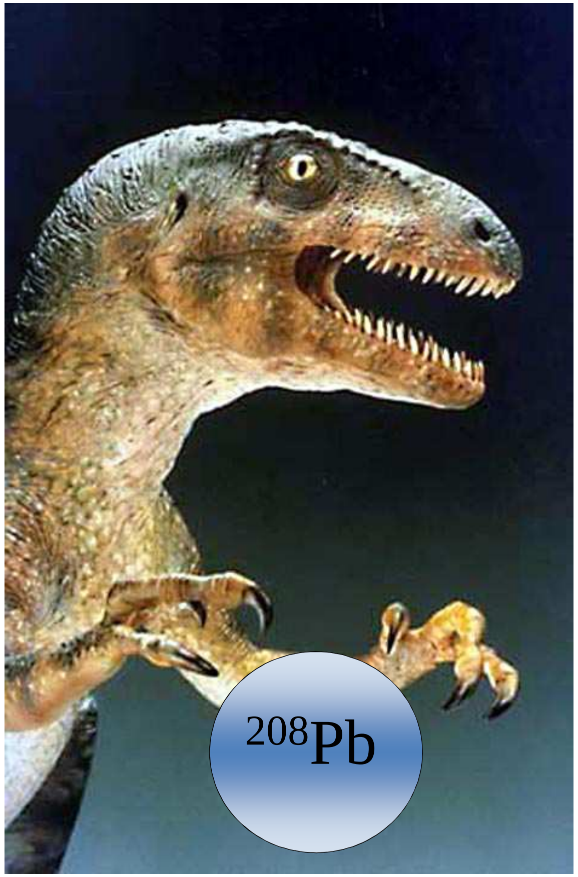
Results from

Lead (^{208}Pb) Radius Experiment : PREX

Elastic Scattering

Parity Violating Asymmetry

E = 1 GeV, $\theta = 5^0$
electrons on lead



Spokespersons

Paul Souder, Krishna Kumar

Guido Urciuoli, Robert Michaels
(speaker)

Graduate Students

Ahmed Zafar, Chun Min Jen,
Abdurahim Rakham (Syracuse)

Jon Wexler (UMass)

Kiadtisak Saenboonruang (UVa)

Ran March – June 2010

in Hall A at Jefferson Lab

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Feb 10, 2012

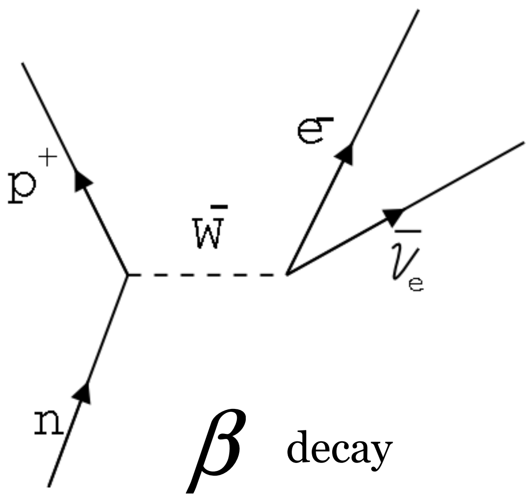
Standard Electroweak Model

The **Glashow-Weinberg-Salam Theory** unifies the electromagnetic and weak interactions.

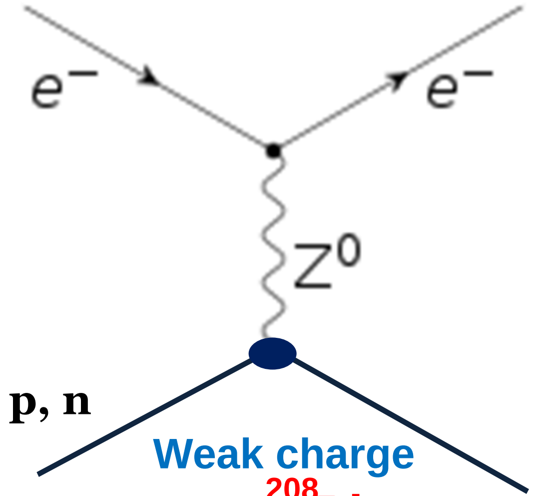
Left –handed fermion fields (quarks & leptons)
= doublets under SU(2)

Right-handed fields = singlets under SU(2)

Parity Violation



β decay



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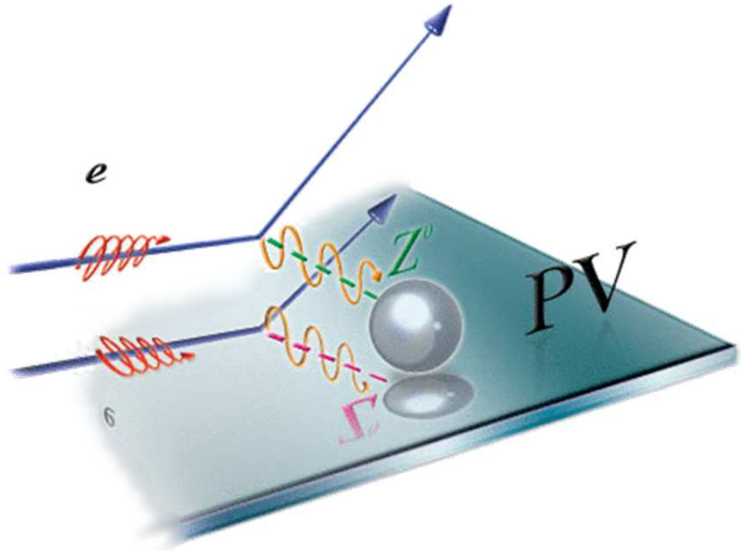
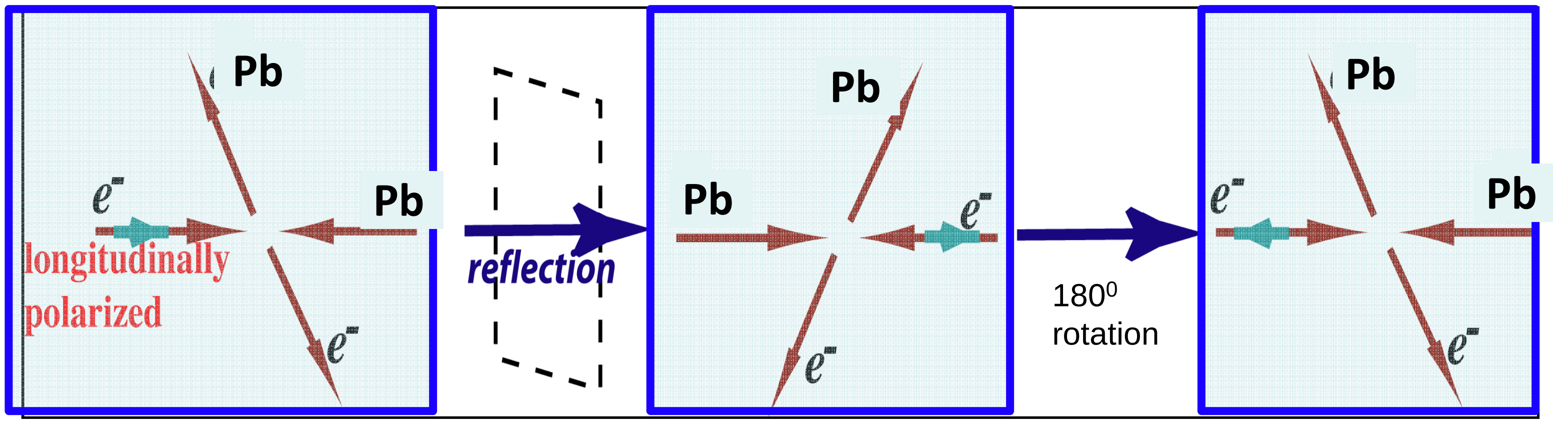
A piece of the weak interaction

violates parity (mirror symmetry)

which allows to isolate it.



Parity Transformation



Positive spin

Negative spin

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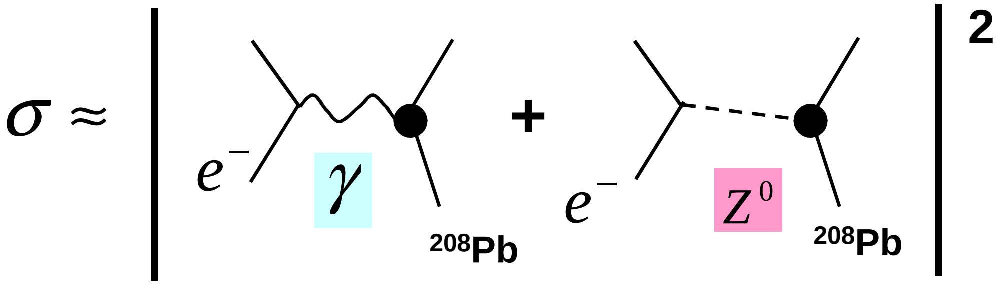
Jefferson Lab
Thomas Jefferson National Accelerator Facility

Parity Violating Asymmetry

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim 10^{-4} \times Q^2 \sim 10^{-6}$$



A_{PV} from interference

Applications of A_{PV} at Jefferson Lab

- **Nucleon Structure**

  Strangeness $s\bar{s}$ in proton (HAPPEX, G0 expts)

- **Test of Standard Model of Electroweak** $\sin^2\theta_W$

  e – e (MOLLER) or **e – q** (PVDIS)
  elastic e – p at low Q^2 (QWEAK)

This talk → • ***Nuclear Structure (neutron density) : PREX***

Idea behind PREX

Z^0 of Weak Interaction :

Clean Probe Couples Mainly to Neutrons

(T.W. Donnelly, J. Dubach, I Sick 1989)

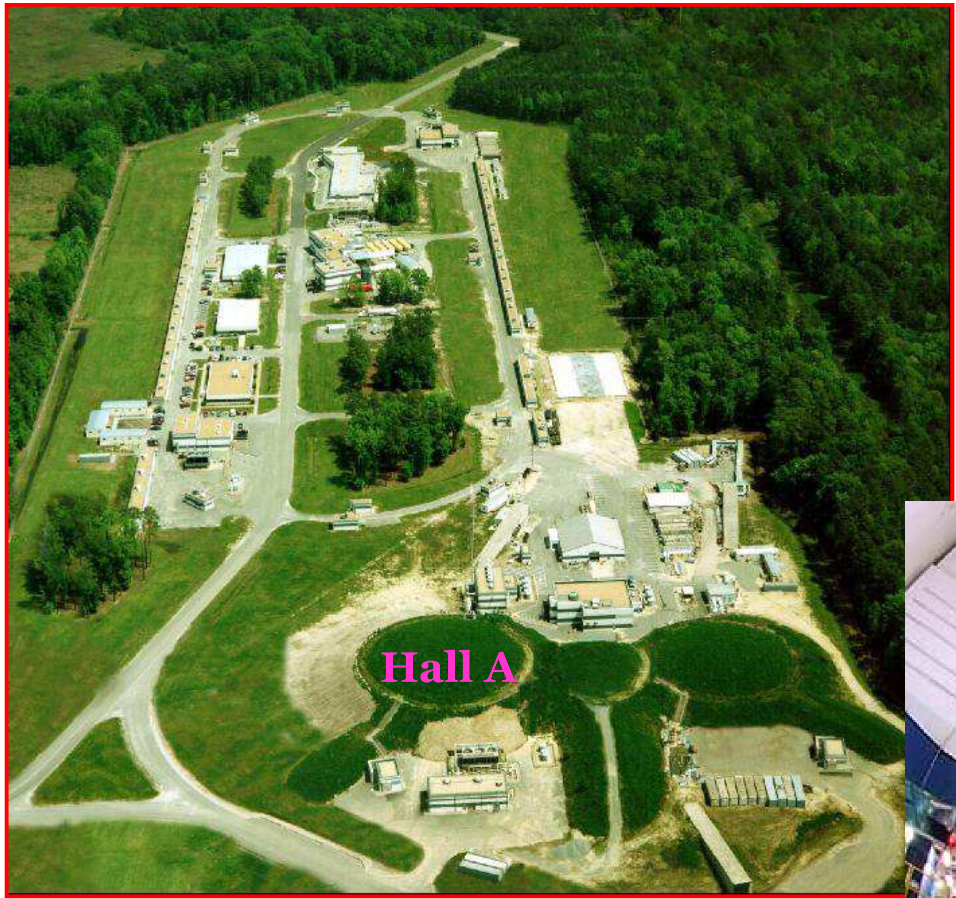
In PWIA (to illustrate) :

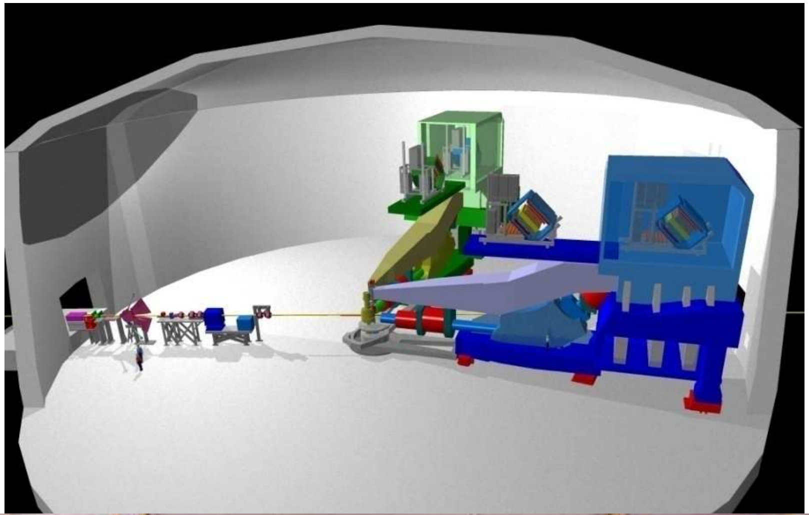
$$A = \frac{\left(\frac{d\sigma}{d\Omega}\right)_R - \left(\frac{d\sigma}{d\Omega}\right)_L}{\left(\frac{d\sigma}{d\Omega}\right)_R + \left(\frac{d\sigma}{d\Omega}\right)_L} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}}\left[\underbrace{1 - 4\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_P(Q^2)}\right]$$

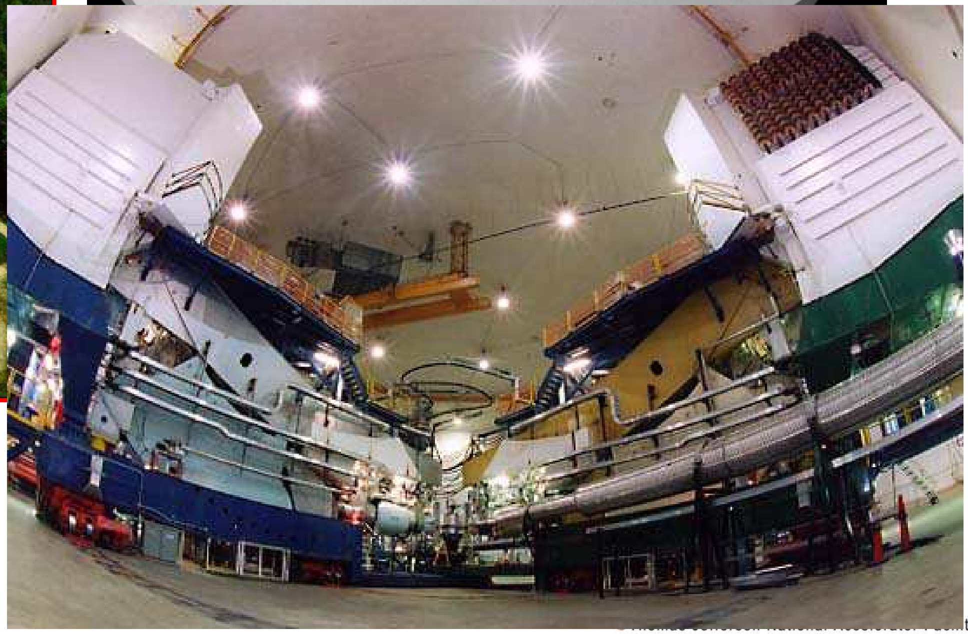
w/ Coulomb distortions (C. J. Horowitz) :

$$\frac{dA}{A} = 3\% \quad \rightarrow \quad \frac{dR_n}{R_n} = 1\%$$

Hall A at Jefferson Lab







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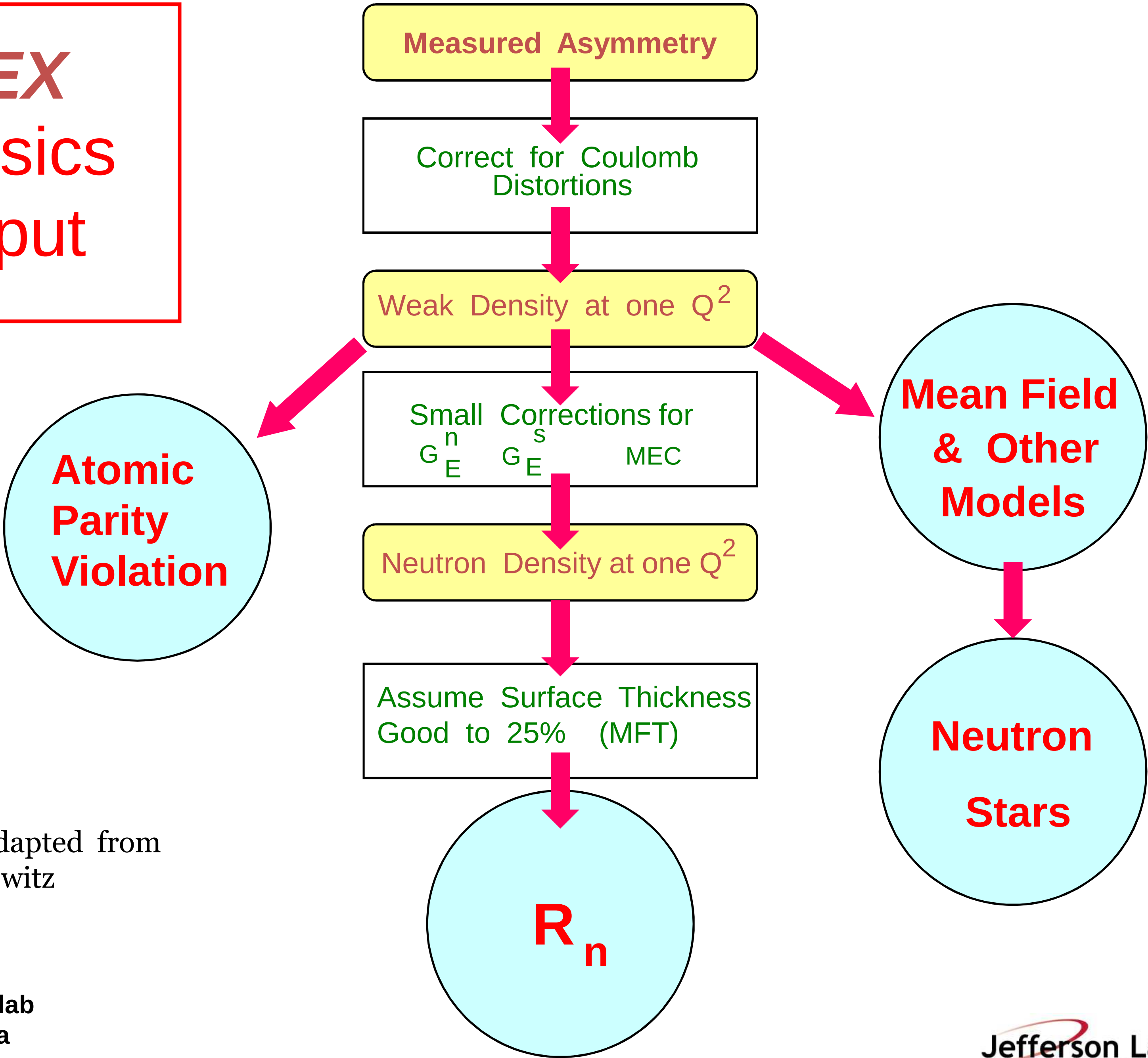
PREX

Physics Output



Slide adapted from
C. Horowitz

Fundamental Nuclear Physics :

What is the size of a nucleus ?

Neutrons are thought to determine
the size of heavy nuclei like ^{208}Pb.

Can theory predict it ?

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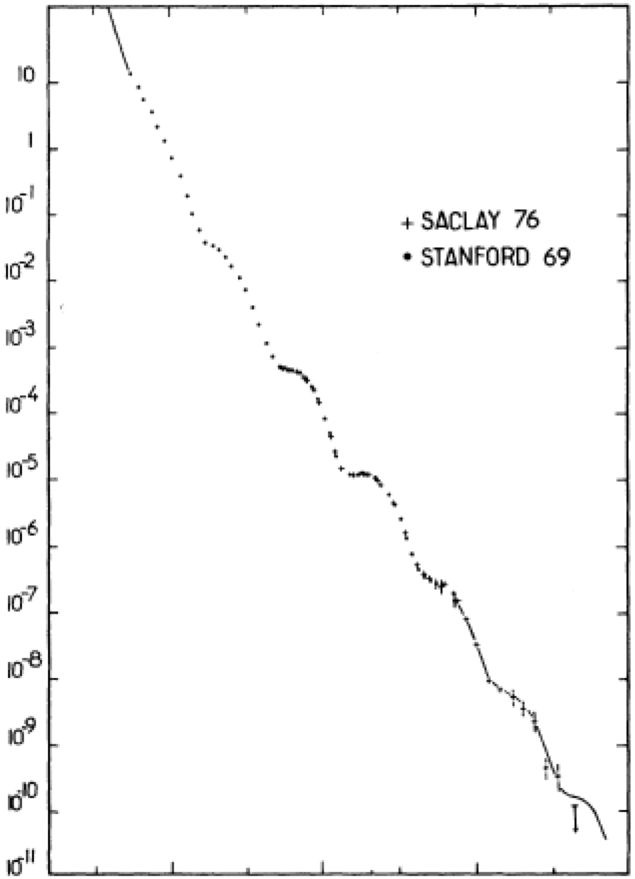
Reminder: Electromagnetic Scattering determines $\rho(r)$

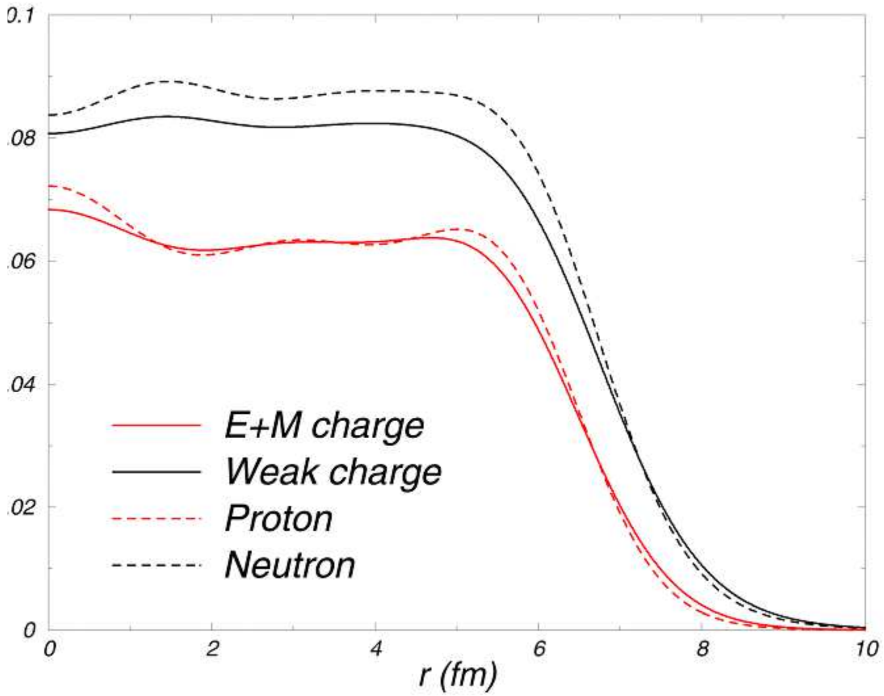
(charge distribution)

^{208}Pb



$q \ (fm)^{-1}$

$\rho(r)$



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Z^0 of weak interaction : sees the neutrons

	proton	neutron
Electric charge	1	0
Weak charge	0.08	1

T.W. Donnelly, J. Dubach, I. Sick
Nucl. Phys. A 503, 589, 1989

C. J. Horowitz, S. J. Pollock, P. A. Souder, R. Michaels
Phys. Rev. C 63, 025501, 2001

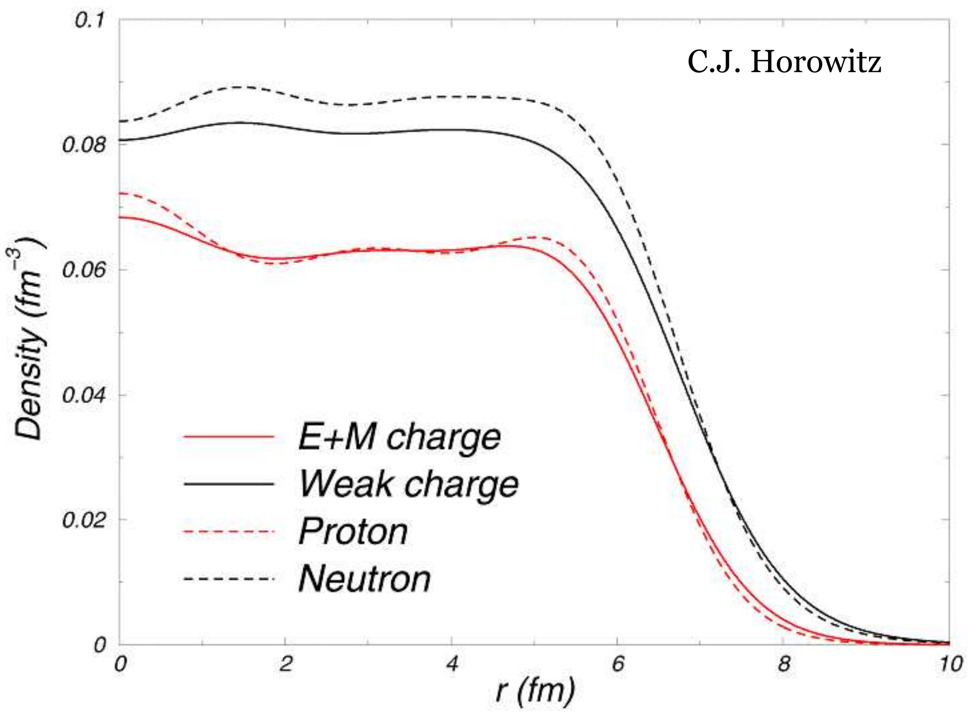
^{208}Pb

Neutron form factor

$$F_N(Q^2) = \frac{1}{4\pi} \int d^3r \; j_0(qr) \; \rho_N(r)$$

Parity Violating Asymmetry

$$A = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[\underbrace{1 - 4\sin^2\theta_W}_{\approx 0} - \frac{F_N(Q^2)}{F_P(Q^2)} \right]$$



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How to Measure

Neutron Distributions, Symmetry Energy

- Proton-Nucleus Elastic
- Pion, alpha, d Scattering
- Pion Photoproduction
- Heavy ion collisions
- Rare Isotopes (dripline)

} Involve strong probes

- Magnetic scattering → Most spins couple to zero.

- PREX (weak interaction)

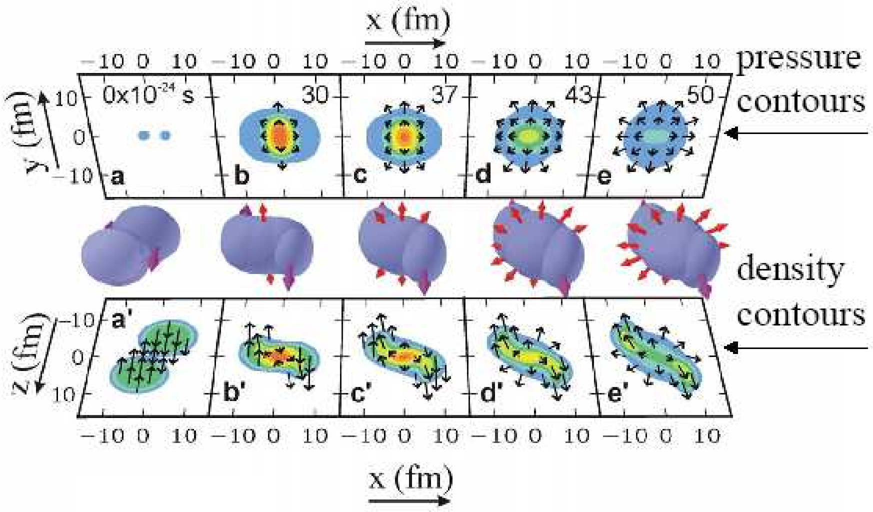
- Theory → MFT fit mostly by data *other than* neutron densities

Example: Heavy Ions

(adapted from Betty Tsang, PREX Workshop, 2008)

Constraining the EOS at high densities by laboratory collisions

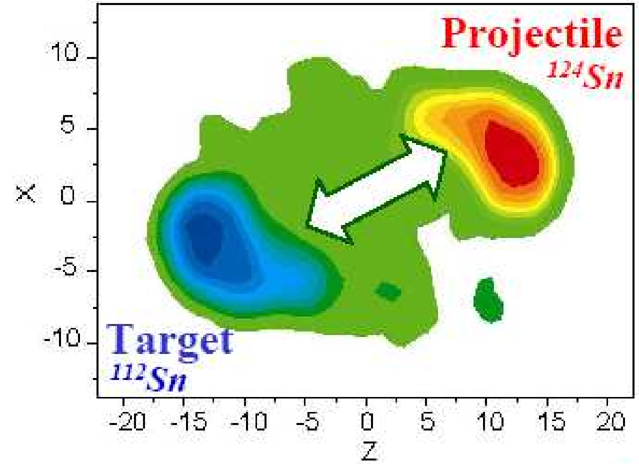
Danielewicz, Lacey, Lynch, Science 298,1592 (2002)

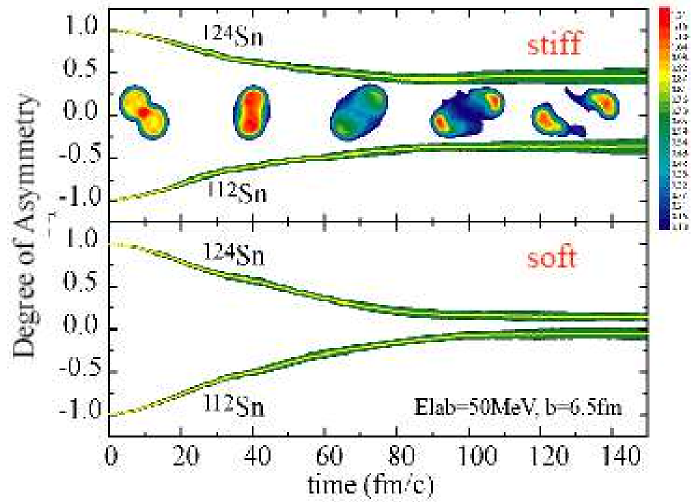


- *Experiment: measure collective flow (emission patterns) of particles emitted in Au+Au collisions from (E/A~1-8 GeV).*
- *Transport model (BUU) relates the measurements to pressure and density.*

Isospin Diffusion (NSCL)

Probe the symmetry energy in ^{124}Sn + ^{112}Sn





Using Parity Violation

Electron - Nucleus Potential $\hat{V}(r) = V(r) + \gamma_5 A(r)$

electromagnetic

$$V(r) = \int d^3r' \; Z \; \rho(r') / |\vec{r} - \vec{r}'|$$

axial

$$A(r) = \frac{G_F}{2\sqrt{2}} \left[(1 - 4\sin^2\theta_W) Z \rho_P(r) - N \rho_N(r) \right]$$

^{208}Pb is spin 0

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{Mott} |F_P(Q^2)|^2$$

⇨ $A(r)$ is small, best observed by parity violation

⇨ $1 - 4\sin^2\theta_W << 1$ neutron weak charge >> proton weak charge

Proton form factor

$$F_P(Q^2) = \frac{1}{4\pi} \int d^3r \; j_0(qr) \; \rho_P(r)$$

Neutron form factor

$$F_N(Q^2) = \frac{1}{4\pi} \int d^3r \; j_0(qr) \; \rho_N(r)$$

Parity Violating Asymmetry

$$A = \frac{\left(\frac{d\sigma}{d\Omega}\right)_R - \left(\frac{d\sigma}{d\Omega}\right)_L}{\left(\frac{d\sigma}{d\Omega}\right)_R + \left(\frac{d\sigma}{d\Omega}\right)_L} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[\underbrace{1 - 4\sin^2\theta_W}_{\approx 0} - \frac{F_N(Q^2)}{F_P(Q^2)} \right]$$

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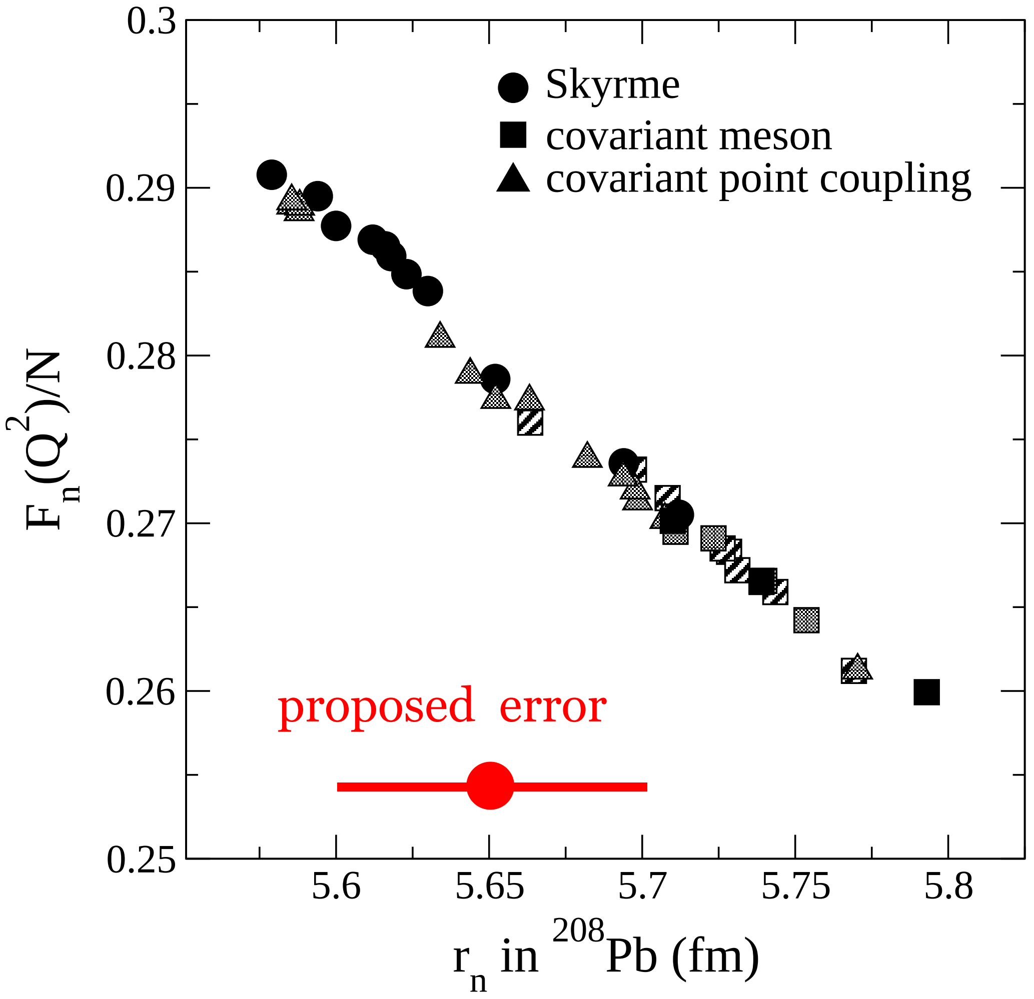
PREX:



Why only one parameter ?

(next slide...)

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Slide adapted from J. Piekarewicz

Nuclear Structure: *Neutron density is a fundamental observable that remains elusive.*

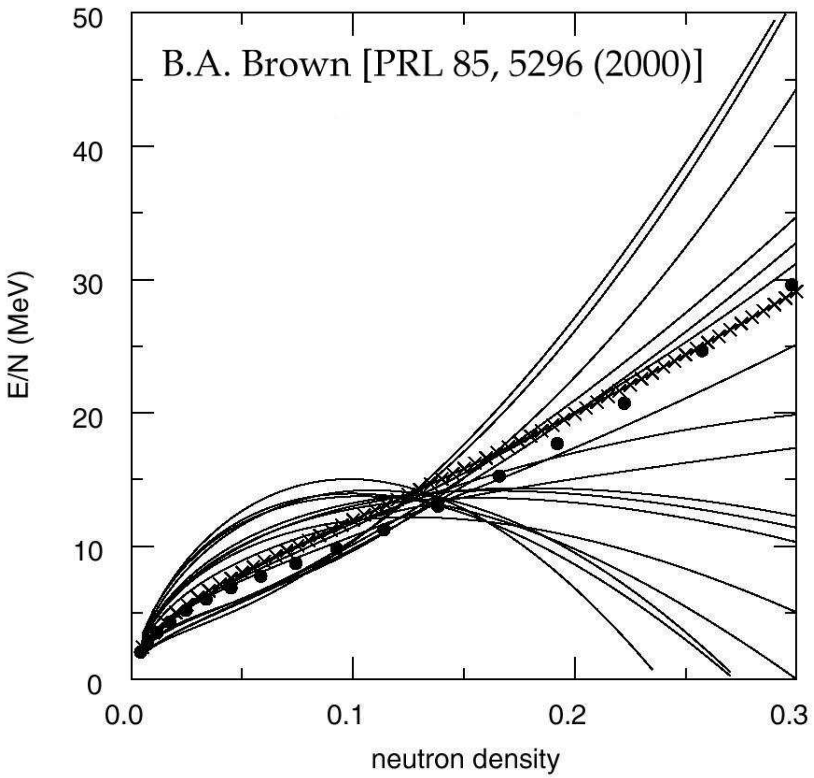


FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of neutron/fm^3.

Reflects poor understanding of symmetry energy of nuclear matter = the energy cost of $N \neq Z$

$$E(n,x) = E(n, x=1/2) + S_v(n)(1-2x^2)$$

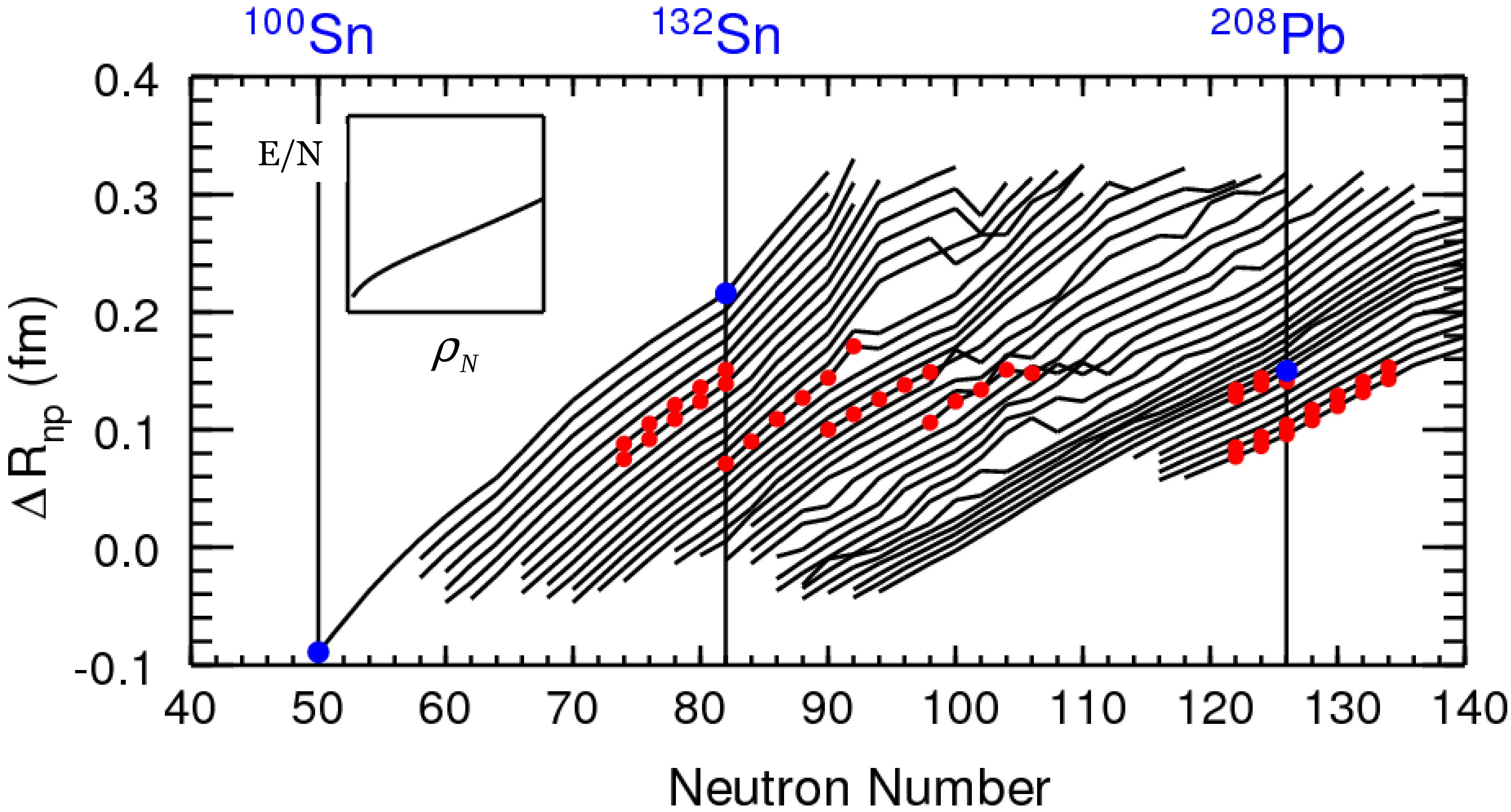
n = n.m. density x = ratio proton/neutrons

- Slope unconstrained by data
- Adding R_N from ^{208}Pb will significantly reduce the dispersion in plot.

Thanks, Alex Brown

PREX Workshop 2008

Skx-s15



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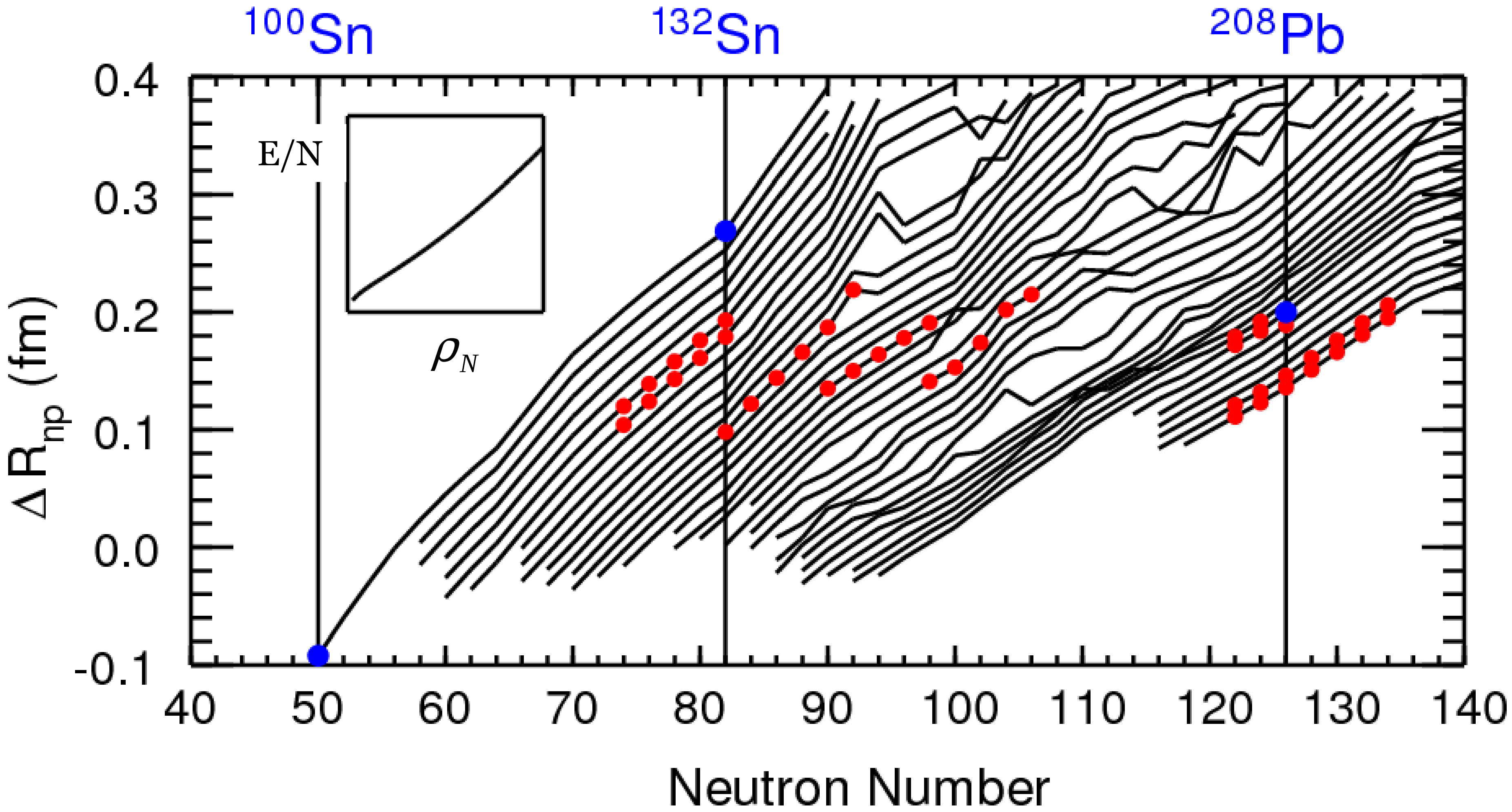
Thanks, Alex Brown

PREX Workshop 2008

Skx-s20



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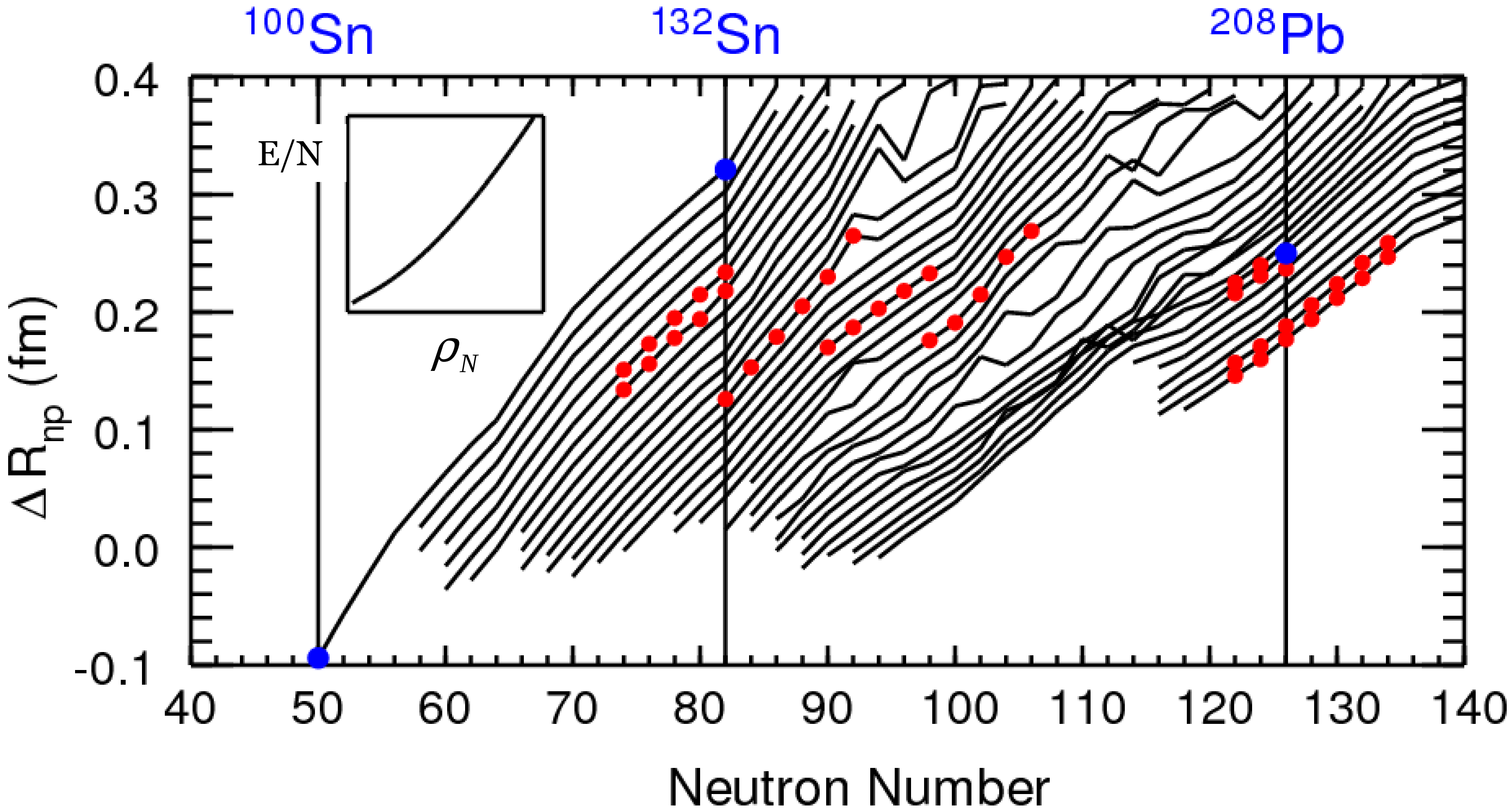
Thanks, Alex Brown

PREX Workshop 2008

Skx-s25



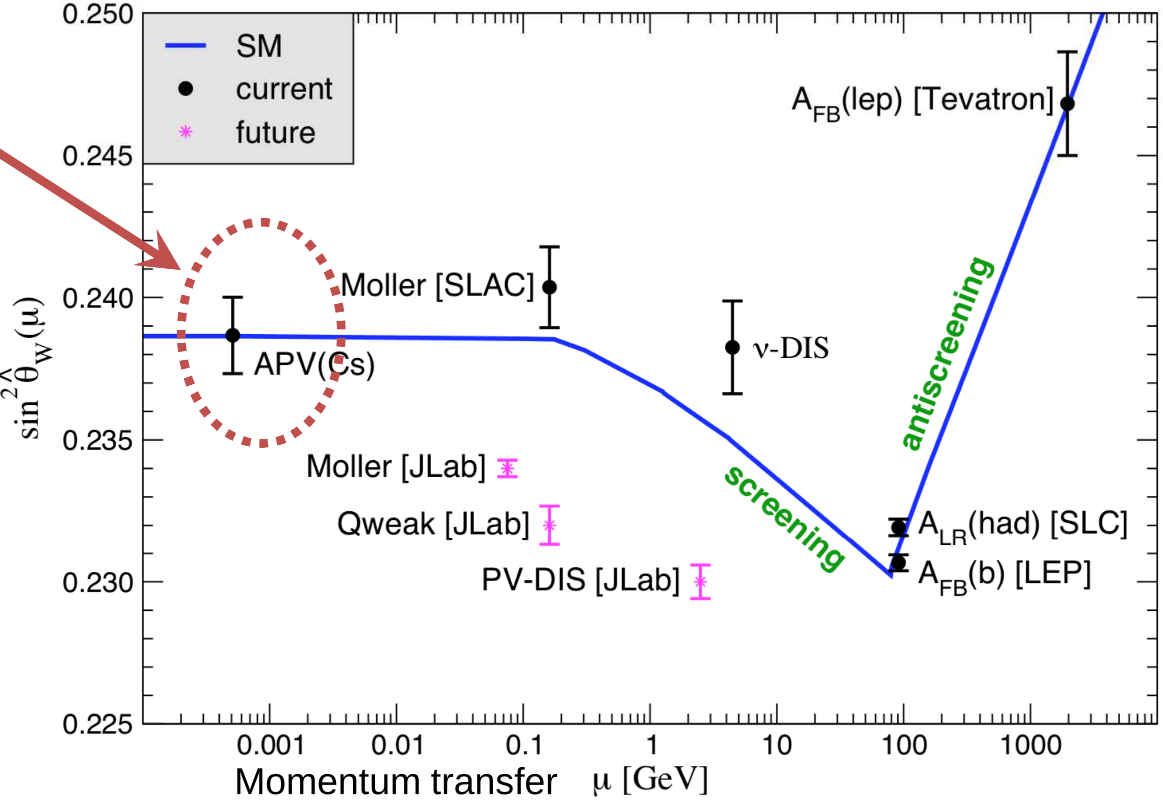
Application: **Atomic Parity Violation**

- Low Q^2 test of Standard Model
- Needs R_N (or APV measures R_N)

Isotope Chain Experiments
e.g. Berkeley Yb

$$H_{PNC} \approx \frac{G_F}{2\sqrt{2}} \int \left[-N\, \rho_N(\vec{r}) + Z(1-4\sin^2\theta_W)\,\rho_P(\vec{r}) \right] \psi_e^{\prime}\, \gamma^5 \psi_e\, d^3r$$

APV



Application :

Neutron Stars

What is the nature of extremely dense matter ?

Do collapsed stars form "exotic" phases of matter ? (strange stars, quark stars)

Crab Nebula (X-ray, visible, radio, infrared)

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Jefferson Lab
Thomas Jefferson National Accelerator Facility

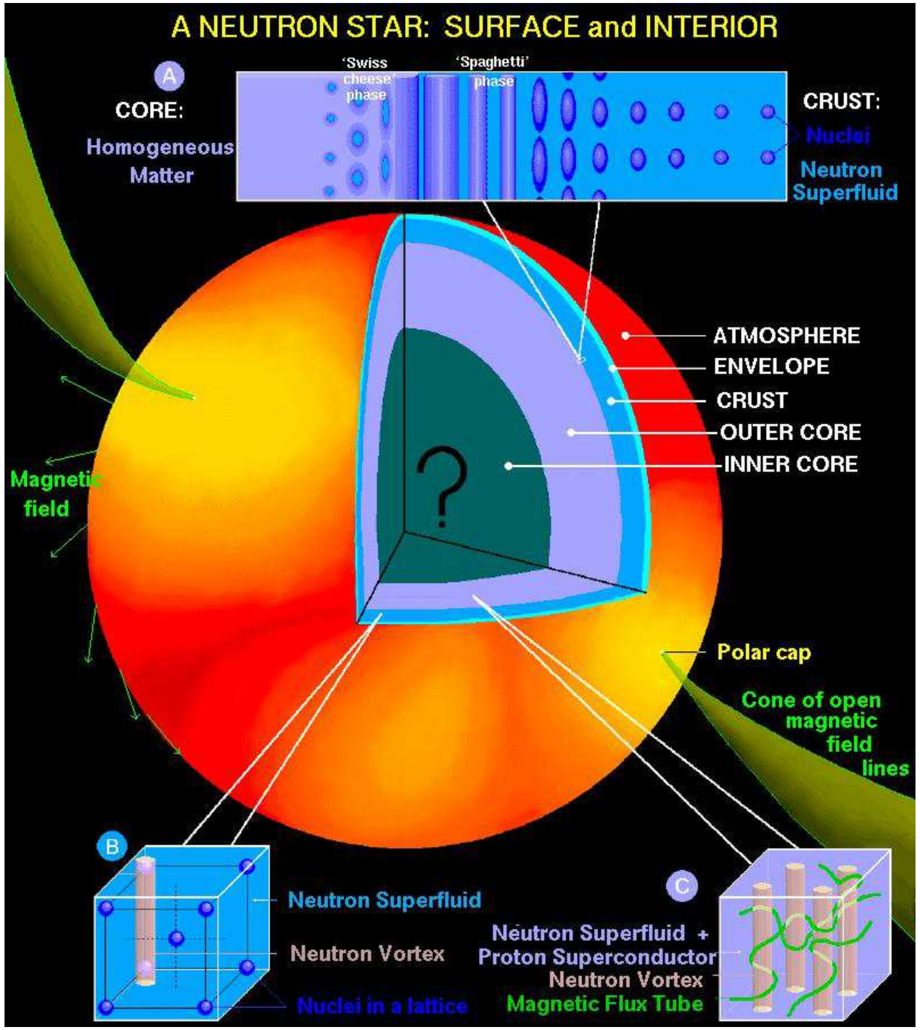


Fig from: Dany Page.

J.M. Lattimer & M. Prakash, Science 304 (2004) 536.

Inputs:

- Eq. of state (EOS) $P(\rho)$ (pressure, density)

PREX helps *here*

- Hydrostatics (Gen. Rel.)

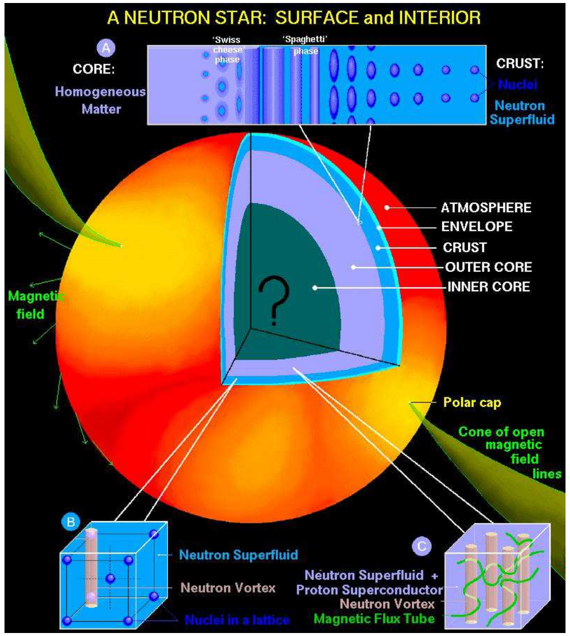
- Astrophysics Observations

Luminosity L
Temp. T
Mass M from pulsar timing

$$L = 4\pi\sigma_B R^2 T^4$$

(with corrections ...)

Mass - Radius relationship



PREX & Neutron Stars

C.J. Horowitz, J. Piekarewicz

- R_N calibrates equation of state (pressure vs density) of Neutron Rich Matter

- Combine PREX R_N with Observed Neutron Star Radii

  Phase Transition to “Exotic” Core ?

  Strange star ? **Quark Star ?**

- Some Neutron Stars seem too cold

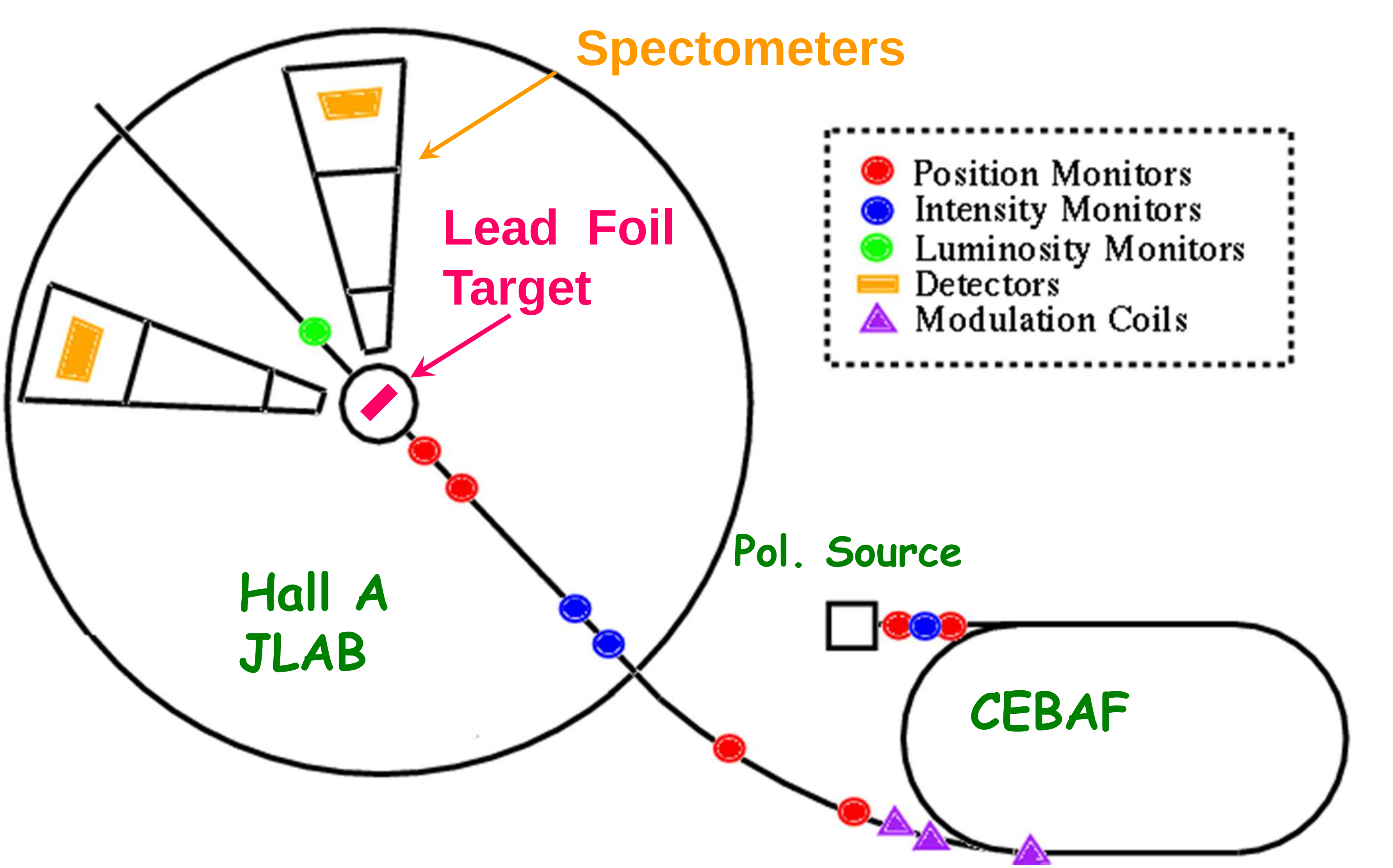
  → Explained by Cooling by neutrino emission (URCA process) ?

  → $R_n - R_p >$ 0.2 fm → URCA probable, else not

Crab Pulsar

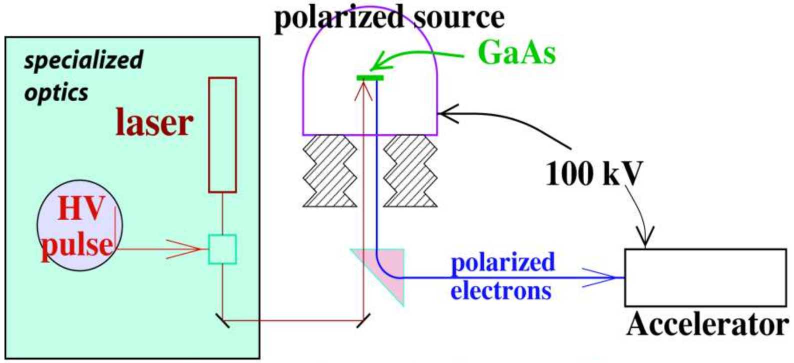
PREX Setup

Parity: "The entire lab is the experiment"



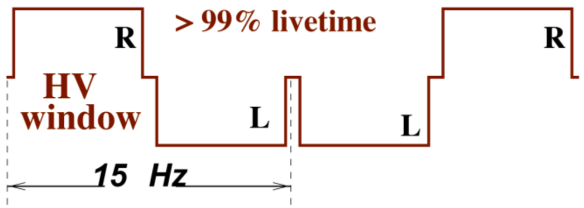
How to do a Parity Experiment

(integrating method)



rapid, random, helicity flipping

Rapid, Random Helicity Flips



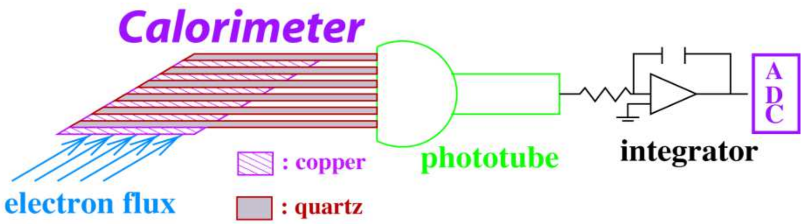
Measure flux F for each window

$$A_{\text{window pair}} = \frac{F_R - F_L}{F_R + F_L}$$

Flux Integration Technique:

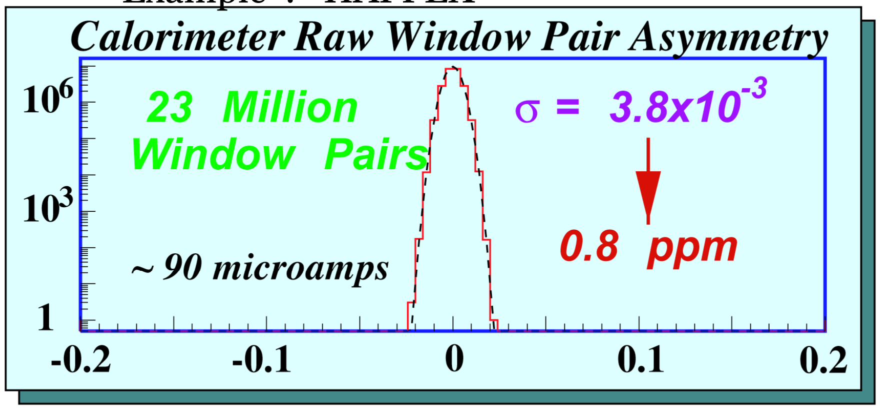
HAPPEX: 2 MHz

PREX: 500 MHz



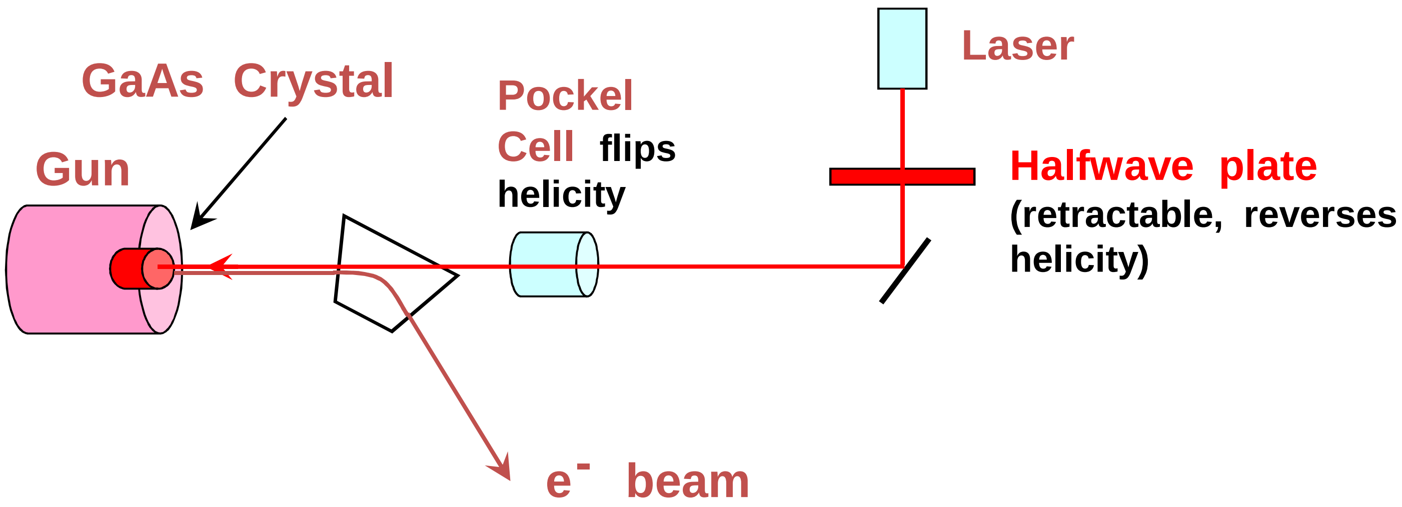
Signal Average N Windows Pairs: $A \pm \frac{\sigma(A)}{\sqrt{N_{\text{windows}}}}$

Example : HAPPEX



No non-gaussian tails to +/- 5σ

Polarized Electron Source



- **Based on Photoemission from GaAs Crystal**
- **Polarized electrons from polarized laser**
- **Need :**
  - Rapid, random helicity reversal
  - Electrical isolation from the rest of the lab
  - Feedback on Intensity Asymmetry

Important Systematic : P I T A Effect (Gordon Cates)

Polarization Induced Transport Asymmetry

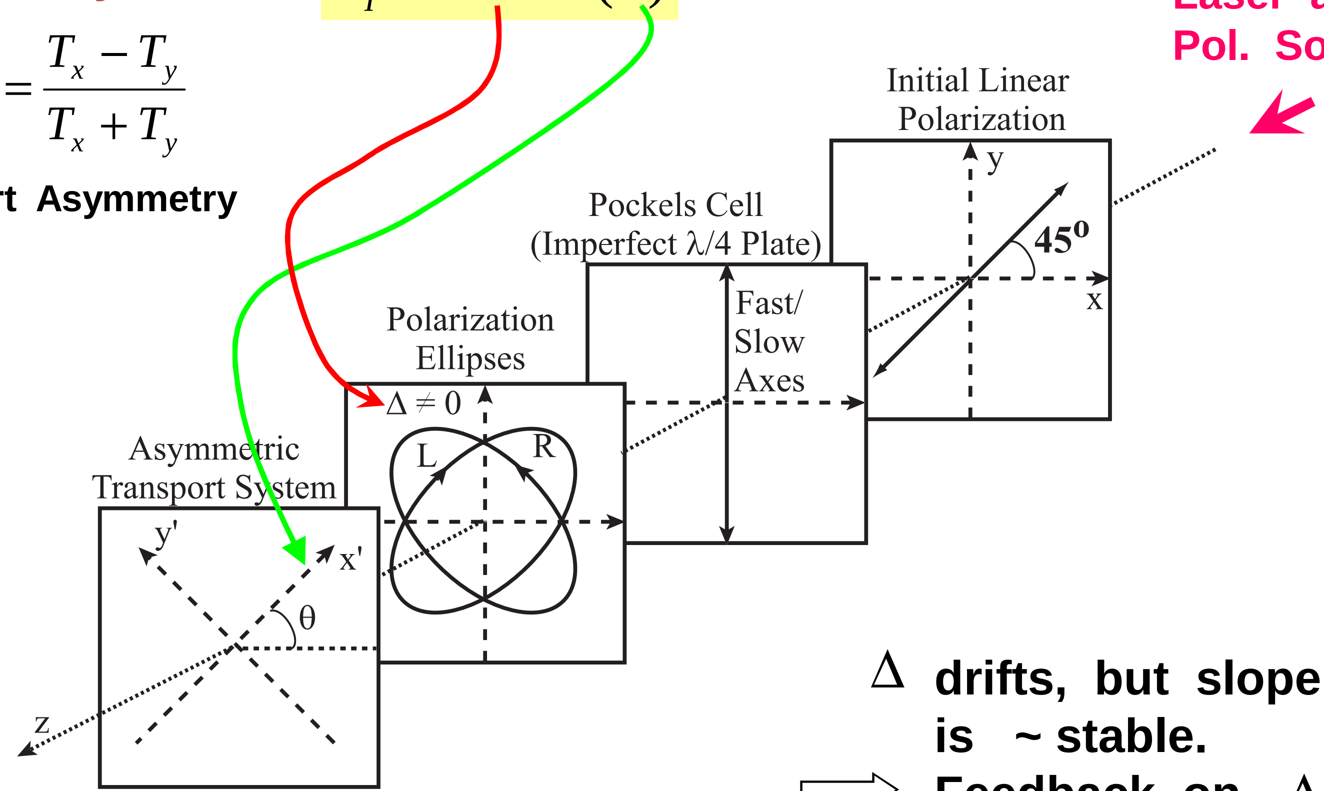
Intensity Asymmetry

$$A_I = \varepsilon \, \Delta \sin(\theta)$$

where $\varepsilon = \dfrac{T_x - T_y}{T_x + T_y}$

Transport Asymmetry

Laser at Pol. Source

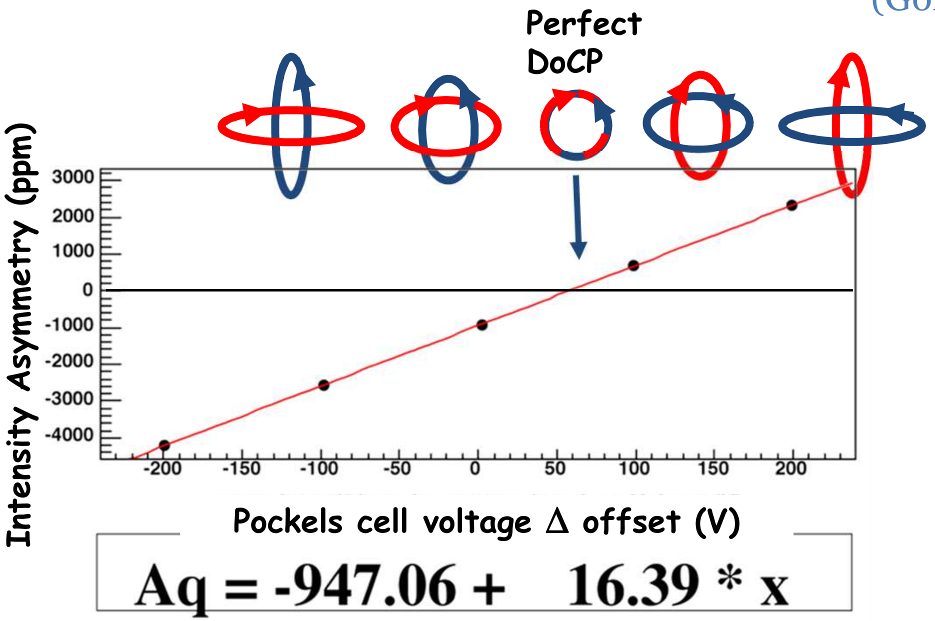


Δ **drifts, but slope is ~ stable.**

⇨ **Feedback on** Δ

Methods to Reduce Systematics

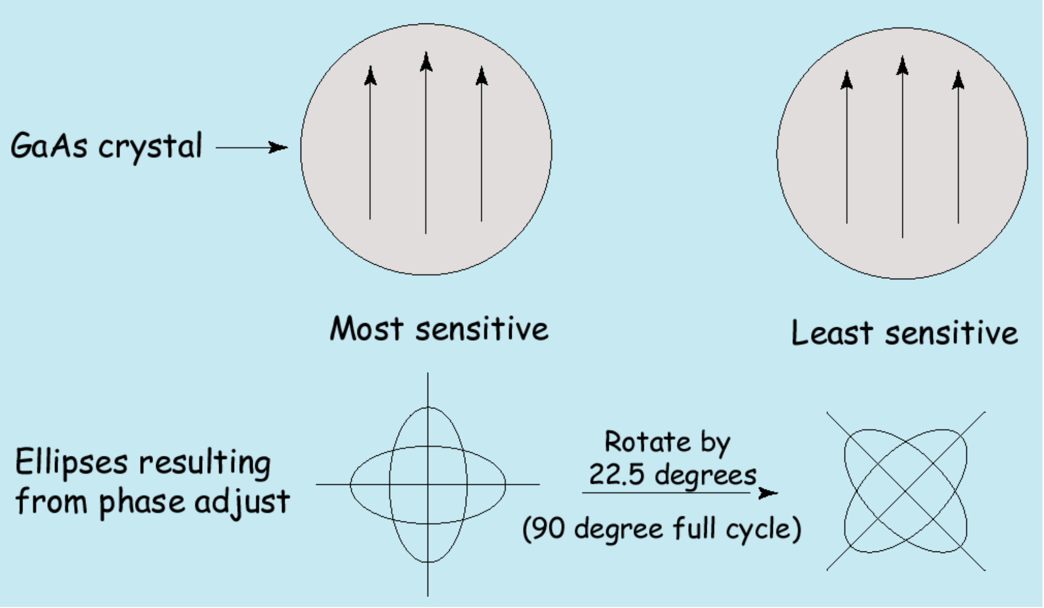
(Gordon Cates, Kent Paschke, Mark Dalton, Rupesh Silwal)



Scanning the Pockels Cell voltage = scanning the residual linear polarization (DoLP)

A simplified picture: asymmetry=0 corresponds to minimized DoLP at analyzer

A rotatable λ/2 waveplate downstream of the P.C. allows arbitrary orientation of the ellipse from DoLP



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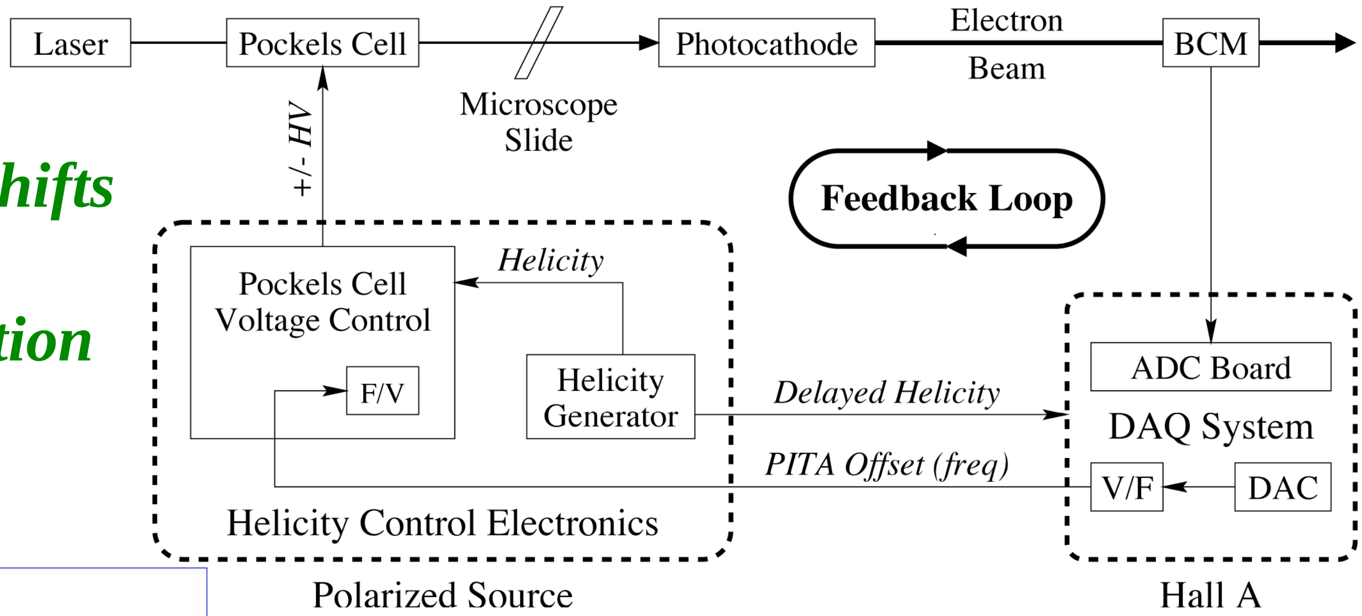
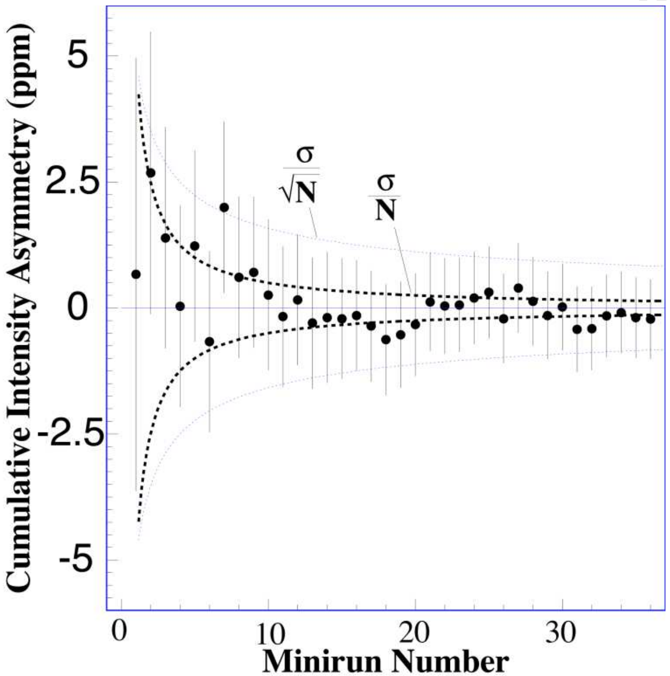
Intensity Feedback



Adjustments for small phase shifts to make close to circular polarization



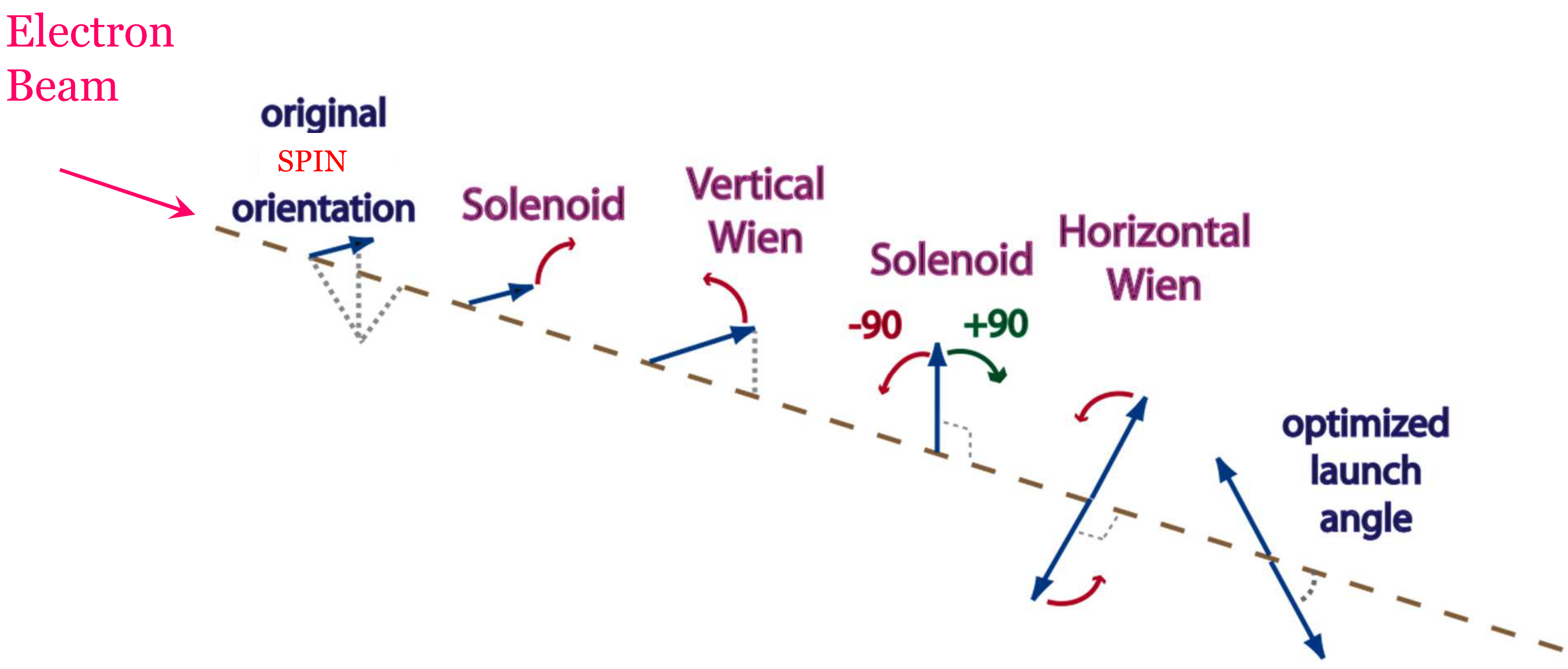
Low jitter and high accuracy allows sub-ppm cumulative charge asymmetry in ~ 1 hour

Double Wien Filter

Crossed E & B fields to rotate the spin

- Two Wien Spin Manipulators in series
- Solenoid rotates spin +/-90 degrees (spin rotation as B but focus as B^2).

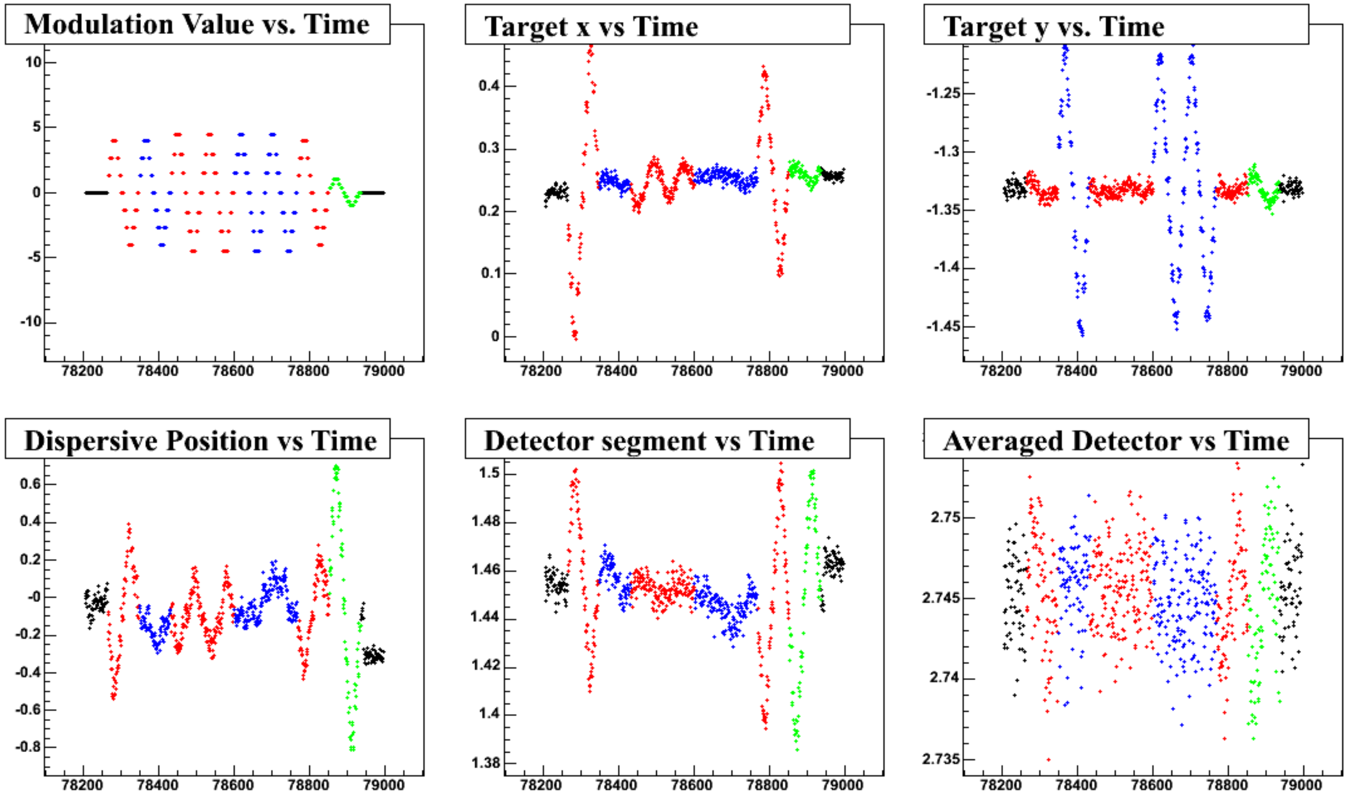
Flips spin without moving the beam !



Beam Asymmetries

$$A_{raw} = A_{det} - A_Q + \alpha\Delta_E + \Sigma\beta_i\Delta x_i$$

Slopes from
- natural beam jitter (regression)
- beam modulation (dithering)



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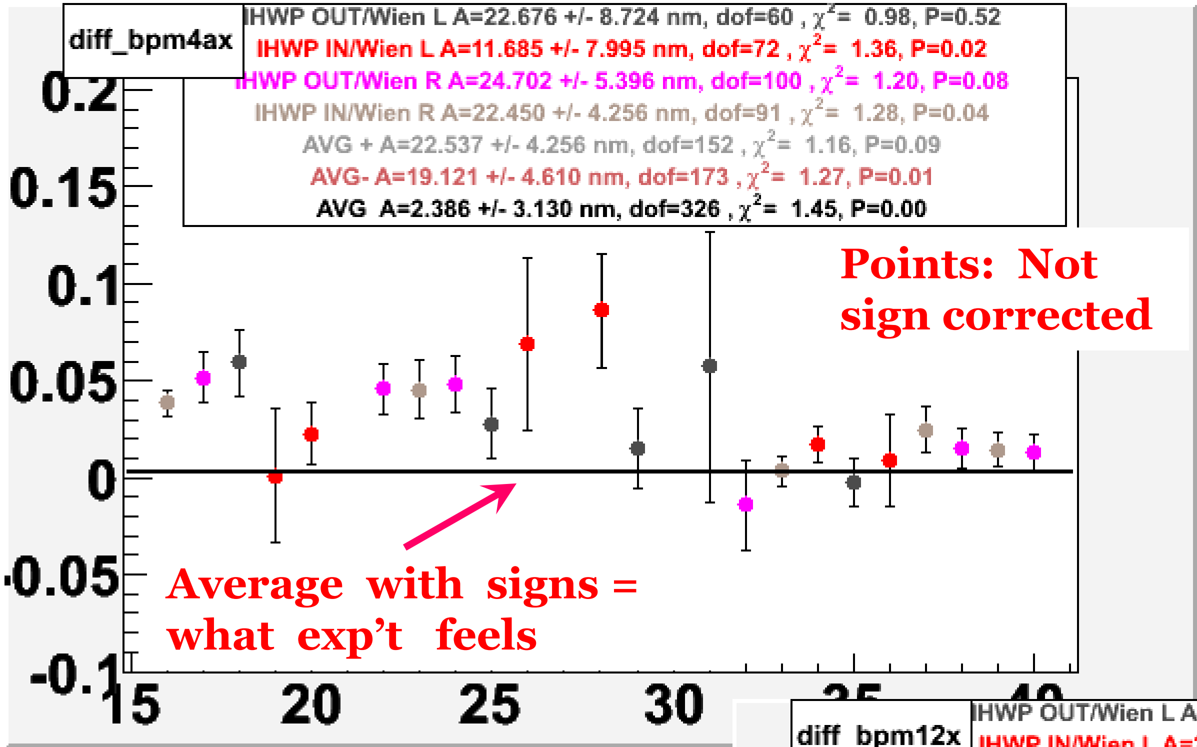
Parity Quality Beam !

(why we love Jlab !)

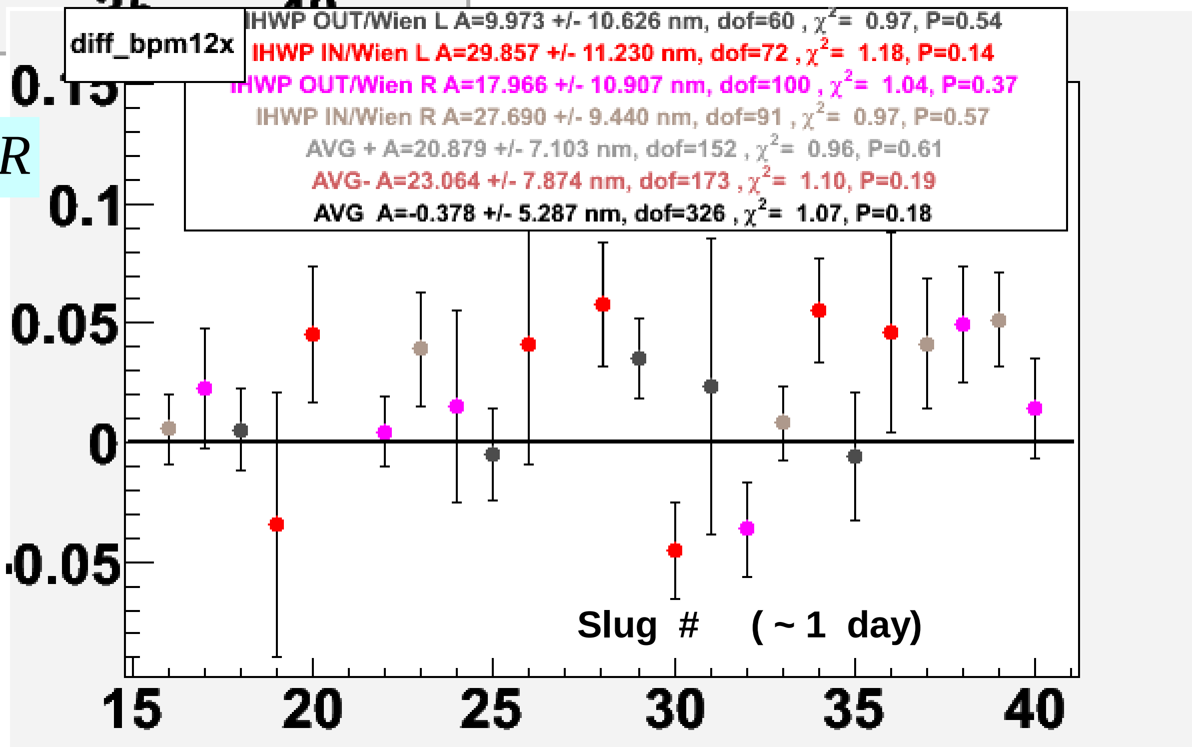


Helicity – Correlated Position Differences

< ~ 3 nm

$< X_R - X_L > \quad for\ helicity\ L, R$

Units: microns



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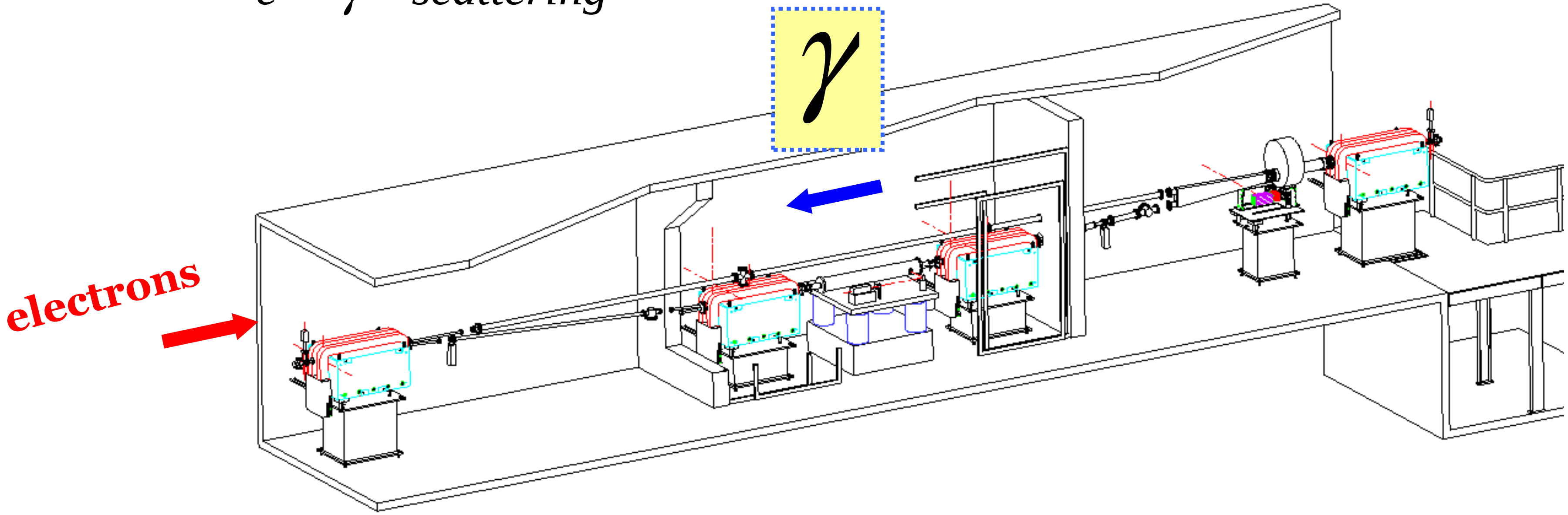
Compton Polarimeter

to measure electron beam's polarization (needed to normalize asymmetry)

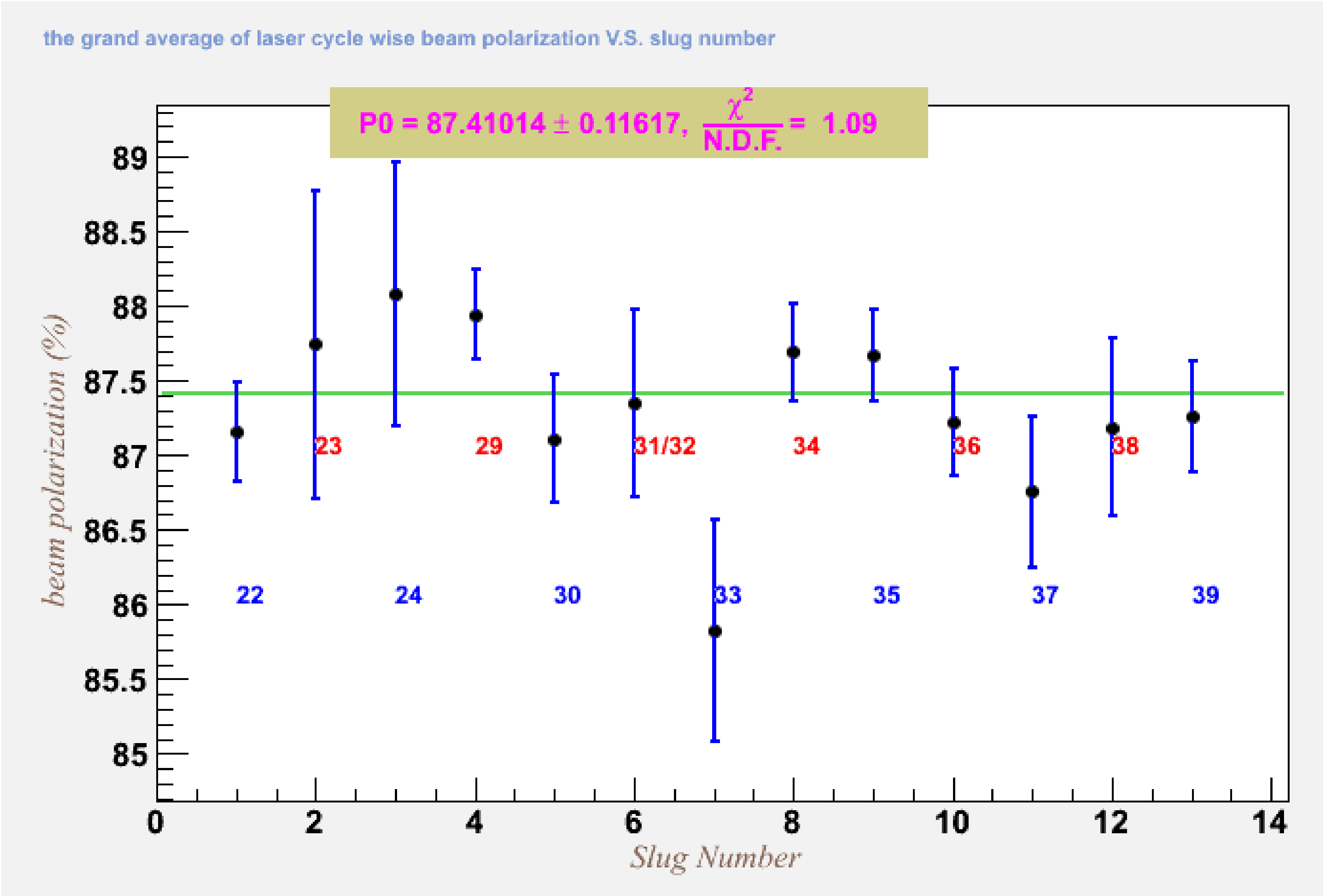
$\vec{e} - \vec{\gamma}$ *scattering*



Upgrade for 1% accuracy at 1 GeV

- **Green Laser** (increased sensitivity at low E)
- **Integrating Method** (removes some systematics of analyzing power)
- **New Photon & Electron Detectors**

Compton Polarimeter Results



Upgraded for PREX

Moller Polarimeter

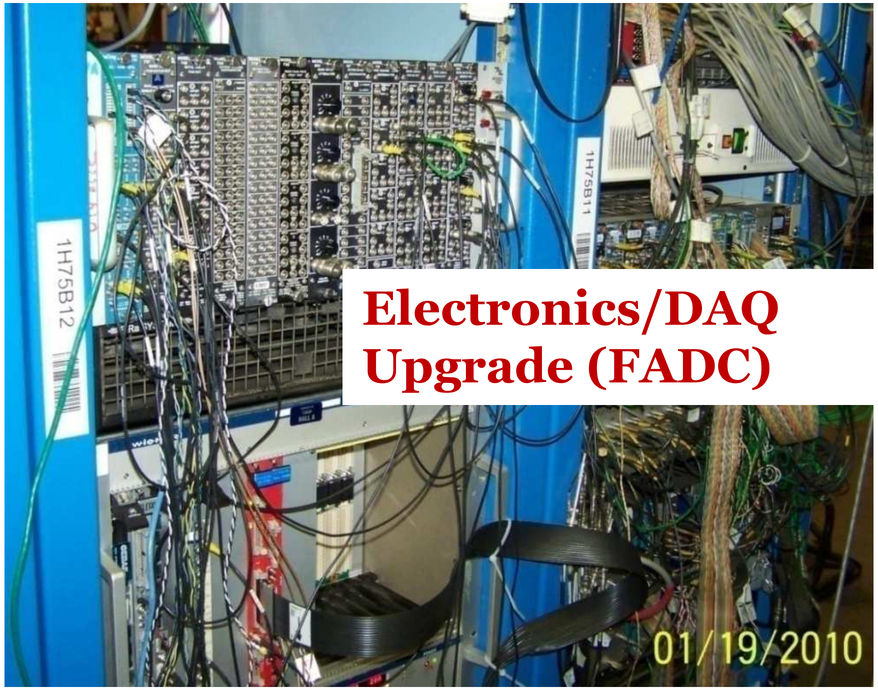
$$\vec{e} - \vec{e} \quad scattering$$

Superconducting Magnet from Hall C

Saturated Iron Foil Targets

1 % Accuracy in Polarization

Magnet and Target



Electronics/DAQ Upgrade (FADC)

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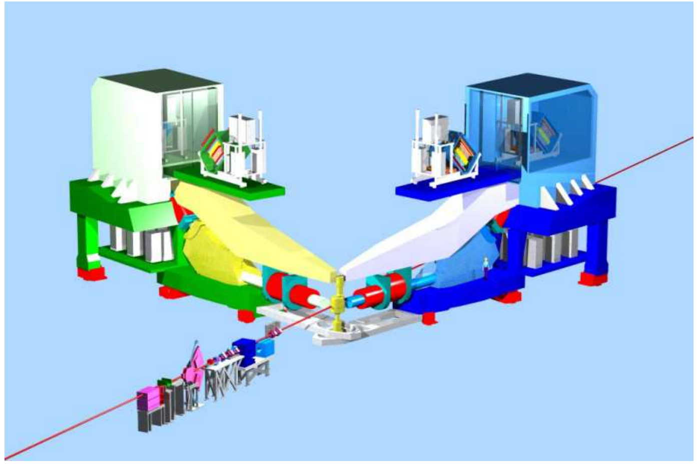
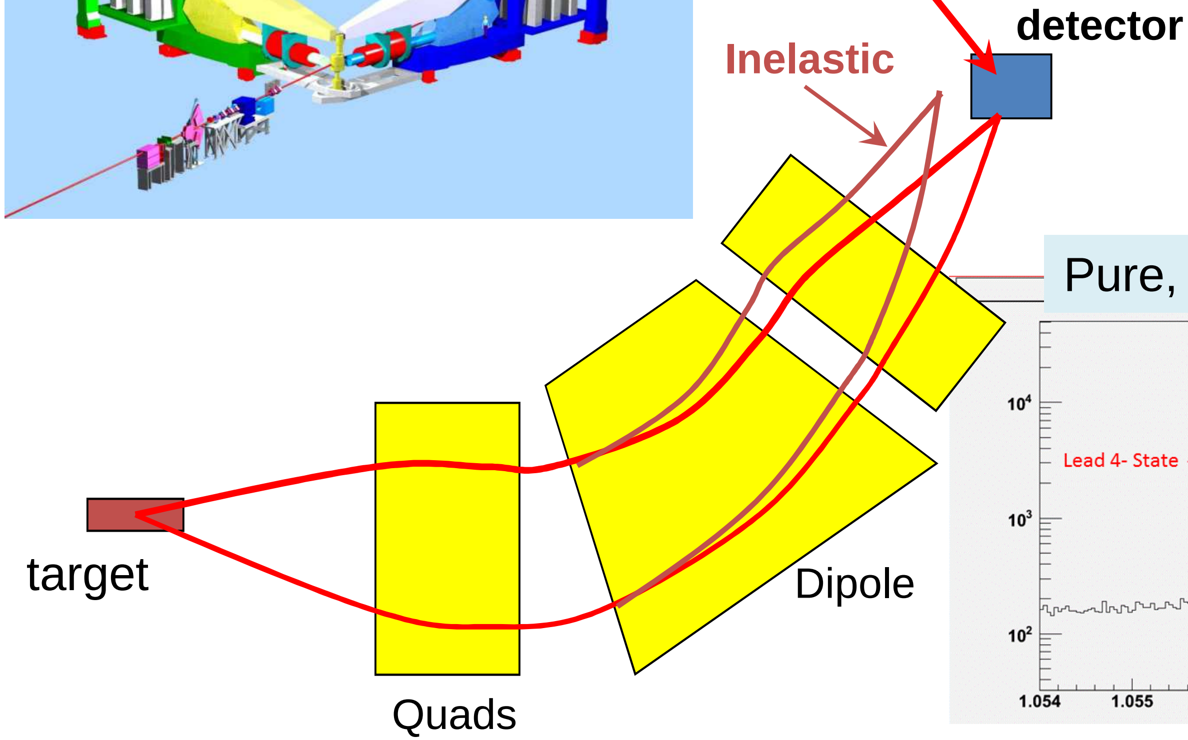
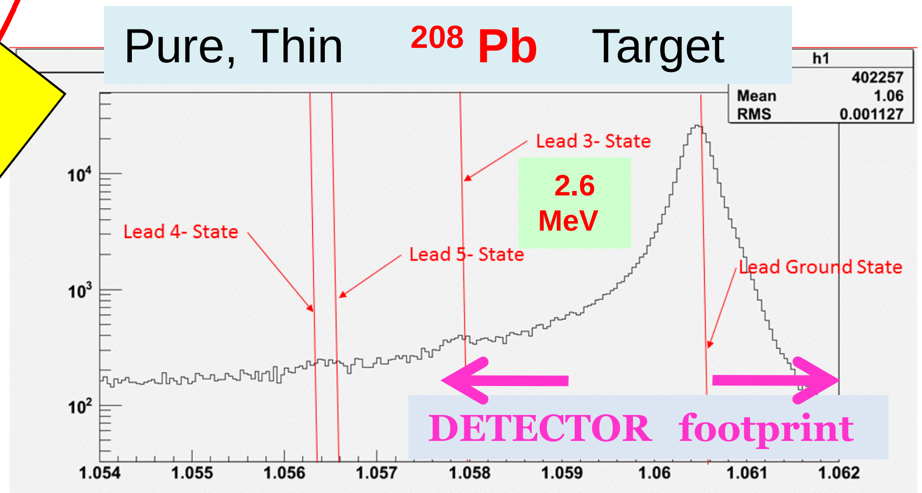
Hall A High Resolution Spectrometers

- **Resolve Elastic Scattering**
- **Discriminate Excited States**



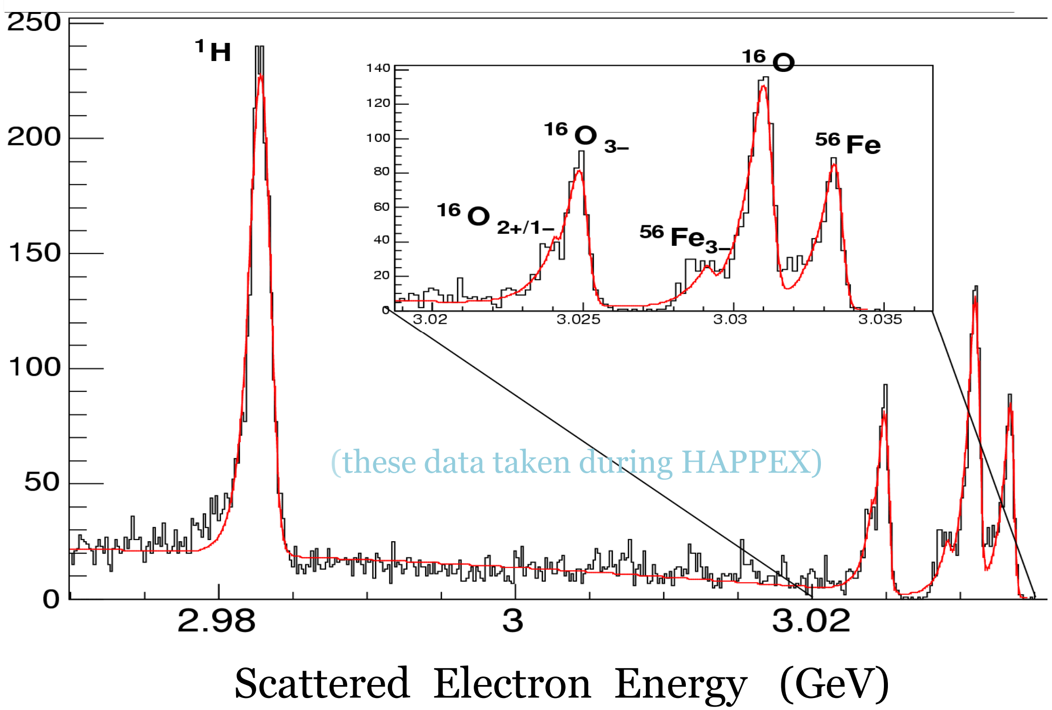




Scattered Electron's Momentum (GeV/c)

Measure θ from Nuclear Recoil

(Nilanga Liyanage,   Kiadtisak Saenboonruang)



δE=Energy loss

E=Beam energy

M_A=Nuclear mass

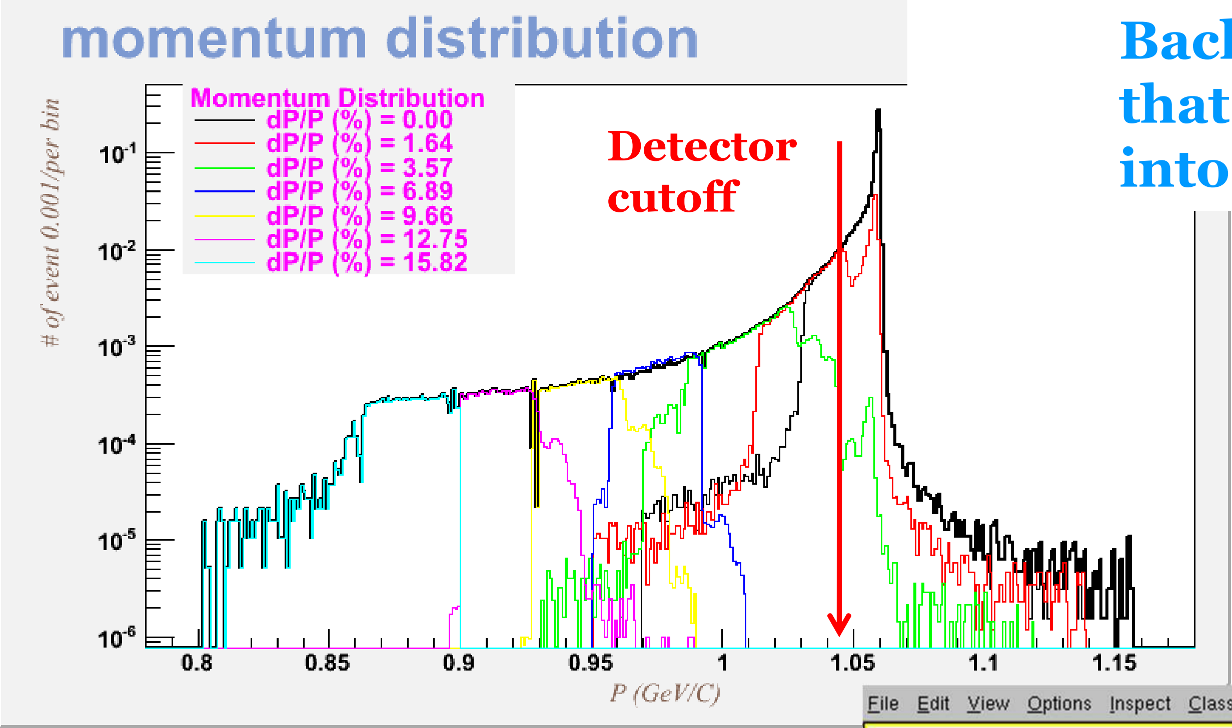
θ=Scattering angle

$$\frac{\delta E}{E} \approx \frac{\theta^2}{2} \frac{E}{M_A}$$

Recoil is large for H, small for nuclei

(3X better accuracy than survey)

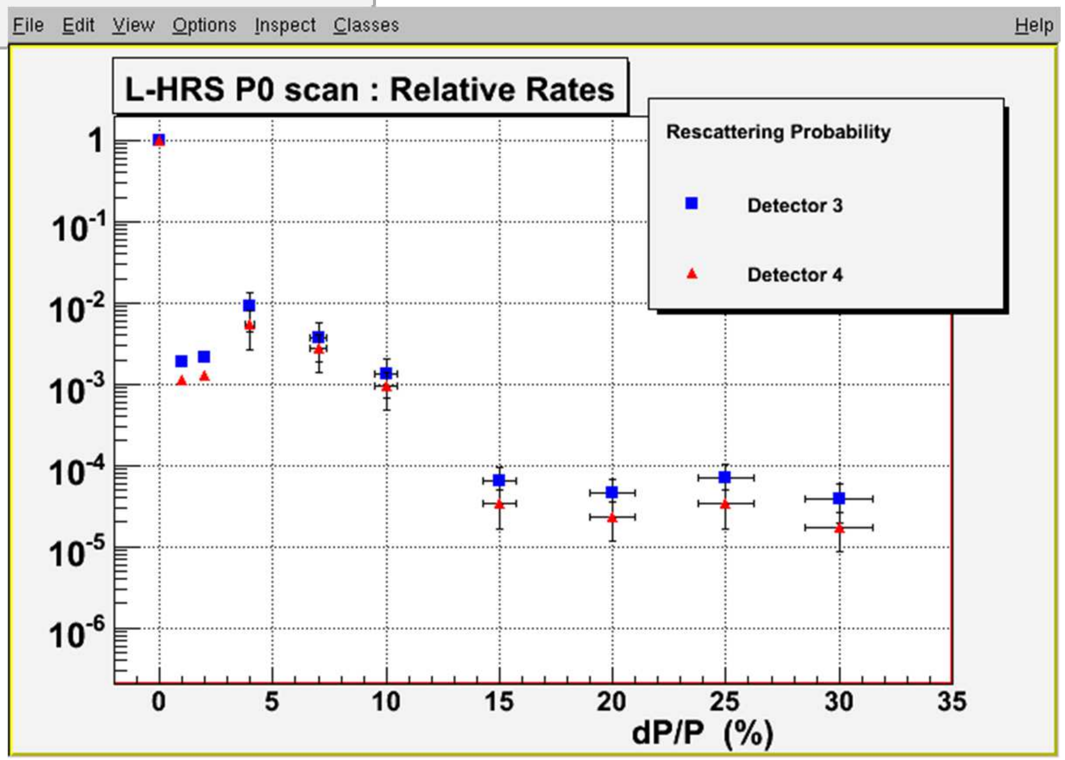
R. Michaels, Jlab
Seminar @ UVa
Feb 10, 2012



Backgrounds that might re-scatter into the detector ?

Run magnets **down**: measure inelastic region

Run magnets **up** : measure probability to rescatter



No inelastics observed on top of radiative tail. Small systematic for tail.

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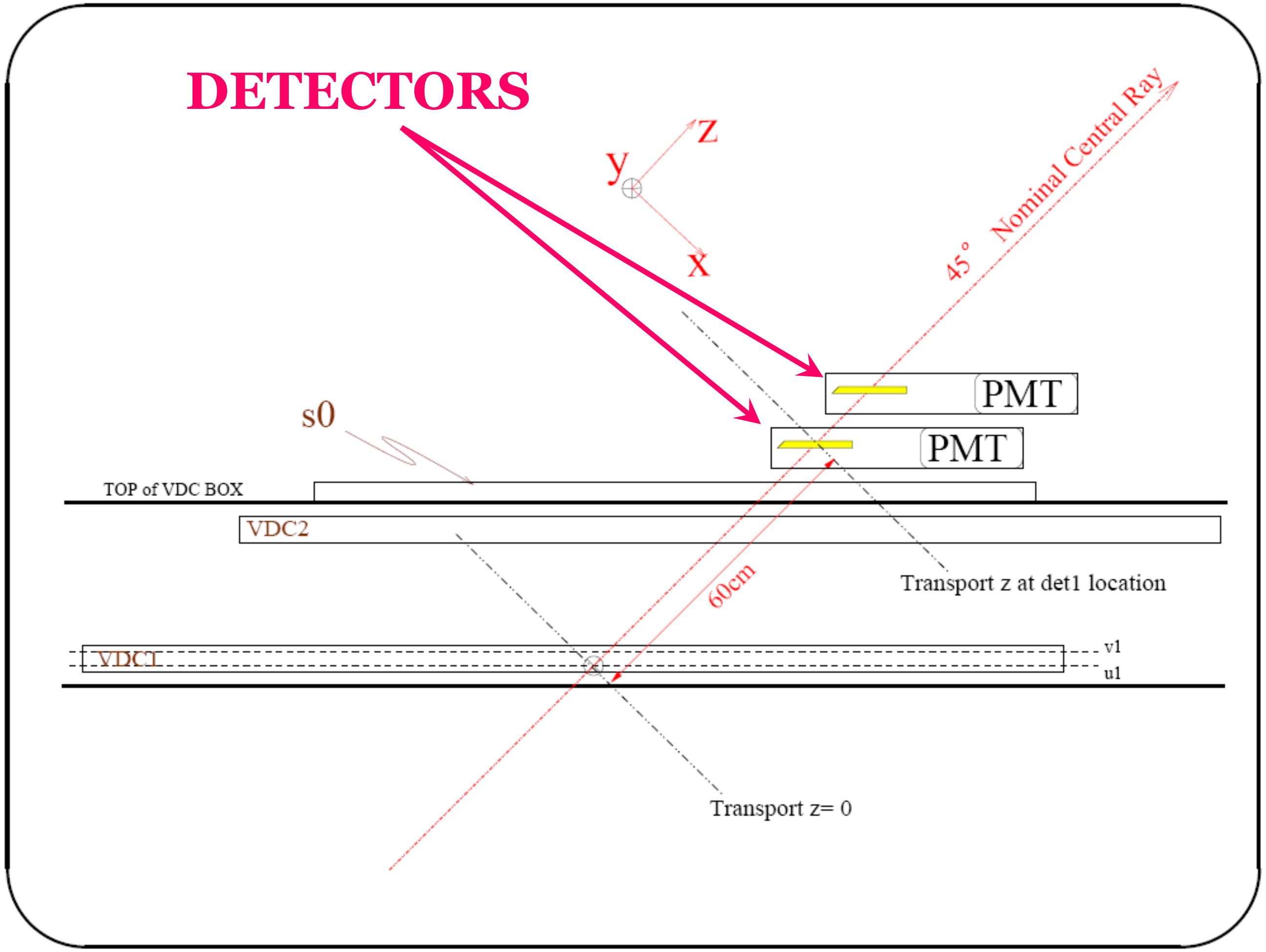
Seminar @ UVa
Feb 10, 2012

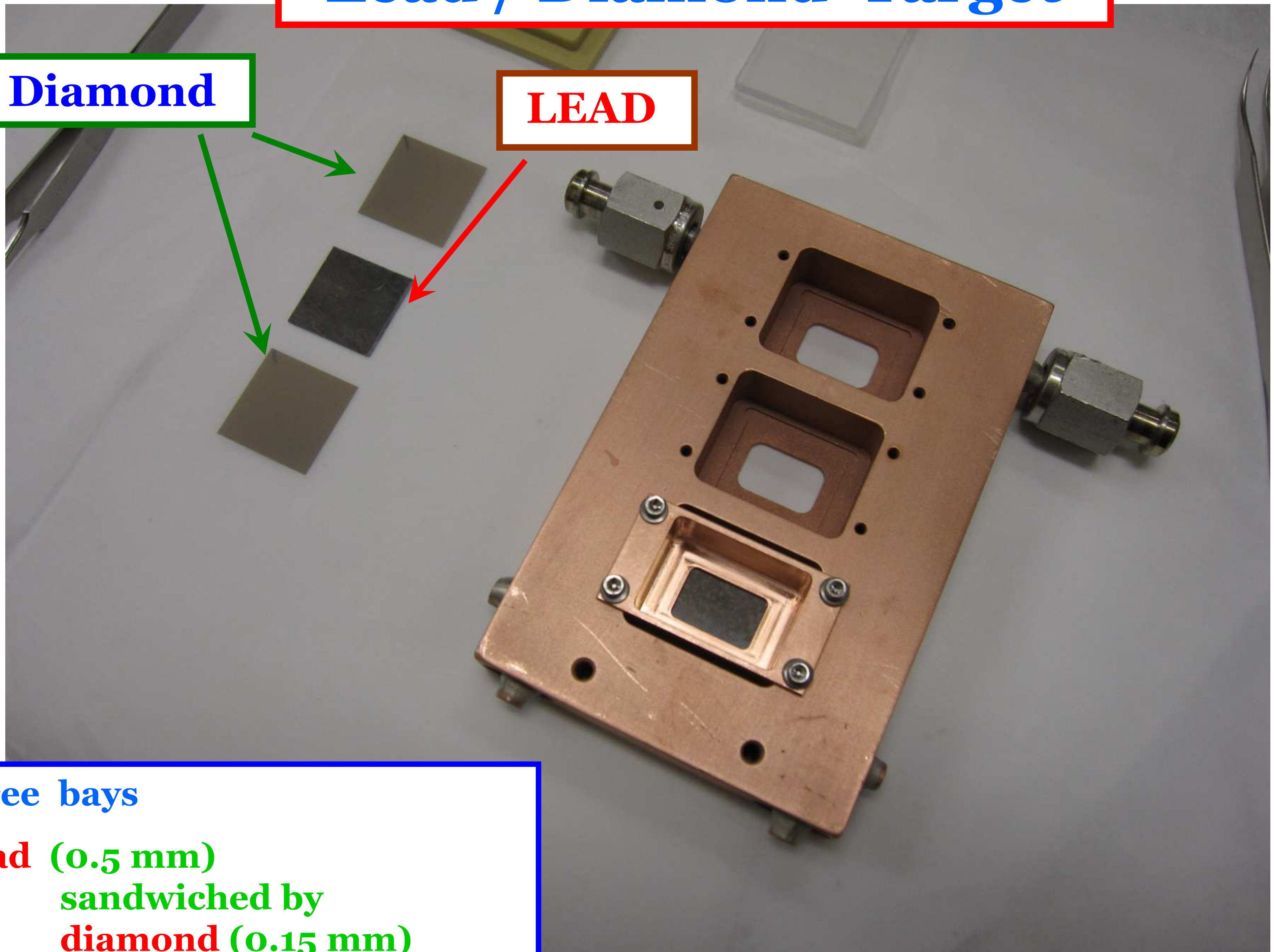
Detector Package in HRS

PREX Integrating Detectors

UMass / Smith



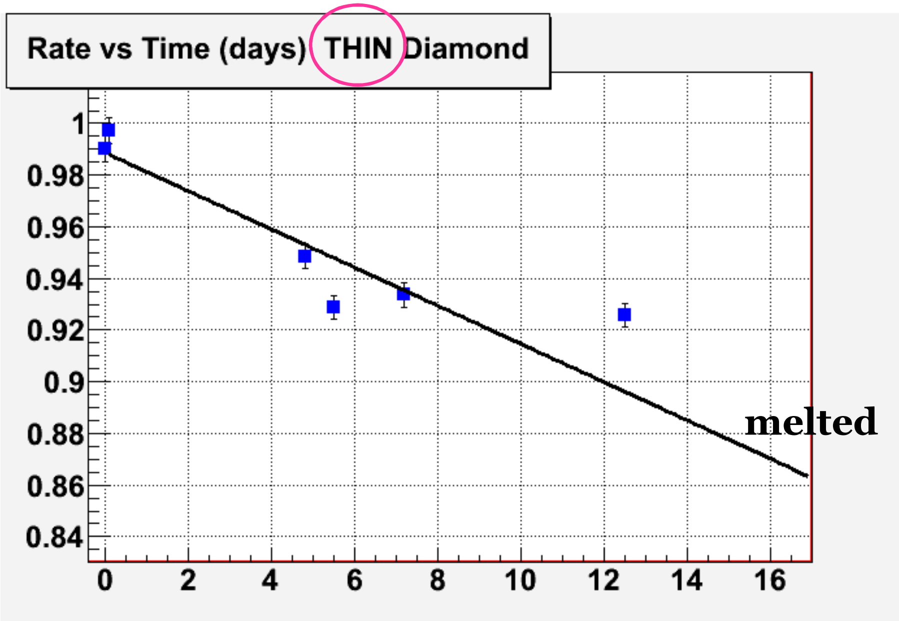
Lead / Diamond Target

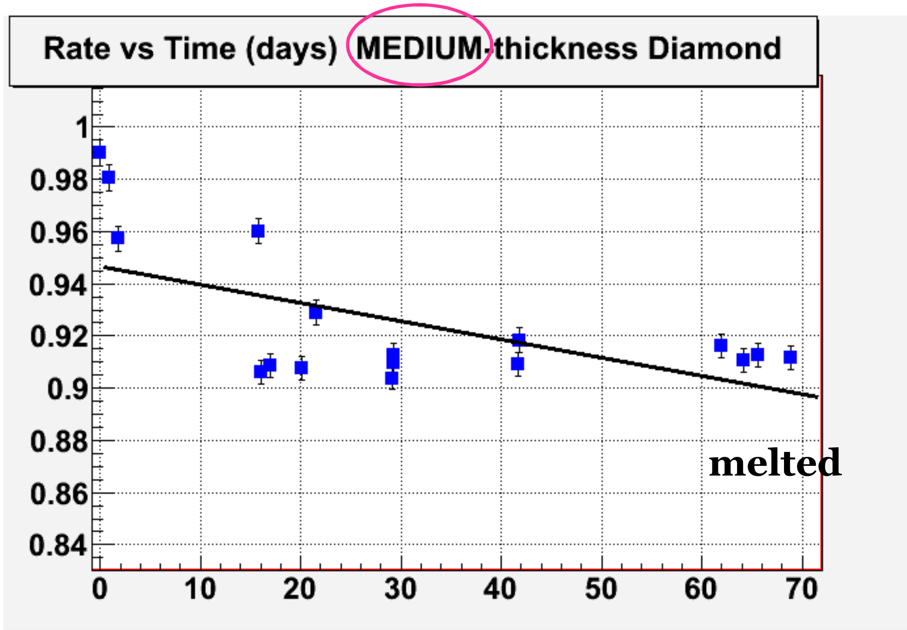


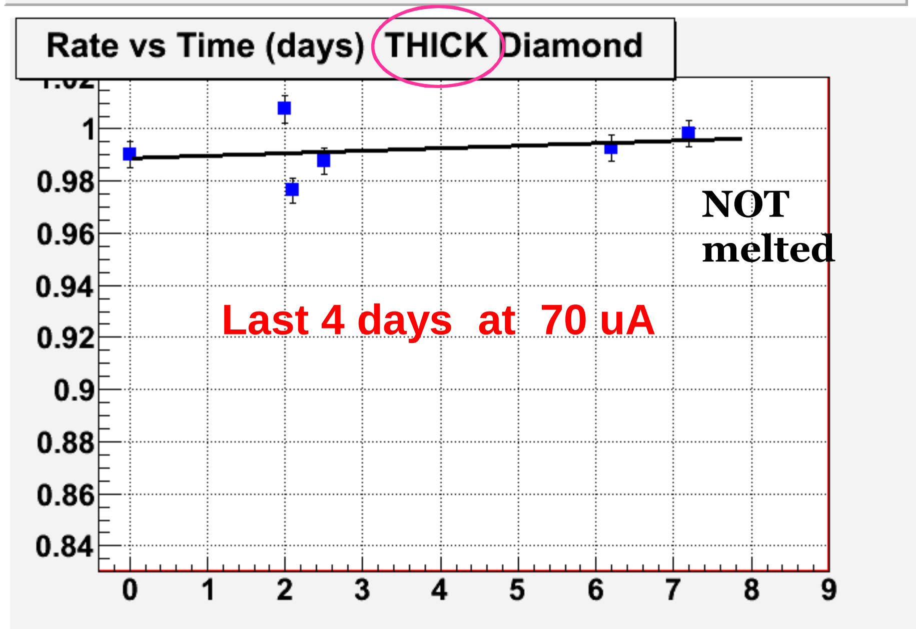
- Three bays
- Lead (0.5 mm) sandwiched by diamond (0.15 mm)
- Liquid He cooling (30 Watts)

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Performance of Lead / Diamond Targets







Targets with thin diamond backing (4.5 % background) degraded fastest.

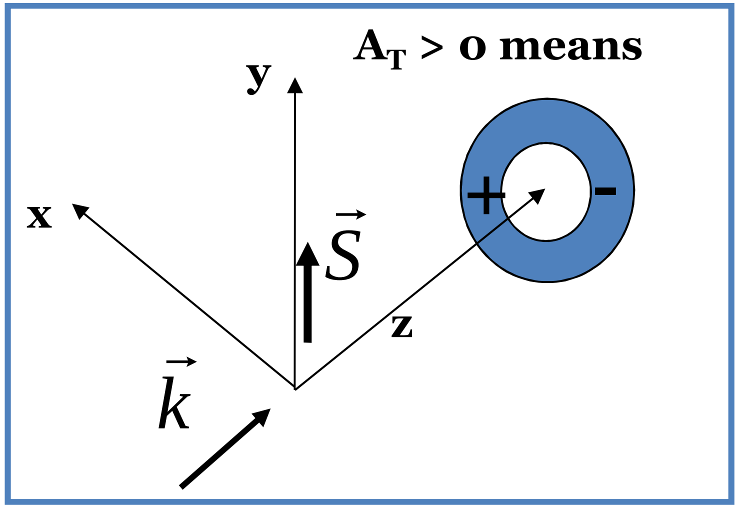
Thick diamond (8%) ran well and did not melt at 70 uA.

→ **Solution: Run with 10 targets.**

Beam-Normal Asymmetry in elastic electron scattering

i.e. spin transverse to scattering plane

$$A_T \equiv \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \propto \vec{S}_e \bullet (\vec{k}_e \times \vec{k}'_e)$$



Possible systematic if small transverse spin component

New results PREX

Preliminary !
Publication in preparation

$$^{208}Pb: \quad A_T = +0.13 \pm 0.19 \pm 0.36 \ ppm$$

$$^{12}C: \quad A_T = -6.52 \pm 0.36 \pm 0.35 \ ppm$$

- **Small A_T for ^{208}Pb is a big (but pleasant) surprise.**
- **A_T for ^{12}C qualitatively consistent with ^{4}He and available calculations (1) Afanasev ; (2) Gorchtein & Horowitz**

PREX-I Result

Systematic Errors

Error Source	Absolute (ppm)	Relative (%)
Polarization (1)	0.0083	1.3
Beam Asymmetries (2)	0.0072	1.1
Detector Linearity	0.0076	1.2
BCM Linearity	0.0010	0.2
Rescattering	0.0001	0
Transverse Polarization	0.0012	0.2
Q^2 (1)	0.0028	0.4
Target Thickness	0.0005	0.1
^{12}C Asymmetry (2)	0.0025	0.4
Inelastic States	0	0
TOTAL	**0.0140**	**2.1**

(1) **Normalization Correction** applied

(2) **Nonzero correction** (the rest assumed zero)

Physics Asymmetry

$$A = 0.656\ ppm \pm 0.060(stat) \pm 0.014(syst)$$

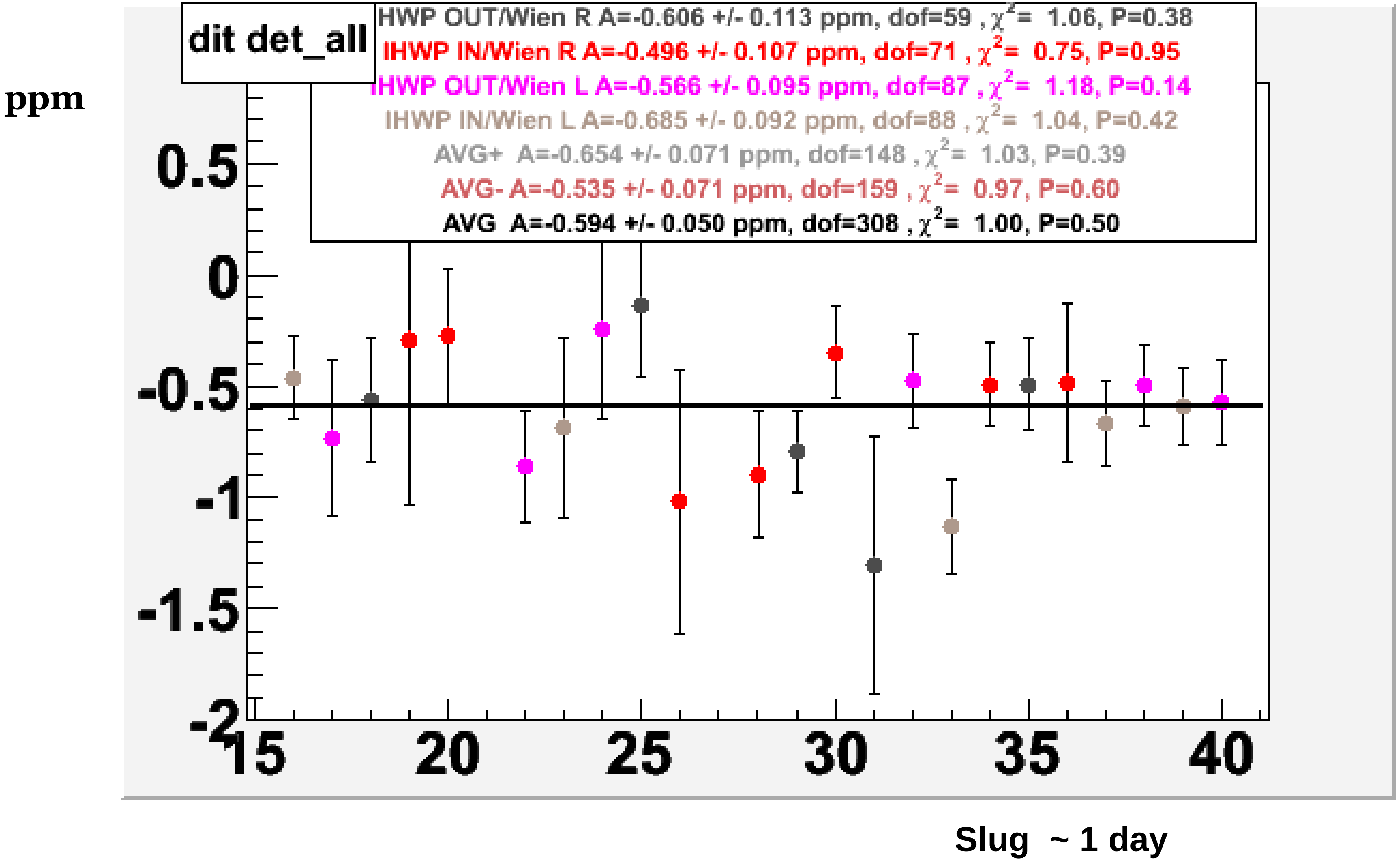
→ **Statistics limited (9%)**

→ **Systematic error goal achieved ! (2%)**

A physics letter was recently accepted by PRL.

arXiv 1201.2568 [nucl-ex]

PREX Asymmetry (P$_e$ x A)



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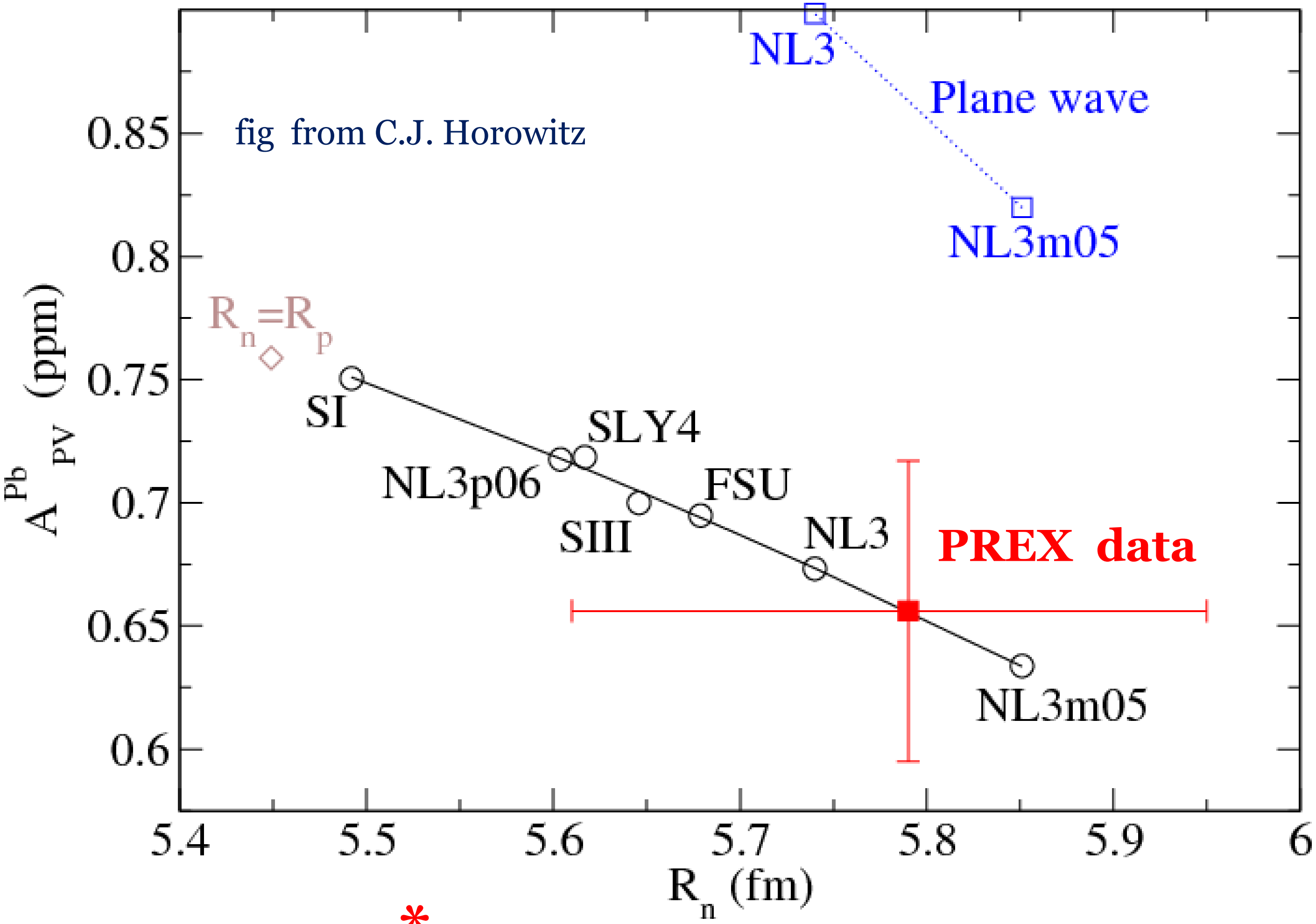
Asymmetry leads to R_N

Establishing a neutron skin at ~95 % CL

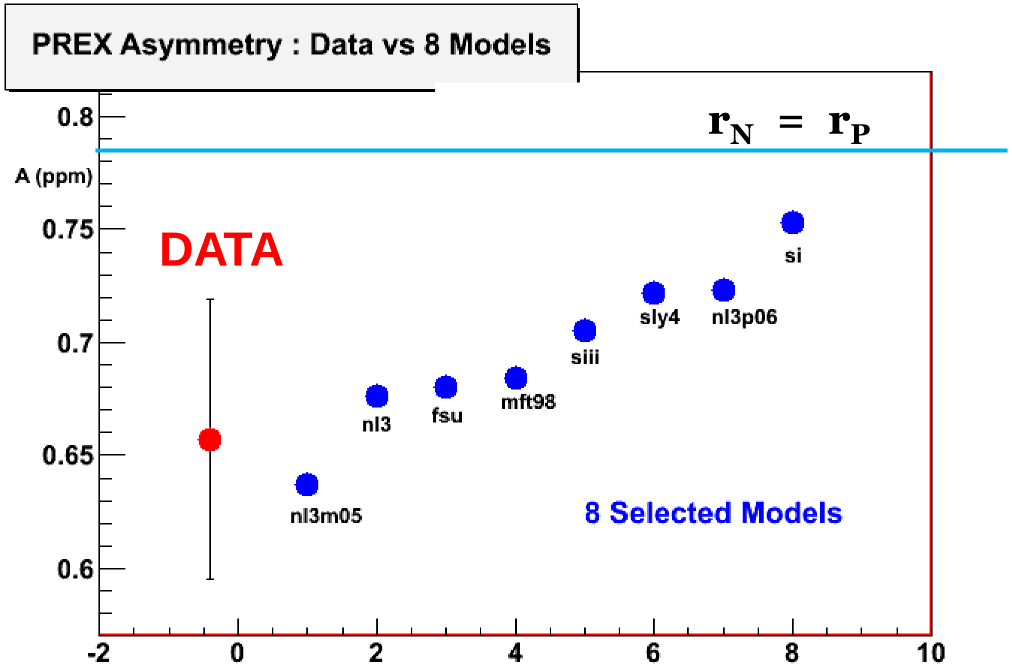
* **Neutron Skin = R_N - R_P = 0.33 + 0.16 - 0.18 fm**

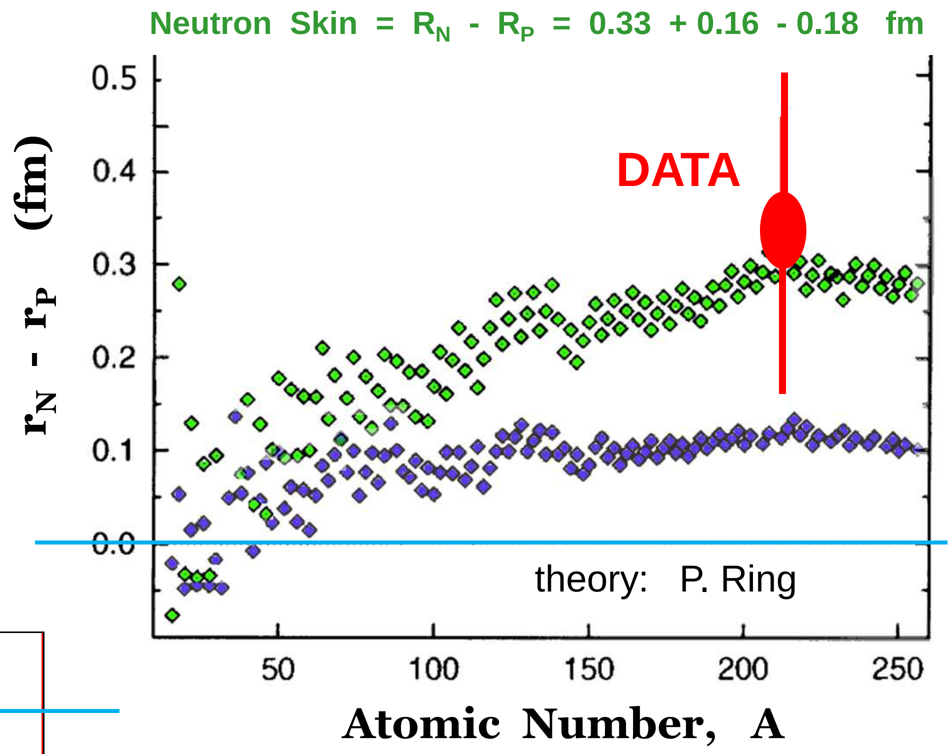


* Interpretation requires the acceptance function for spectrometer: $\varepsilon(\theta)$

PREX-I Result, cont.

$$A = 0.656\ ppm \pm 0.060(stat) \pm 0.014(syst)$$



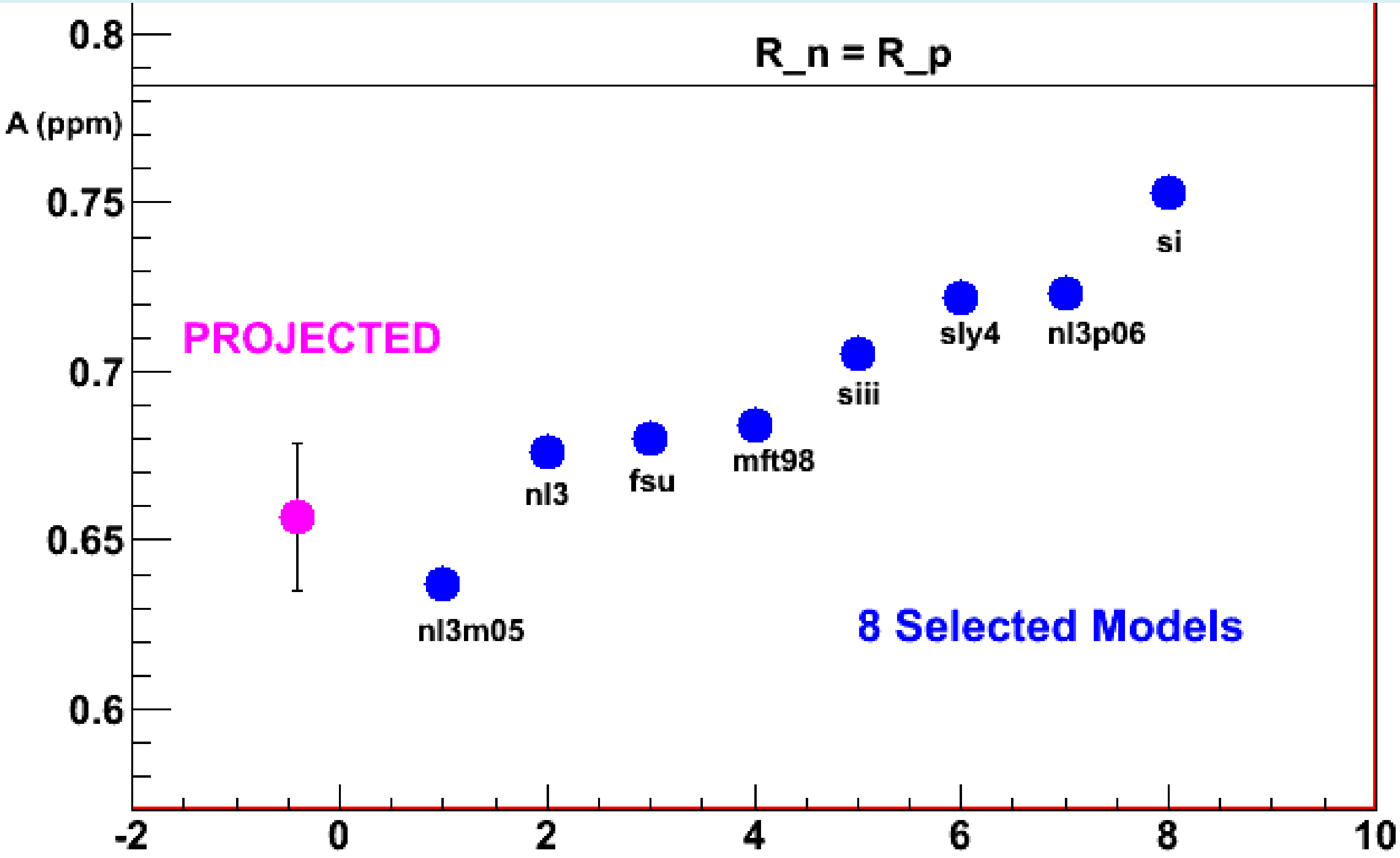


A physics letter was recently accepted by PRL.

arXiv 1201.2568 [nucl-ex]

PREX-II Approved by PAC (Aug 2011)

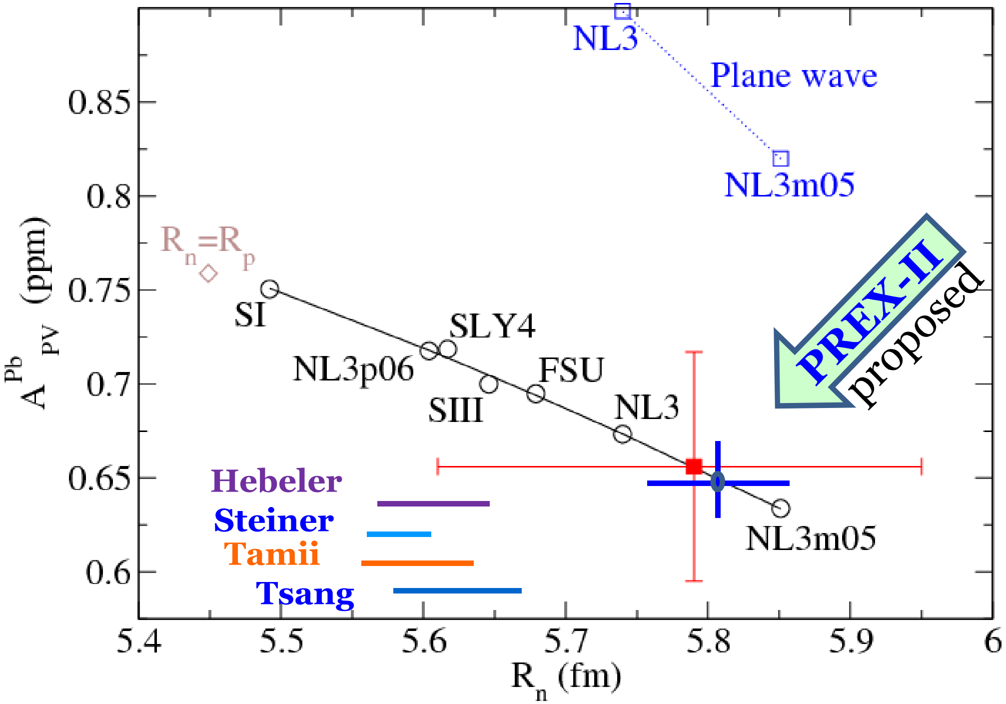
"A" Rating 35 days to run in 2013 or 2014



PREX-II: Kent Paschke, Krishna Kumar, Paul Souder, Guido Urciuoli, Robert Michaels

Recent R_n Predictions Can Be Tested By PREX at Full Precision

PREX could provide an electroweak complement to R_n predictions from a wide range of physical situations and model dependencies



These can be tested with

$\delta(A_{PV})/A_{PV} \sim 3\%$

$\delta(R_n)/R_n \sim 1\%$

Recent R_n predictions:

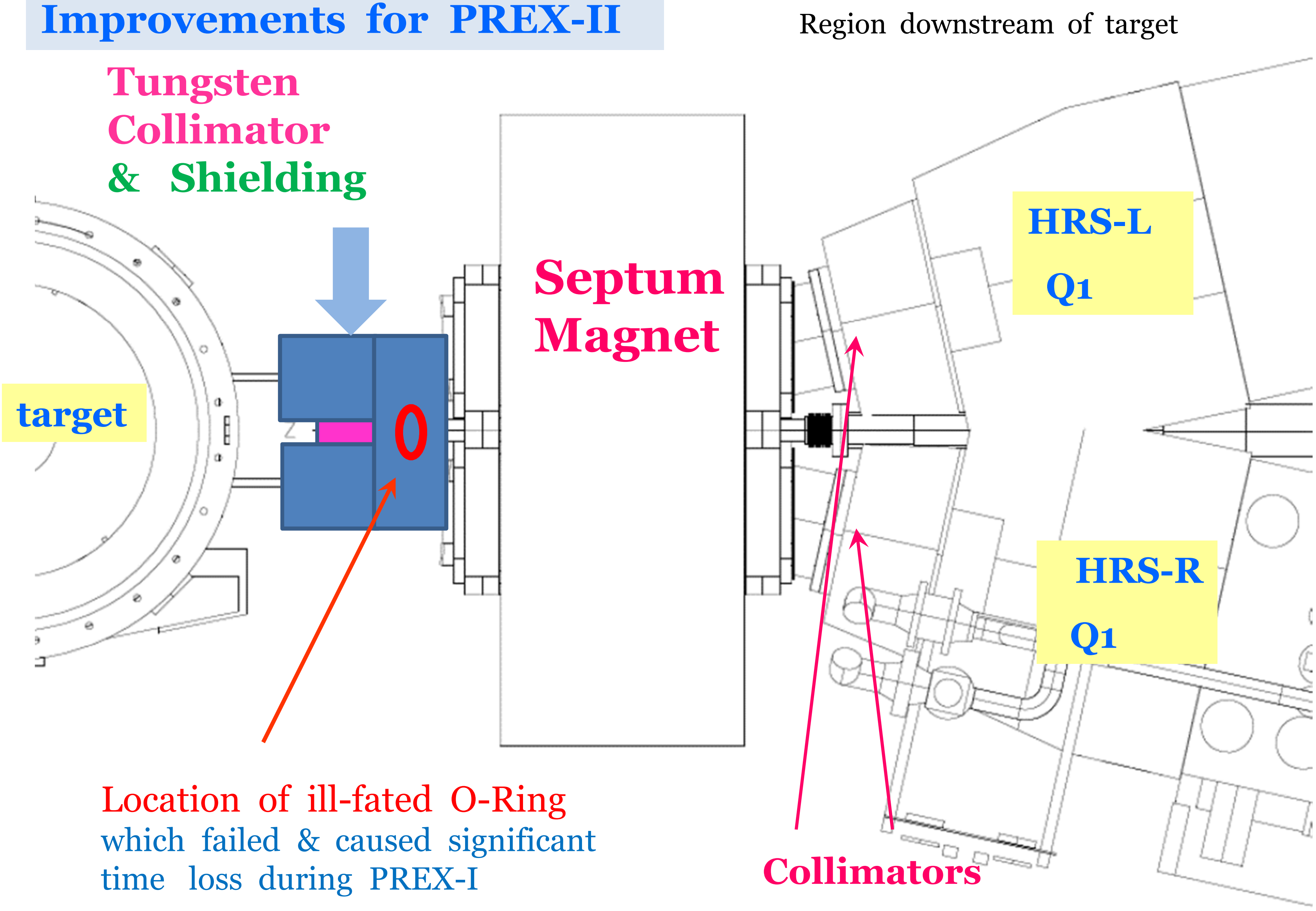
Hebeler *et al.* Chiral EFT calculation of neutron matter. Correlation of pressure with neutron skin by Brown. Three-neutron forces!

Steiner *et al.* X-Ray n-star mass and radii observation + Brown correlation. (Ozel *et al* finds softer EOS, would suggest smaller R_n).

Tamii *et al.* Measurement of electric dipole polarizability of ^{208}Pb + model correlation with neutron skin.

Tsang *et al.* Isospin diffusion in heavy ion collisions, with Brown correlation and quantum molecular dynamics transport model.

Improvements for PREX-II



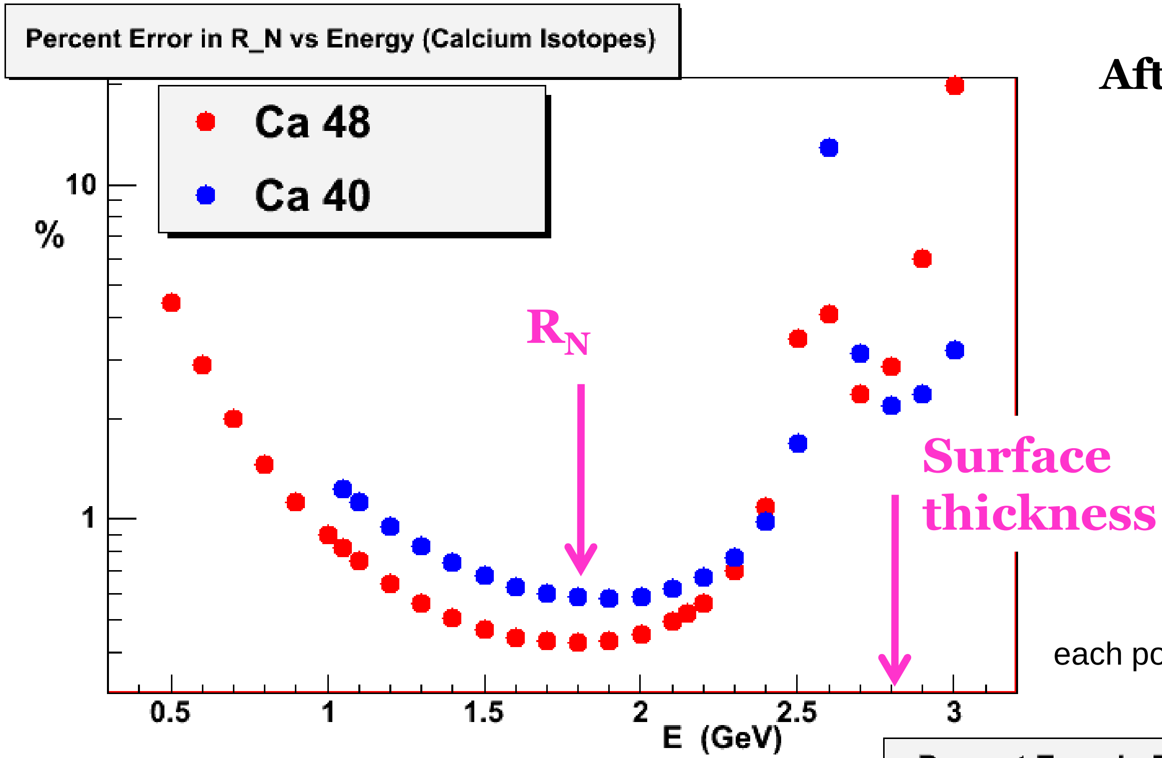
Location of ill-fated O-Ring which failed & caused significant time loss during PREX-I

→ PREX-II to use all-metal seals

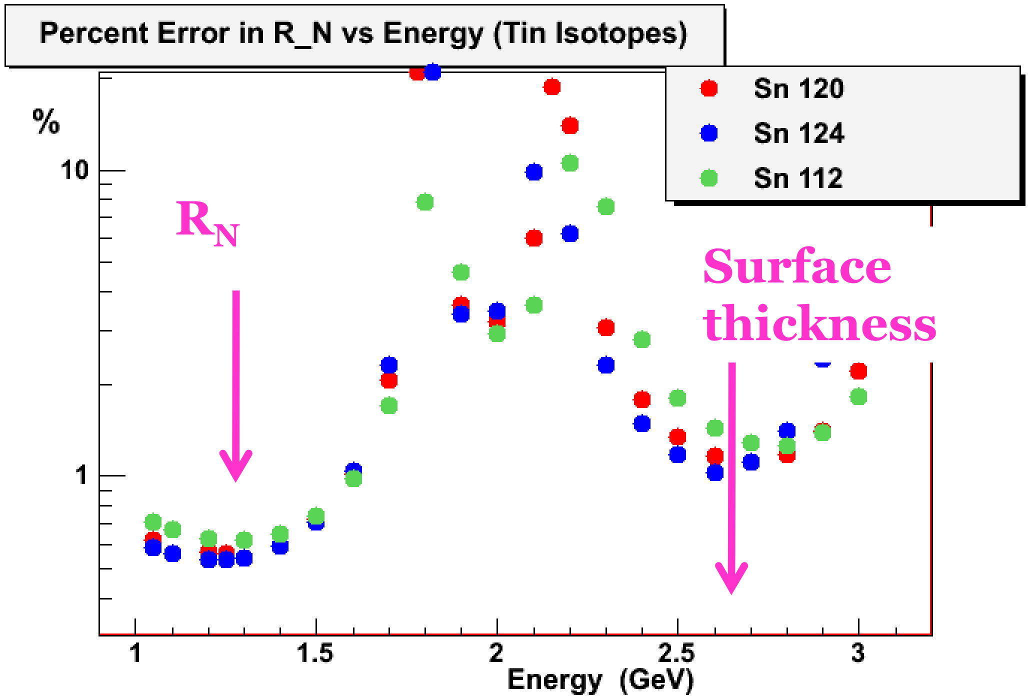
After PREX ...

Other Nuclei ?

and Shape Dependence ?



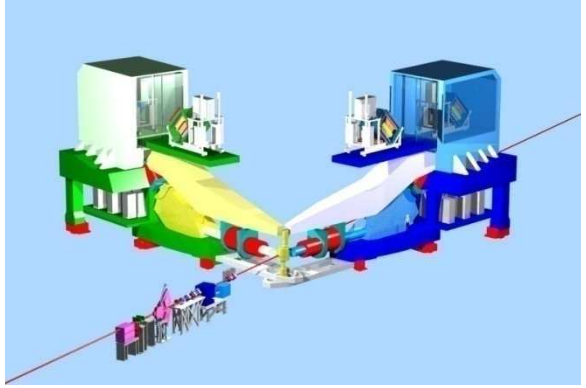
each point 30 days



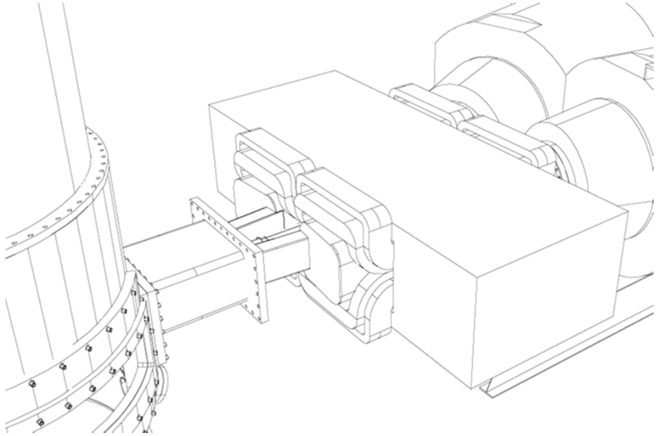
Parity Violating Electron Scattering Measurements of Neutron Densities
Shufang Ban, C.J. Horowitz, R. Michaels

J. Phys. G39 014104 2012

R. Michaels, Jlab
Seminar @ UVa
Feb 10, 2012



Possible Future PREX Program ?



Each point 30 days stat. error only

Nucleus	E (GeV)	dR_N / R_N	comment
^{208}Pb	1	1 %	**PREX-II** (approved by Jlab PAC, A rating)
^{48}Ca	2.2 (1-pass)	0.4 %	natural 12 GeV exp't will propose @ next PAC
^{48}Ca	2.6	2 %	surface thickness
^{40}Ca	2.2 (1-pass)	0.6 %	basic check of theory
tin isotope	1.8	0.6 %	apply to heavy ion
tin isotope	2.6	1.6 %	surface thickness

Not proposed (last four rows)

R. Michaels, Jlab
Seminar @ UVa
Feb 10, 2012

Shufang Ban, C.J. Horowitz, R. Michaels **J. Phys. G39 014104 2012**

UVa Participants in Jlab Parity-Violation & PREX

Gordon Cates

Kent Paschke
PREX-II spokesperson

Nilanga Liyanage

Xiaochao Zheng

Mark Dalton

Diancheng Wang

Rupesh Silwal

Kiadtisak Saenboonruang
Thesis on PREX-I

Also: Chao Gu, Xiaoyan Deng, Ge Jin, Richard Lindgren, Vladimir Nelyubin, Seamus Riordan, Ramesh Subedi, Al Tobias

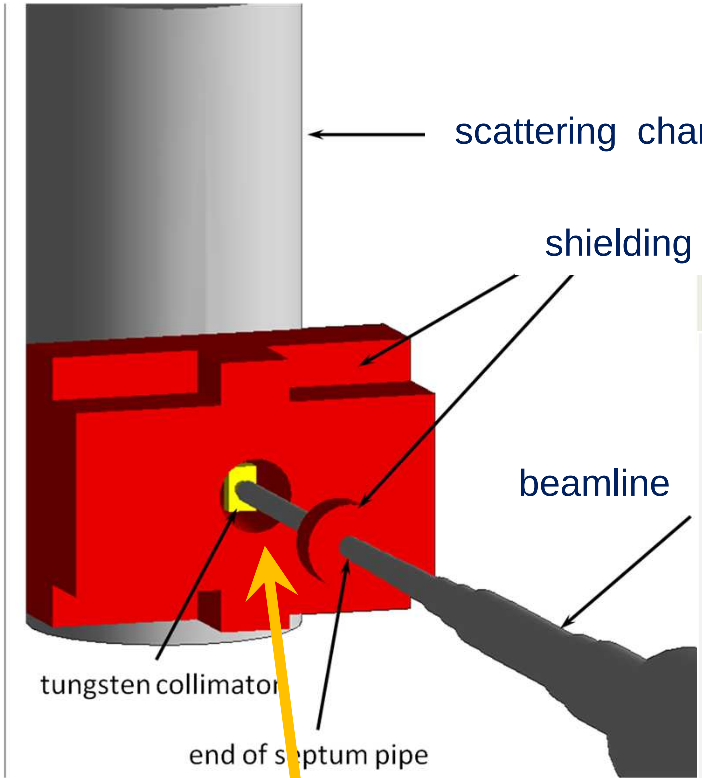
PREX : Summary

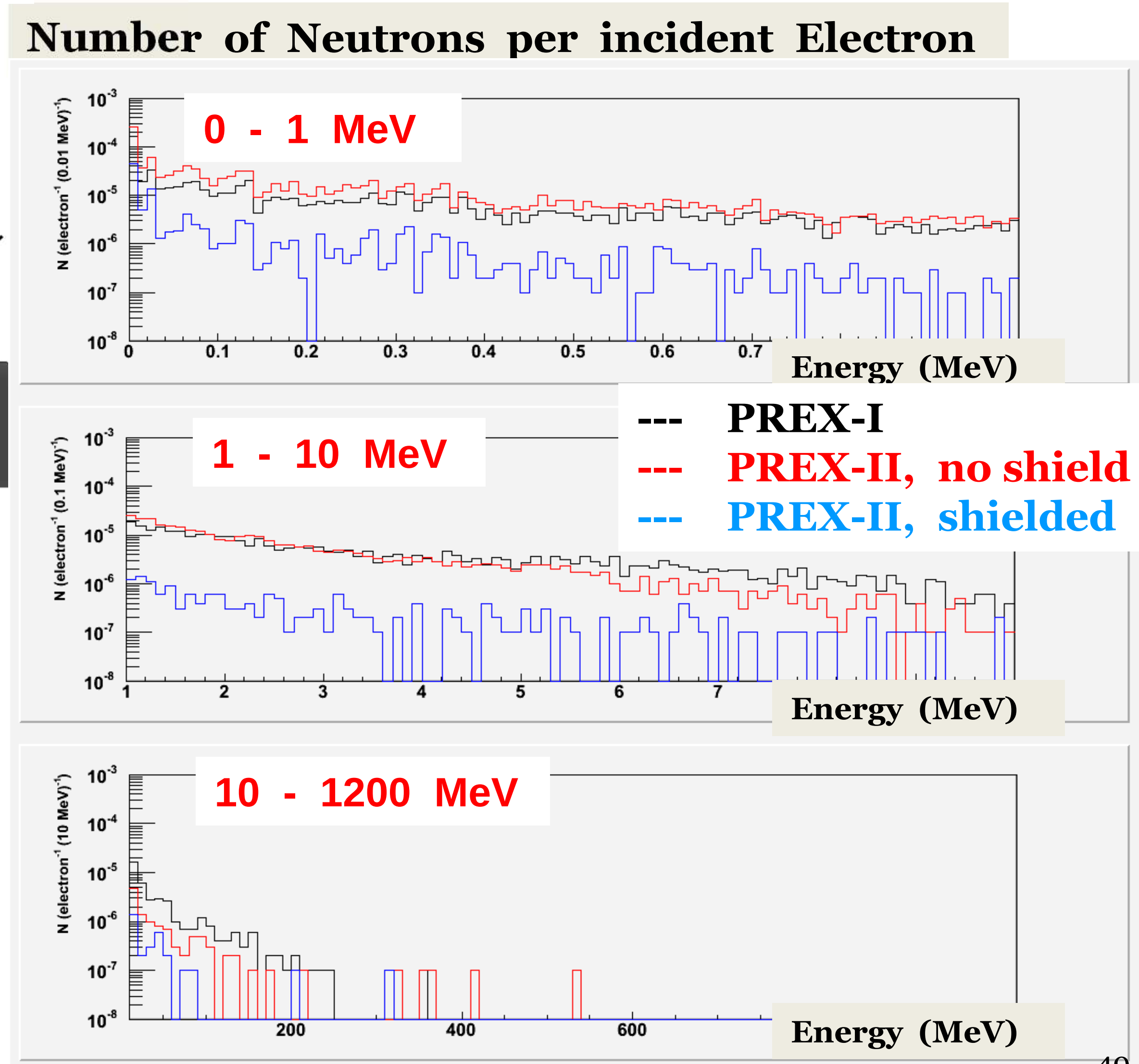
- Fundamental Nuclear Physics with many applications
- PREX-I achieved a 9% stat. error in Asymmetry (original goal : 3 %)
- Systematic Error Goals Achieved !!
- Significant time-losses due to O-Ring problem and radiation damage
- PREX-II approved (runs in 2013 or 2014)

Extra Slides

Geant 4 Radiation Calculations

PREX-II shielding strategies





Strategy

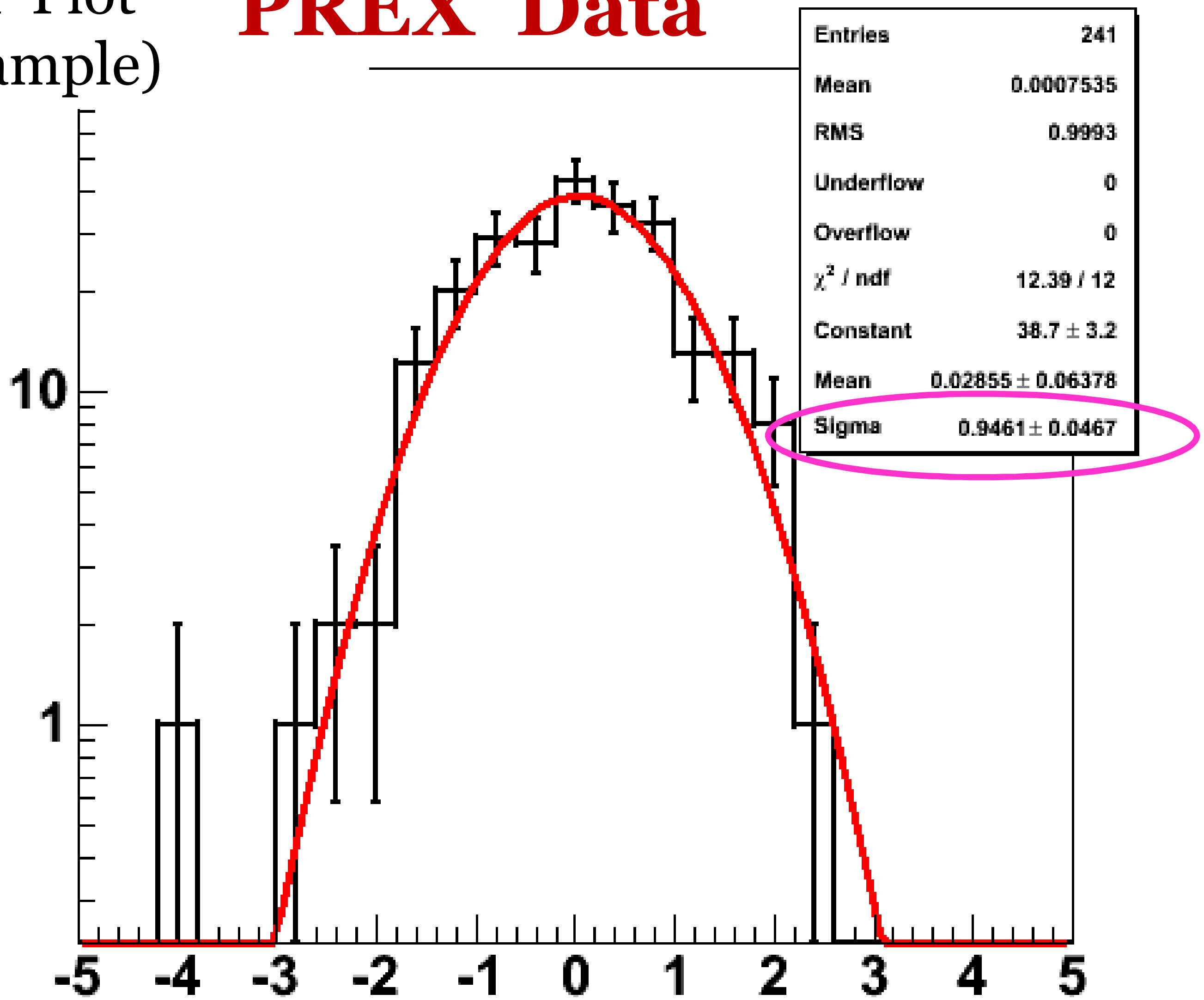
- **Tungsten (W) plug**

$$0.7^0 < \theta < 3^0$$

- **Shield the W**
- **x 10 reduction in 0.2 to 10 MeV neutrons**

Pull Plot (example)

PREX Data



$$(A - \bar{A}) / \sigma$$

Corrections to the Asymmetry are Mostly Negligible

- Coulomb Distortions ~20% = the biggest correction.
- Transverse Asymmetry (to be measured)
- Strangeness
- Electric Form Factor of Neutron
- Parity Admixtures
- Dispersion Corrections
- Meson Exchange Currents
- Shape Dependence
- Isospin Corrections
- Radiative Corrections
- Excited States
- Target Impurities

(Strangeness through Target Impurities:) Horowitz, *et.al.* PRC 63 025501

Optimum Kinematics for Lead Parity: E = 1 GeV if $\theta = 5^\circ$

<A> = 0.5 ppm. Accuracy in Asy 3%

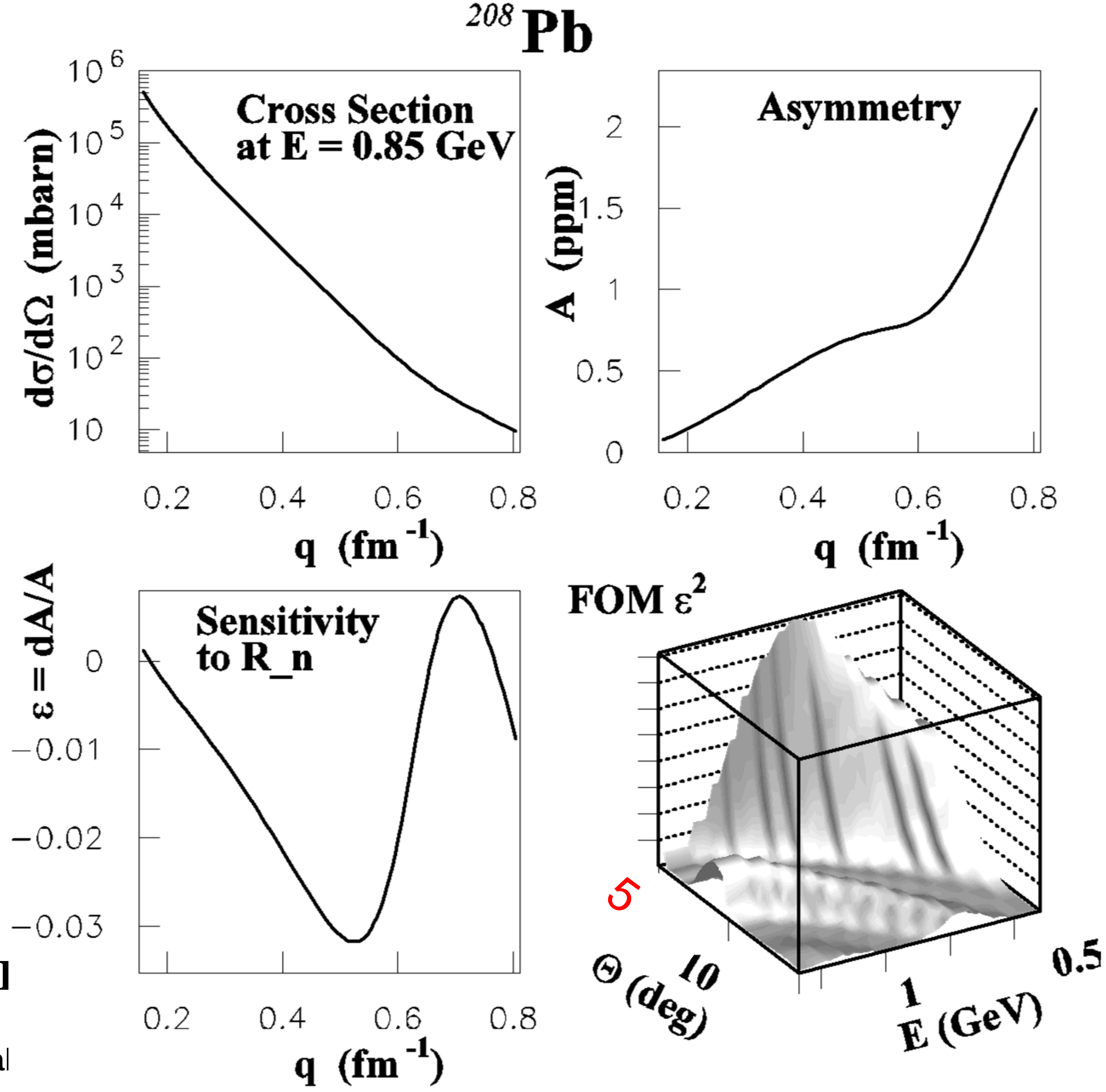


Fig. of merit

$$FOM = \frac{d\sigma}{d\Omega} \times A^2$$

Min. error in R_n

maximize:

→ $FOM \times \varepsilon^2$

1 month run

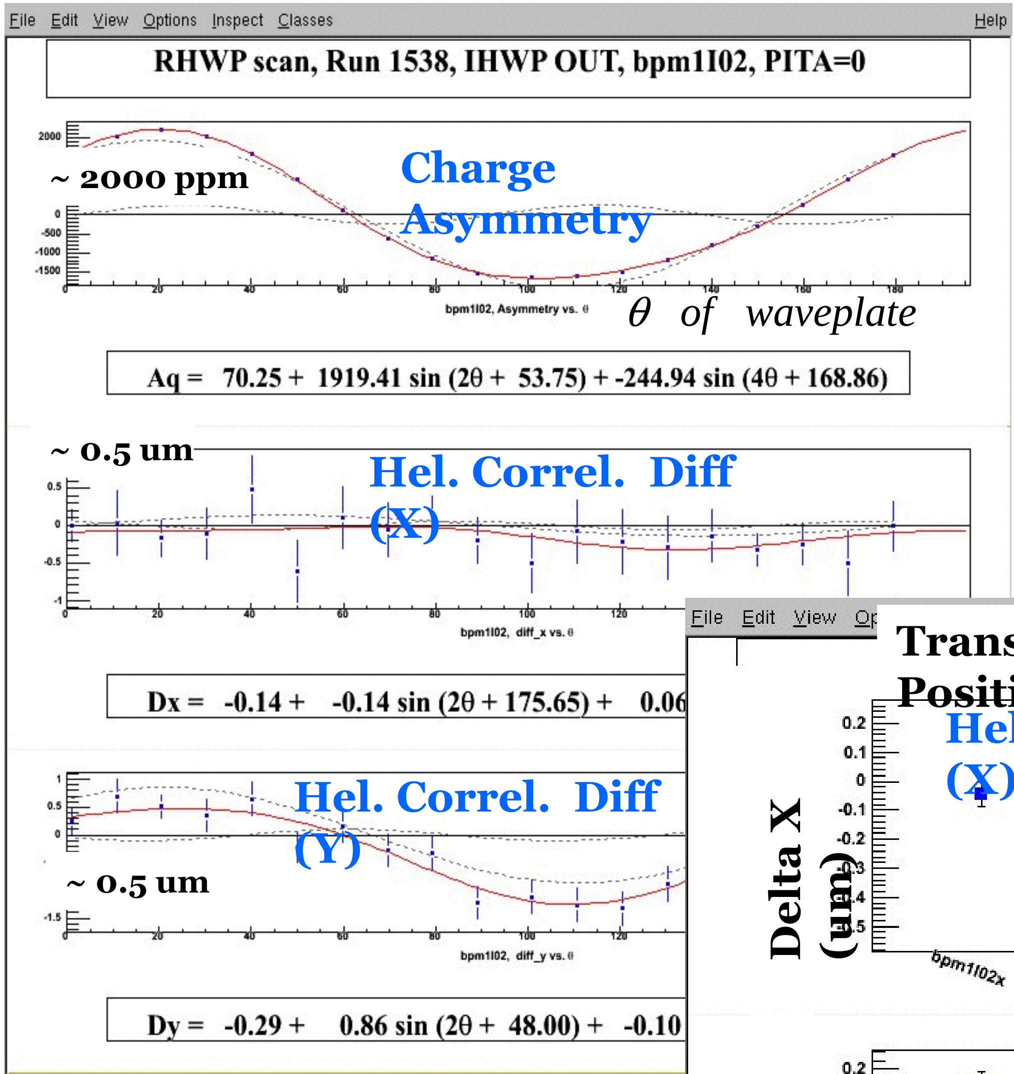
→ 1% in R_n

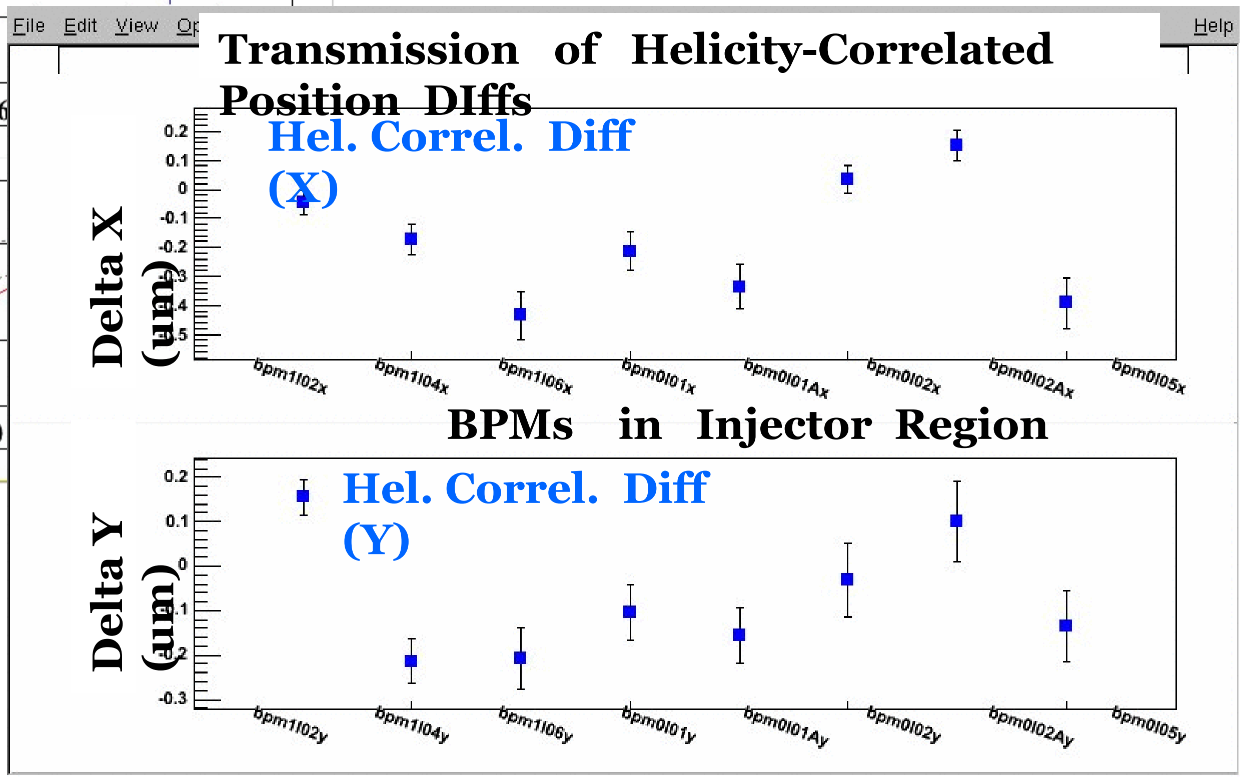
(2 months x 100 uA
→ 0.5% if no systematics)

Source Studies

Kent Paschke, Gordon Cates, Mark Dalton, Rupesh Silwal

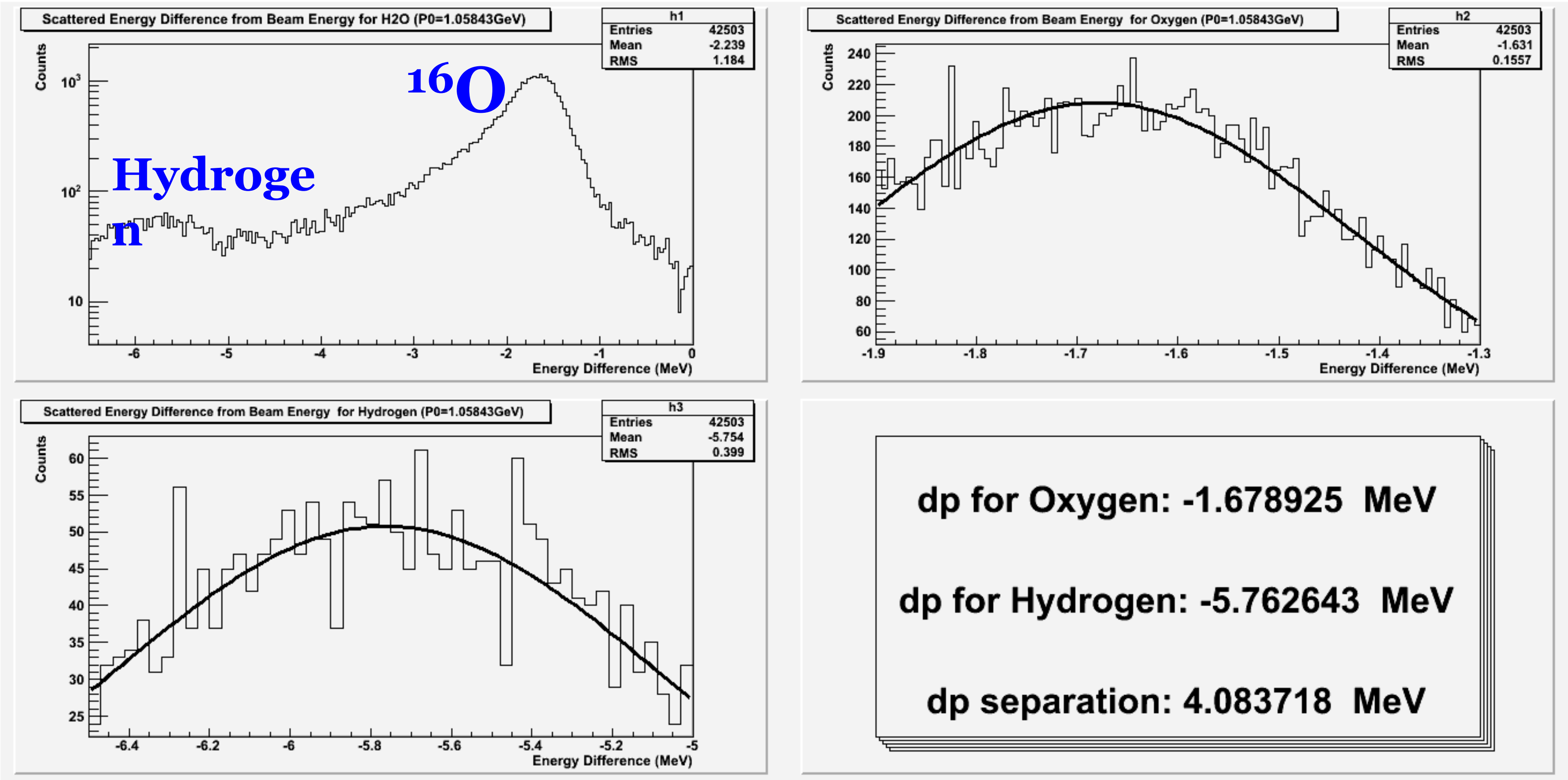
Optimizing laser optics to minimize helicity-correlated systematics.





Water Cell : Measure $< \theta >$ (agrees with survey)

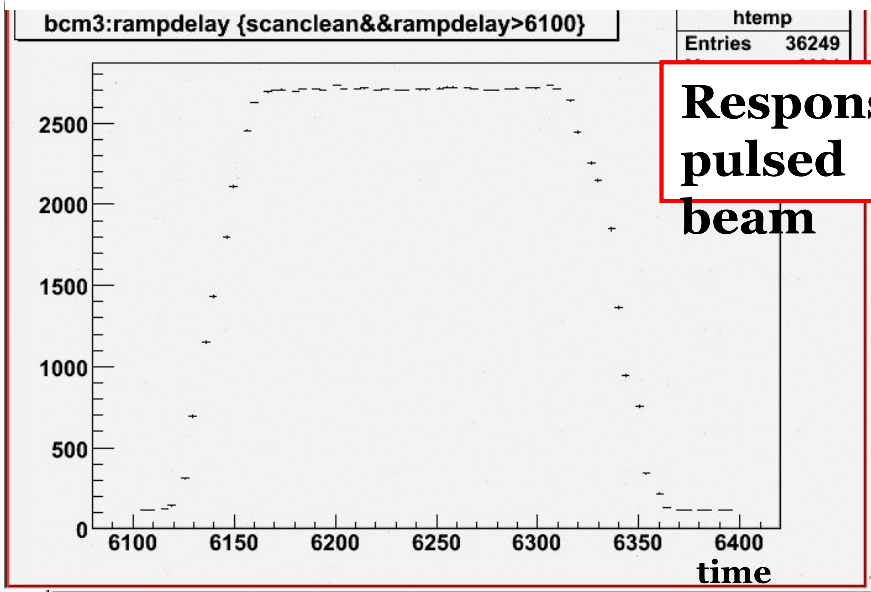
Nilanga Liyanage, Seamus Riordan, Kiadtisak Saenboonruang,



Pocket Cell Related Systematic Error

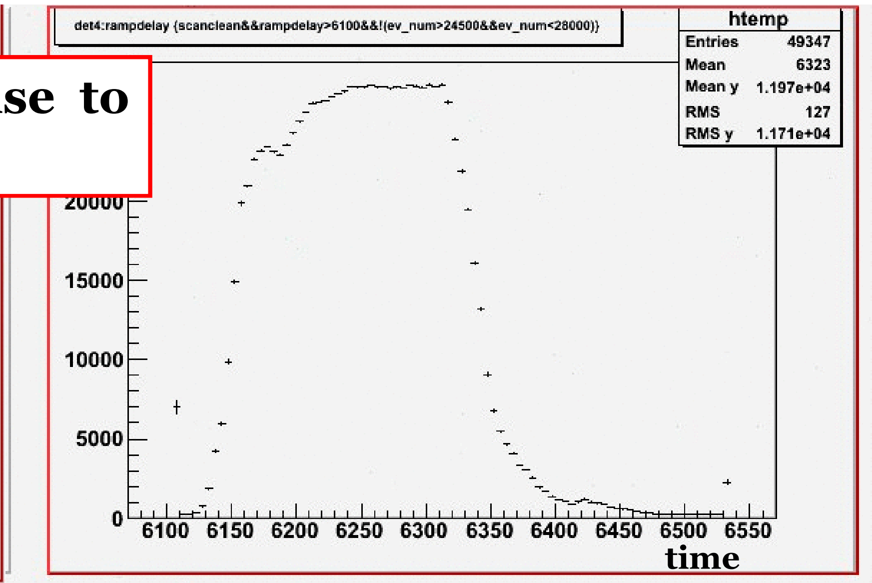
An instability in Pockel Cell "bleeds" into the itegration gate. It depends on helicity.

Beam Current



Response to pulsed beam

Detector (1 of 4)



Want small time constants, and same for detectors and bcm

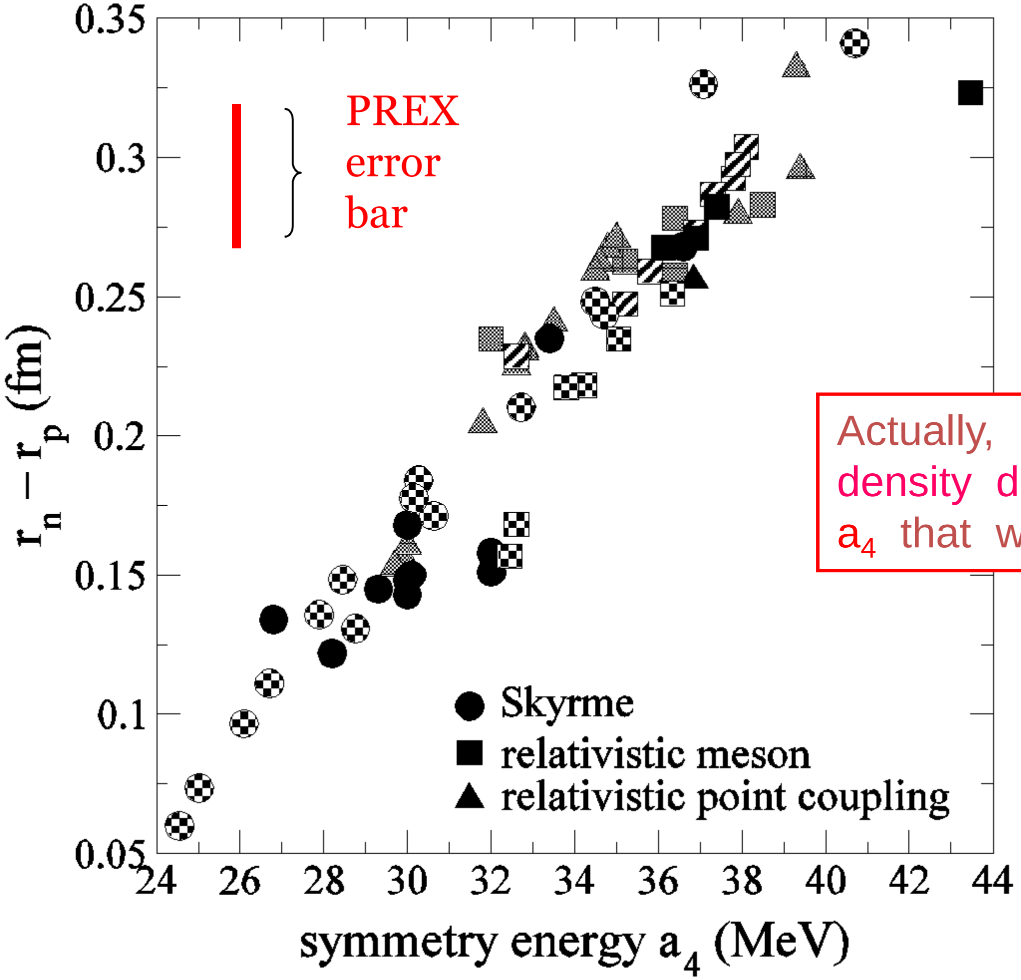
PREX: pins down the symmetry energy (1 parameter)

$$\frac{E}{A} \approx -a_v + a_4 \left(\frac{N-Z}{A} \right)^2 + a_s / A^{1/3} + \ldots$$

energy cost for unequal # protons & neutrons

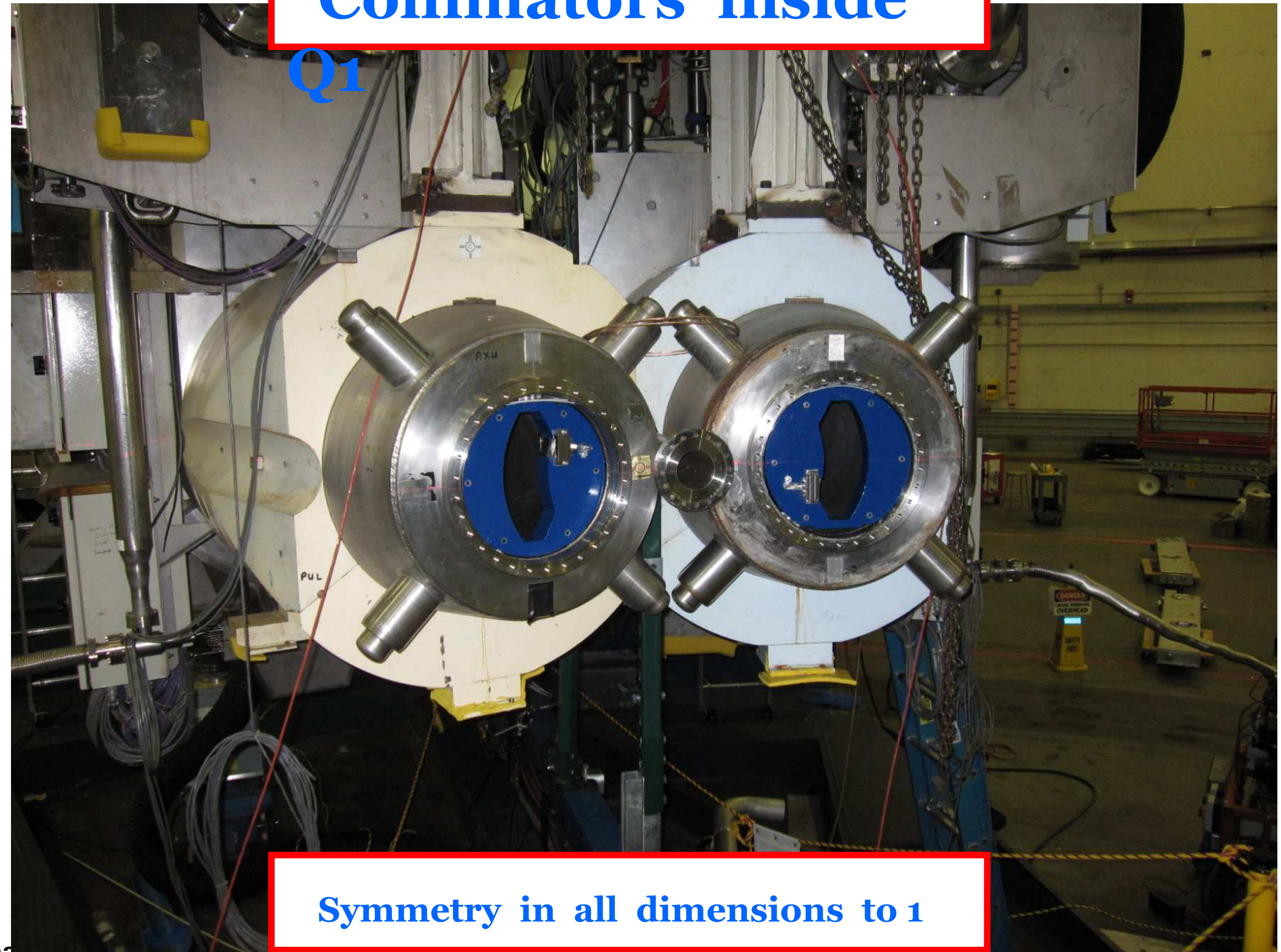
(R.J. Furnstahl)

^{208}Pb



Actually, it's the density dependence of a_4 that we pin down.

Collimators inside Q1



Symmetry in all dimensions to 1 mm

(slide from C. Horowitz)

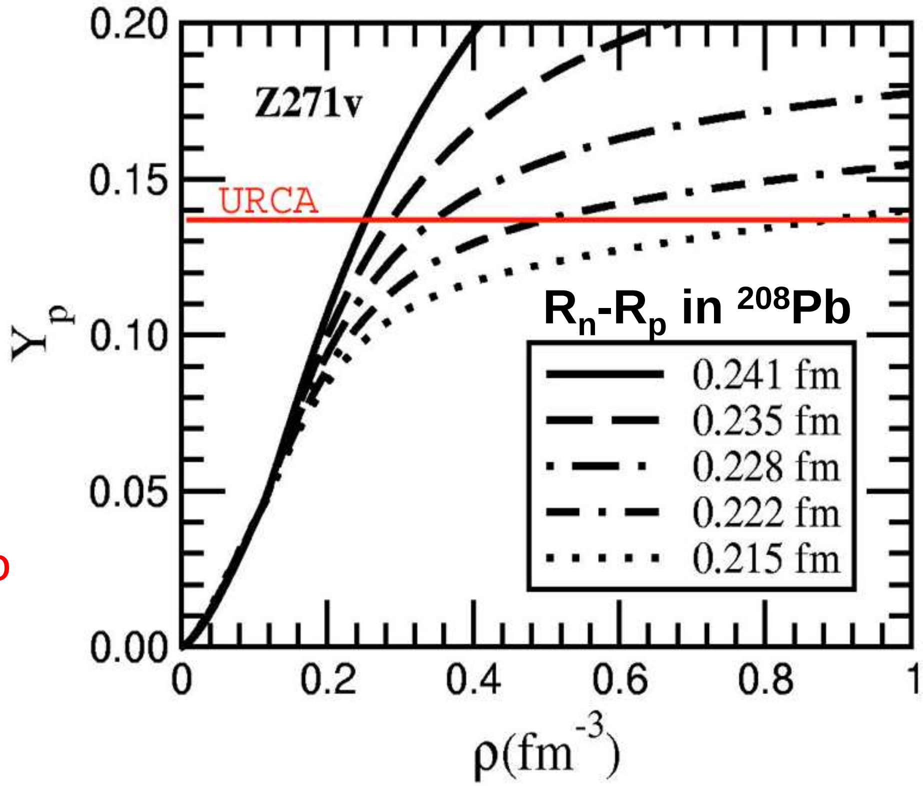
Pb Radius vs Neutron Star Radius

- The ^{208}Pb radius constrains the pressure of neutron matter at subnuclear densities.
- The NS radius depends on the pressure at nuclear density and above.
- Most interested in density dependence of equation of state (EOS) from a possible phase transition.
- Important to have both low density and high density measurements to constrain density dependence of EOS.
  - If Pb radius is relatively large: EOS at low density is stiff with high P. If NS radius is small than high density EOS soft.
  - This softening of EOS with density could strongly suggest a transition to an exotic high density phase such as quark matter, strange matter, color superconductor, kaon condensate…

(slide from C. Horowitz)

PREX Constrains Rapid Direct URCA Cooling of Neutron Stars

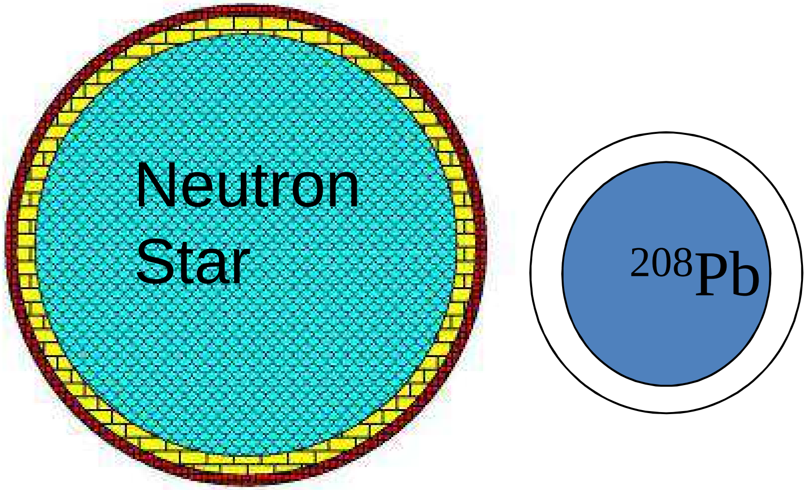
- Proton fraction Y_p for matter in beta equilibrium depends on symmetry energy S(n).
- R_n in Pb determines density dependence of S(n).
- The larger R_n in Pb the lower the threshold mass for direct URCA cooling.
- If R_n-R_p<0.2 fm all EOS models do not have direct URCA in 1.4 $M_\odot$ stars.
- If R_n-R_p>0.25 fm all models do have URCA in 1.4 $M_\odot$ stars.

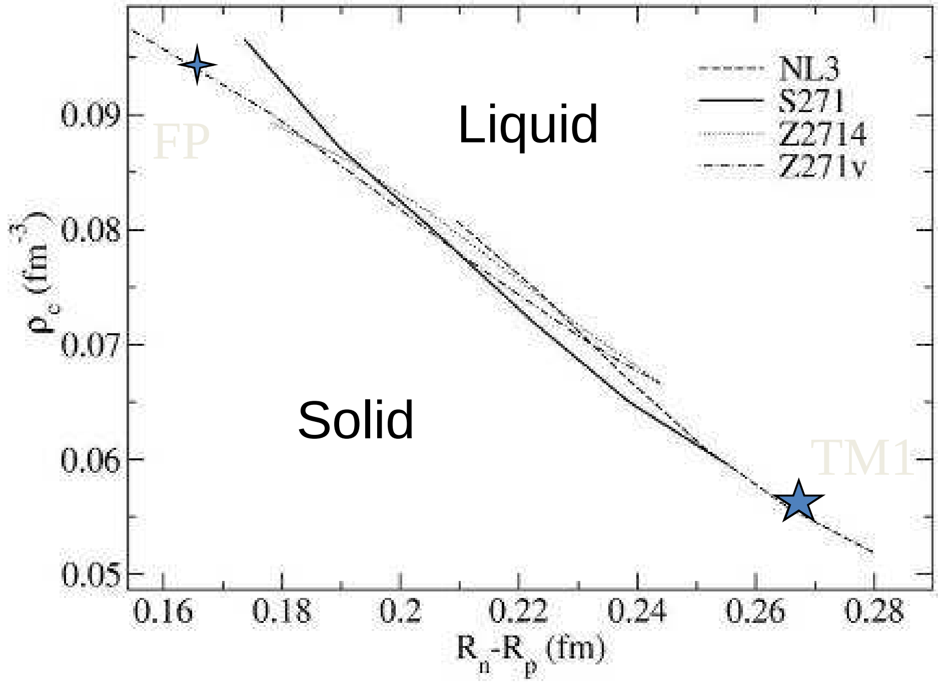


If Y_p > red line NS cools quickly via direct URCA reaction $n \rightarrow p+e+\bar{\nu}$

Neutron Star Crust vs Pb Neutron Skin

C.J. Horowitz, J. Piekarawicz





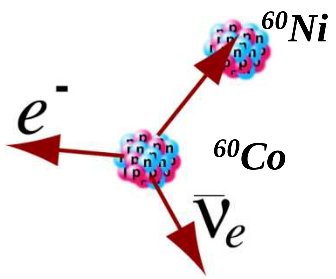
- Thicker neutron skin in Pb means energy rises rapidly with density → Quickly favors uniform phase.
- Thick skin in Pb → low transition density in star.

Weak Interaction

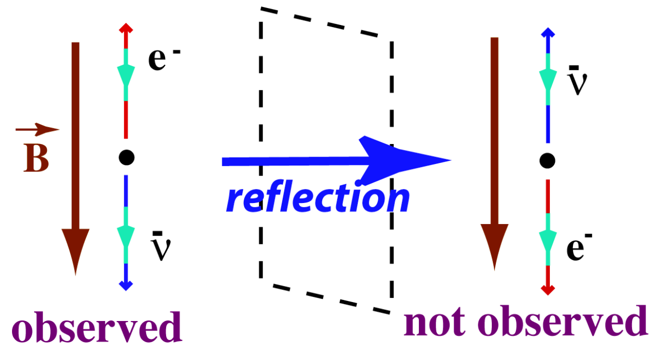
1930's - The weak nuclear interaction was needed to explain nuclear beta decay

Contact interaction with charge exchanged
or, mediated by a heavy, charged boson

1950's - Discovery of parity-violation by the weak interaction



Weak decay of ^{60}Co Nucleus



V-A theory described W's as only interacting with left-handed particles!

	Left	Right
W Charge	$T = \pm\frac{1}{2}$	zero