SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL
FROM QUARKS AND GLUONS TO HADRONS AND NUCLEI

PRISMA

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

HPNC Opportunities at Mainz

Misha Gorshteyn - JGU Mainz

Workshop on Hadronic Parity Non-Conservation
KITP Santa Barbara, California, March 15-16 2018

OUTLINE

P2 @ MESA: low-energy PVES with unprecedented precision

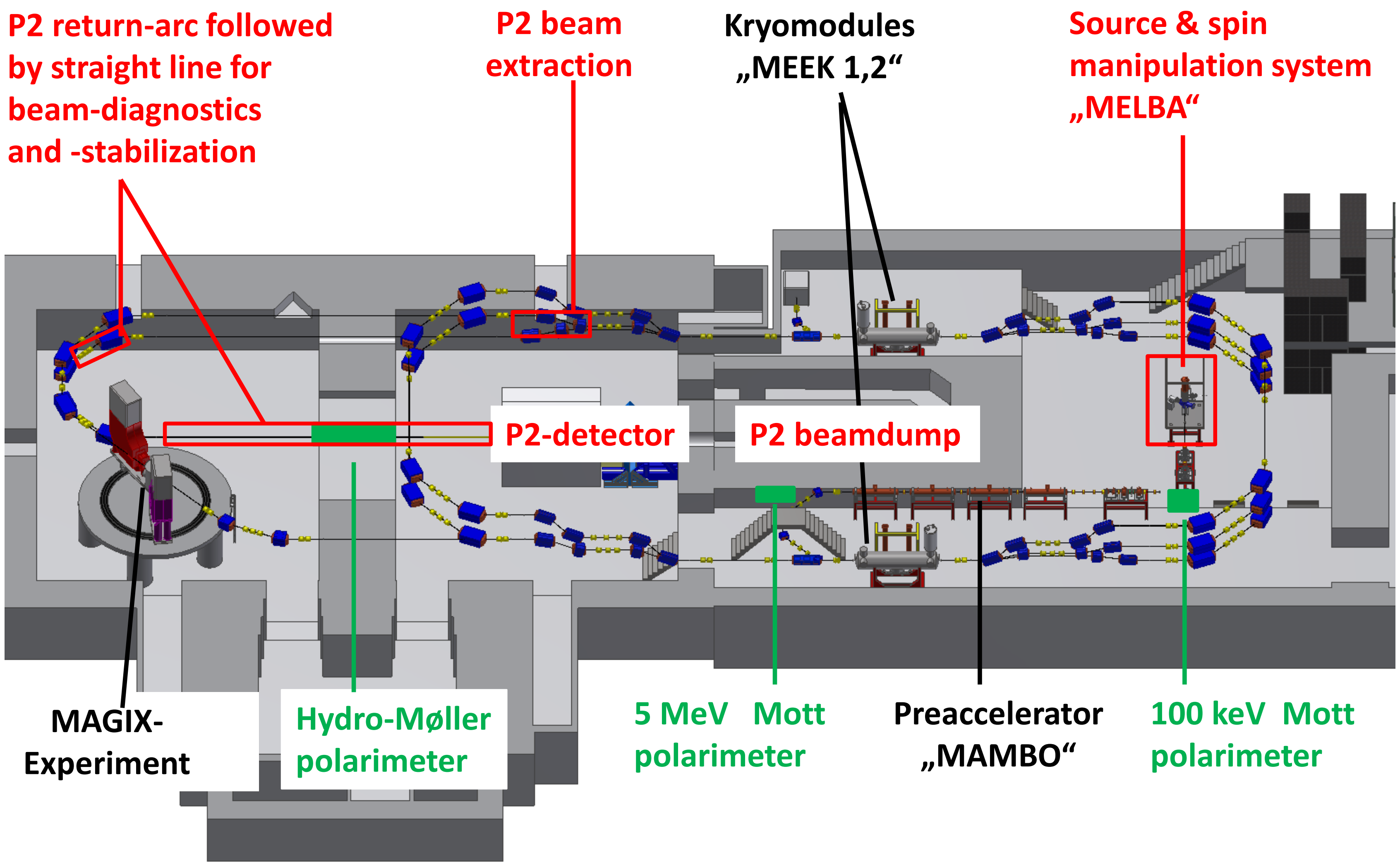
Threshold semi inclusive π^+ production with polarized e-beam

Long-range PV effects from HPNC

PNC in Yb and Dy isotopes

Summary & Outlook

MESA = Mainz Energy-recovering Superconducting Accelerator



(Mostly) fits in the existing facility
Construction of a new hall 2018
Commissioning 2019
Running 2020

Extracted beam mode (P2)

E = 155 MeV, I = 150 μA

Polarization > 85%

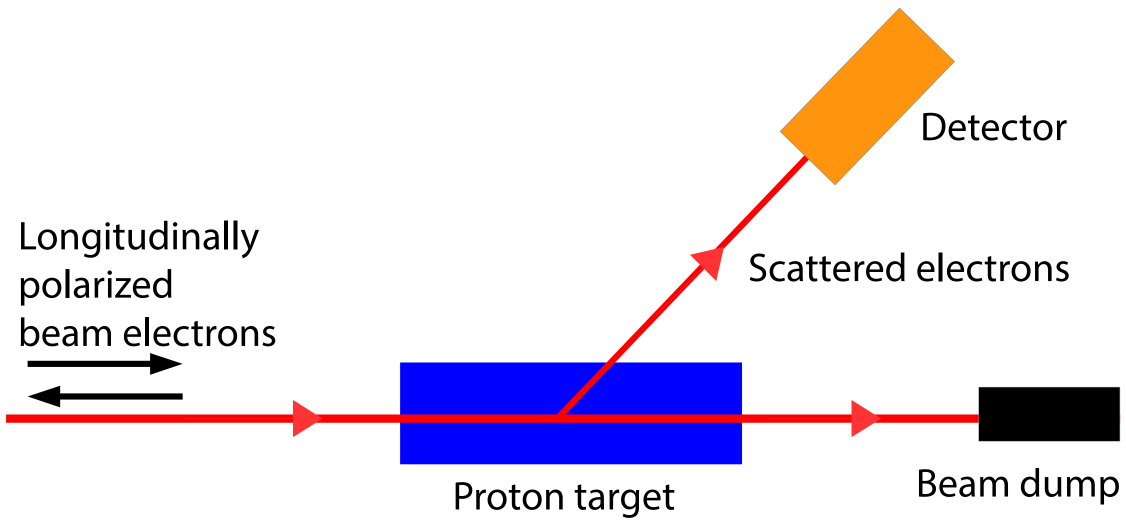
Energy-recovery mode (MAGIX)

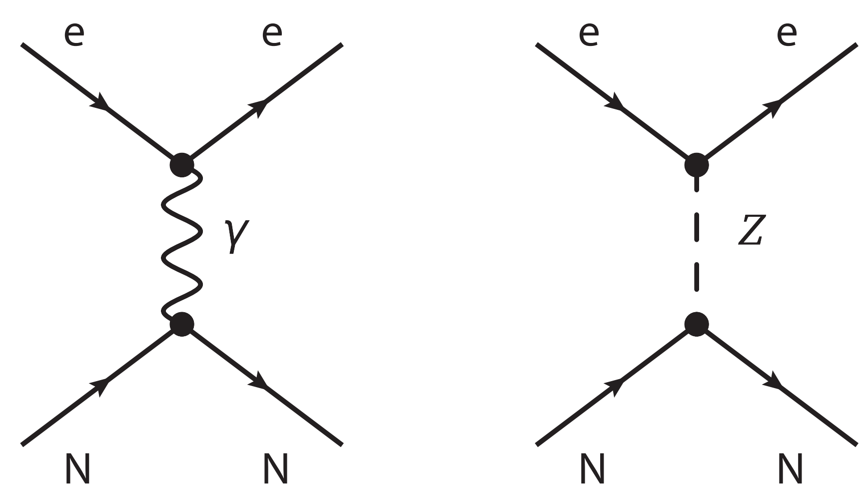
E = 105 MeV, I = 10 mA

MAGIX:
Dark photon search
DM beam dump exp.
Proton radii
Nuclear physics

P2:
Weak charge of the proton
Weak charge of C-12
Neutron skins

P2 Experiment





Parity-violating asymmetry at low Q^2

$$A^{\mathrm{PV}} = \frac{-G_{\mathrm{F}} Q^2}{4\pi\alpha_{\mathrm{em}}\sqrt{2}} \left[Q_{\mathrm{W}}(\mathrm{p}) - F(E_{\mathrm{i}}, Q^2)\right]$$

Proton's weak charge ~ WMA

$$Q_{\mathrm{W}}(\mathrm{p}) = 1 - 4\sin^2\theta_{\mathrm{W}}$$

Enhanced sensitivity to WMA

$$\frac{\Delta \sin^2\theta_{\mathrm{W}}}{\sin^2\theta_{\mathrm{W}}} = \frac{1-4\sin^2\theta_{\mathrm{W}}}{4\sin^2\theta_{\mathrm{W}}} \cdot \frac{\Delta Q_{\mathrm{W}}(\mathrm{p})}{Q_{\mathrm{W}}(\mathrm{p})} \approx 0.09 \cdot \frac{\Delta Q_{\mathrm{W}}(\mathrm{p})}{Q_{\mathrm{W}}(\mathrm{p})}$$

Correction term ~ known

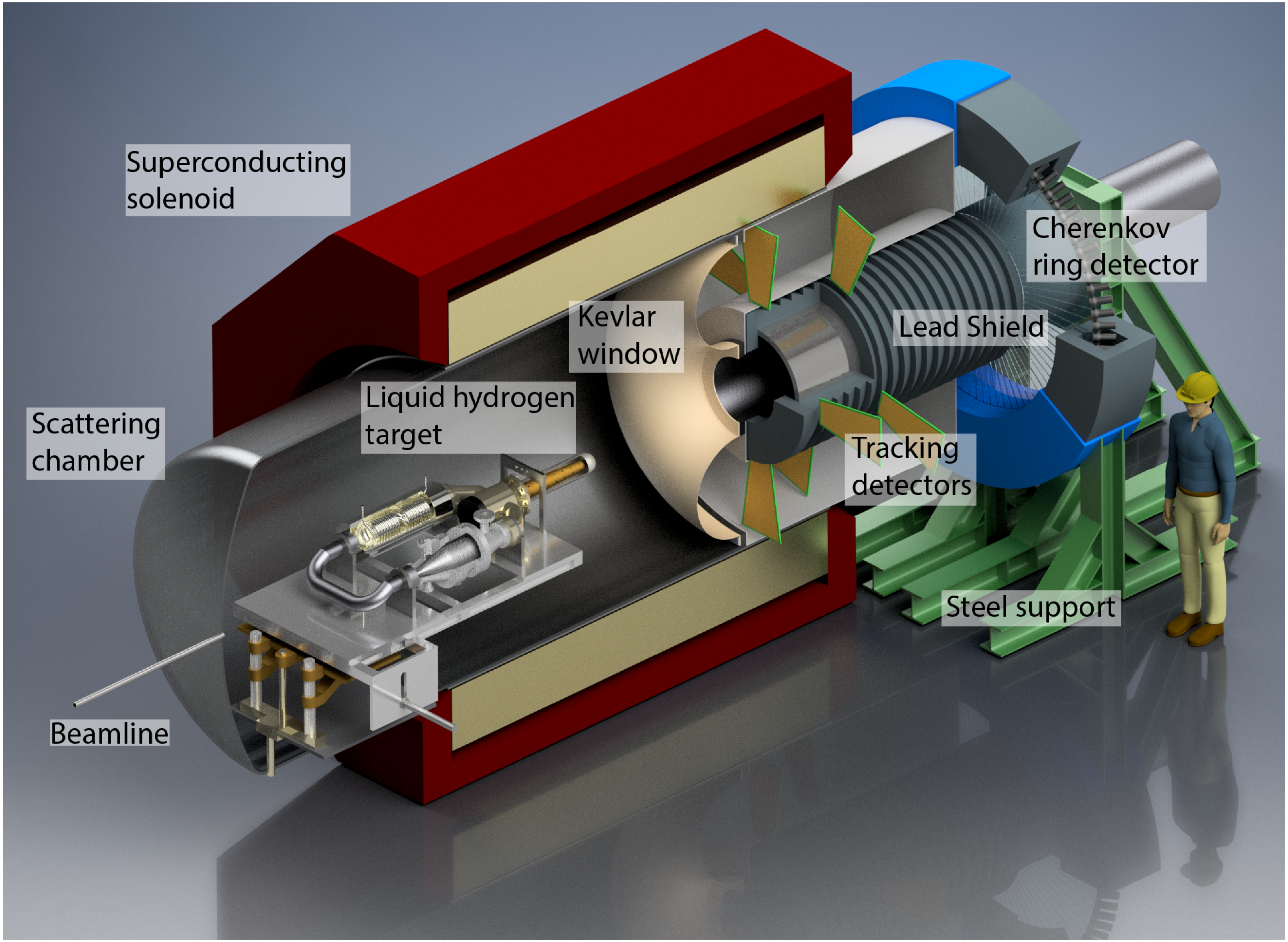
$$F(E_{\mathrm{i}}, Q^2) \equiv F^{\mathrm{EM}}(E_{\mathrm{i}}, Q^2) + F^{\mathrm{A}}(E_{\mathrm{i}}, Q^2) + F^{\mathrm{S}}(E_{\mathrm{i}}, Q^2)$$

C-12 weak charge ~ WMA

$$Q_{\mathrm{W}}(^{12}\mathrm{C}) = -24\sin^2\theta_W$$

No gain in precision but much easier to measure experimentally

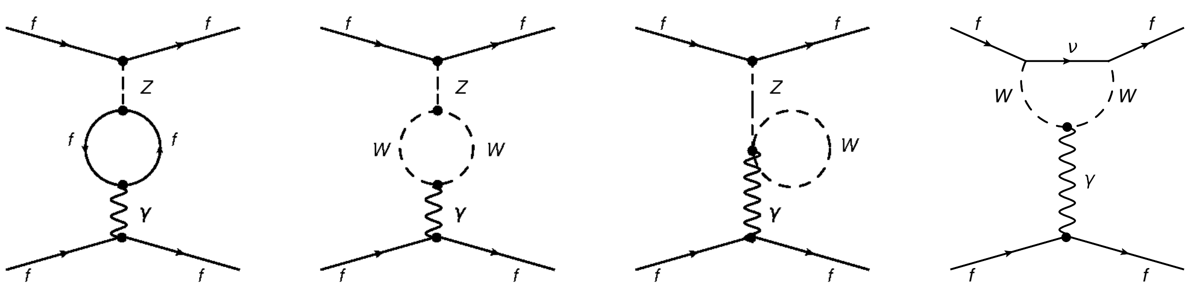
P2 Setup

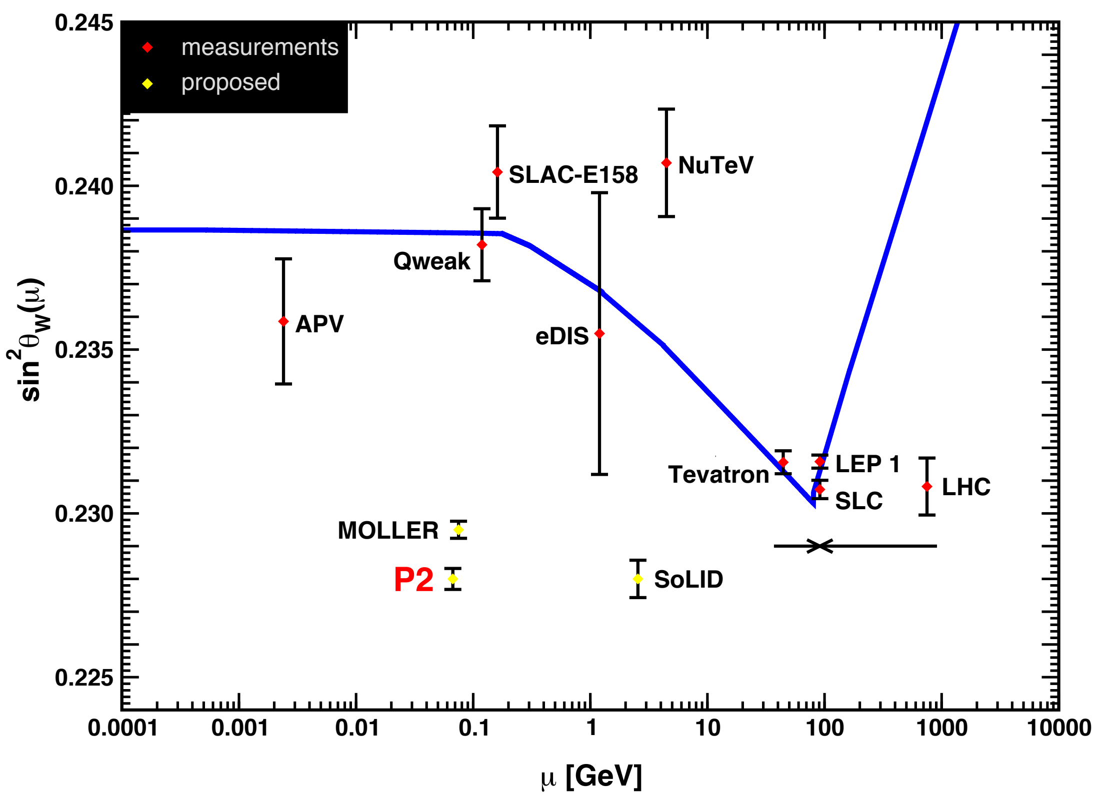


Superconducting solenoid
Cherenkov ring detector
Kevlar window
Lead Shield
Liquid hydrogen target
Scattering chamber
Tracking detectors
Steel support
Beamline

P2 Impact

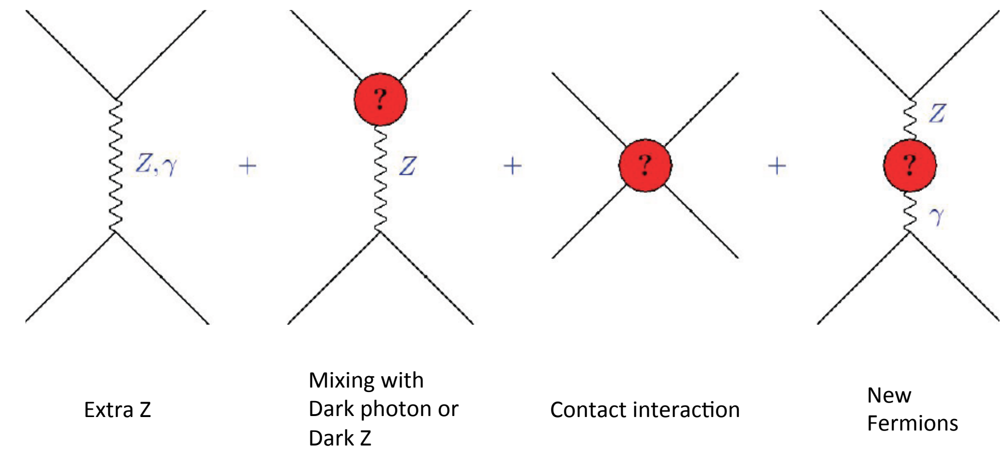
1-loop radiative corrections: running WMA

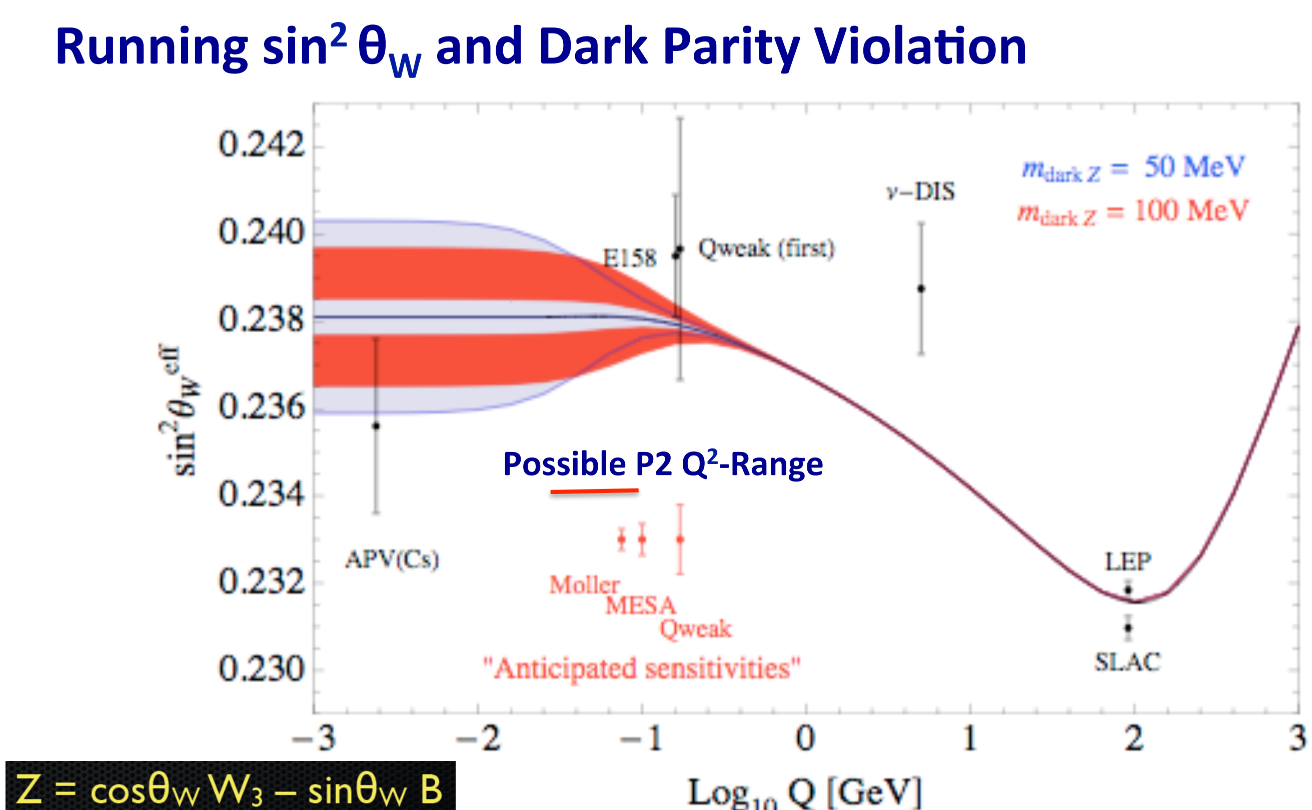




Competitive and complementary
to Z-pole measurements

Sensitive test of SM and beyond





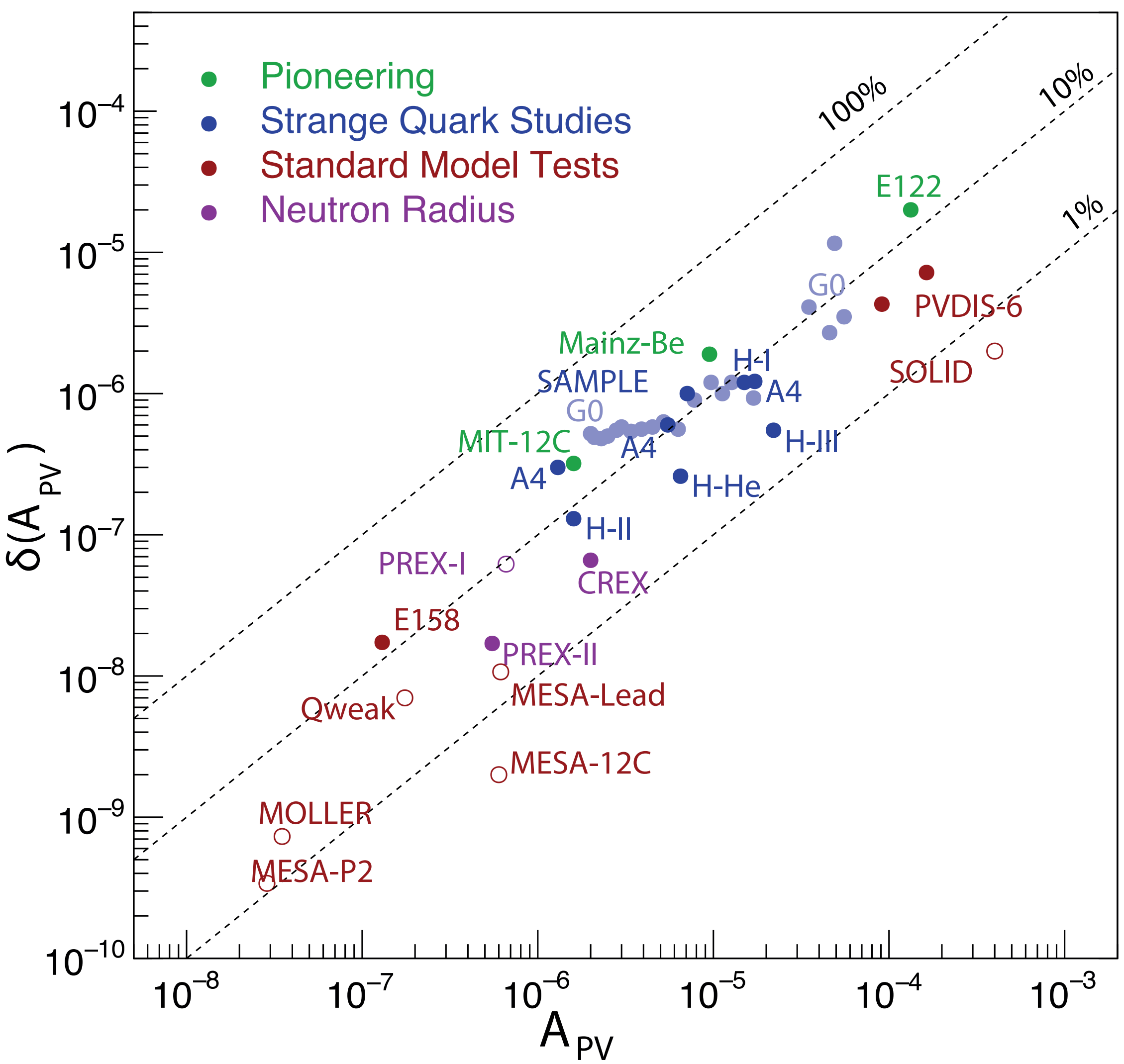
$Z = \cos\theta_W W_3 - \sin\theta_W B$

$A = \sin\theta_W W_3 + \cos\theta_W B$

Bill Marciano

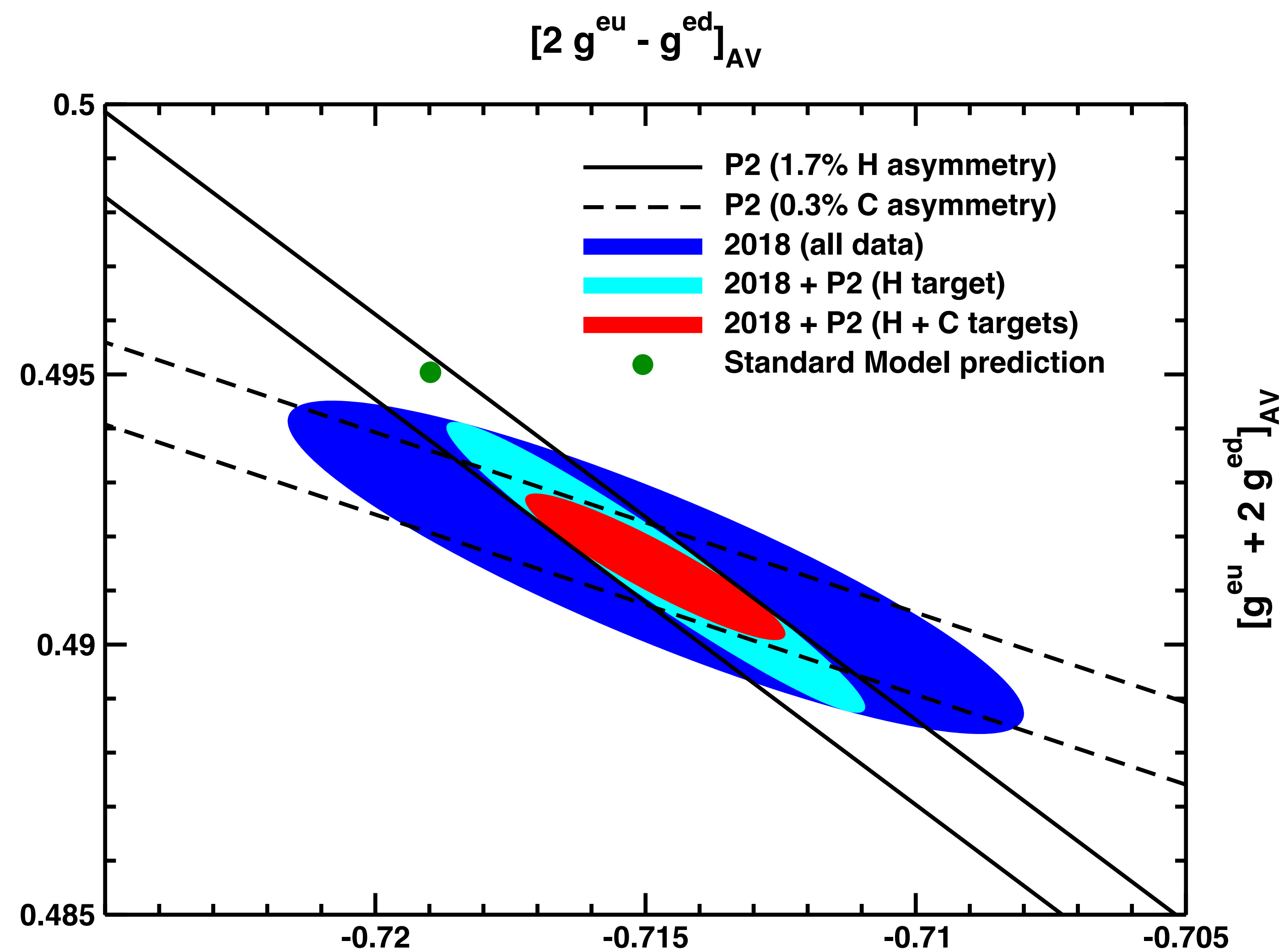
PVES @ MESA: Impact

Experimental "hardness"



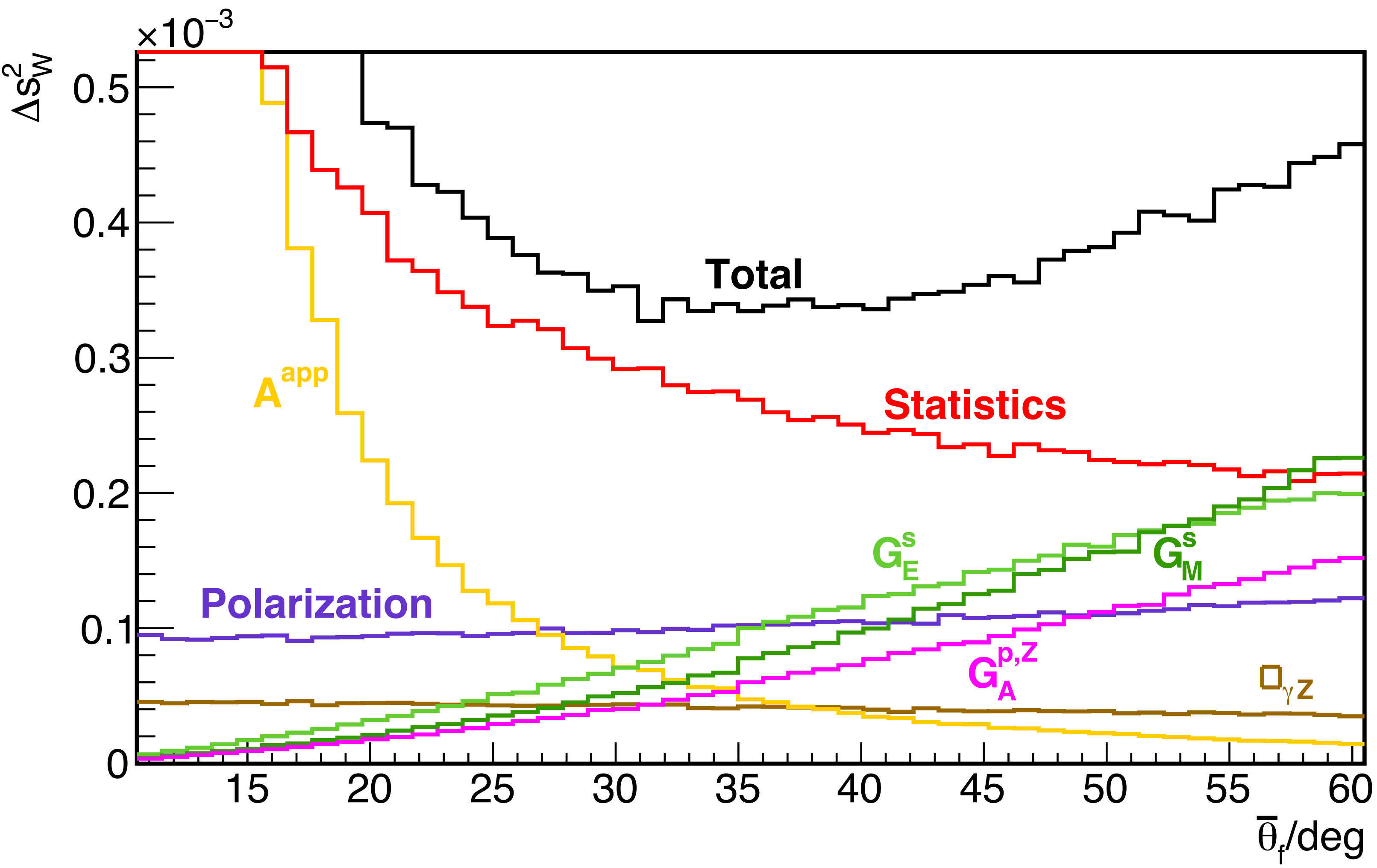
Effective four-fermion operators

$$\mathcal{L} = -\frac{G_F}{\sqrt{2}} \sum_q [g_{AV}^{eq} \bar{e}\gamma^\mu\gamma_5 e\, \bar{q}\gamma_\mu q + g_{VA}^{eq} \bar{e}\gamma^\mu e\, \bar{q}\gamma_\mu\gamma_5 q]$$



10000 hours of data taking

P2 Error Budget

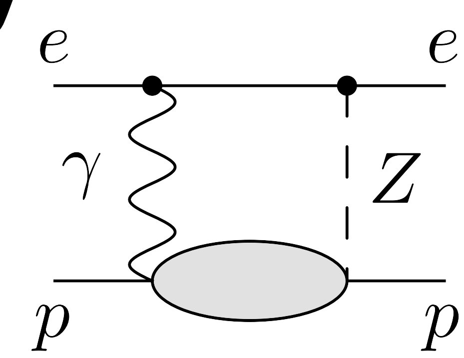


E_{beam}	$155\,\text{MeV}$
$\bar{\theta}_{\text{f}}$	$35°$
$\delta\theta_{\text{f}}$	$20°$
$\langle Q^2 \rangle_{L=600\,\text{mm},\ \delta\theta_{\text{f}}=20°}$	$6 \times 10^{-3}\ (\text{GeV/c})^2$
$\langle A^{\text{exp}} \rangle$	$-39.94\,\text{ppb}$
$(\Delta A^{\text{exp}})_{\text{Total}}$	$0.56\,\text{ppb}\ (1.40\,\%)$
$(\Delta A^{\text{exp}})_{\text{Statistics}}$	$0.51\,\text{ppb}\ (1.28\,\%)$
$(\Delta A^{\text{exp}})_{\text{Polarization}}$	$0.21\,\text{ppb}\ (0.53\,\%)$
$(\Delta A^{\text{exp}})_{\text{Apparative}}$	$0.10\,\text{ppb}\ (0.25\,\%)$
$\langle s^2_{\text{W}} \rangle$	$0.231\,16$
$(\Delta s^2_{\text{W}})_{\text{Total}}$	$3.3 \times 10^{-4}\ (0.14\,\%)$
$(\Delta s^2_{\text{W}})_{\text{Statistics}}$	$2.7 \times 10^{-4}\ (0.12\,\%)$
$(\Delta s^2_{\text{W}})_{\text{Polarization}}$	$1.0 \times 10^{-4}\ (0.04\,\%)$
$(\Delta s^2_{\text{W}})_{\text{Apparative}}$	$0.5 \times 10^{-4}\ (0.02\,\%)$
$(\Delta s^2_{\text{W}})_{\Box_{\gamma Z}}$	$0.4 \times 10^{-4}\ (0.02\,\%)$
$(\Delta s^2_{\text{W}})_{\text{nucl. FF}}$	$1.2 \times 10^{-4}\ (0.05\,\%)$
$\langle Q^2 \rangle_{\text{Cherenkov}}$	$4.57 \times 10^{-3}\ (\text{GeV/c})^2$
$\langle A^{\text{exp}} \rangle_{\text{Cherenkov}}$	$-28.77\,\text{ppb}$

Statistics based on 10 000 hours data
MESA - heavy duty machine - > 4000 h/year

P2 Error Budget - Theory

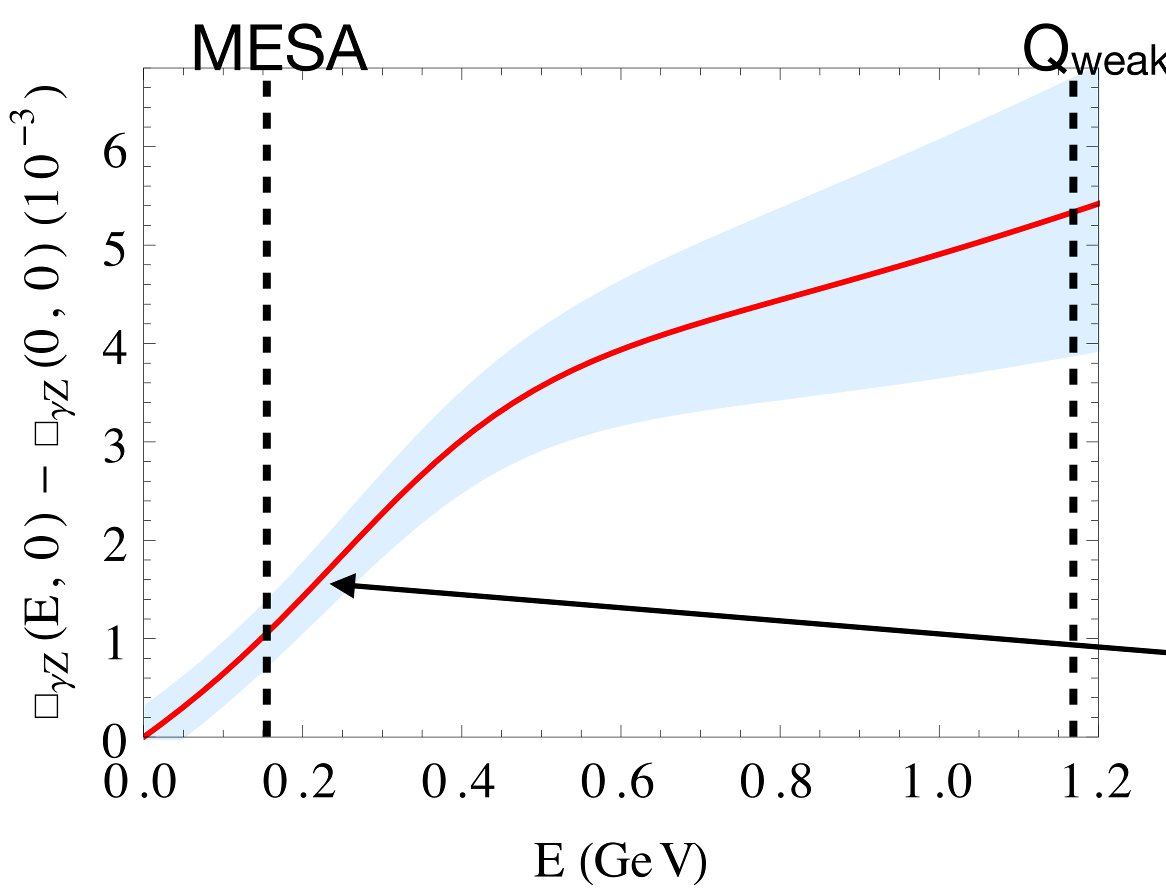
To match exp. precision: full set of 1-loop RC
Universal corrections —> running
A few non-universal corrections (boxes)
γZ-box special: γ sensitive to long-range part of interaction, strong energy dependence

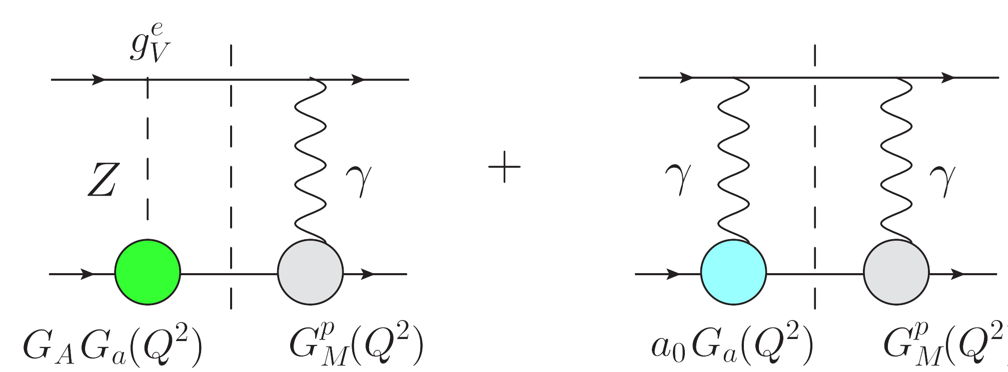


MG, Horowitz 2009

Energy dependence of the γZ-box under control for P2
Advantage w.r.t. Q_{weak} - strong motivation for P2

MG, Horowitz, MJRM 2011
MG, Spiesberger, Zhang 2016
MG, Spiesberger 2016





At low energy uncertainty dominated by the proton's anapole moment

for C-12 - need a reliable estimate of γZ-box including nuclear structure
- work in progress with Jens Erler and H. Spiesberger

P2 Error Budget - Theory

$$A^{\rm PV} = \frac{-G_{\rm F}Q^2}{4\pi\alpha_{\rm em}\sqrt{2}}\left[Q_{\rm W}({\rm p}) - F(E_{\rm i},Q^2)\right]$$

$$F(E_{\rm i},Q^2) \equiv F^{\rm EM}(E_{\rm i},Q^2) + F^{\rm A}(E_{\rm i},Q^2) + F^{\rm S}(E_{\rm i},Q^2)$$

Strangeness contribution - suppressed by $Q^2 \sim 0.006$ GeV^2;
SFF known from experiment (global fit to all PVES data)
Recent lattice QCD evaluations - small

Green et al. (LHPC) 2015;
Sufian et al (χQCD) 2017;
Alexandrou et al. (ETMC) 2018

Contribution of the proton's axial FF - non-negligible in P2 kinematics!
Electron's weak charge is small, but $[1-\epsilon^2]^{1/2}$ is large (compare to $Q_{\rm weak}$)

$$F^{\rm A}(Q^2) \equiv \frac{\left(1-4\sin^2\theta_{\rm W}\right)\sqrt{1-\epsilon^2}\sqrt{\tau(1-\tau)}G_{\rm M}^{\rm p,\gamma}G_{\rm A}^{\rm p,Z}}{\epsilon(G_{\rm E}^{\rm p,\gamma})^2 + \tau(G_{\rm M}^{\rm p,\gamma})^2}$$

Large uncertainty due to proton's anapole moment

$$G_A^{ep}(Q^2) \;=\; G_a(Q^2)\left[G_A(1+R_A^{T=1}) + \frac{3F-D}{2}R_A^{T=0} + \Delta s(1+R_A^{(0)})\right]$$

$$G_A^{ep} = -1.04 \pm 0.44$$

Zhu, Puglia, Holstein, Ramsey-Musolf 2001

Global fit to PVES data - similar uncertainty

$$G_A^{ep} = -0.62 \pm 0.41$$

Gonzalez-Jimenez, Caballero, Donnelly 2014

Anapole moment @ MESA

Backward measurement - a must to better constrain the axial form factor

Two options:
a parallel measurement - then 10 000 hours of data
or two dedicated measurement - à 1000 on H and D targets

P2 backward-angle experiment	
Integrated luminosity	$8.7 \cdot 10^7 \mathrm{fb}^{-1}$
Statistical uncertainty	$\Delta A_{\mathrm{stat}} = 0.03$ ppm
False asymmetries	$\Delta A_{\mathrm{HC}} < 0.01$ ppm
Polarimetry	$\Delta A_{\mathrm{pol}} = 0.04$ ppm
Total uncertainty	$\Delta A_{\mathrm{tot}} = 0.05$ ppm

Table 16. Performance of a possible P2 backward-angle measurement parallel to the P2 forward experiment. The beam energy used for this calculation is 200 MeV, the Standard Model expectation for the asymmetry is $A^{\mathrm{PV}} \approx 7.5$ ppm.

Backward measurement will address $F^{\mathrm{S}} + F^{\mathrm{A}} = 0.398 \cdot \left(G_{\mathrm{M}}^{s} + 0.442 G_{\mathrm{A}}^{\mathrm{p},Z}\right) \pm 0.011$

Forward measurement depends on $F^{\mathrm{S}} + F^{\mathrm{A}} = 0.0040 \cdot (G_{\mathrm{M}}^{s} + 0.691 G_{\mathrm{A}}^{\mathrm{p},Z})$

Uncertainty without backward measurement: $\Delta(F^{\mathrm{S}} + F^{\mathrm{A}}) = 0.00076$

$Q_W^p = 1 - 4\sin^2\theta_W \approx 0.07$

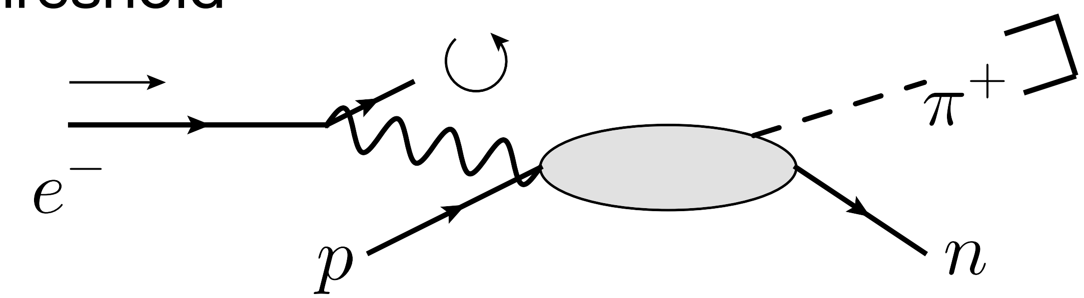
Uncertainty with backward measurement: $\Delta(F^{\mathrm{S}} + F^{\mathrm{A}}) = 0.00016$

HPNC @ MESA

At present: planned energy 155 MeV - just below the pion production threshold

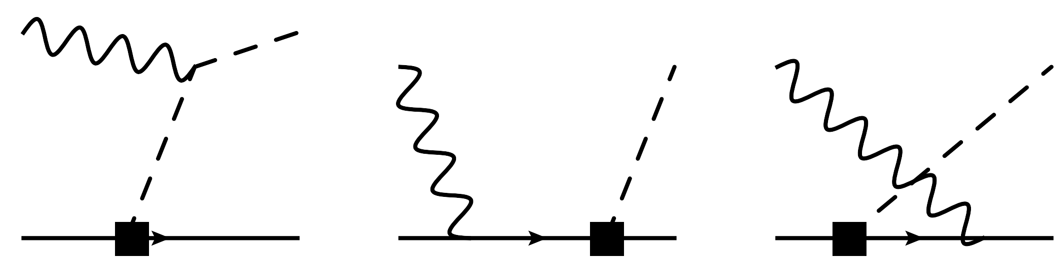
There may be a possibility to upgrade to ~ 200 MeV

Would permit to access PV pion production near threshold



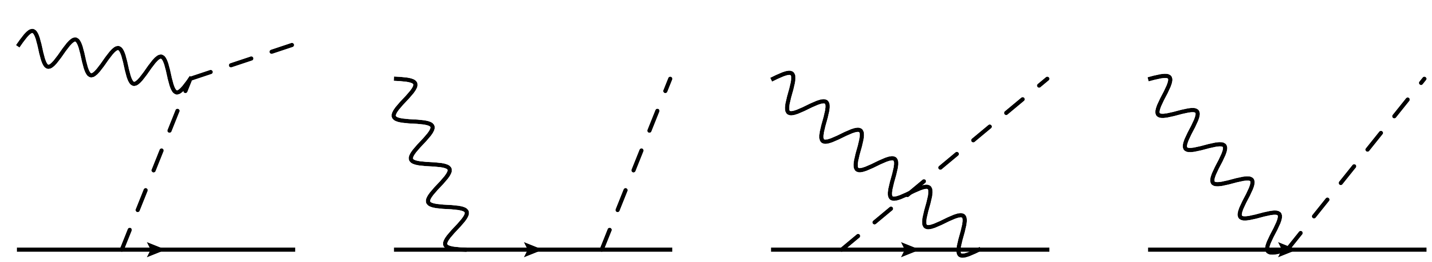
Idea from *Chen, Ji 2001*:
detect only charged pion in the final state
Weizsäcker-Williams approximation —>
quasi-real photon carries all the beam momentum and polarization

PV amplitude ~ h^1_π



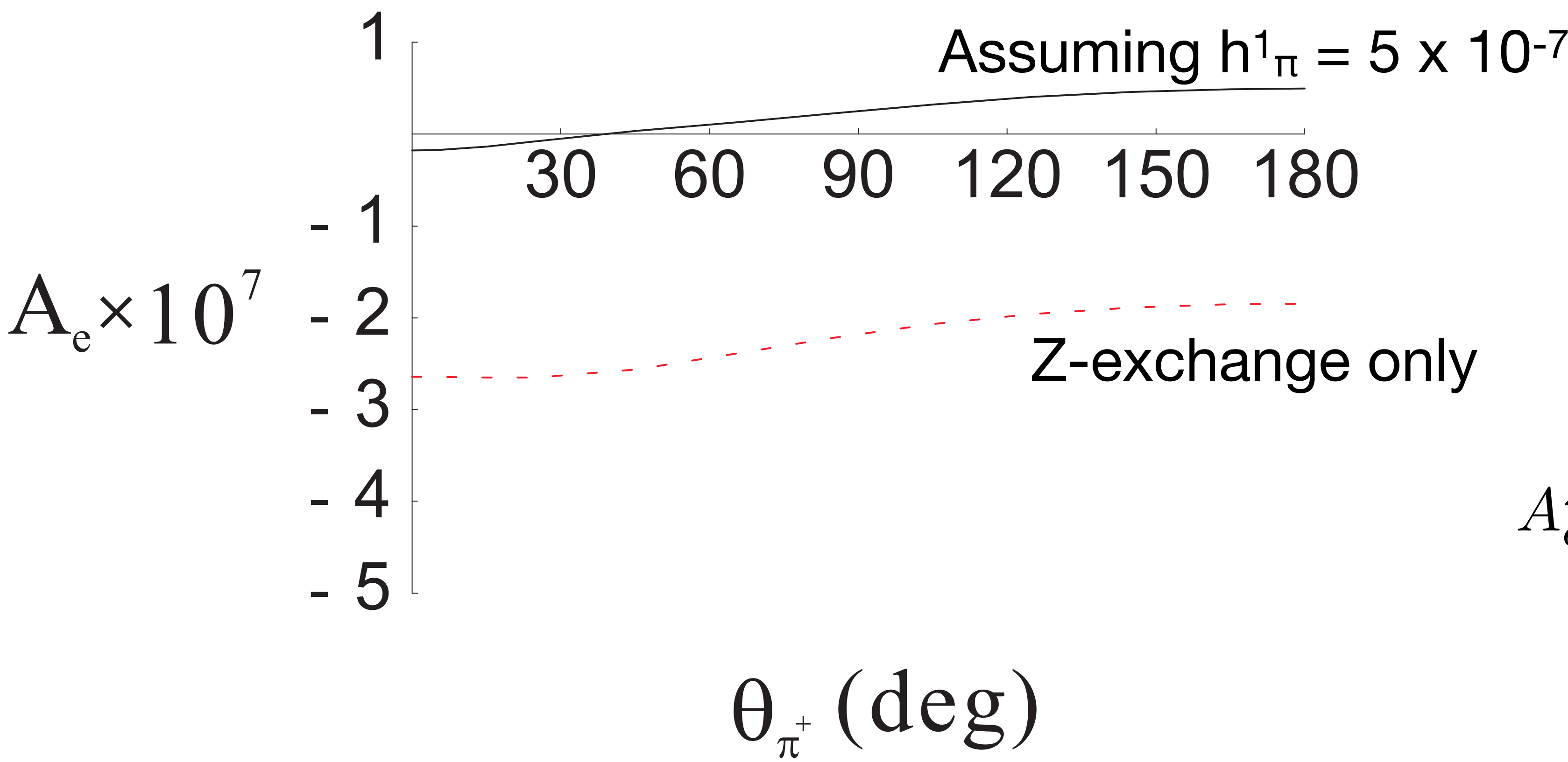
interferes with

PC amplitude ~ $g_{\pi NN}$



HPNC @ MESA

Chen, Ji 2001



$$A_e^{h^1_\pi} \approx \frac{\sqrt{2}(\mu_p - \mu_n)}{g_{\pi NN}} h^1_\pi \approx 0.5 h^1_\pi$$

$$A_e^Z \approx -2\sqrt{2}(1 - 2\sin^2\theta_W)\frac{G_F\langle Q^2\rangle}{4\pi\alpha}$$

h^1_π contribution partially cancels Z-exchange;
harder to measure but a good measurement has high potential impact

Asymmetry ~ 5-6 times larger than in elastic P2 experiment (-4×10^{-8} to 1.5%)
Cross section is large - may be doable
Precision? Hard to say - 25%? 10%? - need a dedicated feasibility studies

HPNC @ MESA

BUT:

P2 forward detector cannot detect charged pions (Cherenkov, magnetic field, distance)

P2 backward detector cannot detect charged pions + need higher energy to produce pions at backward angles

Need a pion spectrometer - one exists in A1 @ Mainz - can it be used?

Cannot be done as a parasitic measurement to P2
- but still may be possible if a strong case can be made - the message to this workshop

Theory reservations: analyzing power would lead to a false asymmetry that is potentially large

The beam polarization is not 100% longitudinal

Azimuthal-modulated asymmetry $\vec{S}_e \cdot [\vec{k} \times \vec{q}_\pi] \sim \sin\phi$

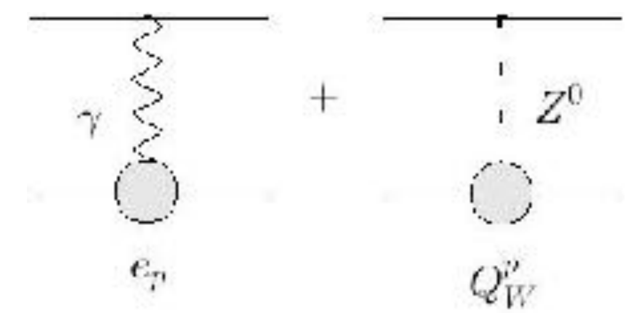
$$A^\perp \sim \frac{m_e}{E}\delta P_\perp \frac{\mathrm{Im}T_{\gamma p\to\pi^+ n}}{|T_{\gamma p\to\pi^+ n}|}$$

~ 10^{-3} x 1% x (q_π/M ~ 5-10 x 10^{-3}) —> 10^{-7}

One will need a dedicated measurement of a.p.
2π azimuthal coverage of the detector

Side note: long-range PV forces from HPNC

$$T^{ep}_{1\gamma+Z} = \frac{1}{Q^2} + \{R^2_{Ch.},\, \mu^p, \ldots\} - \frac{G_F}{4\sqrt{2}\pi\alpha}(Q^p_W + Q^2\{R^2_W,\, \mu^p_W, \ldots\})$$



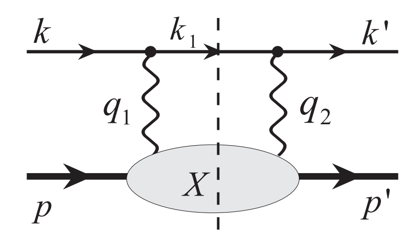
Radiative corrections (mostly 2γ-exchange) induce an intermediate range term

$$T^{ep}_{1\gamma+2\gamma} \to \frac{1}{Q^2} + \frac{\alpha}{\pi} C_{2\gamma}(E)\ln(Q^2/E^2) + \{R^2_{Ch.},\, \mu^p, \ldots\}$$

Calculate $C_{2\gamma}(E)$ from a near-forward dispersion relation - a sum rule
Large collinear log - from the WW approximation inside the loop

Gorchtein 2014

$$2\mathrm{Im}T_{2\gamma} \;=\; e^4 \int \frac{d^3\vec{k}_1}{(2\pi)^3 2E_1} \frac{\ell_{\mu\nu}\cdot \mathrm{Im}W^{\mu\nu}}{(q_1^2+i\epsilon)(q_2^2+i\epsilon)}$$



Importantly: $C_{2\gamma}(E=0) = 0$ (due to symmetries)
Leads to a formal redefinition of the charge radius in terms of observables

$$R^2_{Ch} \sim \left[T^{exp} - \frac{1}{Q^2}\right]_{Q^2\to 0} \longrightarrow R^2_{Ch} \sim \left[T^{exp} - \frac{1}{Q^2}\right]_{E\to 0,\, Q^2\to 0}$$

Do these effects matter in practice? - Depends on precision you want to achieve for R_{Ch}

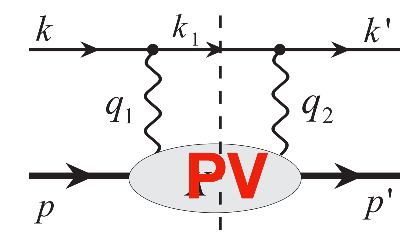
Side note: long-range PV forces from HPNC

Consider 2γ-exchange in presence of PNC in the hadronic system

$$T^{ep}_{Z+PV2\gamma} = -\frac{G_F}{4\sqrt{2}\pi\alpha}\left[Q_W^p + \frac{8\sqrt{2}\alpha^2}{G_F}C^{PV}_{2\gamma}(E)\ln(Q^2/E^2)\right]$$

$C^{PV}_{2\gamma}(E)$ from a near-forward dispersion relation

$$2\mathrm{Im}T^{PV}_{2\gamma} = e^4\int\frac{d^3\vec{k}_1}{(2\pi)^3 2E_1}\frac{\ell_{\mu\nu}\mathrm{Im}W^{\mu\nu}_{PV}}{(q_1^2+i\epsilon)(q_2^2+i\epsilon)}$$



Forward PV Compton tensor $\mathrm{Im}W^{\mu\nu}_{PV} \sim \epsilon^{\mu\nu\alpha\beta}P_\alpha q_\beta \frac{F_3^{2\gamma}}{2(Pq)}$

$$C^{PV}_{2\gamma}(E) = \frac{1}{M}\int\frac{d\omega}{\omega^2}F_3^{2\gamma}(\omega)\left[\frac{\omega}{2E}\ln\left|\frac{E+\omega}{E-\omega}\right| + \frac{\omega^2}{4E^2}\ln\left|1-\frac{E^2}{\omega^2}\right|\right]$$

Vanishing of $C^{PV}_{2\gamma}(0)$ is non-trivially protected by an exact sum rule

$$C^{PV}_{2\gamma}(0) \sim \int\frac{d\omega}{\omega^2}F_3^{2\gamma}(\omega) = 0$$

Lukaszuk 2002; Kurek, Lukaszuk, 2004

The sum rule proven for the first time in relativistic ChPT

MG, Spiesberger 2016

Side note: long-range PV forces from HPNC

Presence of HPNC leads to a redefinition of the weak charge

$$Q_W = -\frac{4\sqrt{2}\pi\alpha}{G_F Q^2} A^{exp}\Big|_{Q^2\to 0} \longrightarrow Q_W = -\frac{4\sqrt{2}\pi\alpha}{G_F Q^2} A^{exp}\Big|_{E\to 0,\, Q^2\to 0}$$

What is the impact for current experiments?

A model estimate of $C^{PV}_{2\gamma}(E)$ for P2, Qweak kinematics (h^1_π, d_Δ + SR constraint):

small at current precision level - but may become significant if pushing beyond 10^{-4}

Why is the correction small? - only natural hadronic scales present

Potentially larger effects for nuclei (much lower scales - nuclear PV polarizabilities)

An effect for C-12 @ MESA (0.3% measurement) - will HPNC interfere?

PNC in Yb, Dy atoms - group of Dima Budker

Why PV with Yb?

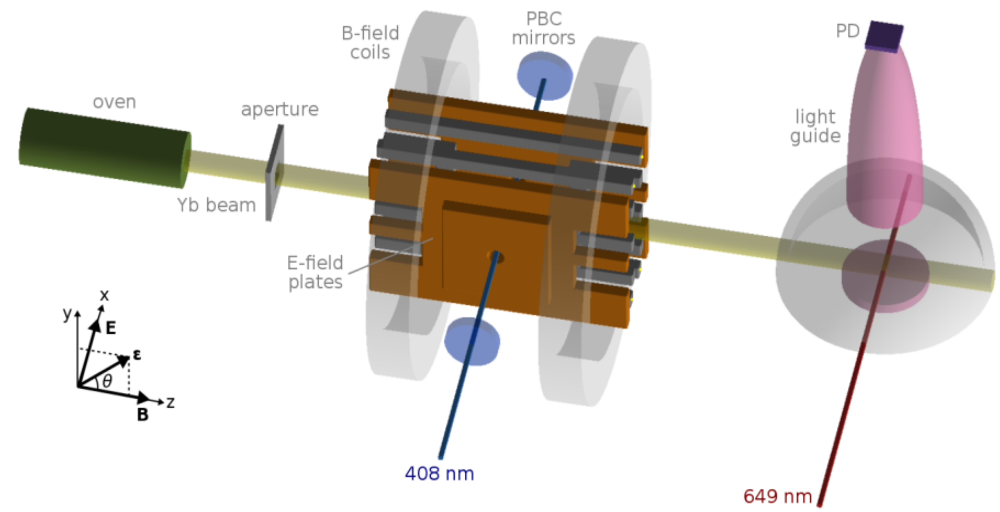
- Largest PV-effect observed in any atom
- Seven stable isotopes including two with nuclear spin

Goals (Milestones)

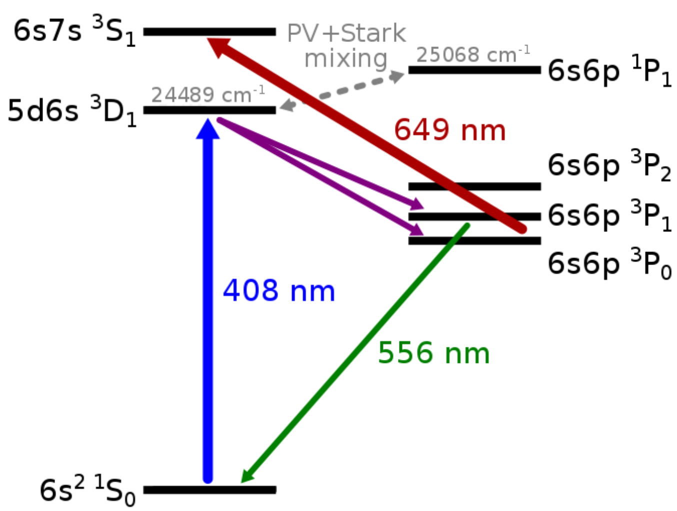
1. Verify dependence of Qw on neutron number
2. Measure the Yb anapole moment
3. Probe neutron skins of Yb nucleus

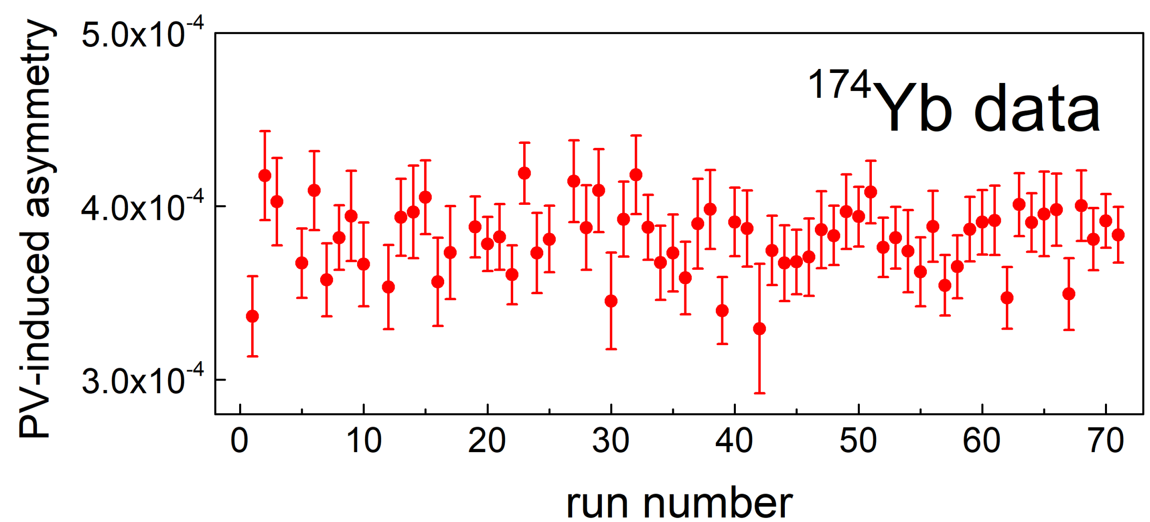
Method

Optically excite the $^1S_0 \rightarrow {}^3D_1$ transition in a region of crossed E- and B-fields, that define handedness. Field reversals flip handedness resulting in a left-right asymmetry in the excitation rate.



Rotational Invariant: $\left(\vec{\varepsilon}\cdot\vec{B}\right)\left(\vec{E}\times\vec{\varepsilon}\cdot\vec{B}\right)$





Current status

Finishing up Qw comparison between ^{176}Yb, ^{174}Yb, ^{172}Yb, ^{170}Yb.
Then moving on to anapole.
Currently achieving 3% accuracy in 1 hr.
Need 0.5% for anapole, neutron skins.

Yb roadmap

1. Measure Qw dependence on neutron number (almost completed)
2. Probe spin-dependent PV (anapole)
3. Precisely measure isotopic dependence to observe neutron skin effects

References

1 . K. Tsigutkin, D. Dounas-Frazer, A. Family, J. E. Stalnaker, V. V. Yashchuk, and D. Budker, Phys. Rev. Lett. 103, 071601 (2009).
2. D. Antypas, A. Fabricant, L. Bougas, K. Tsigutkin, and D. Budker, Hyperfine Interact. 238, 21 (2017).

Slide - courtesy of Dionysios Antipas

Conclusions & Outlook

Strong PV program in Mainz that can have impact on HPNC:

PVES - proton's anapole moment, PV π^+ threshold production

- backward measurement will reduce a.m. error by factor 4
- PV π^+ production: potentially a clean way to access h^1_π;
- dedicated study of possible setup and systematics needed

HPNC induces energy-dependent, long-range PV forces
- potentially important

Atomic PNC - weak charges, anapole moments, neutron skins;

UCN facility TRIGA - neutron β-decay plans at the moment;
- TRIGA is thought to be a user facility in the future;
- HPNC with UCN may become an option in Mainz, too

MITP Scientific Program

"Bridging the Standard Model to New Physics with the Parity-Violating Program at Mainz"

April 23 - May 4, 2018

https://indico.mitp.uni-mainz.de/event/123/

Organizers: Jens Erler, Hubert Spiesberger, MG

Topics:

Weak mixing angle at low energy with MESA

Neutron beta decay with TRIGA

Hadronic PNC

Precision low-energy tests in a global context

Invited speakers:

Bill Marciano, Michael Ramsey-Musolf, Barry Holstein, Mike Snow, John Hardy, Vincenzo Cirigliano, Krishna Kumar, Chuck Horowitz, David Armstrong, Paul Souder, Frank Maas, Dima Budker, Werner Heil