Acknowledgements:
The PREX, CREX, E158 and MOLLER Collaboration
The Accelerator Divisions at SLAC & Jefferson Laboratory
V. Cirigliano, J. Erler, C. Horowitz, W. Marciano, M. Ramsey-Musolf, J. Piekerewicz

The Parity-Violation Program at Jefferson Lab

Krishna S. Kumar
UMass, Amherst

EINN2019
Paphos, Cyprus
November 2, 2019

Outline

- **Introduction to Parity-Violating Electron Scattering**
  - Relativistic electron scattering and nuclear size
  - Neutral weak interactions

Historical introduction for graduate students

- **Elastic Scattering off a Heavy Doubly Magic Nucleus**
  - PREX Experimental Overview
  - First Result from 2010 Run
  - Summer 2019 PREX-II Run and upcoming CREX run

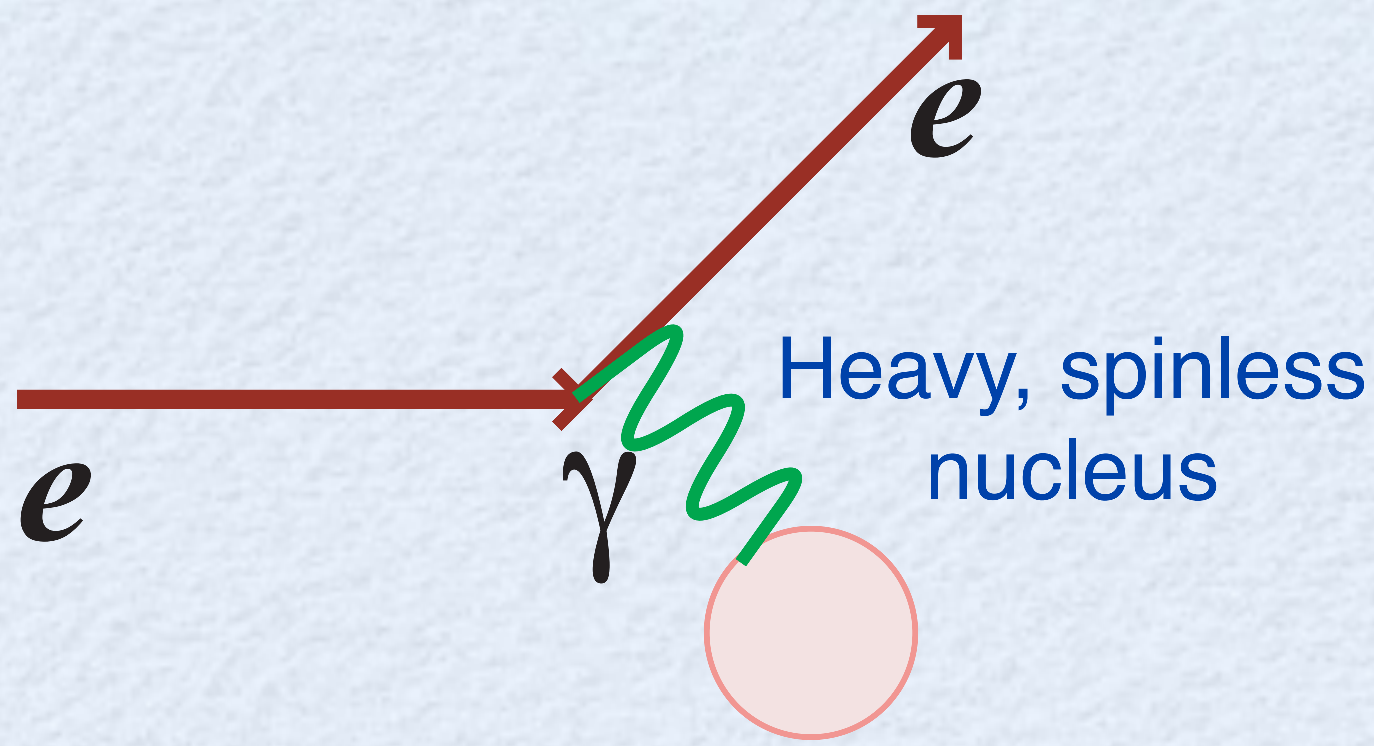
PRL 108 (2012) 112502

PRC 85 (2012) 032501

- **Scattering off electrons, protons and quarks**
  - Program to Search for New Neutral Current Interactions Beyond the Standard Model
    - The past: E158, Qweak. The future: MOLLER, SOLID, P2
  - Novel probes of partonic structure
  - Neutral Current Structure Functions at an EIC
- **Summary and Outlook**

Relativistic Electron Scattering

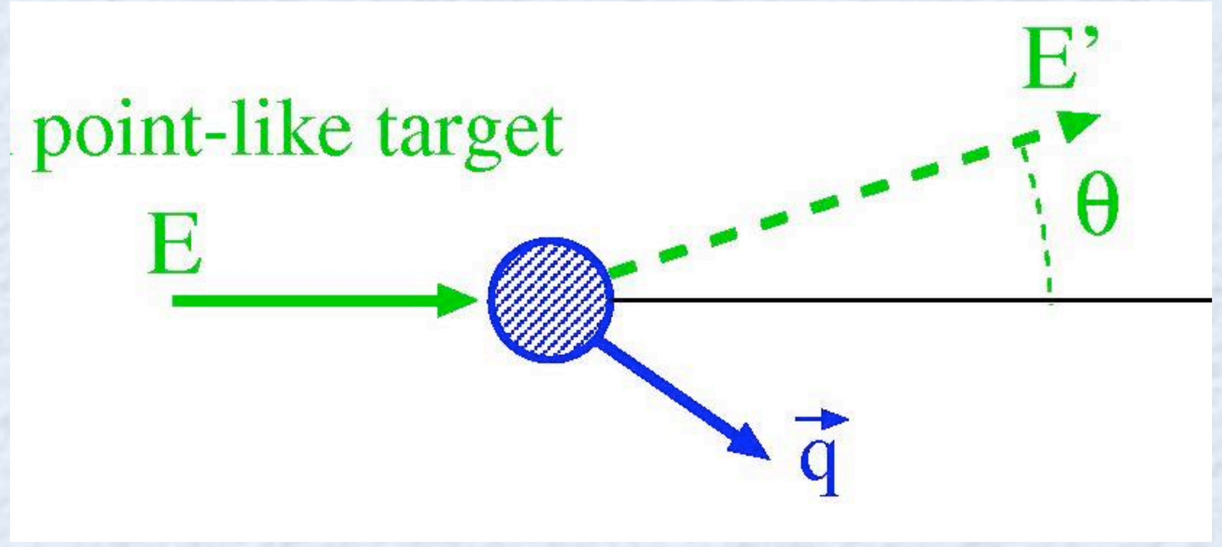
and nuclear size



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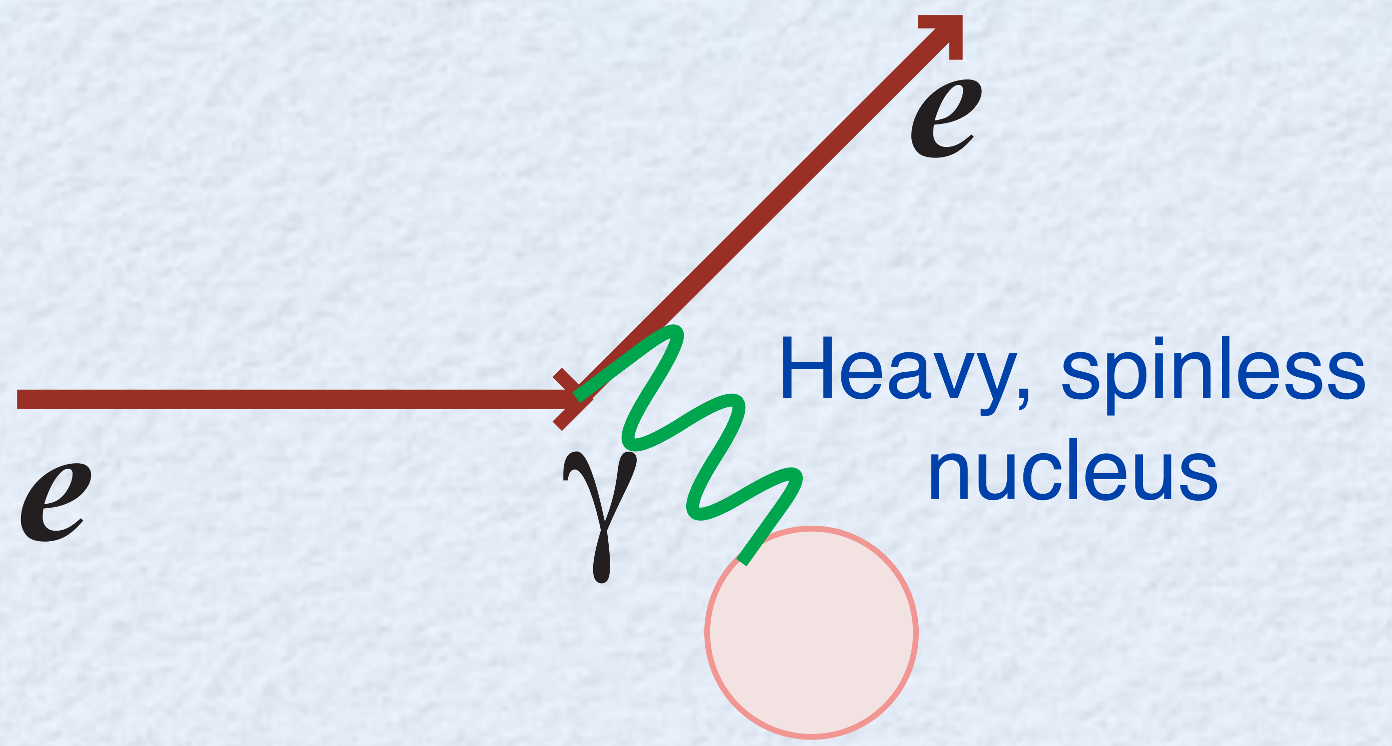

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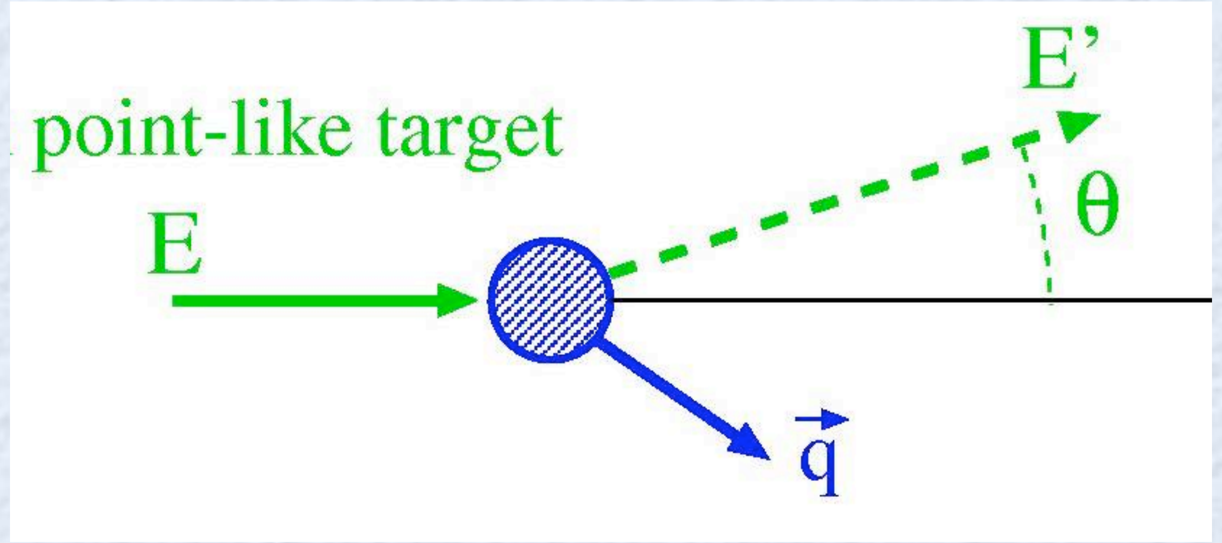

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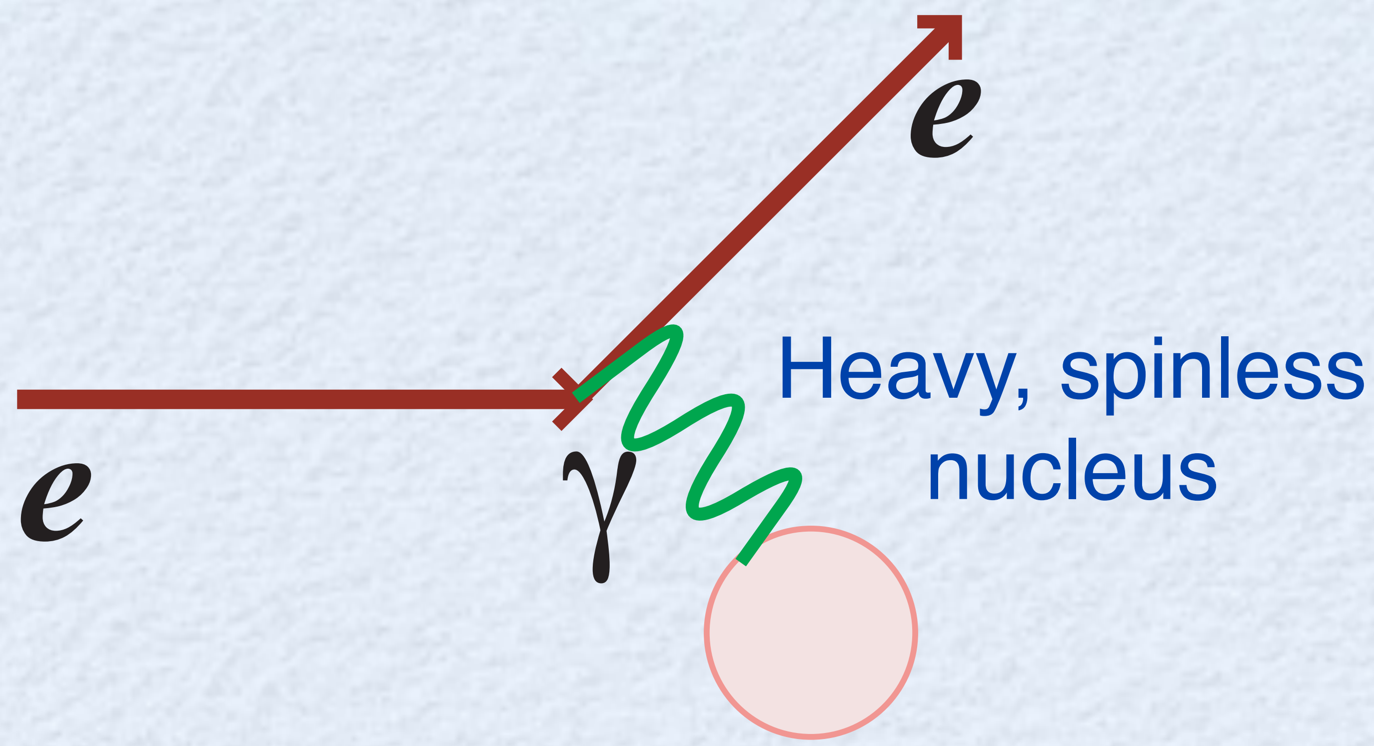
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} |F(q)|^2$$

As Q increases, nuclear size modifies formula

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

Relativistic Electron Scattering

and nuclear size



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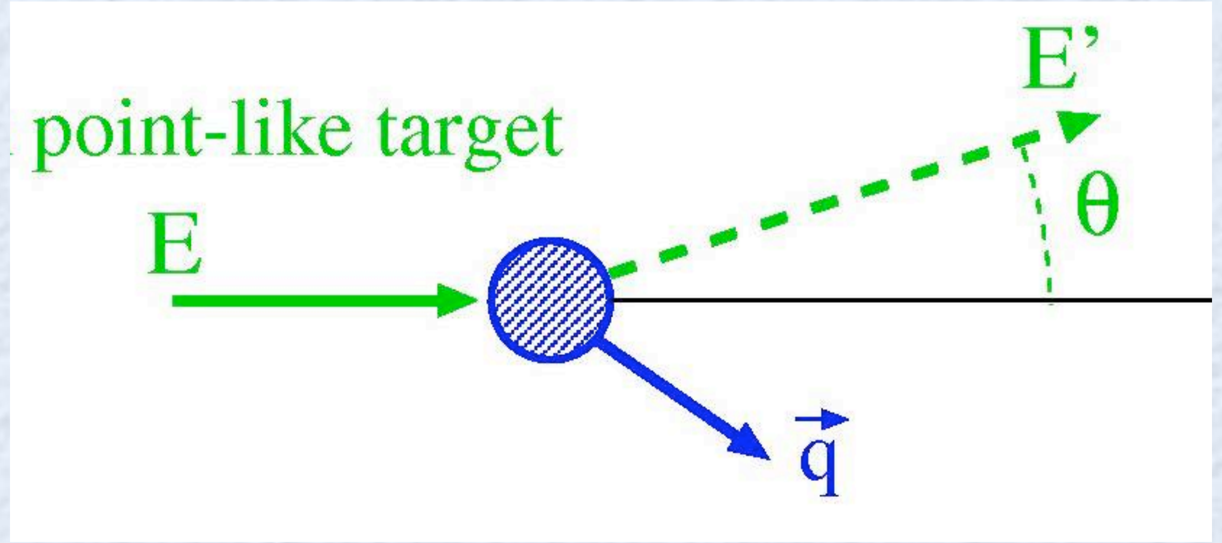

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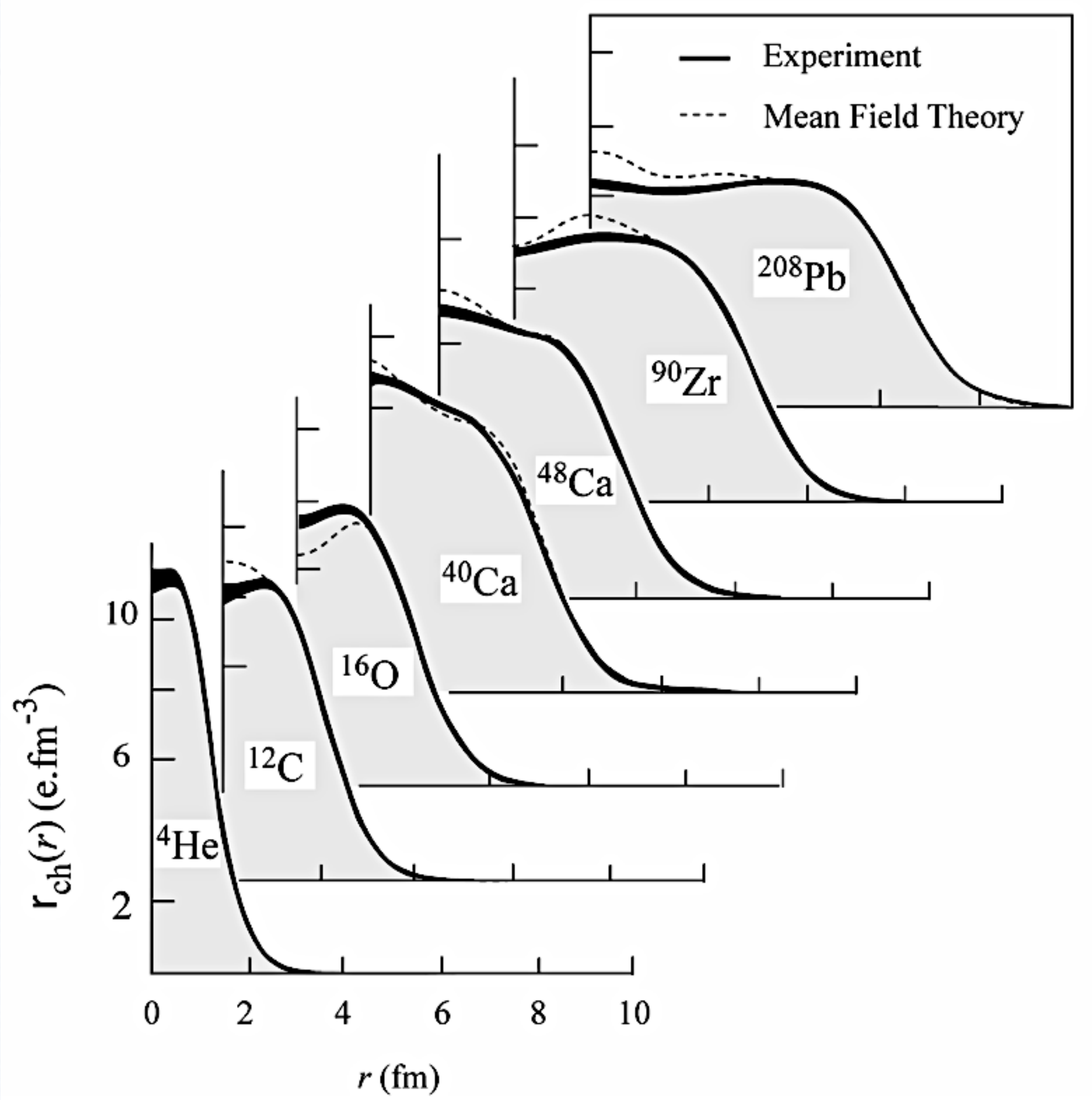
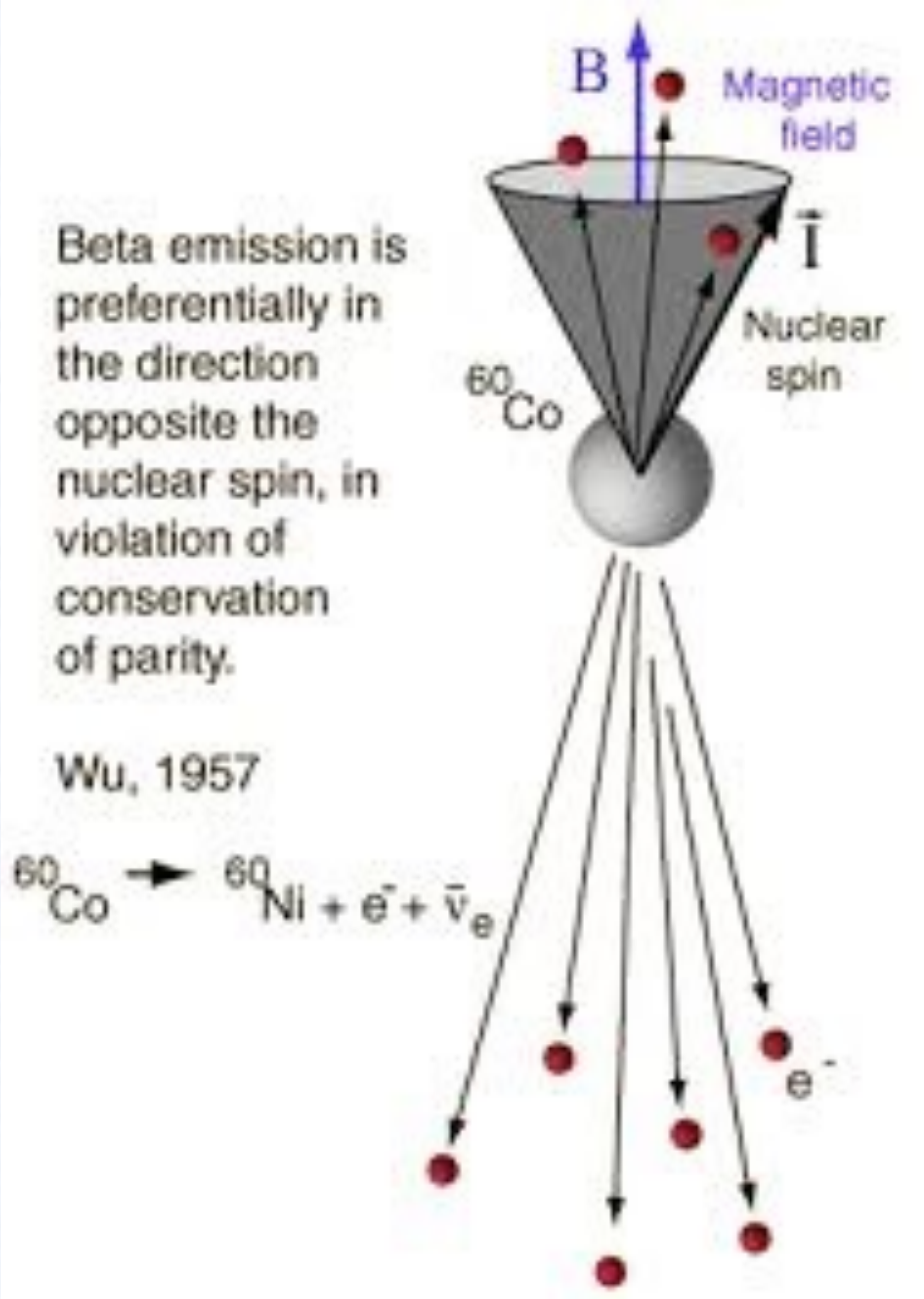


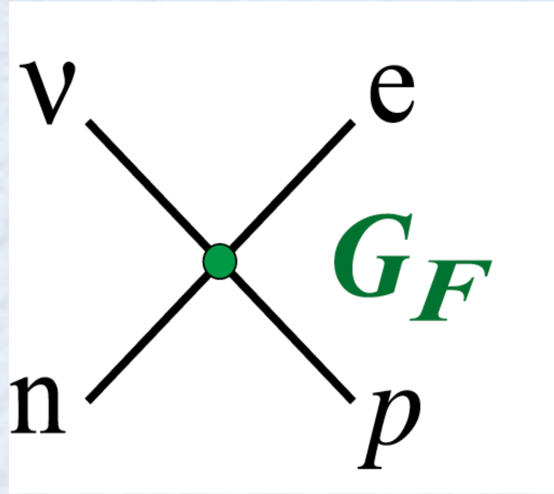
Neglecting recoil, form factor F(q) is the Fourier transform of charge distribution

Electroweak Scattering

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



Nuclear β Decay



charge and flavor-changing

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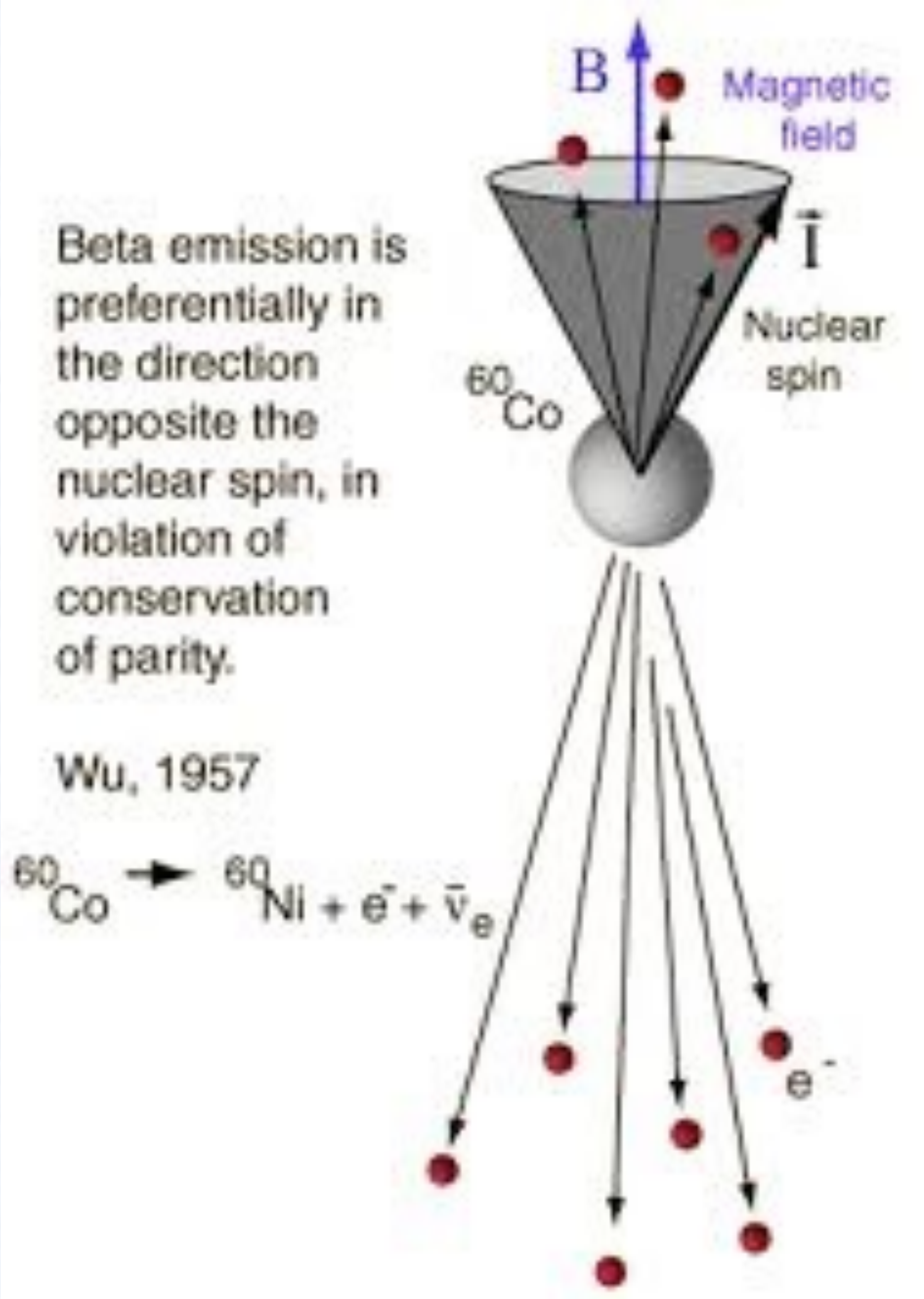

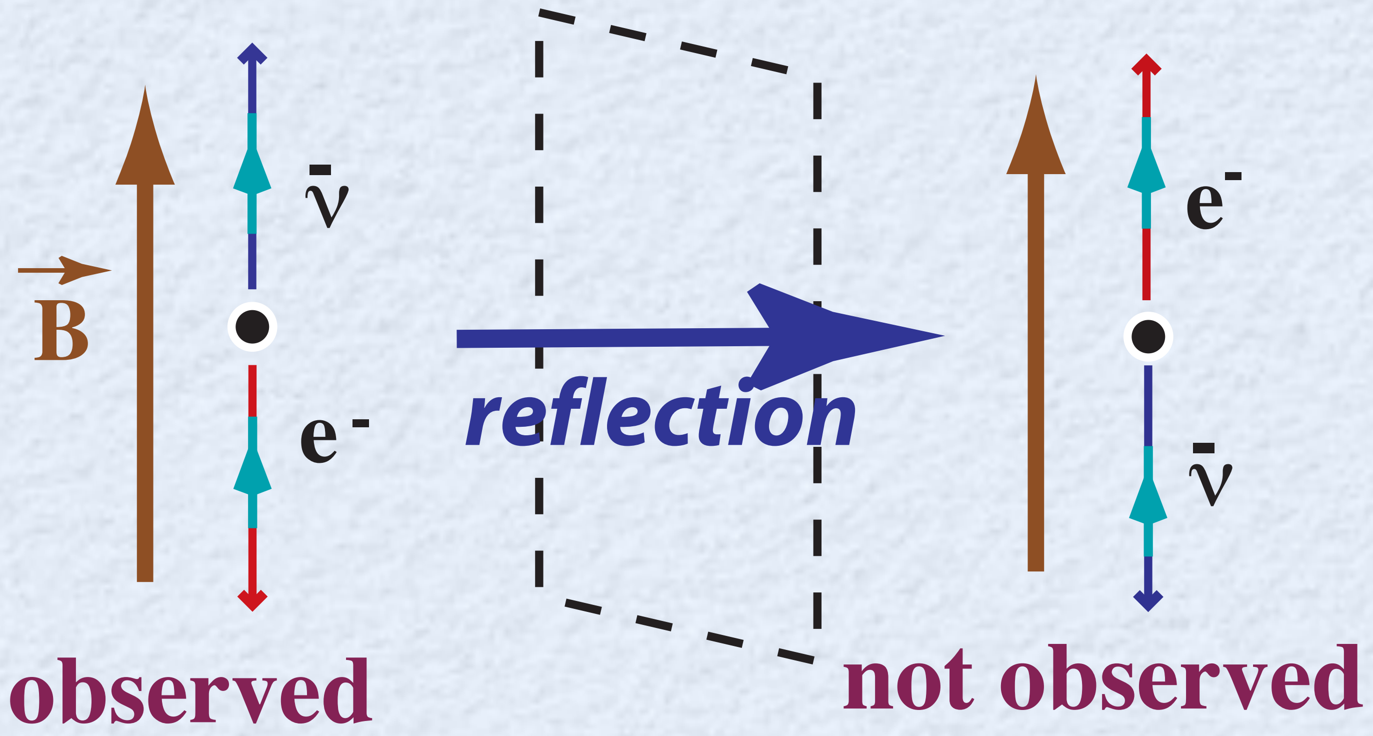

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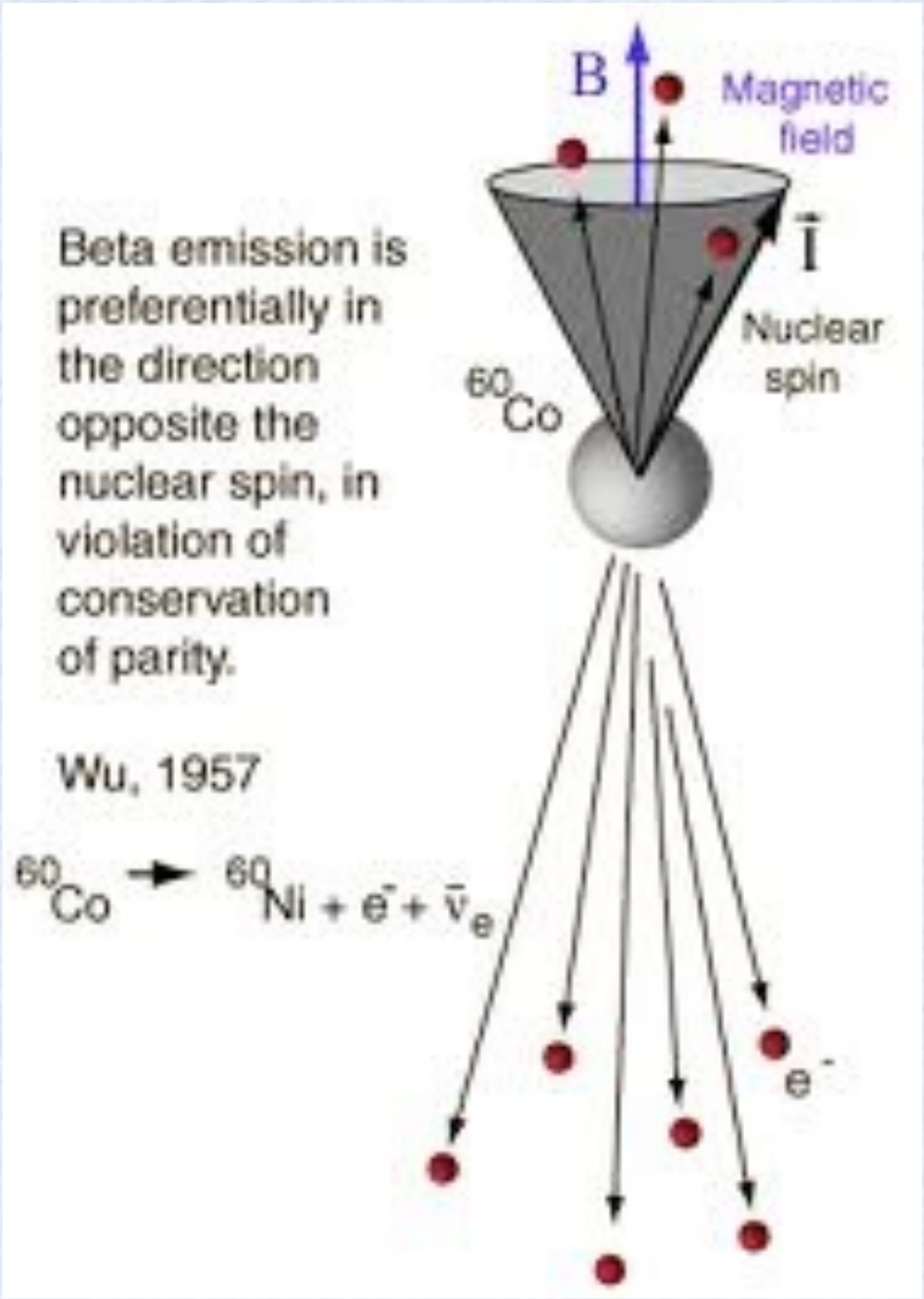

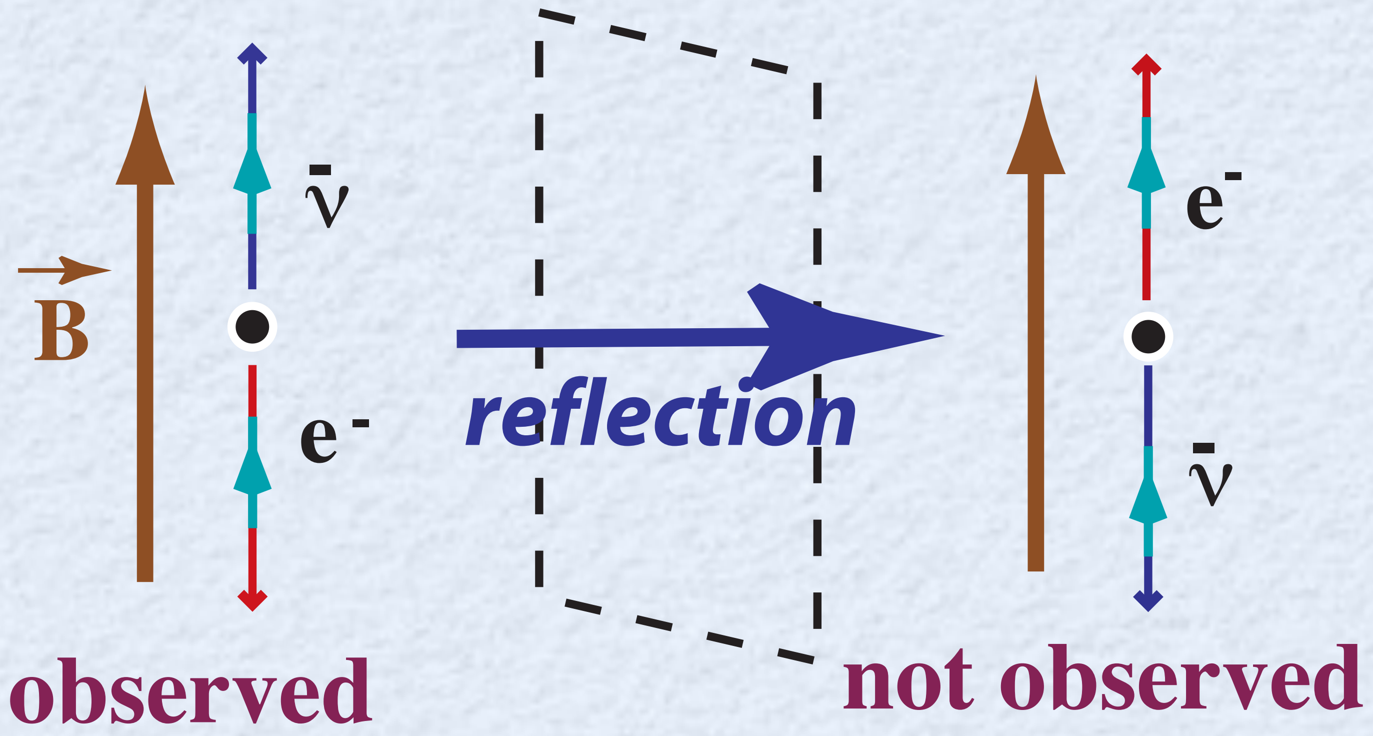

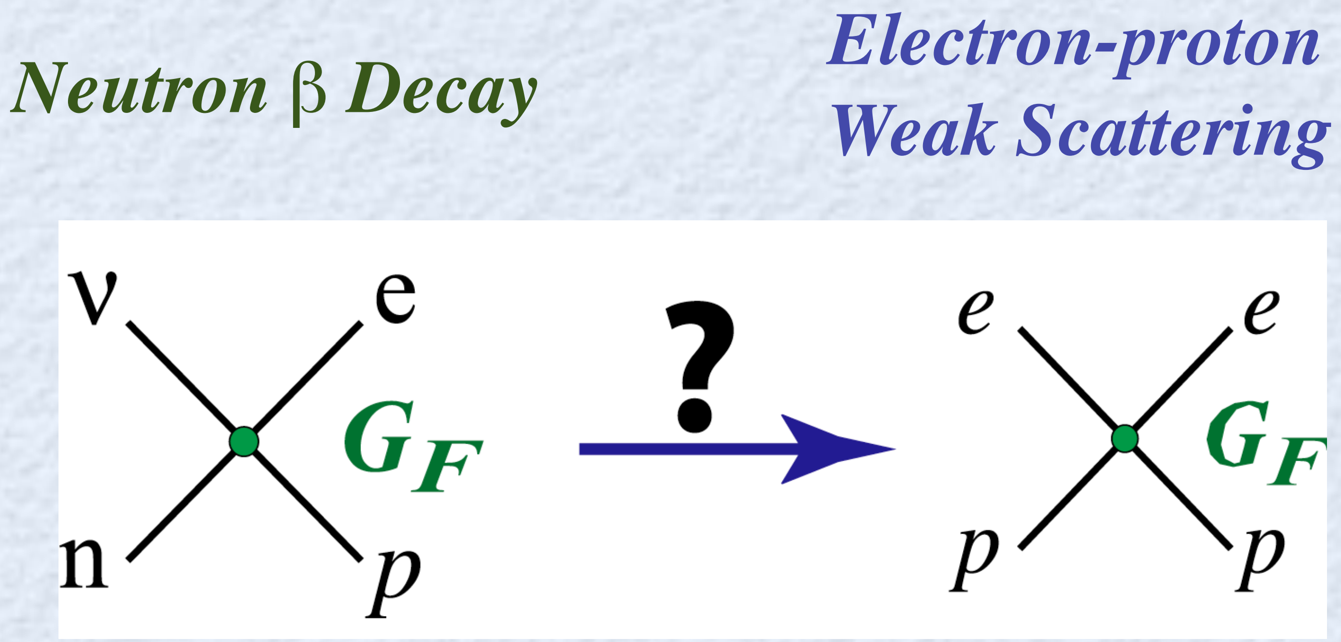

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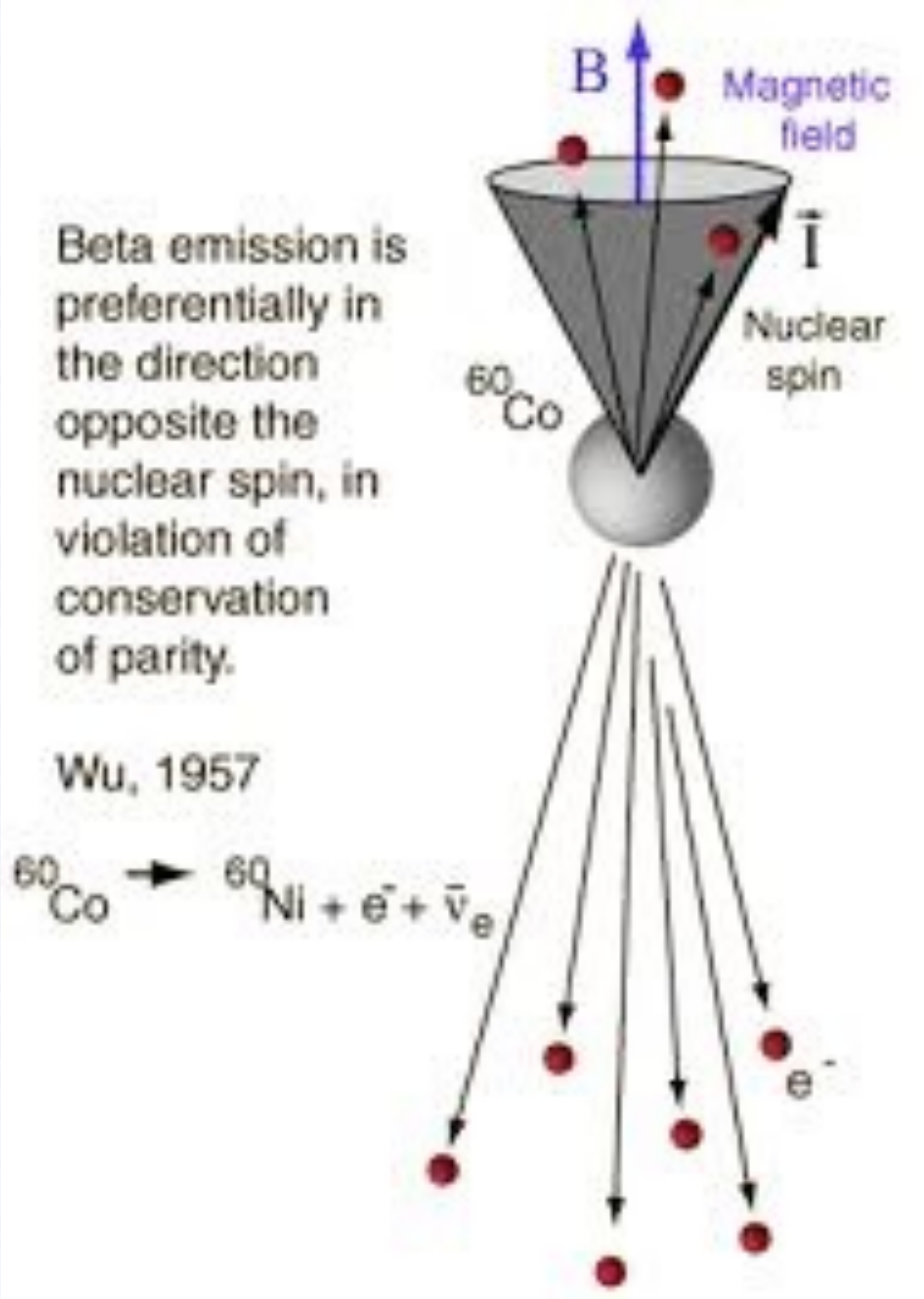
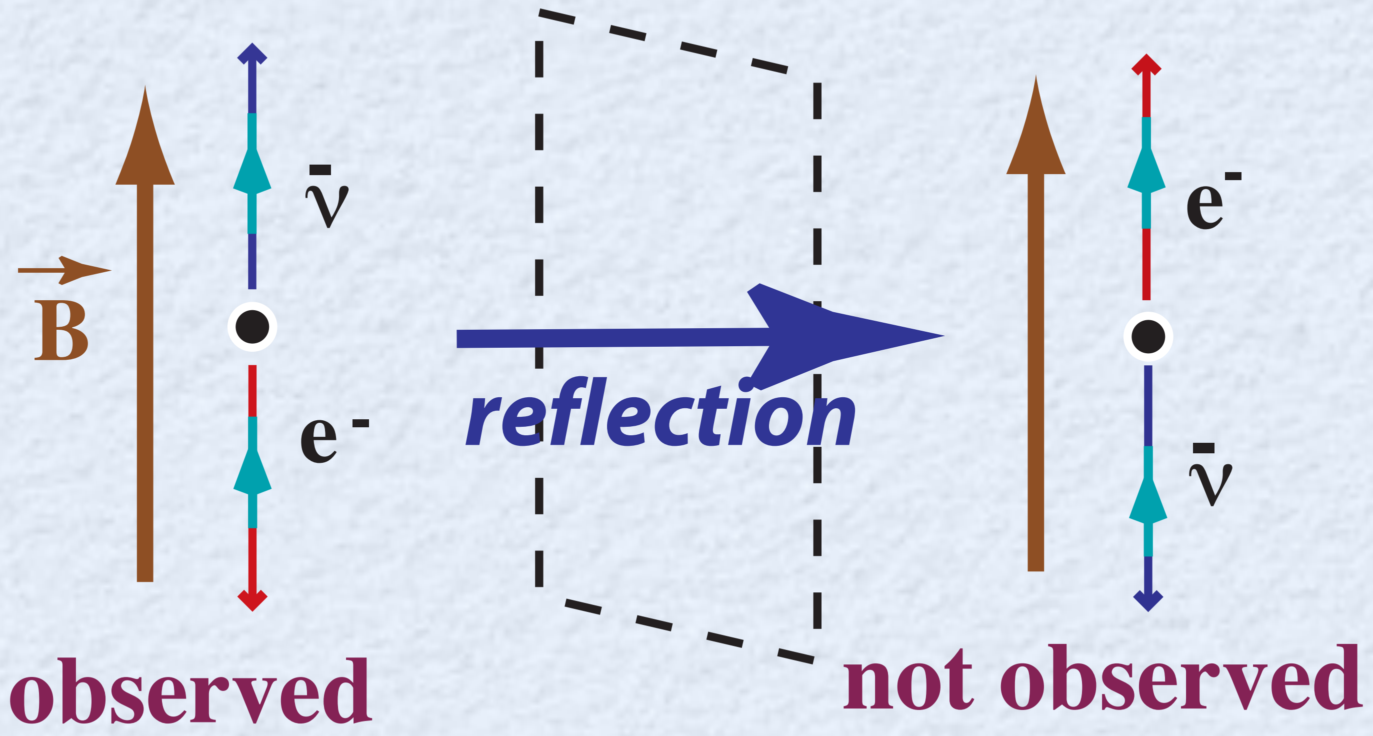
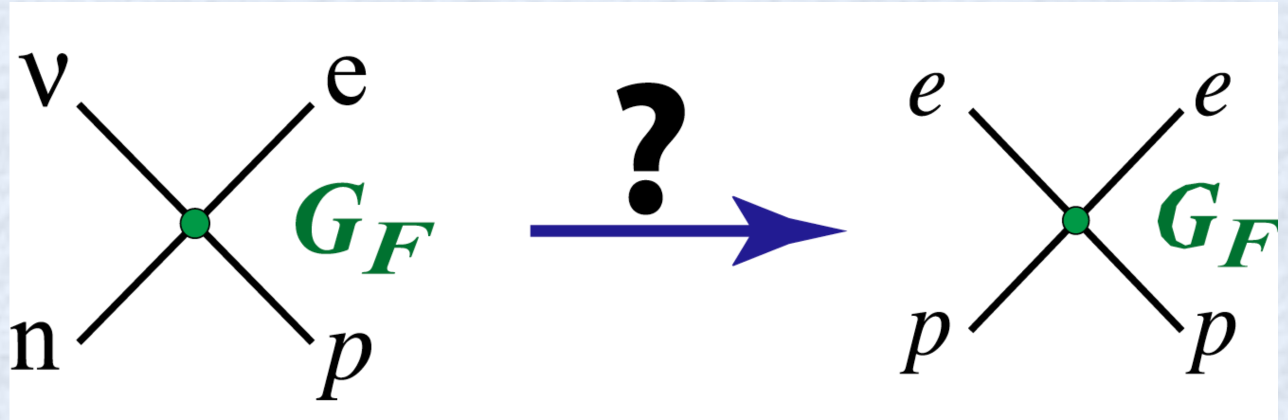




Neutron β Decay

Electron-proton Weak Scattering



$$\sigma \;\alpha\; |A_{EM} + A_{weak}|^2$$
$$\sim |A_{EM}|^2 + 2A_{EM}A^*_{weak} + \ldots$$

Electroweak Scattering

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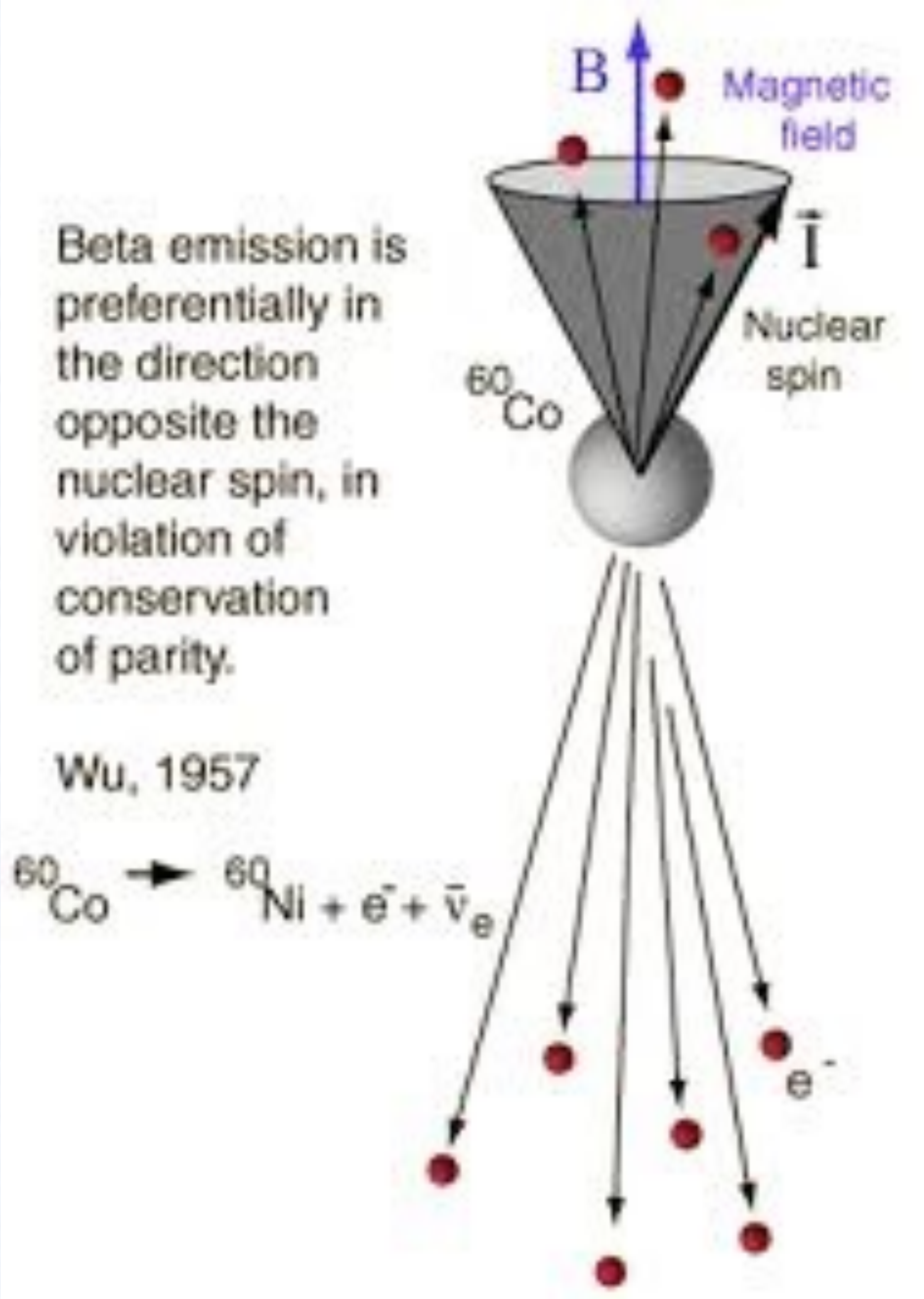

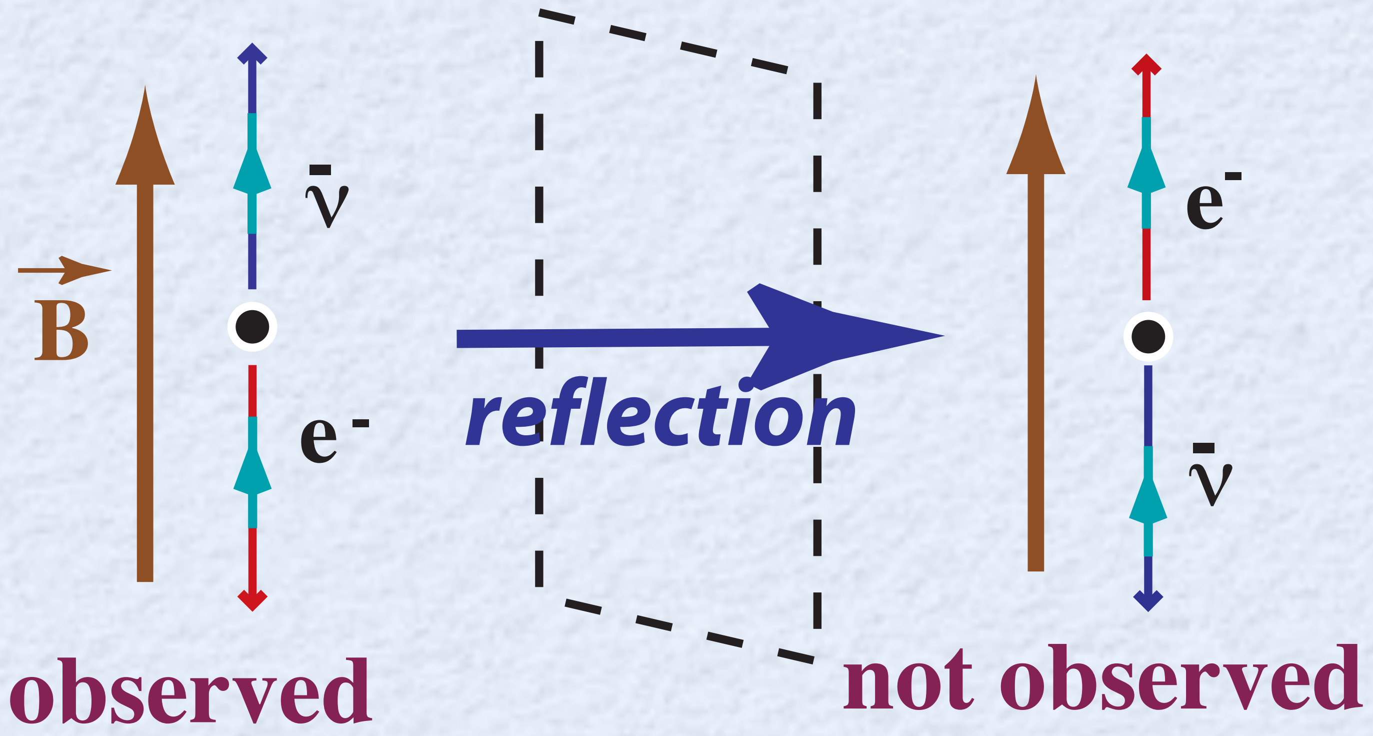

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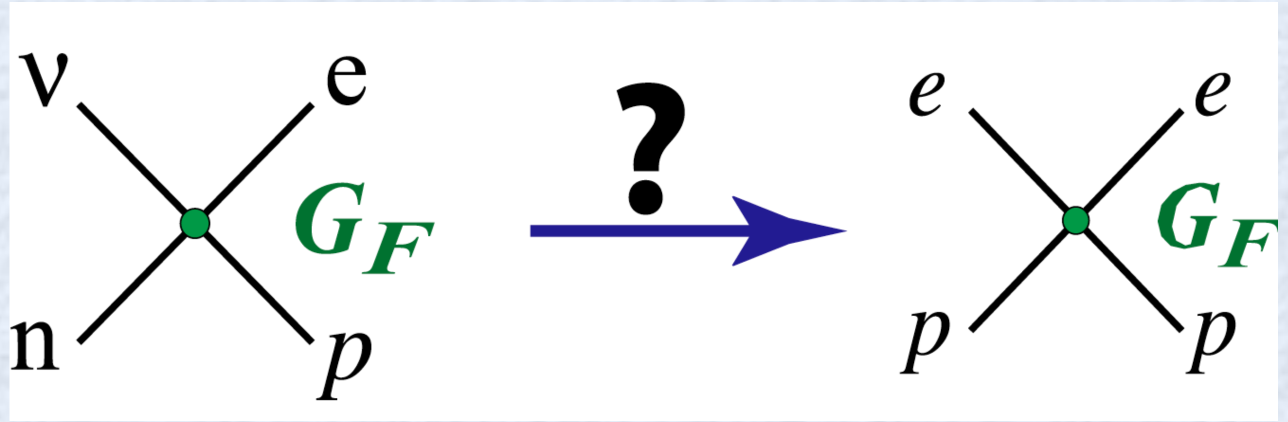

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Parity-violating

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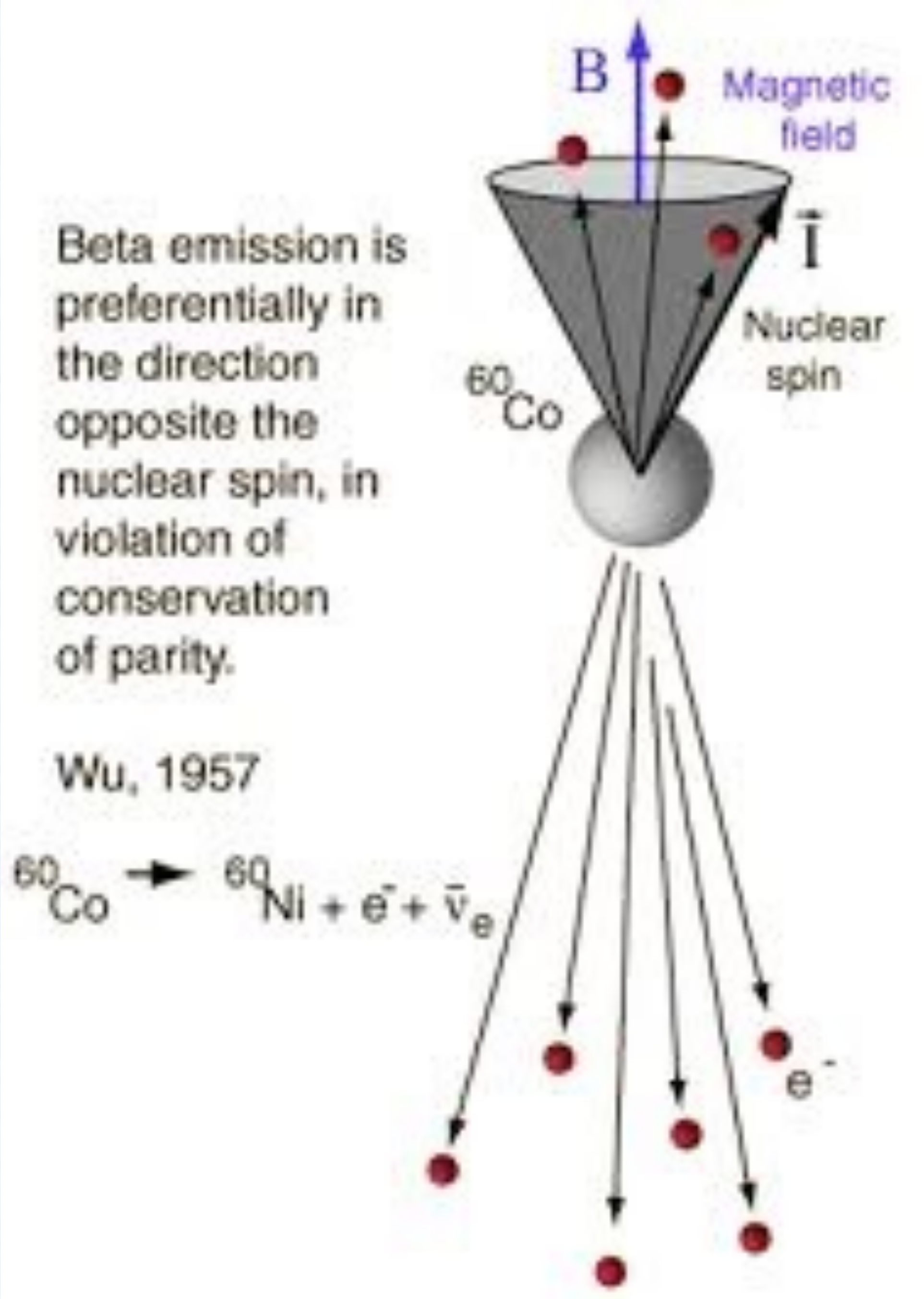

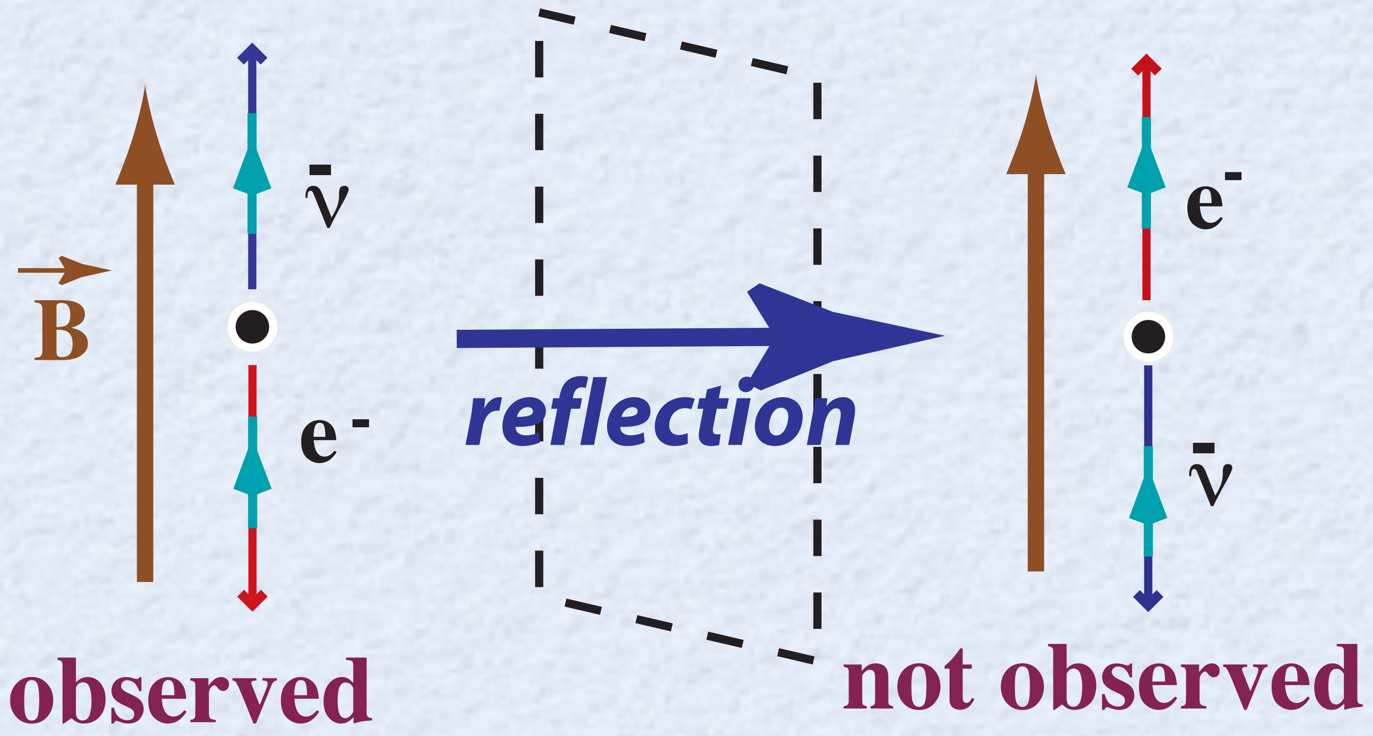

$$A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} = -A$$

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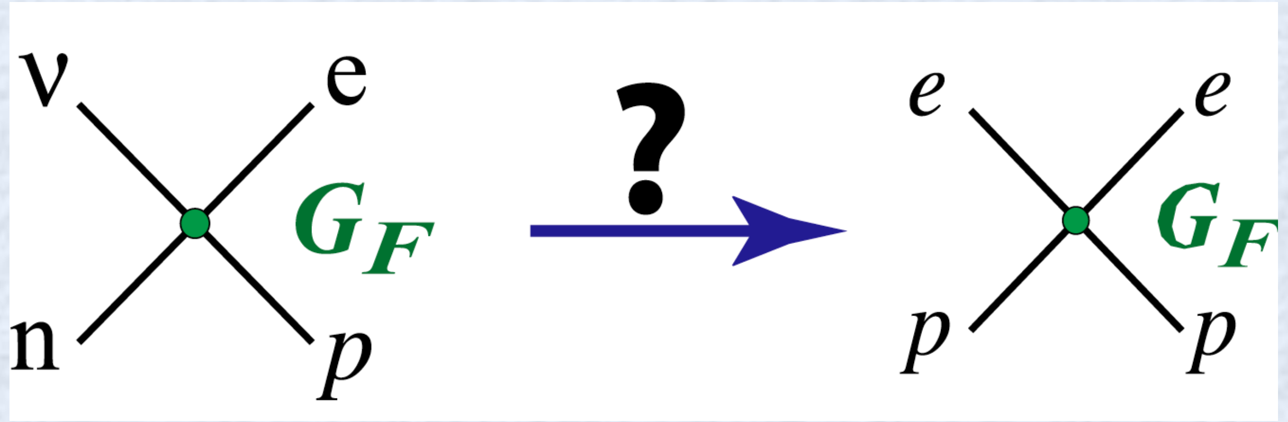

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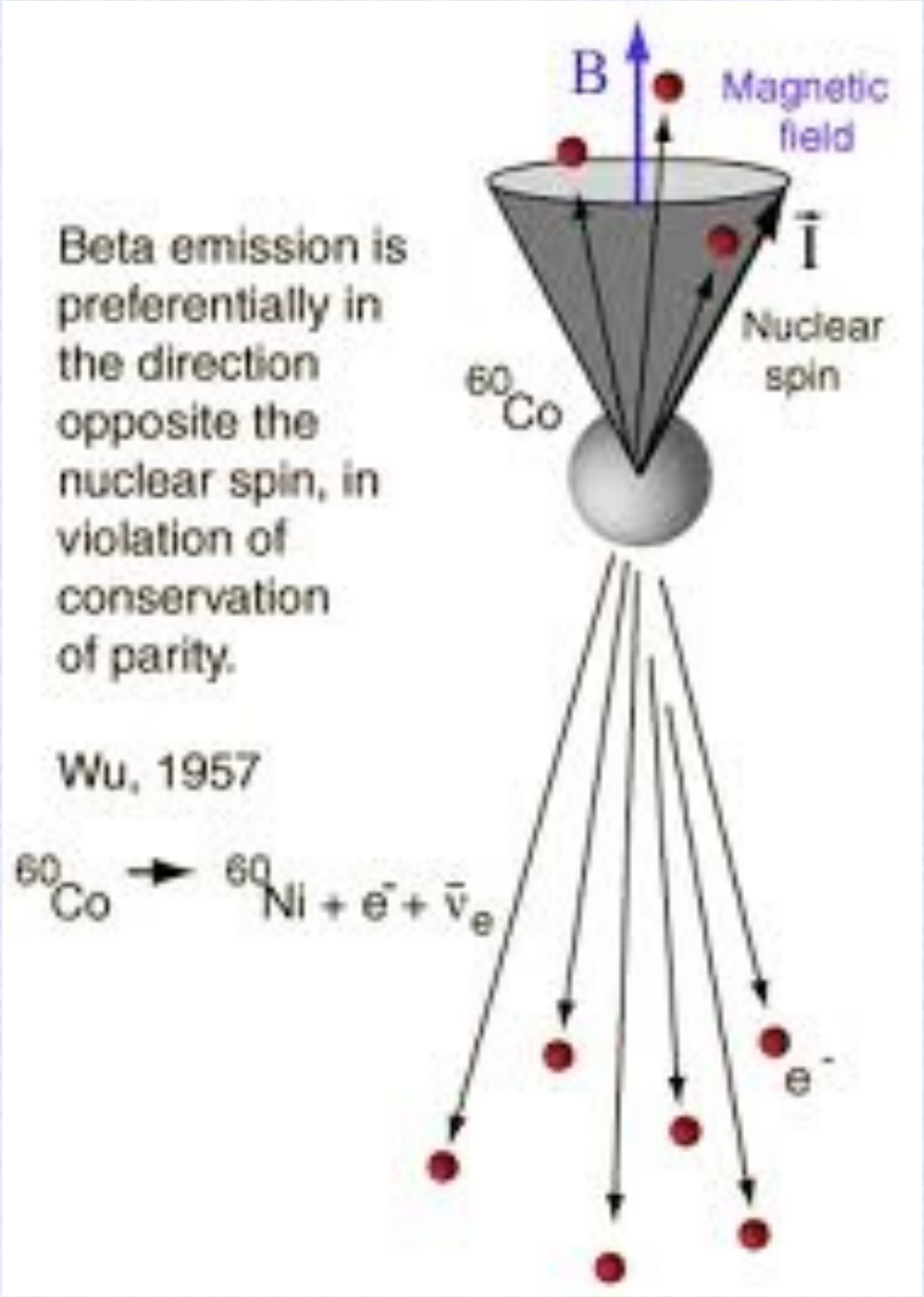

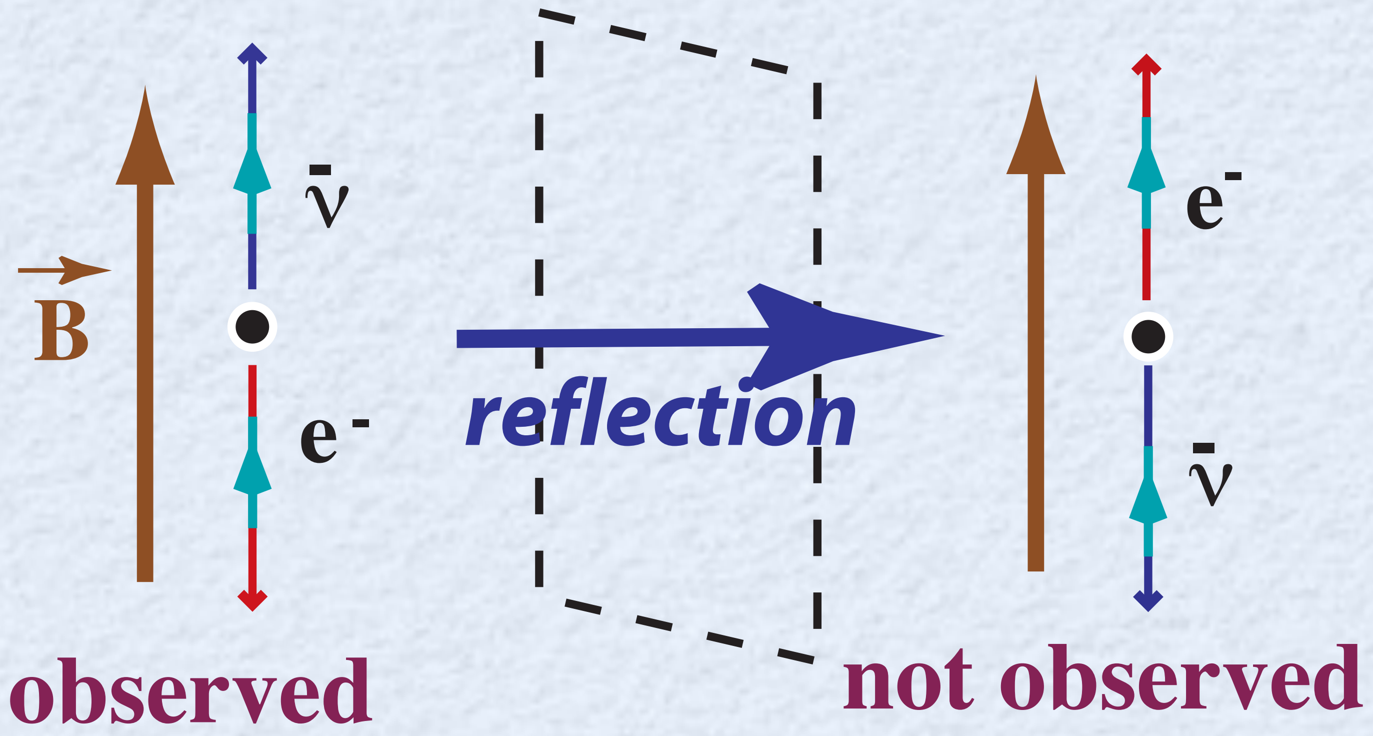

Neutron β Decay

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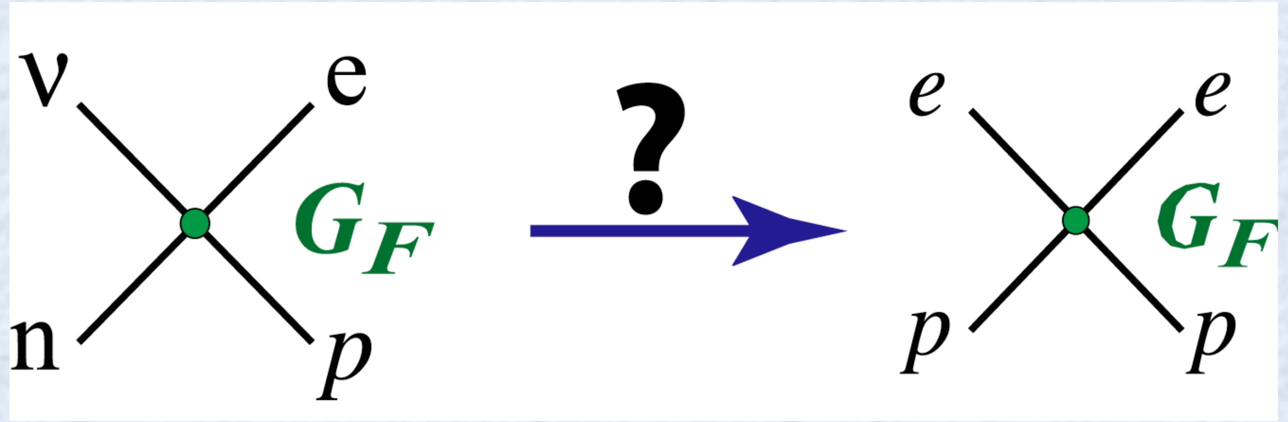

$$A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} = -A \sim \frac{A_{weak}}{A_{EM}} \sim \frac{G_F Q^2}{4\pi\alpha}$$

$$\sigma \propto |A_{EM} + A_{weak}|^2$$

$$\sim |A_{EM}|^2 + 2A_{EM}A^*_{weak} + \ldots$$

Parity-violating

$$A_{PV} \sim 10^{-4} \cdot Q^2 \ (\mathrm{GeV}^2)$$

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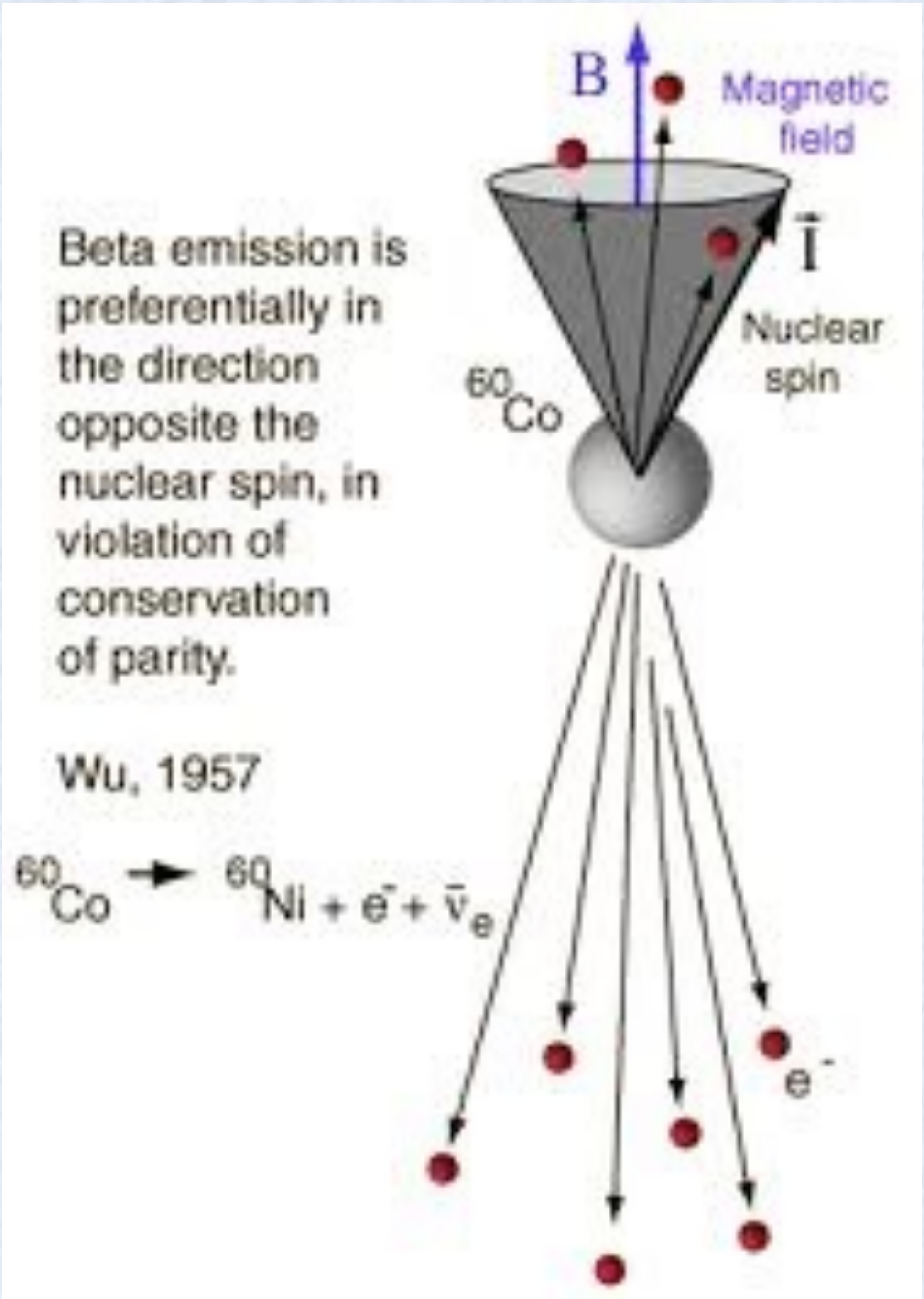

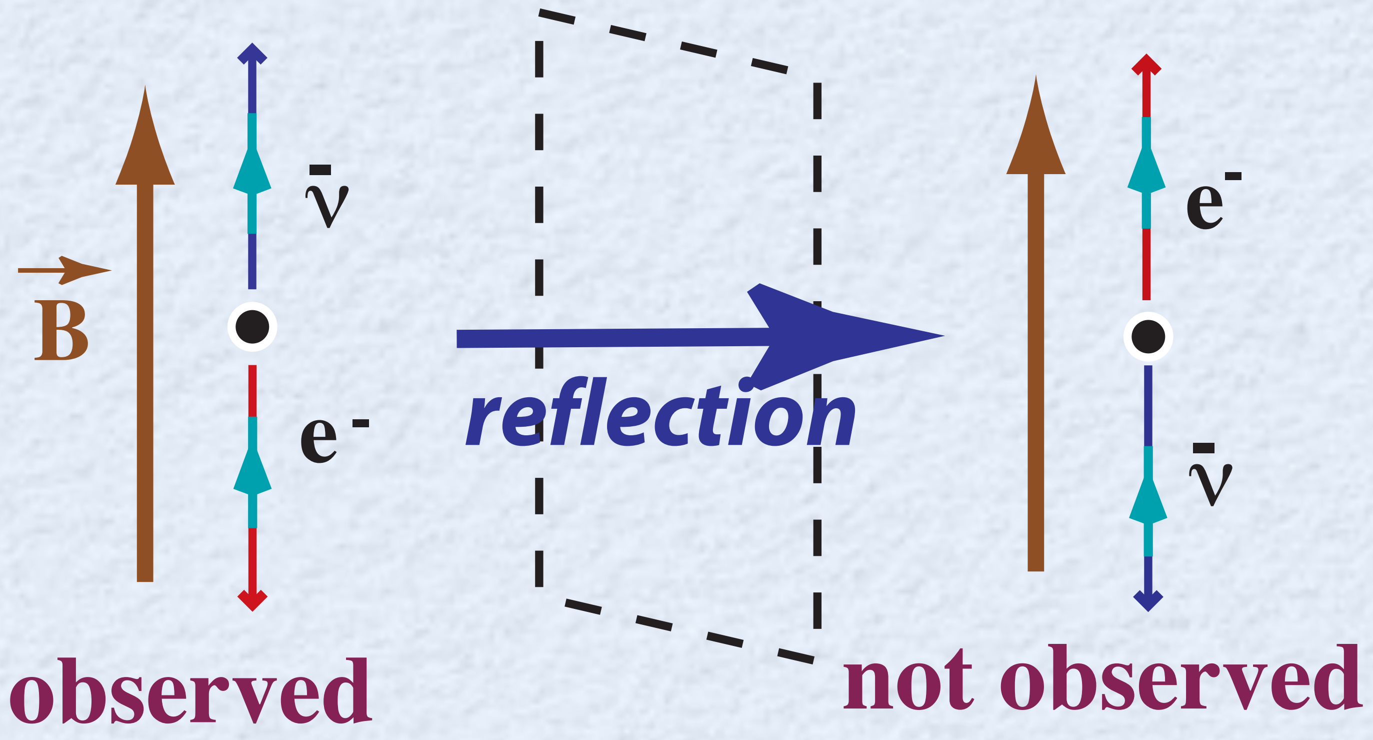

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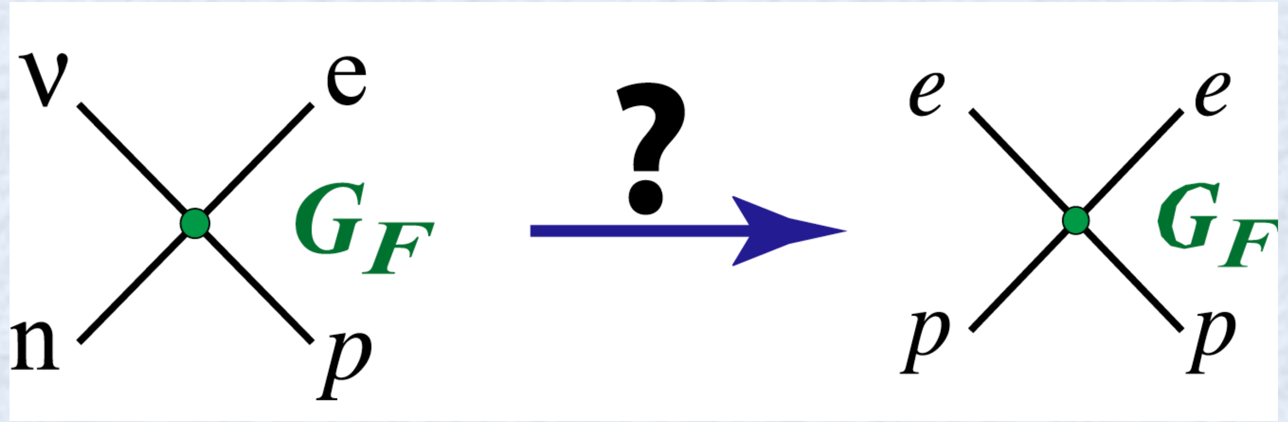

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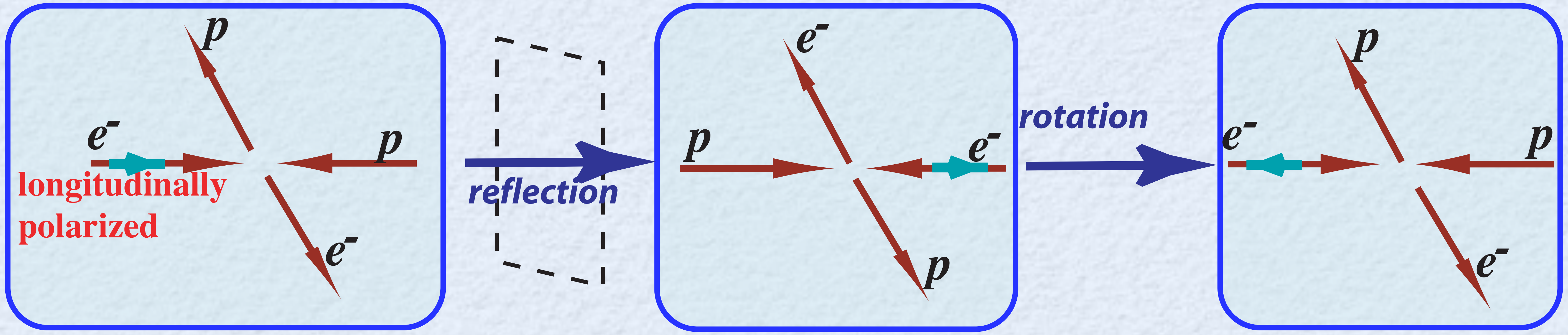

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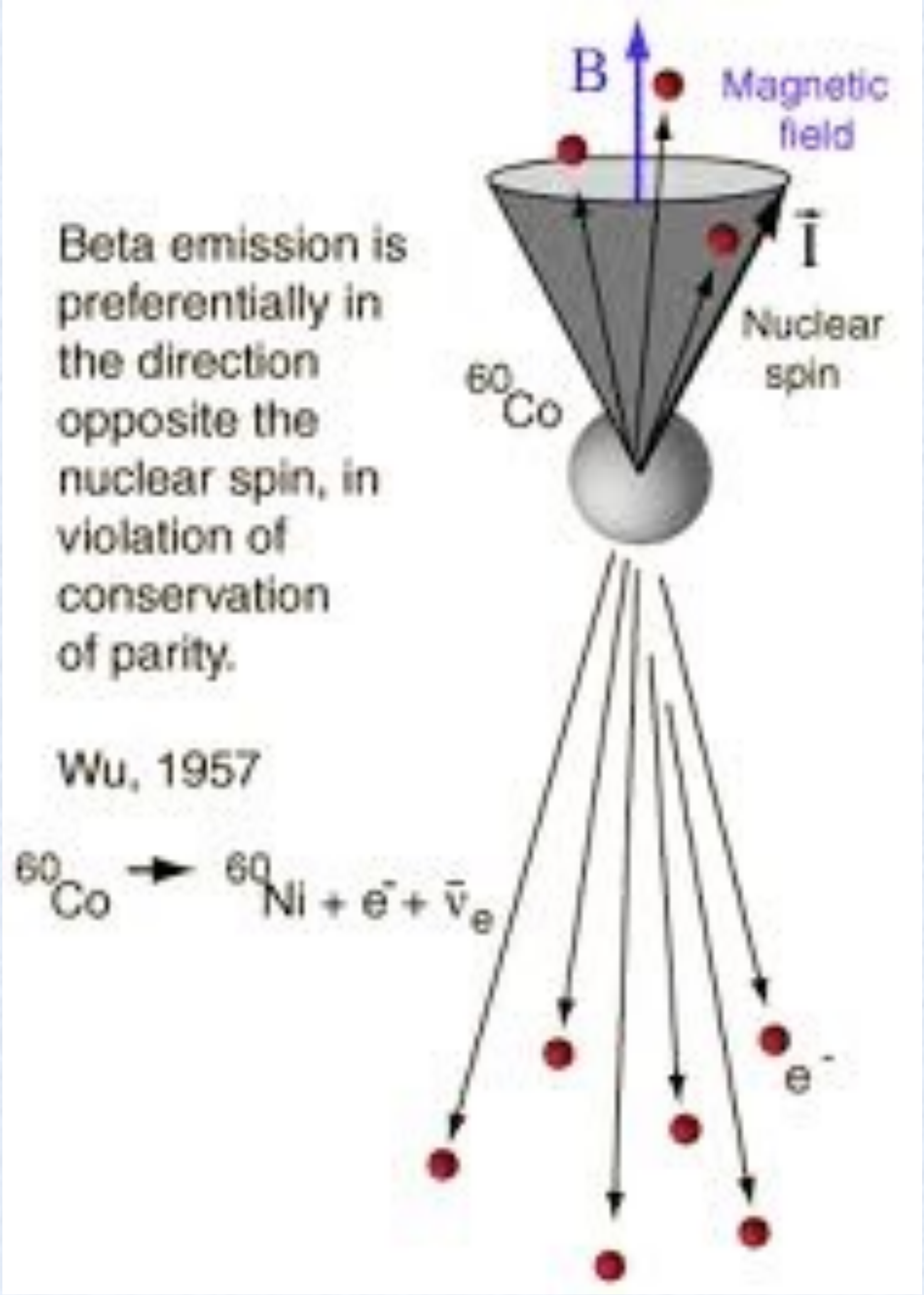

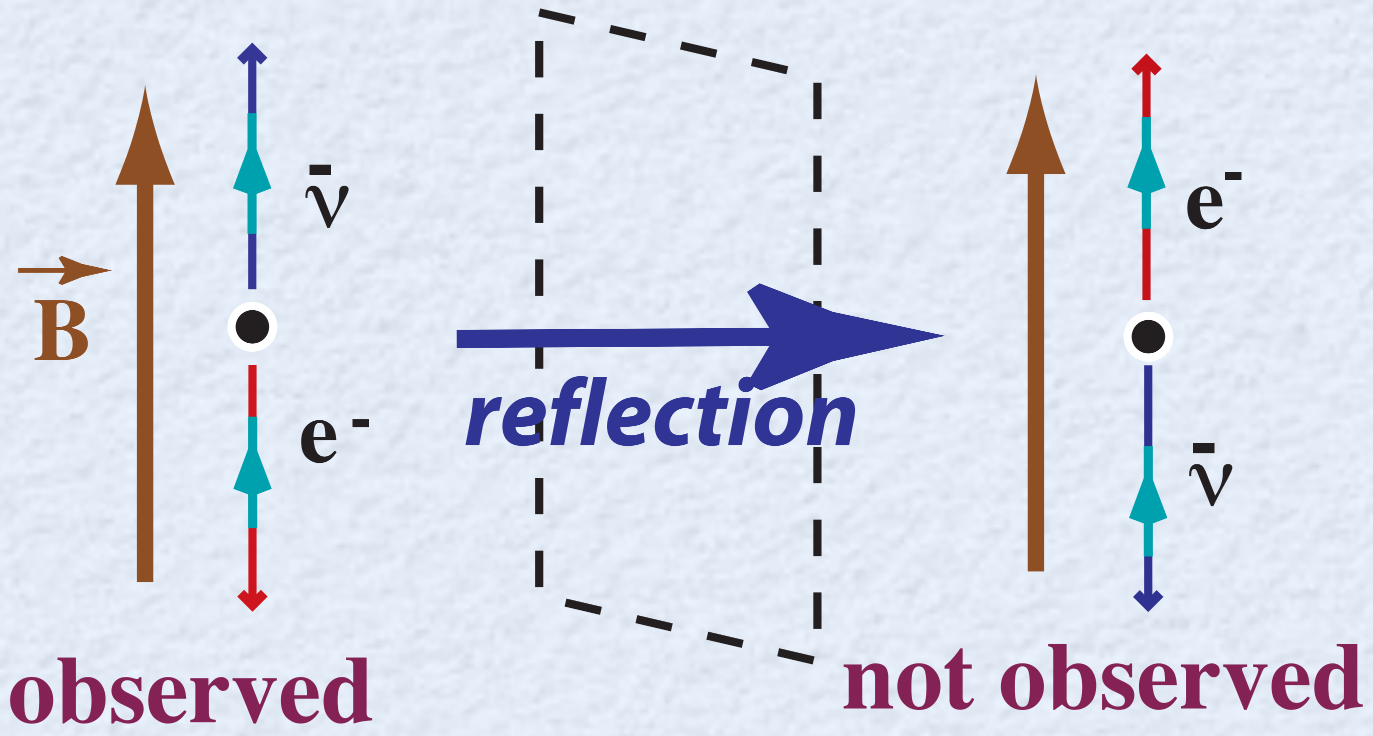

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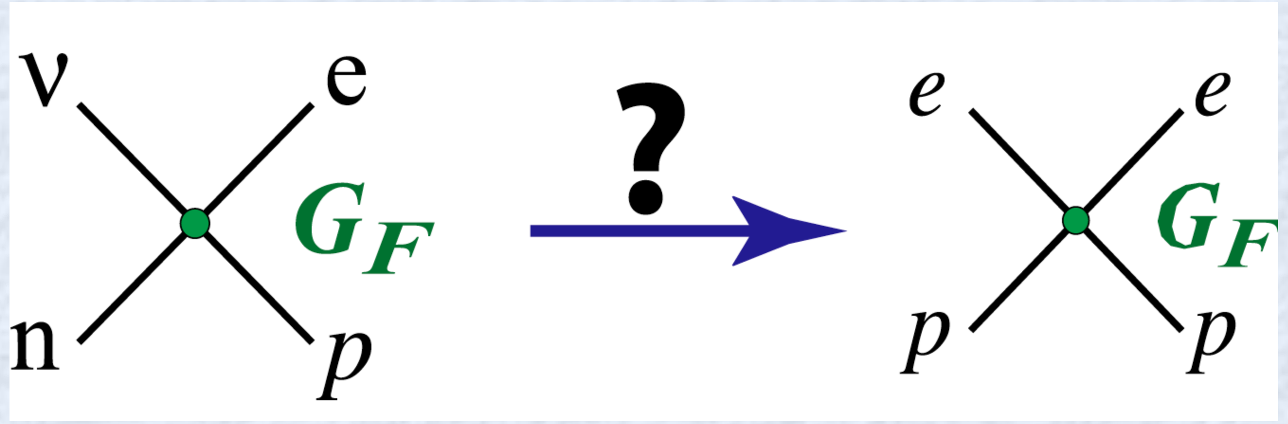

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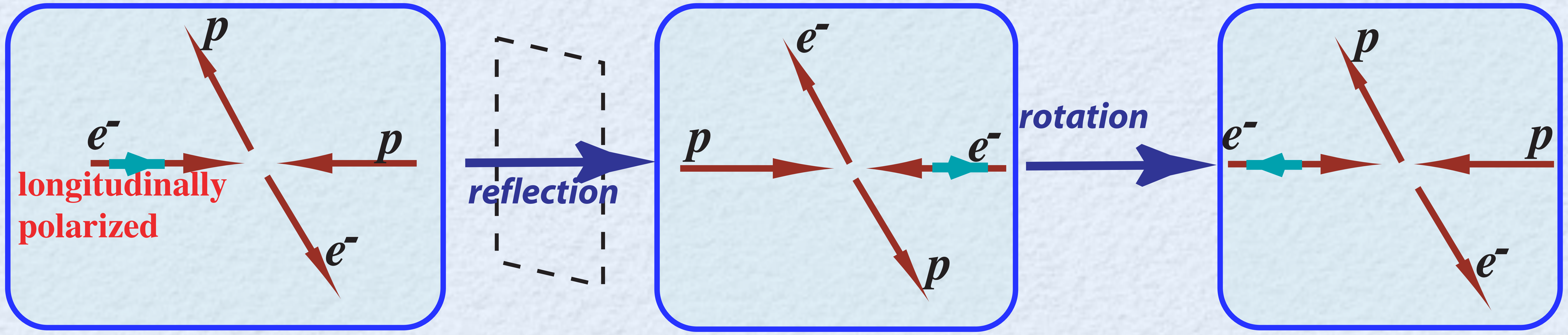

- *longitudinally polarize one beam with the ability to change its sign*
- *Measure fractional rate difference with a sensitivity of a part in 10,000*

Neutral Weak Interaction Theory

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

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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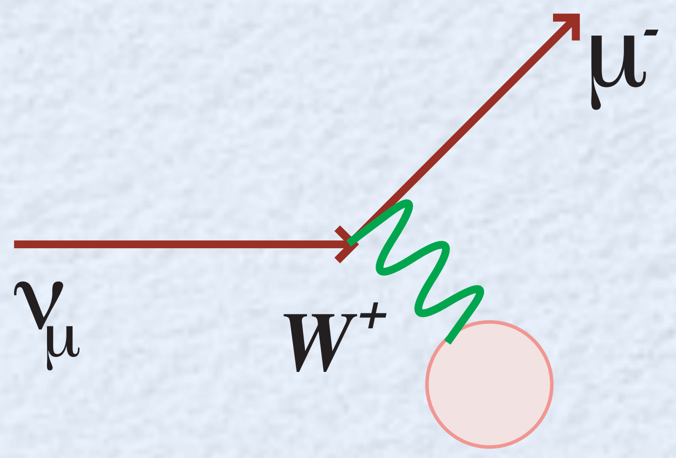

Charged Current

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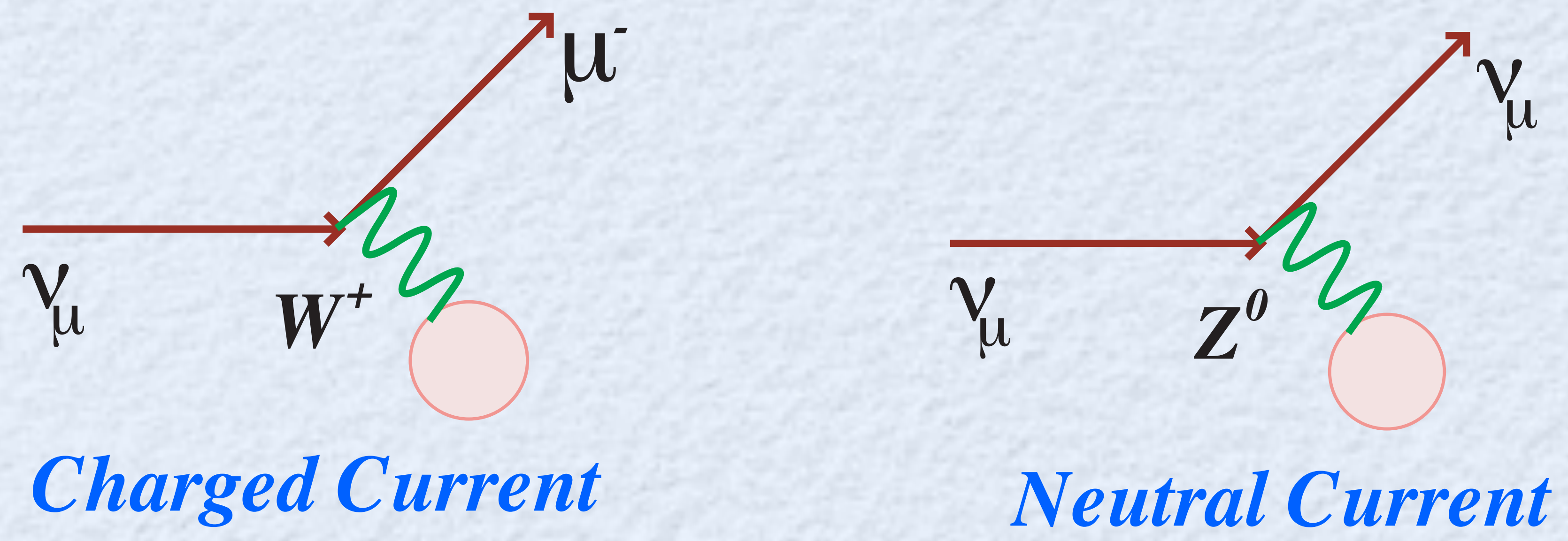

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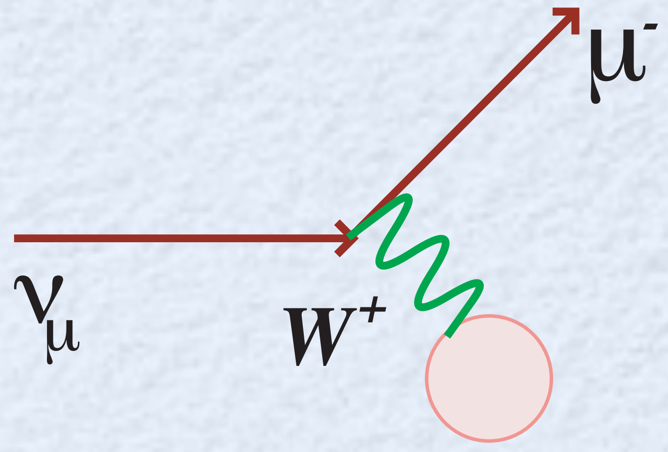

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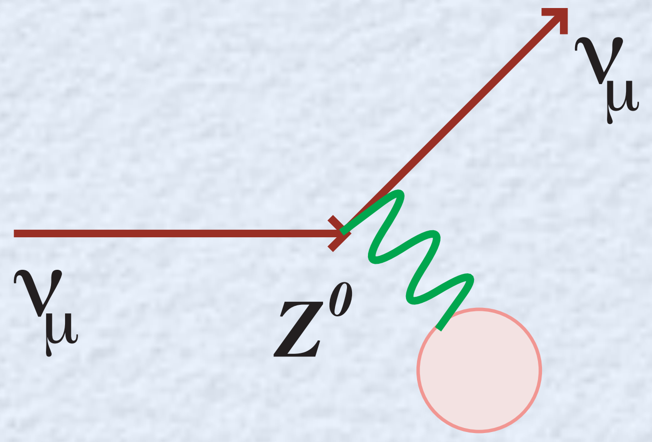

Neutral Current

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

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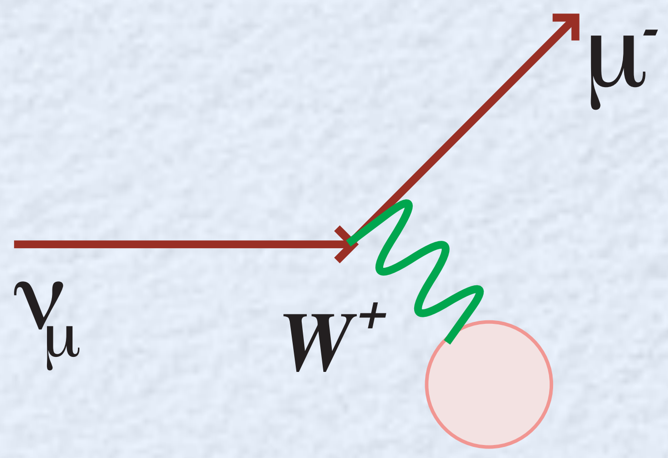

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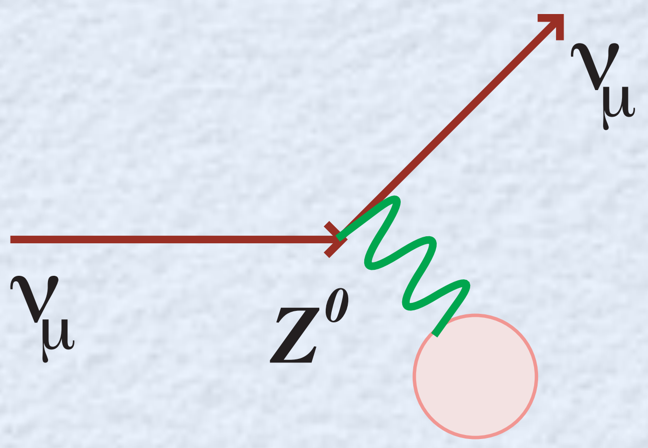

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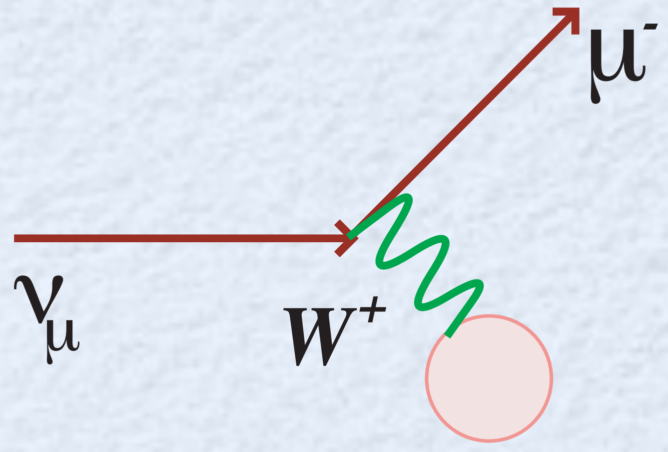

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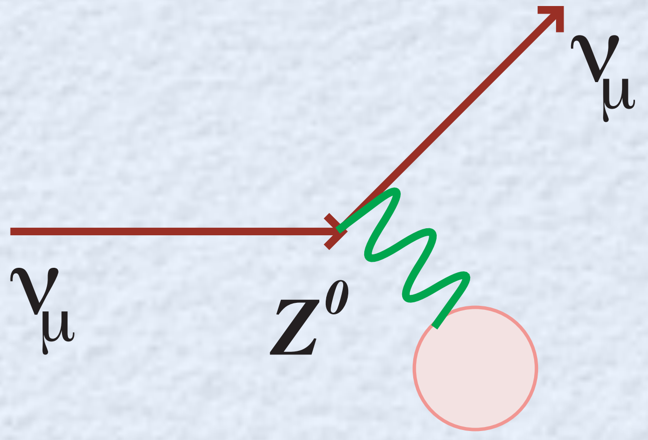

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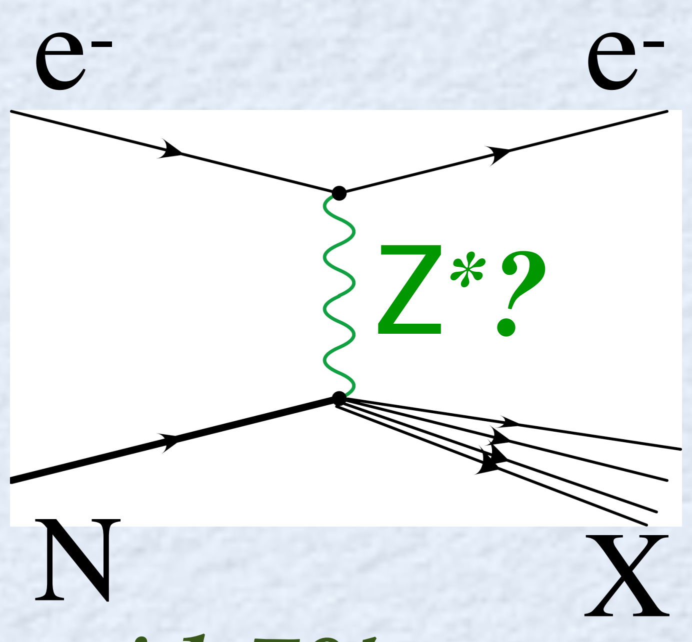
electron-nucleon deep inelastic scattering



pressing problem in mid-70's

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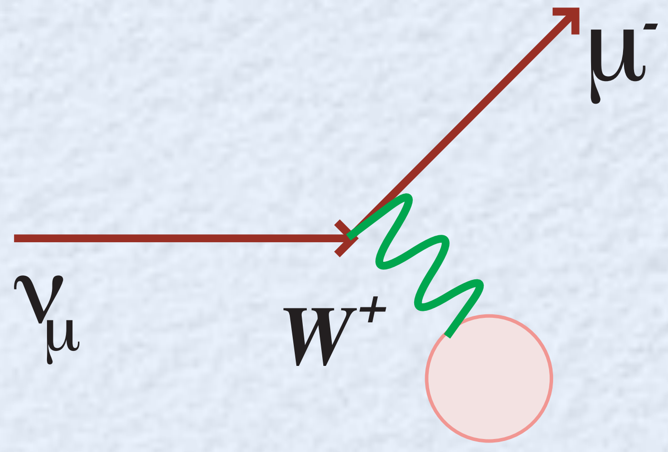

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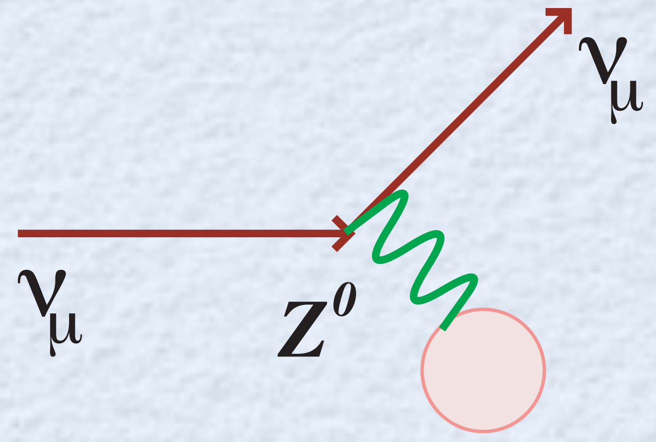

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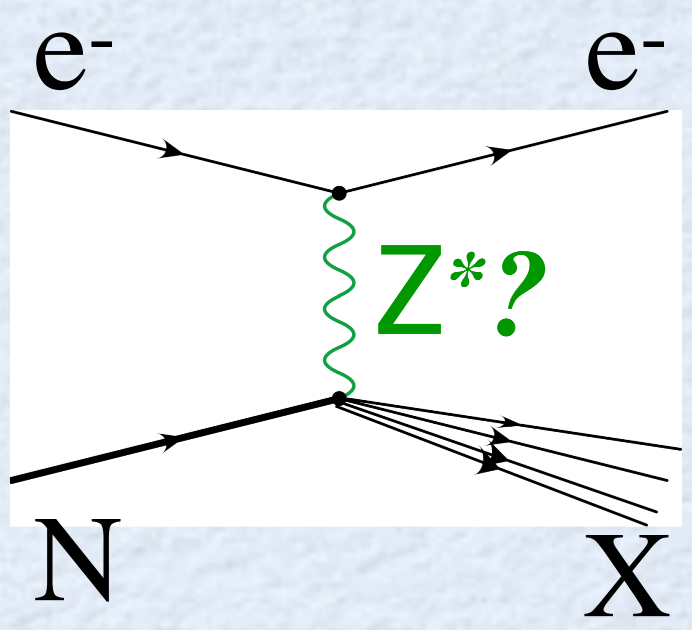
electron-nucleon deep inelastic scattering



pressing problem in mid-70's

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

Weinberg model

Parity is violated

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

or

$$\begin{pmatrix} \nu \\ e \end{pmatrix}_l \quad \begin{pmatrix} E^0 \\ e \end{pmatrix}_r$$

Parity is conserved

Seminal Experimental Measurement: E122 at the Stanford Linear Accelerator Center

First table-top atomic parity violation searches: negative!

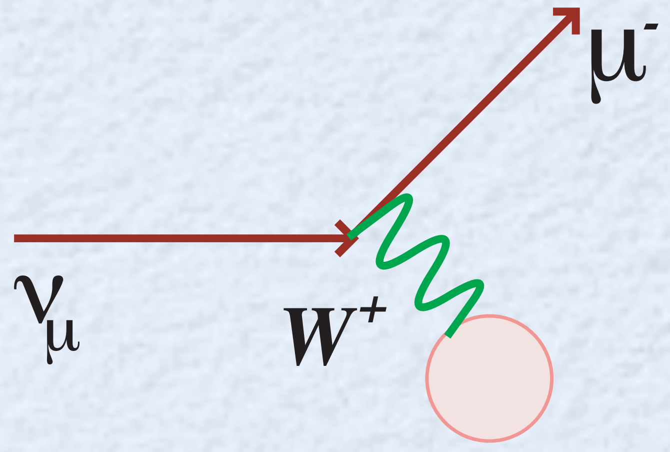
Neutral Weak Interaction Theory

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

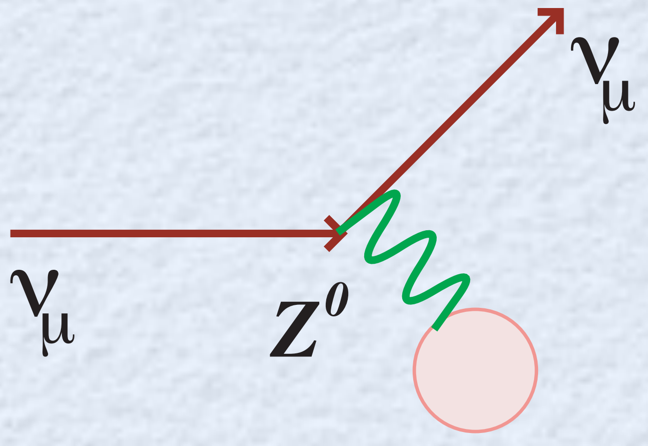
The Z boson incorporated

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

One free parameter: weak mixing angle θ_W



Charged Current



Neutral Current

Do lepton-nucleon neutral current interactions exhibit parity violation?

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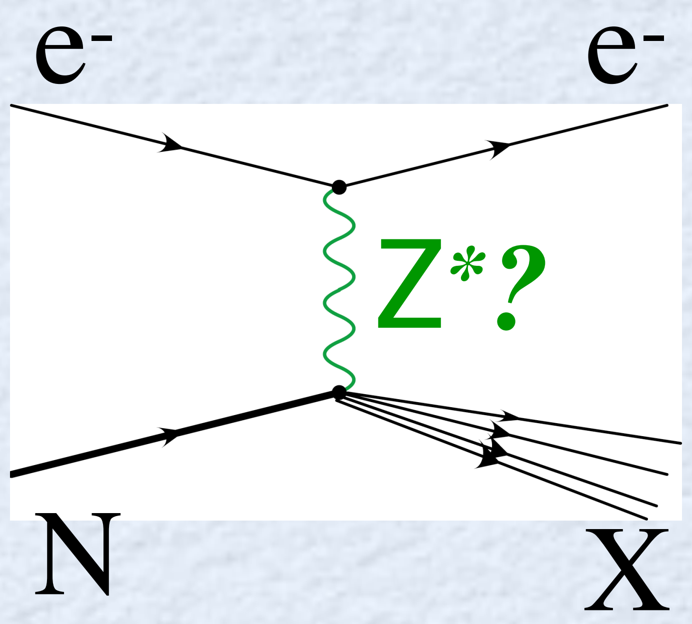

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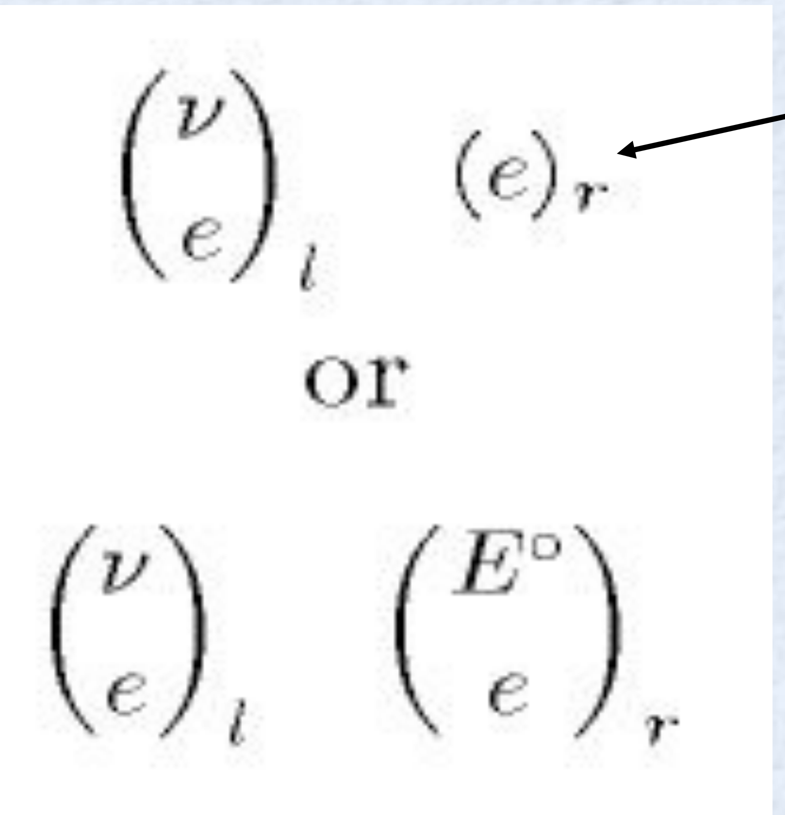


Weinberg model

Parity is violated

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

Parity is conserved

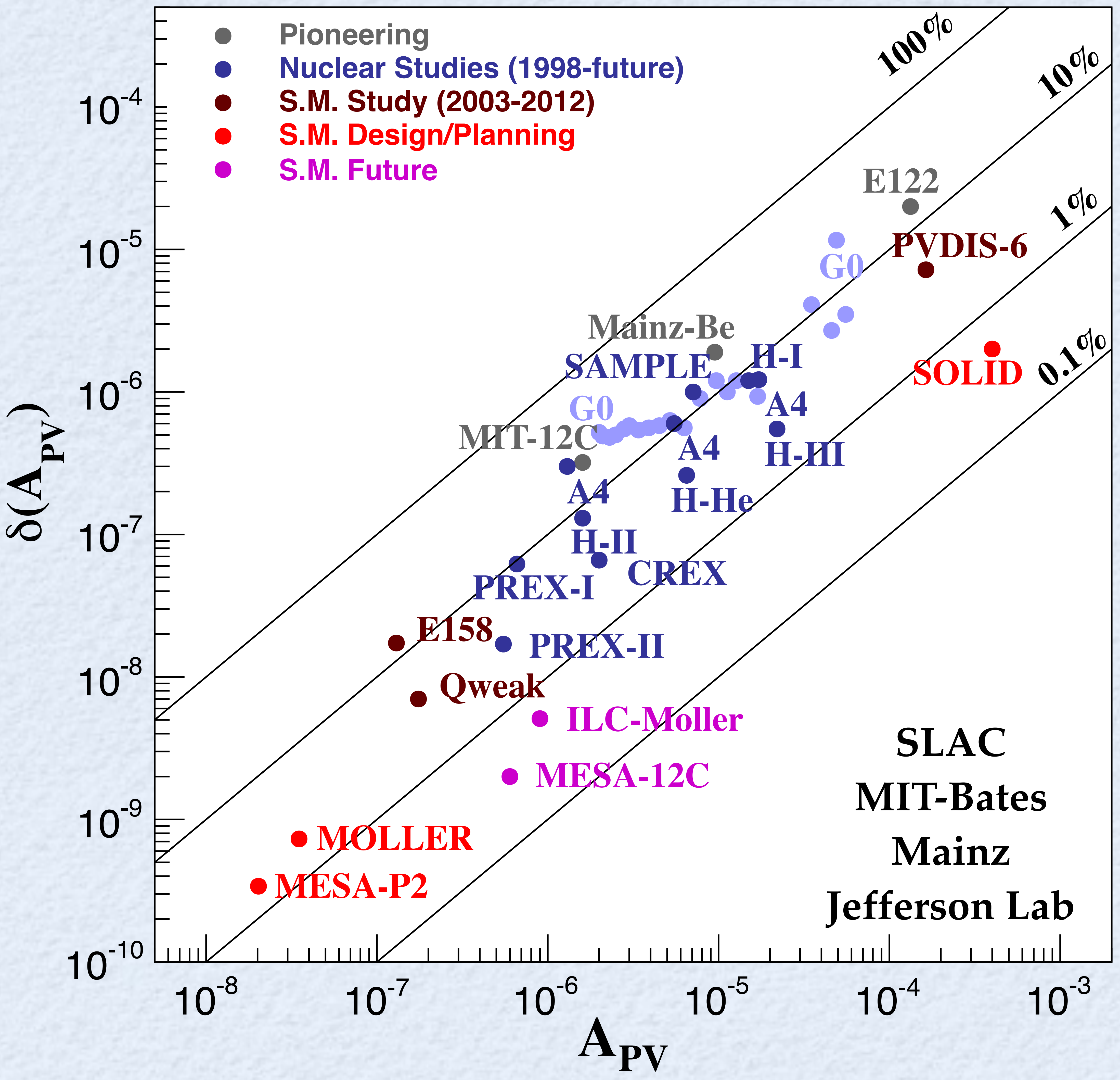
Seminal Experimental Measurement: E122 at the Stanford Linear Accelerator Center

- *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!

4 Decades of Technical Progress

Continuous interplay between probing hadron structure and electroweak physics



Parity-violating electron scattering has become a precision tool

- *Beyond Standard Model Searches*
- *Strange quark form factors*
- *Neutron skin of a heavy nucleus*
- *QCD structure of the nucleon*

Mainz & MIT-Bates in the mid-80s

JLab program launched in the mid-90s

E158 at SLAC measured PV Møller scattering

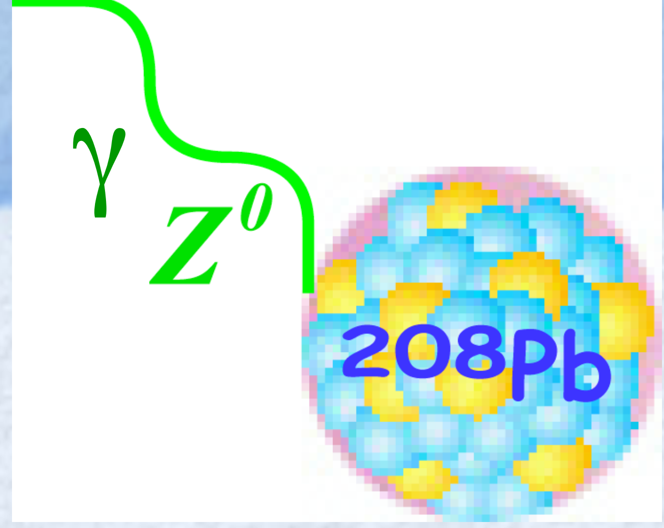
State-of-the-art:

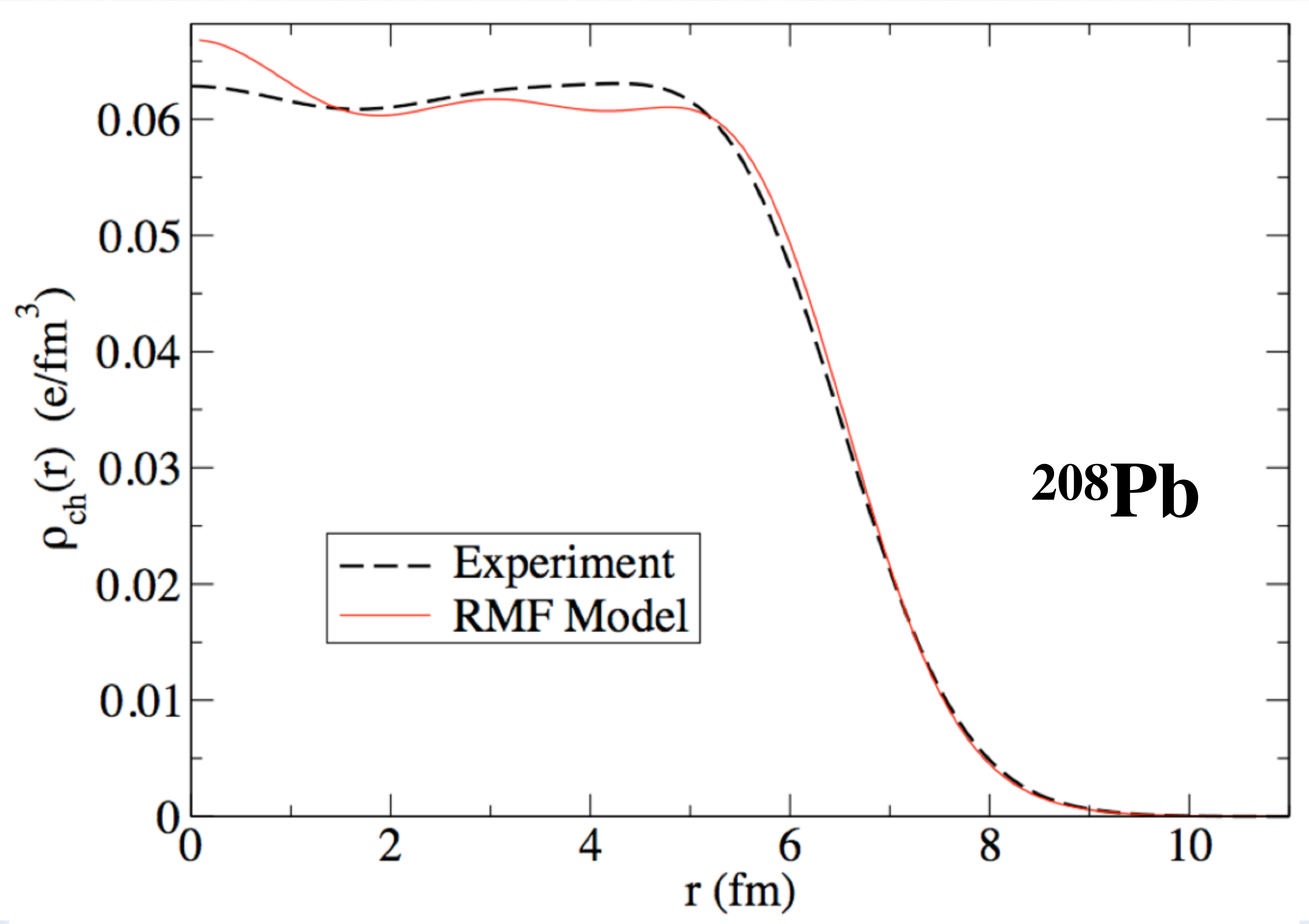
- *sub-part per billion statistical reach and systematic control*
- *sub-1% normalization control*

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

Pb-Radius EXperiment

PREX Concept





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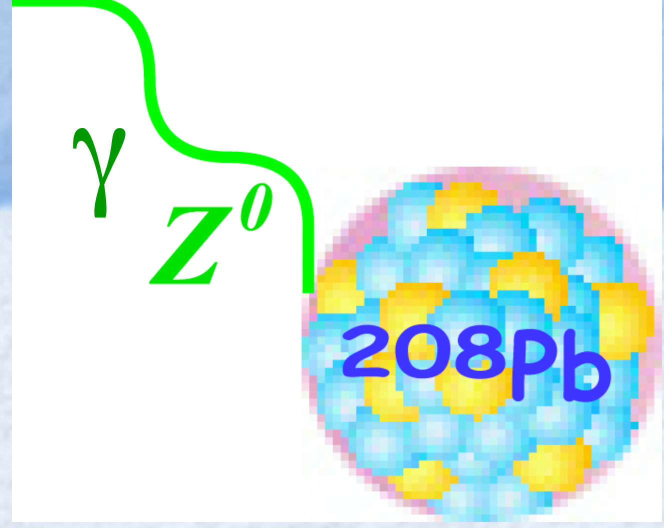

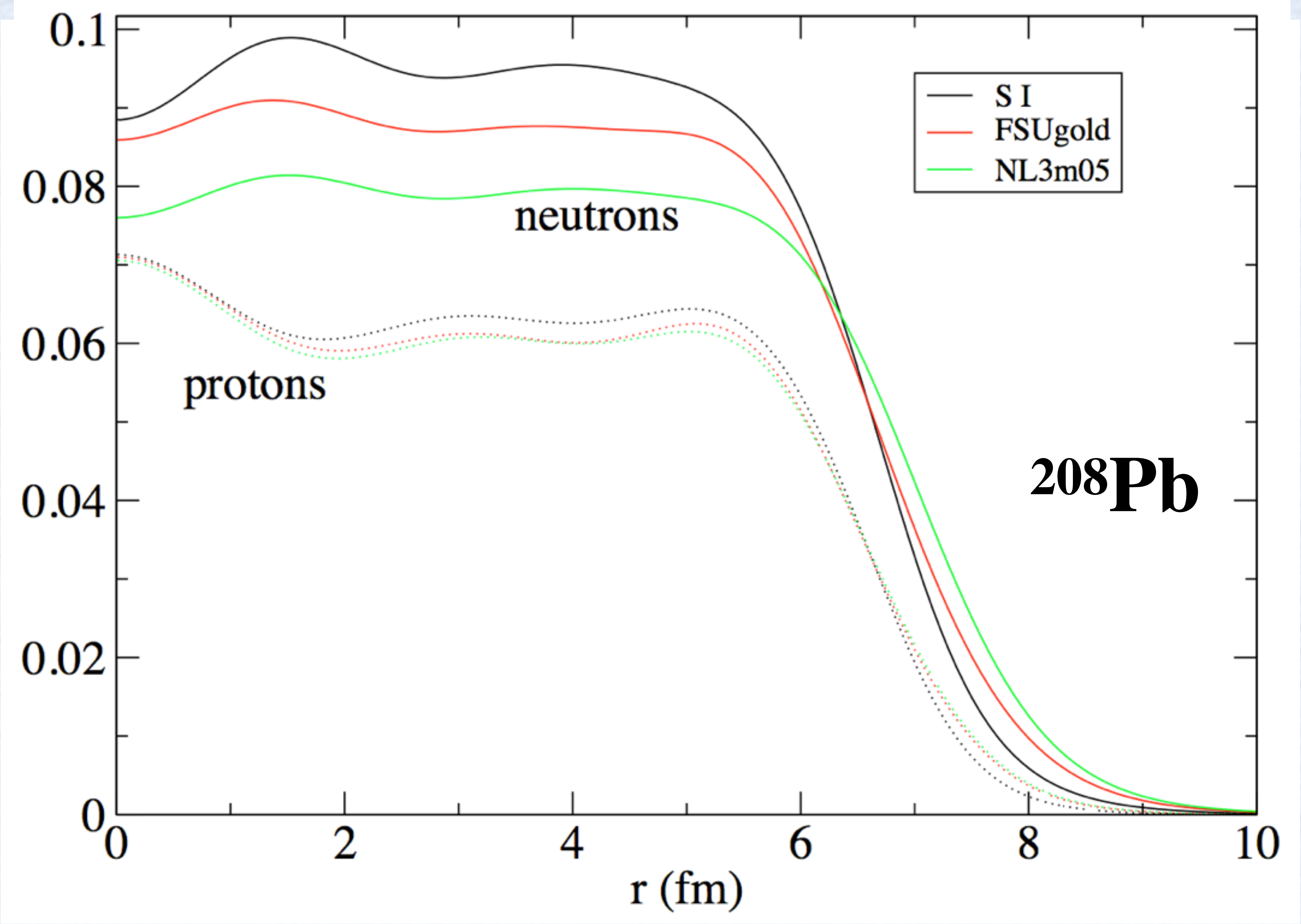

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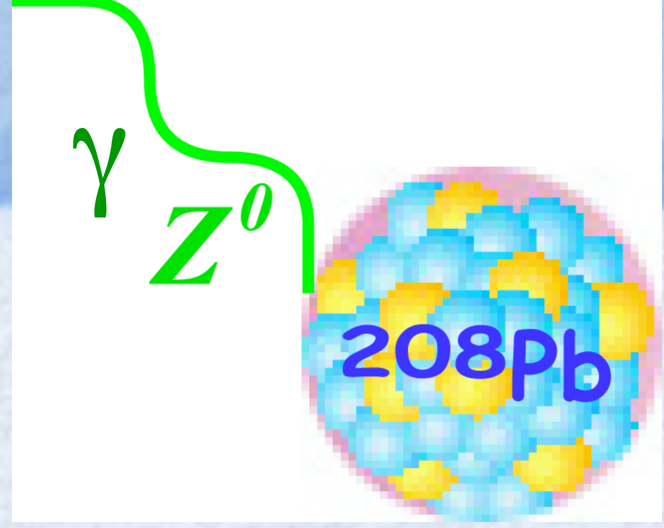
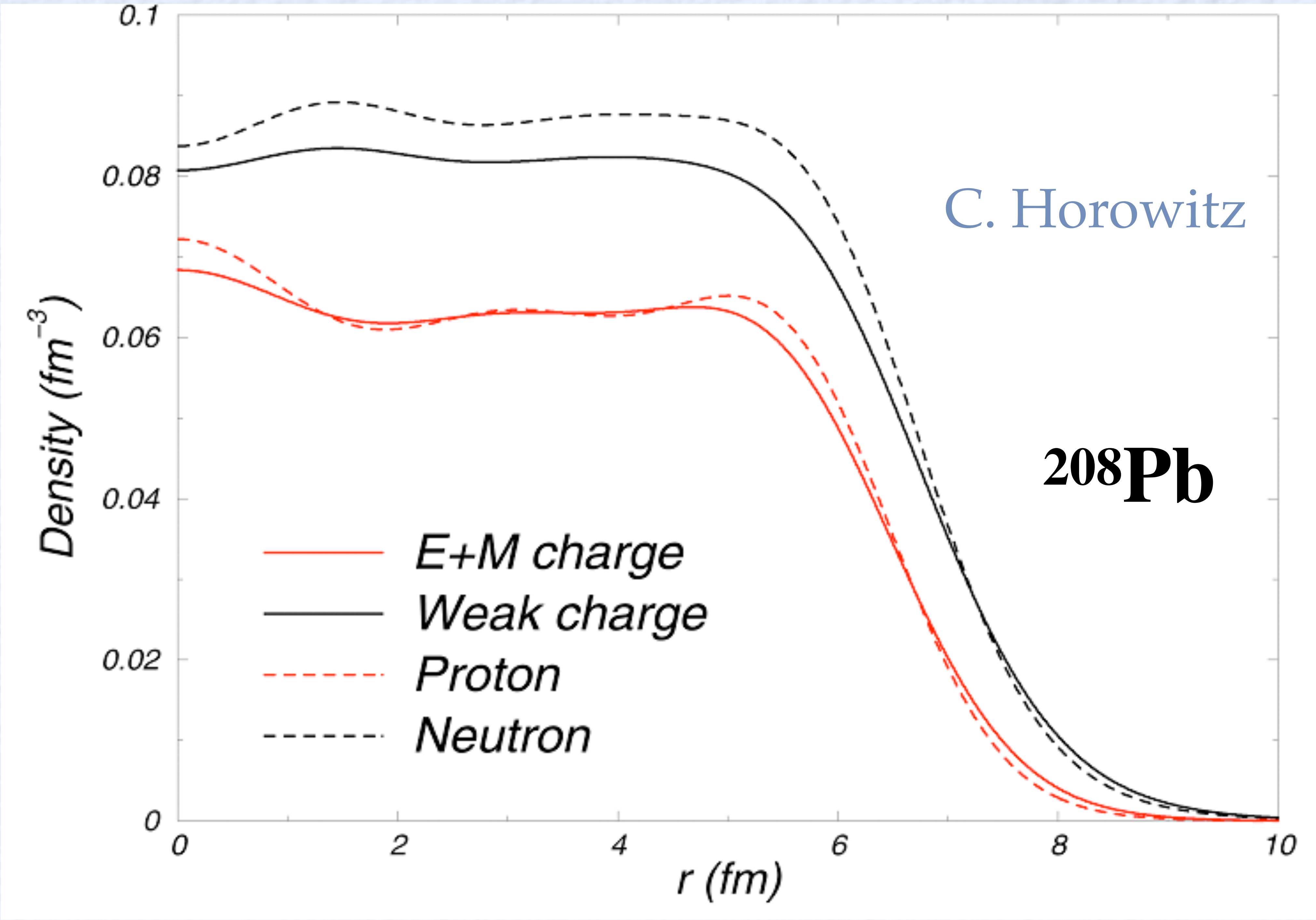
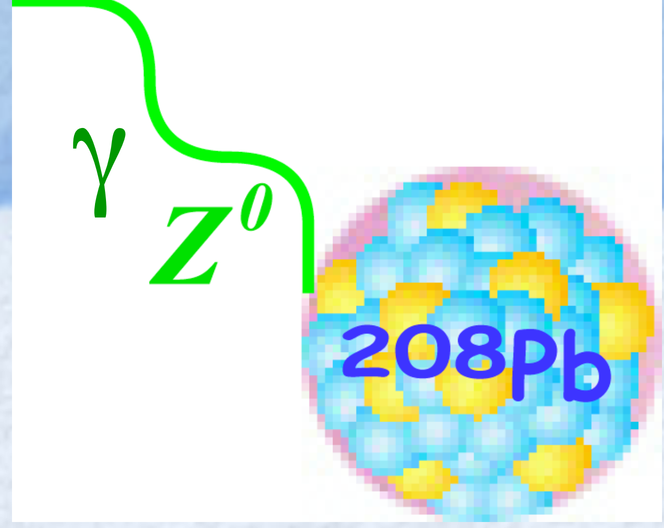


$Q^p_{EM} \sim 1$ $Q^n_{EM} \sim 0$ $Q^n_W \sim -1$ $Q^p_W \sim 1 - 4\sin^2\theta_W$



Pb-Radius EXperiment   PREX Concept



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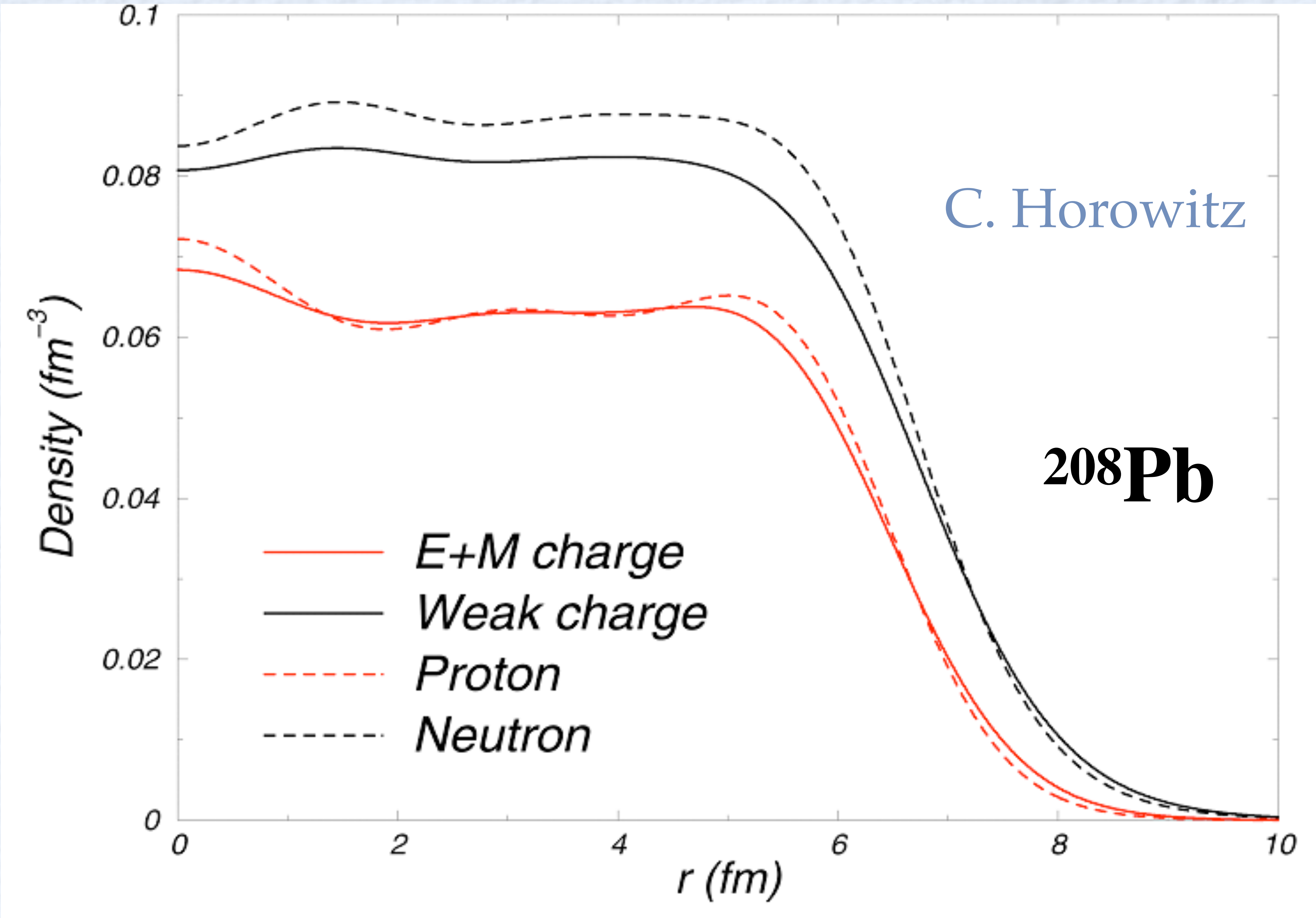
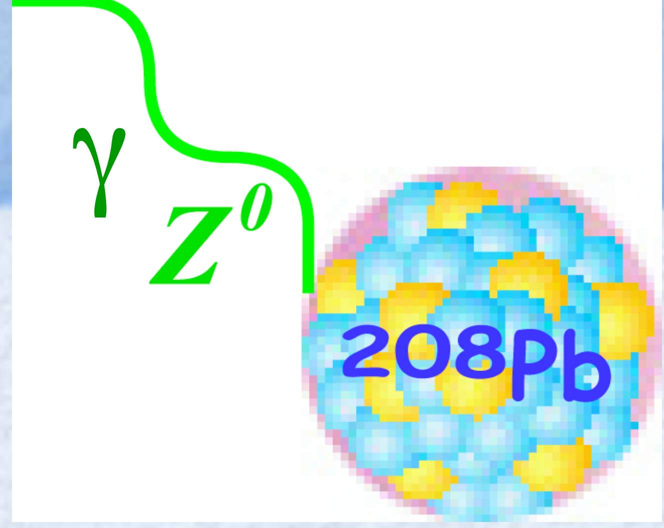


$$\mathcal{M}_{EM} \propto \frac{4\pi\alpha}{Q^2} F_{ch}(Q^2) \qquad \mathcal{M}_{Weak} \propto \frac{G_F}{\sqrt{2}} \gamma_5 F_W(Q^2)$$

PREX Concept



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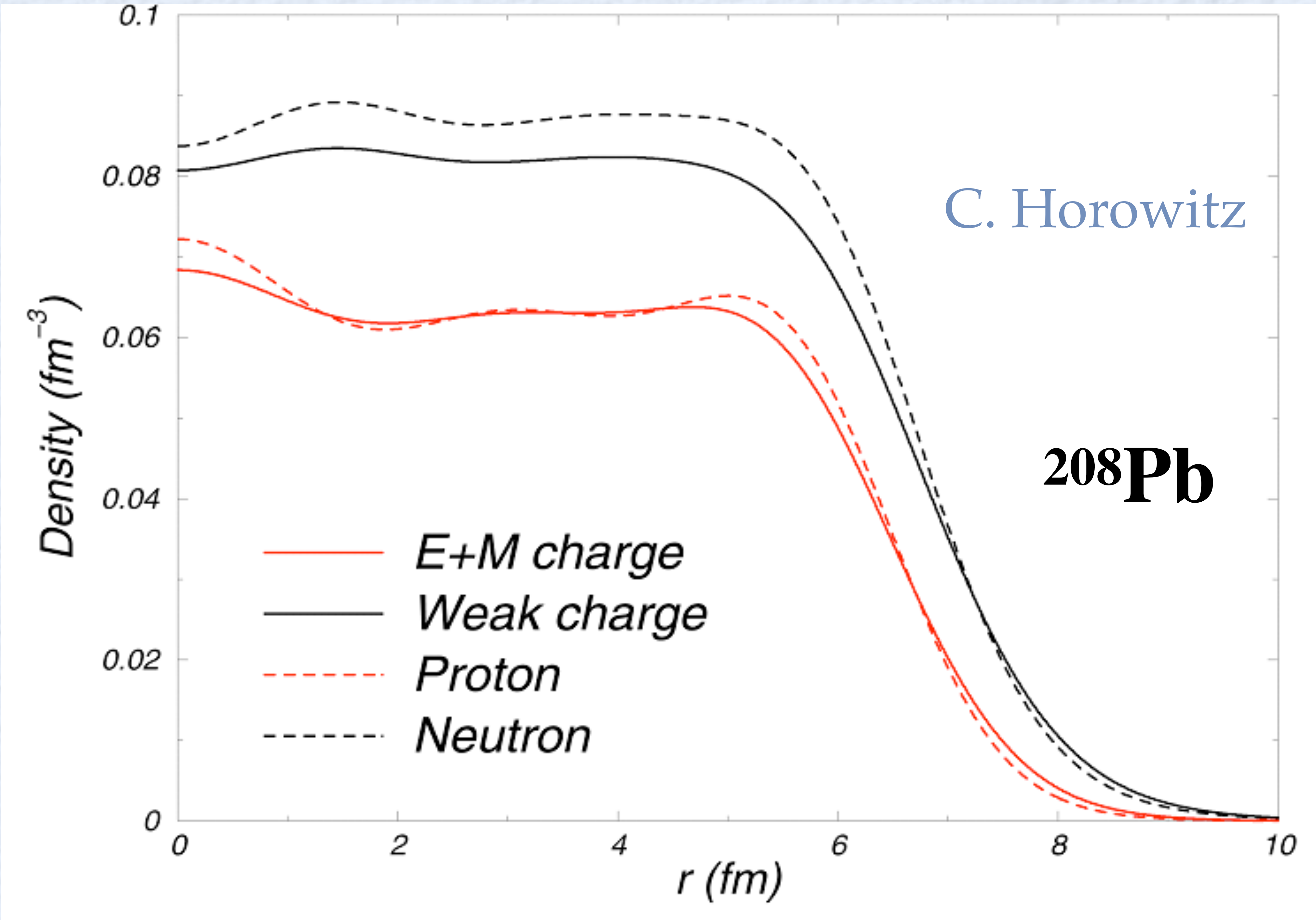

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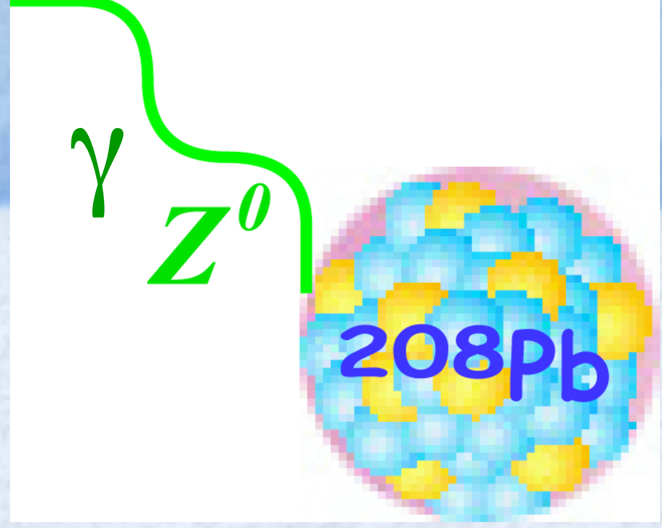
F_{ch} and F_W: Functions of single nucleon form factors F_p and F_n

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

Small corrections involving electric form factors G_E (p,n,s)

PREX Concept

Pb-Radius EXperiment



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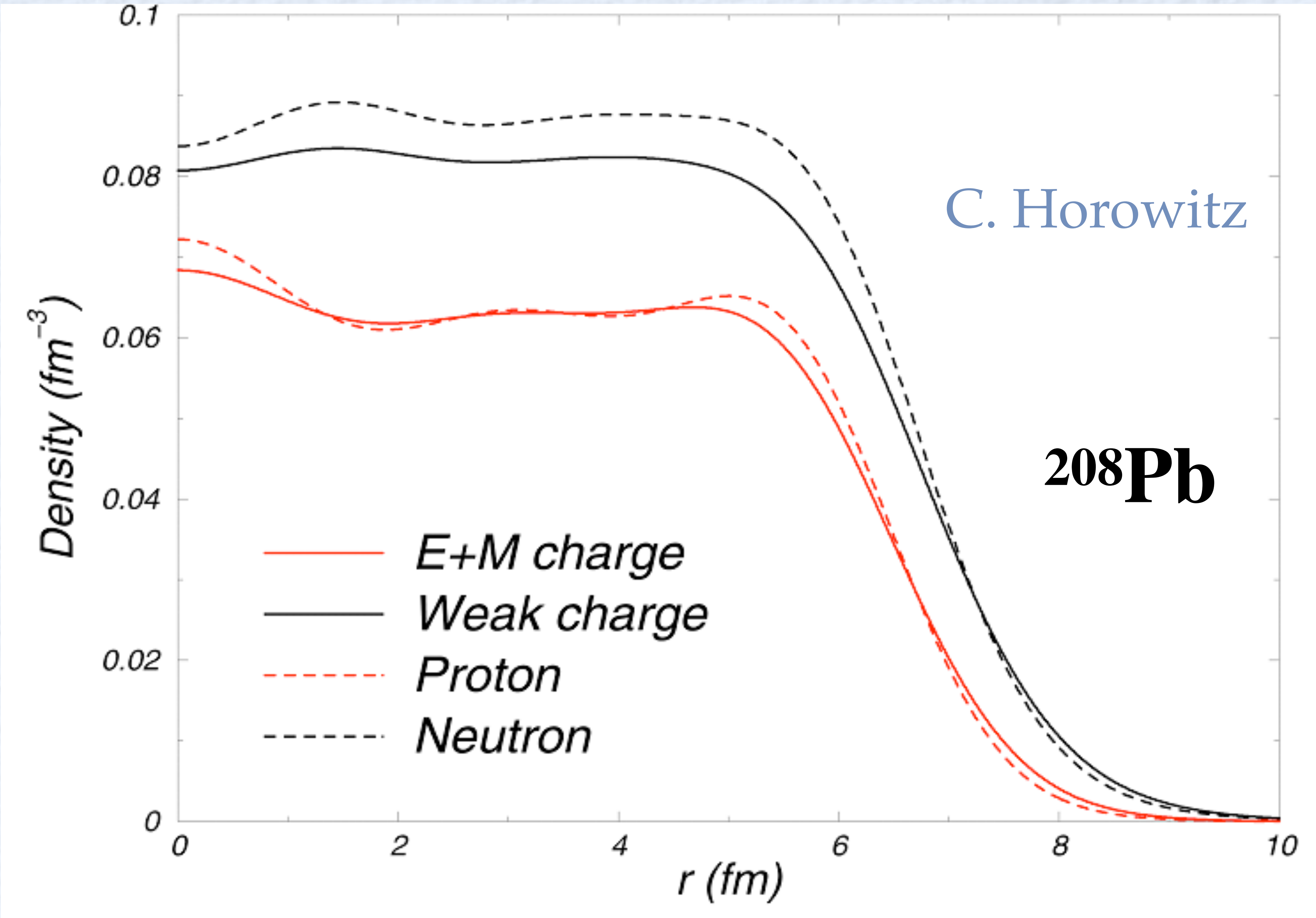

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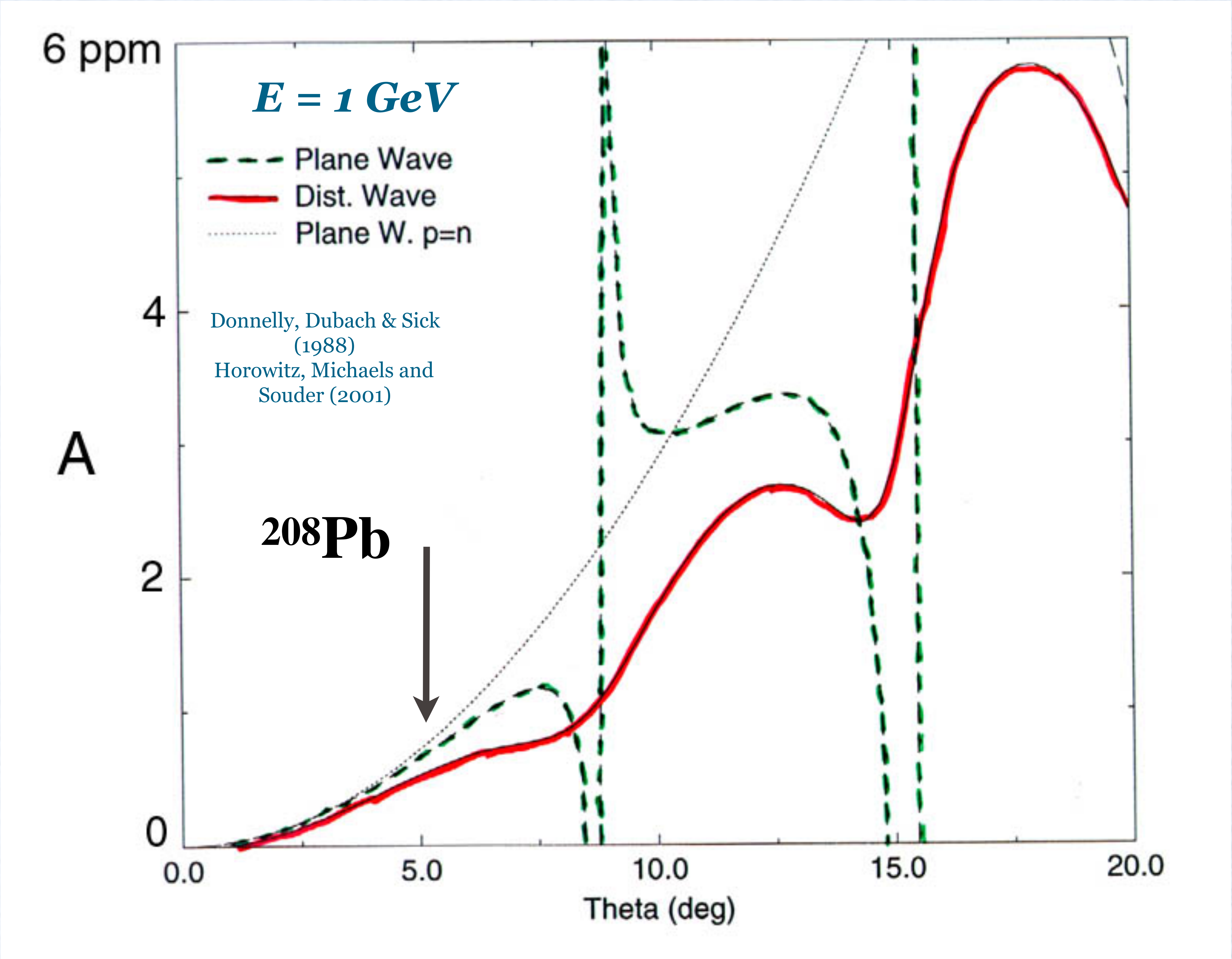

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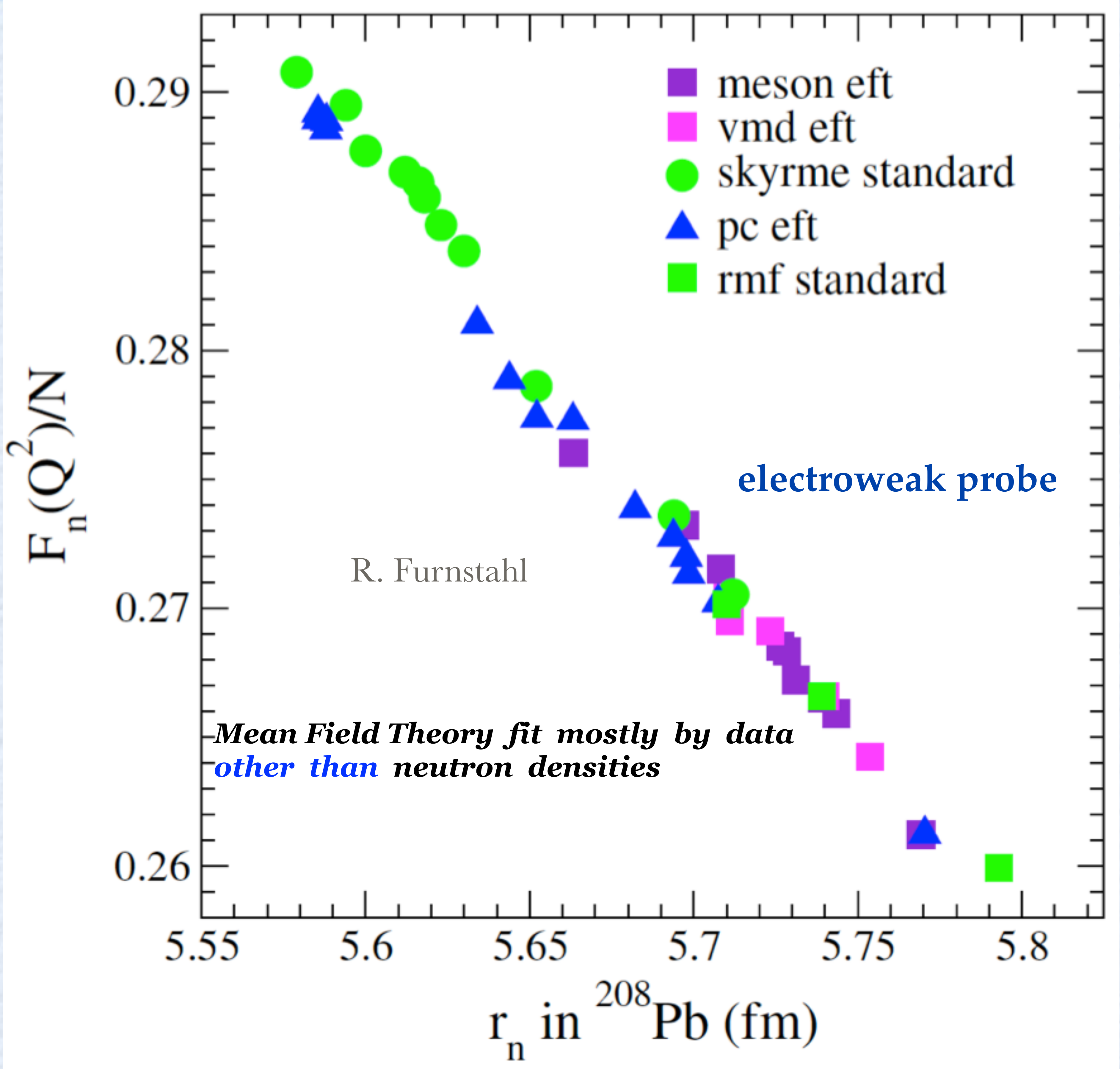

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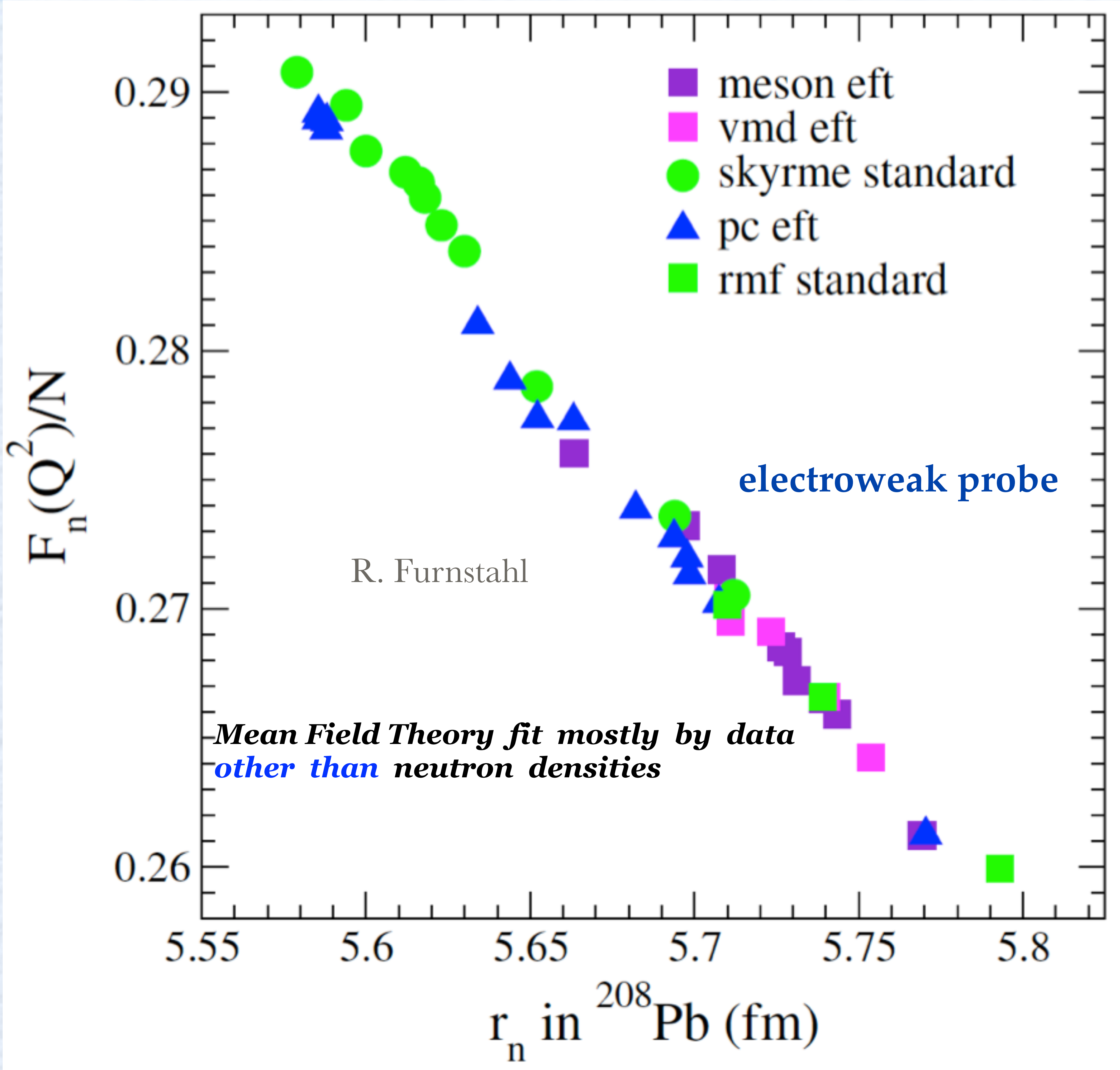

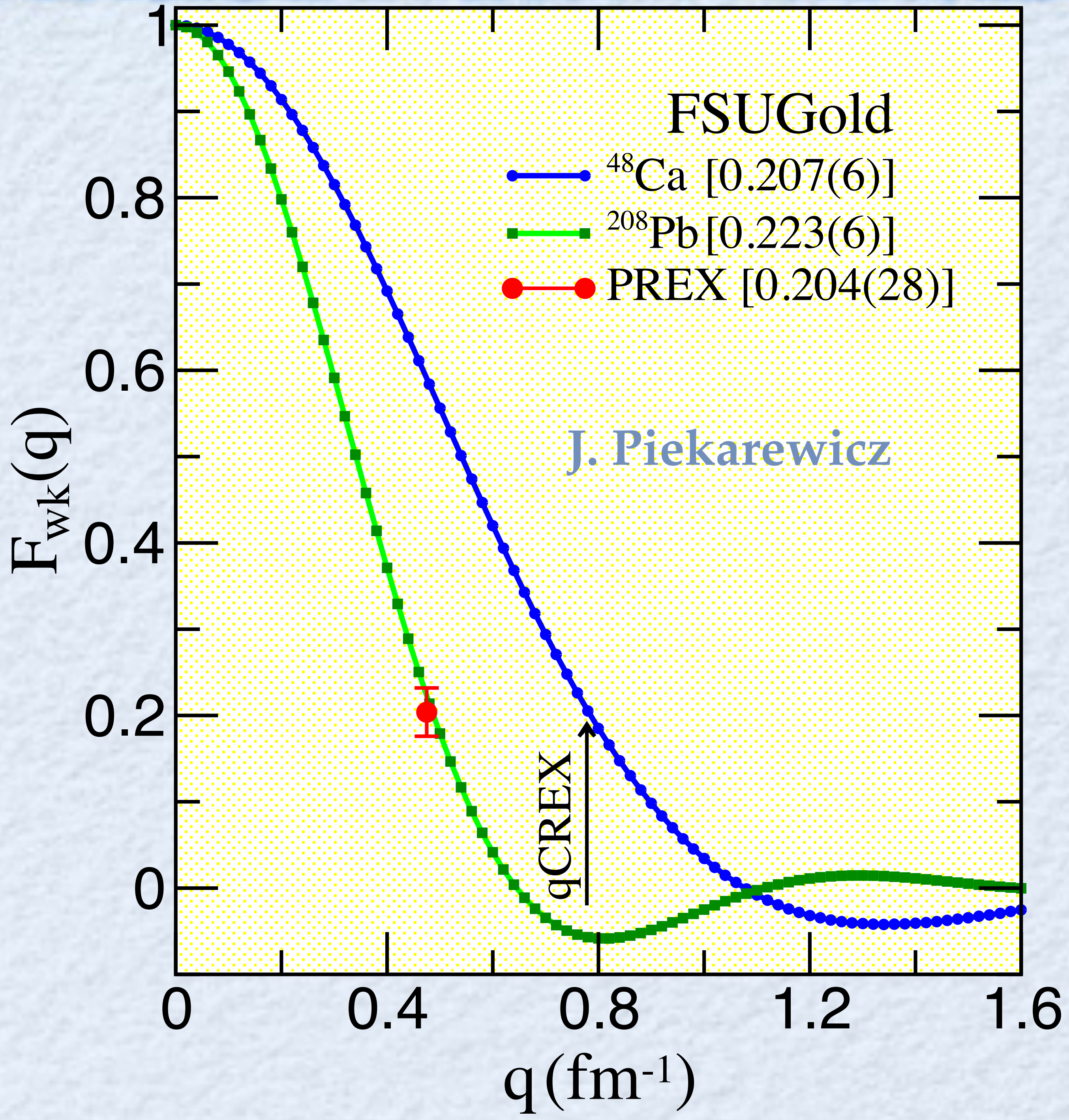

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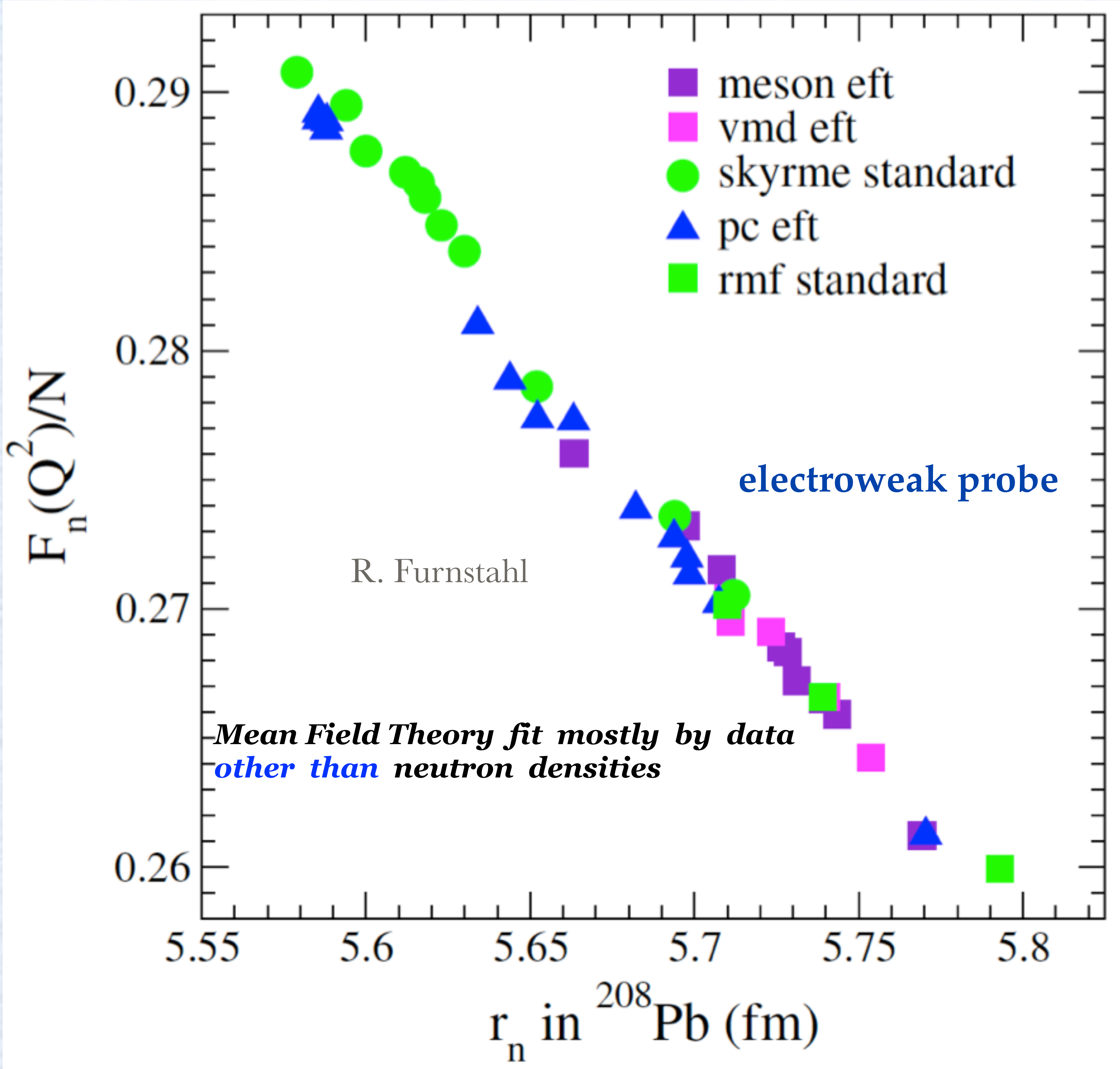


$Q^2 \sim 0.007\ GeV^2$

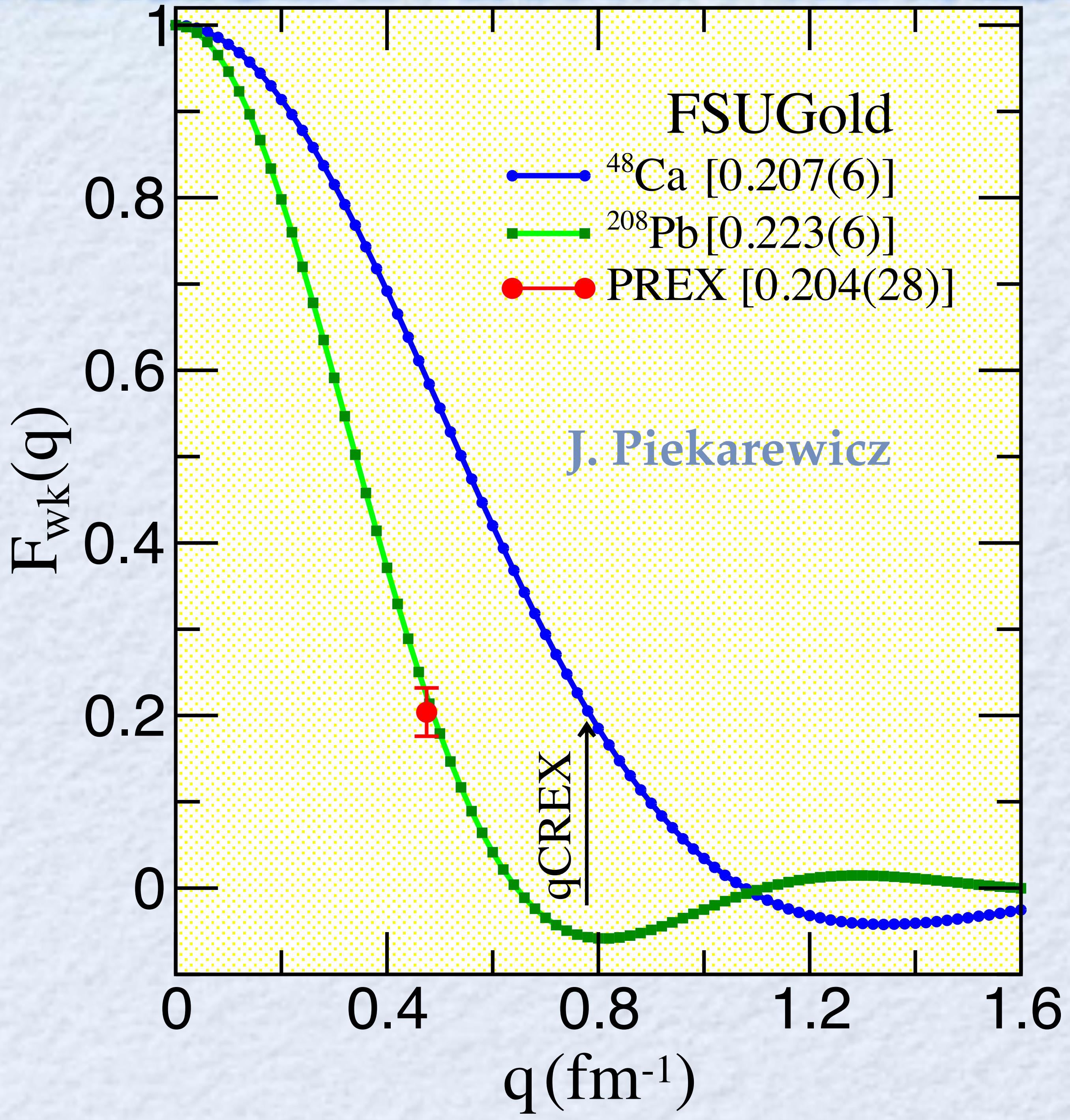
5^o scattering angle

⇓

$A_{PV} \sim 0.5$ ppm

Rate ~ 4 GHz

$\delta(A_{PV}) \sim 15$ ppb!



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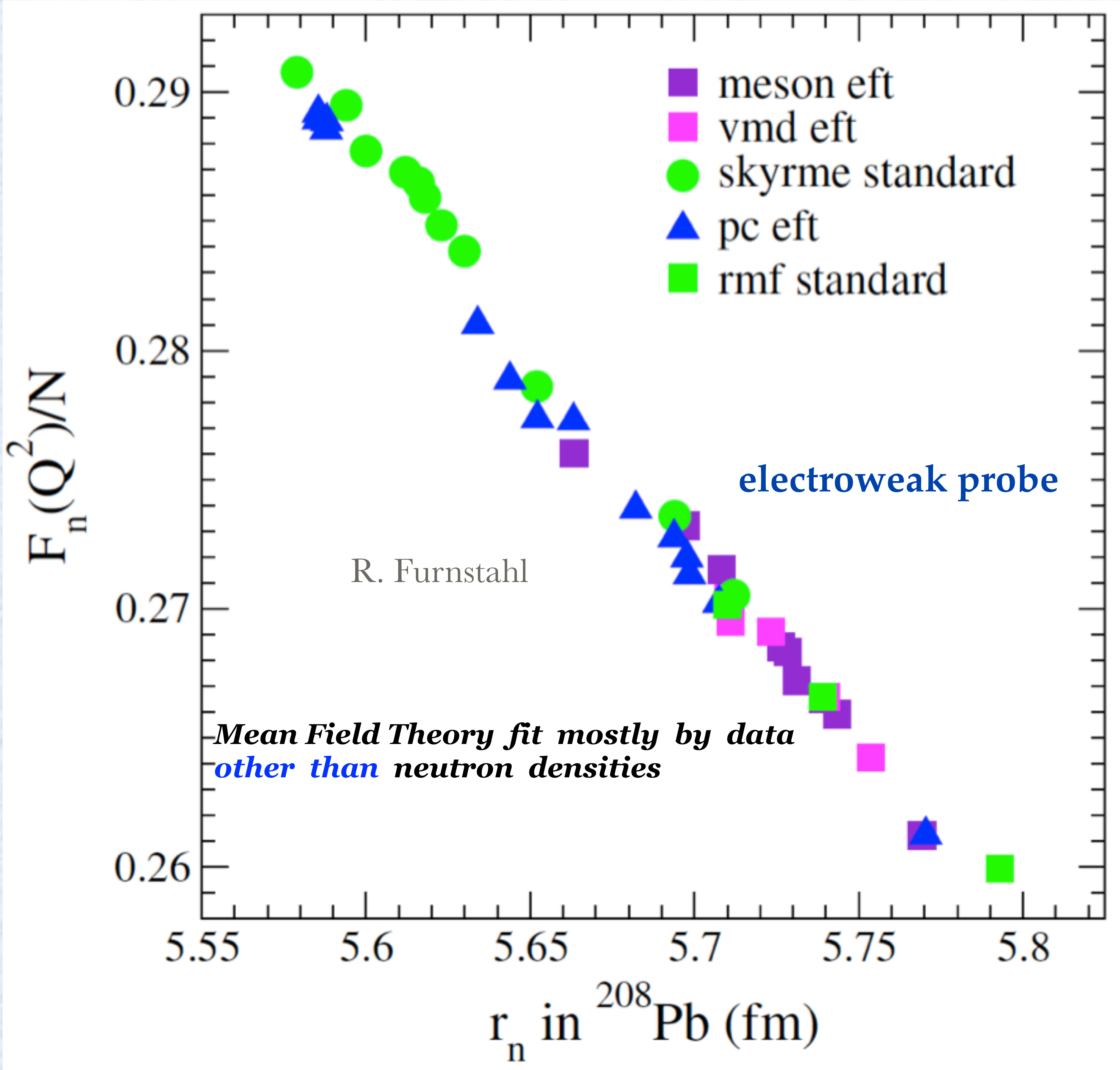

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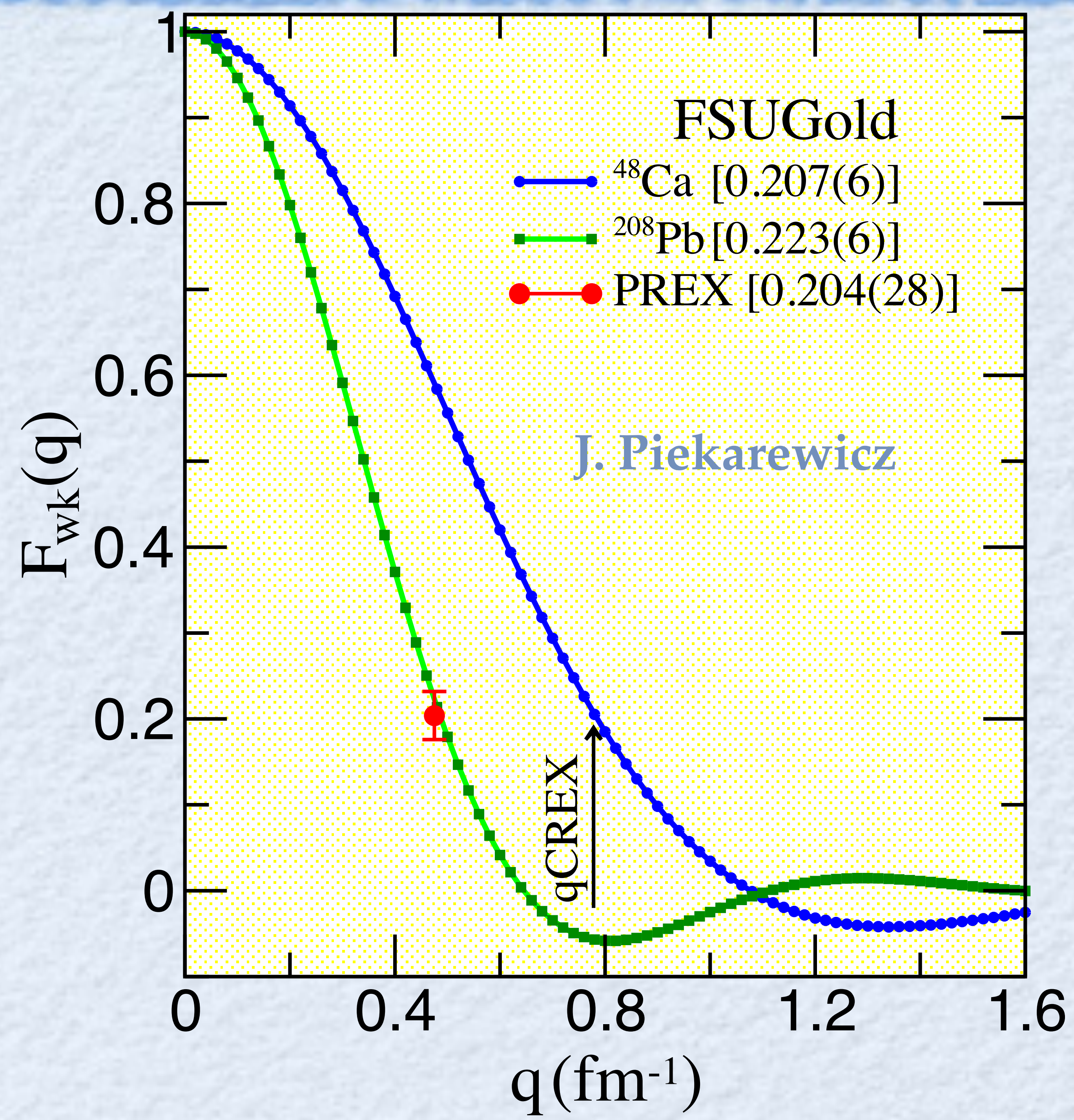

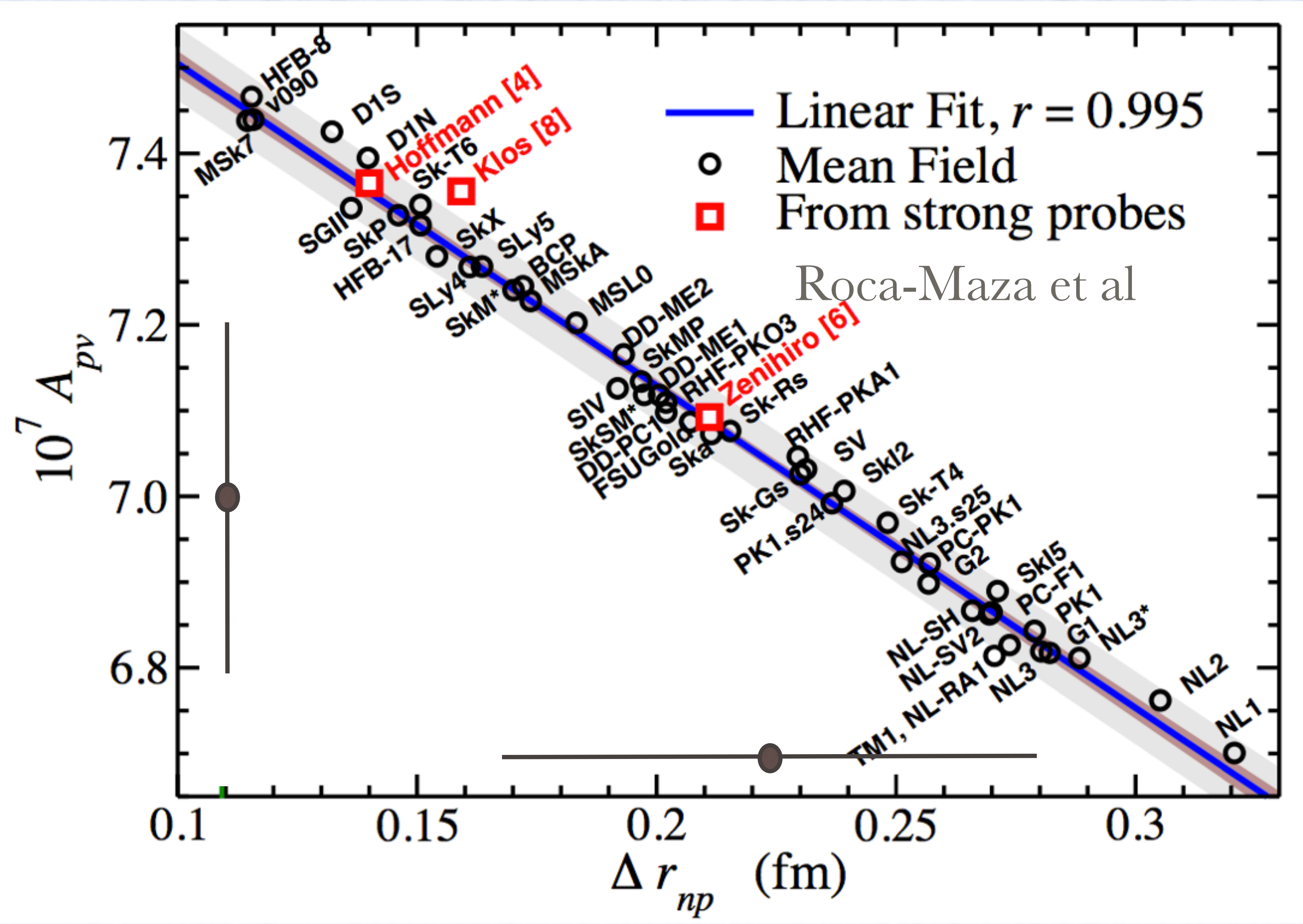

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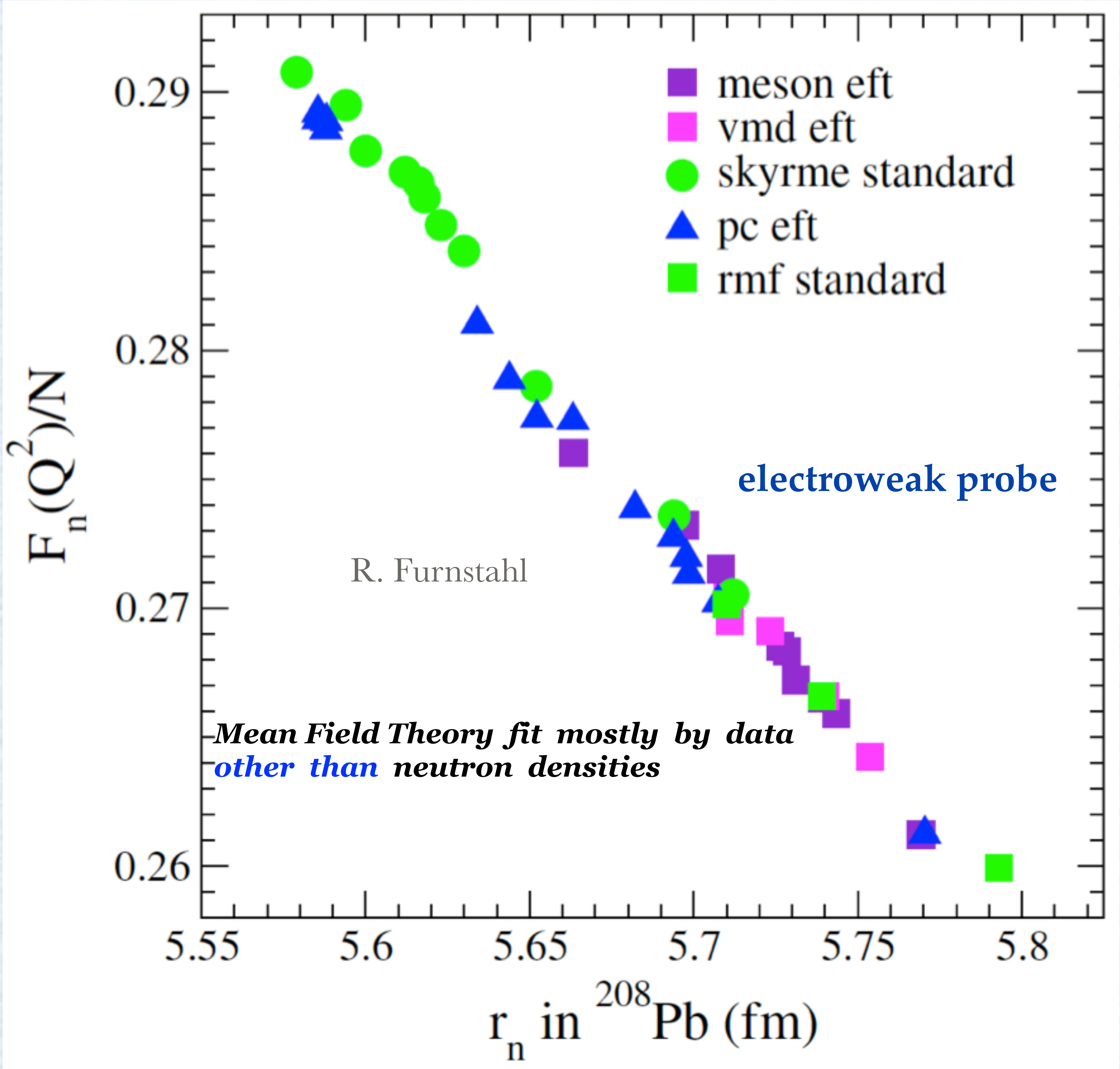

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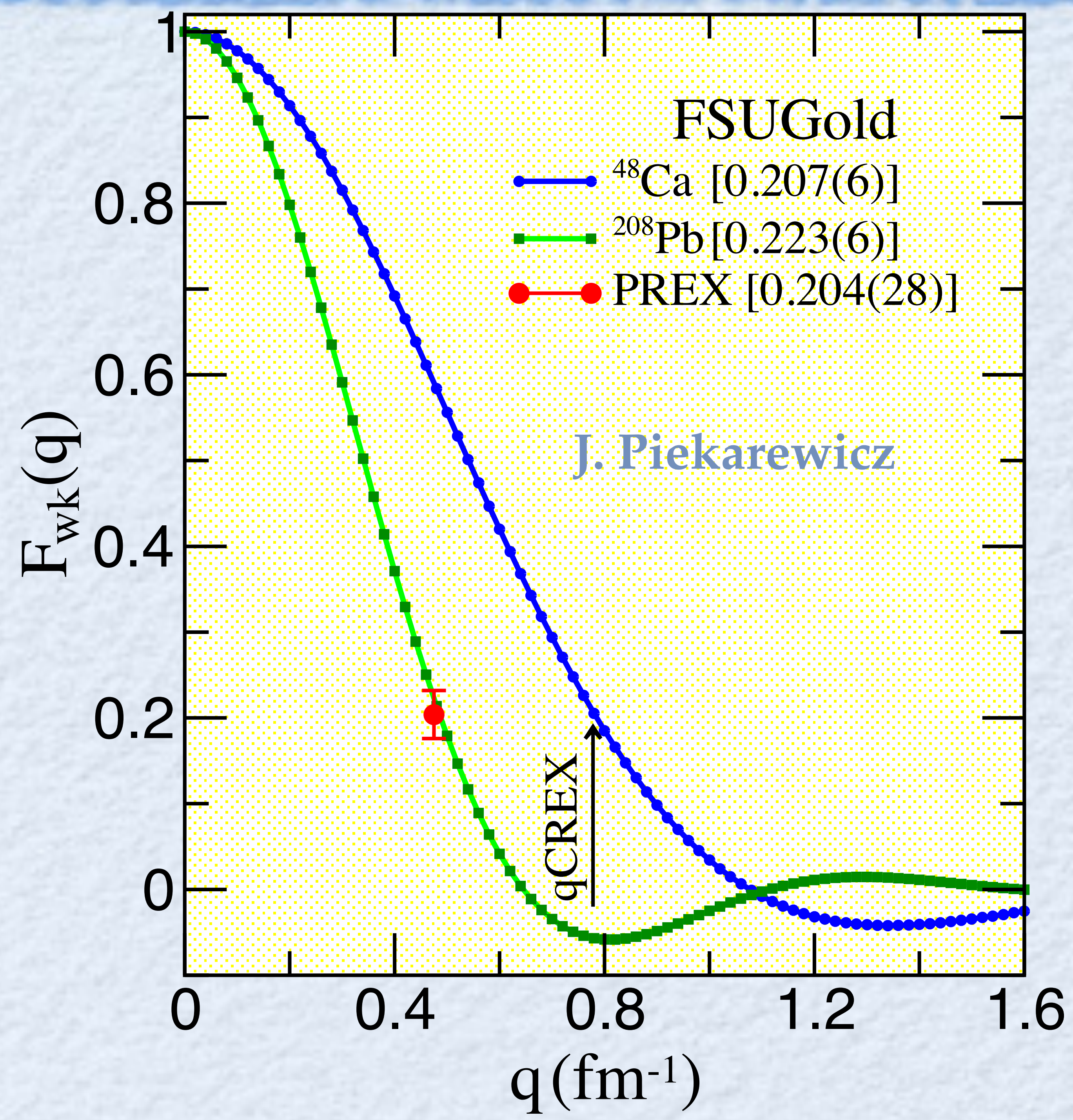
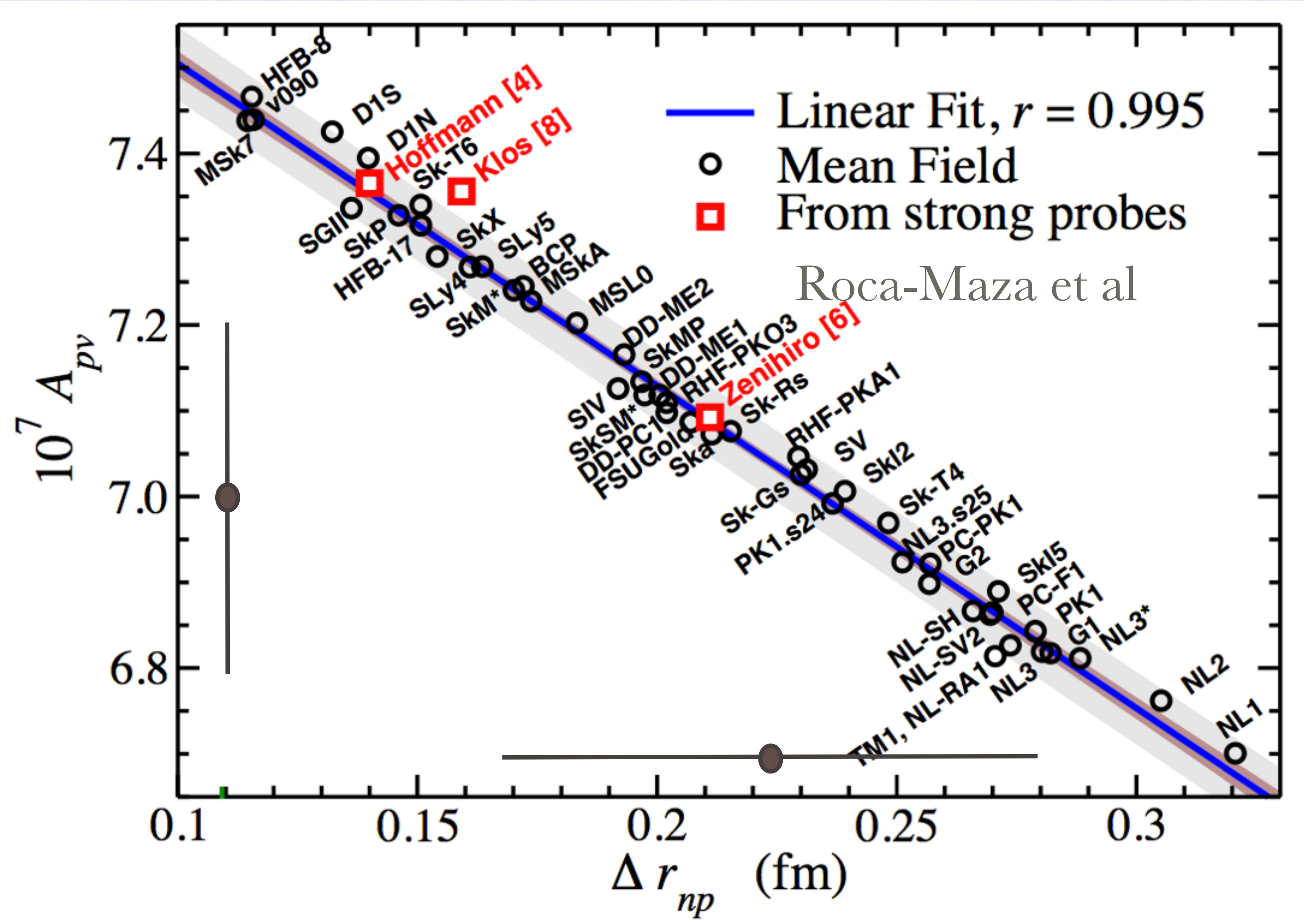


- ***Clean "translation" from A_{PV} uncertainty to neutron RMS radius uncertainty***
- ***A_{PV} uncertainty dominated by statistics!***



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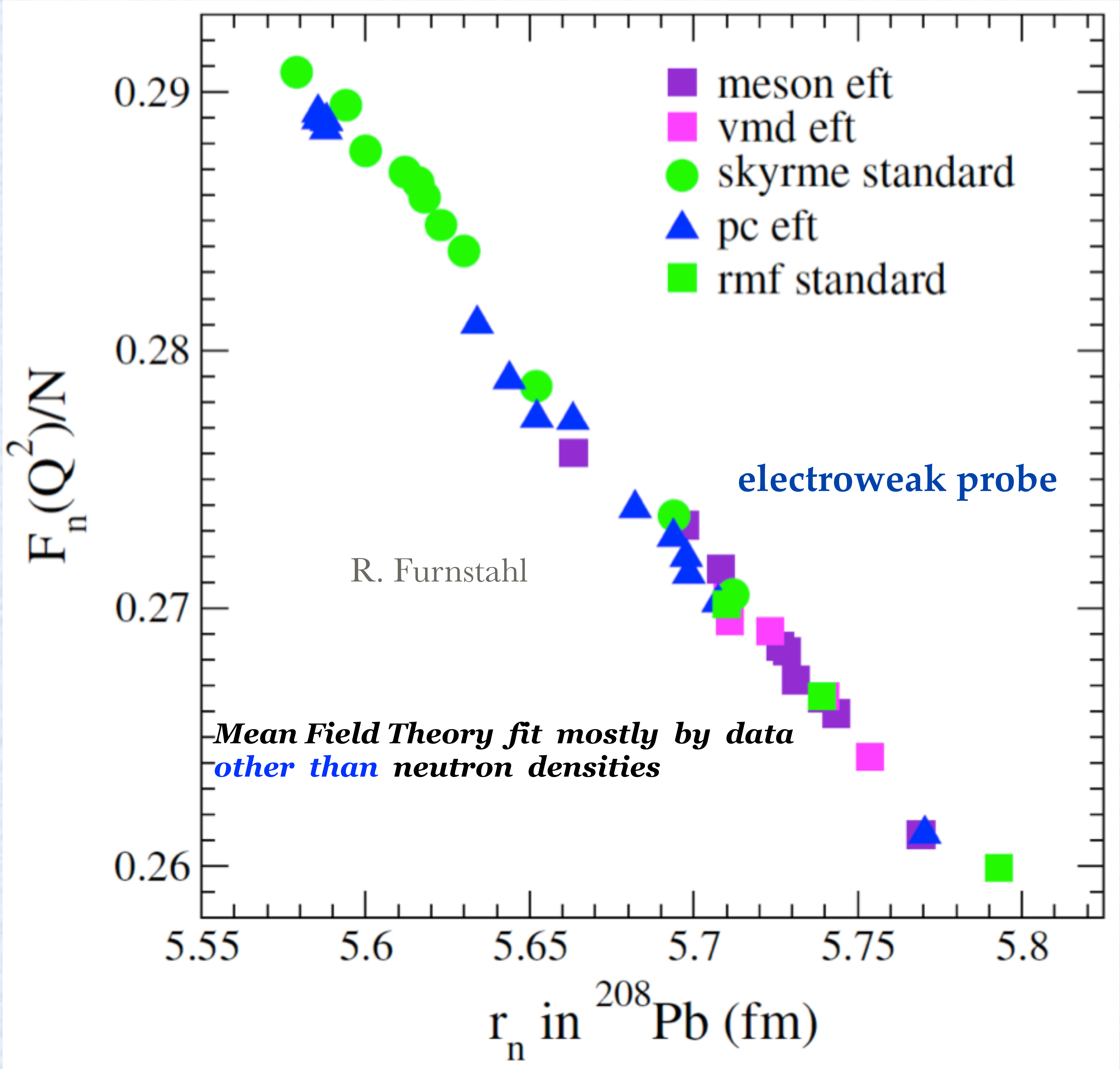

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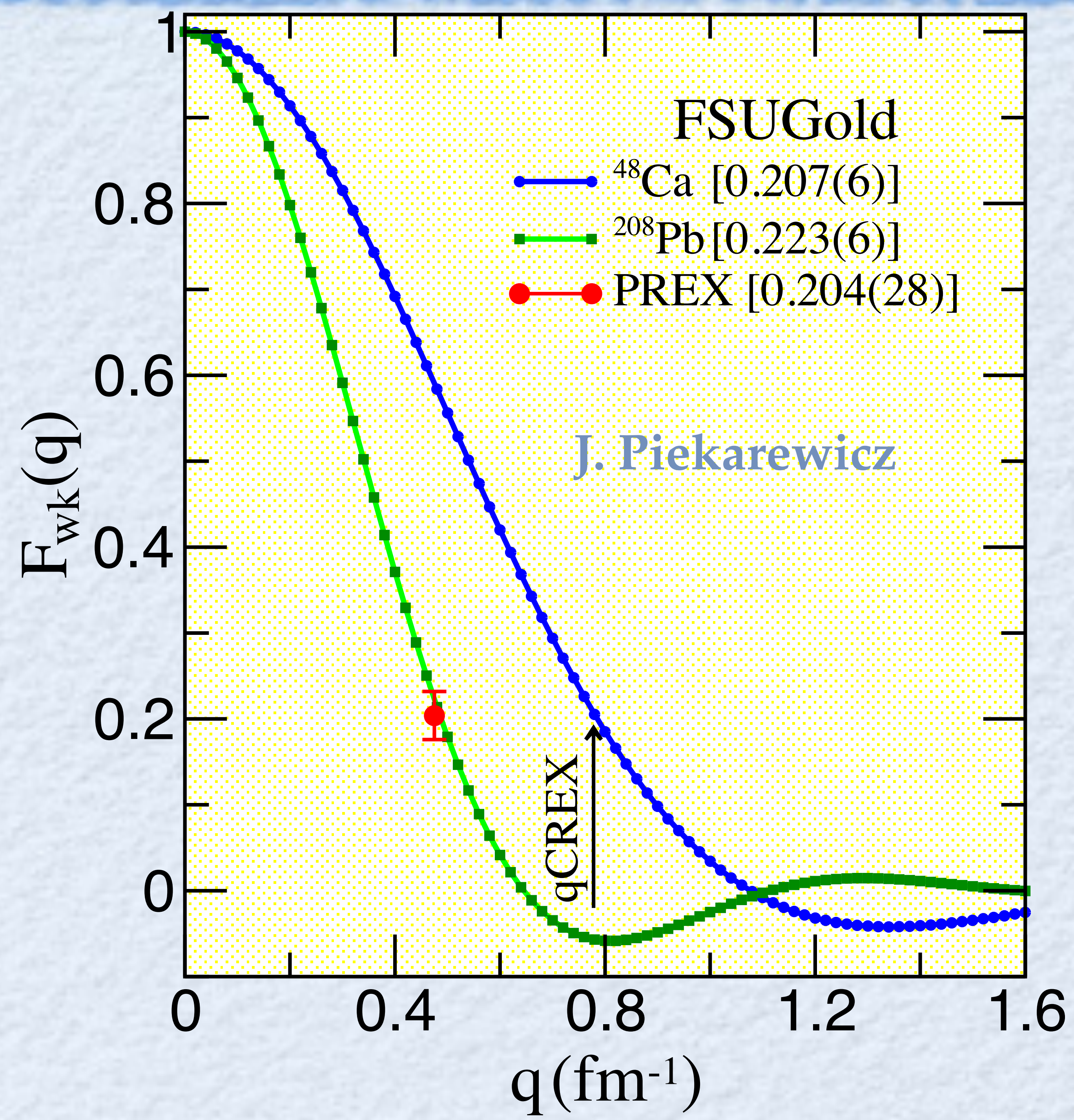
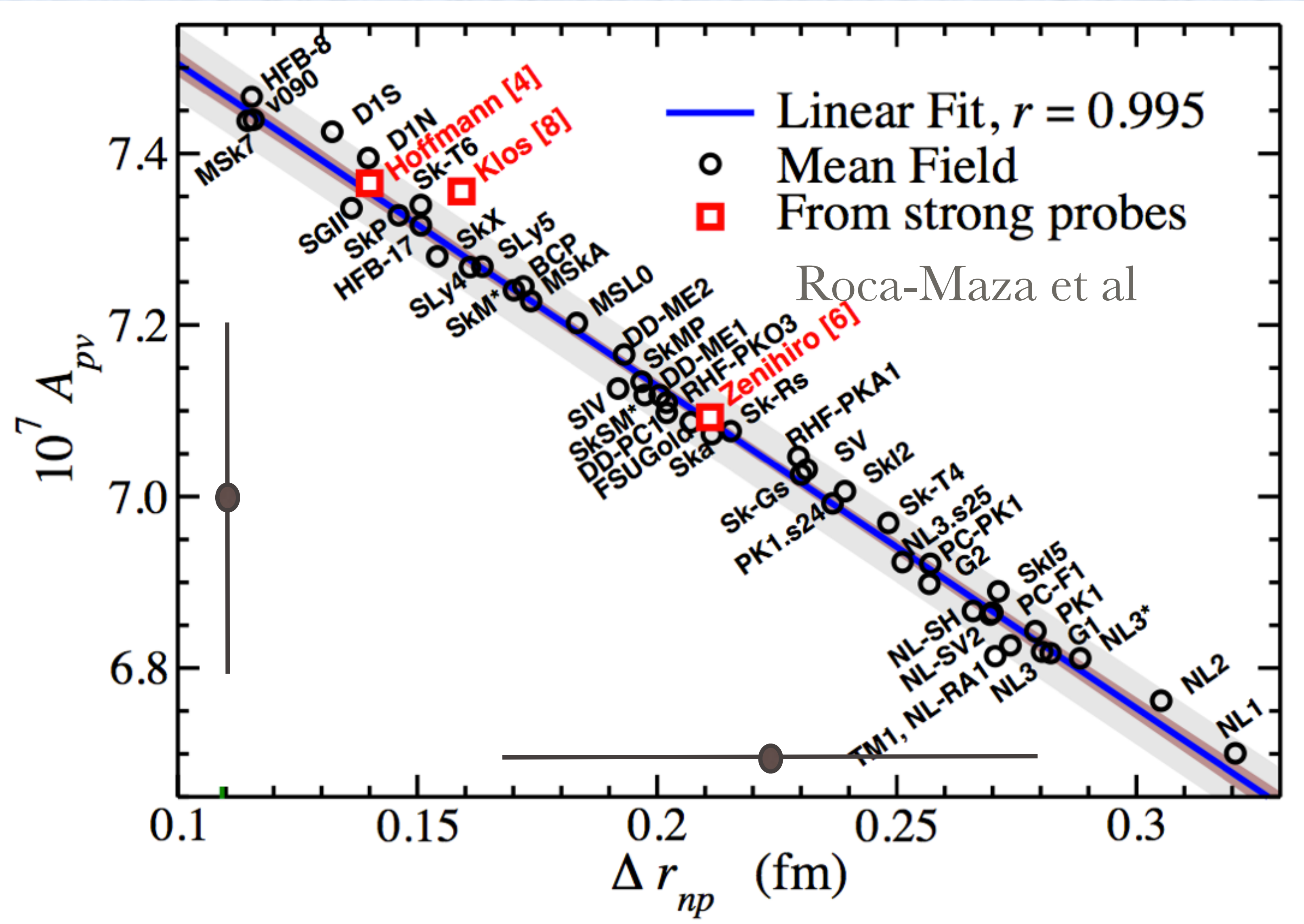




- *Clean "translation" from A_{PV} uncertainty to neutron RMS radius uncertainty*
- *A_{PV} uncertainty dominated by statistics!*

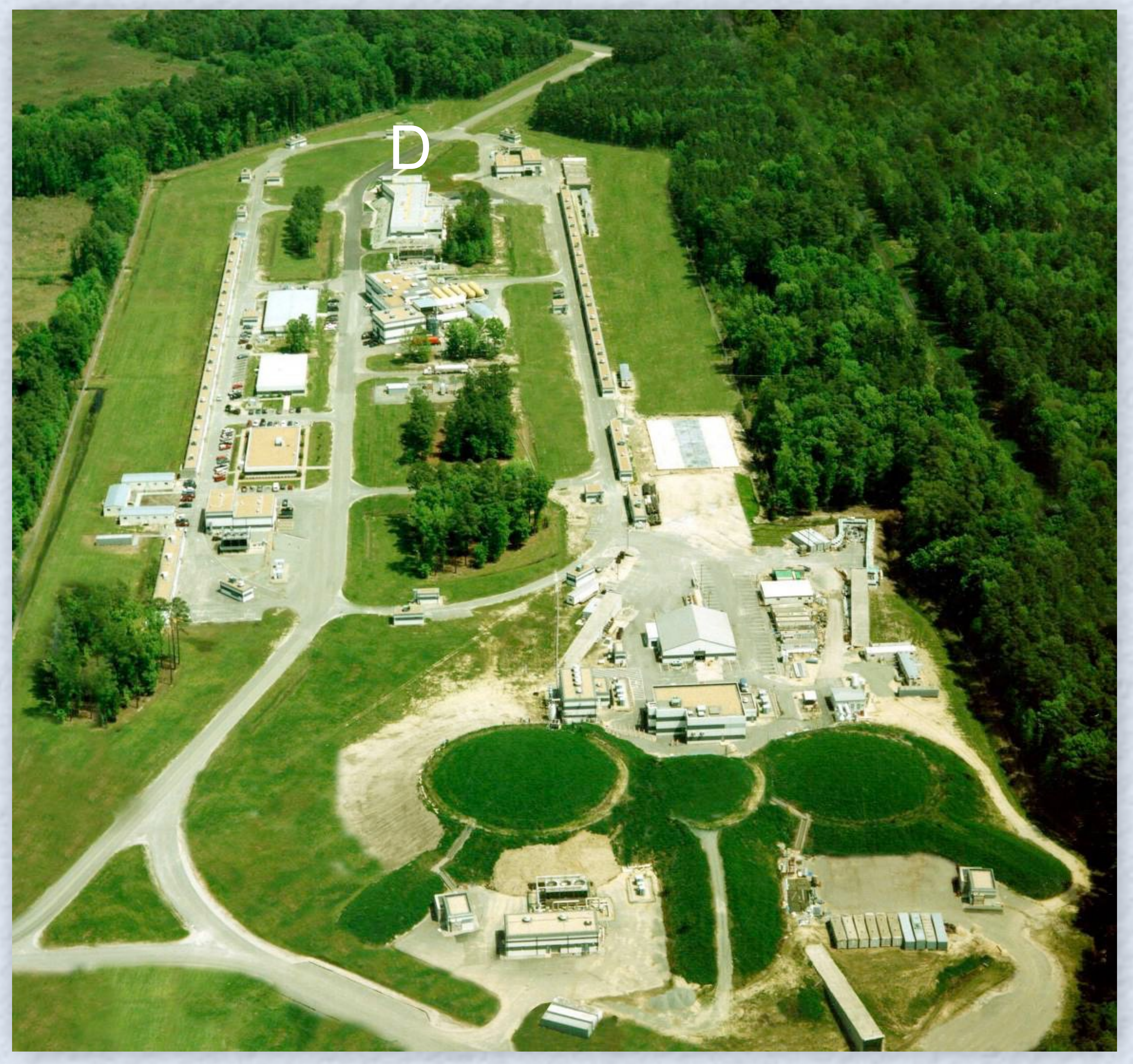
At this level of precision, one must account carefully for radiative corrections

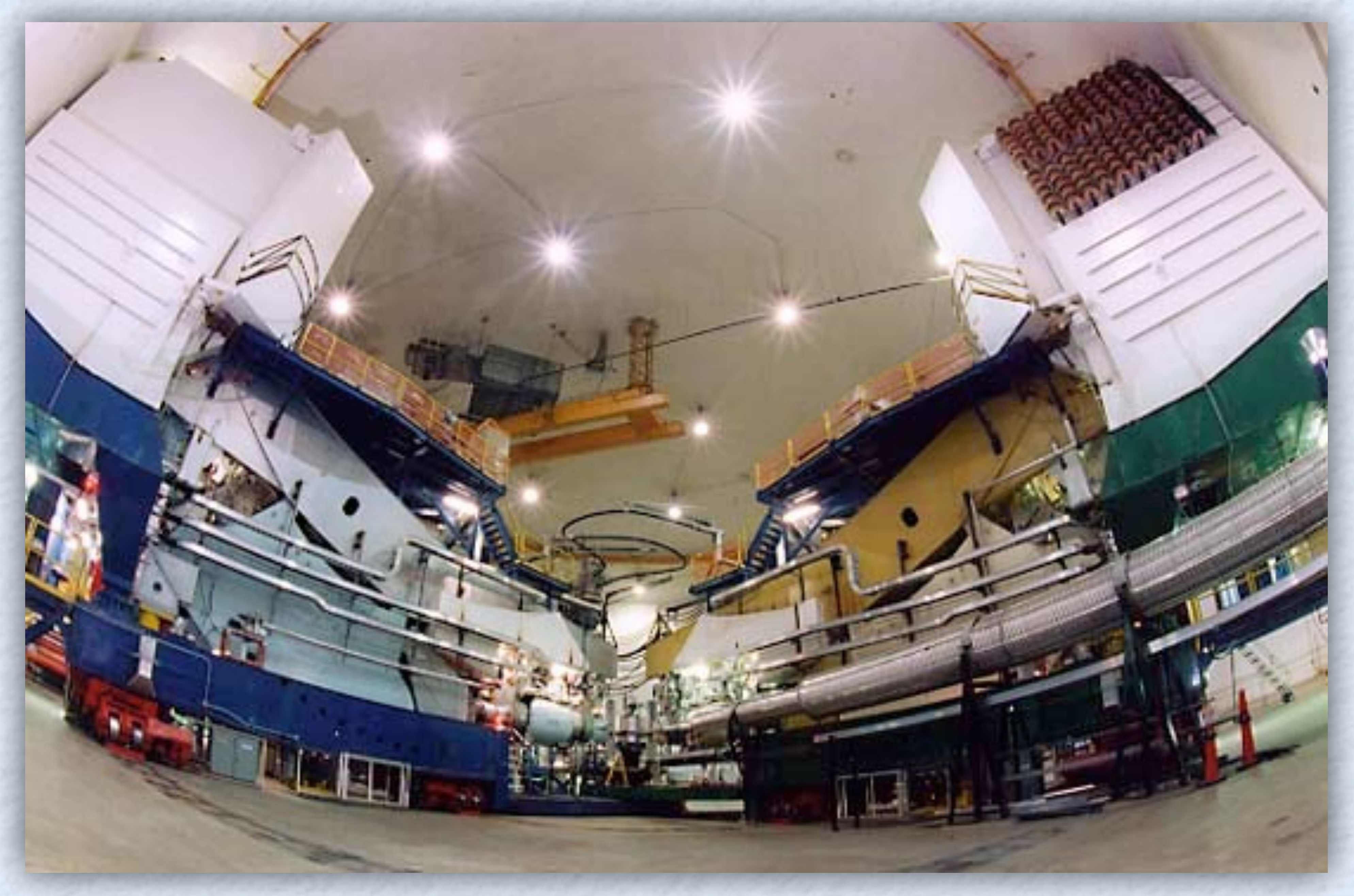
PREX Overview

1 GeV electron beam, 50-70 μA

high polarization, ~89%

helicity reversal at 120 Hz





0.5 mm isotopically pure ^{208}Pb target

5° scattered electrons

Q^2 =0.007 GeV^2/c^2

new thin quartz detectors

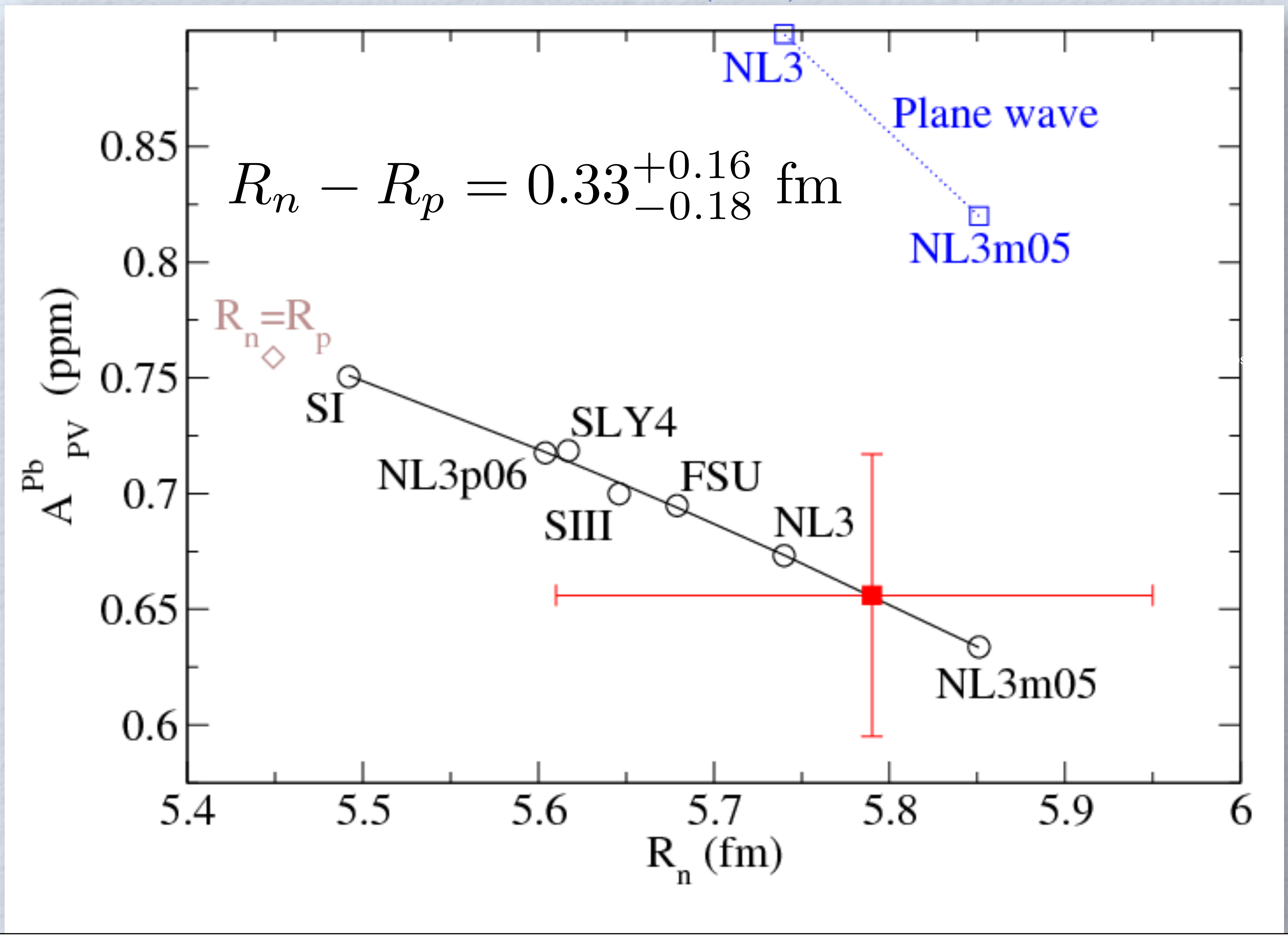
PREX Overview

PREX Overview

The Neutron Skin

First Run took place in Spring 2010 and was published in 2012

PRL 108 (2012) 112502



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

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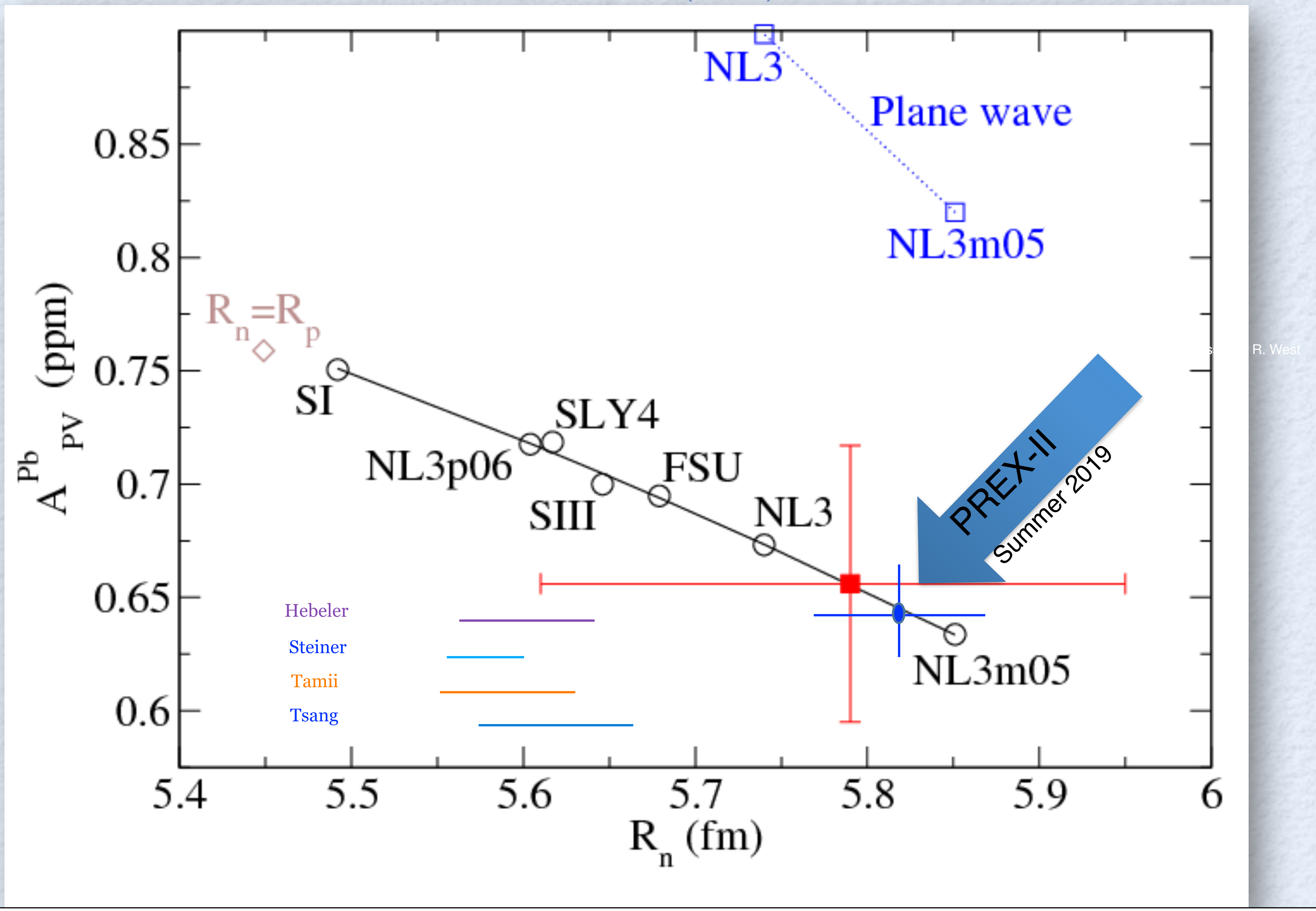

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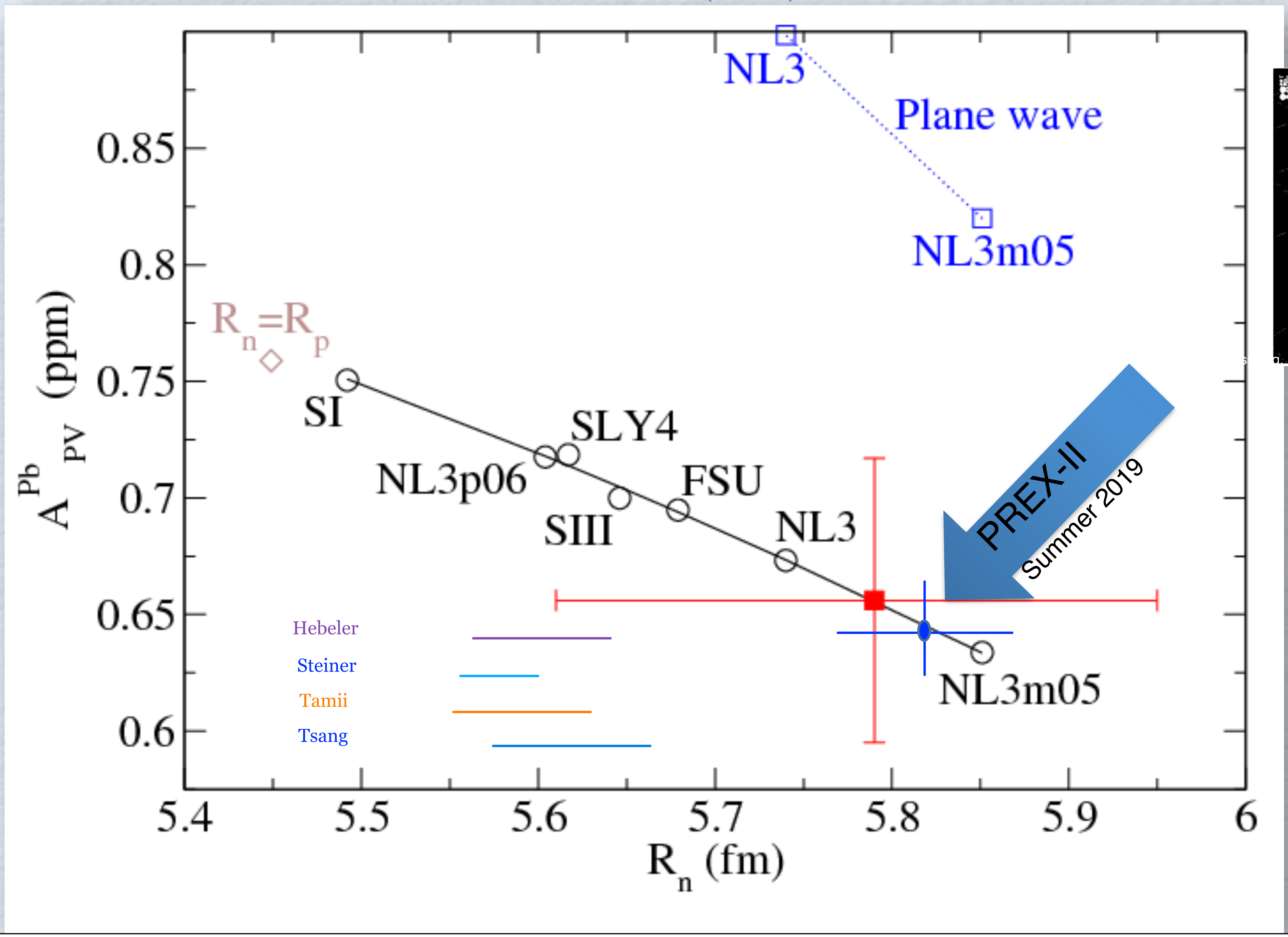
The Neutron Skin and Neutron Stars

First Run took place in Spring 2010 and was published in 2012

PRL 108 (2012) 112502



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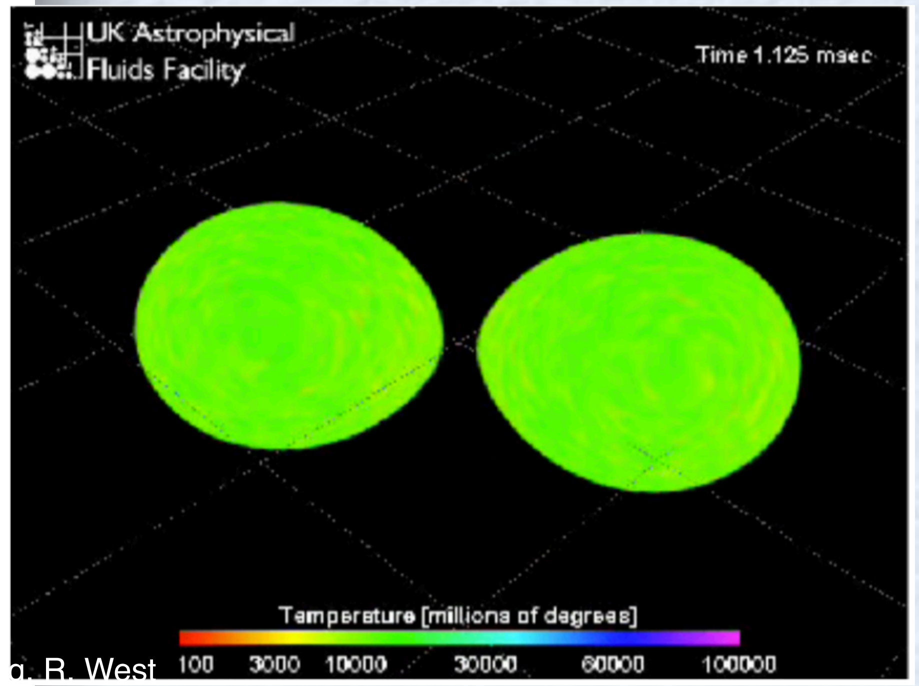
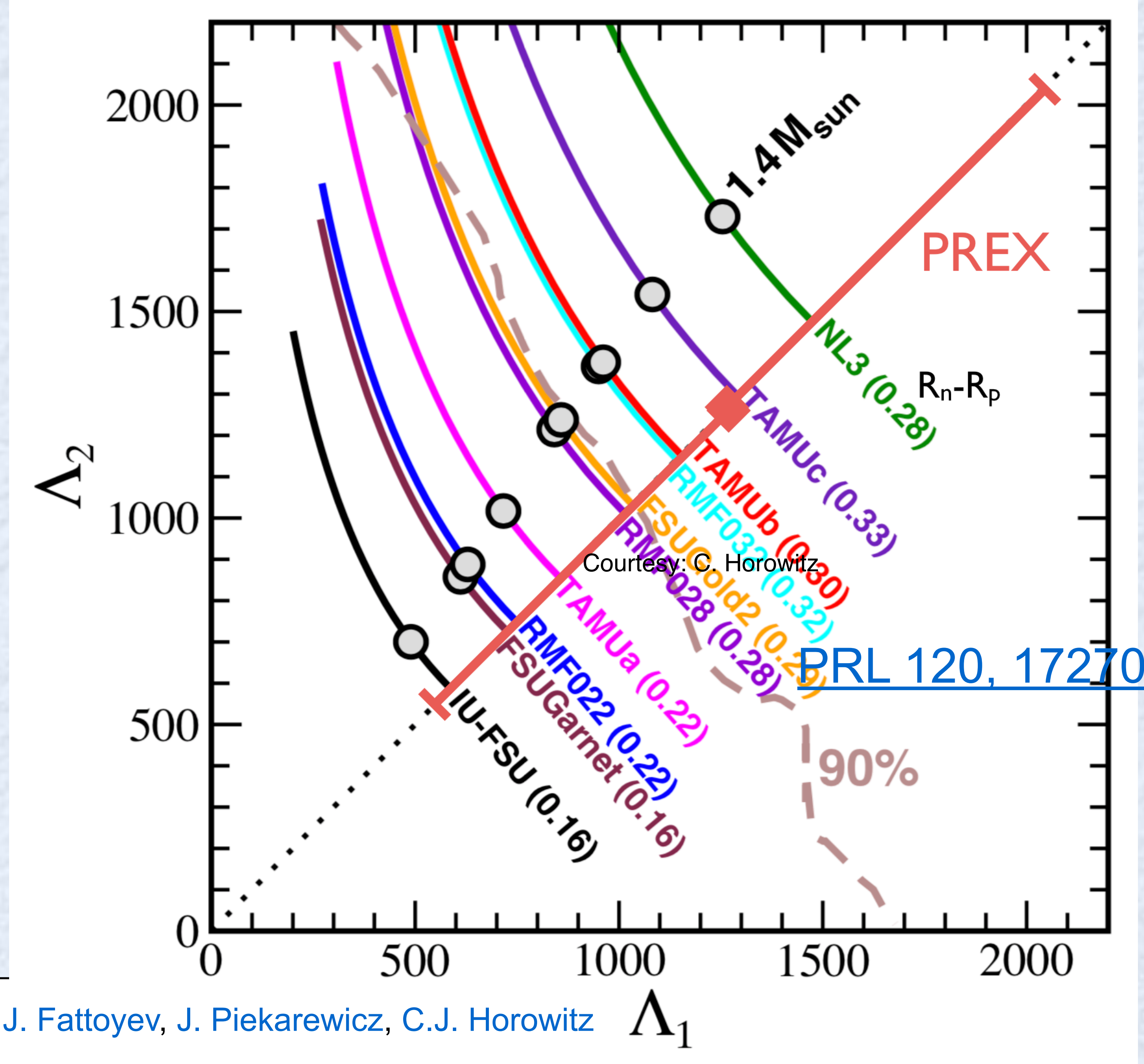
Renewed Interest in more precision!



$\Lambda \propto R^5$

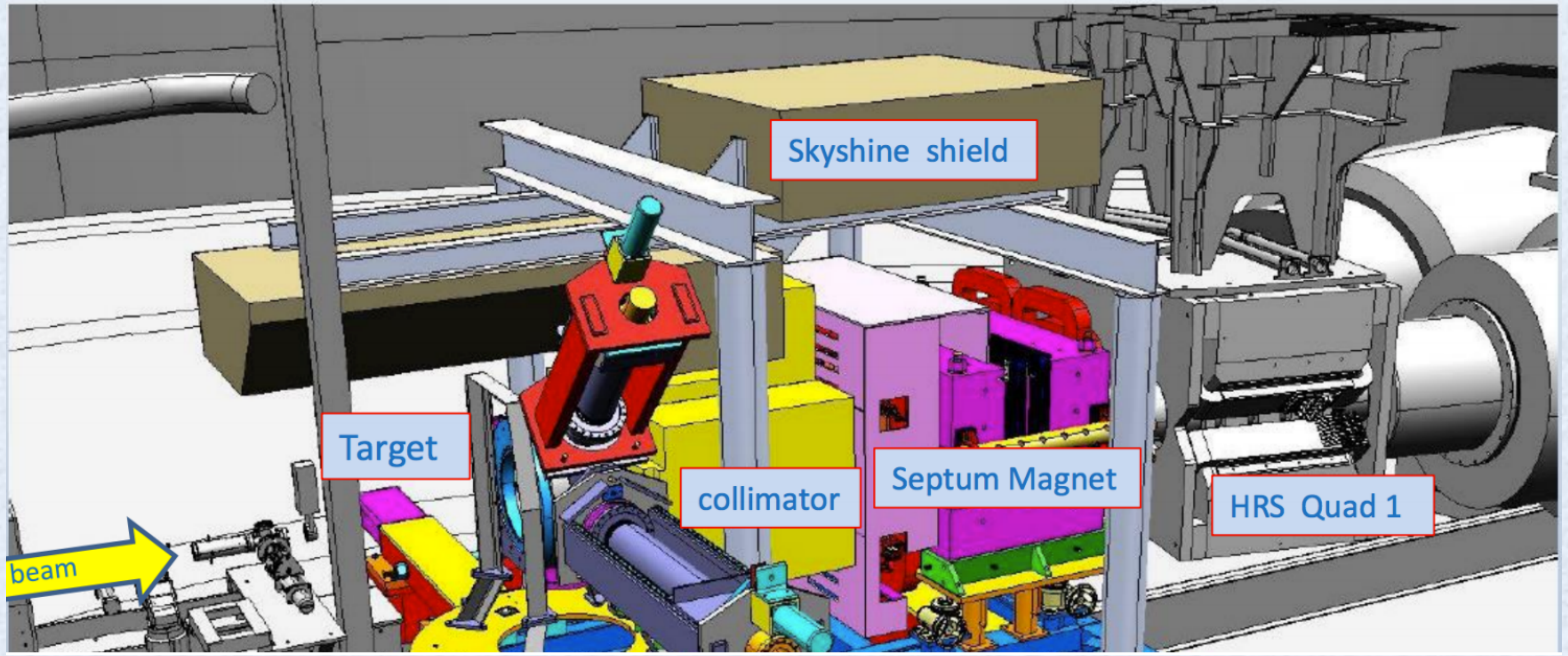
Clear correlation between neutral star tidal deformability and nuclear neutron skin



PRL 120, 172702 (2018

F.J. Fattoyev, J. Piekarewicz, C.J. Horowitz

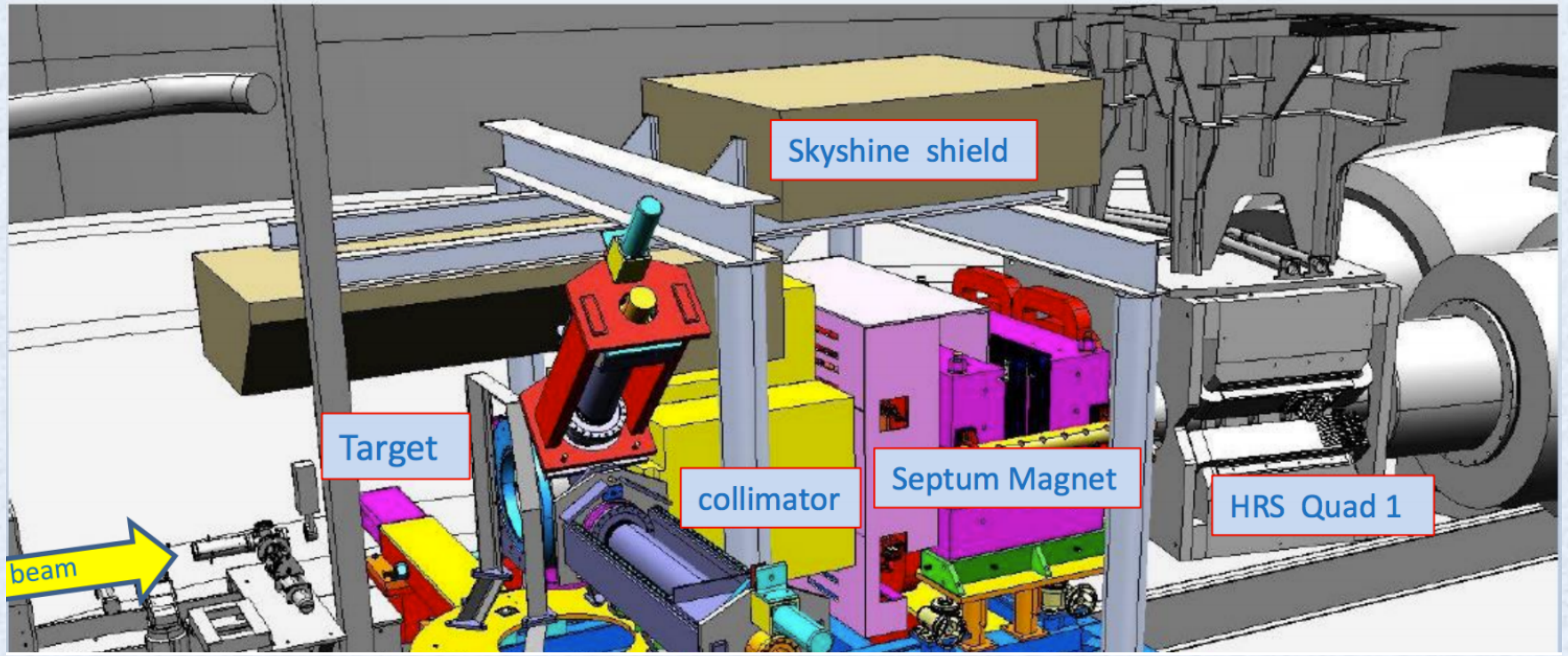
Summer 2019 Run

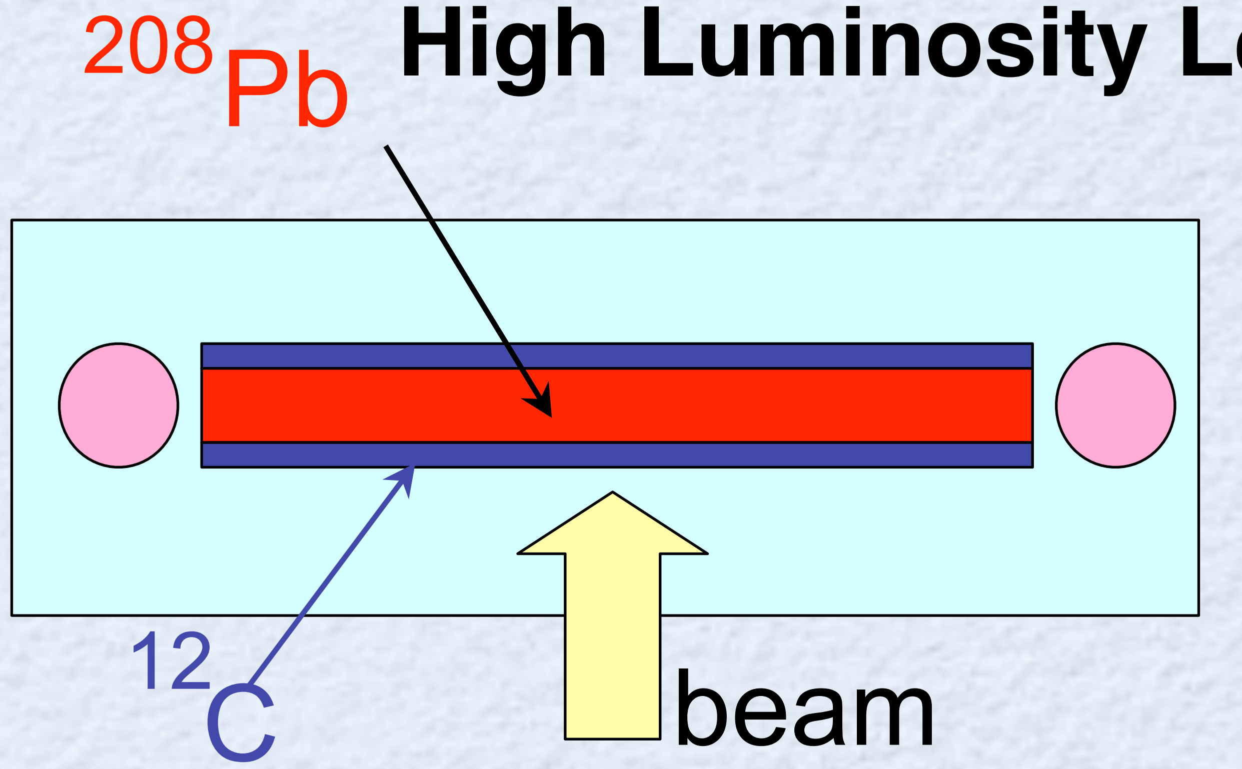


- Physics running took place in July/August 2019
- 126 Coulombs on target; 116 passed online cuts
- On track to achieve proposal goal:
  - about 3% stat and 1.5% syst. uncertainties

My view! Gordon Conference rules!

Summer 2019 Run





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- *Diamond backing provides conductive cooling*
- *Active cryo-cooling with available He lines*

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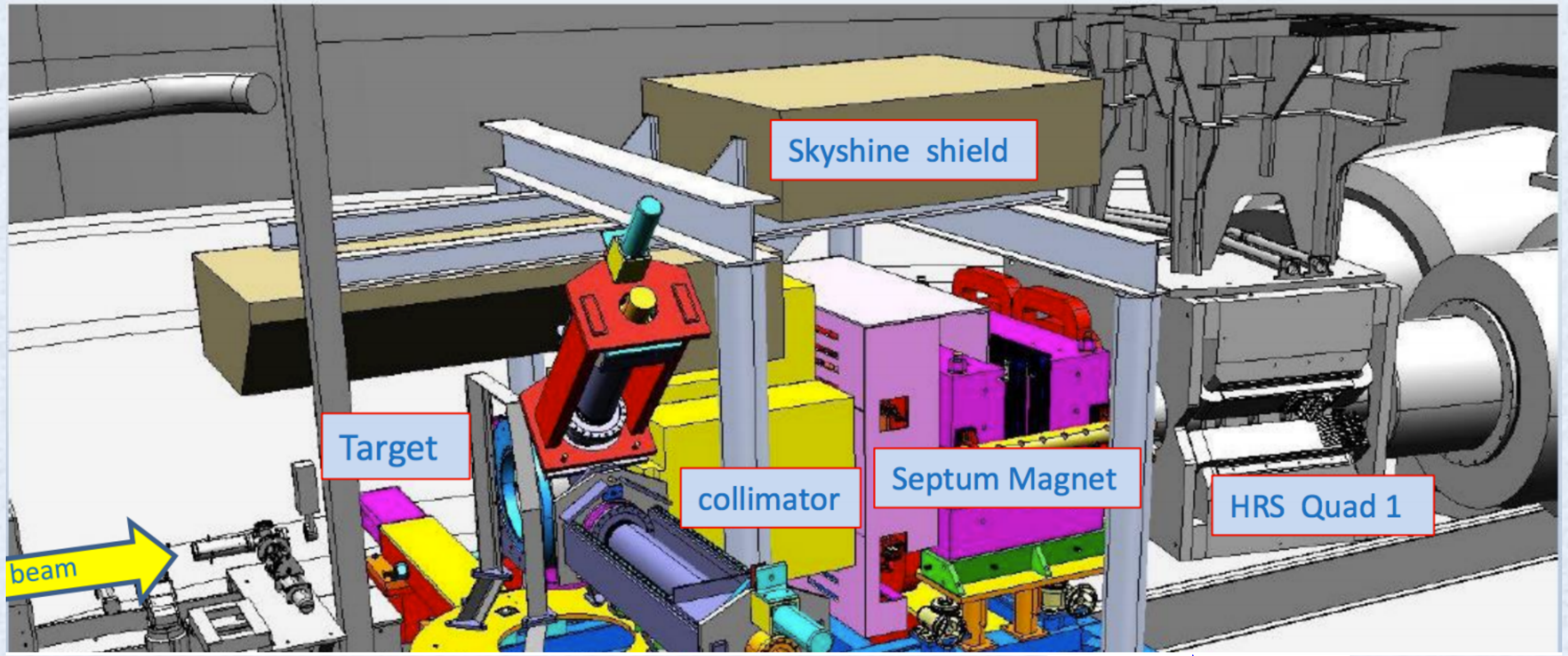
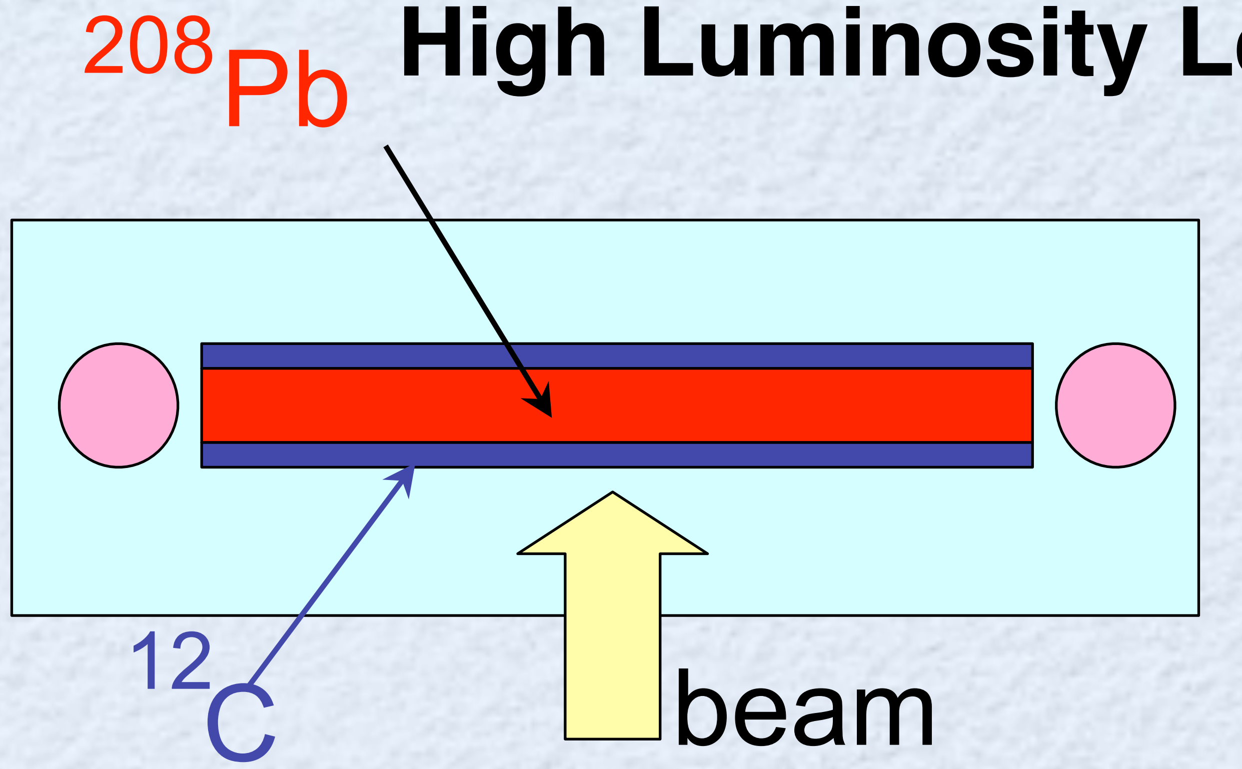


High Luminosity Lead Target



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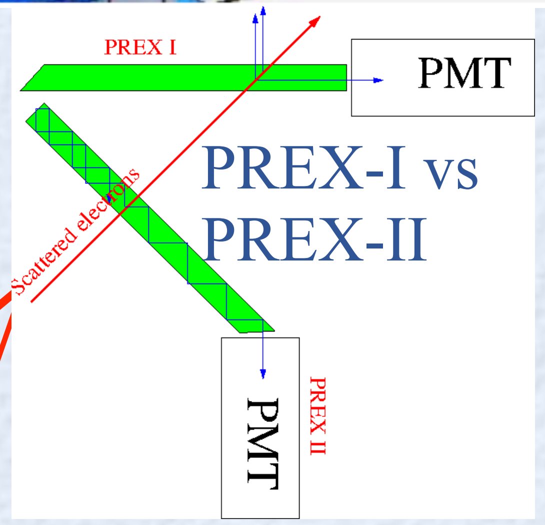
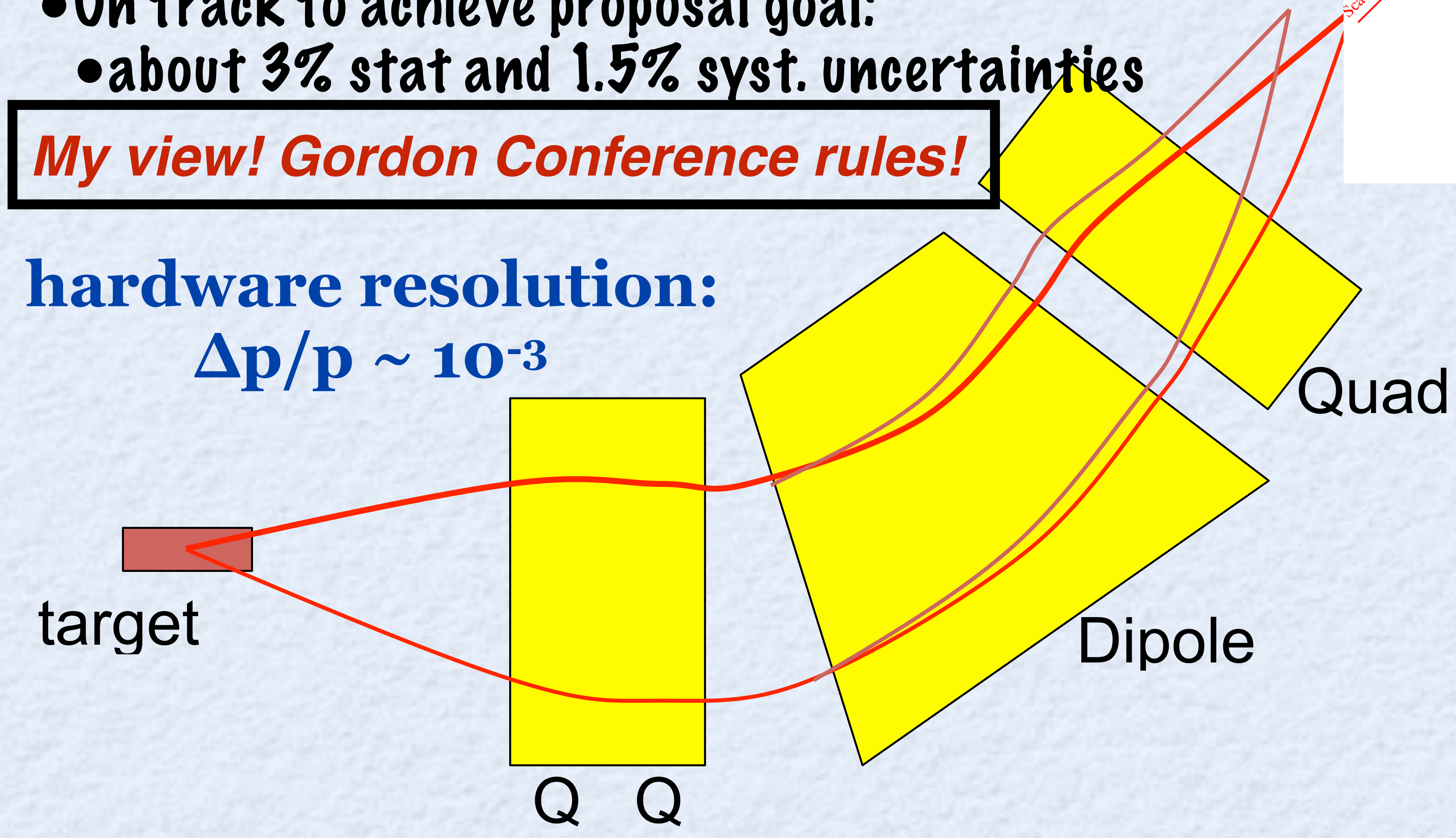
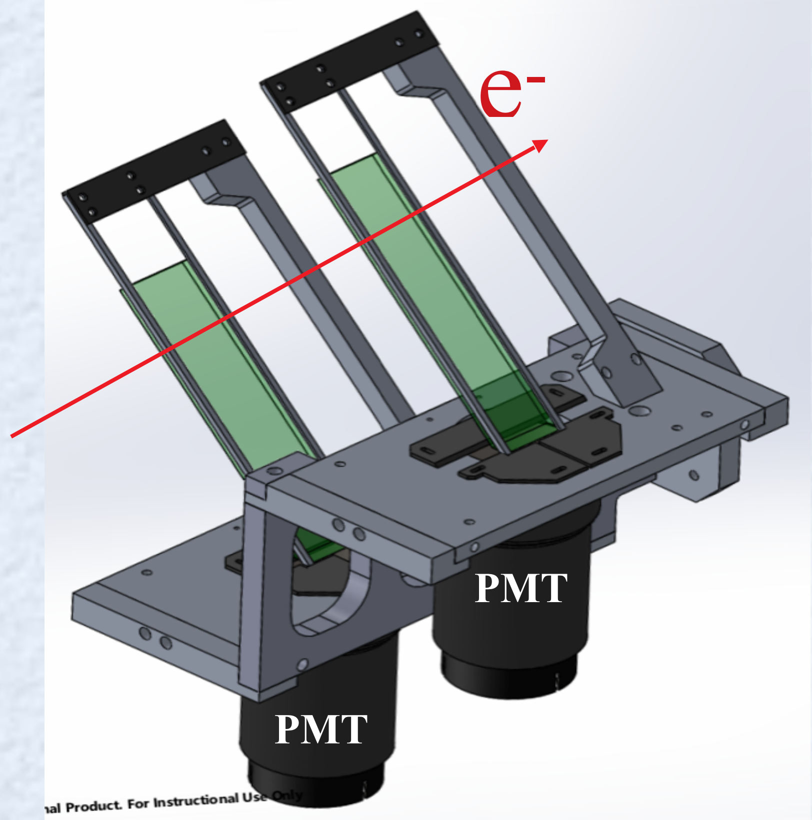


hardware resolution:
$\Delta p/p \sim 10^{-3}$





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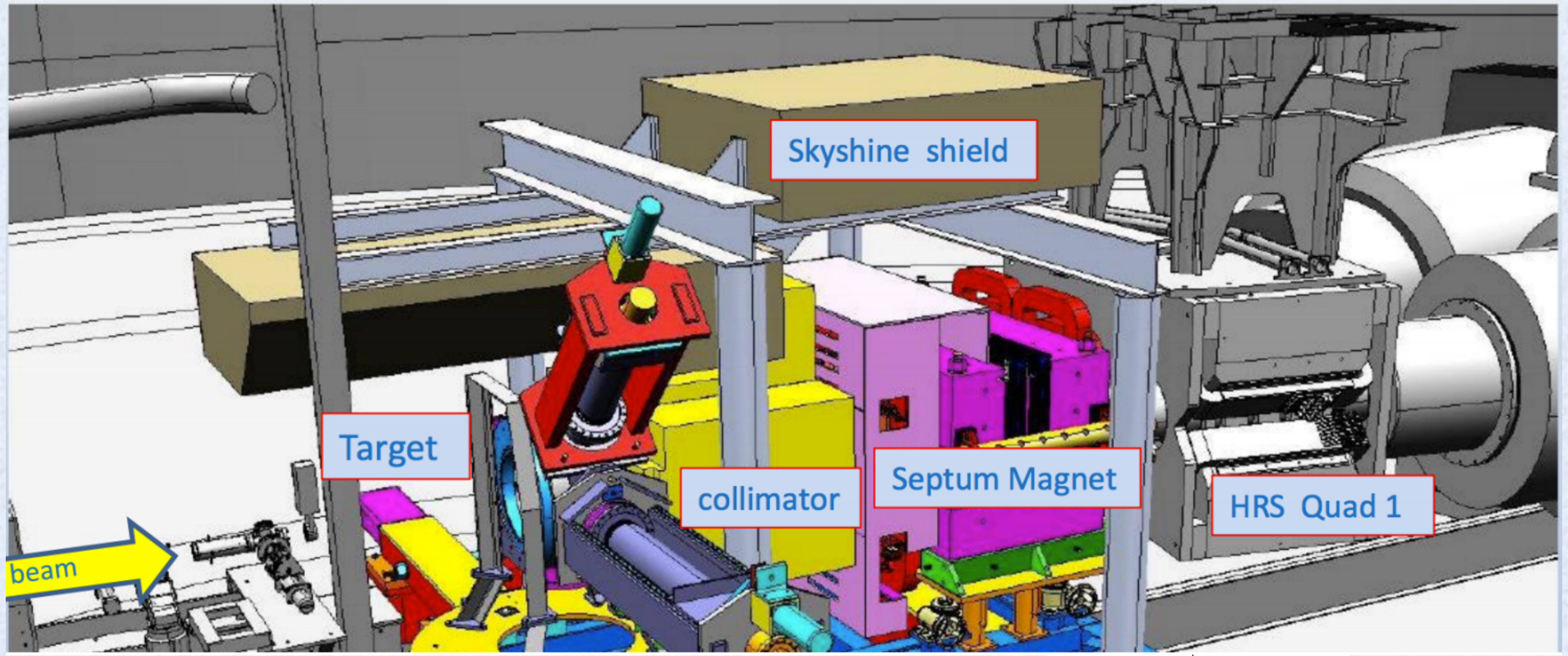

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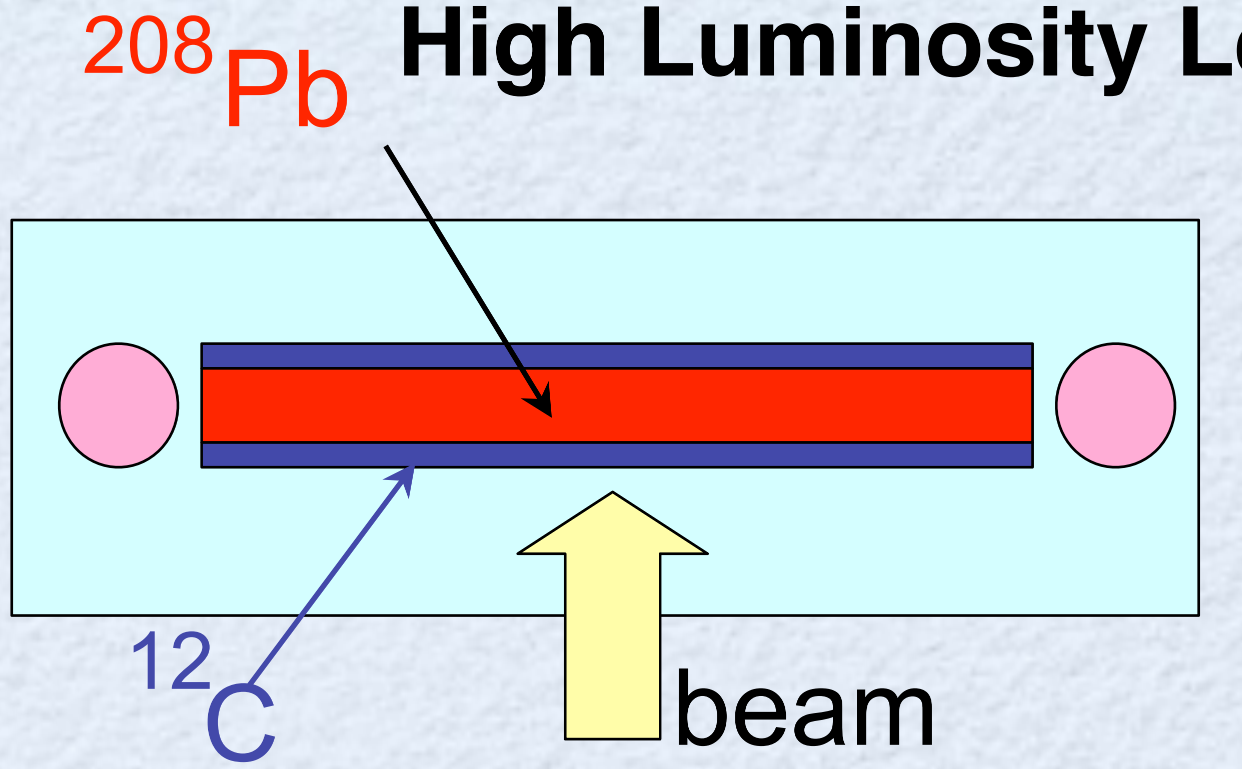

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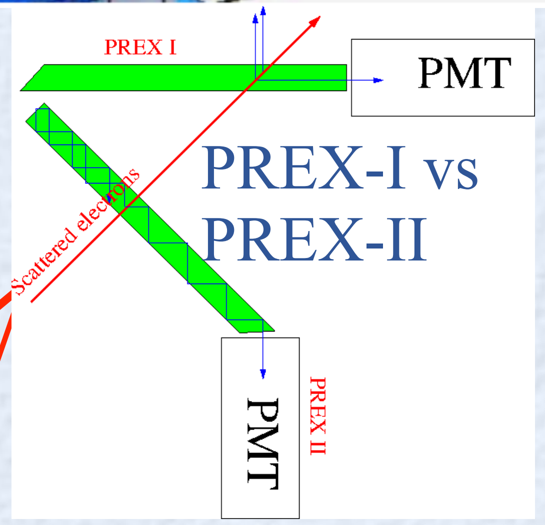

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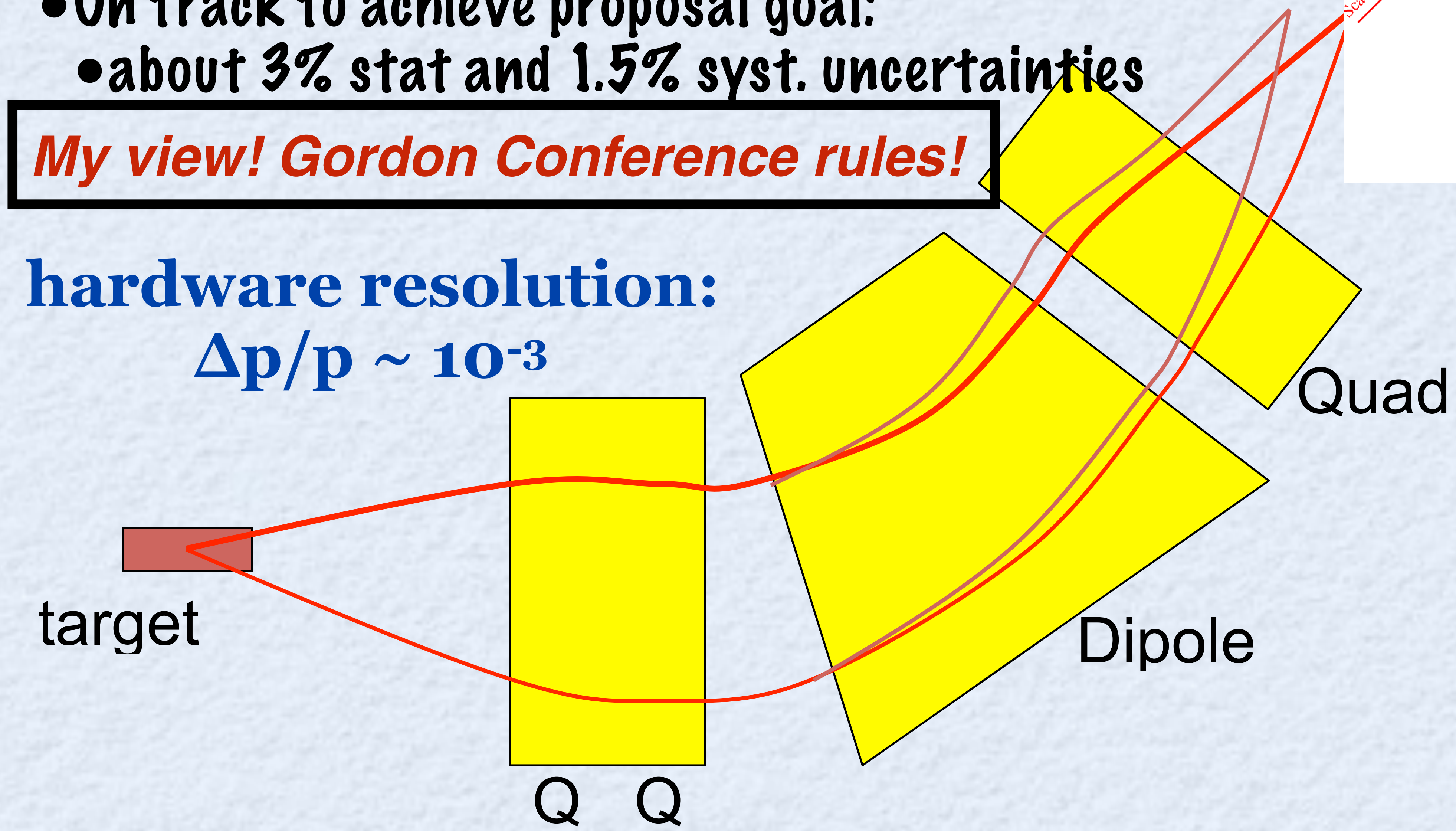
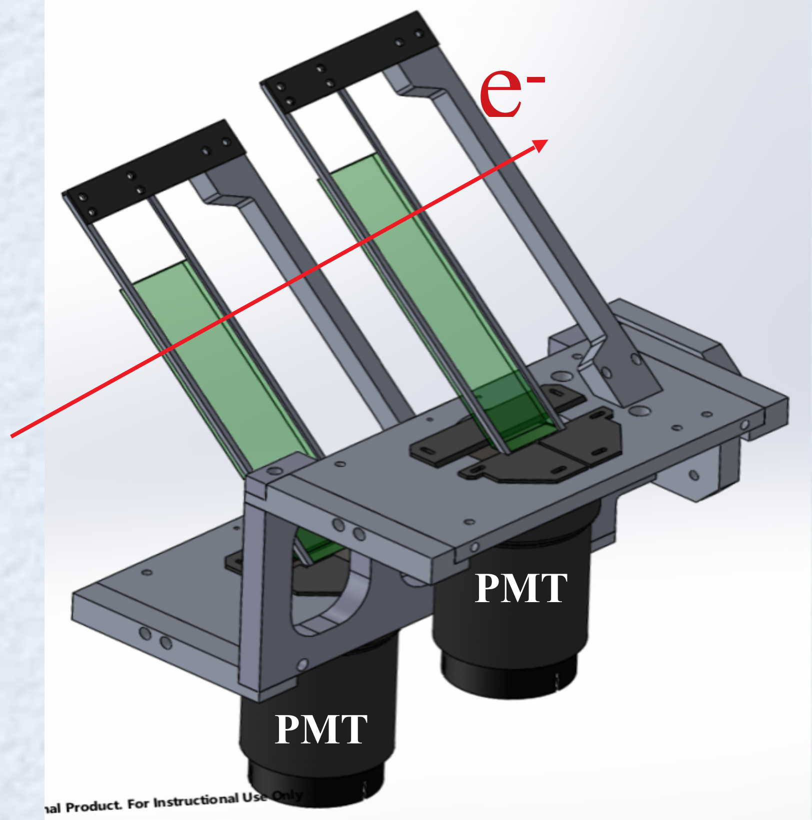
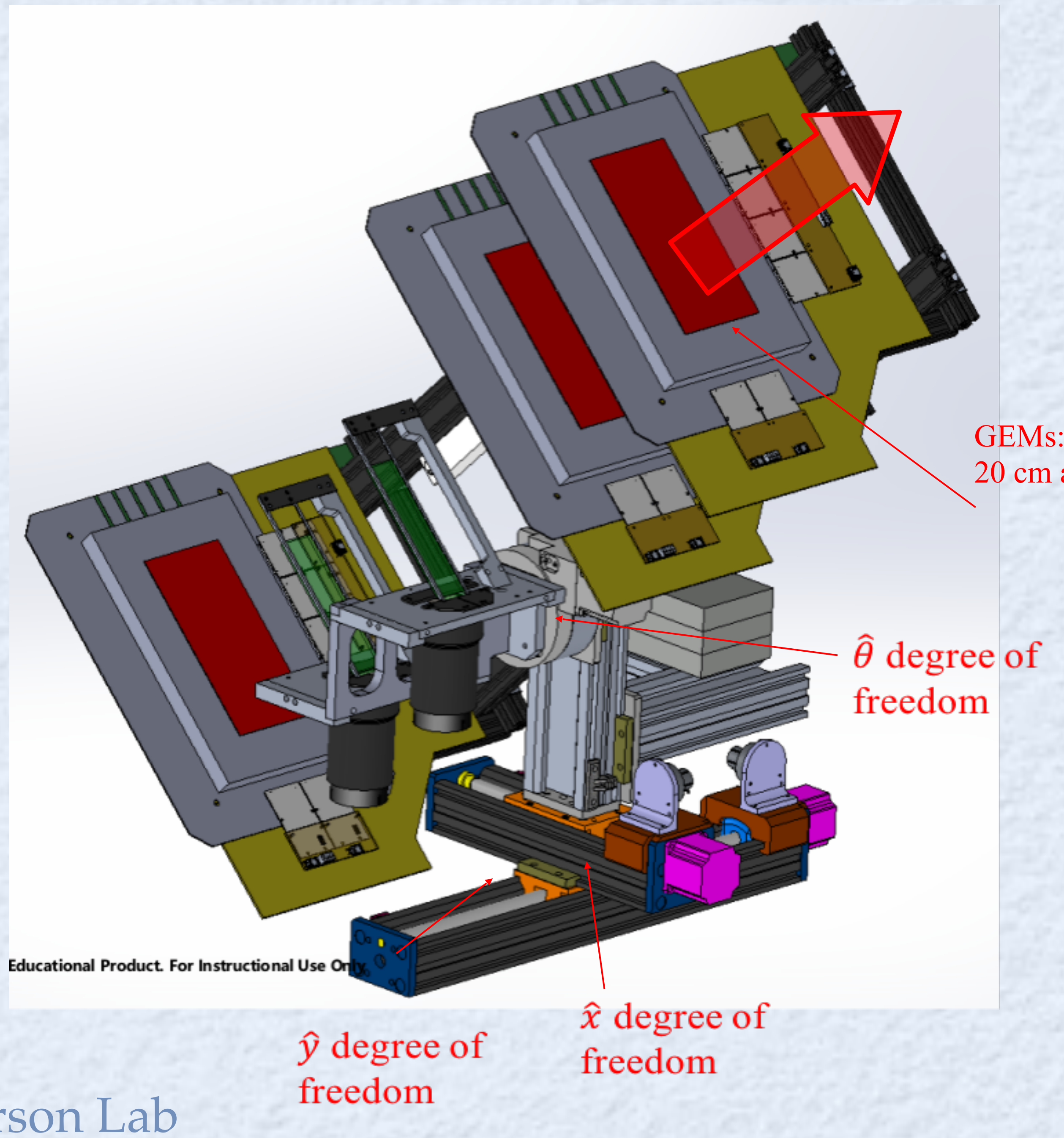
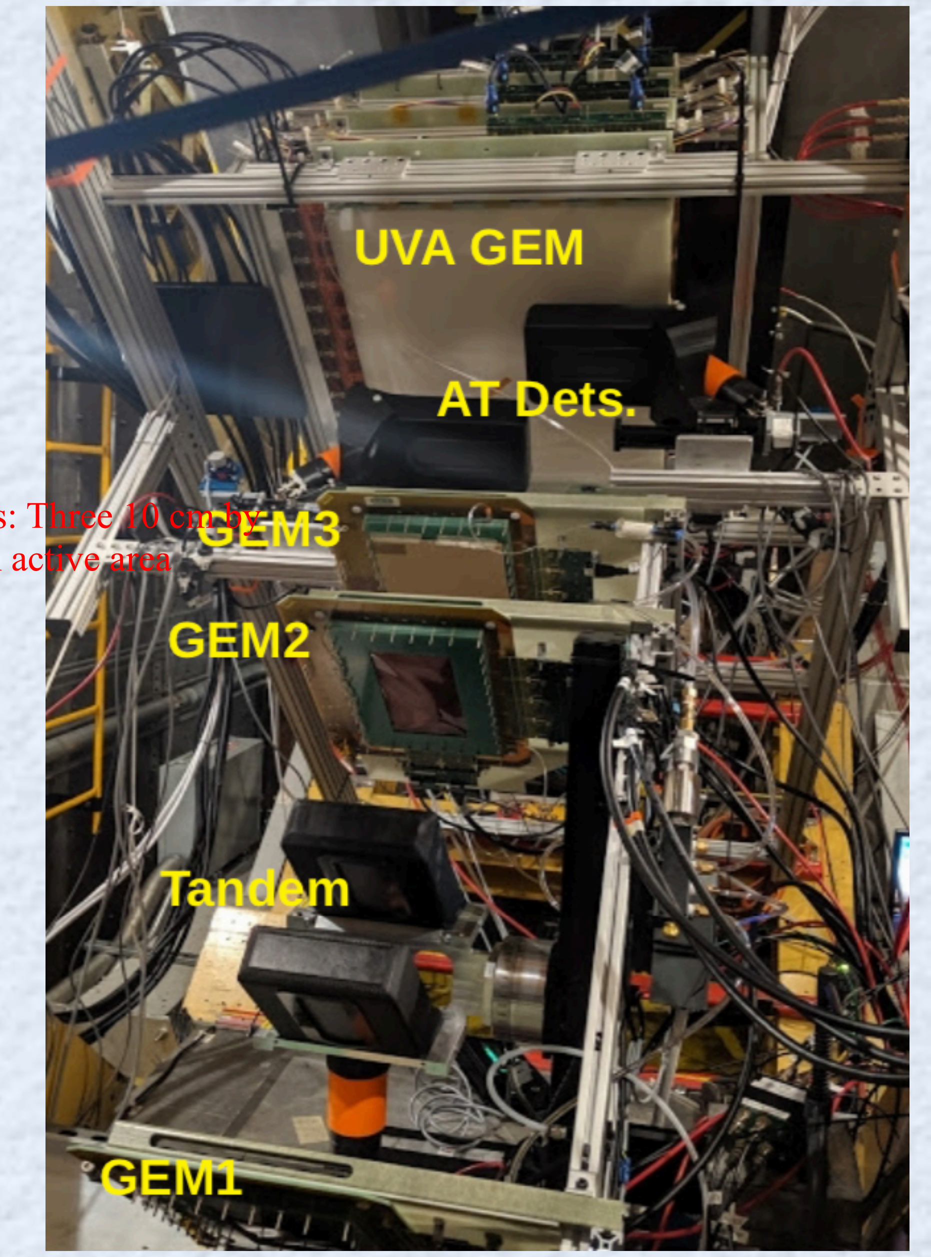
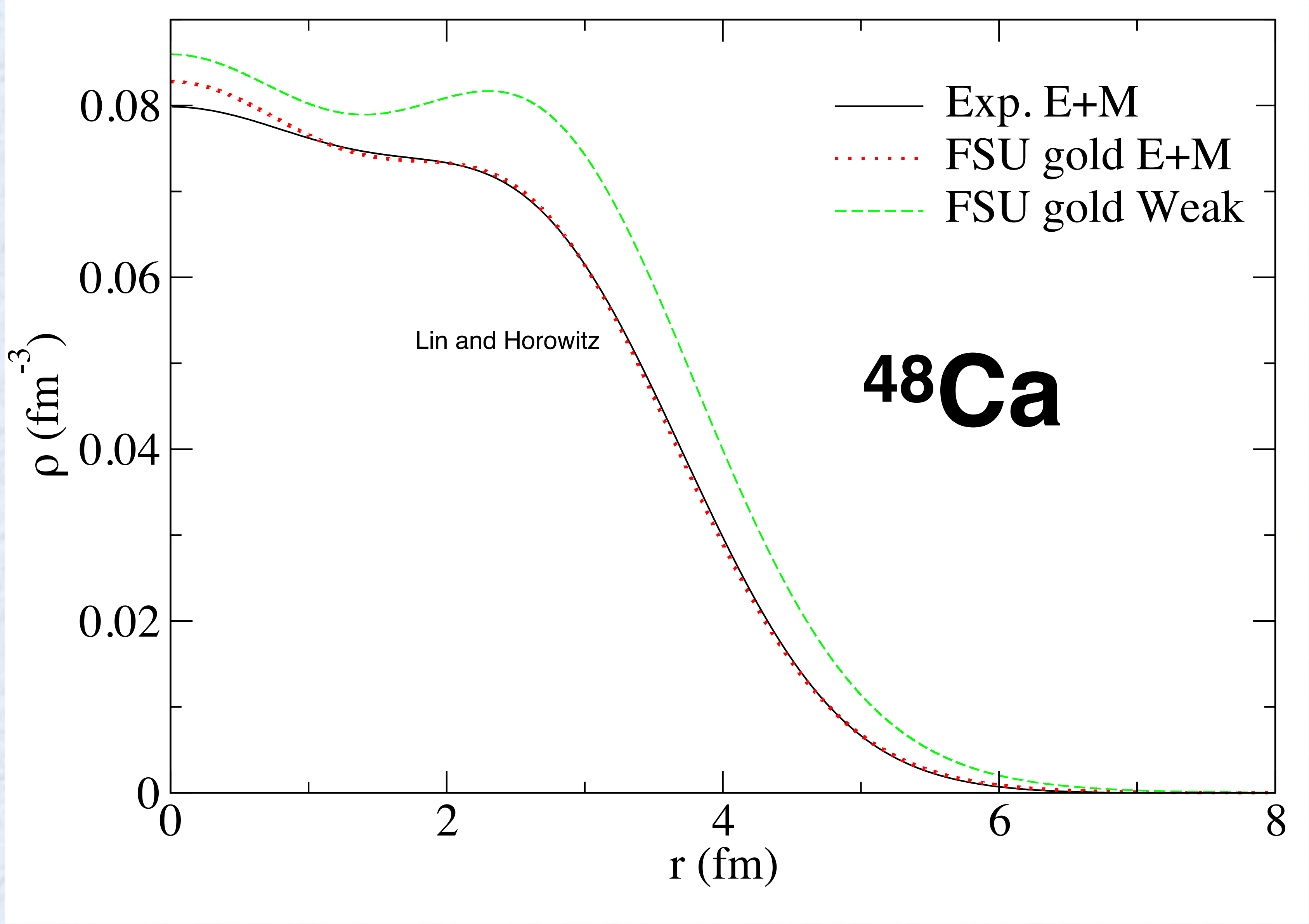








CREX Motivation



Starts December 2!

Optimum Q ~ 160 MeV

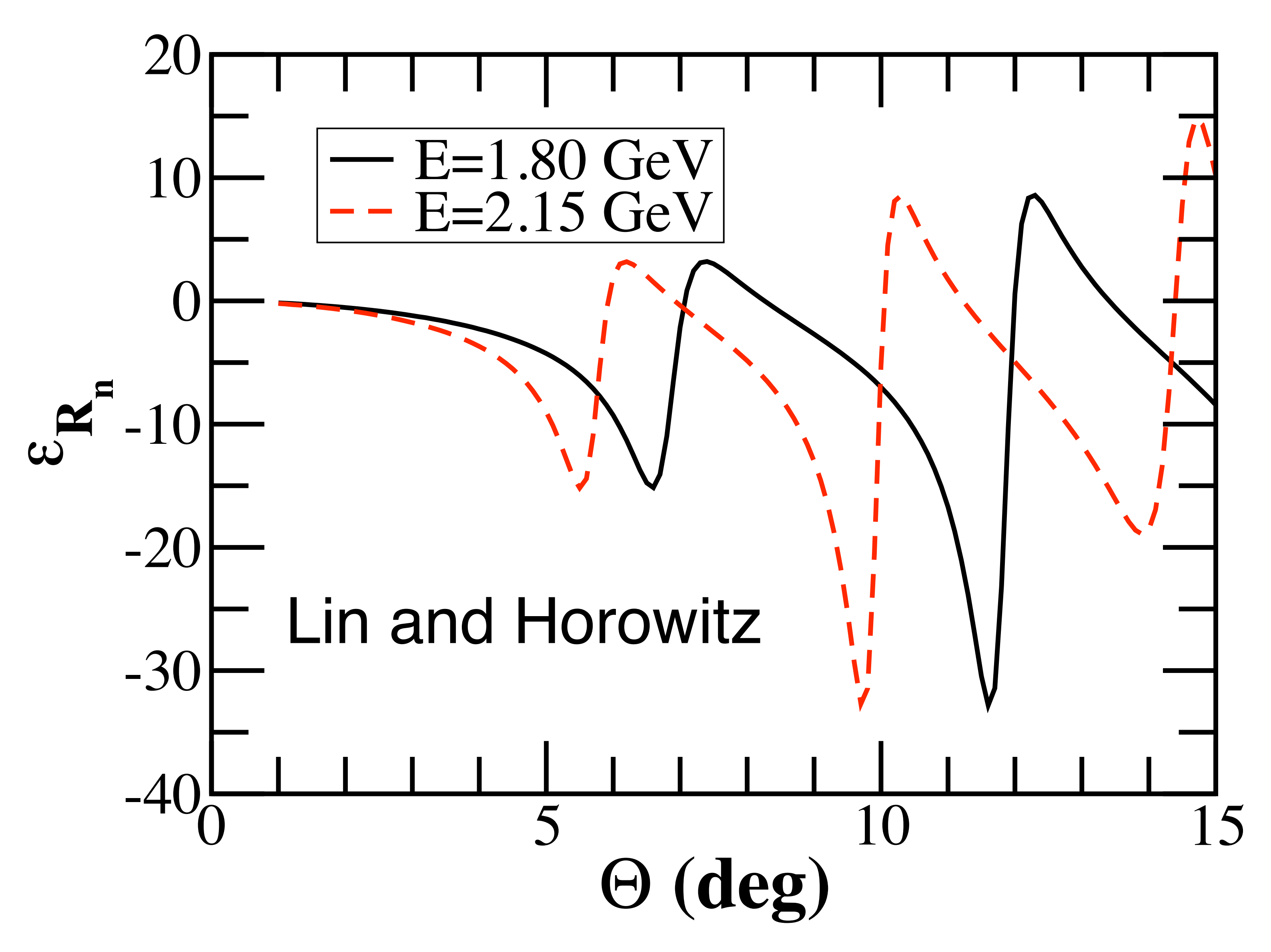
2 GeV → 5 degrees

A_{PV} ~ 3.8 ppm

Rate ~ 40 MHz

$\delta(A_{PV})$ ~ 3 %

$\delta(R_n) \sim \pm\, 0.02\ fm$



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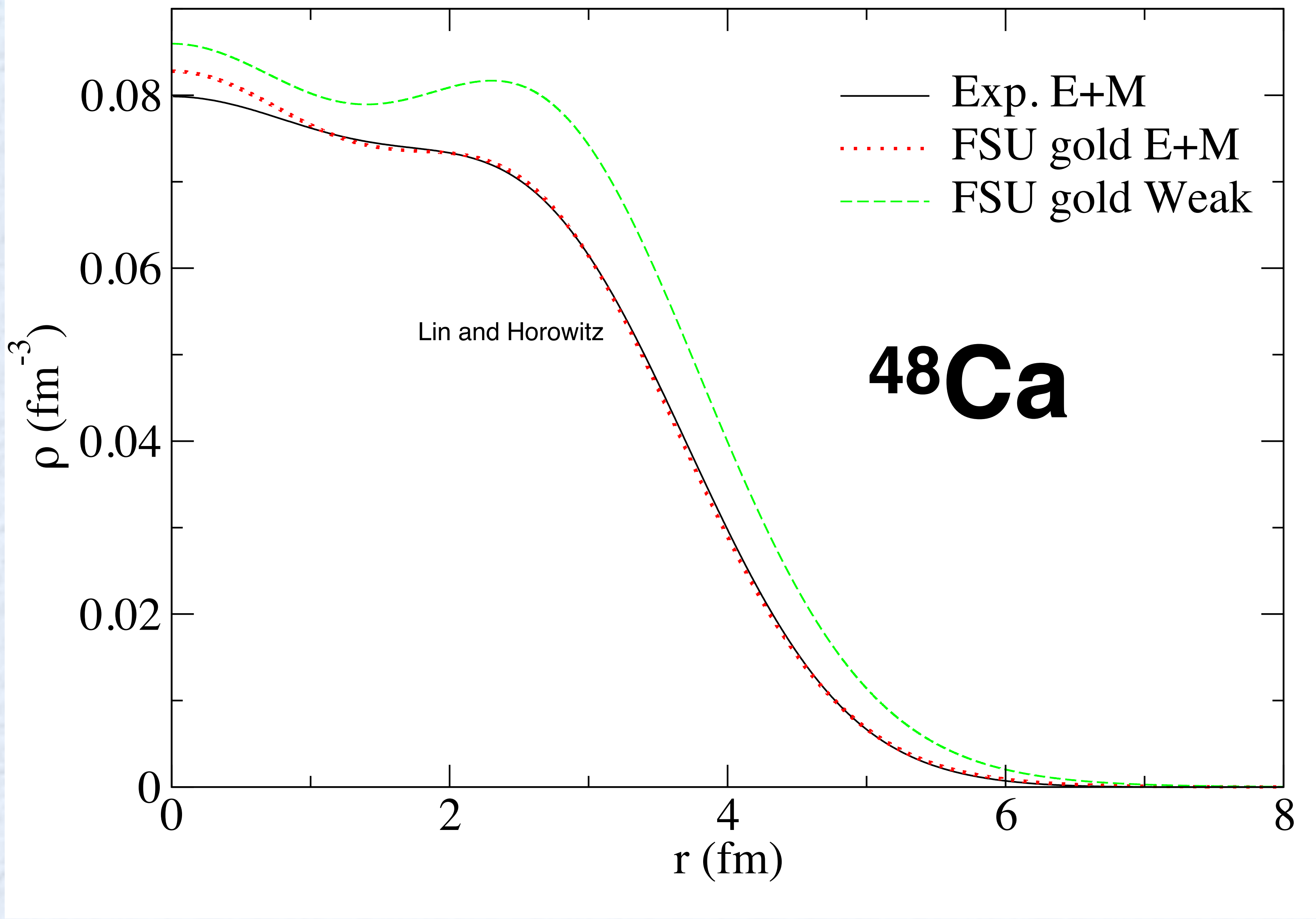

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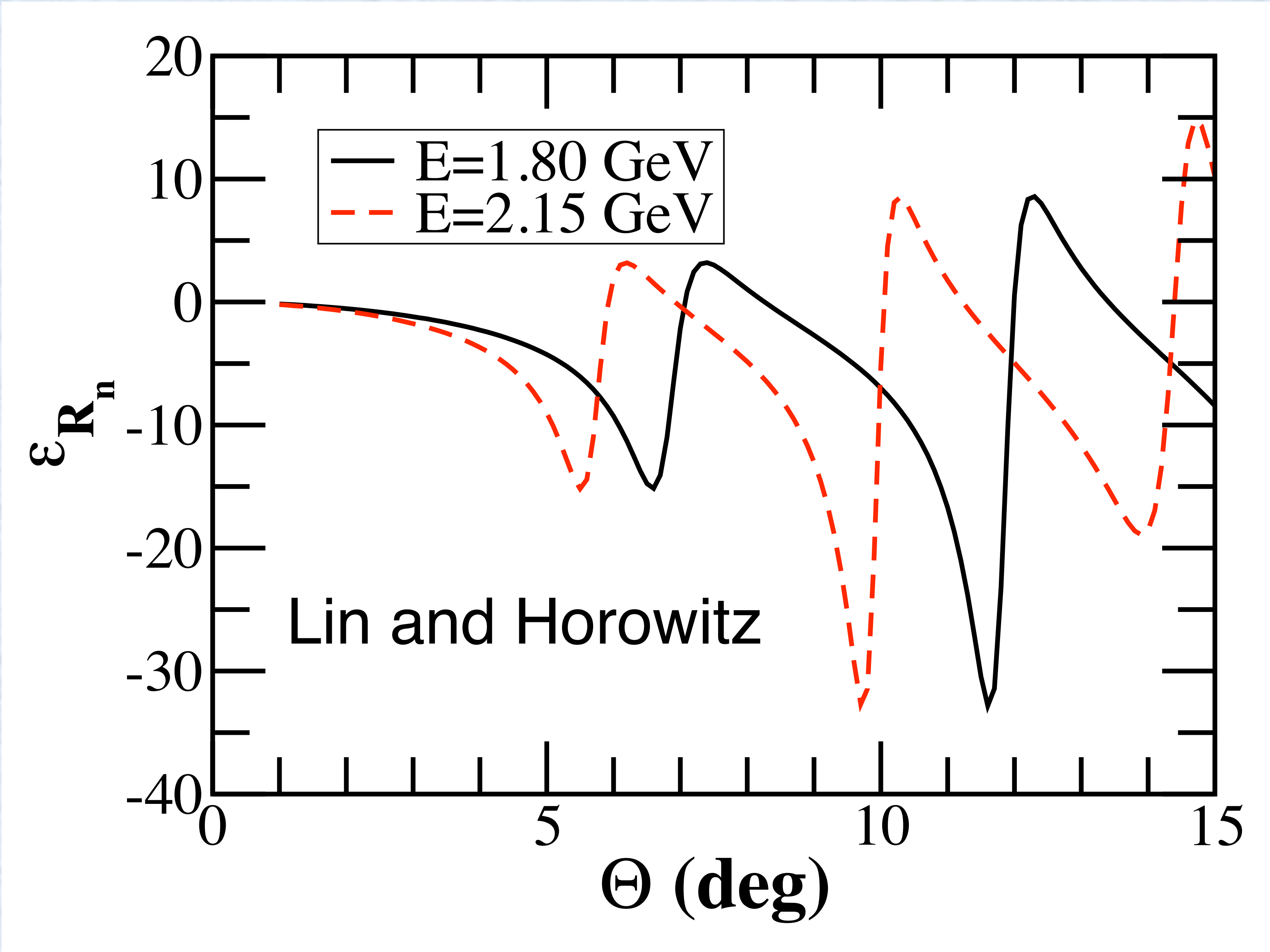
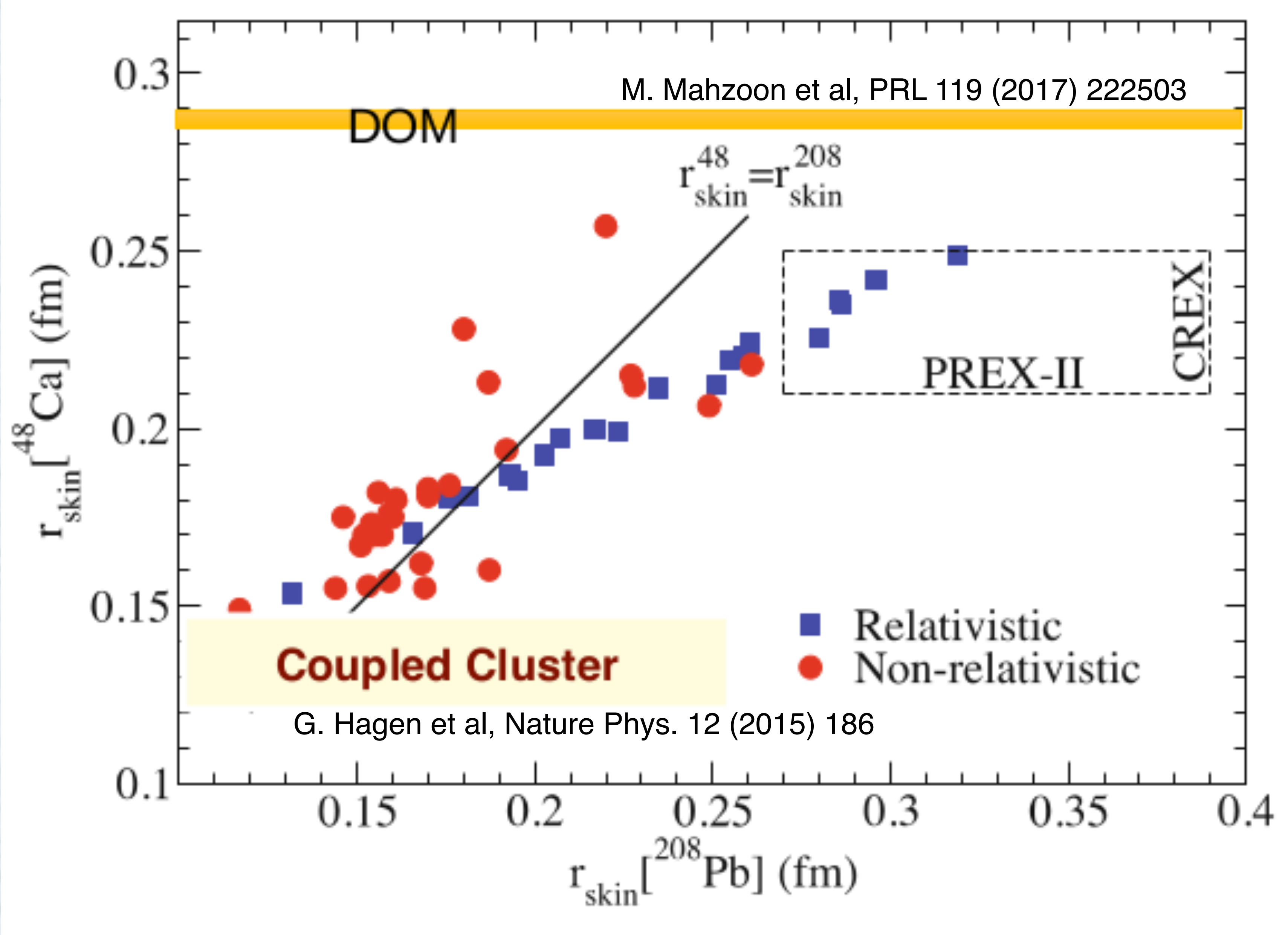


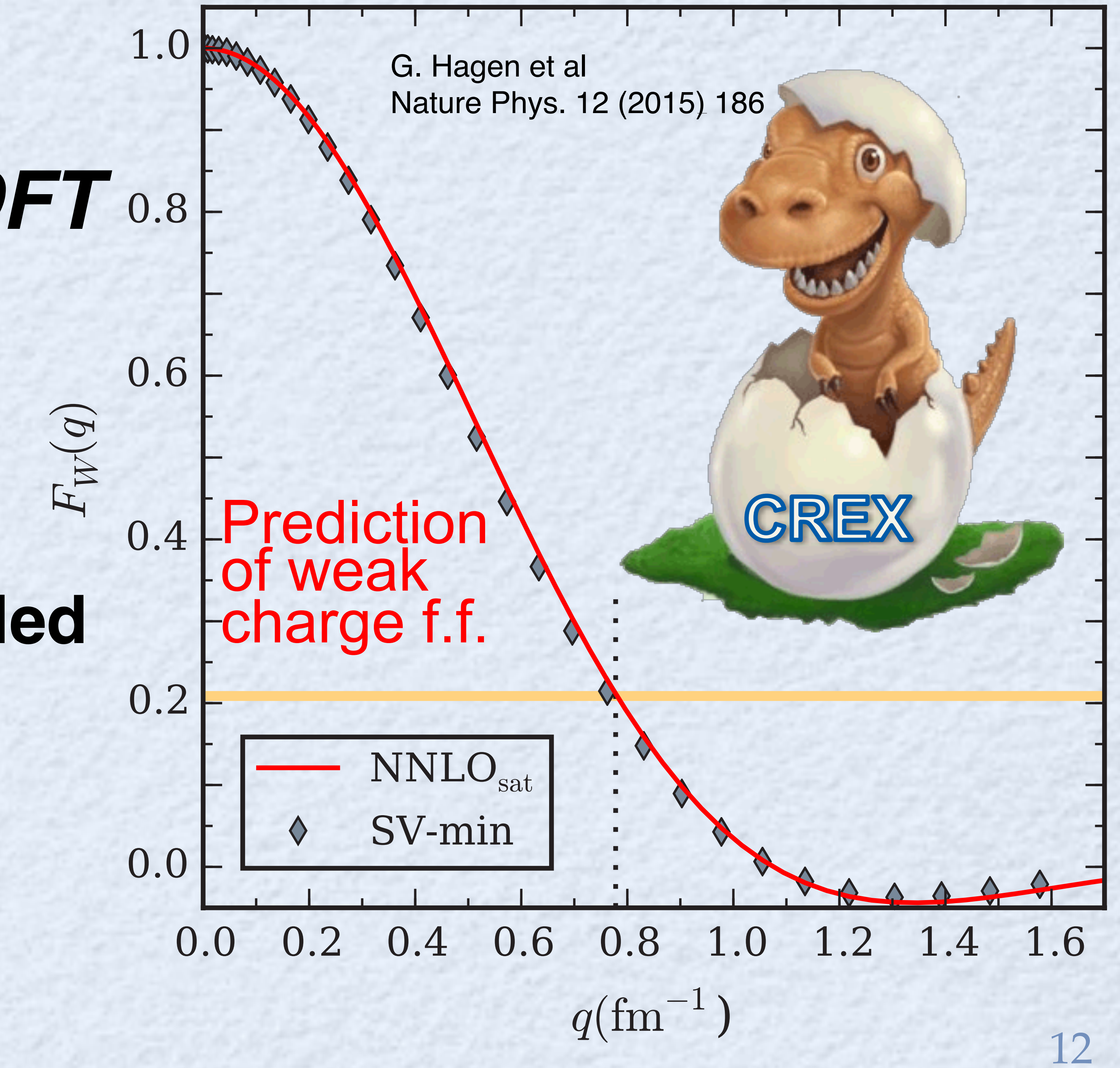


- ***Bridge ab initio calculations and DFT***
- ***3 neutron forces***

Three firm predictions!

Diffractive Optical Model (DOM) and Coupled Cluster (CC) predictions very different!

QMCpi-II prediction (Martinez et al, PRC 100 (2019) 024333) similar to CC



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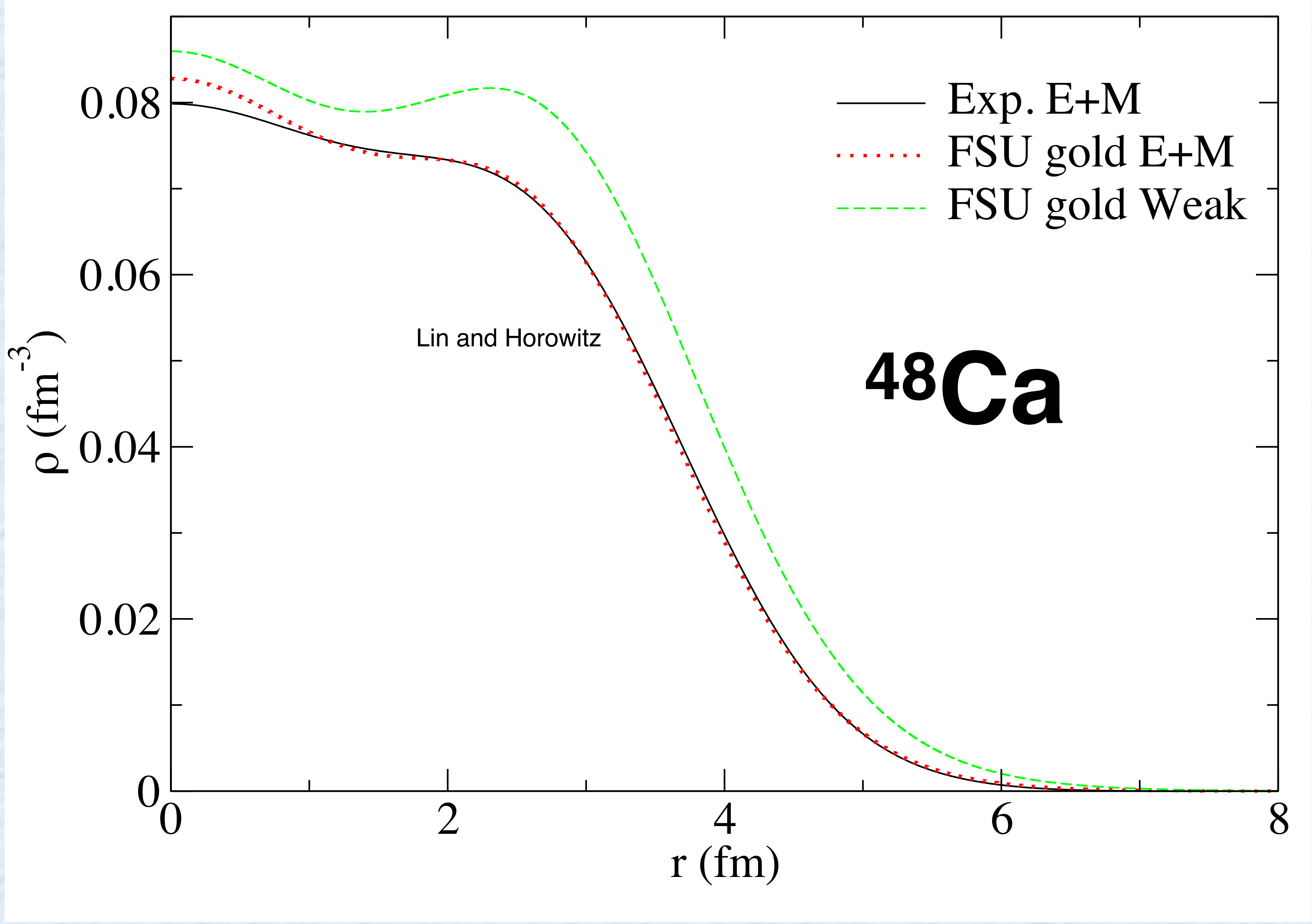

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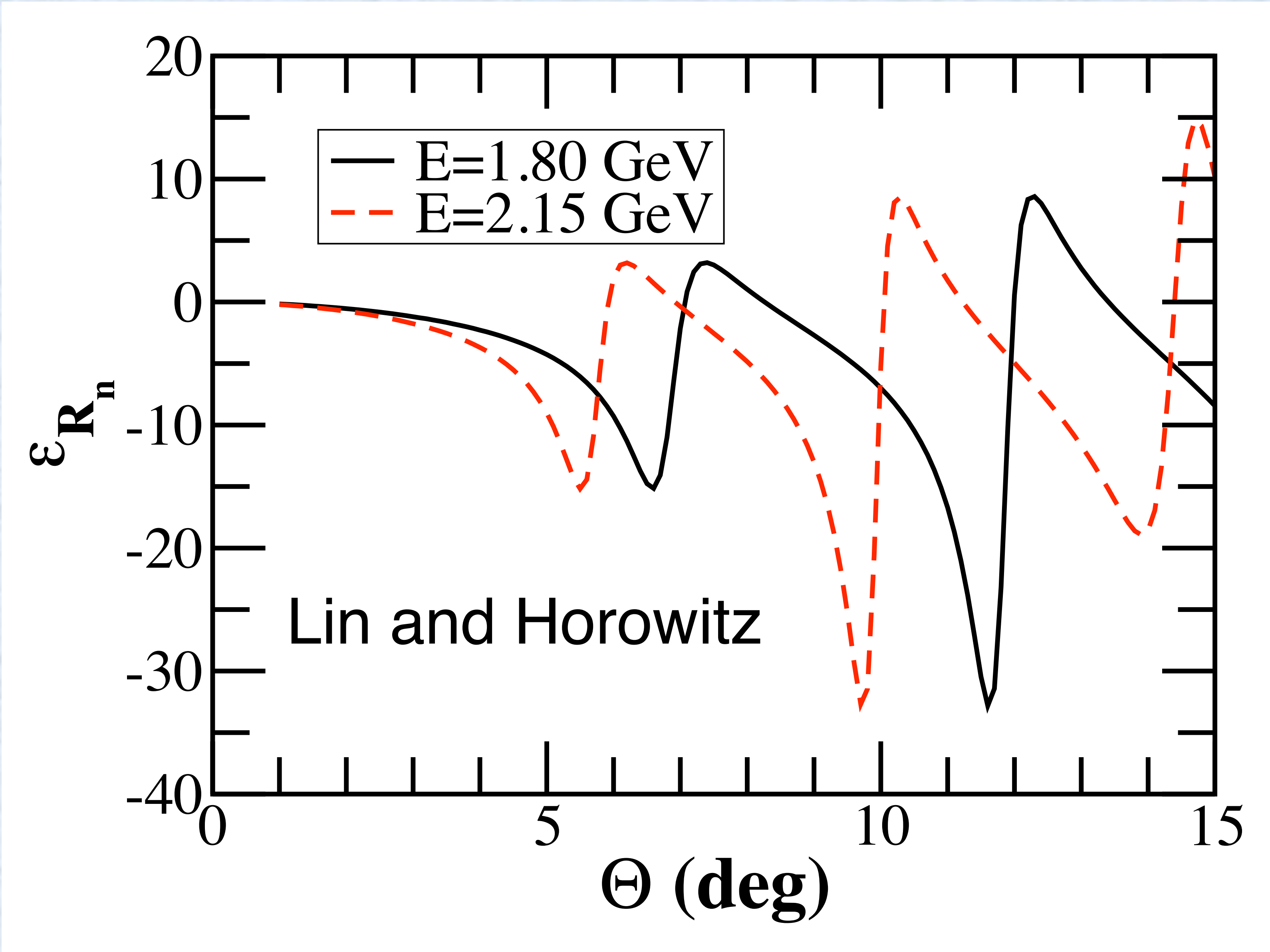

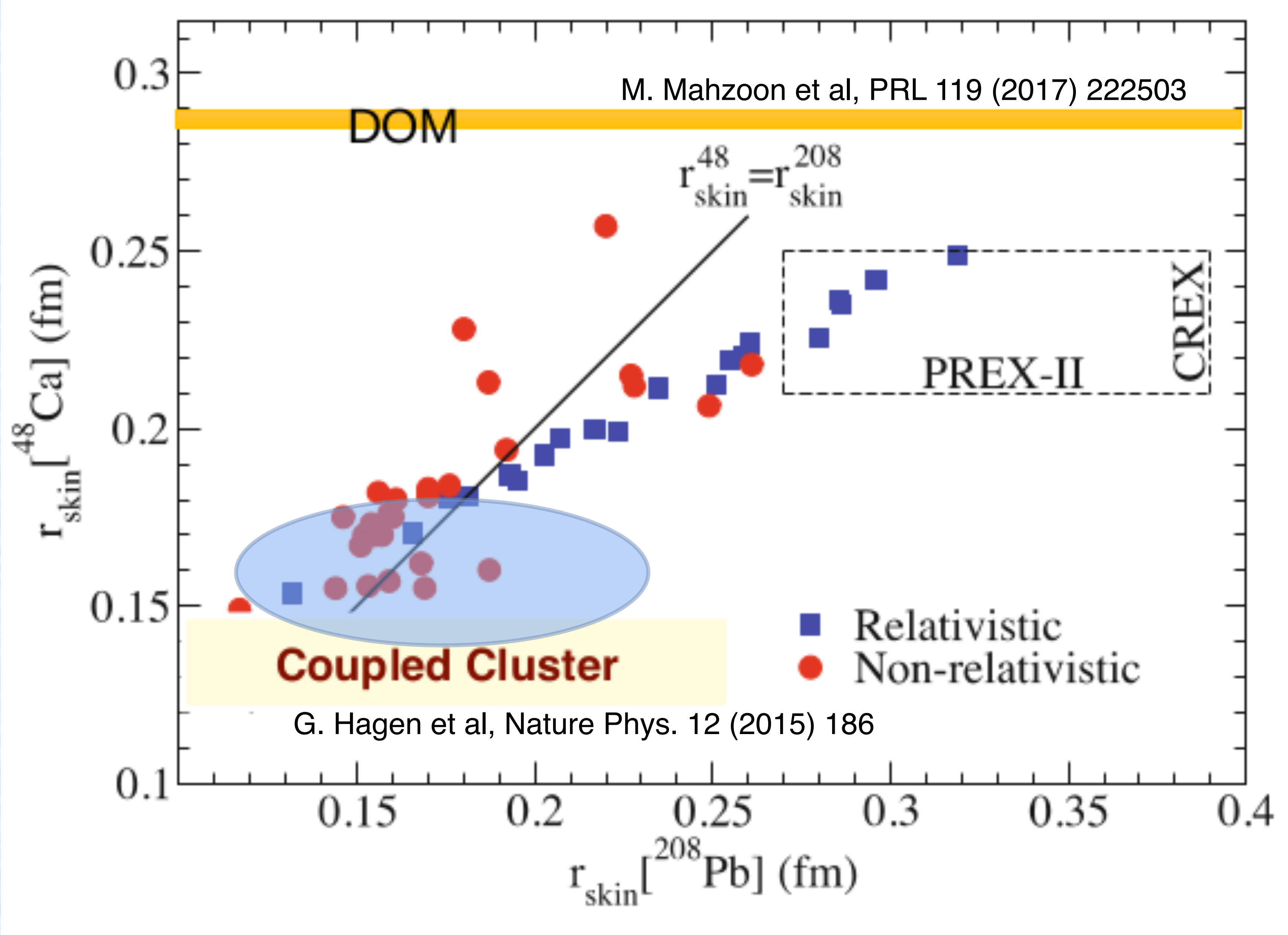

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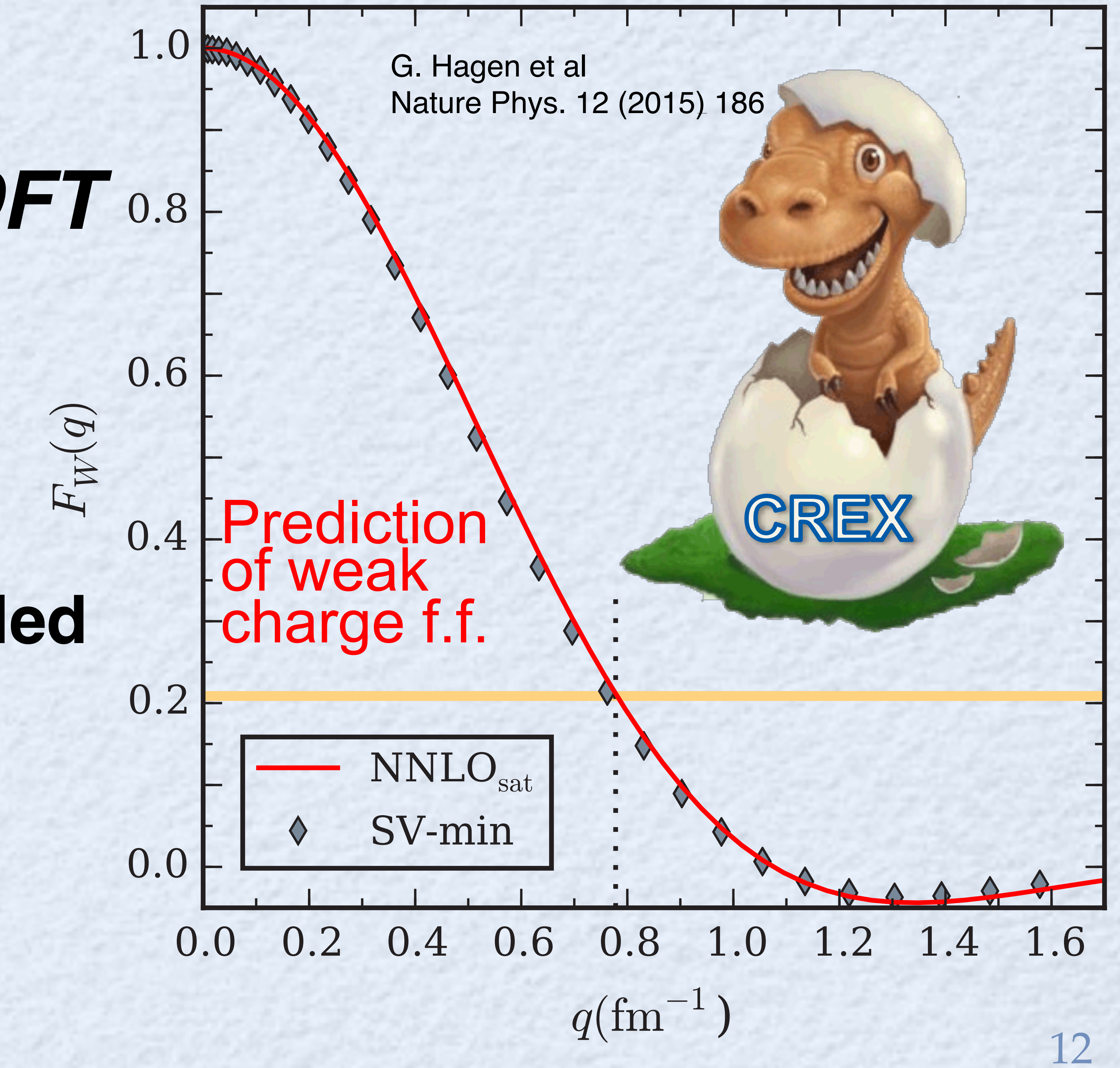

Physics down to a length scale of 10^{-19} m well understood but.....

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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Modern Electroweak Physics

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The High Energy Frontier: Collider Physics

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A comprehensive search for clues requires, in addition:

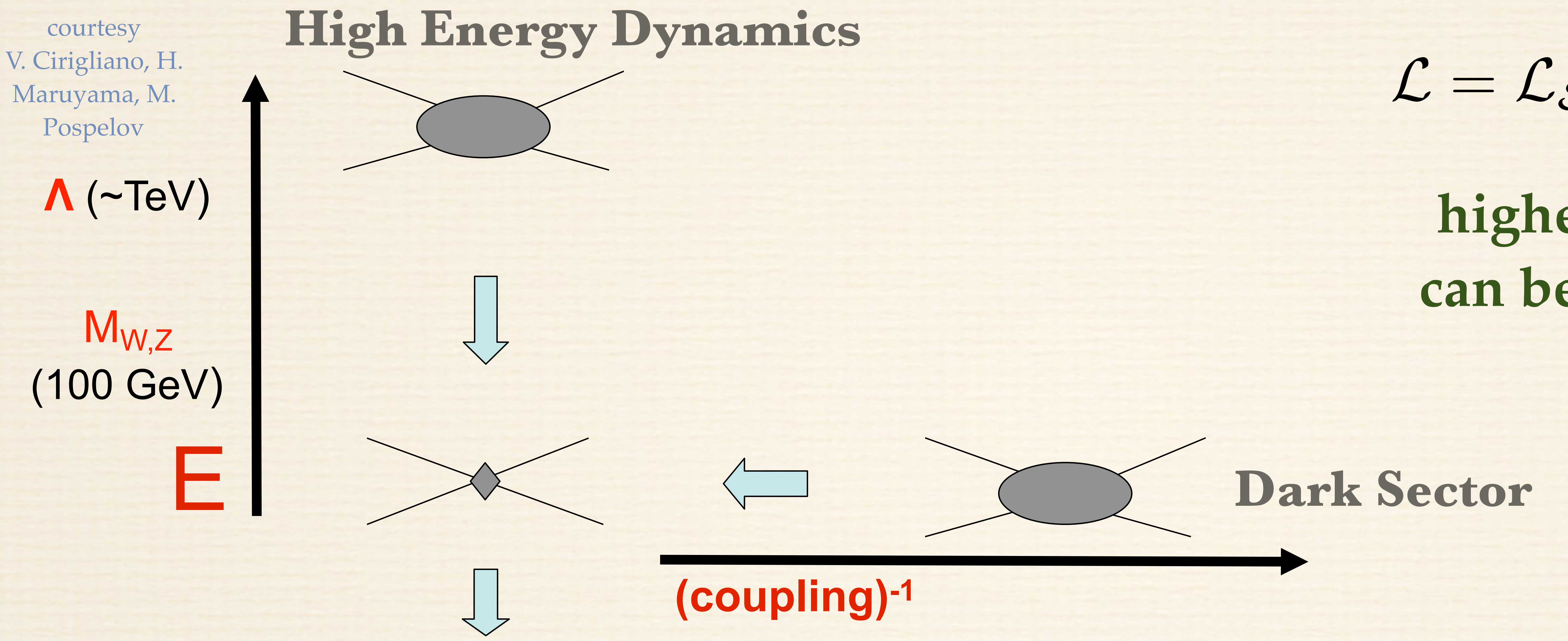
The Intensity/Precision Frontier

- **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....

Indirect Clues

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



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

higher dimensional operators can be systematically classified

Heavy Z's, light (dark) Z's, L-R models, compositeness, extra dimensions, SUSY…

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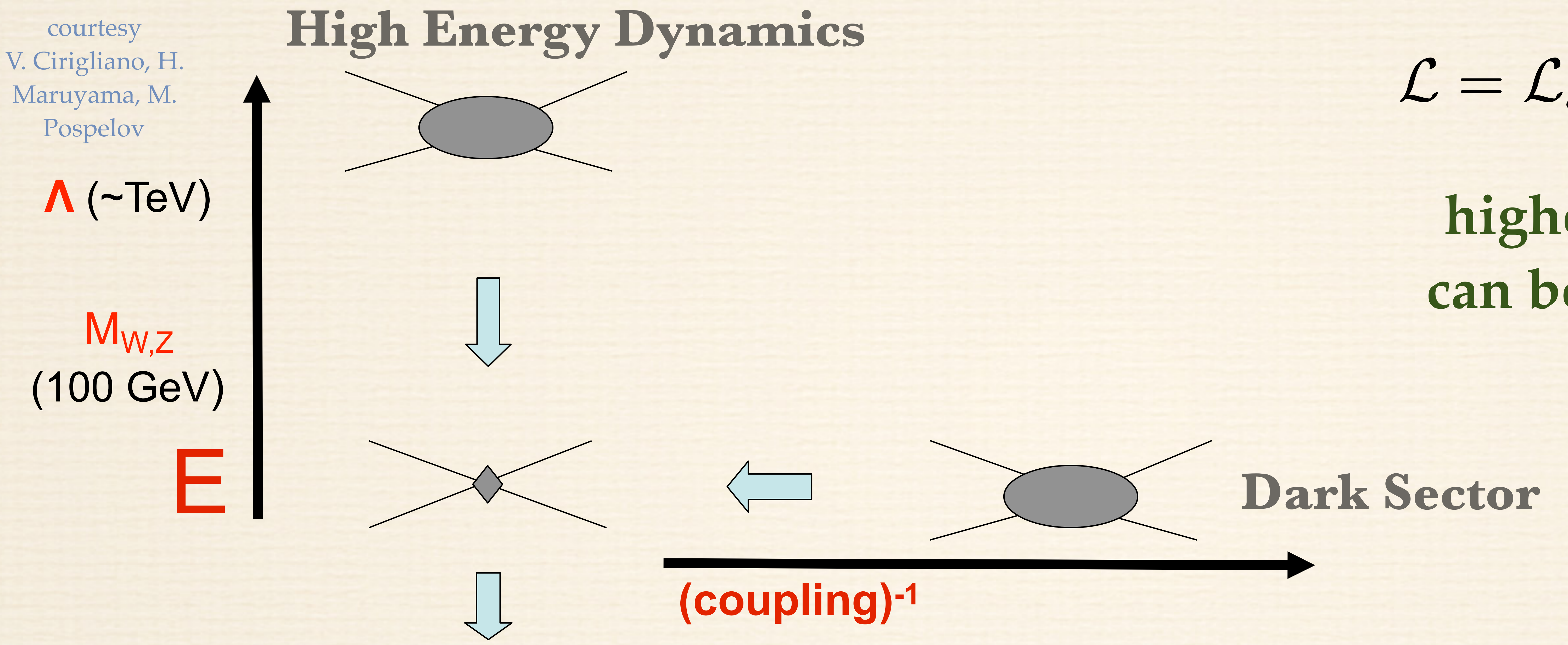

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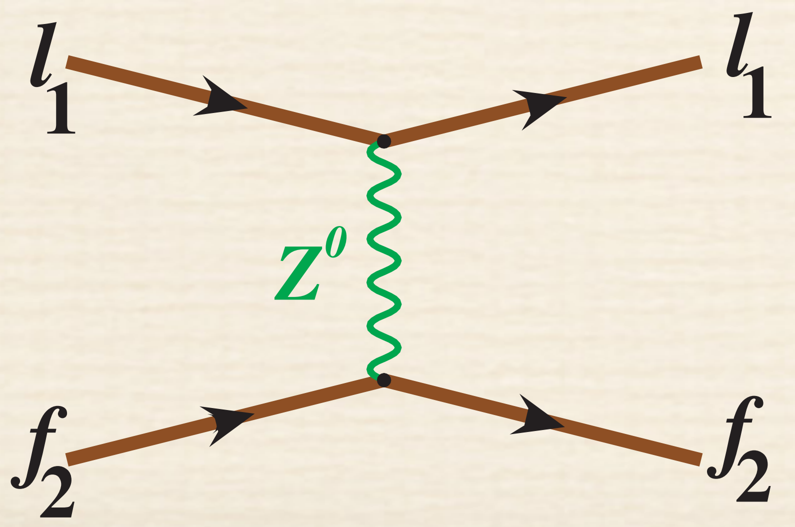
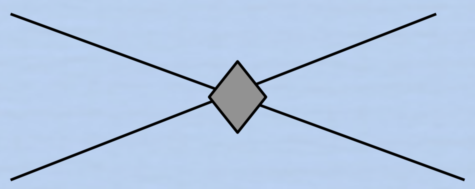
Search for new neutral superweak forces



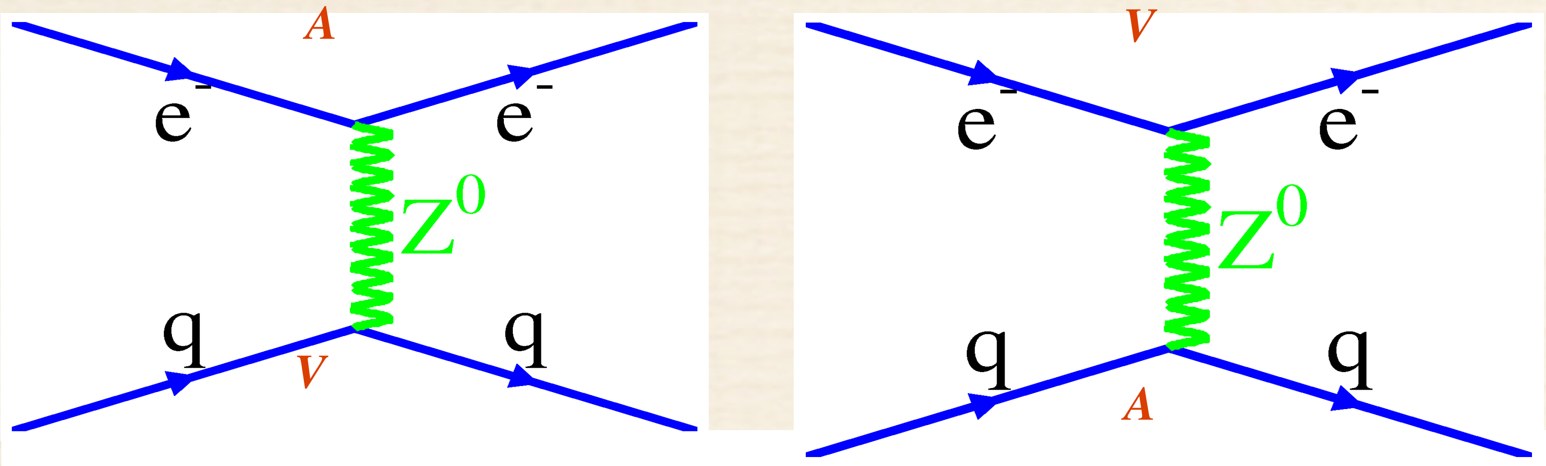
Look for tiny but measurable deviations from precisely calculable predictions for SM processes



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

must reach Λ ~ several TeV

WNC Couplings



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

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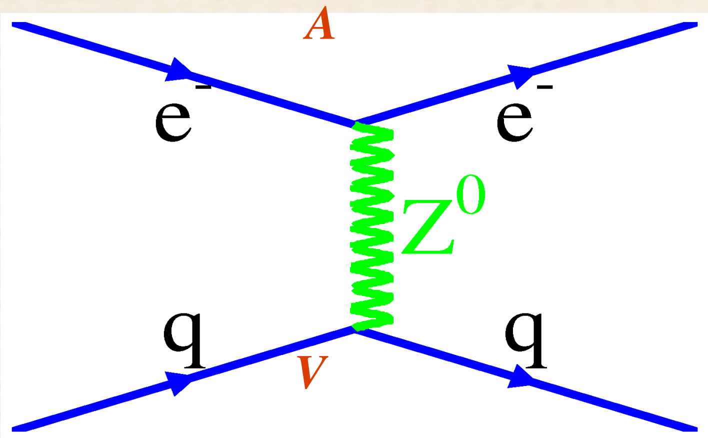

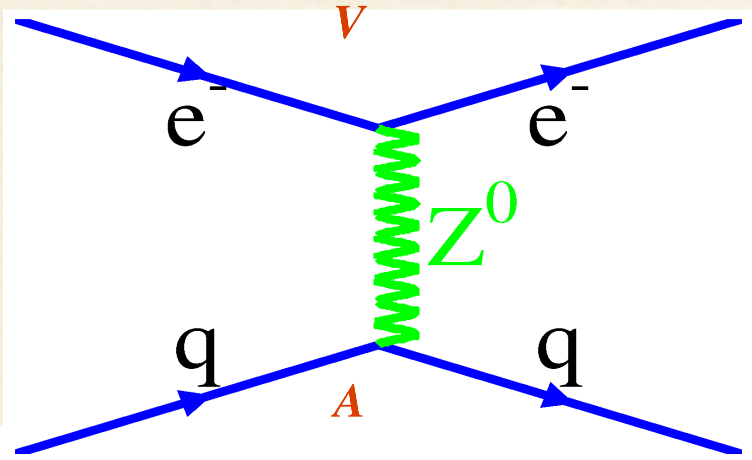

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C_{1u}	$=$	$-\frac{1}{2}+\frac{4}{3}\sin^2\theta_W$	$\approx$	-0.19
C_{1d}	$=$	$\frac{1}{2}-\frac{2}{3}\sin^2\theta_W$	$\approx$	0.35
C_{2u}	$=$	$-\frac{1}{2}+2\sin^2\theta_W$	$\approx$	-0.04
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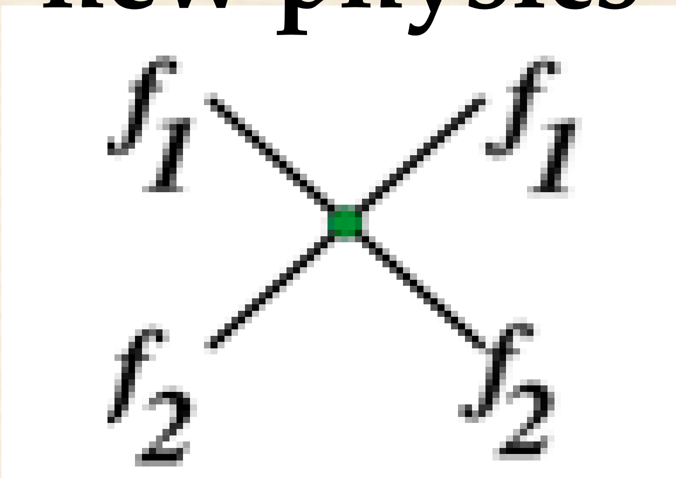
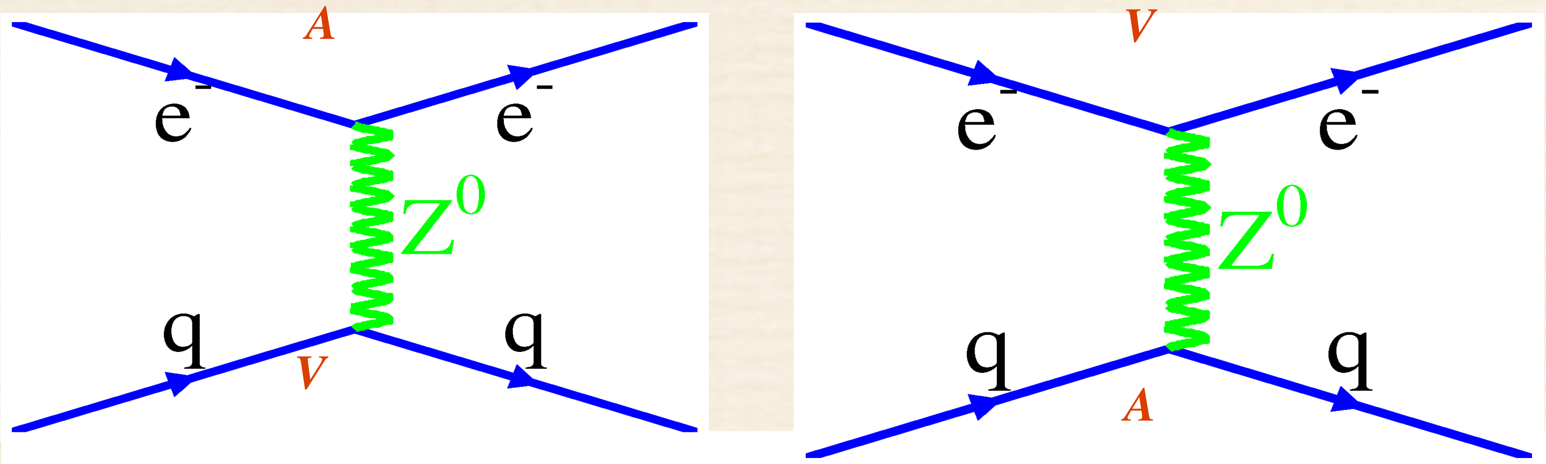
+

new physics



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

WNC Couplings



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

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

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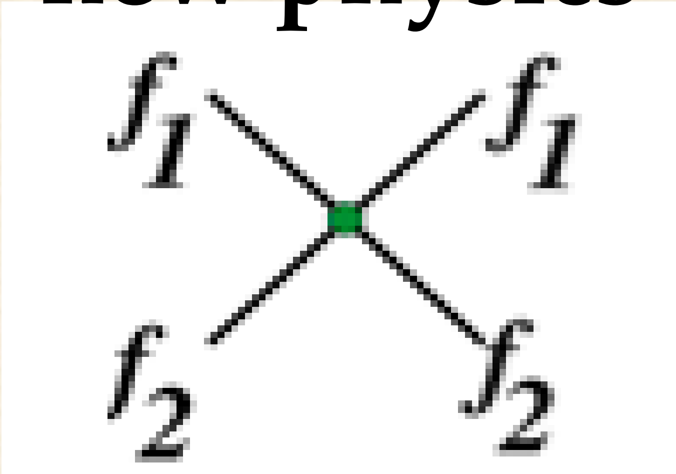

$$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2 \Rightarrow$$

PV elastic e-N scattering, Atomic parity violation

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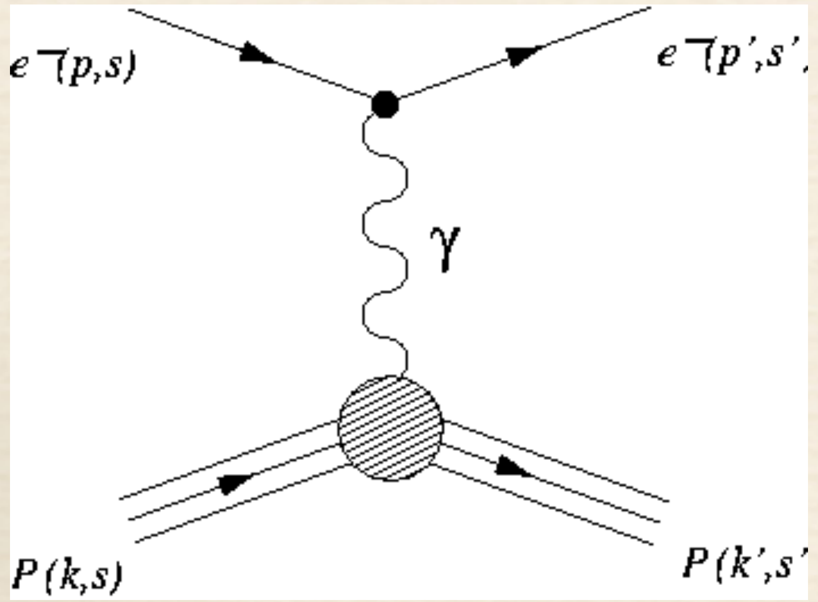

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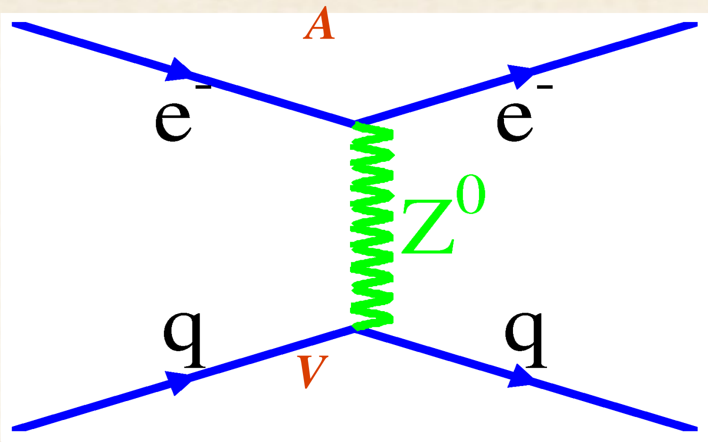

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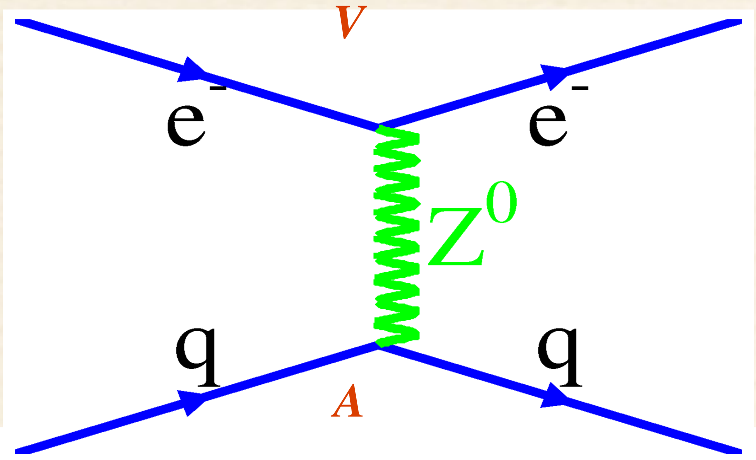

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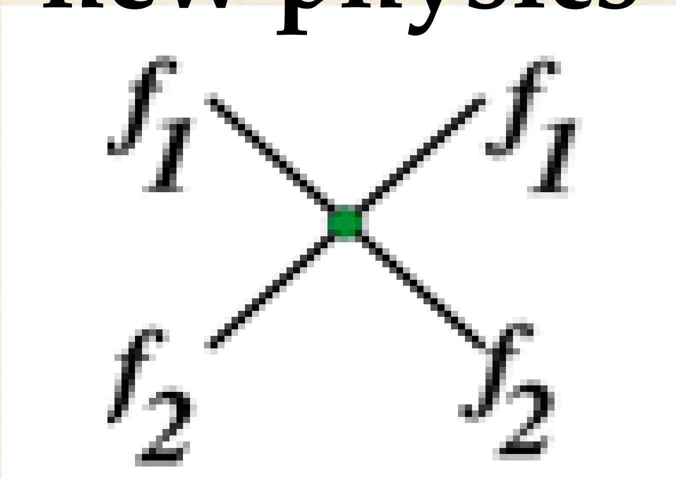

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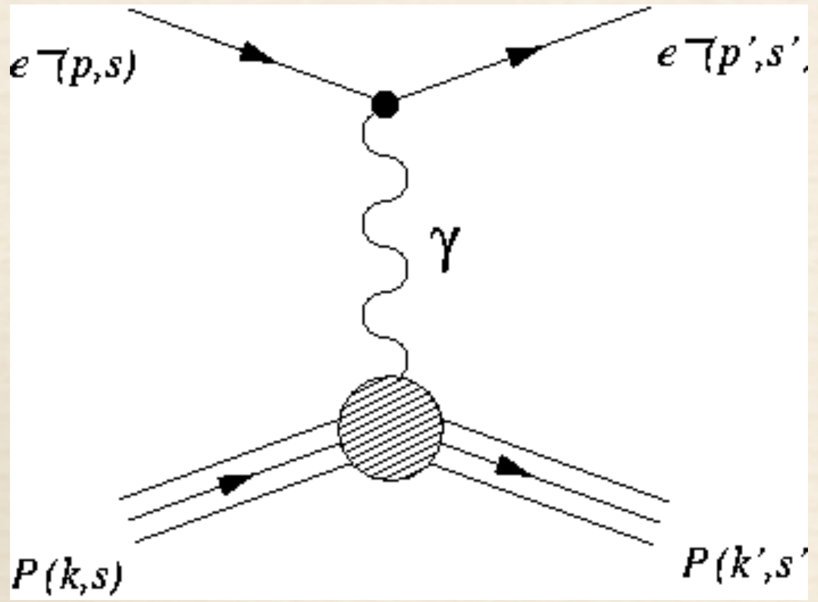

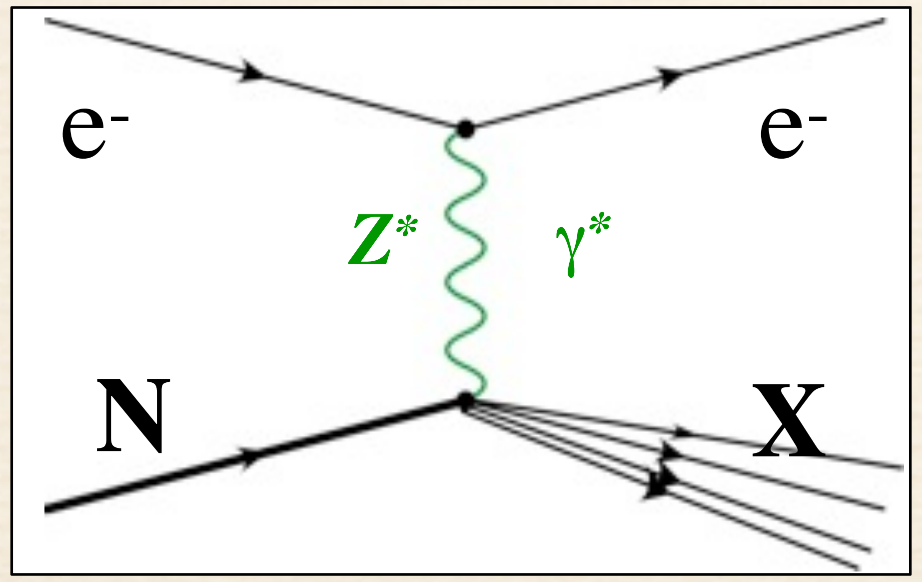

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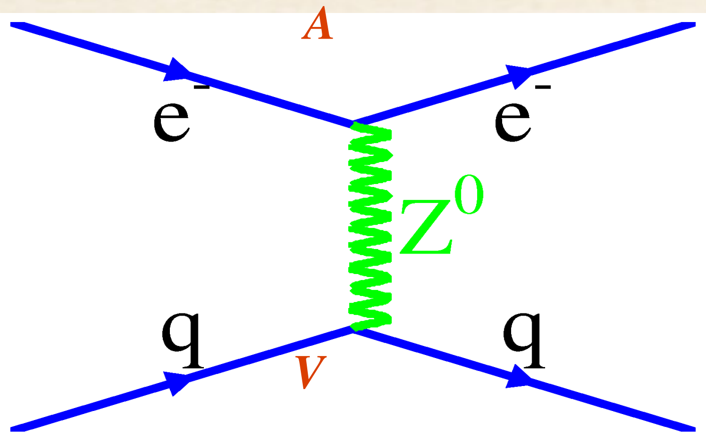

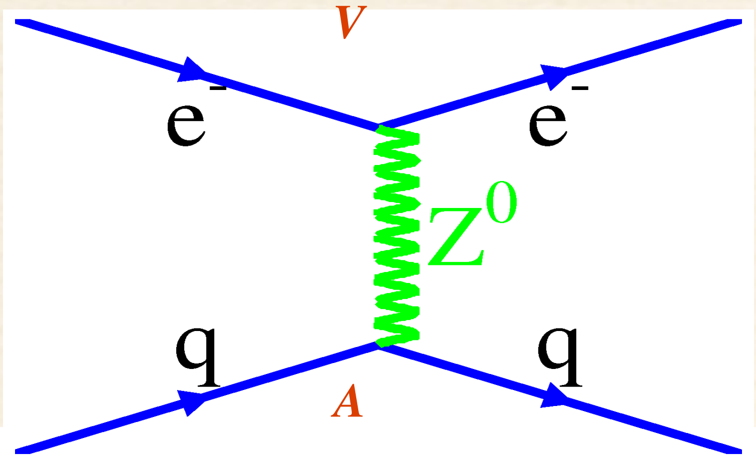

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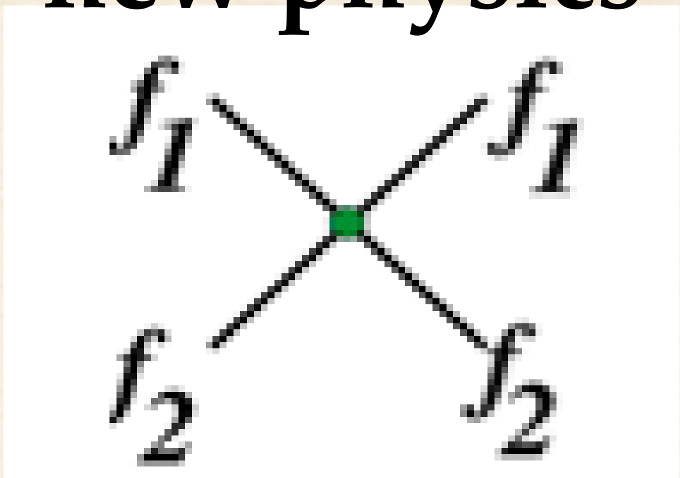

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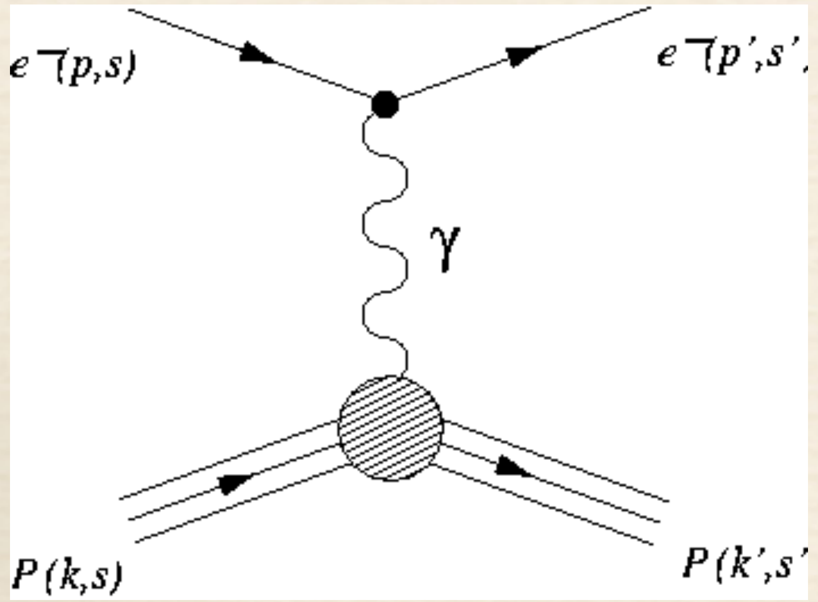
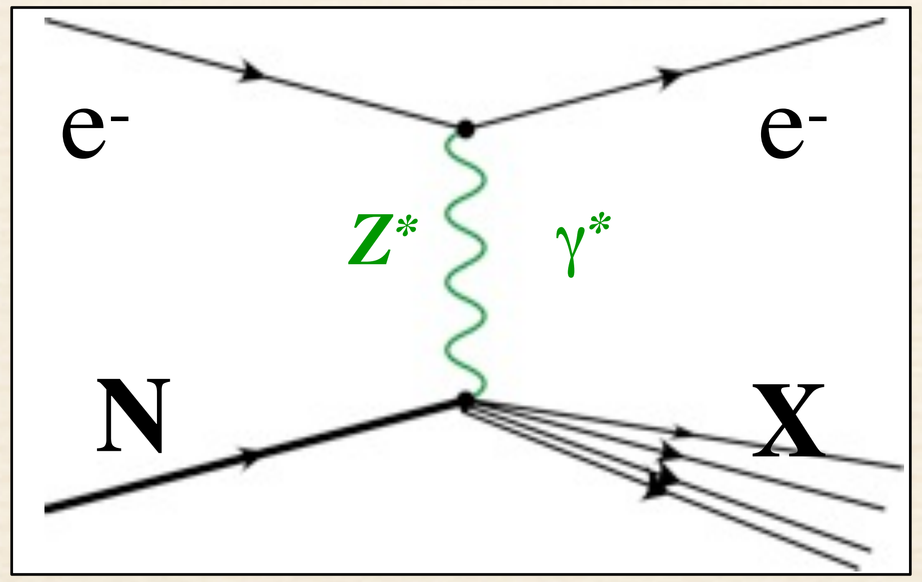
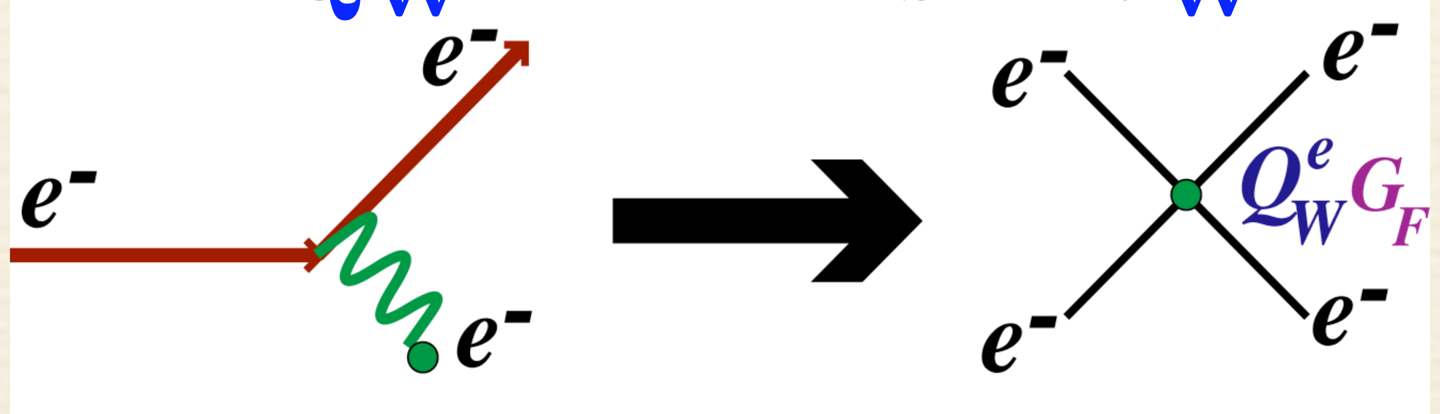


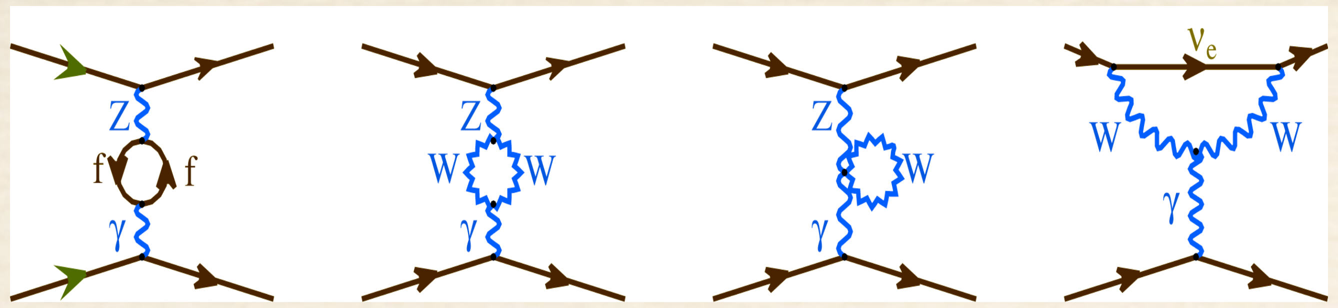


$$Q_W = 1 - 4\sin^2\theta_W$$

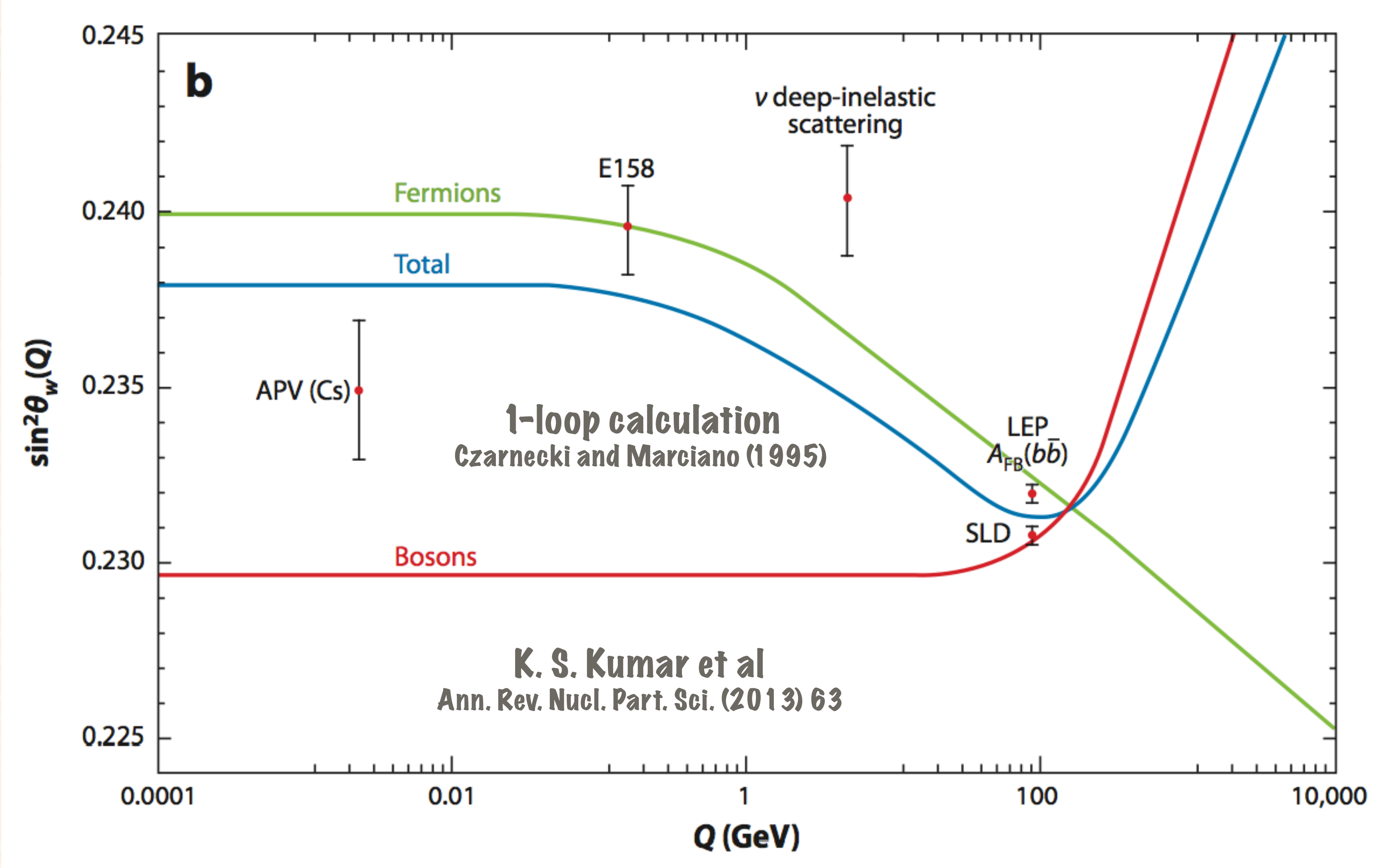


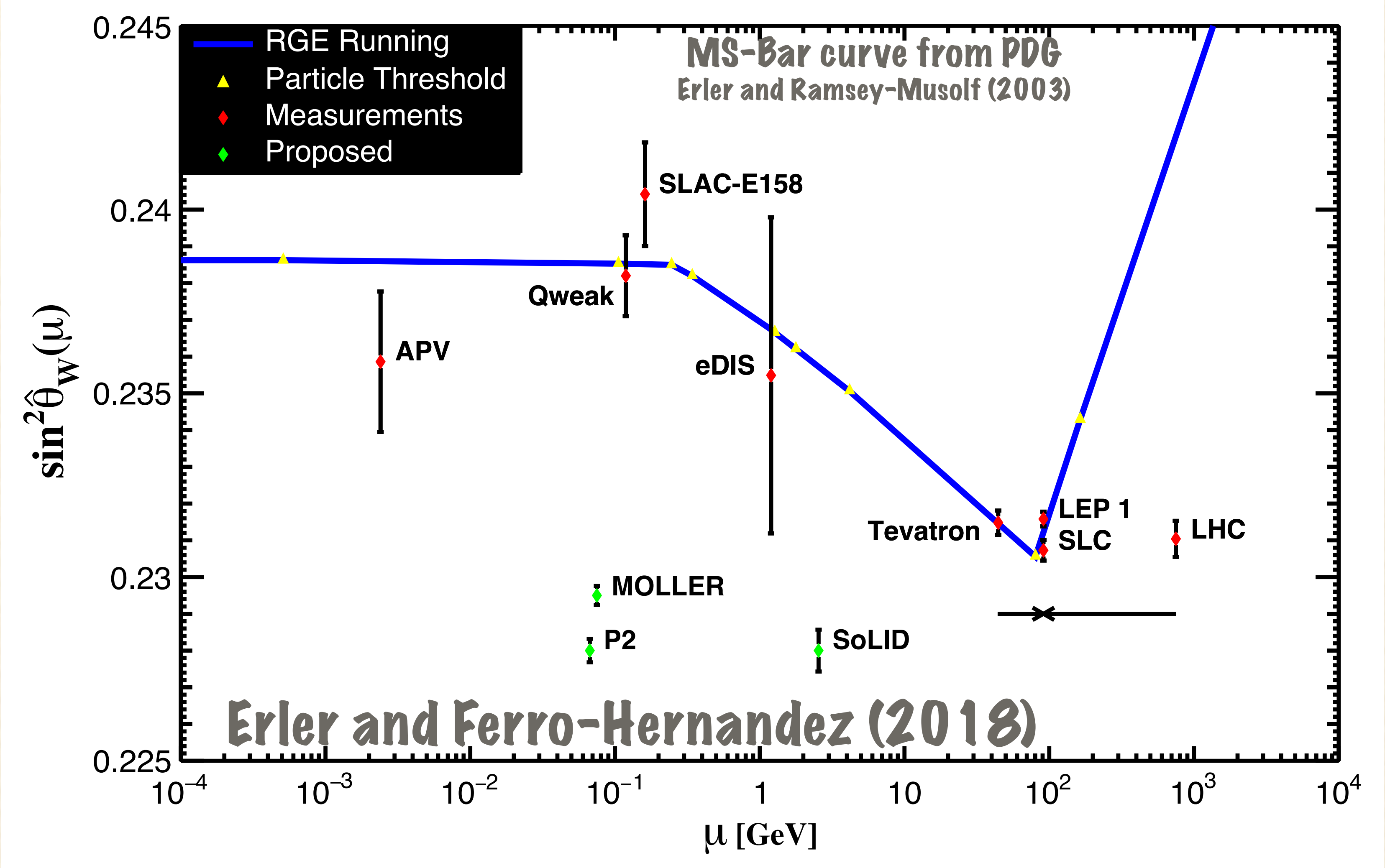
Thumb Rule: Weak mixing angle must be measured to sub-0.5% precision

WNC "Bookkeeping"



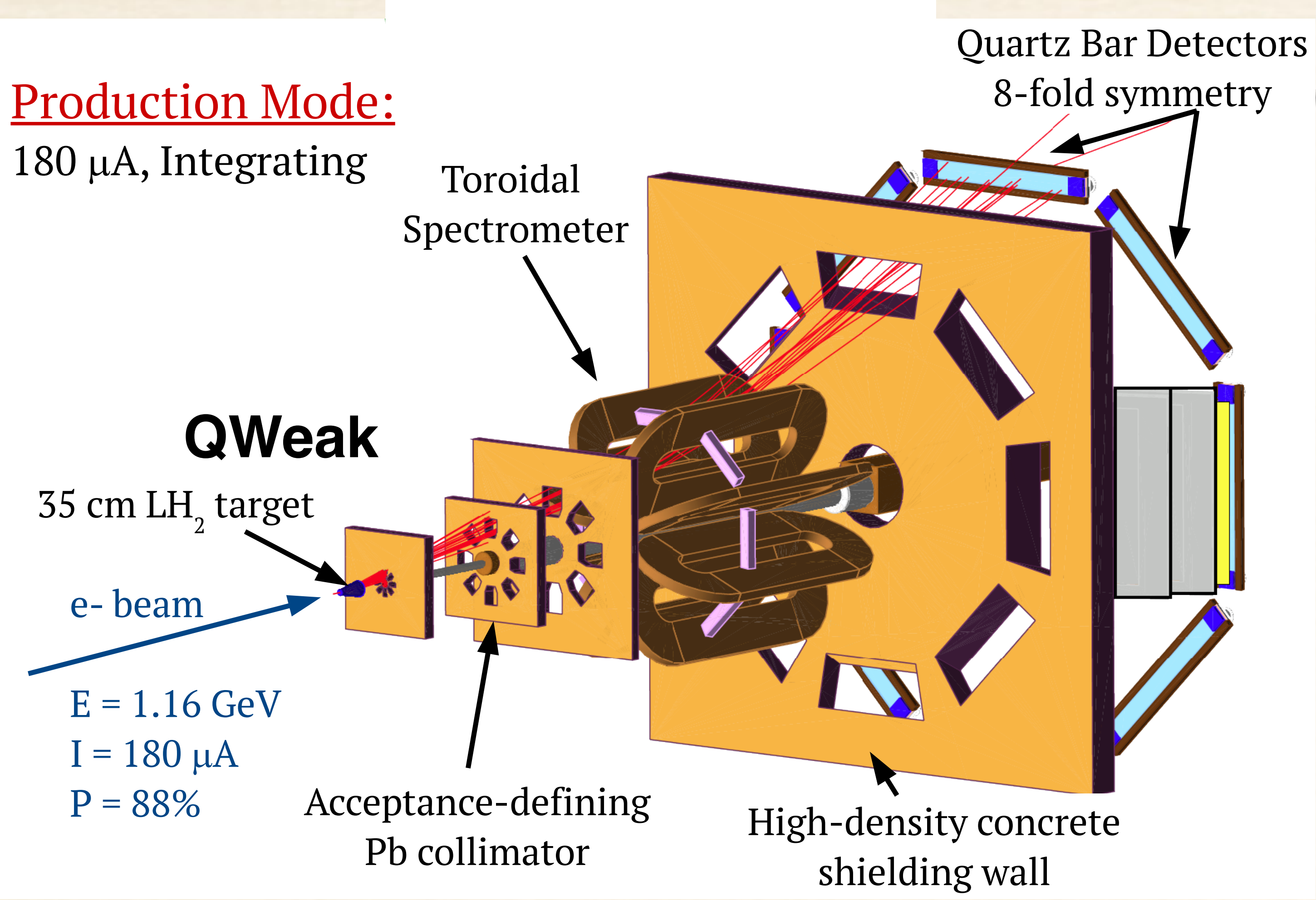
Electroweak Radiative Corrections causes weak mixing angle to "run"



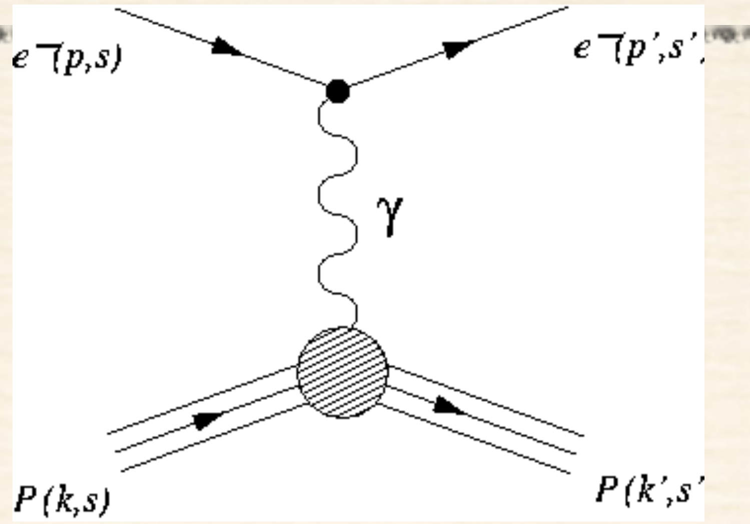


- ✦**Atomic Parity Violation: Cs-133**
  - ✦ future measurements and theory challenging
- ✦**Neutrino Deep Inelastic Scattering: NuTeV**
  - ✦ future measurements and theory challenging
- ✦**PV Møller Scattering: E158 at SLAC**
  - ✦ statistics limited, theory robust
  - ✦ next generation: MOLLER (factor 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 ^2H in valence quark region
  - ✦ factor of 5 to 8 improvement possible: SOLID

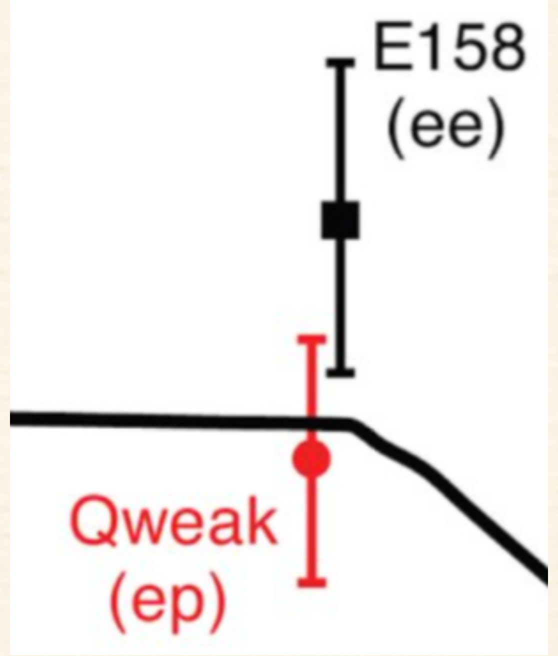
Semi-Leptonic: Recent Past and Future

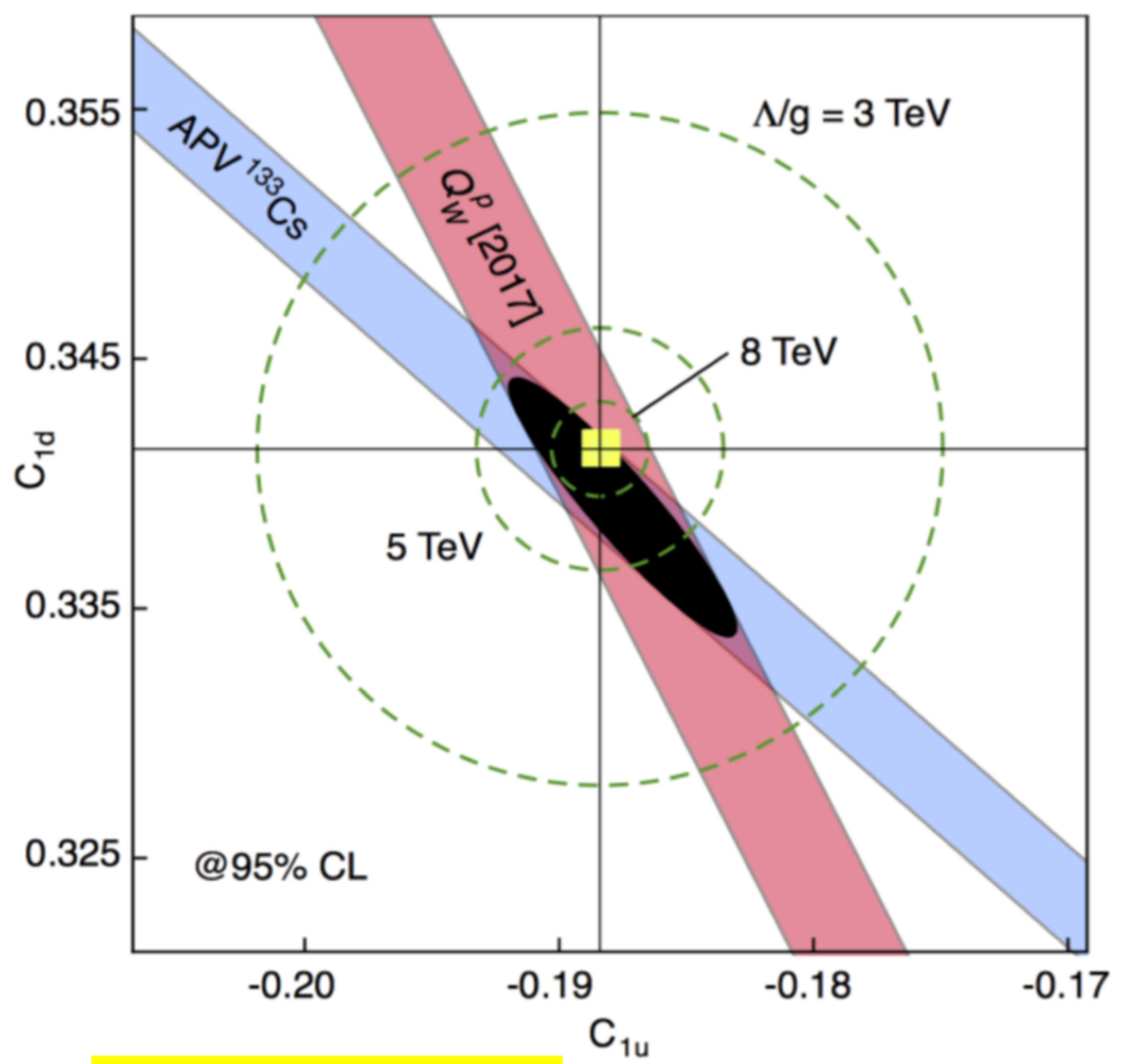


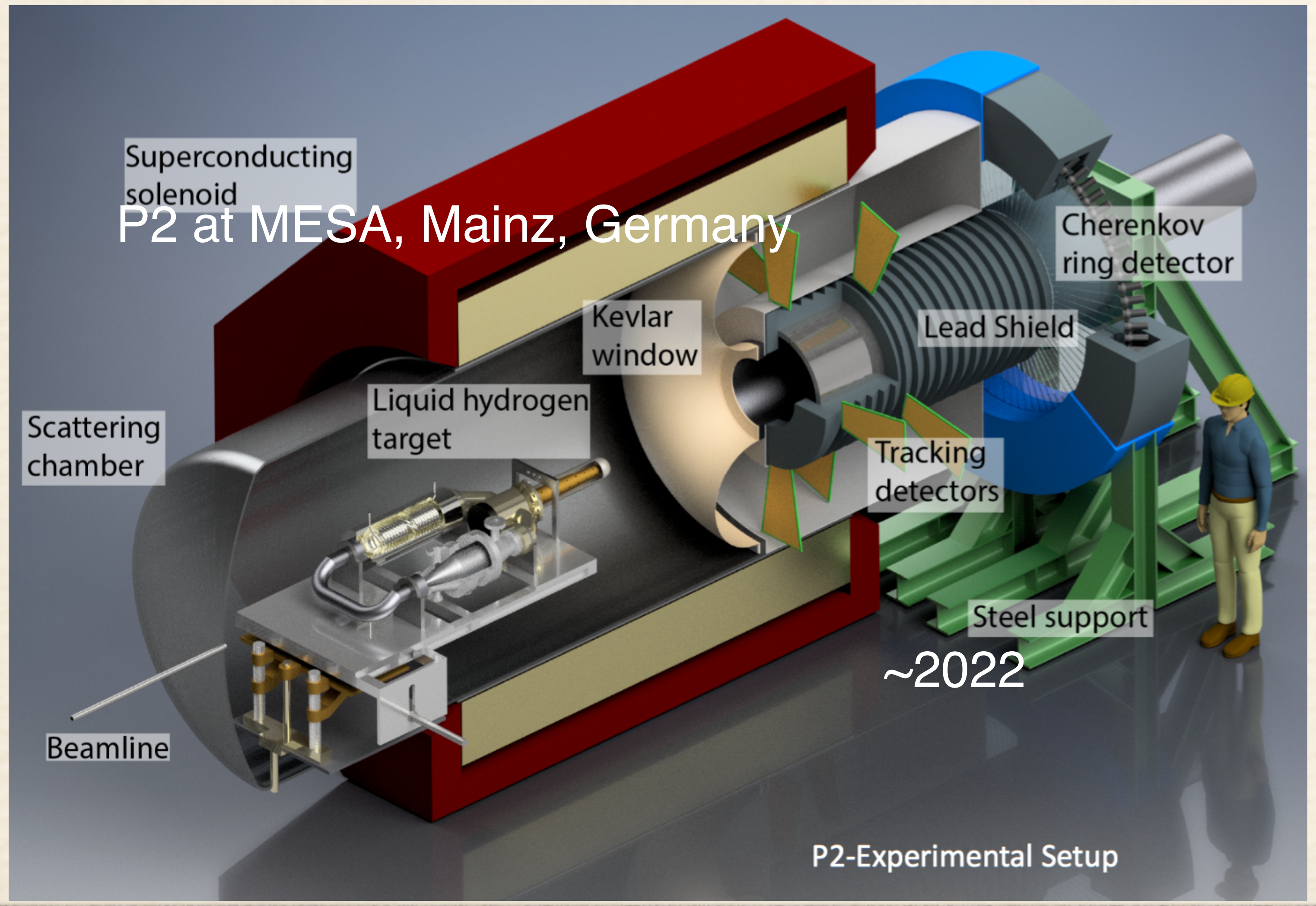
$$A_{ep} = -226.5 \pm 7.3(\mathrm{stat}) \pm 5.8(\mathrm{syst})\ \mathrm{ppb}$$

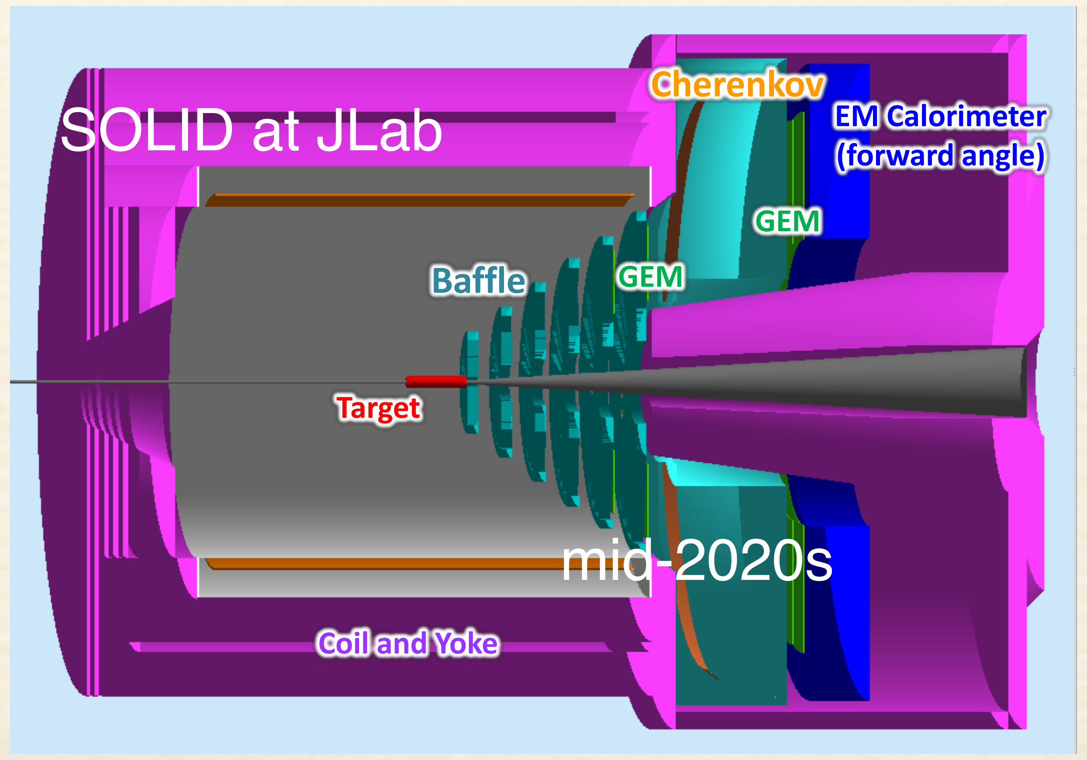


Nature 557 (2018) no.7704, 207-211

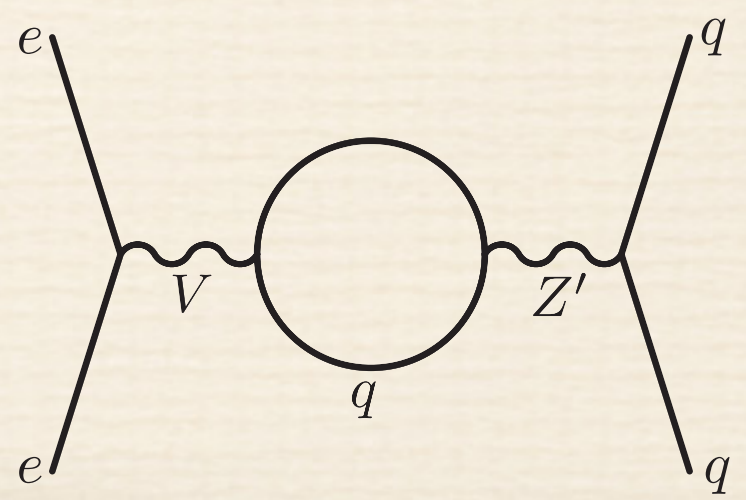








Leptophobic Z'

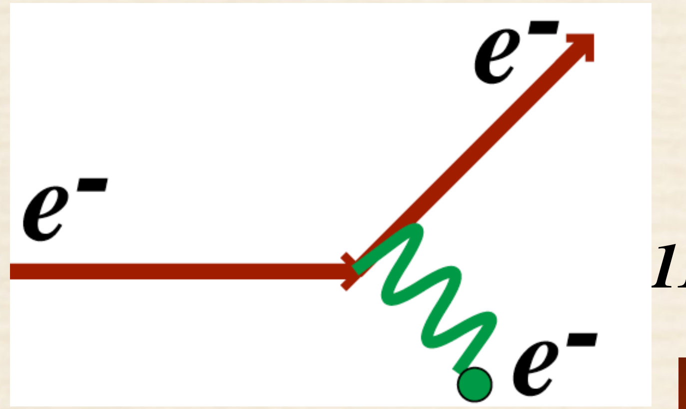


11 GeV Møller scattering

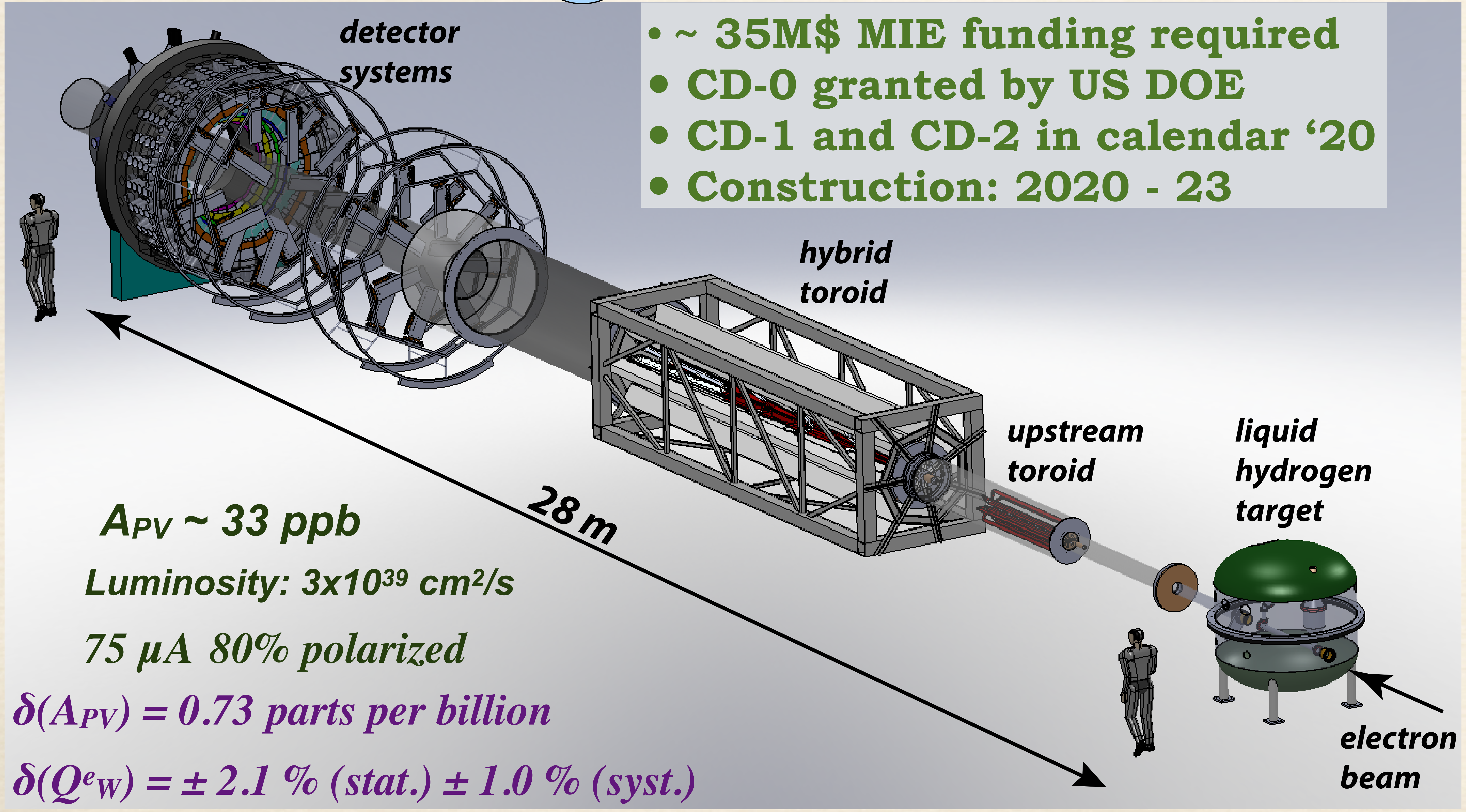
Using Møller scattering (purely leptonic!), improve on E158 by a factor of 5

MOLLER at JLab

Measurement **O**f **L**epton **L**epton **E**lectroweak **R**eaction



- ~ 35M$ MIE funding required
- CD-0 granted by US DOE
- CD-1 and CD-2 in calendar '20
- Construction: 2020 - 23



A_{PV} ~ 33 ppb

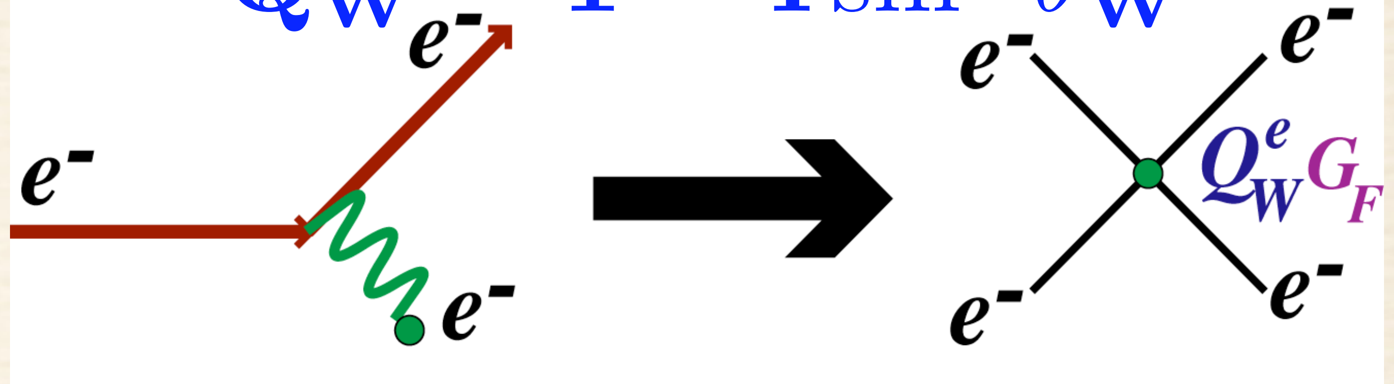
Luminosity: 3×10^{39} cm²/s

75 μA 80% polarized

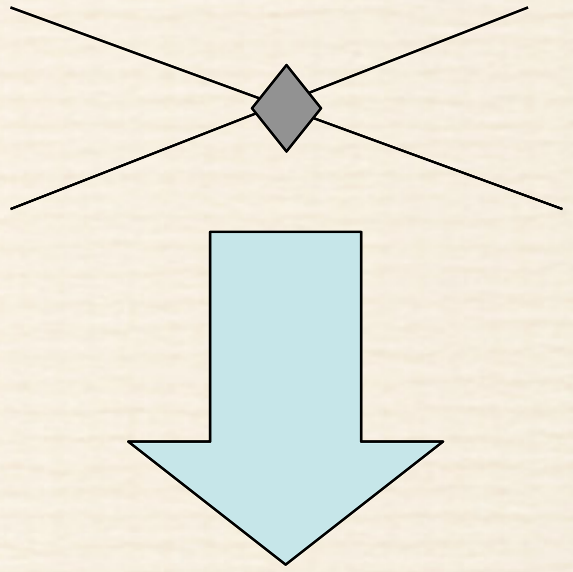
$\delta(A_{PV})$ = 0.73 parts per billion

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

$$Q_{W_e} = 1 - 4\sin^2\theta_W$$



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



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

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

95% C. L. Reach

Comparison with e⁺e⁻ Collisions

Best reach on purely leptonic contact interaction amplitudes: LEP200

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

$$g_{ij} = 4\pi\eta_{ij}$$

Model	η^f_{LL}	η^f_{RR}	η^f_{LR}	η^f_{RL}
$LL^\pm$	± 1	0	0	0
$RR^\pm$	0	± 1	0	0
$VV^\pm$	± 1	± 1	± 1	± 1

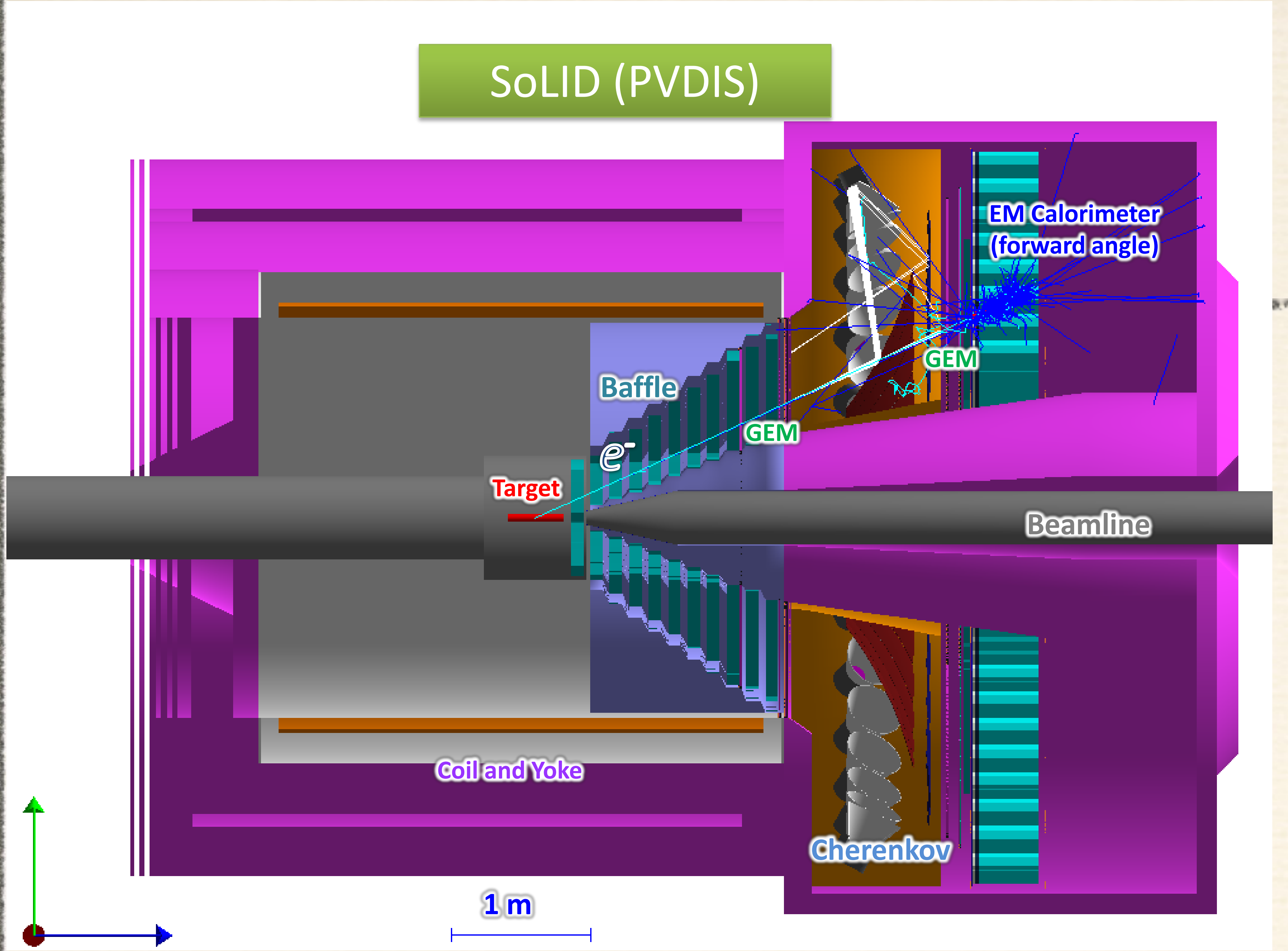
LEP200 Reach $\Lambda^{ee}_{LL} \sim 8.3$ TeV

E158 Reach $\Lambda^{ee}_{LL} \sim 12$ TeV

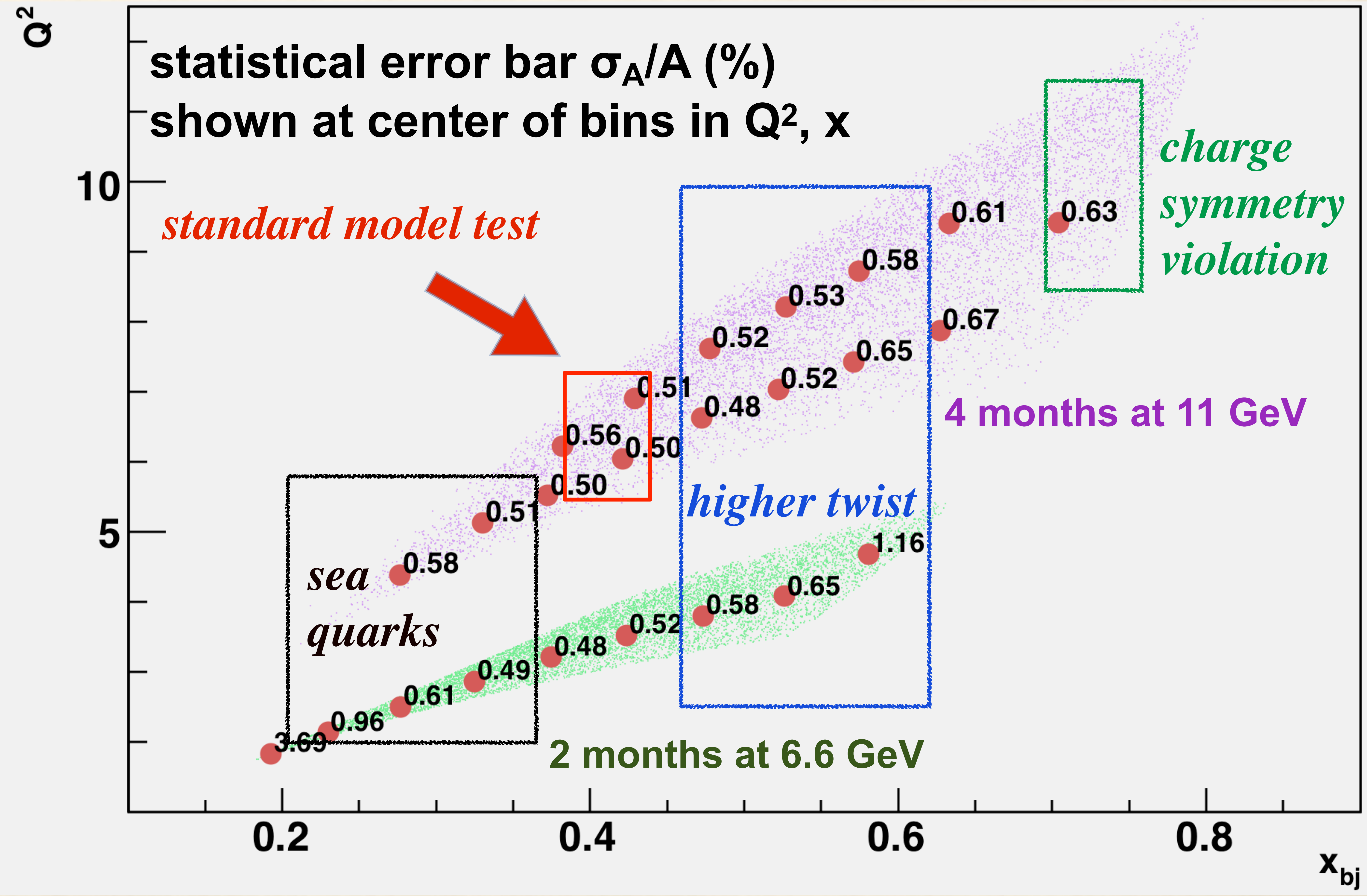
MOLLER Reach $\Lambda^{ee}_{LL} \sim 27$ TeV

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

PVDIS at 12 GeV: SOLID



Strategy: **sub-1% precision** over broad kinematic range: **sensitive Standard Model test** *and* **detailed study of hadronic structure contributions**



Requirements

- *High Luminosity with E > 10 GeV*
- *Large scattering angles (for high x & y)*
- *Better than 1% errors for small bins*
- *x-range 0.25-0.75*
- *W^2 > 4 GeV^2*
- *Q^2 range a factor of 2 for each x*
  - (Except at very high x)
- *Moderate running times*

Longstanding issue in nucleon structure: d(x) as x → 1

SOLID: d/u with the Proton

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

first principles: using electroweak neutral current structure functions

$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V \frac{f(y)}{2}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

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quark-parton model and pdfs

$$a(x) \approx \frac{3}{4}\left[\frac{6C_{1u}u(x) - 3C_{1d}d(x)}{u(x) + \frac{1}{4}d(x)}\right] \sim \left[\frac{u(x) + 0.912d(x)}{u(x) + 0.25d(x)}\right]$$

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- **Slightly lower-x**

- **Statistics-dominated!**
- **"For free": just replace LD2 with LH2**

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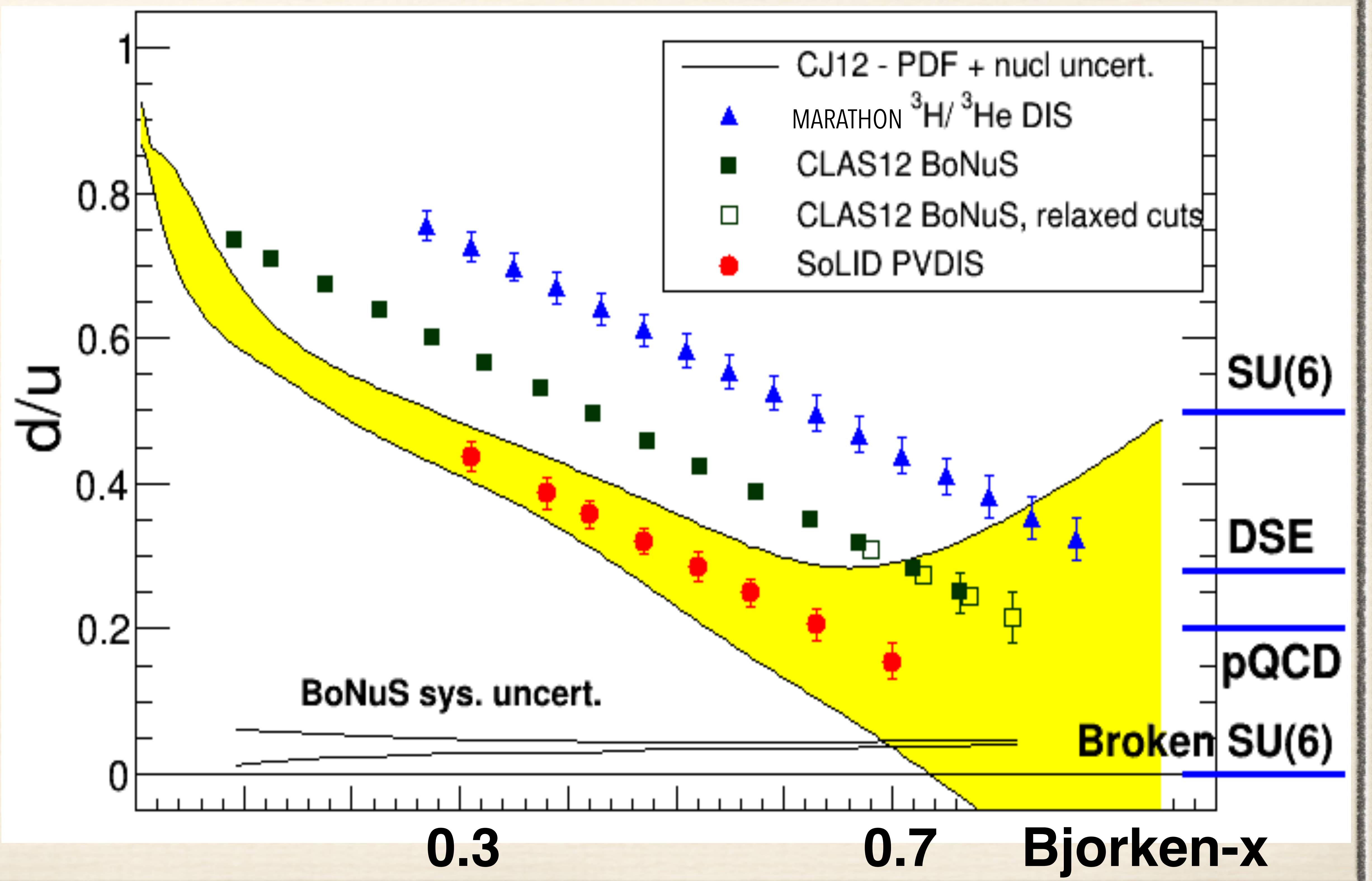

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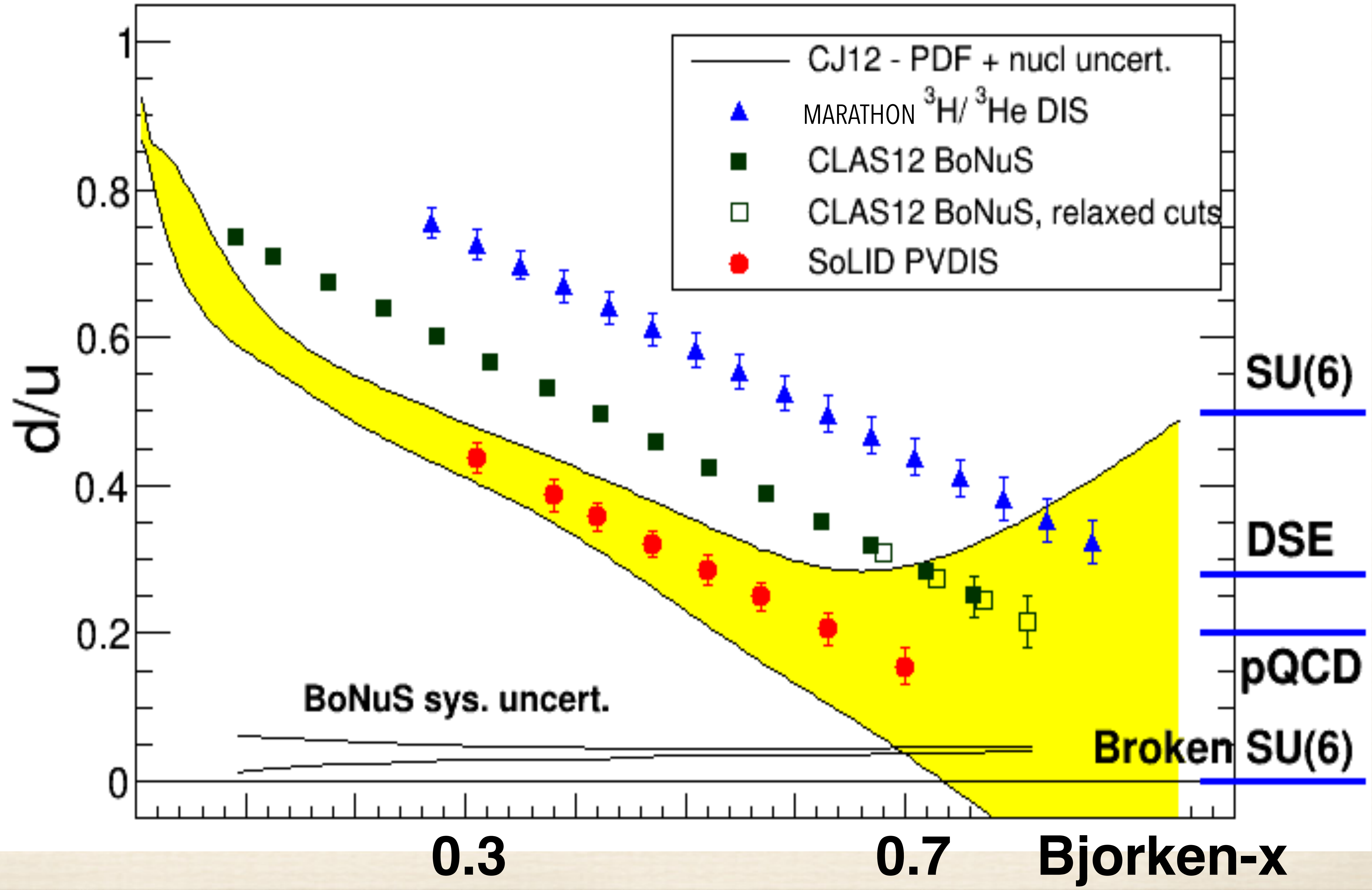


By comparing and contrasting the three methods:

- **Robust extraction of d/u from JLab**
- **Possible new Insights into higher twist effects**
- **Possibly disentangle charge symmetry violation**
- **Nuclear dynamics at high-x**

Cloet, Bentz, Thomas, PRL 109 (2012) 182301

^{48}Ca PVDIS

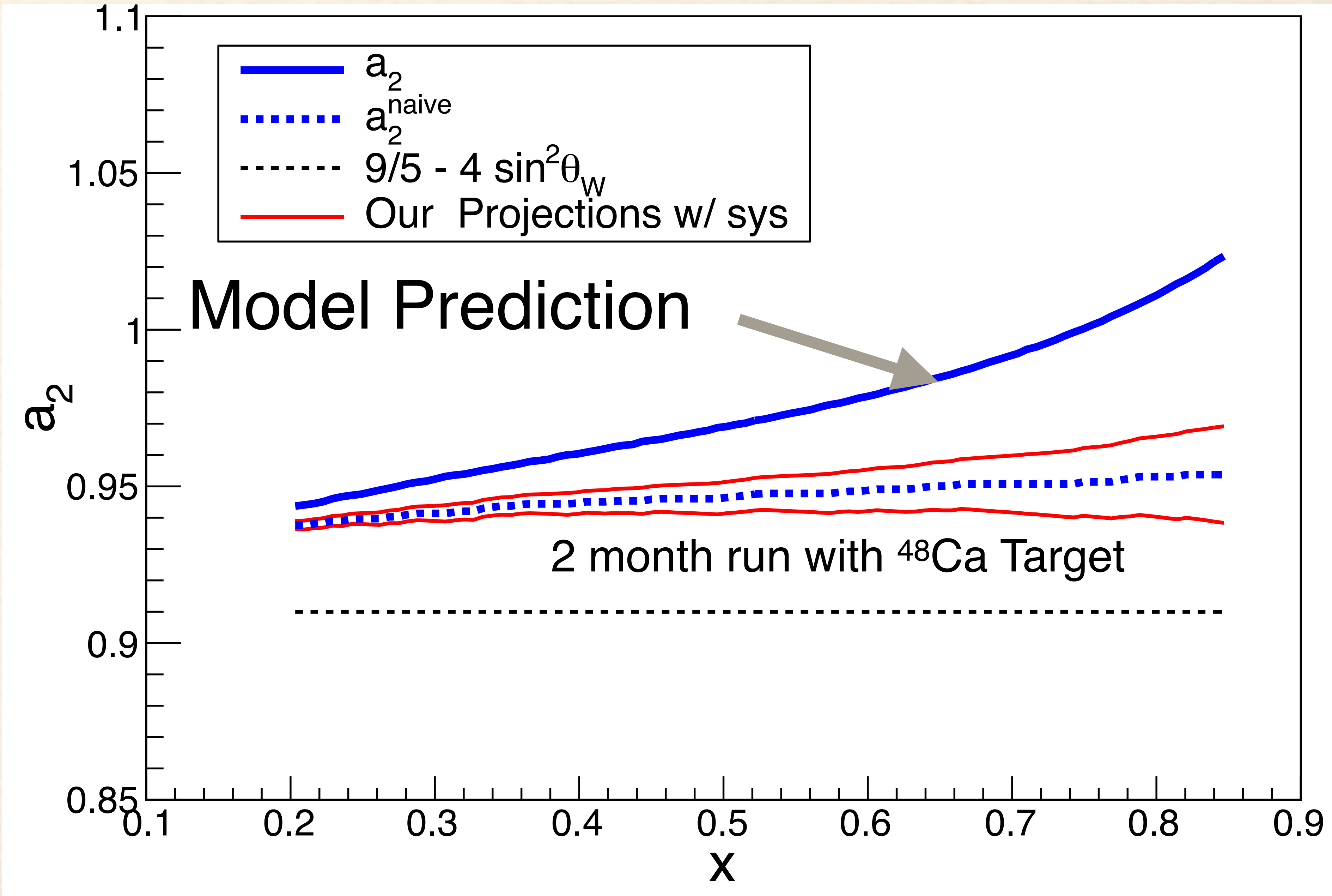
Consider PVDIS on a heavy nucleus

- Neutron or proton excess in nuclei leads to a isovector-vector mean field (ρ exchange)
- shifts quark distributions: "apparent" charge symmetry violation
- Isovector EMC effect: could be responsible for at least 2/3 of NuTeV anomaly

- **new insight into medium modification of quark distributions**

$$a_2 \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+} + \ldots$$

Great leverage for insight into isospin dependence of the EMC effect in an inclusive measurement



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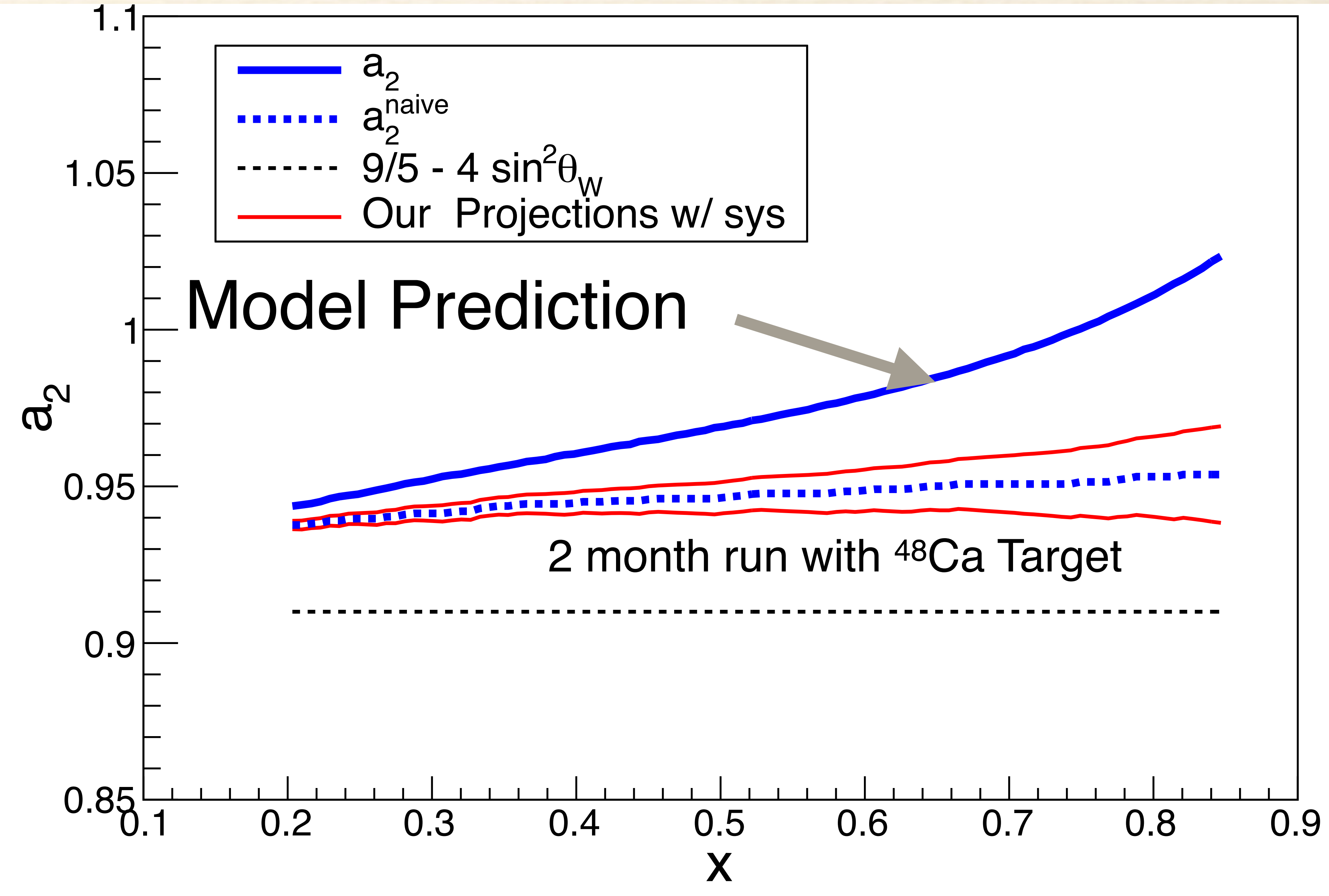
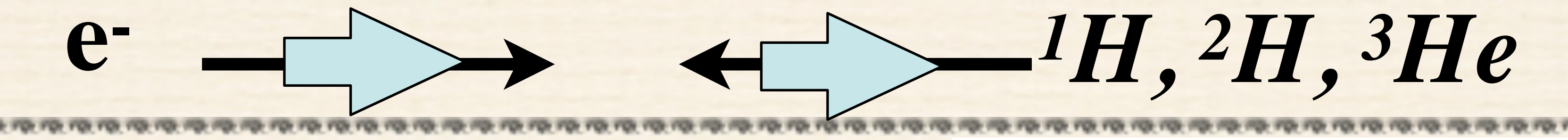


- ***methods of flavor decomposition of medium modifications challenging***
- ***must disentangle small effects***
- ***Precise isotope cross-section ratios in purely electromagnetic electron scattering: MUCH reduced sensitivity to the isovector combination***

EIC Structure Functions

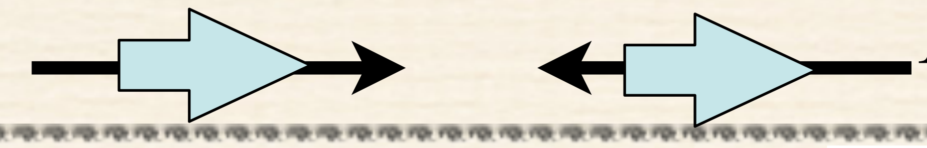


The core physics topics of the EIC have driven designs that reach a new regime of extraordinarily high polarized luminosity, state-of-the-art collider detector technology and precision polarimetry

$$\frac{1}{2m_N} W^i_{\mu\nu} = -\frac{g_{\mu\nu}}{m_N} F^i_1 + \frac{p_\mu p_\nu}{m_N (p\cdot q)} F^i_2 + i\frac{\epsilon_{\mu\nu\alpha\beta}}{2(p\cdot q)}\left[\frac{p^\alpha q^\beta}{m_N} F^i_3 + 2q^\alpha S^\beta g^i_1 - 4xp^\alpha S^\beta g^i_2\right] - \frac{p_\mu S_\nu + S_\mu p_\nu}{2(p\cdot q)} g^i_3 + \frac{S\cdot q}{(p\cdot q)^2} p_\mu p_\nu g^i_4 + \frac{S\cdot q}{p\cdot q} g_{\mu\nu} g^i_5$$

Ji, Vogelsang, Blümlein, ...
Anselmino, Efremov & Leader, Phys. Rep. **261** (1995)

EIC Structure Functions

e$^-$  $^1H, ^2H, ^3He$

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***polarized* electron, *unpolarized* hadron**

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***unpolarized* electron, *polarized* hadron**

$$A_{TPV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_V \frac{g_5^{\gamma Z}}{F_1^\gamma} + g_A f(y)\frac{g_1^{\gamma Z}}{F_1^\gamma}\right]$$

proton

$F_1^{\gamma Z} \propto u + d + s$

$F_3^{\gamma Z} \propto 2u_v + d_v$

$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$

$g_5^{\gamma Z} \propto 2\Delta u_v + \Delta d_v$

deuteron

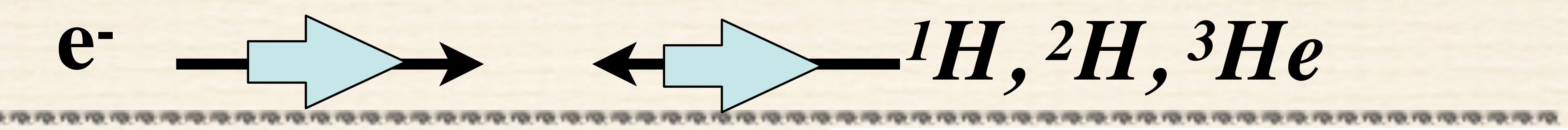
$F_1^{\gamma Z} \propto u + d + 2s$

$F_3^{\gamma Z} \propto u_v + d_v$

$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$

$g_5^{\gamma Z} \propto \Delta u_v + \Delta d_v$

EIC Structure Functions



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deuteron

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$$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$$
$$g_5^{\gamma Z} \propto \Delta u_v + \Delta d_v$$

- **First measurements of novel electroweak spin structure functions**
- **6-flavor separation of polarized quark pdfs using *just inclusive* measurements**
- **exploit both polarized proton and deuteron (or helium-3)**
- **weak mixing angle (averaging for deuteron polarization) at high Q^2**

Summary and Outlook

- ✦ **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 dynamics at the TeV scale (P2, MOLLER, SOLID)
    - *complementary to colliders; would help interpret potential anomalies*
    - *precision measurement of the weak mixing angle*
- ✦ **Logical progression of this physics into the EIC**

Exciting times for the next decade and beyond!

MOLLER Context Summary

best contact interaction reach for leptons at low OR high energy: similar to LHC reach with semi-leptonic amplitudes

To do better for a 4-lepton contact interaction would require:
Giga-Z factory, linear collider, neutrino factory or muon collider

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

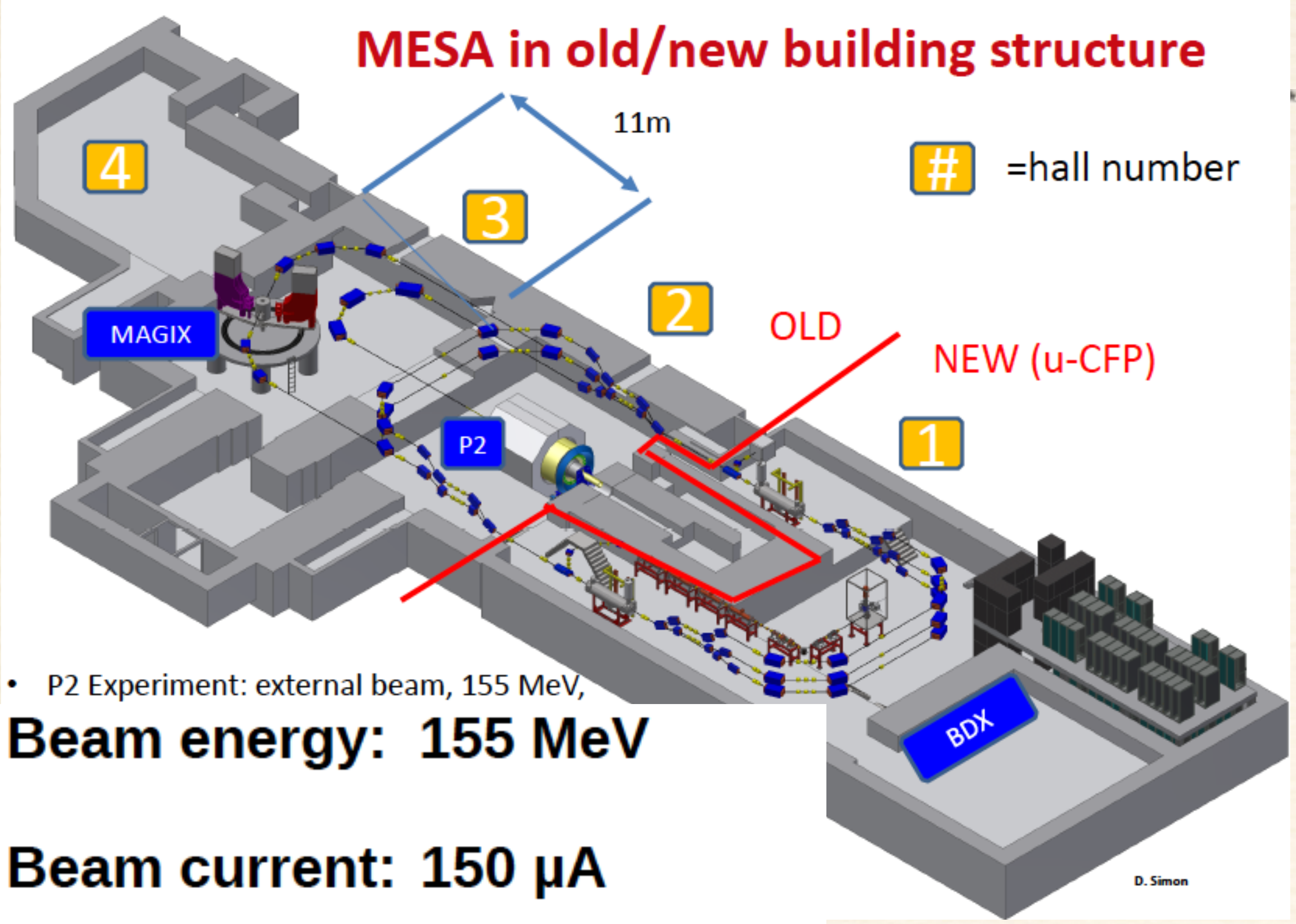
Best projected uncertainty among projects being considered over next 10 years

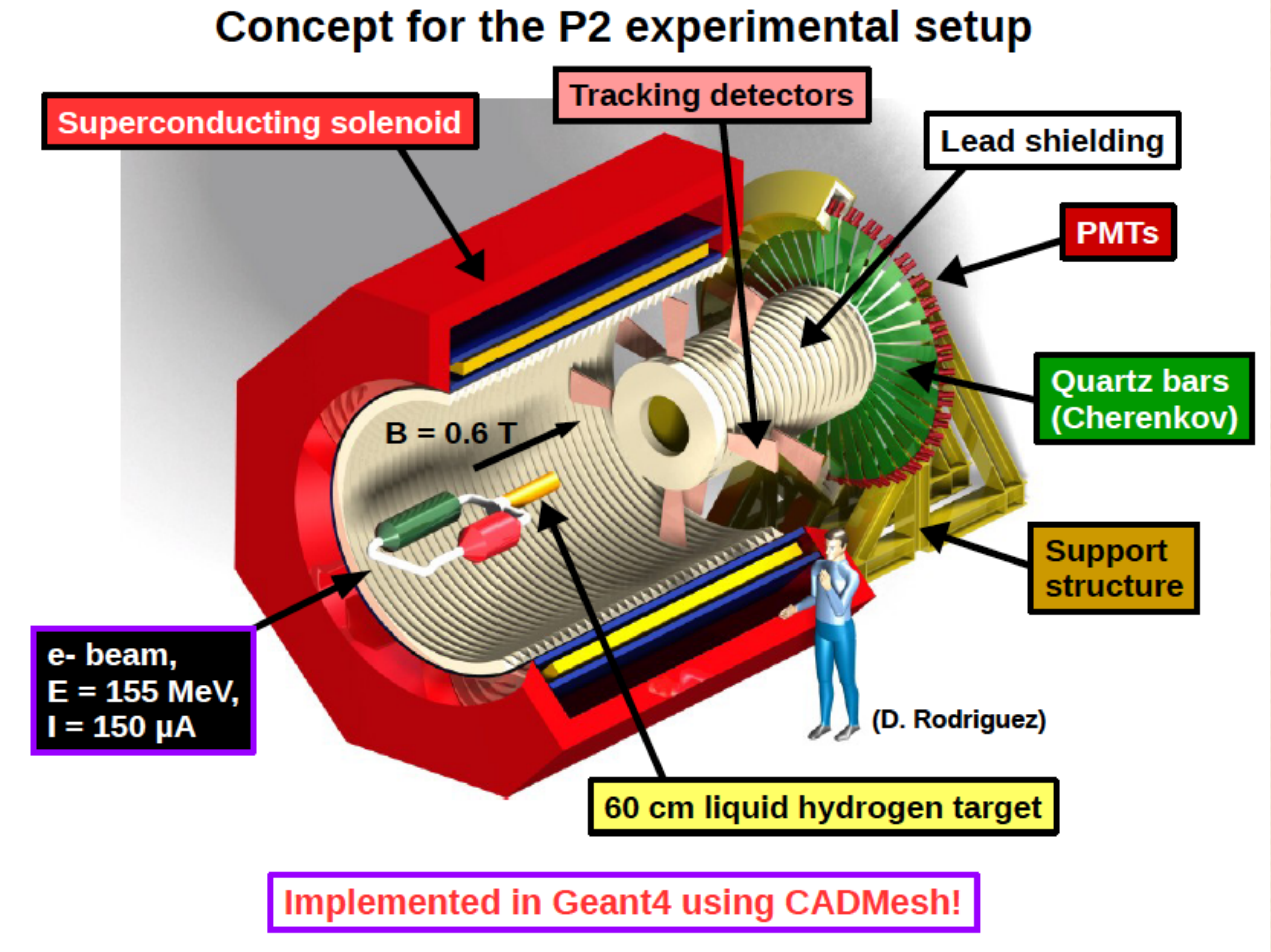
- **If LHC sees ANY anomaly in Runs 2 or 3 (~2022)**
  - The unique discovery space probed by MOLLER will become a pressing need, like other sensitive probes (e.g. g-2 anomaly)
- **Discovery scenarios beyond LHC signatures**
  - Purely Leptonic Contact Interactions
  - Lepton Number Violating Amplitudes
  - Light Dark Matter Mediators
  - Lorentz Violation
  - ...

Improve on JLab Qweak by a factor of ~ 3

P2 at Mainz

F. Maas





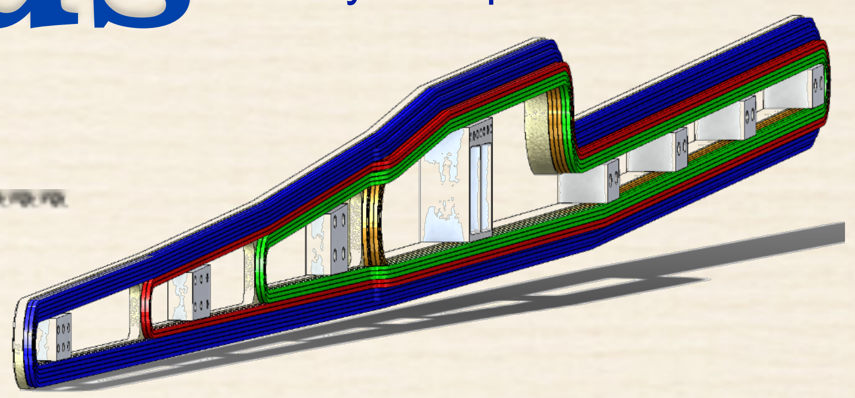
Beam energy:	**155 MeV**
Beam current:	**150 µA**
Polarization:	**(85±0.5)%**
Target:	**60 cm lH2**
Acceptance:	**2π·(35°±10°)**
Rate:	**0.5 THz**
Runtime:	**10000 h**
ΔA^{app}:	**0.1 ppb**

$\langle A^{exp} \rangle$	-28.35	ppb	
ΔA^{exp}	0.44	ppb	(1.5%)
$\langle Q^2 \rangle$	0.0045	GeV^2	
$\Delta \sin^2 \theta_W$	0.0003		(0.13%)

1

- New MESA hall ready mid 2018
- Start of installation 2018, commissioning 2019
- Start of data taking end of 2019

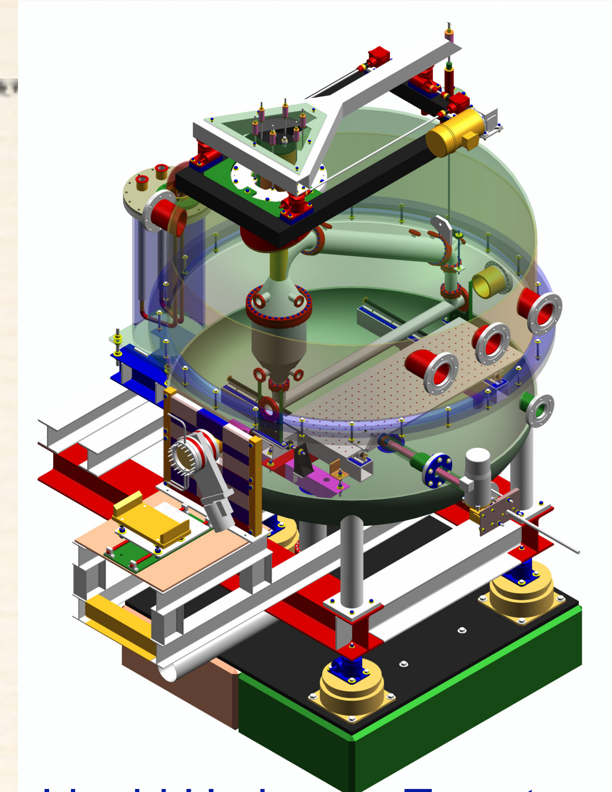
MOLLER Apparatus

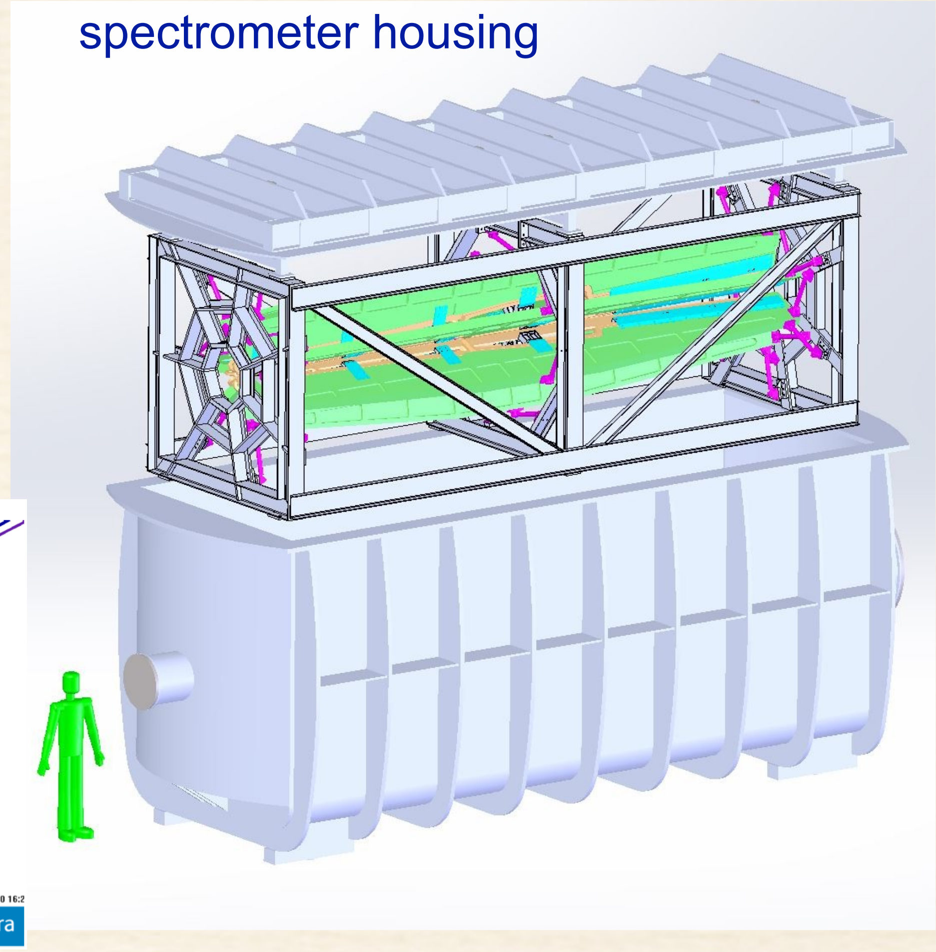


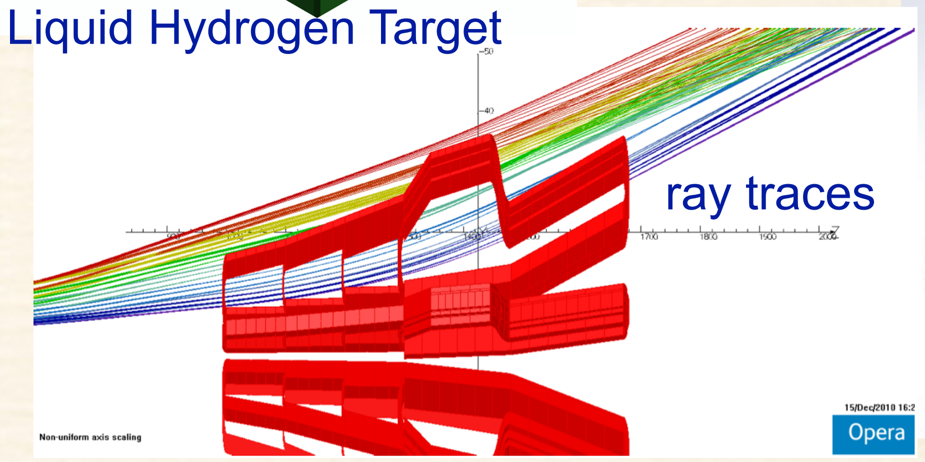
Technical Challenges

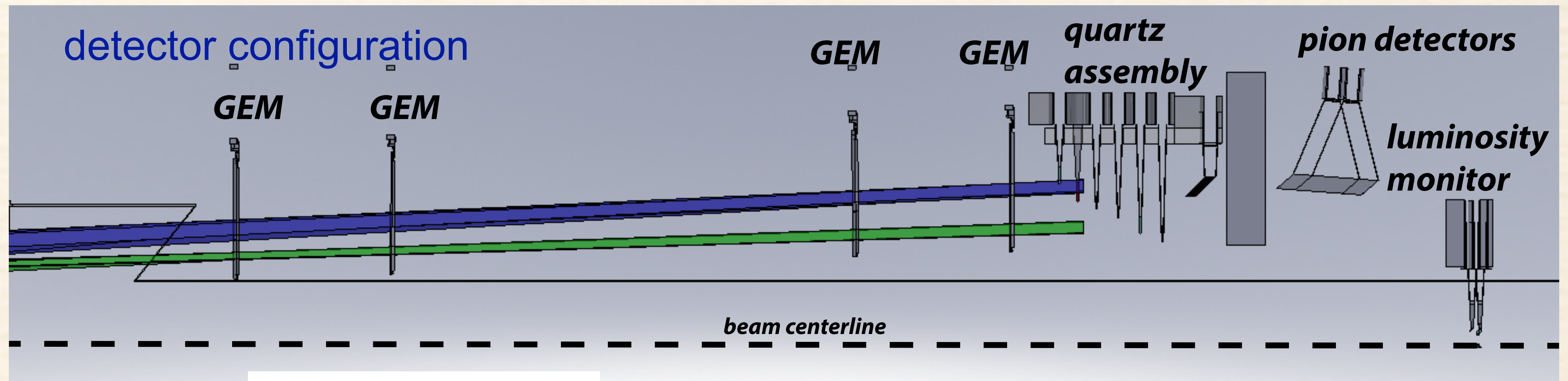
Evolutionary Improvements
from Technology of Third
Generation Experiments

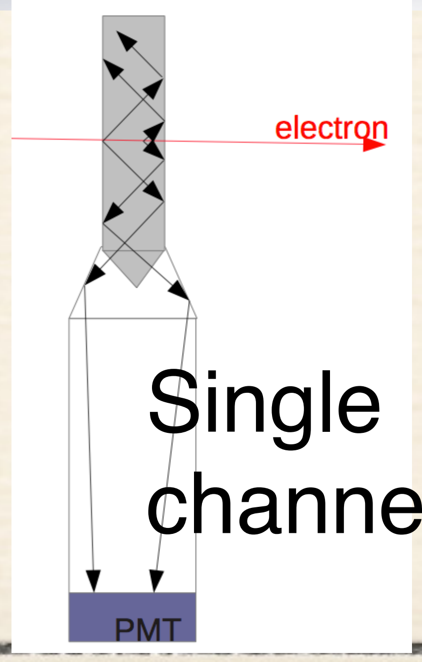
- ~ 150 GHz scattered electron rate
- 1 nm control of beam centroid on target
- > 10 gm/cm² liquid hydrogen target
  - **1.5 m: ~ 5 kW @ 85 µA**
- Full Azimuthal acceptance w/ θ_{lab} ~ 5 mrad
  - **novel toroidal spectrometer pair**
  - **radiation hard, highly segmented integrating detectors**
- Robust & Redundant 0.4% beam polarimetry

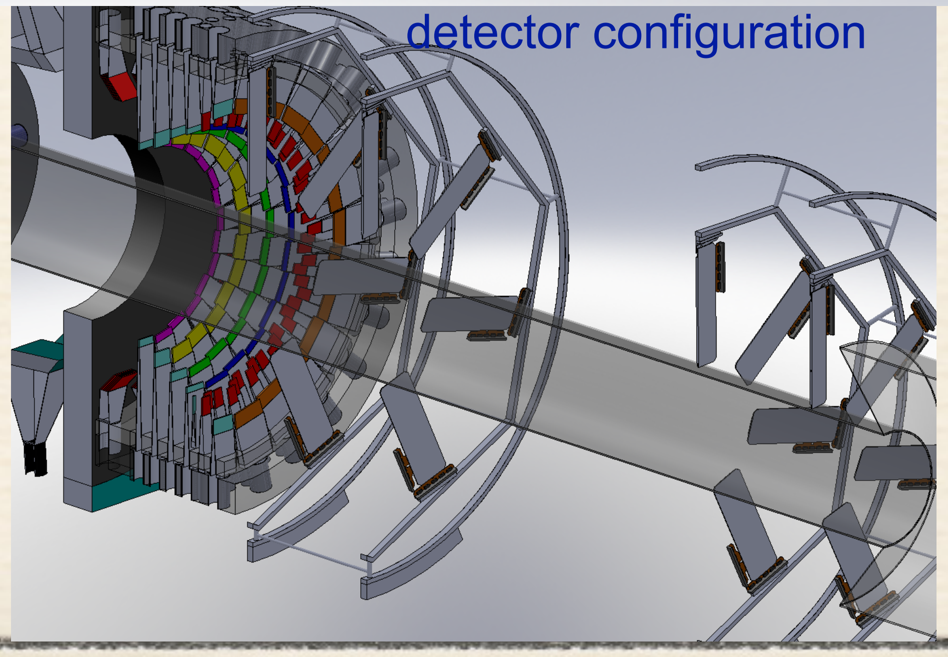




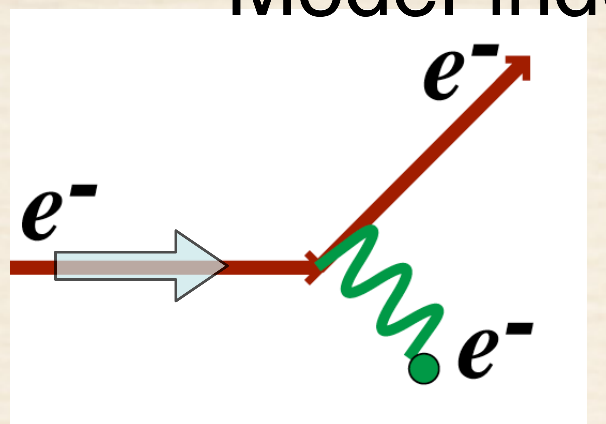








Model-independent Picture of 4-Fermion Flavor Diagonal Contact Interactions

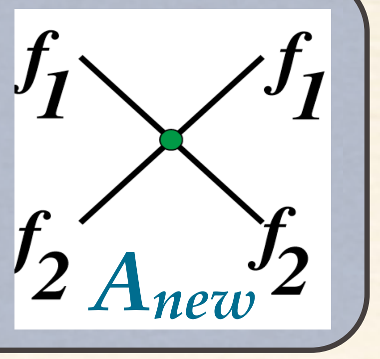


MOLLER Reach

Use Common Language for Low Energy and High Energy Measurements

on Z_0 resonance: A_Z is imaginary

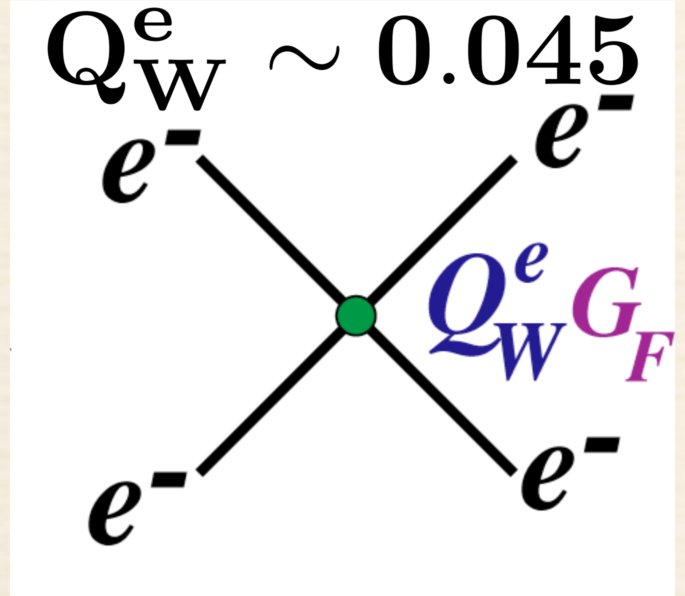
New heavy physics: no direct coupling to SM gauge bosons



$$\left|\mathbf{A_Z}+\mathbf{A_{new}}\right|^2 \rightarrow \mathbf{A_Z^2}\left[\mathbf{1}+\left(\frac{\mathbf{A_{new}}}{\mathbf{A_Z}}\right)^2\right]$$

no interference term!

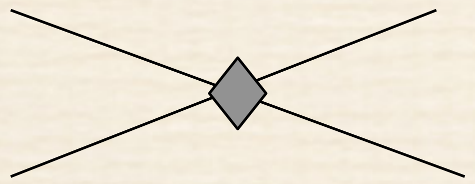
Additionally, A_{new} could be mediated by a new light boson: “dark Z”



$$\frac{\delta \mathbf{Q_W^e}}{\mathbf{Q_W^e}} = \mathbf{2.4\%} \quad \Rightarrow \quad \mathbf{A_{new}} \sim \mathbf{0.001 \cdot G_F}$$

unprecedented sensitivity!

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

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

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

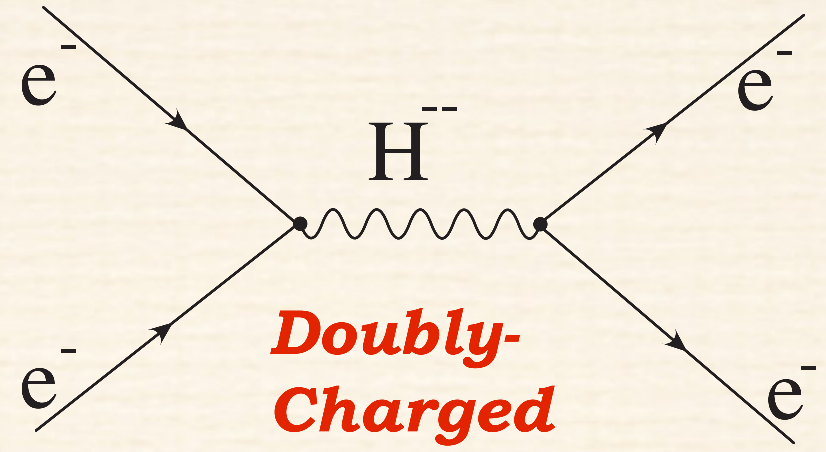
Unique Opportunity: Purely Leptonic Reaction at $Q^2 \ll M_Z^2$

New Physics Examples

Deviations From Theory Prediction Interpretable as New Physics

Many different scenarios give rise to effective 4-electron contact interaction amplitudes: significant discovery potential

Lepton Number Violation

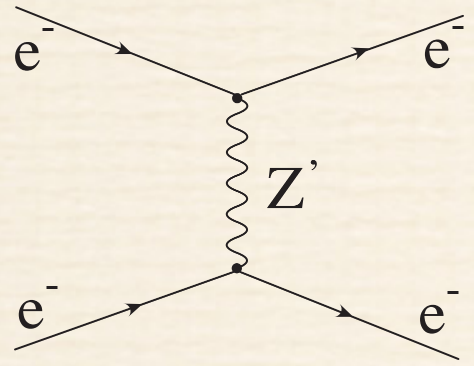


Doubly-Charged Scalar

$$\left|\frac{\Delta Q_W^e}{Q_W^e}\right| = 0.14\frac{|h_{ee}|^2}{(M_\Delta/1\ \mathrm{TeV})^2}$$

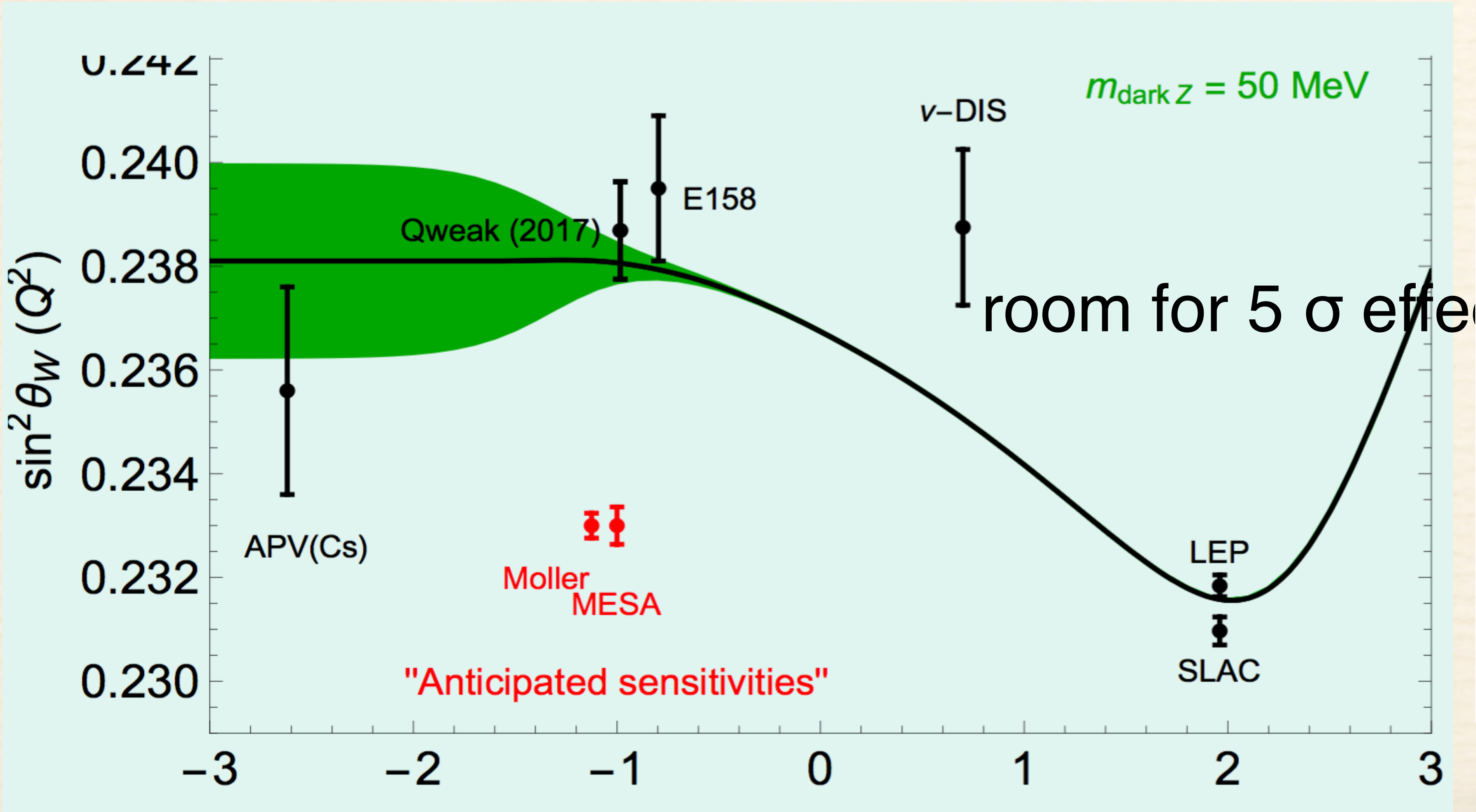
5 σ for $h_{ee} \sim 1$ and $M_\Delta \sim 1$ TeV

See Michael's talk! (and send me the slides!)



Heavy Photons (A' mixed with Z_0): The Dark Z

H. Davoudiasl, H-S. Lee and W. Marciano



room for 5 σ effe

Constraining Lorentz Invariance

Ralf Lehnert, J. Phys.: Conf. Ser. **952** (2018) 012008

$$\delta A(t) = \frac{G_F}{\sqrt{2}\pi\alpha}\frac{E_k\, y\,(1-y)\sin^2\theta_W}{(y^2-y+1)^2}\,\vec{k}(t)\cdot\vec{\xi}$$
$$= \frac{G_F}{\sqrt{2}\pi\alpha}\frac{E_k^2\, y\,(1-y)\sin^2\theta_W}{(y^2-y+1)^2}\times$$
$$\left[\sqrt{\xi_X^2+\xi_Y^2}\sqrt{1-\cos^2\alpha\sin^2\chi}\,\cos\Omega_\oplus t + c_0\right]$$

Unique Opportunity: Purely Leptonic Reaction at $Q^2 << M_Z^2$

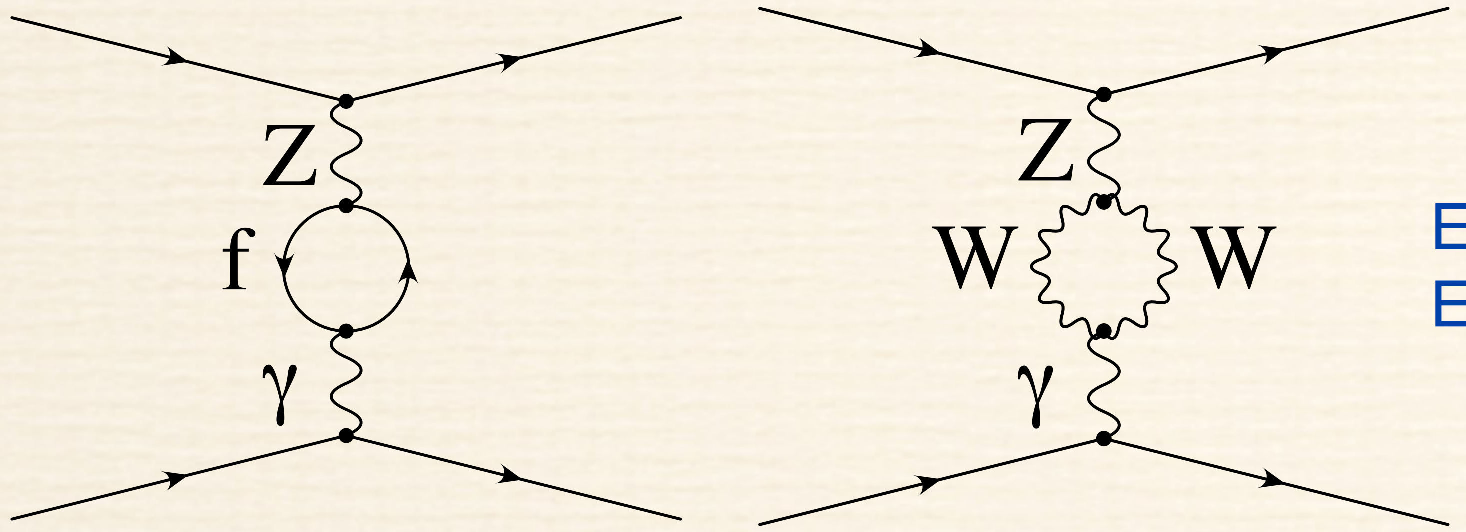
Electroweak Theory

EW Theory Prediction Uncertainty Well Below Projected Experimental Uncertainty

Czarnecki and Marciano (1995)

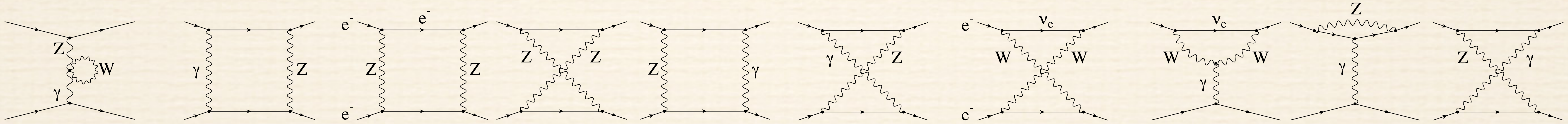
$$A_{PV}(ee) \propto \rho G_F \left[1 - 4\kappa(0)\sin^2\theta_W(m_Z)_{\overline{MS}}\right] + \cdots$$

Dominant Contribution at 1-loop



κ(0) known better than 1% of itself

Erler and Ramsey-Musolf (2003)
Erler and Ferro-Hernandez (2018)



δ(Q^e_W) (theory) = 0.6%, another factor of 2 improvement with full two-loop calculation

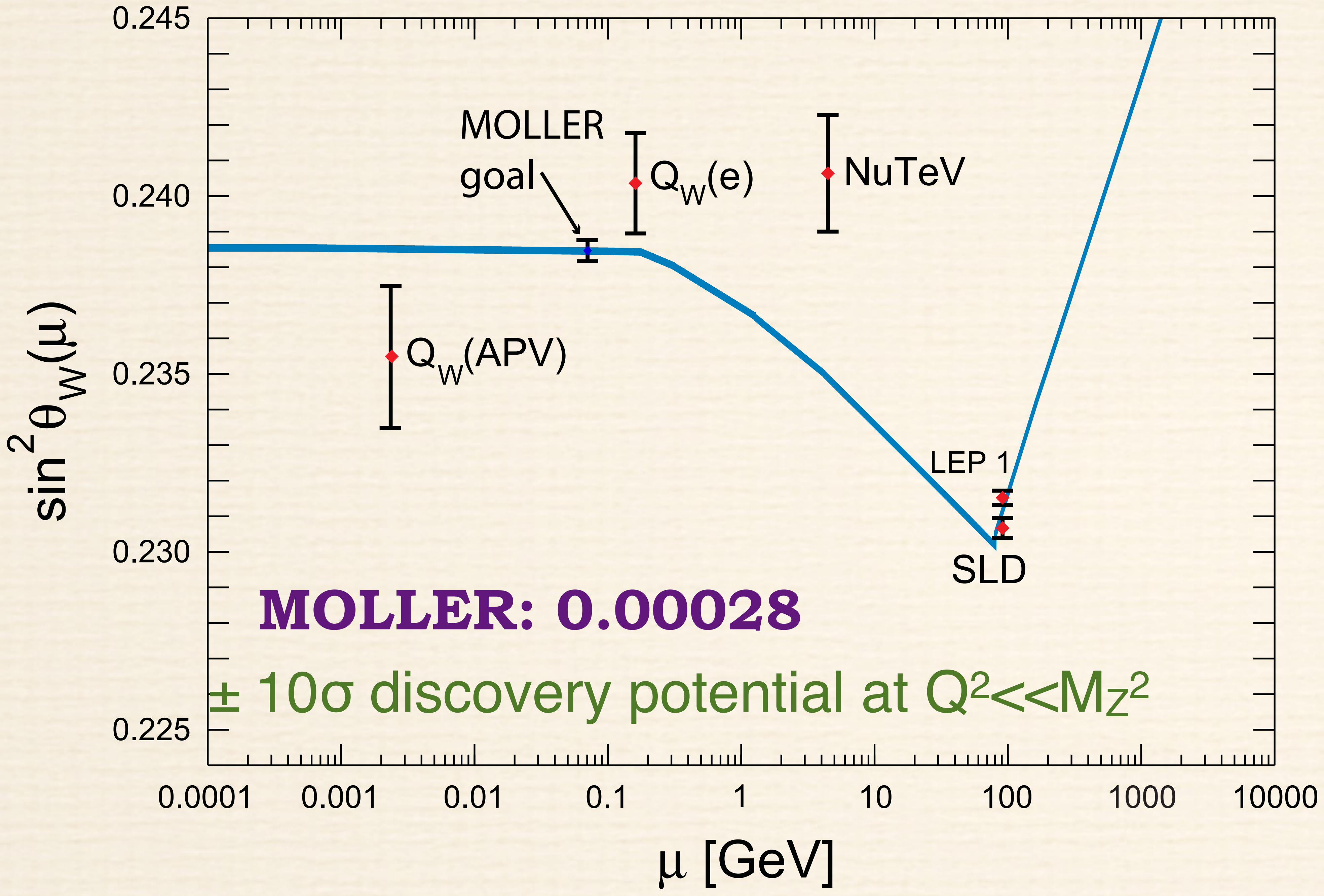
MOLLER δ(Q^e_W) goal = ± 2.1 % (stat.) ± 1.1 % (syst.)

See talks by:
- **A. Aleksejev**
- **A. Freitas**
- **R. Ferro Hernandez**
- **H. Patel**
- **M. Ramsey-Musolf**

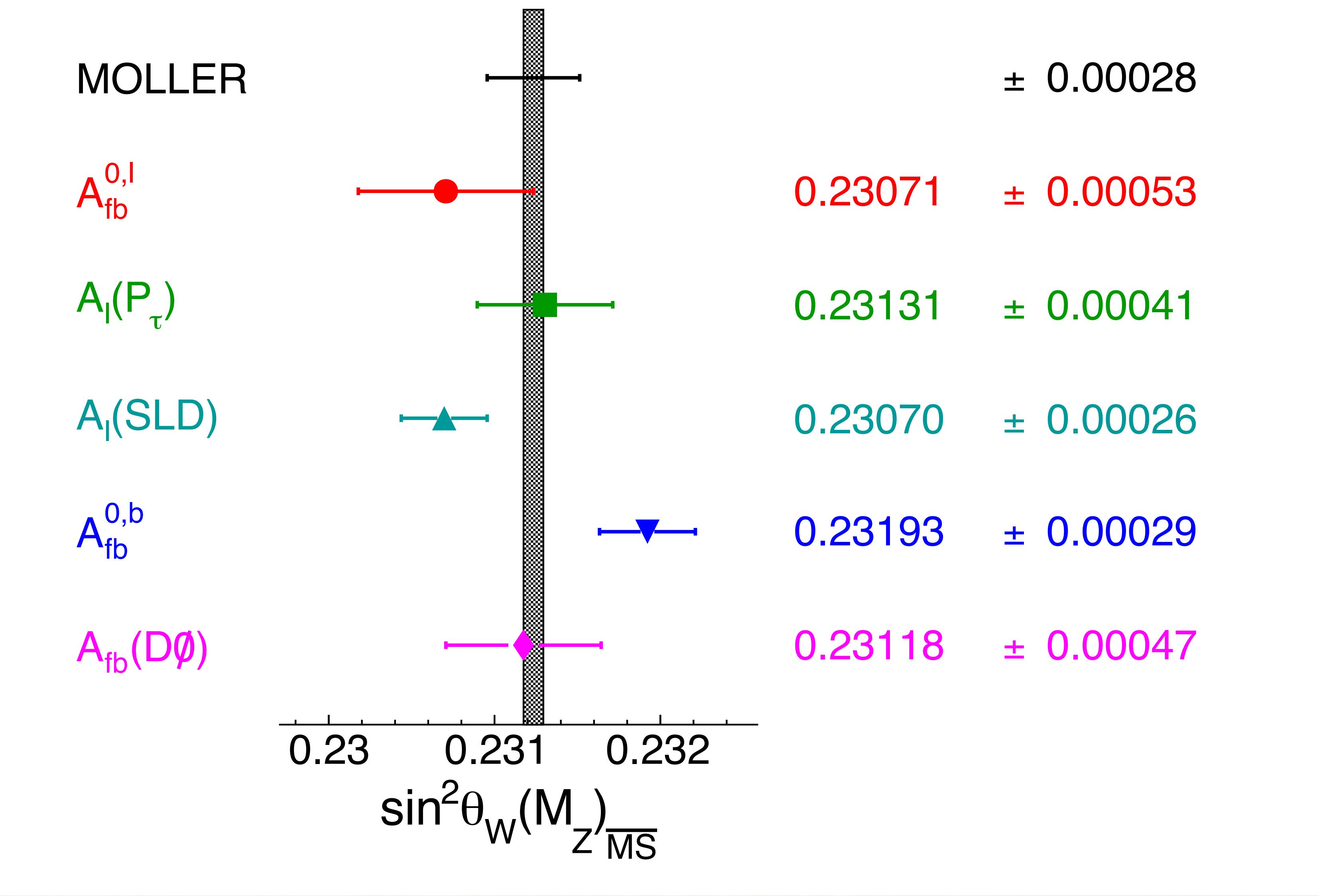
A Fundamental Parameter of the Electroweak Theory

$\sin^2\theta_W$

MOLLER Projection: ***$\delta(\sin^2\theta_W) = \pm\, 0.00024$ (stat.) $\pm\, 0.00013$ (syst.)***



Z resonance measurements:
no interference term



Future projections
(similar time scale)

Mainz P2: ~ 0.00032

Final Tevatron: ~ 0.00041

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

Note: systematics-dominated (pdf uncertainties)

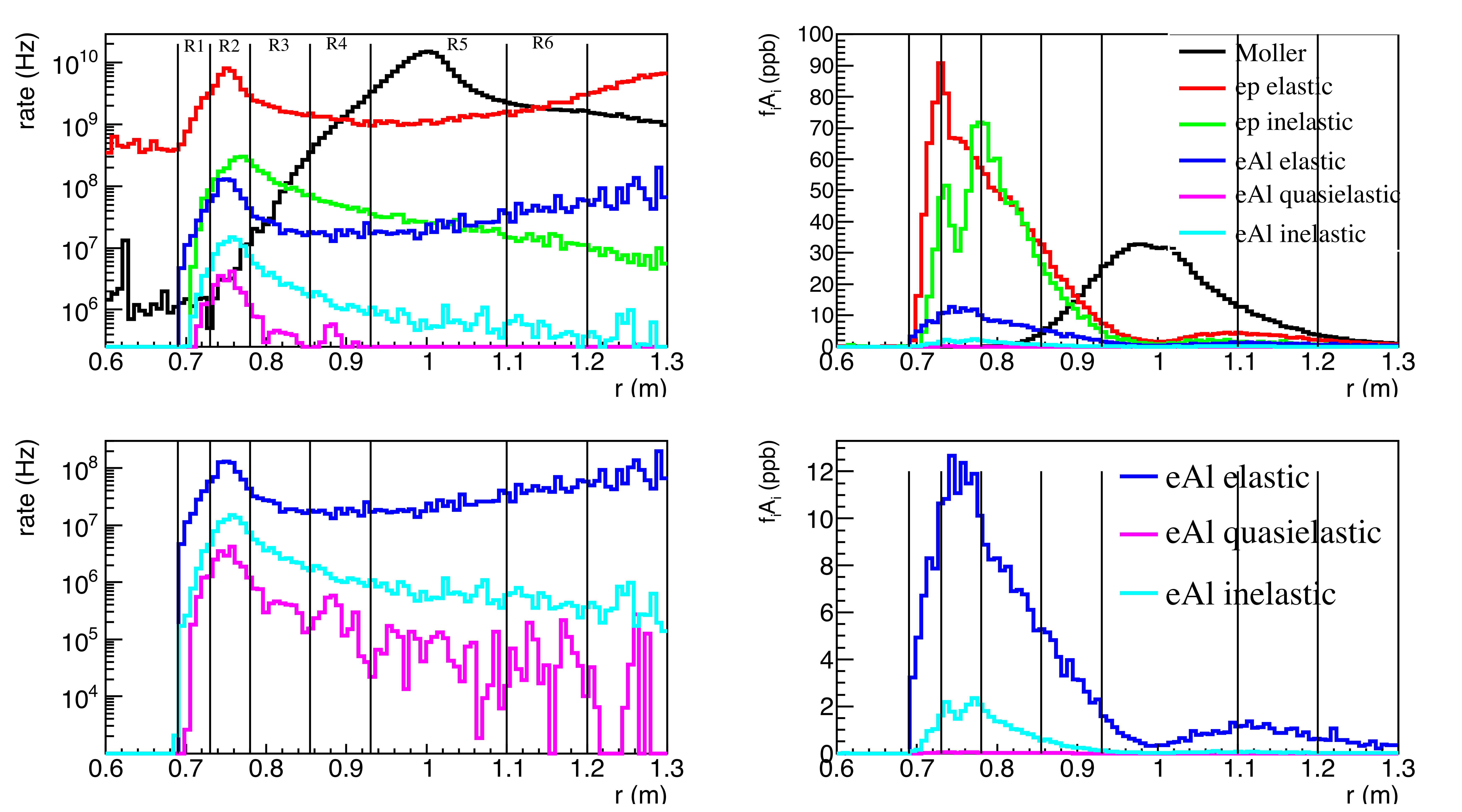
MOLLER Uncertainty Table

Beam Property	Assumed Sensitivity	Accuracy of Correction	Required 2 kHz random fluctuations	Required cumulative helicity-correlation	Systematic contribution
Intensity	1 ppb / ppb	$\sim 1\%$	< 1000 ppm	< 10 ppb	~ 0.1 ppb
Energy	-1.4 ppb / ppb	$\sim 10\%$	< 108 ppm	< 0.7 ppb	~ 0.05 ppb
Position	0.85 ppb / nm	$\sim 10\%$	$< 47\ \mu$m	< 1.2 nm	~ 0.05 ppb
Angle	8.5 ppb / nrad	$\sim 10\%$	$< 4.7\ \mu$rad	< 0.12 nrad	~ 0.05 ppb

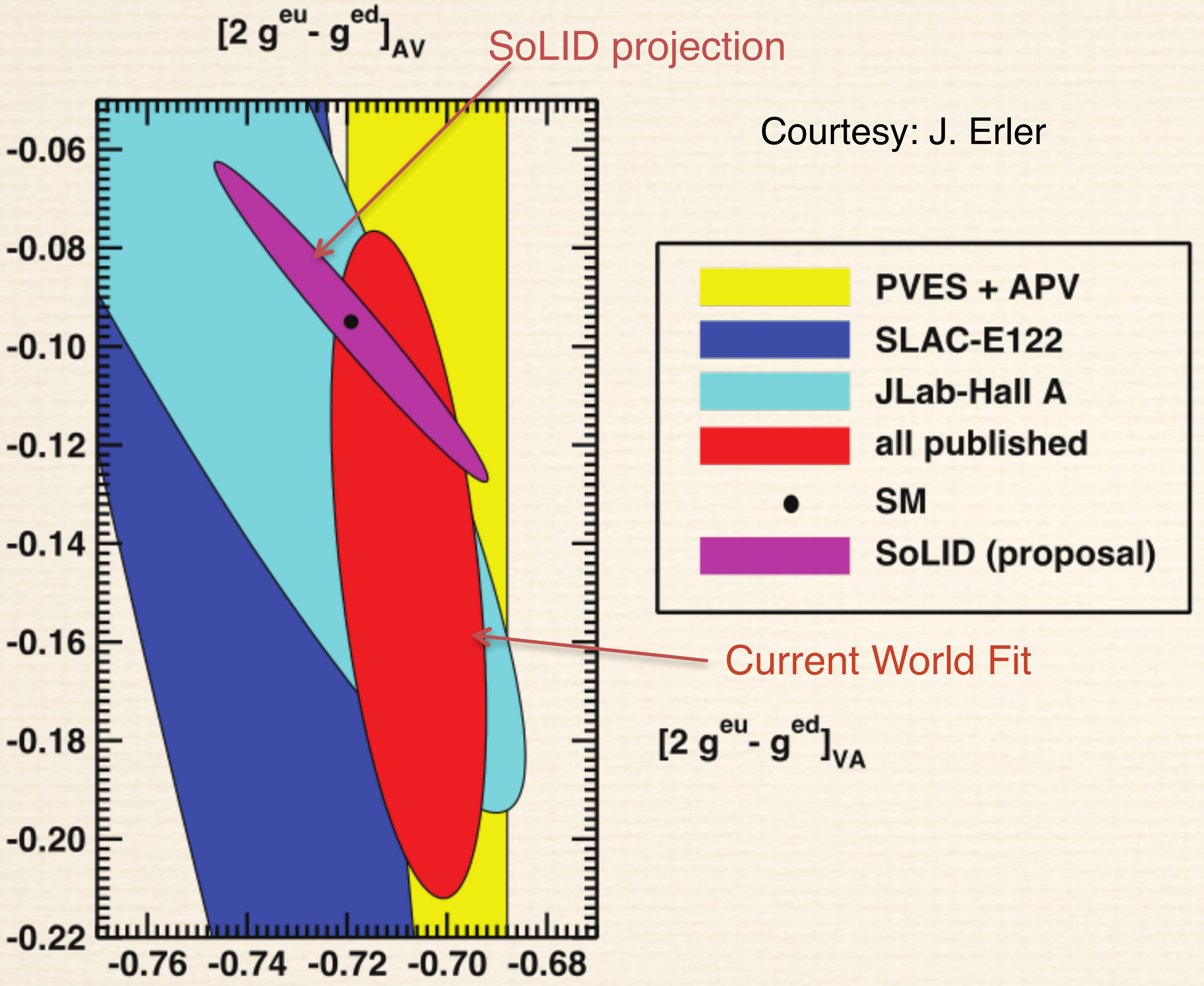
Error Source	Fractional Error (%)
Statistical	**2.1**
Absolute Normalization of the Kinematic Factor	0.5
Beam (second order)	0.4
Beam polarization	0.4
$e + p(+\gamma) \to e + X(+\gamma)$	0.4
Beam (position, angle, energy)	0.4
Beam (intensity)	0.3
$e + p(+\gamma) \to e + p(+\gamma)$	0.3
$\gamma^{(*)}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

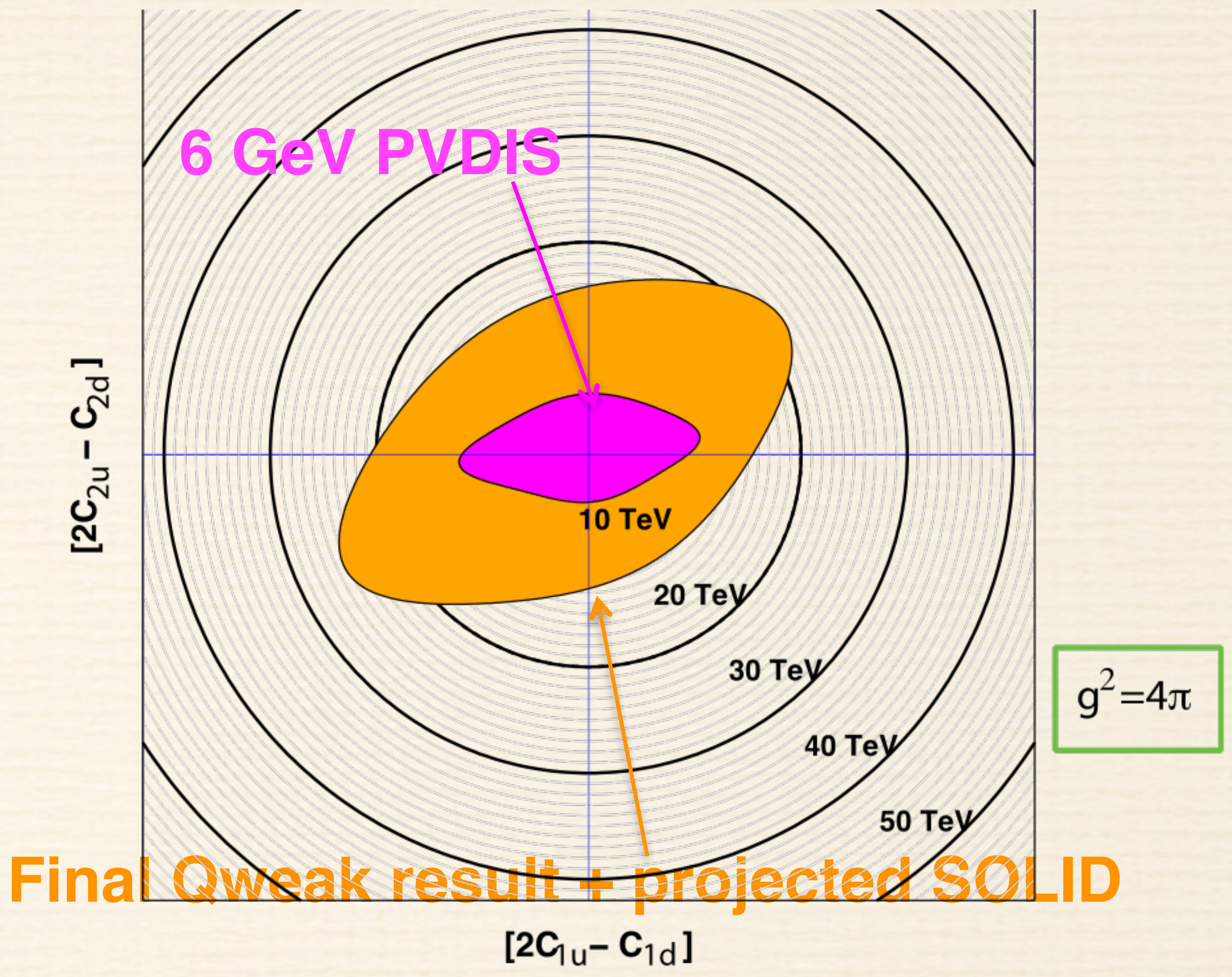
All systematics required at sub-1% level

Rate and Asymmetry

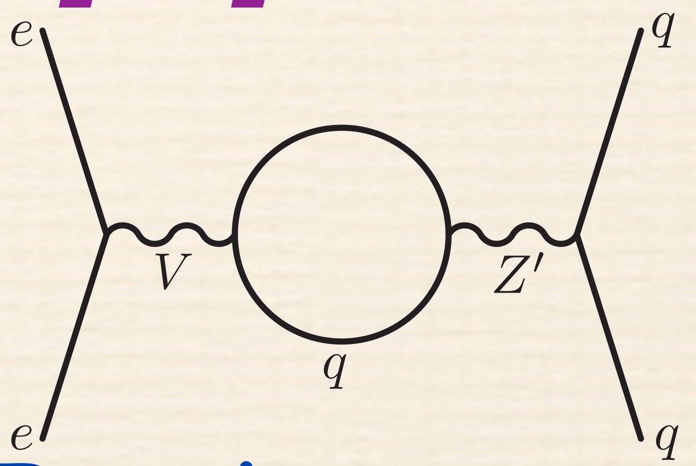


SoLID New Physics Sensitivity





Leptophobic Z'



Qweak, P2 and SOLID will expand sensitivity that will match high luminosity LHC reach with complementary chiral and flavor combinations

SOLID can improve sensitivity: 100-200 GeV range

Normalization Errors

Goal for total systematic error ~ 2% achieved!

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

$$A_{phys} = \frac{A_{sig}}{P_{beam}}$$

Two independent methods, polarized Møller and Compton Scattering

Both methods achieved ~ 1.5%: expected to reach sub-1% for PREX-II/CREX

Absolute angle calibration via nuclear recoil variation

Recoil is large for H, small for nuclei

Water cell target

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

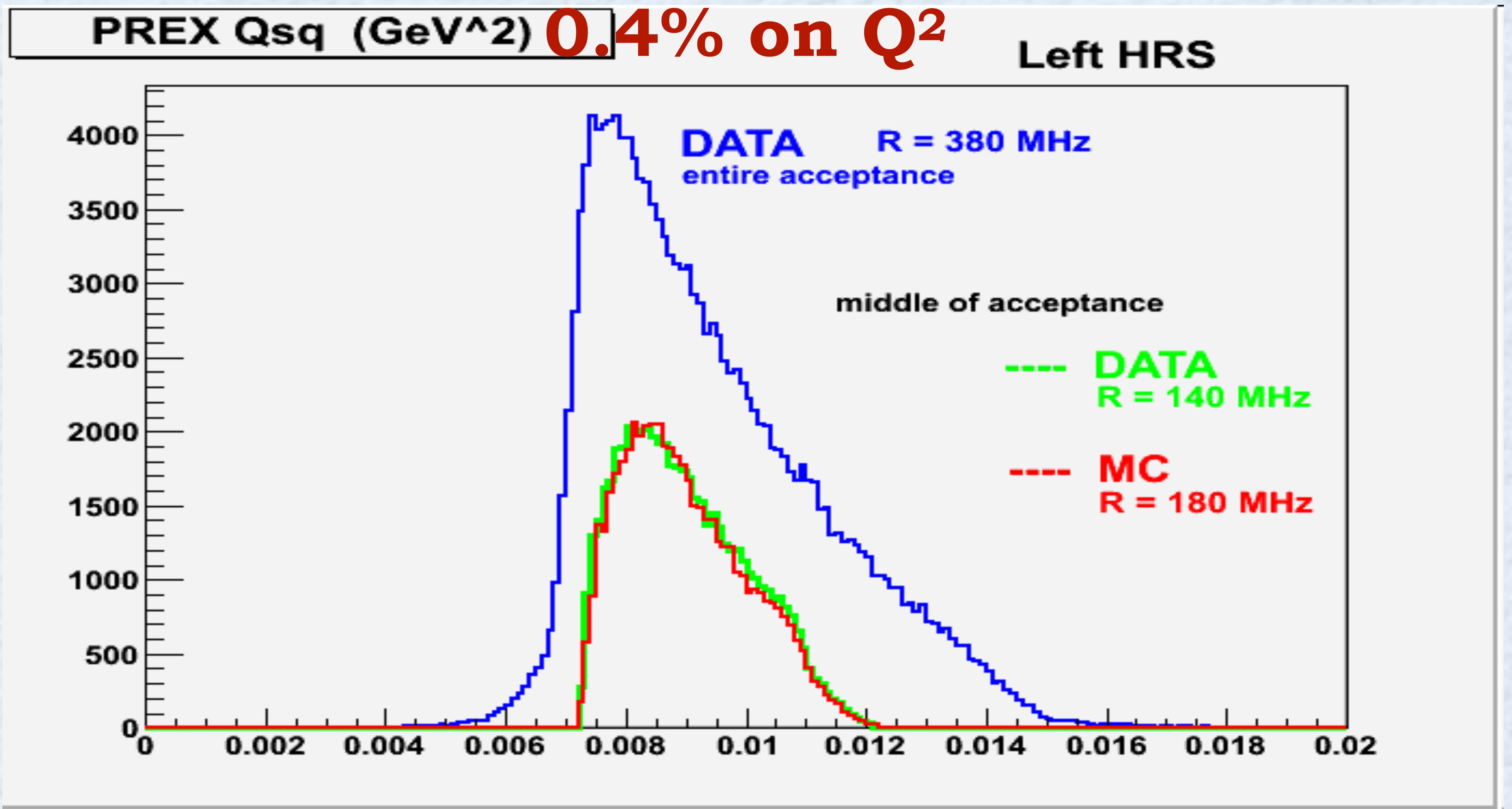
4-momentum transfer $Q^2 = 4EE'\sin^2\frac{\theta}{2}$

calibration

E: spin precession in machine
E': NMR in HRS B field
scattering angle: survey ~ 1 mr

Q^2 distribution obtained by low rate runs; trigger on quartz pulse-height

0.4% absolute calibration achieved:



Final Result

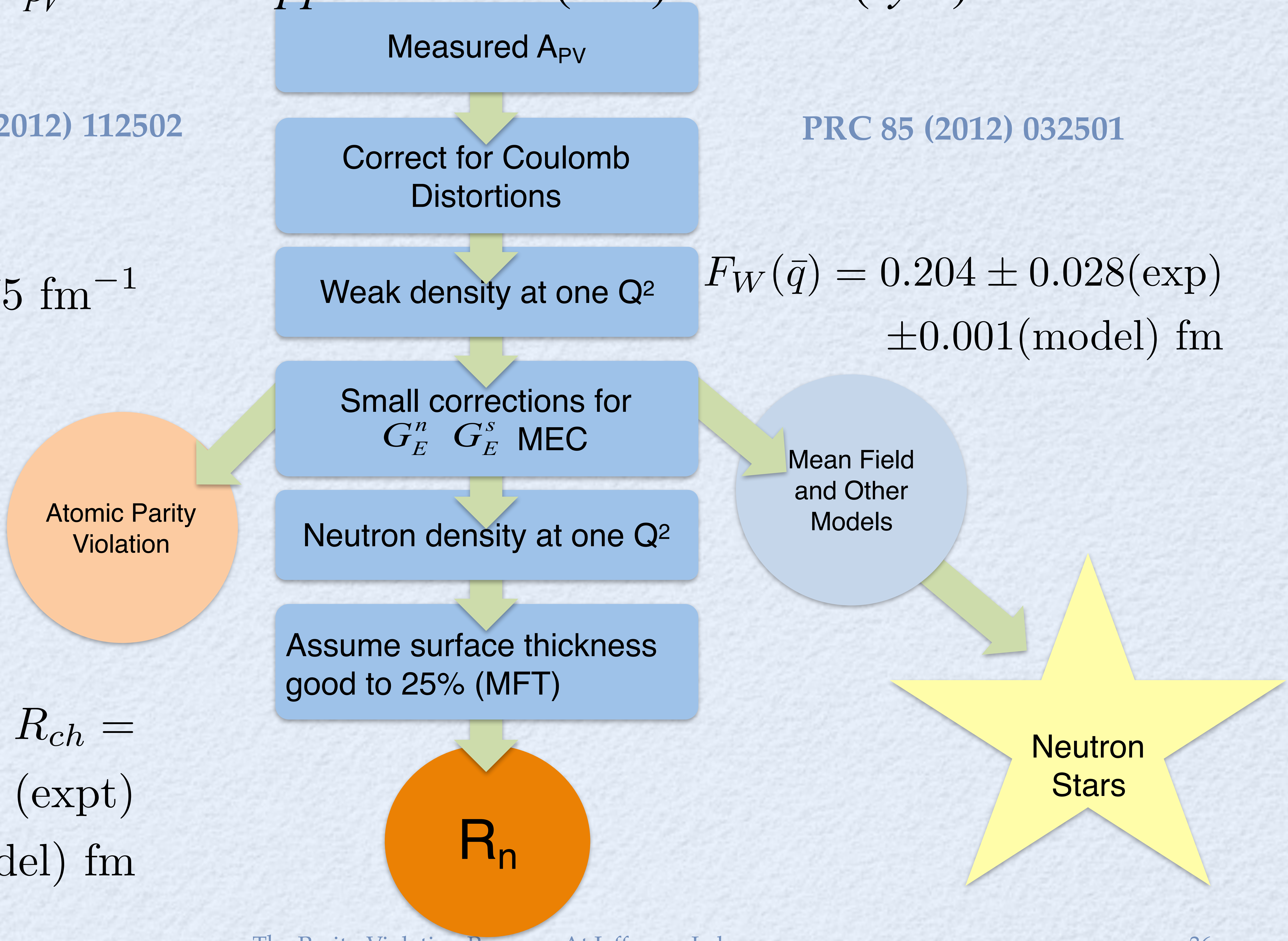
$$A_{PV} = 0.656\ ppm \pm\ 0.060(stat) \pm 0.014(syst)$$

PRL 108 (2012) 112502

PRC 85 (2012) 032501

$$\bar{q} = 0.475\ \mathrm{fm}^{-1}$$

$$F_W(\bar{q}) = 0.204 \pm 0.028(\mathrm{exp}) \pm 0.001(\mathrm{model})\ \mathrm{fm}$$

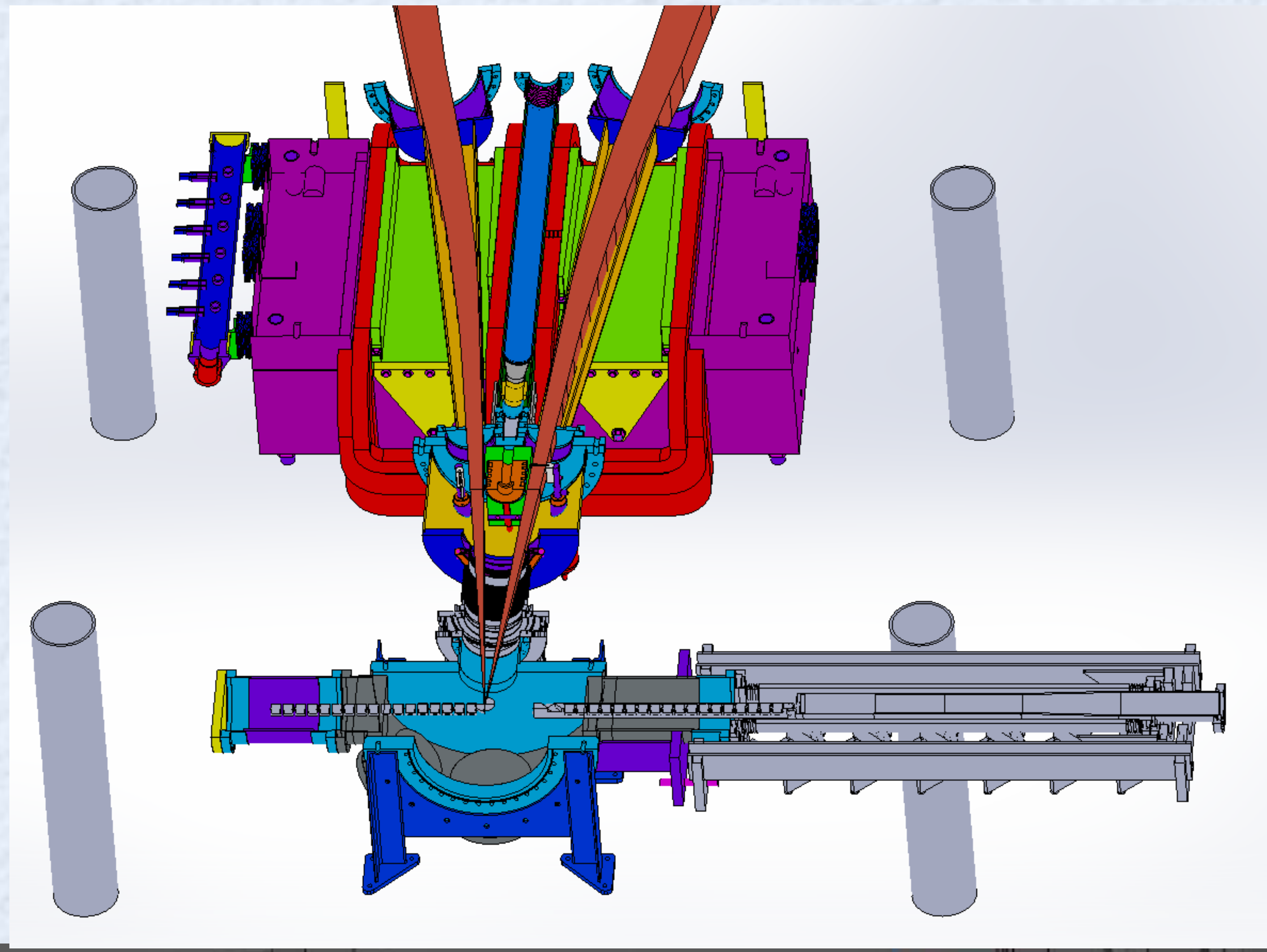


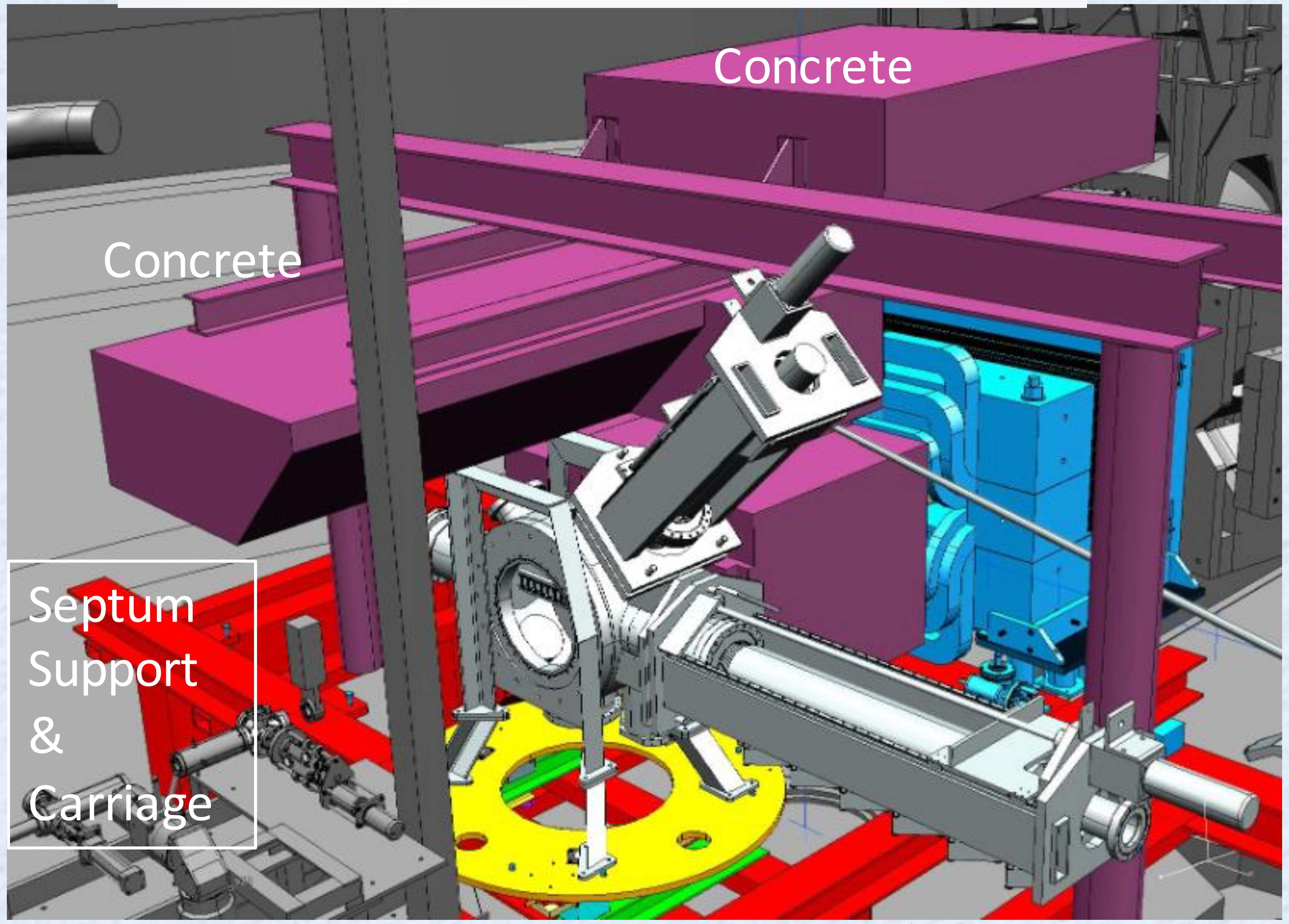
$$R_W - R_{ch} = 0.32 \pm 0.12\ (\mathrm{expt}) \pm 0.03\ (\mathrm{model})\ \mathrm{fm}$$

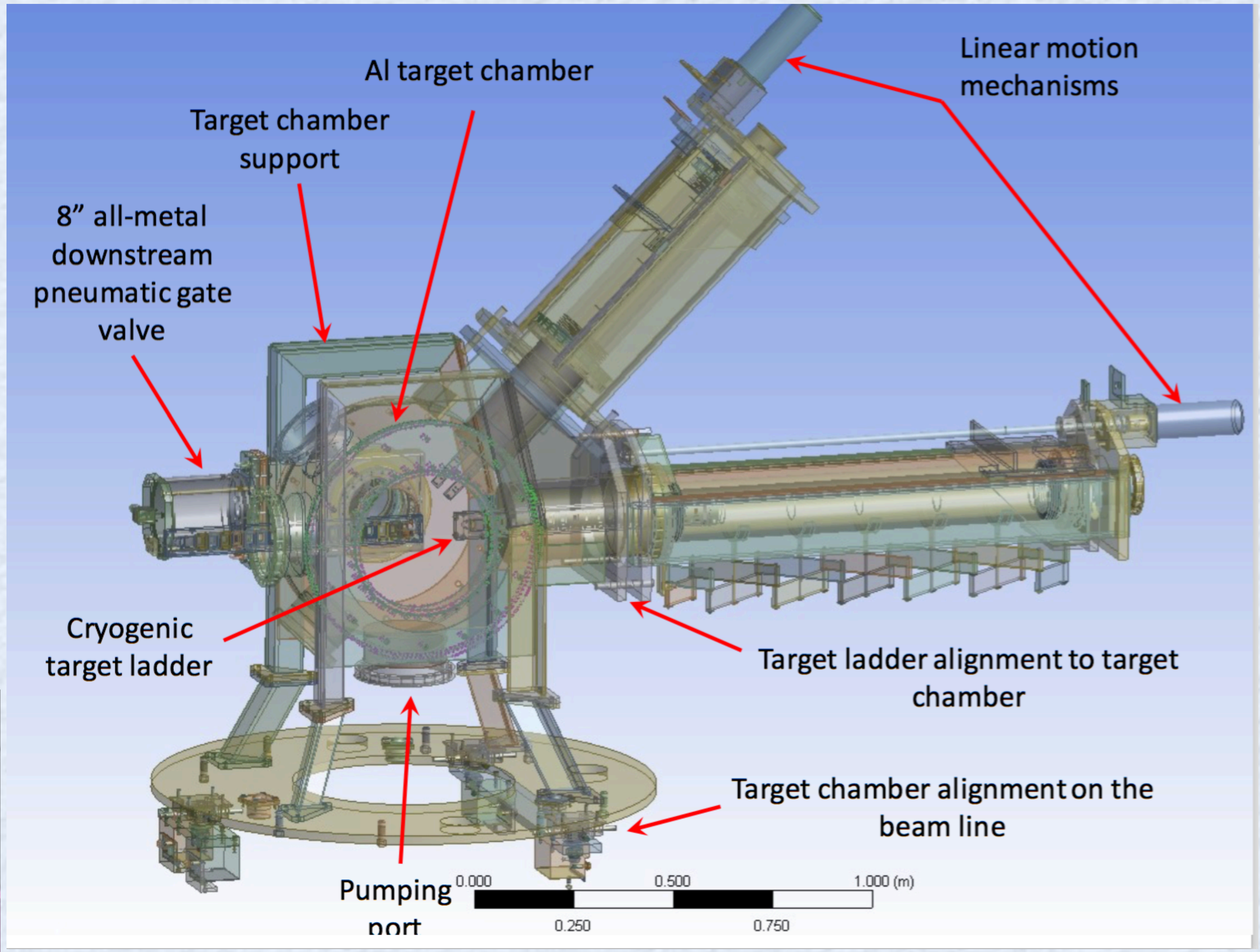
PREX/CREX Parameters

	PREX-I	PREX-II	CREX
Ebeam	1.0 GeV	1.0 GeV	2.1 GeV
A_{PV}	0.65 ppm	0.65 ppm	2.5 ppm
Rate	1 GHz	1.5 GHz	40 MHz
$\delta(A_{PV})_{stat}$	9%	3.5%	4%
$\delta(R_n)$	0.18 fm	0.07 fm	0.02 fm
Charge	0.1%	0.1%	0.1%
Beam	1.1%	0.5%	0.3%
Non-linearity	1.0%	0.3%	0.3%
Transverse	0.2%	0.2%	0.1%
Beam Polarization	1.1%	0.8%	0.8%
Inelastics	0.1%	0.1%	0.2%
Effective Q^2	0.4%	0.4%	0.4%
Total Systematic	2%	1.1%	1%

Target Region Redesign

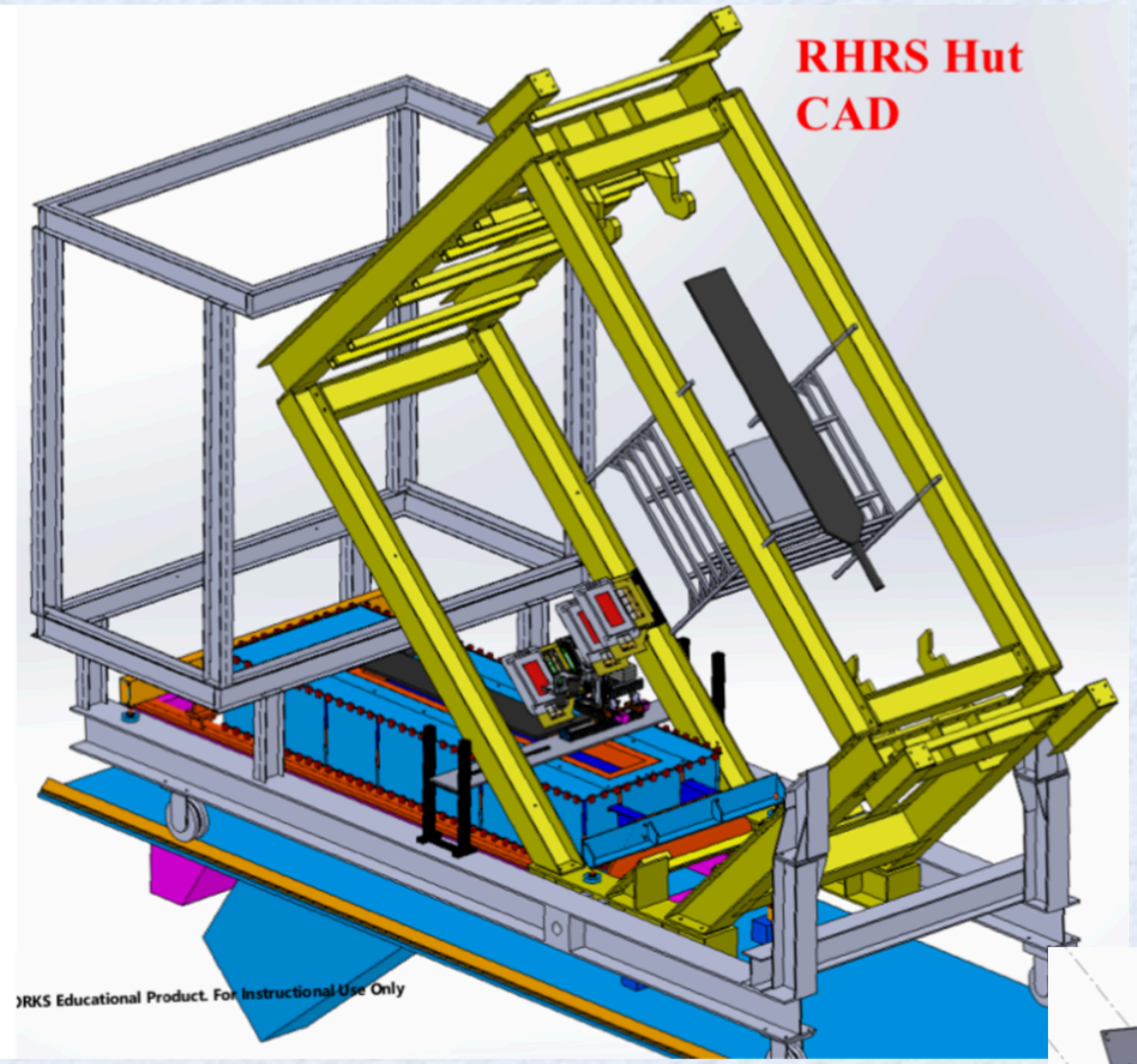


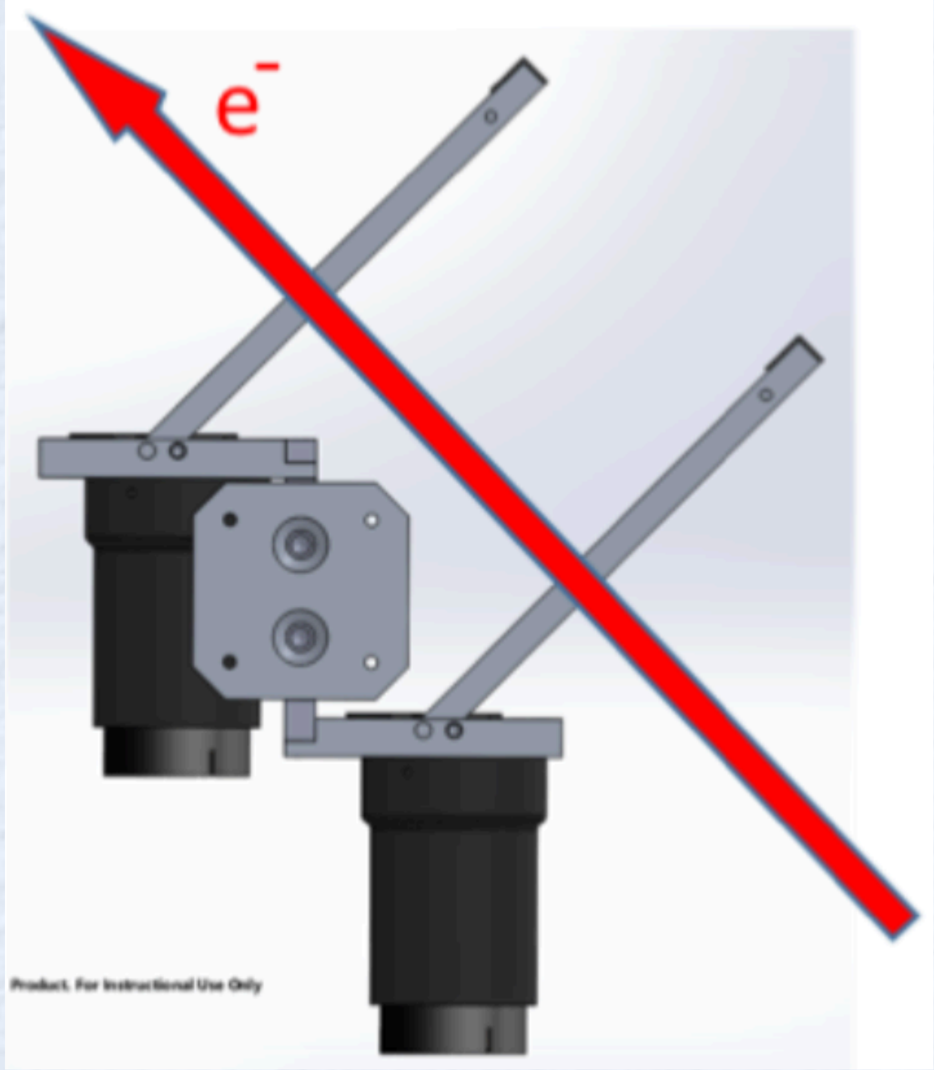


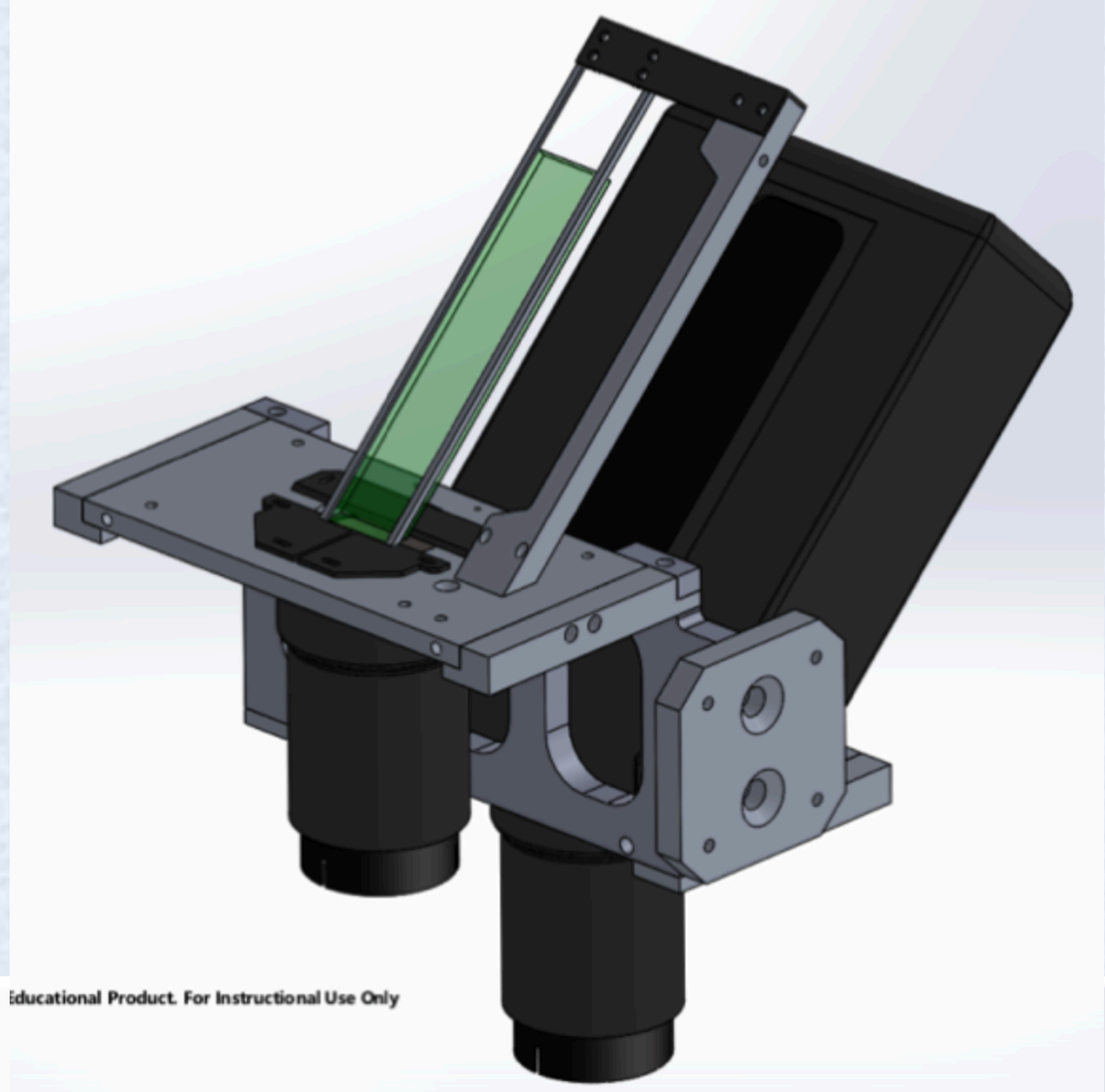


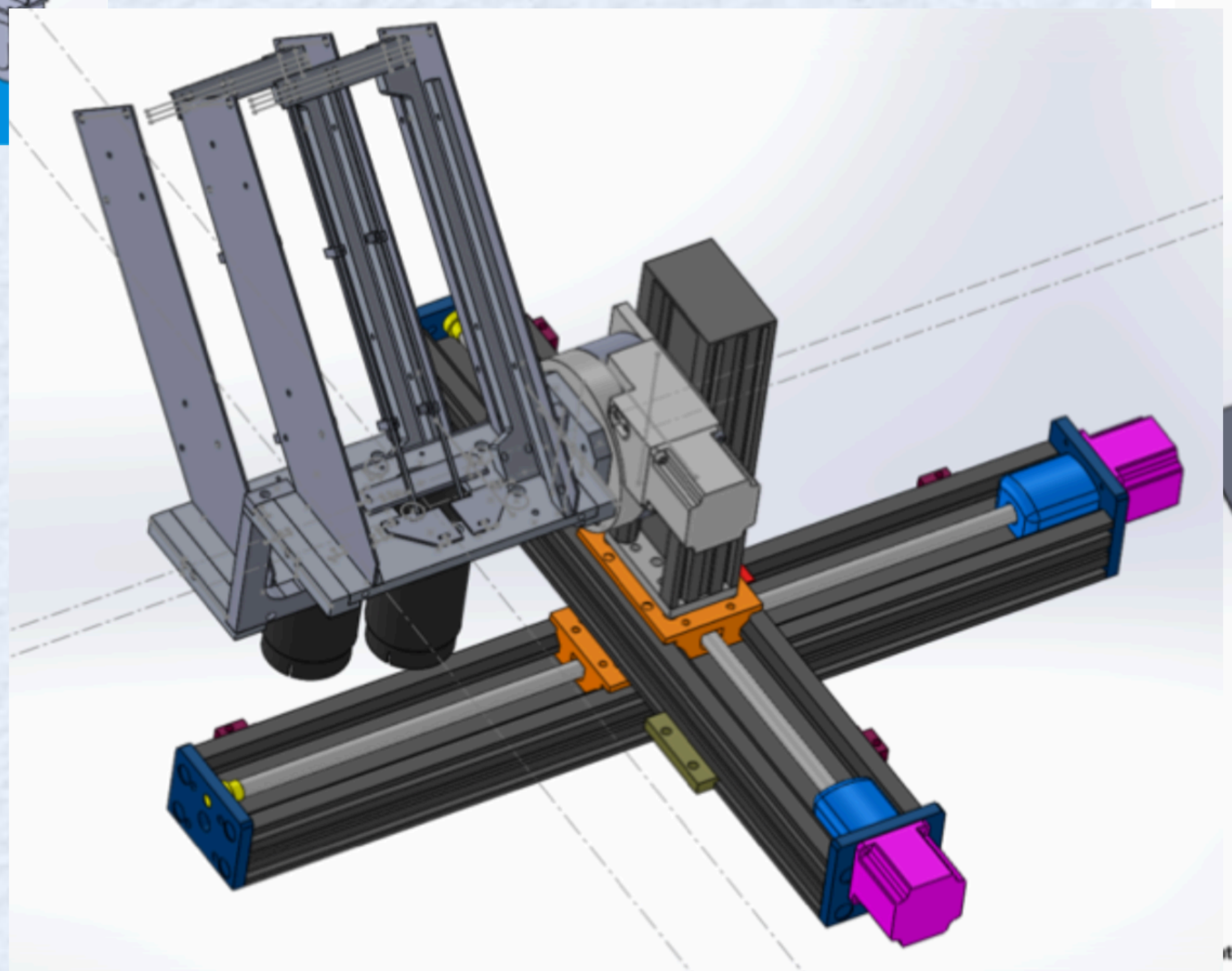
Extensive simulation, design and engineering effort ongoing for robust, efficient and safe operation of these high luminosity experiments

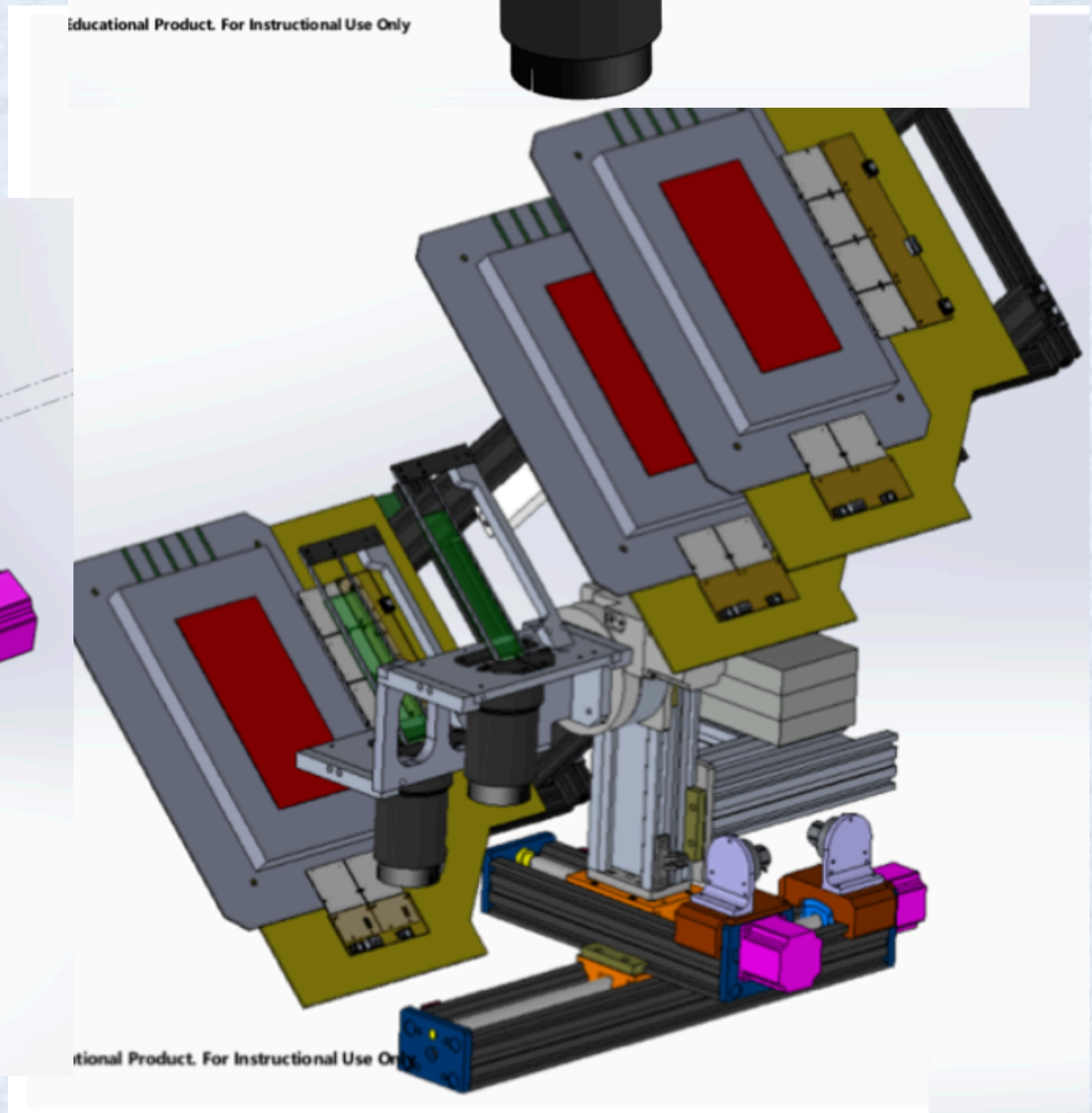
Focal Plane Detectors







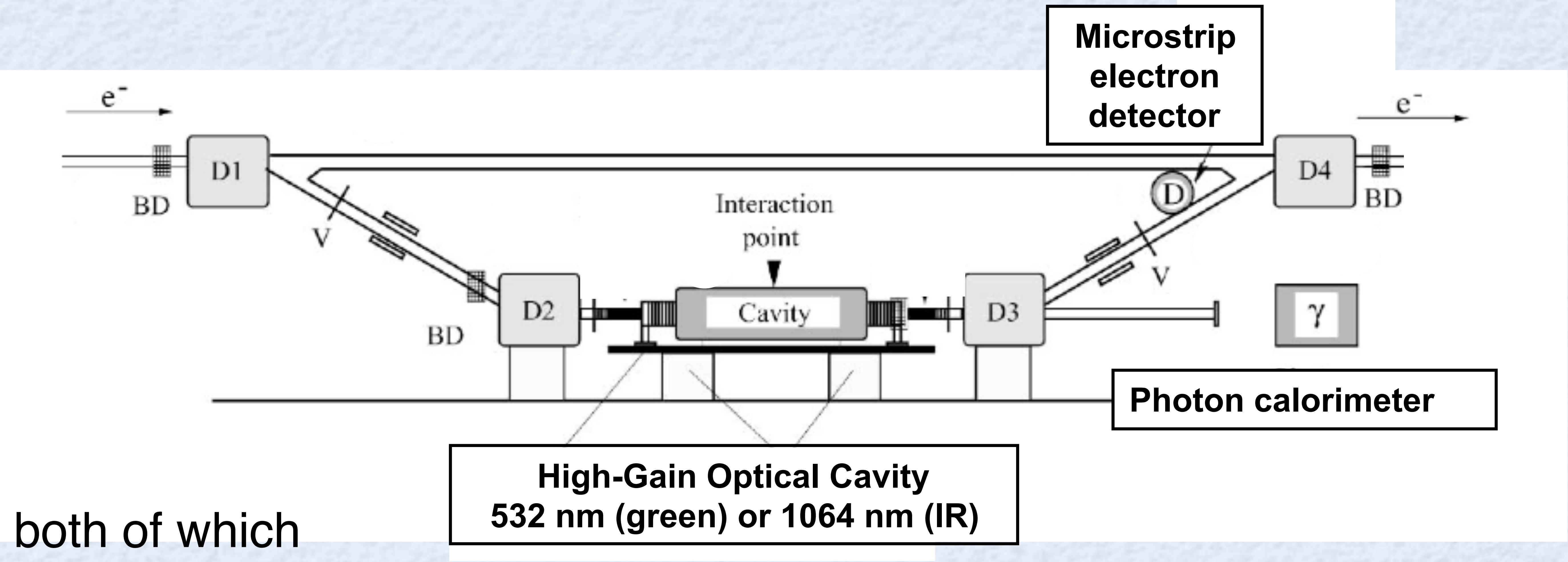




Mechanical design that combines the “counting” mode “Q^2 detectors” with the integrating mode main detectors

Beam Polarimetry

$$A_{phys} = \frac{A_{sig}}{P_{beam}}$$

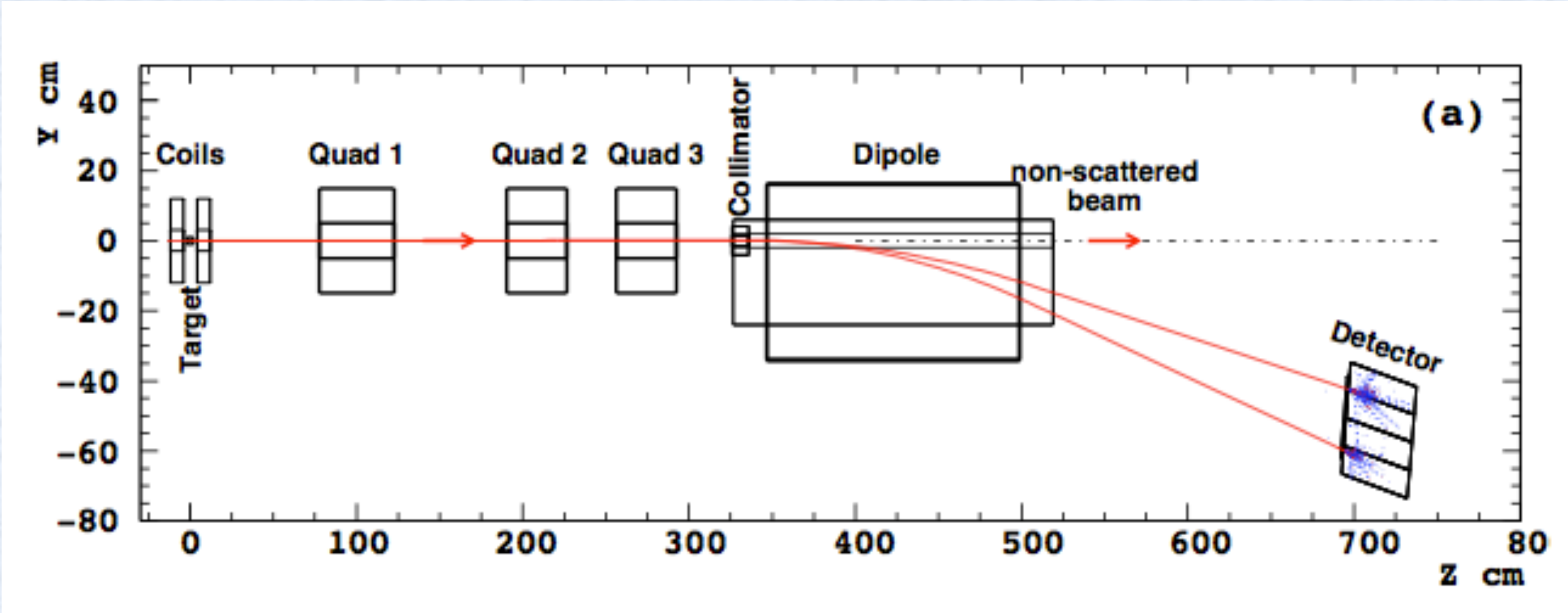


Two independent methods, both of which received recent upgrades

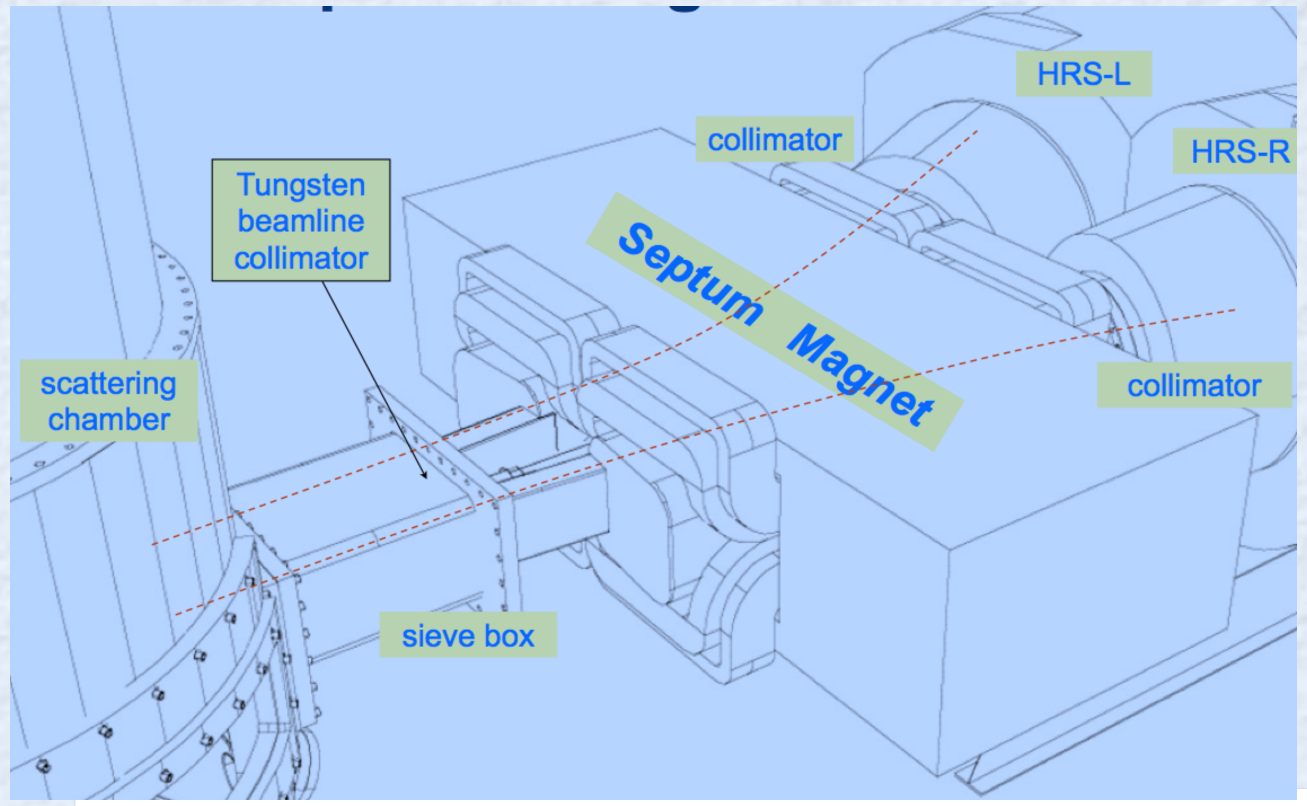
Both methods expected to reach sub-1% for future measurements: ultimate goal is sub-0.5%

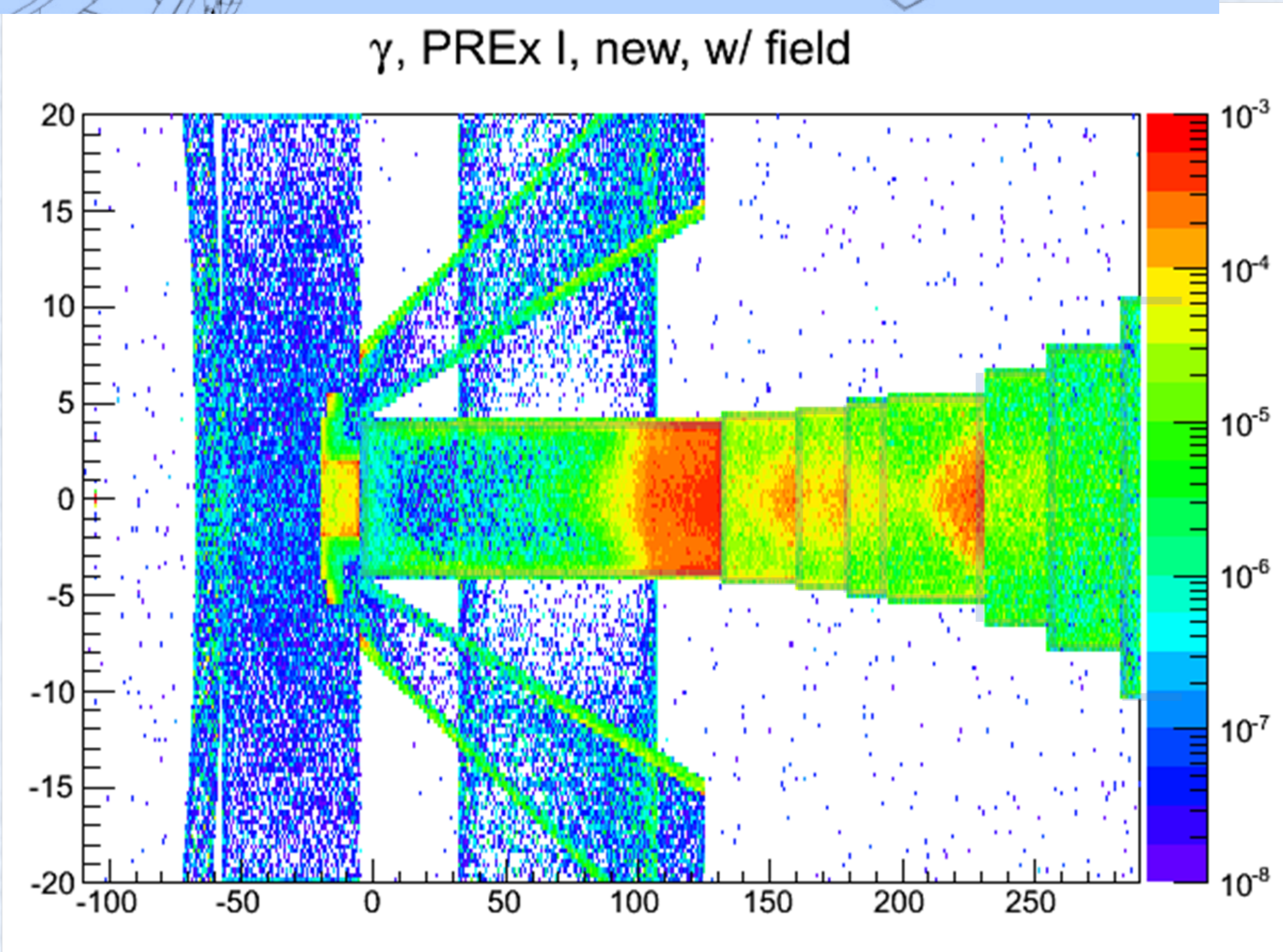
- Compton Polarimeter
  - green laser (increased sensitivity at low E)
  - integrating method (analyzing power)
  - new photon & electron detectors

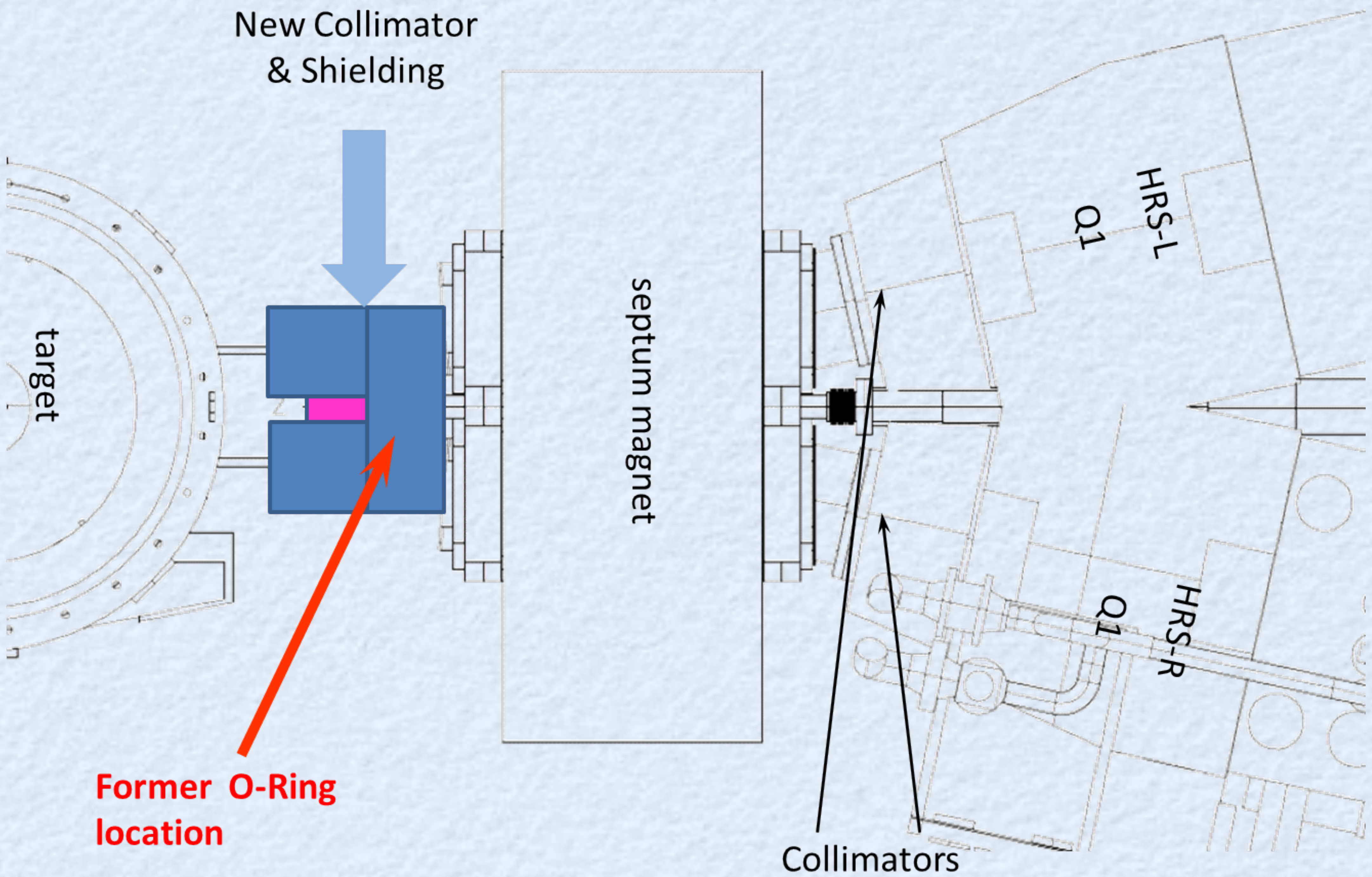
- Møller Polarimeter
  - electronics and DAQ
  - High field magnet for foil saturation: improved calibration of foil polarization

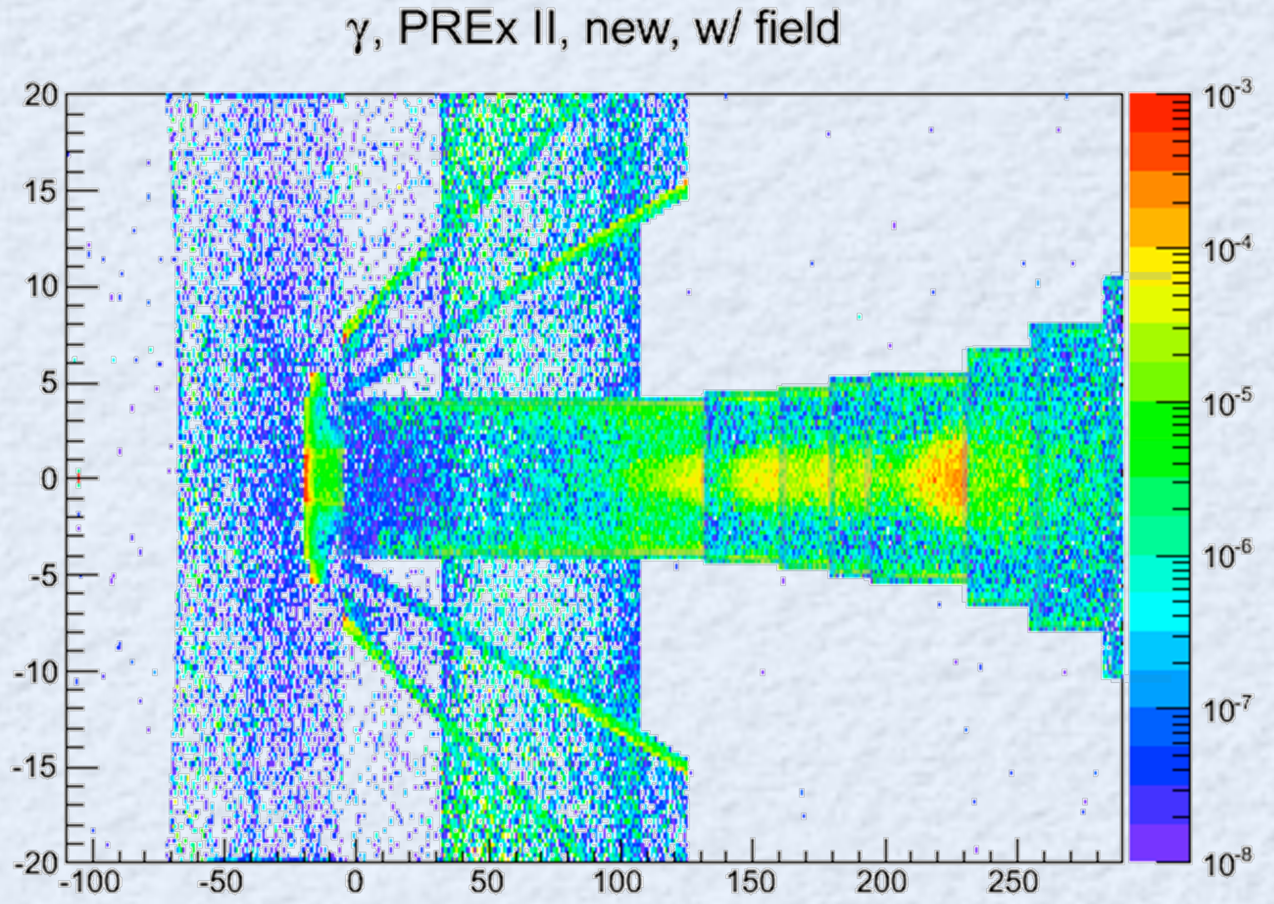


New Beamline Design



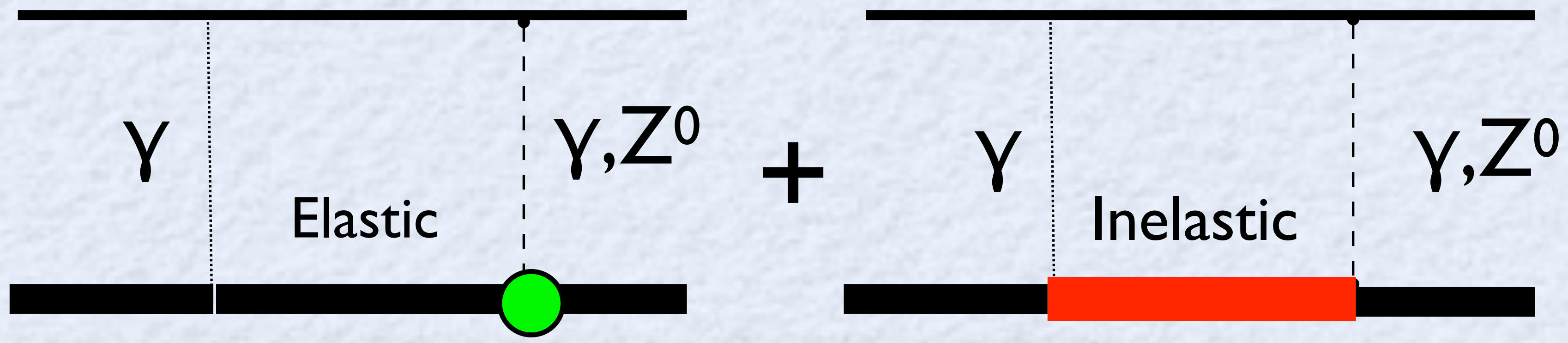


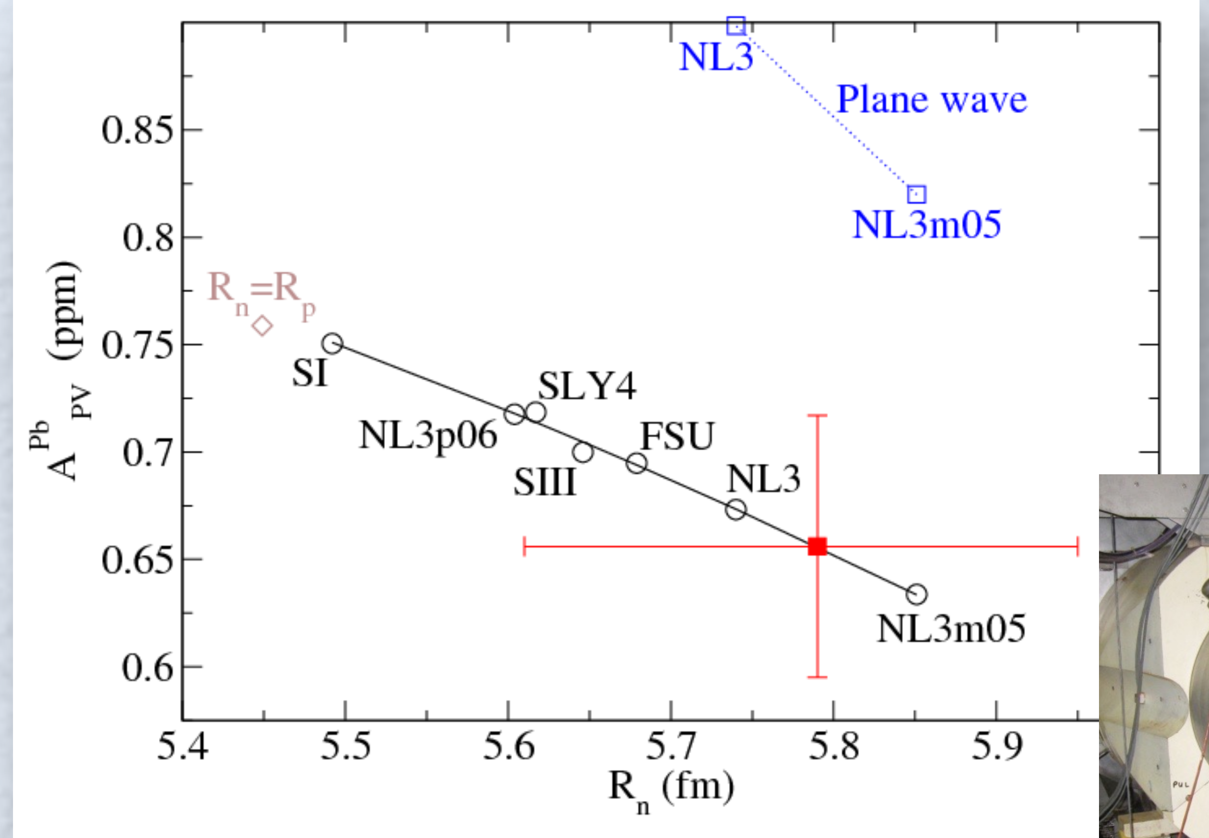


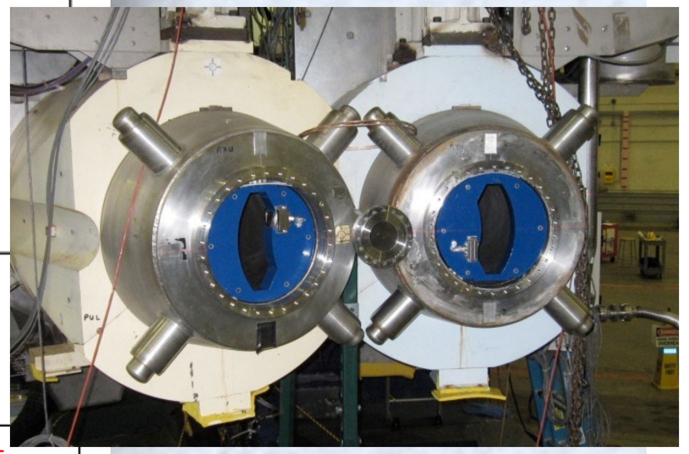


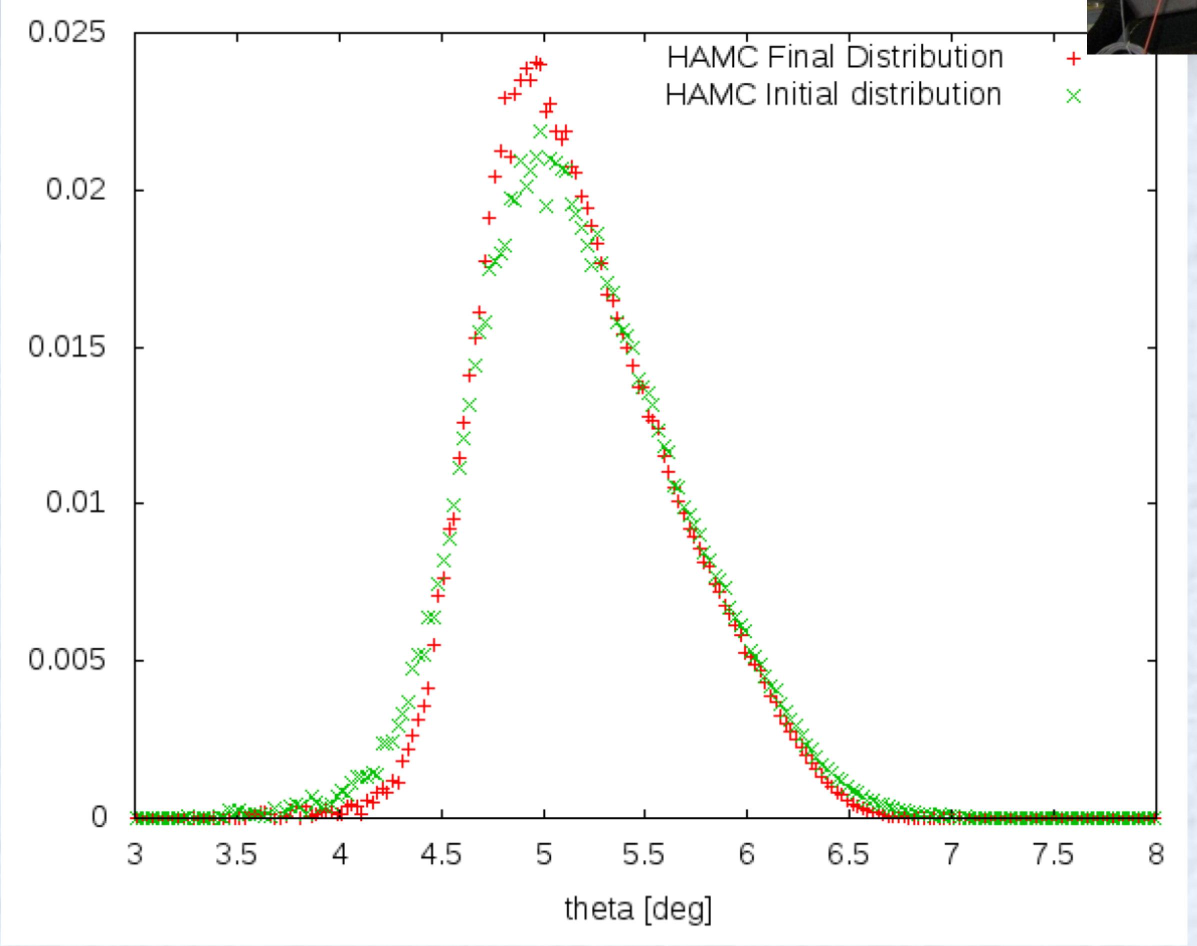
- **Redesign beamline seals to eliminate o-ring**
- **Neck down tungsten collimator to confine neutrons to one location and add water cooling**
- **Neutrons moderated by new shielding**
- **Small adjustment to septum current will realize an additional ~25% gain in statistical reach**

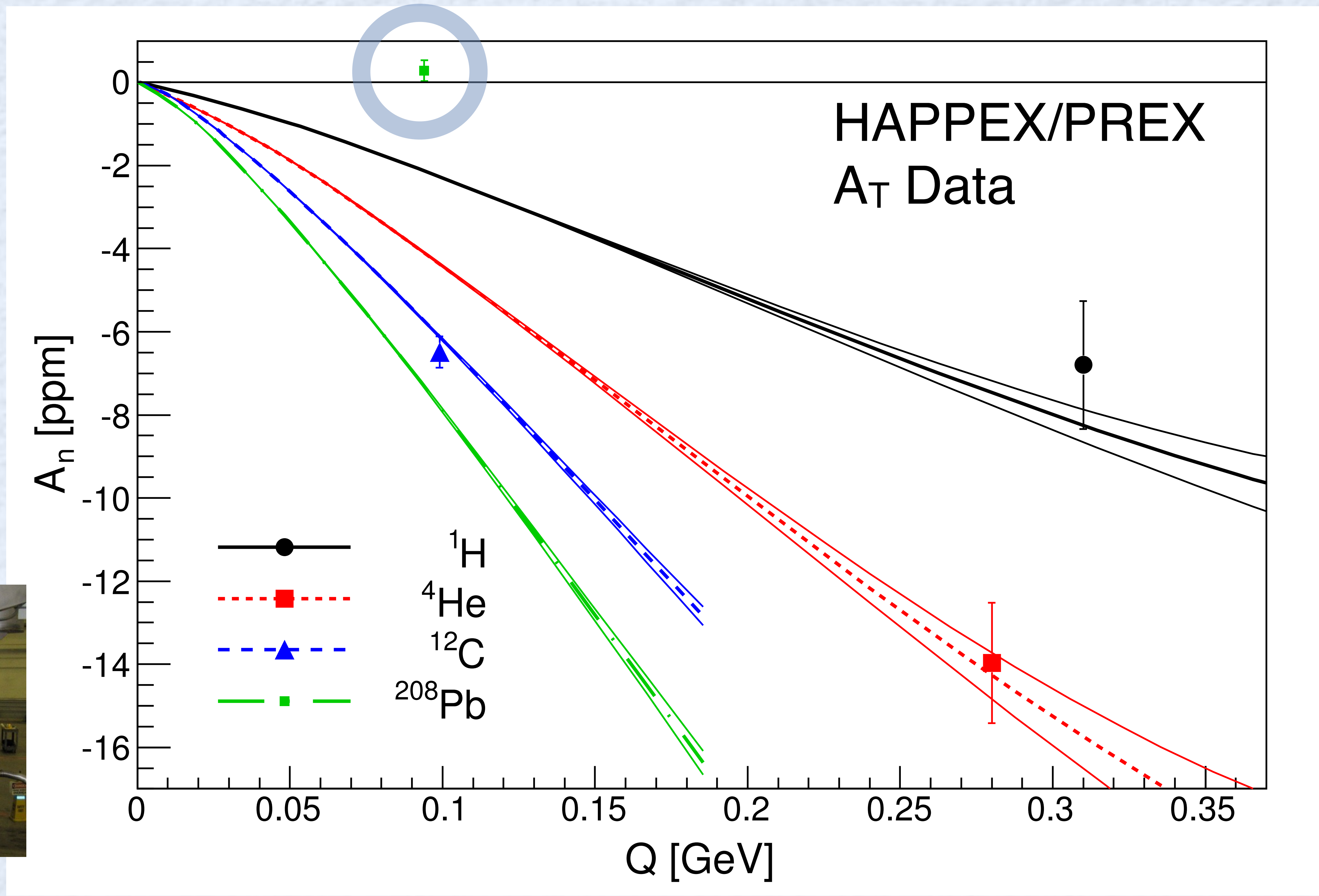
Input from Vector Analyzing Power







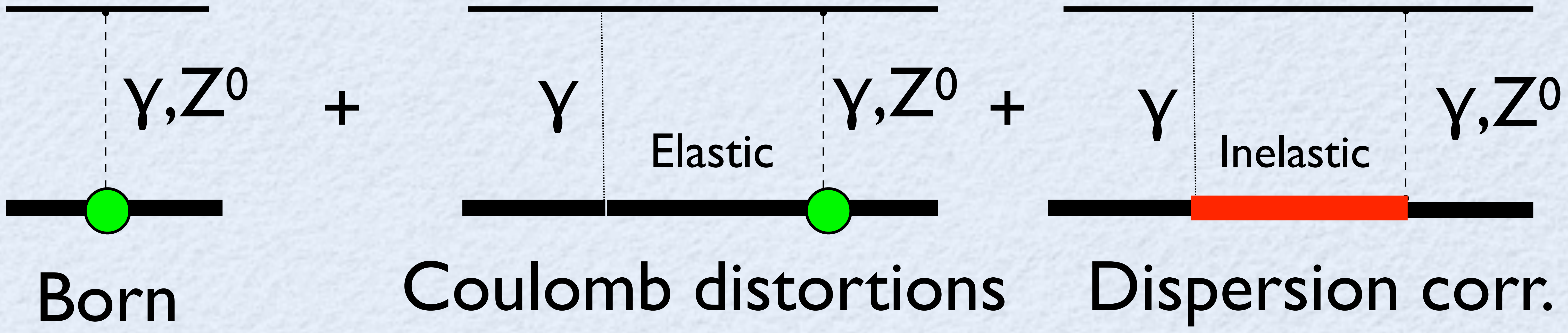




- **What does the Pb-208 A_T result imply?**
  - dispersion corrections on top of Coulomb distortions?
  - What if it is a very sensitive cancellation?
    - *What happens when we run again at slightly different kinematics?*
    - *What if Ca-48 doesn't have this accidental cancellation?*
  - should other electroweak corrections be revisited?

Radiative Corrections

C.Horowitz



- Coulomb distortions are coherent, order Zα. Important for PREX (Z=82)
  - Sum elastic intermediate states to all orders in Zα by solving Dirac equation for electron moving in coulomb (V) + weak potential (A) of nucleus.
  - Coulomb distortions reduce A_{pv} by ~30%, but accurately calculated (uncertainty estimated to be sub-1% of correction)
- Dispersion corrections are of order α (not Zα).
- Note: Both Coulomb distortion and dispersion corrections can be important for Transverse Beam Asymmetry A_n for ^{208}Pb

Tree-level prediction: ~ 250 ppb

E158 Implications

Tree-level prediction: ~ 250 ppb

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

Final E158 Result

E158 Implications

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

Tree-level prediction: ~ 250 ppb

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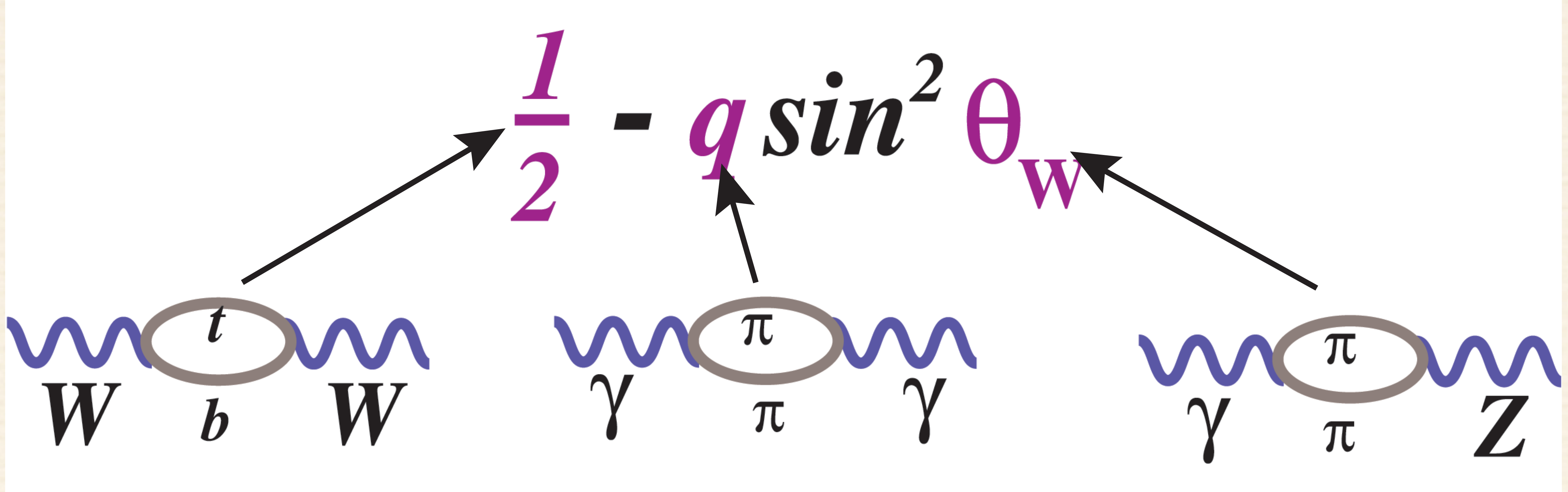

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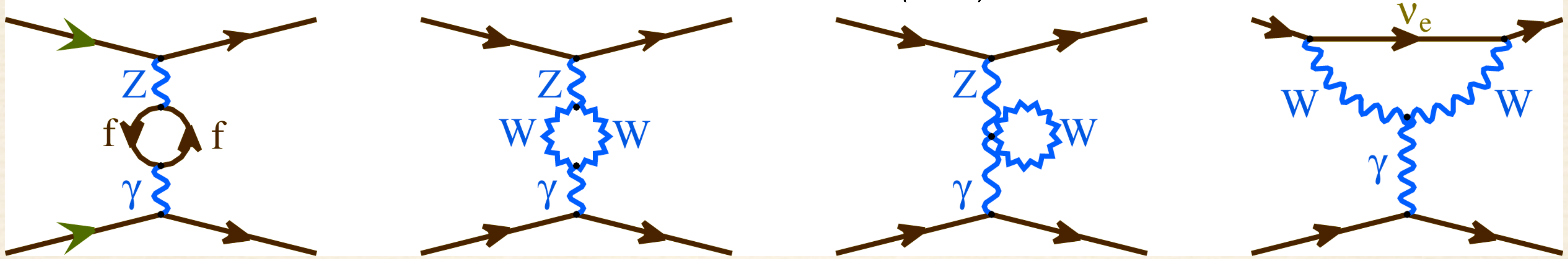

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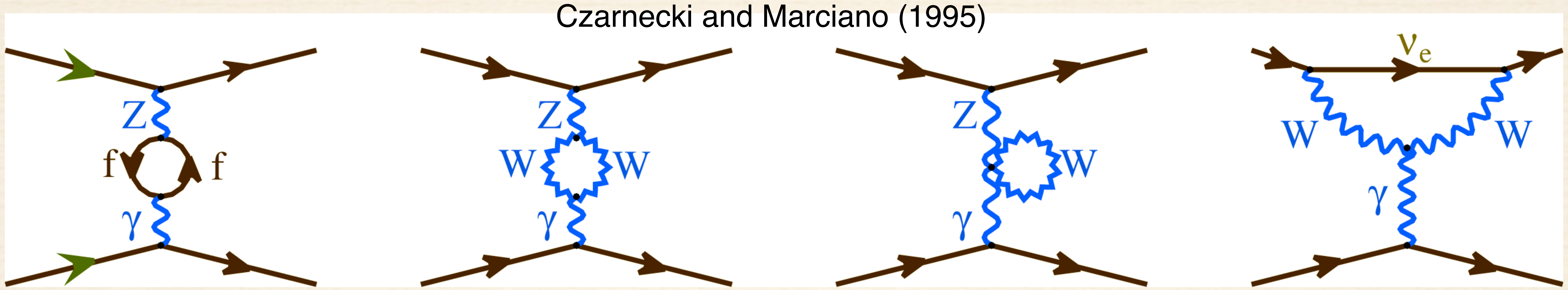

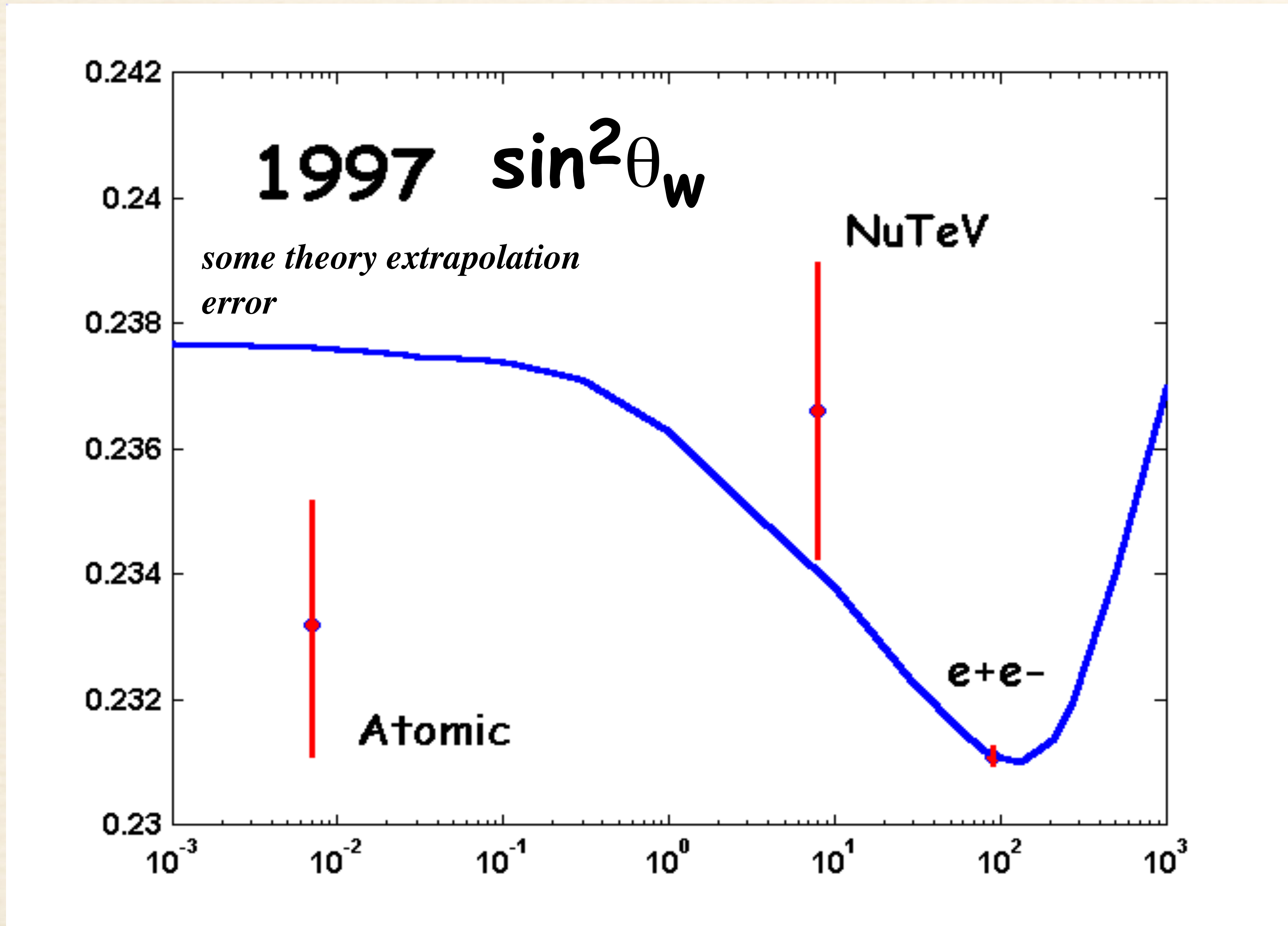

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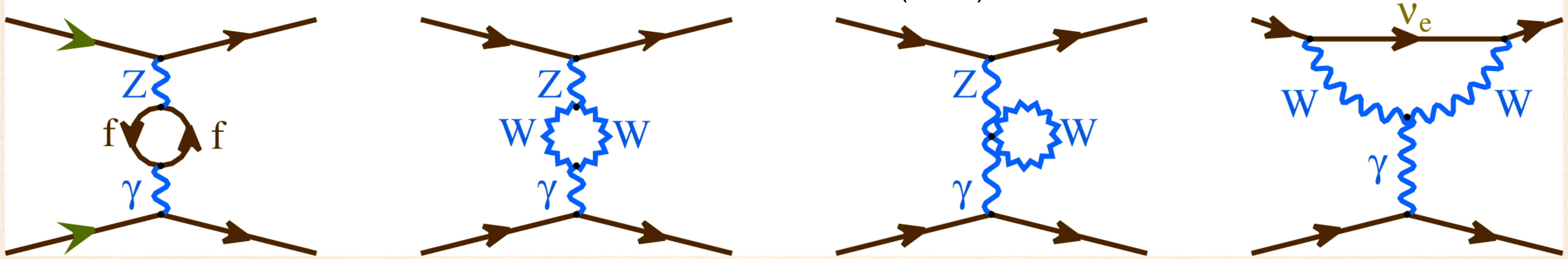

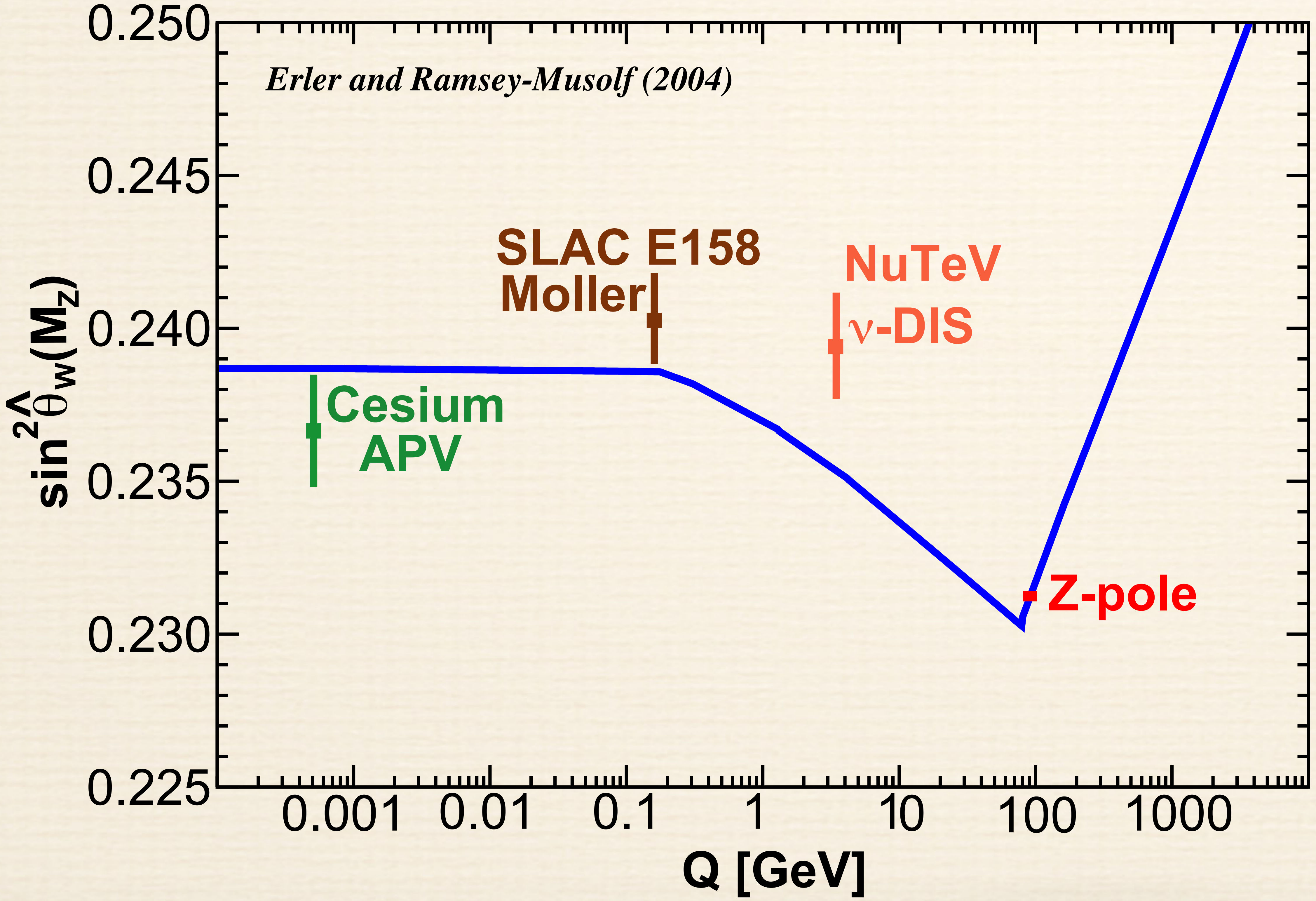

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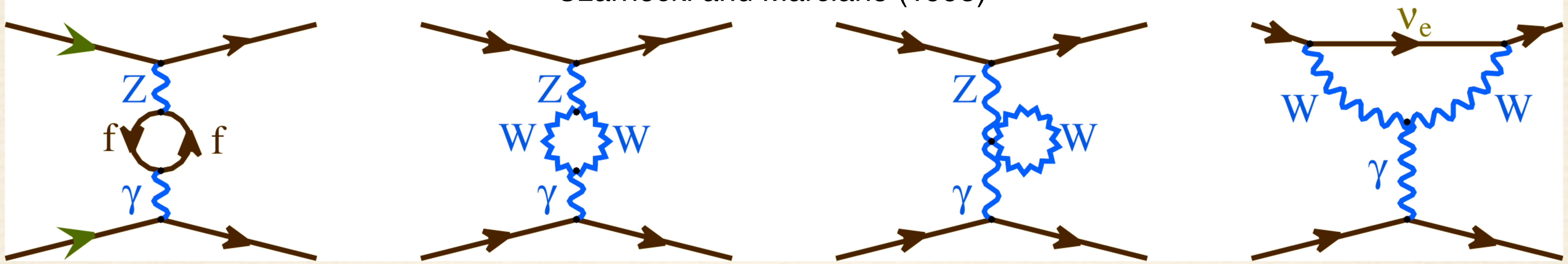

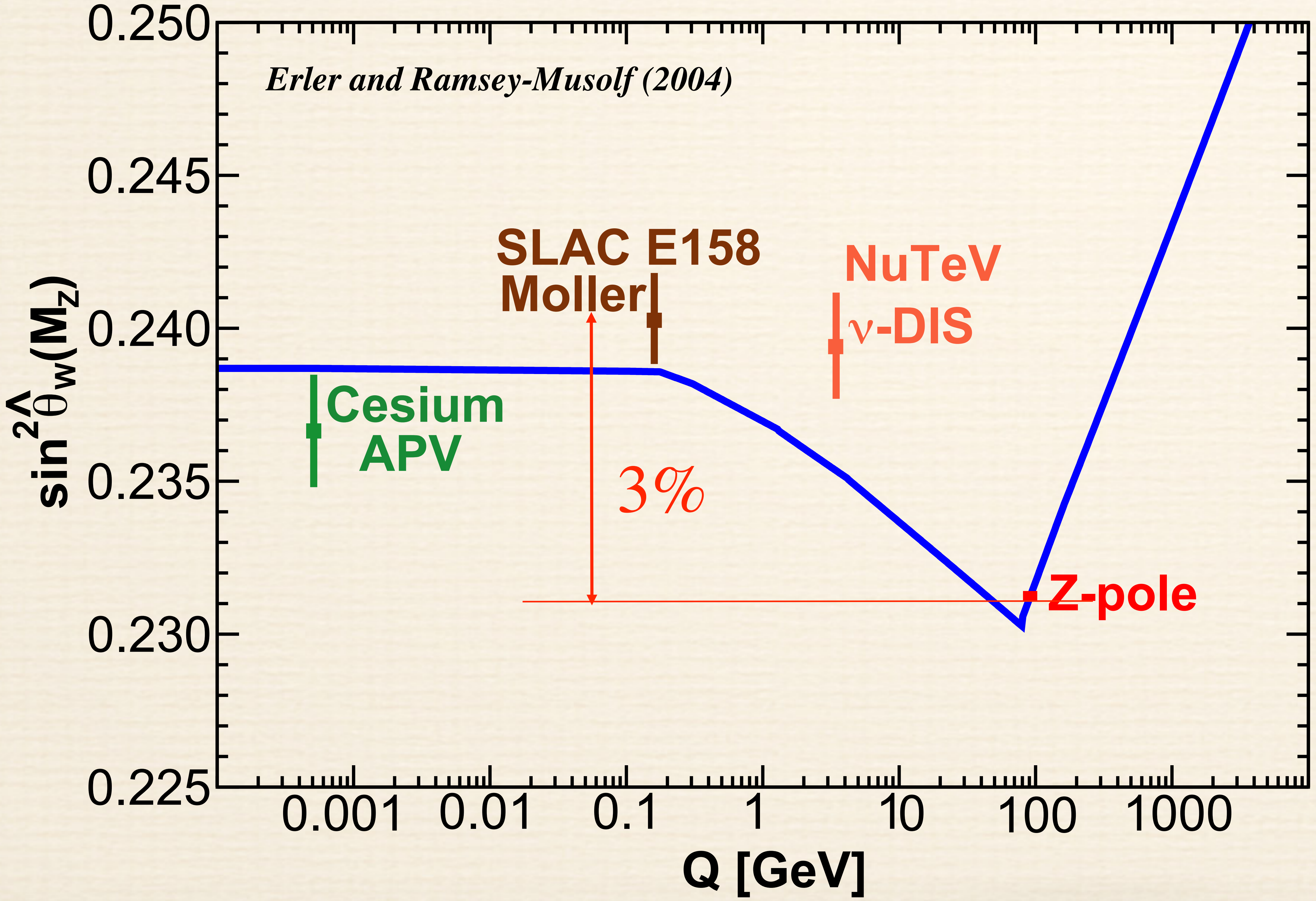

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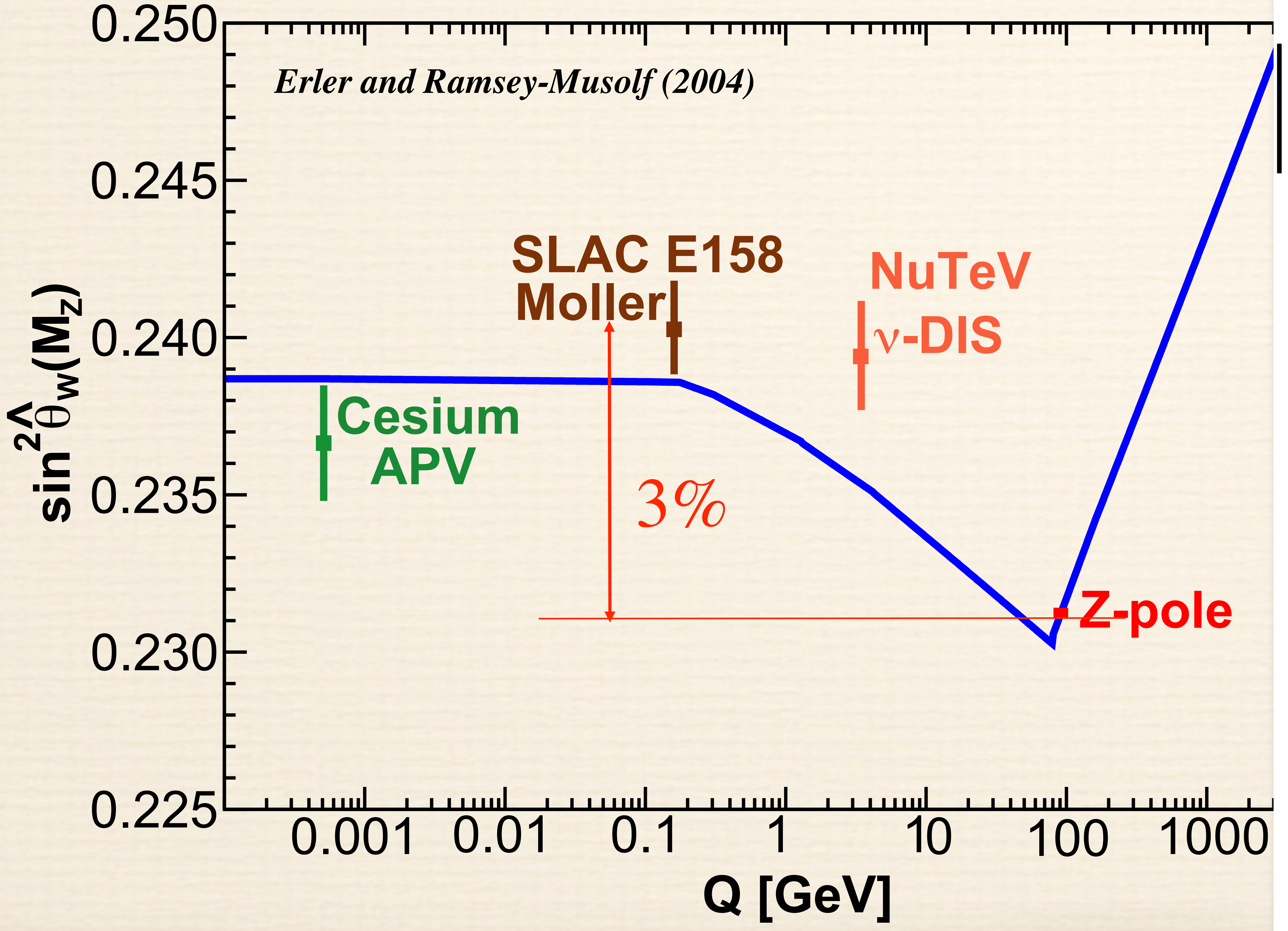
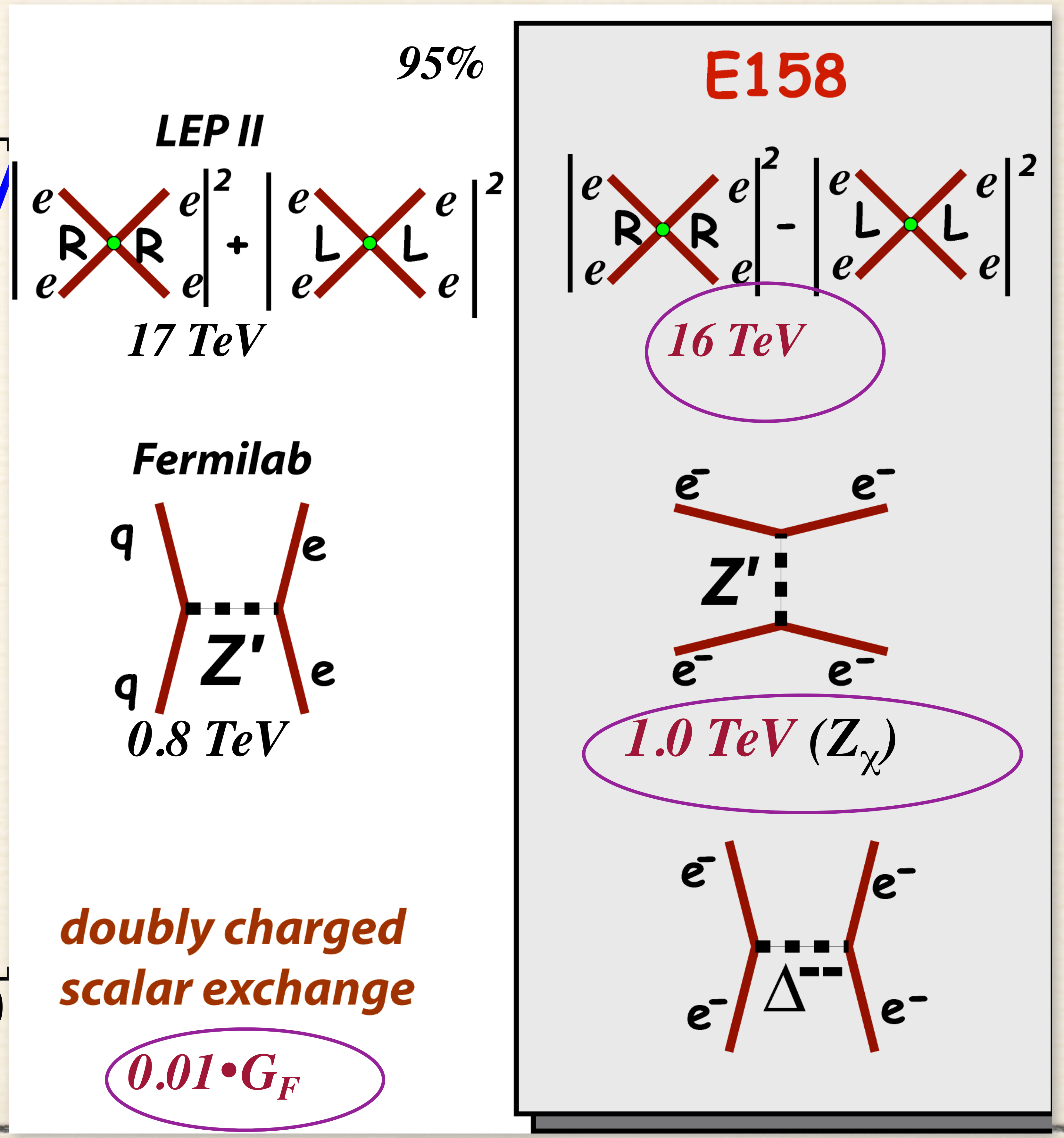


Limits on "New" Physics



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Nature
Vol 435 26 May 2005

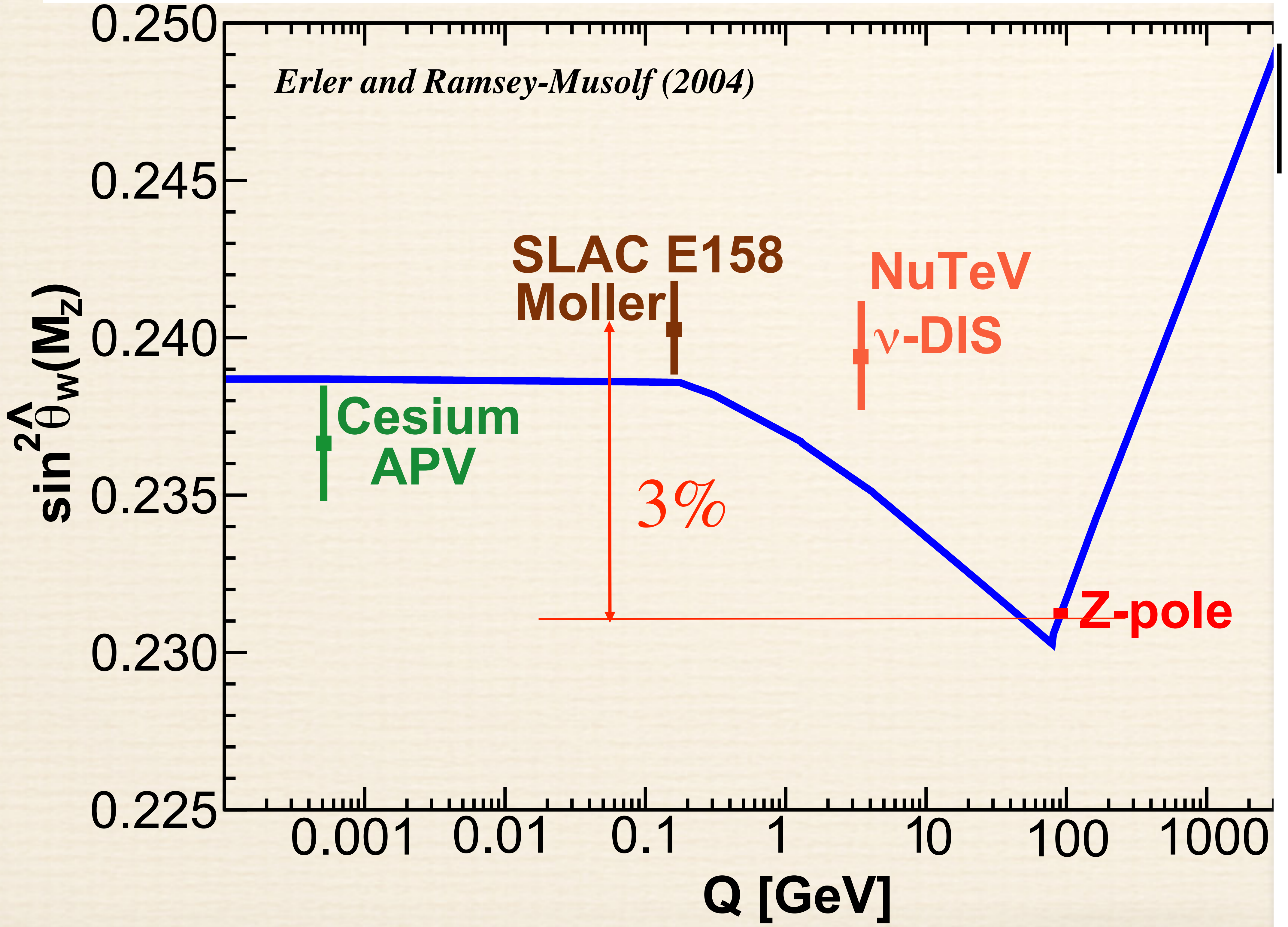
NEWS AND VIEWS

PARTICLE PHYSICS

Electrons are not ambidextrous

Andrzej Czarnecki and William J. Marciano

The best low-energy measurement yet obtained of the electroweak mixing angle — a central parameter of the standard model of particle physics — is the last hurrah for Stanford's powerful two-mile linear accelerator.



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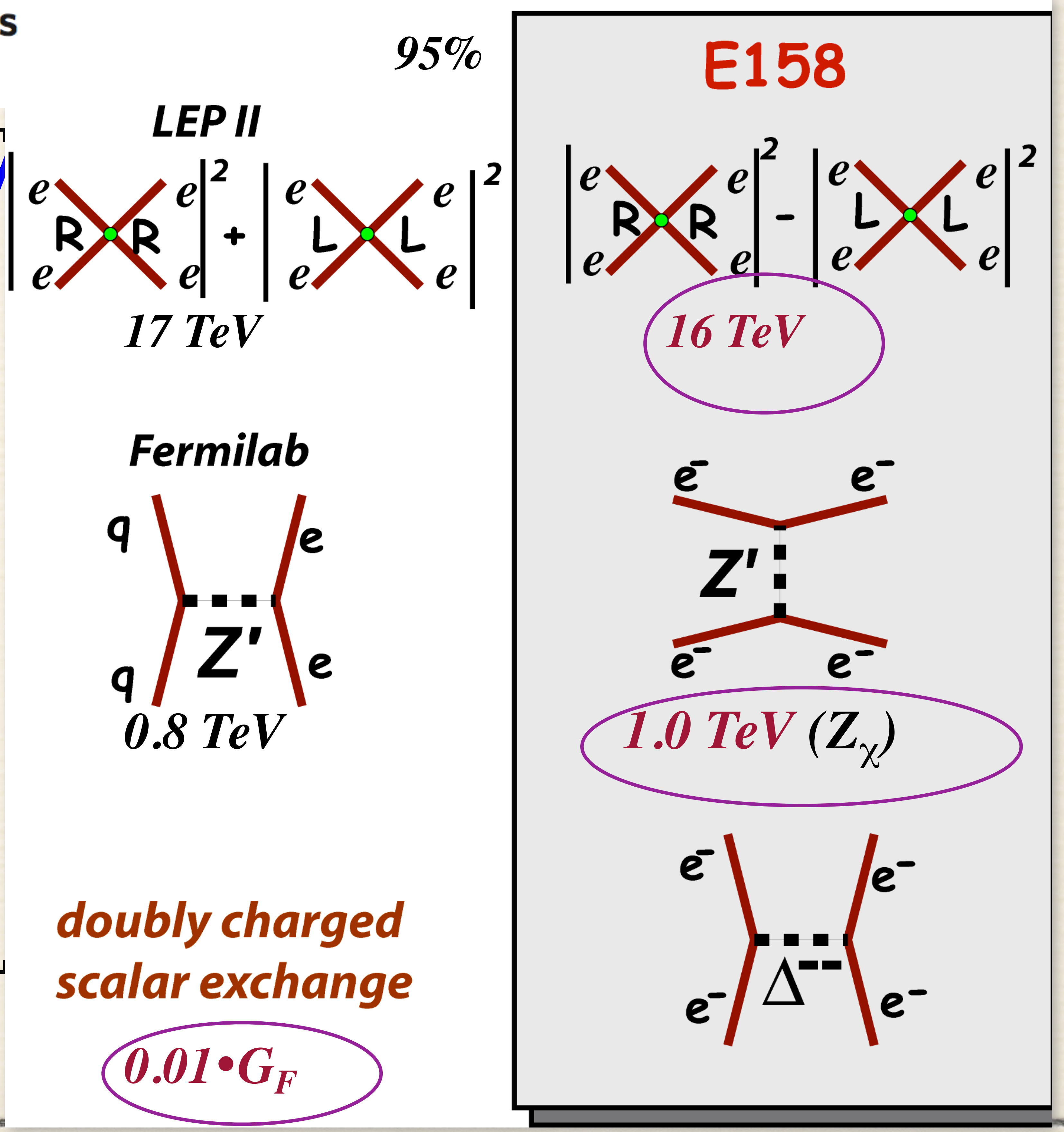

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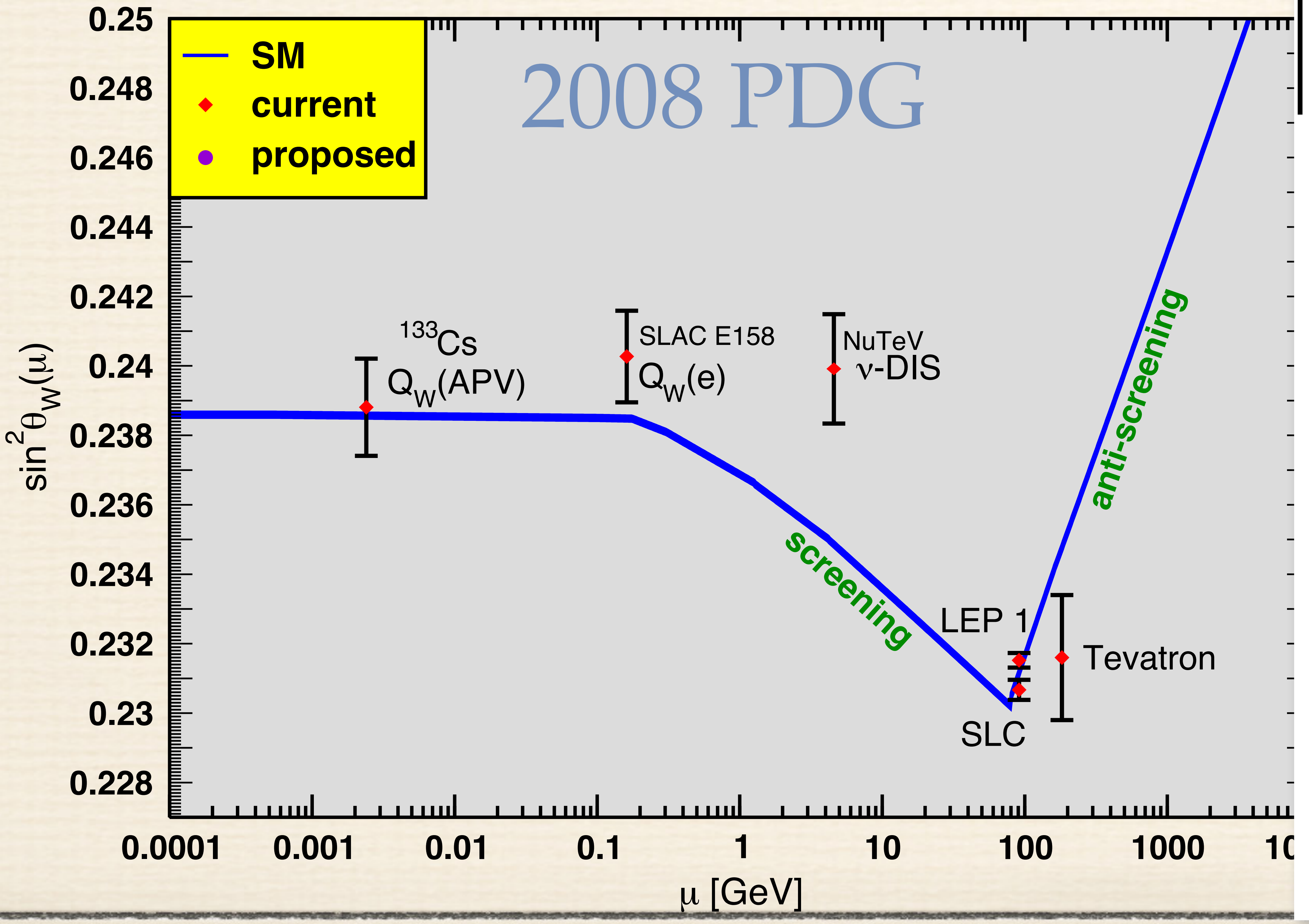
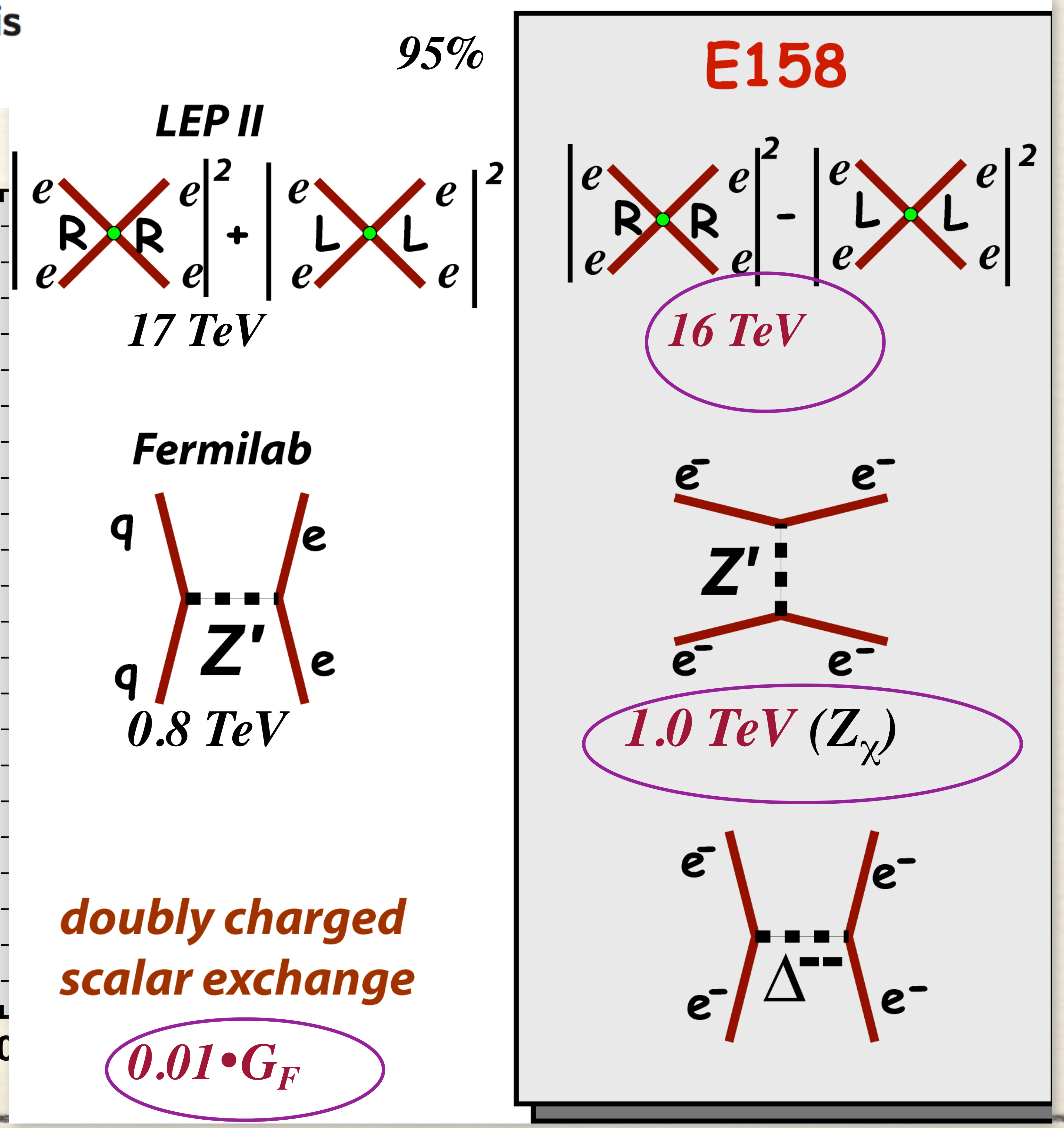


Limits on "New" Physics



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

Final E158 Result

E158 Implications

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

Nature
Vol 435 26 May 2005
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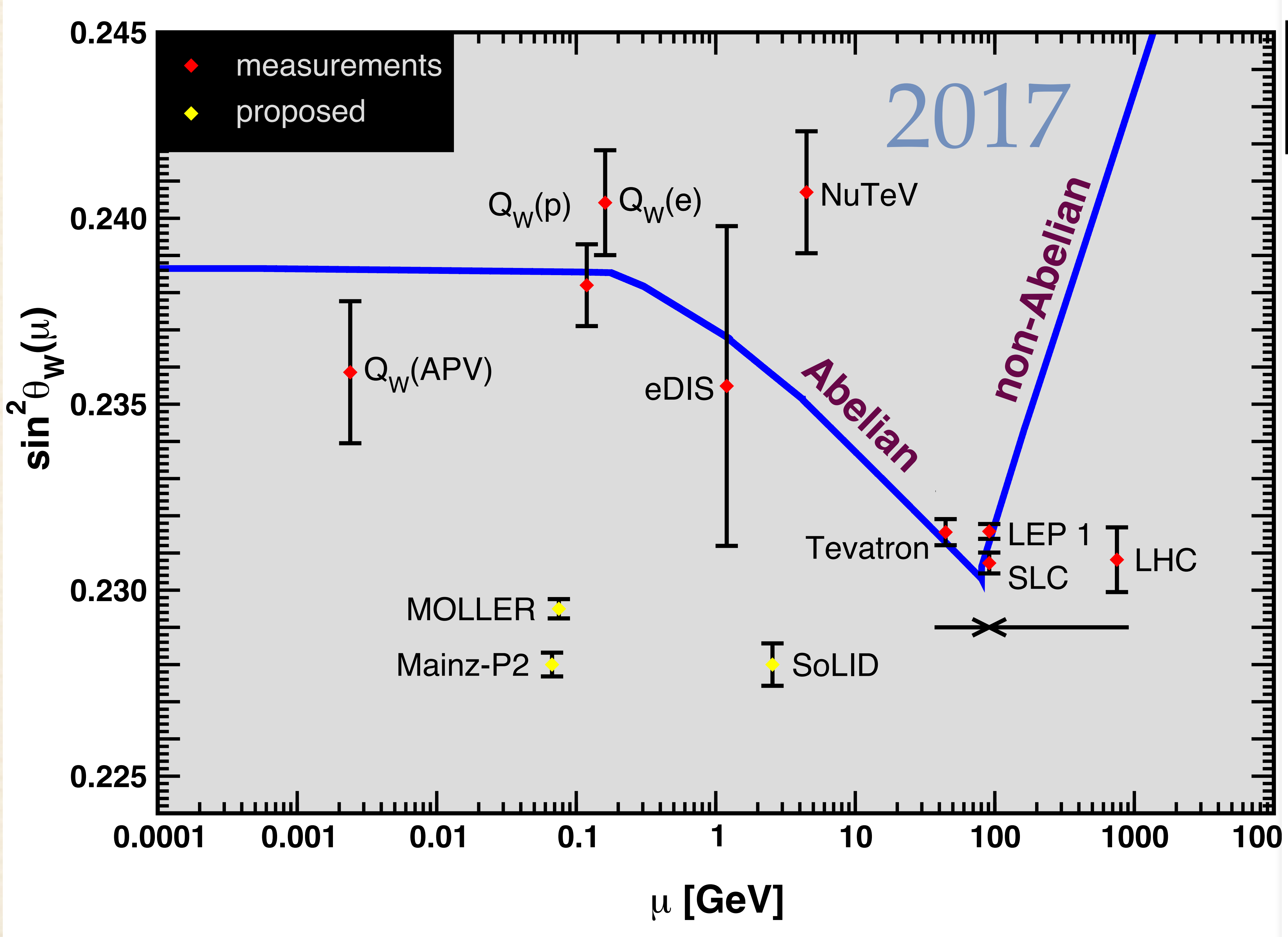

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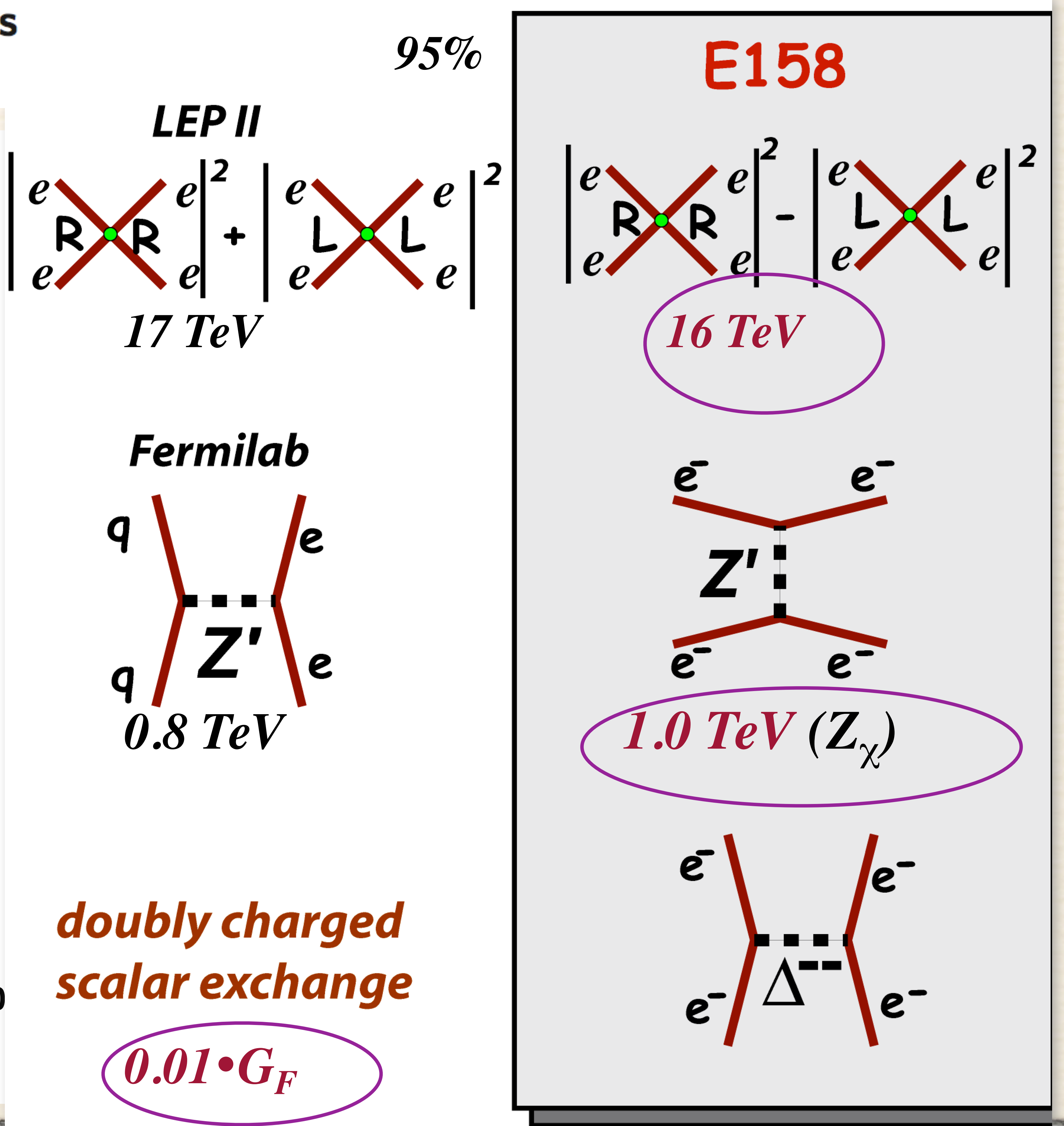

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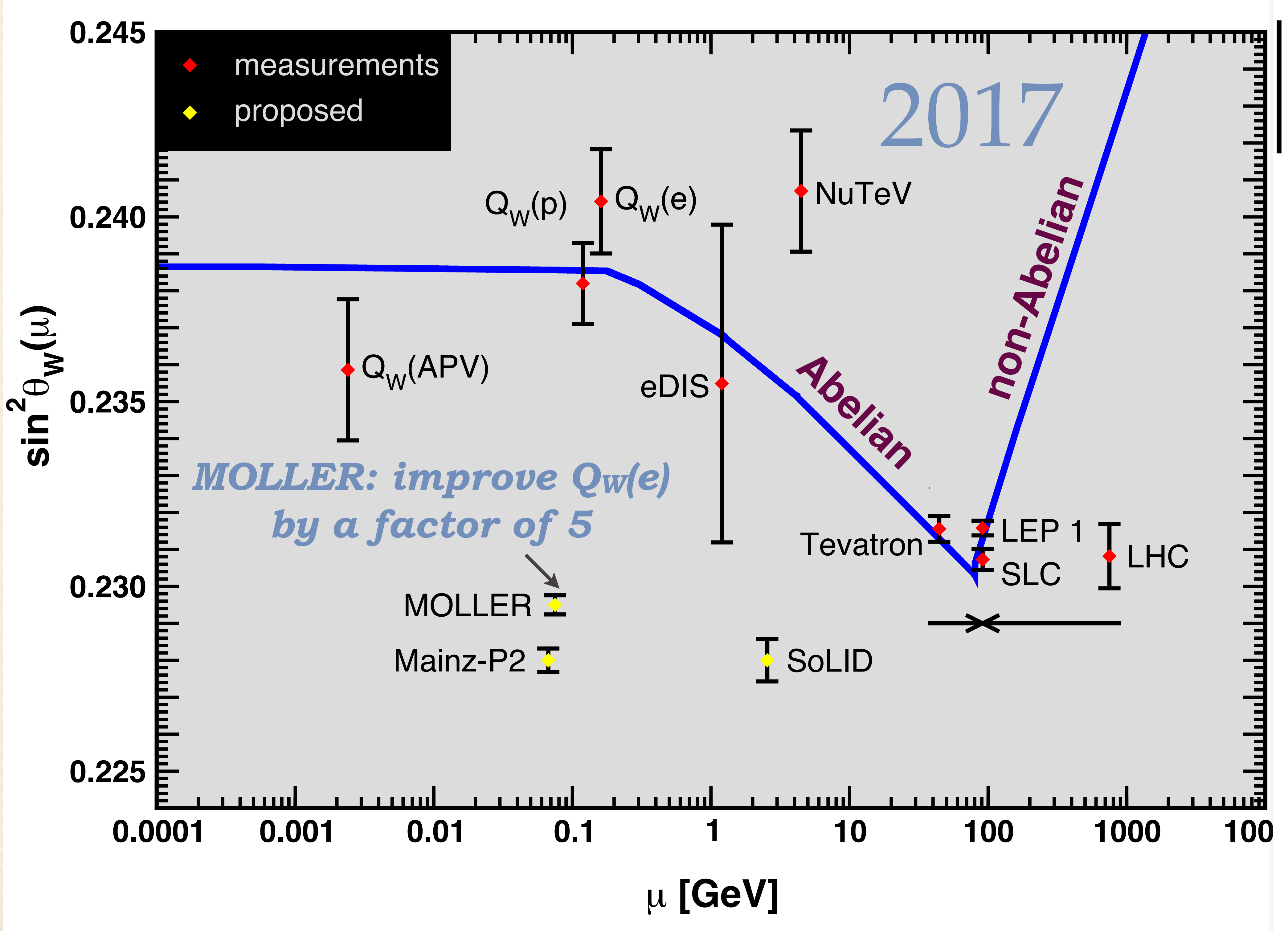

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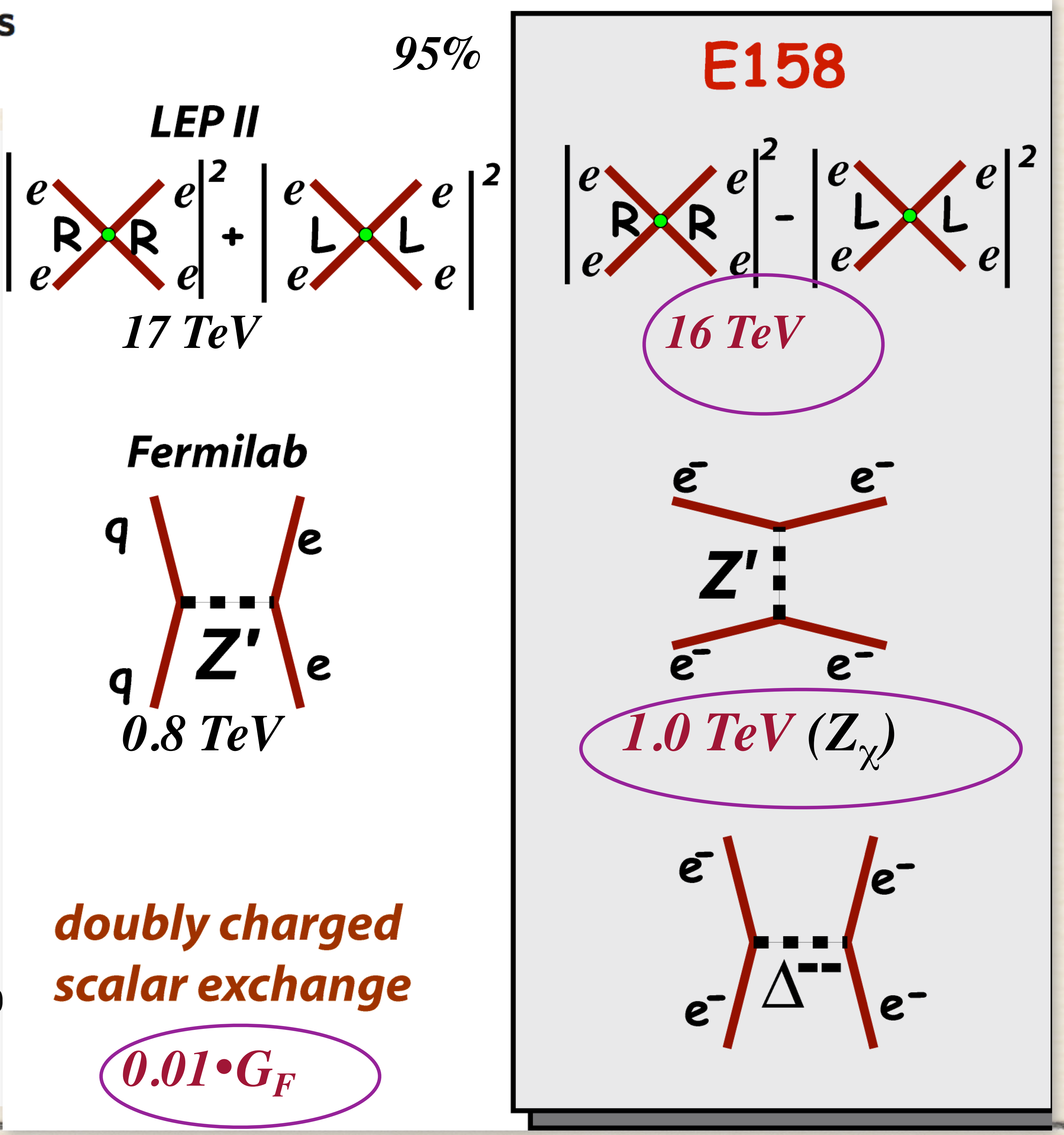
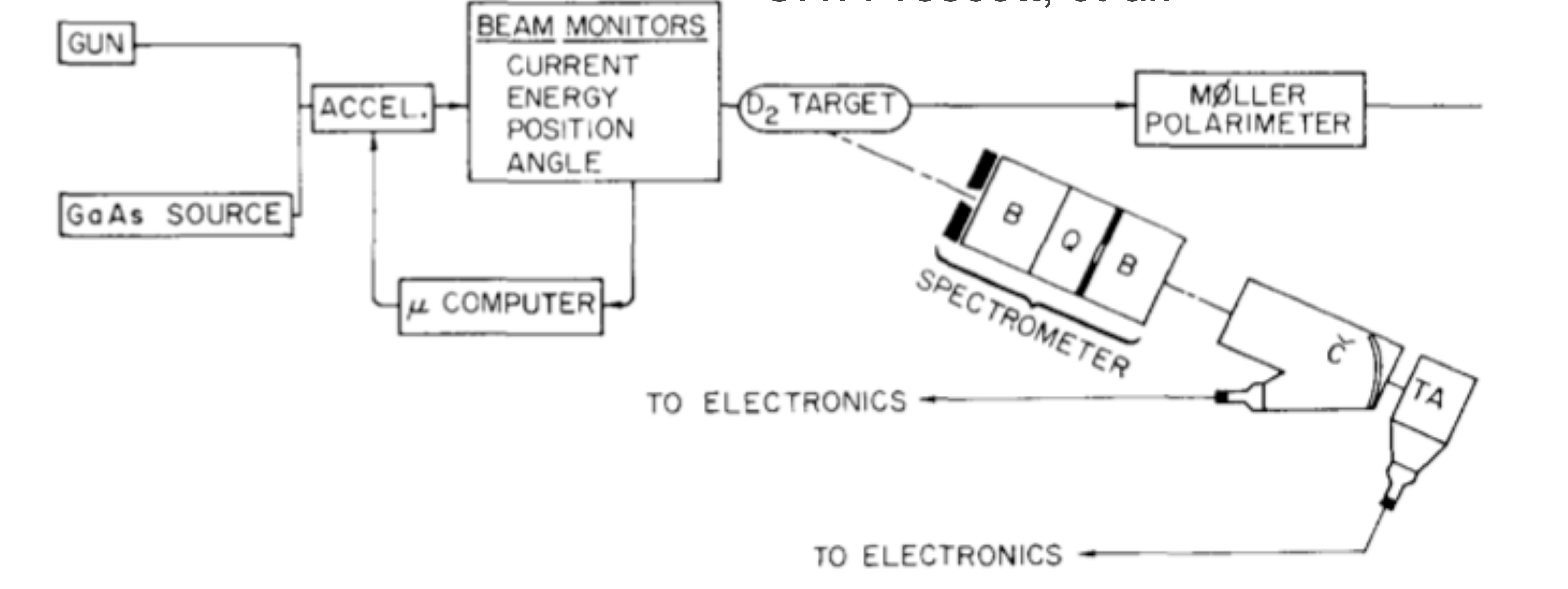


Anatomy of a Parity Experiment

The E122 Experiment at the Stanford Linear Accelerator Center

C.Y. Prescott, *et al*.



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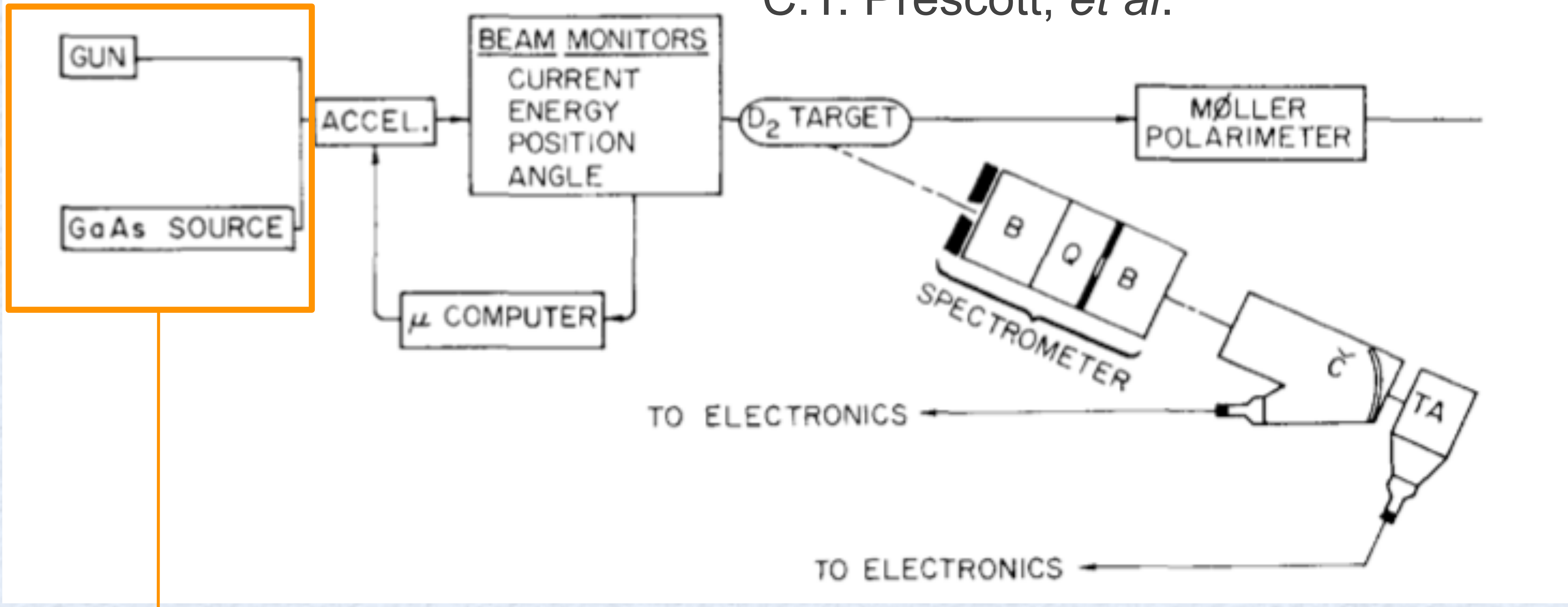
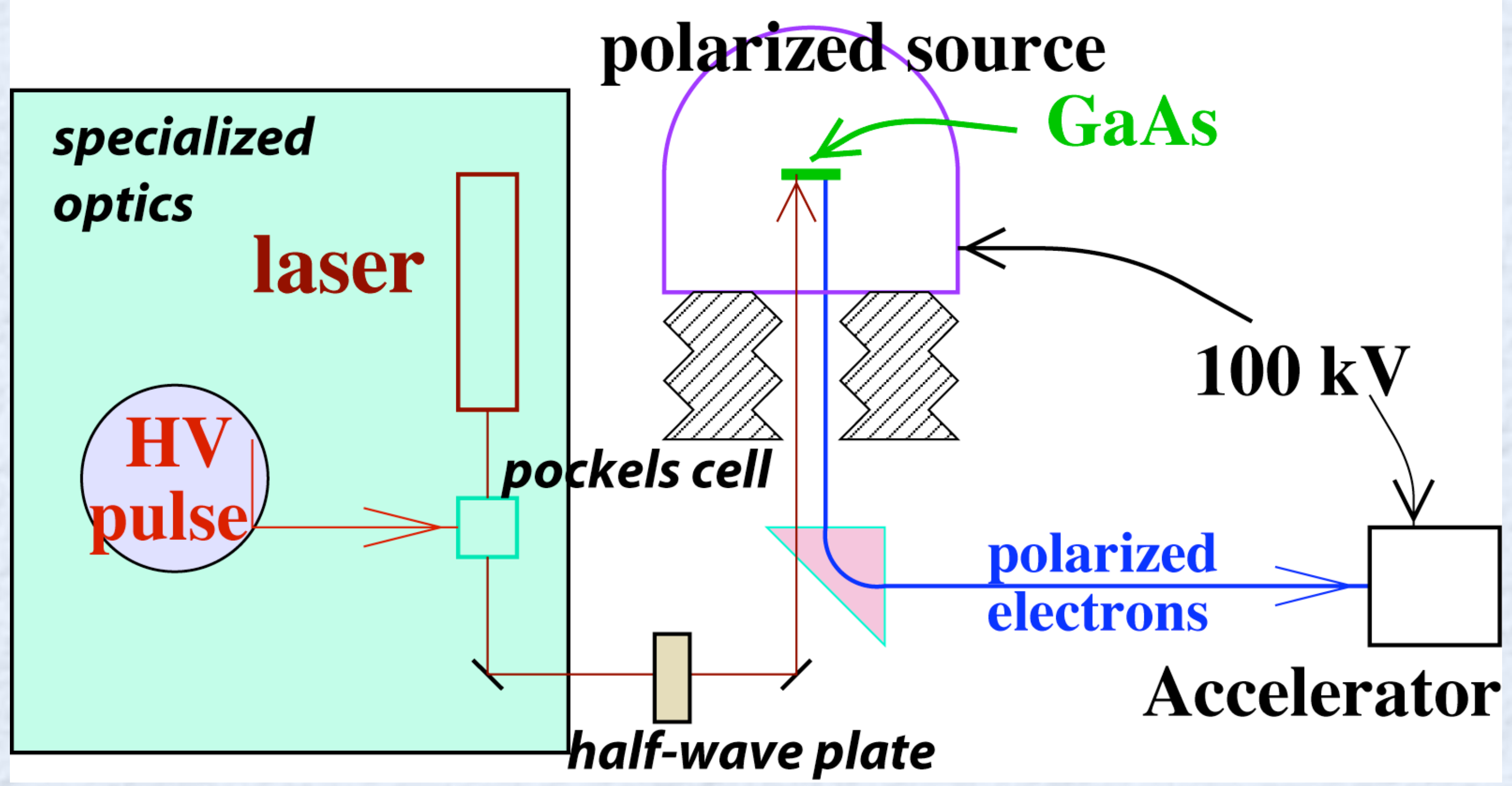
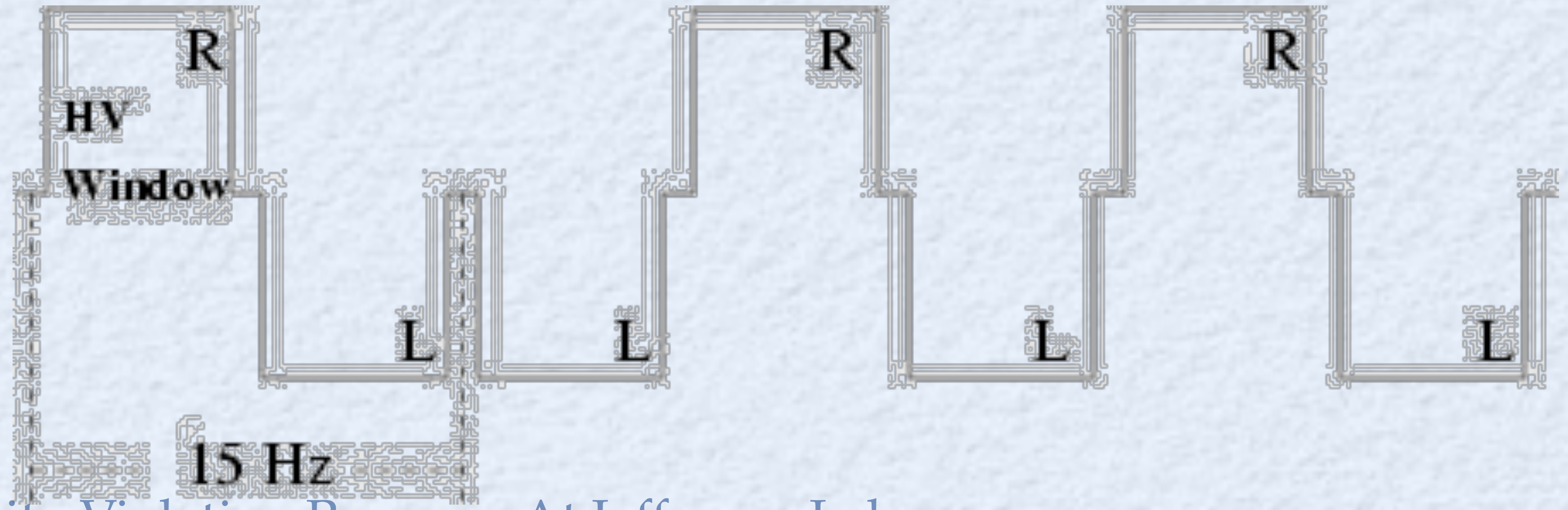




✧ **Beam helicity sequence is chosen pseudo-randomly**

- Helicity state, followed by its complement
- Data analyzed as "pulse-pairs"



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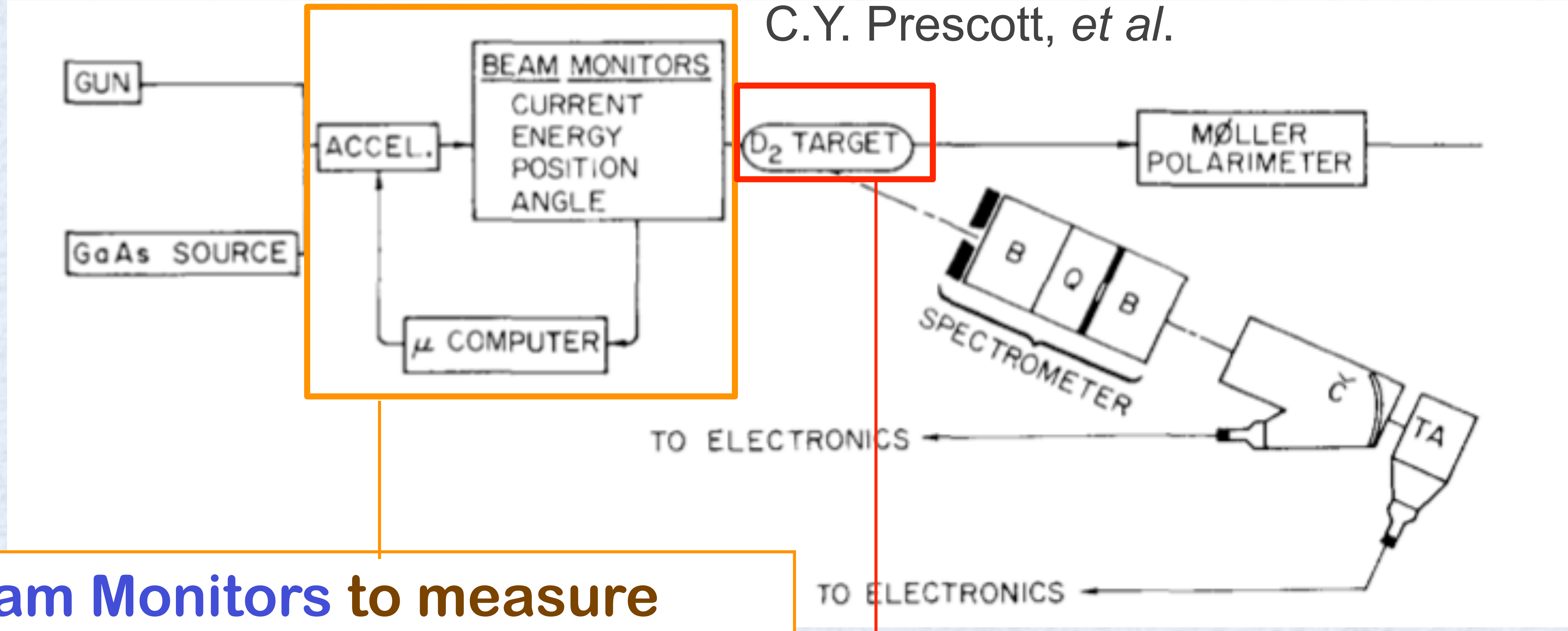

- **Beam Monitors to measure helicity-correlated changes in beam parameters**

- **High-power cryotarget 30 cm long for high luminosity**

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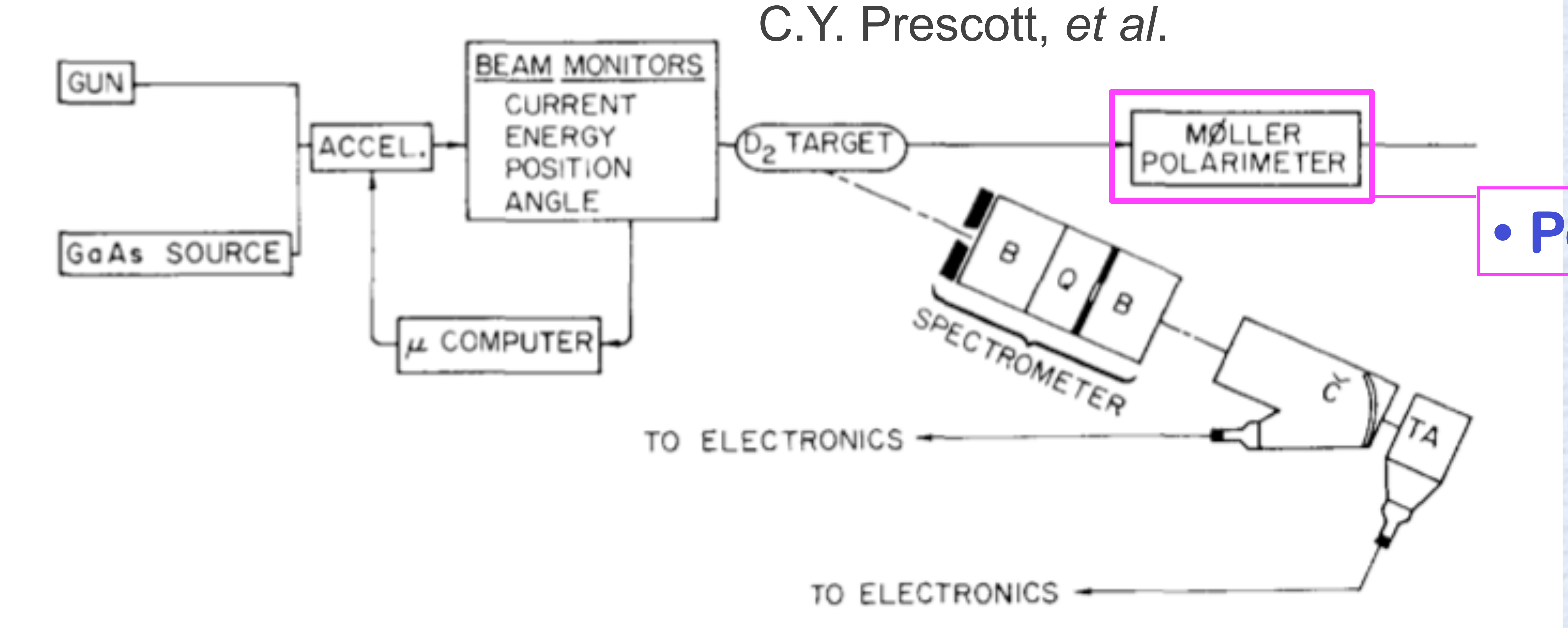

• **Polarimetry**

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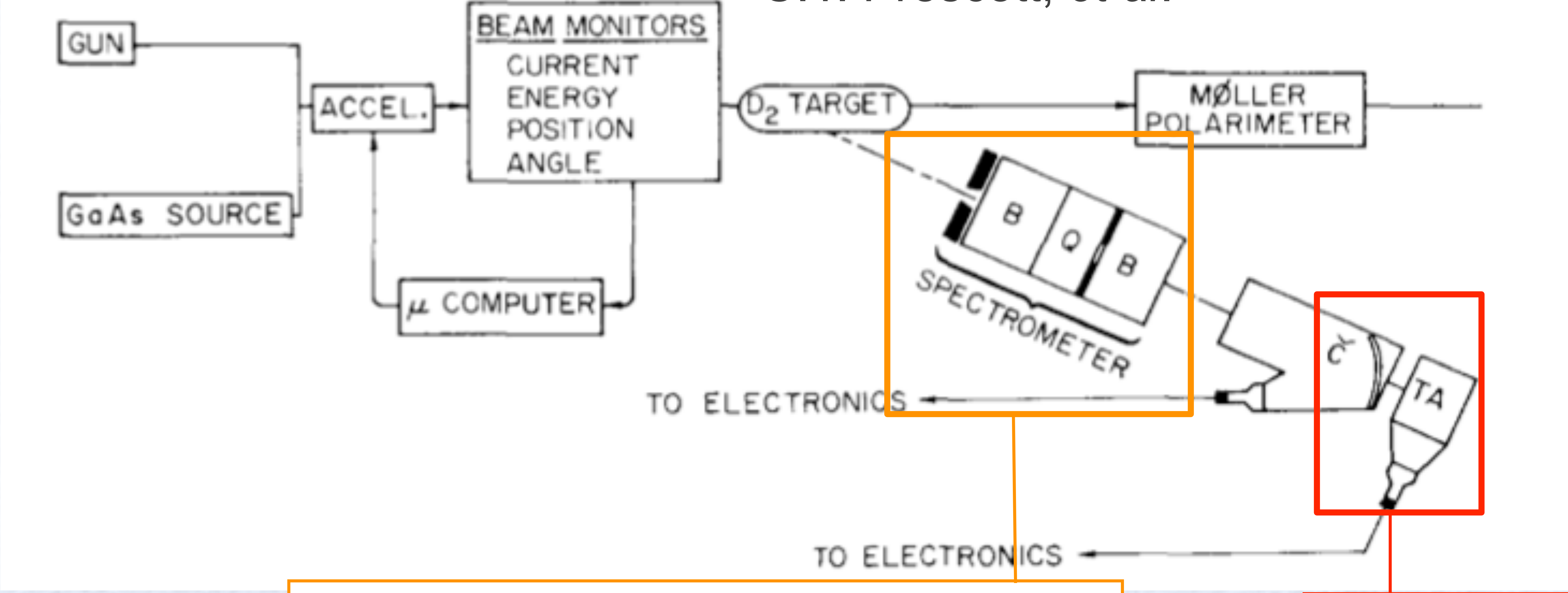

- **Magnetic spectrometer** directs flux to background-free region

- **Flux Integration** measures high rate without deadtime