“Asymmetry of antimatter in the proton” from SeaQuest and SpinQuest perspectives

https://www.nature.com/articles/s41586-021-03282-z

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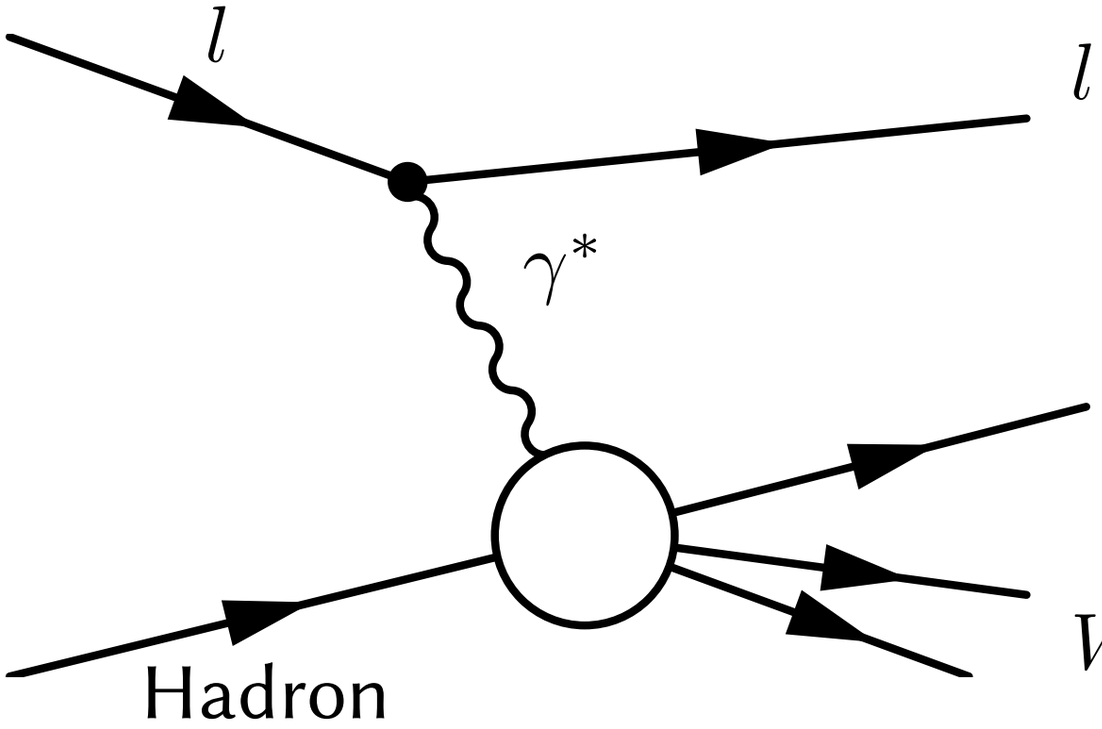
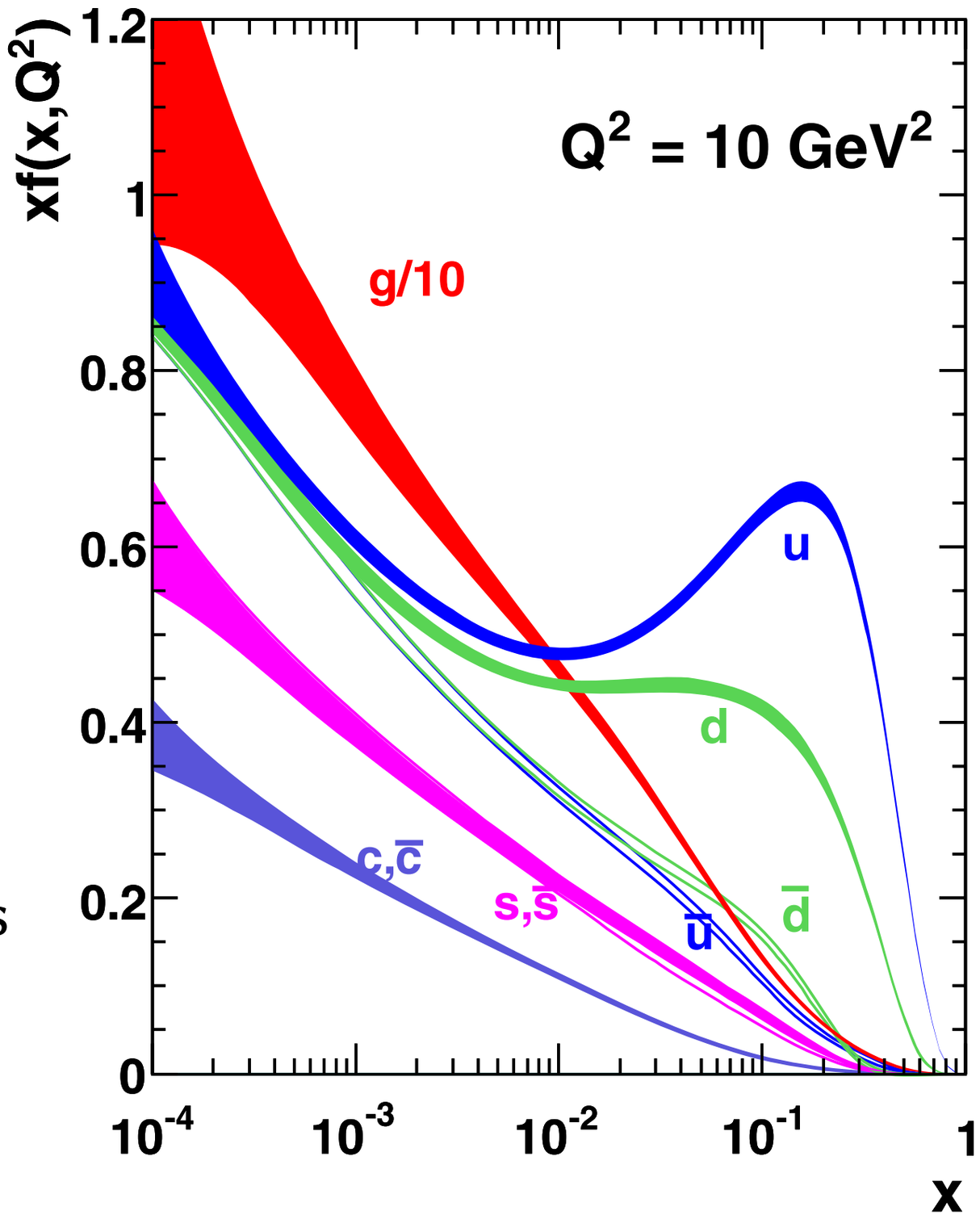
Nuclear Physics Seminars at BNL

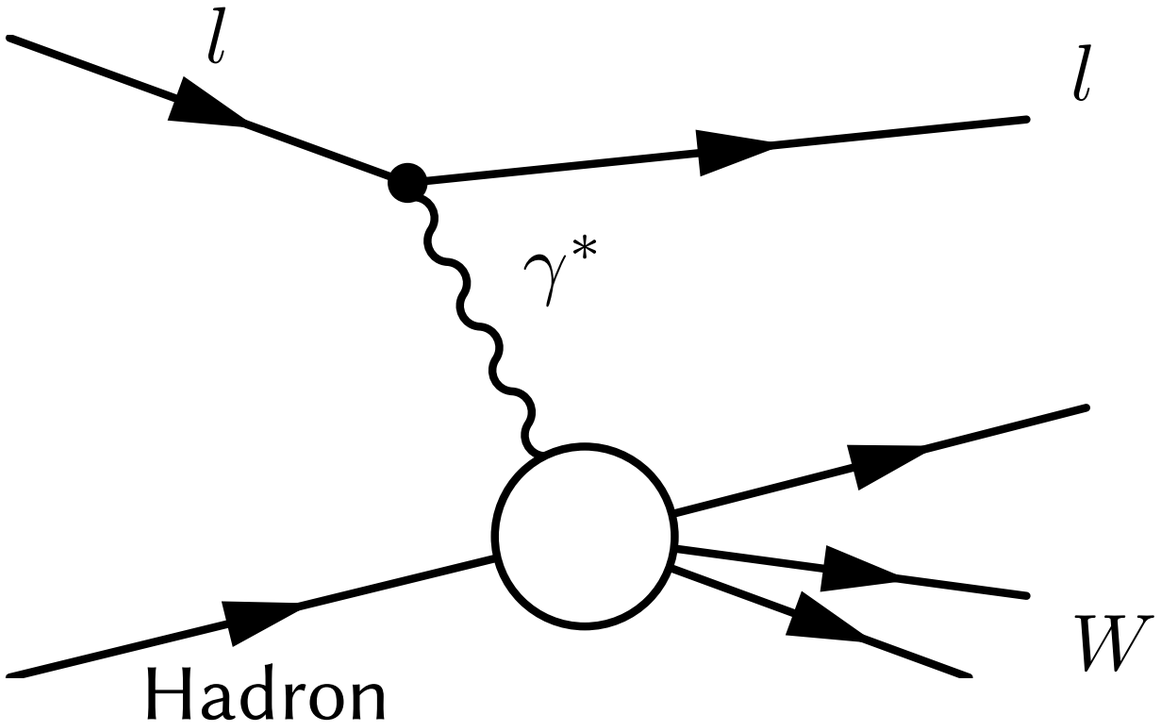
Structure of the Proton

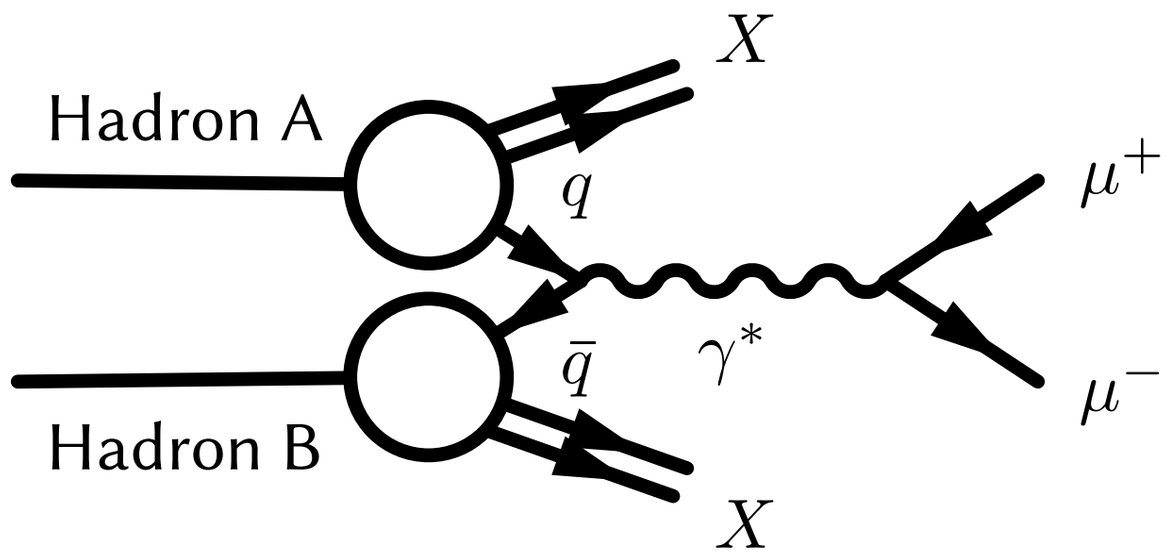


- Deep Inelastic scattering experiments have investigated the proton structure
  - Scattering with all charged partons (u, d, $\bar{u}$, $\bar{d}$, $\cdots$)
  - Great achievement for u, d quarks PDFs



Structure of the Proton





- Deep Inelastic scattering experiments have investigated the proton structure
  - Scattering with all charged partons (u, d, $\bar{u}$, $\bar{d}$, $\cdots$)
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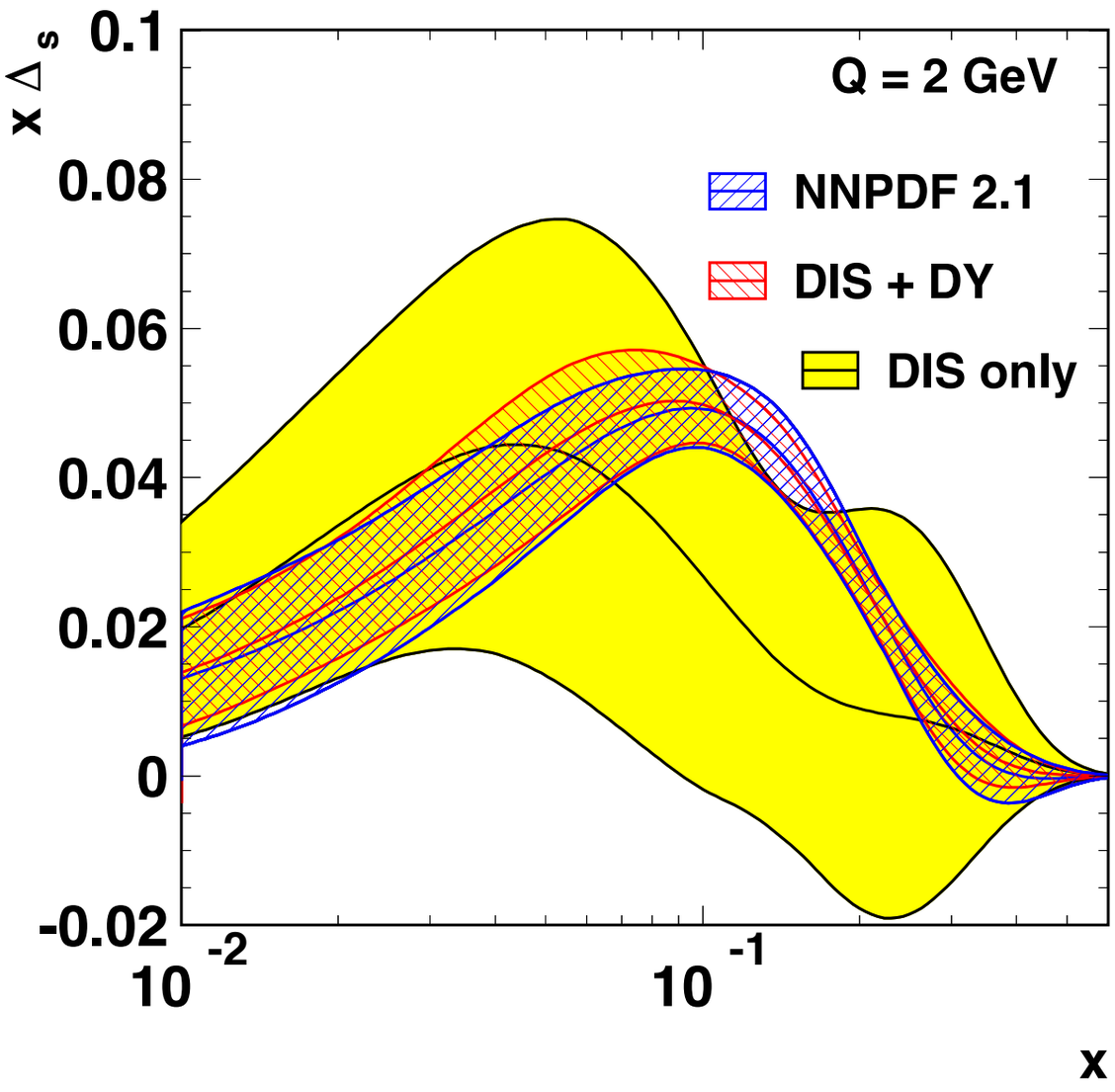
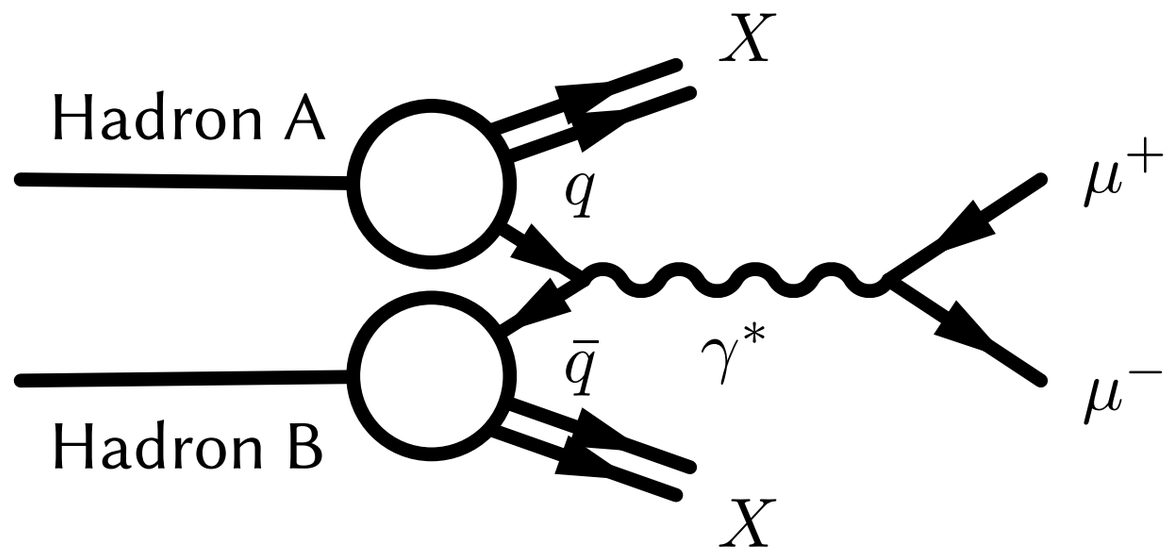
- Drell–Yan process
  - $q + \bar{q} \rightarrow \gamma^* \rightarrow l + \bar{l}$
  - Antiquark is always involved in the reaction
  - Antiquarks PDFs

Structure of the Proton



$$\Delta_s(x) = \bar{d}(x) - \bar{u}(x)$$

More precise results when Drell–Yan process is included



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Antiquarks PDFs

- Gluon splitting: Flavor Independent

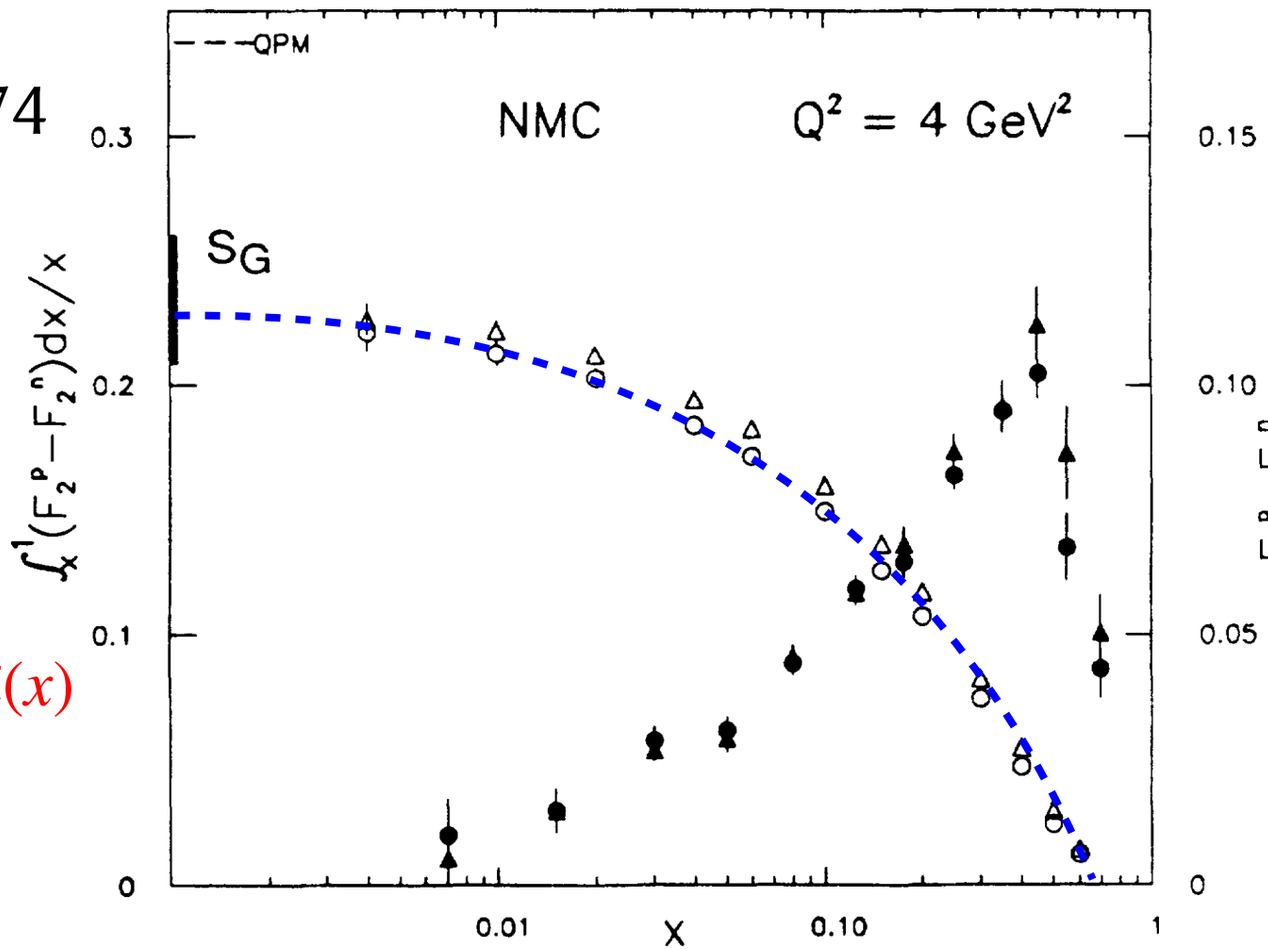
$$\bar{u}(x) = \bar{d}(x), \int_0^1 dx\bar{u}(x) = \int_0^1 dx\bar{d}(x)$$

- Gottfried sum rule: PRL 18 (1967) 1174

$$S_G = \int_0^1 dx \frac{F_2^p - F_2^n}{x}$$

$$= \frac{1}{3} + \int_0^1 dx(\bar{u}(x) - \bar{d}(x)) = \frac{1}{3}$$

$$= 0 \text{ if } \int_0^1 dx\bar{d}(x) = \int_0^1 dx\bar{u}(x)$$



- NMC Experiment (DIS) @ CERN

$S_G = 0.235 \pm 0.026 < 1/3$

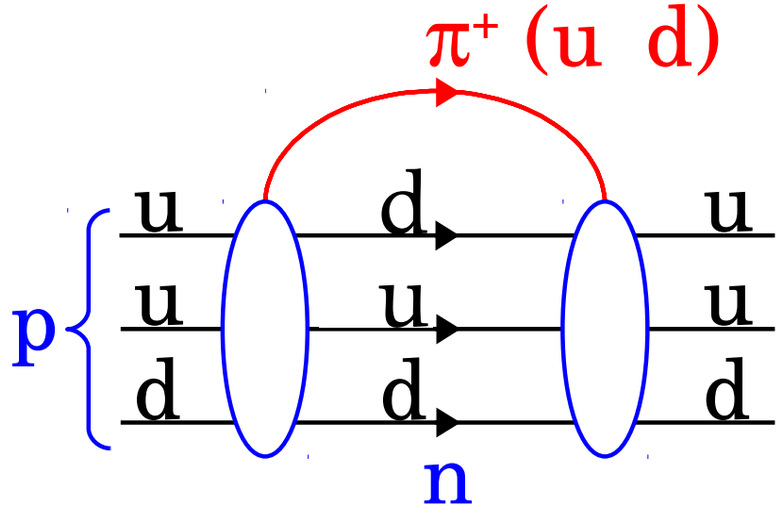
$$\rightarrow \int_0^1 \bar{d}(x)\, dx - \int_0^1 \bar{u}(x)\, dx = 0.147 \pm 0.039$$

Antiquark Flavor Asymmetry

Models

- Pauli blocking: small effect (few %)

- Pion Cloud model (Phys. Rev D 58 (1998) 092004)
  - $|p\rangle = |p_0\rangle + \alpha\,|N(udd)\pi^+(u\bar{d})\rangle + \beta\,|\Delta(uuu)\pi^-(\bar{u}d)\rangle + \gamma\,|\Lambda K\rangle + \cdots$
  - $\alpha > \beta \rightarrow \bar{d} > \bar{u}$

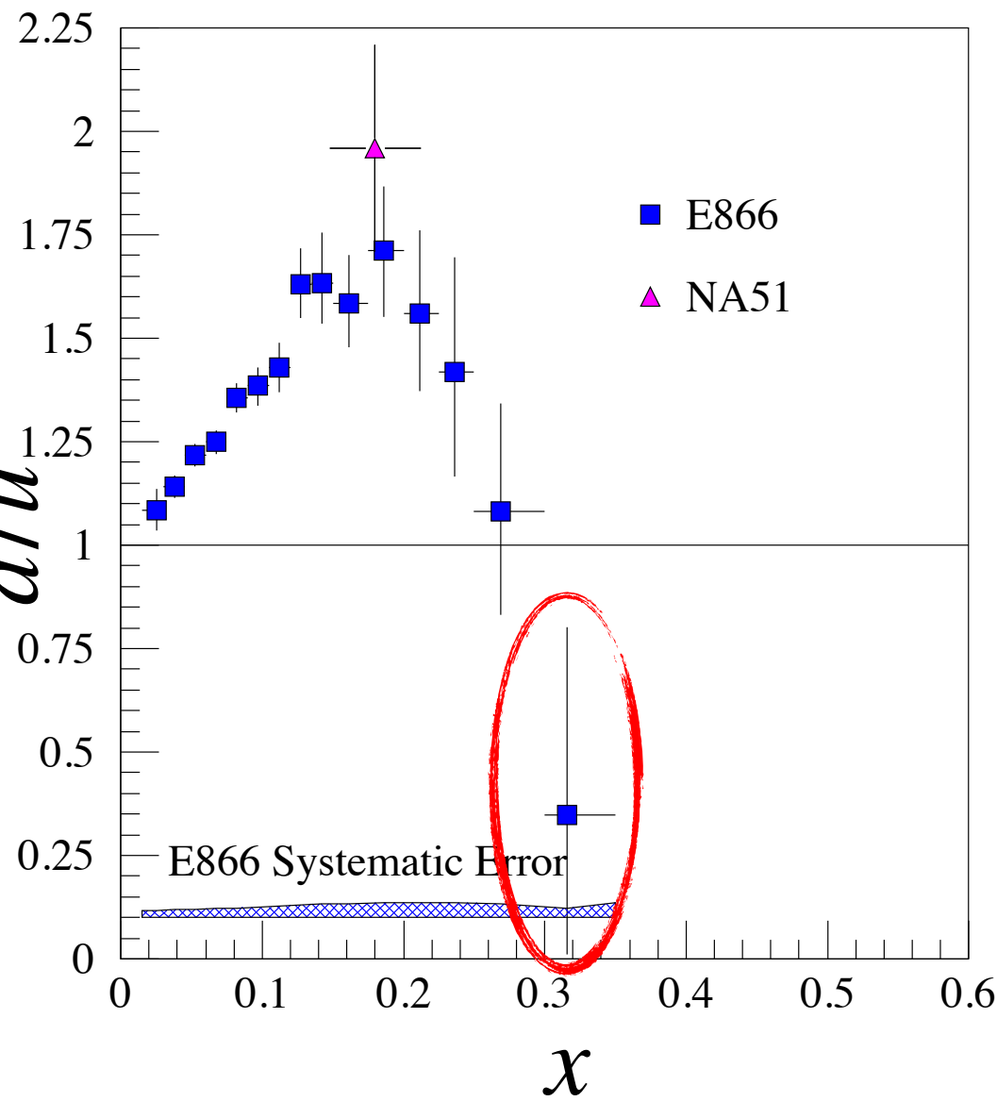


- Statistical Parton Distributions (Nucl. Phys. A 948 (2016) 63)
  - Parton distribution calculated under the assumption of
    - ★ Quarks obey Fermi-Dirac function
    - ★ Gluons obey Bose-Einstein function
  - $\bar{d} > \bar{u}$

x-dependence

- NA51 Experiment (Drell–Yan) @ Fermilab
  x-dependence of $\bar{d}/\bar{u}$ @ $x = 0.17$
  - Significant Flavor Asymmetry
    $\bar{d}/\bar{u} = 1.9$ @ $x = 0.17$

- E866 Experiment (Drell–Yan) @ Fermilab
  x-dependence of $\bar{d}/\bar{u}$ @ $0.015 < x < 0.35$
  - Significant Flavor Asymmetry
    $\bar{d}/\bar{u} \sim 1.7$ @ $x \sim 0.2$
  - $\bar{d}/\bar{u} < 1.0$ @ $x \sim 0.3$??
    with large statistical uncertainty



E906/SeaQuest aims at measuring $\bar{d}/\bar{u}$ in wide x range

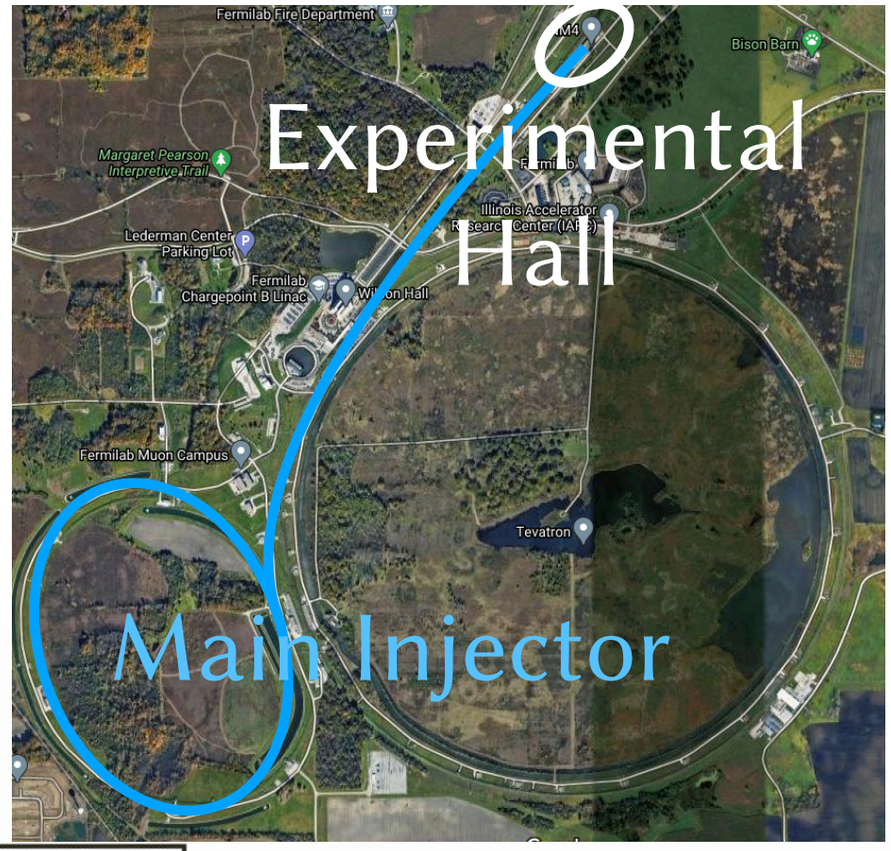
E906/SeaQuest Experiment

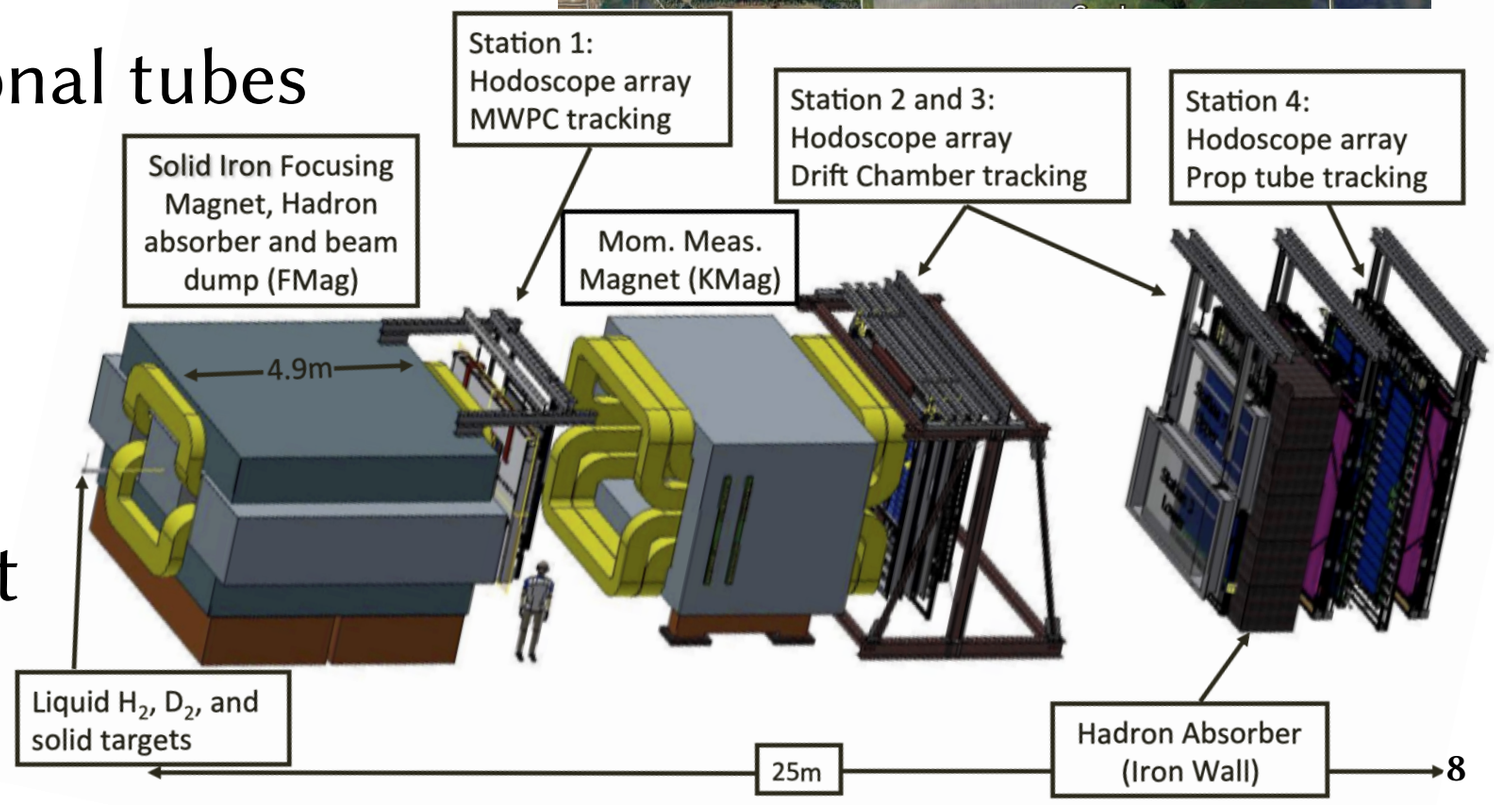
- Performed at Fermilab
  - 120 GeV proton beam by Main Injector

- Fixed target Drell–Yan experiment
  - Muon momentum ~ 40 GeV

- 4 tracking stations
  - Drift chambers/proportional tubes
  - Hodoscopes

- Focusing magnet (beam dump), momentum measurement magnet





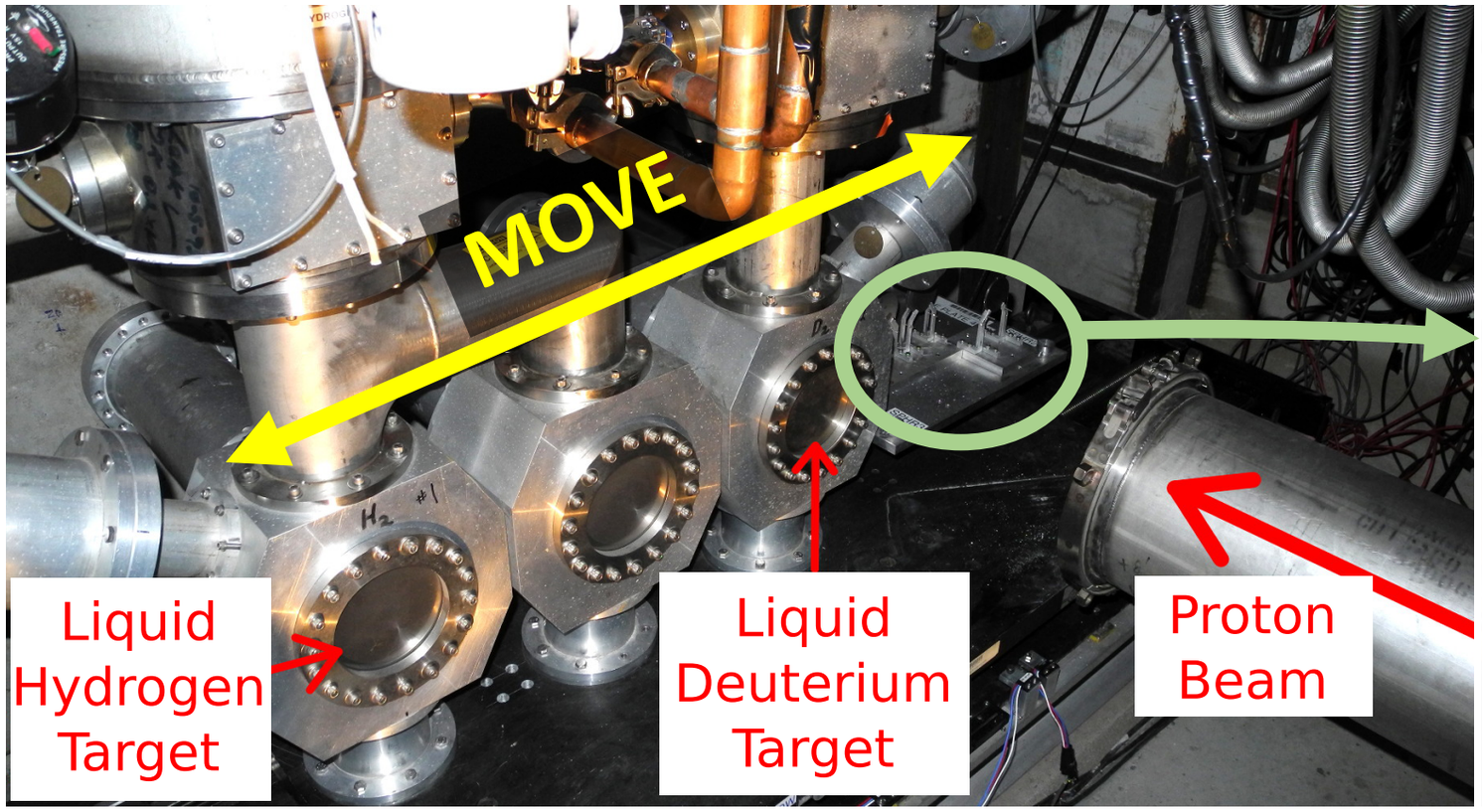
Proton Beam

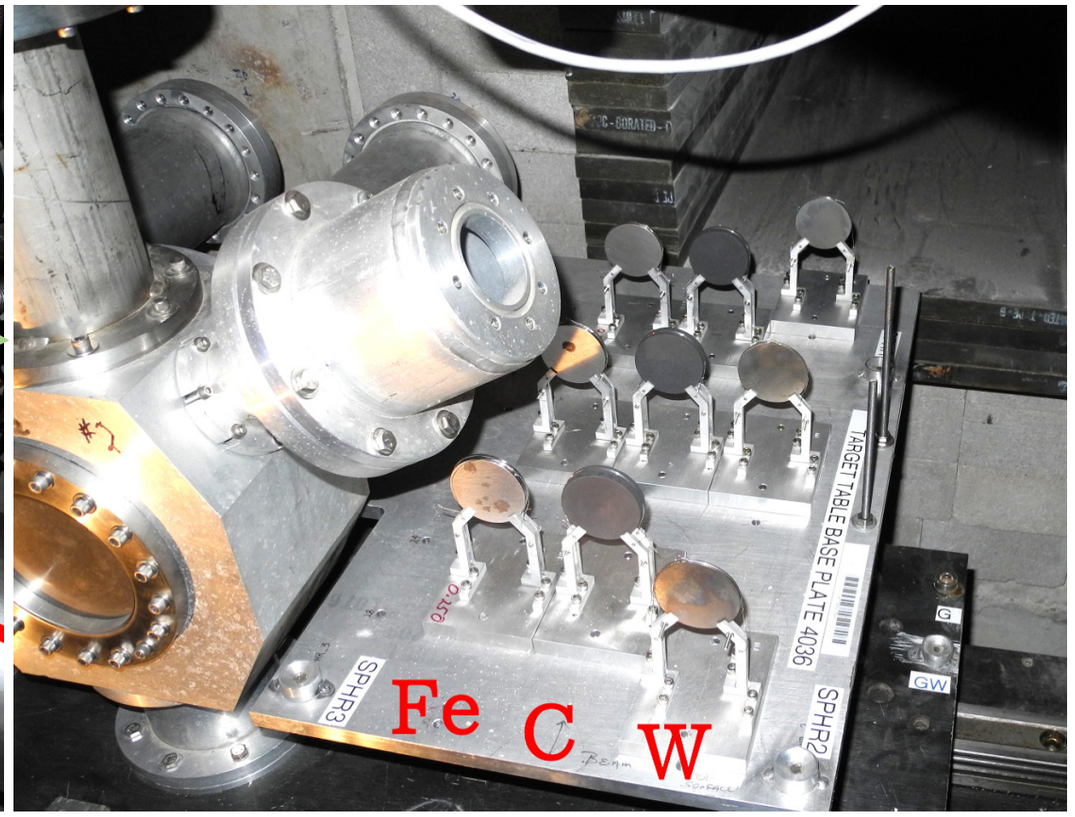
- Beam energy: 120 GeV
  - Center of mass energy: $\sqrt{s} \sim 15$ GeV

- 5 seconds of the beam (spill) is provided every 60 seconds
  - The other 55 seconds of the beam is used for neutrino experiments at Fermilab
  - The targets of SeaQuest are swapped during this 55 seconds

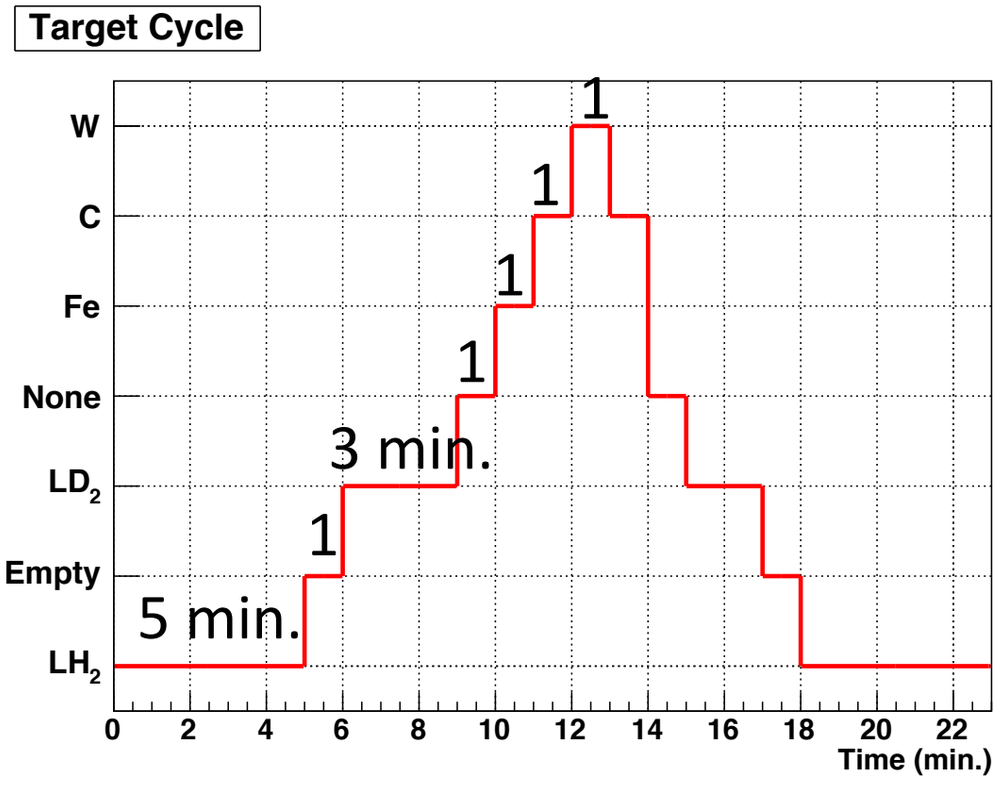
- Beam bunch...RF-bucket
  - Frequency: 53 MHz (comes every 19 ns)
  - Typical number of the proton in one bunch is 40k
    ★ $\sim 2 \times 10^{12}$ protons per second, $\sim 10^{13}$ protons per spill
  - Duty factor (indicates stability of beam intensity)
    $= \langle I \rangle^2 / \langle I^2 \rangle \sim$ 20-40 %

Target



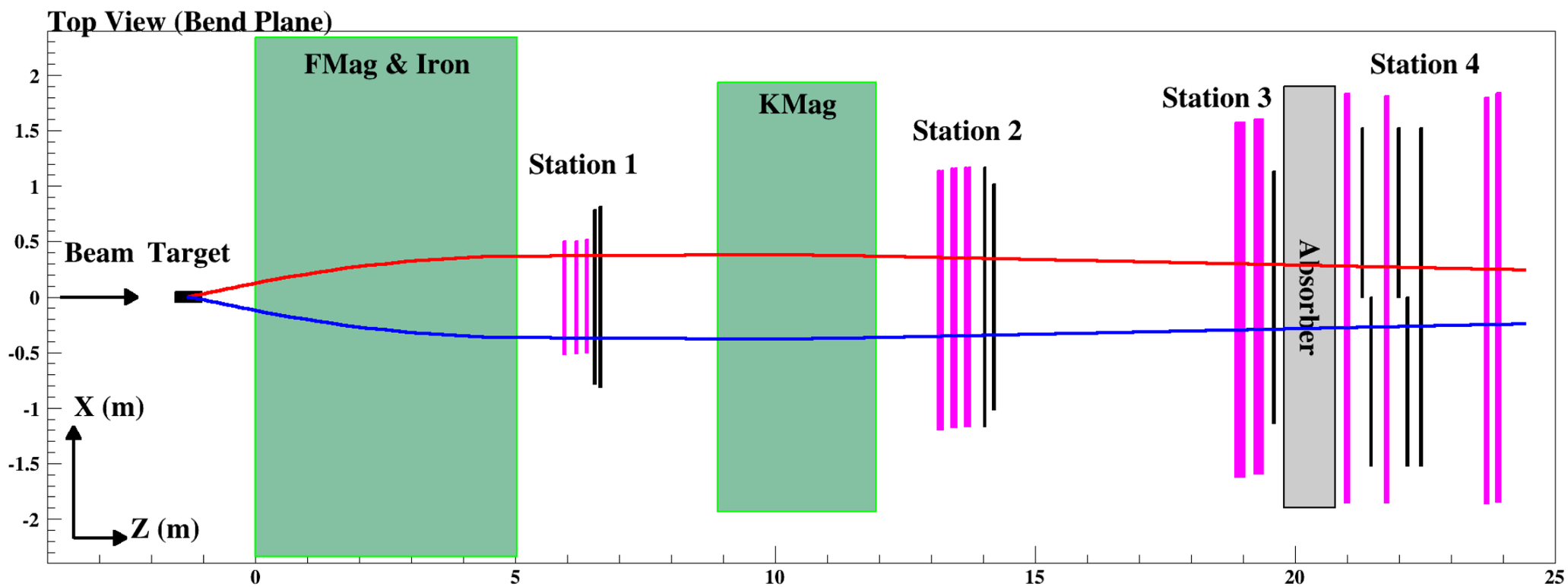


- Liquid targets: LH2, LD2
- Solid targets: Fe, C, W
- Empty, none targets data are also taken
- Move the target table during the beam off

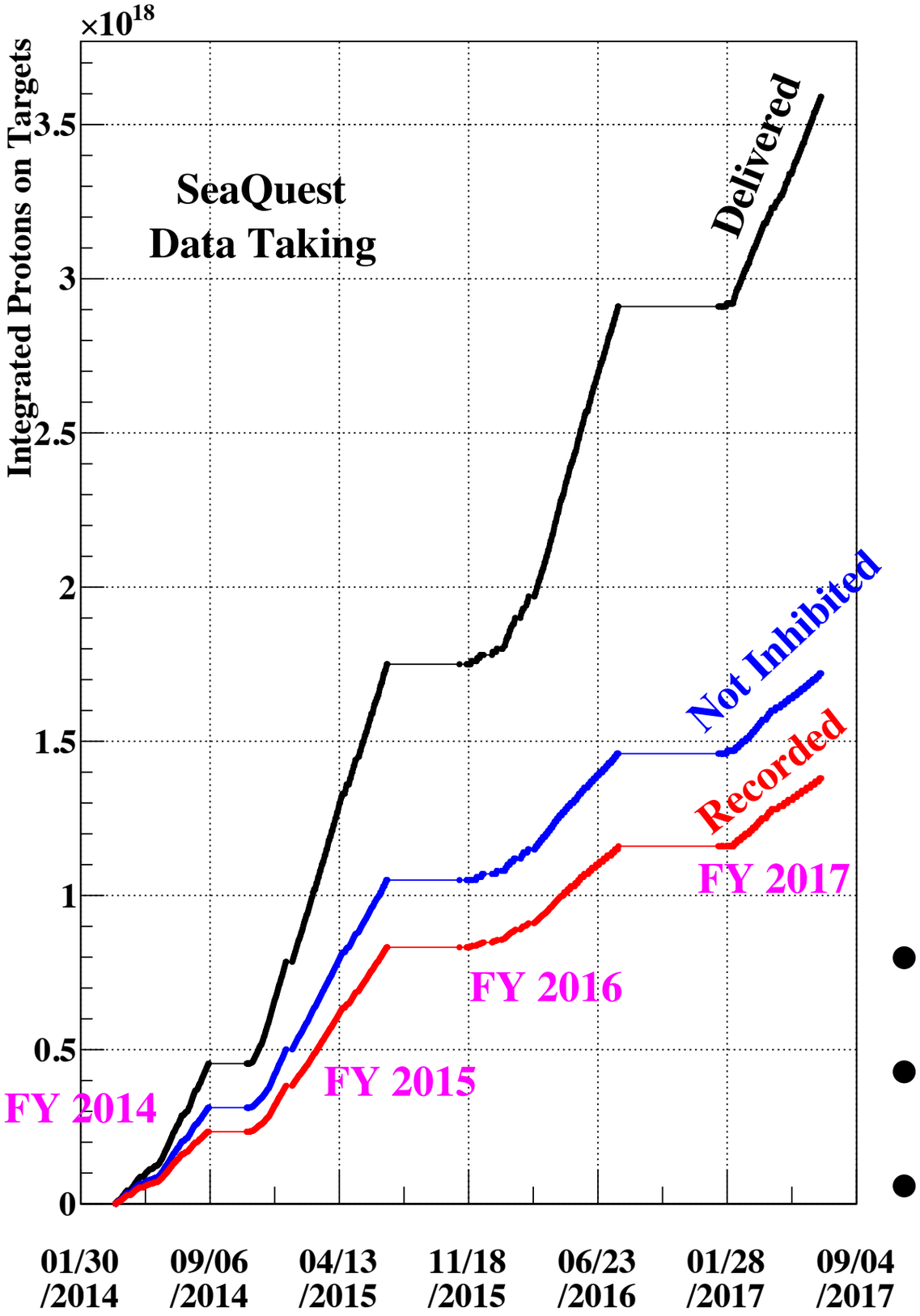


Trigger

- FPGA-based trigger
  - Trigger road
    - ★ Road which muons from Drell–Yan pass through determined by simulation
    - ★ Formed with combination of (H1, H2, H3, H4) hodoscopes
  - Trigger fires when proper combination of μ^+ and μ^- trigger roads fire (Dimuon trigger)
  - Trigger focuses on the high-mass dimuons



Timeline

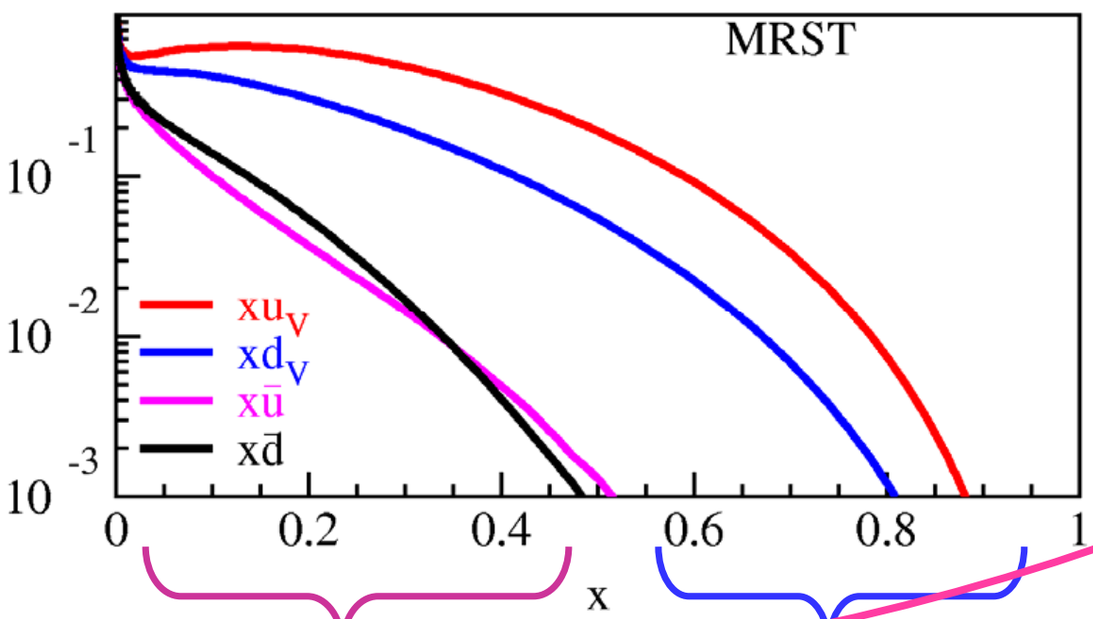


Year	Month	Description
2011	08	Finish spectrometer construction
2012	03-04	Commissioning data taking (Run I)
	-05	Detector upgrade
2013	-11	Physics data taking (Run II)
2014	-09	
	11-	Physics data taking (Run III)
2015	-07	
	10-	Physics data taking (Run IV)
2016	-08	
	11-	Physics data taking (Run V)
2017	-07	
2021	02	Publish paper in Nature

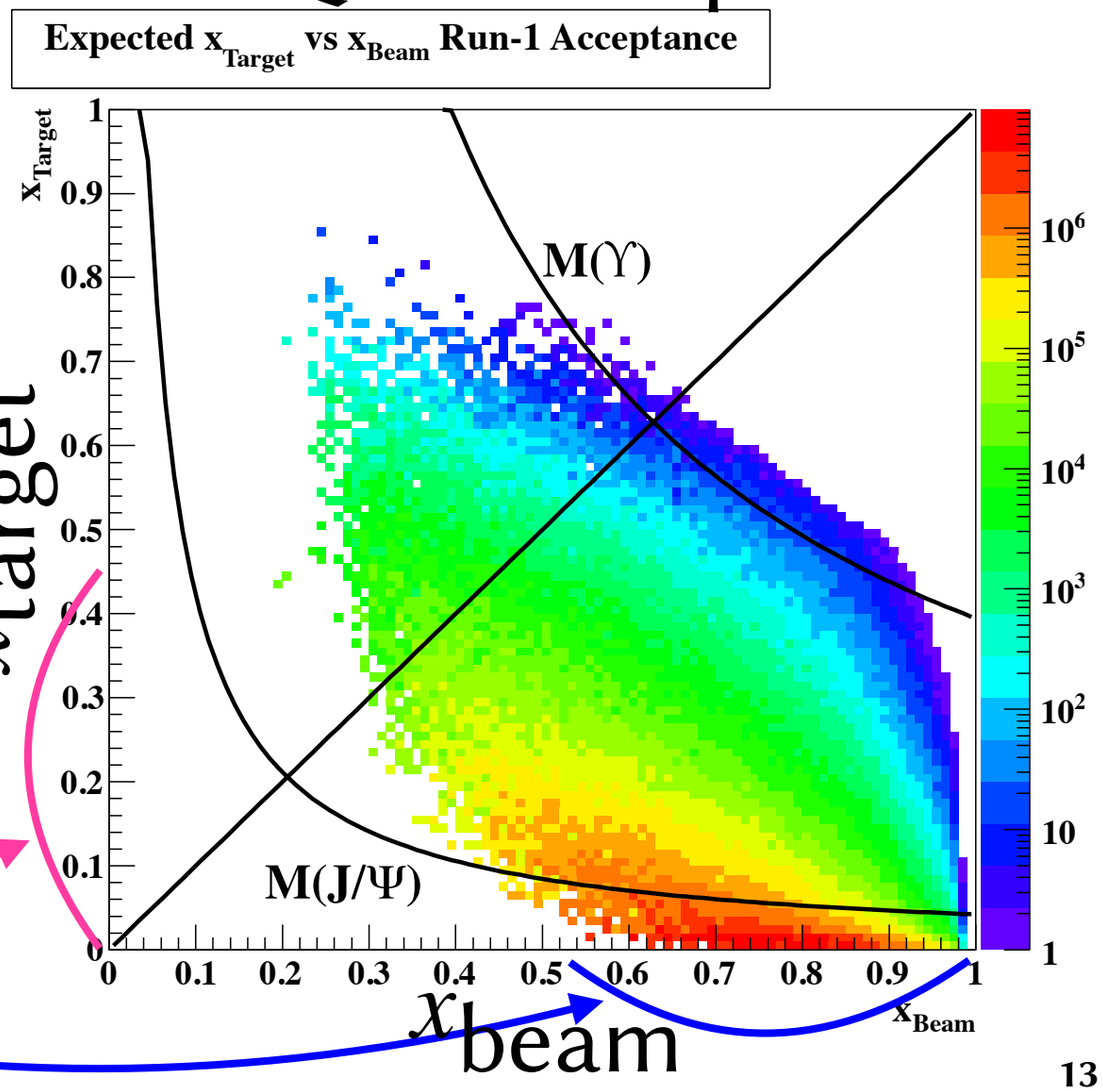
- Finished data taking (2017.07)
- Recorded protons on targets: 1.4×10^{18}
- Analysis has been completed with Run II & Run III data

p-p Drell–Yan Process

- $$\frac{d^2\sigma}{dx_t dx_b} = \frac{4\pi\alpha^2}{9x_t x_b}\frac{1}{s}\sum e^2[\bar{q}_t(x_t)q_b(x_b) + \bar{q}_b(x_b)q_t(x_t)]$$
  - $x_t \ll x_b$: Forward detection
  - $\bar{q}$ at large x is small
    - ★ Second term $\bar{q}_b(x_b)q_t(x_t)$ can be ignored
  - *Access antiquarks in target proton*
  - Cross section ratio ∝ 1/s
    - ★ 800 GeV (E866) ⟶ 120 GeV (E906)



SeaQuest acceptance



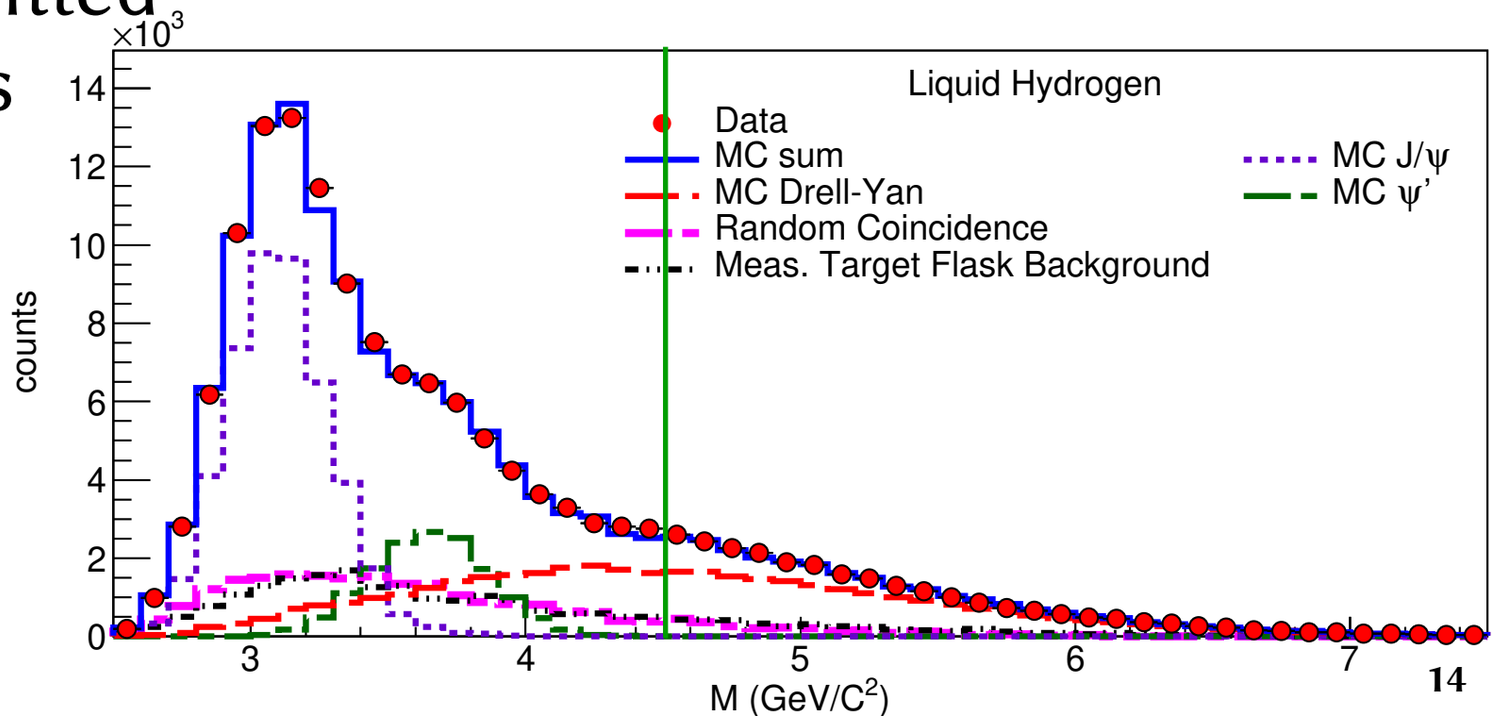
Measurement

- Cross section ratio of p–d to p–p Drell–Yan process

$$\frac{1}{2}\frac{\sigma^{pd}}{\sigma^{pp}} \approx \frac{1}{2}\left[1+\frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]\Bigg|_{x_b \gg x_t}$$

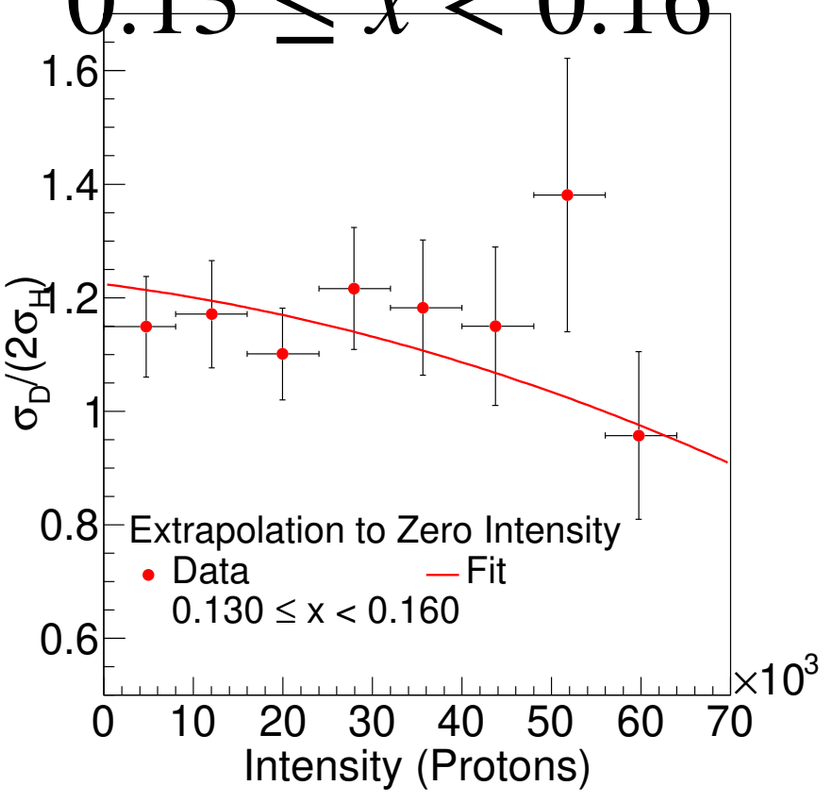
  - Measure p-d and p-p Drell–Yan dimuons
  - Extract cross section ratio
  - Convert cross section ratio to antiquark flavor asymmetry $\bar{d}/\bar{u}$

- Dimuon mass distribution fitted with estimated components
  - Well fitted:
    Detectors & reconstruction work as expected
  - Drell–Yan dimuons:
    Mass > 4.5 GeV/c^2

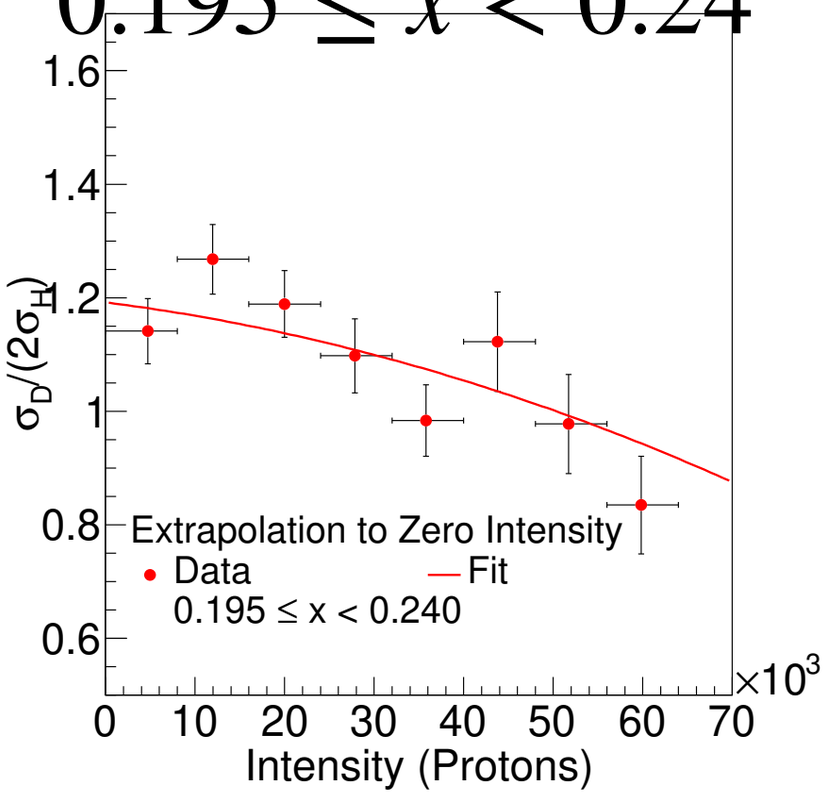


Beam Intensity Dependence

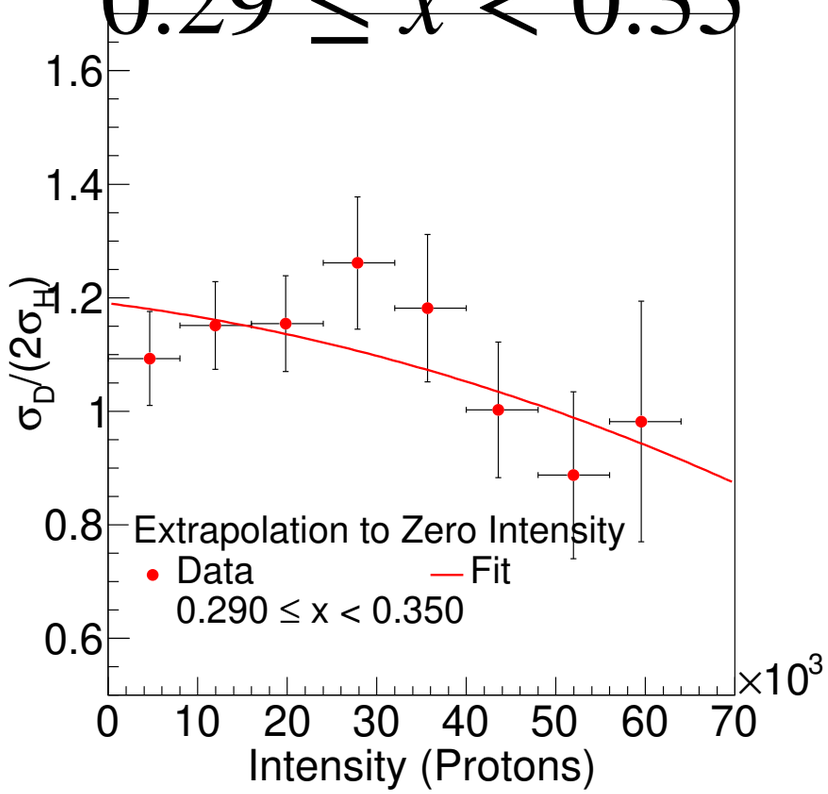
$0.13 \leq x < 0.16$



$0.195 \leq x < 0.24$



$0.29 \leq x < 0.35$

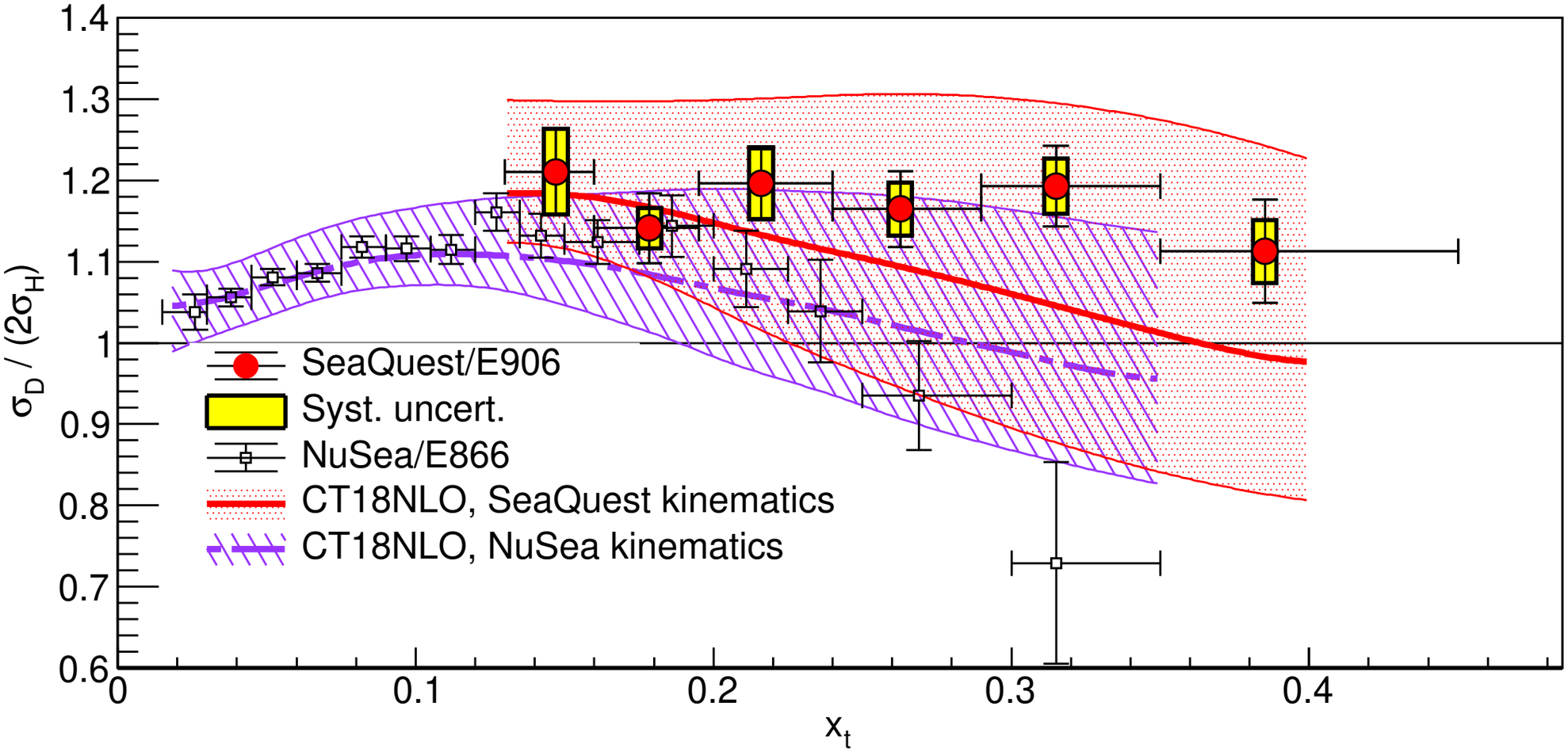


- Cross section ratio ($\sigma^{pd}/2\sigma^{pp}$) has beam intensity dependence
  - ▸ Higher beam intensity $\longrightarrow$ More hits on detectors
    - ★ Random background
    - ★ Lower reconstruction efficiency

- Instead of figuring out the effect separately, fit [Cross section ratio] vs [Beam Intensity] as a function of beam intensity (extrapolation method)

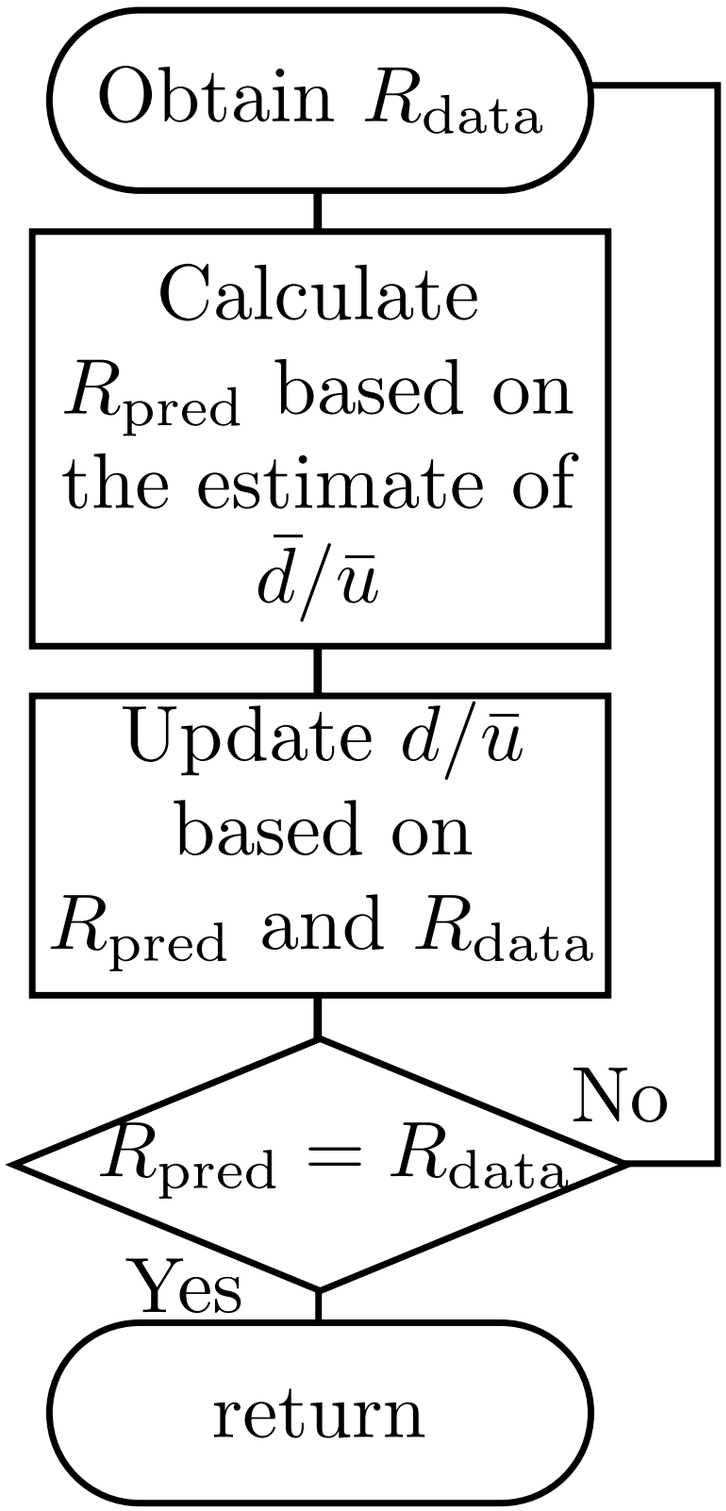
$$f(I) = R_x + aI + bI^2$$

Cross Section Ratio



- Cross section ratio ($0.13 < x_t < 0.45$)
  - Difference between E866 is because of
    - ★ the difference of the kinematics (x_b range)
    - ★ the difference of the scale (E866: 54 $(\mathrm{GeV/c})^2$, E906/SeaQuest: 22-44 $(\mathrm{GeV/c})^2$)
- Agrees well with CT18NLO

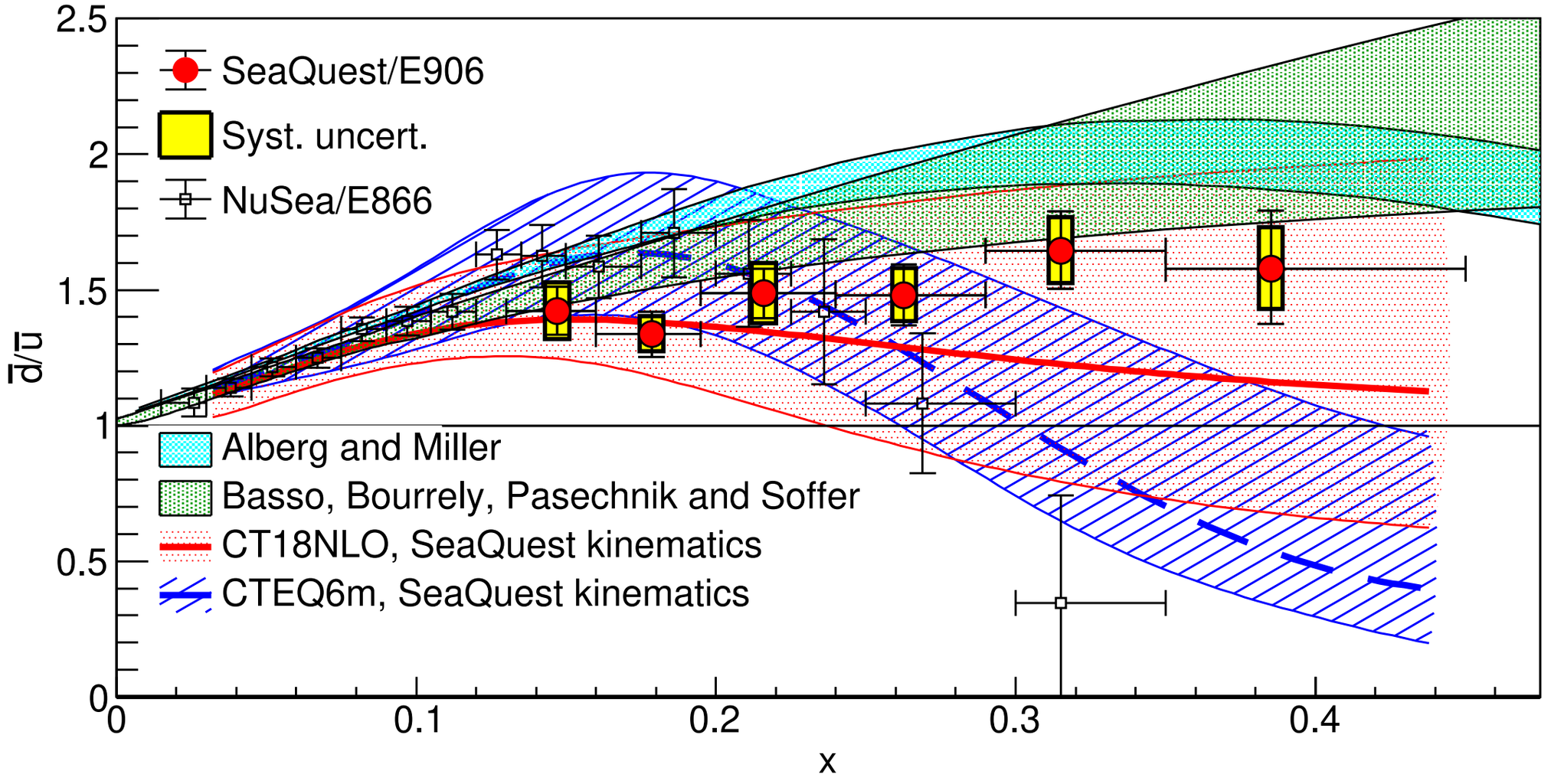
Extract $\bar{d}/\bar{u}$



Iterative analysis was performed to extract $\bar{d}/\bar{u}$

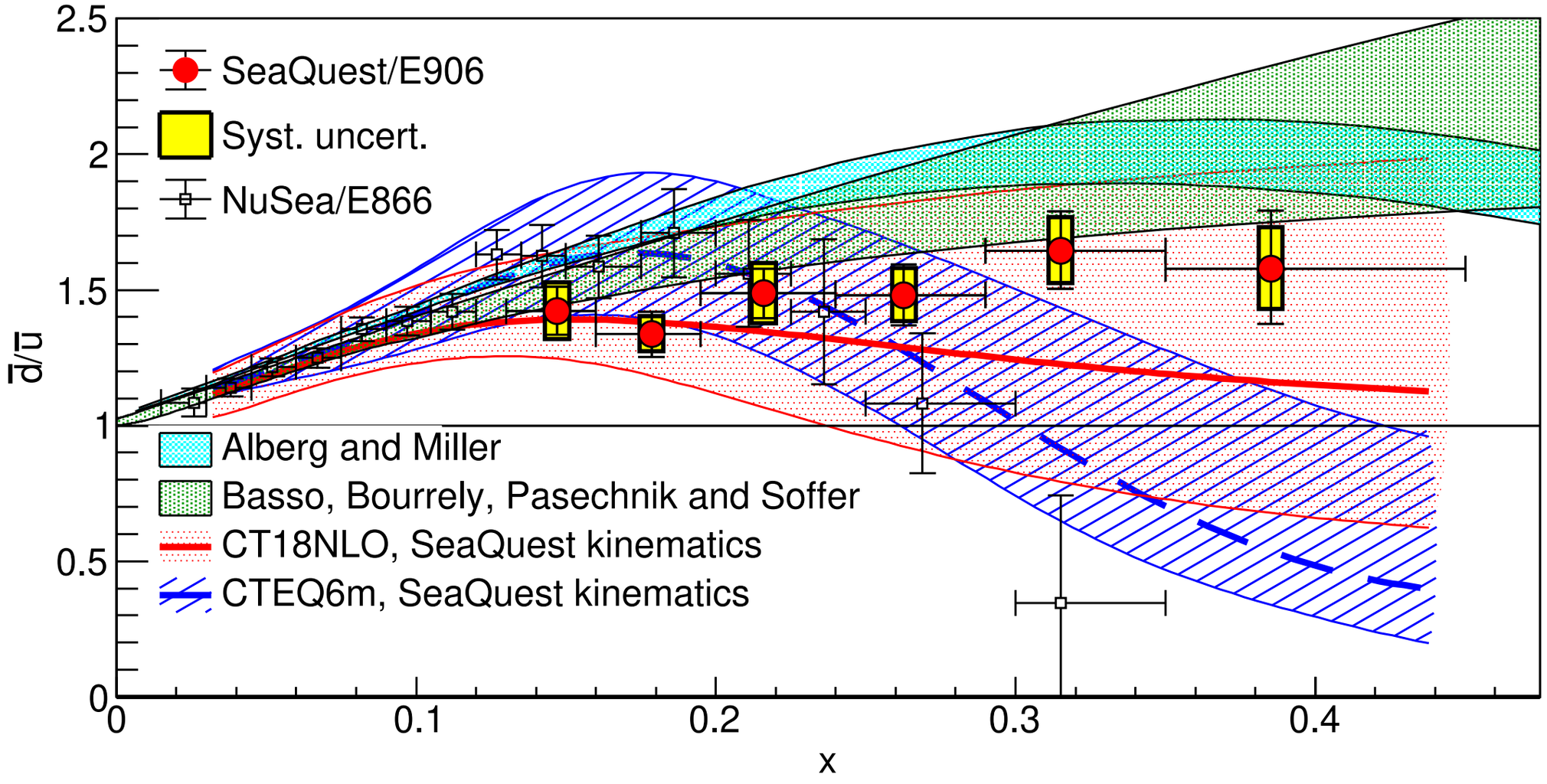
1. Calculate cross section from data (R_{data})
2. Set the estimate of $\bar{d}/\bar{u}$ (= 1.0 at the first iteration)
3. Using cross section formula (NLO), calculate cross section ratio (R_{pred})
   - CT10, CT14, CT18, MMHT2014 PDFs were used
   - All other parton distributions and $\bar{d} + \bar{u}$ were fixed
   - Cross sections were calculated in each (x_t, x_b) bins
4. Update $\bar{d}/\bar{u}$ based on the difference of ratios
5. Repeat until the difference became small enough

$\bar{d}/\bar{u}$ Results



- E906/SeaQuest: First $\bar{d}/\bar{u}$ measurement at high x region
- Trends between two experiments at higher x region are quite different

Origin of $\bar{d}/\bar{u}$ asymmetry?



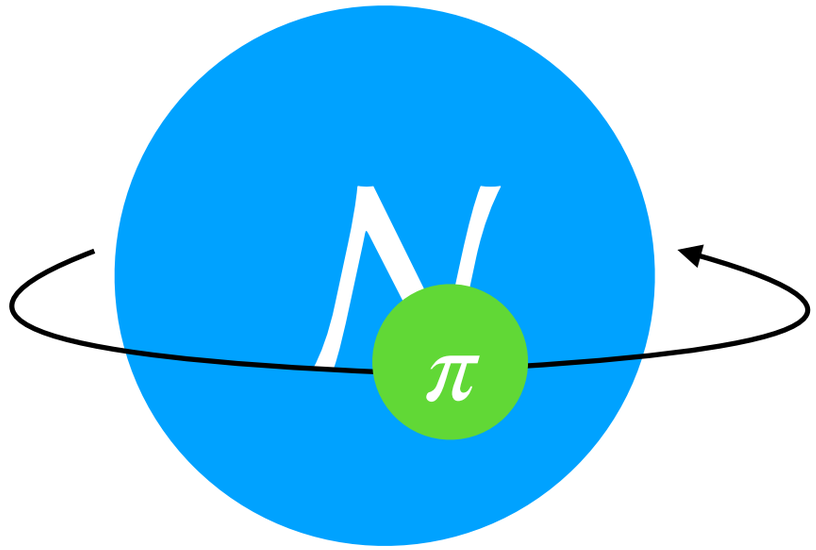
- SeaQuest result agrees well with both meson cloud model (light blue band) and statistical model (green band)
  - Which model is more likely?

- Investigate in another view: spin structure

Orbital Angular Momentum

- π could model
  - Naively imagine that $\pi^+(\bar{d}u)$ floats around neutron
  - Orbital angular momentum of antiquarks should be large

- Statistical model
  - Orbital angular momentum of antiquarks is not large



Distinguishable by measuring the contribution of orbital angular momentum of antiquarks on the proton spin

Proton Spin Puzzle

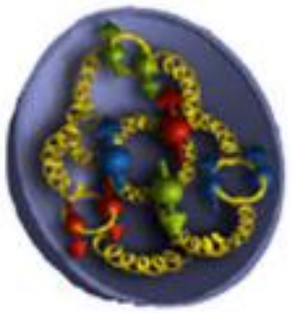
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma\,?$$

-1980s

RHIC

gluon spin 30-50%

from $x = 0.05$ to $x = 0.2$



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L_q + L_g$$

spin of quarks and antiquarks

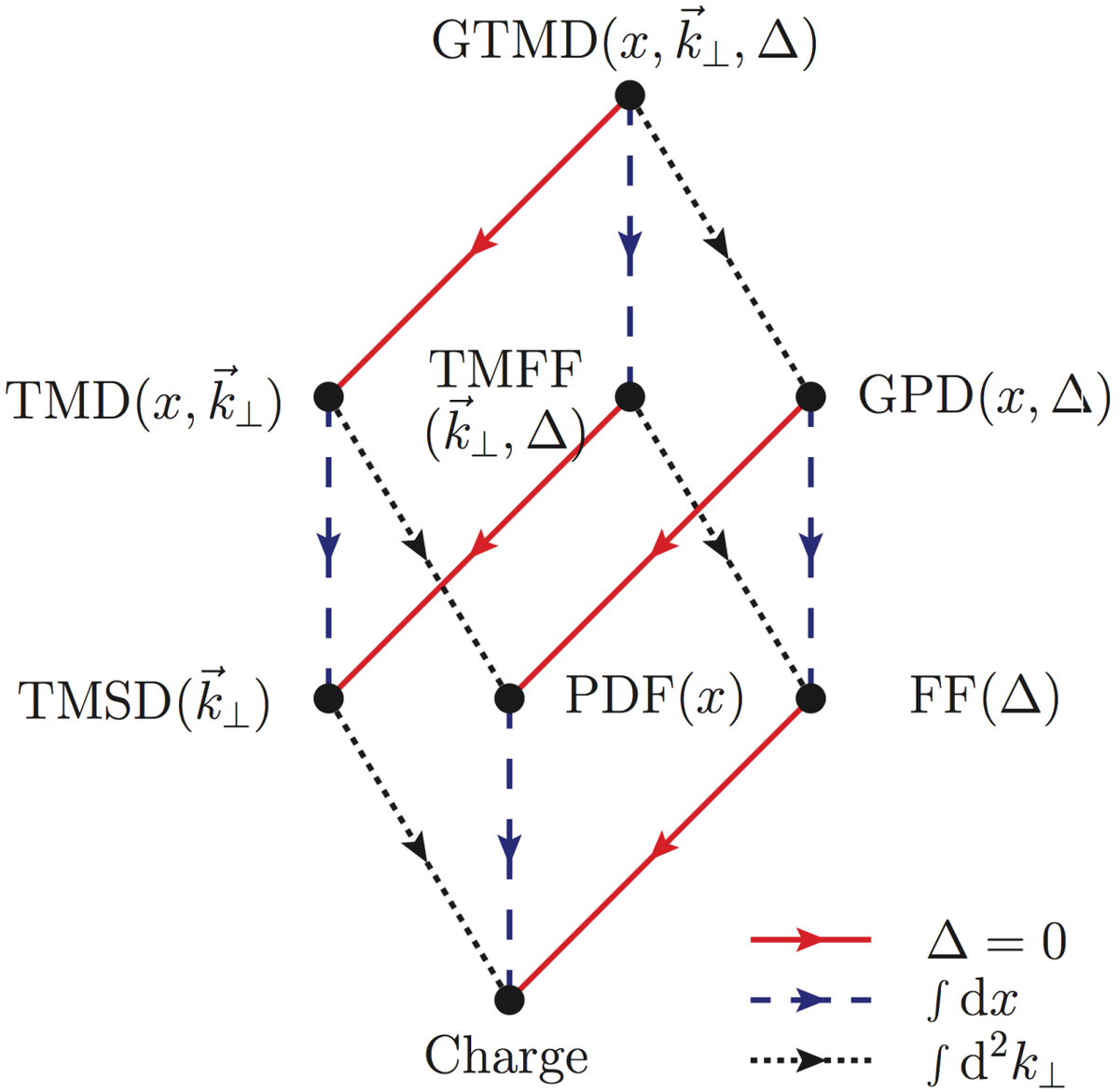
~25%

EMC at CERN (1989)

Orbital Angular Momentum

Access Spin Structure

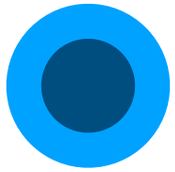
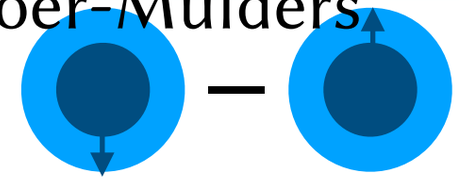
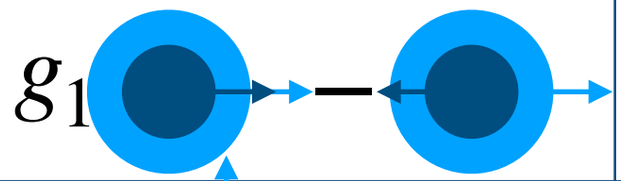
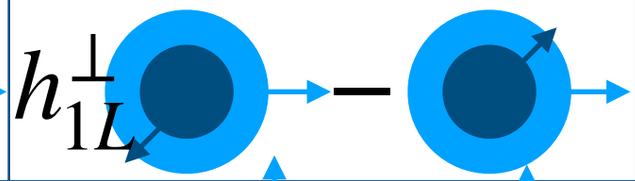
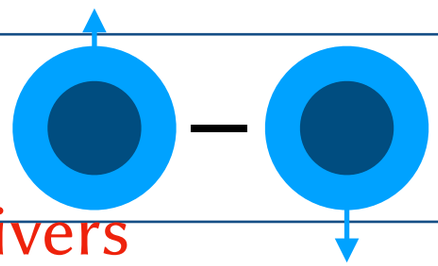
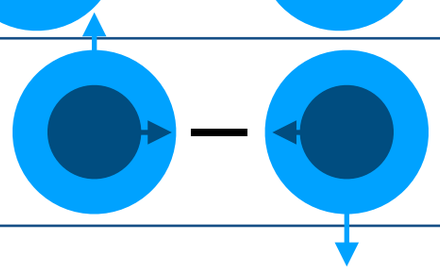
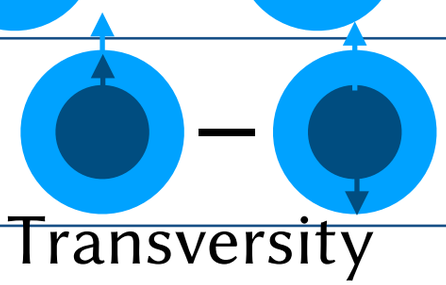
Multi-dimensional Distribution Functions



- GPDs: Generalized Parton Distributions
  - Functions of x and Δ (momentum transfer)
    $\downarrow$ (Fourier transform) $\downarrow$
    x and r (transverse position)

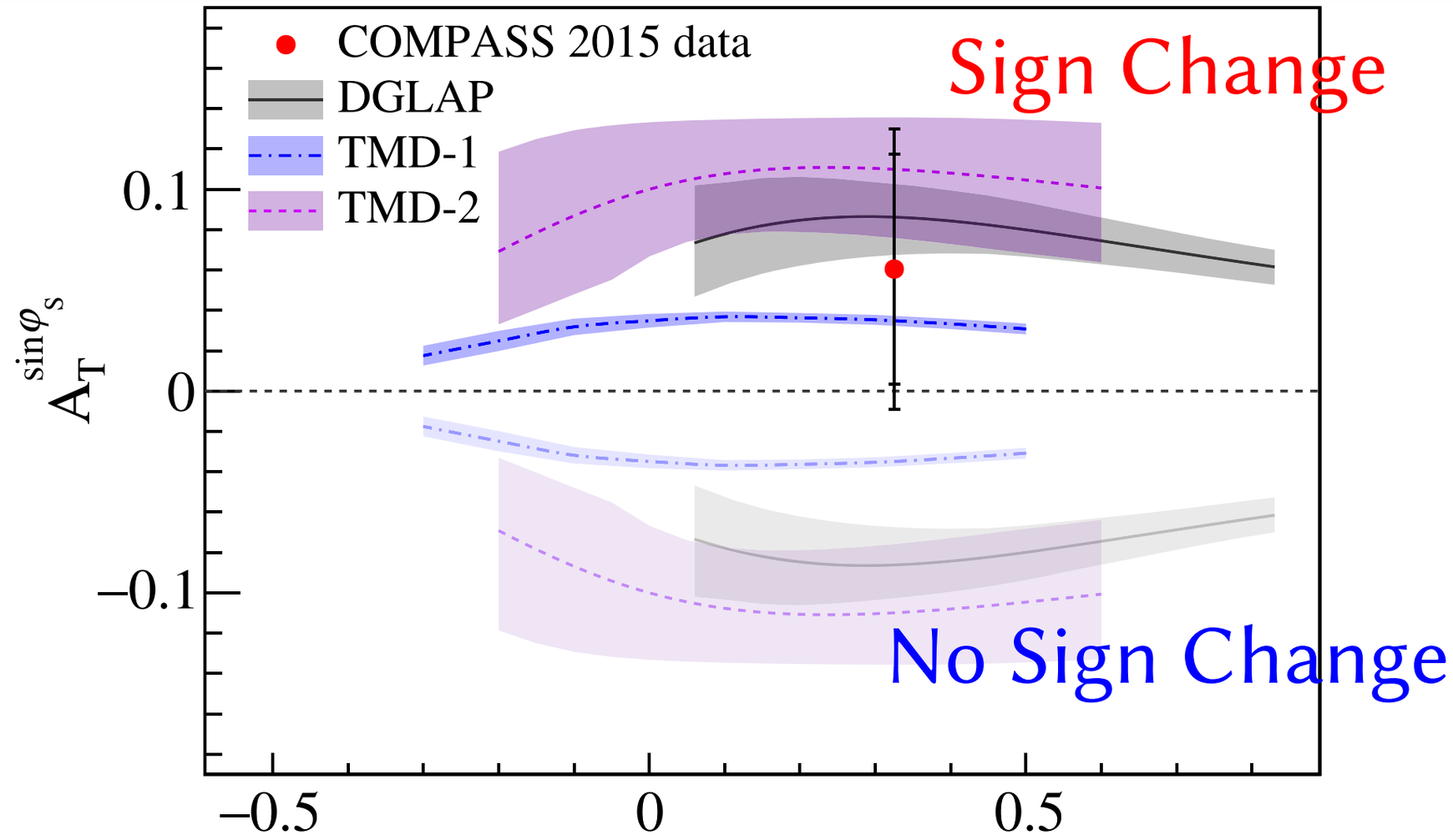
- TMDs: Transverse-Momentum dependent Distributions
  - Functions of x (longitudinal momentum) and $\vec{k}$ (transverse momentum)

TMDs

		Quarks		
		Unpolarized	Longitudinally Polarized	Transversally Polarized
Nucleon	U	f_1 		$h_1^\perp$  Boer-Mulders
	L		g_1 	$h_{1L}^\perp$ 
	T	$f_{1T}^\perp$  Sivers	$g_{1T}^\perp$ 	h_{1L}  Transversity

- Sivers function
  - Unpolarized Quarks : Transversally Polarized Nucleon
  - Correlation between the transverse momentum of a quark and the spin of the parent hadron
  - If the quarks don't have orbital motion, Sivers function vanishes

Sivers Asymmetry of Quarks



- SIDIS experiments have already measured nonzero Sivers asymmetry of quarks.
- COMPASS has measured the Sivers asymmetry in Drell–Yan and indicated the sign of the asymmetry is opposite of that of SIDIS
- Sivers function of antiquarks have not been measured yet

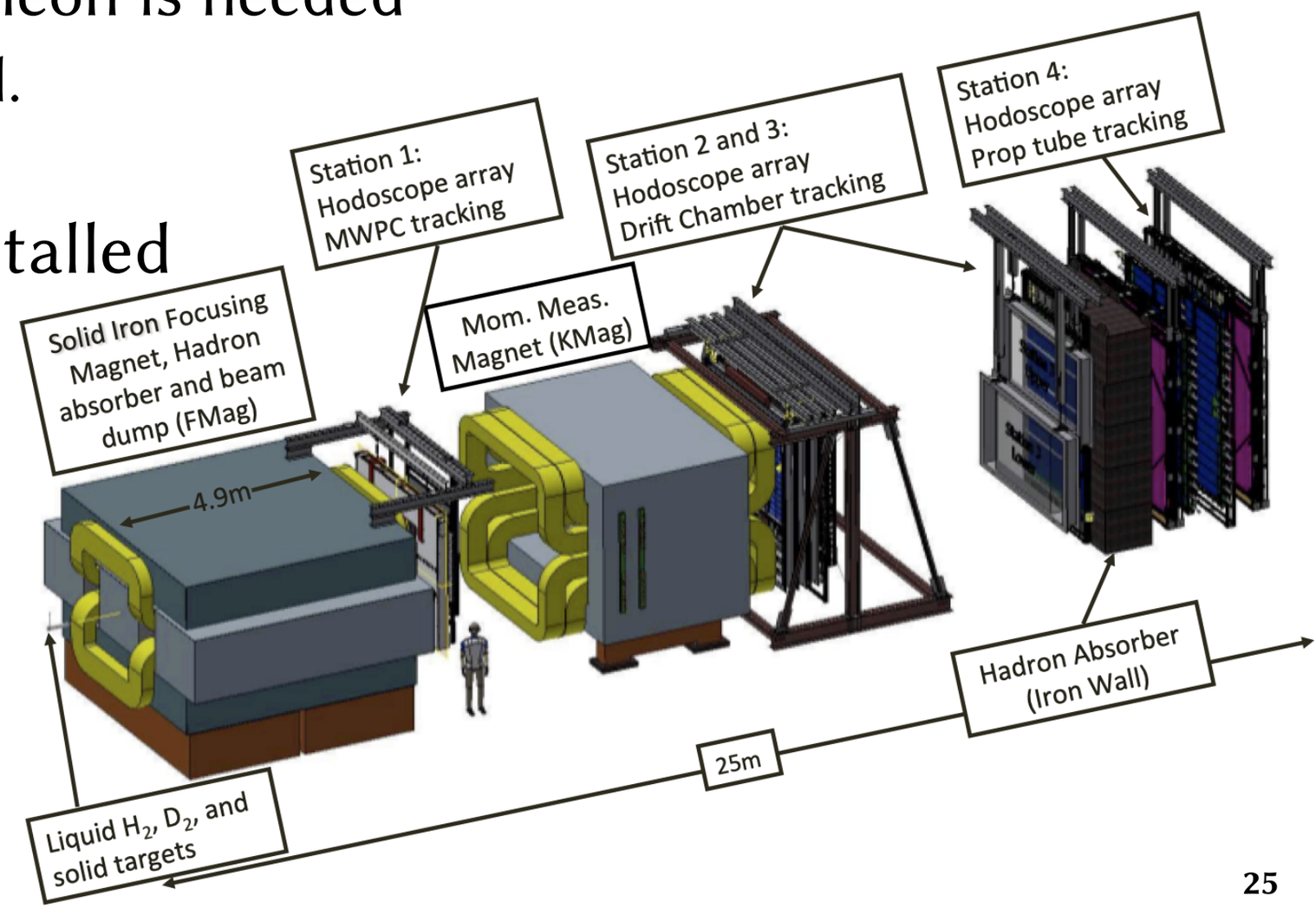
E1039/SpinQuest

- Basically the same spectrometer as SeaQuest

- SpinQuest will measure **antiquarks Sivers functions** via polarized Drell–Yan
  - First measurement of antiquarks Sivers functions
  - Transversally polarized nucleon is needed
    - ★ SeaQuest targets are unpol.

- Polarized targets will be installed
  - NH3, ND3
  - 1.5 m upstream than SeaQuest to have better target/dump separation

- (Dark photon hodoscopes are installed)



Timeline

- (2017.07: SeaQuest experiment data taking was completed)
- Detector maintenance and polarized target preparation/ installation are now in progress
- Commissioning
  - Planned in May 2021
  - Fermilab announced that the beam time will be shorten for this year (-the end of May?)
    - ★ Commissioning targets and detectors or only targets
  - Data taking will be from next year
    - ★ Two years data taking is planned

Sivers Asymmetry

- $A_N^{\text{Sivers}} \propto \dfrac{f_1^q(x_1) \cdot f_{1T}^{\perp,\bar{q}}(x_2) + f_{1T}^{\perp,q}(x_2) \cdot f_1^{\bar{q}}(x_1)}{f_1^q(x_1) \cdot f_1^{\bar{q}}(x_2) + f_1^q(x_2) \cdot f_1^{\bar{q}}(x_1)}$
  - Magenta: Negligible because of acceptance
  - Red: Sivers function of antiquark in target
  - Blue: PDF of antiquark in target

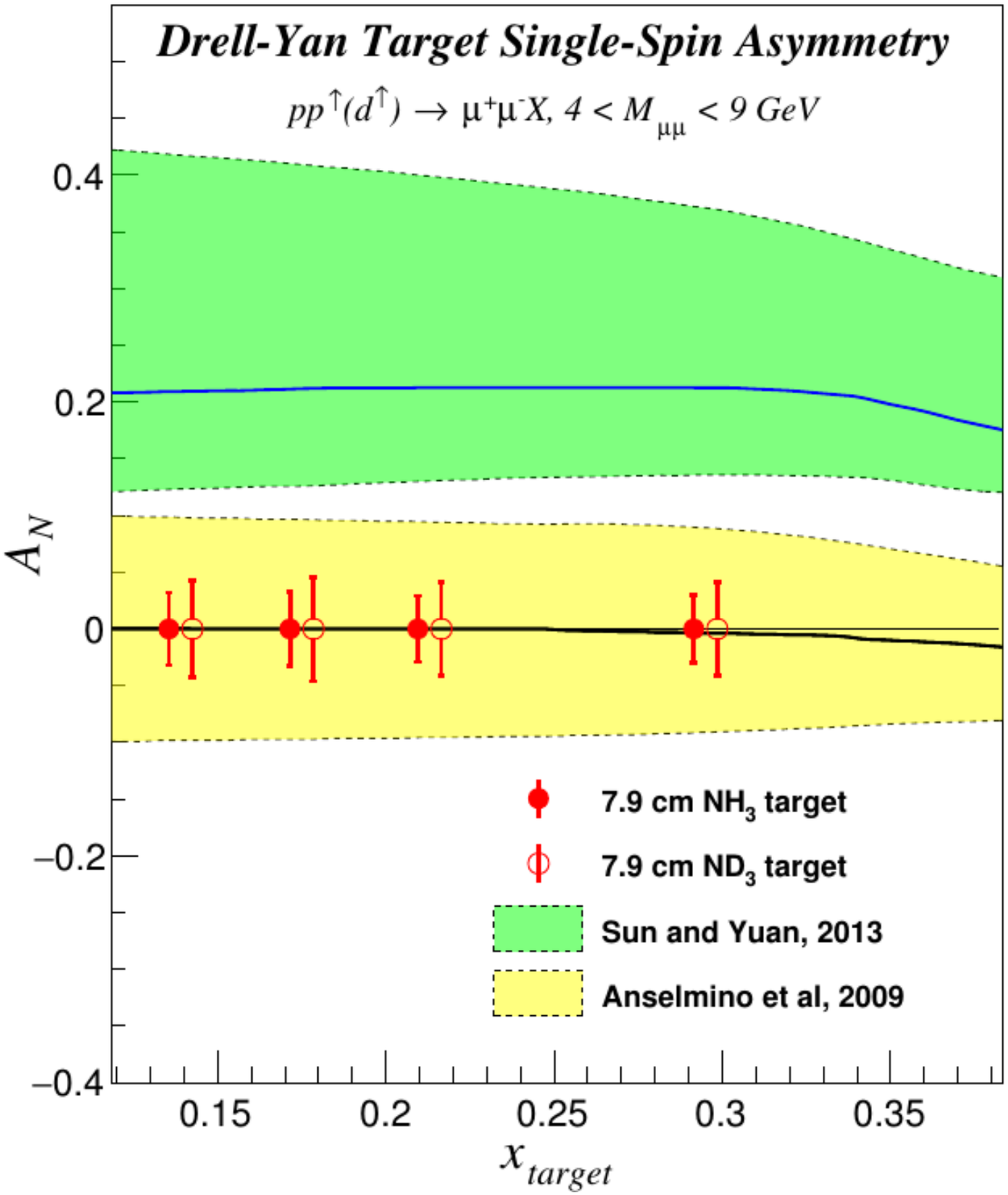
- $f_{1T}^{\perp,\bar{q}} \propto A_N^{\text{Sivers}} \propto \dfrac{N_L - N_R}{N_L + N_R}$
  - Left-right asymmetry of the virtual photon direction
  - We will measure left-right asymmetry to extract the Sivers asymmetry (and Sivers function)

Sensitivity

- Expected sensitivity of SpinQuest on Sivers Asymmetry
  - Two years of combined operation on the NH3 and ND3 targets

- Expected error is small enough
  - We can distinguish the two theoretical models by measurement

- We will give a first measurement of antiquarks Sivers functions



Summary

- SeaQuest
  - Nature paper "The asymmetry of antimatter in the proton" has been published (24th February)
  - Extracted $\bar{d}/\bar{u}$ in $0.13 < x < 0.45$ by proton-proton and proton-deuterium Drell–Yan processes
  - $\bar{d}/\bar{u} > 1.0$ for all the measured range
    - ★ Support both meson cloud model and statistical model

- SpinQuest
  - First measurement of antiquark Sivers function
  - Installing polarized targets and detectors maintenance are in progress
  - Commissioning is planned this year, data taking is planned from next year
    - ★ Two years physics run is planned
  - Expected sensitivity is good enough to distinguish two existing models