Acknowlegements:
PREX/CREX and MOLLER Collaborations, C. Gal, C. Horowitz, C. Palatchi, B. Reed

Parity-Violating Electron Scattering off Nuclei

New Results from PREX and CREX at Jefferson Lab

Krishna Kumar
University of Massachusetts, Amherst

Precision Tests with Neutral Current Coherent Reactions with Nuclei
MITP Topical Workshop, May 23-27 2022

Outline

- ✦ **Elastic Electroweak Electron Scattering**
  - ★ The weak force component in electron scattering is parity-violating
  - ★ A wide range of particle and nuclear physics topics over 4 decades
  - ★ Newest application: neutron RMS radius of a heavy nucleus
- ✦ **The Latest Jefferson Laboratory Results**
  - ★ *PREX2: Precision Measurement on ^{208}Pb* (Phys.Rev.Lett. 126 (2021) 17, 172502)
  - ★ *CREX: Followup precision measurement on ^{48}Ca*
- ✦ **Implications and Outlook**

Outline

- ✦ **Elastic Electroweak Electron Scattering**
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  - ★ Newest application: neutron RMS radius of a heavy nucleus

Historical Perspective
~ 20 minutes

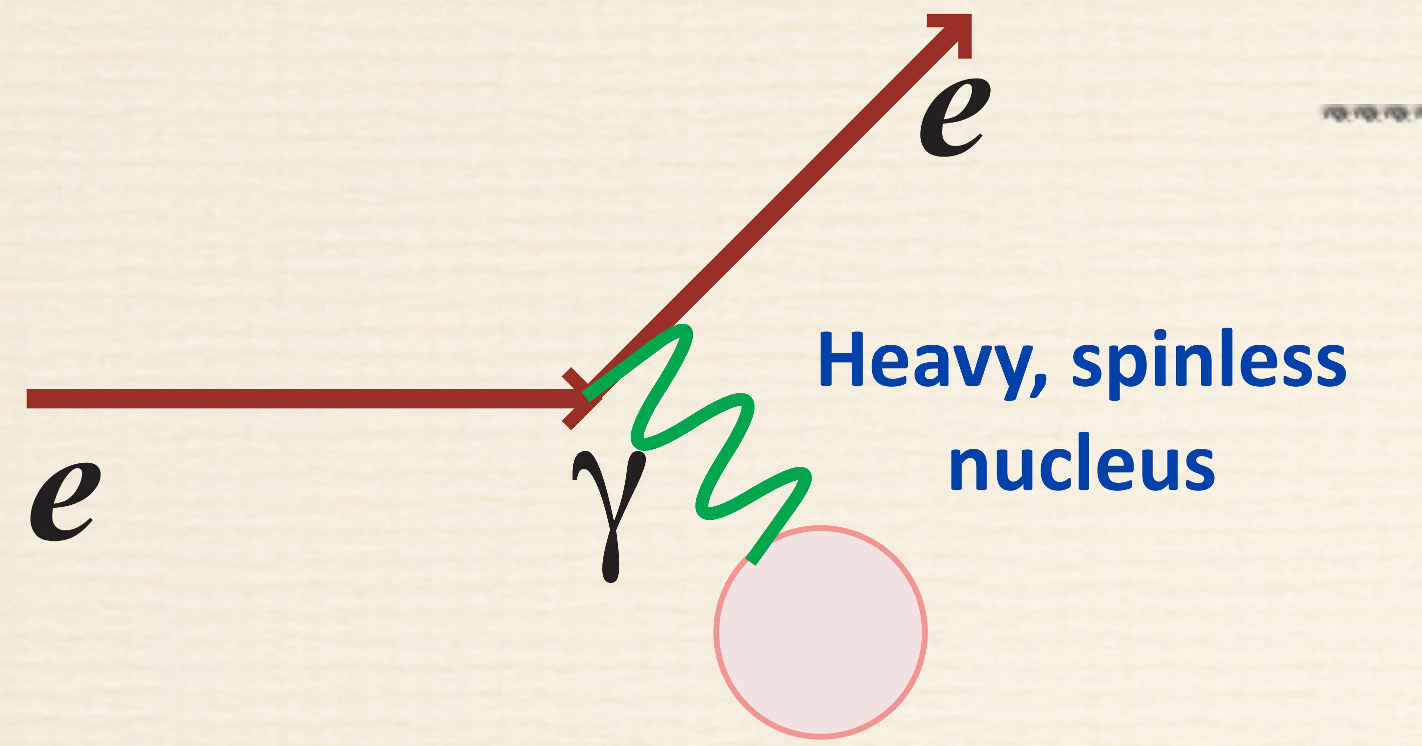
- ✦ **The Latest Jefferson Laboratory Results**
  - ★ *PREX2: Precision Measurement on ^{208}Pb* (Phys.Rev.Lett. 126 (2021) 17, 172502)
  - ★ *CREX: Followup precision measurement on ^{48}Ca* Paper submission to ArXiv and PRL TODAY!

Experimental Measurements
~ 25 minutes

- ✦ **Implications and Outlook** This can morph into a discussion session

Relativistic Electron Scattering

and nuclear size

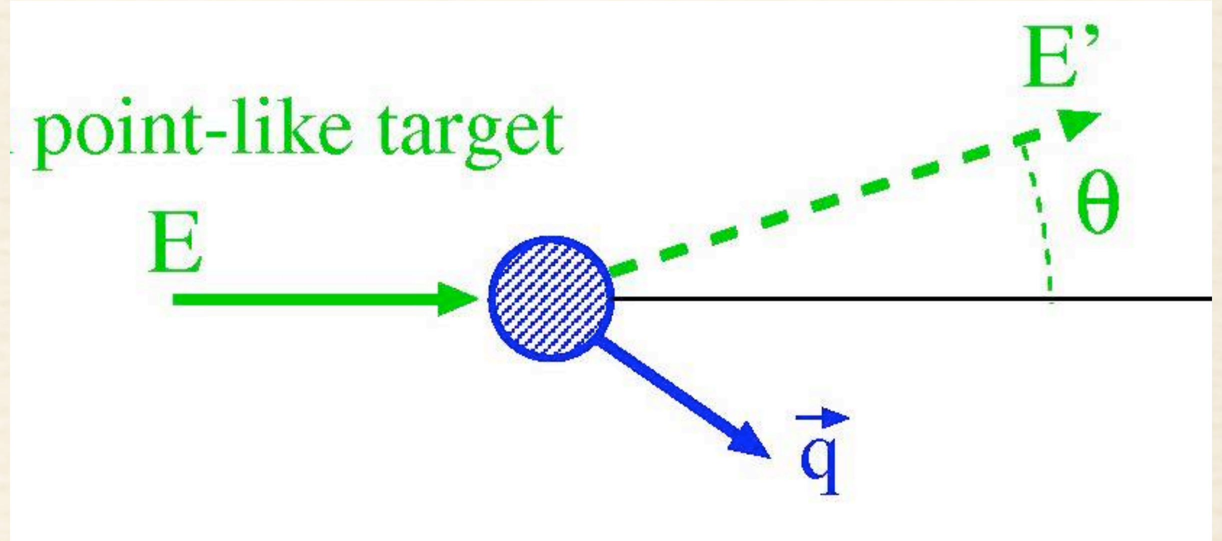


$$q^2 = -4EE'\sin^2\frac{\theta}{2}$$

4-momentum transfer

$$Q \approx \frac{hc}{\lambda}$$

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



Differential Cross Section

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

Relativistic Electron Scattering

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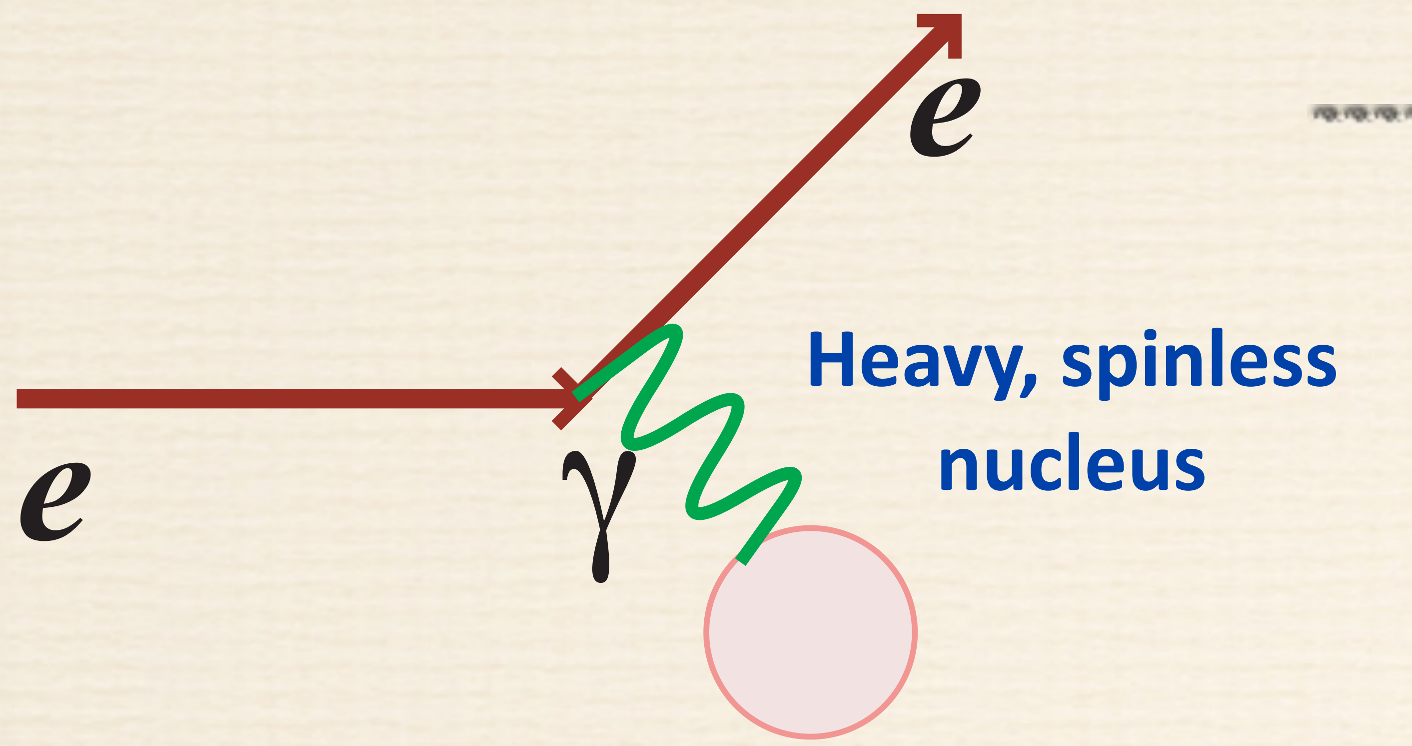

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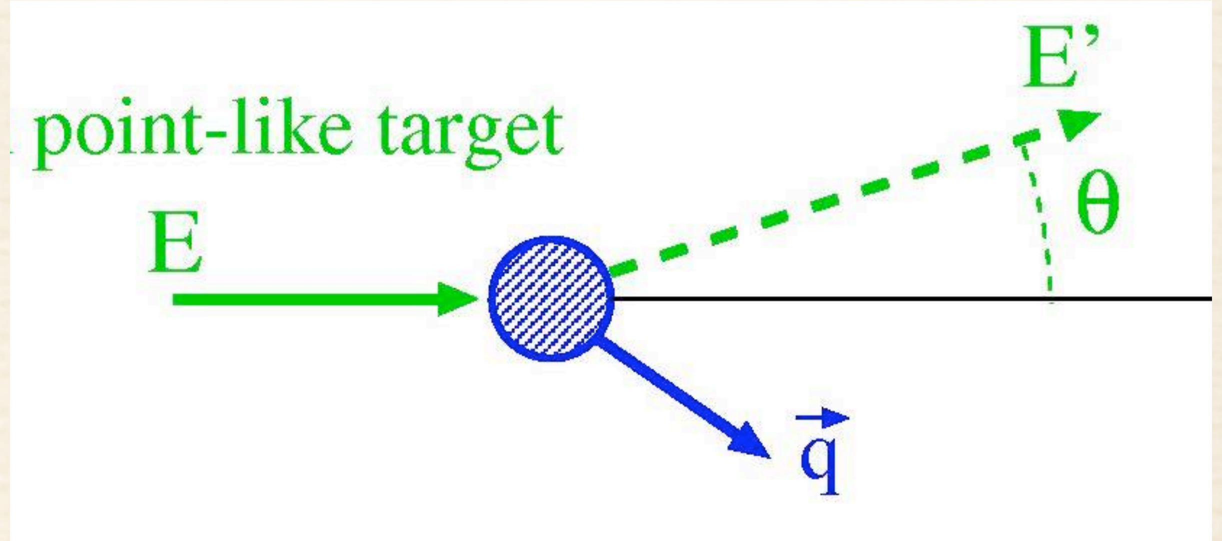

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As Q increases, nuclear size modifies formula

Neglecting recoil, form factor F(q) is the Fourier transform of charge distribution

Relativistic Electron Scattering

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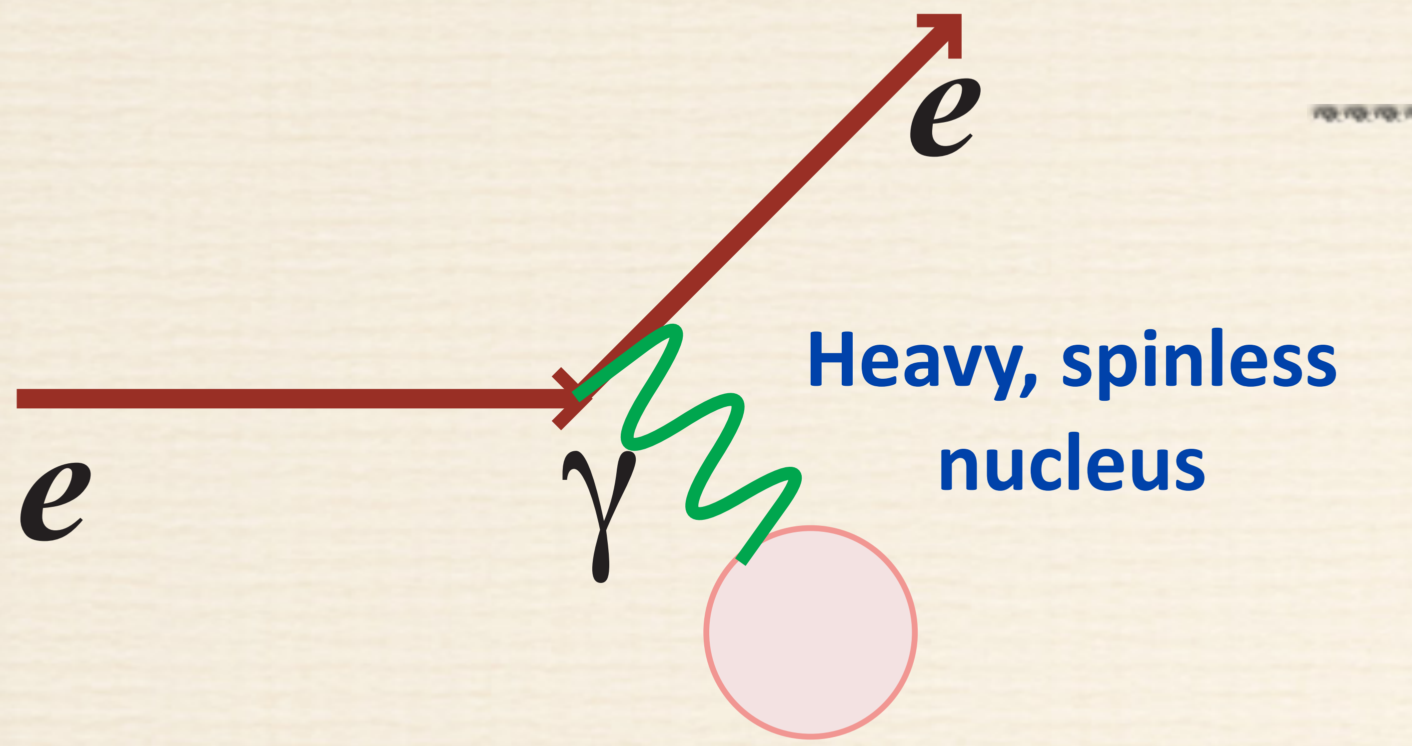

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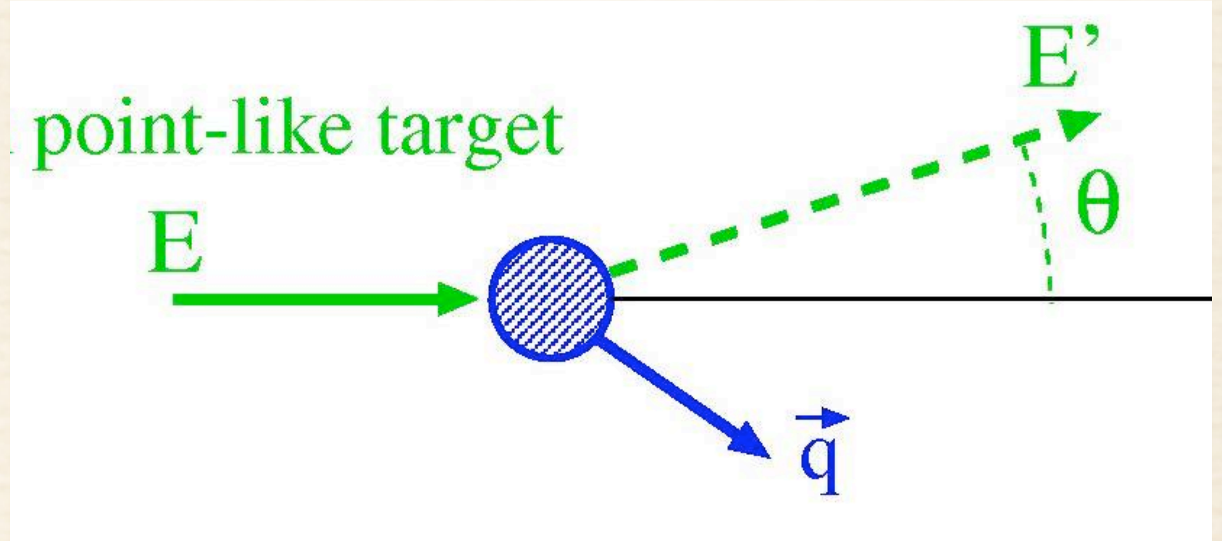

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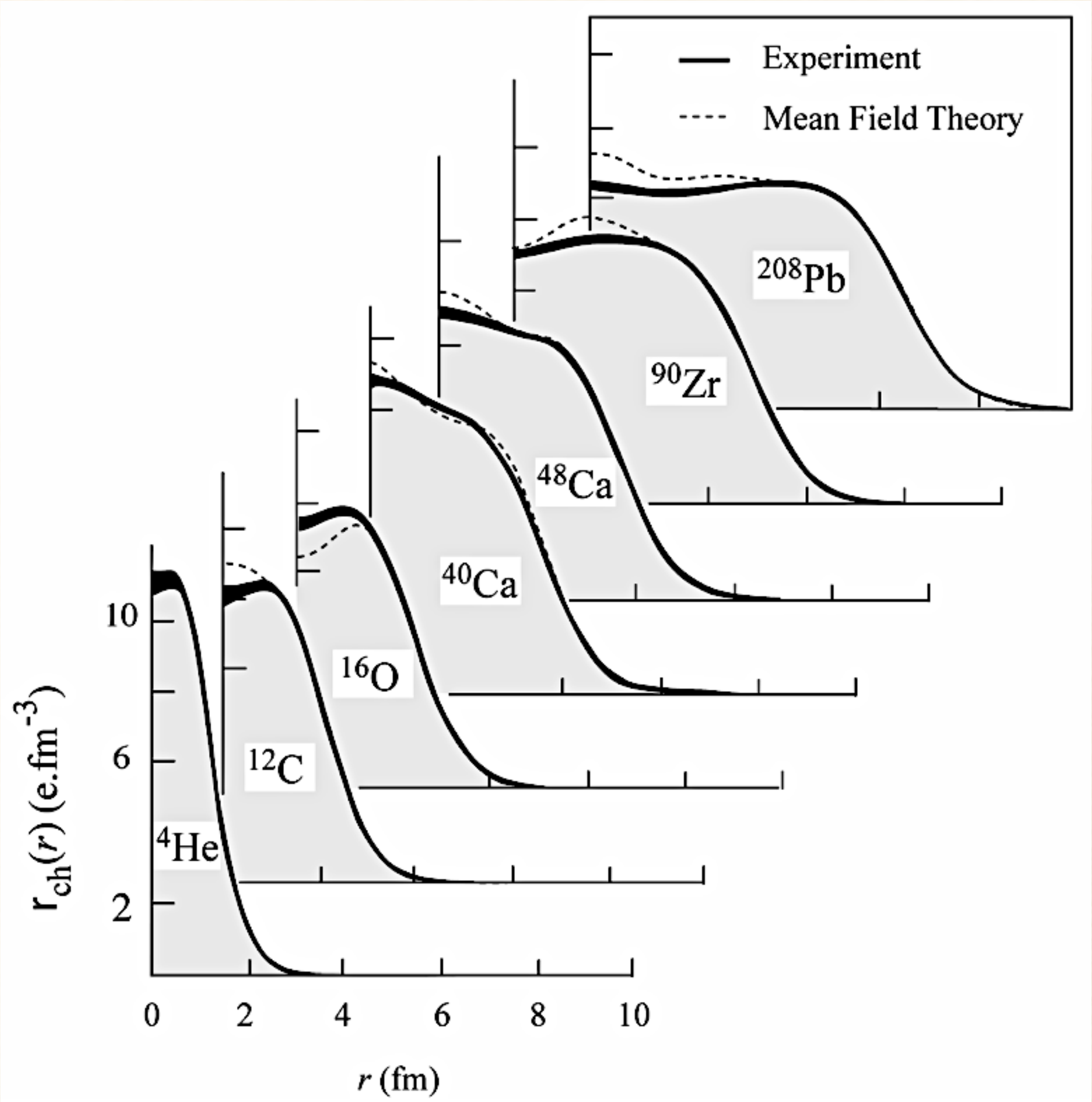

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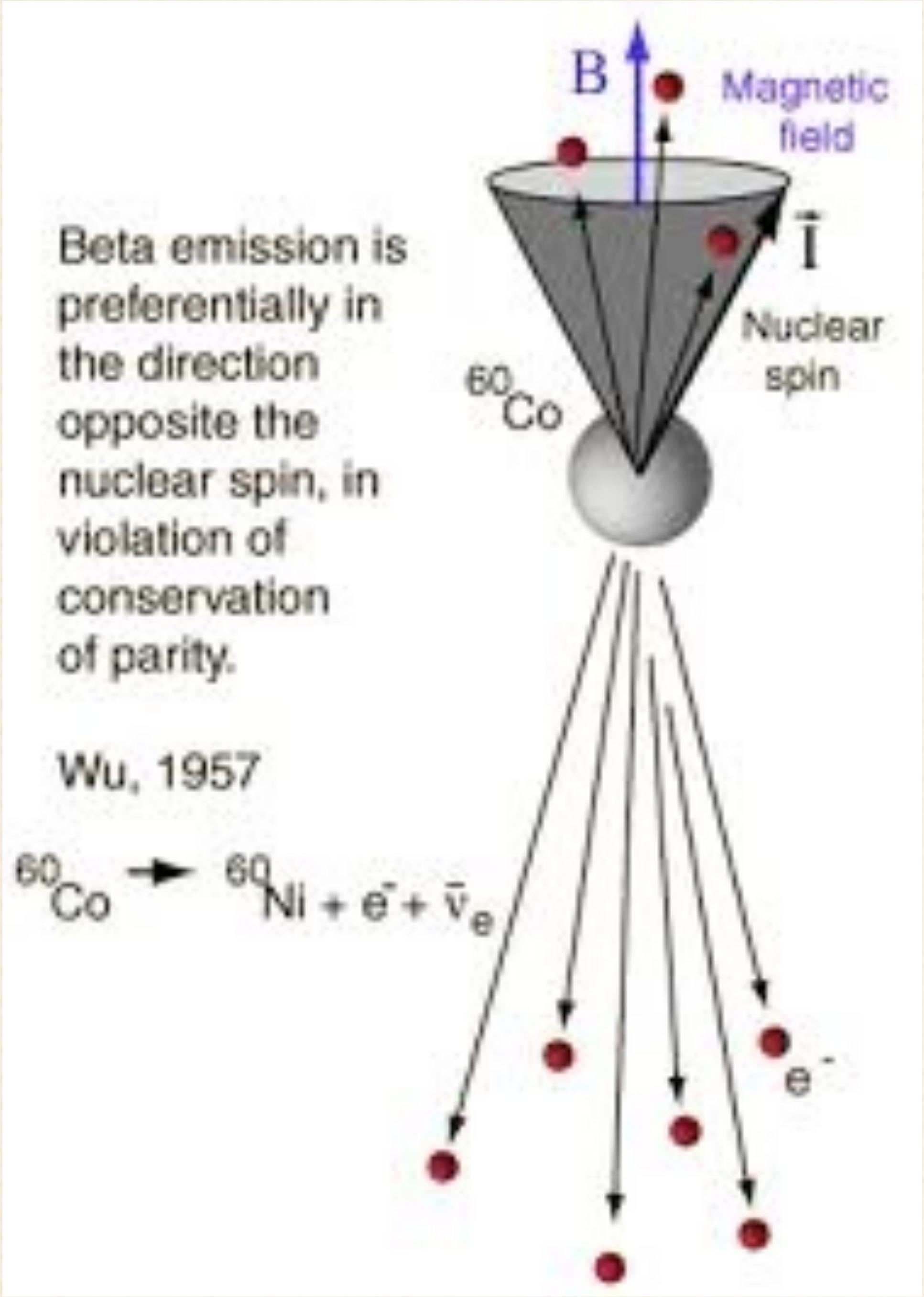
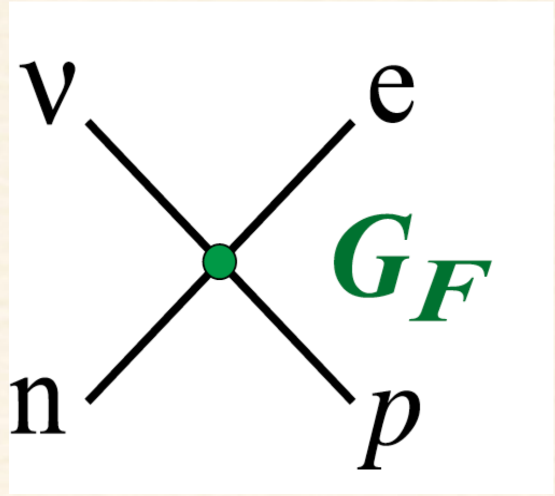
1958: Zel'dovich speculation: Is Electron Scattering Parity-Violating?

Electroweak Scattering



Nuclear β Decay



charge and flavor-changing

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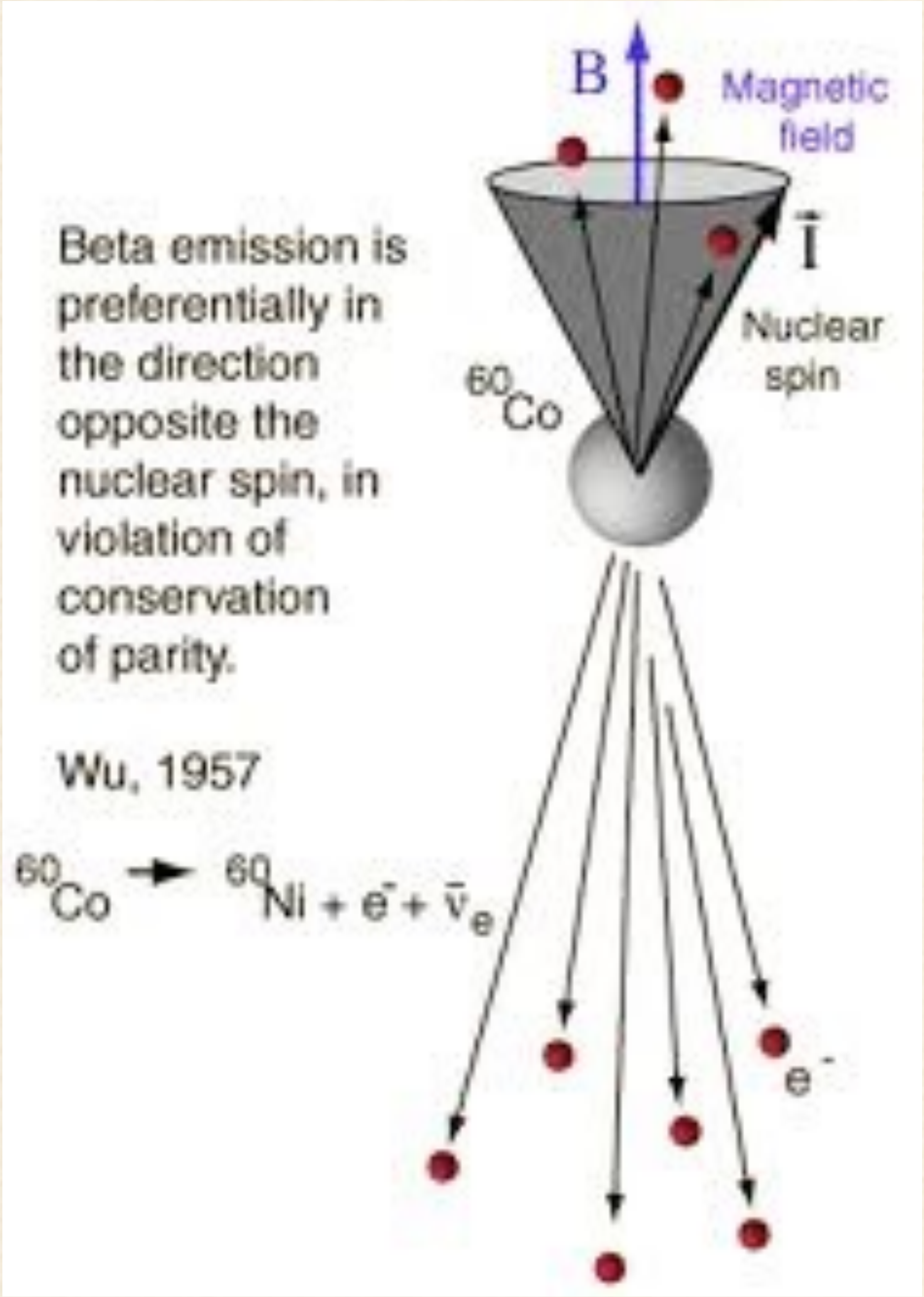

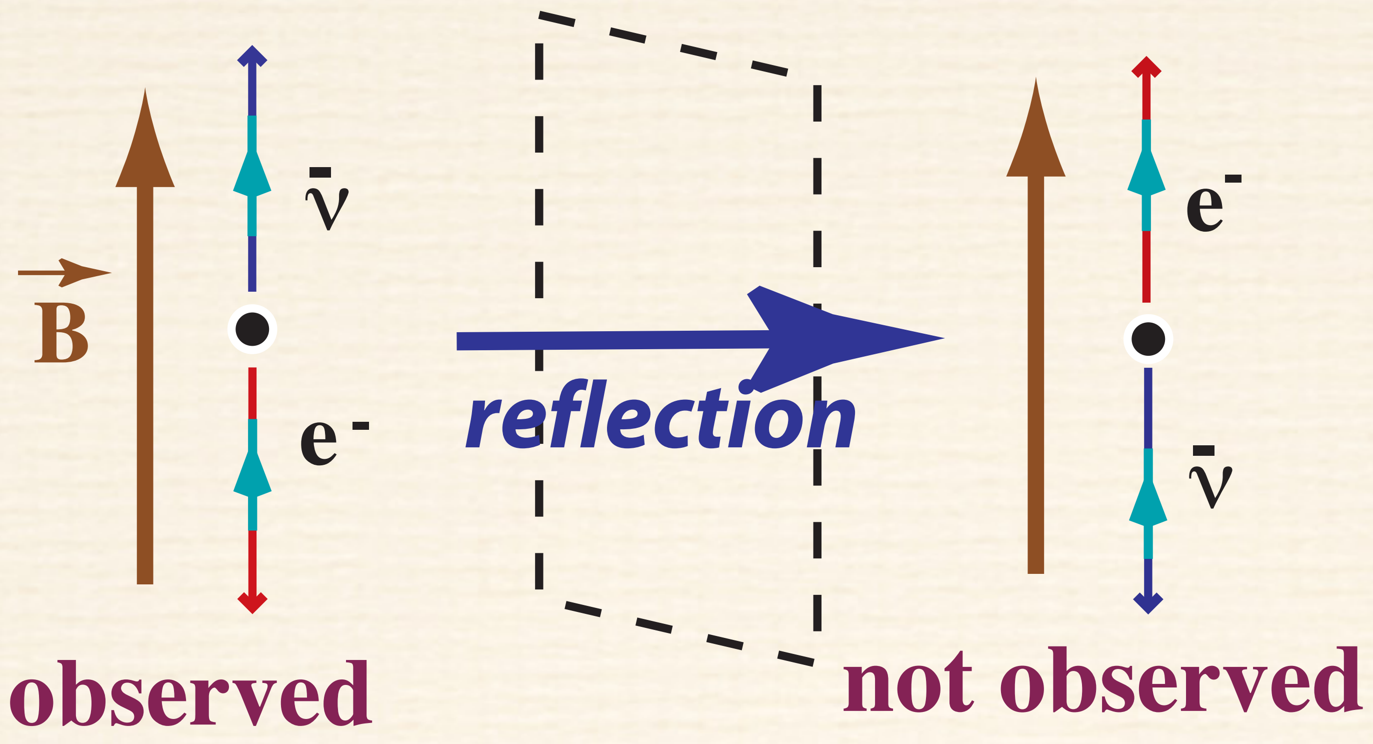

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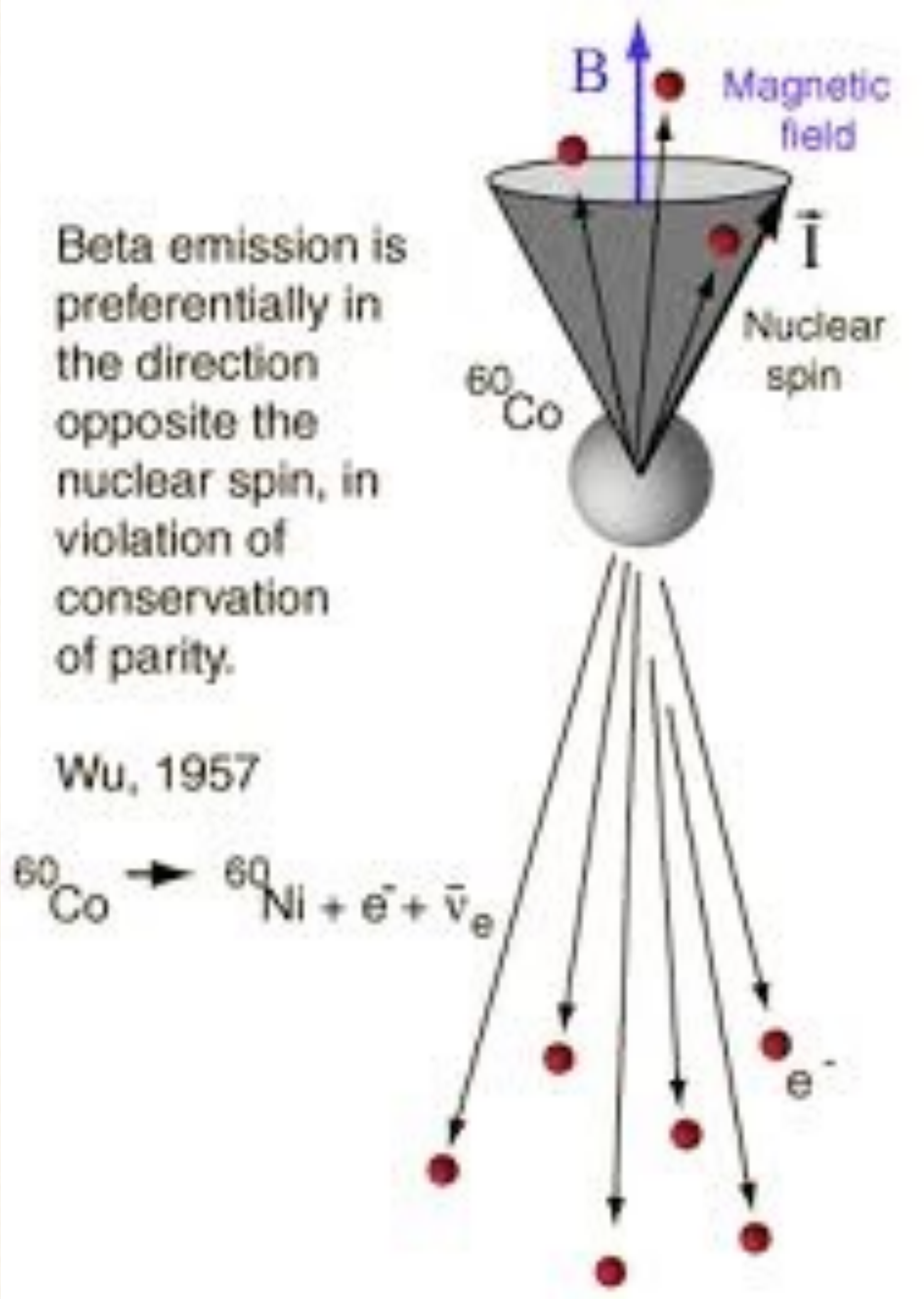
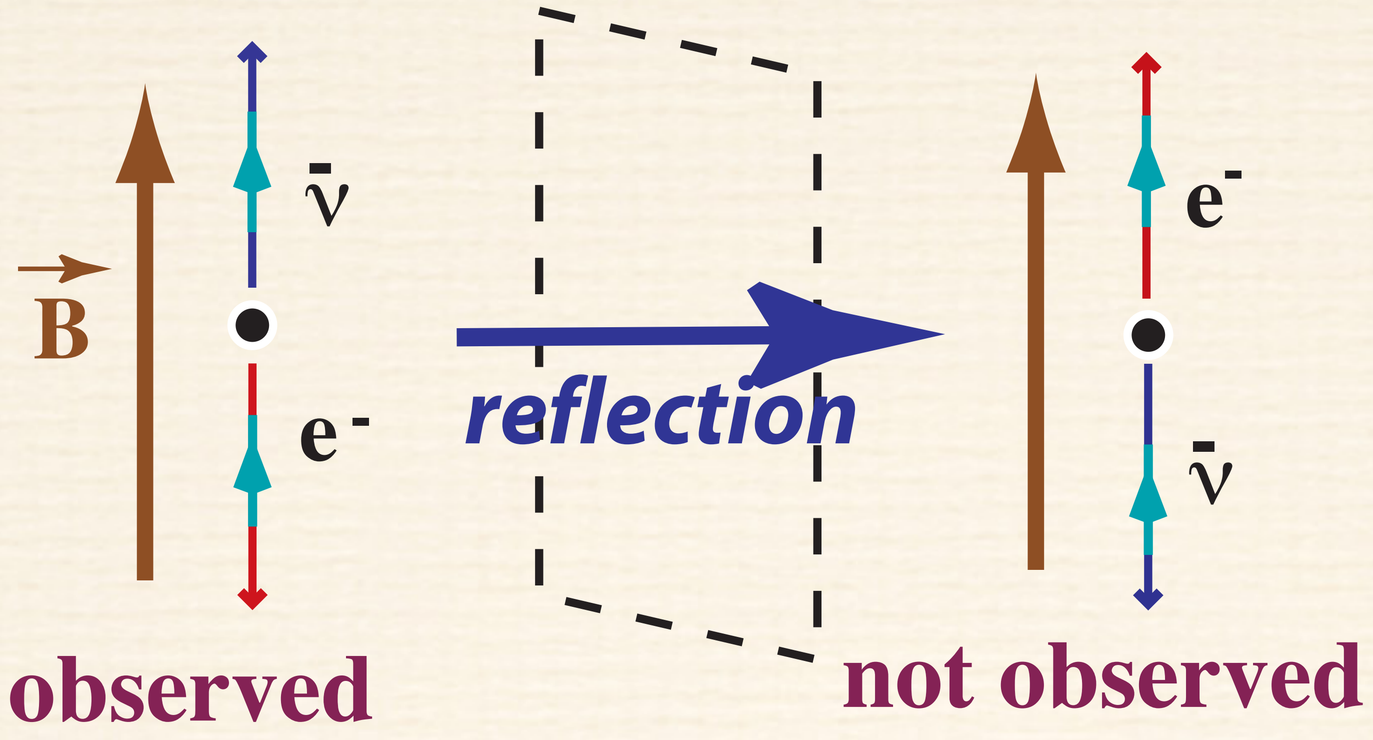
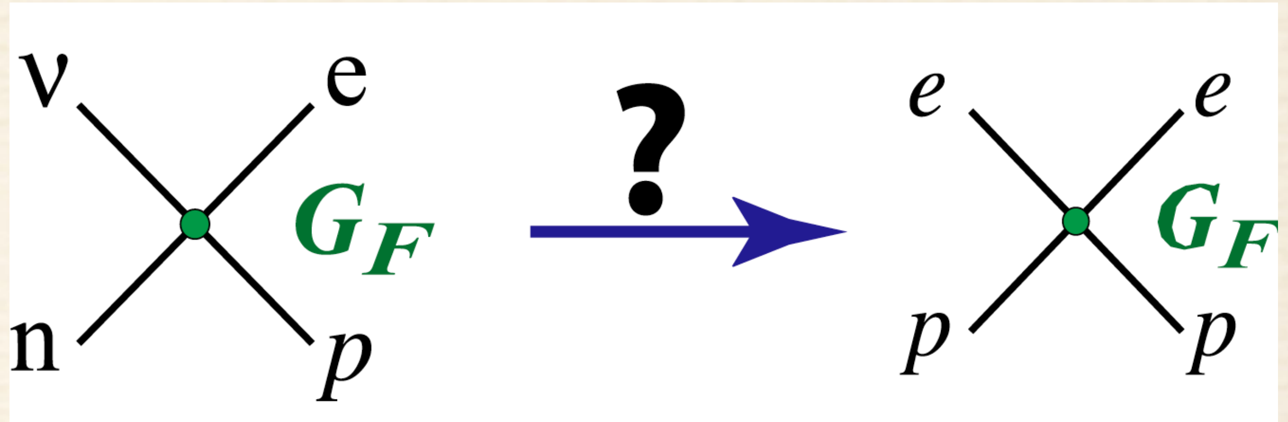




Neutron β Decay

Electron-proton Weak Scattering



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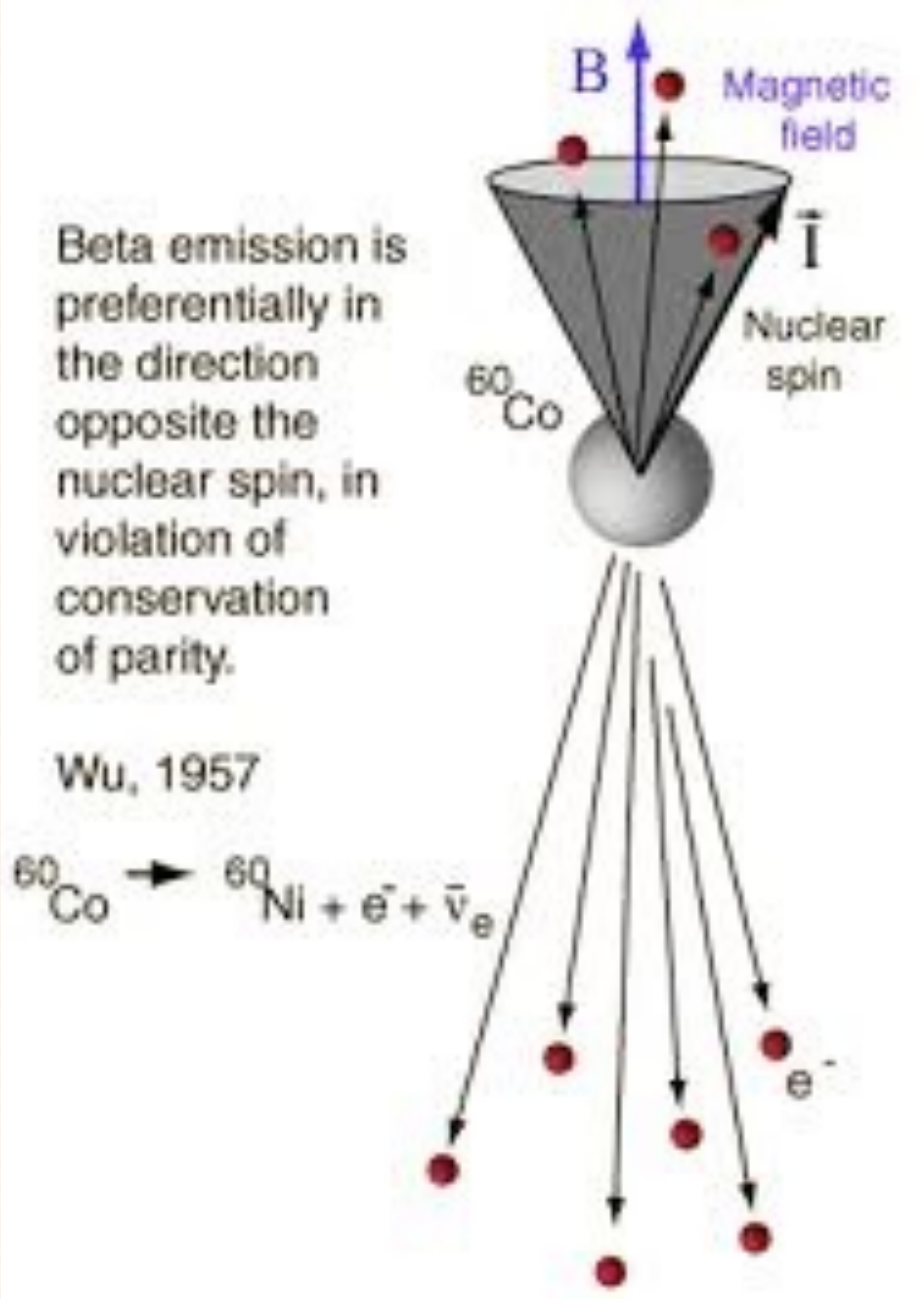

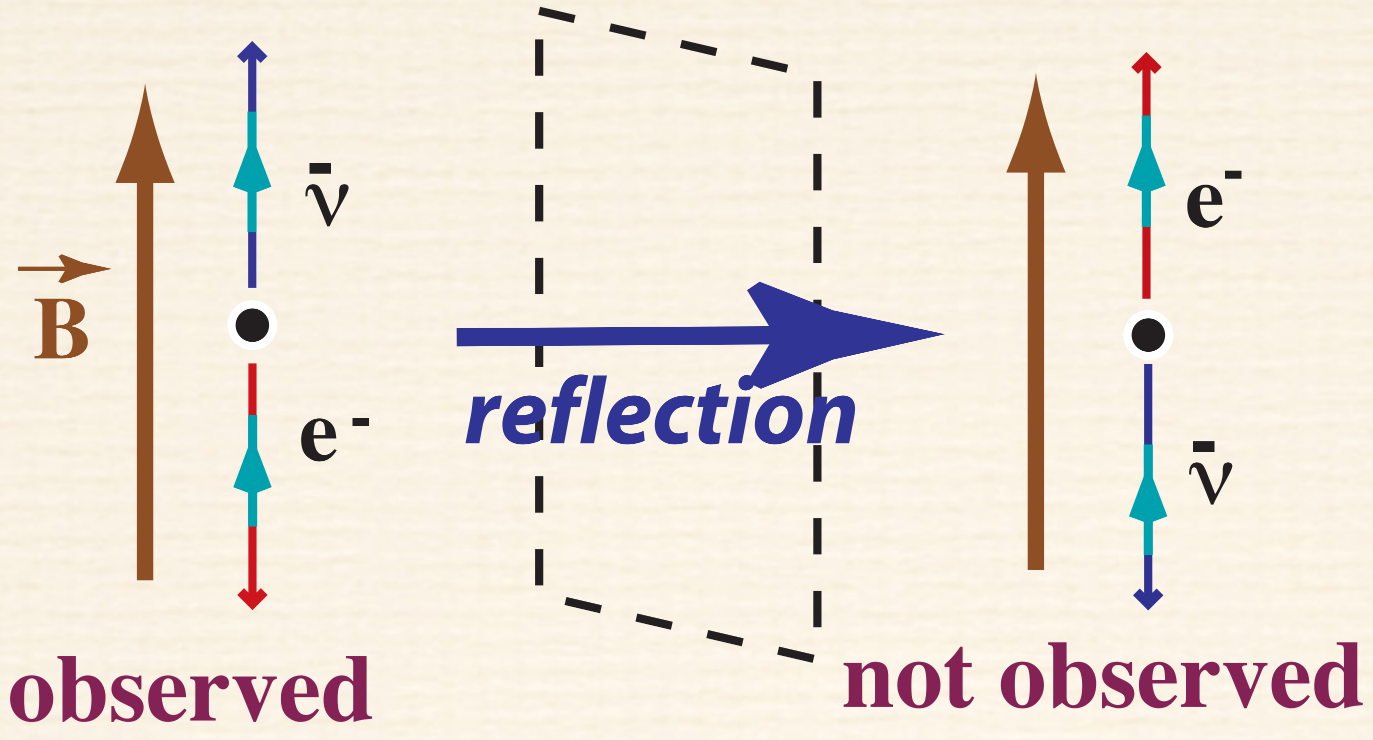

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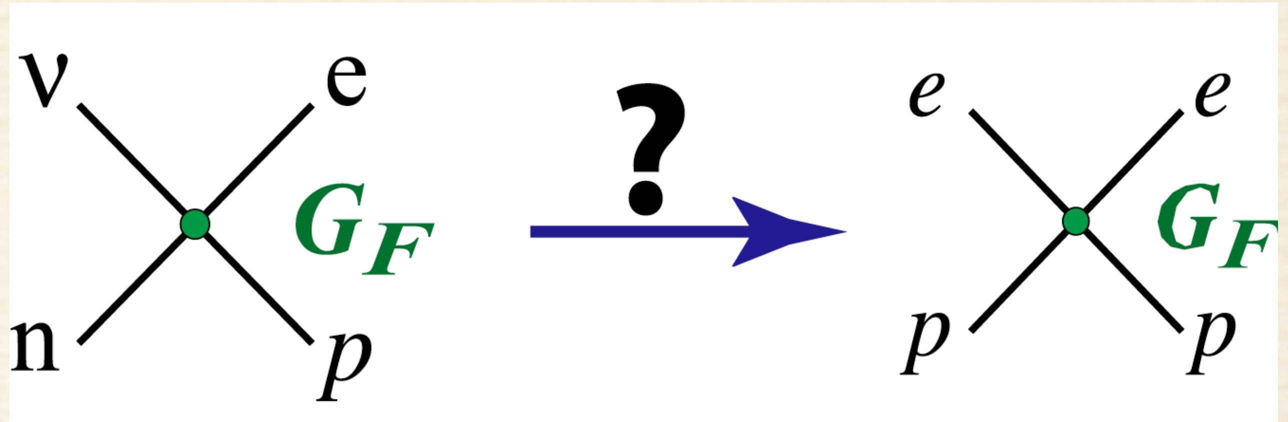

$$\sigma \;\alpha\; \left|A_{EM} + A_{weak}\right|^2$$

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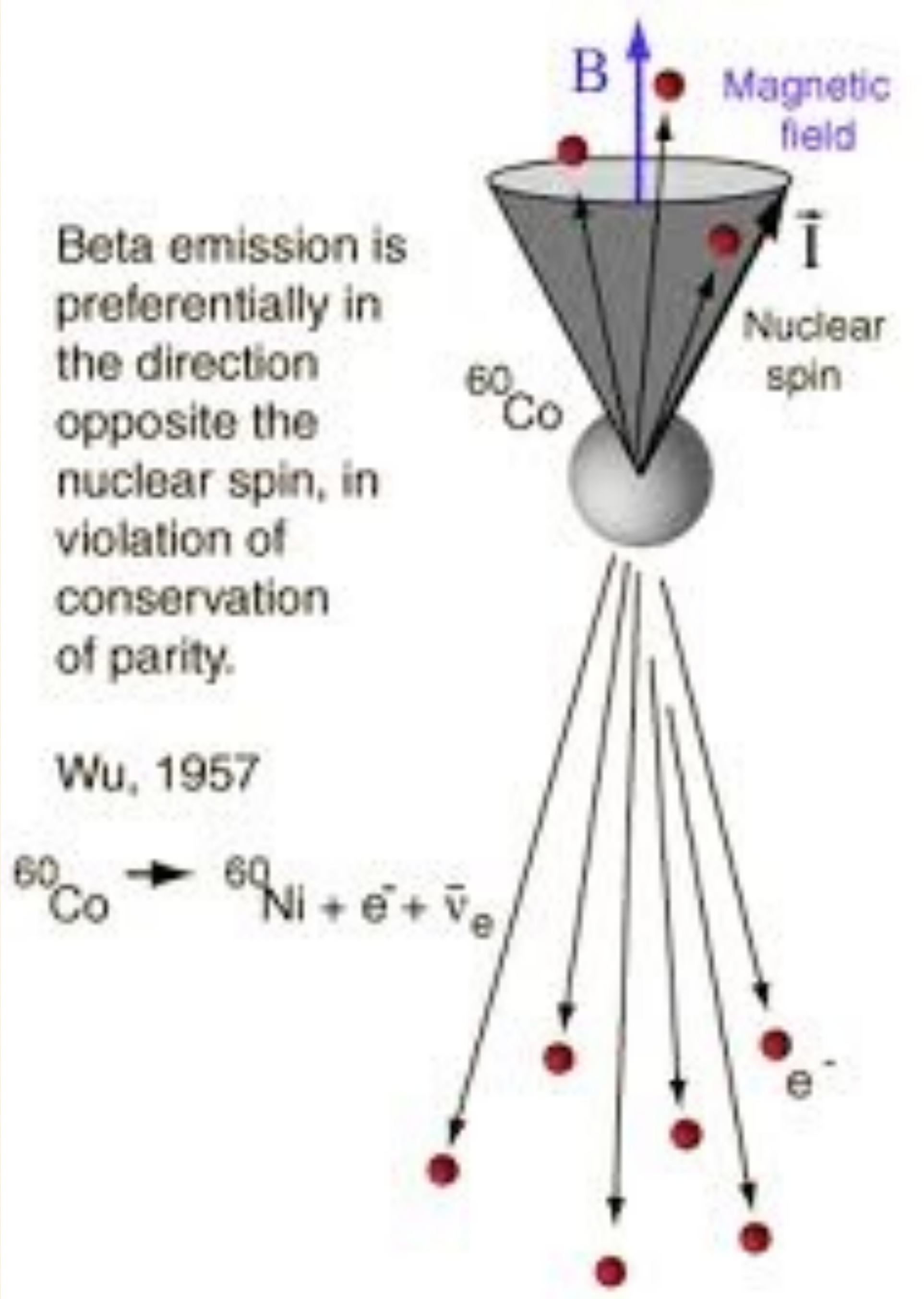

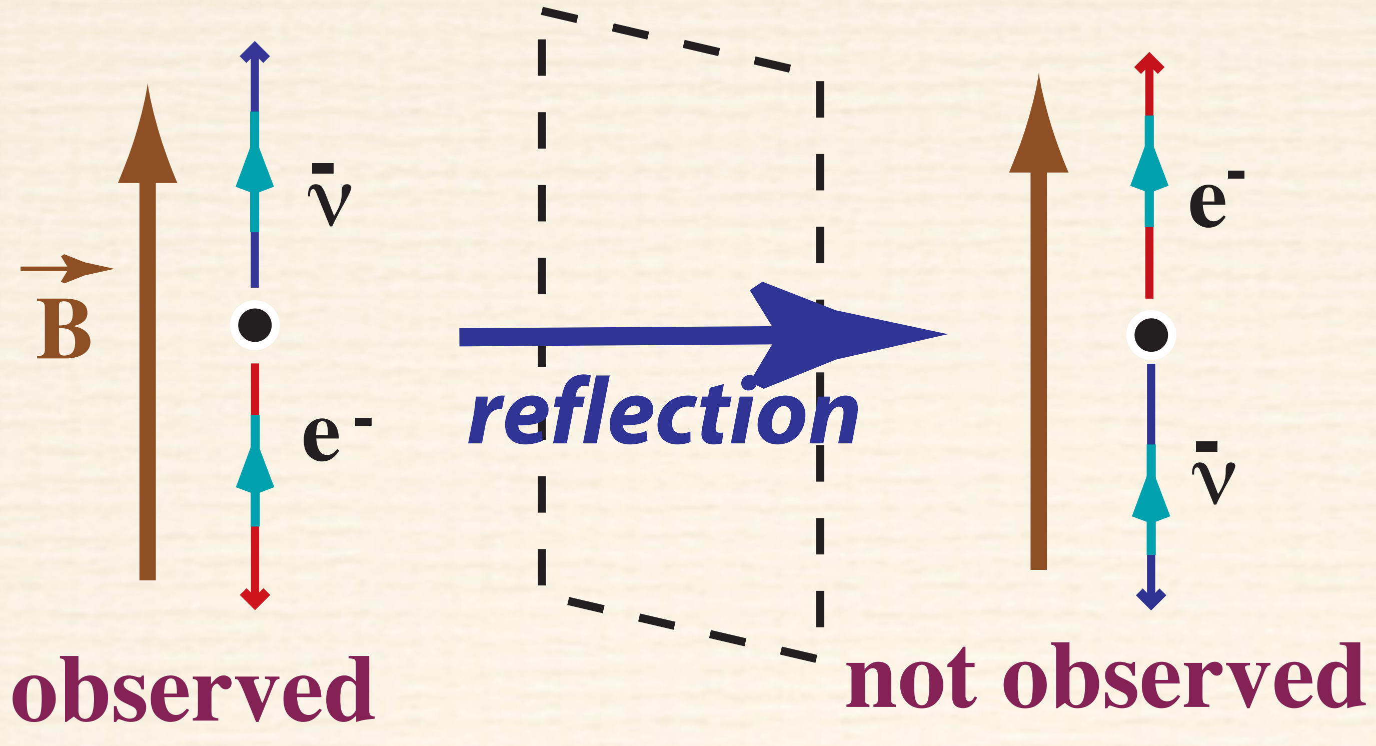

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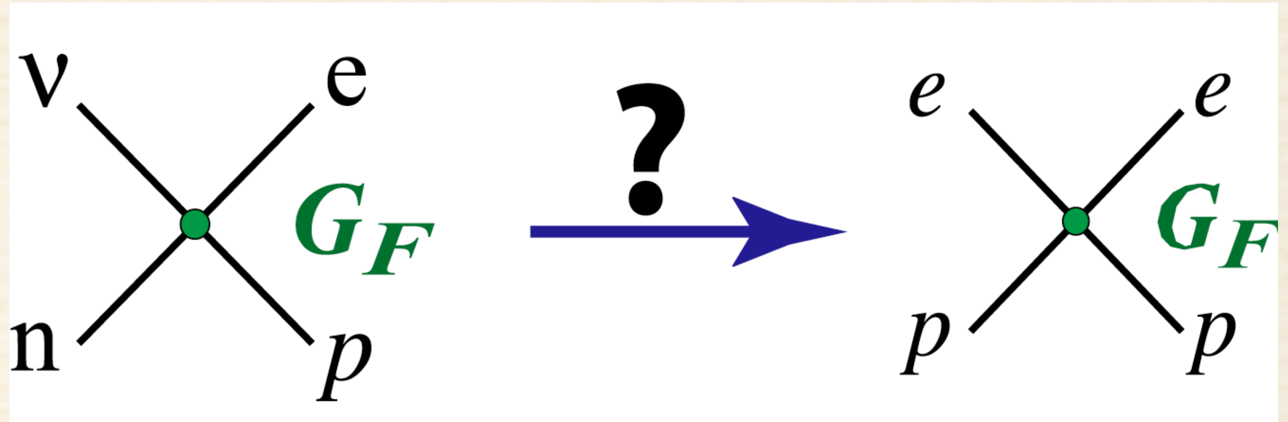

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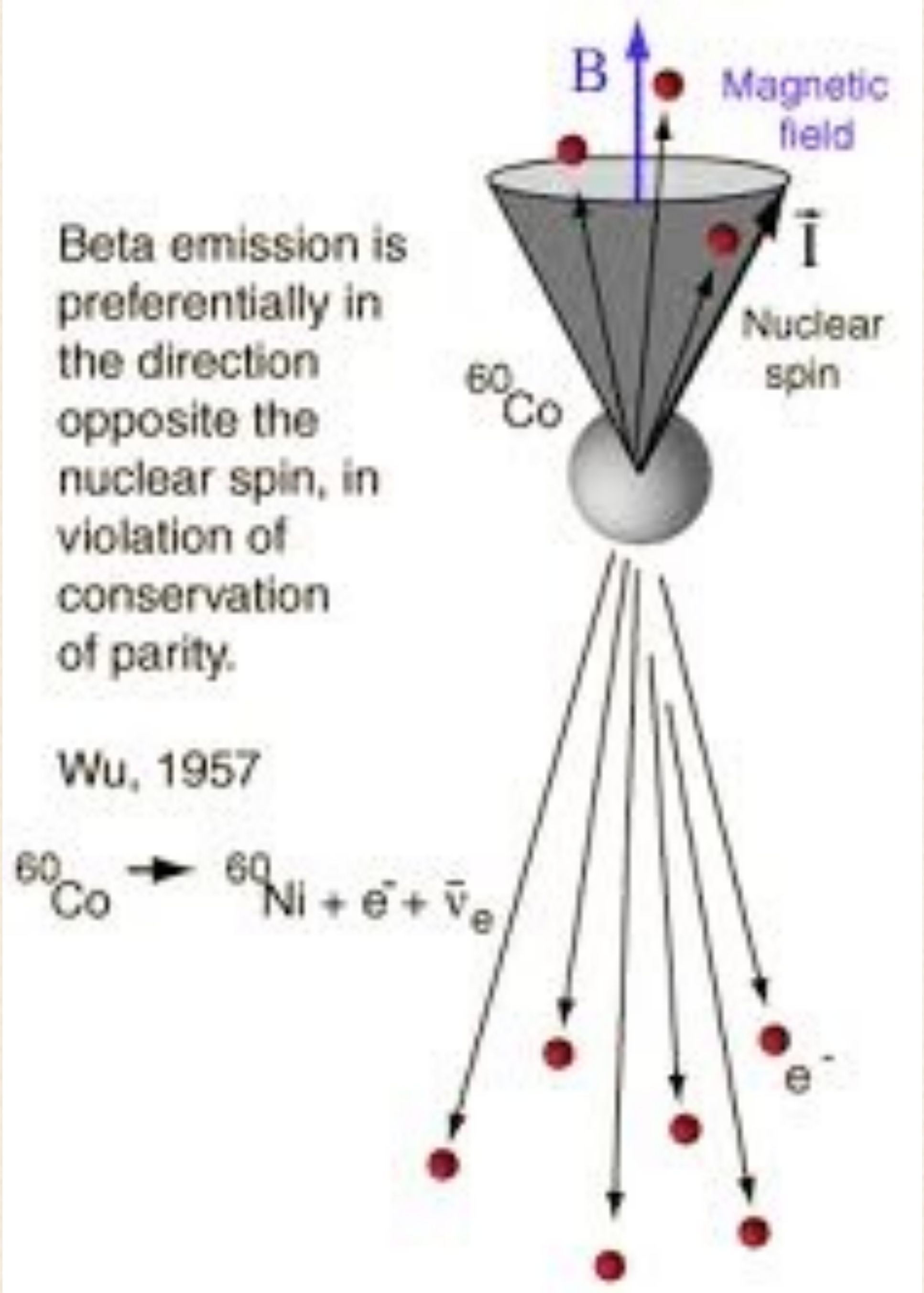

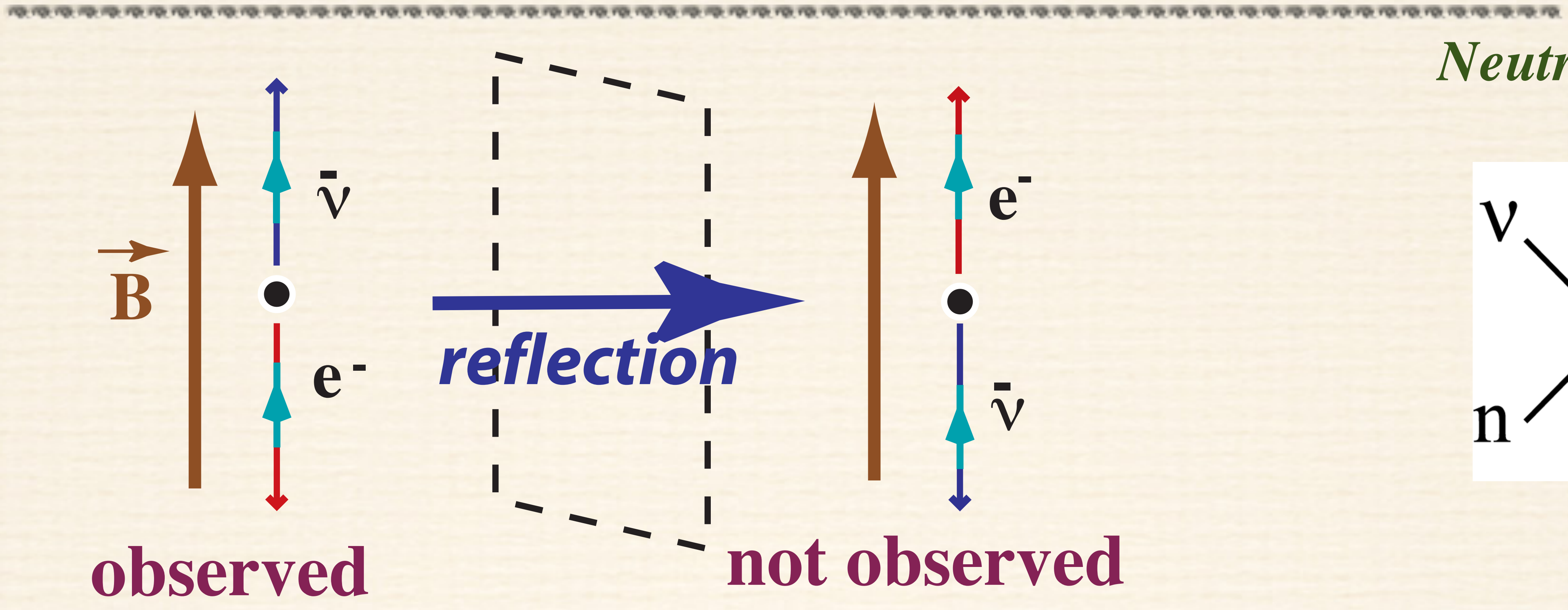

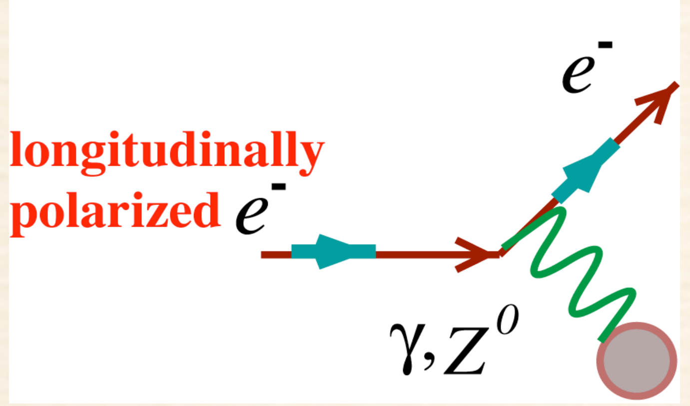

$$A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} = -A_{LR}$$

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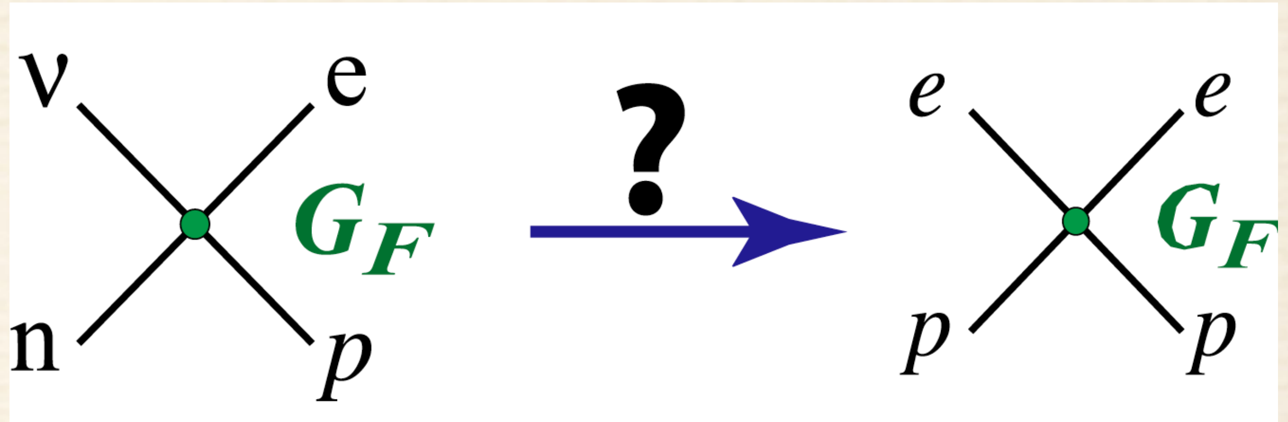

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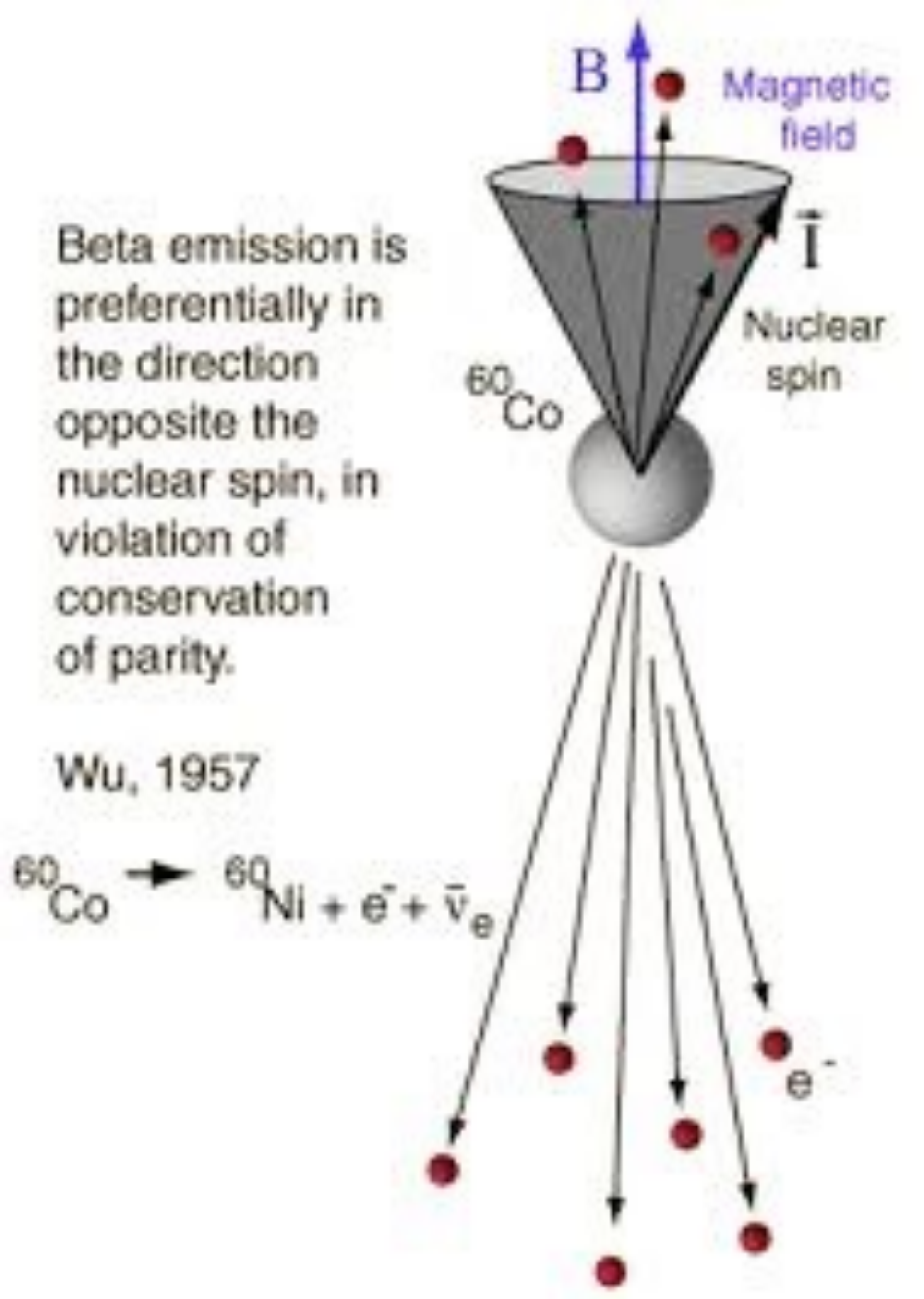

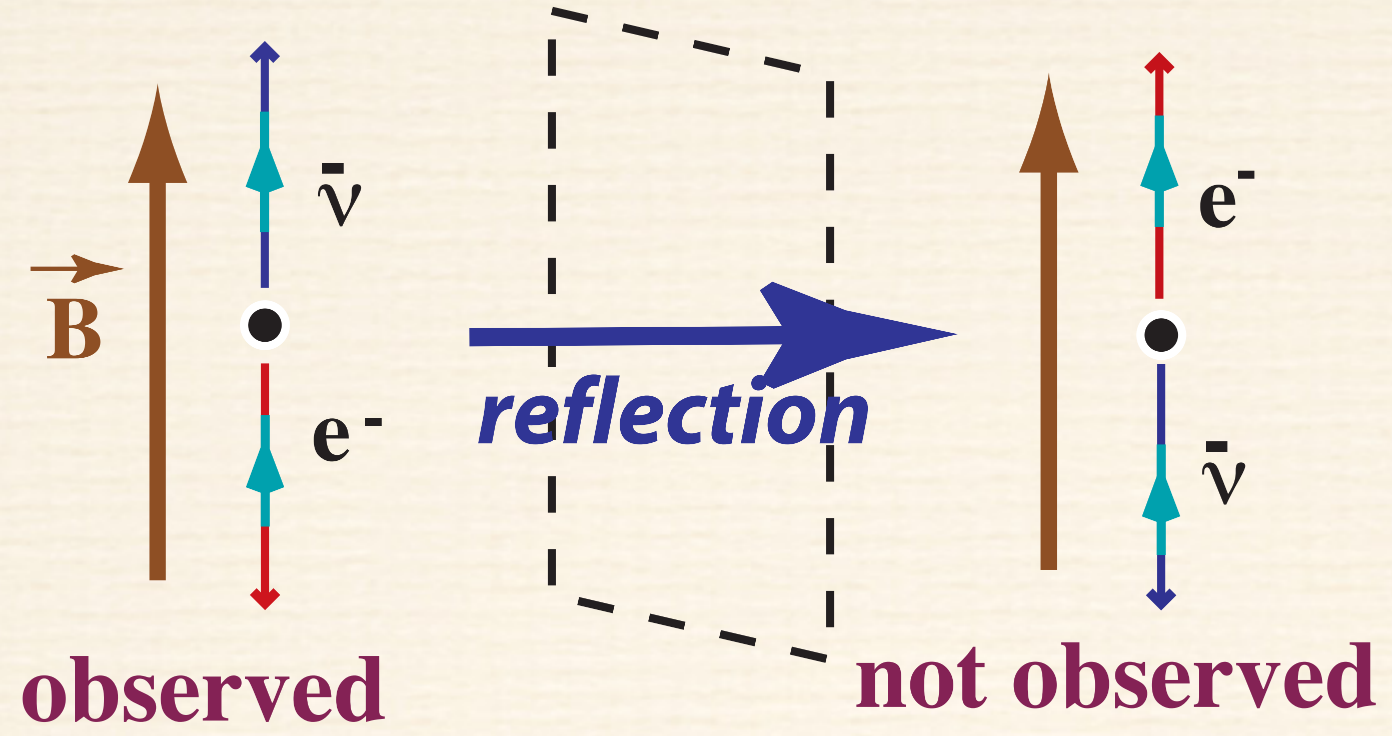

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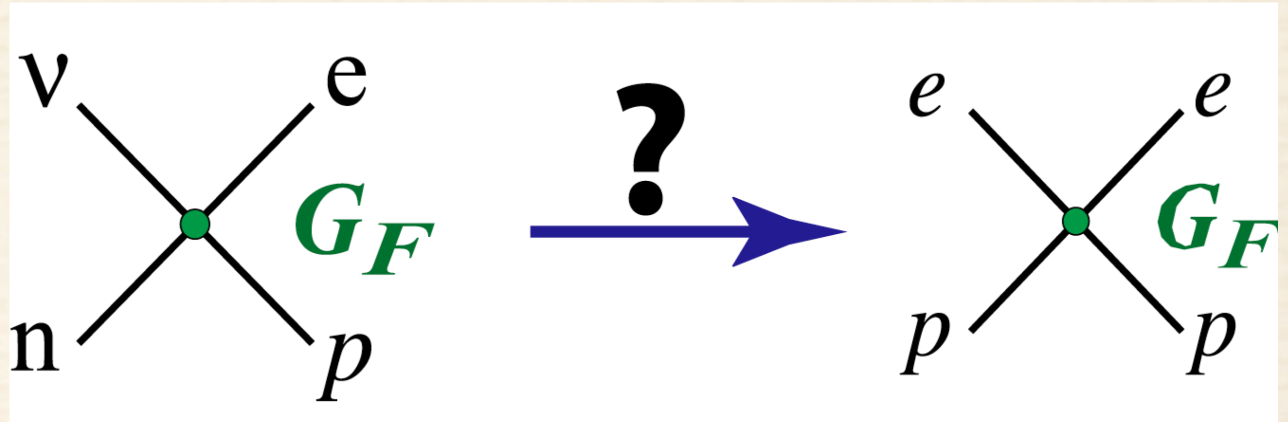

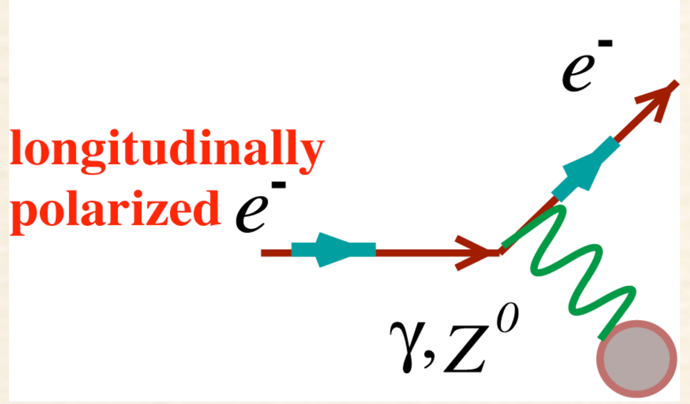

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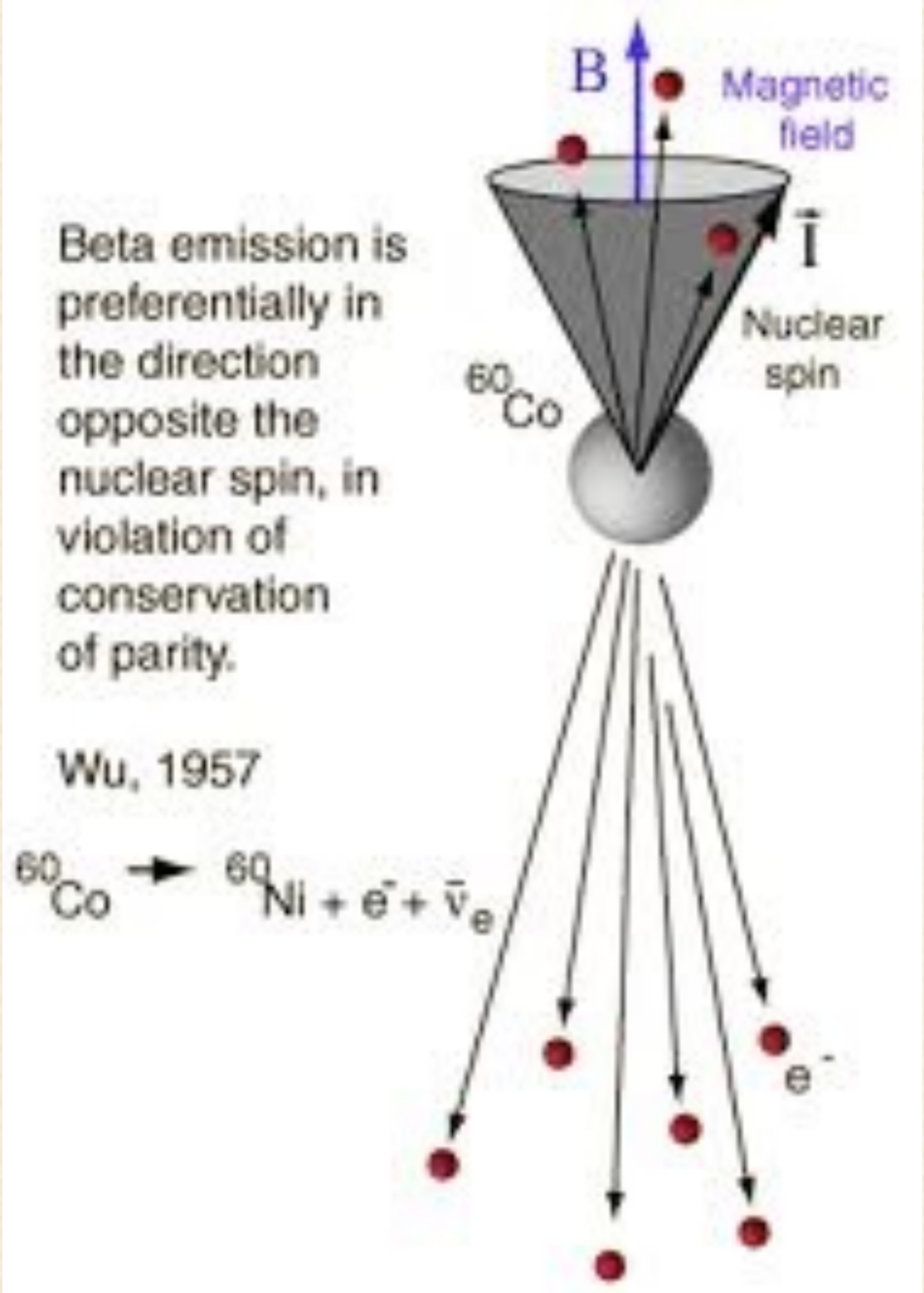

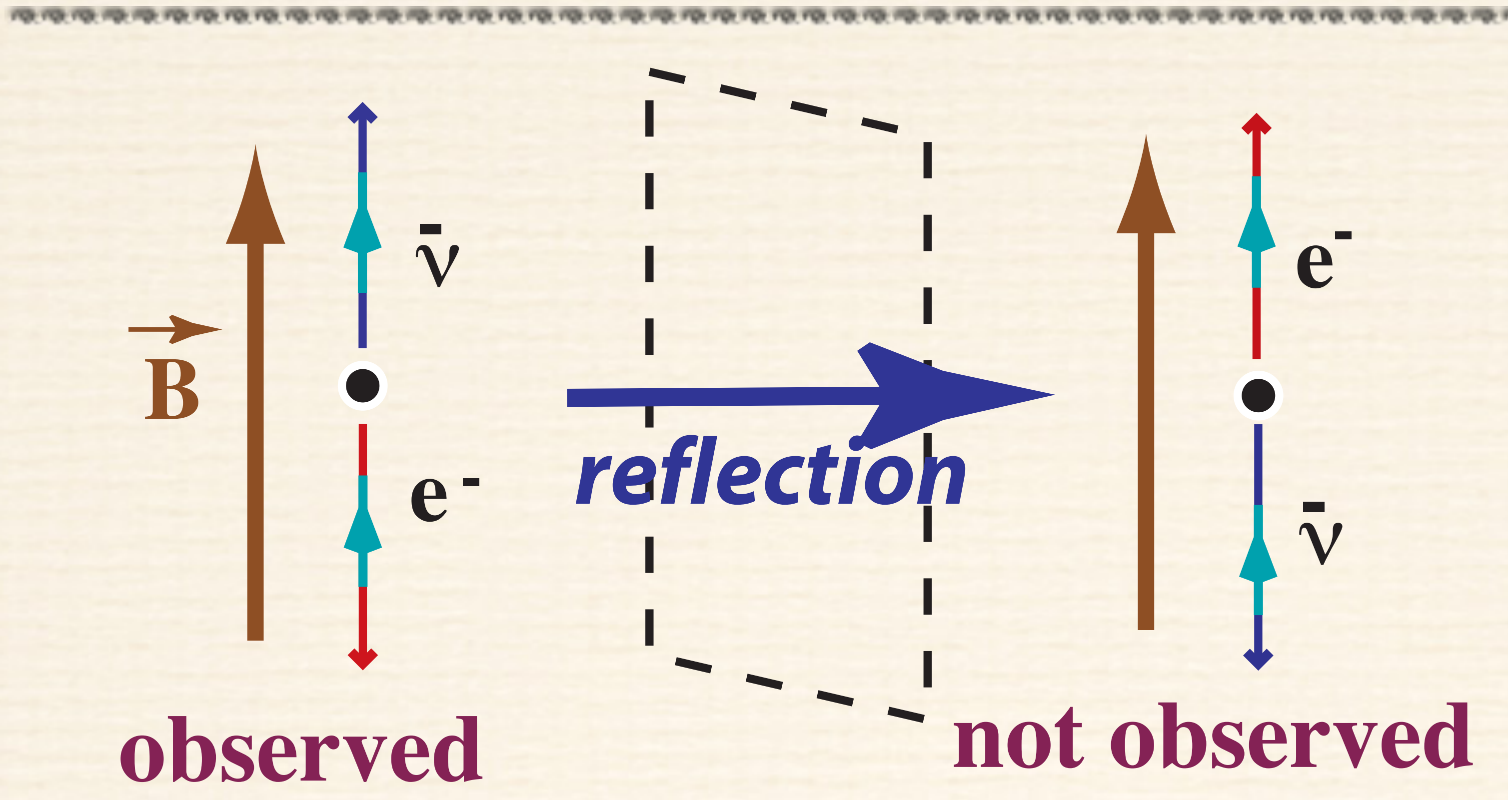

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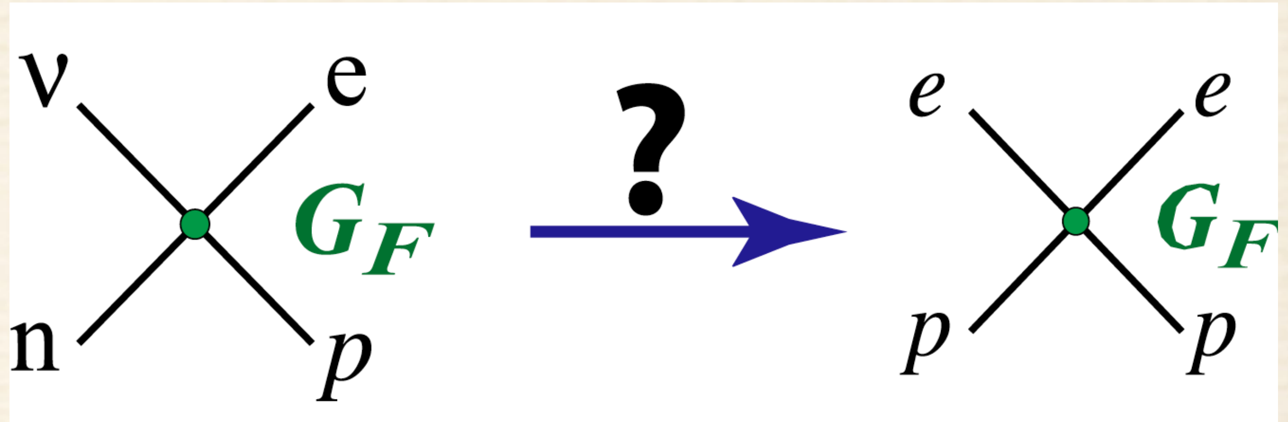

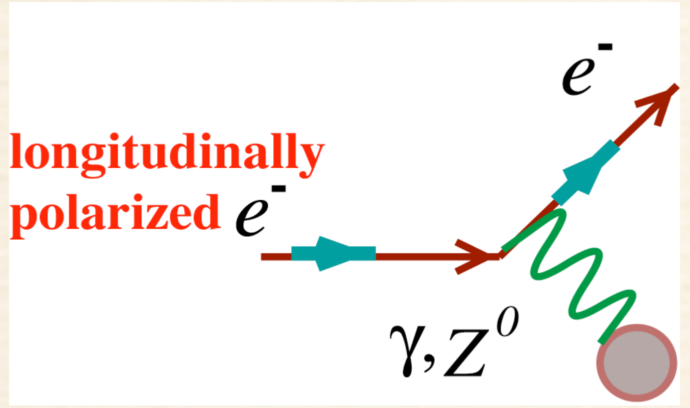

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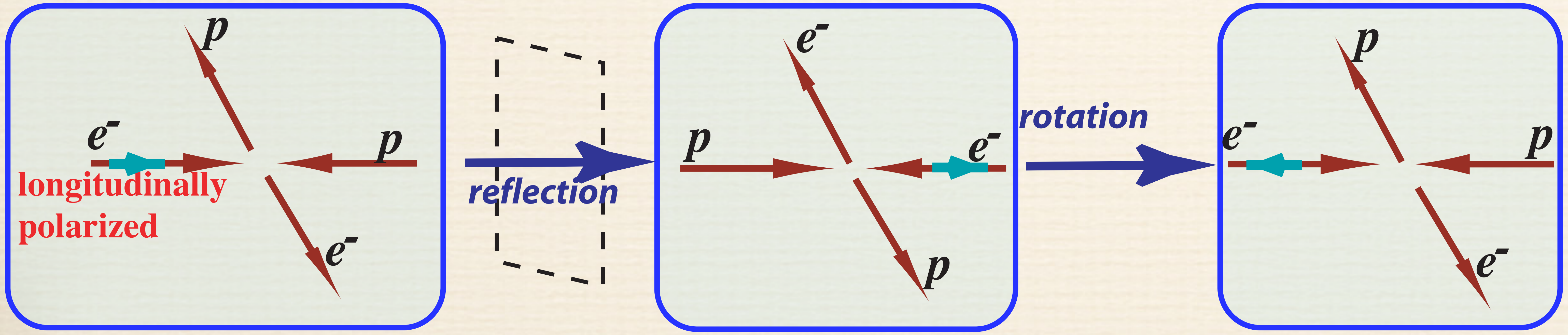

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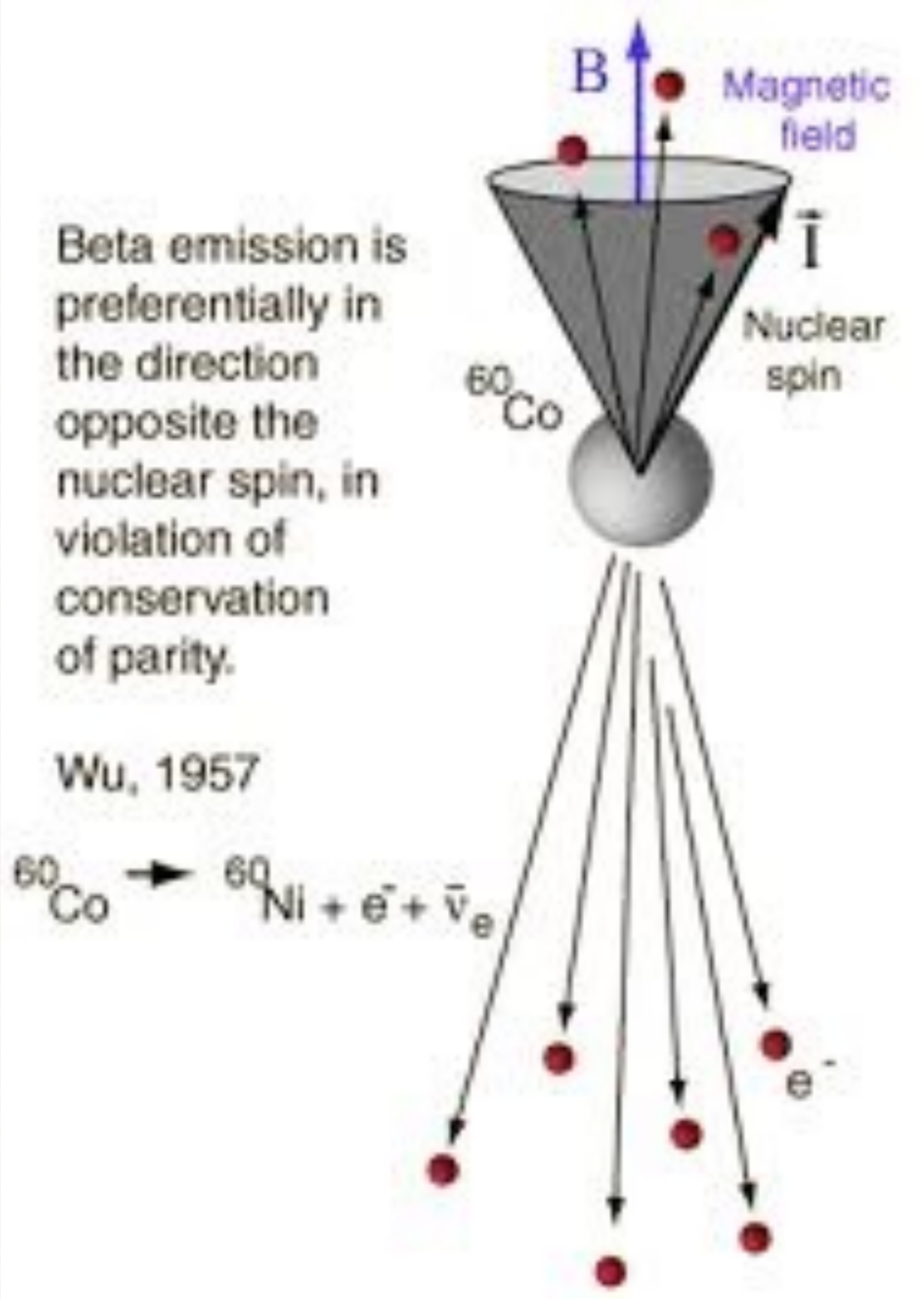

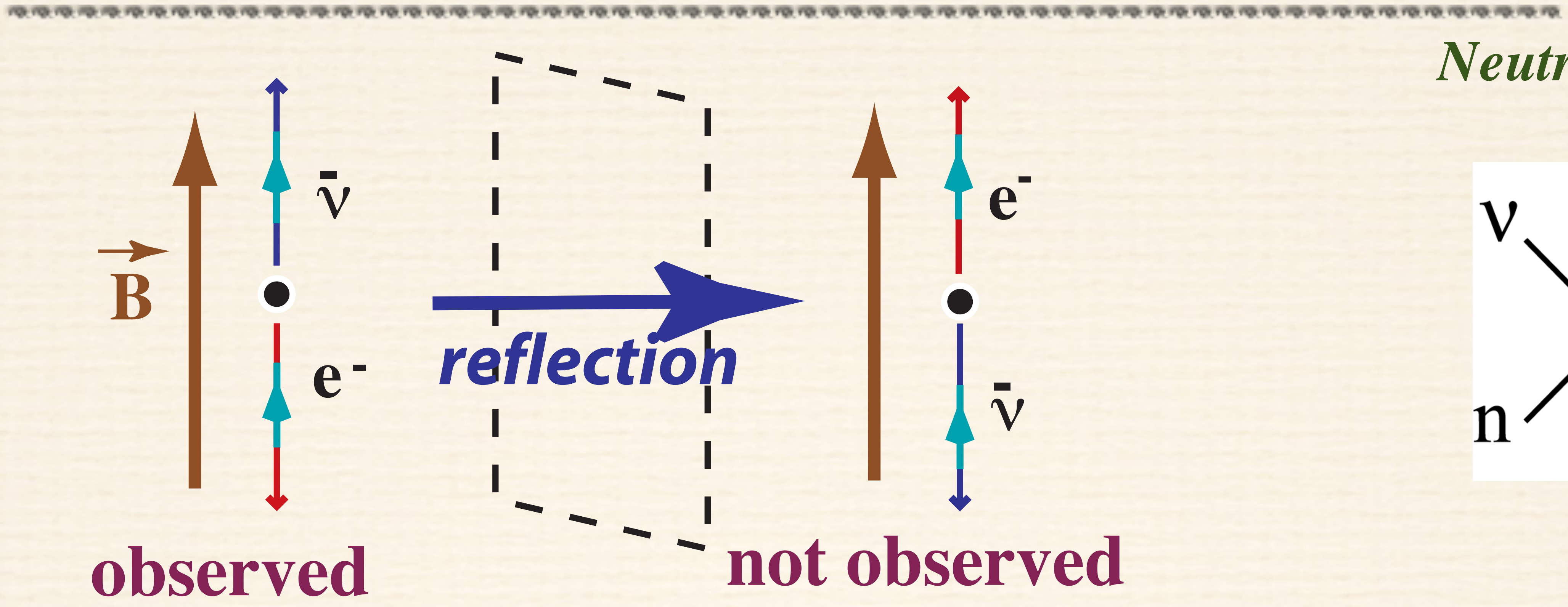

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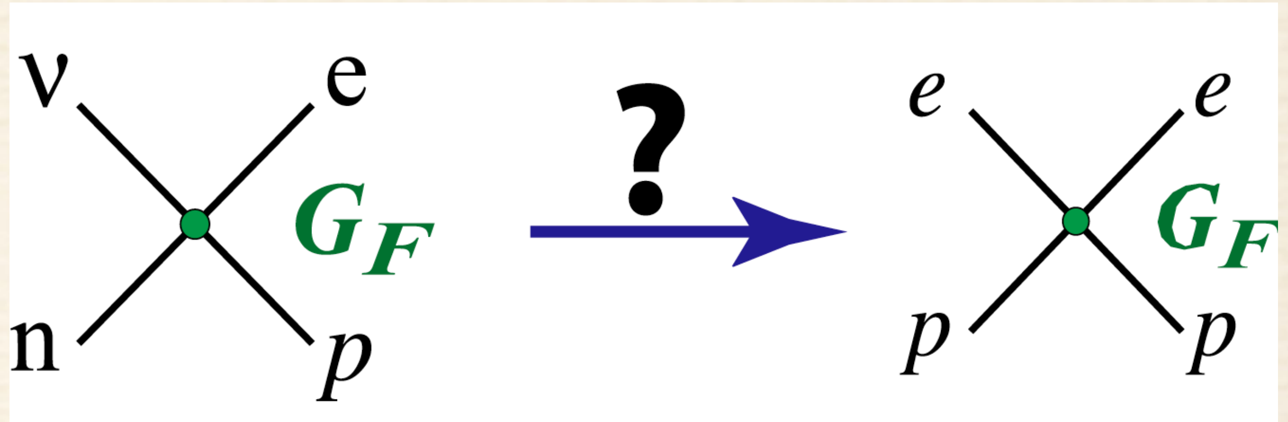
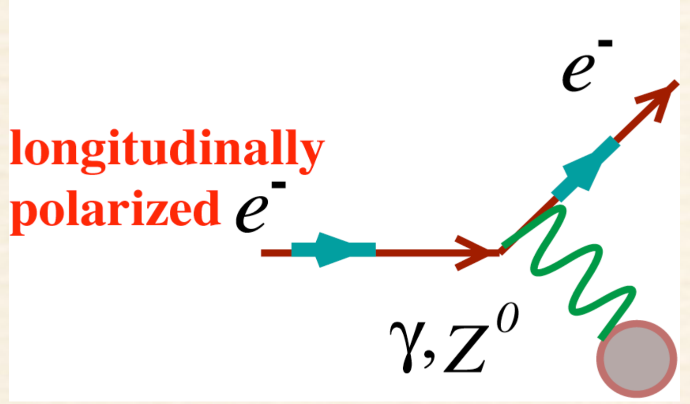
Electron-proton Weak Scattering





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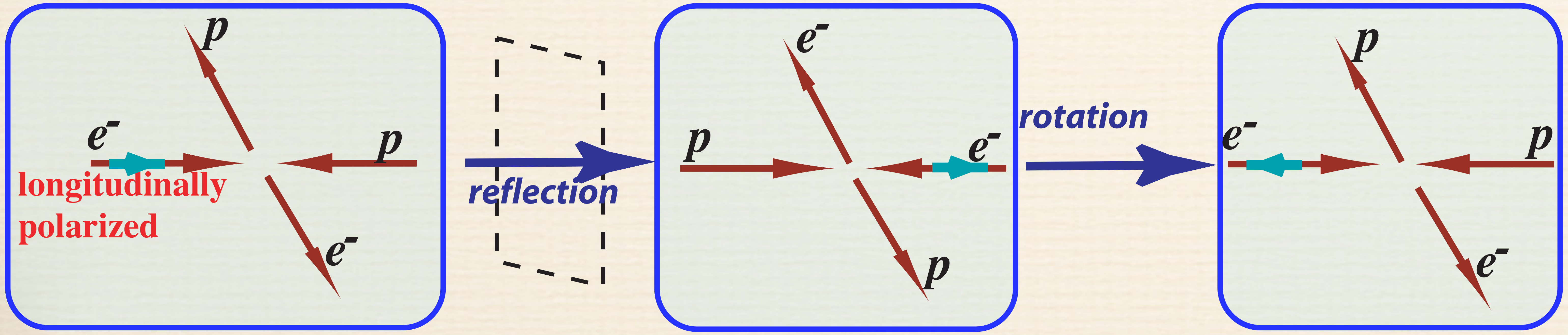

- *longitudinally polarize one beam with the ability to change its sign*
- *Measure fractional rate difference with a sensitivity of a part in 10,000*

Glashow, Weinberg and Salam: $SU(2)_L \times U(1)_Y$

Neutral Weak Interaction Theory

The Z boson incorporated *One free parameter: weak mixing angle θ_W*

Left-	**Right-**	
$0, \pm 1, \pm \frac{1}{3}, \pm \frac{2}{3}$	$0, \pm 1, \pm \frac{1}{3}, \pm \frac{2}{3}$	**γ Charge**
$T = \pm \frac{1}{2}$	zero	**W Charge**
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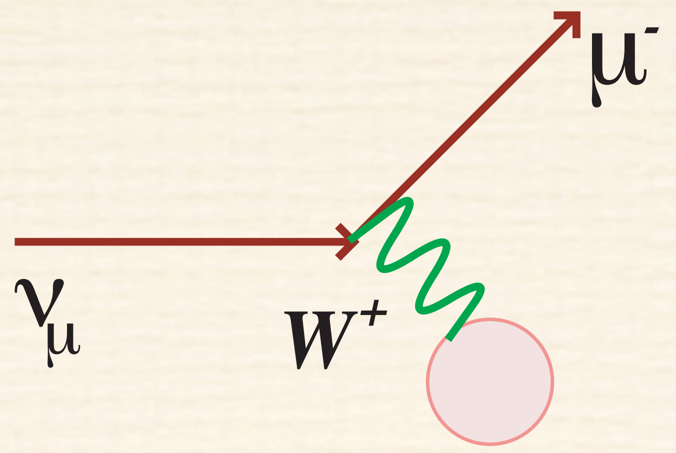

Charged Current

Glashow, Weinberg and Salam: $SU(2)_L X\, U(1)_Y$

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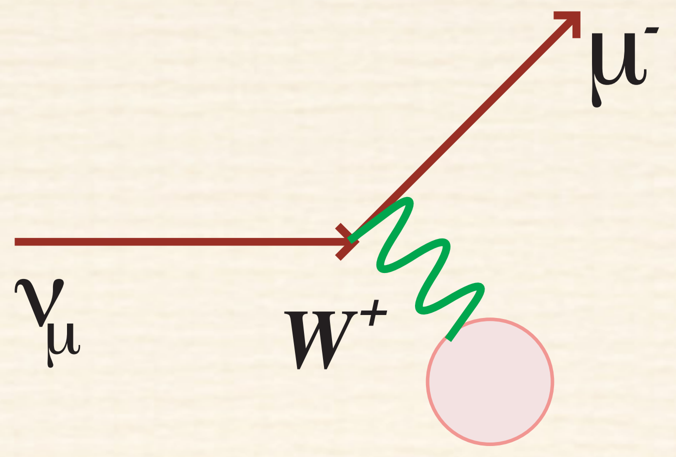

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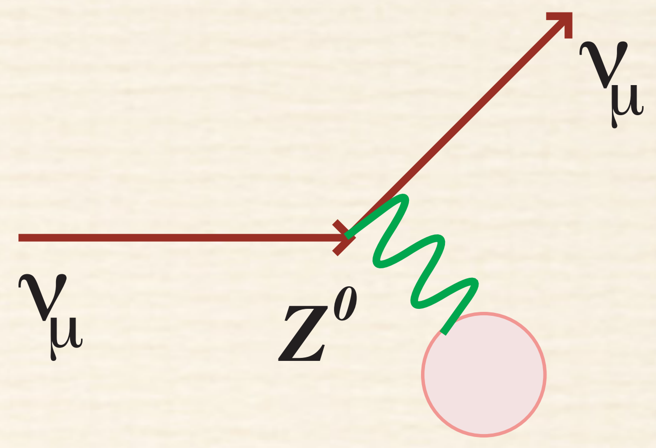

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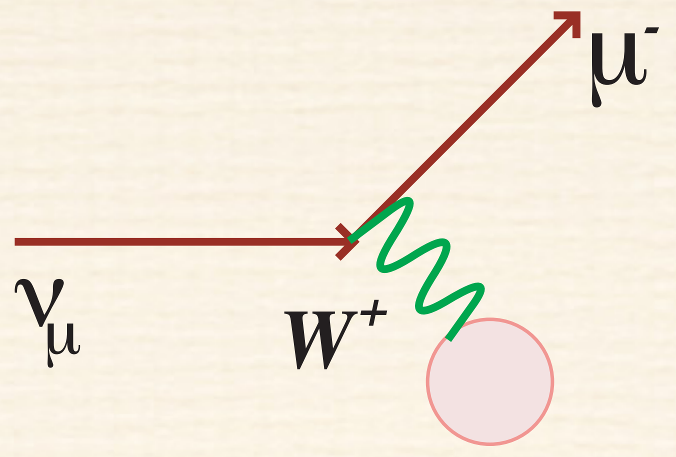

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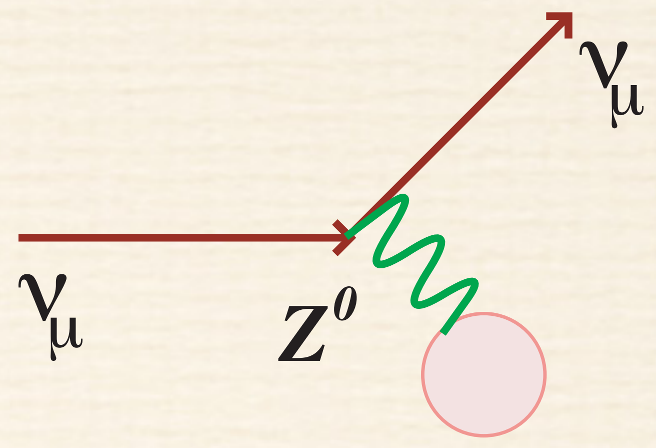

Neutral Current

First weak neutral current observation in the early '70s via neutrino beam scattering in a bubble chamber

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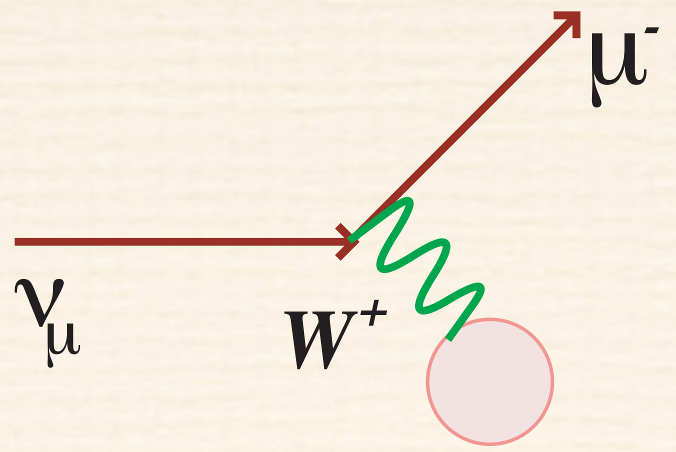

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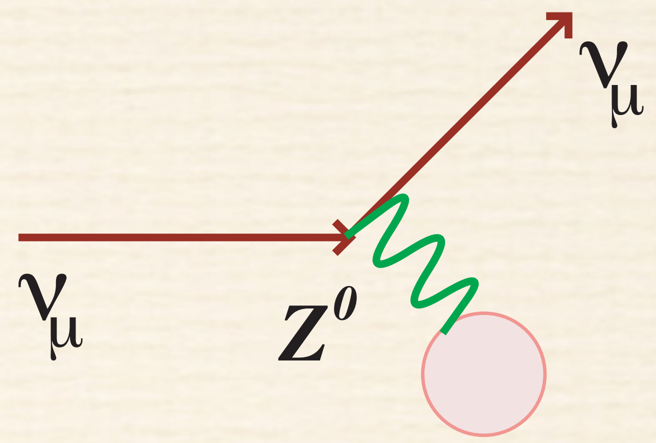

Neutral Current

First weak neutral current observation in the early '70s via neutrino beam scattering in a bubble chamber

Mid-'70's **Do lepton-nucleon neutral current interactions 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

Glashow, Weinberg and Salam: $SU(2)_L \times U(1)_Y$

Neutral Weak Interaction Theory

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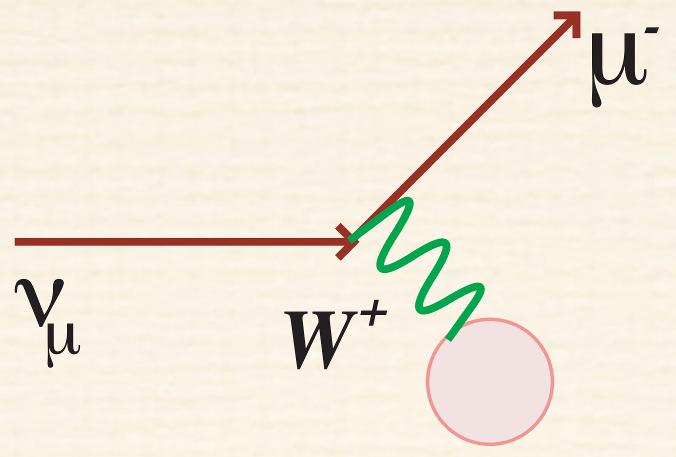

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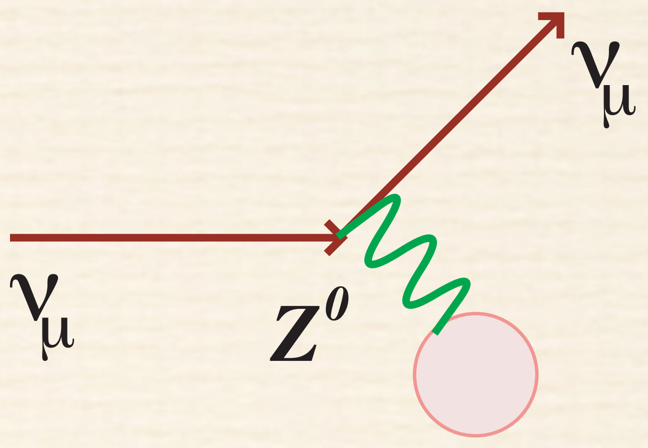

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$$A_{PV} \sim 10^{-4}$$

Parity is conserved

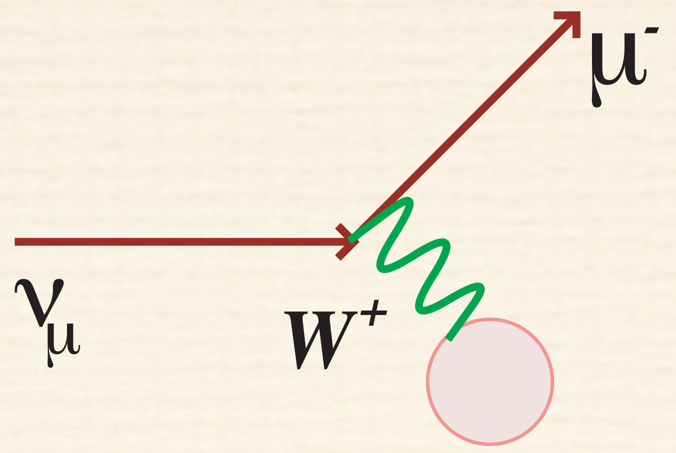
First table-top atomic parity violation searches: negative!

Glashow, Weinberg and Salam: $SU(2)_L \times U(1)_Y$

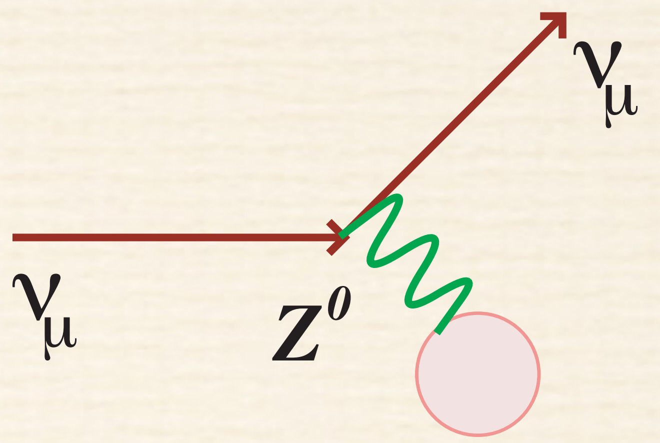
Neutral Weak Interaction Theory

The Z boson incorporated *One free parameter: weak mixing angle θ_W*

Left-	Right-	
$0, \pm 1, \pm\frac{1}{3}, \pm\frac{2}{3}$	$0, \pm 1, \pm\frac{1}{3}, \pm\frac{2}{3}$	γ Charge
$T = \pm\frac{1}{2}$	zero	W Charge
$T - q\sin^2\theta_W$	$-q\sin^2\theta_W$	Z Charge



Charged Current



Neutral Current

First weak neutral current observation in the early '70s via neutrino beam scattering in a bubble chamber

Mid-'70's **Do lepton-nucleon neutral current interactions exhibit parity violation?**

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

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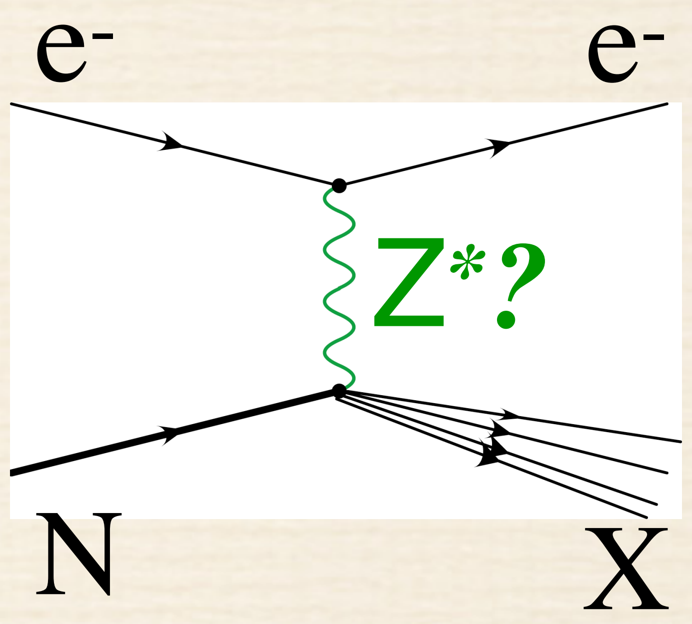

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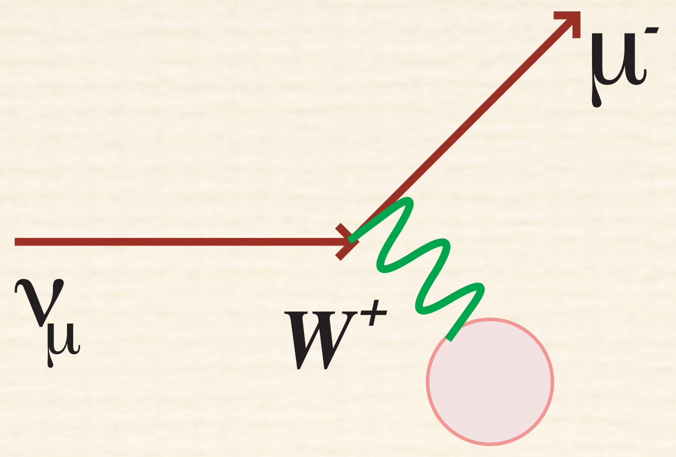

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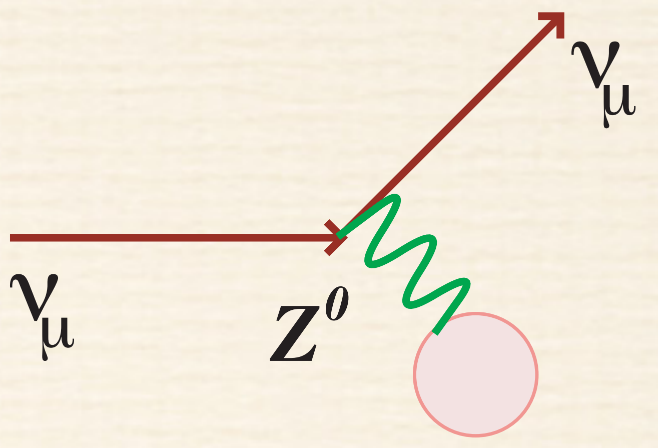

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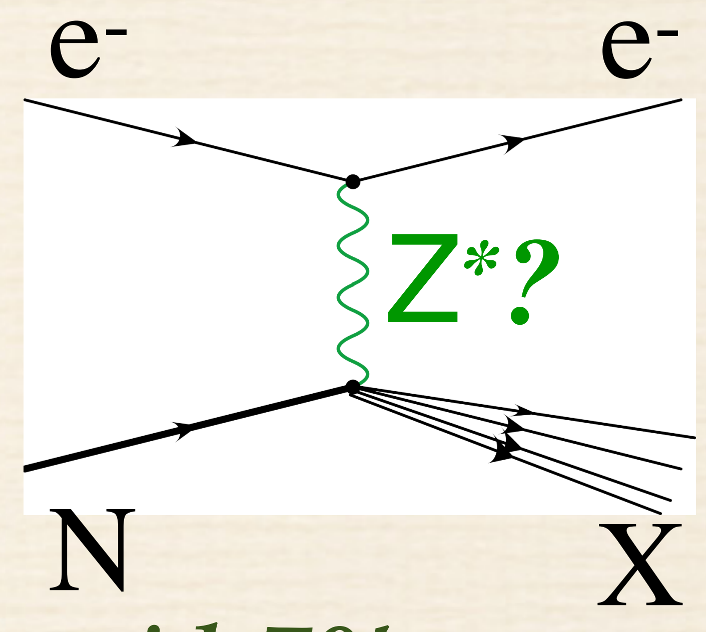

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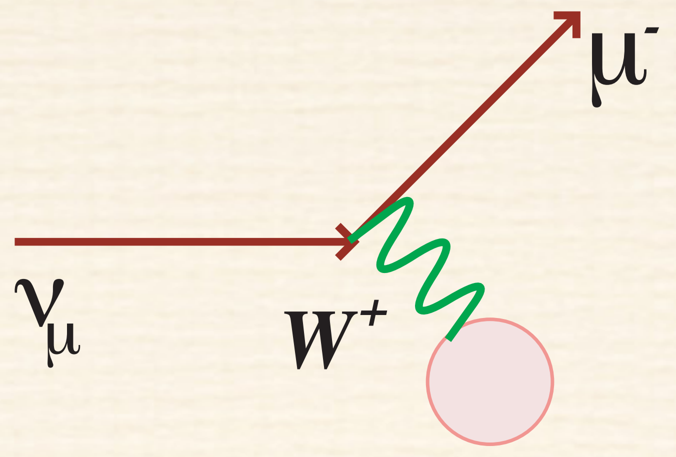

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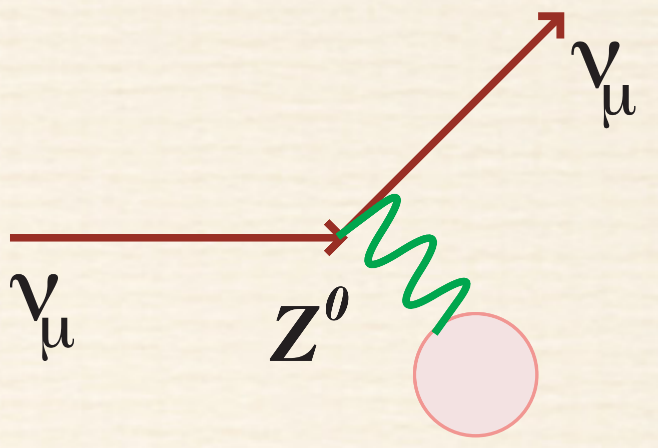

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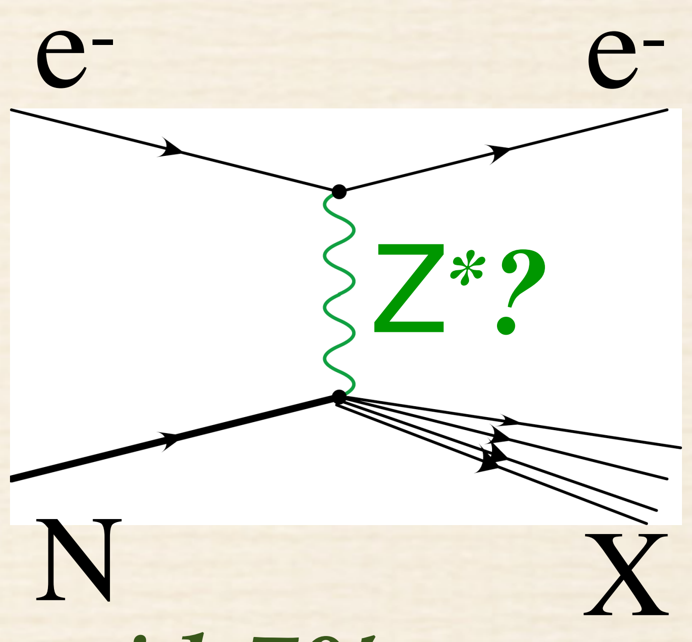

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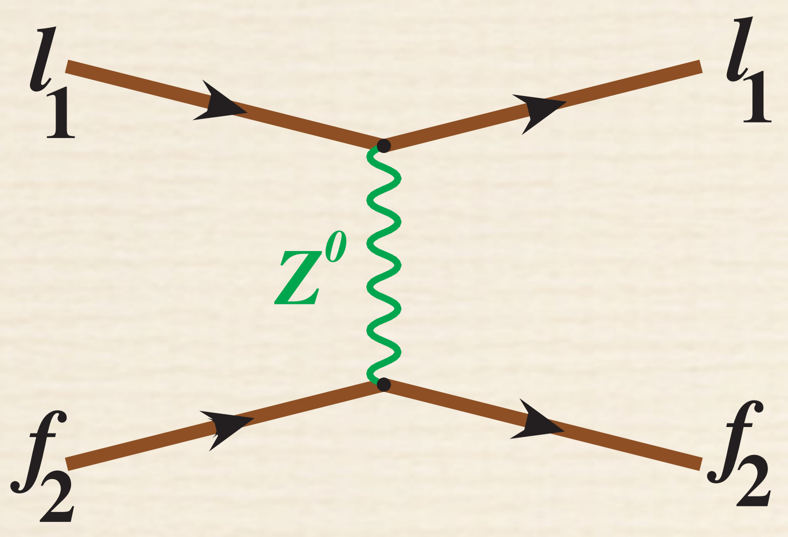
- *Parity Violation in Weak Neutral Current Interactions*
- *$\sin^2\theta_W$ = 0.224 ± 0.020: same as in neutrino scattering*

First table-top atomic parity violation searches: negative!

Semi-Leptonic and Leptonic Weak Neutral Currents at $Q^2 \ll M_Z{}^2$



✦ Neutrino Scattering

✦ Weak-Electromagnetic Interference with Electrons

- *opposite parity transitions in heavy atoms*
- *Spin-dependent electron scattering*

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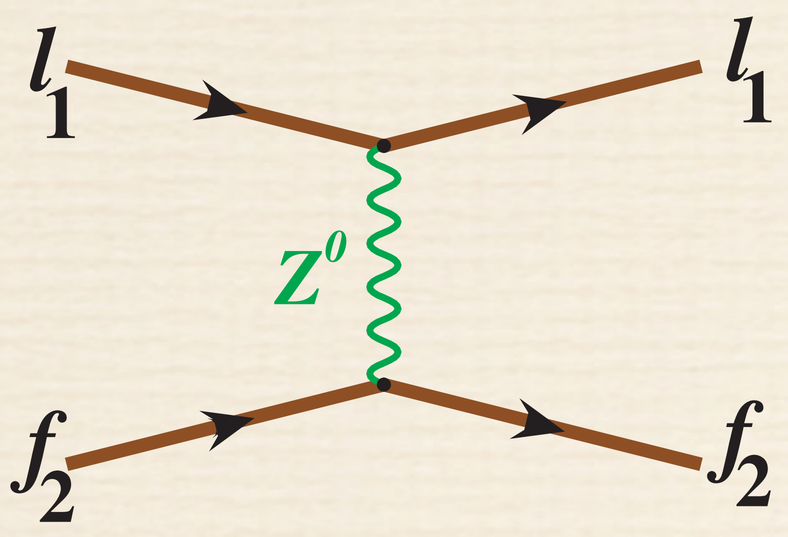

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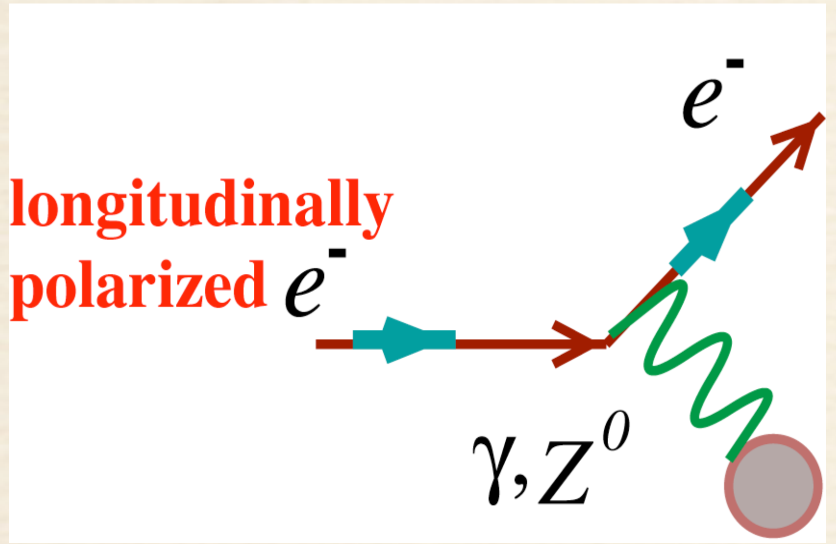
Parity-violating Electron Scattering (PVES)



g_V is a function of $\sin^2\theta_W$

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

$$A_{PV} \sim 10^{-5} \cdot Q^2 \ \textit{to} \ 10^{-4} \cdot Q^2$$

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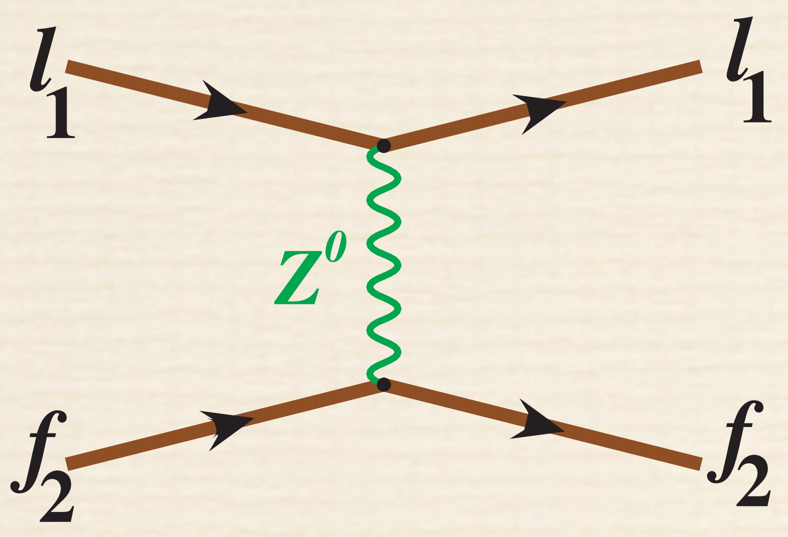

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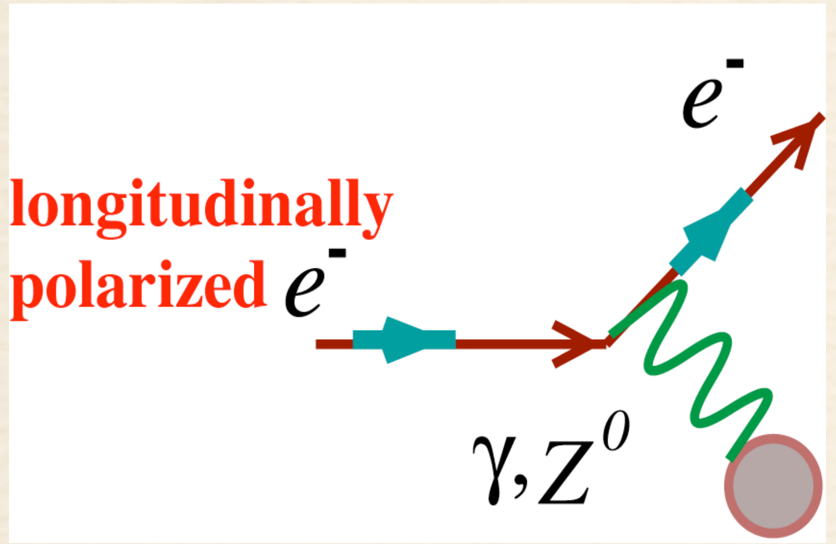

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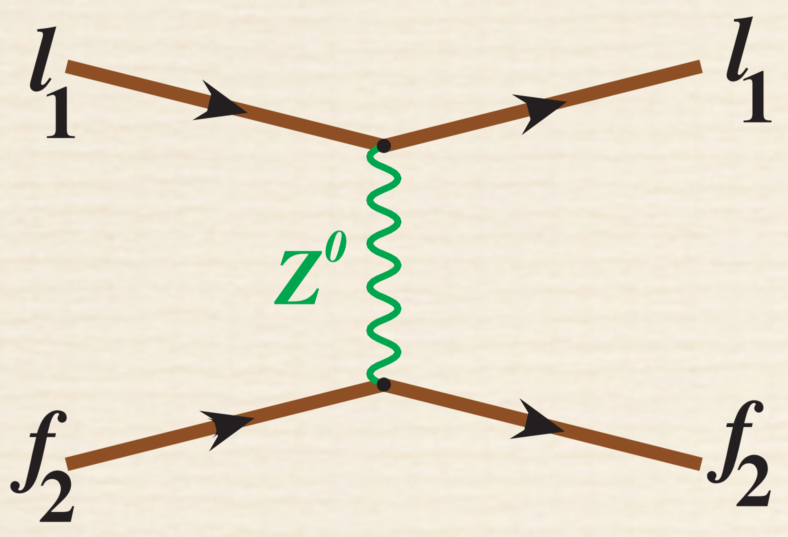

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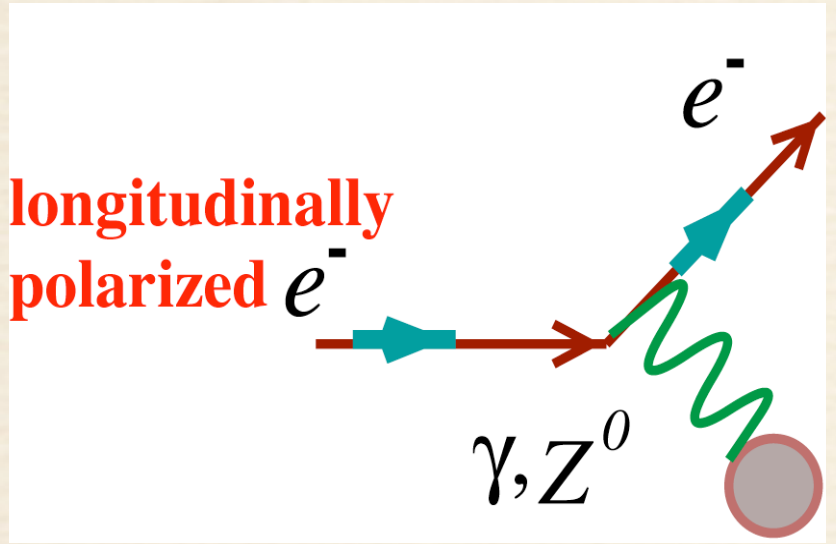

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Specific choices of kinematics and target nuclei probe different physics:

- *Mid-70s to late-80's, goal was to show $\sin^2\theta_W$ was the same as in neutrino scattering*
- *Since early 90's: target couplings probe novel aspects of hadron structure*
  - ✦ *strange quark form factors and later the neutron RMS radius of heavy nuclei*
- *Since late 90's: precision measurements with carefully chosen kinematics can probe physics at the multi-TeV scale*

Standard Model Tests in the 80's

Elastic scattering from $(J^\pi, T) = (0^+, 0)$ ***nuclei*** *Feinberg (1975)*

For a simple nucleus like ^{12}C, A_{PV} in elastic scattering at forward angle insensitive to nuclear structure: clean measurement of $\sin^2\theta_W$

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- ***Spawned a new generation of experimenters and experiments***

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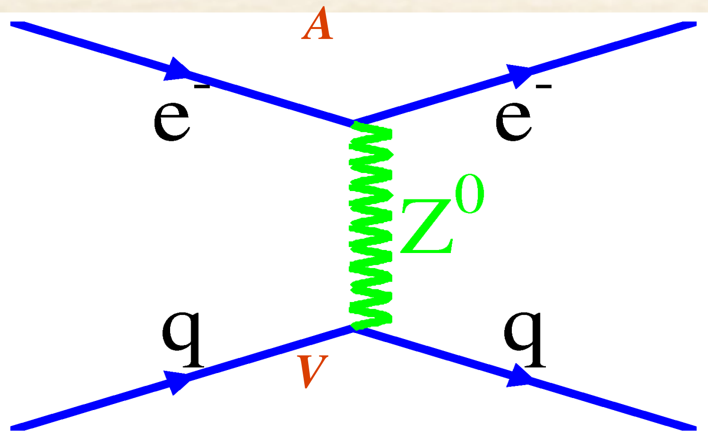
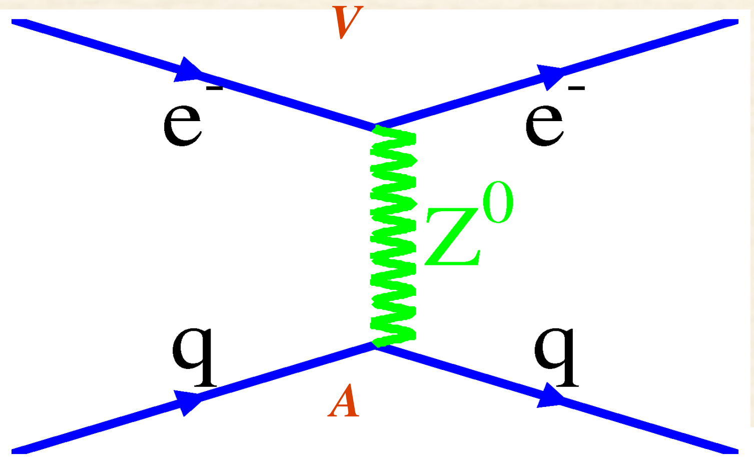


$C_{1i} \equiv 2 g_A^e g_V^i$



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

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}} [\bar{e}\gamma^\mu \gamma_5 e (C_{1u} \bar{u}\gamma_\mu u + C_{1d} \bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e (C_{2u} \bar{u}\gamma_\mu \gamma_5 u + C_{2d} \bar{d}\gamma_\mu \gamma_5 d)]$$

New Physics Motivation after LEP-I

Unravelling "New Dynamics" in the Early Universe:
how did nuclear matter form and evolve?

Nuclear Physics Initiatives:
"Low" Energy: $Q^2 << M_Z^2$

courtesy
V. Cirigliano,
H. Maruyama,
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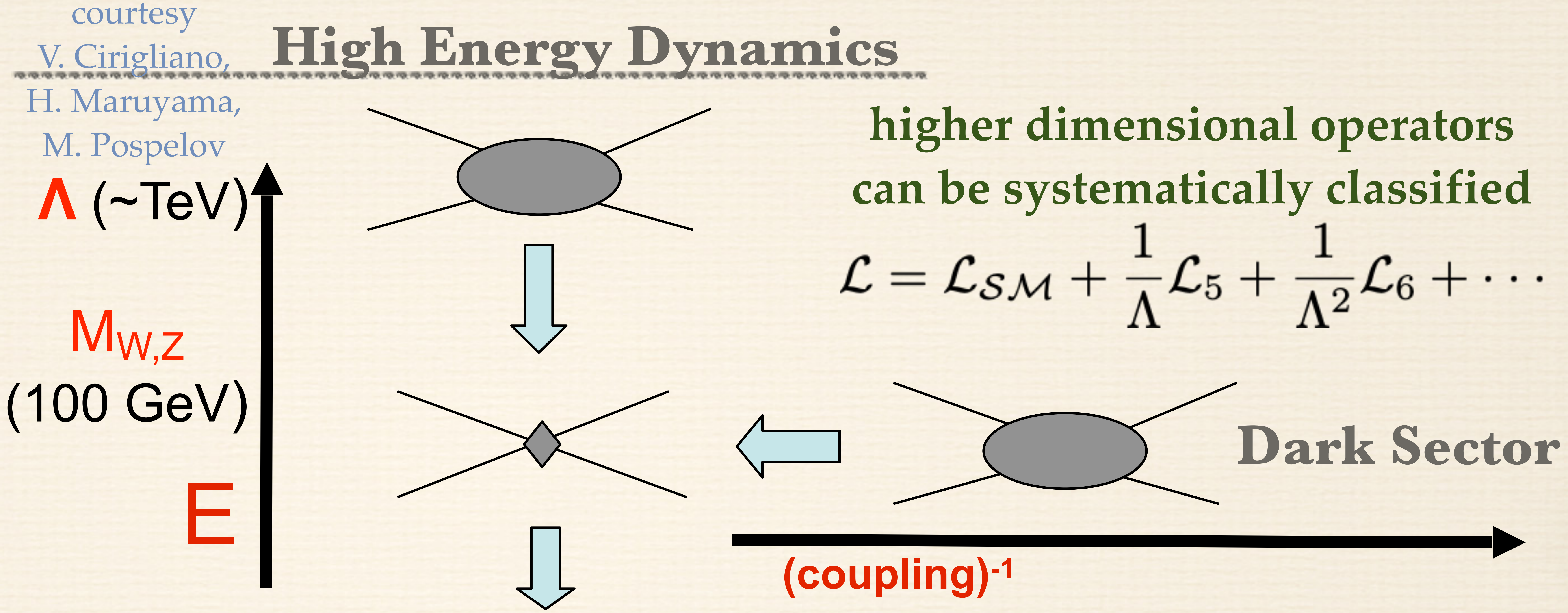

higher dimensional operators can be systematically classified

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

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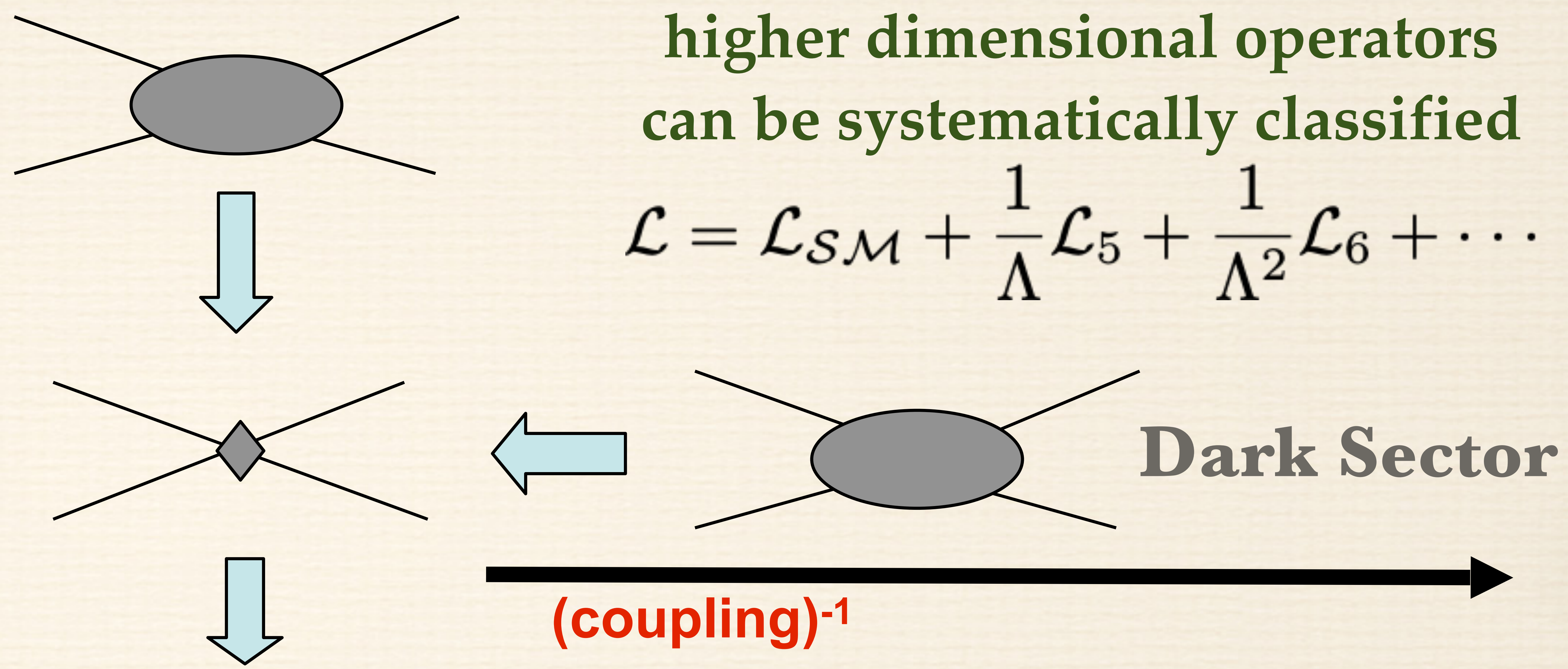
High Energy Dynamics

Λ (~TeV)

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

E



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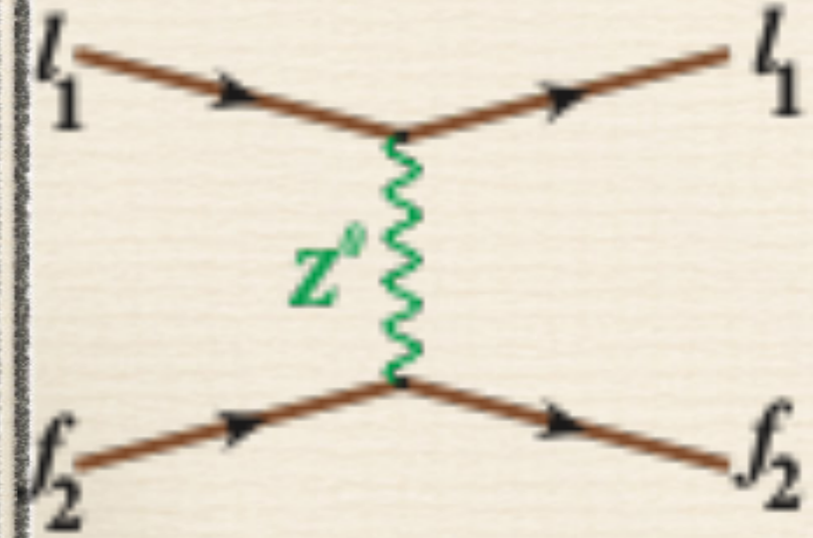
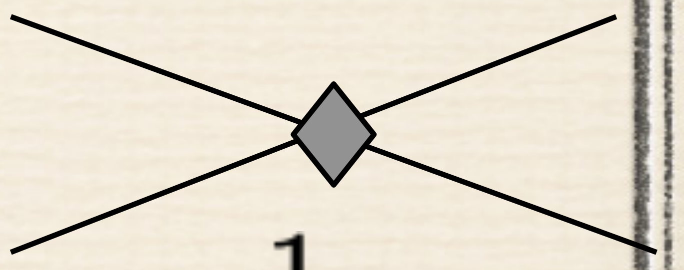
Leptonic and Semileptonic Weak Neutral Current Interactions



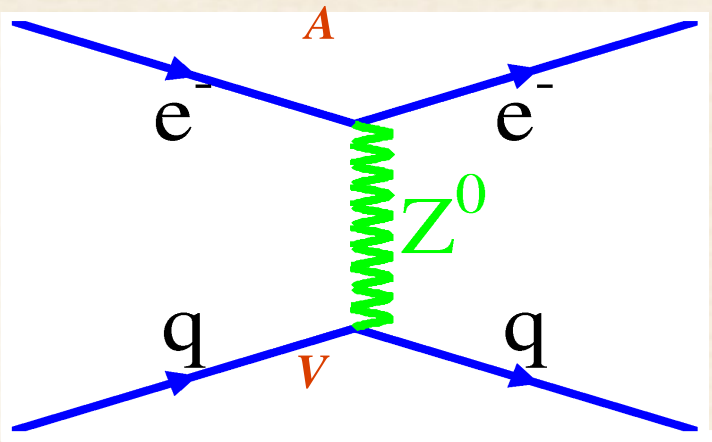
Search for new flavor diagonal neutral currents
Tiny yet measurable deviations from precisely calculable SM processes



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

must reach Λ ~ 10 TeV

WNC Couplings



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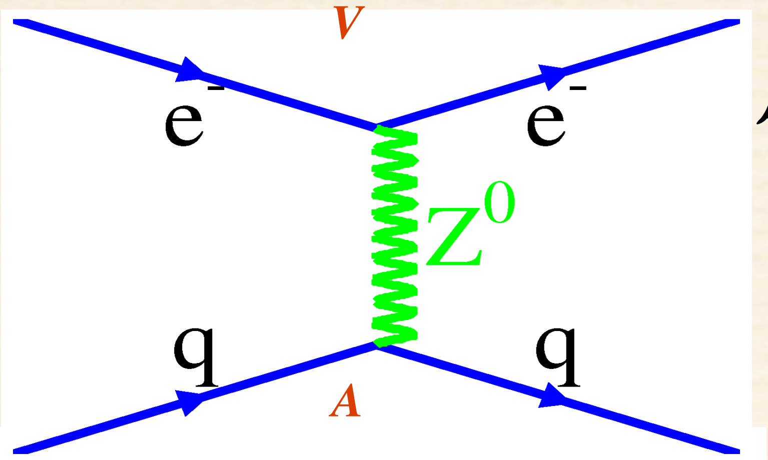

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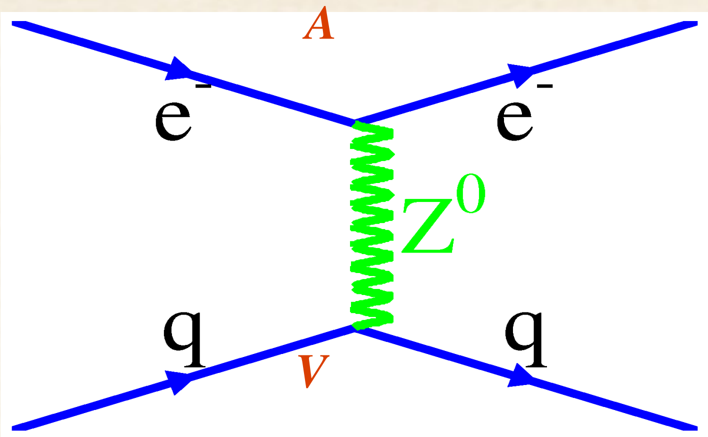

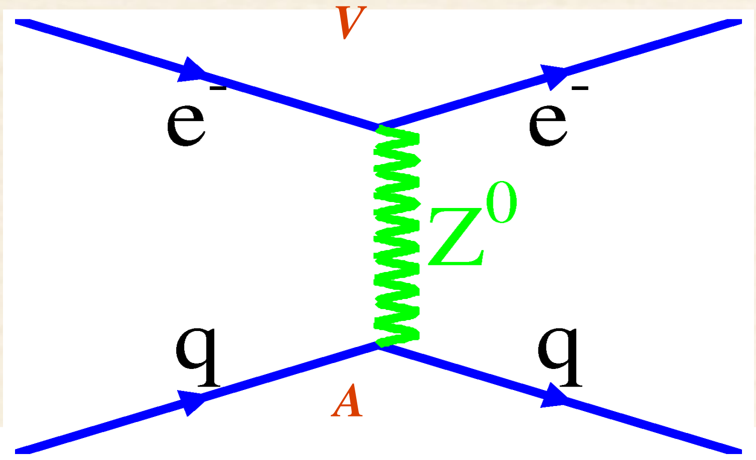

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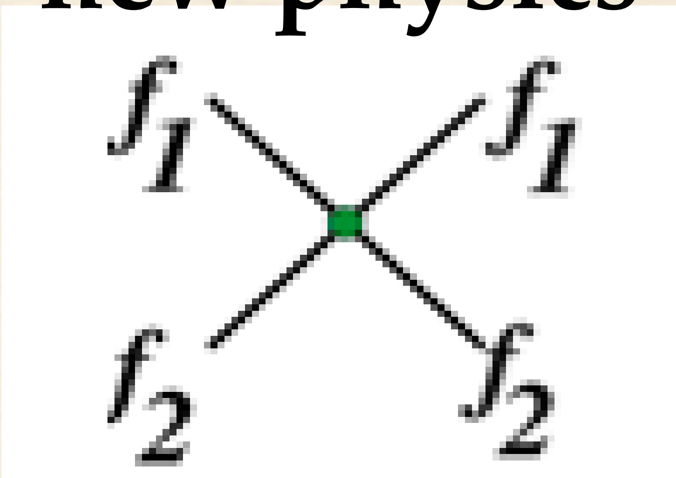
$$\begin{array}{lcrcr} C_{1u} & = & -\frac{1}{2}+\frac{4}{3}\sin^2\theta_W & \approx & -0.19 \\ C_{1d} & = & \frac{1}{2}-\frac{2}{3}\sin^2\theta_W & \approx & 0.35 \\ C_{2u} & = & -\frac{1}{2}+2\sin^2\theta_W & \approx & -0.04 \\ C_{2d} & = & \frac{1}{2}-2\sin^2\theta_W & \approx & 0.04 \end{array}$$

+

new physics



$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda_{ij}^2} \bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma_\mu f_{2j}$$

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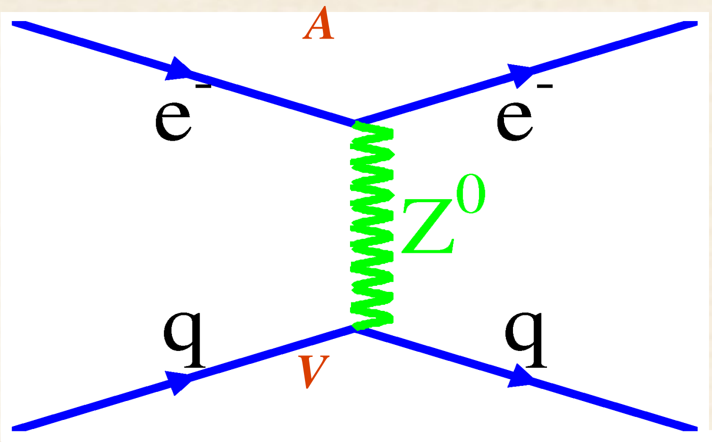

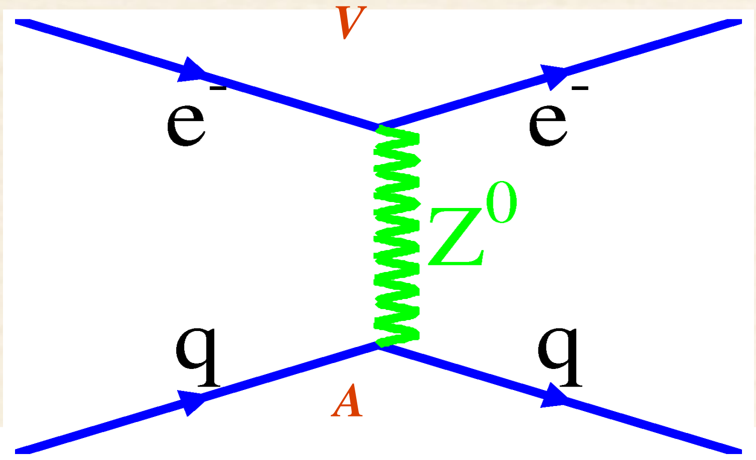

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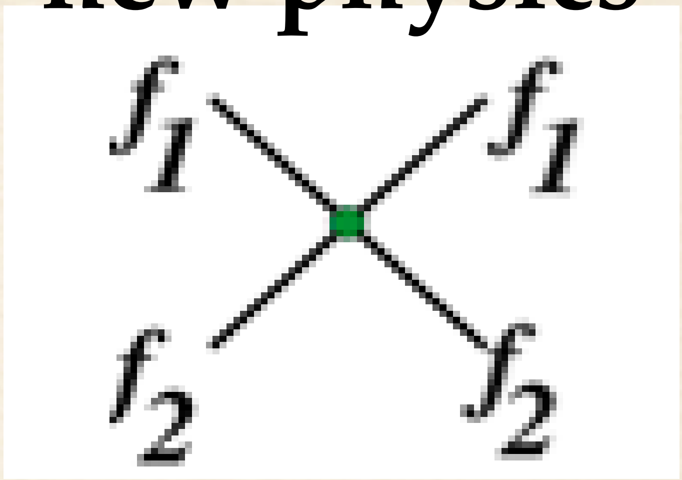
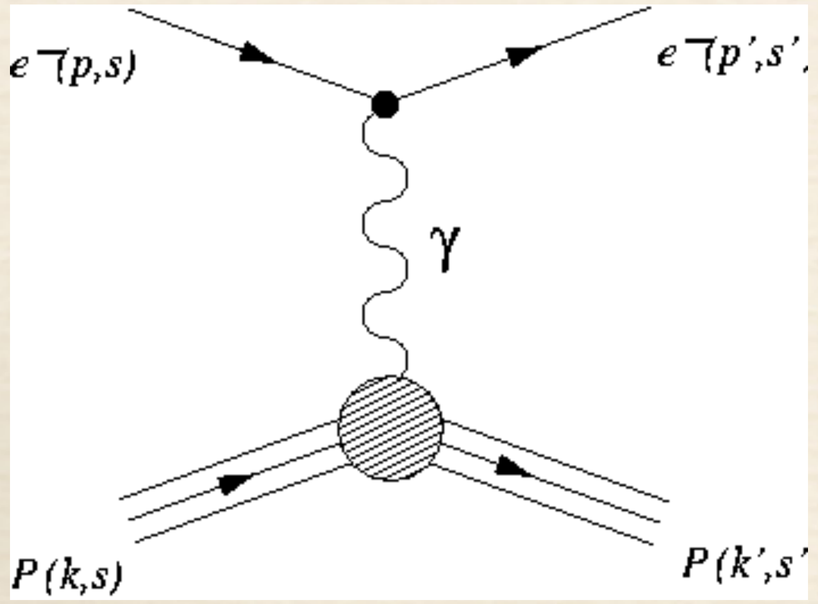


$$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2 \Rightarrow$$

PV elastic e-N scattering, Atomic parity violation



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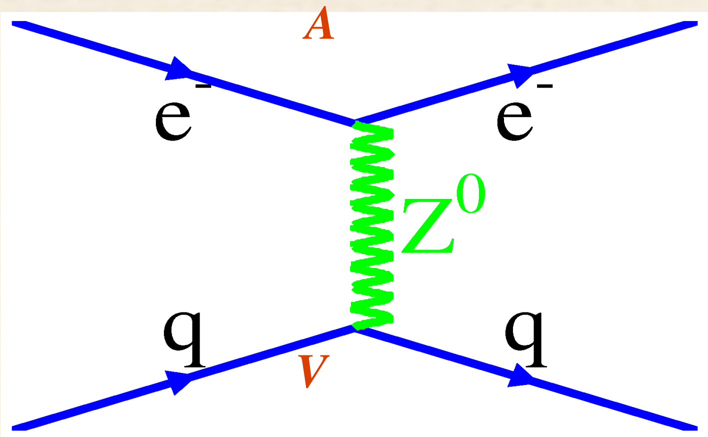

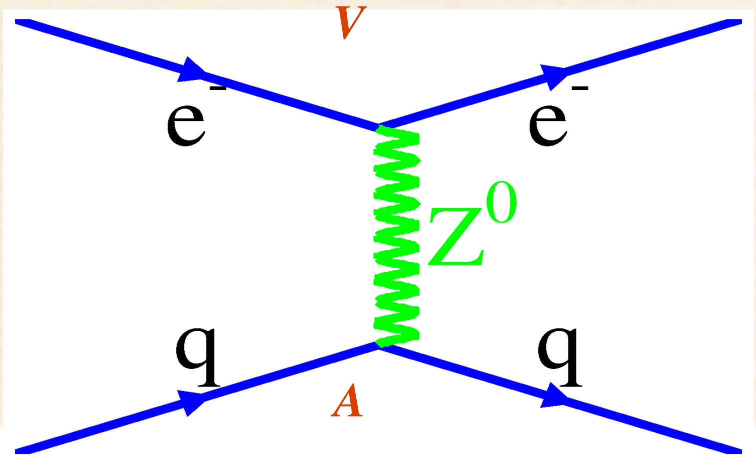

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$$+\bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)]$$
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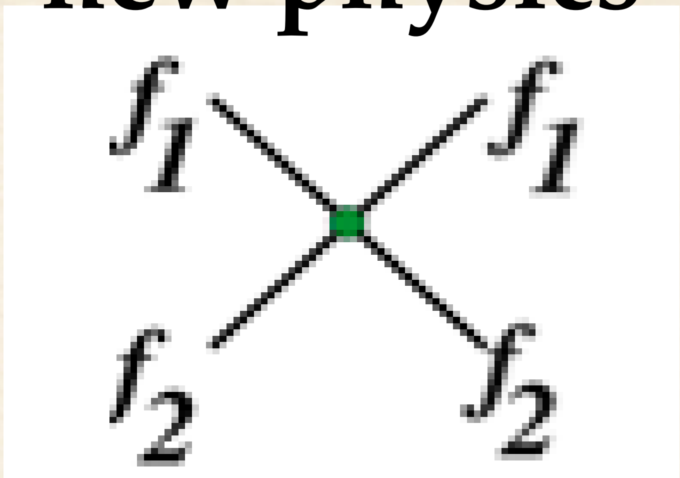
$$\begin{array}{lcrcr} C_{1u} & = & -\frac{1}{2}+\frac{4}{3}\sin^2\theta_W & \approx & -0.19 \\ C_{1d} & = & \frac{1}{2}-\frac{2}{3}\sin^2\theta_W & \approx & 0.35 \\ C_{2u} & = & -\frac{1}{2}+2\sin^2\theta_W & \approx & -0.04 \\ C_{2d} & = & \frac{1}{2}-2\sin^2\theta_W & \approx & 0.04 \end{array}$$

+

new physics



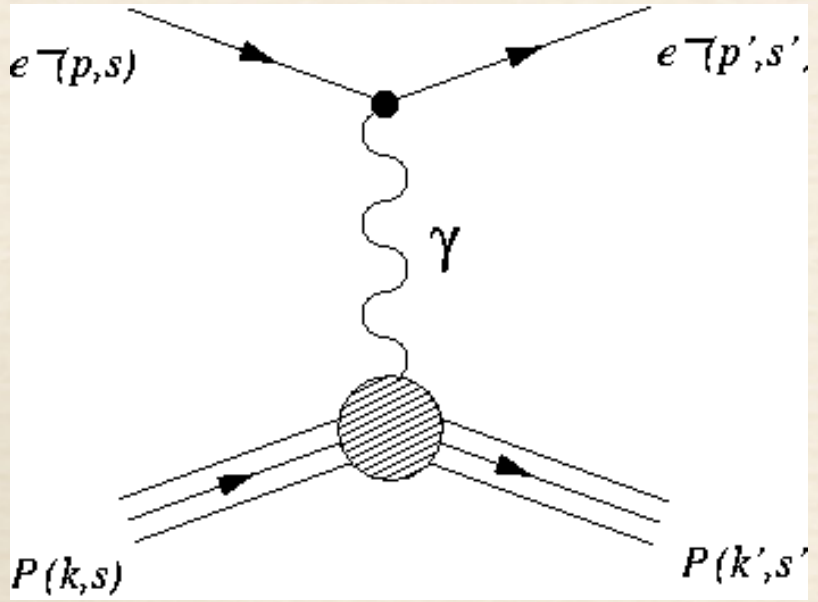
$$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2 \Rightarrow$$

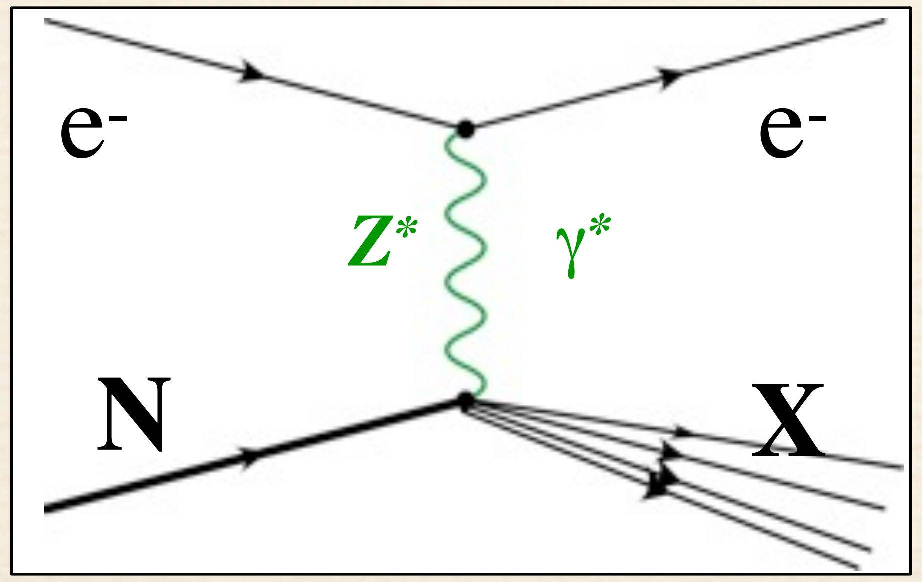
PV elastic e-N scattering, Atomic parity violation

$$C_{2q} \propto (g_{RR}^{eq})^2 - (g_{RL}^{eq})^2 + (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2 \Rightarrow$$

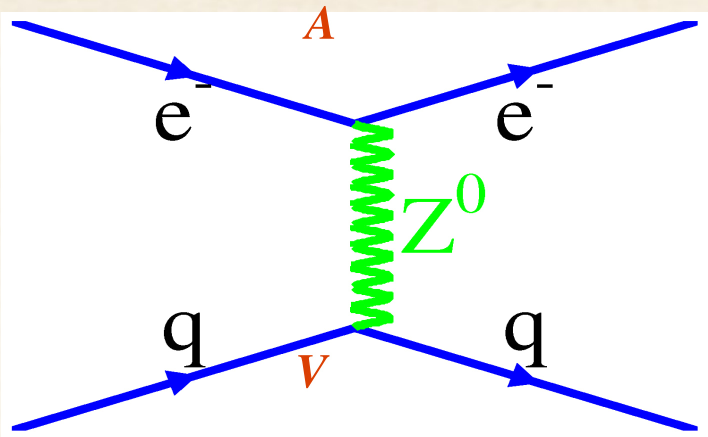
PV deep inelastic scattering

$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda_{ij}^2} \bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma_\mu f_{2j}$$

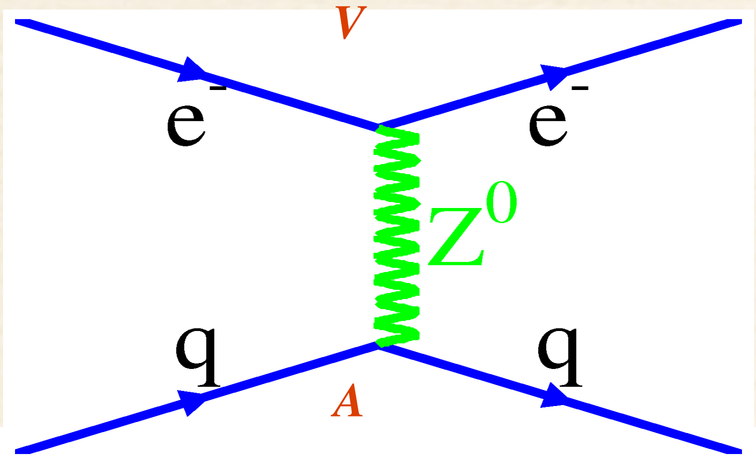




WNC Couplings



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



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

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)] + C_{ee}(e\gamma^\mu\gamma_5 e\bar{e}\gamma_\mu e)$$

C_{1u}	$=$	$-\frac{1}{2}+\frac{4}{3}\sin^2\theta_W$	$\approx$	-0.19
C_{1d}	$=$	$\frac{1}{2}-\frac{2}{3}\sin^2\theta_W$	$\approx$	0.35
C_{2u}	$=$	$-\frac{1}{2}+2\sin^2\theta_W$	$\approx$	-0.04
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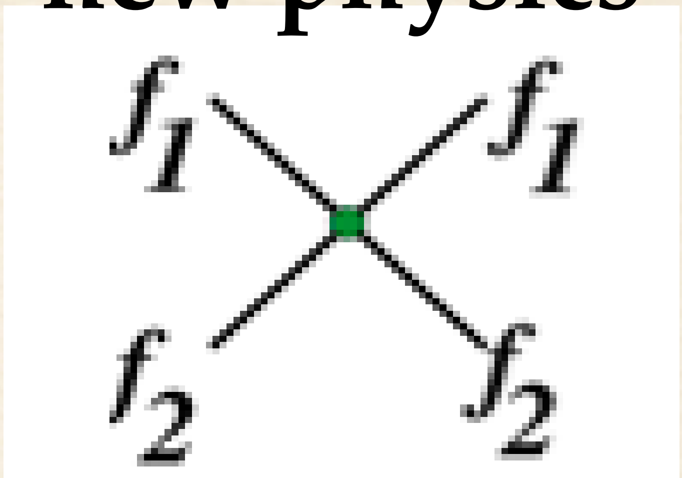
+ new physics

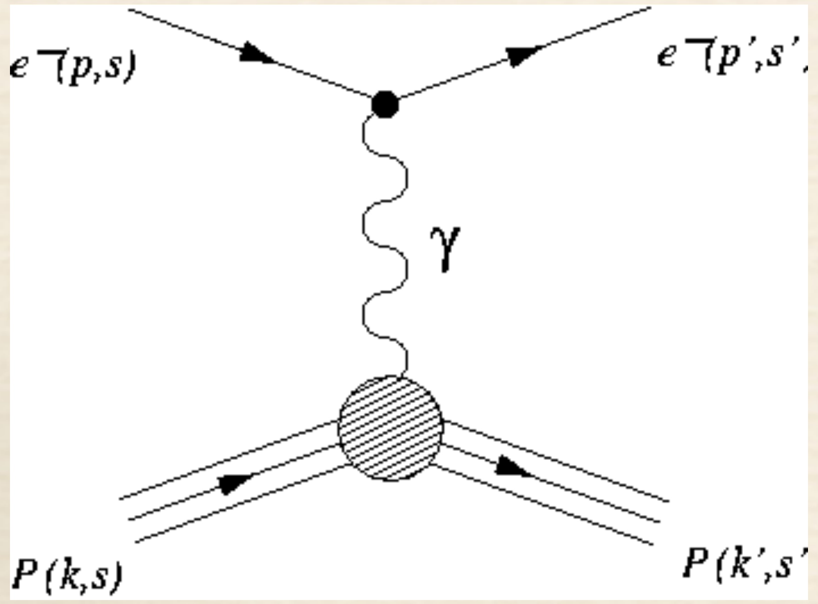


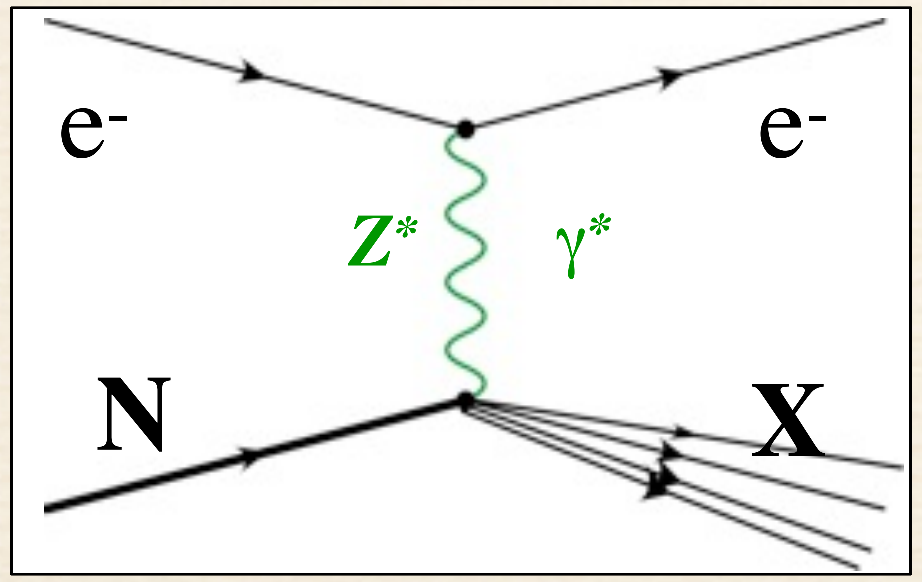
$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$ ⇨ ***PV elastic e-N scattering, Atomic parity violation***

$C_{2q} \propto (g_{RR}^{eq})^2 - (g_{RL}^{eq})^2 + (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$ ⇨ ***PV deep inelastic scattering***

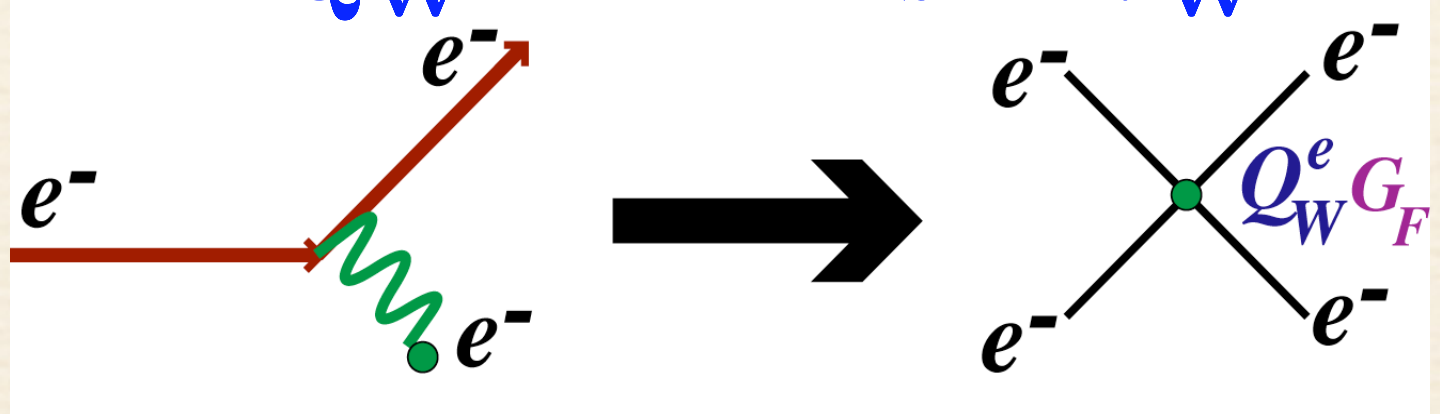
$C_{ee} \propto (g_{RR}^{ee})^2 - (g_{LL}^{ee})^2$ ⇨ ***PV Møller scattering***

$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda_{ij}^2}\bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma_\mu f_{2j}$$



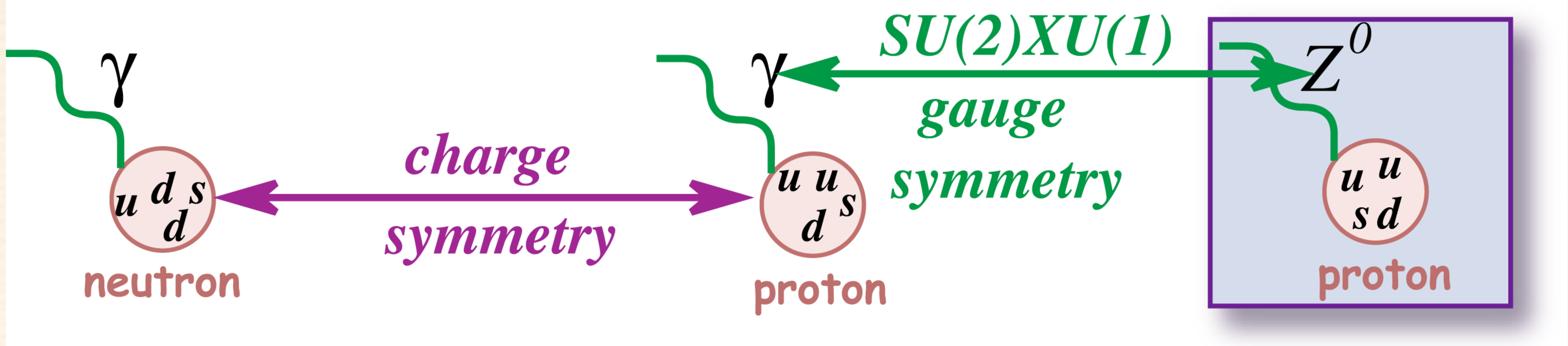


$Q_W = 1 - 4\sin^2\theta_W$



1990 - 2010

PV Electron-Nucleon Elastic Scattering: Nucleon Strange Quark Form Factors



$$G_p^Z \sim (1 - 4\sin^2\theta_W)\, G_p^\gamma - G_n^\gamma - G_s$$

$\Rightarrow$ $G_E^s(Q^2), G_M^s(Q^2)$

1990 - 2010

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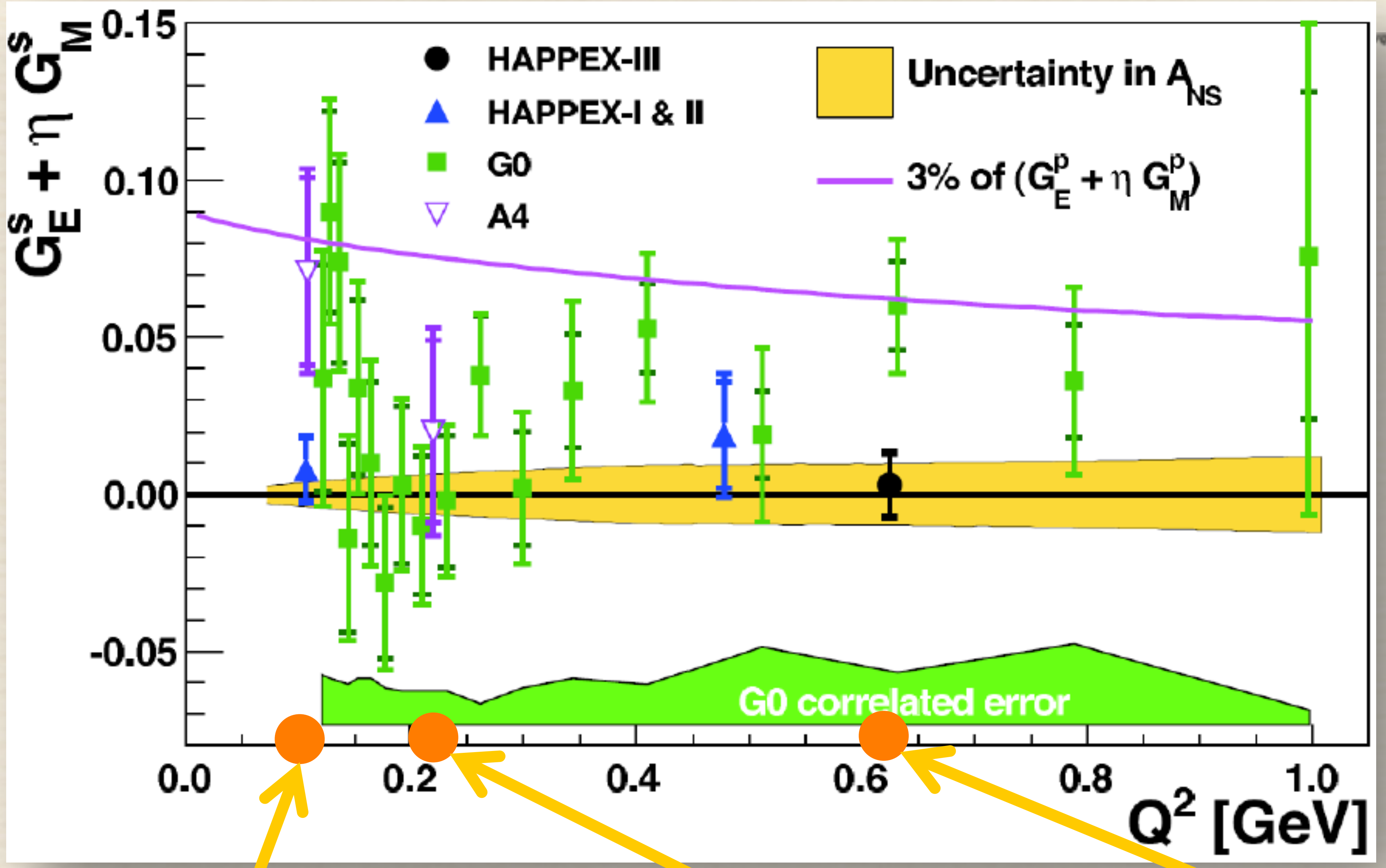

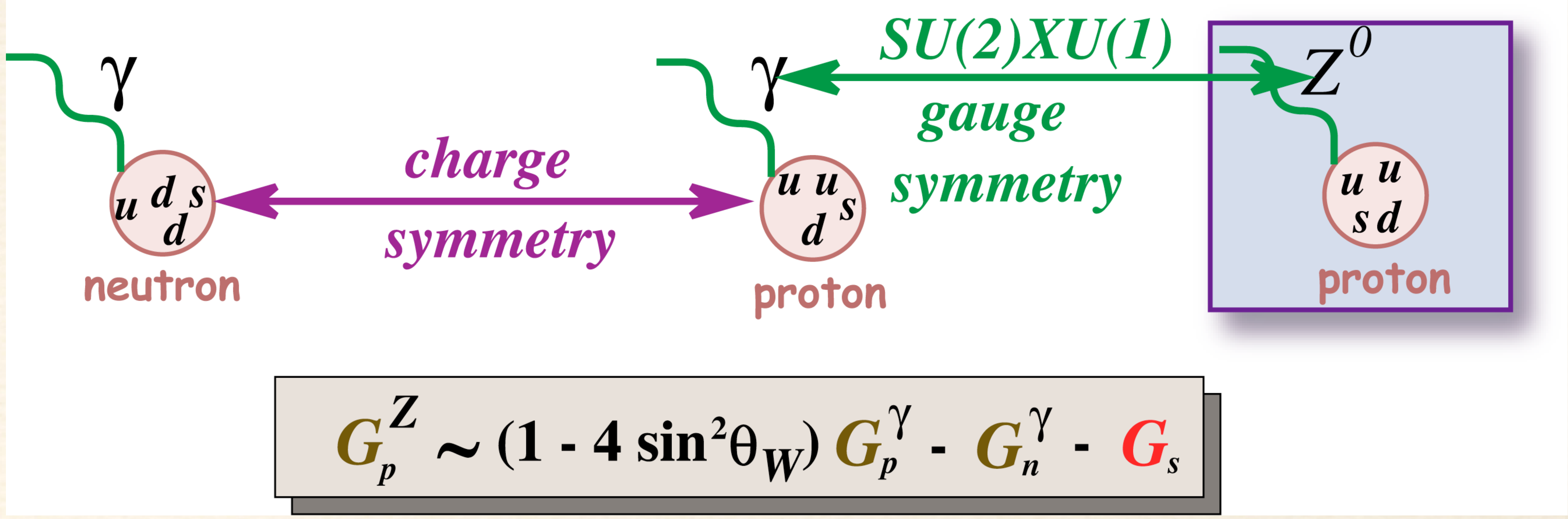

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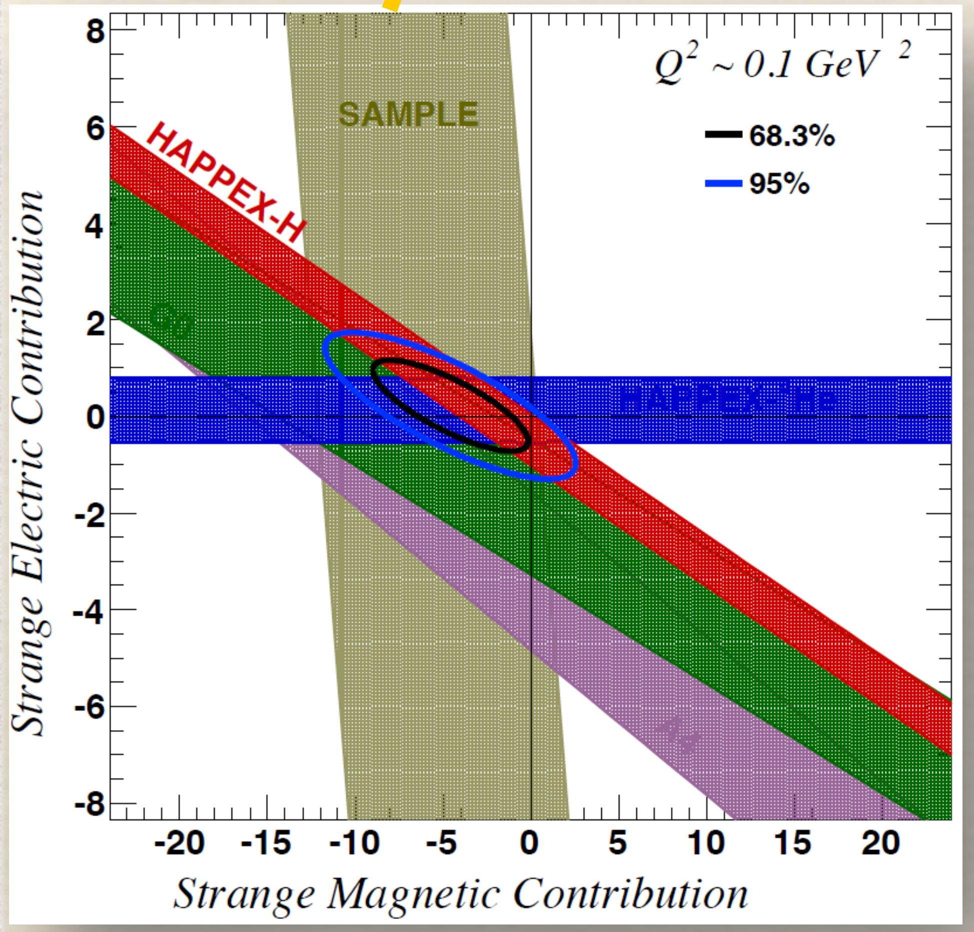

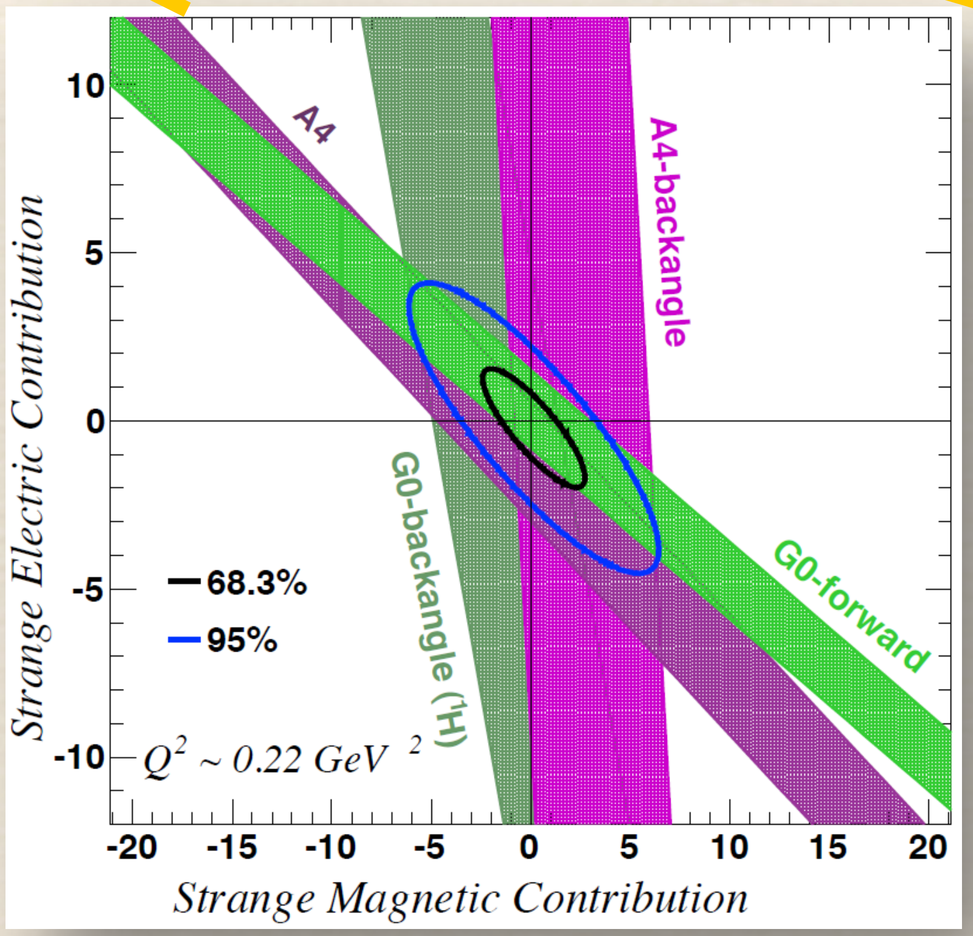

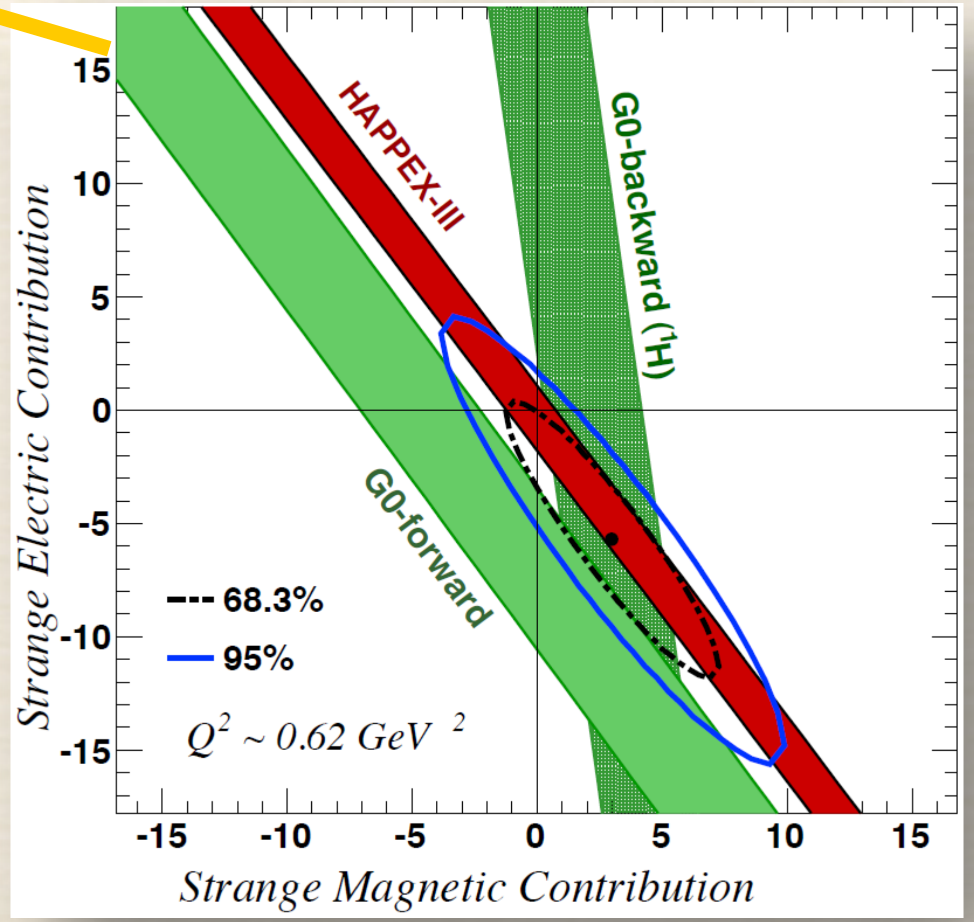

1990 - 2010

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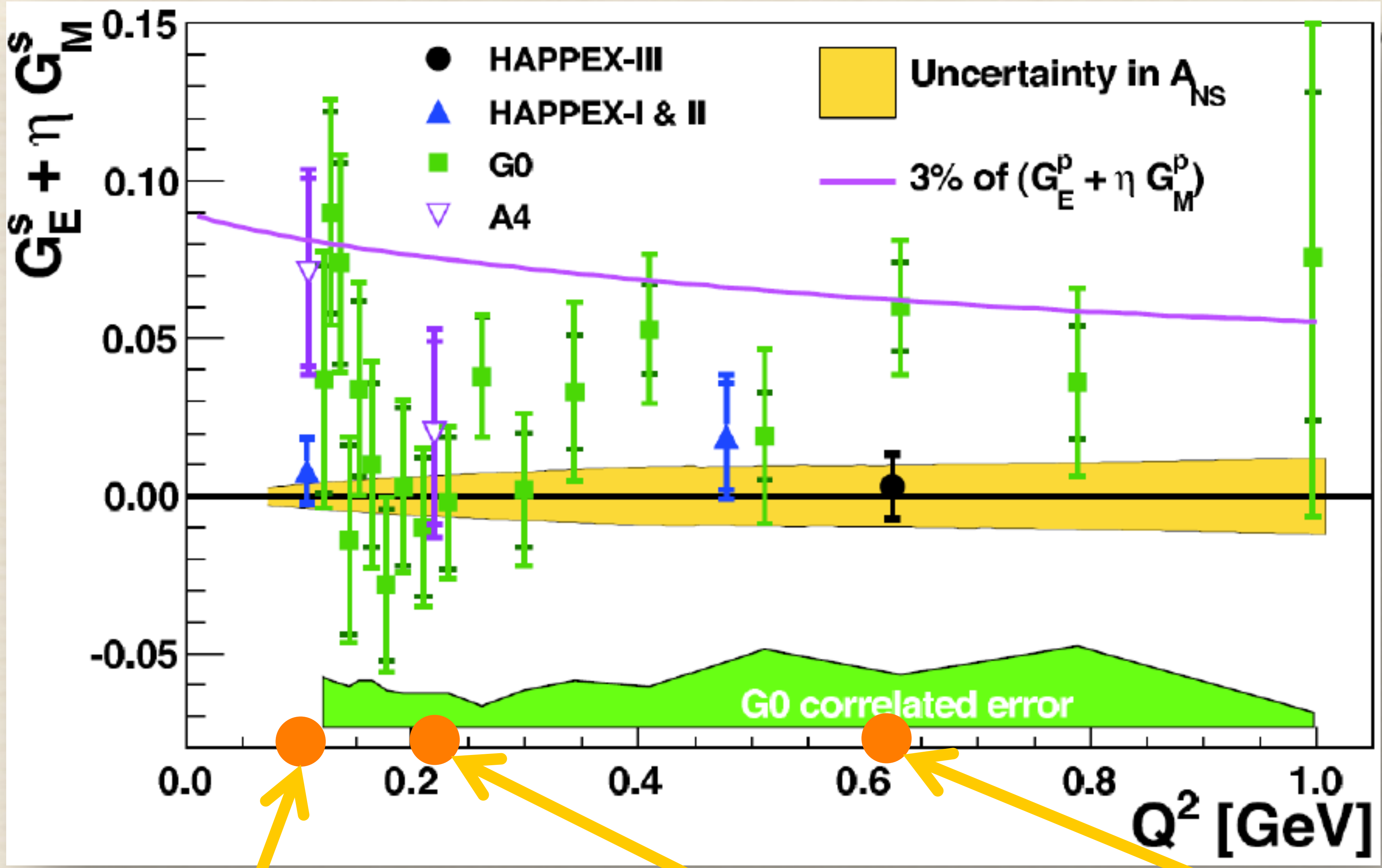
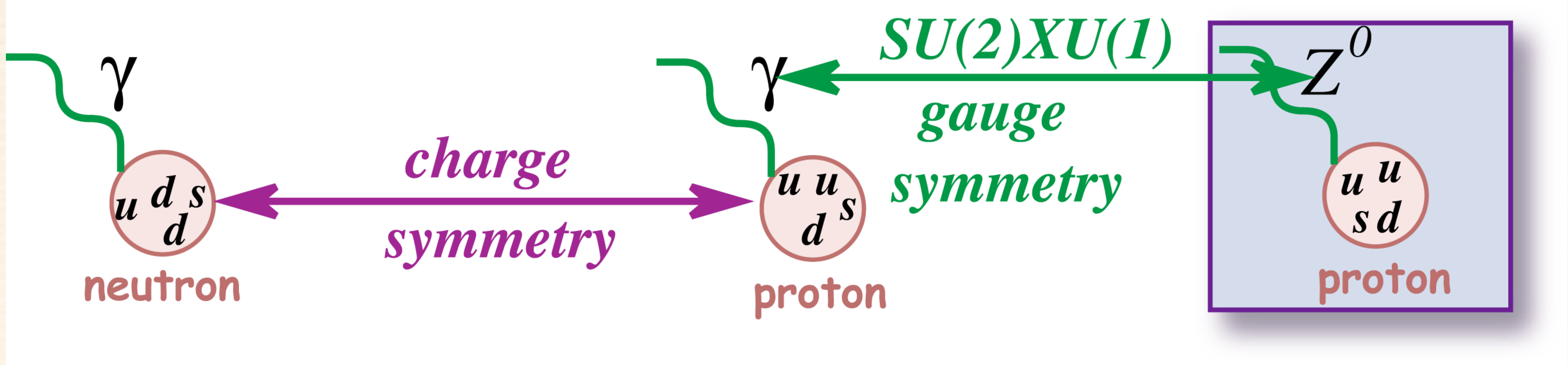
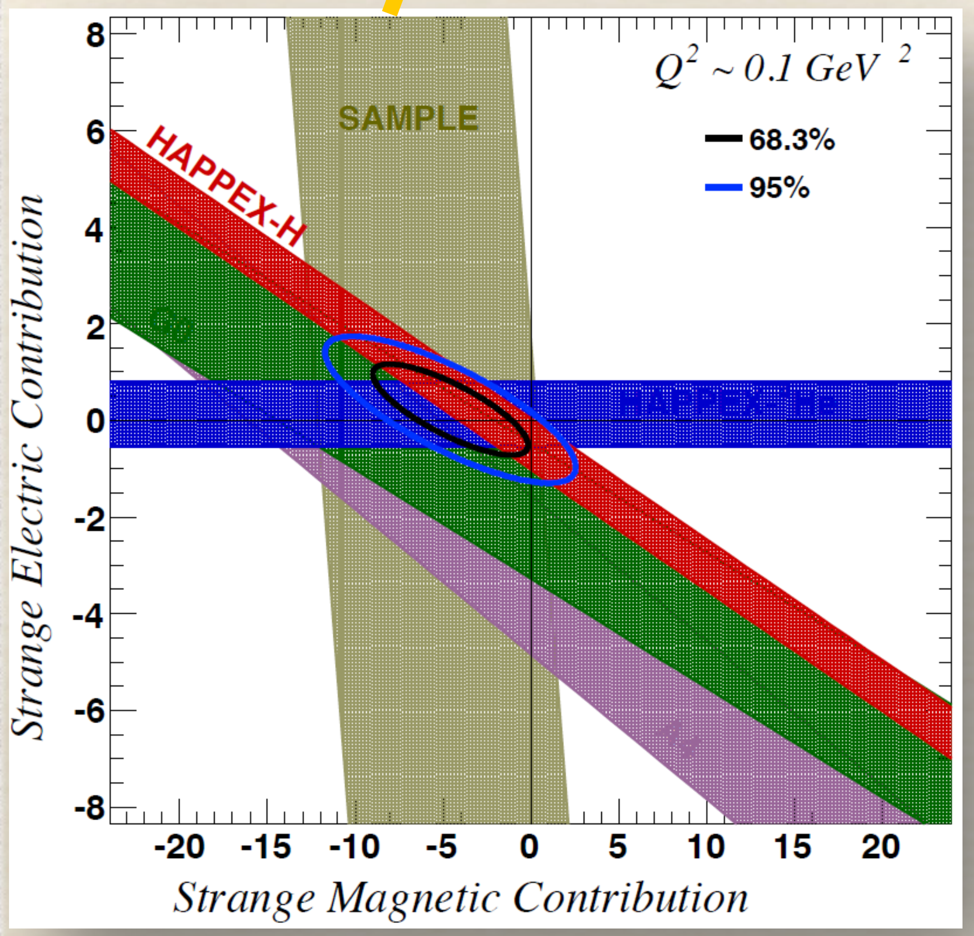


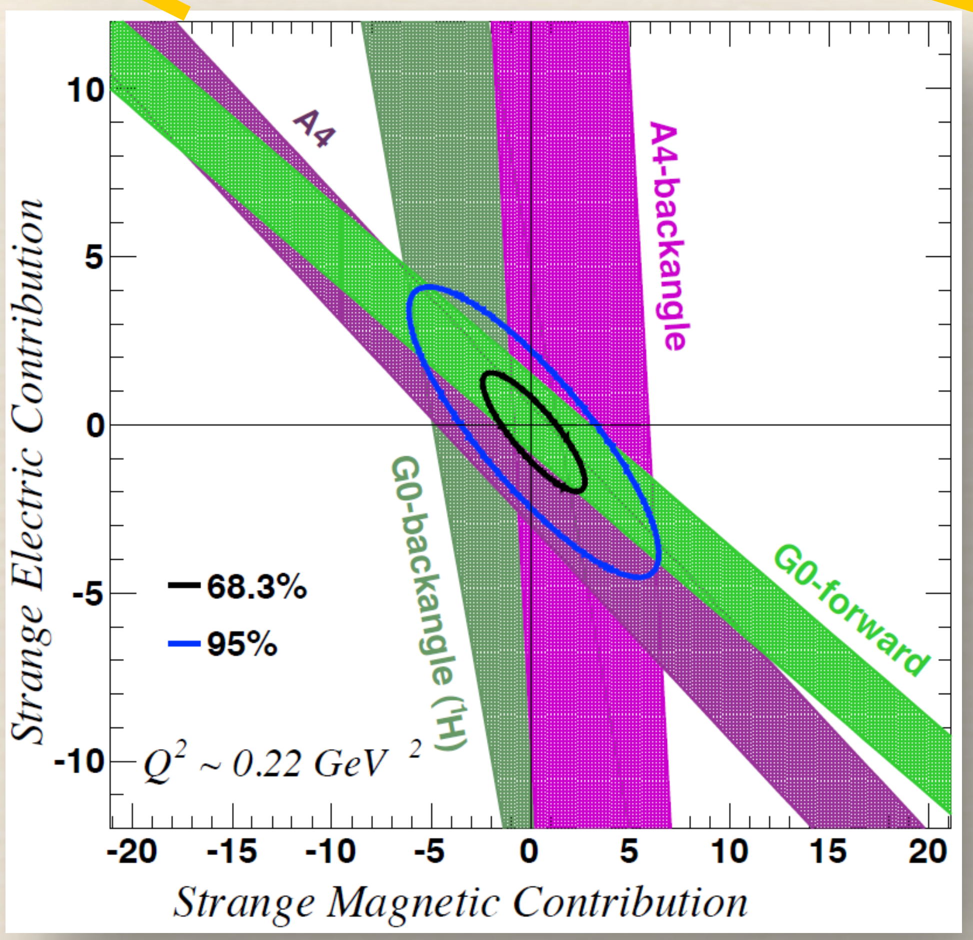


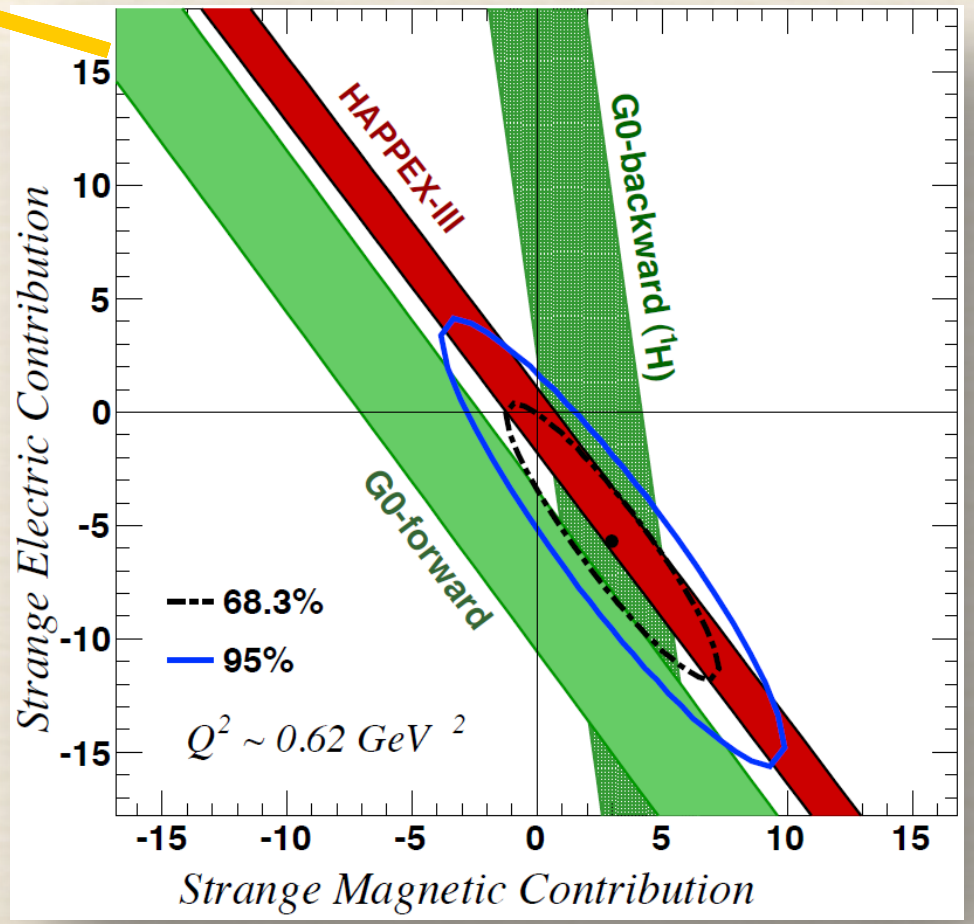
$$G_p^Z \sim (1 - 4\sin^2\theta_W)\, G_p^\gamma - G_n^\gamma - G_s$$

$\Rightarrow$ $G_E^s(Q^2), G_M^s(Q^2)$

- Sensitive Flavor separation at three Q^2 values
- Strange quarks are no more than a few % of EM structure
- Modern lattice QCD results are in agreement





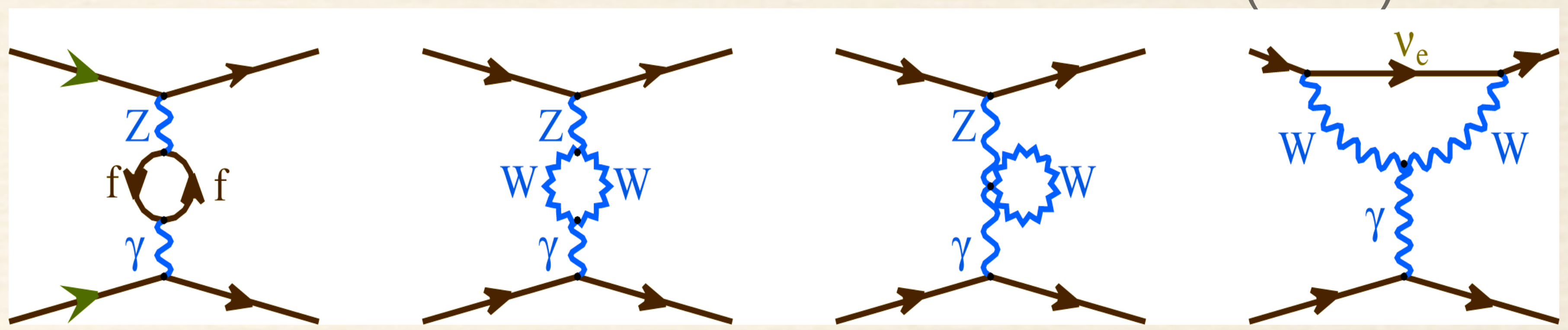


Thumb Rule: Weak mixing angle must be measured to sub-0.5% precision

Snapshot of Standard Model Tests

Electroweak Radiative Corrections causes weak mixing angle to “run”

Czarnecki and Marciano (1995)



✦ Atomic Parity Violation: Cs-133

- ✦ future measurements and theory challenging

✦ Neutrino Deep Inelastic Scattering: NuTeV

- ✦ future measurements and theory challenging

✦ PV Møller Scattering: E158 at SLAC

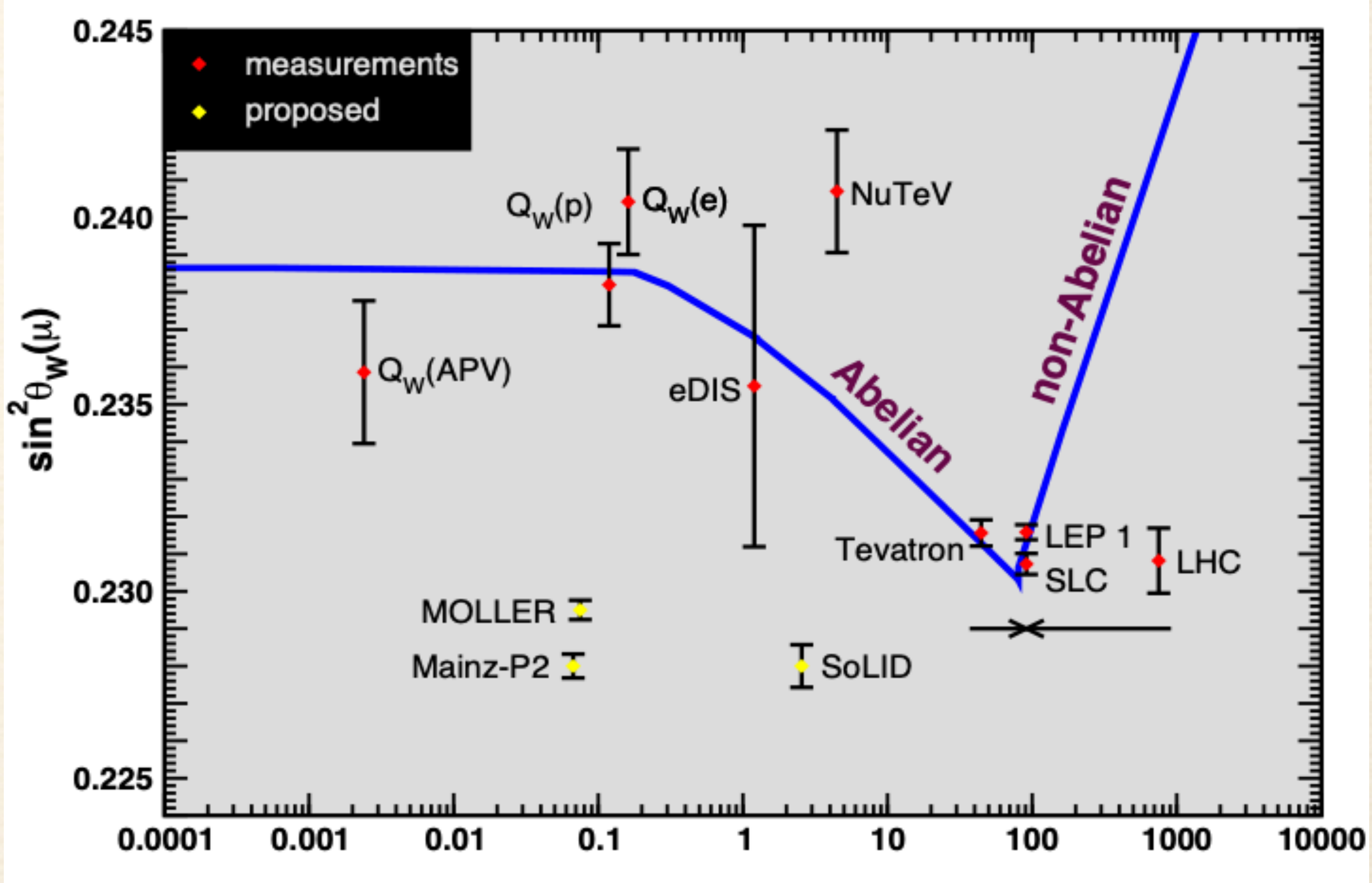
- ✦ statistics limited, theory robust
- ✦ next generation: MOLLER (factor of 5 better)

✦ PV elastic e-p scattering: Qweak

- ✦ theory robust at low beam energy
- ✦ next generation: P2 (factor of 3 better)

✦ PV Deep Inelastic Scattering: PVDIS

- ✦ theory robust for ^{2}H in valence quark region
- ✦ next generation: SOLID (factor of 8 better)

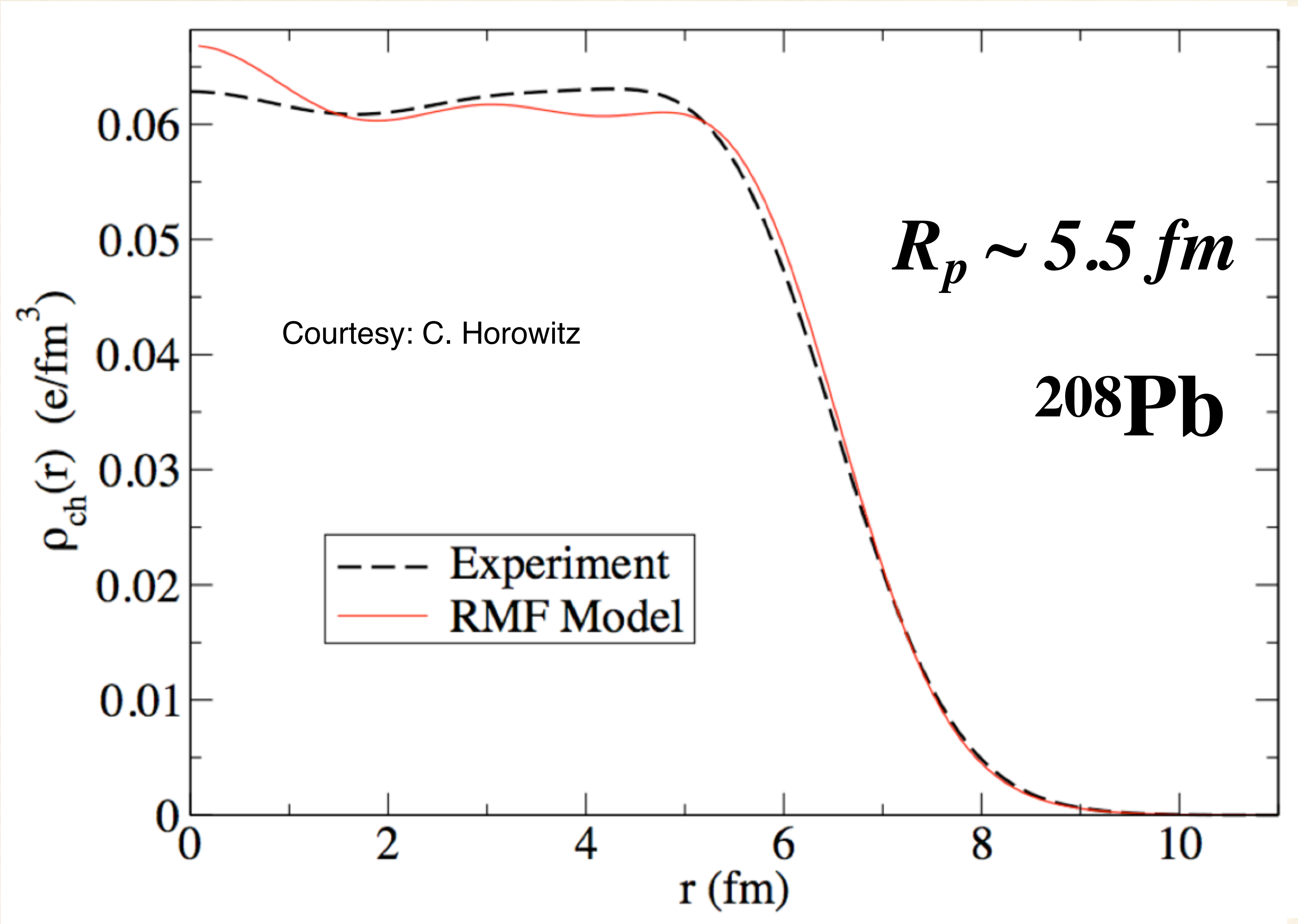


Courtesy: J. Erler

EM Charge vs Weak Charge Density

C.J. Horowitz et al: *Phys.Rev.C* 63 (2001) 025501
• e-Print: nucl-th/9912038 [nucl-th]

New PVES nuclear application: the neutron skin



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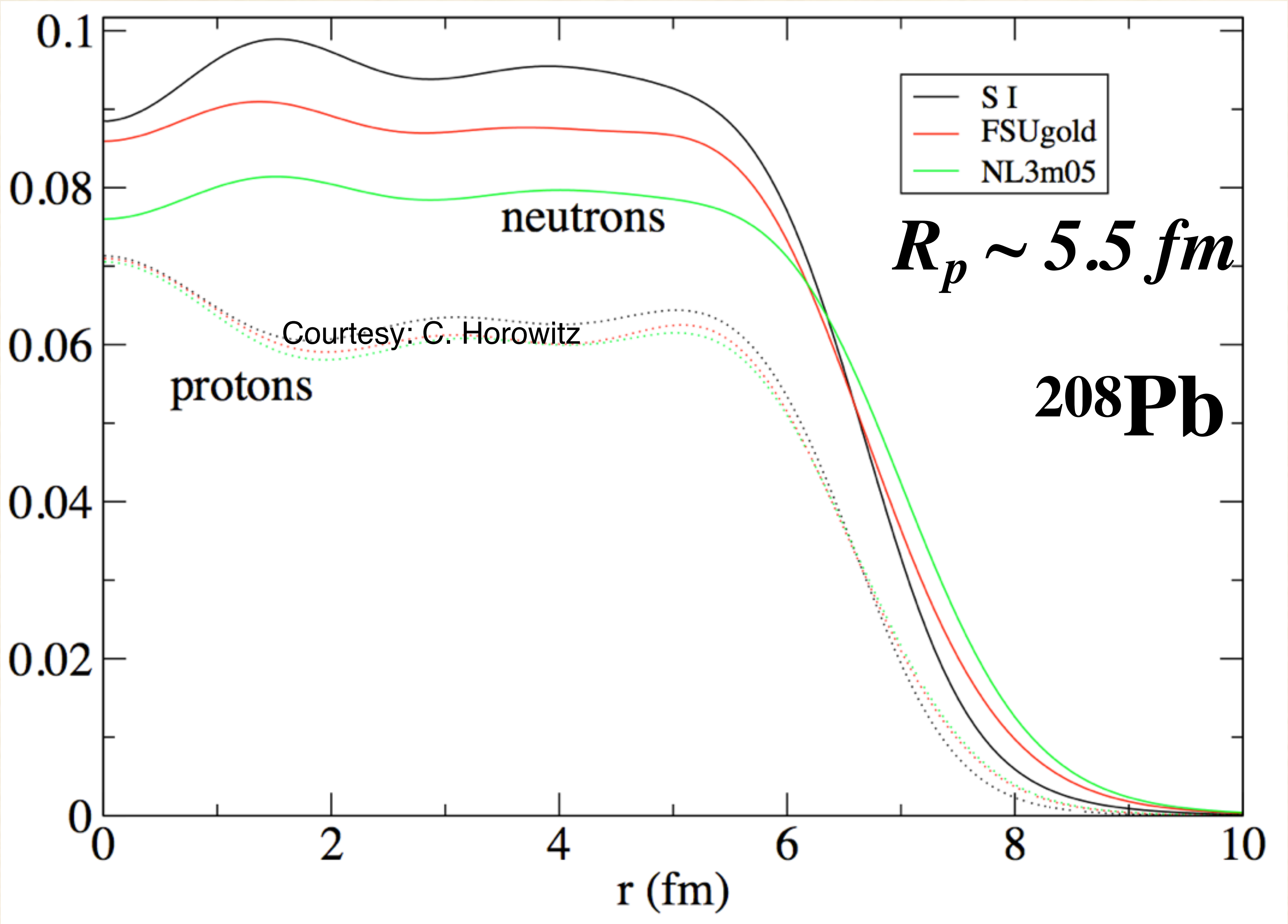

neutrons expected to occupy a larger volume

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

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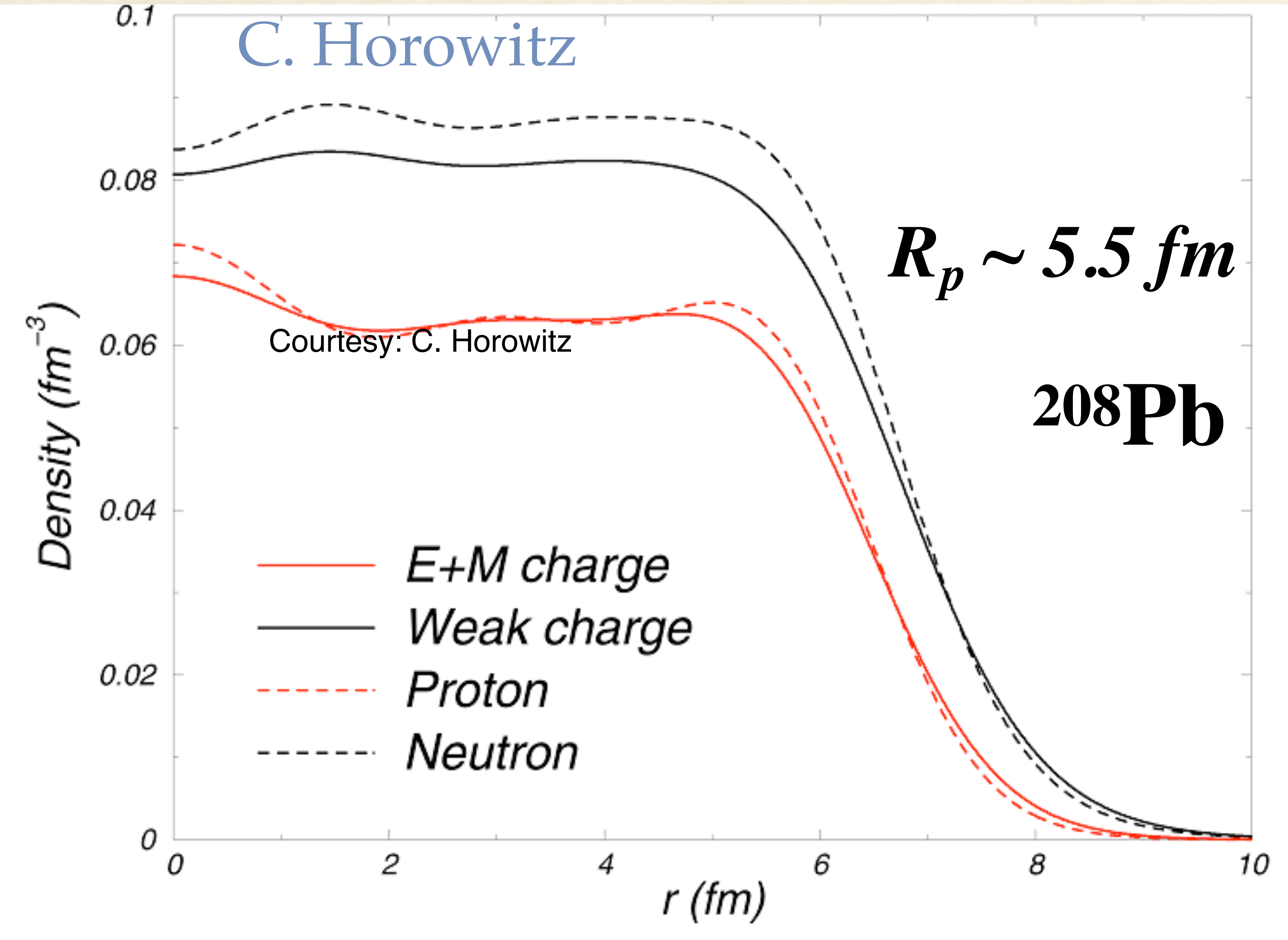

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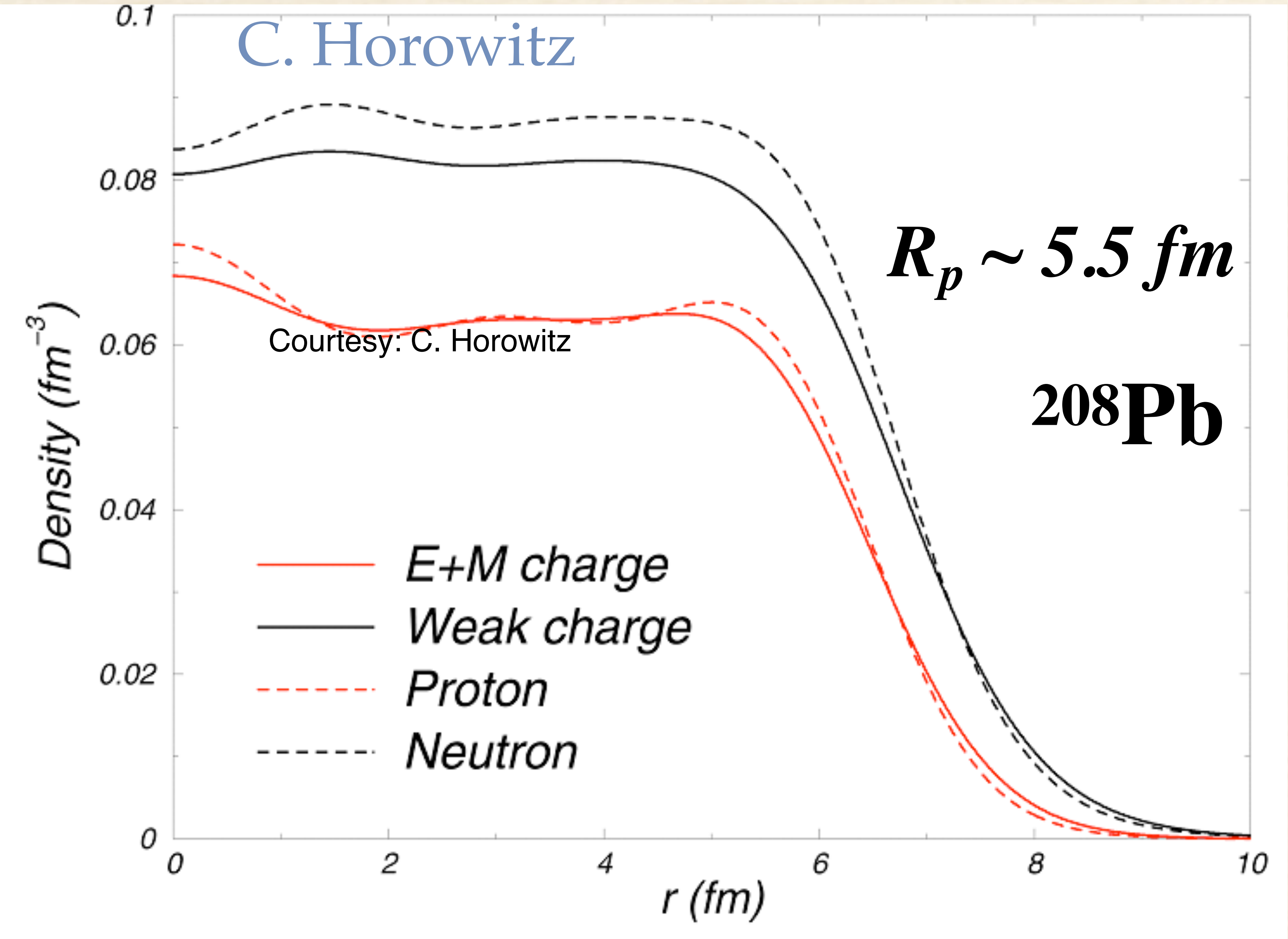

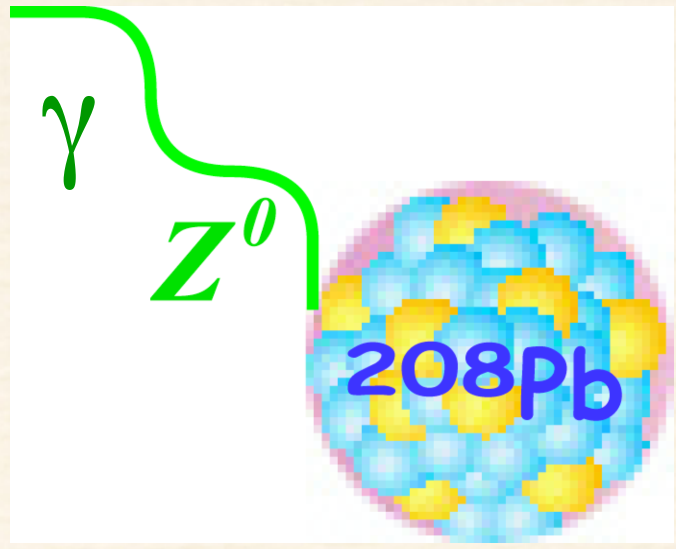

	proton	neutron
Electric (γ) charge	1	0
Weak (Z^0) charge	-0.08	1

$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)}$$

neutrons expected to occupy a larger volume

parity-violating electron scattering can directly constrain the RMS radius r_n of a heavy spinless nucleus

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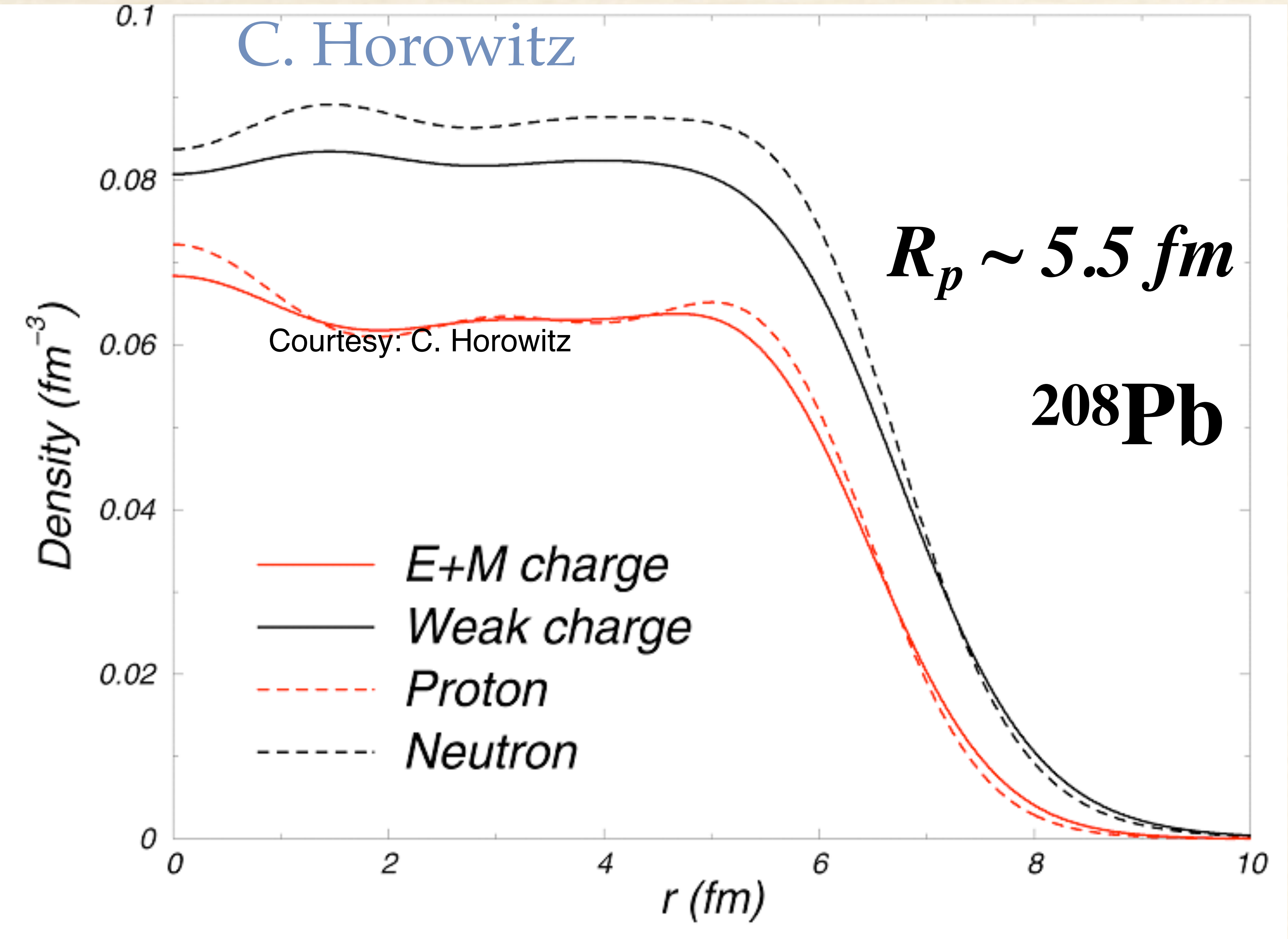

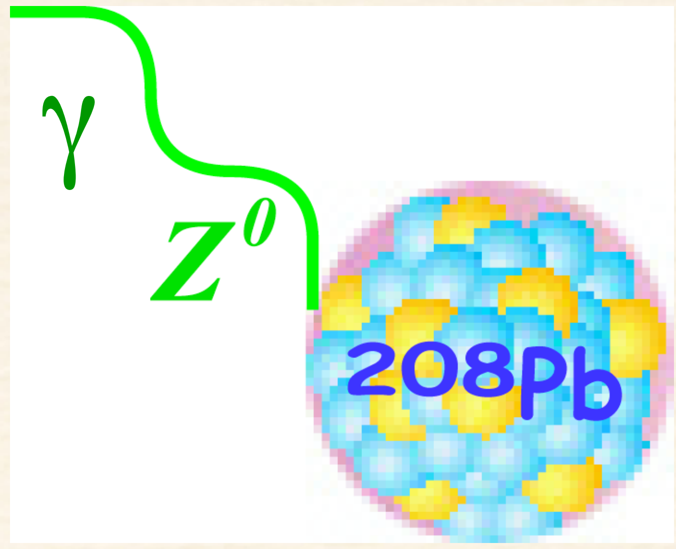

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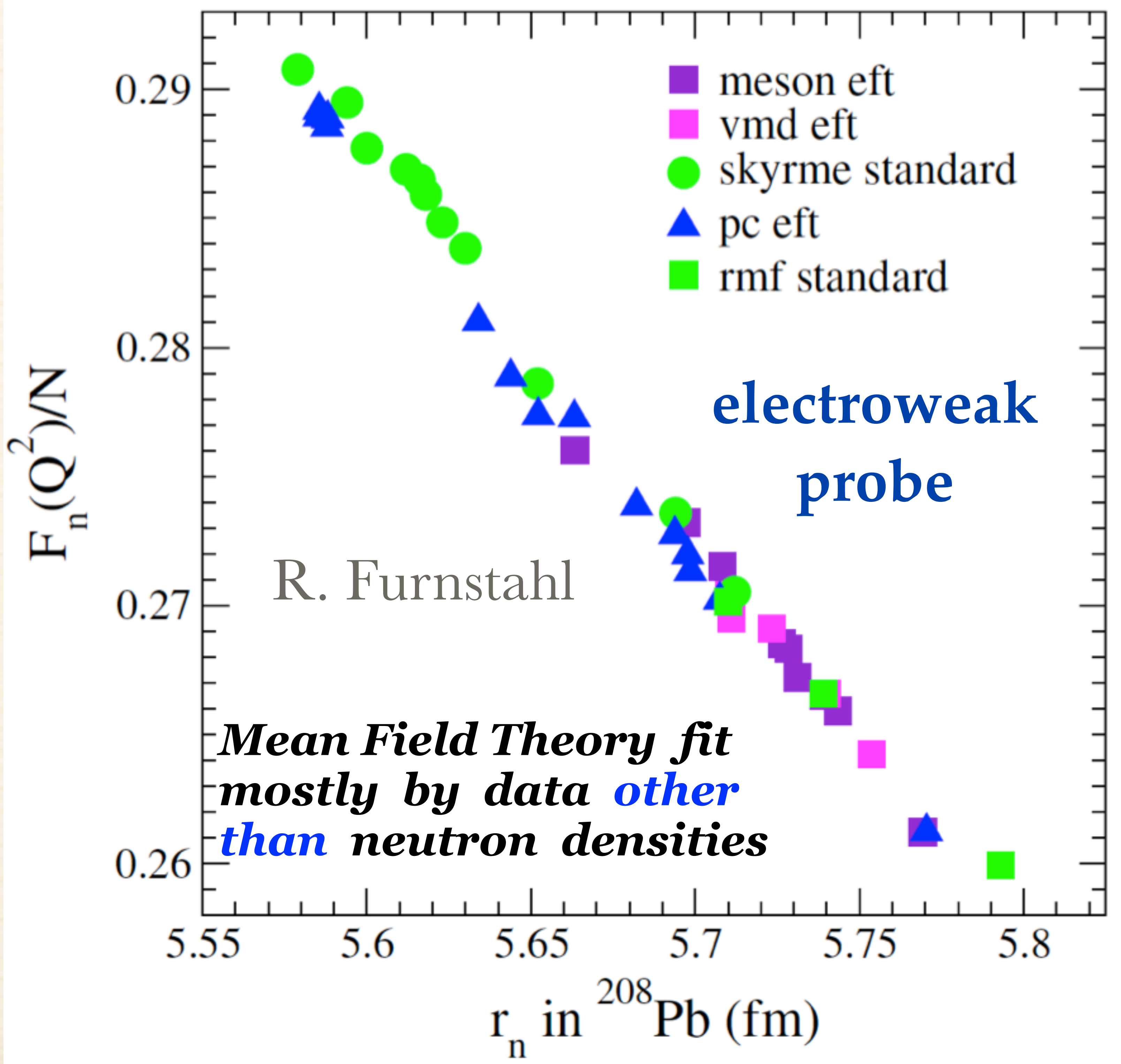


neutrons expected to occupy a larger volume

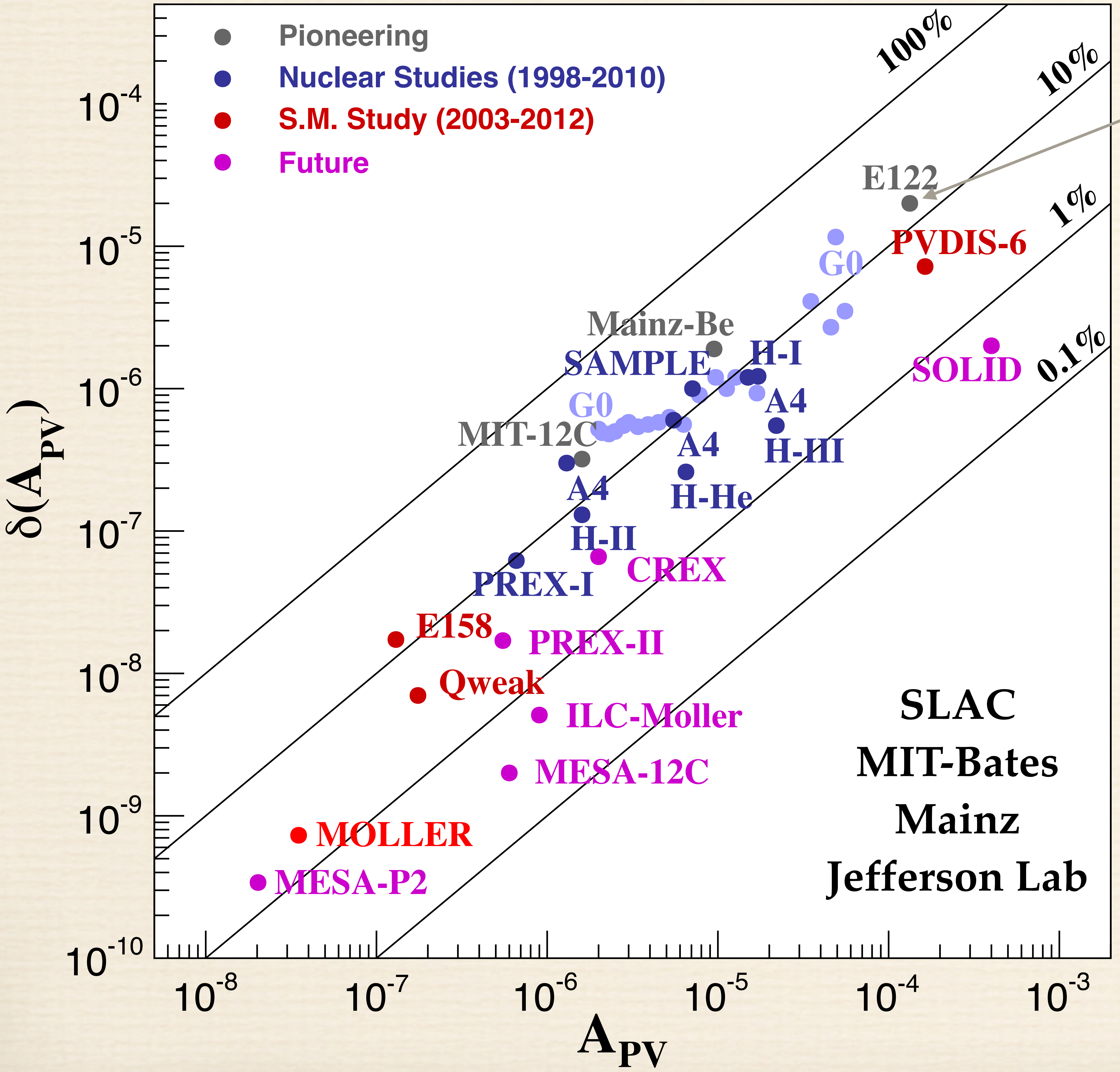
parity-violating electron scattering can directly constrain the RMS radius r_n of a heavy spinless nucleus

Continuous interplay between probing hadron structure and electroweak physics

4 Decades of Progress

Parity-violating electron scattering has become a precision tool

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*

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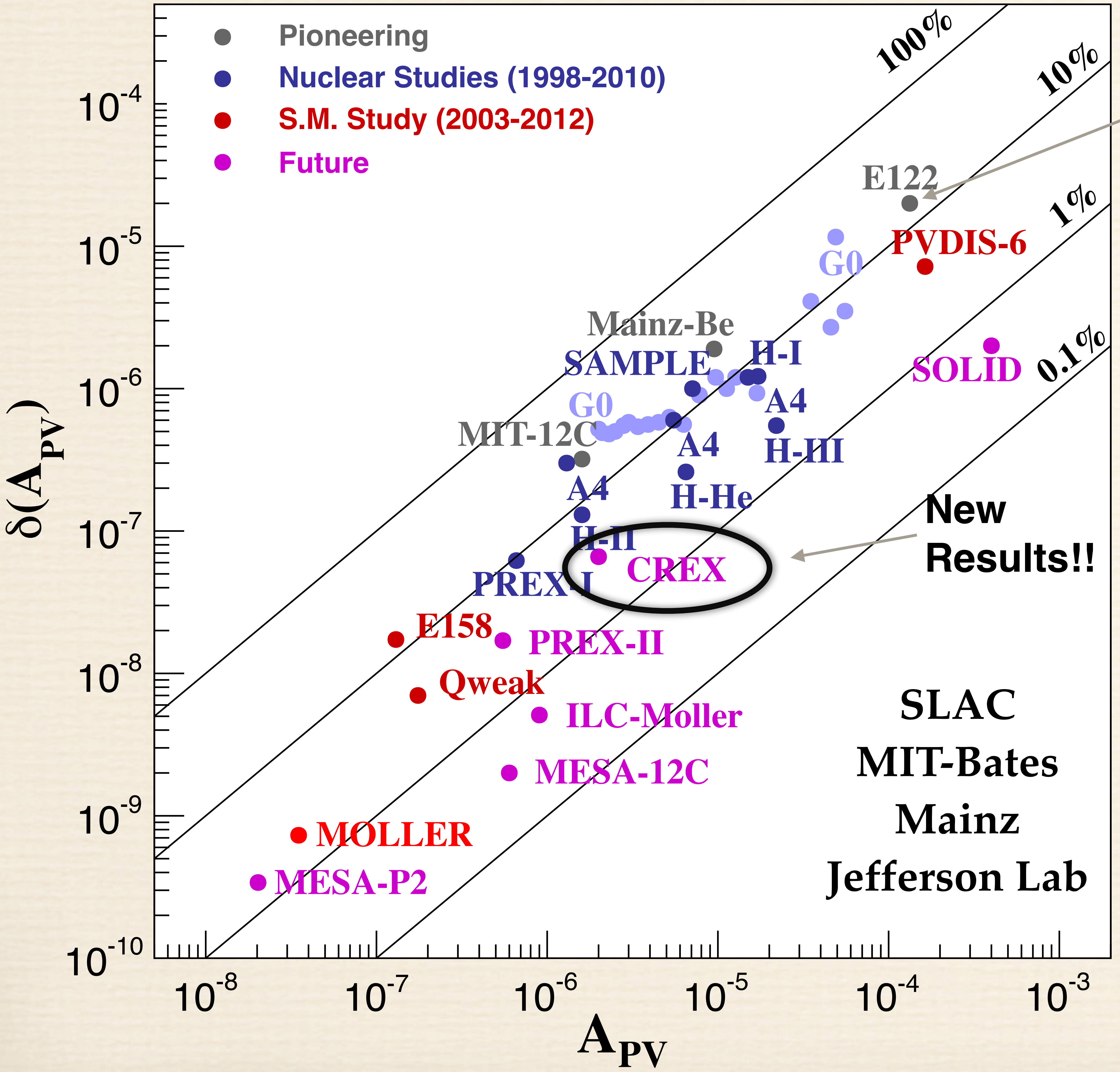

Pioneering electron-quark PV DIS experiment SLAC E122

New Results!!

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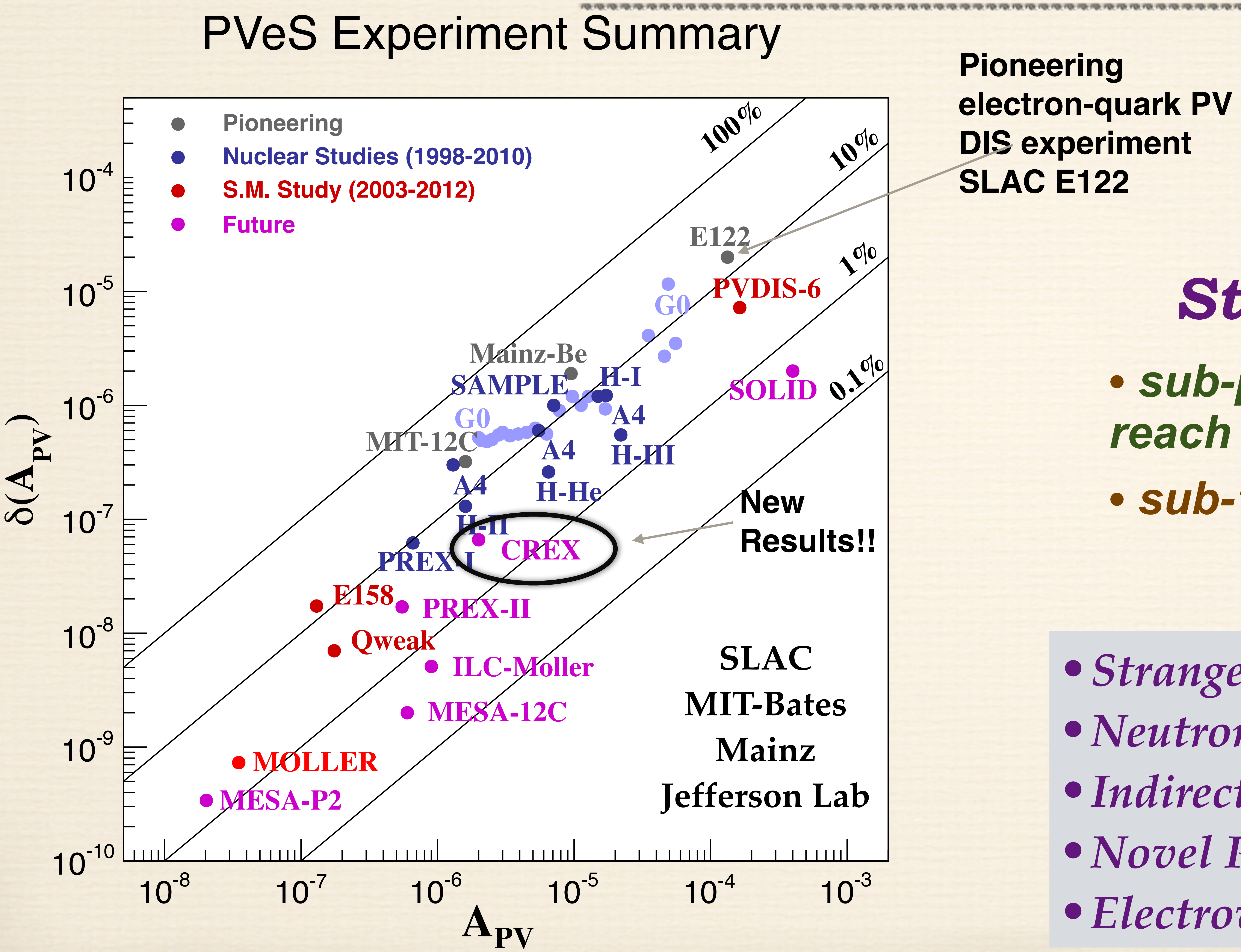

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Physics Topics

- *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*

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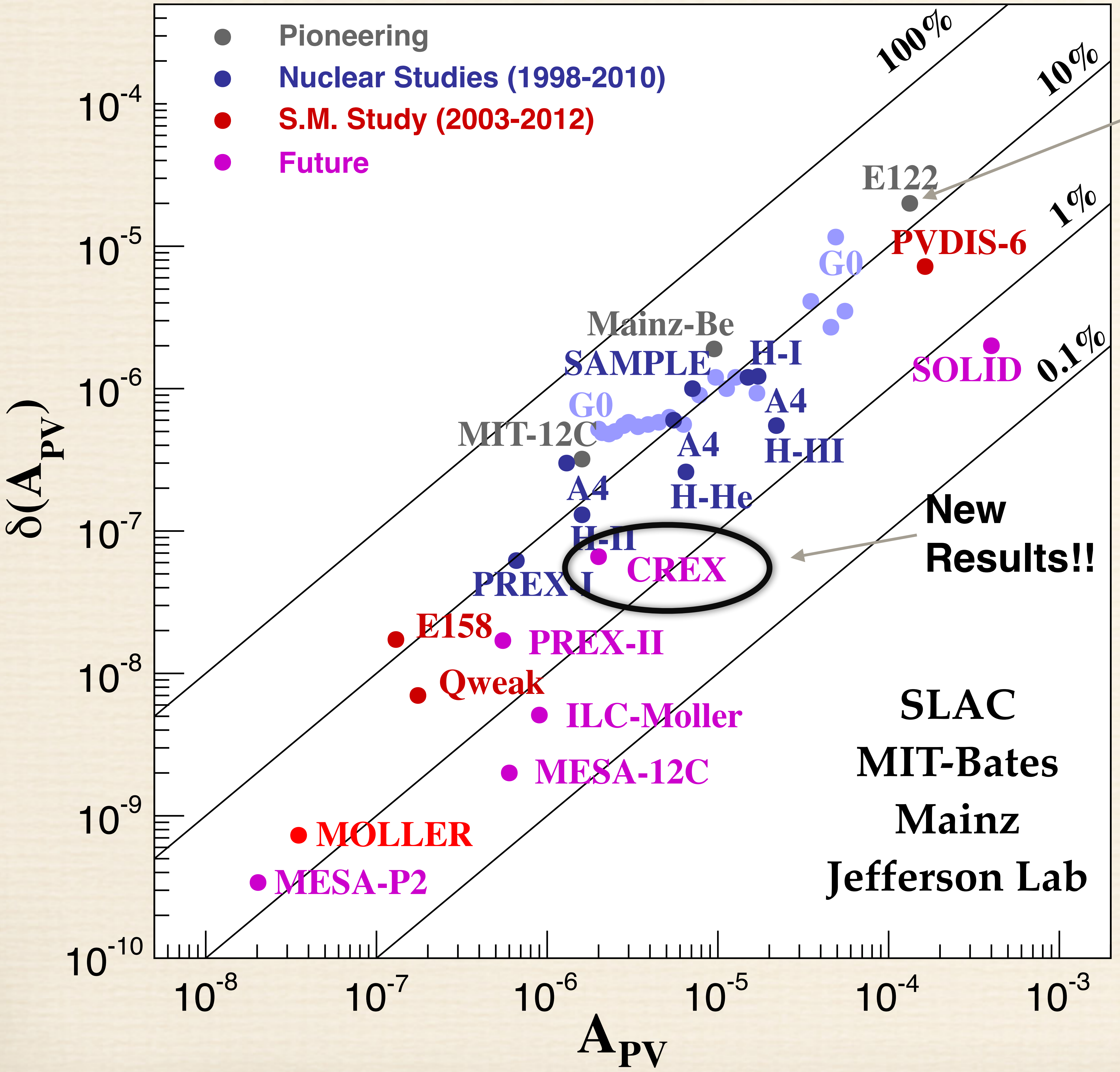

Pioneering electron-quark PV DIS experiment SLAC E122

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

State-of-the-art:

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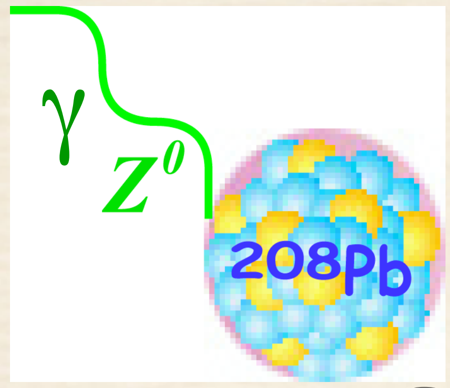
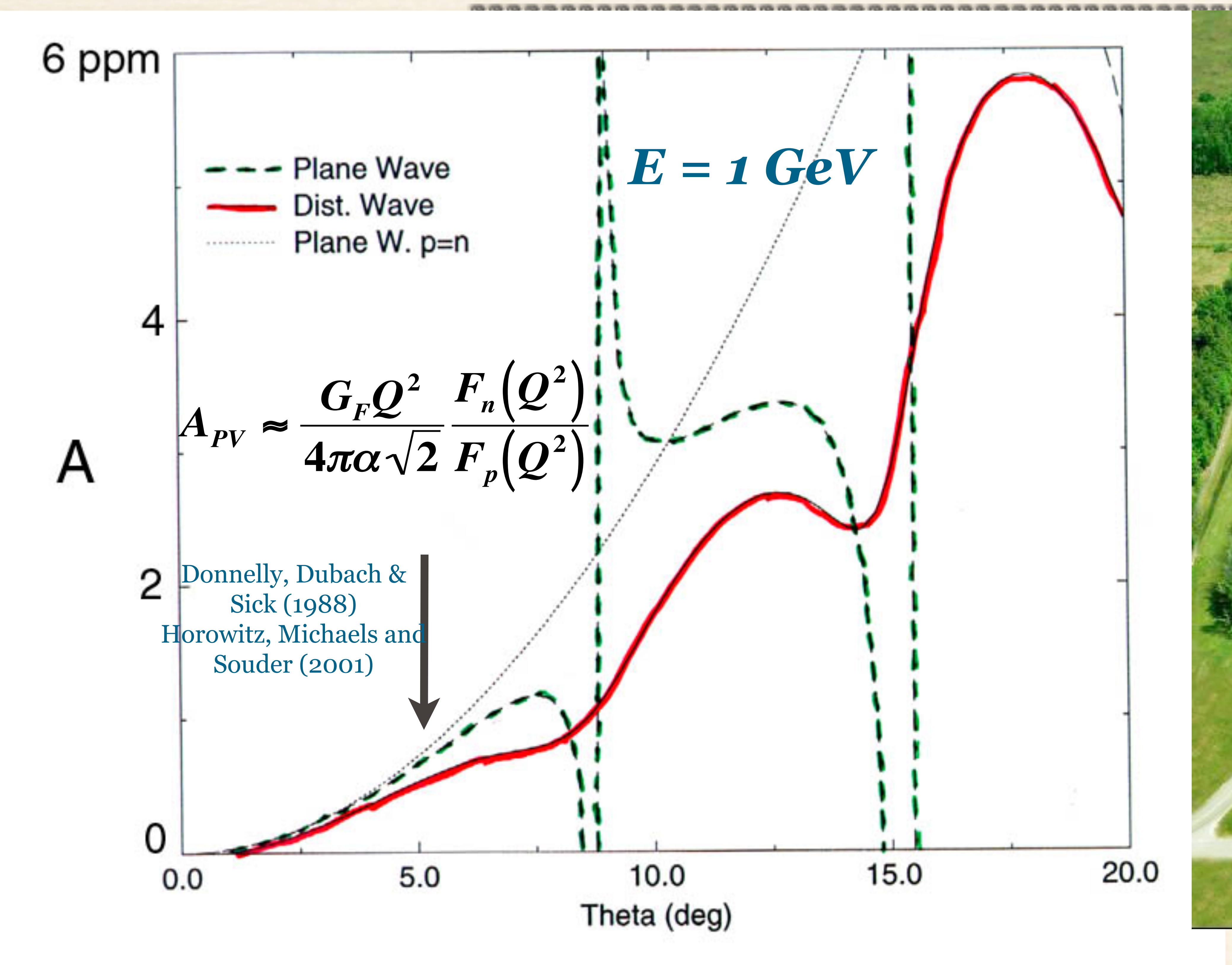
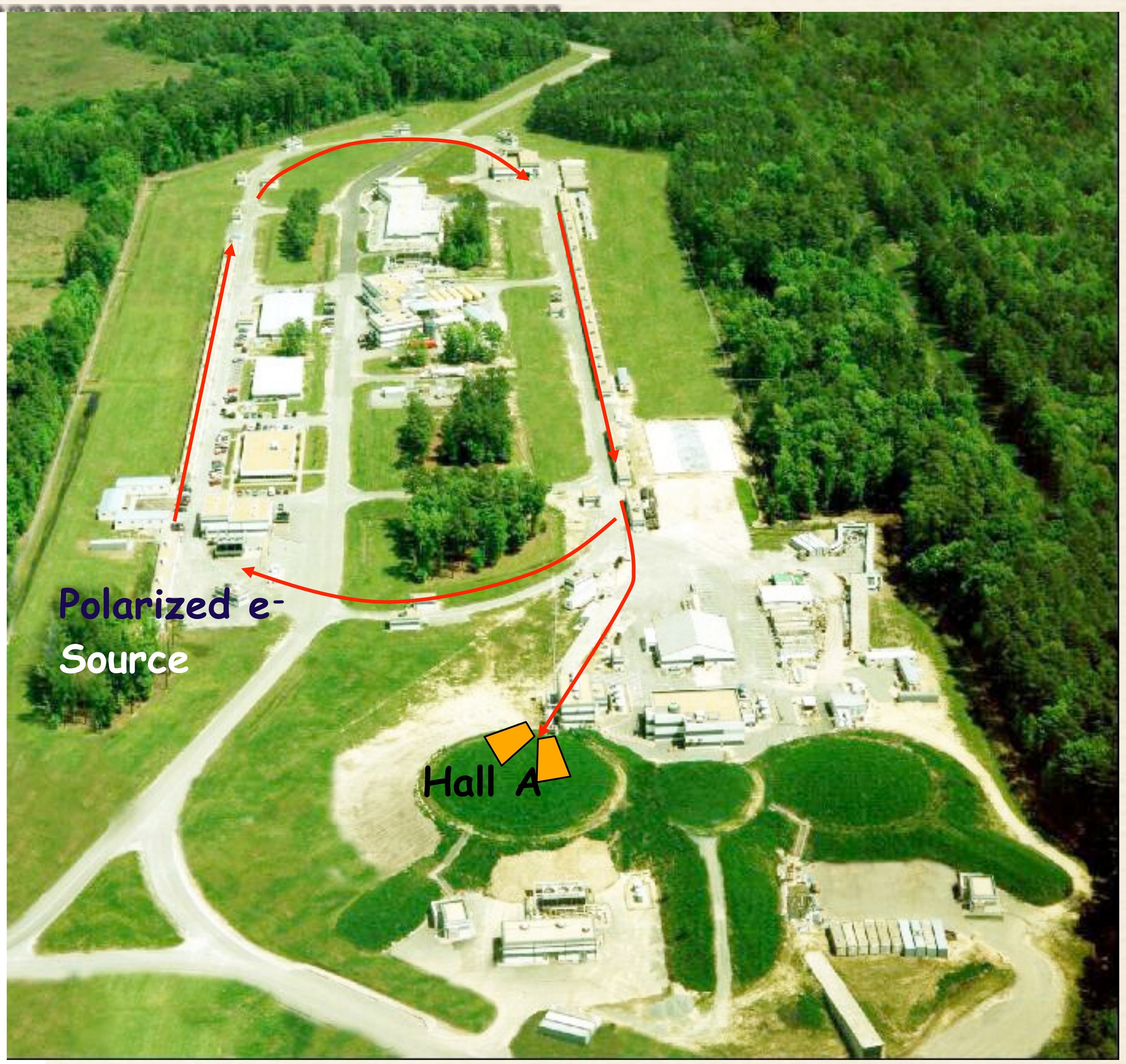
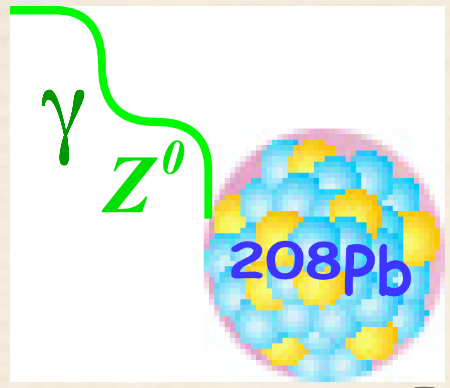
The Lead (Pb) Radius EXperiment PREX



The Pb Radius EXperiment
Concept: PREX
at the Thomas Jefferson National Accelerator Facility







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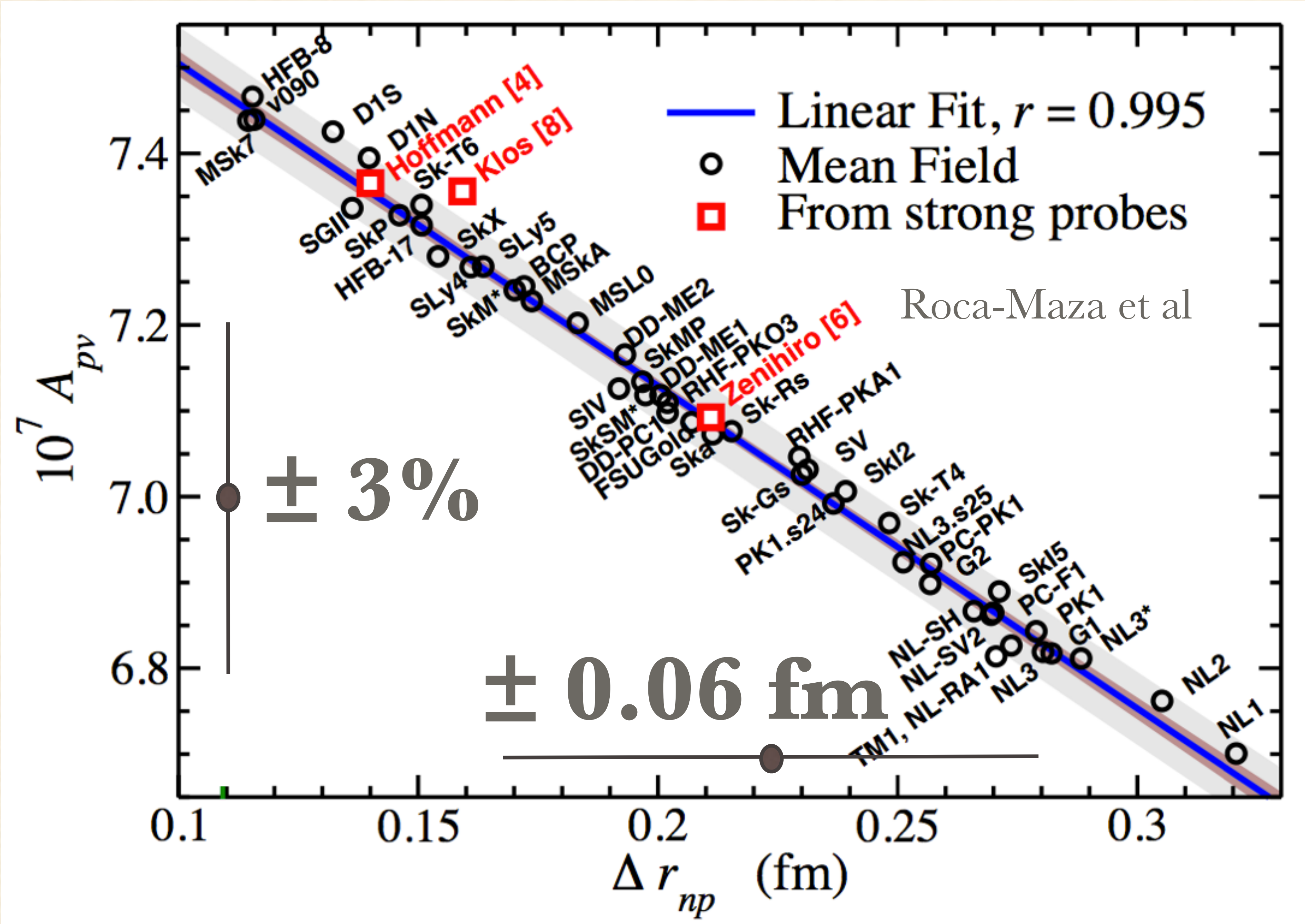

$Q^2 \sim 0.01\ \mathrm{GeV}^2$

$A_{PV} \sim 0.7$ ppm

Rate ~ 1 GHz

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

$\Delta(R_n) \sim 0.06$ fm

The Pb Radius EXperiment

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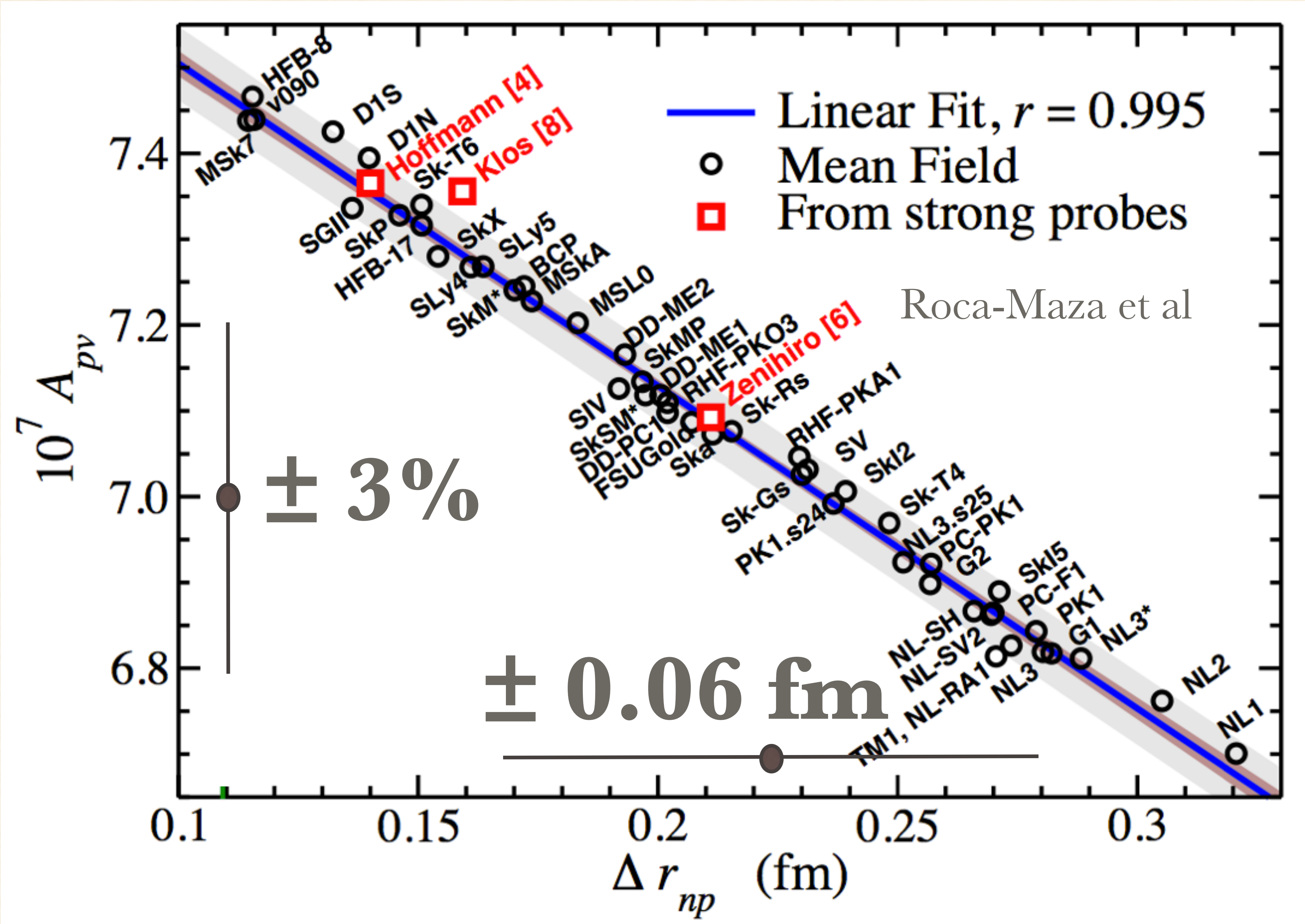

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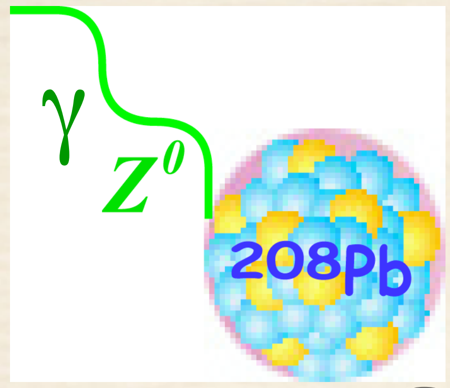
> 10^{15} events!



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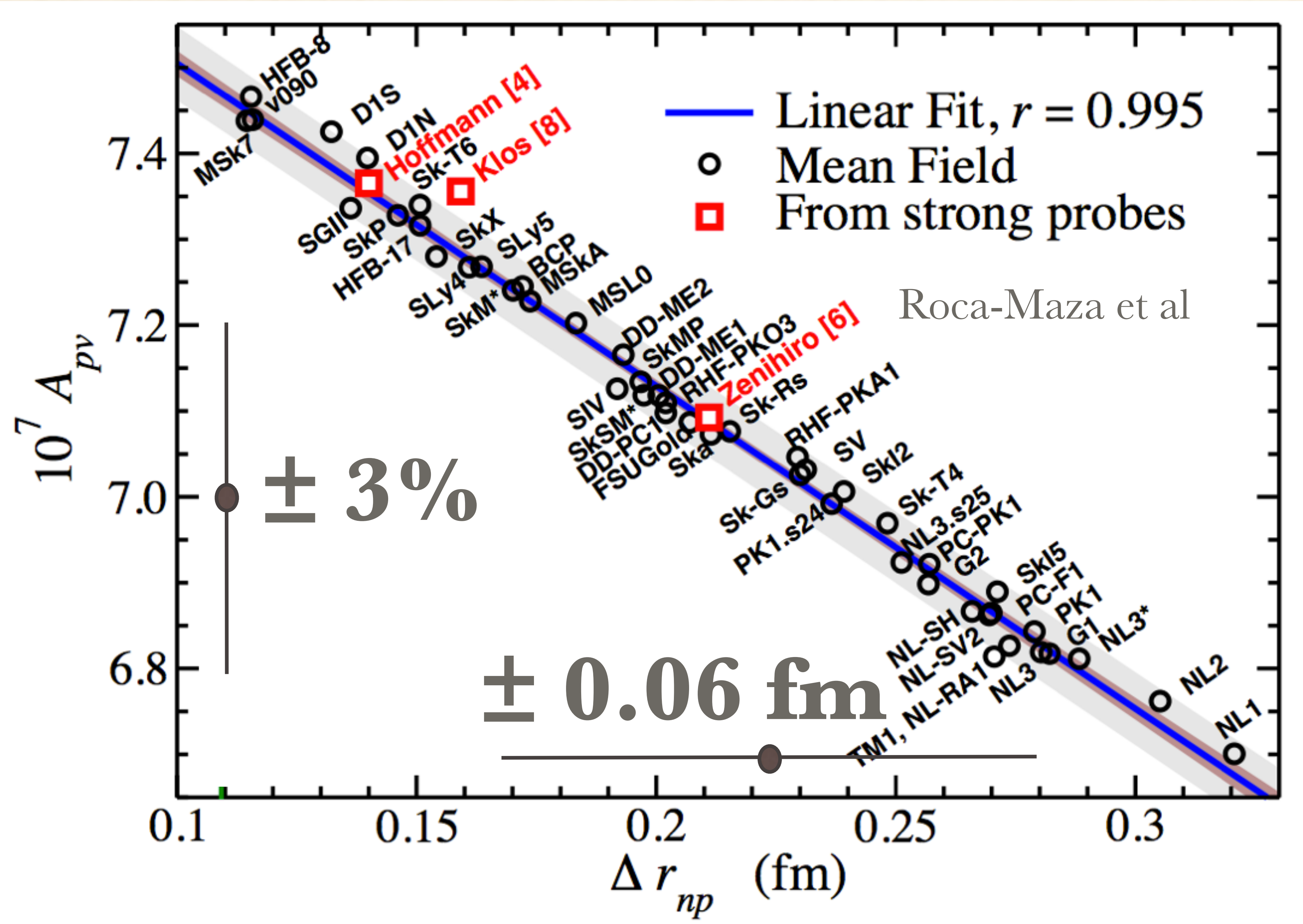

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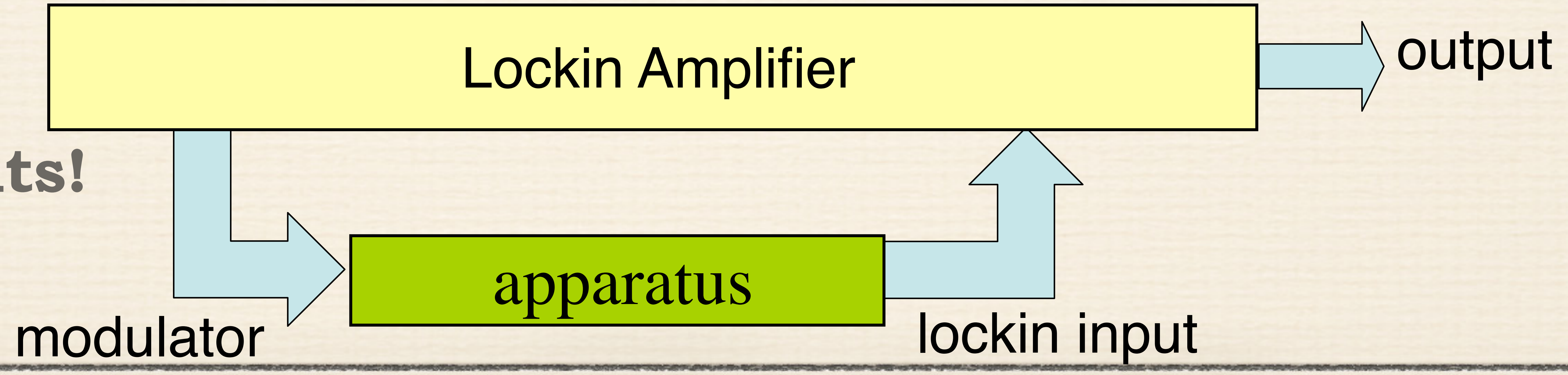
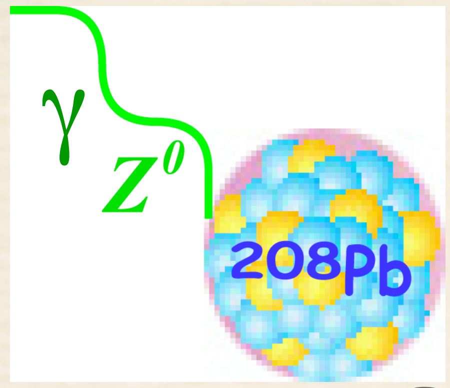
Tiny signal buried in known background

> 10^{15} events!





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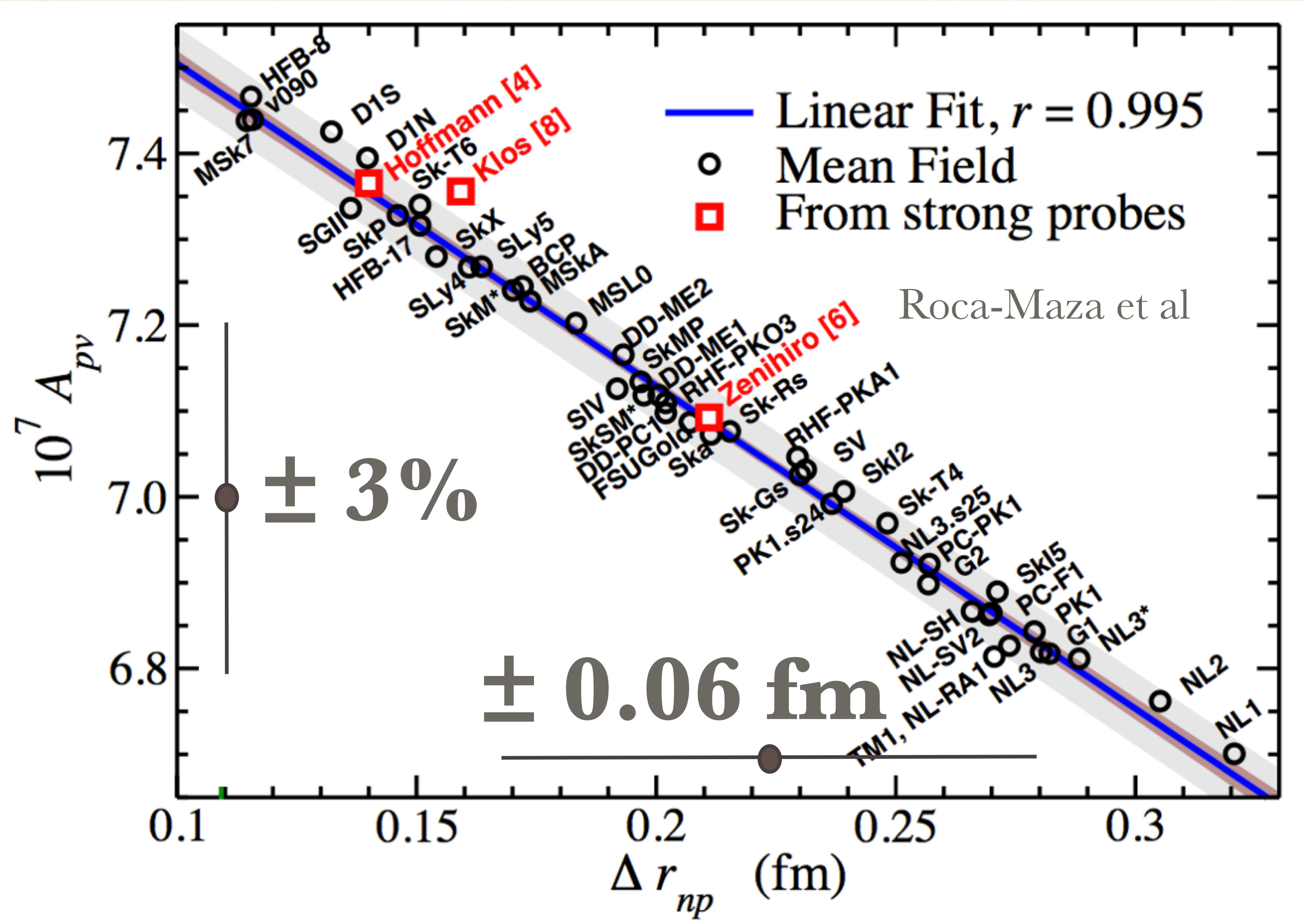

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$A_{PV} \sim 0.7$ ppm

Rate ~ 1 GHz

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$\Delta(R_n) \sim 0.06$ fm

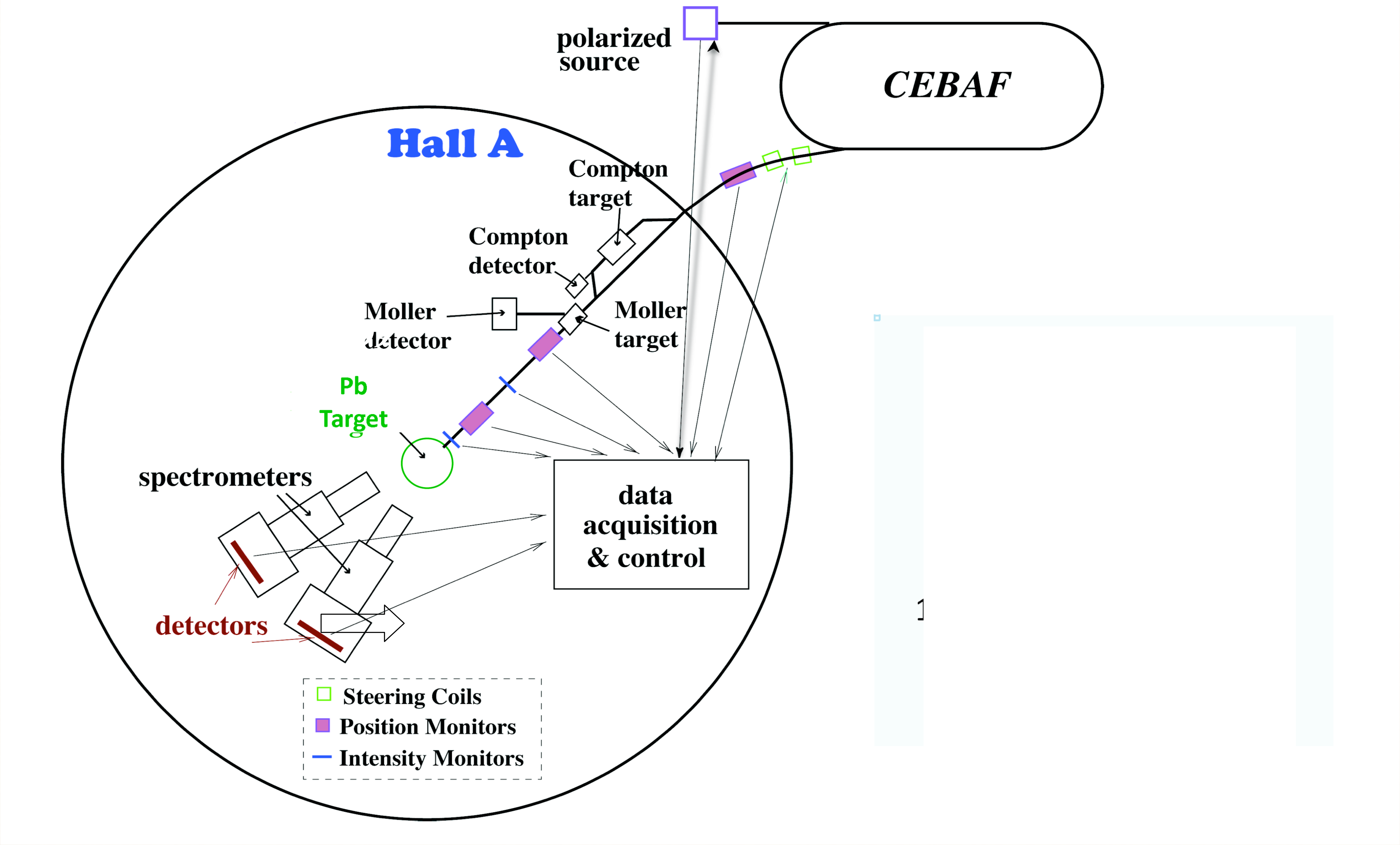
Tiny signal buried in known background

Lockin Amplifier → output

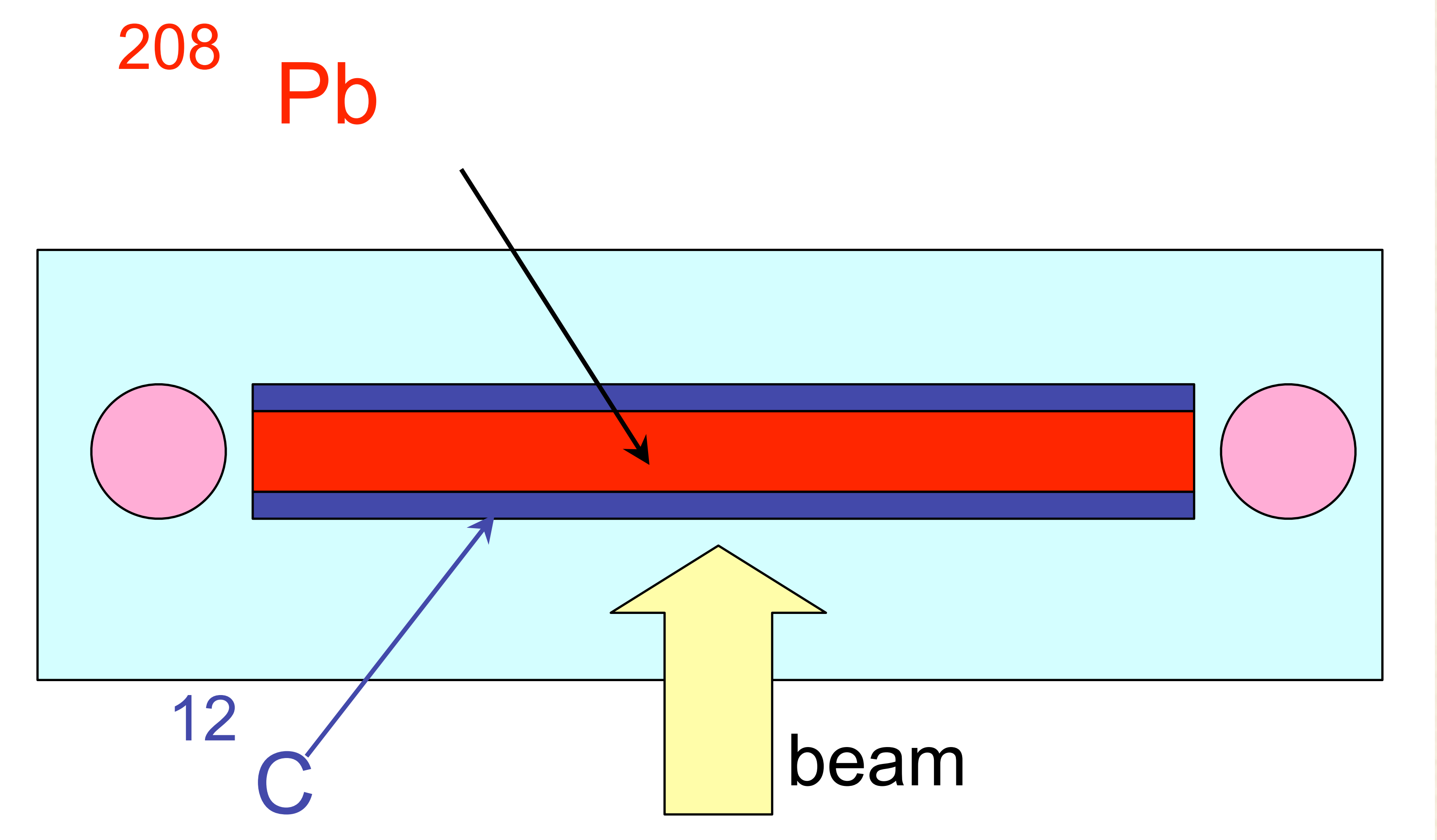
> 10^{15} events!

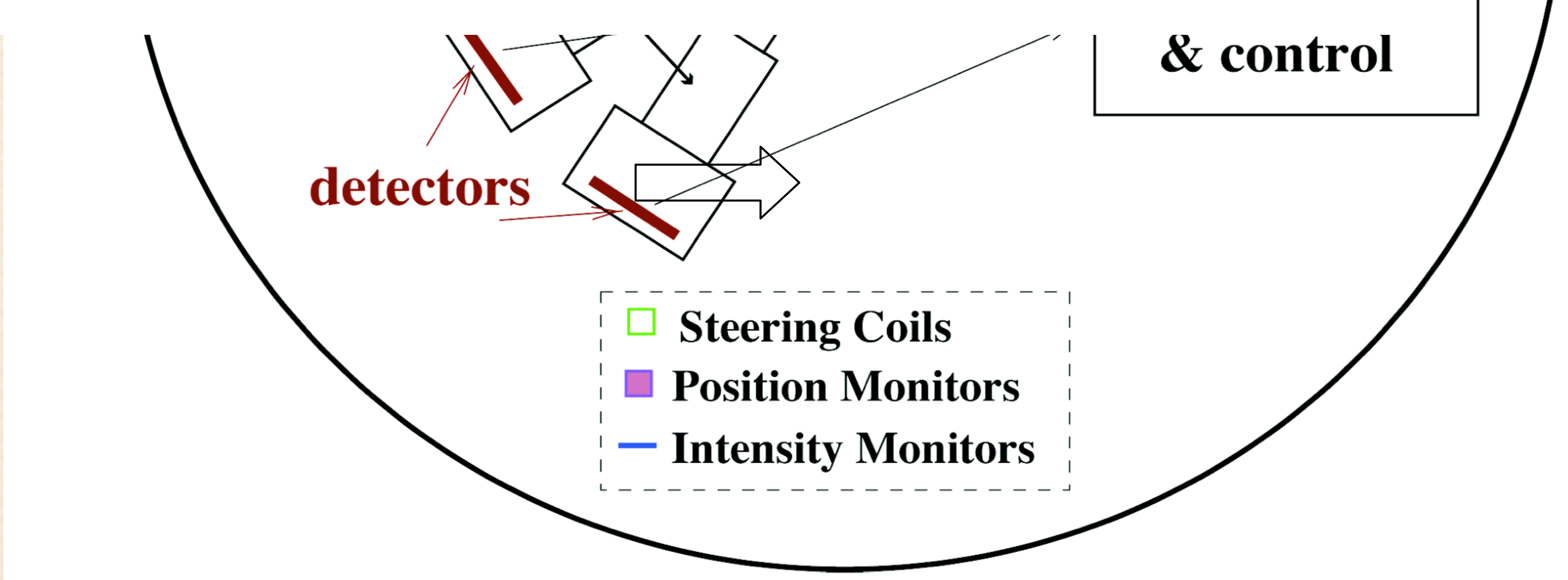
injector → *accelerator* → *target* → *spectrometer* → *detector*

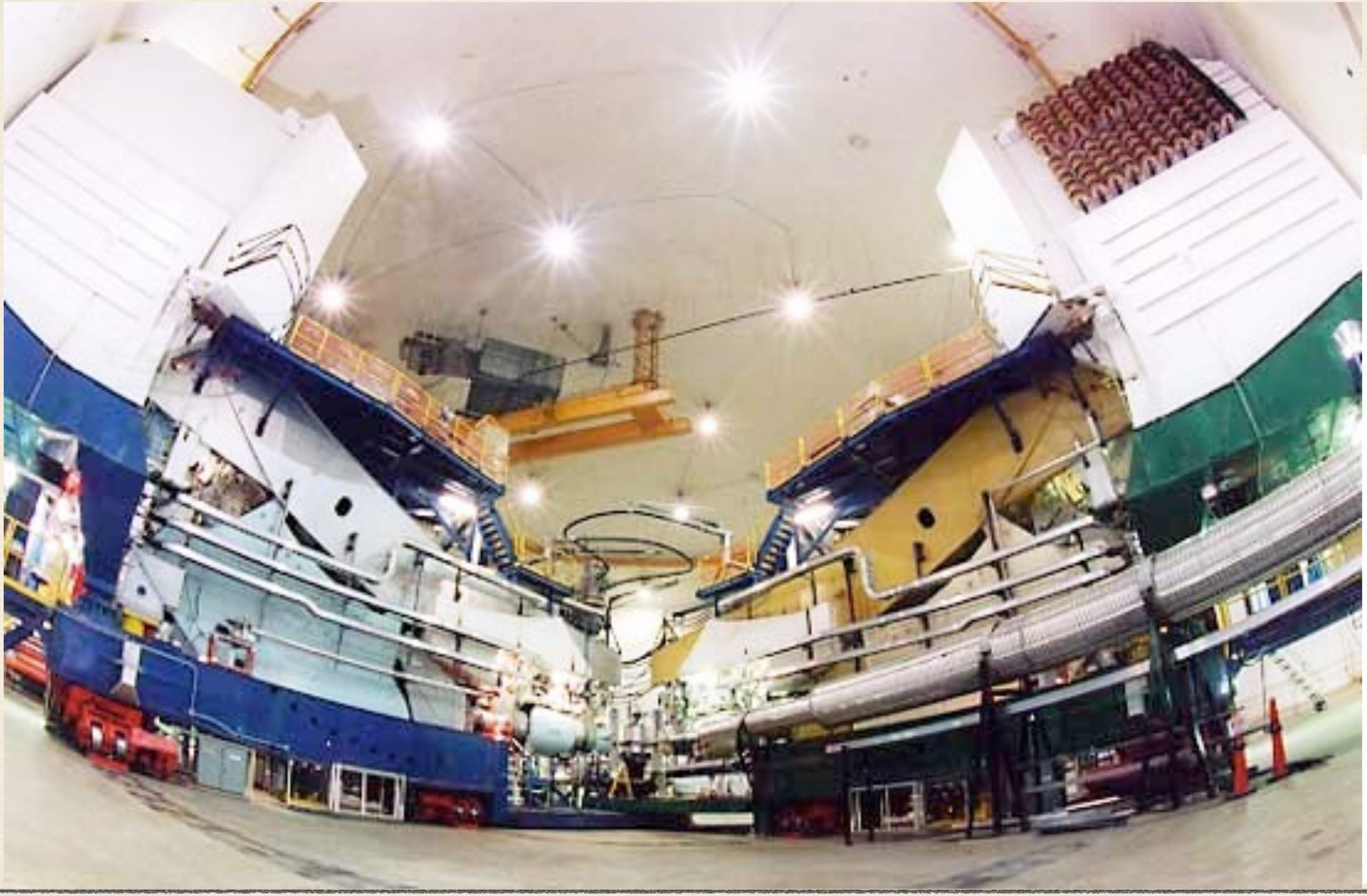
PREX @JLab Hall A: Overview



PREX @JLab Hall A: Overview



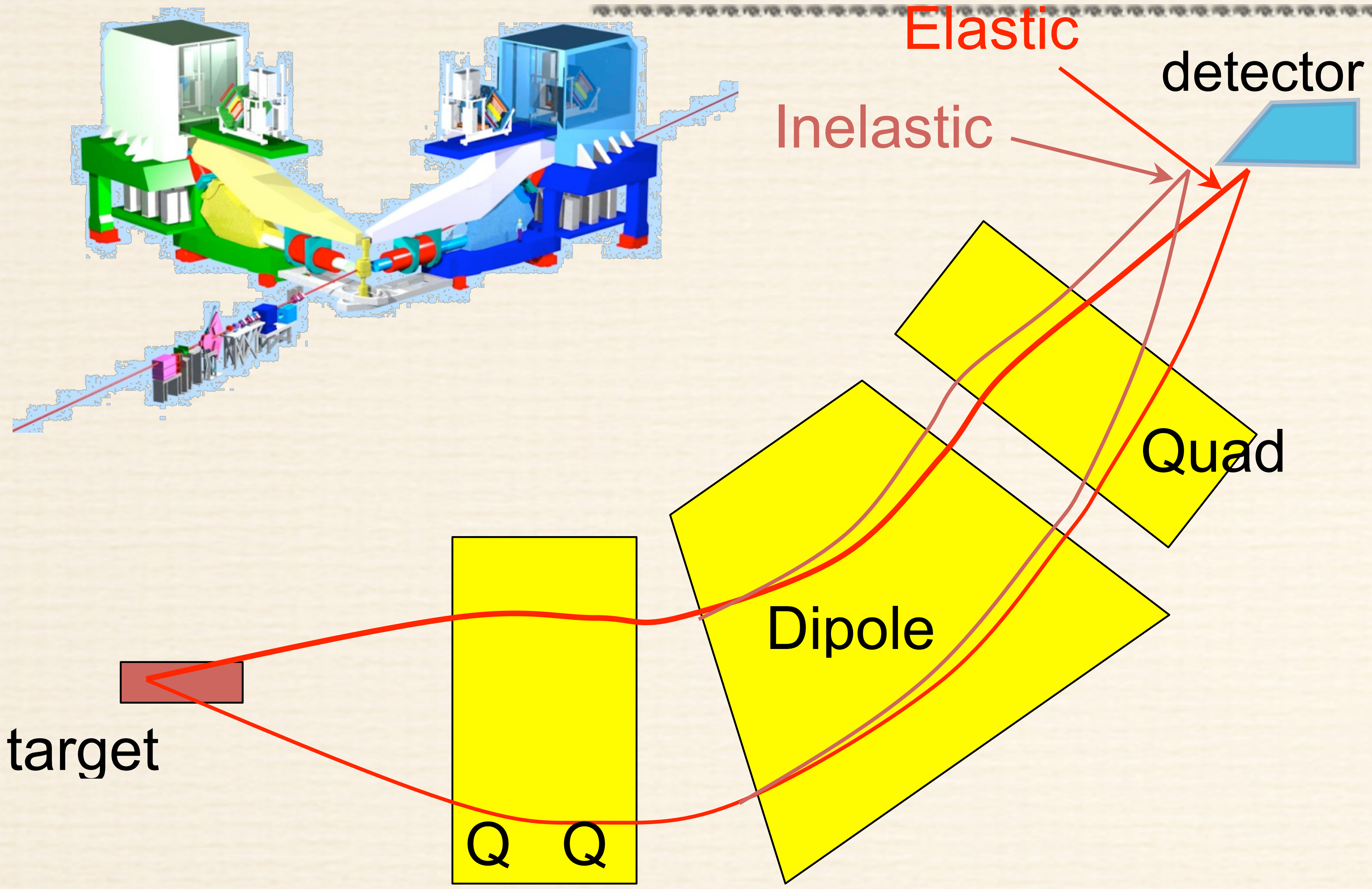


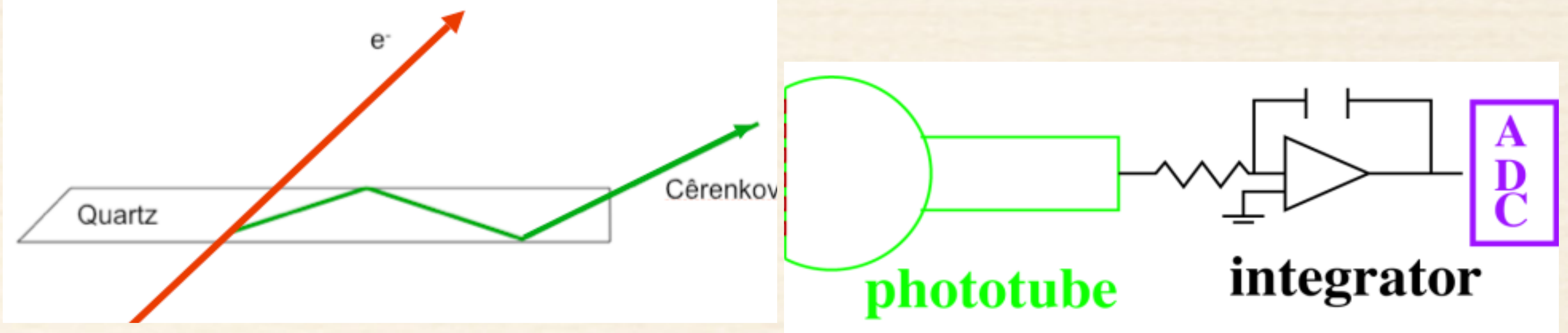


second major SLAC E122 innovation: “flux integration”

High Flux, Low Background

Hall A High Resolution Spectrometers





3 GHz scattered flux

1×10^{-4} statistical uncertainty 30 times per second

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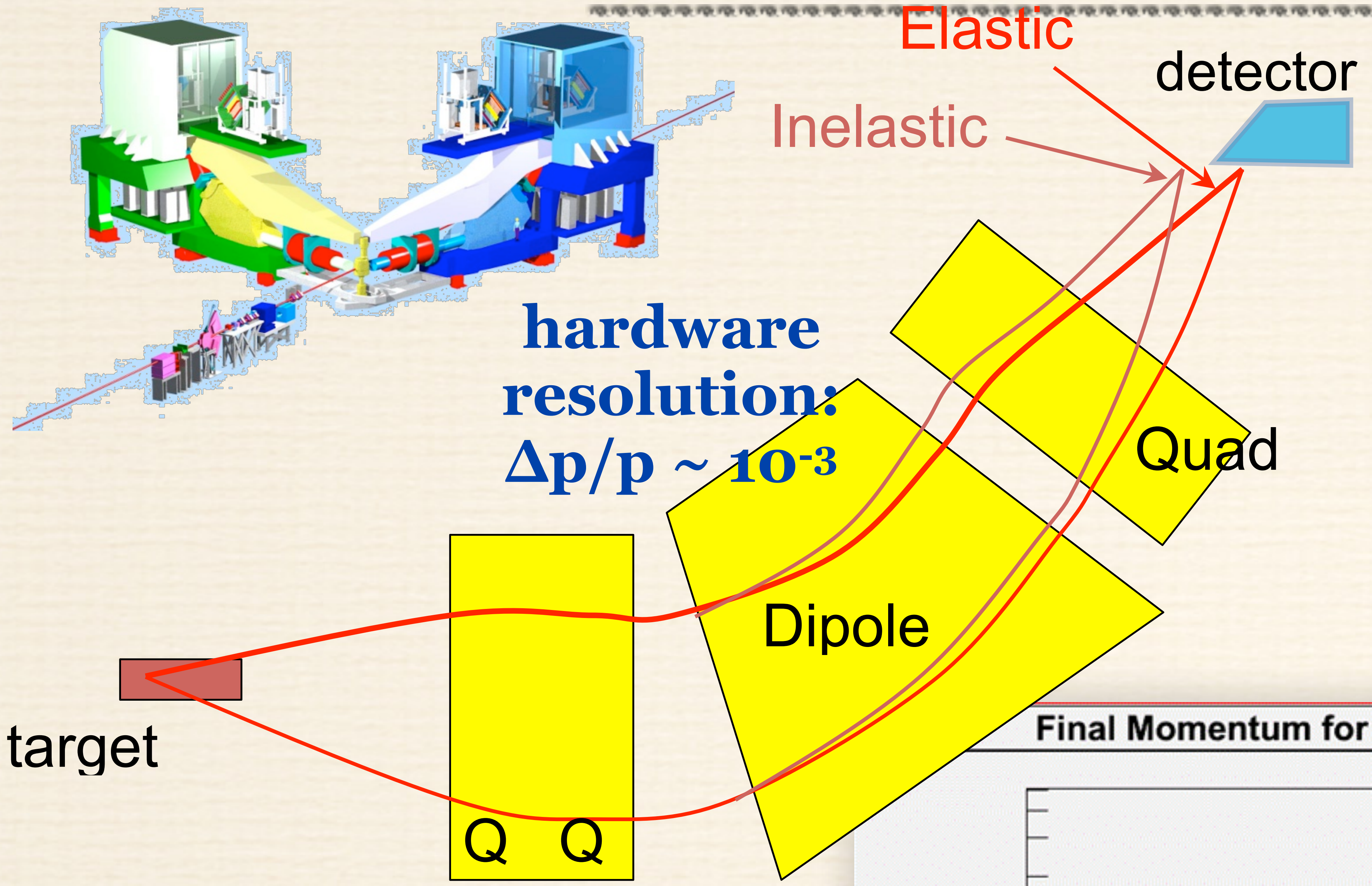
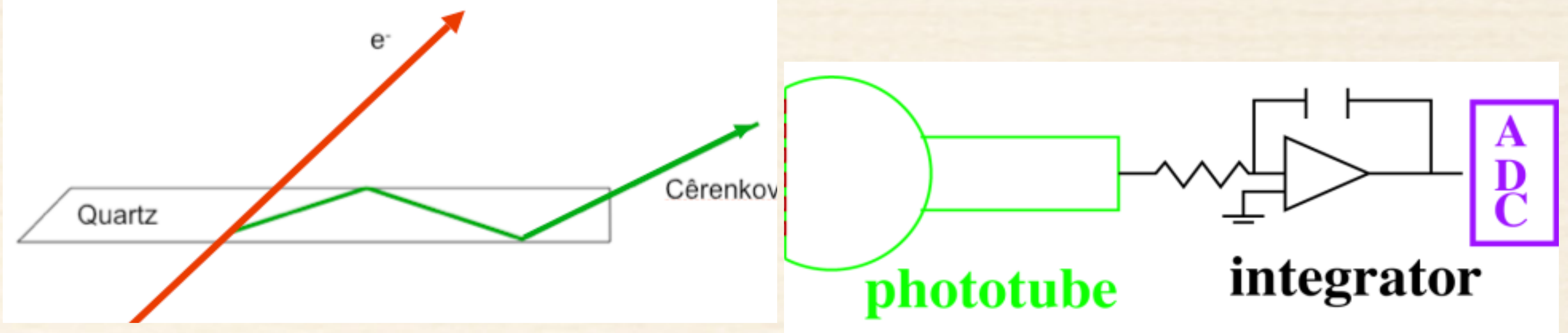


hardware resolution: $\Delta p/p \sim 10^{-3}$



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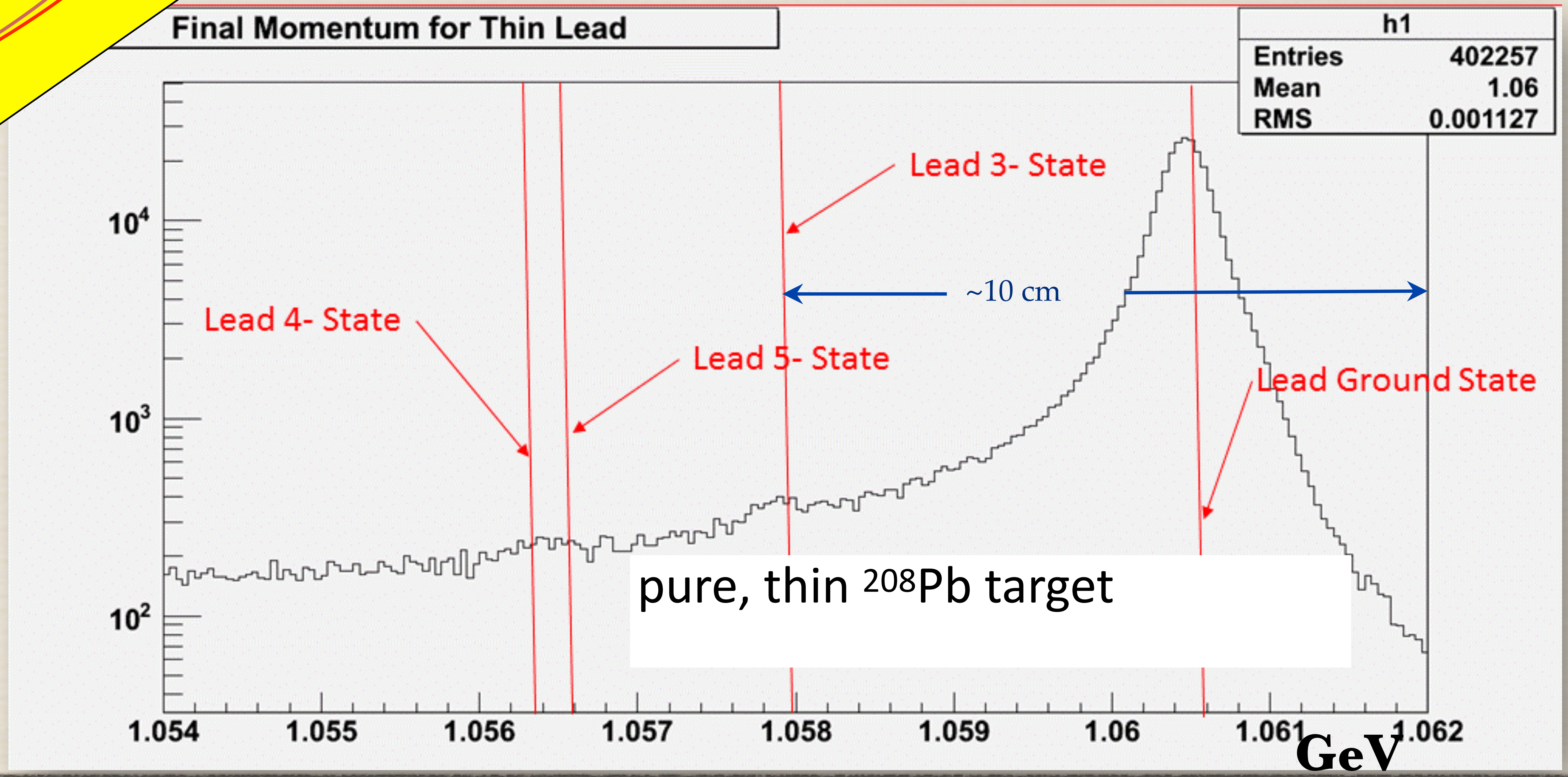
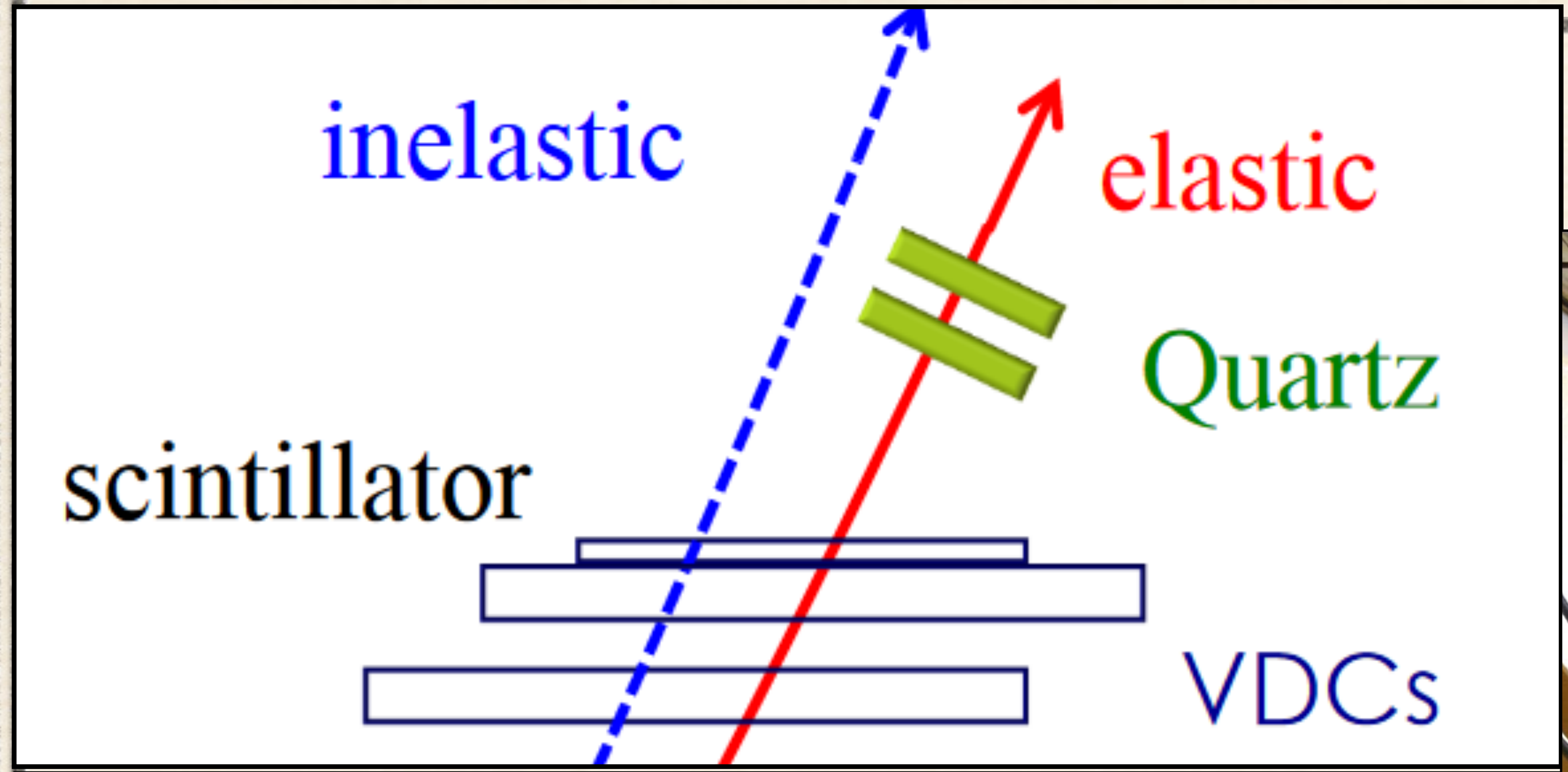
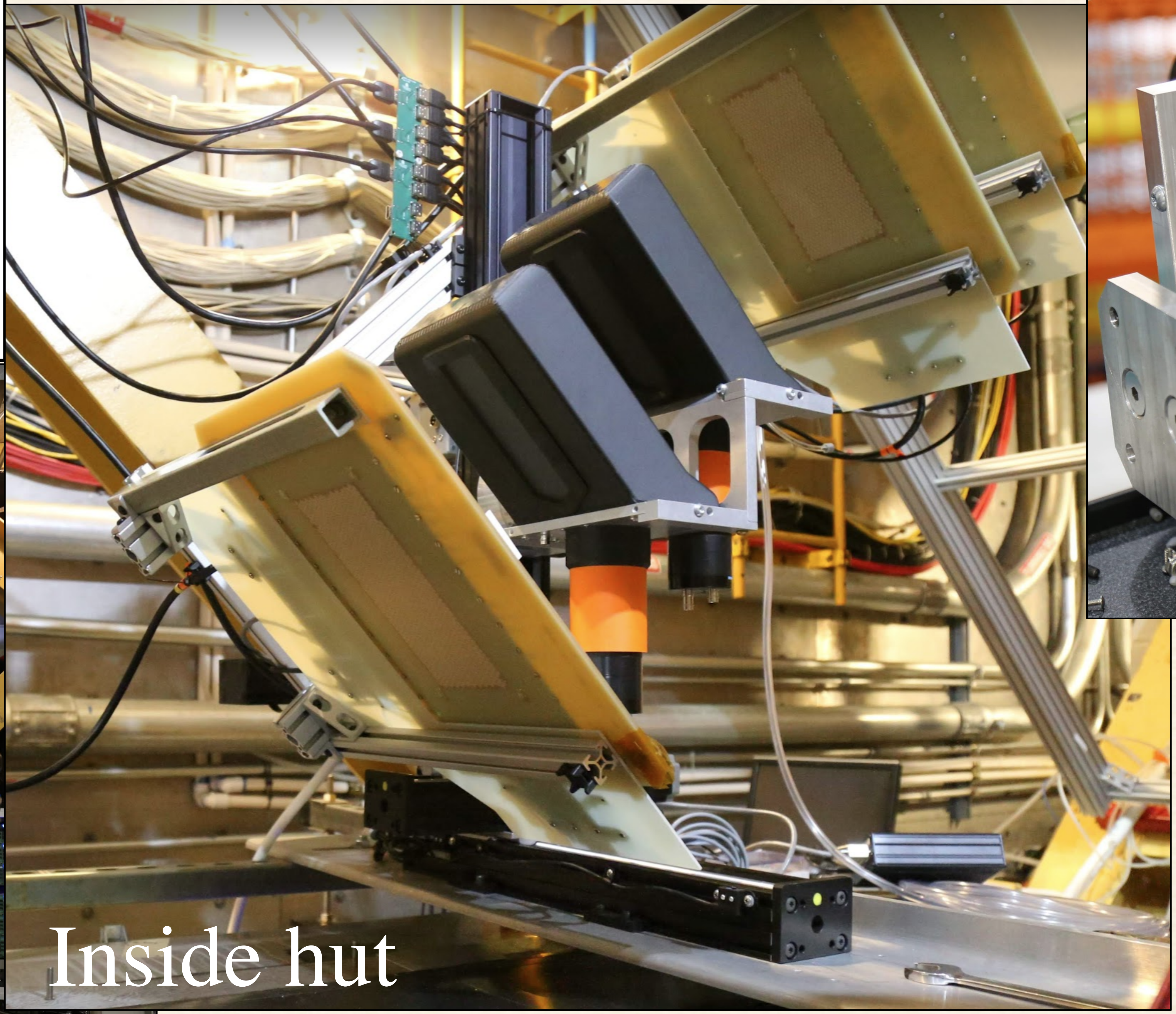
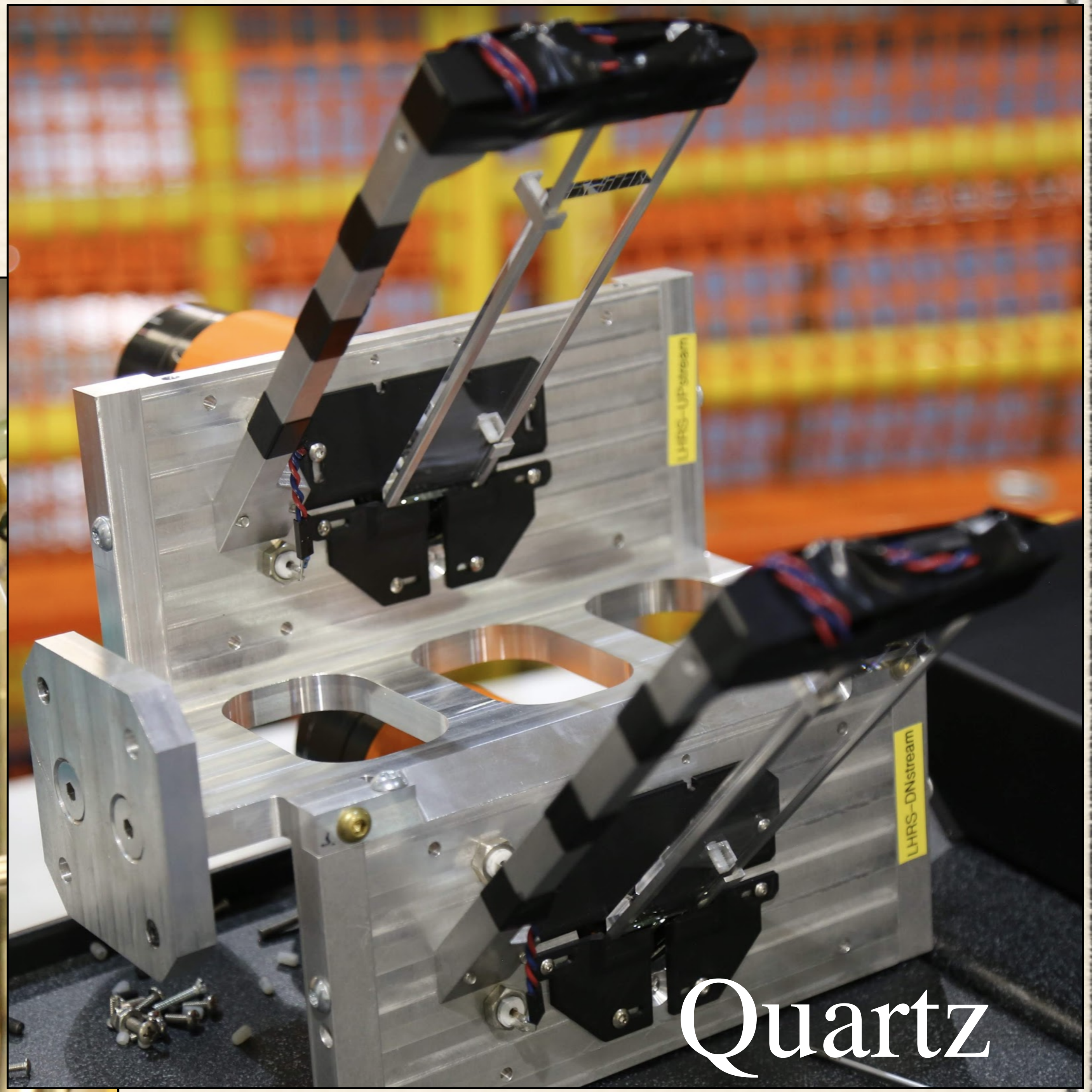


Inelastic backgrounds negligible

Inside the HRS "Counting Hut"







- Integrating detectors (reduce deadtime effects)
- Thick and thin quartz bars (different systematics)

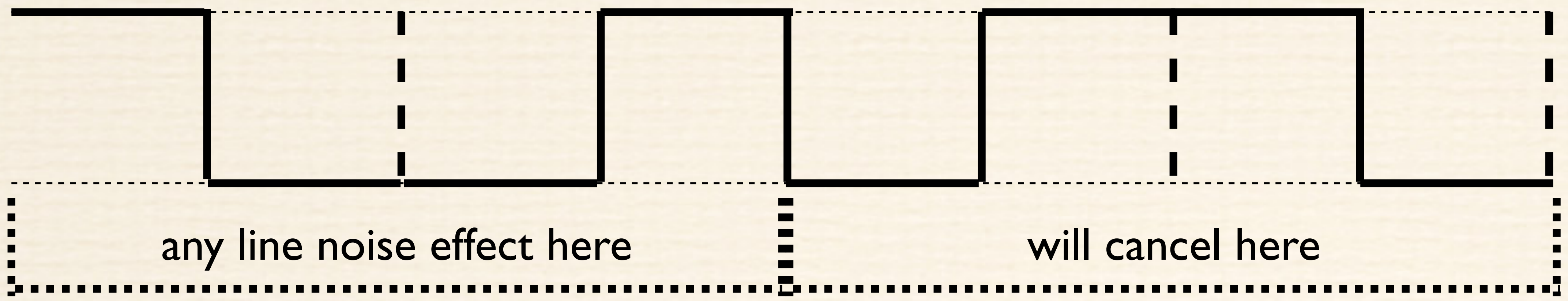
CW electron beam: scattered signal rate ~ 3 GHz

Flux Integration

10 ppb (average 3.3×10^6 s)

sequence of "window multiplets"

Example: at 240 Hz reversal



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

Detector D, Current I: $F = D/I$ $\quad A_{pair} = \frac{\Delta F}{2F} + \Delta A$

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30 Hz Stat. Width: 100 ppm ➡ N = 100 M: 10 ppb (average 3.3×10^6 s)

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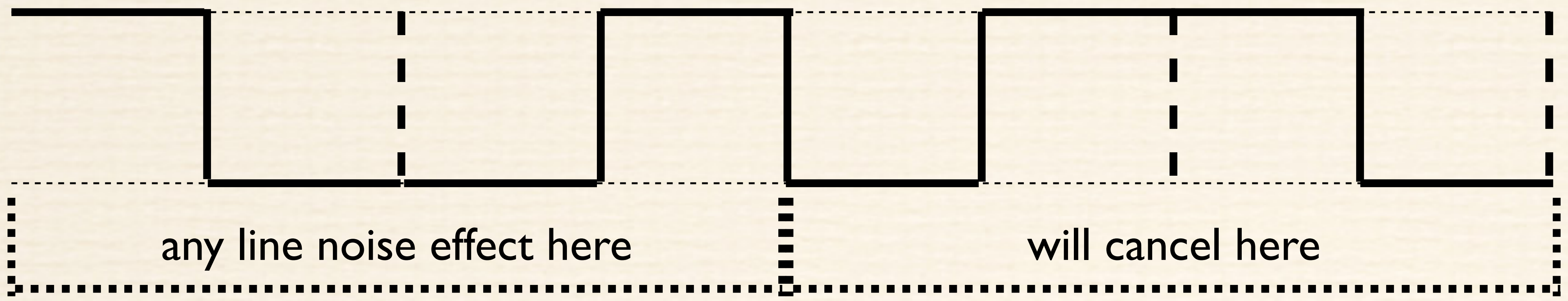

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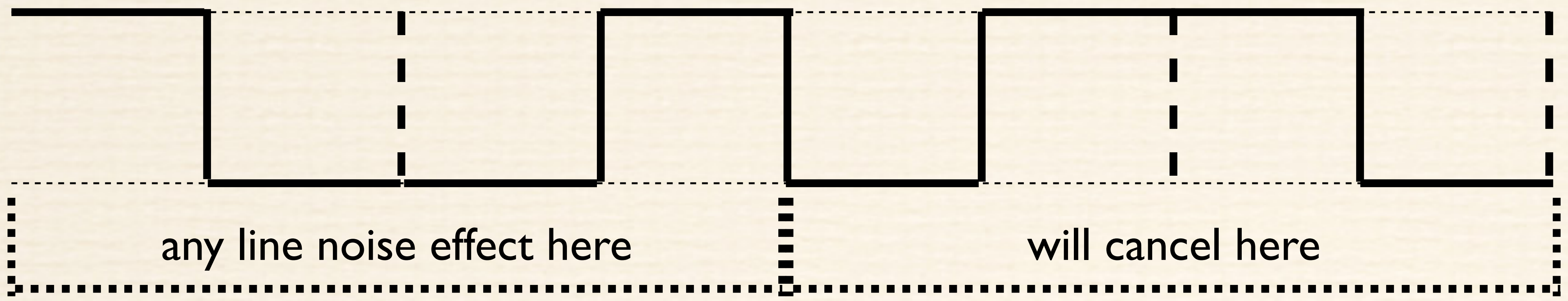

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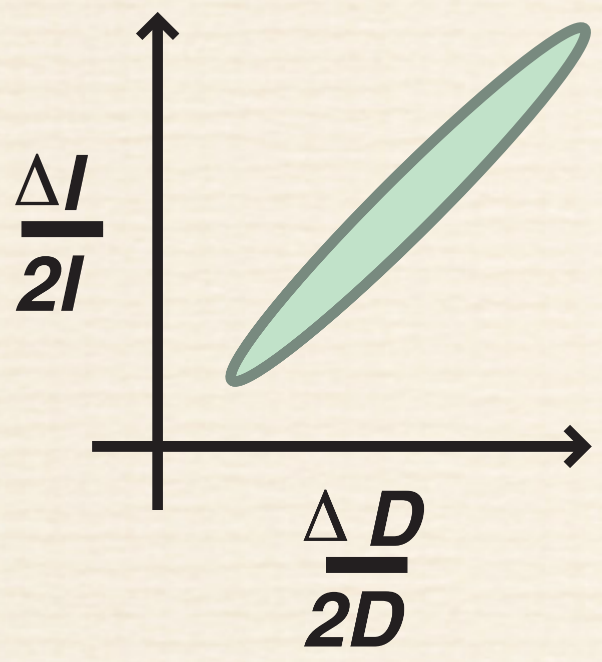

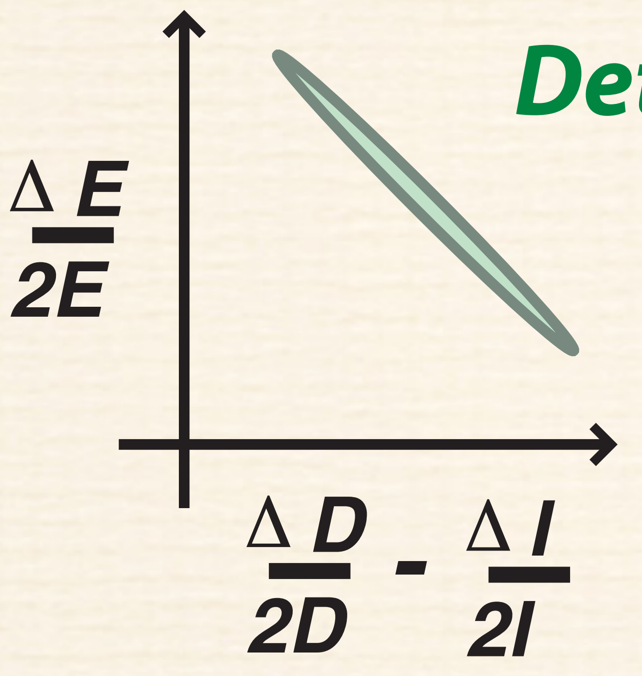

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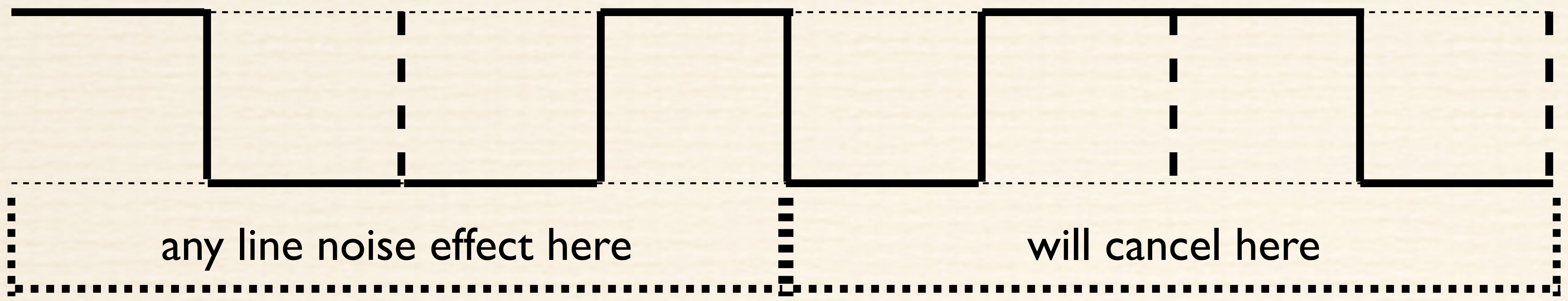

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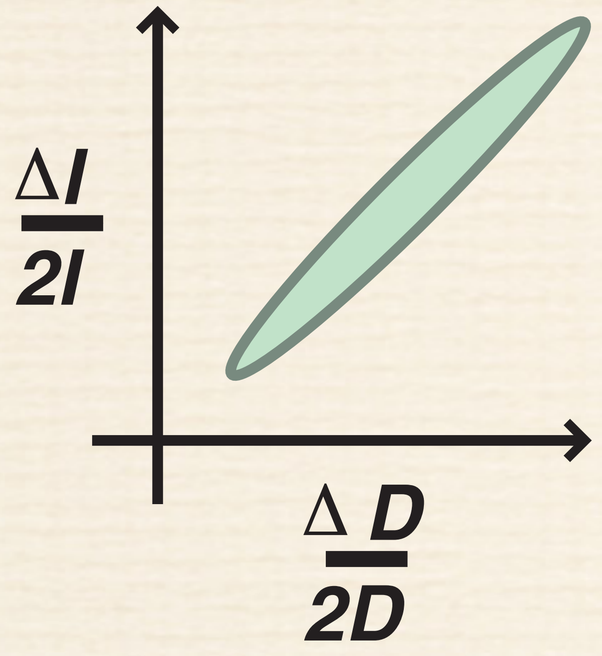

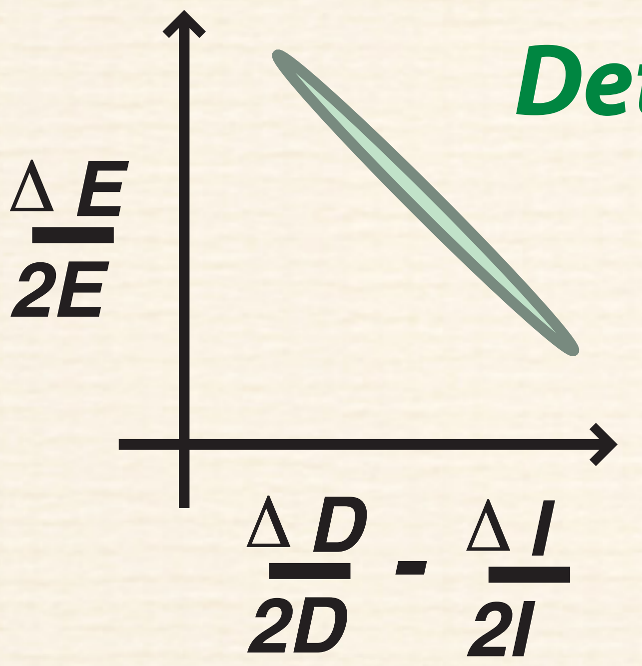

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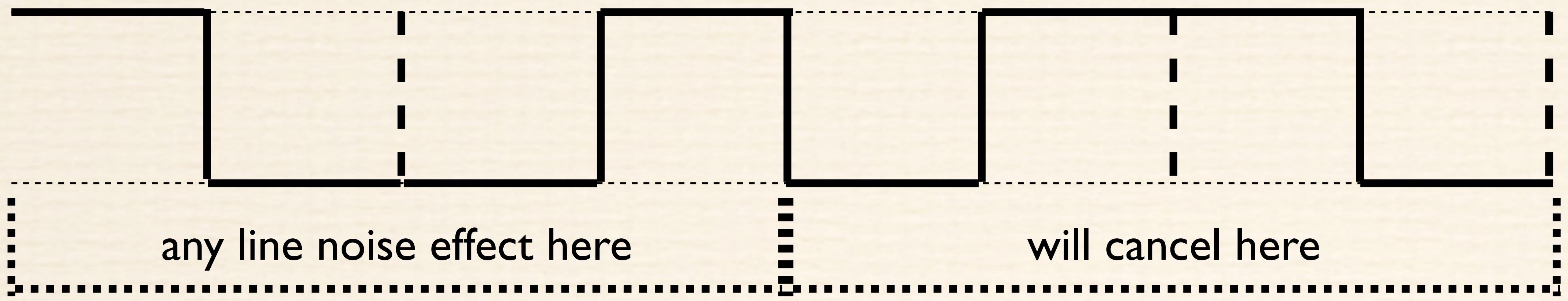

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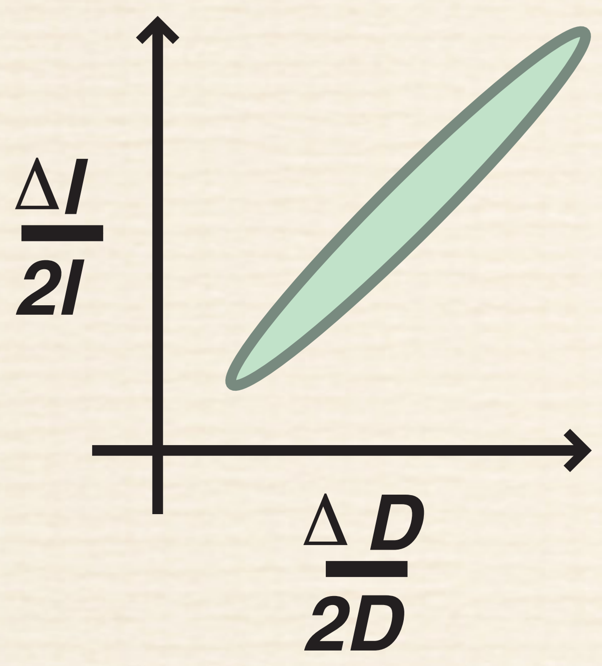

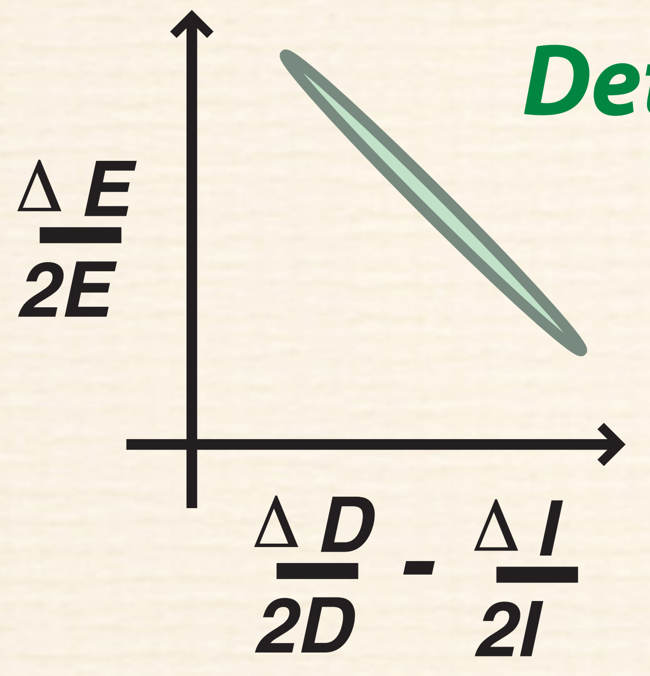

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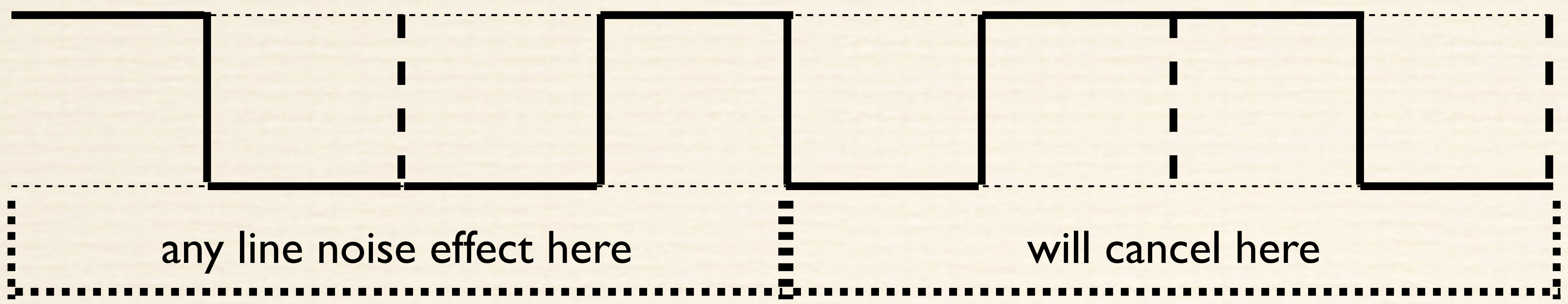

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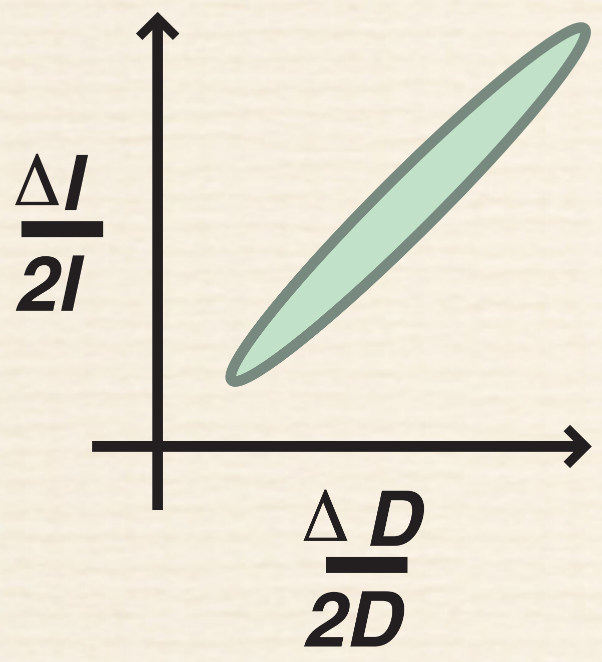

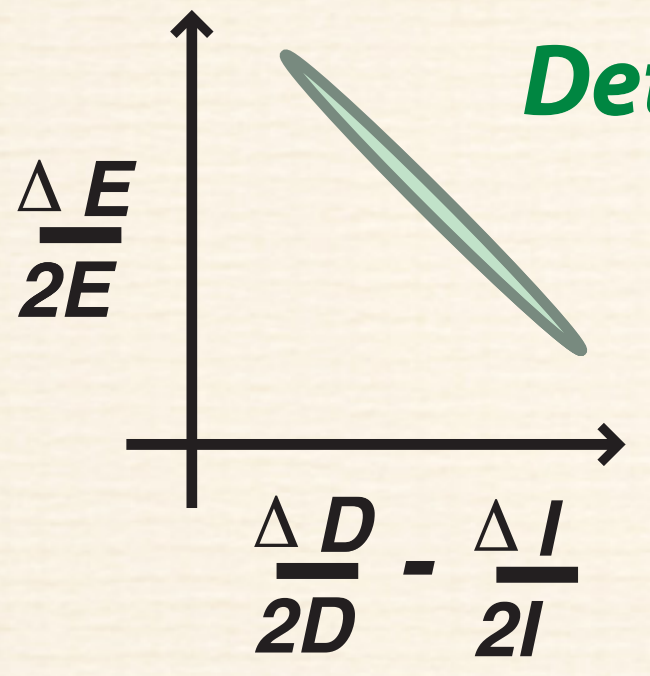

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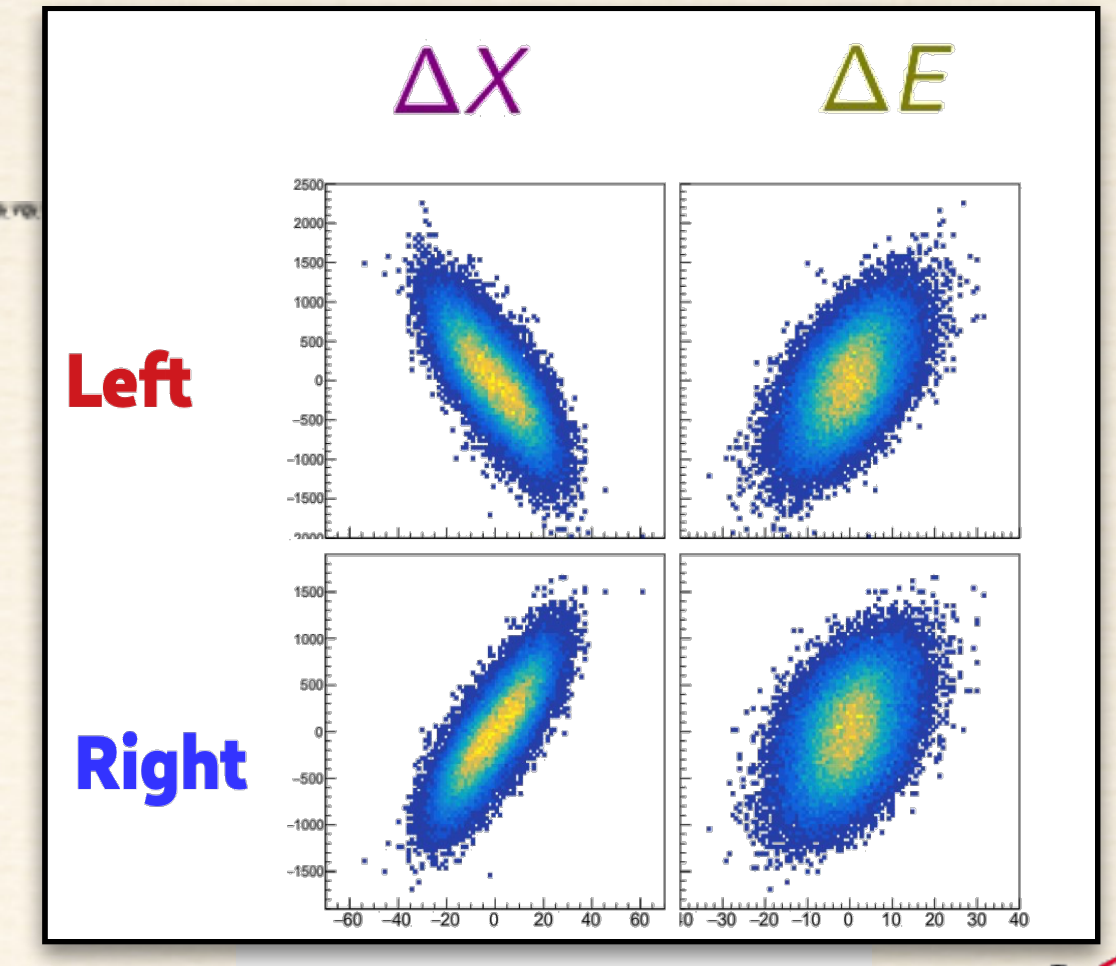
Goal: corrections no bigger than statistical uncertainty: ~ppm, microns over minutes, ~ppb, nm over days,

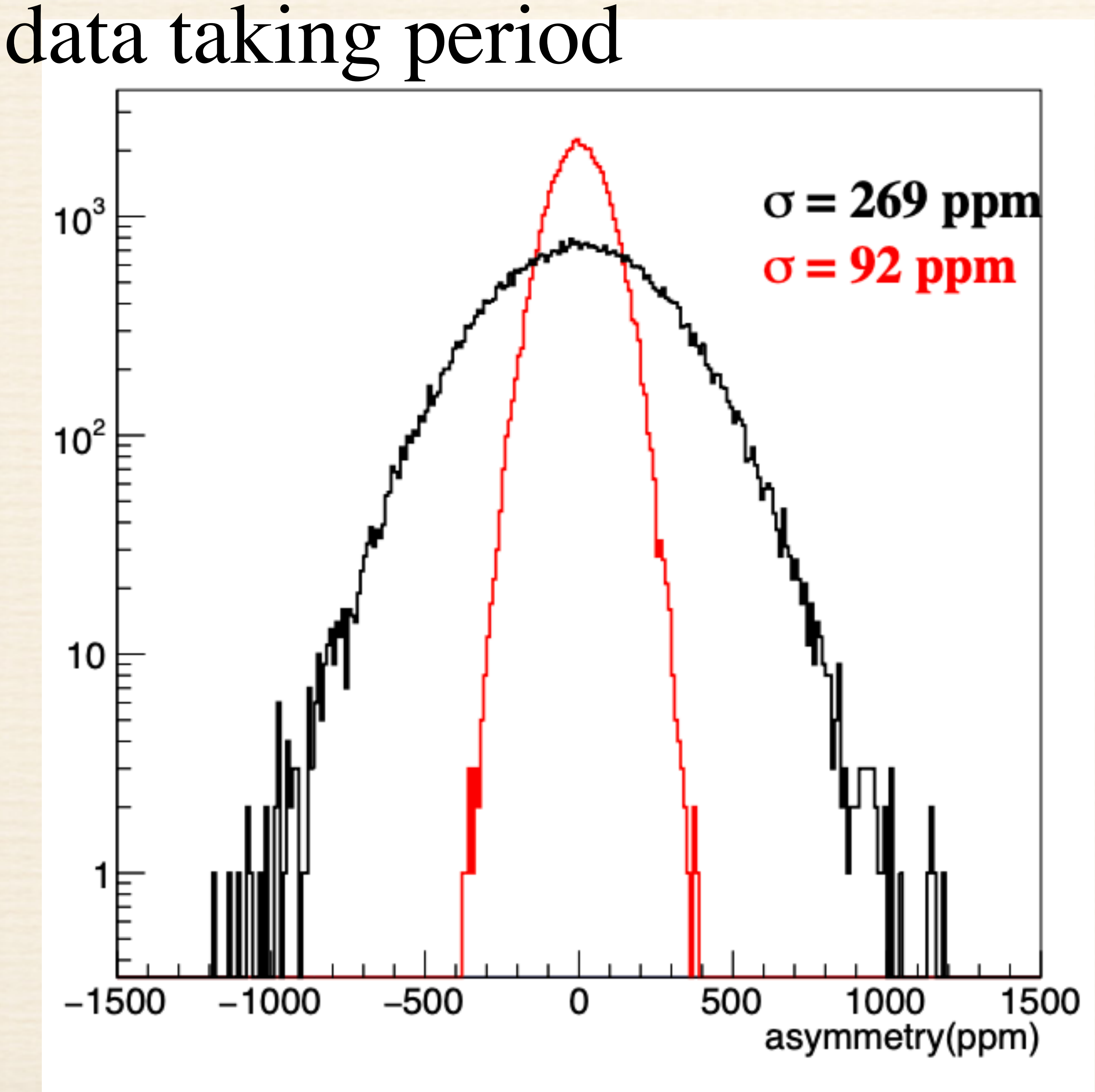
Corrections for Beam Fluctuations

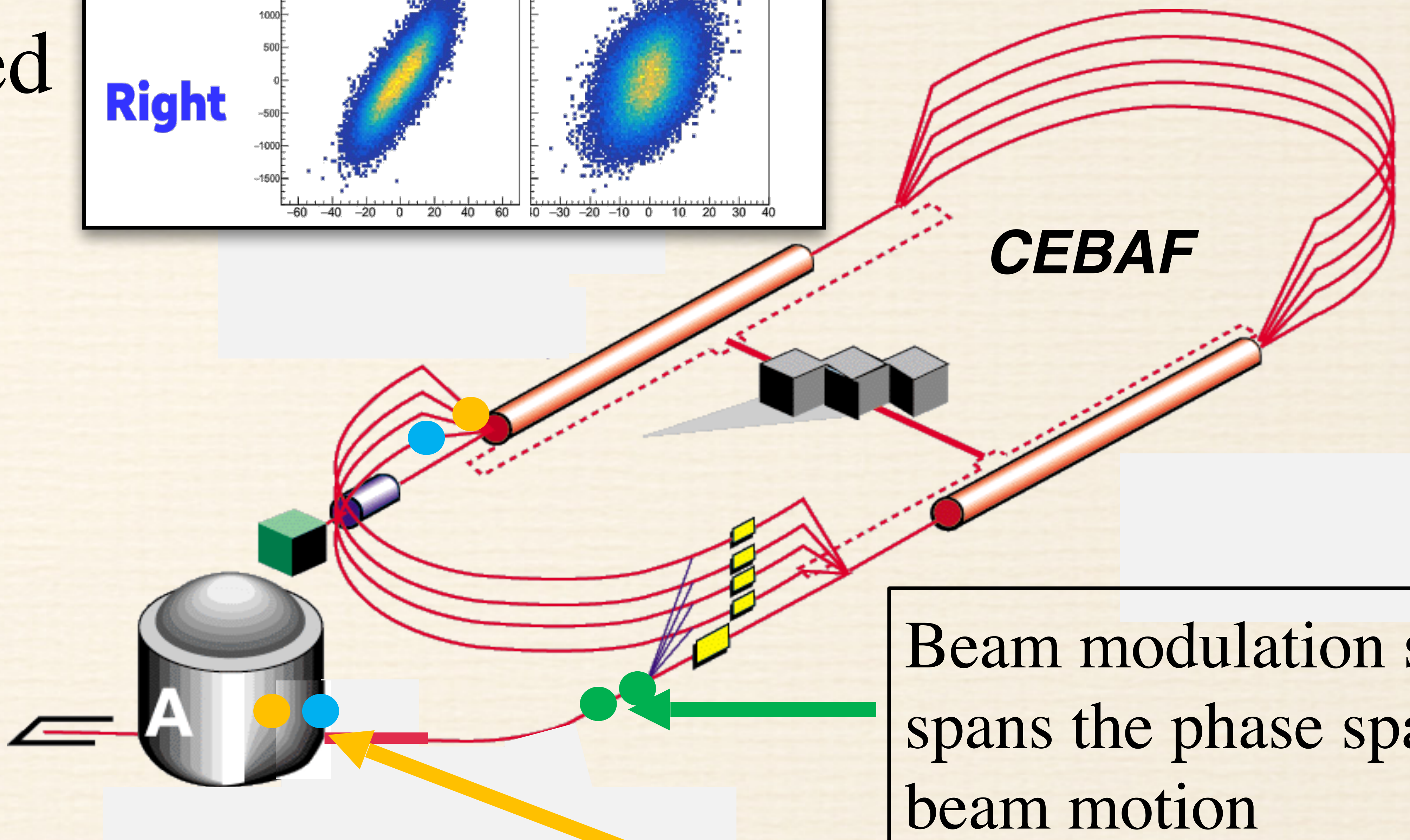
- To span the 5 dimension phase space of beam motion at the target (position, angle, energy) we made use of a set of 6 coils and an energy vernier
  - This modulation is automated and was performed throughout the data taking period



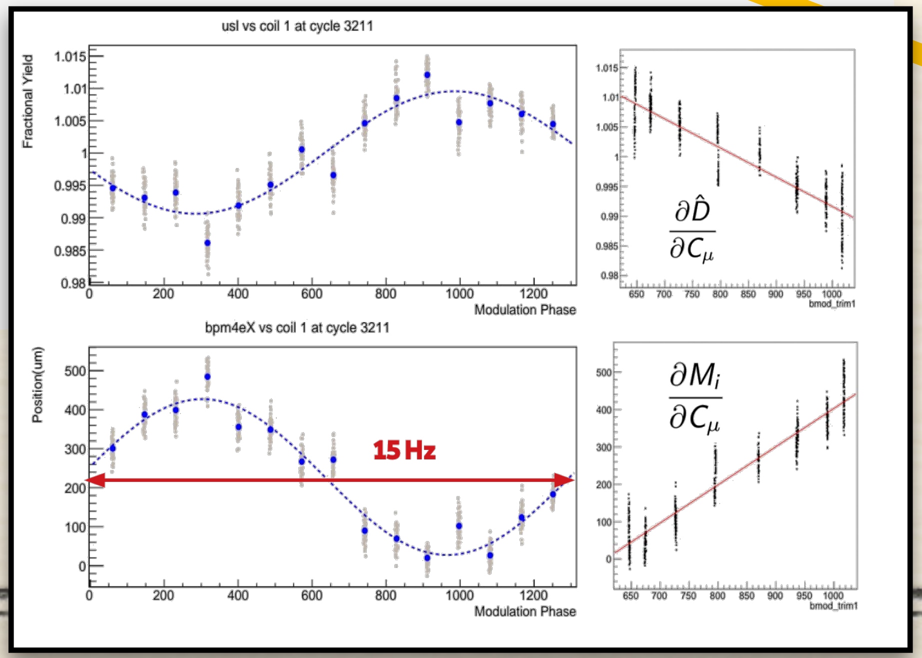
$A_{corr} = A_{det} - A_Q$
$+ \alpha\, \Delta_E + \Sigma \beta_i\, \Delta x_i$

$A_{corr} \sim 500$ ppb





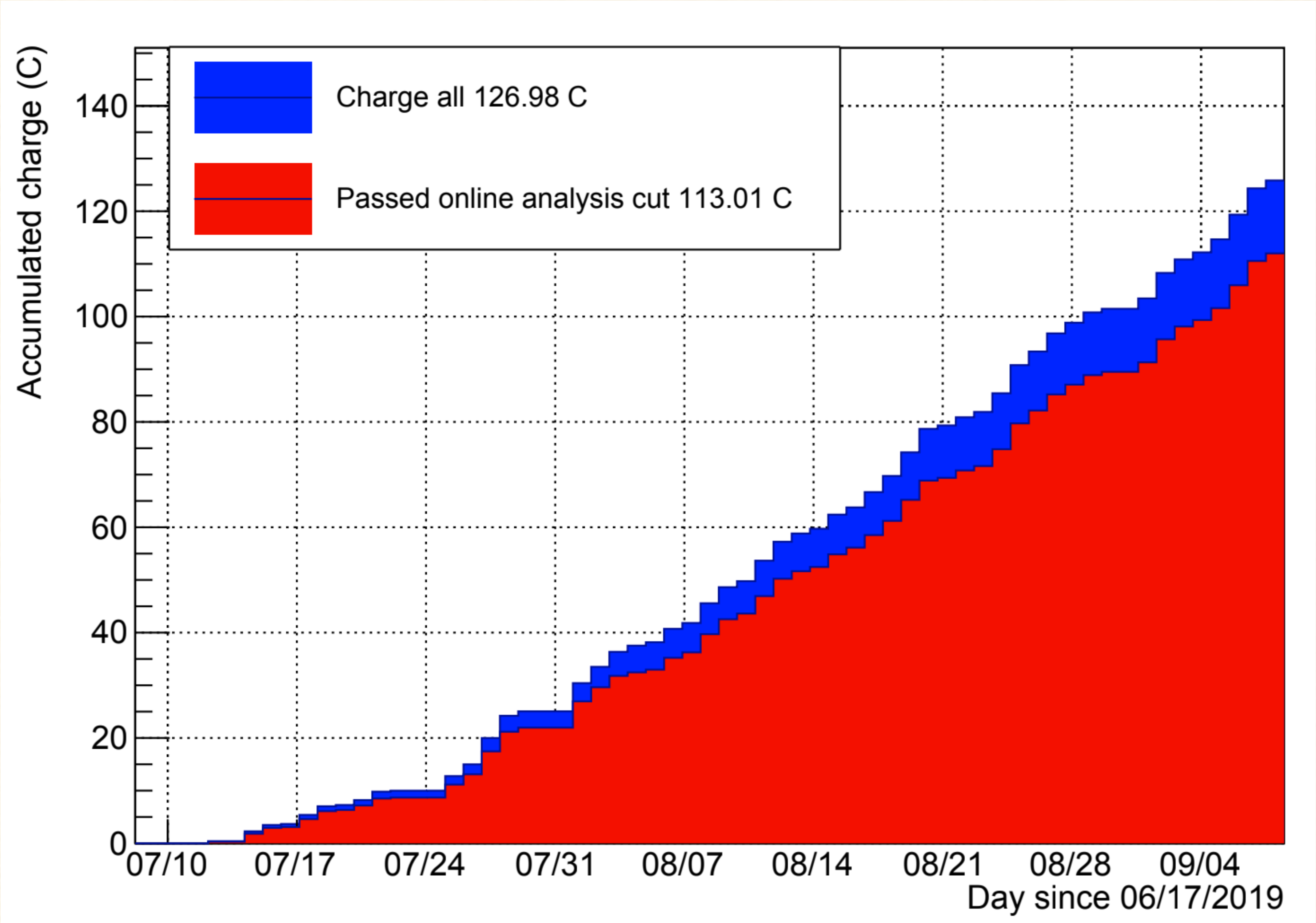
Beam modulation system spans the phase space of beam motion



Beam monitors determine trajectory and parameters onto target

PREX-2 Run: Summer 2019

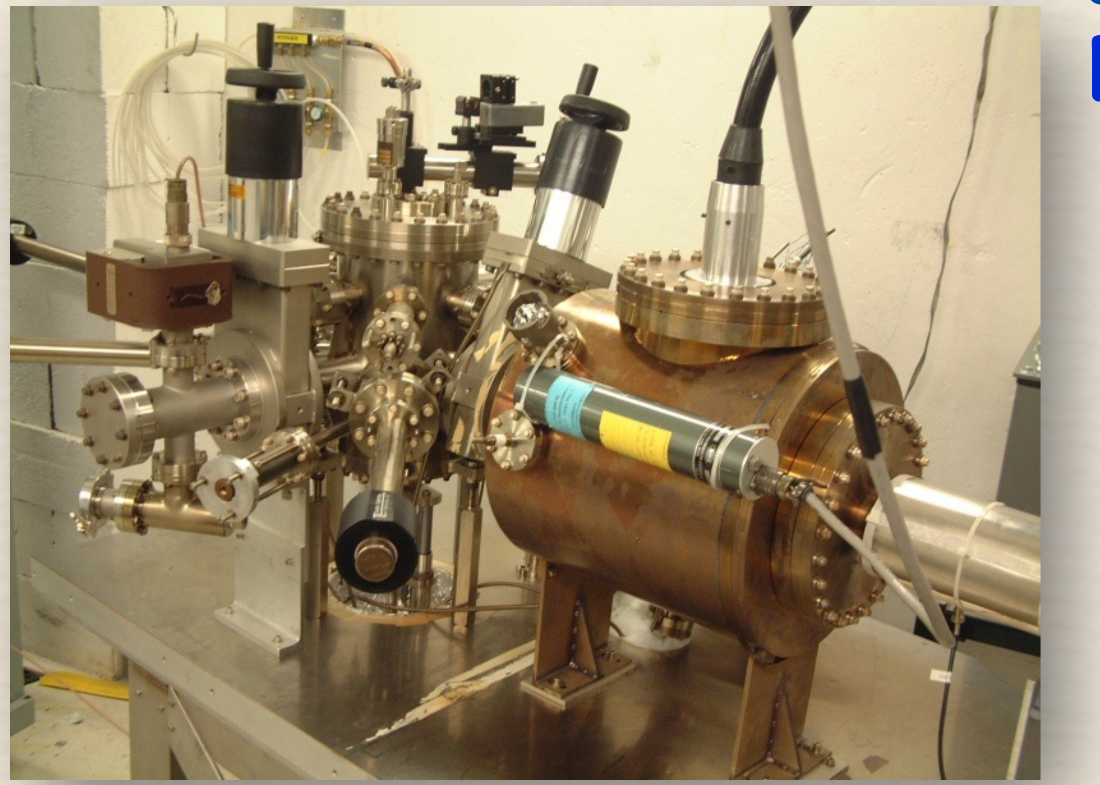
- 13 Ph.D. students, 7 postdocs, a total of about 80 scientists
- Very close watch on-line data stream - beam conditions, detector response, etc.
- Frequent contact with machine operators to maintain running conditions
- “prompt" analysis flagged subtle probe: review of beam performance by PhD students in weekly shifts



- At the end of the experiment after our realtime analysis we collected about 113 C of charge on target with only about 14 C being excluded in calibrations or due to poor beam conditions (mostly, trip recovery, beam excursions, or beam monitor issues)

PREX-2 ran from June to September 2019

Stability of Polarized Beam for PREX-2



Beam helicity is chosen pseudo-randomly at multiple of 30 Hz

$A_{corr} \sim 500$ ppb

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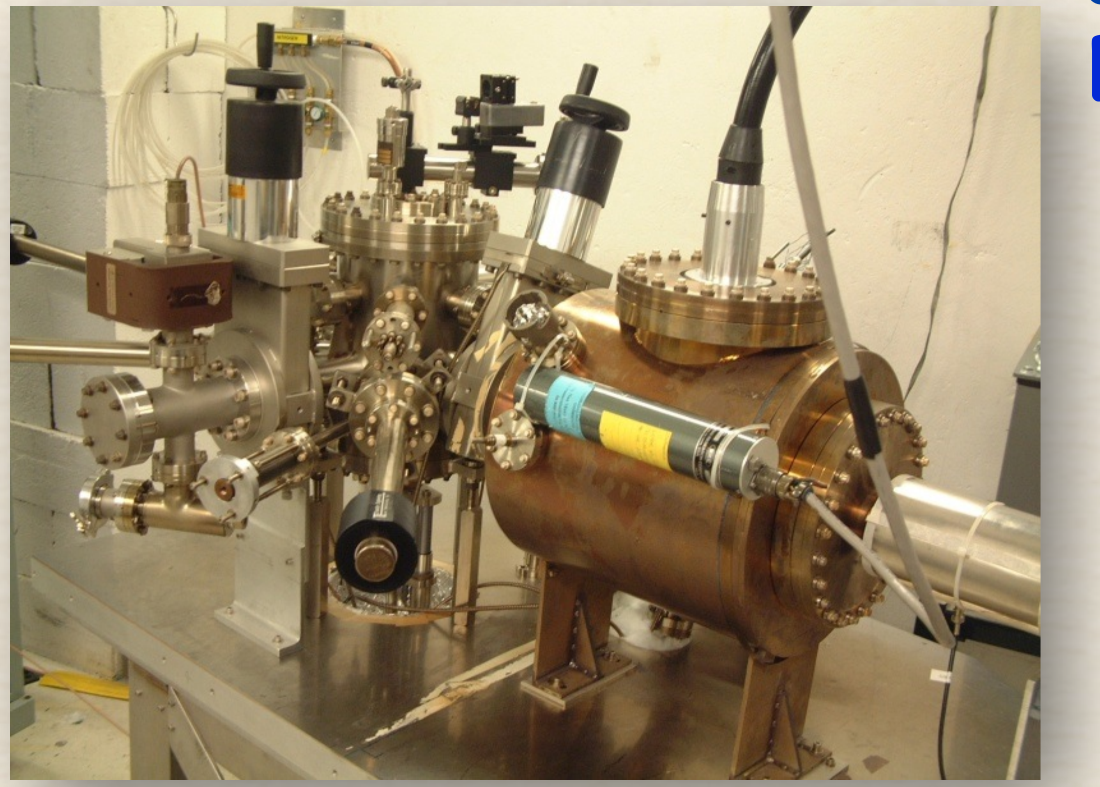

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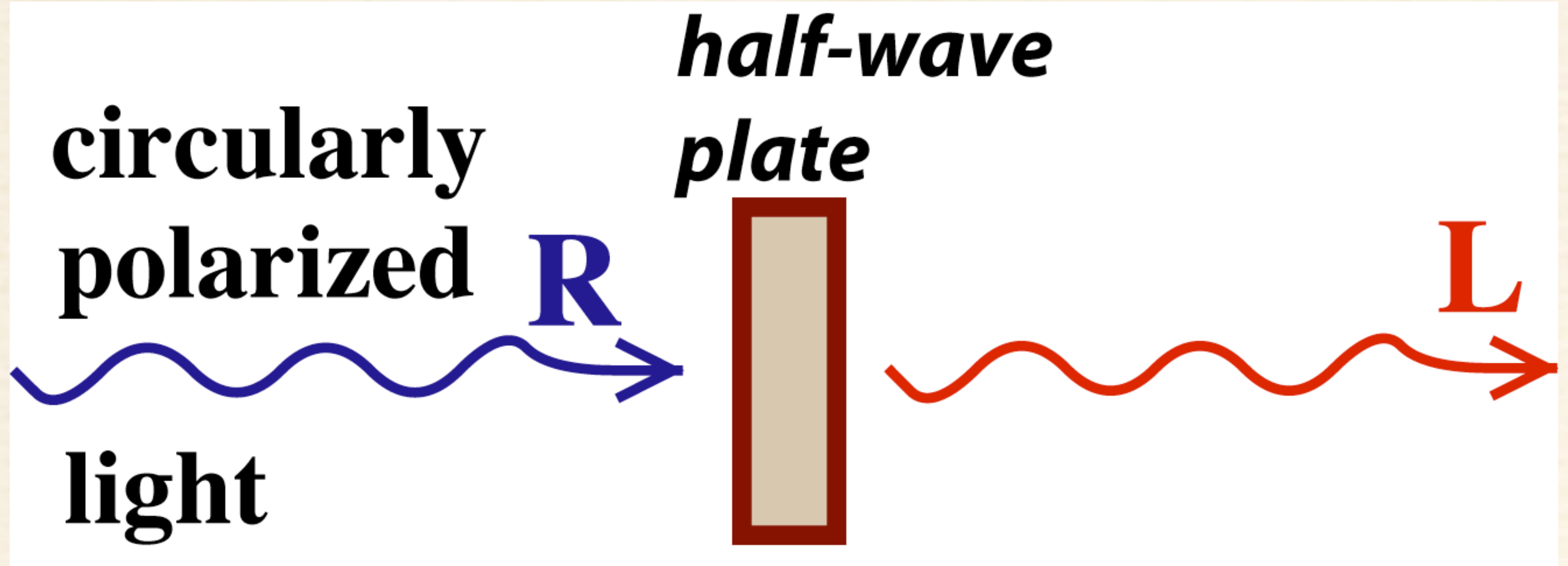

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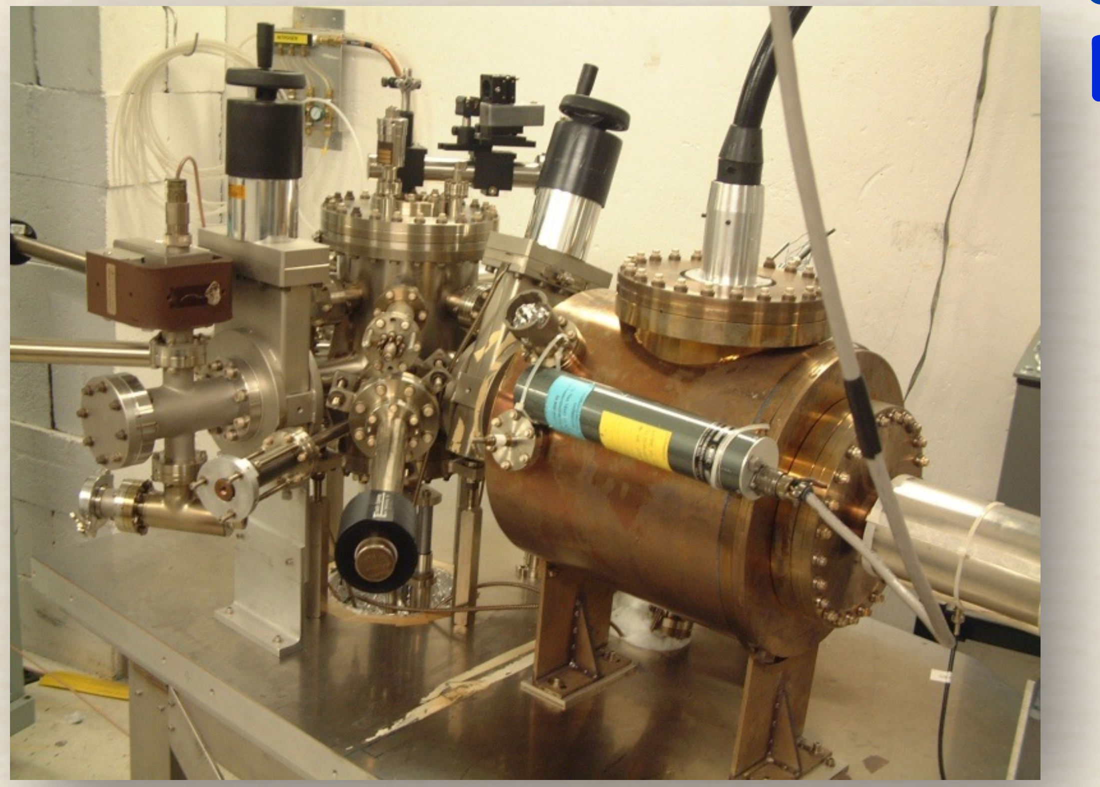

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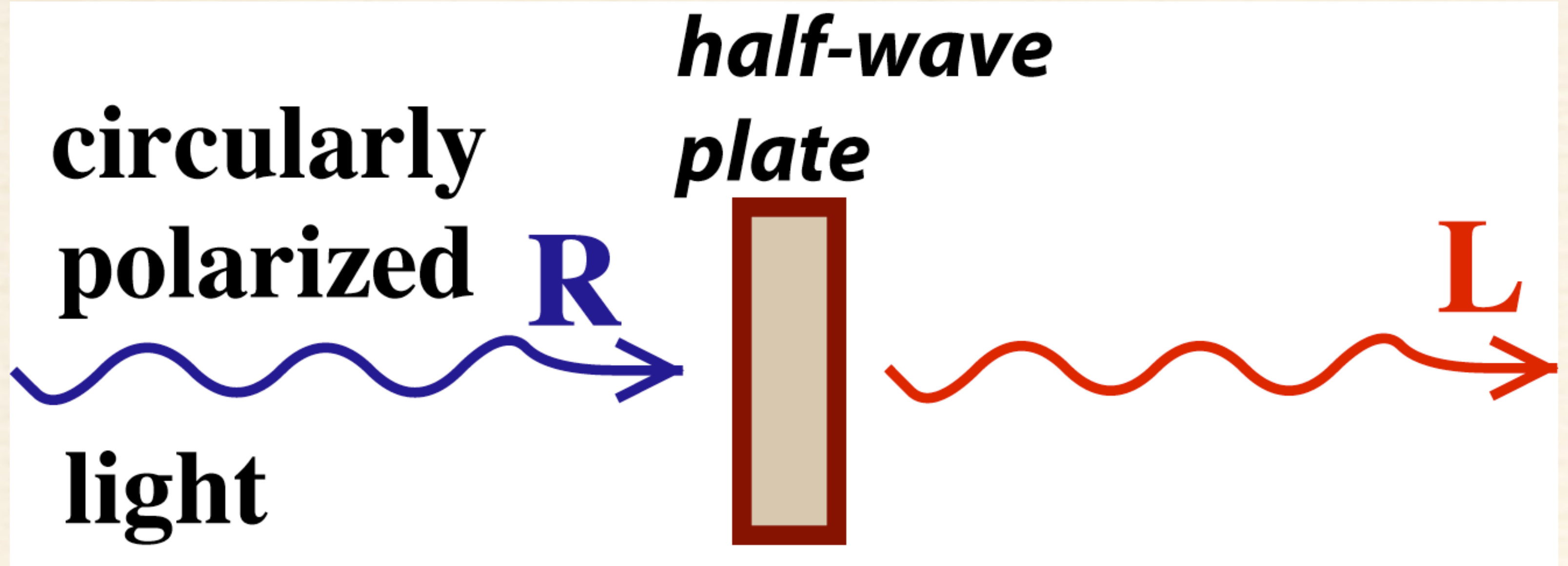

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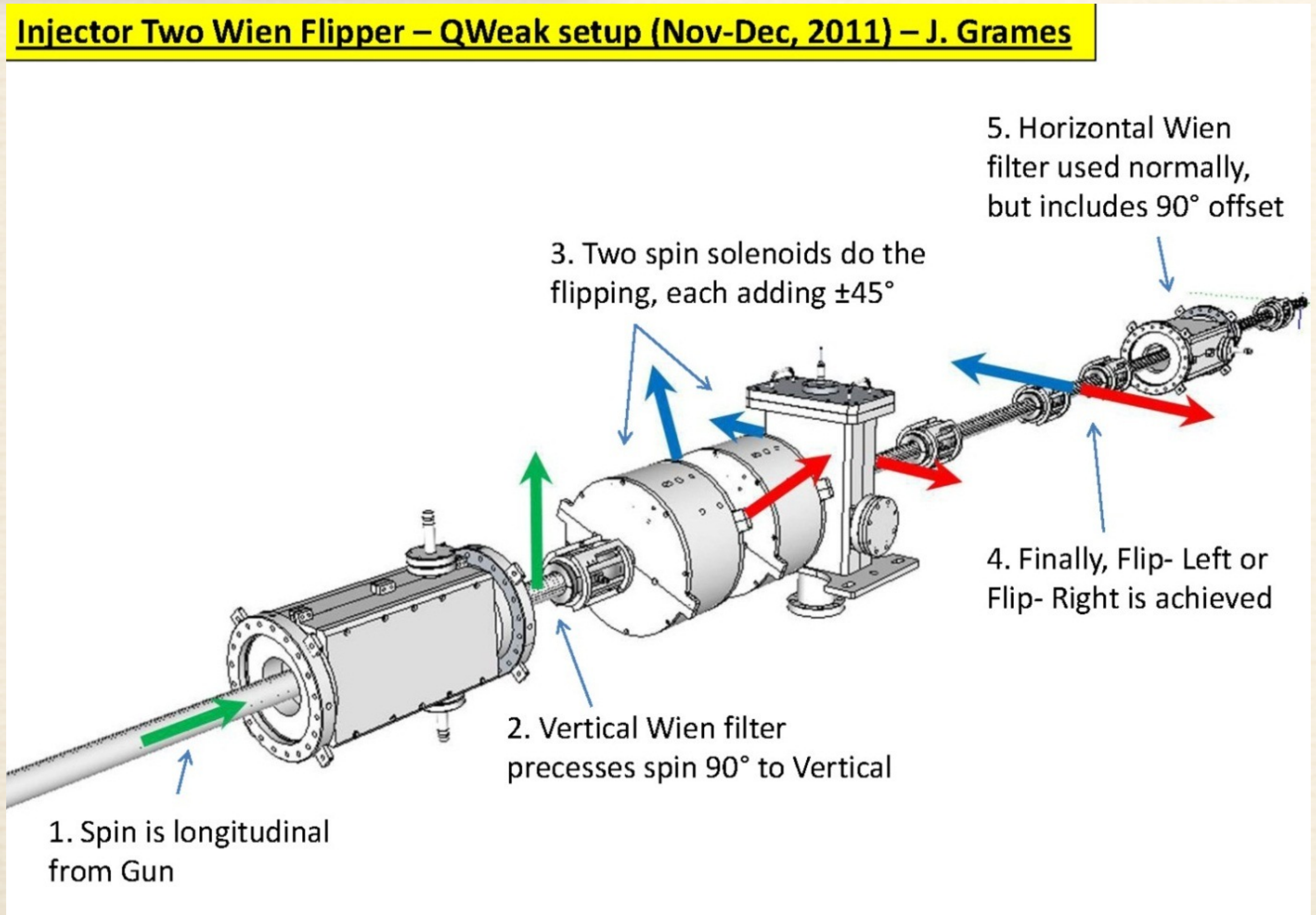

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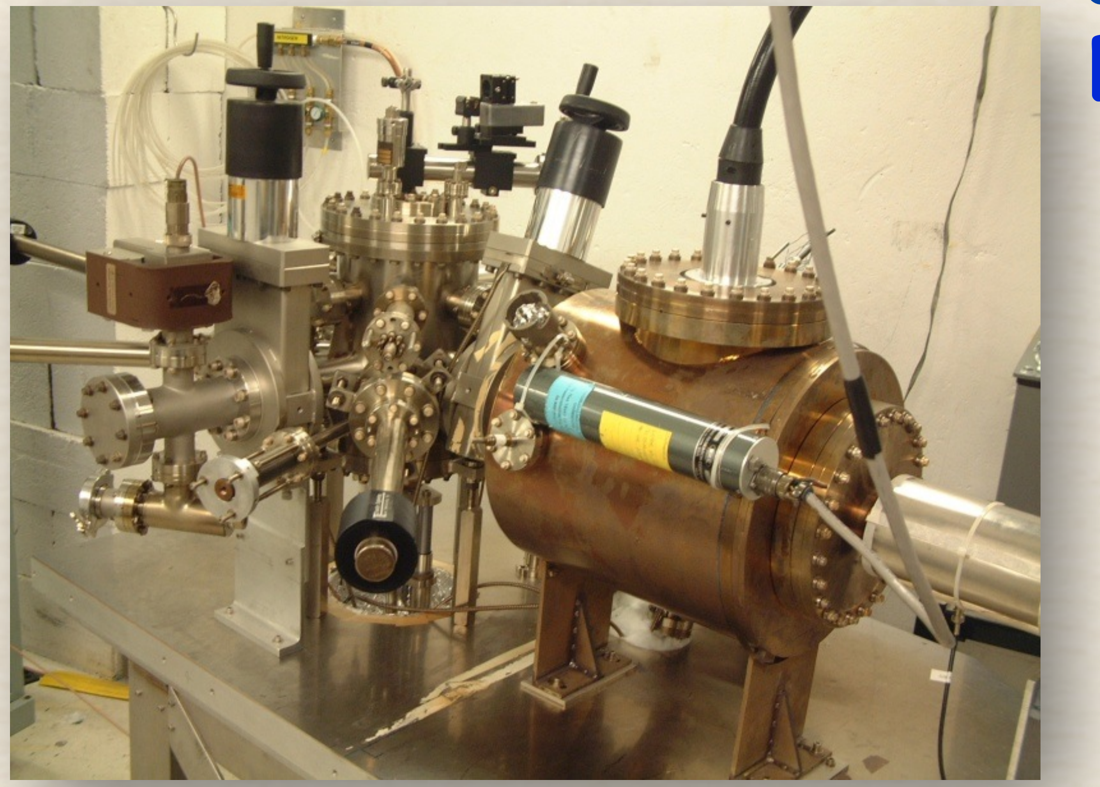

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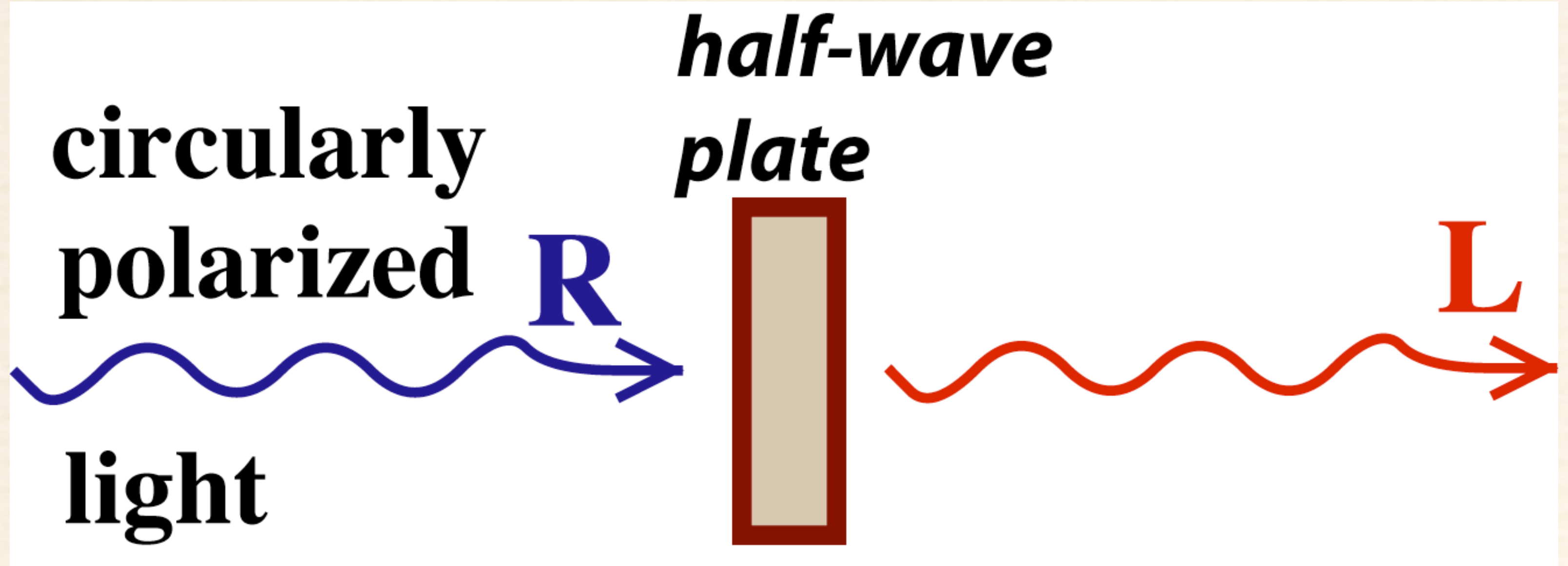

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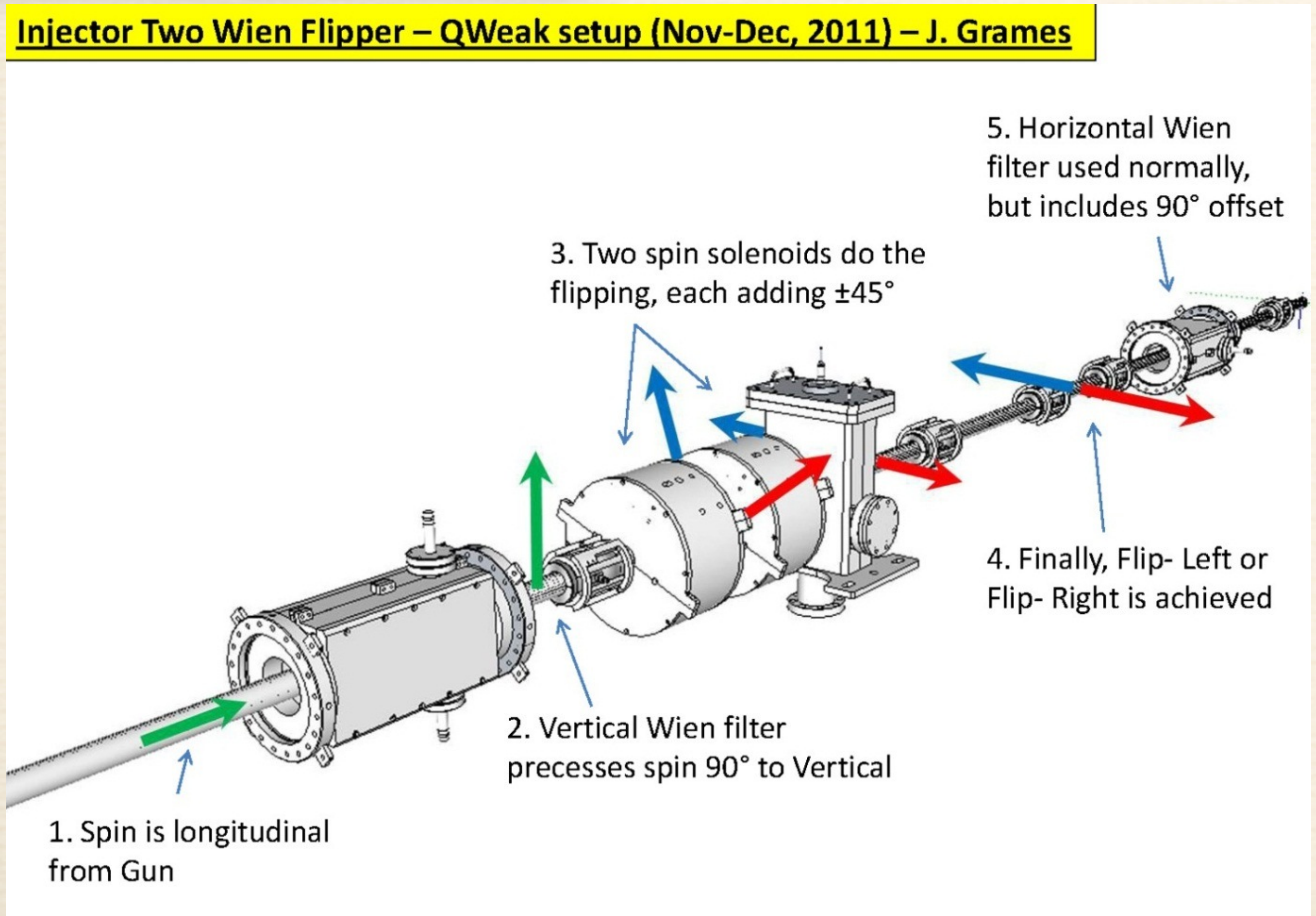
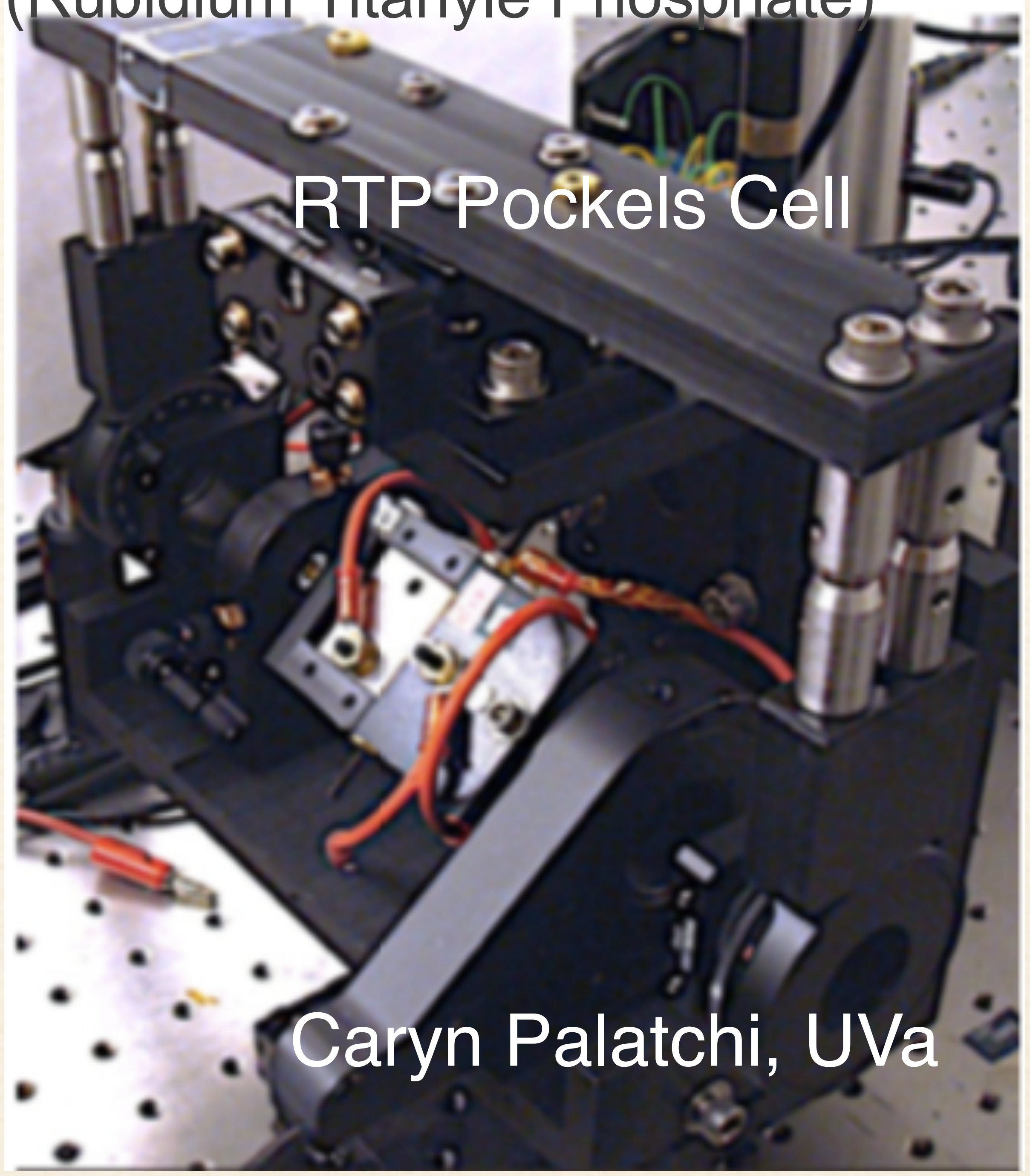


(Rubidium Titanyle Phosphate)



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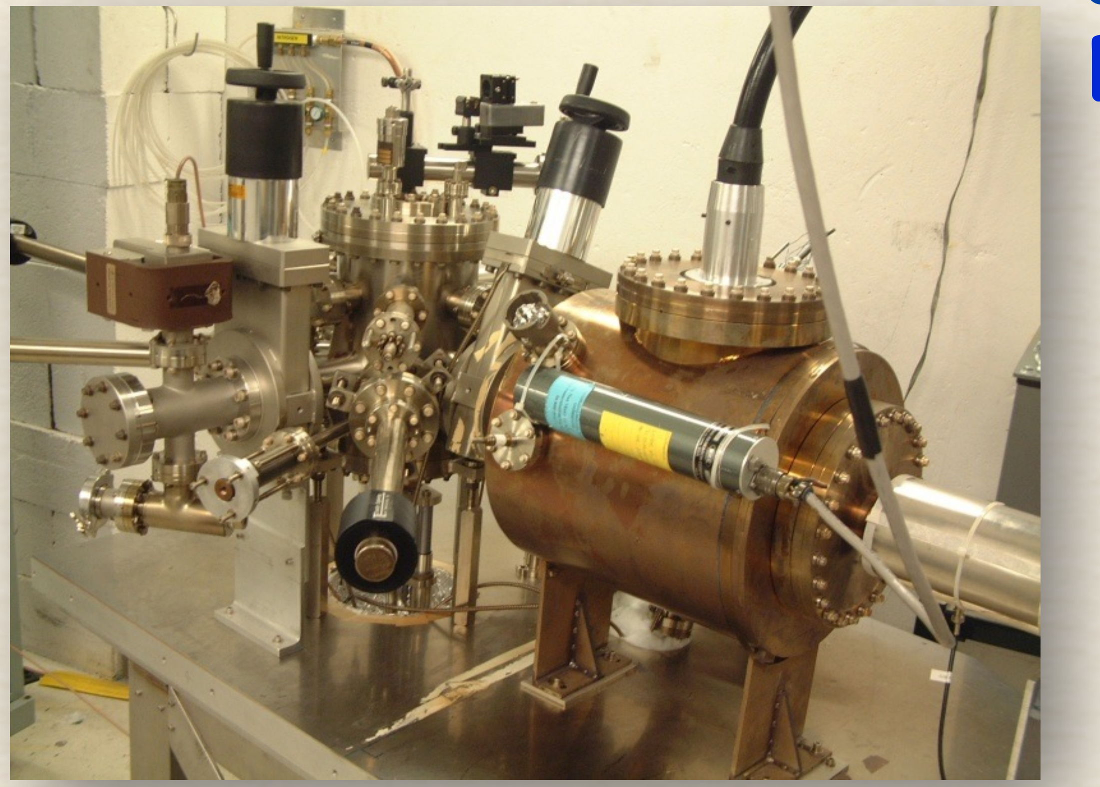

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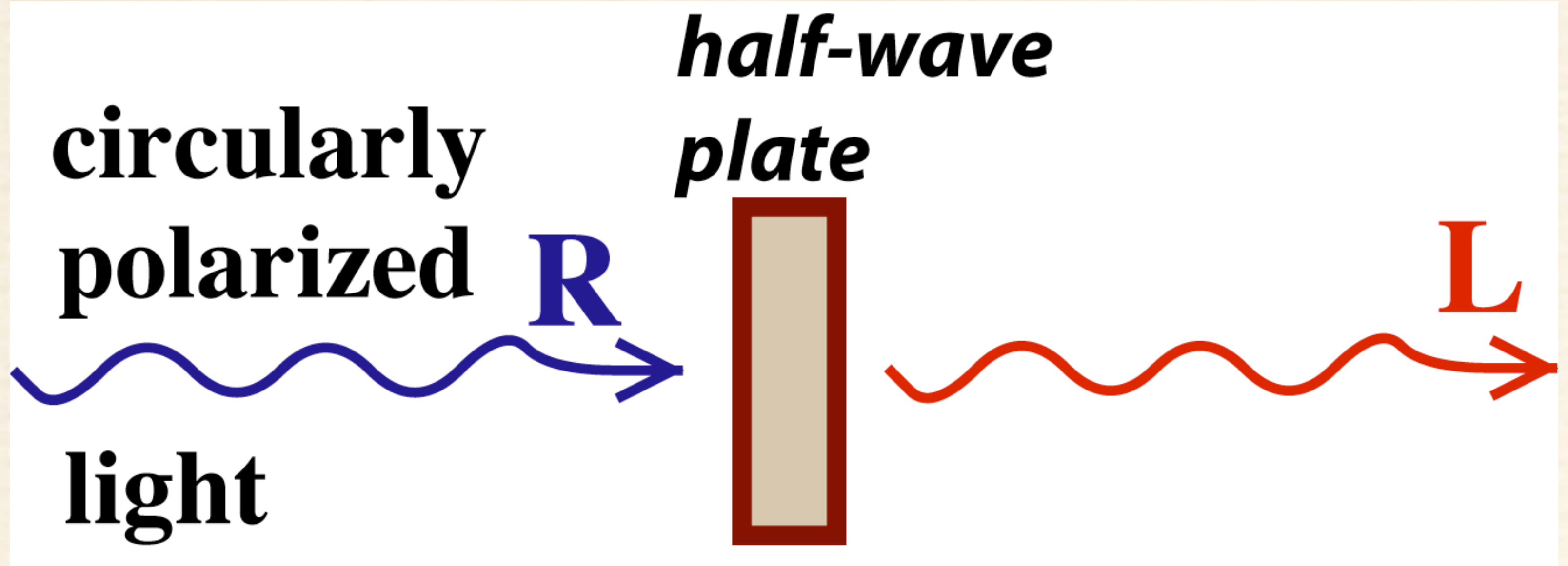

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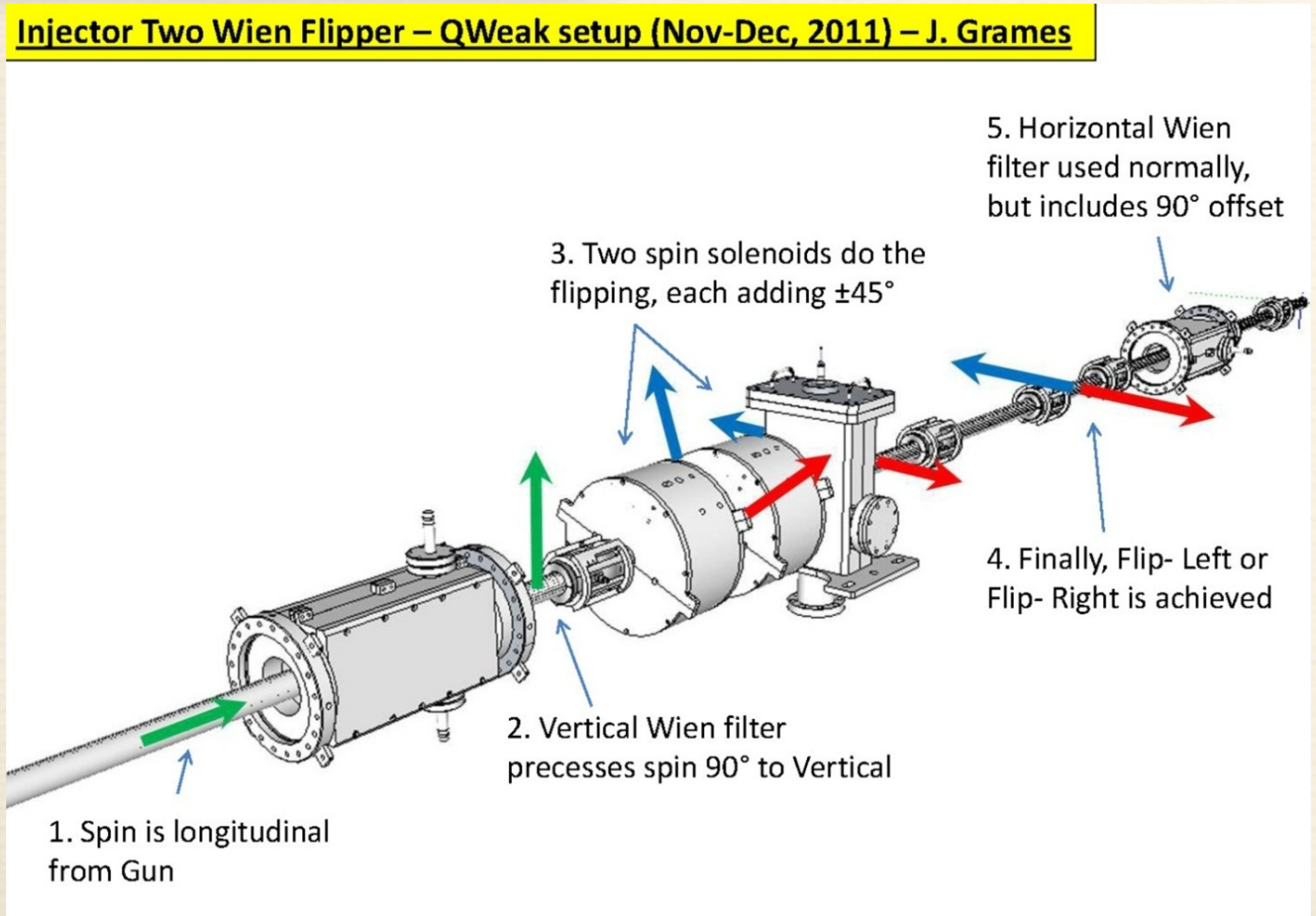

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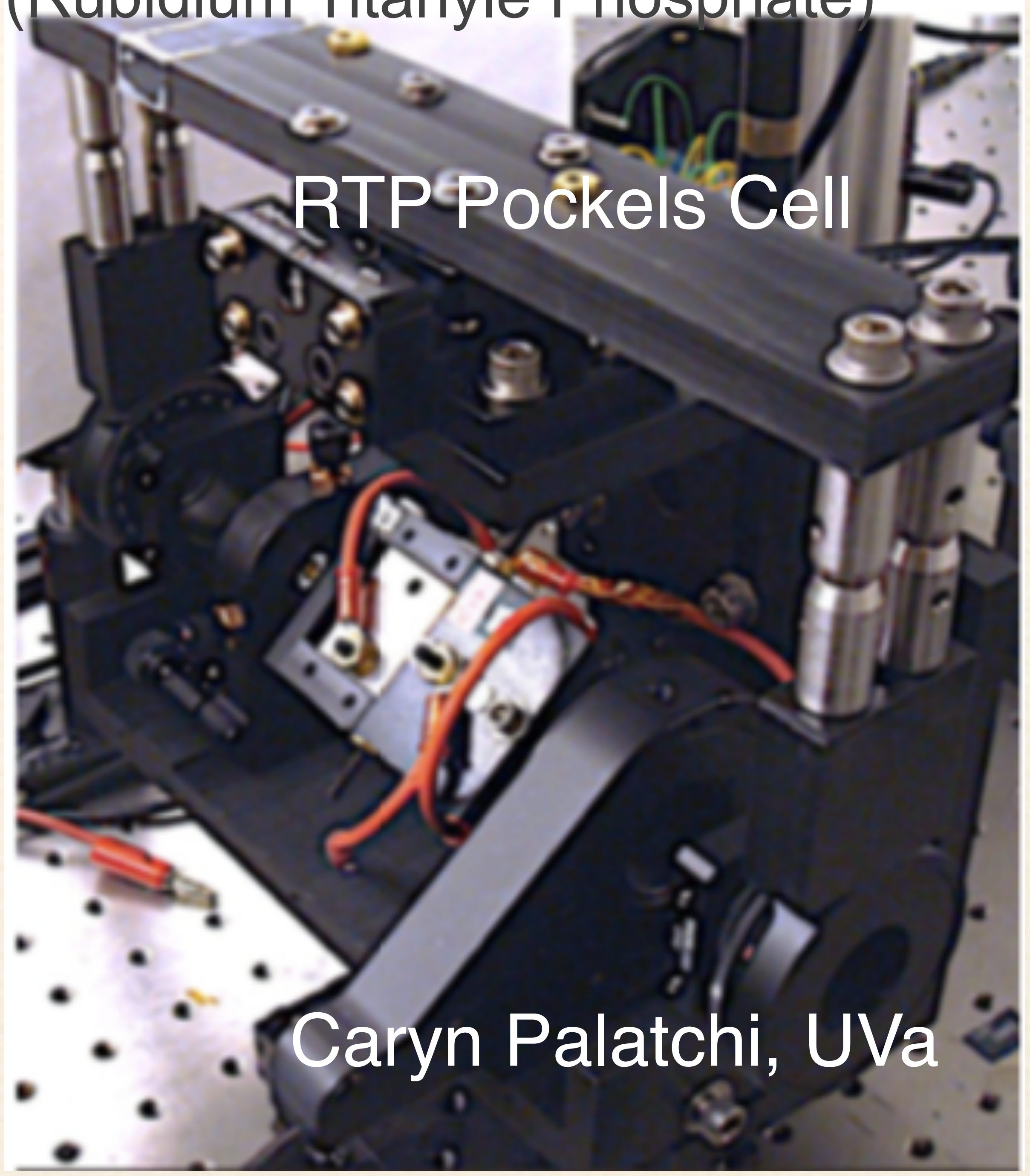
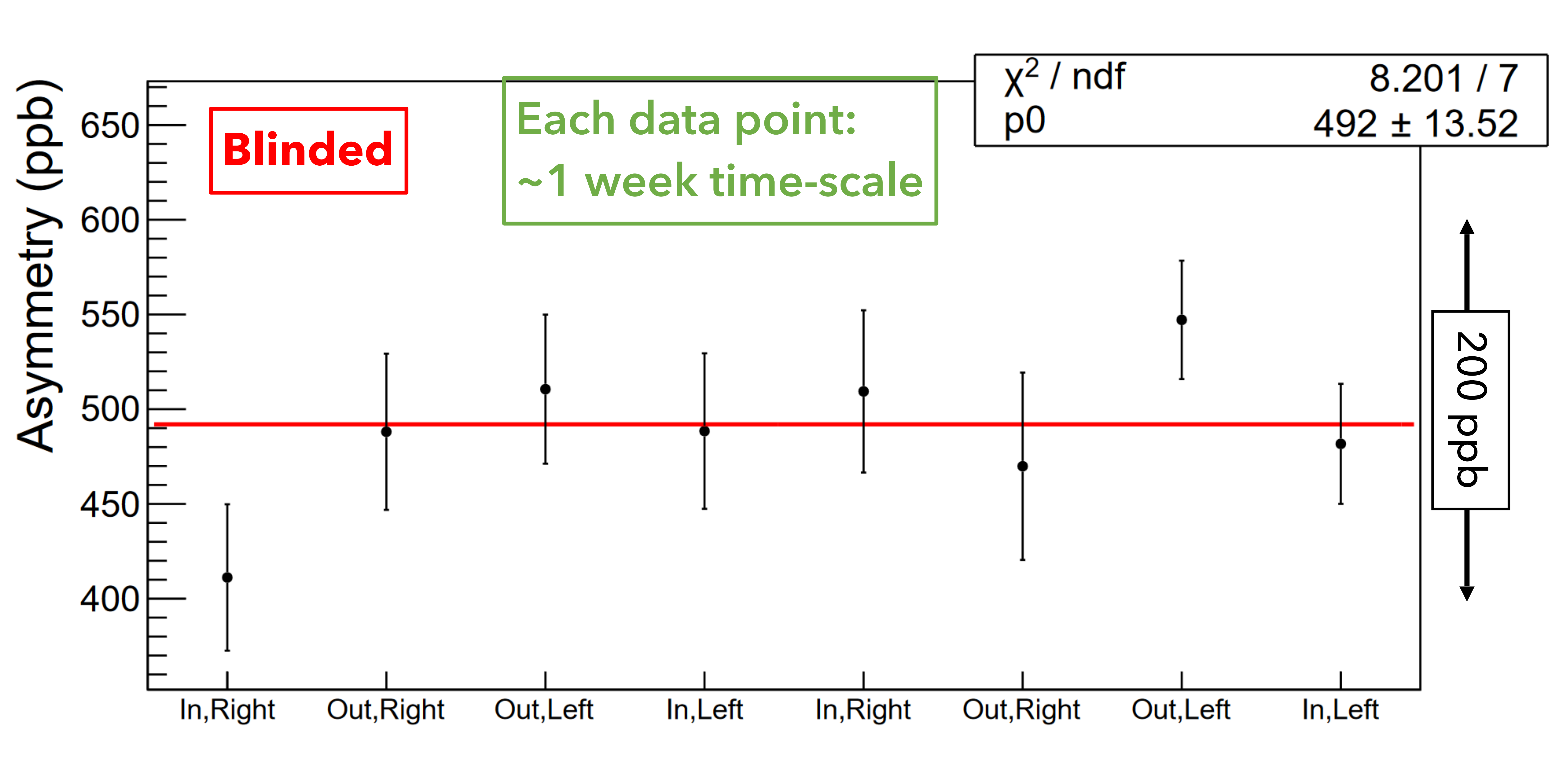


PREX-2 Run Grand Average

Parameter	Value
ΔX_t(nm)	0.15
ΔY_t(nm)	0.85
θx (nrad)	-0.2
θy (nrad)	0.02
$\Delta E/E$ (ppb)	0.5

Sub-nrad, nm, ppb level

Data Overview: Corrected Asymmetry



Half Wave Plate: IN/OUT

Wien: Left/Right

Raw Blinded Detector Asymmetry

492.0 ± 13.5 ppb

Total beam corrections:

(60.4 ± 2.5)ppb

- The corrected asymmetry removed effects from beam asymmetries and noise
- Still to come: polarization and background corrections

Beam Correction Analysis

Warning! Only interesting to parity experimentalists!

Multivariate Regression:

$$\chi^2 = \sum \left(A_{raw} - \sum_i \beta_i \Delta M_i\right)^2, \quad \frac{\partial \chi^2}{\partial \beta_i} = 0$$

- χ^2 minimization
- Variation in β_i dominated by **'strength sharing'**
- Bias by **(anti-)correlated electronic noise**
- Slope 'diluted' by **monitor resolution**

Beam Modulation:

- **Modulation amplitude** $\sim$ 100 um
  - beam random jitter 10 um
  - monitor resolution 0.4 um

Powerful new technique implemented exploiting the the advantages of two traditional methods while avoiding the potential pitfalls

Tau Ye (SBU)
Paul Souder
Kent Paschke
KK

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Lagrange Multiplier

$$\mathcal{L} = \chi^2 + \sum_\mu \lambda_\mu \left(\frac{\partial D}{\partial C_\mu} - \sum_i \beta_i \frac{\partial M_i}{\partial C_\mu}\right)$$

χ^2 **minimization** with **beam modulation sensitivities constraints**:

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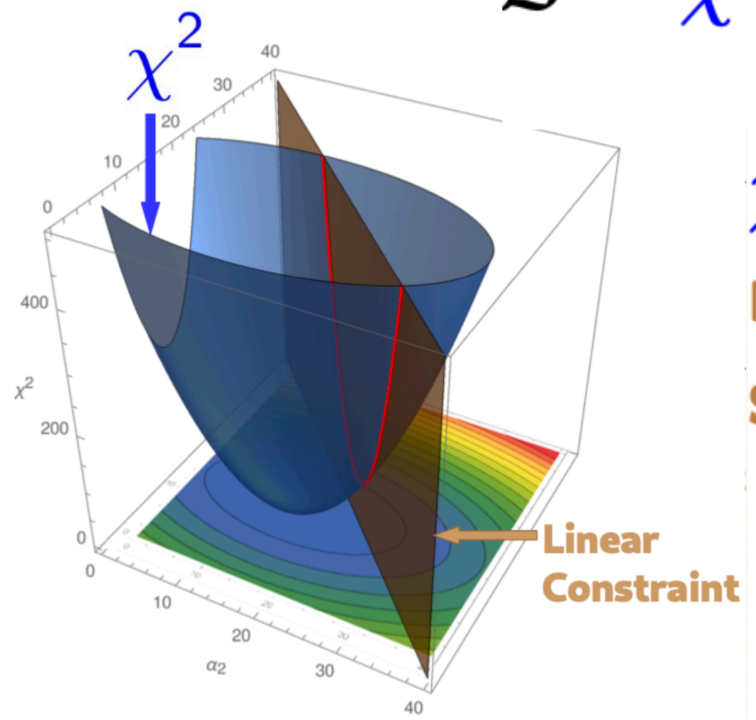

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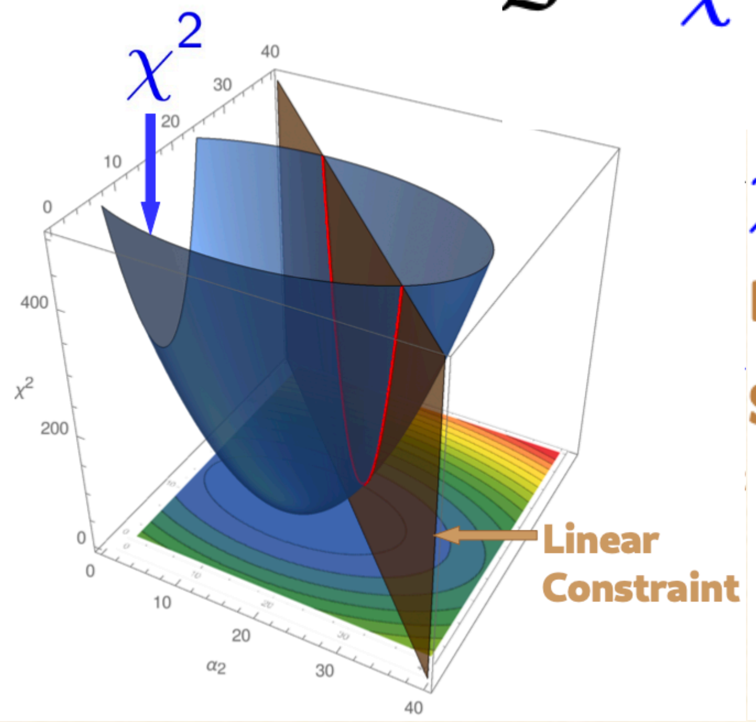

χ^2 minimization with **beam modulation sensitivities constraints**:

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Ranking eigenvectors by eigenvalue $\lambda_1 > \lambda_2 > \lambda_3 ...$

	Mean(nm)	Error(nm)	RMS(um)
X1	-3.96	2.12	14.9
Y1	2.31	1.38	9.6
E	-1.83	1.01	7.0
Y2	-1.61	0.46	3.3
X2	-1.01	0.38	2.6
	0.16	0.2	1.3
	0.15	0.12	0.9
	0.02	0.11	0.7
	-0.08	0.07	0.4
	-0.02	0.06	0.3
	-0.04	0.05	0.3
	-0.01	0.04	0.3

Tau Ye (SBU)
Paul Souder
Kent Paschke
KK

Beam Correction Analysis

Warning! Only interesting to parity experimentalists!

Multivariate Regression:

$$\chi^2 = \sum \left(A_{raw} - \sum_i \beta_i \Delta M_i\right)^2, \quad \frac{\partial \chi^2}{\partial \beta_i} = 0$$

- χ^2 minimization
- Variation in β_i dominated by **'strength sharing'**
- Bias by **(anti-)correlated electronic noise**
- Slope 'diluted' by **monitor resolution**

Beam Modulation:

- **Modulation amplitude** $\sim$ 100 um
  - beam random jitter 10 um
  - monitor resolution 0.4 um

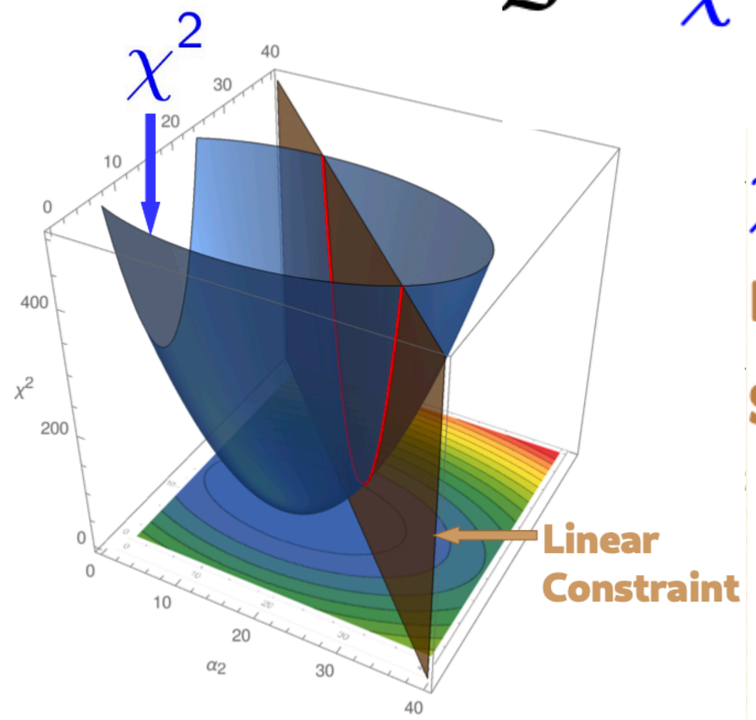
Lagrange Multiplier

$$\mathcal{L} = \chi^2 + \sum_\mu \lambda_\mu \left(\frac{\partial D}{\partial C_\mu} - \sum_i \beta_i \frac{\partial M_i}{\partial C_\mu}\right)$$

χ^2 **minimization** with **beam modulation sensitivities constraints**:

$$\frac{\partial \mathcal{L}}{\partial \beta_i} = 0, \quad \frac{\partial \mathcal{L}}{\partial \lambda_\mu} = 0$$

Powerful new technique implemented exploiting the the advantages of two traditional methods while avoiding the potential pitfalls



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Paul Souder
Kent Paschke
KK

Ranking eigenvectors by eigenvalue $\lambda_1 > \lambda_2 > \lambda_3 ...$

	Mean(nm)	Error(nm)	RMS(um)
X1	-3.96	2.12	14.9
Y1	2.31	1.38	9.6
E	-1.83	1.01	7.0
Y2	-1.61	0.46	3.3
X2	-1.01	0.38	2.6
	0.16	0.2	1.3
	0.15	0.12	0.9
	0.02	0.11	0.7
	-0.08	0.07	0.4
	-0.02	0.06	0.3
	-0.04	0.05	0.3
	-0.01	0.04	0.3

	Mean(ppb)	Std.E.(ppb)	RMS(ppm)
X1	-22.33	16.46	191
Y1	22.5	10.5	88
E	-70.44	36.45	257
Y2	-2.84	4.46	36
X2	9.7	5.7	40
	1.27	0.95	7
	-0.01	1.33	12
	1.06	1.46	11
	0.26	0.61	5
	0.24	0.42	3
	0.18	0.54	5
	0.06	0.39	3
Total	-60.38		

Beam Correction Analysis

Warning! Only interesting to parity experimentalists!

Multivariate Regression:

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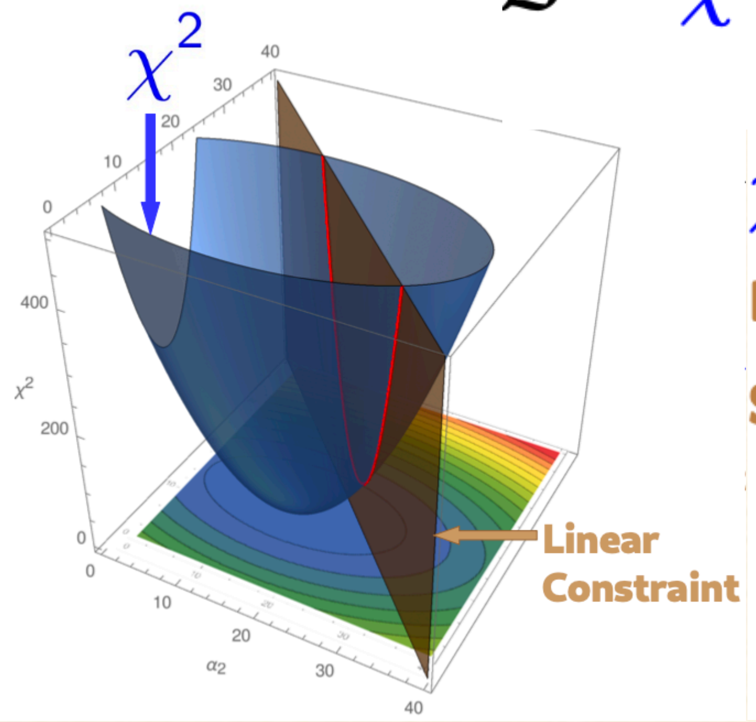

Tau Ye (SBU)
Paul Souder
Kent Paschke
KK

	ΔA (ppb)	$\sigma(\Delta A)$(ppb)	χ^2/ndf
dit vs Lagrange	2.2	3.5	86.4 / 95
Lagrange vs Reg	-1.0	1.2	91.2 / 95

Systematic Uncertainty in Beam Correction

$$\boxed{A_{beam} = -60.38 \pm 2.5 \text{ ppb.}}$$

Ranking eigenvectors by eigenvalue $\lambda_1 > \lambda_2 > \lambda_3$...

	Mean(nm)	Error(nm)	RMS(um)
X1	-3.96	2.12	14.9
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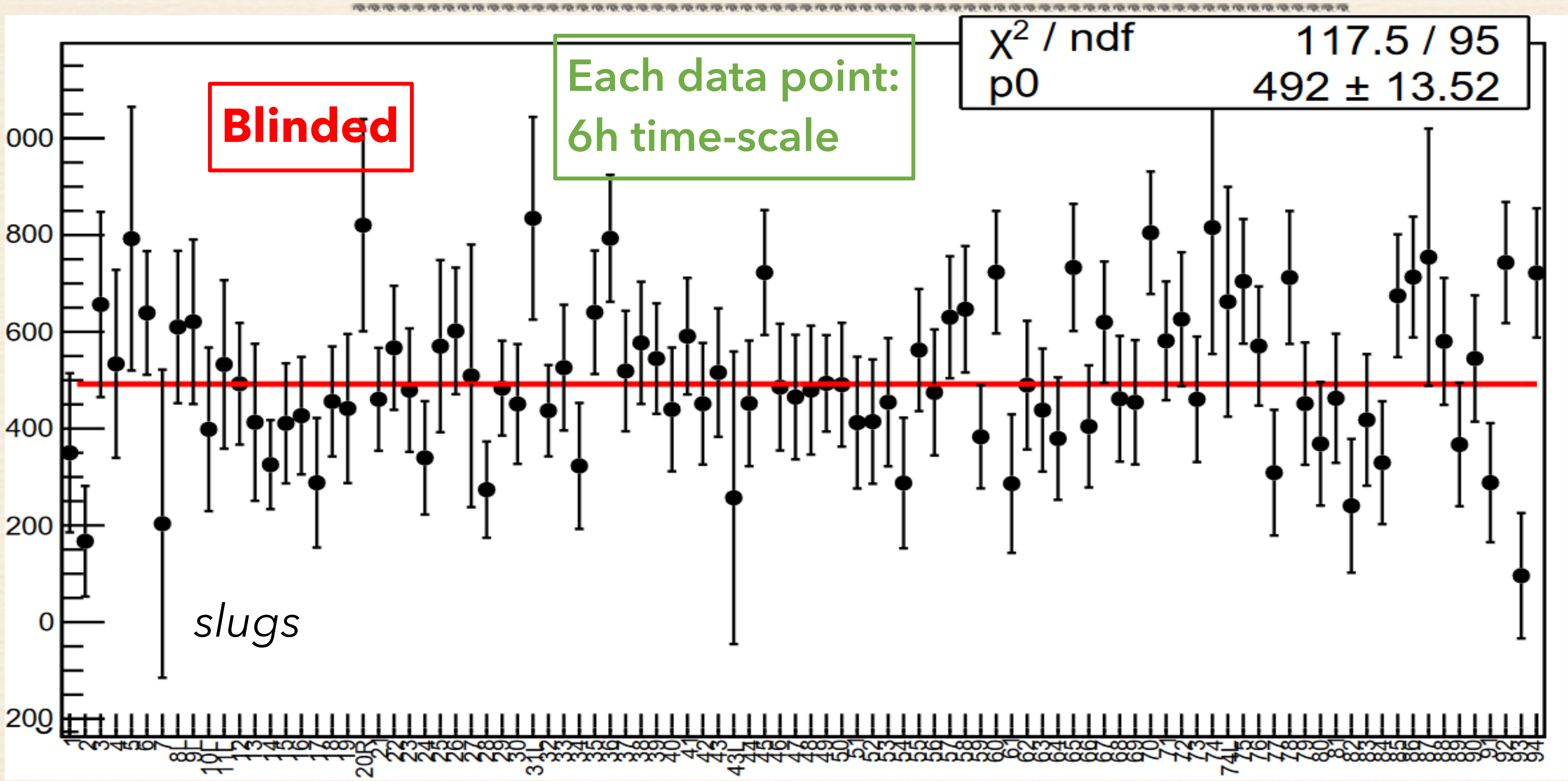
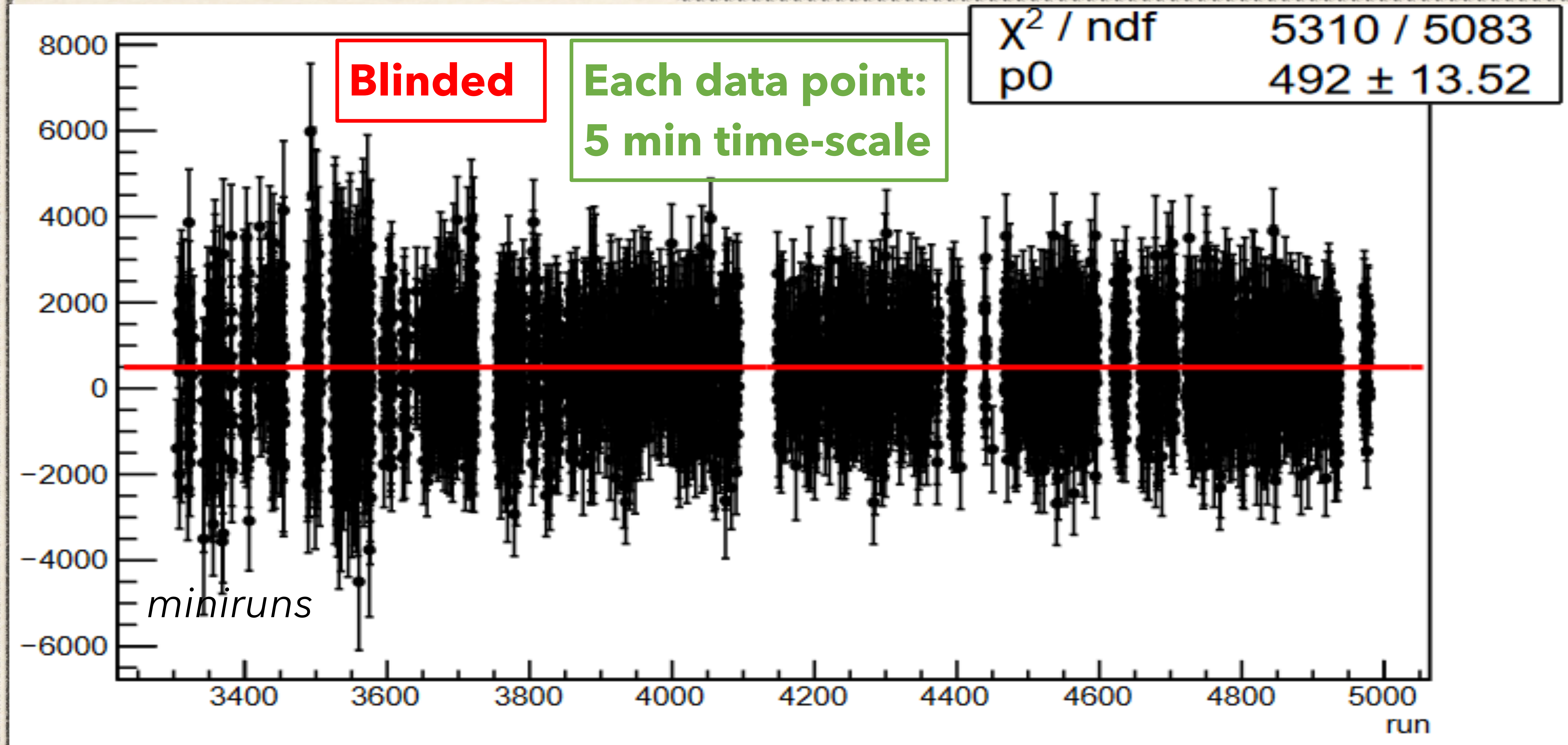
	1.06	1.46	11
	0.26	0.61	5
	0.24	0.42	3
	0.18	0.54	5
	0.06	0.39	3
Total	-60.38		

6 hour time scale

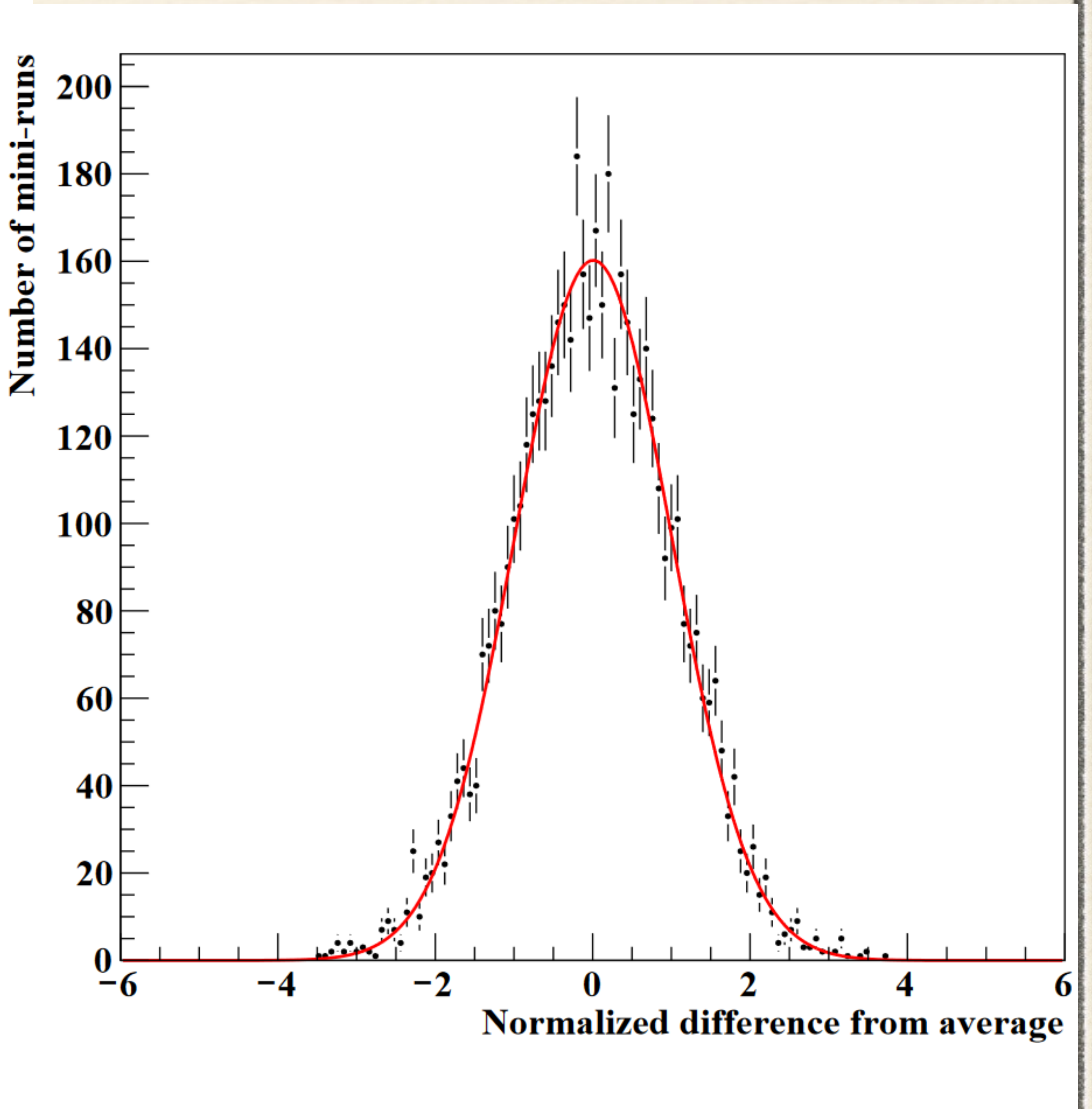


- The corrected asymmetry removed effects from beam asymmetries and noise
- Still to come: polarization and background corrections

5 minute time scale



"pull" plot



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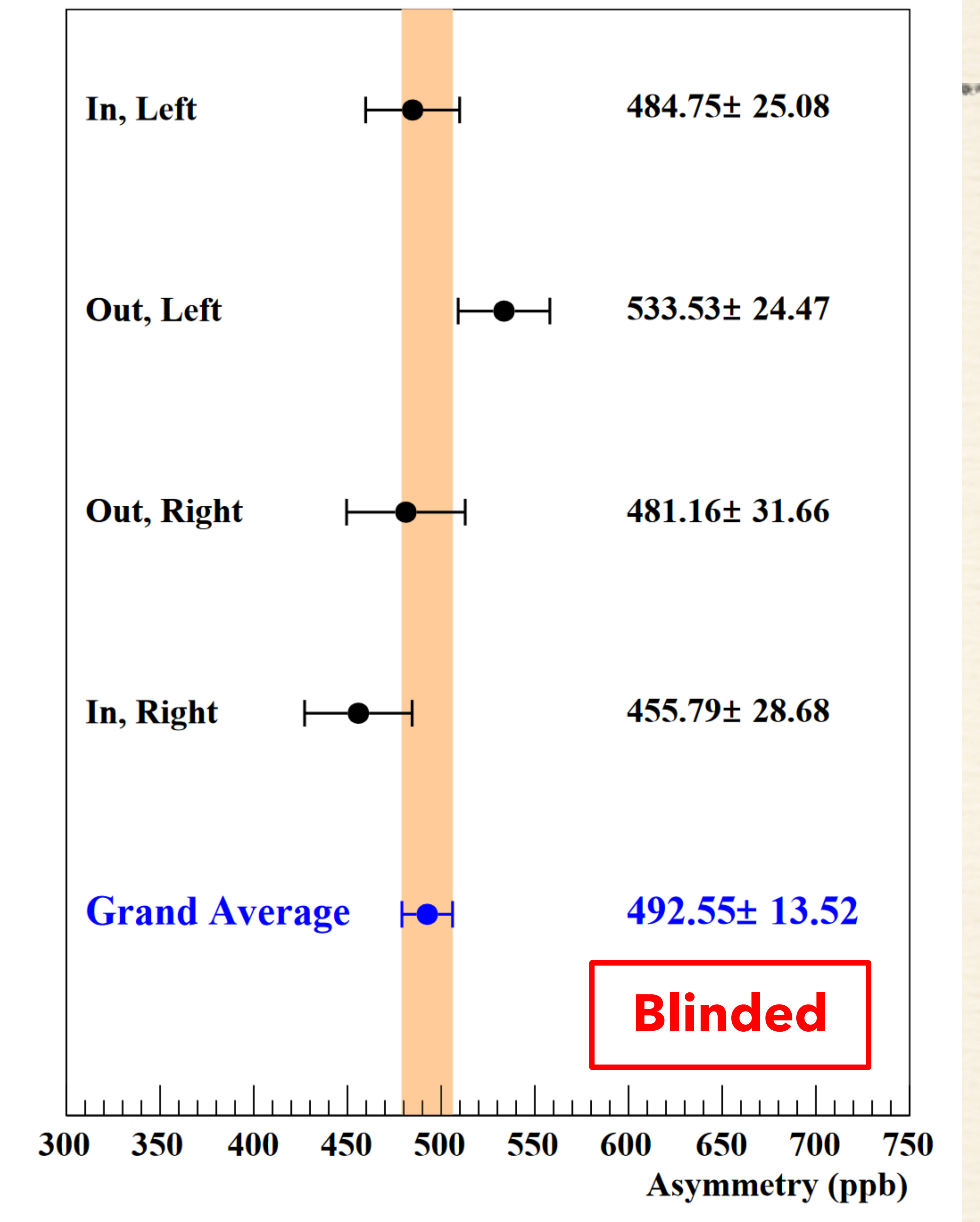
Corrected Results



$$A_{PV} = R_{acceptNorm} \frac{A_{corr}/P_e - \sum_i A_i f_i}{1 - \sum_i f_i}$$

$$A_{corr} = A_{raw} + A_{beam} + A_{nonLin} - A_{blind}$$

Blinded A_{PV}:

(549.4 ± 16.1)ppb

	A_{PV} uncertainty contribution [ppb]	A_{PV} uncertainty contribution [%]
Polarization	5.23	0.95%
Acceptance normalization	4.56	0.83%
Beam correction	2.98	0.54%
Non-linear detector response	2.69	0.49%
Carbon dilution	1.45	0.26%
Charge correction	0.25	0.04%
Inelastic contamination	0.12	0.02%
Total	**8.16**	**1.48%**

When taken all into account the experimental systematic uncertainty comes to just shy of 1.5%

Unblinding

Blinded A_{PV}:
(549.4 ± 16.1)ppb

"Blinding box": an additive term on every octet asymmetry, randomly selected (flat) at the start of the run, from ± 160 ppb

Unblinding

Blinded A_{PV}:
(549.4 ± 16.1)ppb

Unblinded A_{PV}:
(550.0 ± 16.1)ppb

"Blinding box": an additive term on every octet asymmetry, randomly selected (flat) at the start of the run, from ± 160 ppb

Blinding term turned out to be 0.5313 ppb !!!

Unblinding

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Unblinded A_{PV}:

(550.0 ± 16.1)ppb

"Blinding box": an additive term on every octet asymmetry, randomly selected (flat) at the start of the run, from ± 160 ppb

Blinding term turned out to be 0.5313 ppb !!!

This is entirely just luck-of-the-draw

	Blindedasym - rawasym (ppb)	
ops	0.5313	Roadkill stew sounds mighty good right NOW. --- Unspecified collaborator
test1	6.0223	Roadlife stew sounds mighty good right NOW. --- Unspecified collaborator
test2	-96.6812	Porkbean stew sounds mighty good right NOW. --- Unspecified collaborator
test3	53.2091	Suspicious stew sounds mighty good right NOW. --- Unspecified collaborator
test4	-121.4924	Road-kill stew sounds mighty good right NOW. --- Unspecified collaborator

The Weak Radius and the Neutron Skin

Calculations led by Chuck Horowitz

$$R_W = 5.795 \pm 0.082 \text{ fm} \rightarrow 1.4\%$$

$$R_W - R_{ch} = 0.292 \pm 0.082 \text{ fm}$$

$$R_n - R_p = 0.278 \pm 0.078 \text{ fm}$$

This includes statistical and systematic uncertainty.
There is model uncertainty (from the surface thickness) of 0.013 fm
and radiative γ-Z box correction* uncertainty of 0.006 fm

✳ Thank you Jens Erler and Mikhail Gorchtein for the updated electroweak gamma-Z box corrections

Compare and Combine with PREX-I

Measured at different angles, so different Q2 (and rather different sensitivities)

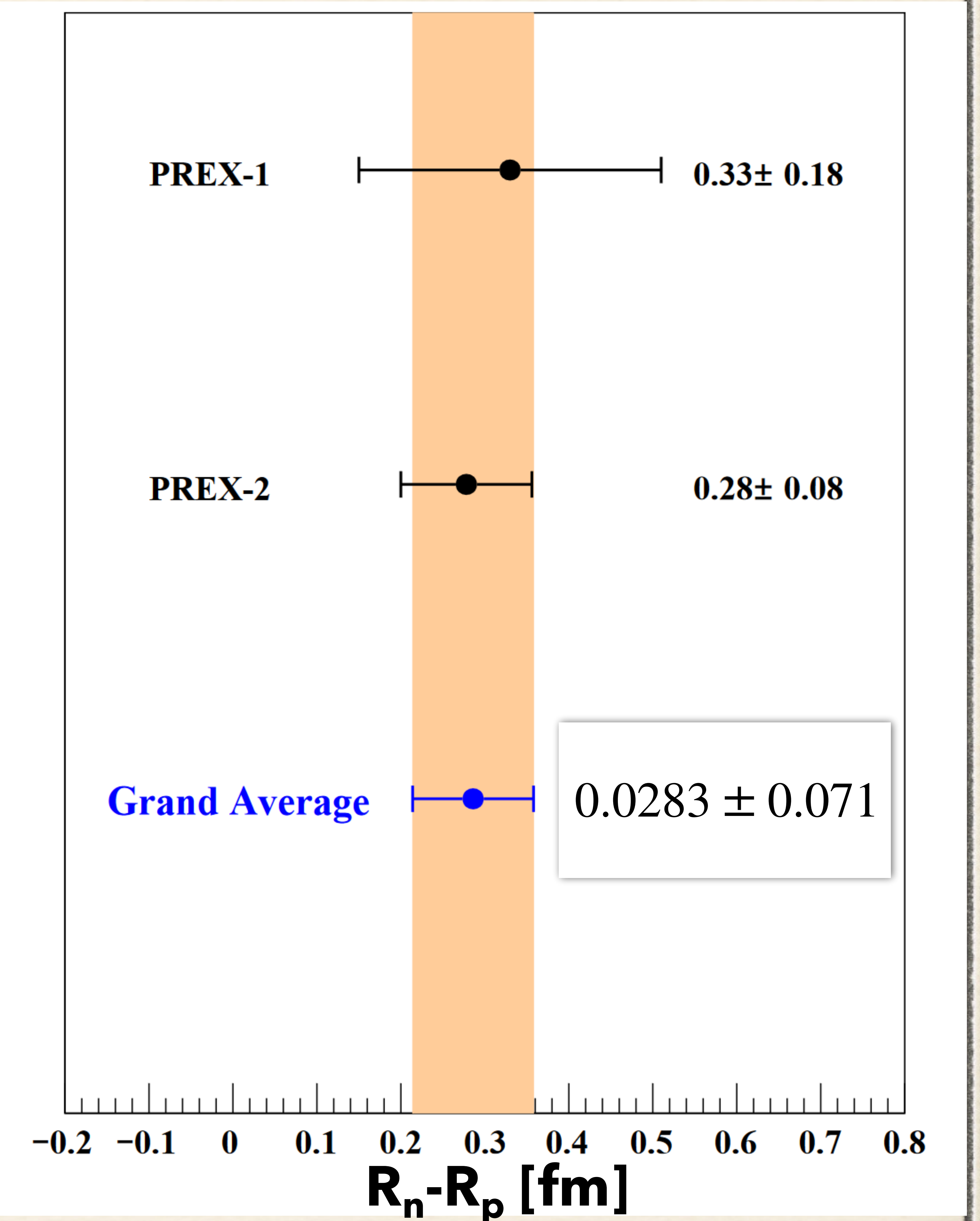
PREX-1 $Q^2 = 0.0088\text{GeV}^2$

$$A_{PV} = [656 \pm 60(\text{stat}) \pm 14(\text{syst})]\text{ppb} \rightarrow 9.4\%$$

PREX-2 $Q^2 = 0.0062\text{GeV}^2$

$$A_{PV} = [550 \pm 16(\text{stat}) \pm 8(\text{syst})]\text{ppb} \rightarrow 3.3\%$$

^{208}Pb Parameter	Value
Weak radius (R_W)	5.800 ± 0.075 fm
Interior weak density (ρ^0_W)	-0.0796 ± 0.0038 fm^{-3}
Interior baryon density (ρ^0_b)	0.1480 ± 0.0038 fm^{-3}
Neutron skin ($R_n - R_p$)	0.283 ± 0.071 fm



PREX-2 Result Summary

Published in: *Phys.Rev.Lett.* 126 (2021) 17, 172502
• e-Print: 2102.10767 [nucl-ex]

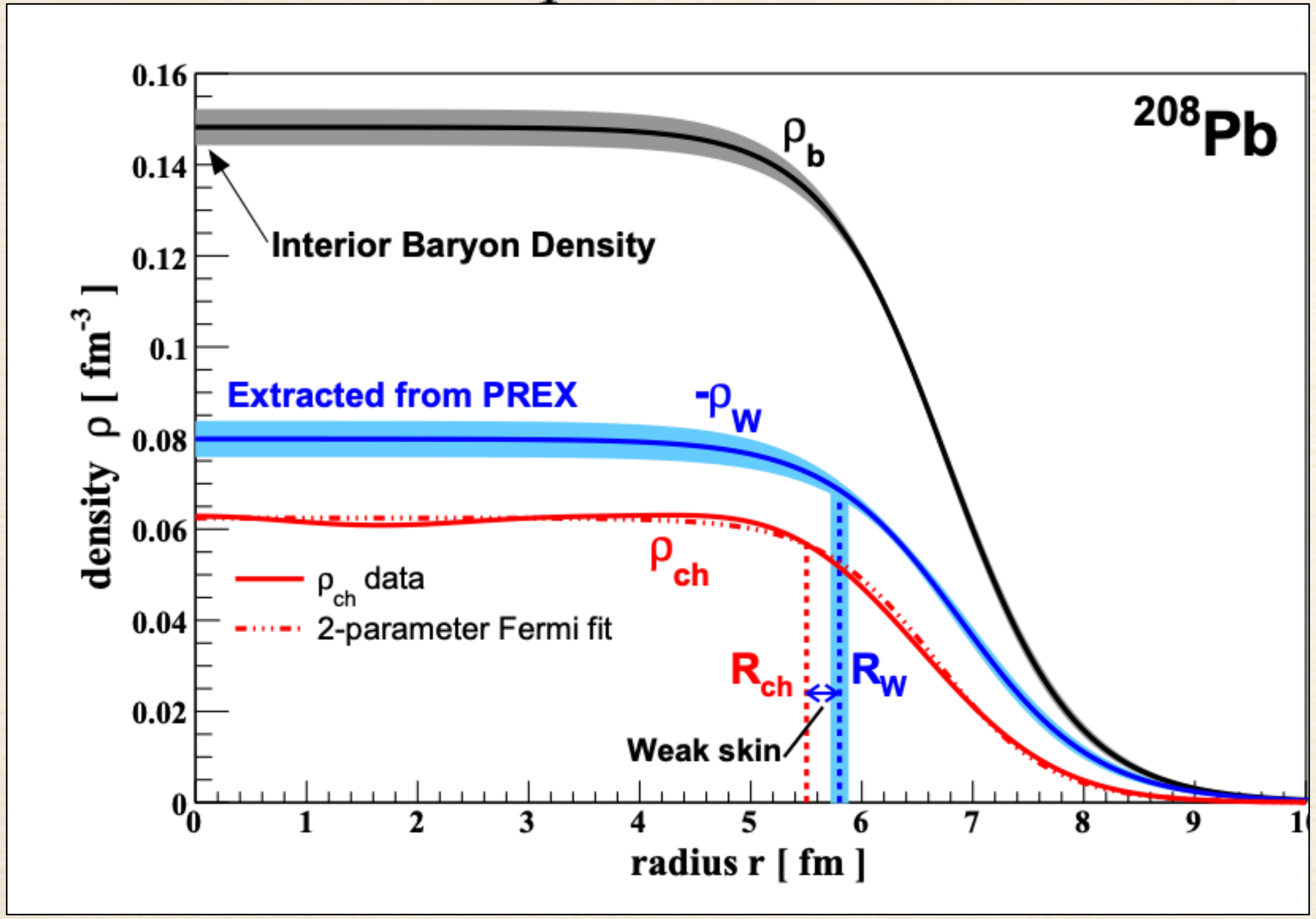
150 citations in 15 months…

$$A_{PV} = 550 \pm 16(\mathrm{stat}) \pm 8\ (\mathrm{syst})$$

Implied neutron skin thickness PREX-1 and PREX-2

$$R_n - R_p = 0.283 \pm 0.071\ \mathrm{fm}$$

More about implications later and in C. Horowitz talk



Garnered Press Attention

APS Viewpoint "highlighting exceptional research"

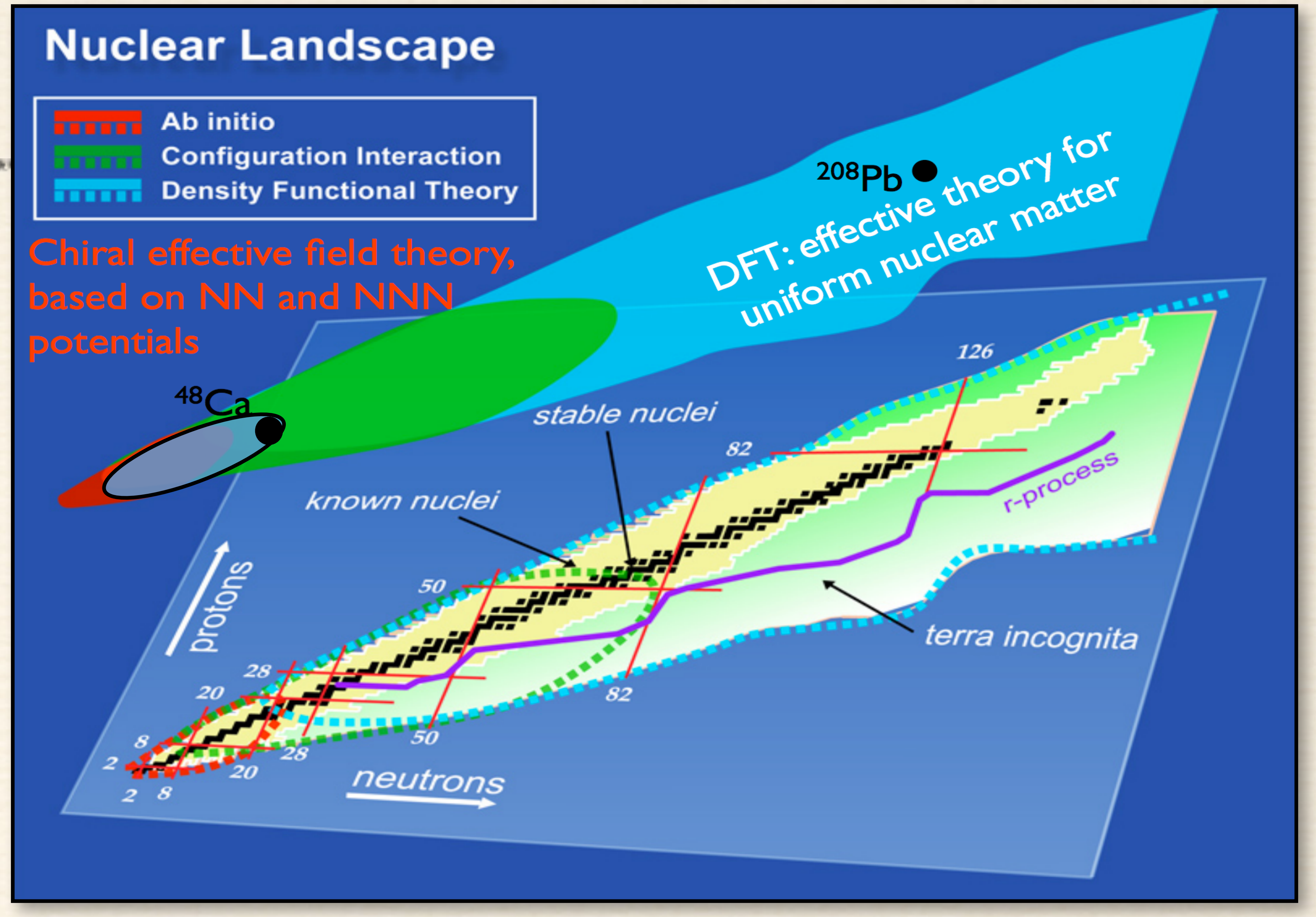
New Experimental Result: CREX

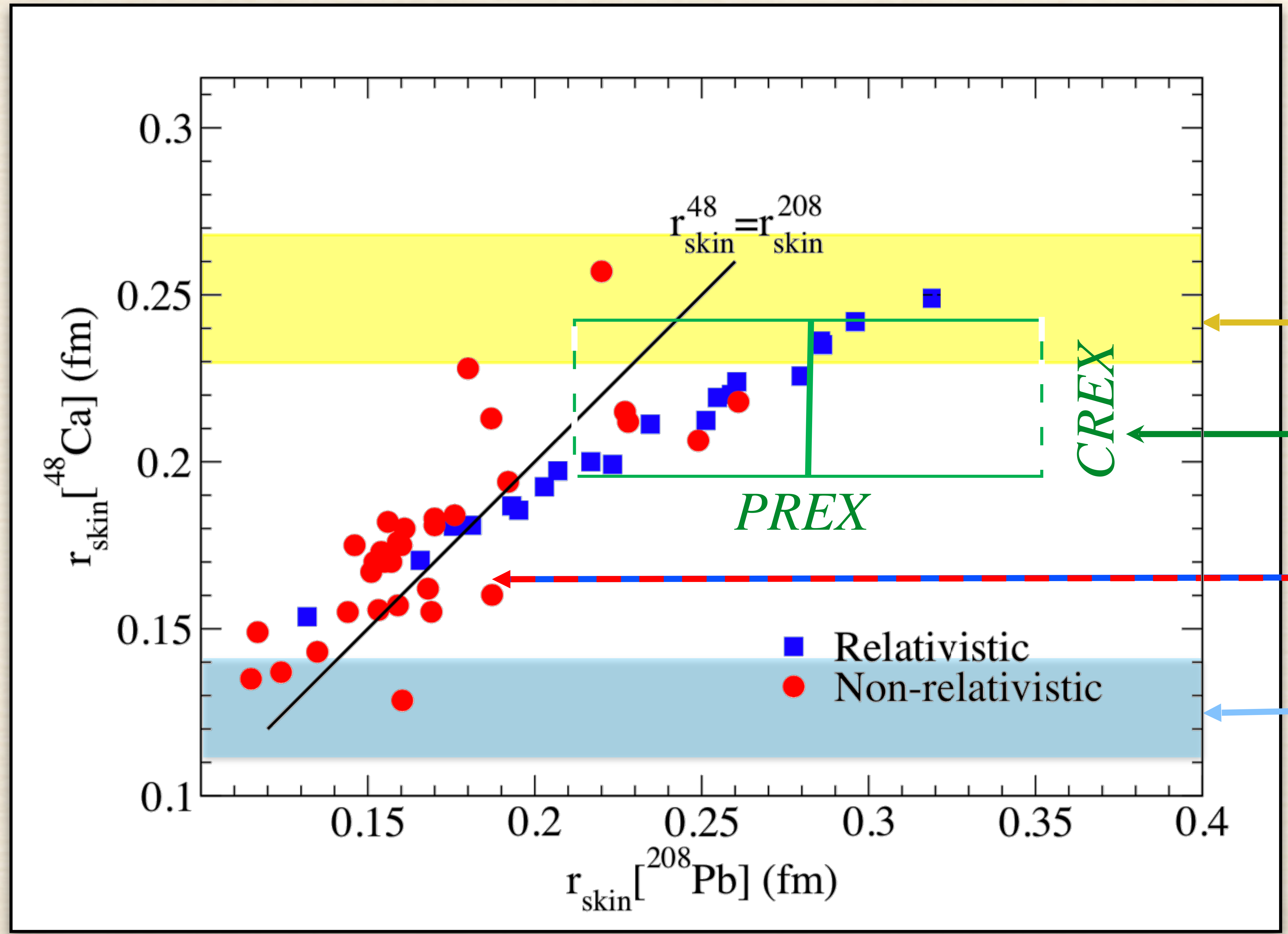
Motivation for Measuring a Second Nucleus

PREX: ^{208}Pb large, uniform nucleus, DFT

CREX: neutron FF ^{48}Ca

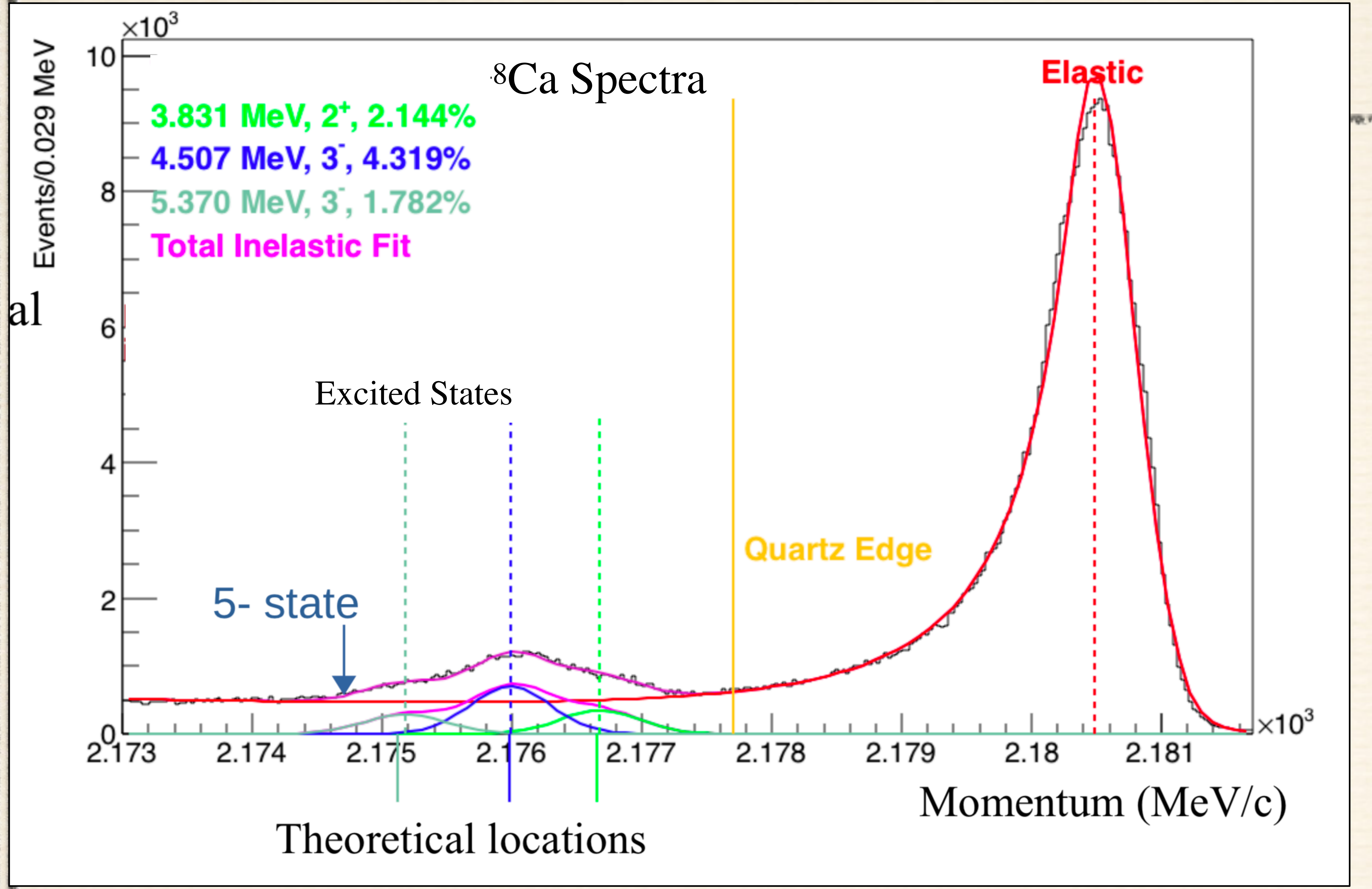
- moderate size system
- finite size effects
- Within reach of microscopic calculations (which suggest the importance of 3-nucleon forces)





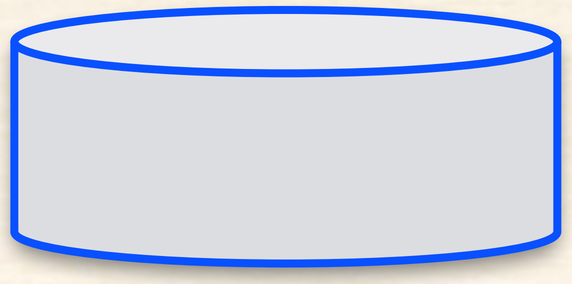
- DOM (Dispersive Optical Model)
  W. Dickoff *et al*, PRL 119, 222503(2017)
- *Arbitrary CREX central value*
- DFT (Relativistic, Non-relativistic)
  Fattoyev, Piekarewicz, PRC 85, 015802 (2012)
- Coupled cluster calculations predict a neutron skin of: $0.12 \leqq R_{skin} \leqq 0.15$ fm
  G. Hagen *et al*, Nature Physics **12**, 186–190 (2016)

^{48}Ca Target



al

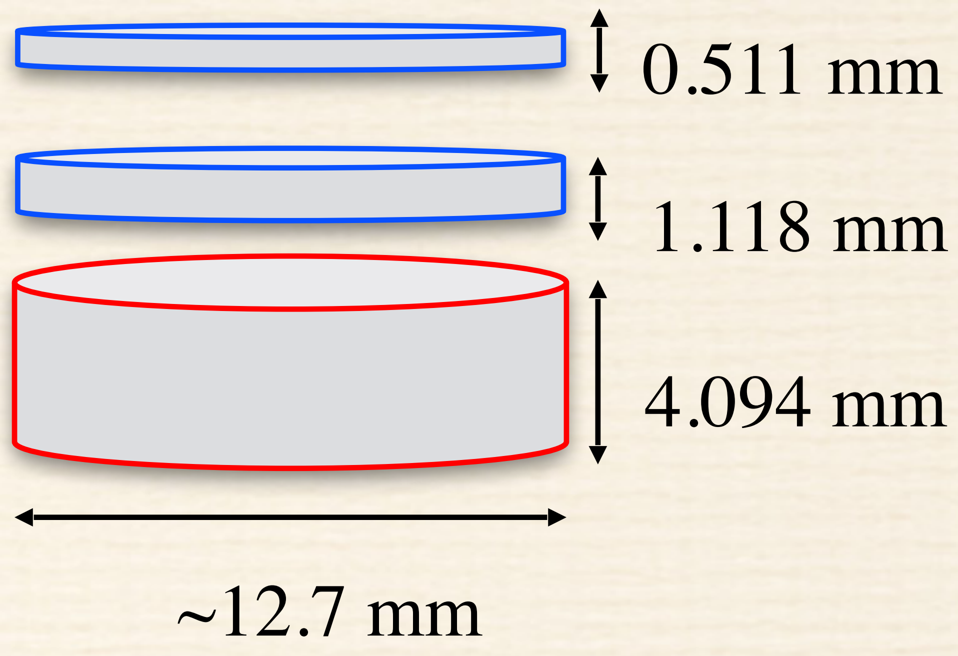
Target 1



Element:	Calcium
Symbol:	Ca
Isotope:	48
Series:	LO
Batch:	140042

- Single puck
- 5mm thick
- 96% ^{48}Ca
- 3.84% ^{40}Ca

Target 2



Element:	Calcium
Symbol:	Ca
Isotope:	48
Series:	
Batch:	900242

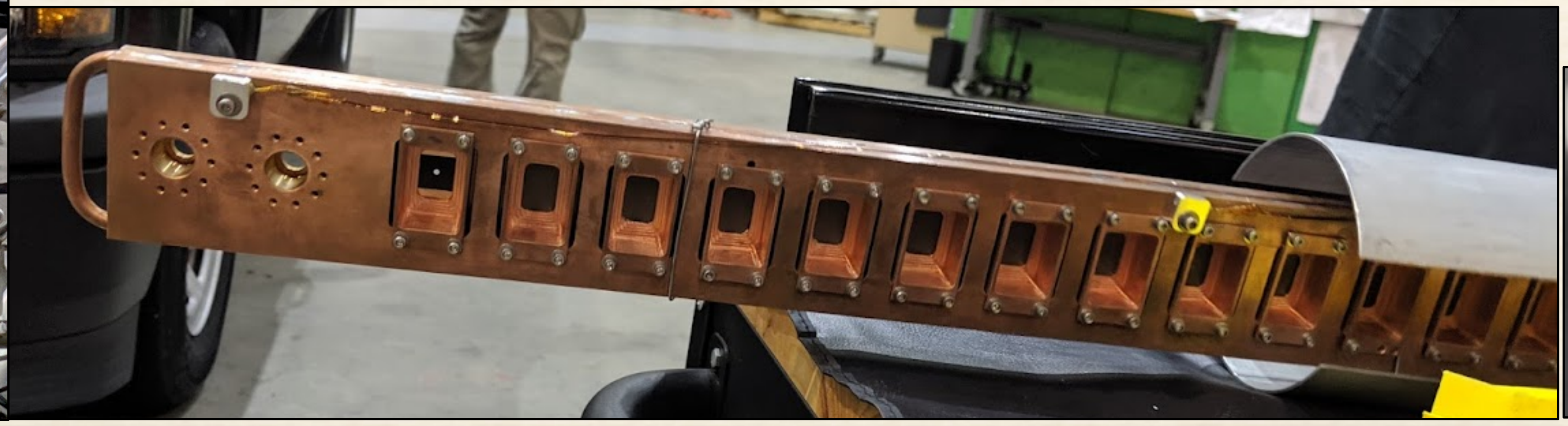
*Oak Ridge

- 1puck+2 foils sandwiched
- ~5.7mm thick total
- ~91.7% ^{48}Ca
- ~7.96% ^{40}Ca

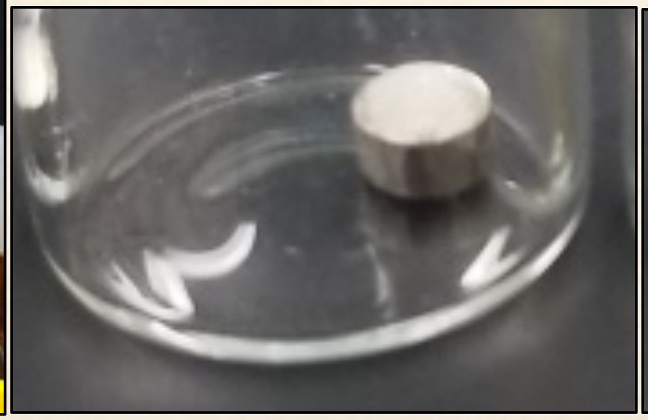
Stored in mineral oil until installed
Protected against oxidation

Delicate Installation

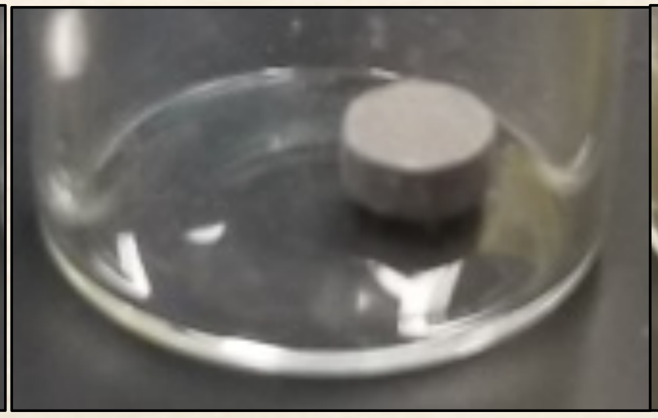
Cooled Copper Target Ladder



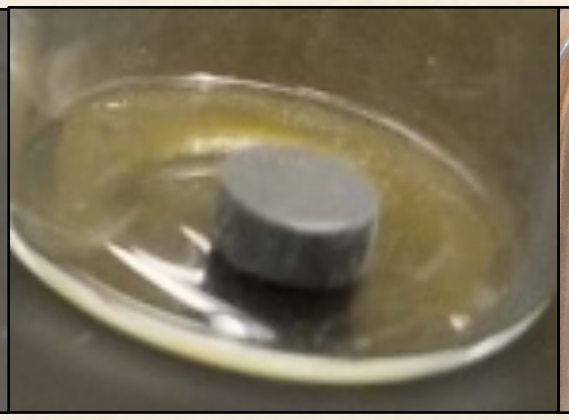
sanded



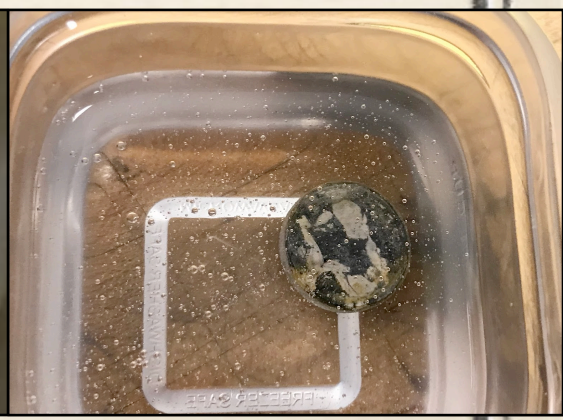
Oxidized 1hr



Oxidized 24hr



mineral oil



The CREX Physics Runs

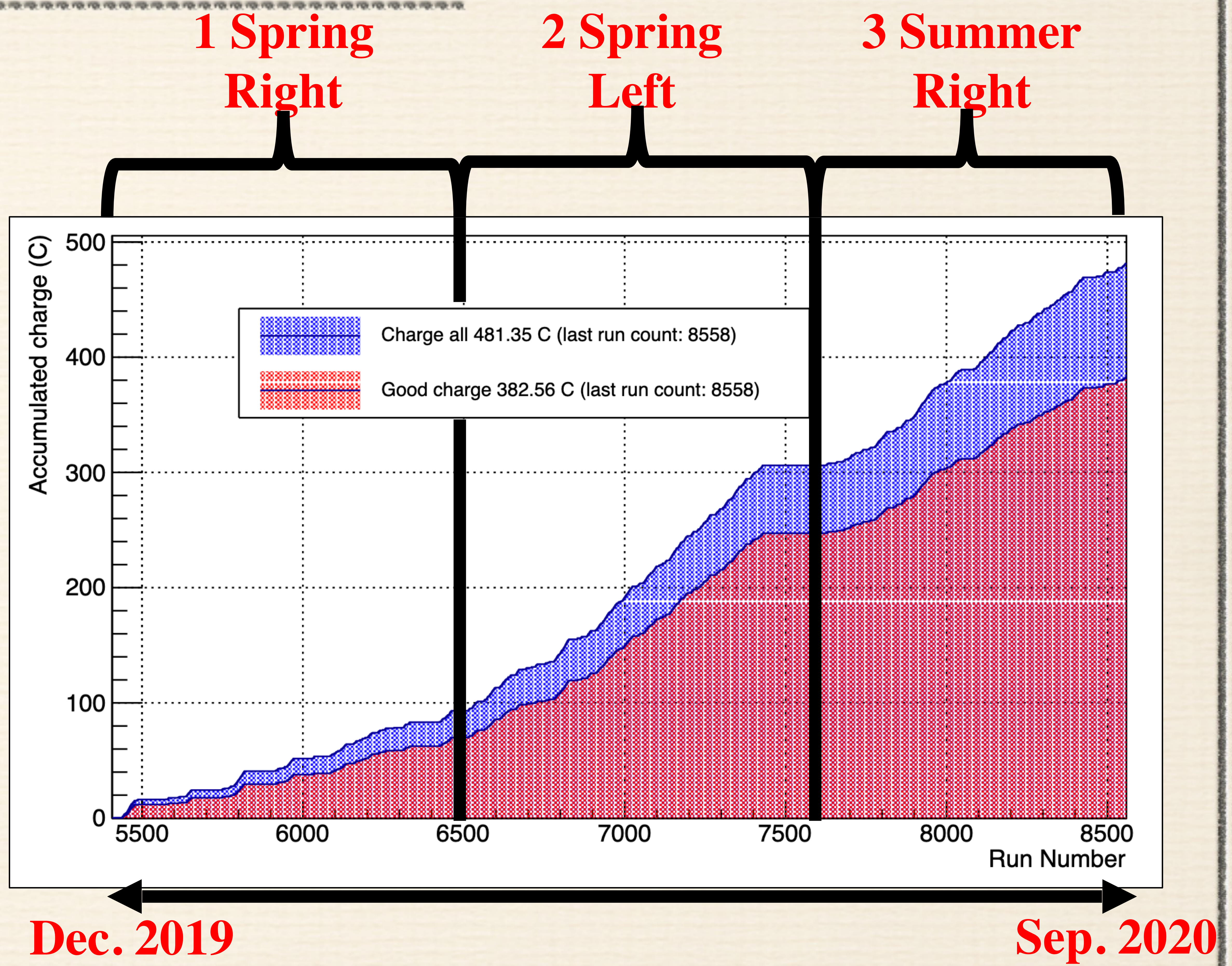
13 Ph.D. students, 7 postdocs, a total of about 80 scientists

Data Divided Into 3 Run Periods

- Part 1) Wien* Right Spring
- Part 2) Wien* Left Spring

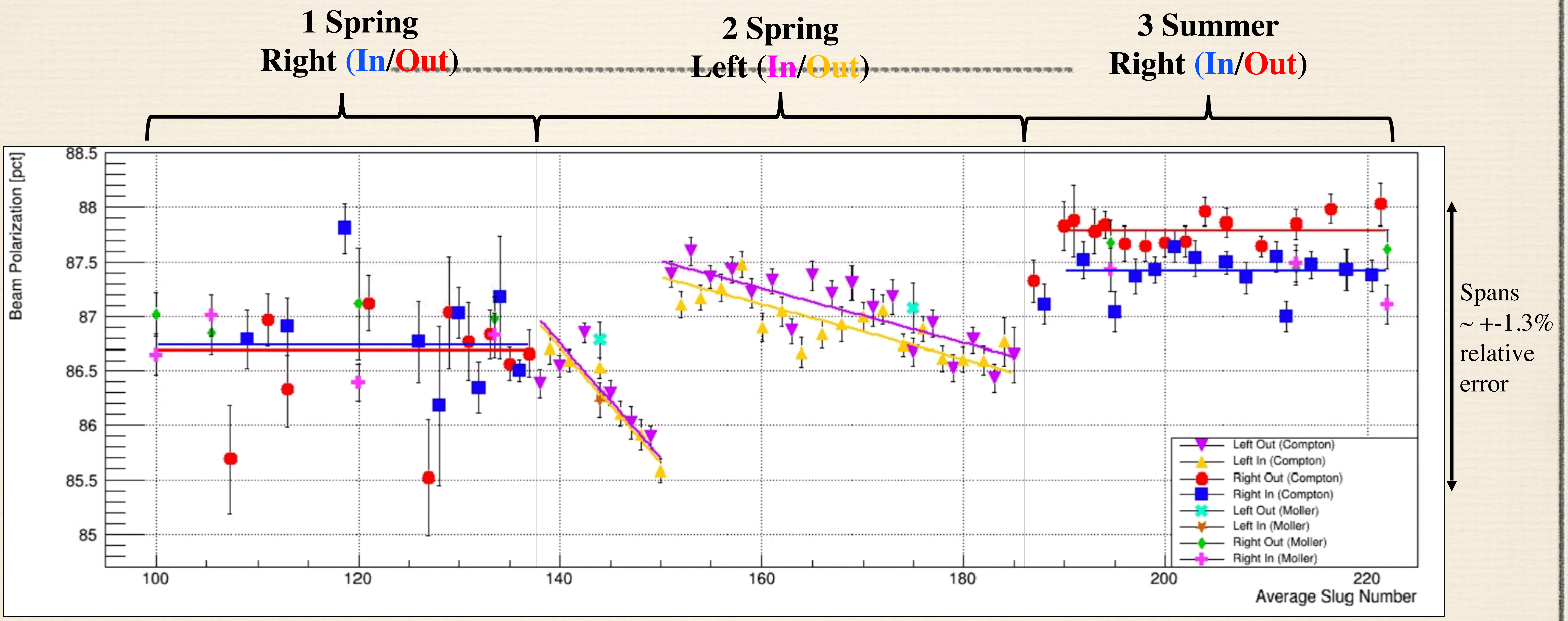
  …Covid hit….
- Part 3) Wien* Right Summer
- * "Wien" = Spin Manipulator

- Very close watch on-line data stream - beam conditions, detector response, etc.
- Frequent contact with MCC operators to maintain running conditions
- "prompt" analysis process flagged more subtle problems
- Daily grooming and review in "WAC" process
- (analysis development leader Paul King)



- **At the end of the experiment after our realtime analysis we collected about 383 C of charge on target which passed online analysis cuts(i.e. not excluded in calibrations or due to poor beam conditions, trip recovery, beam excursions, or beam monitor issues)**

Beam Polarimetry



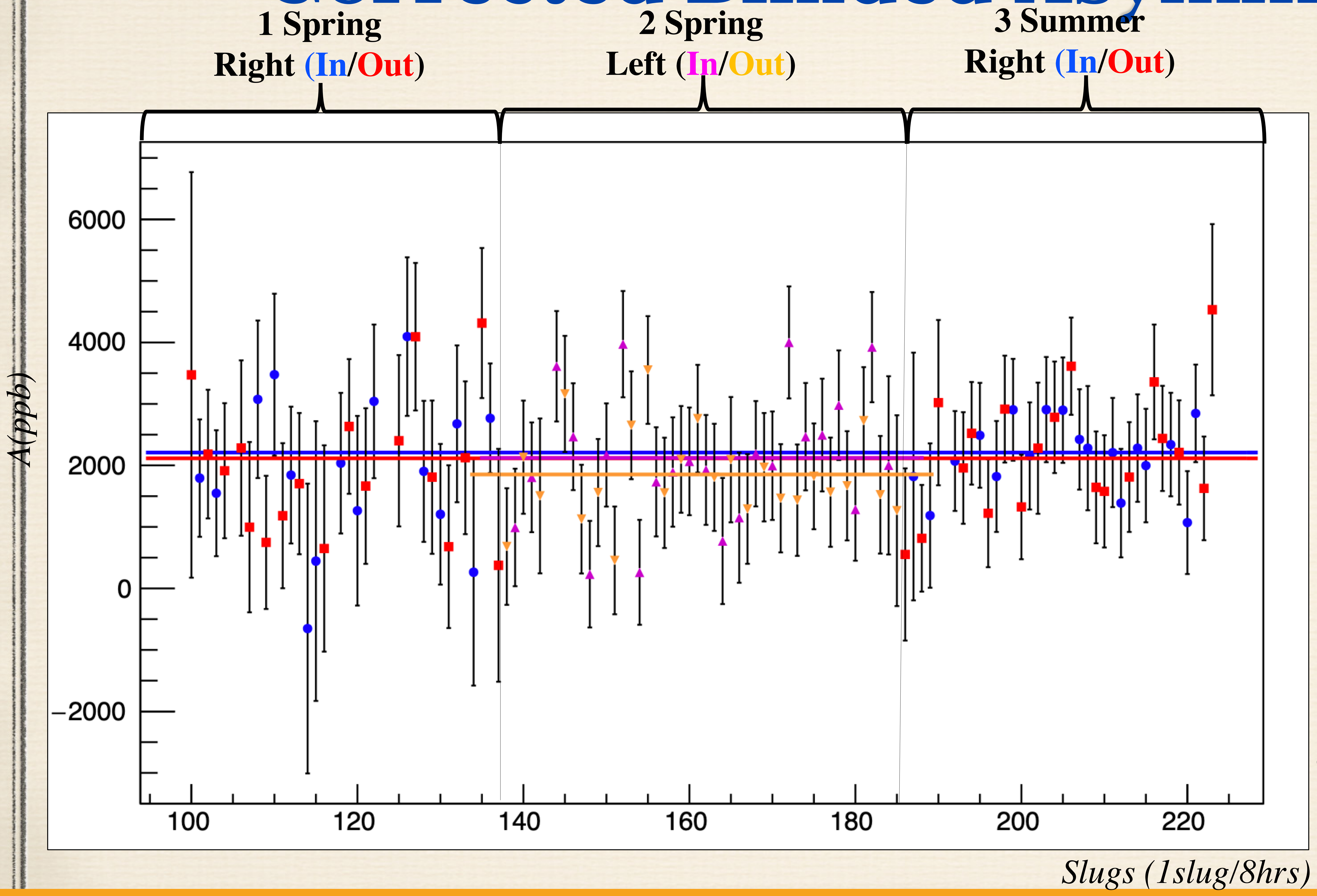
Acknowledgments: A.J. Zec, J. C. Cornejo, M. Dalton, C. Gal, D. Gaskell, C. Palatchi, K. Paschke, A. Premithilake, B. Quinn

Average Compton polarization:
87.10 ± (0.52% dP/P)

CREX Polarimetry Result:
P_e=87.09 +/- (0.44% dP/P)

Average Moller polarization:
87.06 ± (0.85% dP/P)

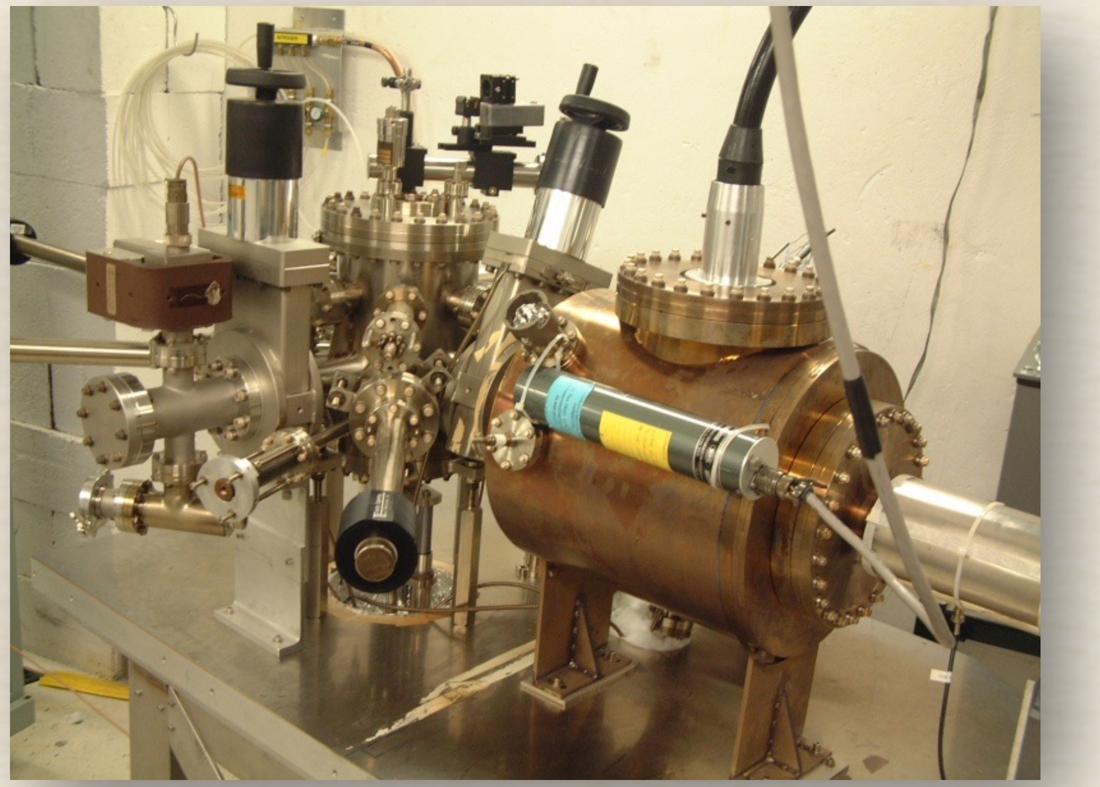
Corrected Blinded Asymmetries



We were looking at the final data set after carefully removing unstable run periods with multiple checks on log books by about the middle of Summer 2021

Statistical Uncertainty: 80 to 90 parts per billion

Stability of Polarized Beam for CREX



Beam helicity is chosen pseudo-randomly at 30 Hz

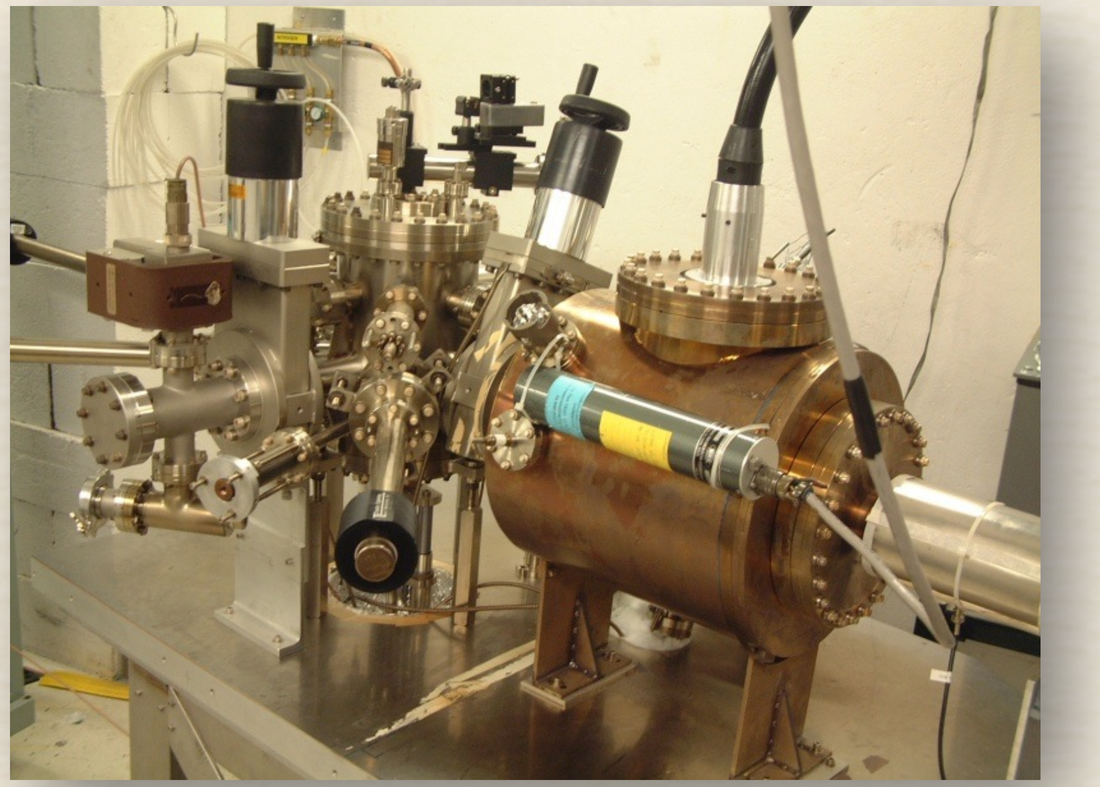
$A_{corr} \sim 2000$ ppb

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

Wien	Weight	X (nm)	Y (nm)	θ X (nrad)	θ Y (nrad)	E dpp
R 1	18.0%	1.6 $\pm$ 3.7	-2.4 $\pm$ 2.0	-0.26 $\pm$ 0.17	-0.11 $\pm$ 0.12	$-2.0 \pm 2.0e^{-9}$
Left	45.2%	-4.1 $\pm$ 1.6	0.3 $\pm$ 1.1	0.08 $\pm$ 0.04	-0.024 $\pm$ 0.10	$0.32 \pm 1.5e^{-9}$
R 2	36.9%	-2.8 $\pm$ 4.1	-0.2 $\pm$ 1.7	-0.06 $\pm$ 0.09	-0.28 $\pm$ 0.17	$0.84 \pm 1.9e^{-9}$
	Avg	-2.6 $\pm$ 1.8	-0.4 $\pm$ 0.9	-0.03 $\pm$ 0.05	-0.13 $\pm$ 0.08	$0.09 \pm 1.0e^{-9}$

- Three independent techniques agree across 3-parts of data set
- For beam correction, decided to use 12 BPM Lagrange Multiplier 3-part eigenvector correction, 5% slope uncertainty
- Left/right symmetric detectors, so correction dominated by E

Stability of Polarized Beam for CREX



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12BPM Eigenvector Lagrange Analysis ($\frac{\delta \mathrm{slope}}{\mathrm{slope}} = 5\%$)			
Monitor	Part 1	Part 2	Part 3
evMon 0 (E)	-482.8	61.8	-0.9
evMon 1 (X)	22.3	3.8	164.0
evMon 2 (Y)	52.2	-7.3	-46.7
evMon 3	65.4	9.1	49.4
evMon 4	9.6	-1.2	4.4
evMon 5	162.9	-10.9	-9.3
evMon 6	-0.1	1.5	2.4
evMon 7	5.4	1.5	-15.4
evMon 8	7.1	-2.1	0.0
evMon 9	-12.4	-3.0	-9.2
evMon 10	-2.0	-1.6	9.3
evMon 11	-7.3	0.2	6.2
Net Corrections	-179.6	51.9	154.4
Local corrections' err	25.9	3.2	9.0
Avg Correction's weight	15.6%	47.5%	36.9%
Avg Correction (ppb)	53.5	5.4	

Wien	Weight	X (nm)	Y (nm)	θ X (nrad)	θ Y (nrad)	E dpp
R 1	18.0%	1.6 ± 3.7	-2.4 ± 2.0	-0.26 ± 0.17	-0.11 ± 0.12	$-2.0 \pm 2.0e^{-9}$
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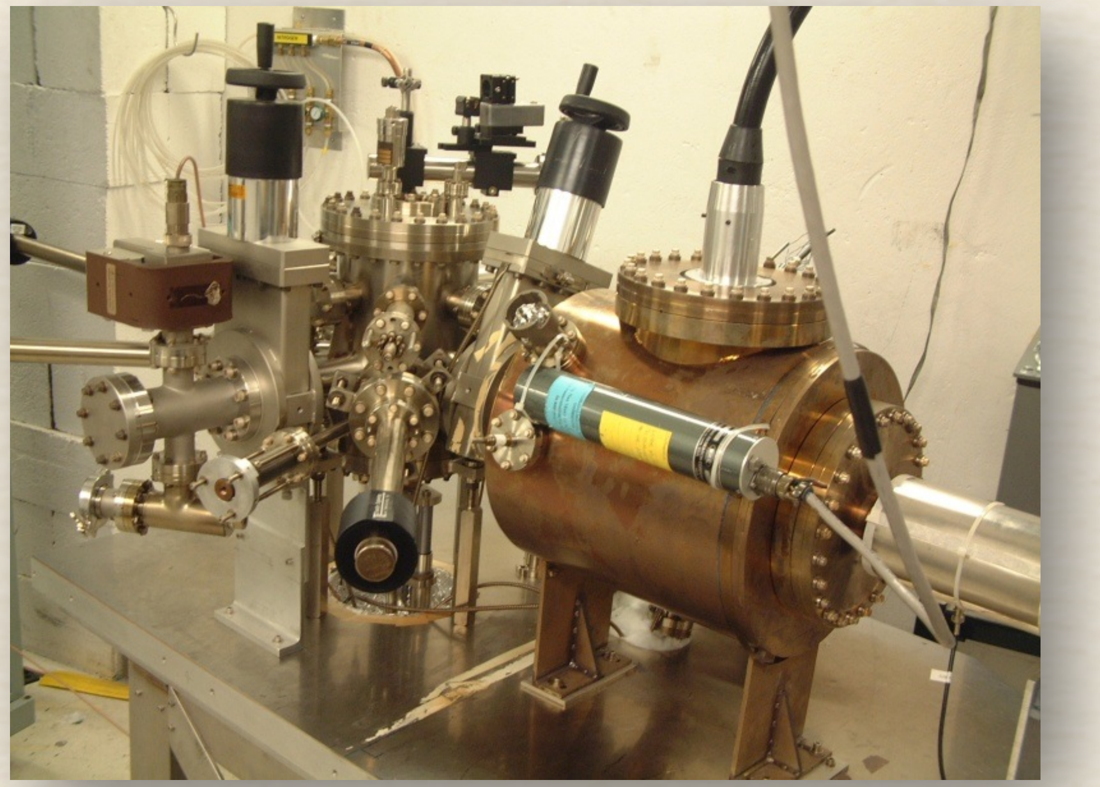

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Left	45.2%	-4.1 $\pm$ 1.6	0.3 $\pm$ 1.1	0.08 $\pm$ 0.04	-0.024 $\pm$ 0.10	$0.32 \pm 1.5e^{-9}$
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evMon 6	-0.1	1.5	2.4
evMon 7	5.4	1.5	-15.4
evMon 8	7.1	-2.1	0.0
evMon 9	-12.4	-3.0	-9.2
evMon 10	-2.0	-1.6	9.3
evMon 11	-7.3	0.2	6.2
Net Corrections	-179.6	51.9	154.4
Local corrections' err	25.9	3.2	9.0
Avg Correction's weight	15.6%	47.5%	36.9%
Avg Correction (ppb)	53.5	5.4	

- Three independent techniques agree across 3-parts of data set
- For beam correction, decided to use 12 BPM Lagrange Multiplier 3-part eigenvector correction, 5% slope uncertainty
- Left/right symmetric detectors, so correction dominated by E

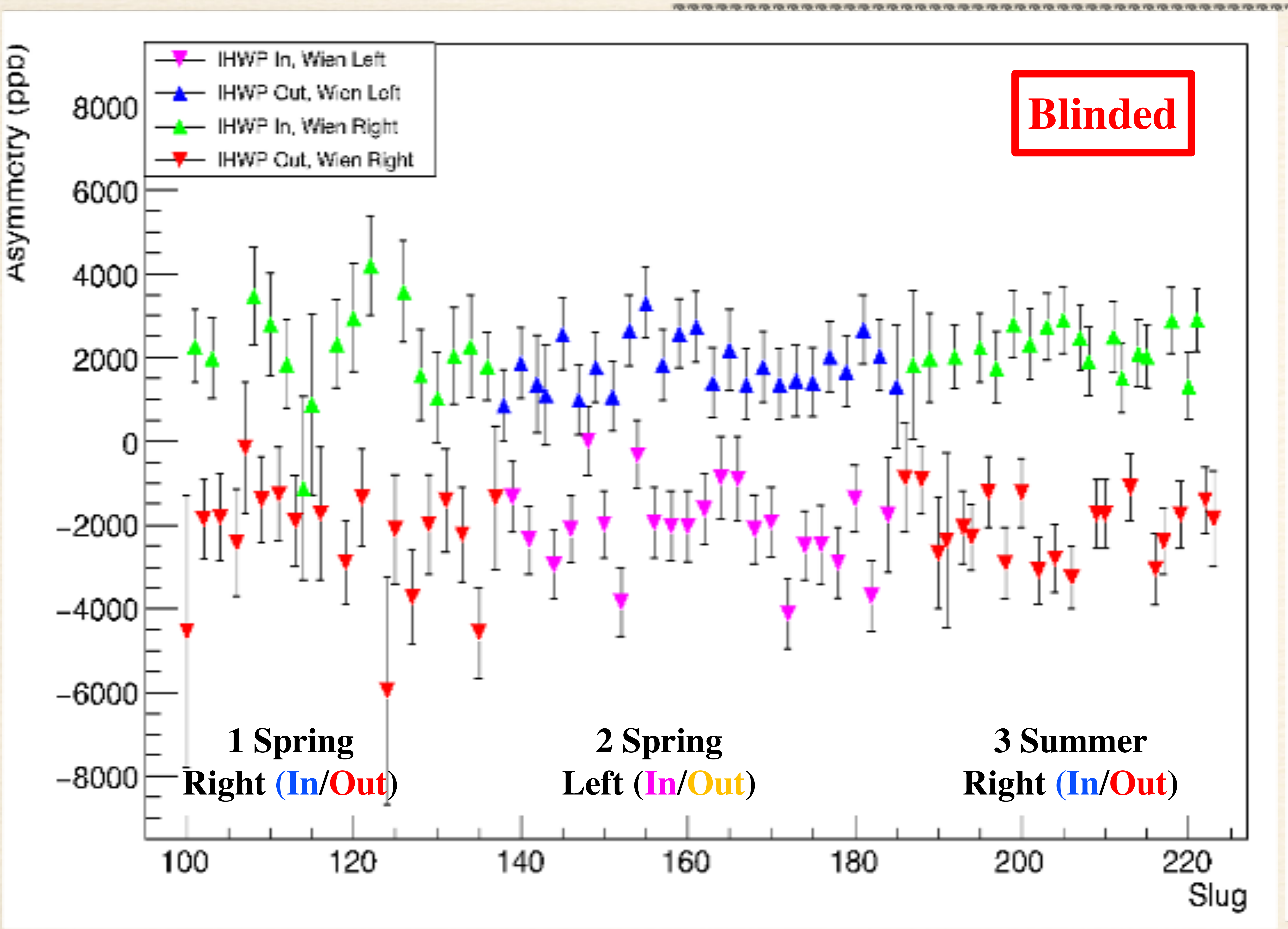
Total beam corrections:

A_{beam}=(53.5 ± 5.4) ppb

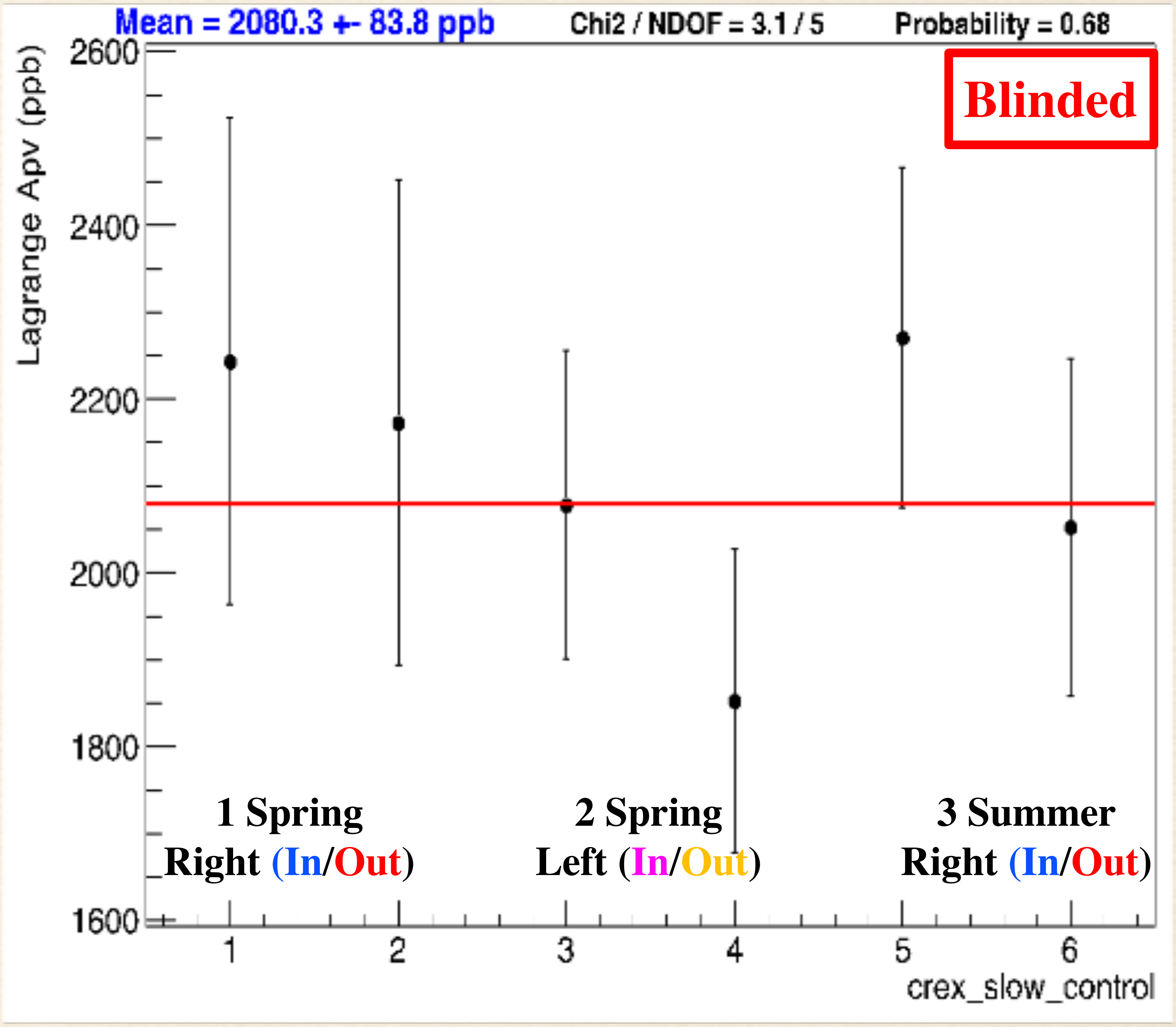
Half Wave Plate: IN/OUT Wien(Spin Manipulator): Left/Right

Demonstration of Systematic Control

Sign-uncorrected, Each point: 8h time-scale



Sign-corrected, Each point: ~1week time-scale



- Entire data set! 6 colors on left correspond to 6 points on the right (zoomed in y-scale)
- Measuring continuously flipping sign by 2 methods (IHWP, Wien)
- The corrected asymmetry removed effects from beam asymmetries and noise

Grand Corrected Asymmetry

Final result averaging over all IHWP
and 3 Part Wien flip configurations

C. Clarke

1 **Right** (**In**/**Out**)
2 **Left** (**In**/**Out**)
3 **Right** (**In**/**Out**)

Wien	Weight	A_{raw} (ppb)	A_{det} (ppb)	A_Q (ppb)
Right 1	17.9%	2460.15 ± 391.95	2207.90 ± 197.69	-94.1 ± 69.6
Left	45.2%	1871.06 ± 278.39	1963.65 ± 124.64	148.1 ± 40.1
Right 2	36.9%	2006.57 ± 335.29	2160.94 ± 137.95	-376.3 ± 38.7
Weighted Average		2026.81 ± 189.88	2080.26 ± 83.77	-88.8 ± 26.2

Blinded Corrected Asymmetry A_{corr}:
2080.3 ± 83.8ppb

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Blinded Corrected Asymmetry A_{corr}:
2080.3 ± 83.8ppb

Careful and painstaking analyses by multiple students on each of the small corrections to extract the physics asymmetry

$$A_{corr} = A_{det} - A_{beam} - A_{trans} - A_{nonlin} - A_{blind}$$

$$A_{phys} = R_{radcorr}\, R_{accept}\, R_{Q^2} \frac{A_{corr} - P_L \sum_i f_i A_i}{P_L(1 - \sum_i f_i)}$$

Grand Corrected Asymmetry

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Unblinding!! Week before Fall DNP Meeting

Blinded A_{PV}:

2334.8 ± 112.4ppb (4.8%)

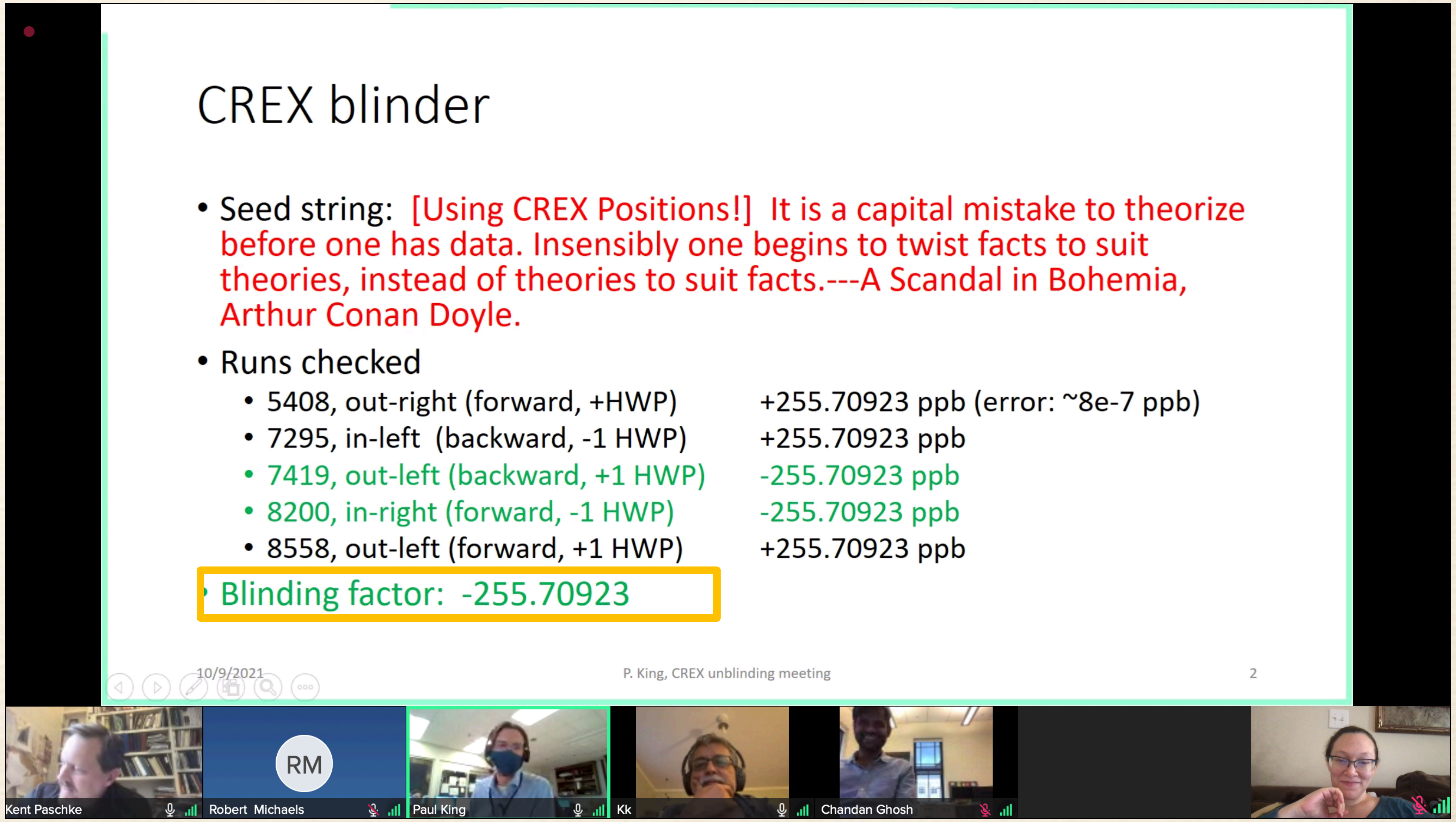
"Blinding box": an additive term on every quartet asymmetry, randomly selected (flat) at the start of the run, from ± 900 ppb

$$A_{phys} = R_{radcorr}\, R_{accept}\, R_{Q^2} \frac{A_{corr} - P_L \sum_i f_i A_i}{P_L (1 - \sum_i f_i)}$$

$$A_{corr} = A_{det} - A_{beam} - A_{trans} - A_{nonlin} - A_{blind}$$

Unblinded A_{PV}:

2658.6 ± 113.2ppb (4.3%)



CREX Result Summary

	A_{PV} uncertainty contribution [ppb]	A_{PV} uncertainty contribution [%]
Polarization	13.1	0.49%
Horizontal Polarization	12.7	0.48%
Vertical Polarization	0.9	0.03%
Acceptance normalization	23.9	0.90%
Beam correction	6.9	0.26%
Non-linear detector response	6.7	0.25%
Ca40 background	3.0	0.10%
Charge correction	1.1	0.04%
Inelastic contamination 2+	18.9	0.71%
Inelastic contamination 3-(1)	10.2	0.38%
Inelastic contamination 3-(2)	3.6	0.13%
Rescattering	0.5	0.02%
Total	**39.6**	**1.5%**

Unblinded Detector Asymmetry A_{corr}:
2336.0 ± 84.8 ppb

$$A_{phys} = R_{radcorr}\, R_{accept}\, R_{Q^2} \frac{A_{corr} - P_L \sum_i f_i A_i}{P_L(1 - \sum_i f_i)}$$

$$A_{corr} = A_{det} - A_{beam} - A_{trans} - A_{nonlin} - A_{blind}$$

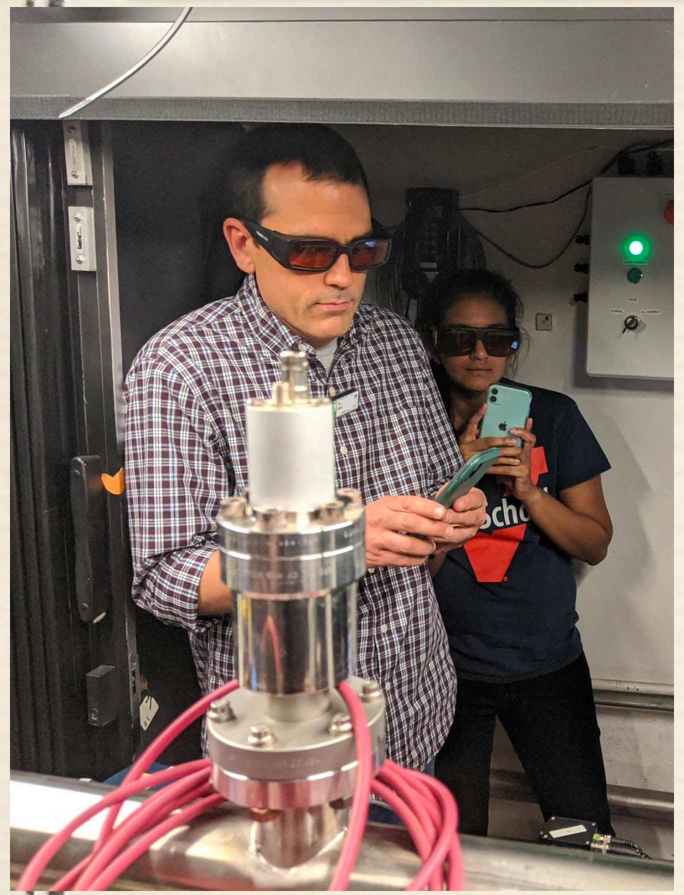
Unblinded A_{PV}:
2668 ± 106 (stat) ± 40 (sys)ppb
[± 113.3 ppb (tot) (4.3%)]

- When taken all into account the experimental systematic uncertainty comes to 1.5%, less than half the 4.0% statistical uncertainty
- Total uncertainty of is 113.3ppb (4.3%)

Our Crew

PhD Student

Students: Devi Adhikari, Devaki Bhatta Pathak, Quinn Campagna, Yufan Chen, Cameron Clarke, Catherine Feldman, Iris Halilovic, Siyu Jian, Eric King, Carrington Metts, Marisa Petrusky, Amali Premathilake, Victoria Owen, Robert Radloff, Sakib Rahman, Ryan Richards, Ezekiel Wertz, Tao Ye, Allison Zec, Weibin Zhang





Post-docs and Run Coordinators: Rakitha Beminiwattha, Juan Carlos Cornejo, Mark-Macrae Dalton, Ciprian Gal, Chandan Ghosh, Donald Jones, Tyler Kutz, Hanjie Liu, Juliette Mammei, Dustin McNulty, Caryn Palatchi, Sanghwa Park, Ye Tian, Jinlong Zhang

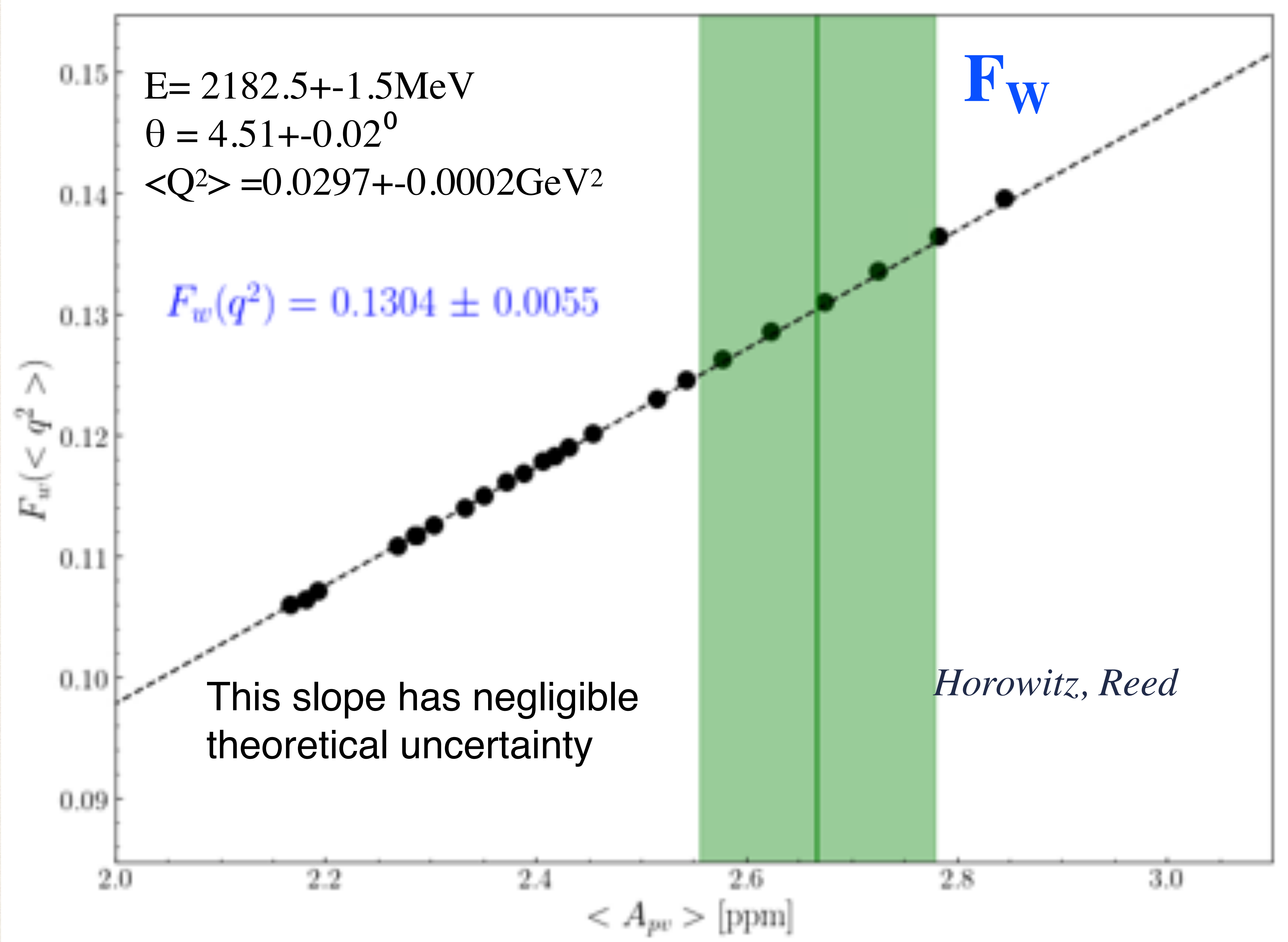
Spokespeople: D. McNulty, J. Mammei, P. Souder, S. Covrig Dusa, R. Michaels, K. Paschke, S. Riordan, K. Kumar

Thanks to the Hall A techs, Machine Control, Yves Roblin, Jay Benesch and other Jefferson Lab staff

Special thanks to: Charles Horowitz and Jorge Piekarewicz for support and insightful conversations
Especially Chuck and grad student Brendan Reed who have worked to help us interpret our results

PREX/CREX
Implications and Outlook

Main Derived Parameter: The Weak Form Factor at $Q^2 = 0.0297$ GeV^2



F_W: 0.1304 ± 0.0055

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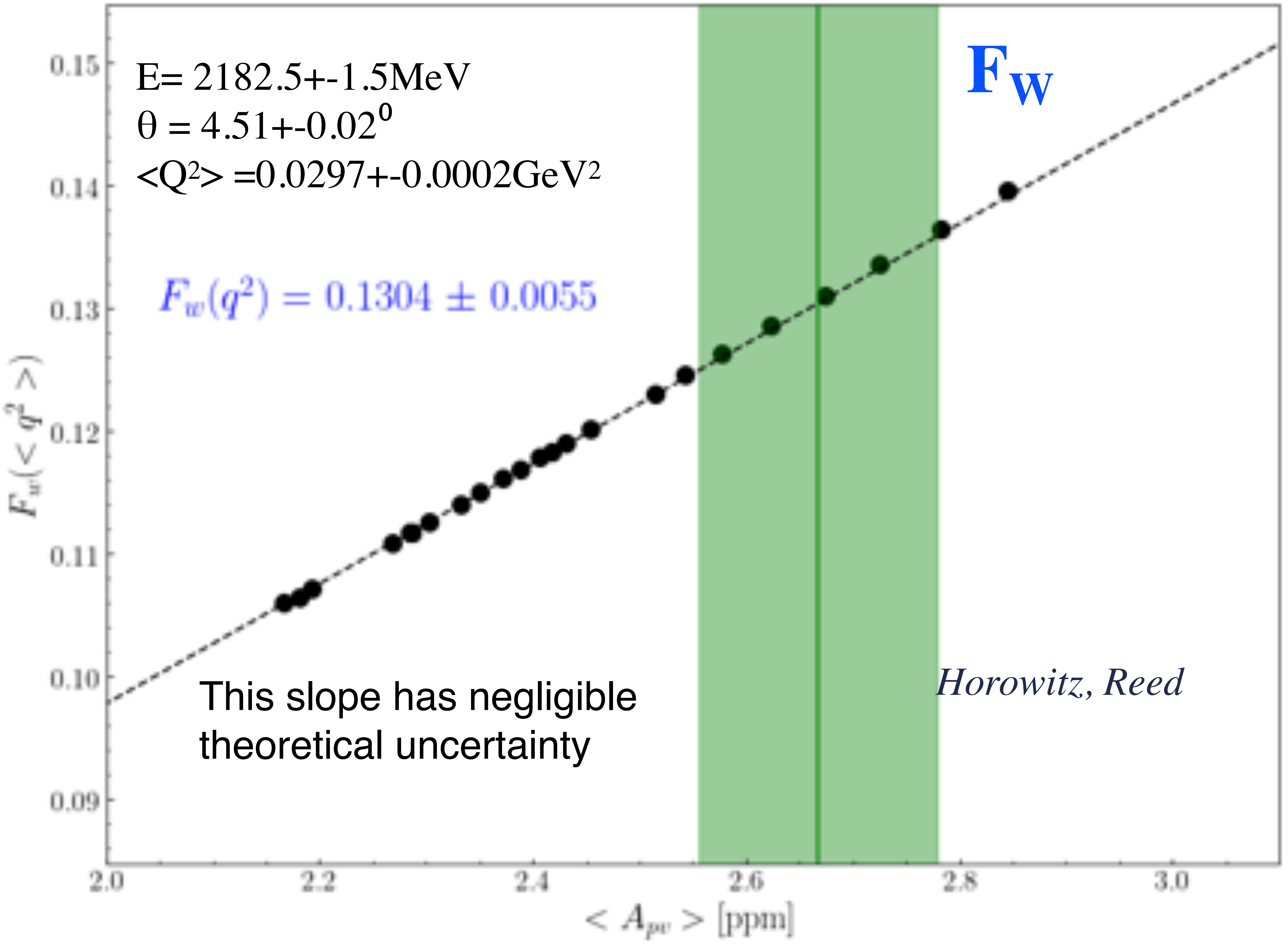

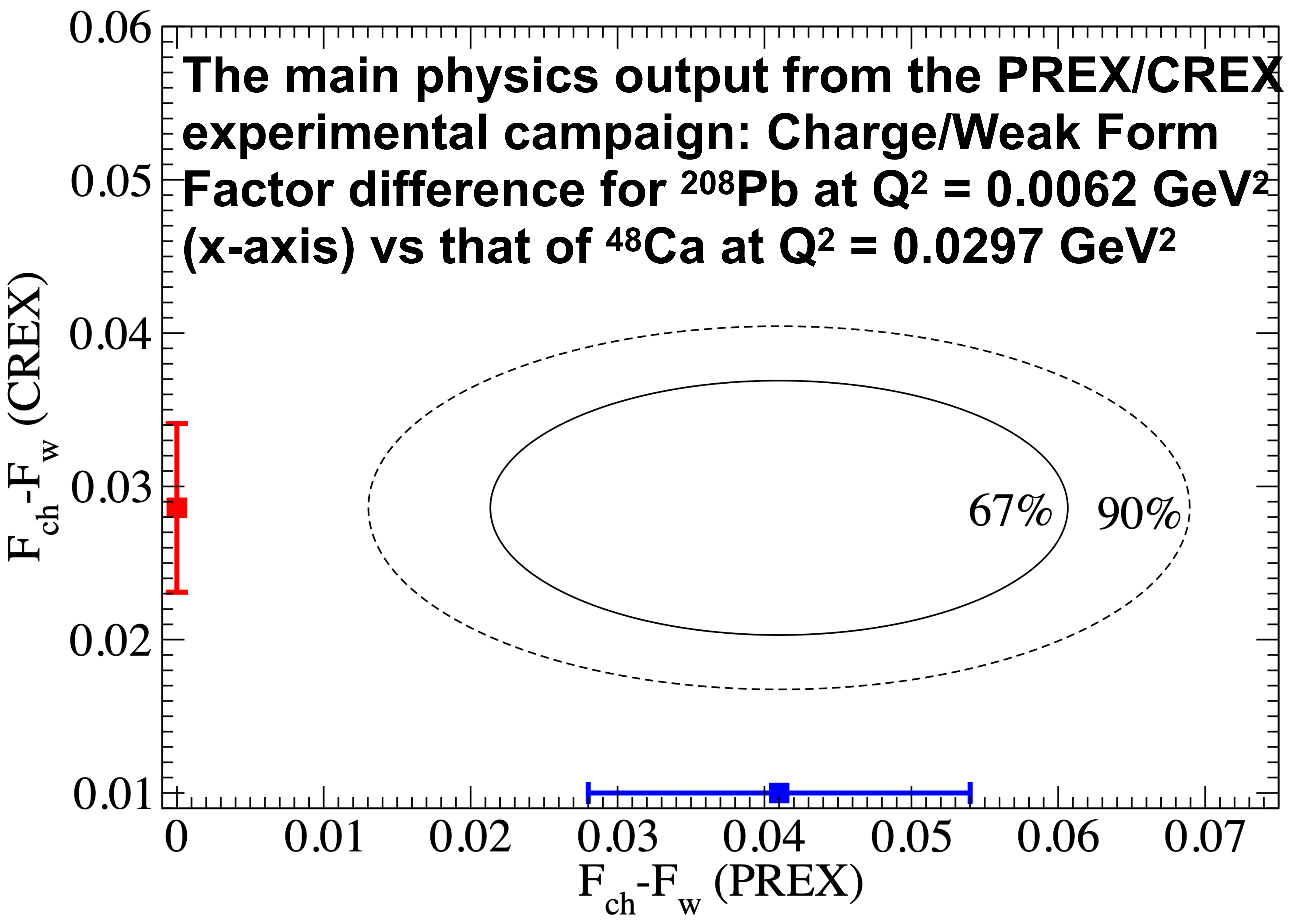

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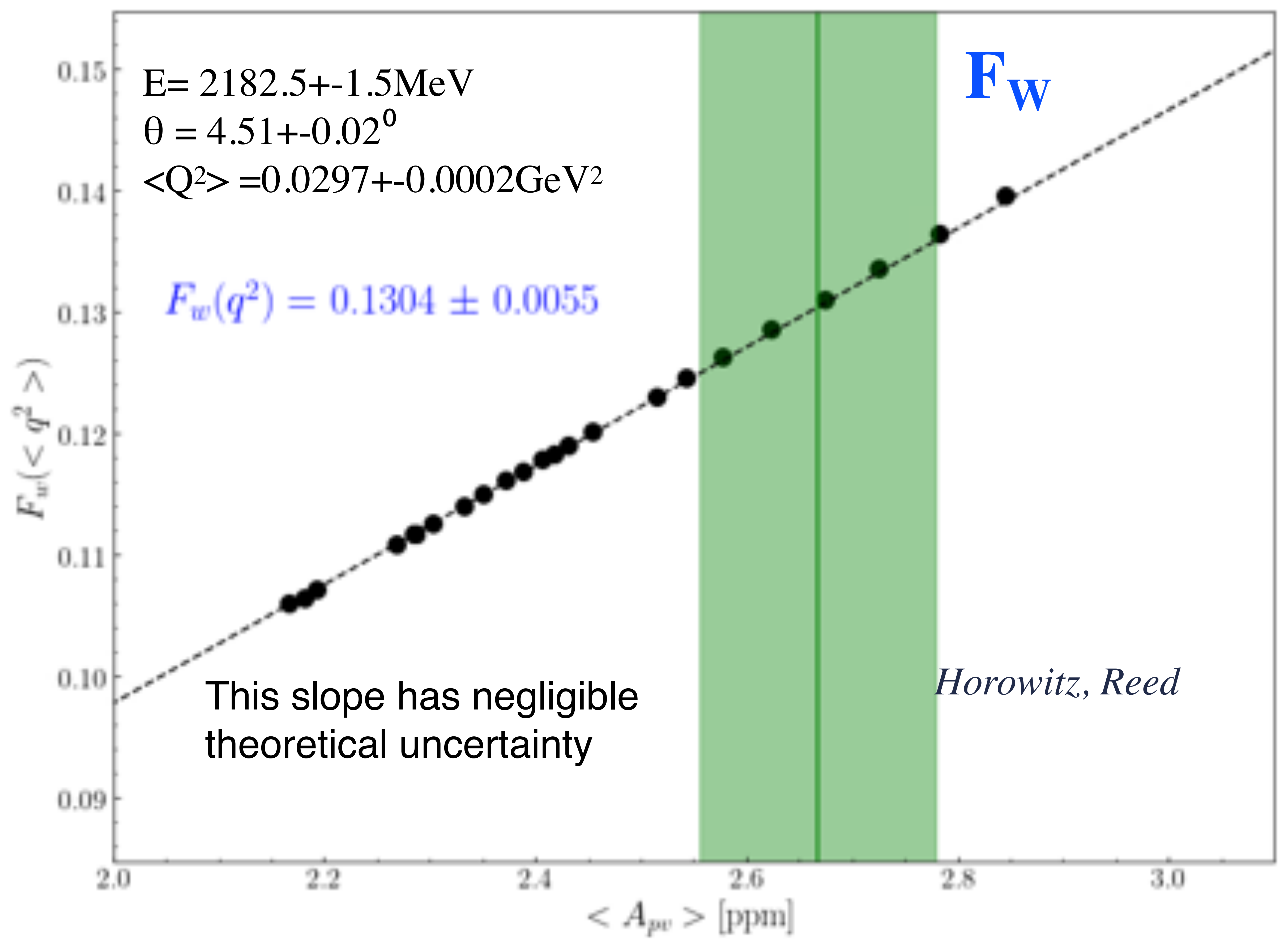

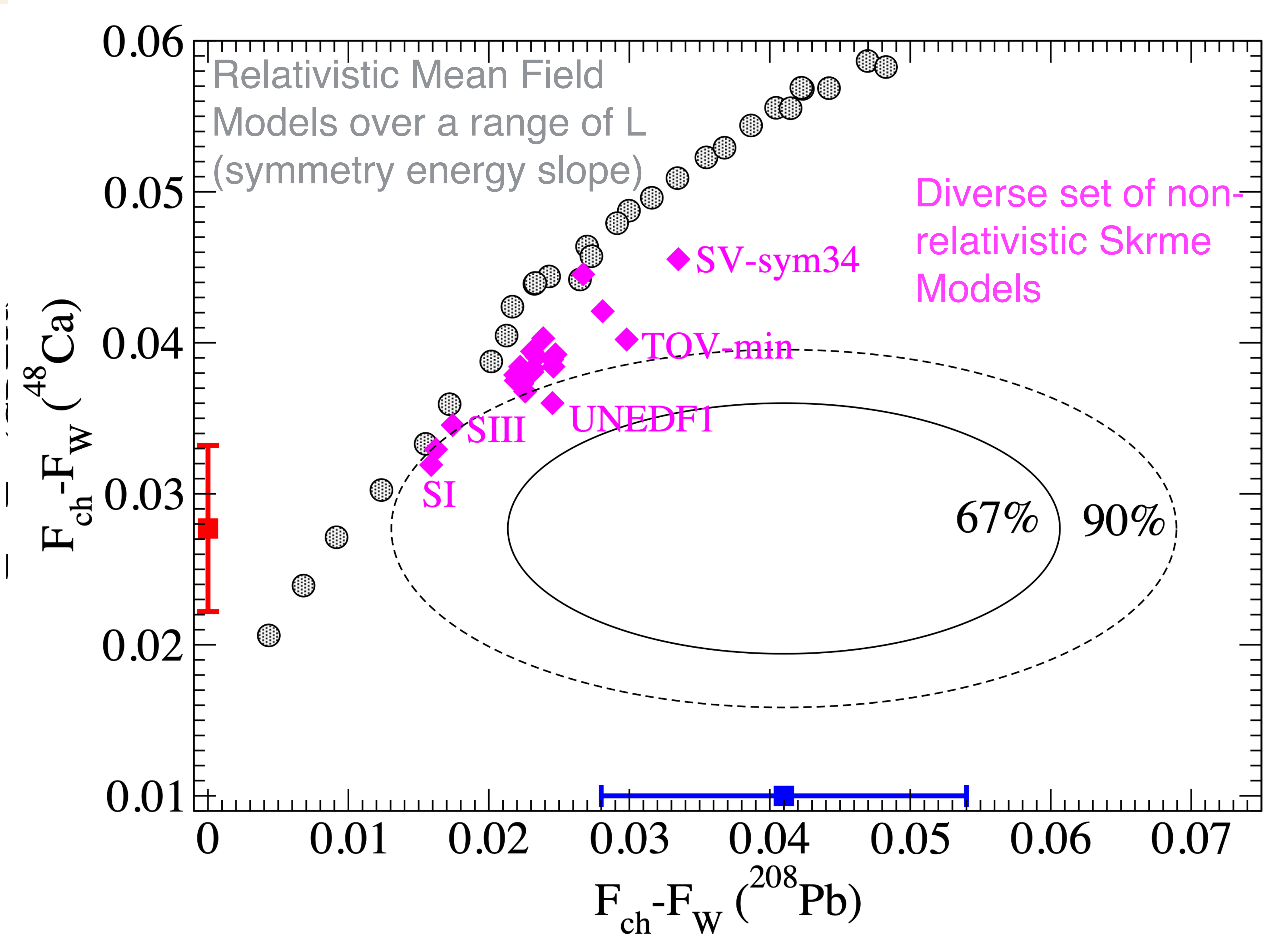

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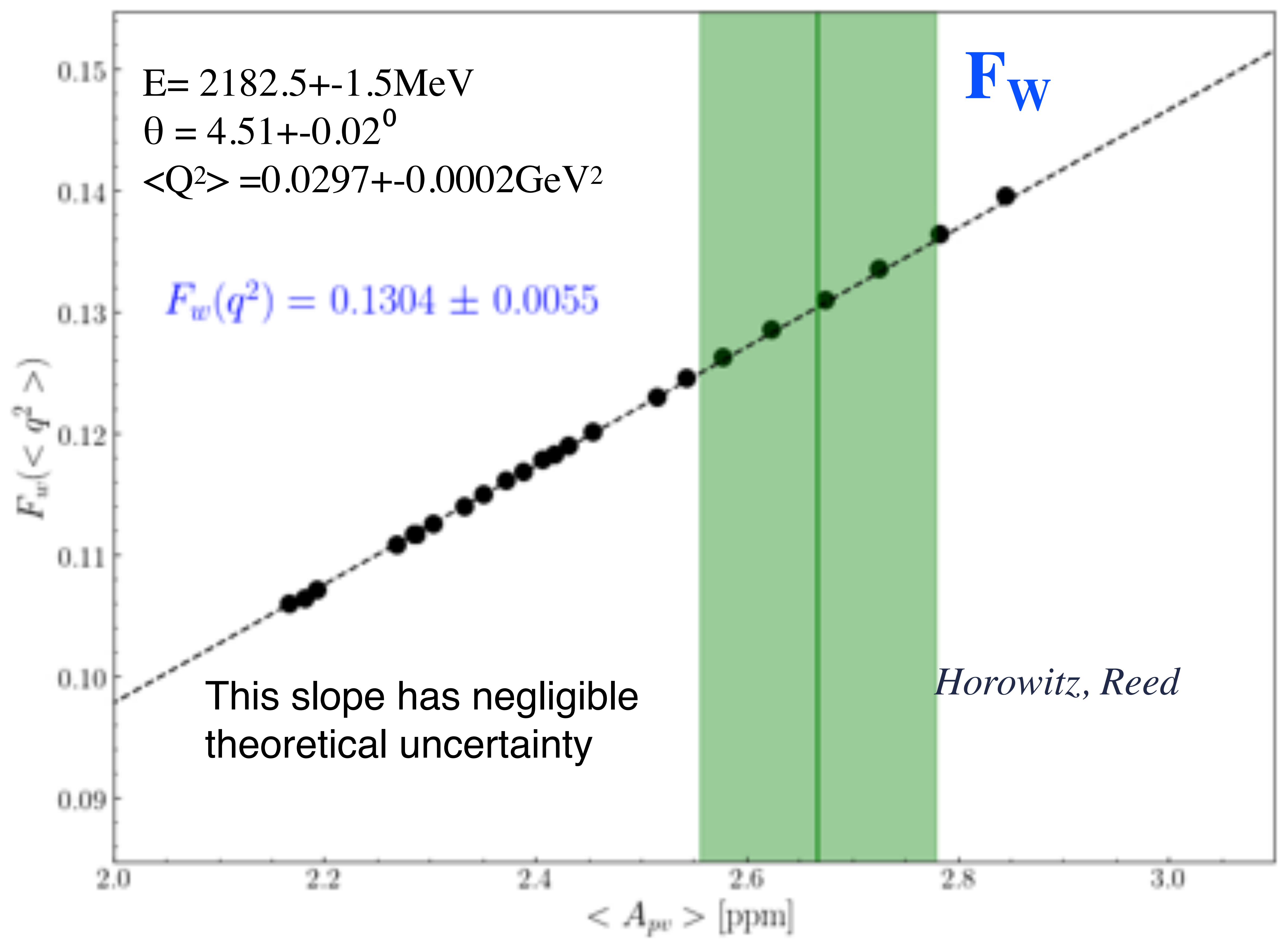
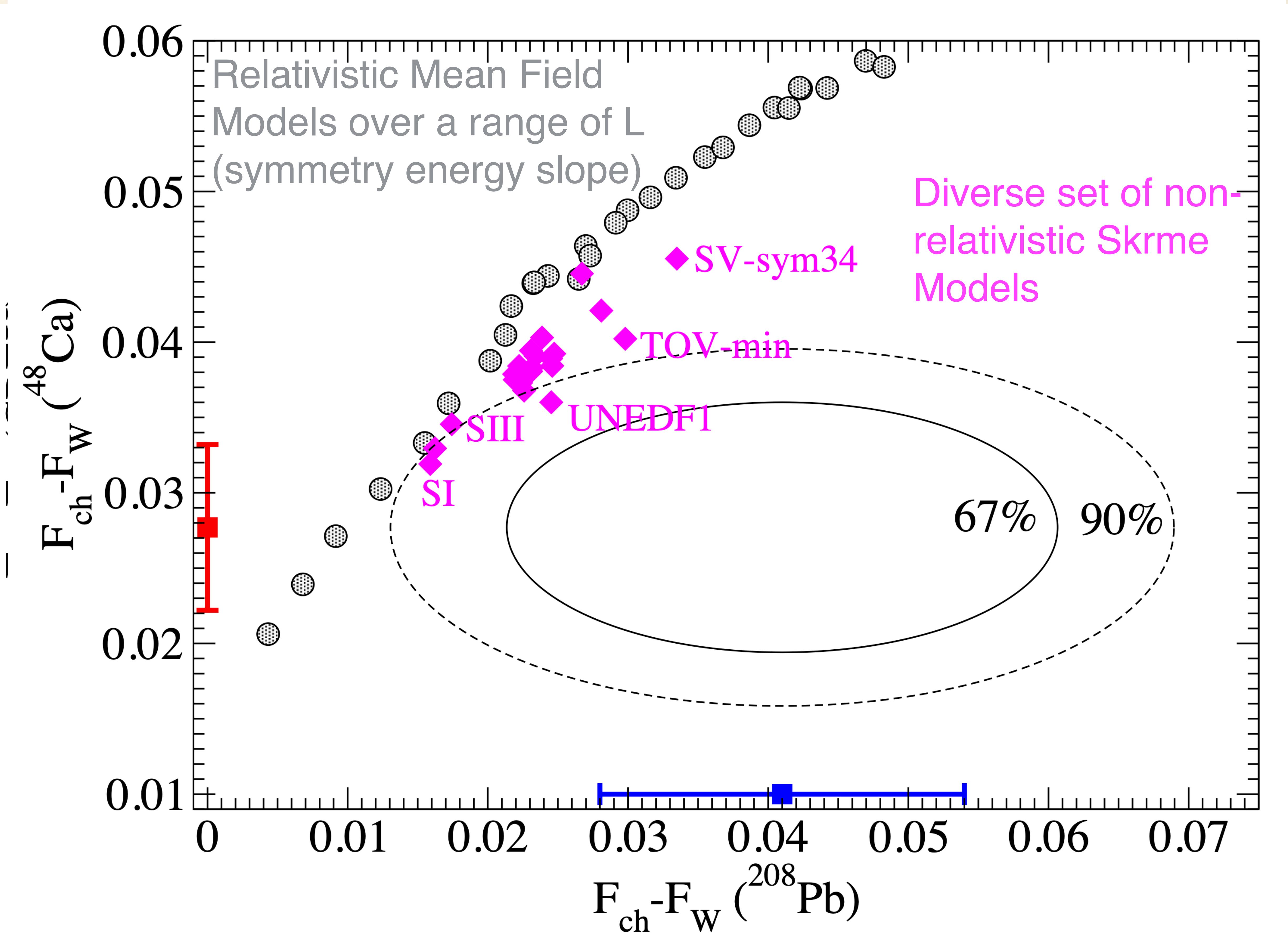
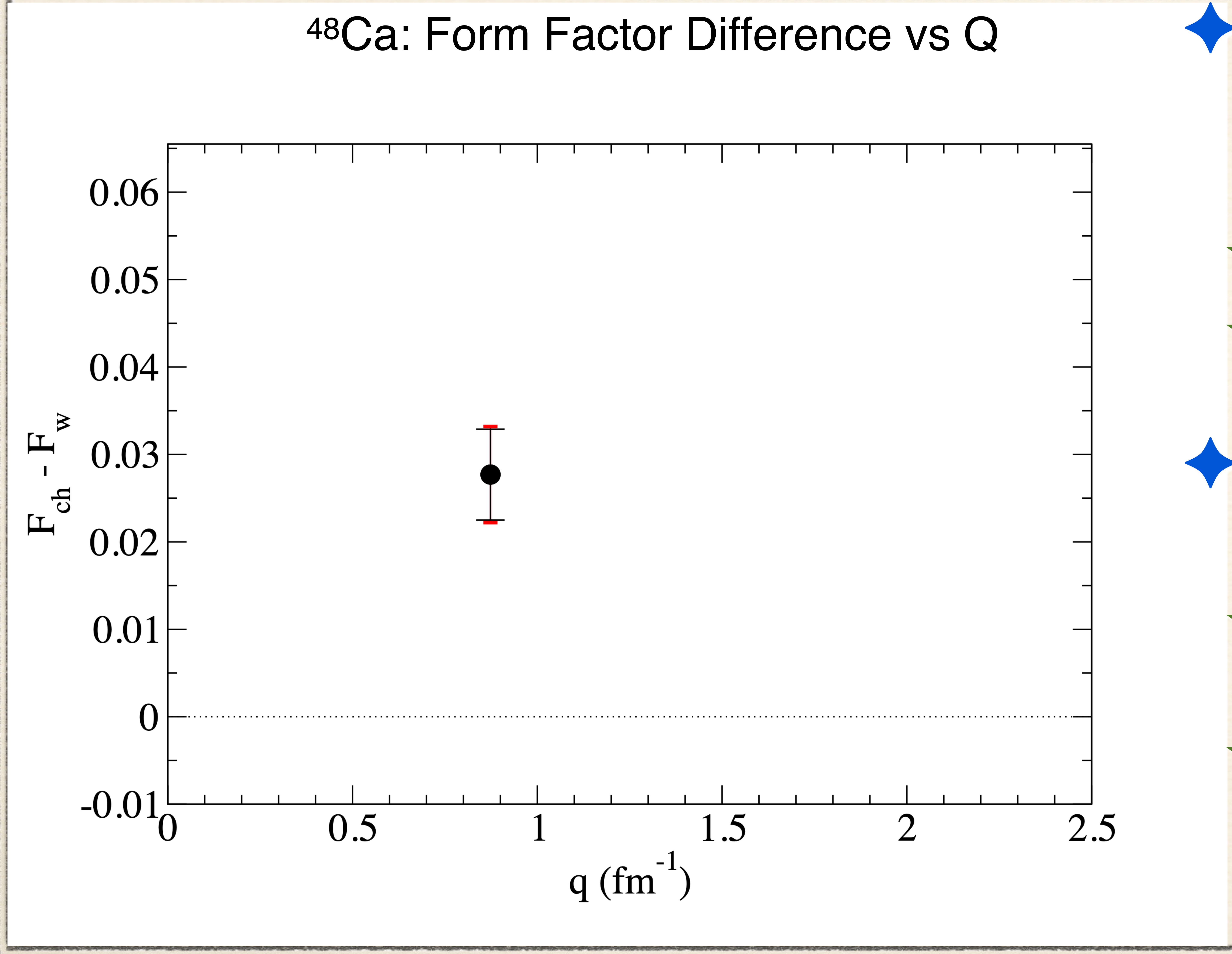




F_W: 0.1304 ± 0.0055

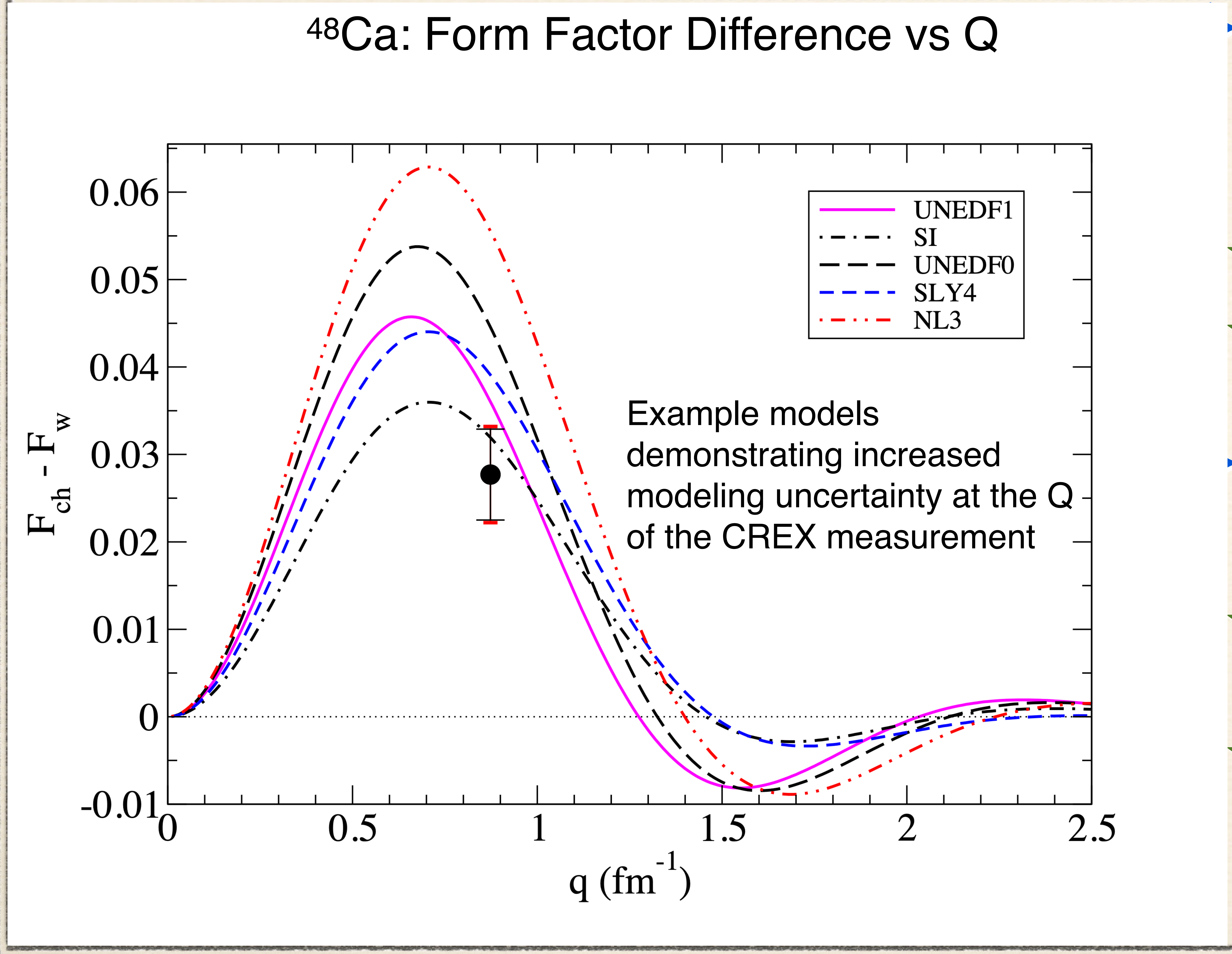
Observation:
CREX result is consistent with a thin neutron skin prediction (e.g. coupled cluster calculations) and is strongly inconsistent with predictions of a very thick skin

CREX Result Discussion and Plans



- **Publication on final CREX results just approved by collaboration TODAY**
  - A_{PV} and Weak Form Factor
  - Neutron Skin Thickness with an uncertainty of ~ +/- 0.035 fm
- **Community Discussion of Implications Beginning**
  - Interplay between ^{208}Pb and ^{48}Ca underscores rich dynamics
  - Full implications for symmetry energy slope L will require continued collaboration between various theoretical and experimental groups

CREX Result Discussion and Plans



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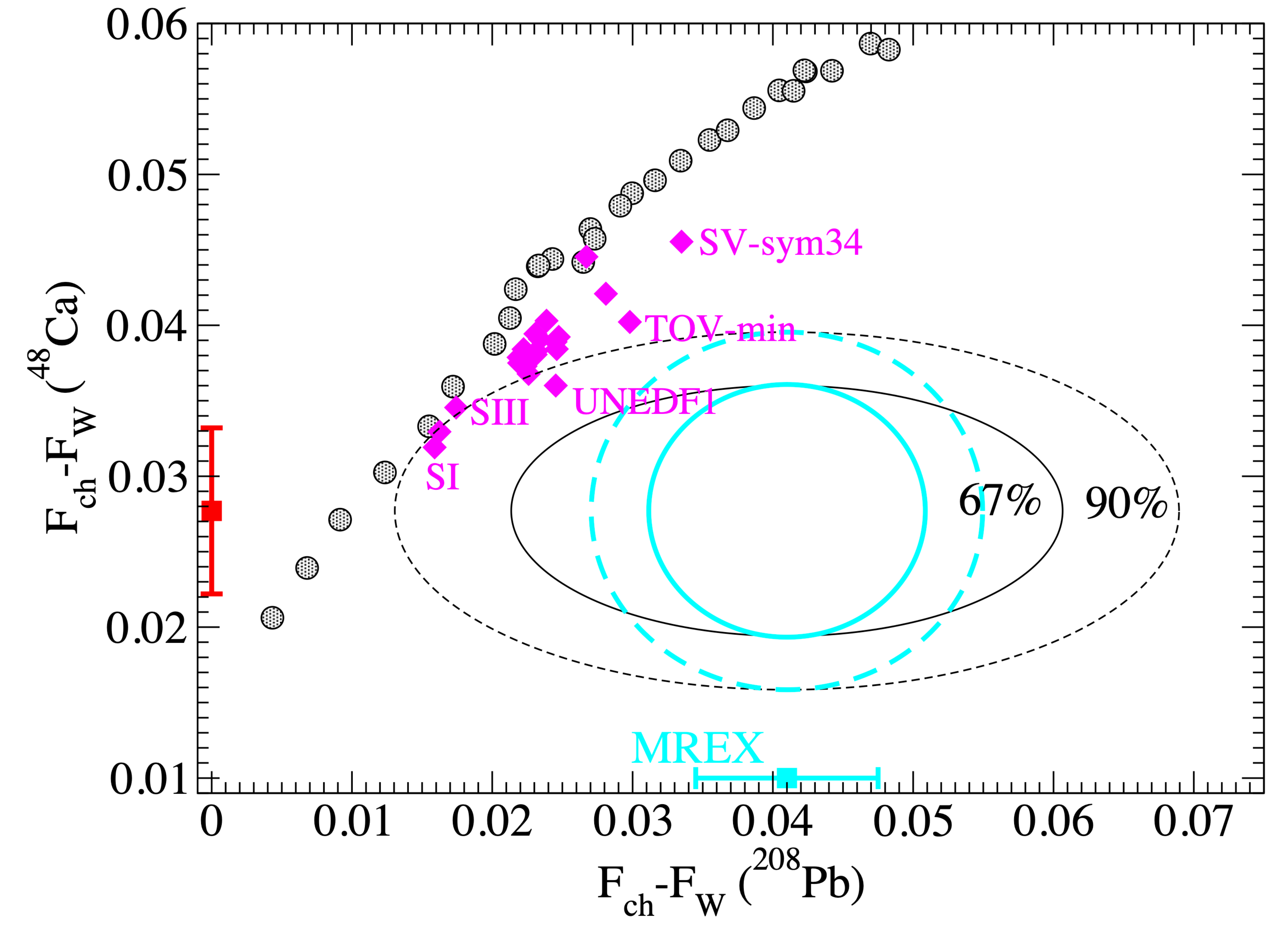
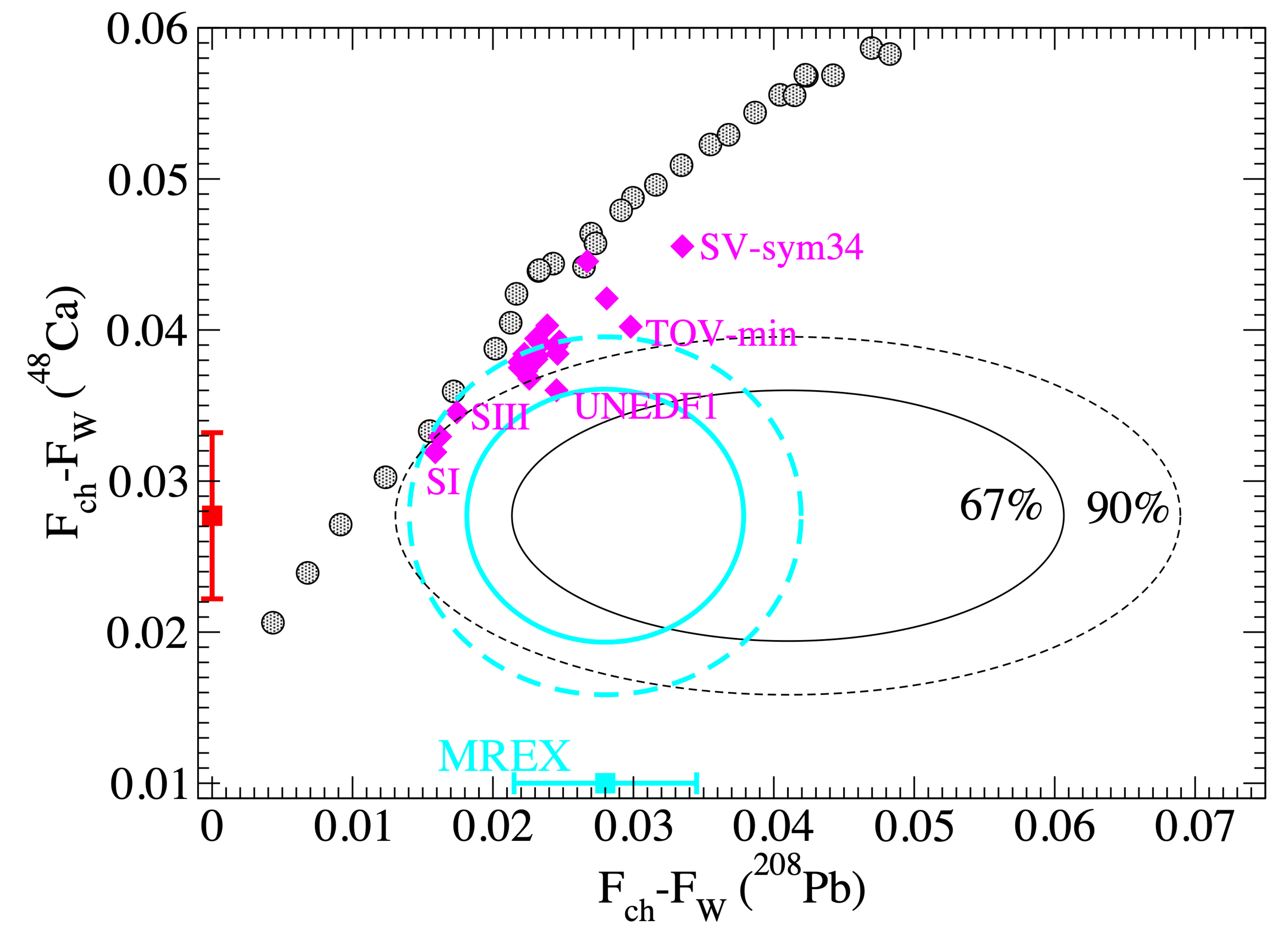
Outlook from PREX & CREX Campaigns

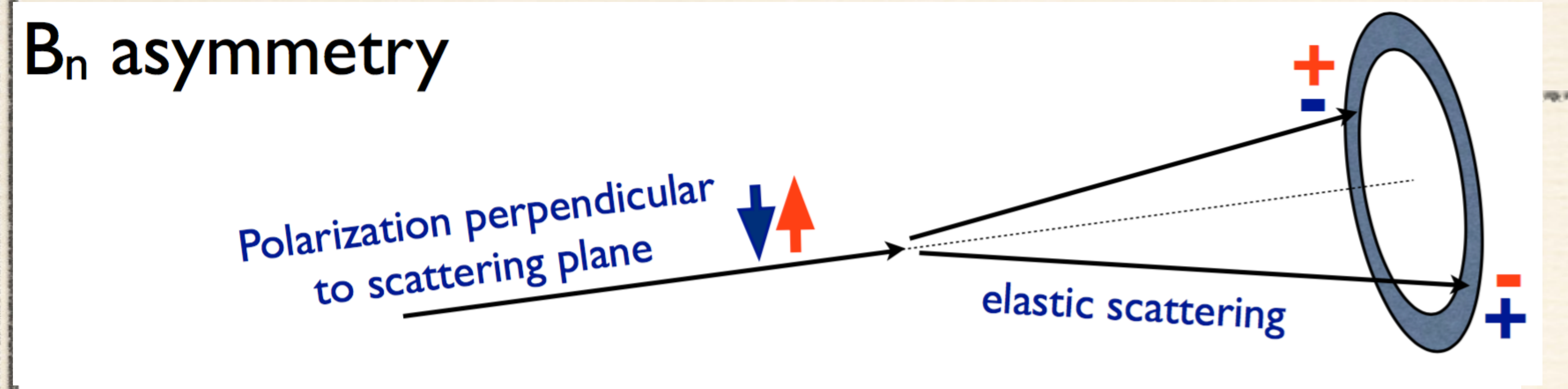
- **The PREX measurement of the neutron skin thickness of ^{208}Pb has very little model uncertainty**
  - ★ There is a clear and transparent line from the statistical uncertainty in the experimental observable (A_{PV}) to the uncertainty in the neutron skin thickness and then on to slope of the symmetry energy: unique among all measurement techniques!
  - ★ Given the above, improved A_{PV} uncertainty is desirable; MREX at Mainz, targeting an uncertainty of +/- 0.04 fm, has become extremely compelling
- **The CREX measurement is the final statement from JLab for ^{48}Ca**
  - ★ Before extracting information on slope of the symmetry energy, the community must collaborate to carefully evaluate modeling uncertainties
  - ★ Along with new NSCL and FRIB measurements on a range of nuclei of similar A, reliable neutron skin estimates could be made across the Periodic Table
  - ★ If found compelling, it might be feasible to devise a new A_{PV} measurement on ^{48}Ca at a different Q value at Mainz

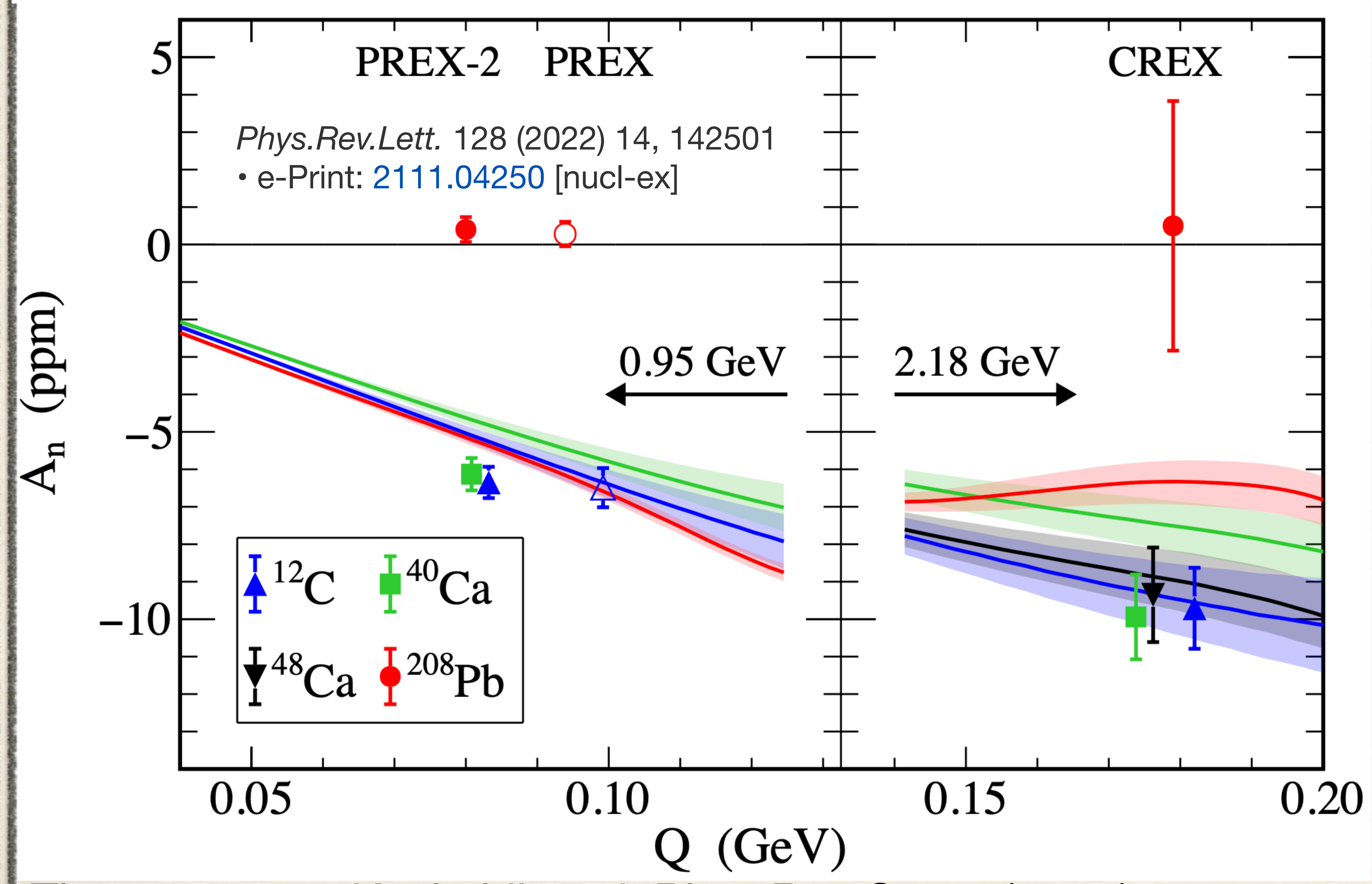
Potential MREX Impact



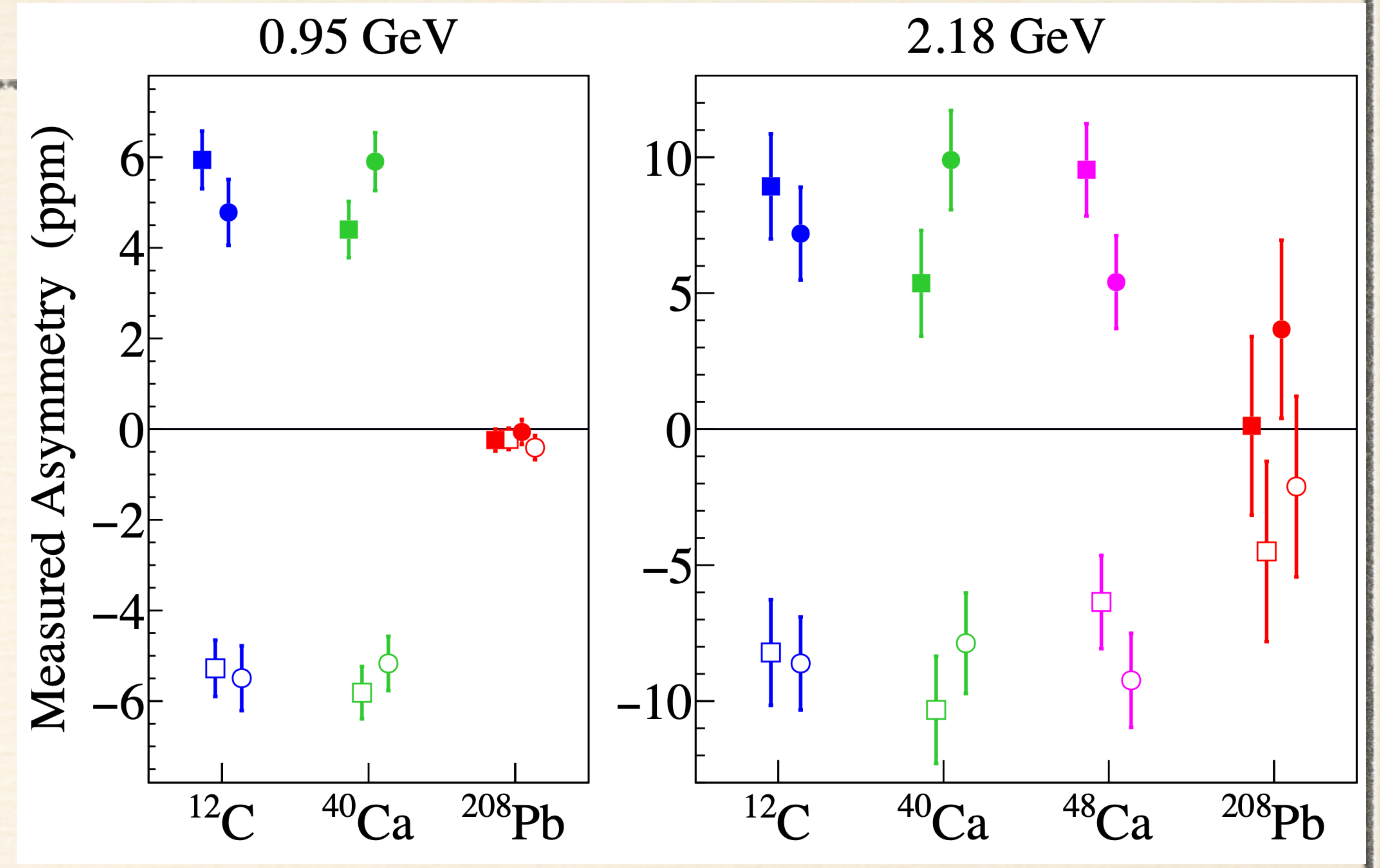


JLab Hall A B_n Measurements on Nuclei



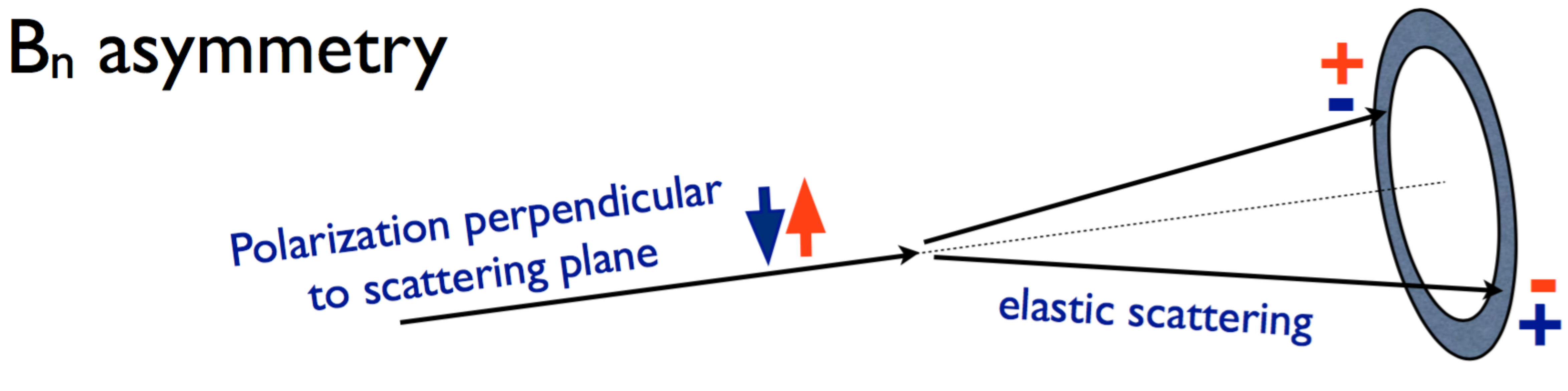


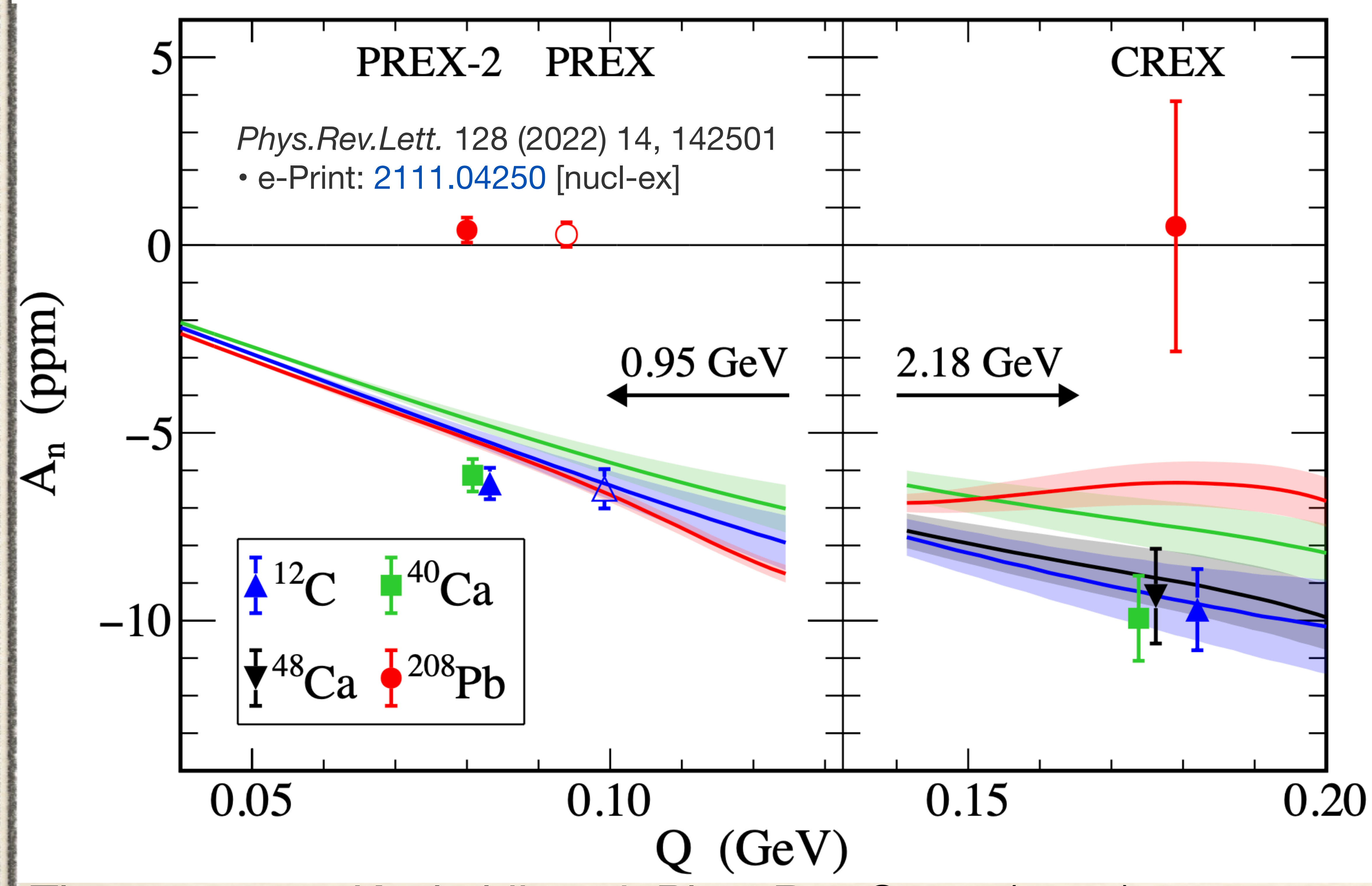
Theory curves: Koshchii et al: Phys.Rev.C 103 (2021) 6, 064316
• e-Print: 2102.11809 • DOI: 10.1103/PhysRevC.103.064316



- ✦ **High Beam Energy**
- ✦ **Very Forward Angle**
- ✦ **Clean Separation of Inelastics**
- ✦ **Tremendous Statistics**

JLab Hall A B_n Measurements on Nuclei





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E_{beam} (GeV)	Target	A_n (ppm)	$A_{avg}^{Z\leq 20}$ (ppm)	$\frac{A_n - A_{avg}^{Z\leq 20}}{\text{uncert}}$
0.95	^{12}C	-6.3 ± 0.4	-6.2 ± 0.2	
0.95	^{40}Ca	-6.1 ± 0.3		
0.95	^{208}Pb	0.4 ± 0.2		$21\ \sigma$
2.18	^{12}C	-9.7 ± 1.1	-9.7 ± 0.6	
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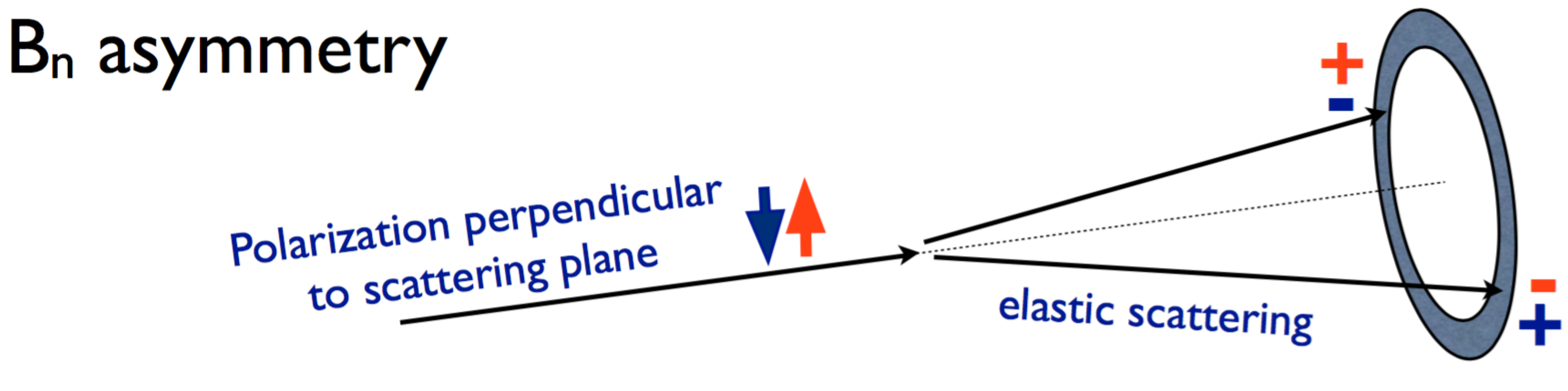

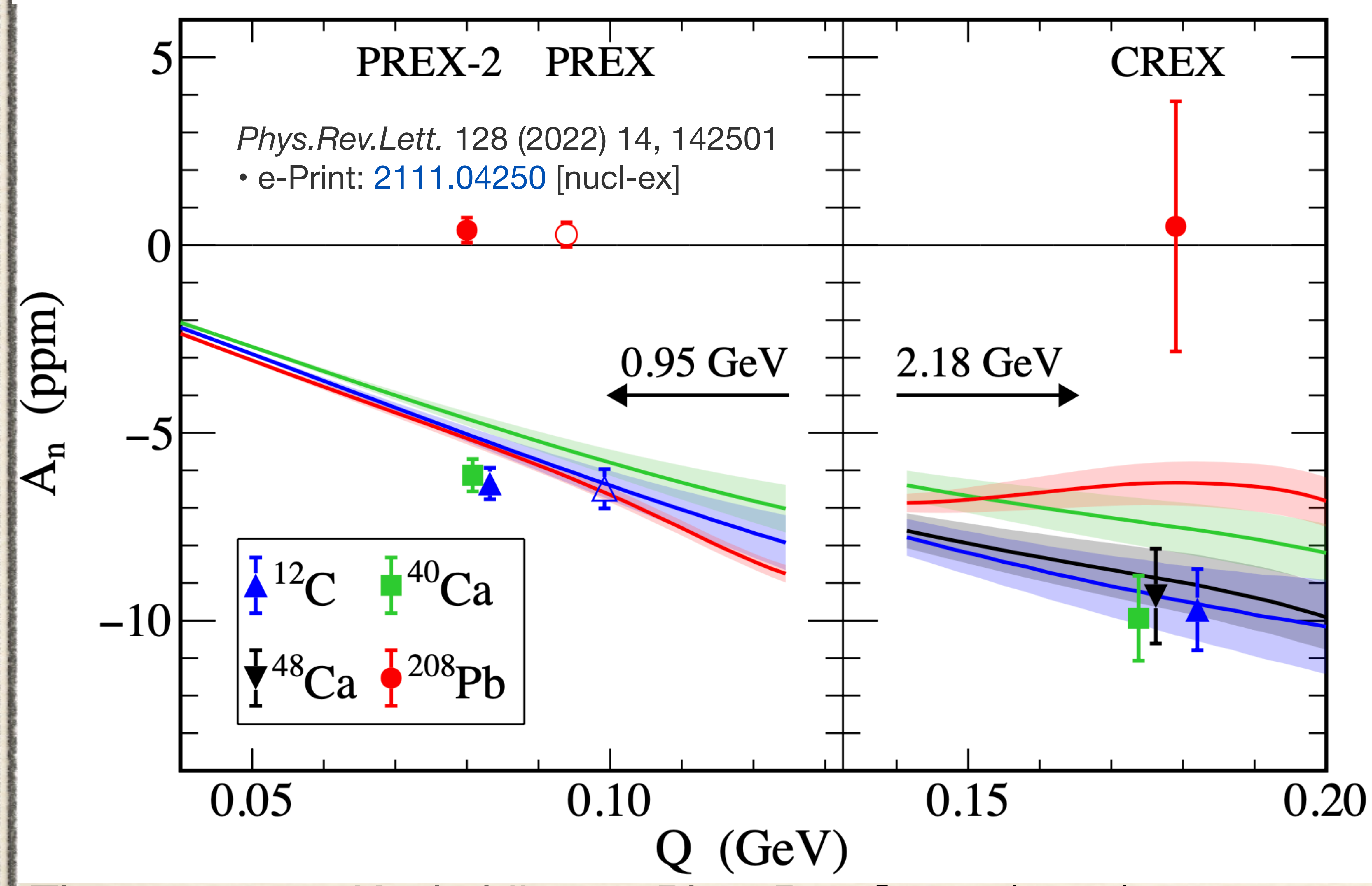

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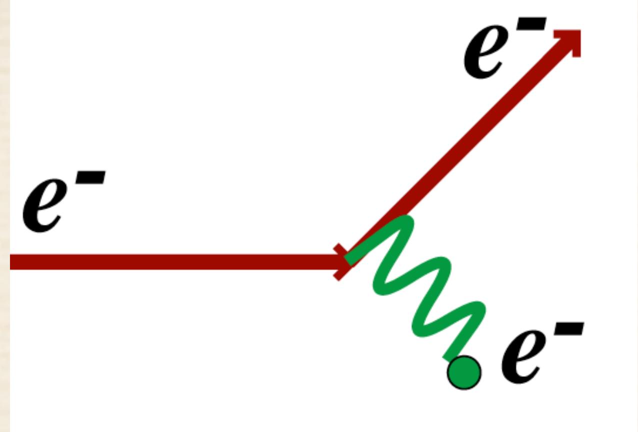
2.18	^{208}Pb	0.6 ± 3.2		$3.2\ \sigma$

Remarkable fact to review 4 different nuclei:

- **He-4: Happex-He, 2.75 GeV, 5 degrees (-14 ppm)**
- **C-12: PREX, CREX: 0.95 GeV, 5 degrees & 2.18 GeV, 5 degrees**
- **Ca-40: PREX CREX: 0.95 GeV, 5 degrees & 2.18 GeV, 5 degrees**
- **Ca-48: CREX, 5 degrees, 2.18 GeV**

All scale by the factor: $\sqrt{\left(\frac{Q^2}{E}\right)}$

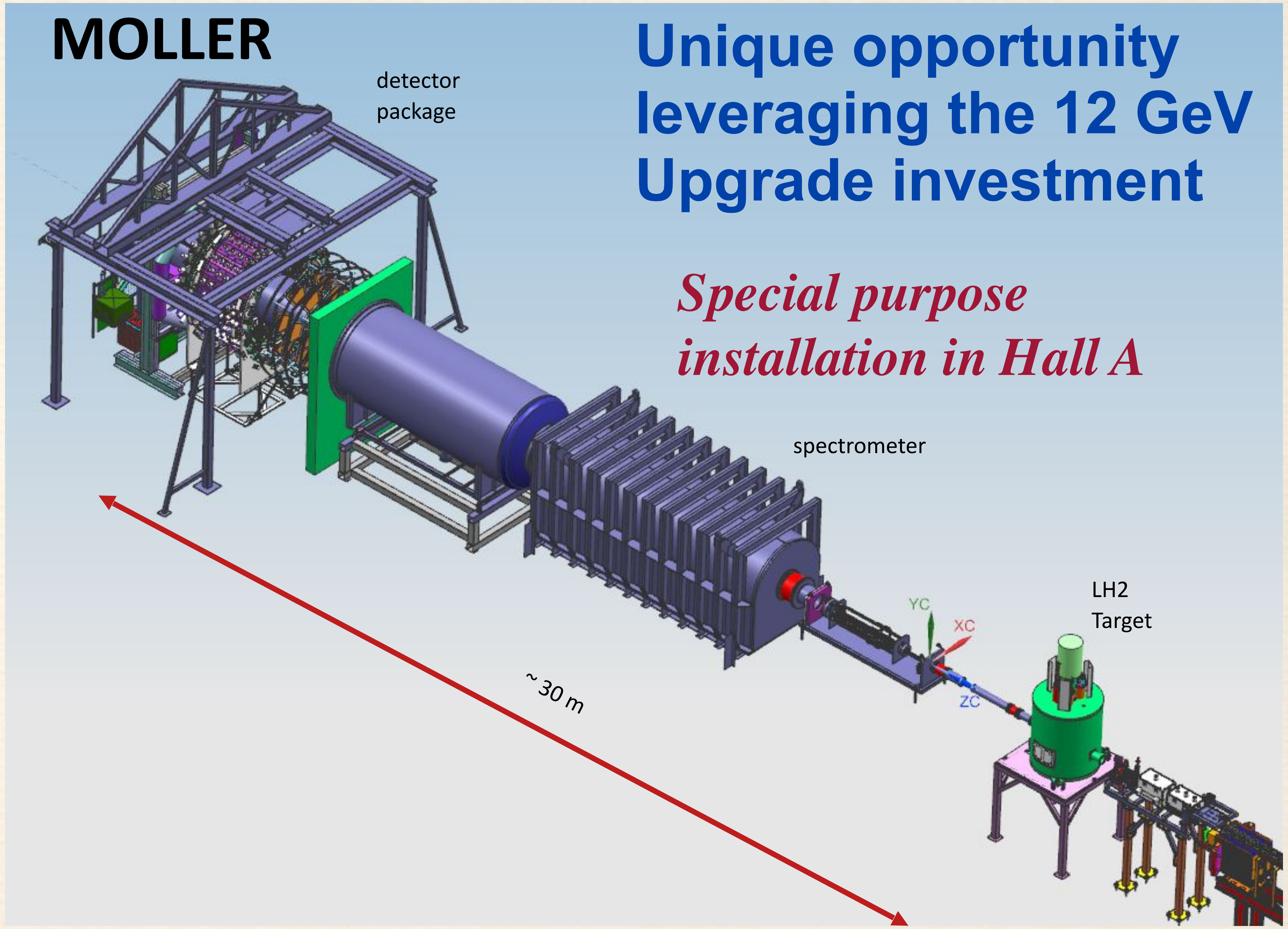
11 GeV Møller scattering



MOLLER at JLab

$A_{PV} \sim 32$ ppb

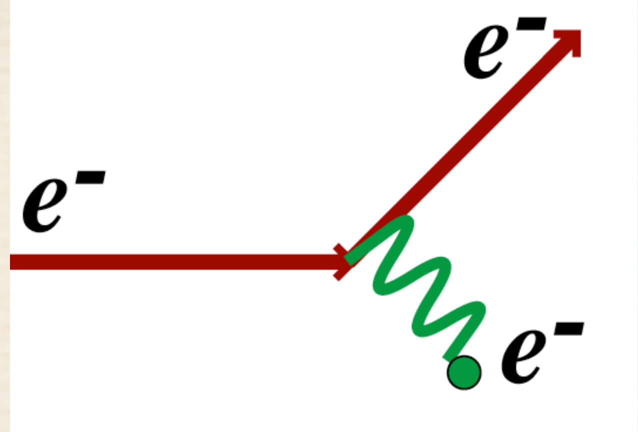
$\delta(A_{PV}) \sim 0.8$ ppb



Unique opportunity leveraging the 12 GeV Upgrade investment

Special purpose installation in Hall A

11 GeV Møller scattering

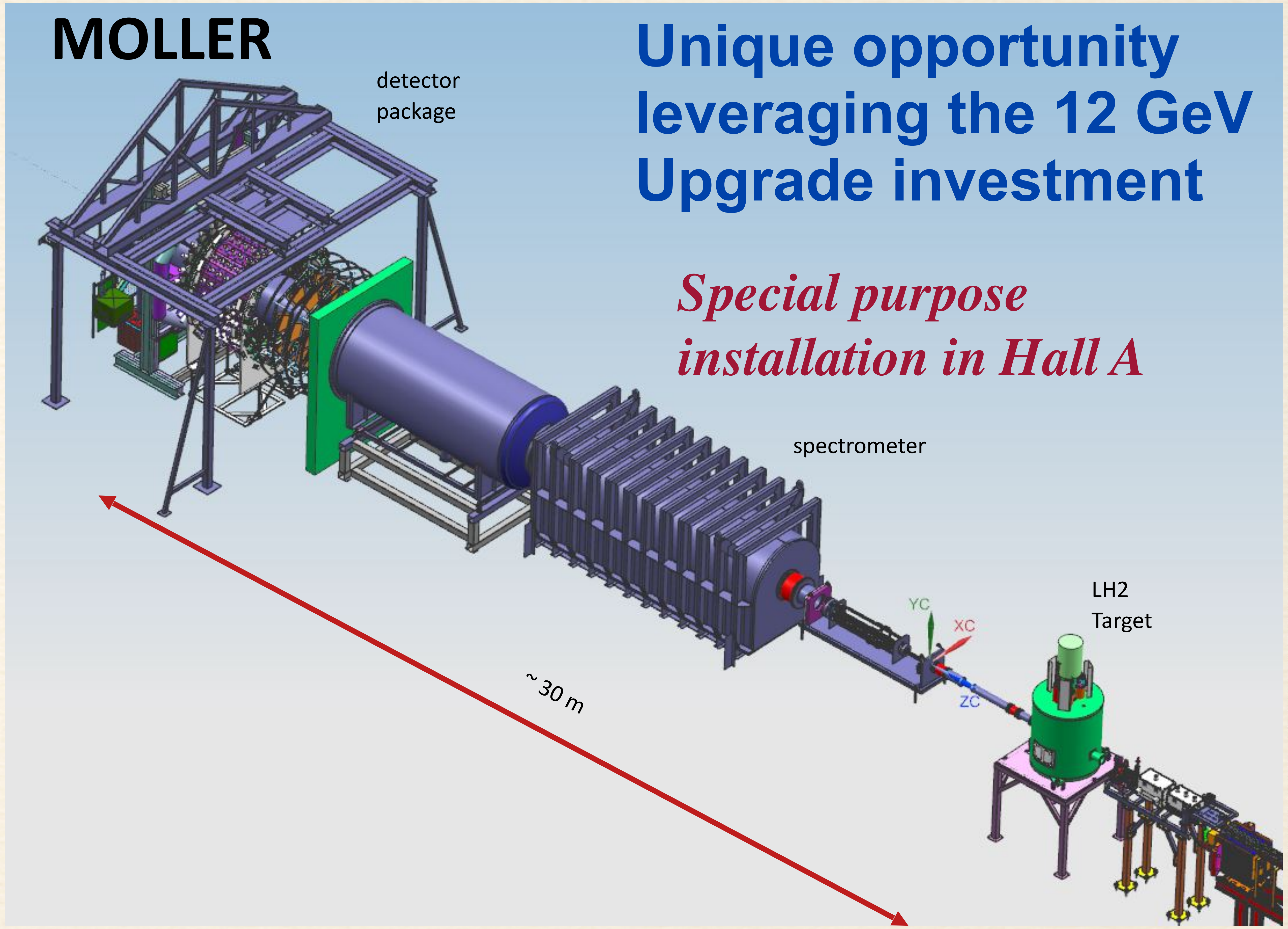


MOLLER at JLab

50 M$ DOE NP MIE

A_{PV} ~ 32 ppb

$\delta(A_{PV})$ ~ 0.8 ppb



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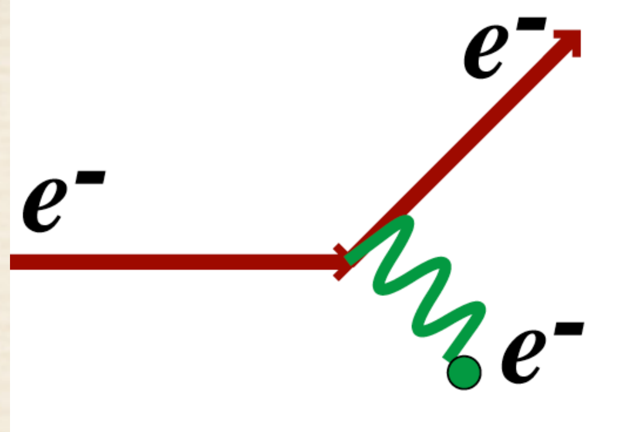


MOLLER at JLab

50 M$ DOE NP MIE

A_{PV} ~ 32 ppb

$\delta(A_{PV})$ ~ 0.8 ppb

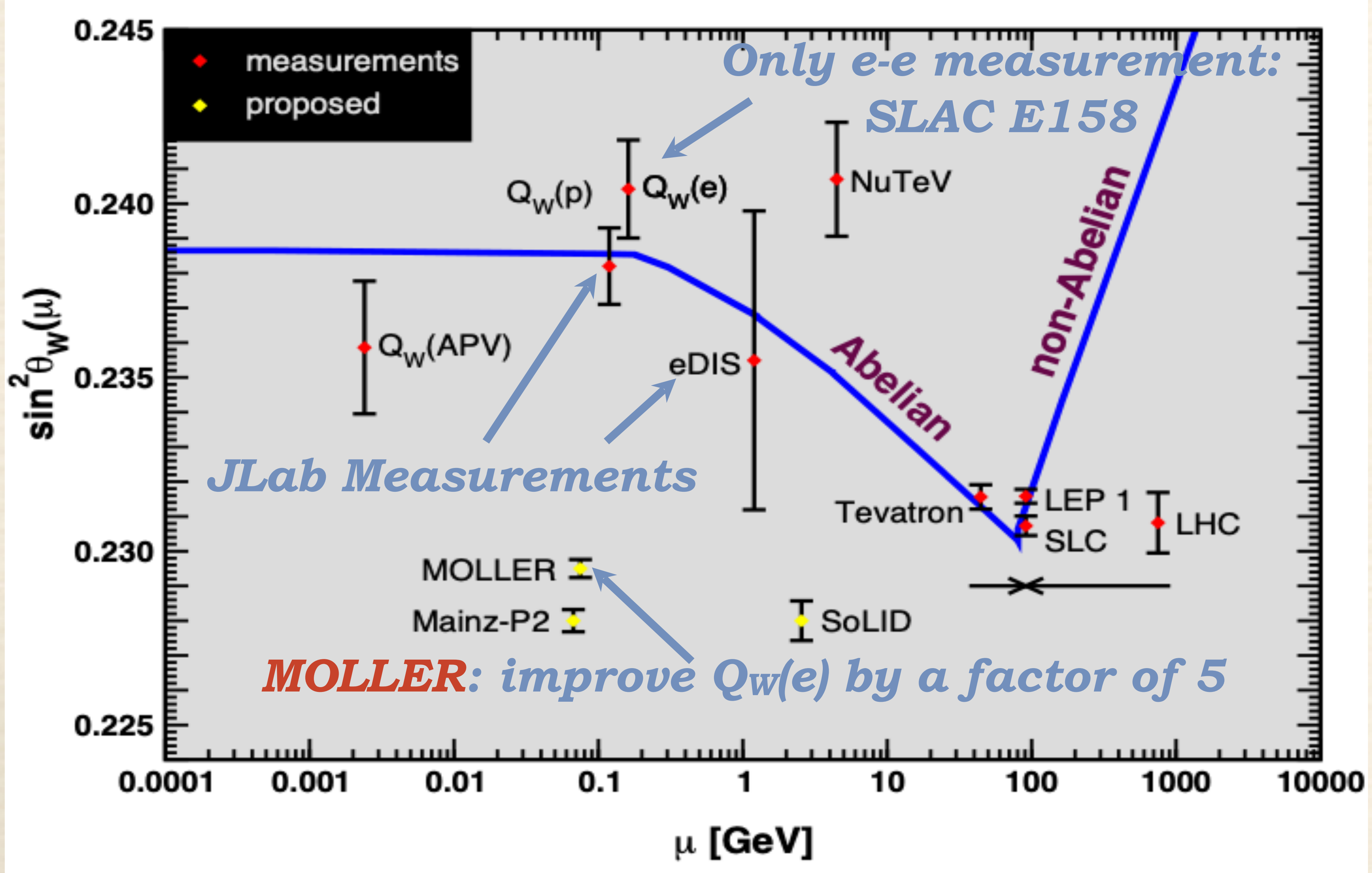
$\delta(\sin^2\theta_W) = \pm\, 0.00023$ (stat.) $\pm\, 0.00012$ (syst.)

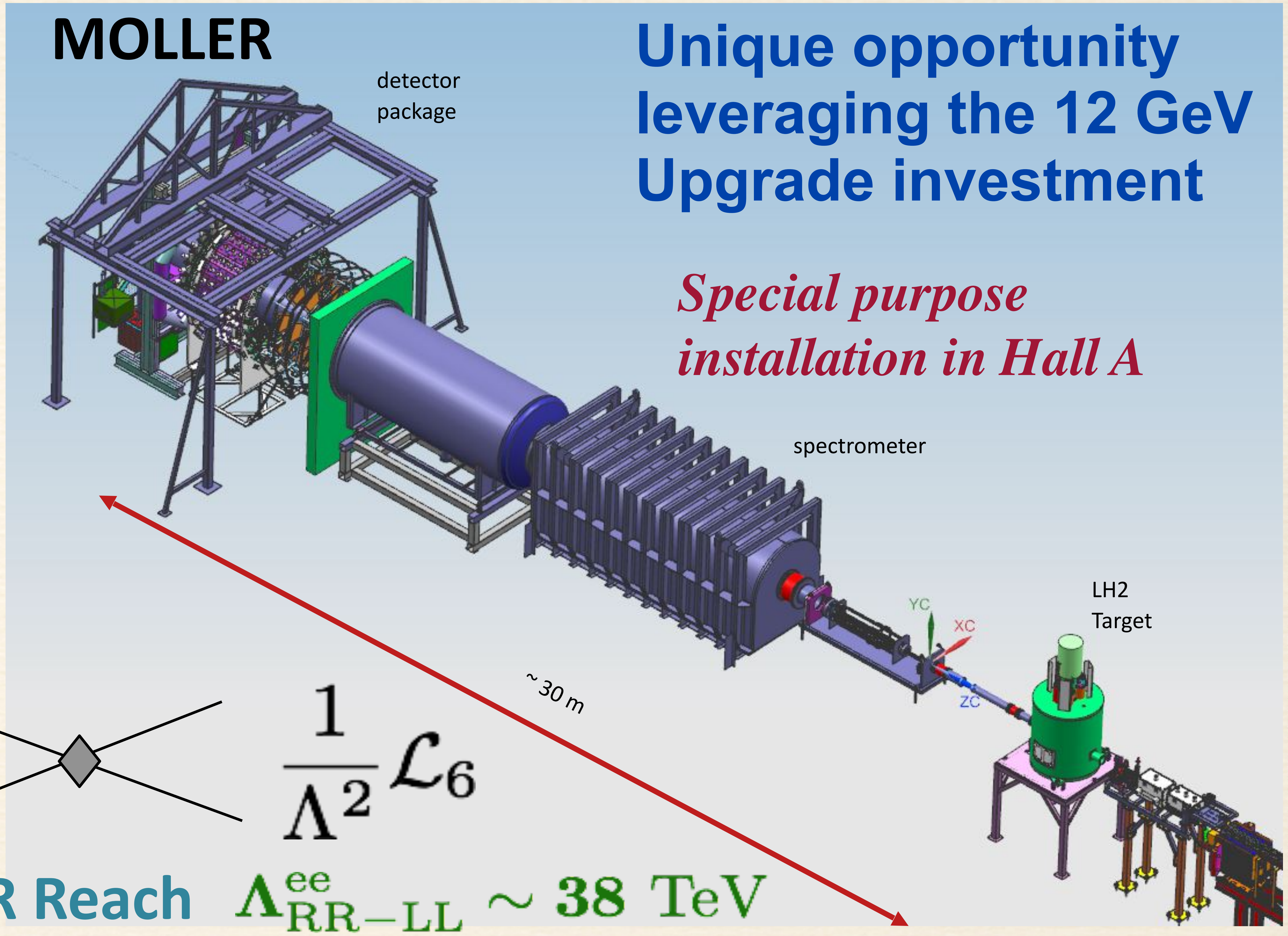
⇨ *~ 0.1%*

- **Unique (purely leptonic) new physics reach**

Search for new flavor diagonal neutral currents

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





Unique opportunity leveraging the 12 GeV Upgrade investment

Special purpose installation in Hall A

A_{new}

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

MOLLER Reach $\Lambda^{ee}_{RR-LL} \sim 38\ \mathrm{TeV}$

Unique discovery space: beyond that of a 500 GeV lepton collider

Take Away Message

New CREX Result

Unblinded A_{PV}:
2668 ± 106 (stat) ± 40 (sys) ppb
[± 113.3 ppb (tot) (4.3%)]

F_W: 0.1304 ± 0.0055

CREX result is consistent with a thin neutron skin (e.g. coupled cluster calculations) and is inconsistent with predictions of a very thick skin

More details in implications in C. Horowitz talk!

Publication in the ArXiv by later today

- **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, MREX..)
  - ★ valence quark structure of protons and neutrons (SOLID)
- **Fundamental Electroweak Physics**
  - ★ Search for new TeV scale dynamics (MOLLER, SOLID, P2, C-12?)
    - *complementary to colliders; would help interpret potential anomalies*
    - *precision measurement of the weak mixing angle*

Looking forward to discussions on how best to optimize the future program at this workshop!