A Peek into Spin Physics

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Colloquium at Kent State Physics

Outline

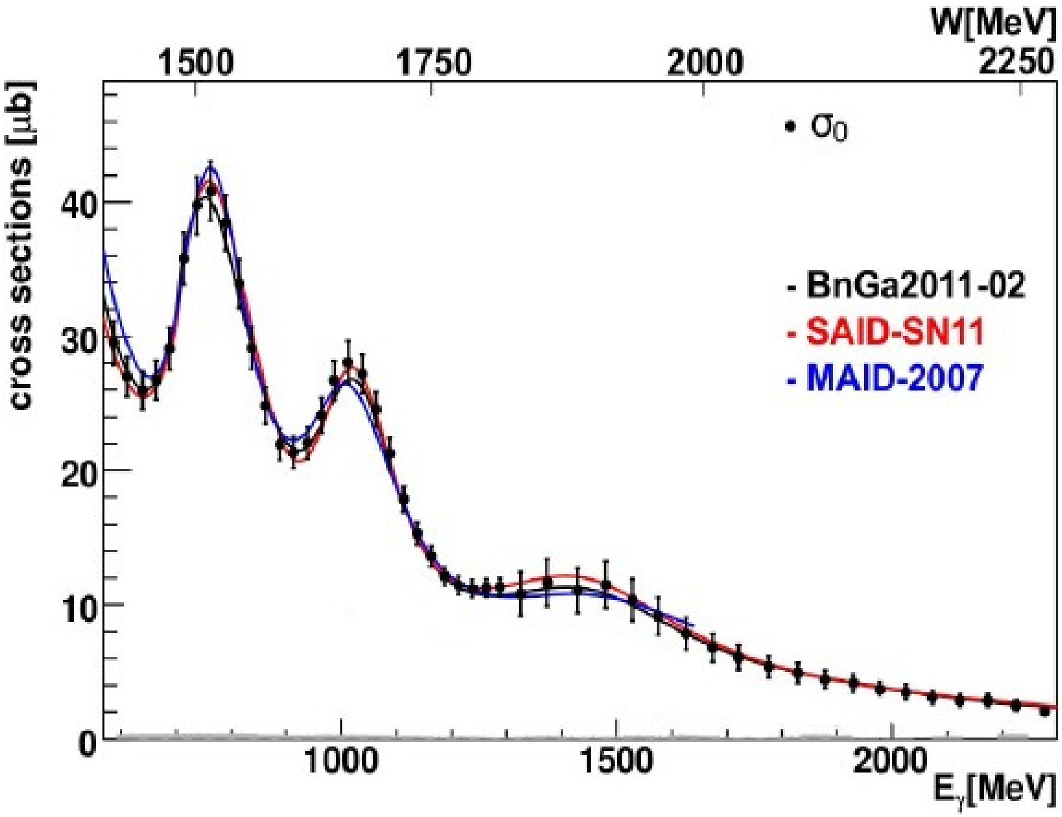
- What is Spin Physics
- How Do we Use It
- An Example Physics
- Instrumentation

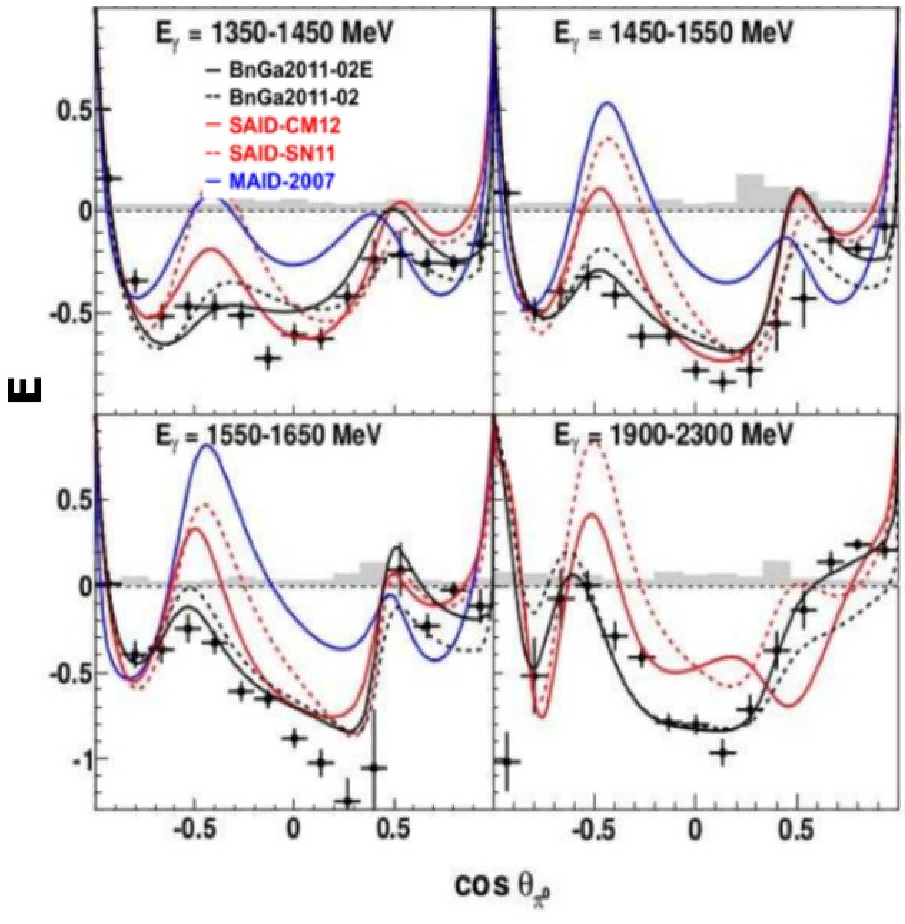
What is Spin Physics

The Physics of exploiting spin

- Spin in nuclear reactions
- Nucleon helicity structure
- 3D Structure of nucleons
- Fundamental symmetries
- Spin probes in beyond SM
- Polarized Beams and Targets,...

What is Spin Physics





What is Spin Physics

- The Physics of exploiting spin :

  By using Polarized Observables

  Spin: *The intrinsic form of angular momentum carried by elementary particles, composite particles, and atomic nuclei.*

  The Spin *quantum number* is one of two types of angular momentum in quantum mechanics, the other being orbital angular momentum.

What is *Spin* Physics

What Quantum Numbers?

What is *Spin* Physics

What Quantum Numbers?

Internal or intrinsic quantum properties of particles, which can be used to uniquely characterize

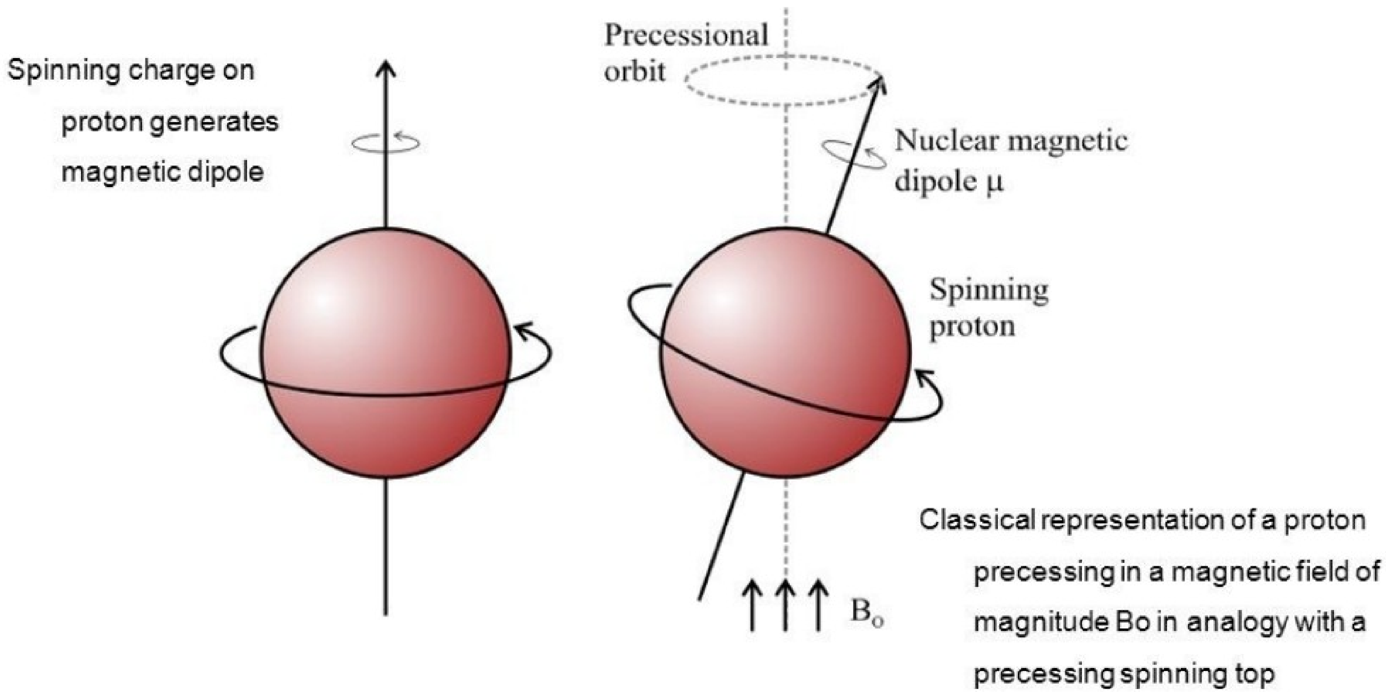
What is *Spin* Physics

What Quantum Numbers?

Internal or intrinsic quantum properties of particles, which can be used to uniquely characterize

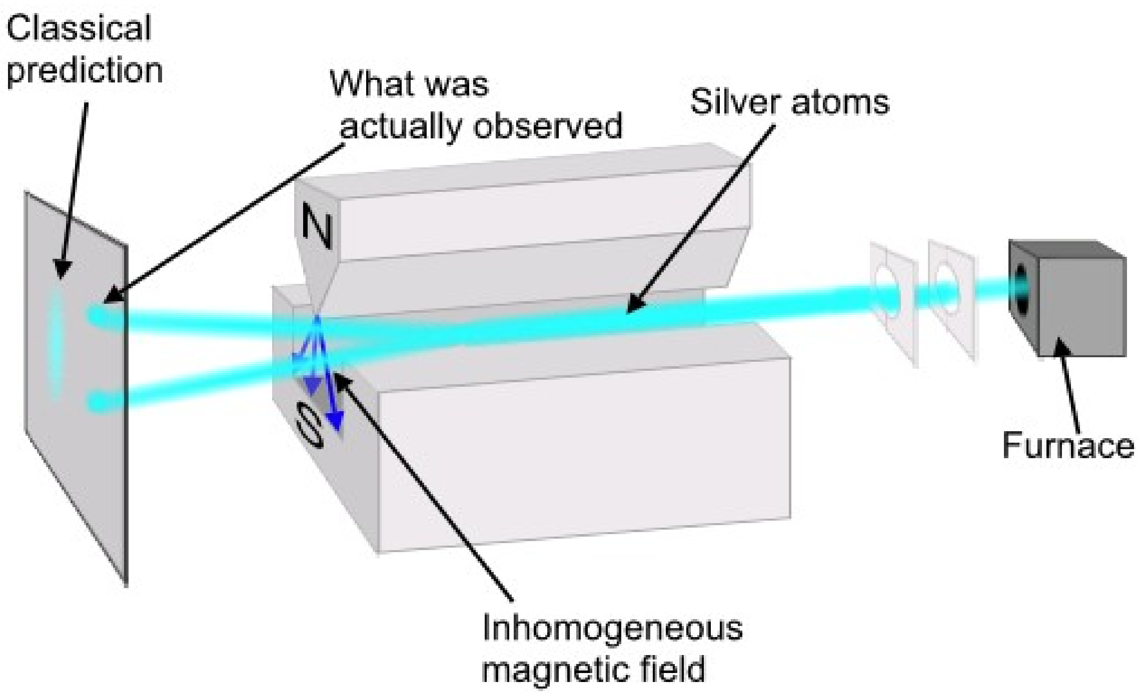
These numbers describe values of conserved quantities in the dynamics of a quantum system

What is *Spin* Physics



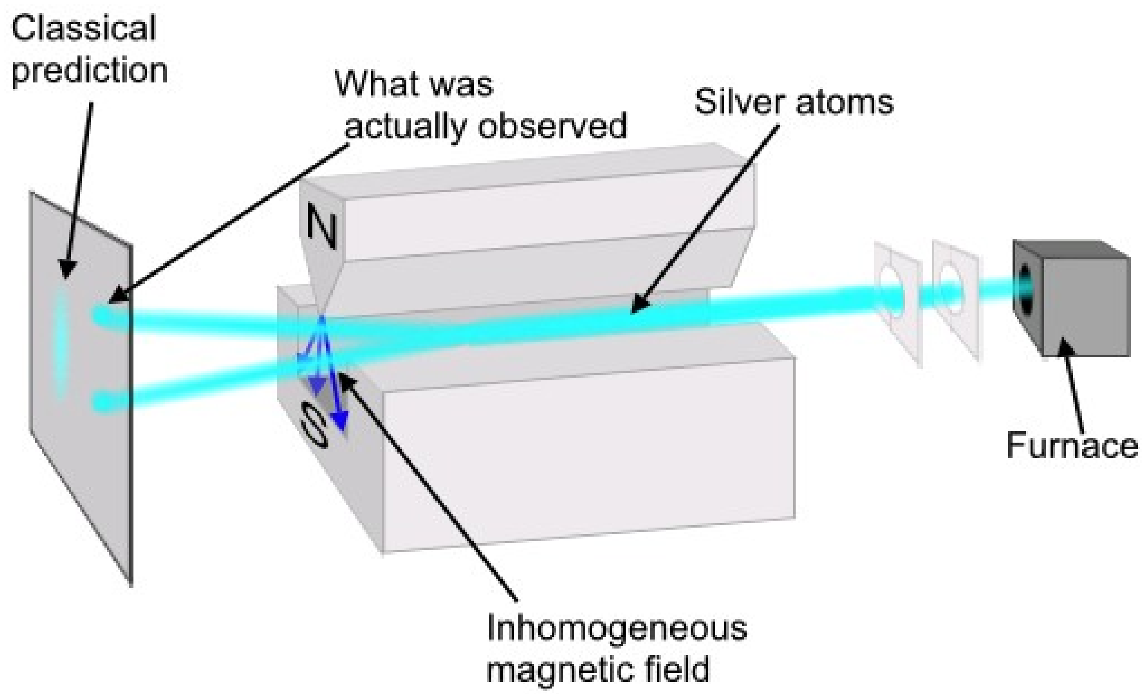
But a particle is not a sphere and spin is solely a quantum-mechanical phenomena

What is *Spin* Physics



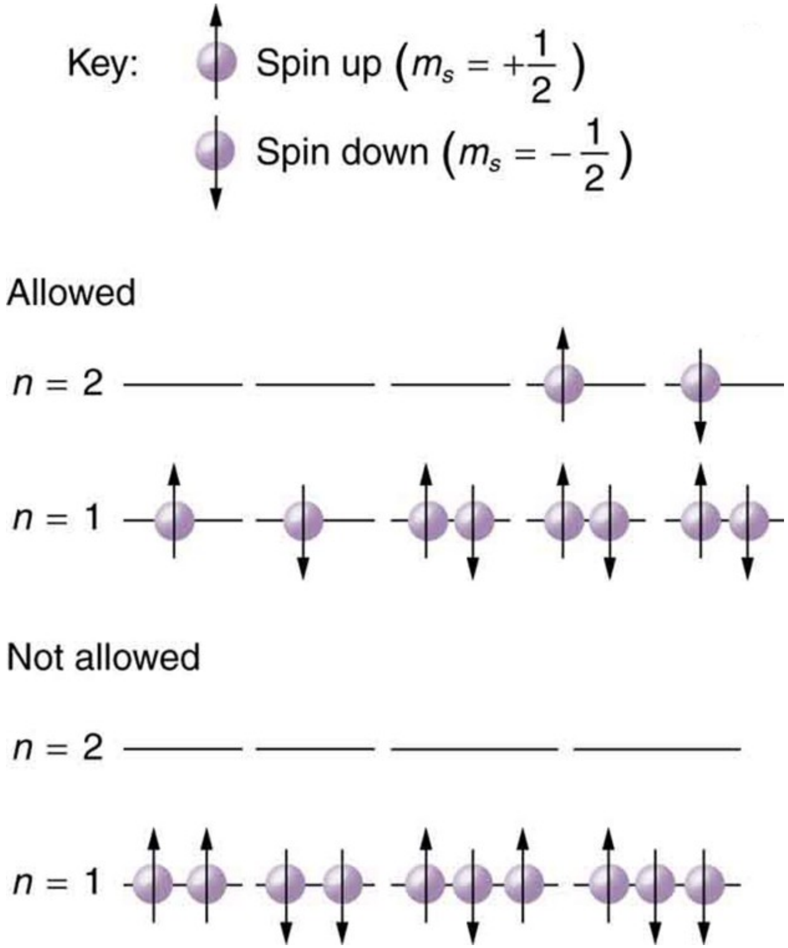
Stern-Gerlach: If spin had continuous values like the classical picture we would see it

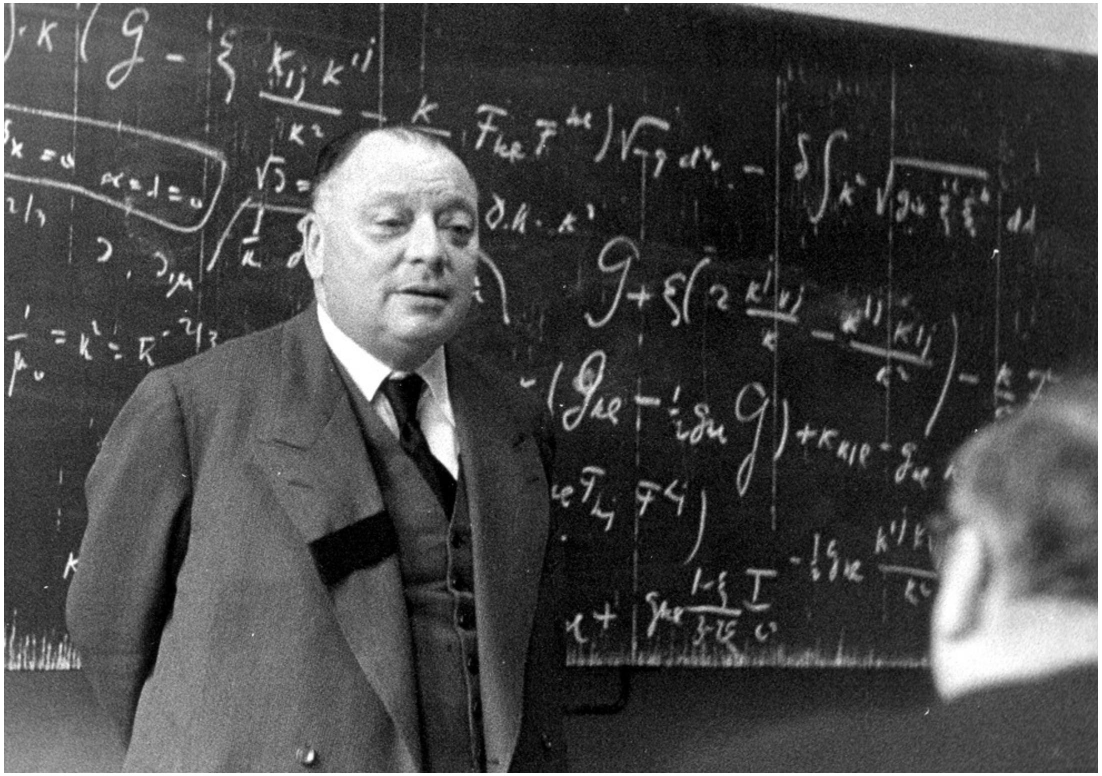
What is *Spin* Physics



Stern-Gerlach: Instead we see spin has only two values in the field with opposite directions:
or *spin-up* and *spin-down*

What is *Spin* Physics





W. Pauli (1925) : *Two fermions cannot share the same set of quantum numbers within the same system*

The Pauli Exclusion Principle: Allowed configuration of electrons

What is *Spin* Physics

- Quark Model

  Murray Gell-Mann → Quarks

  George Zweig → Aces
- Quarks

  - fractional charge

  - spin ½

  - flavors (up, down, …)

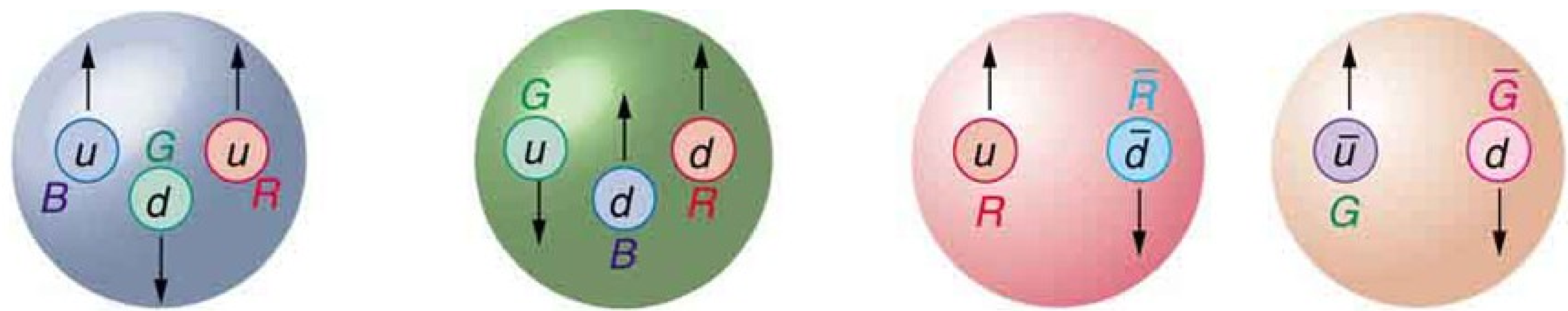
Baryons → 3 quarks: half integer spin

Mesons → quark-antiquark: integer spin

Gell-Mann and Zweig (1964) : *Independently suggested the quark model classification scheme*

Classification in terms of *Valance Quarks* the quarks that contribute to the quantum numbers of the hadrons

What is Spin Physics



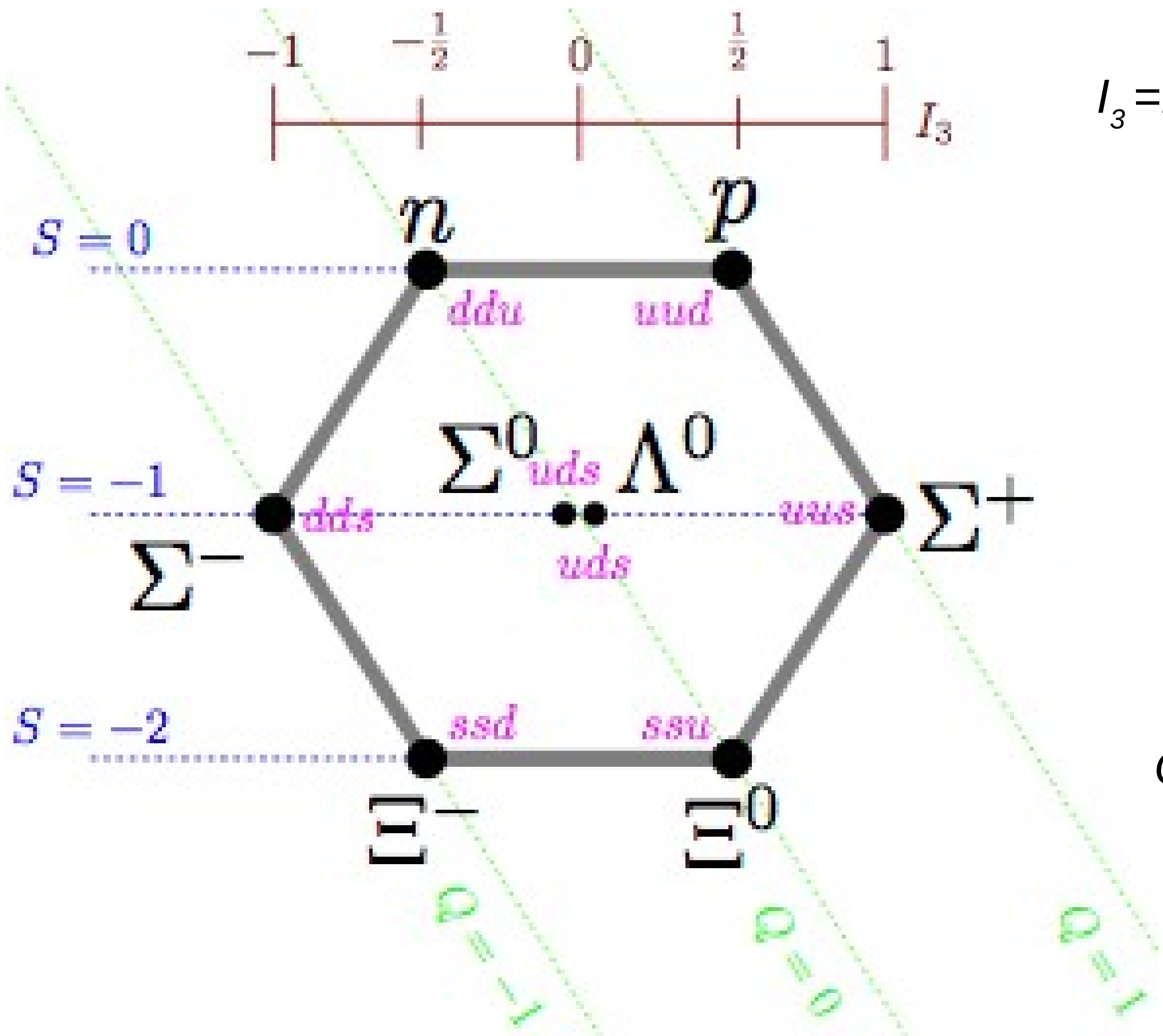
	Proton	Neutron	π^+	π^-
Spin	$\frac{1}{2}+\frac{1}{2}-\frac{1}{2}=\frac{1}{2}$	$-\frac{1}{2}+\frac{1}{2}+\frac{1}{2}=\frac{1}{2}$	$+\frac{1}{2}-\frac{1}{2}=0$	$+\frac{1}{2}-\frac{1}{2}=0$
Charge	$+\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=1$	$+\frac{2}{3}-\frac{1}{3}-\frac{1}{3}=0$	$+\frac{2}{3}+\frac{1}{3}=+1$	$-\frac{2}{3}-\frac{1}{3}=-1$

Building the known particles

What is Spin Physics

$I_3 = 1/2(n_u - n_d)$

Strangeness



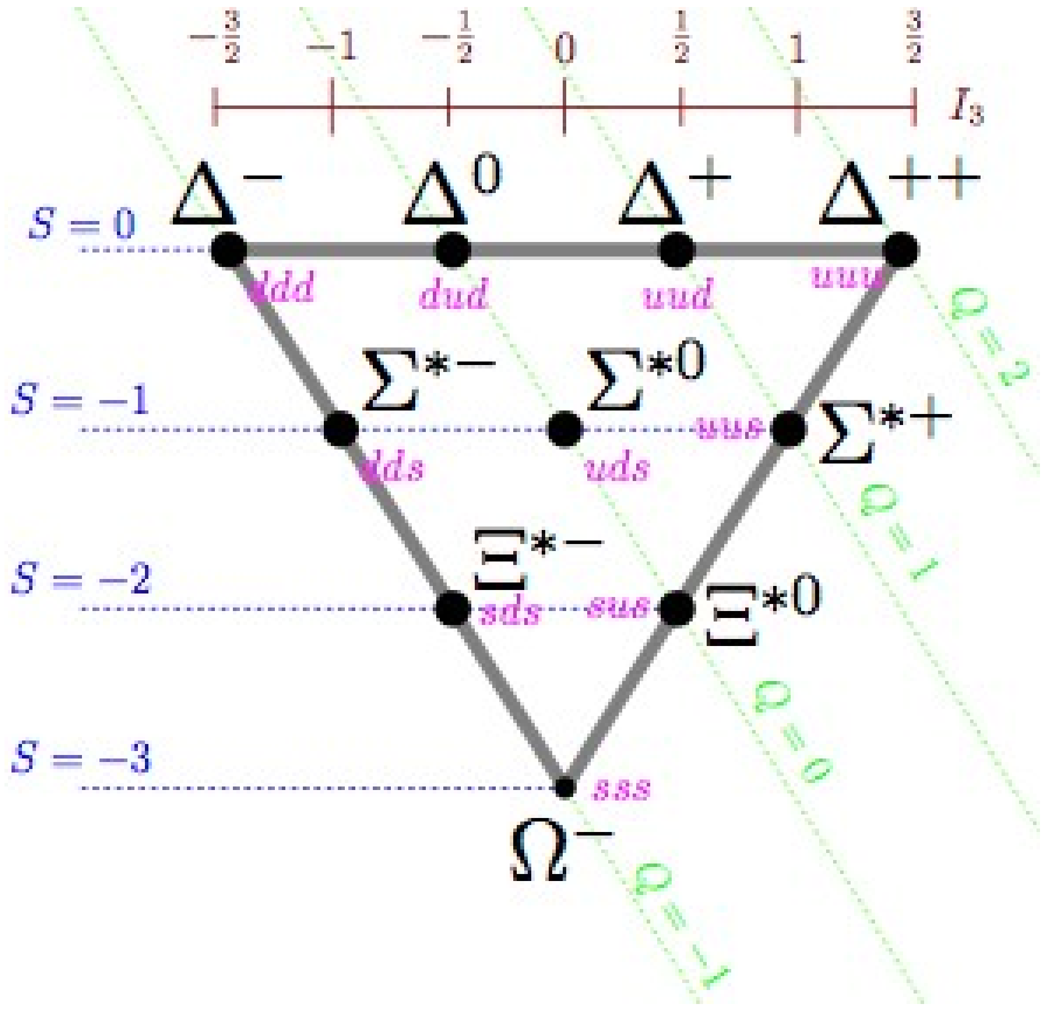
Charge

Baryons with spin ½: *adding quarks to reveal additional quantum numbers*

What is Spin Physics

I_3=1/2(n_u-n_d)

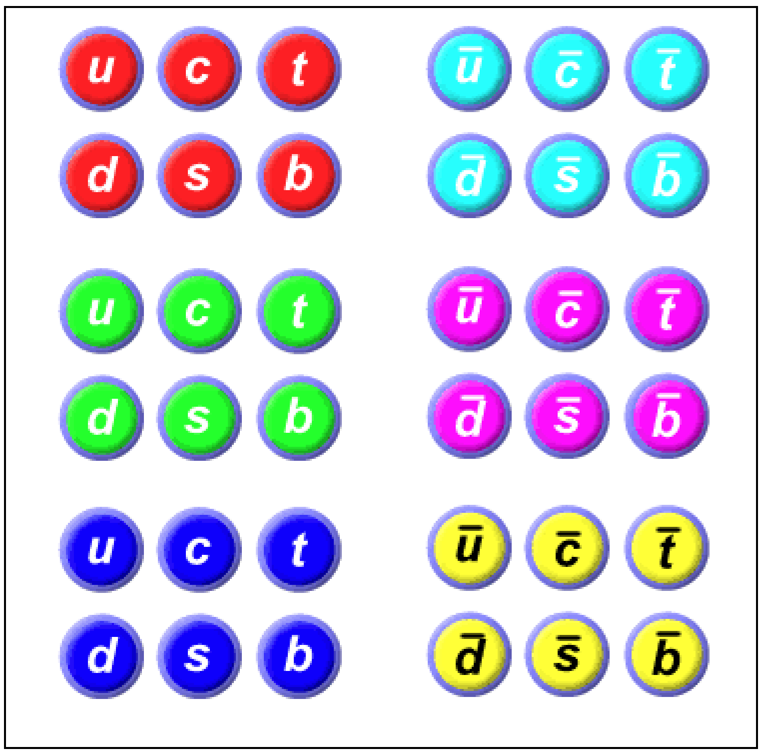
Strangeness

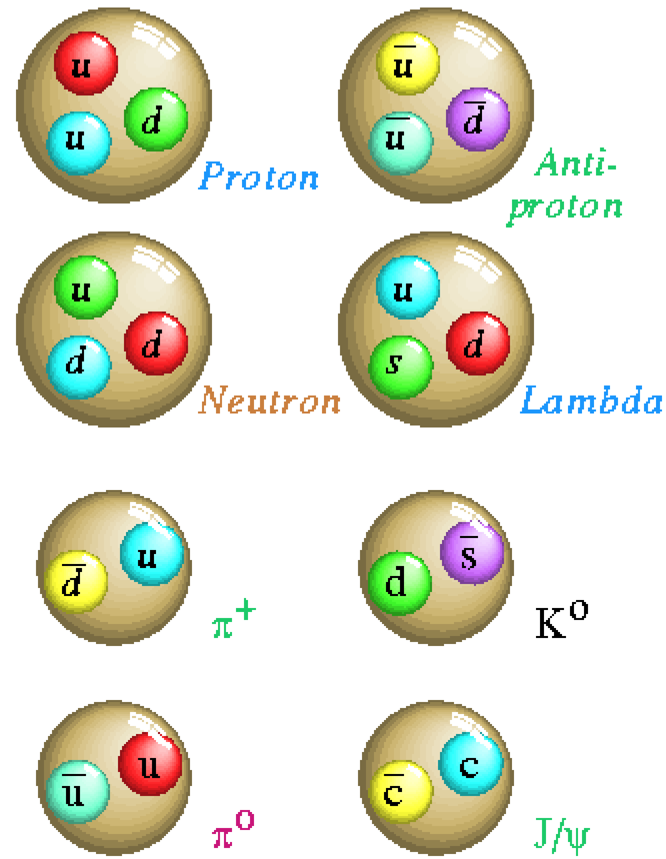


Charge

Baryons with spin 3/2: *adding quarks to reveal additional quantum numbers, new prediction yields color*

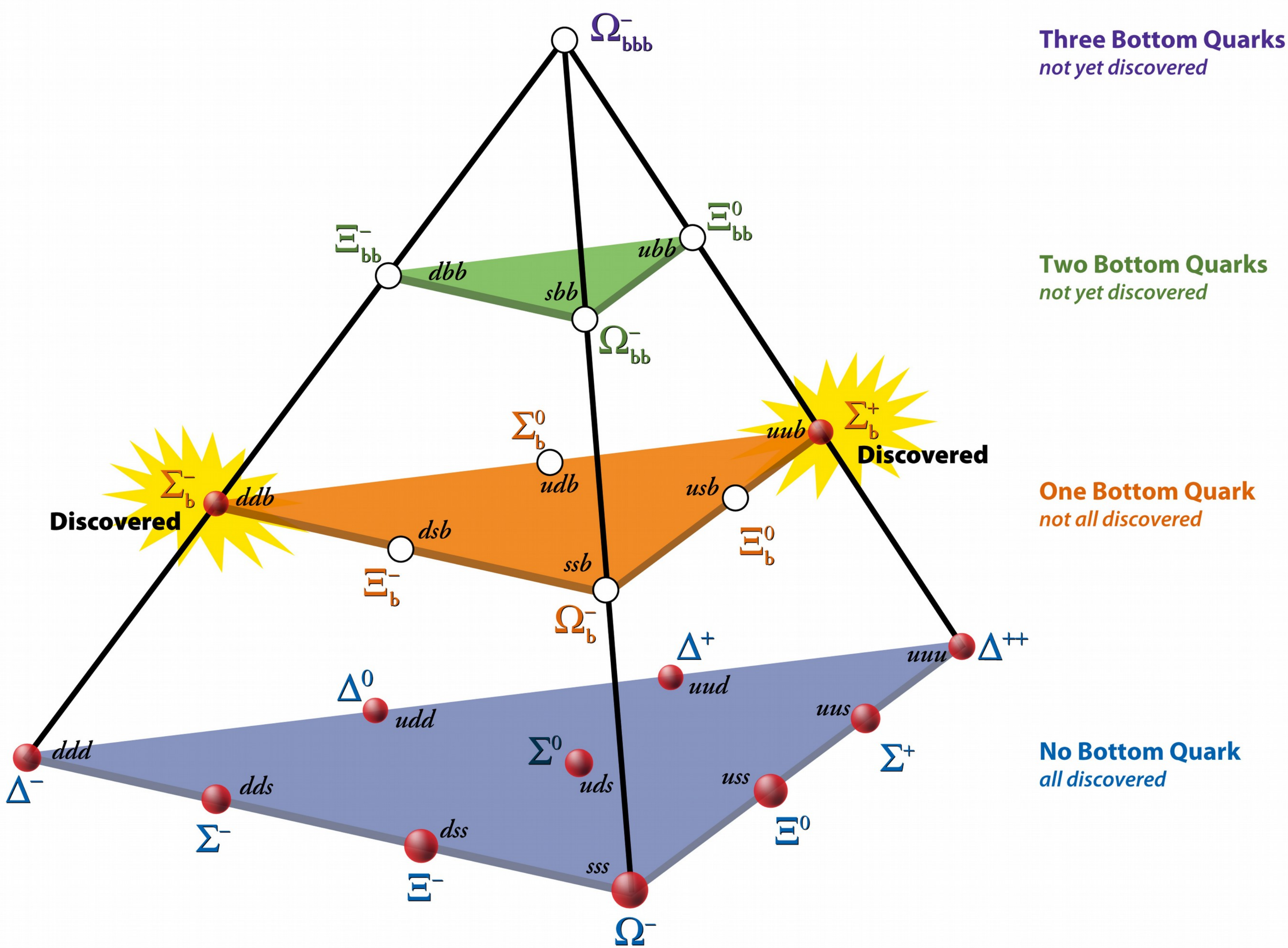
What is Spin Physics

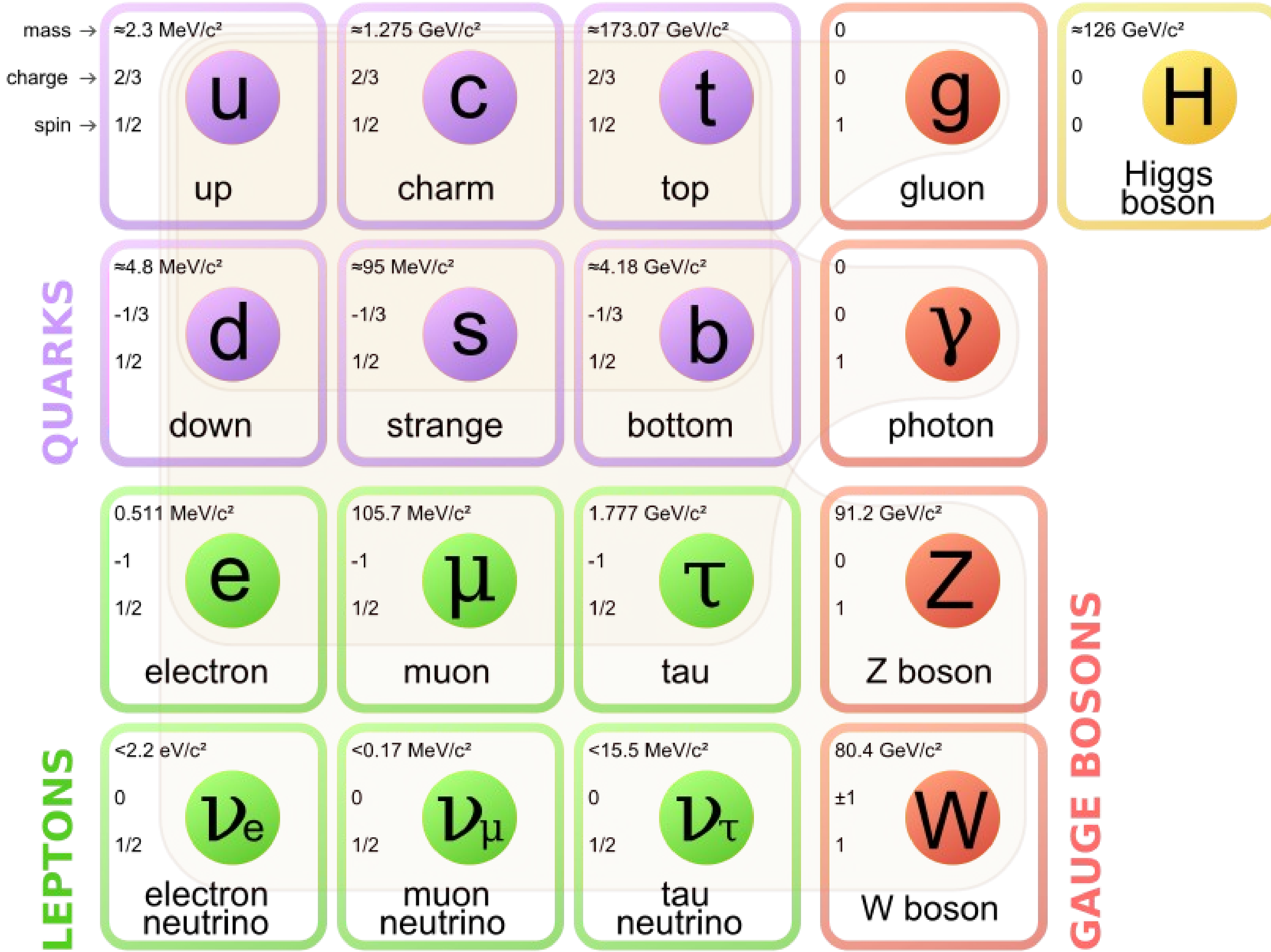




Baryons with spin 3/2: *adding quarks to reveal additional quantum numbers, new prediction yields color*

Baryons with Up, Down, Strange and Bottom Quarks and Highest Spin ($J = 3/2$)





How do we understand the properties of particles: *fundamental attributes of matter like mass, charge and spin*

Some Important Questions

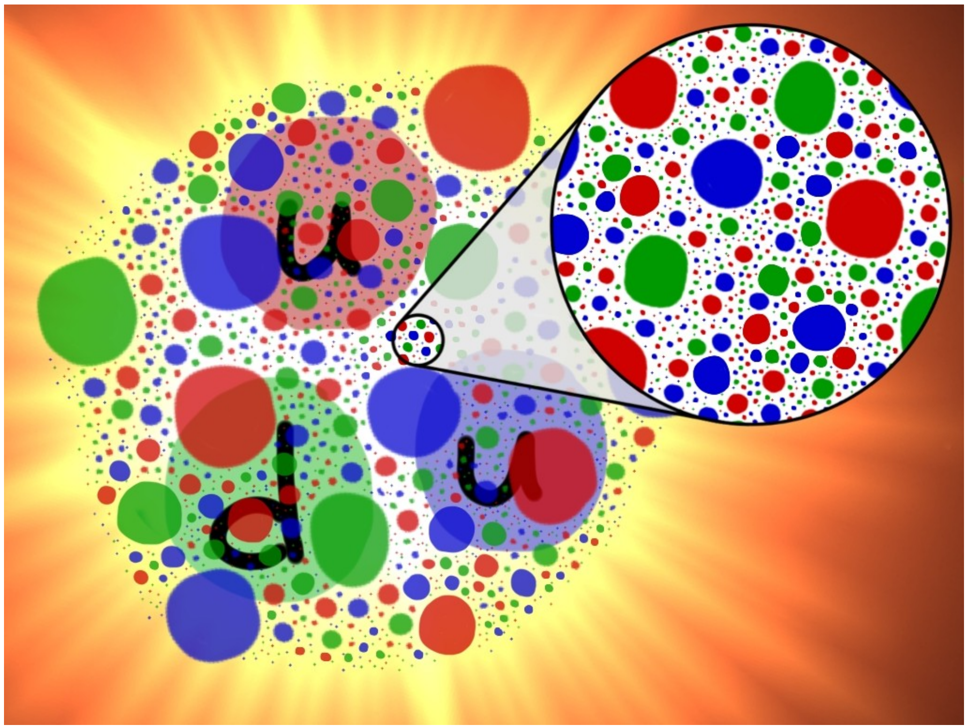
- What are the dynamics inside of composite particles

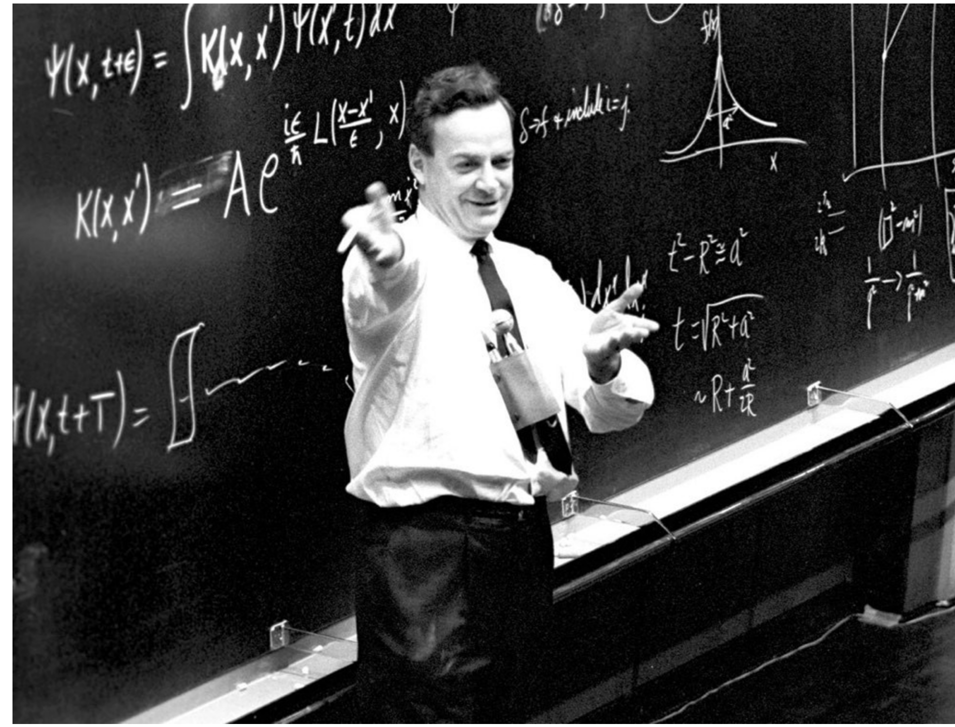
- How do we actually observe quarks (directly)?

- Mass of a d~5 MeV and u~2.3 MeV so whats the mass of the proton (uud)?

- What are the components of spin in the proton?

Parton Model





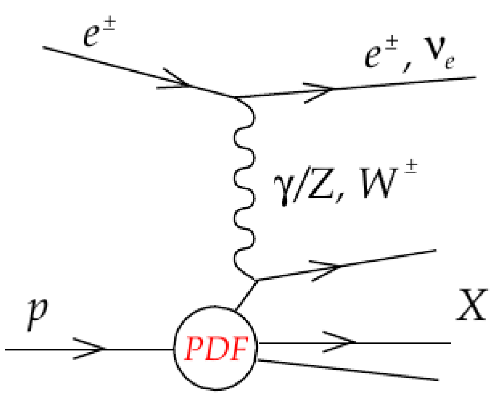
Richard Feynman (1968) : *part of or fraction of total momentum, charge, spin*

- Electron-parton interaction
- Partons: Quarks, Gluons, Antiquarks, vacuum contributions

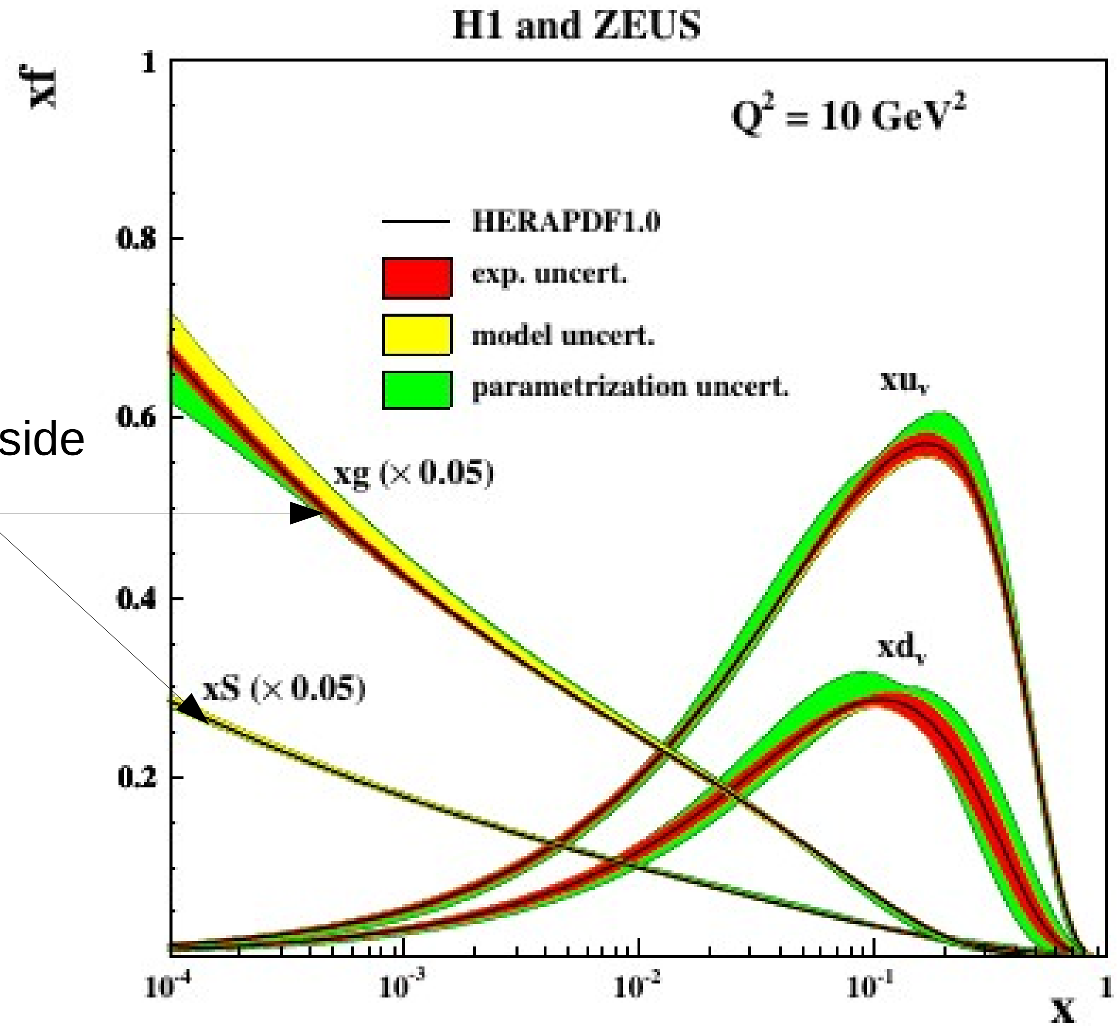
  - not elastic, must take into account all fundamental forces

  - Via Virtual photons

Deep Inelastic Scattering



Virtual Particle Inside the Proton

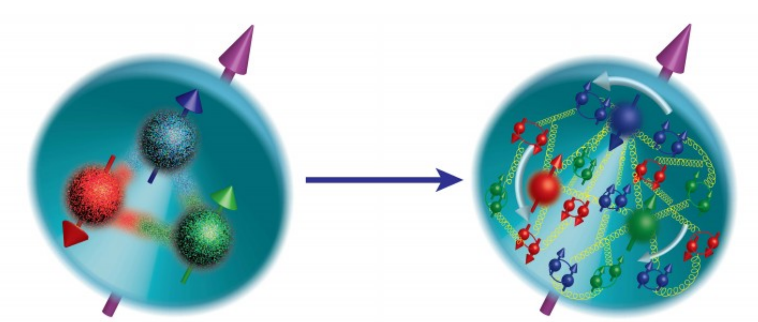


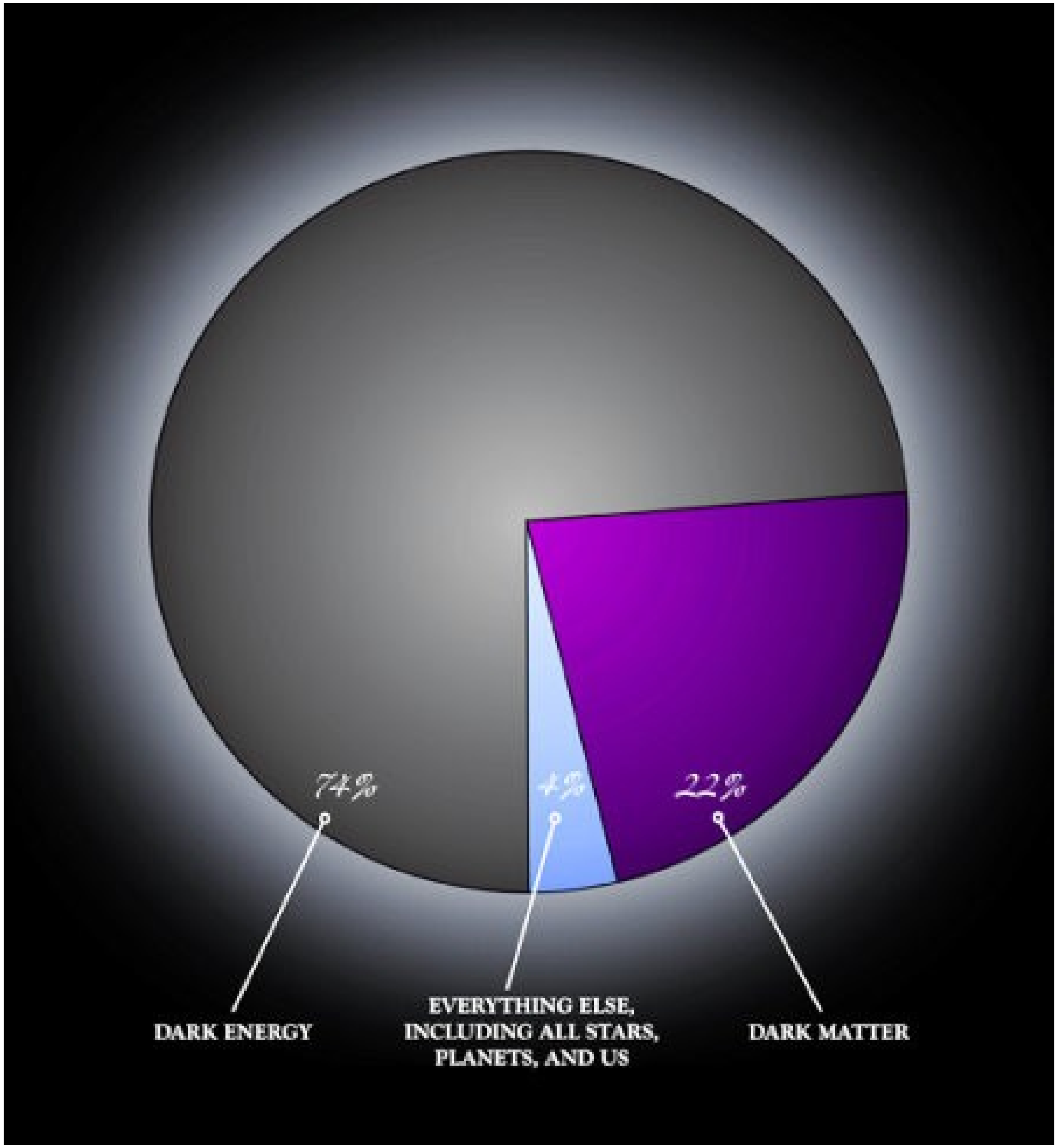
Parton Distribution Functions

Explore internal structure: *1000 times smaller than the size of the proton, or the scale which can be resolved at inside*

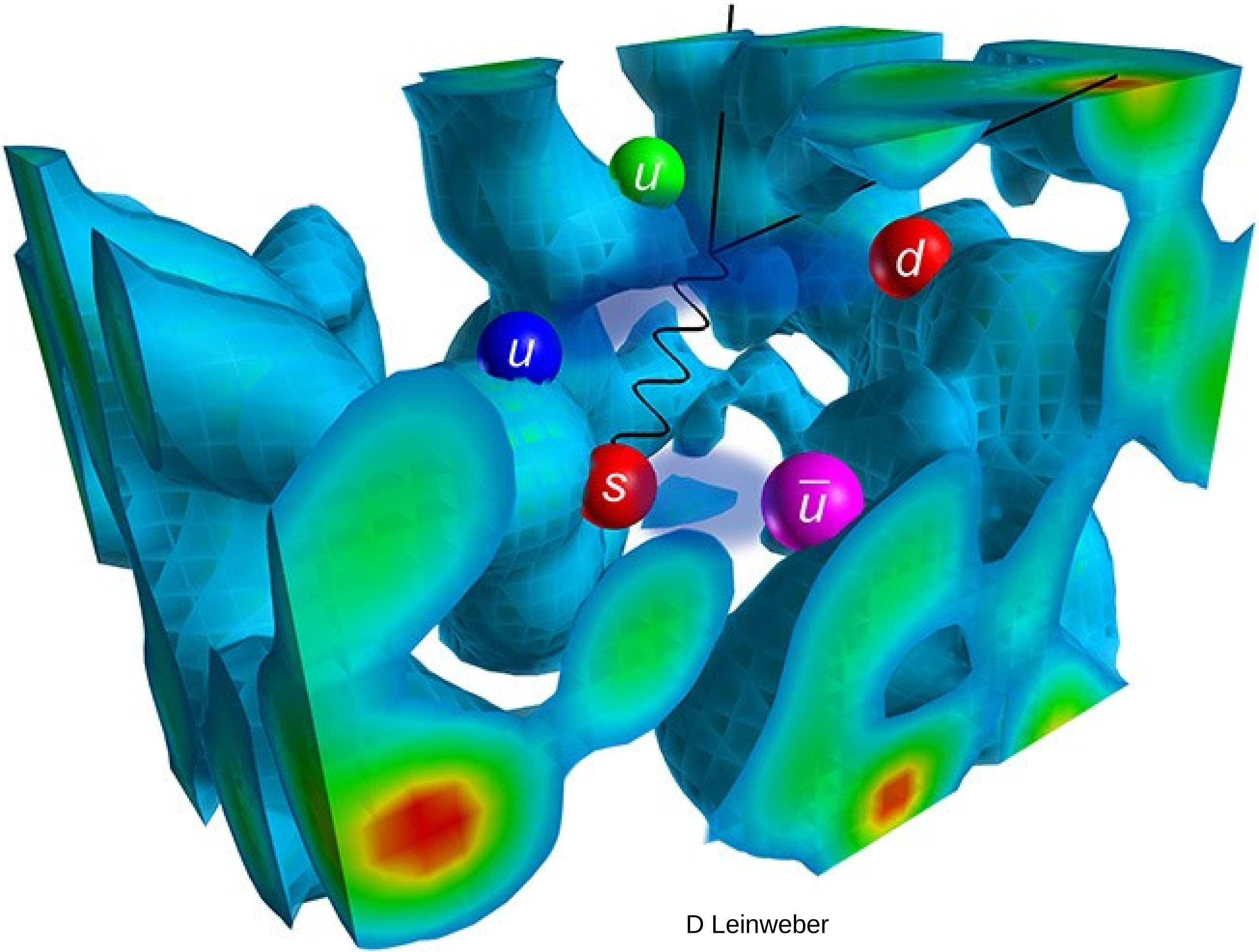
What we Think we Know

- Of the 4-5%, Higgs helps to understand 1% of this
- The mass generated by the Higgs mechanism is very far in value from the characteristic scale of strongly interacting matter
- Where is the rest of the Mass in hadrons
- Where is the rest of the Spin
- Valence quarks masses contribute only about 1% of the proton mass
- Valence quarks contribute 20-30% to the proton spin



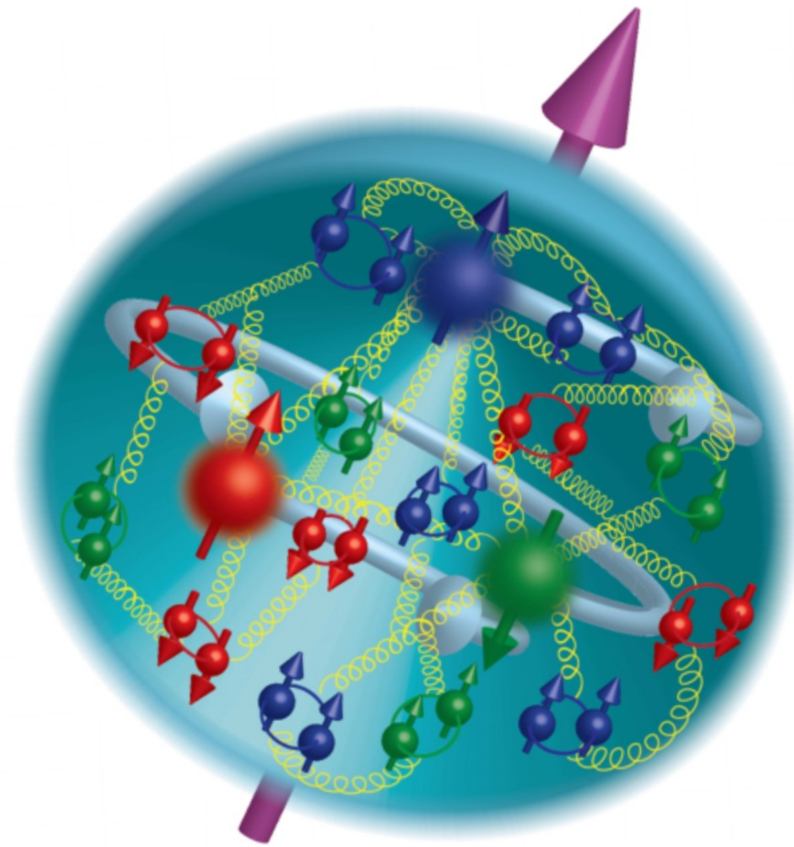


Deep Inside a Proton



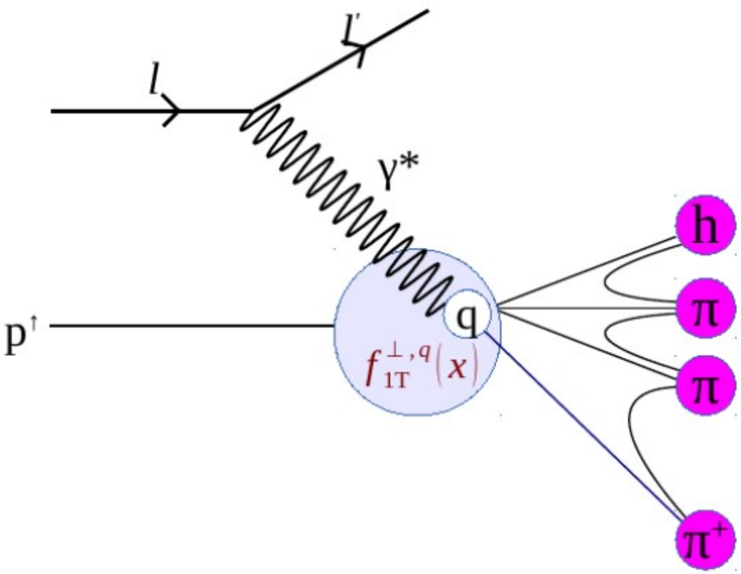
D Leinweber

Deep Inside a Polarized Proton



Accessing Quark Sivers TMDs

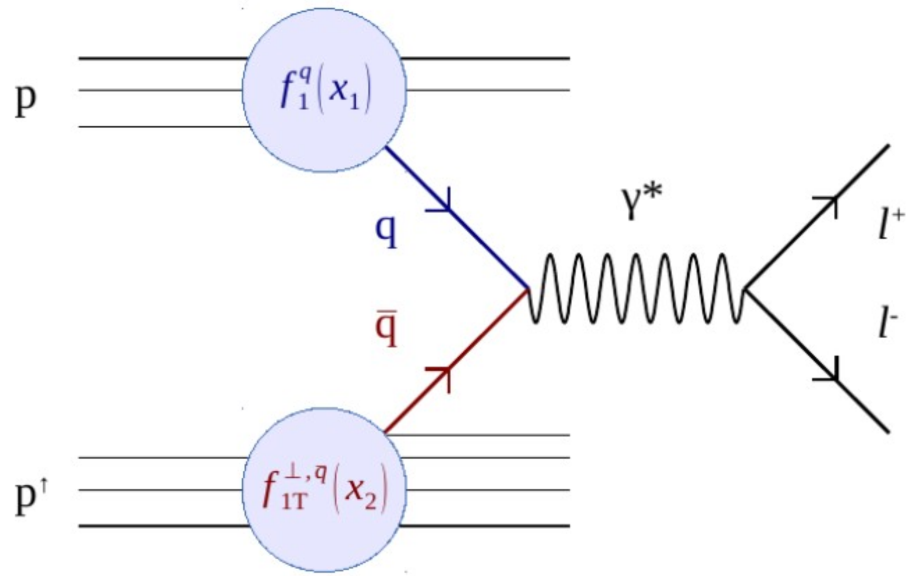
Polarized Semi-Inclusive DIS



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

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

Polarized Drell-Yan



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

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

Origin of Spin

DIS experiment (1988) show 20-30$\%$ of spin carried by valence quarks

"... $g_1(x)$ for the proton has been determined and its integral over x found to be $0.114 \pm 0.012 \pm 0.026$, in disagreement with the Ellis-Jaffe sum rule. ... These values for the integrals of g_1 lead to the conclusion that the total quark spin constitutes a rather small fraction of the spin of the nucleon." [J. Ashman et al., Phys. Lett., vol. B206 (1988) 364]

We need a theoretical formulation to address the proton spin puzzle
Lattice QCD

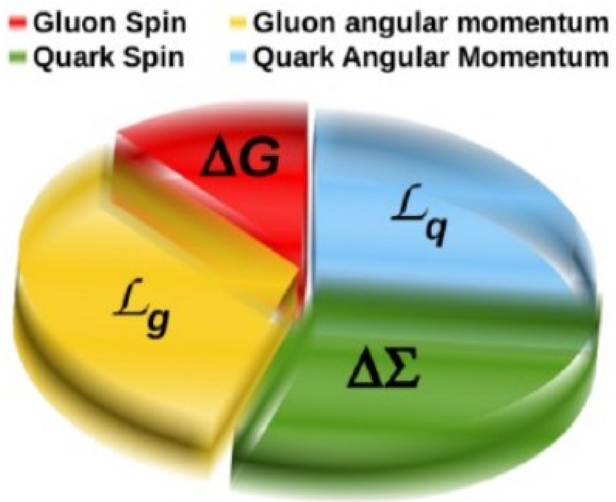
Spin Sum Rule (Ji):

$$\frac{1}{2} = \sum_q J^q + J^G = \sum_q \left(L^q + \frac{1}{2}\Delta\Sigma^q\right) + J^G$$

L_q: **Quark orbital angular momentum**
$\Delta\Sigma_q$: **intrinsic spin**
J^G: **Gluon part**

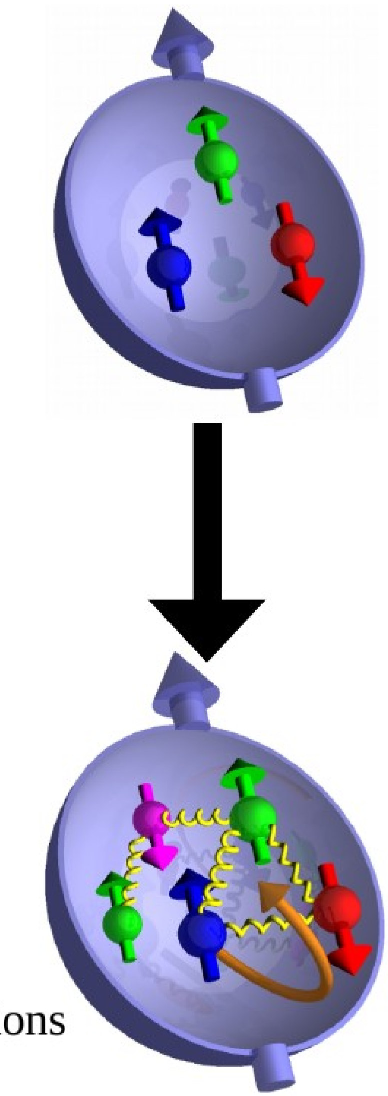
- **naive non-relativistic SU(6) quark model:** $\Delta\Sigma = 1$, $L_q = 0$, $J_g = 0$

How does it fit together: *Valance quarks contribute but so do the contributions from the vacuum and gluons*



Proton Spin Puzzle

- Naive understanding of Proton spin not correct
- Add Gluon spin, Orbital Angular Momentum



$$S_{proton} = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_q \rangle + \langle L_g \rangle$$

Quark Spin (Including sea quarks)

Gluon Spin

Orbital Angular Momentum Contributions

How do we access the different parts of the spin puzzle?

The Evolution of Spin

- Our understanding of the nucleon and its spin evolves:

1970s | 1980s/2000s | Now

  - ✧ A strongly interacting, relativistic bound state of quarks and gluons
  - ✧ Understanding it fully is still beyond the best minds in the world

- From quantum mechanics to quantum field theory – QCD:

  - ✧ Spin of a composite object in QM: $\vec{S} = \sum_{i=1}^{N} \vec{s}_i$ ***N*** **is finite!**

  - ✧ Proton spin in QCD = Proton's angular momentum when it is at the rest
    - QCD energy-momentum tensor & angular momentum density:

$$M^{\alpha\mu\nu} = T^{\alpha\nu}x^{\mu} - T^{\alpha\mu}x^{\nu} \qquad J^i = \frac{1}{2}\epsilon^{ijk}\int d^3x M^{0jk}$$

    - Proton spin: $S(\mu) = \sum \langle P,S|\hat{J}^z_f(\mu)|P,S\rangle = \frac{1}{2}$

As a quantum Probability!

Some Spin Physics Projects

- ORNL: DNP proton crystallography with a neutron beam at Spallation Neutron Source (DNP-SNS)
- LHCb: QCD-spin physics in nucleon structure and hadron spectroscopy (SMOG, LHC-SPIN)
- Fermilab: New spin physics program with polarized target and liquefier (E906, E1027, E1039)
- HIGS-TUNL: Spin physics program at Duke with polarized beam and soon polarized target (P-12-16, P-20-09)
- Next Gen HIGS: New design with higher energy and intensity with an active polarized target (HIGS2)
- NIST: Scattering production of paramagnetic complex and target sample experiments (NIST-PTexp)

Spokesperson Project Involvement

Projects at Jefferson Lab

- Hall A
  (E12-11-108) SIDIS with transversely polarized proton target
  (E12-11-108A) Target single spin asymmetries using SoLID
  (LOI-12-15-007) Time-like Compton Scattering in SoLID
- Hall B
  (E12-06-109) Longitudinal spin structure of the nucleon
  (E12-06-119) DVCS with LCAS at 12 GeV
  (E12-07-107) Spin-Orbit Correlations with a longitudinally PT
  (E12-09-009) Spin-Orbit Correlations in Kaon electroproduction in DIS
  (E12-12-001) EMC effect in spin structure functions
  (C12-15-004) DVCS on the neutron with a longitudinally PT
  (C12-11-111) SIDIS on a transversely polarized target
  (C12-12-009) Di-hadron production in SIDIS on a transversely PT
  (C12-12-010) DVCS on a transversely polarized target in CLAS12
- Hall C
  (E12-14-006) Helicity correlations in wide-angle Compton scattering
  (C12-13-011)The deuteron tensor structure function b1
  (C12-15-005)Tensor Asymmetry in the x<1 Quasielastic Region
  (C12-18-005) Time-like Compton Scattering
  (LOI-12-14-001) Search for exotic gluonic states in the nucleus
  (PR12-16-009) Longitudinal and Transverse Target Correlations in WACS
- Hall D
  (LOI-12-15-001) Physics Opportunities with Secondary KL beam at JLab
  (LOI-12-16-005) Target Helicity Correlations in GlueX

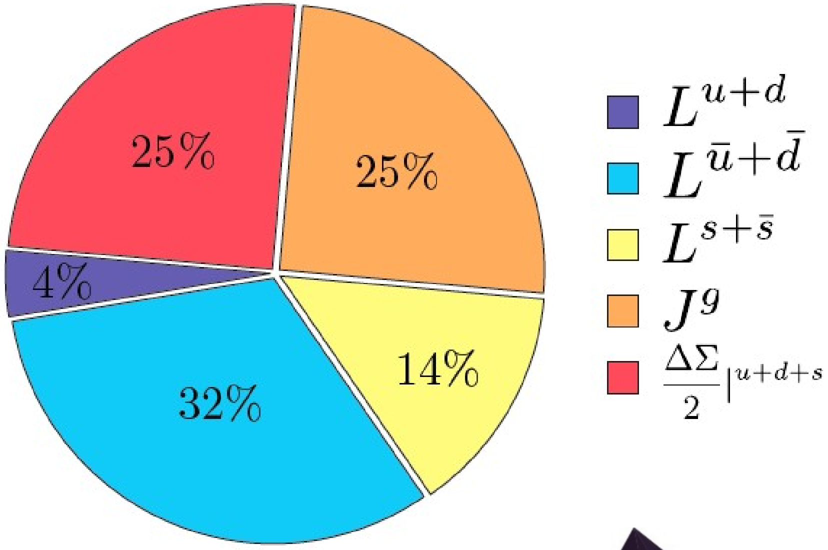
Spokesperson   Project Involvement

Where is the missing spin?

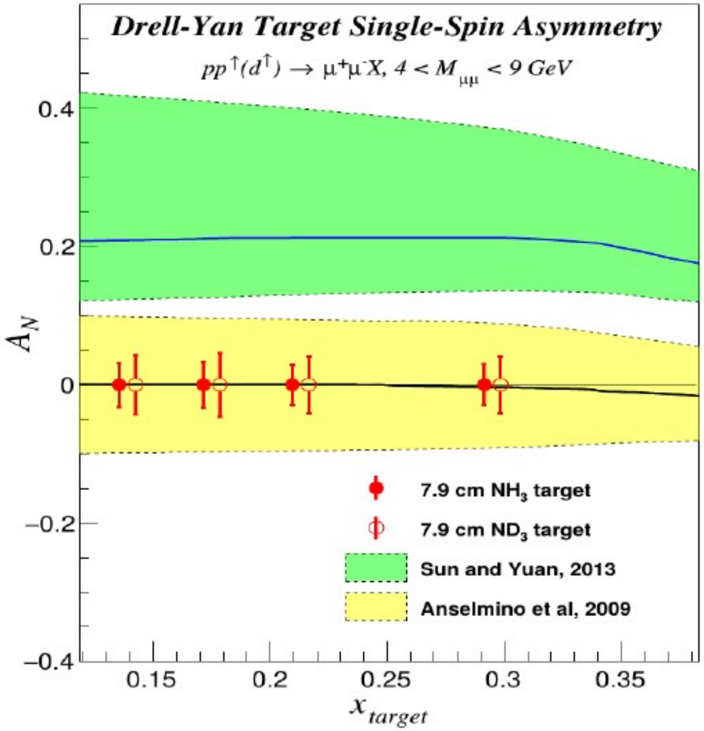
$$S_{proton} = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + J_g + \langle L_q \rangle + \langle L_{\bar{q}} \rangle$$

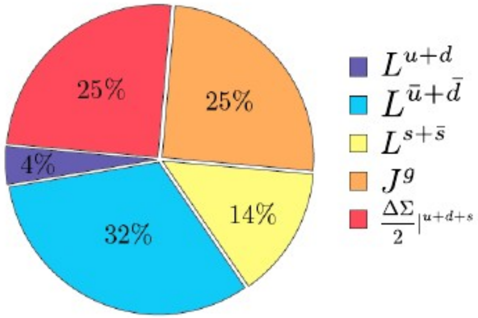
- Lattice QCD calculations indicate as much as 50% come from quark orbital angular momentum (OAM)
- **$\Delta L_{valence}$ ≈ Small**
- *Sea Quark OAM remains largely unexplored*
- *Hints of sea quark OAM have been seen*

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



Polarized Drell-Yan



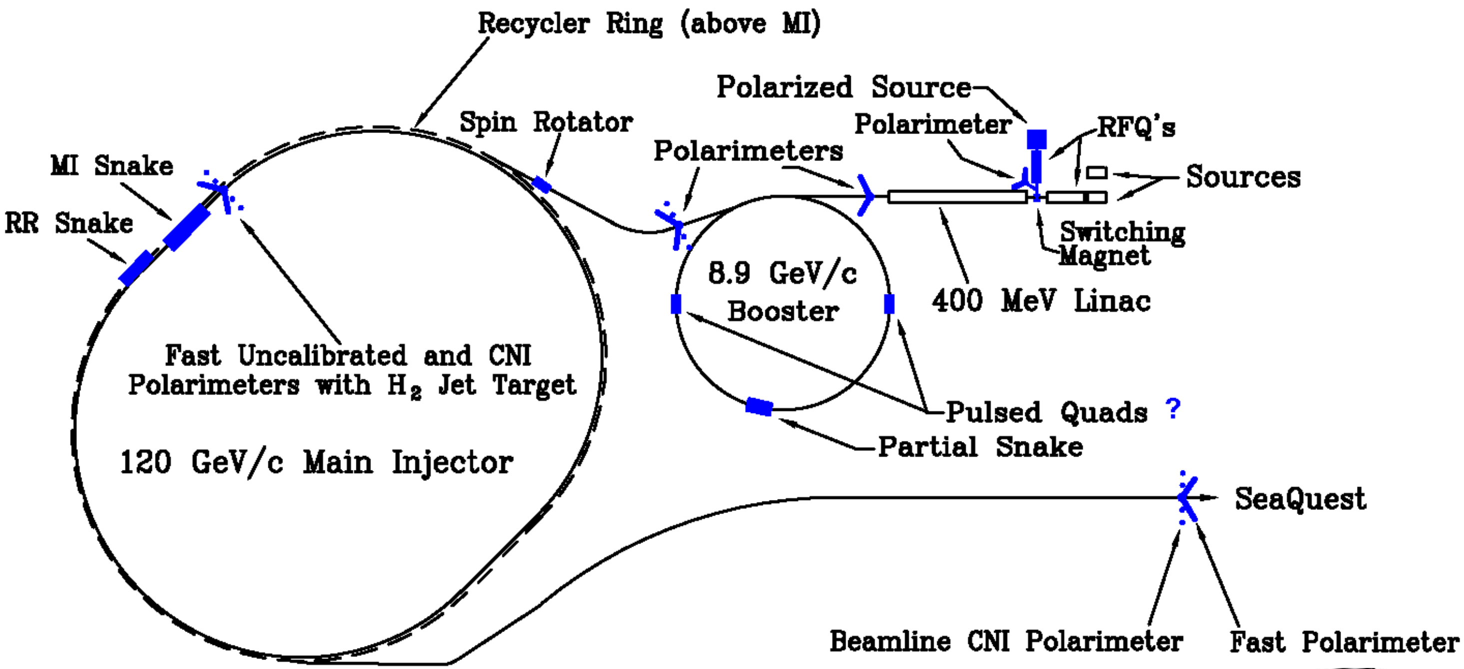


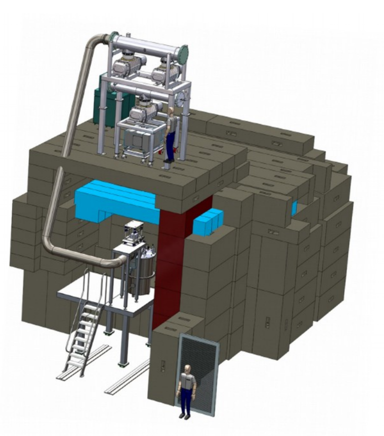
$$A_N\left(p_{beam}+p^{\uparrow}_{target}\rightarrow DY\right)\propto\frac{N_L^{DY}-N_R^{DY}}{N_L^{DY}+N_R^{DY}}\propto\frac{f_{1T}^{\perp,\bar{u}}\left(x_t\right)}{f_1^{\bar{u}}\left(x_t\right)}$$

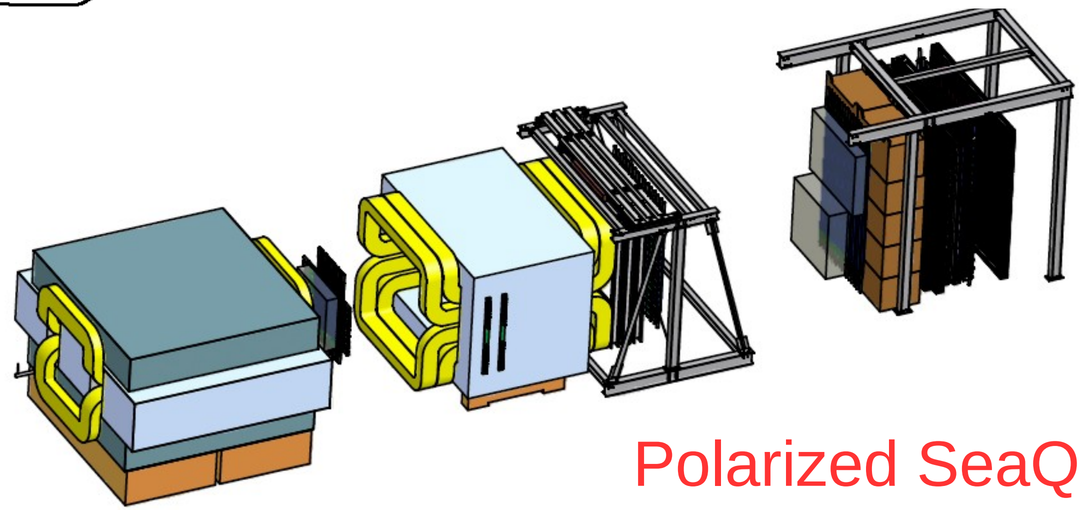
$$A_N\left(p_{beam}+d^{\uparrow}_{target}\rightarrow DY\right)\propto\frac{N_L^{DY}-N_R^{DY}}{N_L^{DY}+N_R^{DY}}\propto\frac{f_{1T}^{\perp,\bar{d}}\left(x_t\right)}{f_1^{\bar{d}}\left(x_t\right)}$$

- First measurement of sea quark Sivers ($\bar{u}$, $\bar{d}$)
- 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?

Experimental Setup for E1039



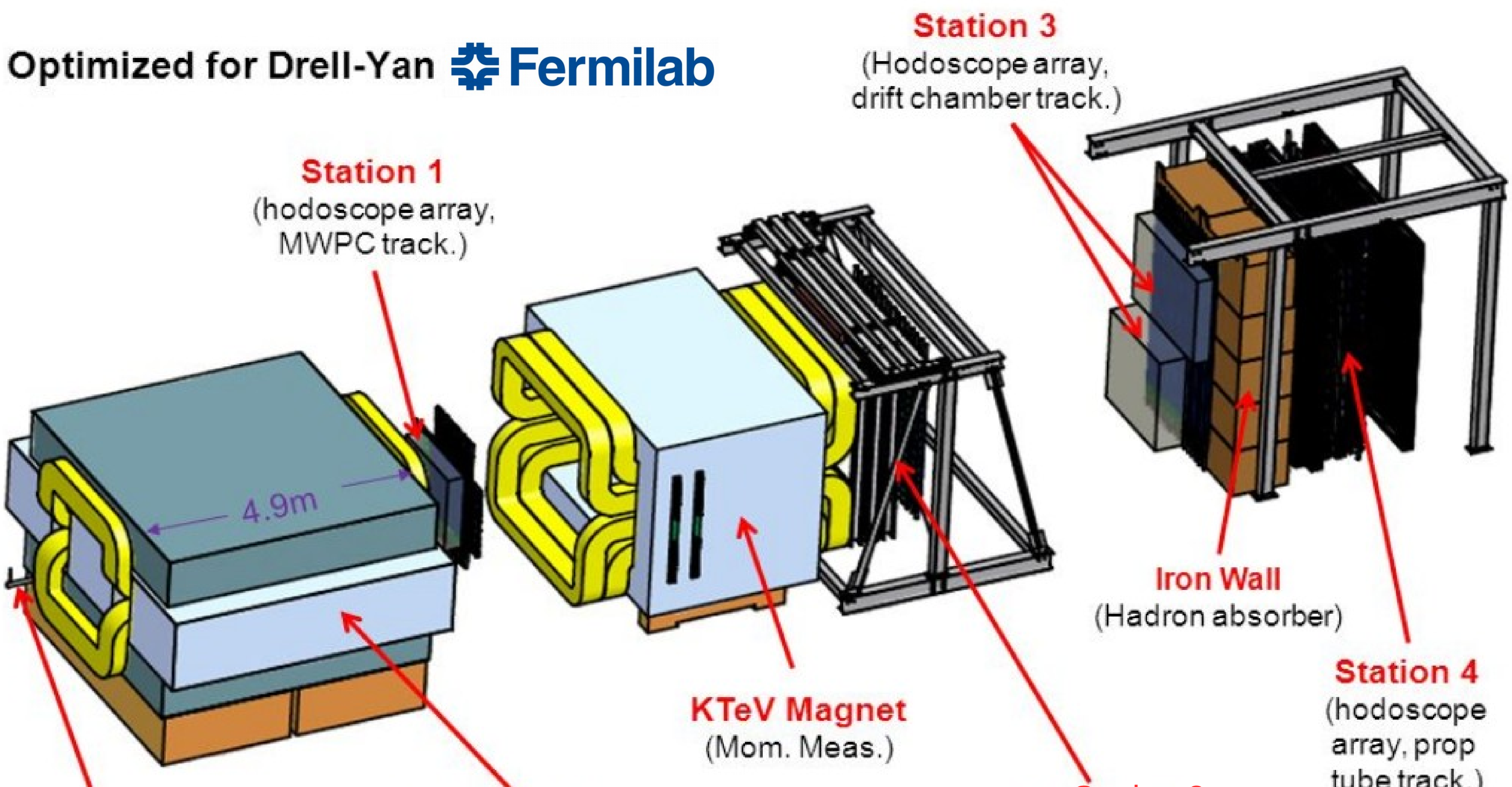




Polarized SeaQuest

Experimental Setup for E1039

Detector Pack



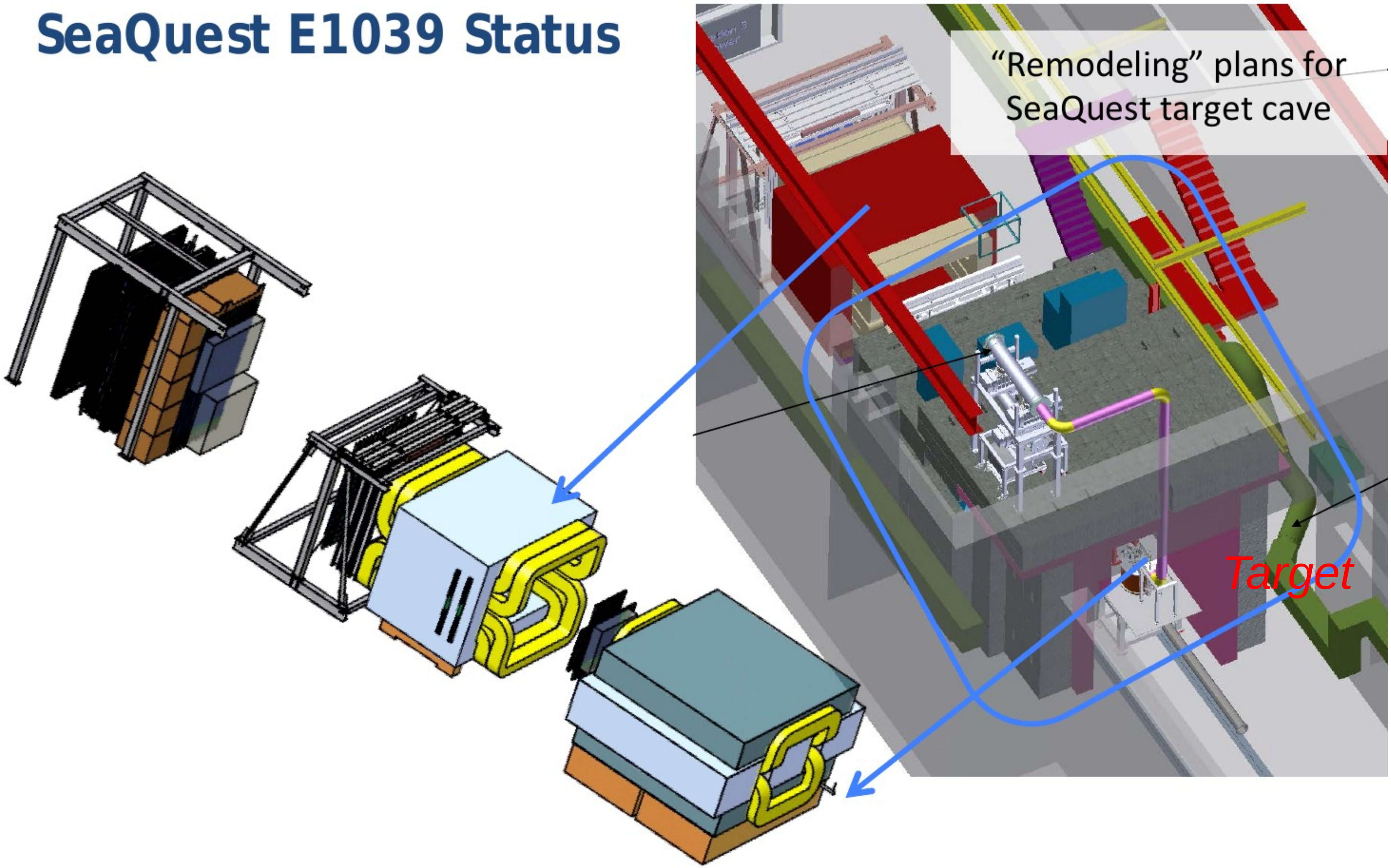
Target Cave: Under Construction

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

Station 2
(Hodoscope array, drift chambers track)

Experimental Setup for E1039

SeaQuest E1039 Status



Polarized target on the Intensity Frontier

Highest Intensity proton beam on polarized target with $4x10^{12}$ per 4s spill

- 8 cm long target cell of solid:

  NH_3 and ND_3

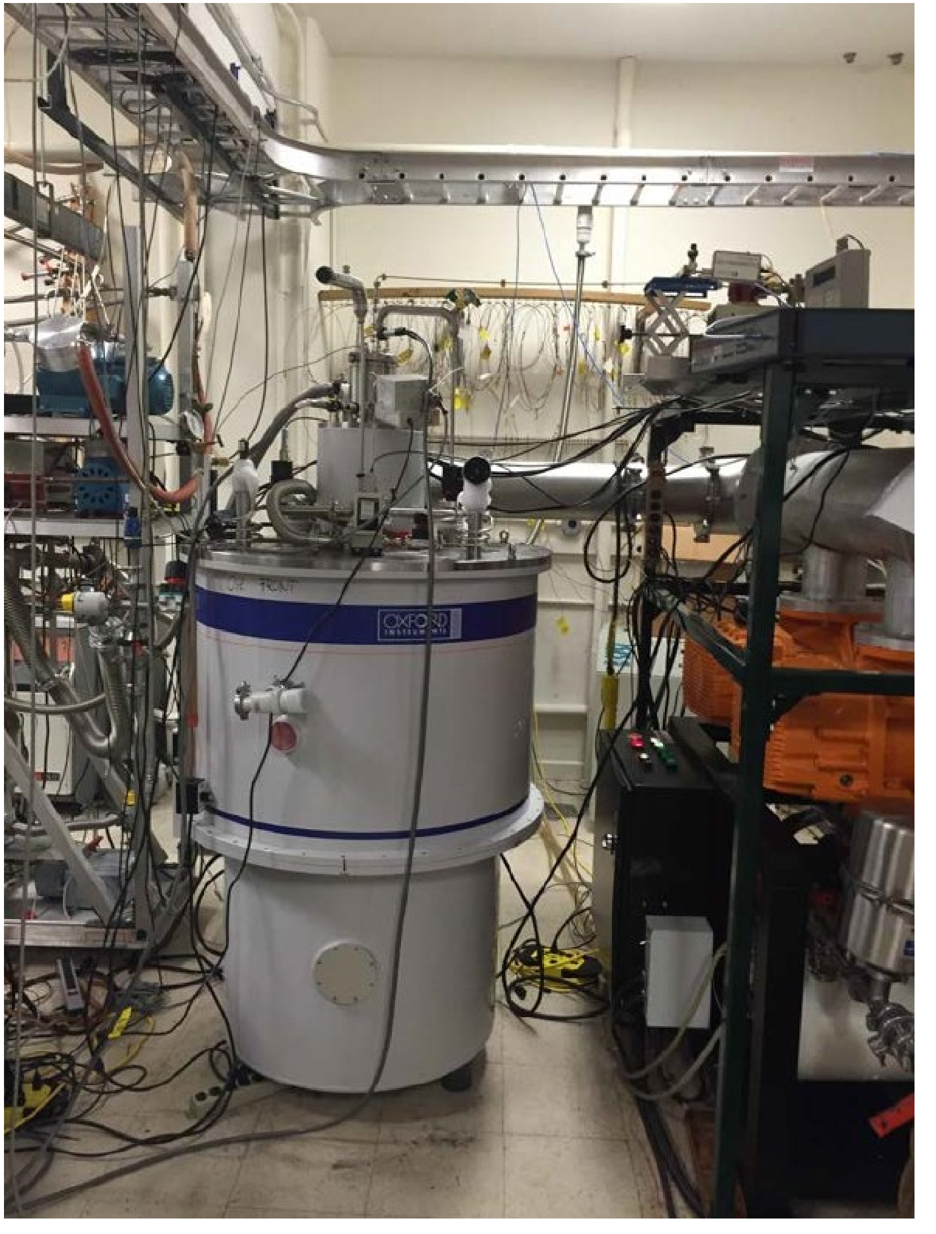
- 2 watts of cooling power:

  14,000 m^3 /hour pumping

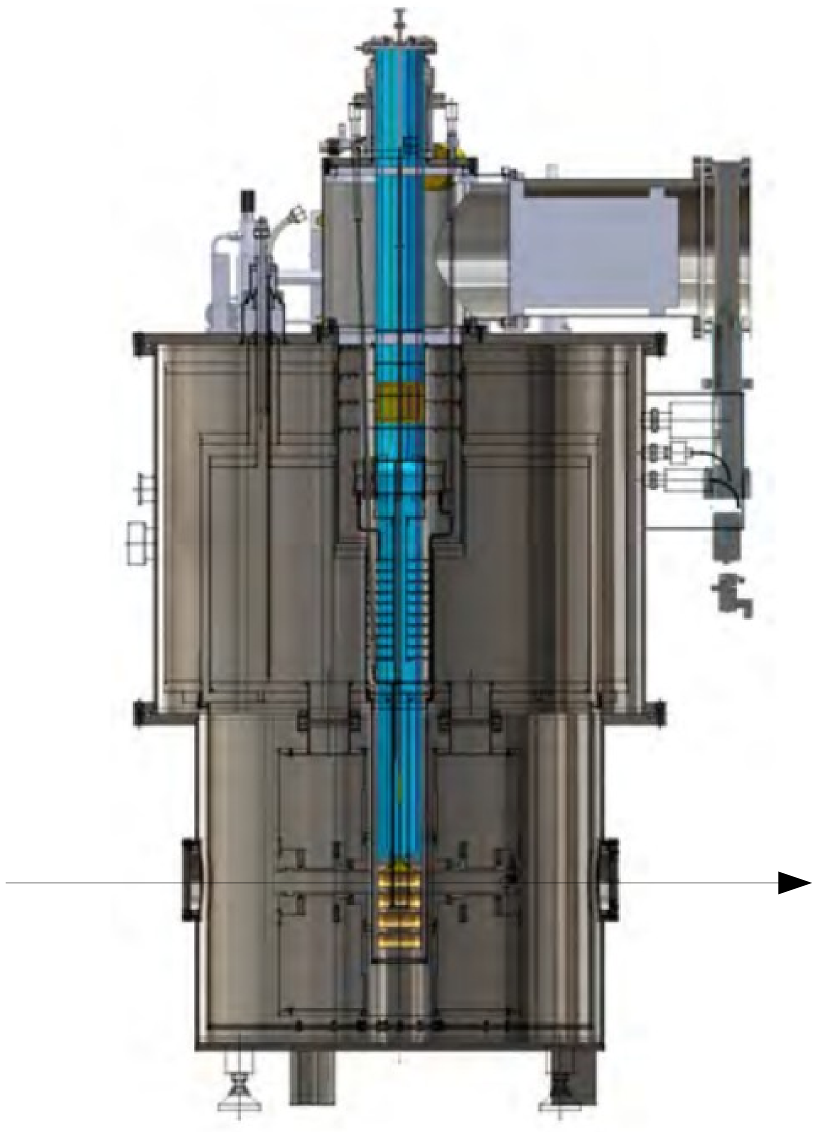
- 5T vertically pointing SC magnet:

  Pushing critical temp each spill

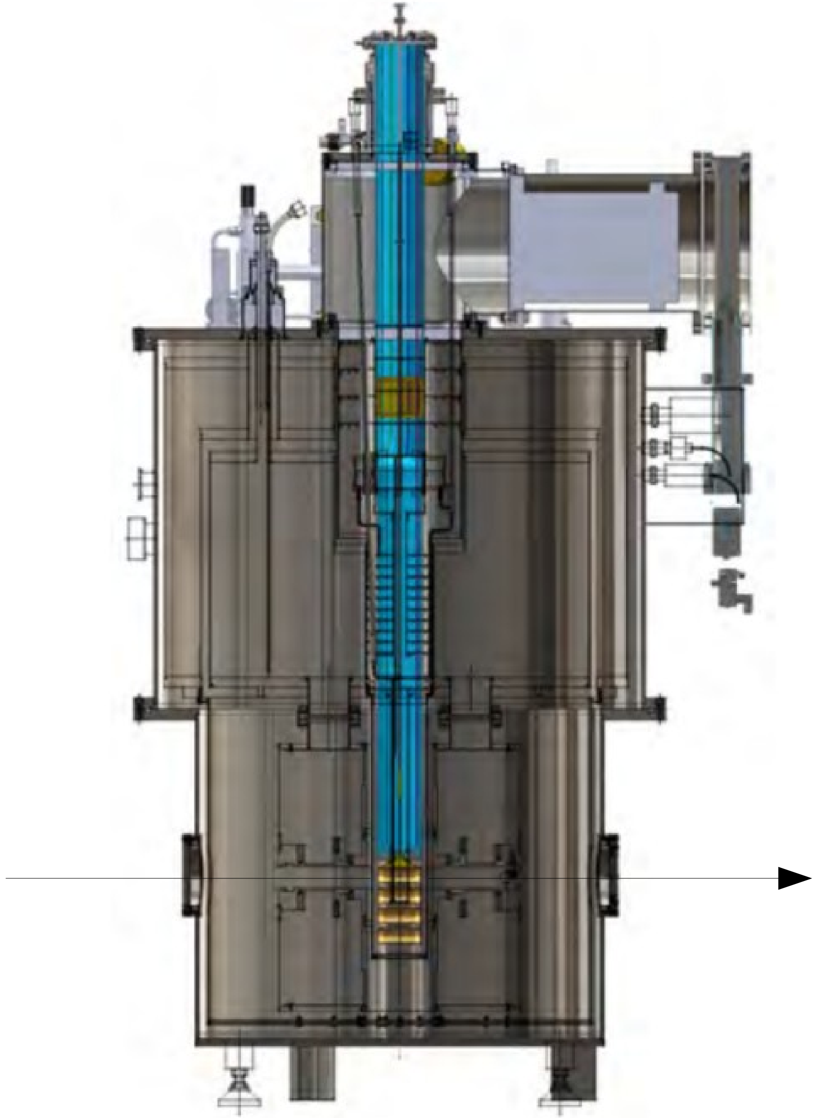
- Luminosity of around $2X10^{35}$ cm^{-2} s^{-1}



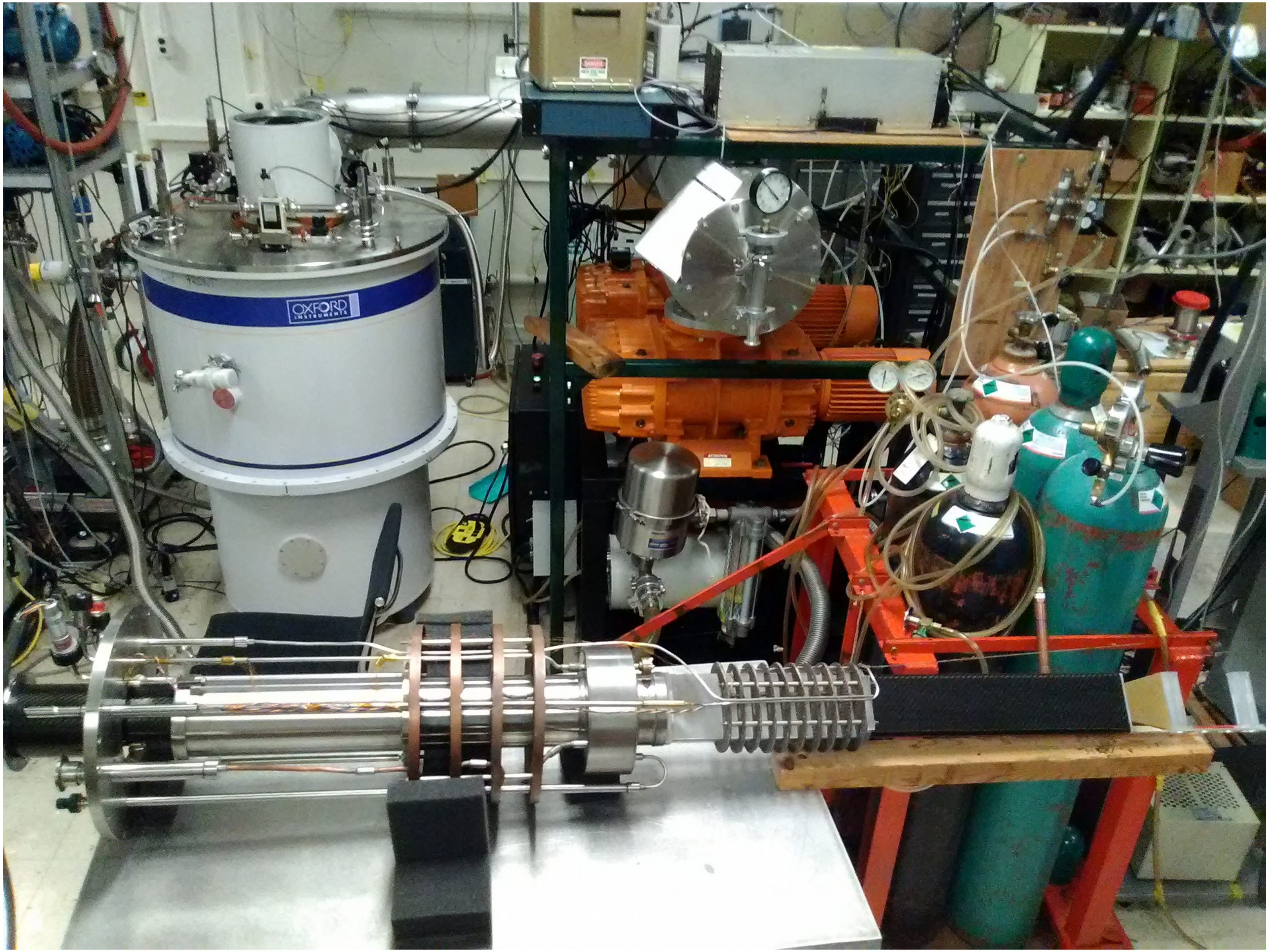
Polarized target on the Intensity Frontier



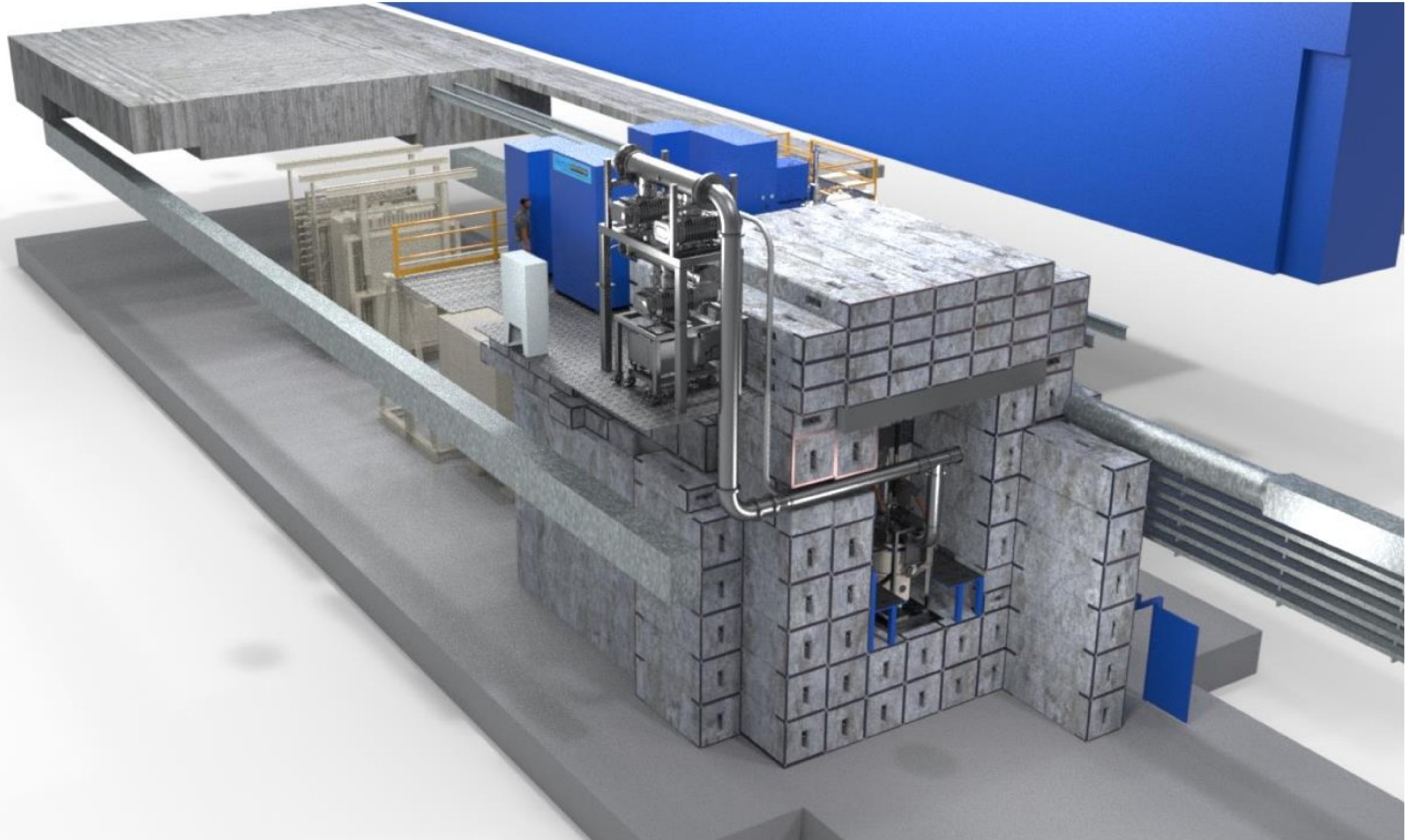
Polarized target on the Intensity Frontier



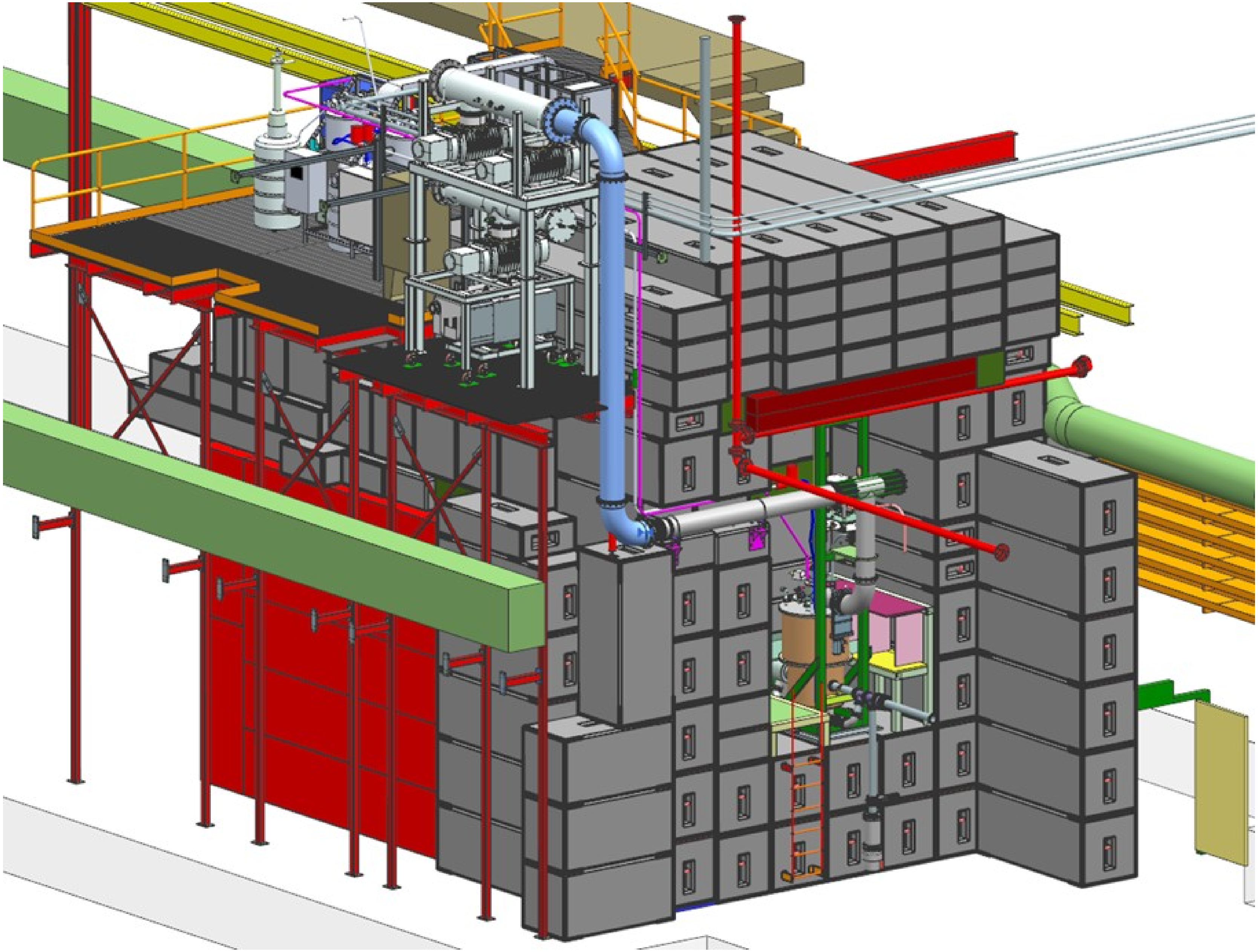
Target System



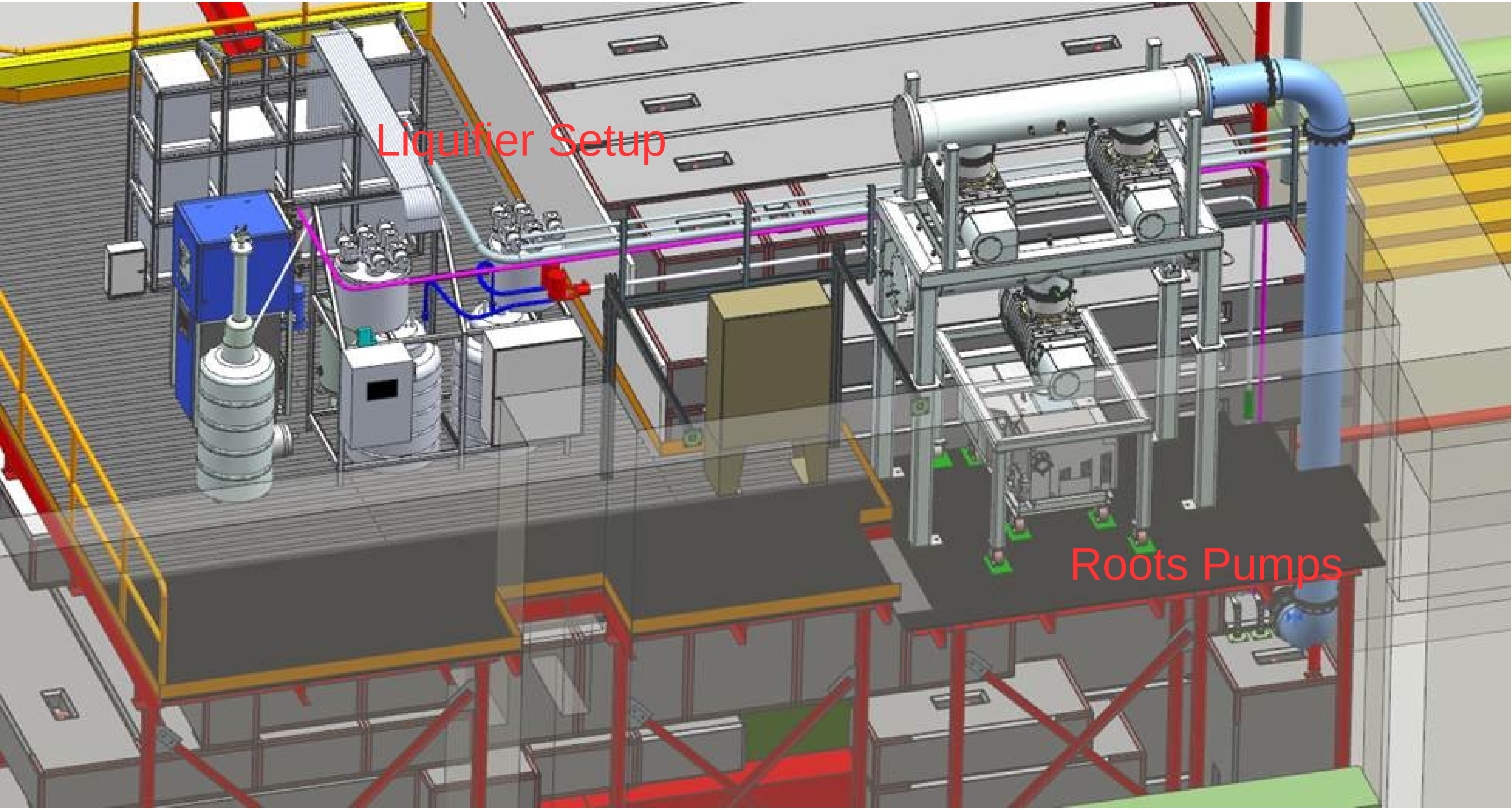
Cave Setup in Fermilab NM4



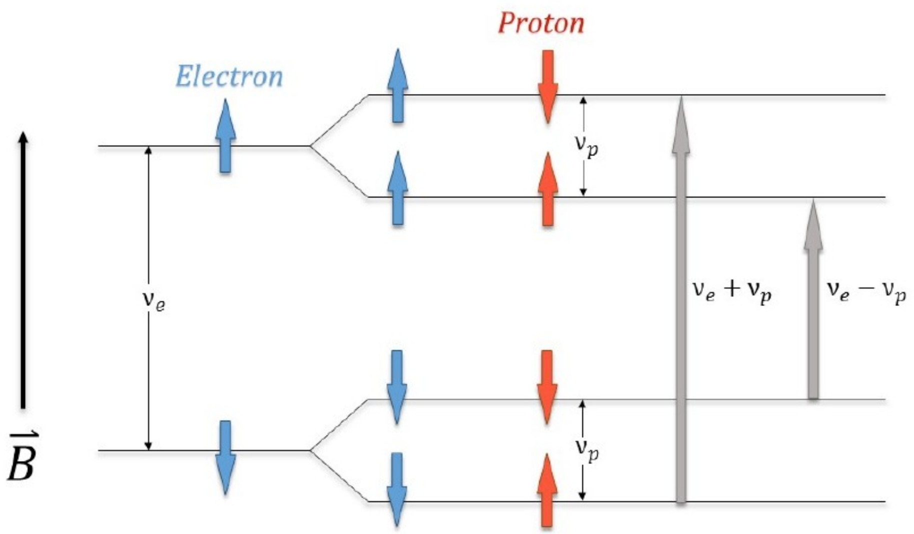
Target Cave from Upstream



Cryo-platform

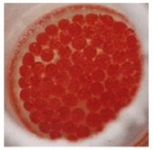


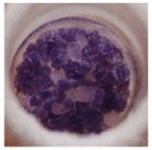
Dynamic Nuclear Polarization



Successful material for DNP characterized by three measures:

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

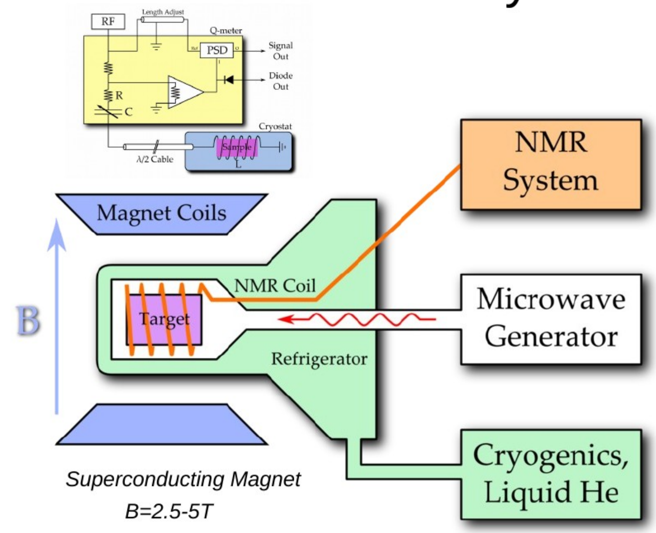




Material	Butanol	Ammonia, NH_3	Lithium Hydride, ^7LiH
Dopant	Chemical	Irradiation	Irradiation
Dil. Factor (%)	13.5	17.6	25.0
Polarization (%)	90-95	90-95	90
Material	D-Butanol	D-Ammonia, ND_3	Lithium Deuteride, ^6LiH
Dil. Factor (%)	23.8	30.0	50.0
Polarization (%)	40	50	55
Rad. Resistance	moderate	high	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)

General System



Polarization Detection

Tuned To Larmor of spin species

Proton (42.6 MHz/T)

Larmor-ESR

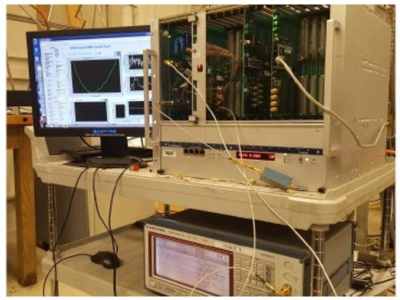
50-185 GHz

~140 GHz at 5T

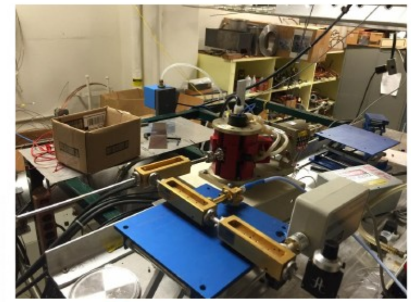
T=0.03-1K

DNP Target System

LANL-UVA



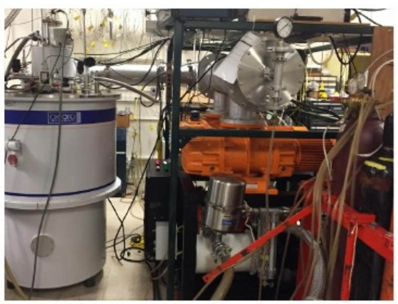
Insert

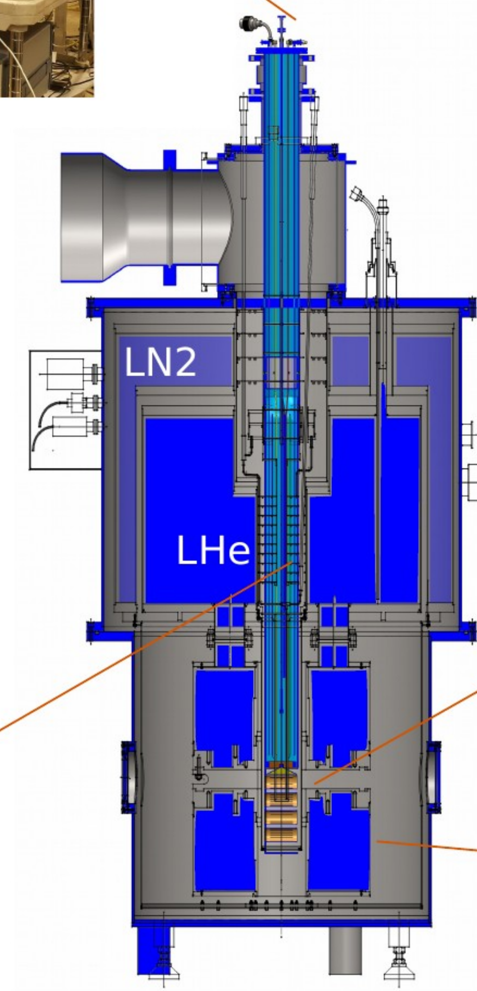


CPI-EIO

NMR

Microwave





Pumps

Target material

NH_3 ND_3

Produced at UVA
NIST irradiation 14 MeV
to 10^{17} e^-/cm^2

œrlikon

Fridge

UVA-LANL

Magnet

OXFORD INSTRUMENTS

5T Superconducting Magnet

- Rotated For Transverse

  original design S. Penttila, Oxford Instrument

  LANL owned Magnet set for 20 years

- Feasibility Study

  Shipped to UVA 2013

  Cooldown in June of that year

  Shipped to Oxford Instruments for rotation

- Back To UVA

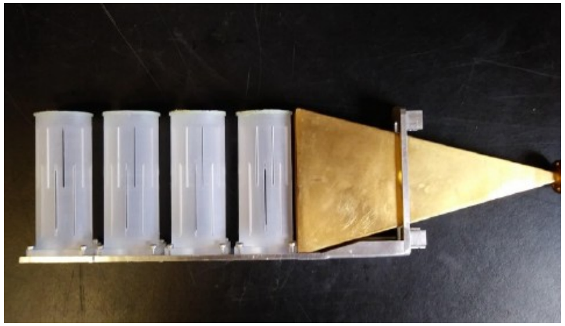
  Third cooldown: good hom. Over 5T in 8cm

  Many cooldowns since

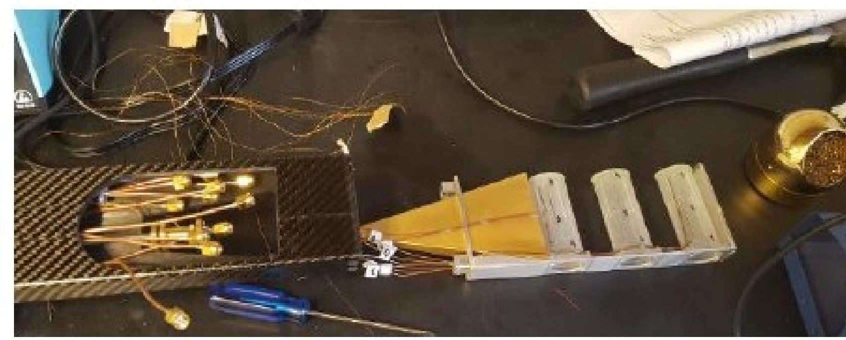
  Systems runs smooth and stable but consumes lots of liquid helium

- 500 L just to cool it after liquid nitrogen pre-cool
- 160 L per day with boil-off, sep, and fridge

Target Inserts



8 cm



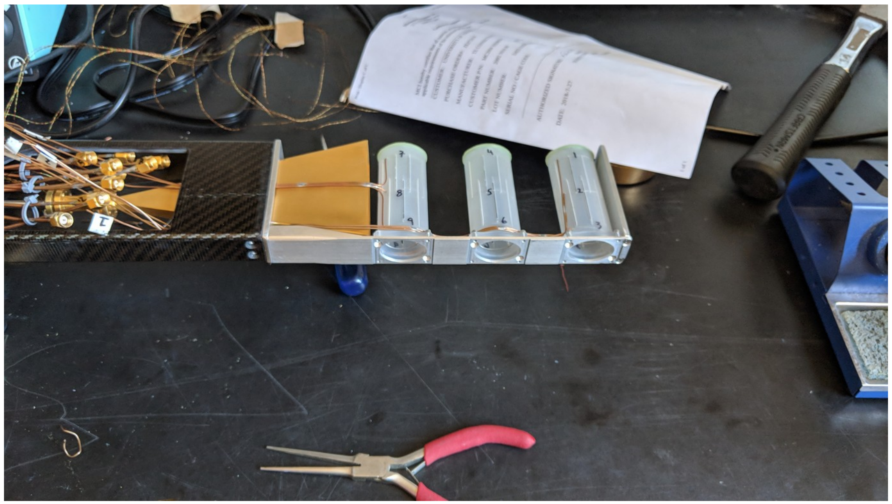
- Two inserts in progress for experimental use: One with four target cups (large), one with three target cups (small).

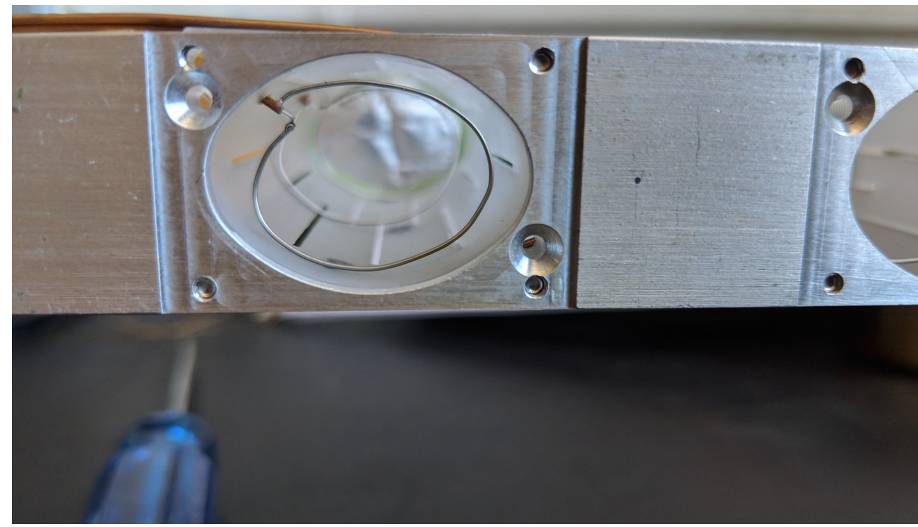
- Inserts surrounded by carbon fiber shell for thermal conductivity and guidance.

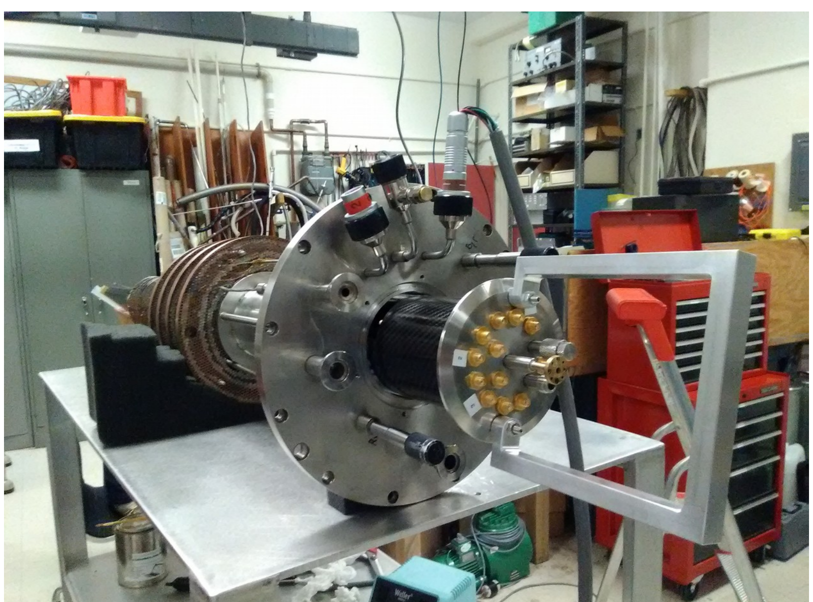
- Work on each insert being done in parallel. Currently, wiring is being done for,

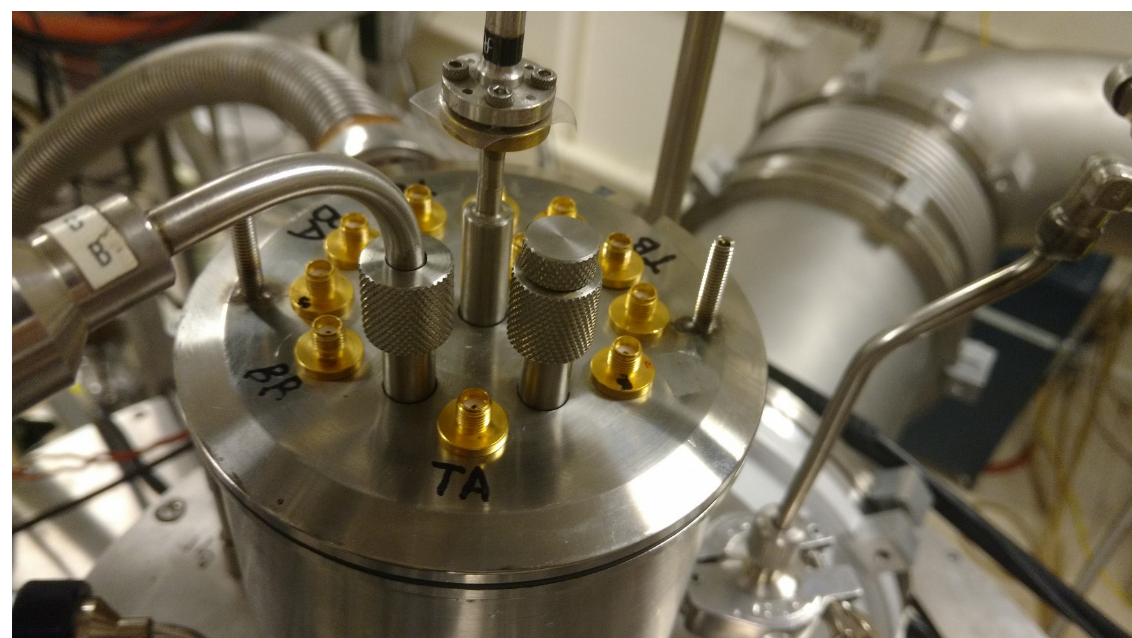
  - NMR coils around target cups.
  - Temperature sensors
    - 3 or 4 target cells per insert
    - 3 coils per target cell (1” apart)
    - 9-12 NMR lines running out of cave

Target Insert









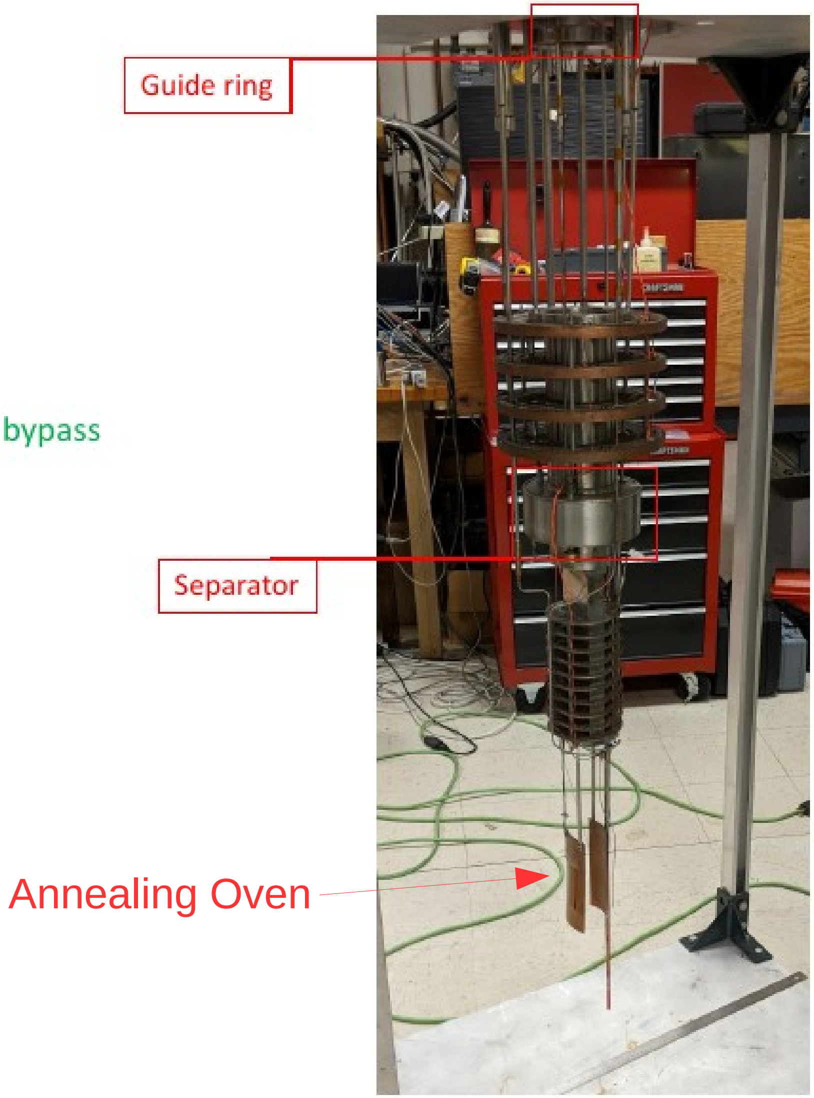
Evaporation Refrigerator

Evaporation Fridge

- Separator replaced and added guide ring to help with installation.
- Modified the insert channel and installed copper annealing plates.
- Installed level probe to monitor helium level.
- Positioned the helium delivery line to be out of beamline.
- Added eight new temperature sensors on system.
- Installed new run and bypass valves with software controls for run and bypass valves. Run valve has PID control, bypass manual/remote.
- Temperature monitor system working in Labview.
- Made two nose pieces with specialized window.
- Installed new liquid helium pressure probe (old probe was leaking).

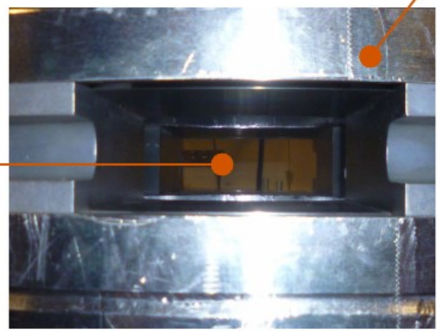
Still to do:

- Need to do cold test for both new valves.
- Need to make new turret flange.
- Helium test nose pieces. Already leak tested.
- Test liquid helium probe.



Final preparations and run

put vacuum chamber back together

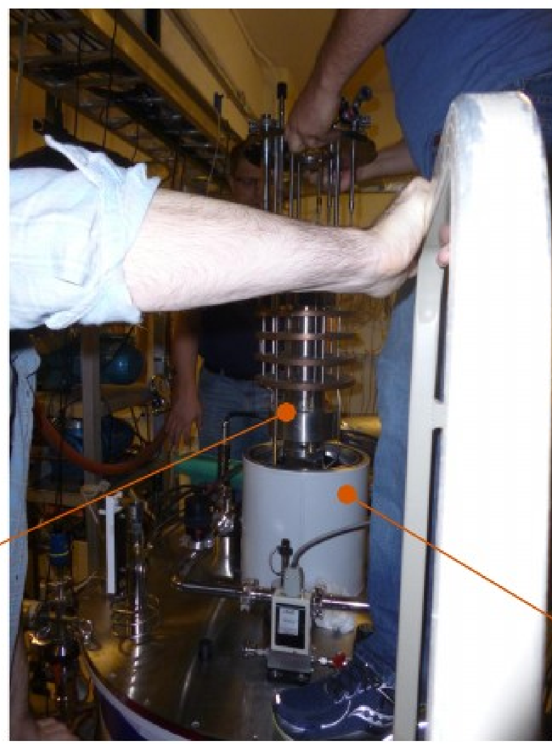


leak checked fridge shell + nose

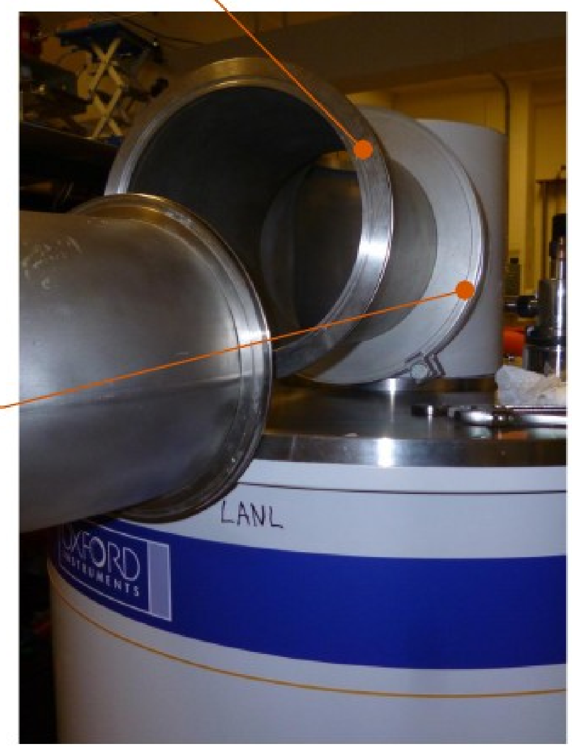
Putting it all Together

Final preparations and run

installed fridge



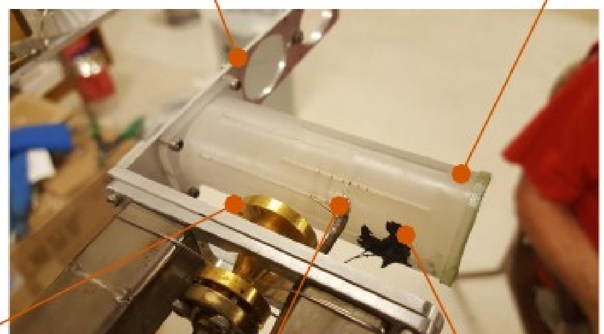
fitted turret to UVA pumping system

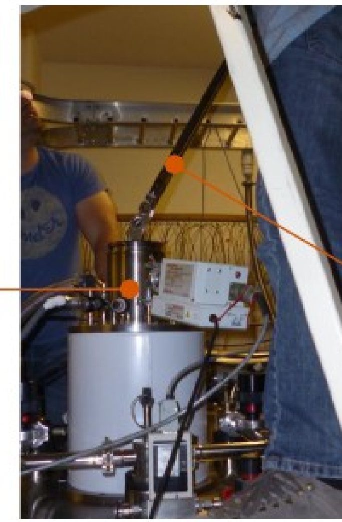


Test Full System

Final preparations and run

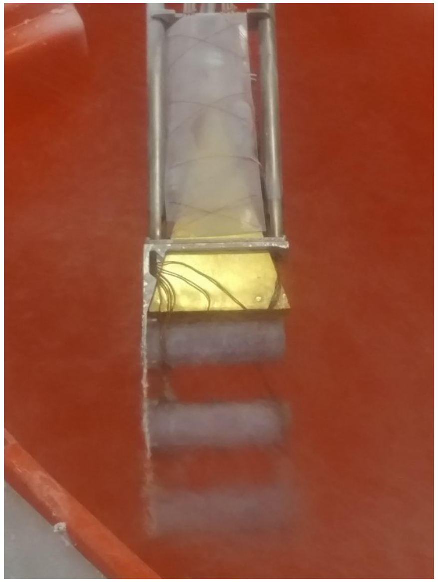
made test target insert, practiced installation





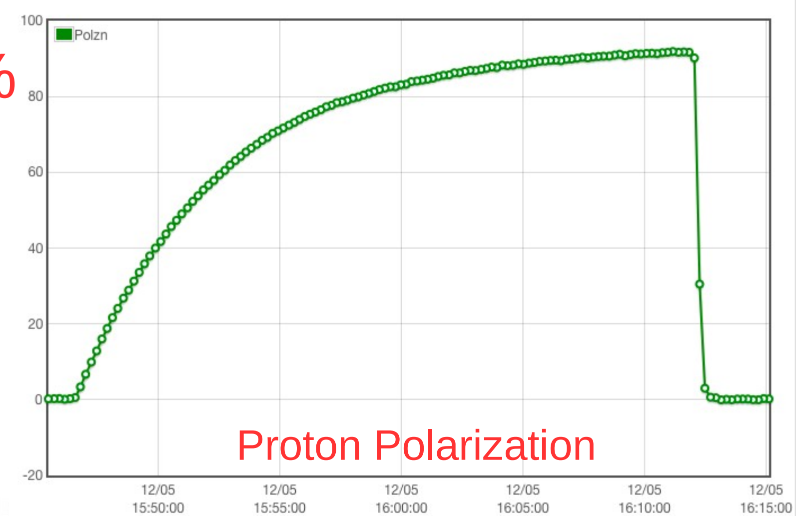
getting cold

Target Performance



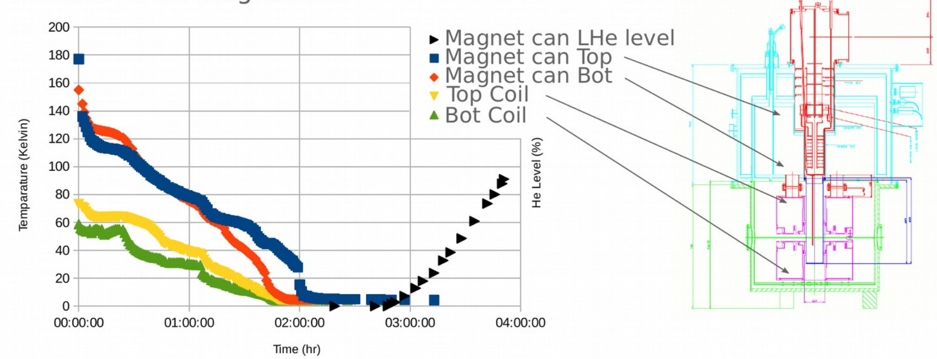
Insert in LN2

95%



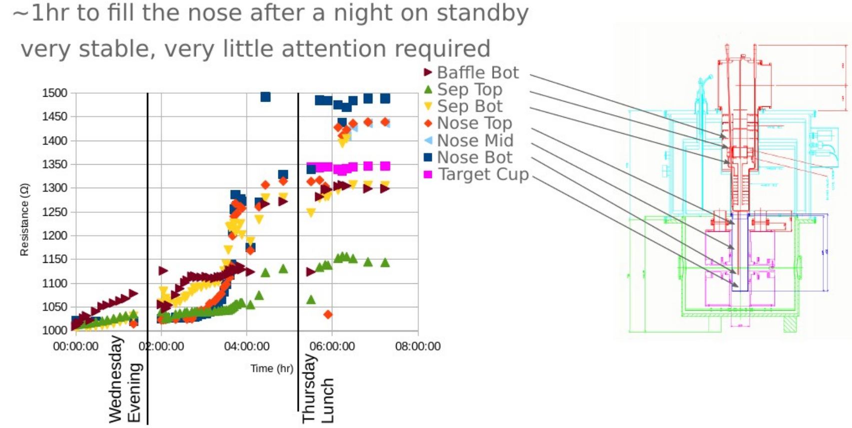
~2.5

~1 hr to to fill magnet can



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

very stable, very little attention required



SeaQuest Dark Sector Physics

- Emerging as a picture of dark matter: Compatible with like dark matter, and allows self-scattering, collision excitation, and annihilation

  - Standard Model forces don't couple to the dark sector, dark forces don't couple to standard model matter

- Vector portal: dark mediator is a massive *U(1)* boson (heavy photon)

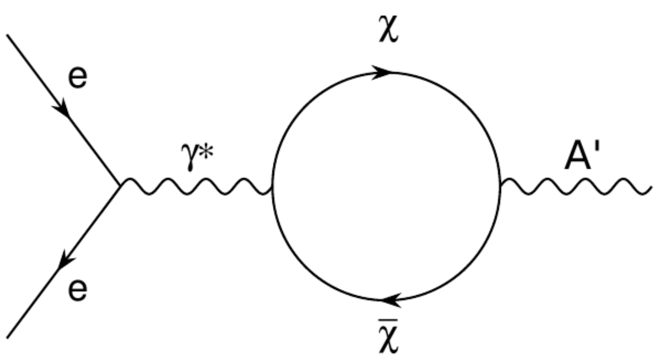
  - Kinetic mixing with the photon has weak coupling to electric charge

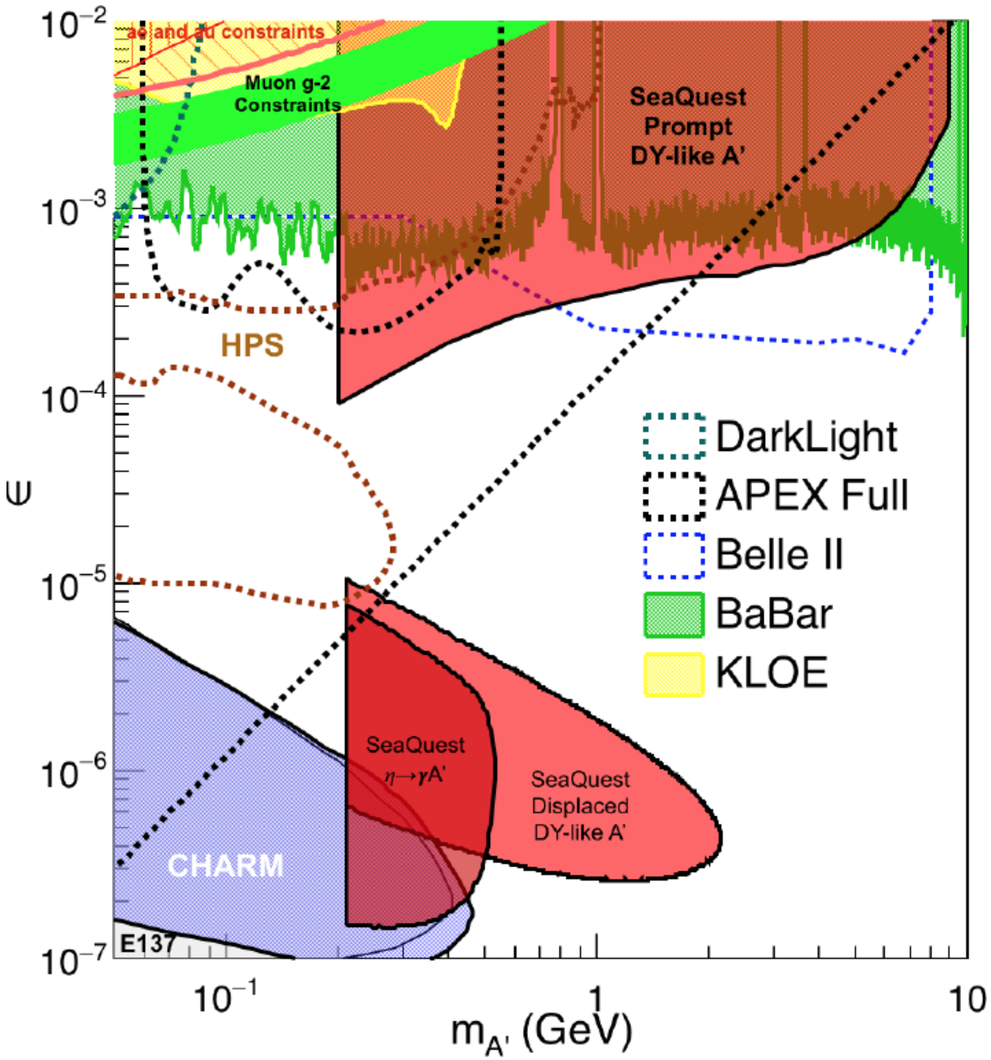
Dark Sector Physics

- Parameter space: mass $m_{A'}$ and coupling strength ϵ

  - Coupling strength governs production and decay to SM

  - Favored region is $m_{A'}$ MeV-GeV and $\epsilon < 10^{-6}$





Join the Effort

http://twist.phys.virginia.edu/E1039/

Send mail to: dustin@jlab.org

A Good time to join the collaboration, experiment receives Nuclear and HEP funding, so everyone in Spin physics is welcome and there is still lots of work to go

Thank You

Beyond This Talk

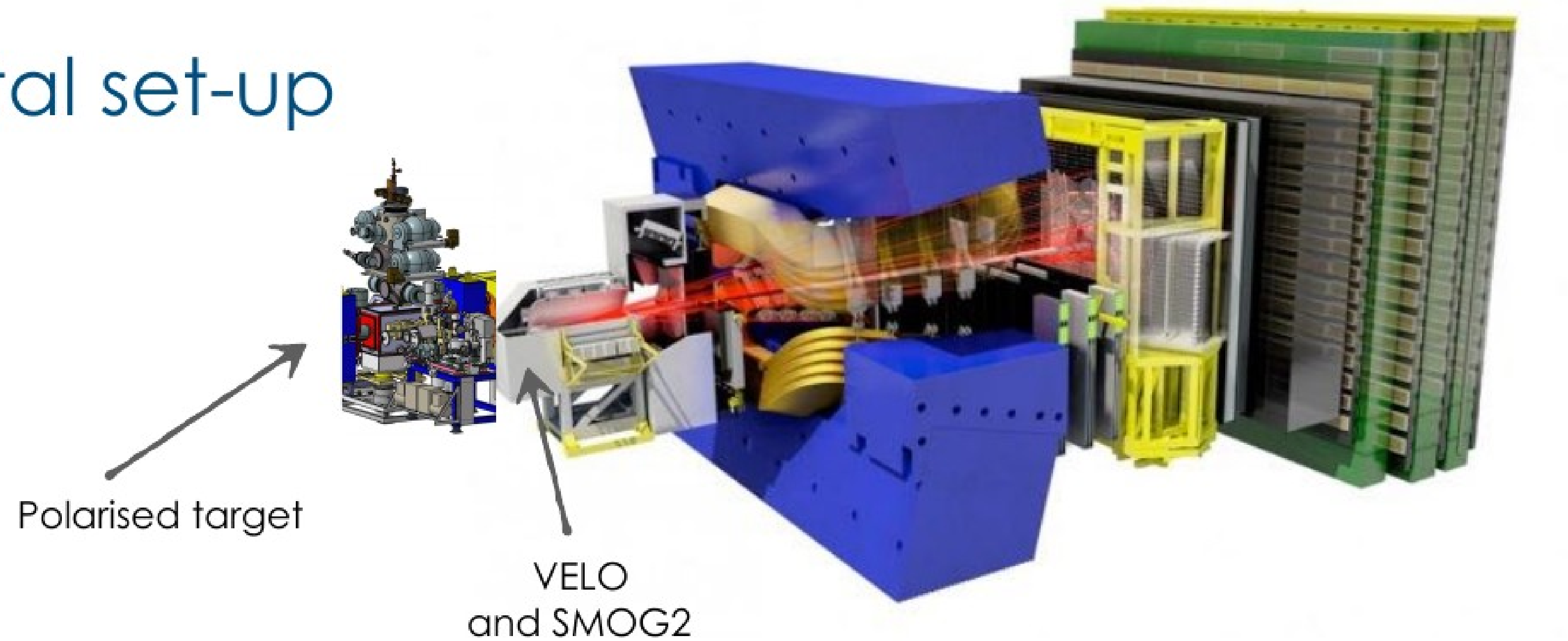
Spin at LHC

Fixed target collisions at the LHC represent an unique possibility for *a laboratory for QCD* in unexplored kinematic regions … in a realistic time schedule

LHCb is very focussed on the project:

The R&D for LHC spin represents a fantastic challenge and is on its road

Experimental set-up



<u>Well consolidated technique</u>

Design follows the successful HERMES Polarised Gas Target which ran at HERA 1996 – 2005, and the follow-up PAX target operational at COSY (FZ Jülich)

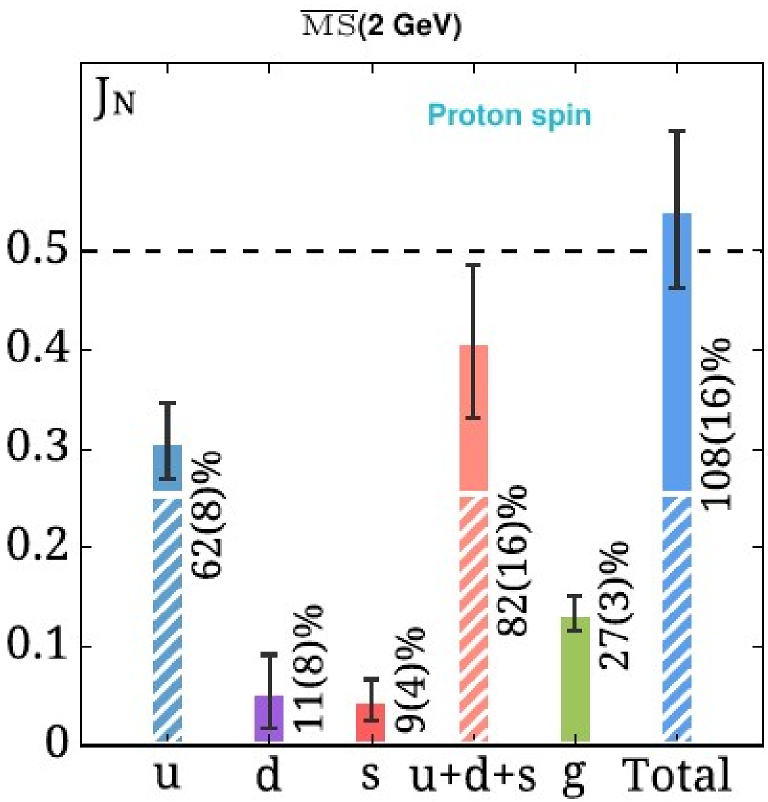
Important differences (i) HERA: multi-user facility (together with ZEUS, H1, HERA-B), but in case of problems usually access was granted quite timely; (ii) COSY: single-user, so access by decision of experimental group.
Requirements for LHC: (i) extreme reliability of all safety systems, in particular the vacuum interlock ABS-TC; (ii) very long running times without possibility of interventions

Completely different requirements for coating of surfaces

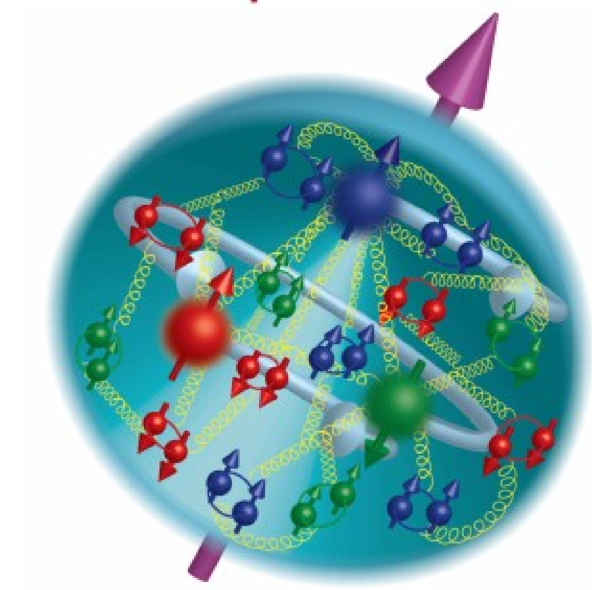
Origin Spin

C. Alexandrou et al., Phys. Rev. Lett. 119, 142002 (2017), [arXiv:1706.02973]

★ **ETM Collaboration: simulations at the physical point**



Better understanding of the spin distribution

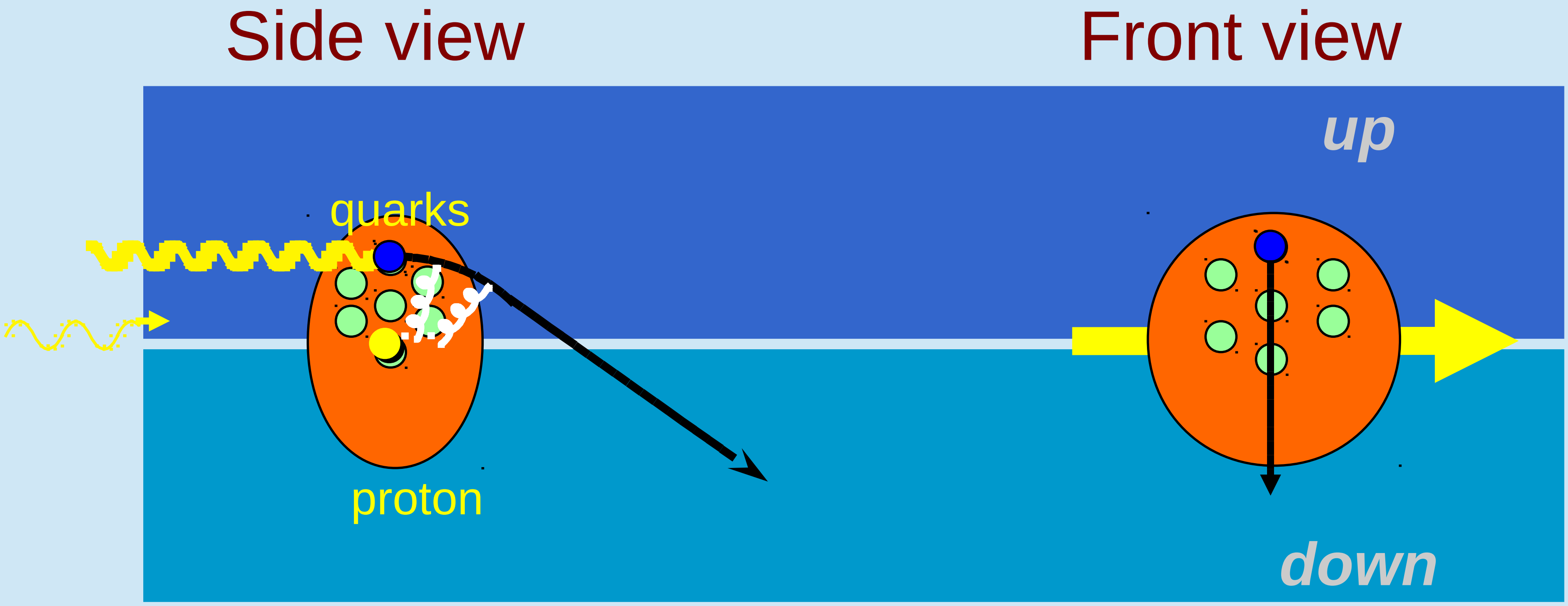


Designed by Z.-E. Meziani

Striped segments: valence quark contributions (connected)
Solid segments: sea quark & gluon contributions (disconnected)

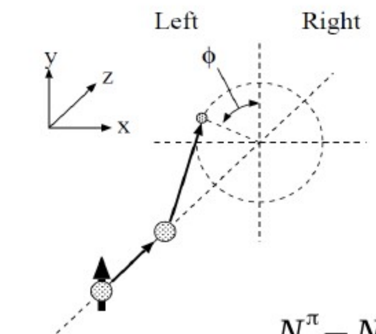
★ **Satisfaction of spin and momentum sum rule is not forced**

Distortion in Transverse Space

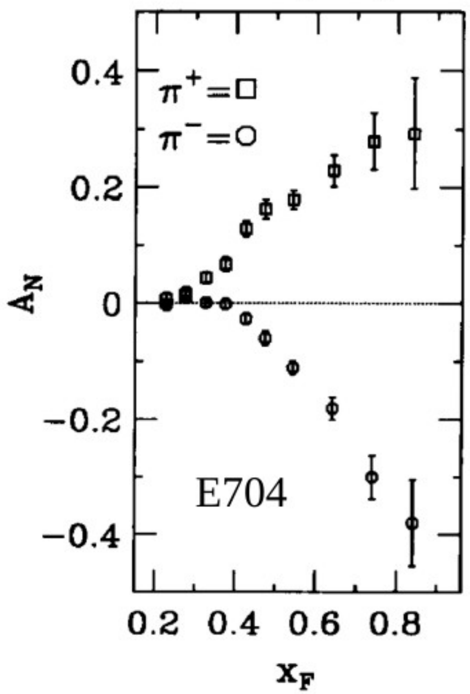


- The presence of spin can distort the distribution of quarks in transverse space (orbital angular momentum of quarks is required)
- A distortion in the distribution of quarks in transverse space can give rise to a nonzero Sivers function

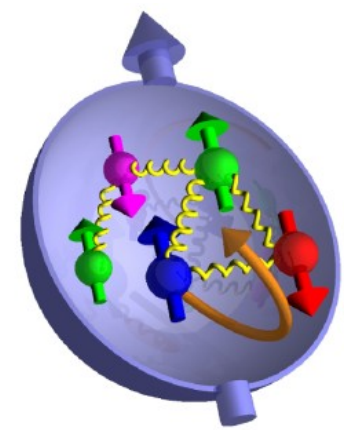
Quark Transverse Momentum and Sivers TMD

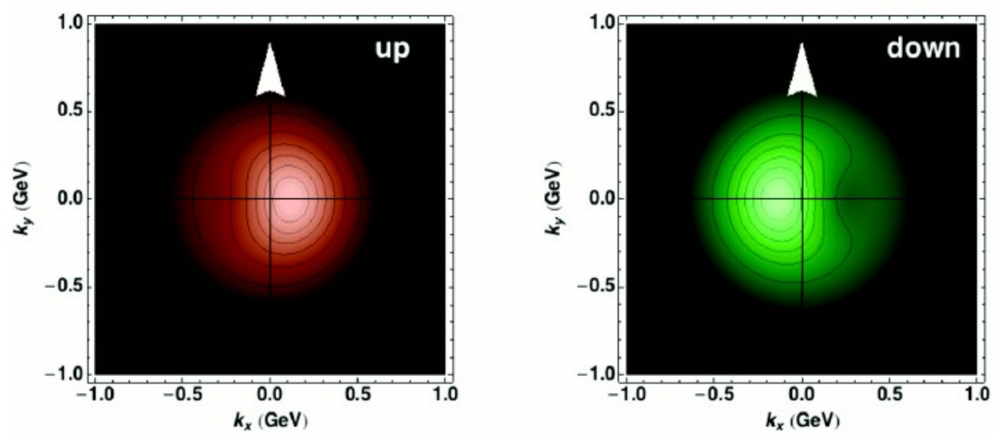


$$A_N(pp^{\uparrow} \to \pi X) \propto \frac{N_L^{\pi} - N_R^{\pi}}{N_L^{\pi} + N_R^{\pi}}$$



- The Sivers Function:
  - One of 8 TMD PDFs: $f_{1T}^{\perp}(x, k_T)$
  - Correlation between proton's transverse spin and transverse parton momentum
- Originally formulated to explain E704
  - Sivers Effect: Intrinsic k_T imbalance leads to asymmetry:





- **Quark Sivers Function Directly accessible with:**
  - **Polarized SIDIS [e+p↑ → e+h +X]**
  - **Polarized Drell-yan [p+p↑ → γ*(μ+μ-)]**

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

Origin of Mass

- ★ **Proton mass interesting probe of QCD dynamics**

- ★ **Valence quark masses contribute only about 1% of proton mass**
  Higgs mechanism not enough, so what gives proton its mass?

- ★ **Mass is a complicated mechanism:**

  Energy-Momentum Tensor [Ji, Phys. Rev. Lett. 74 (1995)]

$$T^{\mu\nu} = \frac{1}{2}\bar{\psi} i \overleftrightarrow{D}^{(\mu}\gamma^{\nu)}\psi + \frac{1}{4}g^{\mu\nu}F^2 - F^{\mu\alpha}F_{\alpha}^{\nu}$$

$$m = \frac{\langle N|\int d^3x T^{44}|N\rangle}{\langle N|N\rangle}$$

- ★ **Very important to compute from first principles and test it against planned measurements**