{CS}-\varphi_S)}\end{pmatrix}\end{bmatrix}\Bigg\}$$

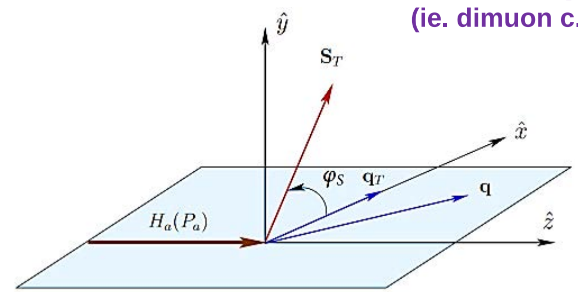
Measure magnitude of azimuthal modulations in cross section:
"Single Spin Asymmetries"



target rest frame



Collins-Soper frame
(ie. dimuon c.m. frame)



target rest frame

credit: M. Chiosso & B. Parsamyan

LO SIDIS and single polarized DY cross sections

SIDIS

$$\frac{d\sigma^{LO}_{SIDIS}}{dxdydzdp_T^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]$$

$$\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\cos 2\phi_h\left(\varepsilon A_{UU}^{\cos 2\phi_h}\right)\right.$$

$$+ S_T\left[\begin{array}{l}\sin(\phi_h-\phi_S)\left(A_{UT}^{\sin(\phi_h-\phi_S)}\right)\\ +\sin(\phi_h+\phi_S)\left(\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\right)\\ +\sin(3\phi_h-\phi_S)\left(\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\right)\end{array}\right]$$

DY

$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2}F_U^1\left\{1+\cos^2\theta+\sin^2\theta\cos 2\varphi_{CS}A_U^{\cos 2\varphi_{CS}}\right.$$

$$\left.+ S_T\left[\begin{array}{l}\left(1+\cos^2\theta\right)\sin\varphi_S A_T^{\sin\varphi_S}\\ +\sin^2\theta\left(\begin{array}{l}\sin(2\varphi_{CS}+\varphi_S)A_T^{\sin(2\varphi_{CS}+\varphi_S)}\\ +\sin(2\varphi_{CS}-\varphi_S)A_T^{\sin(2\varphi_{CS}-\varphi_S)}\end{array}\right)\end{array}\right]\right\}$$

SIDIS asymmetry			PDF ⊗ FF		
$A_{UU}^{\cos 2\phi_h}$	$\propto$	$h_1^{\perp q}\otimes H_{1q}^{\perp h}$	BM	⊗	CF
$A_{UT}^{\sin(\phi_h-\phi_s)}$	$\propto$	$f_{1T}^{\perp q}\otimes D_{1q}^{h}$	Sivers	⊗	FF
$A_{UT}^{\sin(\phi_h+\phi_s)}$	$\propto$	$h_1^{q}\otimes H_{1q}^{\perp h}$	Transv	⊗	CF
$A_{UT}^{\sin(3\phi_h-\phi_s)}$	$\propto$	$h_{1T}^{\perp q}\otimes H_{1q}^{\perp h}$	Pretz	⊗	CF

beam		target	DY asymmetry		
PDF	⊗	PDF			
BM	⊗	BM	$A_T^{\cos 2\varphi_{cs}}$	$\propto$	$h_1^{\perp q}\otimes h_1^{\perp q}$
f_1	⊗	Sivers	$A_T^{\sin\varphi_s}$	$\propto$	$f_1^{q}\otimes f_{1T}^{\perp q}$
BM	⊗	Transv	$A_T^{\sin(2\varphi_{cs}-\varphi_s)}$	$\propto$	$h_1^{\perp q}\otimes h_{1T}^{\perp q}$
BM	⊗	Pretz	$A_T^{\sin(2\varphi_{cs}+\varphi_s)}$	$\propto$	$h_1^{\perp q}\otimes h_1^{q}$

within QCD TMD framework:

$$h_1^{\perp q}\Big|_{SIDIS} = -h_1^{\perp q}\Big|_{DY} \qquad f_{1T}^{\perp q}\Big|_{SIDIS} = -f_{1T}^{\perp q}\Big|_{DY}$$

$$h_1^{q}\Big|_{SIDIS} = h_1^{q}\Big|_{DY} \qquad h_{1T}^{\perp q}\Big|_{SIDIS} = h_{1T}^{\perp q}\Big|_{DY}$$

Drell Yan Advantage

- Complementarity is emphasized by (LO): (Arnold,Metz,Schlegel:PRD79,034005(2009))
  - ➞ in SIDIS: there is 1 $F_{U(L),T}$ per TMD
  - ➞ in DY: at least 2 $F_{(U)T}$ per TMD
    - → same TMDs can be measured in different $F_{(U)T}$
    - → allowing cross checks of TMD extraction & even of underlying formalism

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	PDF ⊗ FF	beam / target: PDF ⊗ PDF	
$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h}$	BM ⊗ CF	BM ⊗ BM	$A_T^{\cos 2\varphi_{cs}} \propto h_1^{\perp q} \otimes h_1^{\perp q}$
$A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$	Sivers ⊗ FF	f_1 ⊗ Sivers	$A_T^{\sin \varphi_s} \propto f_1^{q} \otimes f_{1T}^{\perp q}$
$A_{UT}^{\sin(\phi_h + \phi_s)} \propto h_1^{q} \otimes H_{1q}^{\perp h}$	Transv ⊗ CF	BM ⊗ Transv	$A_T^{\sin(2\varphi_{cs} - \varphi_s)} \propto h_1^{\perp q} \otimes h_{1T}^{\perp q}$
$A_{UT}^{\sin(3\phi_h - \phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$	Pretz ⊗ CF	BM ⊗ Pretz	$A_T^{\sin(2\varphi_{cs} + \varphi_s)} \propto h_1^{\perp q} \otimes h_1^{q}$

$$A_T^{\sin \varphi_s} = \frac{F_T^1}{F_U^1}$$

Complementarity between SIDIS and Drell Yan

- Complementarity is emphasized by (LO): (Arnold,Metz,Schlegel:PRD79,034005(2009))
  - ➡ in SIDIS: there is 1 $F_{U(L),T}$ per TMD
  - ➡ in DY: at least 2 $F_{(U)T}$ per TMD
    - → same TMDs can be measured in different $F_{(U)T}$
    - → allowing cross checks of TMD extraction & even of underlying formalism TMD

- Systematic study of quark TMDs in Drell Yan
  - ➡ requires double-polarization
  - ➡ only then can all 8 leading twist TMD be measured

- Double-Spin Drell Yan
  - ➡ Measure DY with both Beam and Target polarized
    - → broad spin physics program possible
    - → truly complementary to spin physics programs at Jlab and RHIC

(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	$x_t = 0.1 – 0.3$	2×10^{33}	0.14	P_t = 90% f = 0.22	1.1×10^{-3}	2015-2016, 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}	>2024?
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}	>2023?
J-PARC (high-p beam line)	$\pi^- + p$	10-20 GeV $\sqrt{s}$ = 4.4-6.2	$x_b = 0.2 – 0.97$ $x_t = 0.06 – 0.6$	2×10^{31}	---	---	---	>2019? under discussion
fsPHENIX (RHIC)	$p^\uparrow + p^\uparrow$	$\sqrt{s}$ = 200 $\sqrt{s}$ = 510	$x_b = 0.1 – 0.5$ $x_b = 0.05 – 0.6$	8×10^{31} 6×10^{32}	0.08	P_b = 60% P_b = 50%	4.0×10^{-4} 2.1×10^{-3}	>2021?
SeaQuest (FNAL: E-906)	$p + p$	120 GeV $\sqrt{s}$ = 15	$x_b = 0.35 – 0.9$ $x_t = 0.1 – 0.45$	3.4×10^{35}	---	---	---	2012 - 2017
Pol tgt DY‡ (FNAL: E-1039)	$p + p^\uparrow$ $p + d^\uparrow$	120 GeV $\sqrt{s}$ = 15	$x_t = 0.1 – 0.45$	3.0×10^{35} 3.5×10^{35}	0 – 0.2*	P_t = 85% f = 0.176	0.15	2018-2020
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	>2021?

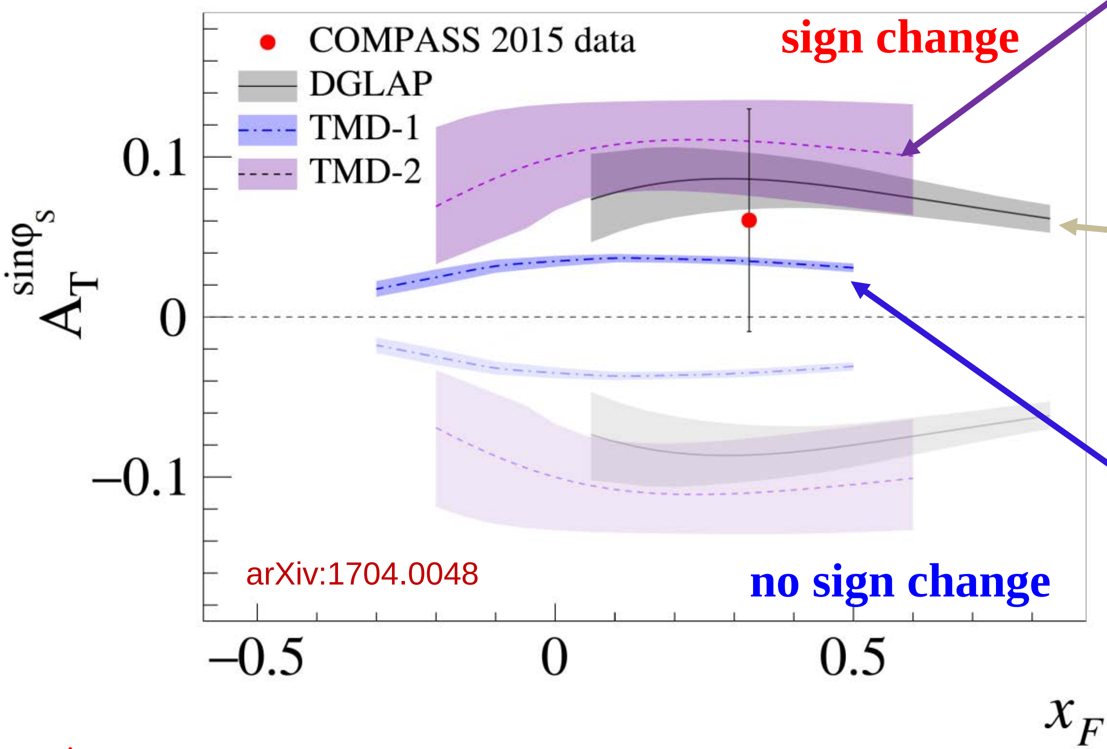
‡ 8 cm NH_3 target / § L= 1×10^{36} $cm^{-2}\,s^{-1}$ (LH_2 tgt limited) / L= 2×10^{35} $cm^{-2}\,s^{-1}$ (10% of MI beam limited)

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

W. Lorenzon (U-Michigan) 10/2017

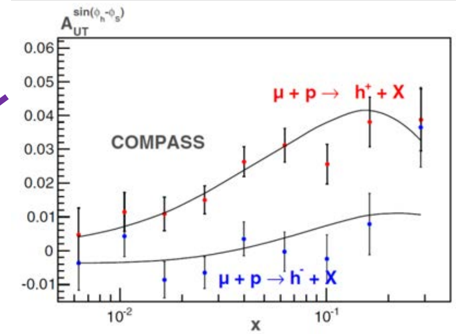
COMPASS 2015 Results

- 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%

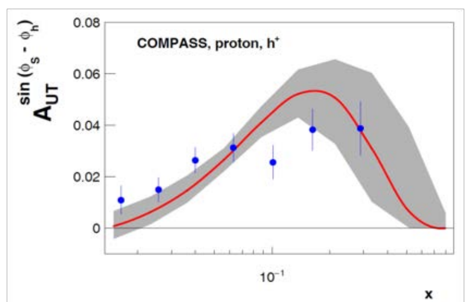


$$A_T^{\sin\varphi_s} = 0.060 \pm 0.057(stat.) \pm 0.040(sys.)$$

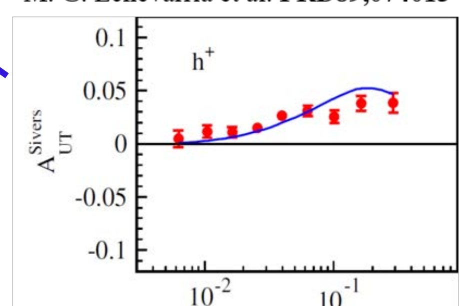
TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**



DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**

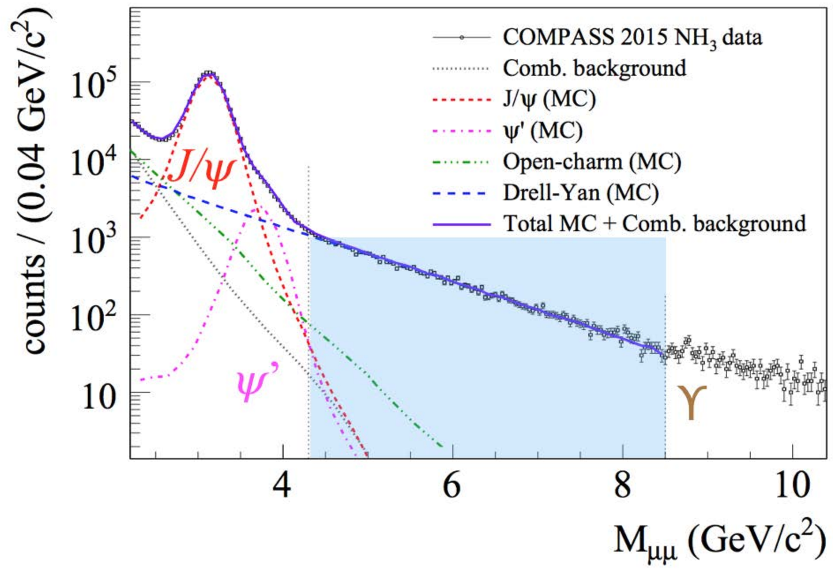


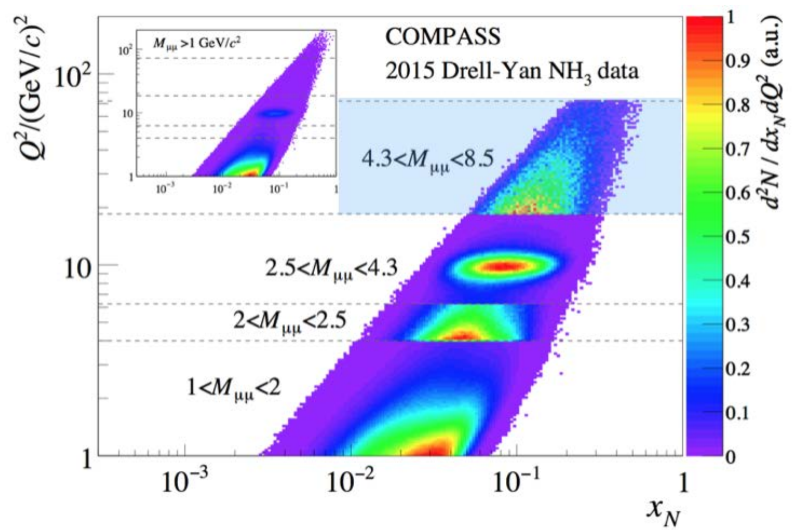
TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



COMPASS 2015 Results - II

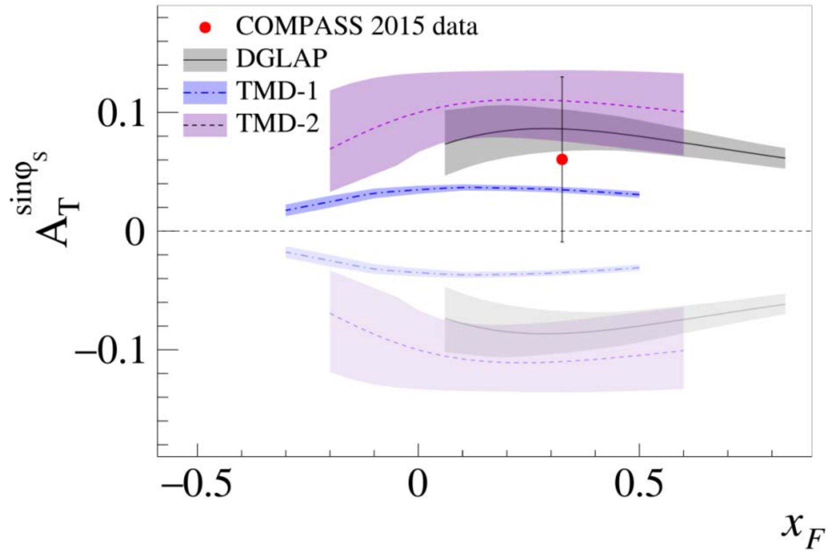
- Drell-Yan analysis performed in the mass range of 4.3 - 8.5 GeV/c^2
  - ➞ Only 4% background in this mass range
  - ➞ DY events [$M(\mu^+\mu^-) > 4$ GeV/c^2): ~35,000
- Phase space for Drell-Yan and SIDIS partially overlap in the x-Q^2 plane
  - ➞ average Q^2 in Drell-Yan is about 2x that in SIDIS
  - ➞ allows to minimize the impact of uncertainties from TMD scale evolution
  - ➞ overlap in kinematic regions of COMPASS Drell-Yan and SIDIS data allows for direct comparisons of TMD amplitudes
- COMPASS probes proton's valence quarks in Drell-Yan and SIDIS





COMPASS Plans

- **First physics results: April 2017**
  - ➡ **~1σ result**
  - ➡ **consistent w/ sign change!**
- 2016-2017: DVCS program.
- 2018: second year of polarized DY planned
  - ➡ improved statistics expected



- COMPASS Beyond 2020 (under study: https://indico.cern.ch/event/502879/)
  - ➡ polarized ^{6}LiD target: flavor separation of TMD SSAs.
  - ➡ long LH_2 and nuclei targets: un-polarized pion-induced DY
  - ➡ 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: W.C. Chang (Academia Sinica) & O. Denisov (Torino)

Current and Future DY 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**

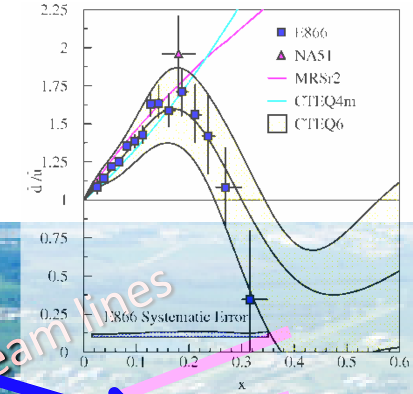
- **E-1039**: SeaQuest w/ pol NH_3/ND_3 targets (2018-2019)

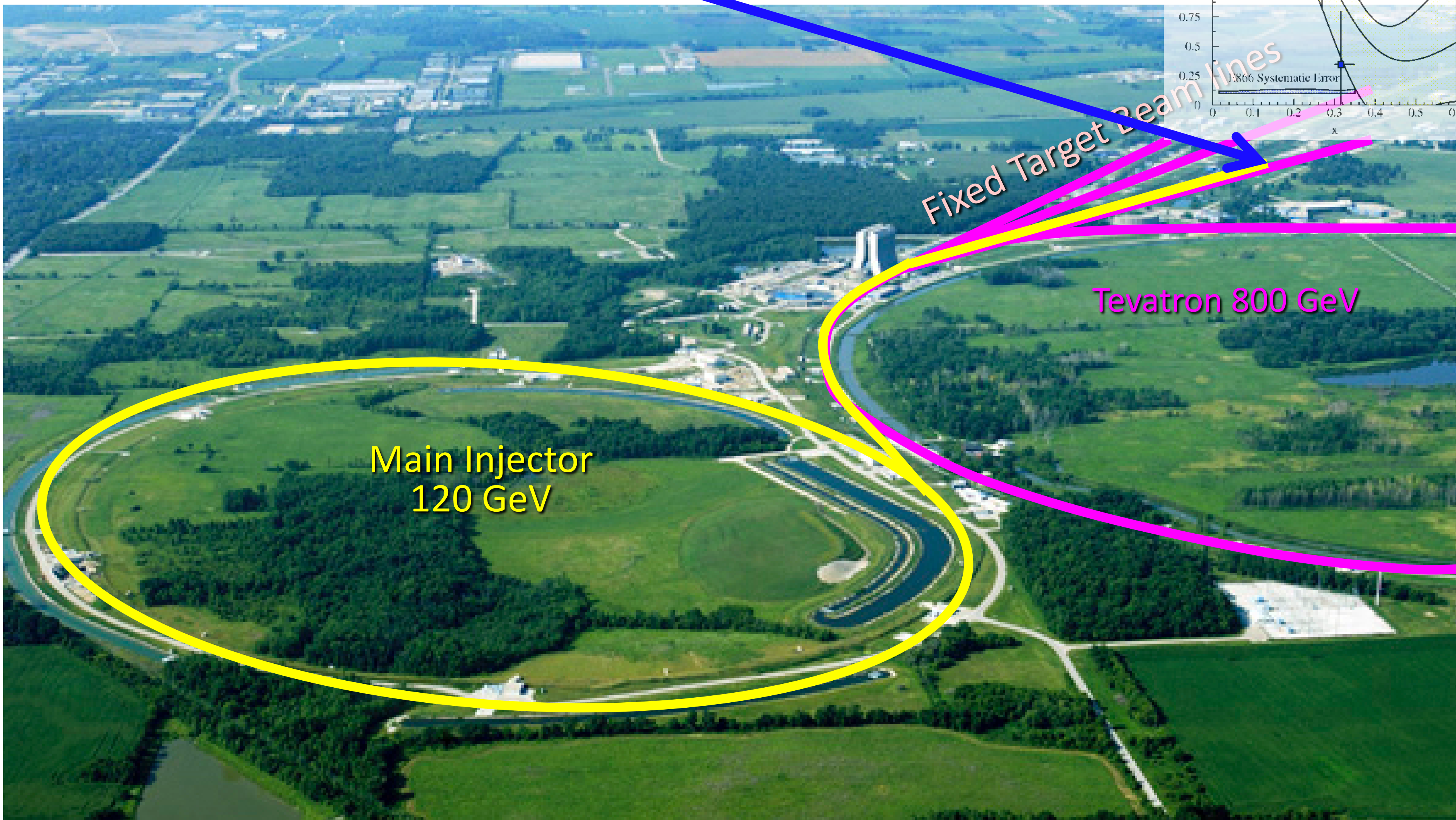
  ➞ probe sea quark distributions

- **E-1027**: pol p beam on (un)pol tgt (2020-2021?)

  ➞ **Sivers sign change** (valence quark)

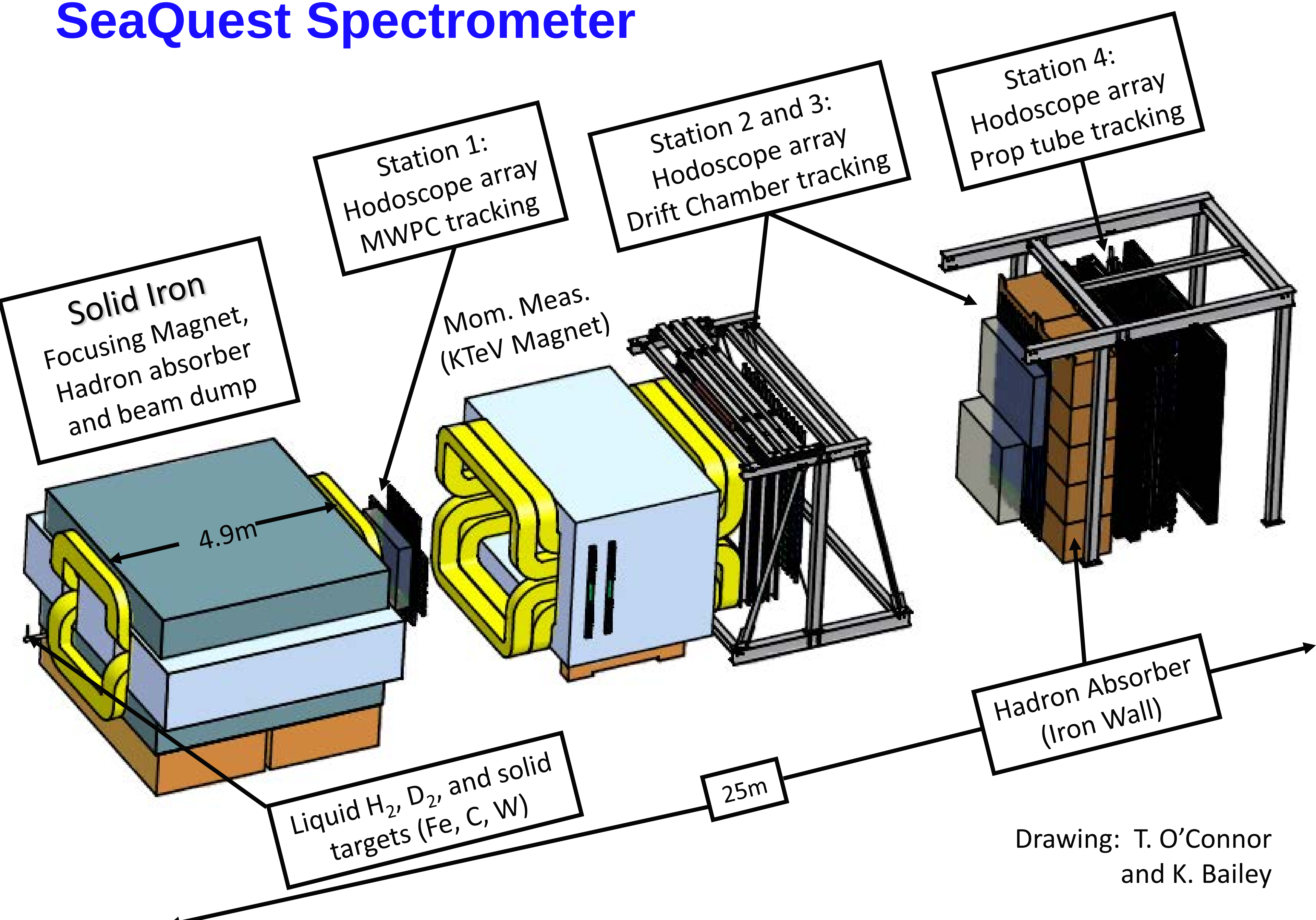
SeaQuest Experiment





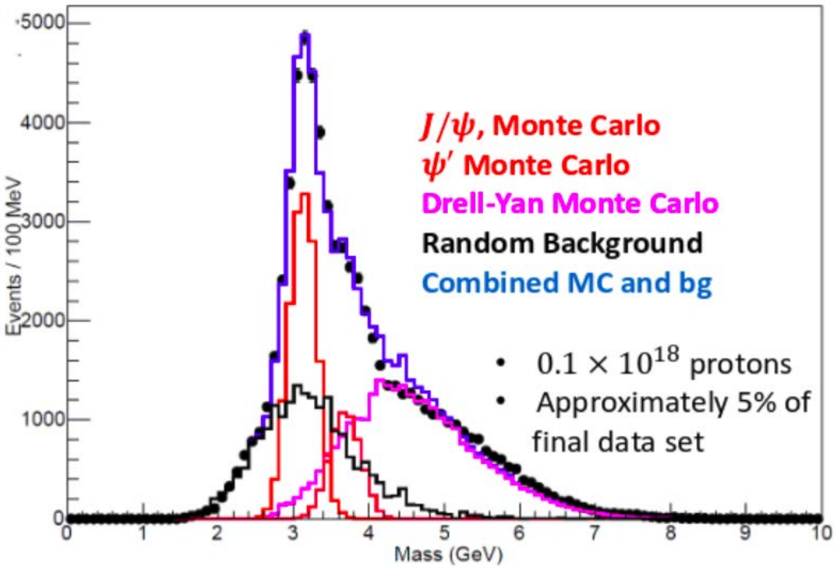
10% of available beam to SeaQuest / 90% to neutrino program

SeaQuest Spectrometer

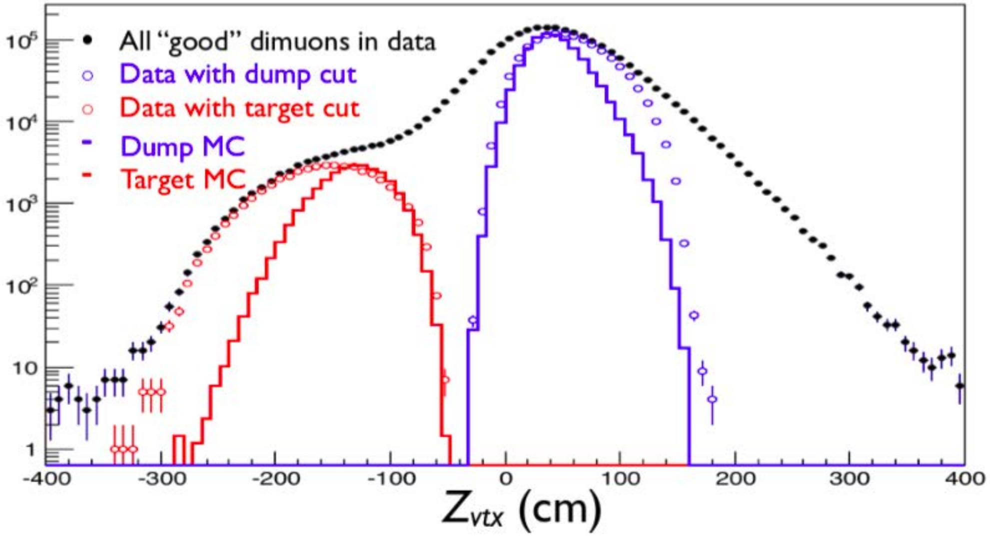


Drawing: T. O'Connor
and K. Bailey

Event Selection & Reconstruction

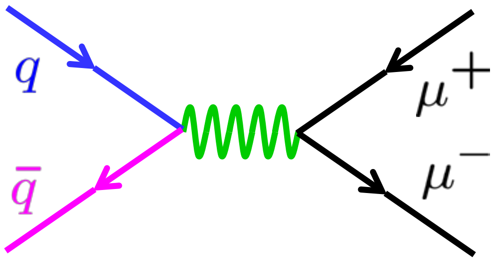


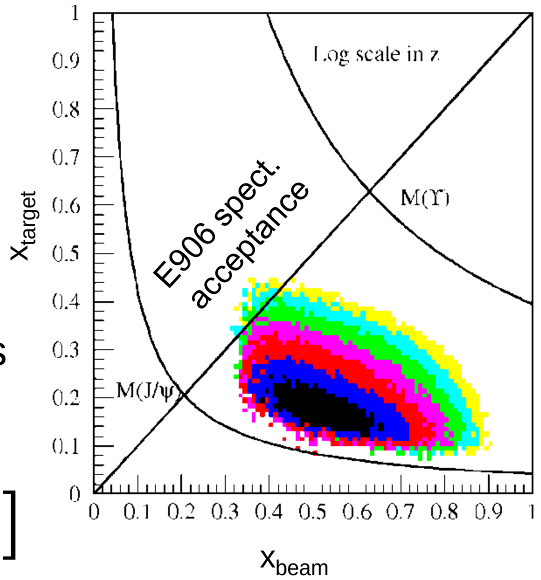
- Monte Carlo describe data well
- Resolution better than expected
  - $\sigma_M(J/\psi)$ ~180 MeV
  - σ_M(D-Y) ~220 MeV
  - J/ψ to ψ' separation
  - lower J/ψ mass cut (more Drell-Yan events)



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

Fixed Target Drell-Yan: Sensitivity to sea quarks





- Cross section: convolution of beam and target parton distributions

$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{x_b x_t s} \sum_{q\in\{u,d,s,\ldots\}} e_q^2 \left[\bar{q}_t(x_t) q_b(x_b) + q_t(x_t)\bar{q}_b(x_b)\right]$$

u-quark dominance
$(2/3)^2$ vs. $(1/3)^2$

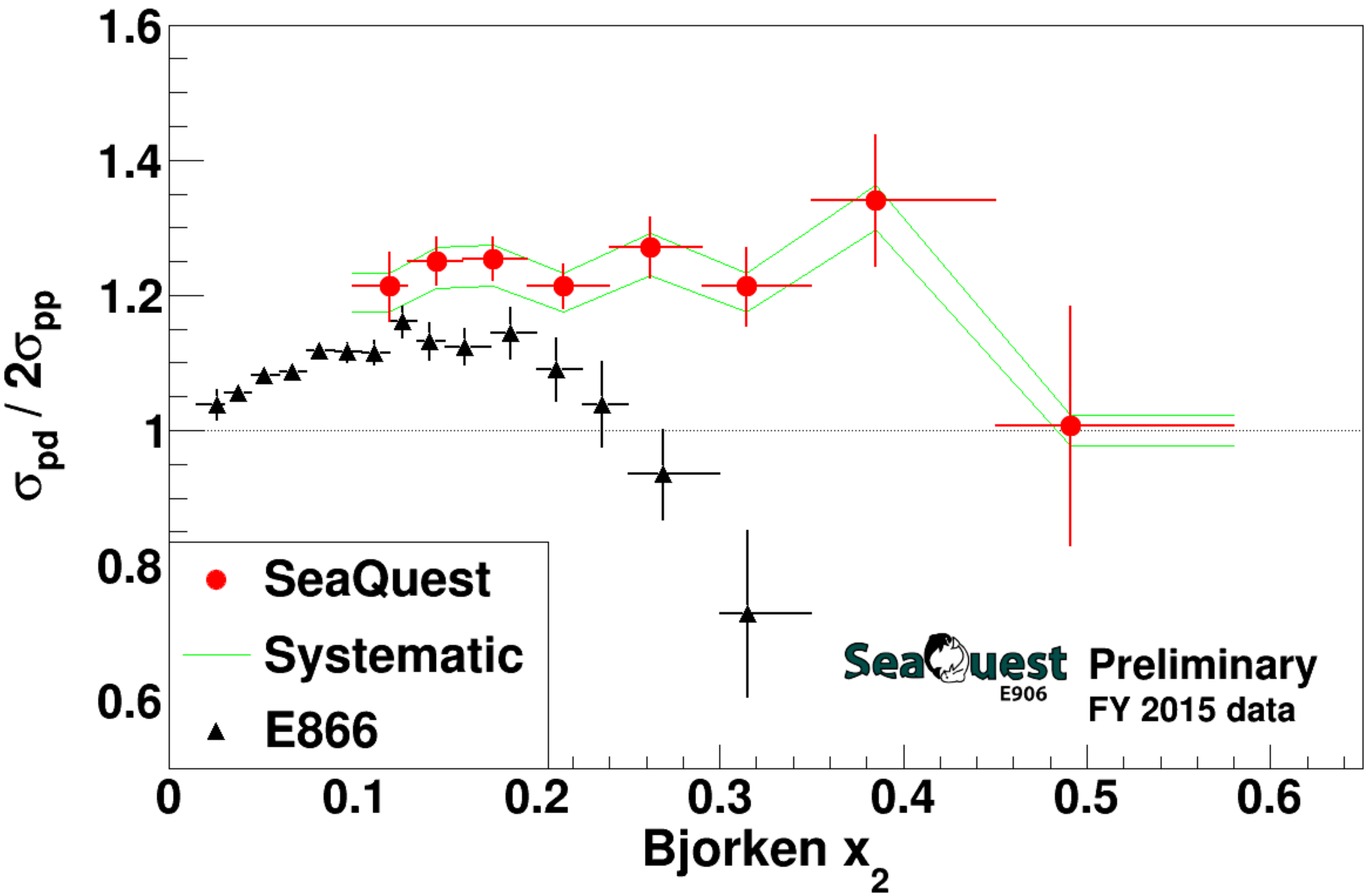
acceptance limited
(Fixed Target, Hadron Beam)

beam: valence quarks at high x

target: sea quarks at low/intermediate x

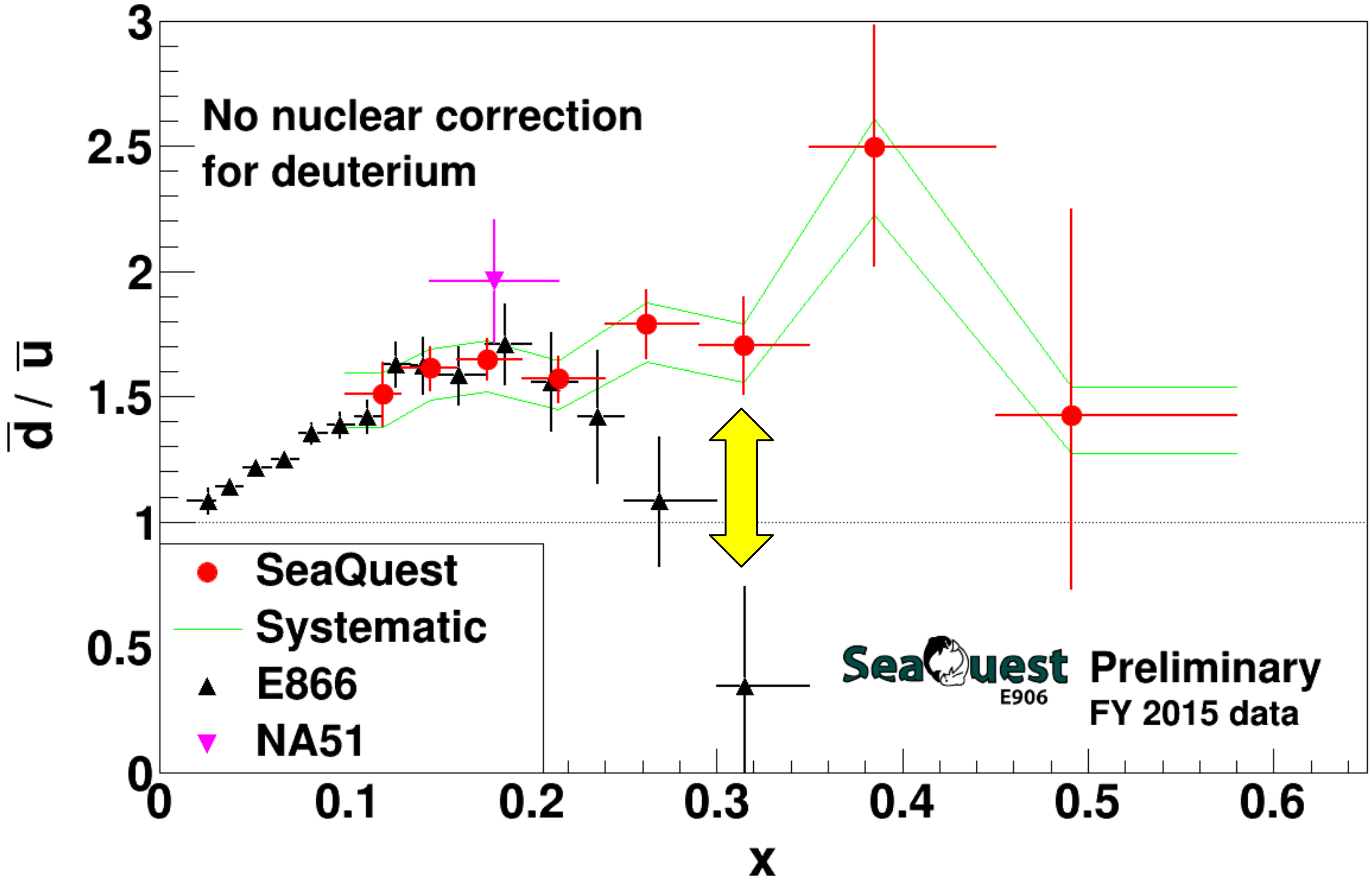
$$\frac{\sigma^{pd}}{2\sigma^{pp}} = \frac{1}{2}\left[1 + \frac{\bar{d}(x)}{\bar{u}(x)}\right]$$

SeaQuest Cross Section Ratio (2015 Data Set)



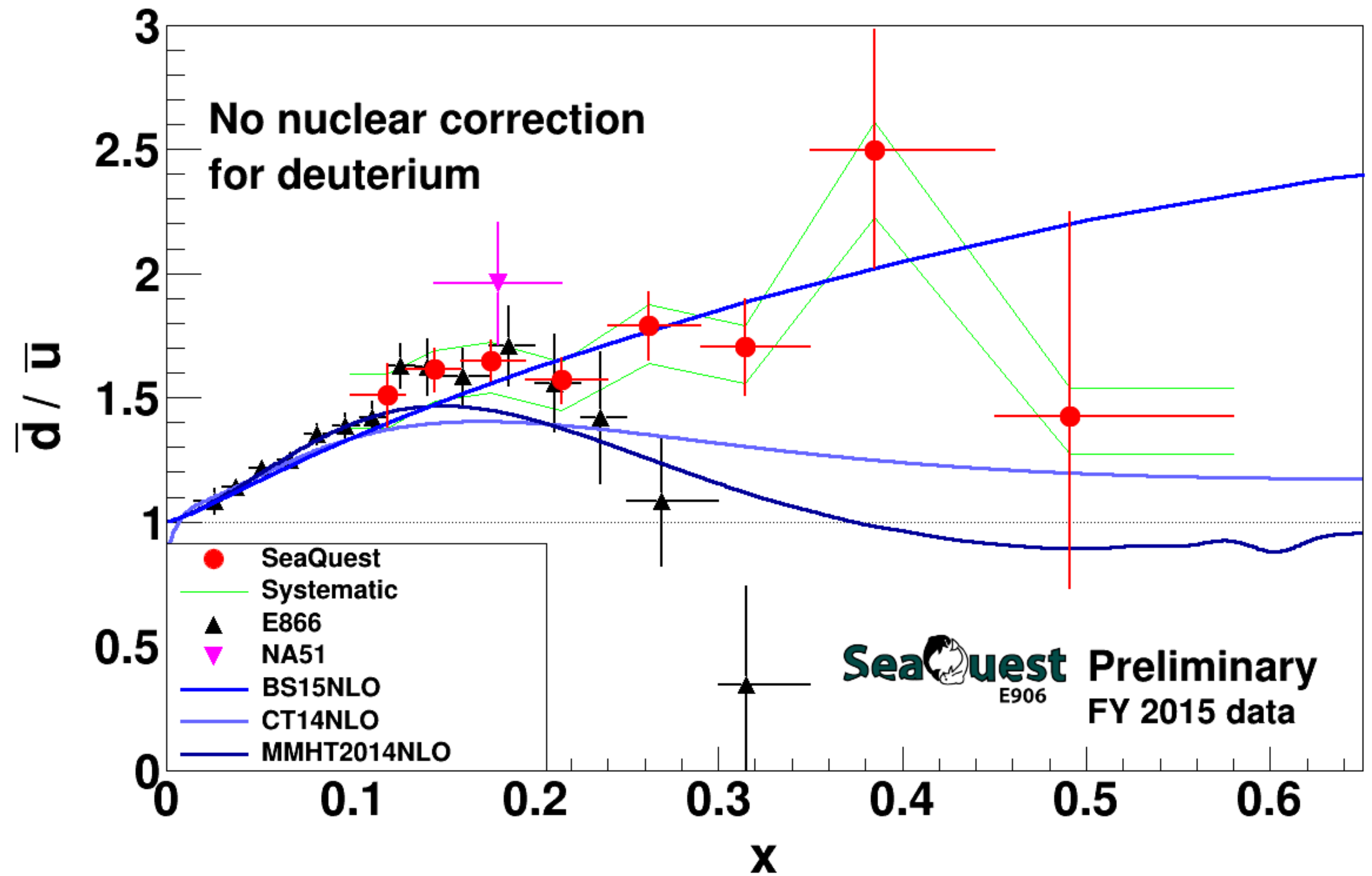
- different kinematics and Q^2 for E866 & SeaQuest data sets
- new chambers installed in March 2016: improve acceptance in high x_2 region
- 30% of anticipated data (~1.2 × 10^{18} pot)
- approved for 5 × 10^{18} pot

SeaQuest Leading Order extraction (2015 Data Set)



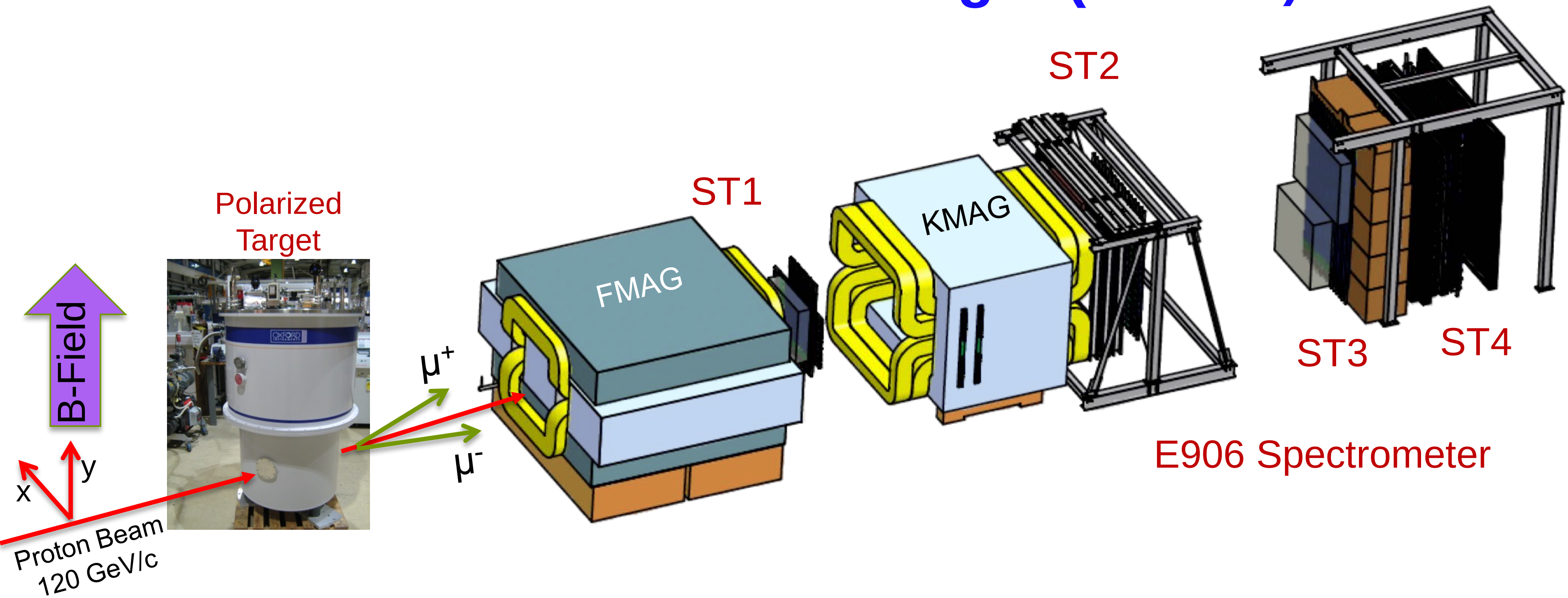
- E866 data is for $Q^2 = 54\ GeV^2$ while SeaQuest data has $Q^2 \approx 29\ GeV^2$
  - difference should be insignificant
- no nuclear correction for deuterium
  - expected larger at higher x, but still small compared to error bars
- is there disagreement at high x?

SeaQuest Leading Order extraction (2015 Data Set)

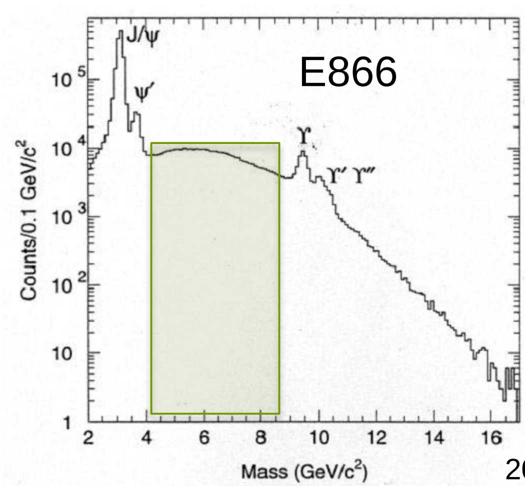


- BS15 (statistical model) calculated using parameters from NPA941(2015)307
- CT14 and MMHT2014 calculated with the LHAPDF library
- PDF scales taken as 29 GeV^2

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



- $2.7 \cdot 10^{12}$ p/spill, one 4s spill/minute
- kinematic range $4 < M < 9$ GeV
- luminosity: $3 \cdot 10^{35}$ /cm²/s (NH_3)
- $\sqrt{s} = 15$ GeV
- move polarized target ~2m upstream
  → improves target-dump separation
  → moves acceptance to lower x_2

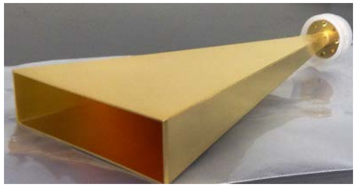


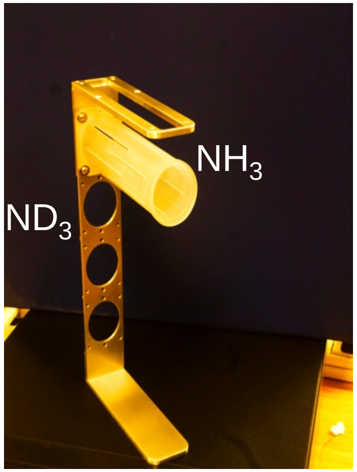
L_{int} = 1.82 *10⁴²/cm² NH_3 / 2.11 *10⁴²/cm² ND_3 for 2 years

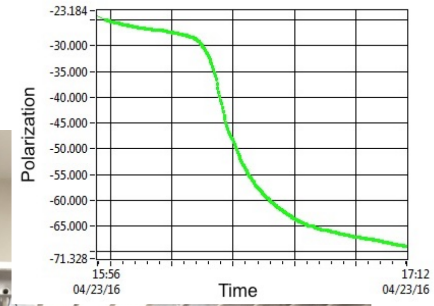
Ref: Andi Klein (LANL)

The Polarized Target

- field: 5T @ 1K
- elliptical: 1.9 cm x 2.1 cm (x,y), l:7.9 cm (z)
- ρ: 0.87 g/cm^3 NH_3 , 1 g/cm^3 ND_3
- packing fraction: 0.6
- dilution factor : 0.176 , 0.3
- Polarization <80%>, <32%>
- IL: 8.6%, 9.5%
- 3 active cells, 1 empty
- Helium consumption 100 l/day

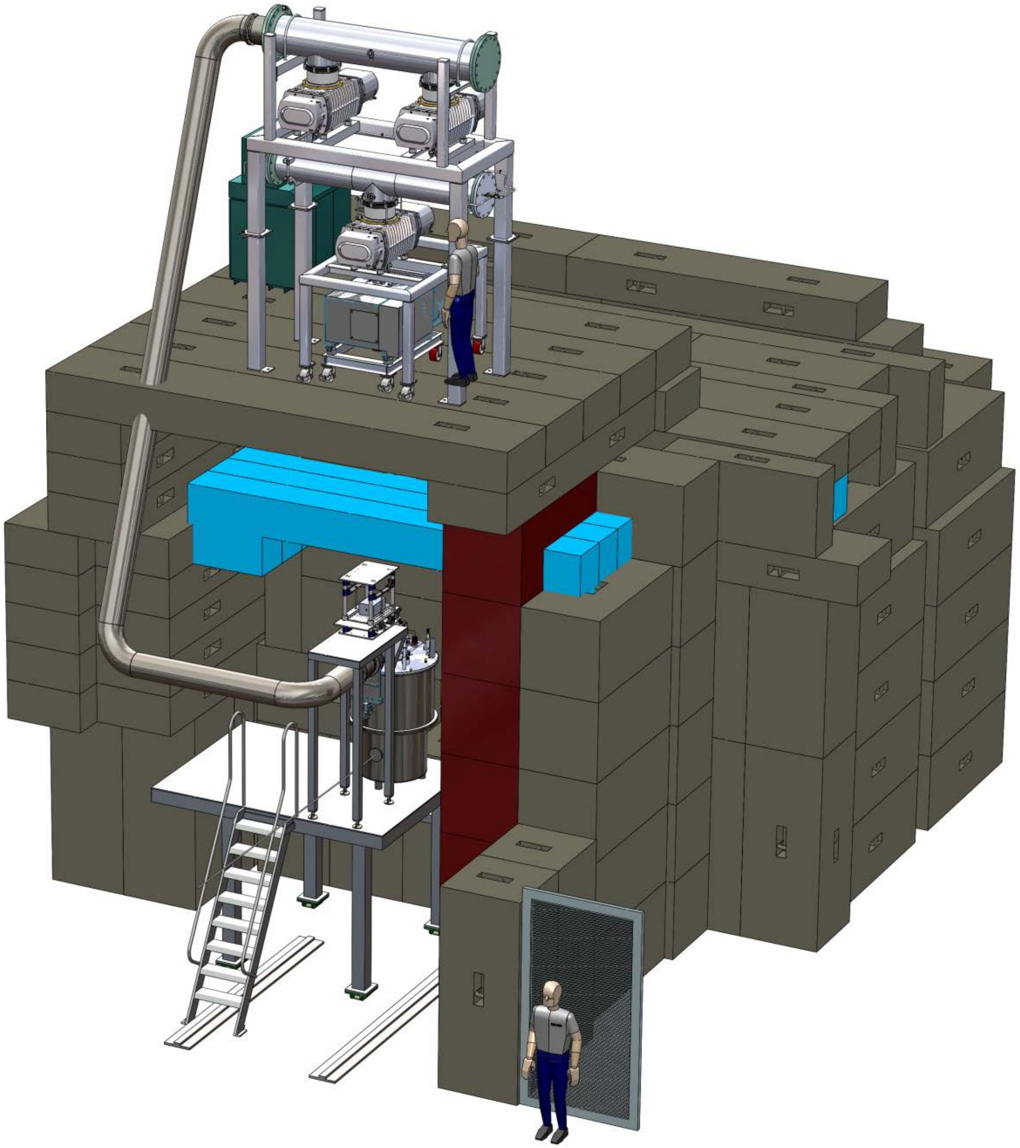






Ref: Andi Klein (LANL)

The E1039 Target and FMAG



Ref: Andi Klein (LANL)

Changes needed :

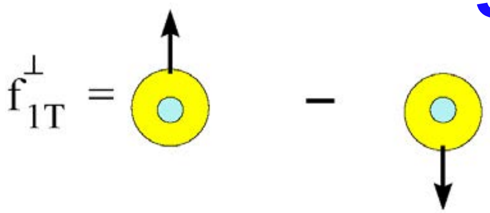
- Collimators upstream
- Closed Loop He system
- 90 degree monitors L/R, T/B

Beam **σ_x=17mm, σ_y=19mm**

Target upstream by ~200cm

- moves acceptance to lower x_2
- better target – dump separation

Sivers Function and Spin Crisis



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 ≈ unmeasured

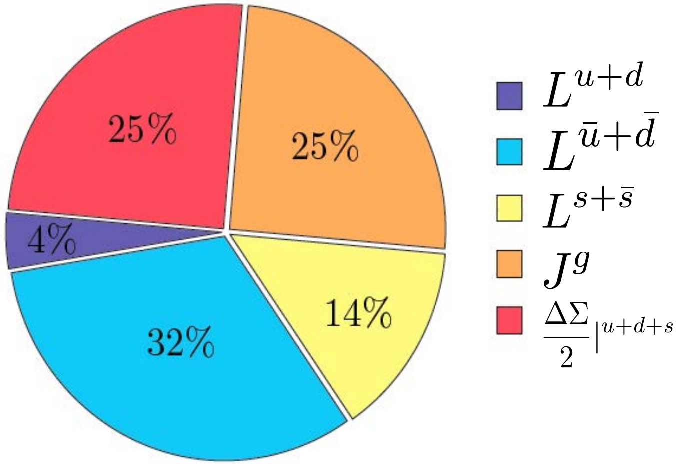
How measure quark OAM ?

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

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

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

Lattice QCD:



$\Delta\Sigma_q \approx 25\%$

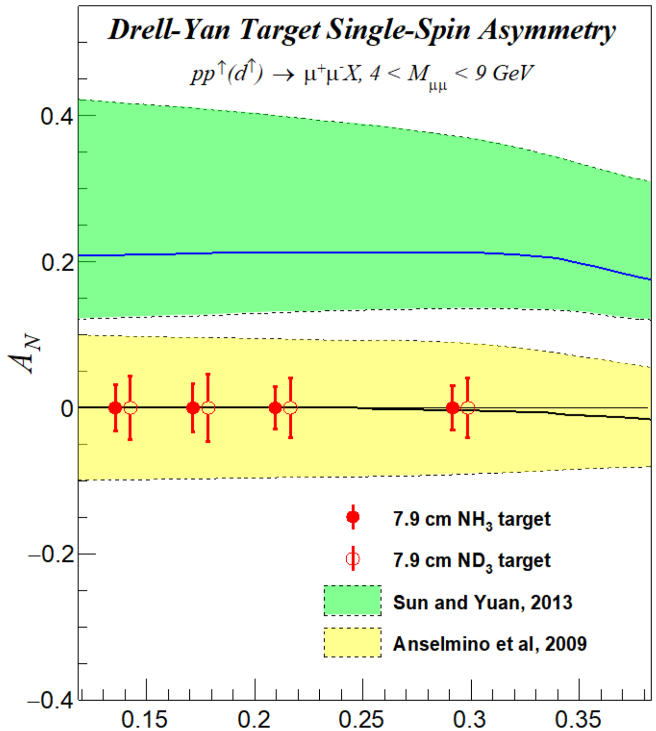
$2\ L_q \approx 50\%$ (4% (valence)+46% (sea))

$2\ J_g \approx 25\%$

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

Projected Statistical Precision with a Polarized Target at (E-1039)

- Probe **Sea Quark Sivers Asymmetry**
  with a polarized proton/deuteron target at SeaQuest



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

Statistics shown for two calendar years of running:

target = NH_3 / ND_3
- L = 1.82 *10^42 /cm^2 / 2.11*10^42 /cm^2
- P = 80% / 32%

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

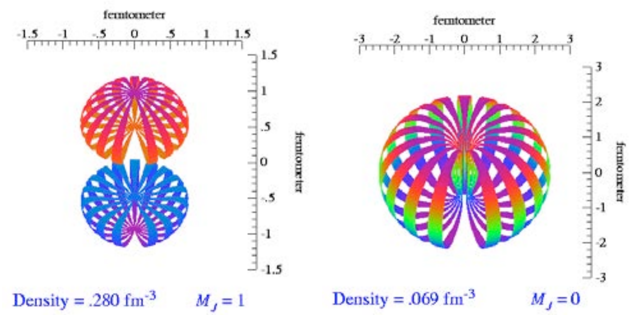
$$A_N^{DY} = \frac{2}{\pi} \cdot A_T^{\sin\varphi_s} \propto f_{1,u}^{q}(x_b) \otimes f_{1T,\bar{u}(\bar{d})}^{\perp q}(x_t)$$

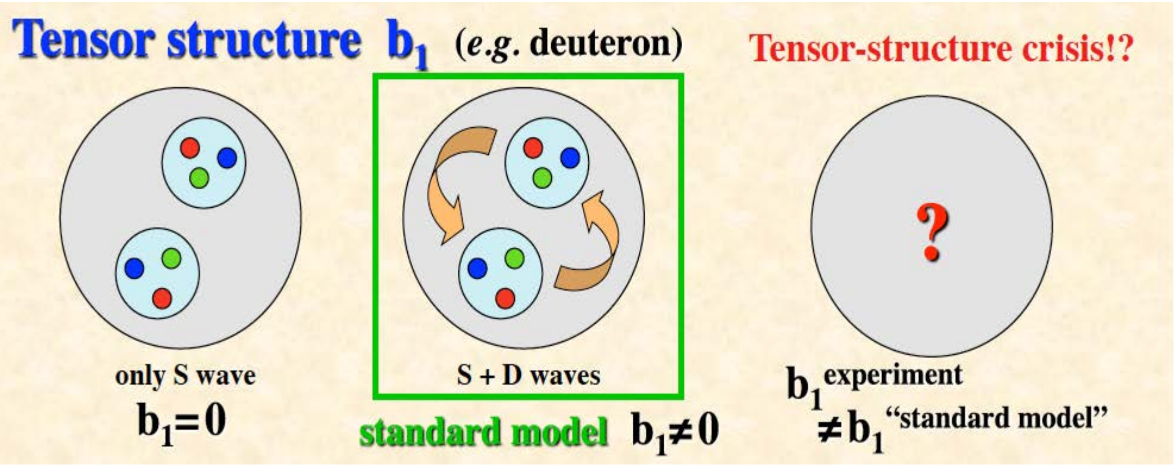
Ref: Andi Klein (LANL)

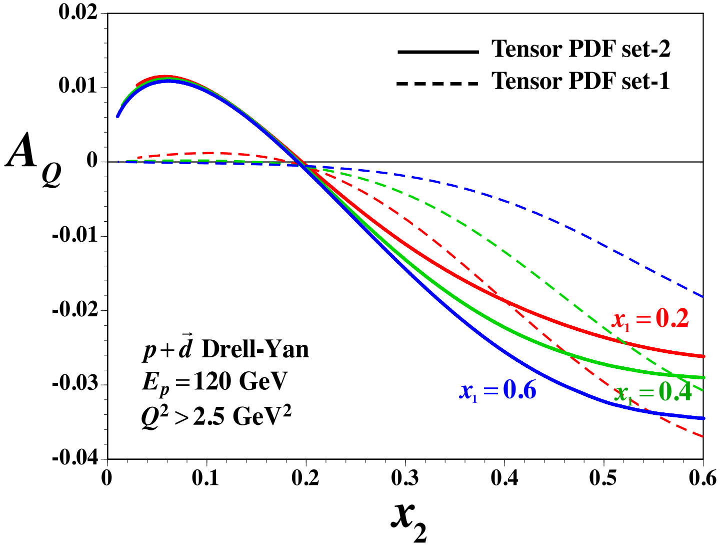
Tensor Polarization of Deuteron

- deuteron is spin 1 particle, opens up new physics

spin-1 system in a B-field leads to
3 sublevels via Zeeman interaction
Vector polarization: $(n^{+} - n^{-})$; $-1 < P_z < +1$
Tensor polarization: $(n^{+} - n^{0}) - (n^{0} - n^{-})$; $-2 < P_{zz} < +1$
Normalization: $(n^{+} + n^{-} + n^{0}) = 1$

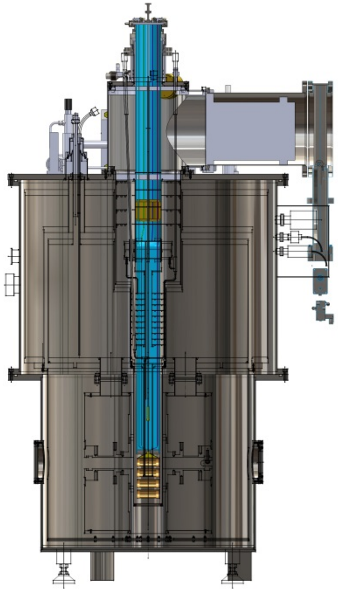






From S. Kumano, arxiv.org/1606.03149

Current Status and Plans for E-1039

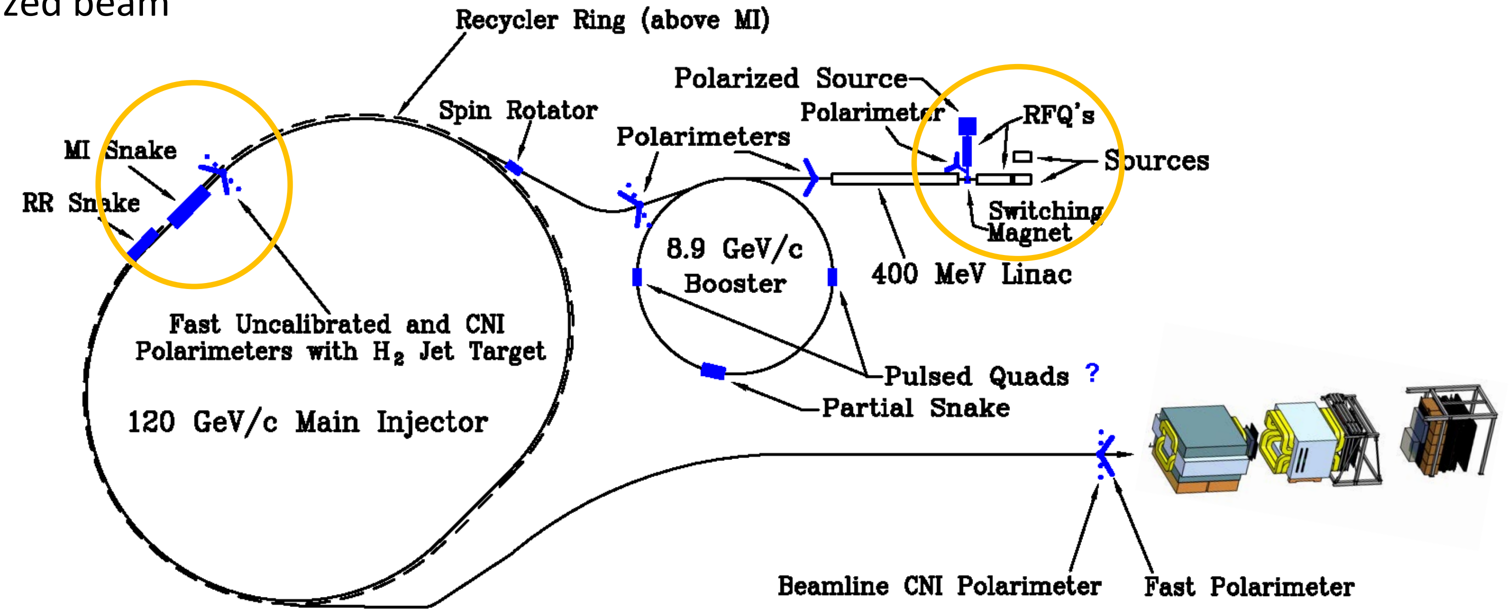


- Current status
  - full system cooldown/test with full extended 8 cm long target
  - reached 92% polarization
  - half of the liquefier system built and delivered, second half will be ordered late this year
  - beamline design 70% finished; now looking for reducing costs
  - currently working on 90% design of the whole installation and beam line
- Funding
  - DoE has provided $2 Mio for E-1039 in Sept 2017
  - Fermilab will pay to decommission E906 and to install E1039
- Plans
  - last system cooldown with both target sticks in Dec 2017
  - move target to FNAL in Jan 2018, system cooldown Feb 2018 at FNAL
  - start beam line commissioning in Mar 2018, and general commissioning in summer 2018
  - start data taking in fall 2018

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

The Plan:

- Use fully understood SeaQuest Spectrometer
- Add polarized beam



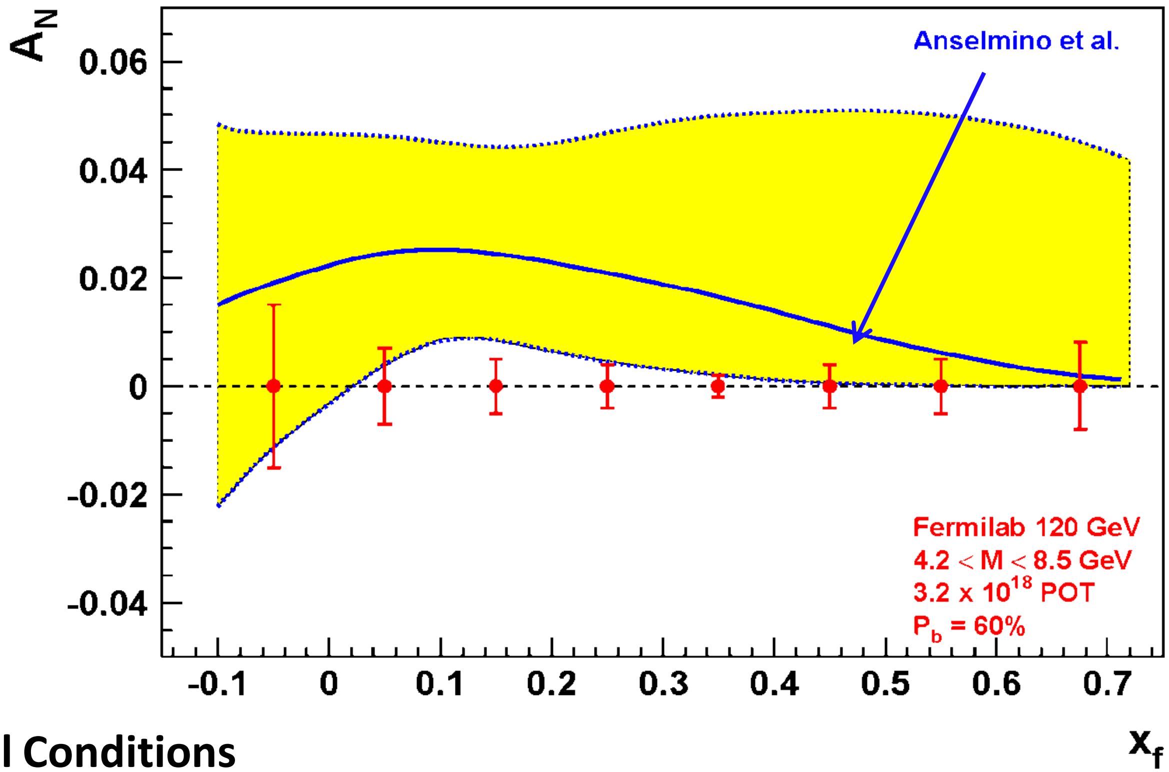
- **Measure sign-change in Sivers Function:**
  - ⟶ QCD (and factorization) require sign change
  - ⟶ major milestone in hadronic physics (HP13)

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

- **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)

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

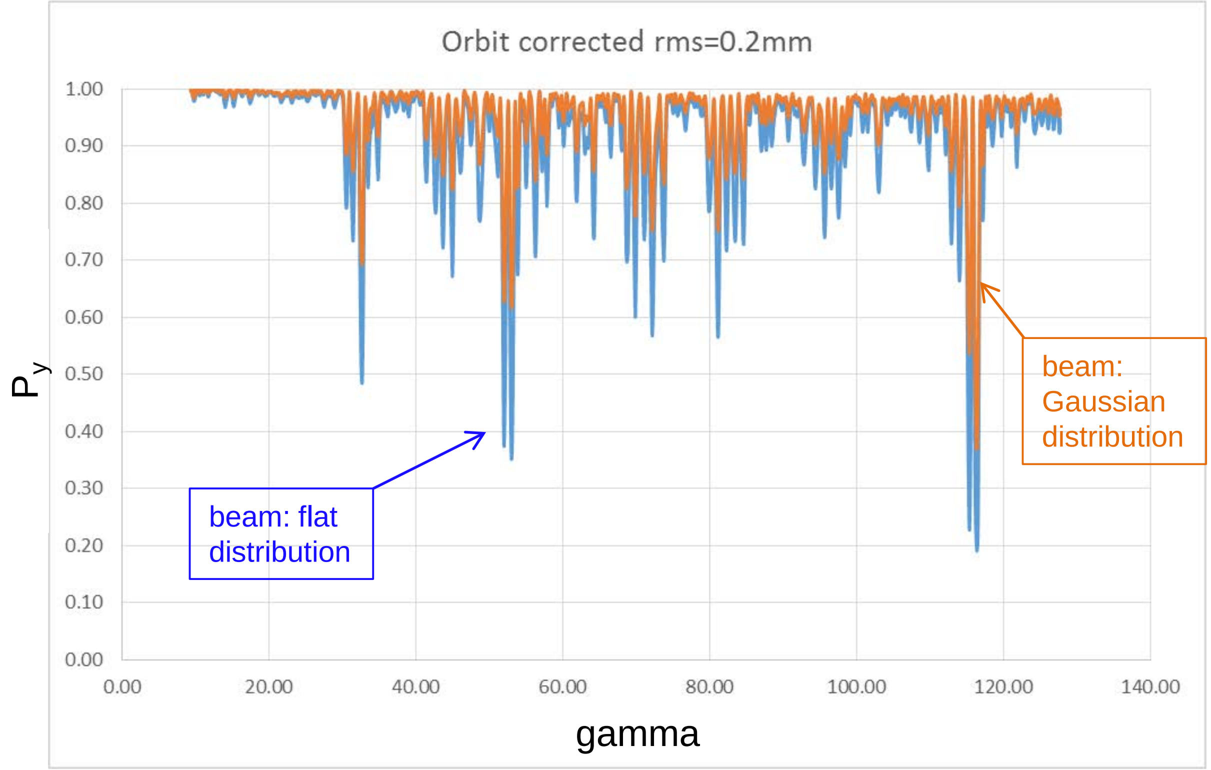
- **Experimental Conditions**
  - same as SeaQuest
  - luminosity: $L_{av} = 2 \times 10^{35}$ (10% of available beam time: $I_{av} = 15$ nA)
  - 3.2×10^{18} total protons for 5×10^5 min: (= 2 yrs at 50% efficiency) with $P_b = 60\%$

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

- Simulations of final polarization as function of Energy in Fermilab Main Injector look promising (Meiqin Xiao (FNAL AD), Etienne Forest (KEK)):
  → point-like snake in correct location, w/ actual ramp rate for acceleration: final polarization: ~ 90%



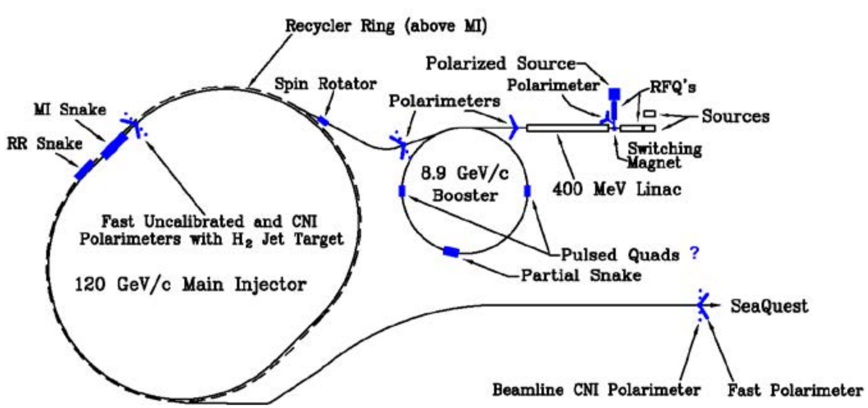
Polarizations with magnet field error and misalignment (from magnet database and survey group), corrected (for SeaQuest running conditions)

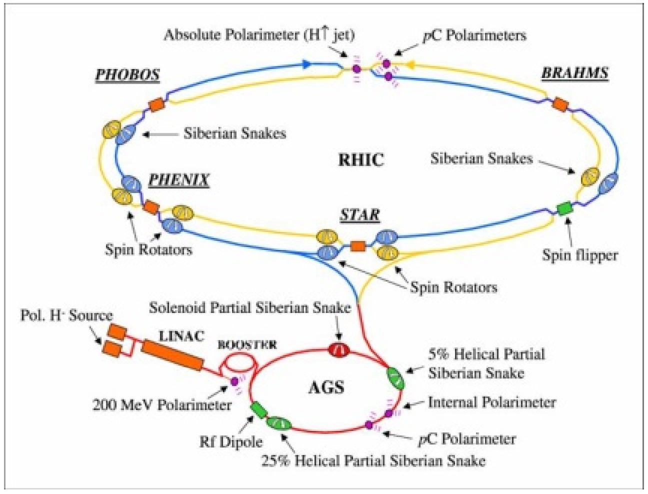
ε_{max} = 20 π mm.mrad in y plane and $\Delta p = 1.25 \cdot 10^{-3}$ in longitudinal plane

Ref: Meiqin Xiao (FNAL)

Polarized protons: Fermilab vs 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

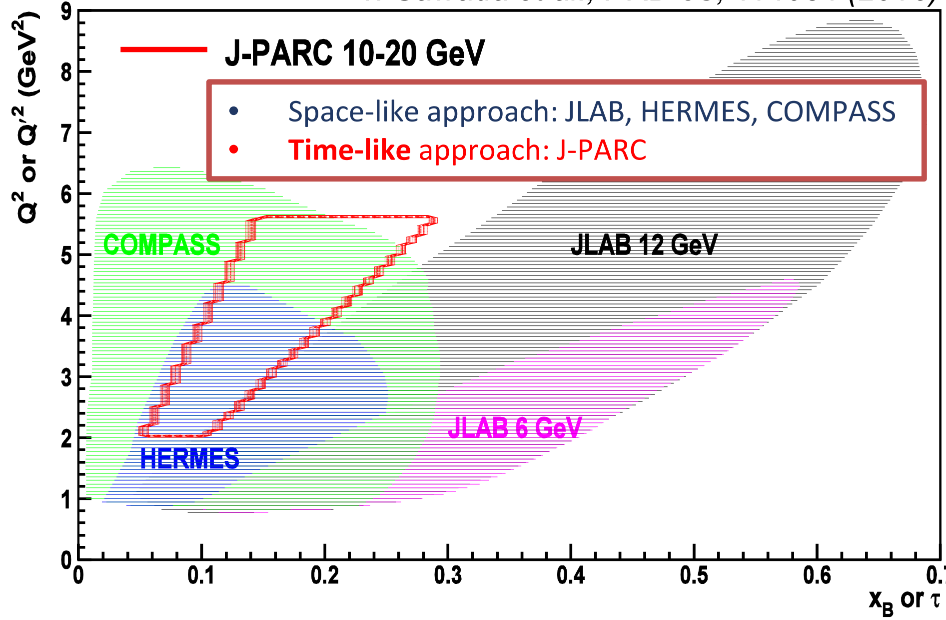




J-PARC Projection & Plans

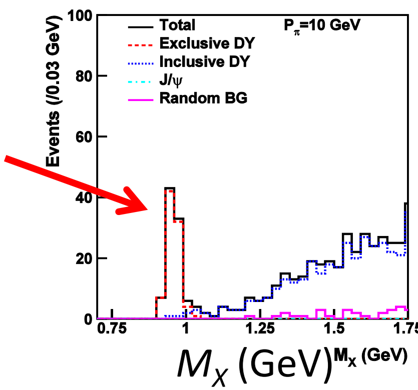
- Accessing GPD of nucleon via exclusive meson-induced Drell-Yan
  - ➡ Test of factorization of exclusive Drell-Yan process
  - ➡ Test of universality of GPD in space-like (DVMP) and time-like processes (DY).

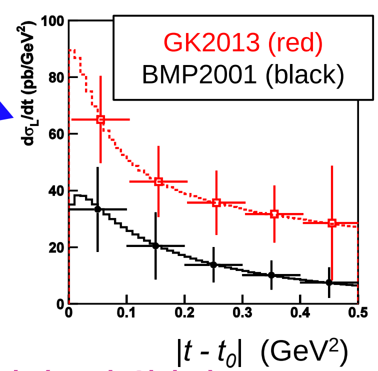
T. Sawada et al., PRD ***93****, 114034 (2016)*



- 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 DY events $(\pi^- p \to \mu^+ \mu^- n)$
  - ➡ Statistical accuracy adequate for discriminating between predictions from two current GPD models.

P_π = 10 GeV



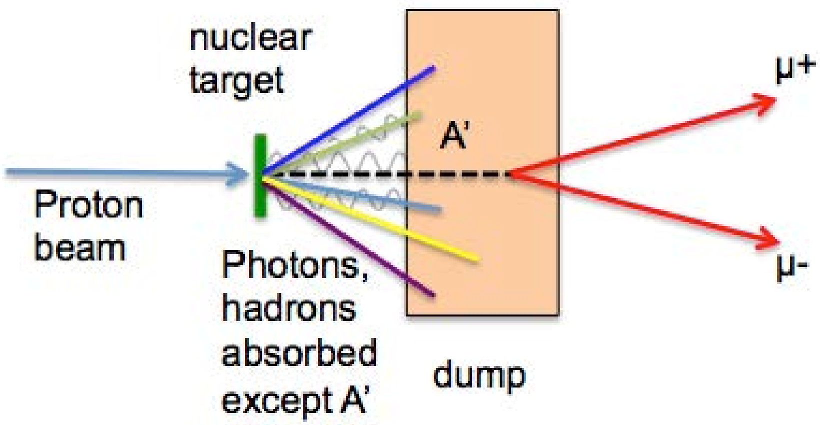


GK2013: P. Kroll et al. Eur.Phys.J.C73, 2278 (2013)
BMP2001: E.R. Berger et al. Phys.Lett.B523, 265 (2001)

Ref: T. Sawada (Acad. Sinica)

Search for Dark Photons at SeaQuest

- Classic Beam Dump Experiment

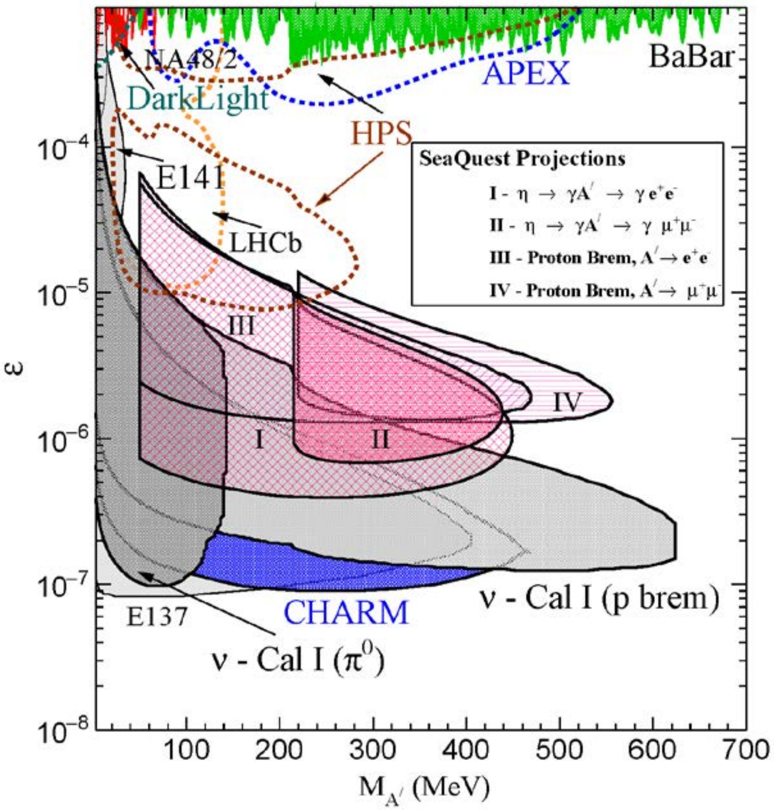


- Minimal impact on Drell-Yan program

  ➞ 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

Polarized Proton Beams and Searches for Dark Forces

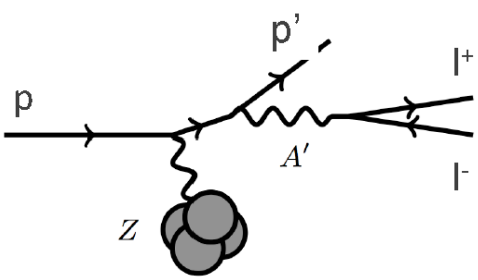
Searches for a dark photon also limit other possibilities

Parity violation studies could prove key

$$\mathcal{L}_{\mathrm{darkZ}} = -(\varepsilon e J^{\mu}_{\mathrm{em}} + \varepsilon_Z \frac{g}{2\cos\theta_W} J^{\mu}_{\mathrm{NC}}) Z_{d\,\mu}$$

[Davoudiasl, Lee, Marciano, 2014]

If the A' is a dark Z, then ...



The dilepton yield can change with proton polarization: the asymmetry can be O(1)!

Conclusions

- There is an exciting Drell-Yan program with polarized/unpolarized beams and targets underway
  - ⟶ although experimentally more challenging, it has some clear advantages over SIDIS
- Different labs offer complementary probes and processes to study hadronic landscape
  - ⟶ focus on strength of each lab to (minimize cost and) optimize physics output
- Future opportunities look very promising
  - ⟶ support from hadronic community (was and remains) vital to move forward
  - ⟶ opportunities to join the Fermilab program
- We have finally seen first results from COMPASS on the sign-change
  - ⟶ statistics still poor; but expect more in 2018
- Now entering an era where we will have first measurement of a sea quark Sivers function (answer some of the questions):
  - ⟶ How much do the quarks and gluons contribute to the nucleon spin?
  - ⟶ In particular, what is the role of the sea quarks?
  - ⟶ Is there significant orbital angular momentum?
  - ⟶ Does TMD formalism work? Does Sivers function change sign (but keep shape and size)?

Thank You