11th Circum-Pan-Pacific Symposium on High Energy Spin Physics
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Measurement of the neutron electric-to-magnetic form factor ratio at high momentum transfer

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Jefferson Lab

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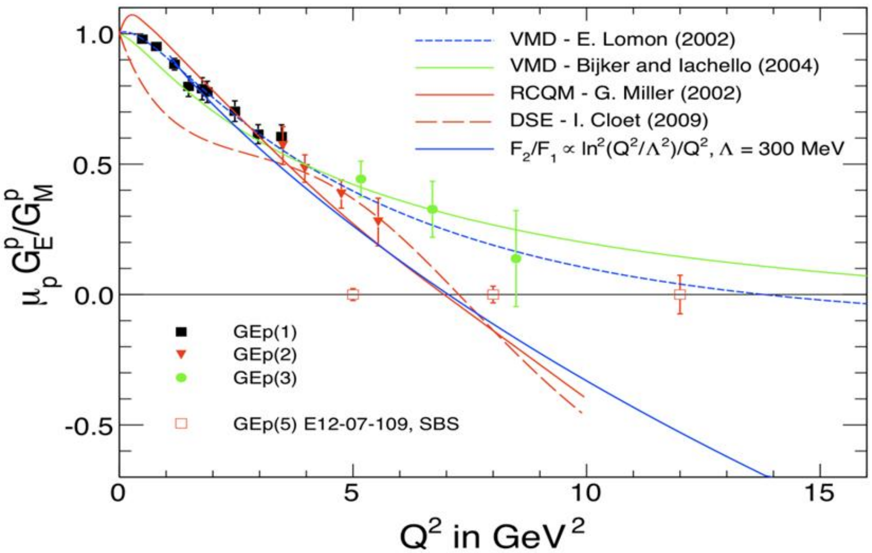
Nucleon form factors

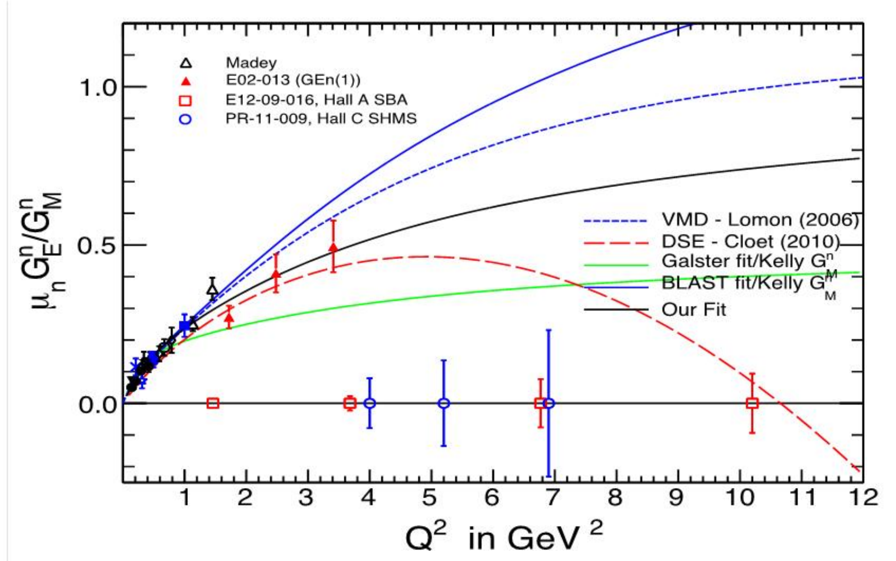
- Fundamental quantities describing spatial nucleon structure
- Neutron electric form factor least known, limited to $Q^2 < 3.4$ (GeV/c)^2
- Measurements of G_{En} in high Q^2 range provide important insight
  - Complete set of form factors in region with small pion cloud contributions
  - Separate isoscalar, isovector form factors, allow separation of up, down quark contributions (neglecting strangeness)
  - Directly sensitive to up and down quark distributions in quark core
  - Model-independent extraction of neutron infinite-momentum frame charge density [Miller (2007) ; Venkat et al. (2010)]
  - Important comparisons to QCD-based calculations
    - Lattice QCD: isovector form factor (e.g. G_{Ep}-G_{En}) cancels disconnected diagrams
    - Region of interest for Dyson-Schwinger Equation calculations

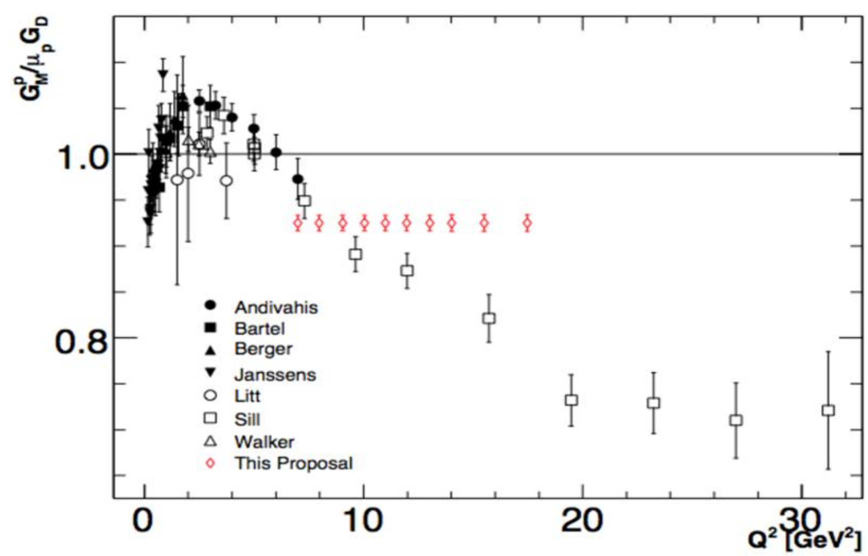
Extending the Q^2 range of form factors

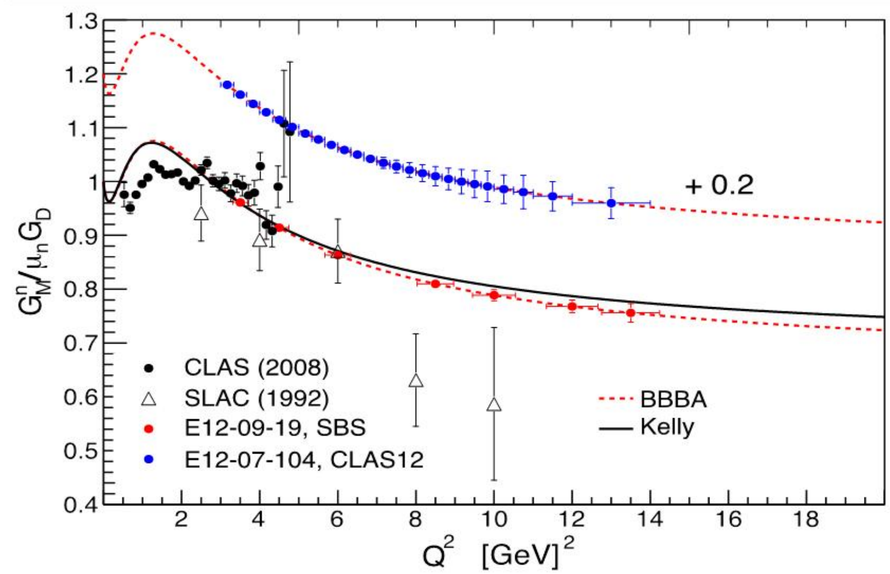
Reach extended by Super-BigBite Spectrometer (SBS) in Hall A:

Use high luminosity + open geometry + GEM detectors









Pushes G_E^p/G_M^p, G_E^n, G_M^n to high Q^2 (>10 GeV^2)

Allows for flavor decomposition to distance scales deep inside the nucleon

The SBS (form factor) program

Taking advantage of large acceptance and high luminosity

E12-09-019: Measurement of G_{Mn}/G_{Mp} to $Q^2 = 13.5\ (GeV/c)^2$
Unpolarized deuterium target: D(e,e'n)/D(e,e'p) cross section ratio
Installation will probably begin in May of 2020

E12-17-004: Measurement of G_{En}/G_{Mn} at $Q^2 = 4.5\ (GeV/c)^2$
Unpolarized deuterium target: D(e,e'n) polarization transfer
Planned to be run in combination with E12-09-019

E12-09-016: Measurement of G_{En}/G_{Mn} to $Q^2 = 10\ (GeV/c)^2$
Polarized helium-3 target: ^{3}He (e,e'n) polarized beam and target

E12-07-109: Measurement of G_{Ep}/G_{Mp} to $Q^2 = 12\ (GeV/c)^2$
Unpolarized hydrogen target: H(e,e'p) polarization transfer

Additionally: SIDIS / TMD
E12-09-018: SIDIS Transverse single-spin asymmetries ^{3}He(e,e'h)X ($h=\pi^{\pm,0}$, $K^{\pm}$)
PR12-15-006: Tagged DIS A(e,e'N) for effective neutron and meson targets

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"GEn-RP"

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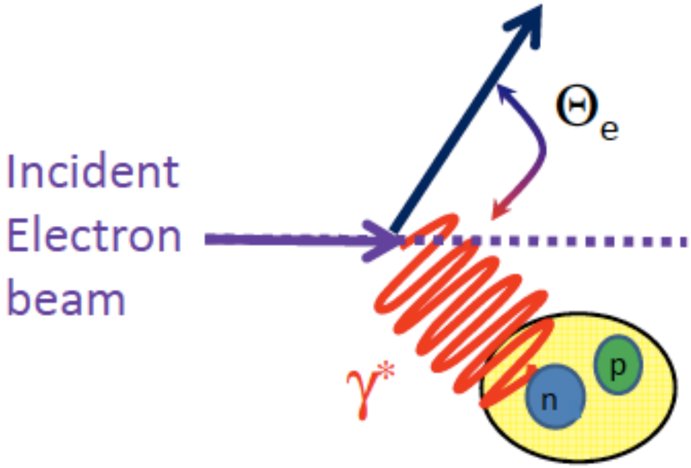
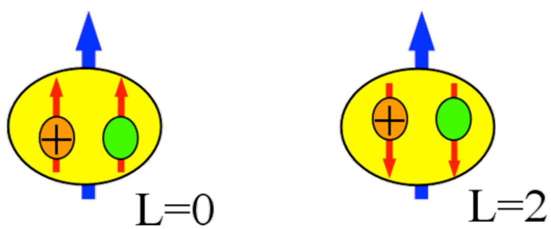
No free neutron target …

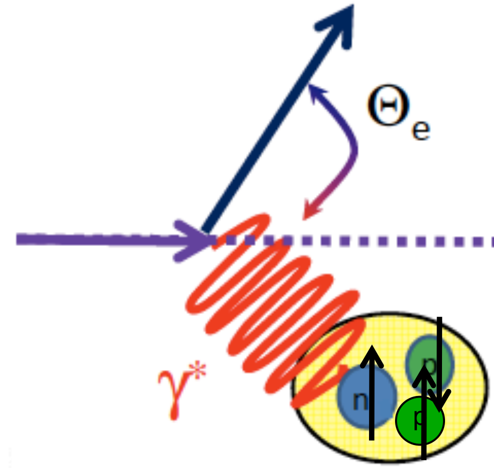
Use the deuteron as neutron target

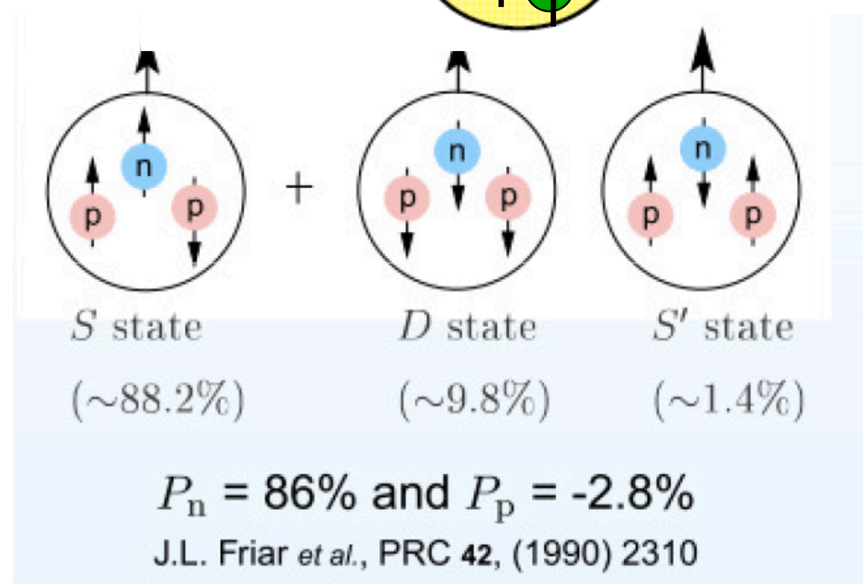




Polarized and unpolarized

Use ^{3}He as a polarized neutron target





Account for nuclear structure and “FSI”

G^n_E in absence of a free neutron target

No free neutron target → elastic and quasi-elastic scattering

Nuclear corrections (FSI, MEC, …)

Smallness of G^n_E does not allow L-T sep. of d(e,e’n) or d(e,e’)–d(e,e’p)

G^n_E

$^3\vec{\mathrm{He}}(\vec{e}$,e’n) quasielastic
Polarized Helium-3
$G^n_E G^n_M$ interference
MAMI A3, A1, Hall A

G_Q from A+T_{20} / ^{2}H(e,e’d)
$G^n_E G^p_E$ interference
Schiavilla+Sick

^{2}H(e,e’d) elastic, A(Q^2)
$G^n_E G^p_E$ interference
Galster, Platchkov, …

$^2\vec{\mathrm{H}}(\vec{e}$,e’n) quasielastic
Vector-polarized deuterium
$G^n_E G^n_M$ interference
Nikhef, Bates/BLAST, Hall C

^{2}H($\vec{e}$,e’$\vec{n}$) quasielastic
Neutron recoil polarization
$G^n_E G^n_M$ interference
Bates, MAMI A3, A1, Hall C

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G^n_E

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SBS / Hall A

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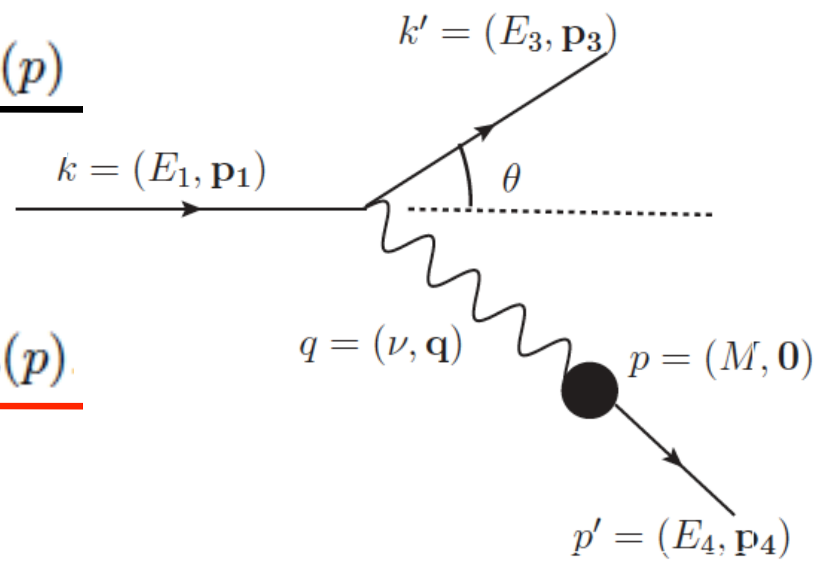
$G^n_E G^n_M$ interference
Bates, MAMI A3, A1, Hall C

SBS / Hall A

Lepton-nucleon scattering

- **Lepton-lepton scattering:**

$$-iM = \bar{u}(k')(ig_e\gamma^\mu)u(k)\left(-i\frac{g_{\mu\nu}}{q^2}\right)\bar{u}(p')(-ig_e\underline{\gamma^\nu)u(p)}$$



- **Lepton-nucleon scattering:**

$$-iM = \bar{u}(k')(ig_e\gamma^\mu)u(k)\left(-i\frac{g_{\mu\nu}}{q^2}\right)\bar{u}(p')(-ig_e\underline{\Gamma^\nu)u(p)}$$

- **Nucleon vertex factor (current)**

$$\Gamma^\nu = \gamma^\nu F_1(q^2) + i\sigma^{\nu\alpha}\frac{q_\alpha}{2M}F_2(q^2)$$

Dirac (F_1) and Pauli (F_2) "form factors"

$$Q^2 = -q^2 \qquad \tau = \frac{Q^2}{4M^2}$$

$$\begin{aligned} G_E(Q^2) &= F_1(Q^2) - \tau F_2(Q^2) \\ G_M(Q^2) &= F_1(Q^2) + F_2(Q^2) \end{aligned}$$

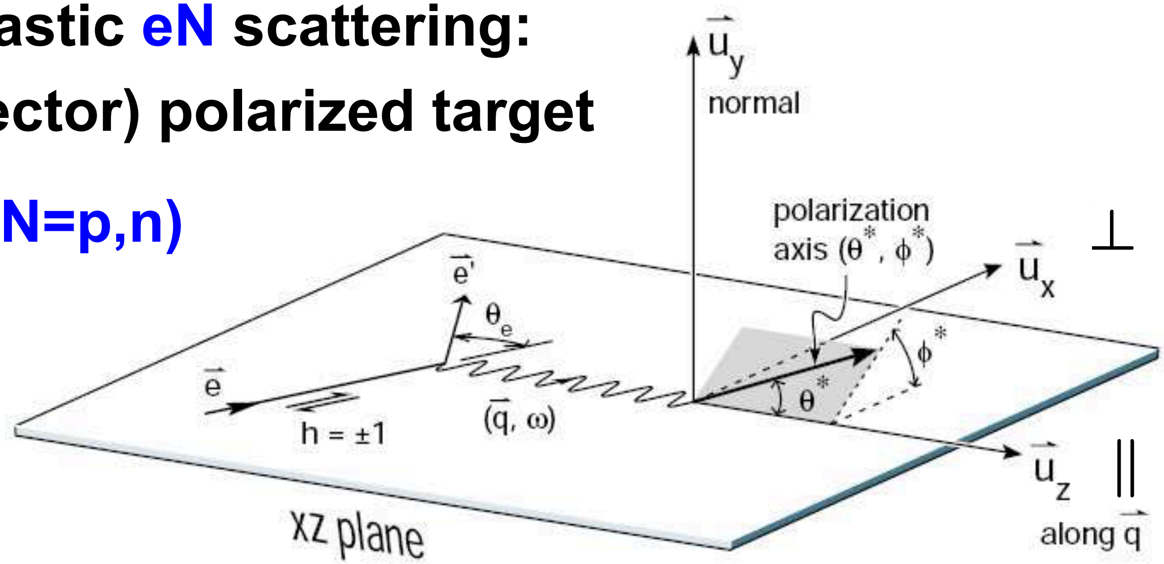
Electric and magnetic "Sachs" form factors

- **Spin dependent, polarized cross section:**
  no more averaging over initial and summing over final spins in the matrix element leads to interference terms

Nucleon form factors and polarization

- **Double polarization in elastic eN scattering:**
  Recoil polarization or (vector) polarized target

  $N(\vec{e},e'\vec{p})$, $\vec{N}(\vec{e},e'p)$, $(N=p,n)$



- **Polarized cross section**

$$\sigma = \sigma_0 \left(1 + P_e \vec{P}_p \cdot \vec{A}\right)$$

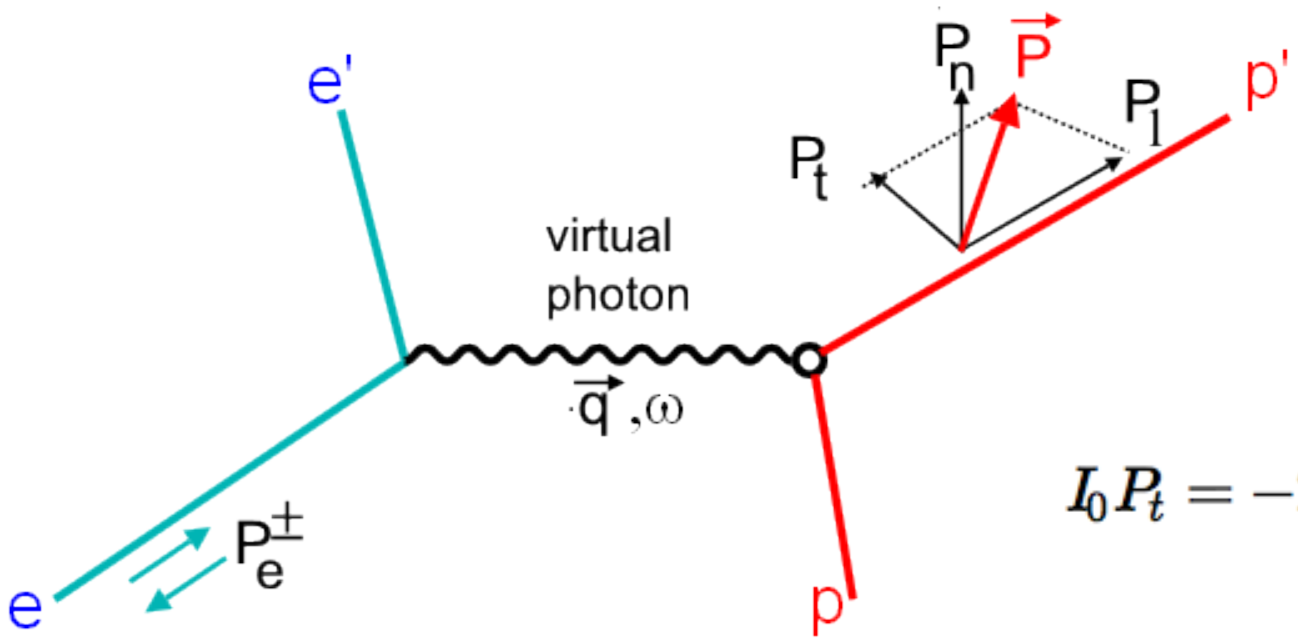
- **Double polarization observable = spin correlation**

$$\boxed{-\sigma_0 \, \vec{P}_p \cdot \vec{A} = \sqrt{2\tau\epsilon(1-\epsilon)} G_E G_M \sin\theta^* \cos\phi^* + \tau\sqrt{1-\epsilon^2} {G_M}^2 \cos\theta^*}$$

- **Asymmetry ratio ("Super ratio")** $\dfrac{P_\perp}{P_\parallel} = \dfrac{A_\perp}{A_\parallel} \propto \dfrac{G_E}{G_M}$

  independent of polarization or analyzing power

Recoil polarization technique



$P_t = P_x$
$P_n = P_y$
$P_l = P_z$

$$I_0 P_t = -2\sqrt{\tau(1+\tau)} G_E G_M \tan\frac{\theta_e}{2}$$

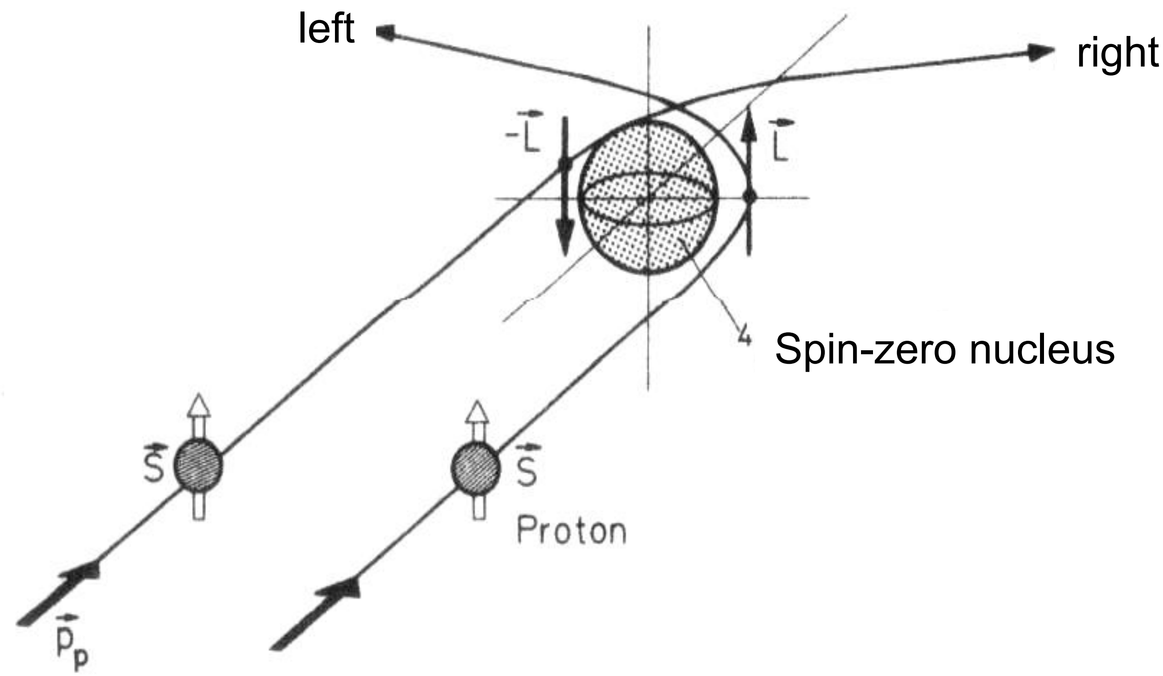
$$I_0 P_\ell = \frac{1}{M}(E_e + E_e')\sqrt{\tau(1+\tau)} G_M^2 \tan^2\frac{\theta_e}{2}$$

$$\frac{G_E}{G_M} = -\frac{P_t}{P_\ell}\frac{(E_e + E_e')}{2M_p}\tan\left(\frac{\theta_e}{2}\right)$$

$$I_0 \propto G_E^2 + \tfrac{\tau}{\epsilon} G_M^2$$

- Use dipole field for spin precession to rotate P_l and P_n
- Applicable to protons and neutrons

Polarimetry



- Strong LS interaction energy allows **hadron polarization** measurements with large analyzing powers
- Analyzing power forward-peaked and decreasing with higher energy
- Normal polarization causes left-right asymmetry
- Sideways polarization causes top-bottom asymmetry

Neutron polarimetry:

Elastic / Proton-Recoil (PR): np → np

Charge Exchange (CE) np → pn

Experimental technique

Measure double-polarized $^2H(\overrightarrow{e}, e'\overrightarrow{n})p$

$$P_x = -hP_e \frac{2\sqrt{\tau(1+\tau)}\tan\frac{\theta_e}{2} G_E G_M}{G_E^2 + \tau G_M^2(1+2(1+\tau)\tan^2\frac{\theta_e}{2}}$$

$$P_y = 0$$

$$P_z = hP_e \frac{2\tau\sqrt{1+\tau+(1+\tau)^2\tan^2\frac{\theta_e}{2}}\tan\frac{\theta_e}{2} G_M^2}{G_E^2 + \tau G_M^2(1+2(1+\tau)\tan^2\frac{\theta_e}{2})}$$

$$\frac{P_x}{P_z} = \frac{1}{\sqrt{\tau+\tau(1+\tau)\tan^2\frac{\theta_e}{2}}} \cdot \frac{G_E}{G_M}$$

- Final-state neutron P_x / P_z → G_{En} / G_{Mn} (precess P_z → P_y in dipole magnetic field)
- Liquid D_2 target (10 cm), 40 μA polarized electron beam (P=80%) Luminosity L = 1.26 x 10^{38} cm^{-2} s^{-1}
- BigBite electron spectrometer and SBS hadron spectrometer apart from polarimeter, identical to G_{Mn} / G_{Mp} E12-09-019 setup
- SBS Neutron polarimeter: acceptance well matched to electron arm
- Dipole magnet, integrated field ~ 2 Tm
- Hadron calorimeter, high p & n efficiency, effective suppression soft background
  + passive Cu analyzer
  + GEM charged-particle tracking systems
  + active CH analyzer and side scintillator planes
- Detecting high-momentum, small angle protons produced by np→pn **AND** low-momentum large-angle protons produced by np→np scattering

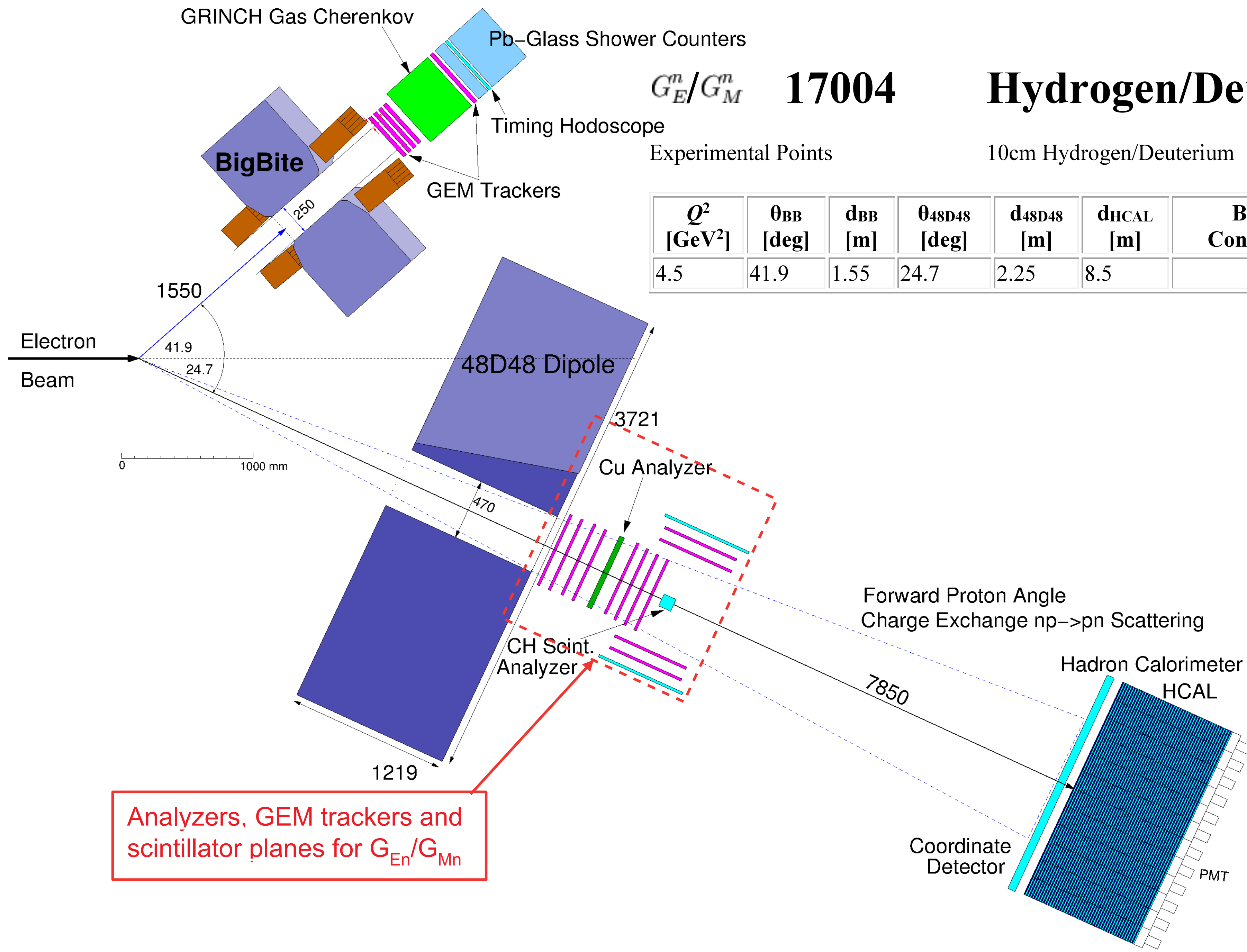
Experimental layout

G_E^n/G_M^n 17004 Hydrogen/Deuterium

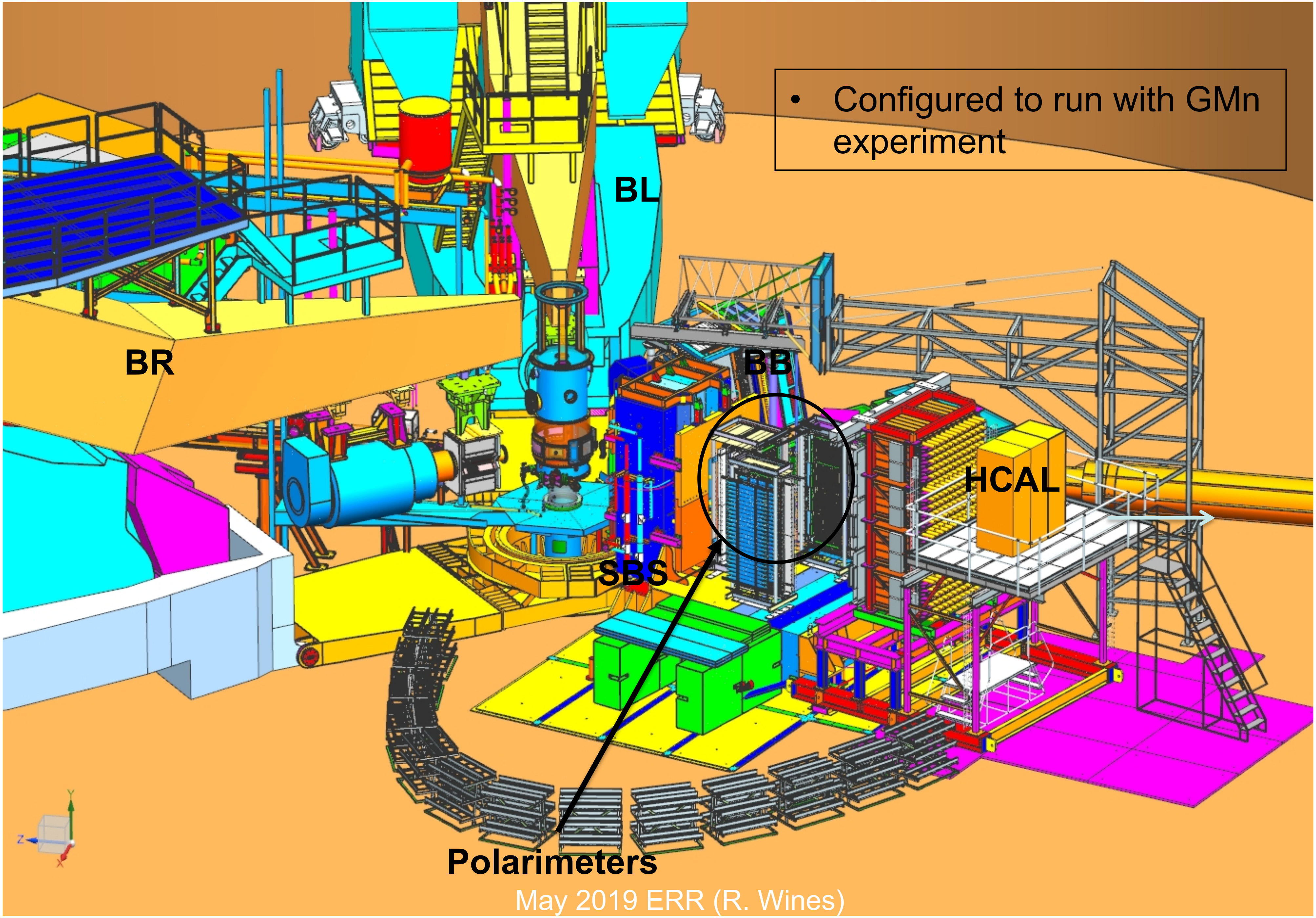
Experimental Points

10cm Hydrogen/Deuterium

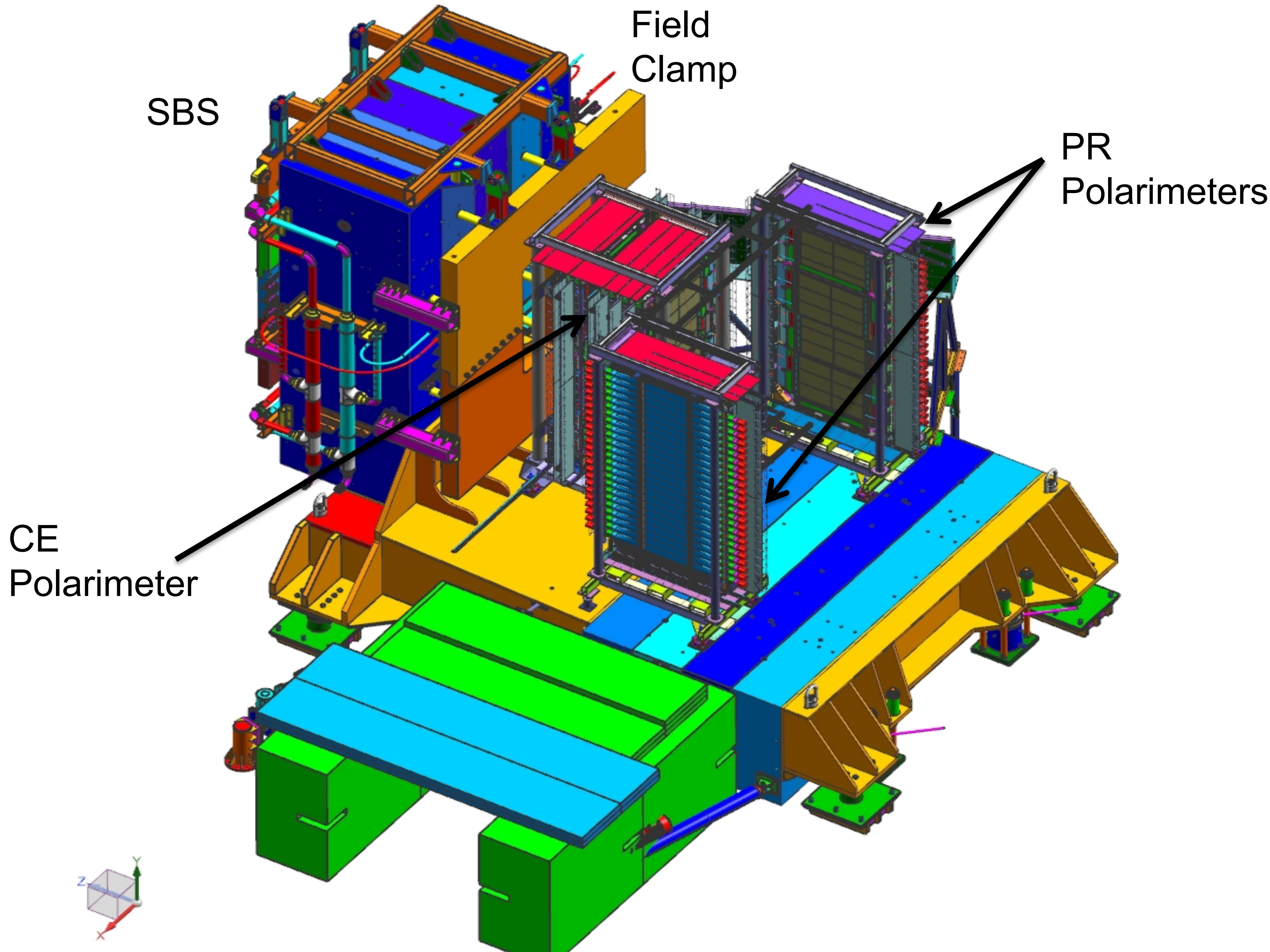
Q^2 [GeV^2]	θ_{BB} [deg]	d_{BB} [m]	θ_{48D48} [deg]	d_{48D48} [m]	d_{HCAL} [m]	Beam Line Configuration #
4.5	41.9	1.55	24.7	2.25	8.5	3



Engineering layout



SBS Neutron Polarimeter



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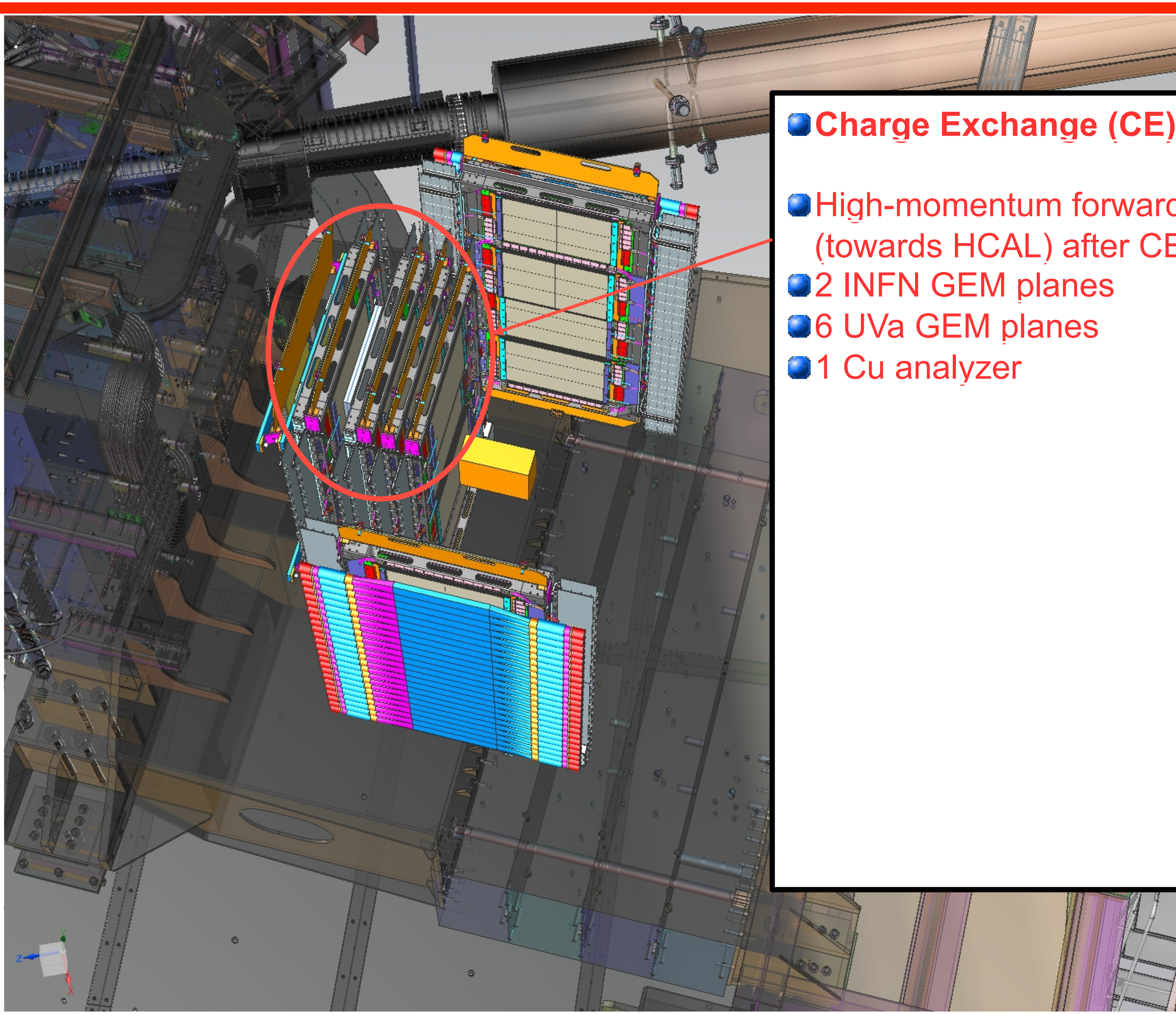
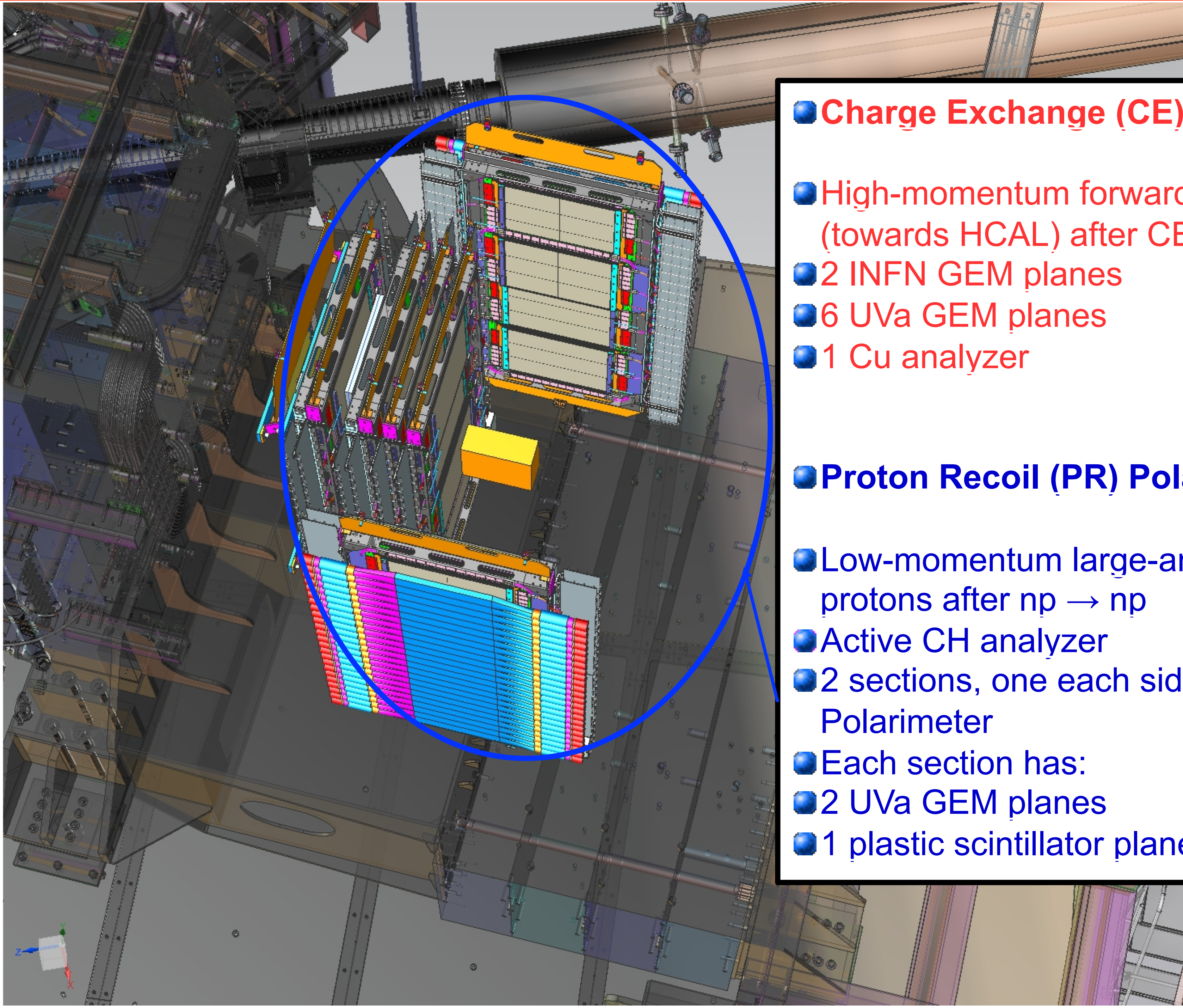


- **Charge Exchange (CE) Polarimeter**
- High-momentum forward protons (towards HCAL) after CE np → pn
- 2 INFN GEM planes
- 6 UVa GEM planes
- 1 Cu analyzer

SBS Neutron Polarimeter



- **Charge Exchange (CE) Polarimeter**
- High-momentum forward protons (towards HCAL) after CE np → pn
- 2 INFN GEM planes
- 6 UVa GEM planes
- 1 Cu analyzer

- **Proton Recoil (PR) Polarimeter**
- Low-momentum large-angle recoiling protons after np → np
- Active CH analyzer
- 2 sections, one each side of CE Polarimeter
- Each section has:
- 2 UVa GEM planes
- 1 plastic scintillator plane

SBS GEM detectors

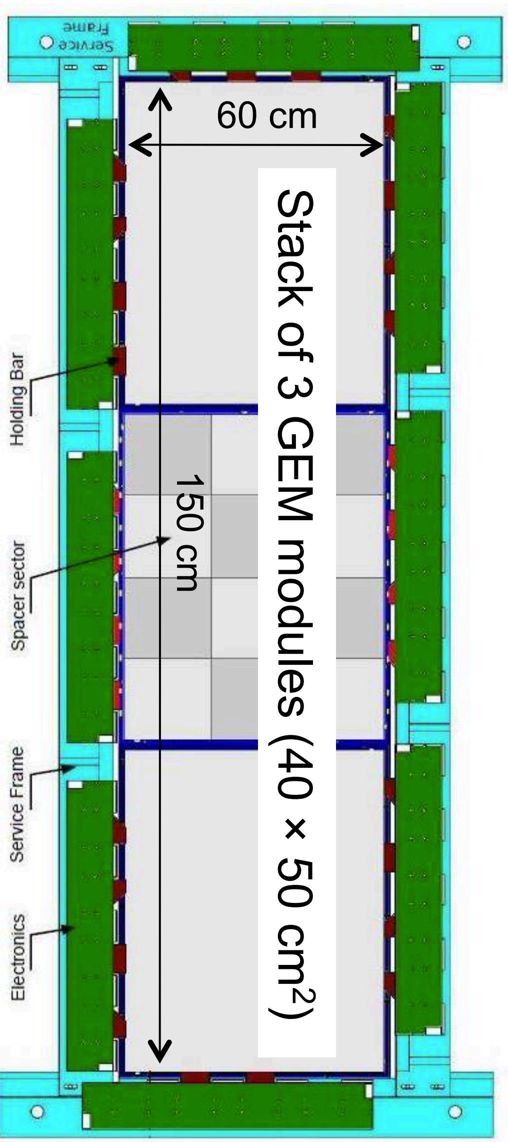
Charge-Exchange (CE) Polarimeter:

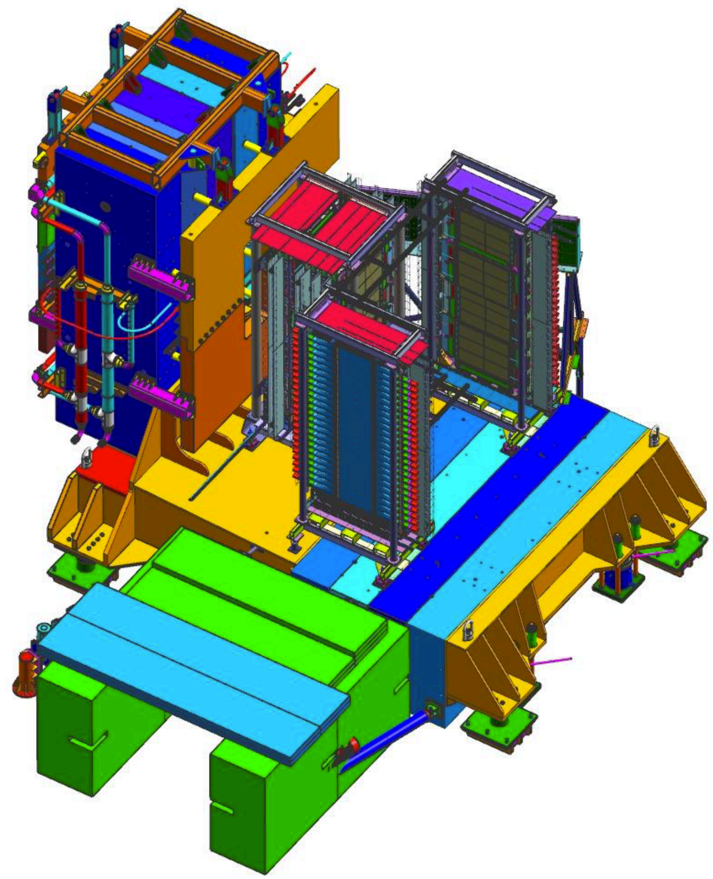
- ➪ 2 INFN + 2 UVa layers, in front of Cu analyzer
- ➪ 4 UVa layers behind the Cu analyzer

Proton-Recoil (PR) Polarimeter:

- ➪ 2 Identical arms, 2 UVa GEM layers in each arm

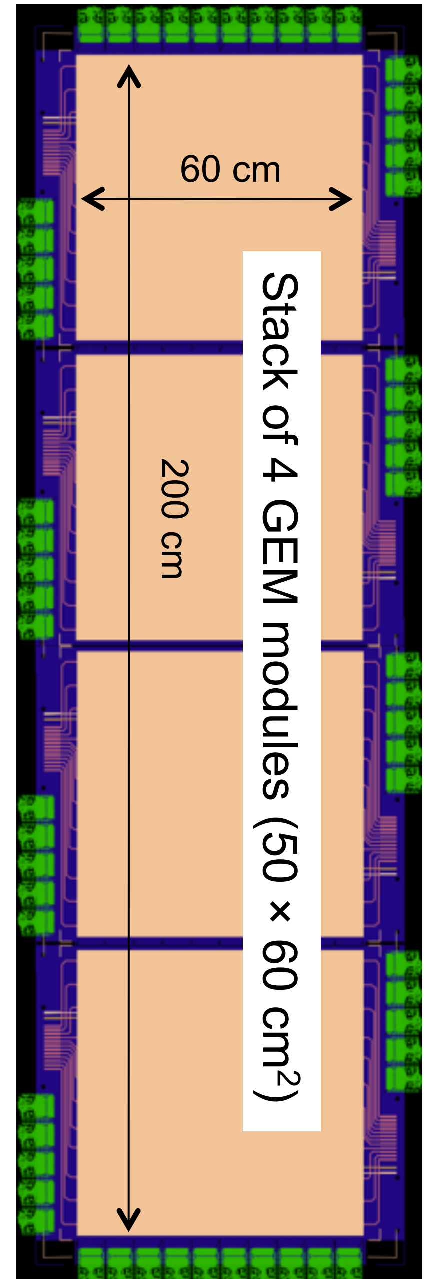
2 INFN GEM layers



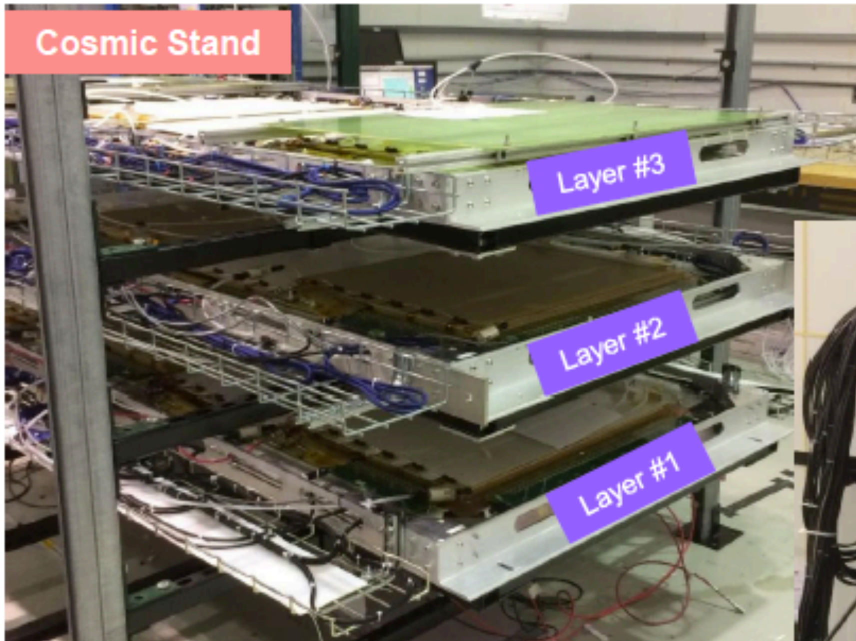


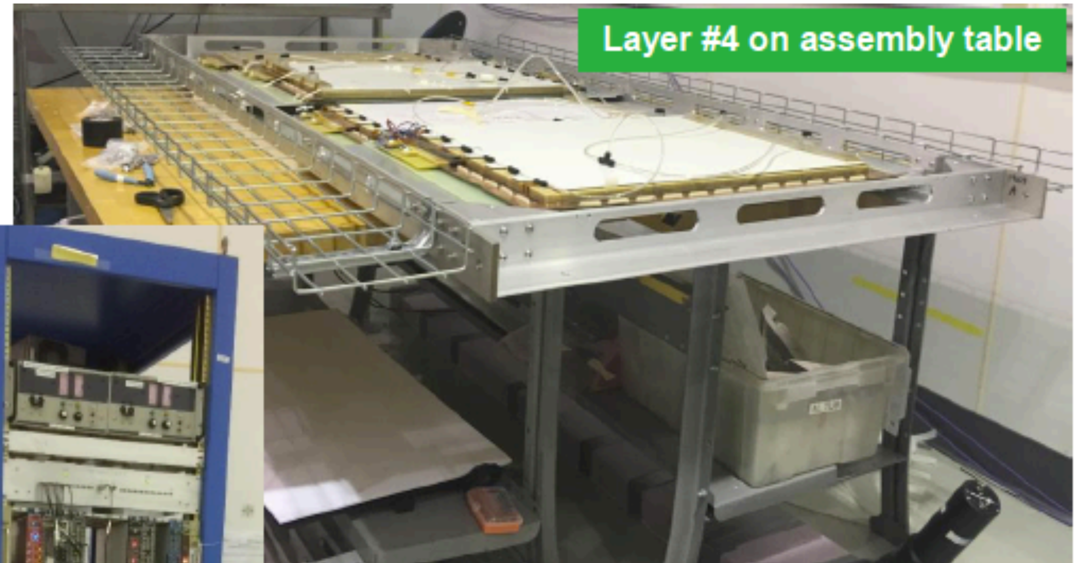
UVa: **K. Gnanvo, S.Jian, N. Liyanage, A. Rathnayake**
HU: **M. Kohl, M. Rathnayake, T. Gautam**
INFN: **E.Cisbani, P. Musico, R. Perrino, L. Re**
and many more ....

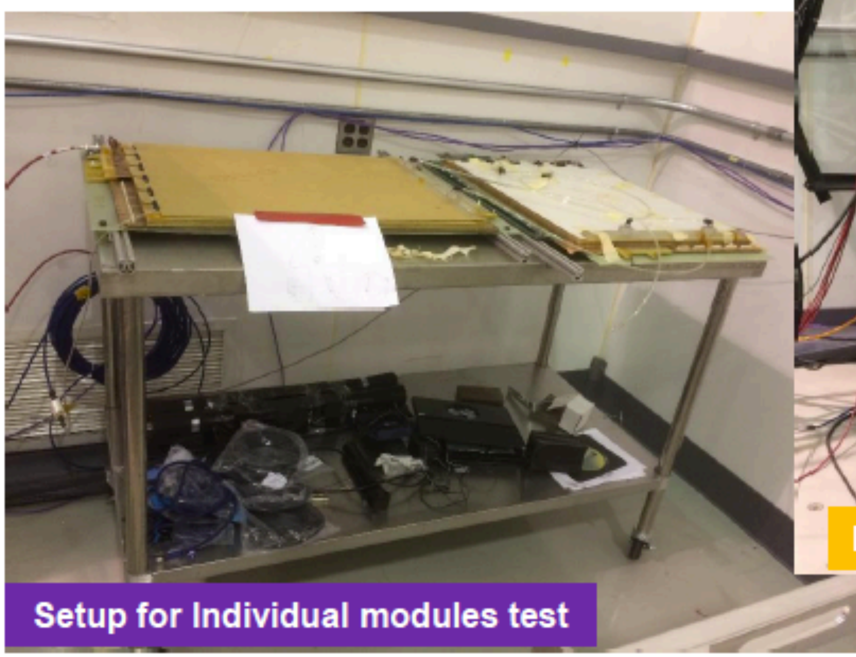
10 UVA GEM layers



SBS GEM detector commissioning (UVa)







Commissioning with cosmics in 2019

Spin precession in SBS dipole

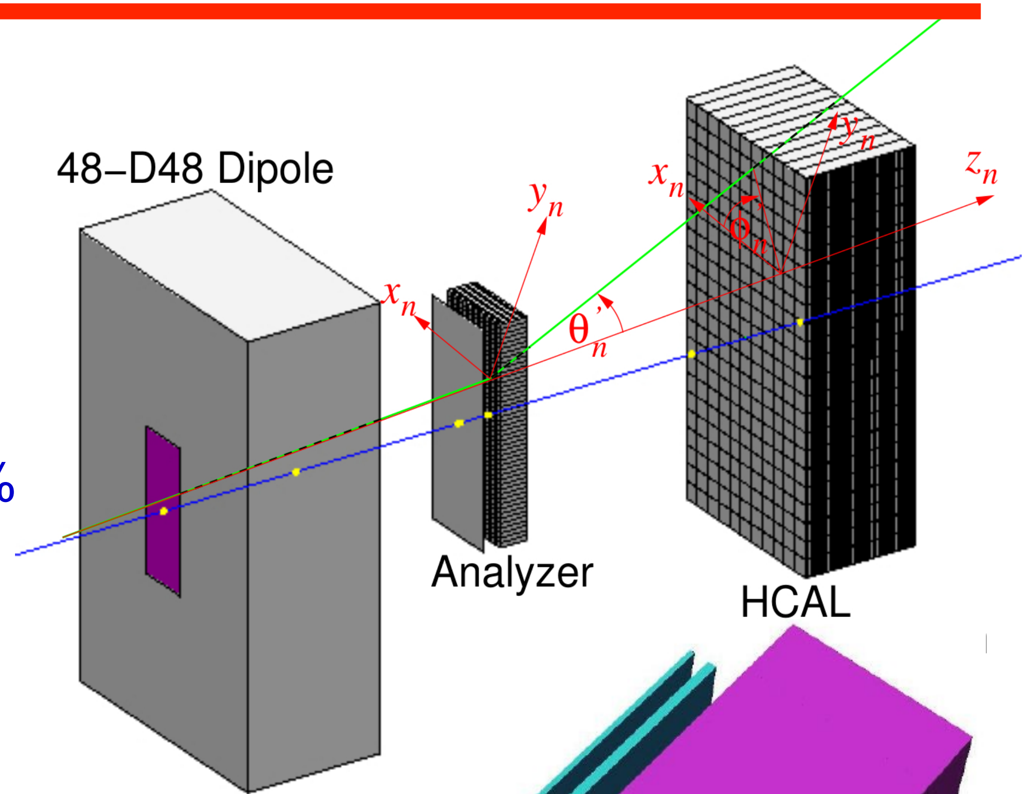
- Nucleon spin precession calculated in Geant4 with TOSCA field map
- Maximum spin transfer z → x ~3%
- Smoothly varying, can be corrected as polarimeter has good position resolution
- Maximum systematic error on P_x / P_z ~ 1%

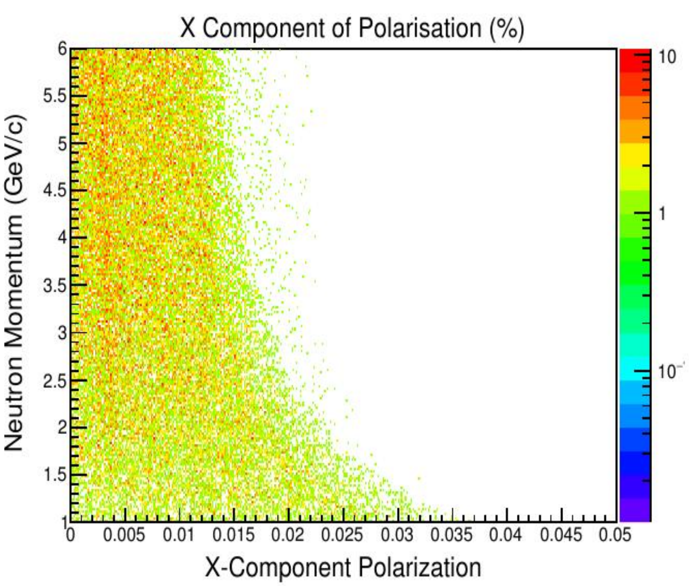
$$\chi = \frac{2\mu_N}{\hbar c \beta_N} \int_L B.dl$$

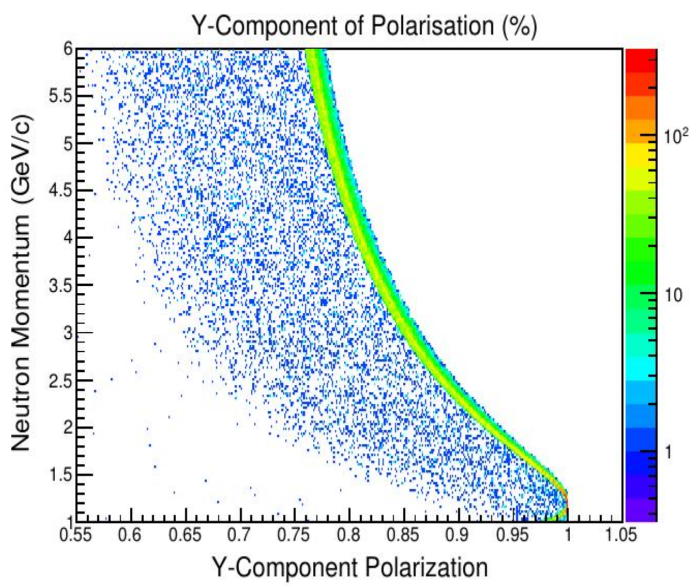
48D48: ~2 Tm

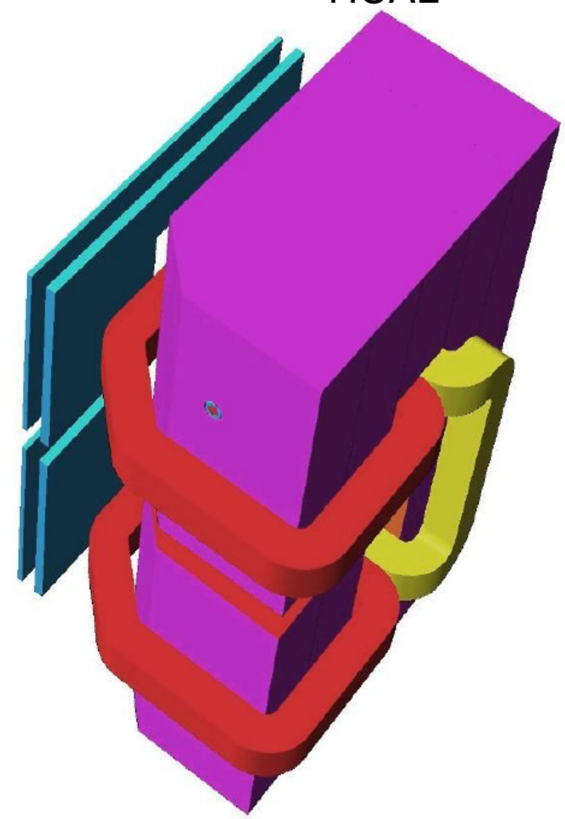
$$A(\chi) = \alpha P_e \sqrt{P_x^2 + P_z^2} \sin(\chi - \chi_0)$$

$$\tan \chi_0 = P_x / P_z \propto G_E / G_M$$







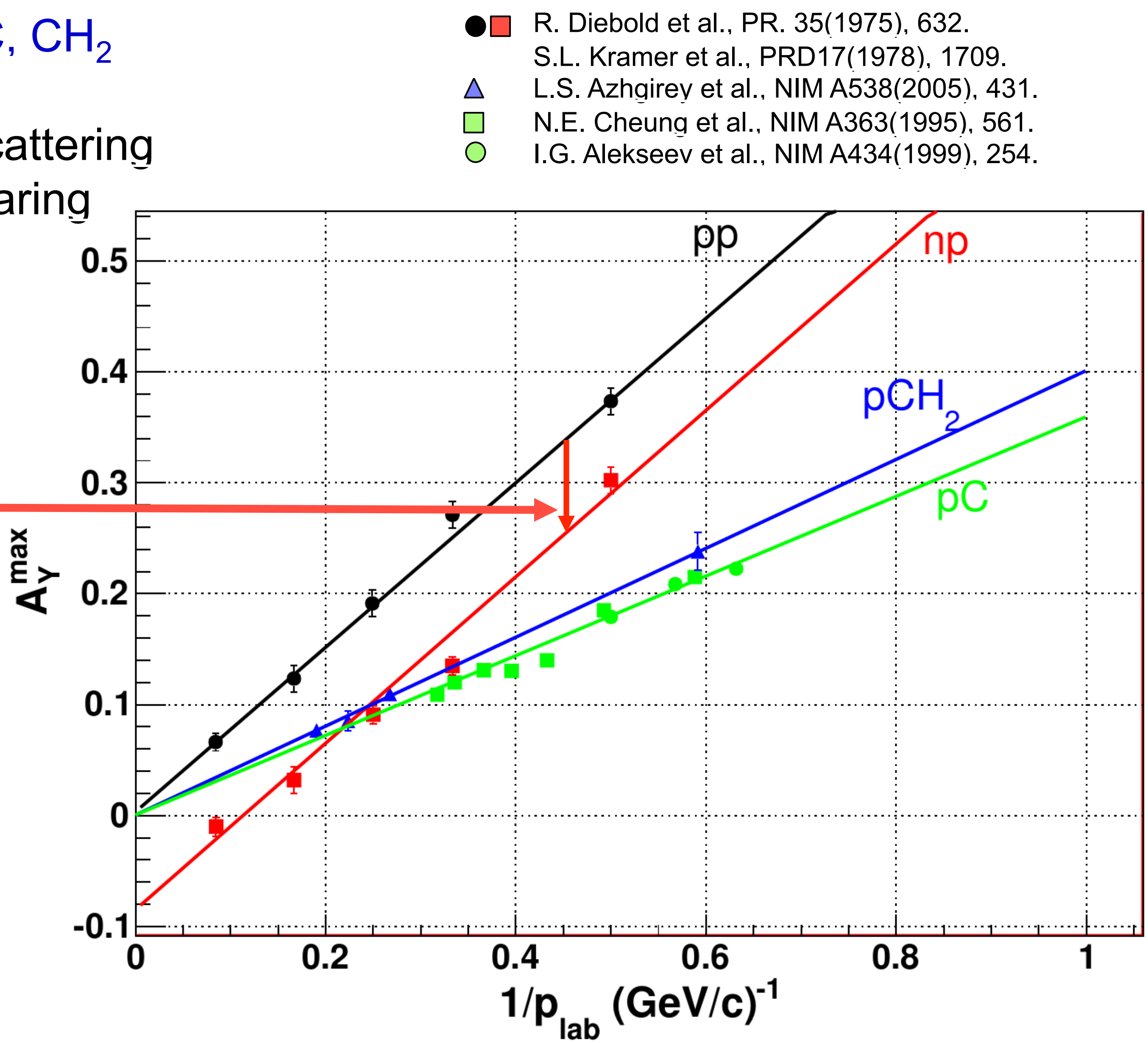


Nucleon polarimetry: N-N analyzing power

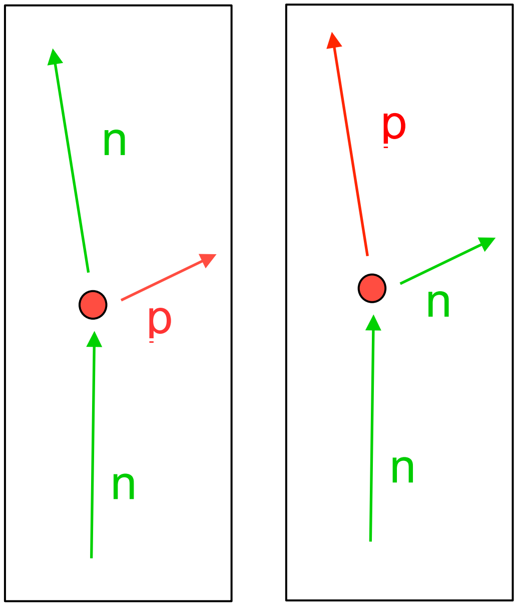
- Elastic np → np or pp → pp for highest A_y value
- Proton A_y measurements C, CH_2
  - empirical p+C value of A_y **~0.5** of free elastic p+p scattering
  - due to Fermi-motion smearing of the elastic signal and inelastic contamination
- pp → pp scales as $1/p_{lab}$
- np → np has similar slope but negative offset
- Up to now no data on nC → npX at p_{lab} ~ several GeV/c (nor for any medium to high-Z nucleus)

Peak Analyzing Power of N-N Scattering

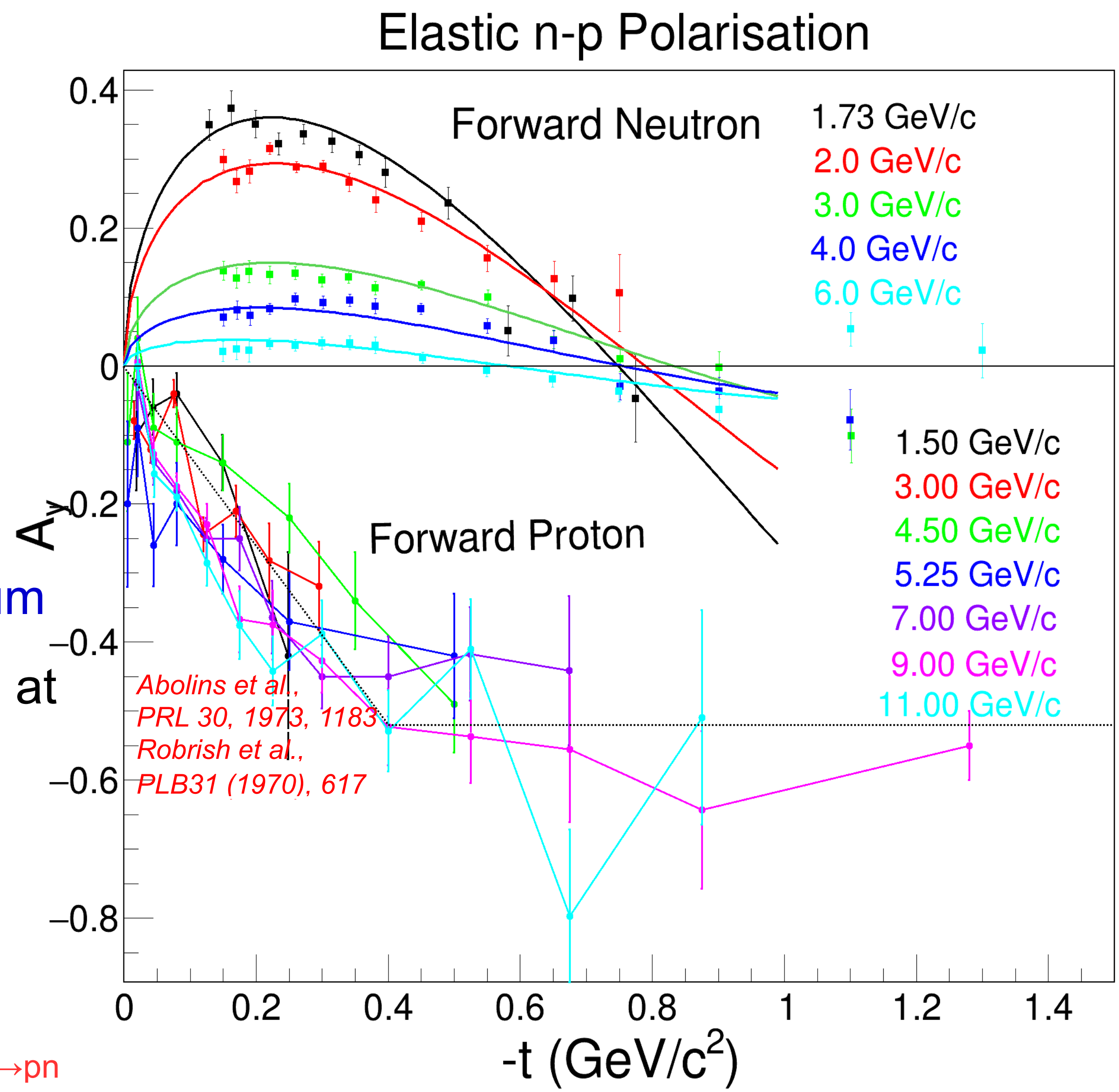
A_y^{max} @ $p_\wedge$ ~ 300 – 400 MeV/c



Analyzing power for elastic n-p scattering



Diebold et al., PRL 35,(1975),632
Fits: Ladygin JINR E13-99-123 (1999)

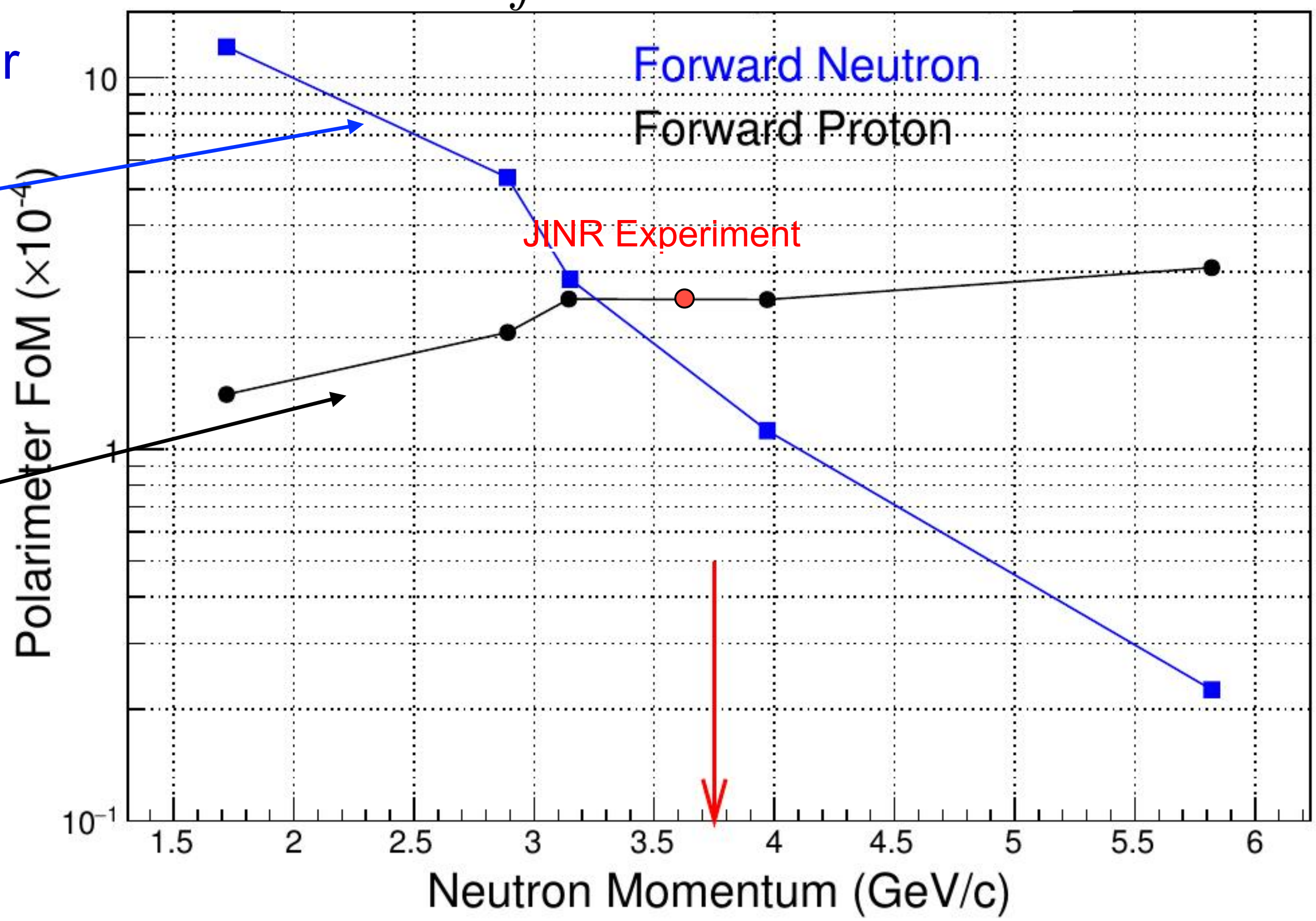


- A_y for n-p (or p-n) falling rapidly with increasing neutron momentum
- A_y for charge-exchange n-p large at sufficiently large t (θ_p ~ few deg.)
- No apparent strong incident momentum dependence for charge-exchange A_y
- $\sigma_{np\rightarrow np}$ factor ~10 higher than $\sigma_{np\rightarrow pn}$

Figure of merit: elastic vs. charge exchange

$$\mathcal{F}^2(p_n) = \int \varepsilon(p_n,\theta_n^{'})\, A_y^2(p_n,\theta_n^{'})d\theta_n^{'}$$

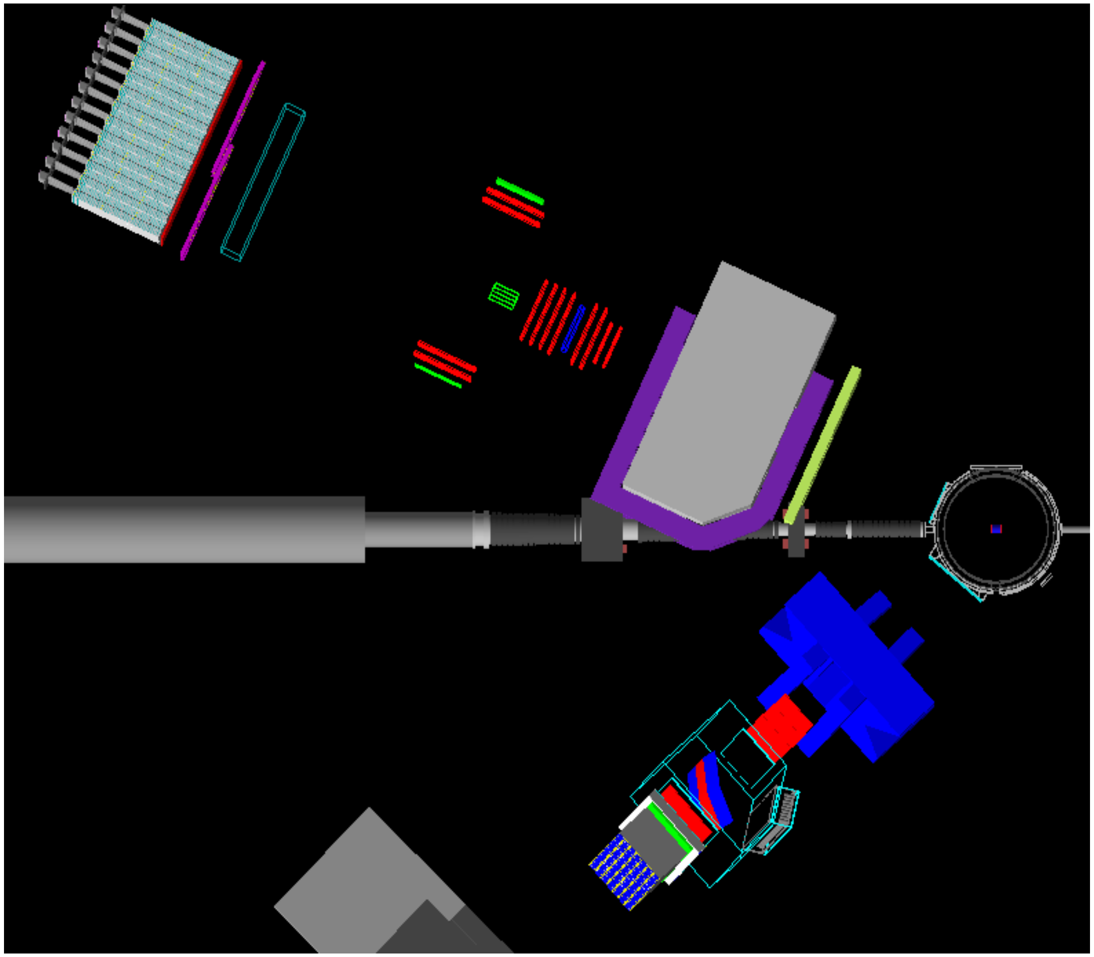
- Plastic scintillator analyzer
- np→np (forward neutron)



- Cu analyzer
- np→pn (forward proton)

- Calculate efficiency of polarimeter as function of q_n by Monte Carlo
- A_y for free np→np: JINR fit to $\boldsymbol{p_n}$ and $\boldsymbol{\theta_n}$ dependence, scale A_y by 0.5 for ^{12}C scattering (agrees with JINR 2016-17 data)
- A_u for np→pn on Cu: new 2016-17 measurement from JINR

Geant4 Monte Carlo simulation



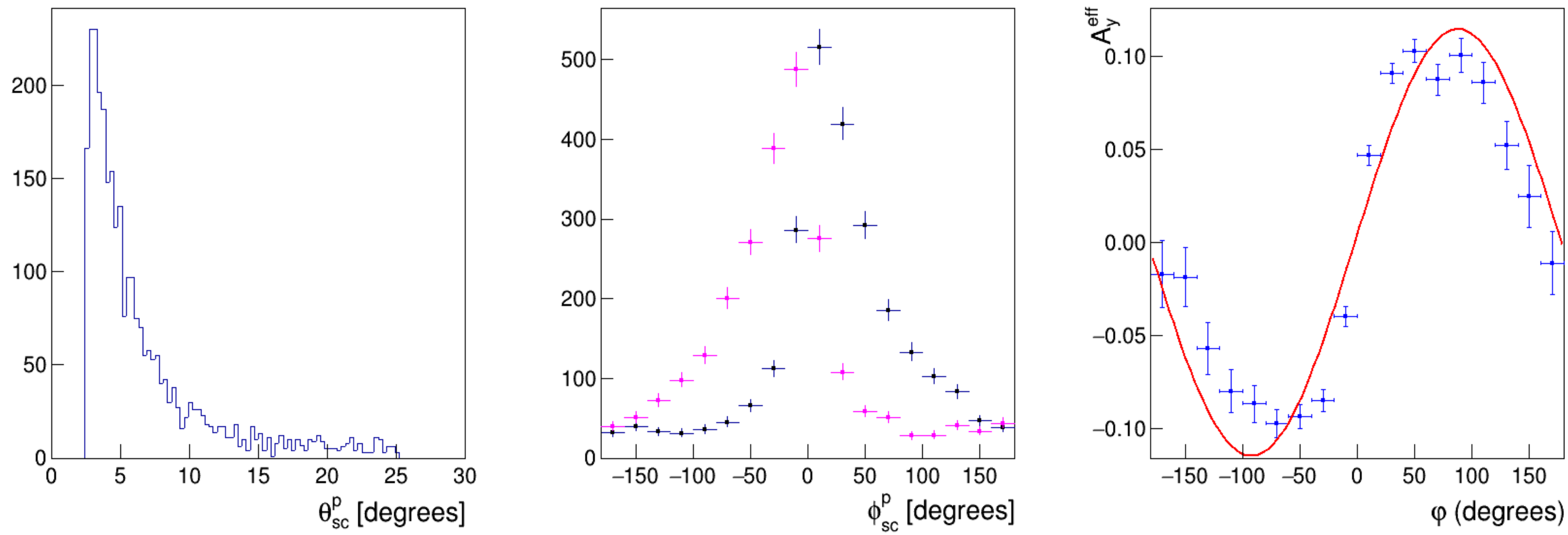
FOM study: D. Hamilton (U. of Glasgow)

Rate studies: W. Tireman (Northern Michigan)

- Realistic description of polarimeter components in g4sbs
- Included spin-dependent hadronic processes and precession
- Full quasi-elastic pseudo-data set simulated for expected luminosity
- Two-arm data analysis performed for both CE and PR polarimeter with realistic detector efficiencies and resolutions
- Analyzing power parametrizations based on Ladygin (x0.5) for PR and Dubna results for CE
- Extracted effective analyzing power (due to depolarization), overall efficiency, FOM and statistical uncertainty on polarization components and form factor ratio

Simulated asymmetries

CE Polarimeter with Cu Analyzer

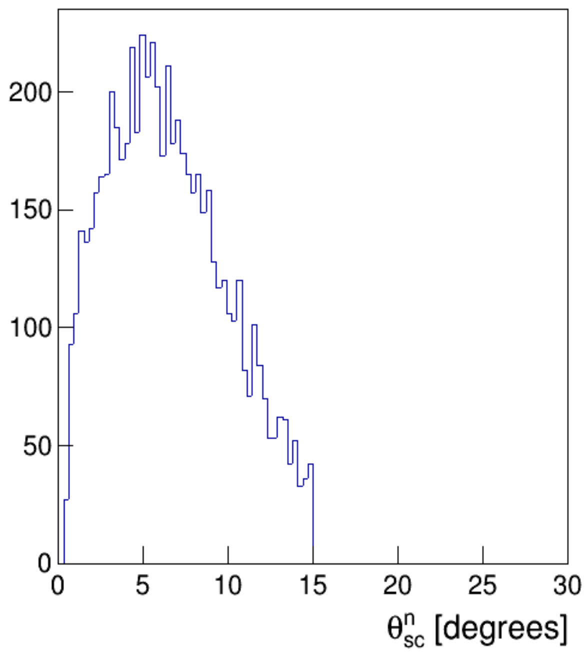


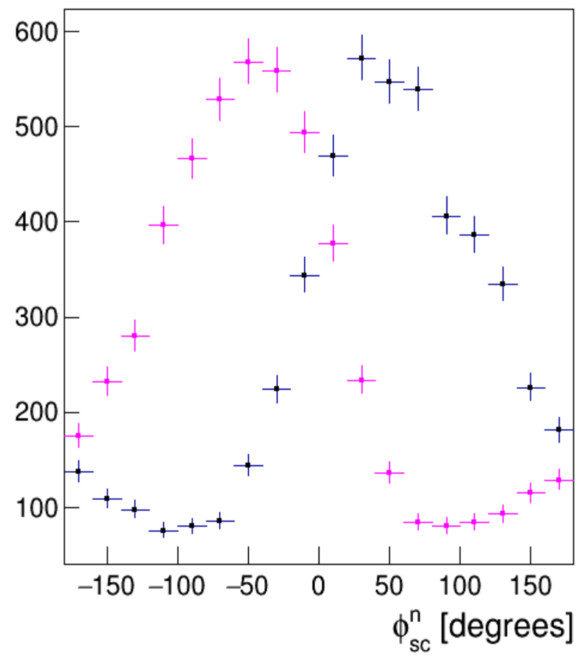
- P = 1 in generator: extract dilution factor and effective analyzing power
- A_y $(np \to pn)$ parametrization for Cu based on 2016-17 JINR results

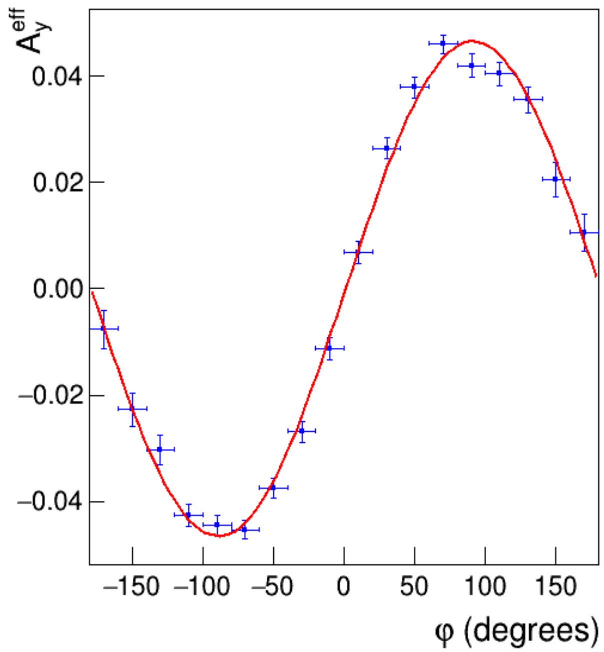
- Polarimeter Efficiency: $\varepsilon = 2.3 \times 10^{-2}$
- Effective analyzing power of CE polarimeter: A_y^{eff} = Dilution x $A_y(np \to pn)$ = 0.89 x 0.12 = 0.11
- Figure of Merit: FOM = $\varepsilon \times (A_y^{eff})^2 = 2.6 \times 10^{-4}$

Simulated asymmetries

PR Polarimeter with Active Analyzer



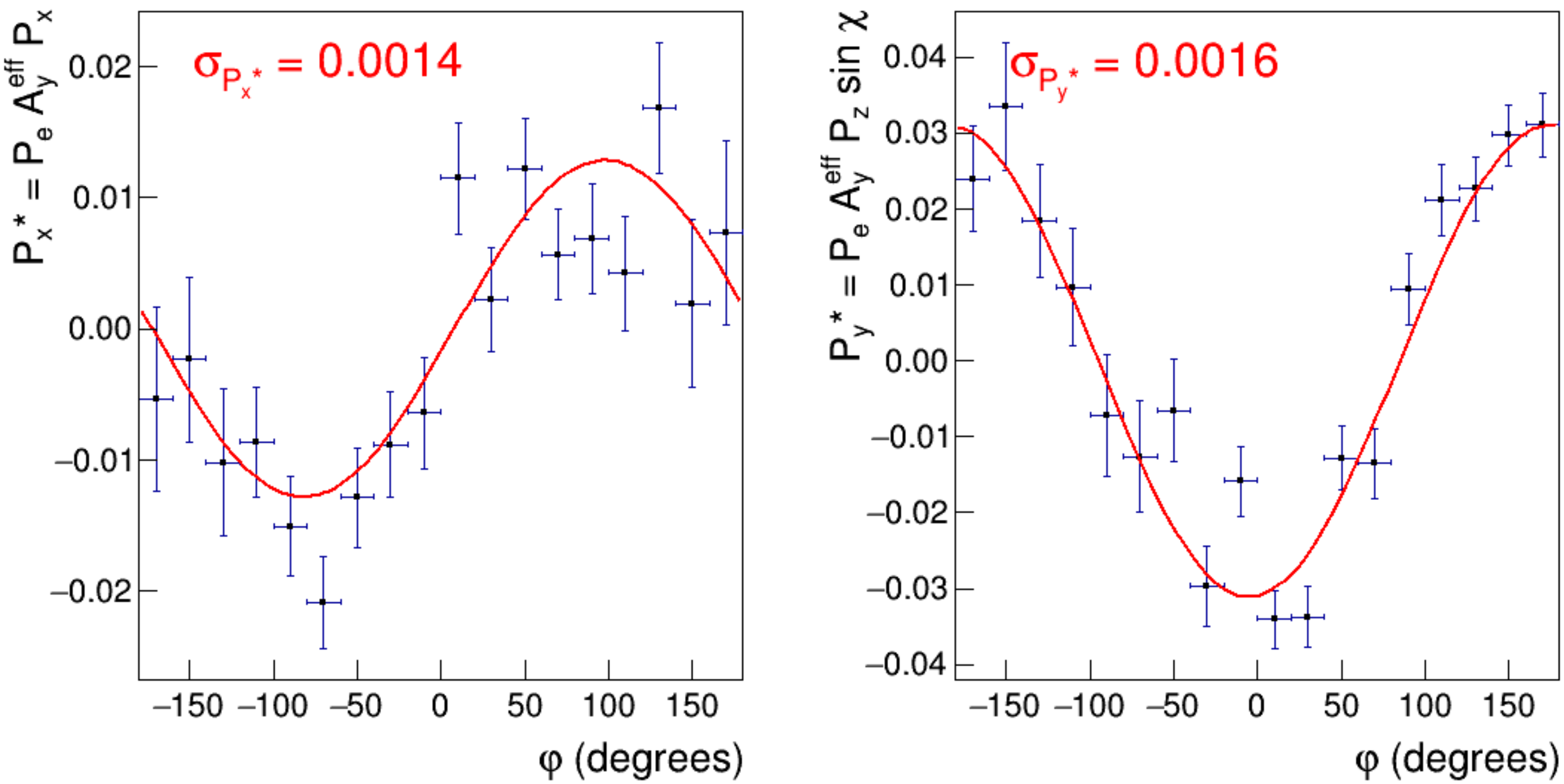




- P = 1 in generator: extract dilution factor and effective analyzing power
- A_y $(np \rightarrow np)$ parametrization for CH based on Ladygin elastic x0.5 (agrees with 2016-17 JINR results)

- Polarimeter Efficiency: $\varepsilon = 3.8 \times 10^{-2}$
- Effective analyzing power of PR polarimeter: A_y^{eff} = Dilution x $A_y(np \rightarrow np)$ = 0.77 x 0.06 = 0.046
- Figure of Merit: FOM = $\varepsilon \times (A_y^{eff})^2 = 0.8 \times 10^{-4}$

Extracted recoil polarization components

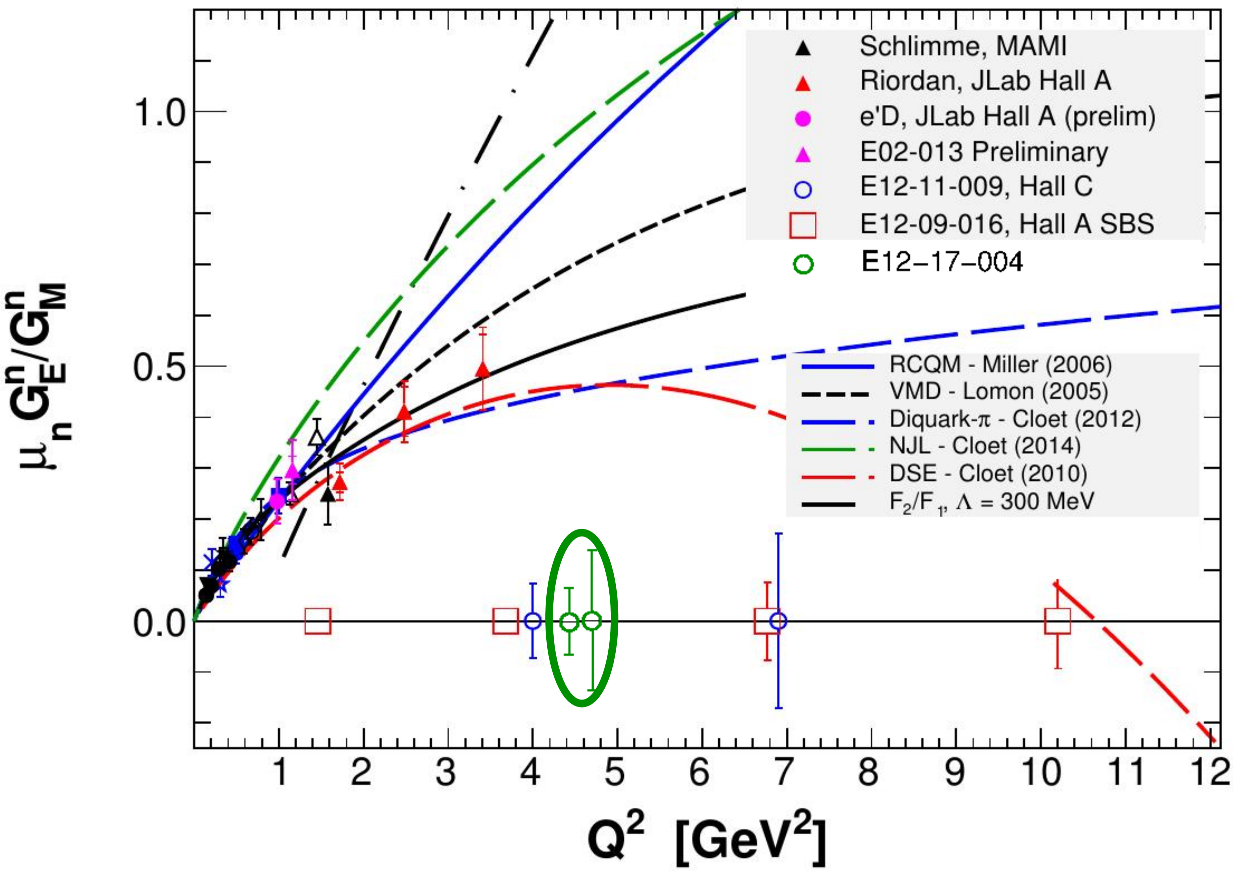


- 4 comb. beam helicity, SBS dipole polarity — $F(\phi_n) = C\{1 \pm |P_x^*| \sin\phi_n \pm |P_y^*| \cos\phi_n\}$
- Unpolarized Distribution — $C = F_{++} + F_{--} + F_{+-} + F_{-+}$
- Polarized Distributions — $F_x = (F_{++} - F_{-+} + F_{+-} - F_{--})/C$, $F_y = (F_{++} - F_{+-} + F_{-+} - F_{--})/C$
- Simulated 20 million QE e-n events with $P_e = 0.8$, $P_x = 0.19$ and $P_z = 0.52$ (typical values)
- Projected uncertainties consistent with FOM

Projected form factor ratio uncertainty

$$\delta P = \sqrt{\frac{2}{N_{inc}\mathcal{F}^2}} \qquad R = \mu_n G_E^n / G_M^n \qquad \left(\frac{\delta R}{R}\right)^2 = \left(\frac{\delta P_x}{P_x}\right)^2 + \left(\frac{\delta P_z}{P_z}\right)^2$$

E_{beam} (GeV)	Q^2 $(GeV/c)^2$	p_n (GeV/c)	Rate (Hz)	Time (hours)	FOM $\times 10^{-4}$	dP (absolute)	dR (absolute)
4.4	4.5	3.15	48.8	120	2.6 (CE)	0.019	0.078
					0.8 (PR)	0.034	0.140
					3.4 (Total)	0.017	0.070



- Estimates from latest g4sbs agree very well with proposal
- *dR* based on Galster G_{En} and Kelly G_{Mn} parametrizations
- Expect overall systematic error to be ~3.0%

Summary

- E12-17-004 will measure the ratio of neutron electric to magnetic form factors by quasielastic electron-deuteron scattering with neutron recoil polarimetry

- The SBS Neutron Polarimeter consists of two independent parts:

  - A polarimeter with an active scintillator array analyzer based on n-p scattering (forward neutron, backward proton)

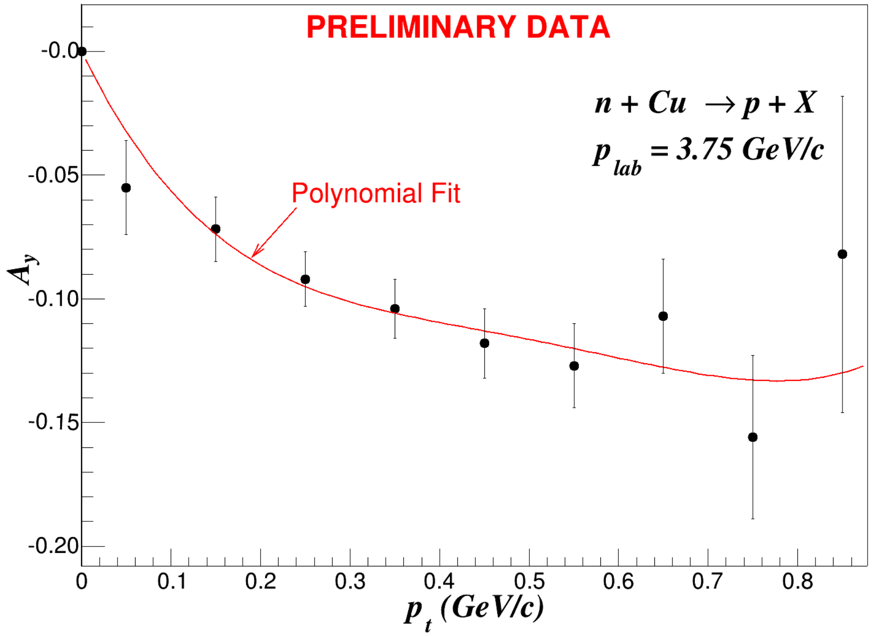
  - A polarimeter with a copper analyzer based on n-p charge exchange (forward proton)

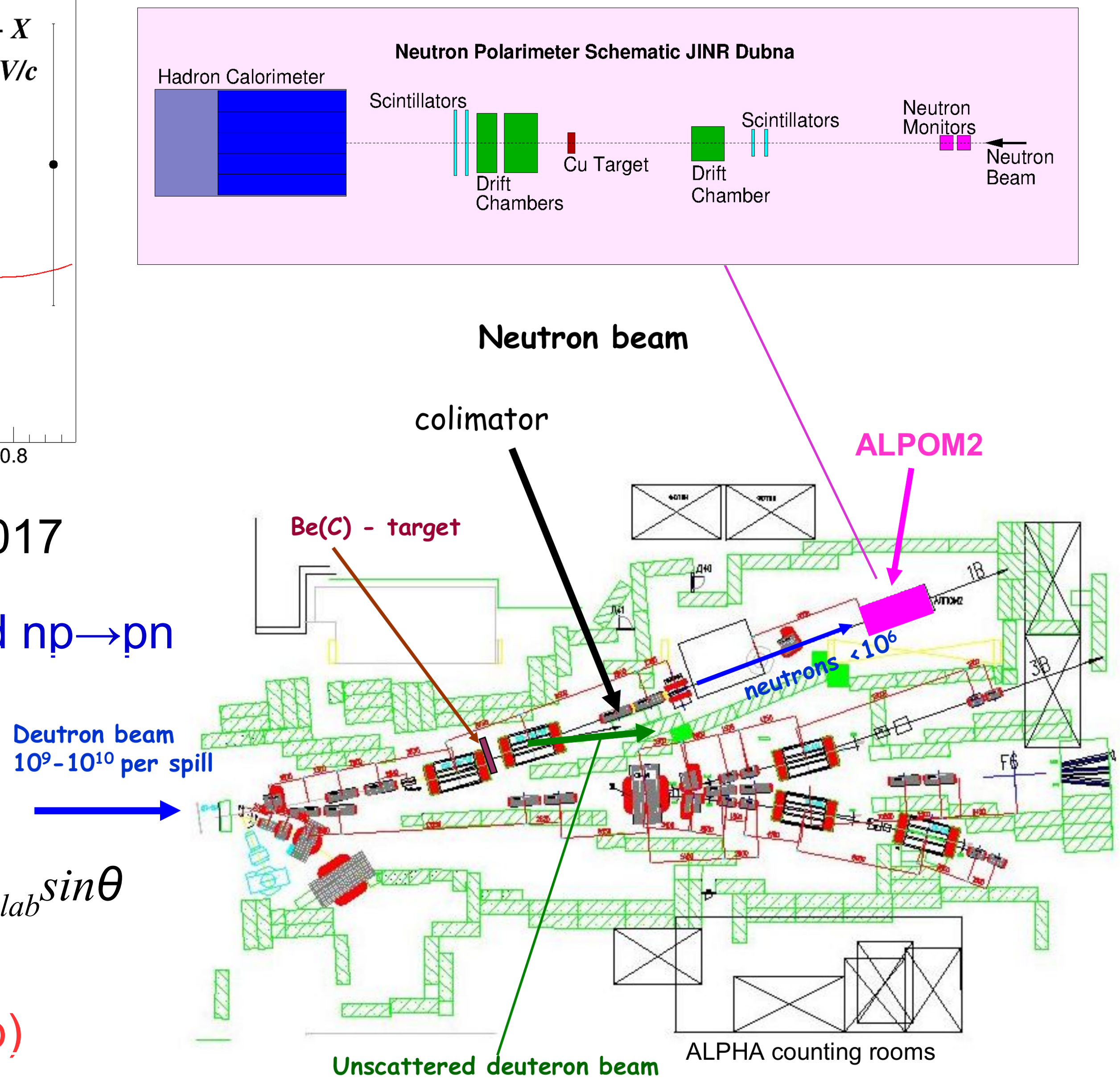
- Simulations for realistic running conditions have been performed within the g4sbs framework (used for other SBS experiments)

- We expect the experiment to run in the early phase of the SBS program (2020-21)

Backup

Analyzing power: JINR Dubna (2016-17)





- JINR Dubna Nov 2016 – Feb 2017
- Measure asymmetries polarized np→pn
- C, CH, CH_2, Cu targets (p_{lab} = 3.0 – 4.2 GeV/c)
- Extract A_y as a function of $p_t = p_{lab} sin\theta$
- Cu asymmetry similar to C (also found, recently, for pn→np)
- Draft publication to be submitted soon