A unique probe of strange quarks in nucleons and the neutron skin of a heavy nucleus

Lecture 2

PARITY-VIOLATING ELECTRON SCATTERING

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Ecole Internationale Joliot-Curie

Lacanau, France (26 Sep. - 2 Oct. 2010)

OUTLINE OF LECTURE 2

- *Experimental Technique*
- *Strange Quark Content of the Nucleon*
- *The HAPPEX and HAPPEXII experiments*
- *The Neutron Skin of a Heavy Nucleus*
- *The PREX Experiment*
- *Future Program of Parity-violating Electron Scattering*
- *Suggested further reading*

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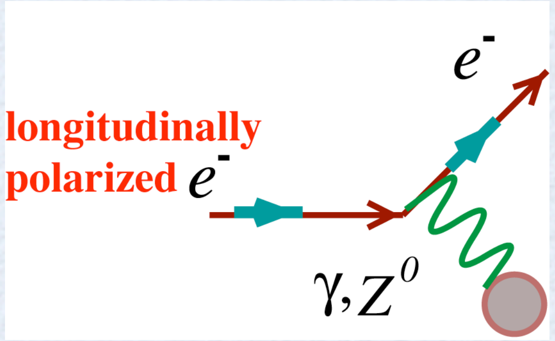
this evening?

REMINDER
Parity-Violating Electron Scattering

Weak Neutral Current (WNC) Interactions at $Q^2 \ll M_Z^2$

Longitudinally Polarized Electron Scattering off Unpolarized Targets

$$\sigma \;\; \alpha \, | A_\gamma + A_{weak} |^2$$



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

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

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

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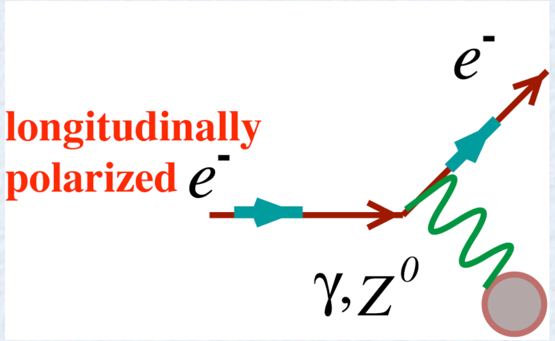

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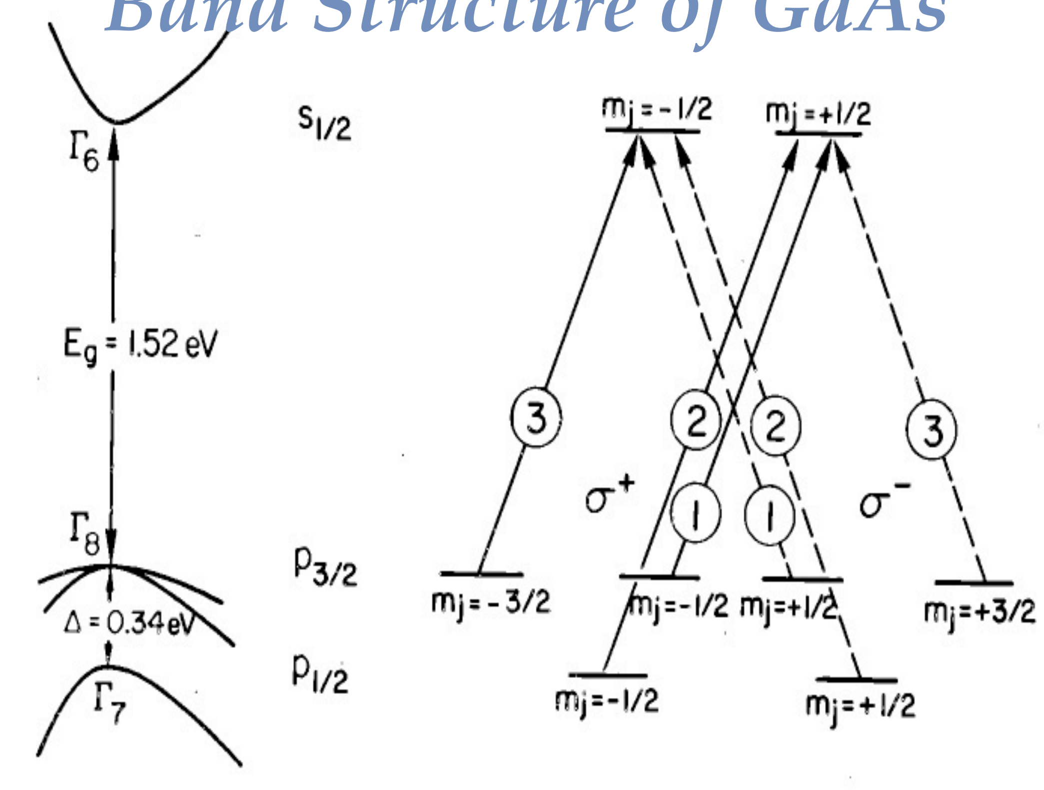
Specific choices of kinematics and target nuclei probes different physics:

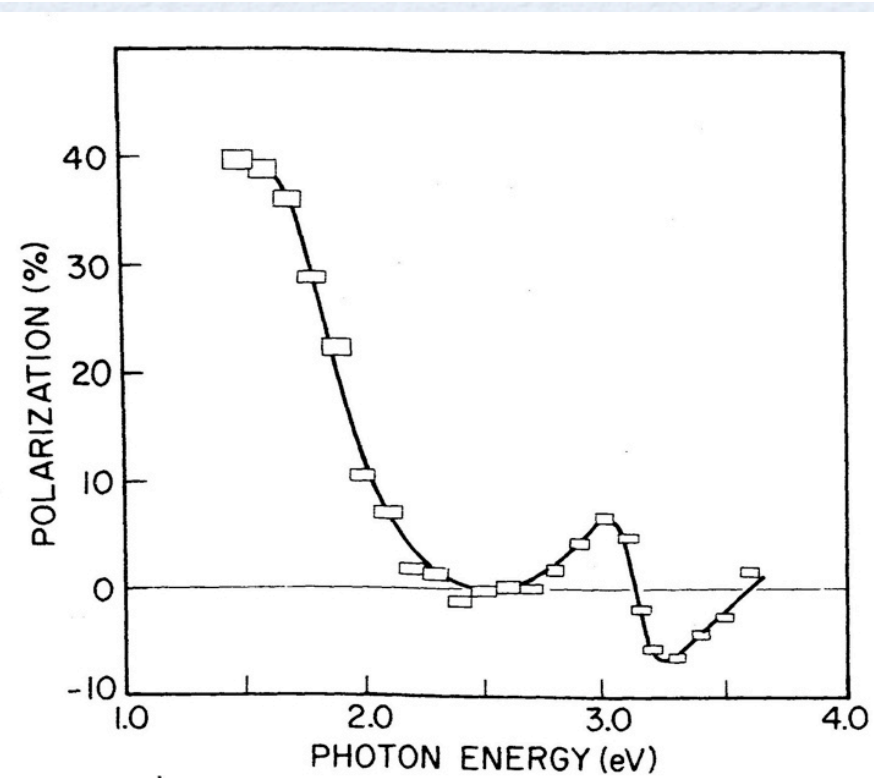
- *In mid 70s, goal was to show $\sin^2\theta_W$ was the same as in neutrino scattering*
- *Since early 90's: target couplings probe novel aspects of hadron structure*
- *Future: precision measurements with carefully chosen kinematics can probe physics at the multi-TeV scale*

EXPERIMENTAL TECHNIQUE

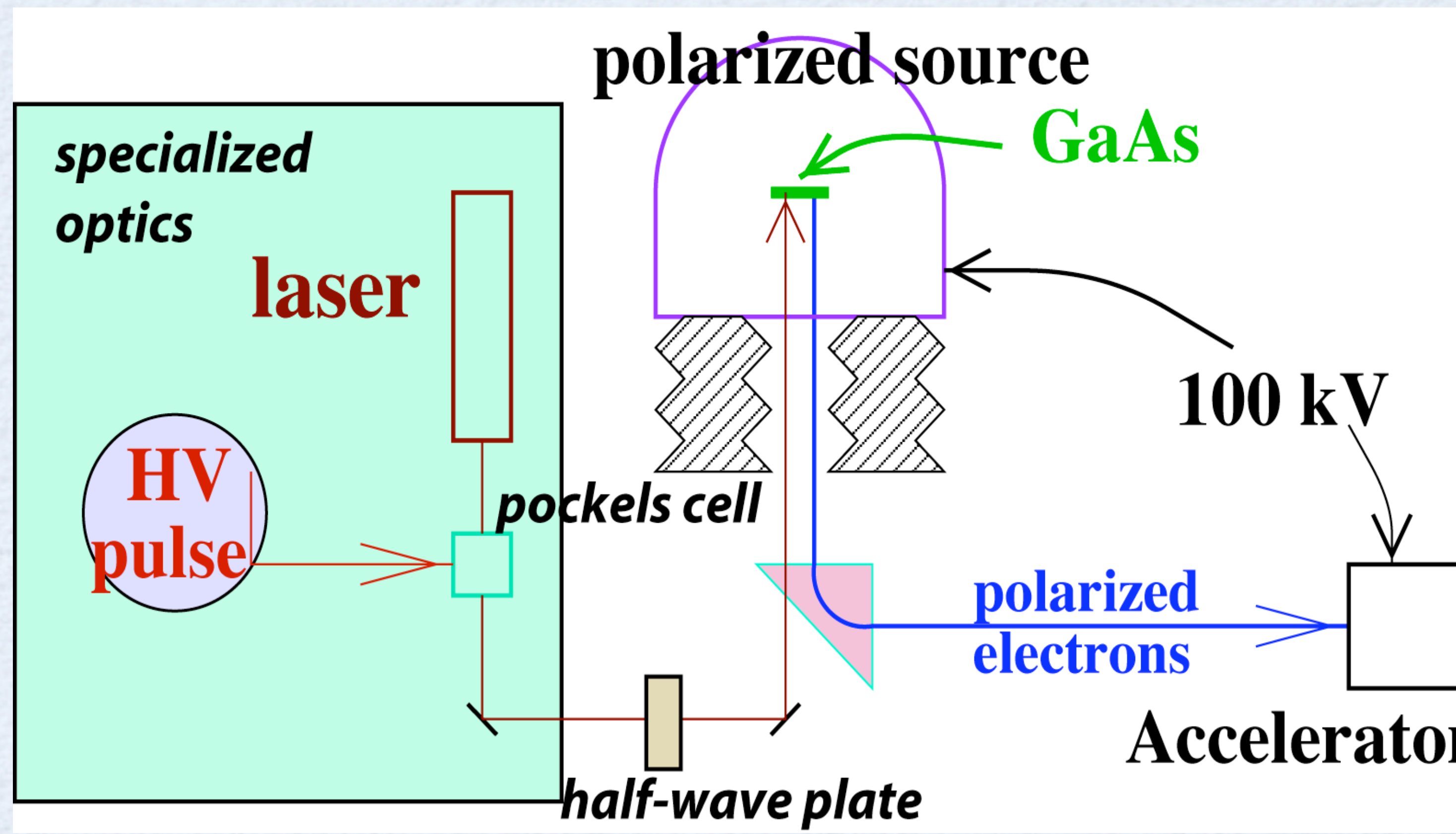
OPTICAL PUMPING
SLAC E122 Technical Innovation #1

Band Structure of GaAs





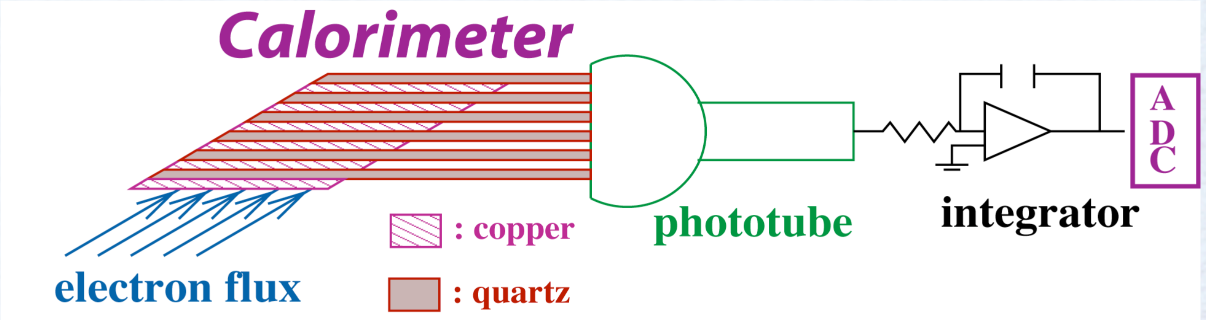
Rapid Beam Helicity Flipping



- Optical pumping of a GaAs wafer
- Rapid helicity reversal: polarization sign flip ~ 100 Hz to minimize the impact of drifts
- Helicity-correlated beam motion: under sign flip, beam stability at the micron level

Flux Integration

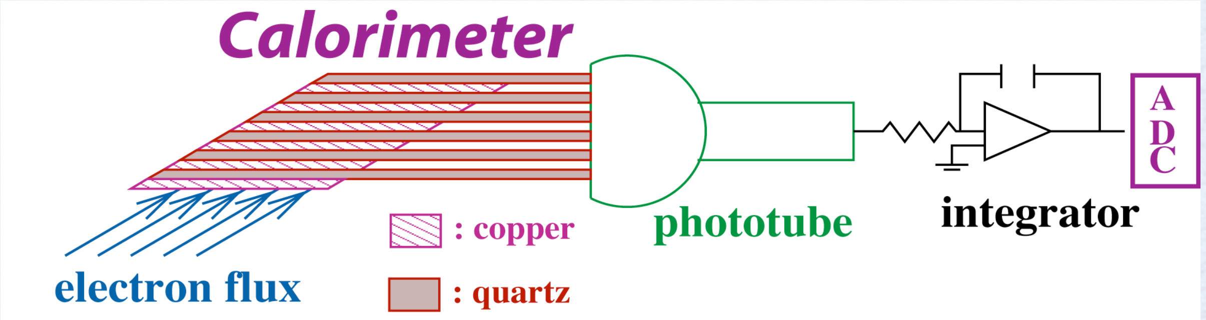
SLAC E122 Technical Innovation #2



"Flux Integration": very high rates

direct scattered flux to background-free region

FLUX INTEGRATION
SLAC E122 Technical Innovation #2



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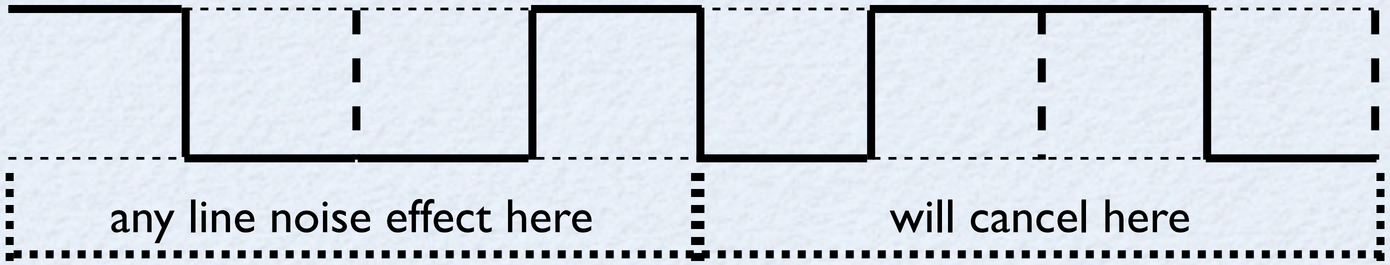
✧ **Beam helicity is chosen pseudo-randomly at multiple of 50 Hz**

- *sequence of "window multiplets"*

Example: at 200 Hz reversal



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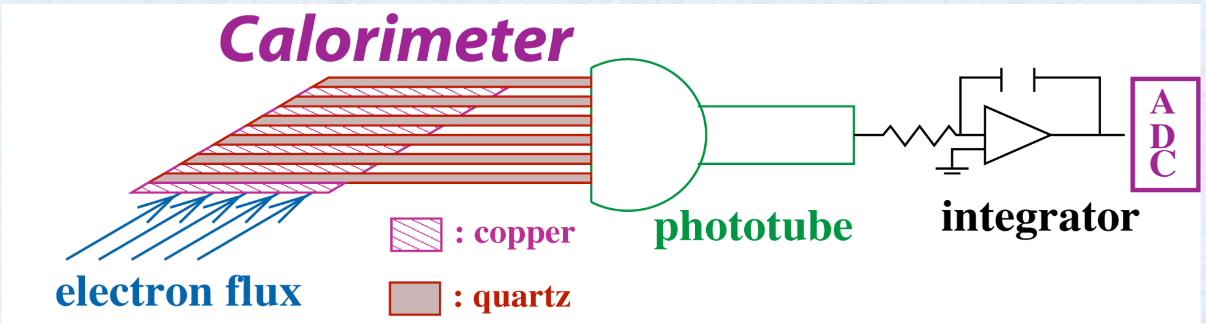

"Flux Integration": very high rates
direct scattered flux to background-free region

Detector D, Current I: F = D/I

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

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

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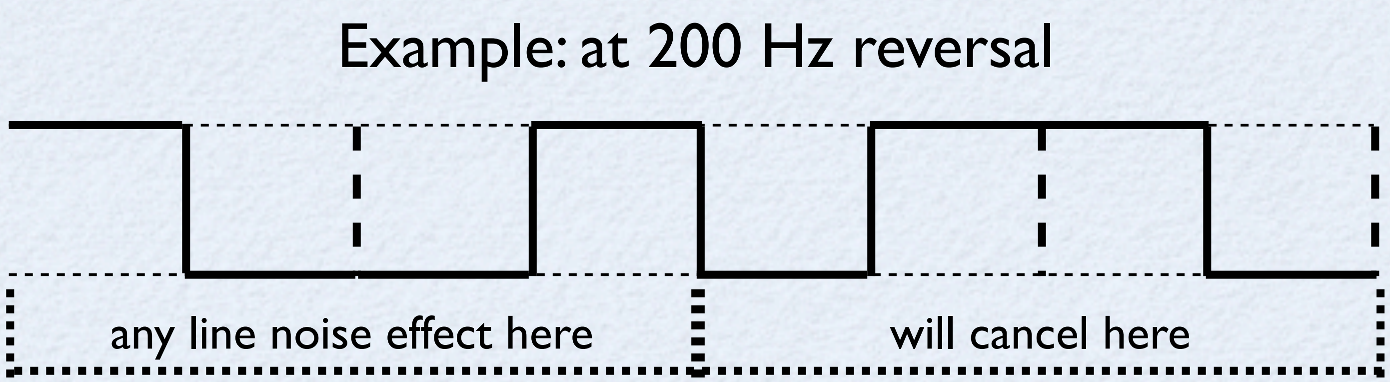

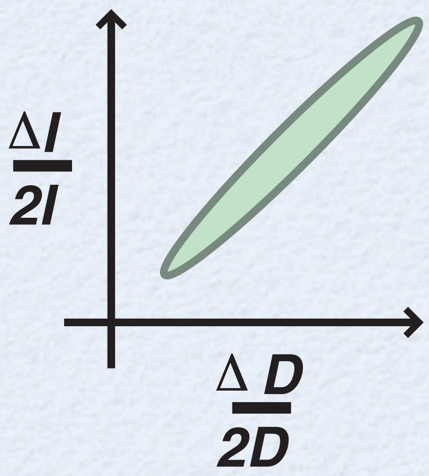

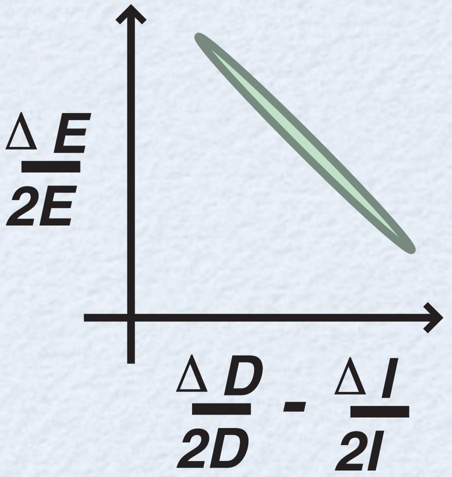

I order: x, y, θ_x, θ_y, E
II order: e.g. spot-size

FLUX INTEGRATION
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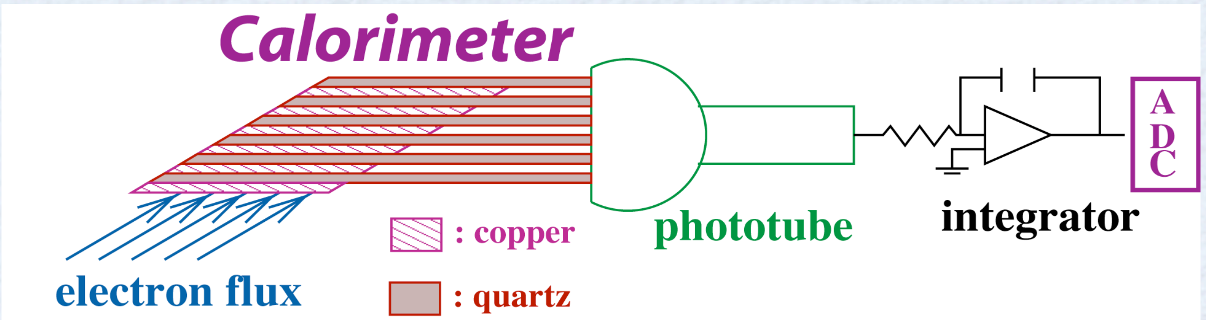

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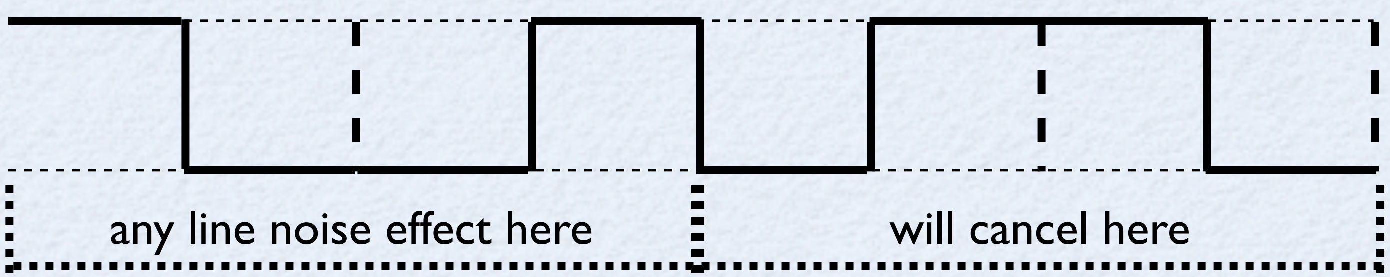
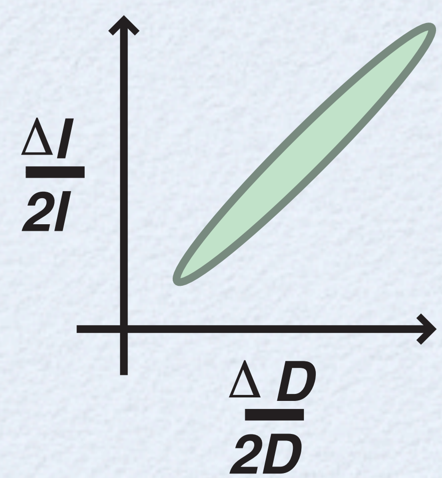
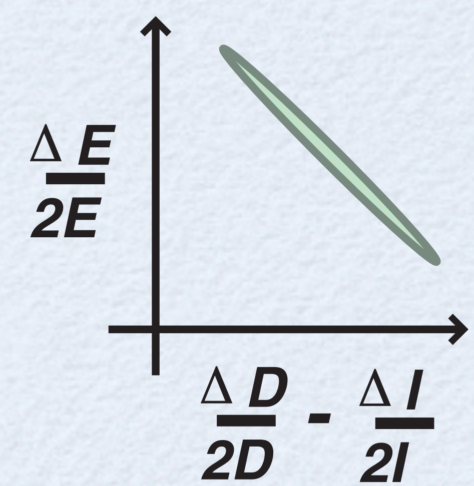






I order: $x, y, \theta_x, \theta_y, E$

II order: e.g. spot-size

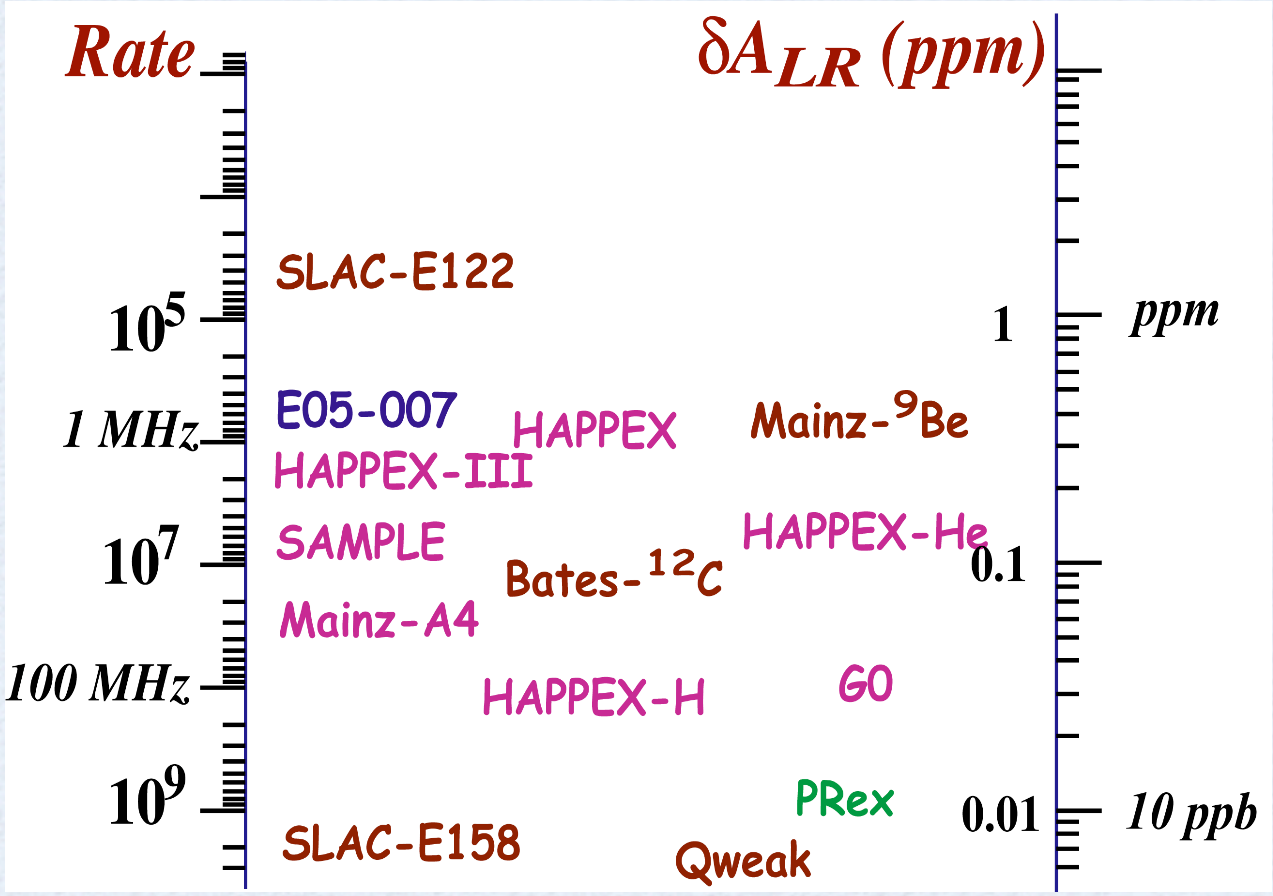
Experimental Challenge & Systematic Control

- ***Must minimize both random and helicity-correlated fluctuations in the integrated window-pair monitor response of electron beam trajectory, energy and spot-size.***

WORLD PROGRAM

Four electron scattering laboratories: SLAC, MIT-Bates, Mainz & JLab

Parity-violating electron scattering has become a precision tool



MOLLER

- *Steady progress in technology*
- *part per billion systematic control*
- *1% normalization control*
- *Intensive R&D on:*
  - -Photocathodes
  - -Polarimetry
  - -High Luminosity cryotargets
  - -Nanometer beam stability
  - -Precision Beam Diagnostics
  - -Counting Electronics
  - -Radiation hard detectors

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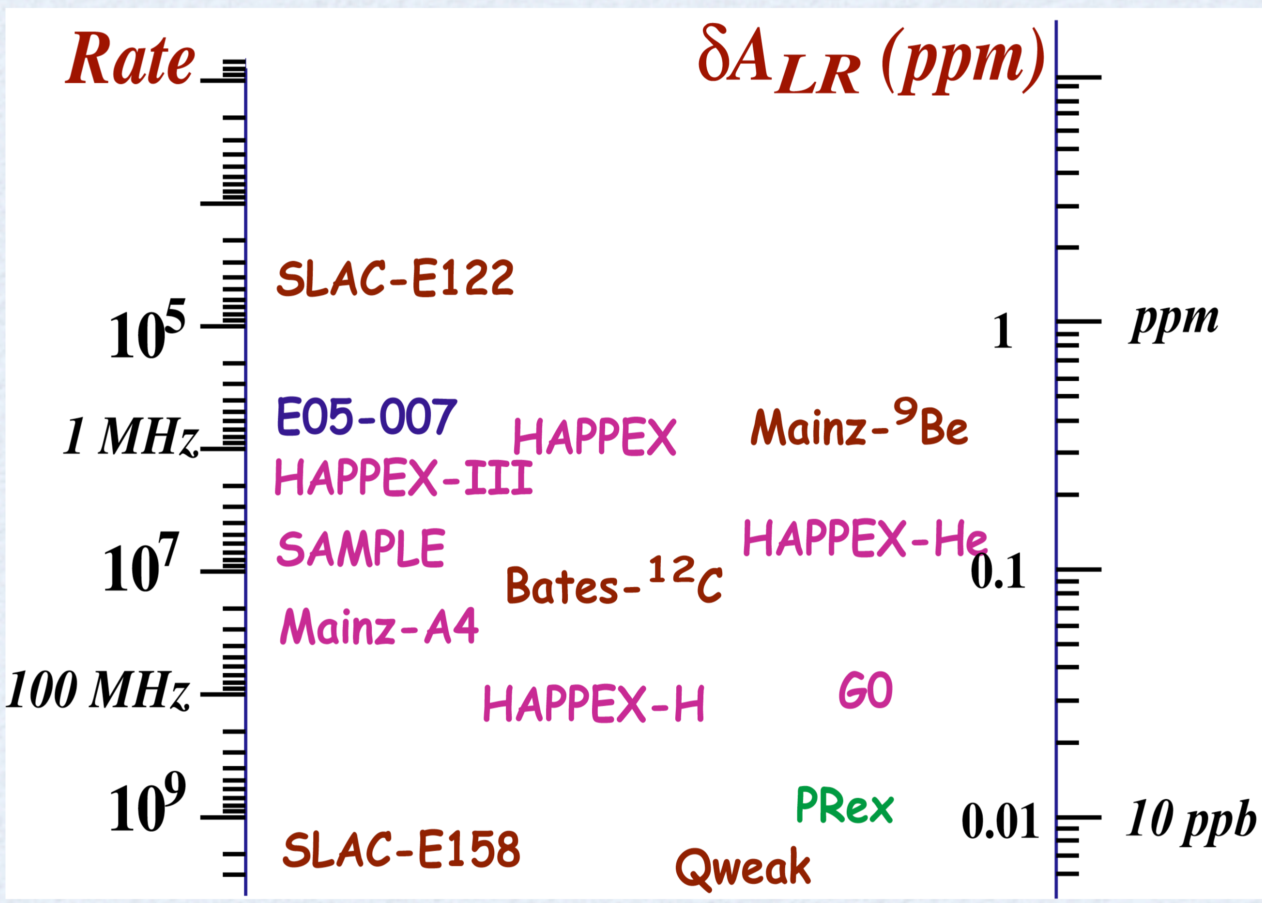

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Jefferson Lab has a bright future with this program

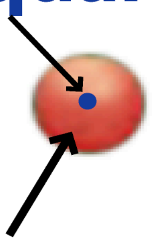
Strange Quarks in Nucleons

Nucleon Flavour Structure

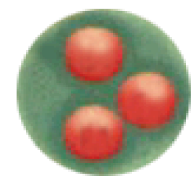
Quantum Chromodynamics is intractable at low Q^2

($\geq$ 0.2 fm)

bare quark



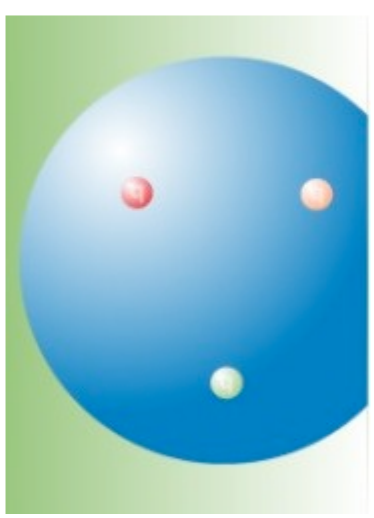
the sea

baryon 

 *meson*

valence quark: bare quark "dressed" with quark-antiquark pairs and gluons

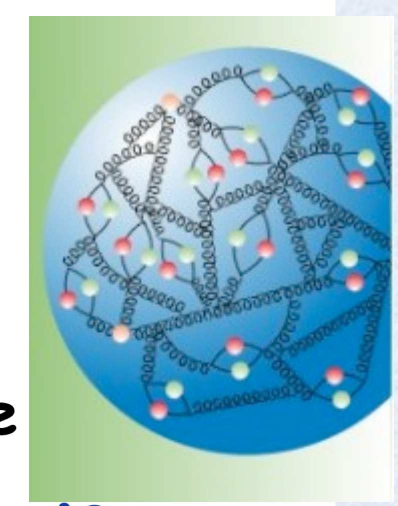
Why don't sea quarks destroy Quark Model predictions?



three flavors dominate: **u, d, s**

Strangeness Flavor:

- relatively light
- no valence contribution
- flavor separation now possible

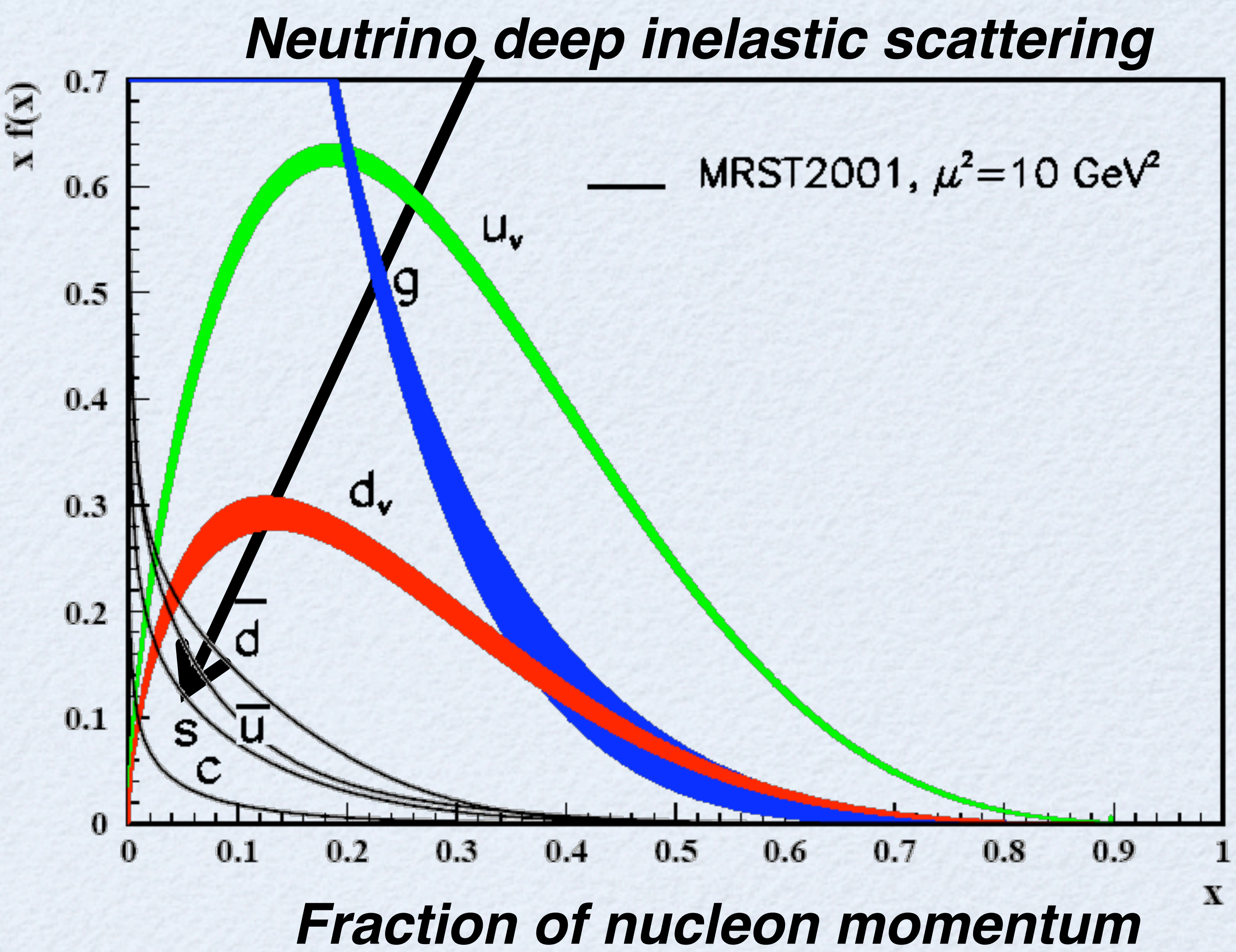


Are proton properties modified?

Nucleon Strangeness

Strange quarks are relatively light;
What can we say about its role?

Lepton-nucleon deep inelastic scattering



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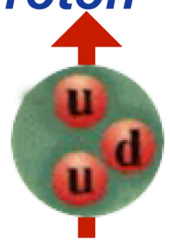
spin dependent deep inelastic scattering

$$S = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \Delta L$$

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

Proton Spin



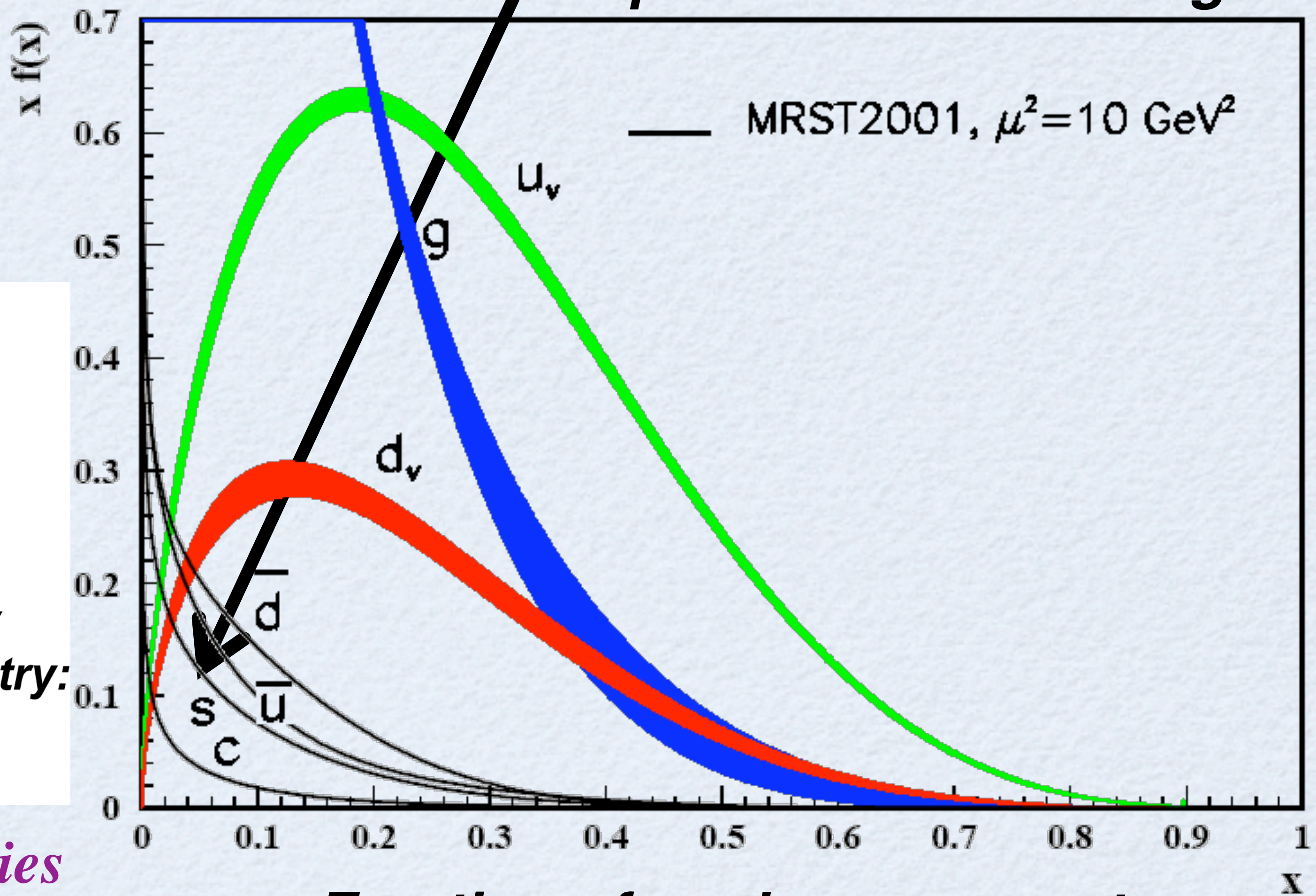
Experiments:
$\Delta\Sigma \sim 0.25$

+ *Hyperon decay*
+ *$SU(3)_f$ Symmetry:*

$\Delta s \sim -0.1$

$SU(3)_f$ symmetry-breaking introduces uncertainties

Neutrino deep inelastic scattering



Fraction of nucleon momentum

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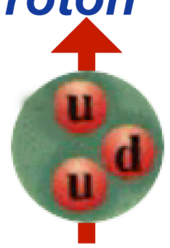

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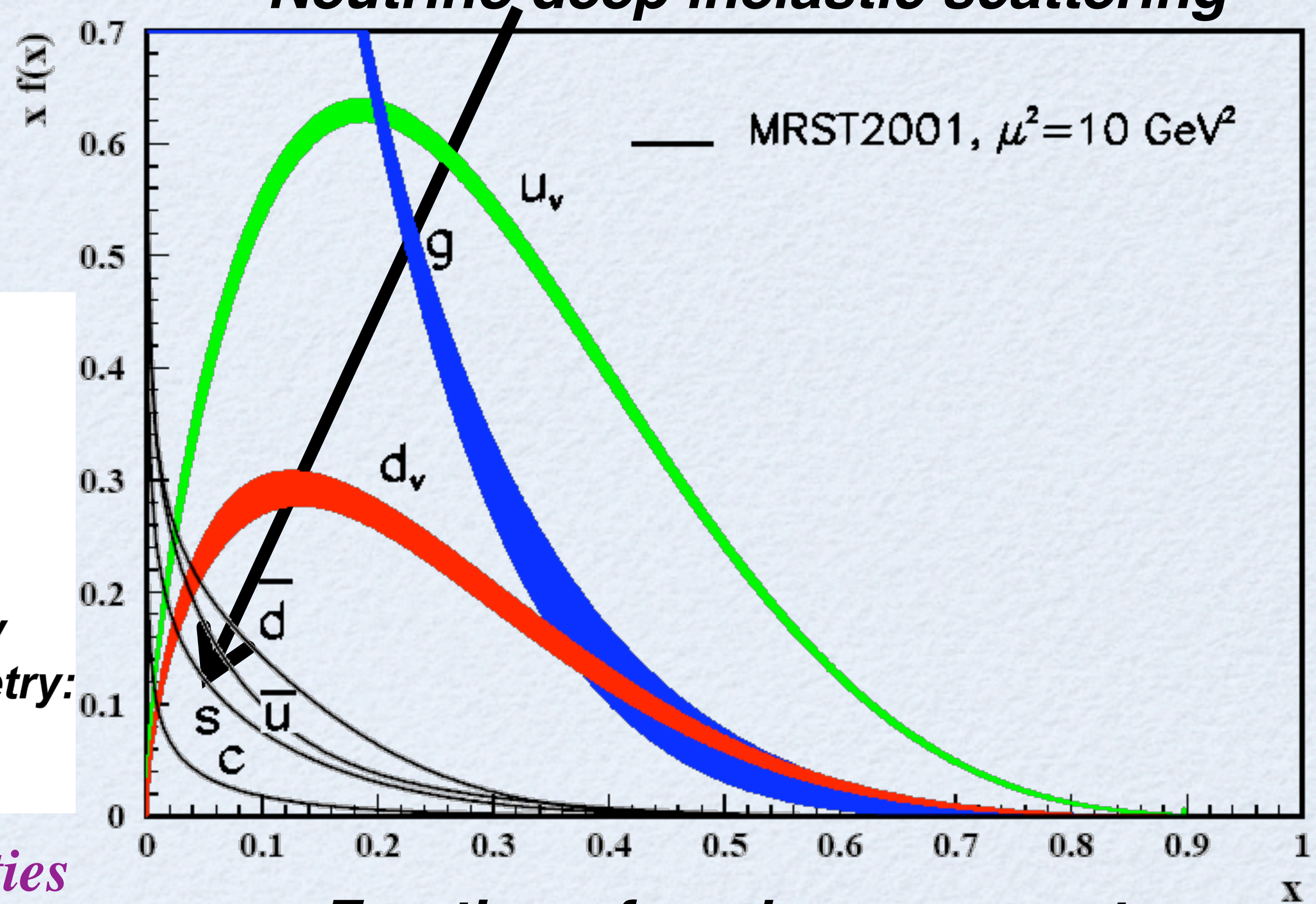

Fraction of nucleon momentum

Semi-inclusive DIS
(Needs fragmentation functions)

$$"\Delta s" = \int_{0.023}^{0.30} \Delta s(x)\,dx = +0.03 \pm 0.03(\text{stat}) \pm 0.01(\text{syst})$$

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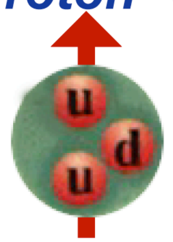

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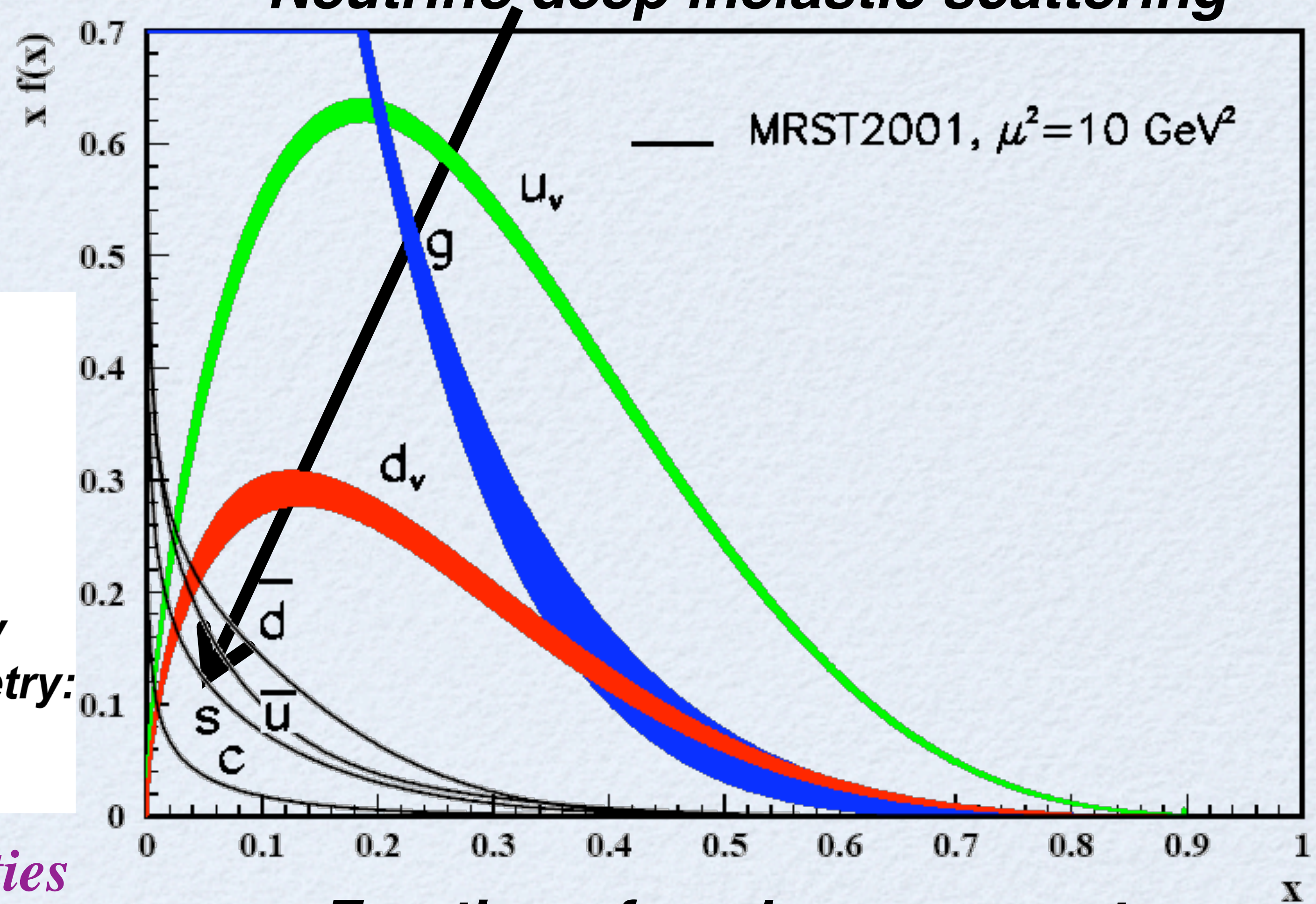

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πN scattering:
Strange mass: 0-20%

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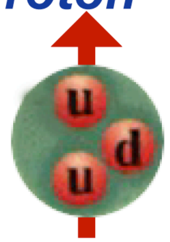

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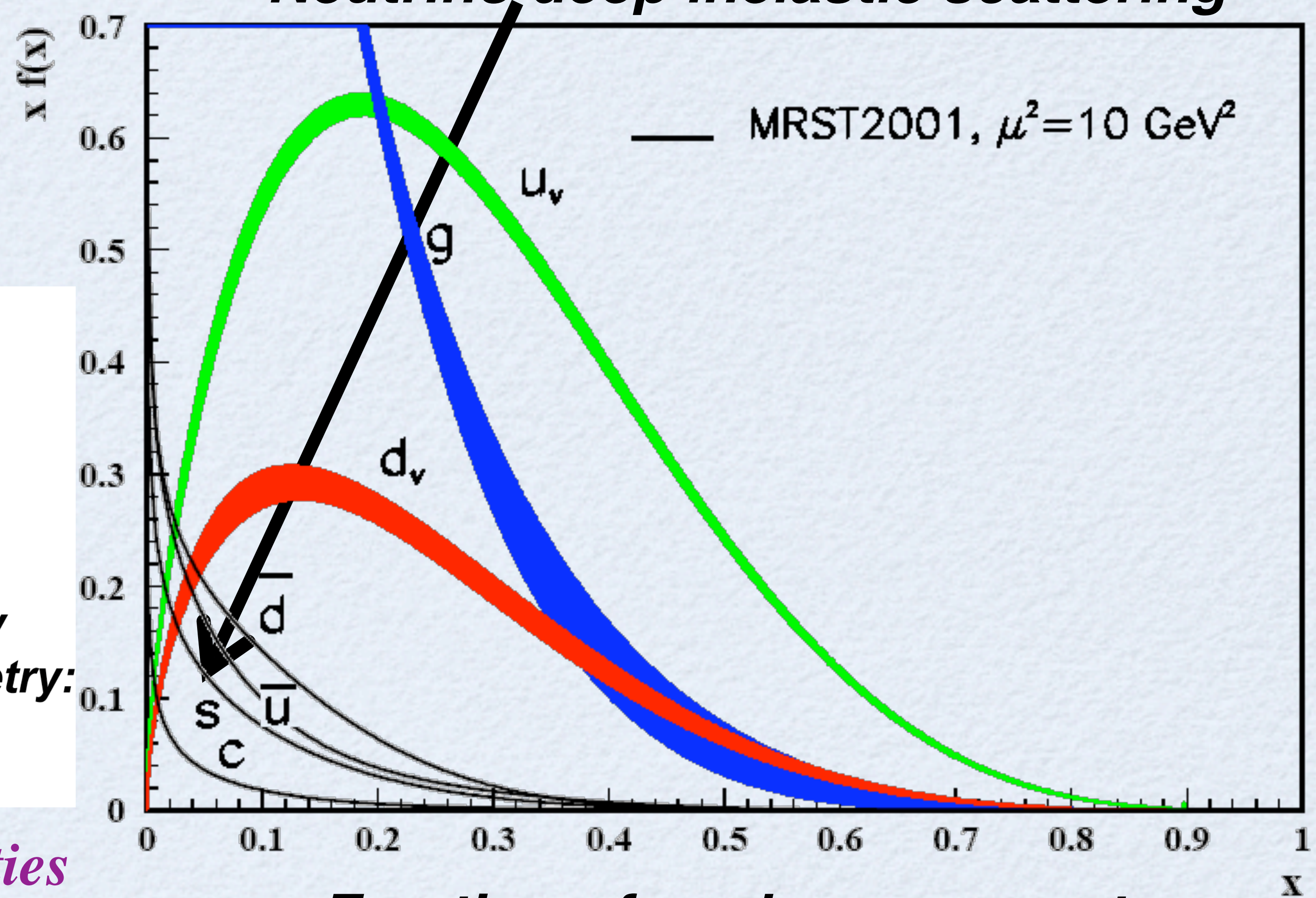

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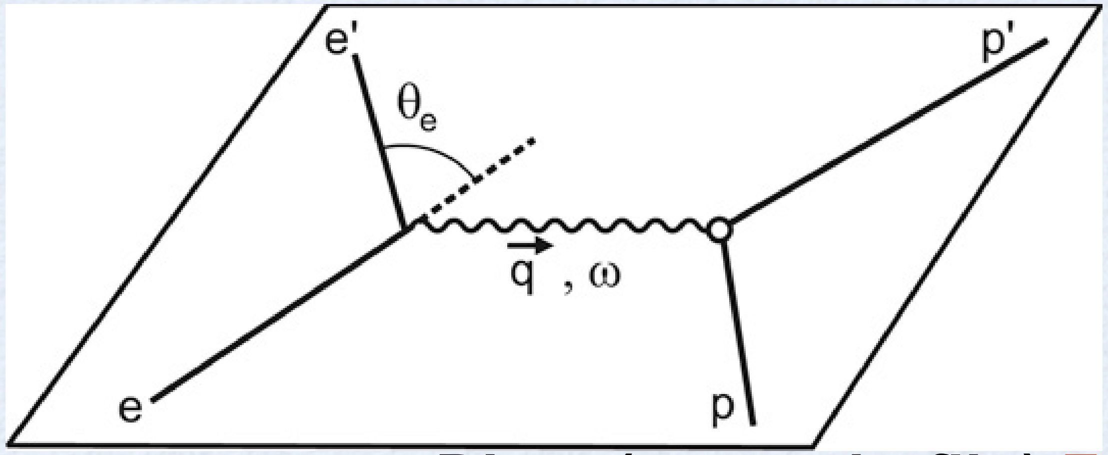
What about the nucleon's charge and magnetization distributions?

Elastic Electron-Proton Scattering



Dirac (non-spin-flip) F_1 and Pauli (spin-flip) F_2 Form Factors

$$\langle N(P')|J^{\mu}_{\mathrm{EM}}(0)|N(P)\rangle = \bar{u}(P')\left[\gamma^{\mu} F_1^N(Q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{2M}F_2^N(Q^2)\right]u(P)$$

Cross-section for Born scattering $\quad Q^2 = -q^2 = -t \qquad Q^2 = 4EE'\sin^2\frac{\theta_e}{2}$

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathtt{Mott}}\left[\left(F_1^2 + \tau F_2^2\right) + 2\tau\left(F_1 + F_2\right)^2\tan^2\frac{\theta}{2}\right] \qquad \tau = \frac{Q^2}{4M^2}$$

Alternatively, Sachs Form Factors G_E and G_M can be used

$$G_E = F_1 - \tau F_2$$
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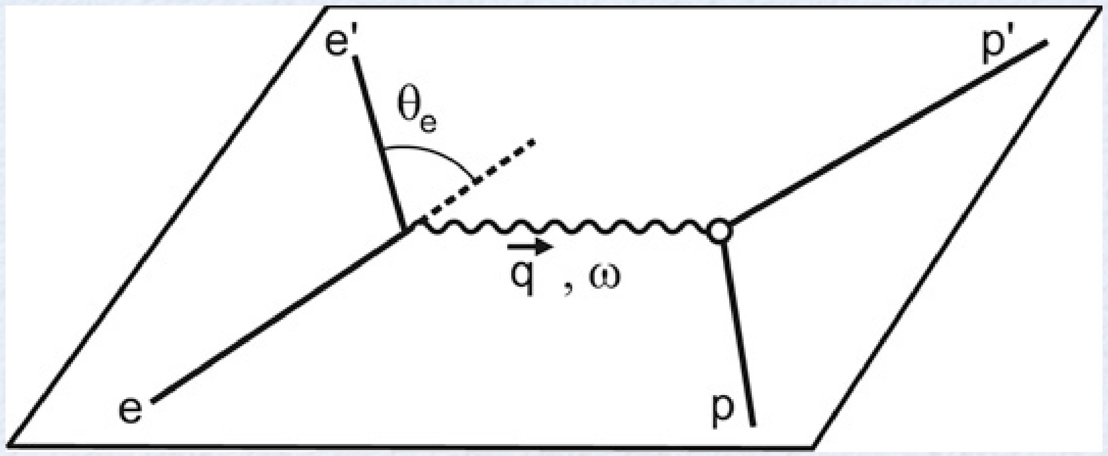
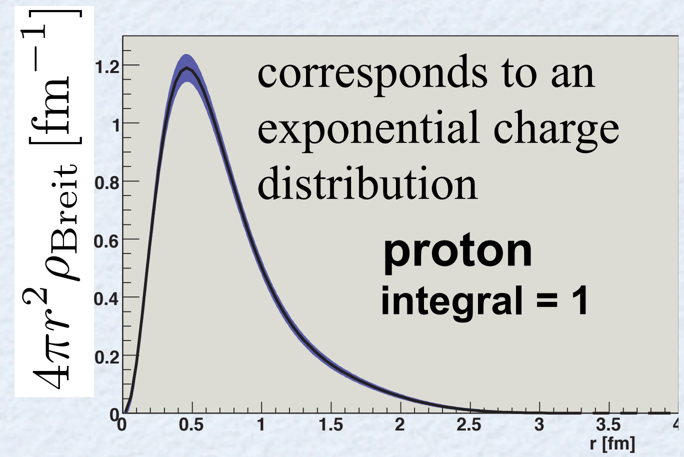
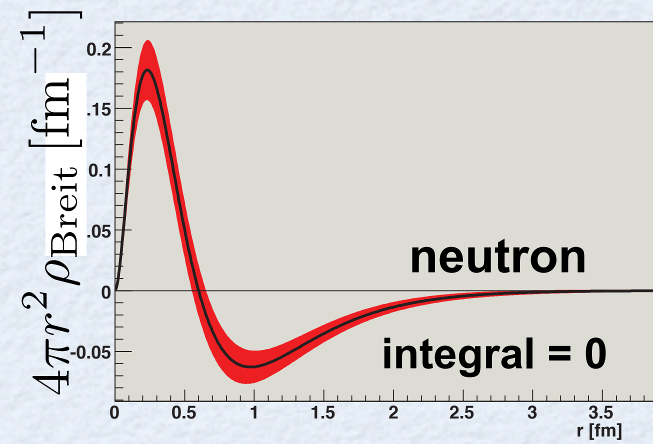
Elastic Electron-Proton Scattering







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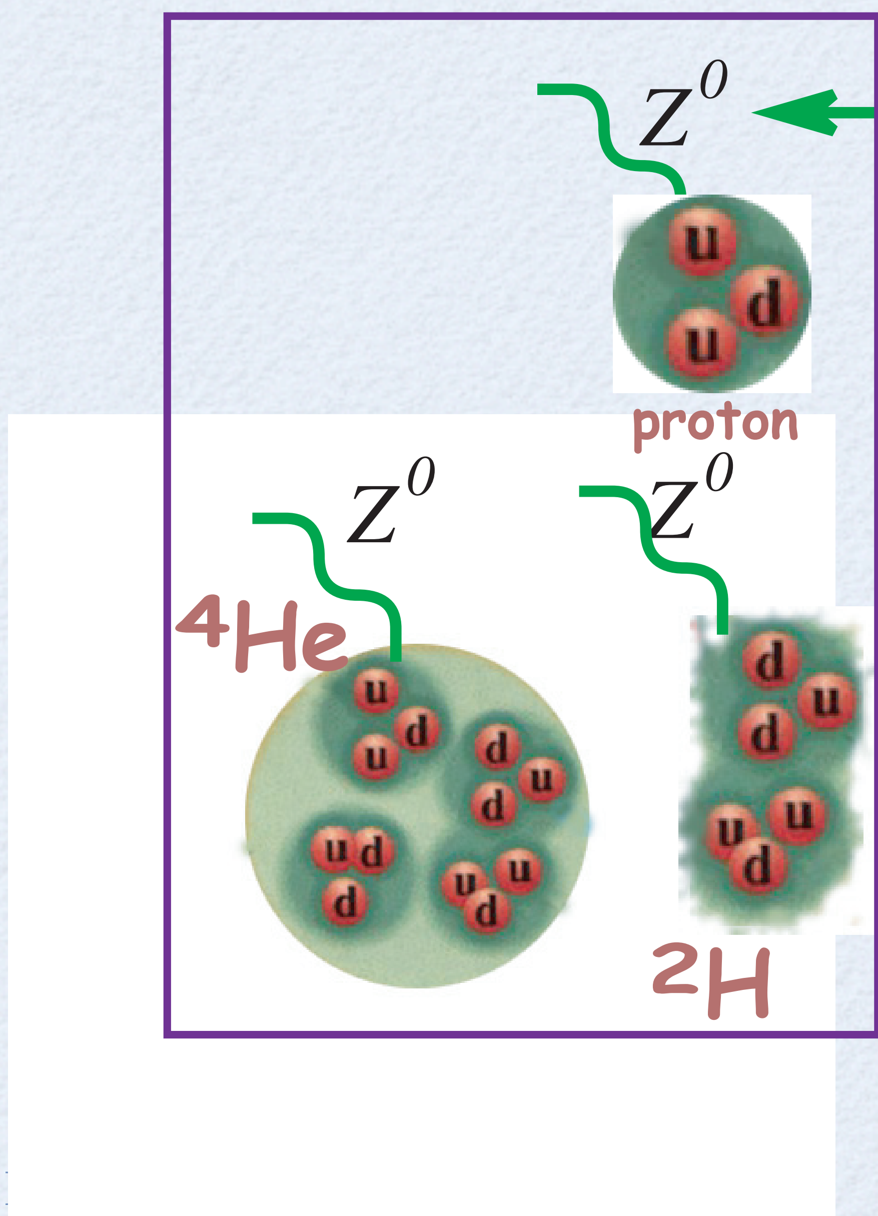
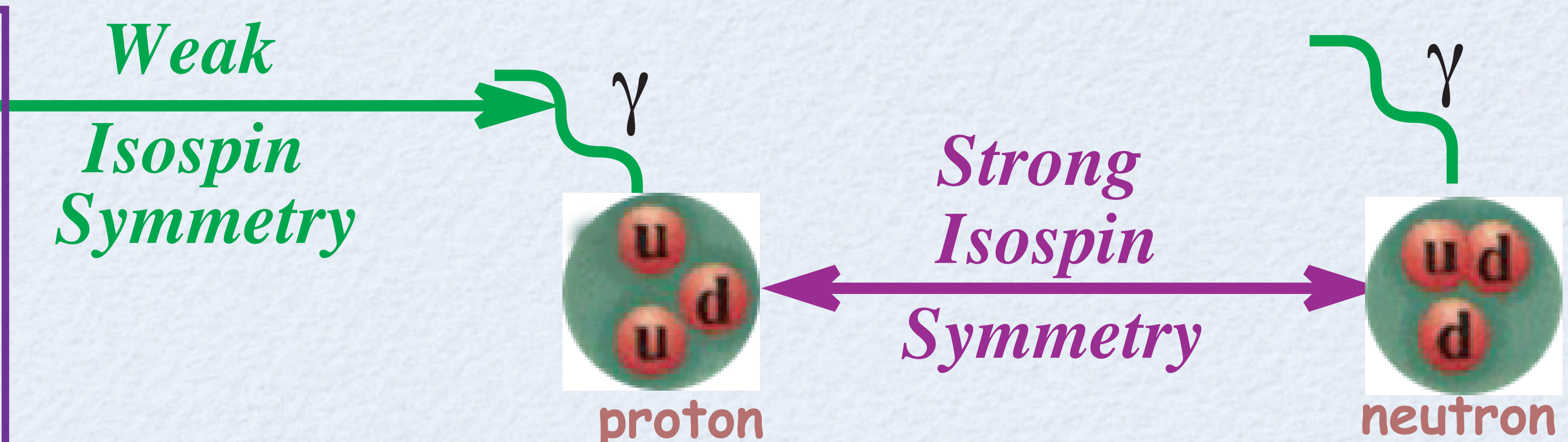
Strange Form Factors

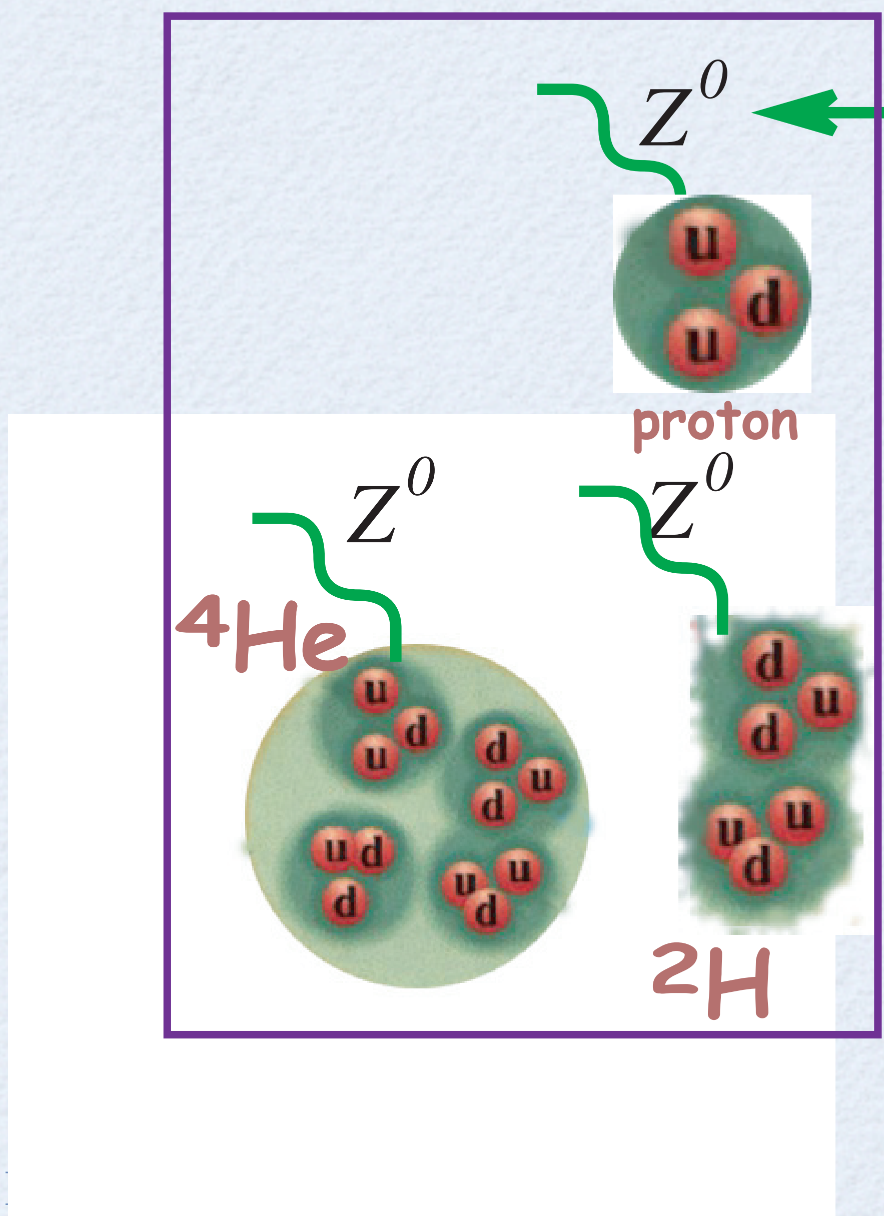


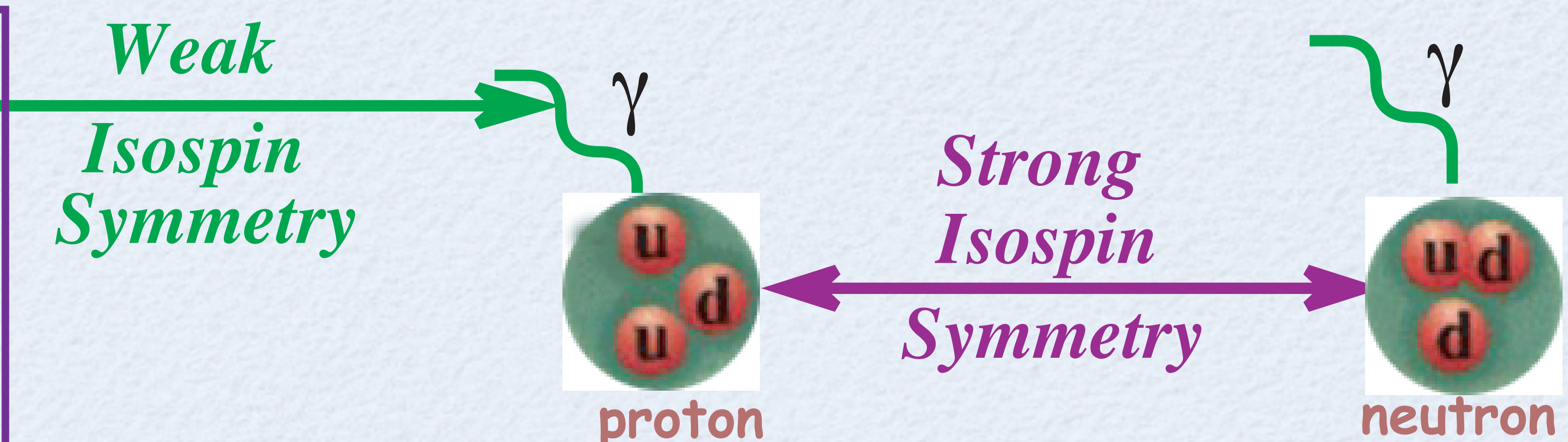


$$G_E^p = \frac{2}{3}G_E^{u,p} - \frac{1}{3}G_E^{d,p} - \frac{1}{3}G_E^s$$

$$G_E^n = \frac{2}{3}G_E^{u,n} - \frac{1}{3}G_E^{d,n} - \frac{1}{3}G_E^s$$

Strange Form Factors





Charge Symmetry

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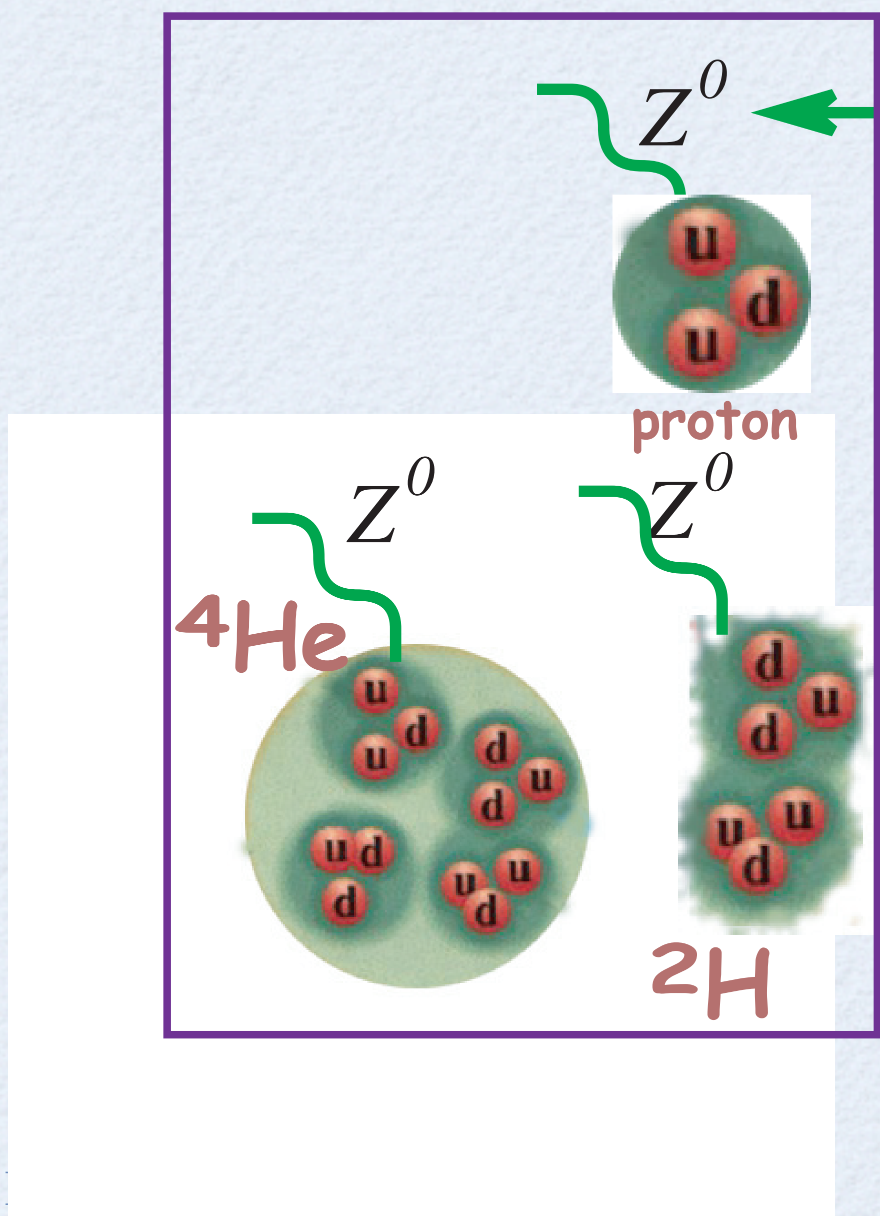
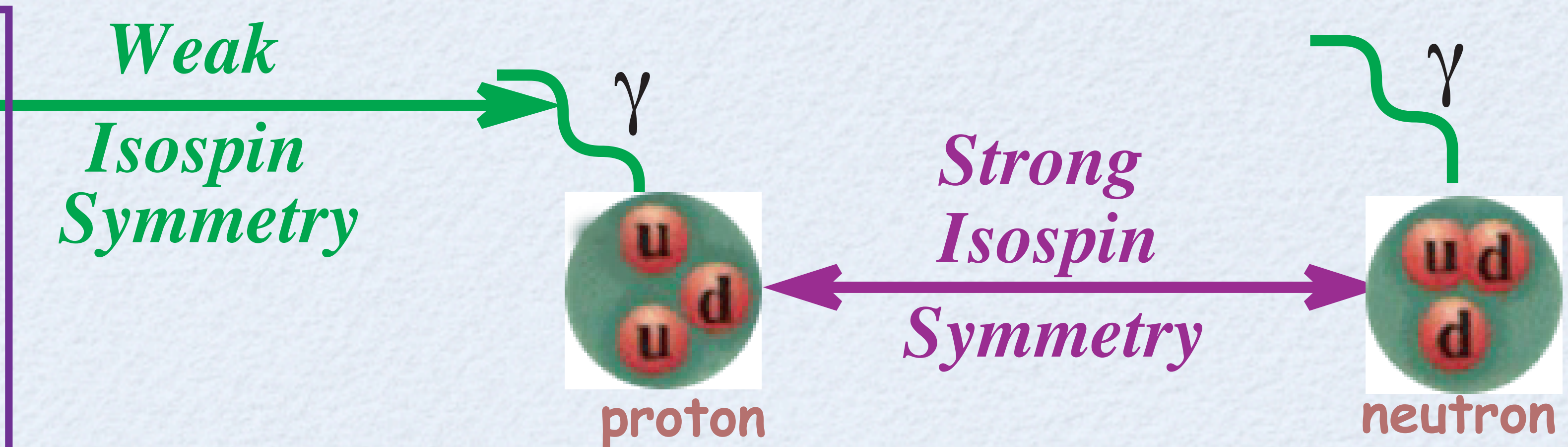
STRANGE FORM FACTORS





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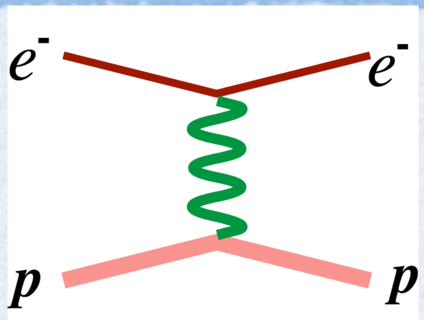
$$G_E^n = \frac{2}{3}G_E^d - \frac{1}{3}G_E^u - \frac{1}{3}G_E^s$$

PARITY VIOLATION



A_{PV} for elastic e-p scattering:

$$A = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right]\frac{A_E + A_M + A_A}{\sigma_p}$$

$$A_E = \epsilon\, G_E^p G_E^Z \qquad A_M = \tau\, G_M^p G_M^Z \qquad A_A = (1-4\sin^2\theta_W)\epsilon' G_M^p \tilde{G}_A$$

Forward angle Backward angle

Spin=0,T=0 (^{4}He): **G^s_E only!**

nuclear corrections require forward angle, low Q^2 only

Deuterium QE (back-angle):

Enhanced G_A

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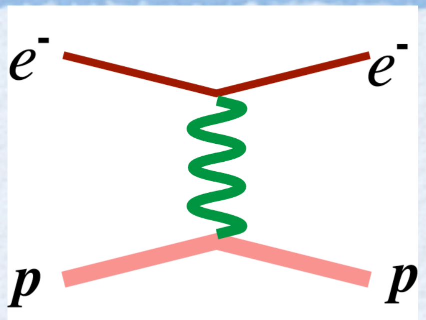

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Deuterium QE (back-angle):

Enhanced G_A

$$G_E^{p,Z} = \left(1 - \frac{8}{3}\sin^2\theta_W\right) G_E^u - \left(1 - \frac{4}{3}\sin^2\theta_W\right) G_E^d - \left(1 - \frac{4}{3}\sin^2\theta_W\right) G_E^s$$

THEORETICAL "BIAS"

Experimental determination of non-zero G^s is unambiguous

R.L. Jaffe, Phys. Lett. B **229** (1989) 275

Various theoretical estimates:

- *Vector Meson Dominance Models*
- *Quark models*
- *Dispersion Theory*
- *Lattice Gauge theory*
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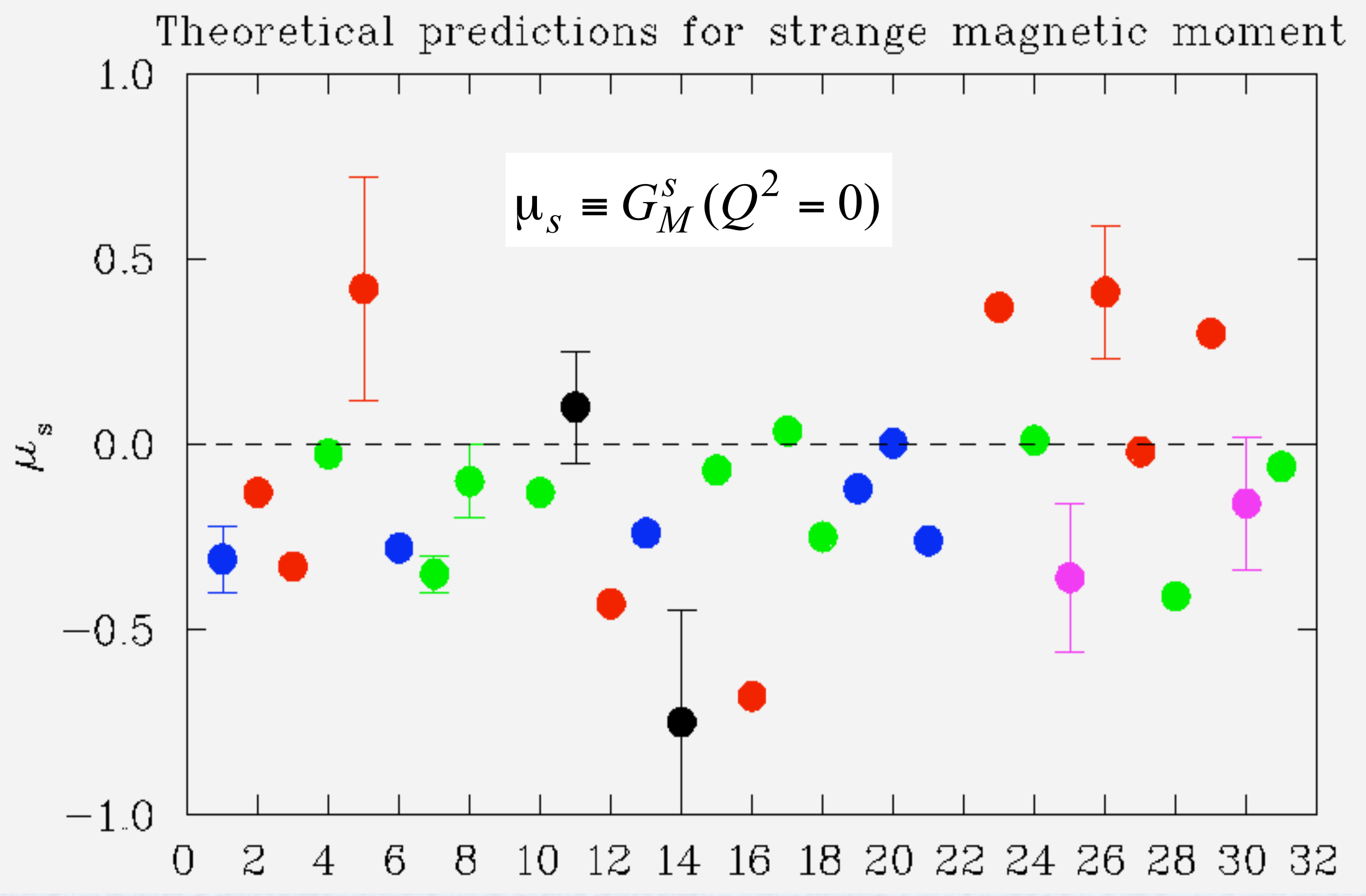

1. **Skyrme Model** - N.W. Park and H. Weigel, Nucl. Phys. A **451**, 453 (1992).
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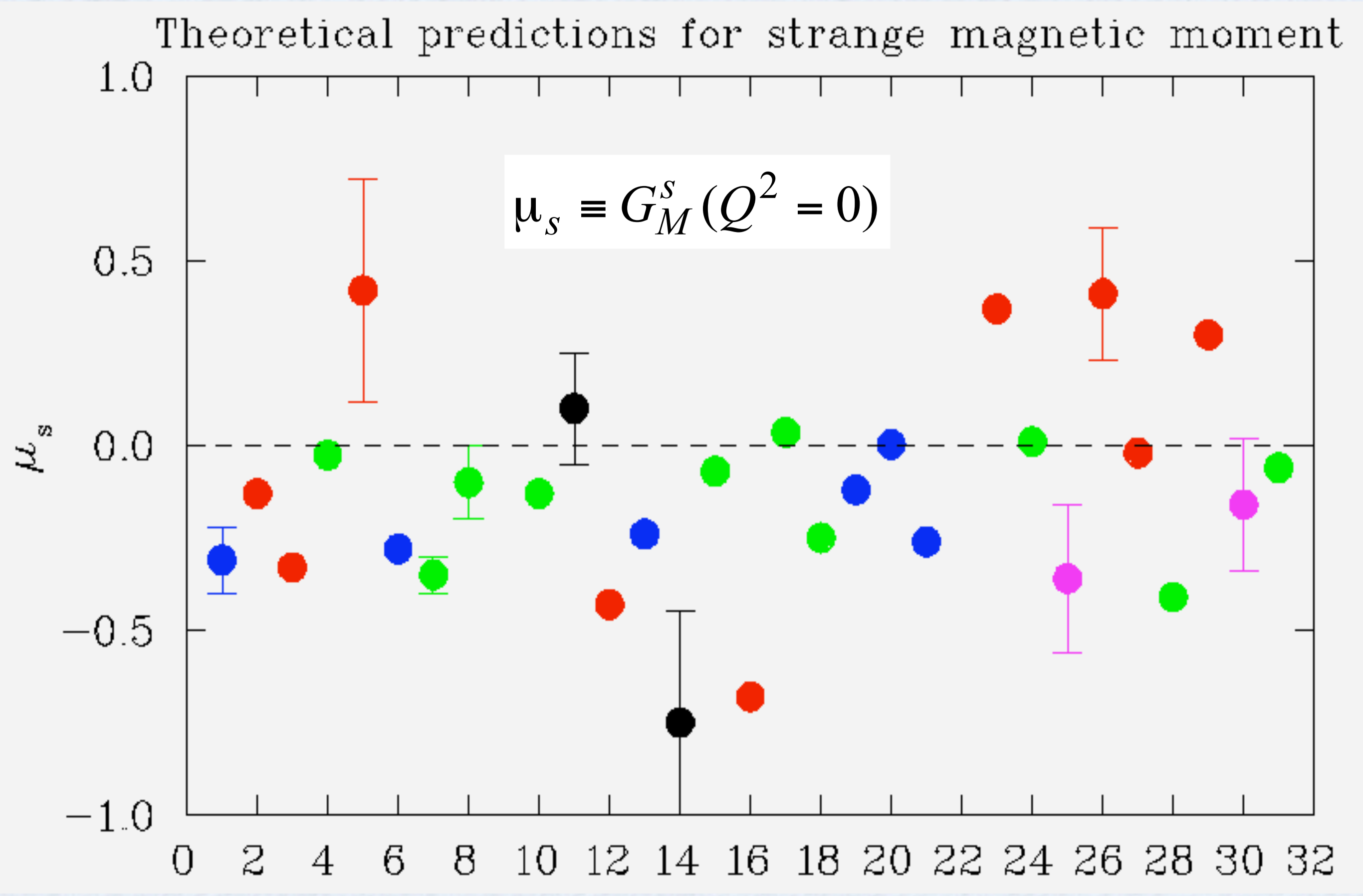

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Little theoretical guidance on Q^2 dependence

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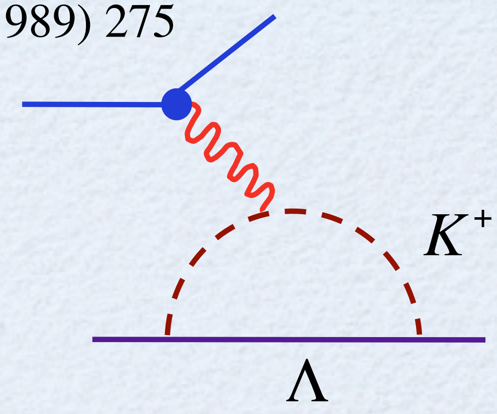

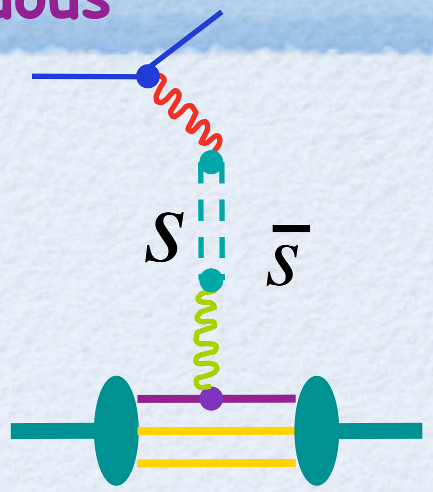

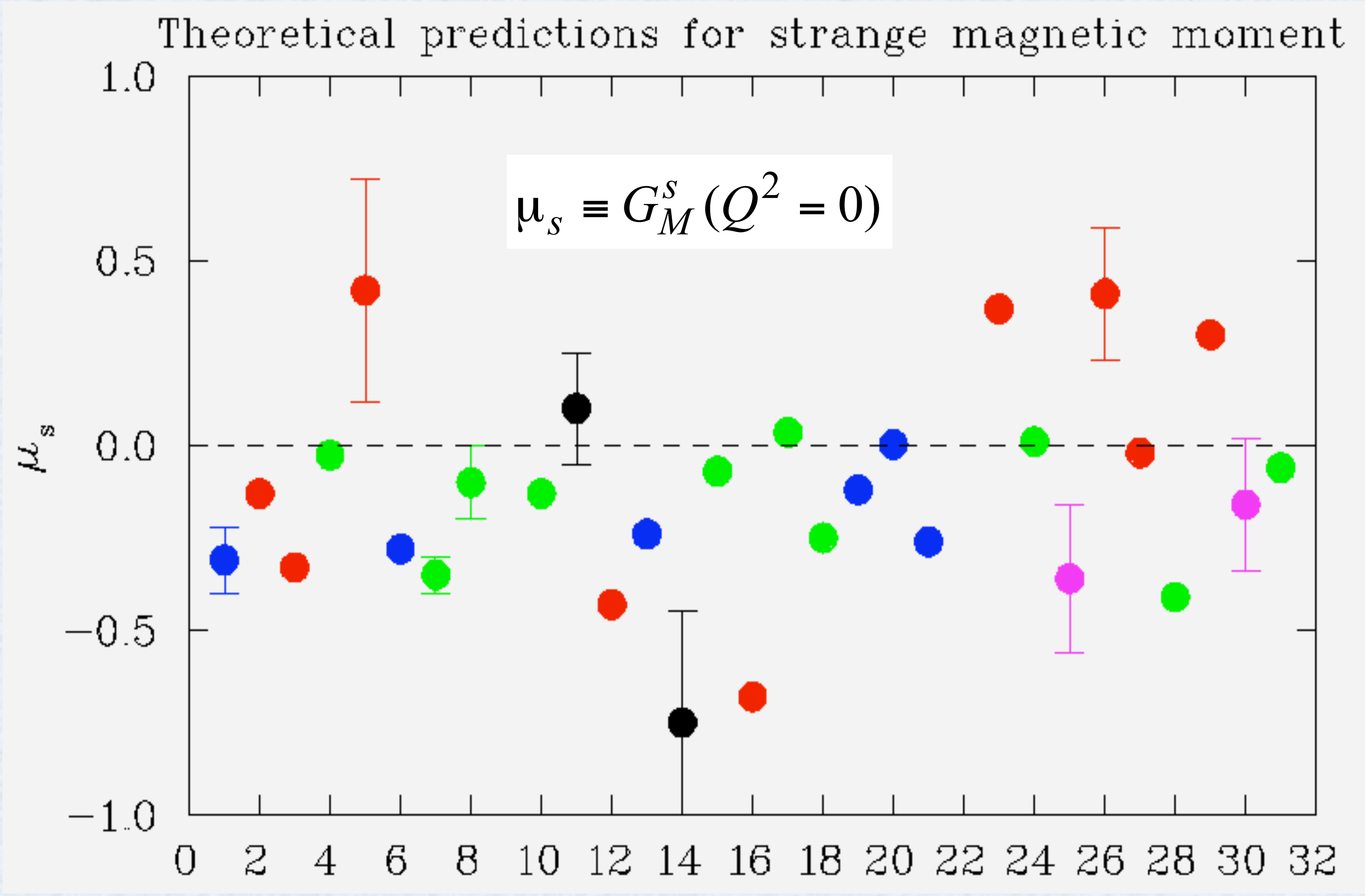

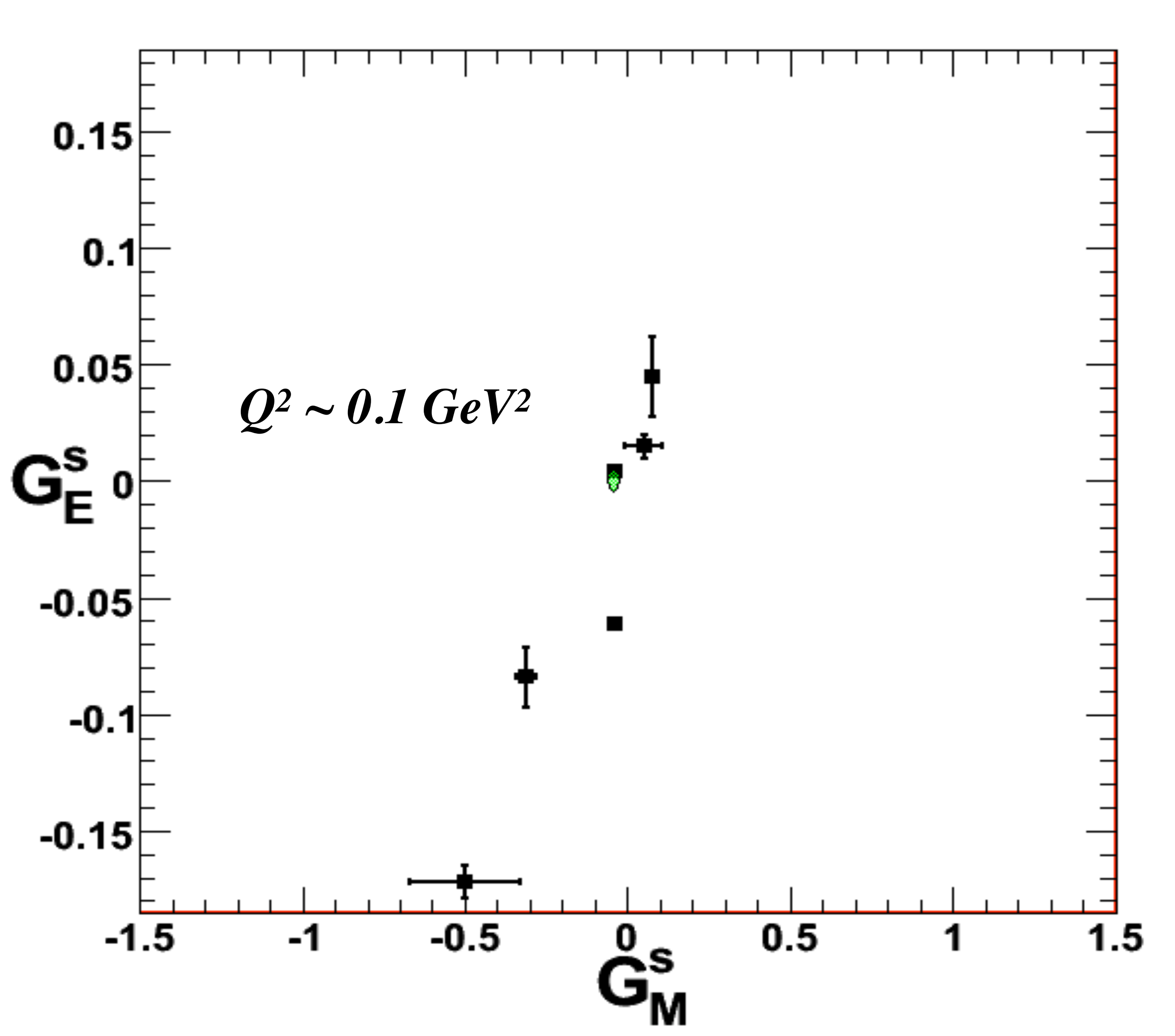

Little theoretical guidance on Q^2 dependence

WORLD PROGRAM

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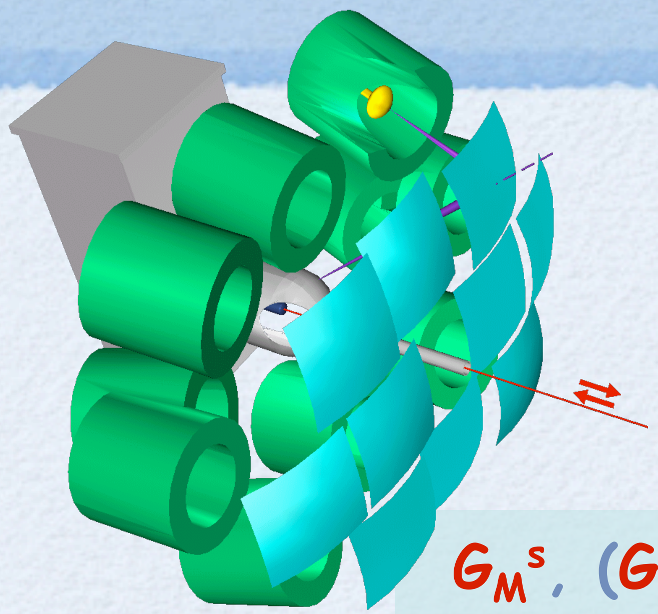
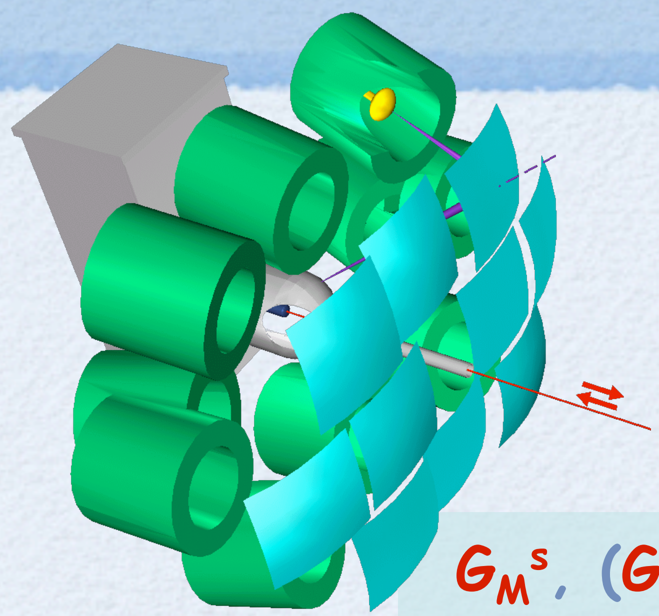


SAMPLE

open geometry, integrating

G_M^s, (G_A) at $Q^2 = 0.1$ GeV^2

World Program



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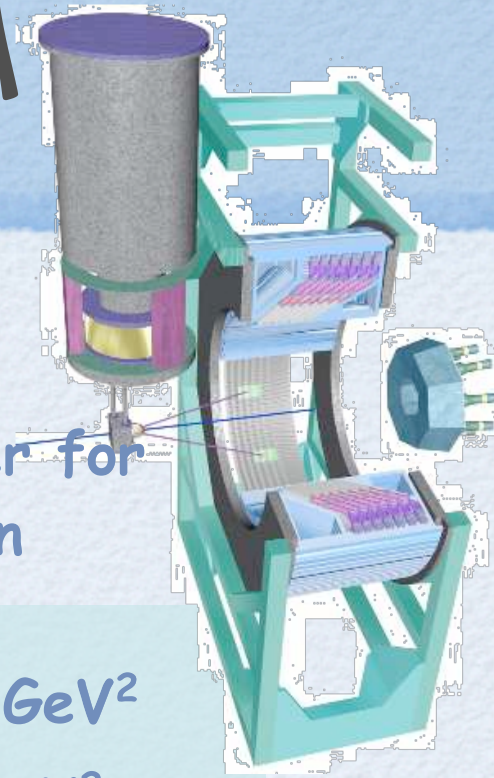
A4



Open geometry

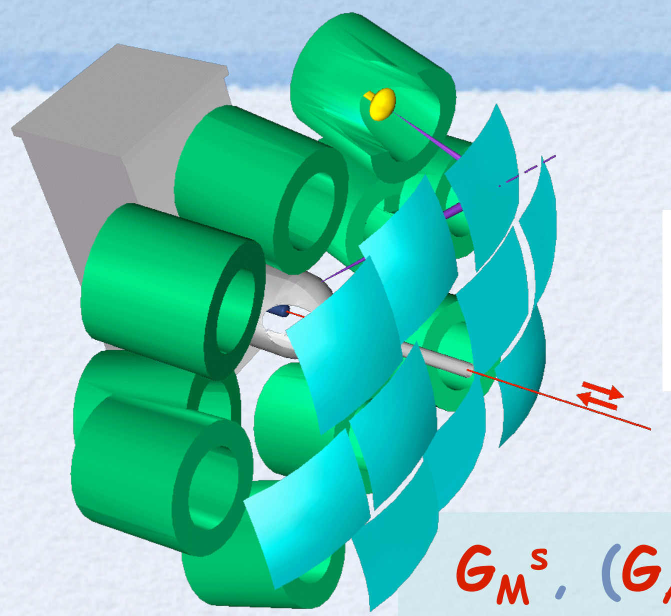
Fast counting calorimeter for background rejection

$G_E^s + 0.23\, G_M^s$ at Q^2 = 0.23 GeV^2

$G_E^s + 0.10\, G_M^s$ at Q^2 = 0.1 GeV^2

G_M^s, G_A^e at Q^2 = 0.23 GeV^2

WORLD PROGRAM



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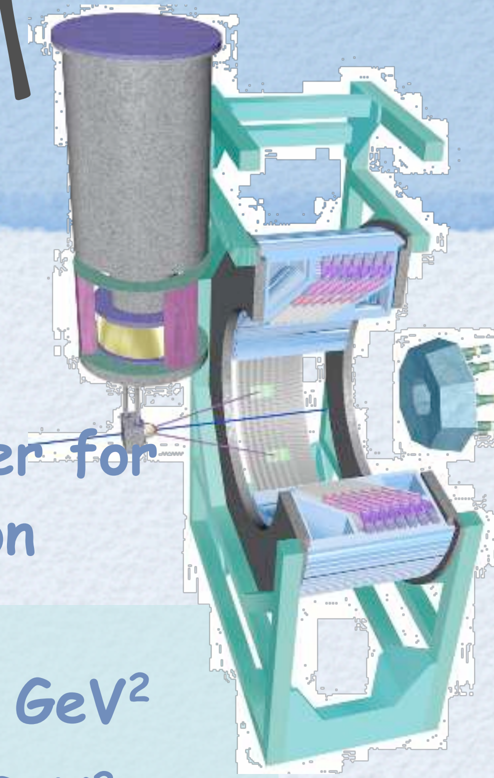

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HAPPEX

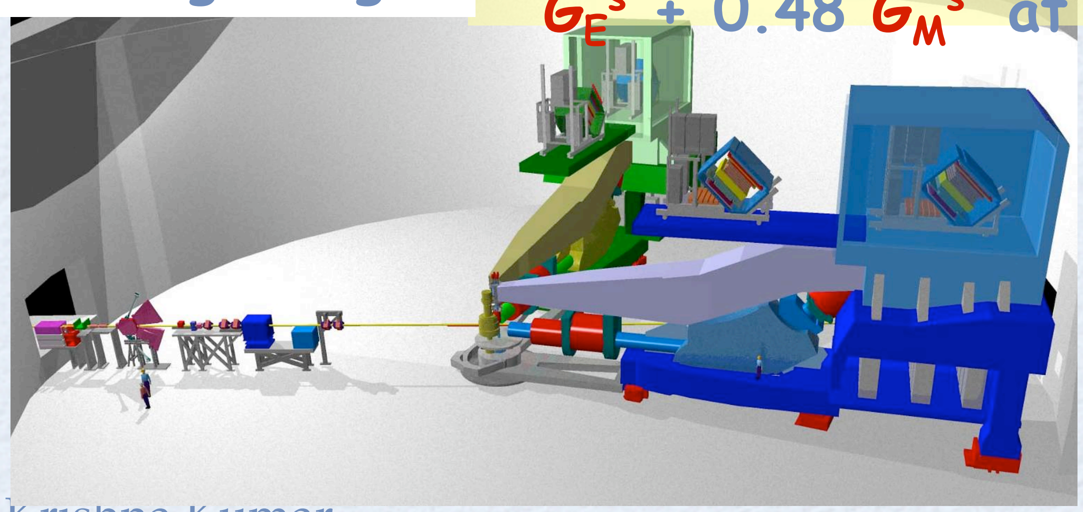
Precision spectrometer, integrating

G_E^s + 0.39 G_M^s at Q^2 = 0.48 GeV^2

G_E^s + 0.08 G_M^s at Q^2 = 0.1 GeV^2

G_E^s at Q^2 = 0.1 GeV^2 (^{4}He)

G_E^s + 0.48 G_M^s at Q^2 = 0.62 GeV^2



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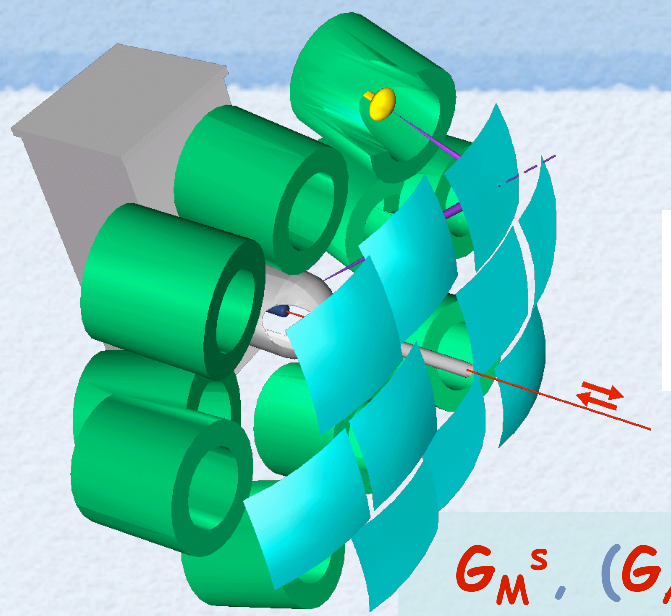

SAMPLE

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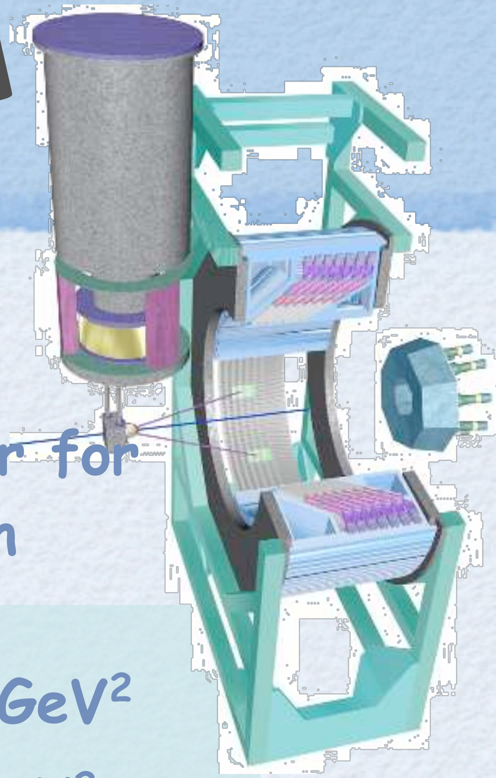

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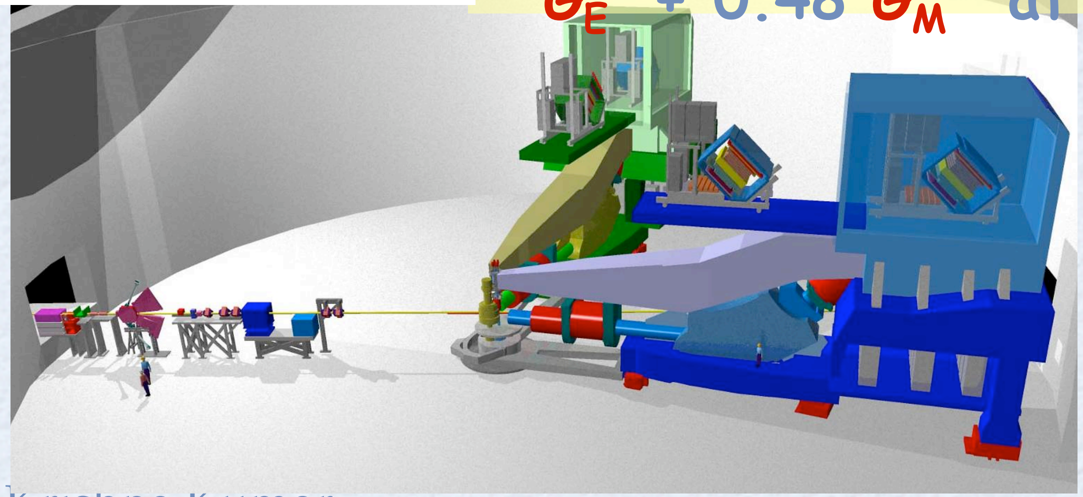
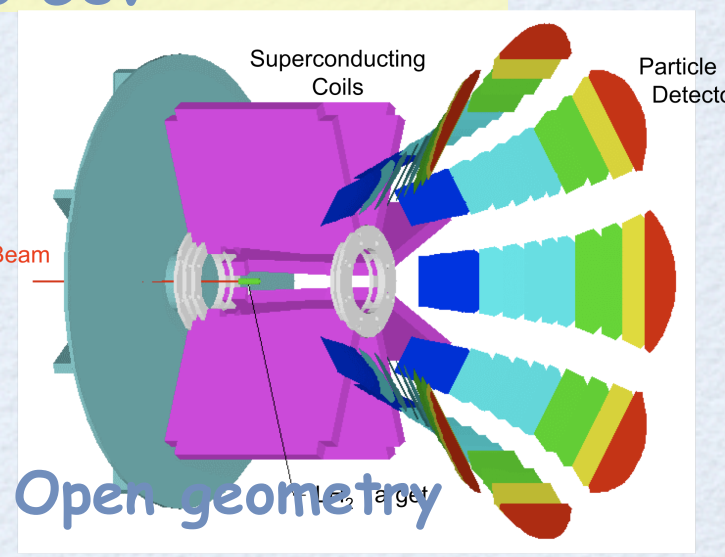


G0



Open geometry

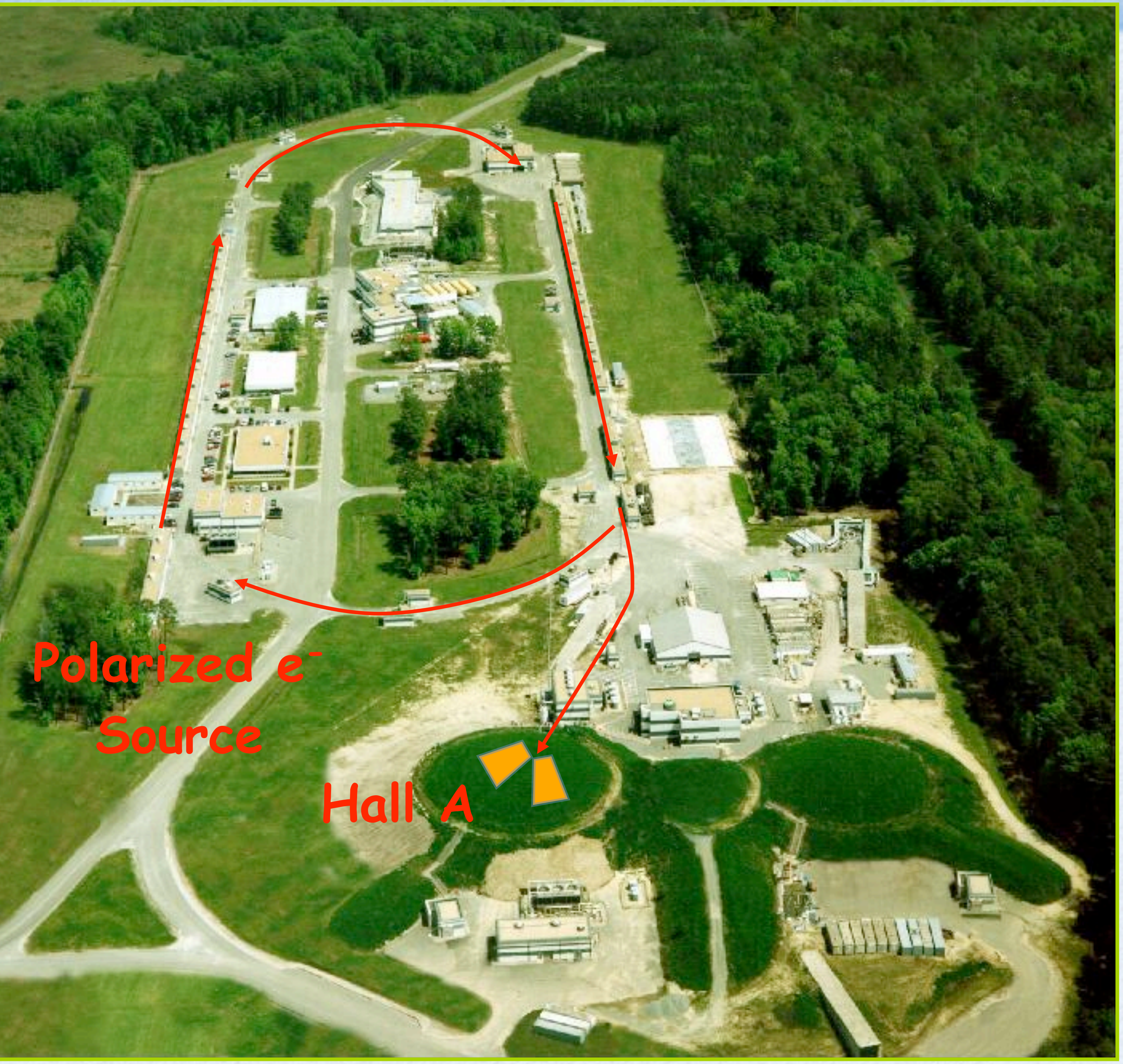
Fast counting with magnetic spectrometer + TOF for background rejection

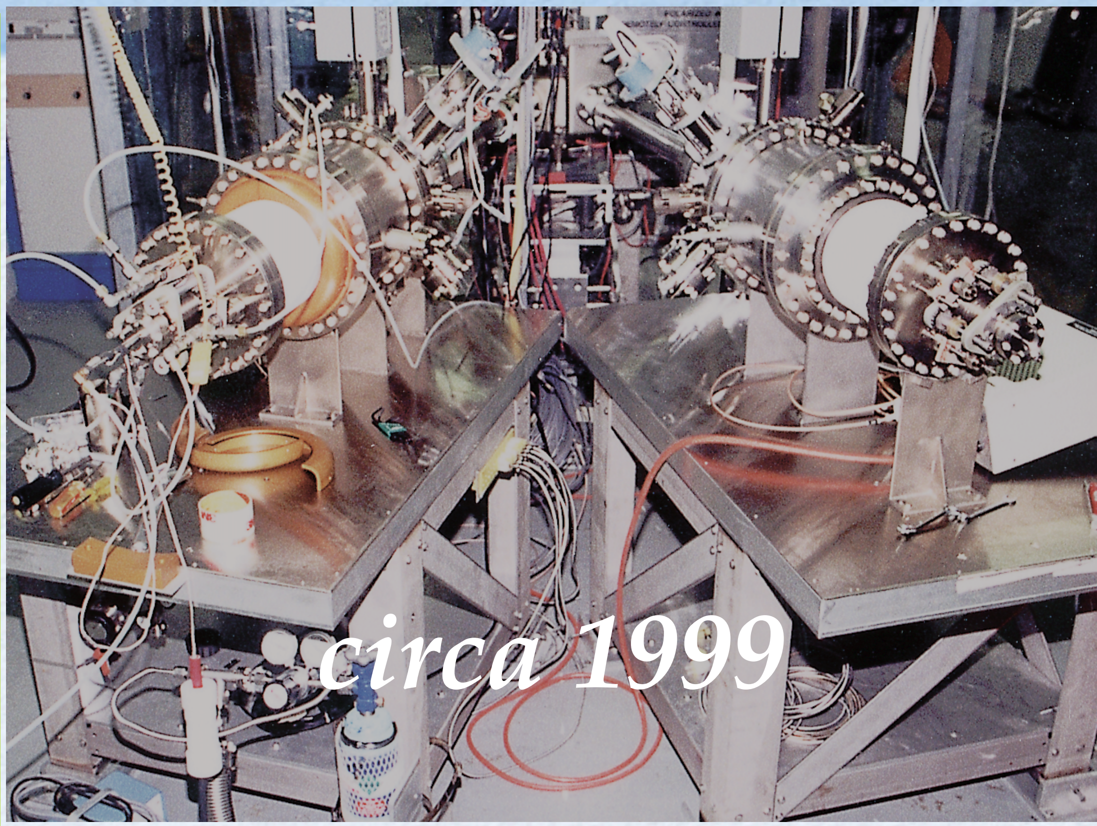
$G_E^s + \eta\ G_M^s$ over Q^2 = [0.12,1.0] GeV^2

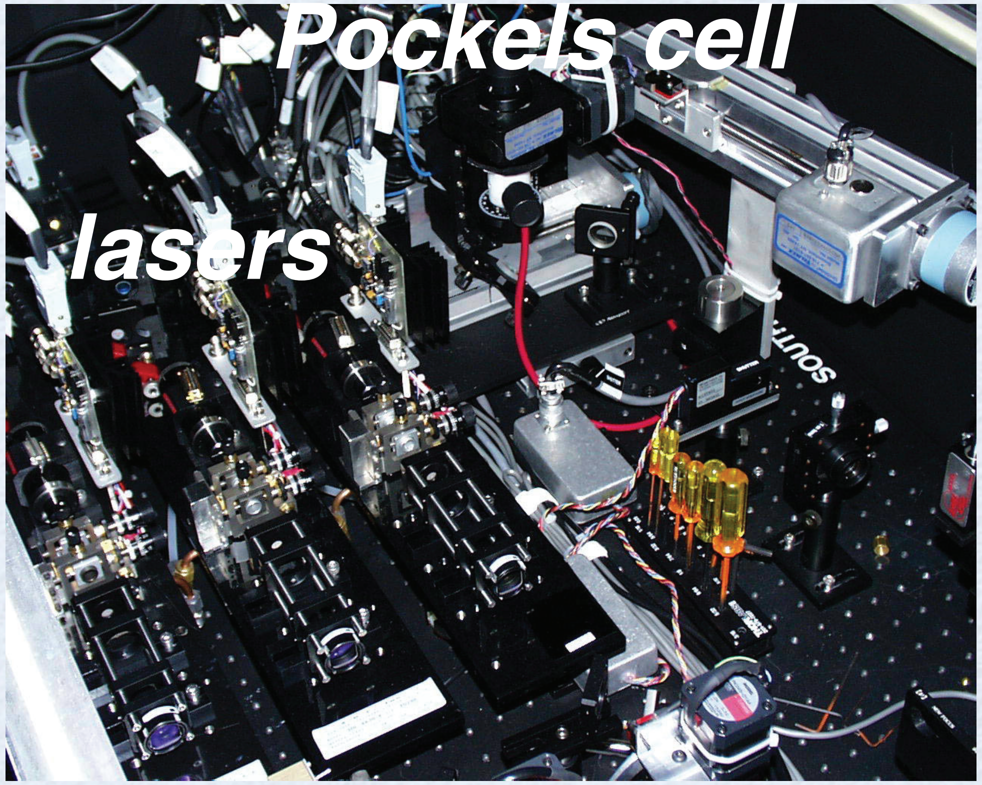
G_M^s, G_A^e at Q^2 = 0.23, 0.62 GeV^2

HAPPEX Experiment

CEBAF at Jefferson Lab

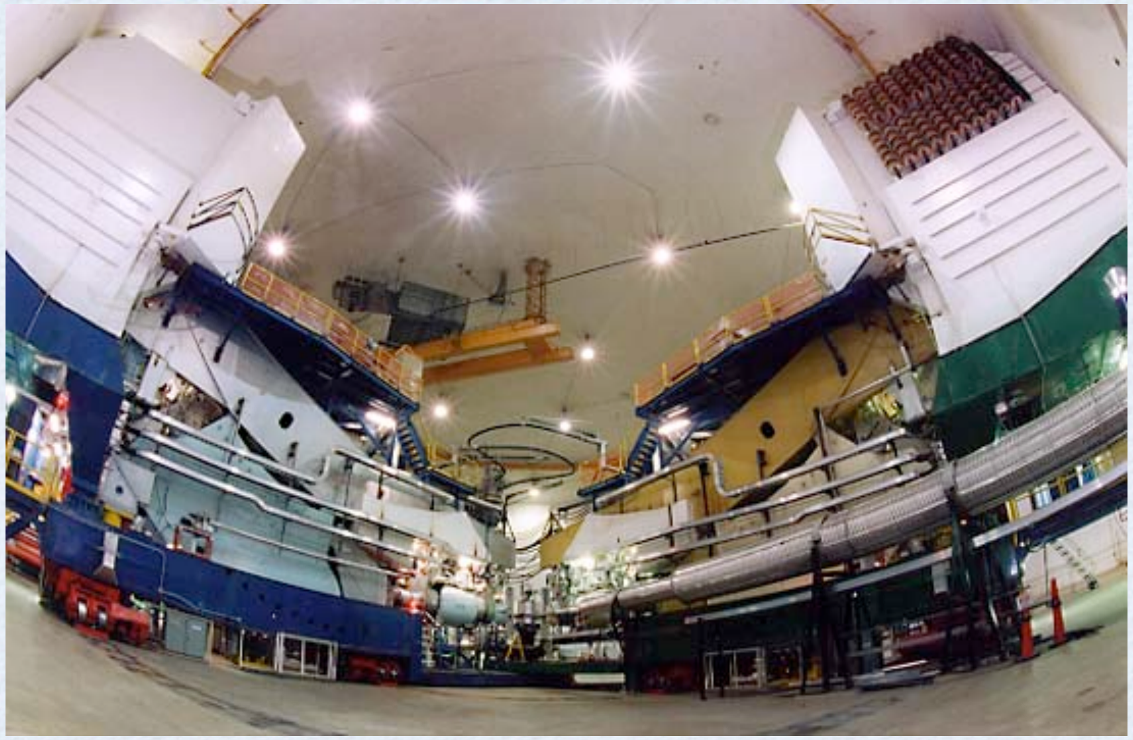




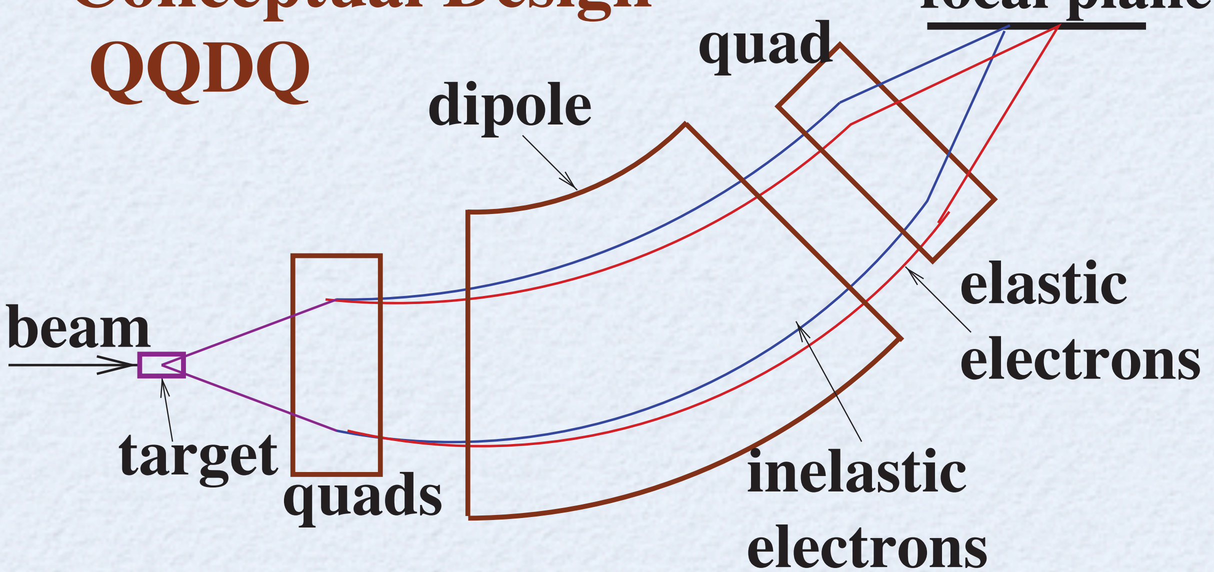


HRS in Hall A

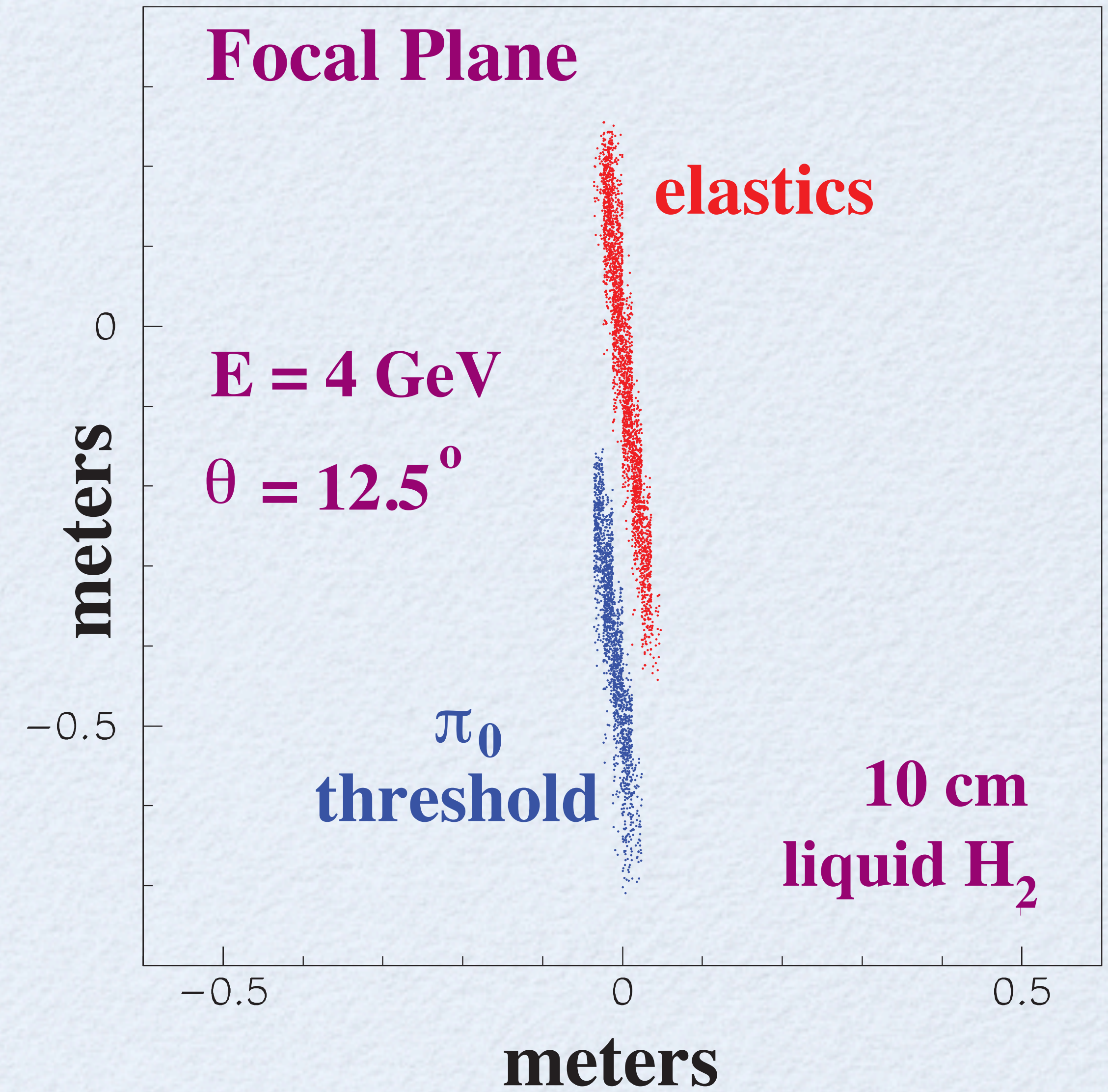
late 1990's

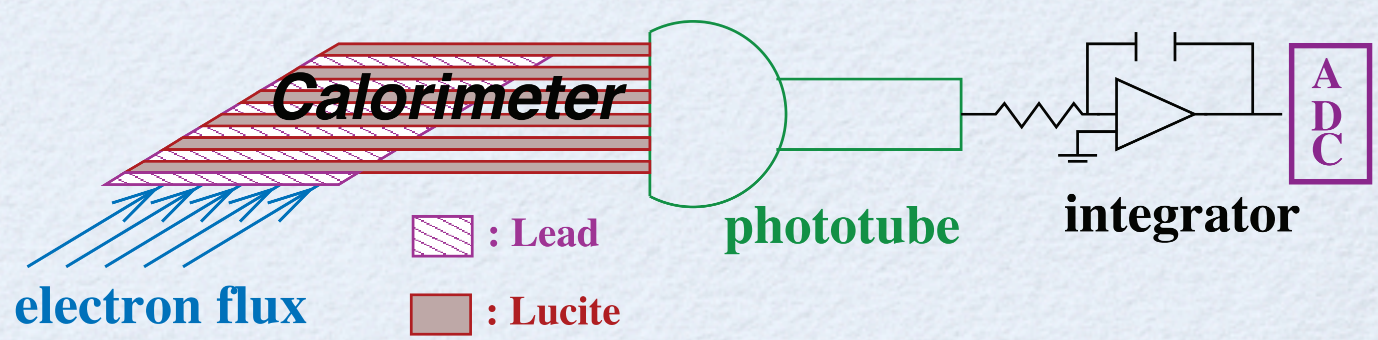


Conceptual Design
QQDQ



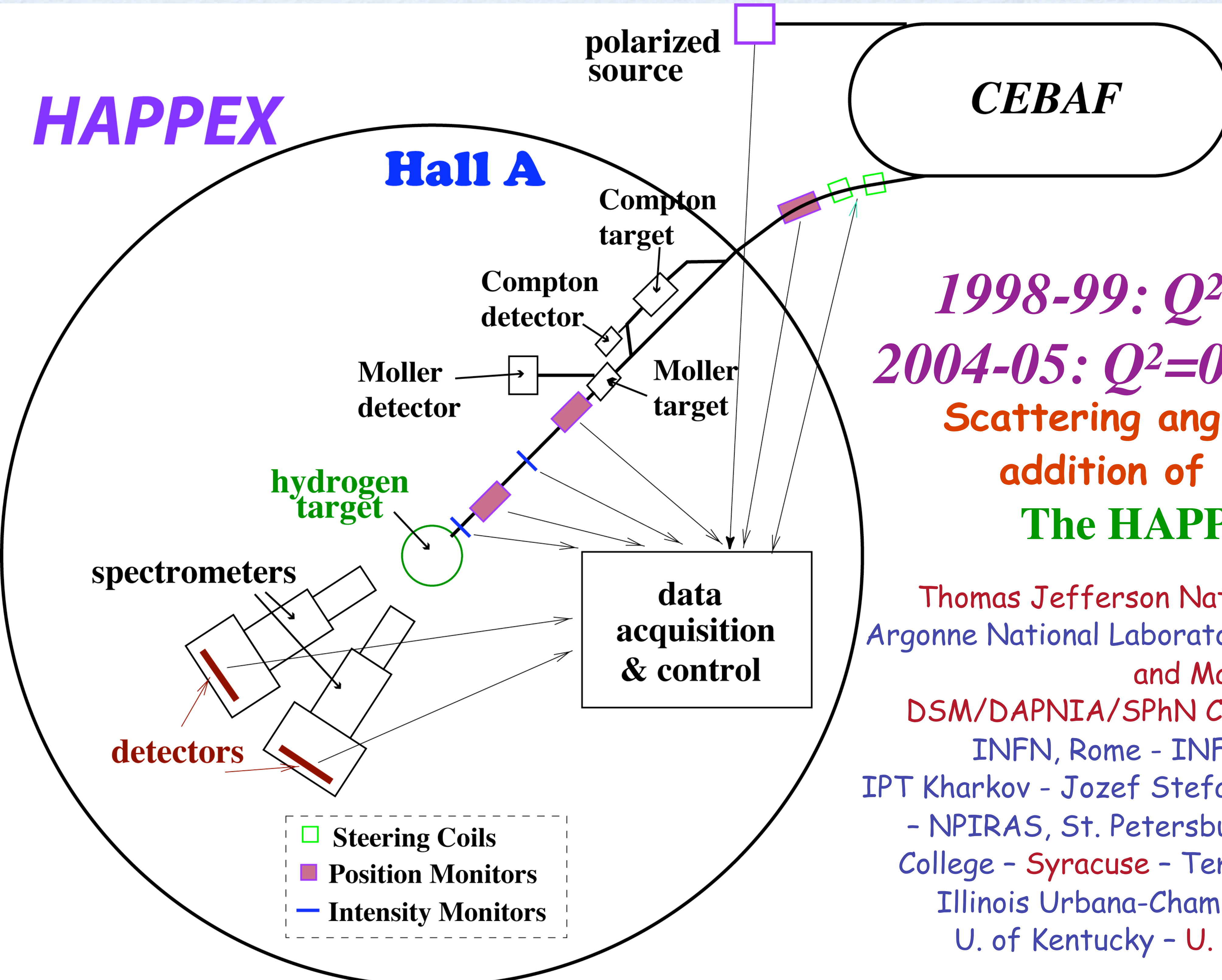
e^- Distribution at Detectors





HAPPEX AT JLAB

Hall A Proton Parity EXperiment



1998-99: Q^2=0.5 GeV^2, ^{1}H

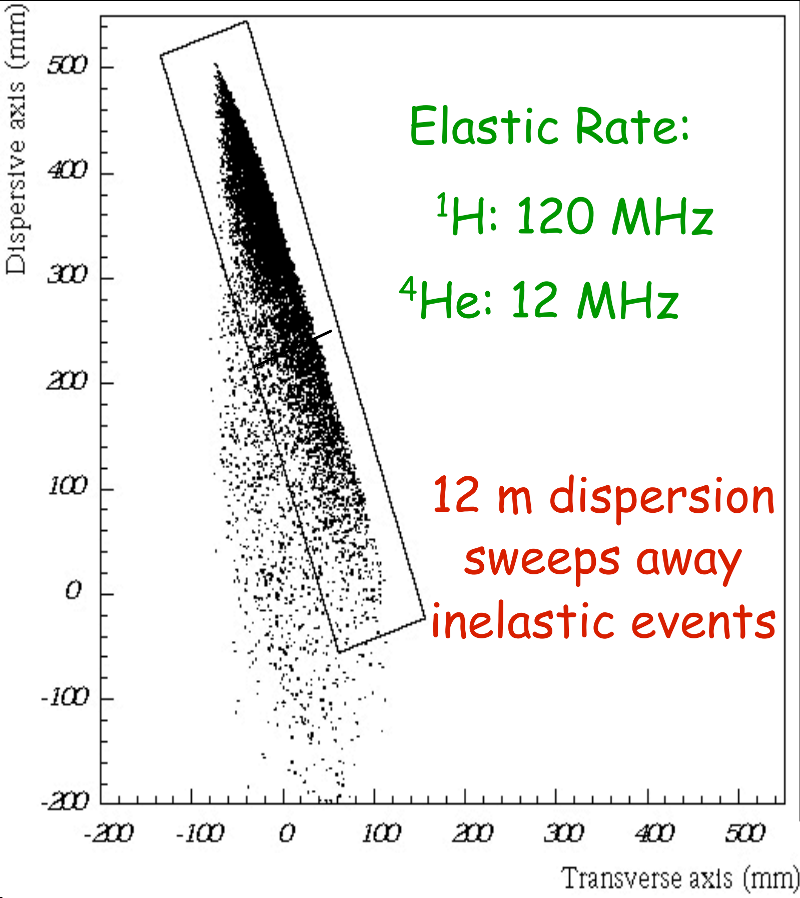
2004-05: Q^2=0.1 GeV^2, ^{1}H, ^{4}He

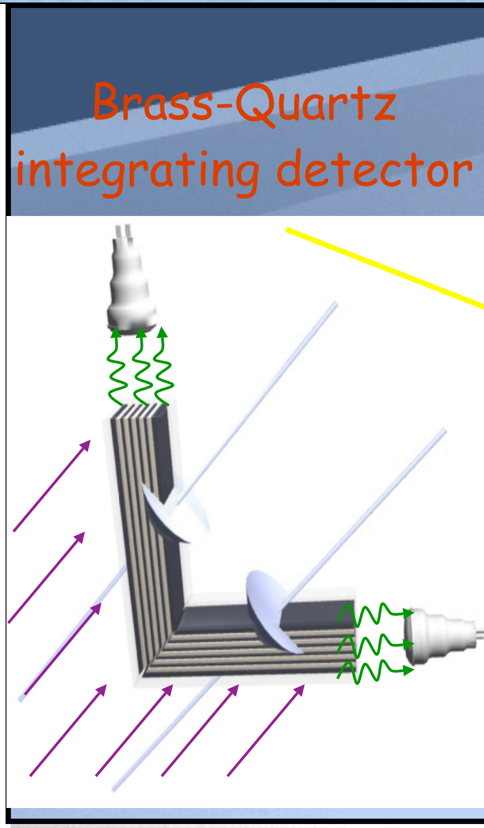
Scattering angle 12.5° to 6° with addition of septum magnets

The HAPPEX Collaboration

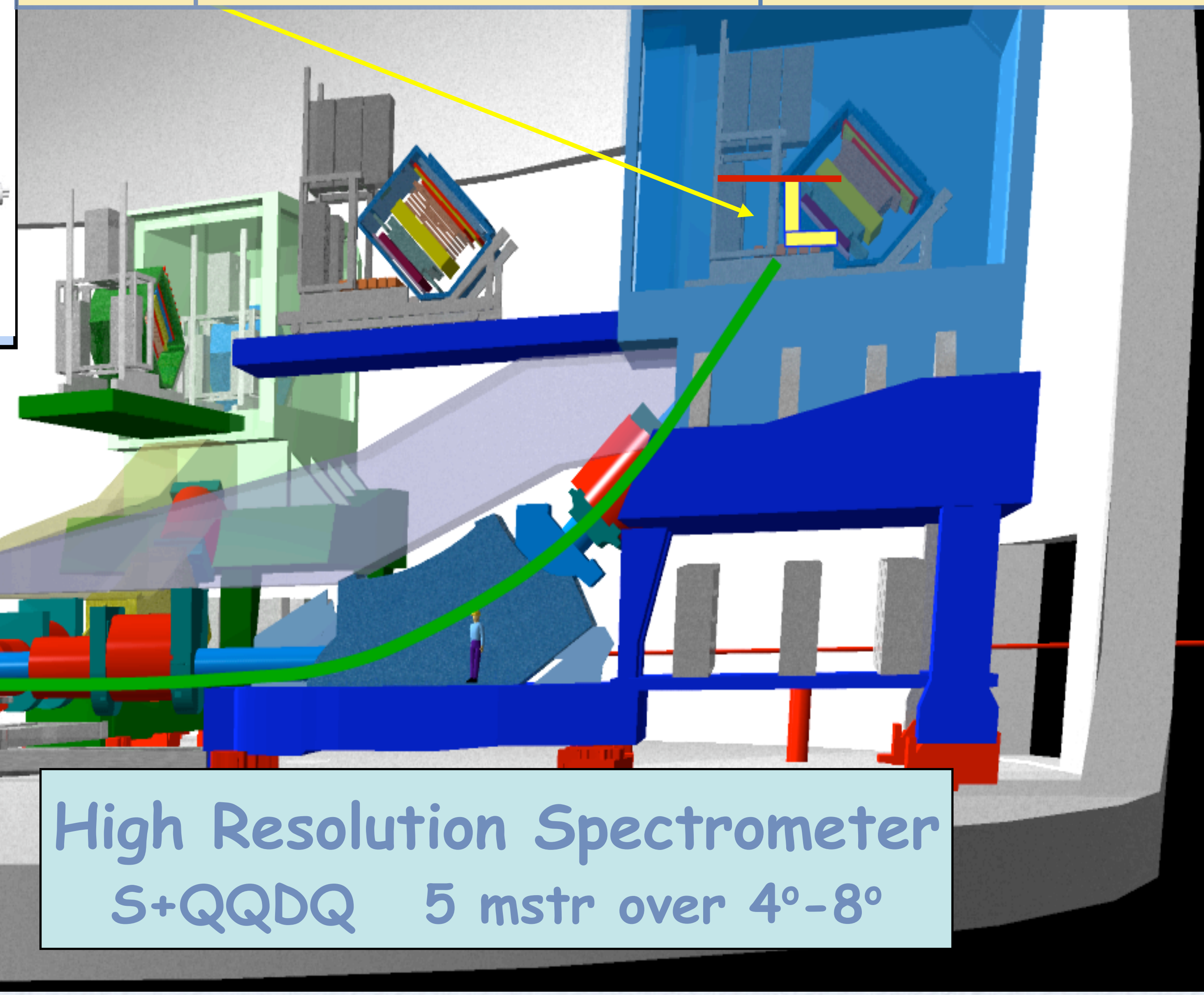
Thomas Jefferson National Accelerator Facility – Argonne National Laboratory – CSU, Los Angeles -William and Mary – Duke – DSM/DAPNIA/SPhN CEA Saclay - FIU – Harvard - INFN, Rome - INFN, Bari – IAE, Beijing – IPT Kharkov - Jozef Stefan Institute – Kent State - MIT – NPIRAS, St. Petersburg – ODU – Rutgers - Smith College – Syracuse – Temple – U. Blaise Pascal – U. of Illinois Urbana-Champagne – UMass, Amherst – U. of Kentucky – U. of Virginia – UST, Heifei

HAPPEXII in Hall A





Forward Angle ~6°, Q^2 ~0.1 GeV^2		
^{1}H	-1.6 (±0.1) ppm	$G_E^s + 0.08 G_M^s$
^{4}He	+7.8 (±4%) ppm	G_E^s



Measurement of A_{PV}

5% Statistical Precision on 1 ppm

-> requires $4x10^{14}$ counts

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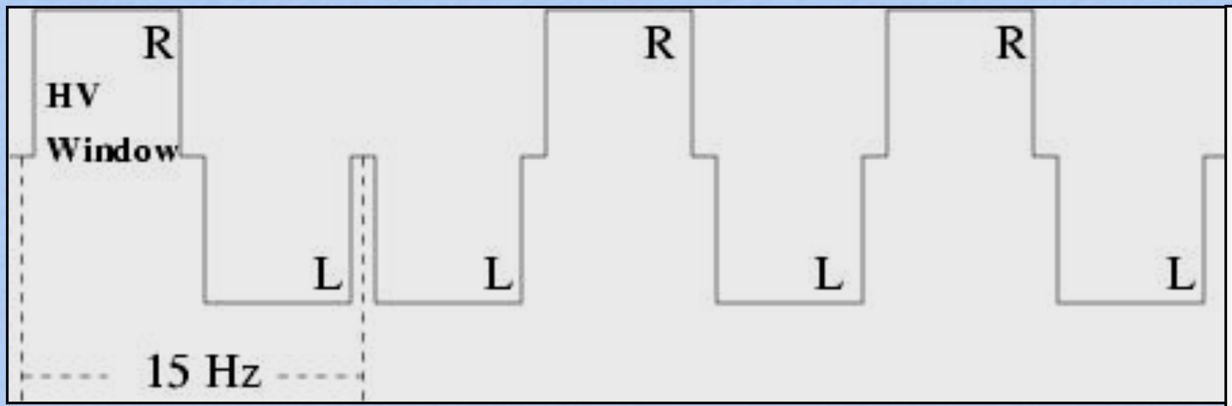
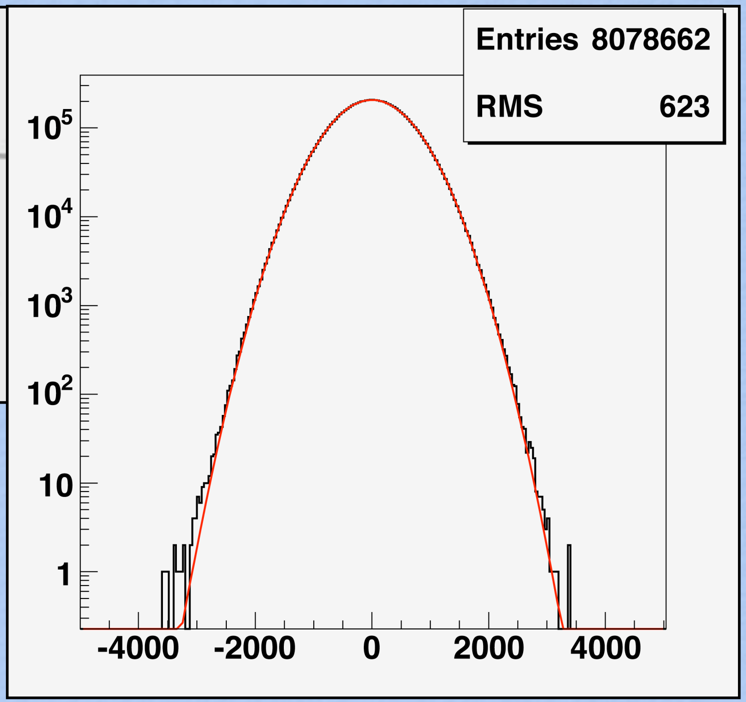
Rapid Helicity Flip: Measure the asymmetry at 10^{-4} level, 30 million times

$$A_{LR} = \frac{N_R - N_L}{N_R + N_L}$$





High Precision requires high **luminosity** and low **noise**

- $>10^{38}/\mathrm{cm}^2/\mathrm{s}$ luminosity: thick target, large I_{beam}
- High beam polarization - 80-85%

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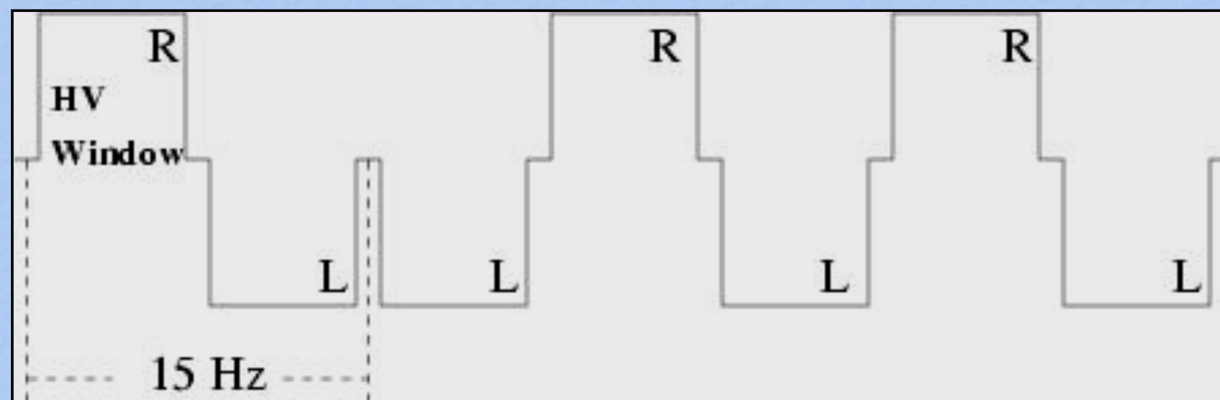

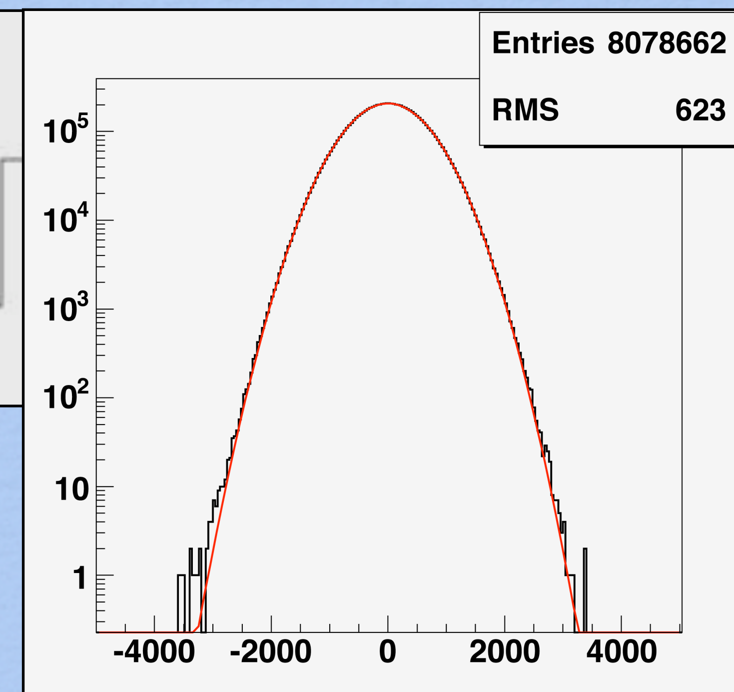

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- Electronics pickup
- Background Asymmetries

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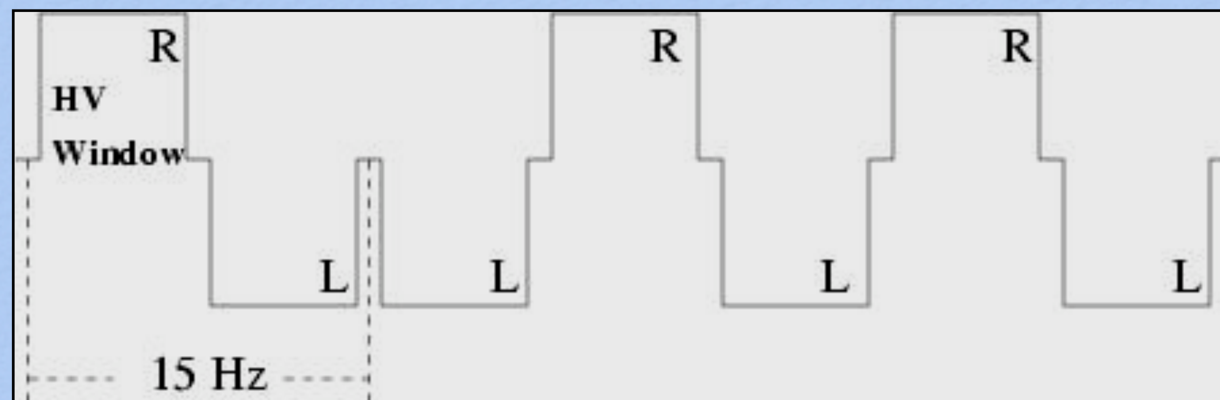

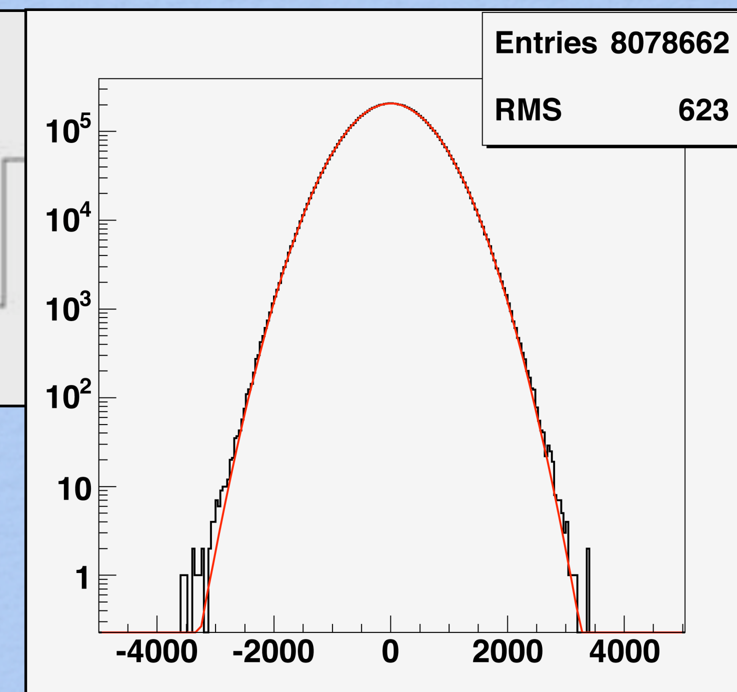

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- **Electronics pickup**
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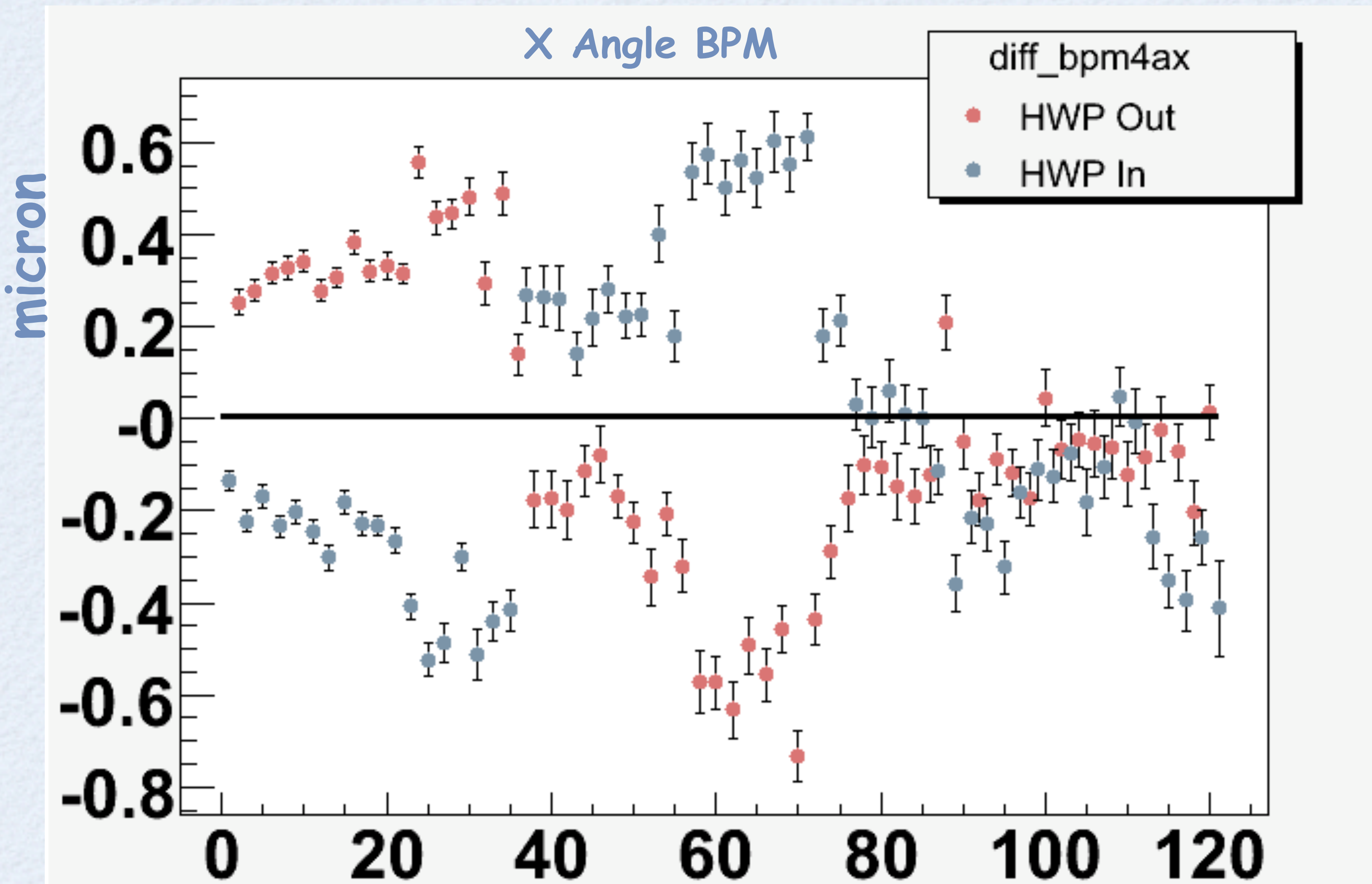
Normalization

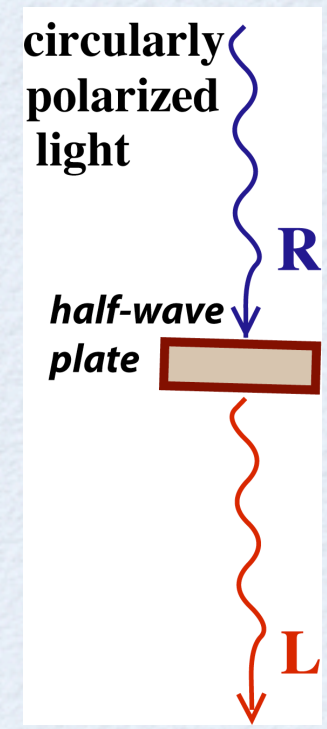
- **Polarimetry** – continuous measurement/monitoring. Control of systematic error
- **Linearity / Deadtime**
- **Background Dilution**

Beam Asymmetries

Position difference goal: 3 nanometers!

Helicity-correlated asymmetries in the electron beam create FALSE ASYMMETRY





Problem: Helicity signal deflecting the beam through electronics "pickup"

Large beam deflections even when Pockels cell is off

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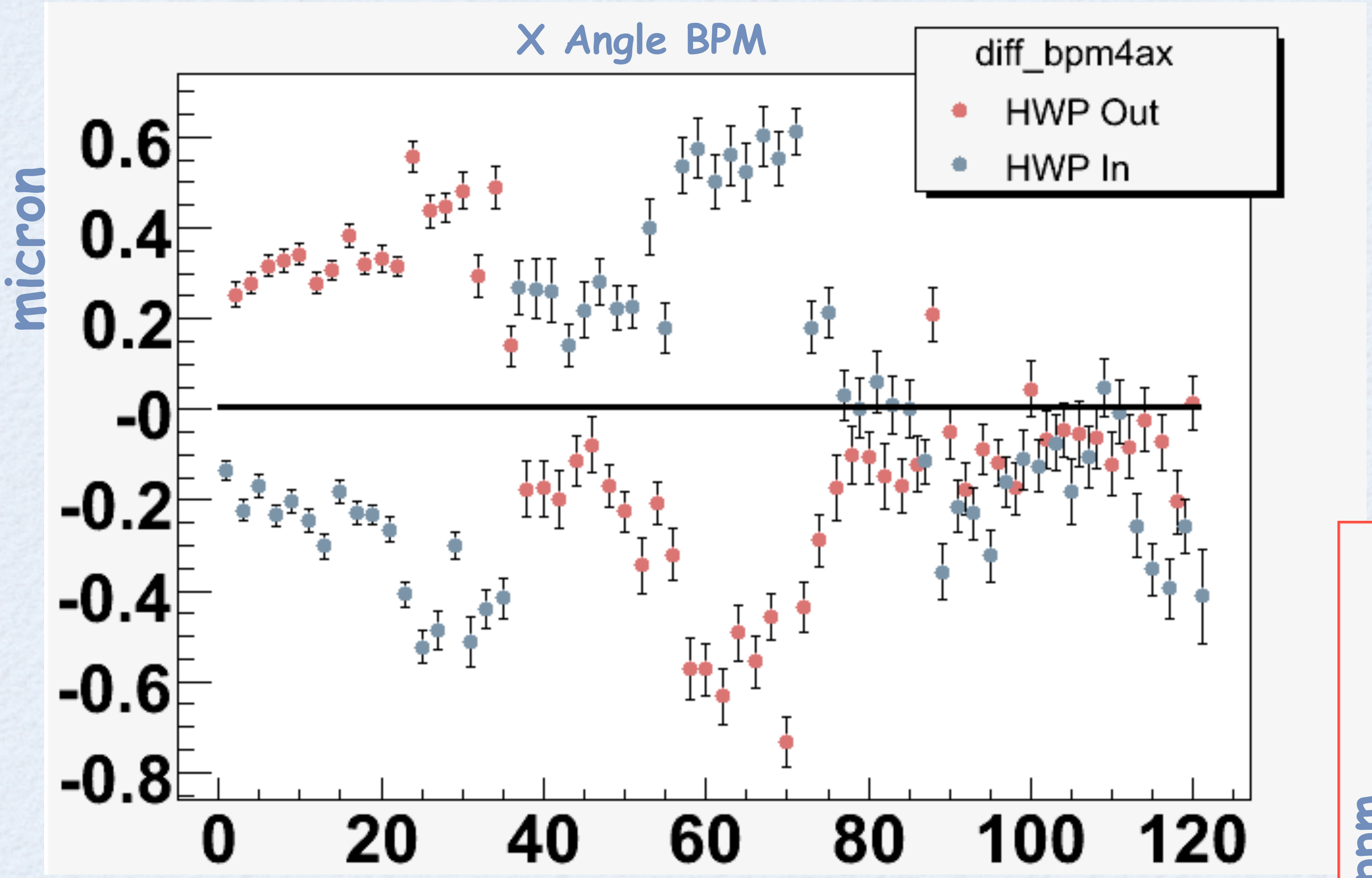
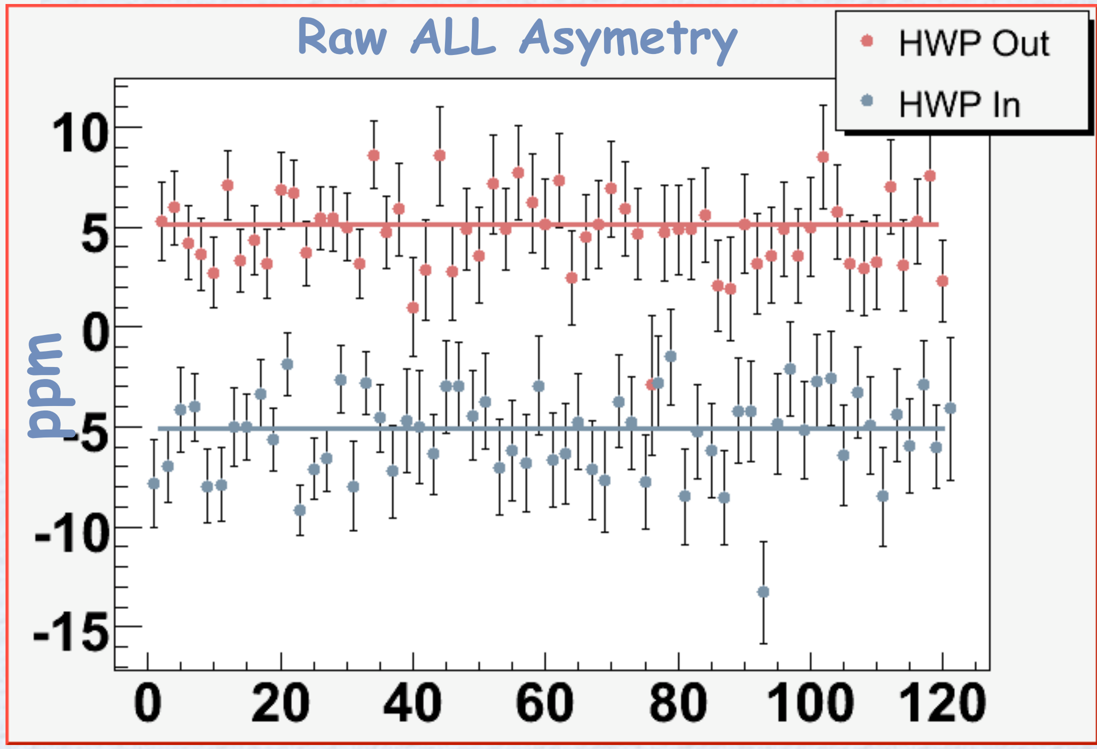


Problem: Helicity signal deflecting the beam through electronics "pickup"

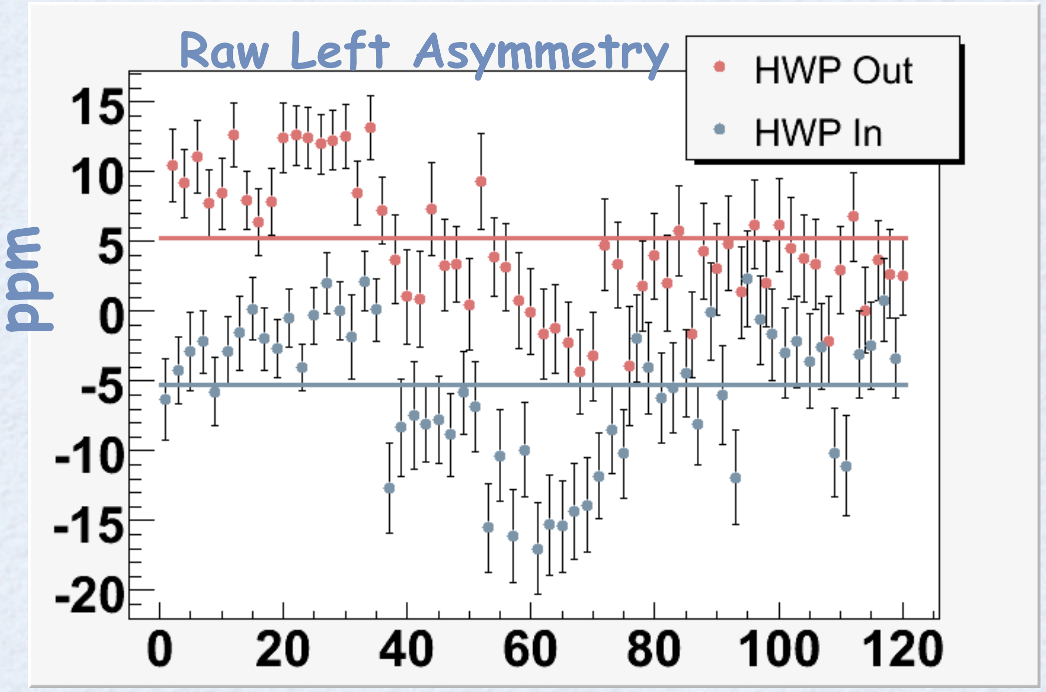
Large beam deflections even when Pockels cell is off

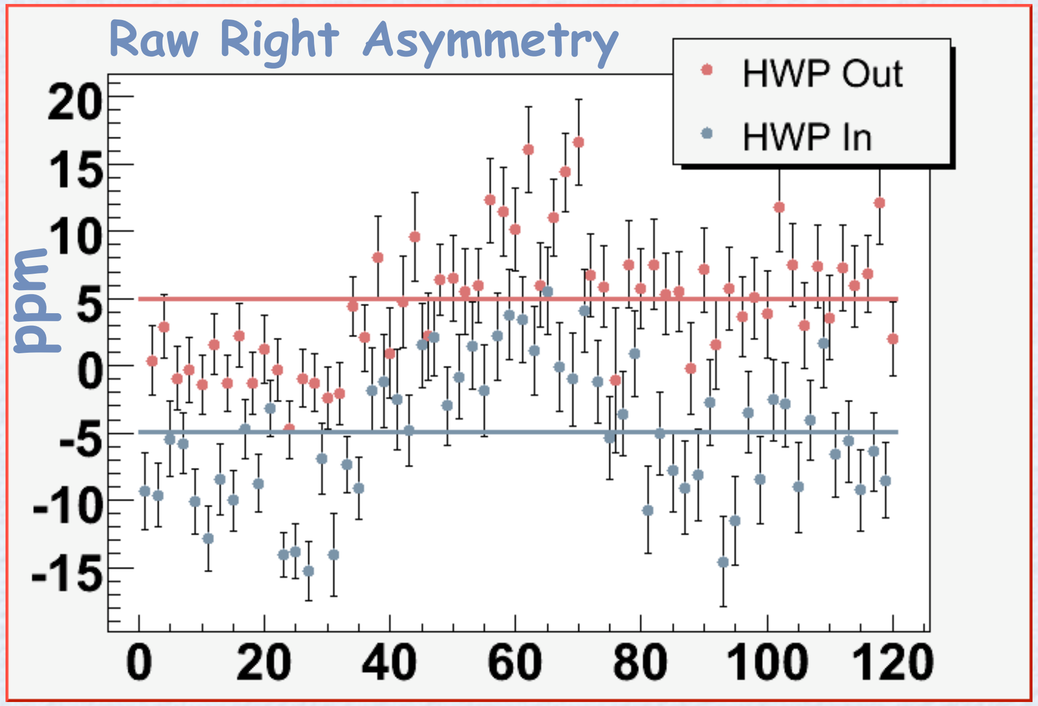
All's well that ends well

- Problem clearly identified as beam steering from electronic cross-talk
- Large position differences mostly cancel in average over both detectors



Beam Asymmetry Corrections to A_{PV}





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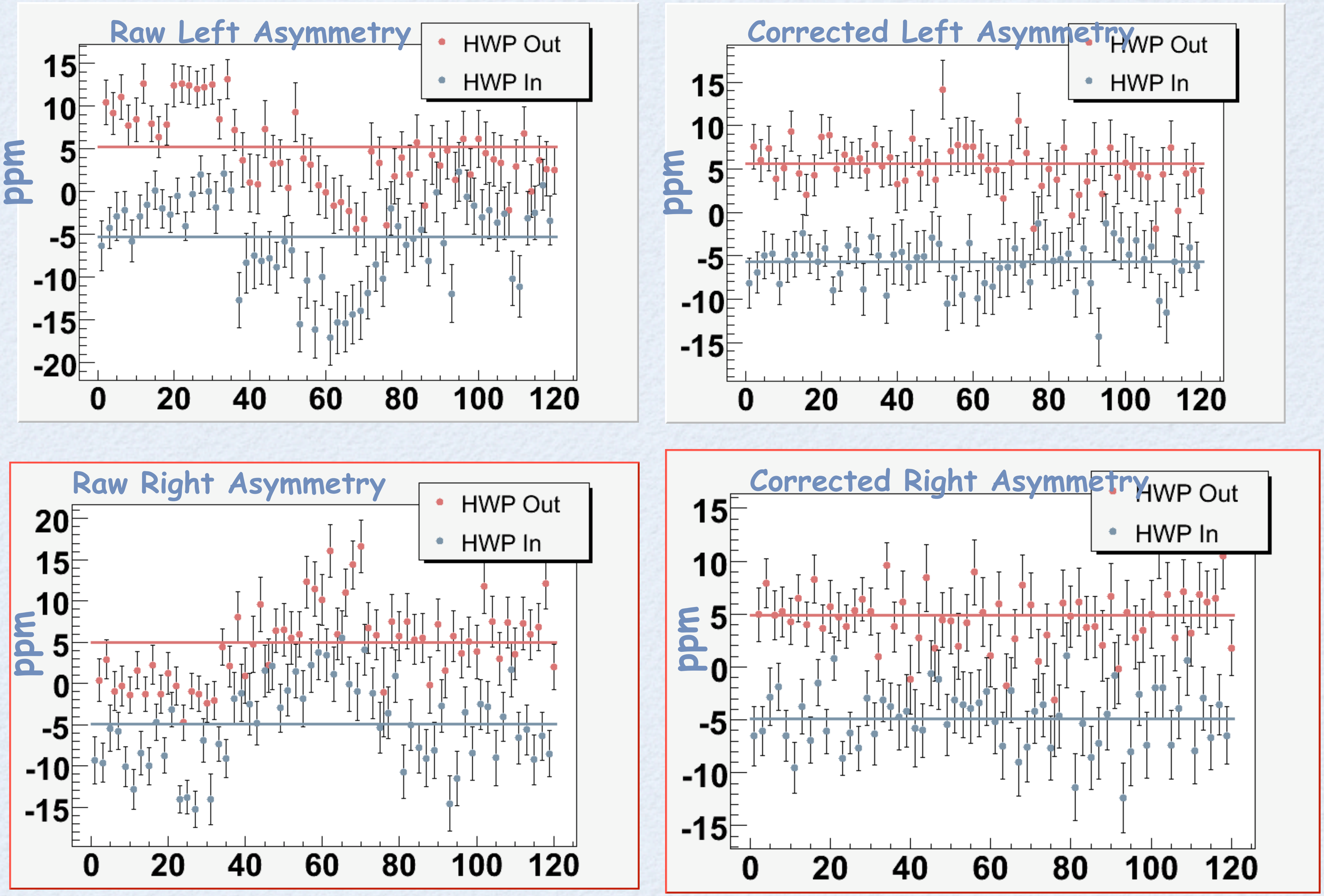

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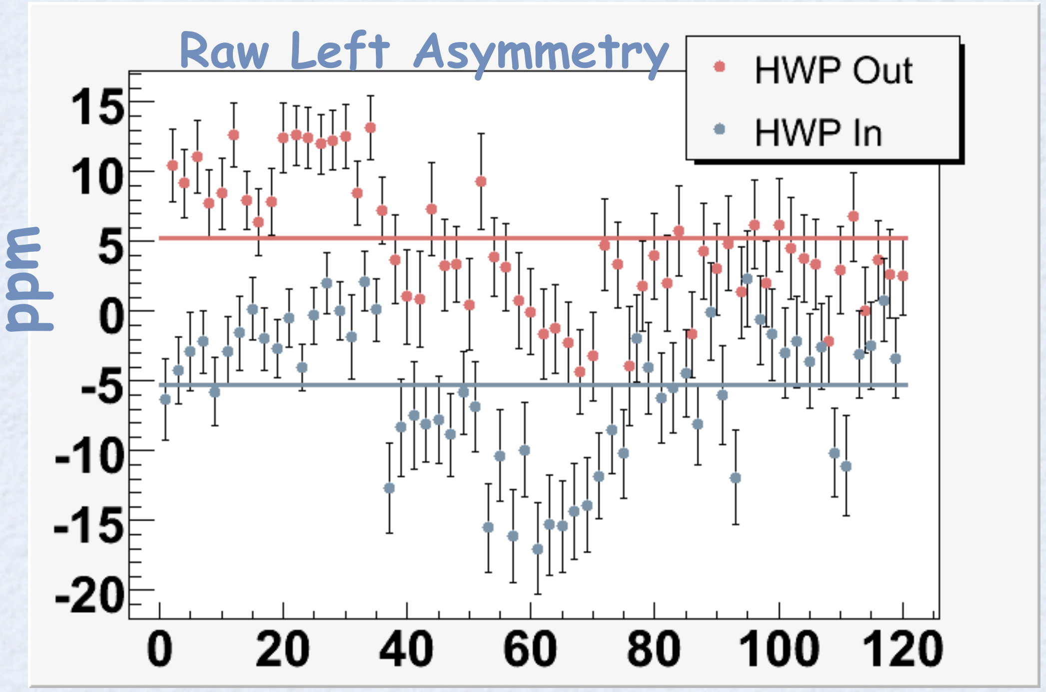
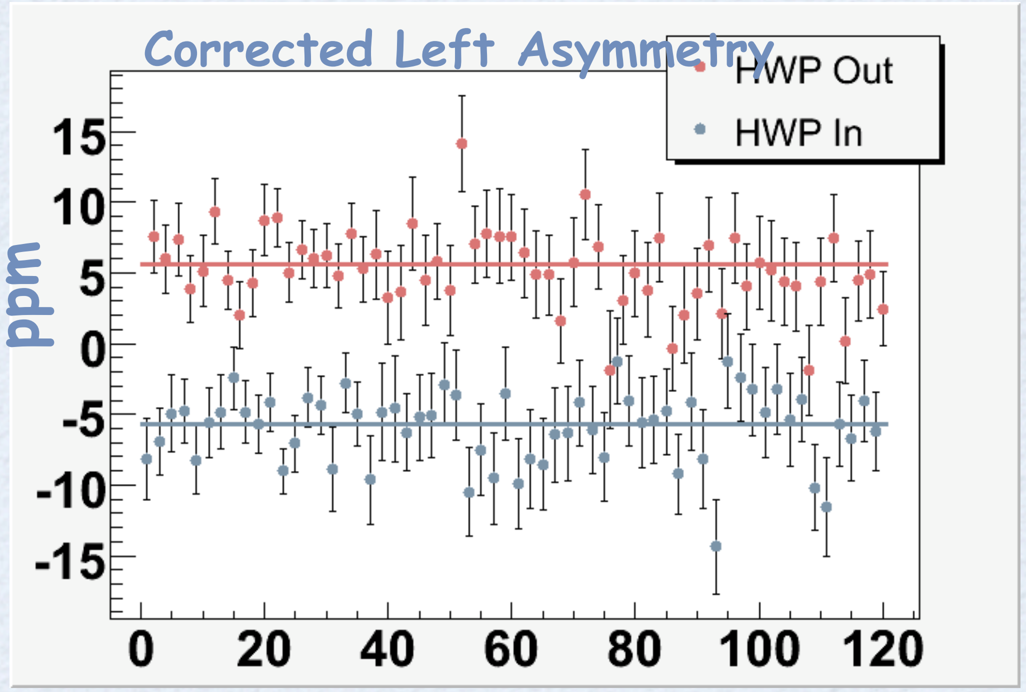
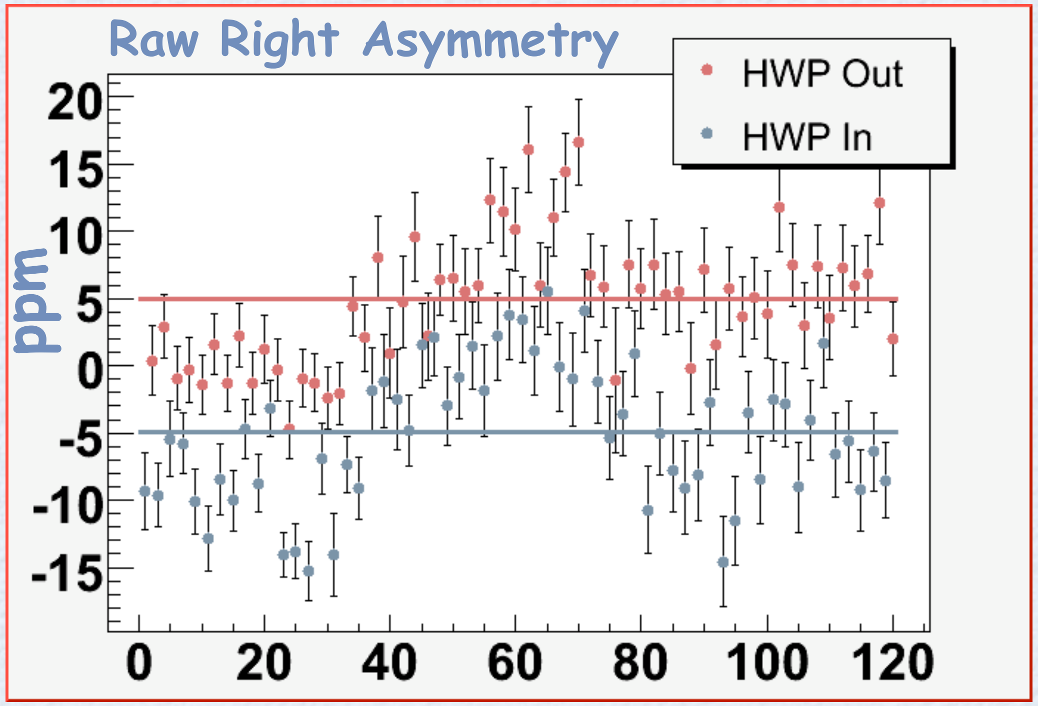
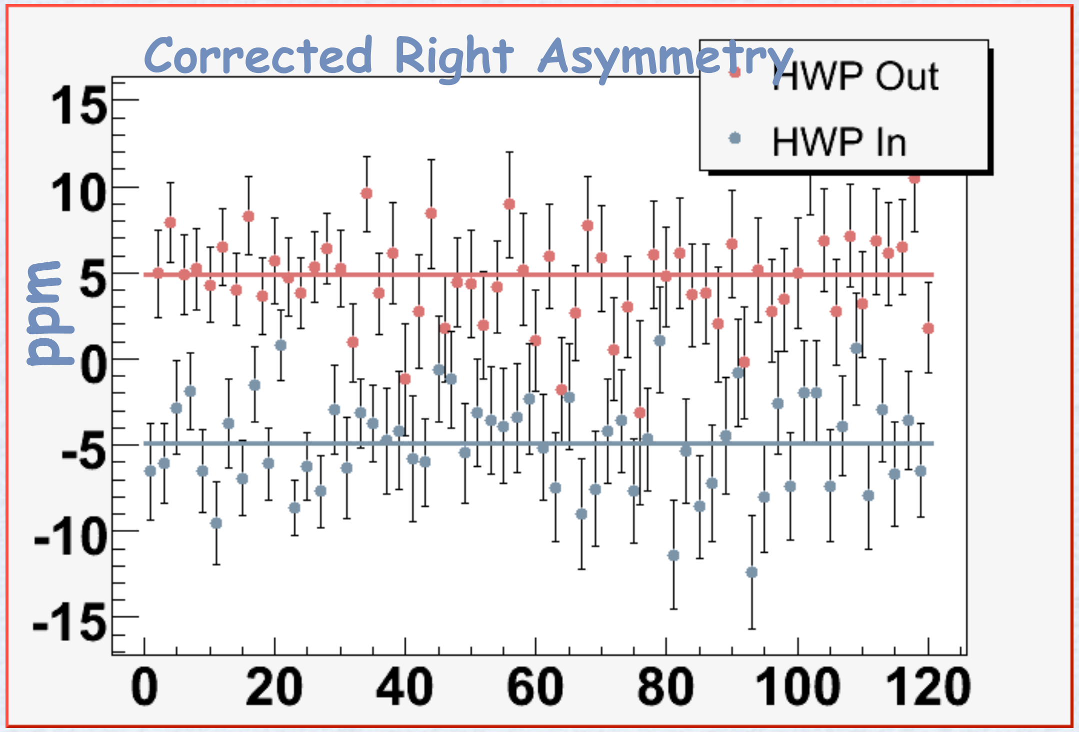








Beam Asymmetries

Energy: -3ppb

X Target: -5 nm

X Angle: -28 nm

Y Target :-21 nm

Y Angle: 1 nm

↓

Using Measured Sensitivities

↓

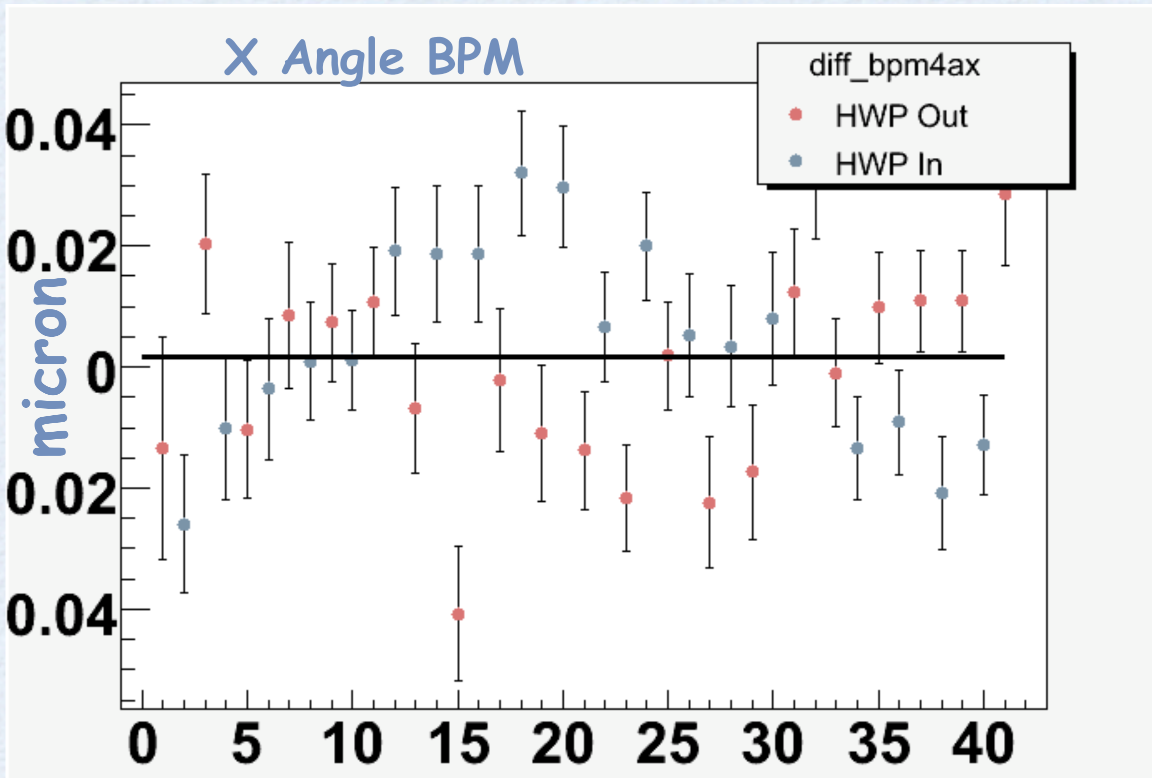
Total Corrections:

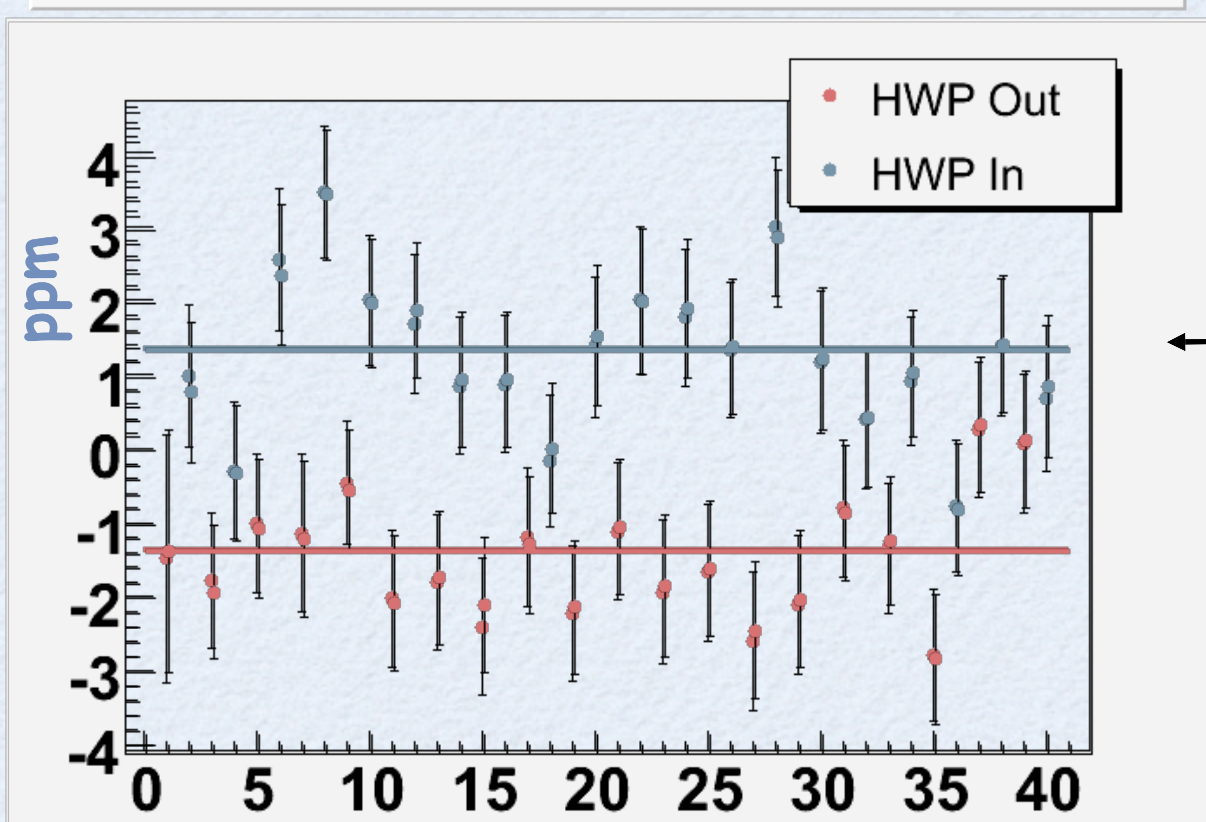
Left: -370 ppb

Right: 80 ppb

All: 120 ppb

HAPPEXII Final Results





Surpassed Beam Asymmetry Goals for Hydrogen Run

Energy: -0.25 ppb

X Target: 1 nm

X Angle: 2 nm

Y Target : 1 nm

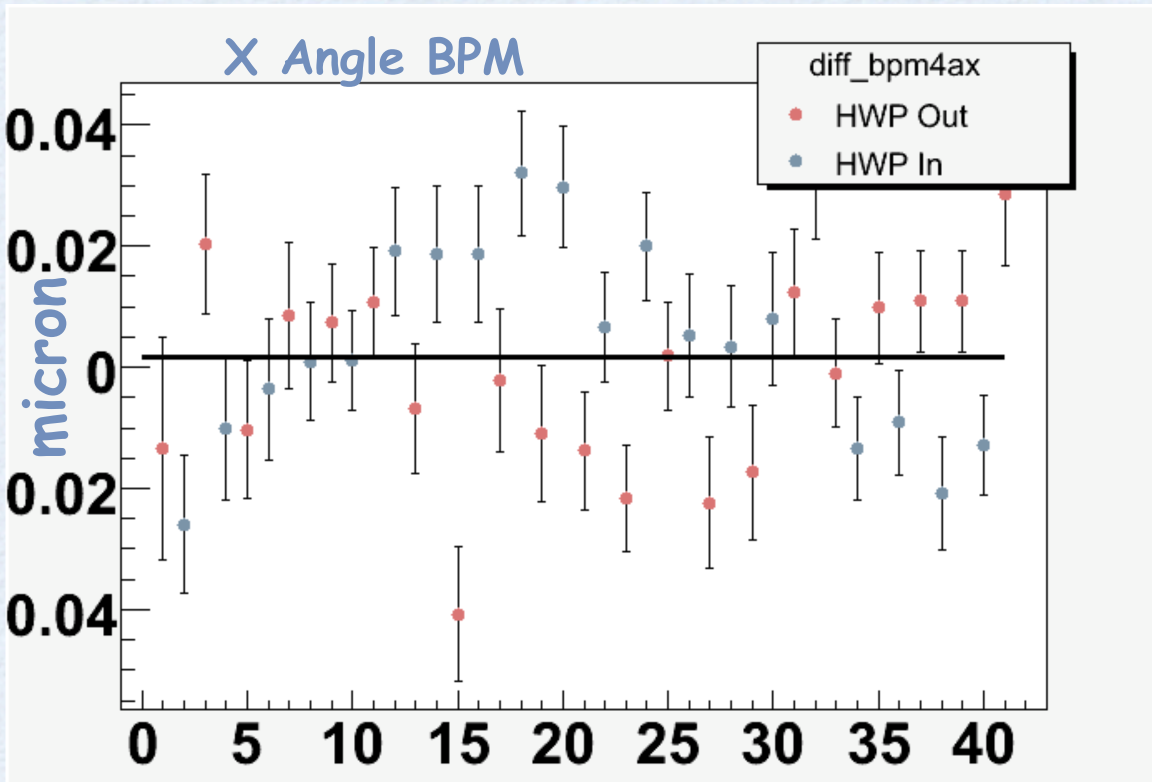
Y Angle: <1 nm

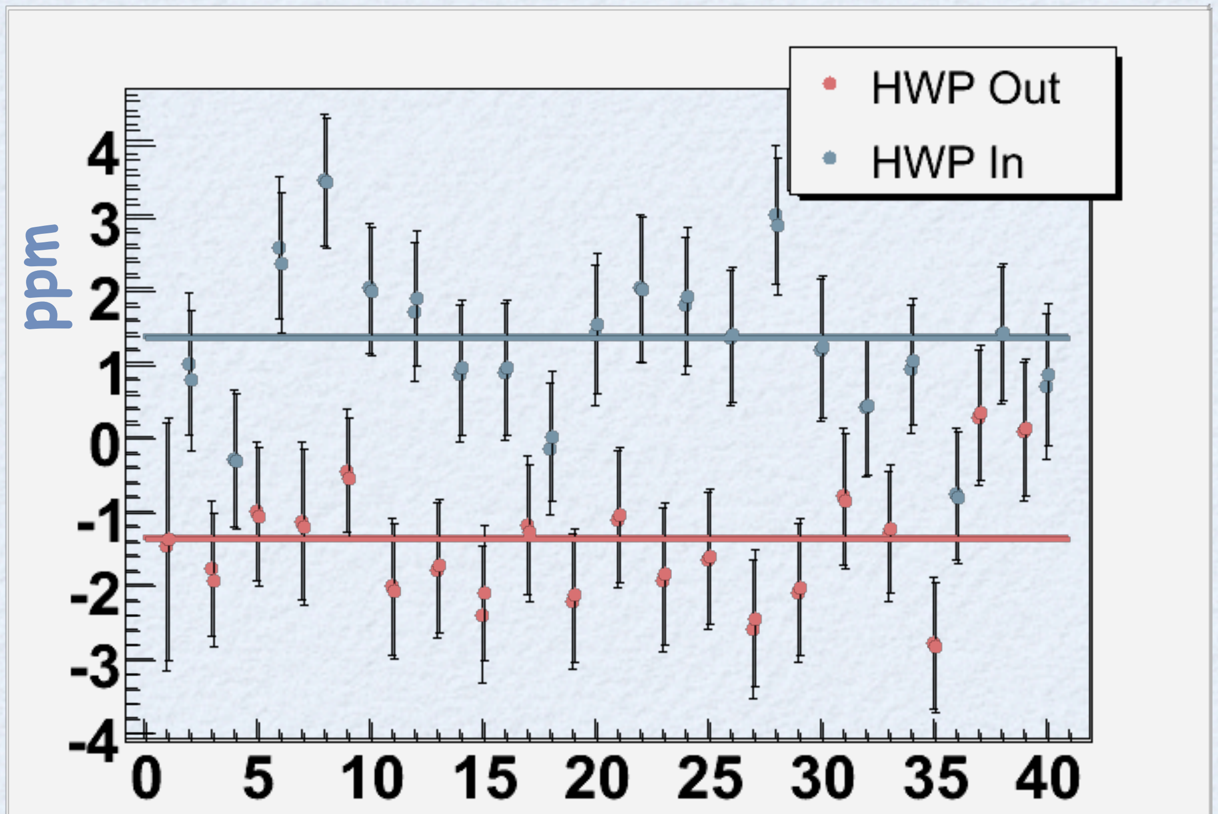
Corrected and Raw, Left arm alone,

Superimposed!

Total correction for beam position asymmetry on Left, Right, or ALL detector: 10 ppb

HAPPEXII Final Results





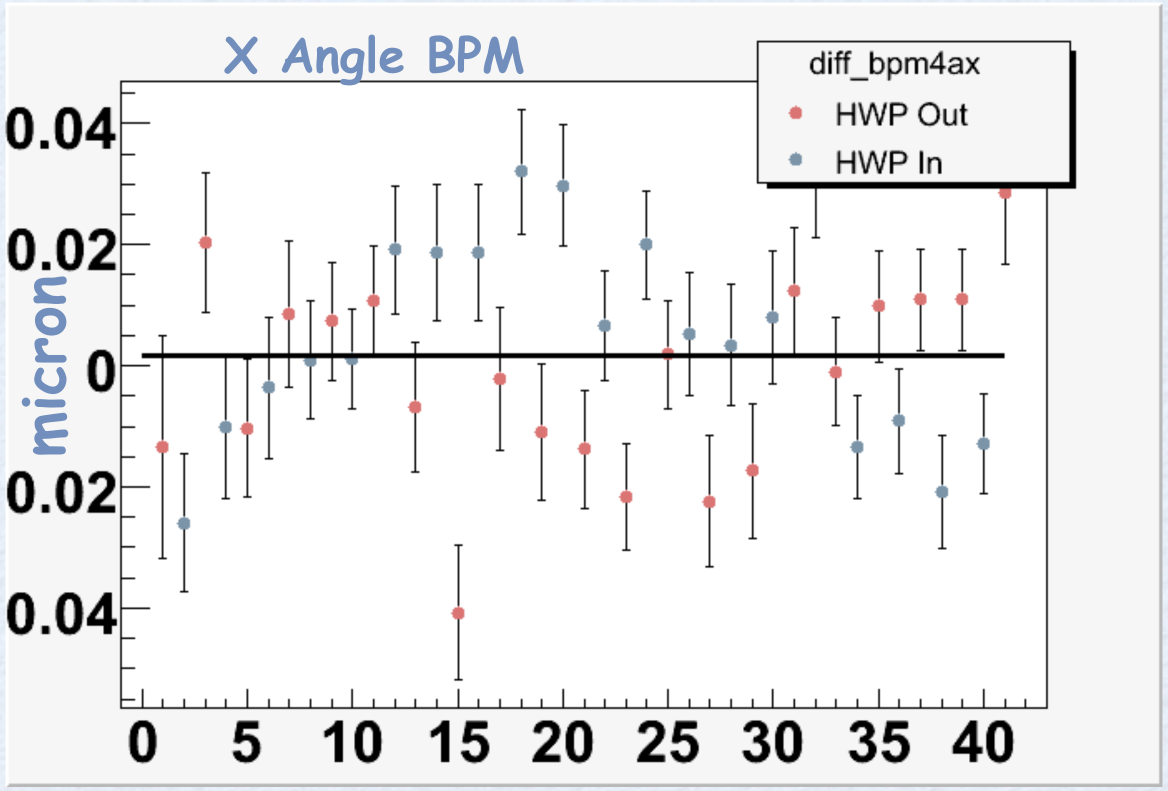
Hydrogen

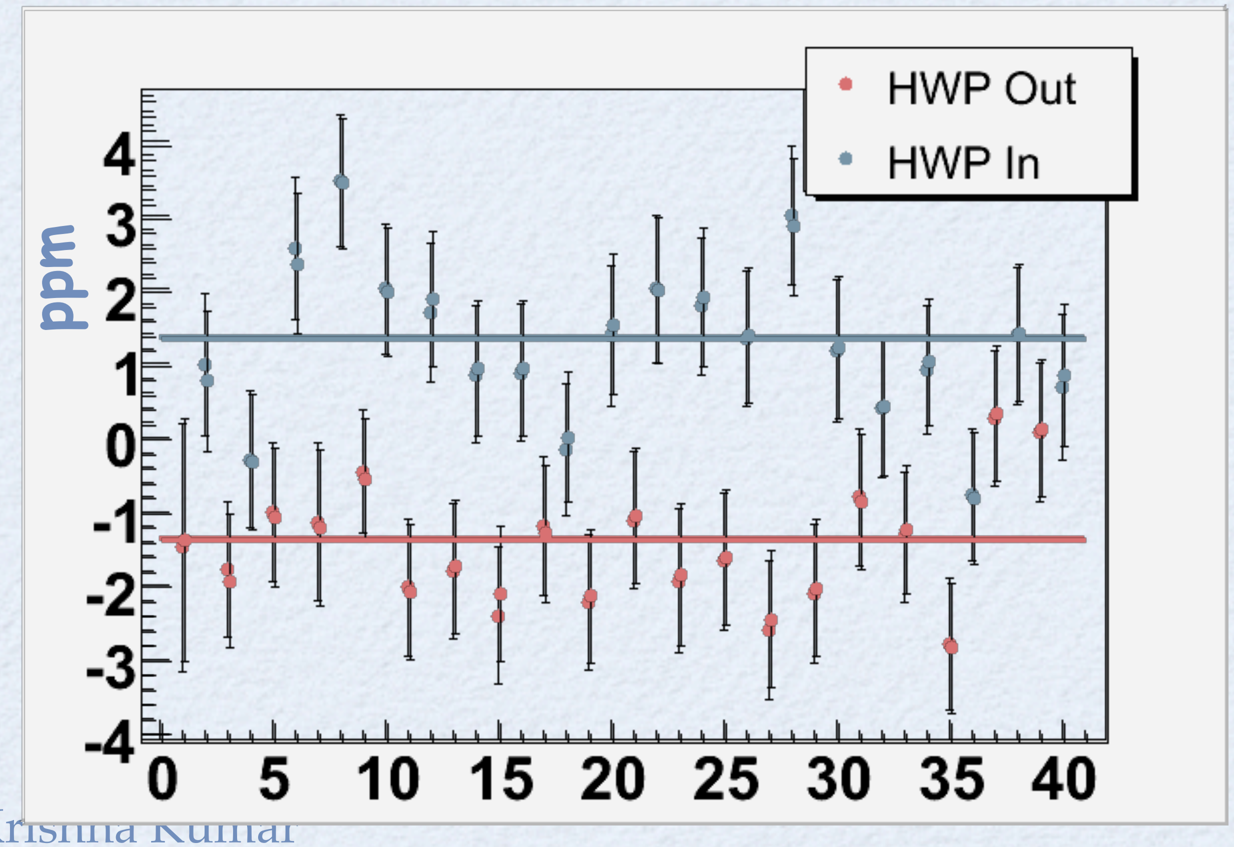
Systematic control ~ 10^{-8}

$A_{PV} = -1.58 \pm 0.12$ (stat) $\pm\ 0.04$ (syst) ppm

$A(G^s=0) = -1.66$ ppm $\pm$ 0.05 ppm

HAPPEXII Final Results





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$A(G^s=0)$ = -1.66 ppm ± 0.05 ppm

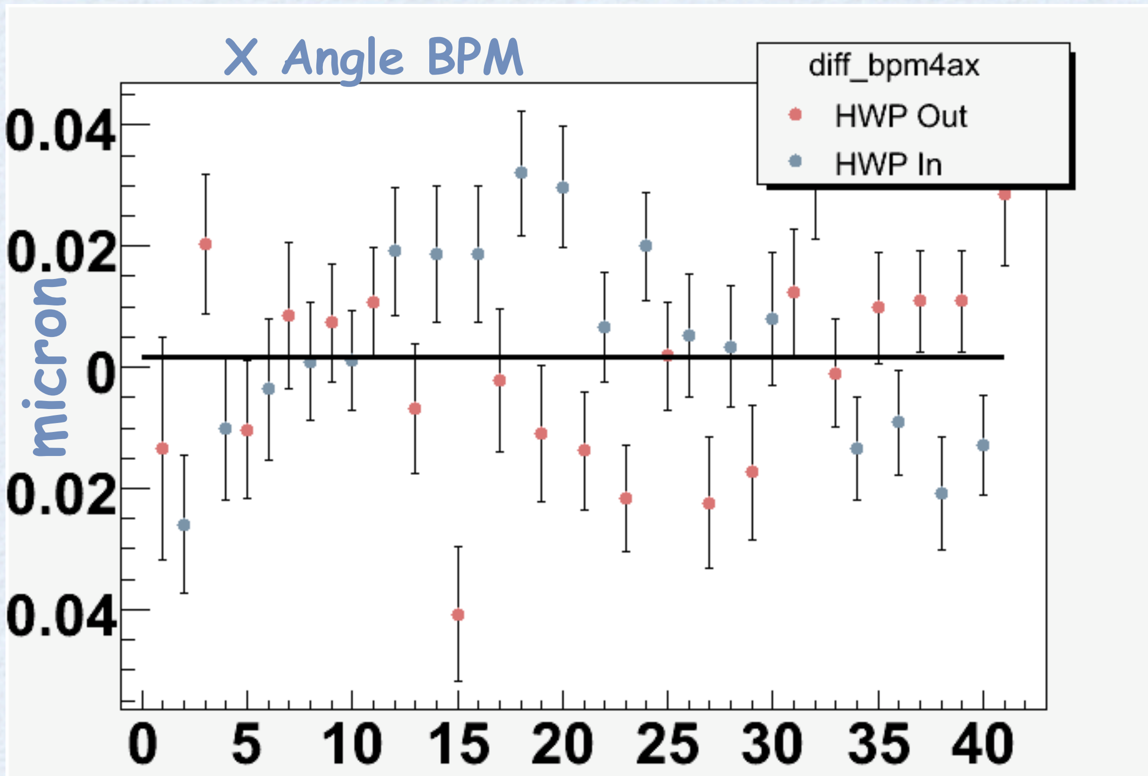
Helium

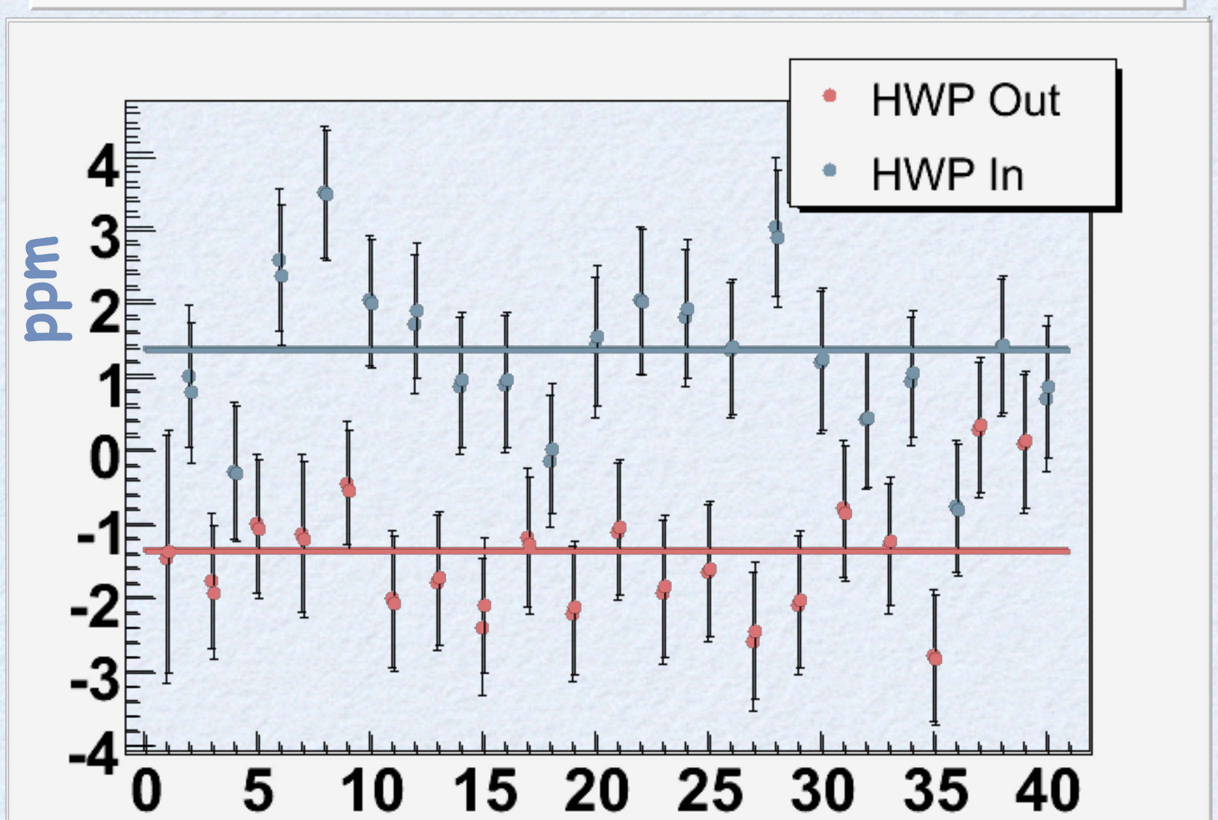
Normalization control ~ 2%

A_{PV} = +6.40 ± 0.23 (stat) ± 0.12 (syst) ppm

$A(G^s=0)$ = +6.37 ppm

HAPPEXII Final Results





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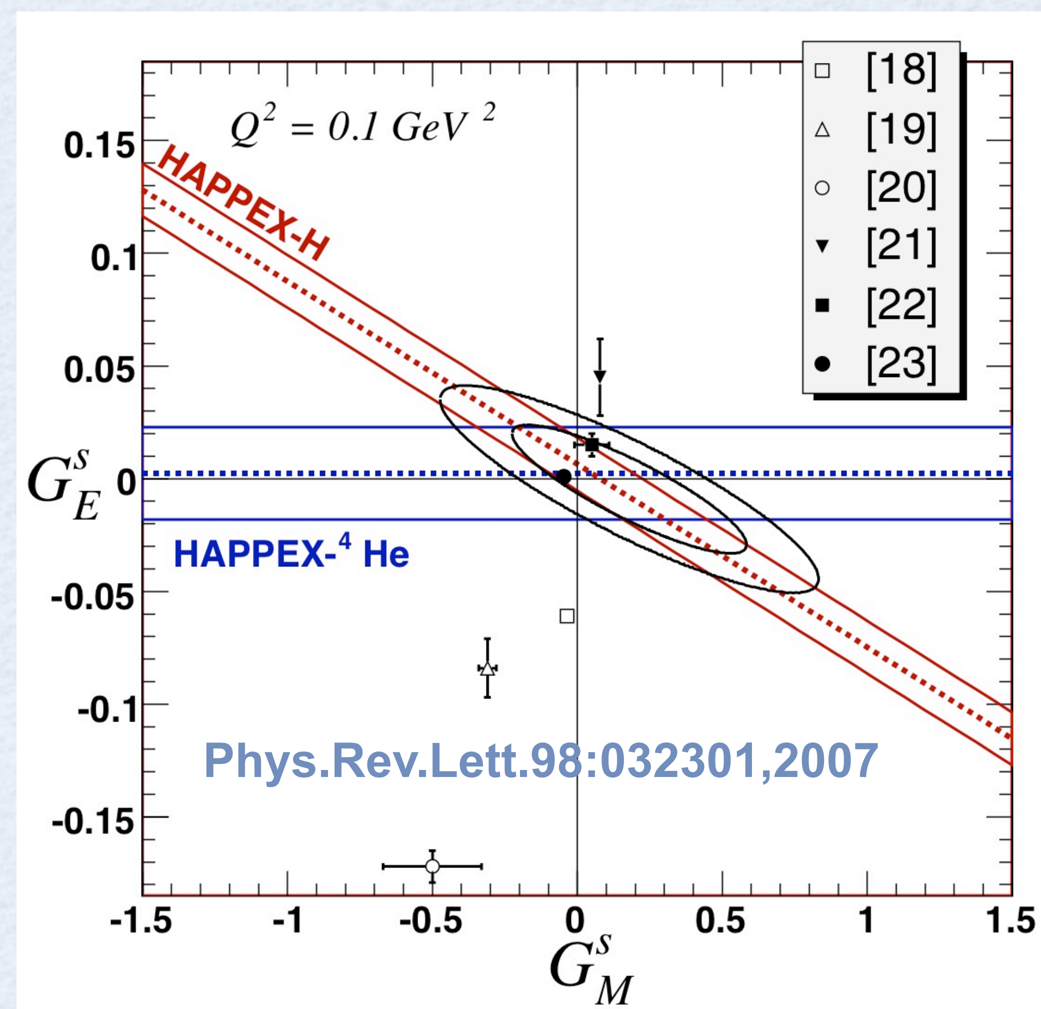
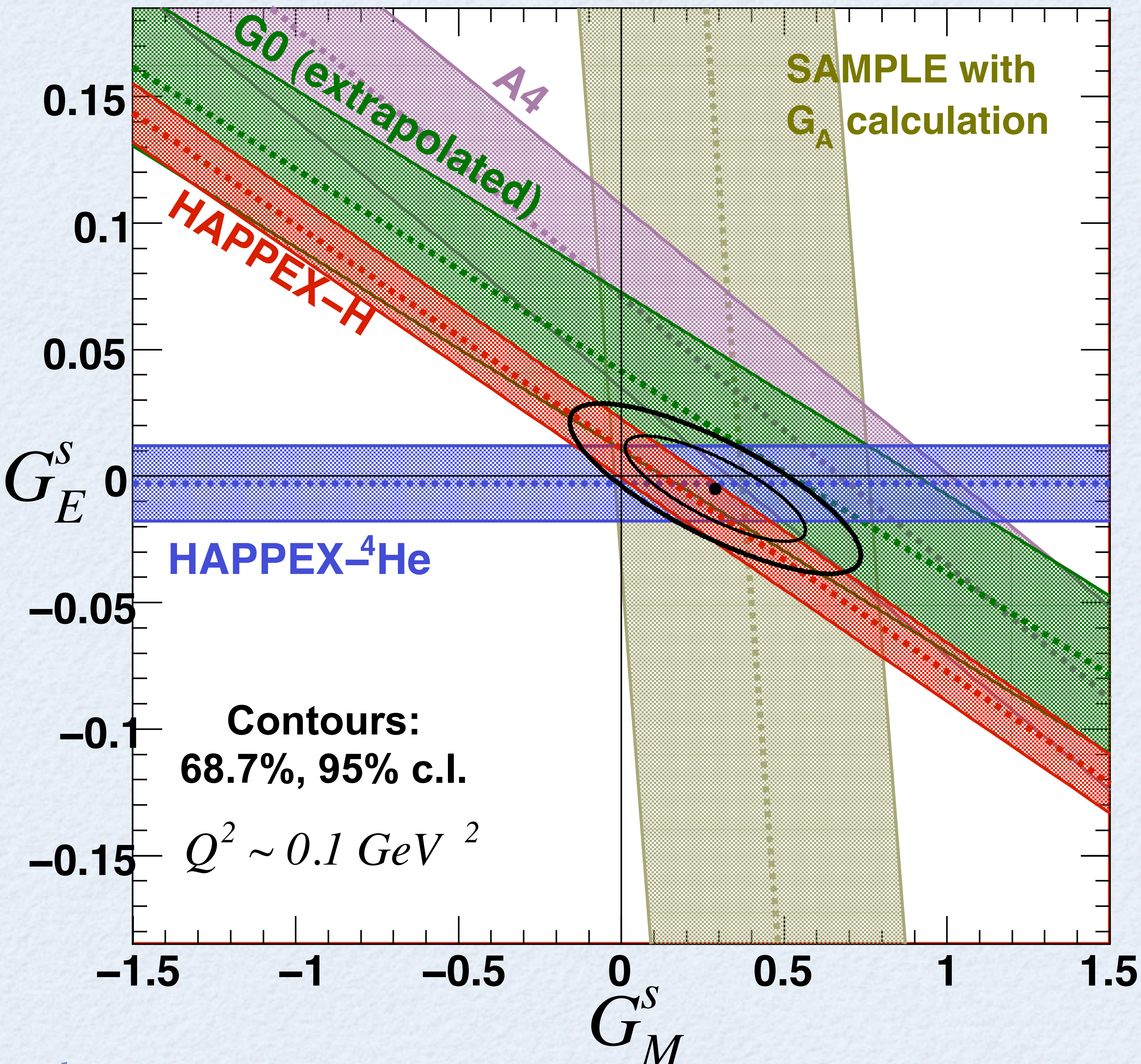


Strangeness Small!



at low Q^2

~3% +/- 2.3% of G_M^P

~0.2 +/- 0.5% of G_E^P

This simple fit ignores numerous (small) issues.

Published fits:

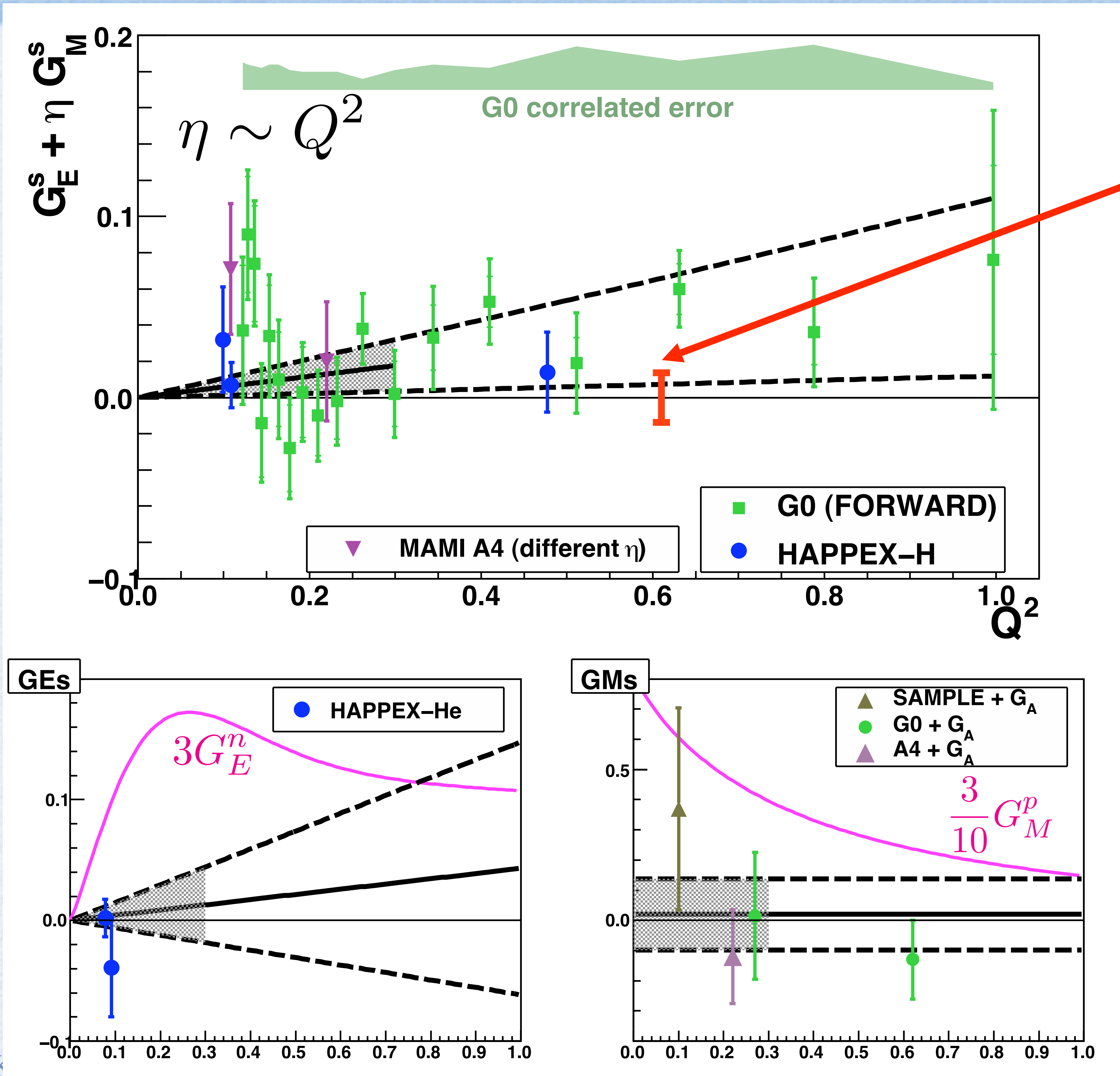
R. Young et al., Phys. Rev. Lett 97, 102002 (2006);

If fit floats G_A^p, G_A^n:
Central value more zero,
error bar slightly larger

J.Liu et al., Phys. Rev. C 76, 025202 (2007)

Very consistent with this analysis

Current Status



HAPPEX-III

$Q^2 \sim 0.62$ GeV^2

Data taking completed in 2009

$\delta(G_E^s + 0.48\, G_M^s) \sim 0.015$

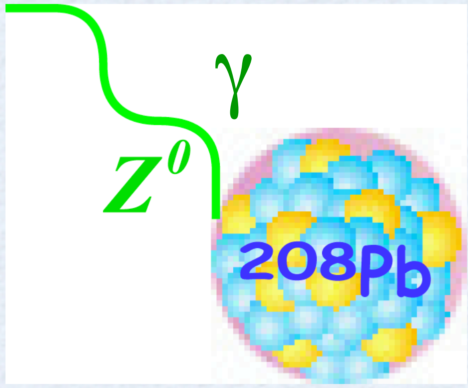
Statistics-limited error bar, with leading systematic error from polarimetry

Also: forward angle point from MAMI-A4 at same Q^2

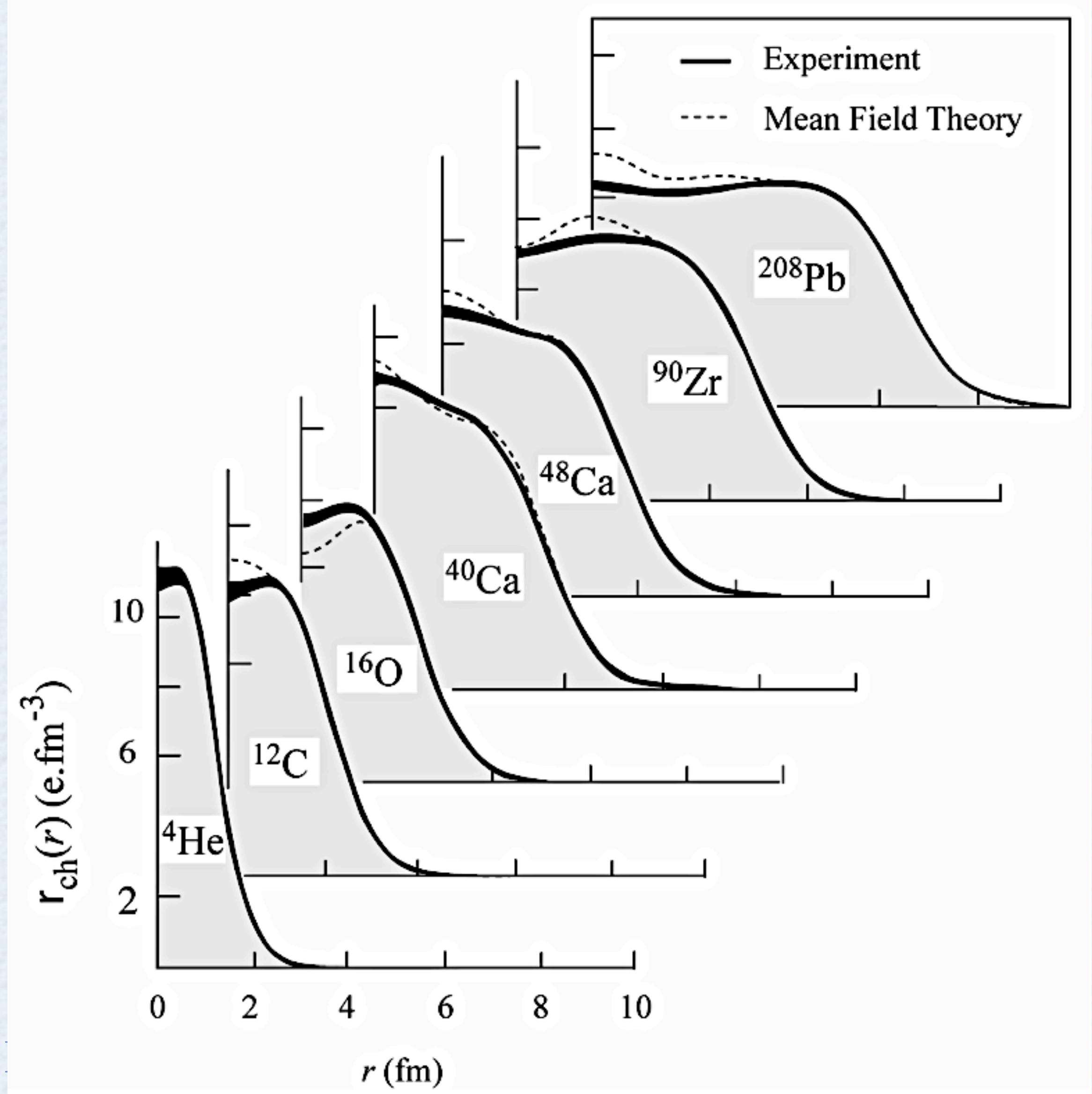
Both expected soon!

Clean Measurement of the Neutron Skin

Electroweak Probe



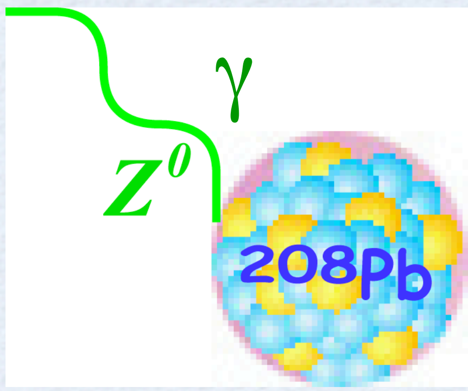
$Q^p_{EM} \sim 1$
$Q^n_{EM} \sim 0$



- The proton distribution of heavy nucleus: mapped via electron scattering
- The neutron distribution:
    - probed with hadrons
    - highly model-dependent
    - neutron "skin" ~ 0.1 - 0.3 fm?
- Neutron density a fundamental observable:
    - Impacts a variety of physics

Electroweak Probe

$Q^p{}_W \sim 1 - 4\sin^2\theta_W$



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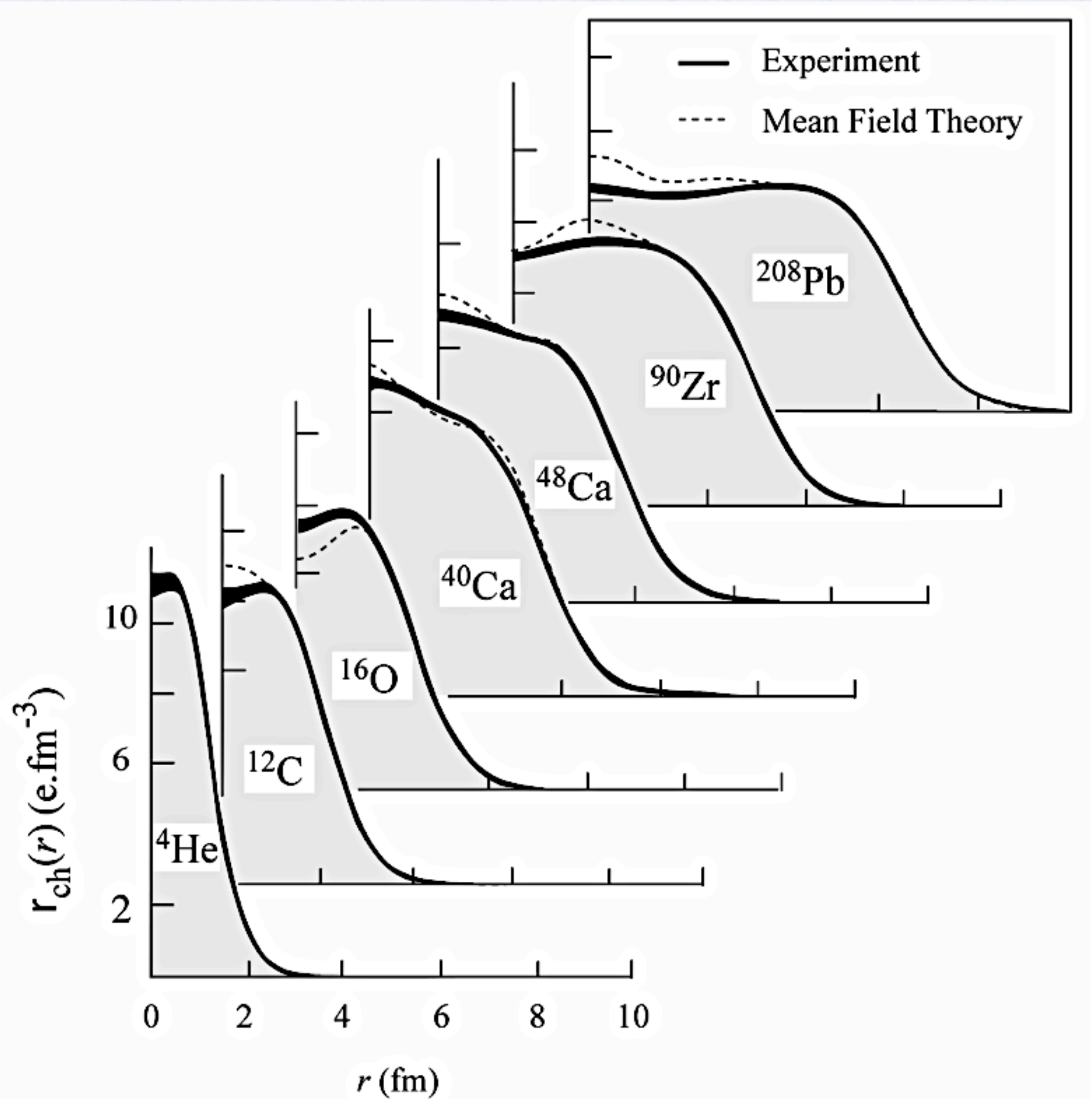

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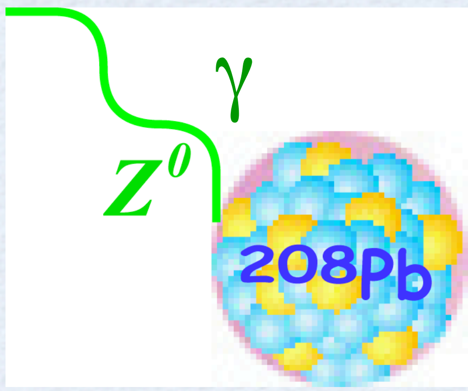


$Q^p_{EM} \sim 1$

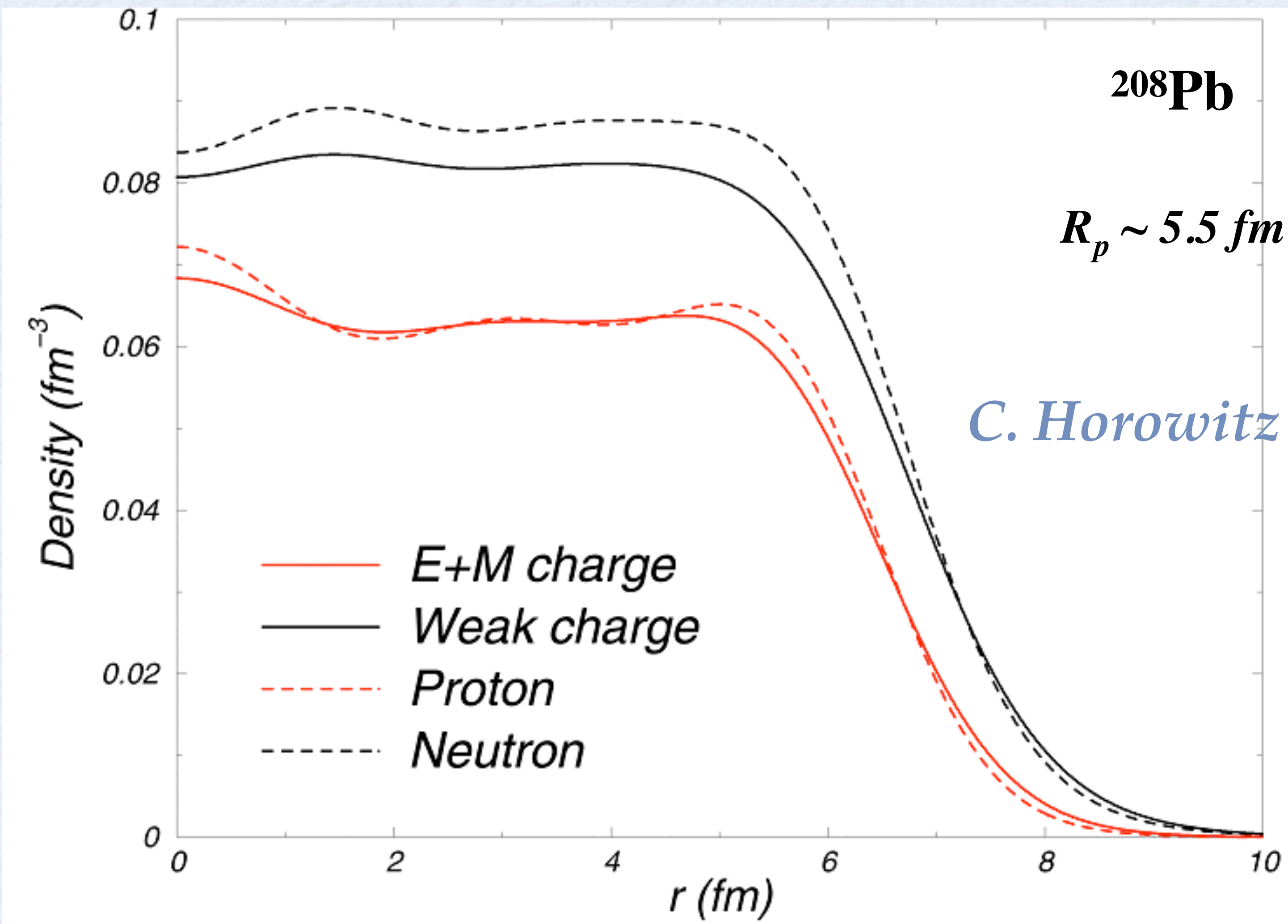
$Q^n_{EM} \sim 0$

$Q^n_W \sim 1$

$$\rho_W(r) = \int d^3r'[G^n_W(r'-r)\rho_n(r') + \frac{Q^p_W}{Q^n_W} G^p_W(r'-r)\rho_p(r')]$$

$$A_{pv} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \frac{F_W(Q^2)}{F_{ch}(Q^2)}$$

$$F_W(Q^2) = \int d^3r \frac{\sin(Qr)}{Qr} \rho_W(r)$$



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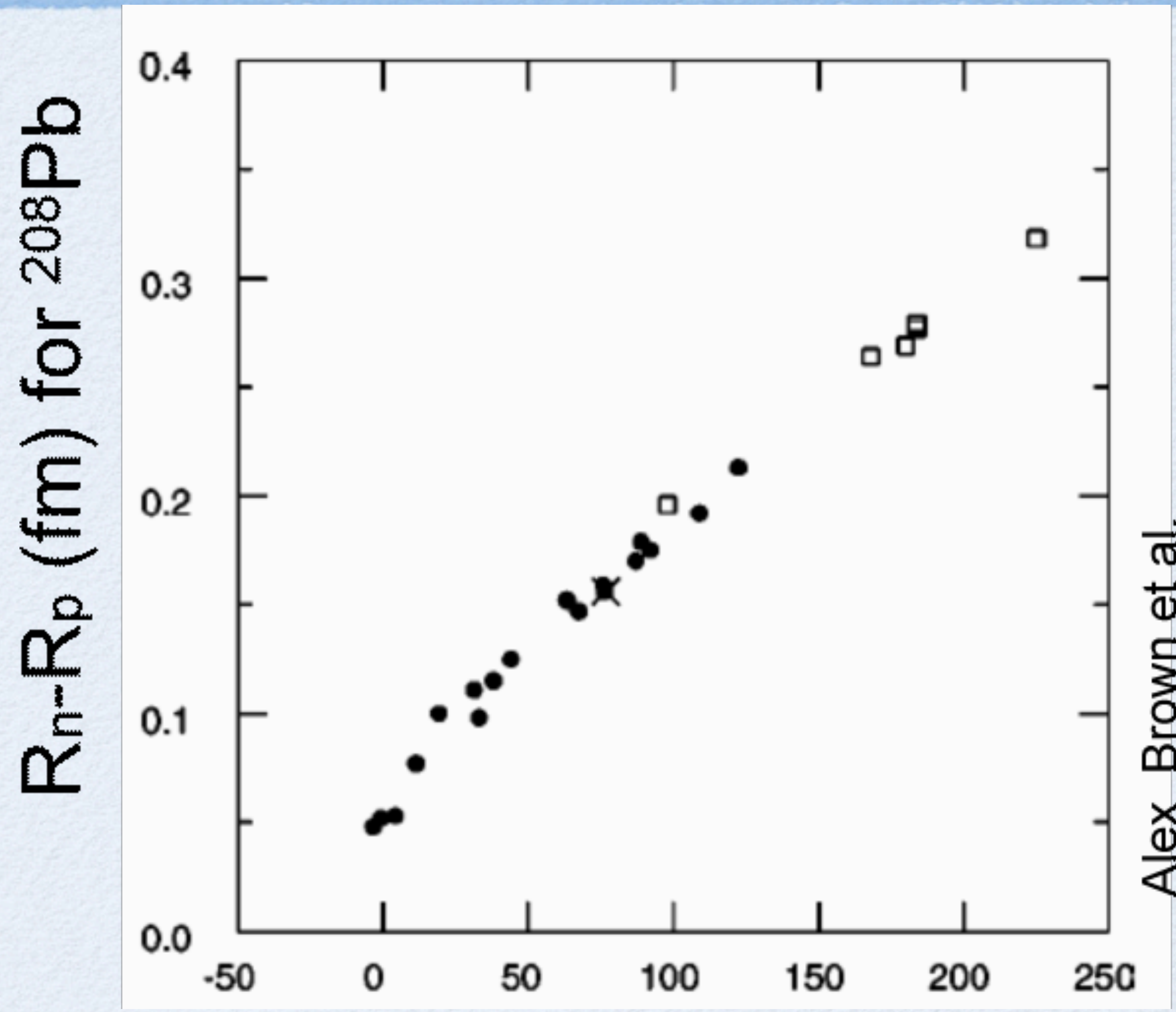
Equation of State

C. Horowitz

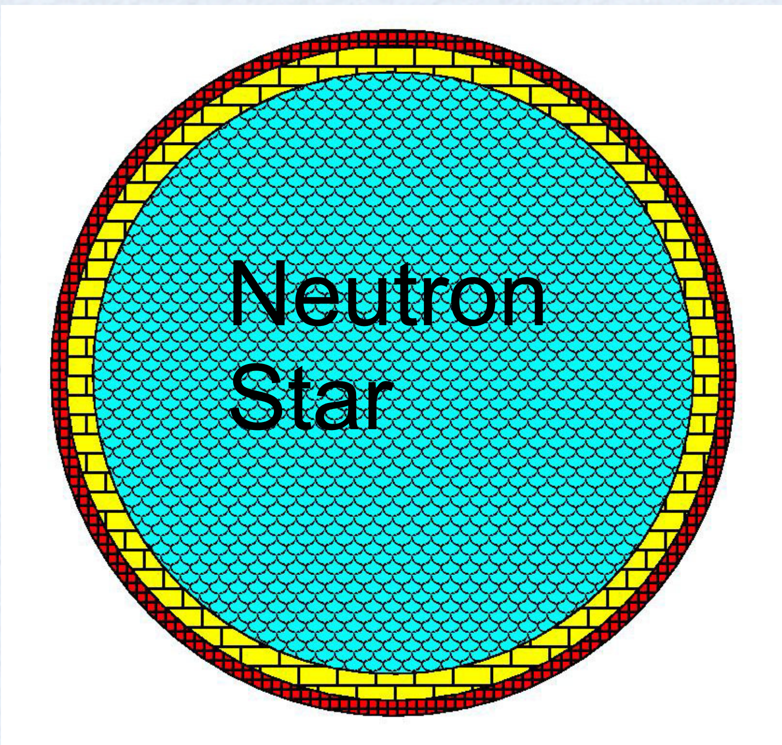
- Pressure forces neutrons out against surface tension. A large pressure gives a large neutron radius.
- Measuring R_n in ^{208}Pb constrains the pressure of neutron matter at some subnuclear density ~0.1 fm^{-3}.

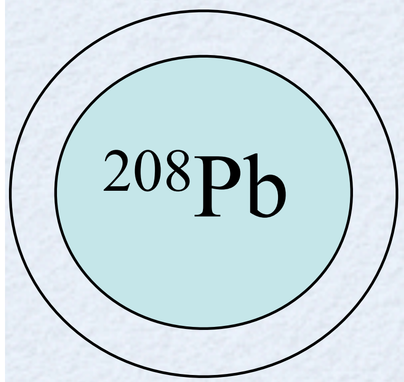


Neutron matter P (MeV/fm^3) at a density of 0.1 fm^{-3}.

Neutron Stars

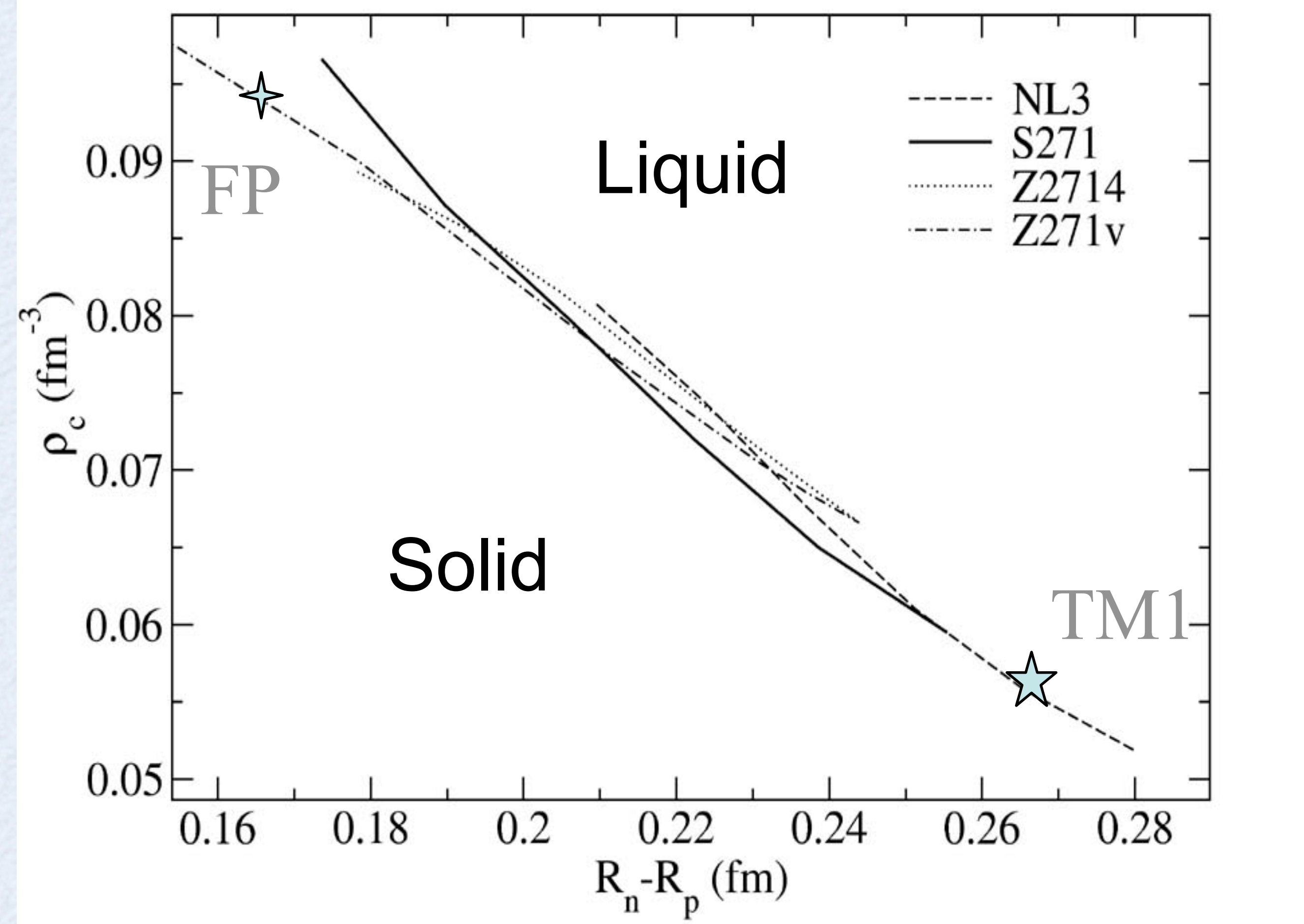
Neutron Star Crust vs ^{208}Pb Neutron Skin





- Neutron star has solid crust (yellow) over liquid core (blue).
- Nucleus has neutron skin.
- Both neutron skin and NS crust are made out of neutron rich matter at similar densities.
- Common unknown is EOS at subnuclear densities.

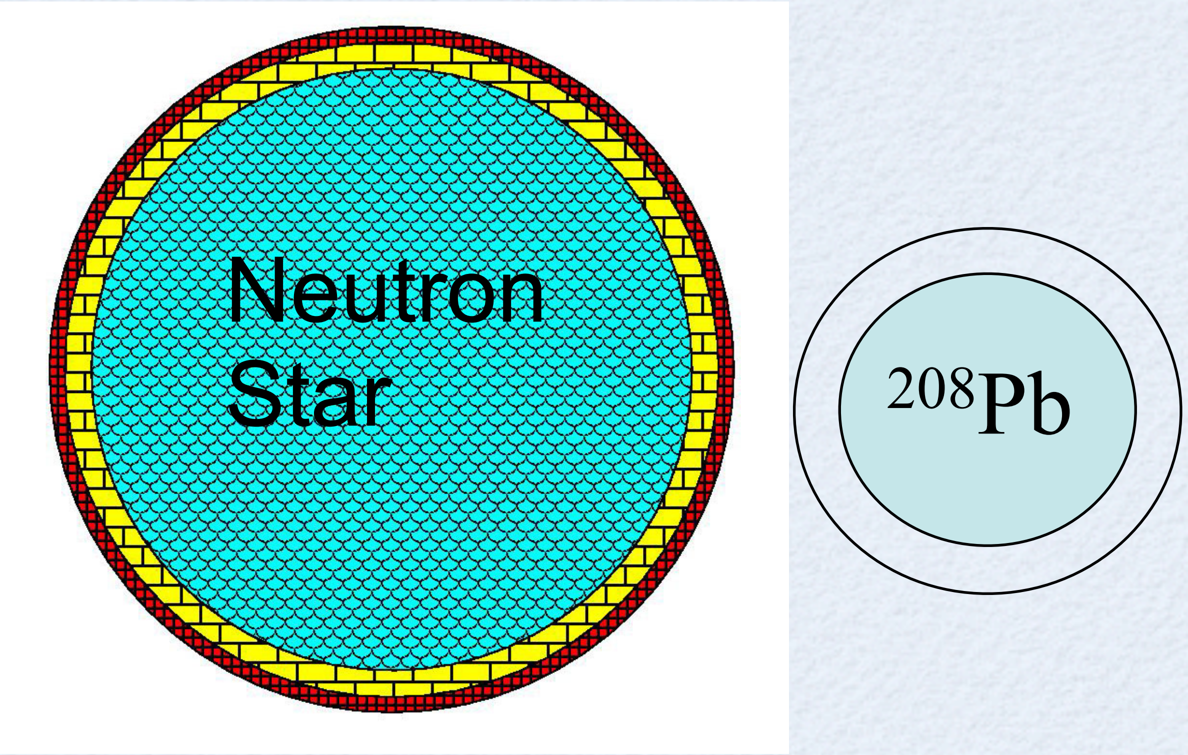
Liquid/Solid Transition Density



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

Neutron Stars

Neutron Star Crust vs ^{208}Pb Neutron Skin



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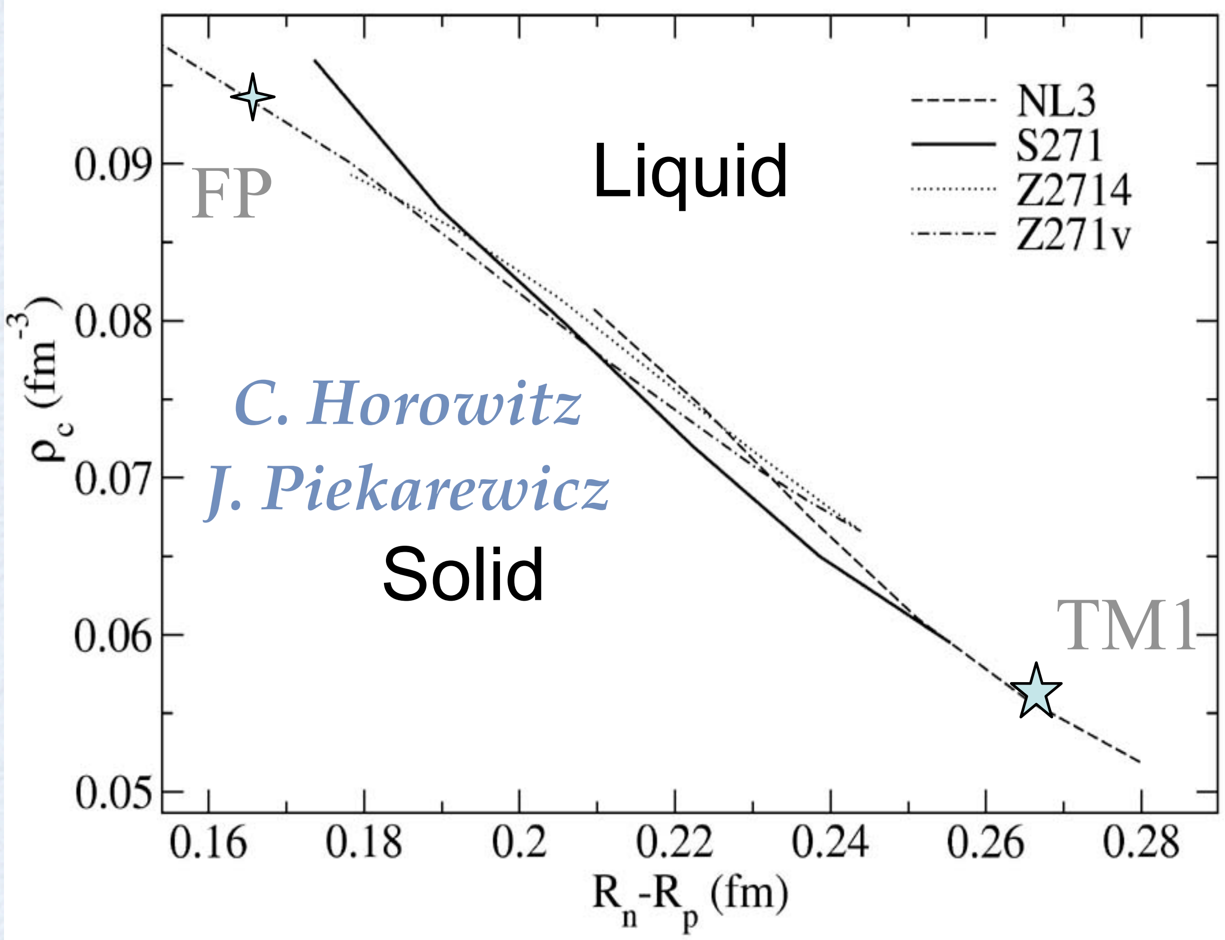

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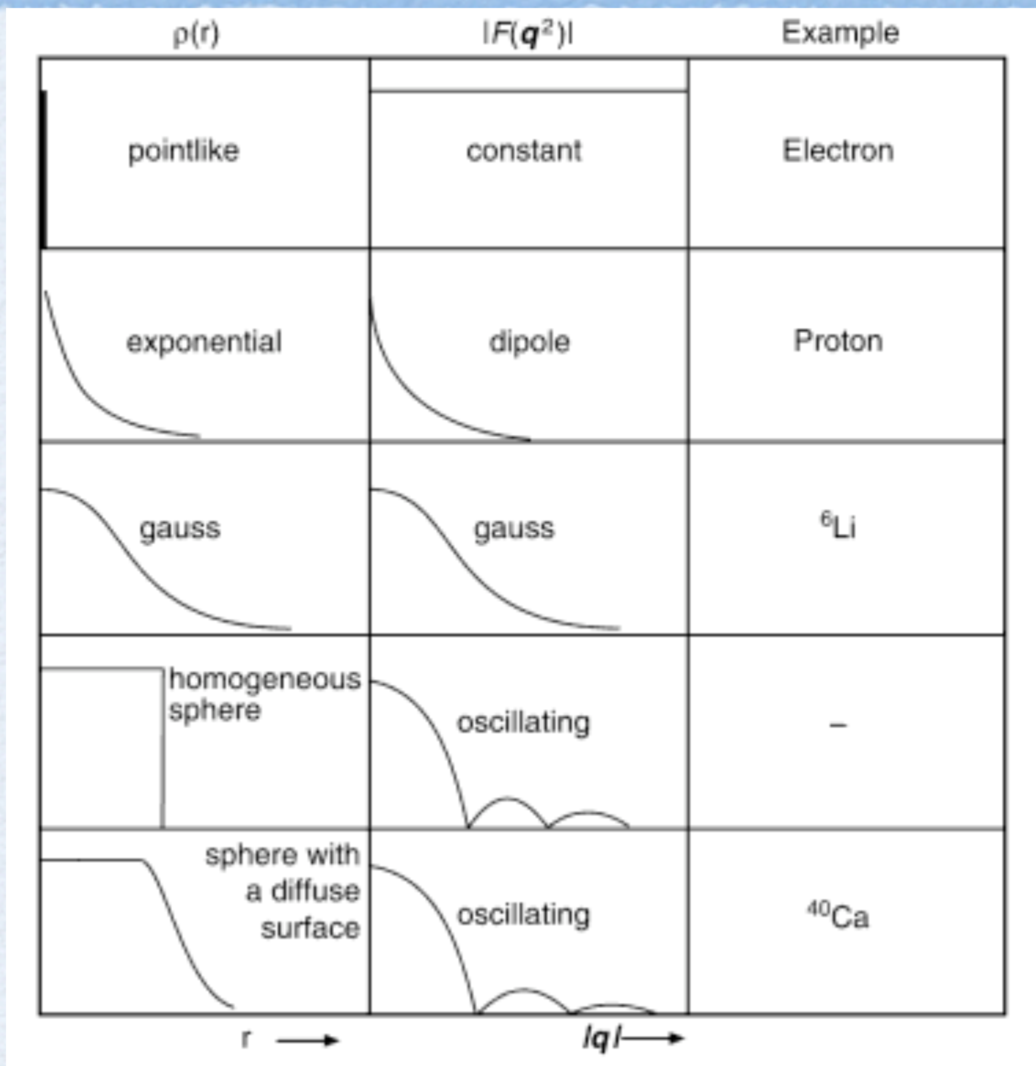

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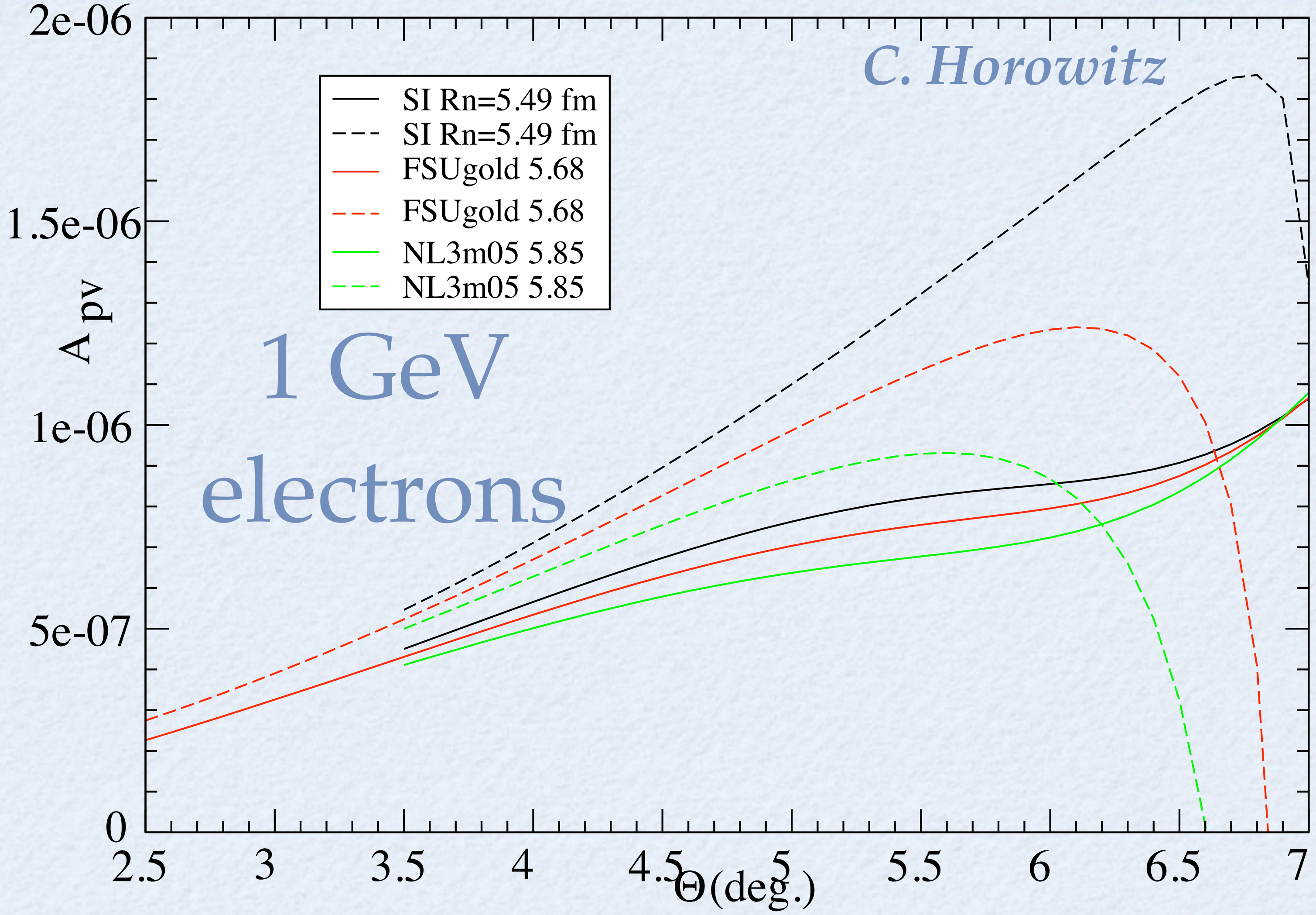

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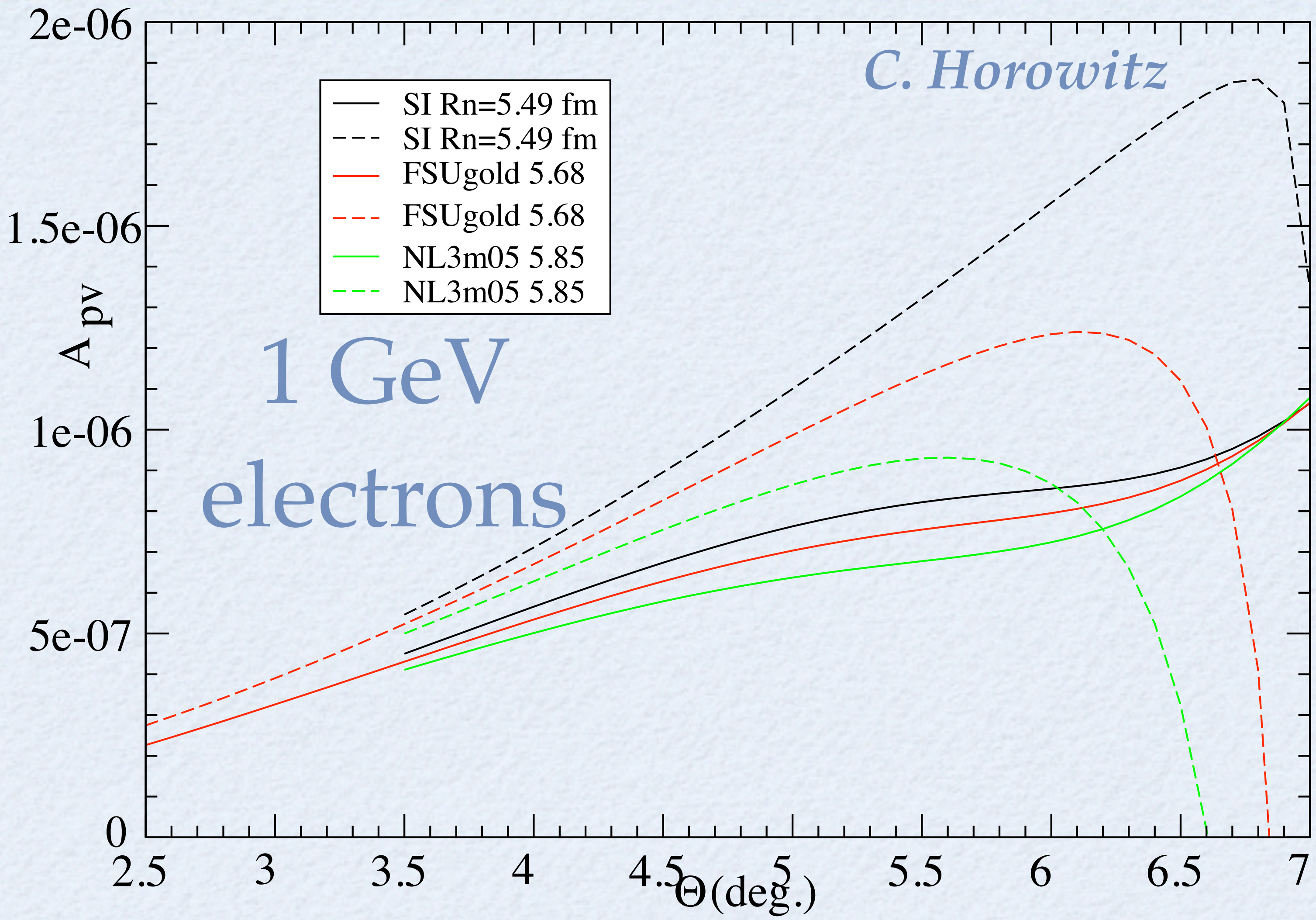
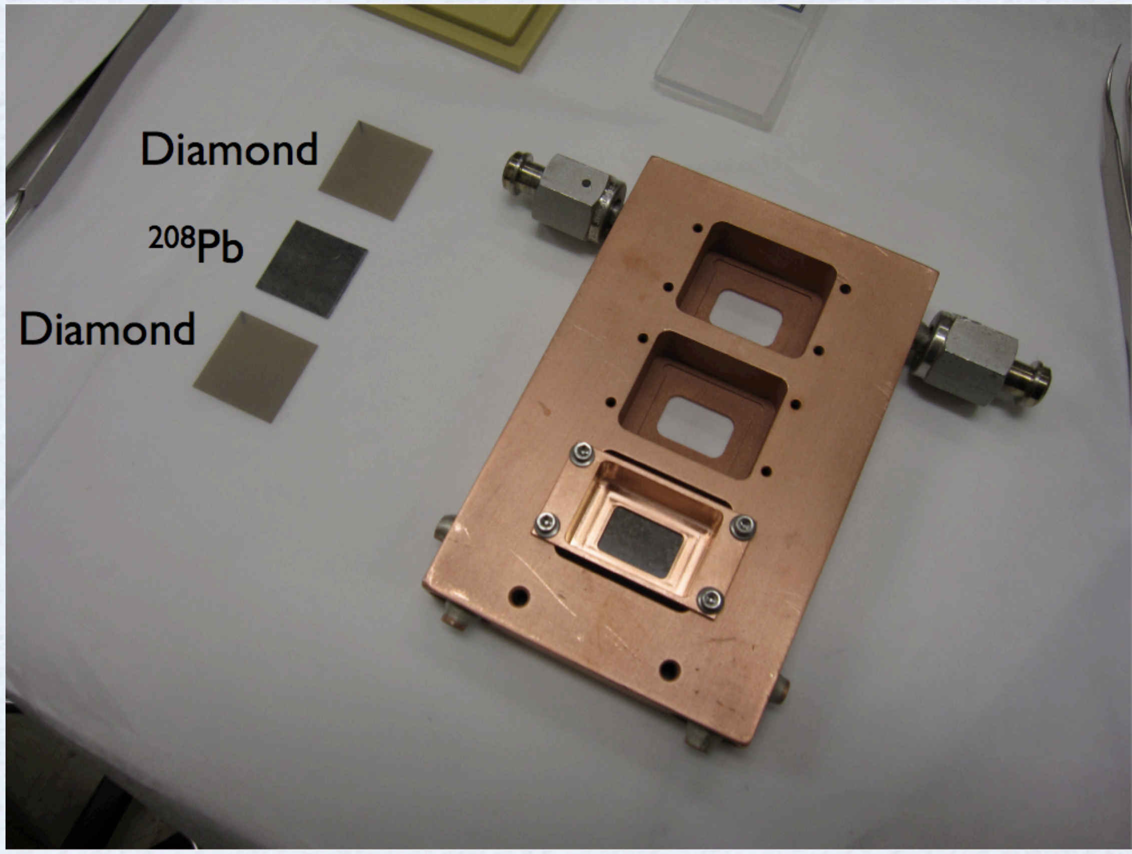


$Q^2 \sim 0.01$ GeV^2 ⇒ $A_{PV} \sim 0.5$ ppm

A technically demanding measurement:

- Rate ~ 2 GHz
- Separate excited state at 2.6 MeV
- Stat. Error ~ 15 ppb
- Syst. Error ~ 1 to 2 %

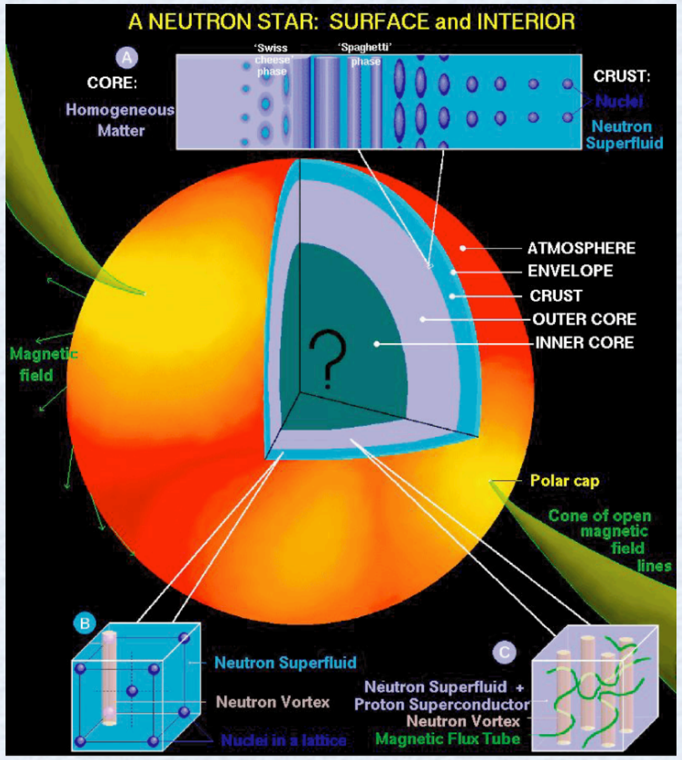
$\delta(A_{PV}) \sim 3\%$ ⇒ $\delta(R_p\text{-}R_n) \sim 0.06$ fm



- *Tight control of beam properties*
- *New "warm" septum*
- *High power Lead target*
- *New 18-bit ADC*
- *New radiation-hard detector*
- *Polarimetry upgrade*

Status and Plans

- *Ran from April-June 2010*
- *20% of statistics collected*
- *Number of technical challenges overcome*
- *Result targeted for Spring 2011*



J.M. Lattimer,
M. Prakash
Science, **304**, 536

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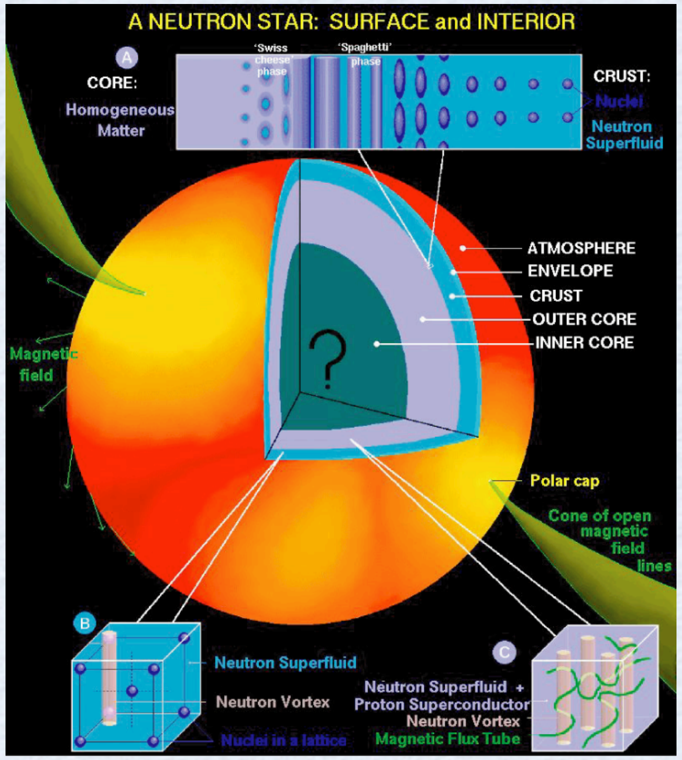

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- Propose to come back either just before or just after 12 GeV upgrade shutdown
- Designing new experiment on ^{48}Ca

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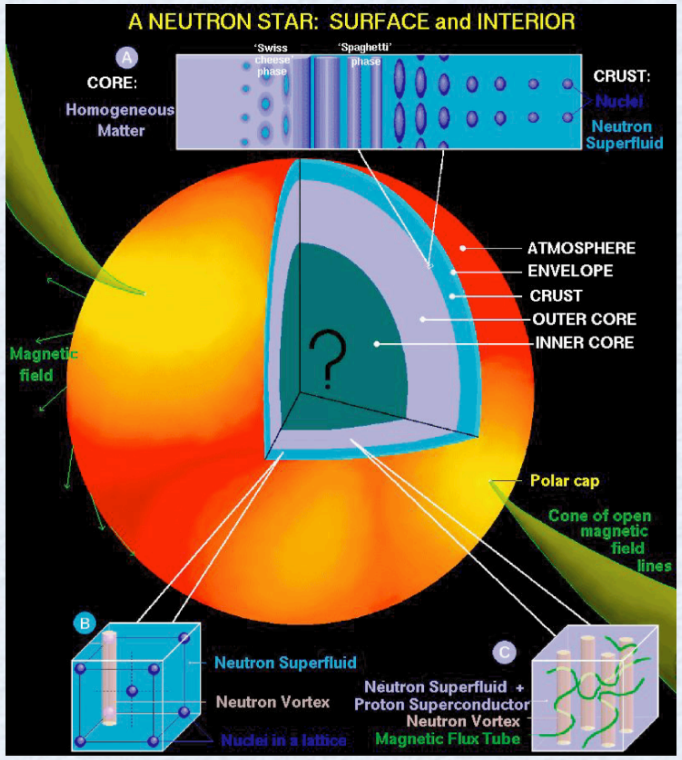

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Statistical error at JLAB Hall A:
assuming 100μA, 5° for 30 days

	E	Rate	A_{pv}	R_n	$t(1\%)$
	(GeV)	MHZ	ppm	%	days
^{208}Pb	1.05	1700	0.72	0.66	**13**
	1.8	53	2.1		
^{120}Sn	1.2	1080	1.06	0.56	**9.4**
^{48}Ca	1.7	270	2.2	0.43	**5.5**
	2.1	21	2.8		

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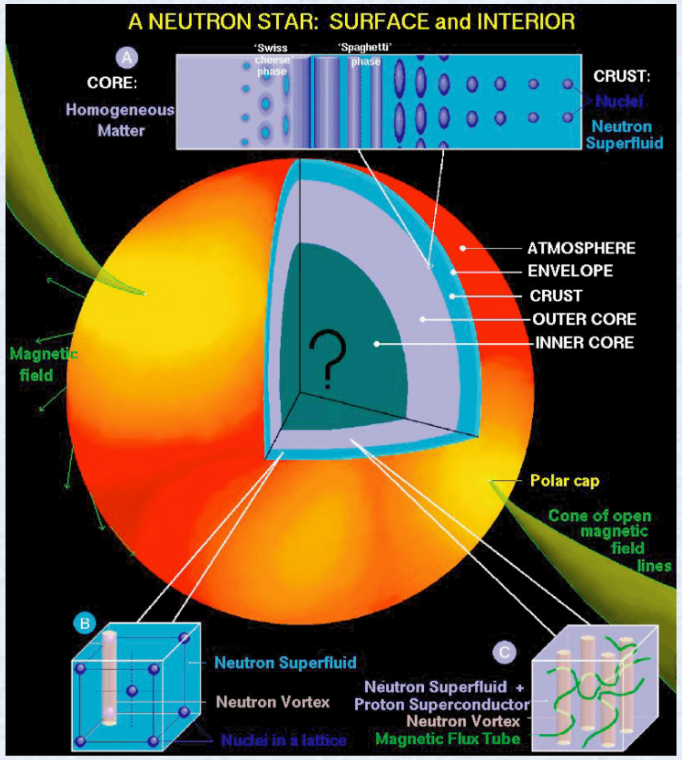

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Science, **304**, 536

^{48}Ca
12 GeV era
Proposal?

- *Far from ^{208}Pb*
- *Compare to ^{40}Ca*
- *Microscopic calculations: 2 & 3 nucleon forces*
- *Important double-beta decay nucleus*

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C. Horowitz and R. Michaels

Summary

parity-violating electron scattering has become a unique, precision tool for nuclear physics

- ***Sensitive limits on strangeness contributions to the charge and magnetization distributions of nucleons: challenge for low energy QCD theory***
- ***Clean measurement of the neutron radius in heavy nuclei: impact on nuclear structure and neutron stars***
- ***Future experiments will probe new aspects of nucleon structure***
- ***Legacy: more and more sensitive measurements & new nuclear systems to search for physics beyond the standard model***

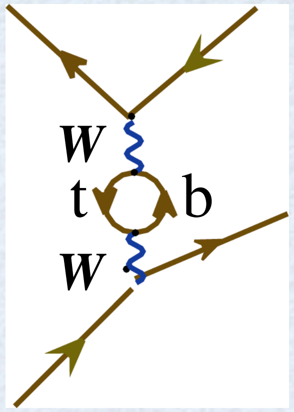
Precision EW Physics

Start with 3 fundamental inputs needed: α_{em}, G_F and M_Z

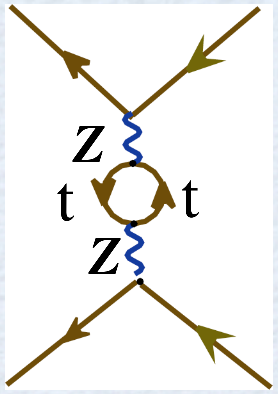
Other experimental observables predicted at 0.1% level:
sensitive to heavy particles via higher order quantum corrections

4th and 5th best measured parameters: $\sin^2\theta_W$ and M_W

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



Muon decay



Z production

$$\Pi_{WW} - \Pi_{ZZ} \propto m_t^2 - m_b^2$$

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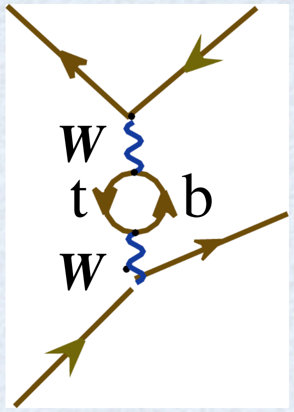

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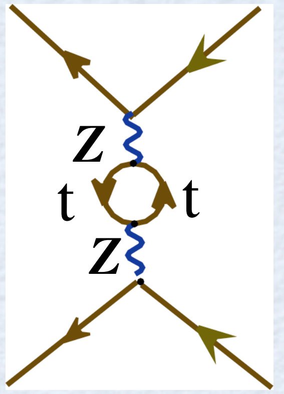

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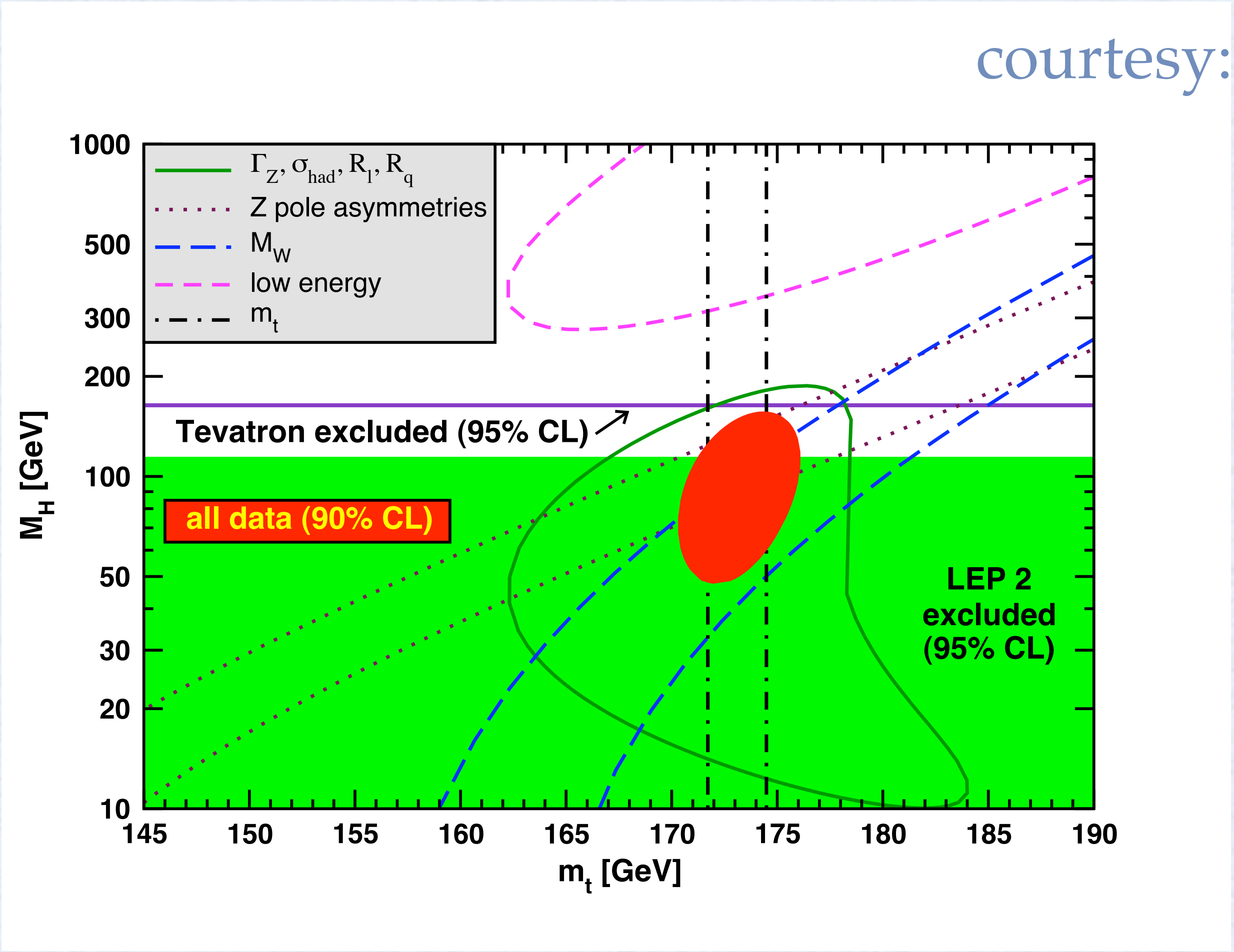

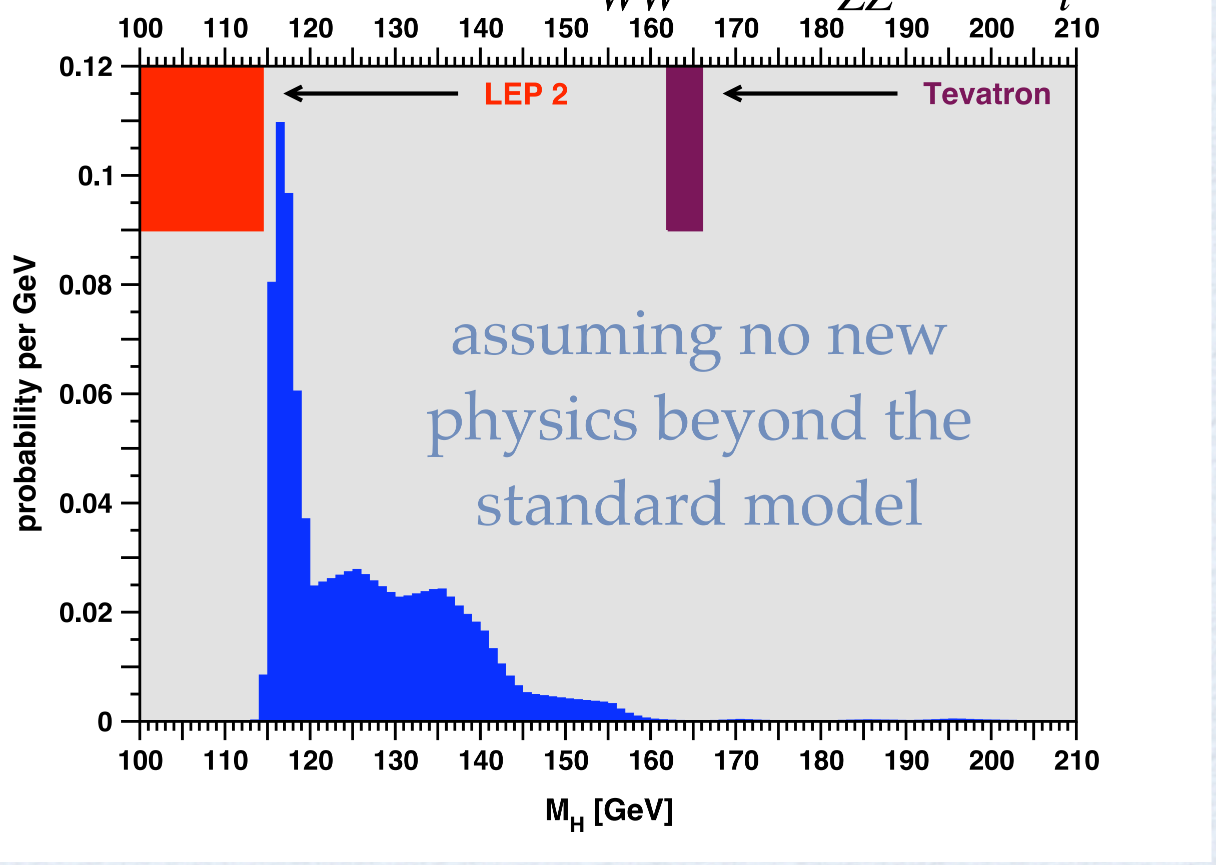

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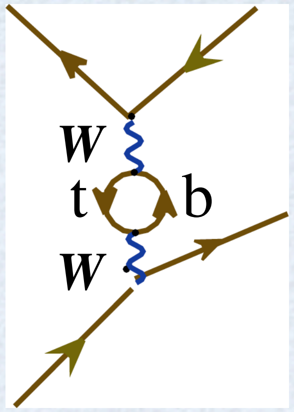

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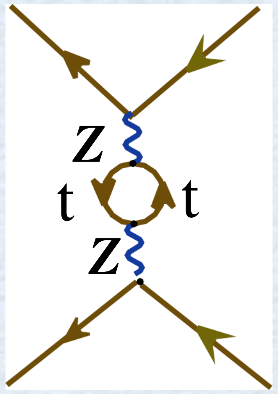

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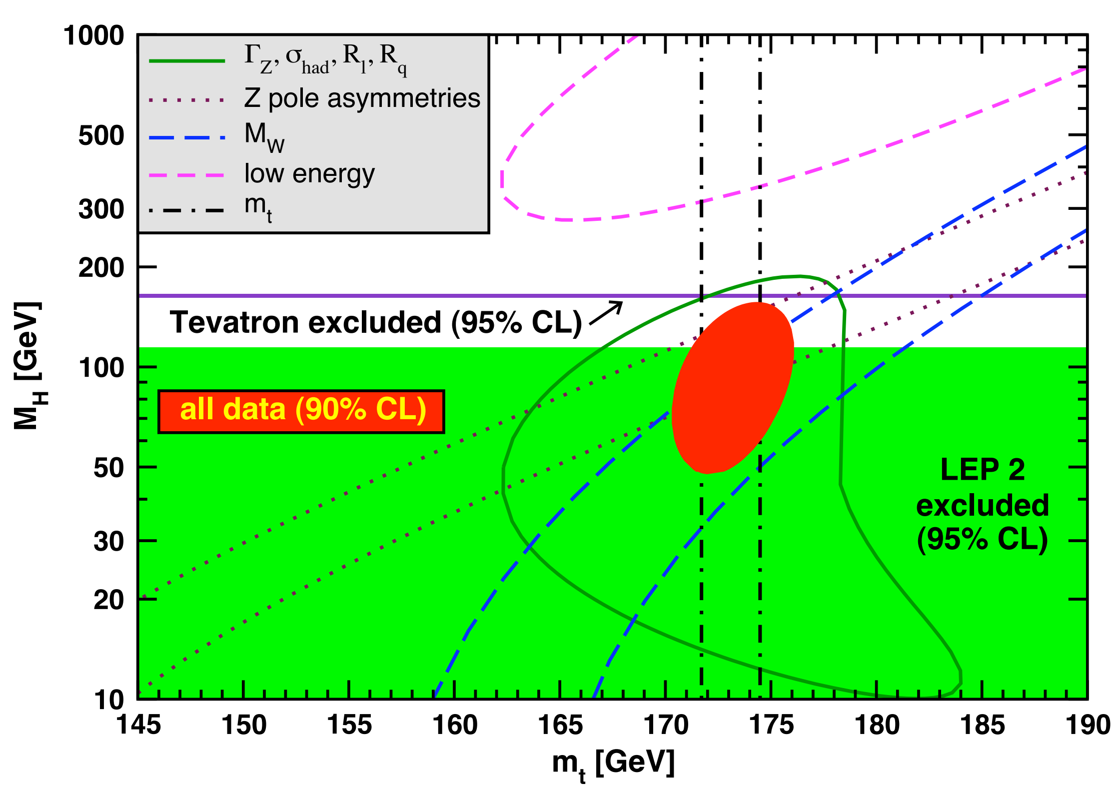

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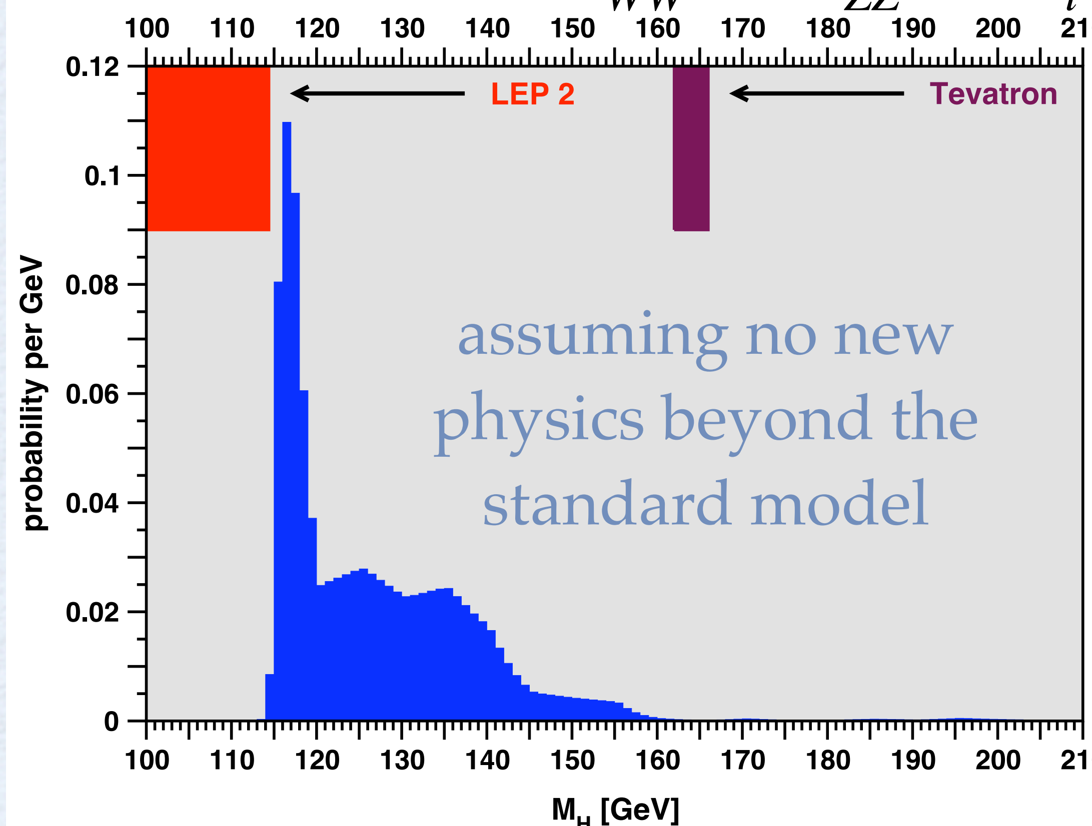
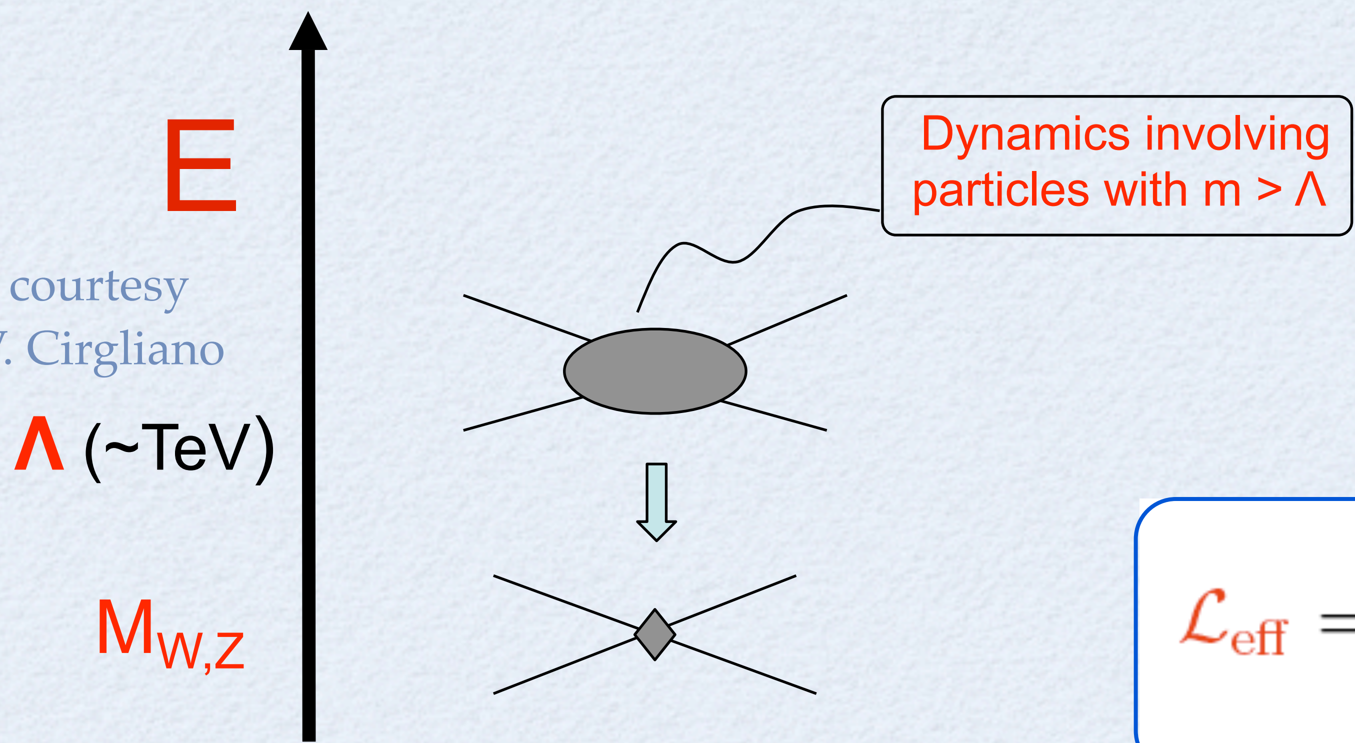


Allows searches for new physics at the TeV scale via small measurement deviations

Comprehensive Search

Neutral Current Interactions at Low AND High Energy



courtesy V. Cirgliano

Many theories predict new forces that disappeared when the universe cooled

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

$$\Downarrow$$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \sum_{d \geq 5} \frac{c_n^{(d)}}{\Lambda^{d-4}} \hat{O}_n^{(d)}[\phi_{SM}]$$

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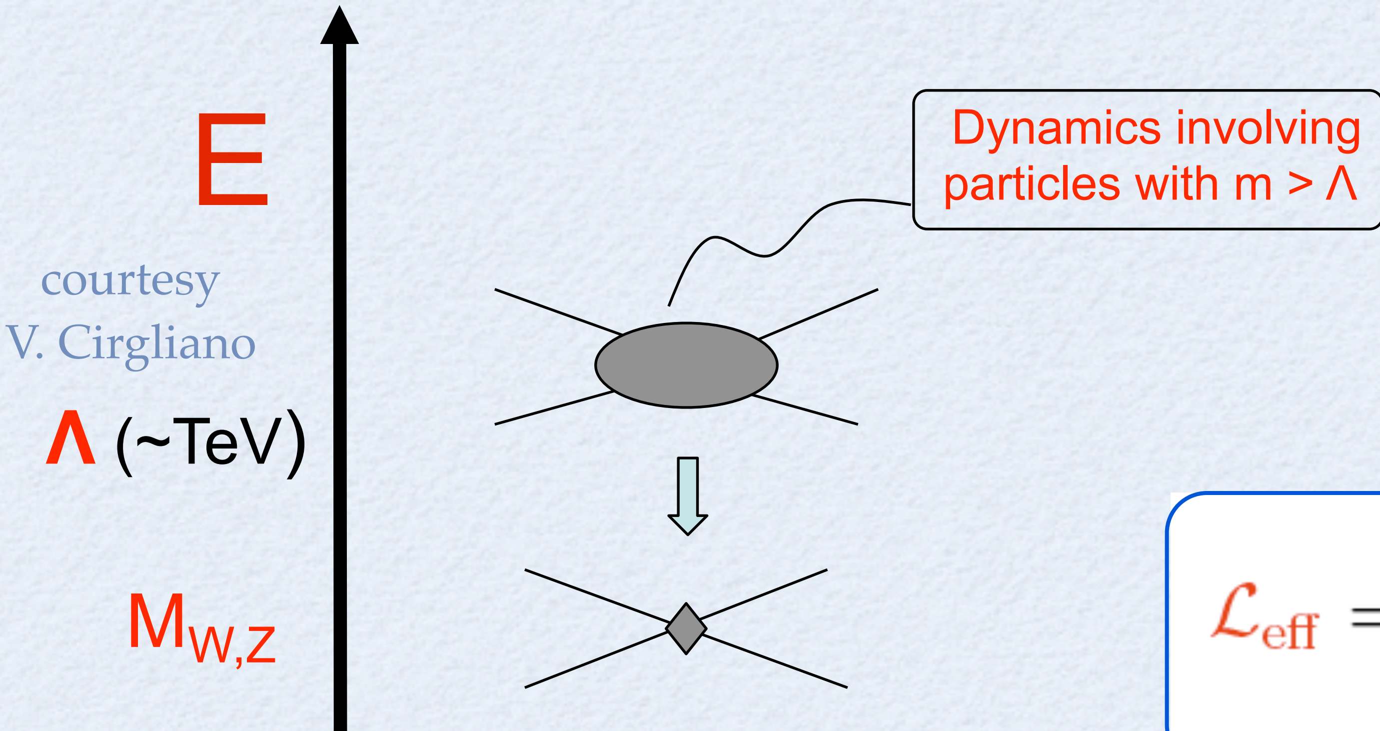

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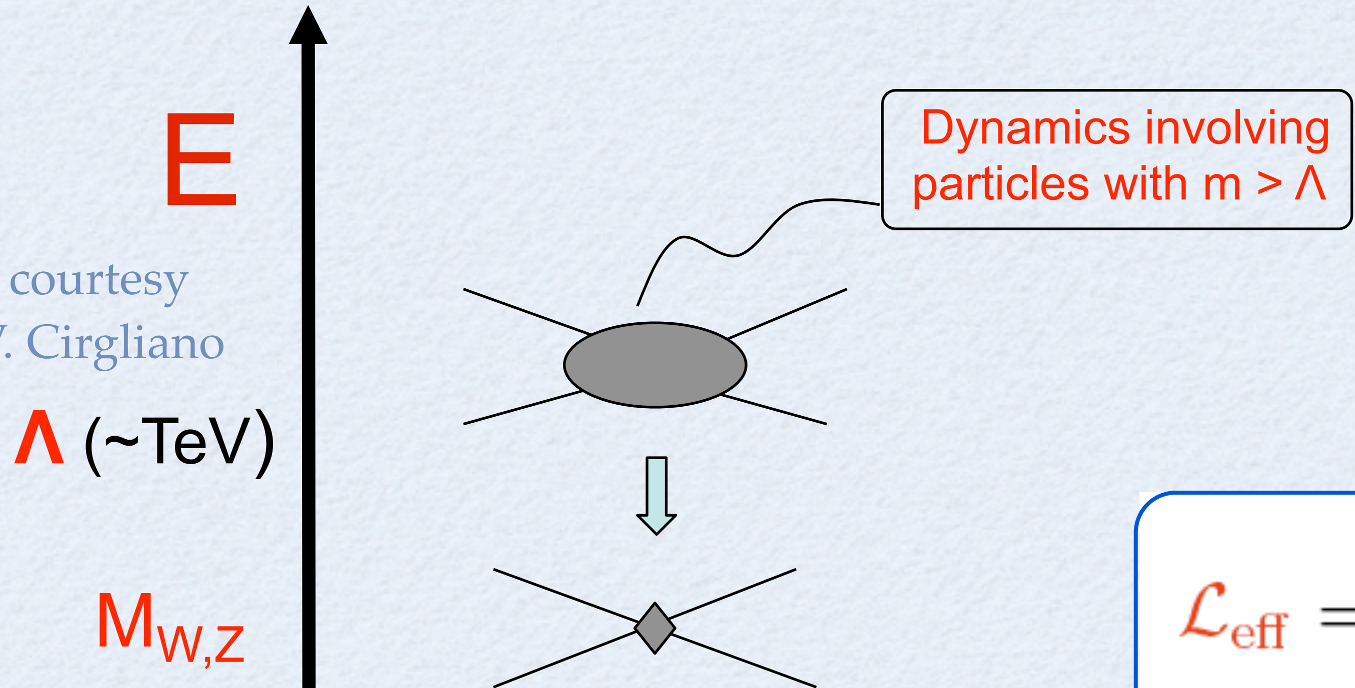
$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{SM} + \sum_{d\geq 5} \frac{c_n^{(d)}}{\Lambda^{d-4}} \hat{O}_n^{(d)}[\phi_{SM}]$$

There are often mechanisms to suppress Flavor Changing Neutral Currents

Comprehensive Search

Neutral Current Interactions at Low AND High Energy

courtesy
V. Cirgliano



Many theories predict new forces that disappeared when the universe cooled

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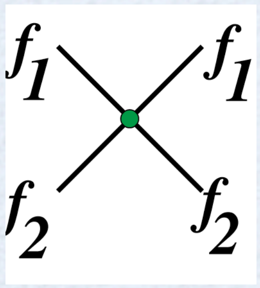
Flavor Diagonal Interactions

Consider $f_1\bar{f}_1 \to f_2\bar{f}_2$ or $f_1 f_2 \to f_1 f_2$

$$L_{f_1 f_2} = \sum_{i,j=L,R} \frac{4\pi}{\Lambda_{ij}^2} \eta_{ij} \bar{f}_{1i}\gamma_\mu f_{1i} \bar{f}_{2j}\gamma^\mu f_{2j}$$



Many new physics models give rise to such terms: Heavy Z's, compositeness, extra dimensions, SUSY…

Colliders vs Fixed Target

Neutral Current Amplitude at Low Energy

One goal of neutral current measurements at low energy AND colliders:
Access $\Lambda > 10$ TeV for as many f_1,f_2 and L,R combinations as possible

Colliders access scales Λ's ~ 10 TeV

Tevatron, LEP, SLC, LEP200, HERA

- L,R combinations accessed are mostly parity-conserving

Z boson production accessed some parity-violating combinations but…

on resonance:
A_Z imaginary

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

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- *Spin-dependent electron scattering*
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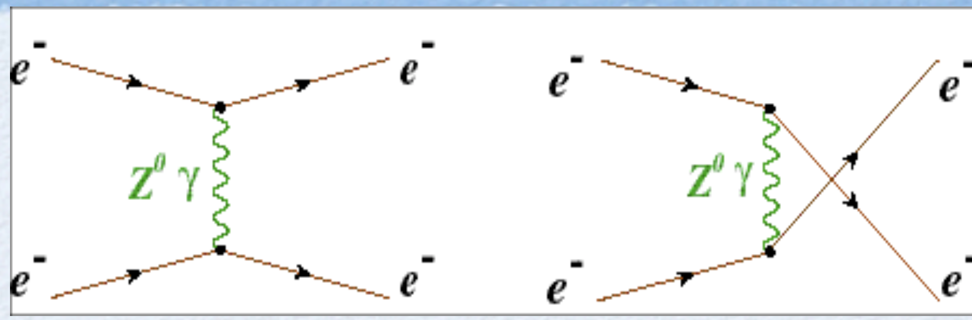
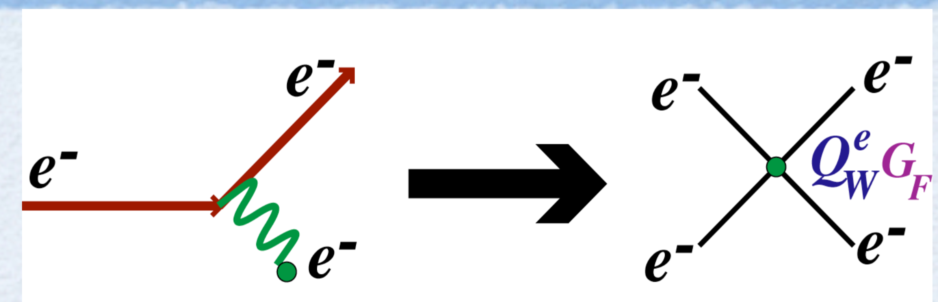
Electromagnetic amplitude interferes with Z-exchange as well as any new physics

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

Electron Weak Charge

Parity-Violating Electron-Electron (Møller) Scattering





Purely leptonic reaction

Derman and Marciano (1978)

$$\mathbf{A_{PV} = -mE \frac{G_F}{\sqrt{2}\pi\alpha} \frac{16 \sin^2 \Theta}{(3 + \cos^2 \Theta)^2} Q_W^e}$$

50 GeV at SLAC: ~ 150 ppb!

E158 at SLAC *Major technical challenges*

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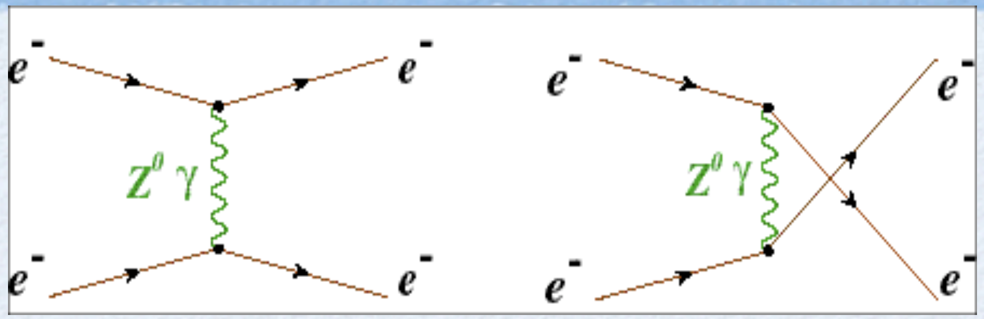

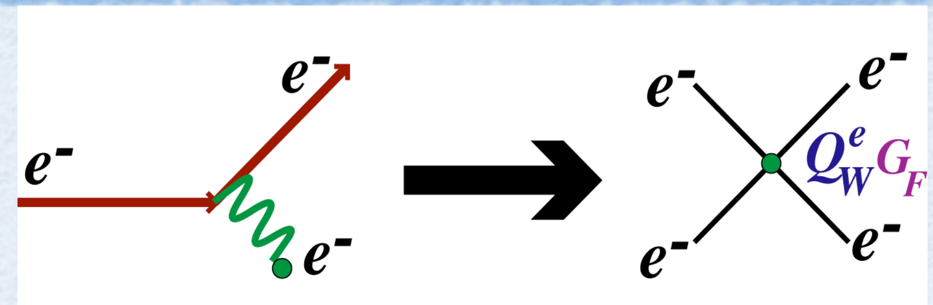

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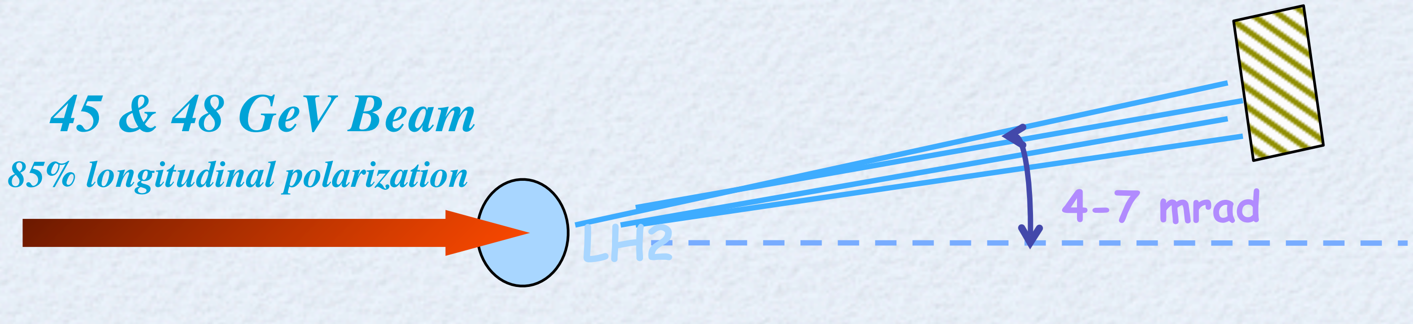

Final Result:

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

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

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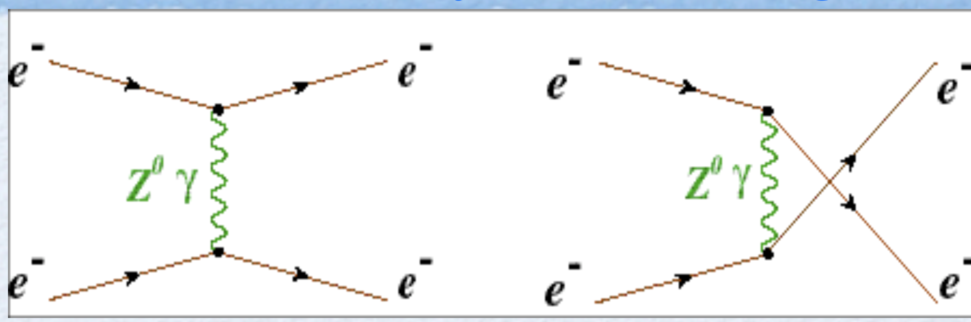

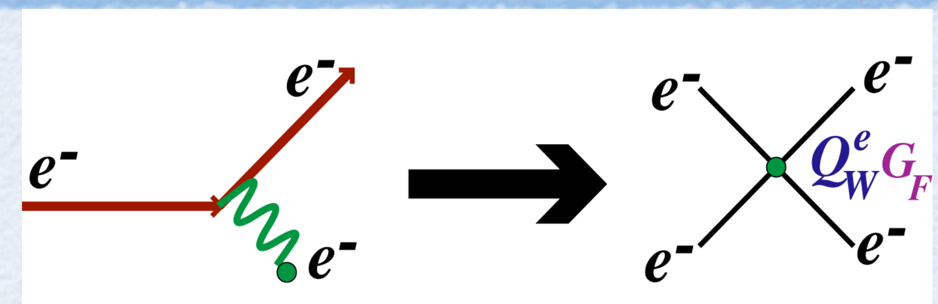

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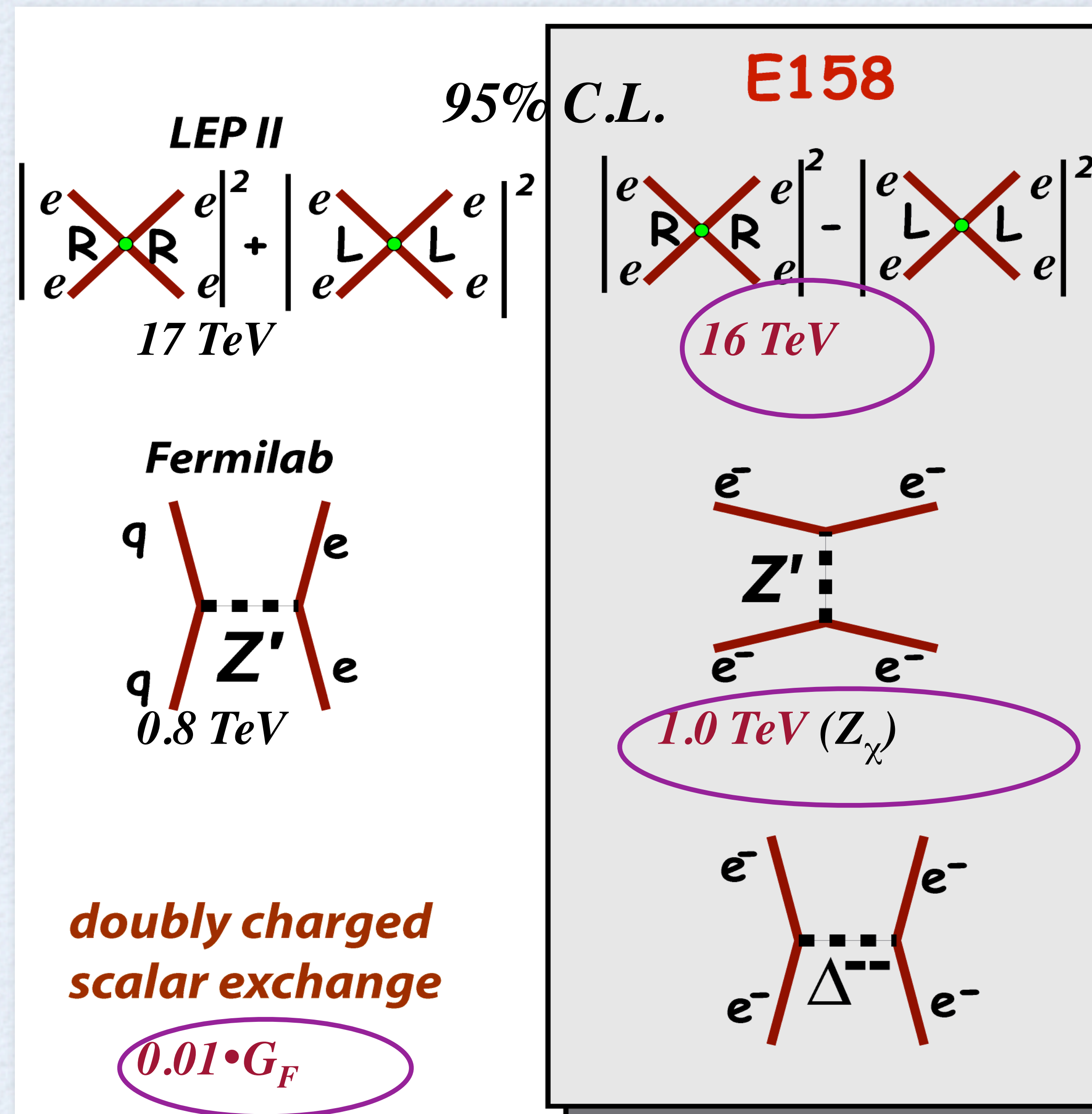
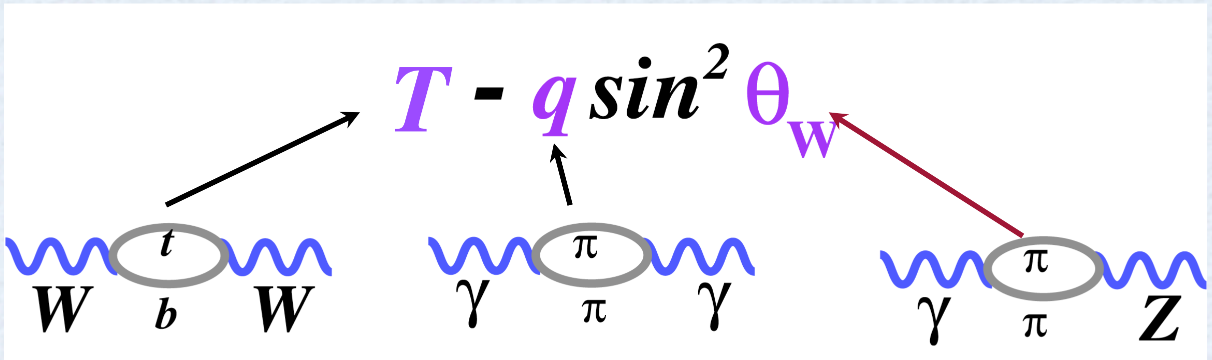
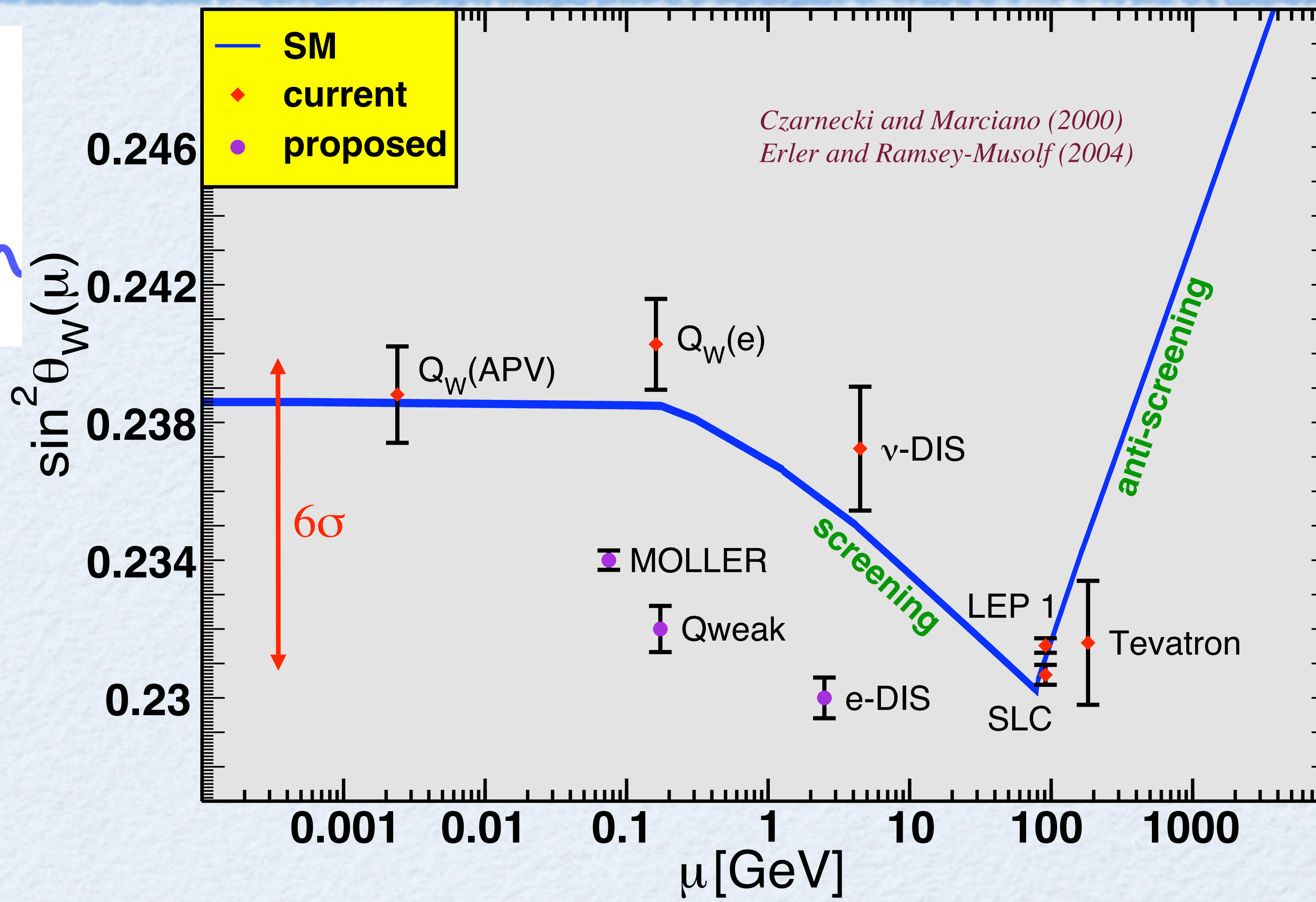


The Weak Mixing Angle

Running of θ_W: Bookkeeping for off-resonance measurements





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- *W-W loop provides indirect m_t*
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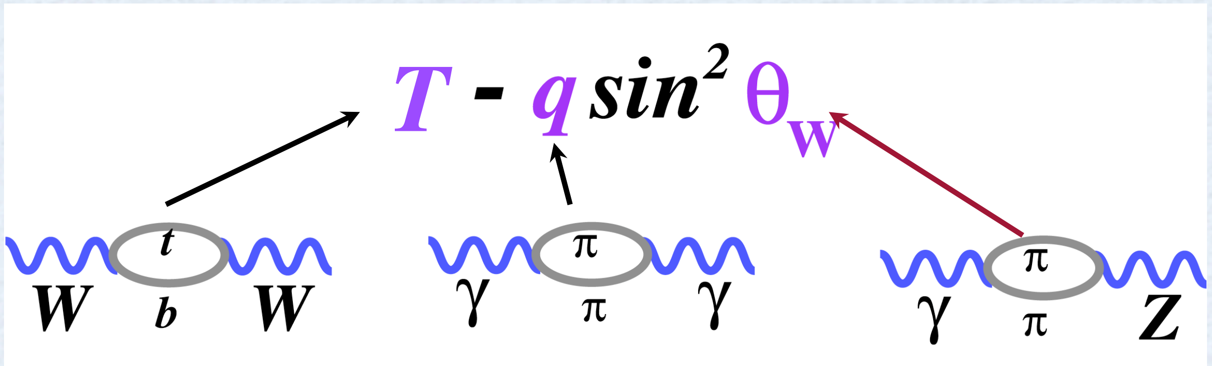

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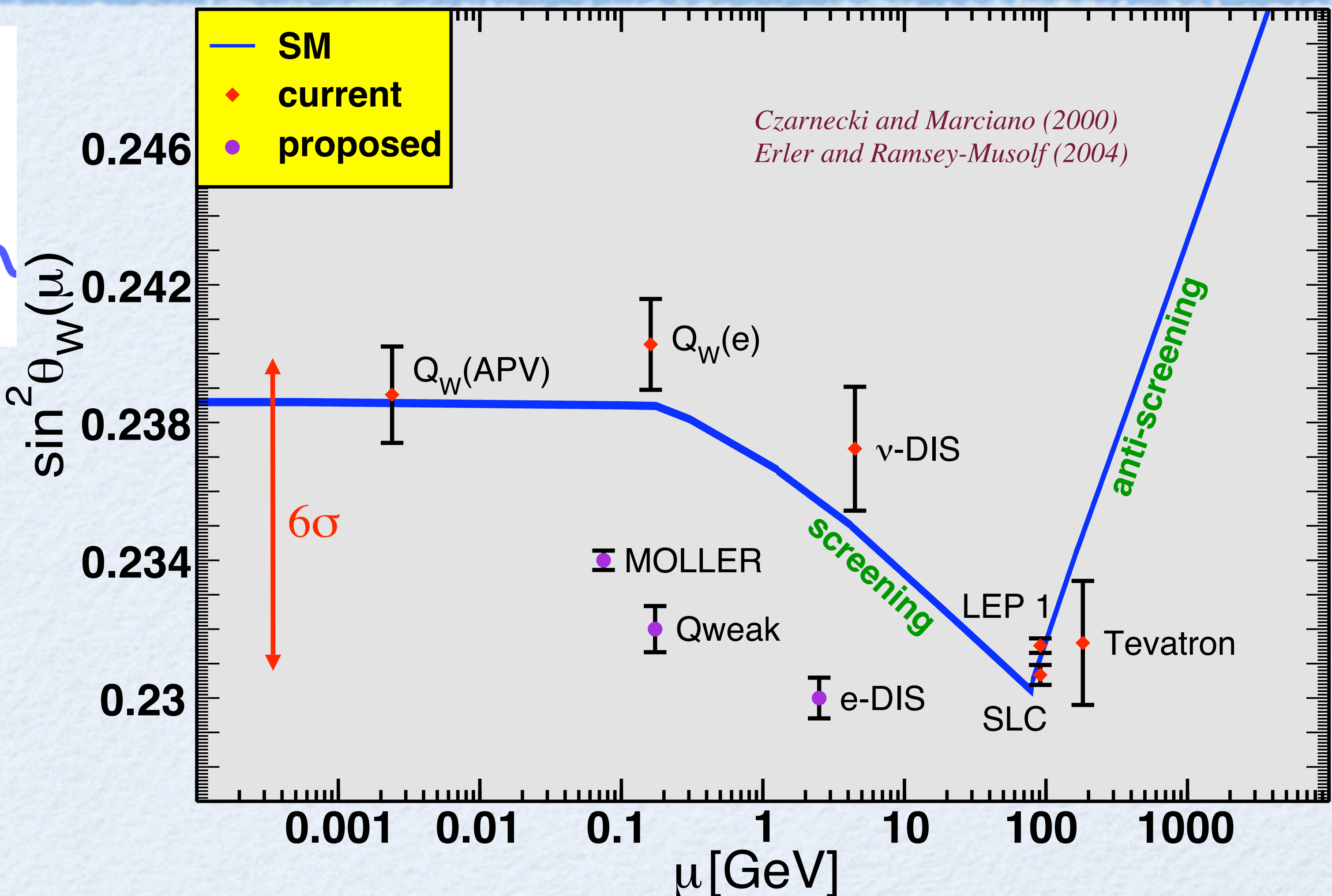

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  - *^{133}Cs Atomic Parity Violation*
  - *NuTeV result requires careful consideration of nuclear corrections*

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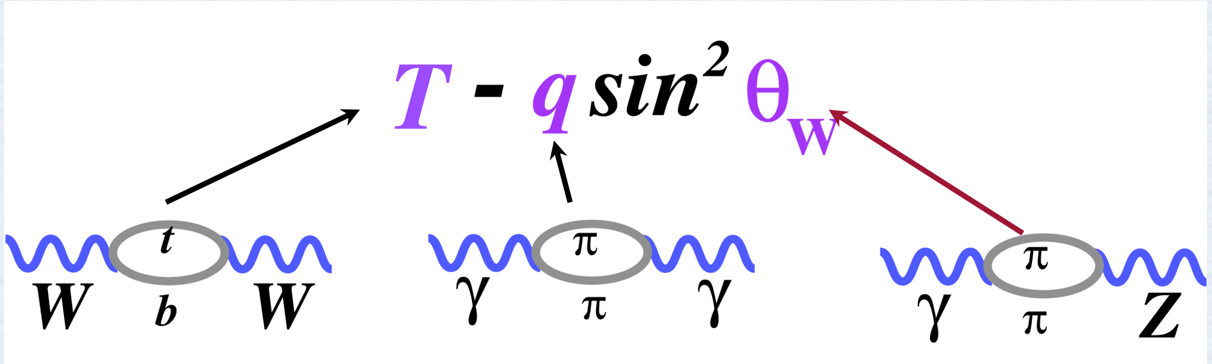

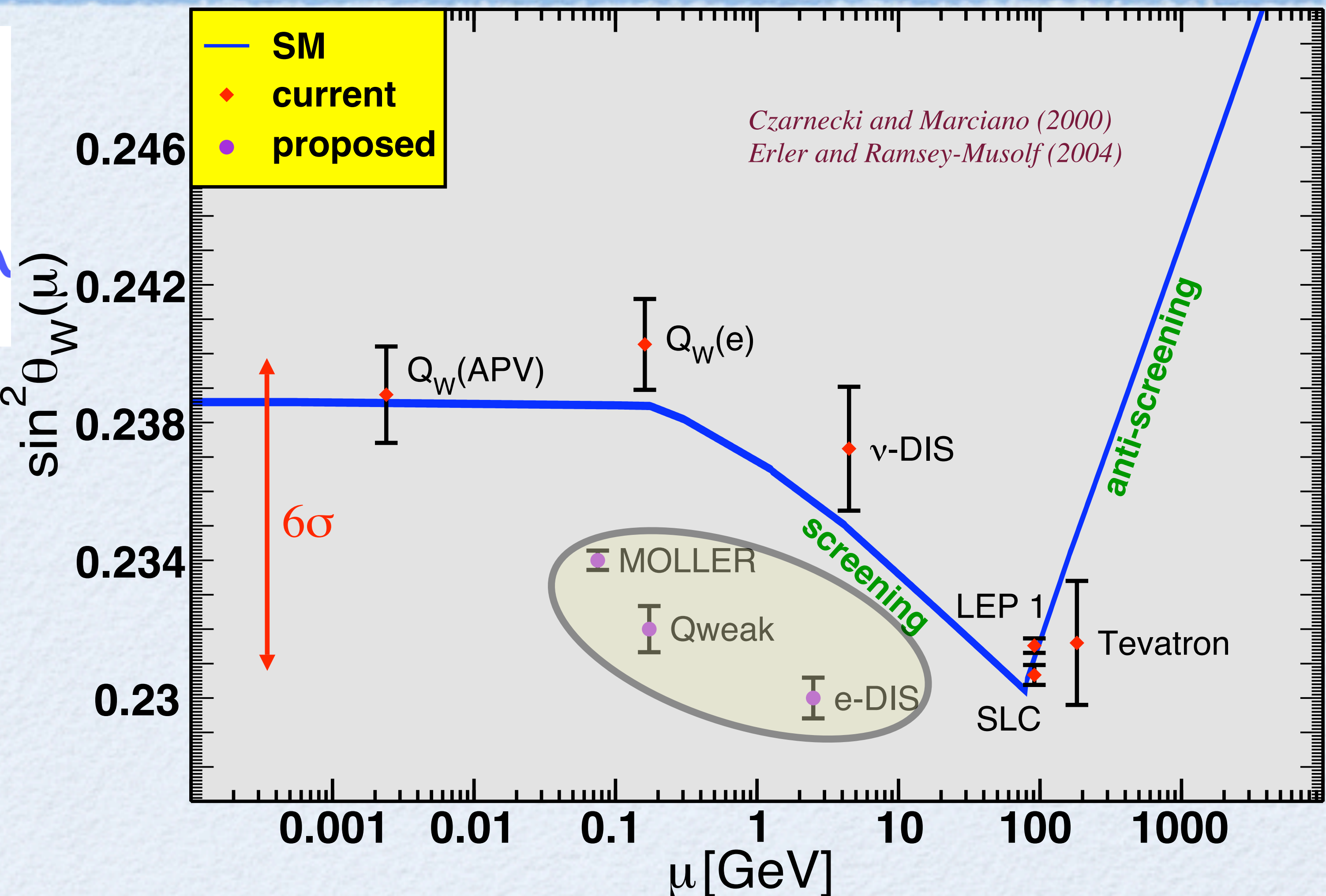

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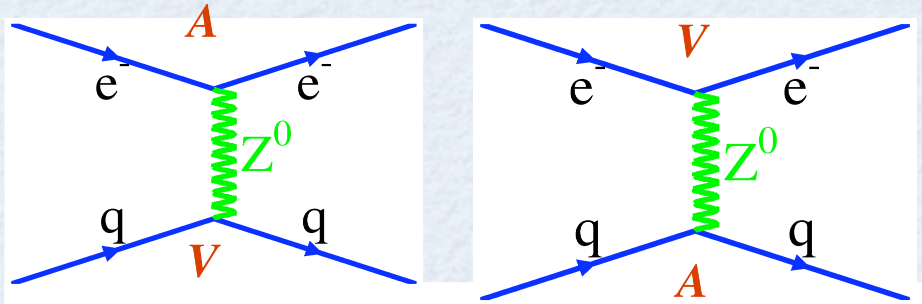
- ***Future Electron Scattering Measurements***
  - *e-q measurements: QWeak (elastic e-p) and deep-inelastic scattering*
  - *Improve on E158 by a factor of 5: MOLLER at 12 GeV JLab*

Quark Weak Charges



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

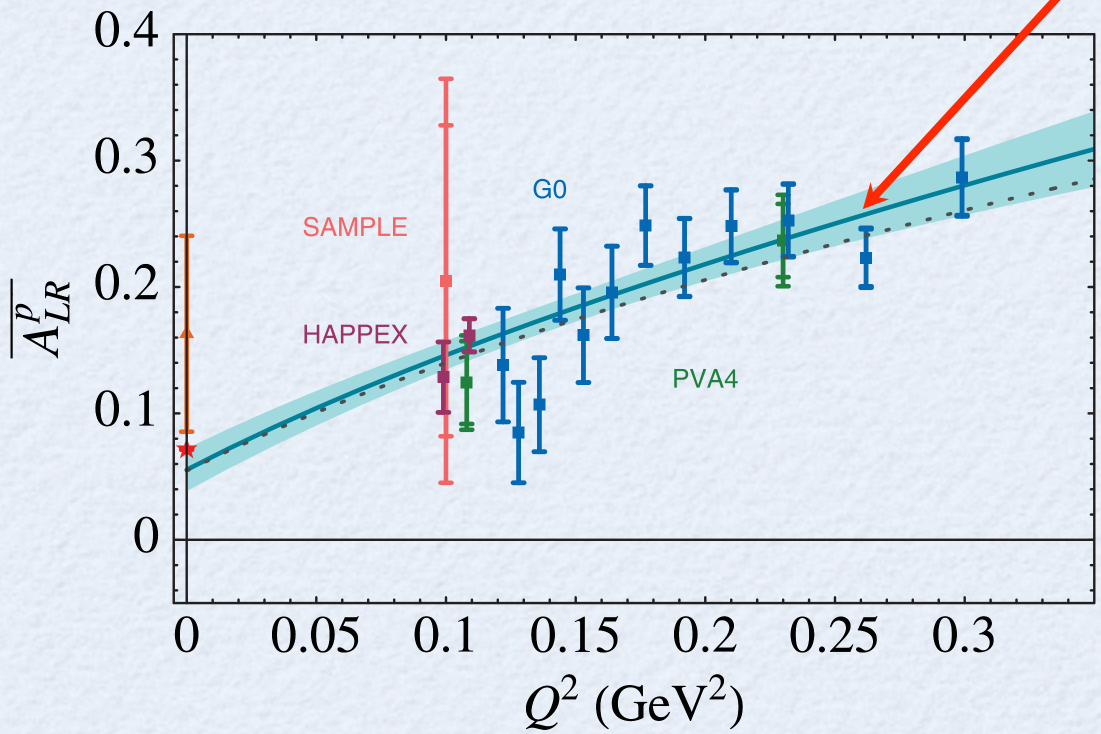
$\delta(C_{1q}) \propto (+\eta_{RL}^{eq} + \eta_{RR}^{eq} - \eta_{LL}^{eq} - \eta_{LR}^{eq}) \Rightarrow$ *PV elastic e-p, APV*

$\delta(C_{2q}) \propto (-\eta_{RL}^{eq} + \eta_{RR}^{eq} - \eta_{LL}^{eq} + \eta_{LR}^{eq}) \Rightarrow$ *PV deep inelastic*

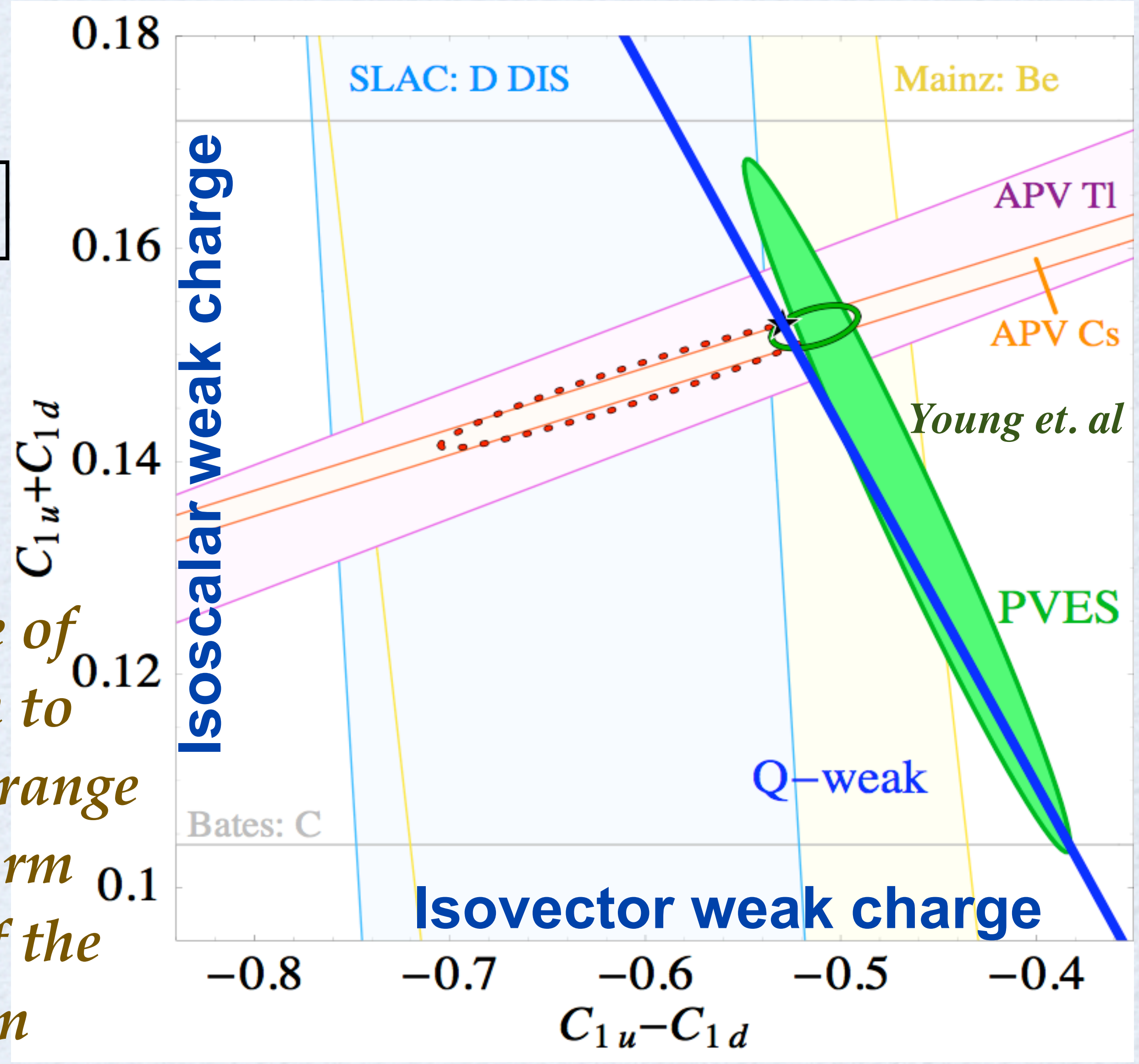
A_{PV} in elastic e-p scattering:

$$A(Q^2 \to 0) = -\frac{G_F}{4\pi\alpha\sqrt{2}}\left[Q^2\, Q_{weak}^p + Q^4 B\left(Q^2\right) \right]$$

$$Q_{weak}^p = 2C_{1u} + C_{1d} \propto 1 - 4\sin^2\vartheta_W$$

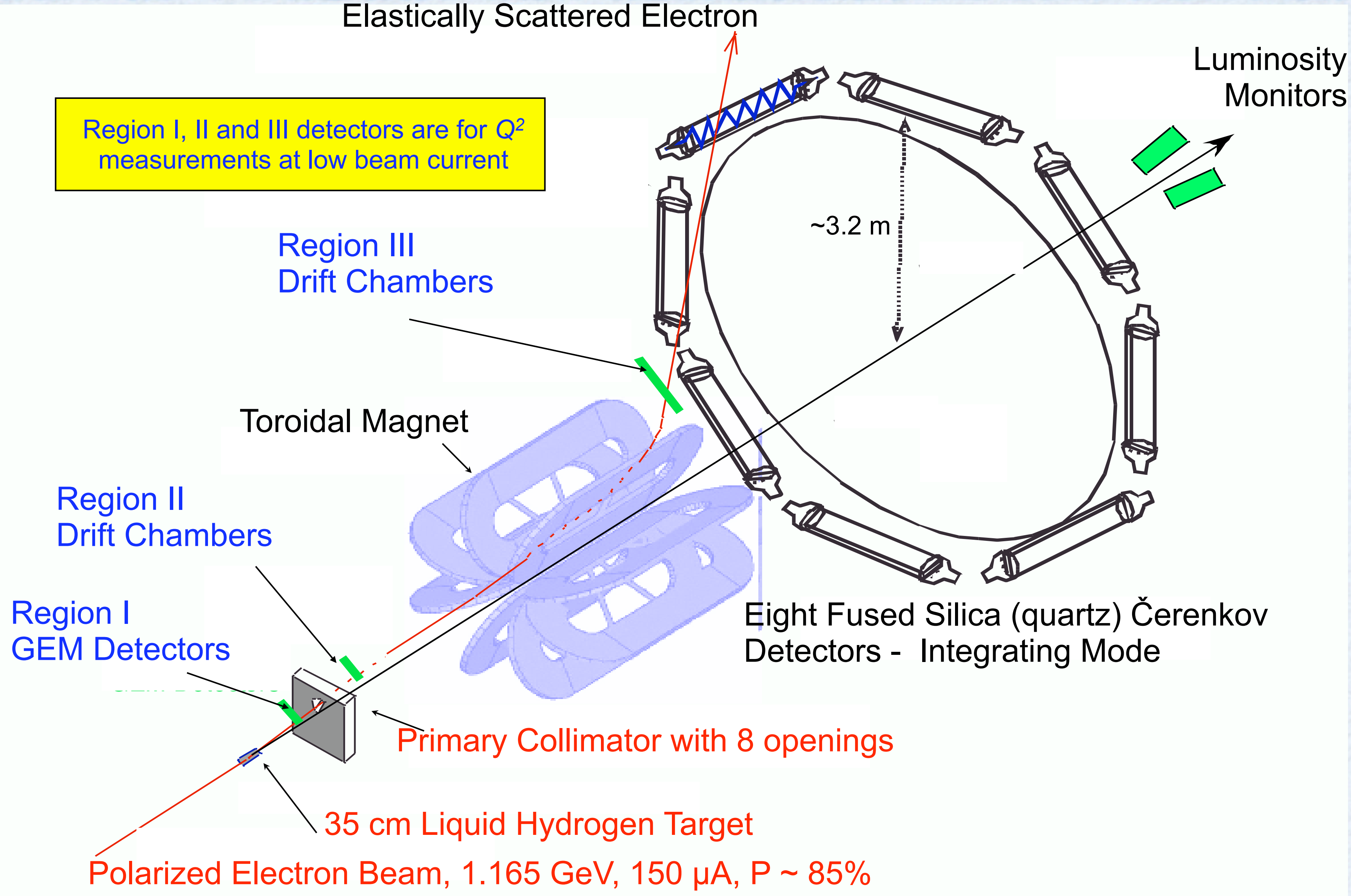


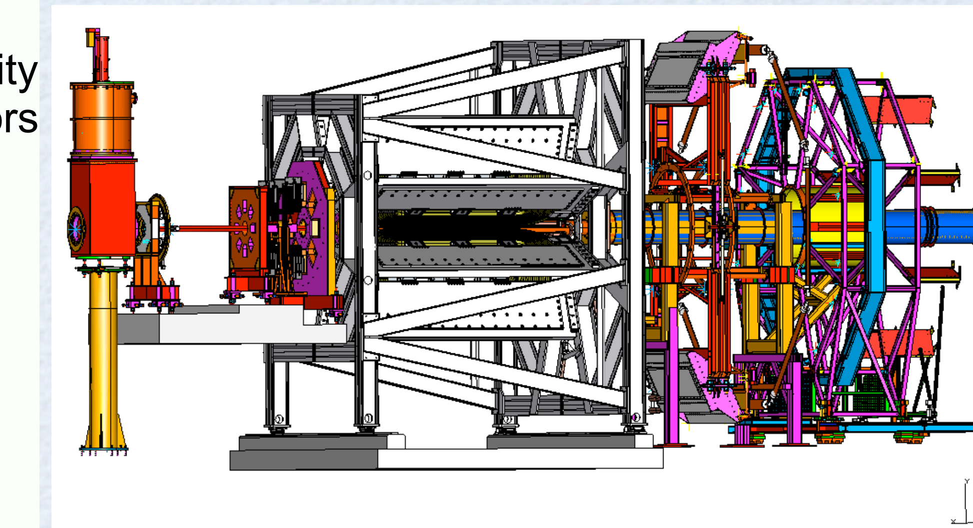
outcome of program to measure strange quark form factors of the nucleon

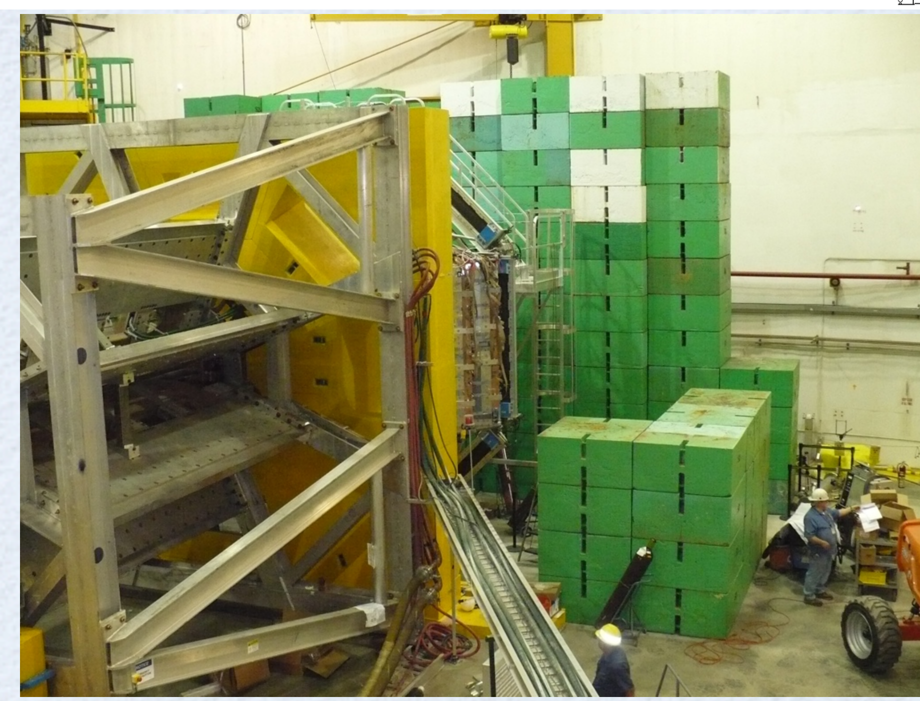


Qweak @ Jefferson Lab

Precision Measurement of the Proton's Weak Charge







- **Design and construction over past several years**
- **Installation recently completed**
- **Commissioning has begun**
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New, complementary constraints on lepton-quark interactions at the TeV scale

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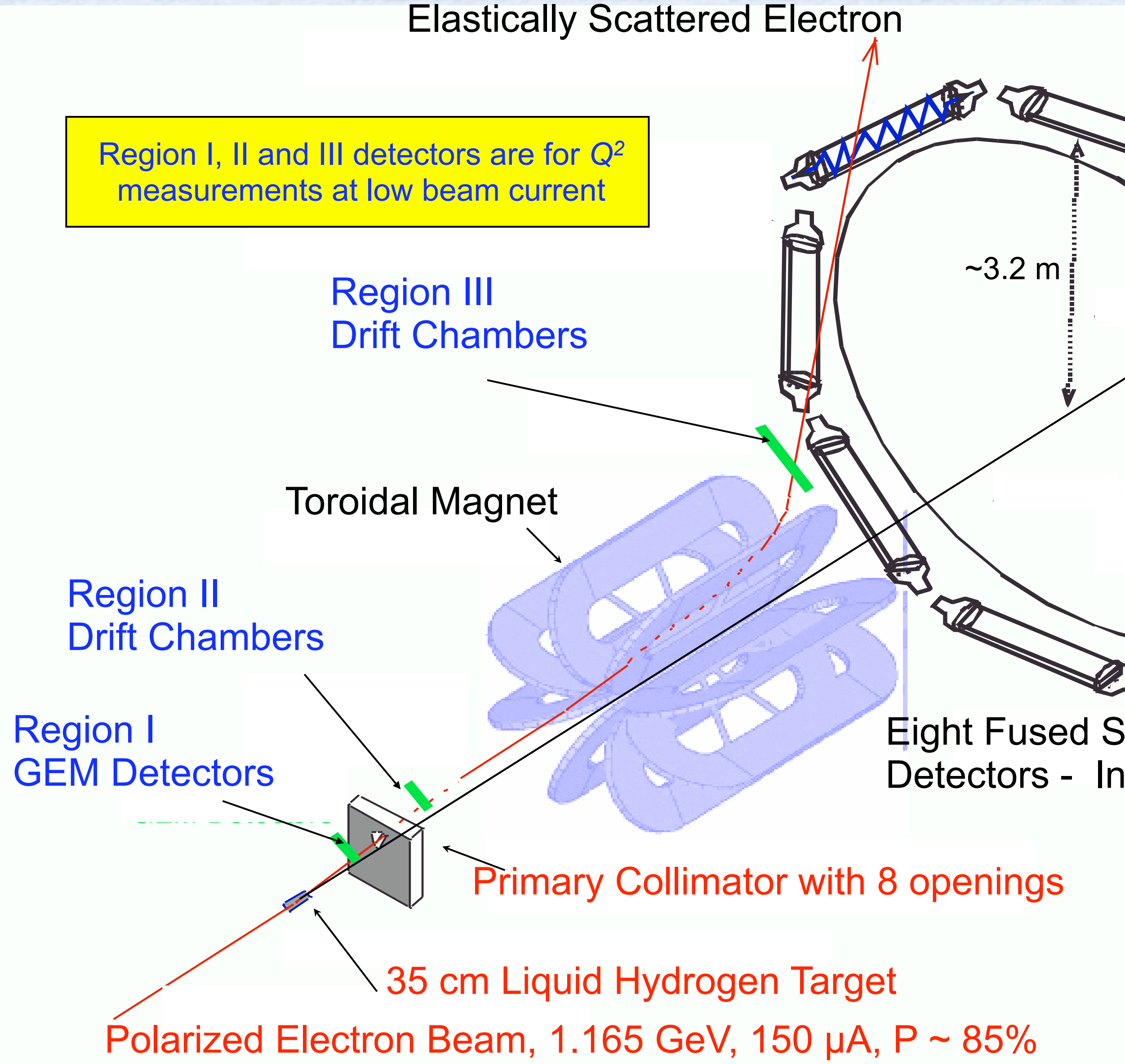
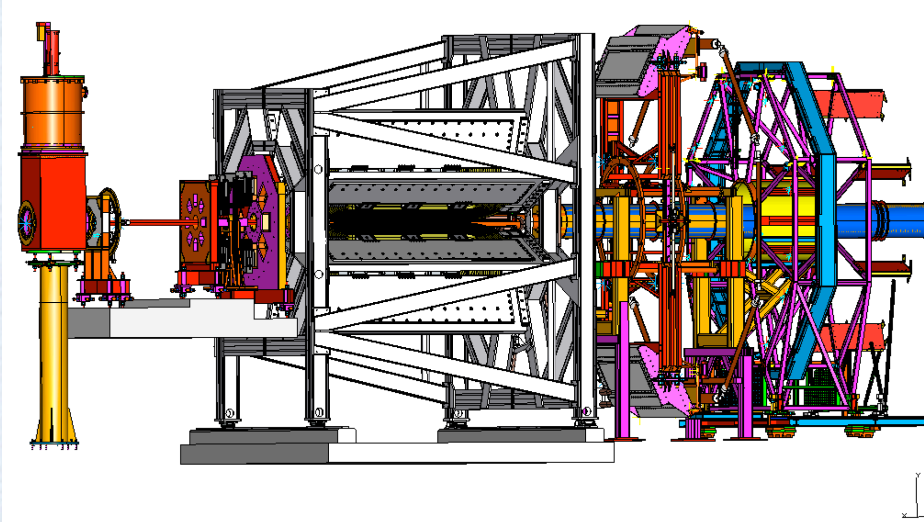
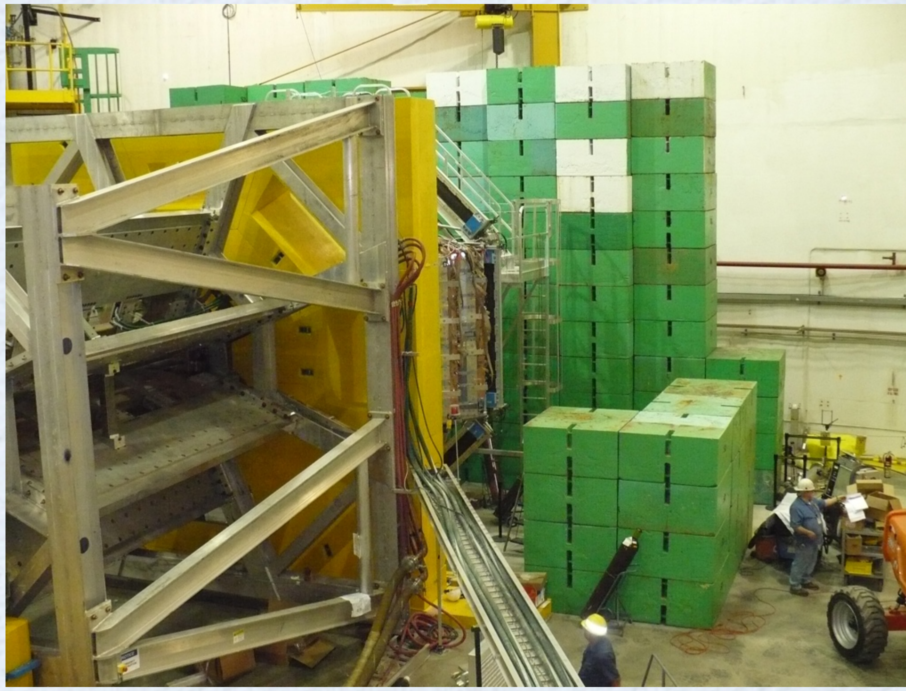


More details: Saturday talk by W. van Oers





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