SPINQUEST

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SPINQUEST

- Introduction
- SpinQuest at Fermilab Goals
- Target and Intensity Frontier
- Status of Collaboration

Fermilab

Introduction

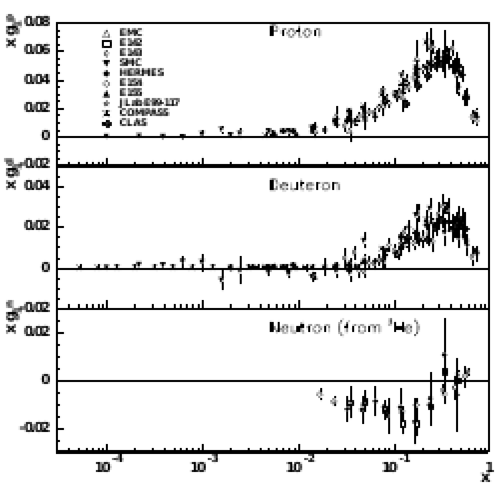
1987 EMC polarized DIS measurements:
contributions of spins of quarks and anti-quarks to the proton spin are small

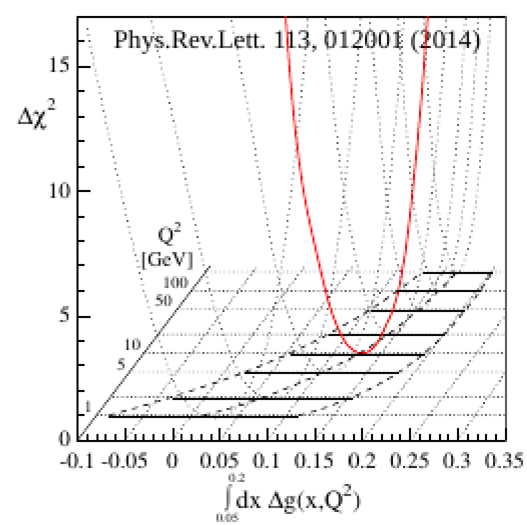
broad world-wide program to resolve the
problem of the nucleon spin composition

In spite of significant experimental and theoretical advances
basic problem remains after 30 years of research

components contributing to proton spin

$$\Delta\Sigma \quad \Delta G \quad L_q \quad L_g$$





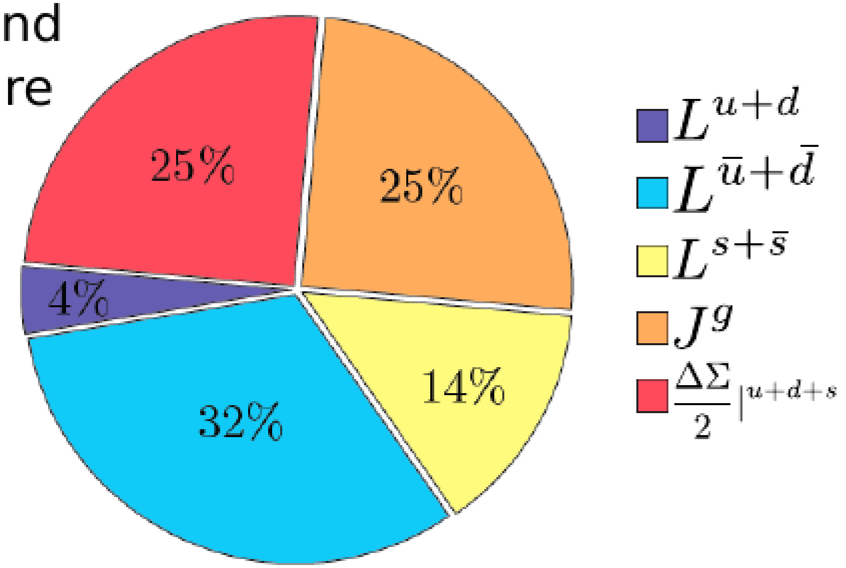
Understanding Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + L_{\bar{q}} + \Delta G + L_g$$

importance of sea quarks

- account for spin of quarks, anti-quarks and gluons - still missing about half the picture
- sea quark OAM could be a major part of missing spin

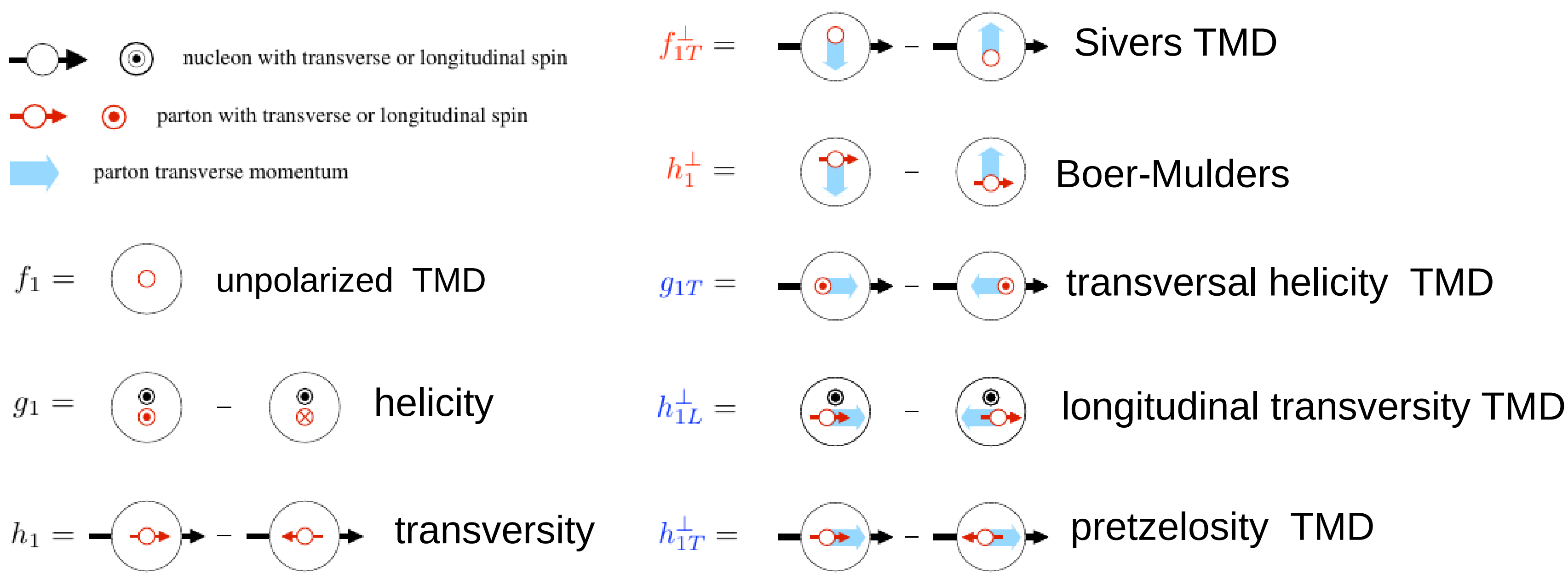
Lattice QCD: K.-F. Liu *et al* arXiv:1203.6388



contribution of OAM of sea quarks remains poorly constrained

important to understand theoretically and experimentally

TMD distribution functions



Quintessential tool to study spin-orbit correlations and provide direct experimental observables for studying orbital angular momentum.

quark pol.

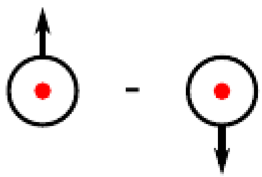
nucleon pol.	U	L	T	
U	f_1		$h_1^{\perp}$	
L		g_1	$h_{1L}^{\perp}$	
T	$f_{1T}^{\perp}$	g_{1T}	h_1	$h_{1T}^{\perp}$

Sivers Function

- Relation between momentum direction of the struck parton and the spin of the nucleon
- Measure correlations between lepton angle distributions and nucleon spin
- Experimentally accessible from multiple processes

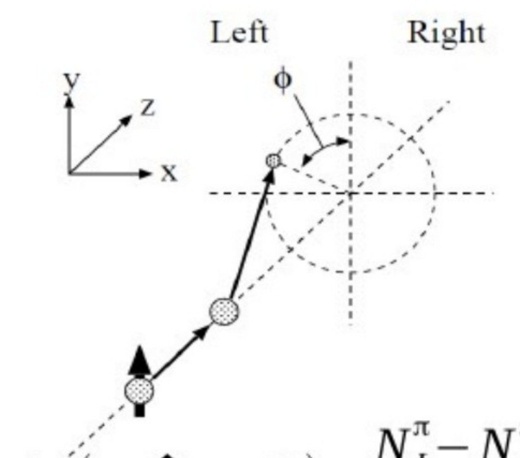
If $A_N \neq 0$, **major discovery**:
"Smoking Gun" evidence for $L_{\bar{u},\bar{d}} \neq 0$

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

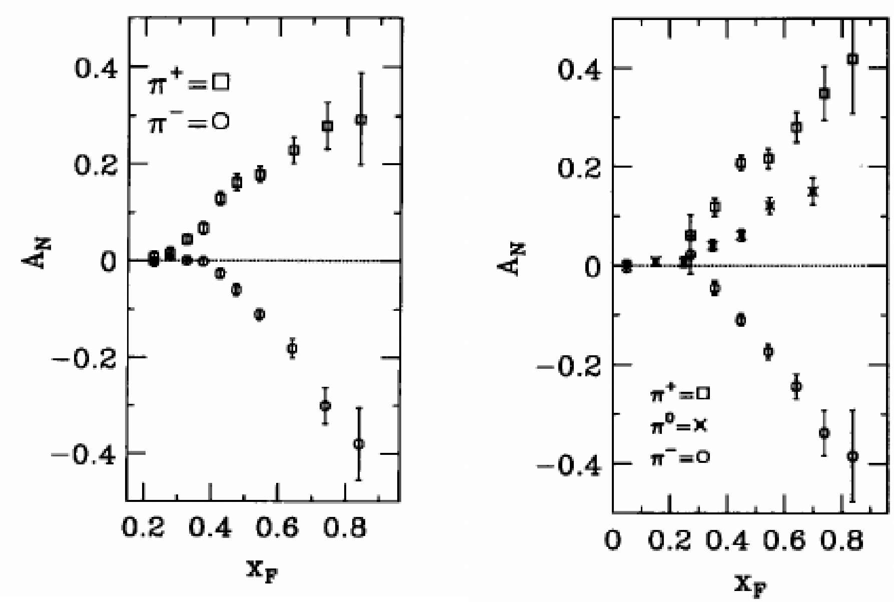


$$A_N^{DY} = \frac{2}{\pi} \cdot A_T^{\sin\varphi_s} \propto f_{1,u}^{q}(x_b) \otimes f_{1T,\bar{u}(\bar{d})}^{\perp q}(x_t)$$

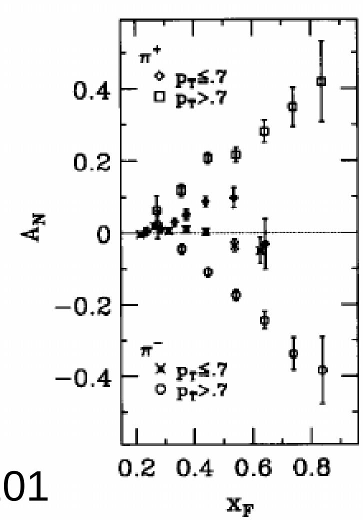
First Looking into Quark Transverse Momentum

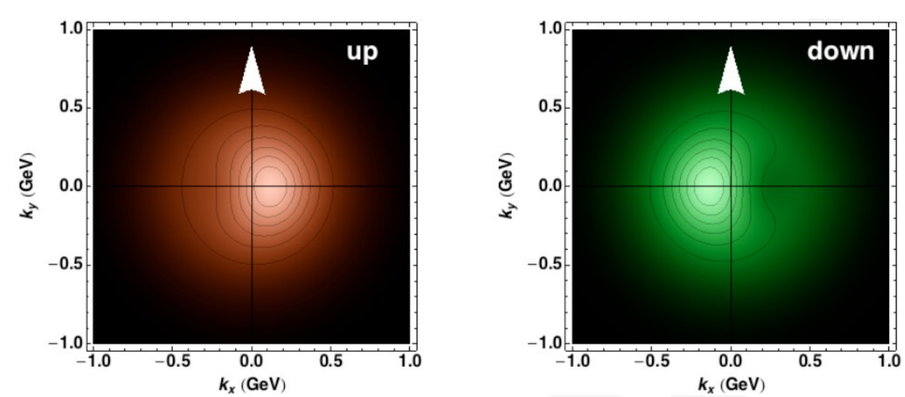


$$A_N(pp^{\uparrow} \rightarrow \pi X) \propto \frac{N_L^{\pi} - N_R^{\pi}}{N_L^{\pi} + N_R^{\pi}}$$



Points to possible intrinsic imbalance and leads to big asymmetry



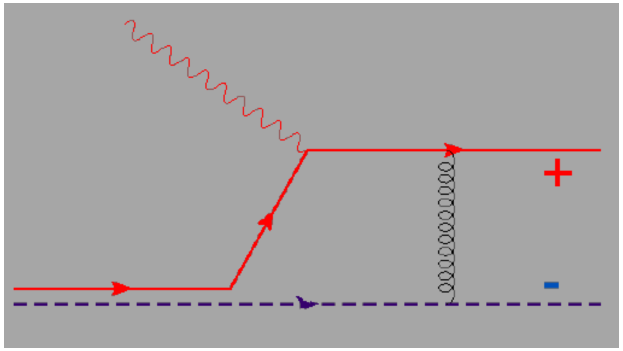


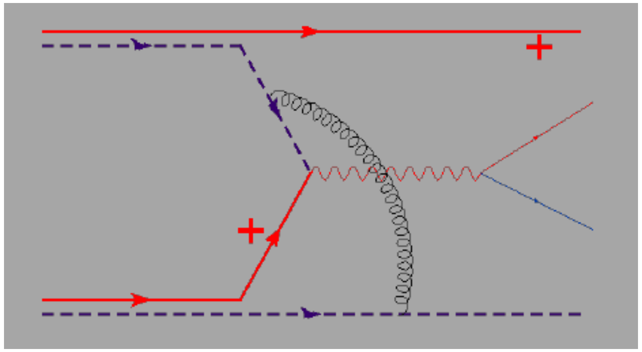
E704 Effect

Phys. Rev. C89 (2014) 042201

A. Bacchetta and M. Contalbrigo, Il Nuovo Saggiatore, vol. 28 pp. 16-27, 2012

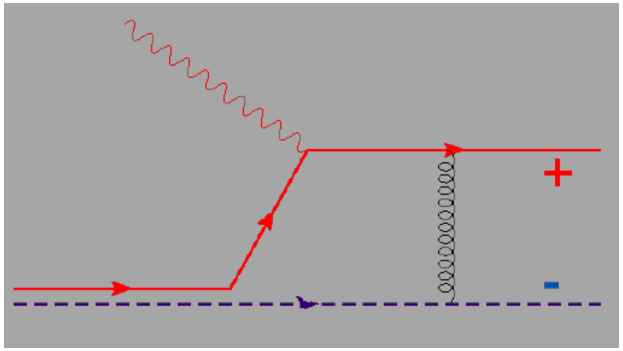
Universality

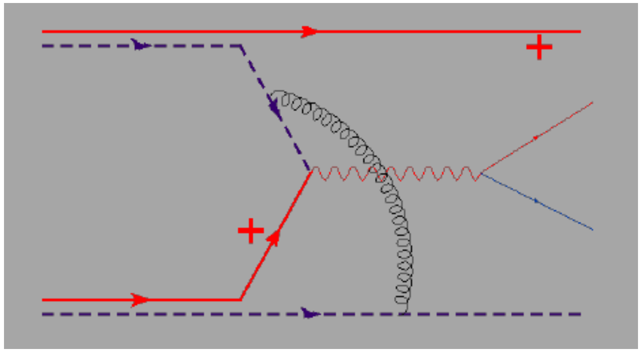




- SSA assumed to be negligible (T-odd)
- Since the past-pointing Wilson lines are appropriate for factorization in the Drell-Yan process, the correct result is not that the Sivers asymmetry vanishes, but that it has opposite signs in DIS and in Drell-Yan.
- Non-perturbative parts in the cross section
- The gauge link provides the phase for the interference and can be interpreted as an interaction of the struck quark with the color field of the target remnant

Universality



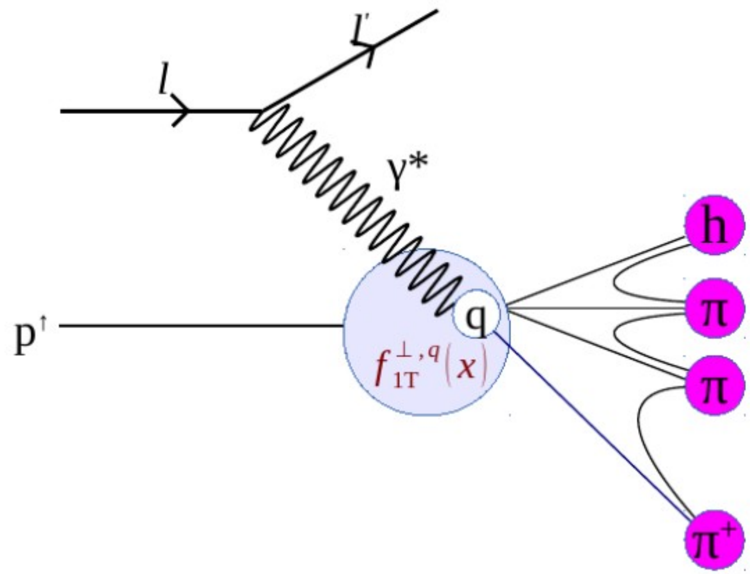


- Colored objects surrounded by gluons with profound consequence of gauge invariance
- Siver function has opposite sign when gluon couple after quark scatters (SIDIS) or before quark annihilates (DY)
- Essential to verify experimentally

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

Accessing Quark Sivers TMDs

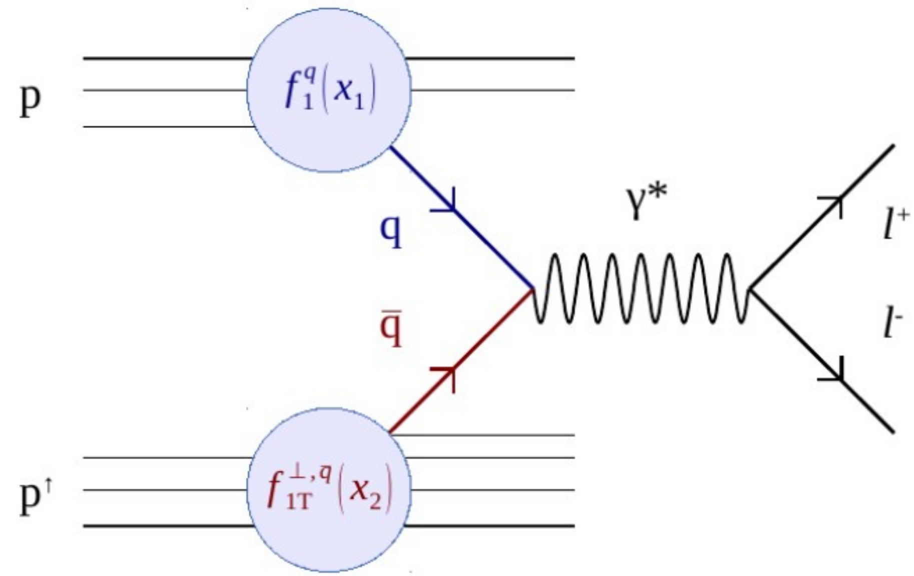
Polarized Semi-Inclusive DIS



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**

Polarized Drell-Yan

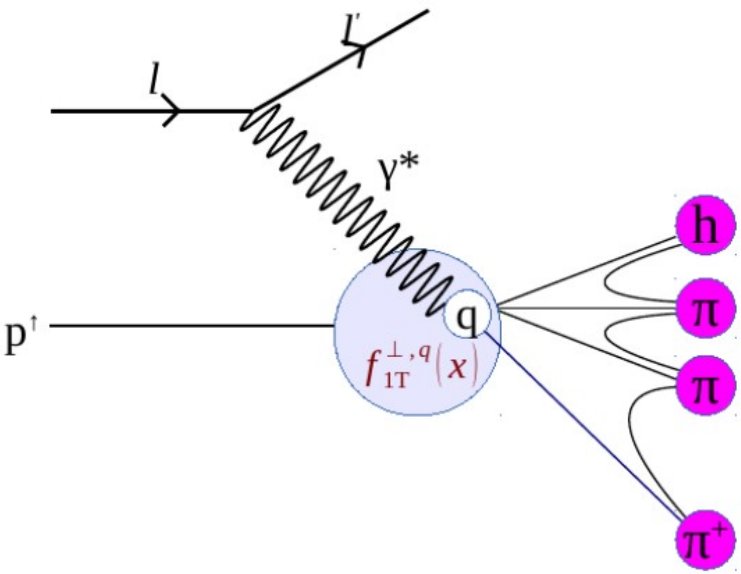


Cleanest probe to study hadron structure:

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

Accessing Quark Sivers TMDs

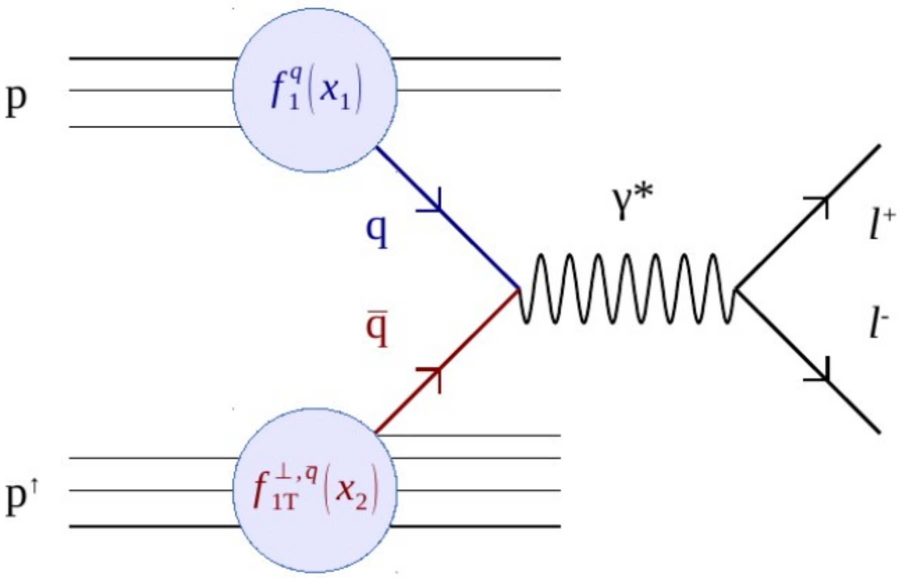
Polarized Semi-Inclusive DIS



$$A_{UT}^{SIDIS} \propto \frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x) \otimes D_1^q(z)}{\sum_q e_q^2 f_1^q(x) \otimes D_1^q(z)}$$

- L-R asymmetry in hadron production
- Quark to Hadron Fragmention function
- Valence-Sea quark: Mixed

Polarized Drell-Yan



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

- L-R asymmetry in Drell-yan production
- **No Quark Fragmention function**
- Valence-Sea quark **Isolated**

LO SIDIS and DY cross sections

SIDIS

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

$$\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{ 1+\cos 2\phi_h\left(\varepsilon A_{UU}^{\cos 2\phi_h}\right) + S_T\begin{bmatrix} \sin\left(\phi_h-\phi_S\right)\left(A_{UT}^{\sin(\phi_h-\phi_S)}\right) \\ +\sin\left(\phi_h+\phi_S\right)\left(\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\right) \\ +\sin\left(3\phi_h-\phi_S\right)\left(\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\right)\end{bmatrix}\right.$$

DY

$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2}F_U^1\left\{ 1+\cos^2\theta+\sin^2\theta\cos 2\varphi_{CS}A_U^{\cos 2\varphi_{CS}} + S_T\begin{bmatrix}\left(1+\cos^2\theta\right)\sin\varphi_S A_T^{\sin\varphi_S} \\ +\sin^2\theta\begin{pmatrix}\sin\left(2\varphi_{CS}+\varphi_S\right)A_T^{\sin(2\varphi_{CS}+\varphi_S)} \\ +\sin\left(2\varphi_{CS}-\varphi_S\right)A_T^{\sin(2\varphi_{CS}-\varphi_S)}\end{pmatrix}\end{bmatrix}\right\}$$

$$\boxed{\mathrm{PDF}\otimes\mathrm{FF}}$$

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

beam target

$$\boxed{\mathrm{PDF}\otimes\mathrm{PDF}}$$

BM $\otimes$ BM	$A_T^{\cos 2\varphi_{CS}}$	$\propto$	$h_1^{\perp q}\otimes h_1^{\perp q}$
f_1 $\otimes$ Sivers	$A_T^{\sin\varphi_S}$	$\propto$	$f_1^{q}\otimes f_{1T}^{\perp q}$
BM $\otimes$ Transv	$A_T^{\sin(2\varphi_{CS}-\varphi_S)}$	$\propto$	$h_1^{\perp q}\otimes h_{1T}^{\perp q}$
BM $\otimes$ Pretz	$A_T^{\sin(2\varphi_{CS}+\varphi_S)}$	$\propto$	$h_1^{\perp q}\otimes h_1^{q}$

within QCD TMD framework:

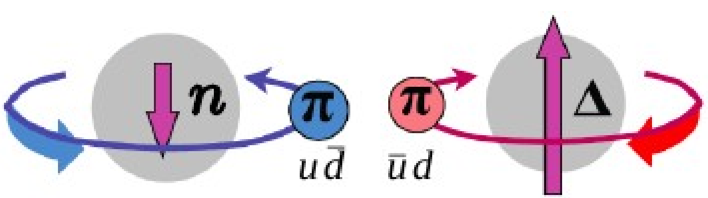
$$h_1^{\perp q}\Big|_{SIDIS} = -h_1^{\perp q}\Big|_{DY} \qquad f_{1T}^{\perp q}\Big|_{SIDIS} = -f_{1T}^{\perp q}\Big|_{DY}$$

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

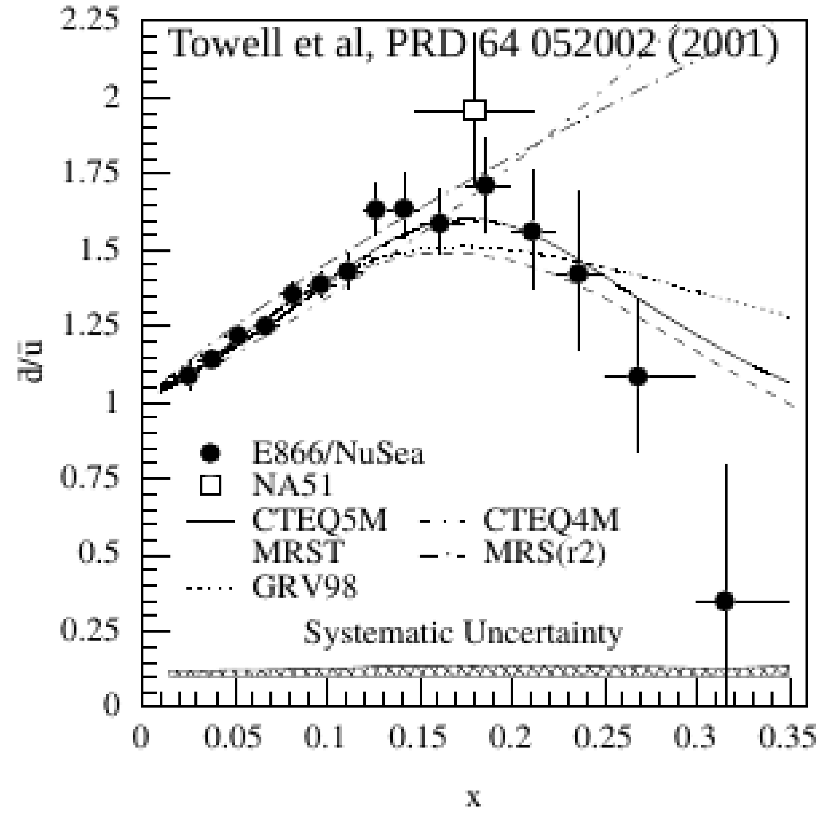
Past DY at Fermilab

- Conservation of parity:

  pions negative parity requires L=1
- E866 results may have point to sea quark OAM



E866/NuSea: enhanced $\bar{d}/\bar{u}$



pion cloud model as possible interpretation

$$|p\rangle \propto |p_0\rangle + |n\pi^+\rangle + |\Delta^{++}\pi^-\rangle + \ldots$$

SeaQuest Status (E906)

Main Injector beam in a slow spill—difficult to obtain good duty factor

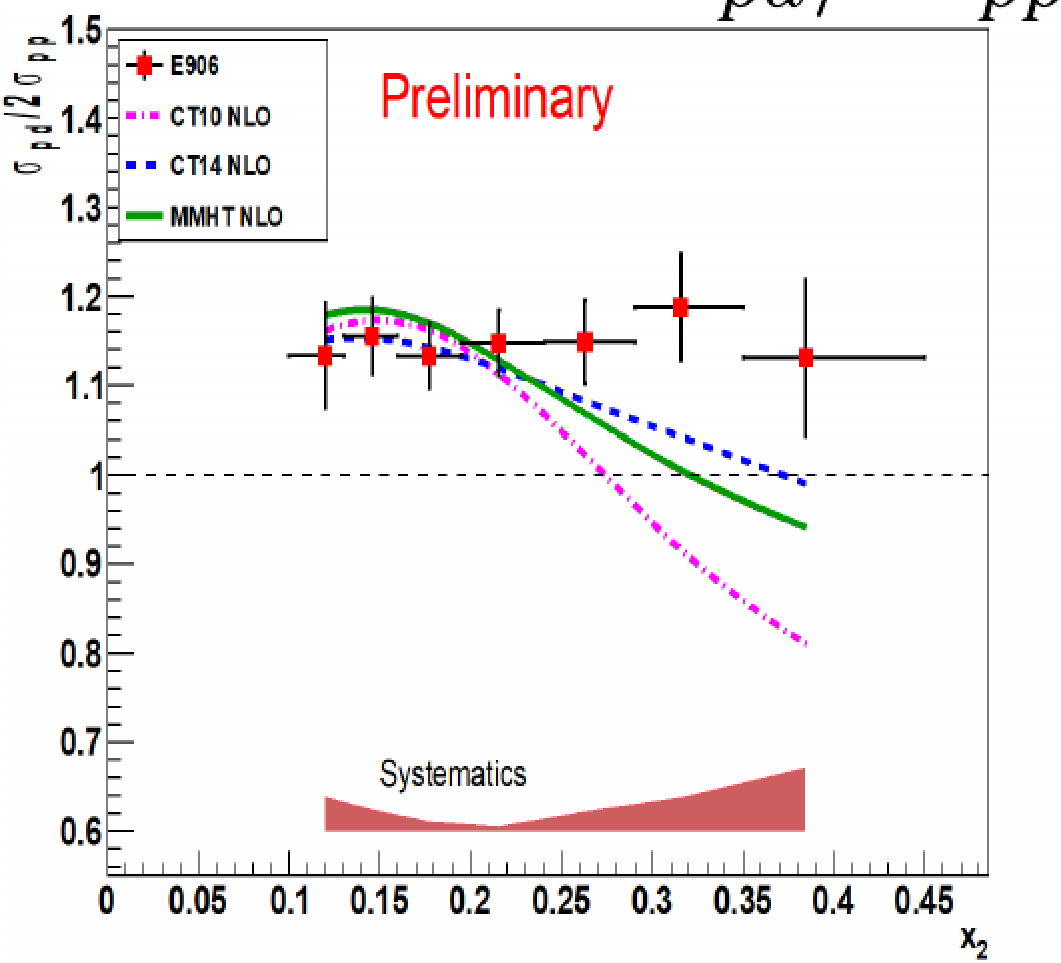
- 1.4×10^{18} of the 5.3×10^{18} approved "live protons"
- 1.7×10^{18} of the 7×10^{18} protons with good duty factor

3.5 x 10^{17} live protons
¼ of recorded protons

Caveats:

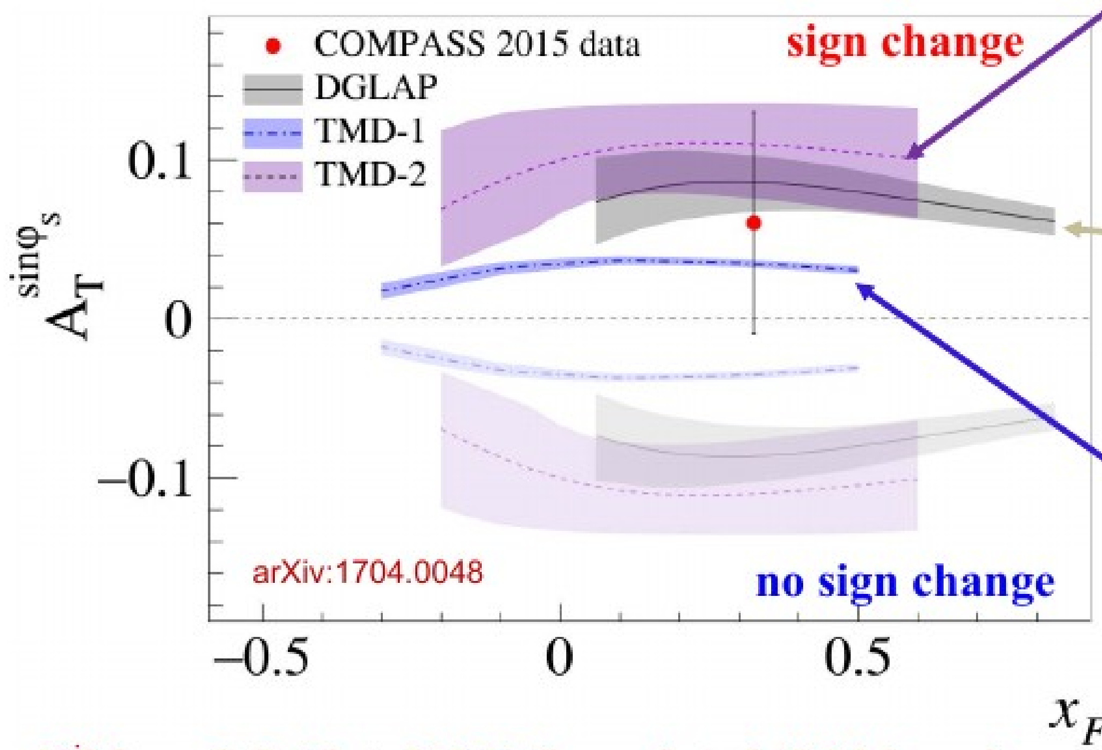
- Rate dependence correction has a kinematic dependence
- Leading order extraction
  - NLO code tested
- Correct method -> global fit
- Large x_{beam} dbar/ubar
- . . .

E906/SeaQuest: $\sigma_{pd}/2\sigma_{pp}$

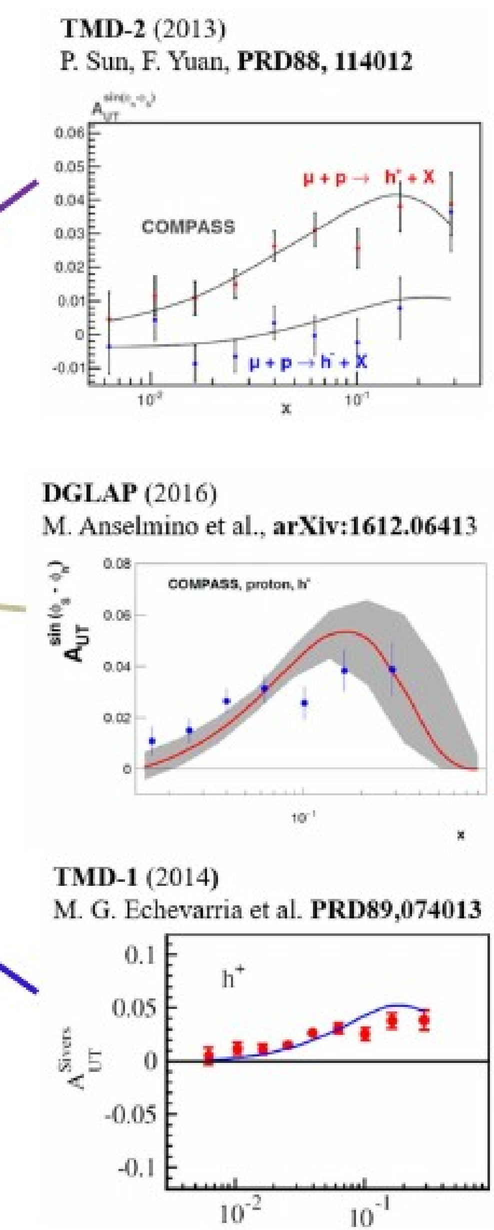


COMPASS 2015

- 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%



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

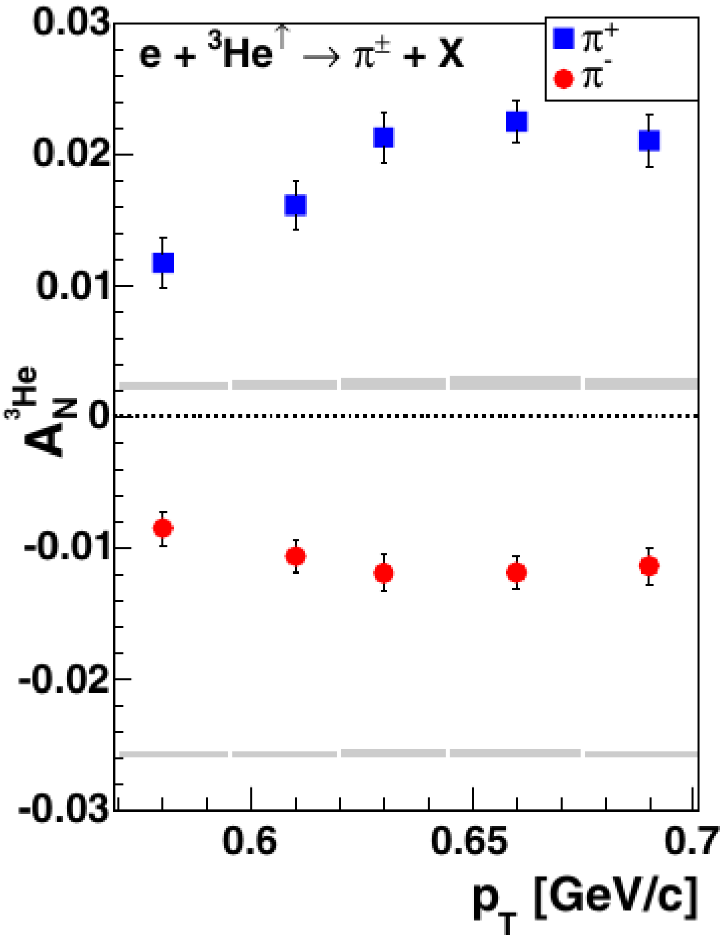


Ref: W.C. Chang (Academia Sinica)

JLab Hall B

$e + {}^3\mathrm{He}^{\uparrow} \to h + X$

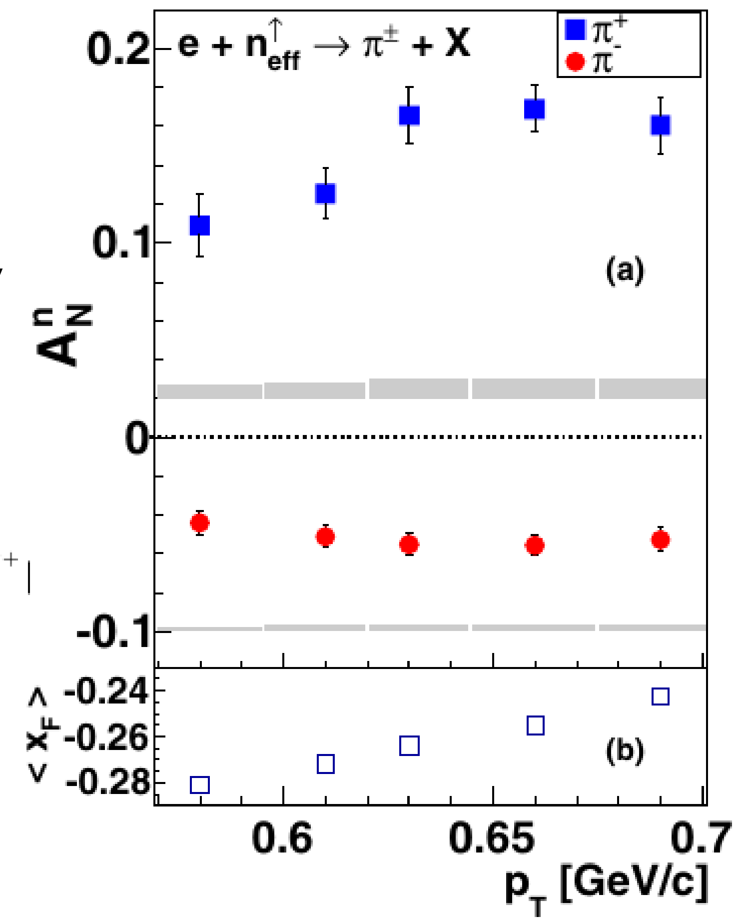
TSSA process preformed under assumption of SIDIS (significant soft process contribute)



Jefferson Lab
Hall A
using a 5.9 GeV
electron beam

$\sqrt{s} = 3.45$ GeV,

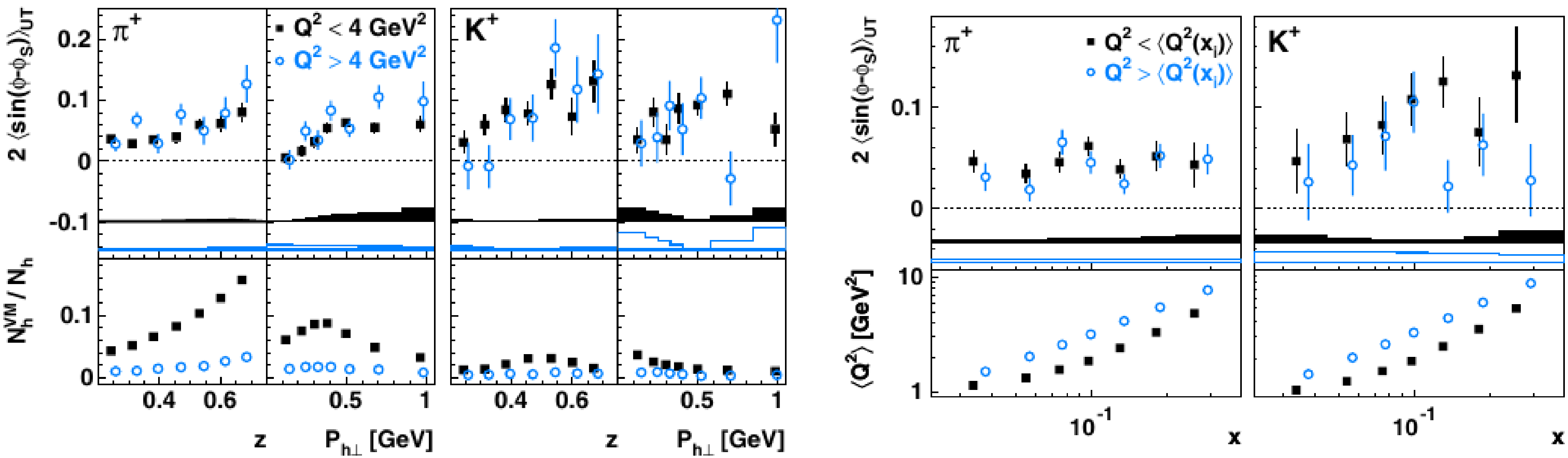
$|A^{\pi^-}| < |A^{\pi^+}| < |A^{K^+}|$



Phys. Rev. C89 (2014) 042201

SIDIS Sivers TMD for sea quarks

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} \propto \ldots + S_T\left[\sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \varepsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right) + \ldots\right] + \ldots$$



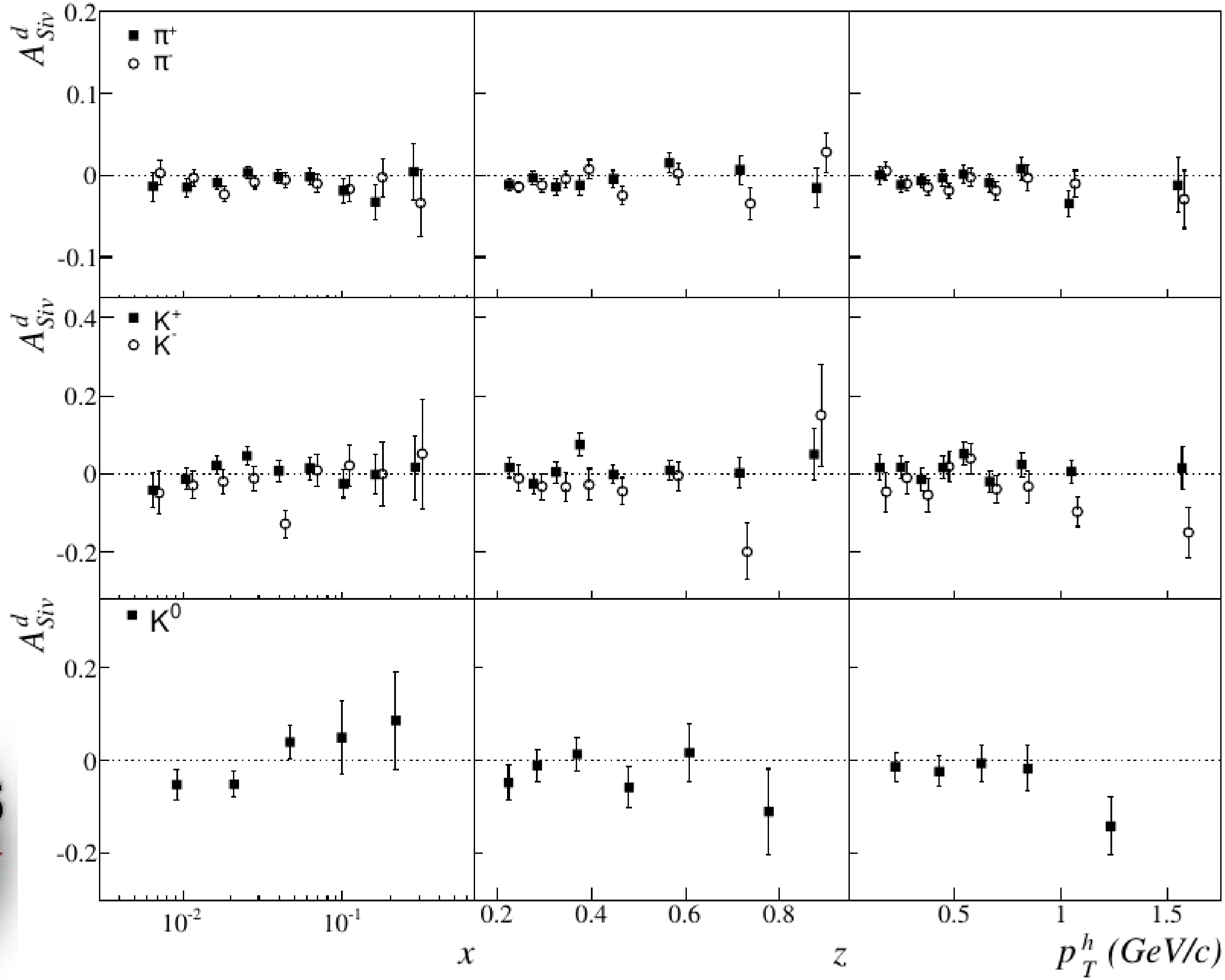
PhysRevLett.103.152002

SIDIS Siver TMD

transversely polarised

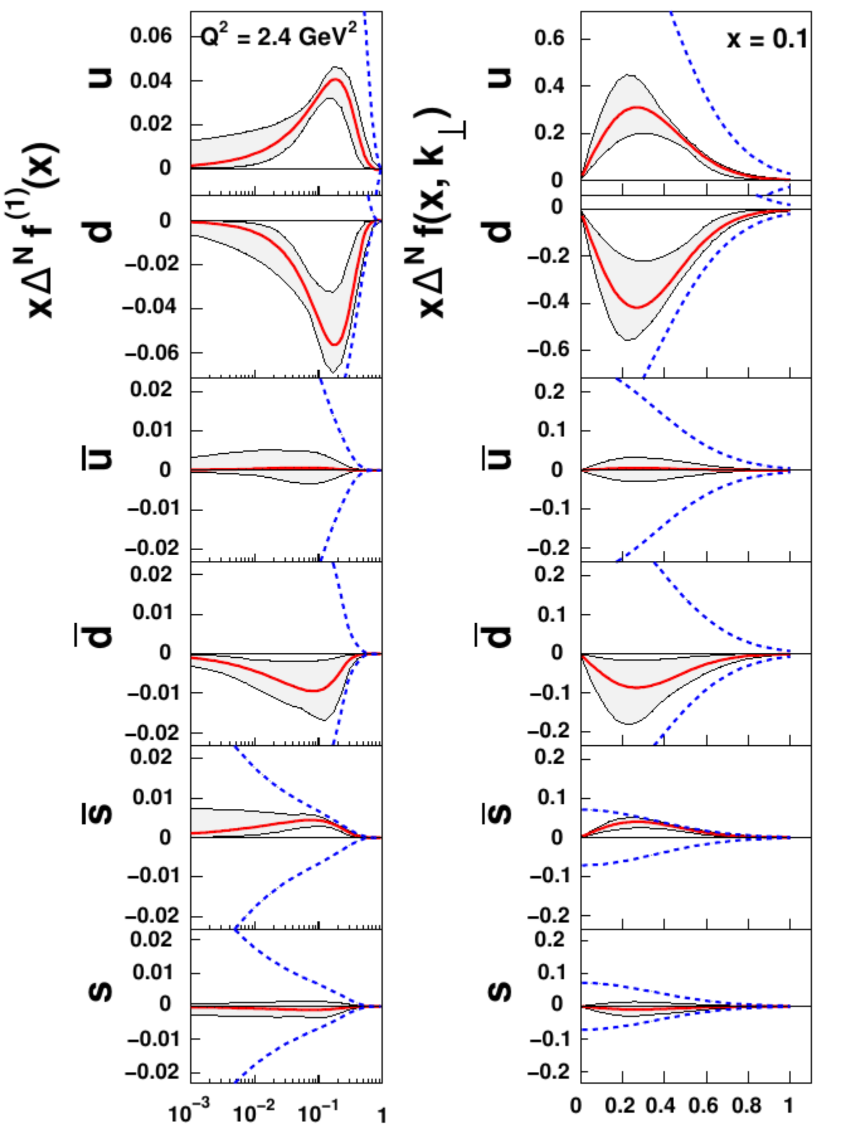
^{6}LiD target

160 GeV/c muons



Physics Letters B 673 (2009) 127–135

Sivers Distribution function



$x\,\Delta^N f(x, k_\perp)$

$$Q^2 = 2.4\ (\mathrm{GeV}/c)^2$$

fit of HERMES and COMPASS data

Sivers Effect for Pion and Kaon Production in Semi-Inclusive Deep Inelastic Scattering

M. Anselmino,[1,2] M. Boglione,[1,2] U. D'Alesio,[3,4] A. Kotzinian,[5,6,7] S. Melis,[1,2] F. Murgia,[4] A. Prokudin,[8,1,2] and C. Türk[1,2]

[1] *Dipartimento di Fisica Teorica, Università di Torino, Via P. Giuria 1, I-10125 Torino, Italy*
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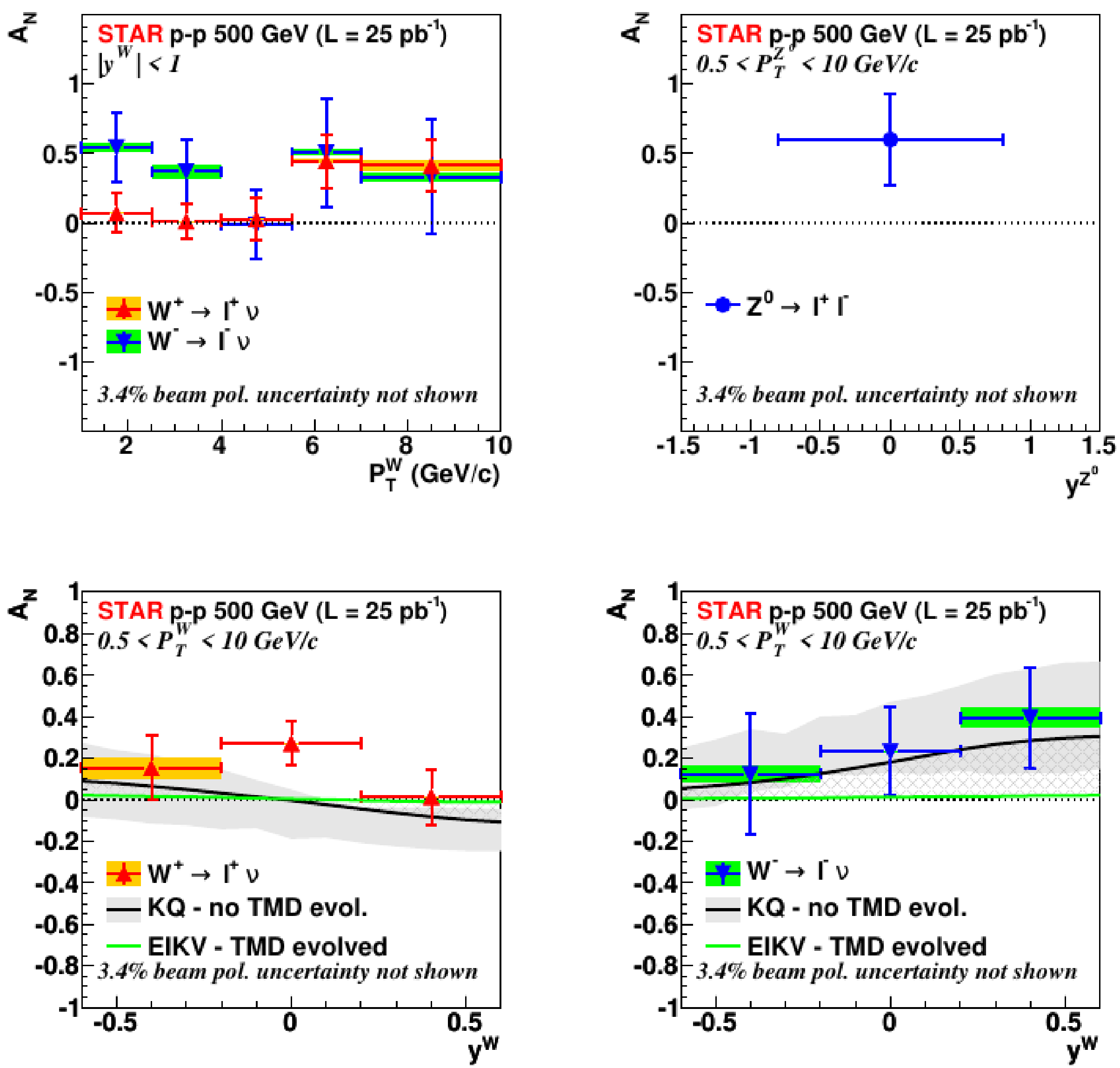
[5] *CEA-Saclay, IRFU/Service de Physique Nucléaire, 91191 Gif-sur-Yvette, France*
[6] *Yerevan Physics Institute, 375036 Yerevan, Armenia*
[7] *JINR, 141980 Dubna, Russia*
[8] *Di.S.T.A., Università del Piemonte Orientale "A. Avogadro", Alessandria, Italy*
(Dated: May 29, 2018)

first moment $x\,\Delta^N f^{(1)}(x)$

Measurement of the transverse single-spin asymmetry in $p^{\uparrow} + p \rightarrow W^{\pm}/Z^{0}$ at RHIC

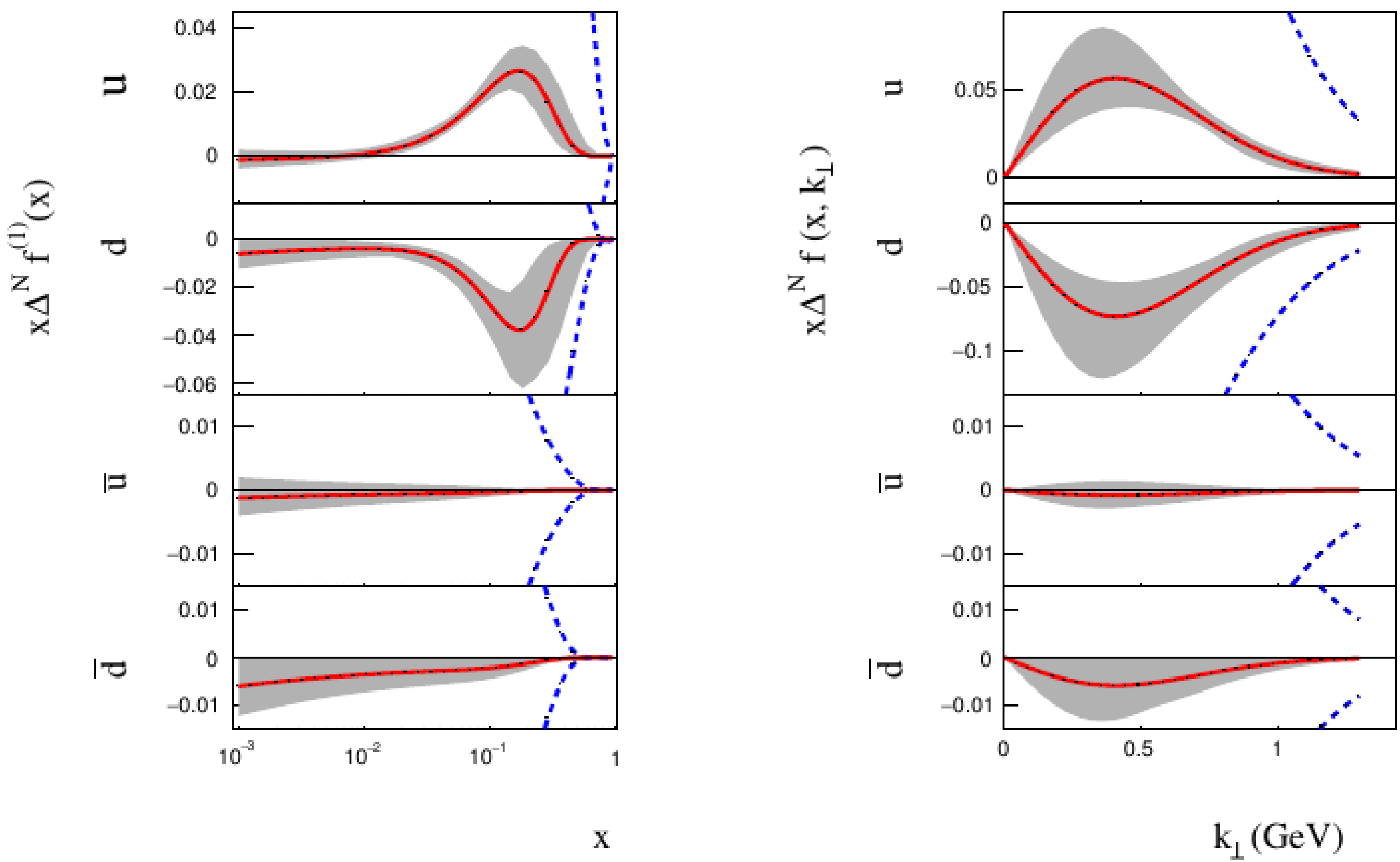
Phys. Rev. Lett. 116, 132301 (2016)



New World Data Fit

M. Anselmino,[a,b] **M. Boglione,**[a,b] **U. D'Alesio,**[c,d] **F. Murgia**[d] **and A. Prokudin**[e,f]

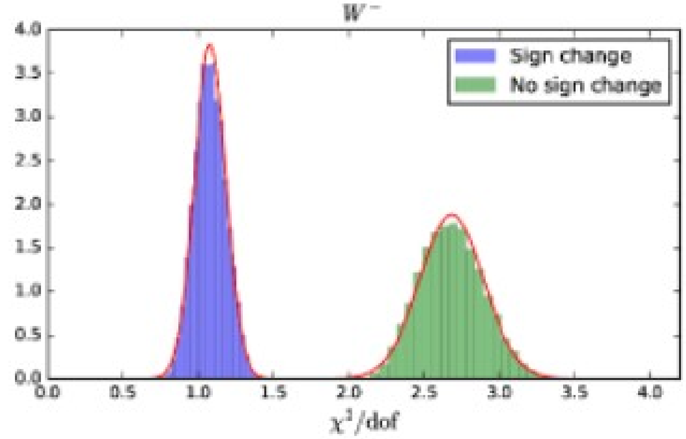
ArXiv ePrint: 1612.06413

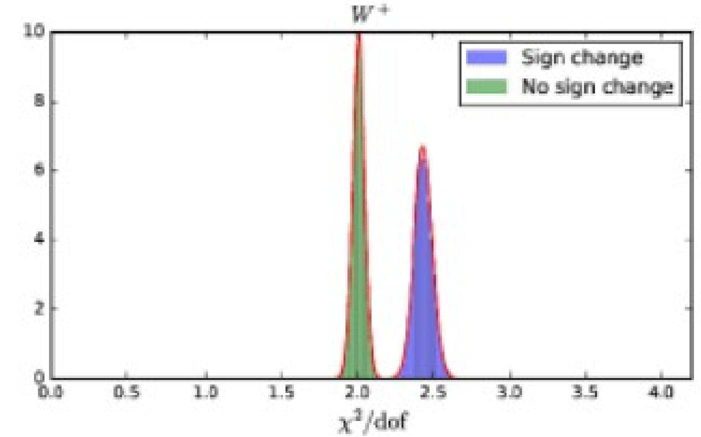


New World Data Fit

"Interesting" example by M. Anselmino et al (2017)

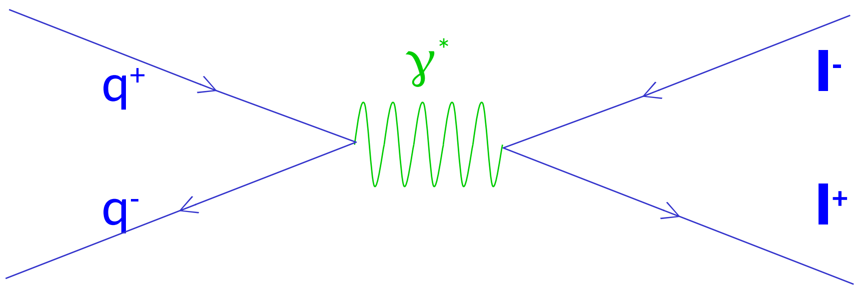
The sign-change (QCD prediction) is tested using the DY data of the W production from RHIC

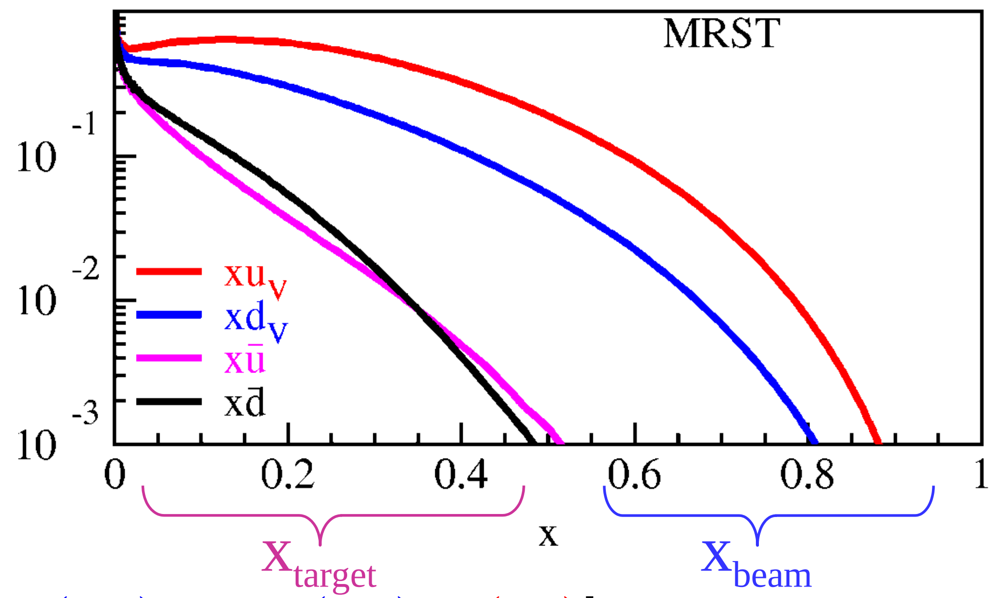




- The chi-square pdf with/without sign-change assumption applied to the DY data from RHIC which are the only available data of Sivers asymmetry from the DY process
- No solid conclusion about the sign-change as predicted by QCD
- Our SpinQuest data will have a big impact

Drell-Yan



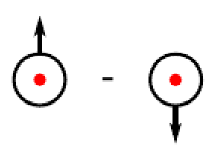


- Cross section is a convolution of beam and target parton distributions

$$\frac{d^2\sigma}{dx_{\mathrm{b}}dx_{\mathrm{t}}} = \frac{4\pi\alpha^2}{x_{\mathrm{b}}x_{\mathrm{t}}s} \sum_{q\in\{u,d,s,\dots\}} e_q^2 \left[\bar{q}_{\mathrm{t}}(x_{\mathrm{t}})q_{\mathrm{b}}(x_{\mathrm{b}}) + \bar{q}_{\mathrm{b}}(x_{\mathrm{b}})q_{\mathrm{t}}(x_{\mathrm{t}})\right]$$

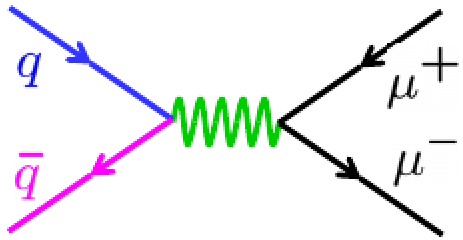
- u-quark dominance

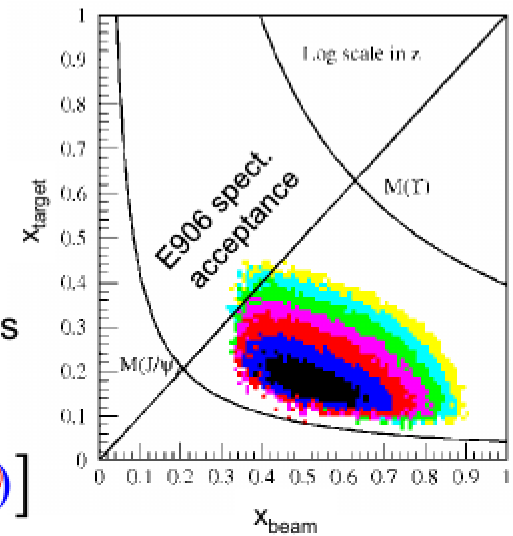
  $(2/3)^2$ vs. $(1/3)^2$

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

Beam	Sensitivity	Experiment
Hadron	Beam quarks target antiquarks	Fermilab, J-PARC RHIC (forward acpt.)
Anti-Hadron	Beam antiquarks Target quarks	J-PARC, GSI-FAIR Fermilab Collider
Meson	Beam antiquarks Target quarks	COMPASS, J-PARC

Fixed Target Drell-Yan: sensitivity to sea quarks





Cross section: convolution of beam and target parton distributions

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

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

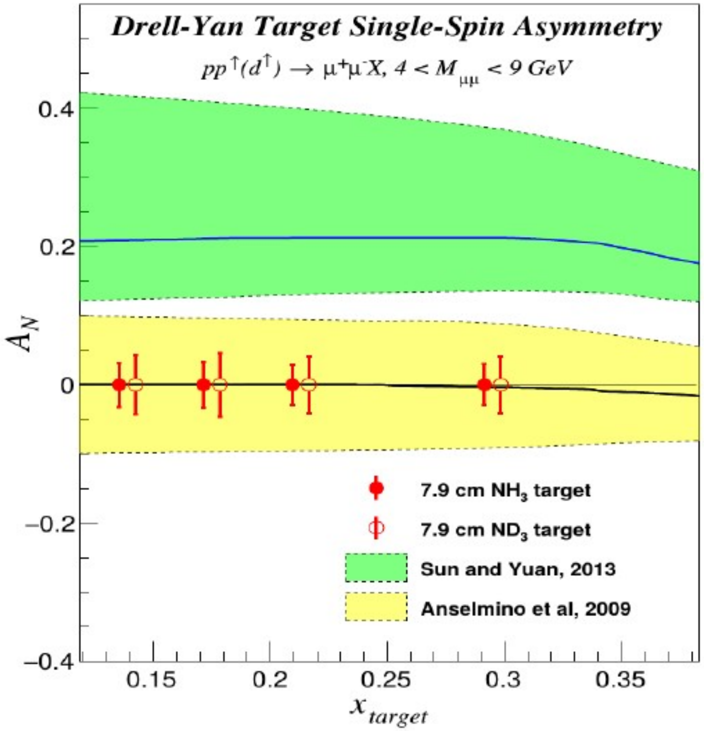
acceptance limited
(Fixed Target, Hadron Beam)

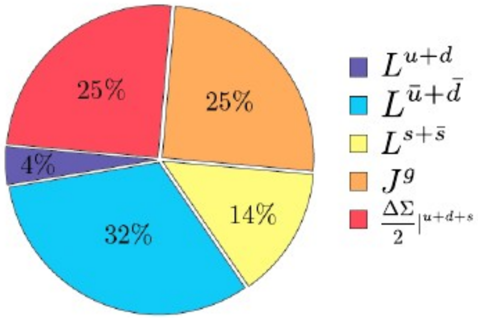
beam: valence quarks at high x

target: sea quarks at low/intermediate x

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

Polarized Drell-Yan





$$A_N\left(p_{beam} + p^{\uparrow}_{target} \rightarrow DY\right) \propto \frac{N_L^{DY} - N_R^{DY}}{N_L^{DY} + N_R^{DY}} \propto \frac{f_{1T}^{\perp,\bar{u}}(x_t)}{f_1^{\bar{u}}(x_t)}$$

$$A_N\left(p_{beam} + d^{\uparrow}_{target} \rightarrow DY\right) \propto \frac{N_L^{DY} - N_R^{DY}}{N_L^{DY} + N_R^{DY}} \propto \frac{f_{1T}^{\perp,\bar{d}}(x_t)}{f_1^{\bar{d}}(x_t)}$$

- First measurement of sea quark Sivers (ū, d̄)
- Sign and value
  - Result has strong implications for O.A.M. in spin puzzle
- If nonzero, “smoking gun” for Sea quark O.A.M.
- If zero, where is proton spin coming from?

SpinQuest Goals

- Separately measure Sivers function for the sea
- Measure Sign and Magnitude
- Measurement of Sivers function for gluons (J/psi SSA)
- Polarized dbar to ubar ratio

Extensions: transversity, tensor charge, tensor polarized observables, dark sector, polarized proton beam,...

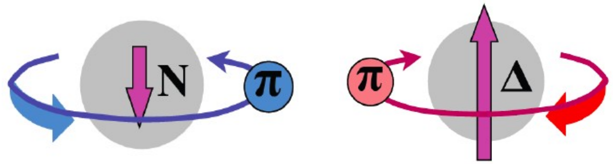
Physics Case

- Exploring the contribution of orbital angular momentum
- Interference between spin-flip and non-flip amplitudes with phase dependence
- Soft gluons

  - Gauge link required for color gauge invariance

  - Testing interplay between time-reversal symmetry and gauge symmetry

SpinQuest Goals

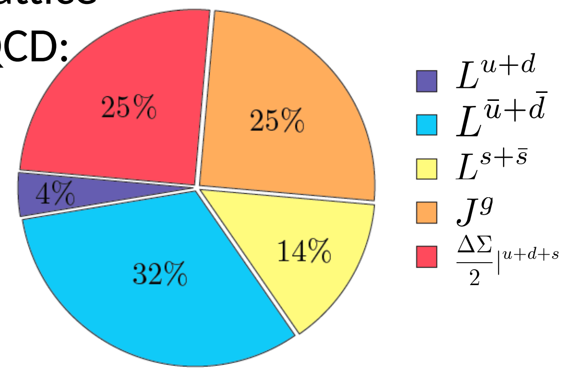


- Consider a nucleonic pion cloud
  $|p\rangle = |p_0\rangle + |N\pi\rangle + |\Delta\pi\rangle + \ldots$

  Pions $J^p=0^-$ Negative Parity
  Need L=1 to get proton's $J^p=\frac{1}{2}^+$

Sea quarks should carry orbital angular momentum.

Lattice QCD:



$\Delta\Sigma_q \approx 25\%$

$2\,L_q \approx 46\%$ (0%(valence)+46%(sea))

$2\,J_g \approx 25\%$

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

QDC Gauge Invariance

- Interference between spin-flip and non-flip amplitudes w/different phases
- Soft gluons
  - "gauge links" required for color gauge invariance
  - Re-interactions are final (or initial) state … and may be process dependent!

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

Proton Beam at FNAL

- 120 GeV proton beam
- $\sqrt{s} = 15.5$ GeV
- Projected Beam for E1039
  - Beam: 5×10^{12} p/spill; spill is 5 s/min
  - Protons on target per year
    - 7×10^{17}

Advantage of the Main Injector

The (very successful) past:

Fermilab E866/NuSea

- Data in 1996-1997
- ^{1}H, ^{2}H, and nuclear targets
- 800 GeV proton beam

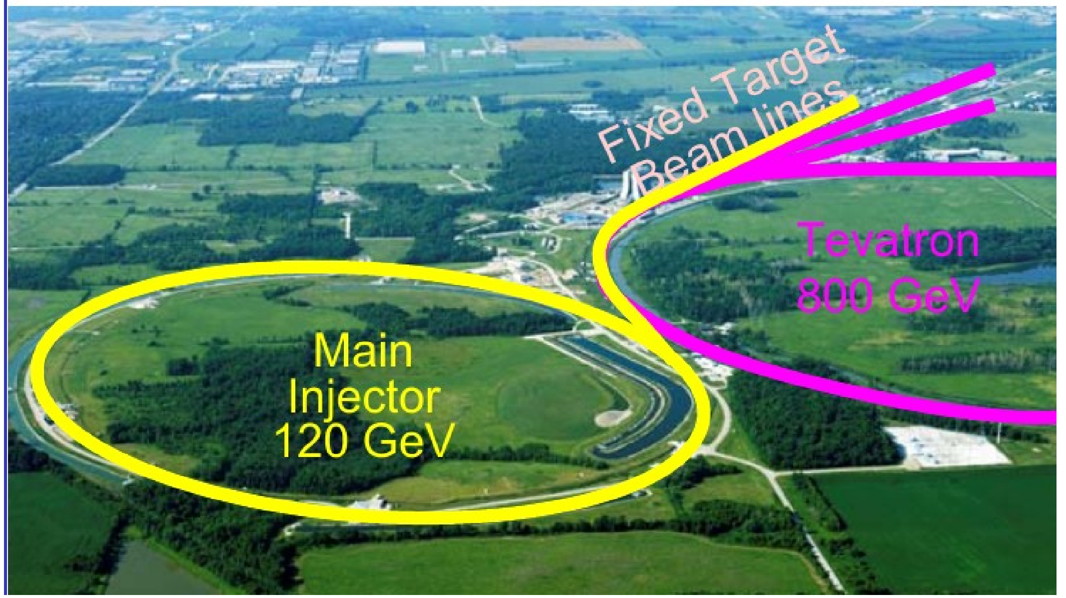
Fermilab E906

- Data in 2010
- ^{1}H, ^{2}H, and nuclear targets
- 120 GeV proton Beam And E1039

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s} \times \sum_i e_i^2 \left[q_{ti}(x_t)\bar{q}_{bi}(x_b) + \bar{q}_{ti}(x_t)q_{bi}(x_b)\right]$$

- Cross section scales as 1/s
  - *7× that of 800 GeV beam*
- Backgrounds, primarily from J/ψ decays scale as s
  - *7× Luminosity for same detector rate as 800 GeV beam*

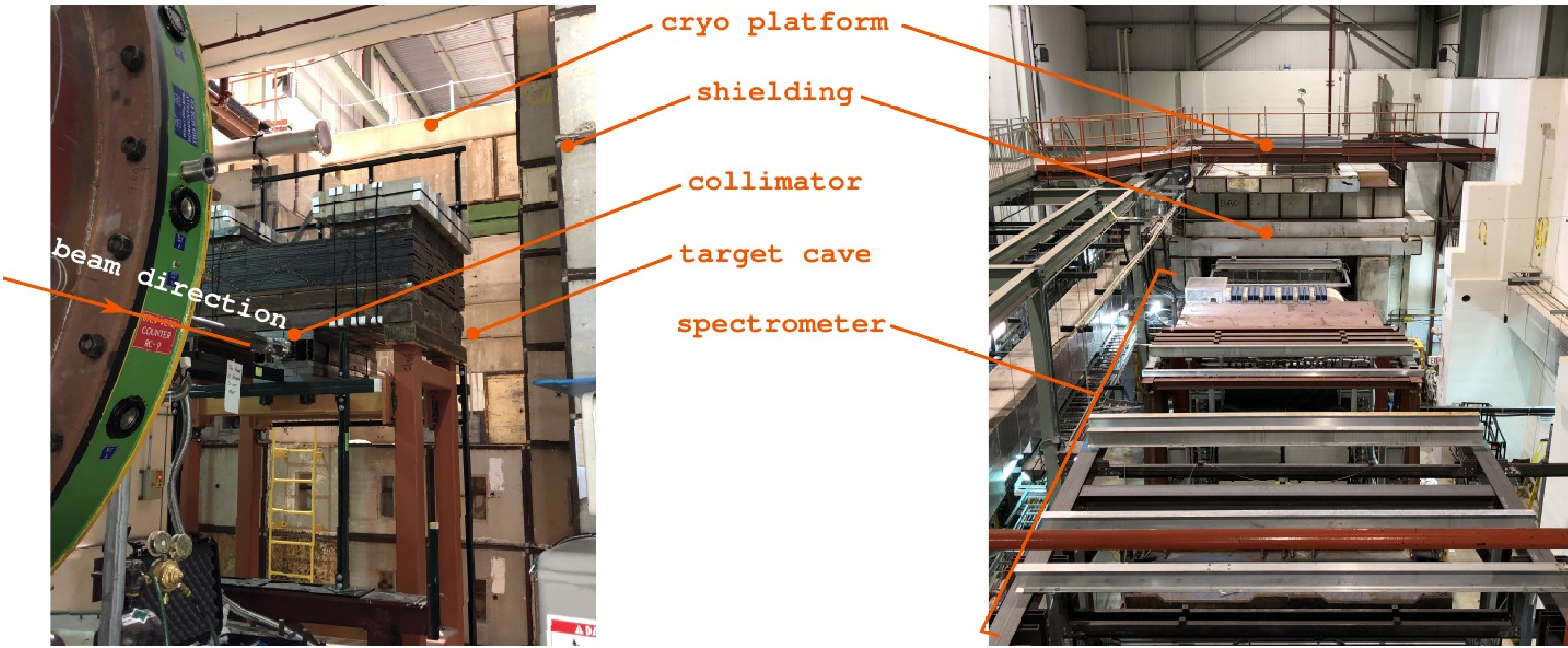
50× statistics!!



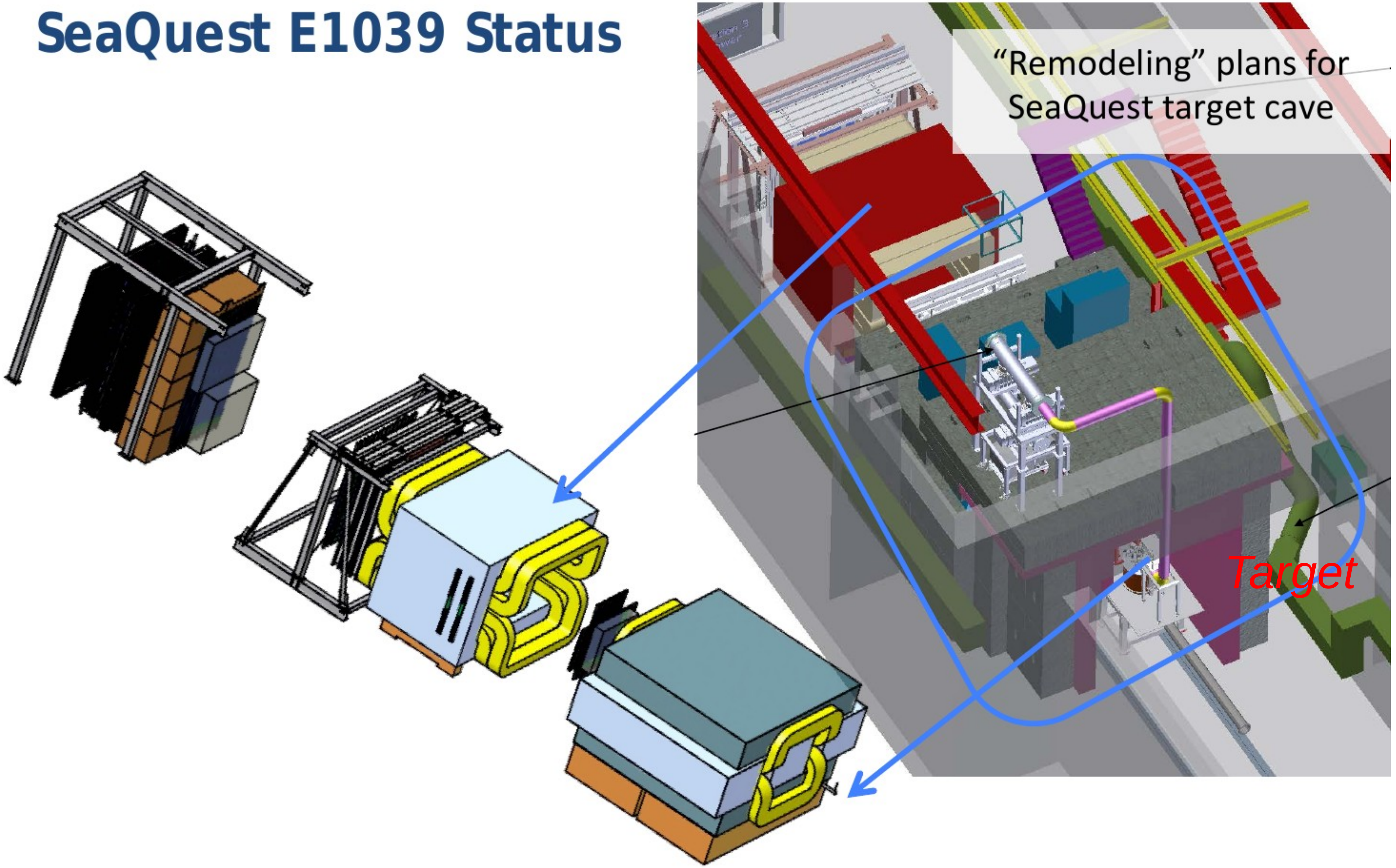
- special thanks to Fermilab support
  - beamline: new collimator
  - new radiation shielding design
  - new cryo platform for polarized target infrastructure
  - polarized target cave: new location 300cm upstream of FMAG

NM3: looking downstream

NM4: looking upstream



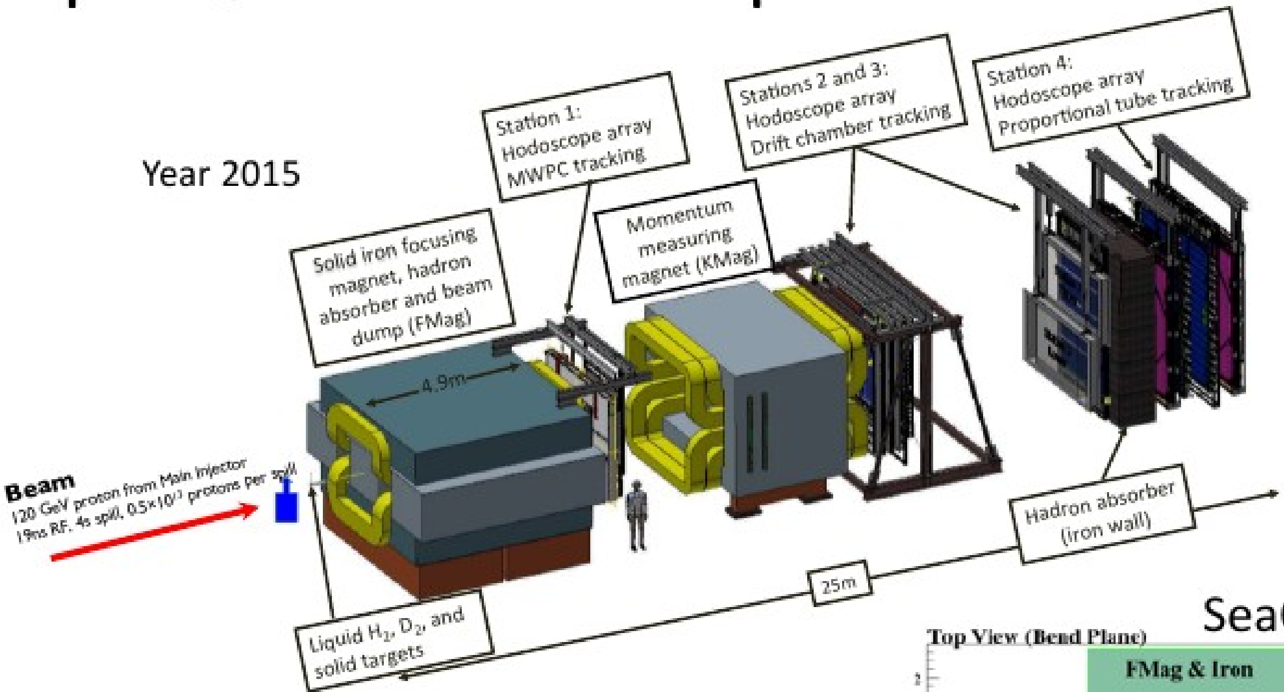
Experimental Setup for E1039



NM4 Detector

SpinQuest Dimuon Spectrometer

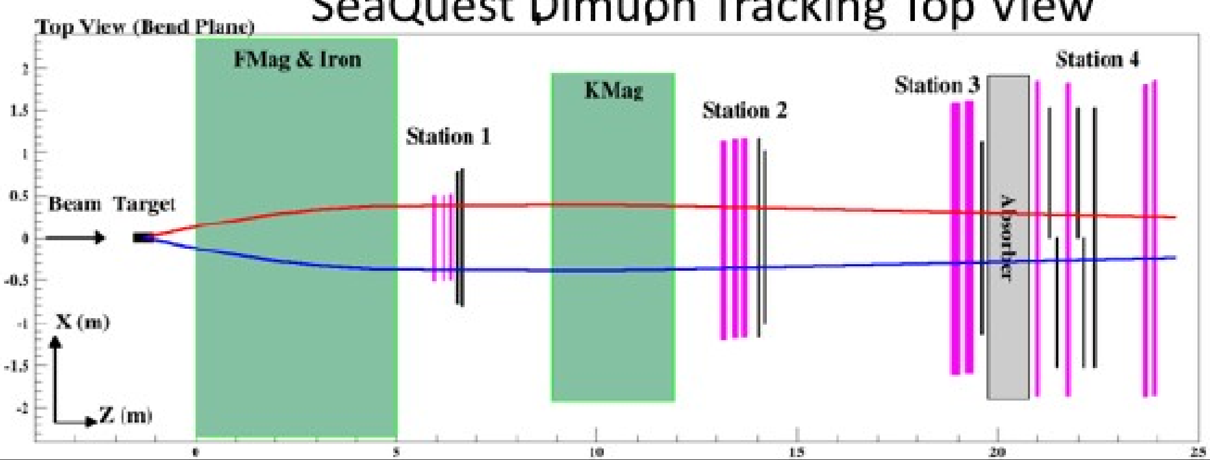
Year 2015



120 GeV protons from the Main Injector

- 4s beam spill very 60 sec
- 19ns RF, ~10s K protons per RF bucket
- 5×10^{12} Proton On Target (POT) per spill
- Total integrated POT for E1039 (2-year): 1.4×10^{18} POT

SeaQuest Dimuon Tracking Top View



E906 unpolarized targets: 2012-2017

- ^{1}H, ^{2}D, ^{12}C, ^{56}Fe, ^{184}W

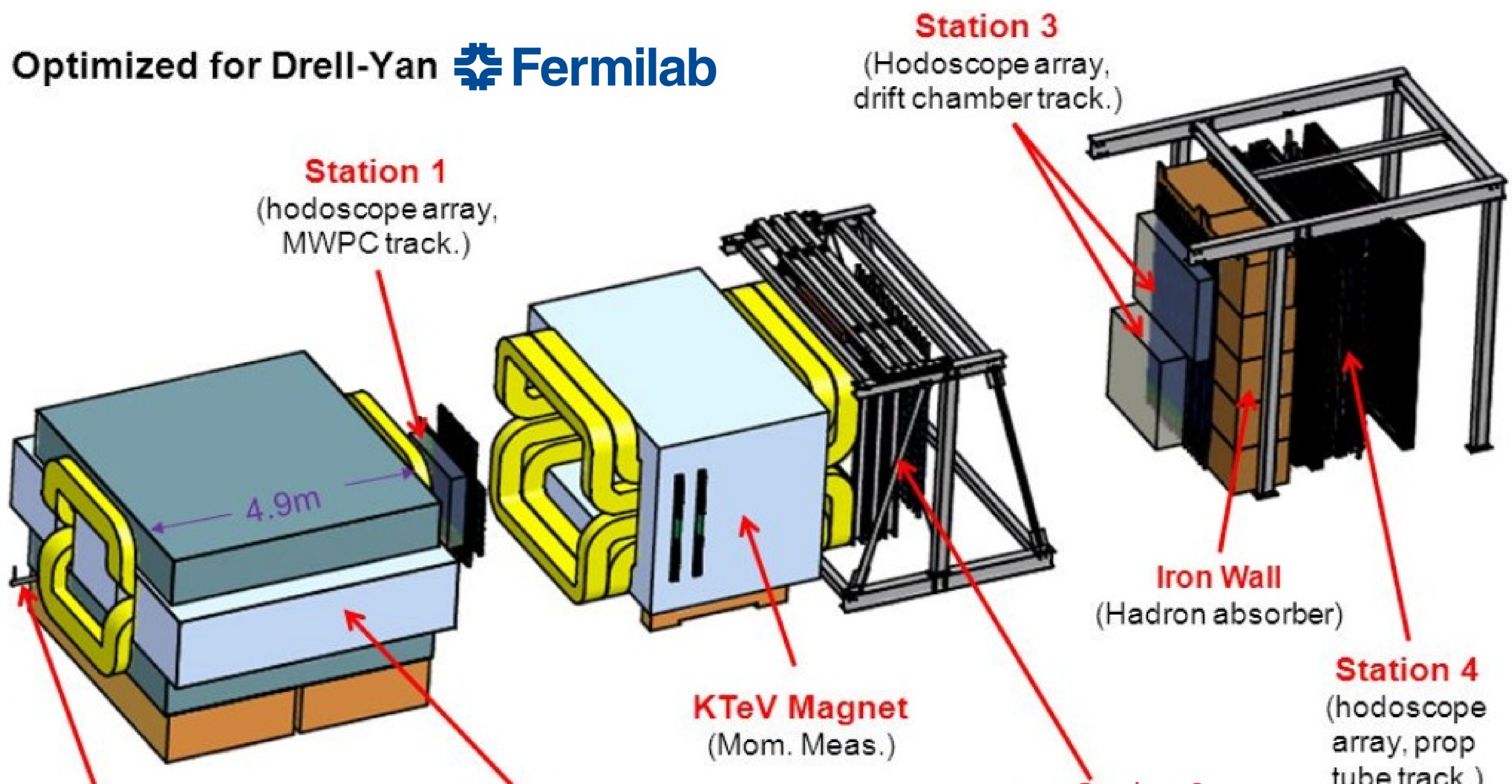
E1039 polarized targets: 2019 – 2021+

- Polarized protons (NH_3)
- Polarized neutrons (ND_3)

E1027 polarized beam

Experimental Setup for E1039

Detector Pack



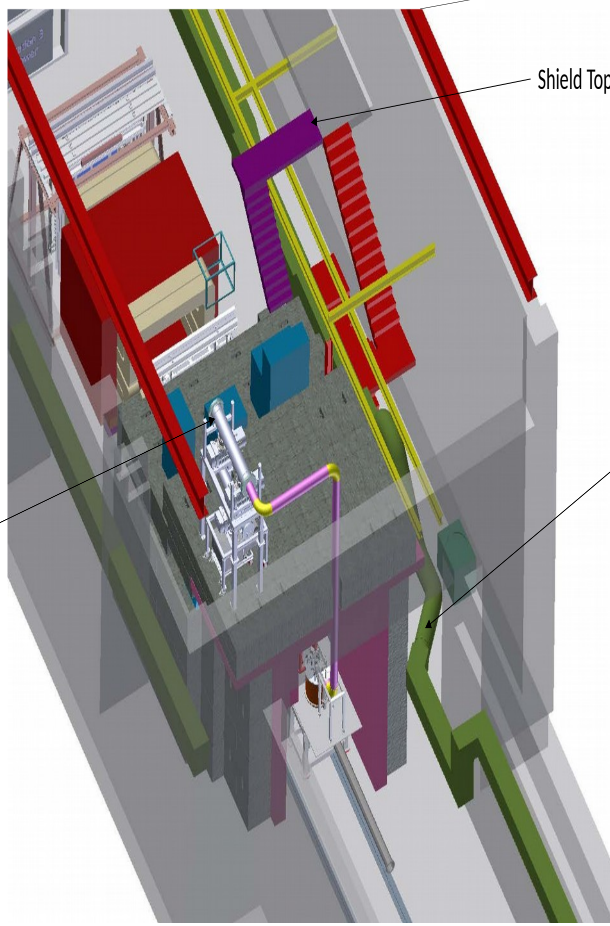
Target Cave: Under Construction

Solid Iron Magnet
(focusing magnet, hadron absorber and beam dump)

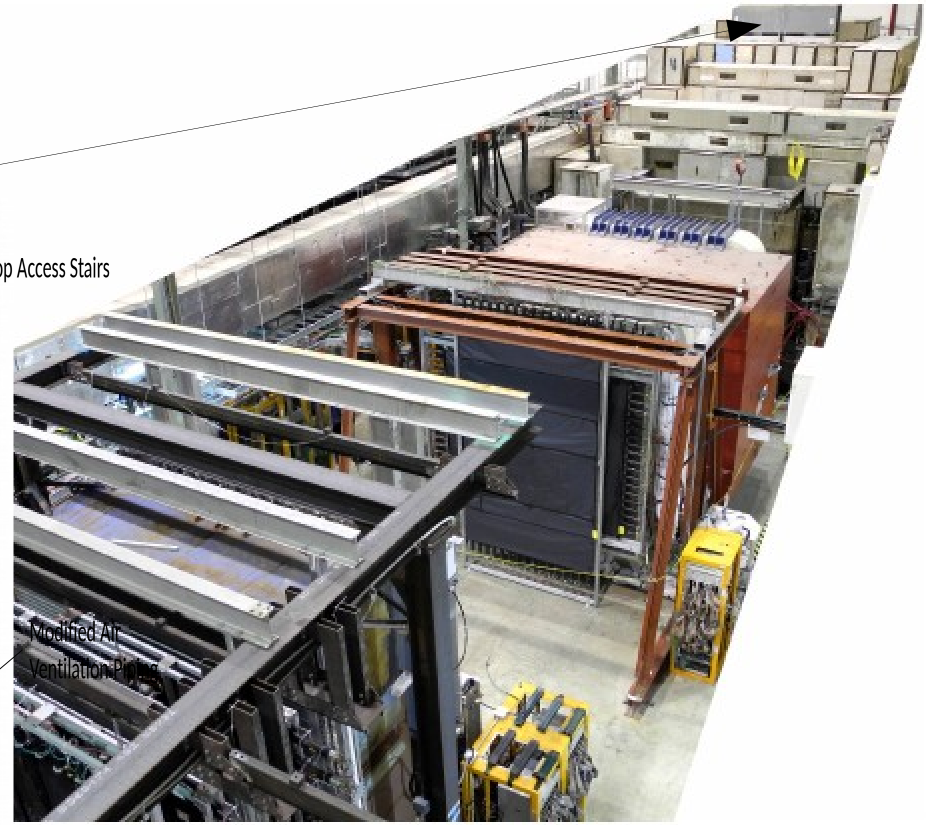
Station 2
(Hodoscope array, drift chambers track)

SpinQuest Experimental Hall

Beam



Target Cave



Target area

F-Mag

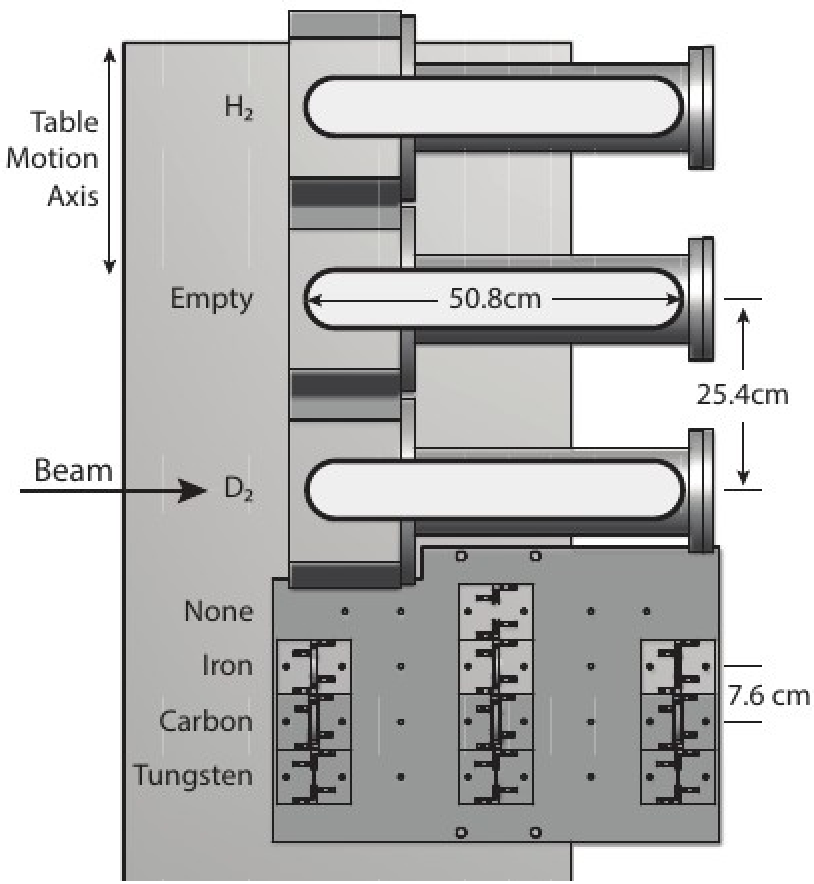
K-Mag

Muon-ID

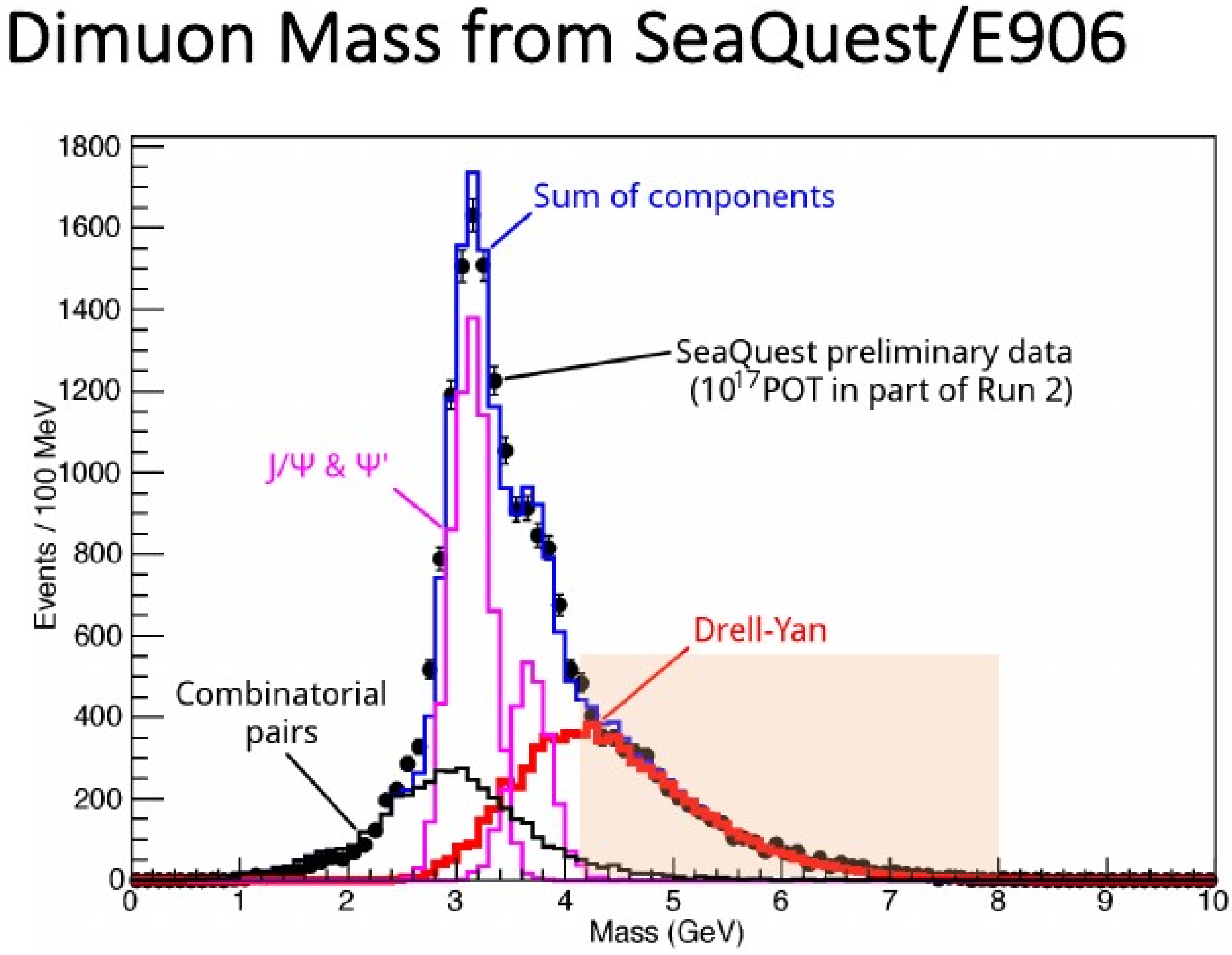
Look from down stream

E906 Unpolarized Physics Program

- Thin targets: ~10% interaction length
  - Liquid H/D
  - Solid C, Fe, W
- Physics
  - Sea quark flavor asymmetry, dbar/ubar
  - Quark energy loss in p+A collisions, dE/dx
  - TMD and more …
- Experimental runs – 6 years
  - 2012 – commissioning
  - 2017 – completed



Preliminary Look from SeaQuest



SeaQuest Status (E906)

Main Injector beam in a slow spill—difficult to obtain good duty factor

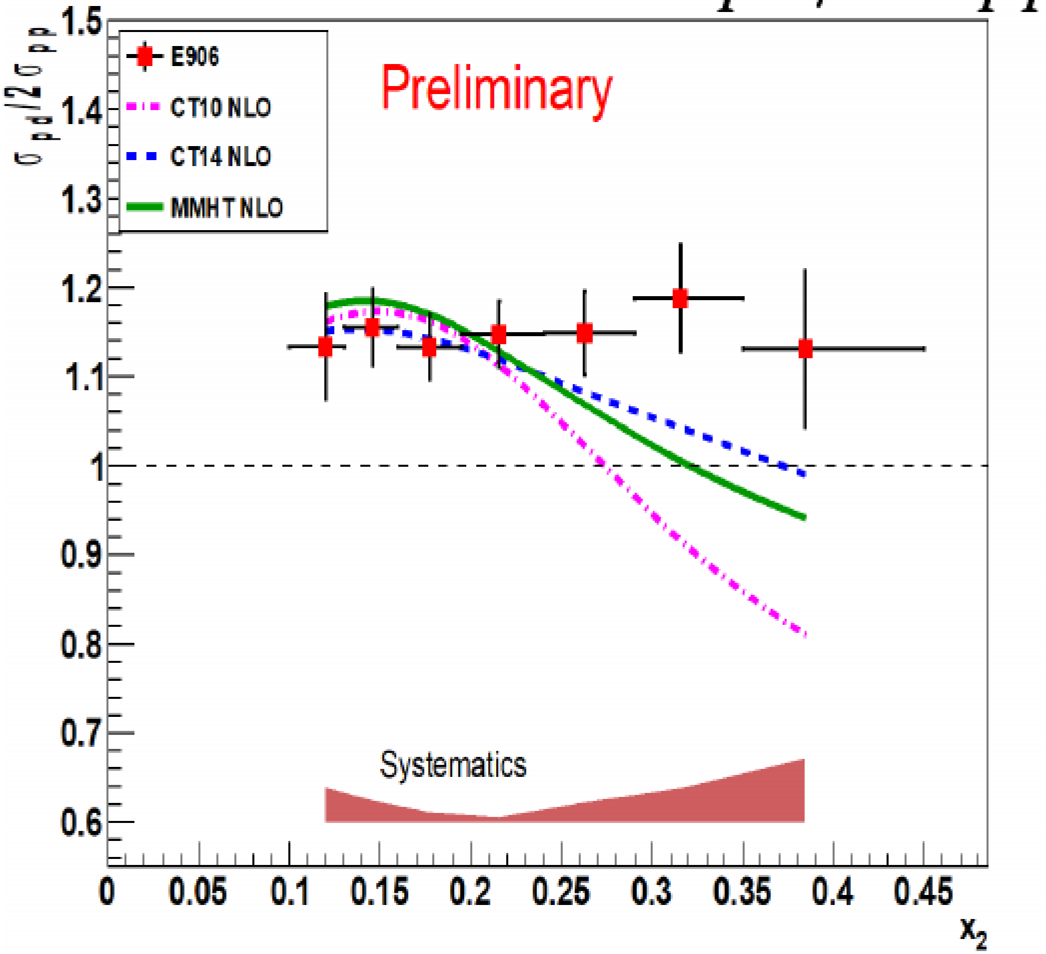
- 1.4×10^{18} of the 5.3×10^{18} approved "live protons"
- 1.7×10^{18} of the 7×10^{18} protons with good duty factor

3.5 x 10^{17} live protons
¼ of recorded protons

Caveats:

- Rate dependence correction has a kinematic dependence
- Leading order extraction
  - NLO code tested
- Correct method -> global fit
- Large x_{beam} dbar/ubar
- . . .

E906/SeaQuest: $\sigma_{pd}/2\sigma_{pp}$

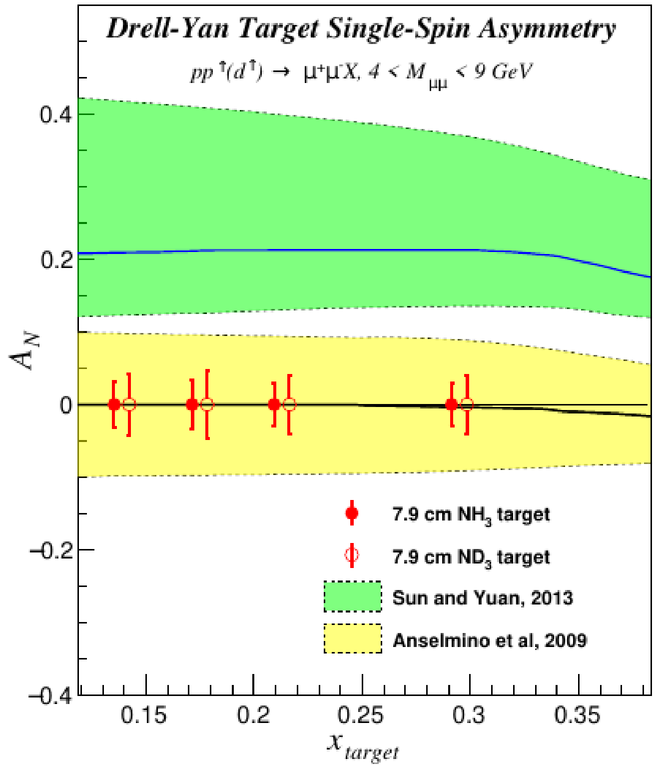


SpinQuest Projections

Projected Drell-Yan Transverse Single Spin Asymmetry

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

$$\delta A = \frac{1}{f}\frac{1}{P}\frac{1}{\sqrt{N^+ + N^-}}$$



x_2 bin	$< x_2 >$	NH_3 ($p^\uparrow$)		ND_3 ($d^\uparrow$)		$n^\uparrow$
		N	ΔA (%)	N	ΔA (%)	ΔA(%)
0.10 - 0.16	0.139	5.0×10^4	3.2	5.8×10^4	4.3	5.4
0.16 - 0.19	0.175	4.5×10^4	3.3	5.2×10^4	4.6	5.7
0.19 - 0.24	0.213	5.7×10^4	2.9	6.6×10^4	4.1	5.0
0.24 - 0.60	0.295	5.5×10^4	3.0	6.4×10^4	4.1	5.1

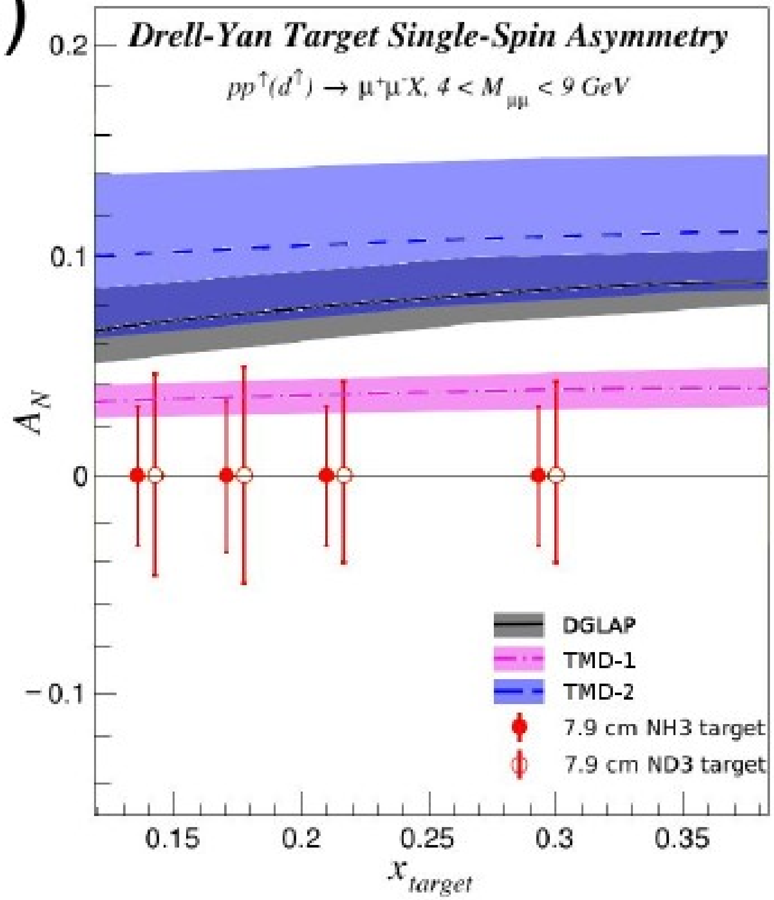
$$f = \frac{N_D \sigma_{D,H}}{N_N \sigma_N + N_D \sigma_D + \Sigma N_A \sigma_A}$$

Others: Nitrogen, Helium, Target cell, Aluminum, Thin beam window, NMR coil, …

Projections of Systematics

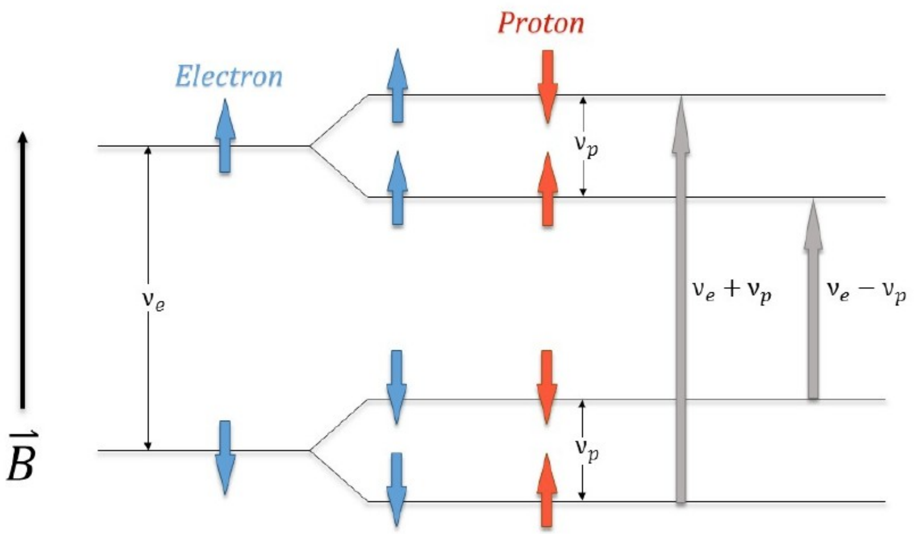
Error estimates (non-exhaustive)

- Statistical: 3%-5% absolute error
  - Dependent on polarization, dilution, events
  - Dependent on run time
- Systematic: Mostly relative error, some absolute. Numbers listed hopeful upper bounds
  - Target: ~6/7% (P/D)
    - Dilution: 3%
    - Packing Fraction: 2%
    - Density: 1%
    - Polarization: 2.5%/4.5% (P/D)
    - Polarization Homogeneity: 2%
    - Uneven Decay: 3%
    - Alignment: small absolute possible
  - Beam: 2.5%
    - Relative Luminosity: 1%
    - Drifts: 2% (Absolute possible)
    - Scraping: 1%
  - Detector: 1% (Some relative, Absolute possible)



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

Dynamic Nuclear Polarization

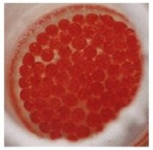
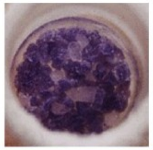


Electron relaxation time ~milliseconds

Proton relaxation time ~10s of minutes

Successful material for DNP characterized by three measures:

1. Maximum polarization
2. Dilution factor
3. Resistance to ionizing radiation

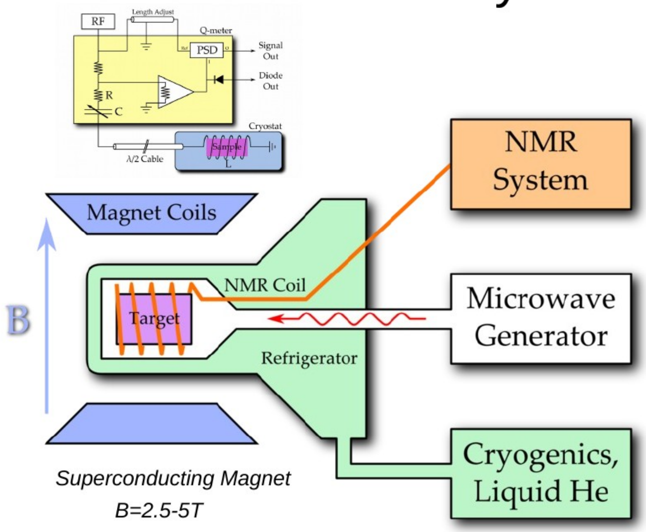




Material	Butanol	Ammonia, NH_3	Lithium Hydride, ^7LiH
Dopant	Chemical	Irradiation	Irradiation
Dil. Factor (%)	13.5	17.6	25.0
Polarization (%)	90-95	90-95	90
Material	D-Butanol	D-Ammonia, ND_3	Lithium Deuteride, ^6LiH
Dil. Factor (%)	23.8	30.0	50.0
Polarization (%)	40	50	55
Rad. Resistance	moderate	high	very high
Comments	*Easy to produce and handle*	*Works well at 5T/1K*	*Slow polarization, but long T_1*

- Dynamic Nuclear Polarization
  - Dope target material with paramagnetic centers:
    chemical or irradiation doping to just the right density (10^{19} spins/cm^3)
  - Polarize the centers: Just stick it in a magnetic field
  - Use microwaves to transfer this polarization to nuclei:
    mutual electron-proton spin flips re-arrange the nuclear Zeeman populations to favor one spin state over the other
- Optimize so that DNP is performed at *B/T* conditions where electron t_1 is short (ms) and nuclear t_1 is long (minutes or hours)

$$P_{TE} = \frac{e^{\frac{\mu B}{kT}} - e^{\frac{-\mu B}{kT}}}{e^{\frac{\mu B}{kT}} + e^{\frac{-\mu B}{kT}}} = \tanh\left(\frac{\mu B}{kT}\right)$$

General System



Polarization Detection

Tuned To Larmor of spin species

Proton (42.6 MHz/T)

Larmor-ESR

50-185 GHz

~140 GHz at 5T

T=0.03-1K

Polarized Target

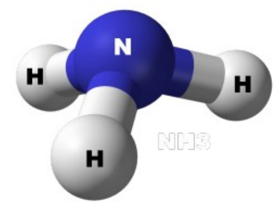
Material	Dens. (g/cm^3)	Length (cm)	Interaction Length (cm)	Dilution Factor	Packing Fraction	$< P_z >$
NH_3	0.867	7.9	91.7	0.176	0.6	80%
ND_3	1.007	7.9	82.9	0.3	0.6	32%

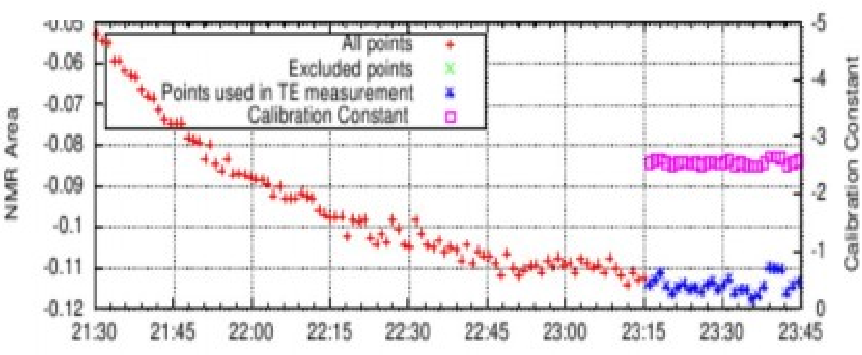
- 3 probes over length of target.
- NMR expected to have 2-3% error for proton 4-5% for deuteron. Deuteron signal order of magnitude smaller.
- If coils moved outside cup, possible increase in uncertainty for deuteron.
- Need time to thermalize. Need 3xt1 (relaxation rate, ~10 min for proton, 1 hour for deuteron). 2-3x more error if rushed.
- Built-in error for neutron polarization from deuteron.

$$\Delta A_N = \frac{1}{f}\frac{1}{P}\frac{1}{\sqrt{N}}$$

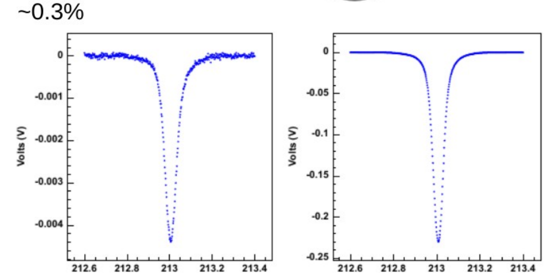
$$f \equiv \frac{N_{p,polarizable}}{N_p + N_n} = \frac{p\times 3}{p\times(7+3)+n\times 7} = \frac{3}{17}$$

$$f \equiv \frac{N_{p,polarizable}\ \sigma_{\pi p}^{DY}}{N_p\sigma_{\pi p}^{DY} + N_n\sigma_{\pi n}^{DY}}$$





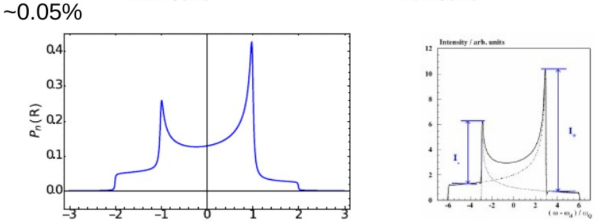
~0.3%



Proton

$$P_{TE} = \tanh\left(\frac{\mu B}{kT}\right)$$

~0.05%



Deuteron

$$P_{TE} = \frac{4+\tanh\frac{\mu B}{2kT}}{3+\tanh^2\frac{\mu B}{2kT}}$$

$$P_z = \frac{R^2-1}{R^2+R+1}$$

Neutron $P_n = (1-1.5\alpha_D)P_d \approx 0.91 P_d$

Polarized Target

Material	Dens. (g/cm^3)	Length (cm)	Interaction Length (cm)	Dilution Factor	Packing Fraction	$< P_z >$
NH_3	0.867	7.9	91.7	0.176	0.6	80%
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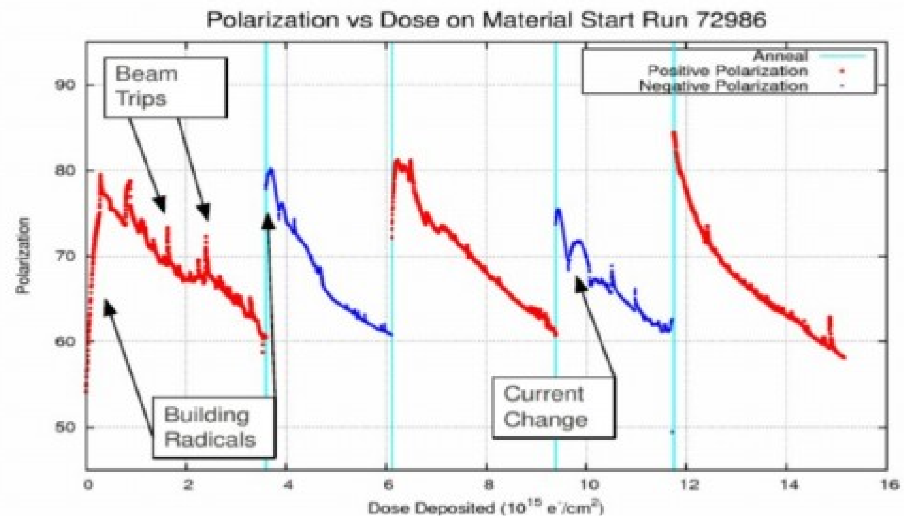
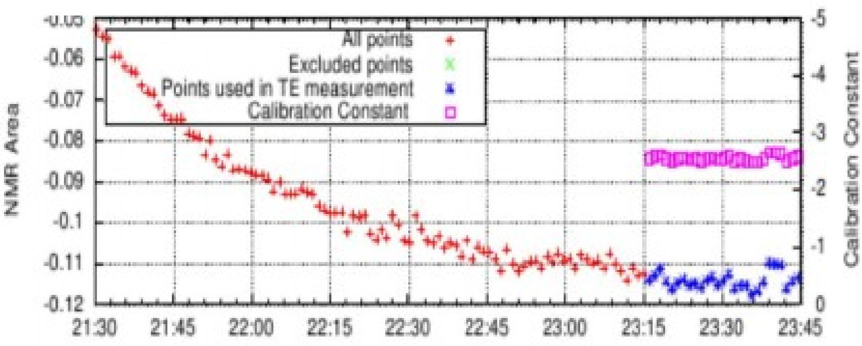
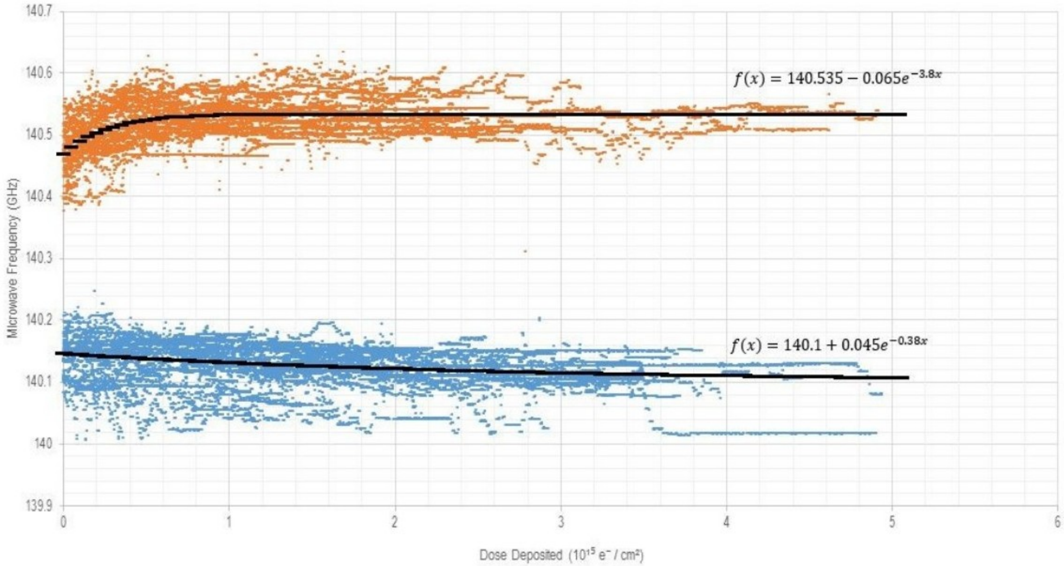
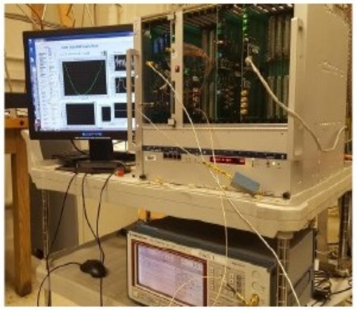






Firsts for Polarized Targets

UVA-LANL: Three completely new NMRs



NMR

UVA: Design

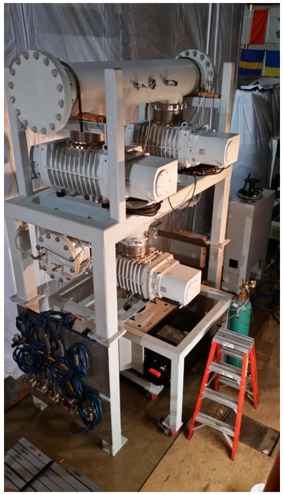
Insert

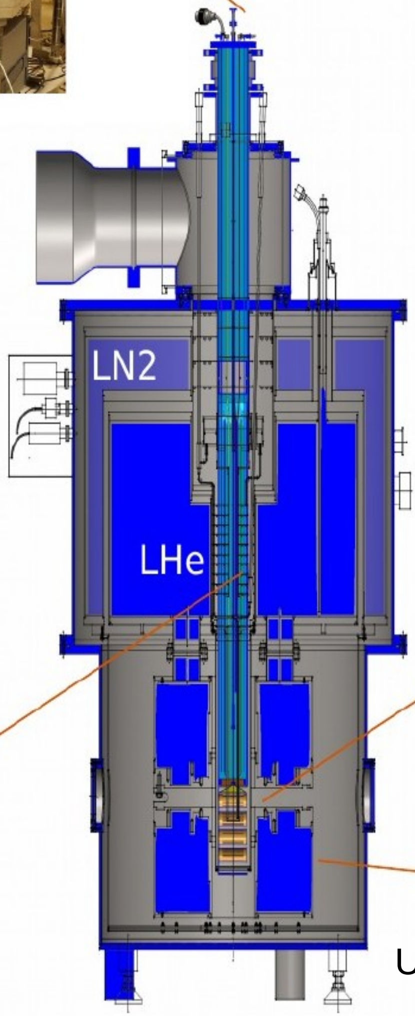
CPI

UVA: Tune System and Automation

Microwave

NIST National Institute of Standards and Technology U.S. Department of Commerce





oerlikon

Pumps

14,000 providing the highest cooling power for 1K system

Target material

UVA: Target Insert with longest cell at 8 cm for 5T

Fridge

UVA: Configure Fridge and Insert, Commission for Optimal running, setup with Actuator

Magnet

OXFORD INSTRUMENTS

UVA: Commissioning, Slow Controls, Quench Study, Beamline interface,...

Polarized target on the Intensity Frontier

Highest Intensity proton beam on polarized target with 4.4×10^{12} over 4.4s spill

- 8 cm long target cell of solid:

  NH_3 and ND_3

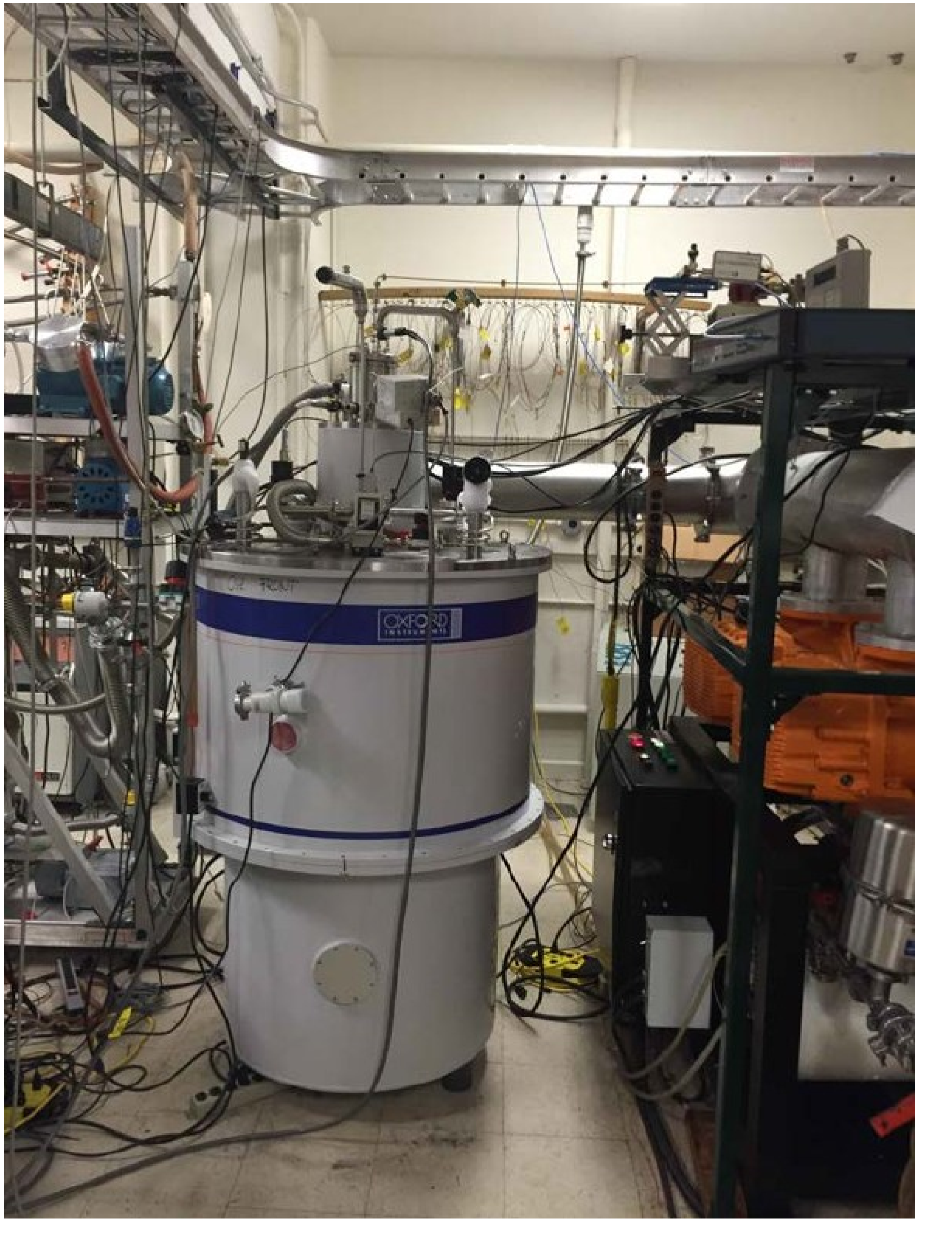
- Several watts of cooling power:

  14,000 m^3/hour pumping

- 5T vertically pointing SC magnet:

  Pushing critical temp each spill

- Luminosity of around $2X10^{35}$ cm^{-2} s^{-1}

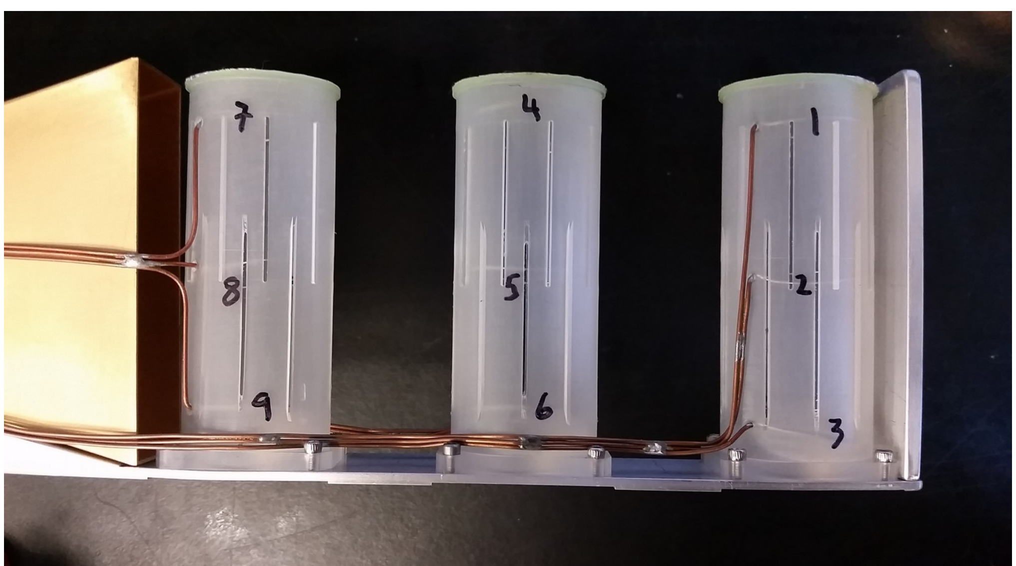


Target Insert

Carbon fiber with copper heat sink

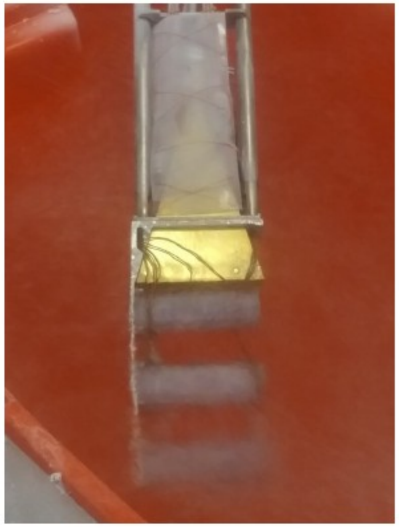
20X27 mm elliptical cells

long cell length microwave horn

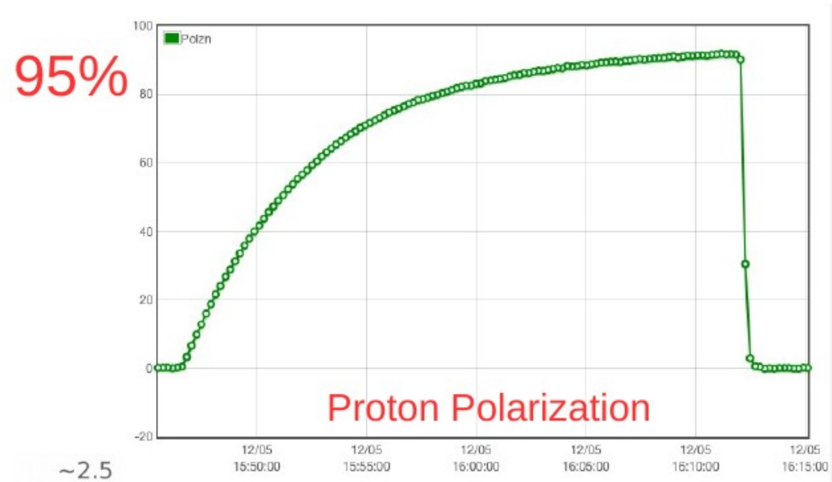


- 3 NMR coils per cell
- 8 cm long target cell of solid:
  NH_3 and ND_3
- Standard Insert has 3 cells
- One centering cell
- Elliptically shaped to match profile

Target Performance

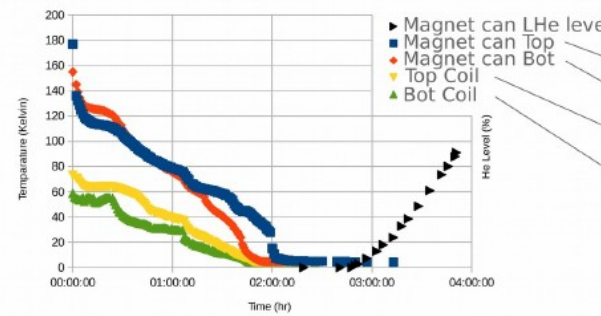


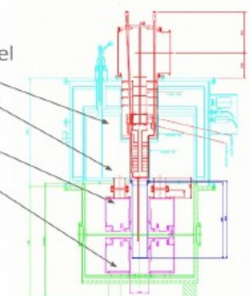
Insert in LN2



~2.5

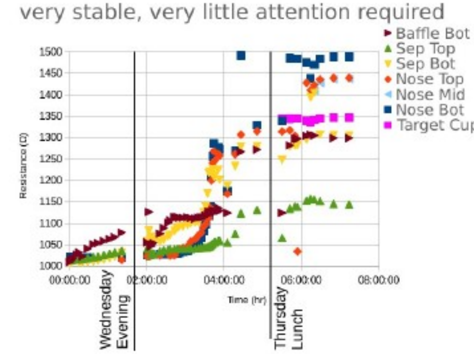
~1 hr to to fill magnet can





~1hr to fill the nose after a night on standby

very stable, very little attention required

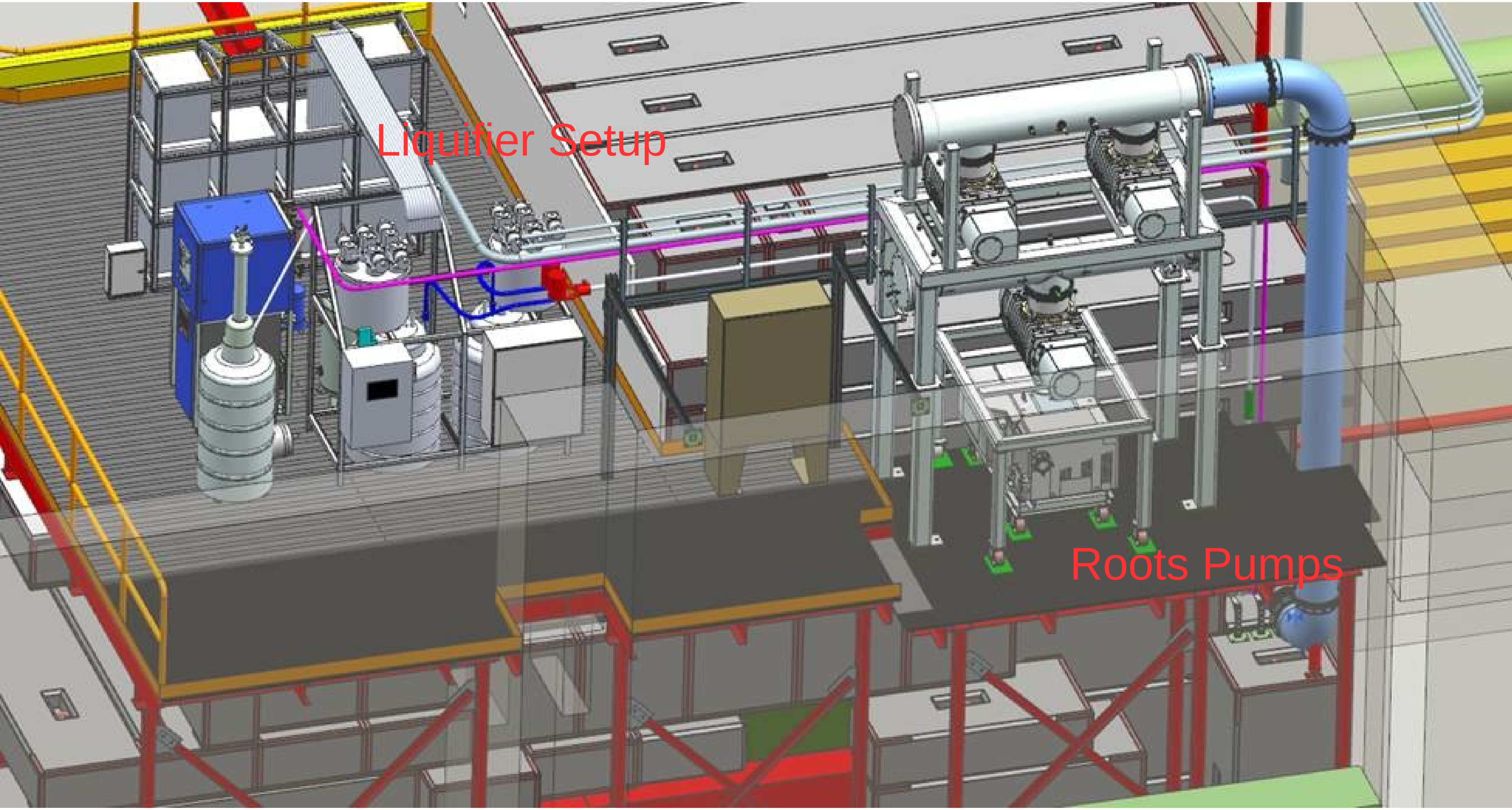


SpinQuest He-Liquefier

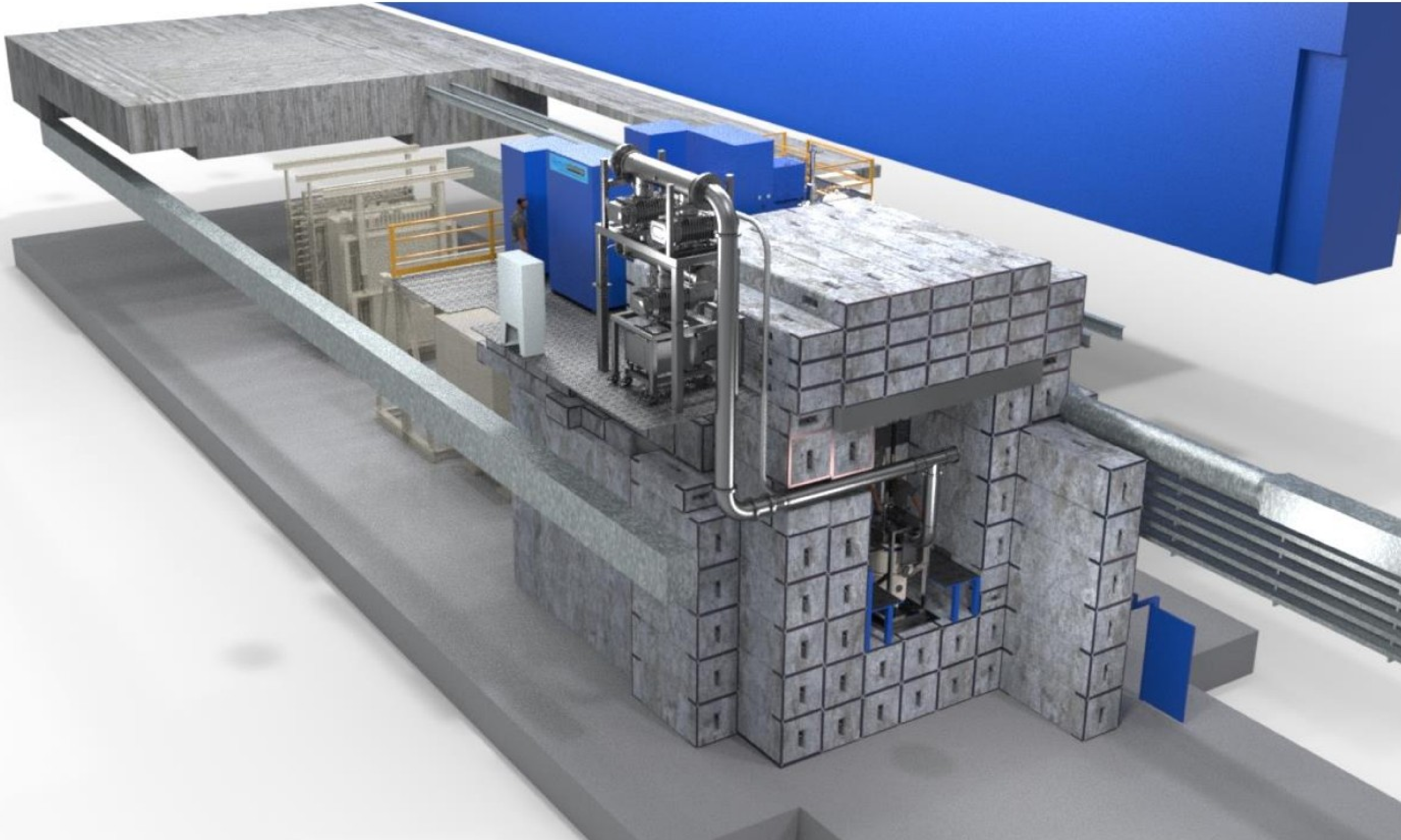
Modern He-Gas Recovery, Purification and Liquefier system

- Model QDHRR100 (2 units: 200 LPD)
- Turn-key/low maintenance system
- 135 LPD required at target for sustainable running
- **200 LPD need before transfer (fill over 60 min.)**
- LANL/UVA purchase for SpinQuest

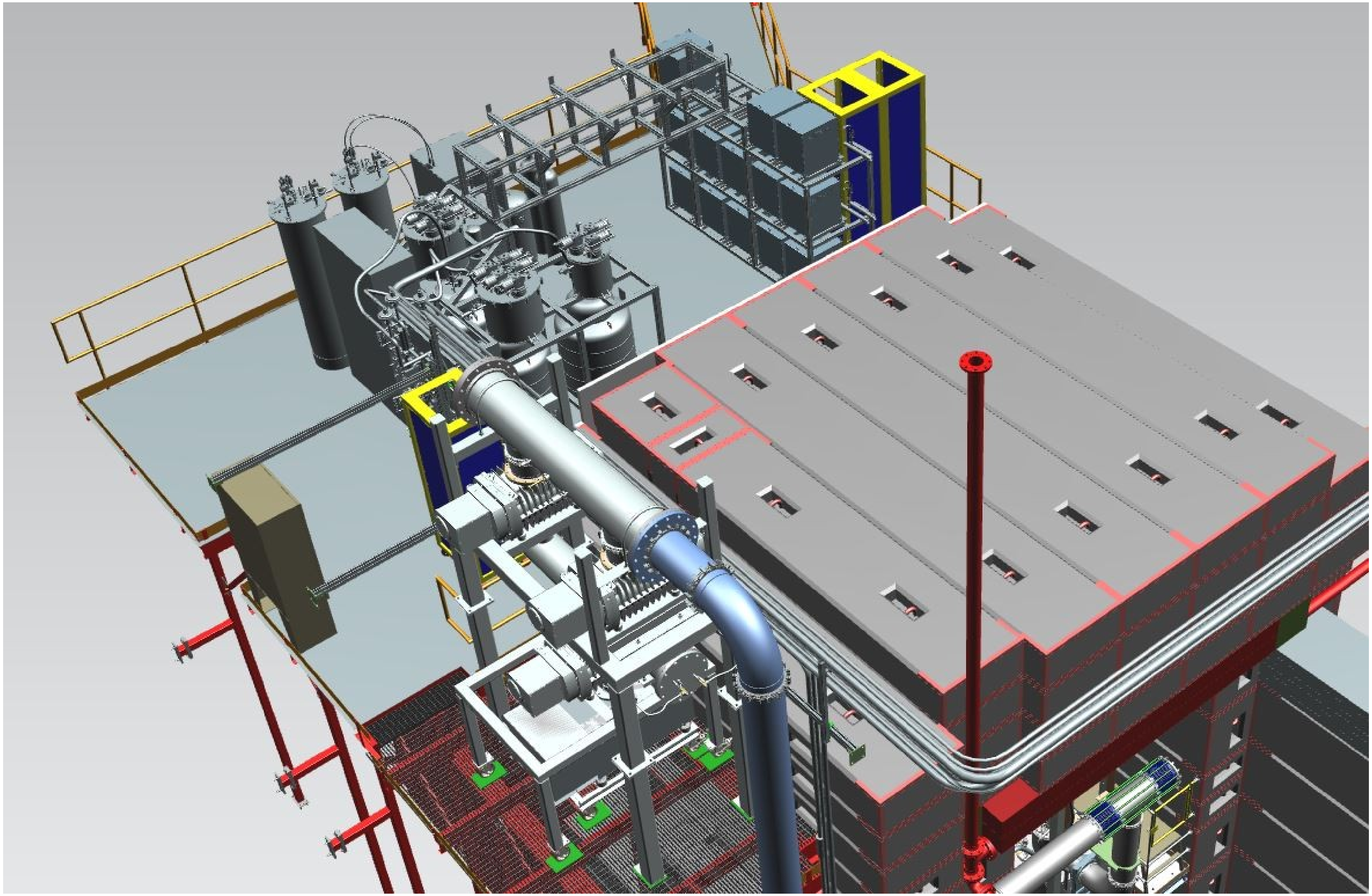
Cryo-platform

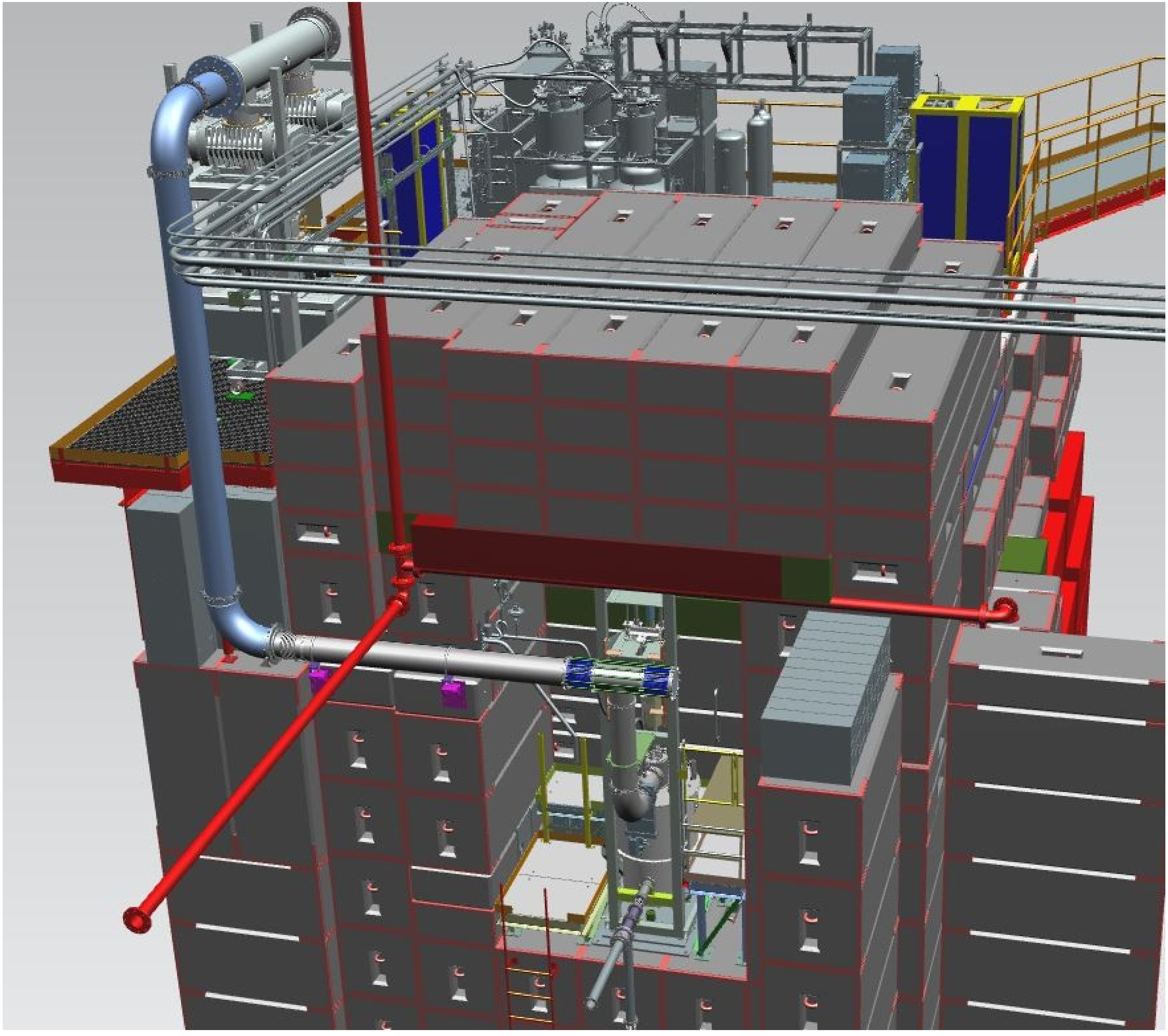


Cave Setup in Fermilab NM4

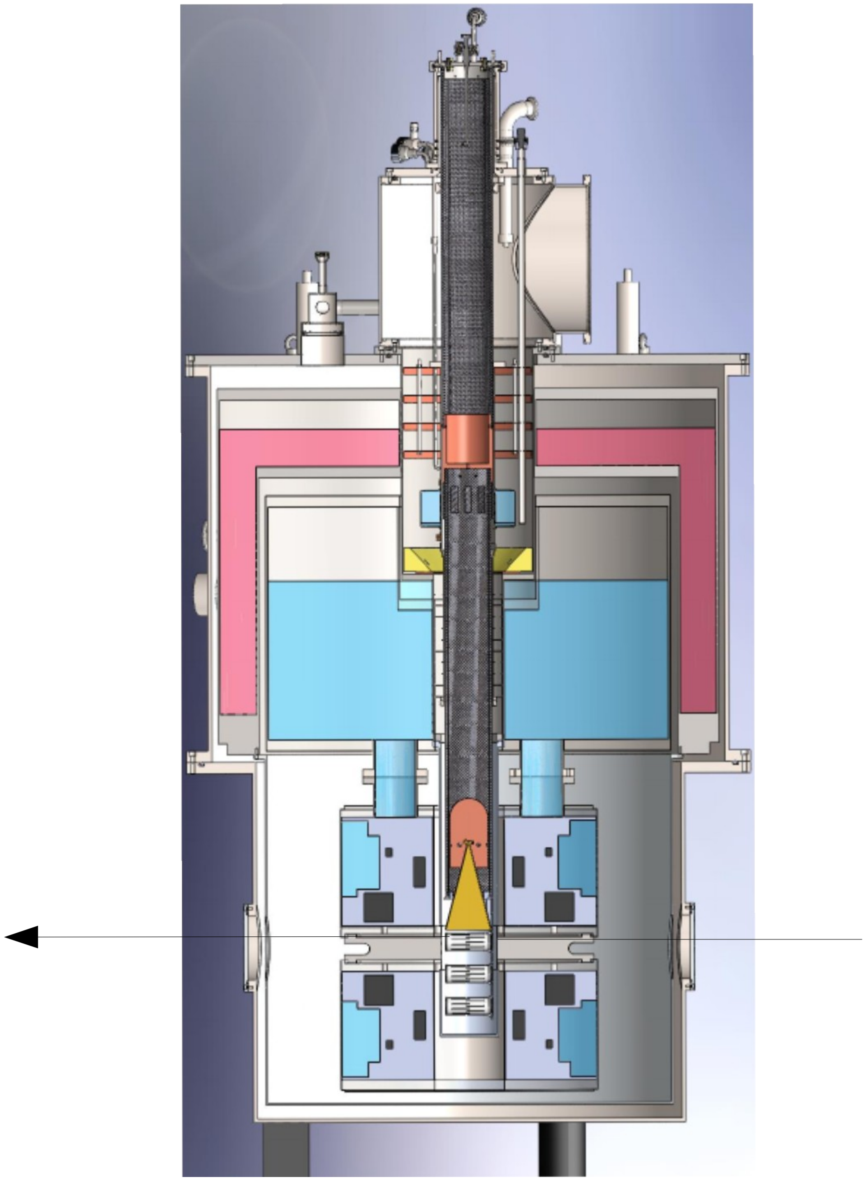


Cryo-Platform

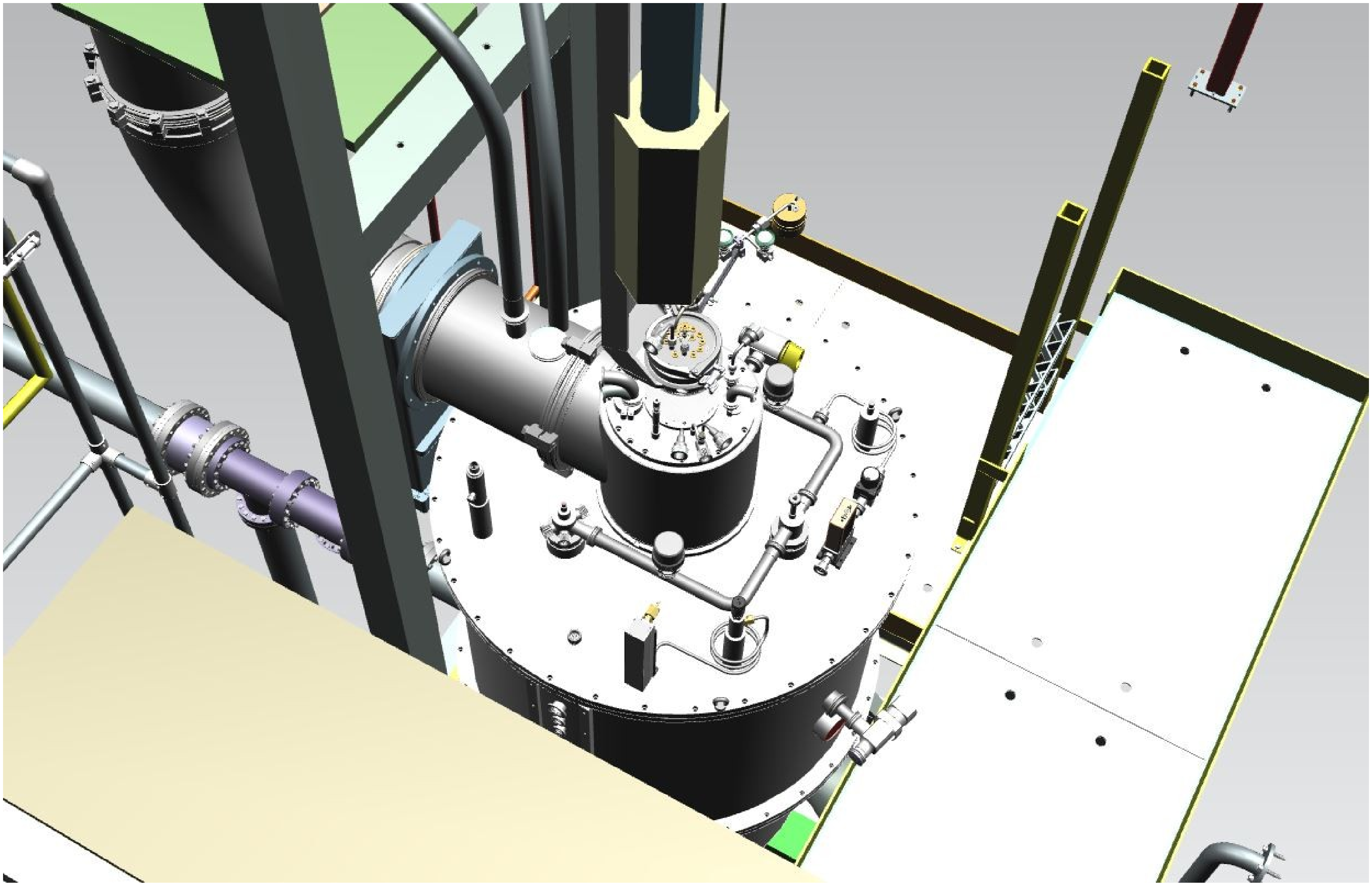




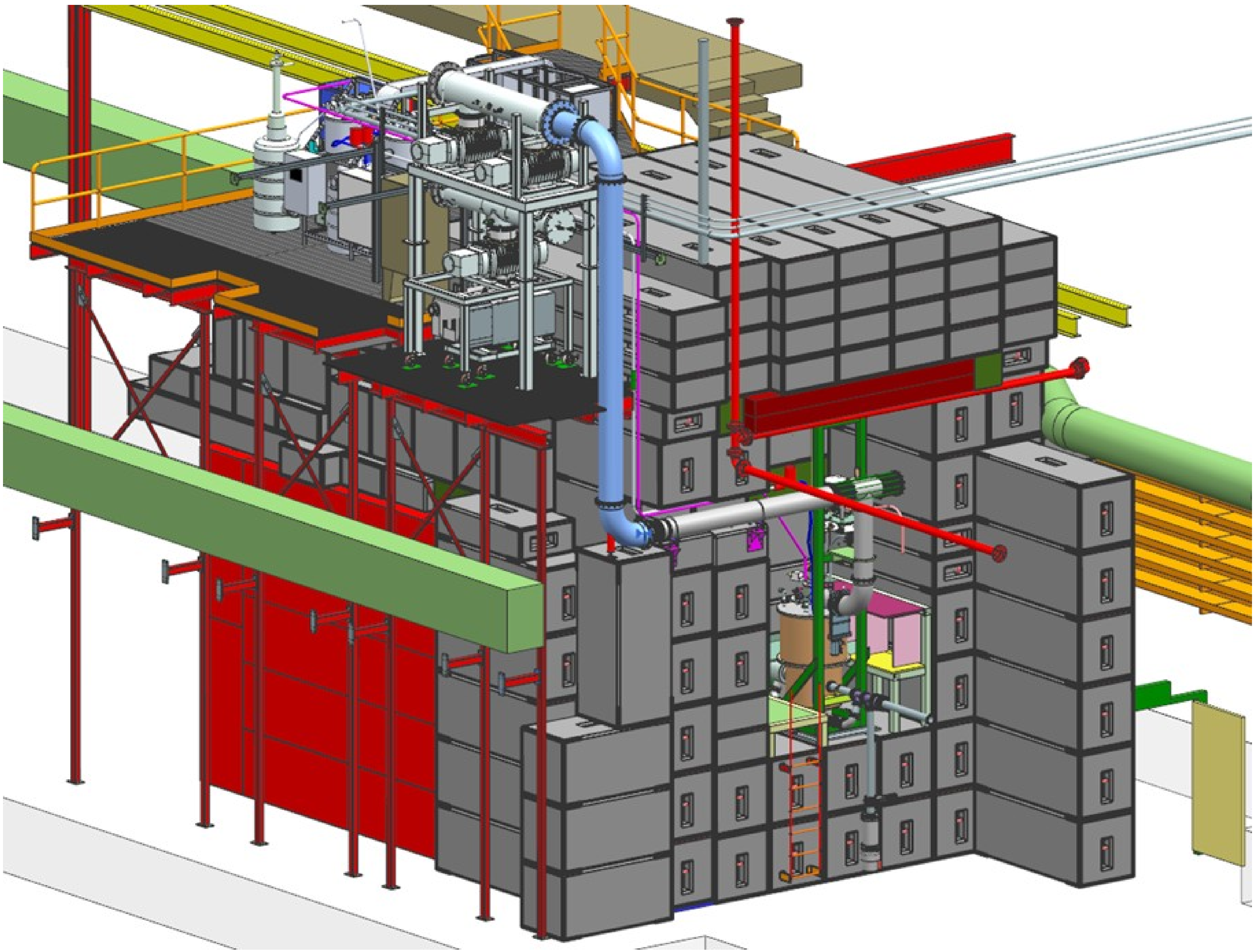
Polarized target on the Intensity Frontier



DNP Fridge Access



Target Cave from Upstream



Polarized Target Frontier

SpinQuest

- Cycle Time: Every 55.6 seconds
- Spill Length: 4.4 seconds
- Beam Intensity: $1.0X10^{12}$ protons/sec

VS

BNL:

Energy	24 GeV
Cycle Time	3 seconds
Spill Length	1 second
Beam Intensity	2×10^{11} protons/pulse

Limiting Factors: - Fridge Cooling Power
- Heat load to SC Magnet
- Cycle Time

BNL : $4.0X10^{12}$ protons/min - 4 cm
FNAL : $5\text{-}4.4X10^{12}$ protons/min - 8 cm

Highest Cooling Power DNP Evaporation System:

- Running at 20 SLPM have 1.4 W of cooling power
  - For 4.4 sec receive 0.4 W of heat load from protons
  - Continuous DNP microwave heat load 0.65 W
- Super conducting magnet critical temperature 7.5 K @ 5T
- Cycle gives time to cool

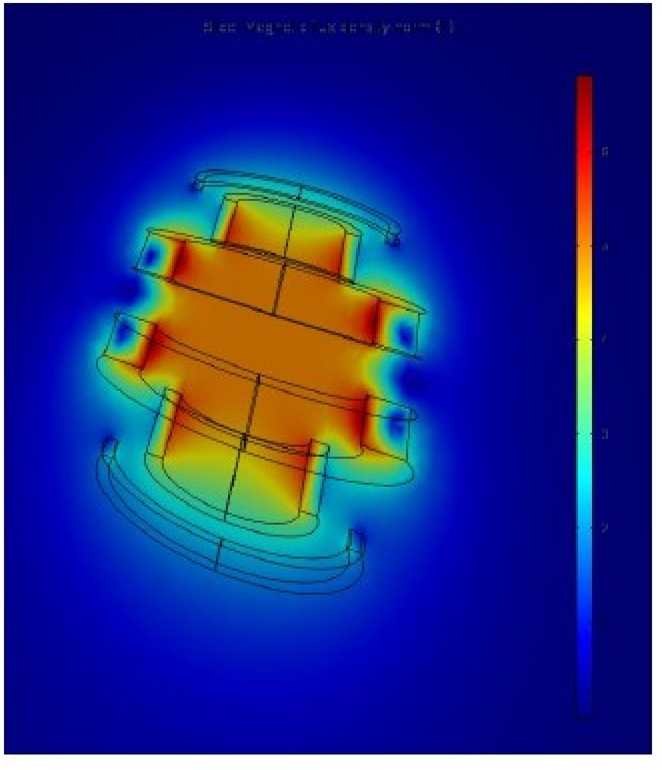
Field Measurement and Map

Measure Homogeneity using NMR and Hall Probe

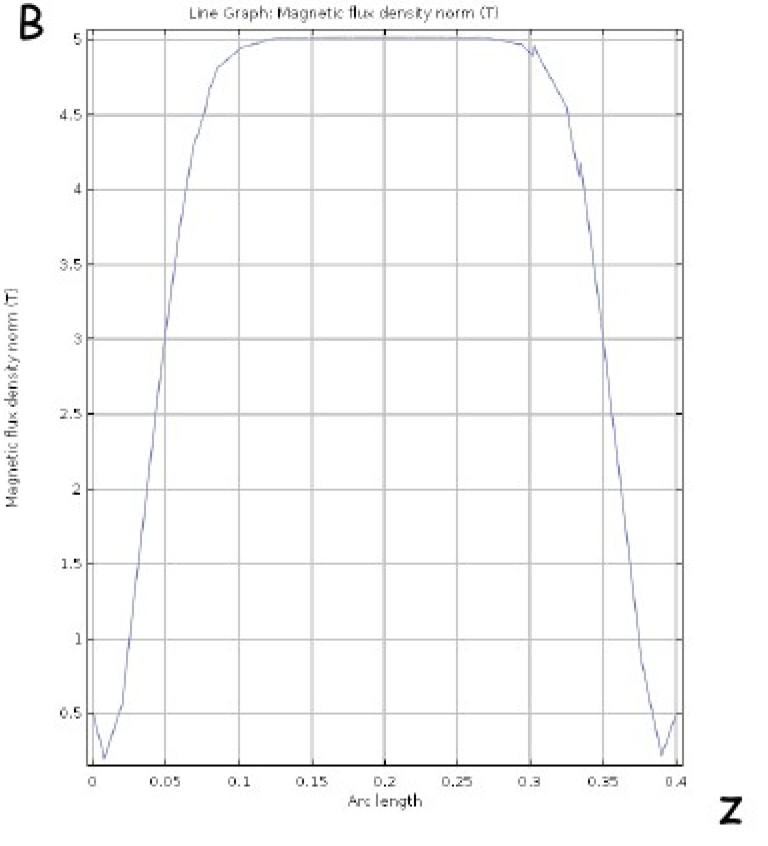
Measure outside fringe field and map to simulated field

Accurate Field Map ✓

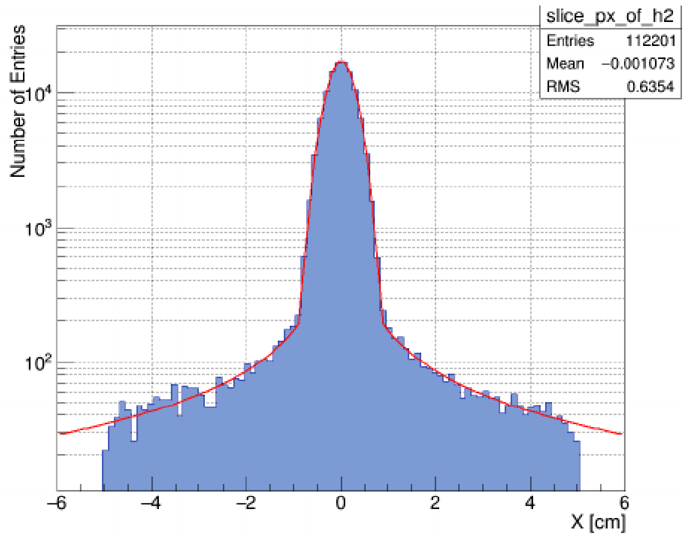
We achieve a high level of homogeneity around the target area & along the beam line:

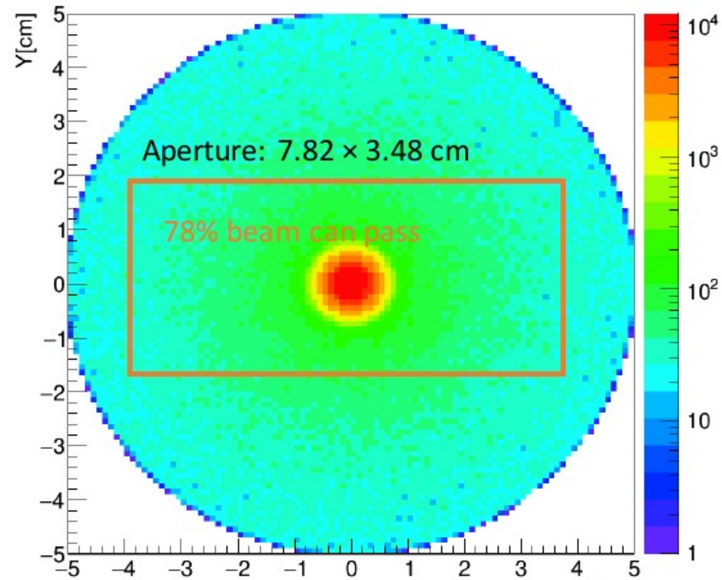


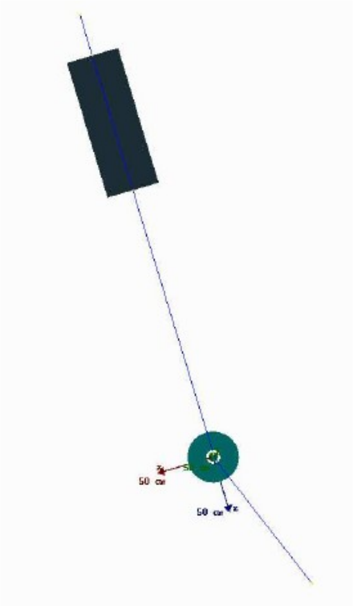
High level of homogeneity in the target area

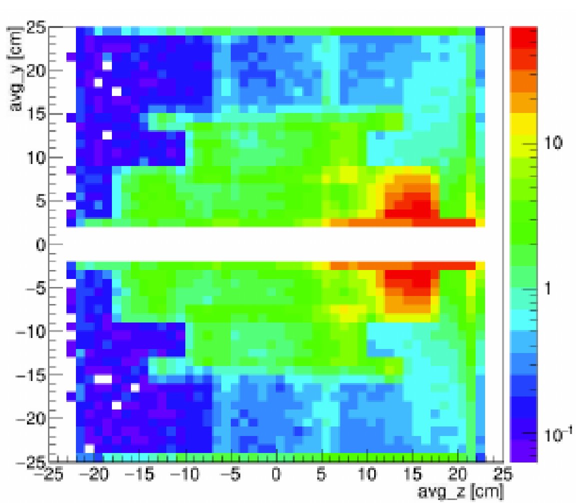


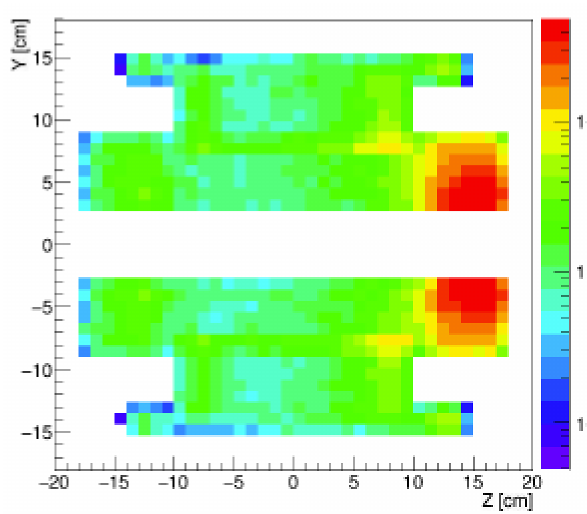
Geant→COMSOL

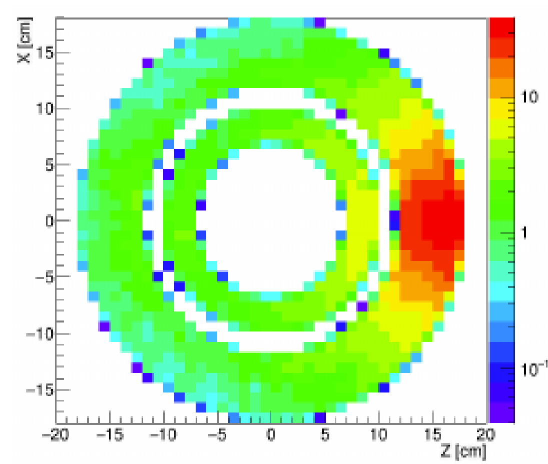




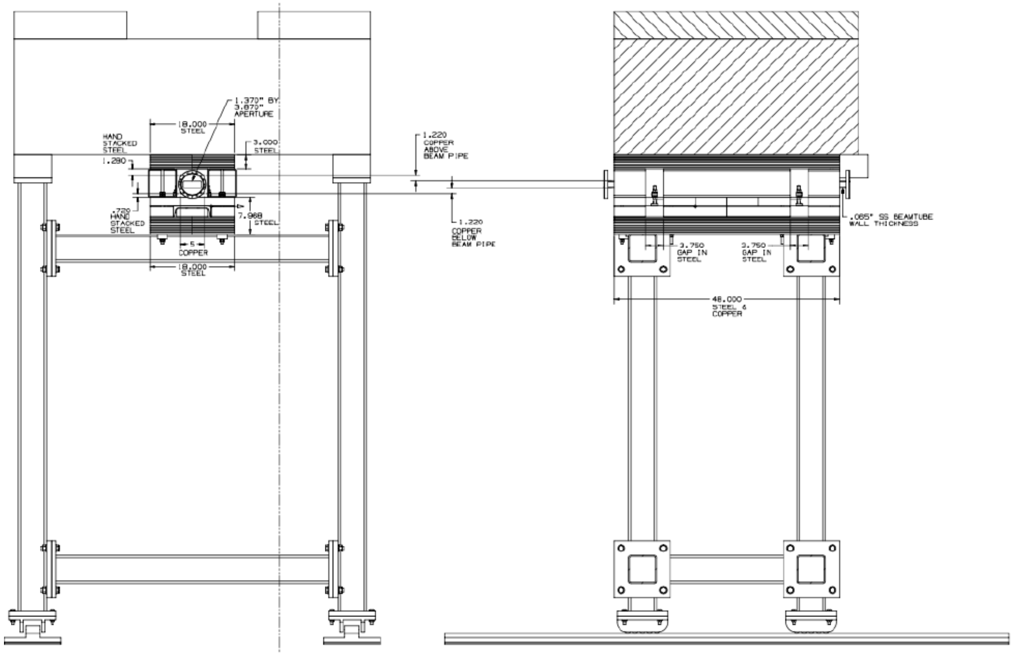


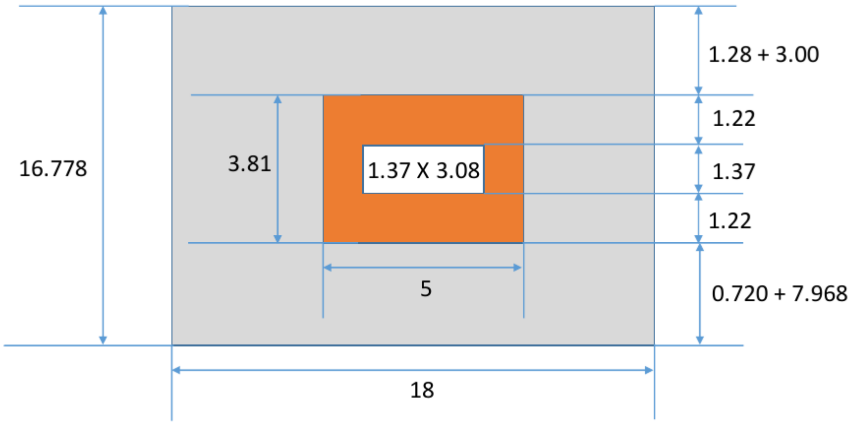


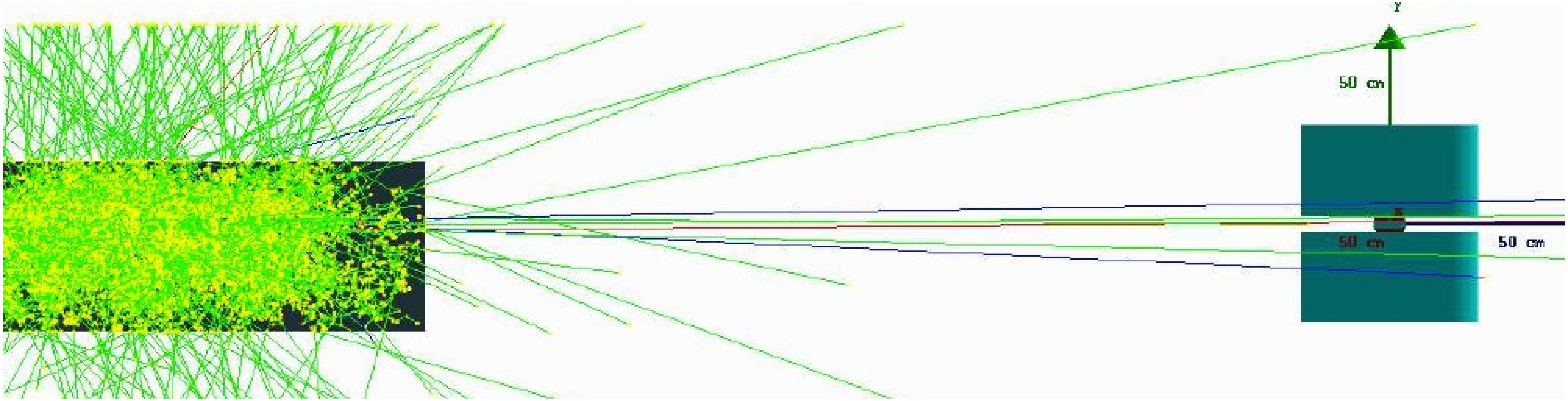




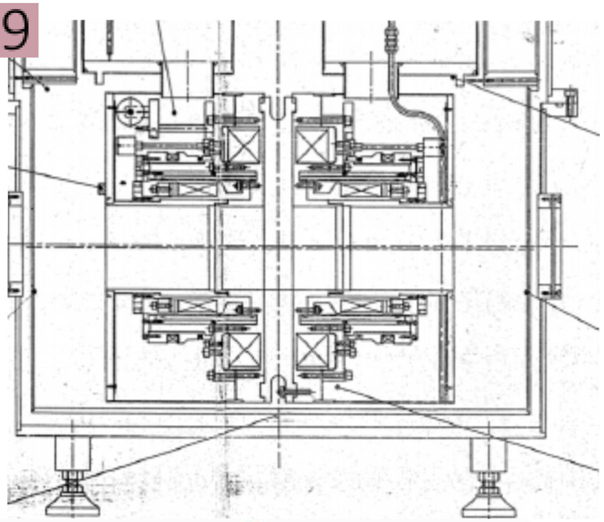
SpinQuest Beam Collimator



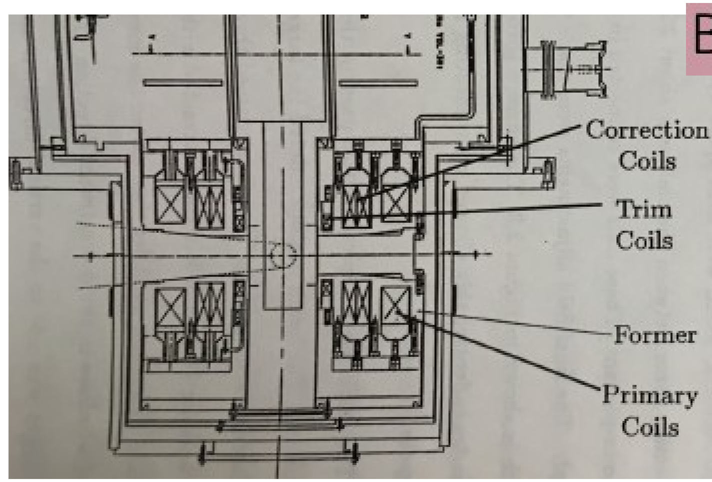




E1039

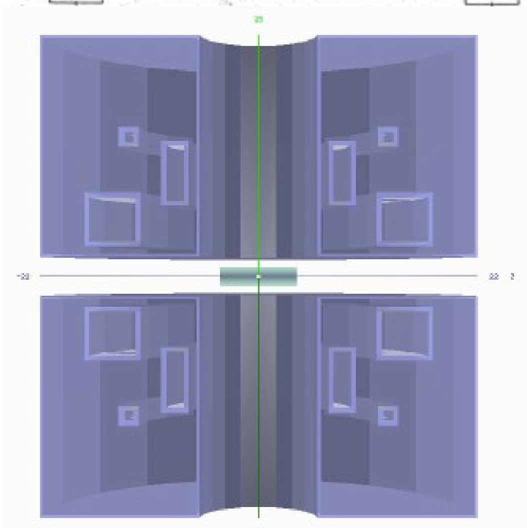


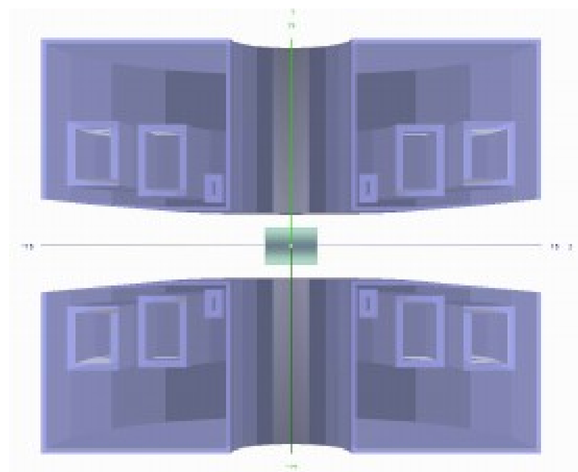
BNL target



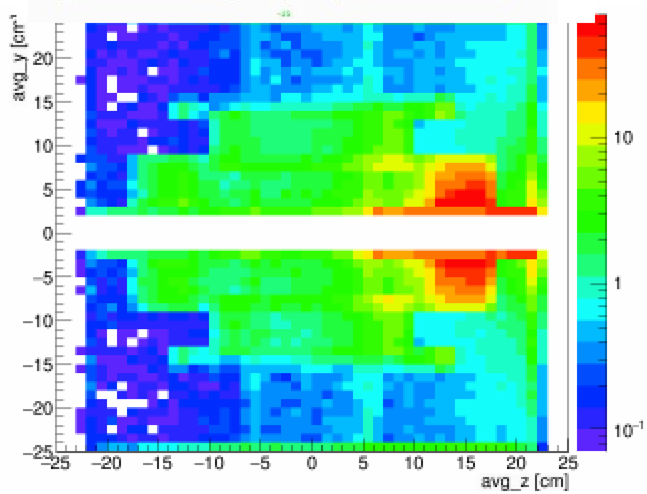
Solidworks → Geat4

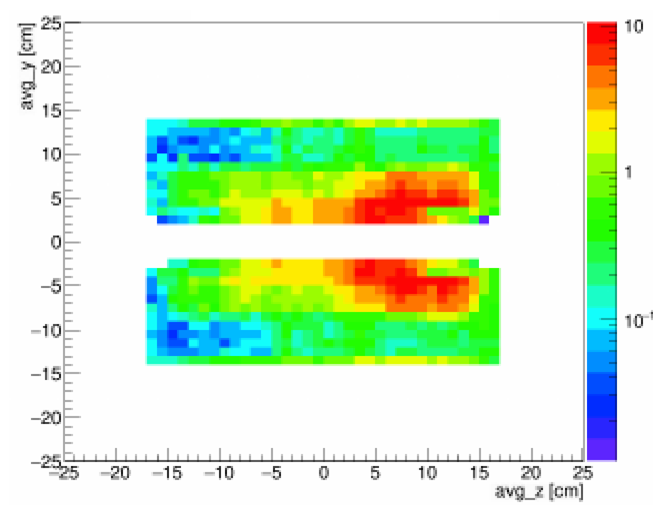
Based on drawings and measurements





Simulation contain SS former, LHe, vessels, target cell, target material



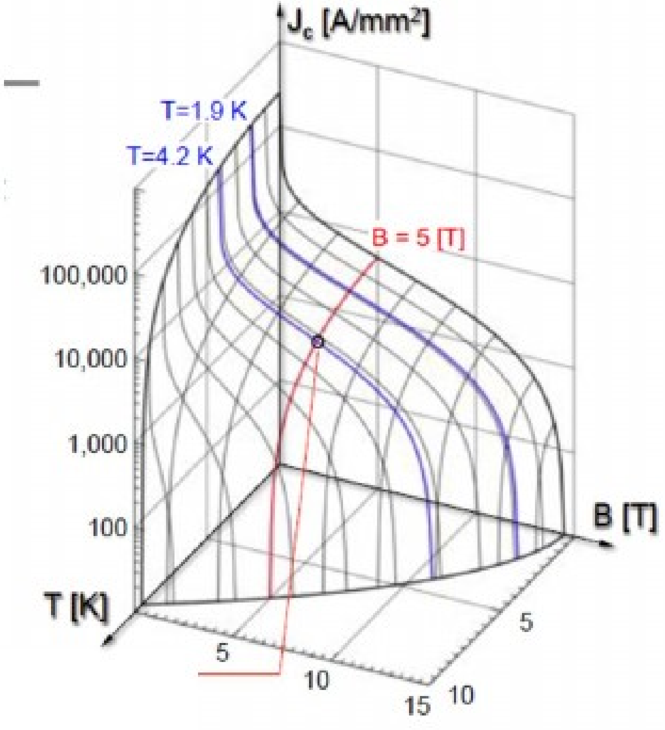


Then look at energy deposition in the SC coils

Quench Threshold

Introduction: Quench definition

Critical surface of a LHC NbTi wire



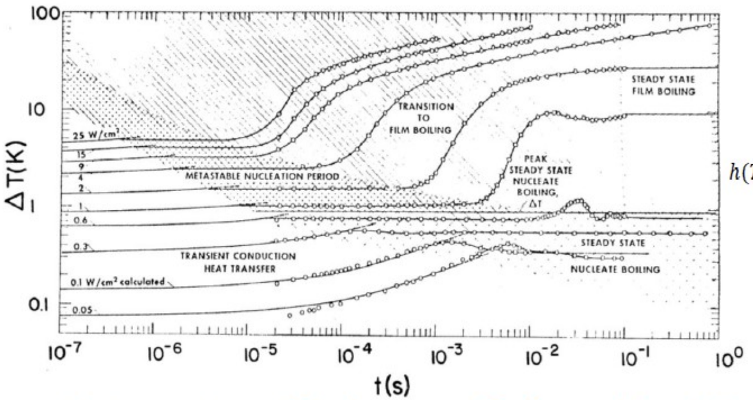
The critical surface is defined from the temperature (T), magnetic field (B), and the surface current (J)

Magnet quench if the T, B or J lie outside the critical surface

For B = 5 T, The maximum temperature that the magnet can hold is around 7.2 K

Physics of the Quench

Approximation Strategy

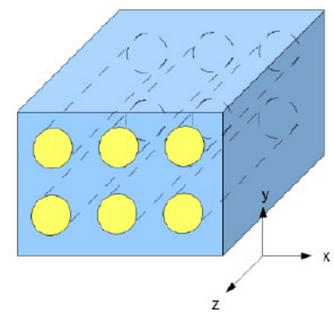


Various regimes of the heat transfer from solid to LHe

$$h(T_s, T_{He}) = a_{FB\text{-}I}(T_s - T_{He}).$$

First, Steady state Film boiling regime is applied

Second, we consider the superconducting magnet as a composite material with the effective thermal parameter



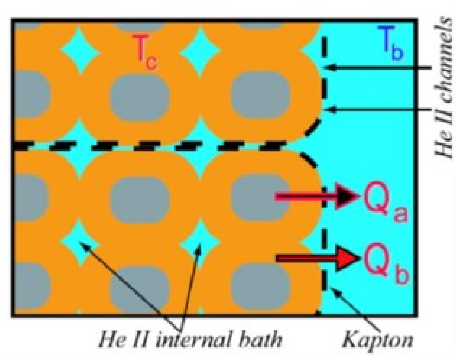
Rayleigh's model consist of parallel cylinders embedded in a continuous matrix

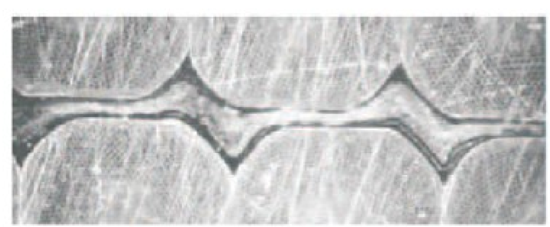
Rayleigh's formula

$$\frac{k_{eff}}{k_m} = 1 + \frac{3\phi}{\left(\frac{k_1 - 2k_m}{k_1 - k_m}\right) - \phi + 1.569\left(\frac{k_1 - k_m}{3k_1 - 4k_m}\right)\phi^{\frac{10}{3}} + \ldots}$$

Third, we parameterize some of the unknown properties by the effective surfaces that are in direct contact with the LHe:

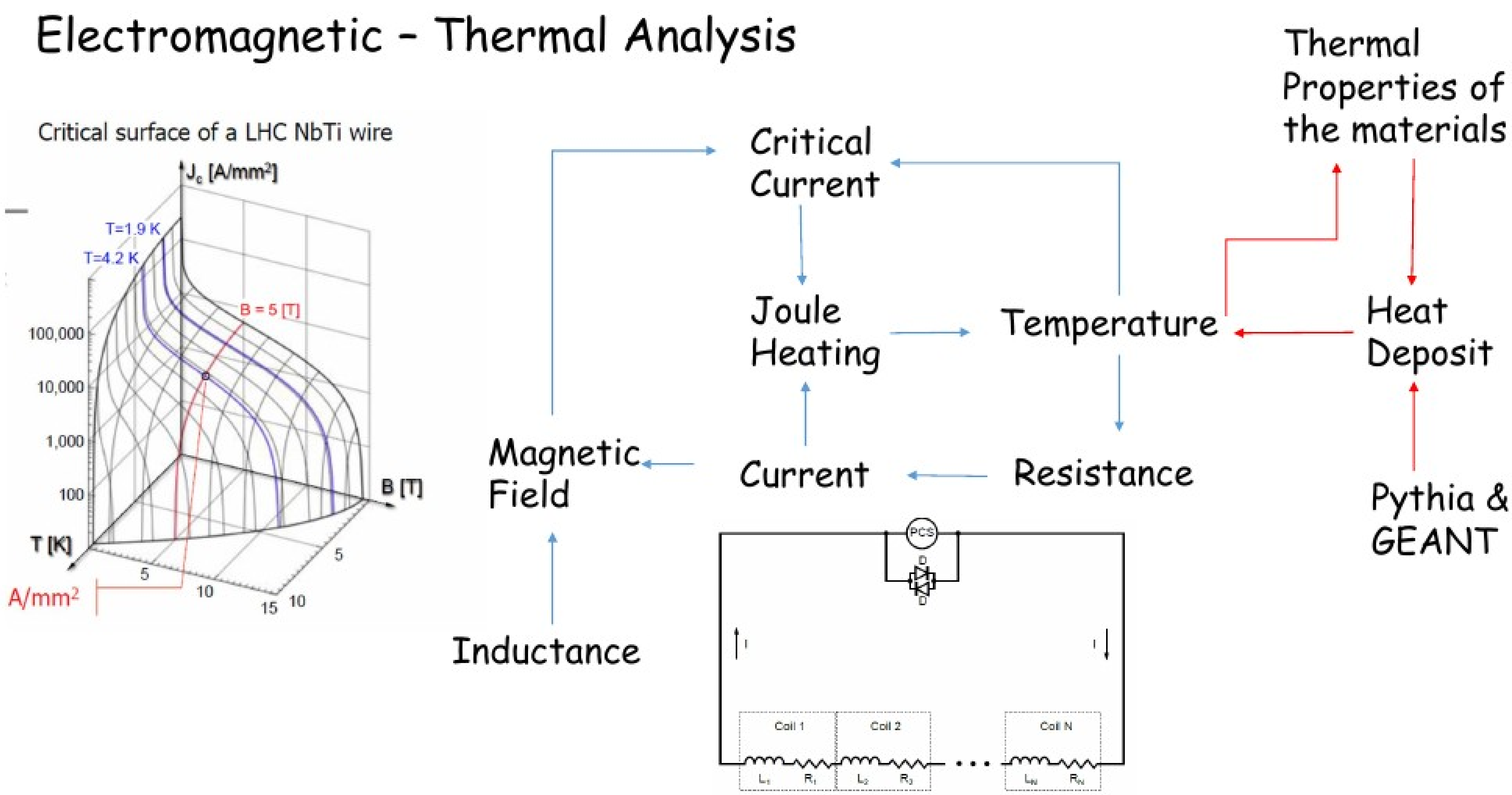
- Perimeter of the He void
- Insulation
- Former





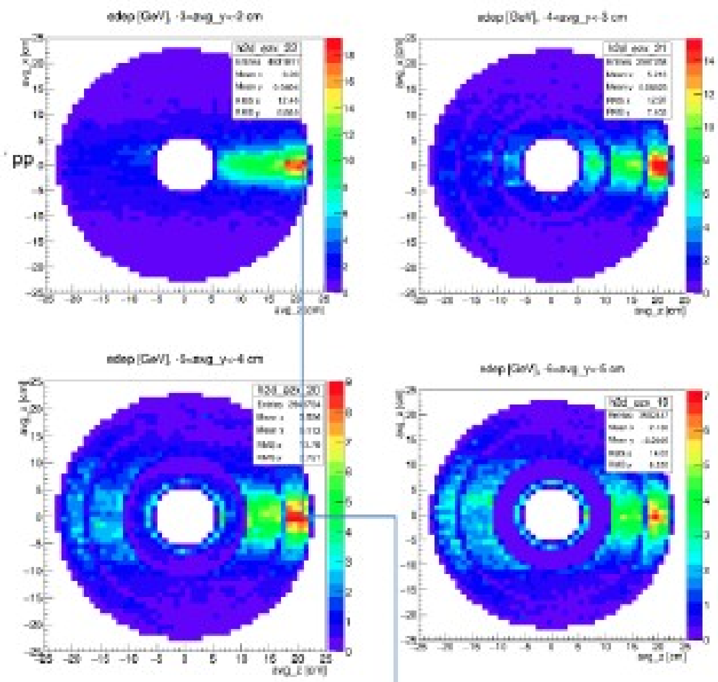
Microscopic view of the cable

SpinQuest Target Manget Analysis

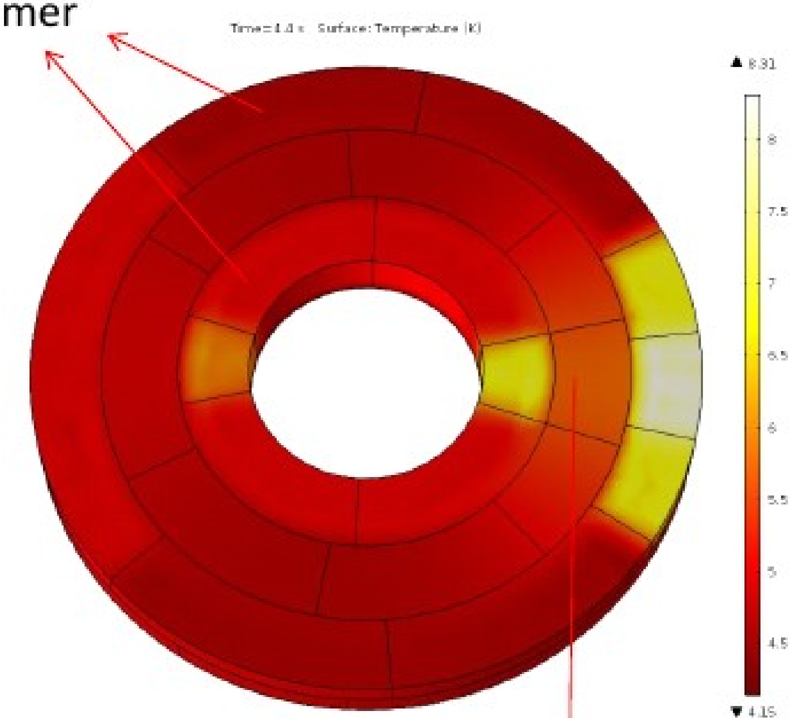


Determine Heat load

What we have currently



Former



Simulation result

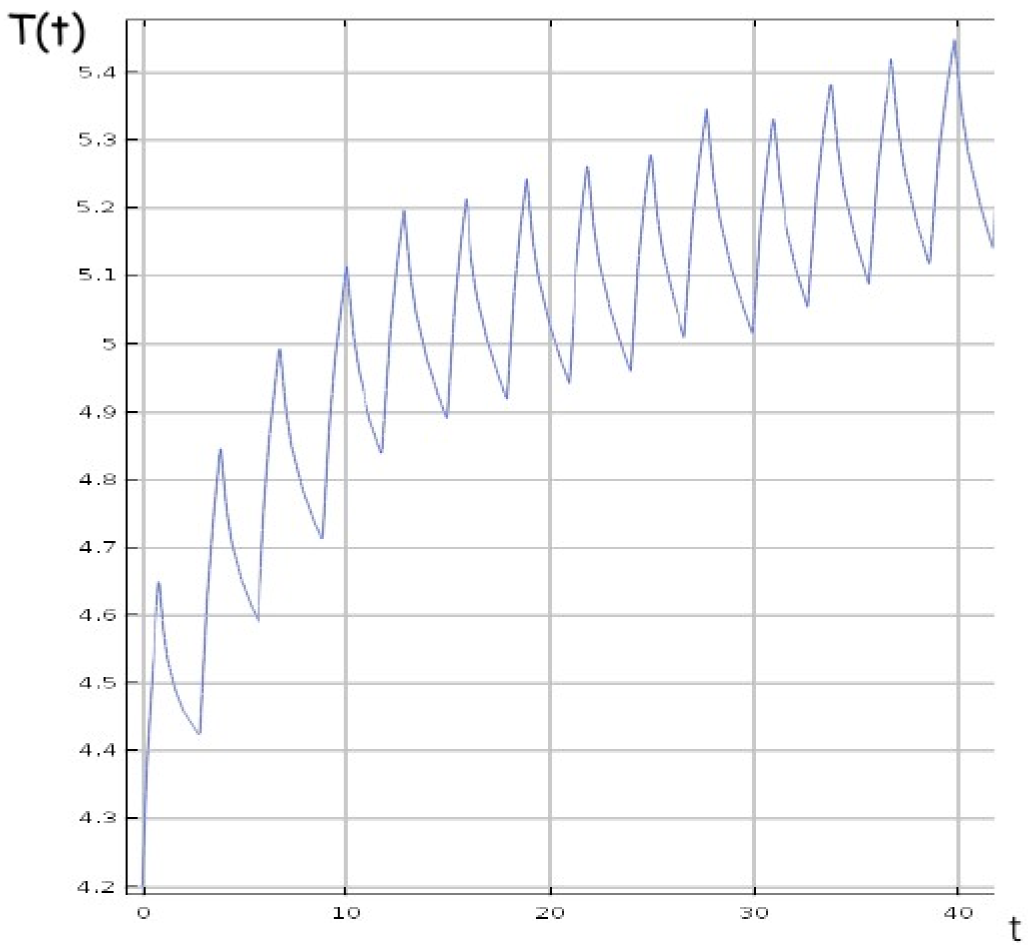
Maximum hot spot
around 18000 W/m^3

Maximum temperature of
coil around 5.7 K

Historical Test

Results on BNL experiment

The maximum temperature of the coil as a function of time



Maximum Temperature profile Tmax(t) for BNL:

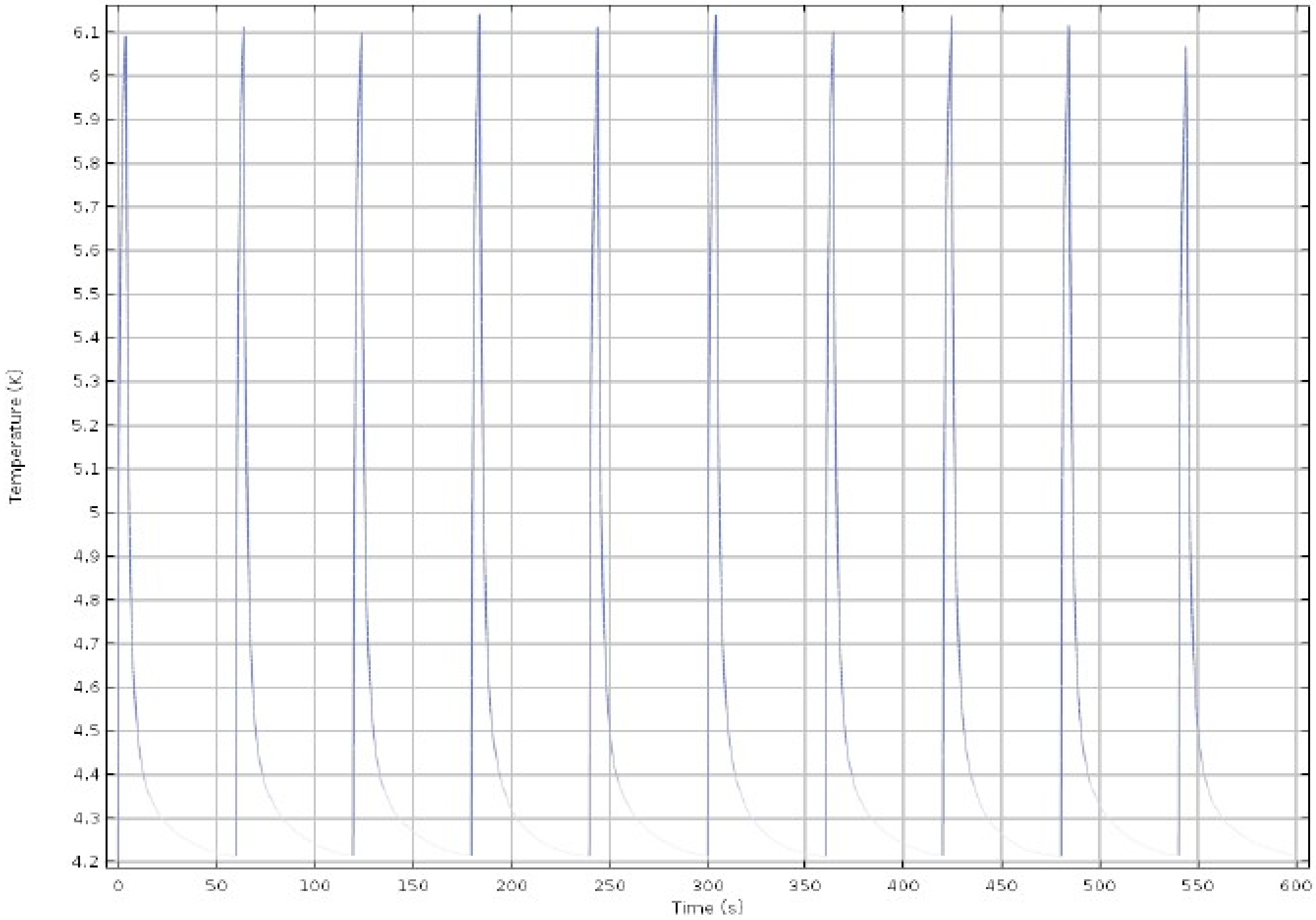
- 24 GeV proton
- 2e11 proton/s
- Teflon Target

Notes:

- The BNL magnet was quenched in this setup (Teflon target & 2e11 proton/s)
- The simulation results “indicate” quench -> The heat is accumulated over time
- There is an issue about numerical convergence issue for longer run that need to be fixed -> require extremely fine Mesh and time step

SpinQuest Target Magnet

The maximum temperature of the coil as a function of time



Maximum Temperature profile Tmax(t) for E1039:

- 120 GeV proton
- 1e12 proton/s
- NH3 Target

Conclusion: It is save to run at 1e12 proton/s but I recommend this intensity to be considered as the upper limit

Prep for Quench Commissioning

Before Commissioning run

- Fix the numerical convergence issue
- Overleaf documentation (collaborative LaTex editor)
- Fine tuning geometry
- Systematic study
- Install 8 temperature sensor (Carlos)
- Create Temperature prediction for those sensors as a function of beam intensity

During Commissioning run

- Compare the simulation prediction vs experiment

Prep for Quench Commissioning

Type-T Thermocouples Cu-CuNi

Insider Schedule

Near Term Goals
• Some spectrometer commissioning with cosmic rays
• Trigger configuration testing
• Long term counters/chambers
• Coarse alignment of spectrometer (reconstructed cosmic tracks)

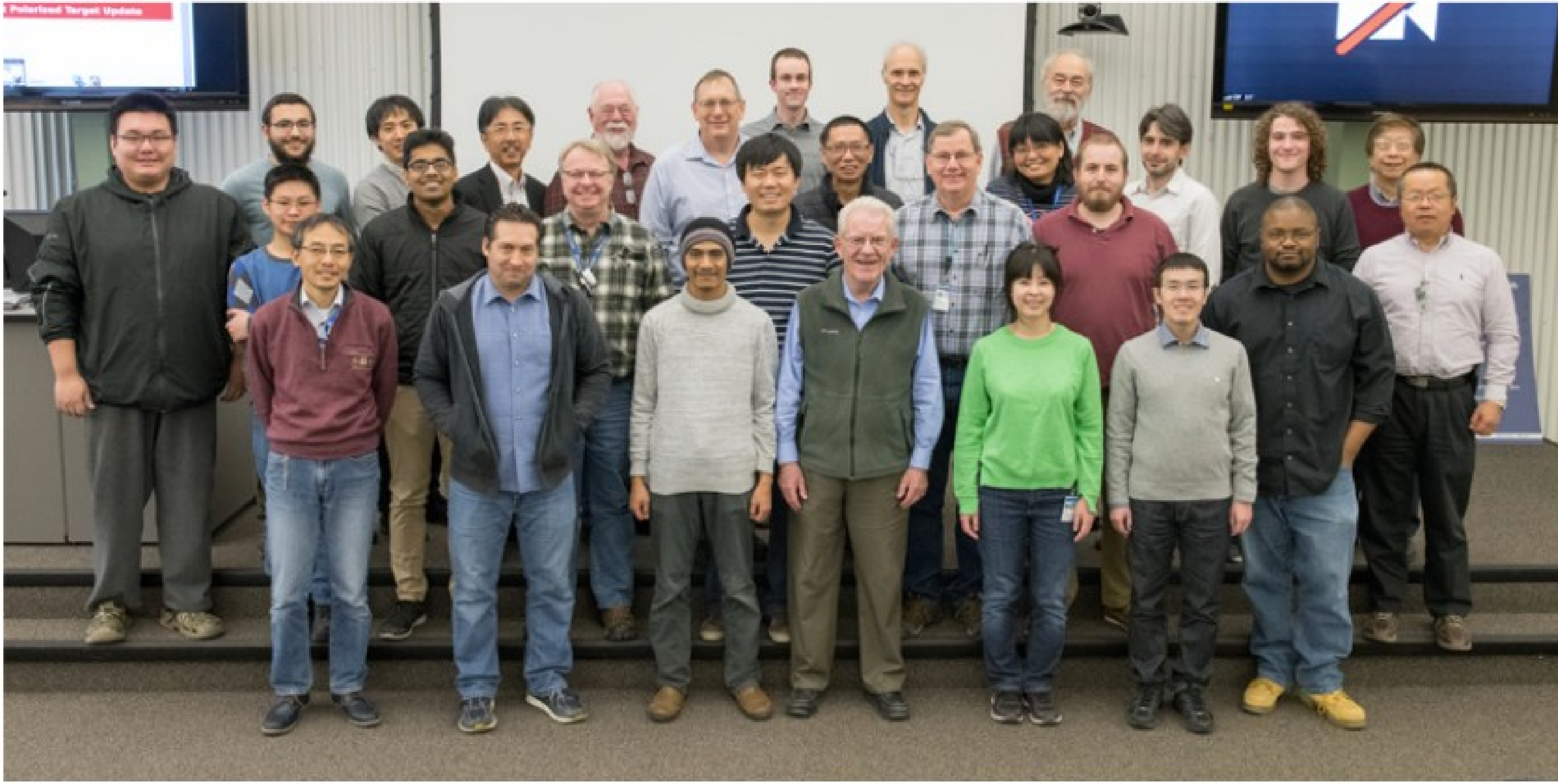
Hall schedule:
• Complete electrical installation for cryo platform: 9/20
• Initial Target Magnet Survey: 9/12
• Install cryo platform decking: 9/23
• Install target in cave: maybe require Inspector (Safety Review)

➡ Need to be running in control room for overnight runs
➡ Running Event Display
➡ Online detector monitoring
➡ Slow controls (detector voltages/currents, environmental monitoring)
➡ Target vacuum plumbing

Accelerator Operations:
➡ Accelerator shutdown underway
➡ Beam to switchyard 11 Nov. - 2 Dec.

Status of Collaboration

SpinQuest/E1039 COLLABORATION



Summer Collaboration Meeting

Collaboration

INSTITUTION	FULL MEMBERS	AFFILIATE MEMBERS
Abilene Christian University	Donald Isenhower (PI), Michael Daugherity, Shon Watson	Haley Stien, John Marsden, Mitchell Schneller, Nathan Rowlands, Roy Salinas, Rusty Towell, Shannon McNease, Yves Ngenzi, Thomas Fitch
Argonne National Laboratory	Paul Reimer (PI), Donald Geesaman	Kawtar Hafidi, Kevin Bailey, Thomas O'Connor, Zhihong Ye, Benjamin Zeidman
Fermi National Accelerator Laboratory	Richard Tesarek (PI), Carol Johnstone, Charles Brown	
KEK	Shin'ya Sawada (PI)	Shigeru Ishimoto
Los Alamos National Laboratory	Kun Liu (SP), Mikhail Yurov, Chun-Min Jen, Ming Liu, Xuan Li, Walter Sondheim, Zhaohuizi Ji	Jan Boissevain, Melynda Brooks, Matt Durham, David Kleinjan, Sho Uemura, Cesar Da Silva, Patrick McGaughey, Andi Klein
Mississippi State University	Lamiaa El Fassi (PI)	Dipangkar Dutta
New Mexico State University	Stephen Pate (PI), Vassili Papavassiliou, Haiwang Yu, Abinash Pun, Forhad Hossain	
RIKEN	Yuji Goto (PI)	
Tokyo Institute of Technology	Kenichi Nakano (PI), Toshi-Aki Shibata	
University of Colorado, Boulder	Edward Kinney (PI)	
University of Illinois, Urbana-Champaign	Jen-Chieh Peng (PI), Yen-Chu Chen, Ching Him Leung	Naomi Makins, Daniel Jumper, Jason Dove, Mingyan Tian, Bryan Dannowitz, Randall McClellan, Shivangi Prasad
University of Michigan	Wolfgang Lorenzon (PI), Minjung Kim, Noah Wuerfel	Daniel Morton, Richard Raymond, Marshall Scott
University of New Hampshire	Karl Slifer (PI), David Ruth	Maurik Holtrop
University of Virginia	Dustin Keller (SP), Joshua Hoskins, Zulkaida Akbar, Carlos Ramirez	Donal Day, Donald Crabb, Jixie Zhang, Oscar Rondon, Liliet Diaz, Arthur Conover, Brandon Kriesten, Simonetta Liuti, Ellen Brown, Blaine Norum, Matthew Roberts
Yamagata University	Yoshiyuki Miyachi (PI), Genki Nukazuka	Takahiro Iwata, Norihiro Doshita

Current Coordinators

Co-spokespersons
K. Liu (LANL) D. Keller (UVA)

Collaboration Coordinators

Run Coordinator x 2	Physics Coordinator	Analysis Coordinator	Systems Coordinator	Shift Coordinator
R. Tesarek (FNAL)	K. Nakano (TokyoTech)	Z. Akbar (UVA)	C. Ramirez (UVA)	Y. Miyachi (Yamagata)
J. Hoskins	Z. Akbar	K. Nakano	Y. Sumo	D. Ruth

Talks Coordinator	Information Coordinator	International Coordinator	Outreach Coordinator	Service Coordinator	Backup Run Coordinator
W. Lorenzon (Michigan)	S. Pate (NMSU)	S. Sawada (KEK)	T.-A. Shibata (TokyoTech)	P. Reimer (ANL)	J. Hoskins (UVA)
V. Papavassiliou	K. Liu	T.-A. Shibata	S. Sawada	D. Keller	M. Yurov

Critical Systems Experts

Polarized Target	Wire Chambers	Hodo.	Prop. tubes	Beam Cerenkov	Slow Control	Offline Software	NIM Trigger	FPGA Trigger	L3 Trigger	DAQ	Online Software
D. Keller (UVA)	C.-M. Jen (LANL)	F. Hossain (NMSU)	Helen Ji (LANL)	R. Tesarek (FNAL)	M. Yurov (LANL)	Postdoc (NMSU)	F. Hossain (NMSU)	M. Kim (UMich)	New PD (MSU)	Y.-C. Chen (UIUC)	K. Nakano (Tokyo)
C. Ramirez (UVA)	C. Brown (FNAL)	C. Ramirez (UVA)	X. Li (LANL)		D. Ruth (UNH)	Z. Akbar (UVA)	C. Brown (FNAL)	N. Wuerfel (UMich)	L. El Fassi (MSU)	Z. Zang (LANL)	K. Liu (LANL)
J. Hoskins (UVA)	K. Nakano (Tokyo)	D. Isenhower (ACU)			J. Hoskins (UVA)					P. Reimer (ANL)	
Z. Akbar (UVA)	L. El Fassi (MSU)									H. Leung (UIUC)	
D. Ruth (UNH)	Y. Goto (RIKEN)										
G. Nukazuka (Yama)	Y. Miyachi (Yama)										
F. Hossain (NMSU)											
A. Conover (UVA)											

Summary and Outlook

Experiments	Run Time	Collision Types	Physics
E906	2012-2017	p + targets (H, D, C, Fe, W)	- dbar/ubar asymmetry - quark dE/dx
E1039	2018 – 2021+	p + pol. targets (NH_3, ND_3)	Sea-quark Sivers, TMDs
E1067(para.) DarkQuest	2017-2021+(para.) 2021+ (dedicated)	p + any targets	dark photon, dark Higgs, ALP …
E1027	202x	Pol. p-beam +	- quark Sivers - TMD, spin

Where we are Going

TMDs probed via DY at SeaQuest

Boer-Mulders functions:

- Unpolarized Drell-Yan: $d\sigma_{DY} \propto h_1^{\perp}\overline{h}_1^{\perp}\cos(2\phi)$ — E906, E1039, E1027

Sivers functions:

- Single transverse spin asymmetry in polarized Drell-Yan:

$A_N^{DY} \propto f_{1T}^{\perp}(x_q) f_{\bar{q}}(x_{\bar{q}})$ — E1039, E1027

Transversity distributions:

- Double transverse spin asymmetry in polarized Drell-Yan:

$A_{TT}^{DY} \propto h_1(x_q) h_1(x_{\bar{q}})$ — E1027

- Drell-Yan and SIDIS involve different combinations of TMDs
- Drell-Yan does not require knowledge of the fragmentation functions
- T-odd TMDs are predicted to change sign from DIS to DY (Boer-Mulders and Sivers functions)

Remains to be tested experimentally! →COMPASS, RHIC, EIC/SeaQuest for sea quarks

SPINQUEST

Please Join The Effort (dustin@virginia.edu)

- https://spinquest.fnal.gov/
- http://twist.phys.virginia.edu/E1039/

Fermilab