Acknowlegements:
The E158, HAPPEX, PREX and MOLLER Collaborations
www.particleadventure.org

Electrons are Not Ambidextrous:

New Insights from a Subatomic Matter of Fact

Krishna Kumar
Stony Brook University, SUNY

Physics Colloquium
BNL, November 4, 2014

Electroweak Nuclear Physics

Outline

- **Electron Scattering & Subatomic Structure**
- **Electron Scattering and the Weak Force**
  - ★ Electrons in the scattering process are NOT ambidextrous
- **Parity-Violating Electron Scattering**
- **Two Modern Applications**
  - ★ The Neutron Skin of a Heavy Nucleus
    - *PREX: First direct electroweak measurement* (Phys.Rev.Lett. 108 (2012) 112502)
    - *PREX-II: Followup precision measurement scheduled for 2016*
  - ★ Search for New Superweak Forces
    - *MOLLER: Proposed ultra-precise weak mixing angle measurement*
- **Outlook**

Electroweak Nuclear Physics

Outline

Fundamental Symmetries, Nuclear Structure, Hadron Physics

✦ Electron Scattering & Subatomic Structure

✦ Electron Scattering and the Weak Force

★ Electrons in the scattering process are NOT ambidextrous

✦ Parity-Violating Electron Scattering

✦ Two Modern Applications

★ The Neutron Skin of a Heavy Nucleus

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★ Search for New Superweak Forces

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✦ Outlook

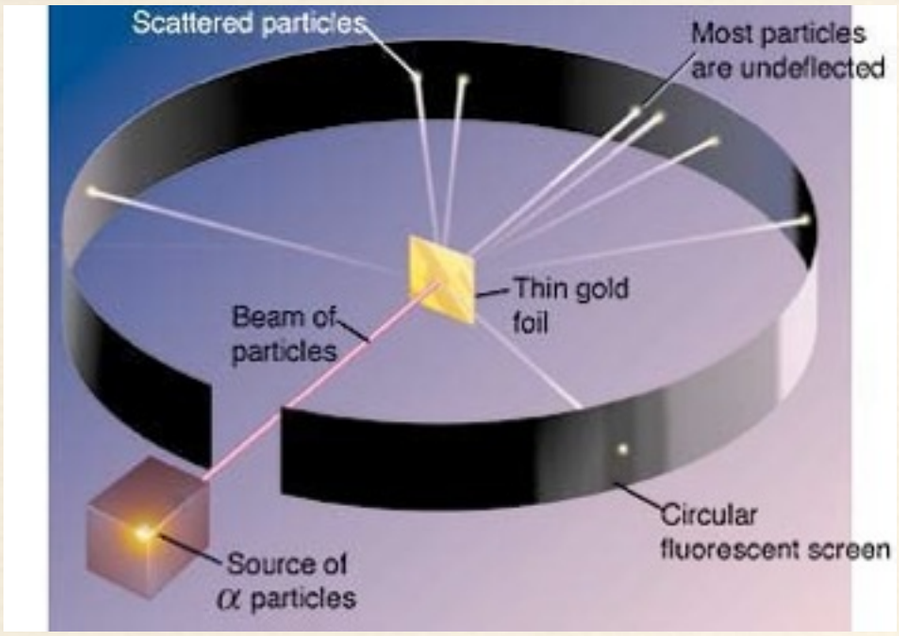
Electron Scattering and the Subatomic Structure

~ 1910

Rutherford Scattering

The first fixed target scattering experiment

Rutherford devised a scattering experiment involving a beam of alpha particles scattering off a gold foil



differential cross section

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right) \times \Delta\Omega$$

$$\frac{\textit{\# alphas scattered into solid angle per unit time}}{\textit{Incident beam intensity}}$$

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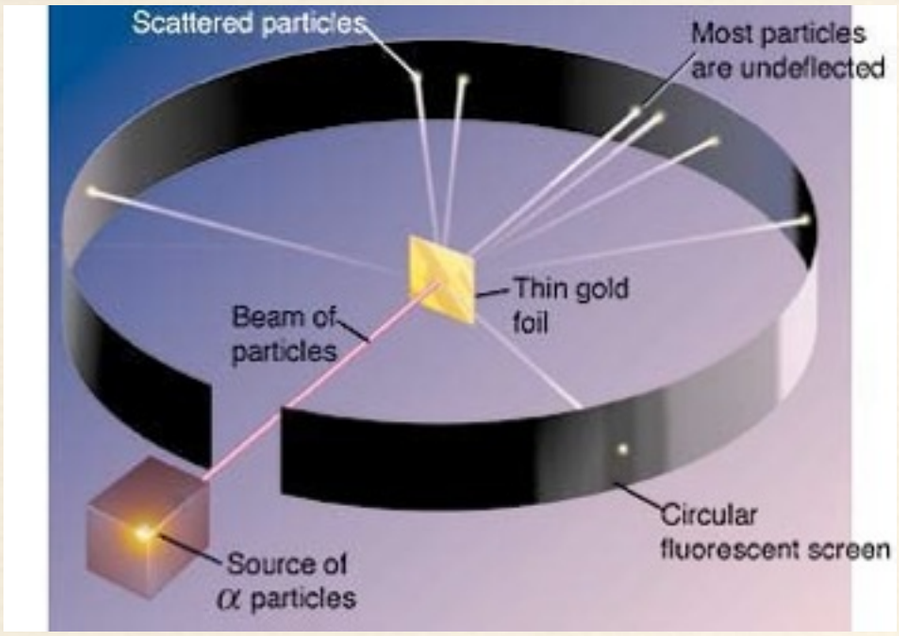

alpha particles & gold atom's positive charge: interaction governed by Maxwell's equations

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right) = \left(\frac{\mathrm{Z_1 Z_2}\alpha}{2\mathrm{mv}^2 \sin^2(\theta/2)}\right)^2$$

Atom's positive charge: static EM potential

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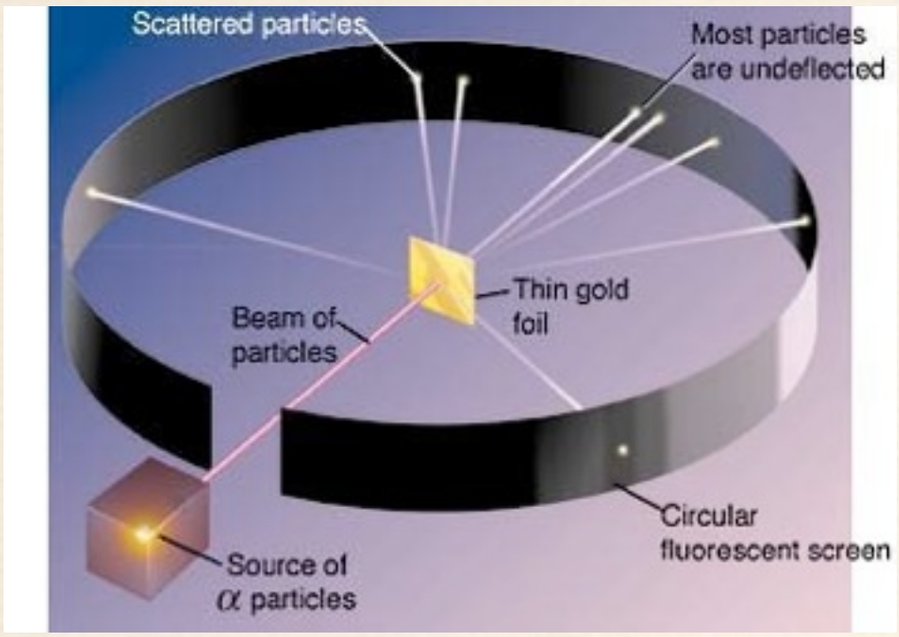

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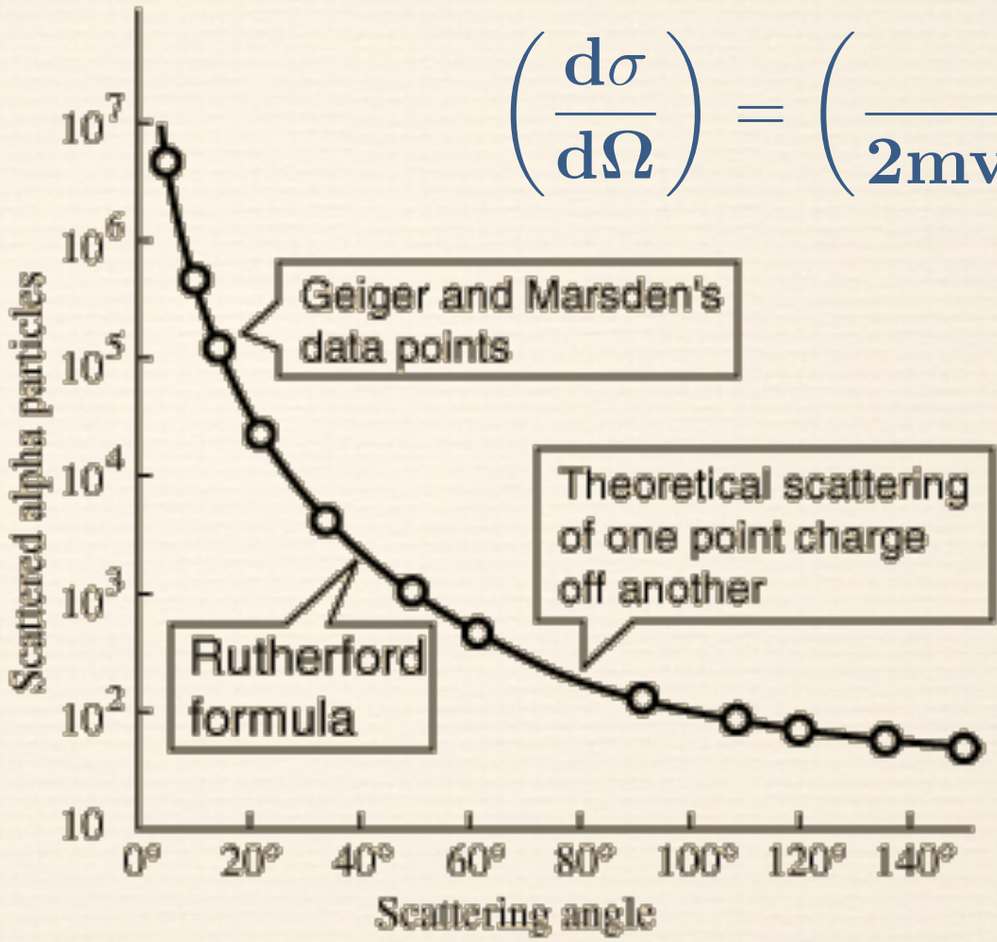

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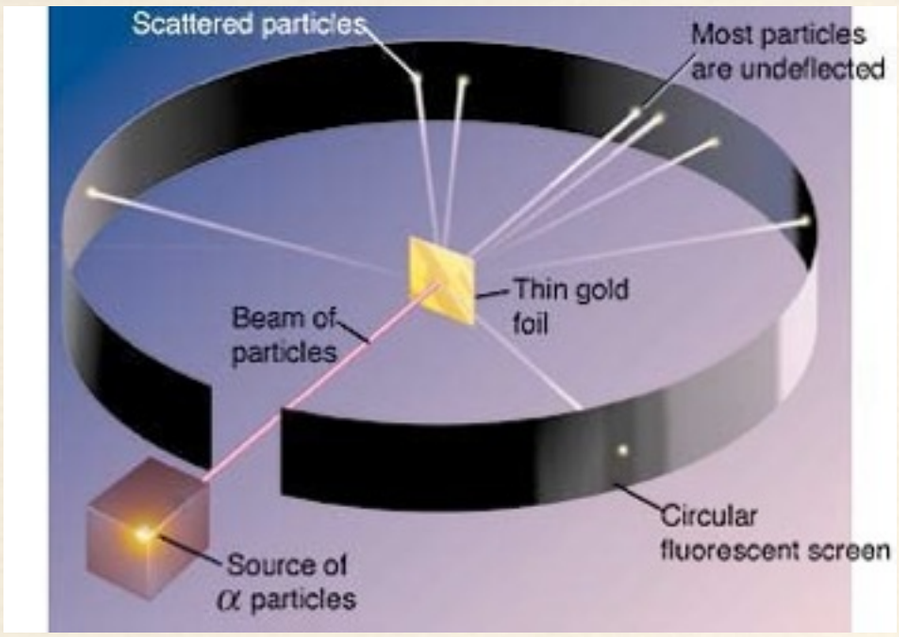

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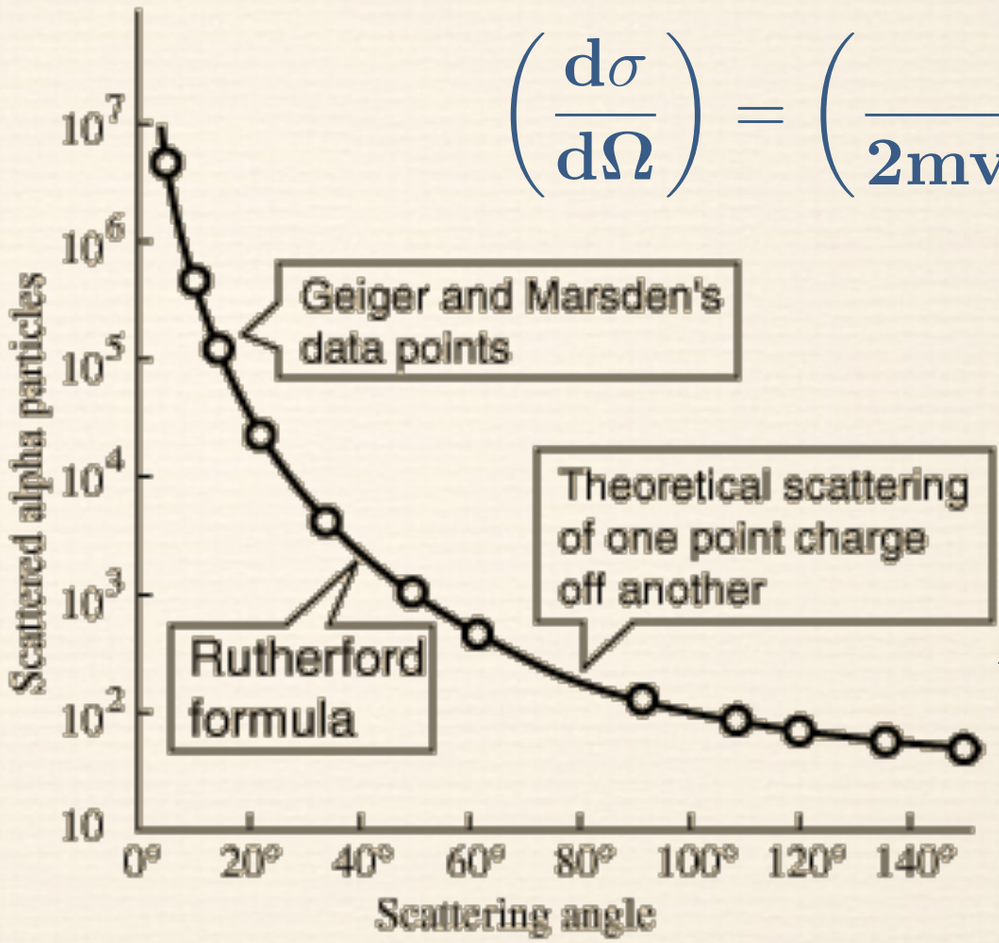
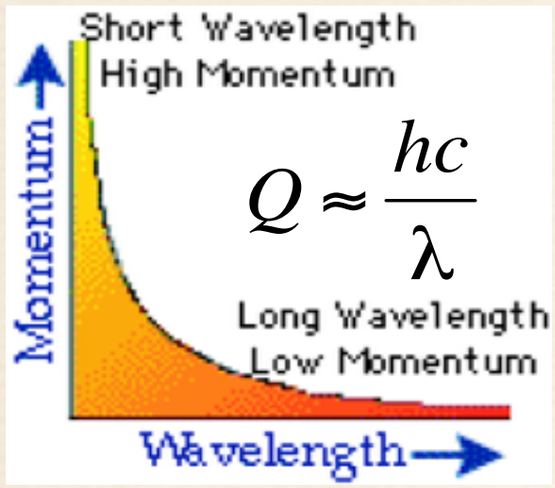


Atom's positive charge: static EM potential

- *Established that atoms have a tiny nuclear core ~ 10^{-14} m, << atomic size of 10^{-10} m*
- *Revolutionized experimentation: particle scattering as a microscope*

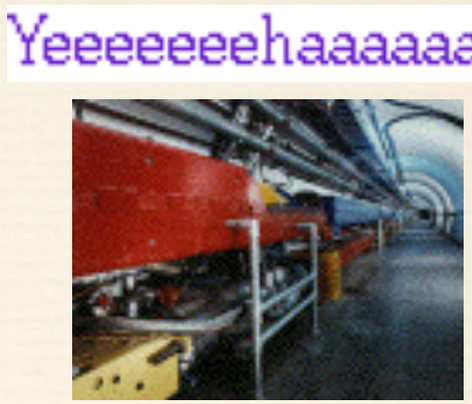
A femtoscope

Electron Scattering



At nuclear scales, particles behave mostly like waves

How to produce femtometer wavelengths in the laboratory?

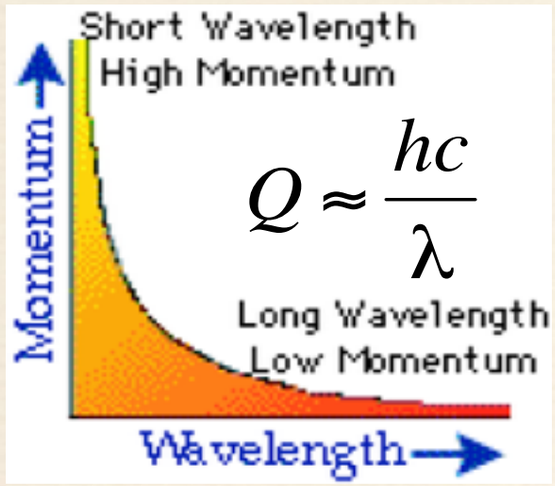


Particle Accelerators

A femtoscope

Electron Scattering

Electron interactions are well-understood



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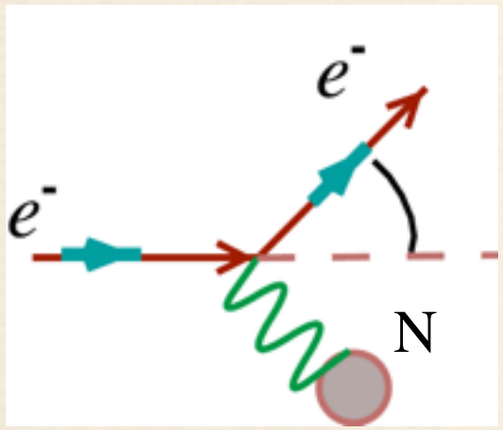
Yeeeeeeehaaaaaaaa!! e-

Particle Accelerators

Quantum Electrodynamics

Dirac: relativistic motion of electrons with spin 1/2



Electron scattering: electromagnetic interaction described as an exchange of a virtual photon.

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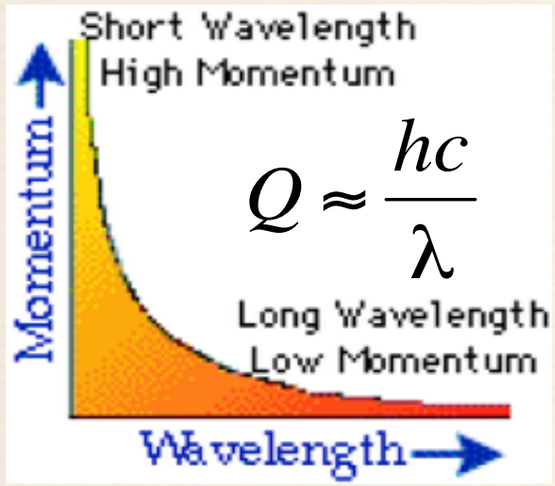

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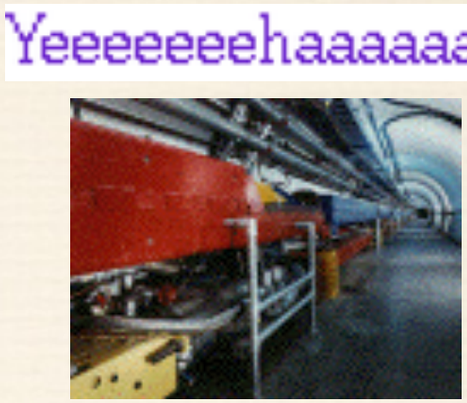

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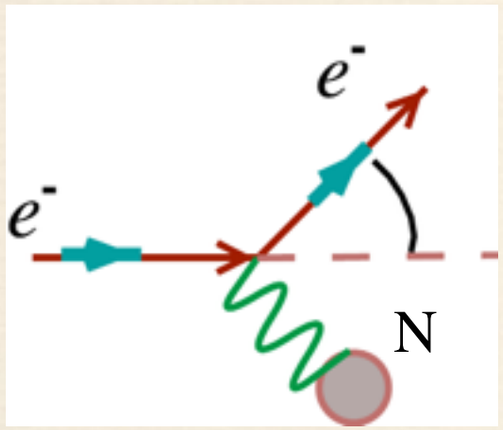

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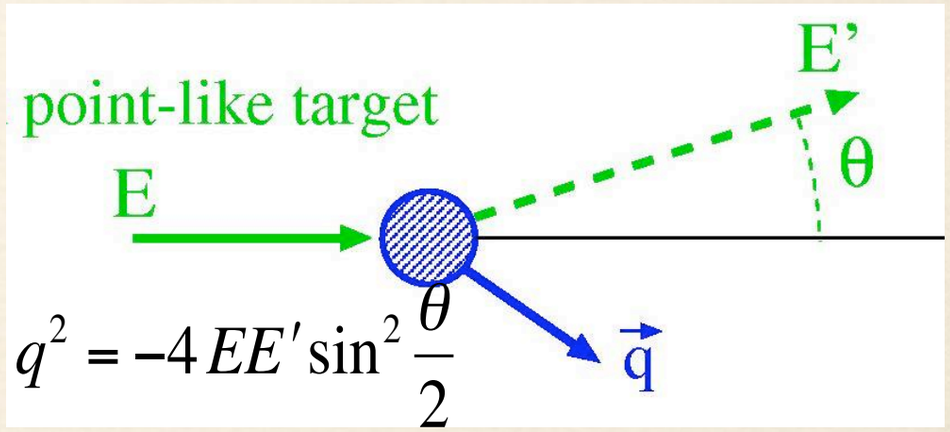

q^2: (4-momentum)^2 of the virtual photon

A femtoscope

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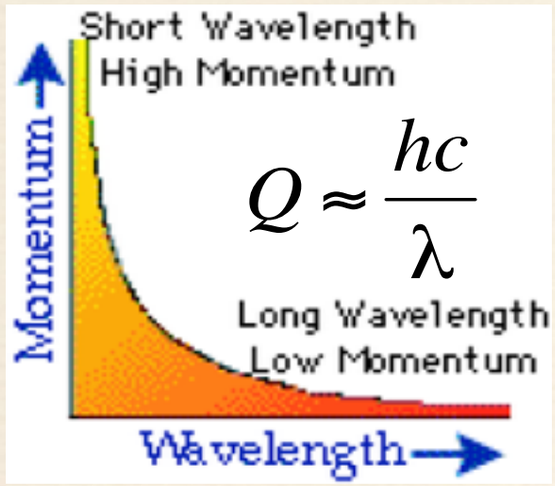

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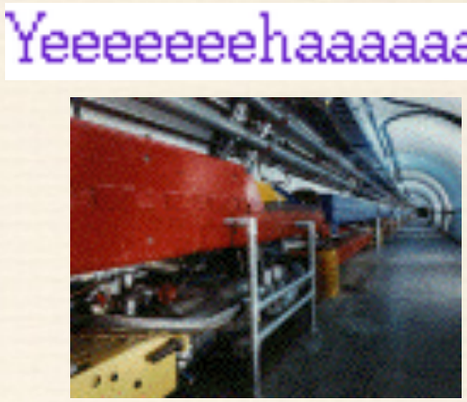

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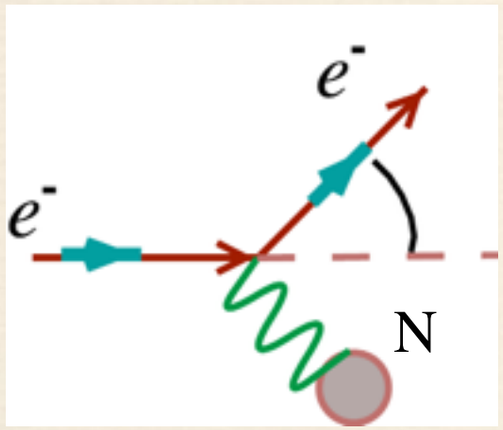

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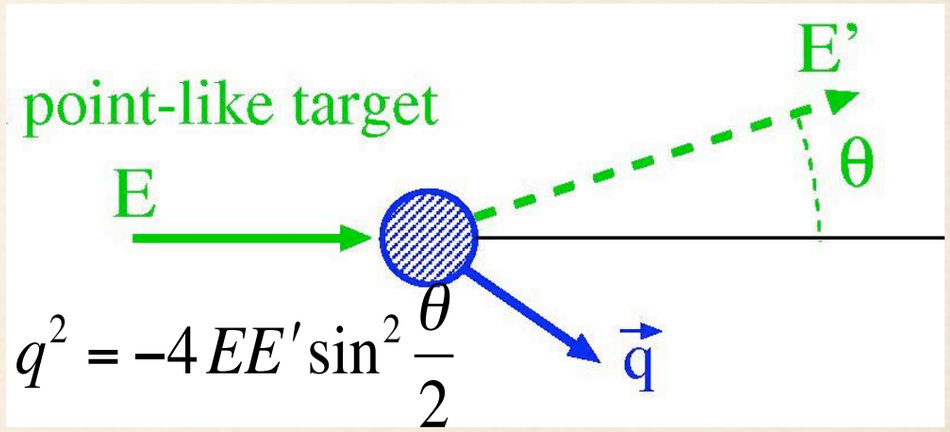
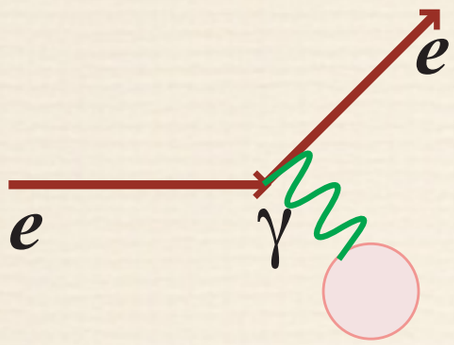


q^2: (4-momentum)^2 of the virtual photon

Powerful technique: high statistics and precise event-by-event kinematic determination

The Size of a Nucleus



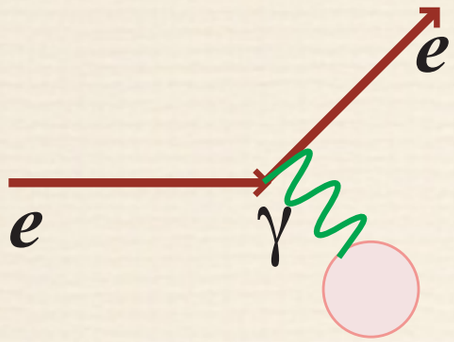
Heavy, spinless nucleus

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{4Z^2\alpha^2E^2}{q^4}$$

If Q sufficiently large (wavelength < 10 fm) , nuclear size modifies formula

The Size of a Nucleus

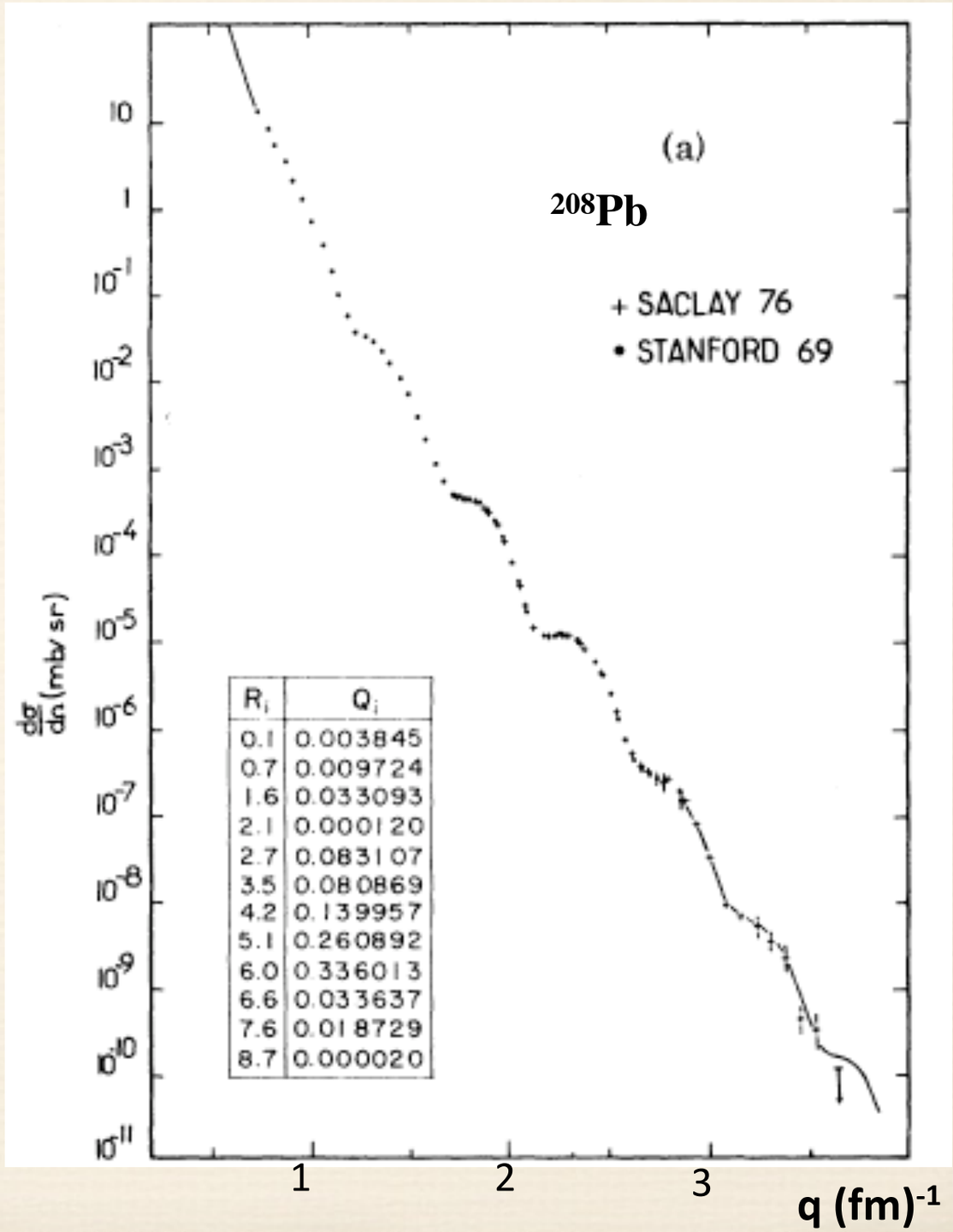
Increase momentum transfer -> shorter wavelength -> higher resolution -> smaller scales



Heavy, spinless nucleus

Differential Cross Section

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} |F(q)|^2$$



R_i	Q_i
0.1	0.003845
0.7	0.009724
1.6	0.033093
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2.7	0.083107
3.5	0.080869
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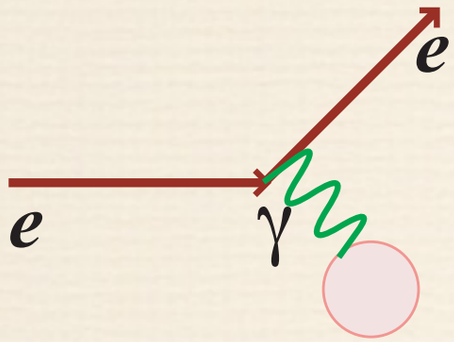

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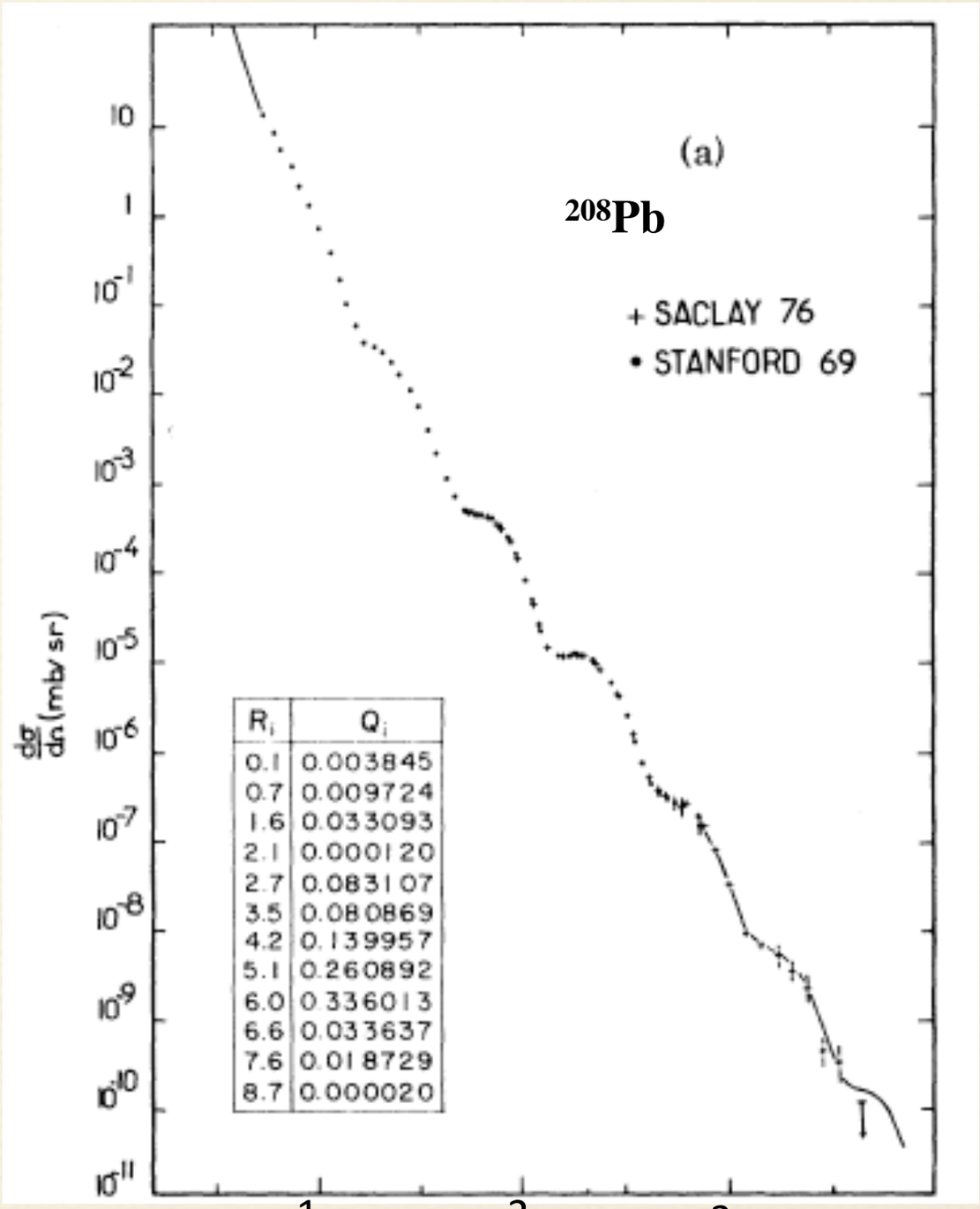
The point-like scattering probability modified: Introduce a "form factor"

$$F(q) = \int e^{iqr}\rho(r)d^3r$$

Form factor is the Fourier transform of charge distribution



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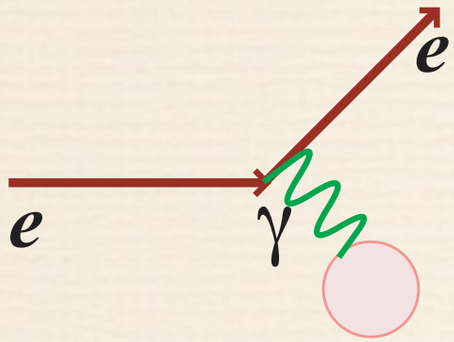

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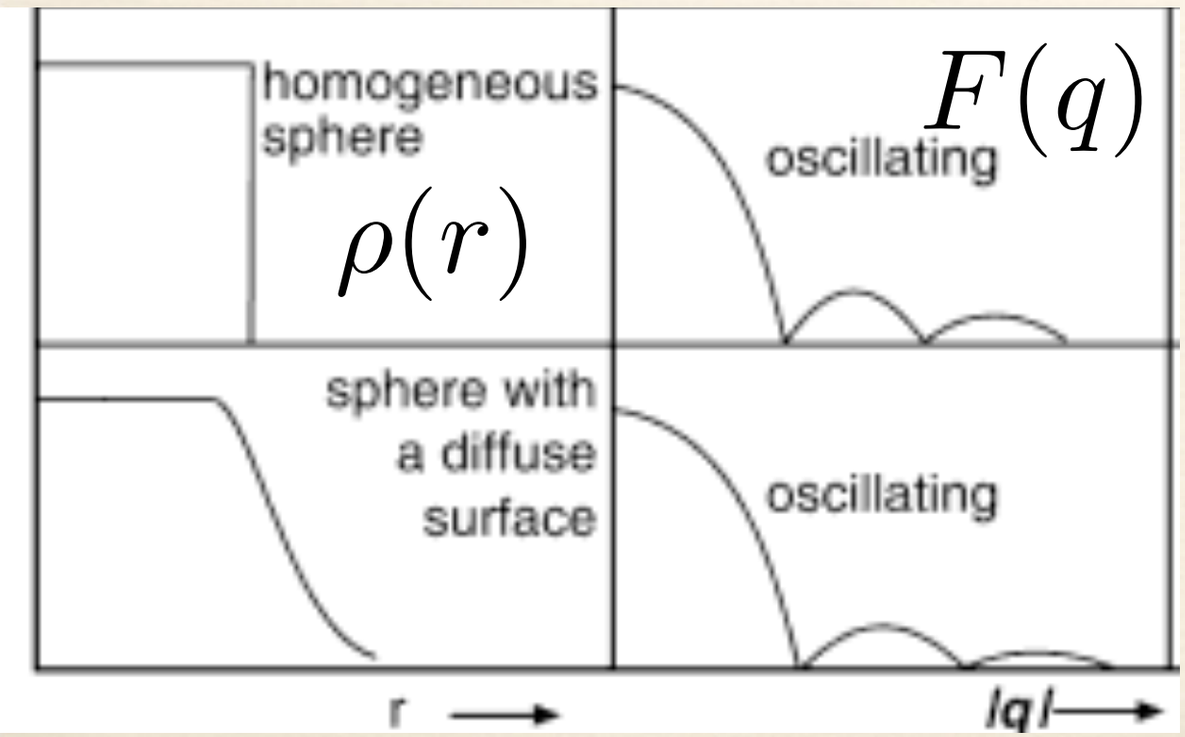

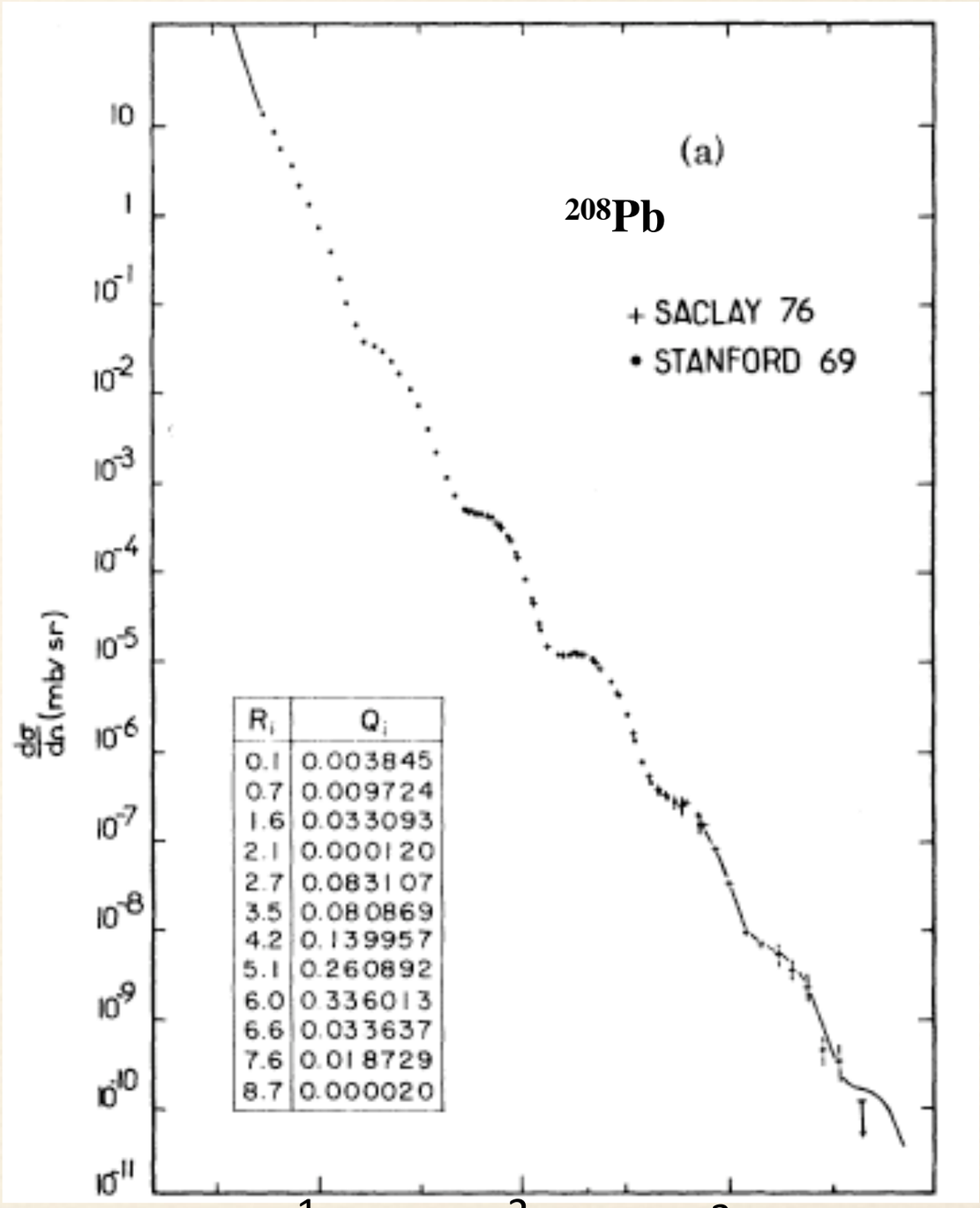

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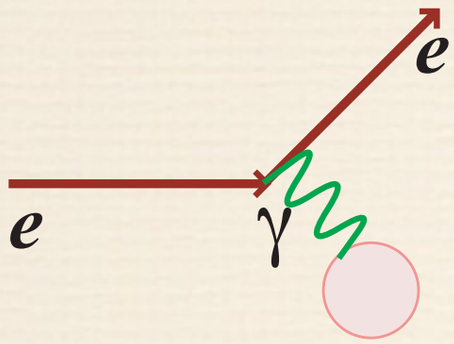

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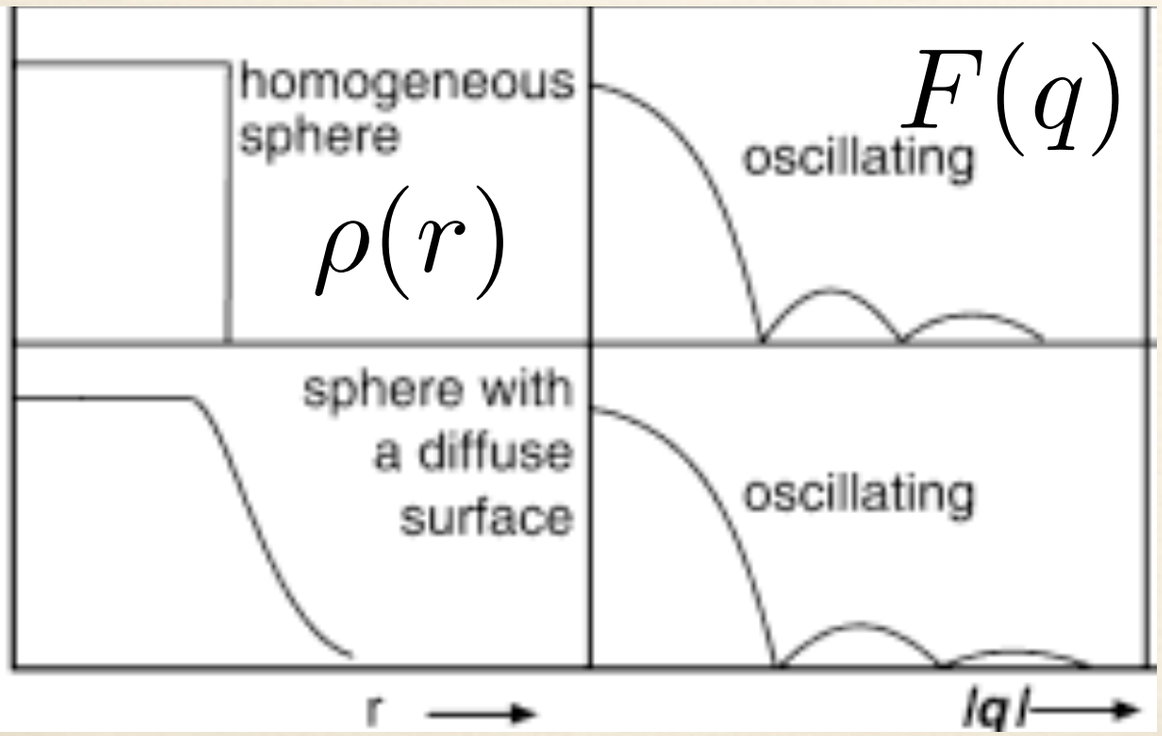
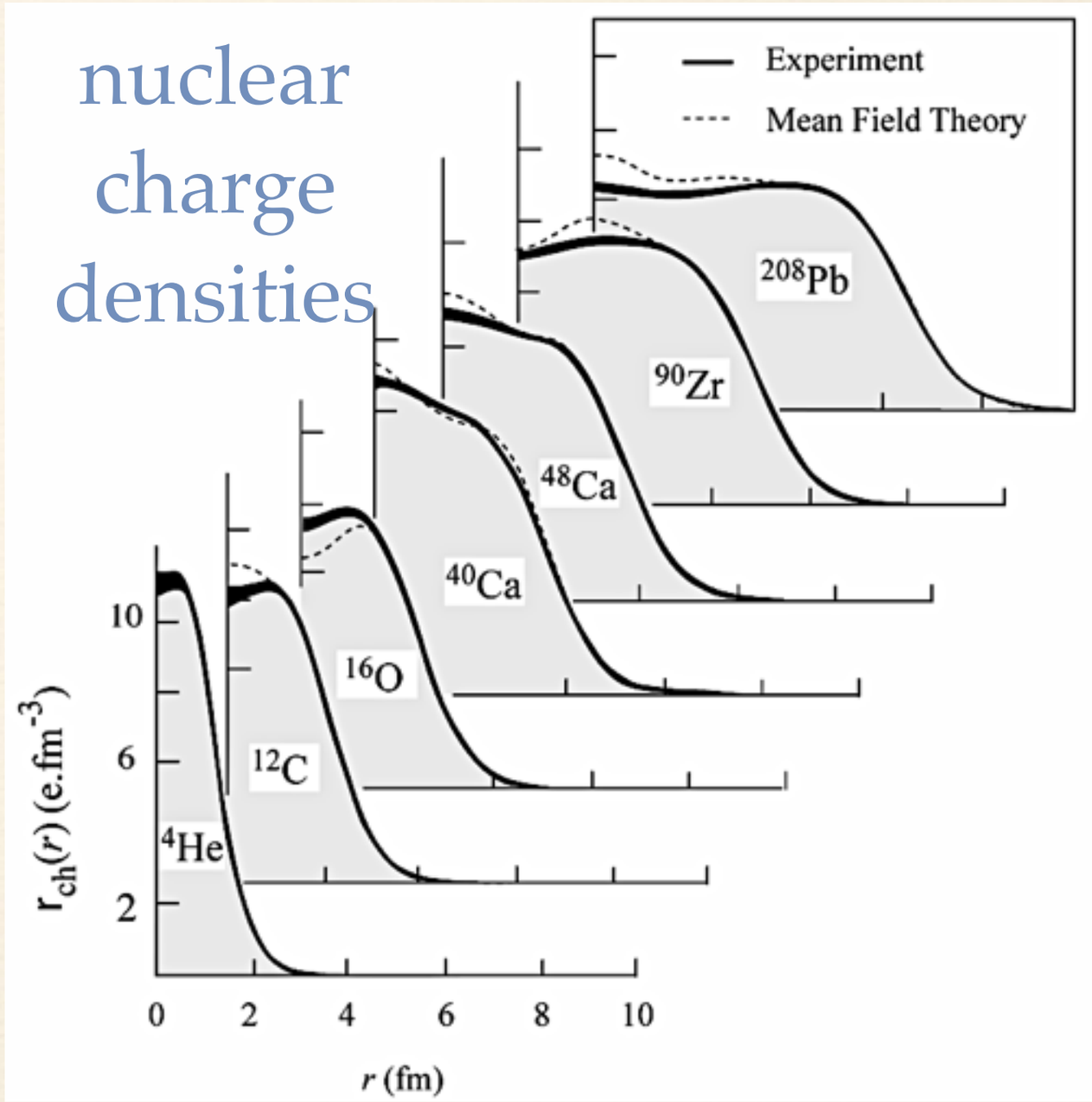


nuclear charge densities



The Size of the Proton

Otto Stern (1932) measured the proton magnetic moment $\mu_p \sim 2.5\ \mu_{Bohr}$:

First indication that the proton was not just a positive, structureless electron

(Nobel prize 1943)

Precise e-p cross section measurements at various scattering angles

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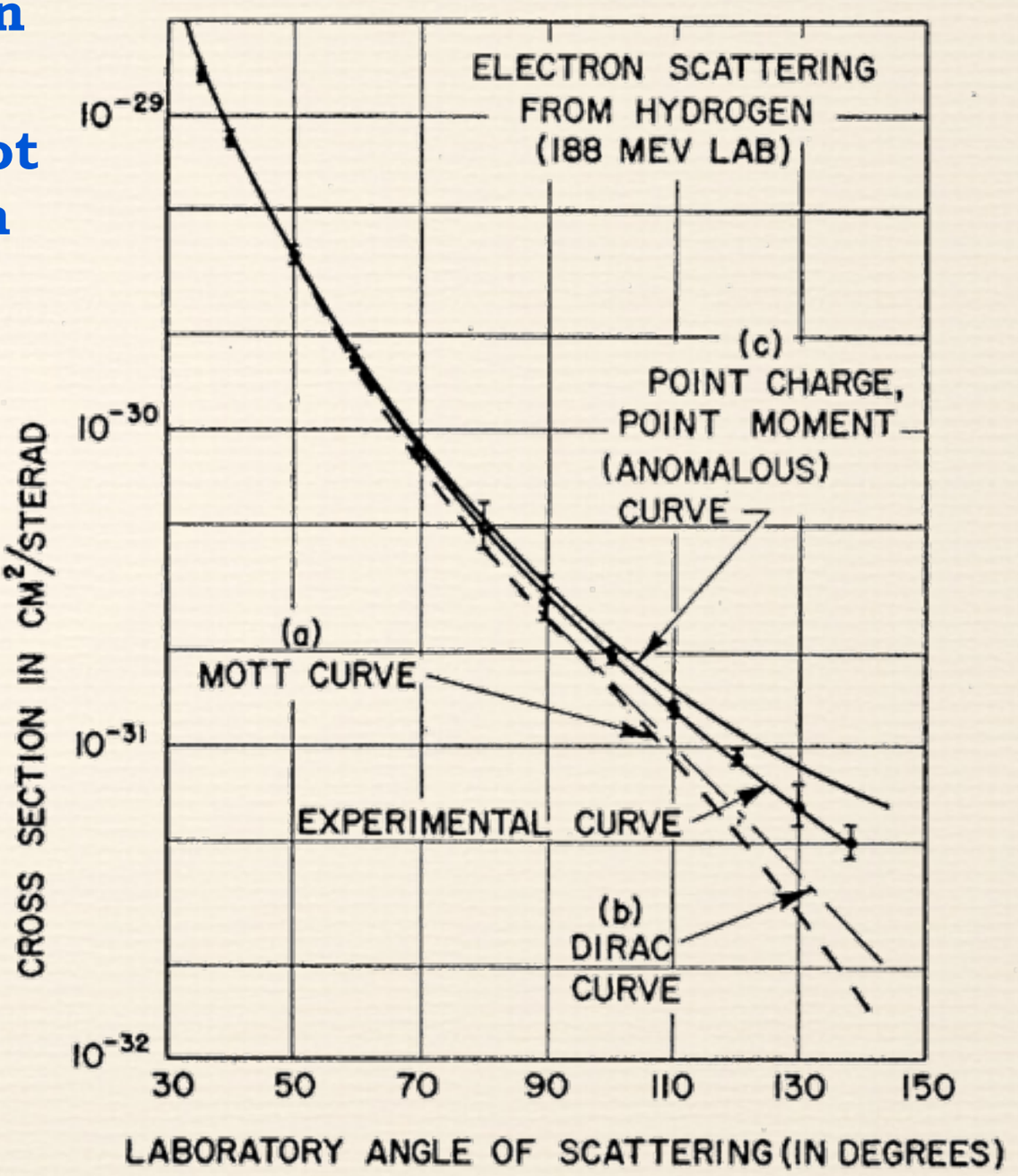

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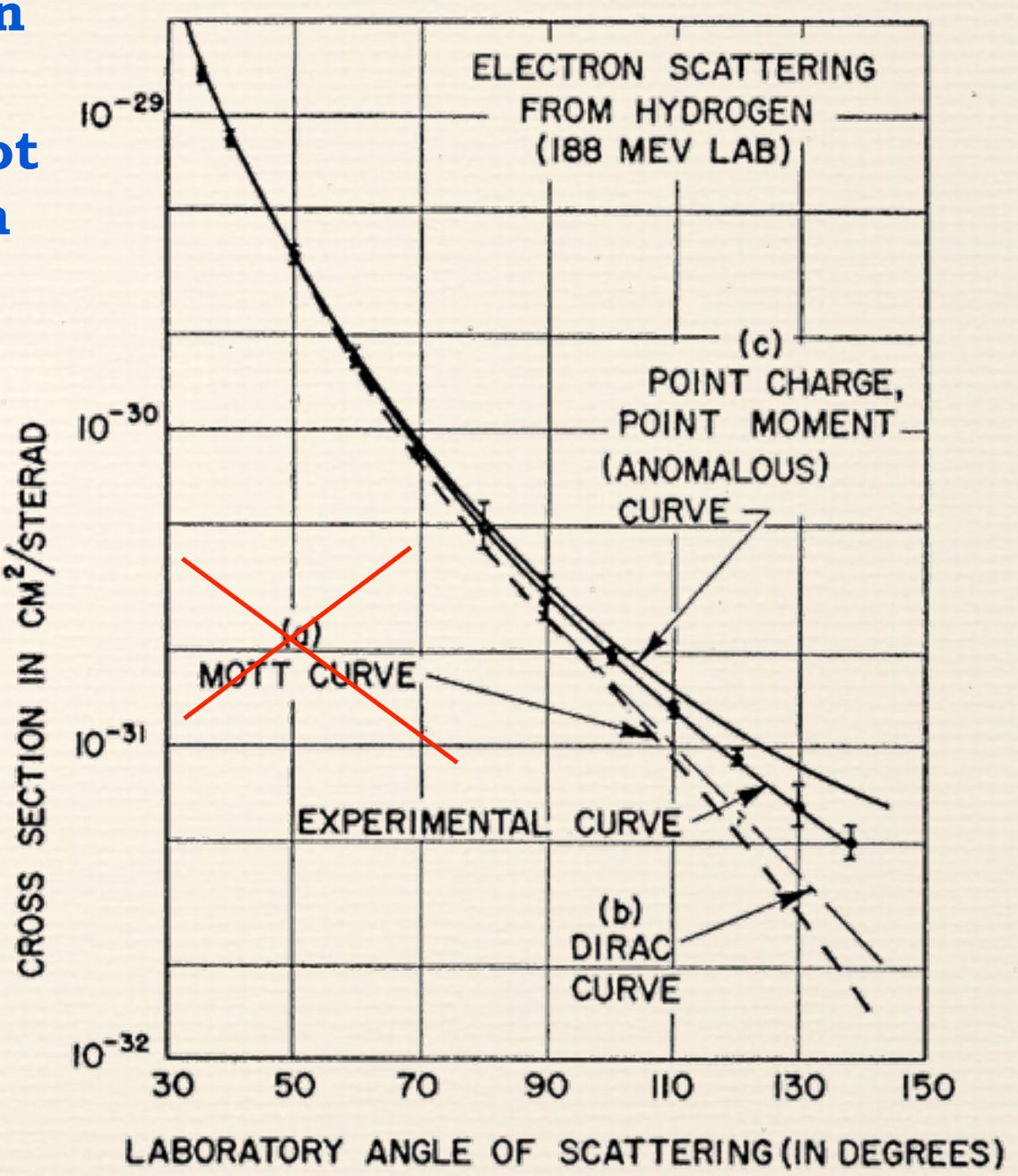

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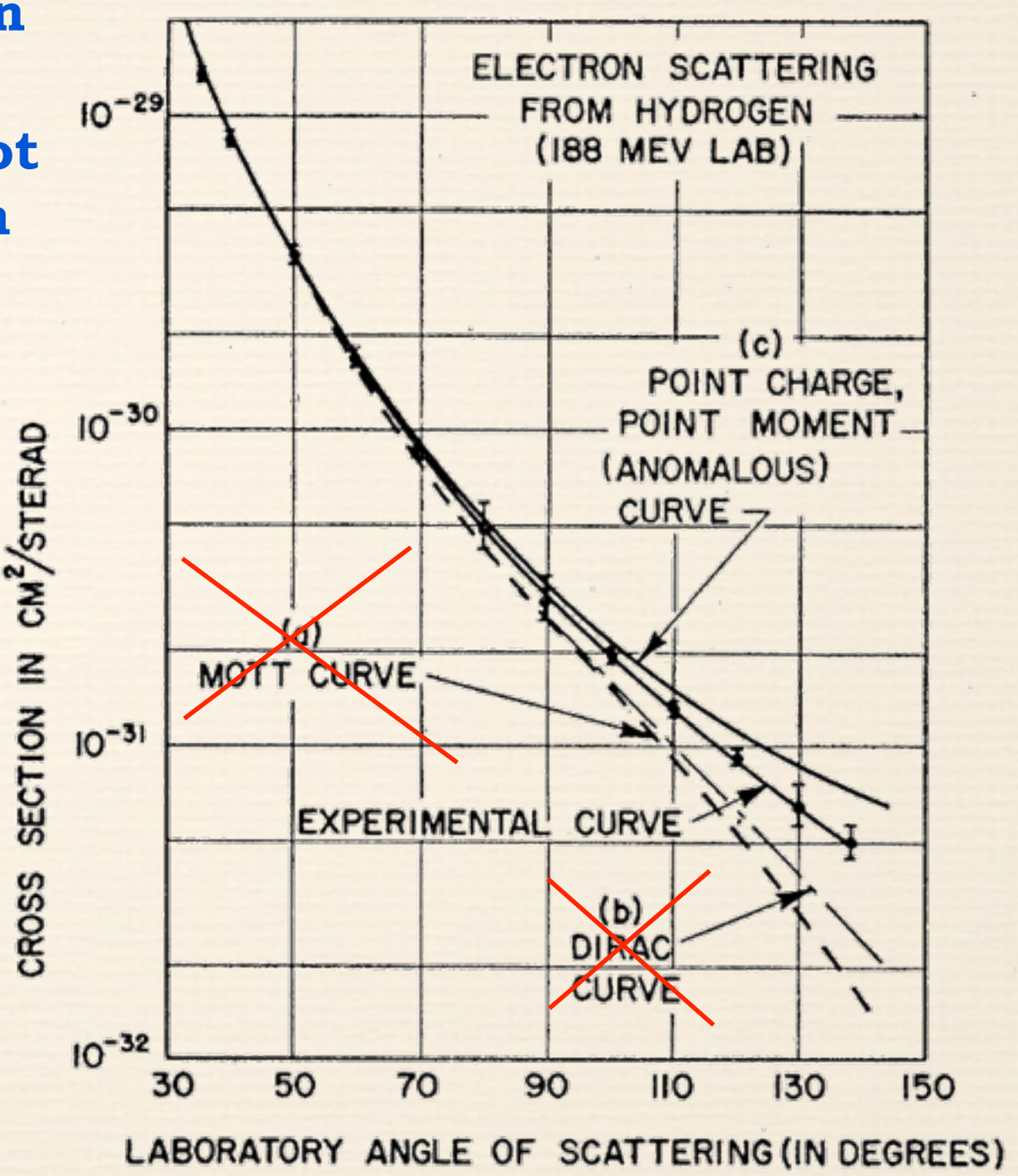

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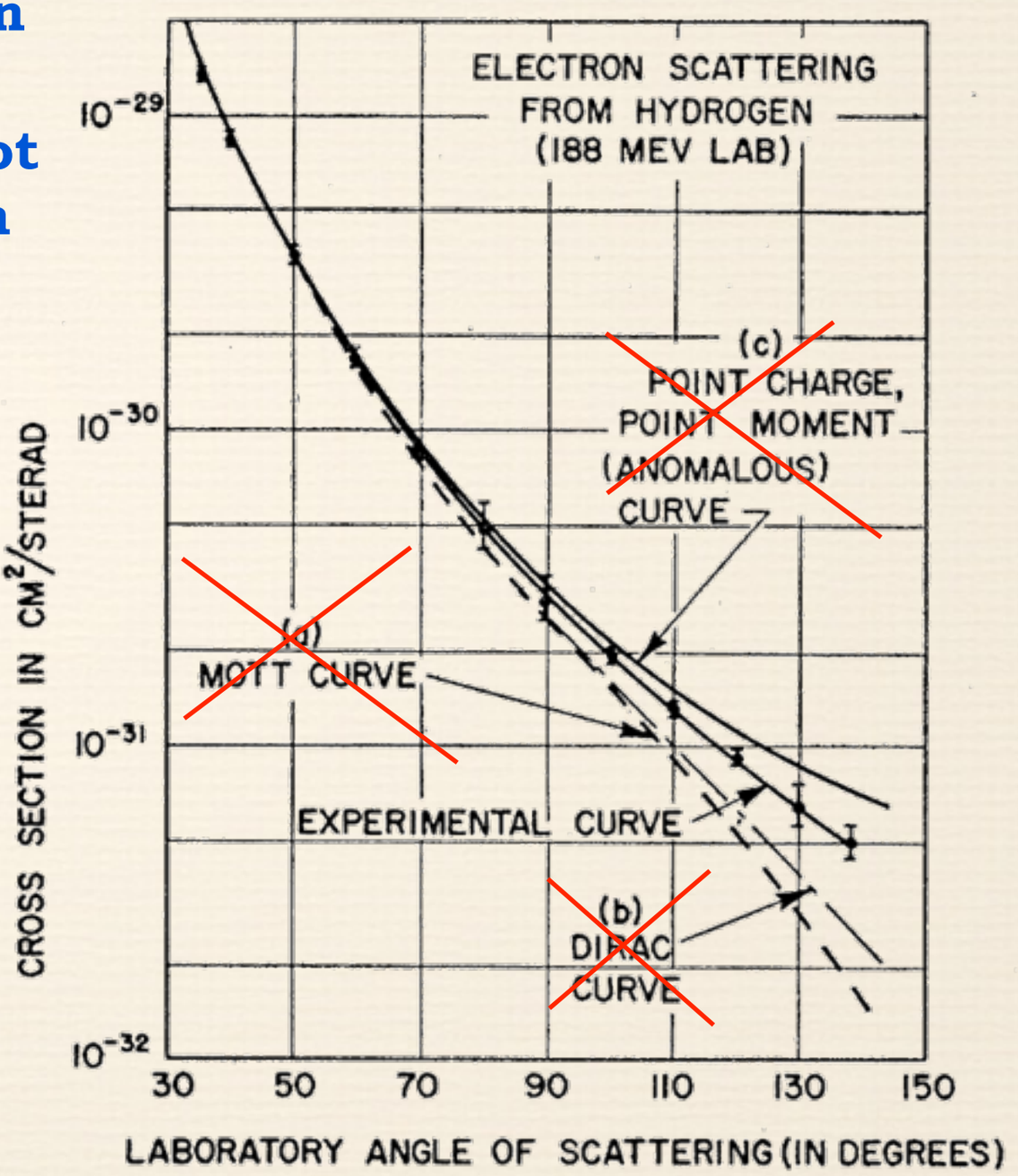

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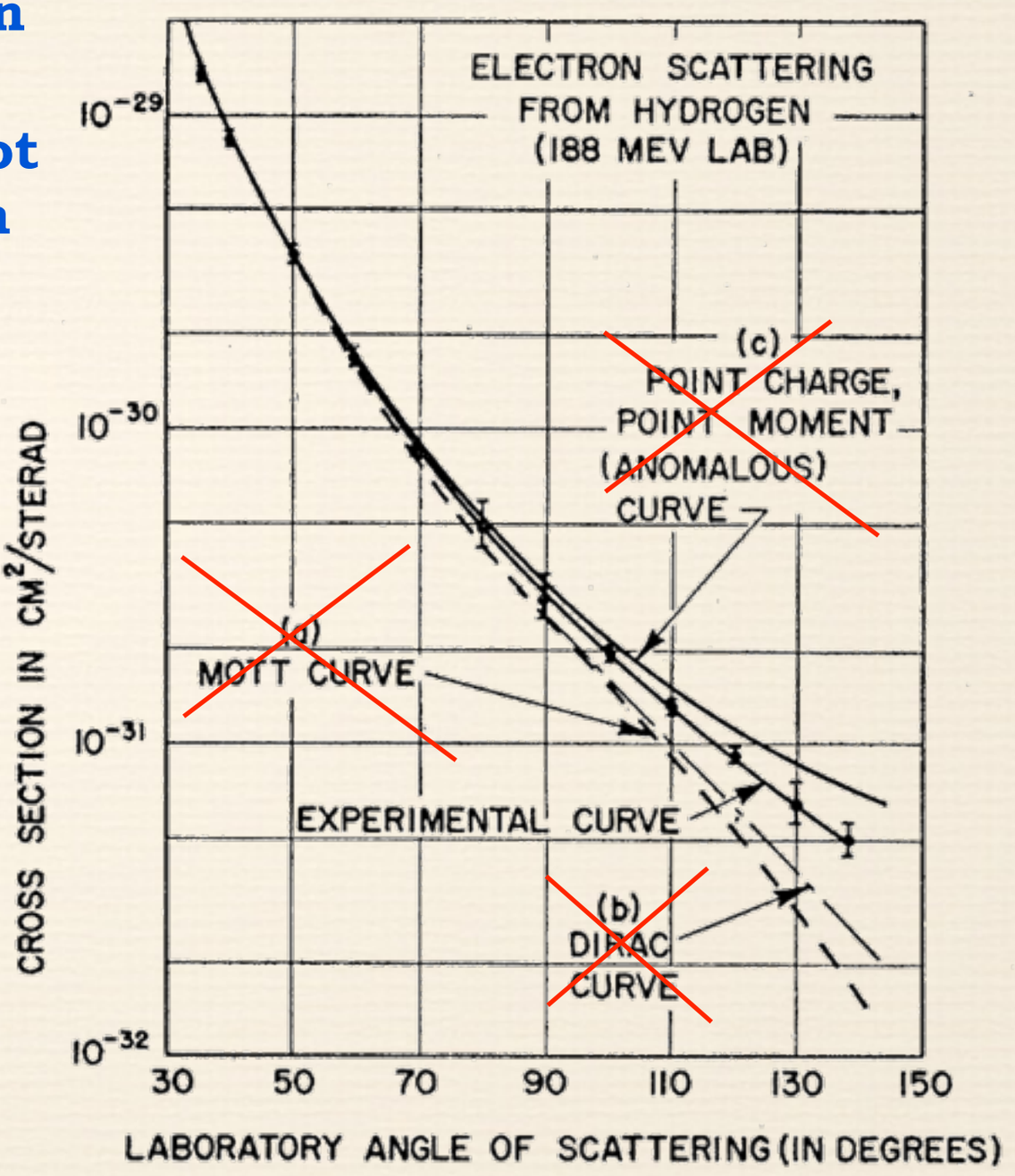
the proton has finite size ~ 1 fm

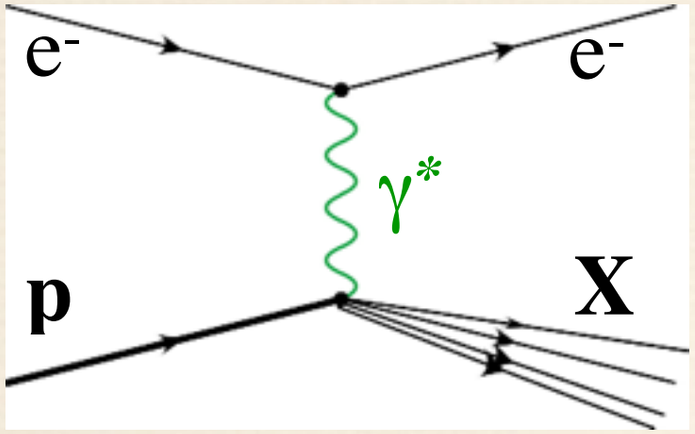
Robert Hofstadter –
Noble Prize 1961



Deep Inelastic Scattering

Point-like Structures in the Proton

Discovery of structureless partons inside protons and neutrons



- ***proton absorbs energy and breaks up***
- ***total observed energy no longer conserved***
- ***need to measure both scattering angle and scattered momentum or energy***

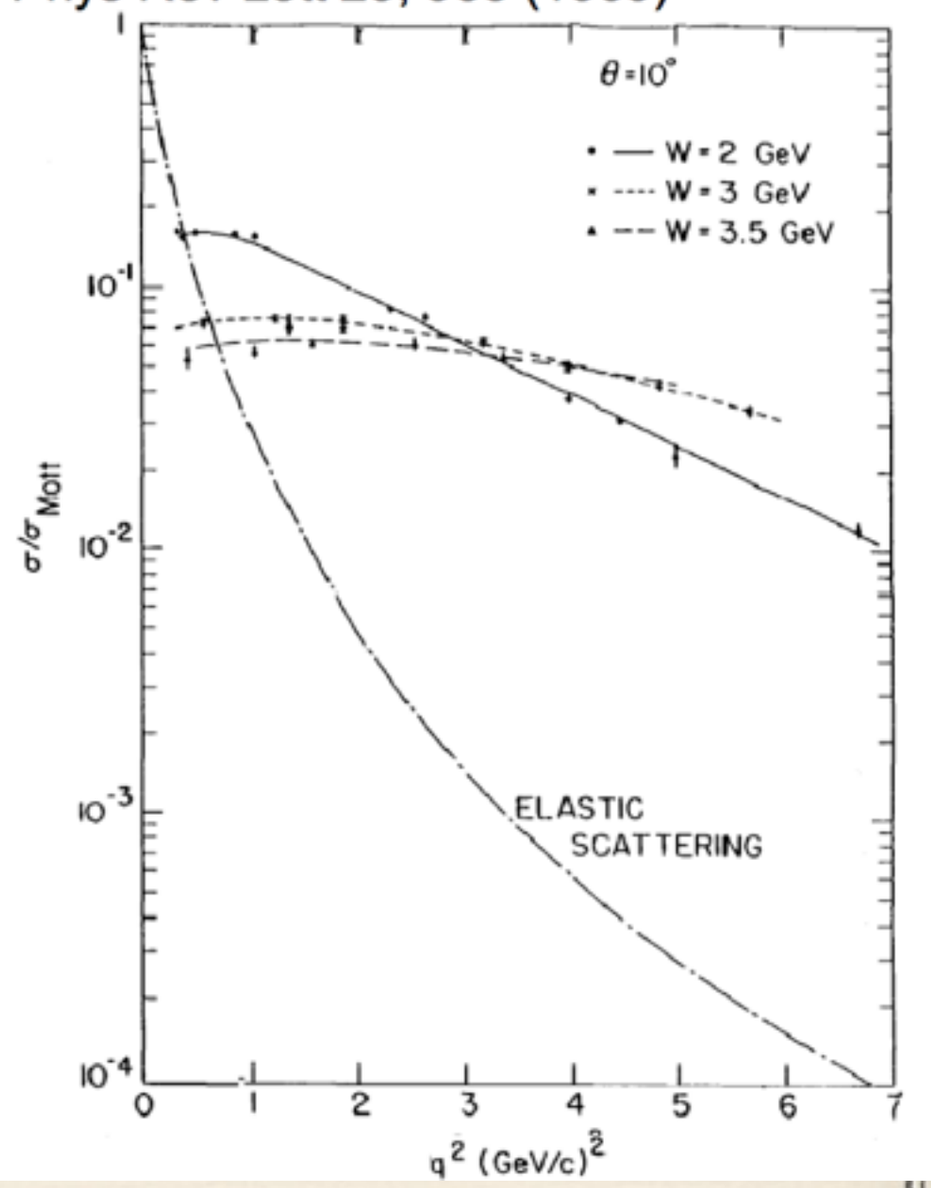
$$\left(\frac{d^2\sigma}{dE'd\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left\{ W_2(Q^2, x) + 2W_1(Q^2, x) \tan^2\left(\frac{\theta}{2}\right) \right\}$$

W_1 and W_2 are structure functions

x is fraction of proton momentum carried by struck fragment

W = Mass of recoiling fragments

M. Briedenbach et al,
Phys Rev Lett 23, 935 (1969)



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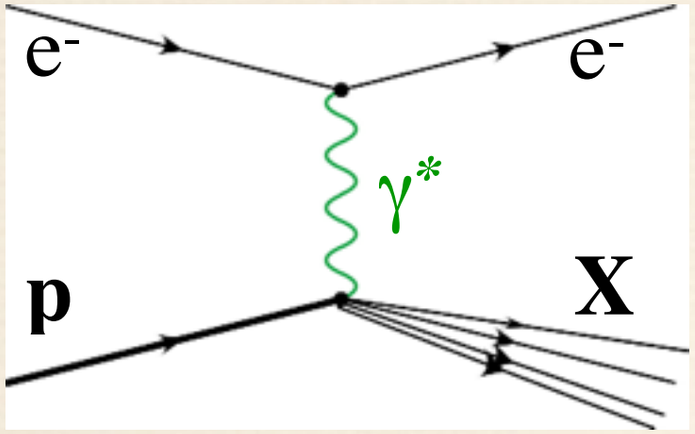

electrons are hitting structureless objects that have negligible size!

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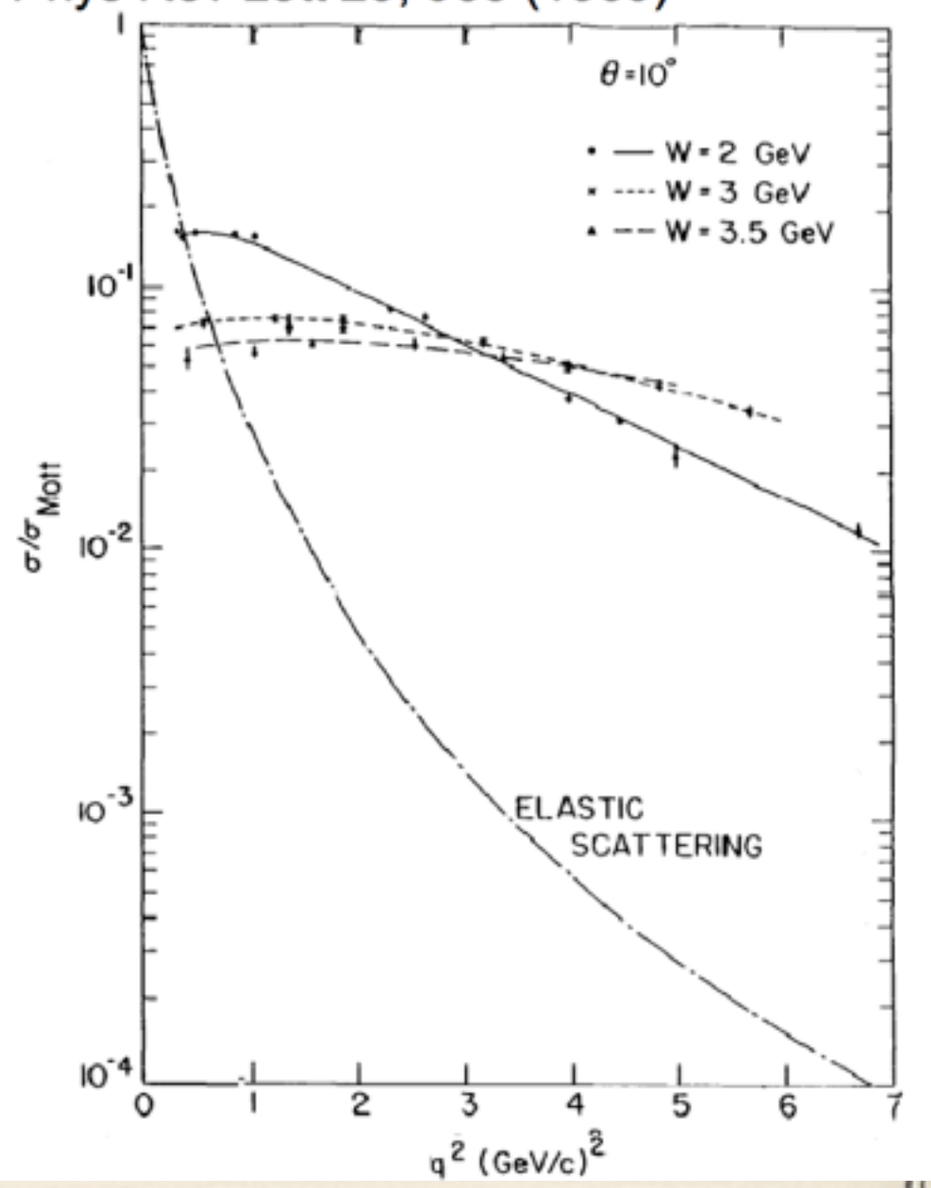
Friedman, Kendall & Taylor:
Nobel Prize 1990,
Measurement at SLAC

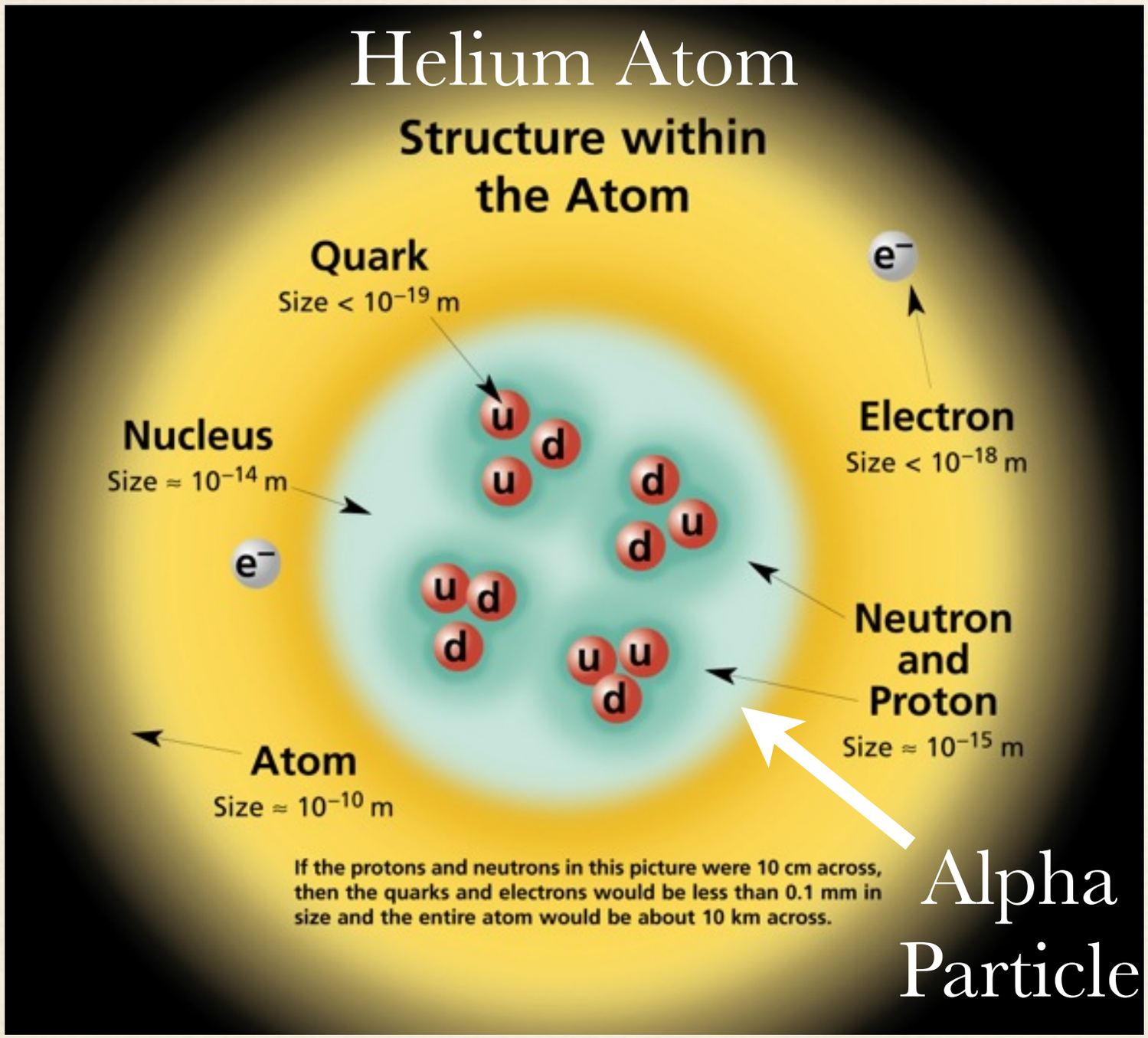
W = Mass of recoiling fragments

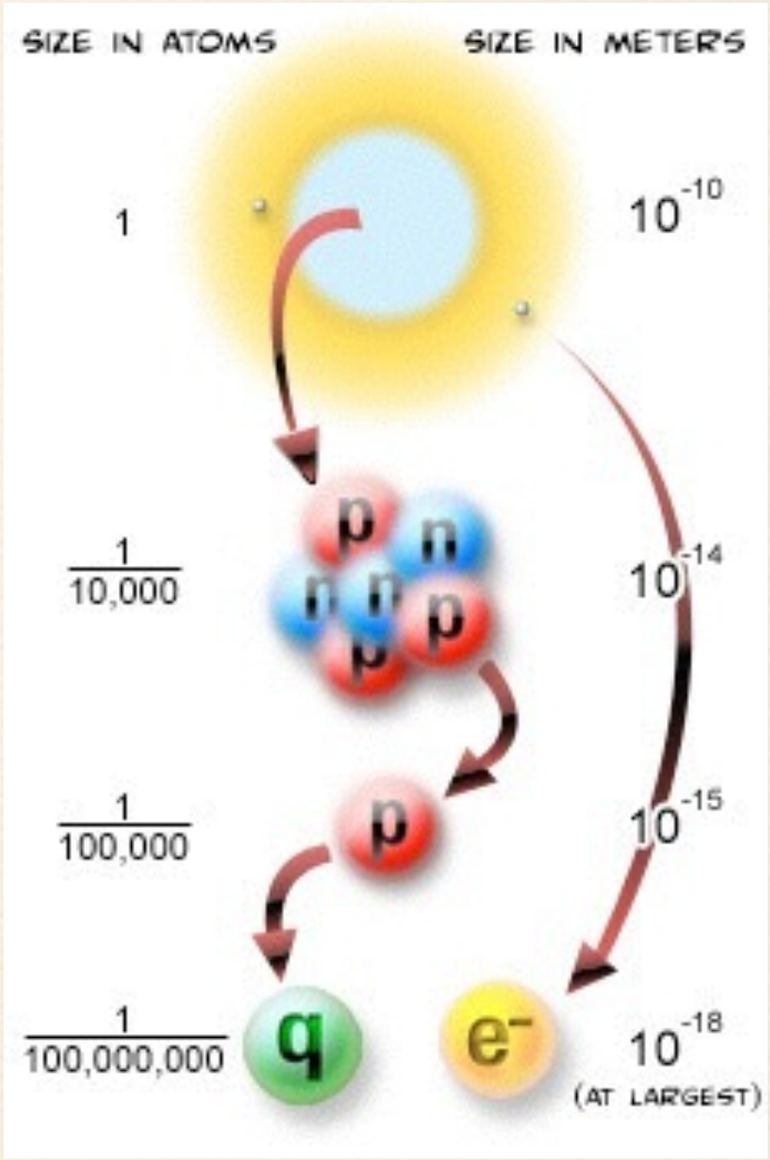
M. Briedenbach et al,
Phys Rev Lett 23, 935 (1969)



Since the 1960's

Subatomic Structure





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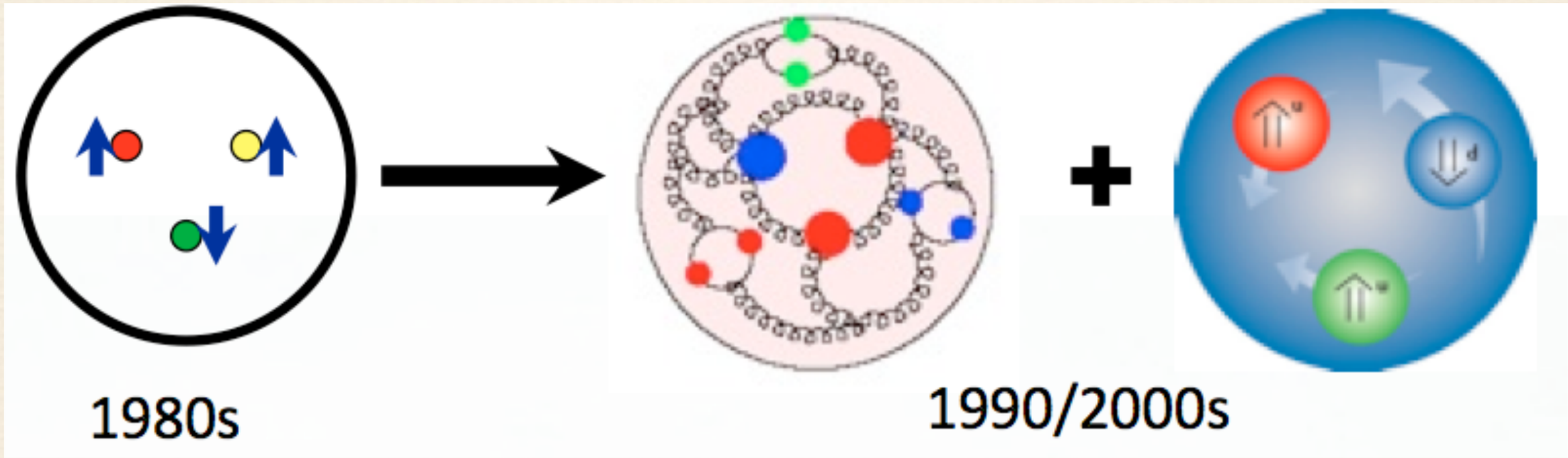
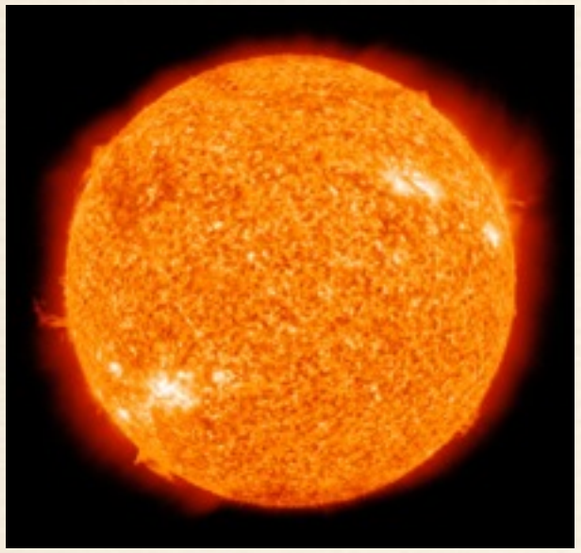
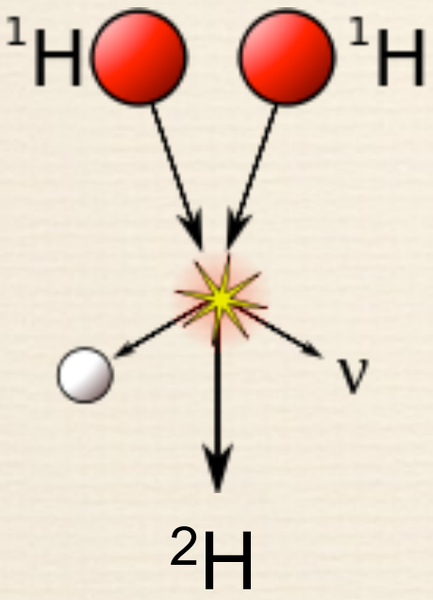


The Weak Force and Particle Handedness

The Weak Force

Solar p-p chain





Radioactivity

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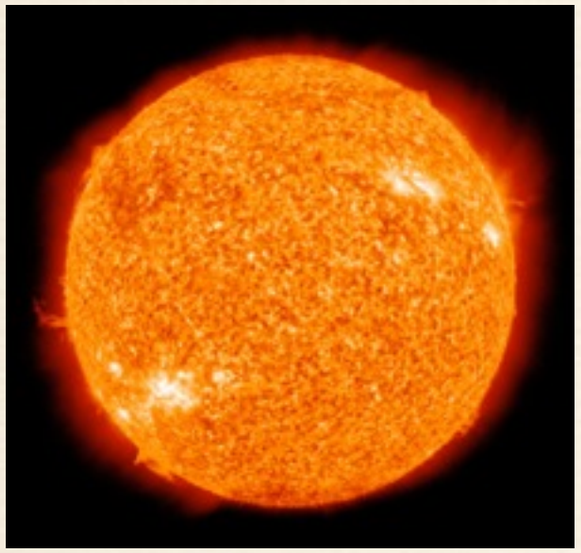
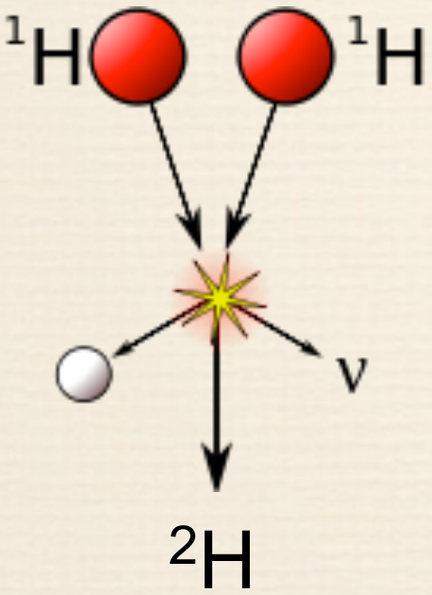


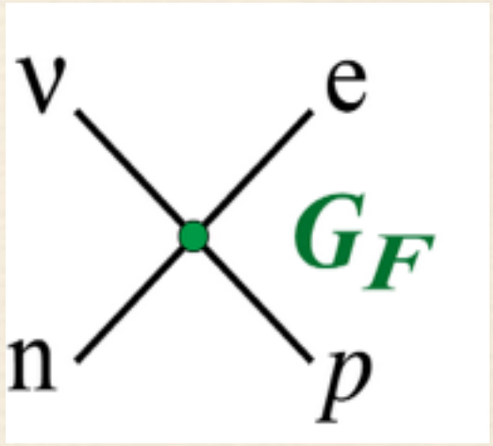


Radioactivity

Fermi Theory for weak interactions

Universal strength: coupling constant G_F

"Effective" low energy theory that explains many observed properties of radioactive nuclear decays



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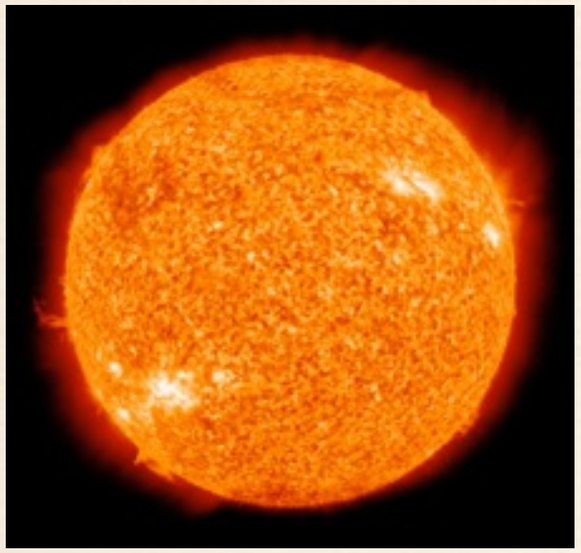

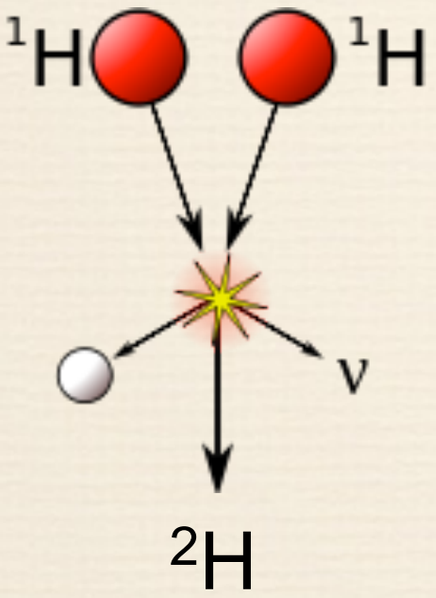

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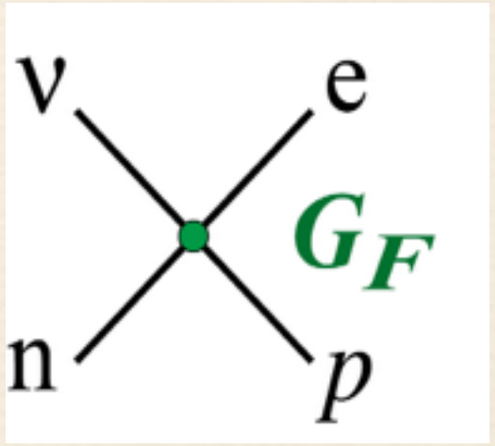
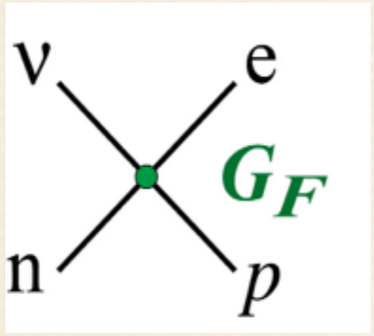


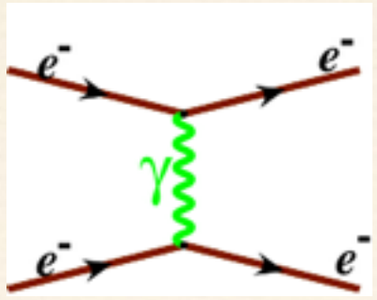
"Effective" low energy theory that explains many observed properties of radioactive nuclear decays

Theory known to breakdown at energy > 100 GeV

Similar to the landmark unification of electric and magnetic forces via Maxwell's Equations

Electroweak Unification





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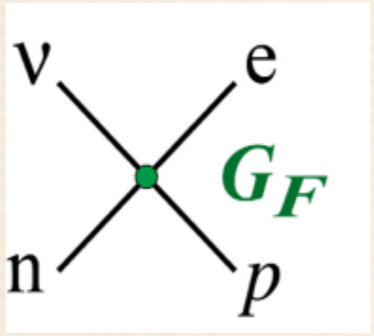

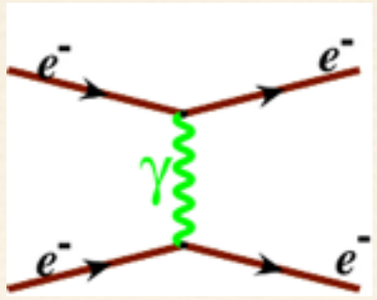

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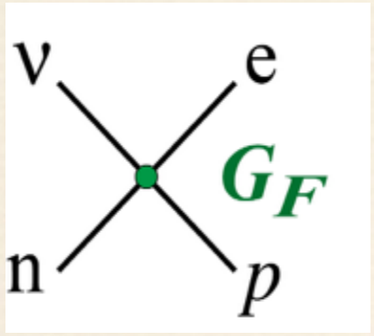

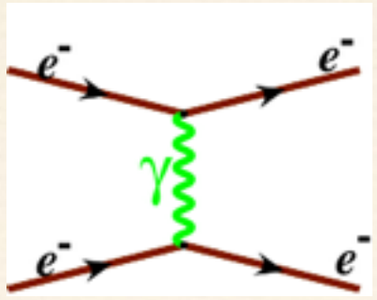

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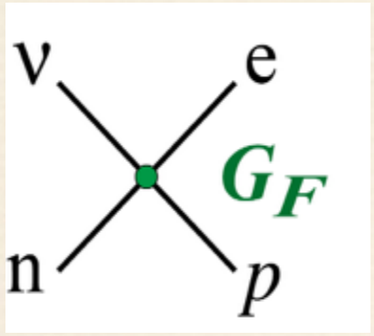

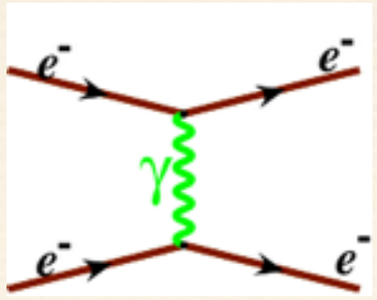

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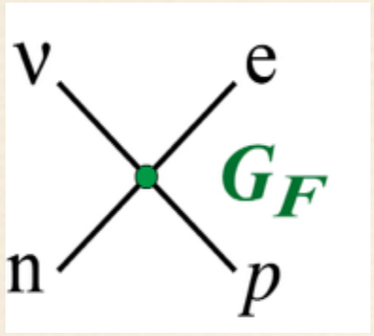

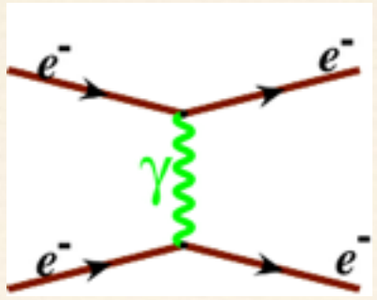

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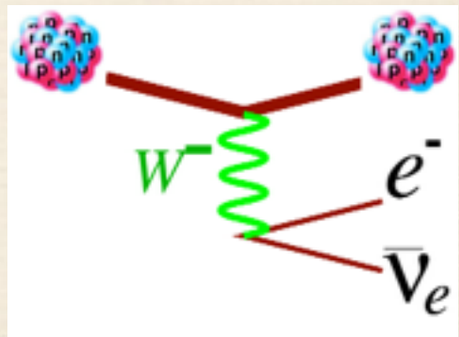
massive force carriers are W bosons ~ 80 GeV ^{60}Co ^{60}Ni



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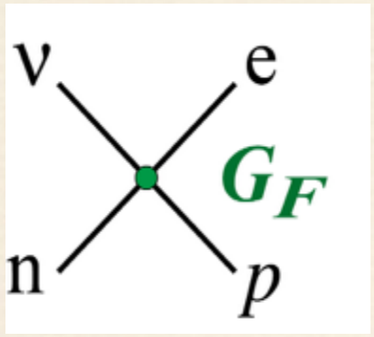

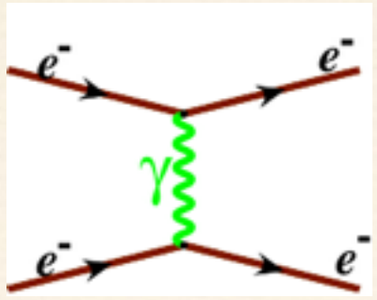

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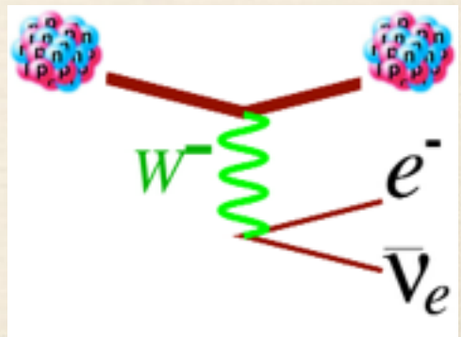


*Weak interactions do **not** obey mirror symmetry*

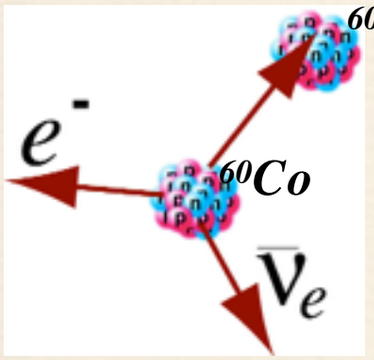
particles involved not ambidextrous

Discovery of Parity Violation in Weak Force Phenomena

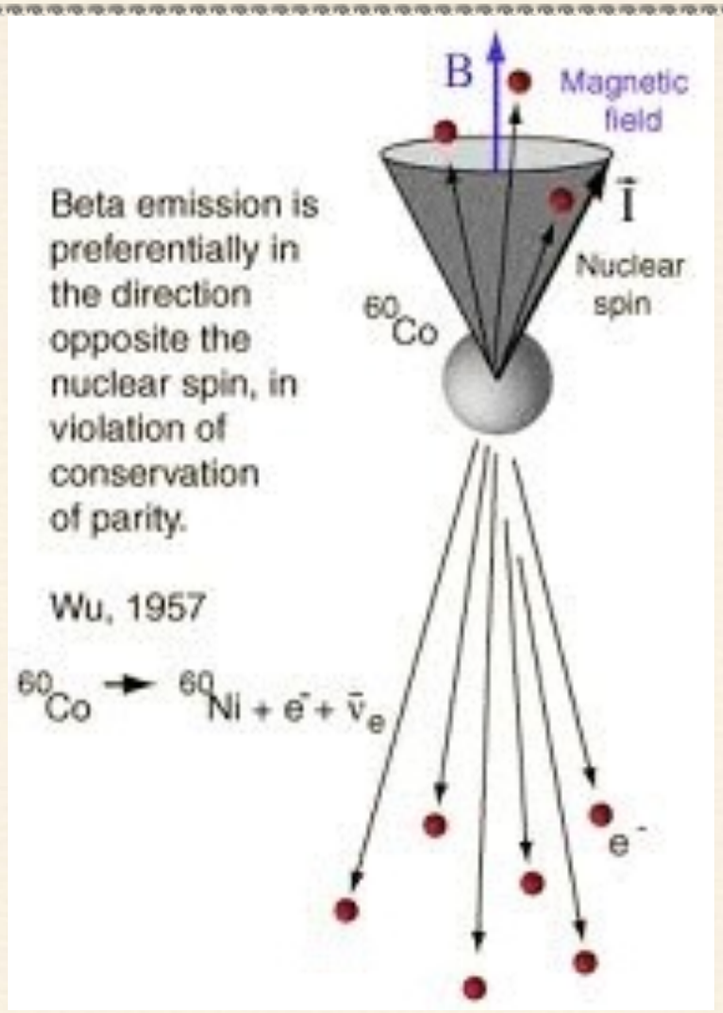
Failure of Ambidexterity

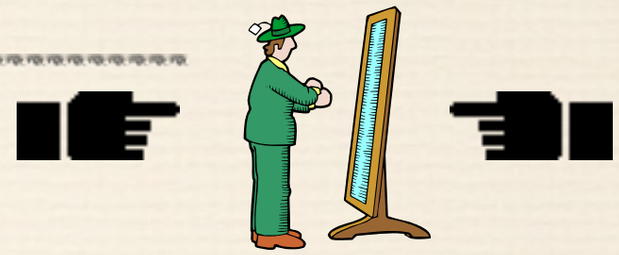
parity transformation (reflection)

$$x, y, z \rightarrow -x, -y, -z$$



Weak decay of ^{60}Co Nucleus





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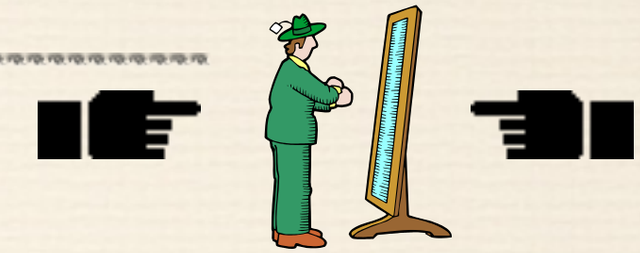

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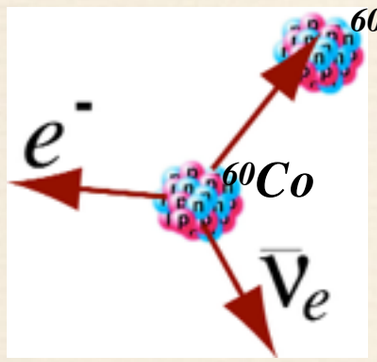

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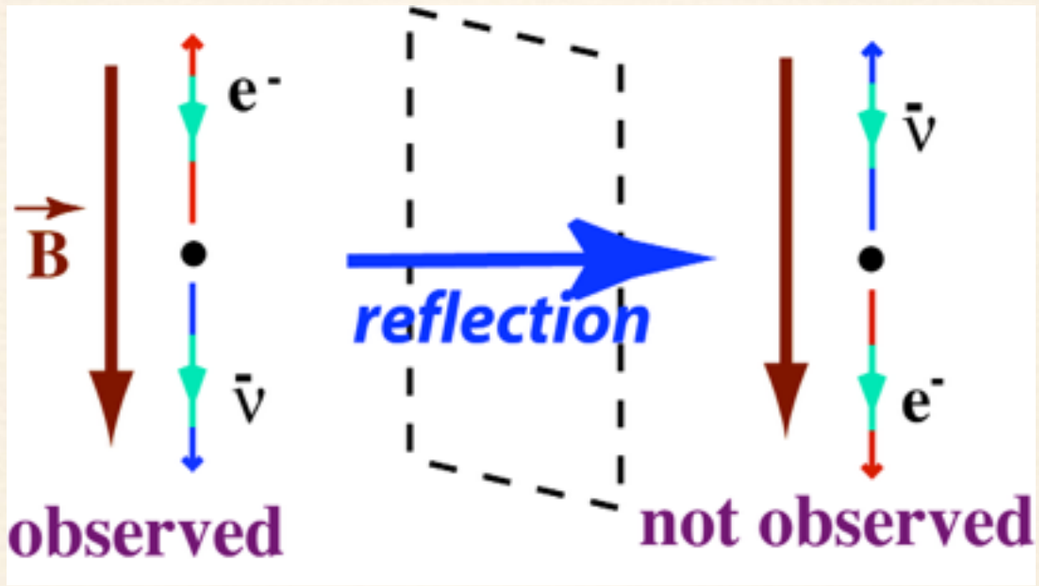

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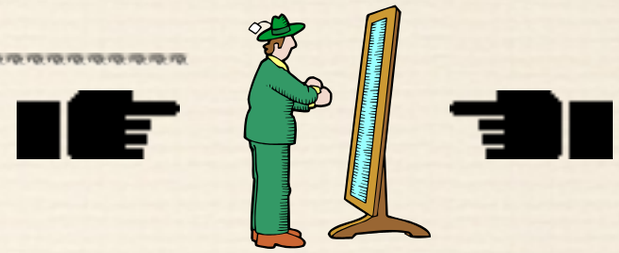

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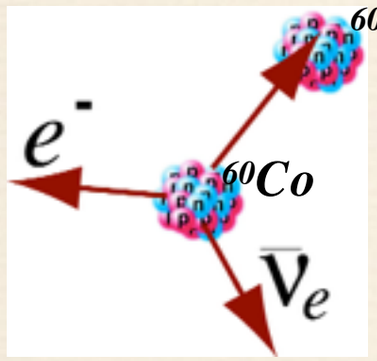

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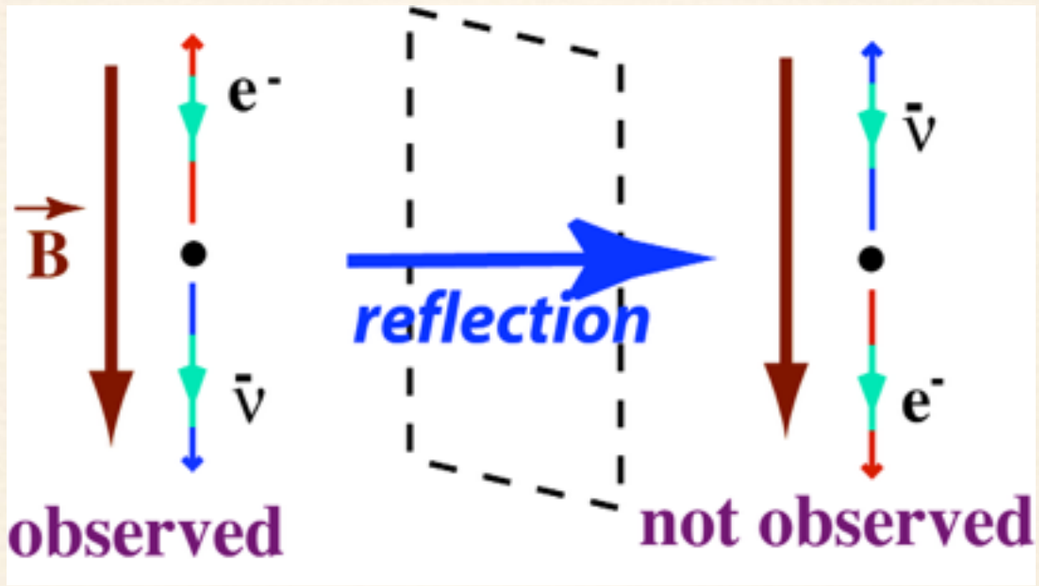

matter particles have spin = 1/2

$$h = \frac{\vec{s} \bullet \vec{p}}{|\vec{s}||\vec{p}|} = \pm 1$$

handedness or ***helicity/chirality***

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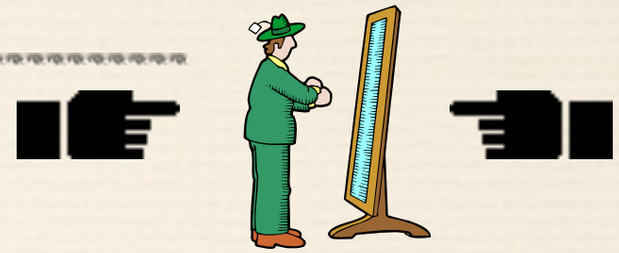

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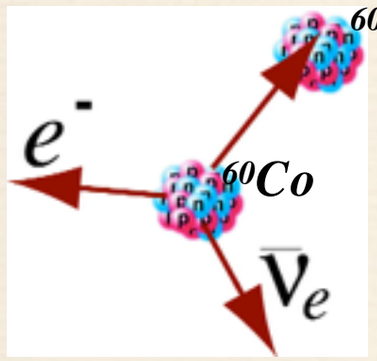

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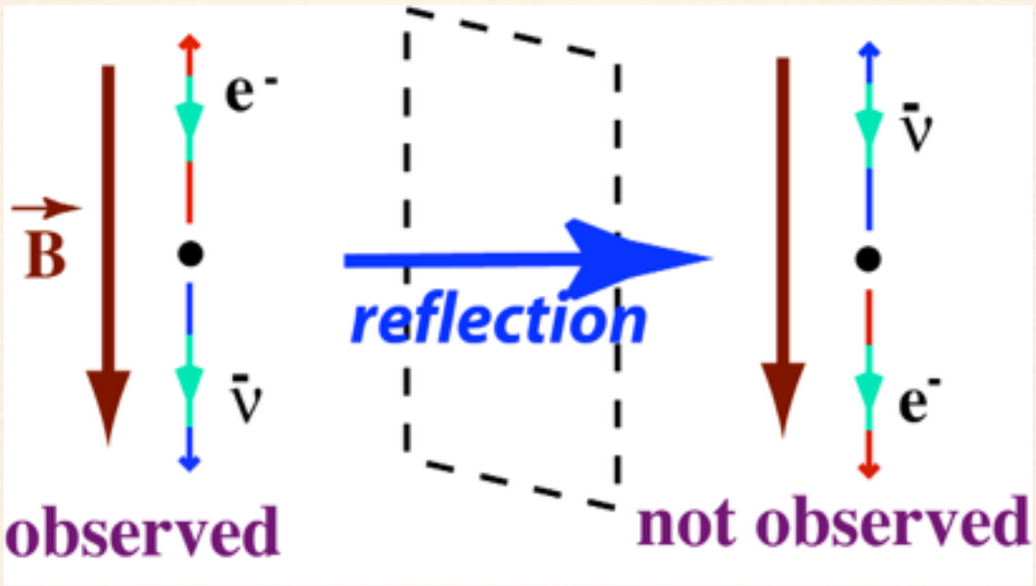

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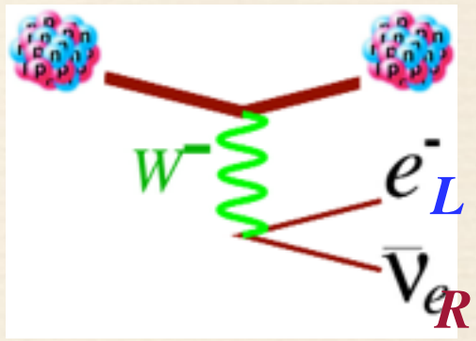
Mirror reflection flips sign of helicity

***Left*-handed** ⟺ ***right*-handed**

Only left-handed particles can exchange W bosons

(right-handed anti-particles)

^{60}Co ^{60}Ni



left-handed electron

right-handed anti-neutrino

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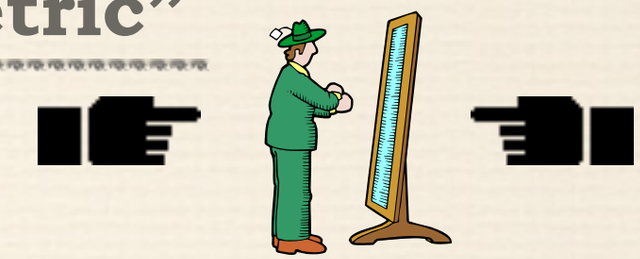
Failure of Ambidexterity

Nature is not "mirror-symmetric"



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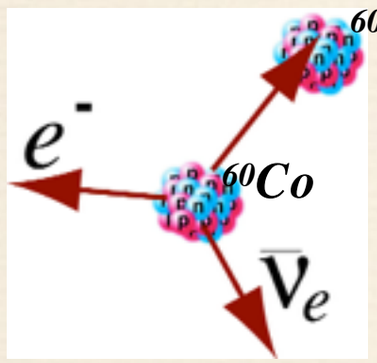

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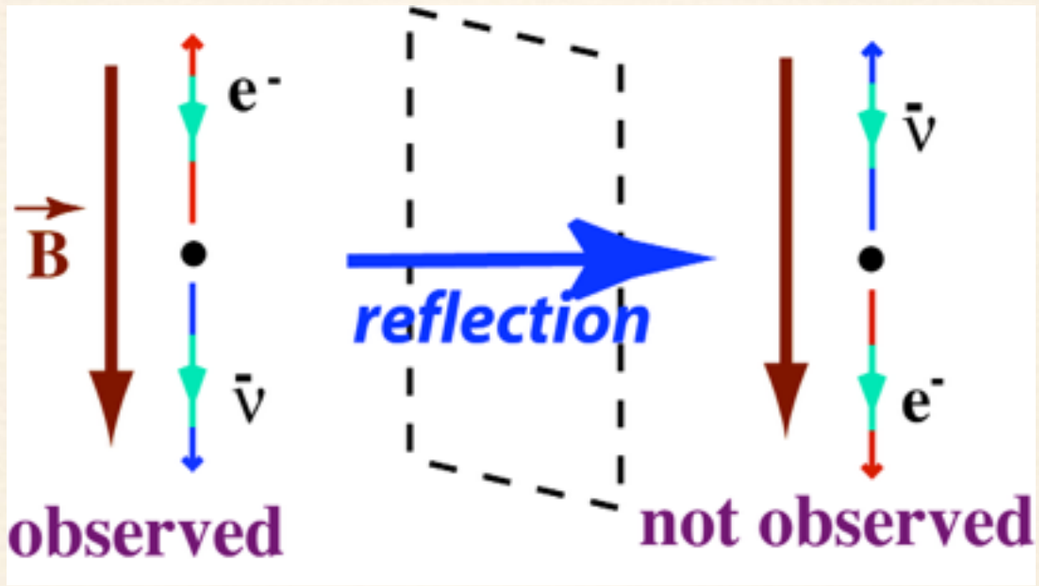

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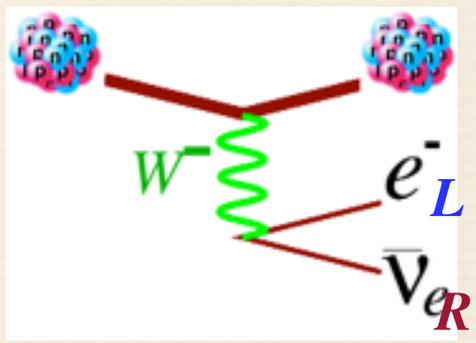

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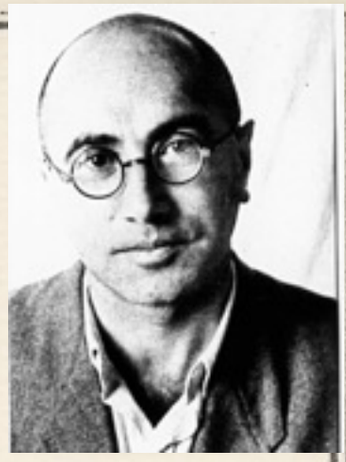
Ya. B. ZEL' DOVICH

Submitted to JETP editor December 25, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) **36**, 964-966 (March, 1959)

Is Electron Scattering Mirror-Symmetric?

A Classic Paper



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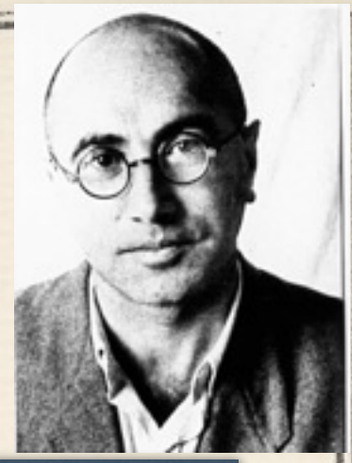
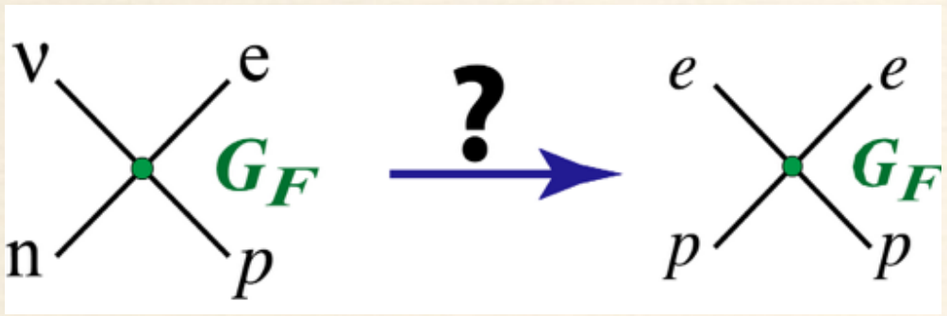


Is there a neutral analog of the "charged" weak force?

Neutron β Decay

Electron-proton Weak Scattering



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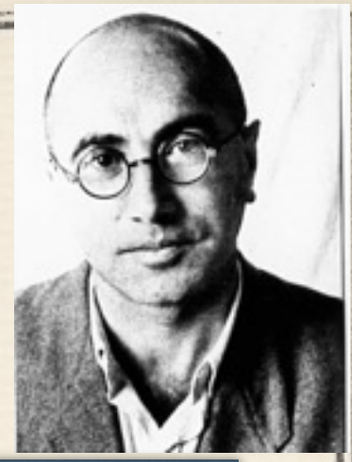

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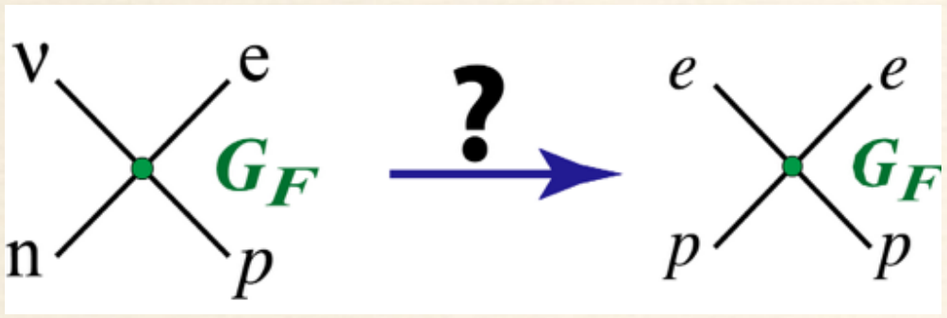
Electron-proton Weak Scattering



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Ya. B. ZEL' DOVICH

Submitted to JETP editor December 25, 1958

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Is Electron Scattering Mirror-Symmetric?

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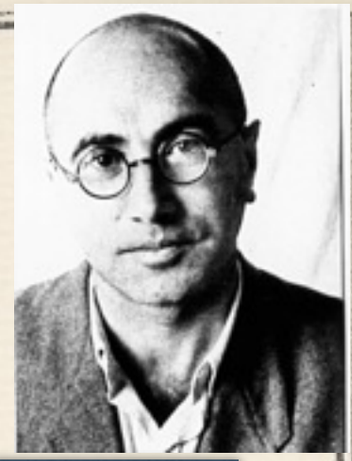

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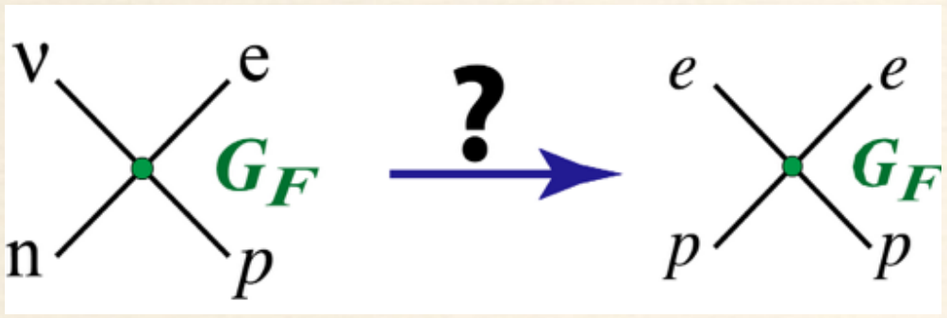

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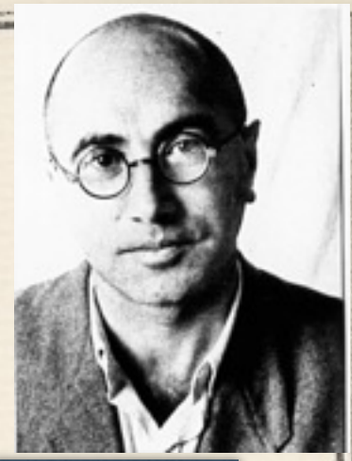

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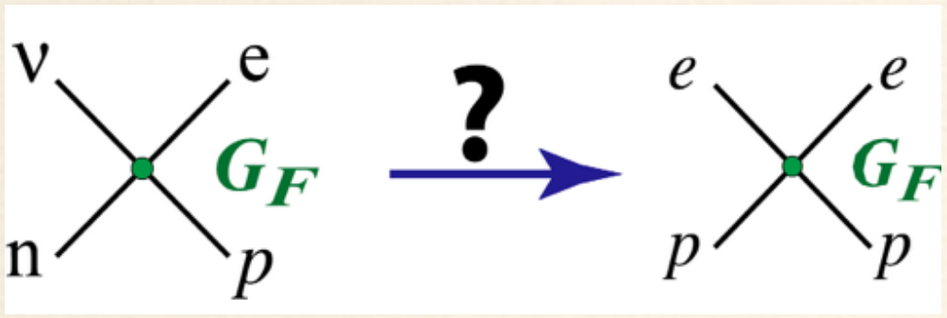

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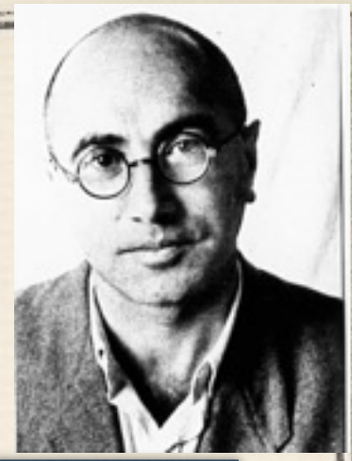

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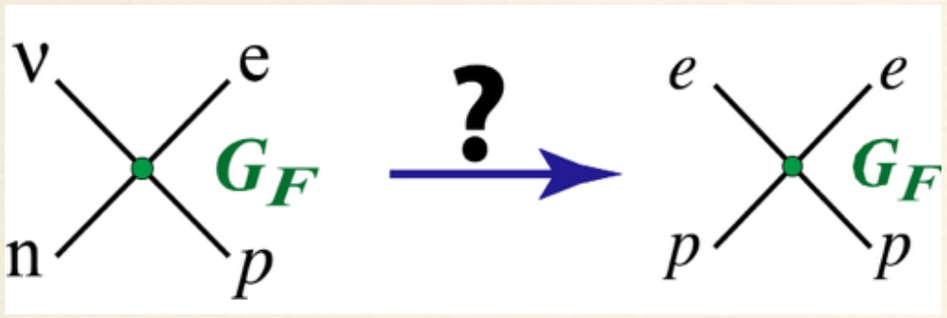

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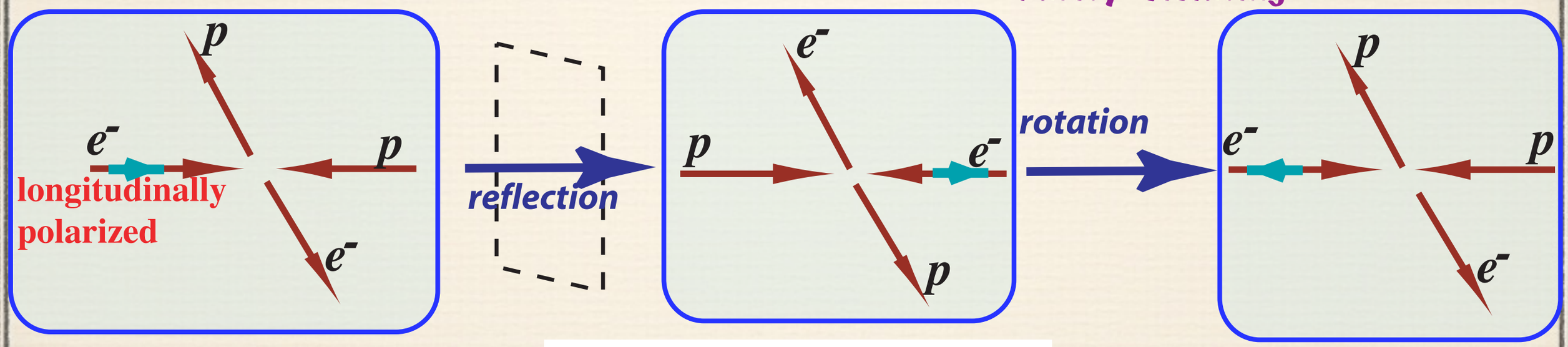

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Parity-Violating Electron Scattering

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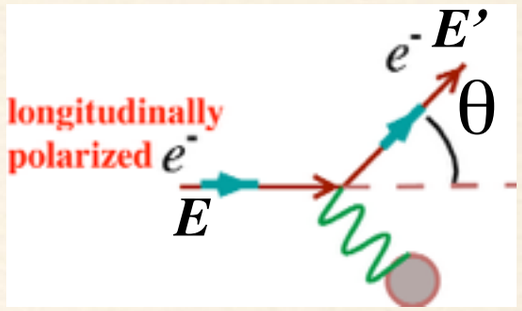

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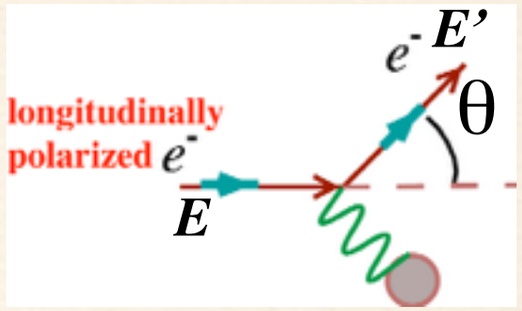

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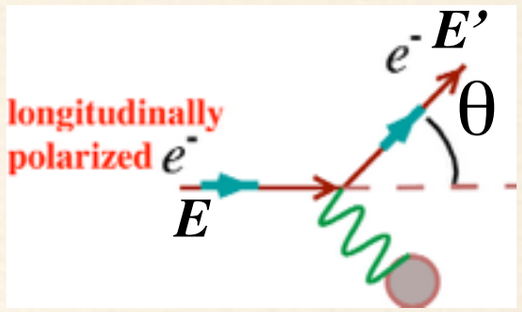

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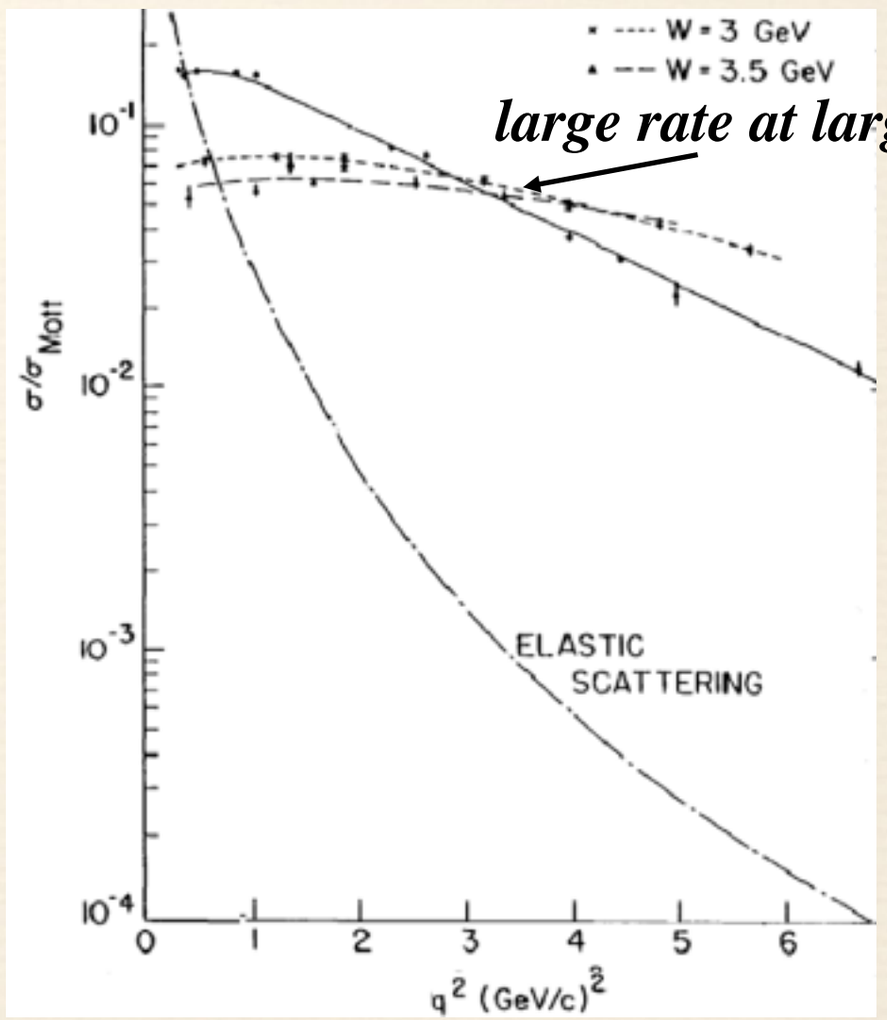

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A Model of Leptons: Steven Weinberg (1967)

Electroweak Theory

	Left- g_L	**Right-** g_R
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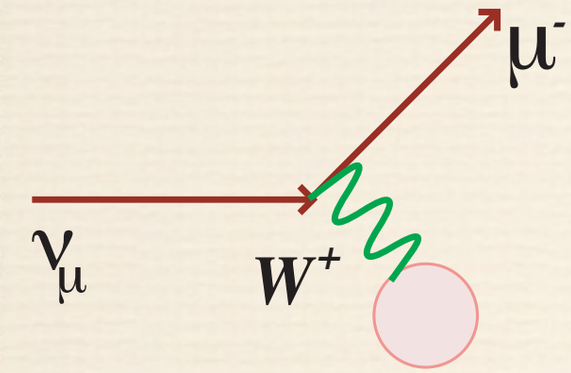

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The correct description of the neutral weak force

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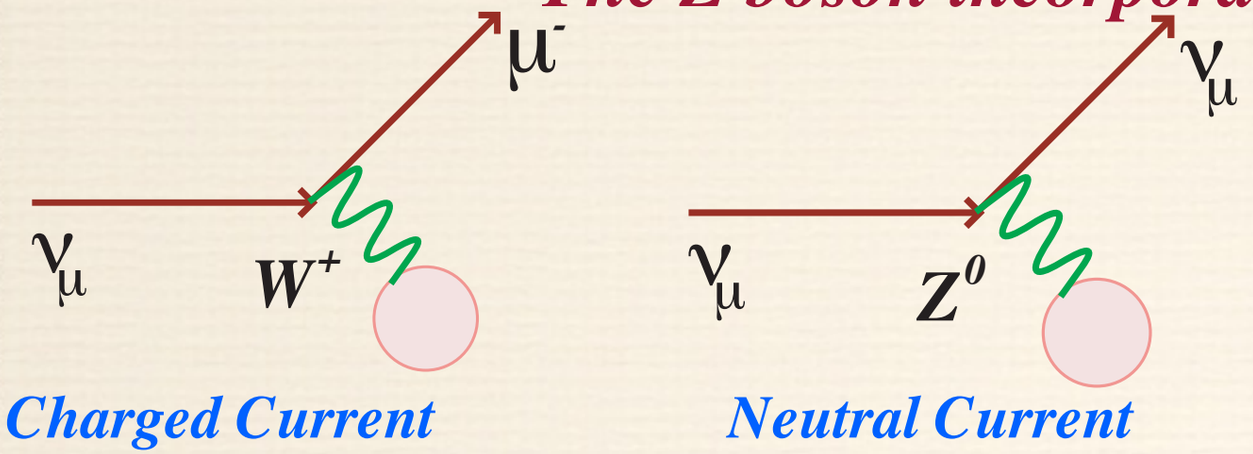

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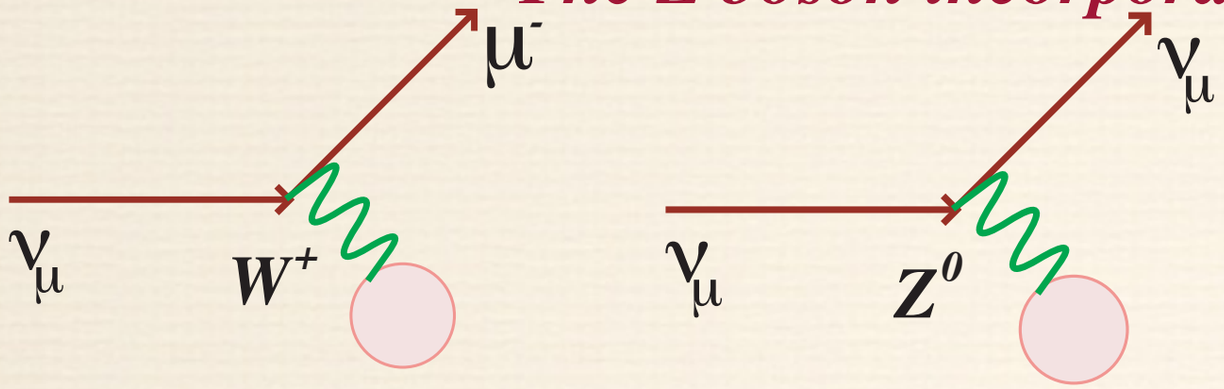

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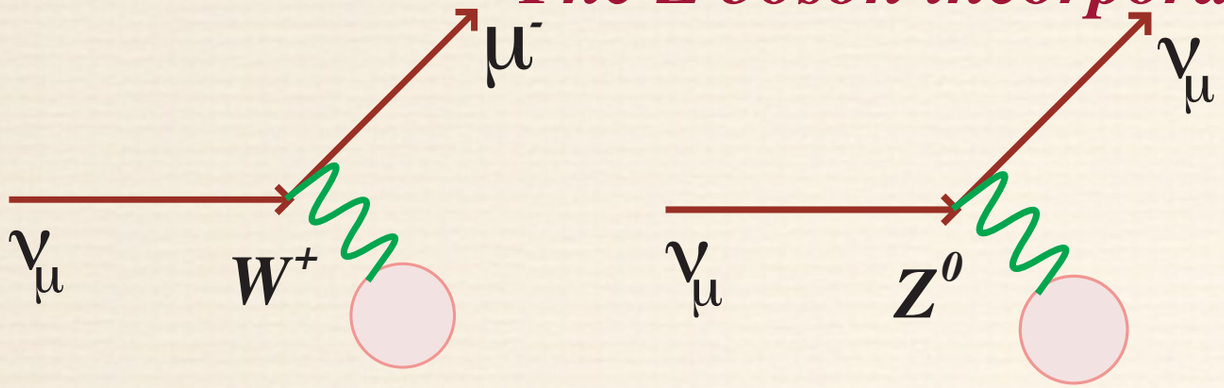

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Does electron-nucleon deep inelastic scattering exhibit parity violation?

$$\begin{pmatrix}\nu\\ e\end{pmatrix}_l \quad (e)_r$$

or

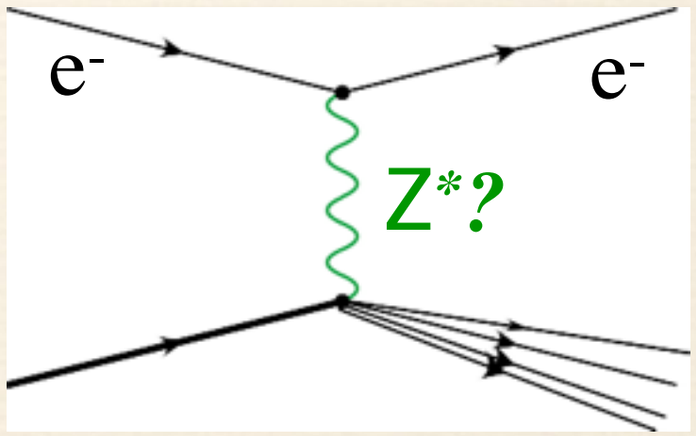
$$\begin{pmatrix}\nu\\ e\end{pmatrix}_l \quad \begin{pmatrix}E^\circ\\ e\end{pmatrix}_r$$

Weinberg model

Parity is violated

$$A_{PV} \sim 10^{-4}$$

Parity is conserved

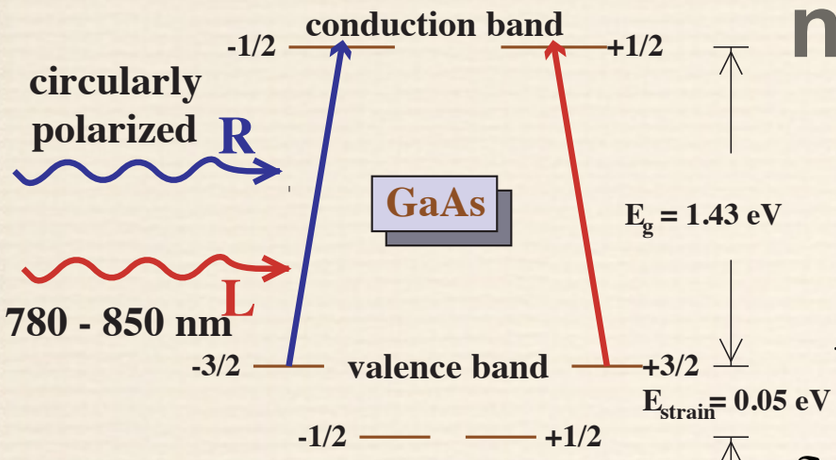


The first atomic parity violation measurements negative!

polarized electron-unpolarized deuteron deep inelastic scattering

SLAC E122

C.Y. Prescott et al, 1978



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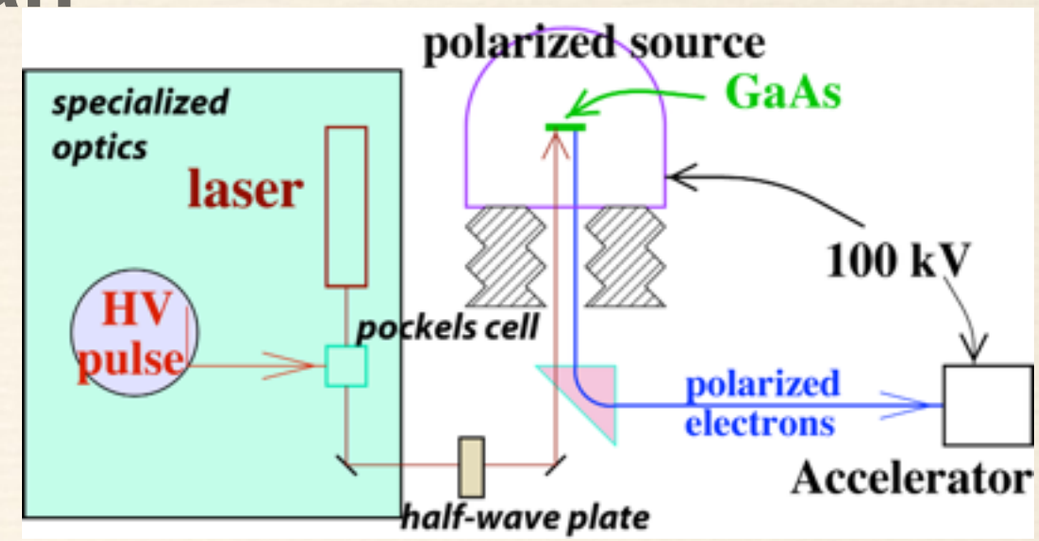

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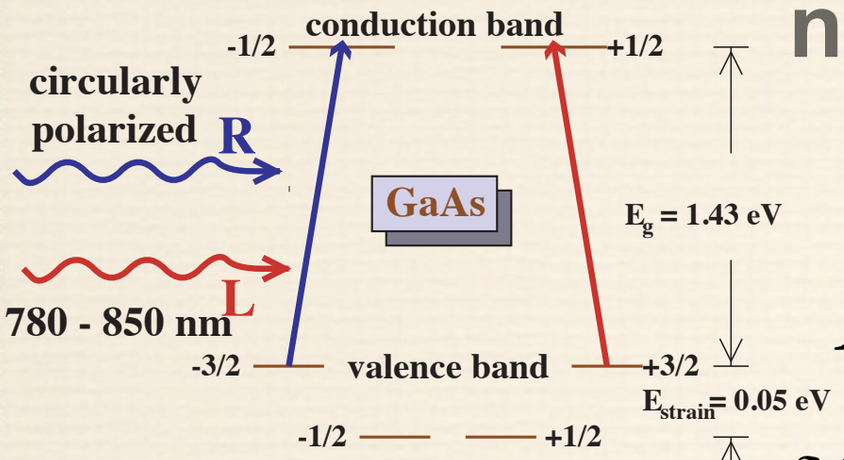

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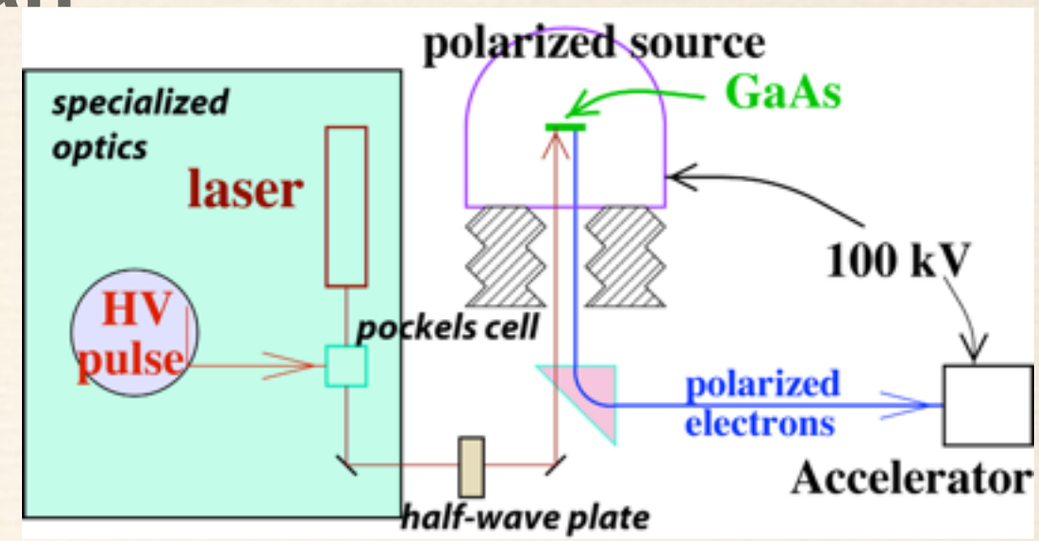

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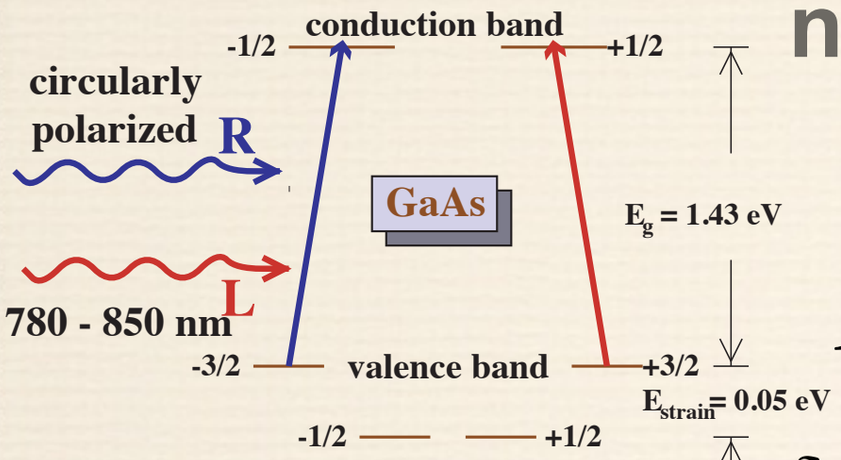

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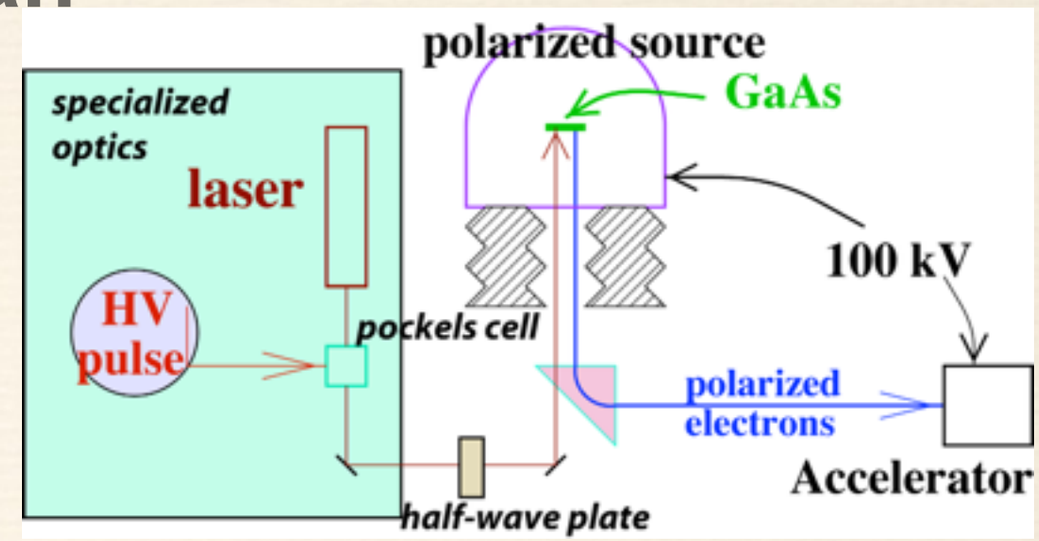

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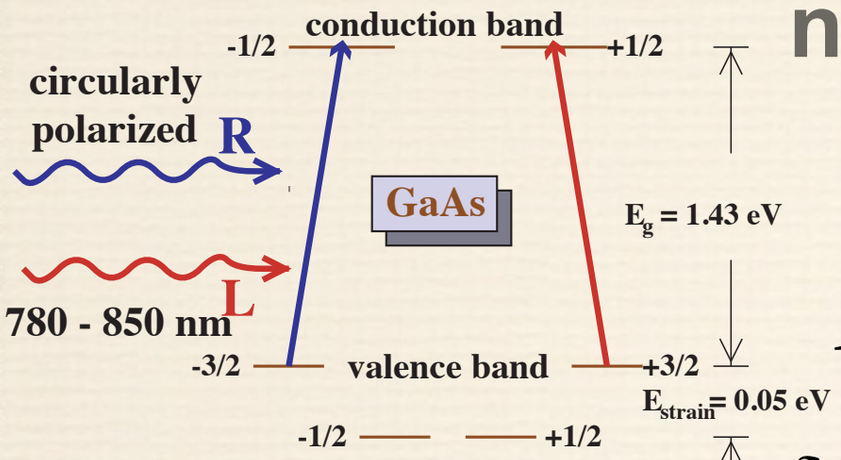

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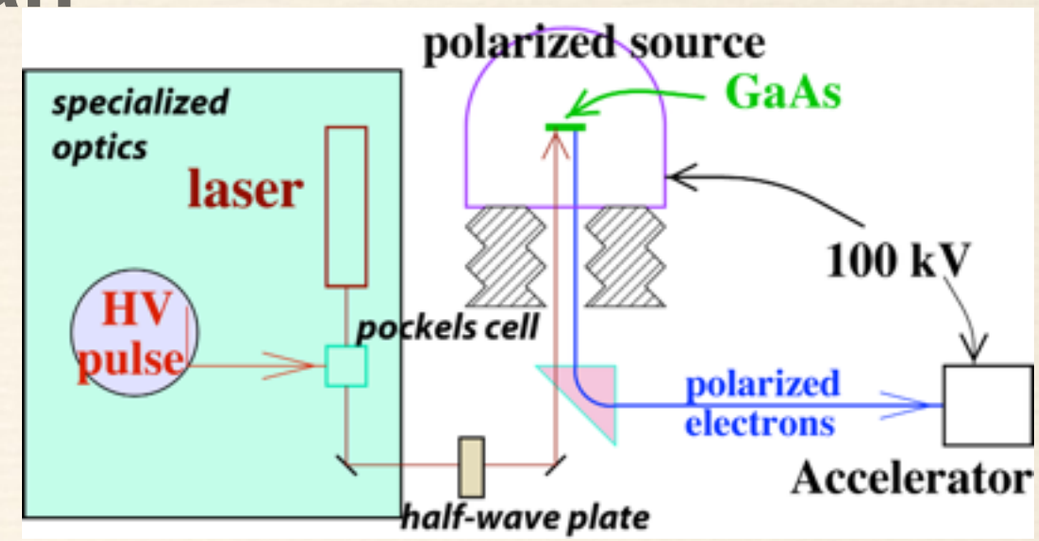

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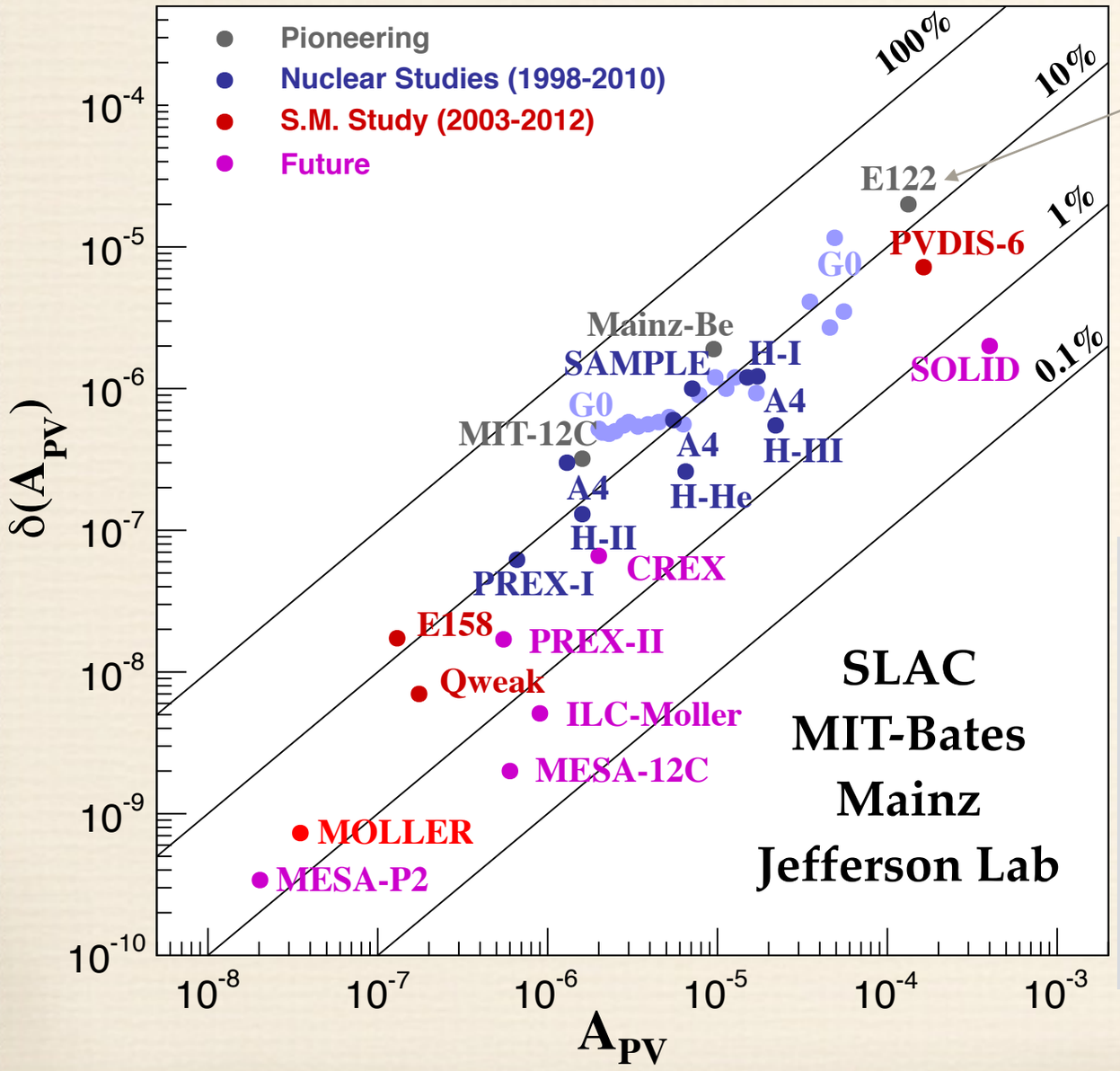
Continuous interplay between probing hadron structure and electroweak physics

4 Decades of Progress

Parity-violating electron scattering has become a precision tool

photocathodes, polarimetry, high power cryotargets, nanometer beam stability, precision beam diagnostics, low noise electronics, radiation hard detectors

PVeS Experiment Summary



Pioneering electron-quark PV DIS experiment SLAC E122

State-of-the-art:

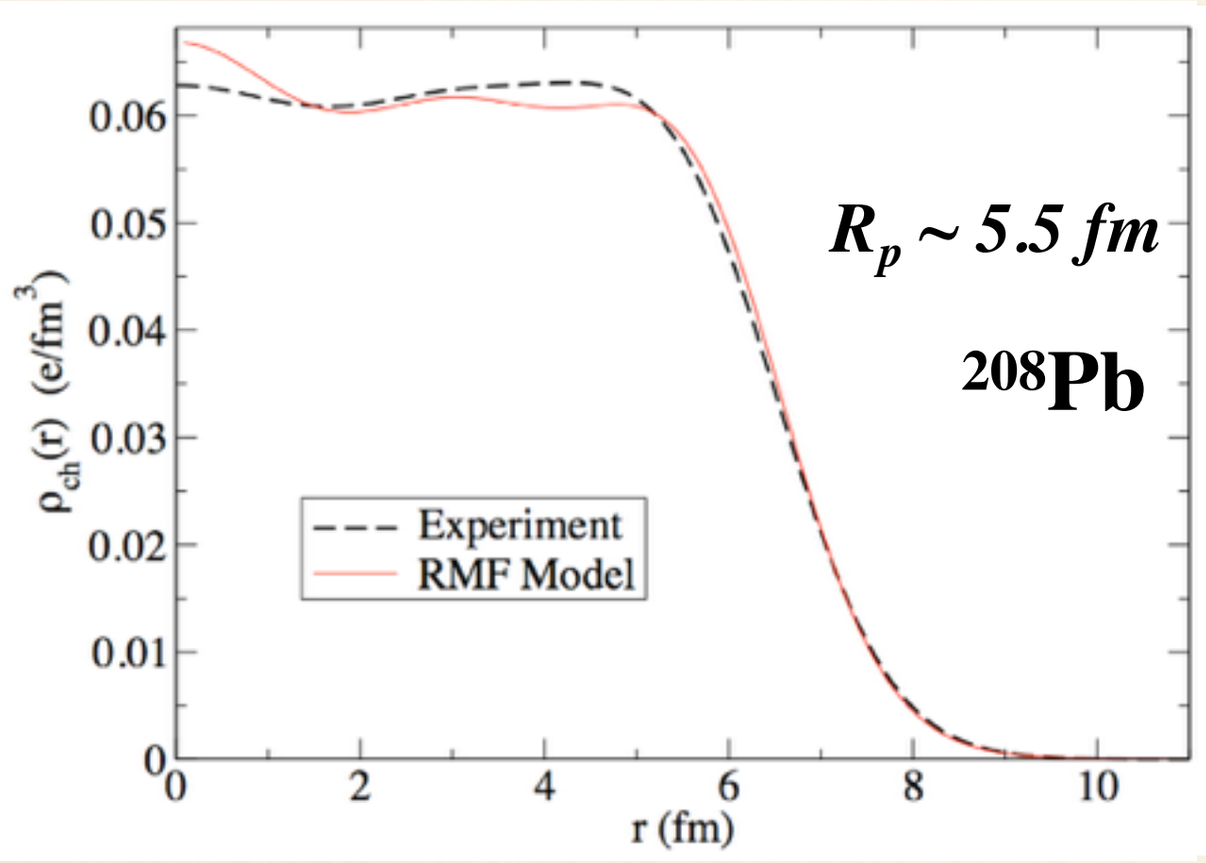
- ***sub-part per billion statistical reach and systematic control***
- ***sub-1% normalization control***

Physics Topics

- *Strange Quark Form Factors*
- *Neutron skin of a heavy nucleus*
- *Indirect Searches for New Interactions*
- *Novel Probes of Nucleon Structure*
- *Electroweak Structure Functions at the EIC*
- *Charge Lepton Flavor Violation at the EIC*

Neutron Skin of a Heavy Nucleus

EM Charge vs Weak Charge Density



$R_p \sim 5.5\ fm$

^{208}Pb

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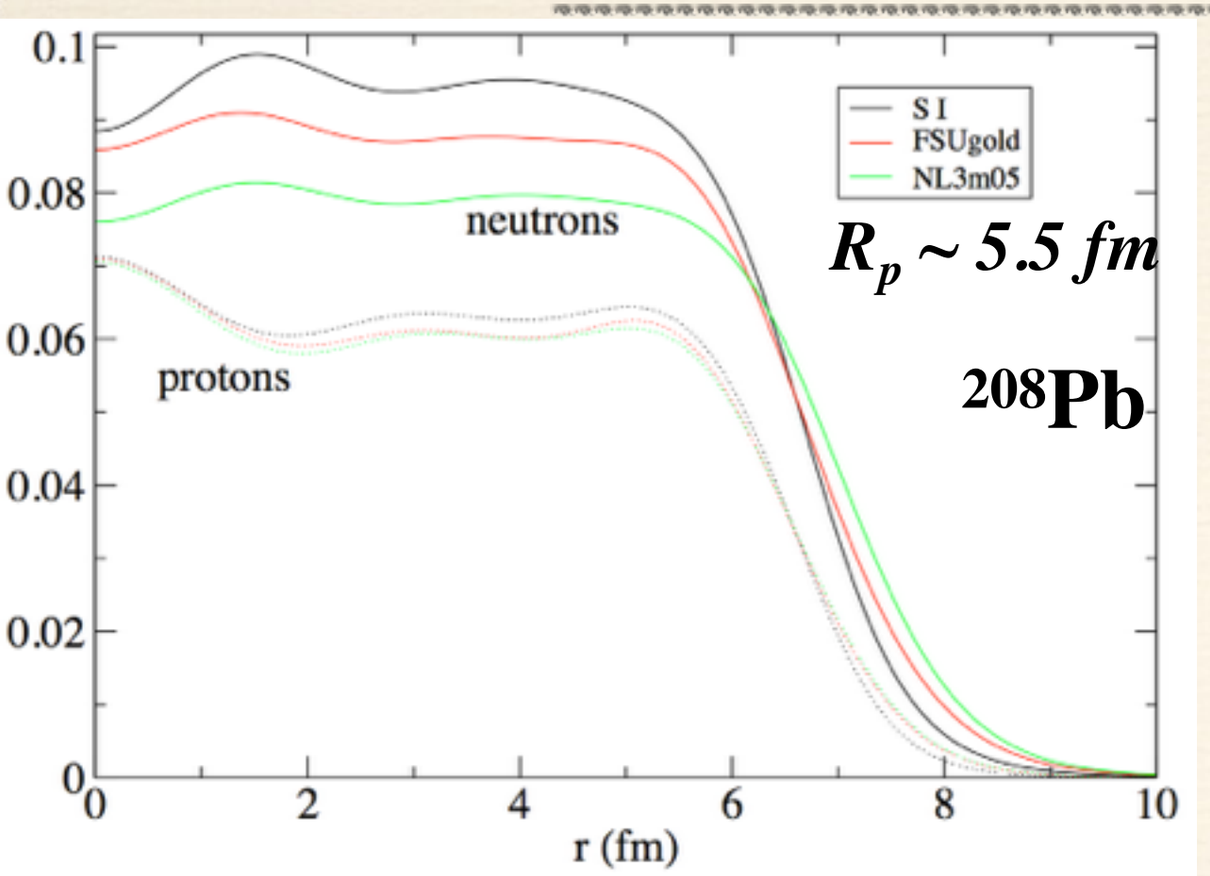

neutrons expected to occupy a larger volume

$Q^p_{EM} \sim 1$ $Q^n_{EM} \sim 0$ $Q^n_W \sim 1$ $Q^p_W \sim 1 - 4\sin^2\theta_W$

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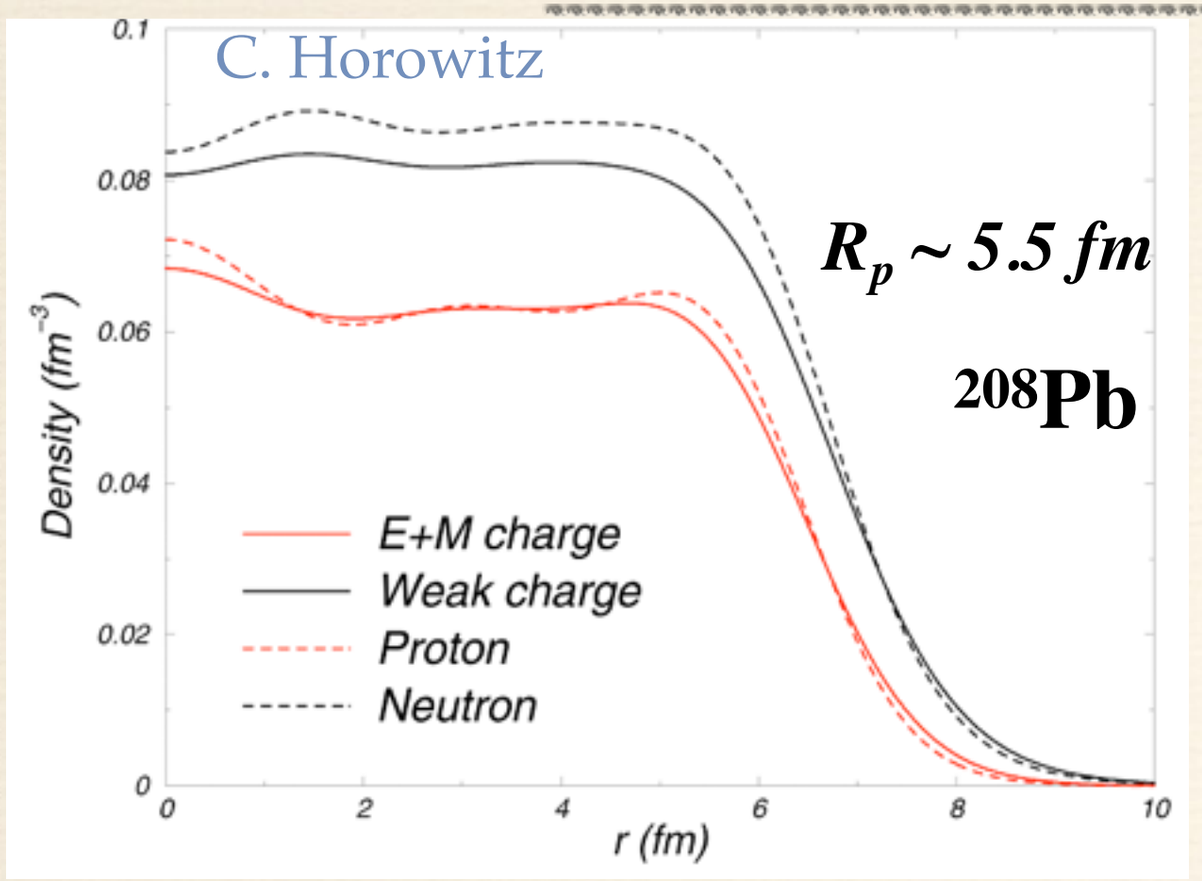

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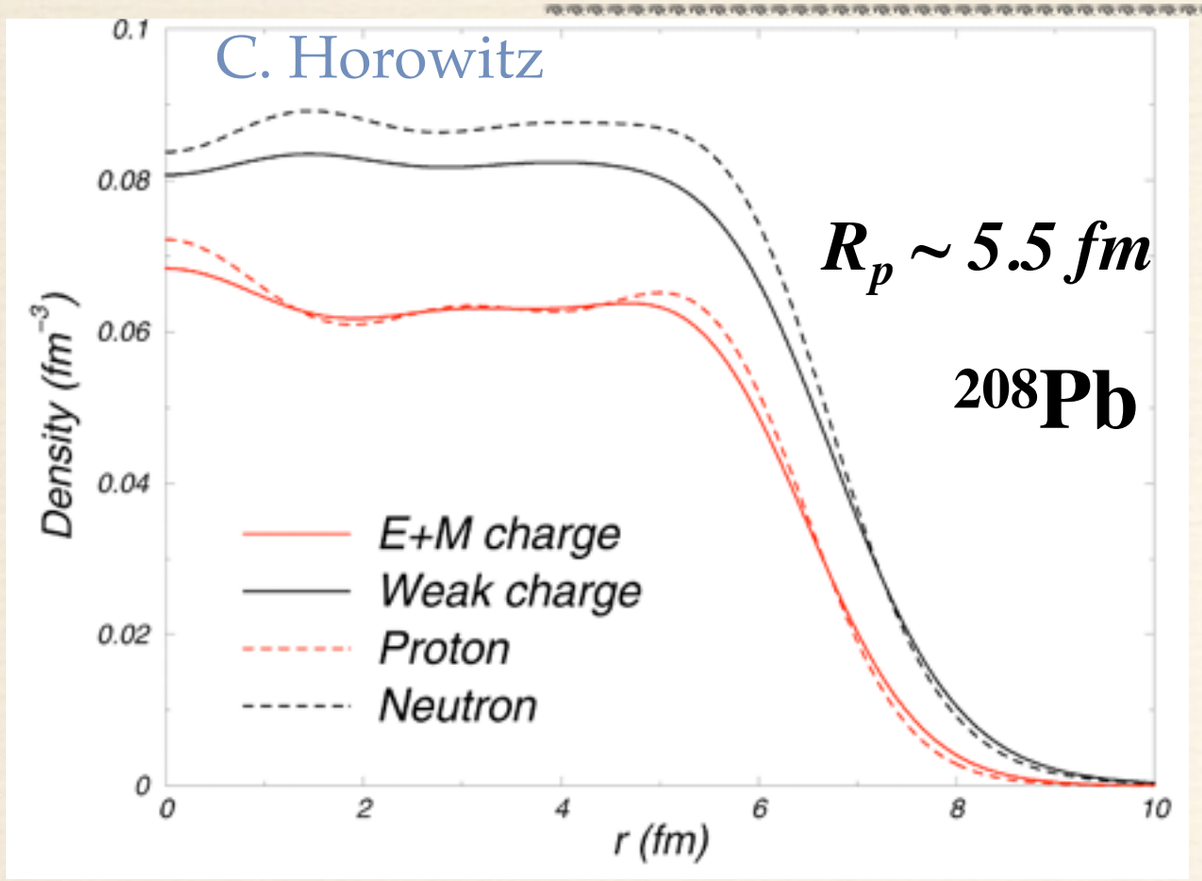

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^{208}Pb

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Weak (	-0.08	1

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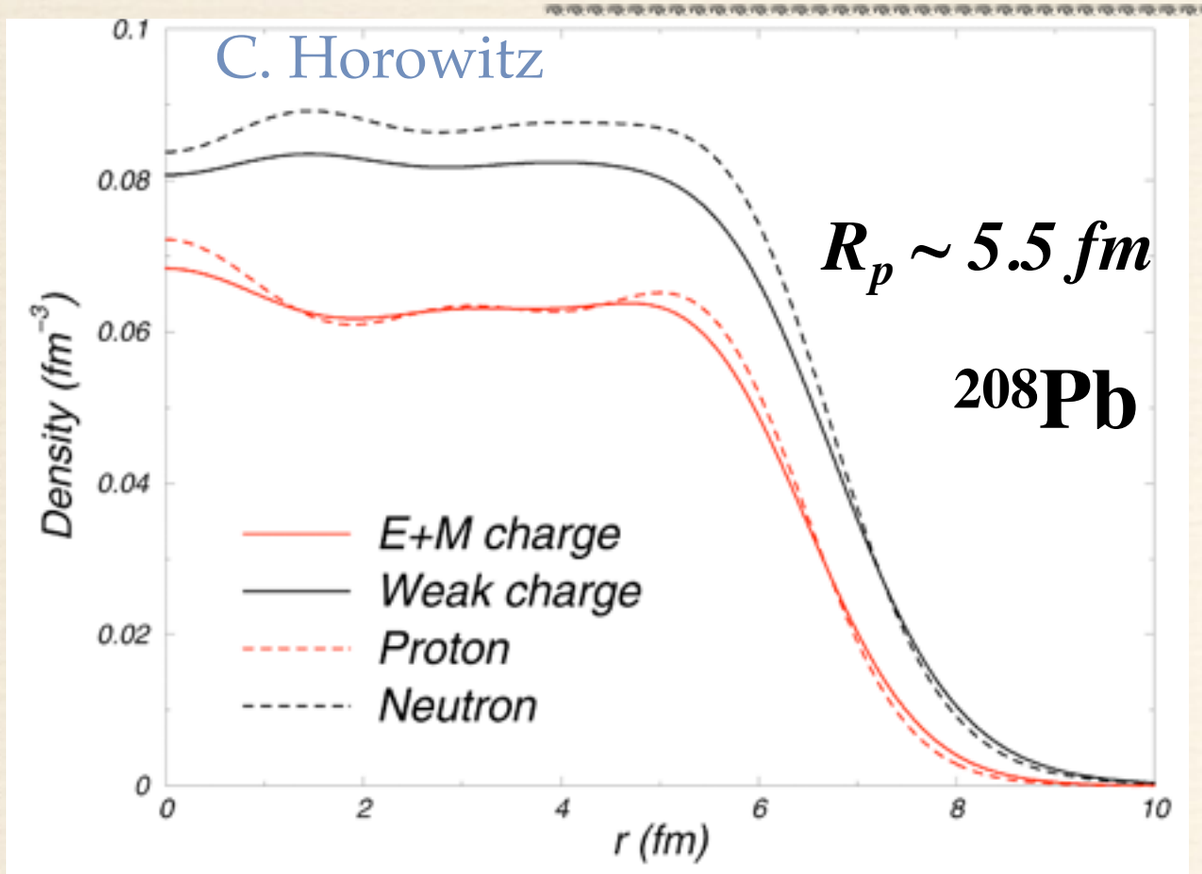

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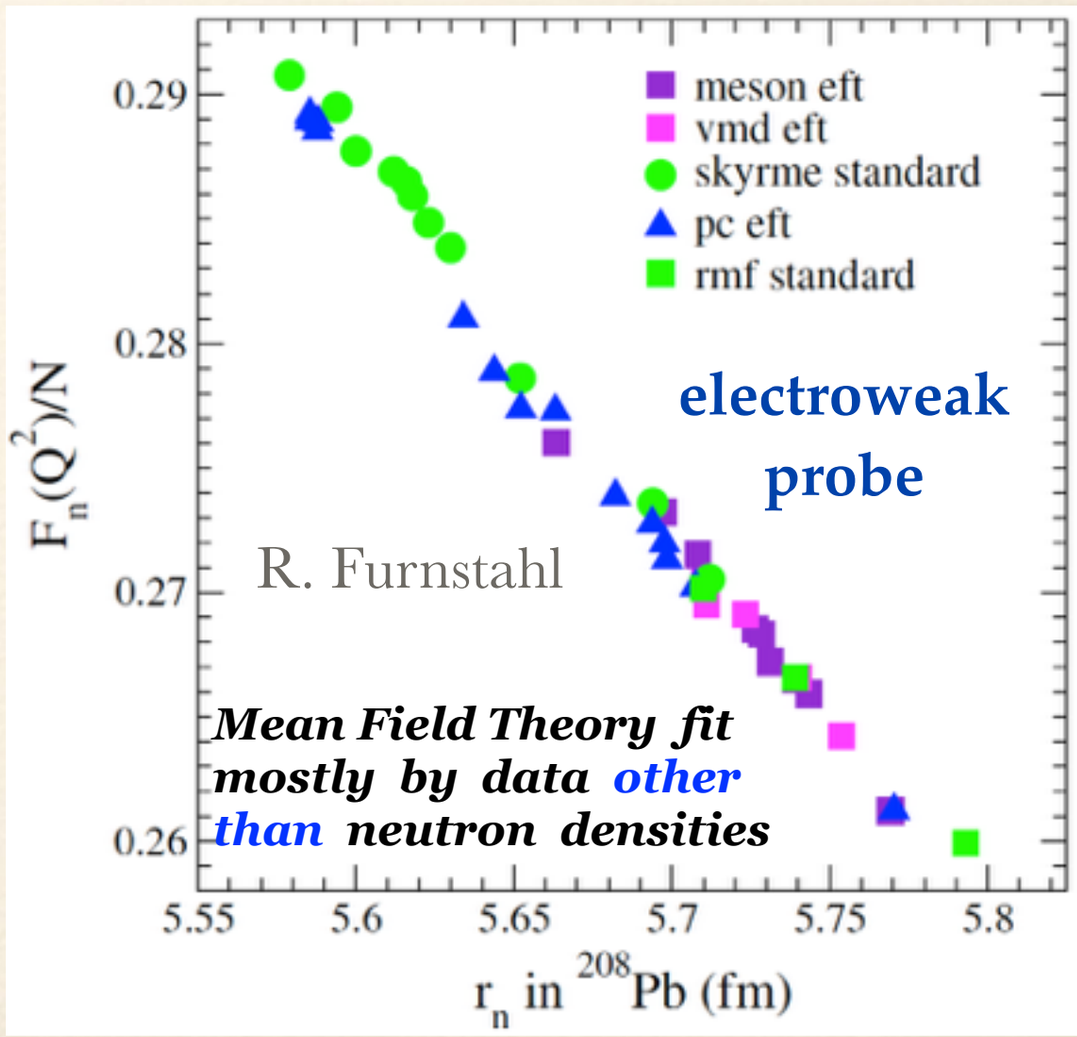
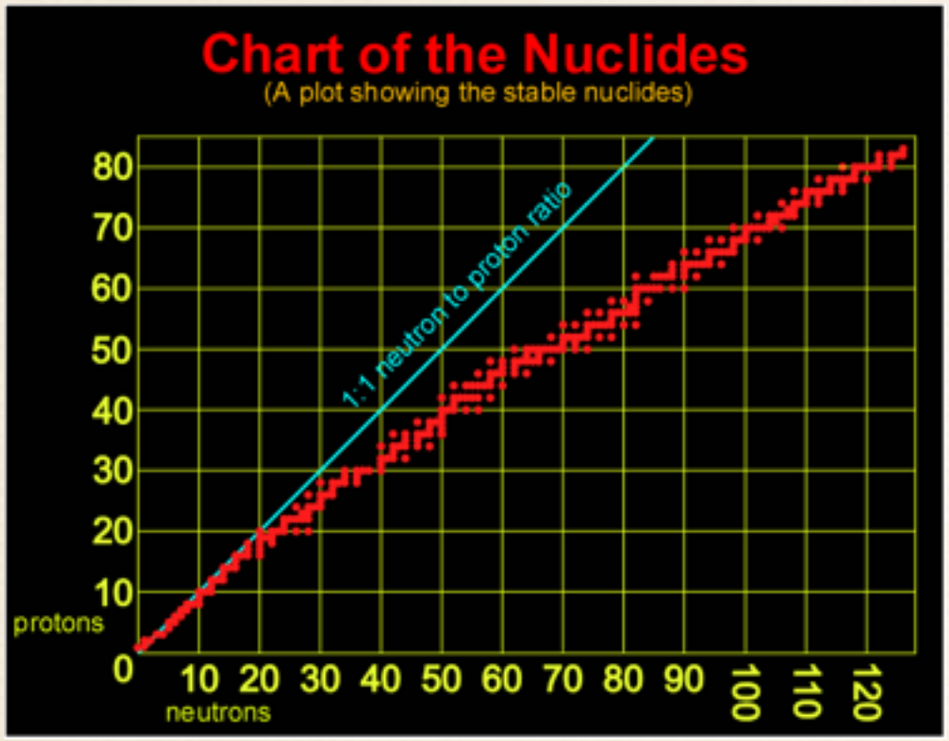
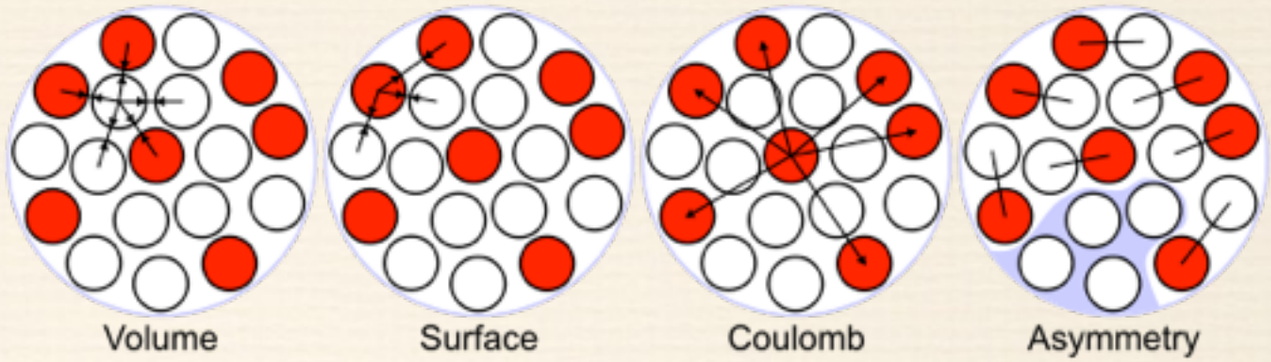


Neutron Distribution in a Nucleus

What is the physics? .....And why is it interesting?





pressure pushes against surface tension

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Neutron Distribution in a Nucleus

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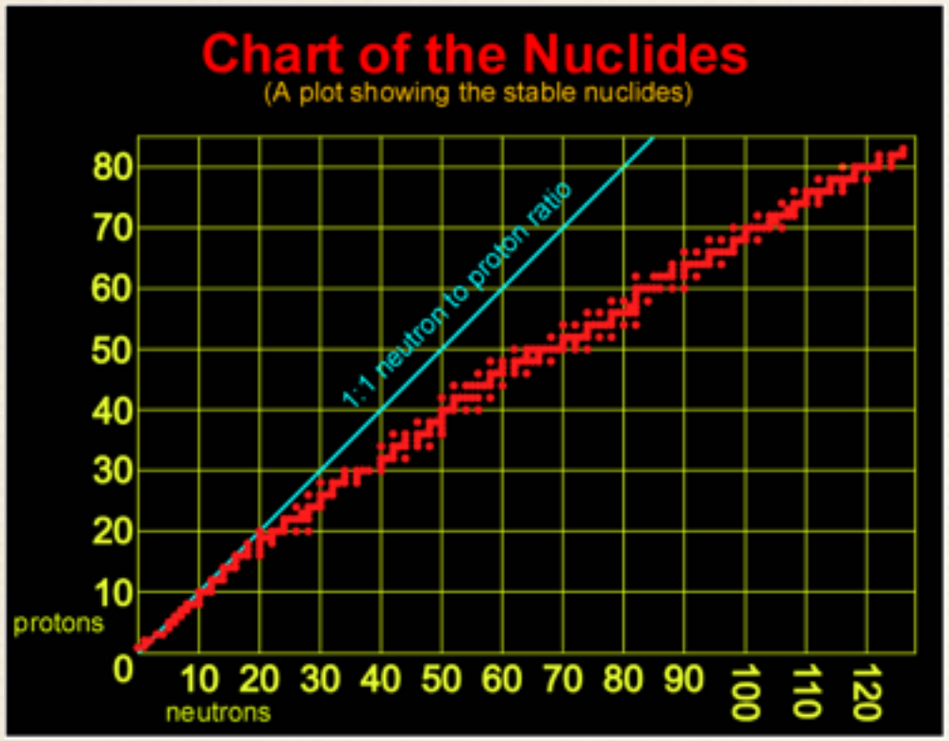

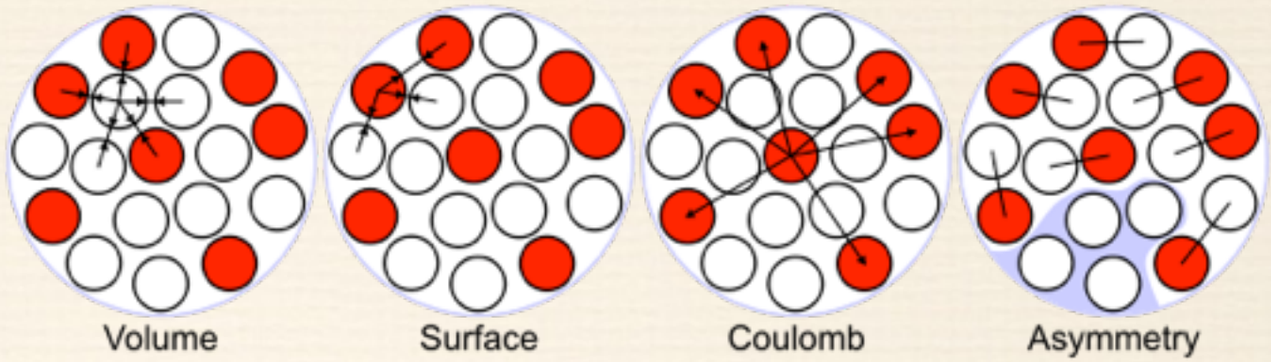

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Involve model dependence and strong force uncertainties

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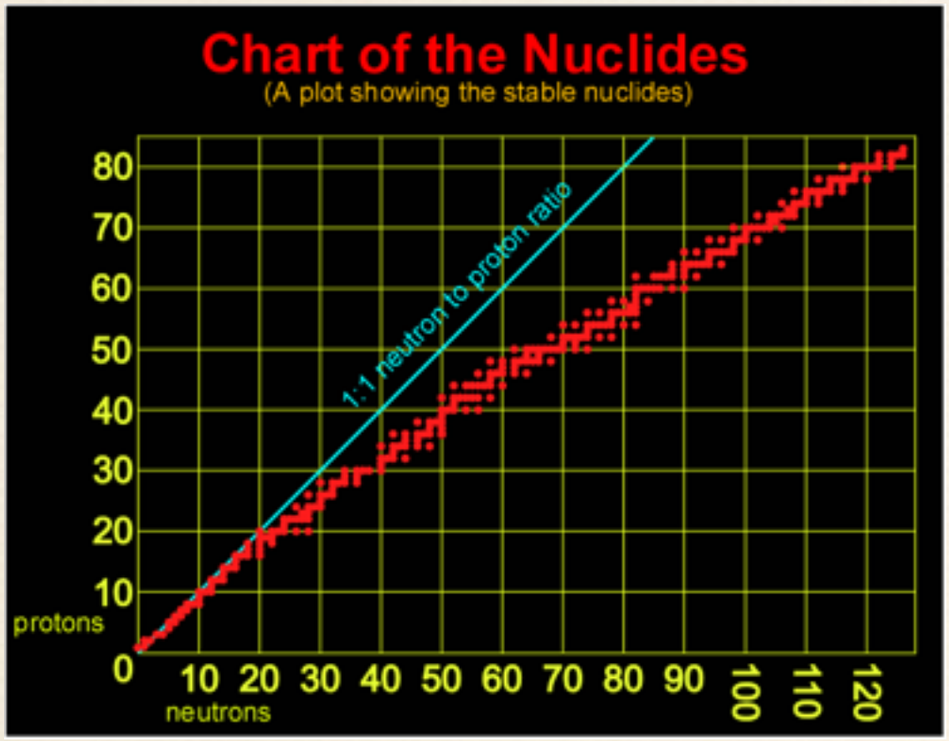

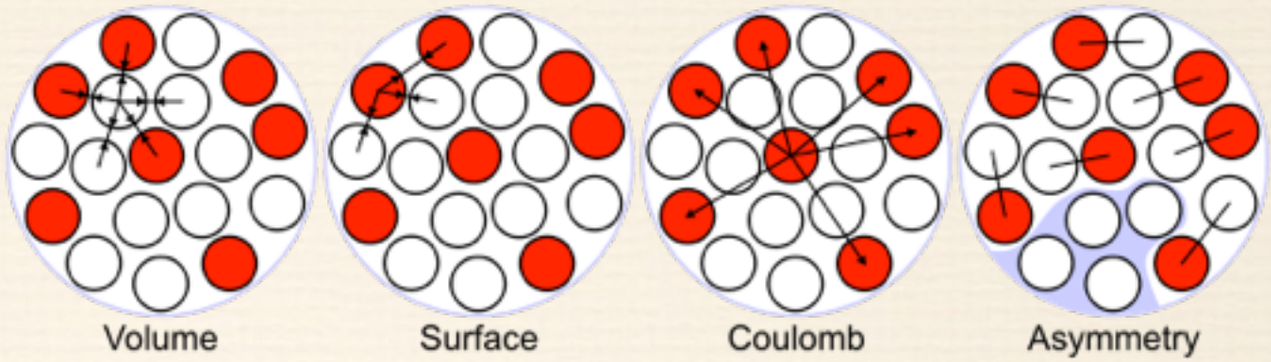

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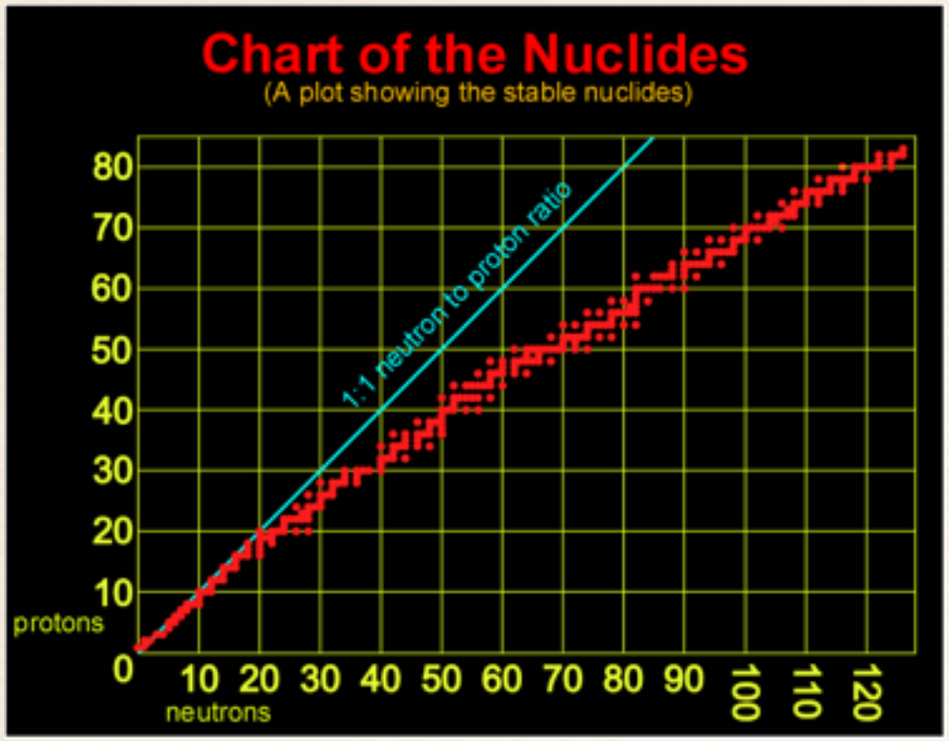

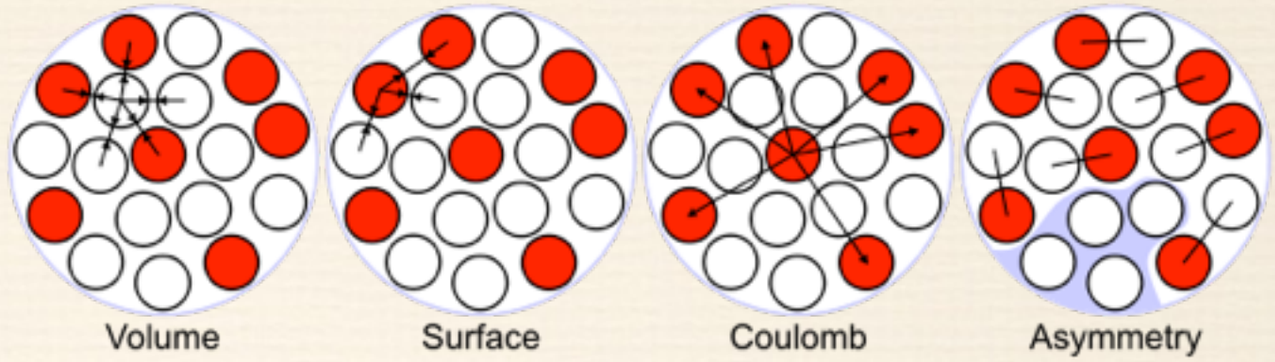

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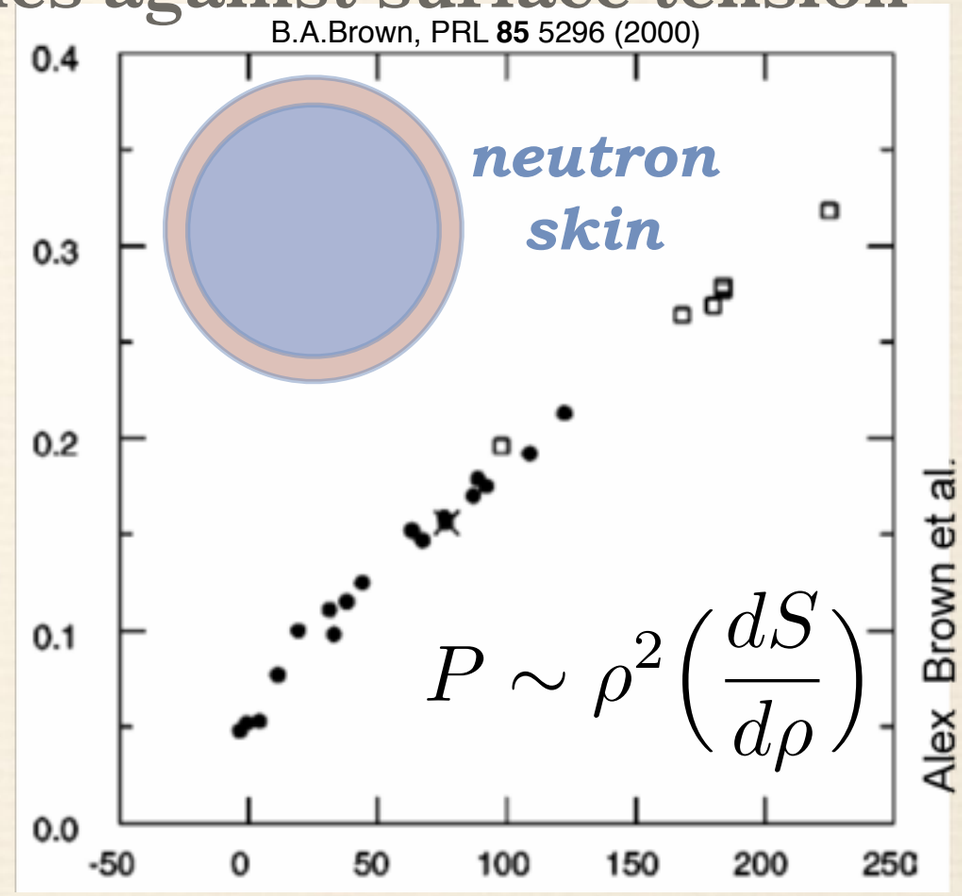
B.A.Brown, PRL **85** 5296 (2000)



Neutron matter P (MeV/fm^3) x100 at a density of 0.1 fm^{-3}.

size of neutron "skin" measures density dependence of symmetry energy

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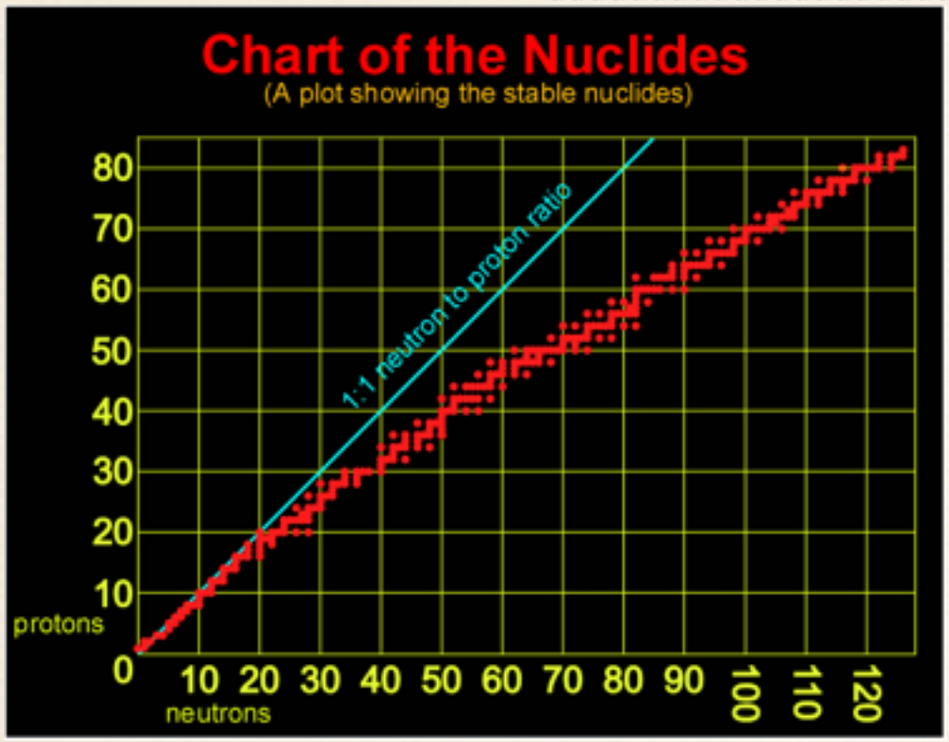

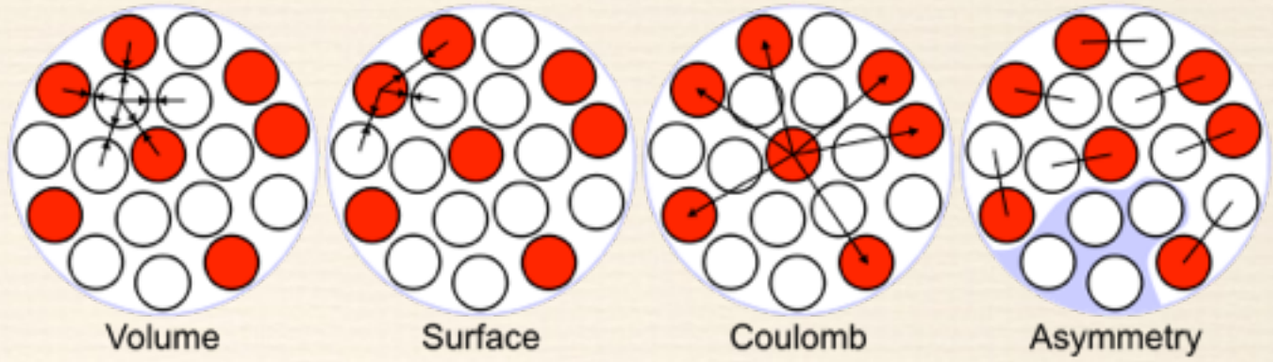

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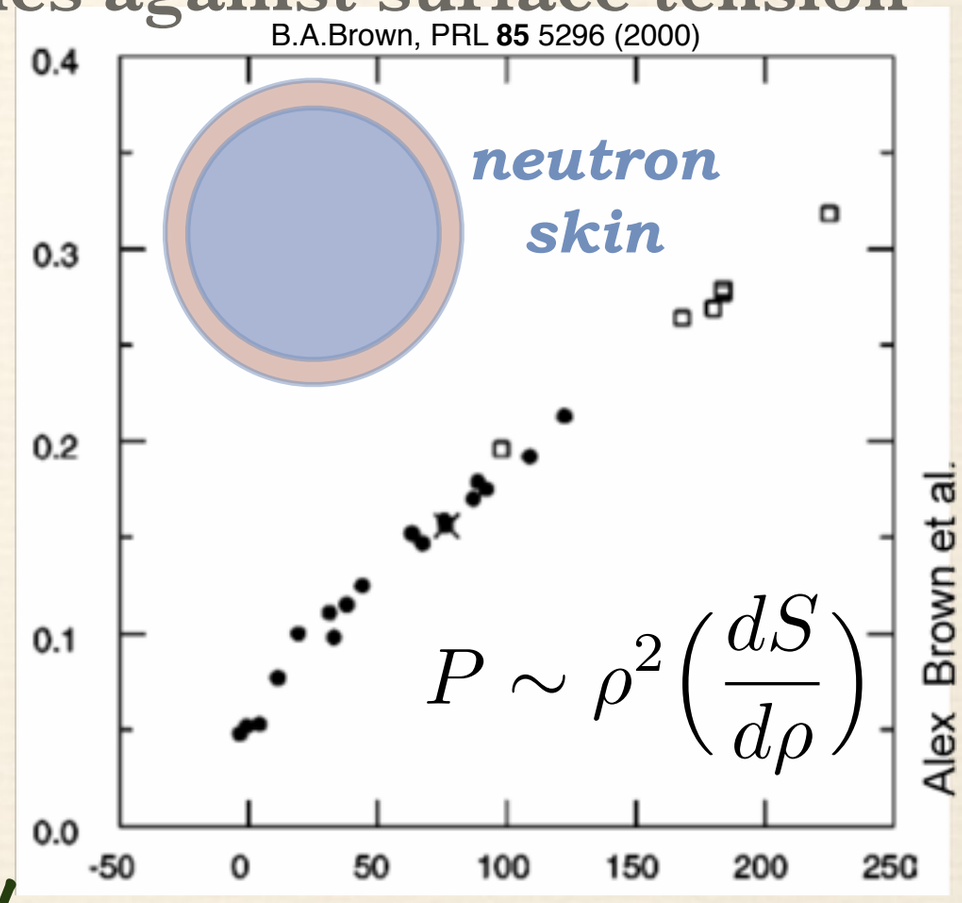
pressure ⇒ density dependence of symmetry energy at subnuclear densities



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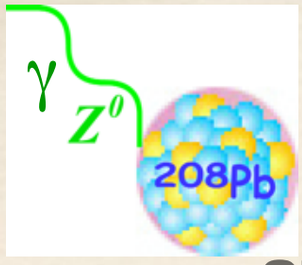
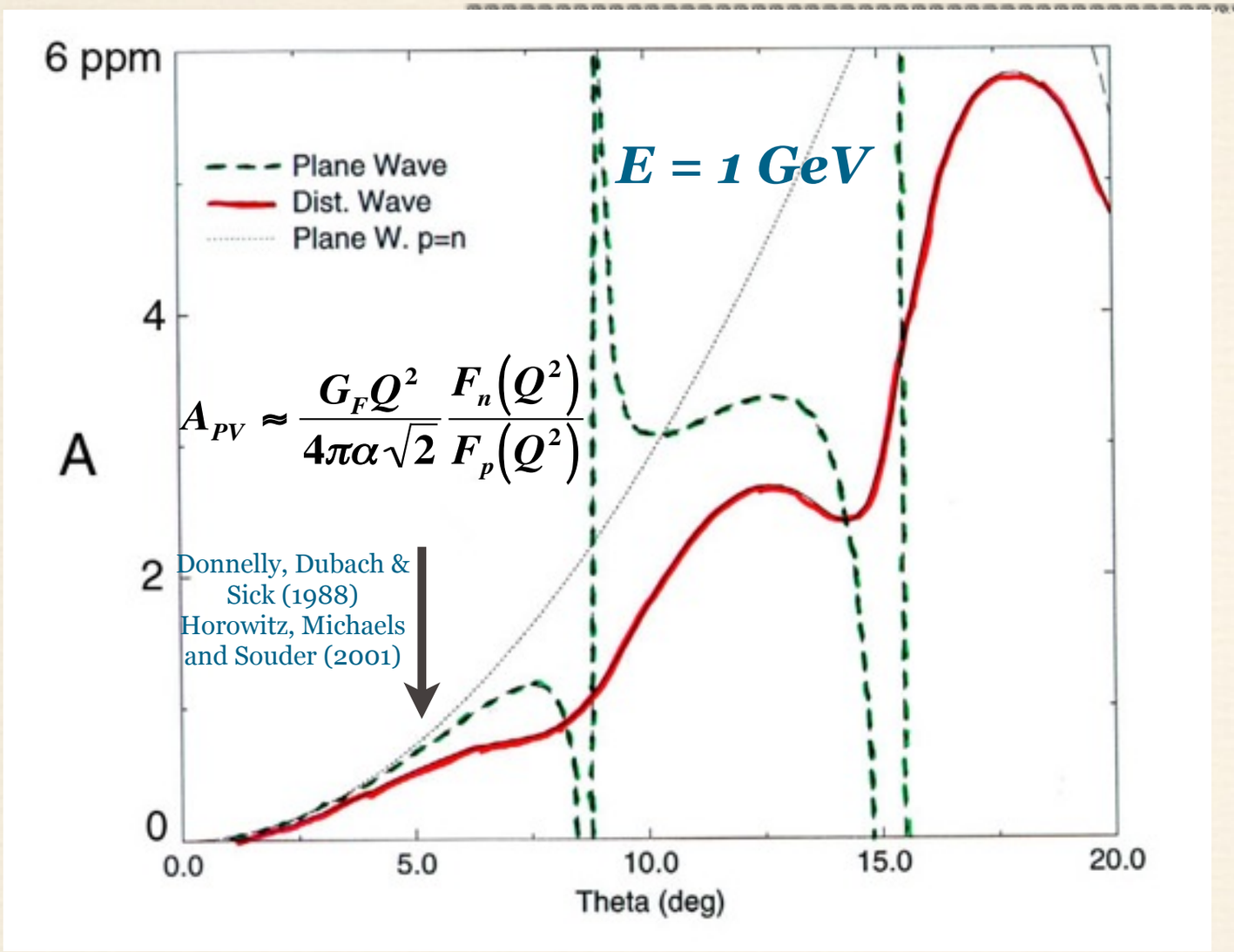
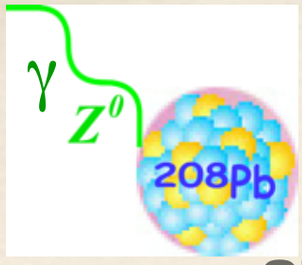


The Pb Radius EXperiment

Concept: PREX

at the Thomas Jefferson National Accelerator Facility





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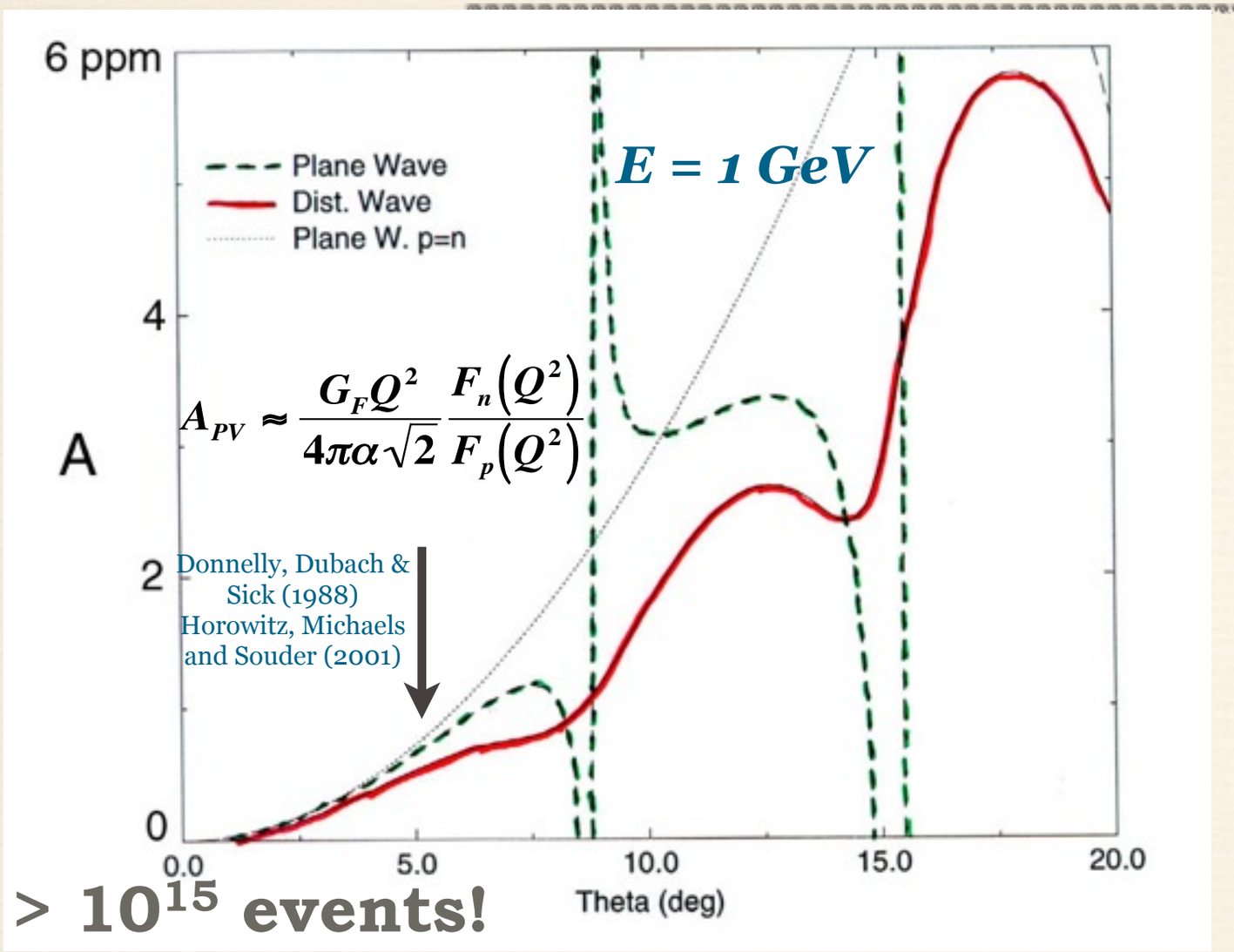
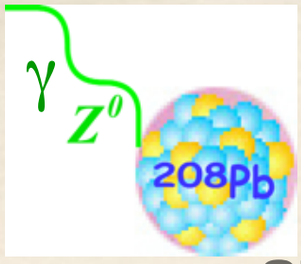


> 10^{15} events!



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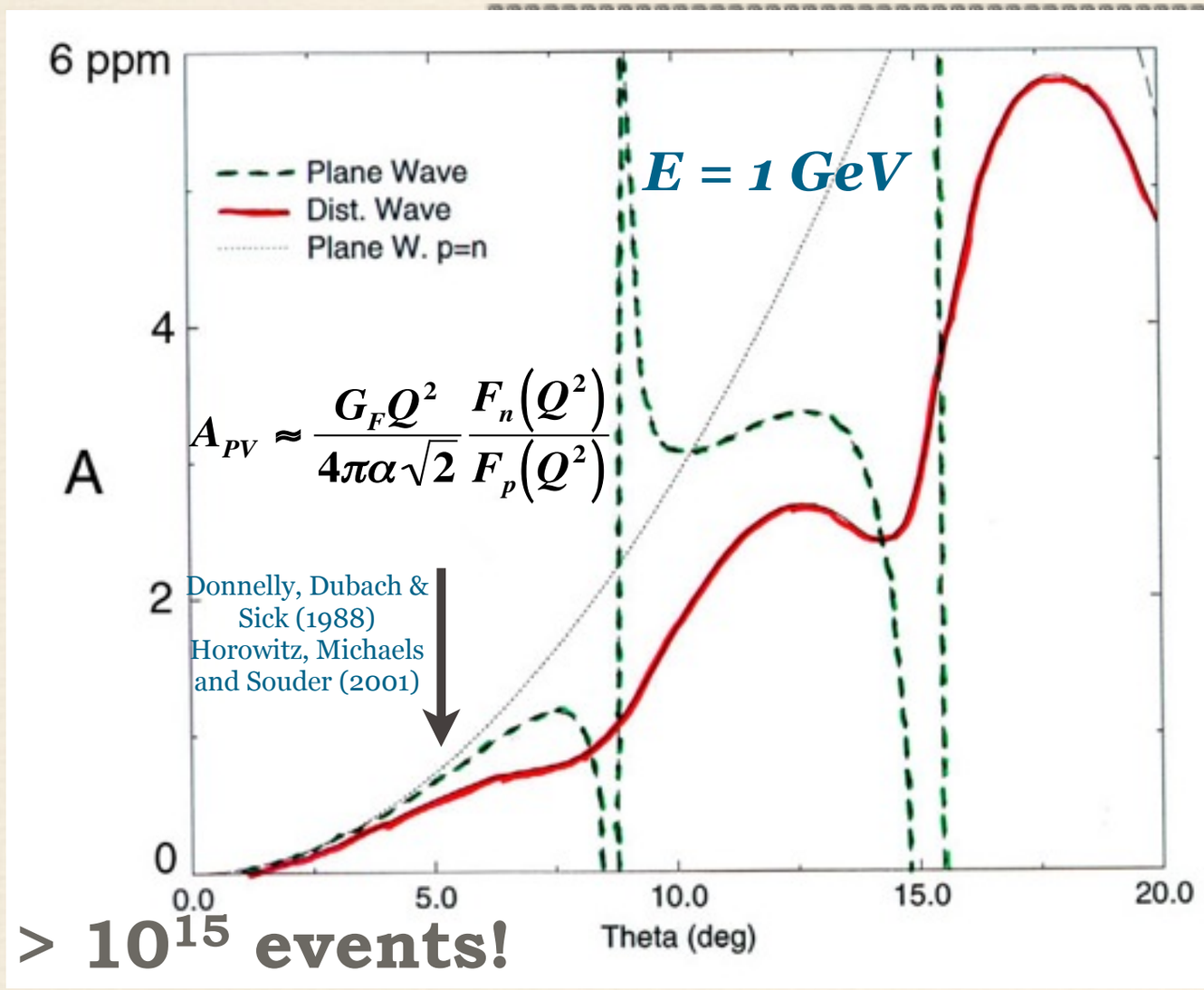

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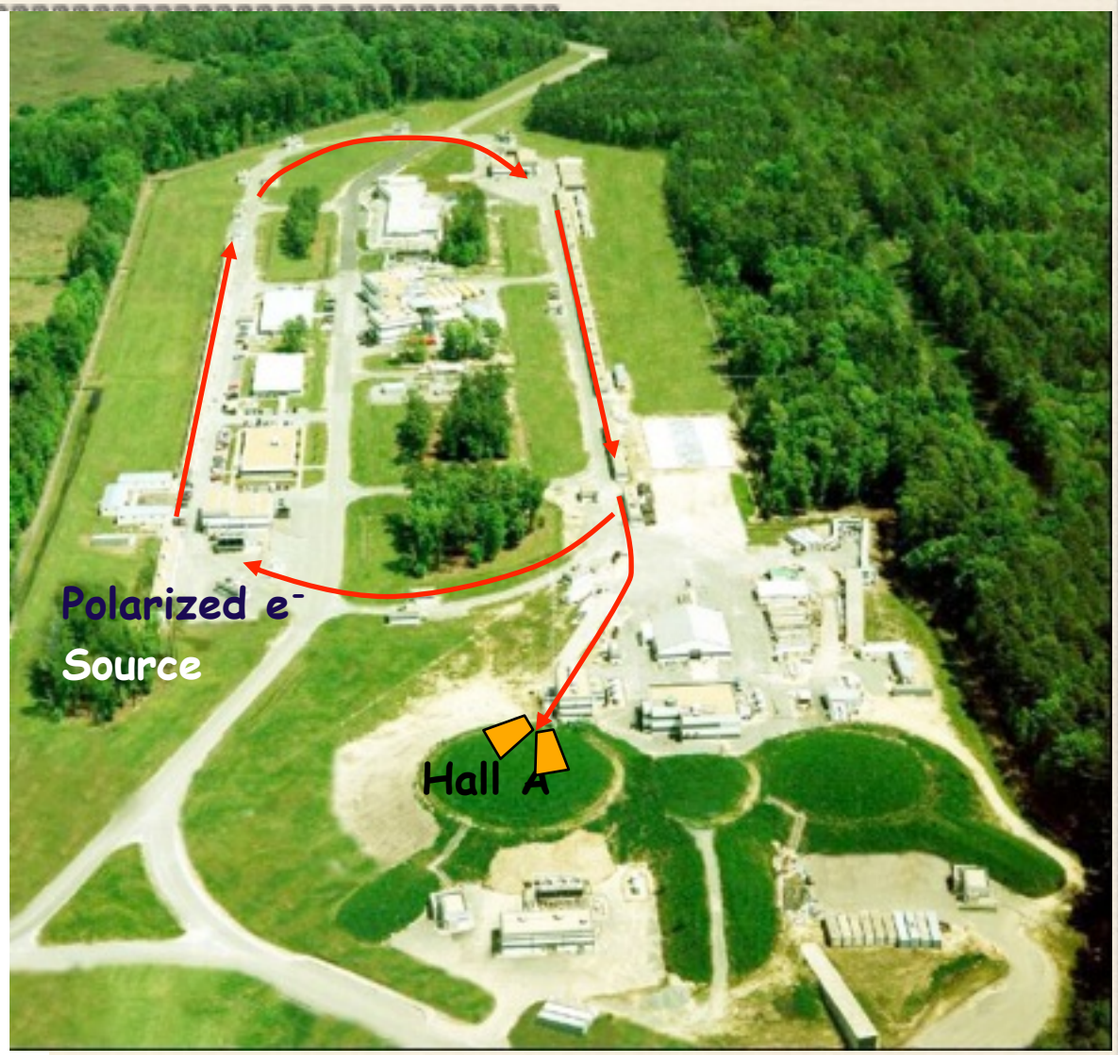

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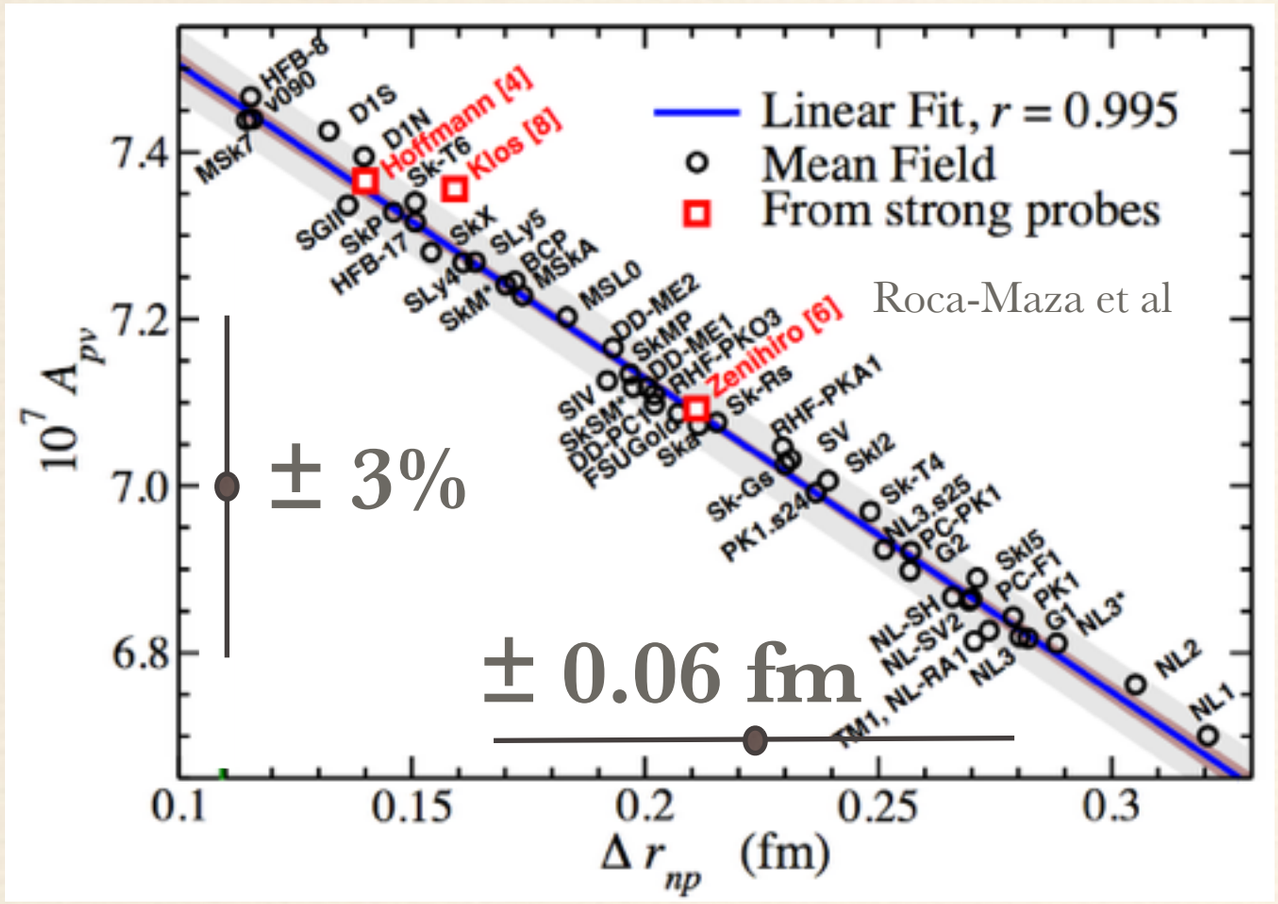

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$A_{PV} \sim 0.7\ ppm$

Rate ~ 1 GHz

$\Delta(A_{PV}) \sim 20\ ppb$

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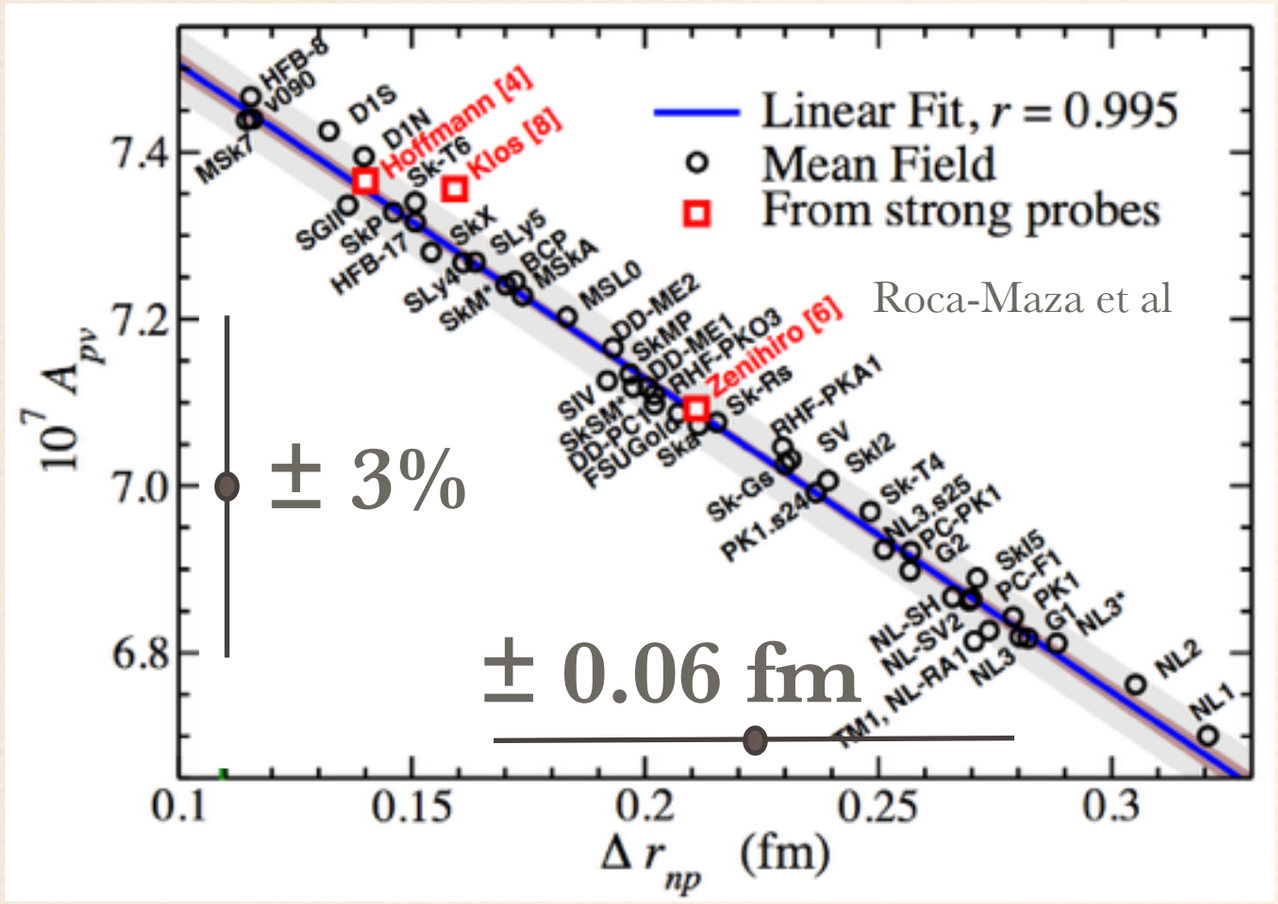

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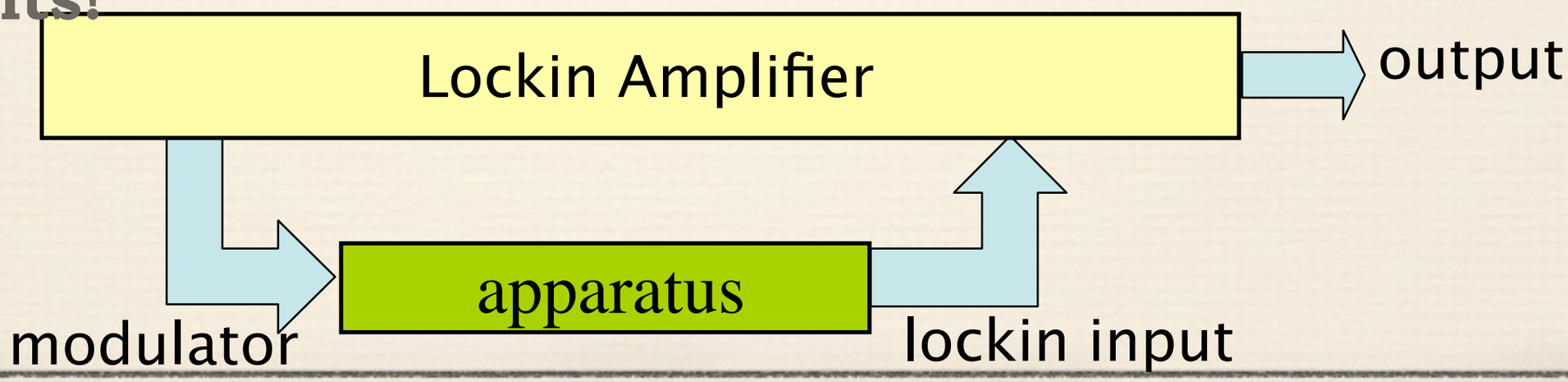

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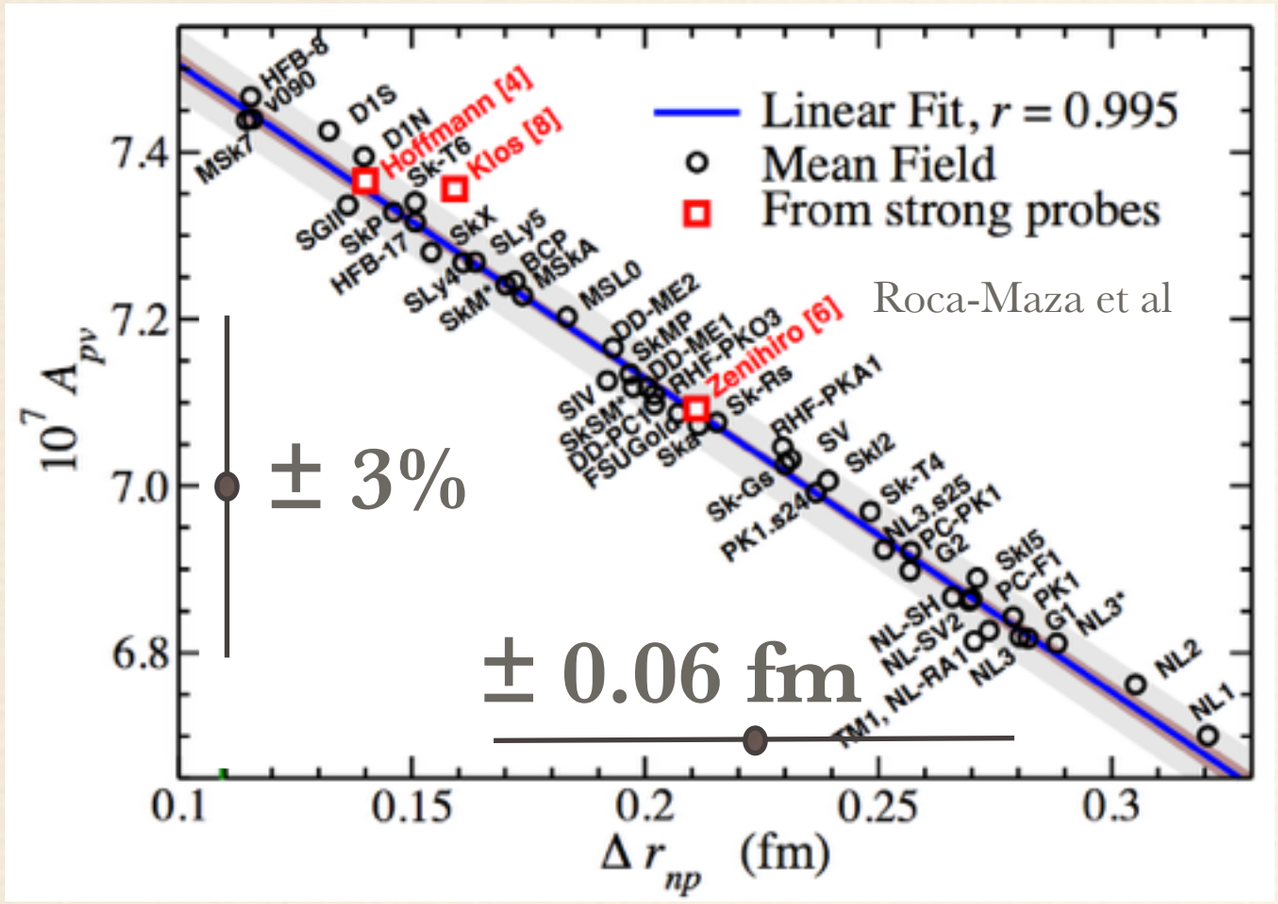

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Lockin Amplifier → output

injector → *accelerator* → *target* → *spectrometer* → *detector*

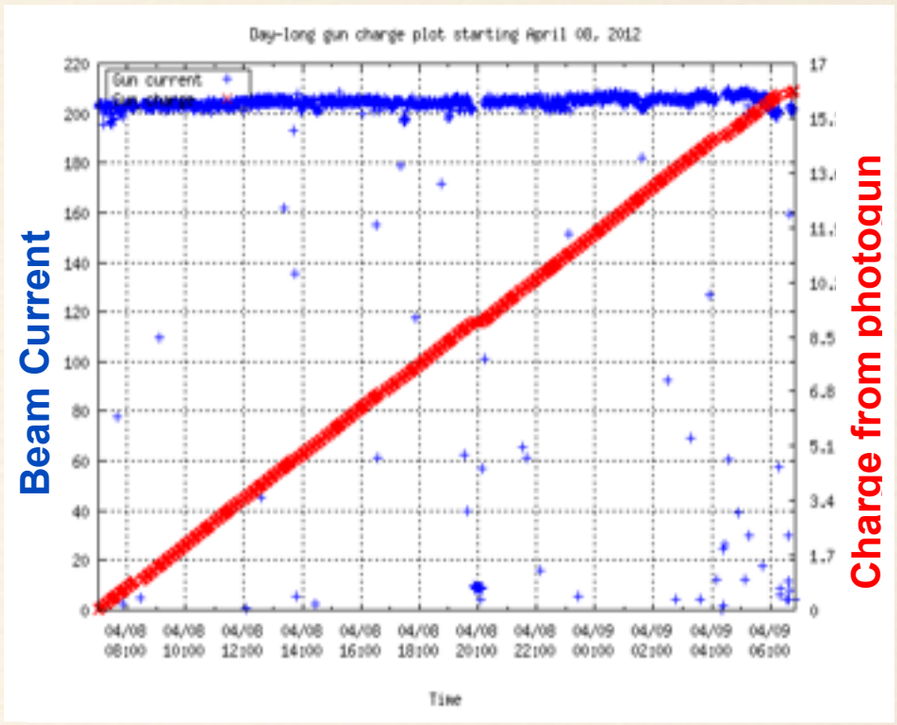
Polarized Beam at JLab

B. Matthew Poelker
2011 E. O. Lawrence Award

Record Performance (2012):
180 μA at 89% polarization

Electron Gun Requirements

- **Ultrahigh vacuum**
- **No field emission**
- **Maintenance-free**



24 Hours

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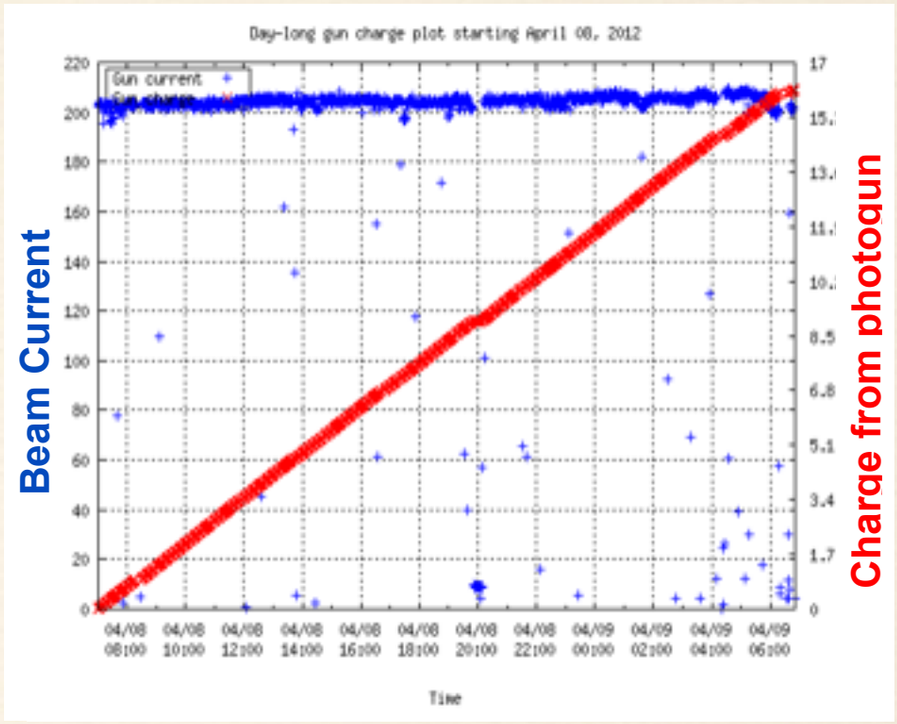

✧ Beam helicity is chosen pseudo-randomly at multiple of 60 Hz

- *sequence of "window multiplets"*

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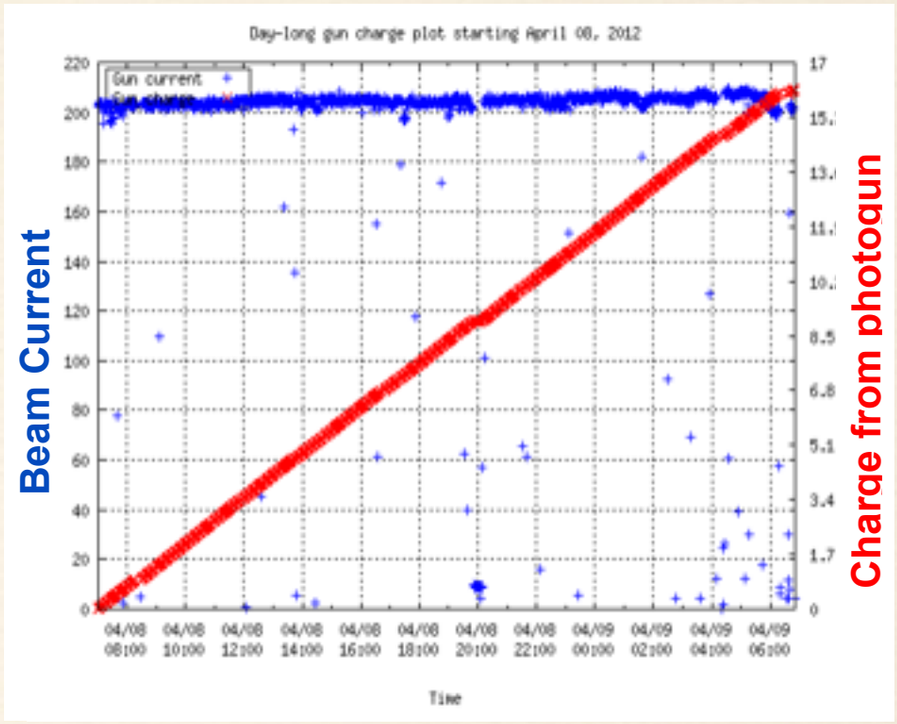

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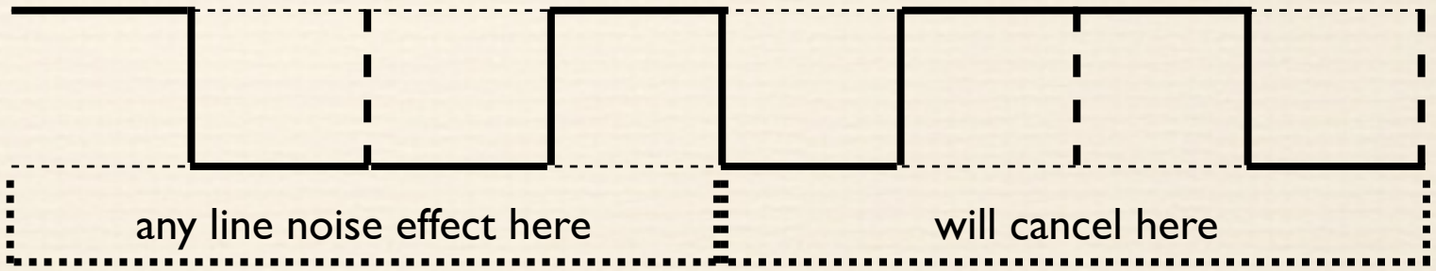
Choose 2 pairs pseudo-randomly, force complementary two pairs to follow

Analyze each "macropulse" of 8 windows together

Example: at 240 Hz reversal



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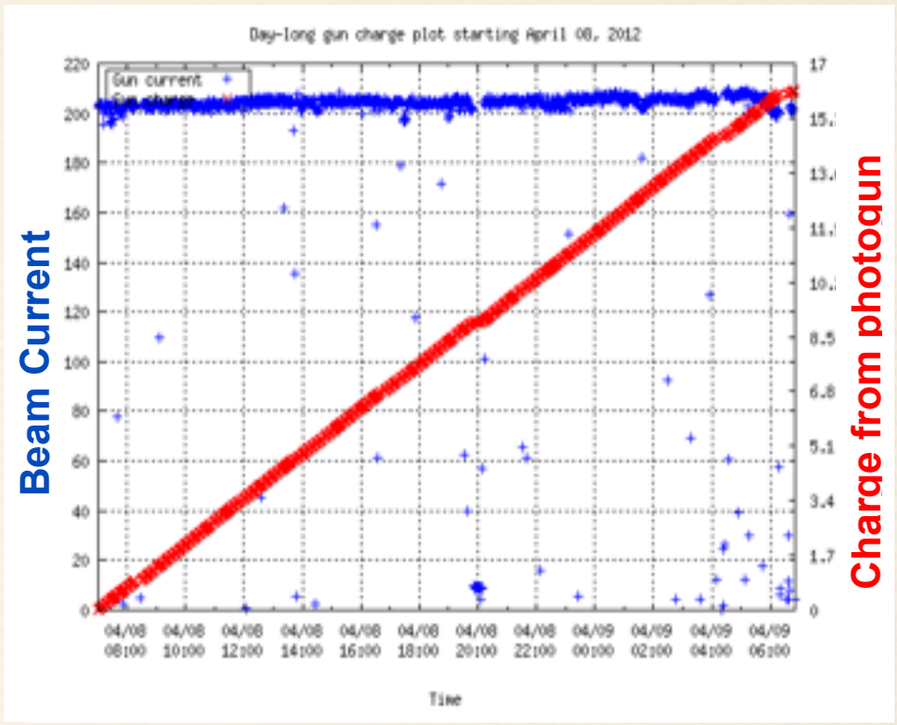

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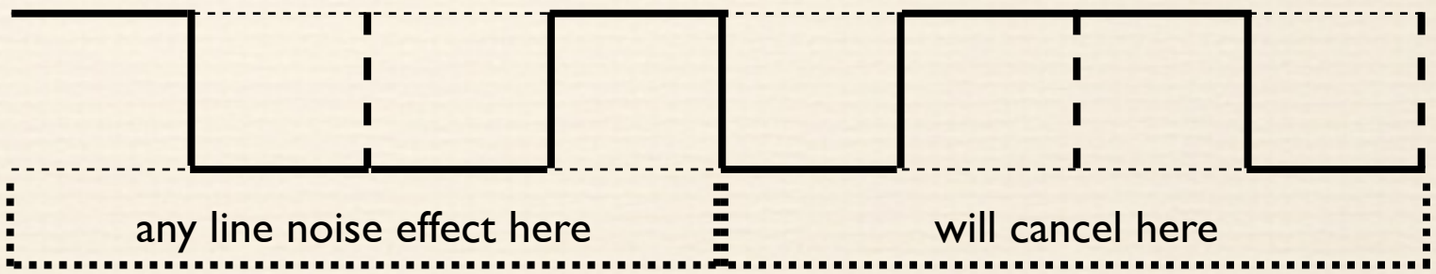
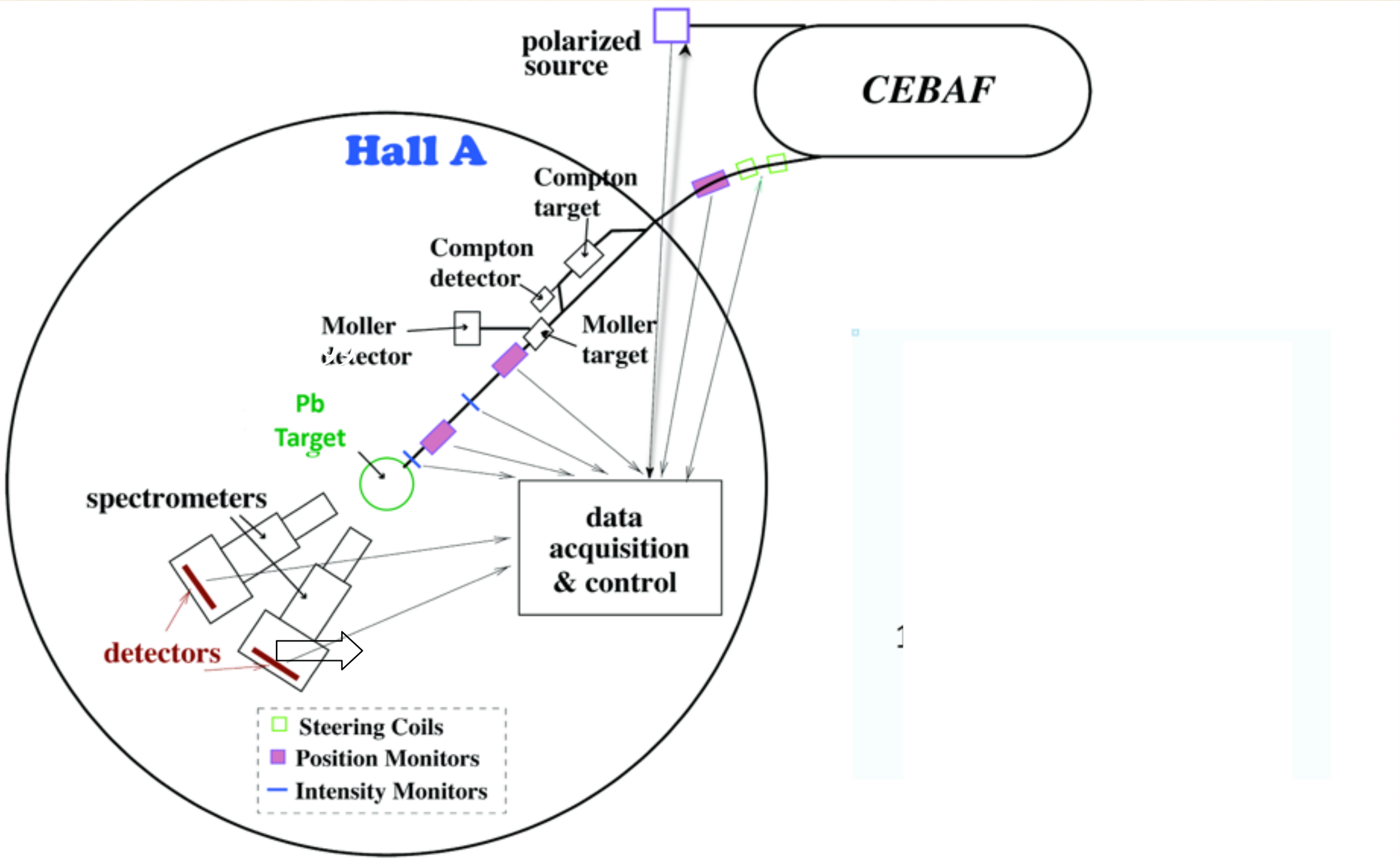


Noise characteristics have been unimportant in past JLab experiments:
Not so for PREX, Qweak and MOLLER....

PREX @ JLab Hall A: Overview



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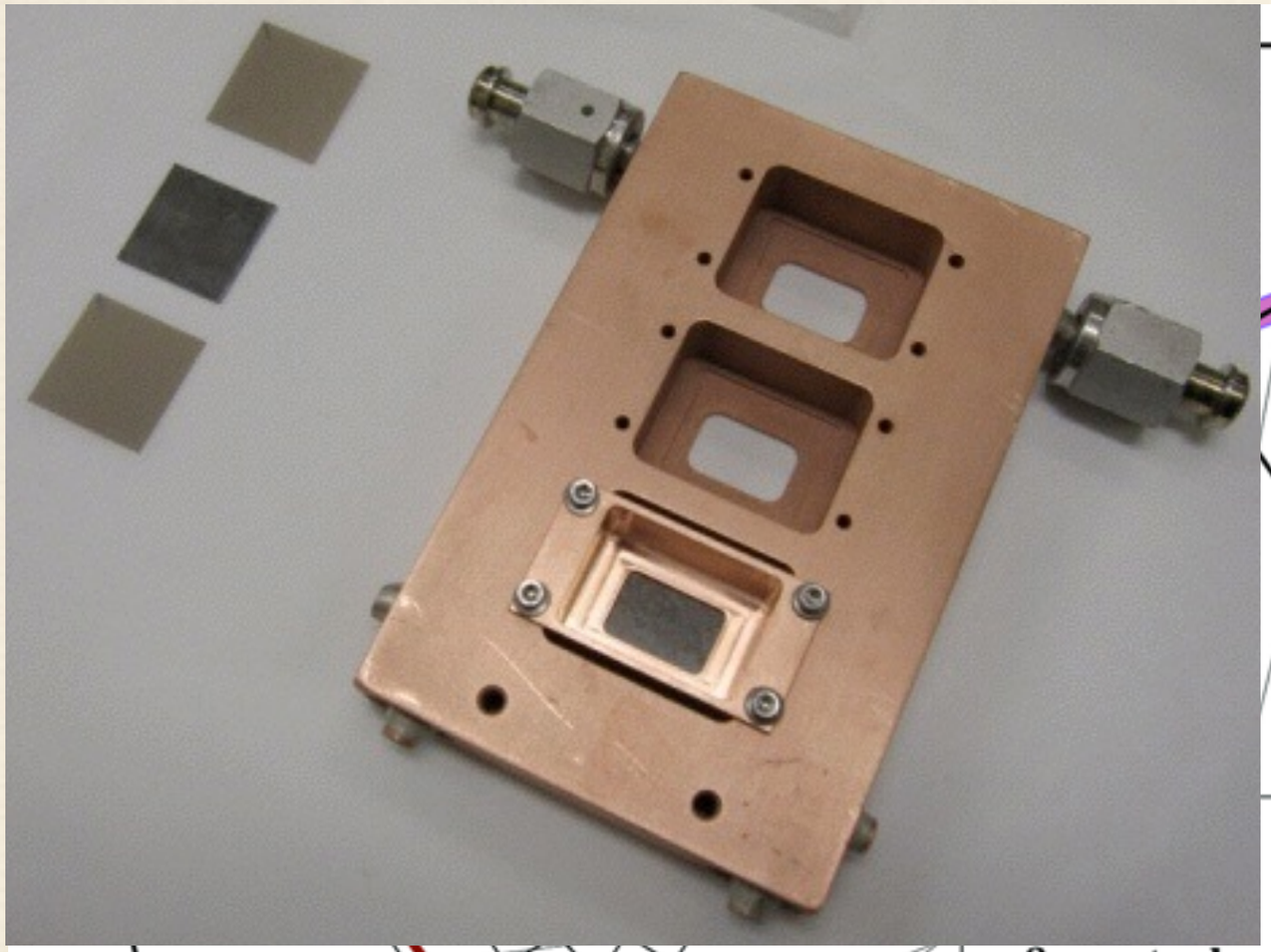

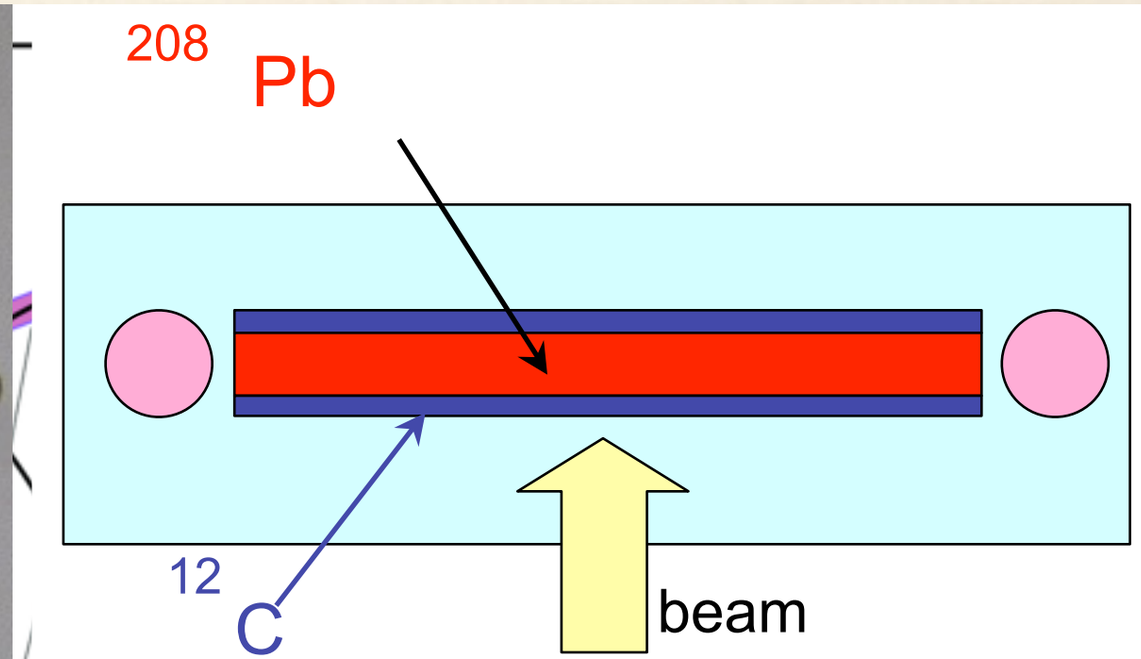

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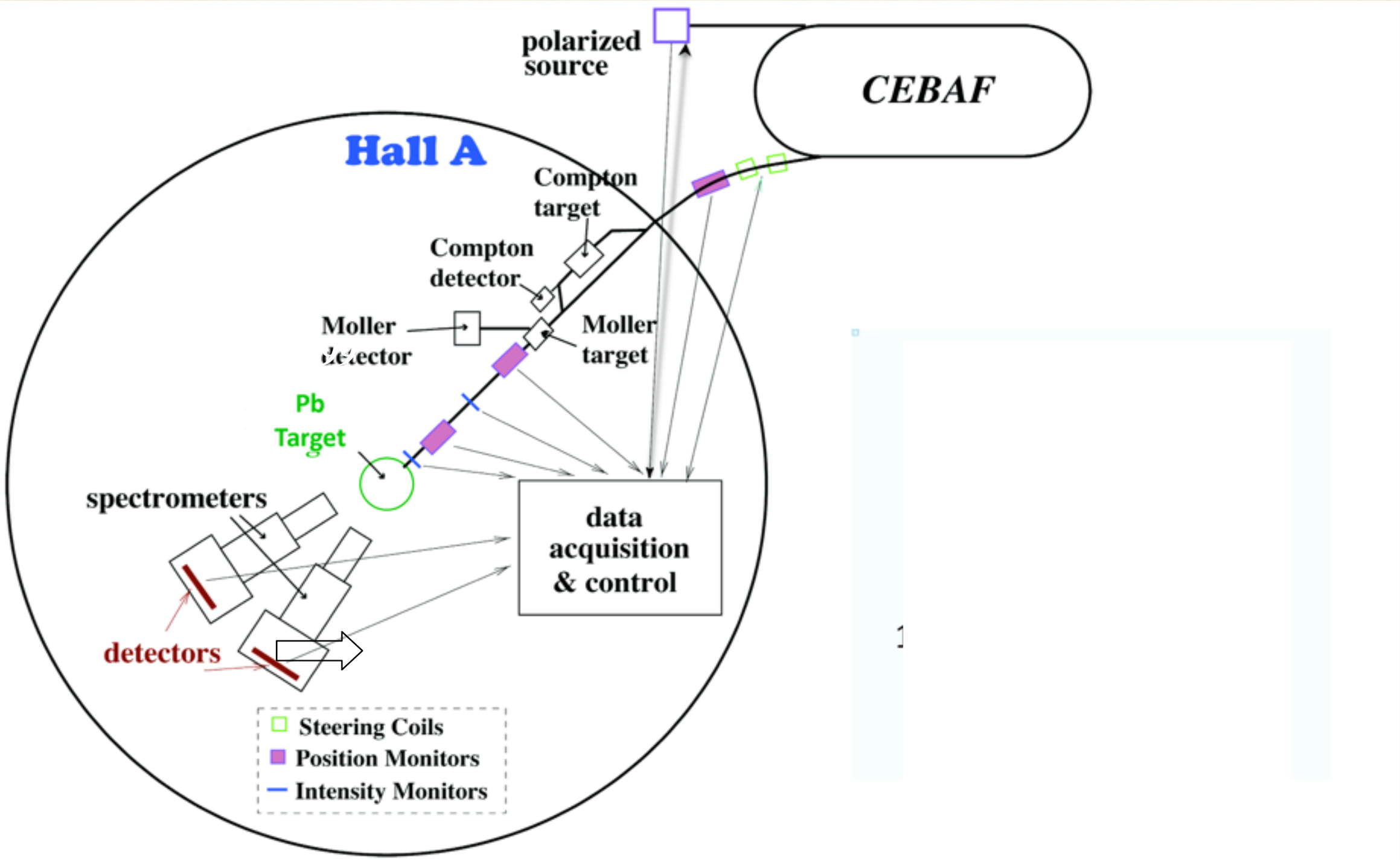

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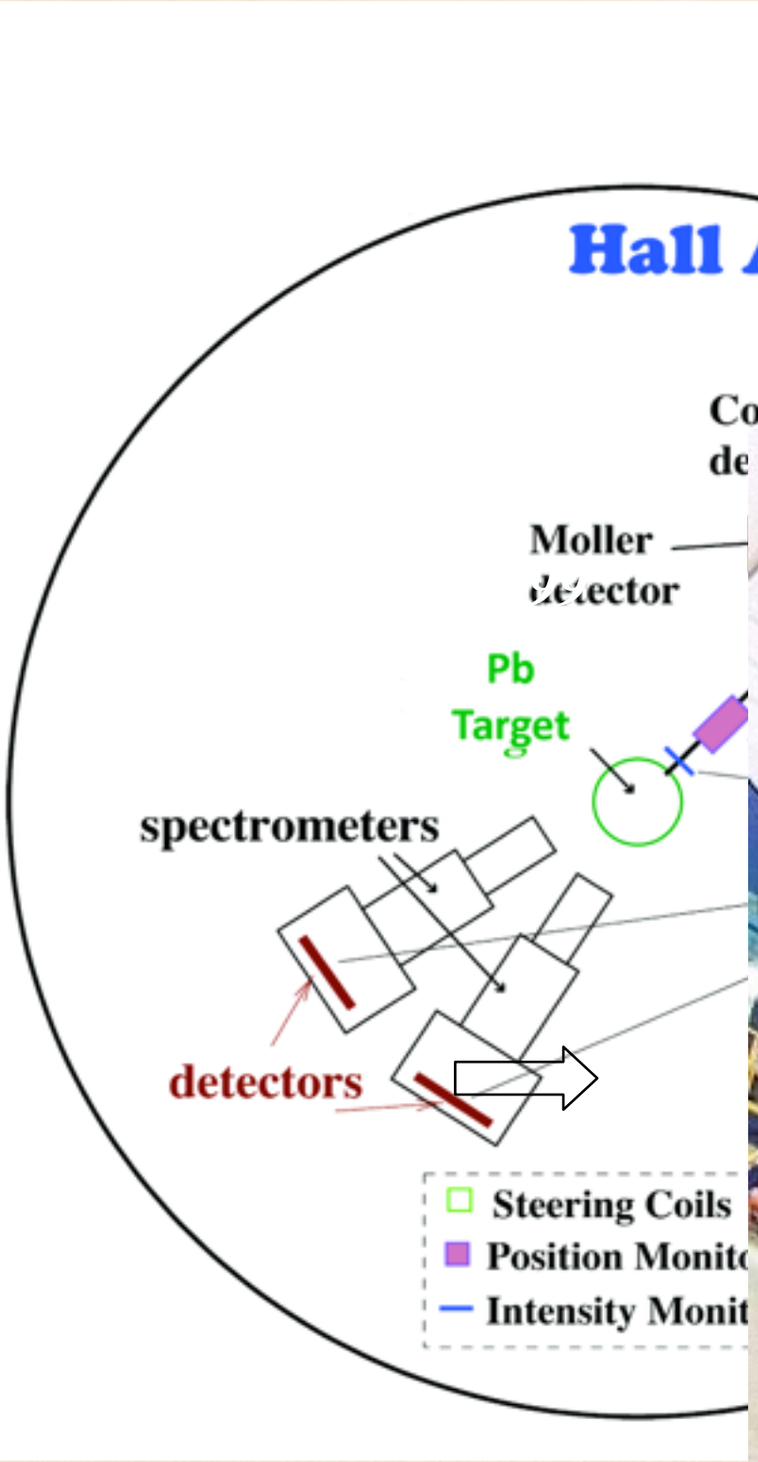
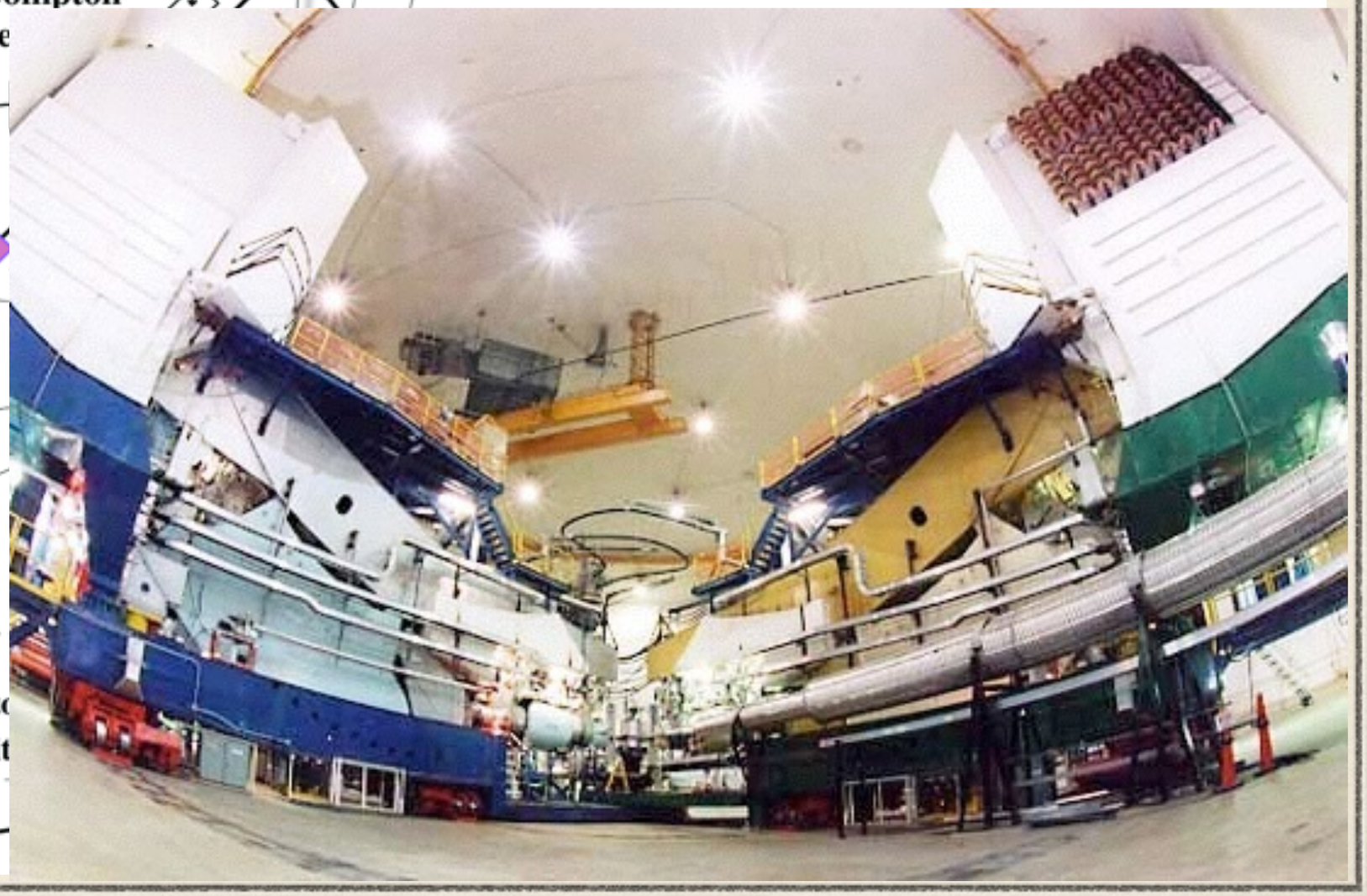
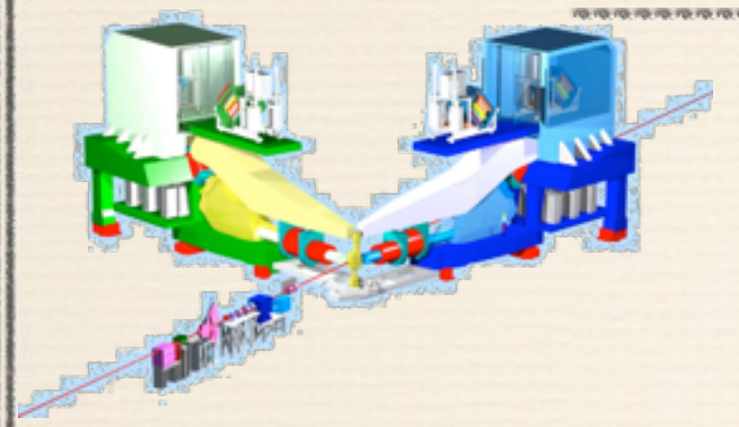


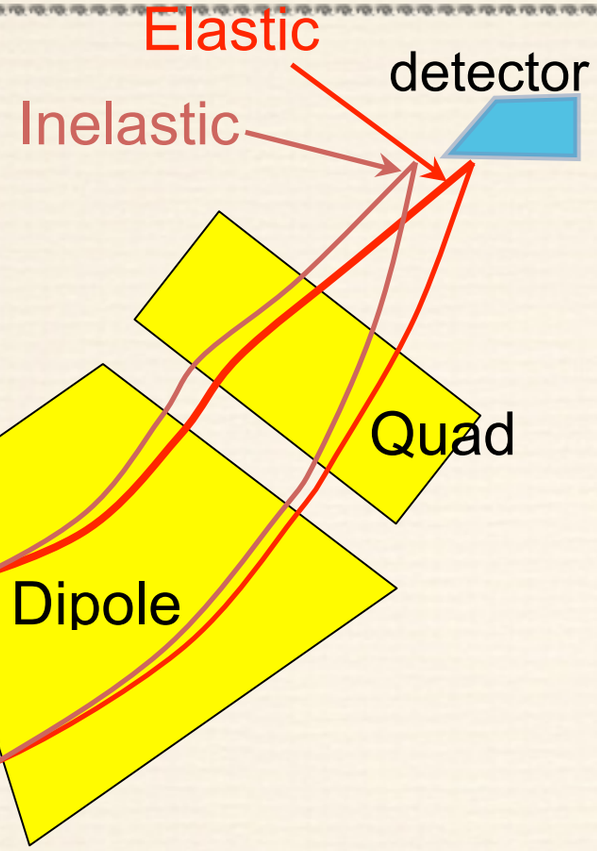


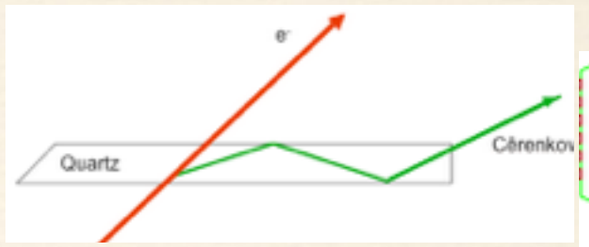
second major SLAC E122 innovation: "flux integration"

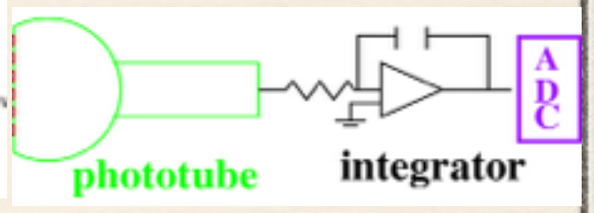
High Flux, Low Background

Hall A High Resolution Spectrometers









1 GHz scattered flux

2 x 10^{-4} statistical error
30 times per second

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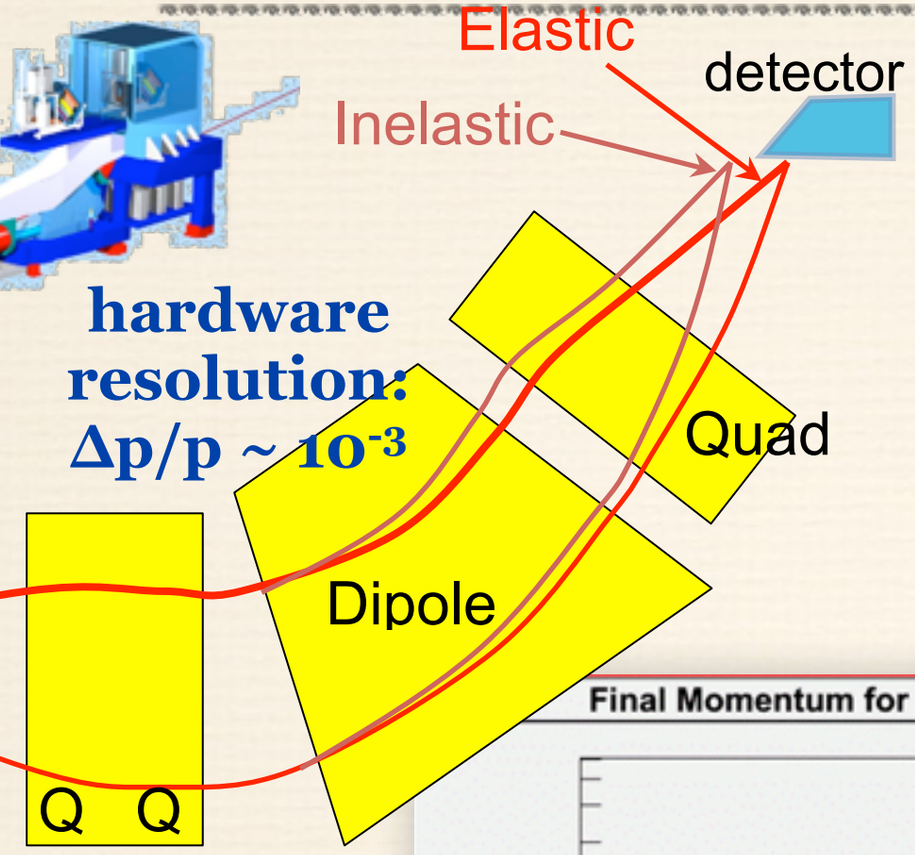
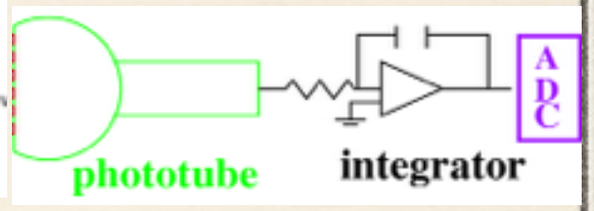


hardware resolution: $\Delta p/p \sim 10^{-3}$



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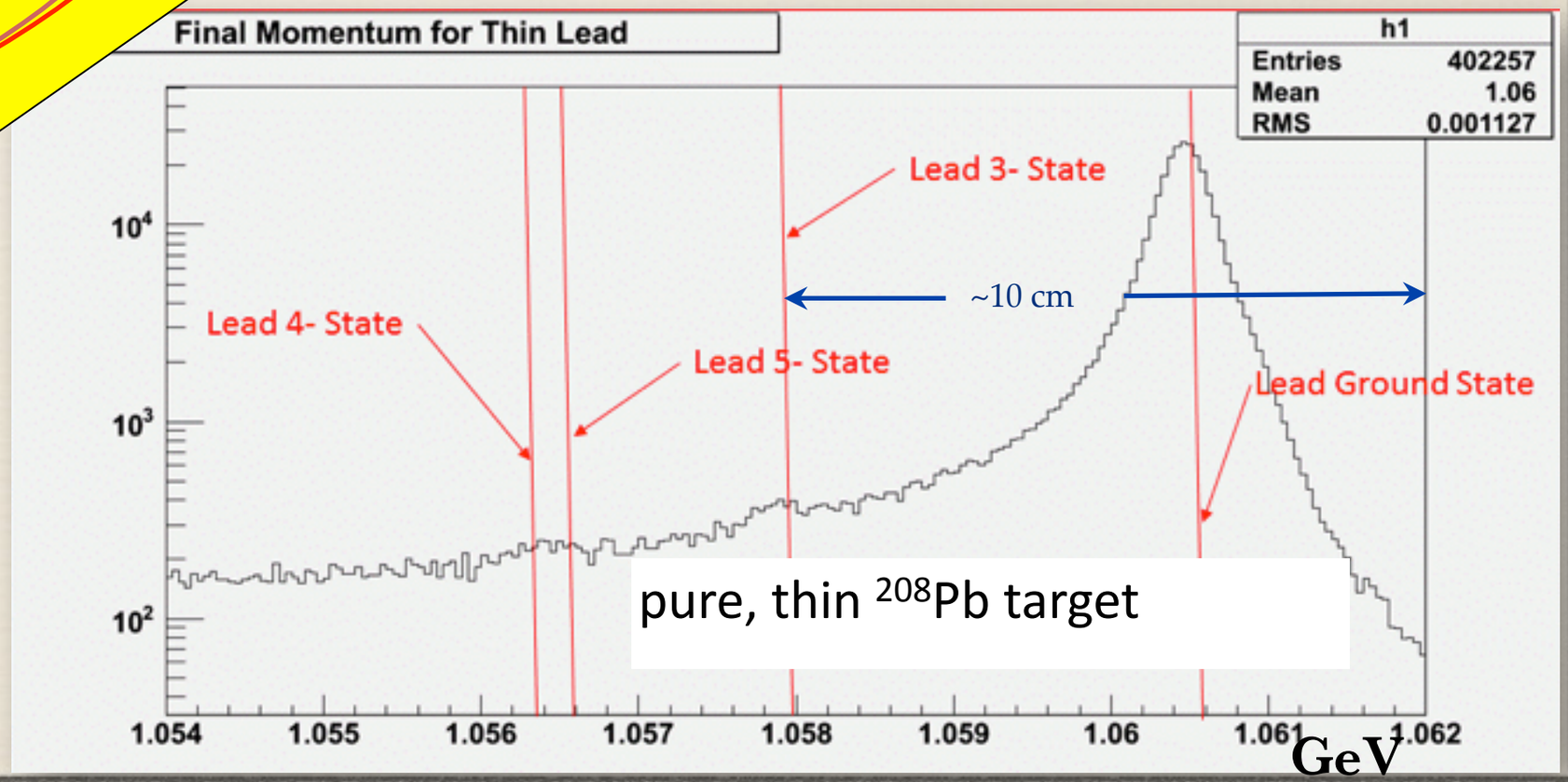
Inelastic backgrounds negligible



CW electron beam: scattered signal rate ~ 1 GHz

Flux Integration

10 ppb (average 10^7 s)

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

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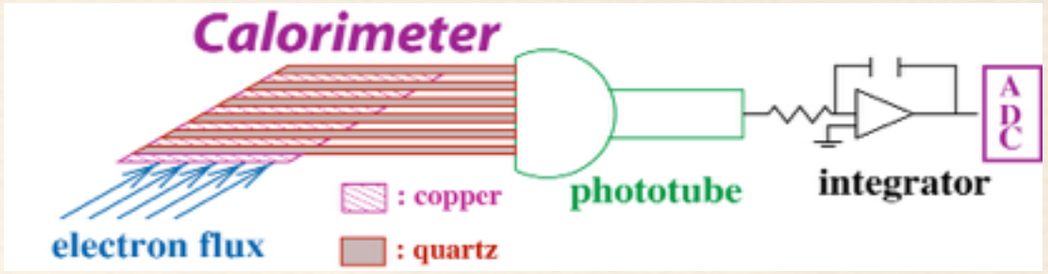

Detector D, Current I: F = D/I

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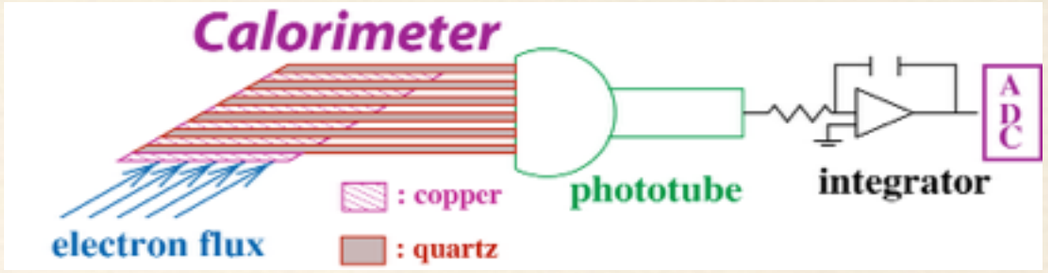

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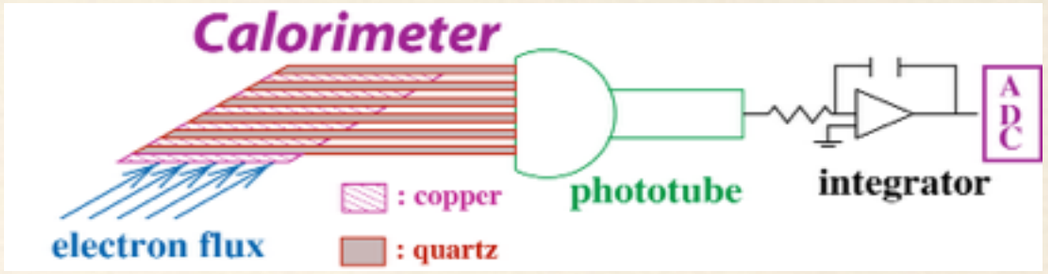
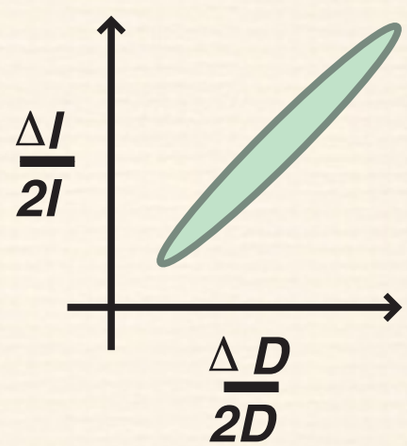
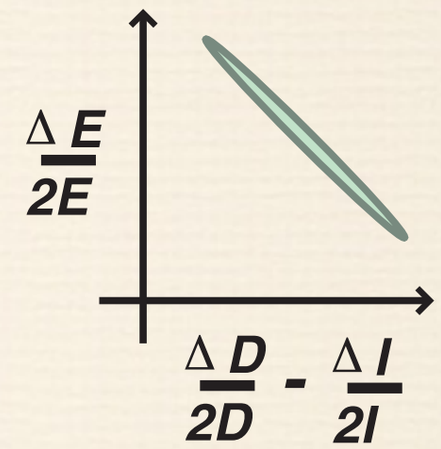


Detector D, Current I: F = D/I

I order: $x, y, \theta_x, \theta_y, E$

II order: e.g. spot-size





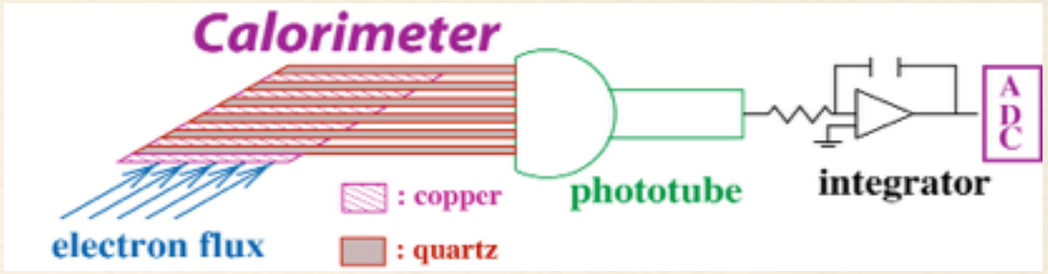
CW electron beam: scattered signal rate ~ 1 GHz

Flux Integration

10 Hz Stat. Width: 100 ppm → N = 100 M: 10 ppb (average 10^7 s)

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

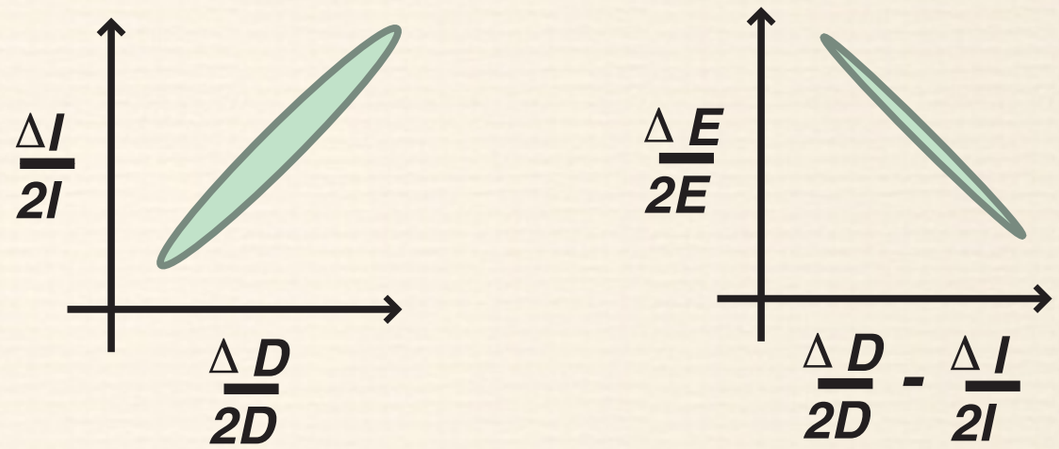
$$A_{pair} = \frac{\Delta F}{2F} + \Delta A$$



Detector D, Current I: F = D/I

I order: $x, y, \theta_x, \theta_y, E$

II order: e.g. spot-size



After corrections, variance of A_{pair} must get as close to counting statistics as possible: ~ 100 ppm at 10 Hz; central value then reflects A_{phys}

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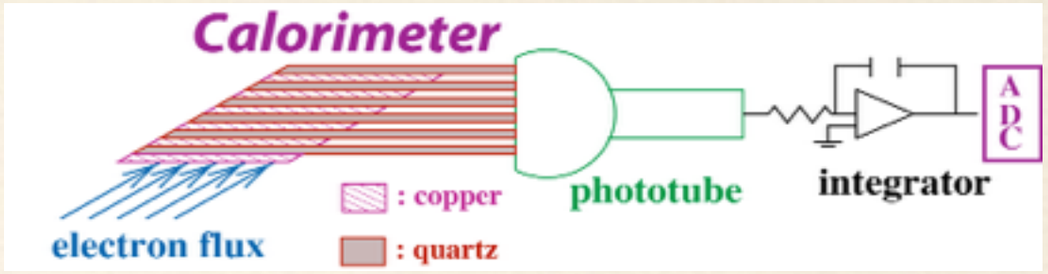

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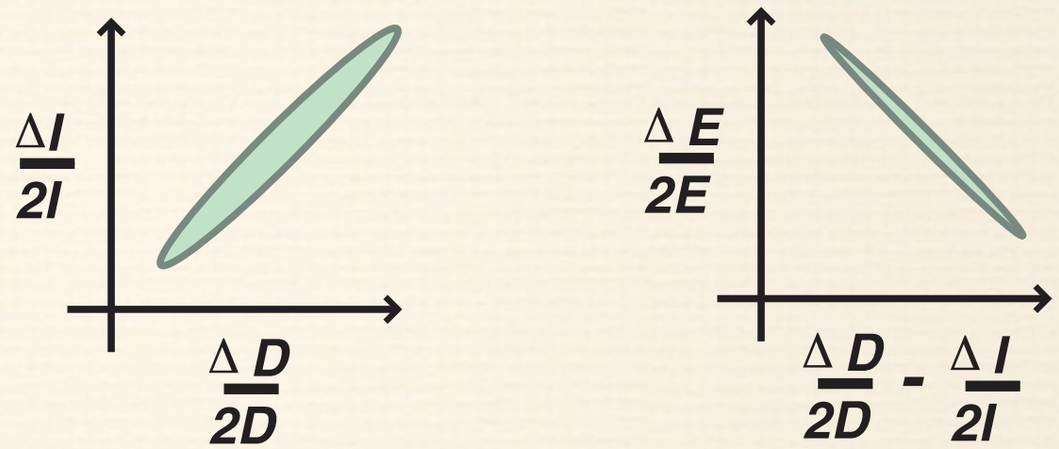

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Must minimize (both) random and helicity-correlated fluctuations in average window-pair response of electron beam trajectory, energy and spot-size.

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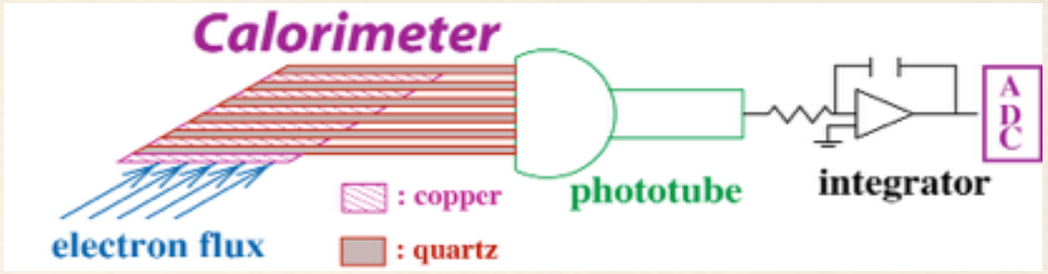

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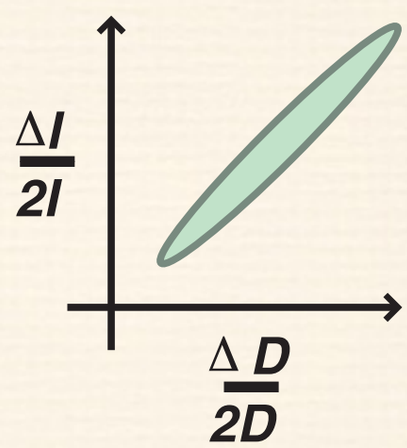
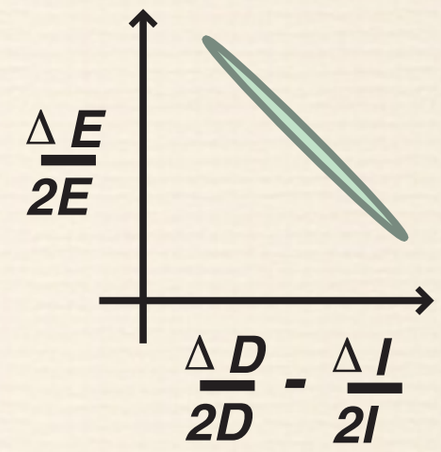
II order: e.g. spot-size





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The characteristics of the JLab beam, both at the 60 Hz time scale (~ppm, microns), to grand averages over several days (~ppb, nm), are critical to extracting a measurement which is dominated by statistical fluctuations.

$A_{raw} \sim 500$ ppb $\quad A_{corr} = A_{det} - A_Q + \alpha \Delta_E + \Sigma \beta_i \Delta x_i$

Beam Stability Performance

PREX-I ran from March to May 2012

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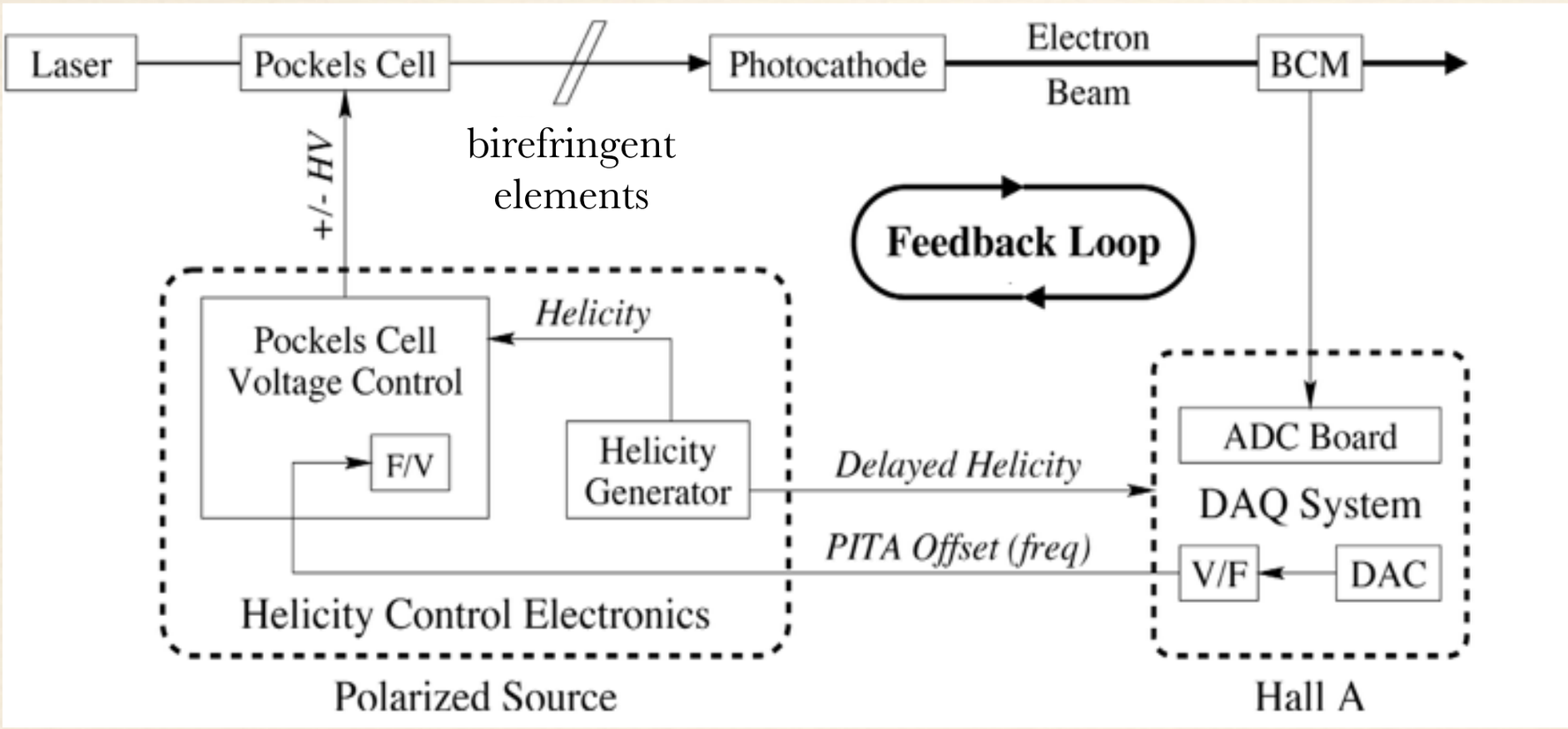
Beam Stability Performance

PREX-I ran from March to May 2012

- *Active feedback of charge asymmetry*
- *Careful laser alignment*
- *Precision beam position monitoring*
- *Active calibration of detector slopes*



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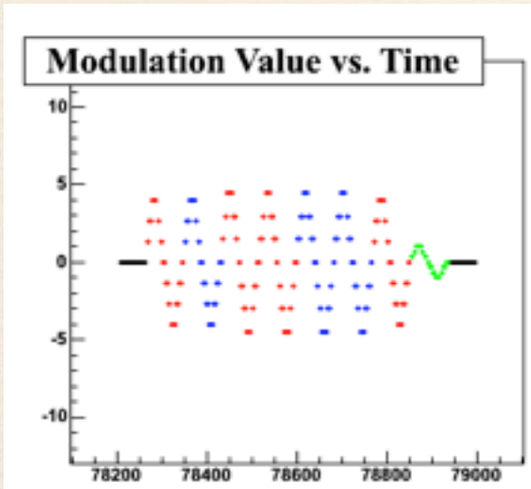

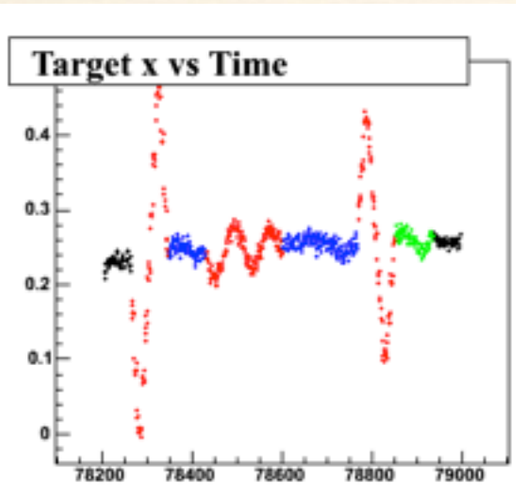

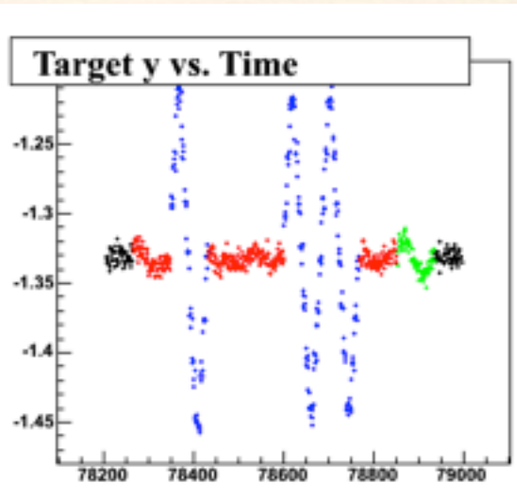

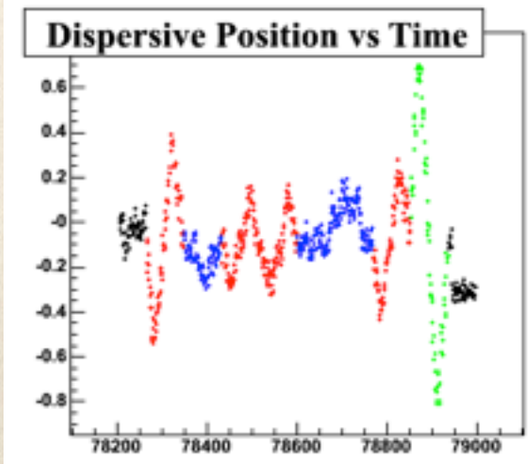

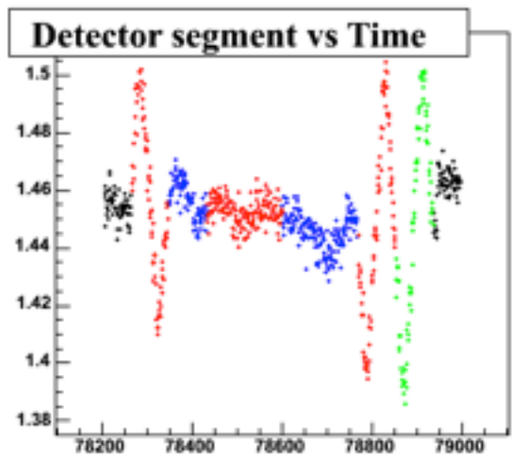

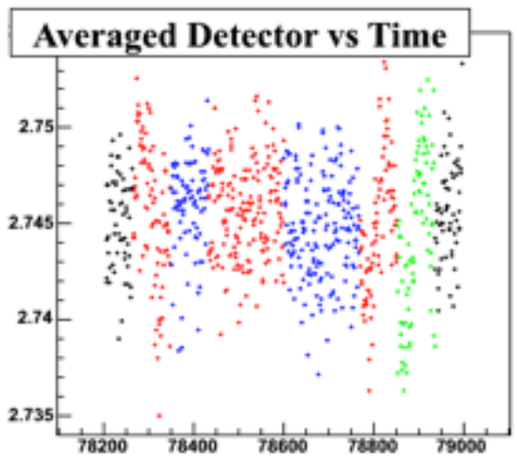

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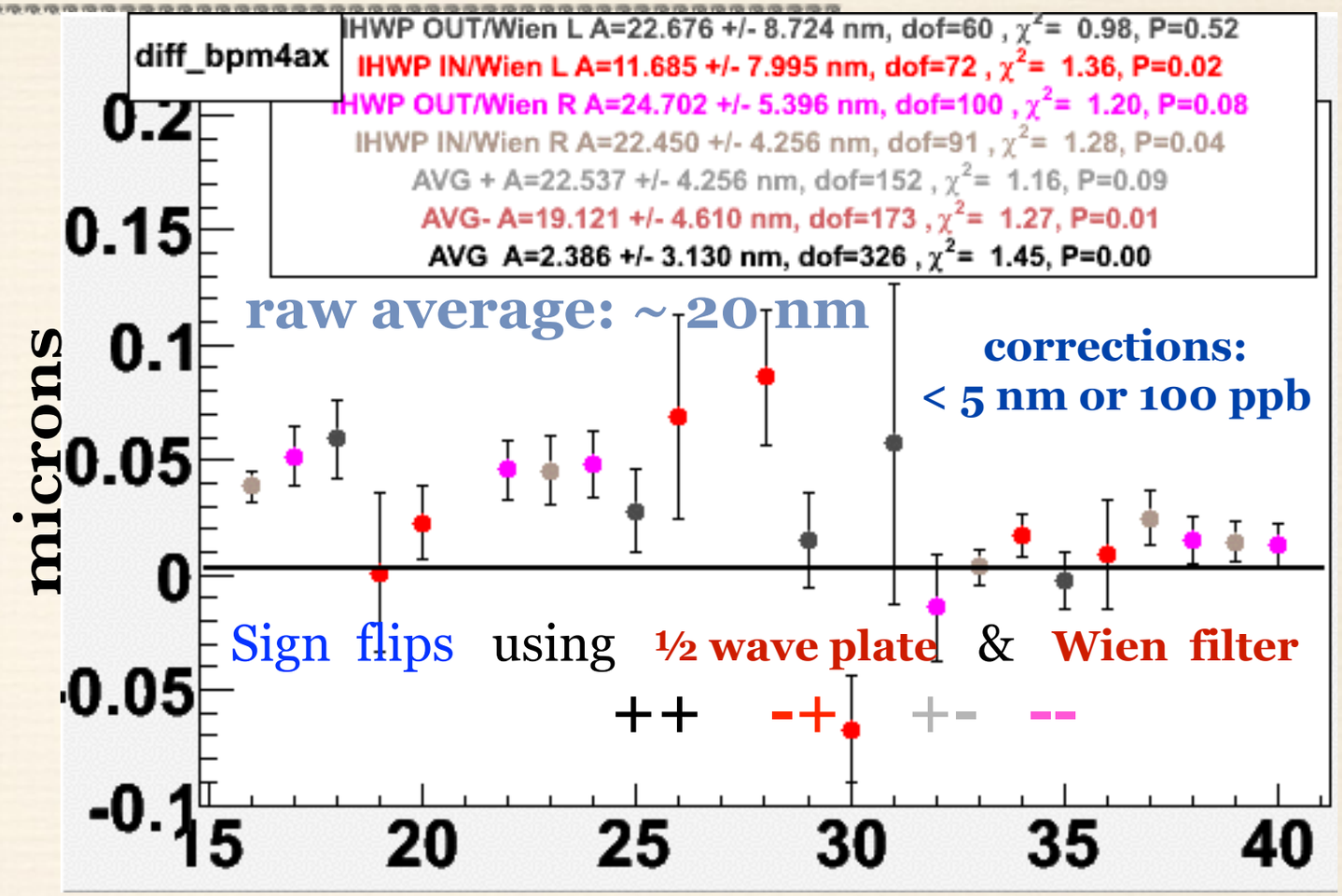

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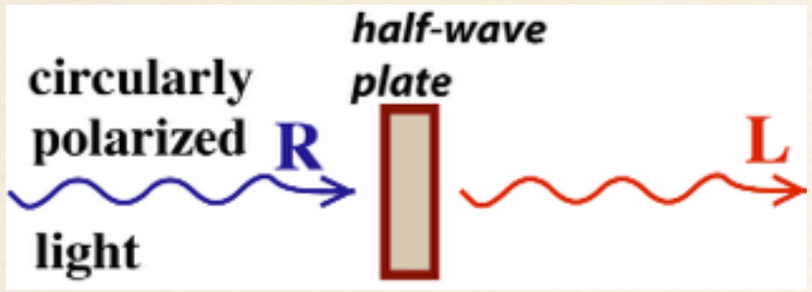
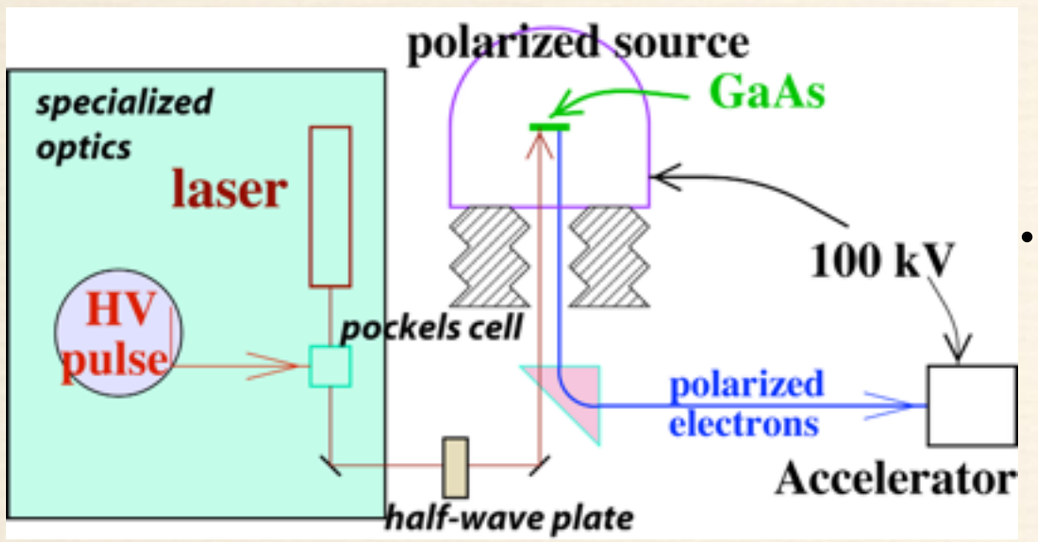
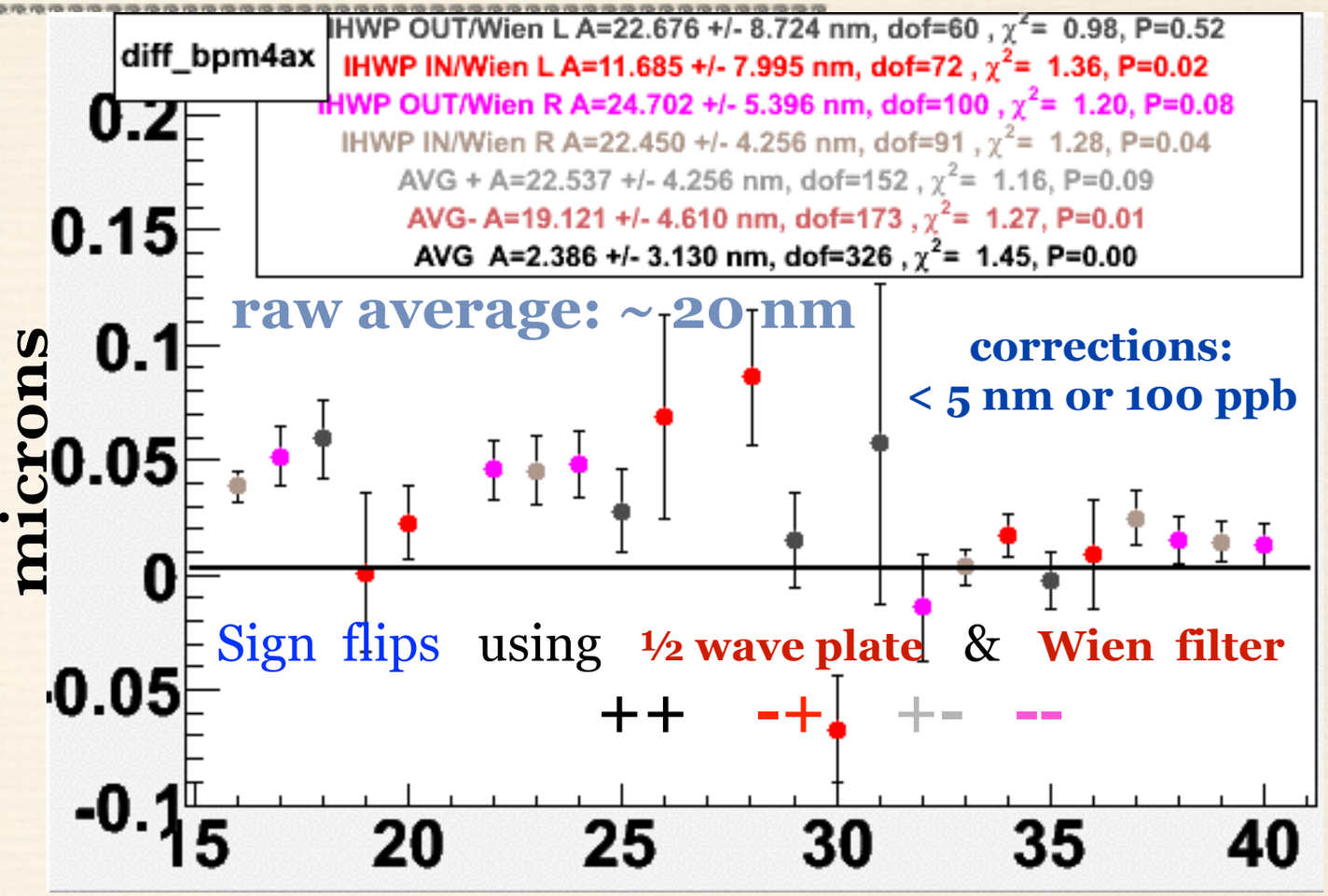
Beam Stability Performance

2 methods of "slow" reversal







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Beam Stability Performance

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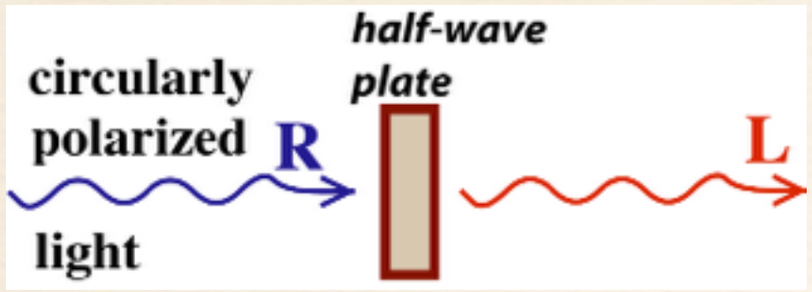
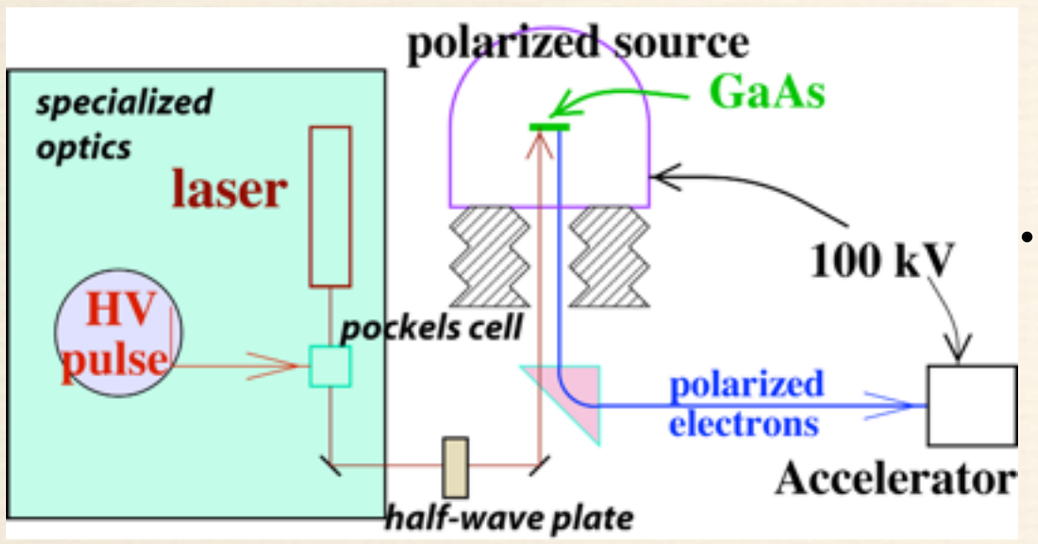
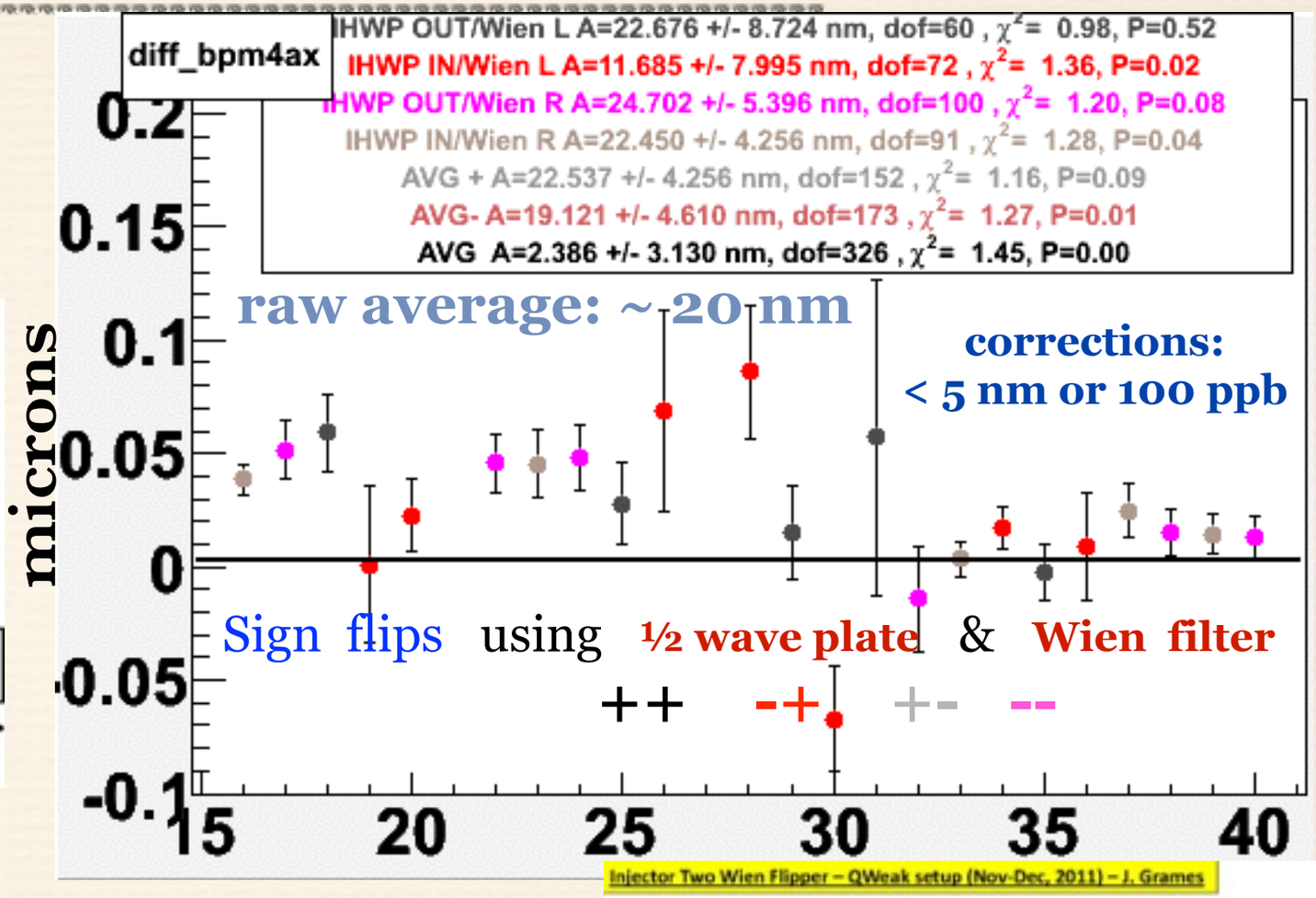
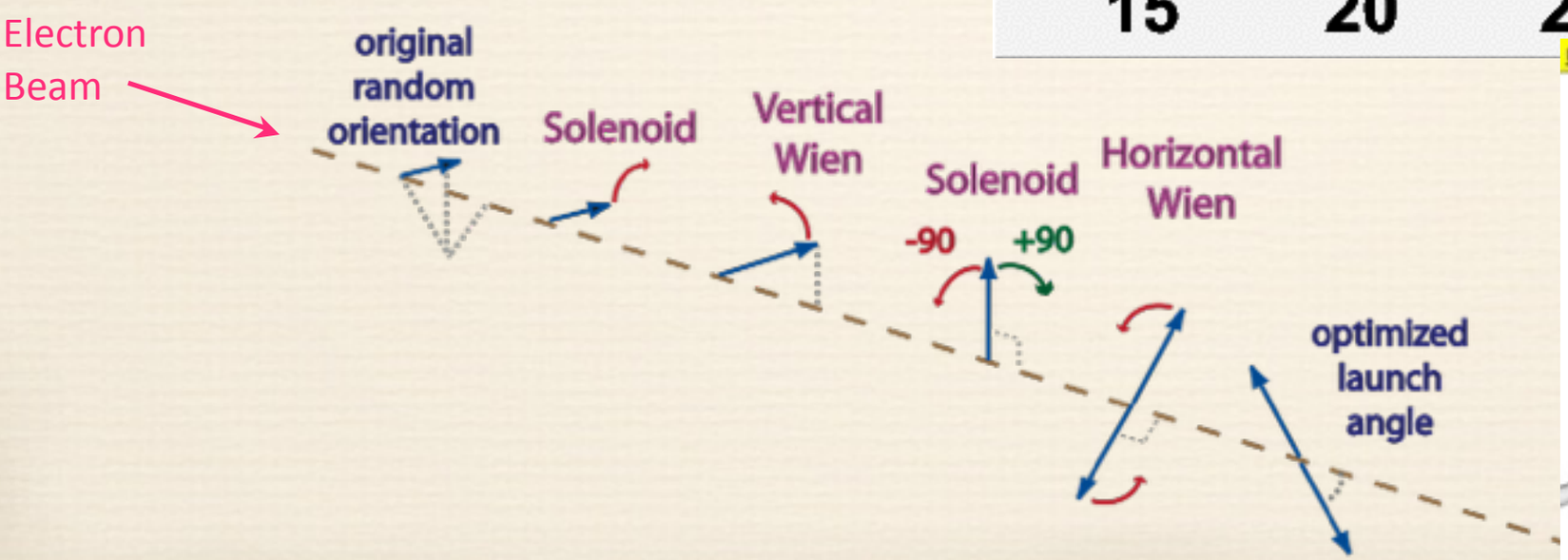
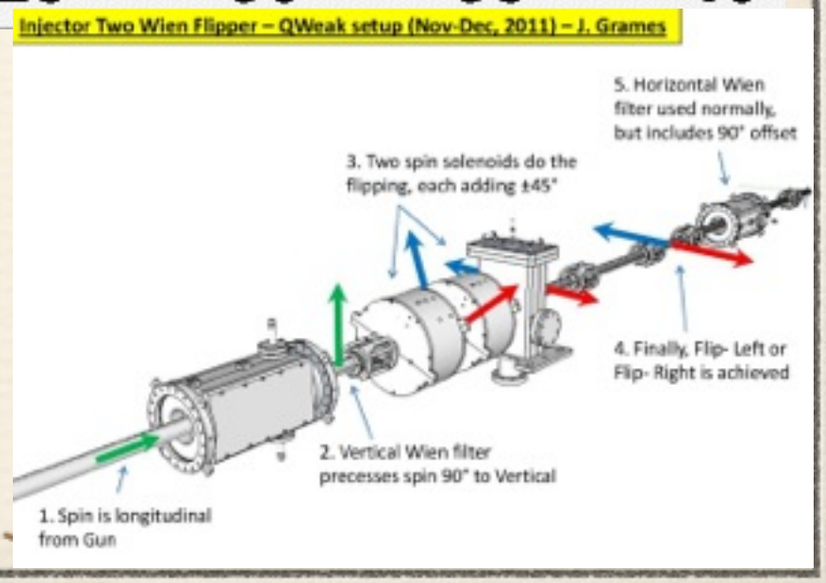


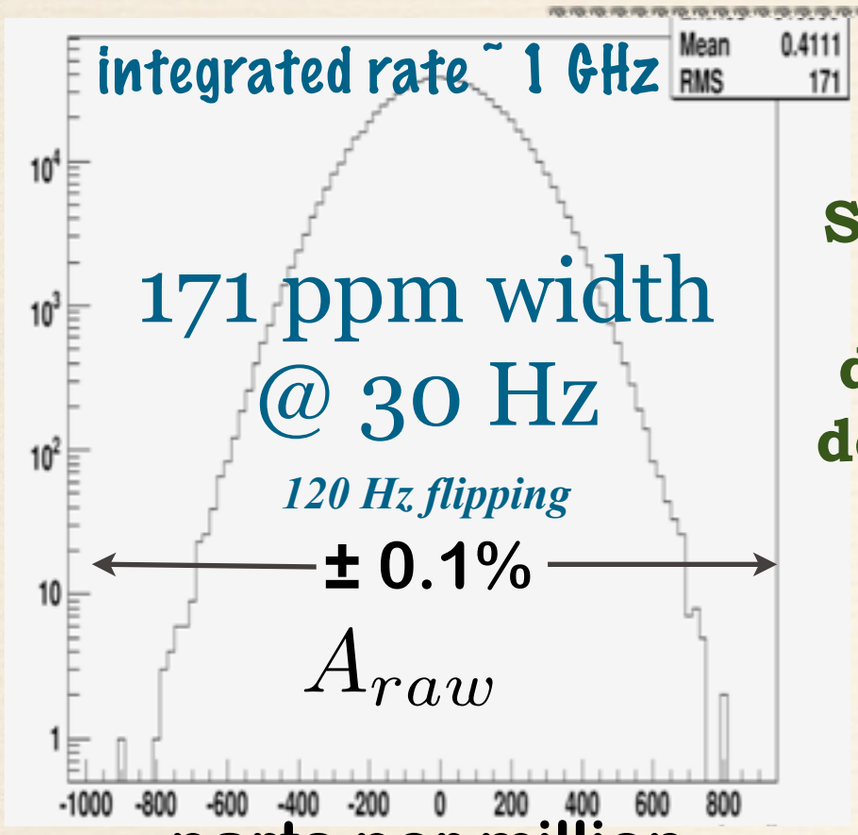




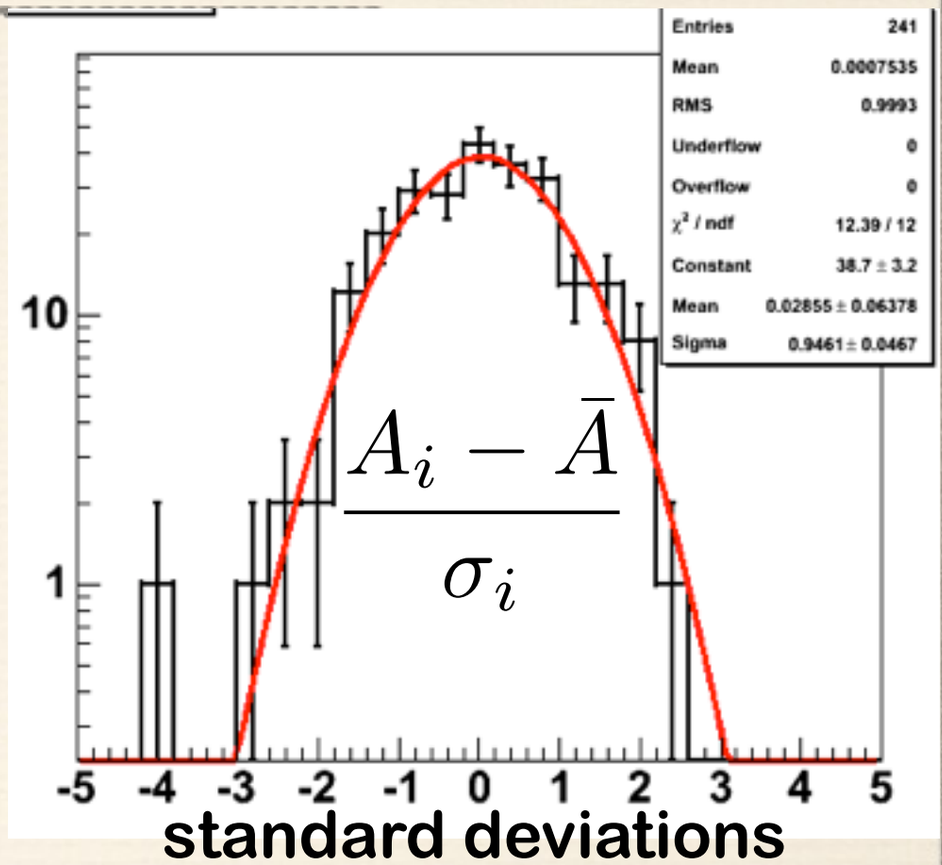




Raw Asymmetry Data



Statistical behavior of data consistent: detector fluctuations dominated by electron counting statistics



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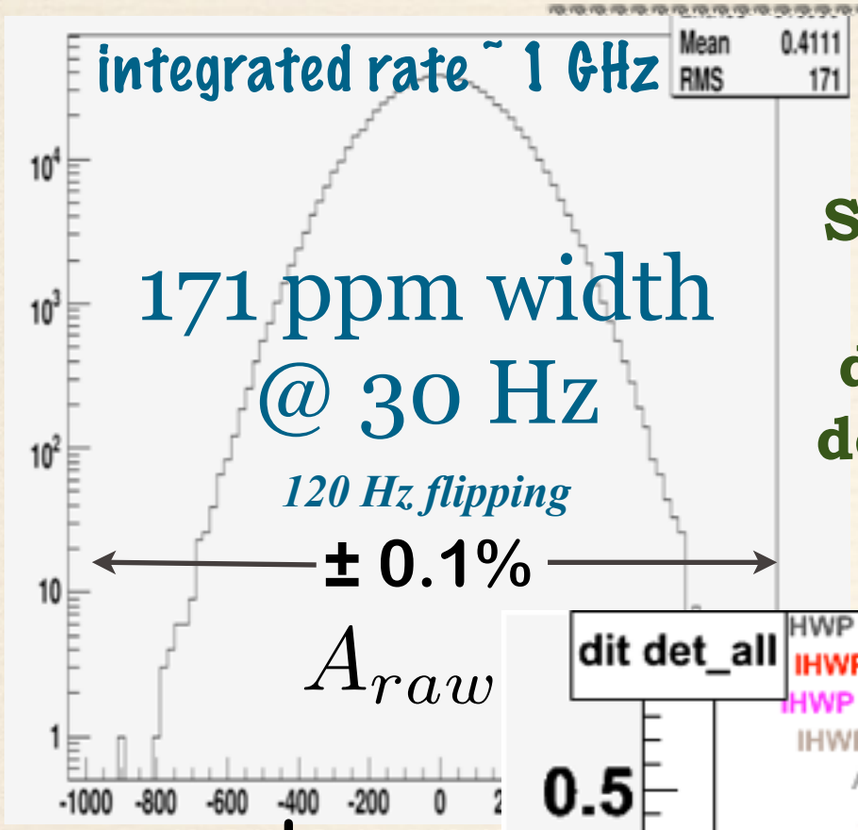

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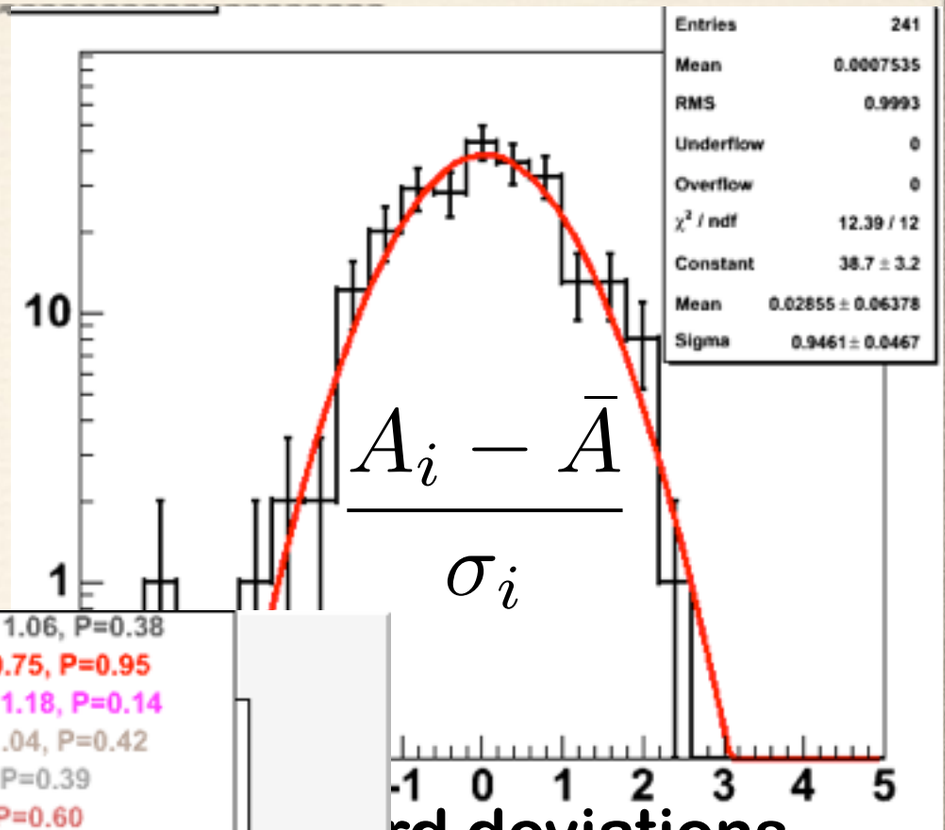
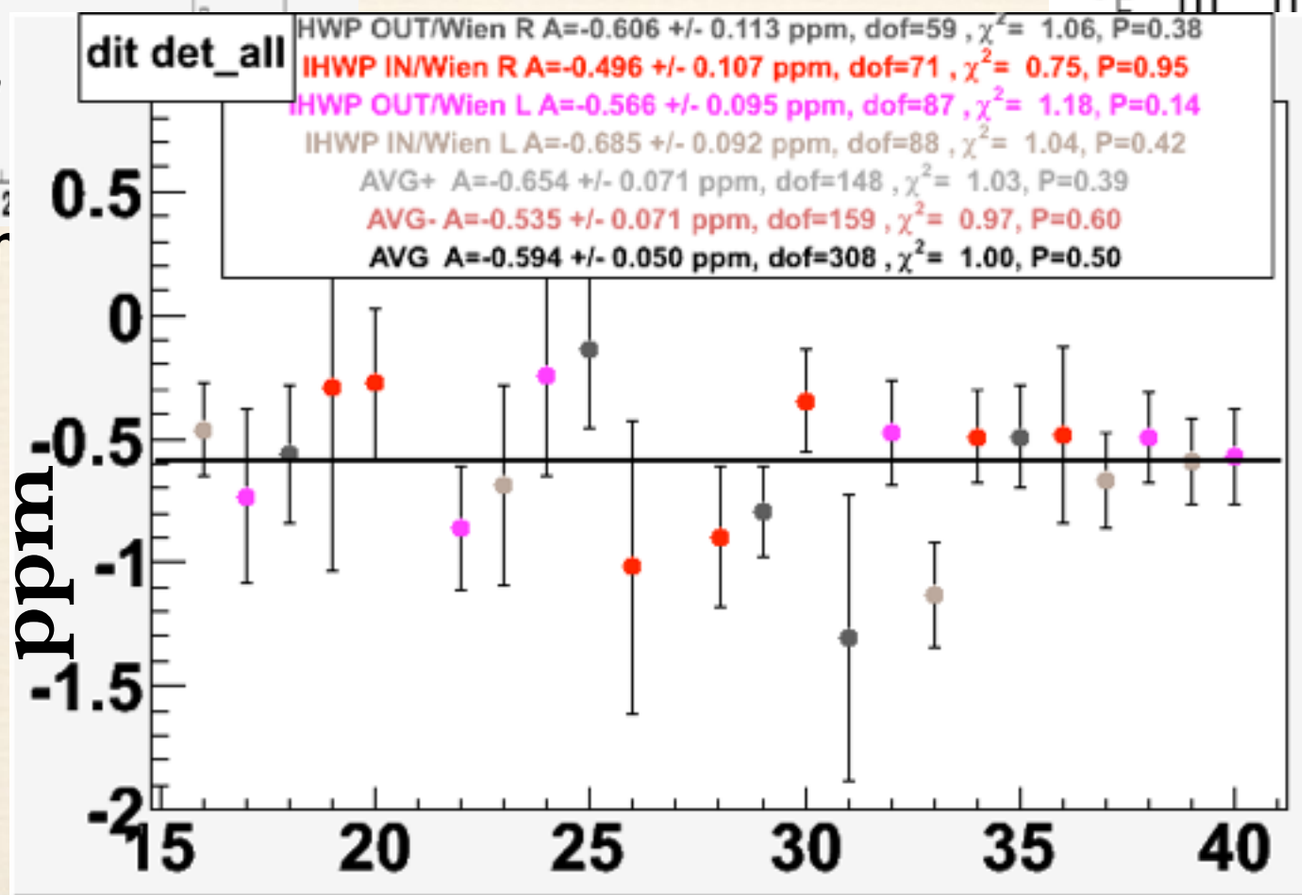
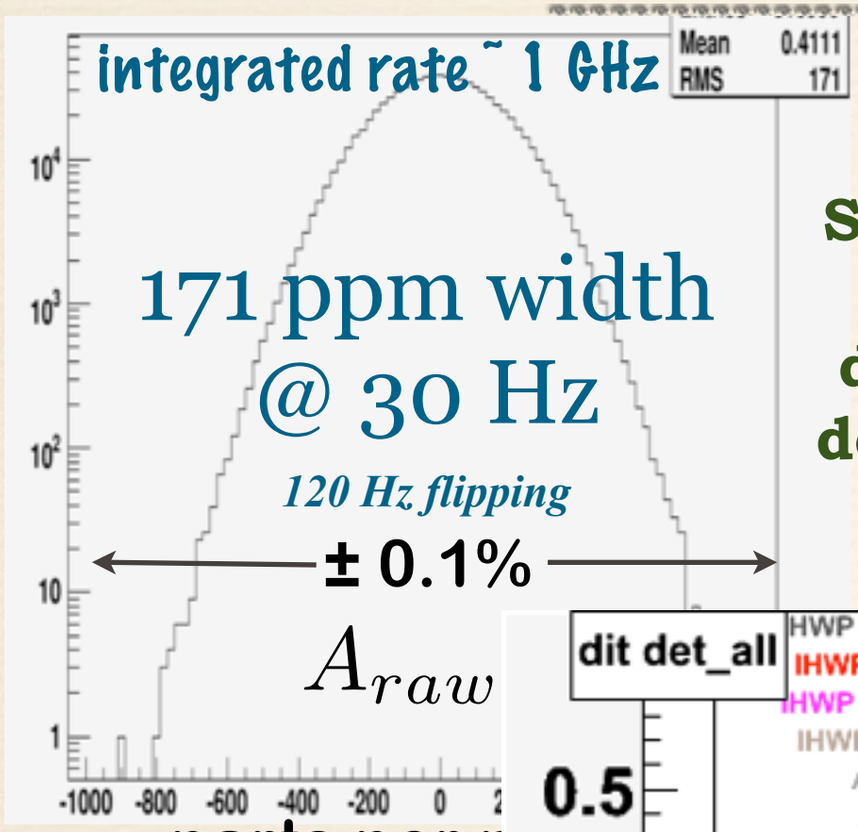




Raw Asymmetry Data

raw statistical error: 50 ppb (8.4%)



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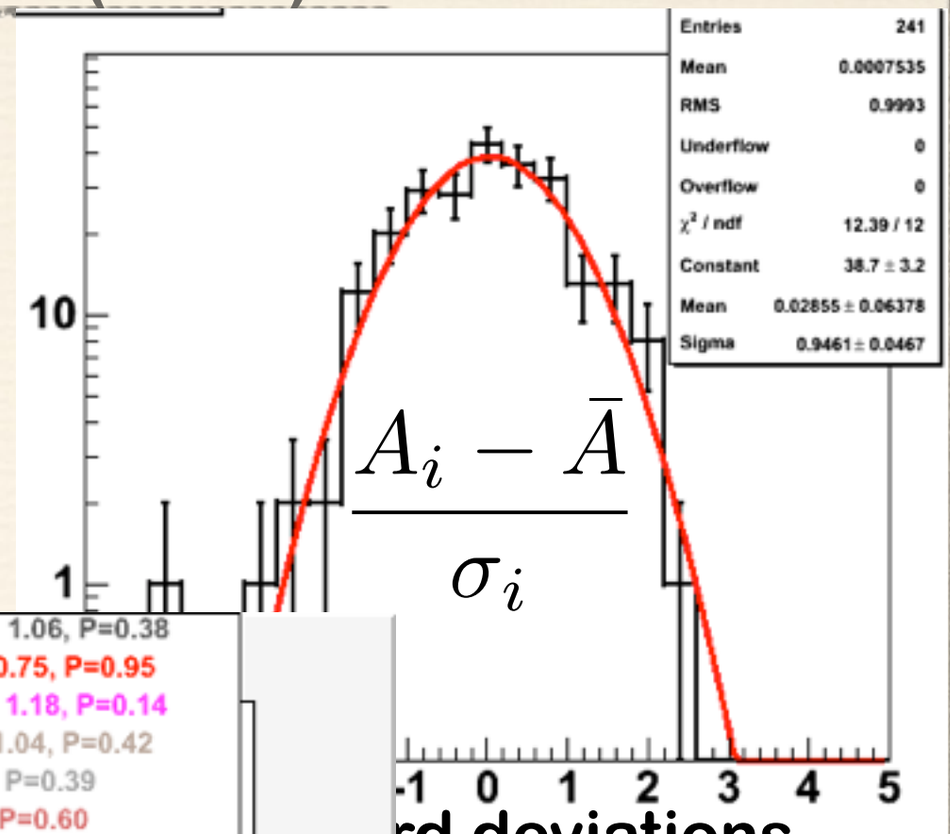

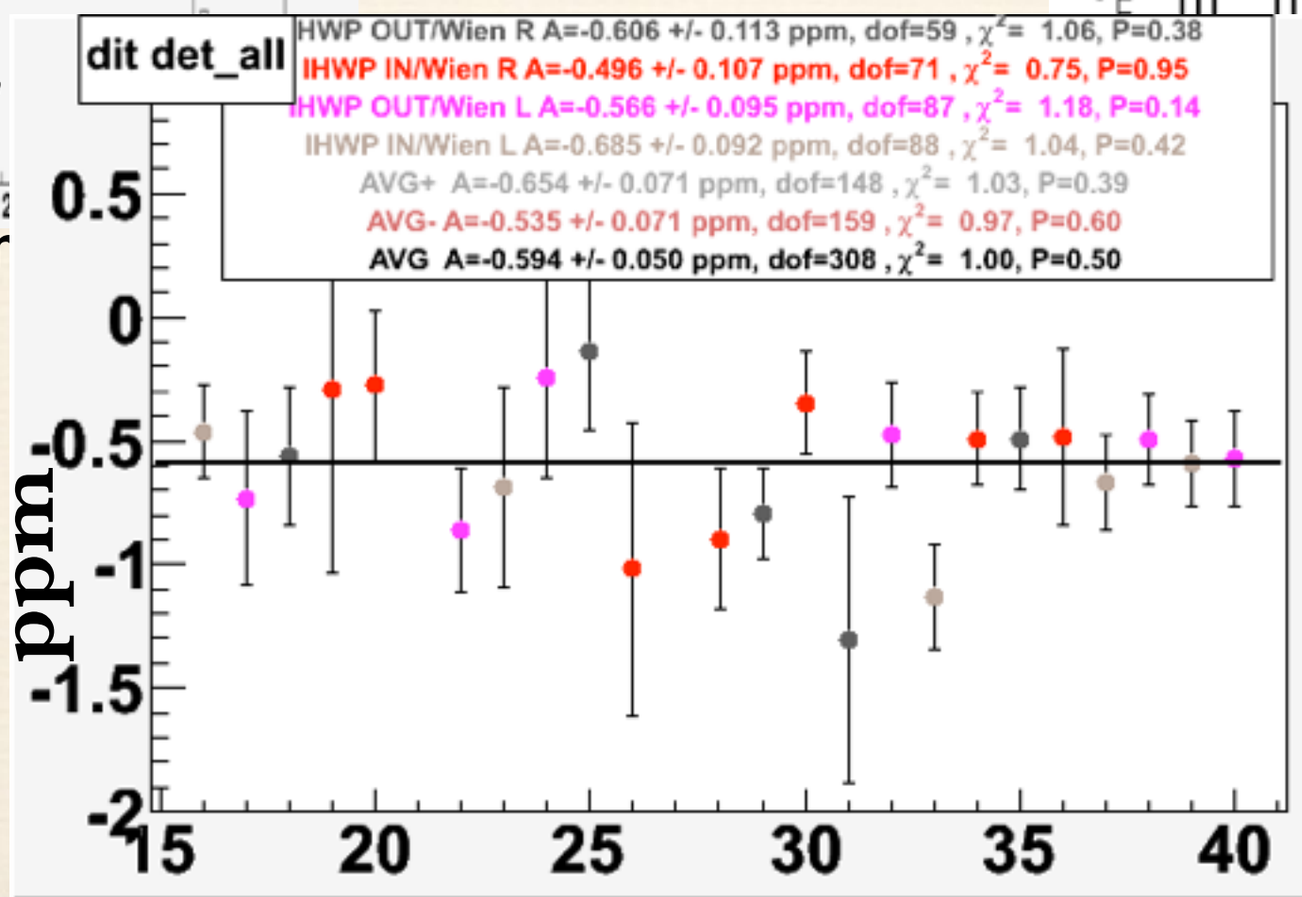

Grand averages of all 4 combinations of slow reversal flips are statistically consistent

606 ± 113
496 ± 107
566 ± 095
685 ± 092

594 ± 50

parts per billion (ppb)

systematic error due to electron beam asymmetries: 7 ppb

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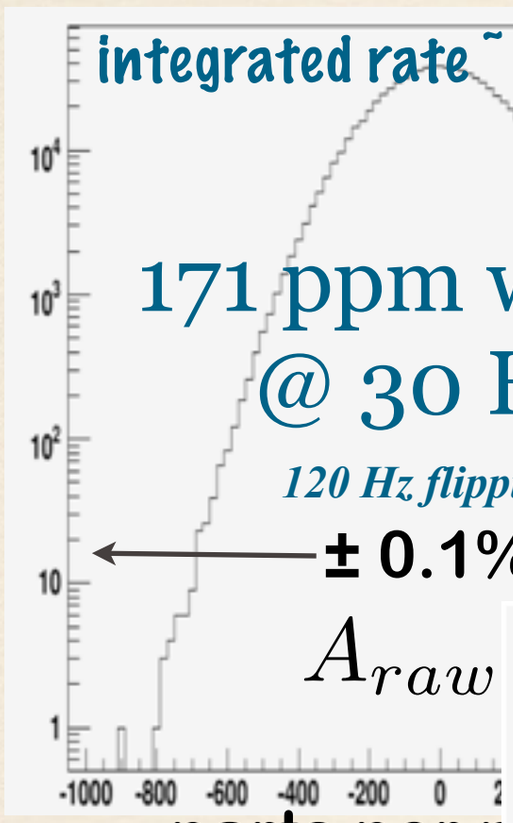

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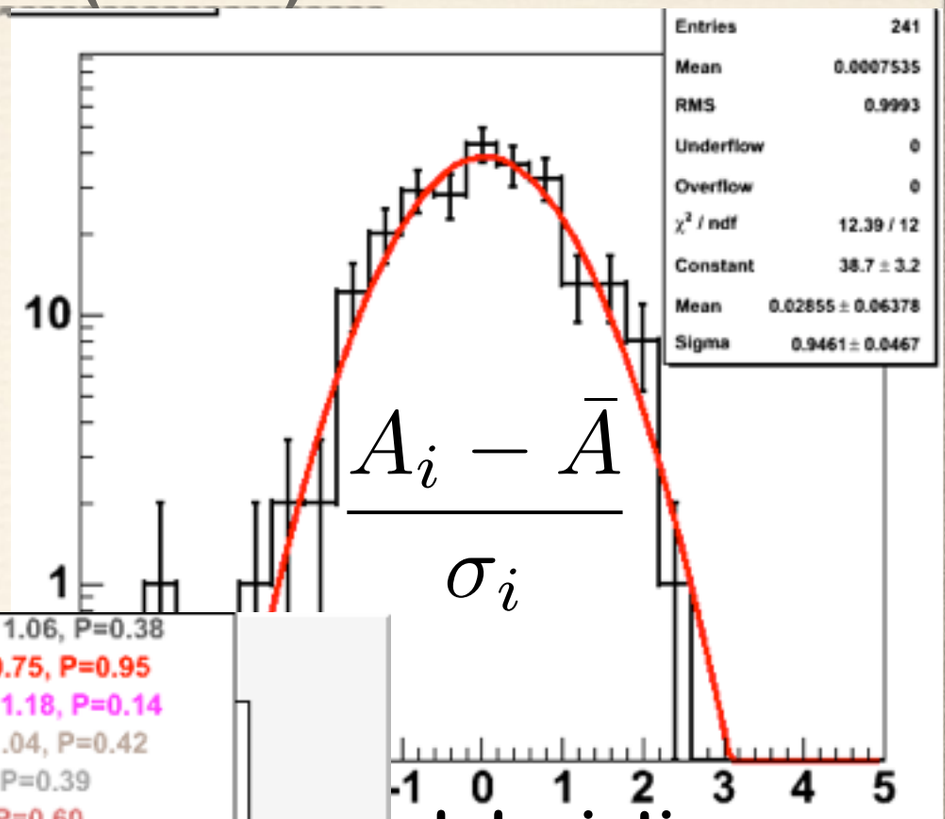

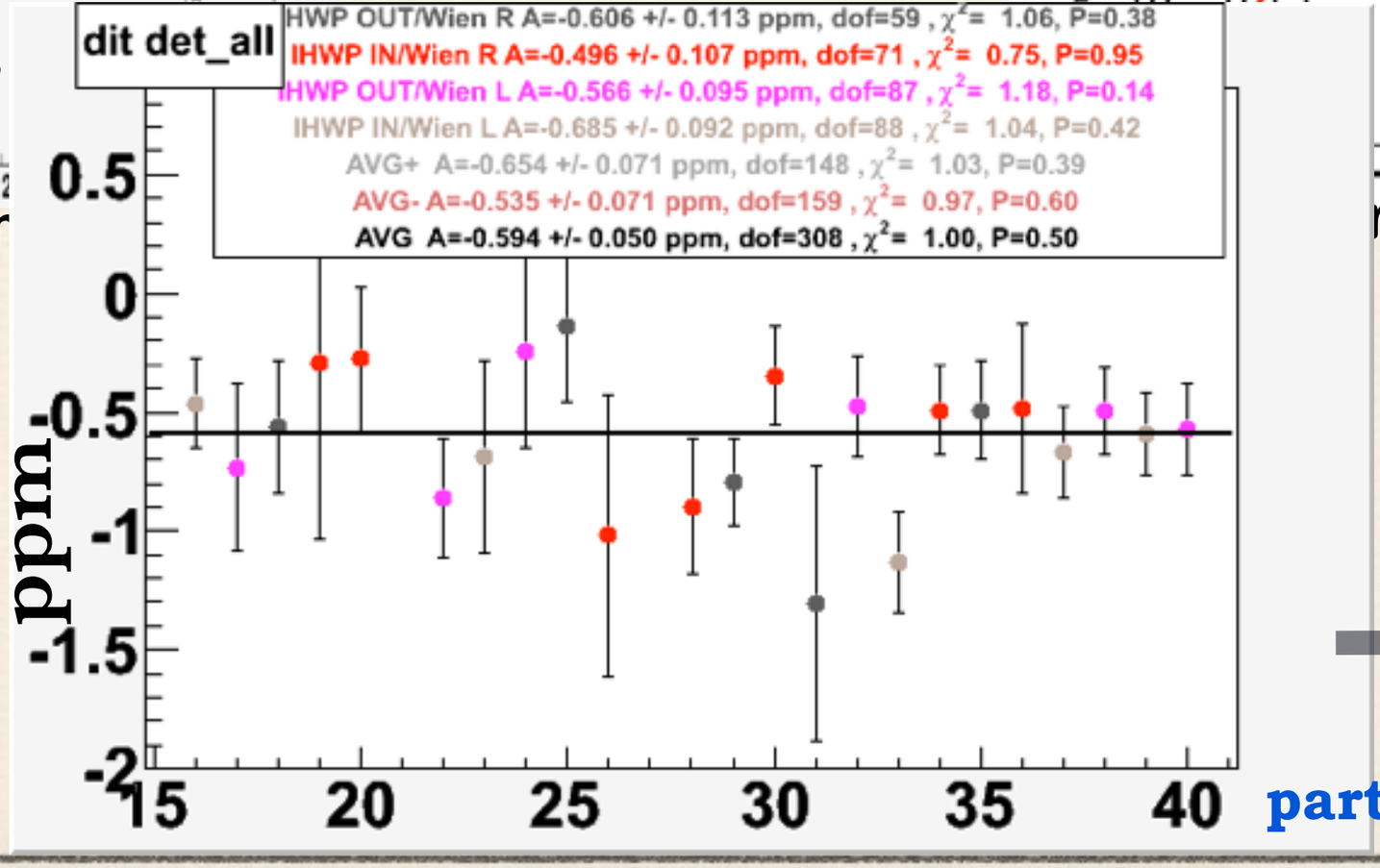

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Phys.Rev.Lett. 108 (2012) 112502

Normalization Errors

Systematic Error	Absolute (ppm)	Relative (%)
Polarization	**0.0083**	**1.3**
Detector Linearity	**0.0076**	**1.2**
Beam current normalization	**0.0015**	**0.2**
Rescattering	**0.0001**	**0**
Transverse Polarization	**0.0012**	**0.2**
Q^2	**0.0028**	**0.4**
Target Backing	**0.0026**	**0.4**
Inelastic States	**0**	**0**
TOTAL	**0.0140**	**2.1**

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Goal for total systematic error ~ 2% achieved!

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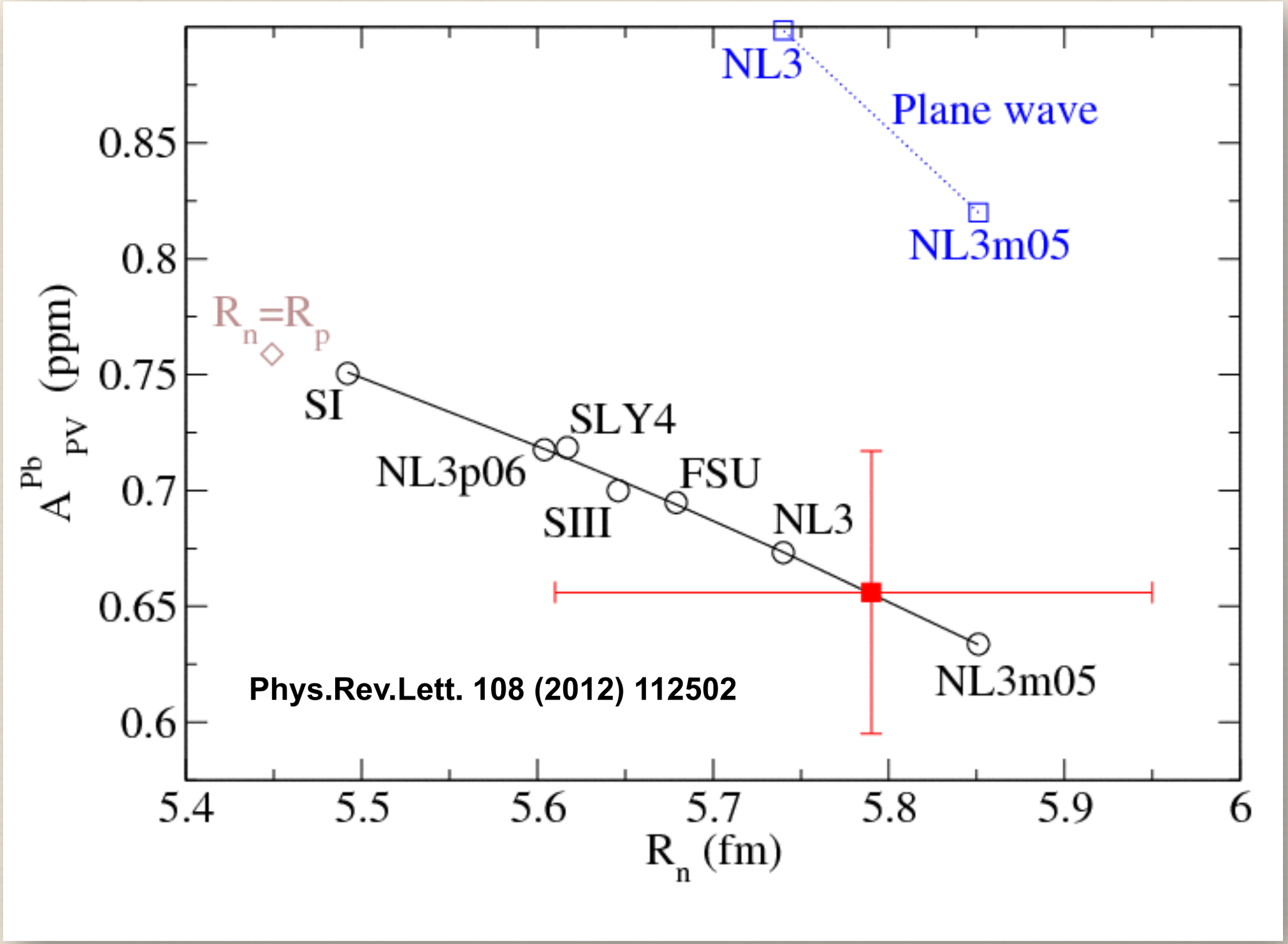
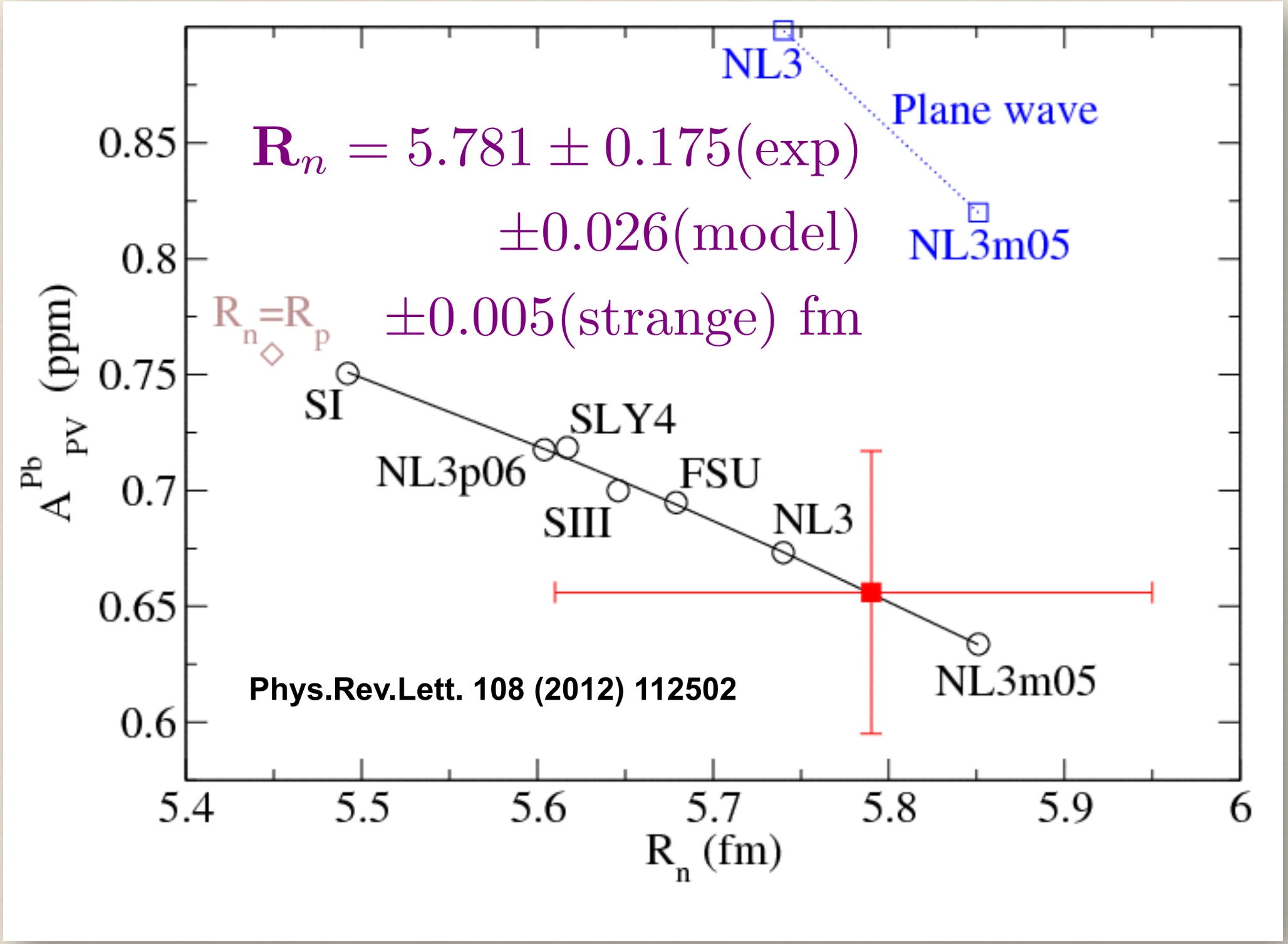
$$A_{PV} = 0.656\ ppm \pm 0.060(stat) \pm 0.014(syst)$$

PREX Result

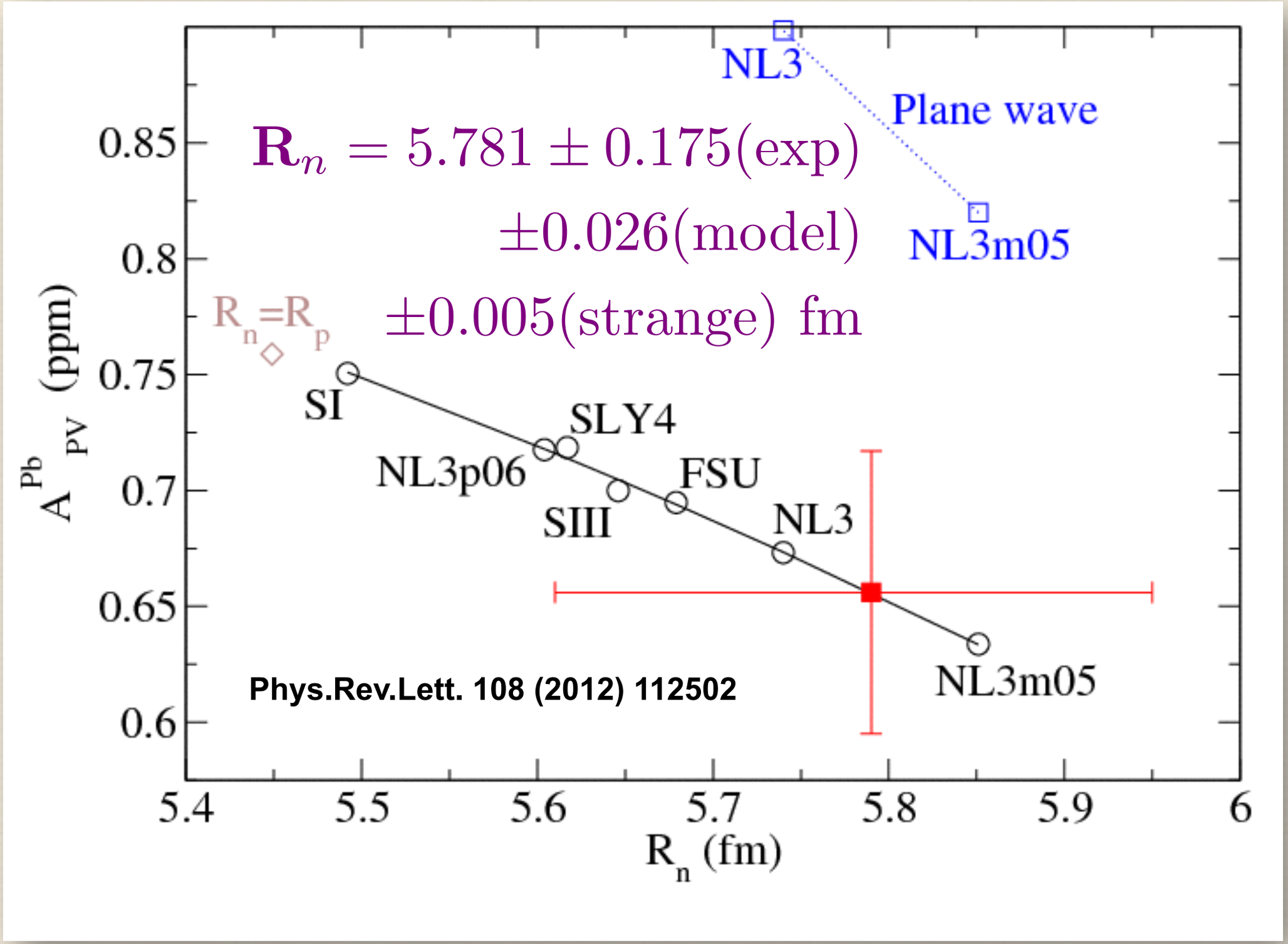

NL3
Plane wave
NL3m05
0.85
0.8
0.75
0.7
0.65
0.6
A_{PV}^{Pb} (ppm)
$R_n = R_p$
SI
SLY4
NL3p06
FSU
SIII
NL3
NL3m05
Phys.Rev.Lett. 108 (2012) 112502
5.4
5.5
5.6
5.7
5.8
5.9
6
R_n (fm)

PREX Result


NL3
Plane wave
NL3m05
$\mathbf{R}_n = 5.781 \pm 0.175(\text{exp})$
$\pm 0.026(\text{model})$
$\pm 0.005(\text{strange})$ fm
$R_n = R_p$
SI
SLY4
NL3p06
FSU
SIII
NL3
NL3m05
Phys.Rev.Lett. 108 (2012) 112502
A_{PV}^{Pb} (ppm)
R_n (fm)
0.85
0.8
0.75
0.7
0.65
0.6
5.4
5.5
5.6
5.7
5.8
5.9
6

$$\mathbf{R}_n - \mathbf{R}_p = 0.302 \pm 0.175(\text{exp}) \pm 0.026(\text{model}) \pm 0.005(\text{strange})\ \text{fm}$$

PREX Result



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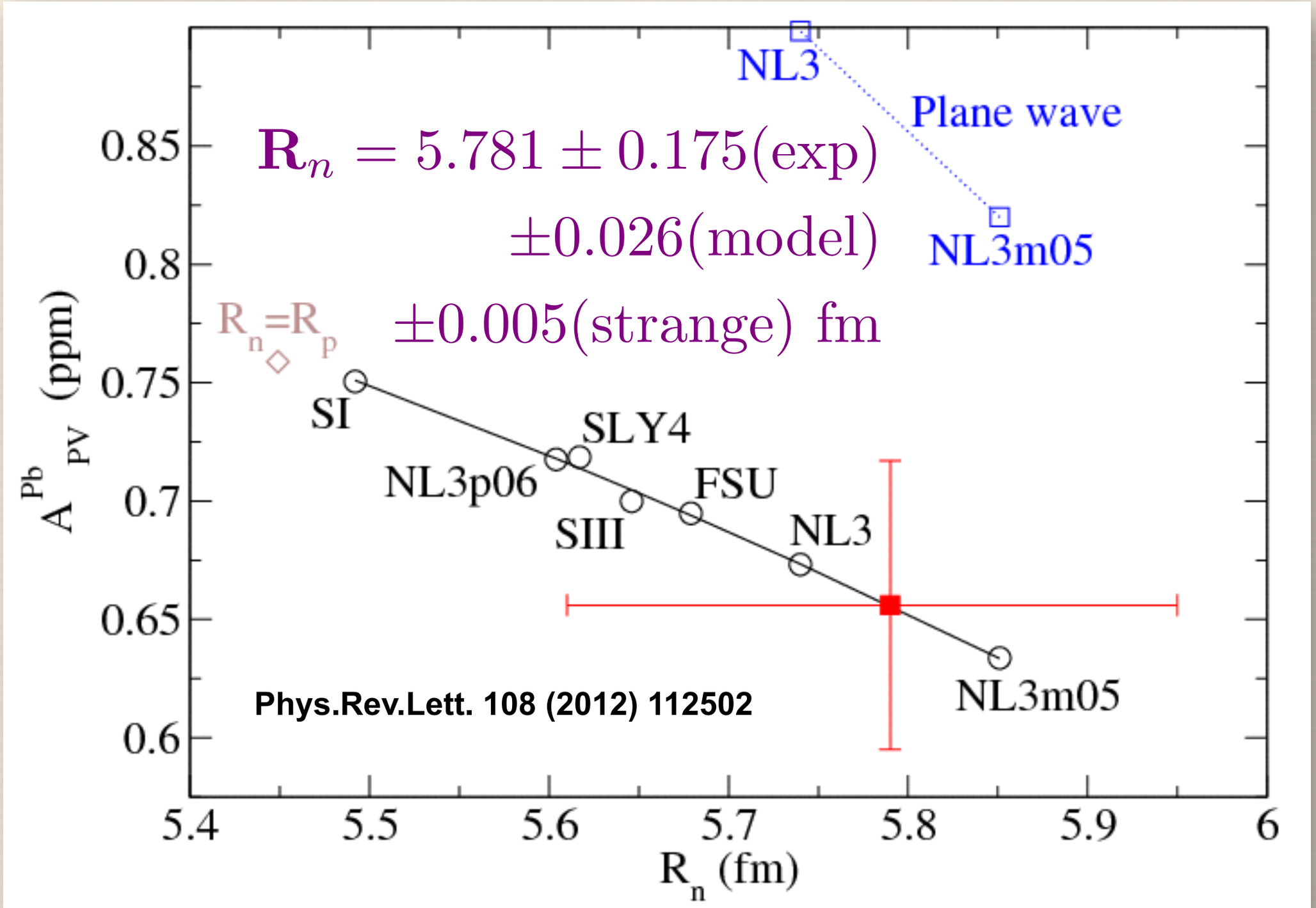
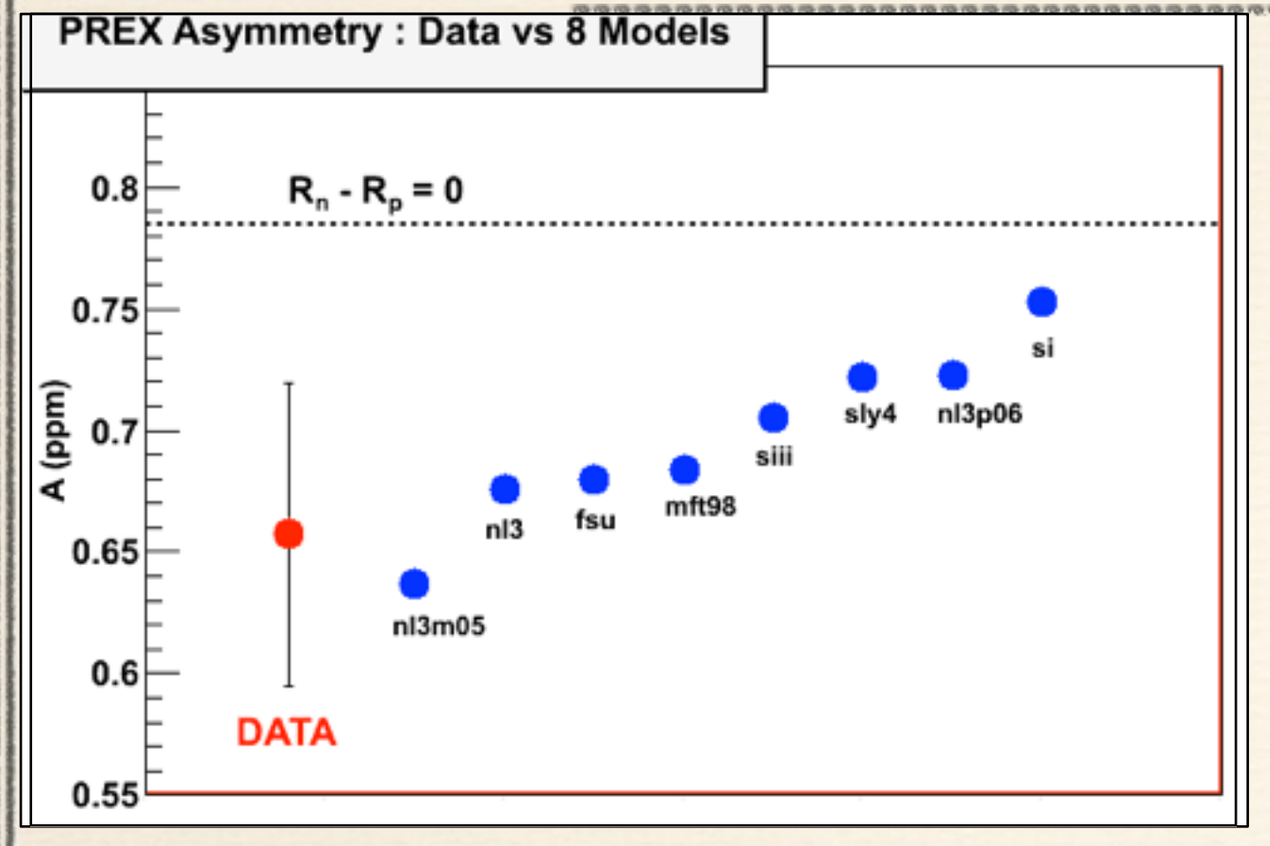
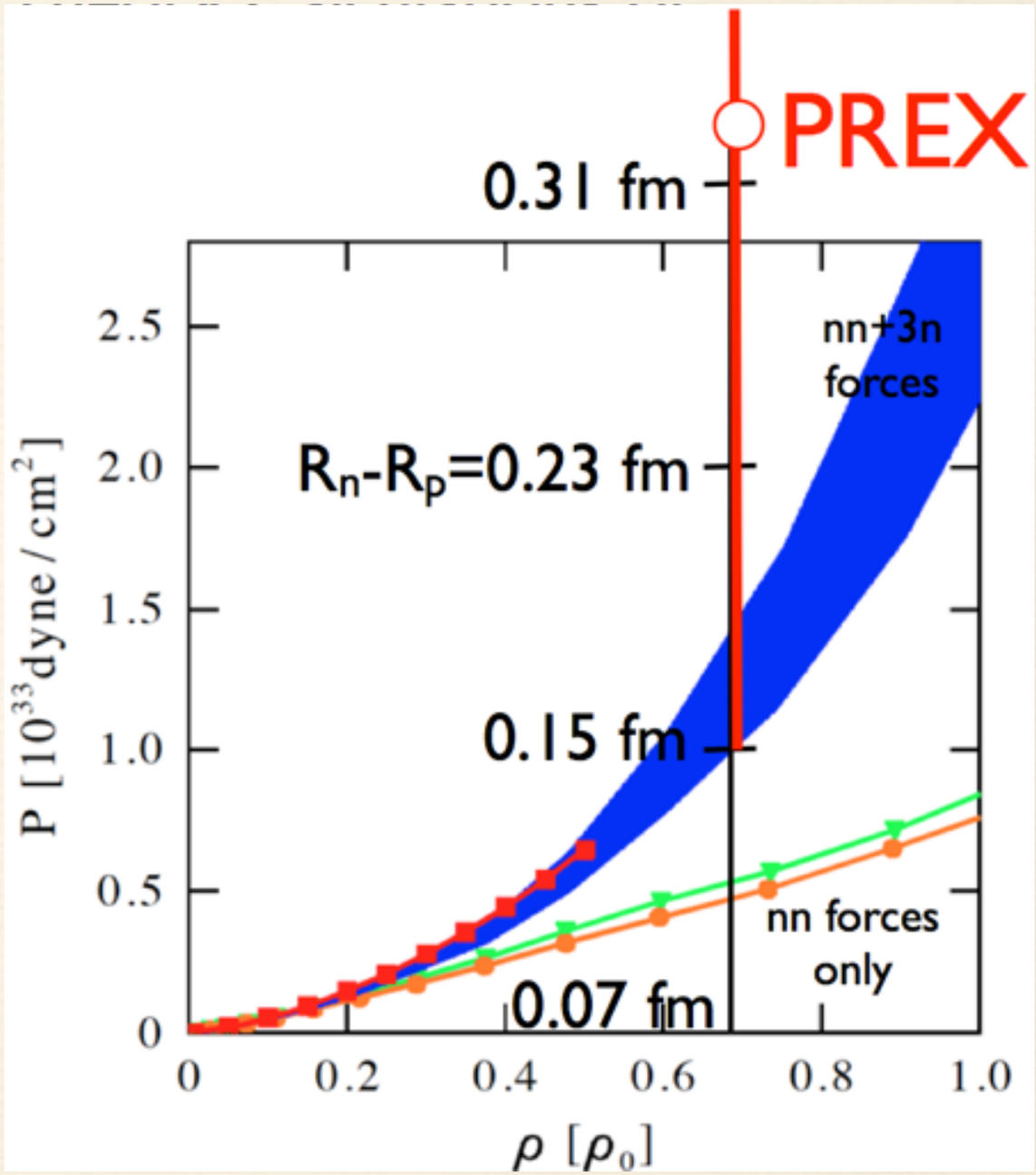
PREX Result



First electroweak indication of a neutron skin of a heavy nucleus (CL ~ 90-95%)

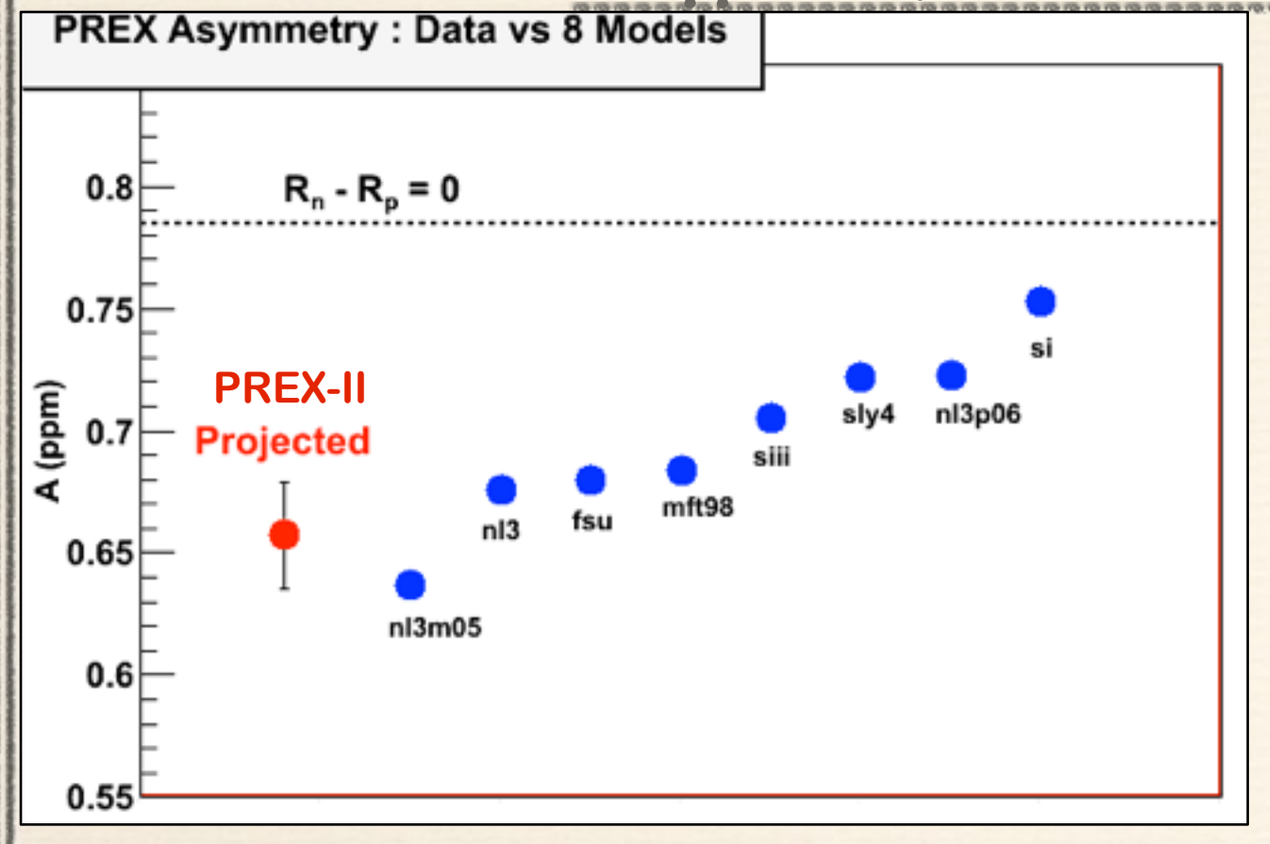
Future Prospects

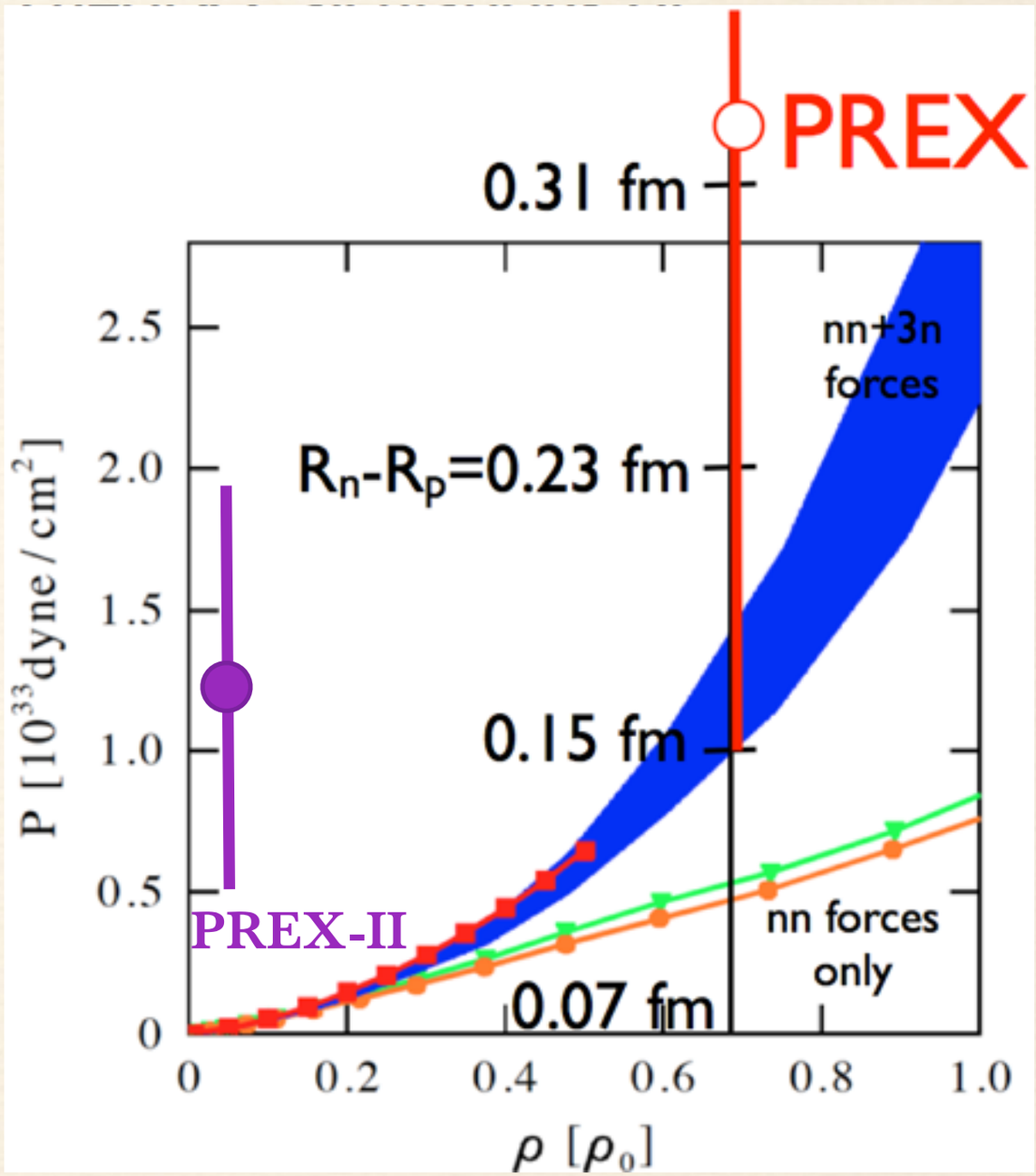




Future Prospects

PREX-II approved; to run Fall 2016 (goal: 3% stat. error)





Future Prospects

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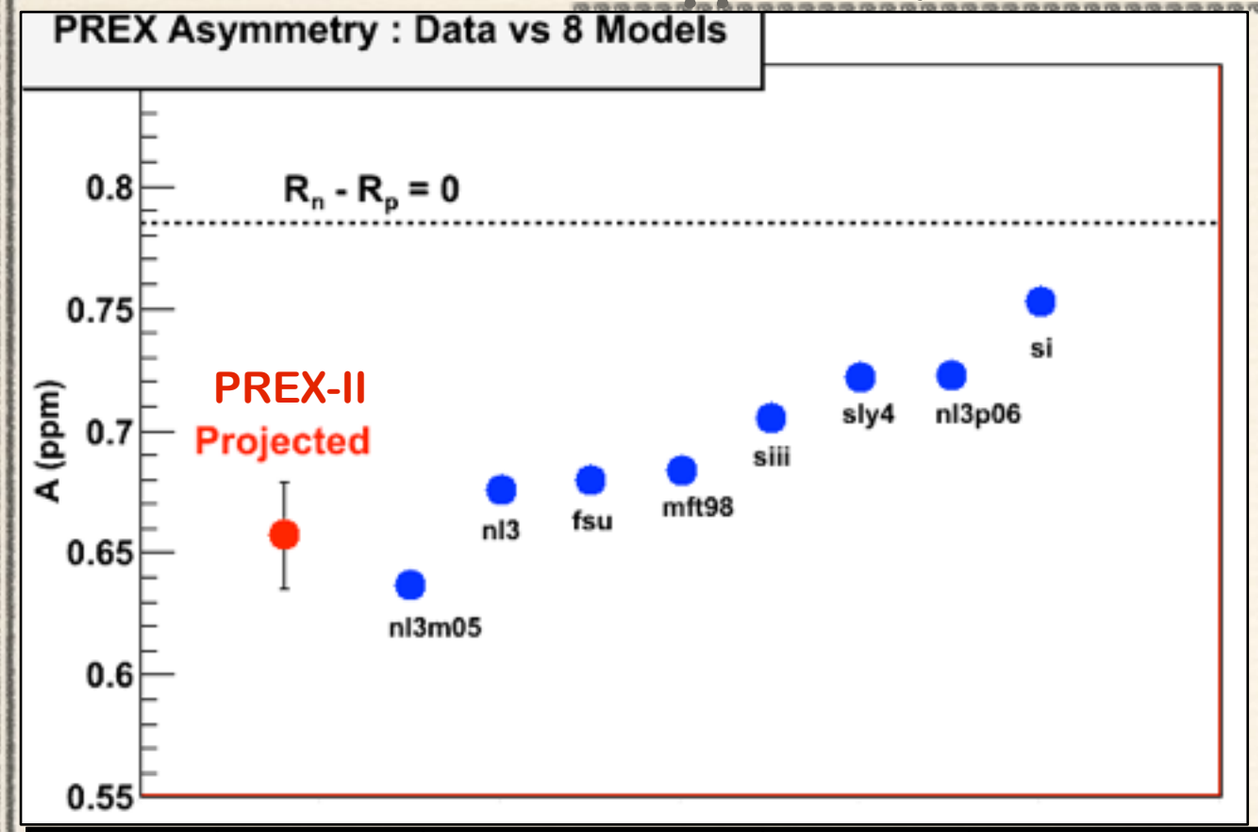
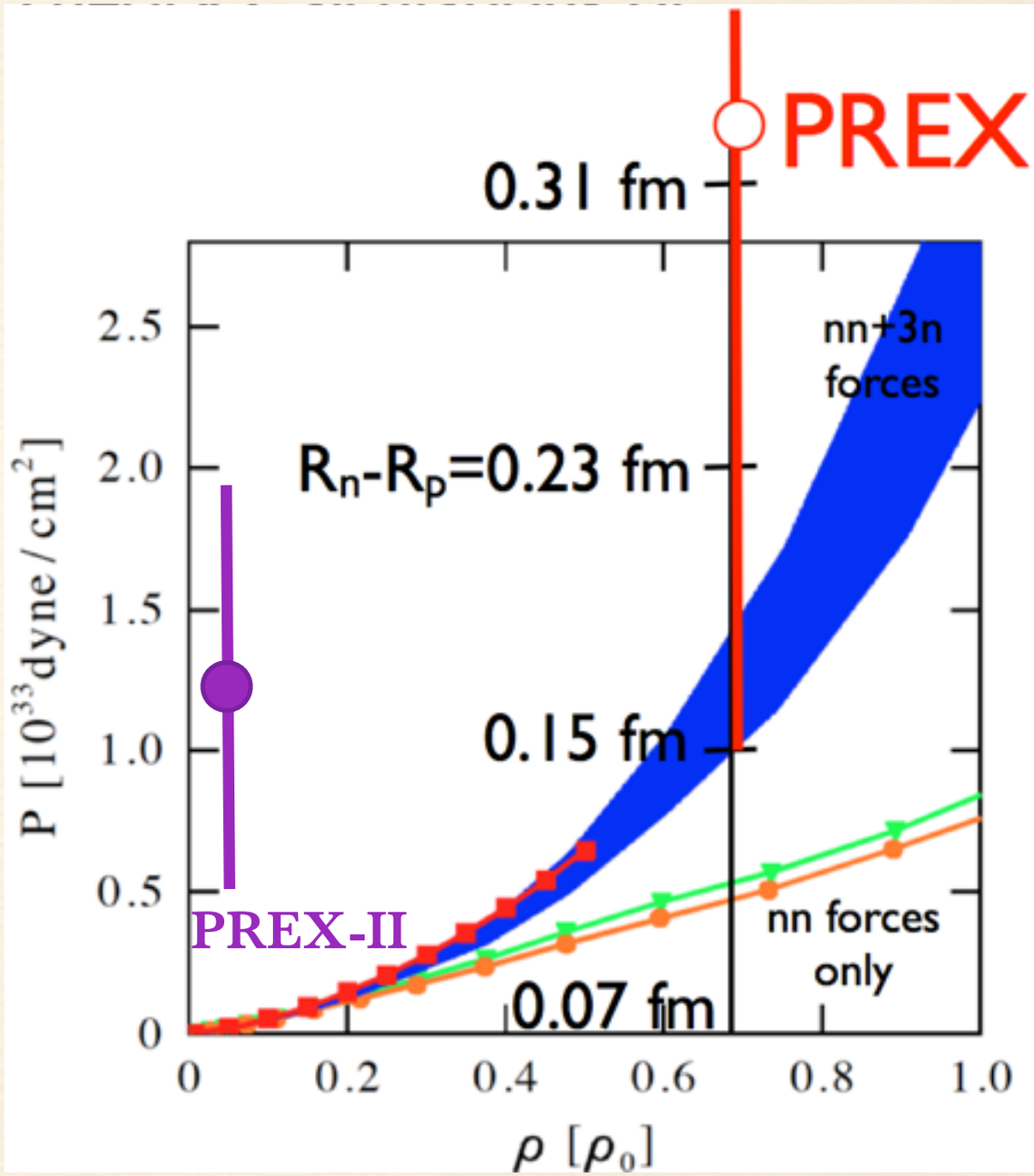


	E (GeV)	Rate (MHz @ 50 μA)	APV (ppm)	days to 1% on R
208	1.05	1700	0.6	30
120	1.25	810	1.1	20
48	1.7	270	2.5	12
	2.2	150	2.8	18



Ultimate goal: further factor of 2 error reduction beyond PREX-II

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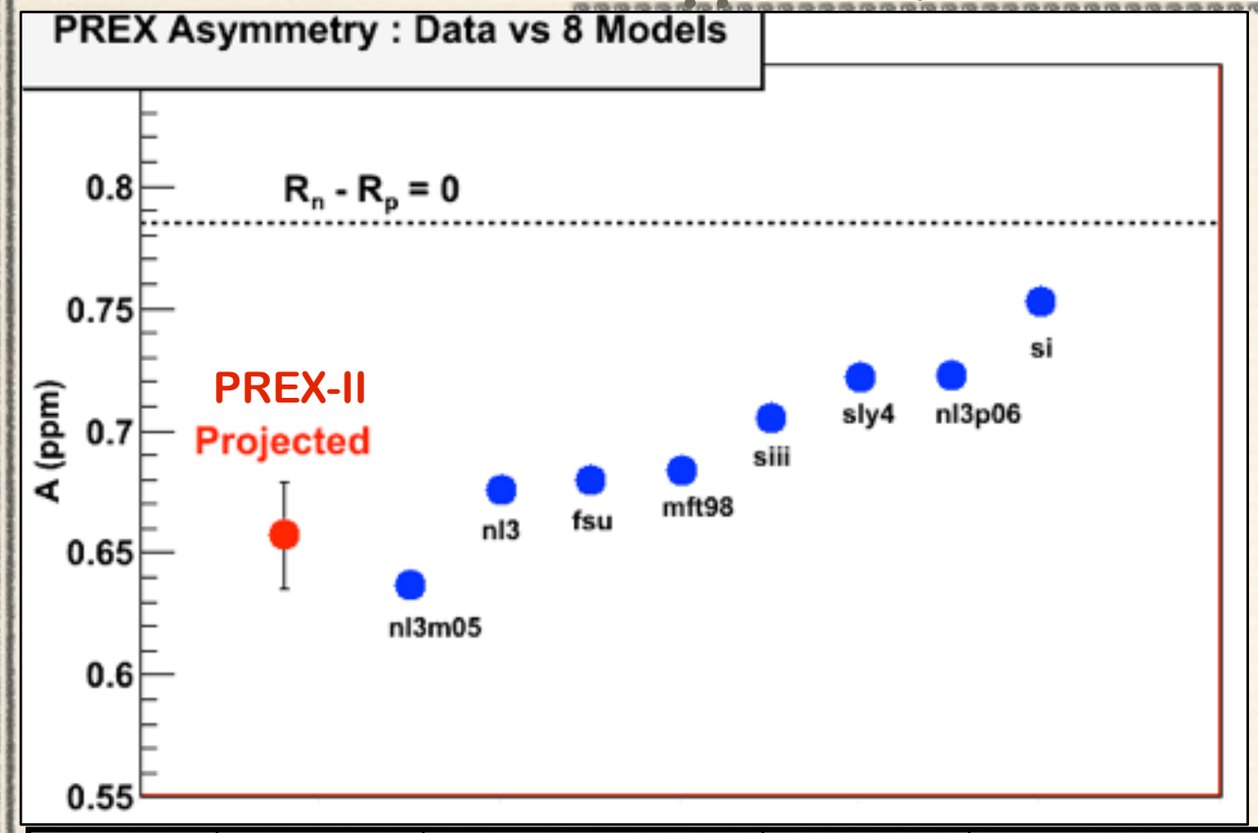

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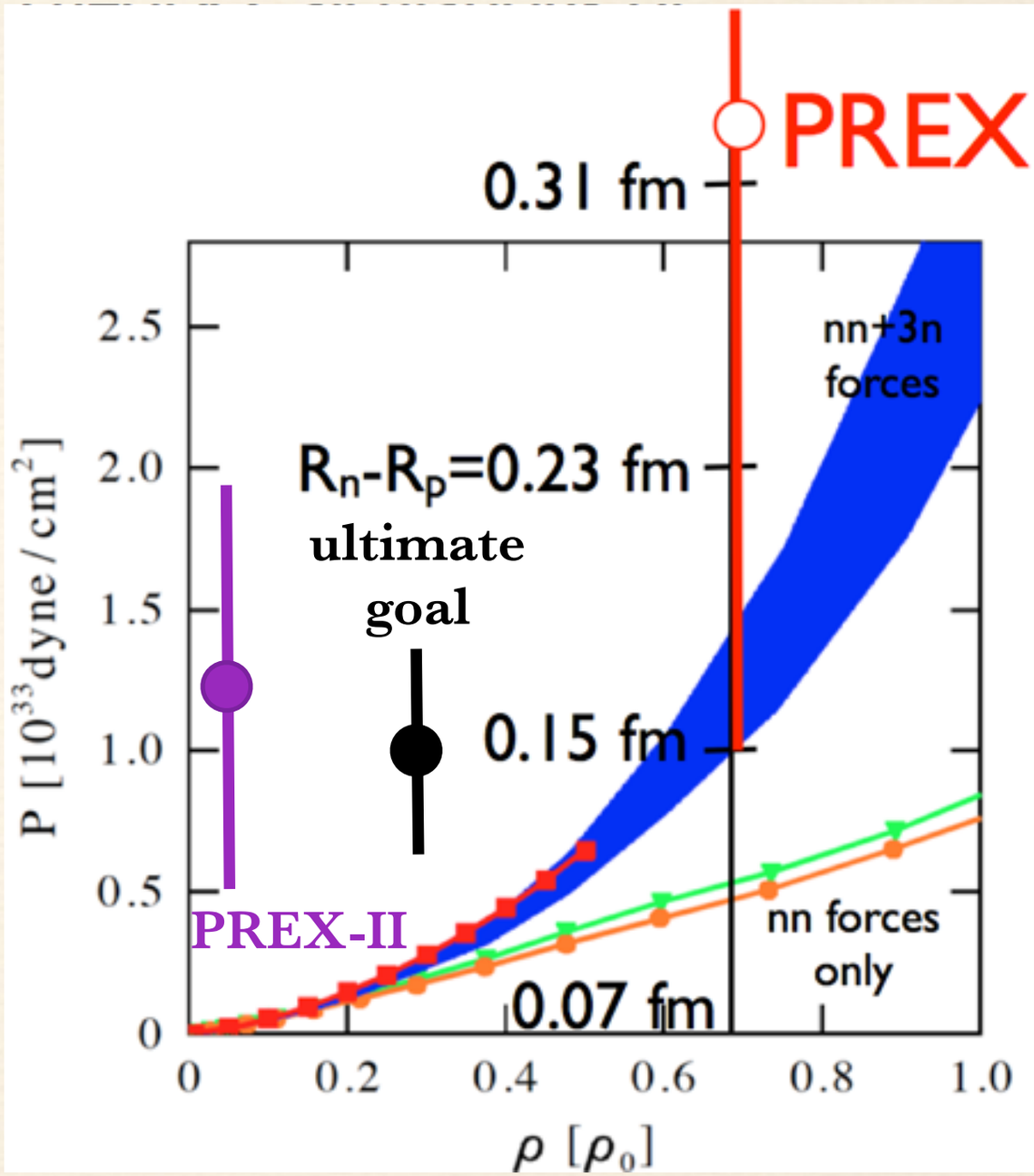


Expand measurements to new Mainz-MESA facility

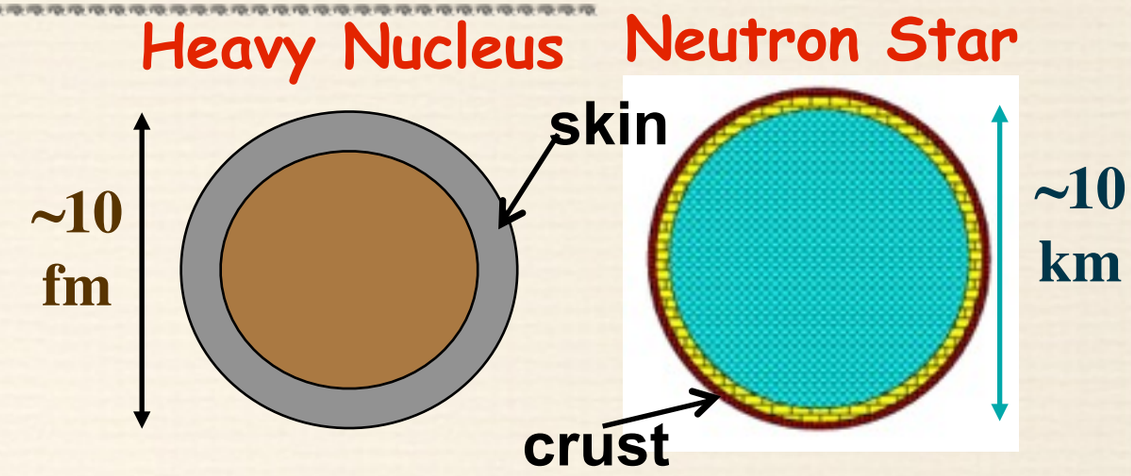
Neutron Skins and Neutron Stars

Horowitz and Piekarewicz, PRL 86 (2001)

Lattimer and Prakash, Science 304 (2004)

- Heavy nucleus has neutron skin
- Neutron star has solid crust over liquid core

Both neutron skin and neutron star crust are made out of neutron rich matter at similar densities.



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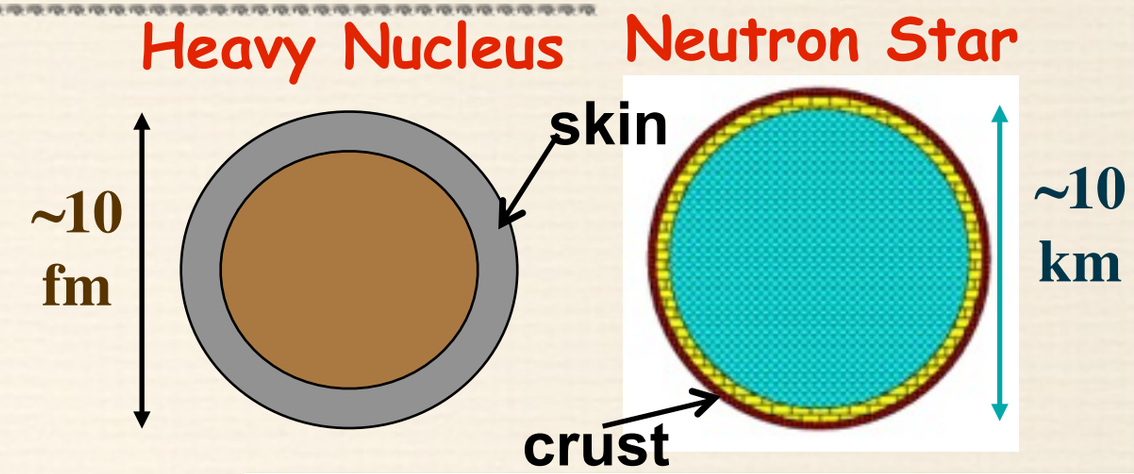

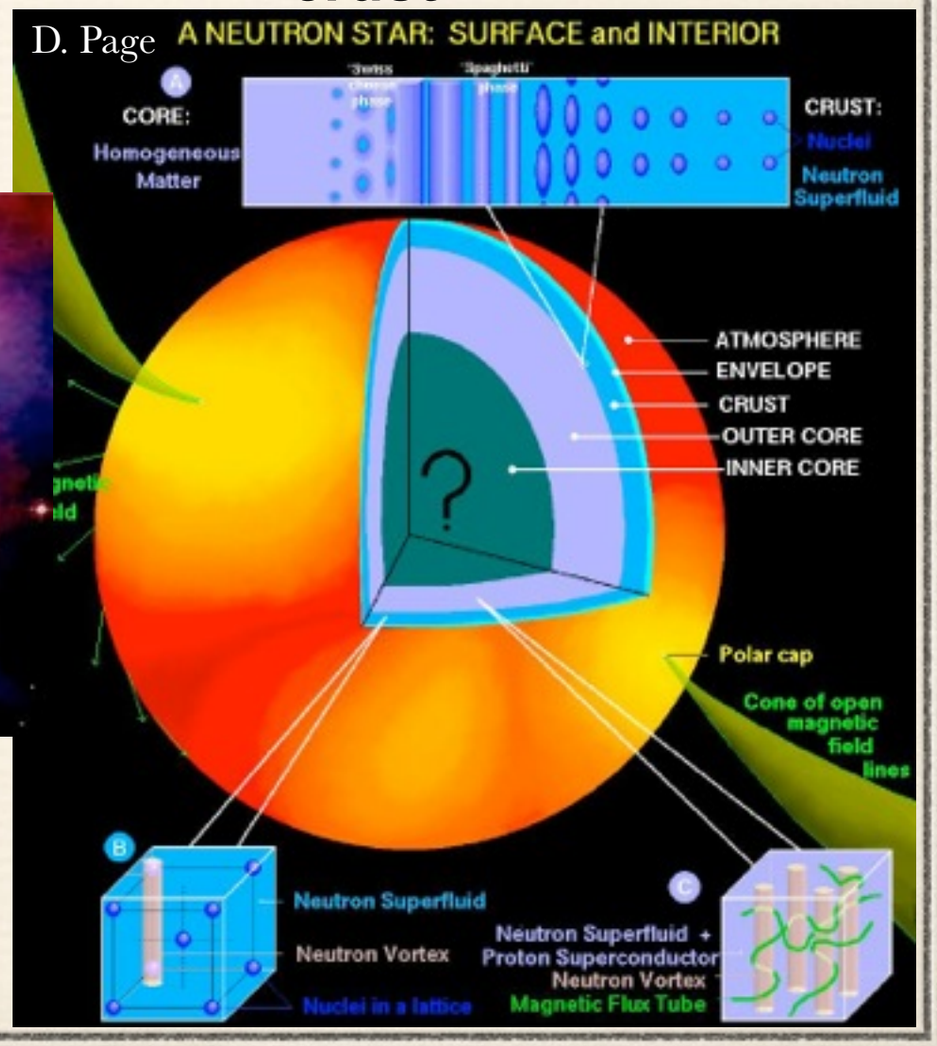

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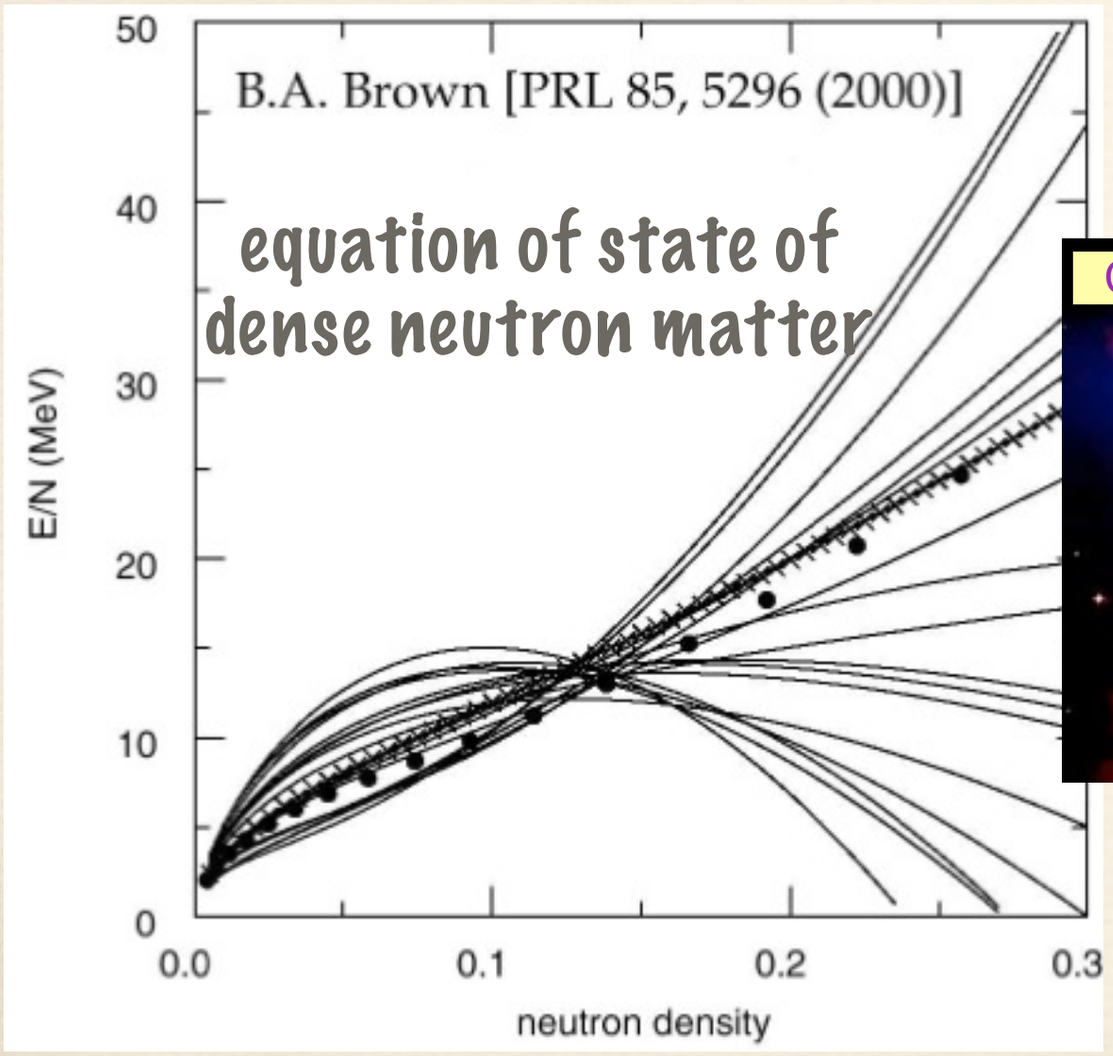

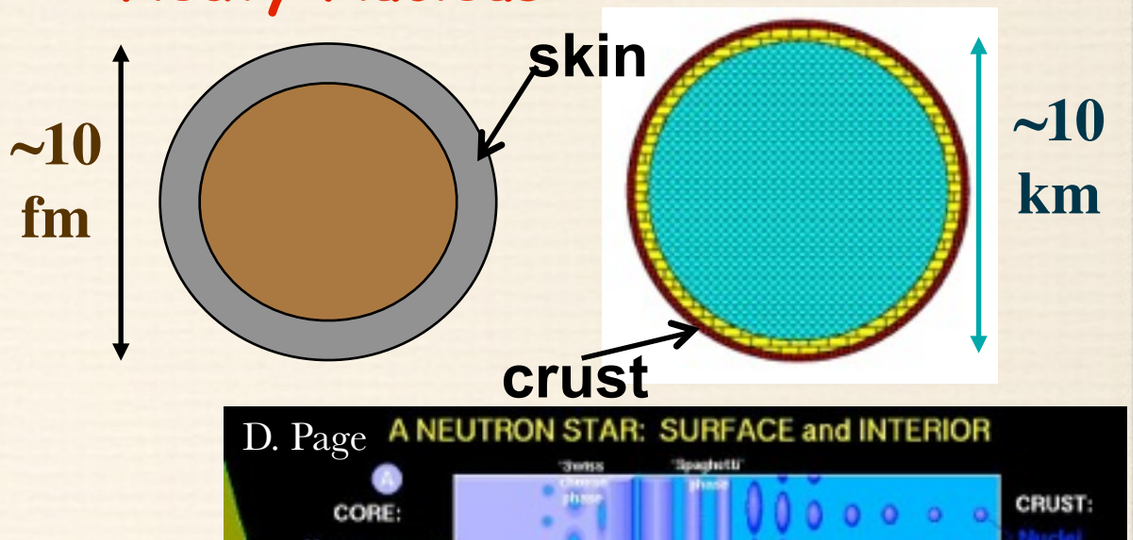

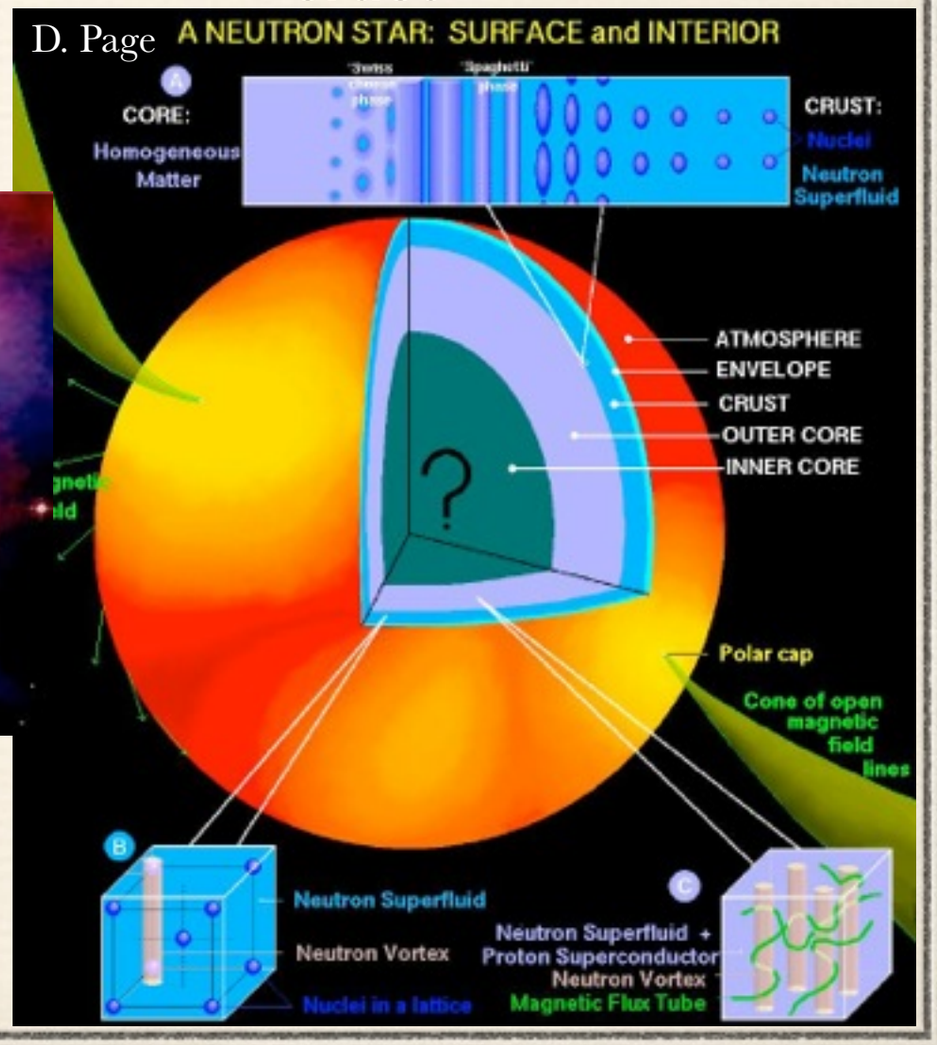

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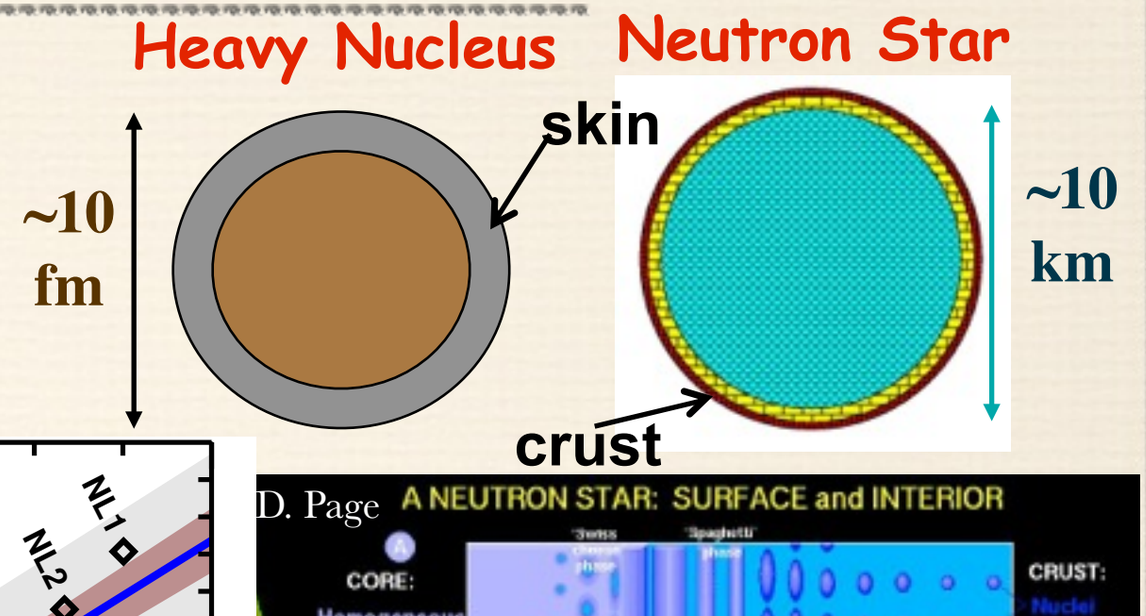

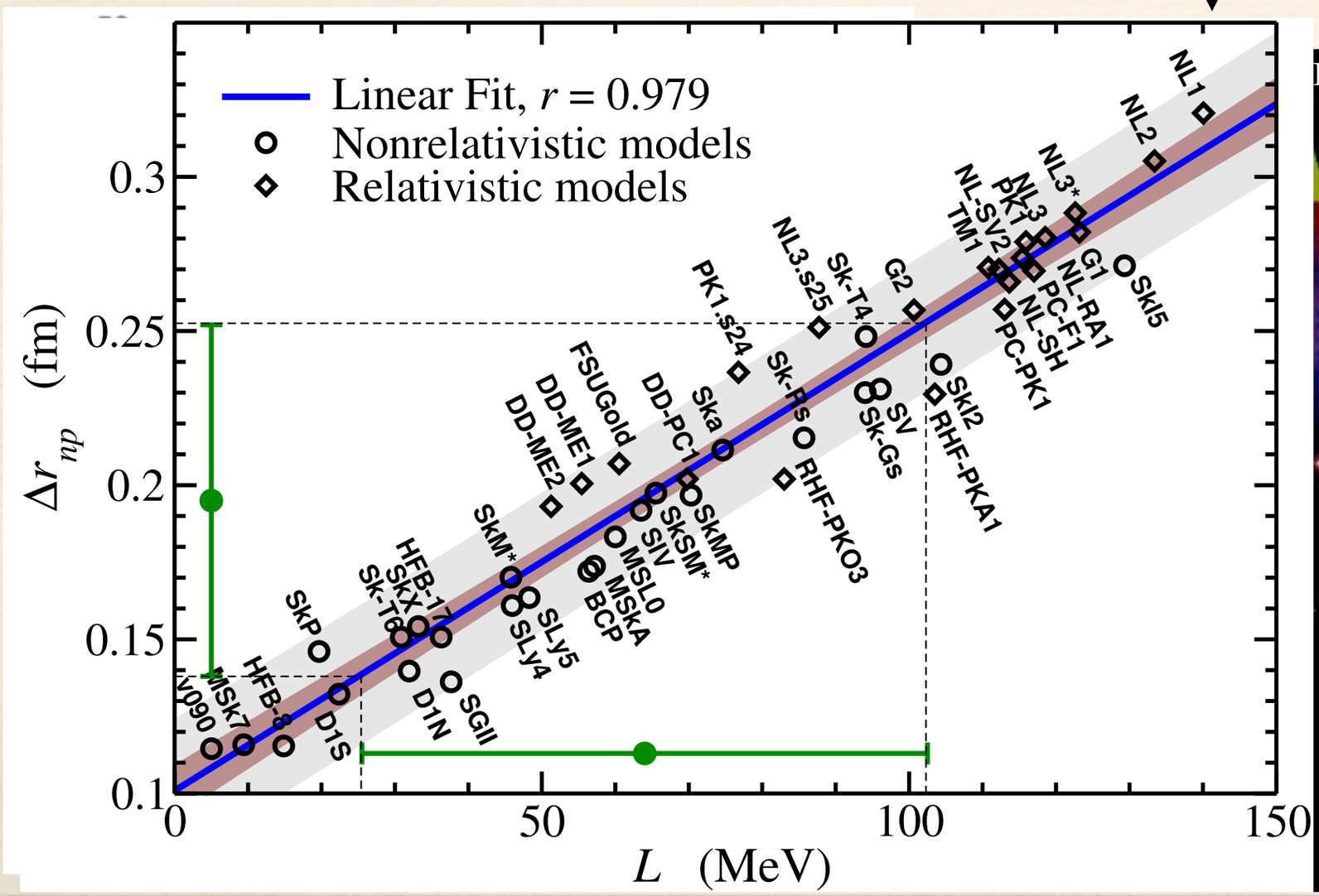

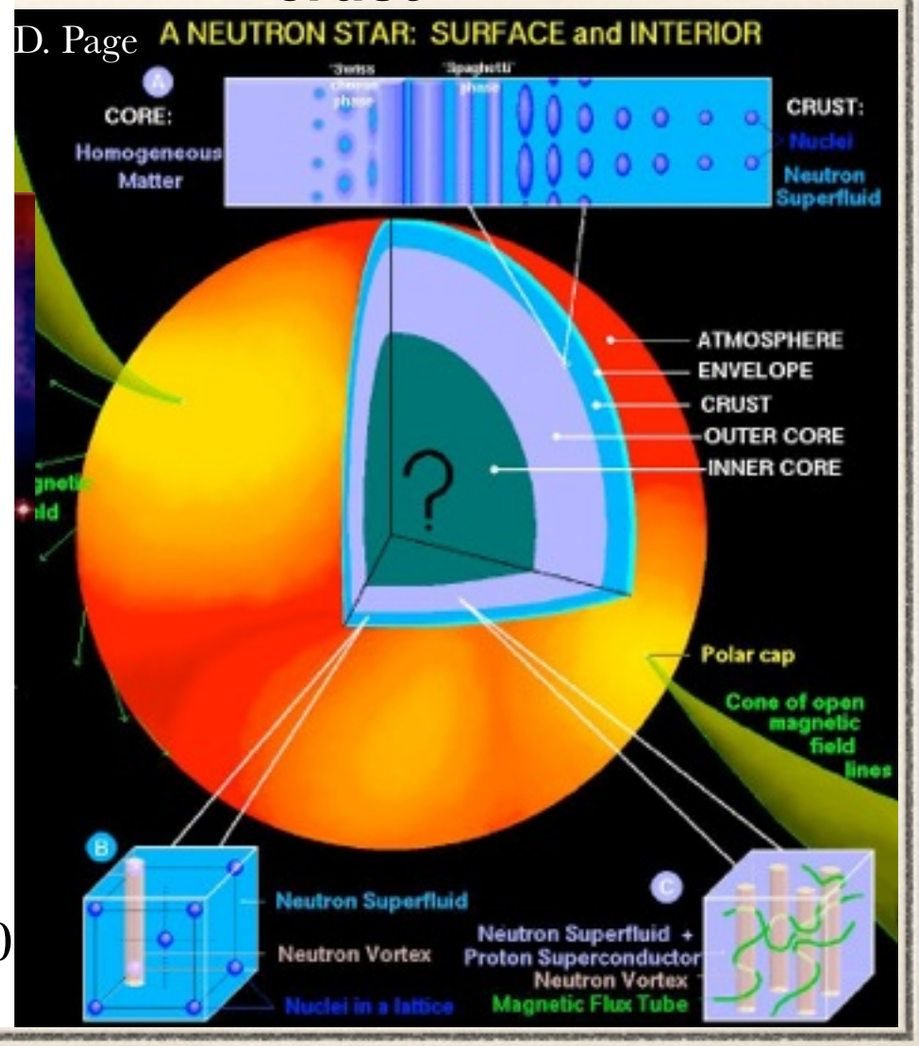

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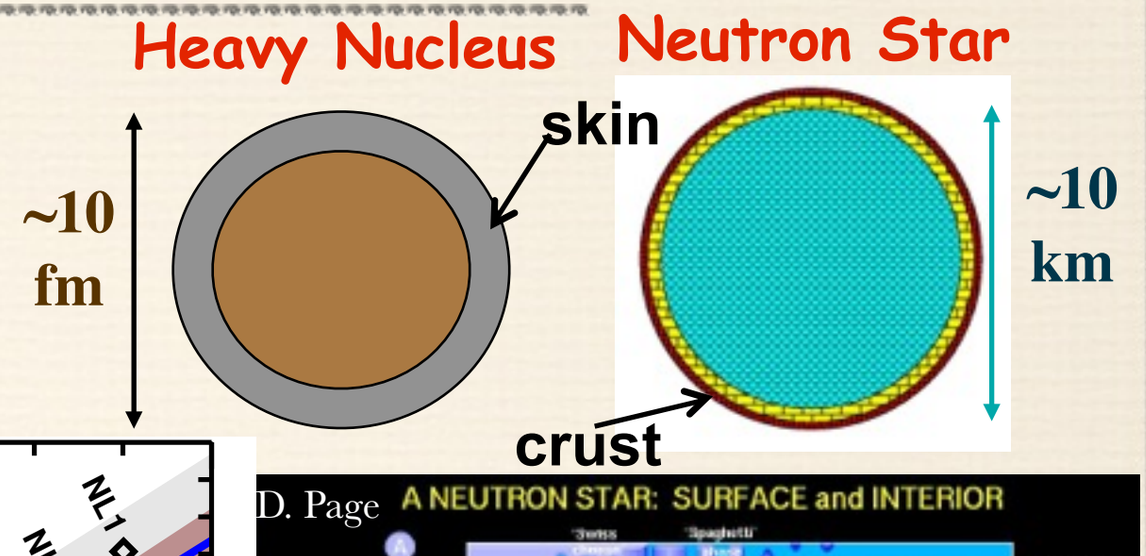
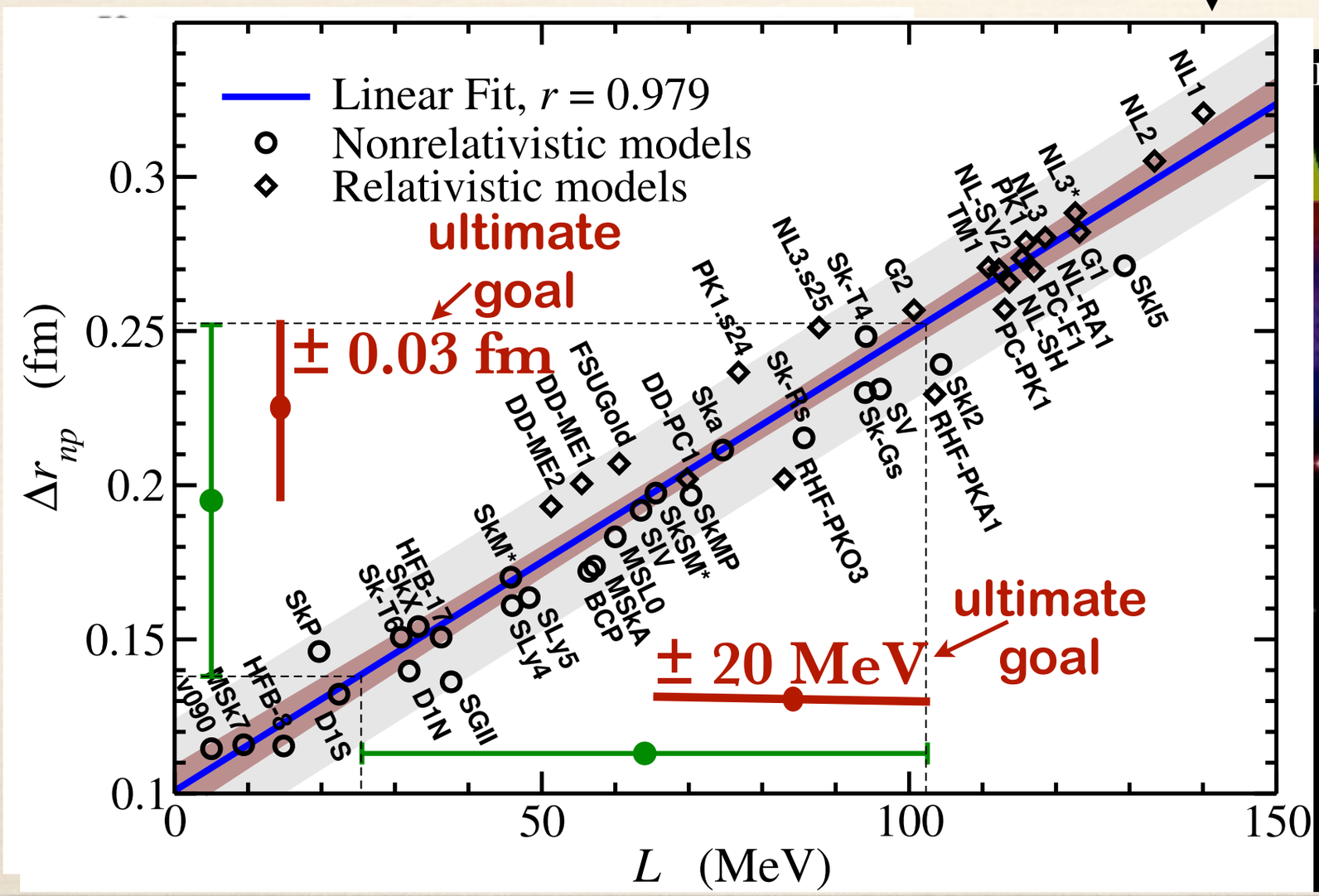
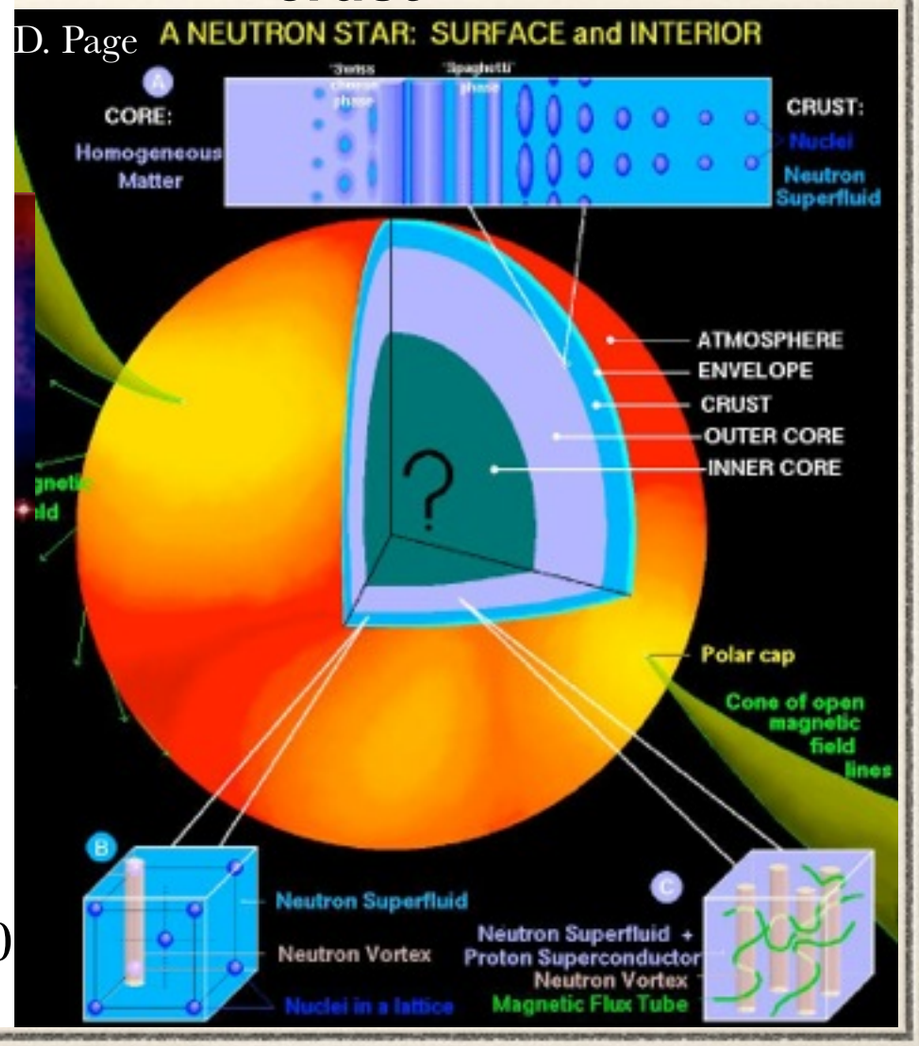
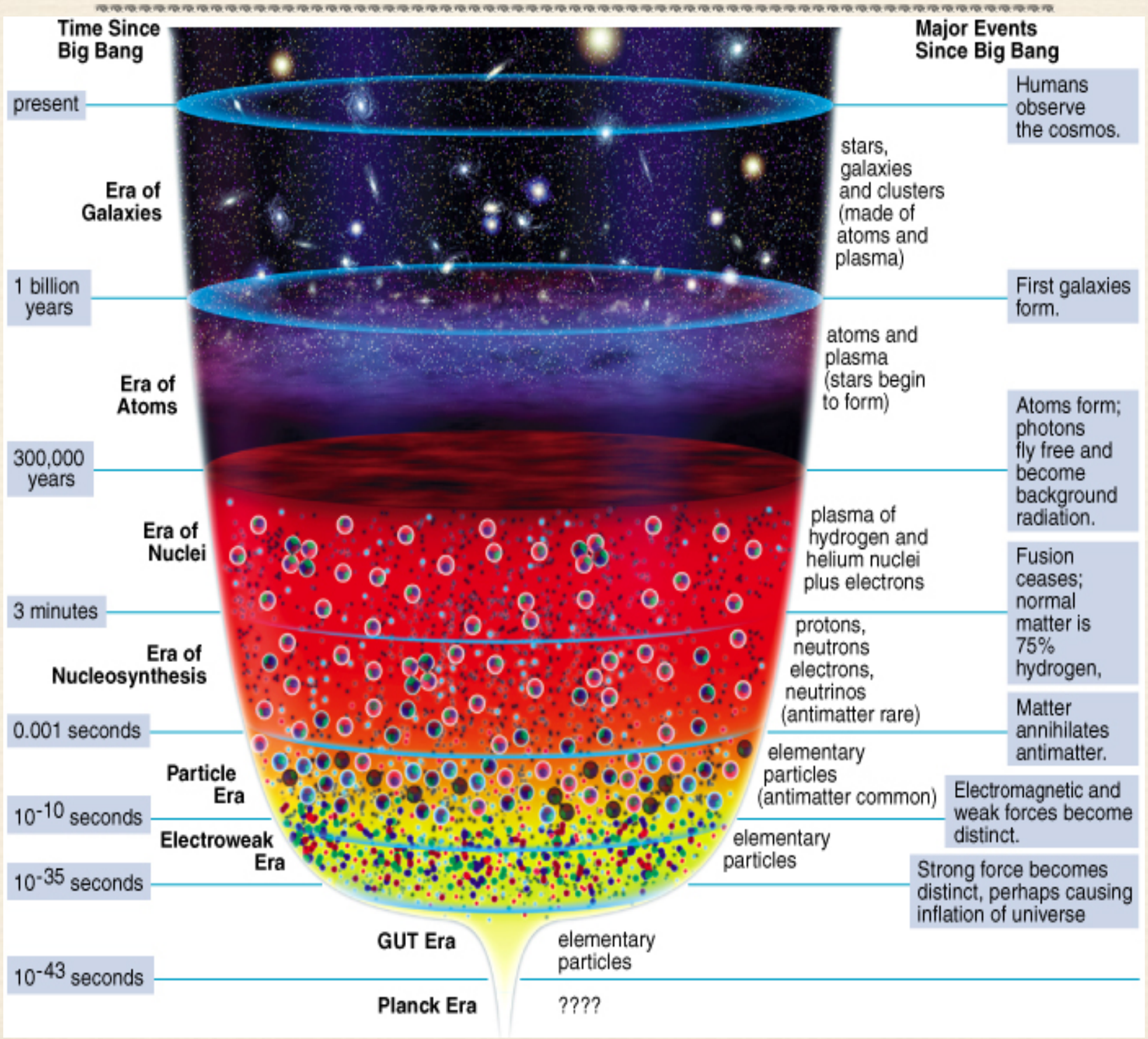






The Evolution of the Universe



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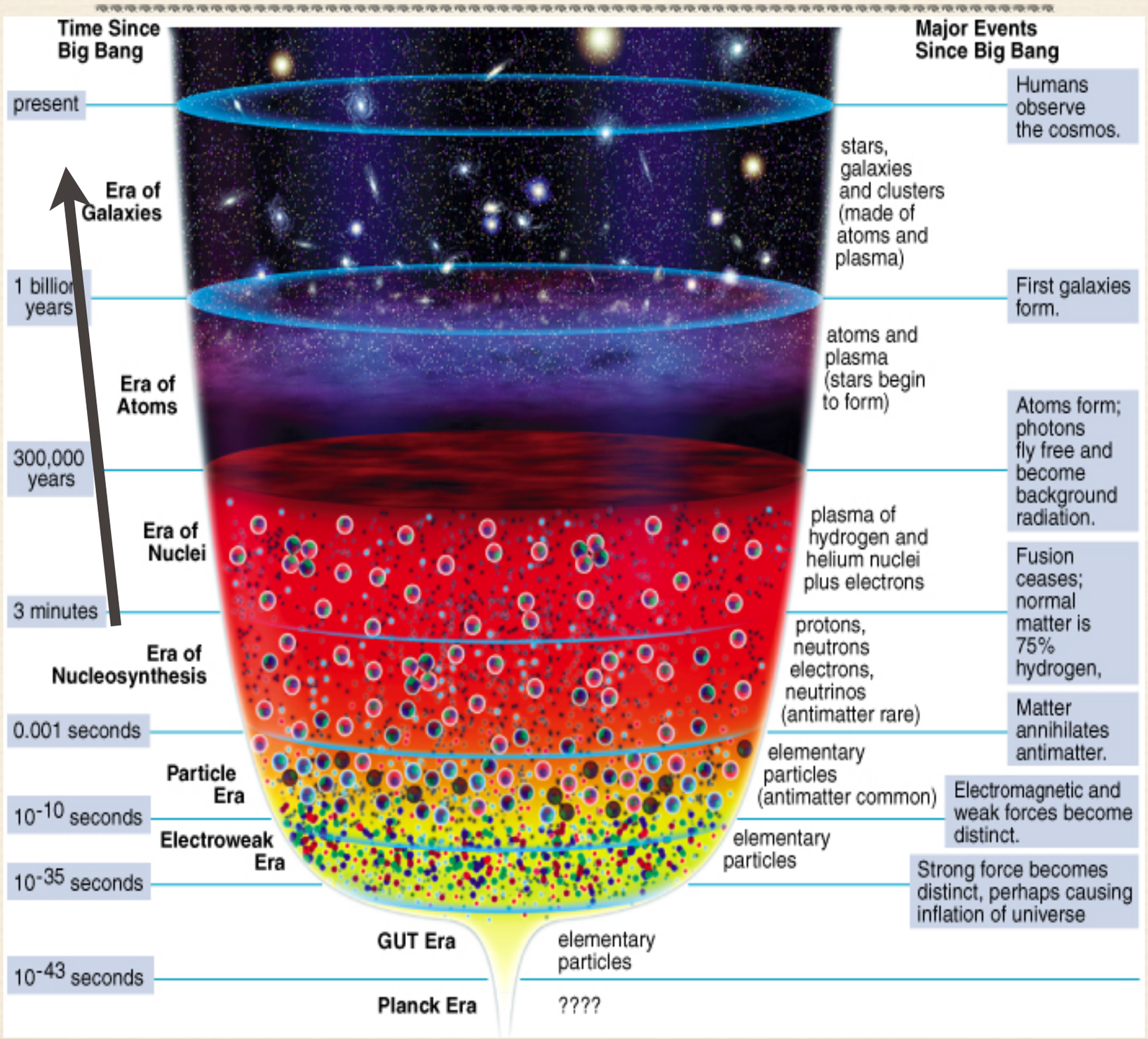

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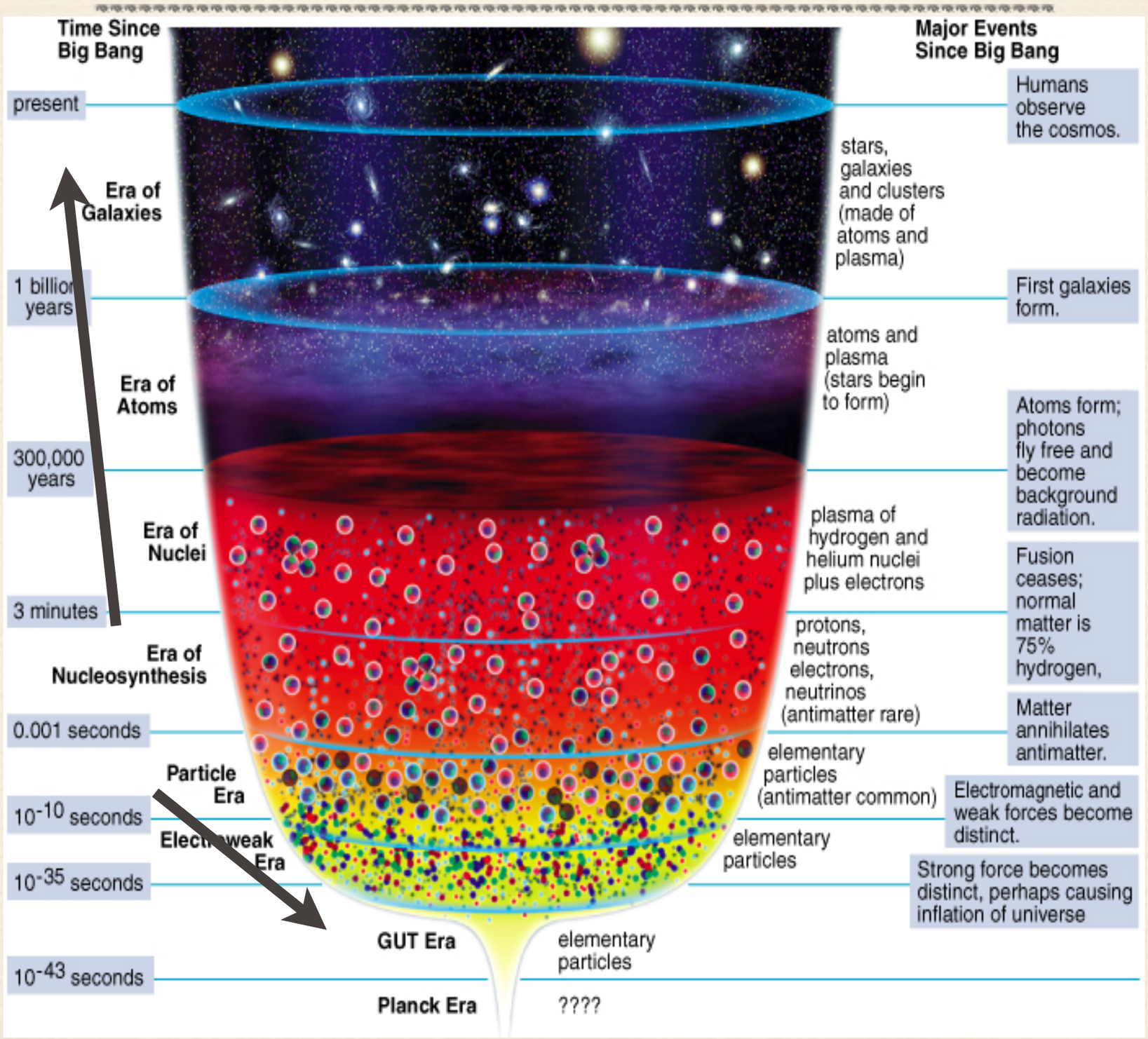

Search for New Superweak Forces

Physics down to a length scale of 10^{-19} m well understood but.....

Modern Electroweak Physics

Many questions still unanswered….

The High Energy Frontier: **Collider Physics**

The Cosmic Frontier: **Particle, Nuclear and Gravitational Astrophysics**

A comprehensive search for clues requires, in addition:

The Intensity/Precision Frontier

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- **Violation of Accidental (?) Symmetries**
  - ★ Neutrinoless Double-Beta Decay, Electric Dipole Moments...
- **Direct Detection of Dark Matter**
- **Measurements of Neutrino Masses and Mixing**
- **Precise Measurements of SM observables**

Intense beams, ultra-high precision, exotic nuclei, table-top experiments, rare processes....

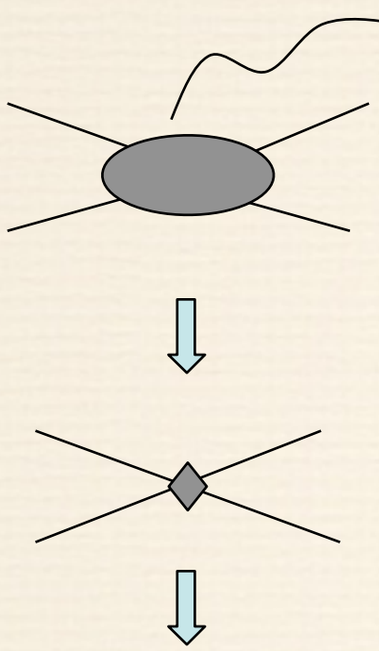
Electroweak Interactions at scales much lower than the W/Z mass

Indirect Clues

E

Λ (~TeV)

$M_{W,Z}$ (100 GeV)



Dynamics involving particles with m > Λ

Many theories predict new forces that disappeared when the universe cooled

courtesy
V. Cirigliano
H. Maruyama

$\mathcal{L}_{SM+\text{Heavy}}$

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

higher dimensional operators can be systematically classified

Heavy Z's and neutrinos, technicolor, compositeness, extra dimensions, SUSY…

SM amplitudes can be very precisely predicted

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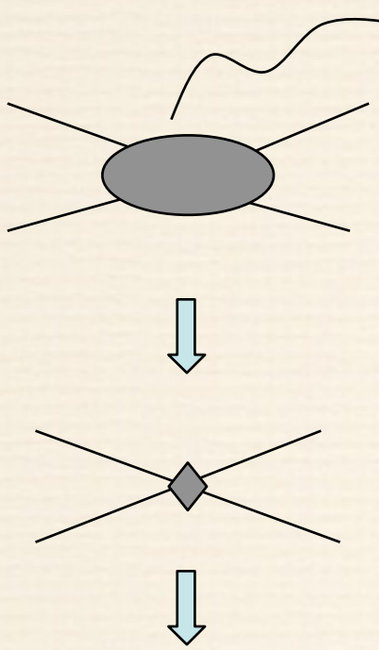

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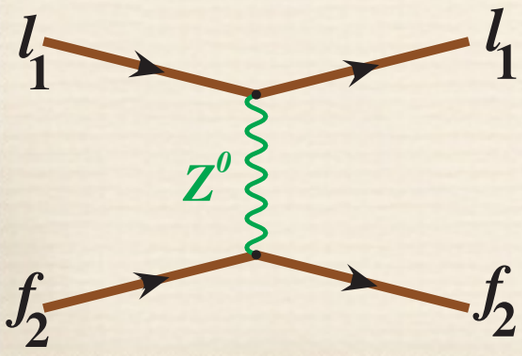
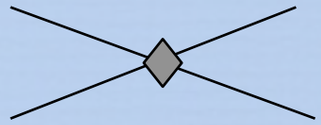
Search for new neutral superweak forces



Look for tiny but measurable deviations from precisely calculable predictions for SM processes



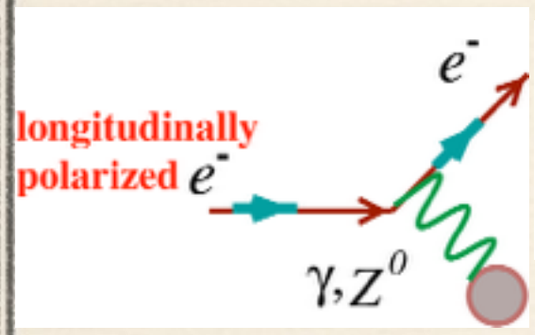
$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

must reach Λ ~ several TeV

All flavor-conserving weak neutral current amplitudes are functions of $\sin^2\theta_W$

Electron's Weak Charge

Parity-violating Electron-Electron Scattering



$$-A_{LR} = A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} \sim \frac{A_{weak}}{A_{\gamma}} \sim \frac{G_F Q^2}{4\pi\alpha} \left(g_A^e g_V^T + \beta\, g_V^e g_A^T\right)$$

g_V *and* g_A *are function of* $\sin^2\theta_W$

Weak Charge Q_W

electron & proton target: **small SM**

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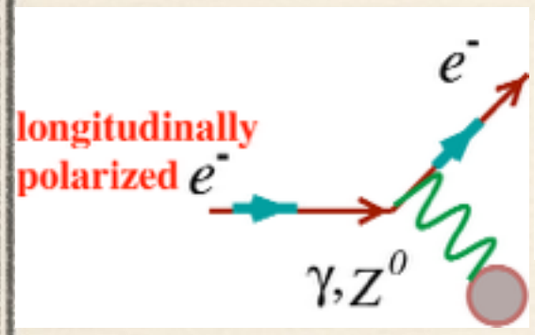

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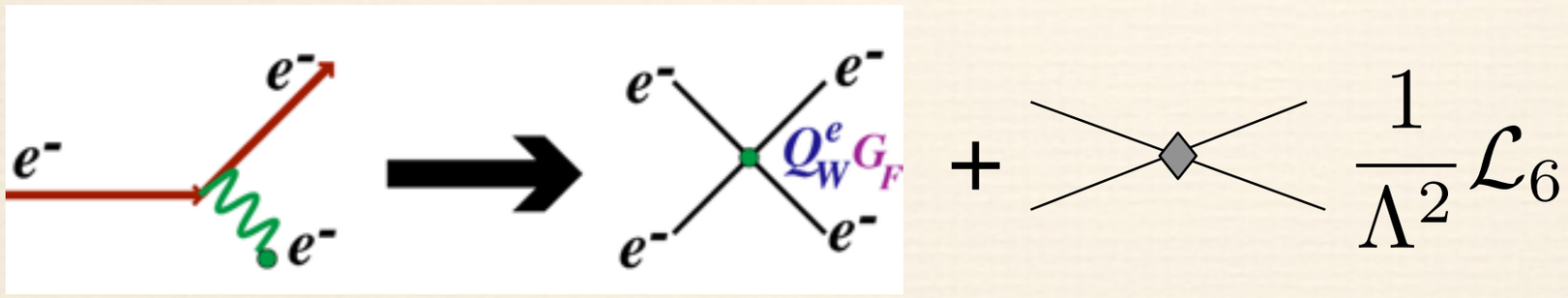

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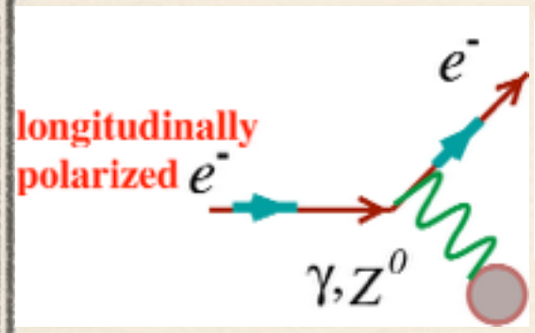

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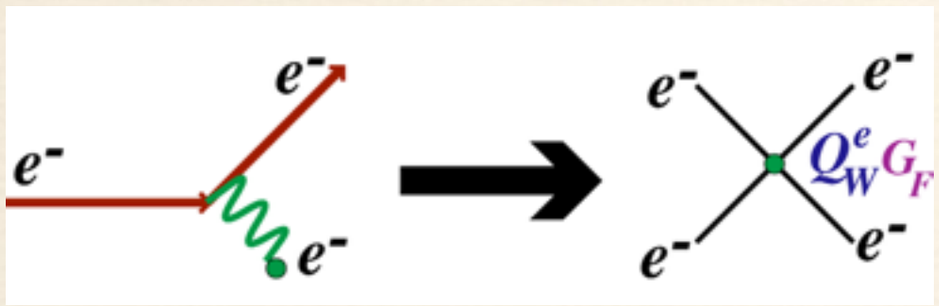
Tiny!



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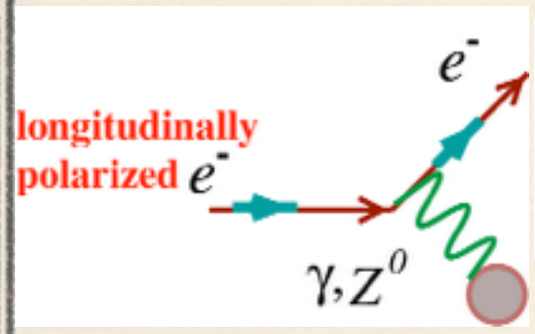

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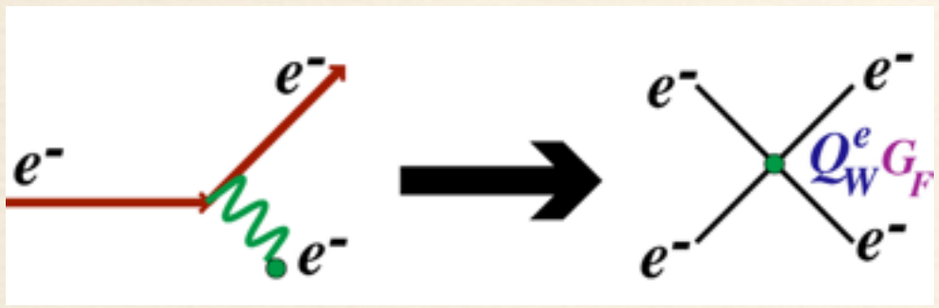

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End Station A at the Stanford Linear Accelerator Center (SLAC)

Tree-level prediction: ~ 250 ppb

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SLAC E158

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SLAC E158

Phys. Rev. Lett. **95** 081601 (2005)

$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$

Final E158 Result

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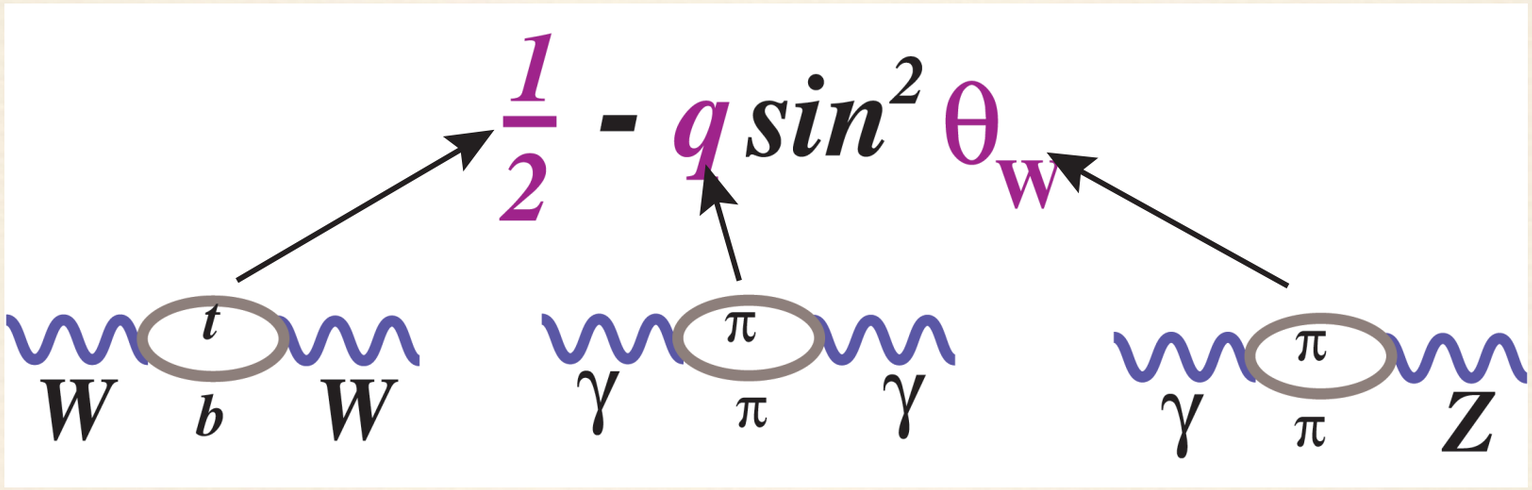

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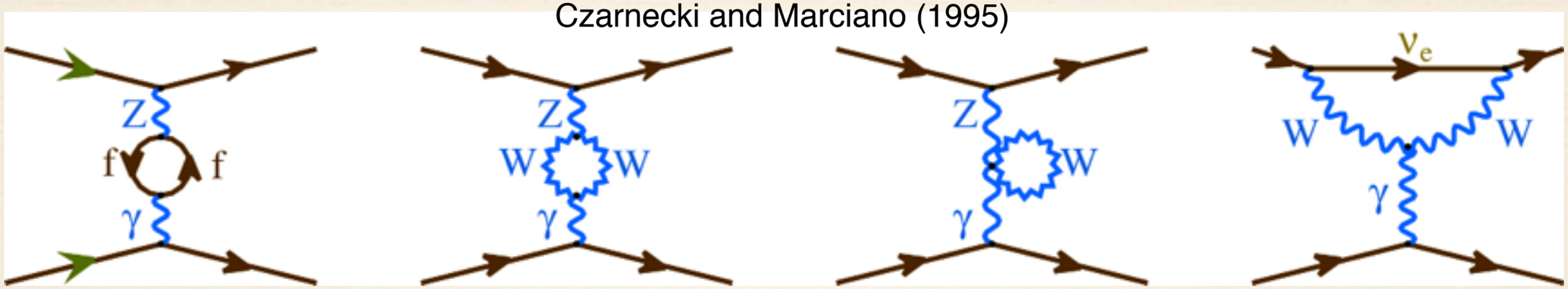

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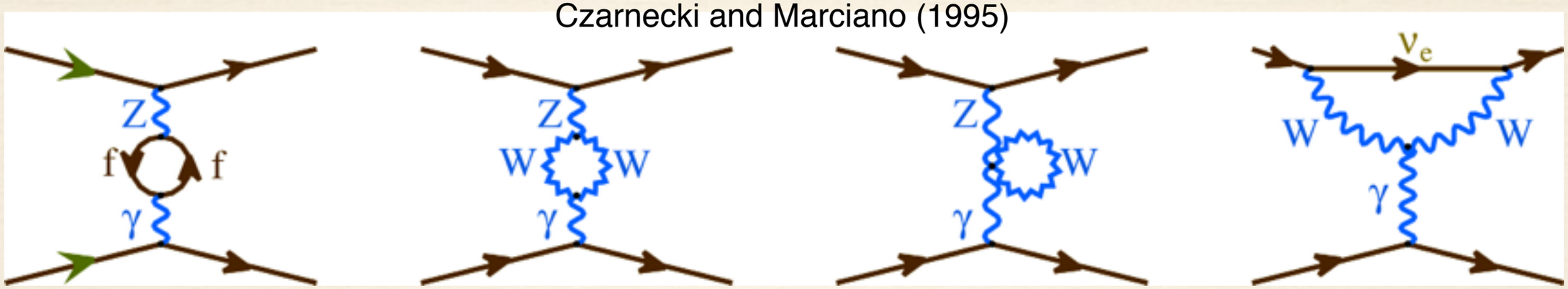

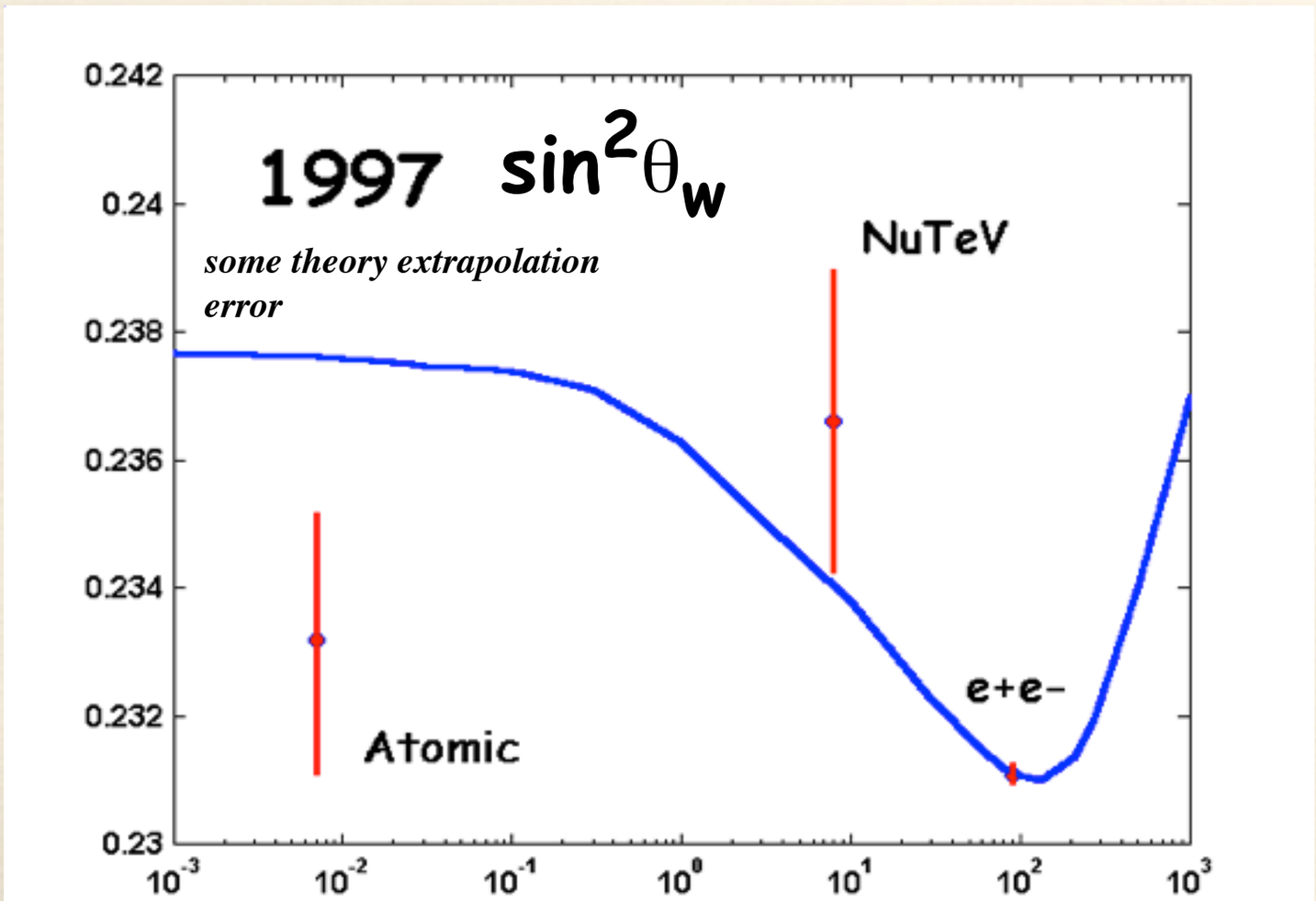

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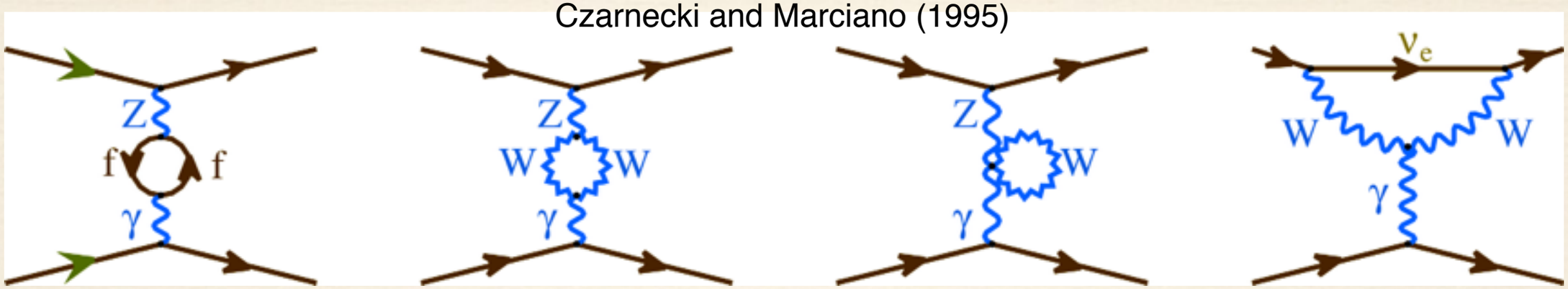

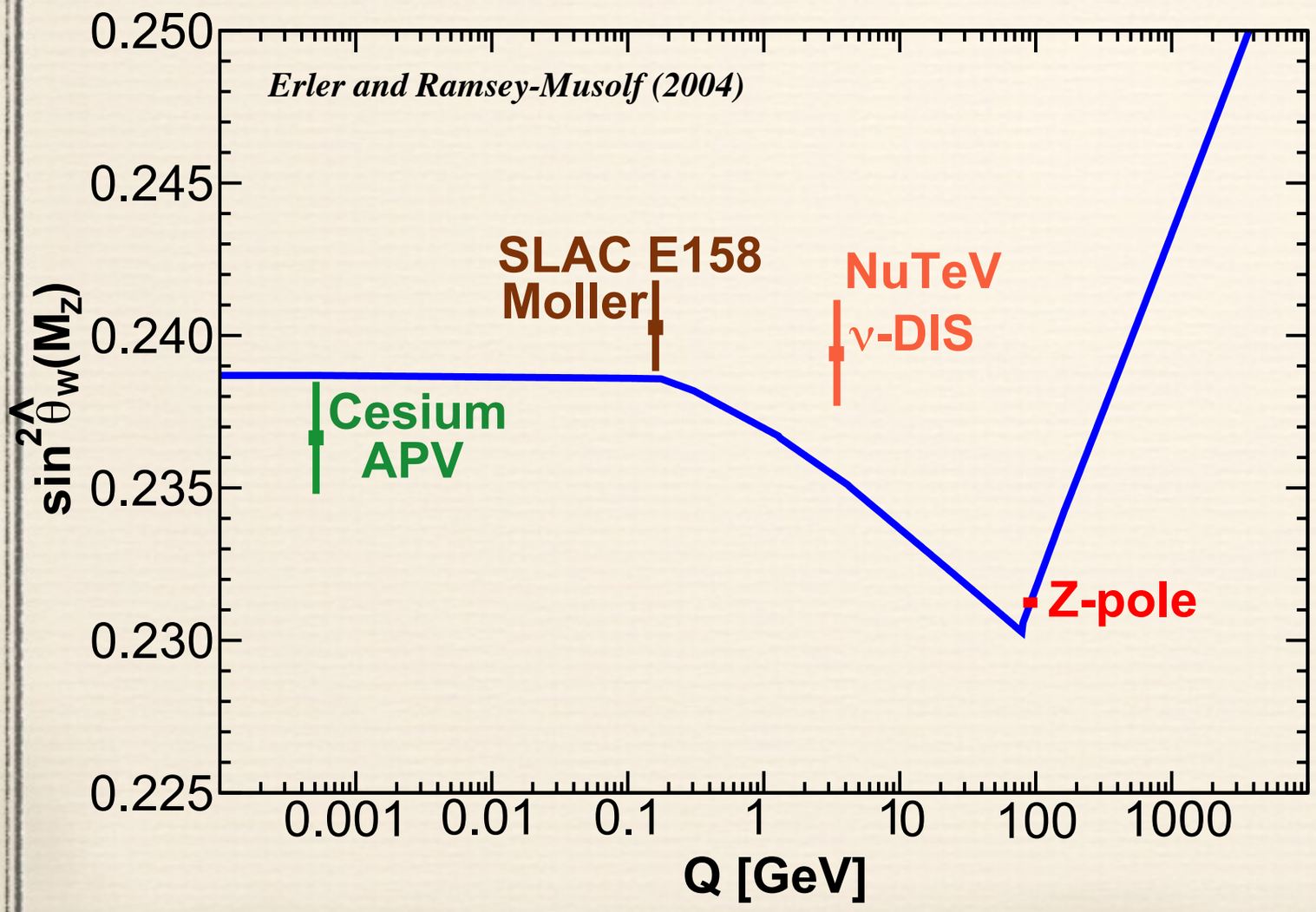

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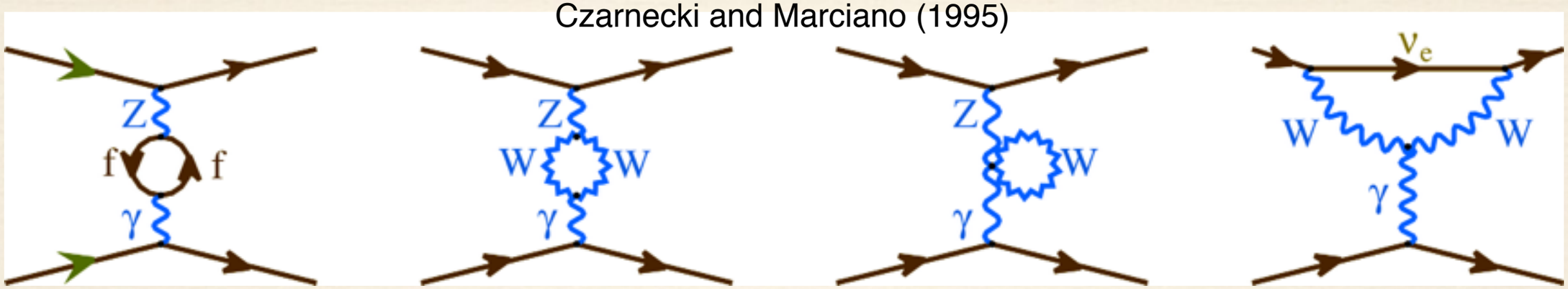

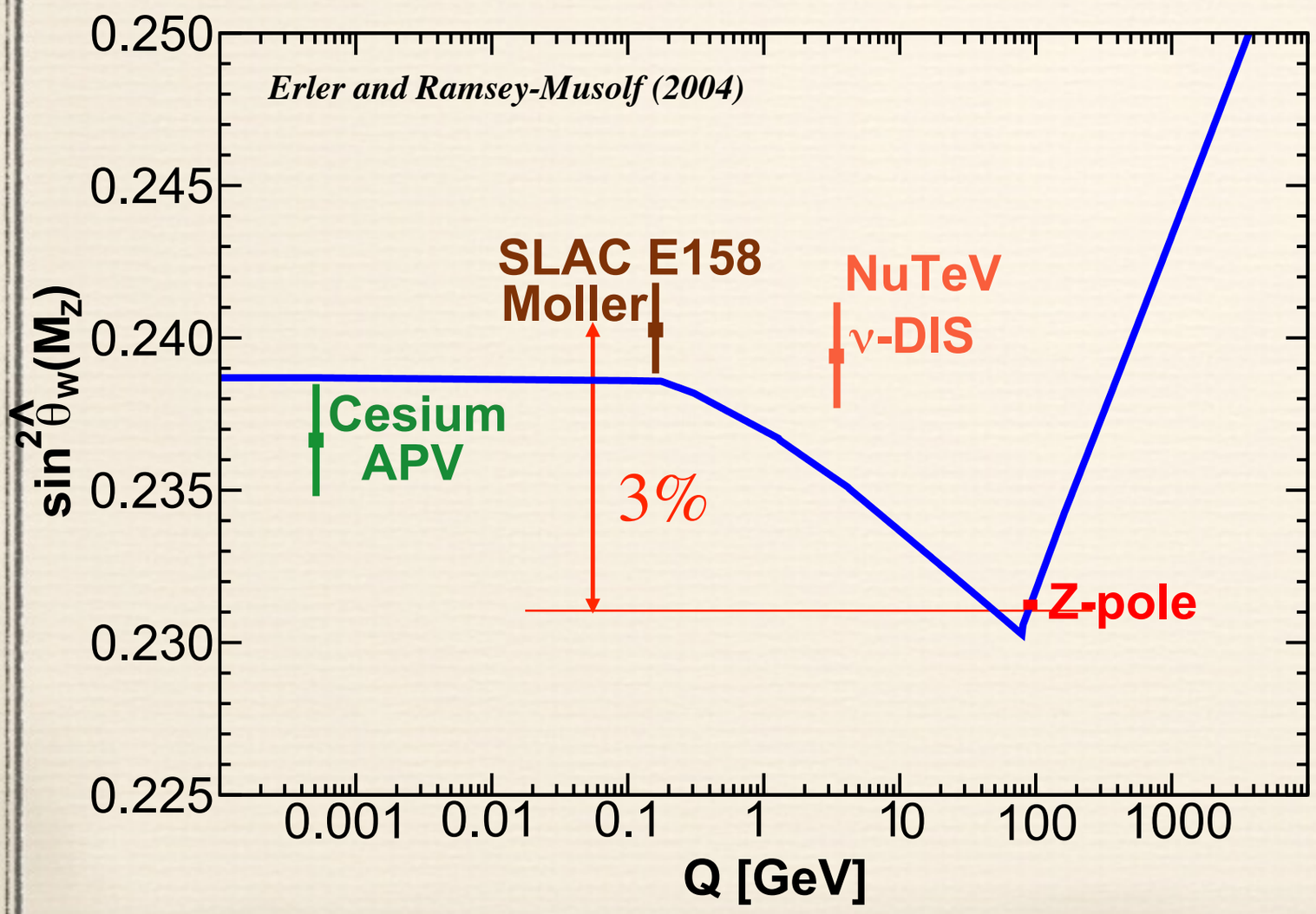

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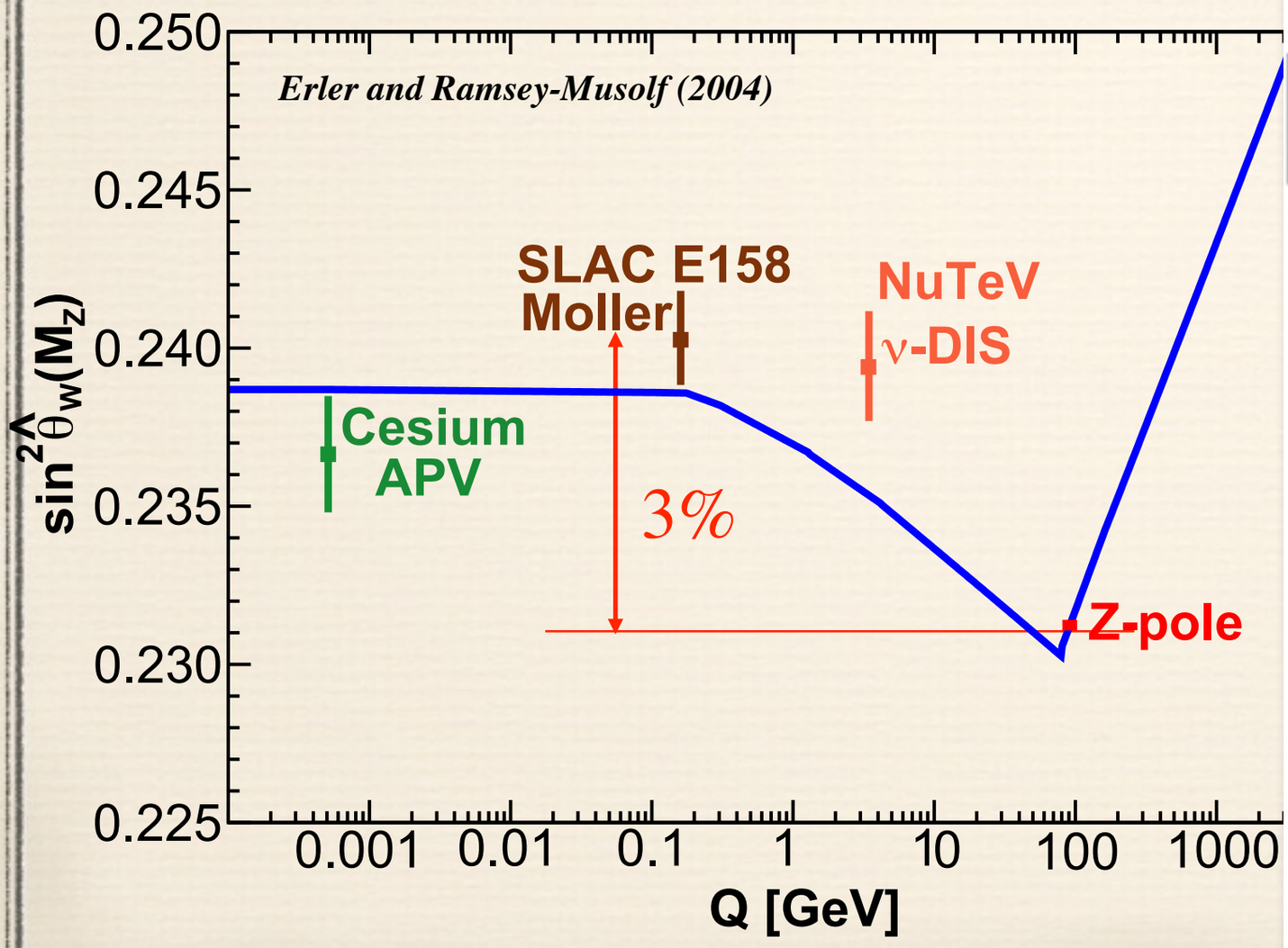
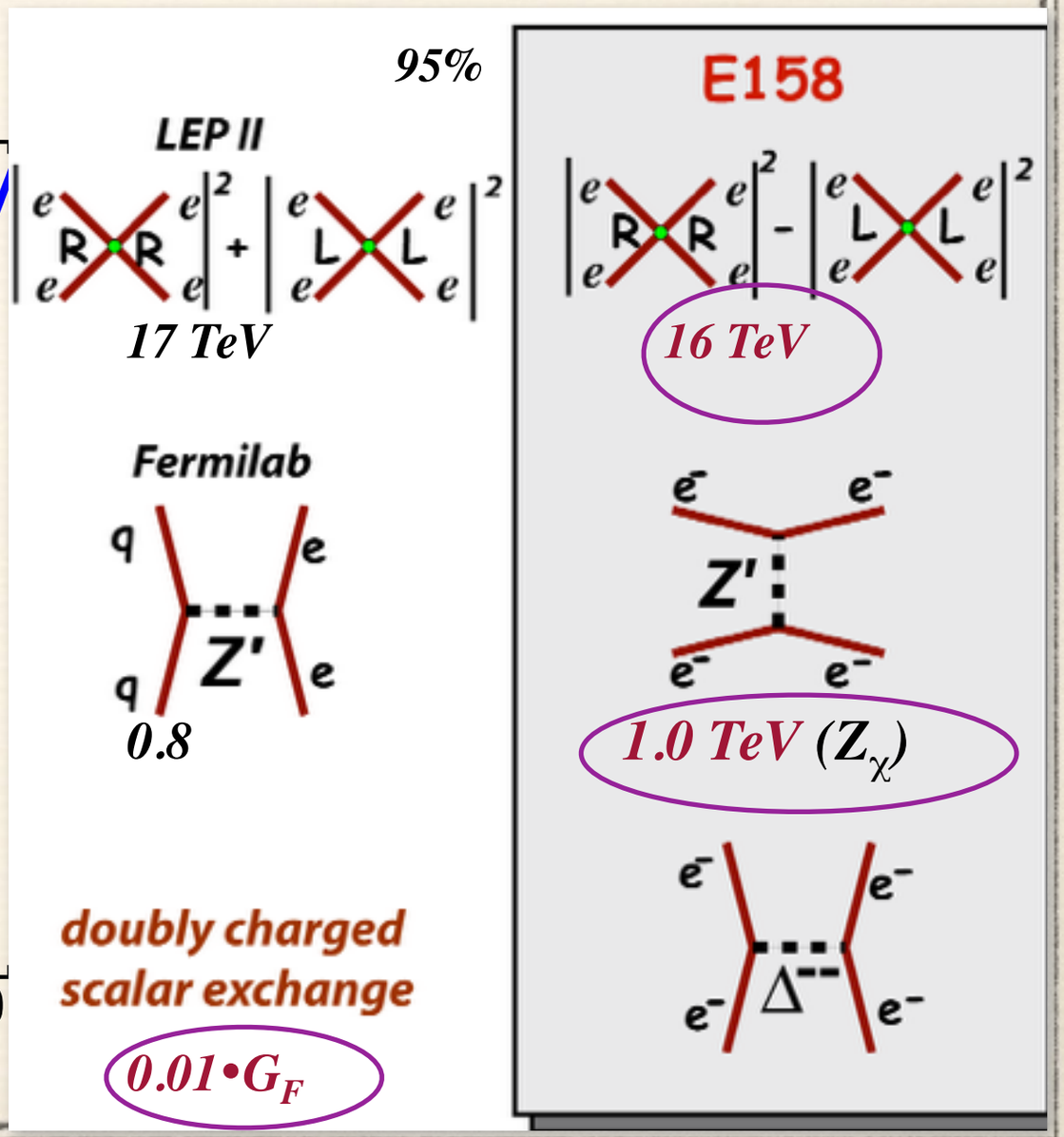
Limits on "New" Physics





Tree-level prediction: ~ 250 ppb

$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$

$$A_{PV} \approx 8 \times 10^{-8} E_{beam} (1 - 4 \sin^2 \vartheta_W)$$

SLAC E158

Phys. Rev. Lett. **95** 081601 (2005)

Final E158 Result

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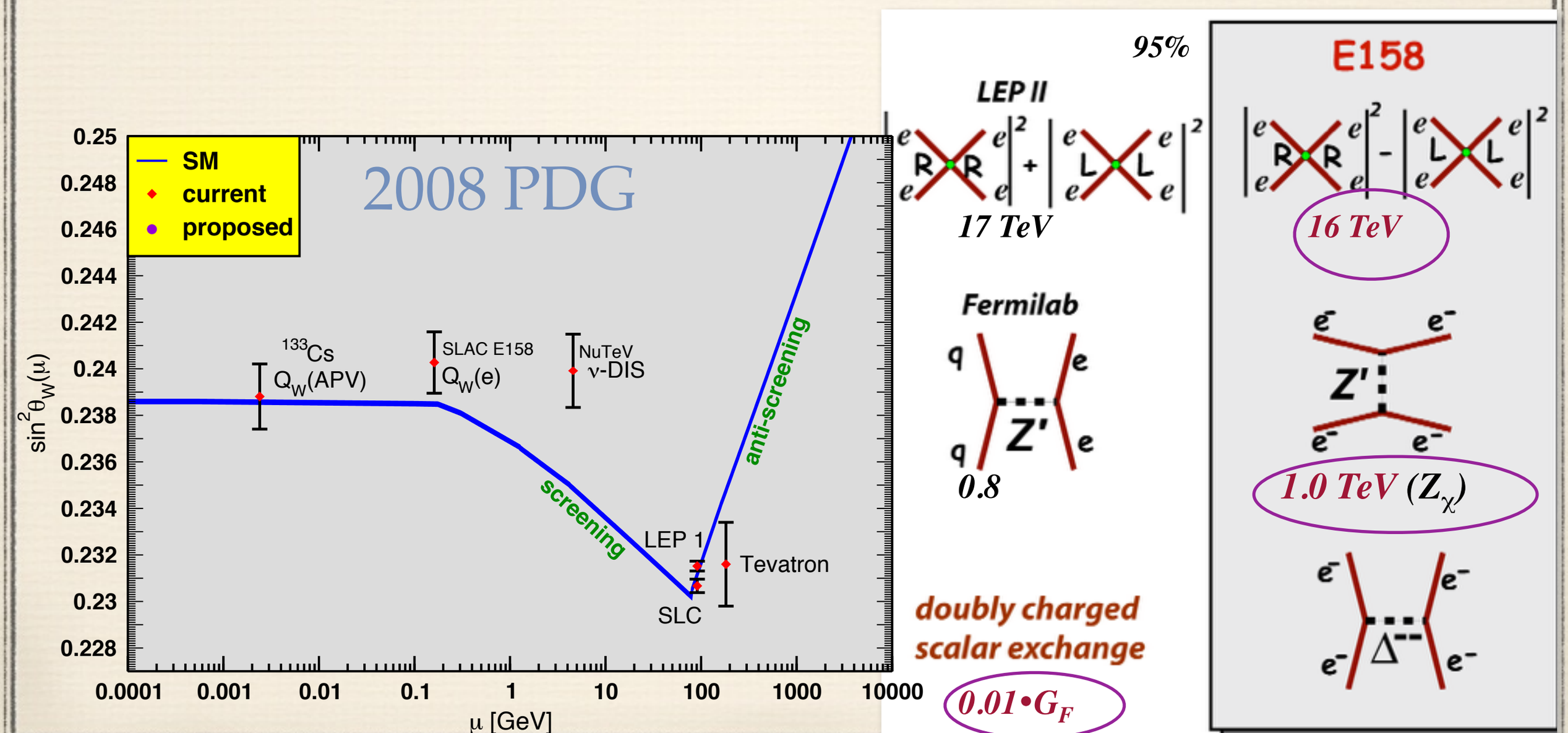

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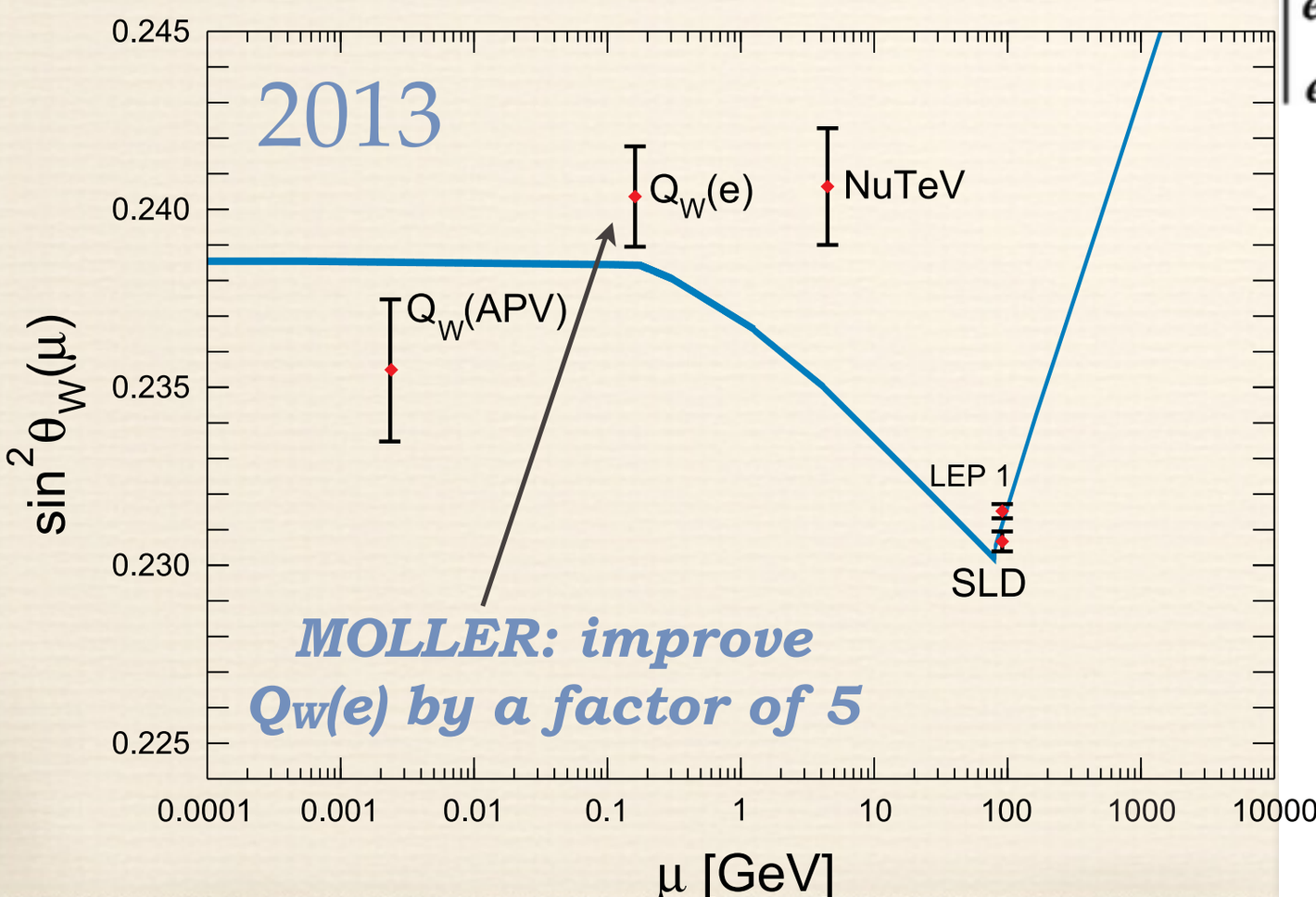
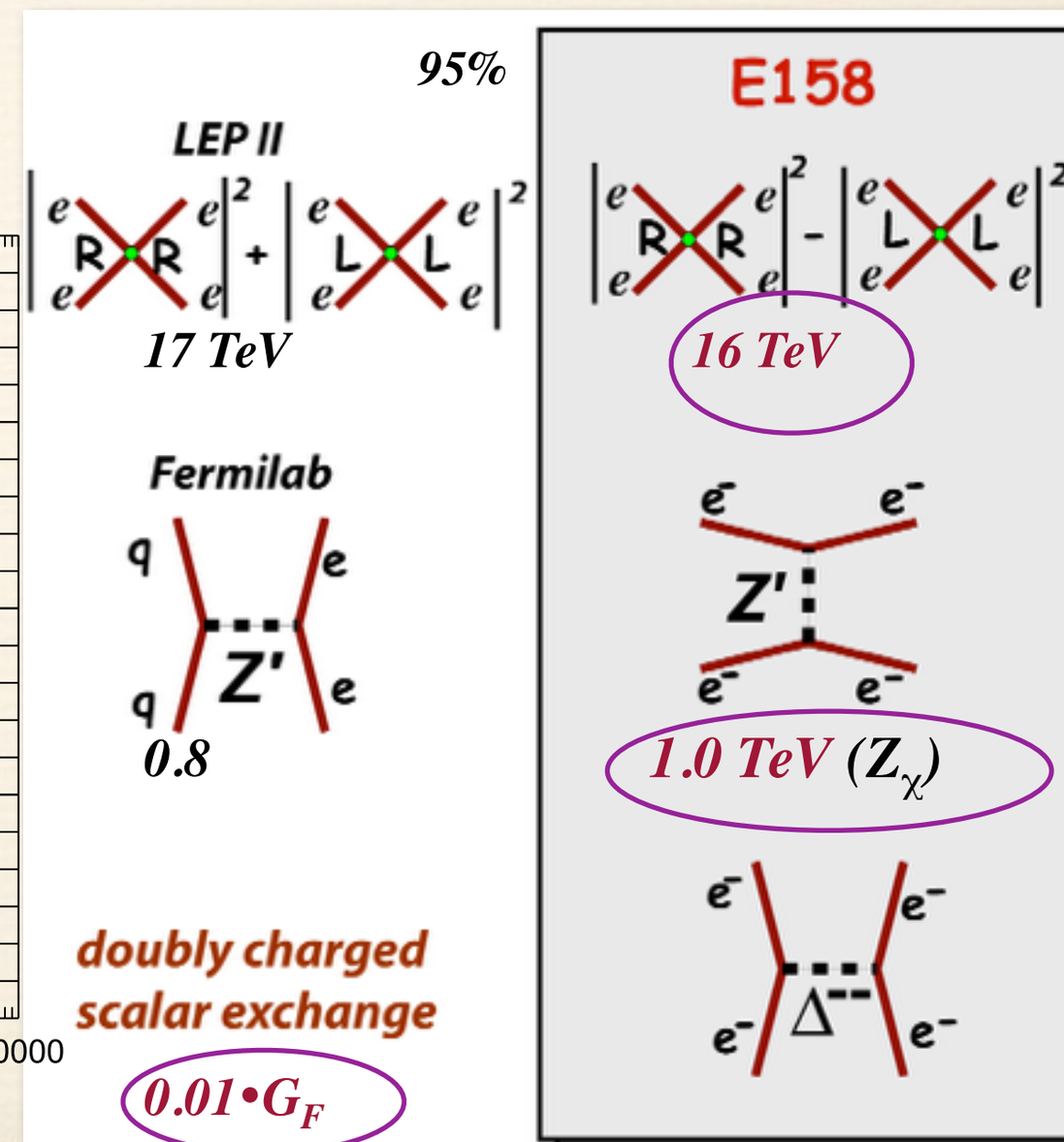
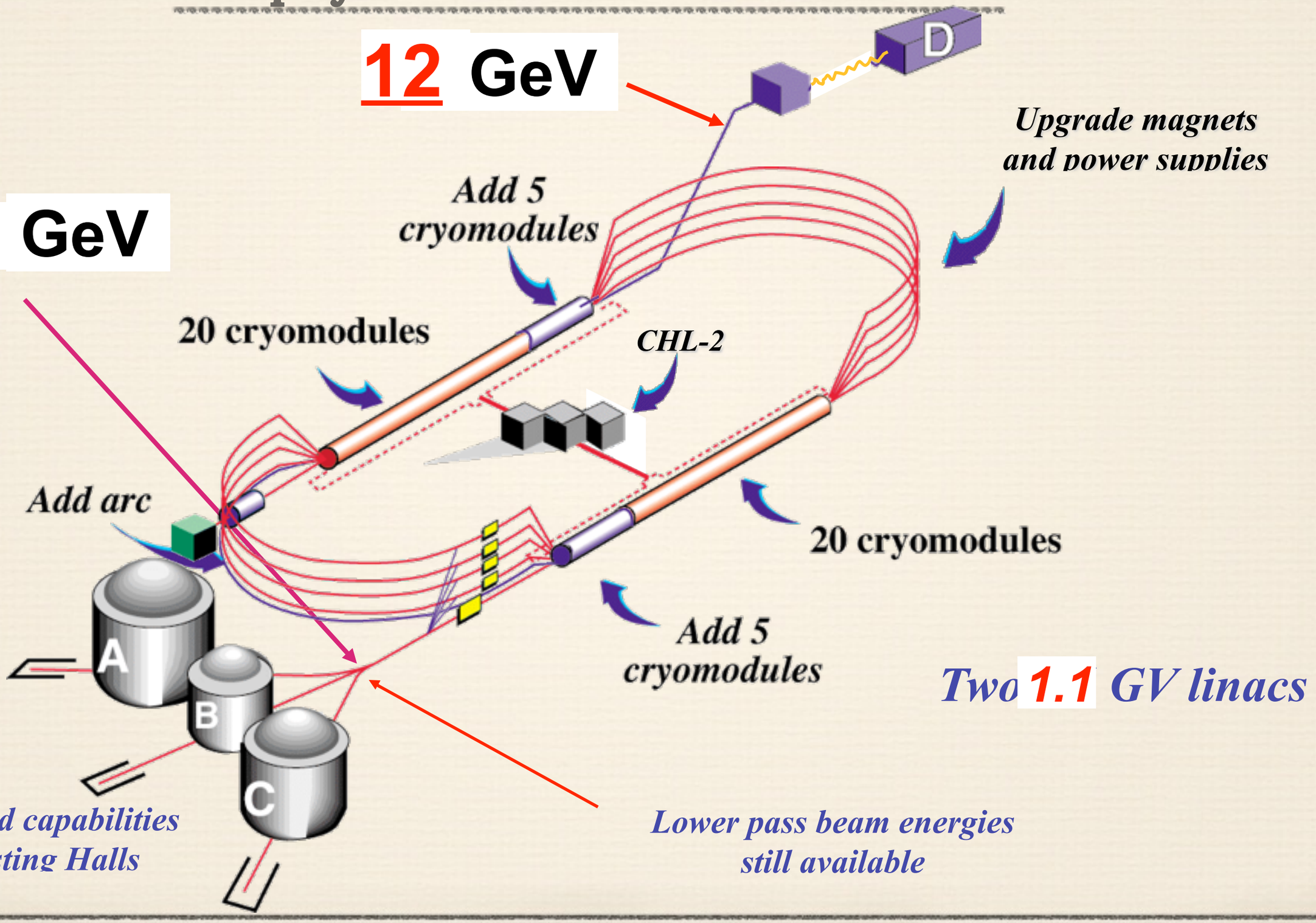




The 12 GeV Upgrade of JLab

First physics beams to Hall A in 2014



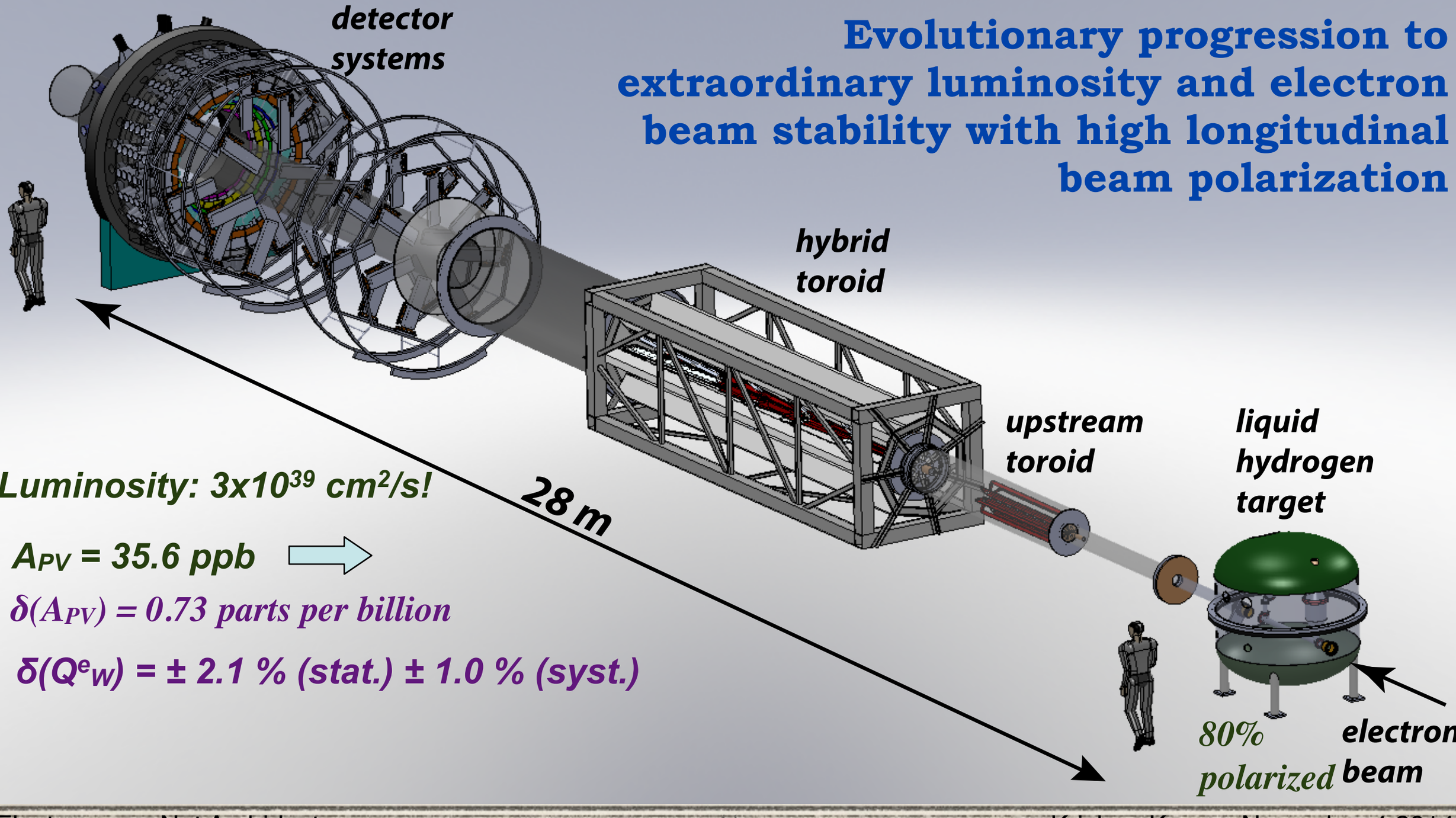
An ultra-precise measurement of the weak mixing angle using Møller scattering

11 GeV Møller scattering

MOLLER at JLab

Measurement Of Lepton Lepton Electroweak Reaction

Unique opportunity leveraging the 12 GeV Upgrade investment



Evolutionary progression to extraordinary luminosity and electron beam stability with high longitudinal beam polarization

Luminosity: 3×10^{39} cm^2/s!

A_{PV} = 35.6 ppb ⇨

$\delta(A_{PV})$ = 0.73 parts per billion

$\delta(Q^e_W) = \pm 2.1\ \%\ (stat.) \pm 1.0\ \%\ (syst.)$

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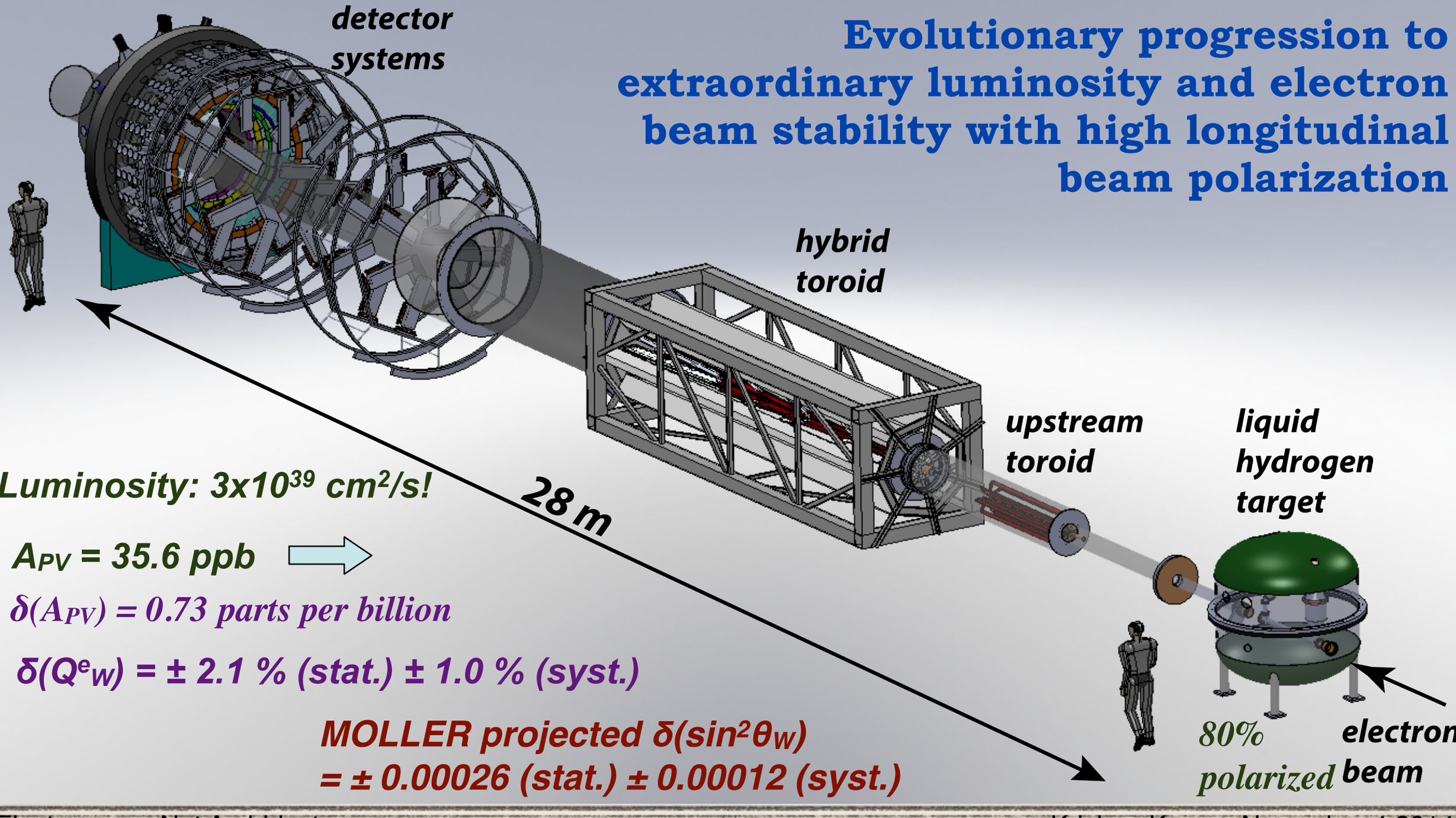

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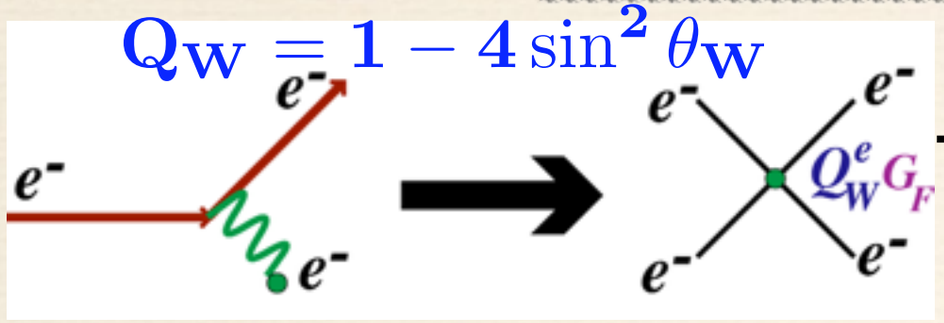
MOLLER projected $\delta(\sin^2\theta_W)$ = ± 0.00026 (stat.) ± 0.00012 (syst.)

best contact interaction reach for leptons at low OR high energy

MOLLER Physics Reach

sensitive to SUSY, doubly-charged scalars, heavy Z' bosons, light dark Z's...

$$Q_W = 1 - 4\sin^2\theta_W$$



$$+ \quad \frac{1}{\Lambda^2}\mathcal{L}_6 \quad \Rightarrow \quad \mathcal{L}_{e_1 e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2} \bar{e}_i \gamma_\mu e_i \bar{e}_j \gamma^\mu e_j$$

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

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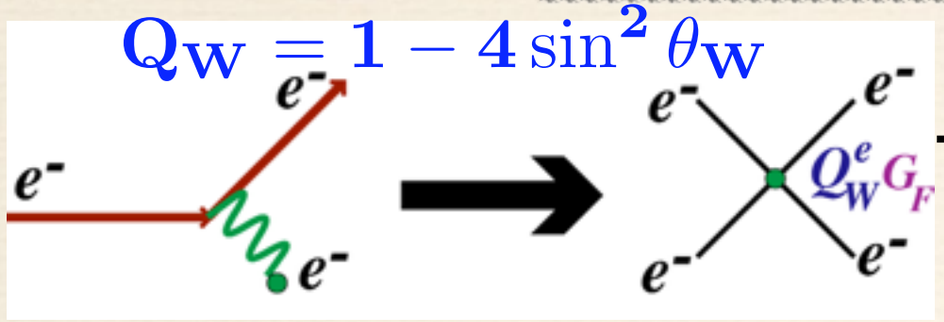

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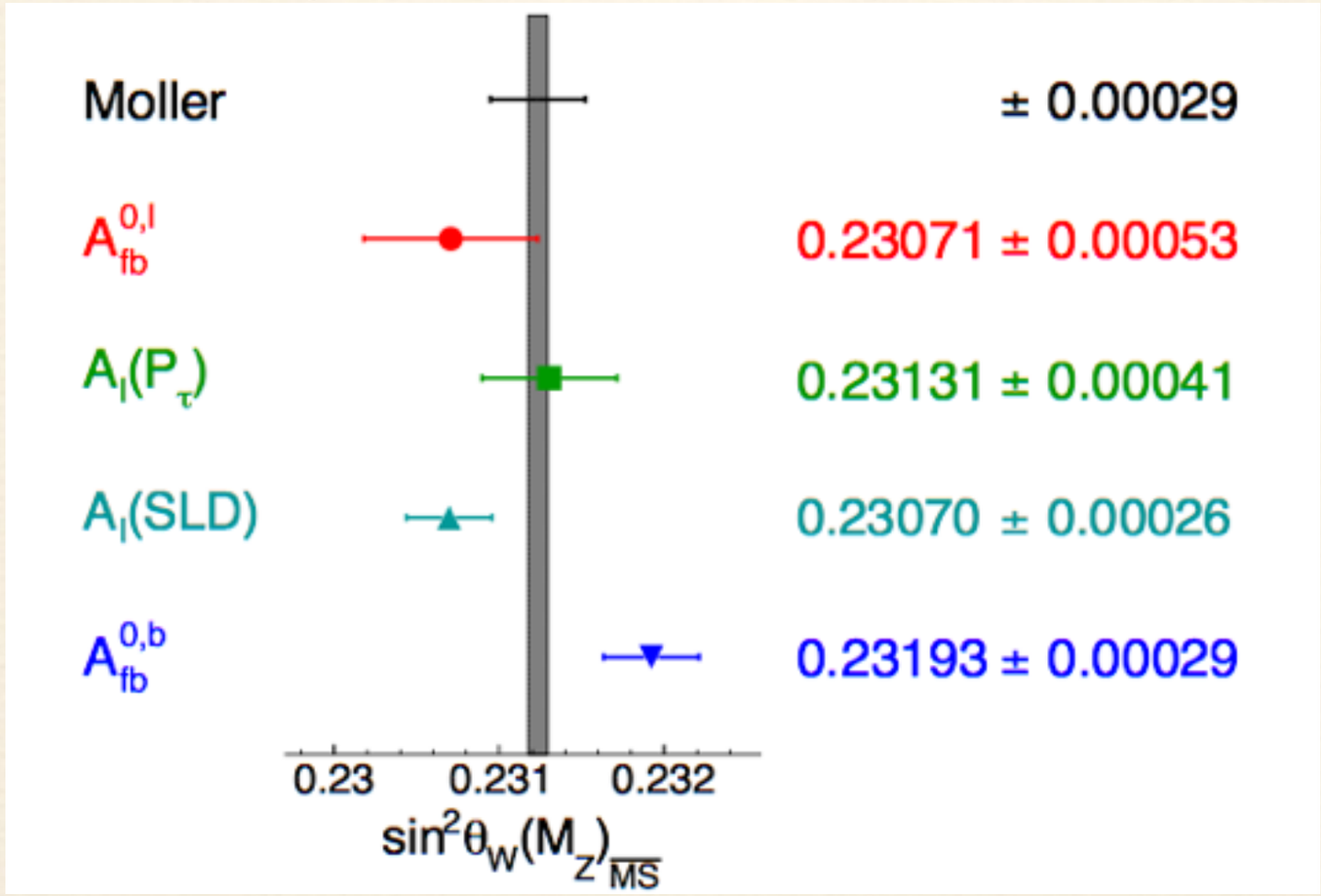
An independent measurement of the weak mixing angle with precision comparable to the two best collider measurements



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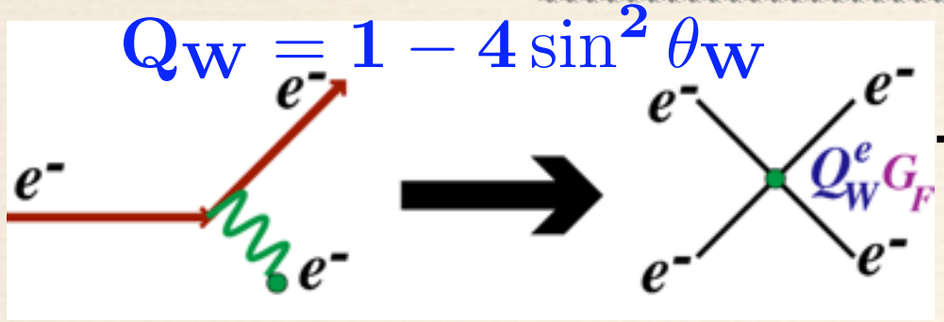

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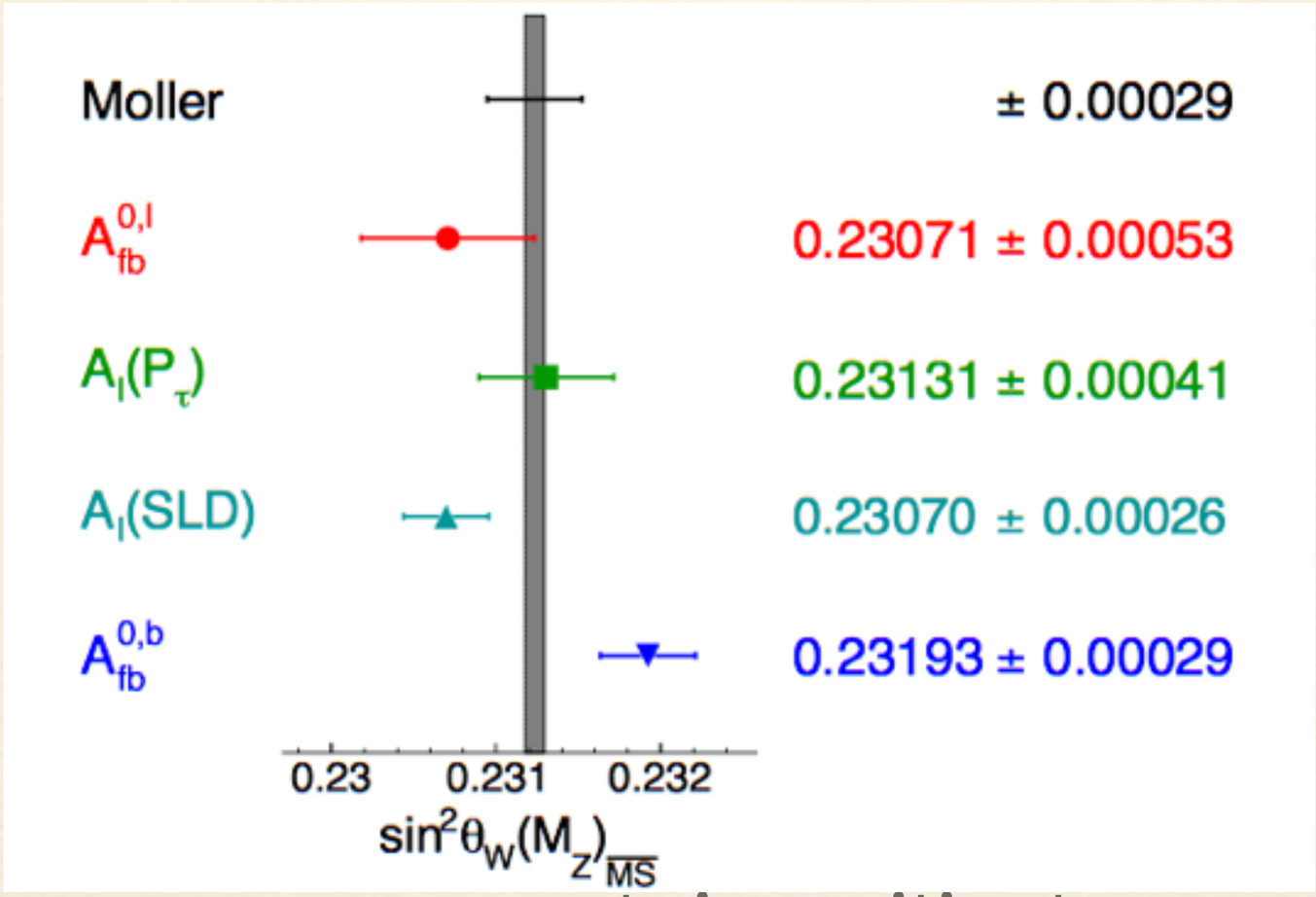


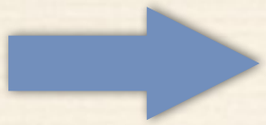
However, Z resonance measurements insensitive to new contact interactions

Unique opportunity leveraging the 12 GeV Upgrade investment

Best Low Q^2 Reach in Next Decade

$$Q_W^e \sim 0.045$$

$$\frac{\delta Q_W^e}{Q_W^e} = 2.4\%$$



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unprecedented sensitivity

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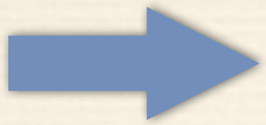

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MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider or neutrino factory

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Best Low Q^2 Reach in Next Decade

$\delta(\sin^2\theta_W) = \pm 0.00024\ (stat.) \pm 0.00013\ (syst.) \Rightarrow \sim 0.1\%$

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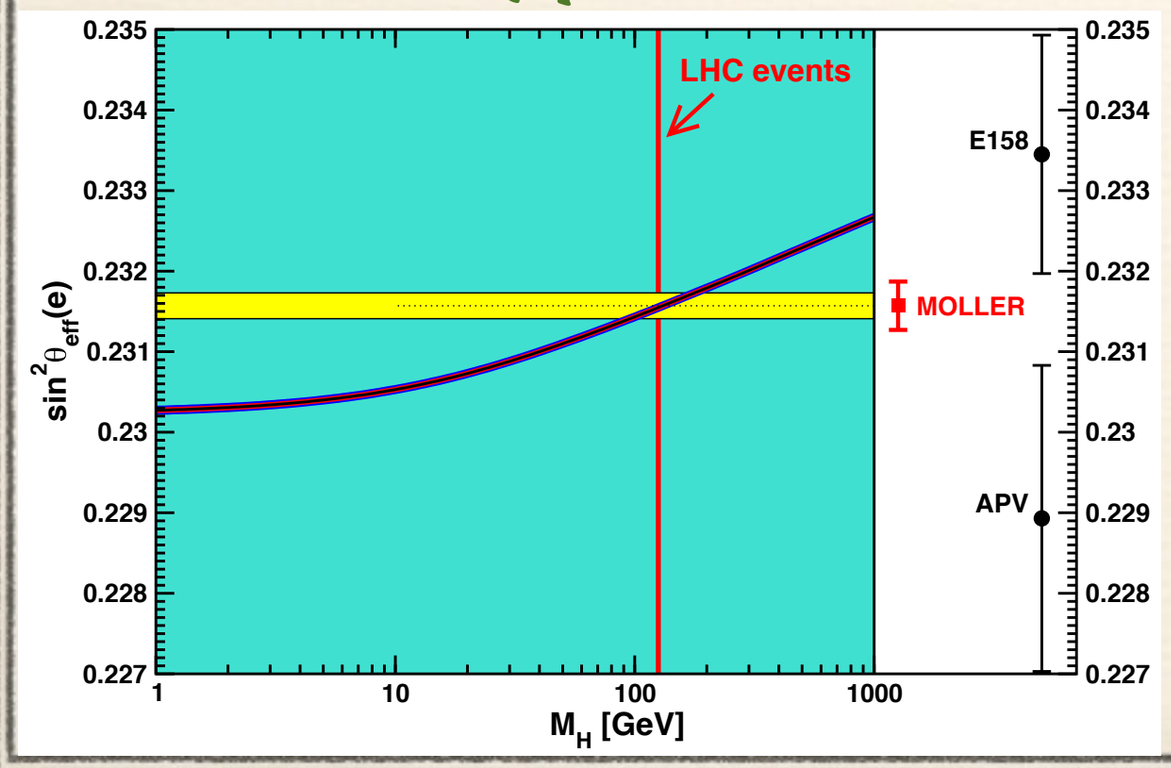
± 10σ discovery potential at $Q^2 << M_Z^2$



Future projections, similar time scale:

Mainz P2: ~ 0.00034

Final Tevatron: ~ 0.00041

LHC 14 TeV, 300 fb^{-1} : ~ 0.00036

Note: systematics-dominated (pdf uncertainties)

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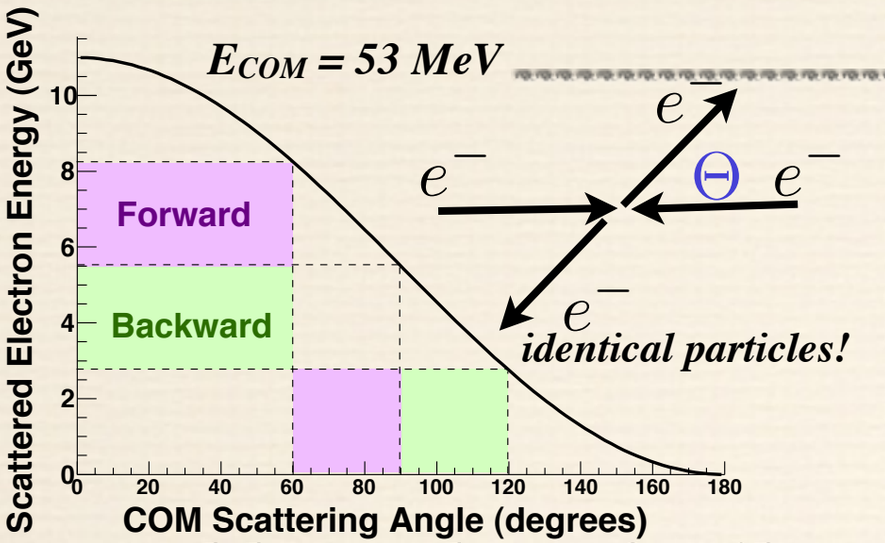
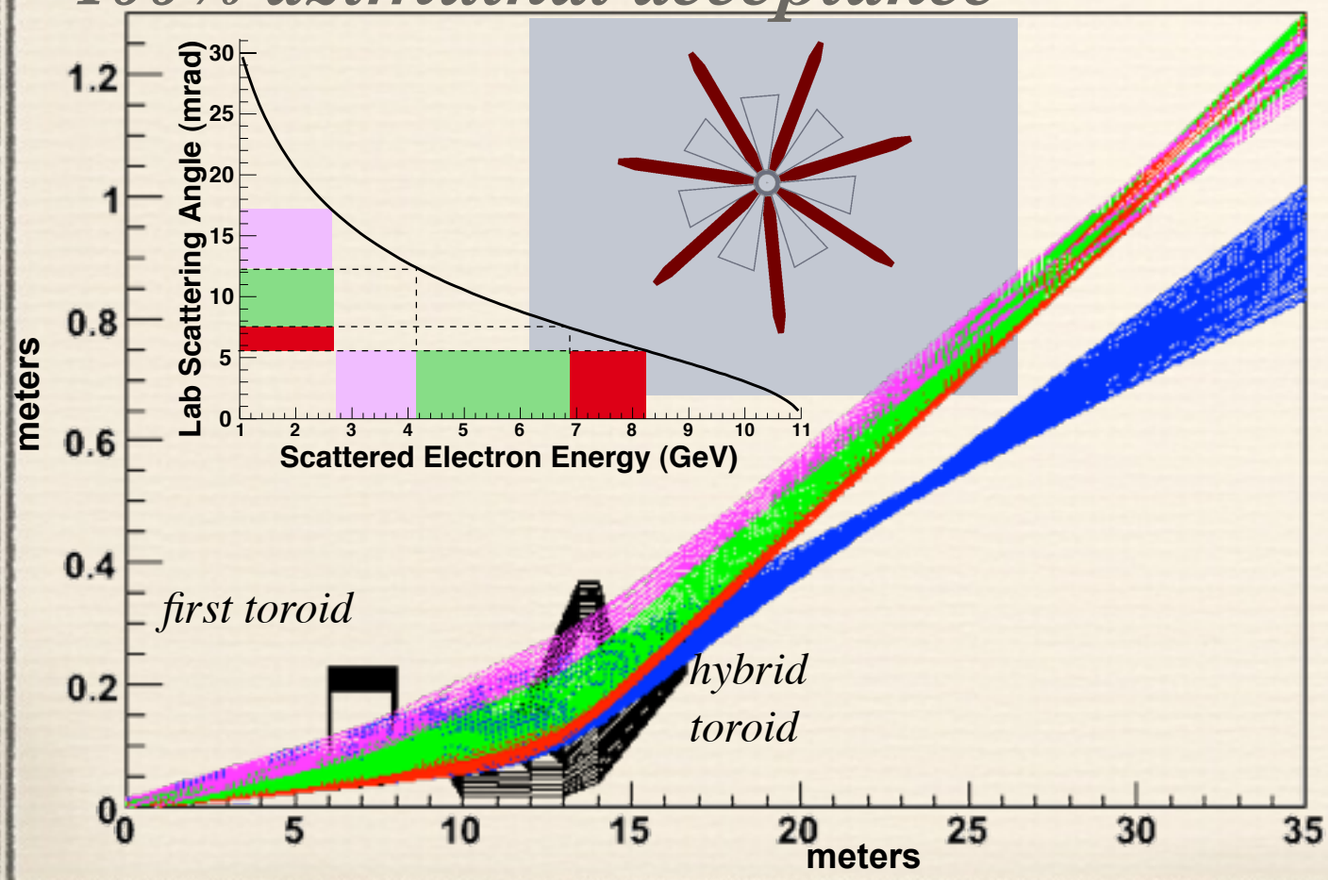
collaboration between U. Manitoba, Stony Brook and MIT

Unique Spectrometer Concept



odd number of coils:

100% azimuthal acceptance



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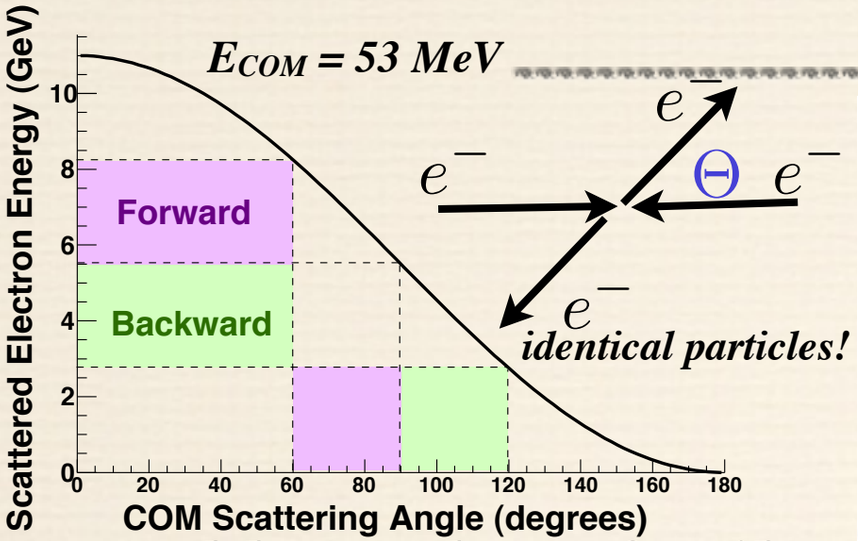

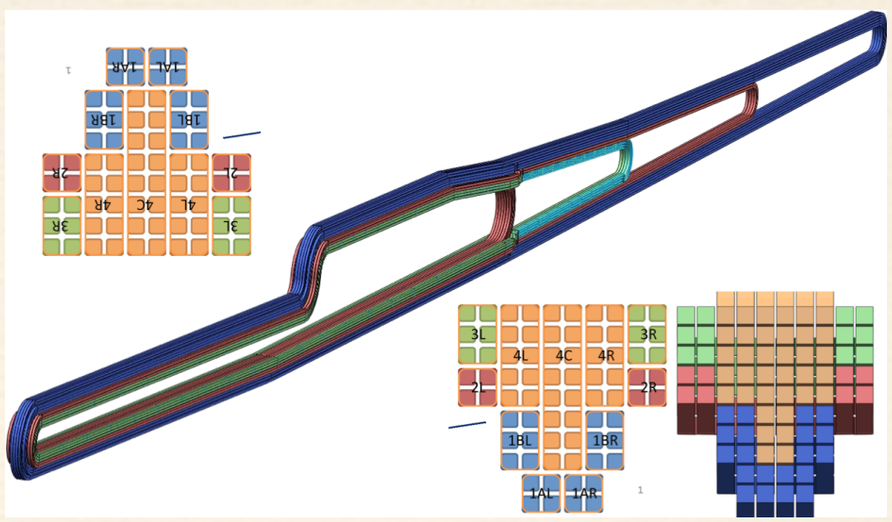

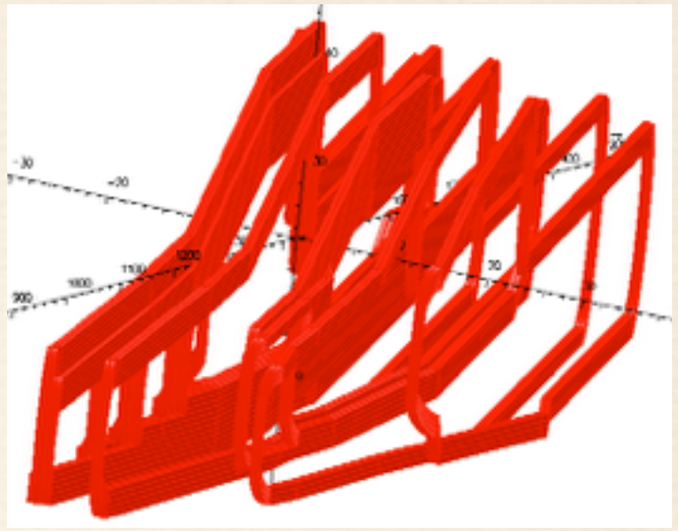

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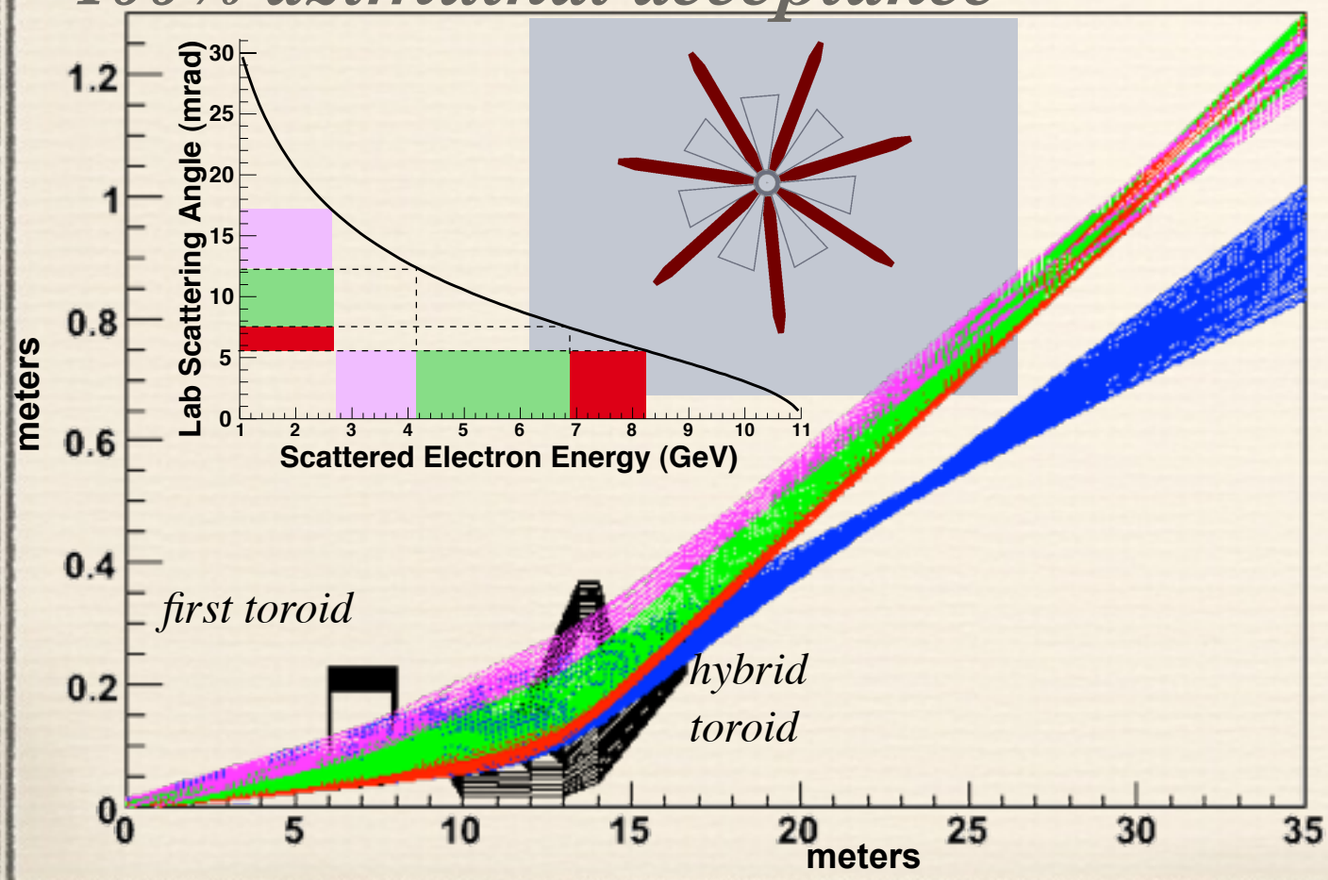

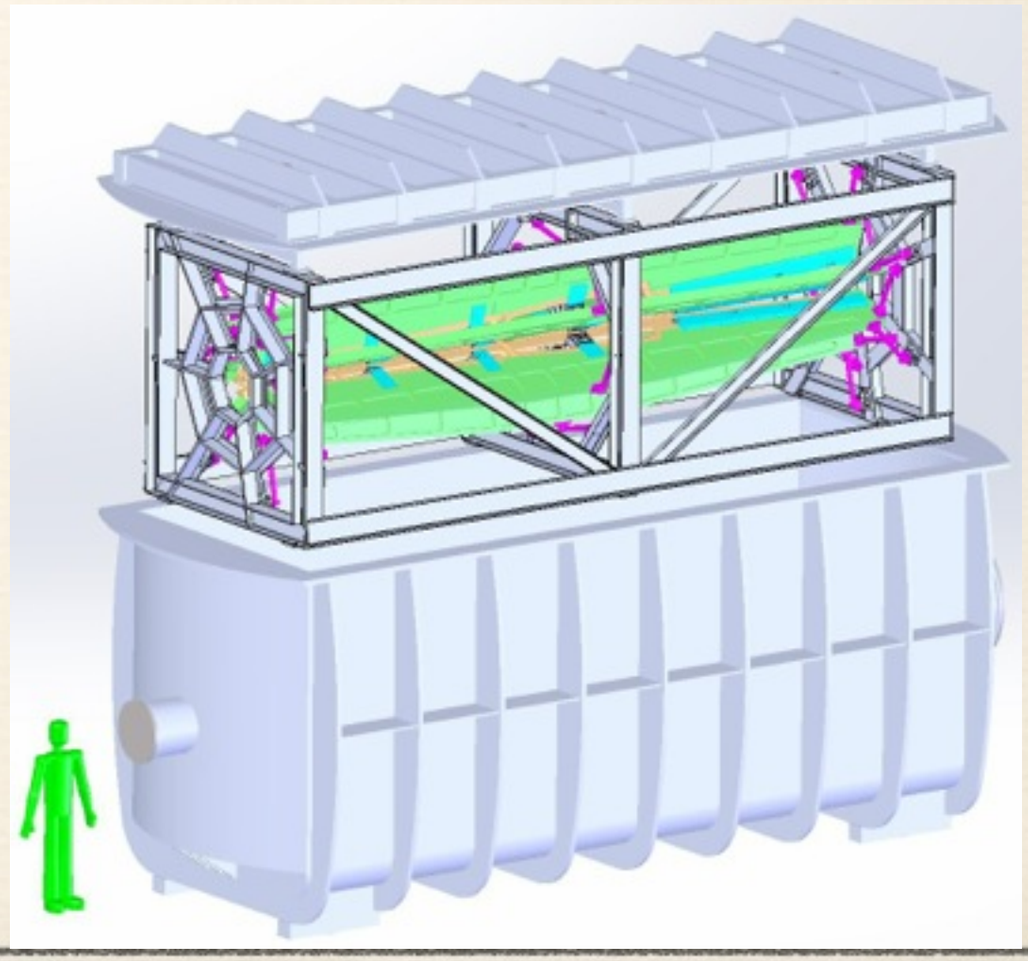

Expertise from several generations of successful parity experiments

MOLLER Status

~120 Collaborators, 30 institutions, 6 countries

Technical Challenges

- ~ 150 GHz scattered electron rate
  - Design to flip Pockels cell ~ 2 kHz
  - 80 ppm pulse-to-pulse fluctuations
- 1 nm control of beam centroid on target
  - Novel "slow helicity reversal" methods
- > 10 gm/cm^2 liquid hydrogen target
  - 1.5 m: ~ 5 kW @ 85 μA
- Full Azimuthal acceptance; θ_{lab} ~ 5 mrad
  - novel two-toroid spectrometer
  - radiation hard, highly segmented integrating detectors
- Redundant 0.4% beam polarimetry
  - Pursue both Compton and Atomic Hydrogen techniques

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  - one of the theory talks by Bill Marciano
  - 6 panelists: T.W.Donnelly, D.Hertzog, C.Horowitz, Z-T.Lu, M.Perelstein, T. Rizzo
  - Positive outcome: unique opportunity highlighted, small theory uncertainty, importance of achieving proposed error bar

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Error Source	Fractional Error (%)
Statistical	**2.1**
Absolute Normalization of the Kinematic Factor	0.5
Beam (second order)	0.4
Beam polarization	0.4
$e + p(+\gamma) \rightarrow e + X(+\gamma)$	0.4
Beam (position, angle, energy)	0.4
Beam (intensity)	0.3
$e + p(+\gamma) \rightarrow e + p(+\gamma)$	0.3
$\gamma^{(*)} + p \rightarrow (\pi, \mu, K) + X$	0.3
Transverse polarization	0.2
Neutral background (soft photons, neutrons)	0.1
Total systematic	**1.1**

All systematics required at sub-1% level

MOLLER is a unique opportunity enabled by the 12 GeV Upgrade

MOLLER Summary

Cannot be done elsewhere in the world

Parameter	Noise (75 μA)	Noise (60 μA)
Statistical Width (0.5 ms)	**~79 ppm**	**~89 ppm**
Target Density Fluctuation	26 ppm	21 ppm
Beam Intensity Resolution	10 ppm	10 ppm
Beam Position Noise	7 ppm	7 ppm
Detector Resolution (25%)	3.1%	3.1%
Electronics Noise	10 ppm	10 ppm
Measured Width	**88 ppm**	**95 ppm**

60 μA, 90% polarization

Run Phases	1 kHz Width	PAC Days (prod)	Stat Error (ppb)	Stat Error (%)	Eff %	Calendar Weeks (prod.)	Comm Weeks	Total Weeks
I	105	14	3.09	10.9	40	5	6	11
II	100	95	1.13	3.9	50	27	3	30
III	95	235	0.68	2.4	60	56	4	60
Total		**344**	**0.57**	**2.01**			**13**	**101**

Commissioning + 3 years (~30 weeks/year)

✦ Scientific Significance

- ★ Unique observable and among the most sensitive in terms of discovery reach, for flavor- and CP-conserving scattering amplitudes, in the next decade
- ★ Textbook legacy

✦ Scope of Future Research Effort

- ★ Purely Leptonic Reaction: theoretical uncertainty already well under control
- ★ A strong, experienced and motivated group of experimental researchers

✦ Feasibility and Three Year Science Output

- ★ Evolutionary development of technical capabilities to reach unprecedented sensitivity

Perspective on Future PVES

MOLLER, SOLID, P2

Sensitive discovery reach over the next decade
for CP-/flavor-conserving and LNV scattering amplitudes

✦ If LHC sees ANY anomaly in Runs 2 or 3 (~2022)

- ★ The unique discovery space probed will become a pressing need, along with other sensitive low energy probes (e.g. g-2 anomaly)

✦ Discovery scenarios beyond LHC signatures

- ★ Hidden weak scale scenarios
- ★ Lepton Number Violating Amplitudes
- ★ Light Dark Matter Mediators
- ★ ...

Summary

✦ Parity-Violating Electron Scattering

- ★ Enabled unique studies of the weak force
- ★ Technical progress has enabled unprecedented precision
- ★ flagship experiments at electron accelerators

✦ Fundamental Nuclear/Nucleon Physics

- ★ Neutron RMS radii of heavy nuclei (PREX, CREX)
- ★ valence quark structure of protons and neutrons (SOLID)

✦ Fundamental Electroweak Physics

- ★ Search for new dynamics at the TeV scale (MOLLER, SOLID, P2)
  - *complementary to colliders; would help interpret potential anomalies*
  - *precision measurement of the weak mixing angle*

A remarkably productive research program that will continue to flourish over the next decade