Probing nucleon's structure using Drell-Yan process with unpolarized/polarized targets at Fermilab

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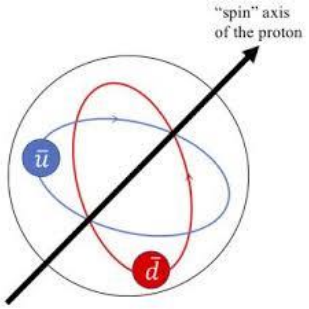
For the E906/E1039 collaboration at Fermilab

SeaQuest E906

CPHI 2020, CERN

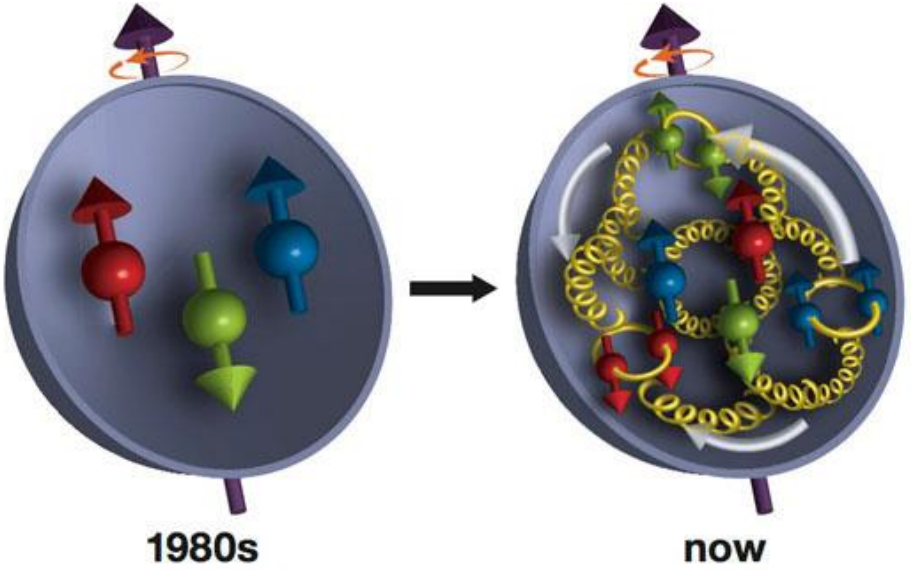


Outline

- Introduction
- Physics goals
  - The SeaQuest experiment
    - $\bar{d}/\bar{u}$ asymmetry
  - The SpinQuest experiment
    - Probing sea-quarks
      - Sivers function, transversity
    - Tensor Charge
    - Tensor polarization

Introduction

- Proton has been discovered a century ago and yet its structure is not fully understood.



  - $\bar{d}/\bar{u}$ asymmetry -> SeaQuest/E906
  - The sea-quark Orbital Angular Momentum, O.A.M. could lead to none zero single-spin asymmetry -> SpinQuest/E1039

The $\bar{d}/\bar{u}$ asymmetry

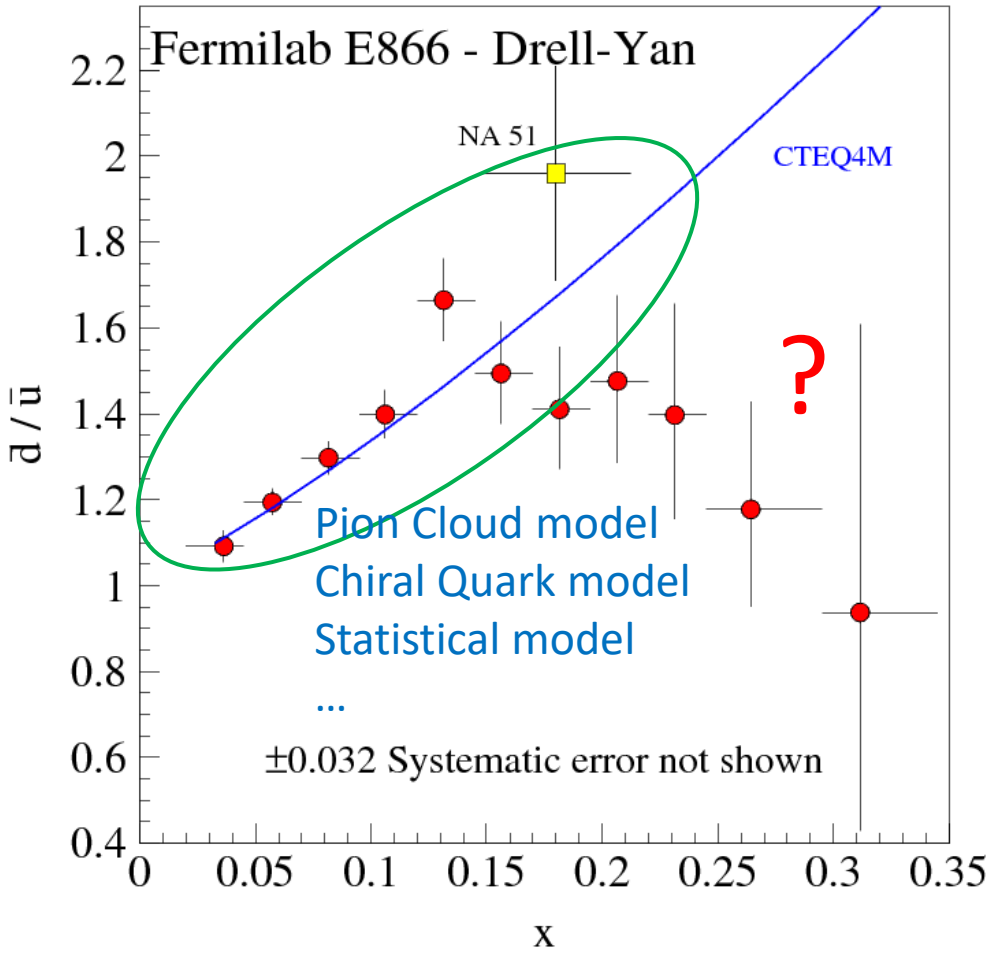
- The Gottfried sum

$$S_G = \frac{1}{3} - \frac{2}{3}\int_0^1 [\bar{d}^p(x) - \bar{u}^p]dx$$

- NMC observes

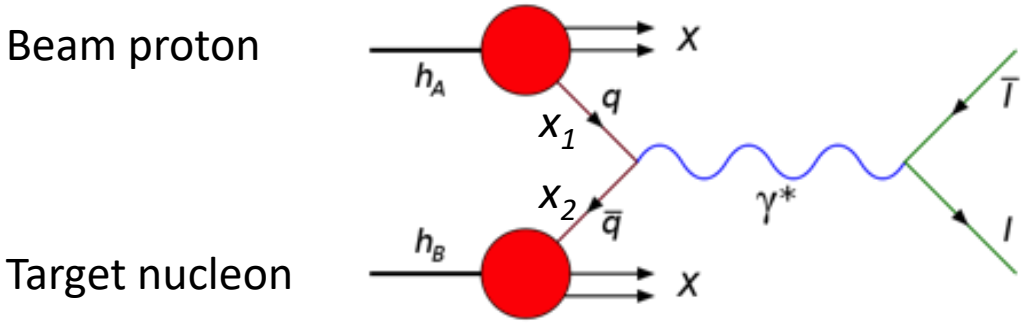
$$\int_0^1 [\bar{d}^p(x) - \bar{u}^p(x)]dx = 0.148 \pm 0.039$$

- E866 shows that the asymmetry has strong dependence on Bjorken x !
- Although with large uncertainty, the dropping in high x is hard to explain.



The SeaQuest experiment

- The Drell-Yan process:

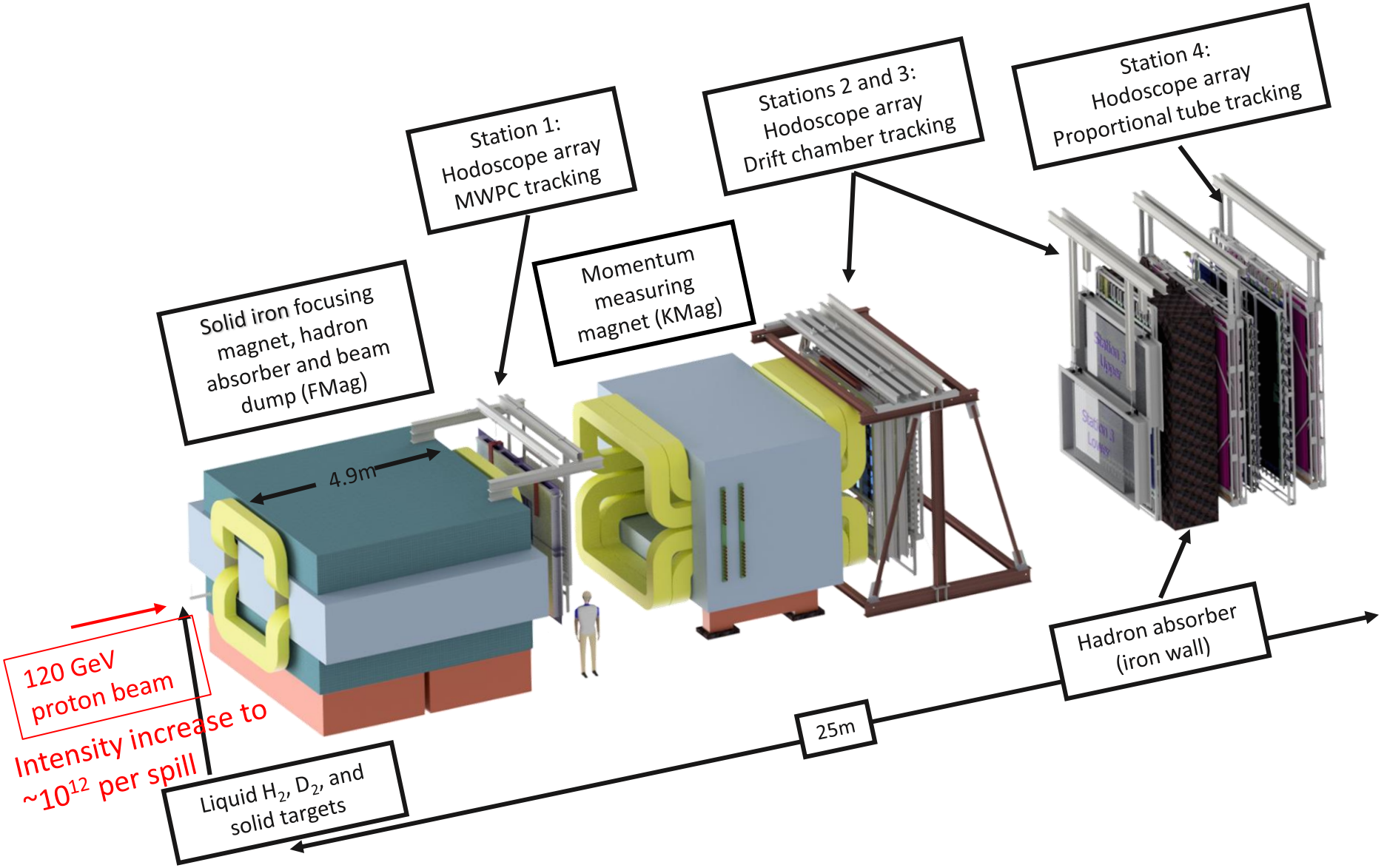


- Due to the acceptance the experiment probes mainly anti-quarks in the target nucleon.

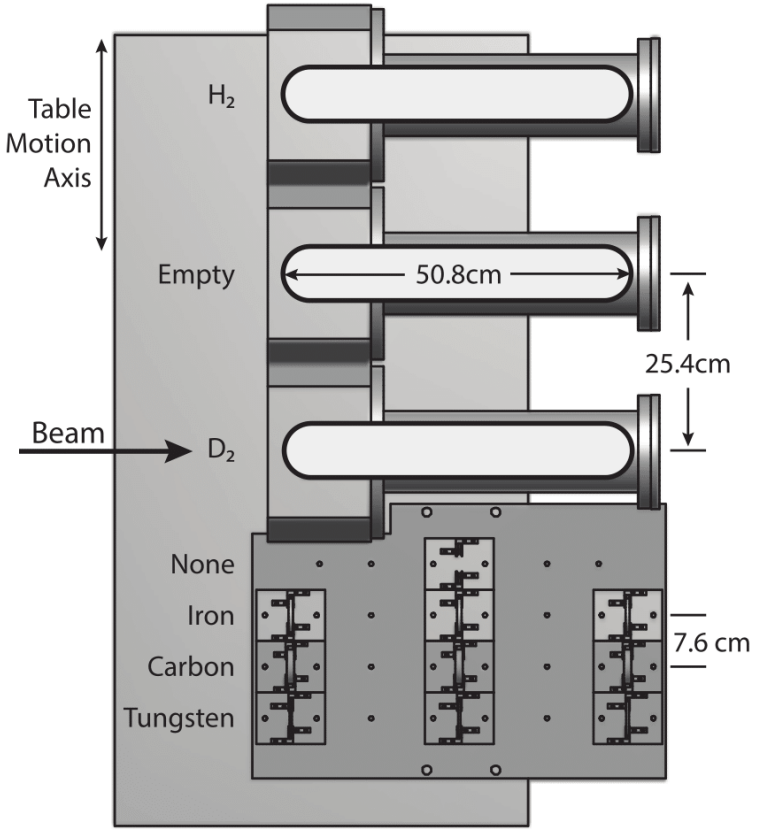
$$\frac{d^2\sigma}{dx_1 dx_2}]_{DY} = \frac{4\pi\alpha^2}{9sx_1x_2}\sum_q e_q^2[f^q(x_1)\cdot f^{\bar{q}}(x_2) + f^{\bar{q}}(x_1)\cdot f^q(x_2)]$$

- To increase statistics, the beam energy is reduced to 120 GeV.
- From cross-section ratio to $\bar{d}/\bar{u}$: $\frac{\sigma^{pd}(x)}{2\sigma^{pp}(x)} \simeq \frac{1}{2}(1+\frac{\bar{d}(x)}{\bar{u}(x)})$

The SeaQuest spectrometer



The targets

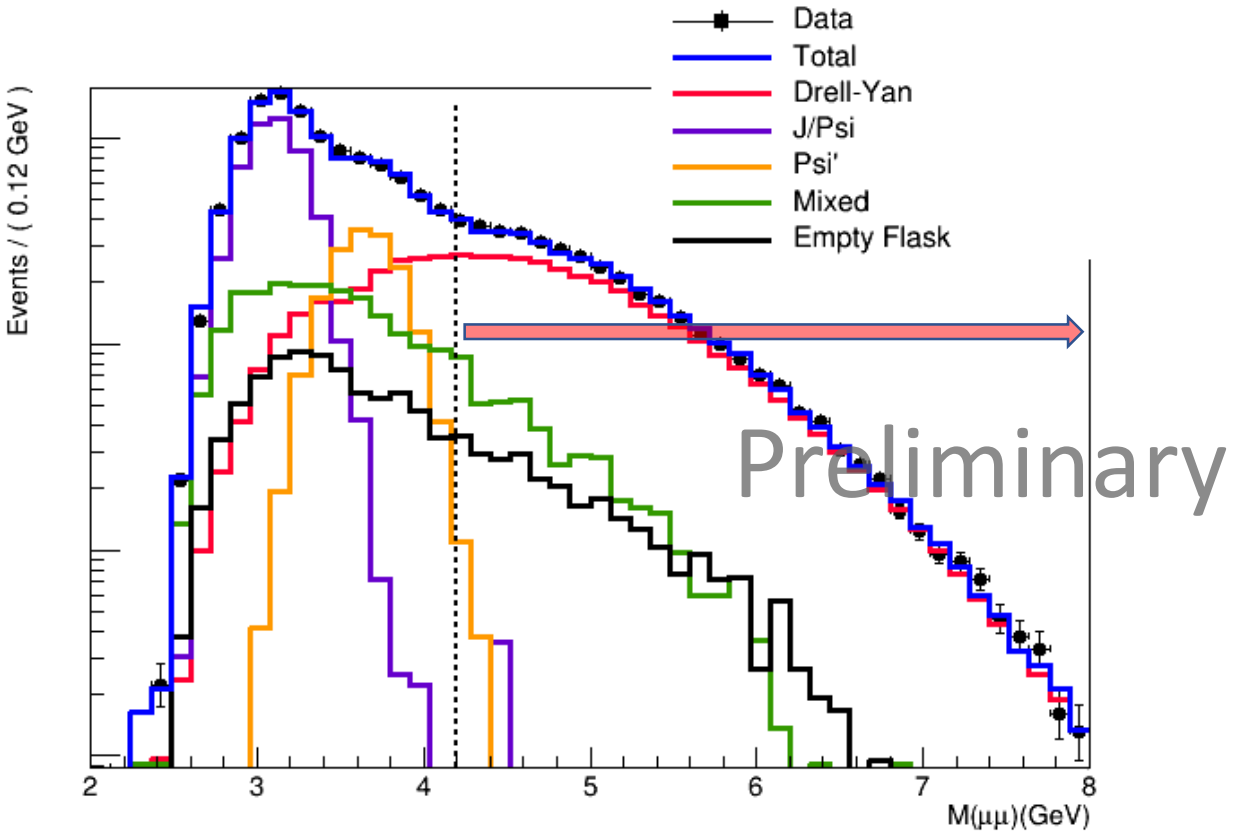


- Changing target, spill by spill.
- Twice as many spills are given to LH2 than LD2.
- Empty flask provides important background events.

The SeaQuest data

- The SeaQuest experiment completed taking data in 2017.
- Preliminary result based on 50% of data.

Dimuon mass distribution

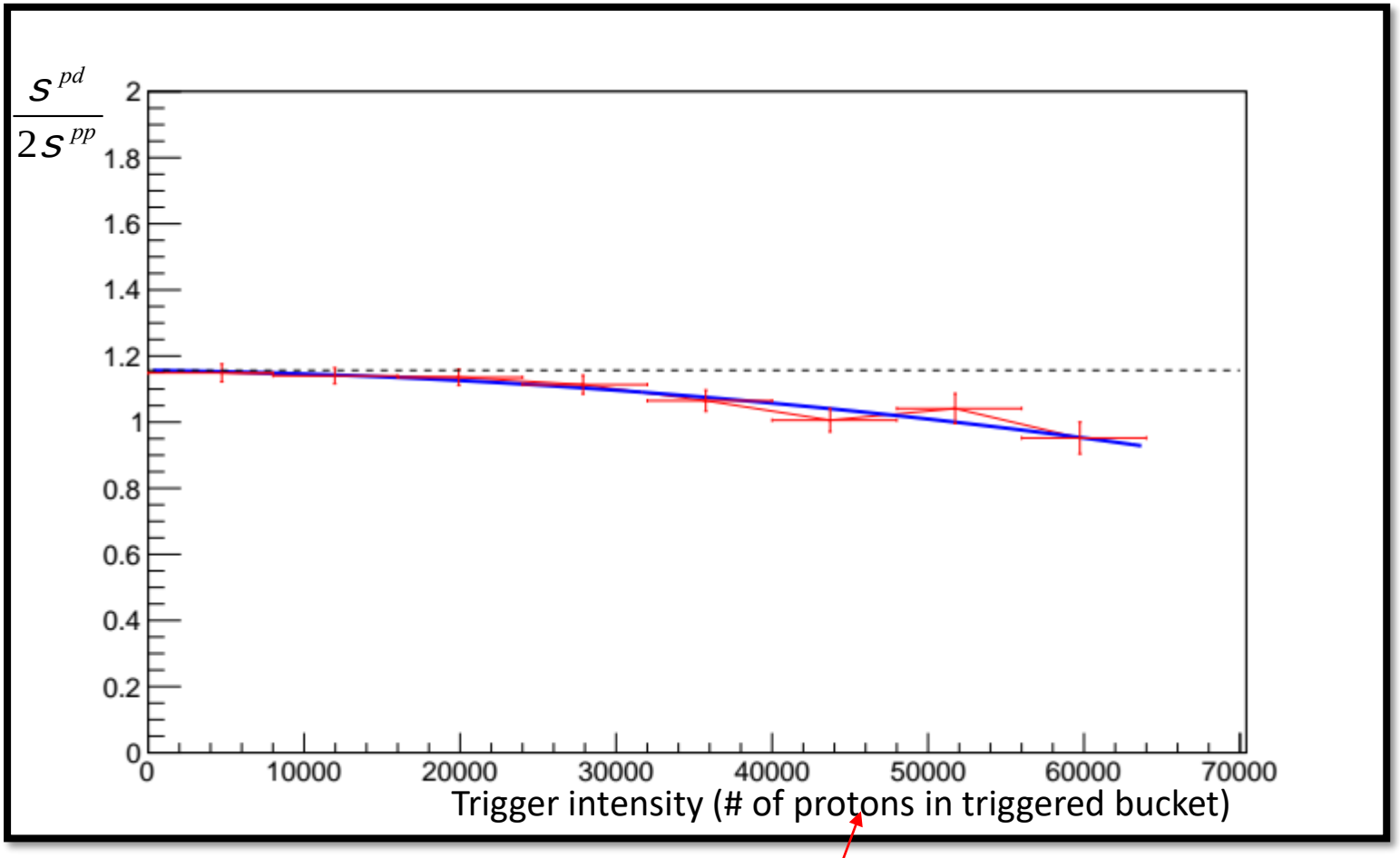


- Reducing of the beam energy with higher intensity, this produces huge background confusing the events from targets.
- "Mixed" background are combinatorial events with tracks from target and FMag after all event selection criteria.

The background and rate dependence

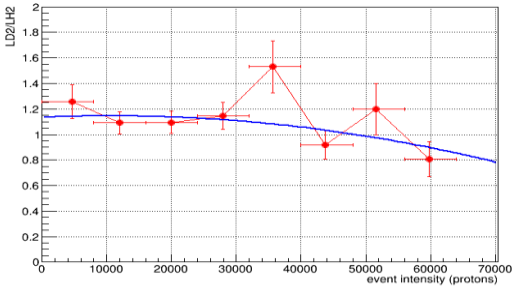
- Extrapolation method based on cross-section ratio dependence on proton intensity is used.
  - This dependence comes from background and the rate dependence of the analysis.
  - Find the dependence of the cross-section ratio on the intensity;
    - fits the distribution with function and project back to zero intensity to get an answer.
  - Difference between the answers obtained using different functions is taken as part of systemic uncertainty.

Cross-section ratio dependence on proton intensity

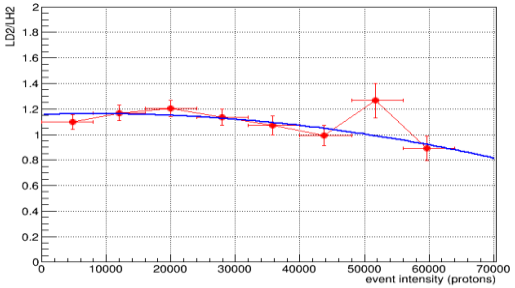


Separation into X_2 bins

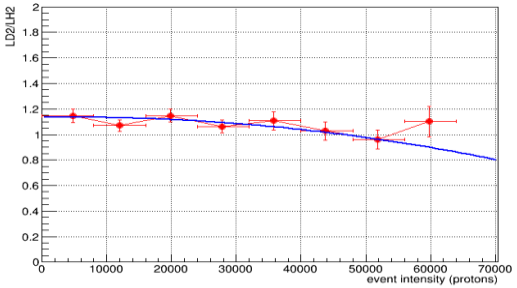
0.100 ↓ 0.130



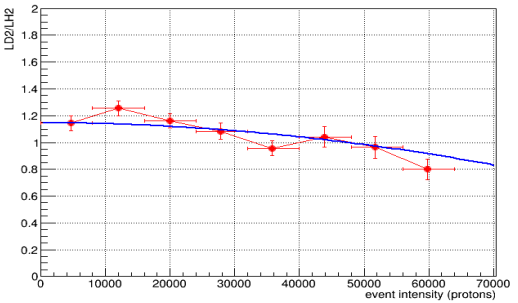
0.130 ↓ 0.160



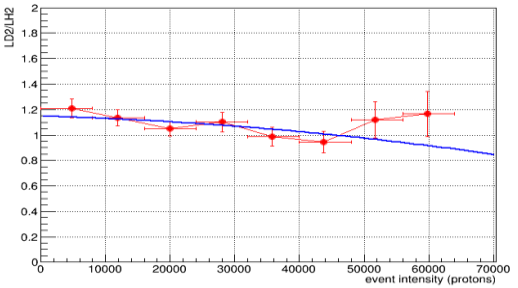
0.160 ↓ 0.195



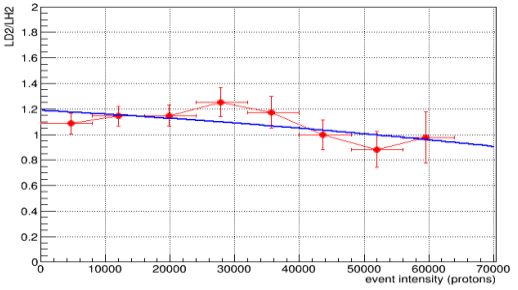
0.195 ↓ 0.240



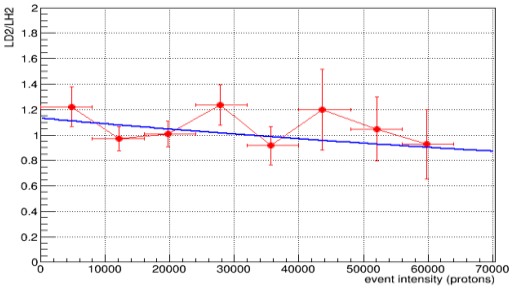
0.240 ↓ 0.290



0.290 ↓ 0.350

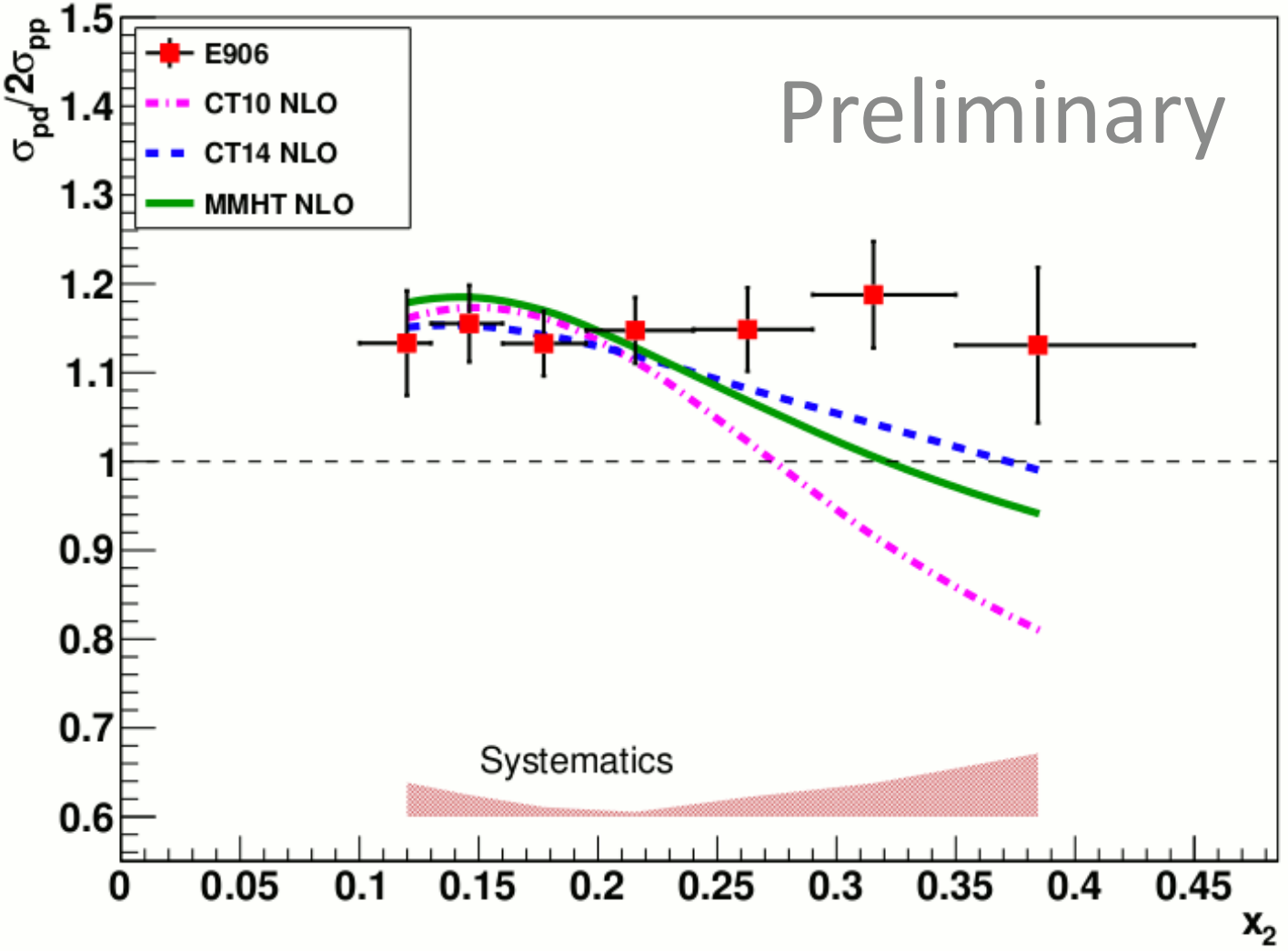


0.350 ↓ 0.450



$$f_i(I_p) = P0_i + (P10 + P11 \cdot x_2)I_p + (P20 + P21 \cdot x_2)I_p^2$$

Cross-section ratio dependence on x_2



Proton spin, large sea quark O.A.M. contribution?

- Proton spin:

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

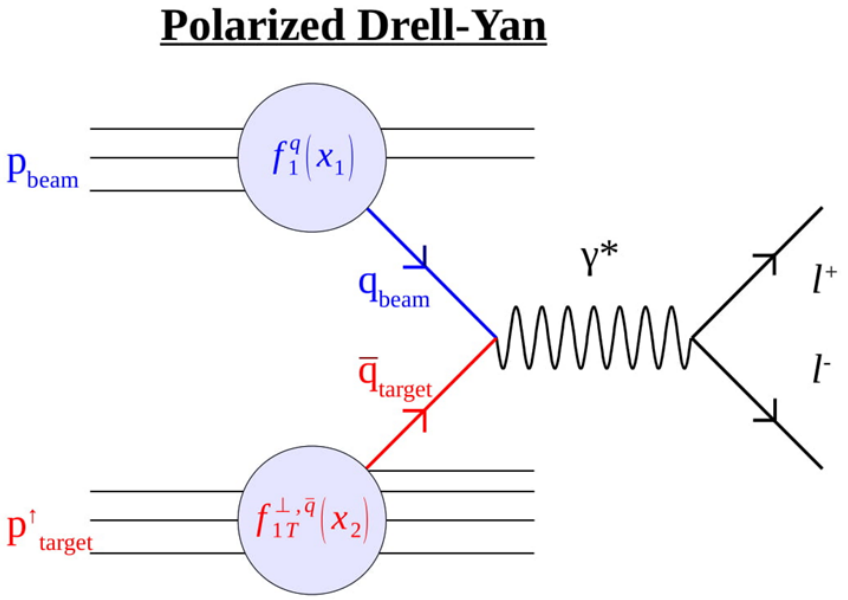
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

$$\frac{1}{2}\Delta\Sigma \approx 25\% \quad \Delta G \approx 0 - 15\%$$

  - Contribution of quark OAM is poorly known.
  - Contribution of sea quark OAM is not measured!
    - Lattice calculation indicates that this might contribute as much as 50%!
    - Sea quark OAM could lead to non-zero Sivers function of sea quark thus single-spin asymmetry. This leads to SpinQuest experiment at Fermilab.

Sea Quark Sivers function in SpinQuest

- Quark Sivers TMD directly accessible using Polarized SIDIS, **Polarized Drell-Yan**

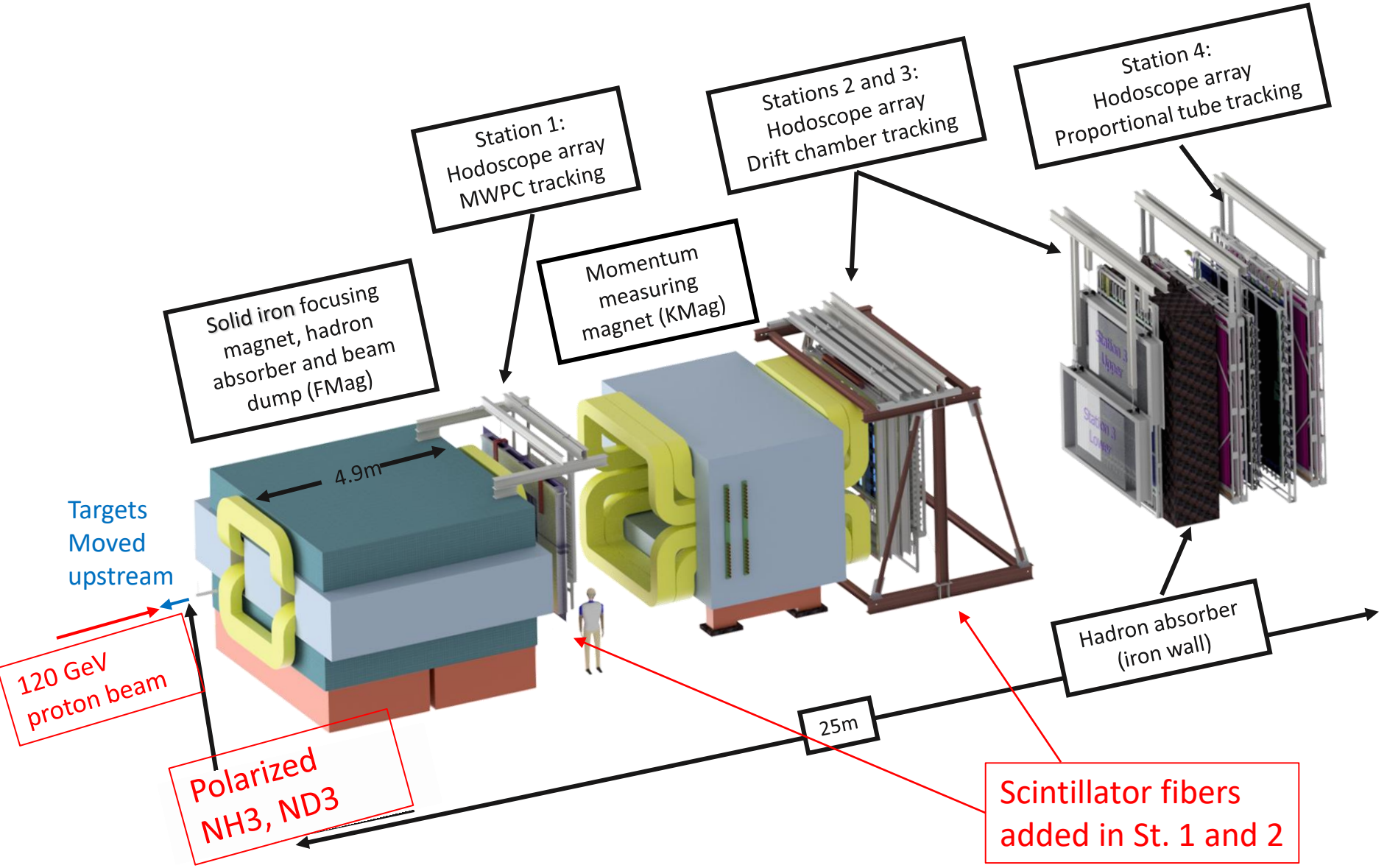


$$A_N^{DY} \propto \frac{\sum_q e_q^2 [f_1^q(x_1) \cdot f_{1T}^{\perp,\bar{q}}(x_2) + 1 \leftrightarrow 2]}{\sum_q e_q^2 [f_1^q(x_1) \cdot f_1^{\bar{q}}(x_2) + 1 \leftrightarrow 2]}$$

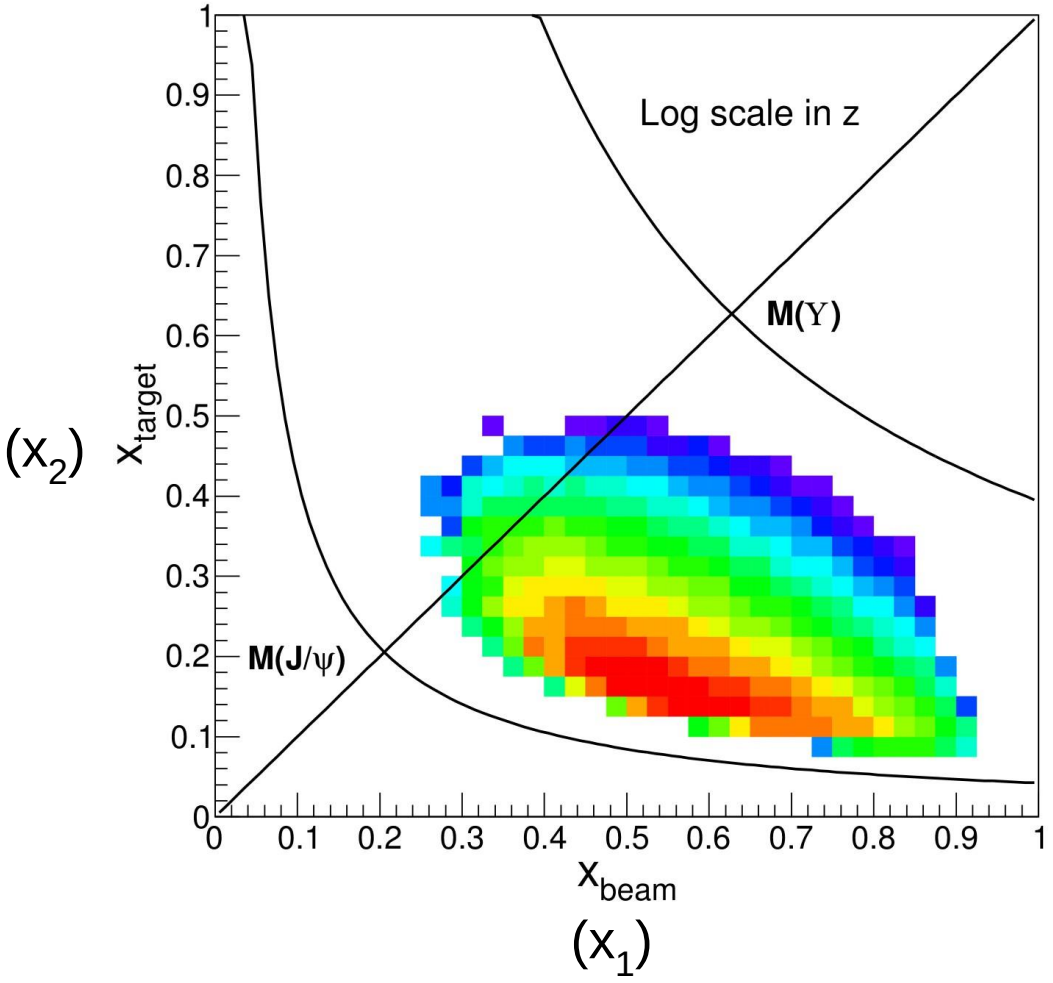
- L-R single spin asymmetry in Drell-Yan production
- **No Quark Fragmention function**
- Valence-Sea quark **Isolated.**

- **A fixed target Drell-Yan Experiment with polarized target isolates sea quark Sivers TMD to target!**

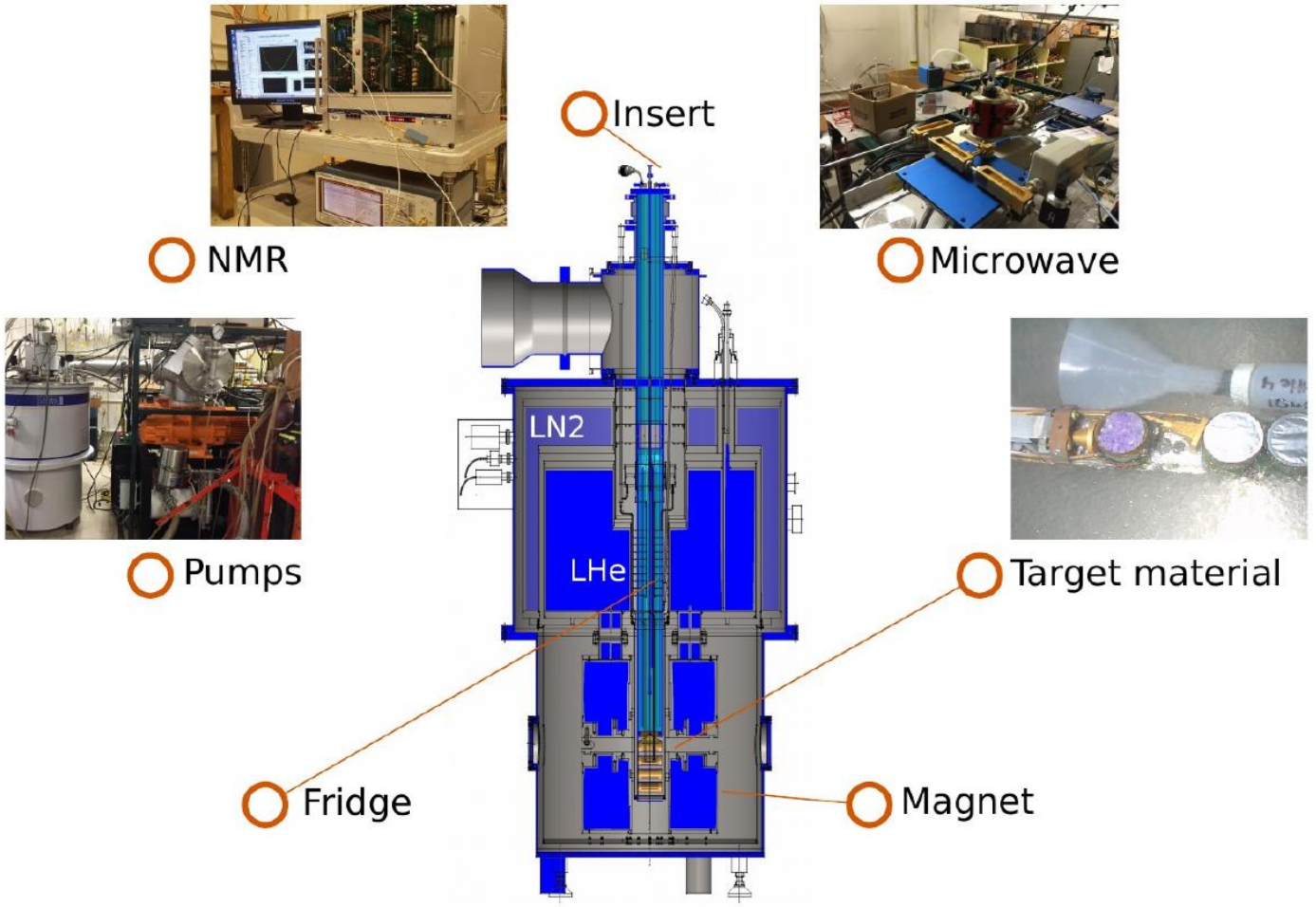
The SpinQuest experiment



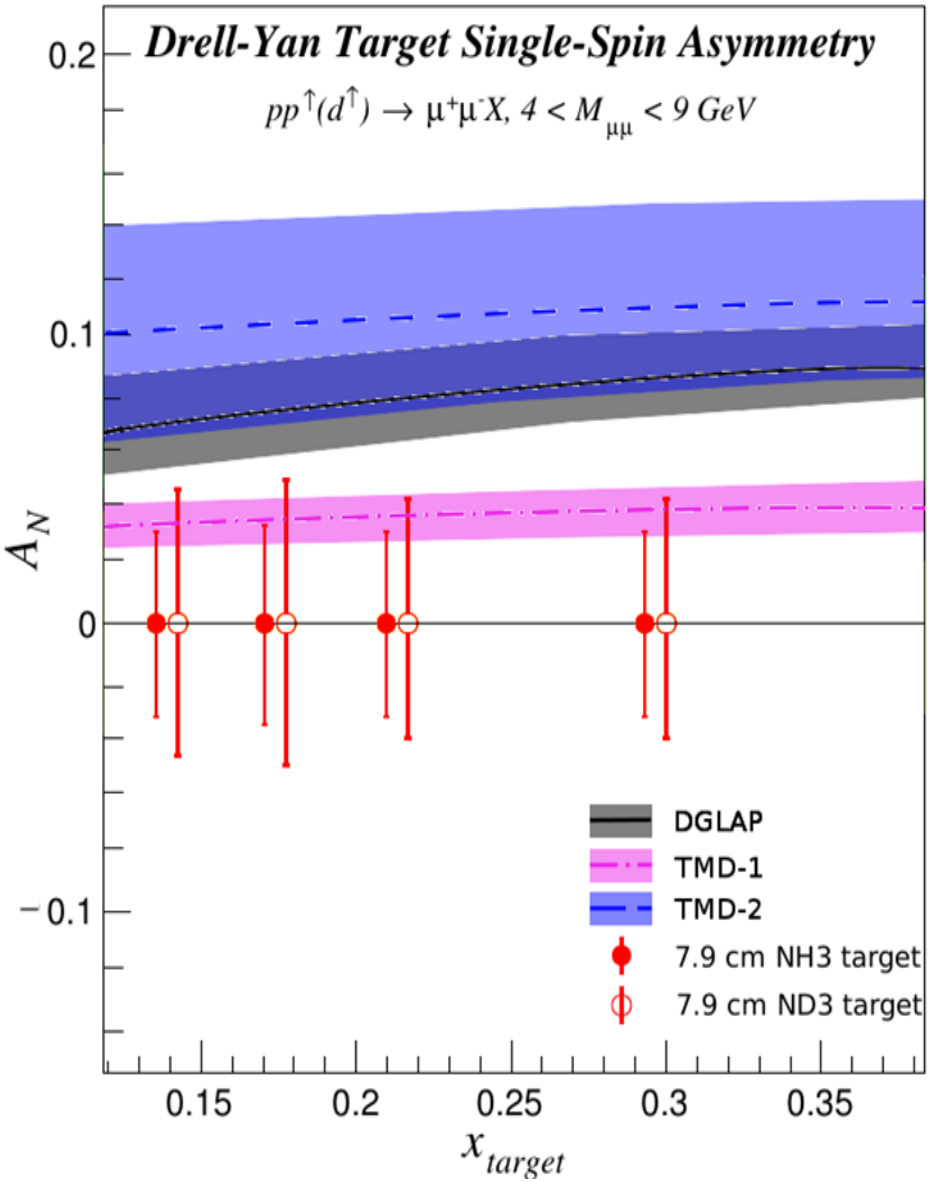
X_1, X_2 distribution of E1039



The polarized target using DNP



Expectation of SpinQuest experiment



None-zero Sivers functions of sea quarks

Sivers function of sea quark neglected

DGLAP: M. Anselmino et al *arXiv:1612.06413*
TMD-1: M. G. Echevarria et al *arXiv:1401.5078*
TMD-2: P. Sun and F. Yuan *arXiv:1308.5003*

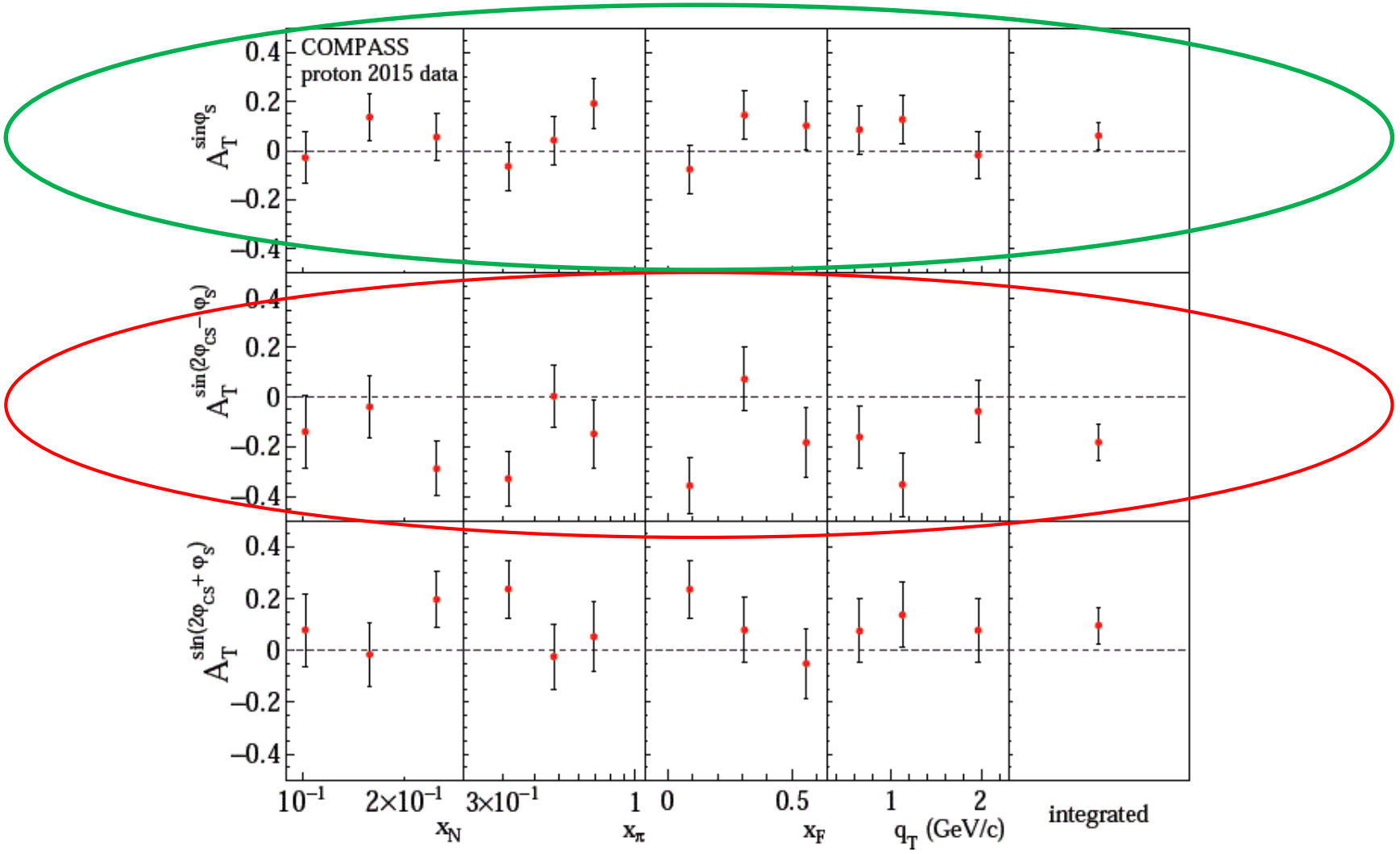
Transversity

- Transversity describes the correlation between (sea) quark's transverse spin and the nucleon's transverse spin.

$$\frac{d\sigma}{dq^4 d\Omega} \propto \hat{\sigma}_U \left\{ 1 + S_T \left[D_1 A_T^{\sin\varphi_S} \sin\varphi_S \right. \right.$$
$$\left. + D_2 \left(A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \right. \right.$$
$$\left. \left. \left. + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) \right) \right] \right\}$$

Transversity convoluted with B-M function

Result of COMPASS, DY (2015)

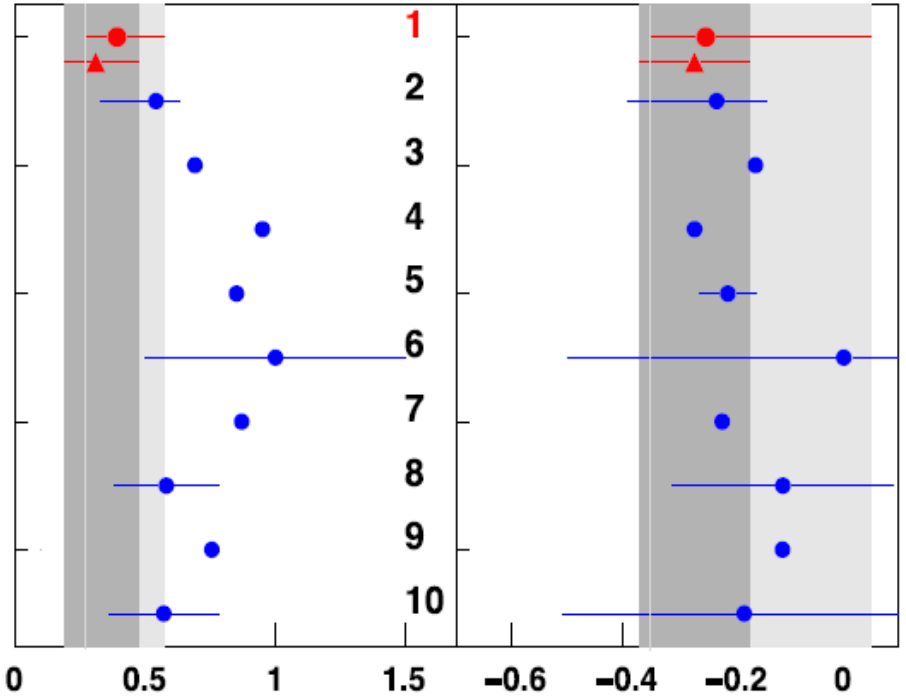


Tensor Charge

$$\delta q = \int_0^1 [h_1^q(x) - h_1^{\bar{q}}(x)]dx$$

Where h_1 is the transversity of given quark.

- $\delta u = 0.39^{+0.18}_{-0.12}$ $\quad$ $\delta d = -0.25^{+0.30}_{-0.10}$
- $\delta u = 0.31^{+0.16}_{-0.12}$ $\quad$ $\delta d = -0.27^{+0.10}_{-0.10}$



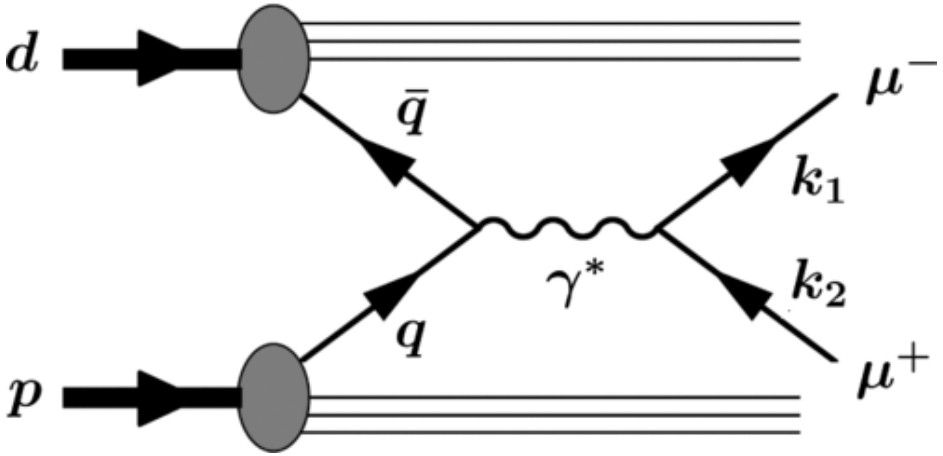
- Global fit with two different Collins Fragmentation Functions.
- This fit neglects the contributions from sea quarks also with limited x range.

Predictions from various models.

E1039, polarized DY, can provide transversity without Fragmentation Functions!

PhysRevD.87.094019

Tensor Polarization



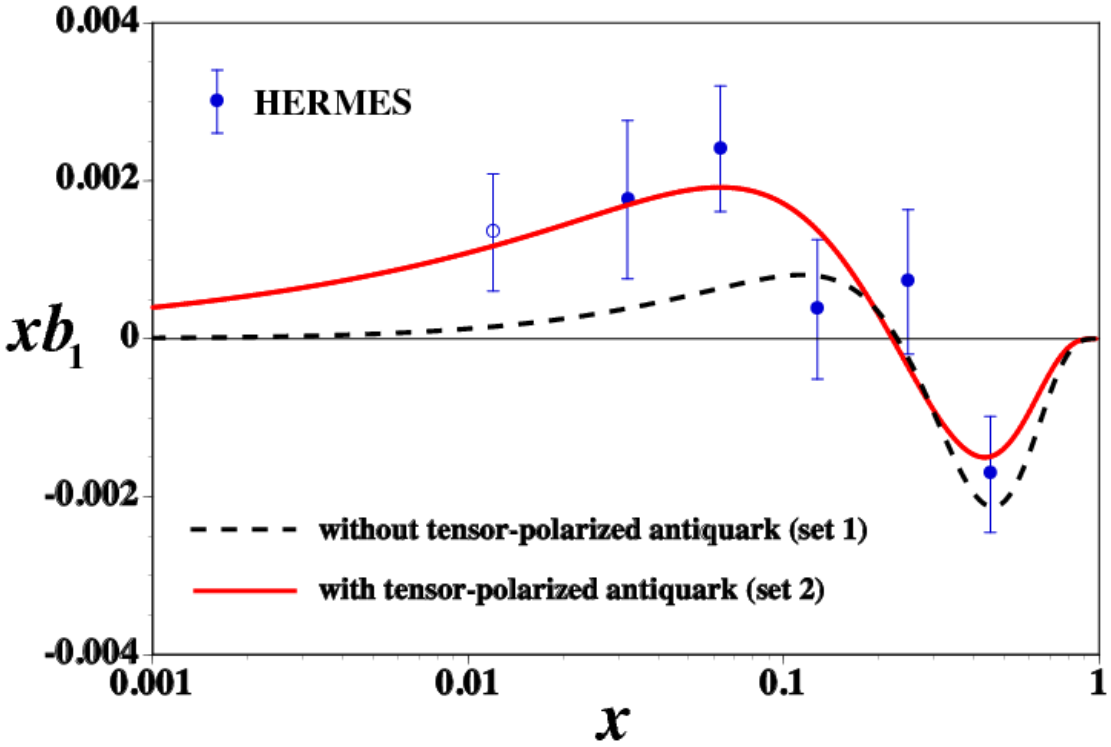
- Tensor polarization in Drell-Yan process of

$$p + d \rightarrow \mu^+ + \mu^-$$

  where deuteron, *d,* is polarized.
- Deutron is spin 1, has three magnetic substates:
  - m = +1, 0, -1
- Tensor polarization terms leads to new PDFs, b1, b2, b3 and b4.
- Where b1 express the difference between |m| = 1 and |m| = 0.

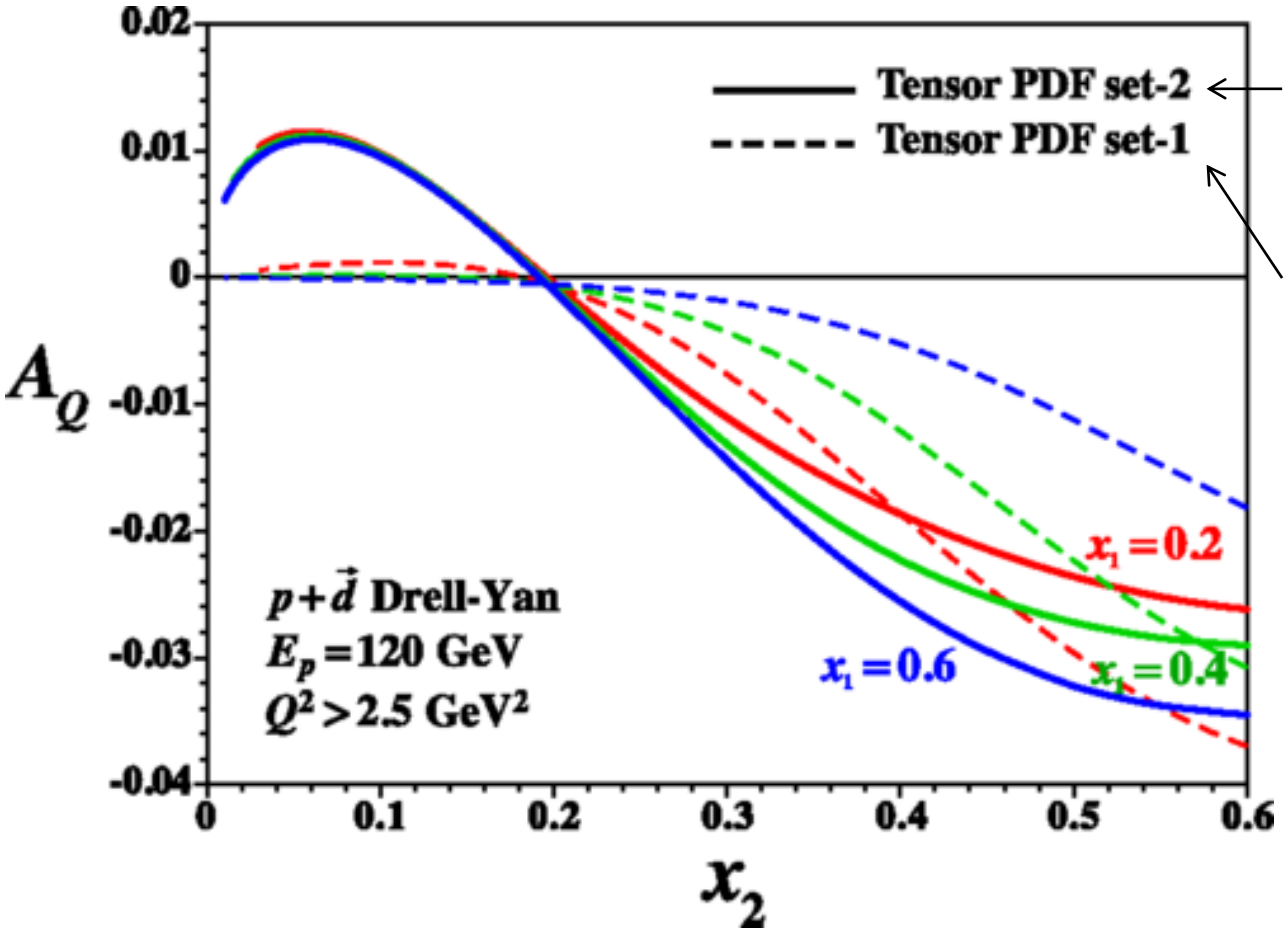
Tensor polarization of antiquark

- Fitting HERMES data with
  - zero tensor-polarized antiquark distributions (set 1)
  - non-zero tensor-polarized antiquark distributions (set 2).
- The HERMES data supports better the case of non-zero tensor polarization PDFs of antiquarks.



S. Kumano and Qin-Tao Song, PhysRev.D 94, 054022

Tensor asymmetry with polarized deuteron, for E1039, predicted



Non-zero tensor polarized anti-quark distribution

Zero tensor polarized anti-quark distribution

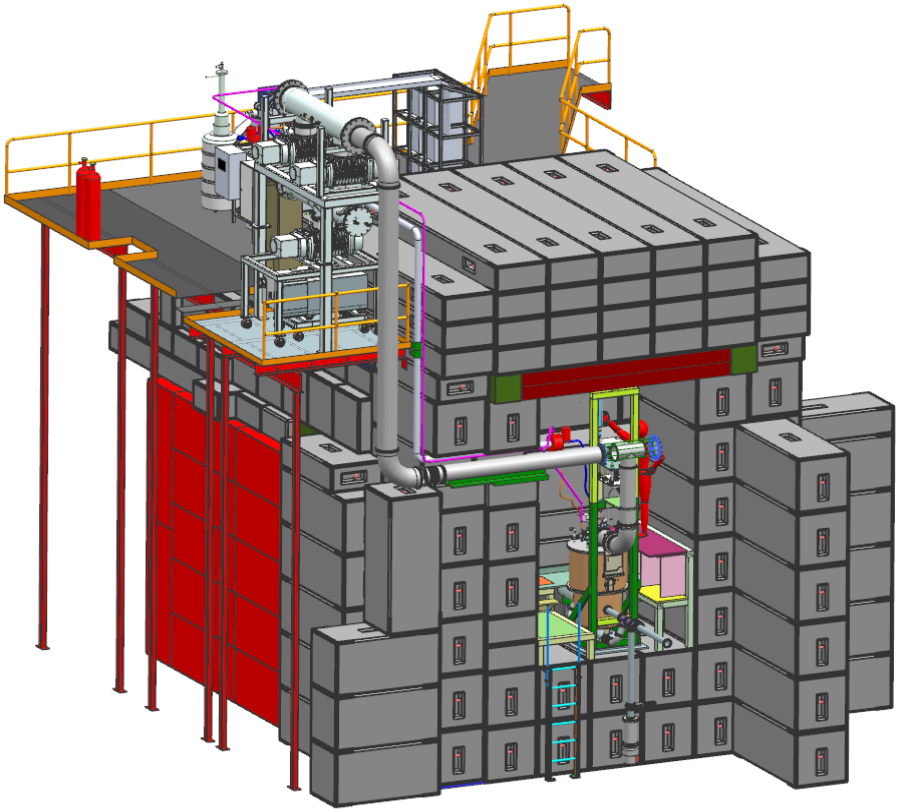
S. Kumano and Qin-Tao Song, PhysRev.D 94, 054022

The E1039 specterometer

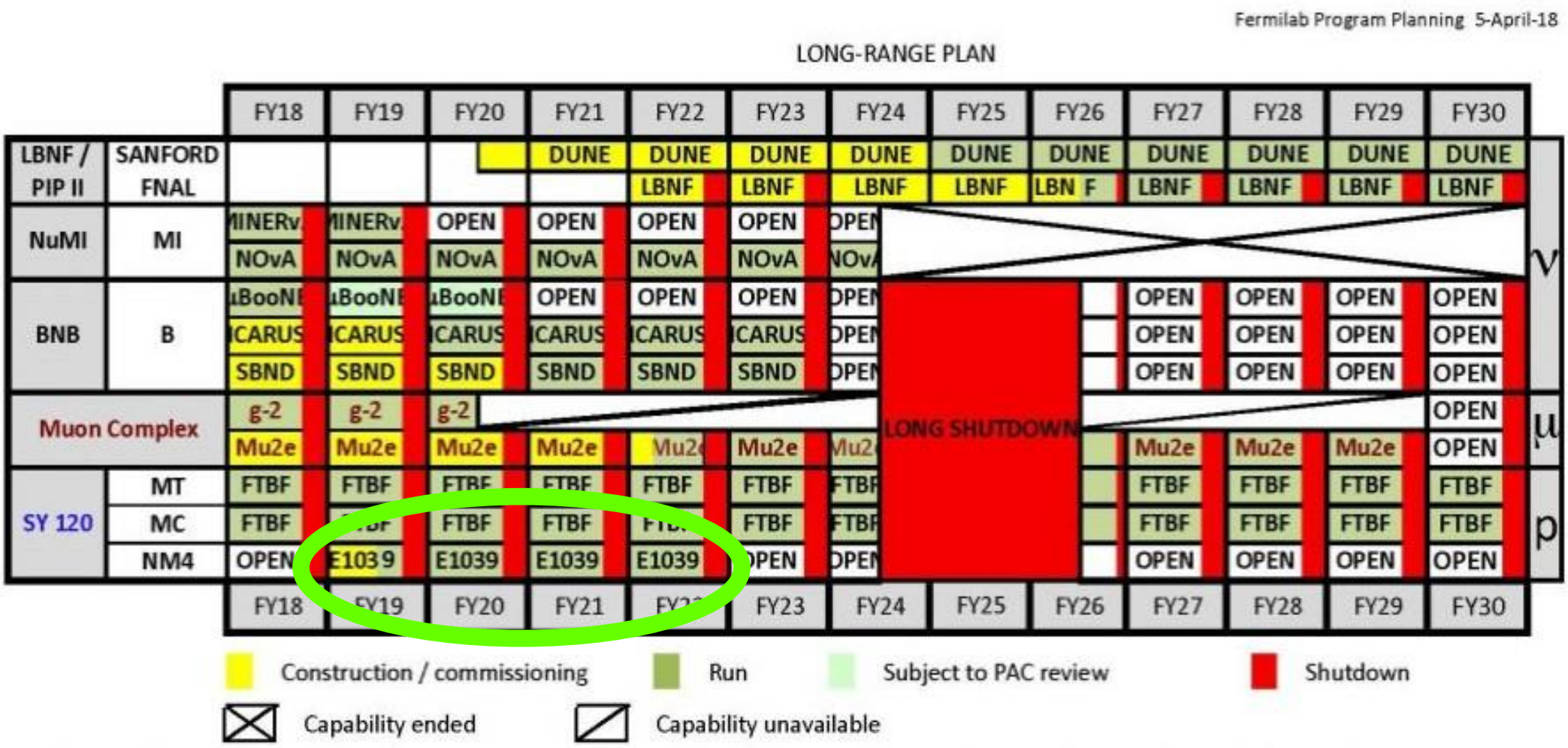
- The spectrometer is basically the same as the Seaquest/E906 experiment.
- New fiber scintillators are added in the station 1 and 2.
  - These will be part of the trigger to improve the *z* resolution; which helps in rejecting background.
  - These can also be used to construct new trigger for Dark Photon search; events from the down stream half of the FMag.

Preparing the experiment

- Beam line and target cave reconstruction are well in progress.
- Installation of polarized target is well in progress.



The schedule

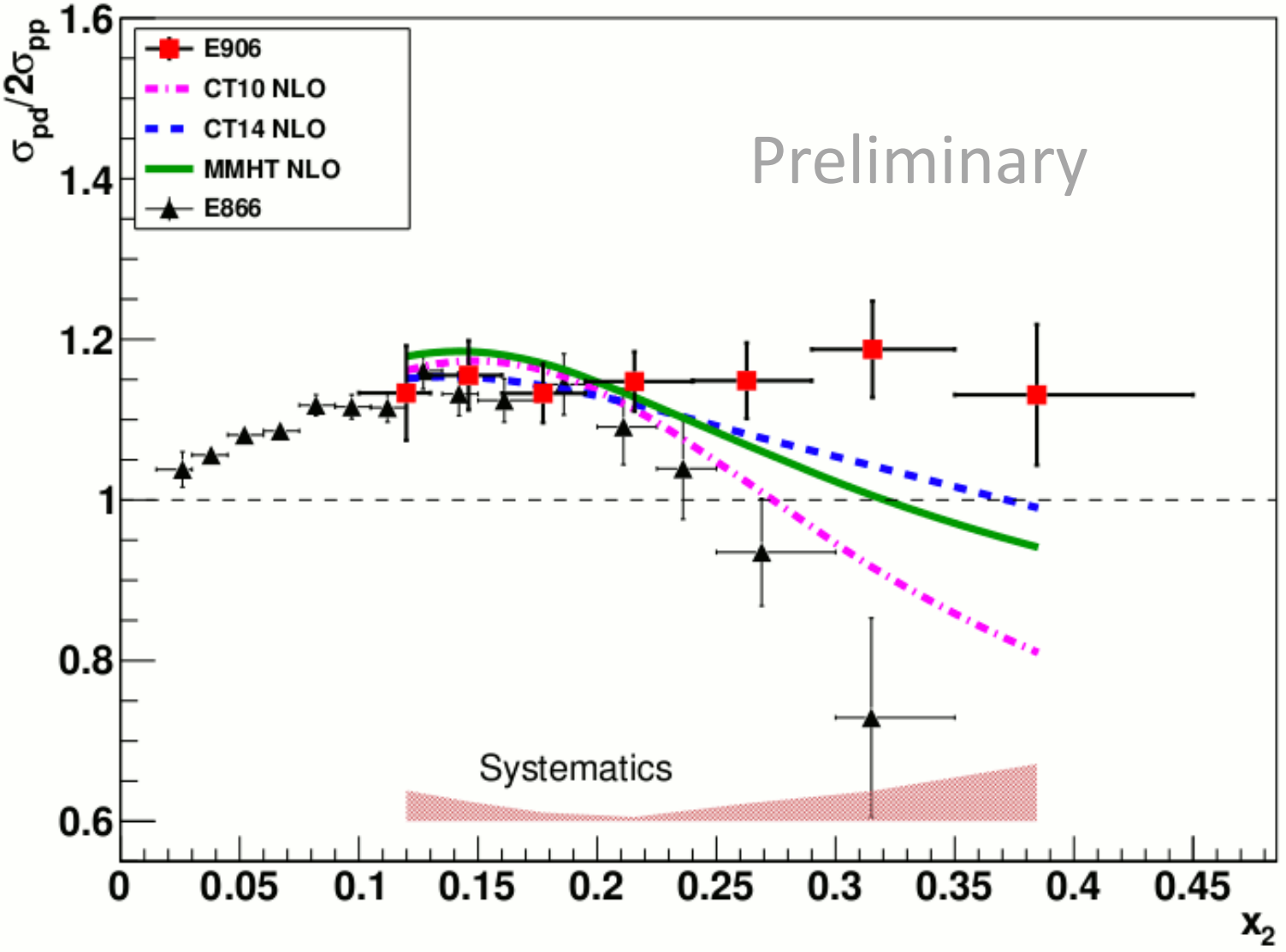


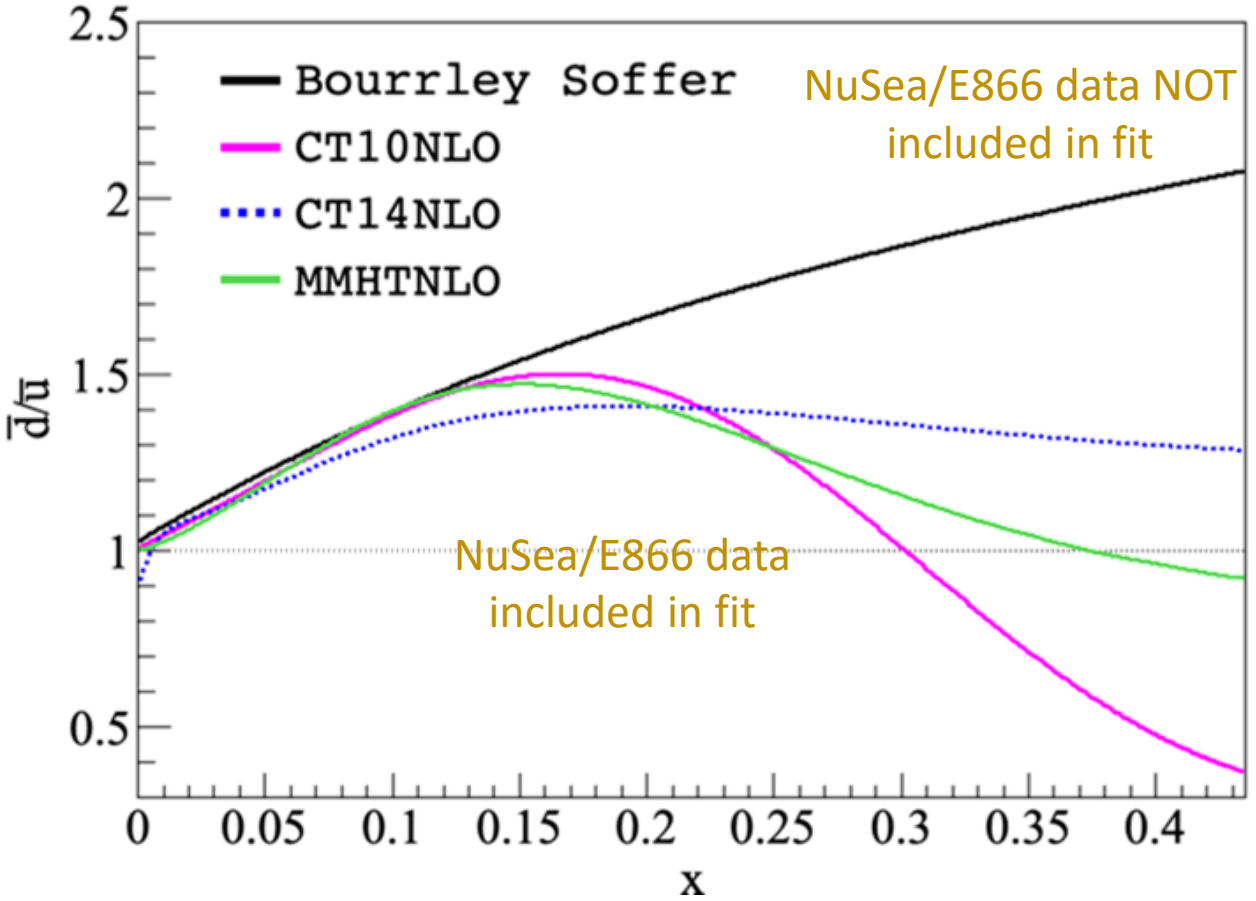
Summary

- The SeaQuest obtained a preliminary result on the cross-section ratio of LD2/LH2, $\bar{d}/\bar{u}$ is still being finalized.
- E1039 will measure the single-spin asymmetry induced by Sivers function of antiquark.
- Study of transversity and contribute to tensor charge.
- Study of the tensor polarization using polarized ND3.
- Expect to take beam in Spring of 2020 with dummy target.

Stay tuned!

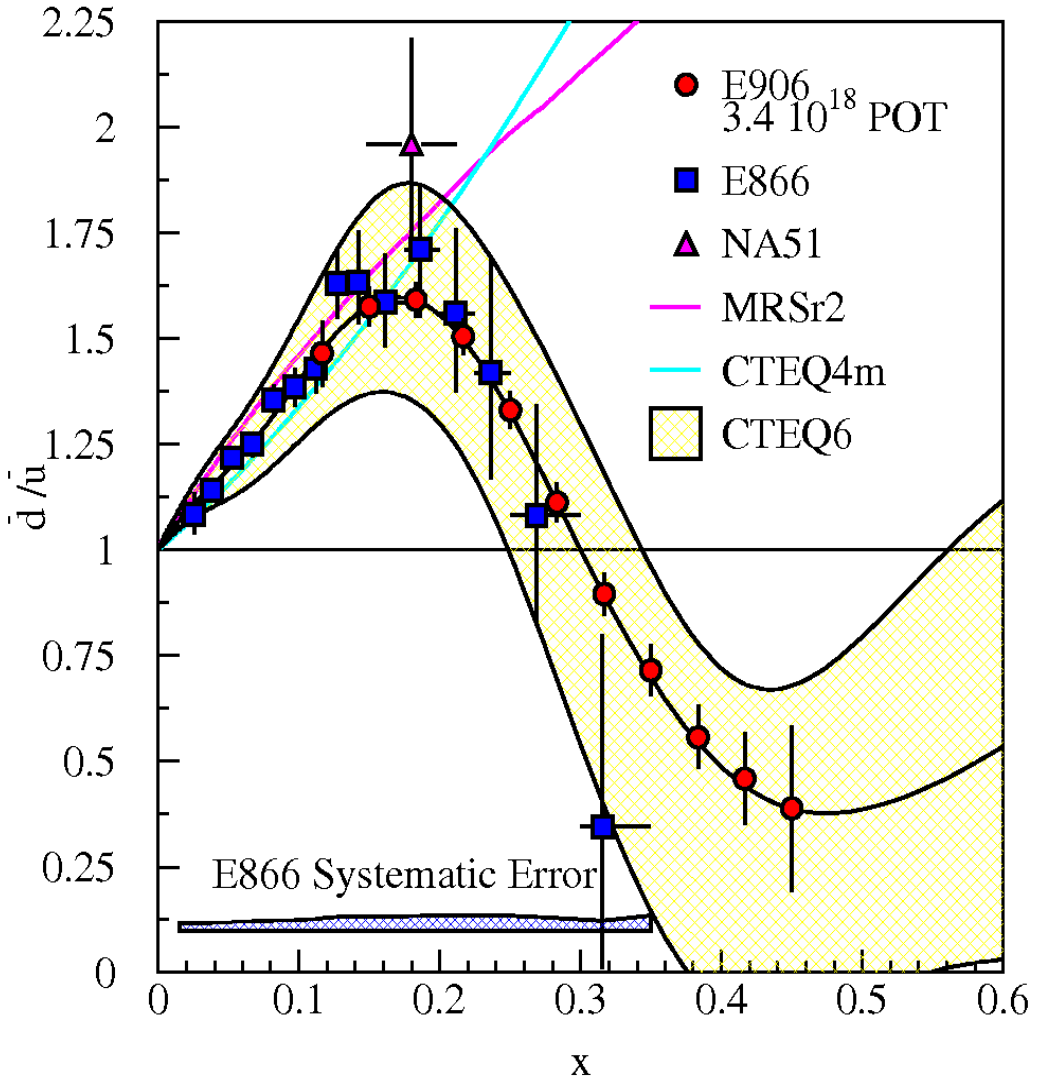
Cross-section ratio dependence on x_2



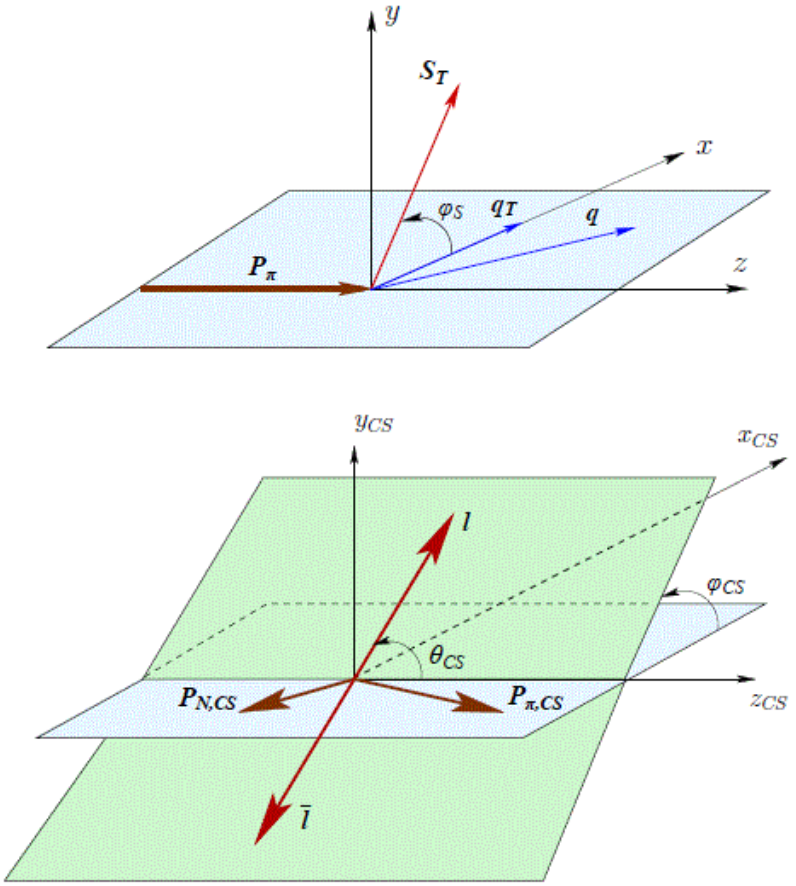

Bourrley Soffer
CT10NLO
CT14NLO
MMHTNLO
NuSea/E866 data NOT included in fit
NuSea/E866 data included in fit
$\bar{d}/\bar{u}$
x
2.5
2
1.5
1
0.5
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

The $\bar{d}/\bar{u}$ asymmetry

- The asymmetry has strong dependence on Bjorken x !
  - It is hard to explain the dropping in high x region!
- The SeaQuest experiment is done taking data in 2017.
- Preliminary result based on 50% of data.



Frames used by COMPASS



Tensor polarization

- Tensor polarization is available when the target particle
  - has spin = 1, such as deuteron and
  - is polarized.
- For a spin 1 particle in magnetic field,
  - Zeeman effects creats three levels, m=+1,0,-1; corresponding populations are p+, p0 and p-.
  - In this case there are
    - vector polarization = p+ - p-
    - tensor polarization = (p+ - p0) - (p0 - p-) = 1 – 3 p0.