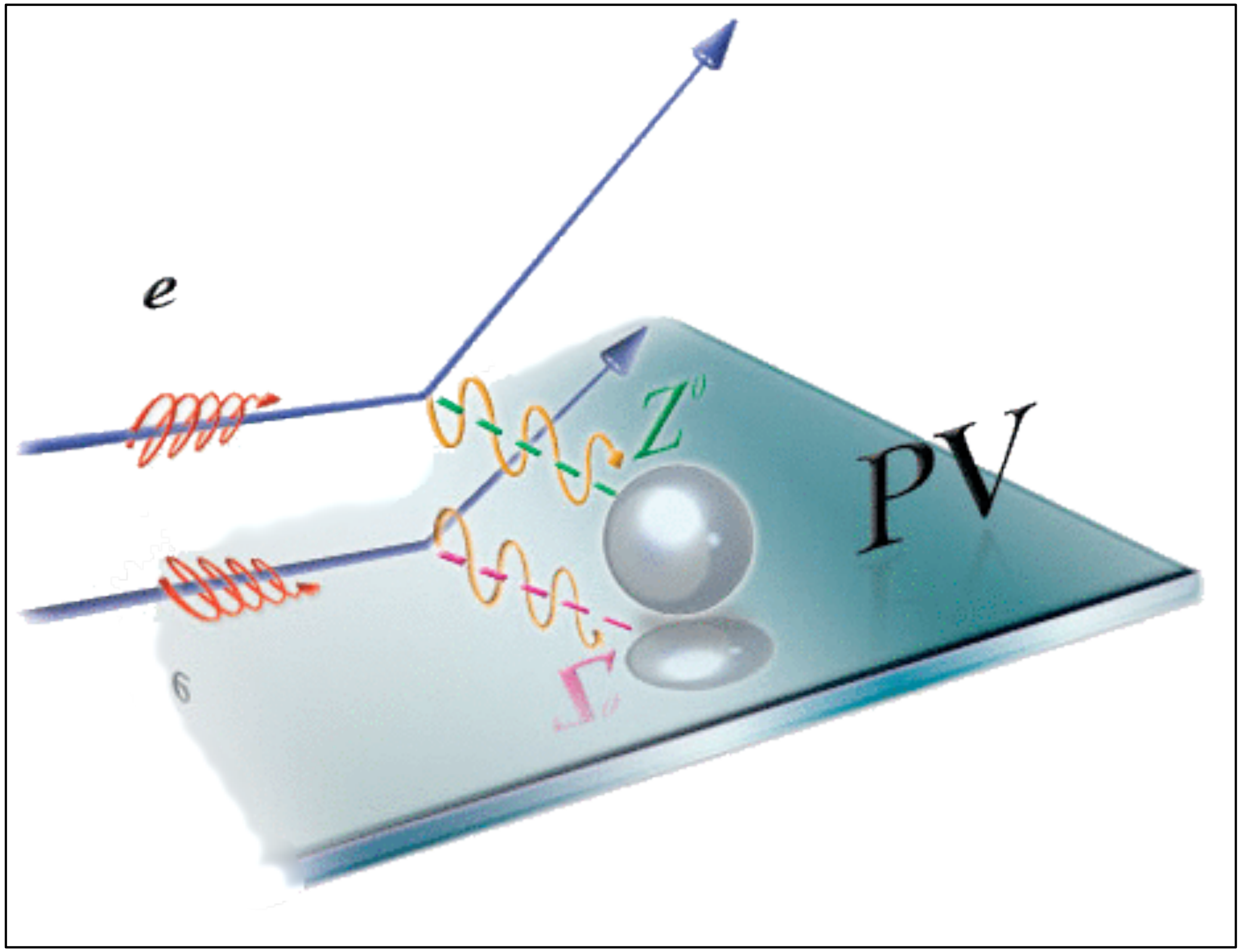
Electrons and Mirror Symmetry

Parity-violating Electron Scattering and the Search for Strange Seas, New Physics and Quark Stars



Kent Paschke

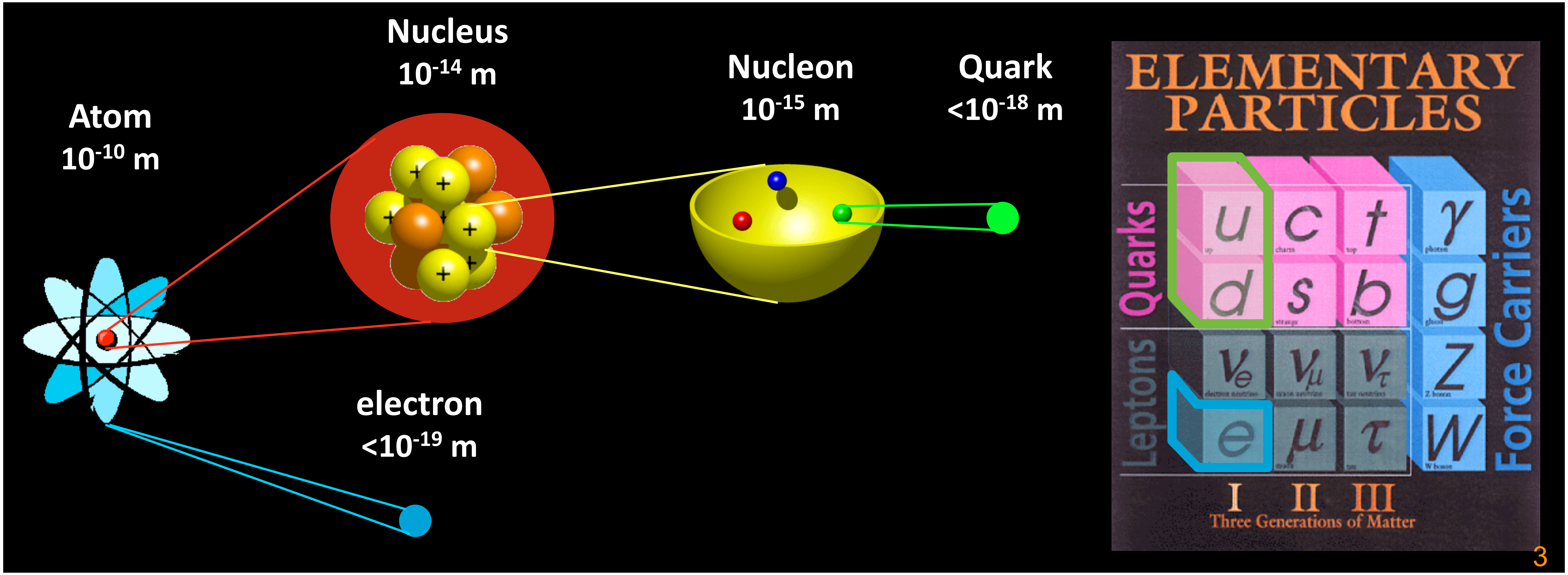
University of Virginia

The present and future program of parity-violating electron scattering

- Framing the question: electron scattering, mirror symmetry, and the electroweak interaction
- Experimental Techniques
- An important question about VERY big nuclei
- Using parity-violation to fish in the nucleon sea
- Indirect searches for new physics

Matter and Interactions

	Gravity	Weak	Electromagnetic	Strong
mediator	(not found)	W^+, W^-, Z^0	γ	gluons
acts on	all	quarks and leptons	Electrically charged	quarks and gluons
Strength at $3\text{x}10^{-17}$ m	10^{-41}	10^{-4}	1	60



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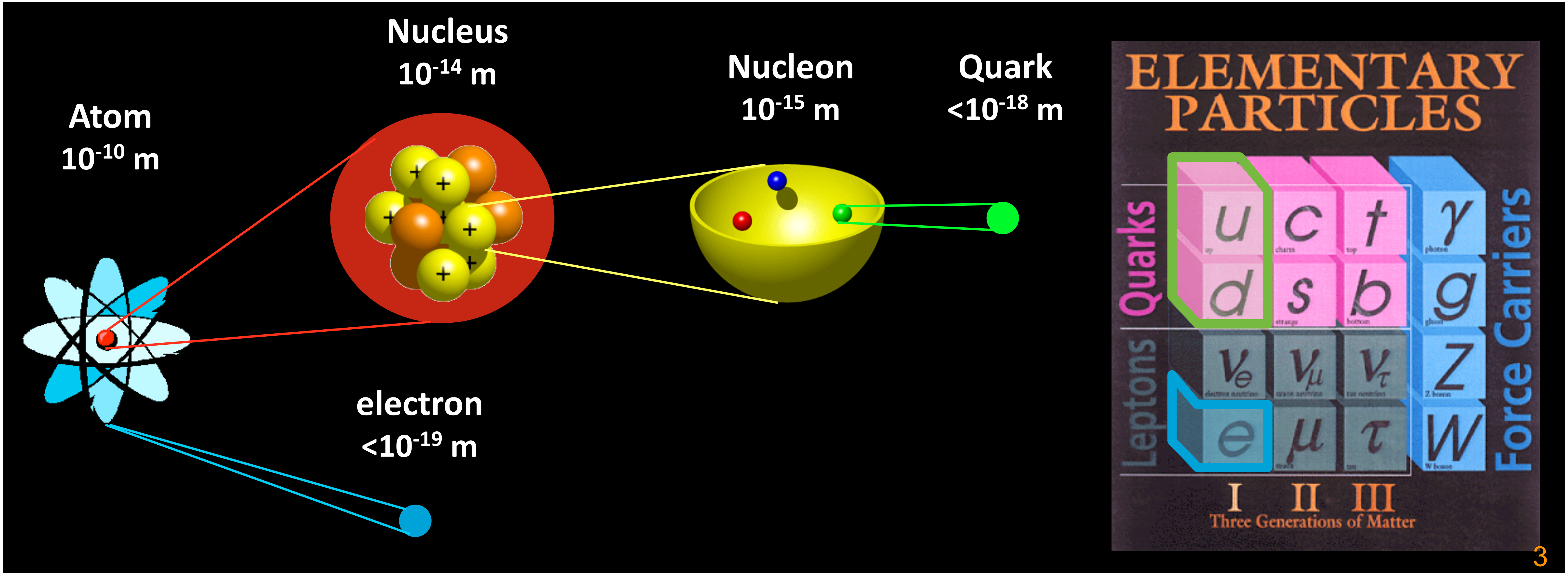
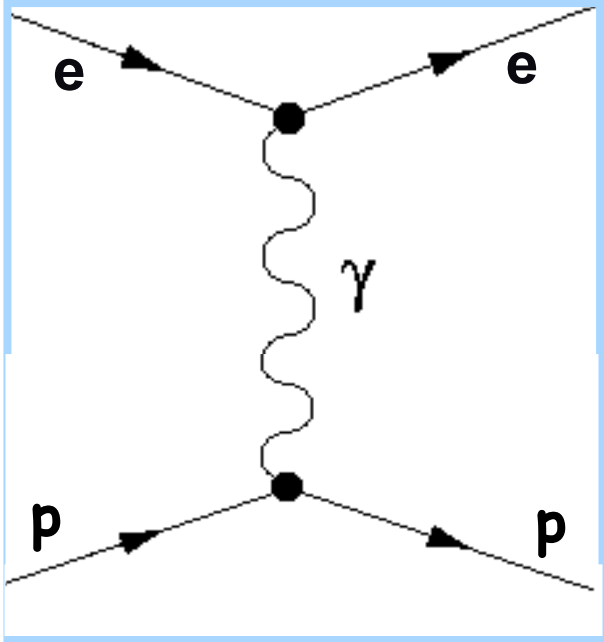
One unified framework for weak and electromagnetic interactions



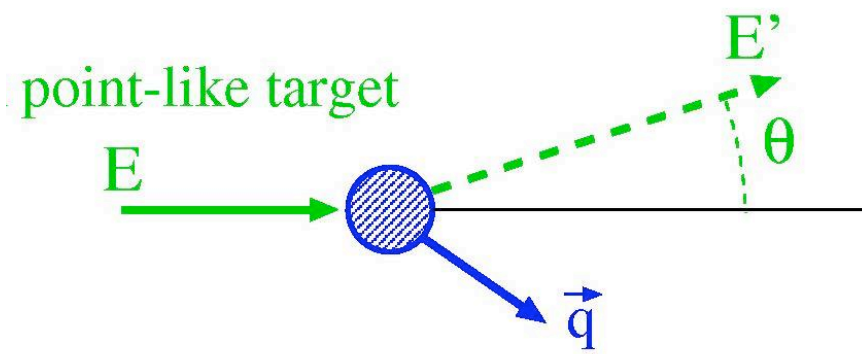
Introduction to electron scattering



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

If photon carries low momentum
-> long wavelength
-> low resolution

Q^2: 4-momentum of the virtual photon



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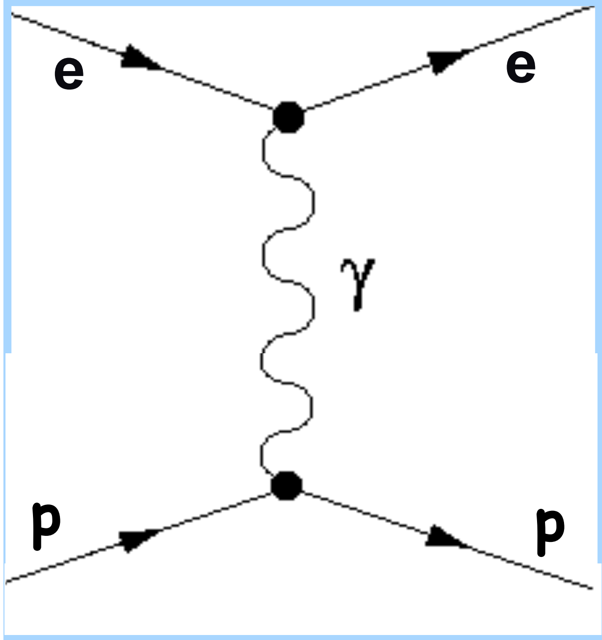

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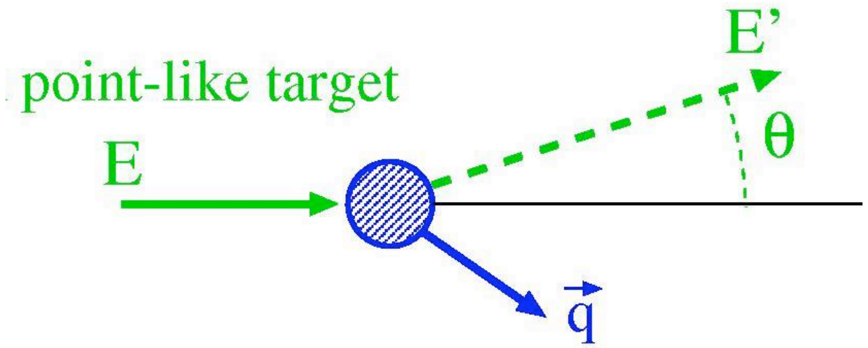
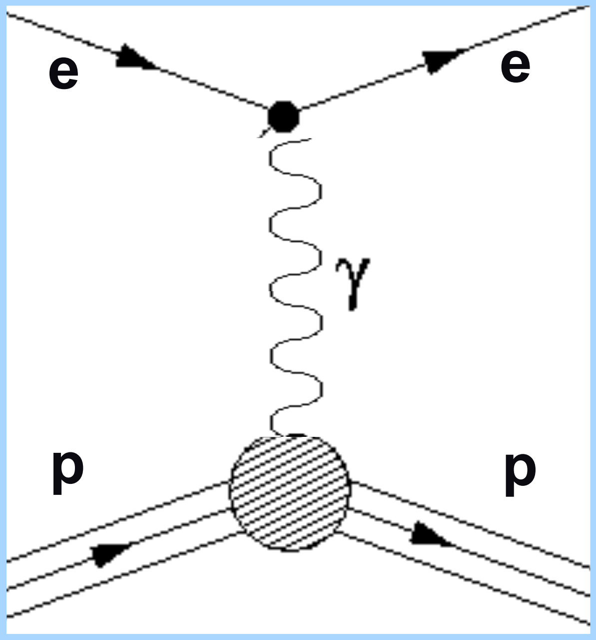
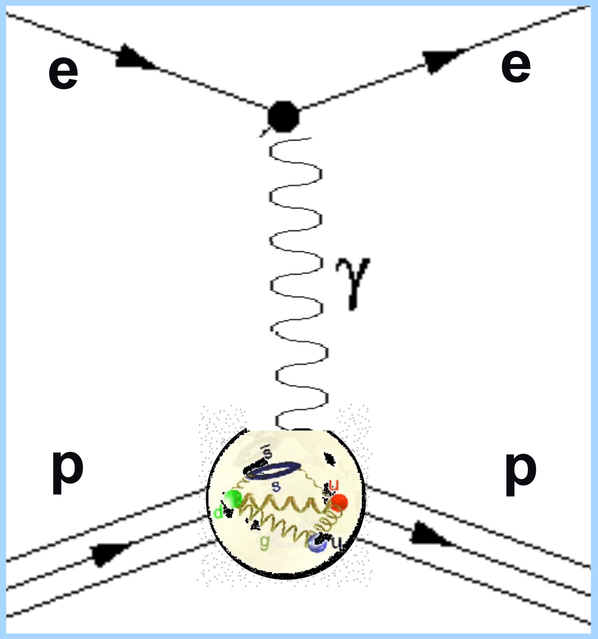




Increasing momentum transfer
-> shorter wavelength
-> higher resolution to observe smaller structures



Parity Symmetry

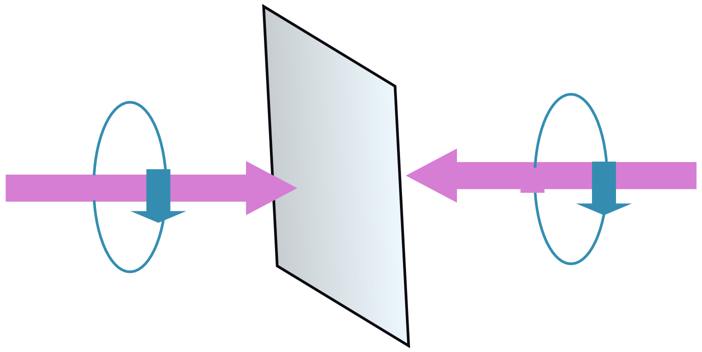
Parity transformation

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

$$\vec{p} \rightarrow -\vec{p}, \quad \vec{L} \rightarrow \vec{L}, \quad \vec{S} \rightarrow \vec{S}$$

Helicity: spin in direction of motion

$$h = \vec{S} \cdot \vec{p} = \pm 1$$



Right handed

Left handed

Parity transformation is analogous to reflection in a mirror:

. . . reverses momentum but preserves angular momentum

. . .takes right-handed (helicity = +1) to left-handed (helicity = -1).

Parity symmetry:

interaction must be the same after parity transformation

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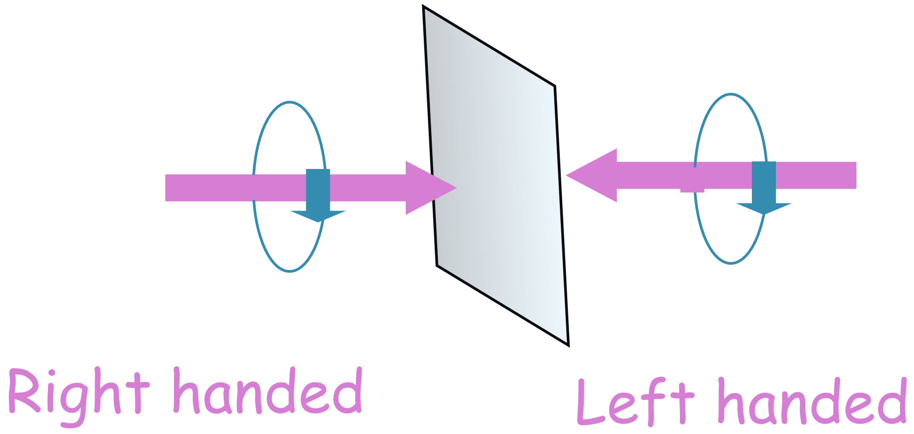

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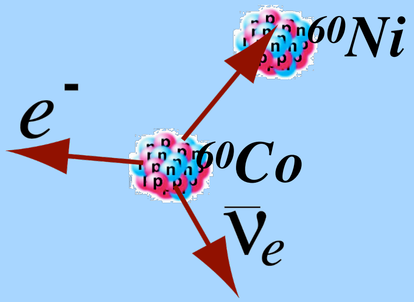
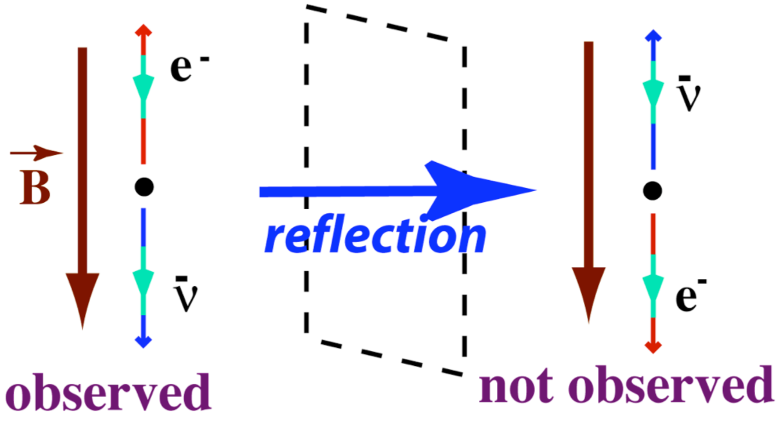
1957 – Parity Violation observed

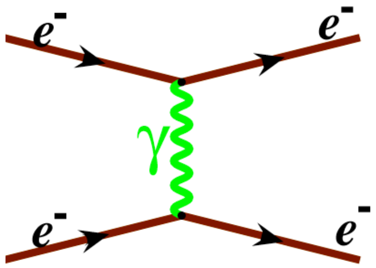
Weak decay of ^{60}Co Nucleus





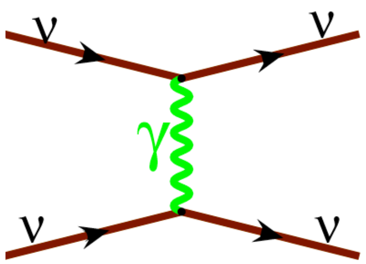
Charge and Handedness

Electric charge determines strength of electric force



observed

Neutrinos are “charge neutral”:
do not feel the electric force



not observed

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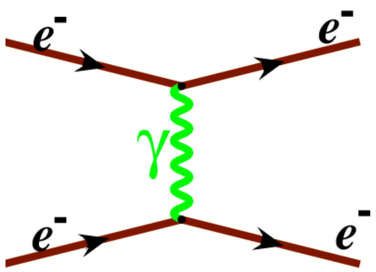

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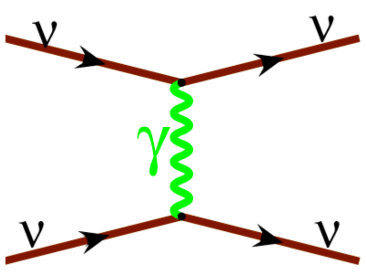
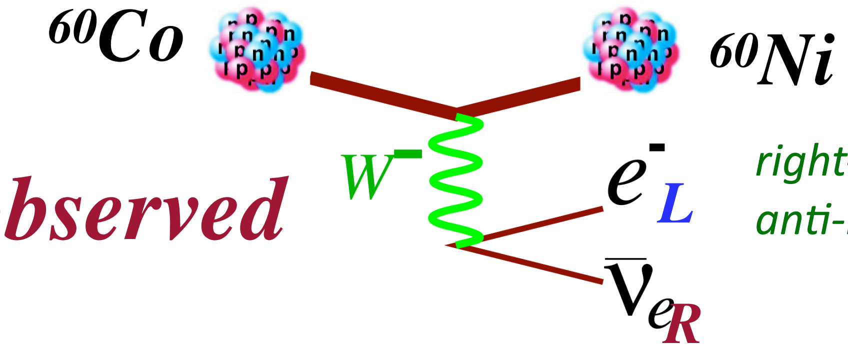


not observed

Weak charge determines strength of weak force

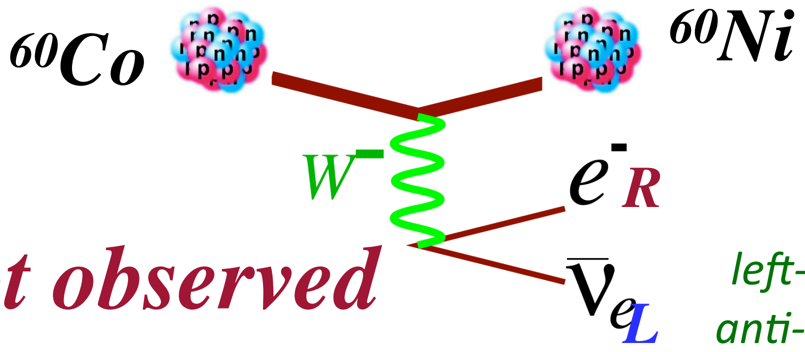
Left-handed particles
(Right-handed antiparticles)
have weak charge

Right-handed particles
(left-handed antiparticles)
are "weak charge neutral"



observed

right-handed
anti-neutrino



not observed

left-handed
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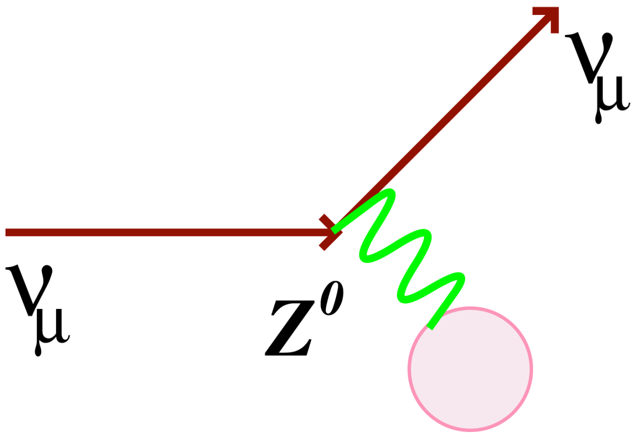
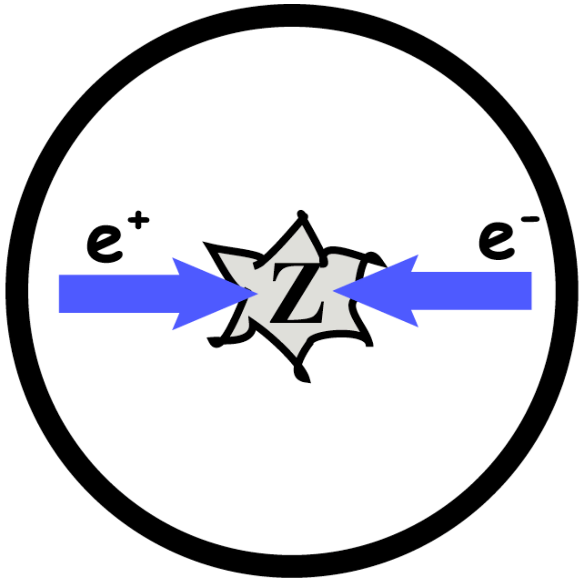
Neutral Weak Force

Electroweak unification implied a pattern of neutral weak charges with only one free parameter: θ_W



Neutral weak force first measured in the early '70s

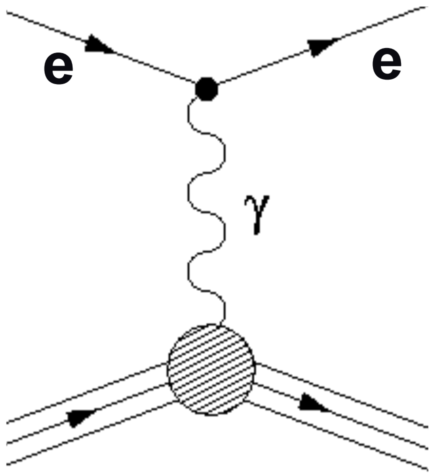
Z bosons produced in electron-positron collisions: precise measurements of Z charge of most fermions



	Left-	**Right-**
γ Charge	$q=0,\pm1,\pm\frac{1}{3},\pm\frac{2}{3}$	$q=0,\pm1,\pm\frac{1}{3},\pm\frac{2}{3}$
W Charge	$T=\pm\frac{1}{2}$	0
Z Charge	$T-q\sin^2\theta_W$	$-q\sin^2\theta_W$

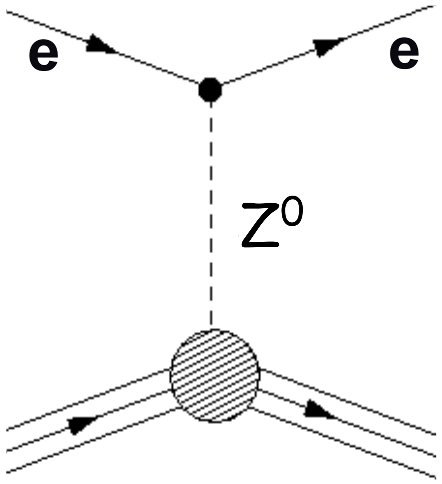
Measurements of Z mass, Z charges validated the electroweak theory

Electron scattering, weakly



Electron scattering is (mostly) electromagnetic scattering.

The weak amplitude is ~10^{-6} smaller.

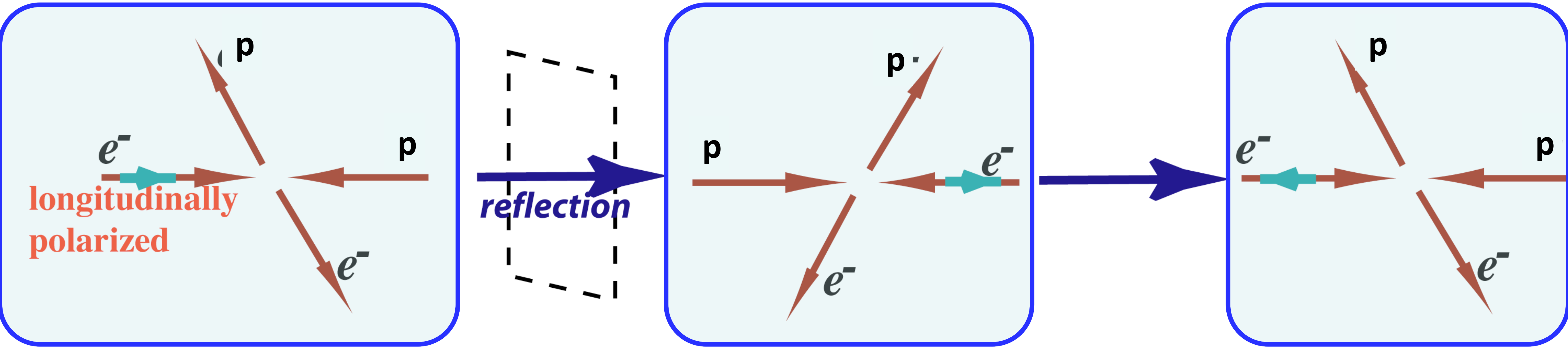


The weak quark charges are different than the EM charge. The weak interaction can be a valuable probe of nuclear matter, complementary to the extensive electromagnetic data set.

Fundamental Weak and EM interactions are predicted with very high precision, but with an apparently incomplete model. Can we find a crack in the Standard Model in precision measurements at low energy?

The challenge: Isolate the tiny effect of the weak interaction.

Mirror Asymmetry

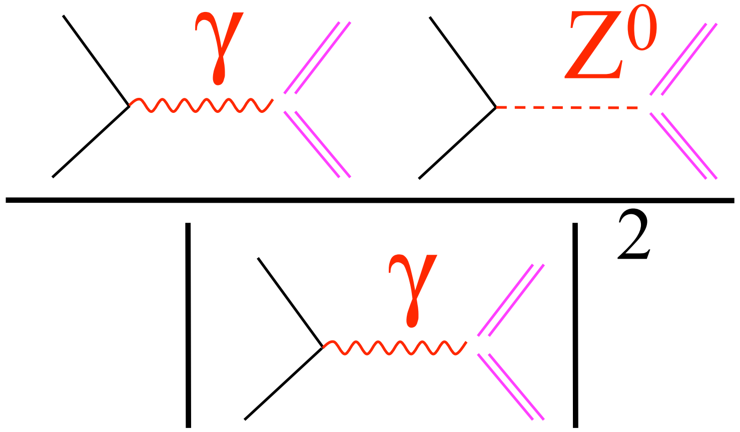


- Incident beam is longitudinally polarized
- Change sign of longitudinal polarization
- Measure fractional rate difference

$$\boxed{\sigma = \left| M_\gamma + M_Z \right|^2}$$

Weak and EM amplitudes interfere:

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim$$



$$\approx \frac{|M_Z|}{|M_\gamma|}$$

A_{PV} ranges from 10^{-4}-10^{-7} (0.1-100 ppm)

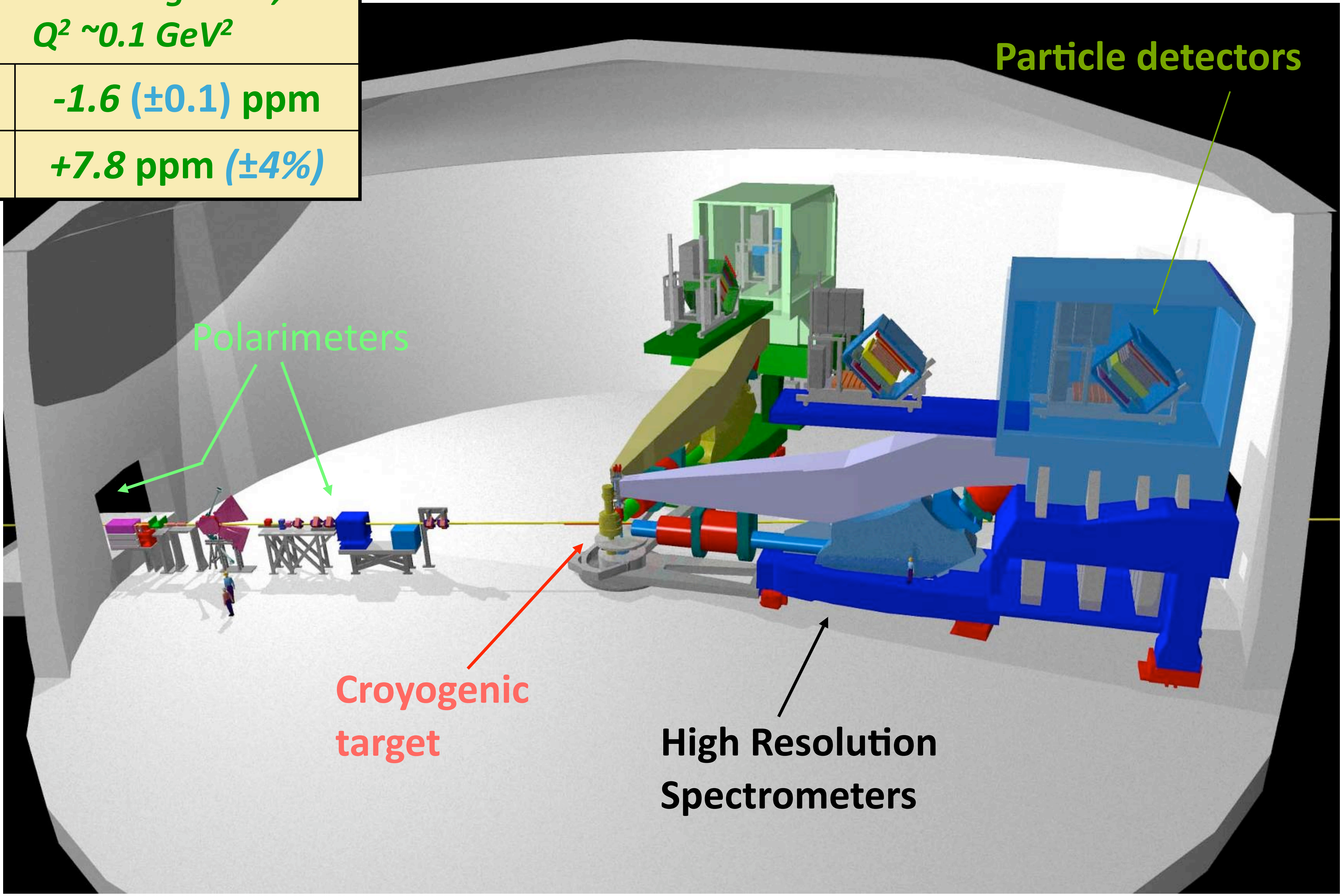
Experimental Technique

Measuring A_{PV}

HAPPEX-II, in Hall A at Jefferson Lab

Strange quark program, ran 2004-2005

Forward Angle ~6°, Q^2 ~0.1 GeV^2	
^1H	*-1.6* (±0.1) ppm
^4He	*+7.8* ppm *(±4%)*



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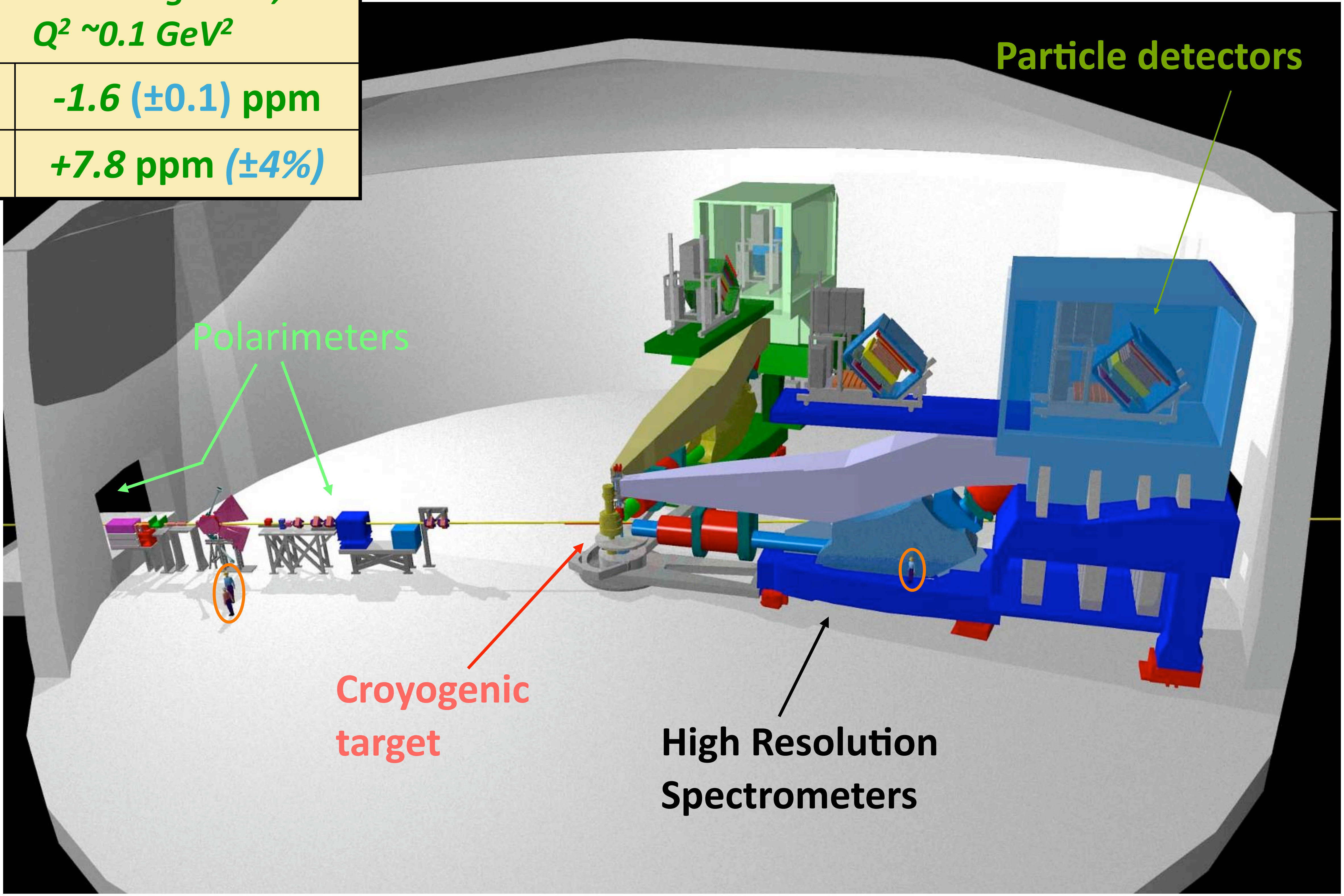


Particle detectors

Polarimeters

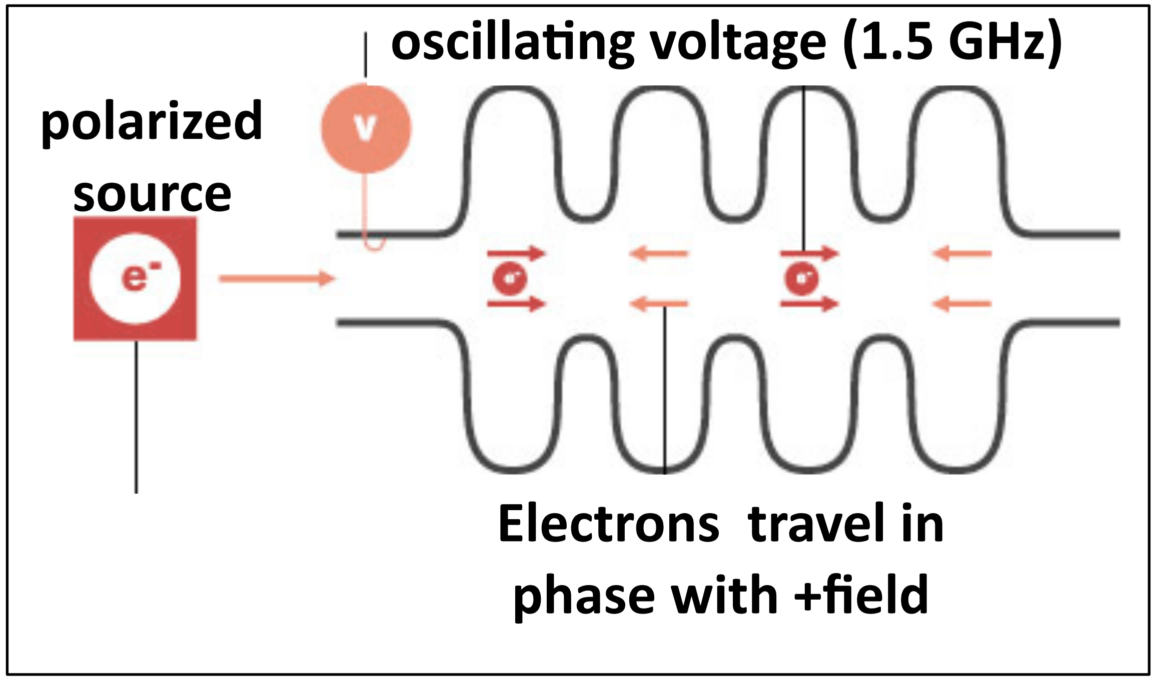
Croyogenic target

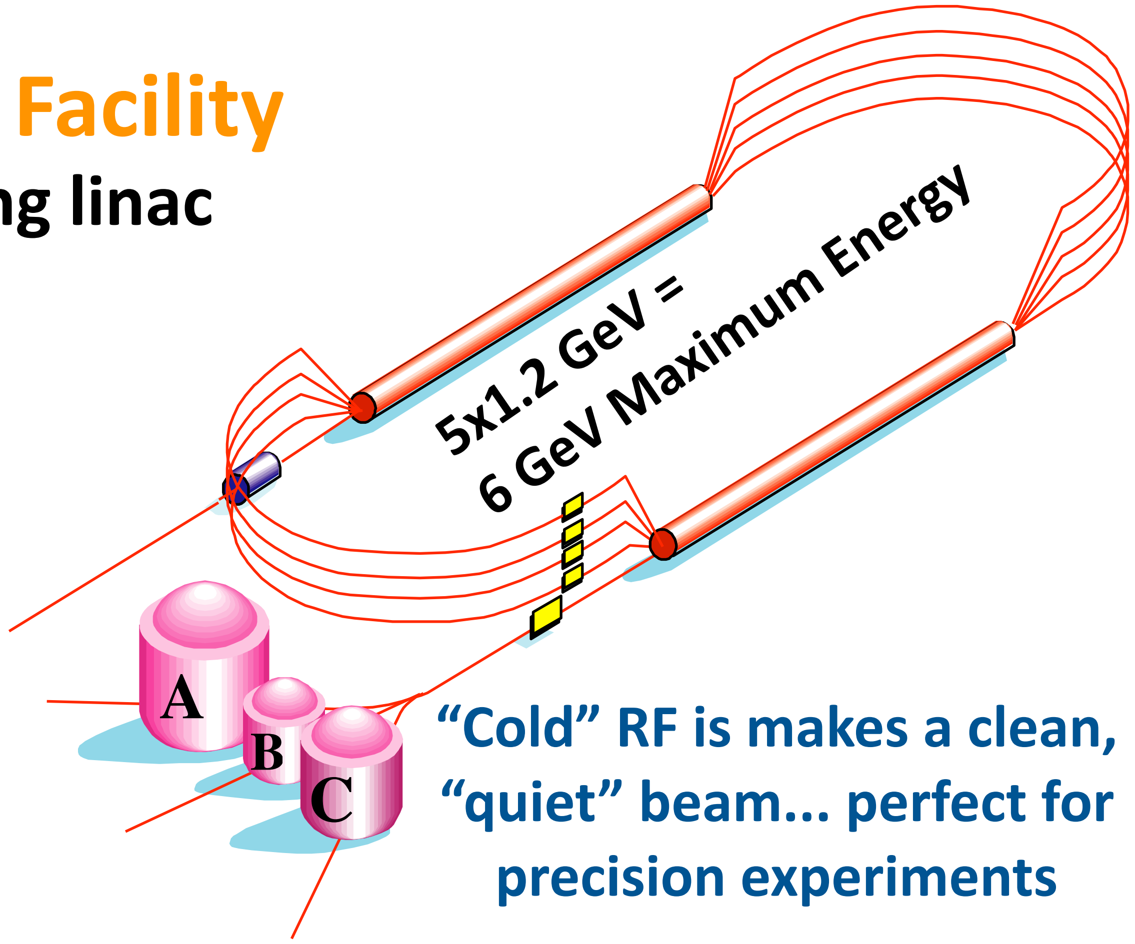
High Resolution Spectrometers

Continuous Electron Beam Accelerator Facility

Superconducting, continuous wave, recirculating linac

- 1500 MHz RF, with 3 interleaved 500 MHz beams





“Cold” RF is makes a clean, “quiet” beam... perfect for precision experiments

Continuous Electron Beam Accelerator Facility

Superconducting, continuous wave, recirculating linac

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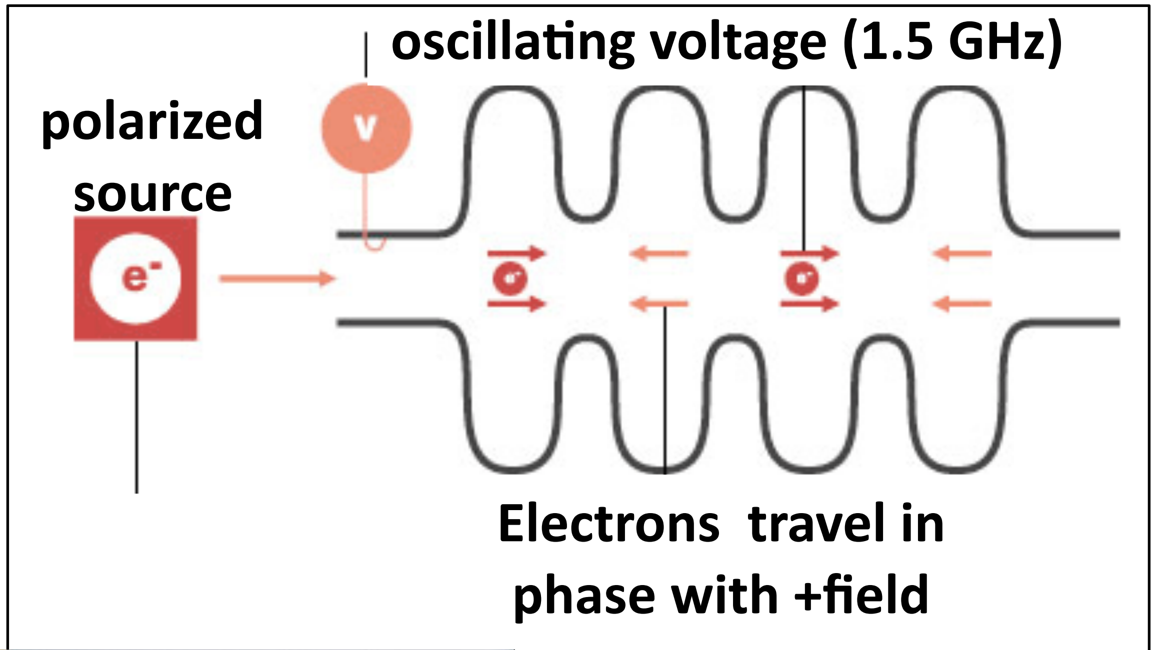
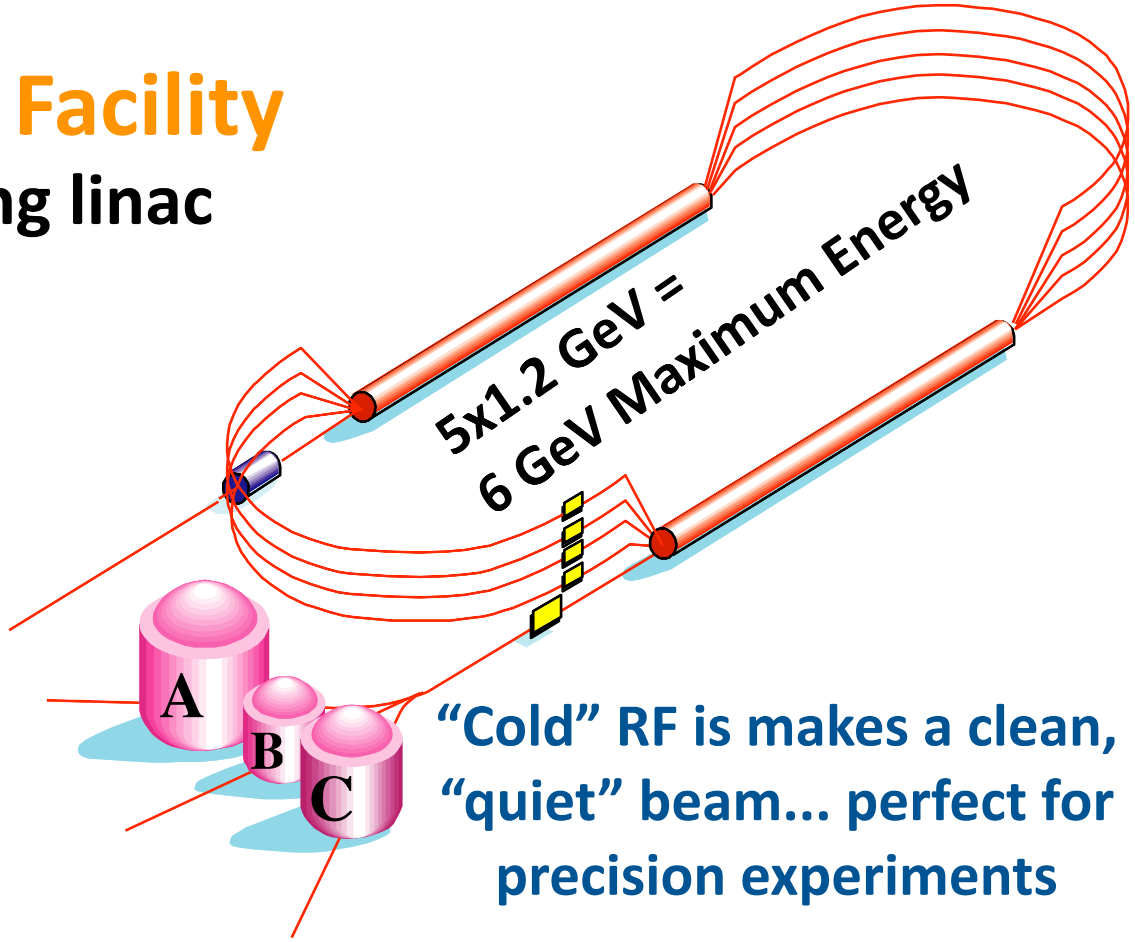


oscillating voltage (1.5 GHz)

polarized source

Electrons travel in phase with +field



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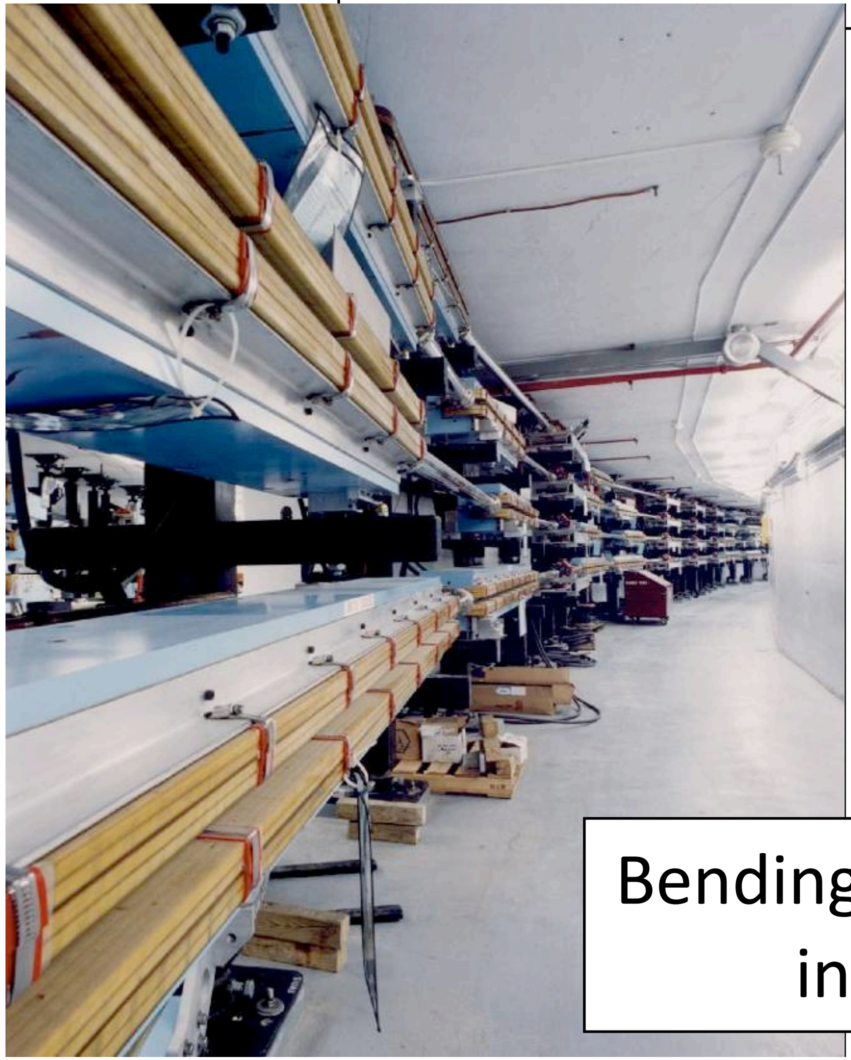

Bending magnets in arc

Linac tunnel

Tiny Signal in a Noisy World

Goal: small asymmetry measured at the few percent level

$$\boxed{A_{PV} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \approx 10^{-6}} \Longrightarrow \boxed{\frac{\sigma_A}{A} = \frac{1}{A}\frac{1}{\sqrt{2N}} = 5\%} \Longrightarrow \boxed{N \sim 10^{14} \text{ !!!}}$$

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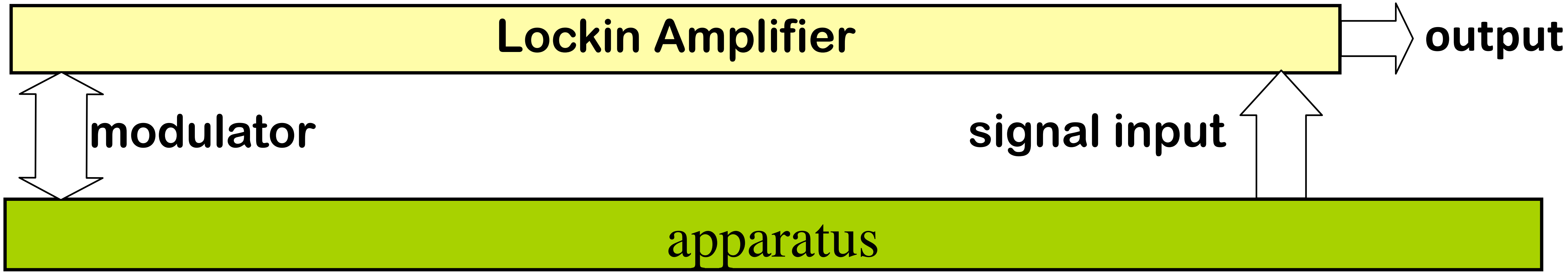
How do you pick a tiny signal out of a noisy environment?



Lockin Amplifier

output

modulator

signal input

apparatus

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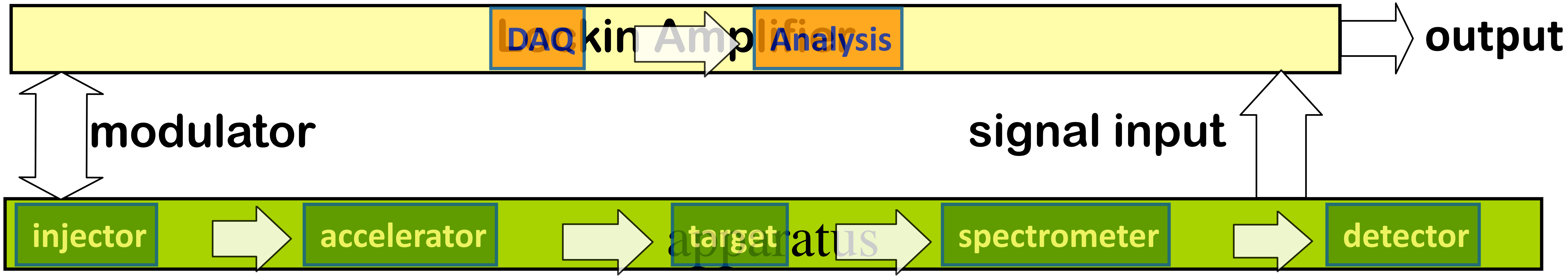


Lockin Amplifier

DAQ → Analysis

output

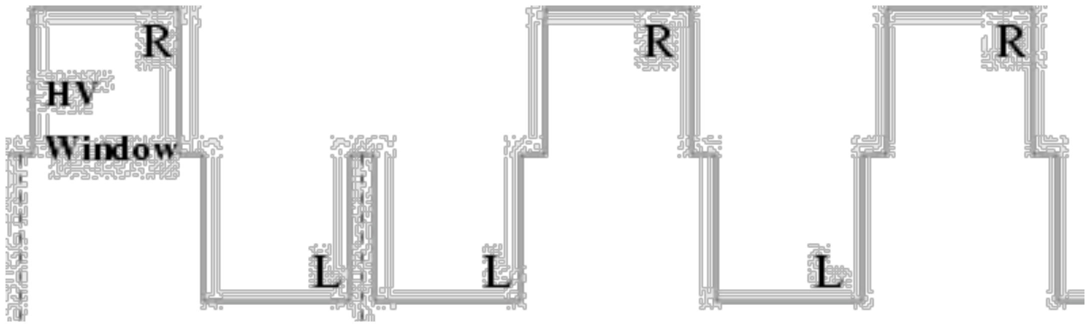
modulator

signal input

apparatus

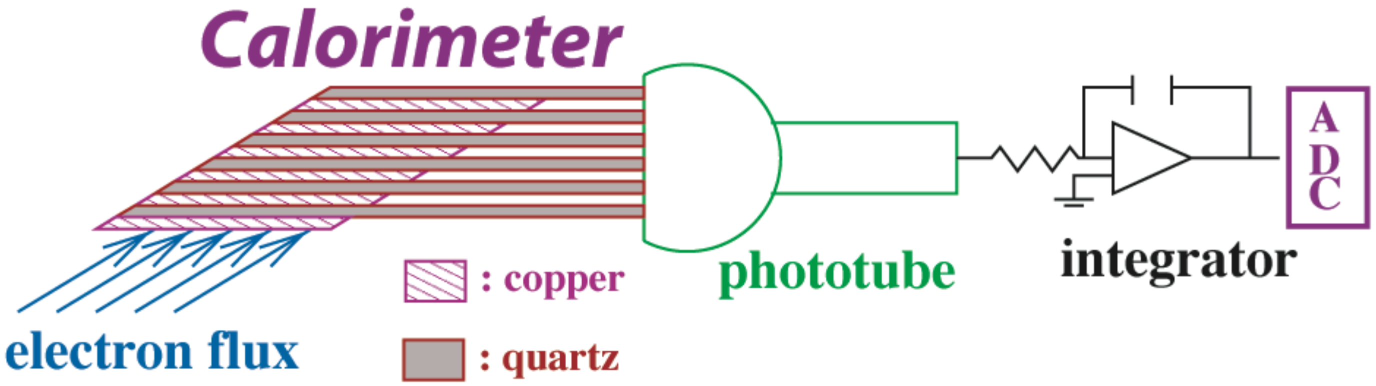
injector → accelerator → target → spectrometer → detector

Beam helicity pairs with fixed time intervals are ordered pseudo-randomly



Analog integration enables very high flux detection

- Scattered electrons directed to detector.
- Phototube current integrated over window.



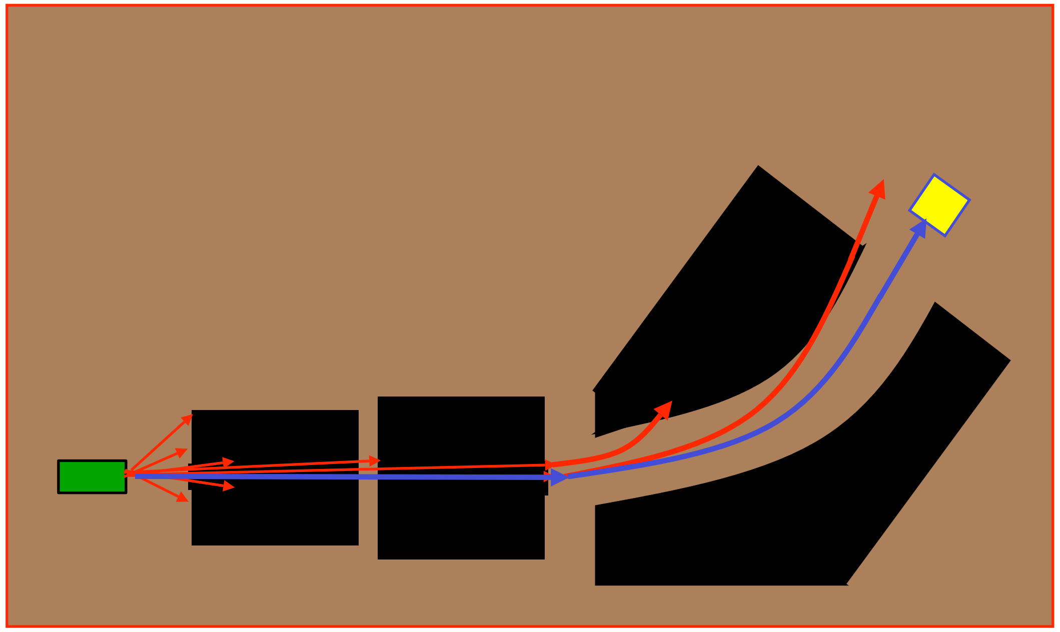
Hall A Spectrometers

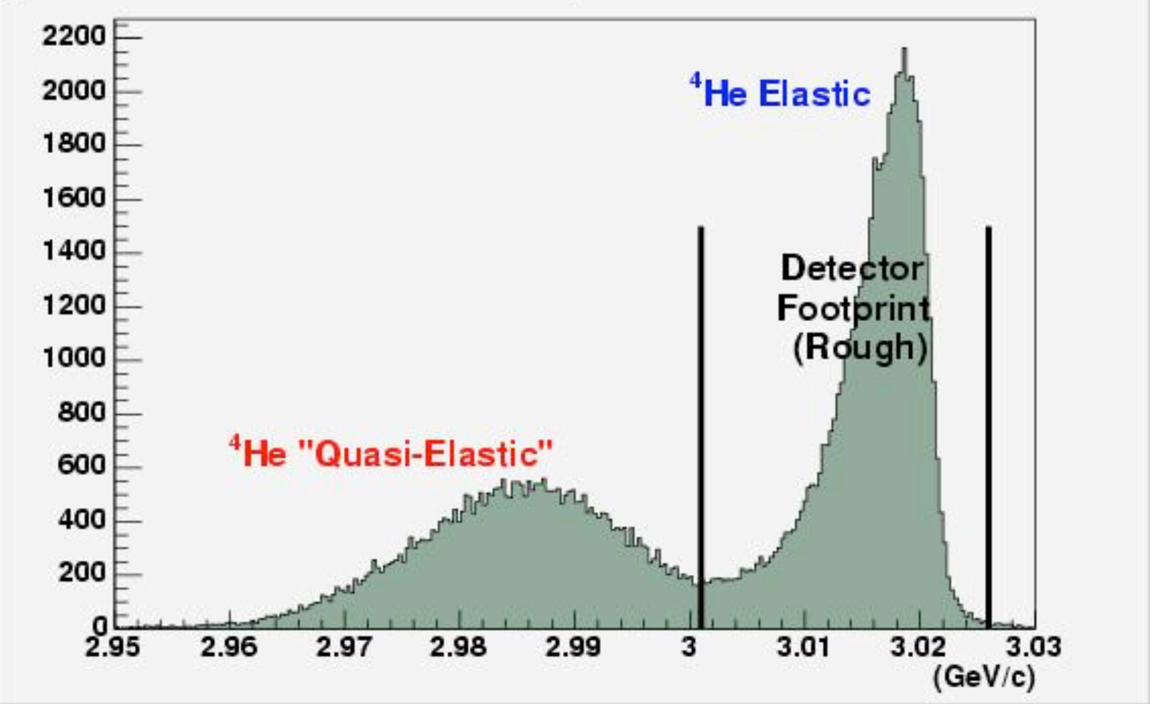
- Bending (dipole) magnet – 450 tons
- 1.6 T magnetic field
- 45^0 bend angle
- 3,500,000 J stored energy
- Resolution (momentum) – 0.01%

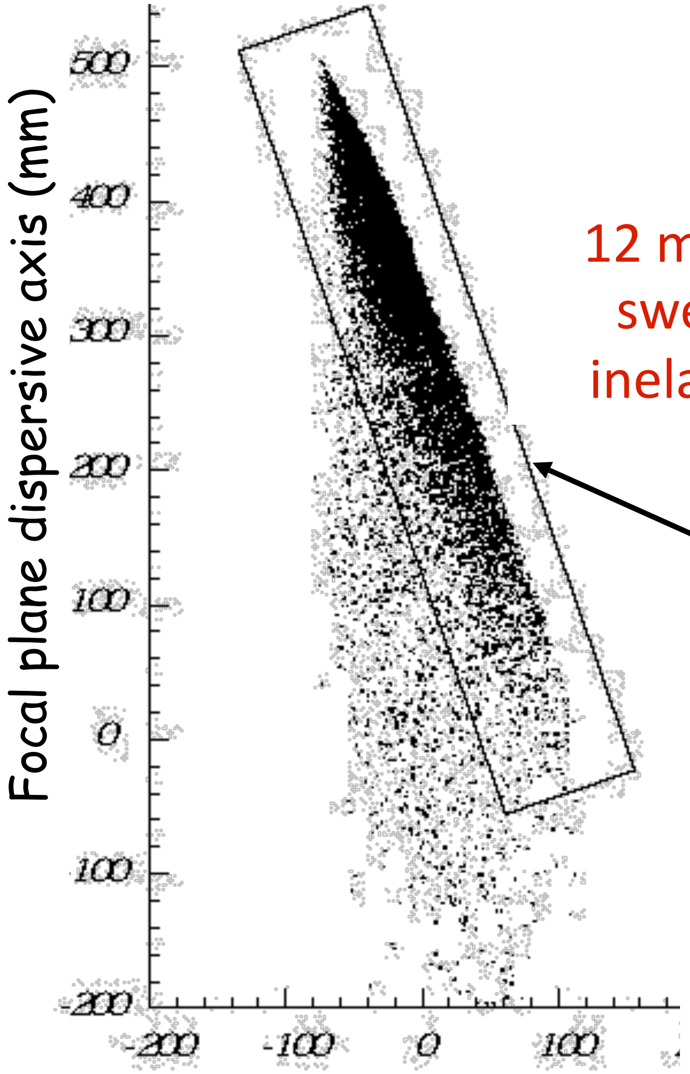
- Total spectrometer – 1000 tons

Spectrometer and Detector

Clean separation of elastic events by magnetic optics





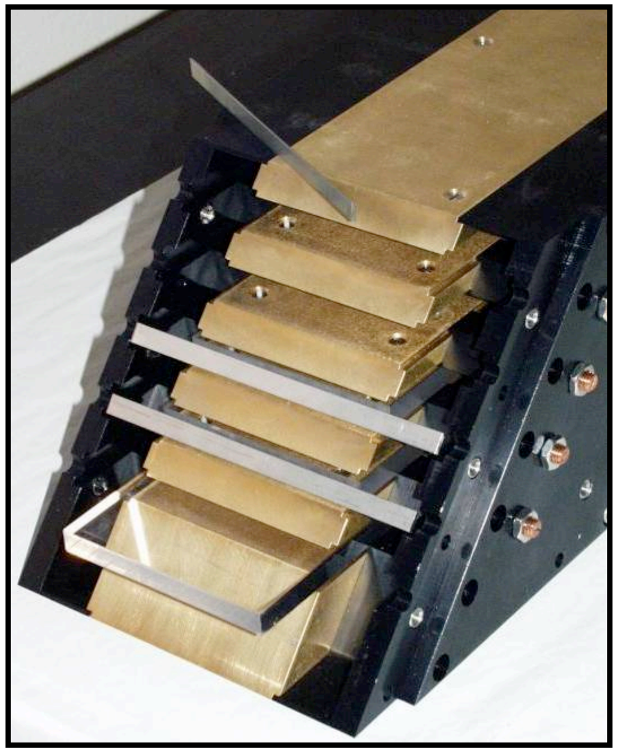


12 m dispersion sweeps away inelastic events

Overlap the elastic line and integrate the flux

Integrating Cerenkov Shower Calorimeter

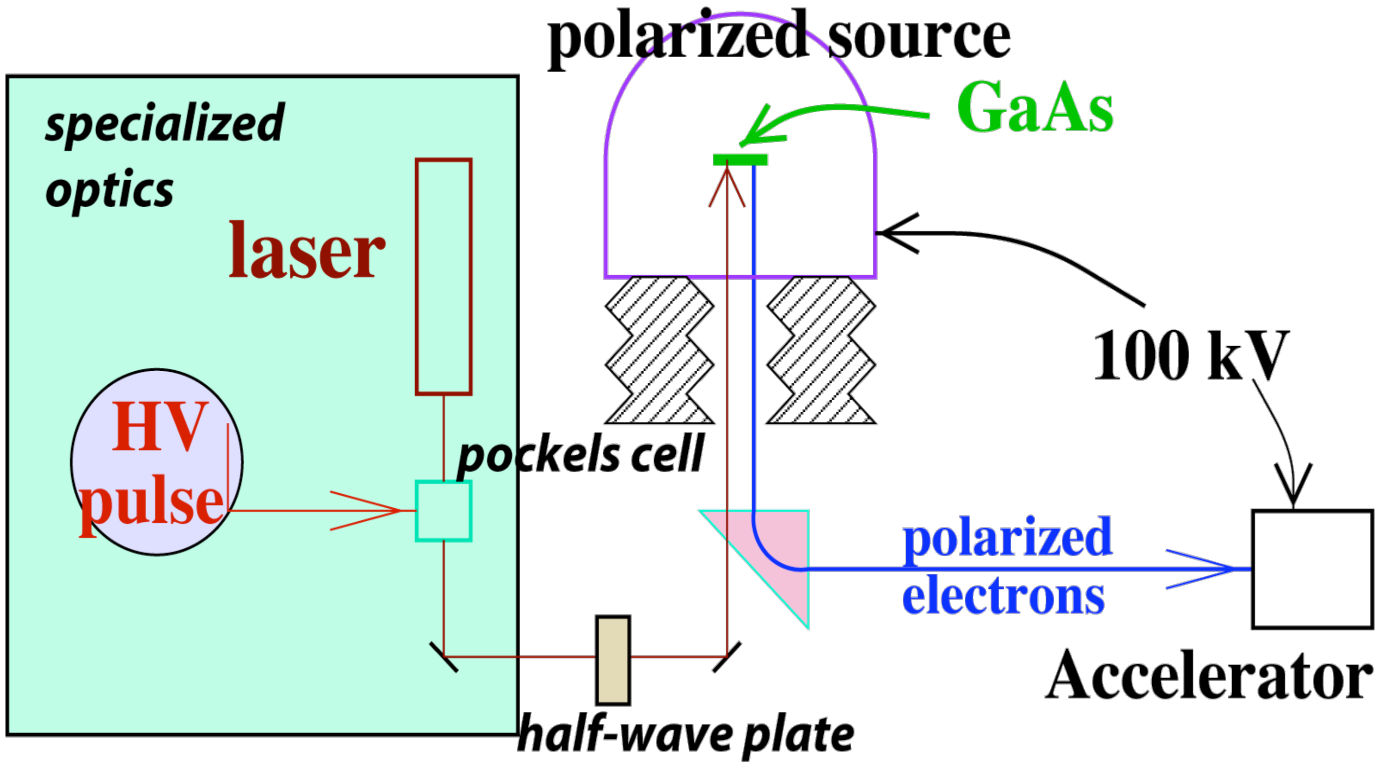
- Electromagnetic shower through brass radiator
- Cerenkov light from shower in quartz layers
- Analog integration of PMT signal

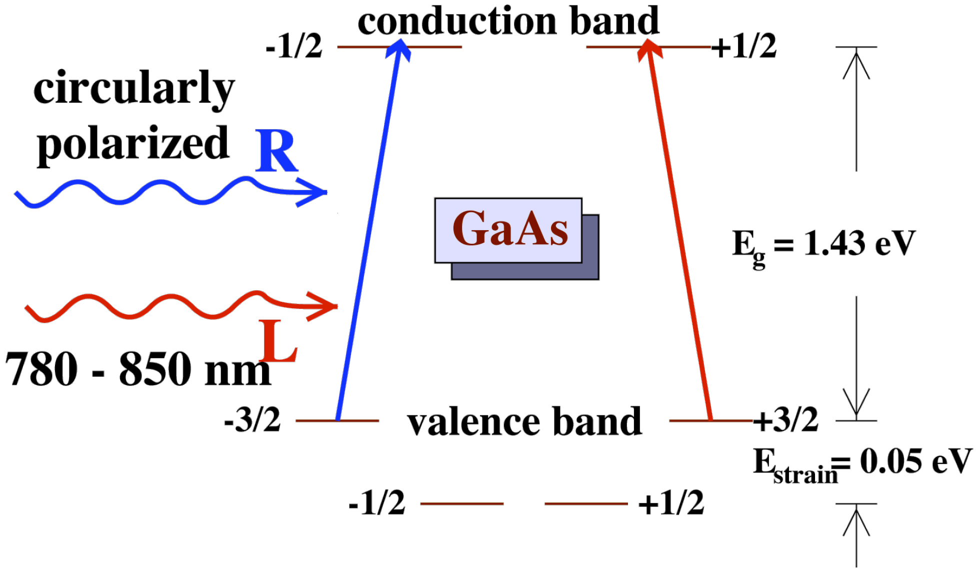


Future Experiments require new spectrometer concepts

Polarized Electrons for Measuring A_{PV}

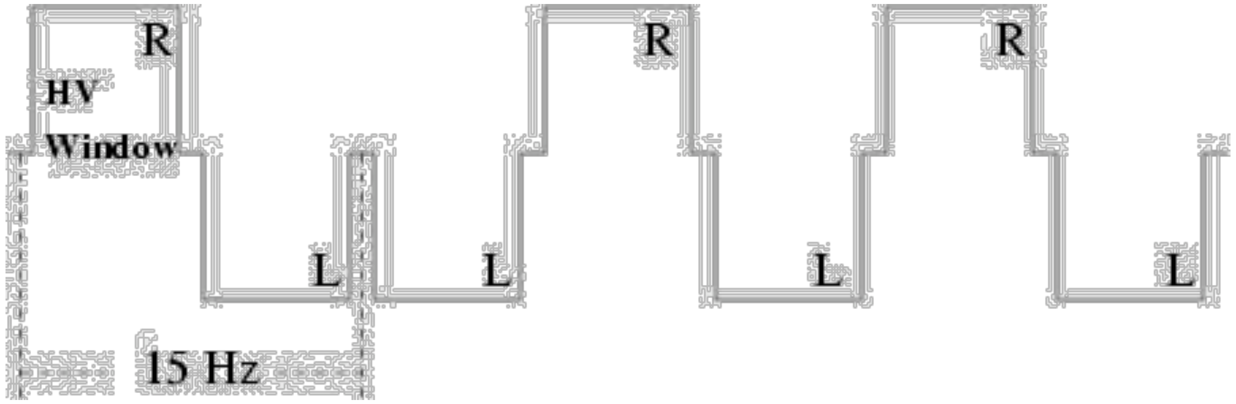
Photoemission from semiconductor cathode





Strain gives high polarization (~85%) but also introduces anisotropy

Electro-optic Pockels cell enables rapid helicity flip



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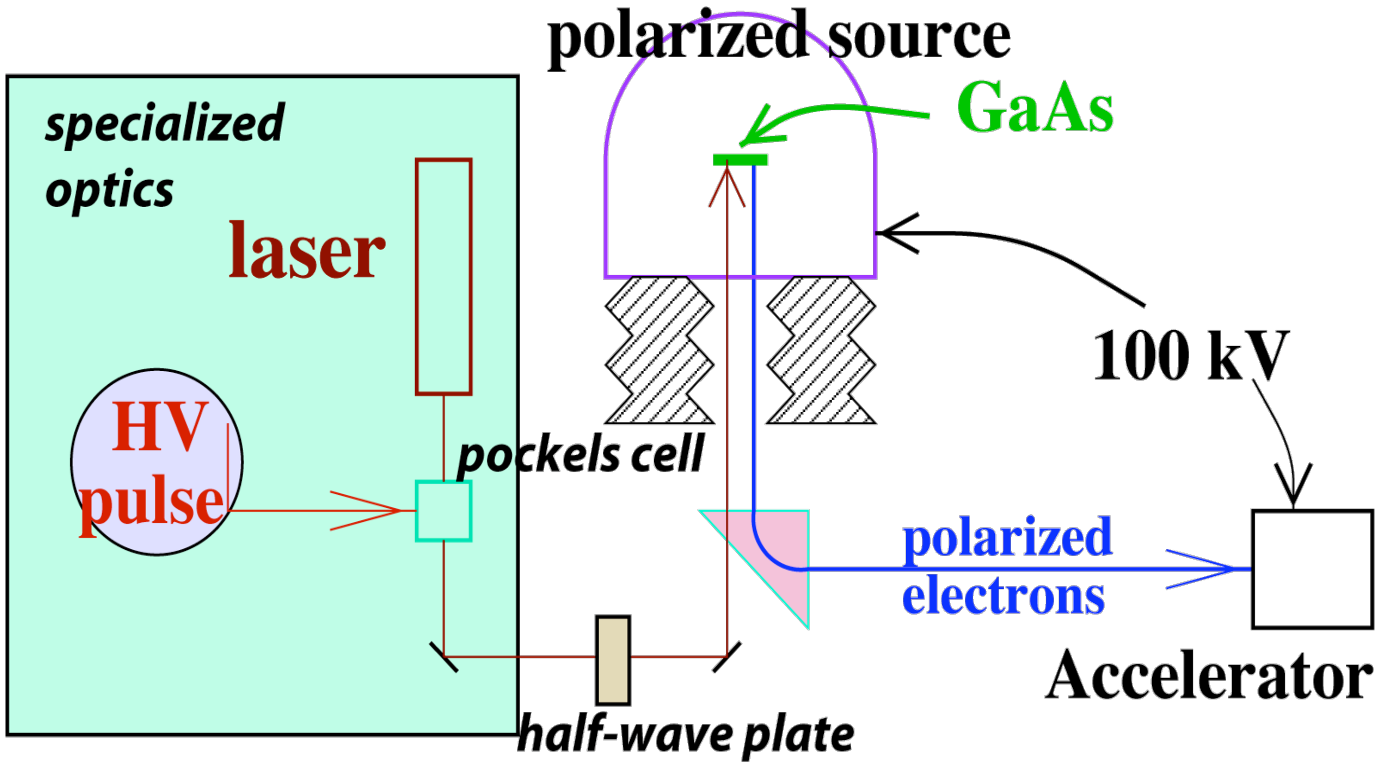
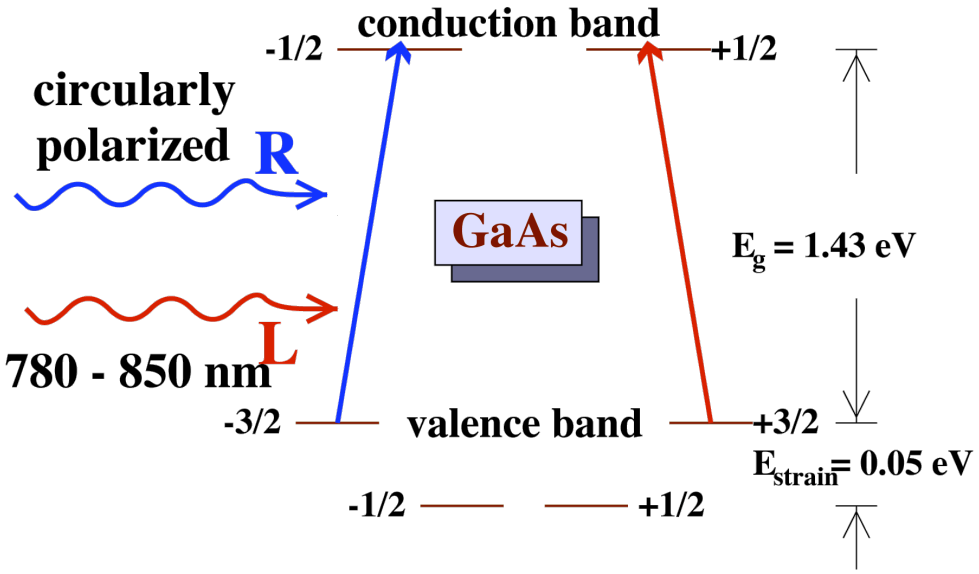
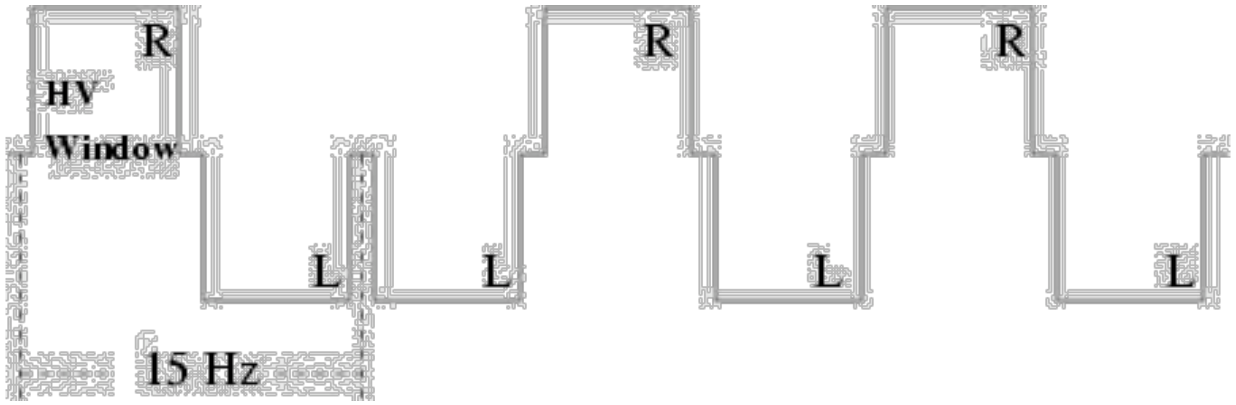




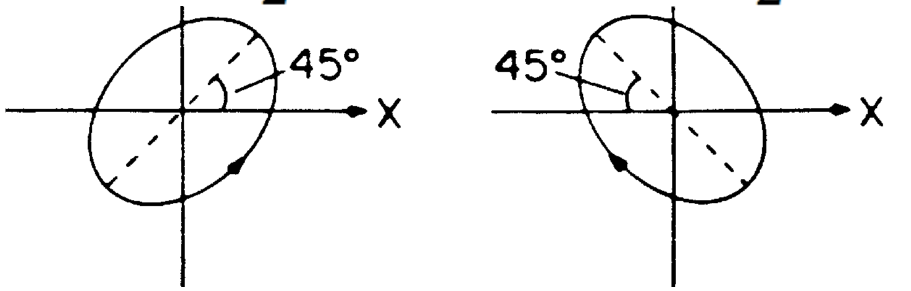
Strain gives high polarization (~85%) but also introduces anisotropy

Uniformity of laser circular polarization is critical

Electro-optic Pockels cell enables rapid helicity flip



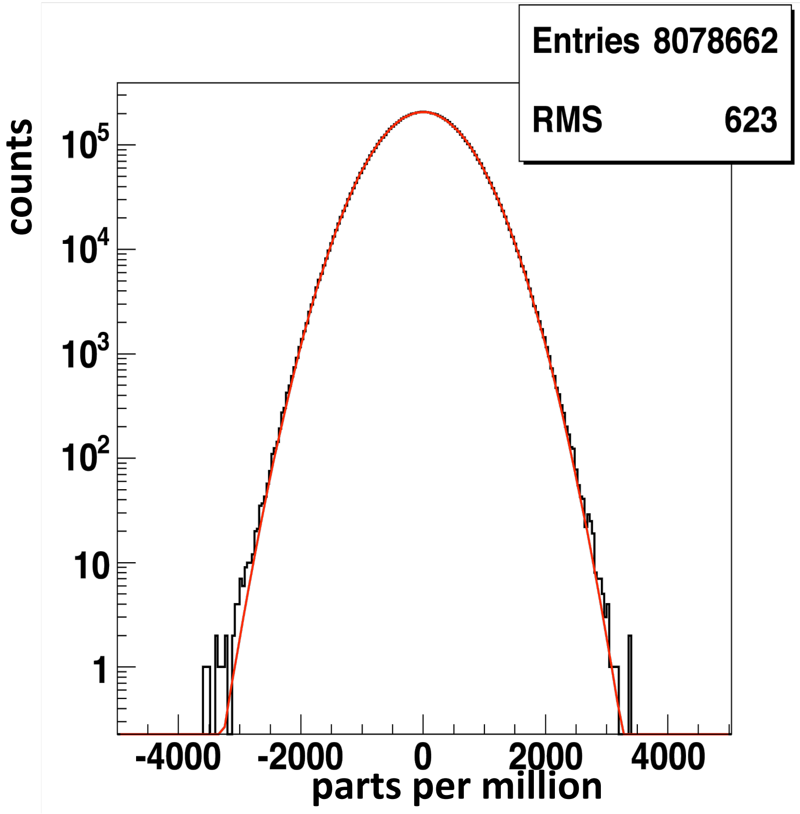
$$\delta = \frac{\pi}{2} - \Delta \qquad \delta = -\frac{\pi}{2} - \Delta$$



Residual linear polarization couples to anisotropy in photocathode to change e^- beam intensity, position, shape along with helicity

Measuring A_{PV}

Data analyzed as "pairs" (consecutive measurements with opposite helicity)



Measure the asymmetry millions of times with 0.06% (600 ppm) precision!

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

calculated at 15Hz

$$\delta(A_{PV}) = \frac{600\,\text{ppm}}{\sqrt{8\times 10^6}}$$

$$= 0.2\,\text{ppm}$$

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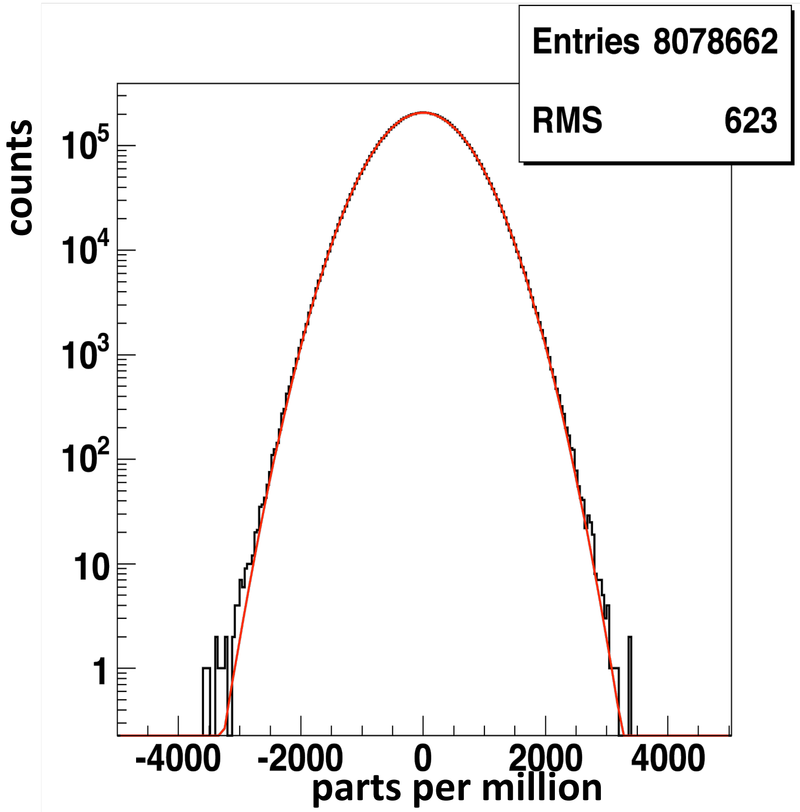

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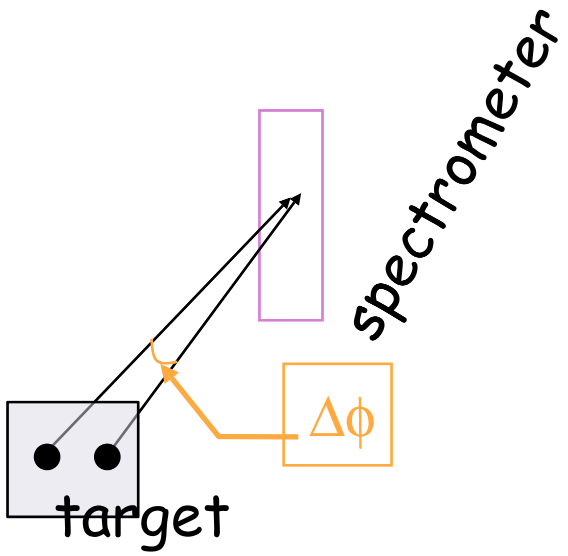
Beam must look the same for the two helicity states!

- **More beam = more signal: so intensity change -> A_{false}**
- **Cross-section vs angle is very steep: position change -> A_{false}**

Corrections are made using measured sensitivities.

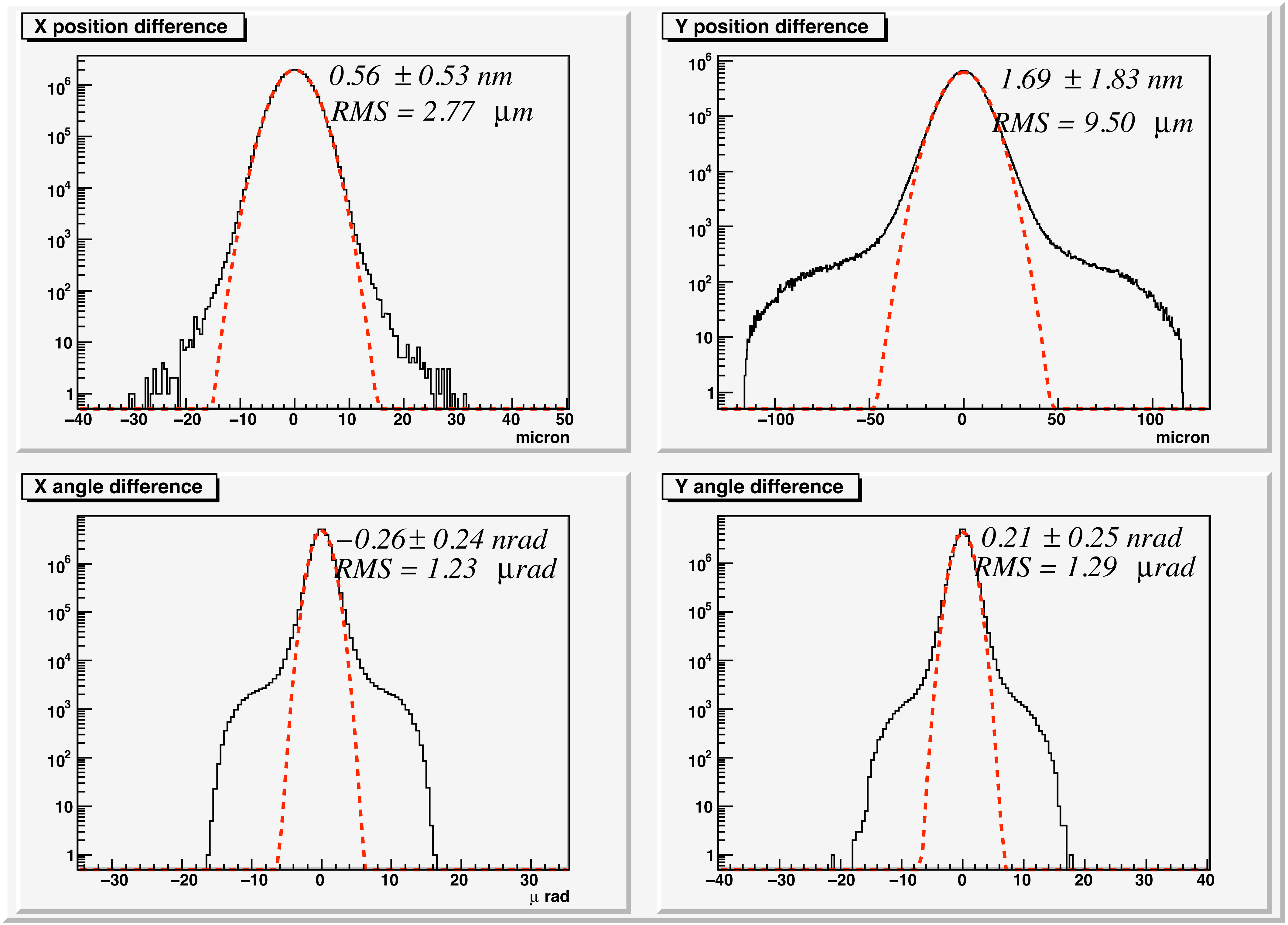
$$A_{cor} = A_{\det} - A_Q + \sum_{i=1}^{5} \beta_i \Delta x_i$$



Major effort was applied to reducing beam asymmetries at the polarized source

Helicity Correlated Position Differences

Over the ~20 million pairs measured in HAPPEX-II, the average position was not different between the two helicity states by more than 1 nanometer

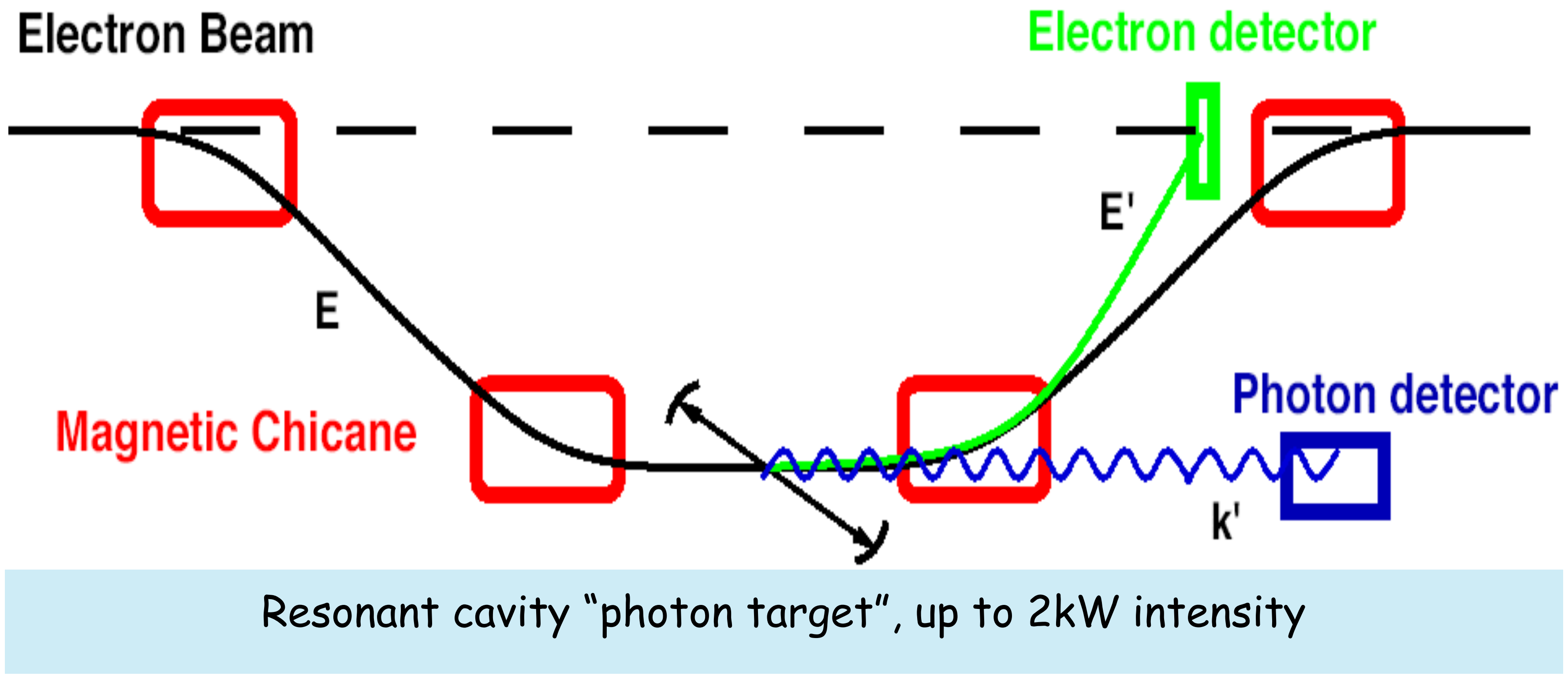


This was still the leading source of systematic uncertainty in the asymmetry

Compton Polarimeter

Precise measure of beam polarization is needed

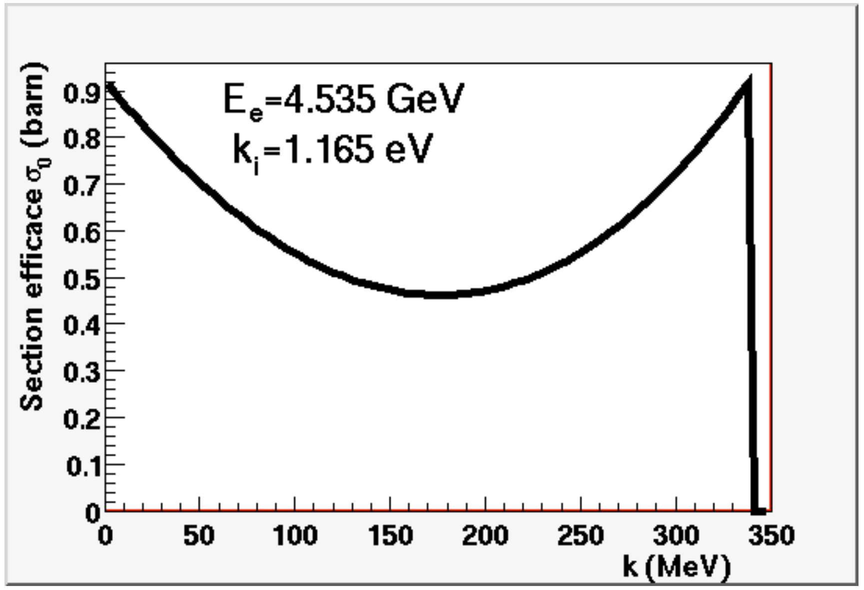
$$A_{\exp} = \frac{n^{+}-n^{-}}{n^{+}+n^{-}} = P_{\gamma} \times P_{e} \times < A_{th} >$$

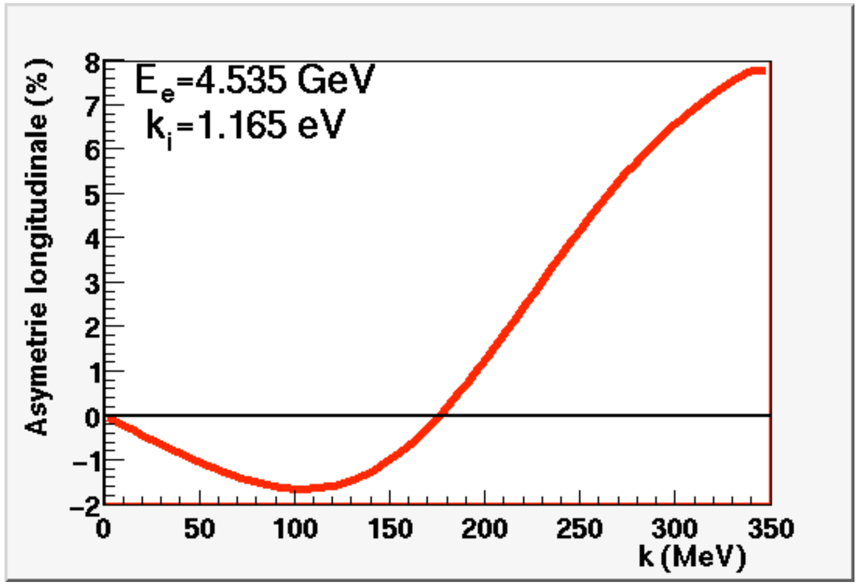


Resonant cavity "photon target", up to 2kW intensity

measure asymmetry independently in:

- **momentum analyzed electrons**
- **photons in calorimeter**





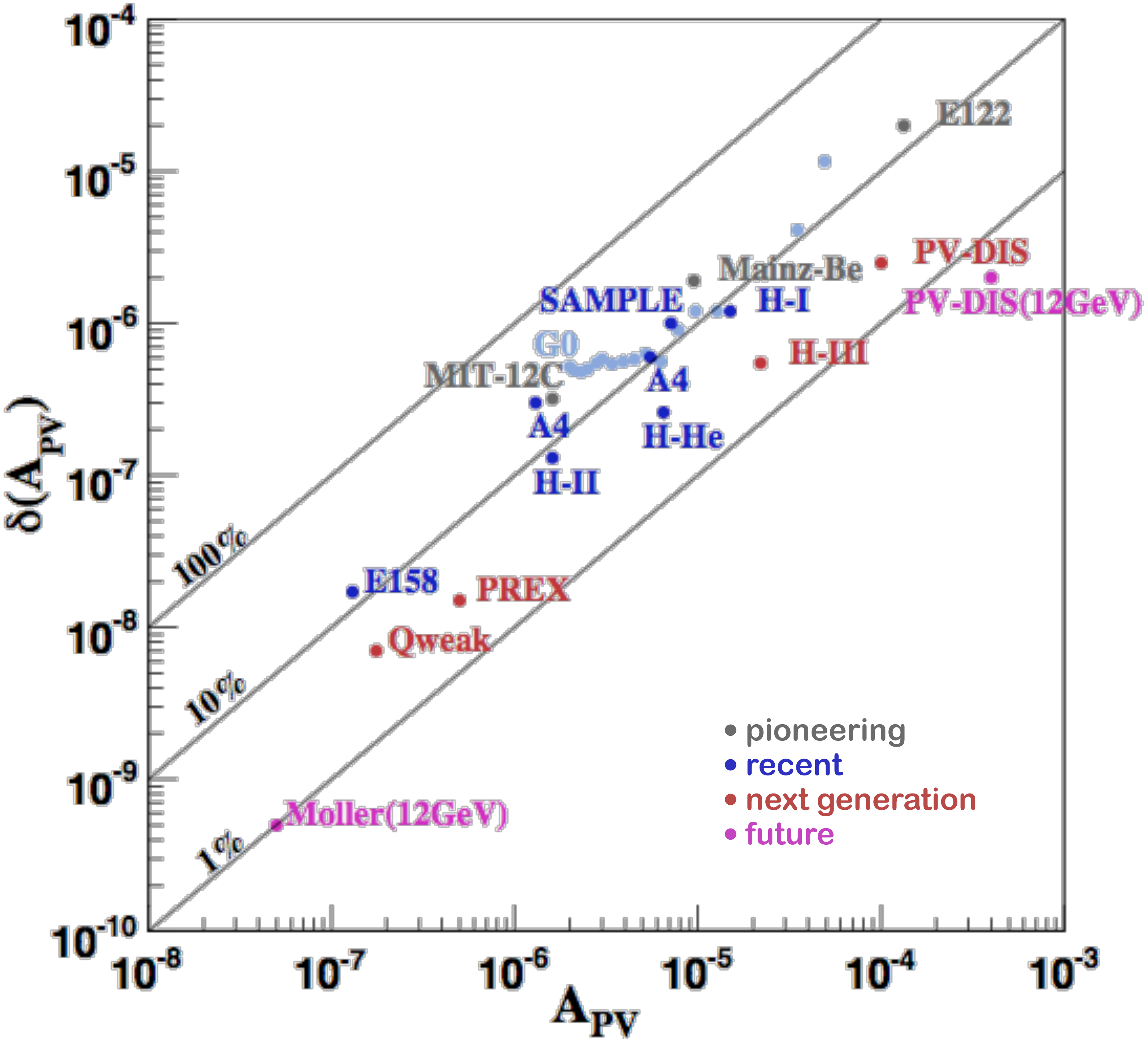
Present Technology

- **Best precision now ~1.5%. 1% is within reach**
- **Existing Moller polarimeter quotes <1% uncertainties, but not continuous monitor (Hall C)**

Future:

- **Upgrade required in Hall A Compton**
- **New Polarimeter to be built in Hall C**
- **Technique can be pushed to ~0.4% for future program**
- **Complementary Atomic Hydrogen Moller polarimeter possible**

Precision Electroweak Physics



Steady progress in technology:

- part per billion systematic control
- 1% systematic control
- Major developments in
  - photocathodes (I & P)
  - polarimetry
  - high power cryotargets
  - nanometer beam stability
  - precision beam diagnostics
  - low noise electronics
  - radiation hard detectors

Parity-violating electron scattering has become a precision tool

Just how big are the really big nuclei?

Form Factors and Extended Targets

The point-like scattering probability is modified to account for Finite Target Extent by introducing the "form factor"

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

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

Form factor is the Fourier transform of charge distribution

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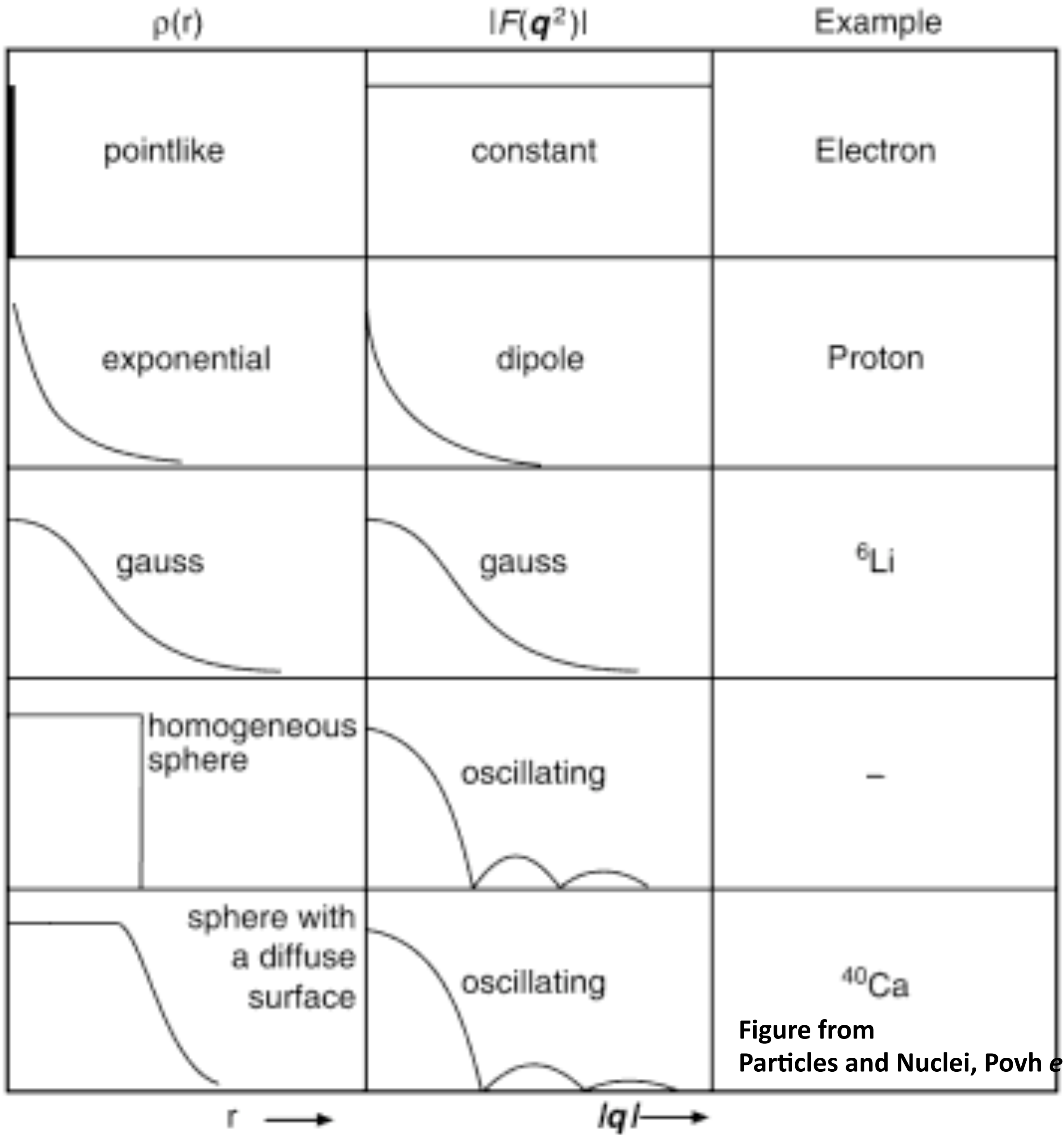

$\rho(r)$	$\lvert F(\boldsymbol{q}^2)\rvert$	Example
pointlike	constant	Electron
exponential	dipole	Proton
gauss	gauss	^{6}Li
homogeneous sphere	oscillating	–
sphere with a diffuse surface	oscillating	^{40}Ca

Figure from
Particles and Nuclei, Povh *et al.*

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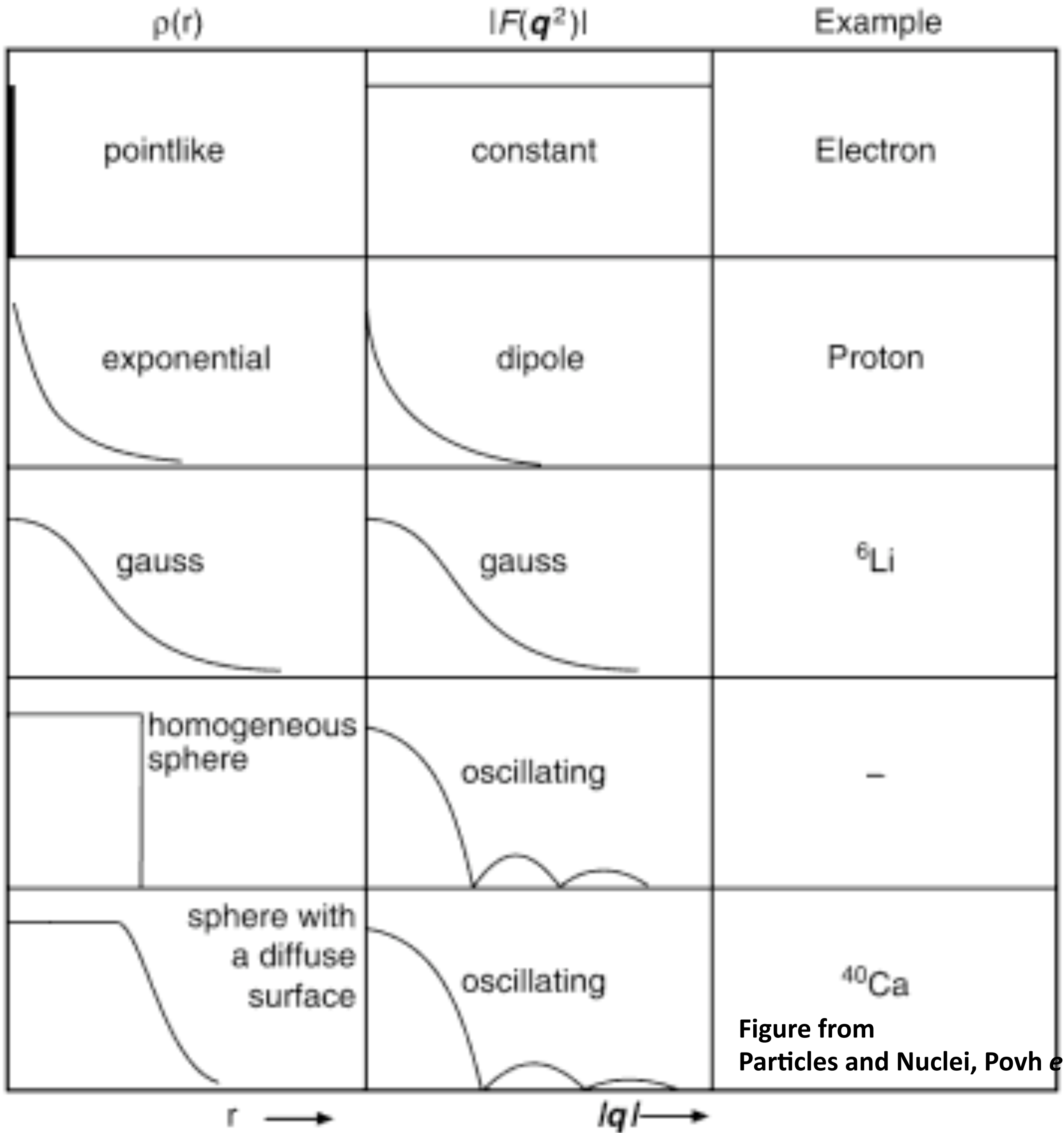

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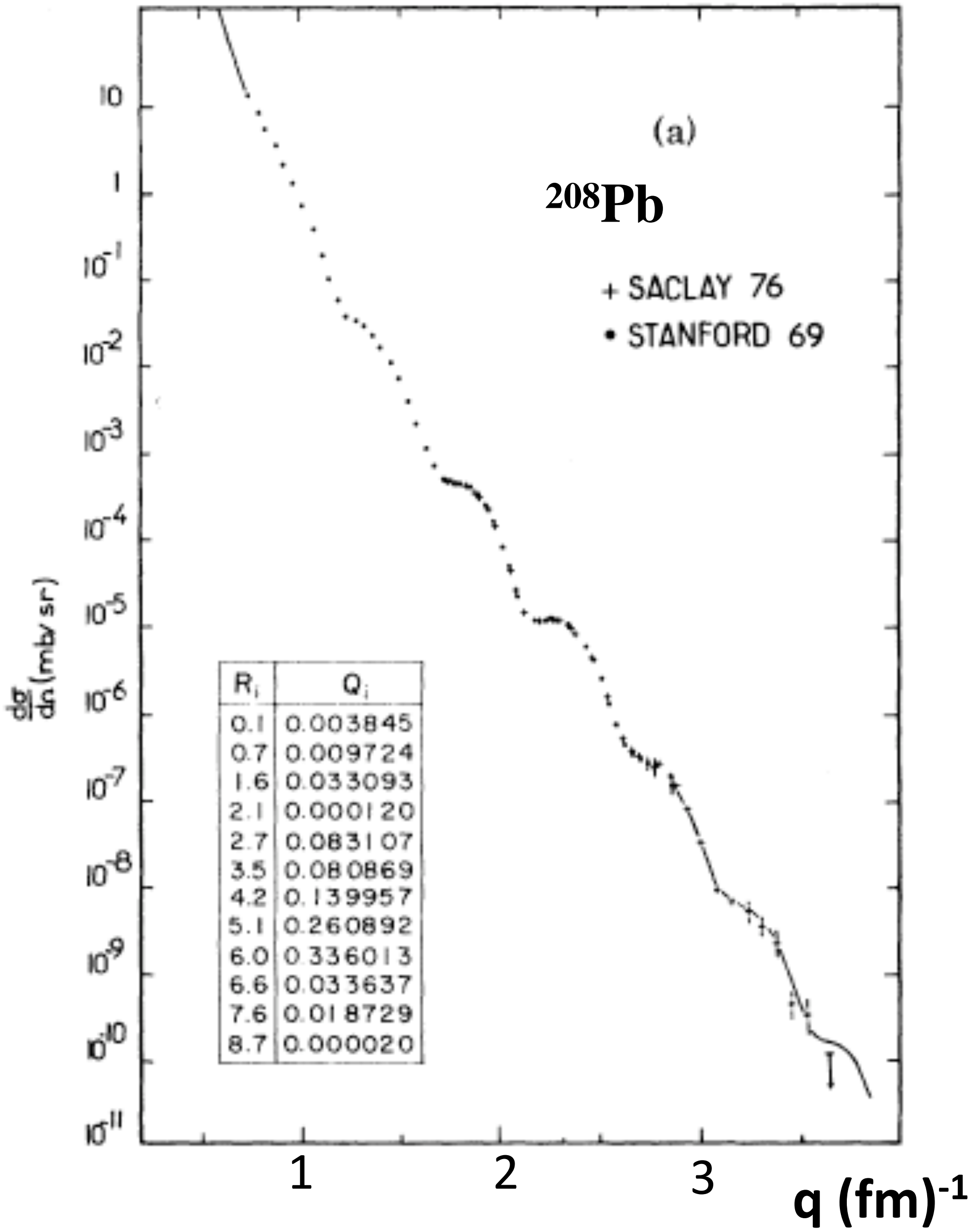

R_i	Q_i
0.1	0.003845
0.7	0.009724
1.6	0.033093
2.1	0.000120
2.7	0.083107
3.5	0.080869
4.2	0.139957
5.1	0.260892
6.0	0.336013
6.6	0.033637
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8.7	0.000020

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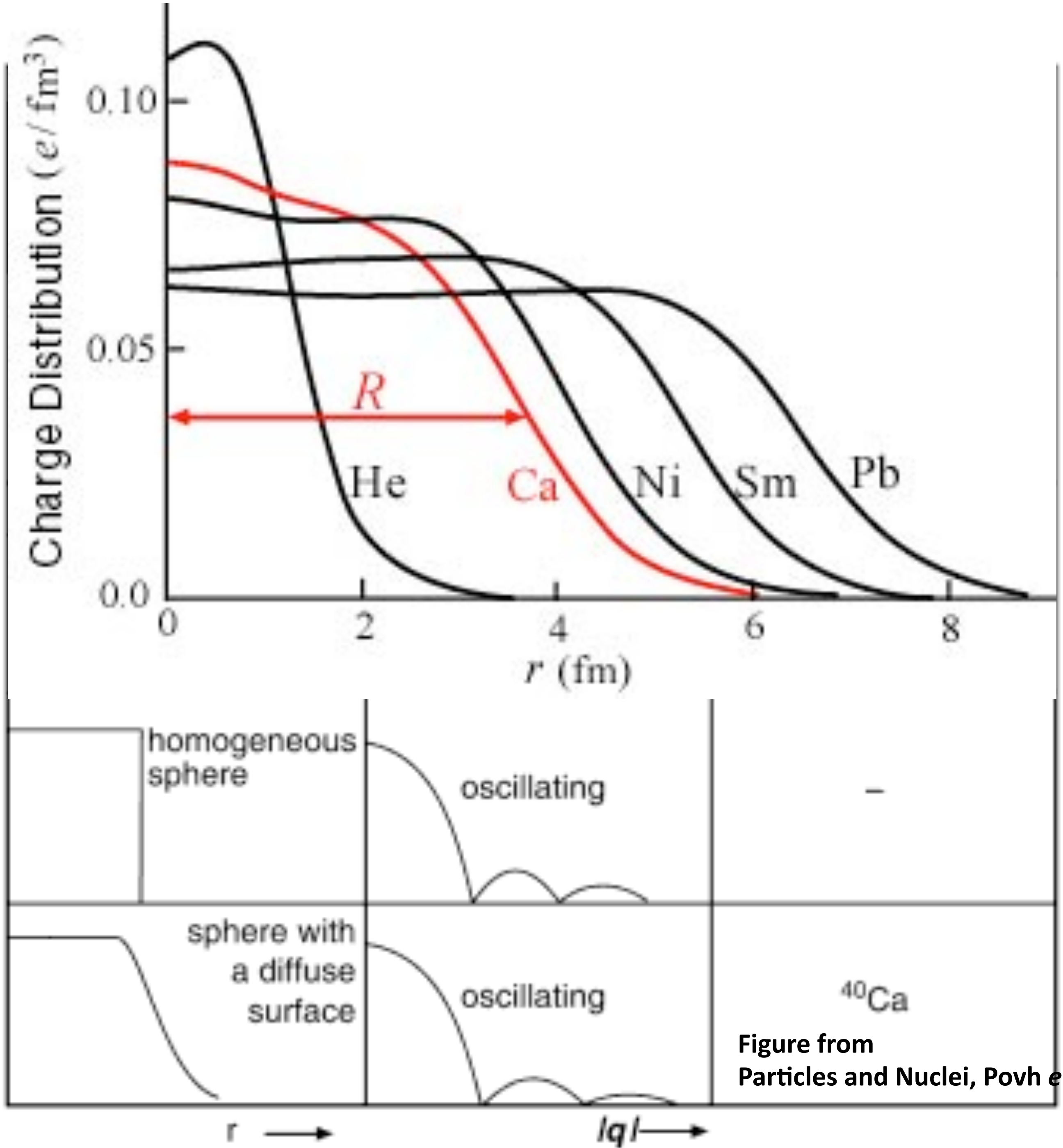

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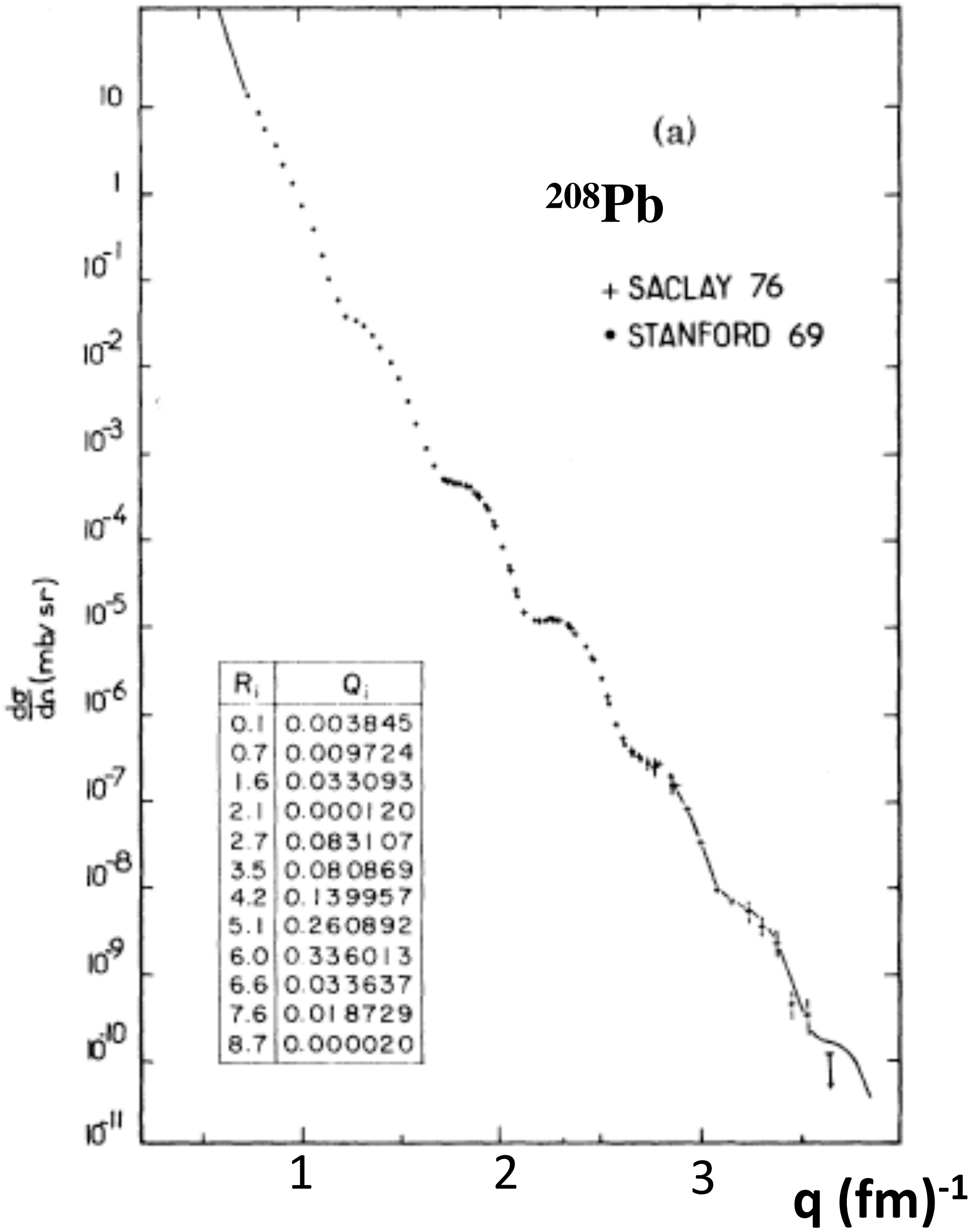

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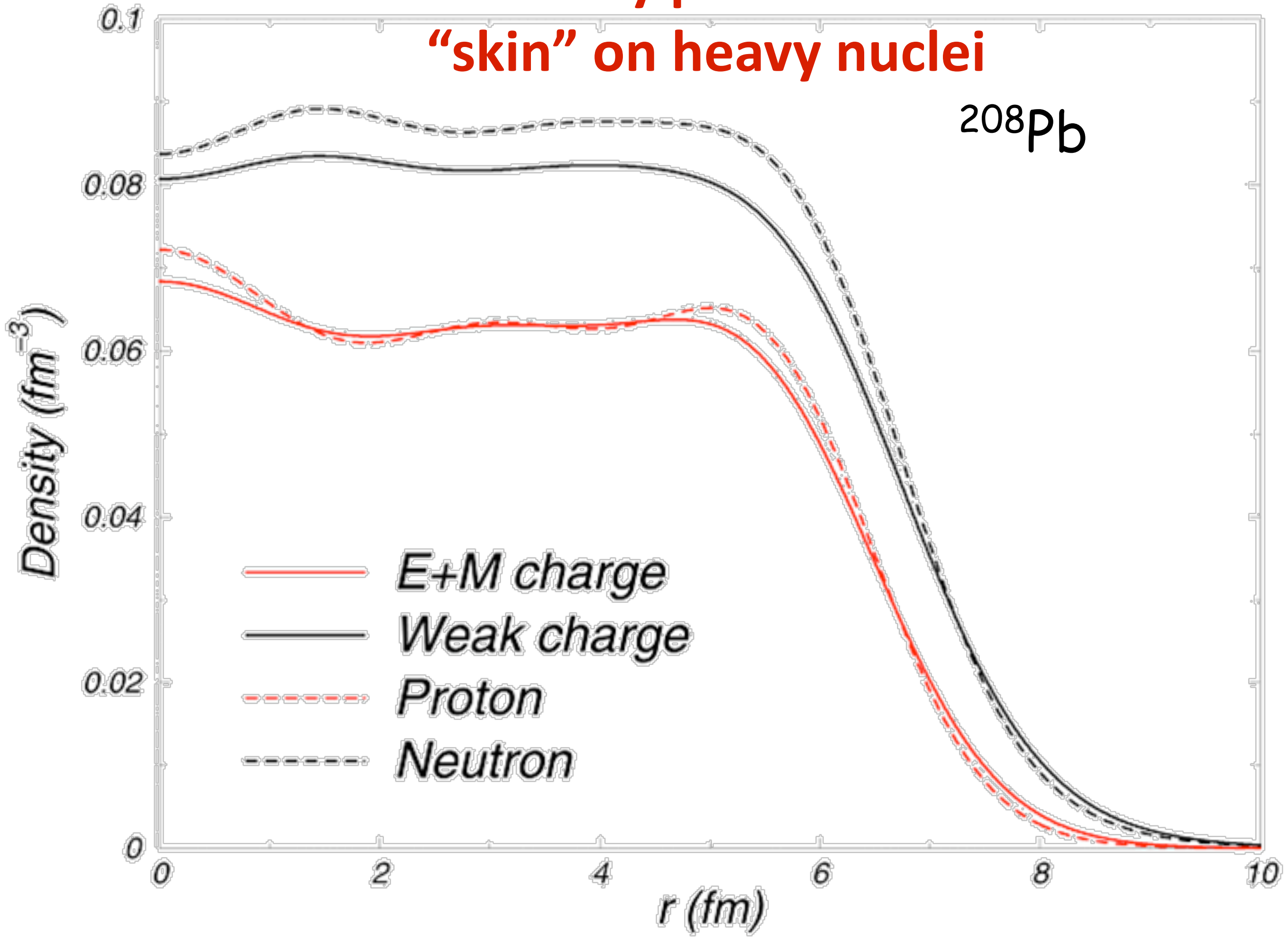
Weak Charge Distribution



Nuclear theory predicts a neutron “skin” on heavy nuclei

^{208}Pb

Weak Charge Distribution

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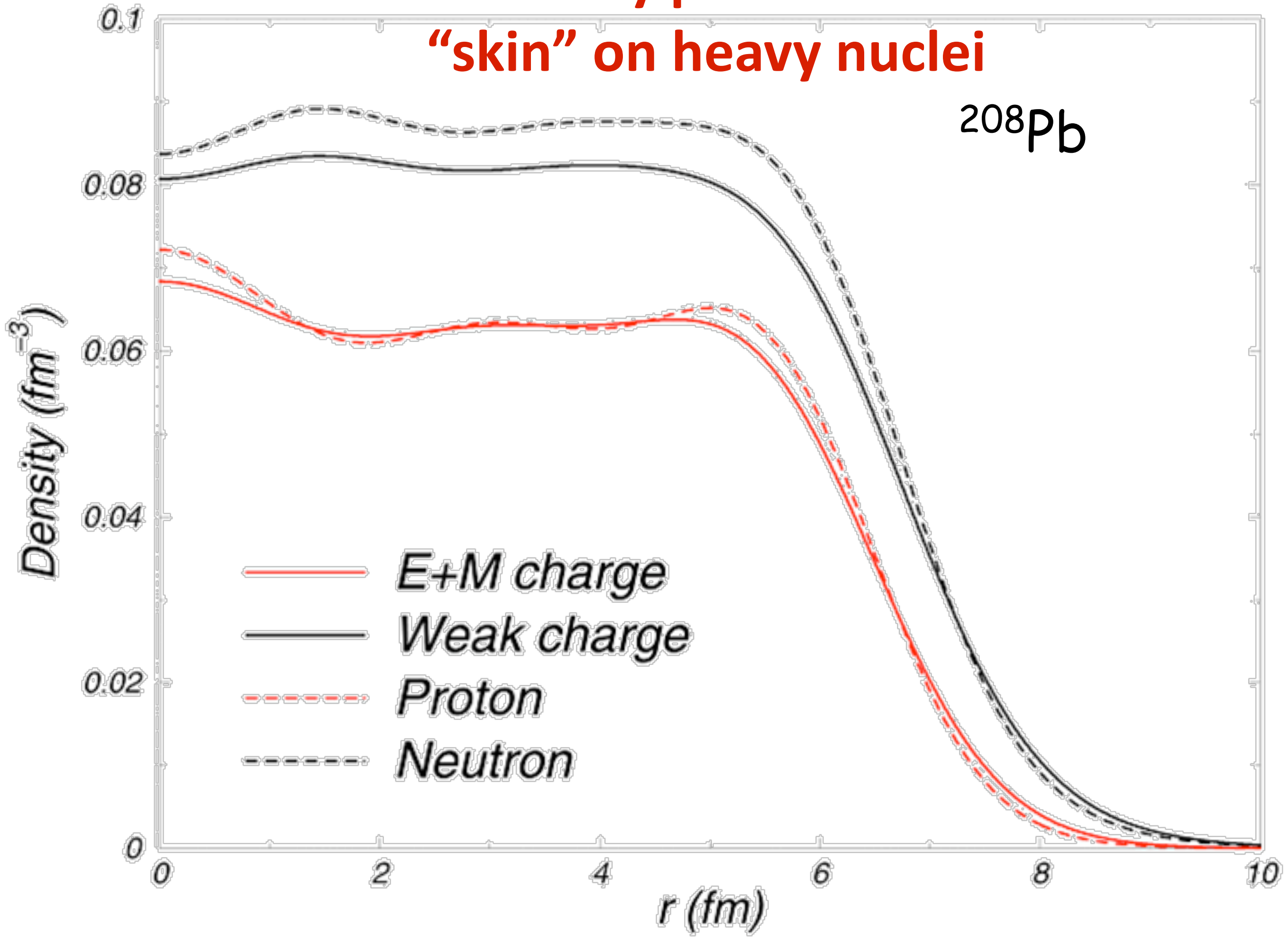

Neutron distribution is not accessible to the charge-sensitive photon.

Hadronic scattering can see neutrons, but with lots of messy QCD complications

	proton	neutron
Electric charge	1	0
Weak charge	0.05	1

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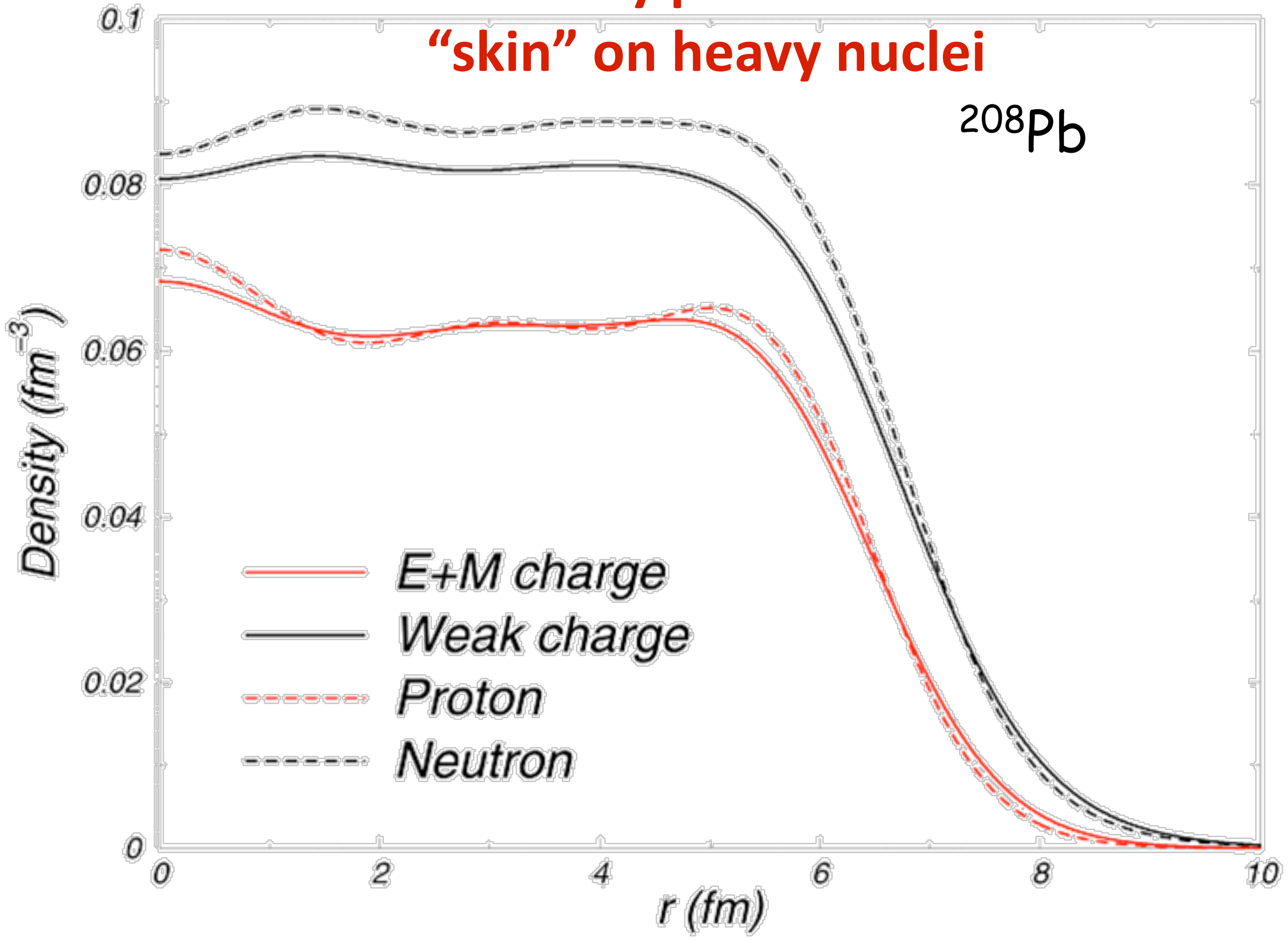

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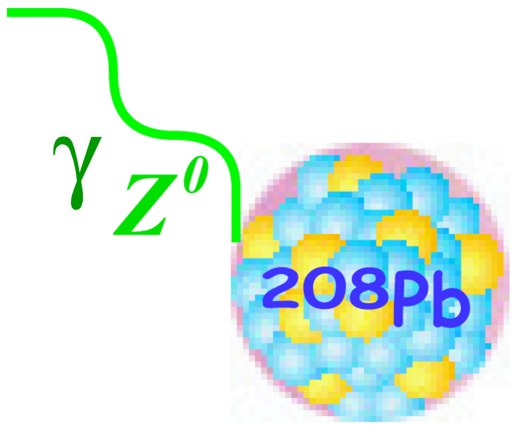
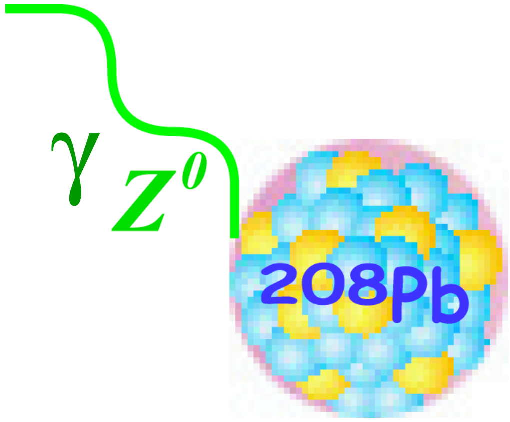


$$M^{EM} = \frac{4\pi\alpha}{Q^2} F_p(Q^2)$$

$$M_{PV}^{NC} = \frac{G_F}{\sqrt{2}}\left[\left(1-4\sin^2\theta_W\right)F_p(Q^2) - F_n(Q^2)\right]$$

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

PREX (Pb-Radius Experiment)



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

6° scattering angle

Rate ~1.5 GHz

Stat. Error ~ 15 ppb (3%)

Syst. Error ~ 5 ppb (1) %

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

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

$$\frac{F_n(Q^2)}{F_p(Q^2)} \Longrightarrow R_n$$

The single measurement of F_n translates to a measurement of R_n via mean-field nuclear models

Neutron Skin Thickness (R_n - R_p):

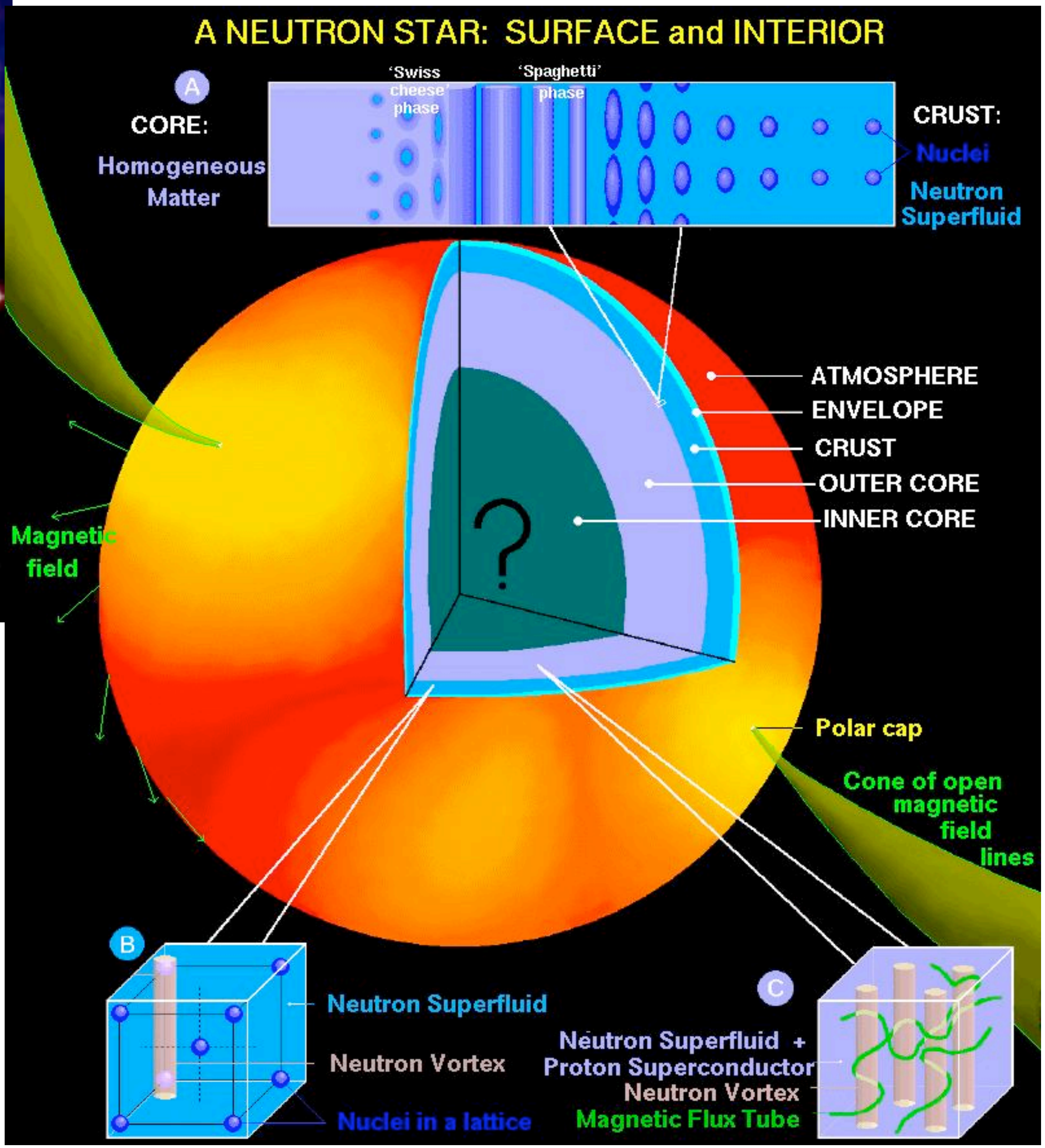
- **key prediction of nuclear theory, so this tests understanding of nuclear structure**
- **related to symmetry energy of Equation of State of neutron-rich nuclei**
- **implications for heavy ion collisions, atomic PV, the description of *really* large nuclei**

From ^{208}Pb to a Neutron Star

R_n calibrates the equation of state of neutron rich matter

Crust Thickness

Explain Glitches in Pulsar Frequency ?



Combine PREX R_n with observed neutron star radii

⟶ Phase Transition to "Exotic" Core ?

⟶ Strange star ? Quark Star ?

Some neutron stars seem too cold

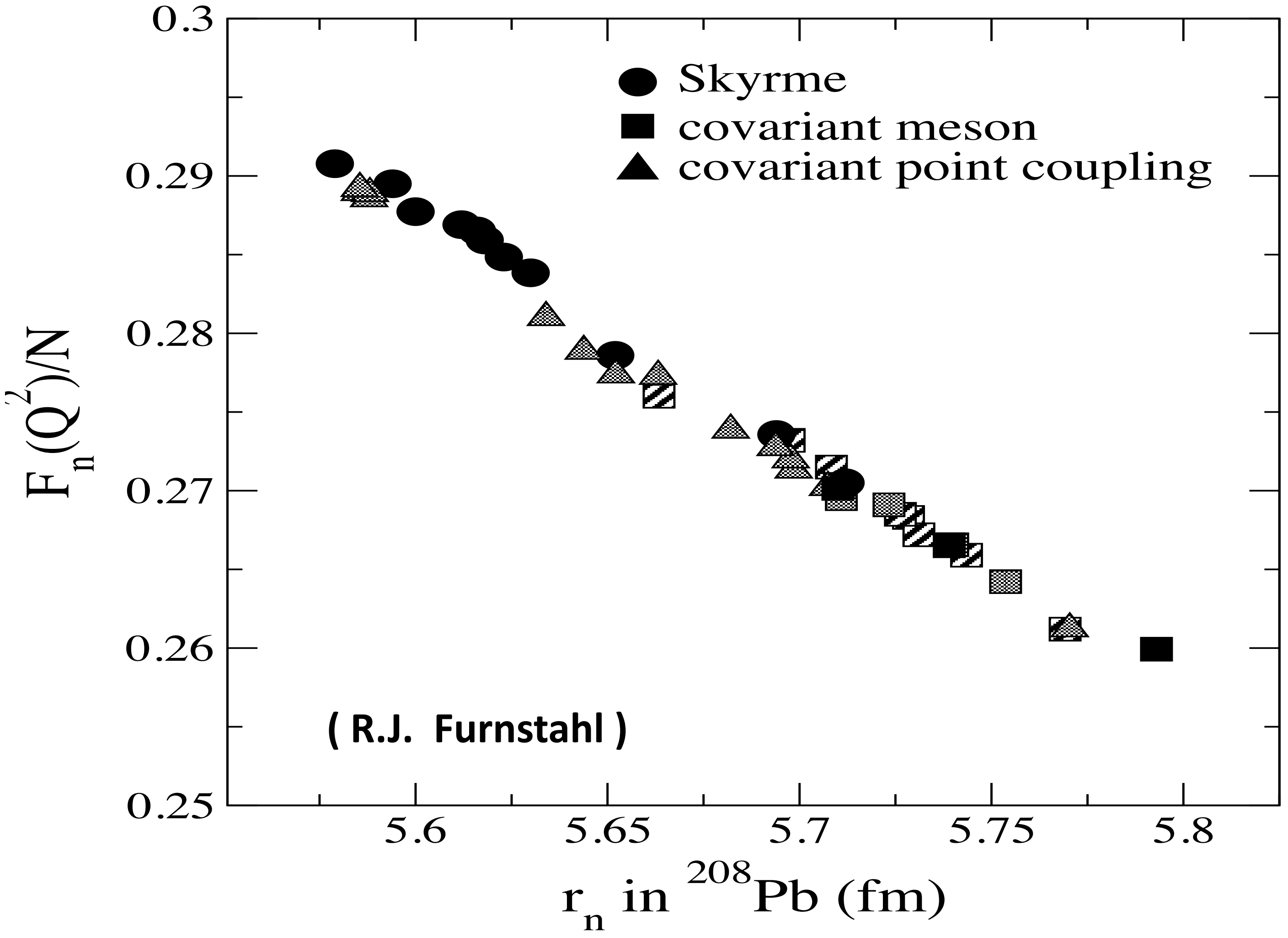
⟶ Cooling by neutrino emission (URCA)

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

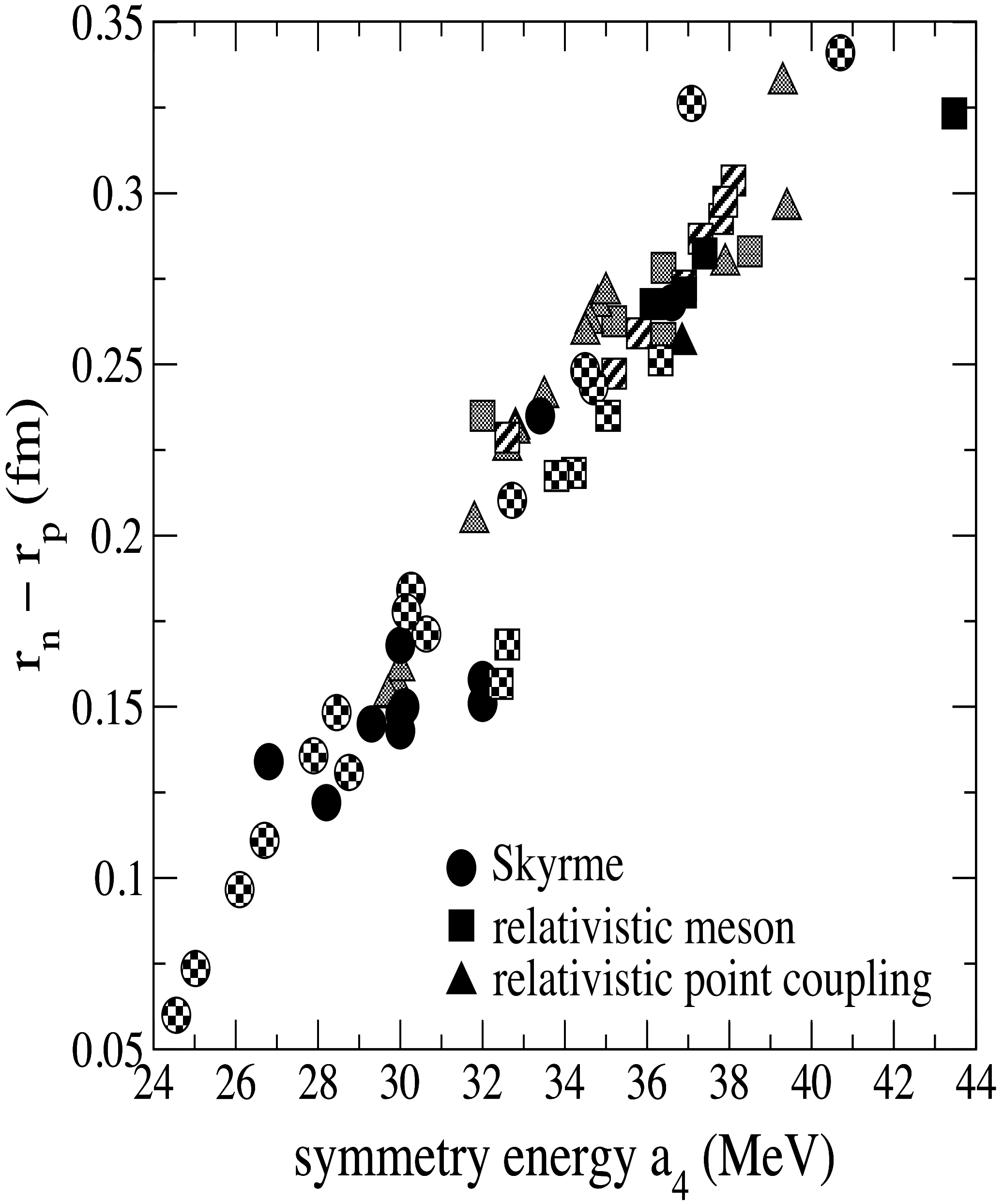
A crucial calibration point for nuclear theory

Models agree:

Measurement at one Q^2 determines r_N ...



...and measuring r_N pins down the symmetry energy



Challenging Experiment

15 ppb absolute measurement

- helicity correlated beam asymmetries
- electronics noise

3% relative error

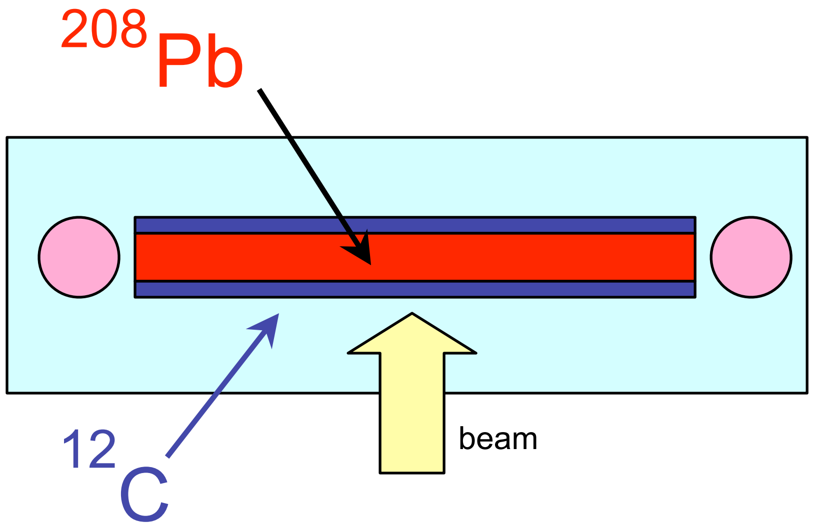
- low-energy electron beam polarimetry
- precise absolute kinematics calibration
- backgrounds

Similar the HAPPEX measurements

- Use Hall A spectrometers
- integrating technique

10X more precise than any previous e$^-$-nucleus scattering!

Lead-Diamond sandwich detector



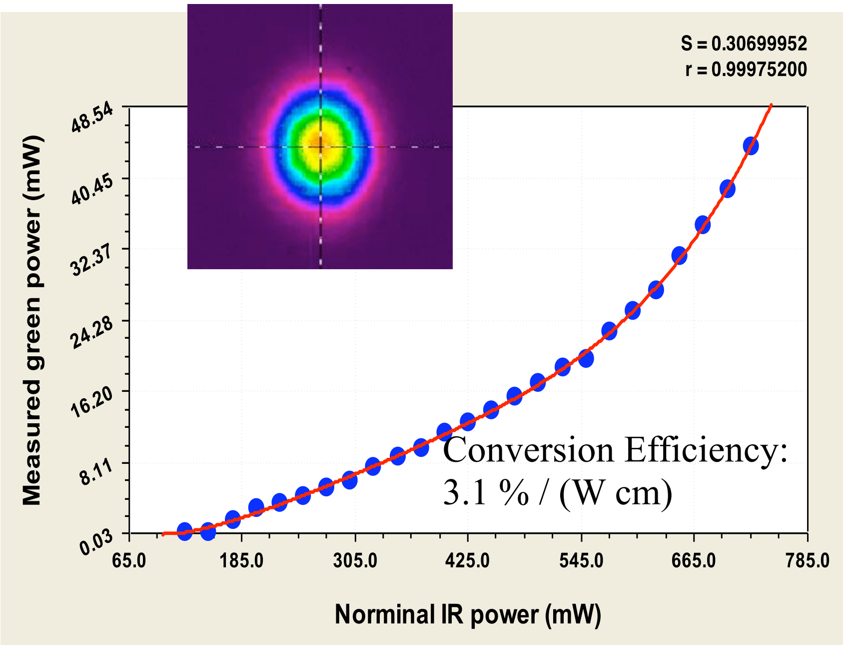
Tests indicate that it can handle the beam current

New Detectors
New ADC electronics
Laser / Source Studies
New Target
New Polarimeter
Detailed Simulations
Accelerator Studies

Scheduled
Early 2010

Compton Polarimeter
upgrade IR to Green light

PPLN Second Harmonic Generation
double 1064 nm to 532 nm

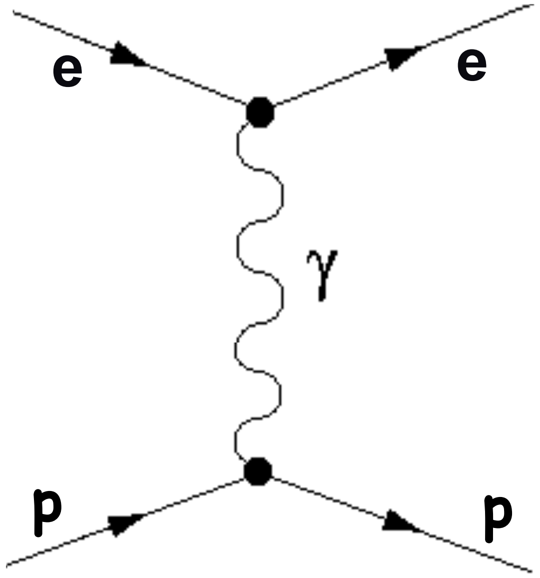


Results from Tharanga Jinasundera (UVa)

Fishing the strange sea

Elastic Electron-Nucleon Scattering

For a point-like target, accounting for target recoil:



Function of (E,θ).

Cross-section for infinitely heavy, fundamental target

τ=Q²/4M² is a convenient kinematic factor

$$\boxed{\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{\mathrm{Mott}} \left\{ 1 + 2\,\tau \tan^2(\theta/2) \right\}}$$

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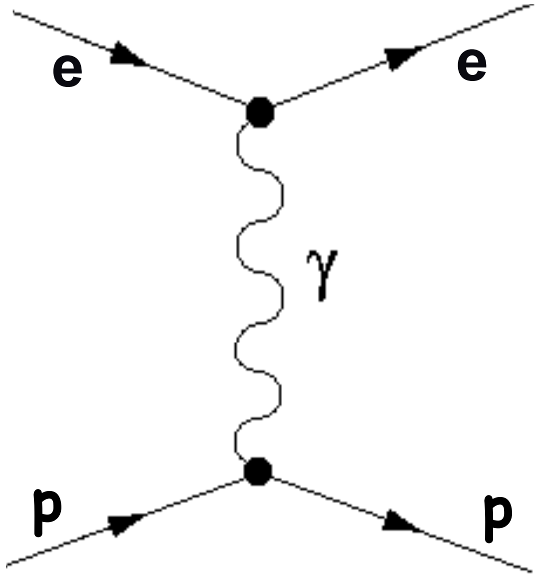
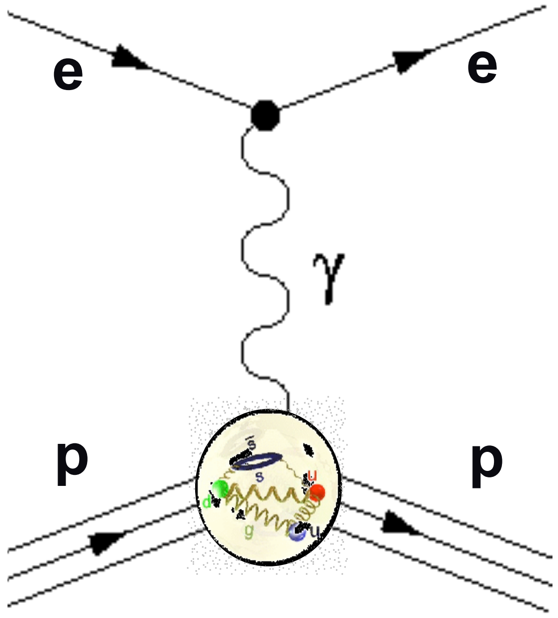


If proton is not point-like: The electric and magnetic form factors G_E and G_M parameterize the effect of proton structure.

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}_{\mathrm{Mott}} \frac{E'}{E} \left\{ \frac{(G_E^2 + \tau\, G_M^2)}{1+\tau} + 2\,\tau\, G_M^2 \tan^2(\theta/2) \right\}$$



If the proton were like the electron:

G_E = 1 (proton charge)

G_M = 1 (and the magnetic moment would be 1 Bohr magneton).

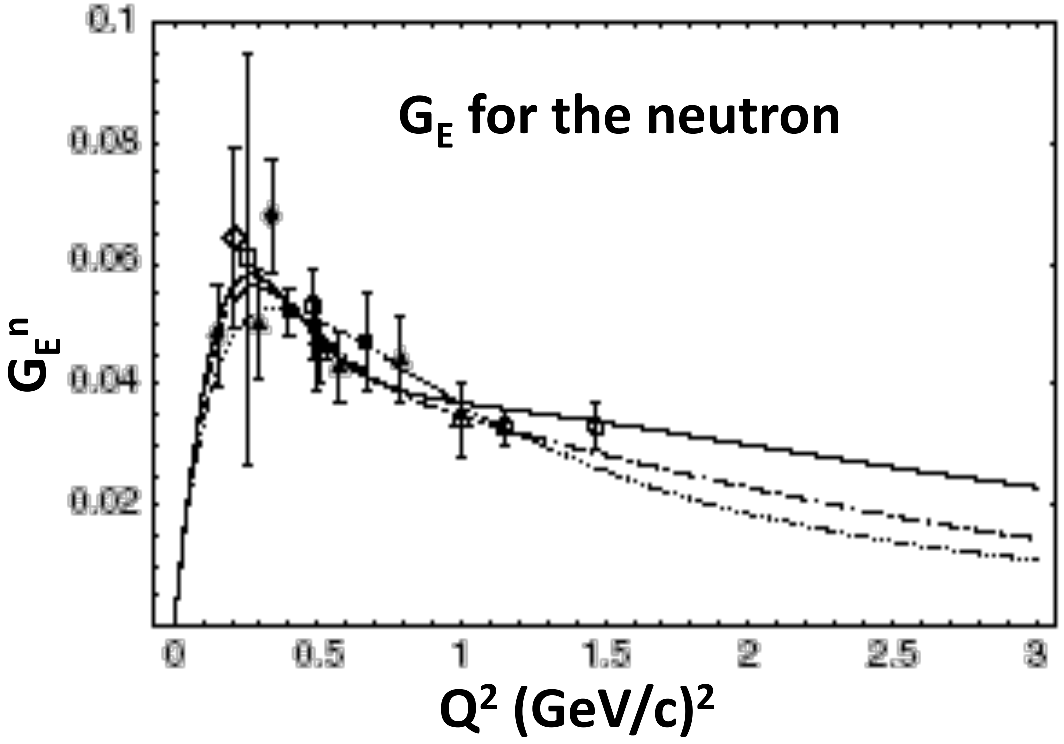
Charge & Current Distributions

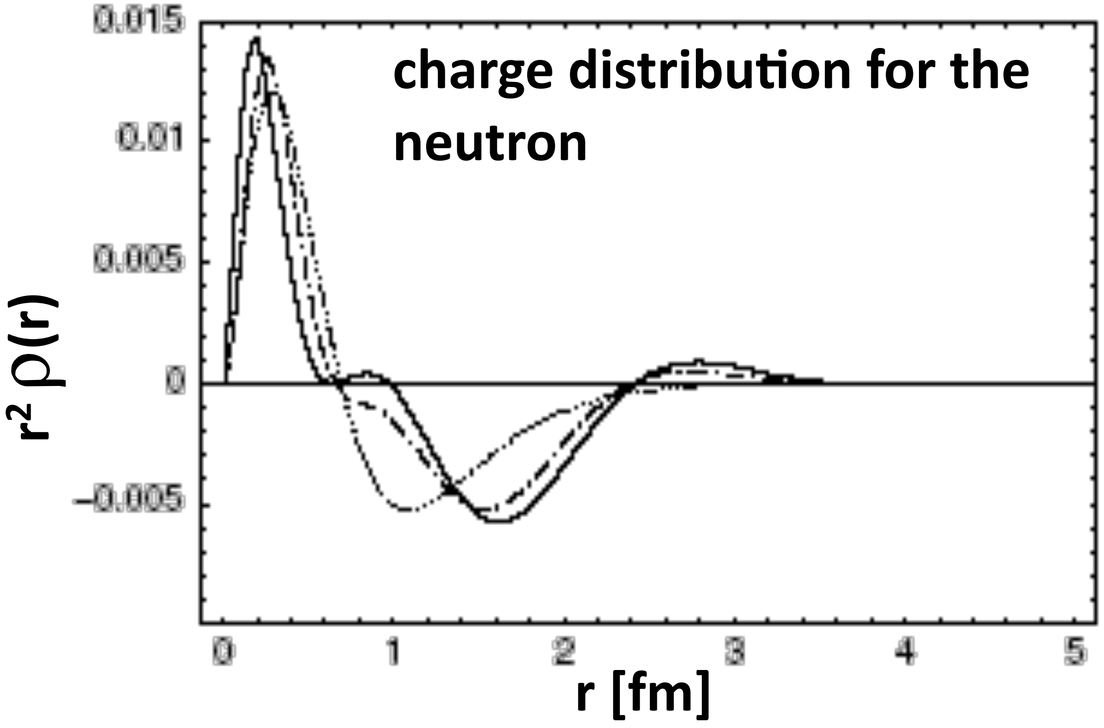
Form factors G_E, G_M are functions of Q^2

-> they measure scattering probability as a function of resolution

Fourier transform of the charge and magnetic current distributions

Electromagnetic form-factors have been well-measured for the proton and neutron


G_E for the neutron


charge distribution for the neutron

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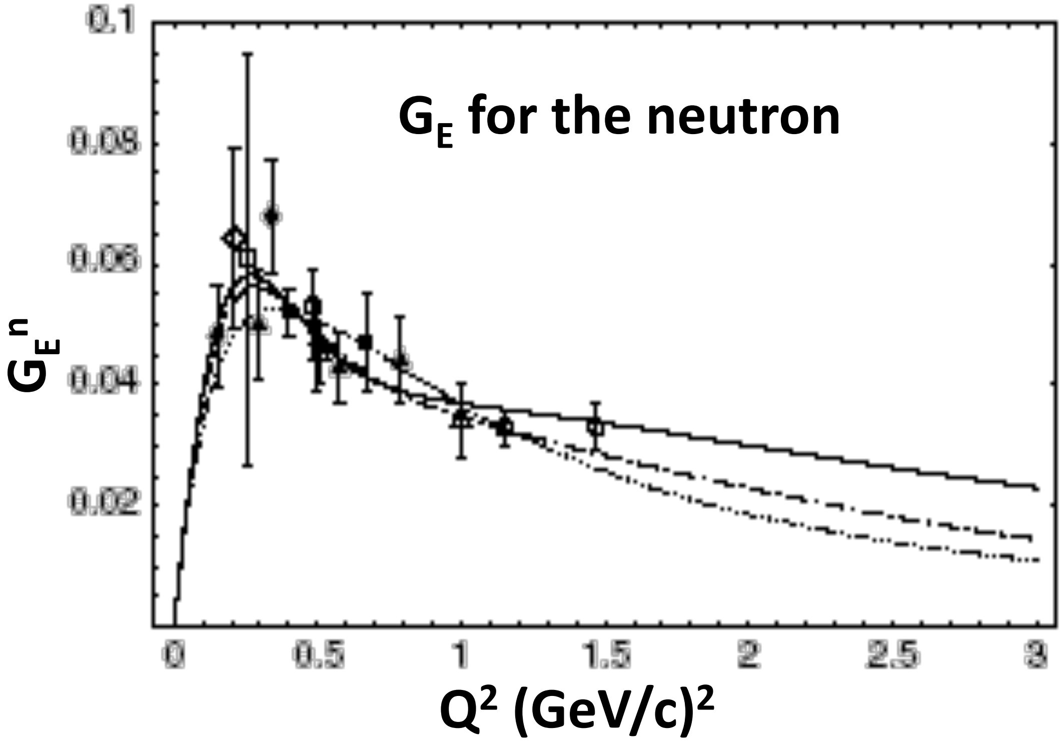

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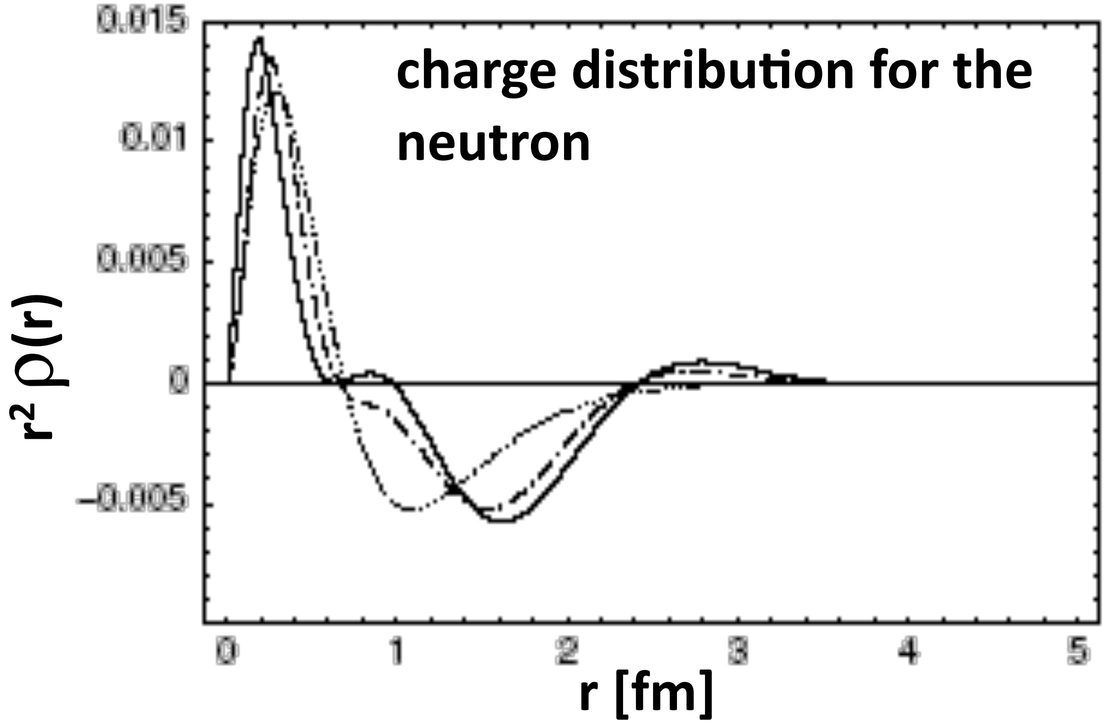


charge distribution for the neutron

At $Q^2 = 0$, the form factor represents an integral over the nucleon

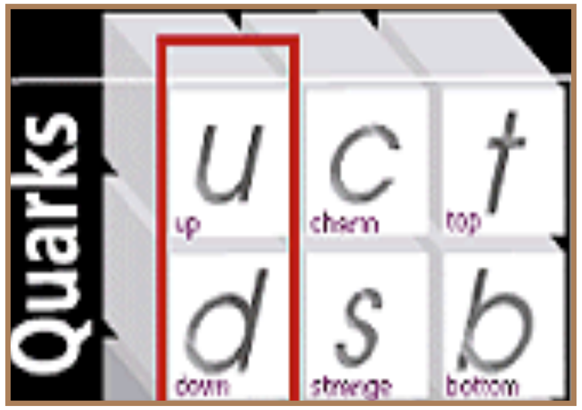
	G_E	G_M
proton	1	2.79
neutron	0	-1.91

anomalous magnetic moment

charge

The Simple Nucleon

The nucleon is composed of three quarks (up and down flavors) interacting via the Strong force (Quantum Chromodynamics)



Increasing mass

The quark flavor content determines the nucleon properties

It's simple: the nucleon is three marbles in a bag!

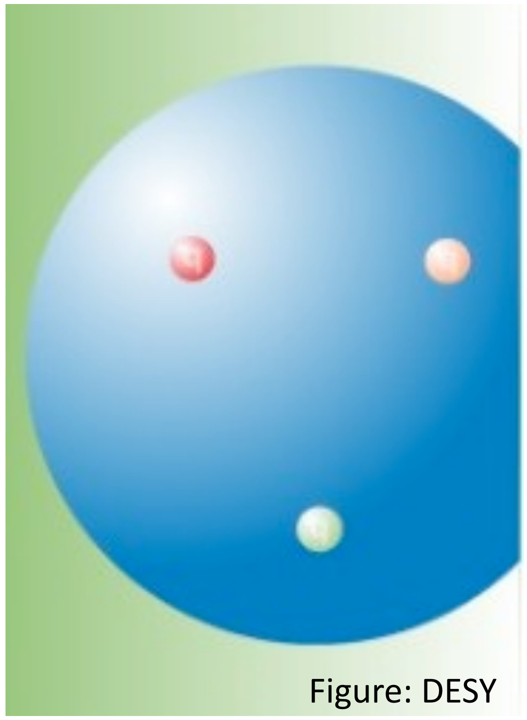


Figure: DESY

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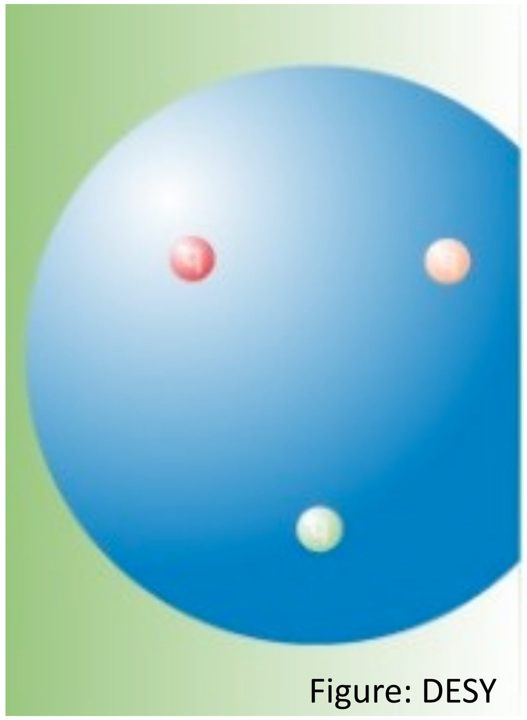
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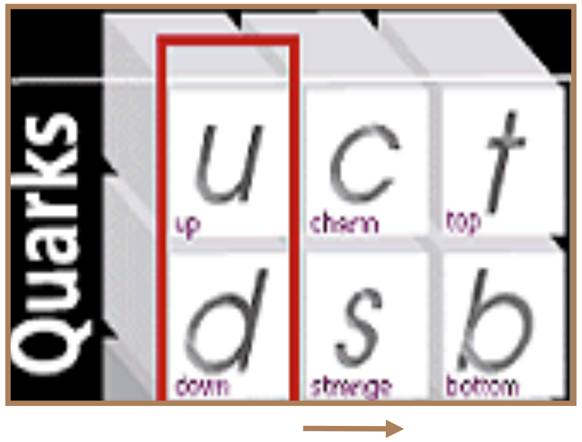

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Not so fast. The strong force is weird!

The nucleon contains three quarks… embedded in a teeming sea of gluons and additional quarks and anti-quarks.

It grows with distance, and is huge at “large” distances (10^{-15} m).

Gluons (strong carriers) interact with themselves. Strong glue is sticky.

The bare mass of the three quarks ~1% of the proton mass.

99% of the mass of the proton is in the sea!

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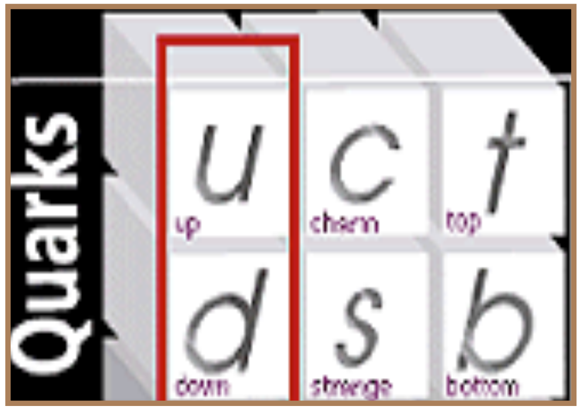

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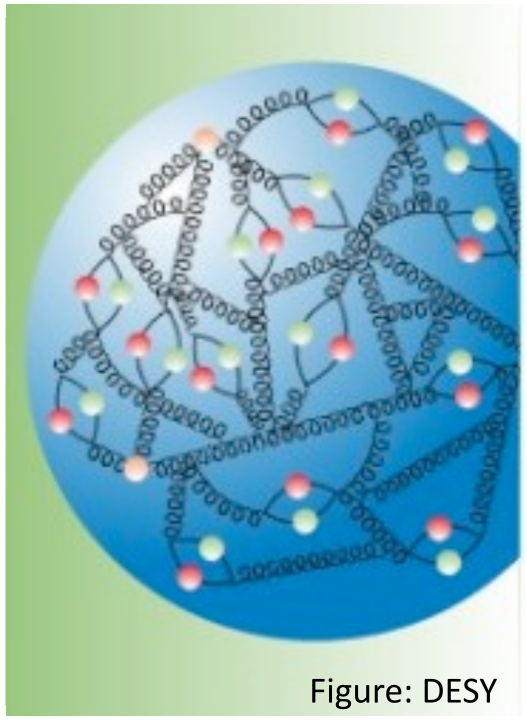

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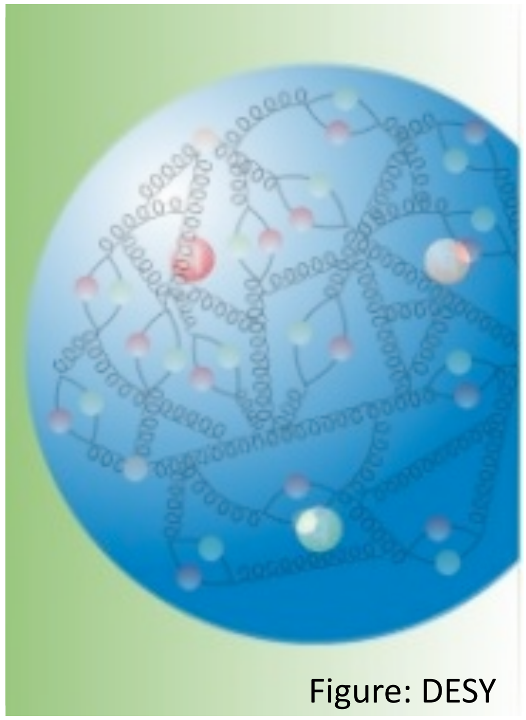

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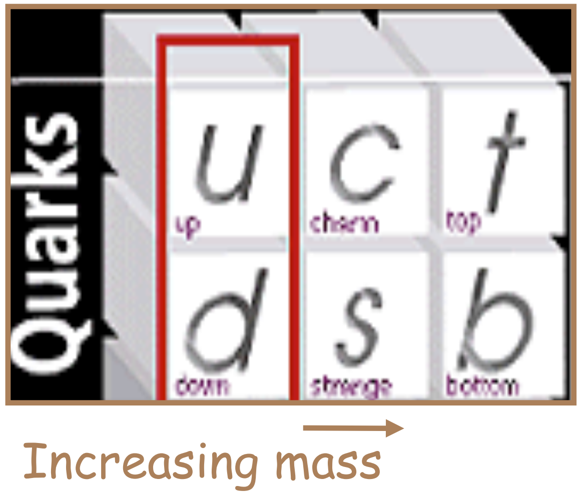

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So why does the simple quark model work so well?

Sea contributions to nucleon static properties are unsettled

mass, spin, charge radius, magnetic moment

By analogy with the electron shell structure that determines the chemical properties of an atom, **the three dominant quarks are referred to as "valence" quarks**. The rest of the quarks and gluons are called the "**sea**".

Strangeness in the Sea

The sea contains all flavors, but

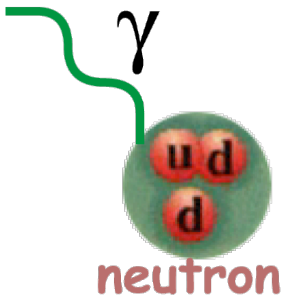
- the u and d sea can't be distinguished from the valance
- the heavier quarks (c,b,t) are too heavy to contribute much

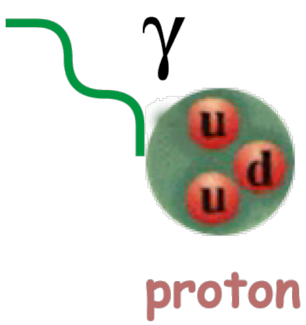
From hard-scattering, we know that the strange sea exists.

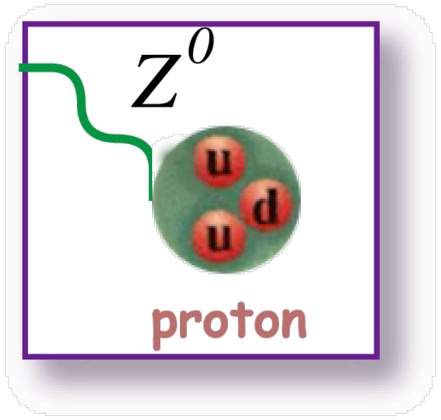
~4% of the momentum of the nucleon is carried by strange quarks

But this is a "deep" probe... Do the strange quarks affect the **static** properties of the nucleon?

Low-Q^2 Elastic electron scattering from the nucleus measures charge radius and magnetic moment



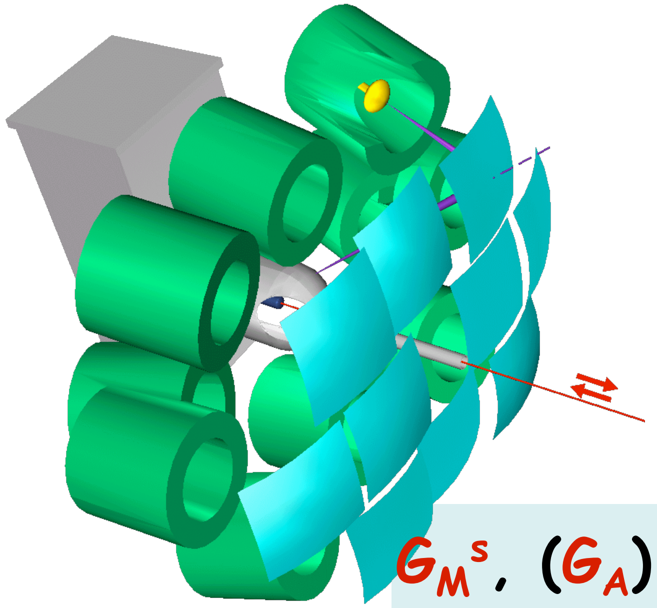




A strange contribution would be the first unambiguous low-energy failure of the naïve quark model

Measuring all three enables separation of up, down and strange contributions

Overview of Strange Quark Program

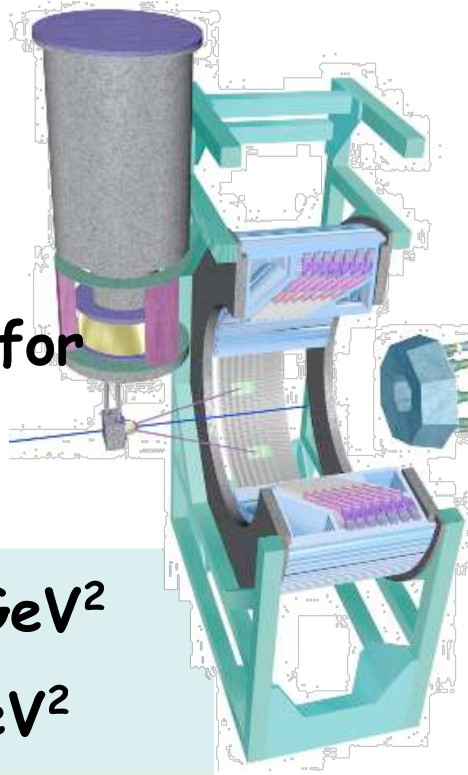


SAMPLE

open geometry, integrating

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

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

HAPPEX

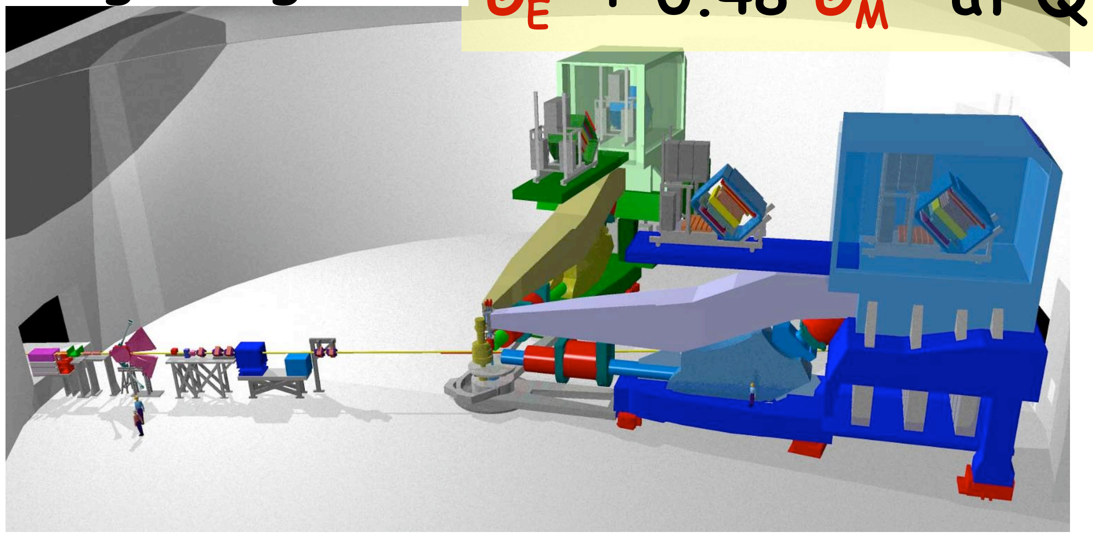
Precision spectrometer, integrating

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

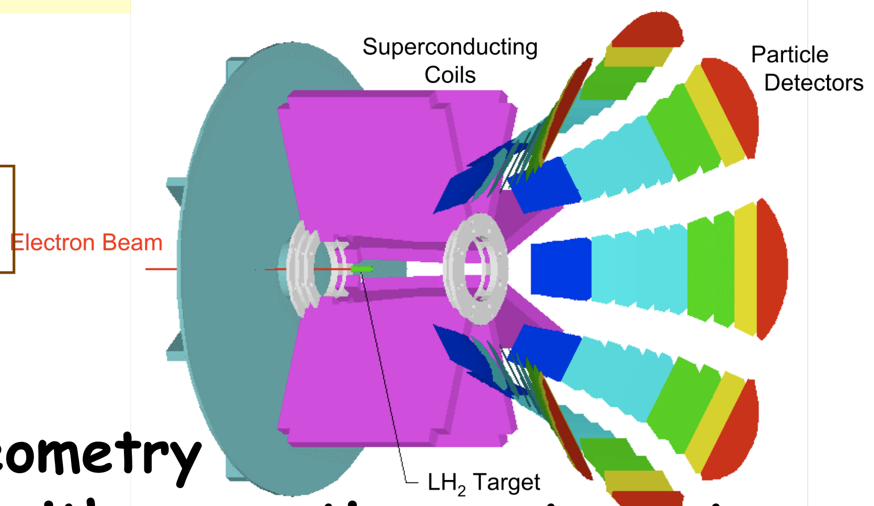
$G_E^s + 0.08\ G_M^s$ at $Q^2 = 0.1$ GeV^2

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



G0

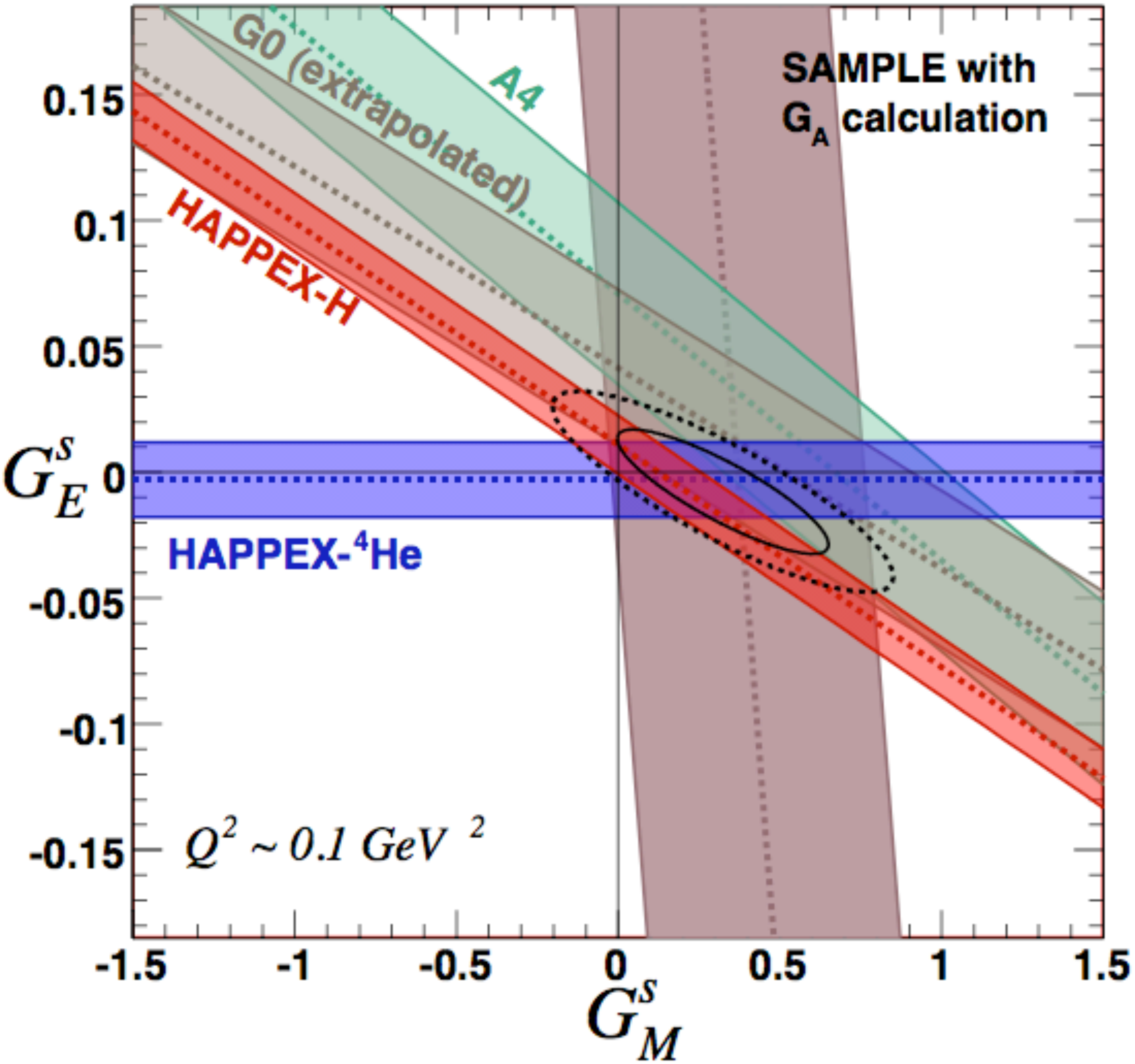


Open geometry
Fast counting with magnetic spectrometer + TOF for background rejection

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

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

World Data at low Q^2



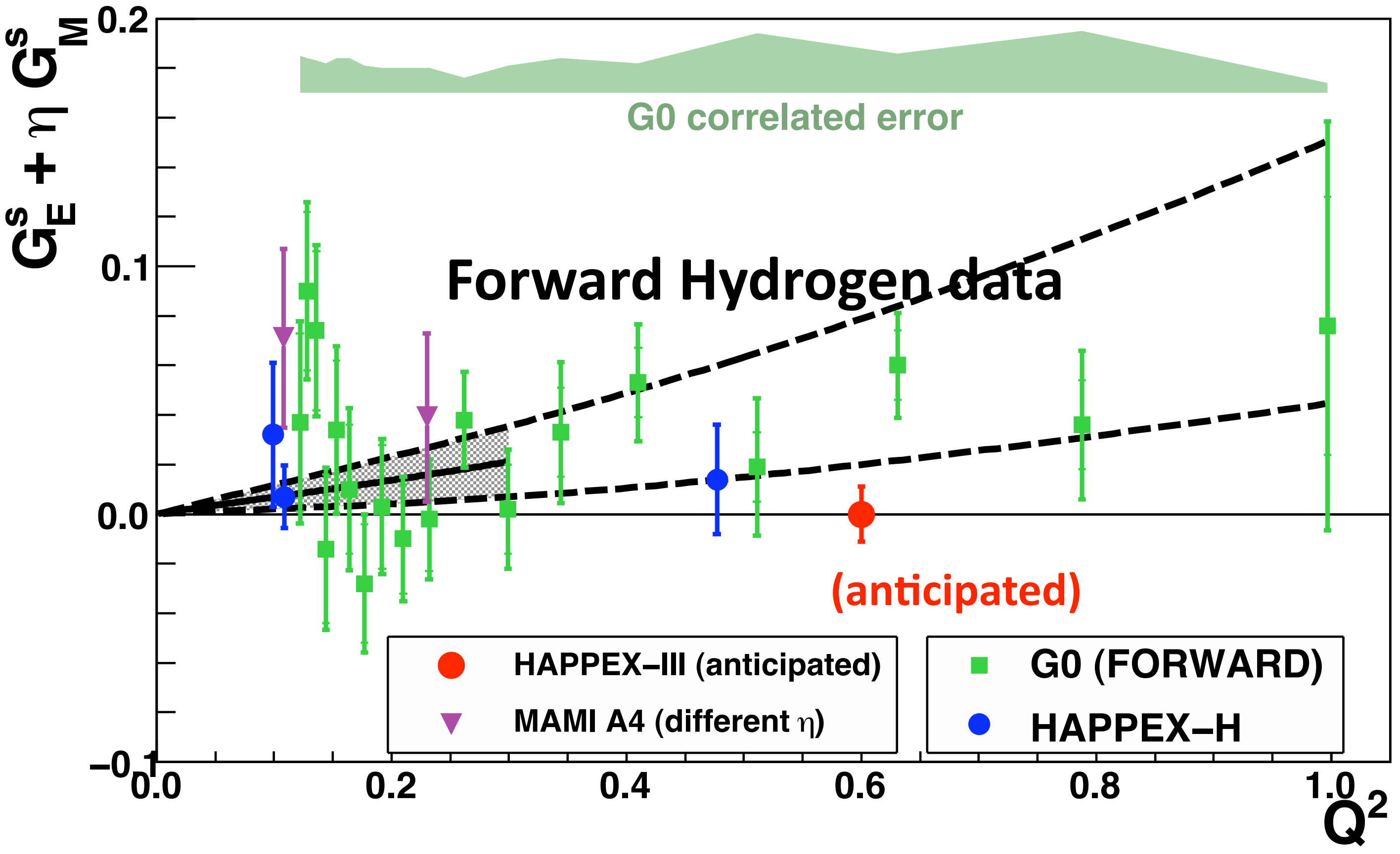
~3% +/- 2.3% of proton magnetic moment

~0.2 +/- 0.5% of Electric distribution

Caution: the combined fit is approximate. Correlated errors and assumptions not taken into account.

For a more careful job, see published fits by:
R. Young et al., Phys. Rev. Lett 97, 102002 (2006)
or
J.Liu et al., Phys. Rev. C 76, 025202 (2007)

A Simple Fit of Global Data

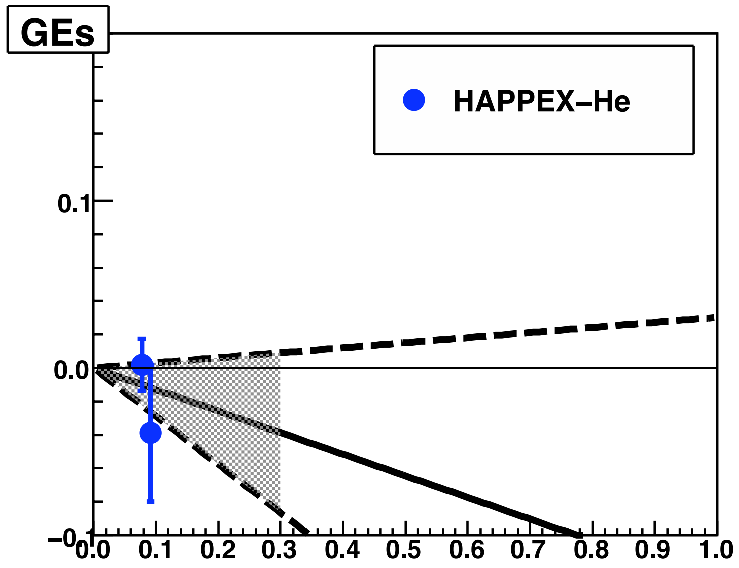


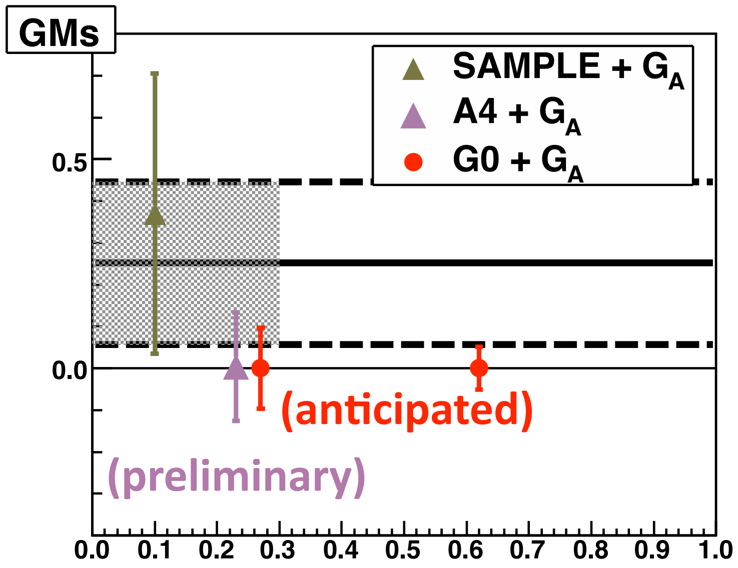
First-order fit at low Q^2:

$G_E^s = \rho_s * \tau$

$G_M^s = \mu_s$

Includes only data $Q^2 < 0.3$ GeV^2





Sizeable contributions at higher Q^2 are not definitively ruled out.

(To be tested by HAPPEX-III and G0)

HAPPEX-III

- usual HAPPEX technology
- More precise polarimetry
- Scheduled Fall 2009

Preliminary A4 Back-angle results included!

Precision on strange quarks has reached level of interpretibility (isospin violation, EMFF) so future program will require new breakthroughs

Peering Beyond the Standard Model

Direct vs Indirect Searches

(according to Hans Christian Andersen)

Direct vs Indirect Searches

(according to Hans Christian Andersen)

Direct vs Indirect Searches

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Direct vs Indirect Searches

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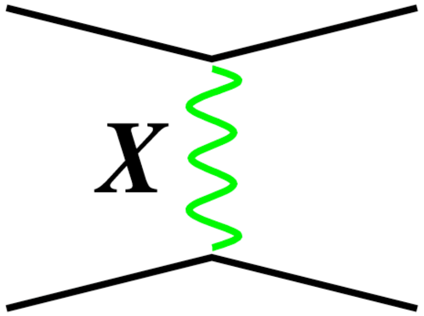
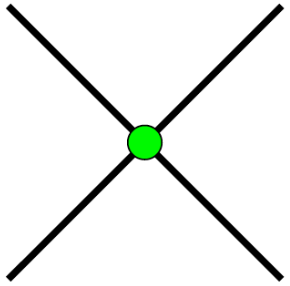
Electroweak Physics Away from Z pole

consider



$$A_X \;\alpha\; \frac{1}{Q^2 - M_X^2} \;\sim\; \frac{4\pi}{\Lambda^2} \longrightarrow$$



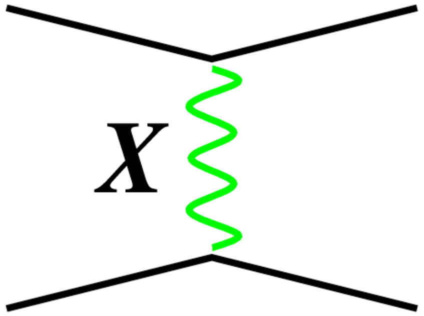
Contact interaction

at $Q^2 = M_Z^2$

On Z resonance, A_Z dominates. Interference with other contact interactions is not visible!

Electroweak Physics Away from Z pole

consider



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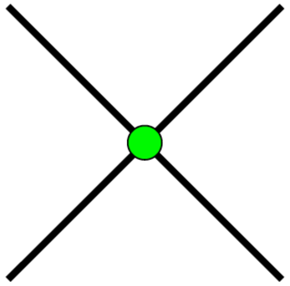

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Precision Z observables establish anchor points for the Standard Model

For low energy measurements, interference with New Physics terms can be found

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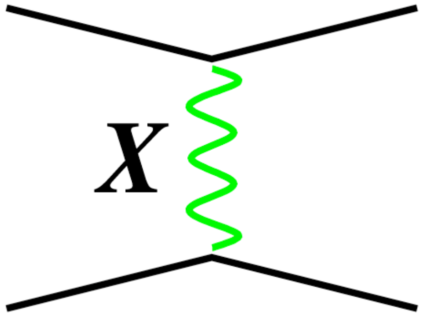
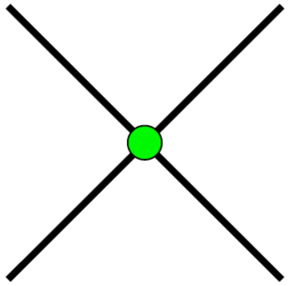


$$A_X \propto \frac{1}{Q^2 - M_X^2} \longrightarrow \quad \sim \frac{4\pi}{\Lambda^2}$$



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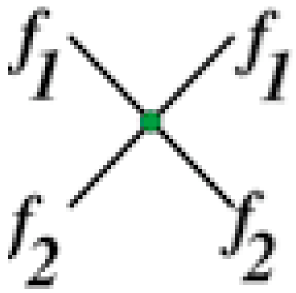
Precision Z observables establish anchor points for the Standard Model

For low energy measurements, interference with New Physics terms can be found

Consider $f_1 f_1 \to f_2 f_2$ **or** $f_1 f_2 \to f_1 f_2$



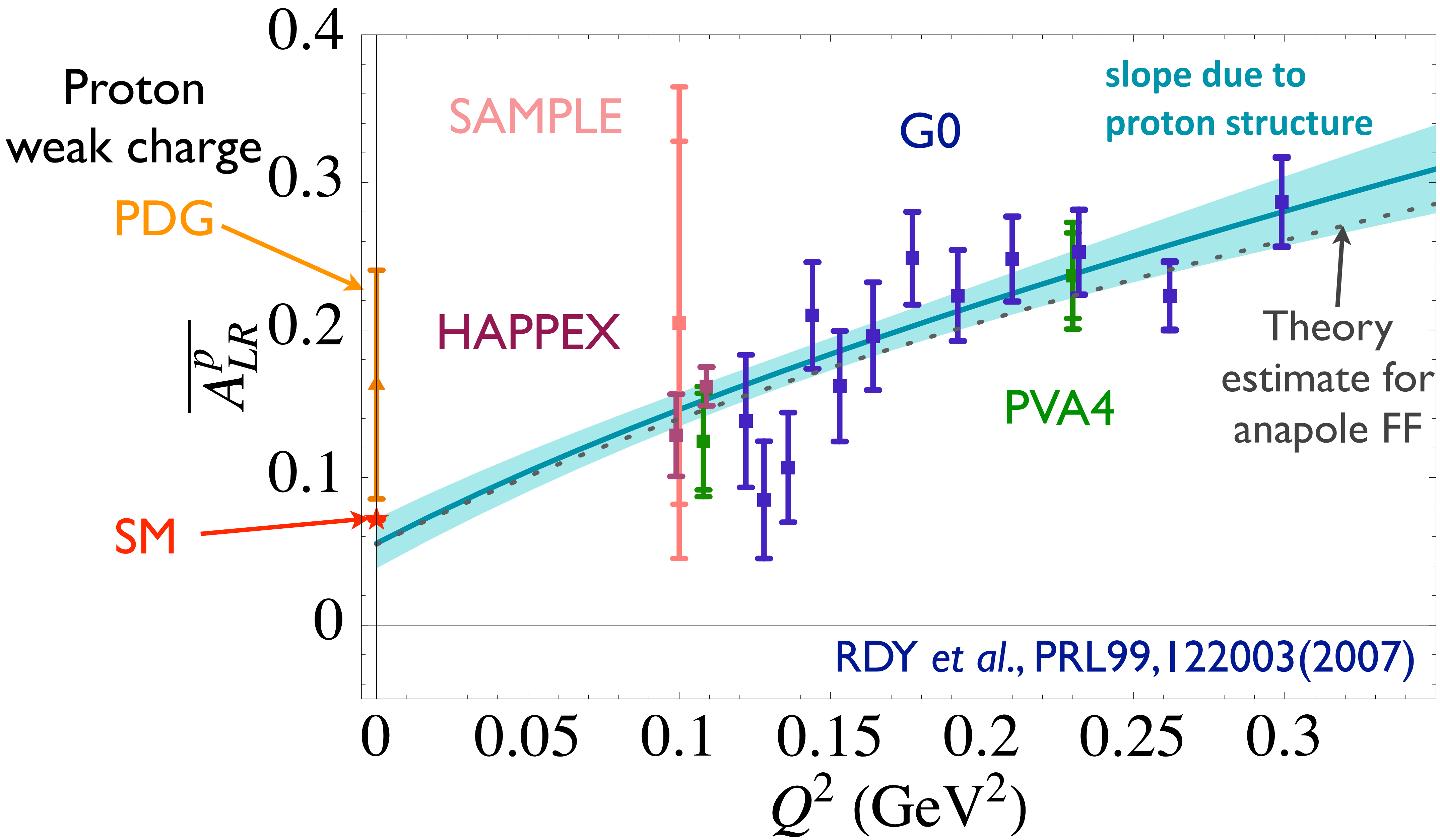
$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{i\,j}^{12})^2}{\Lambda_{ij}^2} \bar{f}_{1i}\gamma_\mu f_{1i} \bar{f}_{2j}\gamma_\mu f_{2j}$$

Eichten, Lane and Peskin, PRL50 (1983)

mass scale Λ, coupling g for each fermion and handedness combination

New terms arise in models for new physics with Λ's at the TeV scale

Proton Weak Charge



Proton weak charge precisely known from EW gauge theory and precision EW at the Z-pole

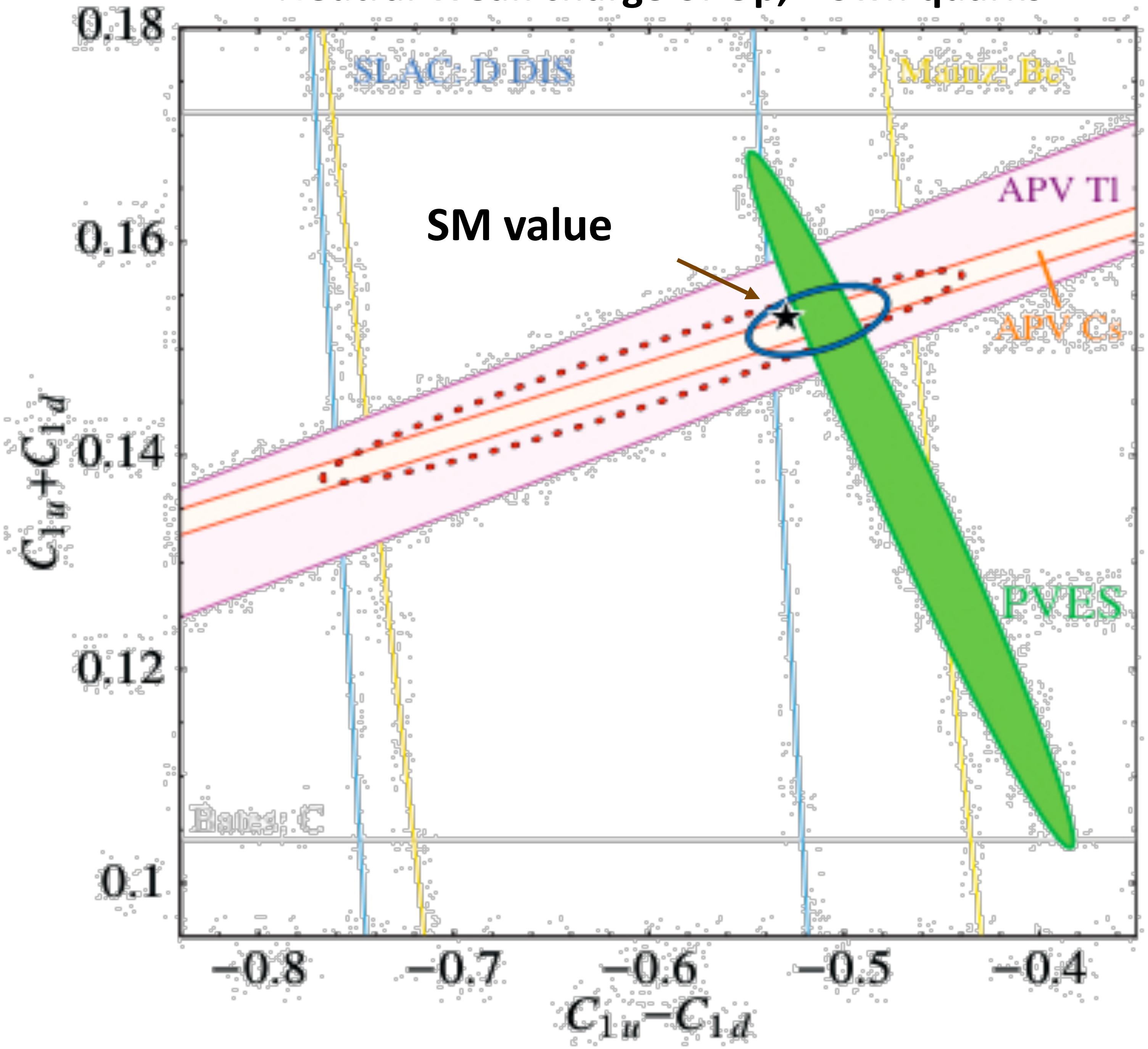
If measurement at low energy comes up different, indicates proton charged for some other (parity-violating) interaction

Global fit of existing strange-quark program data provides constraint on Standard Model

Bounding the vector weak charge

With this parameterization for hadronic effects, what can be said about the Standard Model parameters?

Neutral Weak charge of Up, Down quarks



$Q^p_W = 2\, C_{1u} + C_{1d}$

These "form factor" measurements offer a powerful constraint on new physics

R. Young et al., PRL 99 122003 (2007)

QWeak

Measuring the proton ~~form-factor~~ weak charge

Small angle, low $Q^2 \sim 0.03\ \mathrm{GeV}^2$ to suppress target structure

$$A_{PV} = -\frac{Q^2 G_F}{4\sqrt{2}\pi\alpha}\left[Q_W^p + F(\theta, Q^2)\right]$$

Proton structure F, constrained by strange quark program, contributes ~30% to asymmetry, ~2% to $\delta(Q_W^p)/ Q_W^p$

$$F \sim \frac{Q^2}{4M_P^2}(1+\mu_p)\mu_n + \text{ strange quarks } \mathcal{O}(Q^2) + \mathcal{O}(Q^4)$$

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$$\boxed{A_{PV} \approx -230 \pm 5 \pm 4\ ppb}$$

$$\delta Q_W^p = \pm 4\% \quad \Rightarrow \quad \delta(\sin^2\theta_W) = \pm\ 0.3\%$$

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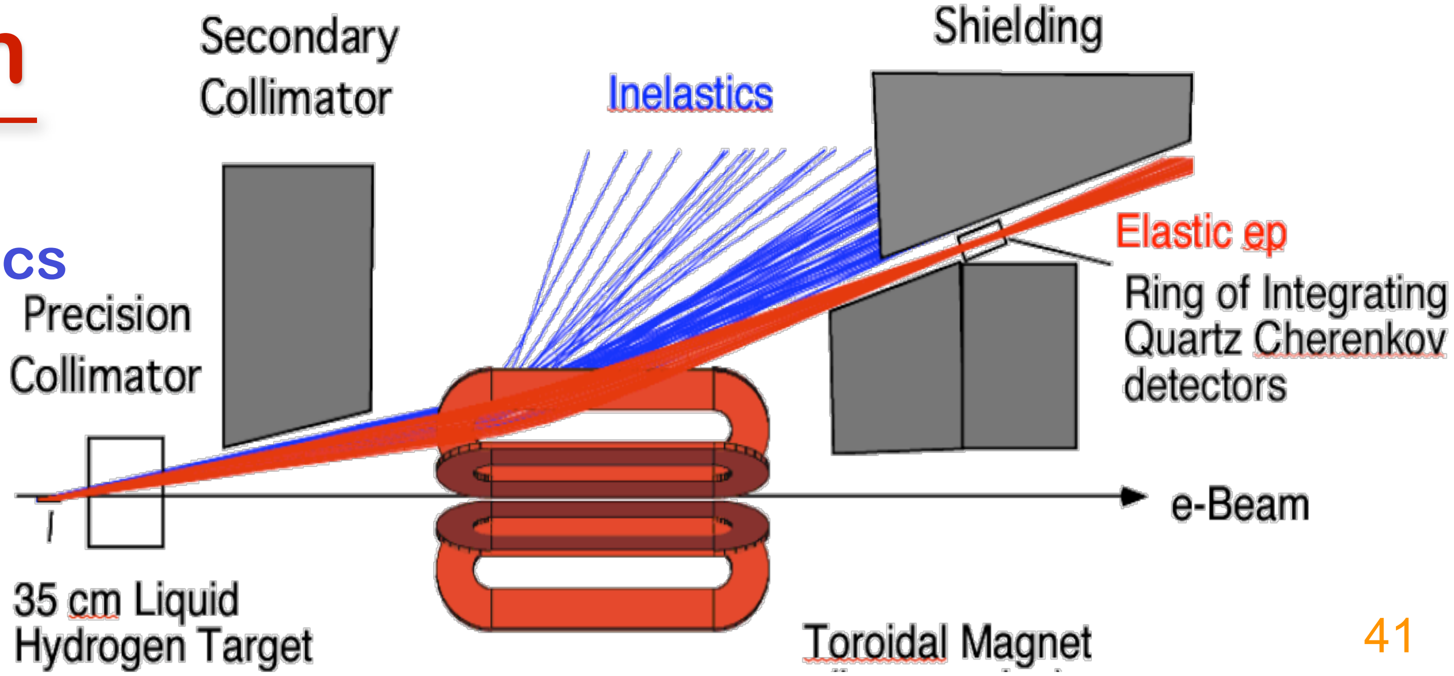
A new standard in precision

- New Spectrometer system
- Control and correction for beam systematics
- Polarimetry approaching 1% (new)
- Low system noise - 6.5 GHz rate!
- High rate, radiation hard readout
- Background and calibration precision

mid-2010 through 2011



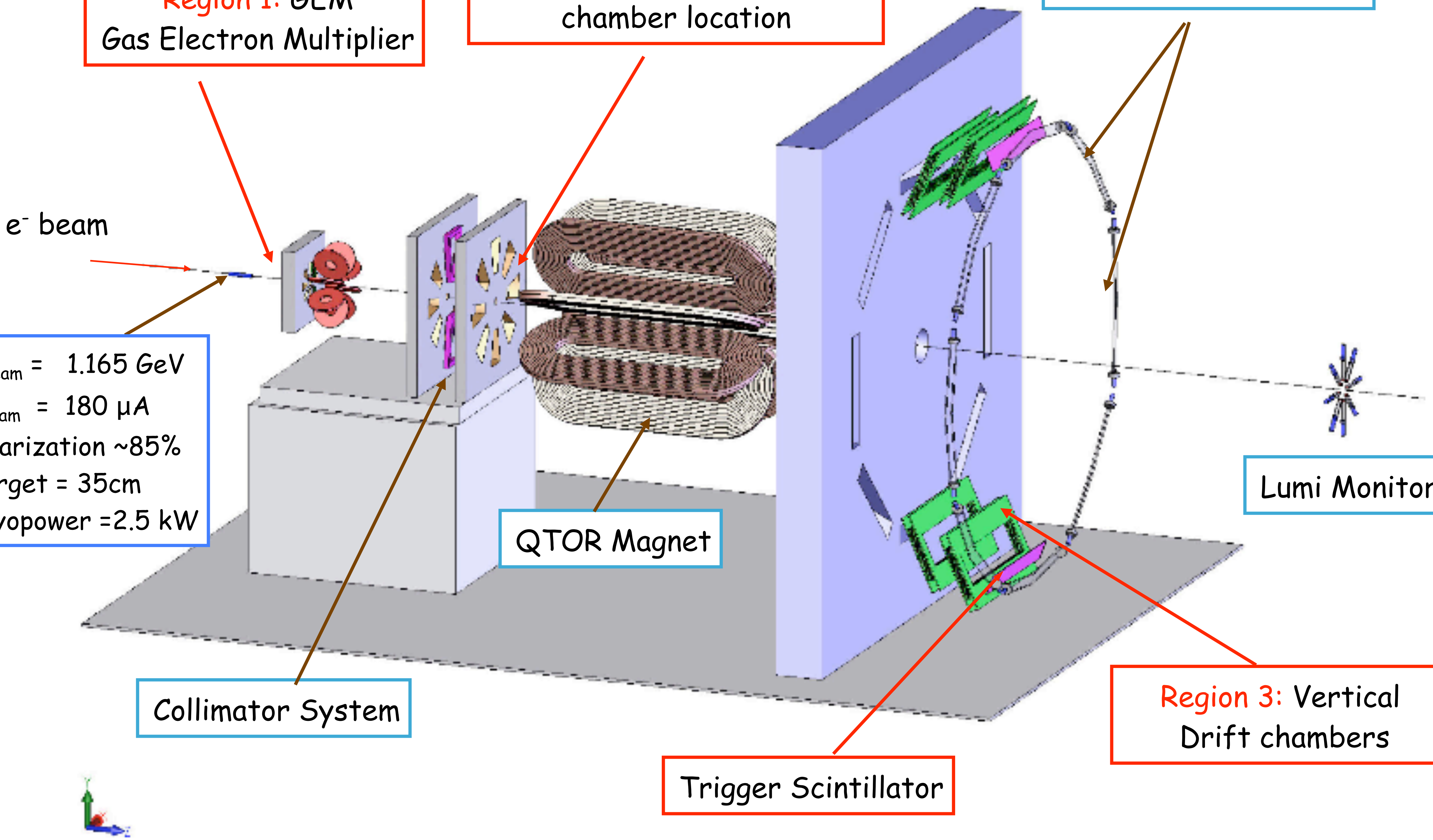
Qweak Spectrometer

Spectrometer

for high rates…

Tracking System

for calibration…



Quartz Cerenkov Bars
(insensitive to
non-relativistic particles)

Region 1: GEM
Gas Electron Multiplier

Region 2: Horizontal drift
chamber location

e^- beam

E_{beam} = 1.165 GeV
I_{beam} = 180 μA
Polarization ~85%
Target = 35cm
Cryopower =2.5 kW

Lumi Monitors

QTOR Magnet

Collimator System

Region 3: Vertical
Drift chambers

Trigger Scintillator

Proton Weak Charge with Qweak

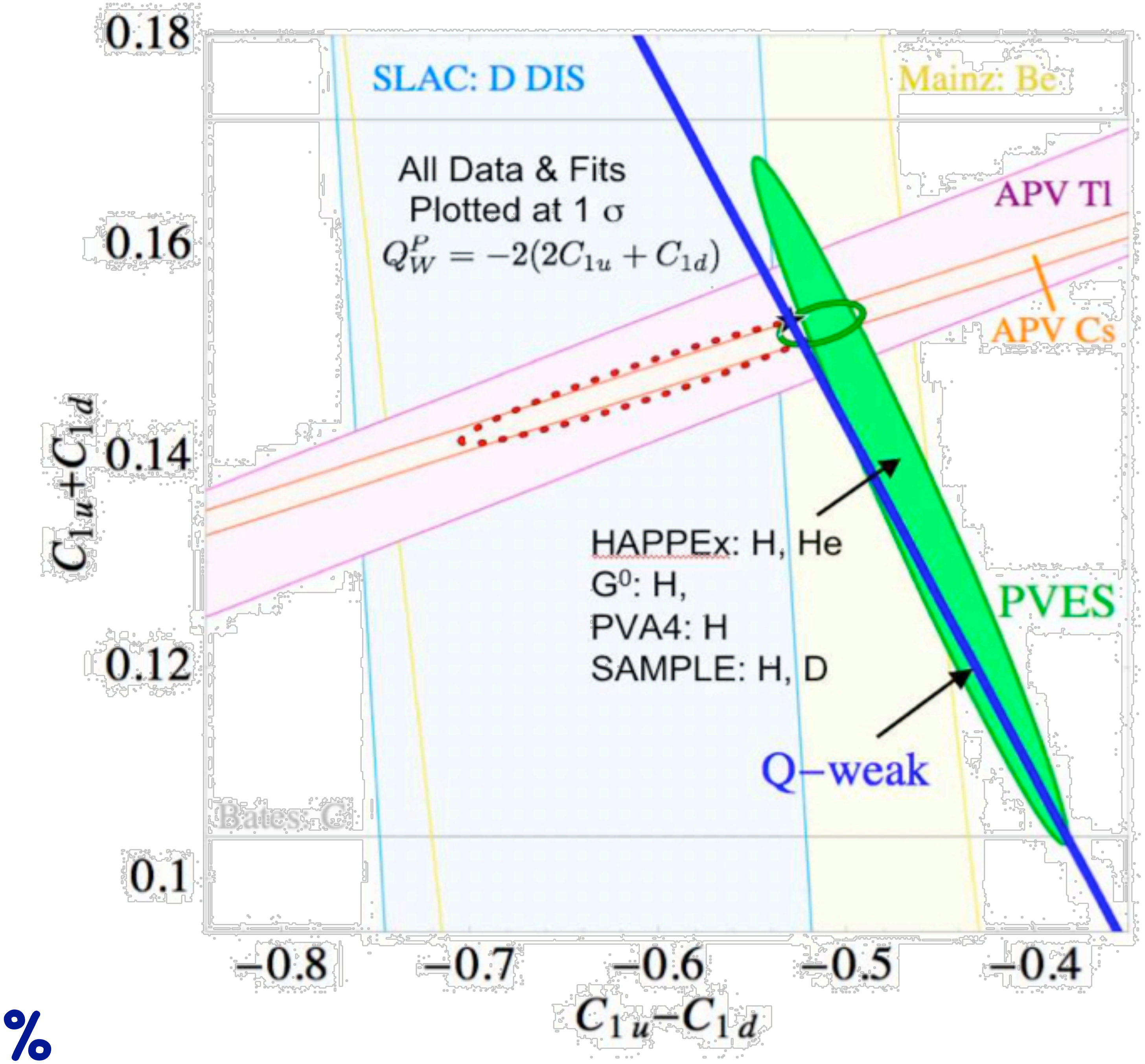


Figure: R.Young

δQ_W^p=4%

$$\boxed{\frac{\Lambda}{g} \sim \frac{1}{\sqrt{\sqrt{2}G_\mu|\Delta Q_W^p|}} \sim 4.6\text{TeV}}$$

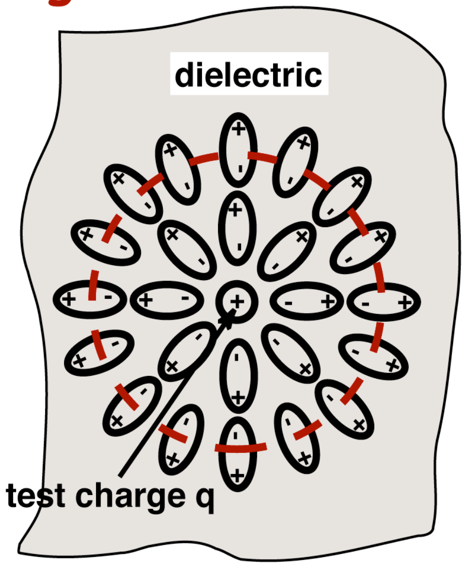
- **Non-perturbative theory** $g \sim 2\pi$ $\Lambda \sim 29$ TeV
- **Extra Z’** $g \sim 0.45$ $m_{Z'} \sim 2.1$ TeV

Weak mixing angle $\sin^2\theta_W$

Weak mixing angle defines weak neutral-current charges

Analogy: Charge embedded in dielectric

total charge enclosed is less than q



total charge depends on relative distance

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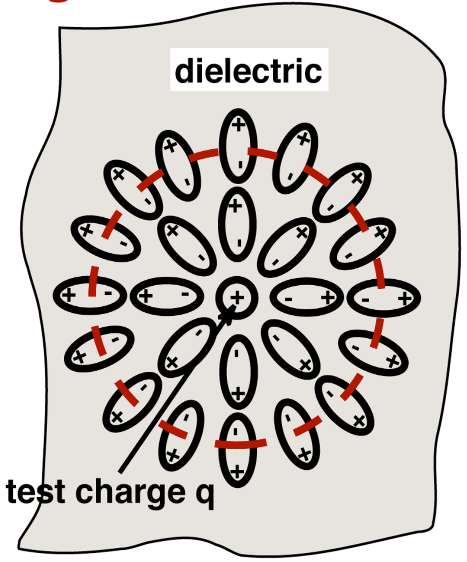
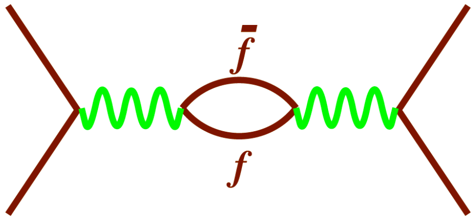


total charge depends on relative distance

In quantum field theory:



Effective charge increases with decreasing distance

Higher-order terms in perturbative expansion

Weak mixing angle $\sin^2\theta_W$

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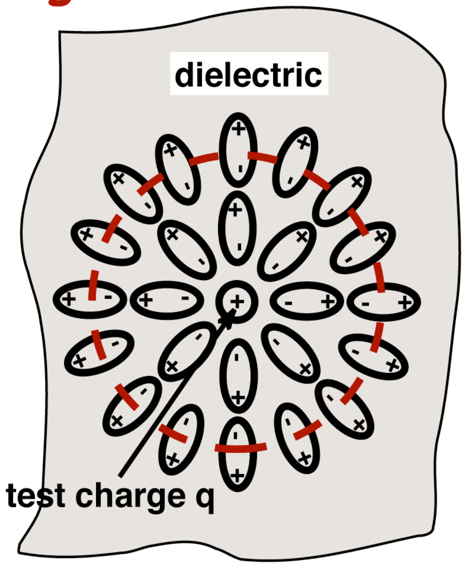

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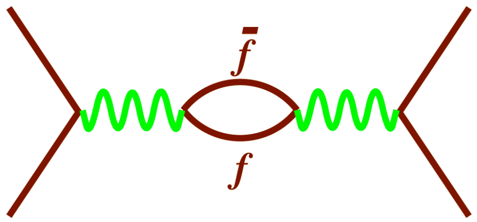


Effective charge increases with decreasing distance

Higher-order terms in perturbative expansion

Renormalization scheme defines $\sin^2\theta_W$ at the Z-pole.

γ-Z mixing and other diagrams are absorbed into the coupling constant

Off the Z-pole, Qweak measures for (new) parity-violating interactions

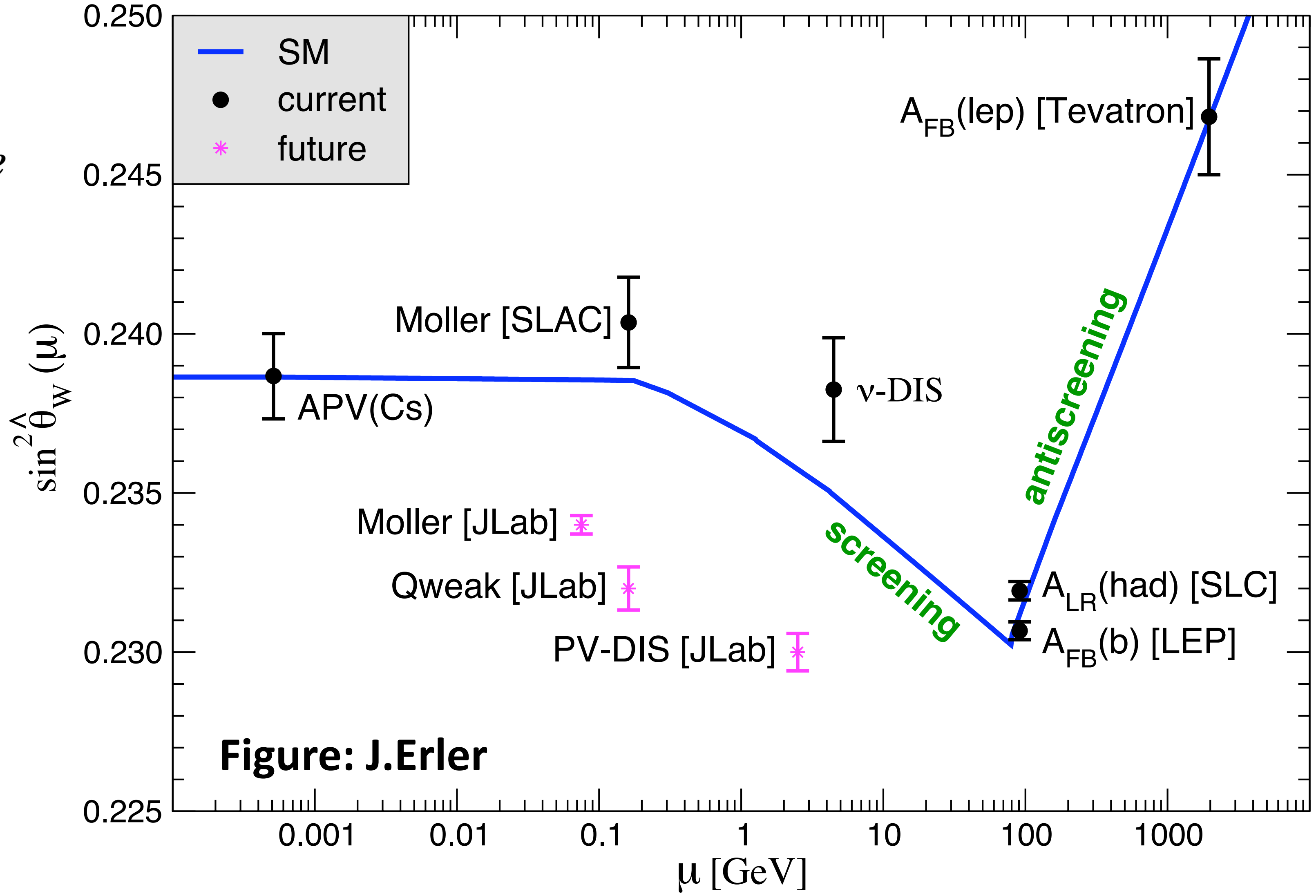
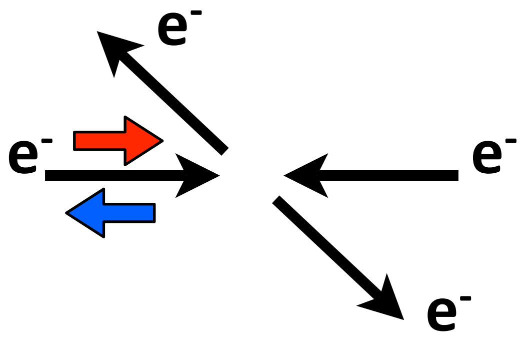


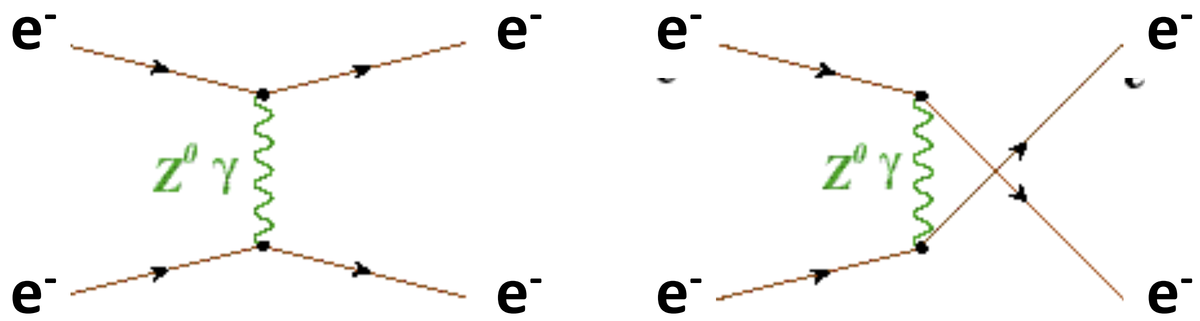
Figure: J.Erler

Parity-Violation at 11 GeV

Møller Scattering at 11 GeV



elastic electron-electron scattering



$A_{PV} \propto E_{lab} Q_W^e$ $Q_W^e \sim 1 - 4\sin^2\theta_W$

Purely Leptonic Reaction

$\theta_{lab} \sim 0.5^o$-1.03^o I_{beam} = 75 μA

E': 2.5-6 GeV   150 cm LH_2 target

~150 GHz !

A_{PV} = -35 ppb   6500 hours, P=80%

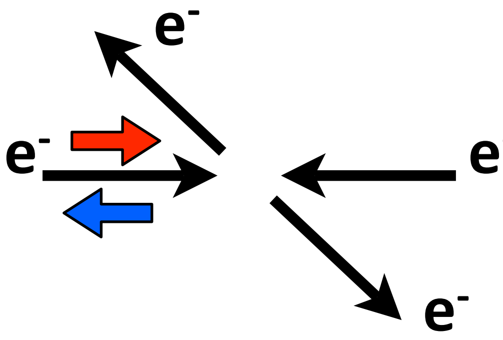
$\delta(A_{PV})$ = 0.73 ppb

δ (Q^e_W) = ± 2.1% (stat) ± 1.0% (syst)

δ ($\sin^2\theta_W$) = ± 0.00029

Matches best collider (Z-pole) measurement!

Møller Scattering at 11 GeV



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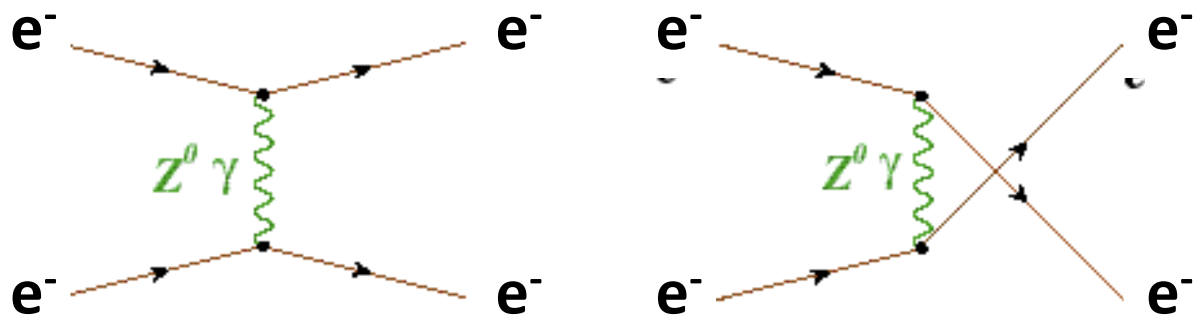

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11 GeV Moller would be a precision electroweak study, comparable to the measurements from BaBar and LEP

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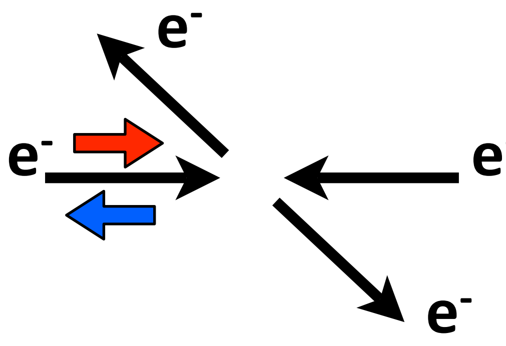

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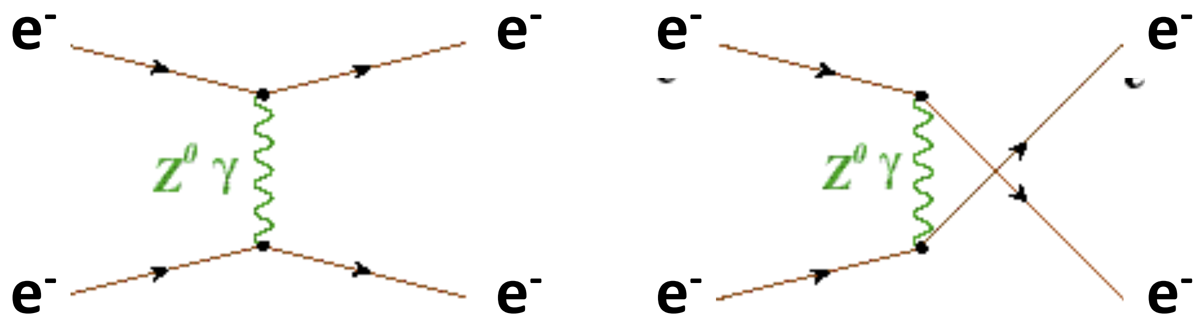

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Matches best collider (Z-pole) measurement!

- **Address important ambiguity in existing electroweak data**
- **Provide important complementary sensitivities to make sense of emerging LHC data**
- **Test for new parity-violating interactions to mass scales >25 TeV**

$\sin^2\theta_W$ in Electroweak Fits

There are only 3 fundamental parameters in the electroweak Standard Model (plus a few others from loop corrections)

Fits over global data set show good consistency (with a few sore points)

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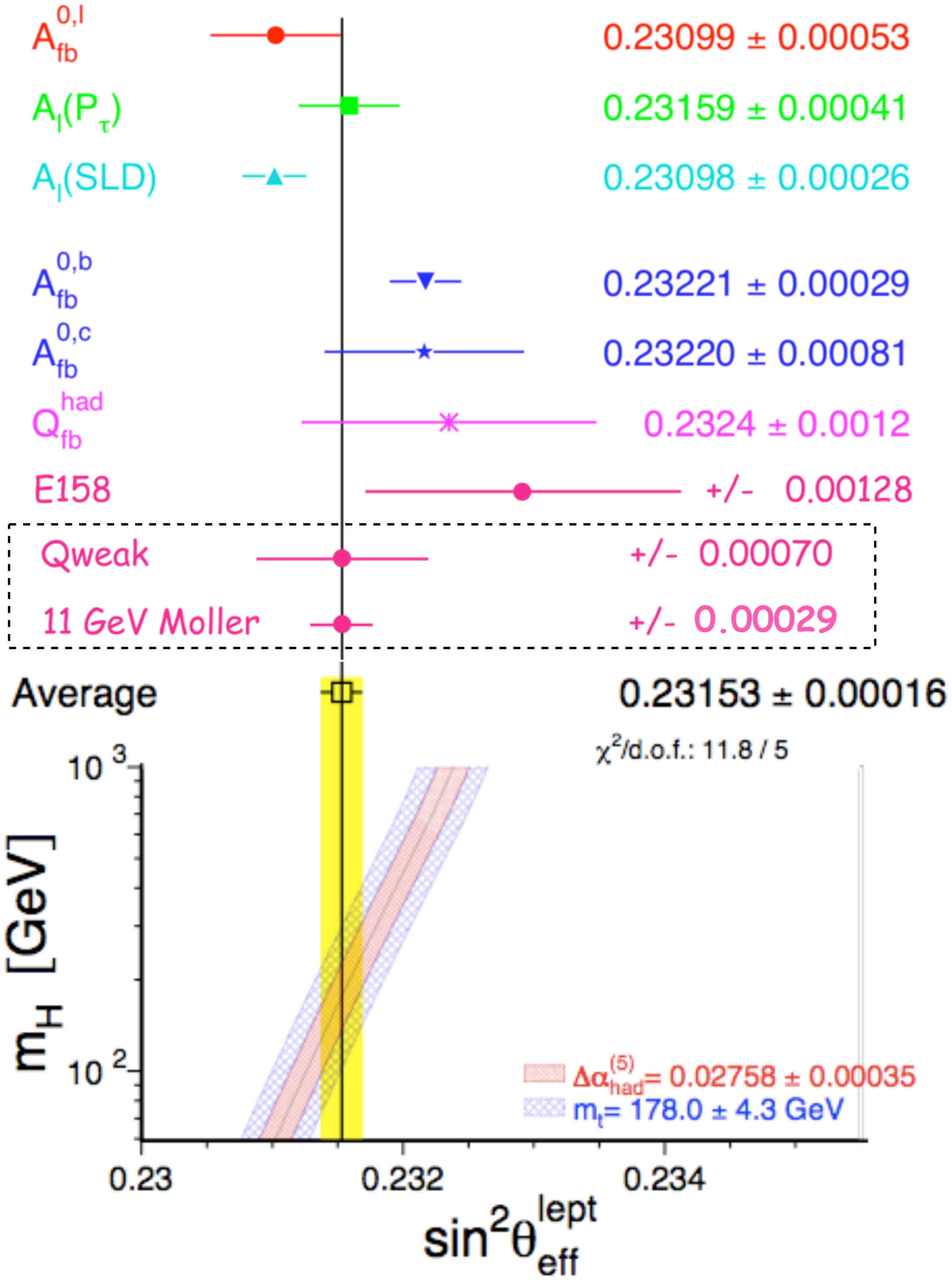

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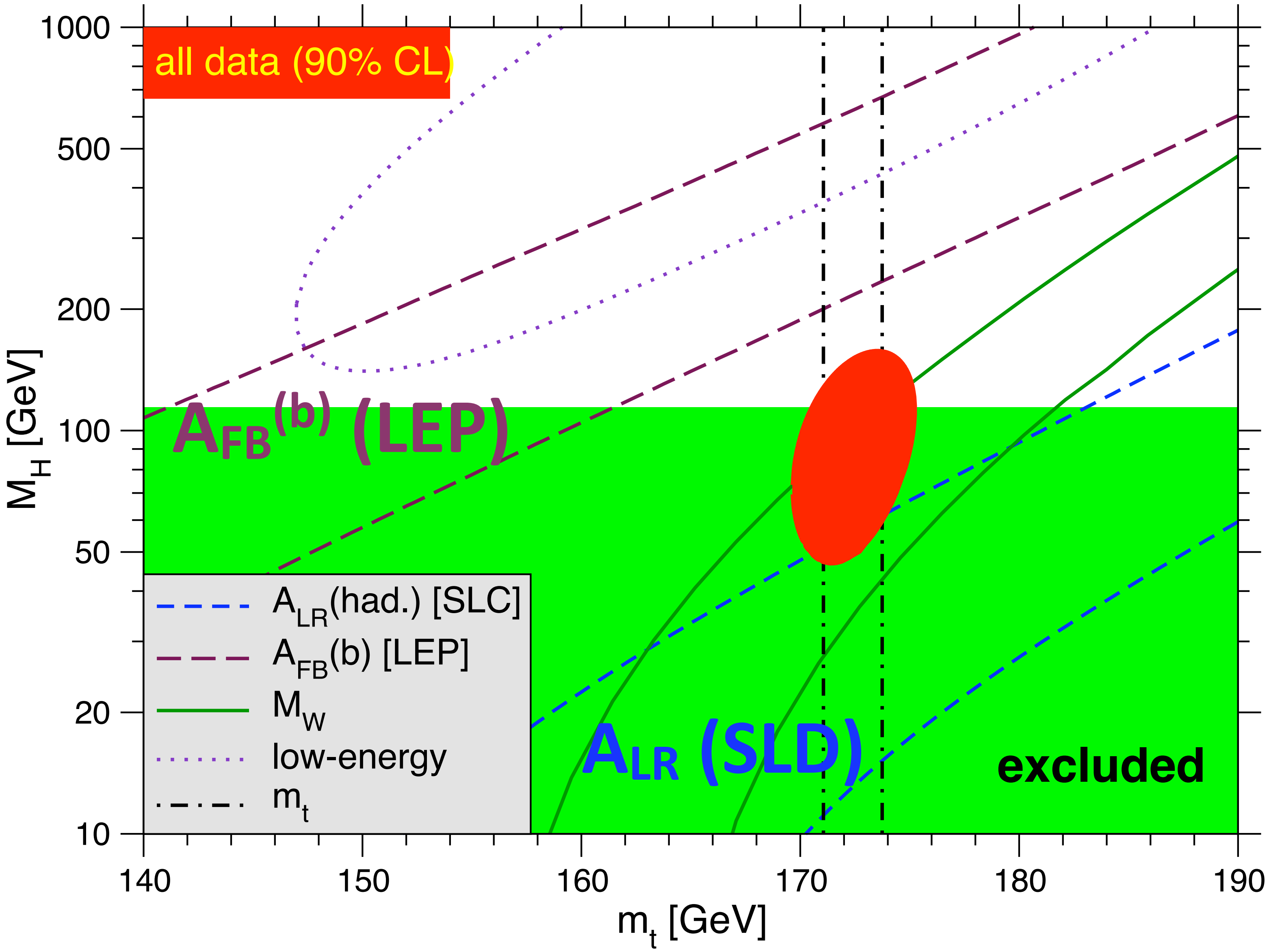

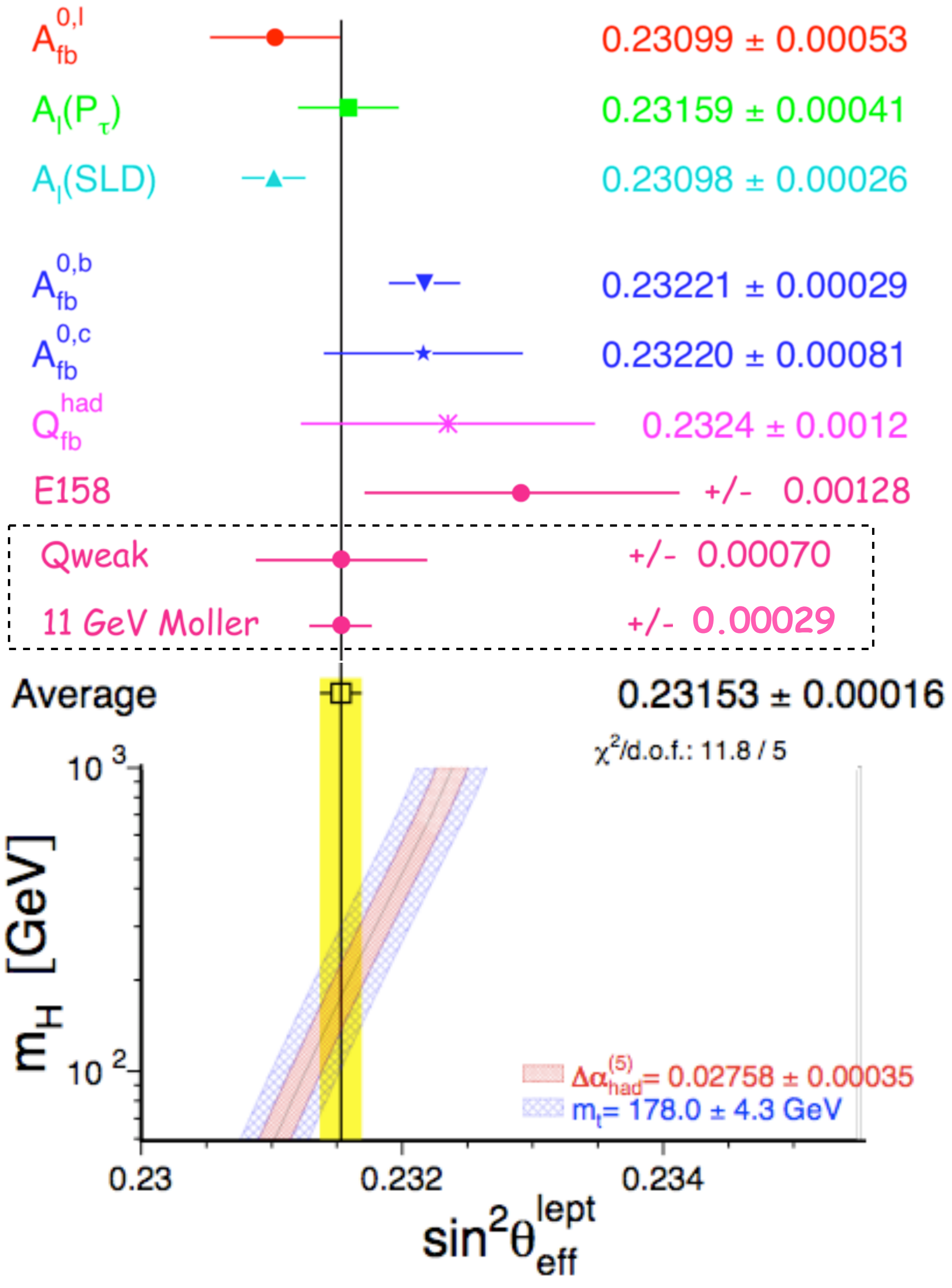

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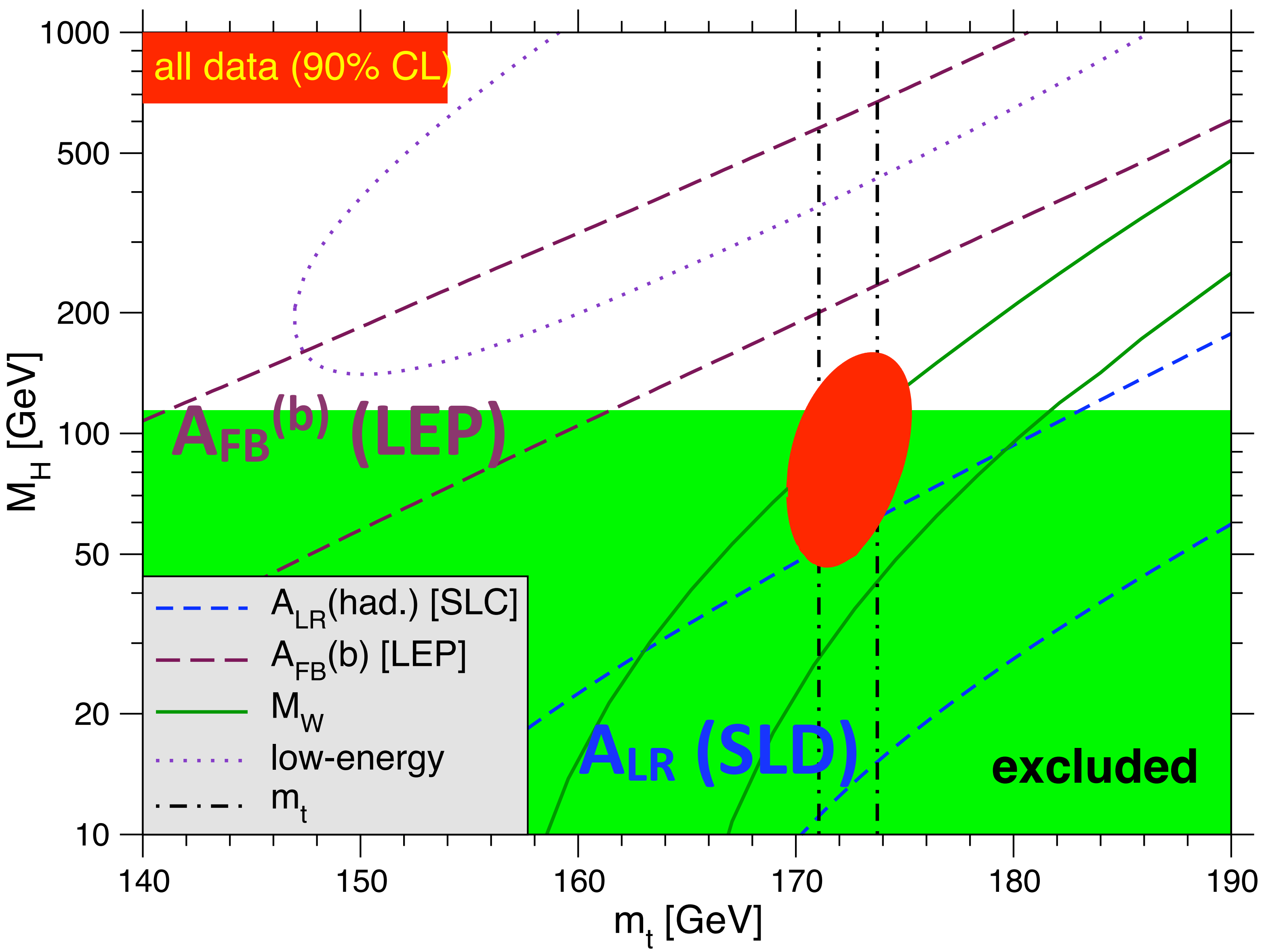
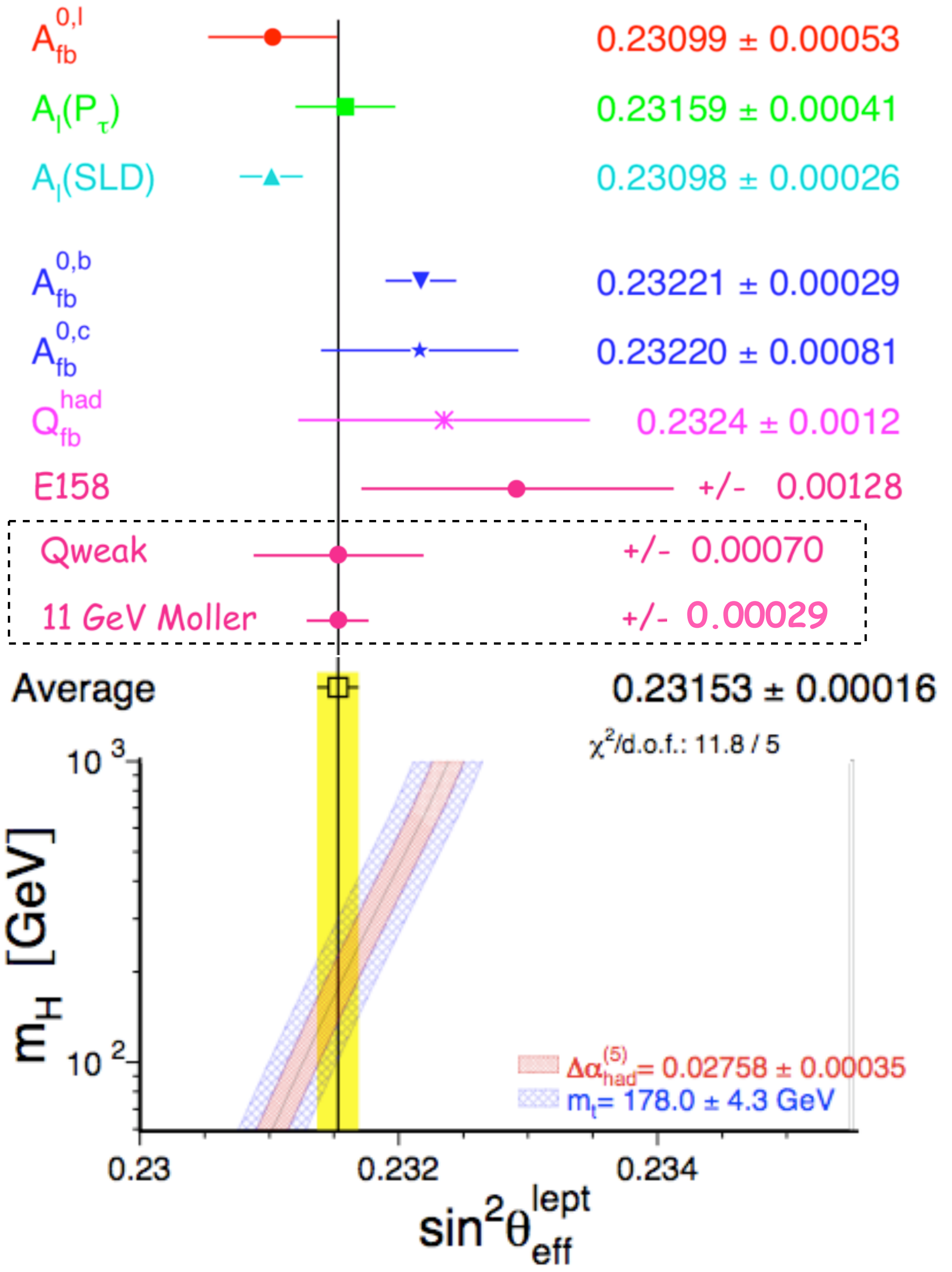
There are only 3 fundamental parameters in the electroweak Standard Model (plus a few others from loop corrections)

Fits over global data set show good consistency (with a few sore points)

11 GeV Moller will provide the only new precision data on $\sin^2\theta_W$ before the ILC or neutrino factory





Complementarity to LHC

- **Most unified theories predict additional neutral Z'**
- **LHC can find these ~5 TeV, can determine properties 1-2 TeV**
- **11 GeV Moller can help pin down couplings**

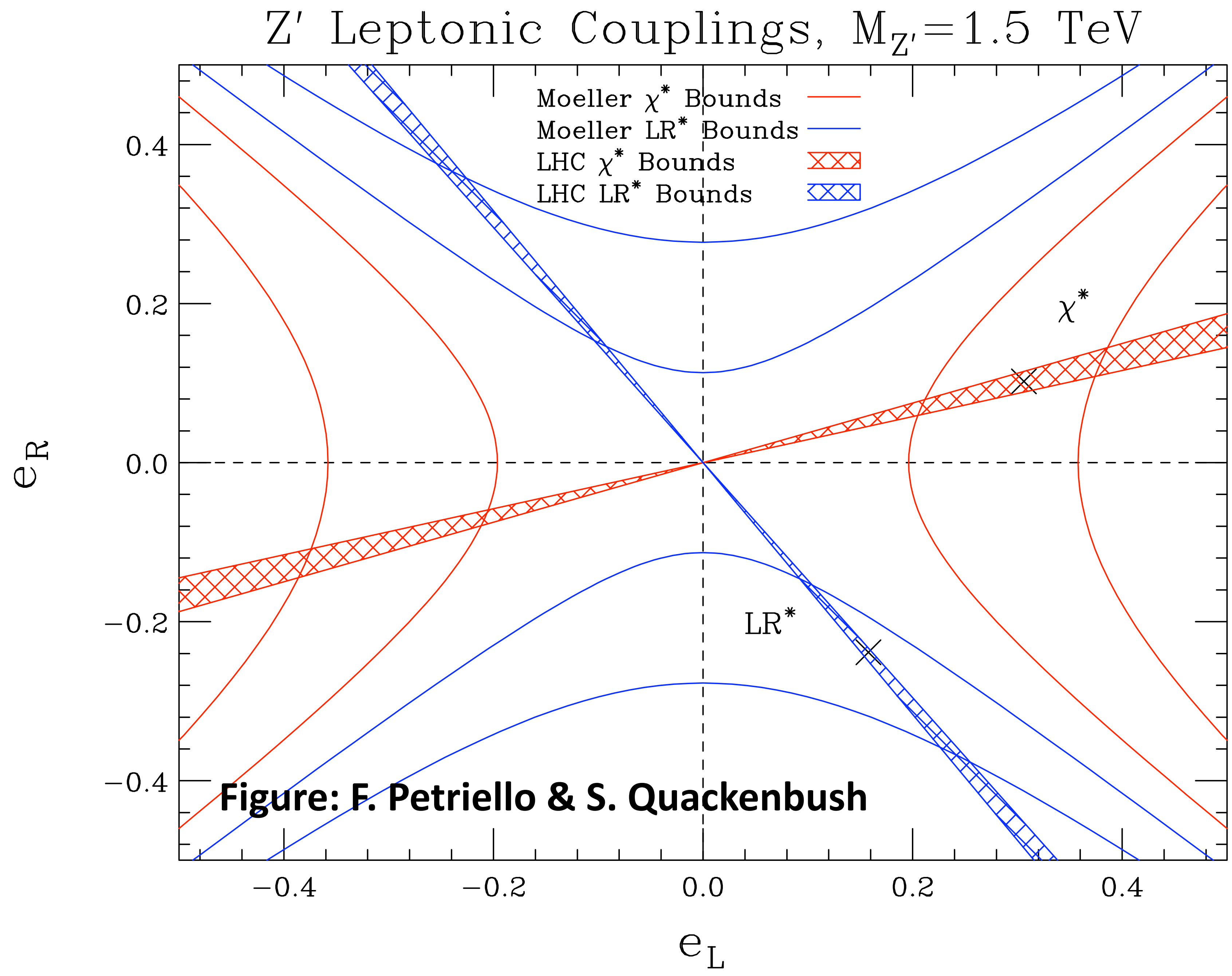


Figure: F. Petriello & S. Quackenbush

Moller sensitivity:

$$\frac{g_{RR}^2 - g_{LL}^2}{\Lambda^2} = \frac{e_R^2 - e_L^2}{M_{Z'}^2}$$

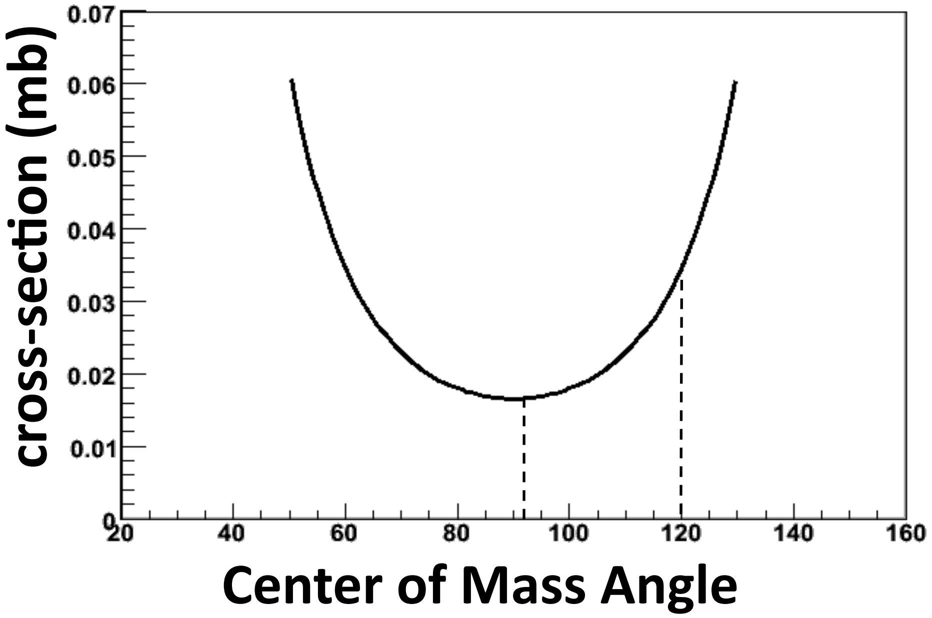
$$\sim \frac{1}{(7.5\mathrm{TeV})^2}$$

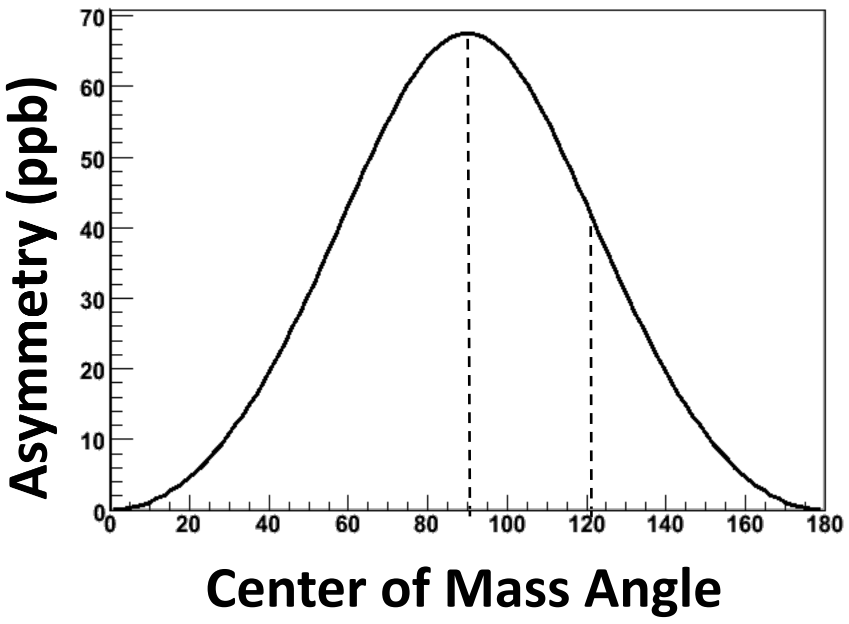
With mass, width, and A_{FB} LHC can get constraint on e_R/e_L

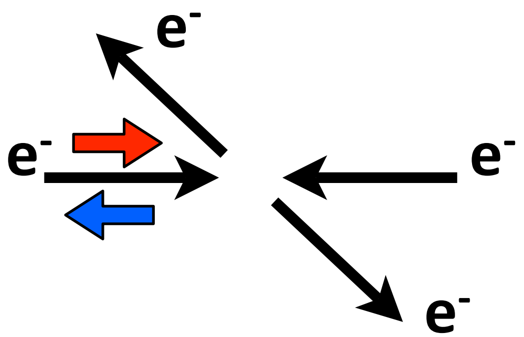
New Challenges

- ~150 GHz Scattered Rate
  - Must flip Pockels cell ~ 2 kHz
  - 80 ppm pair statistical fluctuations
    - electronic noise and density fluctuations <10^{-5}
    - beam jitter ~10 microns or less
    - beam monitoring resolution ~ few micron
- ~1 nm / 0.1 nrad beam position change with helicity
- >10 gm/cm^2 target, 1.5 meter LH_2, ~5kW
- Full azimuthal acceptance for 0.3^o scattering
  - novel two-toroid spectrometer
  - radiation hard integrating detectors
- Robust and redundant 0.4% beam polarimetry
  - Both atomic hydrogen Moller and improved Compton

Spectrometer Concept







identical particles

Highly boosted lab frame

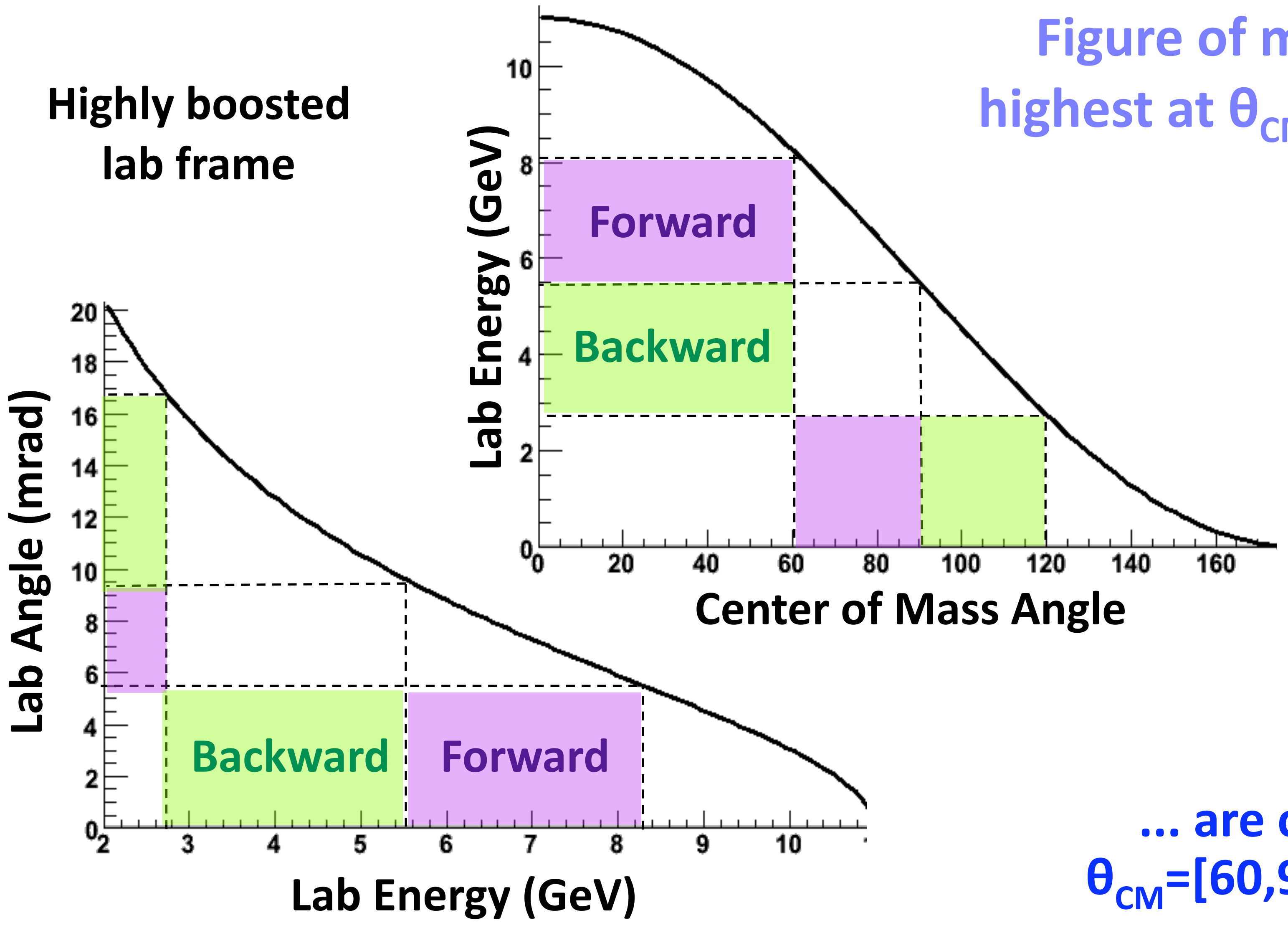
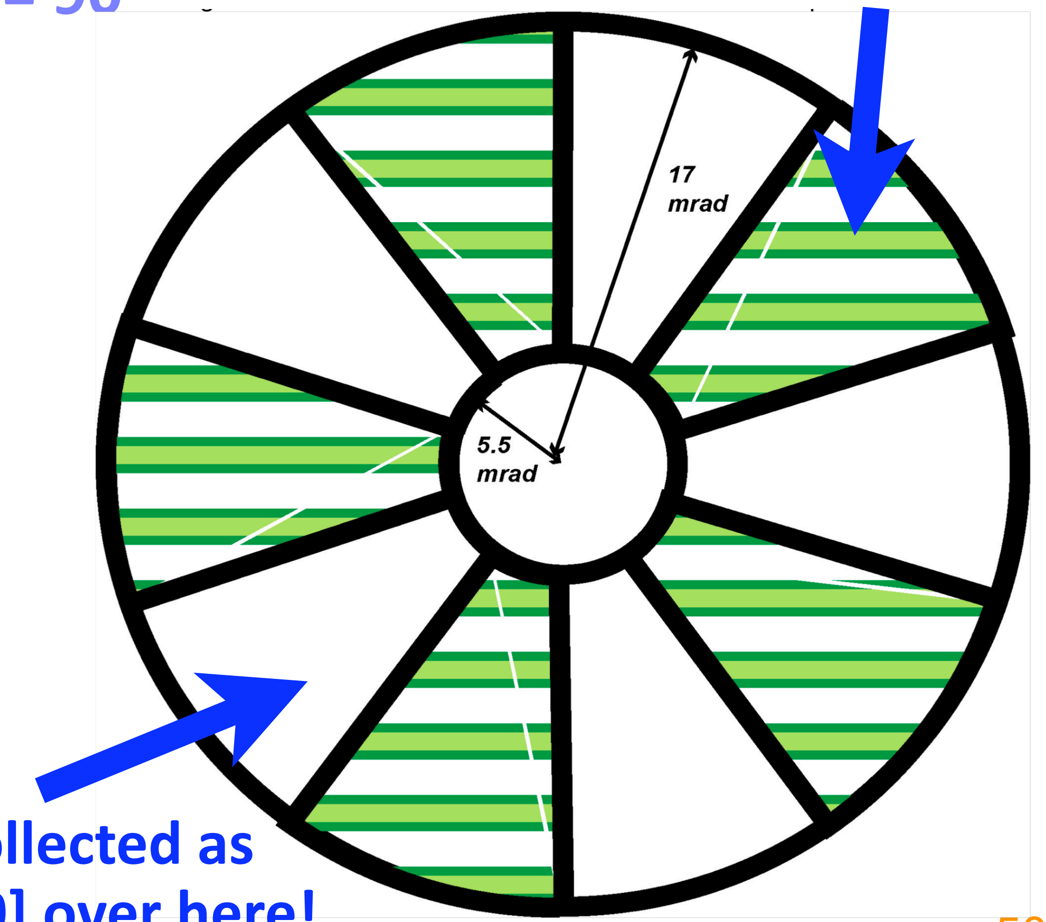


Figure of merit highest at θ_{CM} = 90º

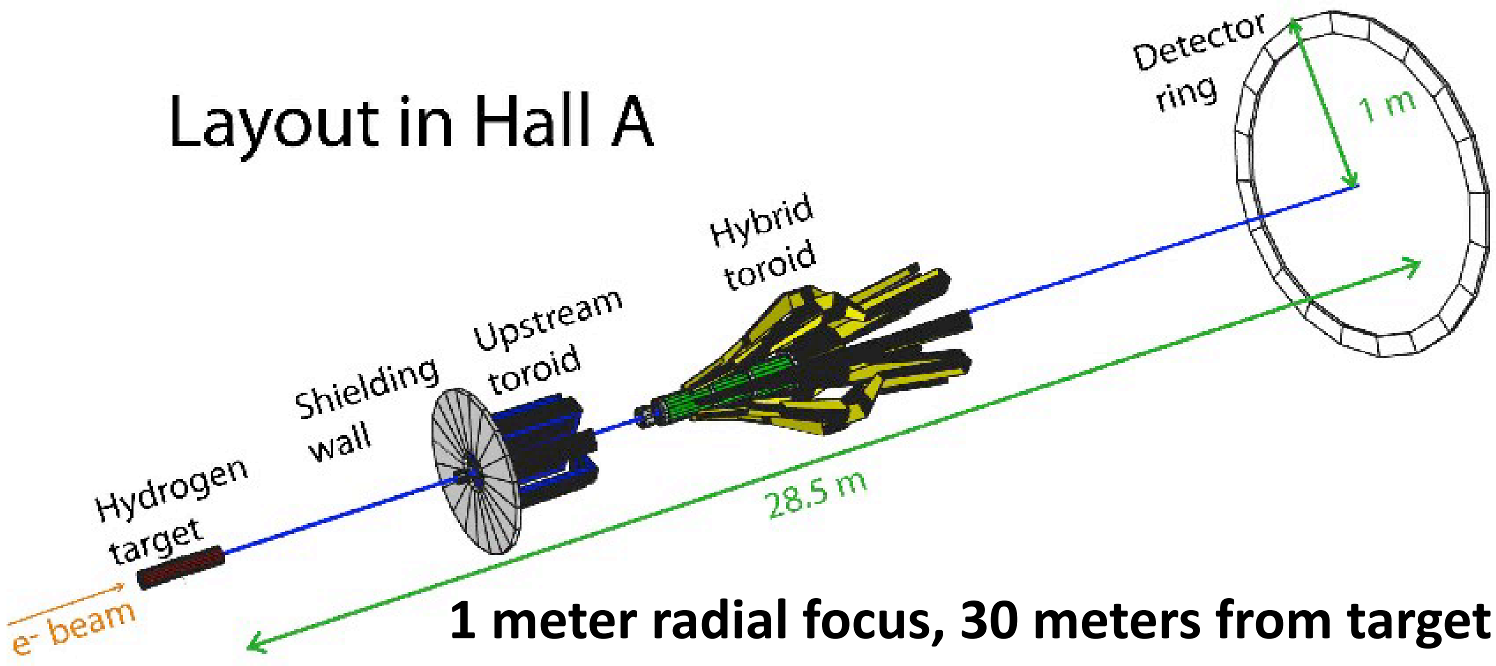
All of those rays of θ_{CM}=[90,120] that you don't get here...



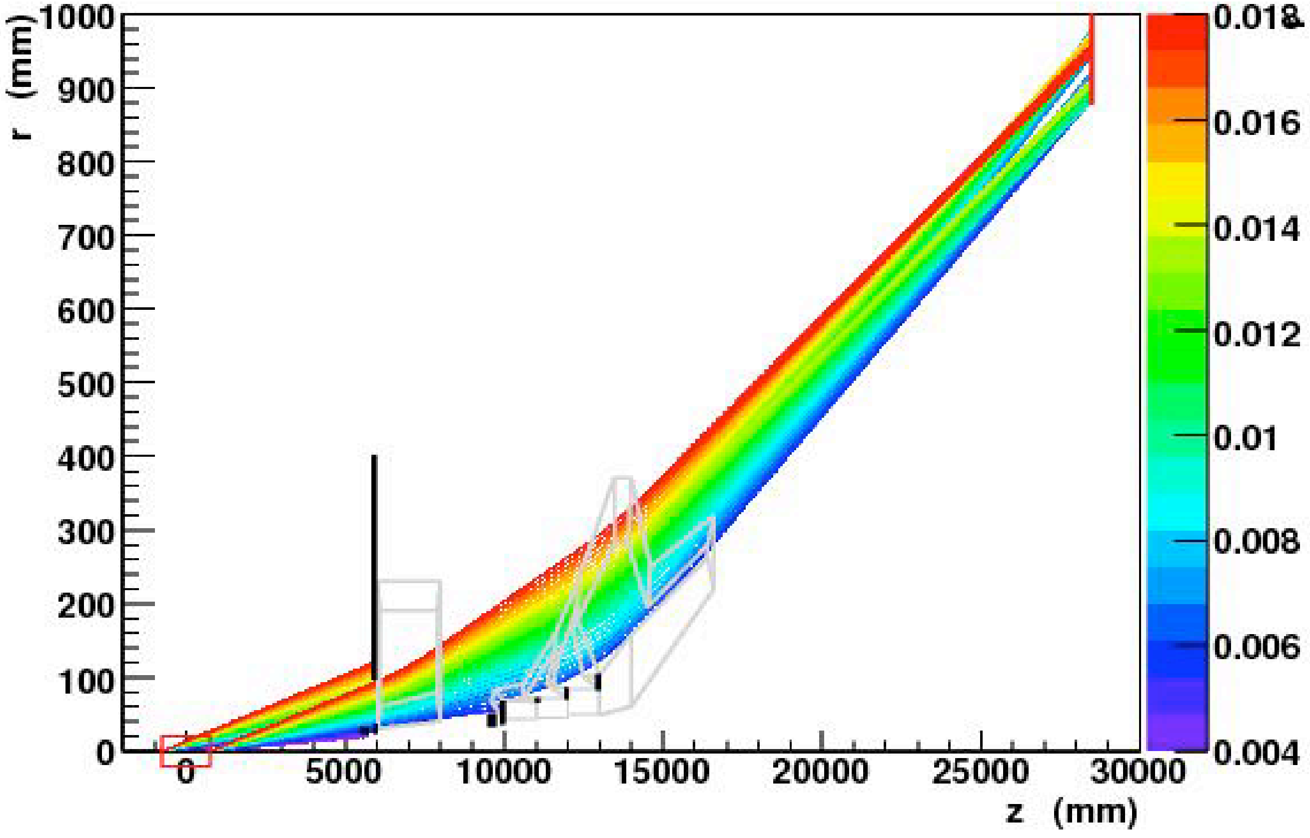
... are collected as θ_{CM}=[60,90] over here!

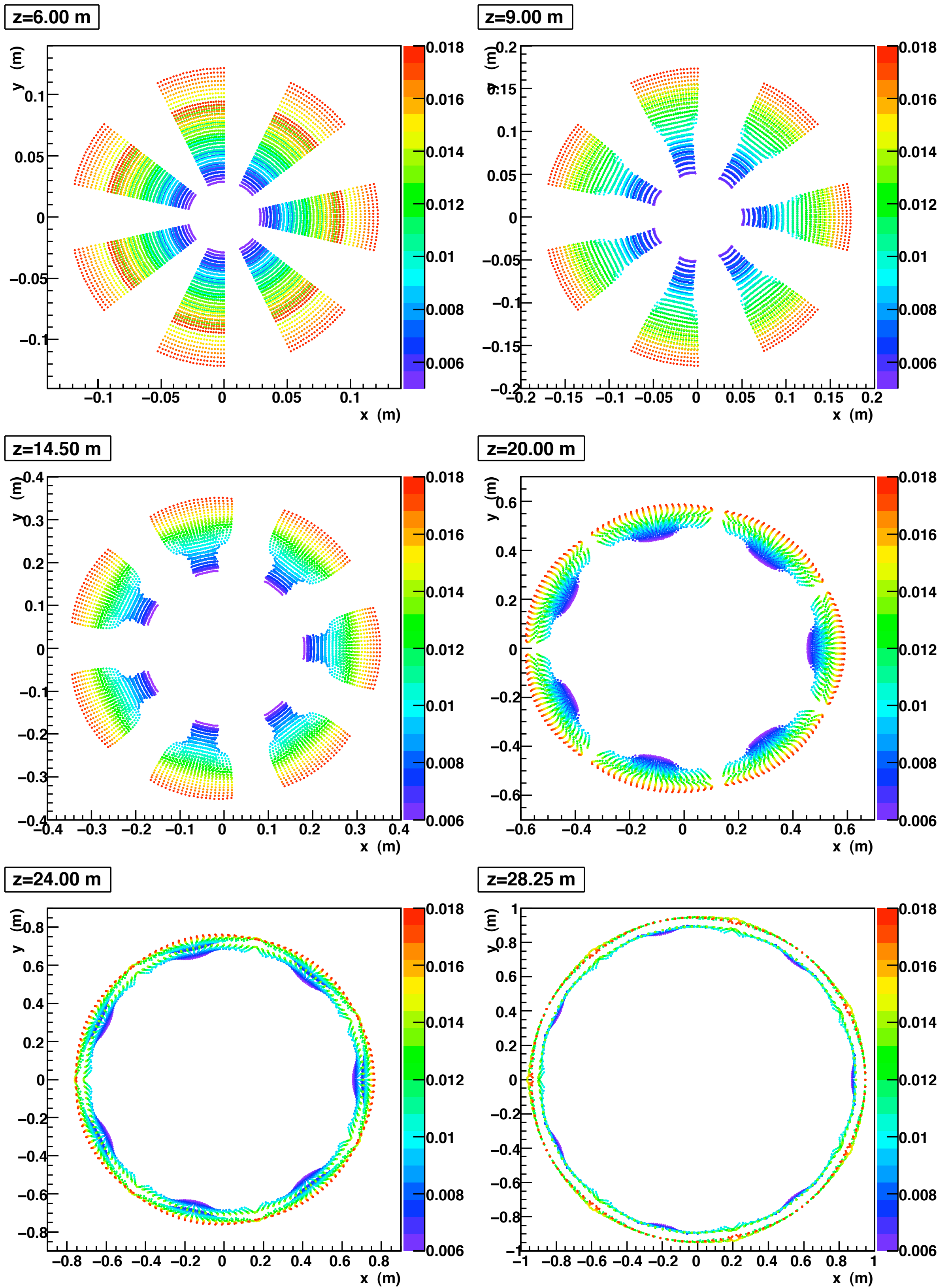
Two Toroid Spectrometer

Layout in Hall A



1 meter radial focus, 30 meters from target
Clean separation from backgrounds

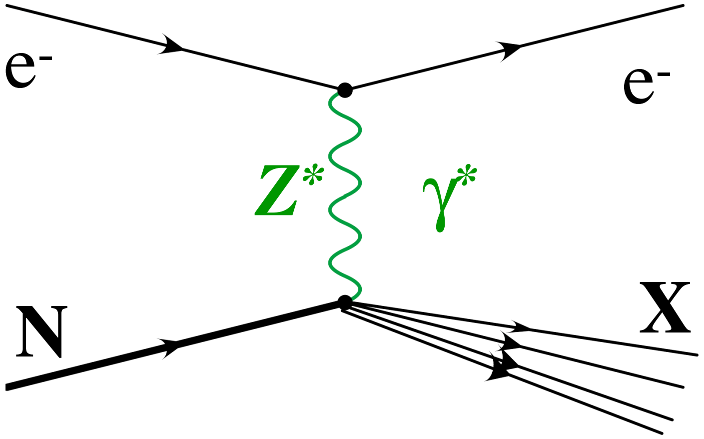




Designed by UVa (Clayton Davis)

Radial Fields (edge effect) creates azimuthal defocussing which populates the full ring at the detector

Deep Inelastic Scattering



Deep Inelastic Regime: Scattering from quarks

Parity-violation in DIS is uniquely sensitive to the poorly known quark axial charges C_{2u} and C_{2d}

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

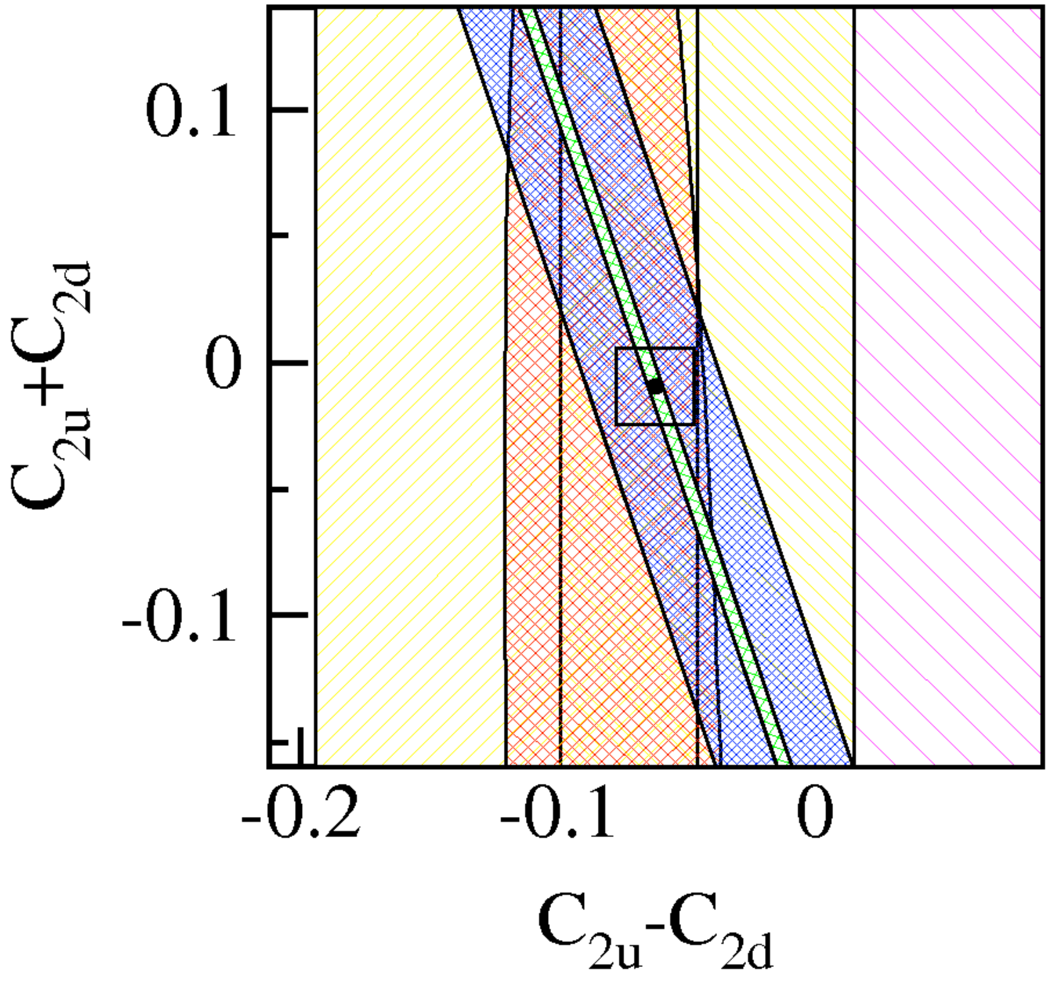
$$a(x) = (2C_{1u} - C_{1d})$$

$$b(x) = (2C_{2u} - C_{2d})$$

Requires Dedicated New Spectrometer System and a broad program of study to separate hadronic and electroweak physics

Proposed design provides sufficient acceptance, resolution, and shielding for broad PVDIS program

- **charge symmetry violation**
- **C_{2q}'s and new physics**
- **higher twist and quark correlations**
- **d/u**
- **PV analog of EMC, nuclear media induced charge asymmetry**
- **new structure functions**



Discussed in detail in X.Zheng's colloquium Feb.6

Solenoid Spectrometer for PVDIS Physics

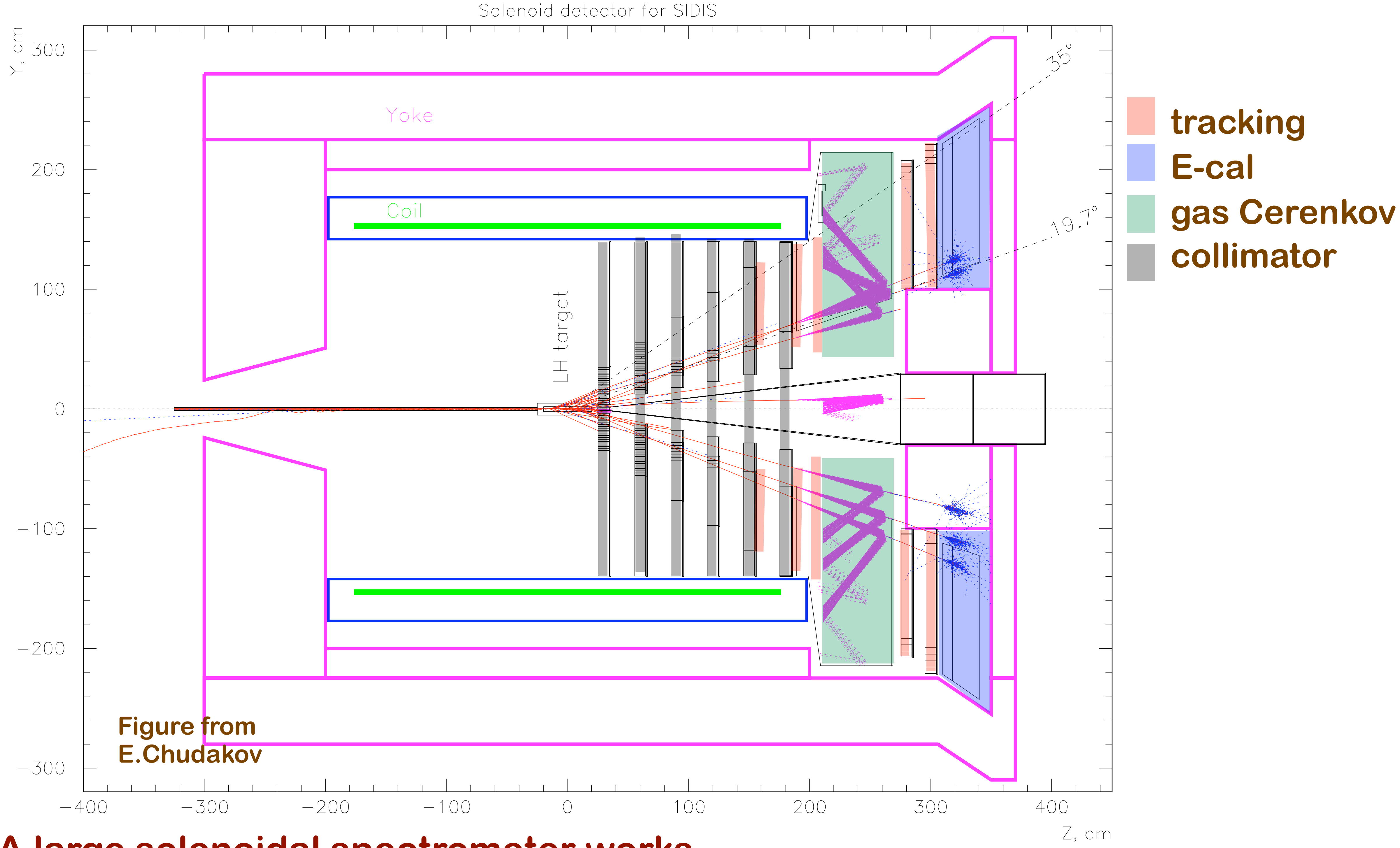


Figure from
E.Chudakov

A large solenoidal spectrometer works

- need BaBar, CDF or CLEOII Solenoid
- fast tracking, particle ID and “parity” counting electronics
- polarimetry ~ 0.4%

- 20^o - 35^o, E’~ 1.5 - 5 GeV
- $\delta p/p \sim 2\%$
- some regions 10’s of kHz/mm^2
- Pion rejection with Cerenkov + segmented calorimeter.

The Parity Program at 11 GeV

Each experiment is a significant technical challenge

- **MOLLER: high rate, low noise, beam asymmetries, backgrounds**
- **PVDIS: fast counting, backgrounds, detector development**
- **BOTH: polarimetry**

Both Experiments will have a big impact with important physics

- **Endorsed by NSAC Long Range Plan**

Proposals were submitted for each to the last PAC

APPROVED!

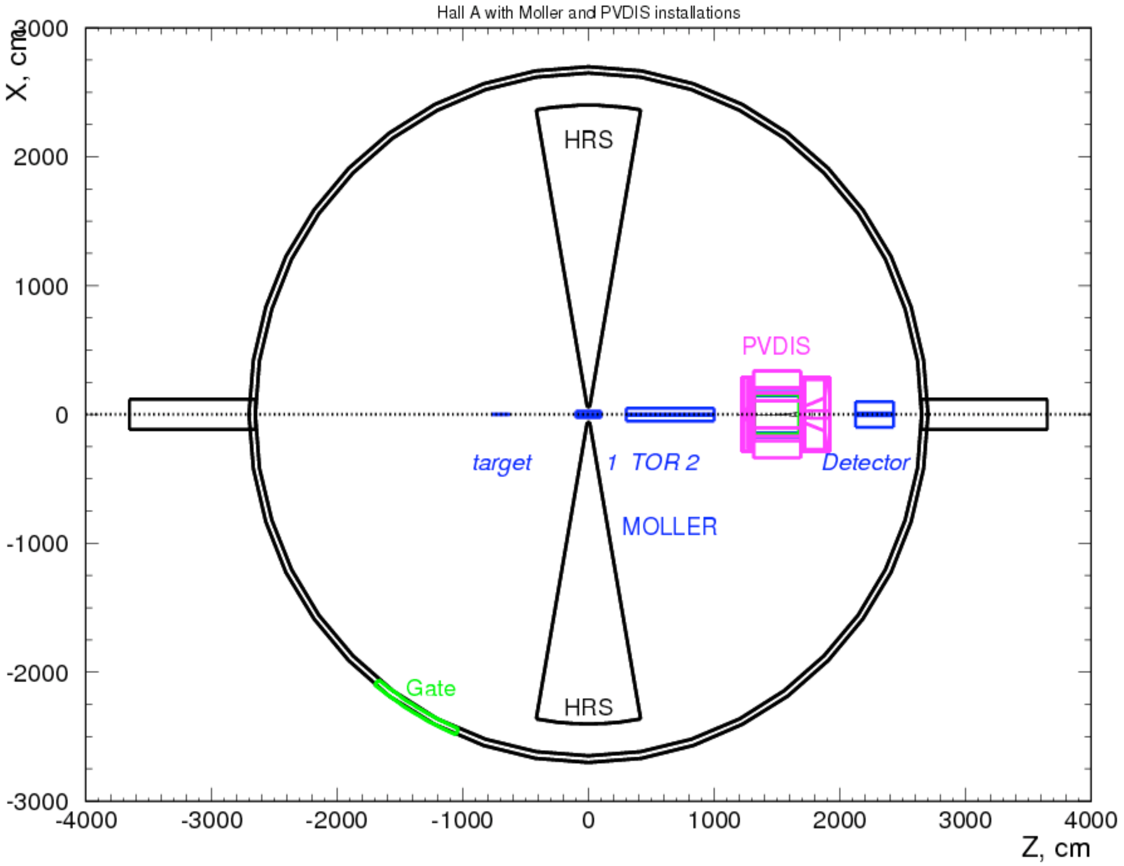
Next step: Technical Design Review in early 2010

These are big projects

- **100+ authors on each proposal**
- **Beam time ~2 years each**
- **Earliest time to run 2015**
- **Estimated construction cost (together) $25 million**
- **Not part of the original JLab upgrade**

Requires independent funding

Moller and PVDIS apparatus in Hall A



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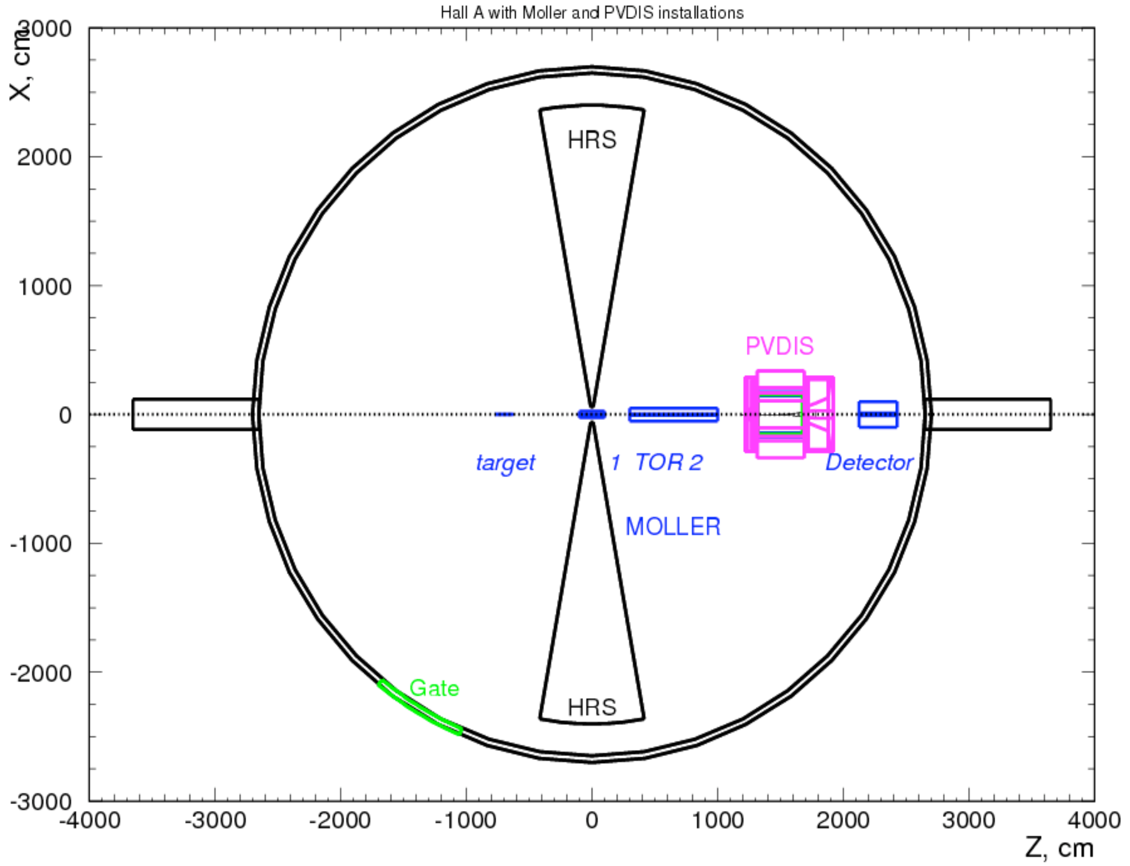

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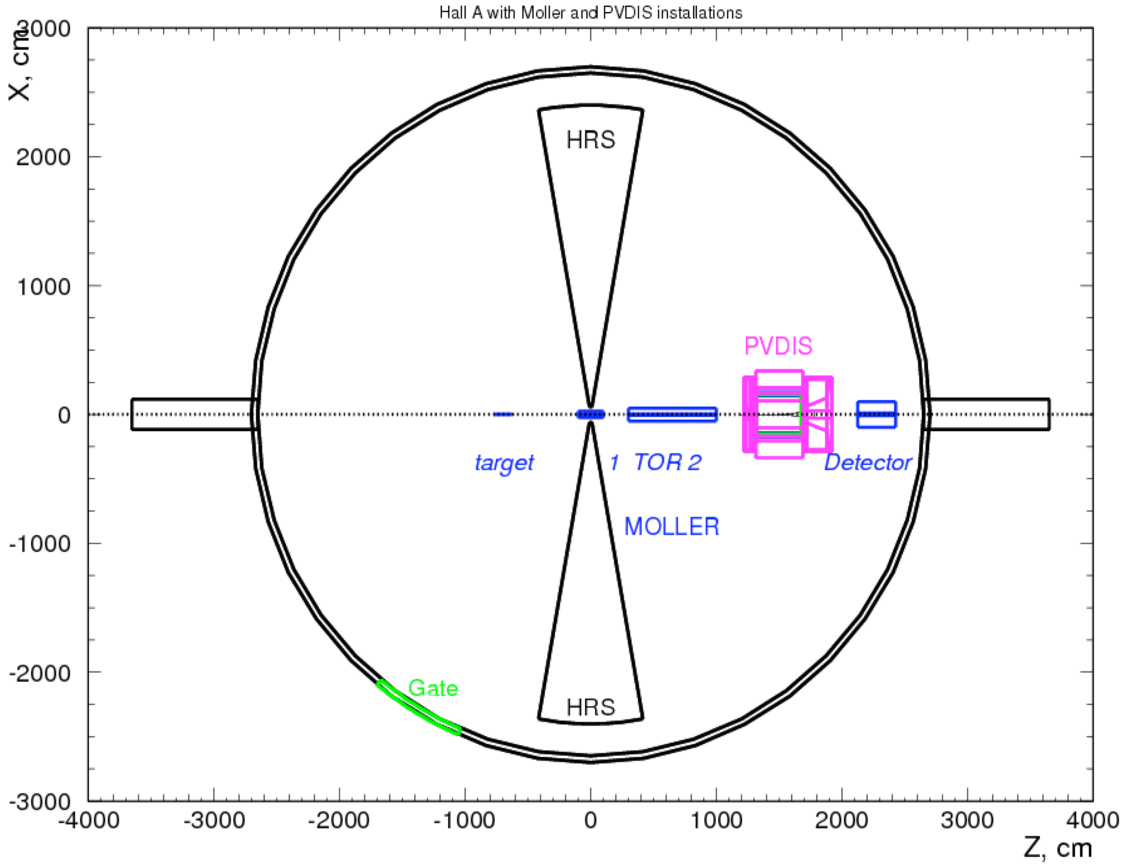
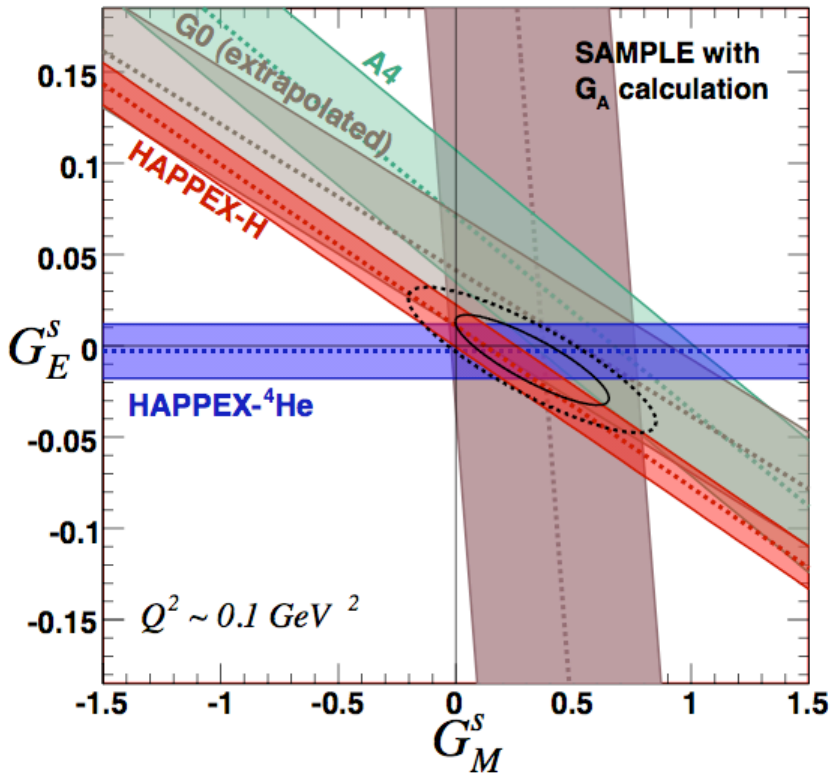
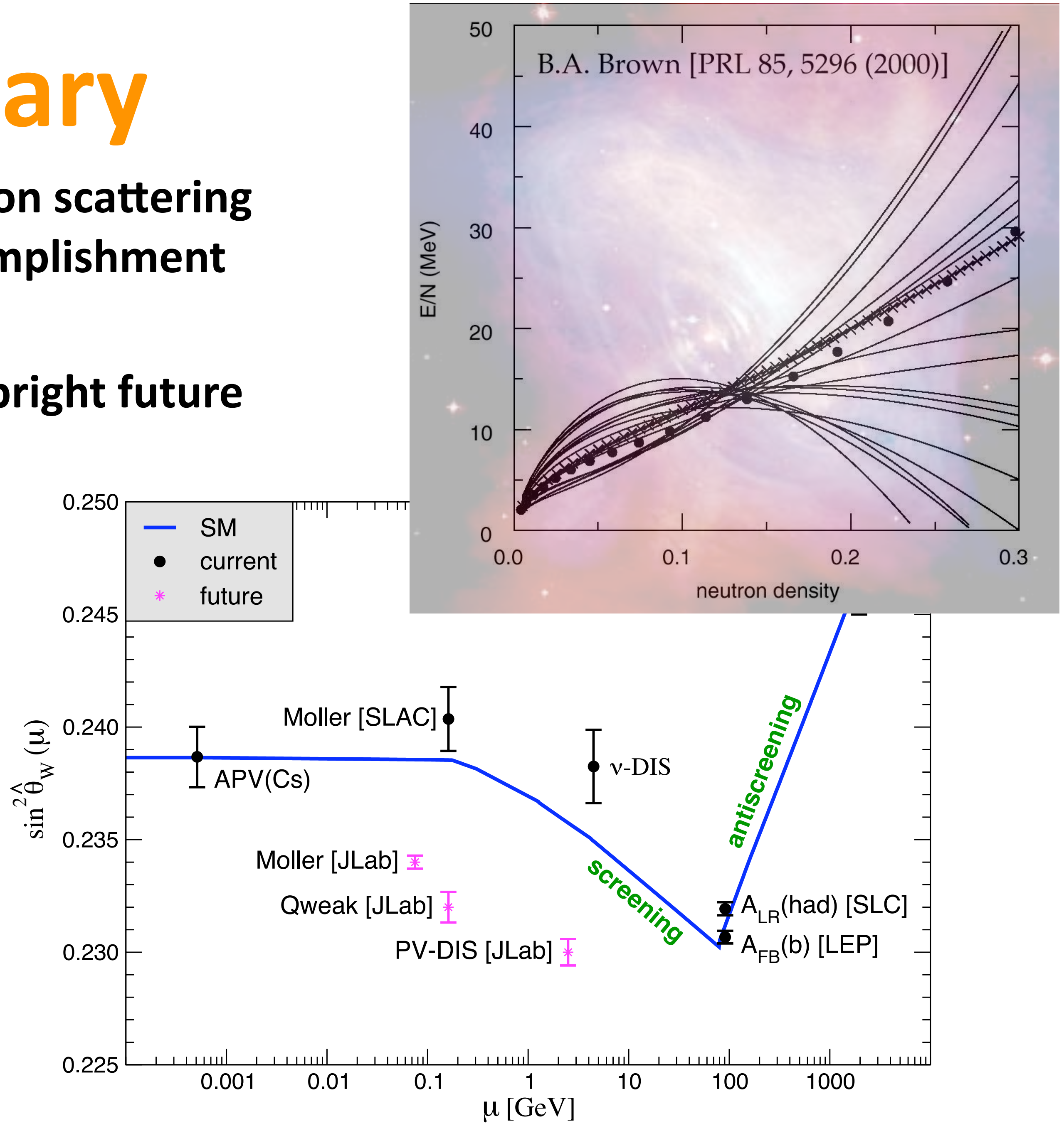


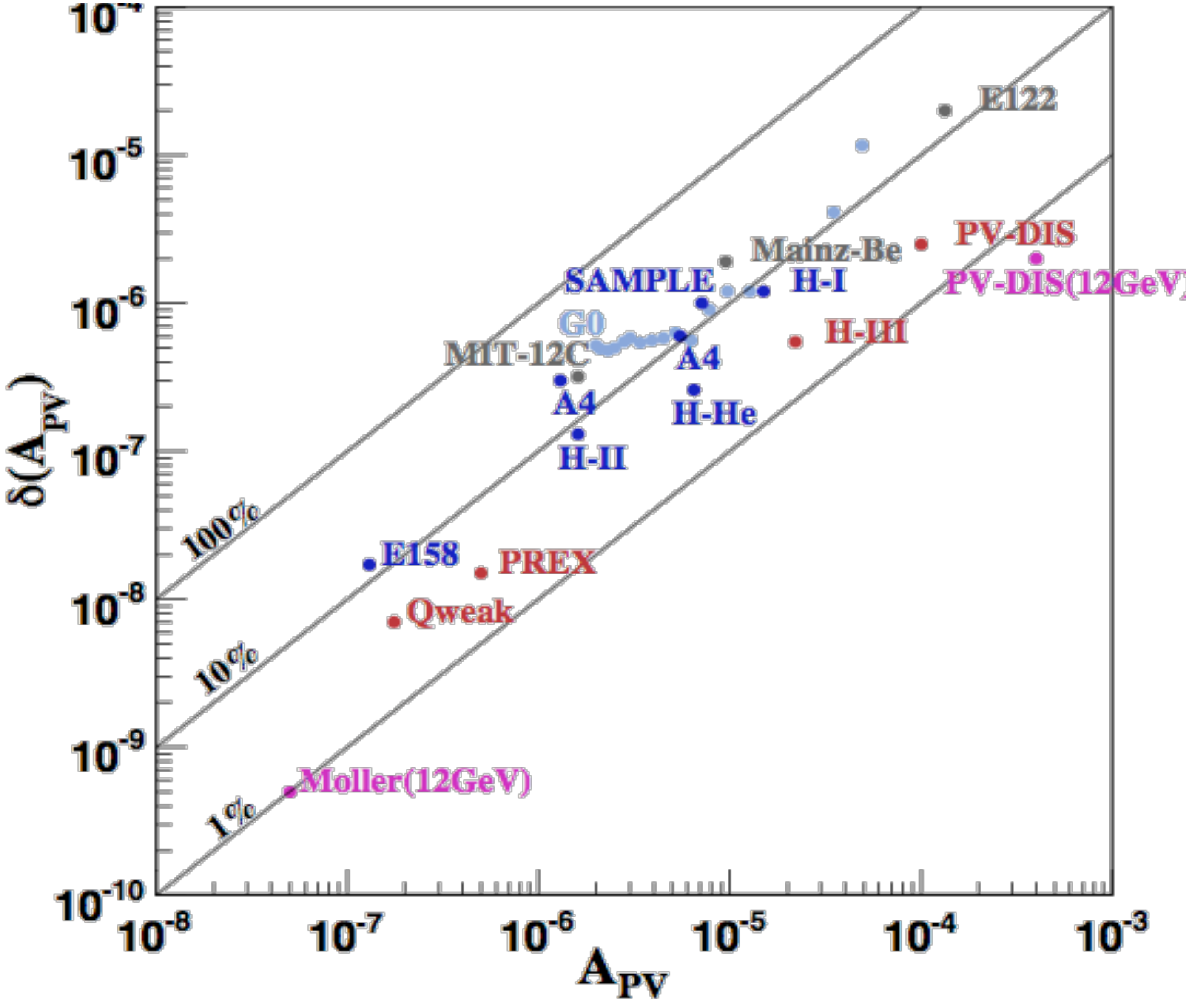
Summary

Parity-violating electron scattering has a record of accomplishment

... and a very bright future







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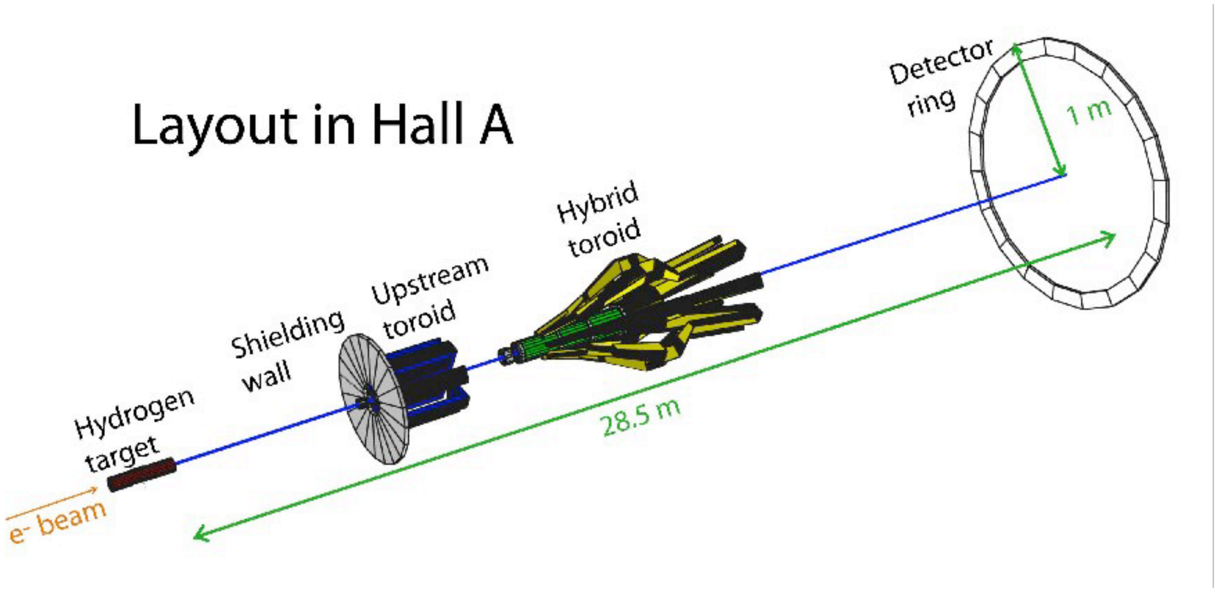


backup

High Precision Compton

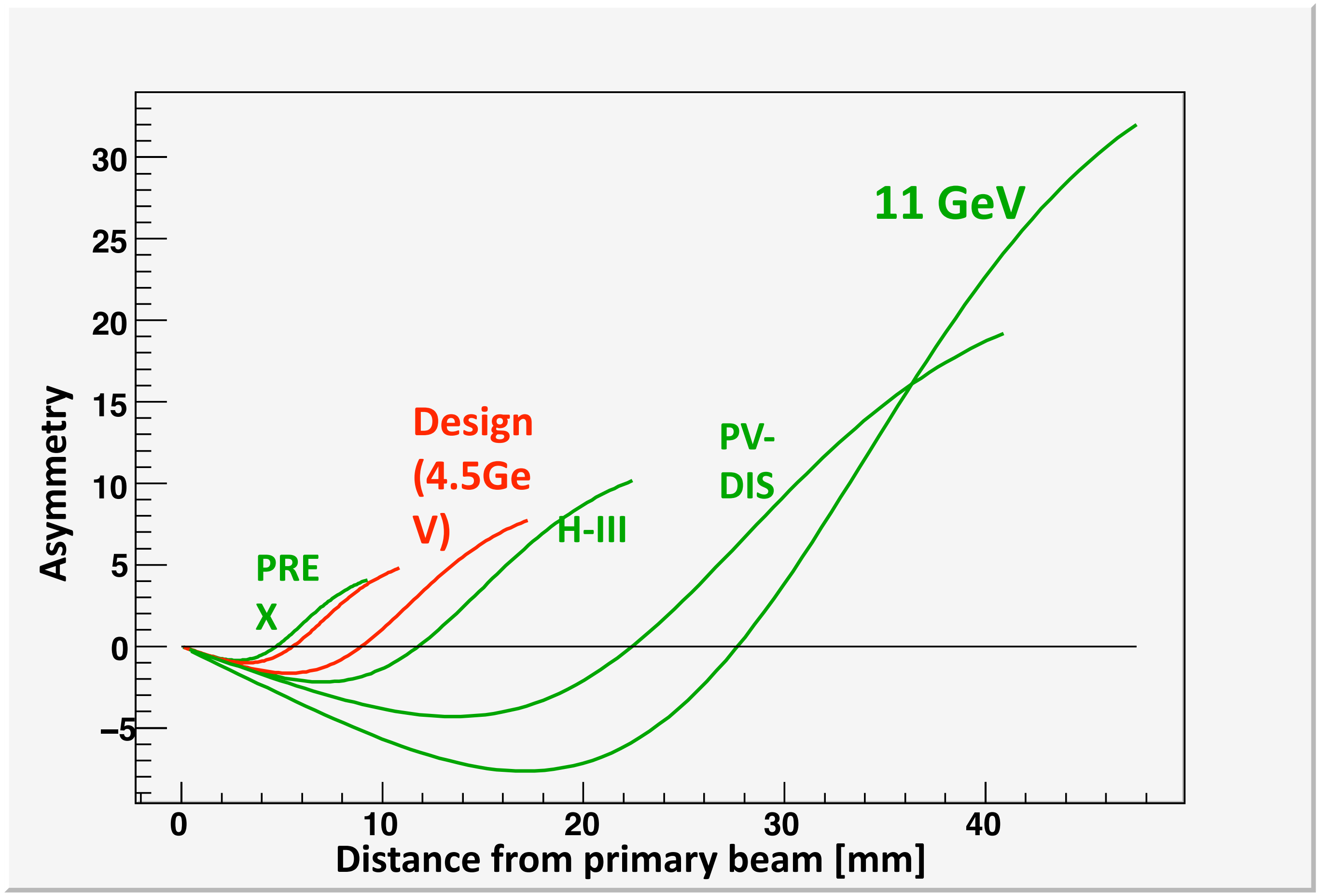
At high energies, SLD achieved 0.5%.

Why do we think we can do better?

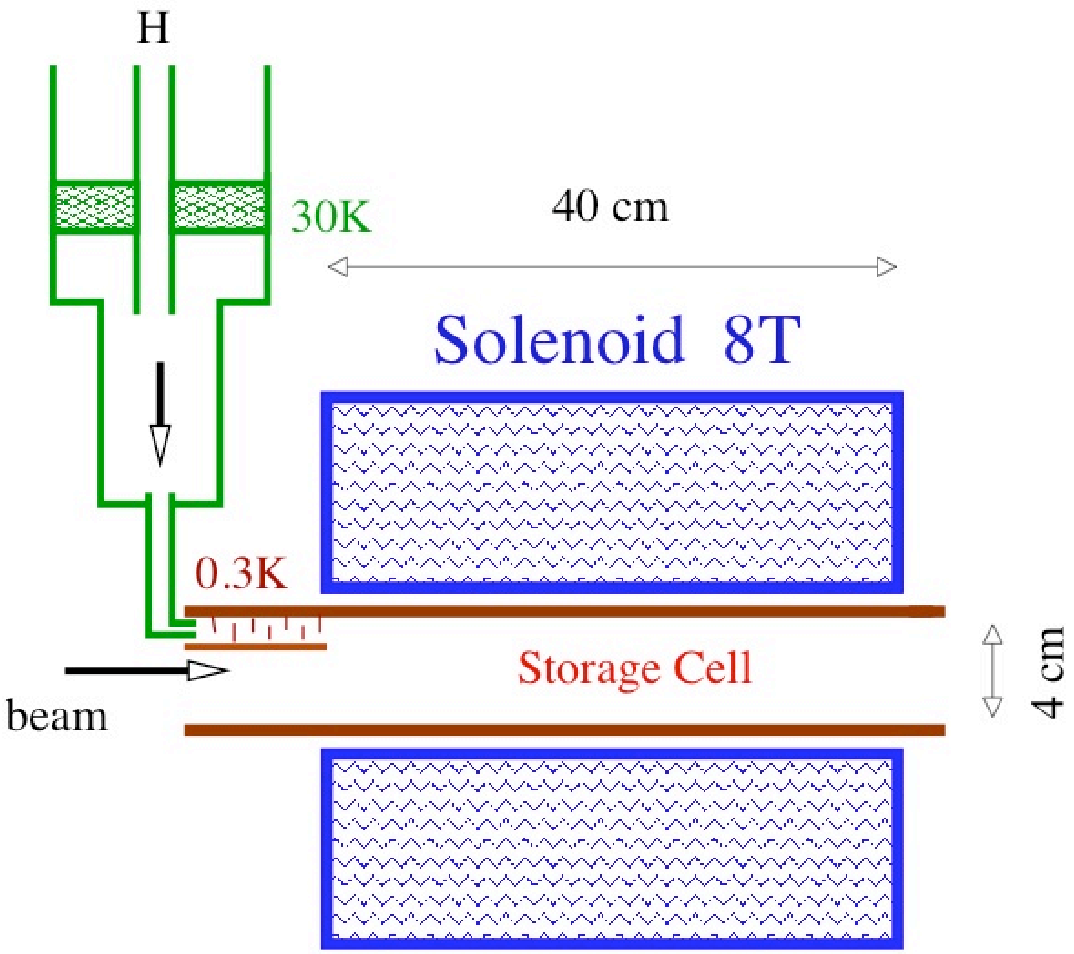
- SLD polarimeter near interaction region
  - No photon calorimeter for production
- Hall A has "counting" mode (CW)
  - Efficiency studies
  - Tagged photon beam
- Greater electron detector resolution

So why haven't we done better before?

- Small asymmetries
  = long time to precision
  = cross-checks are difficult
- No one tried zero-crossing technique
- photon calorimetry gets tricky at small E_γ
- Zero crossing gets hard near the beam



Atomic Hydrogen For Moller Target



10 cm, ρ = $3\text{x}10^{15}/\text{cm}^3$
in B = 7 T at T=300 mK

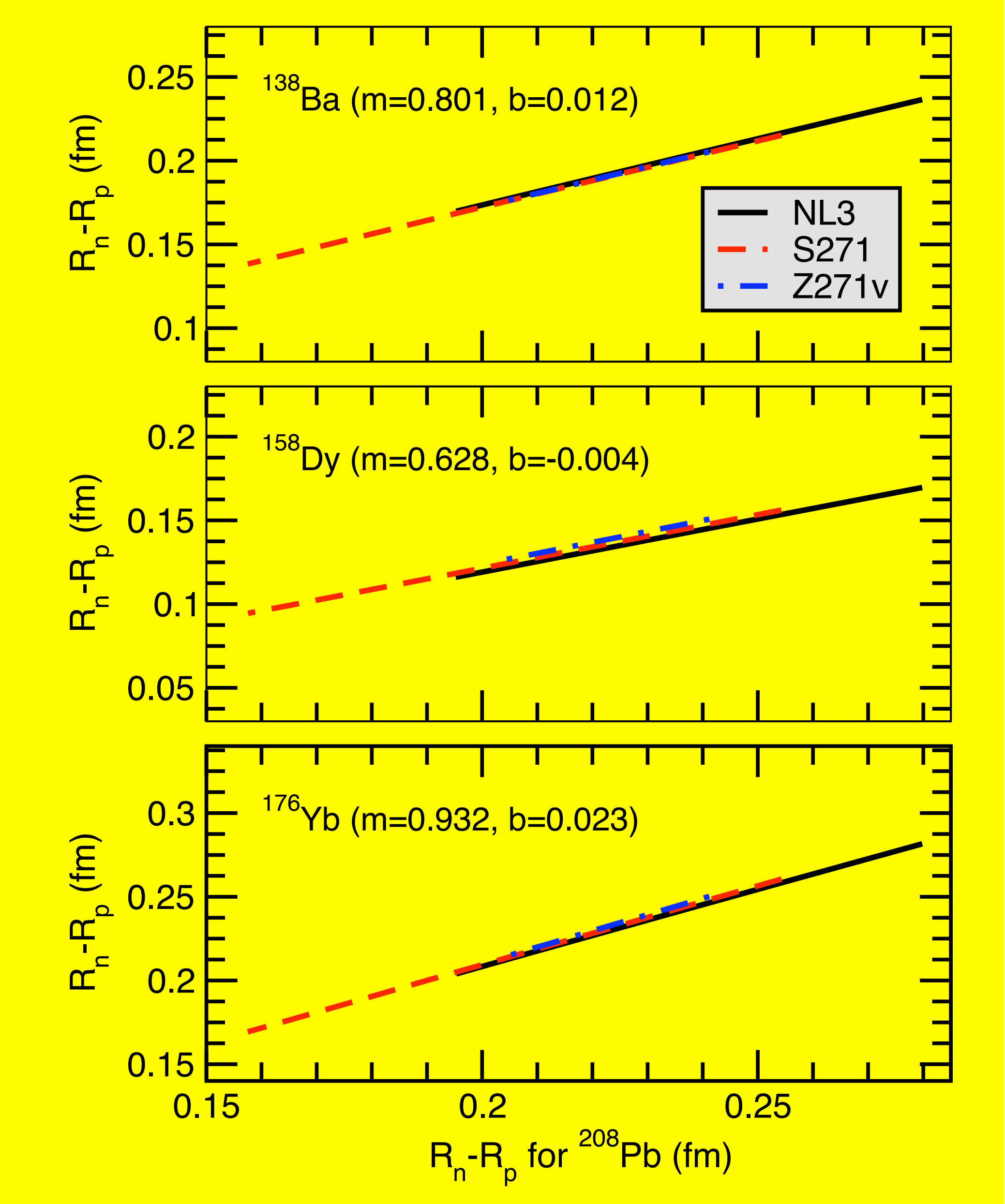
$$\boxed{\frac{n_+}{n_-} = e^{-2\mu B/kT} \approx 10^{-14}}$$

Brute force polarization

Moller polarimetry from polarized atomic hydrogen gas, stored in an ultra-cold magnetic trap

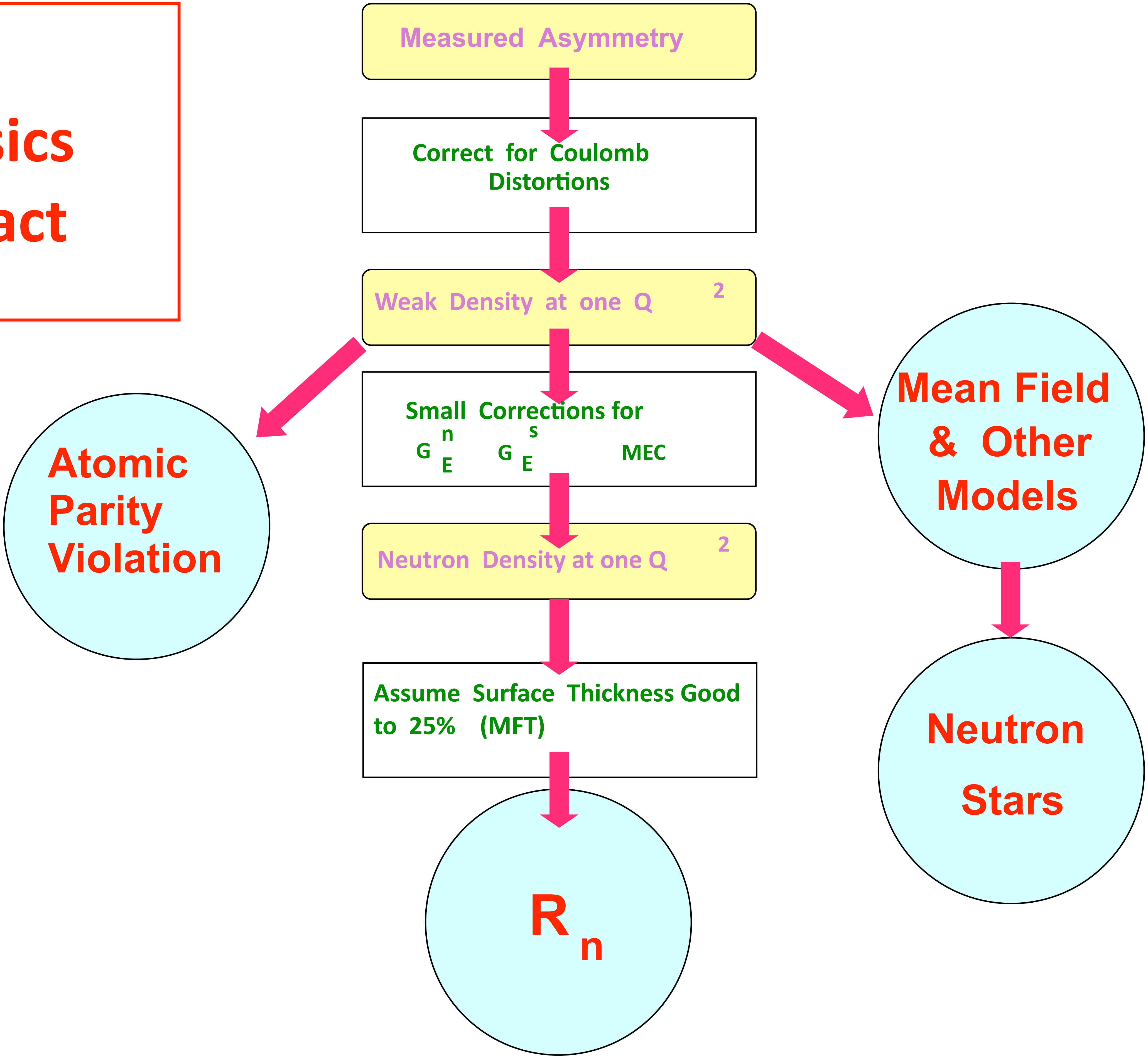
- **100% electron polarization**
- **tiny error on polarization**
- **thin target (sufficient rates but no dead time)**
- **Non-invasive**
- **high beam currents allowed**
- **no Levchuk effect**

E. Chudakov and V. Luppov, IEEE Transactions on Nuclear Science, **v 51, n 4, Aug. 2004, 1533-40**



^{138}Ba (m=0.801, b=0.012)
^{158}Dy (m=0.628, b=-0.004)
^{176}Yb (m=0.932, b=0.023)
NL3
S271
Z271v
R_n-R_p (fm)
R_n-R_p for ^{208}Pb (fm)
0.1
0.15
0.2
0.25
0.05
0.3

PREX
Physics Impact



Measured Asymmetry

Correct for Coulomb Distortions

Weak Density at one Q^2

Small Corrections for G_E^n G_E^s MEC

Neutron Density at one Q^2

Assume Surface Thickness Good to 25% (MFT)

R_n

Atomic Parity Violation

Mean Field & Other Models

Neutron Stars