High Precision Parity Experiments as a Probe for new Physics and Benchmark Measurements

Durham, NC, USA

Michael Gericke

With grateful acknowledgement of the support provided by these funding agencies:

Outline

- PVES measurements
- Recent PVES example
- HPV measurements
- Recent HPV examples
- Common measurement principles and some of the systematic effects
- Some upcoming experiments and precision goals

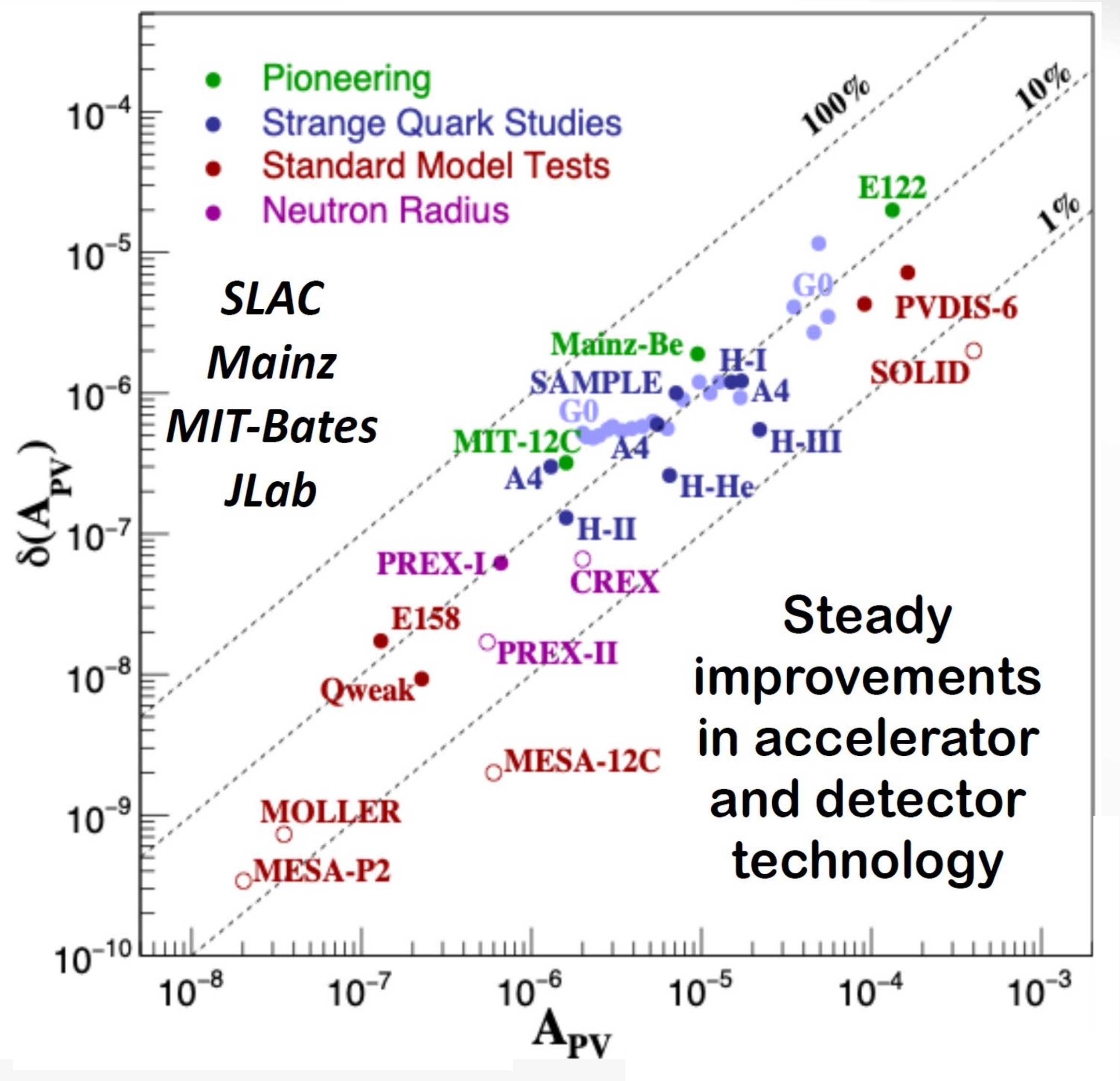
Many PV Measurements

The talk title has a touch of unjustified grandeur, as this talk has some important omissions:

- There is an enormous amount of atomic parity violation effort in both PVES and HPV that I am not discussing
- PVES results produce important results for nucleon quark structure physics, which I am not discussing
- PVES results produce important results and nuclear-astrophysics, such as the neutron radius measurements
- Hadronic PV measurements at higher energies are not discussed
- PV measurements on resonances are also not discussed

PVES Measurements

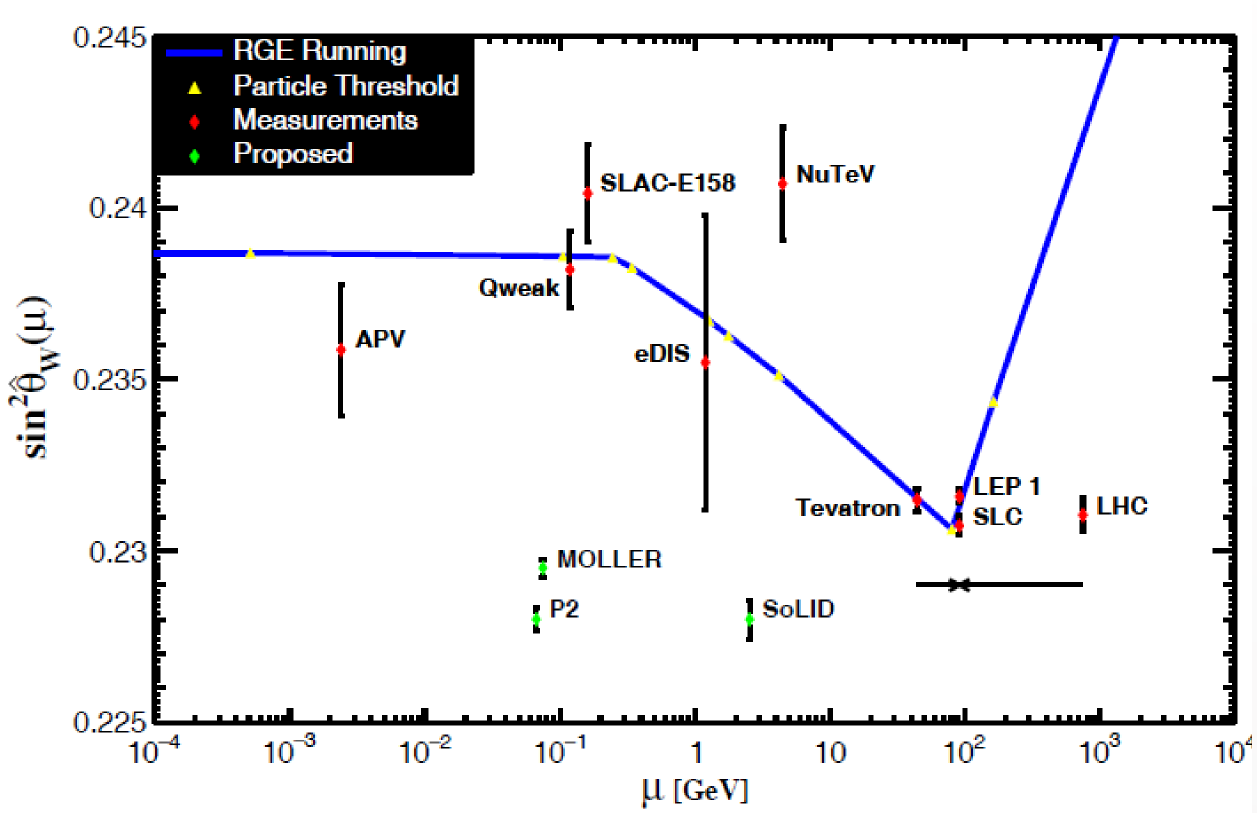
- Long and active history of PVES measurements
- Asymmetries and errors now push on the (sub) ppb level
- Percent-level relative errors now allow for beyond two-loop level investigations of the SM and potential new physics
- Making such measurements requires:
  - High luminosity (beam and high-power targets)
  - Parity quality beam:
    High polarization with high beam stability and systematic control
  - High precision beam polarimetry measurements
  - Better and better detector systems with faster readout



PVES Measurements (focus on BSM tests)

The Weak Mixing Angle

J. Erler (JGU), reproduced with permission



The weak mixing angle is a central parameter of the electroweak part of the Standard Model:

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \sin(\theta_W) & \cos(\theta_W) \\ \cos(\theta_W) & -\sin(\theta_W) \end{pmatrix} \begin{pmatrix} B^0 \\ A \end{pmatrix}$$

SU(2): Gauge fields (B^+, B^-, B^0) and coupling g'

U(1): Gauge field A and coupling g

“On-shell” definition in terms of boson masses:

$$\sin^2(\theta_W) = 1 - \frac{m_W^2}{m_Z^2}$$

“$\overline{\mathrm{MS}}$-Scheme” definition in terms of (running) coupling constants:

$$\sin^2(\hat{\theta}_W) = \frac{g'^2}{g^2 + g'^2}$$

PVES Measurements (focus on BSM tests)

The Weak Mixing Angle

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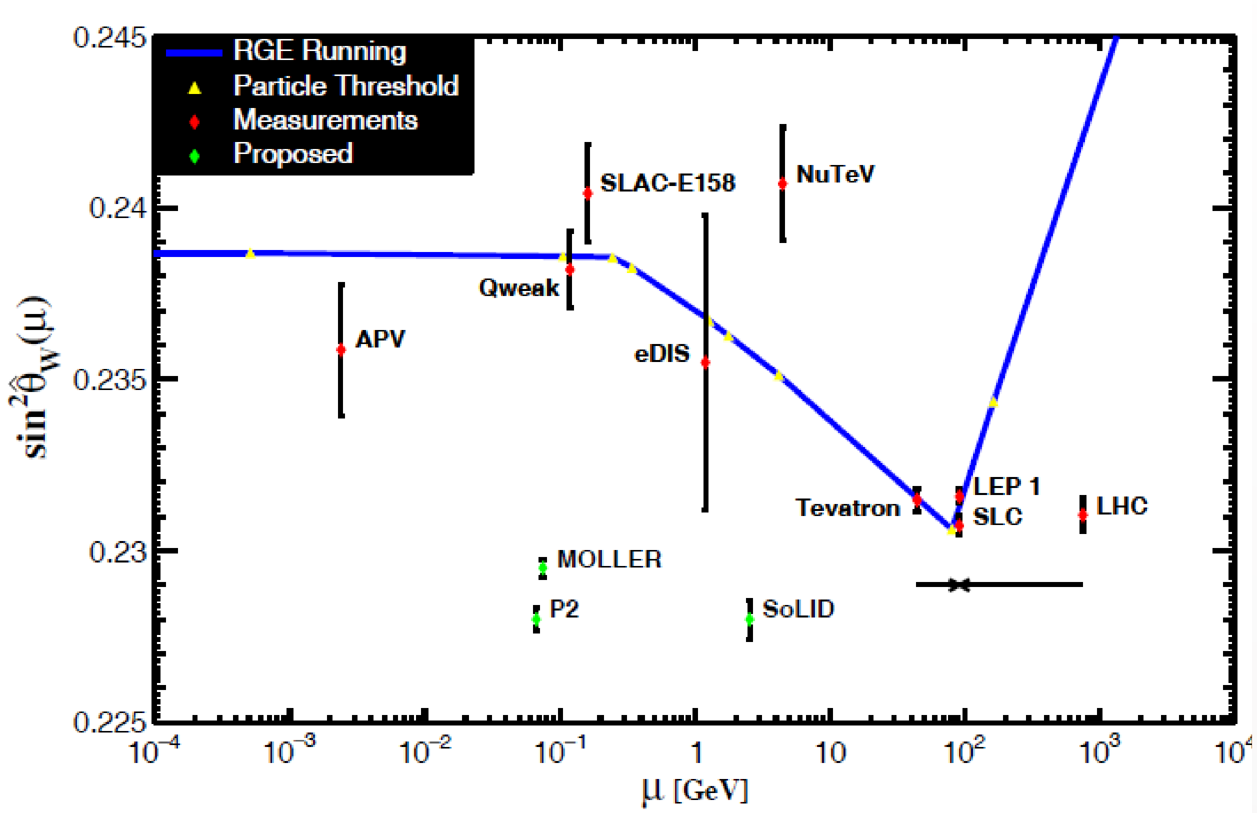
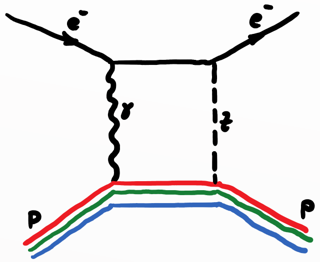
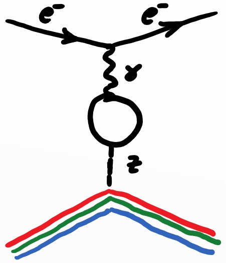
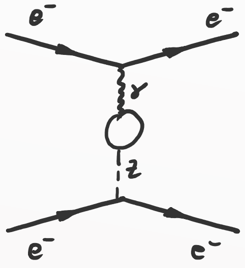
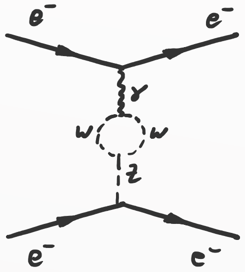


The weak mixing angle changes ("running") with interaction energy (e.g. momentum transfer), due to:

etc.

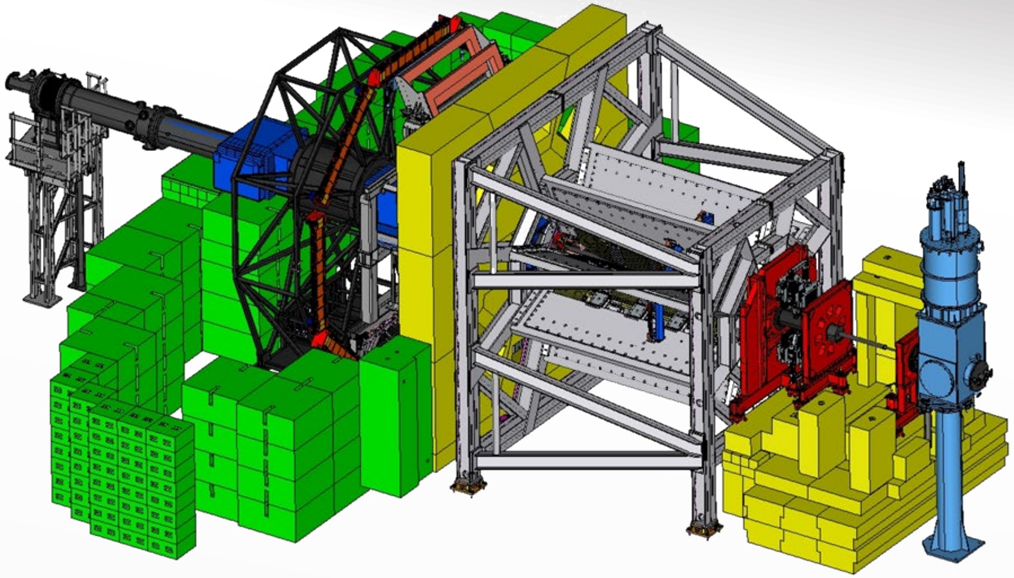
etc.

Different radiative correction apply to different particle interactions (e.g. electron with electrons vs. electron with quarks).

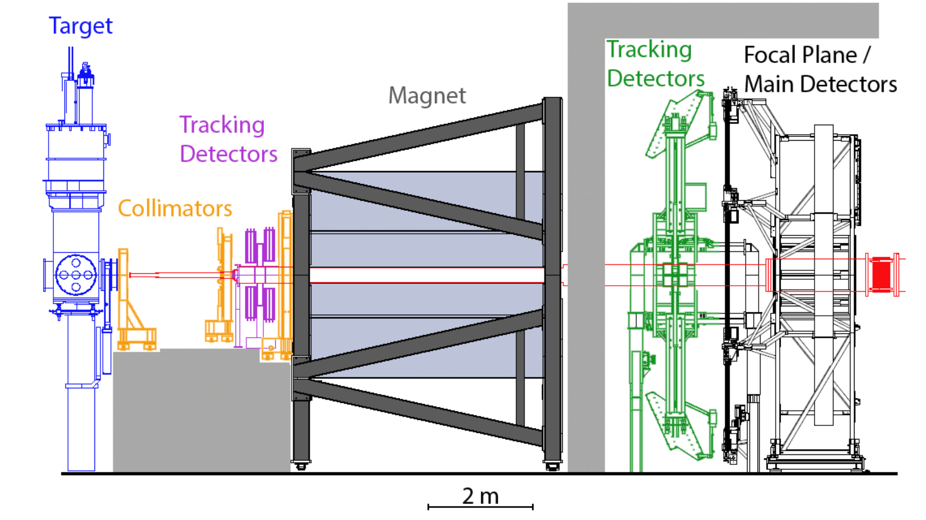
PVES Measurements

The QWeak Experiment $Q_W^p = 1 - 4\sin^2\theta_W$

Measure A_{PV} as a function of electron helicity



Average Q²:	0.0249 ± 0.0006 GeV²
Beam Energy:	1.154 ± 0.003 GeV
Beam Current:	145 μA – 180 μA
Beam Polarization:	0.89 ± 0.018
Target Power:	2.5 kW
Luminosity:	1.7×10^{39} cm^{-2} s^{-1}
Integrated Rate (per detector):	875 MHz (7 GHz total)
Acceptance averaged asymmetry:	–0.23 ppm (nominal)
Standard Model:	$Q_W^p(Q^2 = 0) = 0.0713 \pm 0.0008$



Results (Nature volume 557, pages 207–211 (2018)):

$$A_{PV}(\vec{e},p) = -226.5 \pm 7.3(stat) \pm 5.8(sys) \quad ppb$$

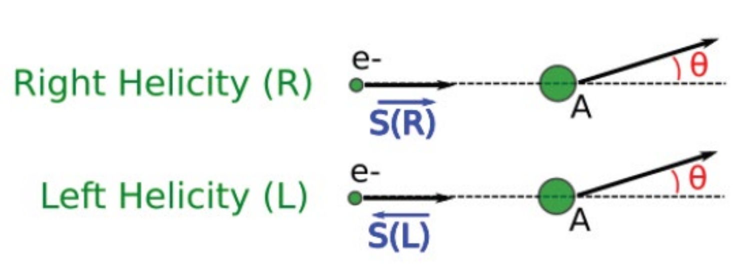
$$Q_W^p = 0.0719 \pm 0.0045$$

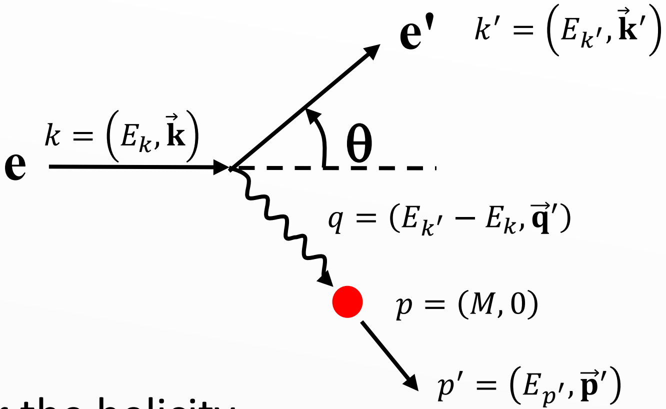
PVES Measurements

Measurement Methodology

Experiments will measure the asymmetry in the number of scattered electrons as a function of beam helicity.

$$A = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

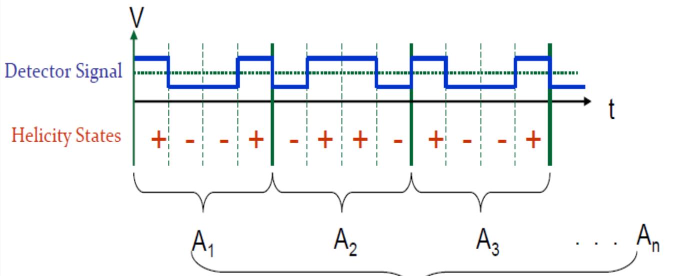




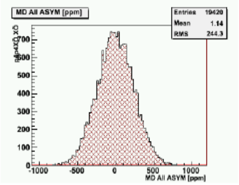
The measured flux will be integrated (both spatially and in time) over the helicity window, to form the measured asymmetry at the pair, quartet, or octet level.

All systematic effect must be taken into account:

$$A_{msr} = \frac{Y^+ - Y^-}{Y^+ + Y^-} = P_e\left(f_p A_{PV} + \sum_b A_b f_b\right) + A_{beam} + A_{inst}$$



$$A_{qrt} = \frac{\sum Y_+ - \sum Y_-}{\sum Y_+ + \sum Y_-}$$



PVES Measurements

Measurement Methodology

- Precision scales with event rate ($\sqrt{N}$) – so the high precision goals require extremely high detector event rates

- Individual detector event counting not always feasible at the highest rates – even with high segmentation and fast electronics

- Integration mode operation of detectors makes sense when:

  - When we deal with high rates, and
  - high segmentation is not an option, and
  - backgrounds can be “eliminated by design”, and
  - technology allows for “low noise operation”

- In this case we measure the integrated detector yield

$$Y_D^{\pm} \simeq \mathcal{L}\sigma_D G_D\left(1 \pm PA_{ph} \pm A_{beam} \pm A_{inst}\right) \pm A_{ped}$$

$$G_D \equiv \Gamma_D Q_{PE} g_{PMT} g_{amp}$$

- Experimental design determines how good this linear approximation will be

PVES Measurements

Measurement Methodology

The faster the helicity reversal the better the approximation of the signal as a linear drift for many experimental effects.

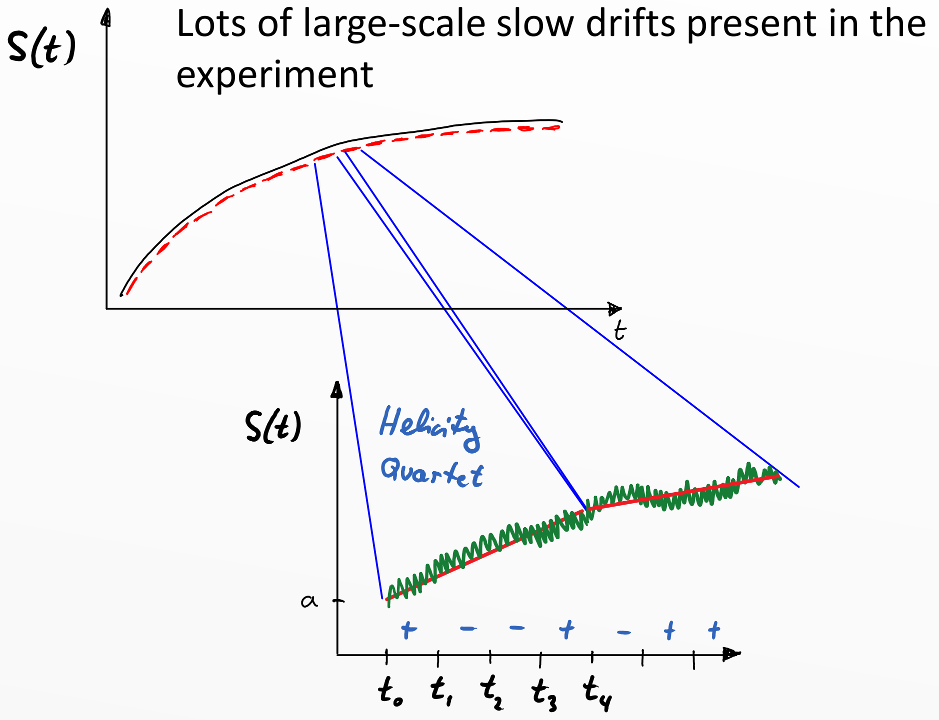
So, locally, the signal “looks like” a linear function of time:

$$Y_{\pm}(t) \approx \left(a + \left.\frac{dY}{dt}\right|_{t_i} t \right)(1 + A_{msr})$$

- The quartet helicity pattern removes linear drifts +--+ or -++-
- An octet helicity pattern removes quadratic drifts +--+-++-
- Pseudo random reversal of the fist sign in quartet patterns removes higher order drifts

Example of these drifts:

- Target drifts (e.g. diurnal variations) and boiling noise
- Detector gain and electronics drifts
- Spectrometer field drifts
- Slow beam drifts

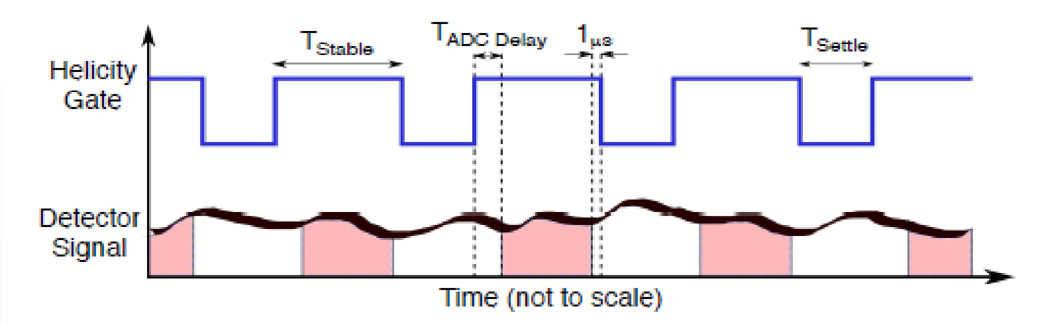


PVES Measurements

Front-end Electronics Design:

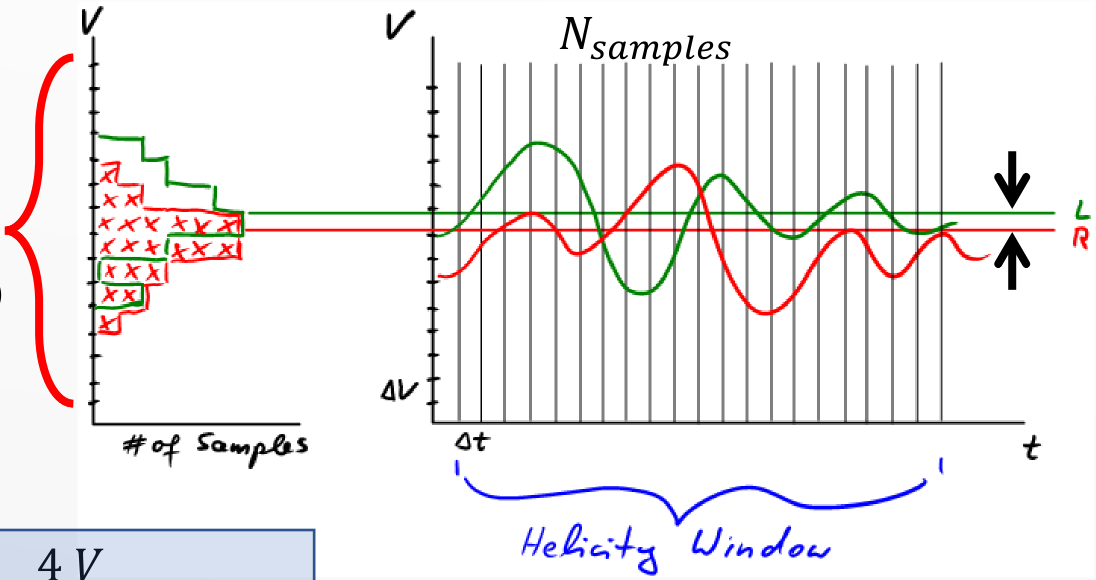
Operating Principle:

- Ver fast and precise (low noise) electronics is a requirement for these types of measurements
- The small asymmetries require oversampling in each helicity window



Digitization:

ADC range and resolution (0 suppressed)



$\sim 0.12\ \mu V$

Using: $n_{pe} \sim 25$

$R \sim 5\ GHz$

$G_{PMT} \sim 1000$

$G_{amp} \sim 100 k\Omega$

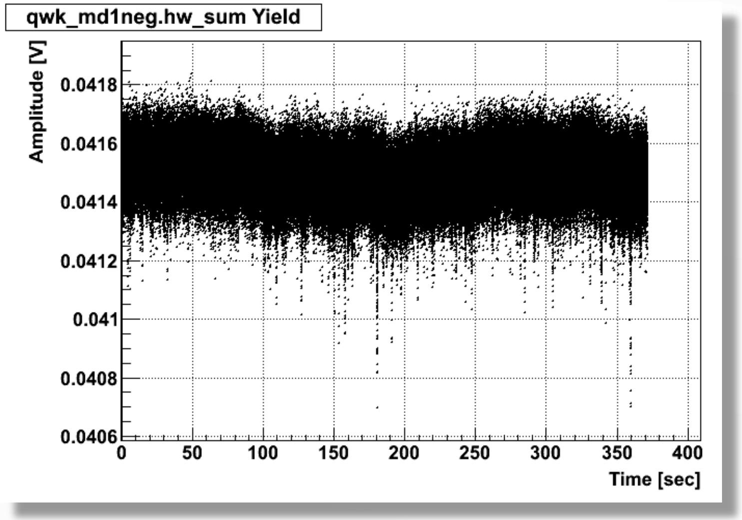
18 bit Resolution: $\Delta V \simeq \frac{4\ V}{2^{17}} \simeq 16\ \mu V$

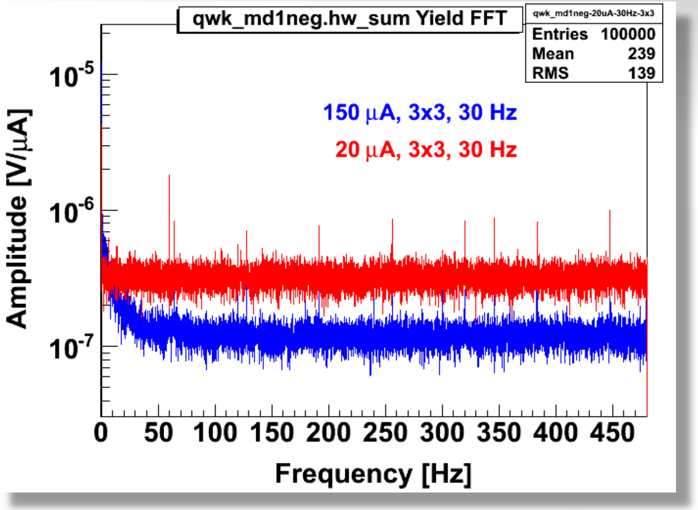
PVES Measurements

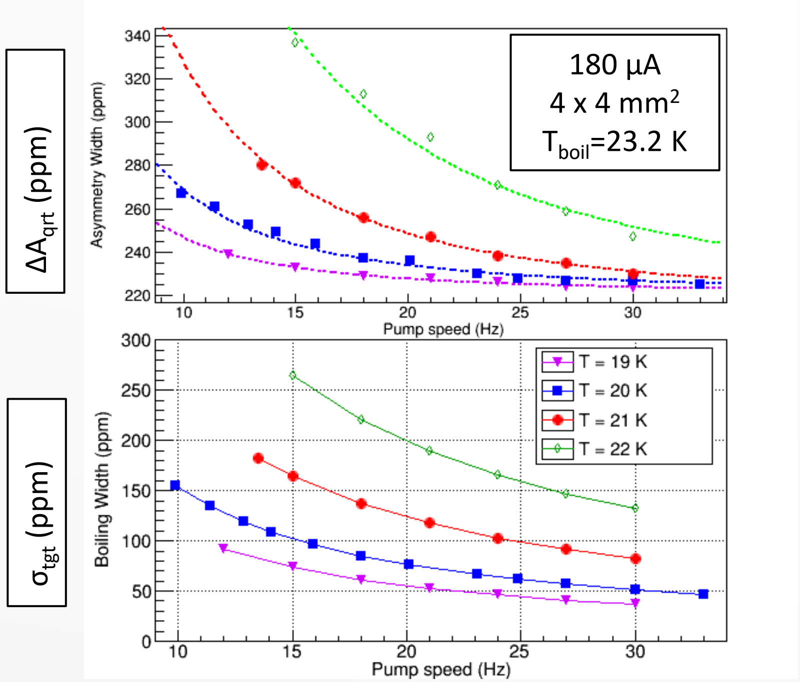
Systematic effect example

Target boiling:

- With high beam power target boiling is inevitable
- Starts around $100\ \mu A$
- Has a ${}^{1}/_{f}$ frequency dependence
- At low helicity reversal this lead to additional width in the detector and asymmetry signal
- Fast helicity reversal minimizes this effect







PVES Measurements

Systematic effect example

Detector symmetry allows measurement of:

- Beam motion
- Beam position
- Beam angle

Performing detector studies that measure the correlation between the detector signal and beam parameters (deliberate variation) is used to remove the corresponding false asymmetries.

Detector symmetry can also be used to measure transverse spin asymmetry.

PVES Measurements

Systematic effect example

Detector symmetry allows measurement of:

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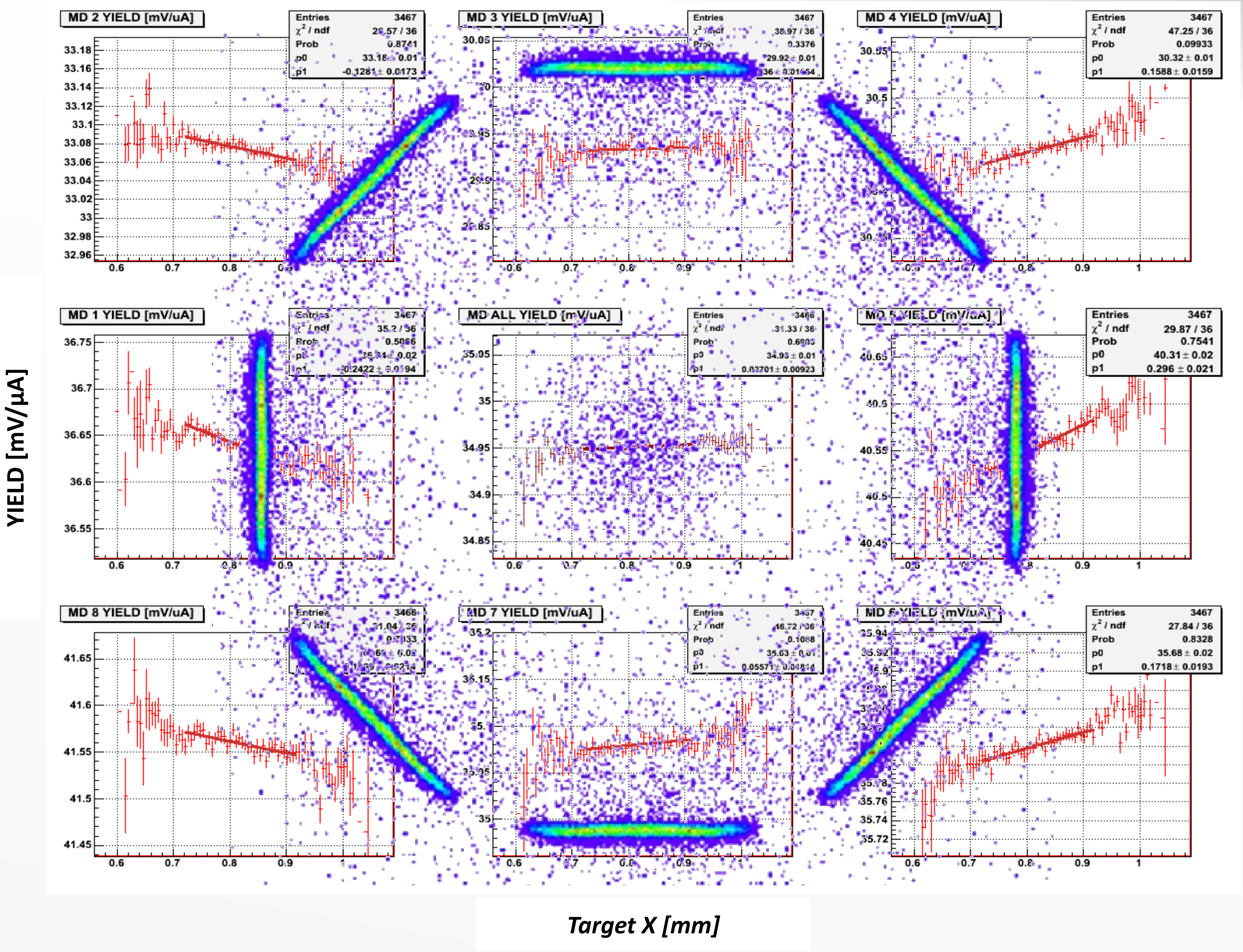
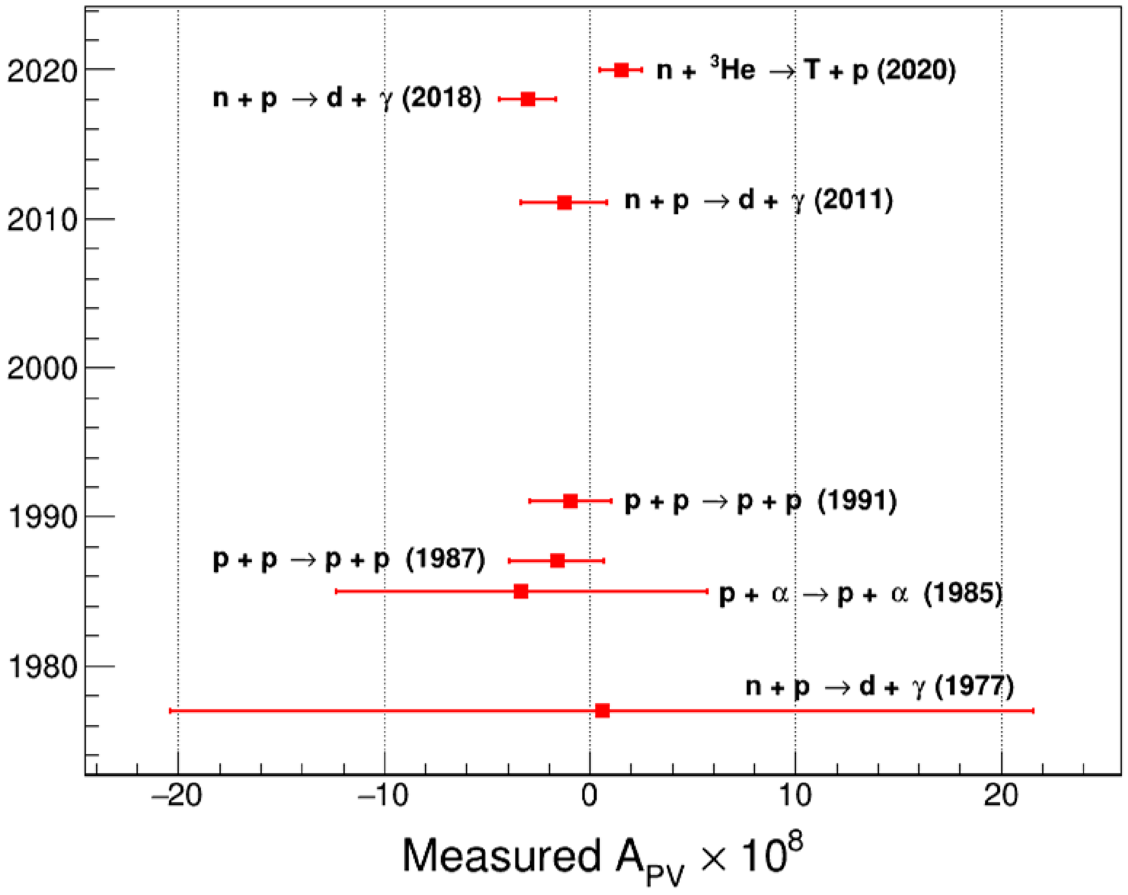
Detector symmetry can also be used to measure transverse spin asymmetry.



HPV measurements

HPV measurements

- Hadronic PV overall is still an active field (there is much that is not included in the figure on the right) , but
- Ideally, we want measurements in simple systems ($np,\ pp,\ pD,\ nD,\ n3He,\ n4He,\ p\alpha$) to understand nPT Strong interaction
- Asymmetries and required errors are small (ppb level)
- Measurements are challenging (some of them), requiring:
    - High-intensity (very) low-energy proton or neutron beams and sources
    - High efficiency polarization/polarimetry
    - Tight control of backgrounds and systematics
    - Better and better detector systems



HPV measurements – NPDGamma

- NPDGamma result (Phys. Rev. Lett. 121, 242002 (2018))
- Prediction (based on DDH best):

$$A_{\gamma PV} \simeq -0.107 h_{\pi}^{1} \approx -5 \times 10^{-8}$$

- Experimental result:

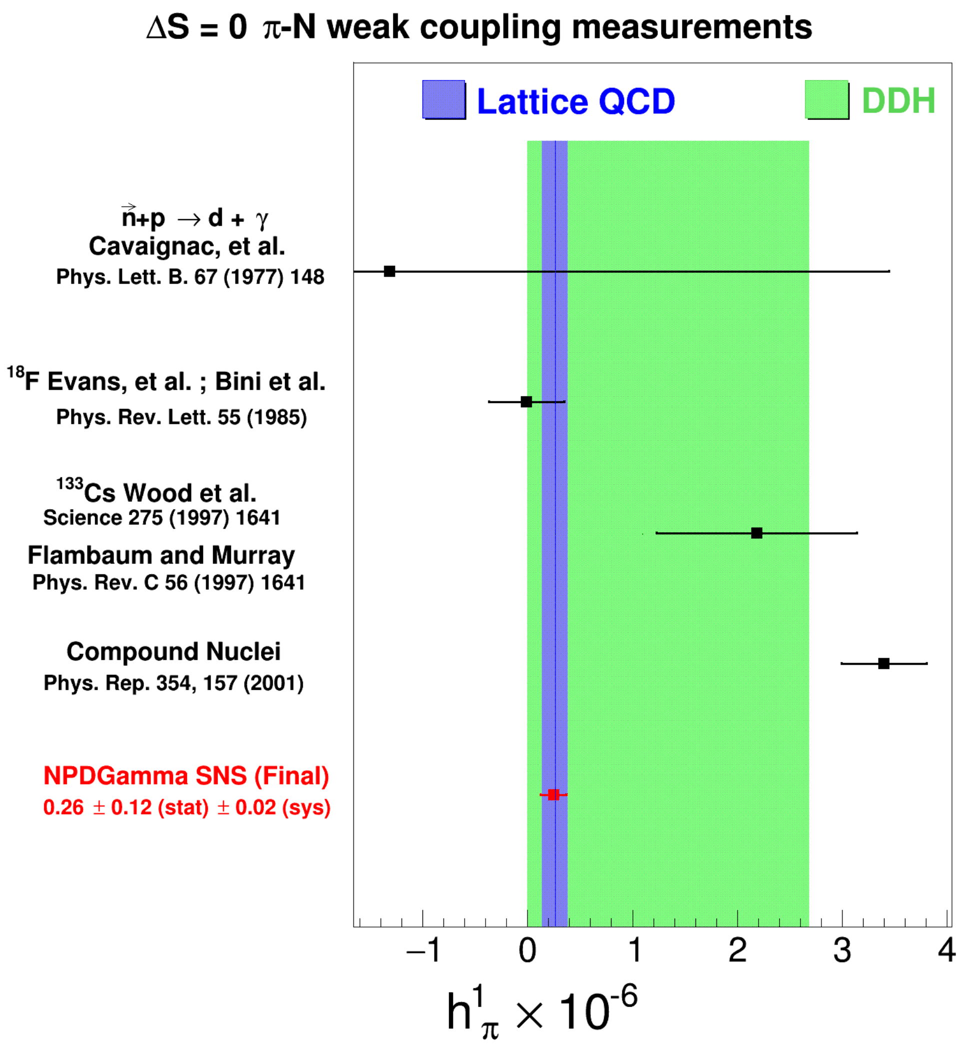
$$A_{\gamma PV} = (-3.0 \pm 1.4 \pm 0.2) \times 10^{-8}$$

- Weak-pion-nucleon coupling result

$$h_{\pi}^{1} = (0.26 \pm 0.12 \pm 0.02) \times 10^{-6}$$

- In pion-less EFT formalism this result gives

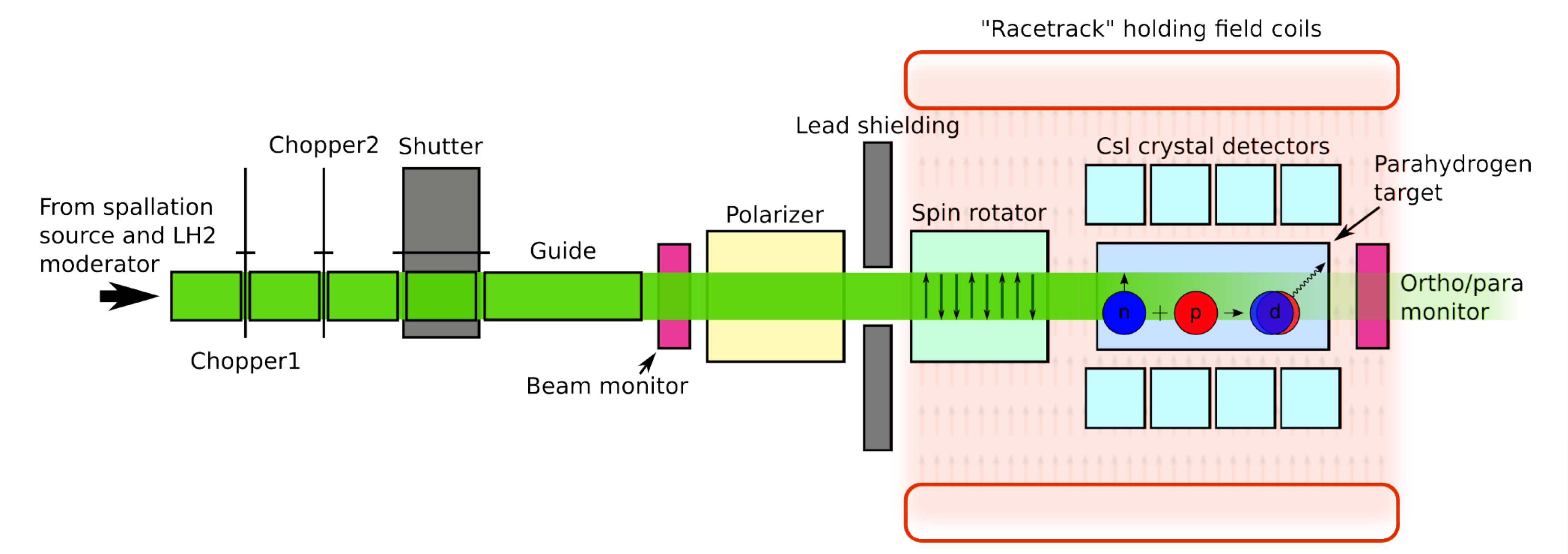
$$\Lambda_0^{{}^3S_1 - {}^3P_1} = (810 \pm 380) \times 10^{-7}$$

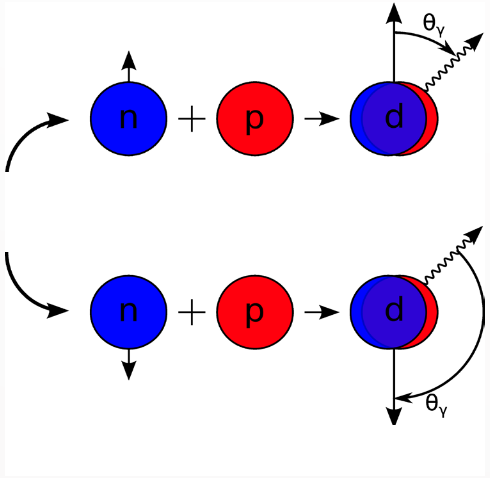


HPV measurements – NPDGamma

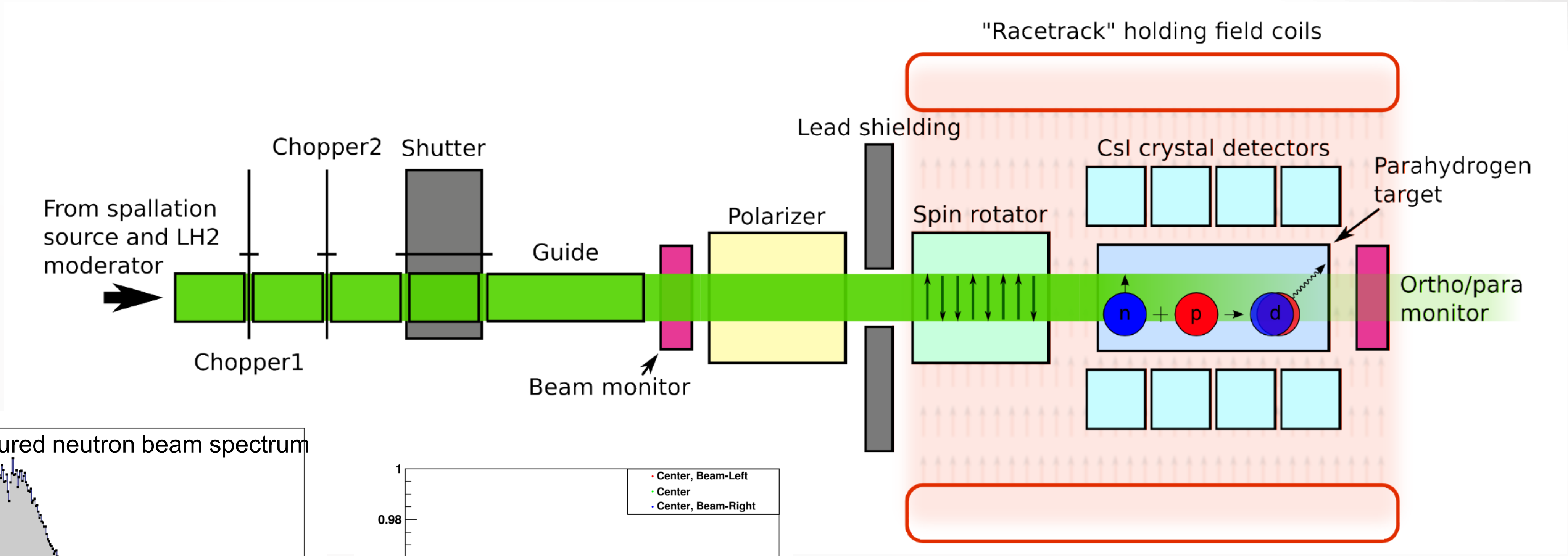
- Measurement of the parity-violating up-down asymmetry in the angular distribution of gamma rays with respect to the neutron spin direction

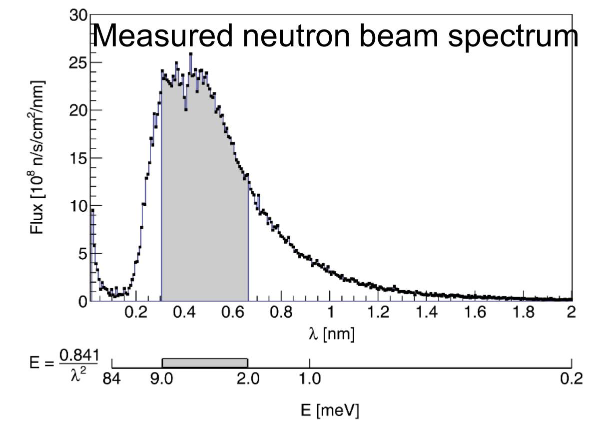
$$A_{meas} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} = P\varepsilon\left(A_{PV} cos(\theta_{\gamma}) + A_{PC} sin(\theta_{\gamma})\right)$$

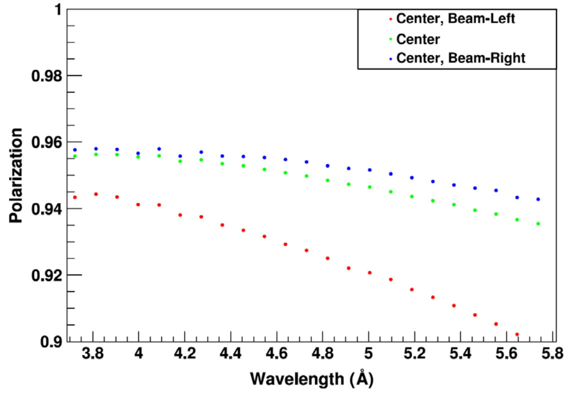


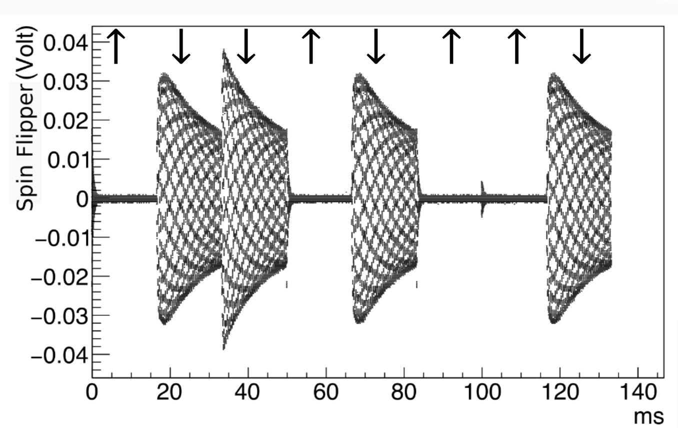


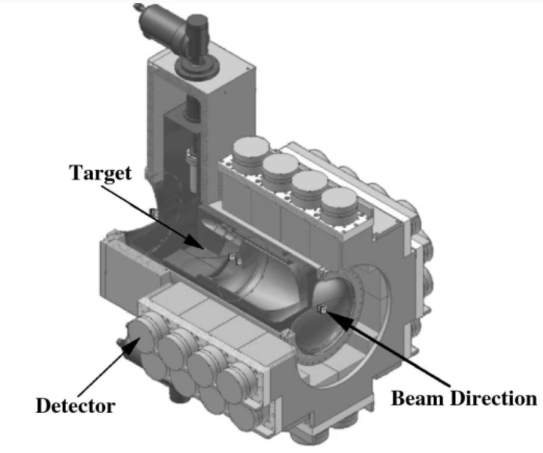
HPV measurements – NPDGamma











HPV measurements – NPDGamma

- Raw asymmetries are measured simultaneously for each detector pair to filter pulse to pulse intensity fluctuations and for a valid spin sequence of eight pulses to suppress detector gain drifts up to second order.

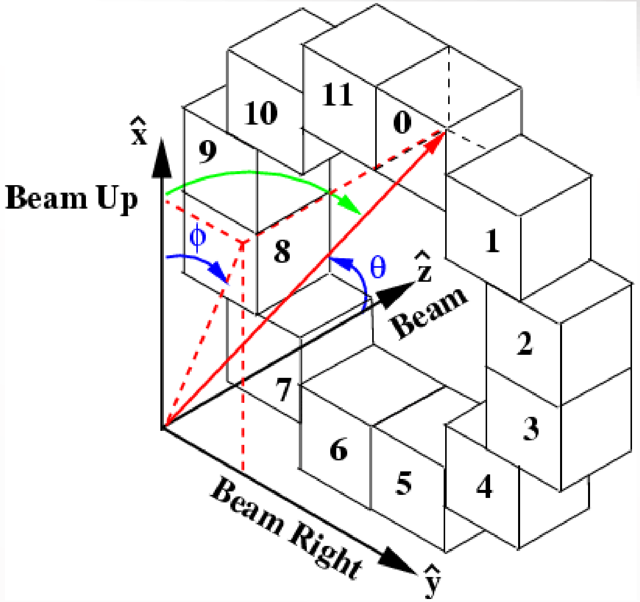
- Point target and detector: $\frac{d\sigma}{d\Omega} \propto \frac{1}{4\pi}\left(1 + A_{\gamma PV}\cos(\theta_\gamma)\right)$

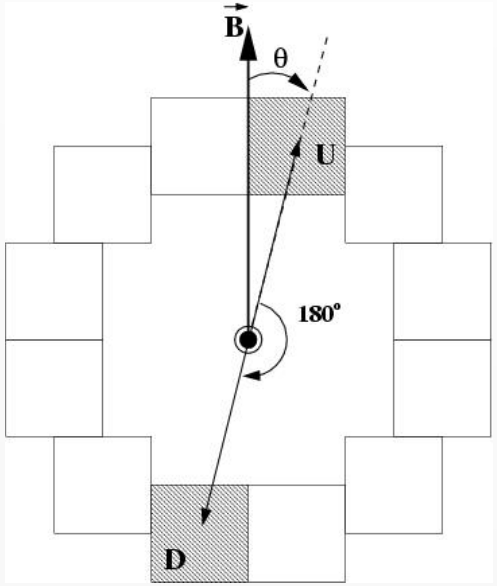
- Acceptance corrected: $\cos(\theta_\gamma)$ $\quad G_d(\langle z, \theta, \phi\rangle)$

- Detector yield: $Y_d = \frac{V_d}{4\pi}\left(1 + A_{\gamma PV}\, G_d\, P_n\, R_n\, S_n\right)$

- Detector pair asymmetry: $A_{meas} = \frac{\sqrt{\alpha}-1}{\sqrt{\alpha}+1}$ $\quad \alpha \equiv \frac{Y_d^{\uparrow}}{Y_d^{\downarrow}} \cdot \frac{Y_{d+6}^{\uparrow}}{Y_{d+6}^{\downarrow}}$

Geometric mean detector pair asymmetry removes beam and pedestal variations.





HPV measurements – n3He

- n3He result (Phys. Rev. Lett. 125, 131803 (2020))

$$A_{PV} = (1.58 \pm 0.97 \pm 0.24) \times 10^{-8}$$

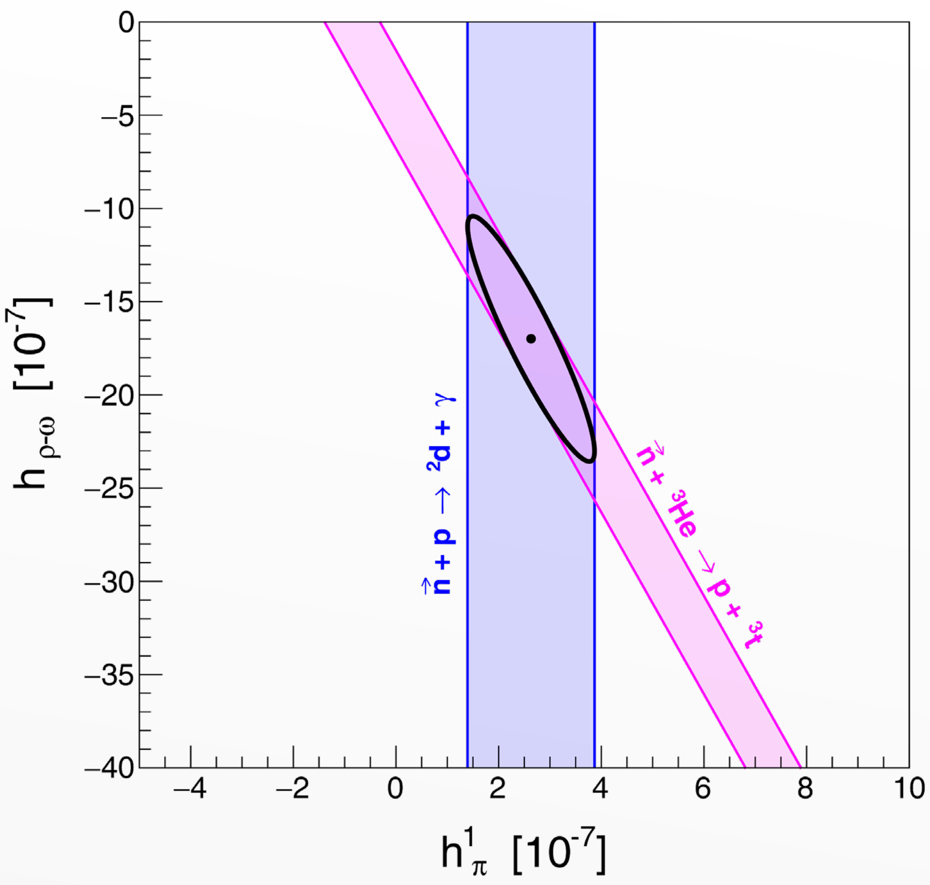
- From NPDGamma

$$h_\pi^1 = (0.26 \pm 0.12 \pm 0.02) \times 10^{-6}$$

- From n3He

$$A_{PV} = -0.185 h_\pi^1 - 0.038 h_\rho^0 - 0.023 h_\omega^0 + 0.023 h_\rho^1 + 0.05 h_\omega^1 - 0.001 h_\rho^2$$

$$\frac{A_{PV}}{0.185} = 0.205 h_{\rho-\omega} - h_\pi^1 = (8.37 \pm 5.4) \times 10^{-8}$$



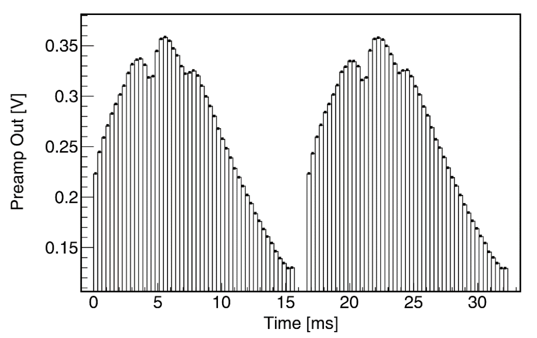
- Which provides a comparison of the pion to heavy meson contribution

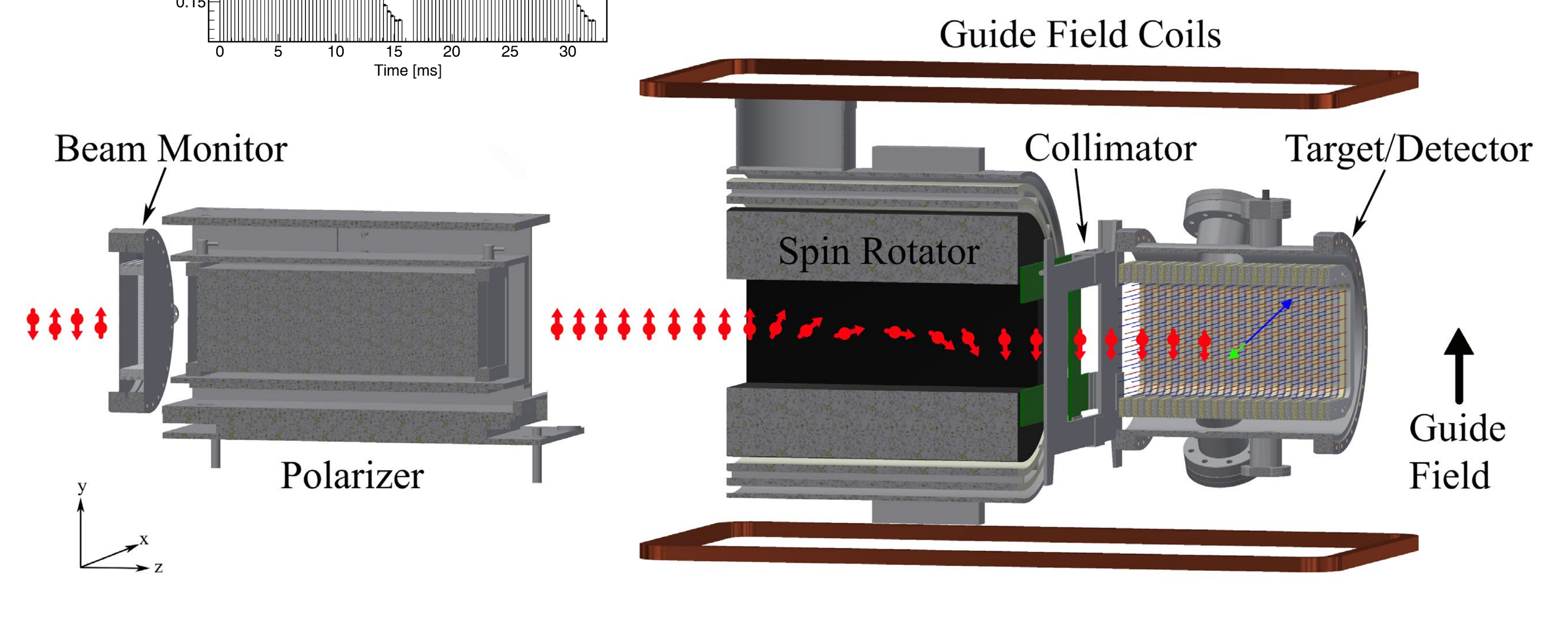
$$h_{\rho-\omega} = h_\rho^0 + 0.605 h_\omega^0 - 0.605 h_\rho^1 - 1.32 h_\omega^1 + 0.026 h_\rho^2 = (-17.0 \pm 6.56) \times 10^{-7}$$

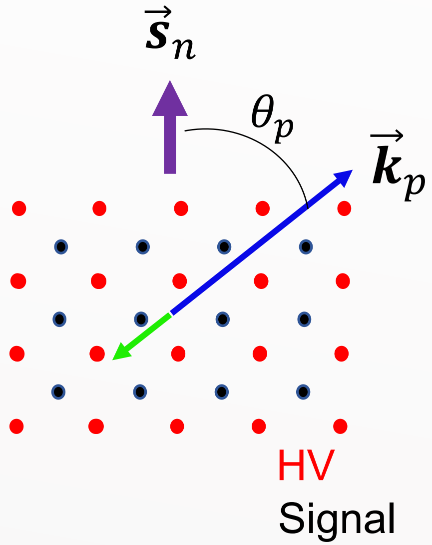
HPV measurements – n3He

- Measurement of the parity-violating up-down asymmetry in the angular distribution of protons with respect to the neutron spin direction

$$A_{meas} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} = P\varepsilon\left(A_{PV}cos(\theta_p) + A_{PC}sin(\theta_p)\right)$$

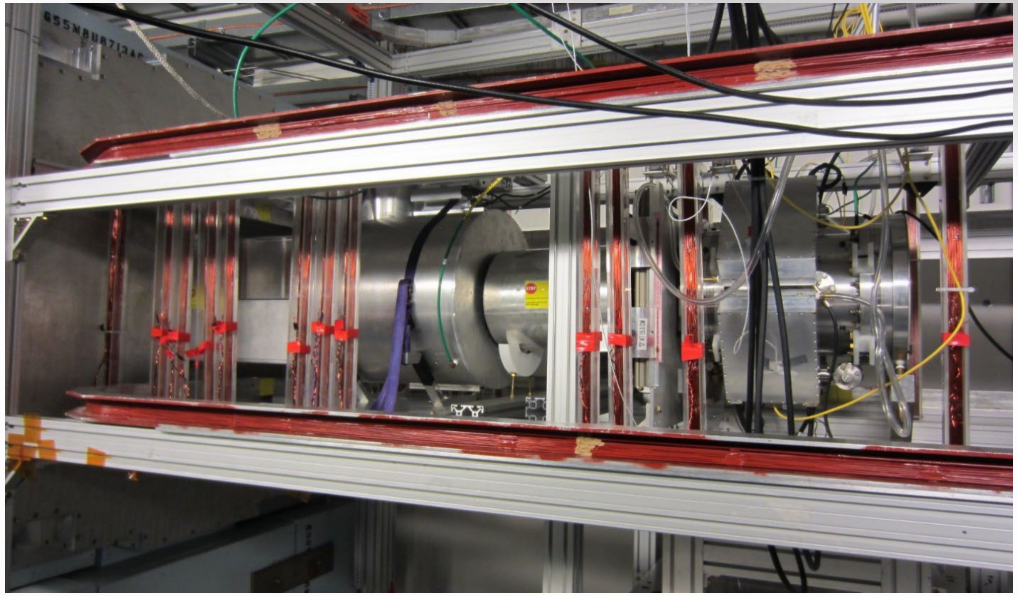


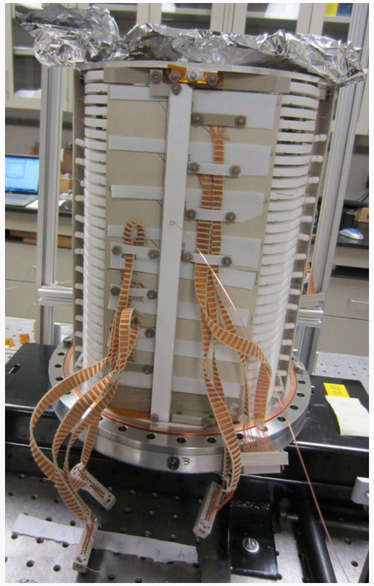


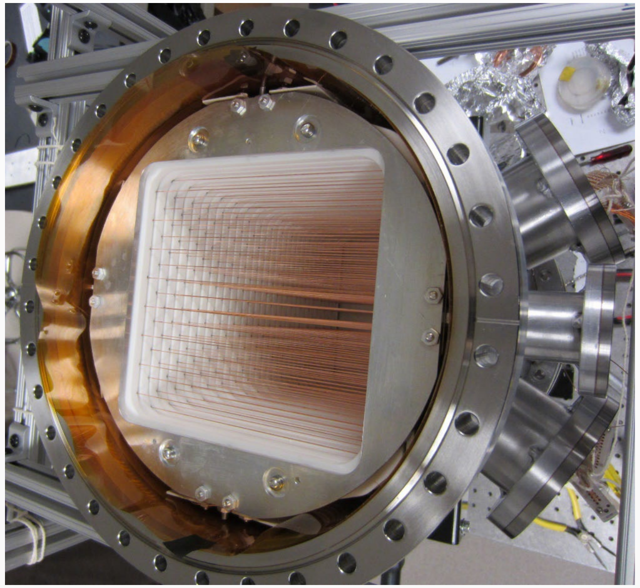


HPV measurements – n3He

- Combined target–detector wire chamber
- Exploit construction symmetry to measure PV and PC asymmetries with the same apparatus
- Tight alignment conditions to make independent measurements
- Measurement of pedestal asymmetries
- Measurement of beam fluctuations and associated asymmetries
- Measure and simulate correlations between wires
- Measure and simulate acceptance for each wire cell
- Multiple analysis with different wire combinations to extract false asymmetries and
- Single wire: $$A_{i,raw} \approx \varepsilon P G_i A_{PV} - \frac{\tilde{p}_i^+}{Y_i^{o+}} A_{Beam} + A_{i,ped}$$
- Wire pair: $$A_{u-d,raw} \approx 2\varepsilon P G_u A_{PV} + A_{u,ped} - A_{d,ped}$$



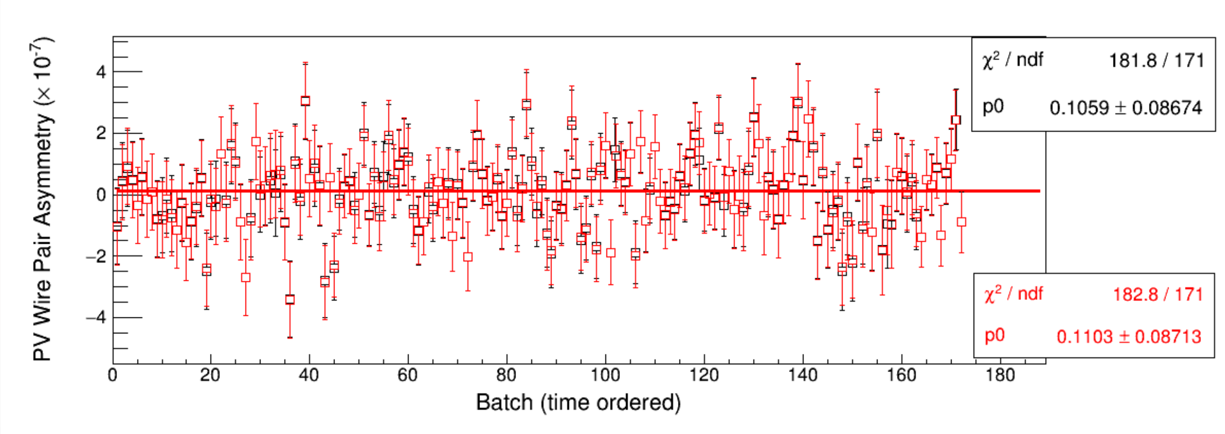


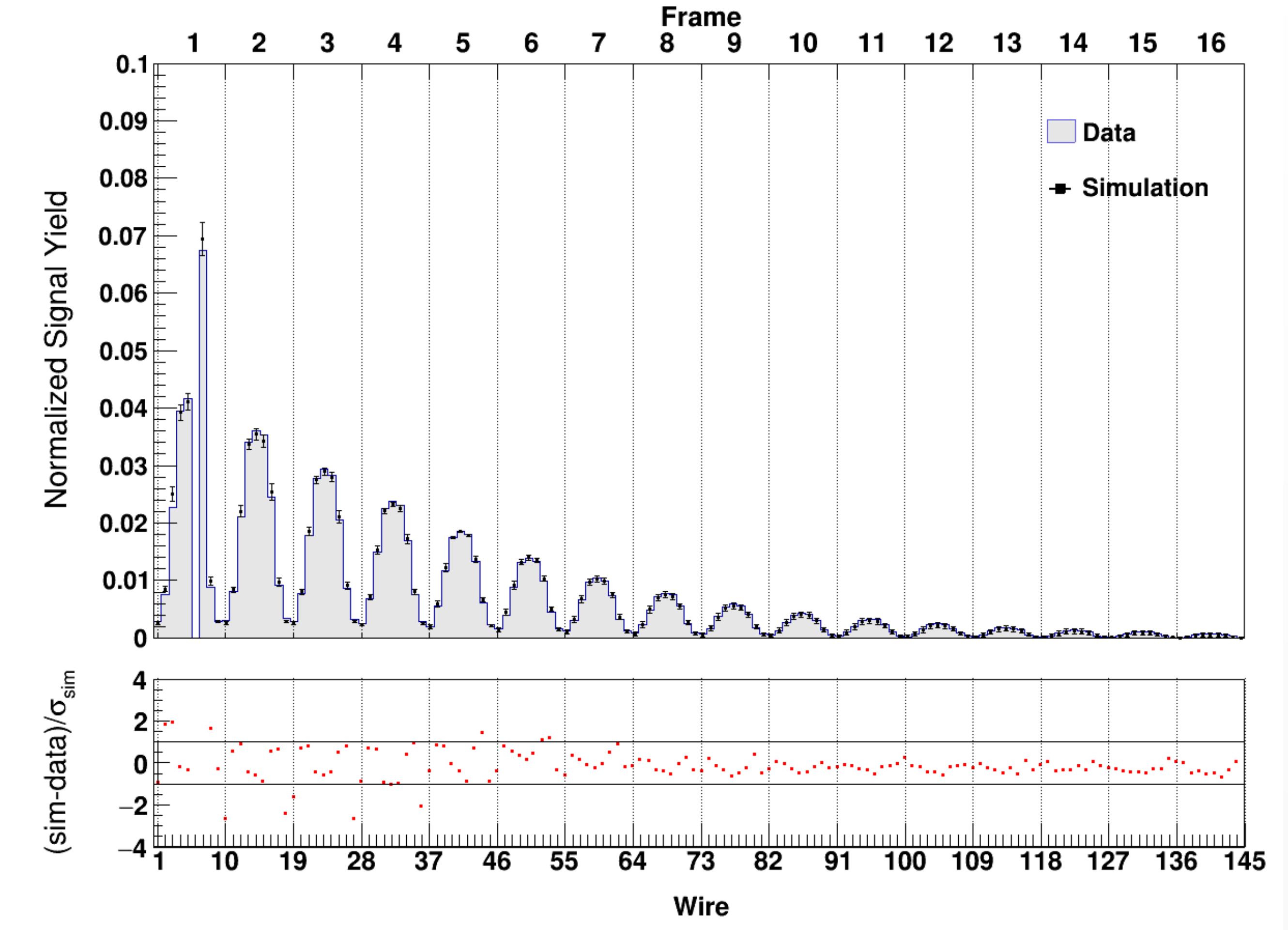


M. McCrea U. Manitoba, Ph.D. Thesis

HPV measurements – n3He

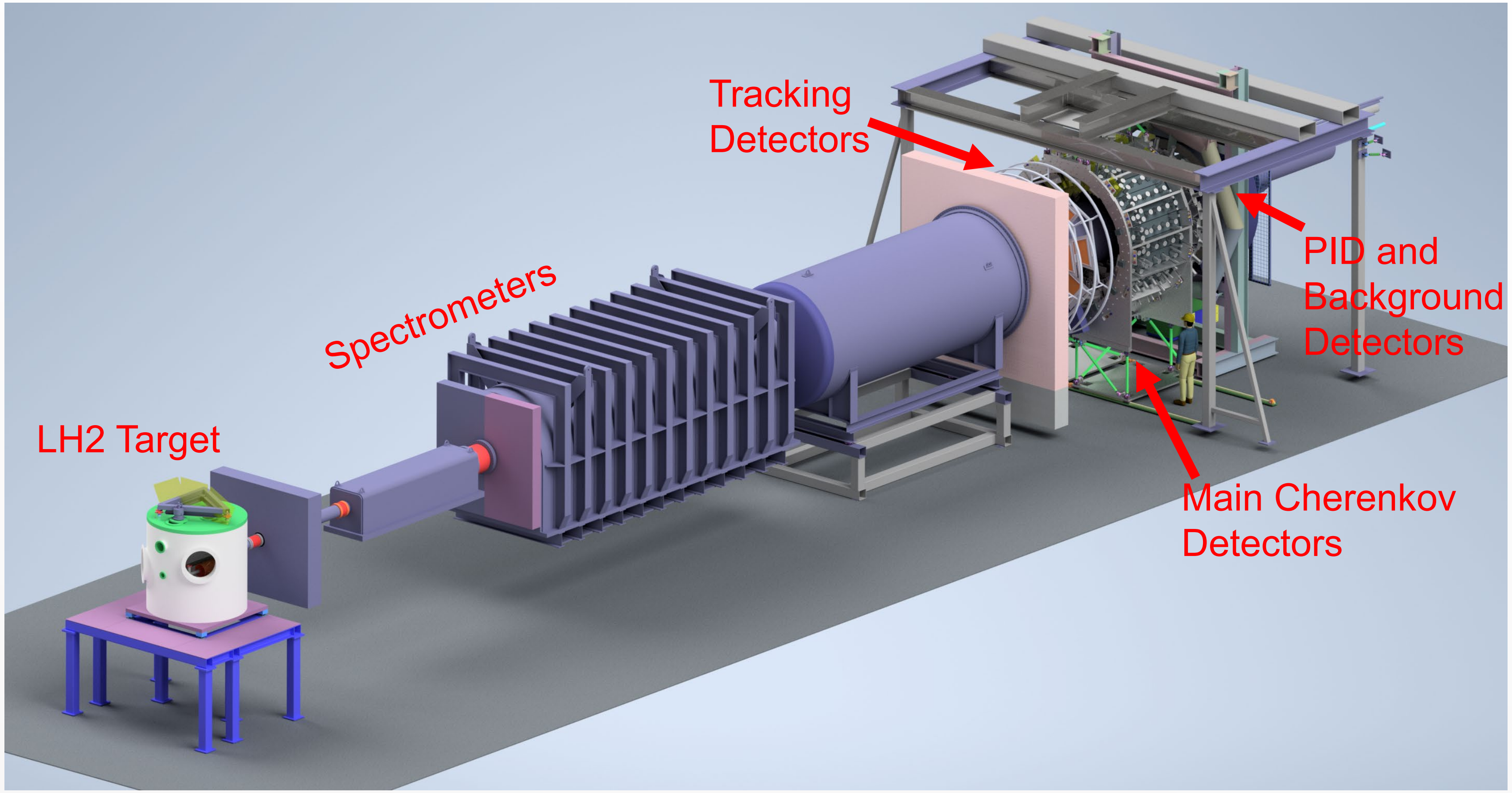
- Integration mode experiments require very good understanding of detector acceptance and correleations
- Interplay between experiment and simulation
- n3He exceedingly well understood target-detector geometry





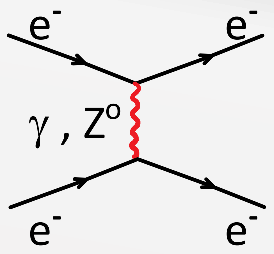
New PV measurements

The MOLLER experiment (Jefferson Lab)



Main Observable:
PV asymmetry with detectors
Weak Charge of the electron

$$A_{PV} = m_e E \frac{G_F}{\pi\alpha\sqrt{2}} \frac{4sin^2\theta}{(3+cos^2\theta)^2} Q_W^e$$



$E_{beam} = 11\ GeV$

$I_{beam} = 65\ \mu A$

$\mathcal{L} = 3 \times 10^{39}\ cm^{-2} \cdot s^{-1}$

$2.75 \leq E_{scat} \leq 8.25\ GeV$

$P_{beam} \geq 90 \pm 0.5\ \%$

$A_{PV} = 32\ ppb$

$\delta A_{PV} = 0.8\ ppb$

$Q_W^e = -(1 - 4sin^2\theta_W)$

$\Delta Q_W^e = 2.4\%$

$\Delta sin^2\theta_W = 0.1\%$

New PV measurements

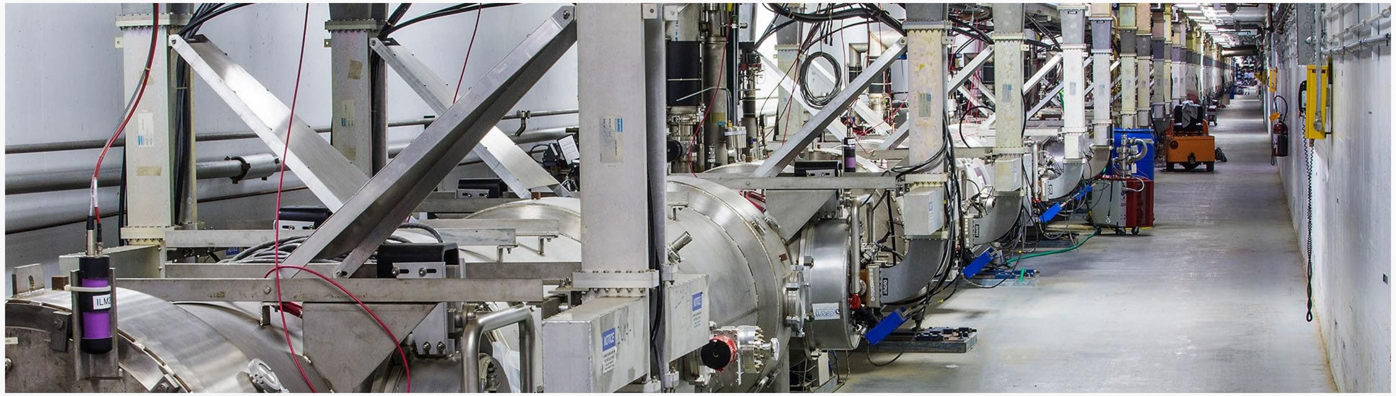
The MOLLER experiment (Jefferson Lab)

MOLLER will run at the Thomas Jefferson National Accelerator Facility, Virgina, USA making use of the high intensity high energy electron beam with the highest possible electron beam polarization.

The experiment will be located in hall A, the largest of the 4 halls.

Particular beam properties that are important include:

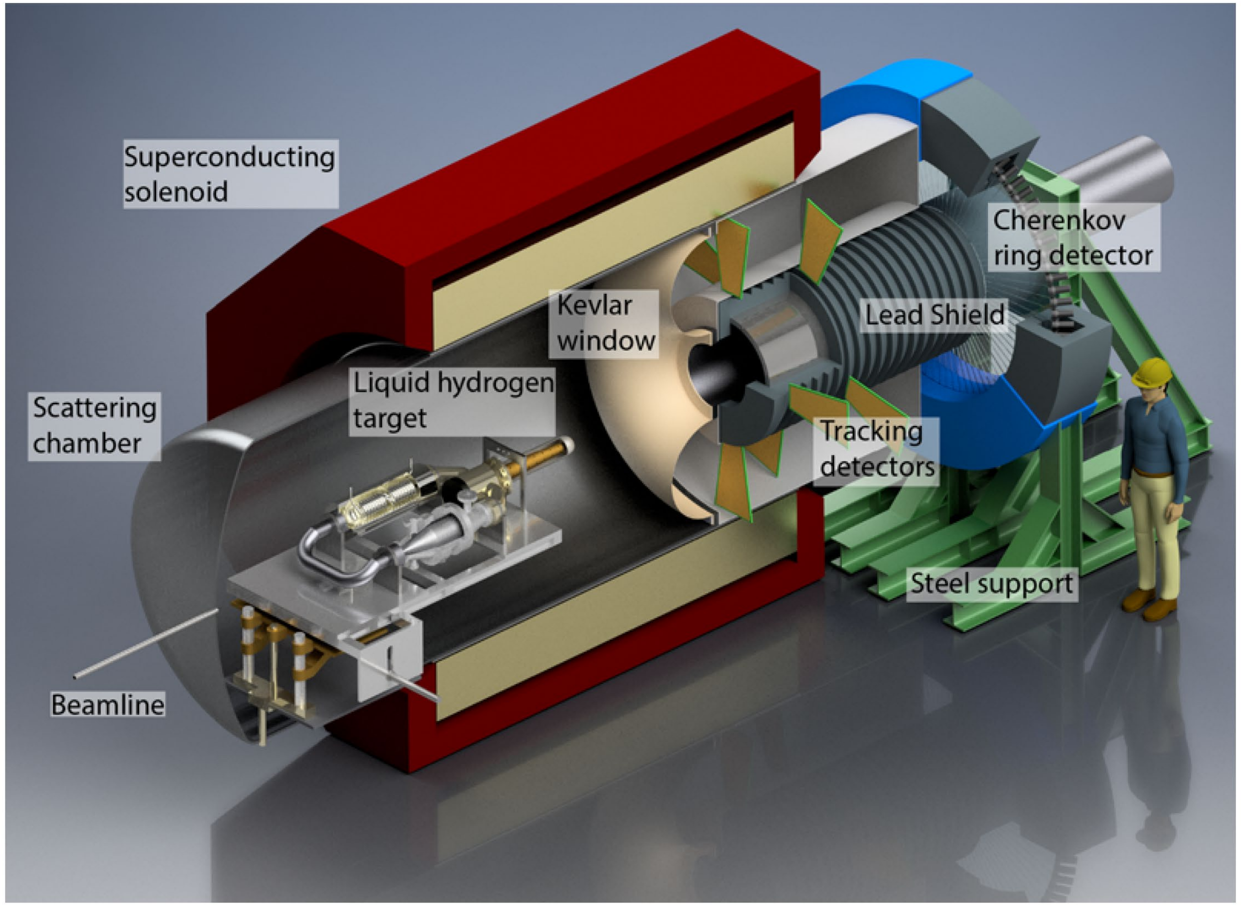
- High luminosity
- Parity quality beam: High polarization with high beam stability and systematic control
- High precision beam polarimetry measurements
- High power LH2 target



P2@MESA

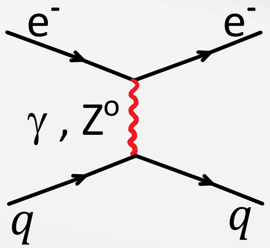
New PV measurements

The P2 Experiment (Mainz MESA Facility – See Talk by Frank Maas, Thursday)



Main Observable:
PV asymmetry with detectors
Weak Charge of the proton

$$A_{PV} = \frac{G_F Q^2}{4\sqrt{2}\ \pi\alpha}\left(Q_W^e - F(Q^2)\right)$$



$E_{beam} = 155\ MeV$

$I_{beam} = 150\ \mu A$

$\mathcal{L} = 2.4 \times 10^{39}\ cm^{-2} \cdot s^{-1}$

$P_{beam} \geq 80 \pm 0.4\ \%$

$A_{PV} = -40\ ppb$

$\delta A_{PV} = 0.6\ ppb$

$Q_W^p = (1 - 4sin^2\theta_W)$

$\Delta Q_W^p = 1.83\%$

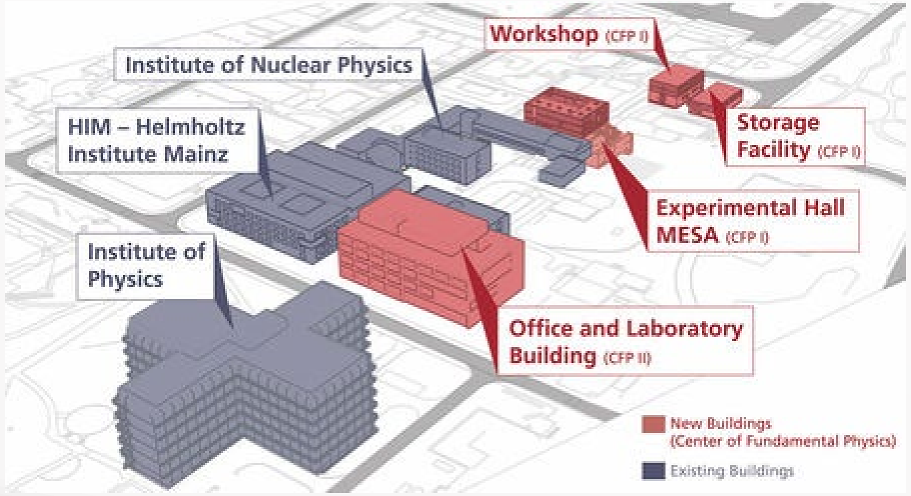
$\Delta sin^2\theta_W = 0.14\%$

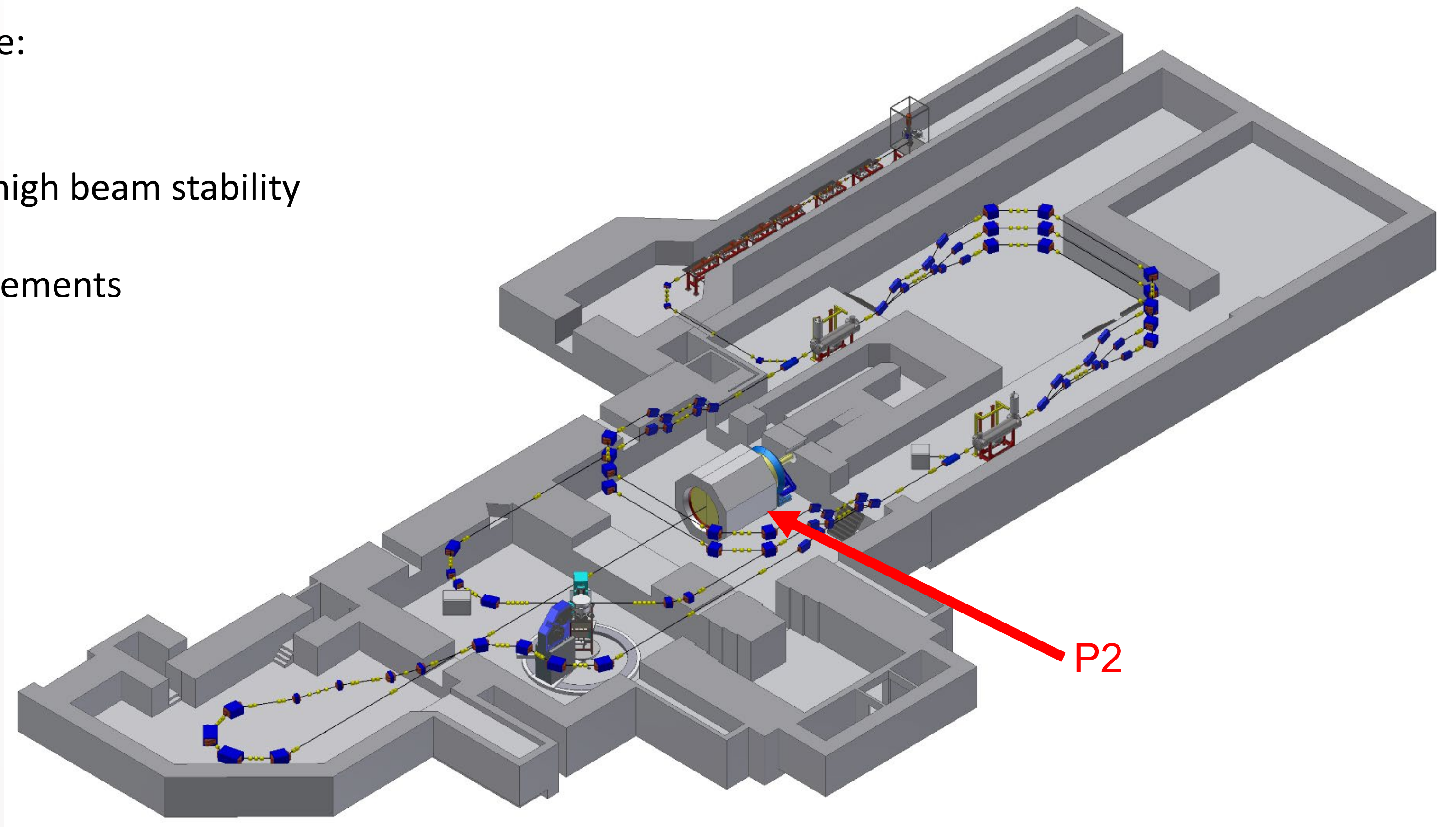
The P2 Experiment (Mainz MESA Facility – See Talk by Frank Maas, Thursday)

P2 will run at the New MESA Facility, Mainz, Germany
making use of the high intensity electron beam with the highest possible electron beam polarization.

Particular beam properties that are important include:

- High luminosity
- Parity quality beam: High polarization with high beam stability and systematic control
- Highest precision beam polarimetry measurements
- High power LH2 target





Thank you