Precision measurements using parity violation electron scattering

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Jefferson Lab
Exploring the Nature of Matter

University of Virginia

Happy 40th Anniversary !!

https://previews.123rf.com/images/ruthblack/ruthblack1502/ruthblack150200016/36448337-40th-birthday-cake-with-sparklers.jpg

SLAC-PUB-2148
July 1978
(T/E)

PARITY NON-CONSERVATION IN INELASTIC ELECTRON SCATTERING*

...

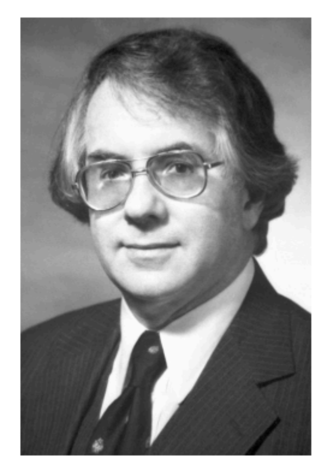
ABSTRACT

We have measured parity violating asymmetries in the inelastic scattering of longitudinally polarized electrons from deuterium and hydrogen. For deuterium near $Q^2 = 1.6\ (\mathrm{GeV/c})^2$ the asymmetry is $(-9.5 \times 10^{-5})\ Q^2$ with statistical and systematic uncertainties each about 10%.

(Submitted to Phys. Lett.)

http://inspirehep.net/record/130569/files/slac-pub-2148.pdf

- C.Y. Prescott *et al.* (E122) first observed the weak neutral current interaction in electron scattering
- This lead to the cementing of $SU(2)_L \times U(1)_Y$ electroweak model
  - 1979 Glashow, Weinberg and Salam were awarded the Nobel Prize in Physics



Sheldon Lee Glashow
Prize share: 1/3

Abdus Salam
Prize share: 1/3

Steven Weinberg
Prize share: 1/3

Parity violating electron scattering

In this experiment a polarized electron beam of energy between 16.2 and 22.2 GeV was incident upon a liquid deuterium target. Inelastically scattered electrons from the reaction

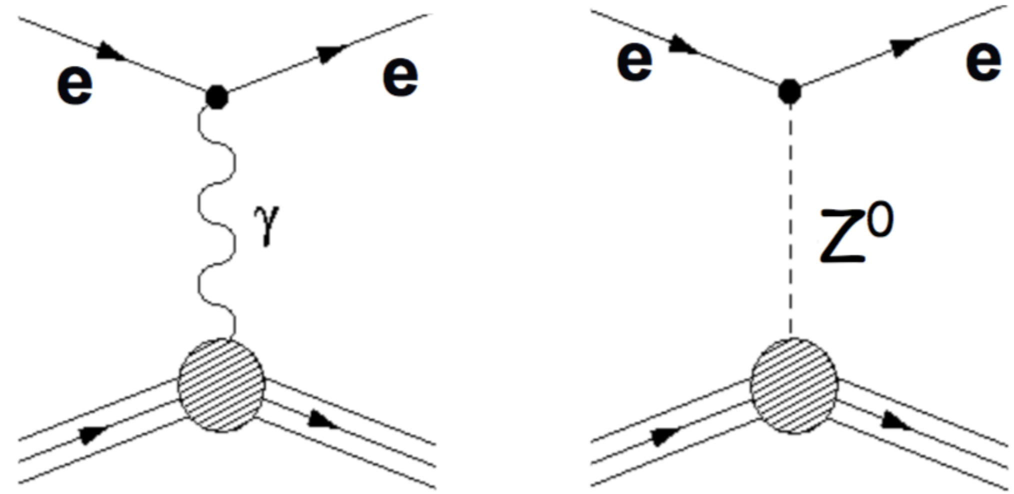
$$e(\text{polarized}) + d \rightarrow e' + X \qquad (1)$$

...

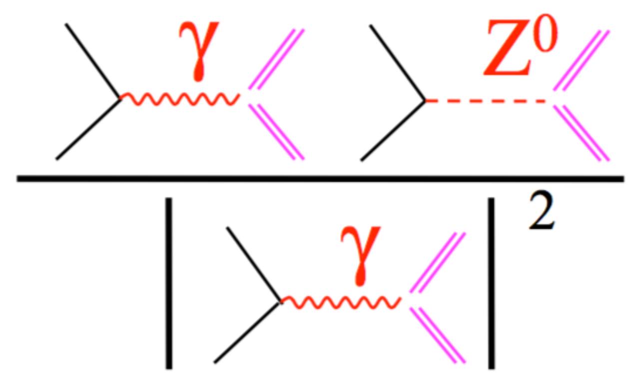
Parity violating effects may arise from the interference between the weak and electromagnetic amplitudes. Calculations of the expected effects in deep inelastic experiments have been reported by several authors(1-7), and asymmetries at the level of $10^{-4}\ Q^2$ are predicted for the kinematics of our experiment.

http://inspirehep.net/record/130569/files/slac-pub-2148.pdf

Parity violating electron scattering



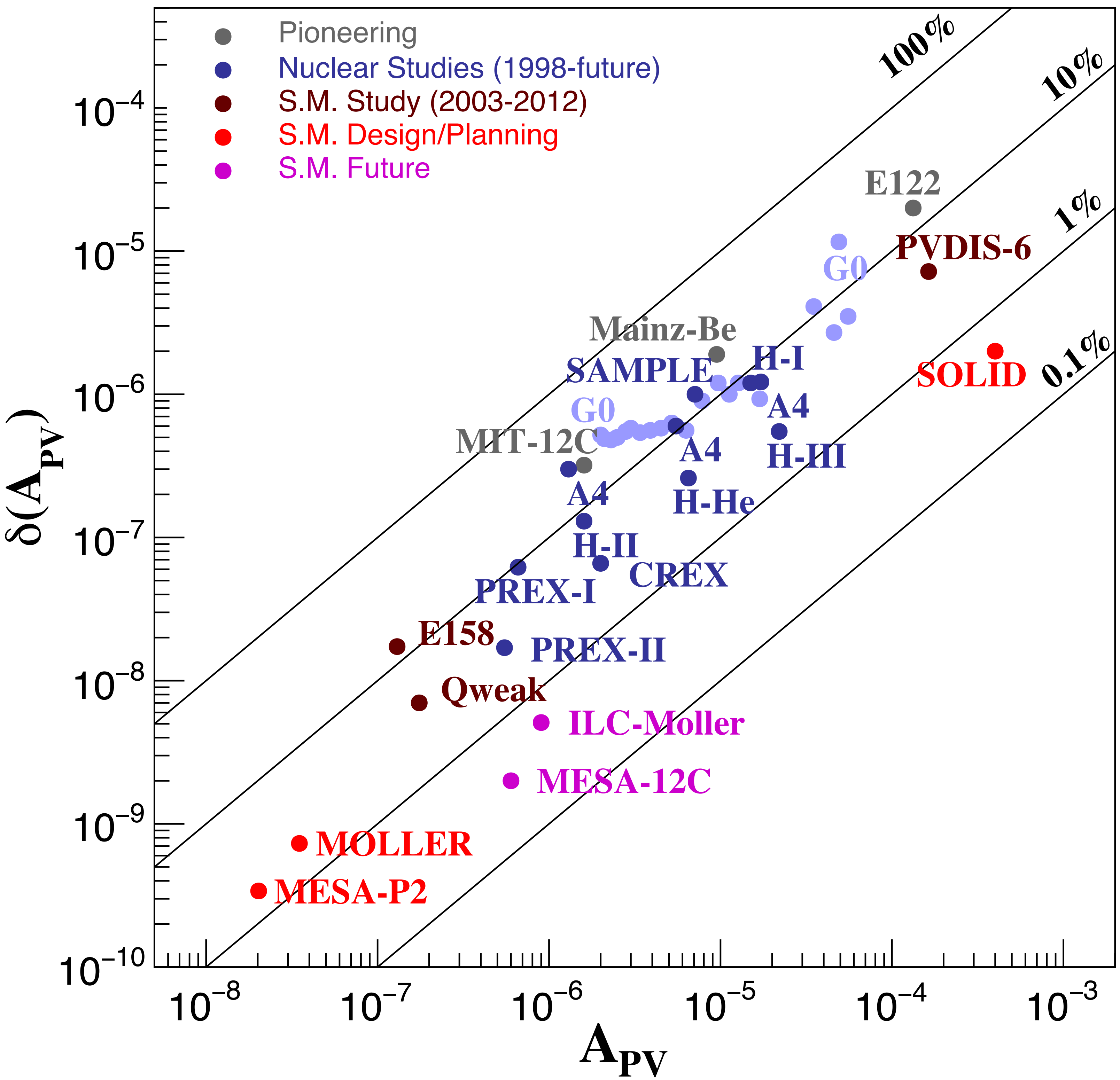
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim$$



$$\propto \frac{|\mathcal{M}_Z|}{|\mathcal{M}_\gamma|} \sim 10^{-4} \times Q^2$$

- uses longitudinally polarized electron beams to scatter off of *e, p, d, Pb* ..
- measures asymmetries in elastic or inelastic scattering
  - generally on the level of ppm or less
- This requires a lot of statistics leading to particular detection choices

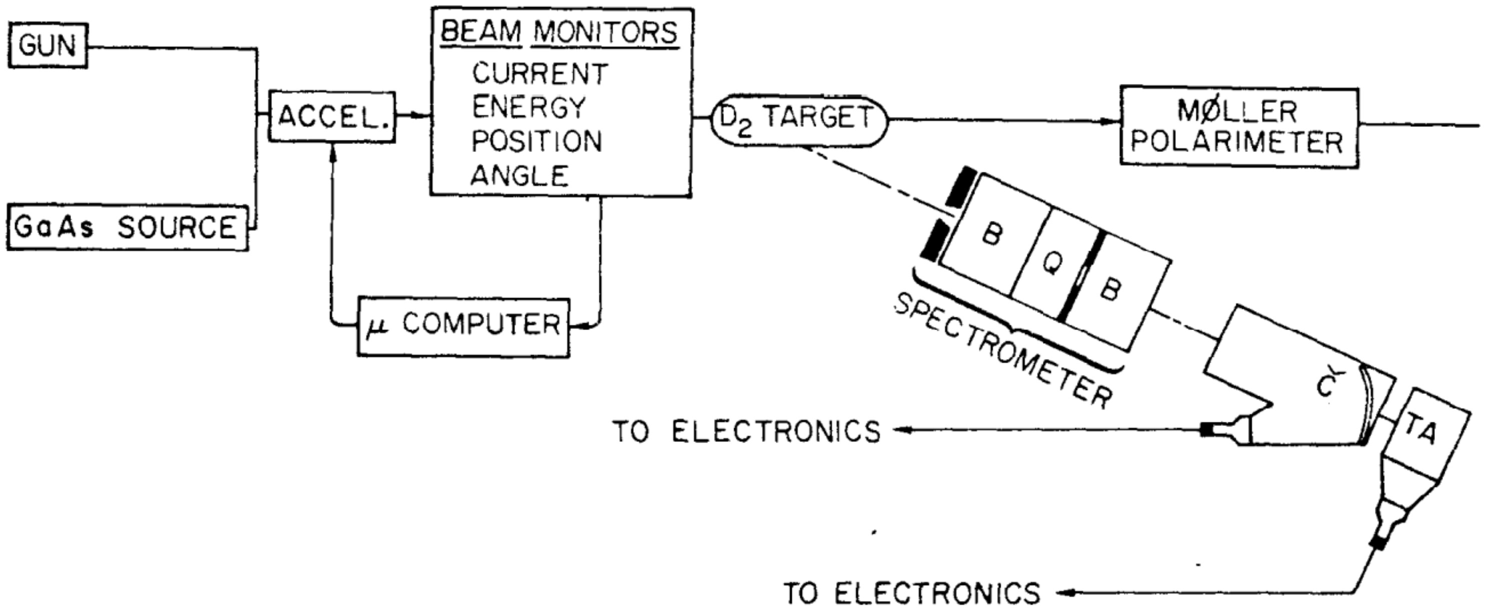
PVES landscape



- PVES has a long history of pushing the limits of precision and discovery
  - E122: (ΔA=10 ppm)
    - pioneering experiment (already had most of the features of modern PVES experiments)
  - G0, A4, HAPPEX (ΔA=0.25 to 2 ppm)
  - E158 (ΔA=17 ppb)
  - Qweak (ΔA=9 ppb)

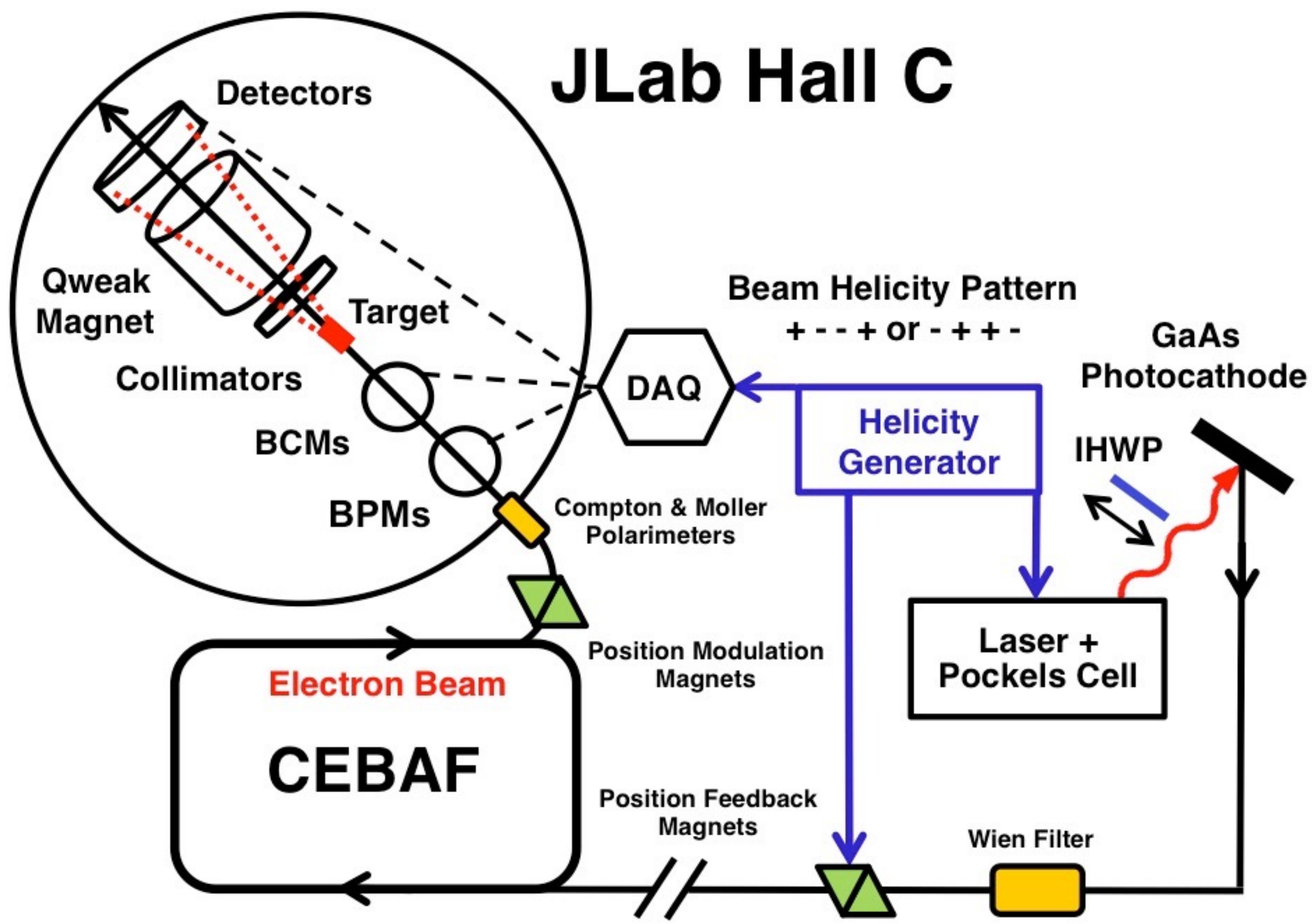
  - Moller (ΔA=0.7 ppb)
  - P2 (ΔA=0.44 ppb)

PVES setup overview



E122

Phys.Lett. B77 (1978) 347-352



JLab Hall C

Qweak

Nature **557**, 207-211 (2018)

Electron source

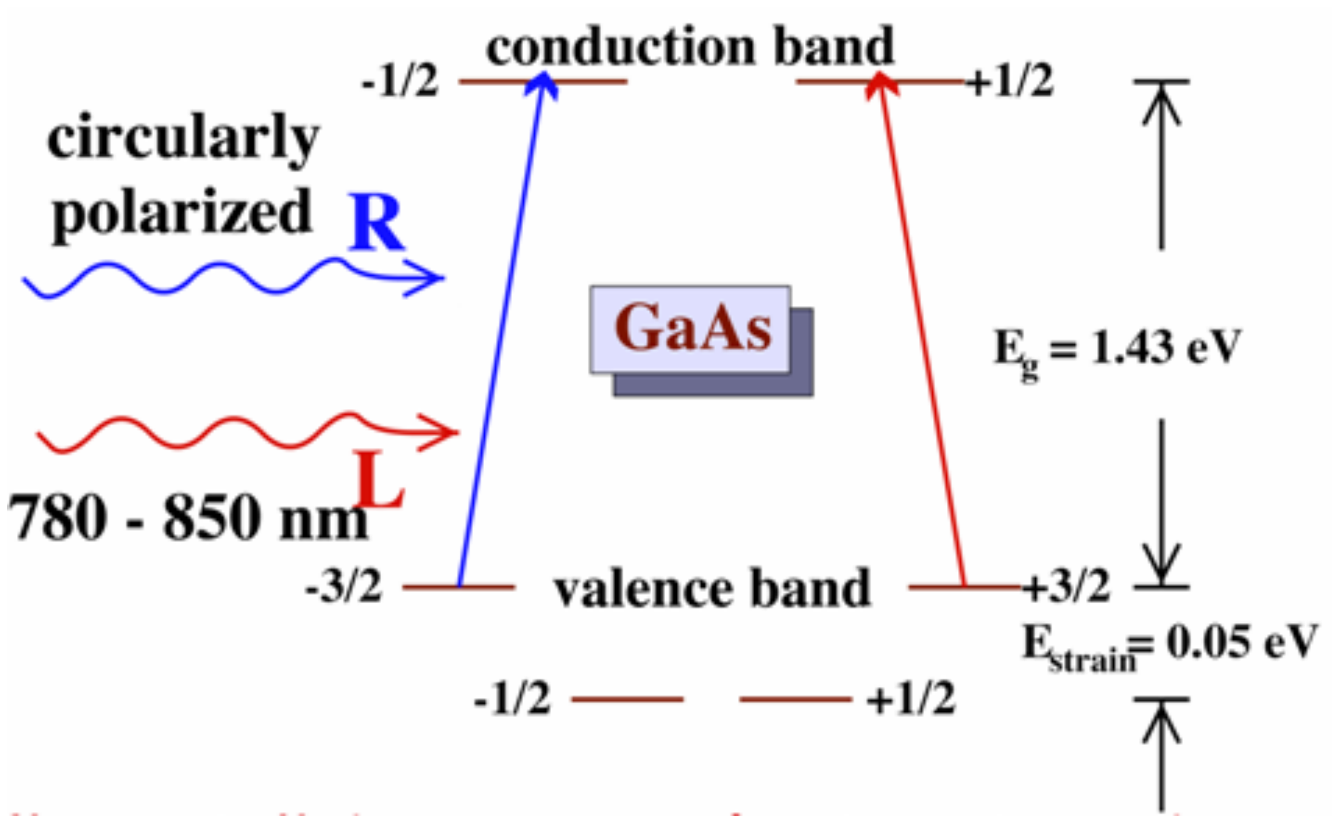
E122

"Of crucial importance to this experiment was the development of an intense source of longitudinally polarized electrons" (Prescott *et al* 1978)

- Produced 37% polarized electrons
- 1.5 us pulses at 120 pulses per second
- random helicity for each pulse
- $4*10^{11}$ electrons per pulse (~8 uA current)

Present

- Regularly produce ~90% polarized electrons (CEBAF) with superlattice cathodes that have high QE and lifetime
- up to 1kHz random helicity flip
- high electron current 180 uA



Future

- faster helicity flips of 2kHz with faster transition times will be needed for the next generation of experiments
- along with high polarization and high currents

Polarimeters

E122

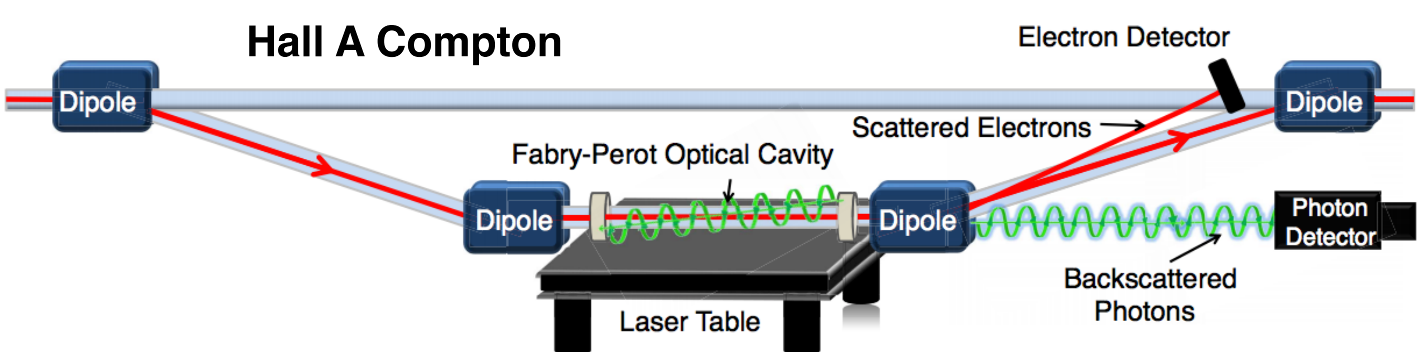
- Moller polarimeter with precision of 3% stat and 5% syst uncertainties

Present

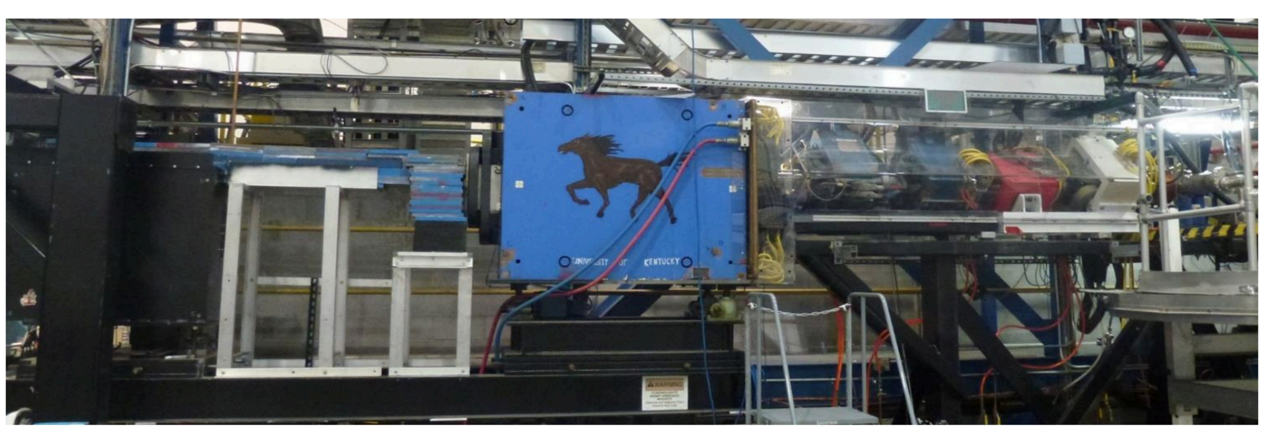
- Three types of polarimeters: Mott, Moller and Compton
- Compton can be run continuously to monitor polarization stability
- All have achieved at least 1% uncertainty (0.5% precision reported by Hall C Moller)

Future

- Plans in place for all three polarimeters to achieve 0.5% or better uncertainty in the next 5 years
- New double Mott polarimeter planned to be used



Hall A Moller



Integrating detectors

E122

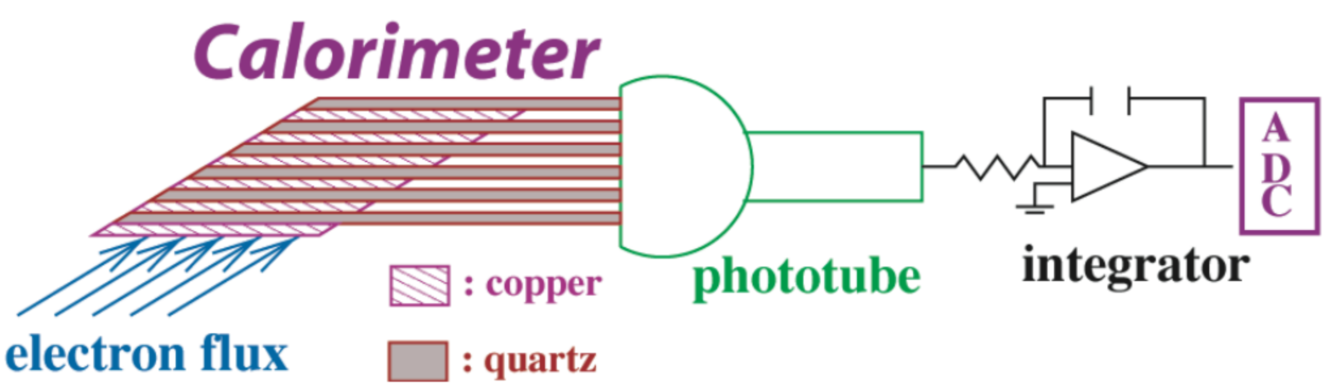
- Integrates all signal in a helicity signal and reads out one number for each detector
- Used nitrogen-filled Cerenkov counter and 9rad length lead glass shower counter
- Detected about 1000 electrons per pulse (120Hz pulse rate)

Present

- Measurements have reached deadtime-less readout at ~6GHz
- Tracking detectors used at low current to better determine the average Q^2

Future

- Experiments are planned to be able to detect 500 GHz rates



Spectrometers

E122

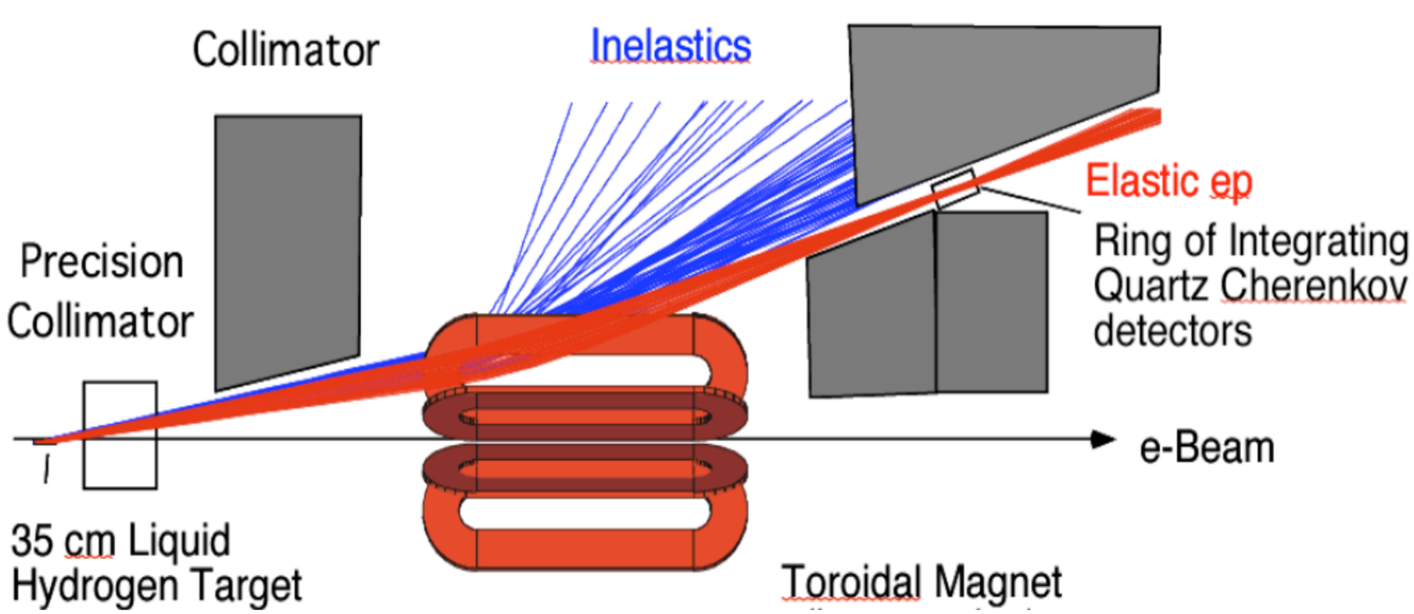
- Magnetic spectrometer used to separate signal from background
- defines and calibrates the acceptance and kinematics for the experiment

Present

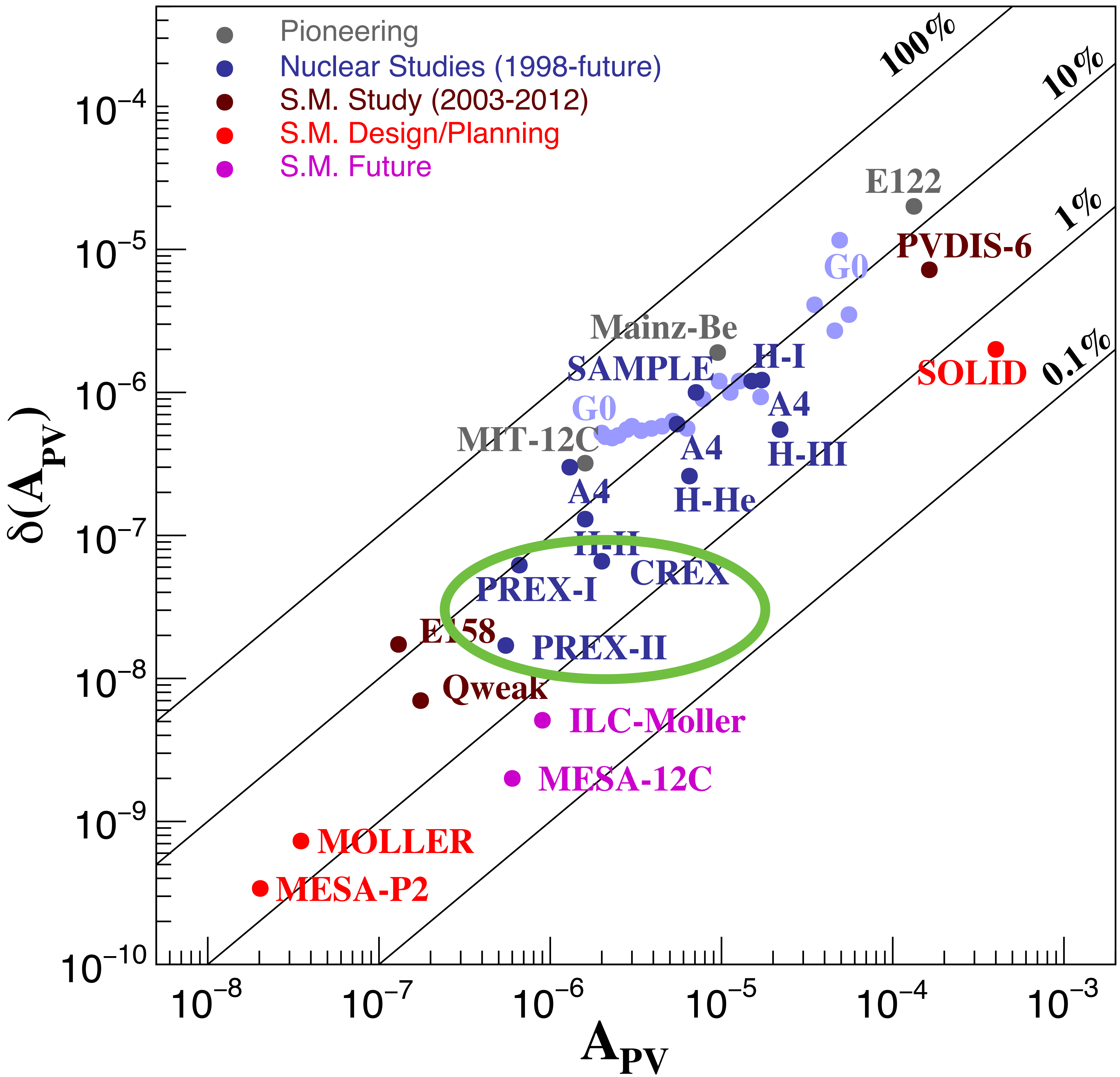
- Different magnetic spectrometers used in conjunction with collimators to better separate signal

Future

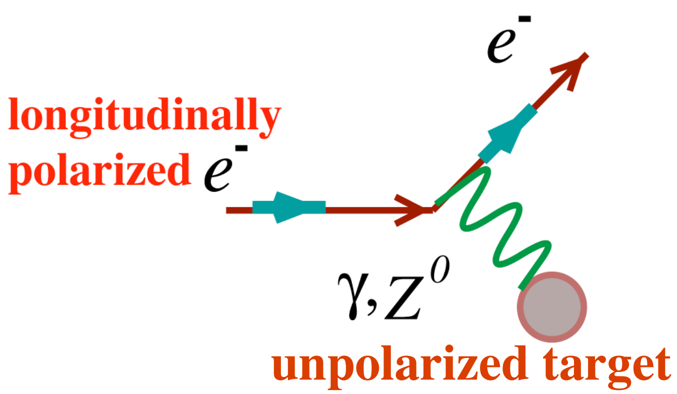
- Novel spectrometer designs are needed to achieve precision for the next generation of experiments



PVES landscape: Upcoming nuclear studies

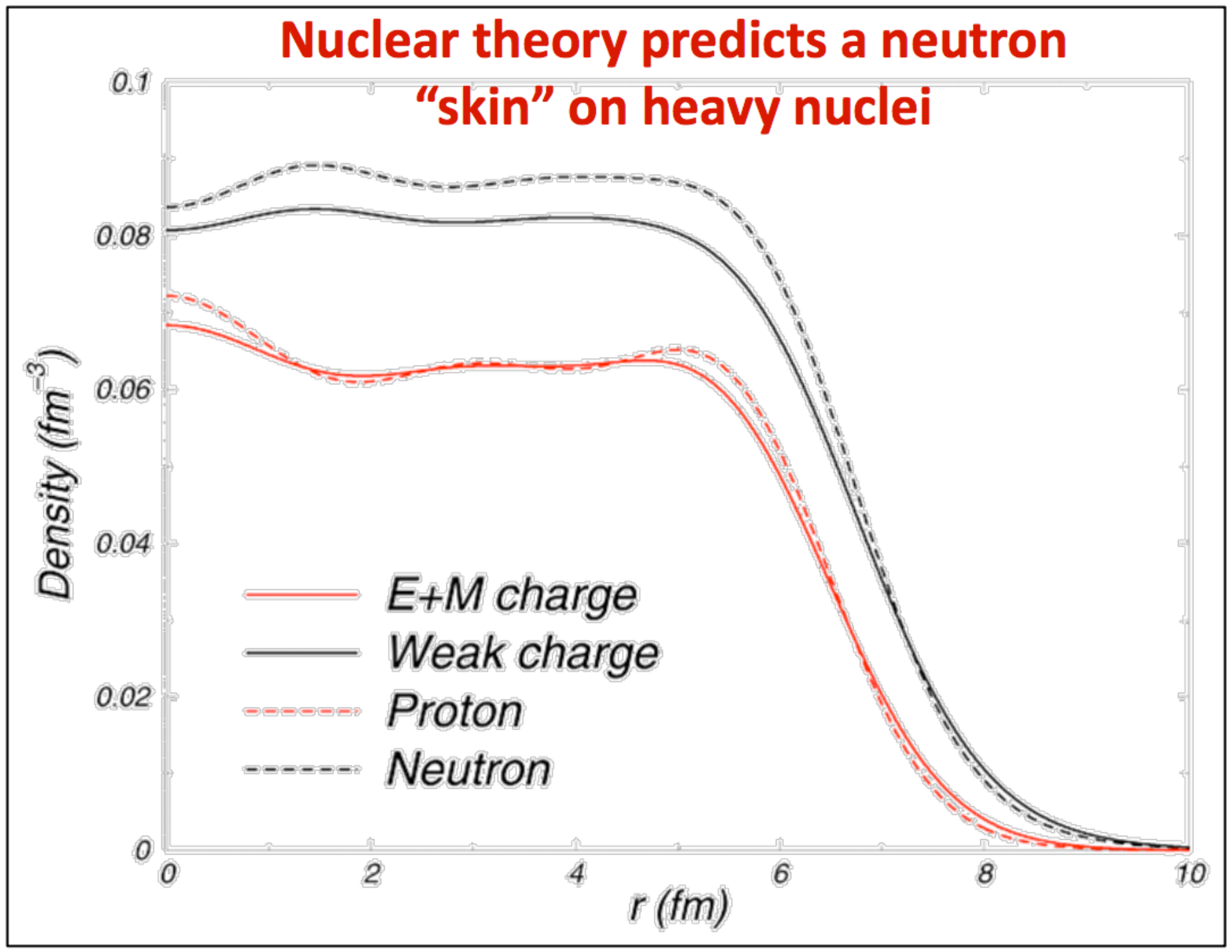


PREXII and CREX



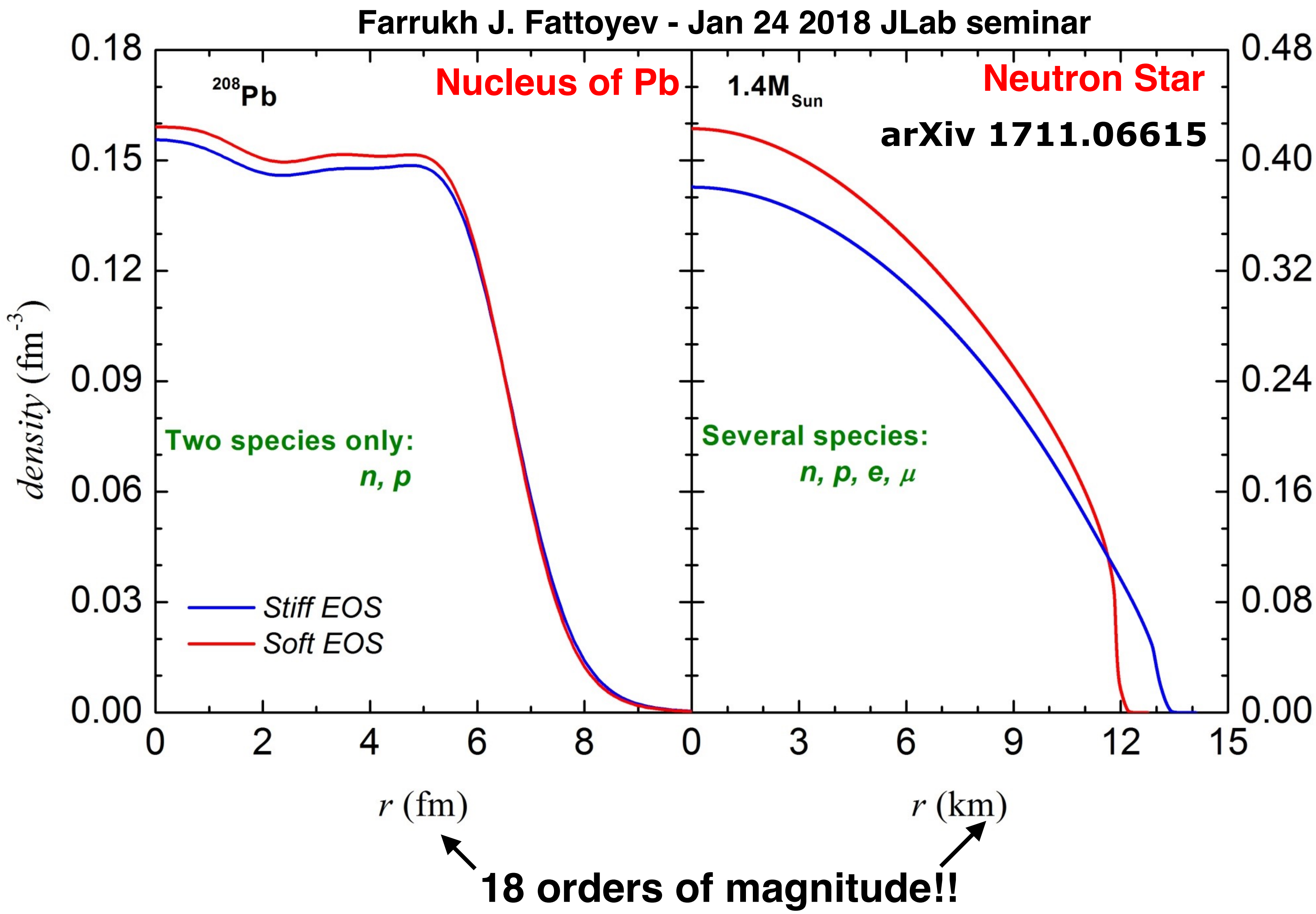
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

$$A_{\rm PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_W}{F_{ch}}$$



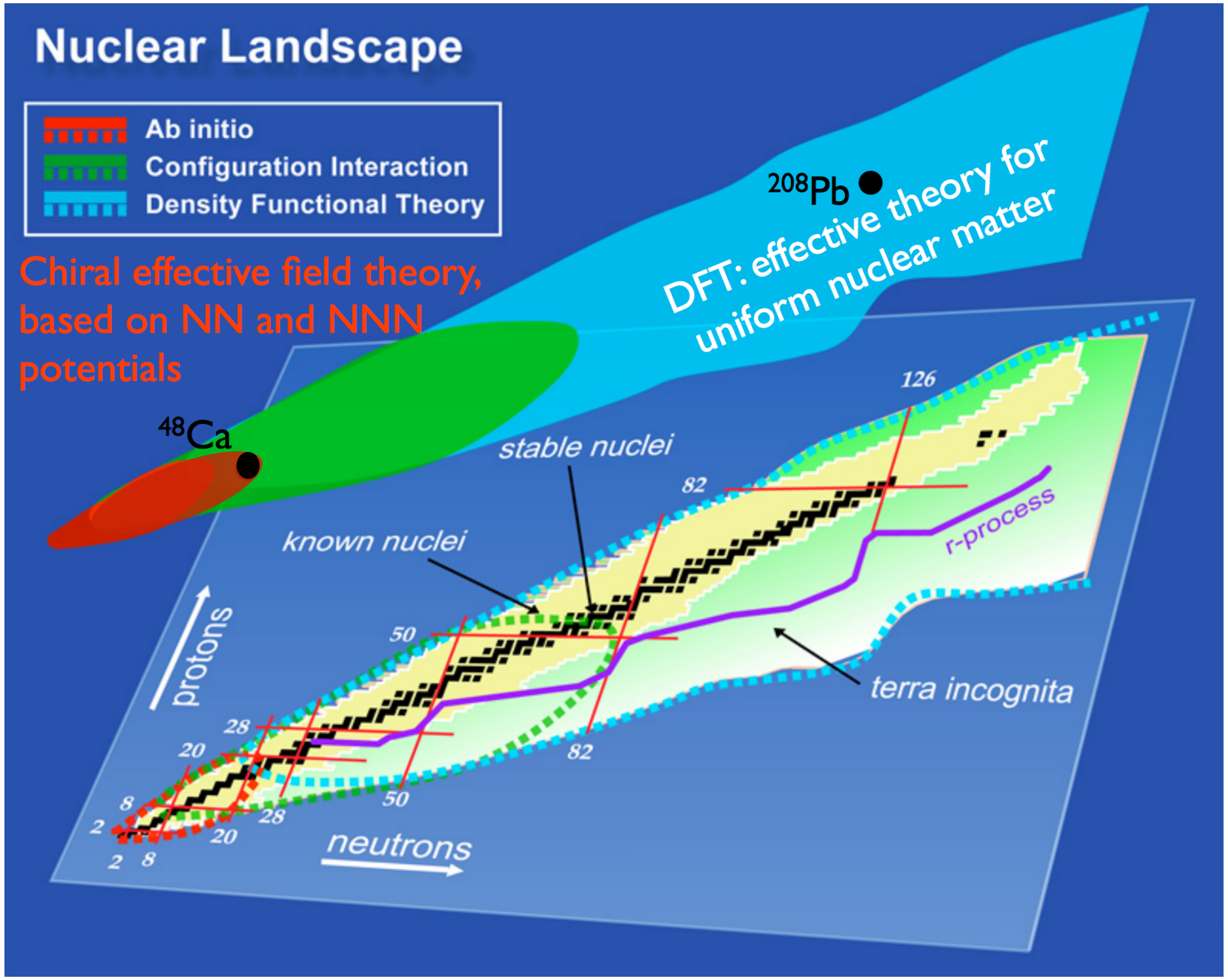
- Some of the additional 44 neutrons inside Pb are pushed out to form a crust
- The neutron radius inside nuclei is not as well understood as the proton radius (i.e. electric charge distribution)
- Using PVES one can directly access the neutron distribution and cleanly measure the neutron radius with minimal theoretical input

Probing neutron stars?



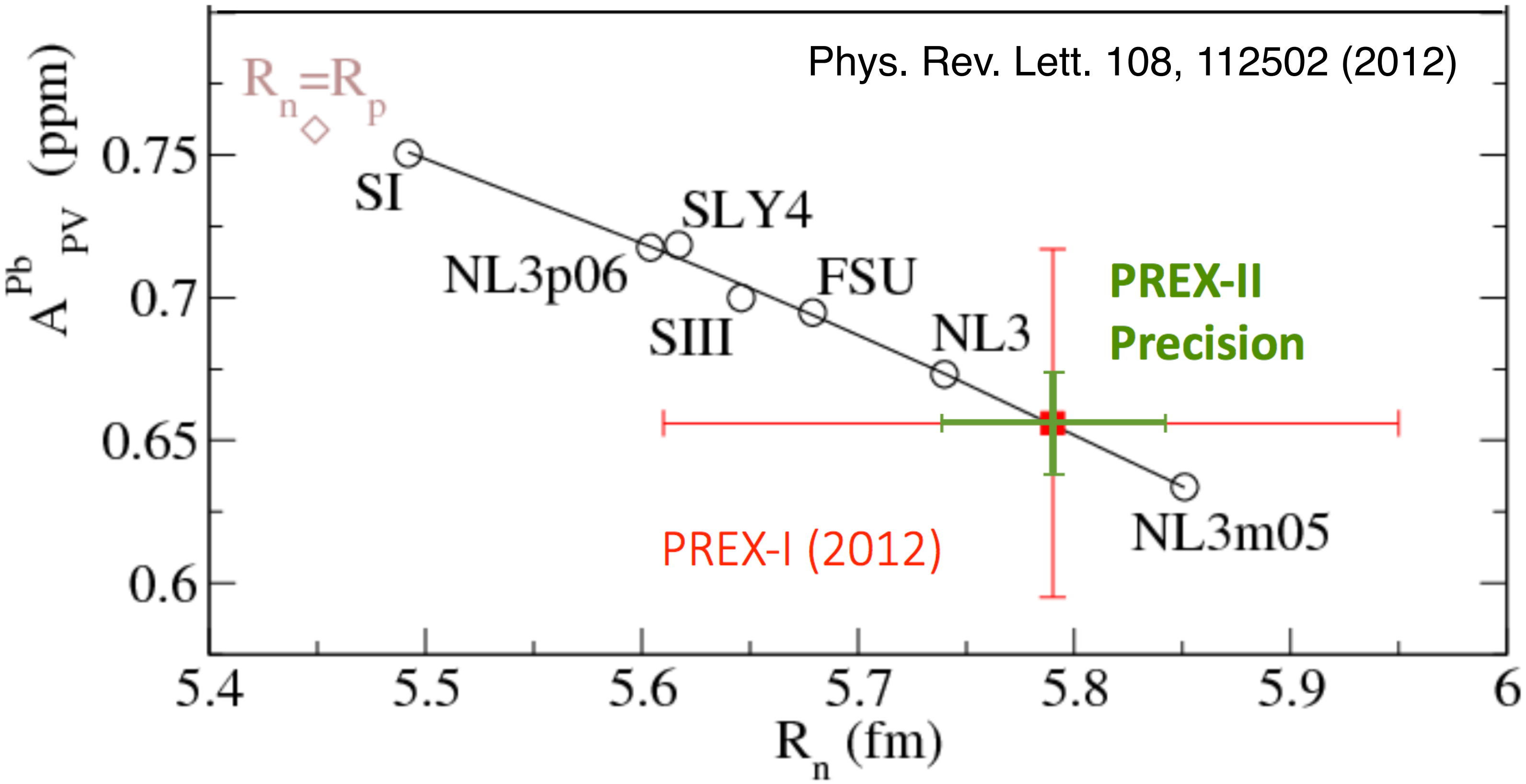
- Both systems are described with the nuclear equation of state
- Measurements in Pb have a high sensitivity to the density dependence of the symmetry energy in the nuclear EOS
- BNS merger results from gravitational waves and from PREX could lead us to conclude a phase transition exists before very high density nuclear matter is reached

Bridging the divide



- By making two measurements at different nuclear densities we can provide crucial input to ab-initio and DFT models
- Recent calculations based on nuclear coupled cluster method (arXiv 1509.07169) make a prediction for the ^{48}Ca $0.12 \leqq R_{skin} \leqq 0.15$ fm

Upcoming runs

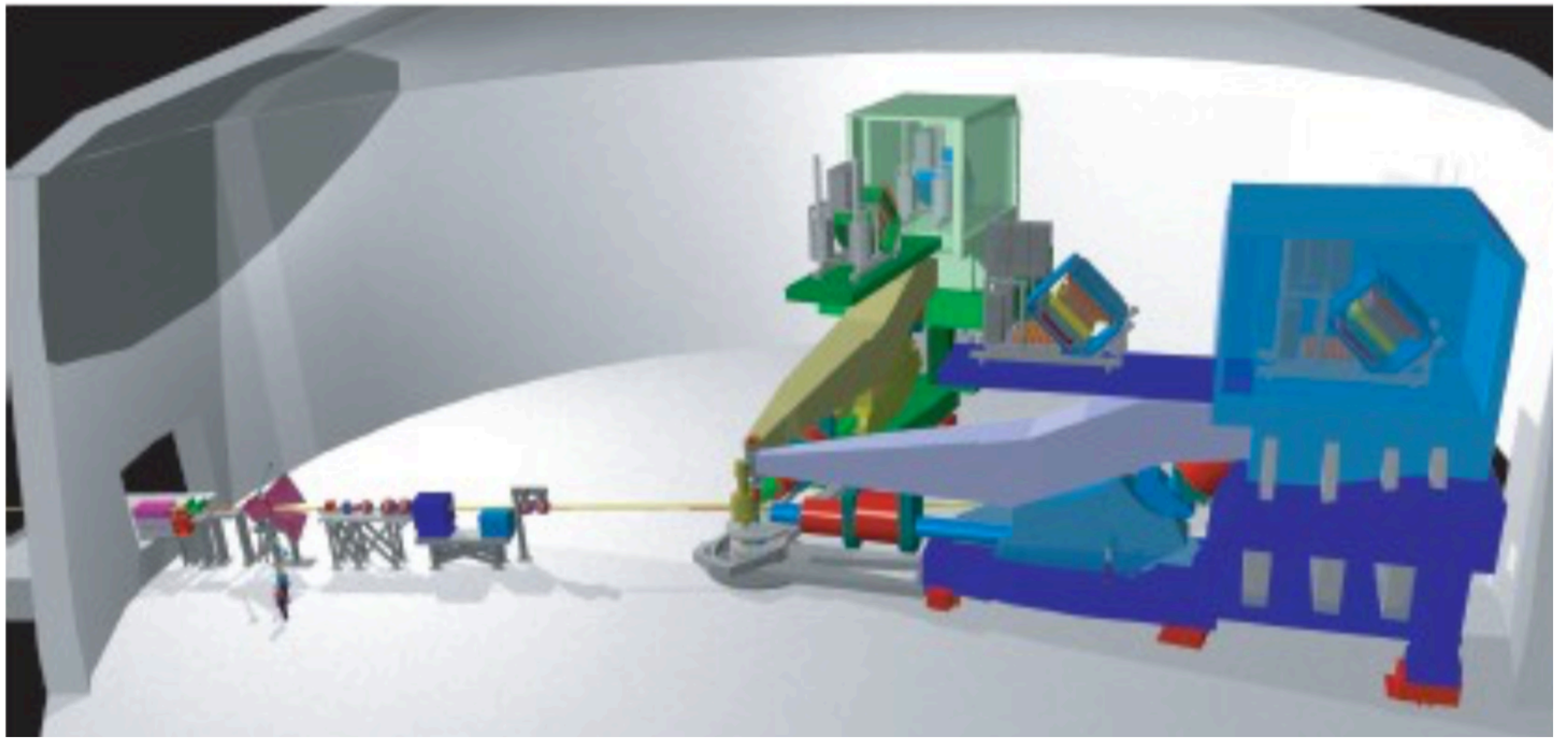


A_{PV} = 0.657 ± 0.060(stat) ± 0.014(syst) ppm

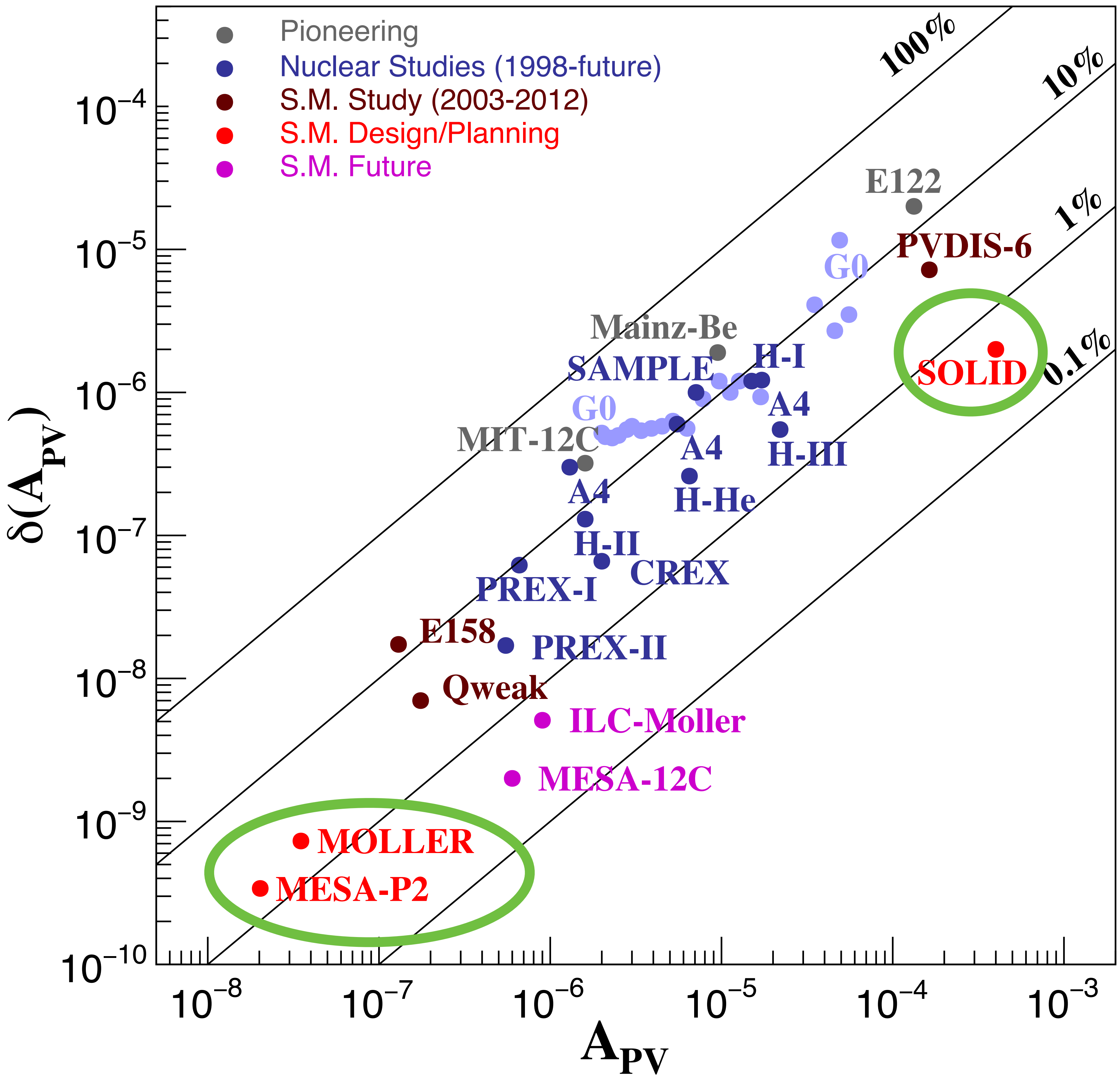
$$R_n - R_p = 0.33^{+0.16}_{-0.18}$$

- Preparations are nearly complete and experimental equipment is being designed and build
- PREXII is scheduled to run in **summer of 2019** and CREX will follow in the fall

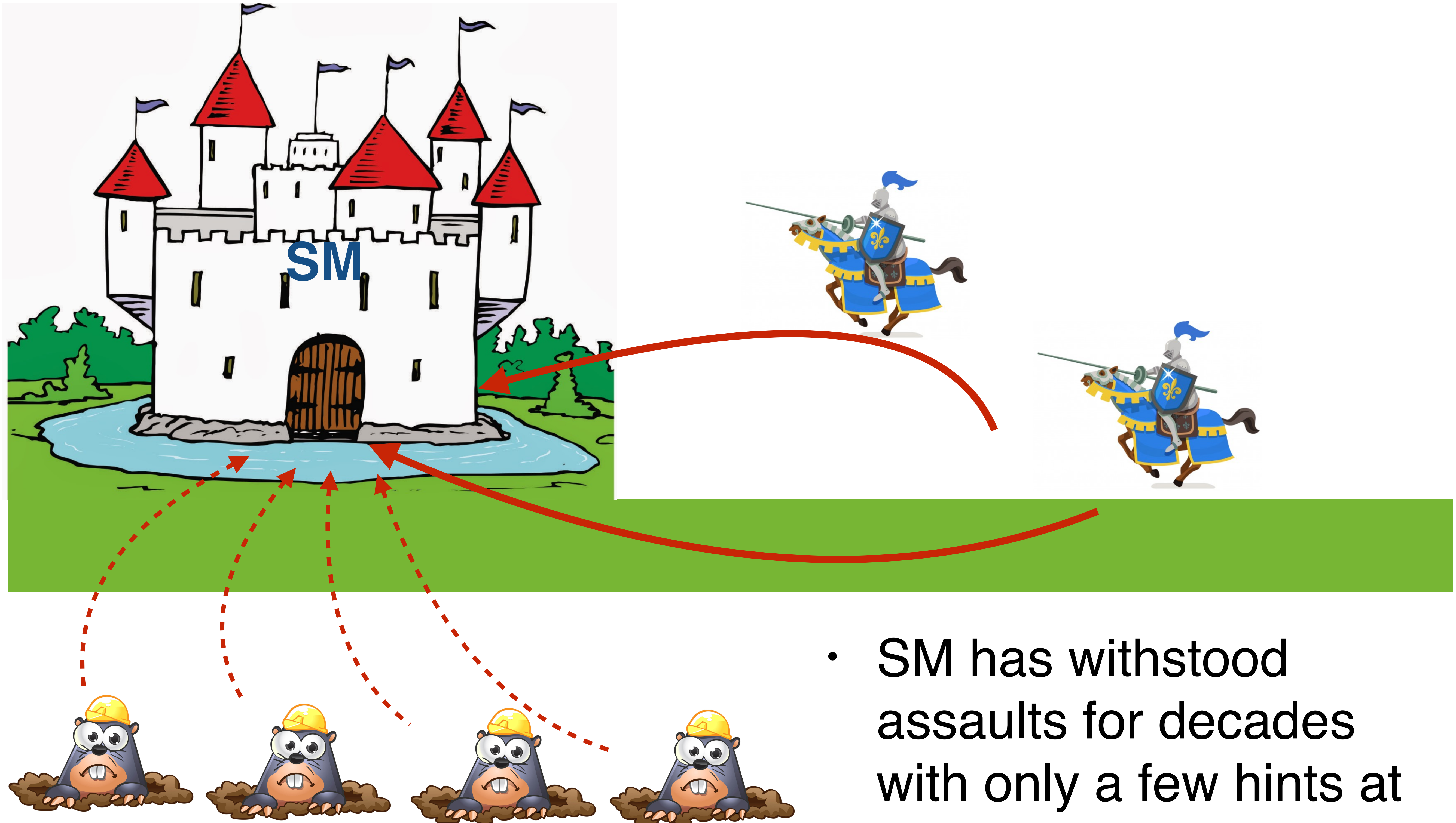
- We expect a decrease of the uncertainty for PREX by a factor of 3 and a brand new measurement for Ca
- Will run with the standard Hall A equipment (@JLab), together with small additions (septum, GEMs and integrating detectors)



PVES landscape: Upcoming BSM studies



Testing the SM



- SM has withstood assaults for decades with only a few hints at something beyond it

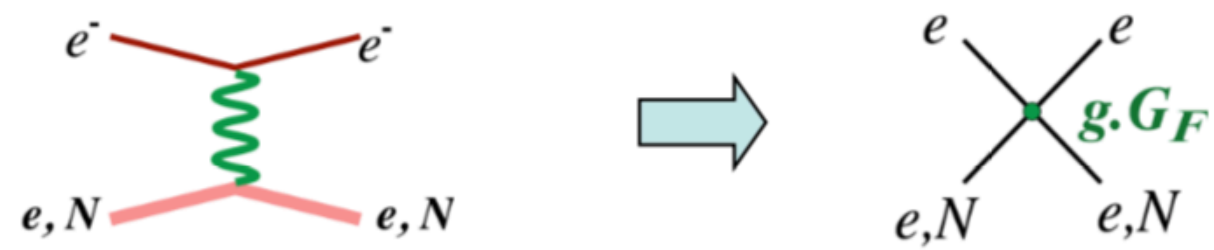
Testing the SM

To fully map out the phase space of possible beyond the SM physics we need a comprehensive strategy with will need to include:

- Direct searches at the LHC need to be complemented by searches at $Q^2 << M_Z^2$
- Dark Matter searches
- Rare/Forbidden processes: EDMs, CP(or T) violations, Lepton flavor violations
- Neutrino physics: neutrinoless double beta decay
- **Precision electroweak measurements**

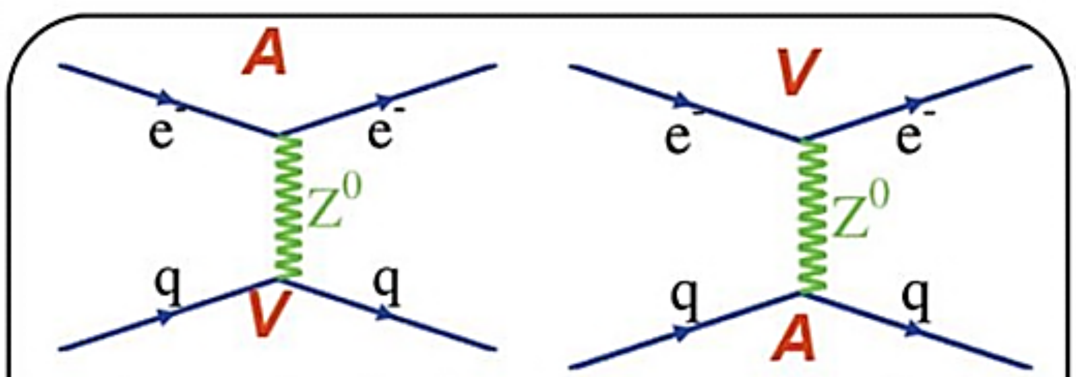
Contact interaction

For electron-fermion scattering:



$$\frac{1}{Q^2 - M^2} \xrightarrow{Q^2 \ll M^2} \frac{1}{M^2}$$

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha}(g_A^e g_V^T + \beta g_V^e g_A^T)$$



$C_{1i} \equiv 2g_A^e g_V^i$ $C_{2i} \equiv 2g_V^e g_A^i$

Forward Scattering **Backward Scattering**

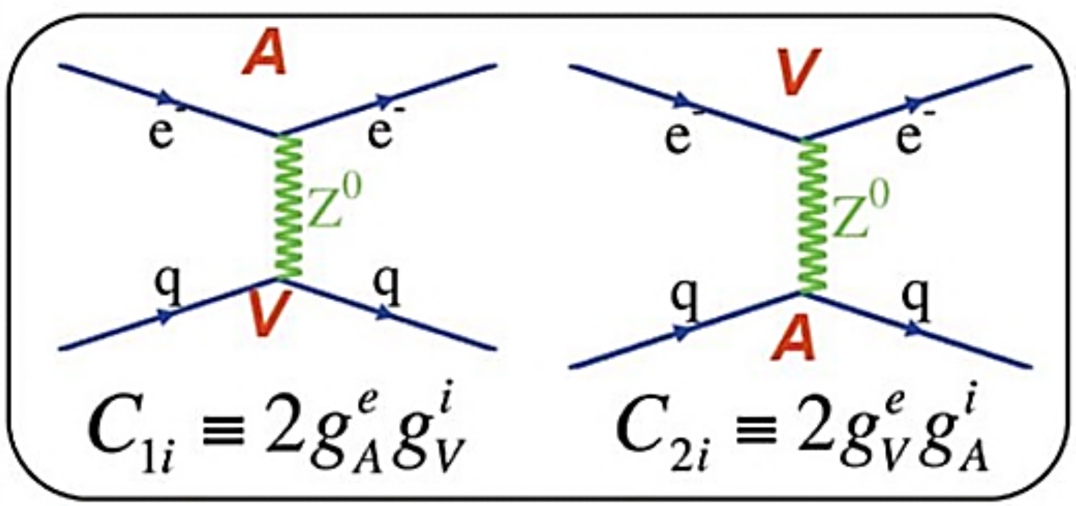
- At low Q^2 (Q^2<<M_Z) the SM Lagrangian is effectively a 4-fermion contact interaction
- Depending on the experimental configuration one can access the vector of axial charge of the target

Contact interaction

For electron-fermion scattering:

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha}(g_A^e g_V^T + \beta g_V^e g_A^T)$$

$$\mathcal{L}_{eq}^{PV} = -\frac{G_F}{\sqrt{2}} \sum_i \left[C_{1i}\bar{e}\gamma_\mu\gamma_5 e\bar{q}\gamma^\mu q + C_{2q}\bar{e}\gamma_\mu e\bar{q}\gamma^\mu\gamma^5 q\right]$$



Forward Scattering

Backward Scattering

$$C_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2(\theta_W) + \delta C_{1u} \approx -0.19$$

$$C_{2u} = -\frac{1}{2} + 2\sin^2(\theta_W) + \delta C_{2u} \approx -0.30$$

$$C_{1d} = \frac{1}{2} - \frac{2}{3}\sin^2(\theta_W) + \delta C_{1d} \approx 0.35$$

$$C_{2d} = \frac{1}{2} - 2\sin^2(\theta_W) + \delta C_{2d} \approx 0.25$$

Vector charge

$$\mathcal{L}_{eq}^{PV} = -\frac{G_F}{\sqrt{2}} \sum_i \left[C_{1i} \bar{e}\gamma_\mu\gamma_5 e \bar{q}\gamma^\mu q + C_{2q}\bar{e}\gamma_\mu e\bar{q}\gamma^\mu\gamma^5 q \right]$$

- Vector charge searches with elastic scattering can be more experimentally accessible

Weak vector charge

Particle	Electric charge	Weak vector charge ($\sin^2\theta_W \approx \frac{1}{4}$)
e	-1	$Q_W^e = -1 + 4\sin^2\theta_W \approx 0$
u	$+\frac{2}{3}$	$-2C_{1u} = +1 - \frac{8}{3}\sin^2\theta_W \approx +\frac{1}{3}$
d	$-\frac{1}{3}$	$-2C_{1d} = -1 + \frac{4}{3}\sin^2\theta_W \approx -\frac{2}{3}$
p(uud)	$+1$	$Q_W^p = +1 - 4\sin^2\theta_W \approx 0$
n(udd)	0	$Q_W^n = -1$

- Weak charge is the analog to the electric charge:
  - also defined as $Q^2 \to 0$ (intrinsic property of particle)
  - combined with the very well defined SM prediction makes it a good place to look for deviations (and new physics)

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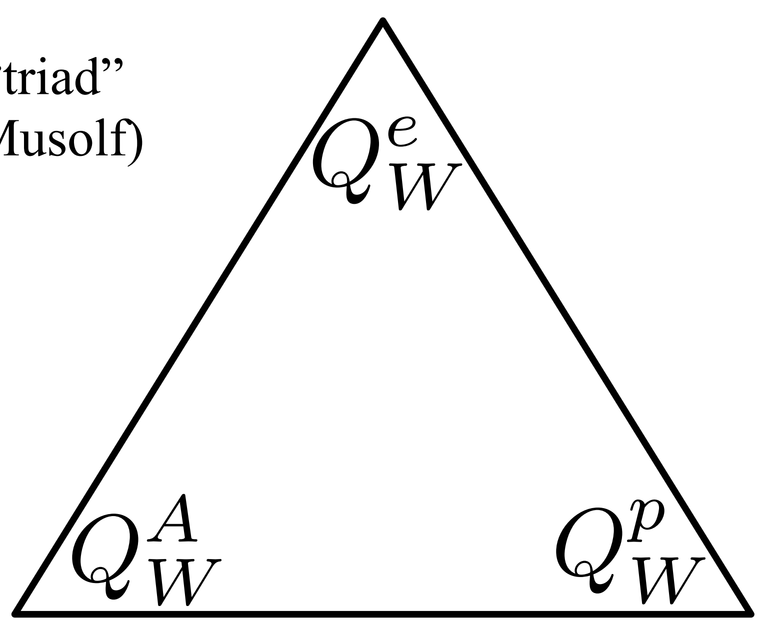
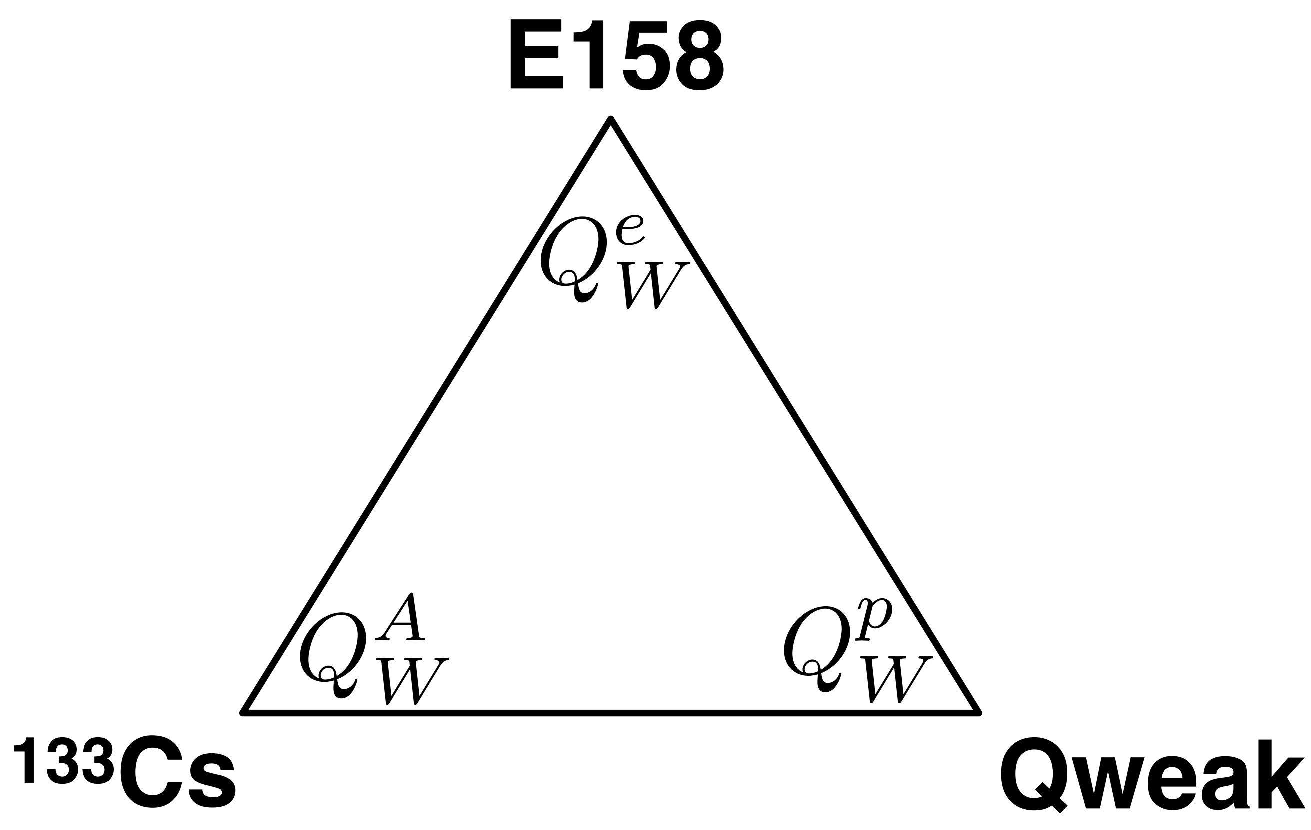
Weak charge "triad"
(M. Ramsey-Musolf)

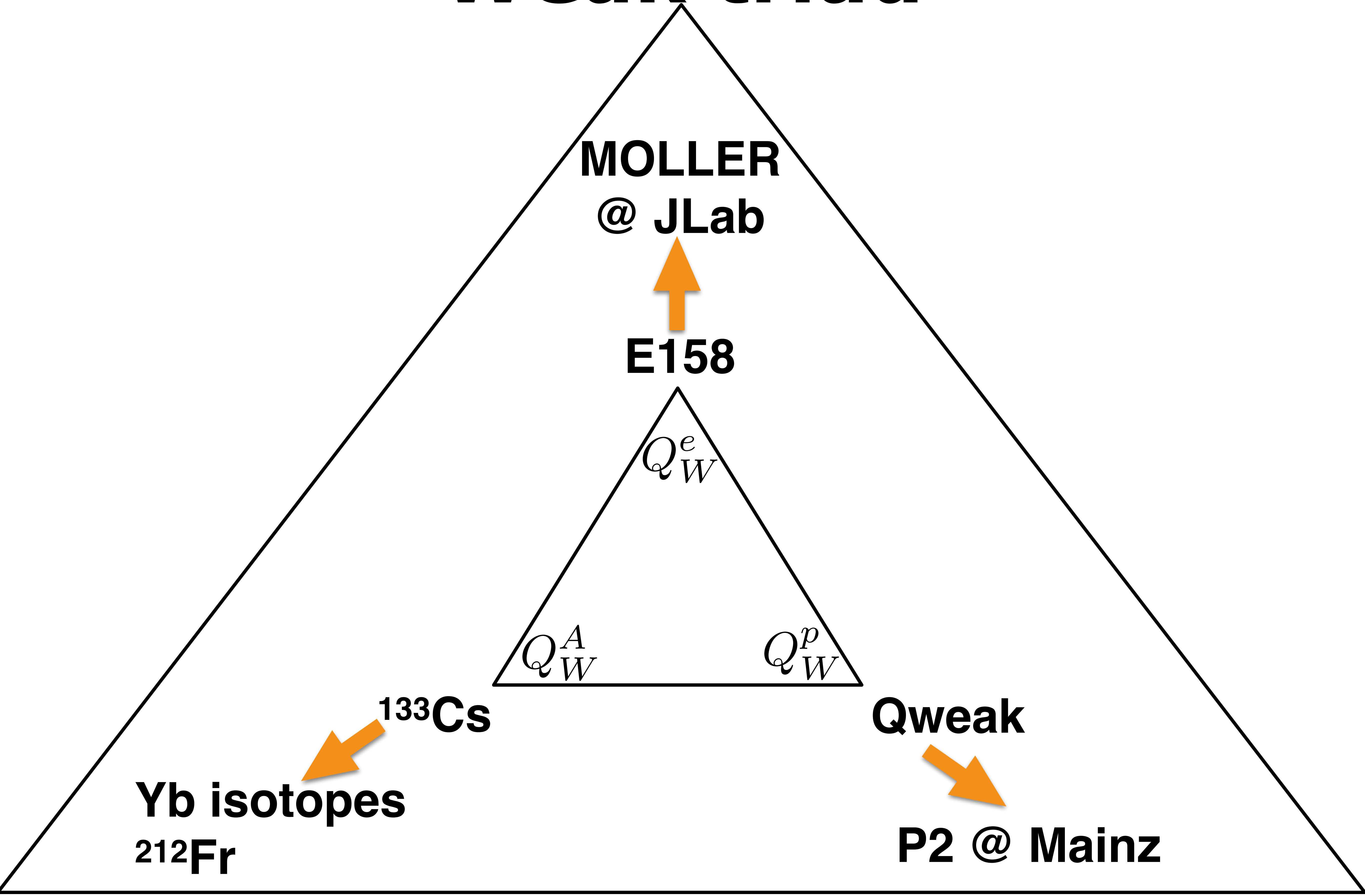


- In the early 2000s E158 made the first measurement of electron weak charge Q^e_W
- Atomic Parity Violation measurements on ^{133}Cs gave unique insights into d-quark weak vector charge
- Qweak directly measures the proton weak vector charge Q^p_W

Weak triad

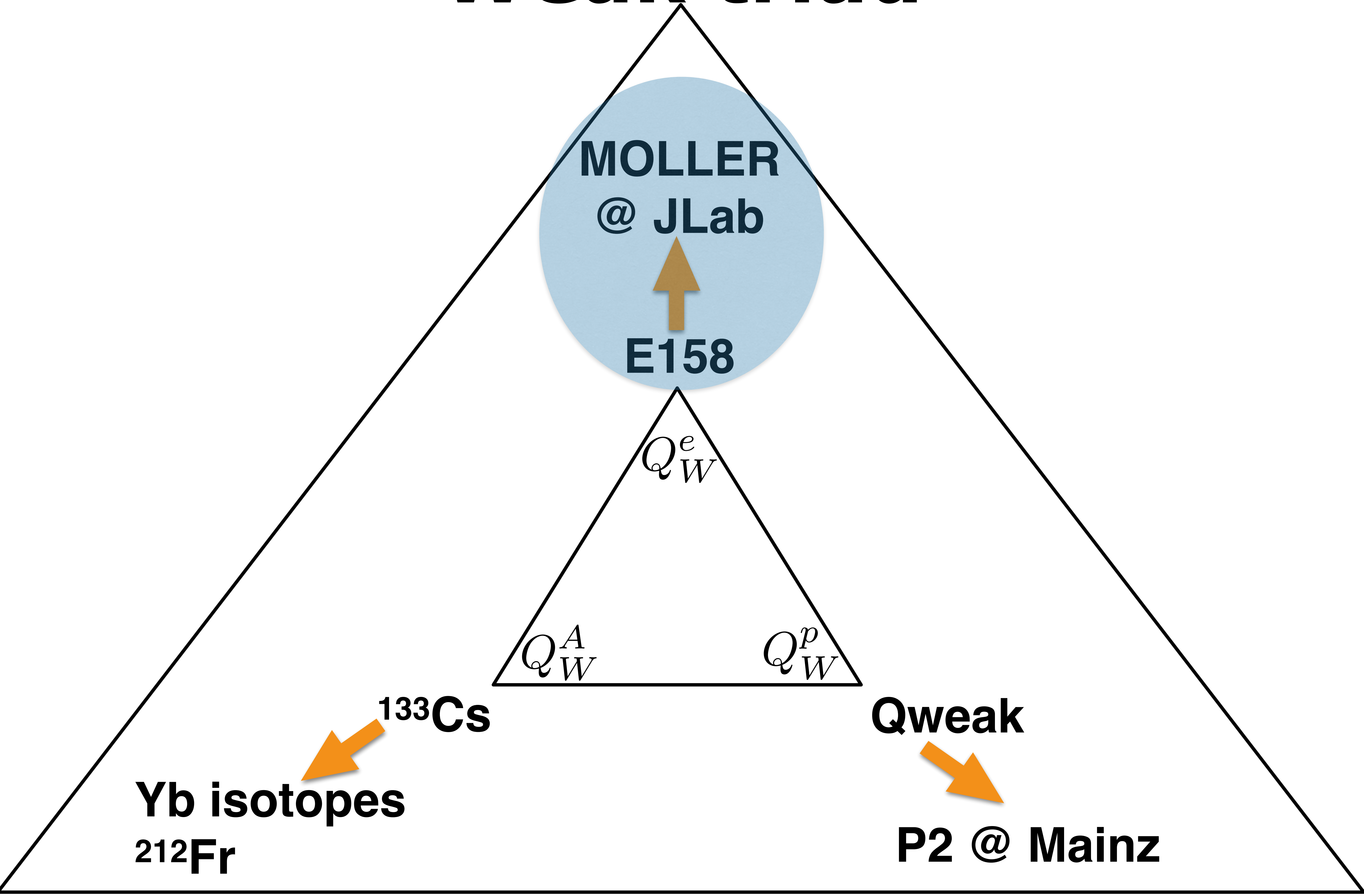


Weak triad



MOLLER
@ JLab
E158
Q_W^e
Q_W^A
Q_W^p
^{133}Cs
Qweak
Yb isotopes
^{212}Fr
P2 @ Mainz

Weak triad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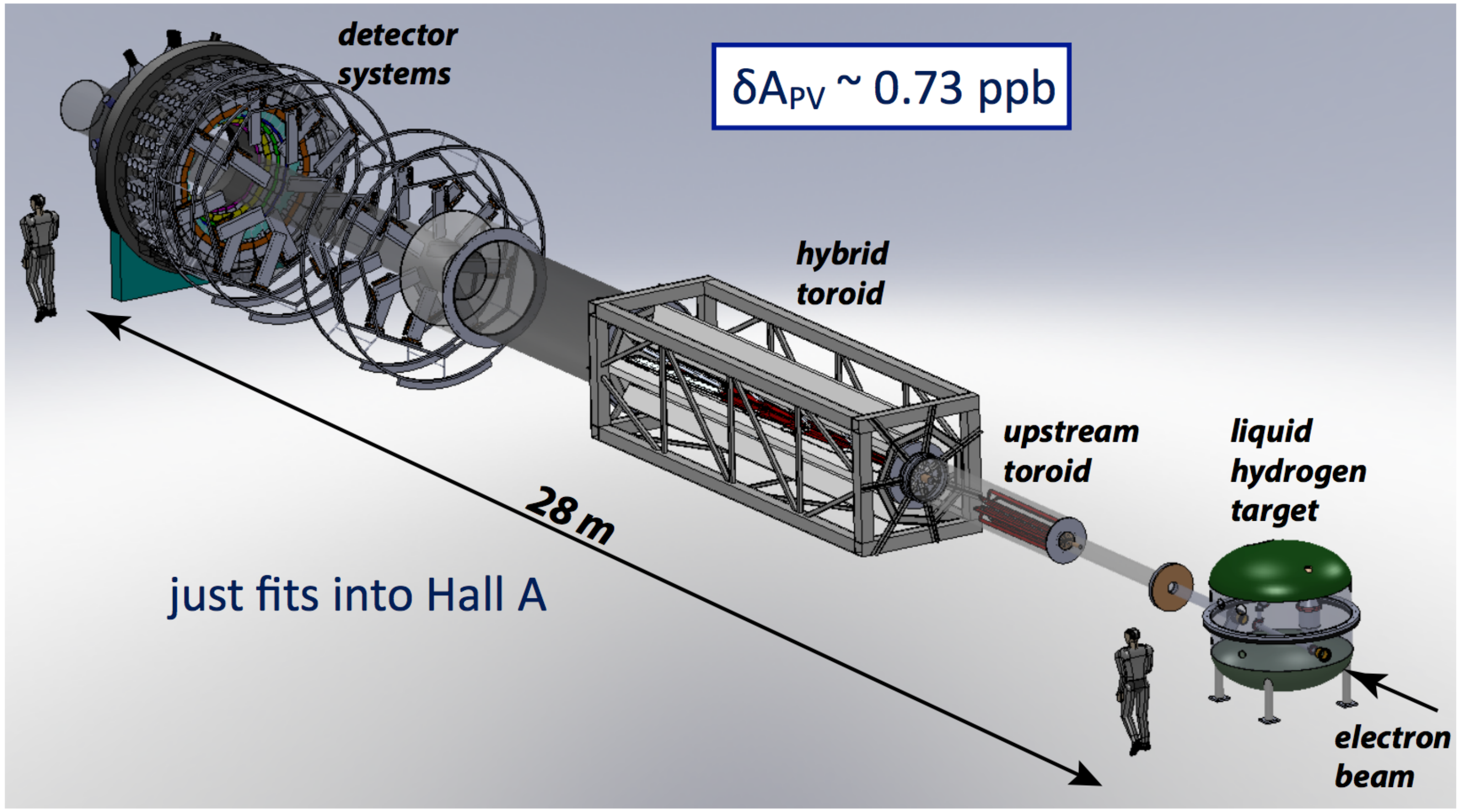
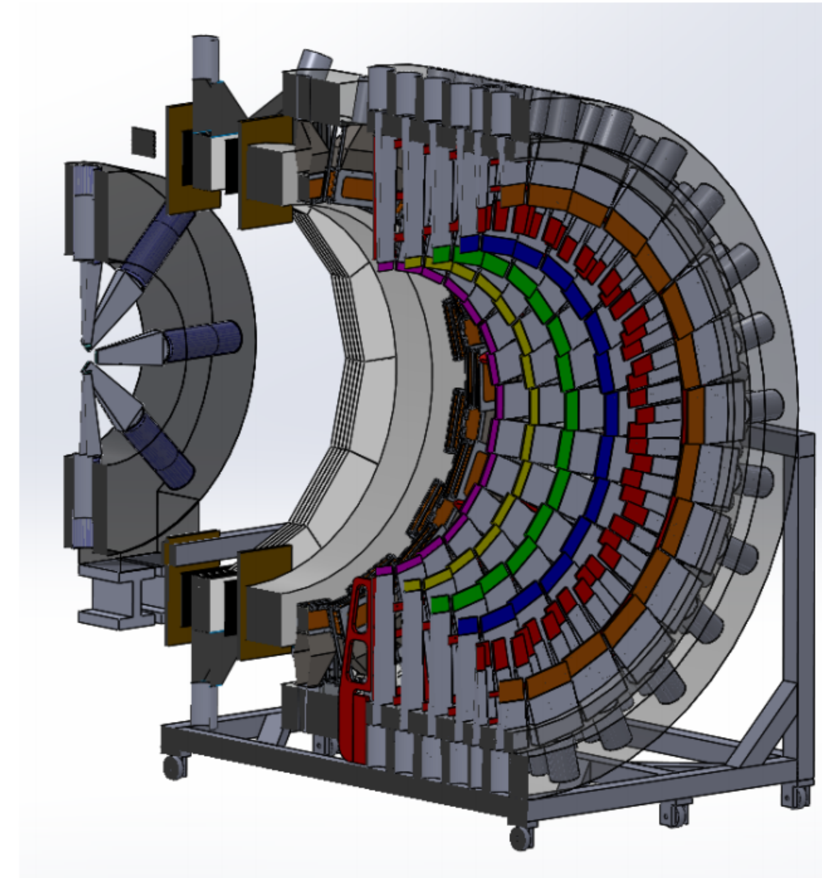
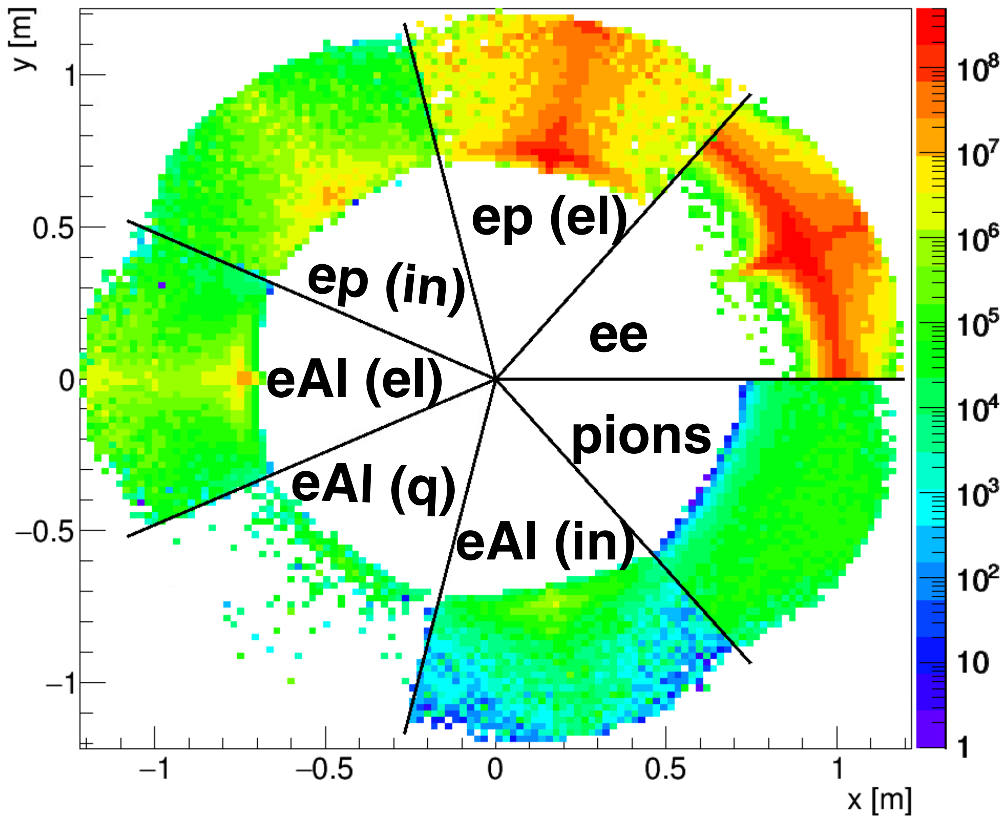




beam energy: 11 GeV
spectrometer E': 2.5 to 8.5 GeV
θ_{lab}: 0.3 to 11 deg

- Fine segmentation on detector allows for measurements of both background and signal
- Novel two toroid design used to separate signal from background into different rings
- Odd number of sectors gives 50% coverage in azimuth but 100% of the acceptance (always get one of the electrons from the event)

MOLLER @ JLab



$$A_{PV} = 35.60 \pm 0.73 \text{ ppb}$$

$$\delta(Q_W^e) = 2.1 \text{ (stat)} \pm 1.0 \text{ (syst) } \%$$

$$\delta(\sin^2\theta_W) = 0.00024 \text{ (stat)} \pm 0.00013 \text{ (syst)} \sim 0.1\%$$

- Will set the highest contact interaction lepton limits (either low or high Q2):

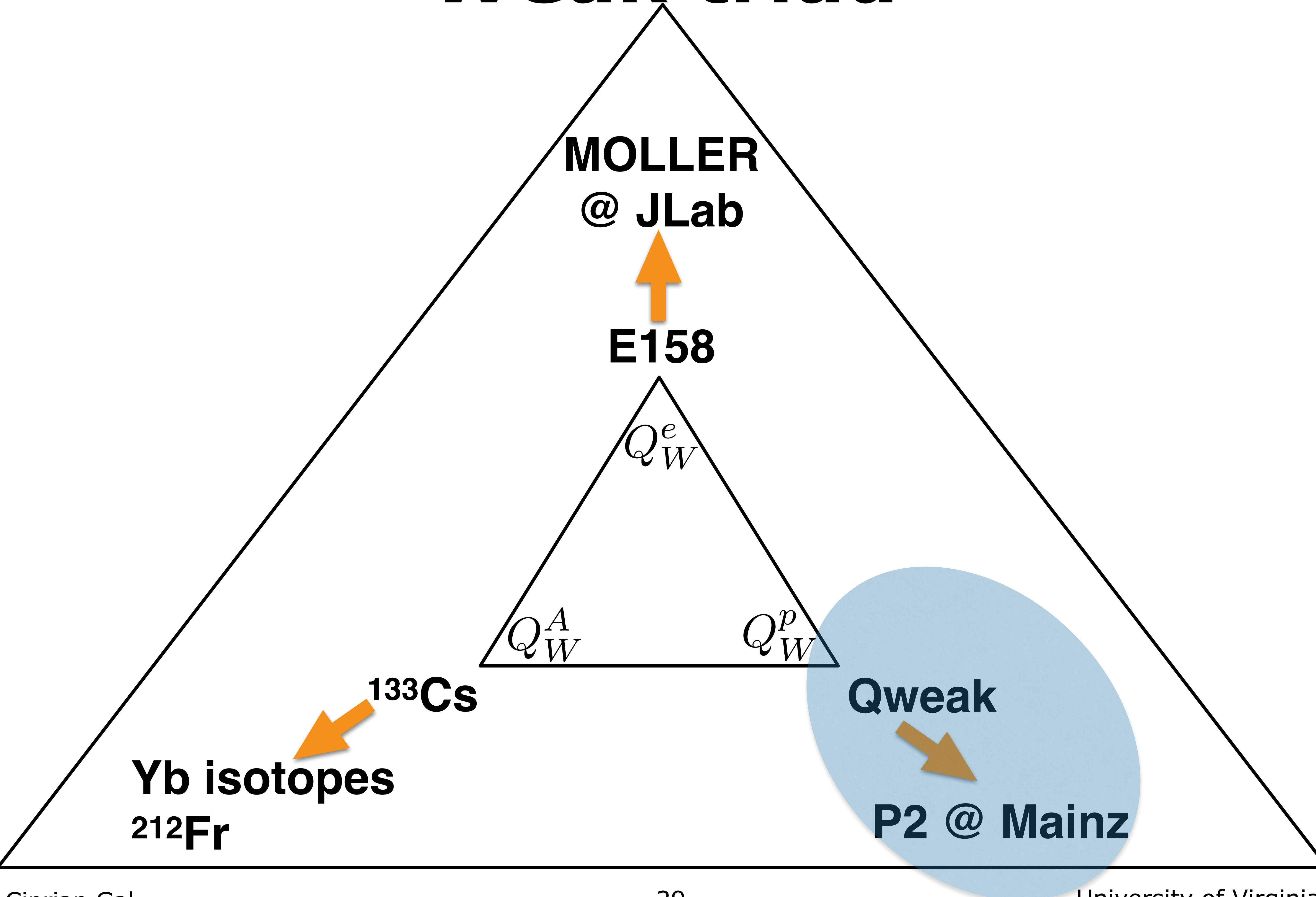
$$\mathcal{L}_{e_1 e_2} = \sum_{\mathbf{i,j=L,R}} \frac{\mathbf{g_{ij}^2}}{\mathbf{2\Lambda^2}} \bar{\mathbf{e}}_\mathbf{i} \gamma_\mu \mathbf{e_i} \bar{\mathbf{e}}_\mathbf{j} \gamma^\mu \mathbf{e_j}$$

$$\frac{\mathbf{\Lambda}}{\sqrt{|\mathbf{g_{RR}^2} - \mathbf{g_{LL}^2}|}} = \mathbf{7.5} \text{ TeV}$$

- Passed CD0 DOE review recently and is planned for a JLab Director's review this winter

- Strong prospects to get results by the middle of the 2020s

Weak triad



MOLLER
@ JLab
E158
Q_W^e
Q_W^A
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^{133}Cs
Yb isotopes
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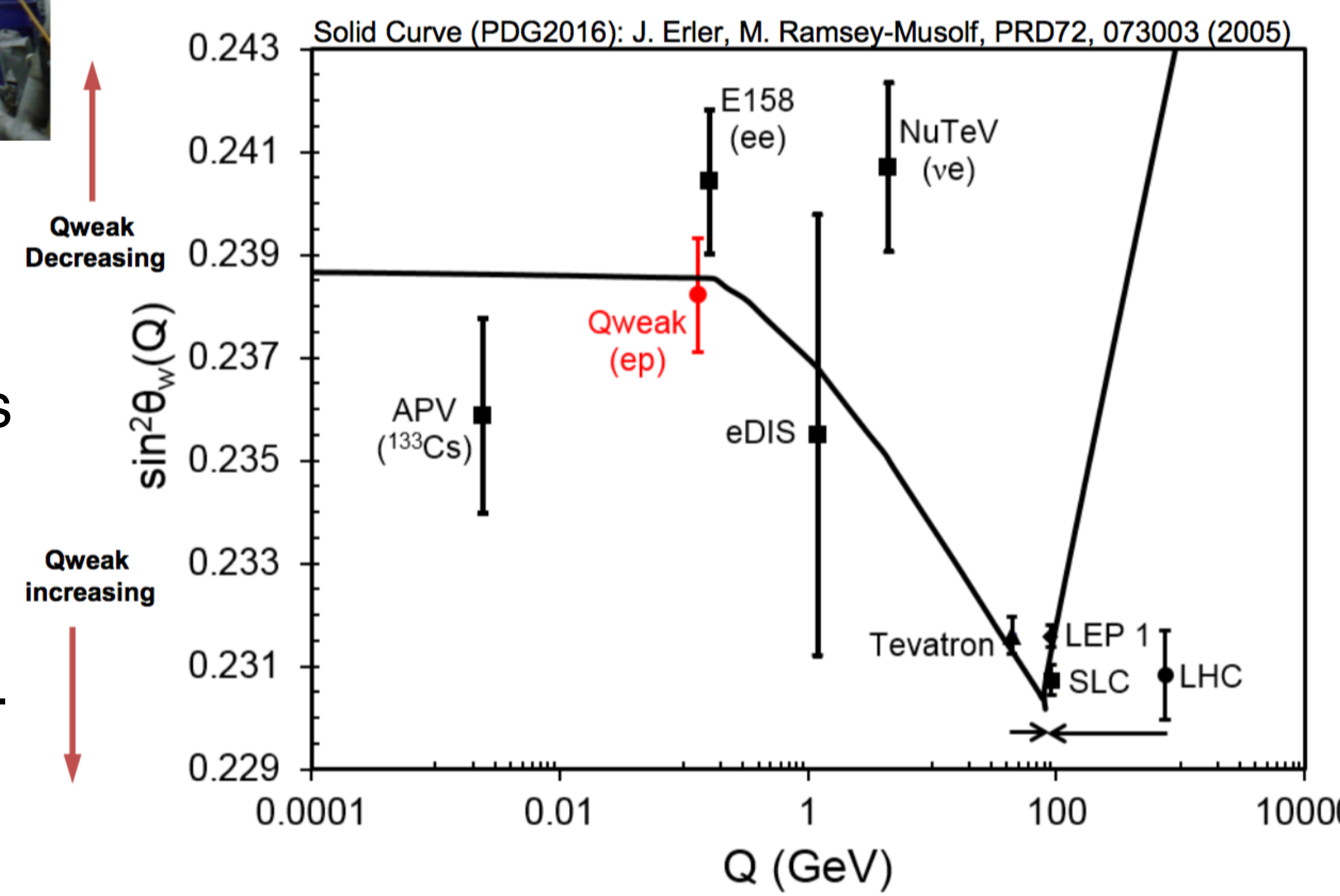
P2 @ Mainz

Qweak

$$A_{PV} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W^p + Q^2 F(\theta, Q^2)\right]$$

- weak mixing angle determined from Global fit of PVES data together with weak charge of the proton (for results and more detail see G. Smith's talk tomorrow)

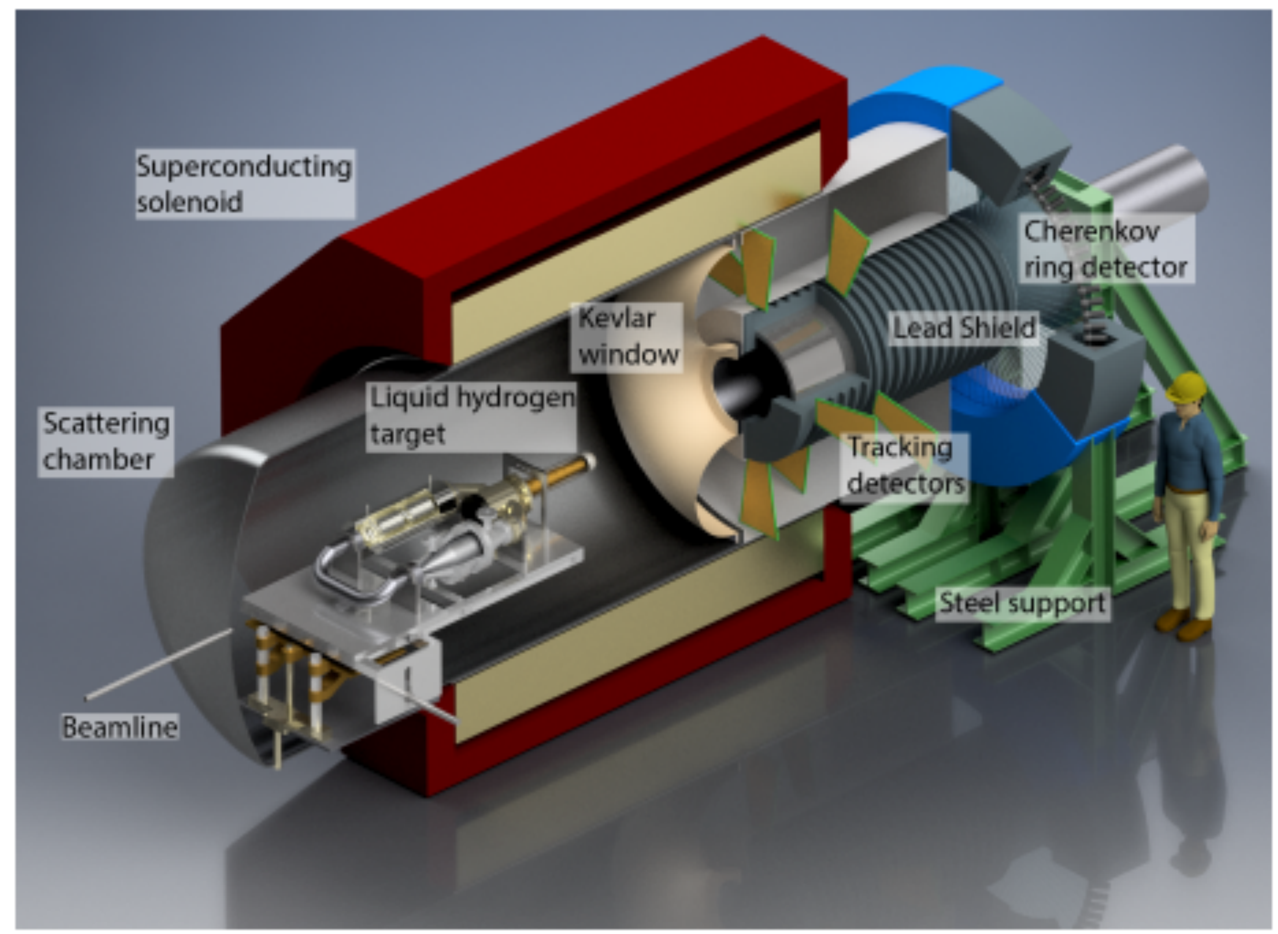


- E158 and Qweak are sensitive to different types of new physics
  - strong consistency with SM for Qweak should put a stronger limit on scalar lepto-quarks (E158 insensitive)

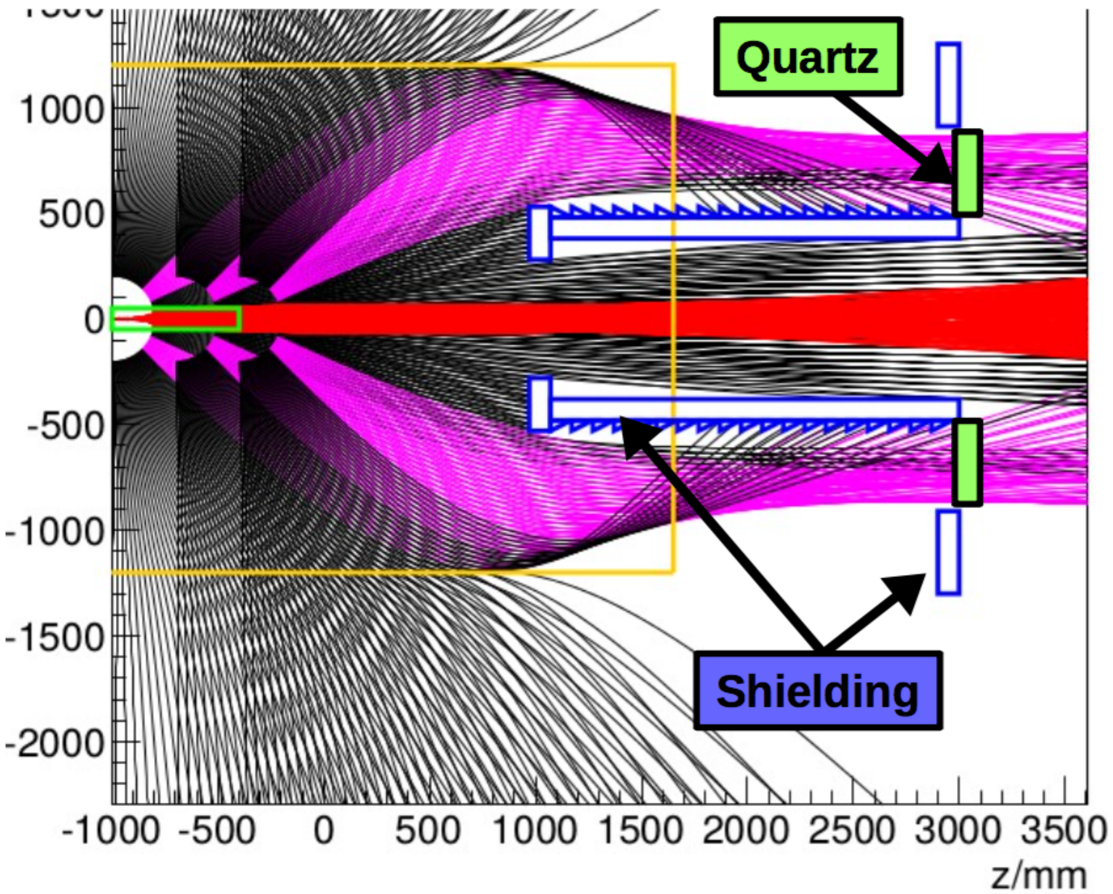
P2 @ Mainz

$$A_{PV} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W^p + Q^2 F(\theta, Q^2)\right]$$

- Will make measurement at significantly lower Q^2 compared to Qweak (0.0048 vs 0.0248 $(GeV/c)^2$)
  - hadronic contributions negligible
- 100x the rate of Qweak
- Scattering angles between 25 and 45 degrees
- 60 cm long target that can take 150 uA of current
- Needs about 1.3 years (11000 hours) to complete main physics program



P2 @ Mainz



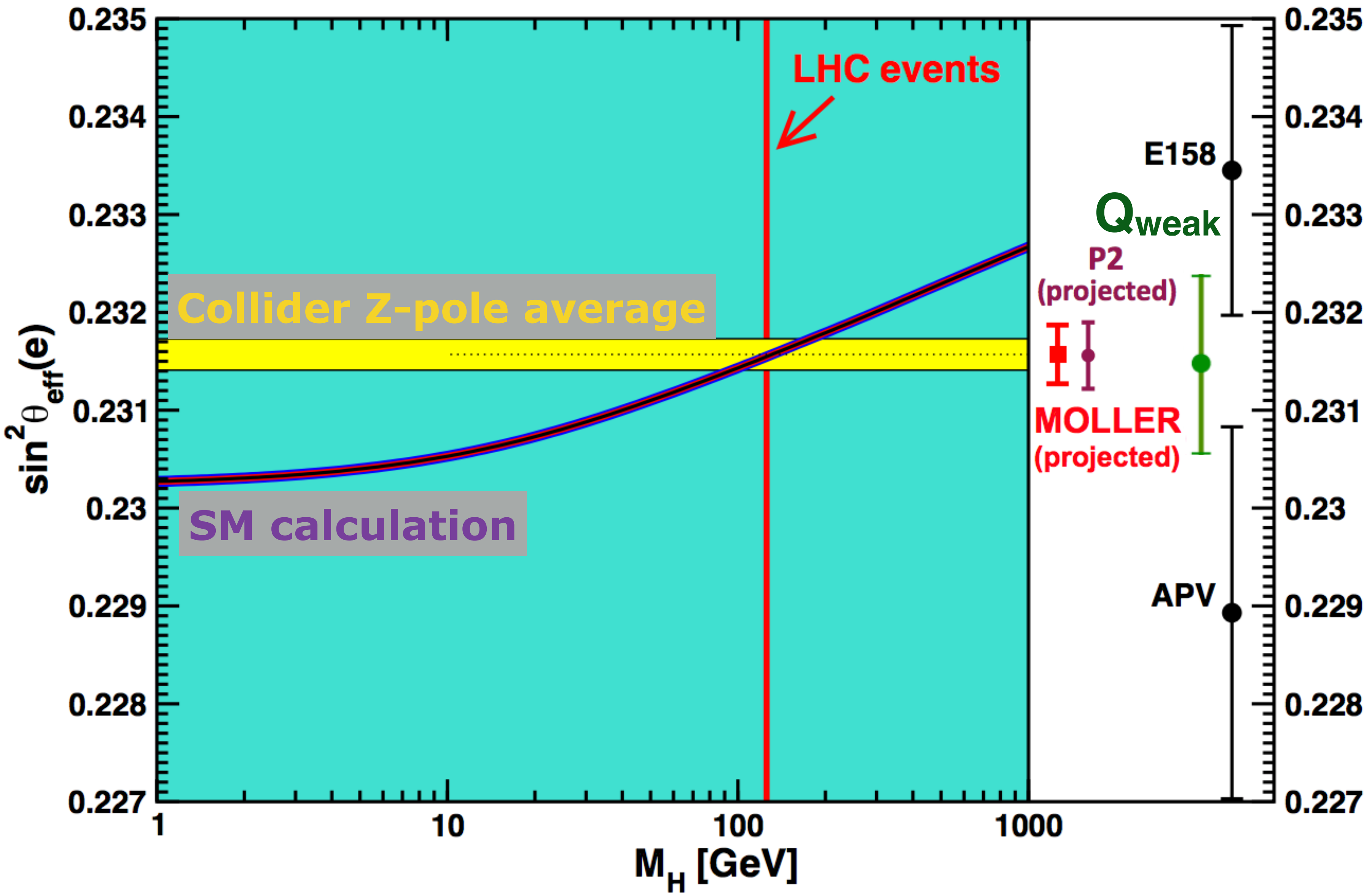
- Solenoid spectrometer enables novel detector configuration
- The new ERL based research machine will support 100-200 MeV parity quality beam
- Development underway and CDR has been submitted to EPJ (https://arxiv.org/abs/1802.04759)

$$A_{PV} = -24.03 \pm 0.44 \text{ ppb}$$

$$\delta(\sin^2\theta_W) = 0.00036 \; (0.15\%)$$

- Will provide test for BSM physics with mass ranges between 70 MeV to 50 TeV
- Expected to run in the early 2020s
  - possible run with Pb (and other nuclei) to better improve neutron radius results from PREX/CREX

Weak mixing angle



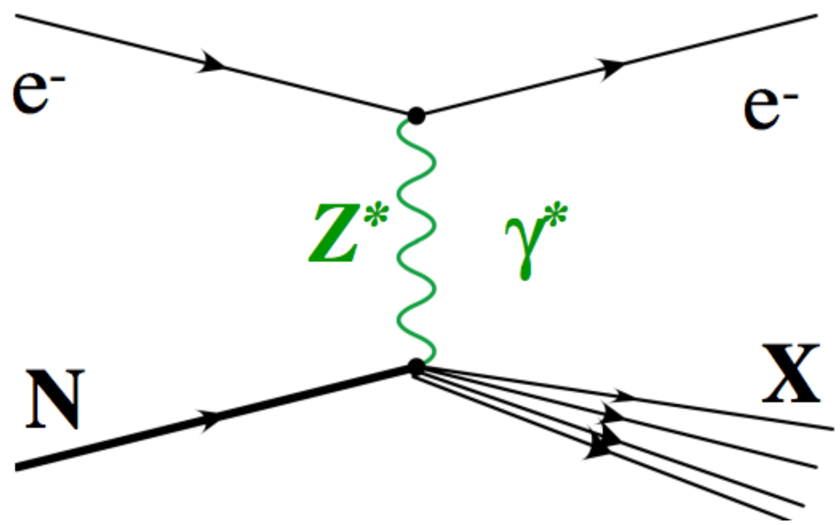
- Both P2 and MOLLER make measurements at very low Q^2 but they will have uncertainties comparable to the best single collider measurement at the Z-pole
  - The low Q^2 nature of the measurements will give significant constraints on physics beyond the Standard Model

The remaining component

$$\mathcal{L}_{eq}^{PV} = -\frac{G_F}{\sqrt{2}} \sum_i \left[C_{1i} \bar{e} \gamma_\mu \gamma_5 e \bar{q} \gamma^\mu q + C_{2q} \bar{e} \gamma_\mu e \bar{q} \gamma^\mu \gamma^5 q \right]$$

- While most of the PV searches so far have focused on vector current extensions to the SM the hadronic-axial vector phase space has been left mostly untouched

PVDIS with SoLID@JLab



- PVDIS uses direct interaction with quarks to access axial-vector component of the interaction where radiative corrections can be directly calculated

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

for Q2 >> 1 and W2 >> 4 GeV2

$$a(x) = \frac{3}{10}\left[(2C_{1u} - C_{1d})\left(1 + \frac{0.6s(x)}{u(x)+d(x)}\right)\right]$$

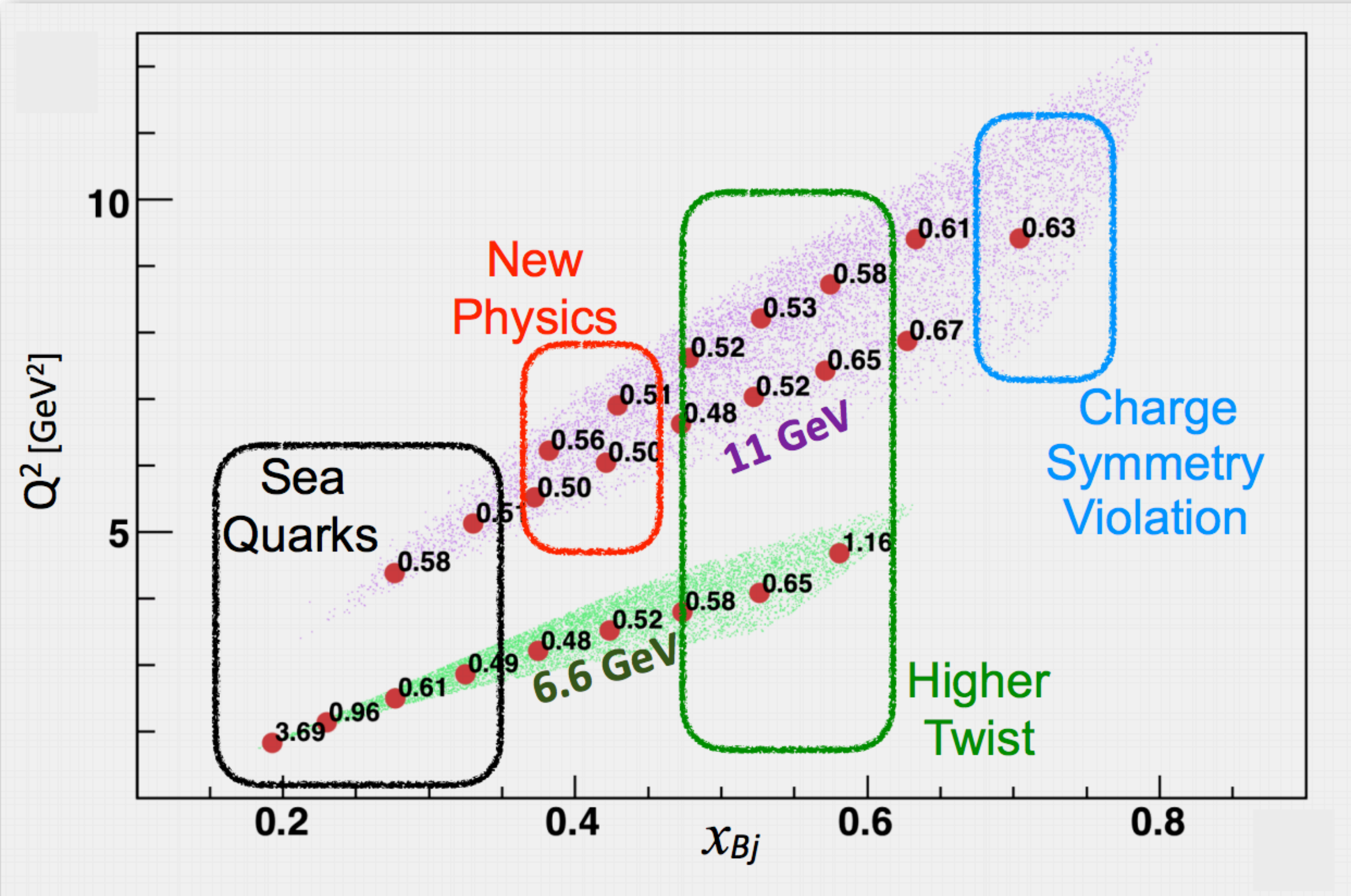
$$b(x) = \frac{3}{10}\left[(2C_{2u} - C_{2d})\left(\frac{u_v(x)+d_v(x)}{u(x)+d(x)}\right)\right]$$

- For a deuterium target the structure functions mostly cancel (assuming charge symmetry)

- PVES in DIS allows for determinations of the axial-vector contributions (C_{2q} terms) without interpretation difficulties due to radiative corrections

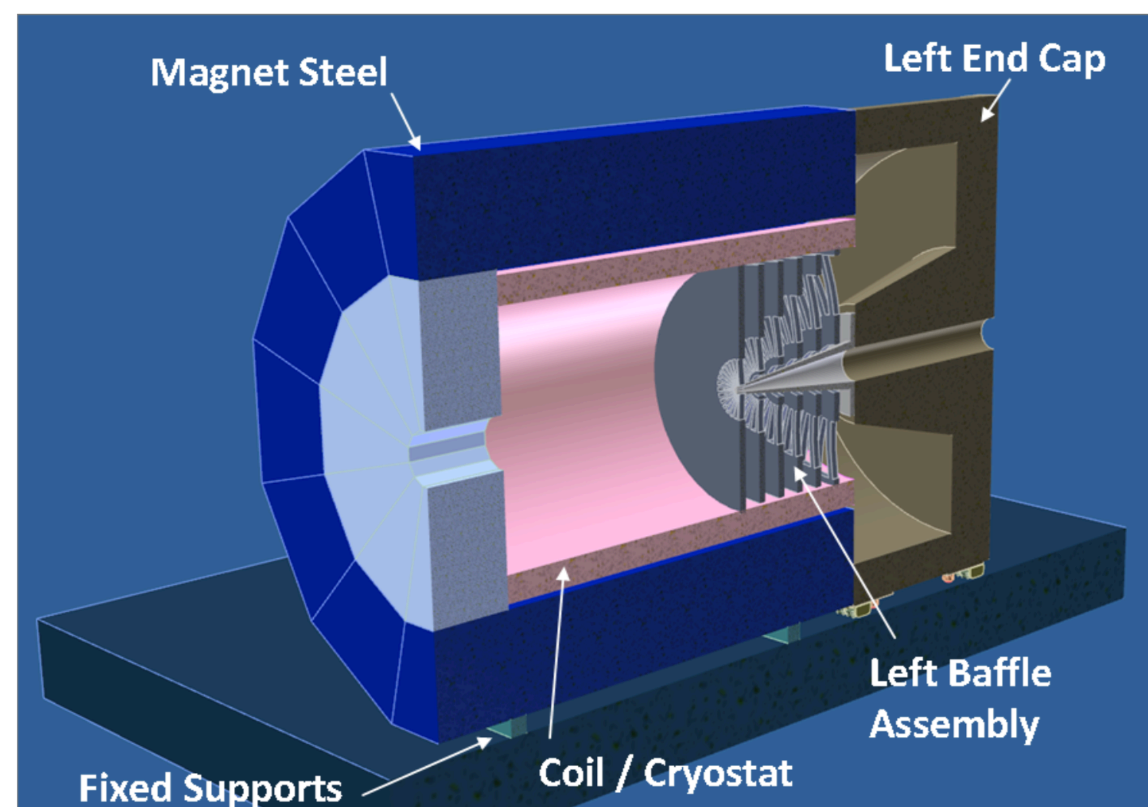
PVDIS with SoLID@JLab

Requires 0.4% *e-* polarimetry

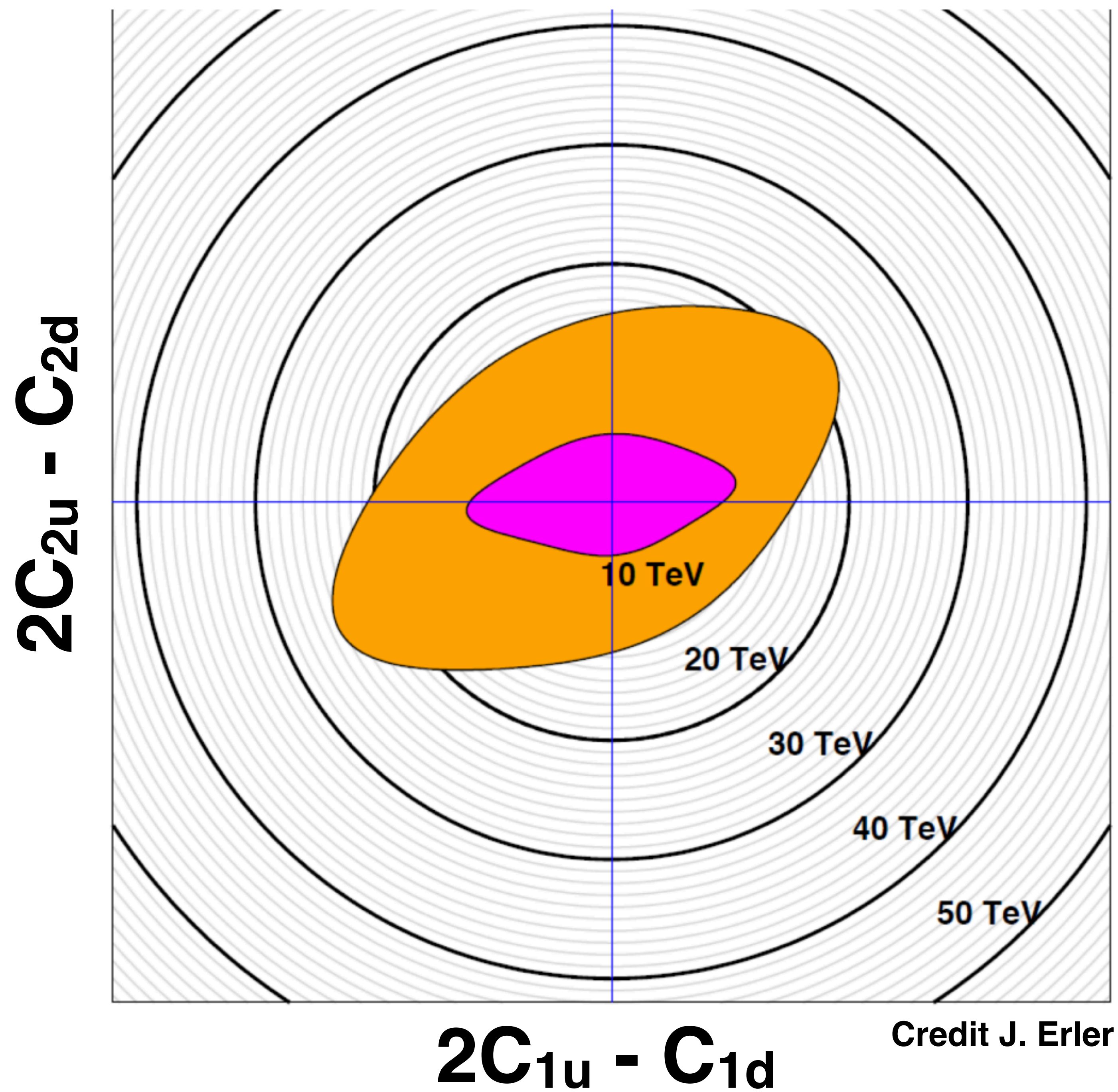


- Large kinematic range allows to measure several interesting effects including:
  - charge symmetry violation
  - higher twist effects
  - d/u ratios without the need to nuclear effects

- The CLEO solenoid is being repurposed for these experiments and more (extensive TMD studies)
- will use GEMs for tracking and Cerenkov + segmented calorimeter
- $\delta p/p$ of ~2%, angle coverage of about 15 degrees (20-35) and scattered energies between 1.5 and 5 GeV



PVDIS with SoLID@JLab



- SoLID (orange) will significantly increase our reach in mass range compared to published data (magenta)

Conclusions

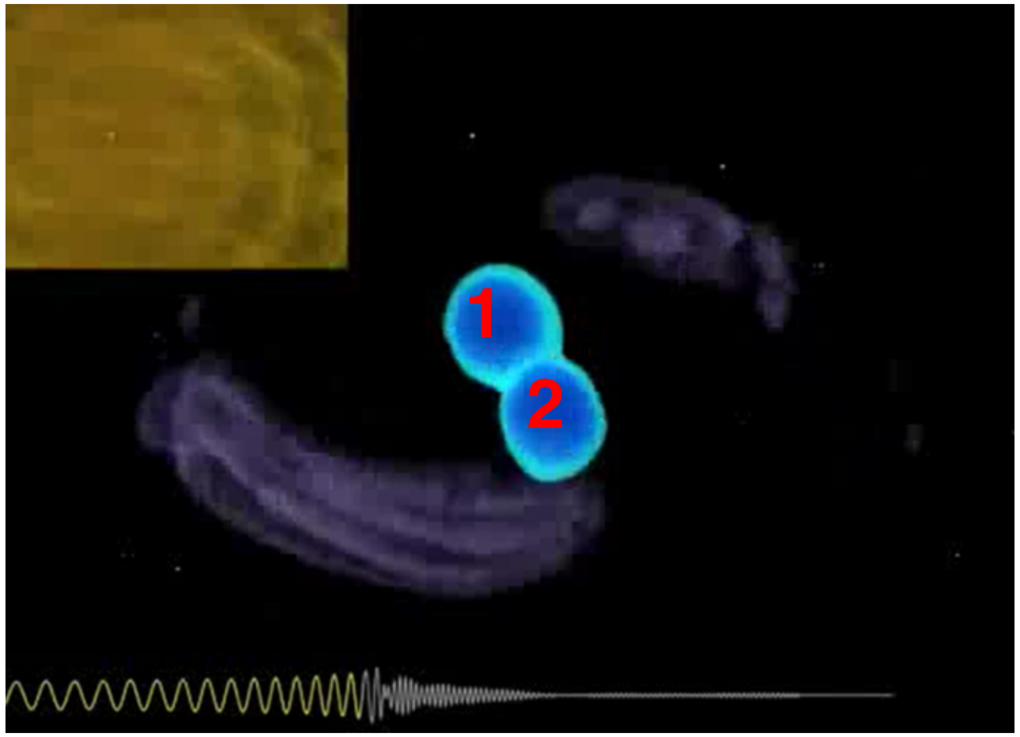
- PVES is a very versatile and clean measurement technique that has been employed to study nuclear and hadronic topics as well as SM tests
  - improved technical capability pushes to higher and higher precision
- The upcoming neutron skin measurements will provide invaluable information about high density nuclear matter
- Electroweak physics will test BSM scenarios in phase space regions not available to direct searches with new interaction mass scales up to 10s of TeV

Backup

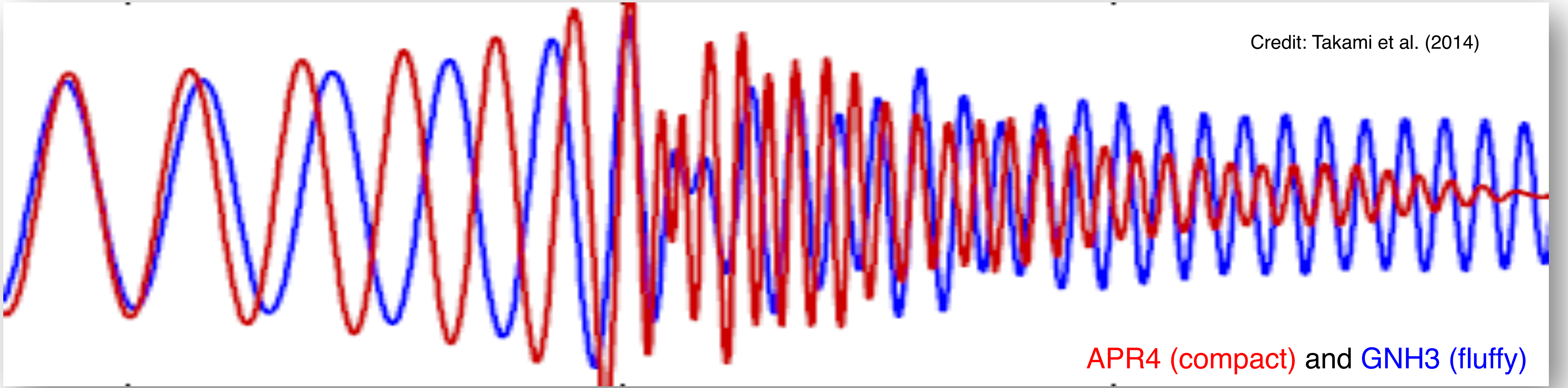
BNS mergers and the nuclear EOS

- Binary neutron star mergers can give us information about the nuclear equation of state

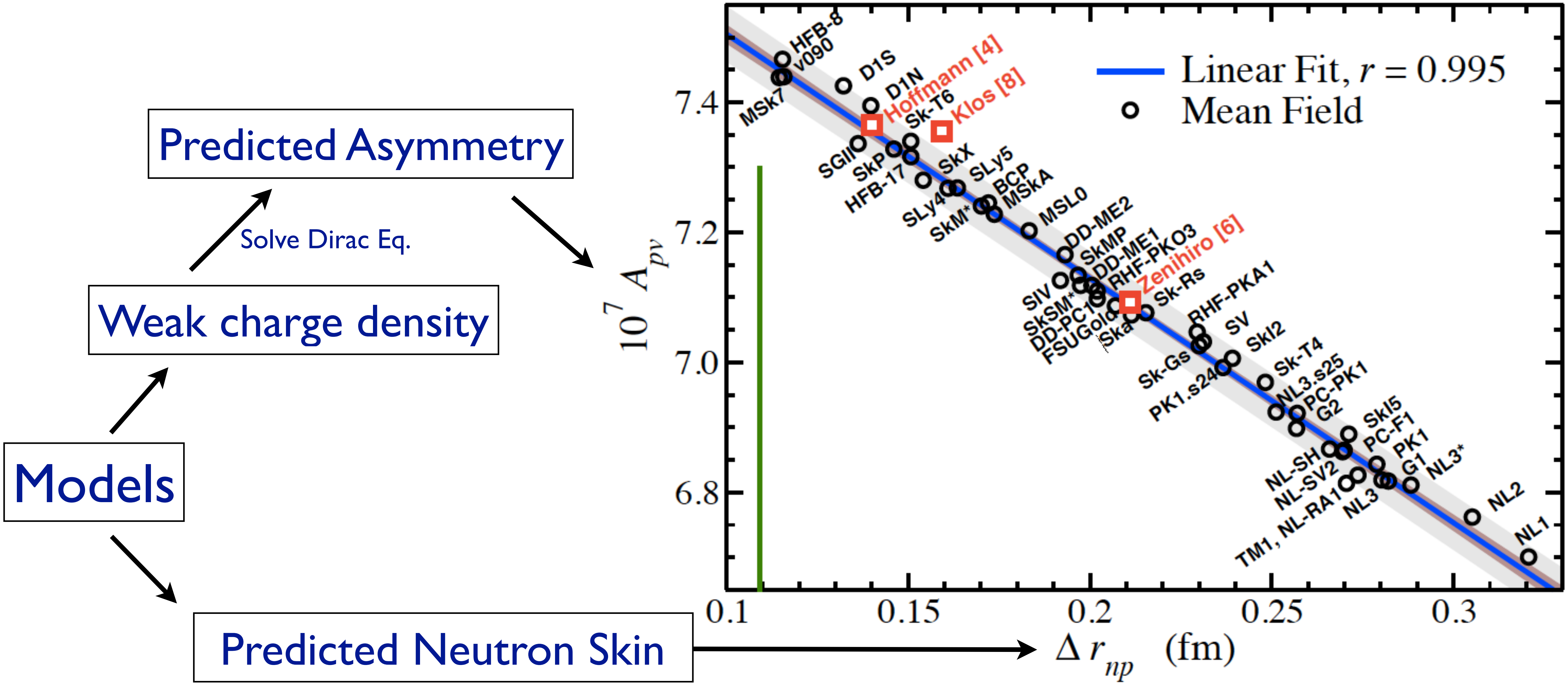
- The waveform and frequency of the inspiral right before the merger are directly correlated to the stiffness of the neutron star



Fattoyev, Piekarewicz, Horowitz
arXiv 1711.06615



Neutron skin extraction



X. Roca-Maza, M. Centelles, X. Vi˜nas, and M. Warda, Phys. Rev. Lett. 106 252501 (2011)

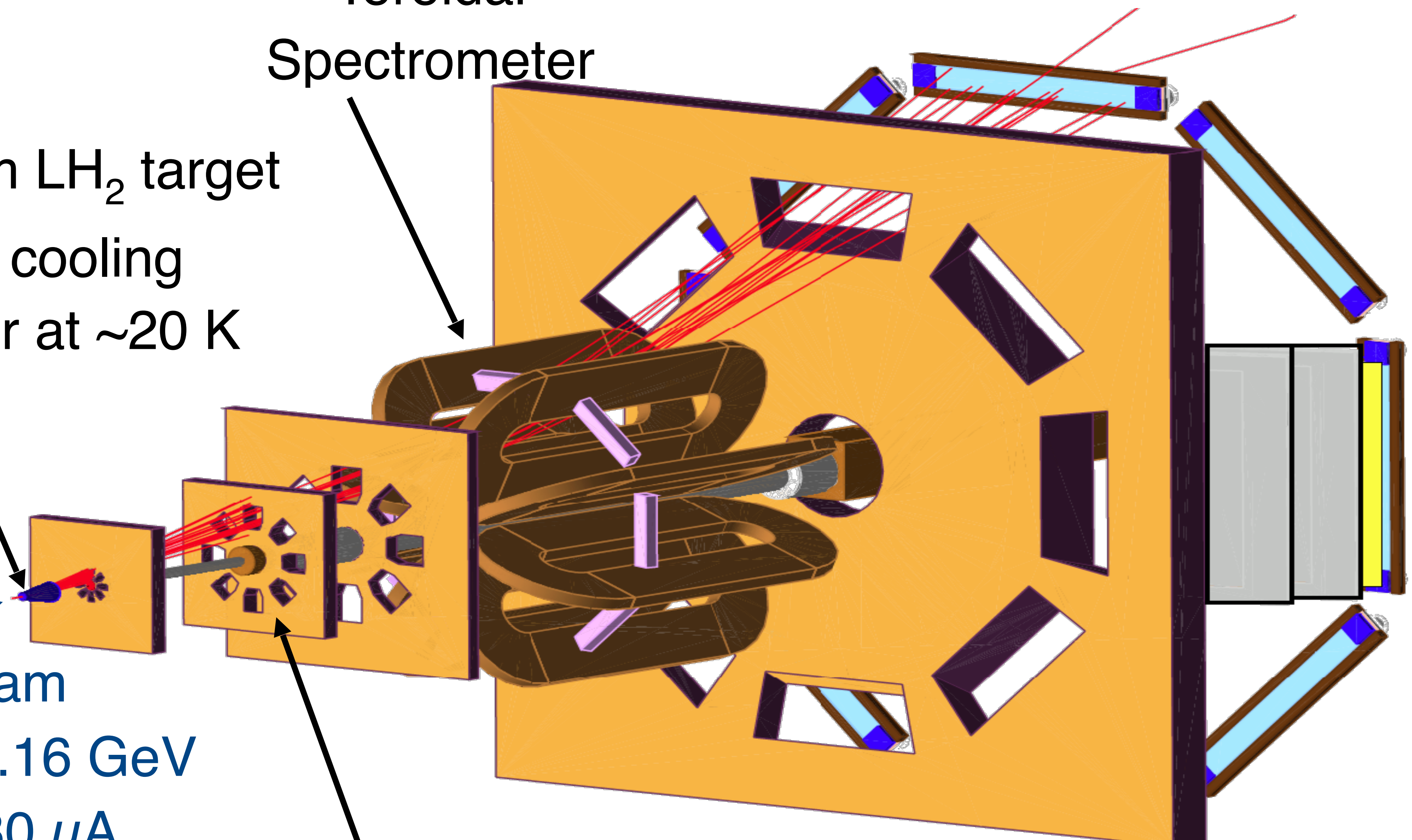
- Clear correlation between APV and the neutron skin from theoretical models
- The minimal theoretical assumptions (Helm model for the weak form factor and different mean field weak charge densities) produce a much small spread than the statistical uncertainty from the final PREX2 result (https://arxiv.org/pdf/1202.1468.pdf)
- This analysis takes into account the significant Coulomb distortions affecting the 208Pb extraction (https://arxiv.org/pdf/nucl-th/9801011.pdf)

Qweak

Toroidal Spectrometer

35 cm LH_2 target

3 kW cooling power at ~20 K



e- beam
E = 1.16 GeV
I = 180 μA
P = 89%

Acceptance defining Pb collimator

$$5.8^o \leq \theta \leq 11.6^o$$

$$A_{PV} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W^p + Q^2 F(\theta, Q^2)\right]$$

Target

E122

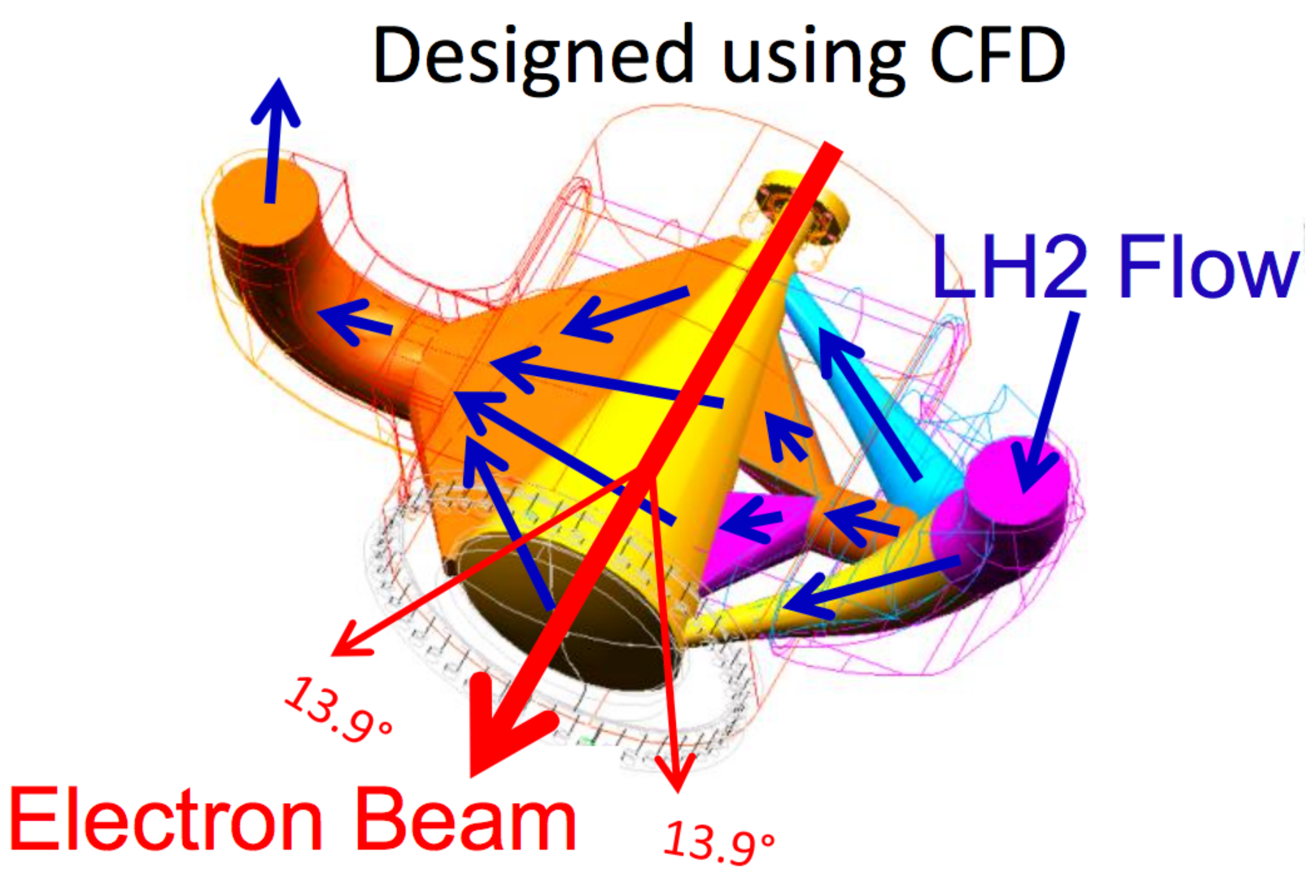
- 30 cm liquid deuterium target

Present

- more than 2.3kW cryo target
- stability measured to better than 40 ppm at 250 Hz

Future

- 1.5 m cryo target
- capable to absorb 4kW and remain stable to better than 25 ppm at 1kHz



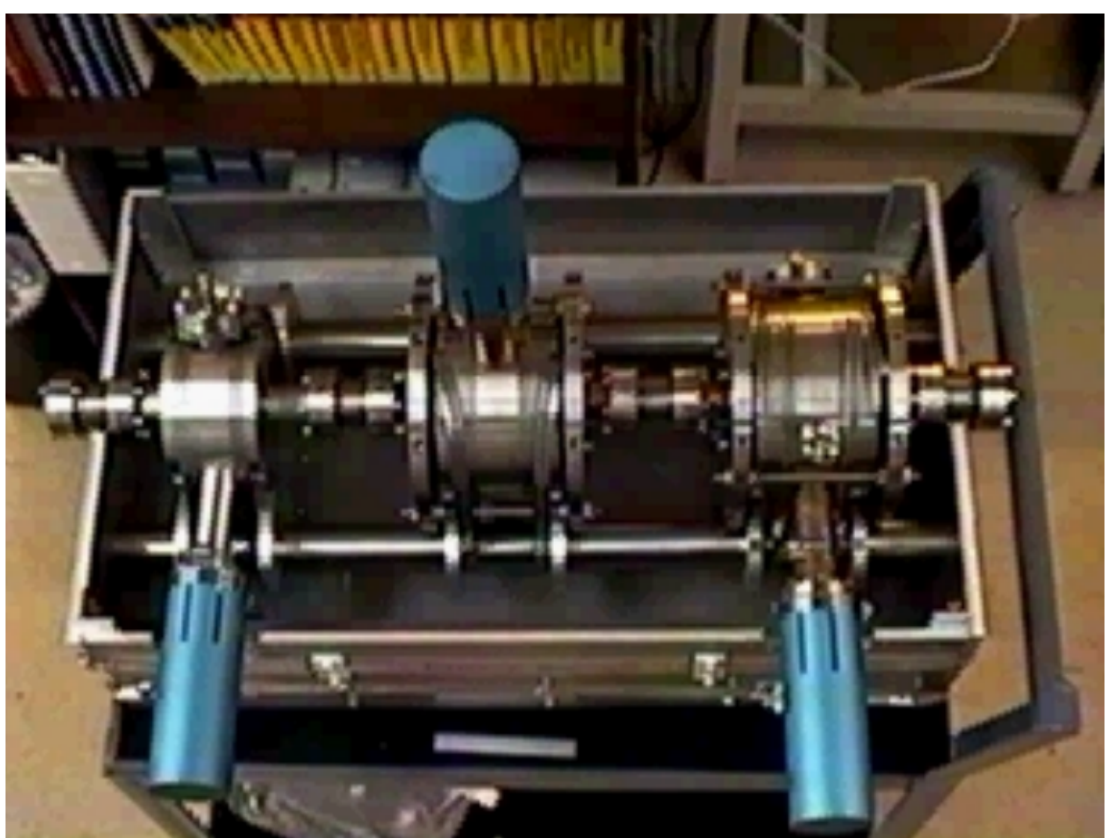
Beam monitors

E122

- measured helicity correlated charge and position differences (10 microns resolution for position differences, 0.02% for charge)
- made use of microwave cavities
- use fast analysis to feedback on accelerator parameters

Present

- we use RF antenna or RF cavities for beam position and charge measurements
- Precisions of ~ 30 ppm for charge and ~1 micron for position at 250 Hz helicity flip rate
- Use fast analysis from the cavities to feedback on the parameters in the injector



Future

- we will need a factor of 3 improvement for the charge measurements
- a further factor of 2 improvements on both angle and position differences

Electroweak radiative corrections

$$Q_W^p = [1 + \Delta\rho + \Delta_e]\left[(1 - 4\sin^2\theta_W(0)) + \Delta_{e'}\right] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$

Correction to Q^p_{Weak}		Uncertainty
Δ *sin* θ_W *(M_Z)*		± 0.0006
Zγ box (6.4% ± 0.6%)	0.00459	± 0.00044
Δ *sin* θ_W *(Q)$_{hadronic}$*		± 0.0003
WW, ZZ box - pQCD		± 0.0001
Charge symmetry		0
Total		± 0.0008

Erler et al., PRD 68(2003)016006.

Calculations of Two Boson Exchange effects on Q_W^p at our Kinematics:

Recent theory calculations applied to entire data set of PV measurements as appropriate in global analysis.

Our ΔA_{ep} precise enough that corrections to higher Q^2 points make little difference in extrapolation to zero Q^2.

Energy Dependence γZ correction:

Hall, N.L., Blunden, P.G., Melnitchouk, W., Thomas, A.W., Young, R.D. Quark-hadron duality constraints on γZ box corrections to parity-violating elastic scattering. Phys. Lett. B 753, 221-226 (2016).

Axial Vector γZ correction:

Peter Blunden, P.G., Melnitchouk, W., Thomas, A.W. New Formulation of γZ Box Corrections to the Weak Charge of the Proton. Phys. Rev. Lett. 107, 081801 (2011).

Q^2 Dependence γZ:

Gorchtein, M., Horowitz, C.J., Ramsey-Musolf, M.J. Model dependence of the γZ dispersion correction to the parity-violating asymmetry in elastic ep scattering. Phys. Rev. C 84, 015502 (2011).

***courtesy of R. Carlini**