The Qweak experiment

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for the Q_{weak} Collaboration

seminar outline

1. Physics motivation/ what is Q_{weak} ?
2. Idea of measurement/ how to extract Q_{weak}
3. Experimental setup
4. What we should worry about – systematics uncertainty...

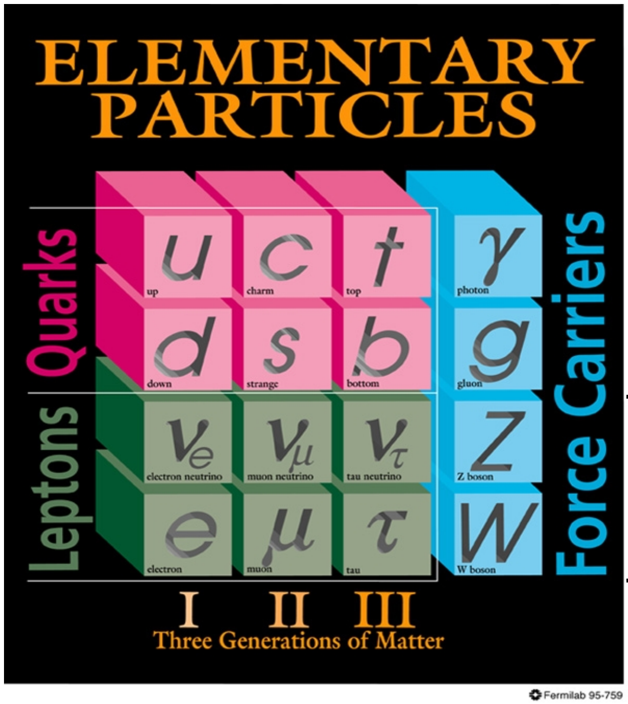
⬇

Let's try our best where we can -> measurement of beam polarization

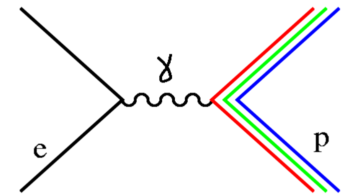
5. Electron Compton polarimeter / how it works
6. Usage of diamond in it (diamond vs Si)
7. Fabrication steps
8. Tests – how we know this works properly

9. Summary

SM and Weak Charges



EM Charge



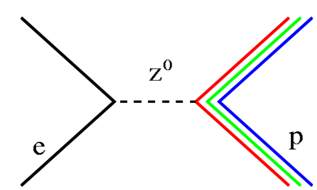
EM — Parity conserving (PC)

STRONG — (PC)

WEAK (Z0, W+,W-) — Parity Violating (PV)

The "charge" of the weak interaction is called "weak charge"

Weak Charge

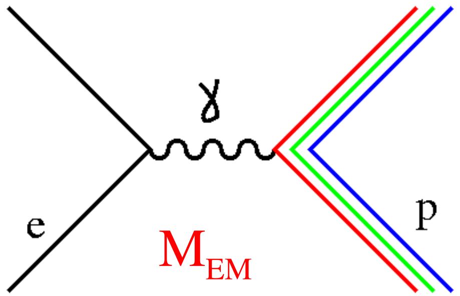


	EM Charge	Weak Charge
q^{up}	+2/3	$1-8/3\sin^2\theta_W \sim 1/3$
q^{down}	-1/3	$-1-4/3\sin^2\theta_W \sim -2/3$
$Q^p=2q^{up}+1q^{down}$	+1	$\boxed{1-4\sin^2\theta_W \sim -0.713}$
$Q^n=1q^{up}+2q^{down}$	0	-1

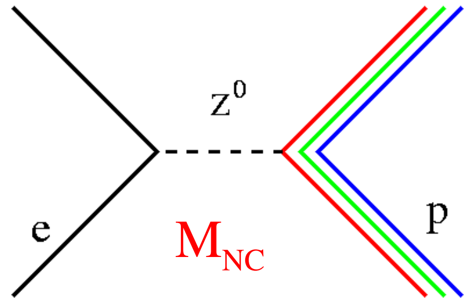
Nether was measured !

The Proton's Weak Charge

As $Q^2 \rightarrow 0$



measures Q^p – proton's electric charge



measures $Q^p{}_{weak}$ – proton's weak charge

$$A = \frac{2M_{NC}}{M_{EM}} = \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2\, Q^p_{weak} + F^p\left(Q^2, \theta\right)\right]$$

$$\xrightarrow[\theta \to 0]{Q^2 \to 0} \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2\, Q^p_{weak} + Q^4 B\left(Q^2\right)\right]$$

contains $G^{\gamma}_{E,M}$ and $G^{Z}_{E,M}$

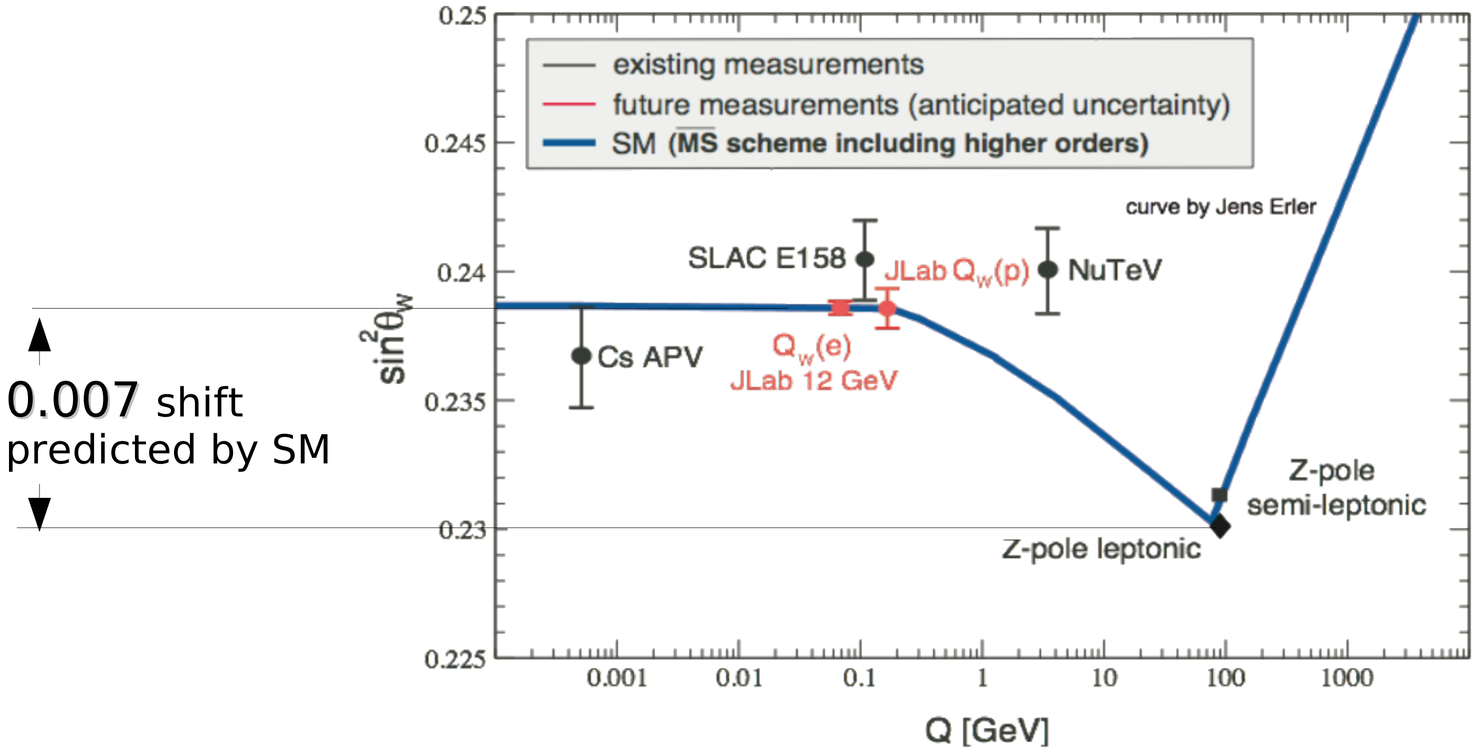
Well constraint from world data:
HAPPEX, G0, A4, and many others

At tree level in the SM (neglecting the radiative corrections) :

$$\boxed{Q^p{}_{weak} = 1\text{-}4\sin^2\theta_W}$$

A sensitive, low-energy extraction of the weak mixing angle.

SM and "Running" of $\sin^2\theta_W$



SM Prediction
Erler, Kurylov & Ramsey-Musolf, Phys. Rev. D 68, 016006 (2003)

present:

"d-quark dominated": Cesium APV (Q^A_W)

"pure lepton": SLAC E158 (Q^e_W)

uncertainties in the theoretical interpretation

future:

"u-quark dominated": Q_{weak} (Q^p_W)

"pure lepton":12 GeV e-e- PV (Q^e_W)

Qweak will be clean with respect to theoretical interpretation (relay on experimental data to remove the dominant hadronic background)

Sensitivity to TeV Scale

The model (Hamiltonian) predicts what we should see:

↓

A sum of "all" possible processes:

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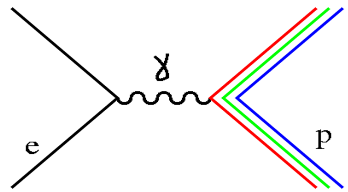

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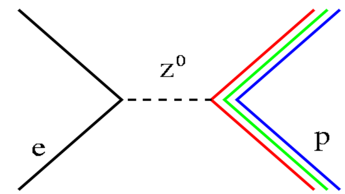

(Tree Level)

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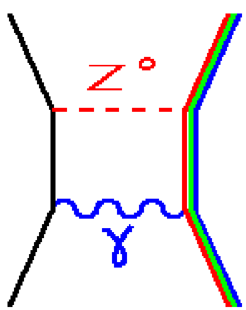

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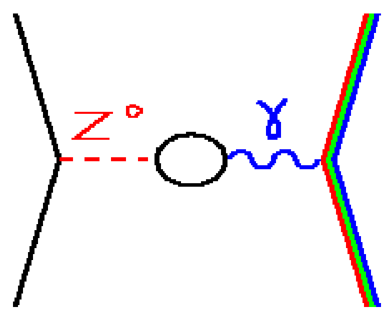

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Boxes, loops
(radiative
corrections)

Is there something more we need to include ? -> NEW PHYSICS

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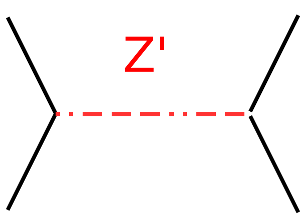

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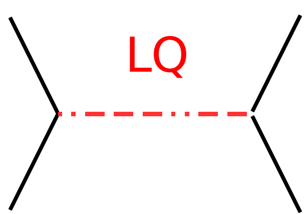

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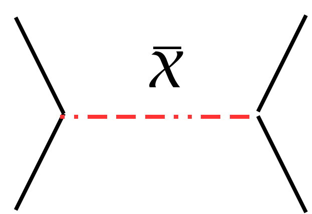
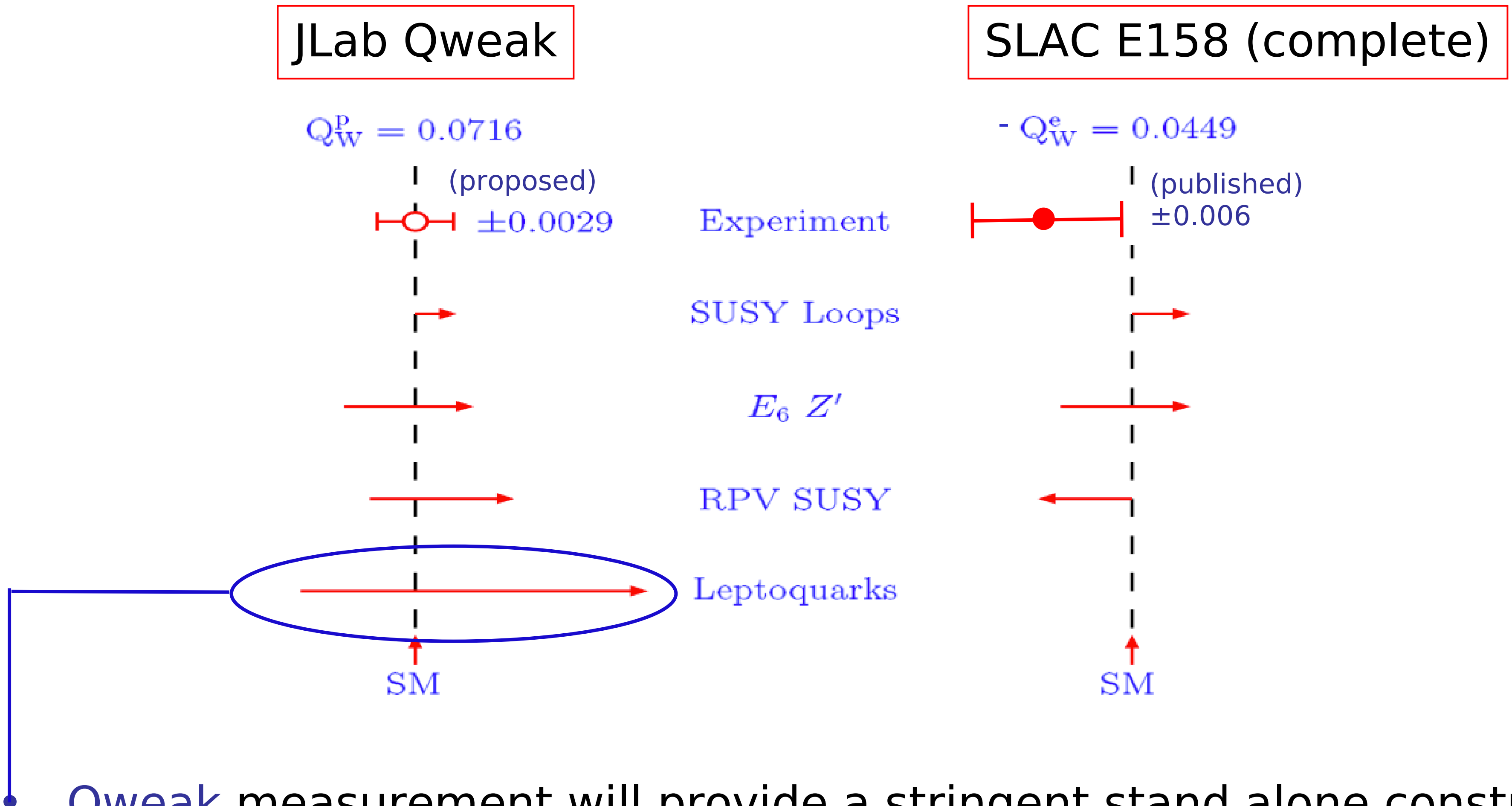


Q^p_{weak} & Q^e_{weak} – Complementary Diagnostics for New Physics



- Qweak measurement will provide a stringent stand alone constraint on Lepto-quark based extensions to the SM.
- Q^p_{weak} (semi-leptonic) and Moller (pure leptonic) together make a powerful program to search for and identify new physics.

Erler, Kurylov, Ramsey-Musolf, PRD **68**, 016006 (2003)

The Qweak Collaboration/Experiment:

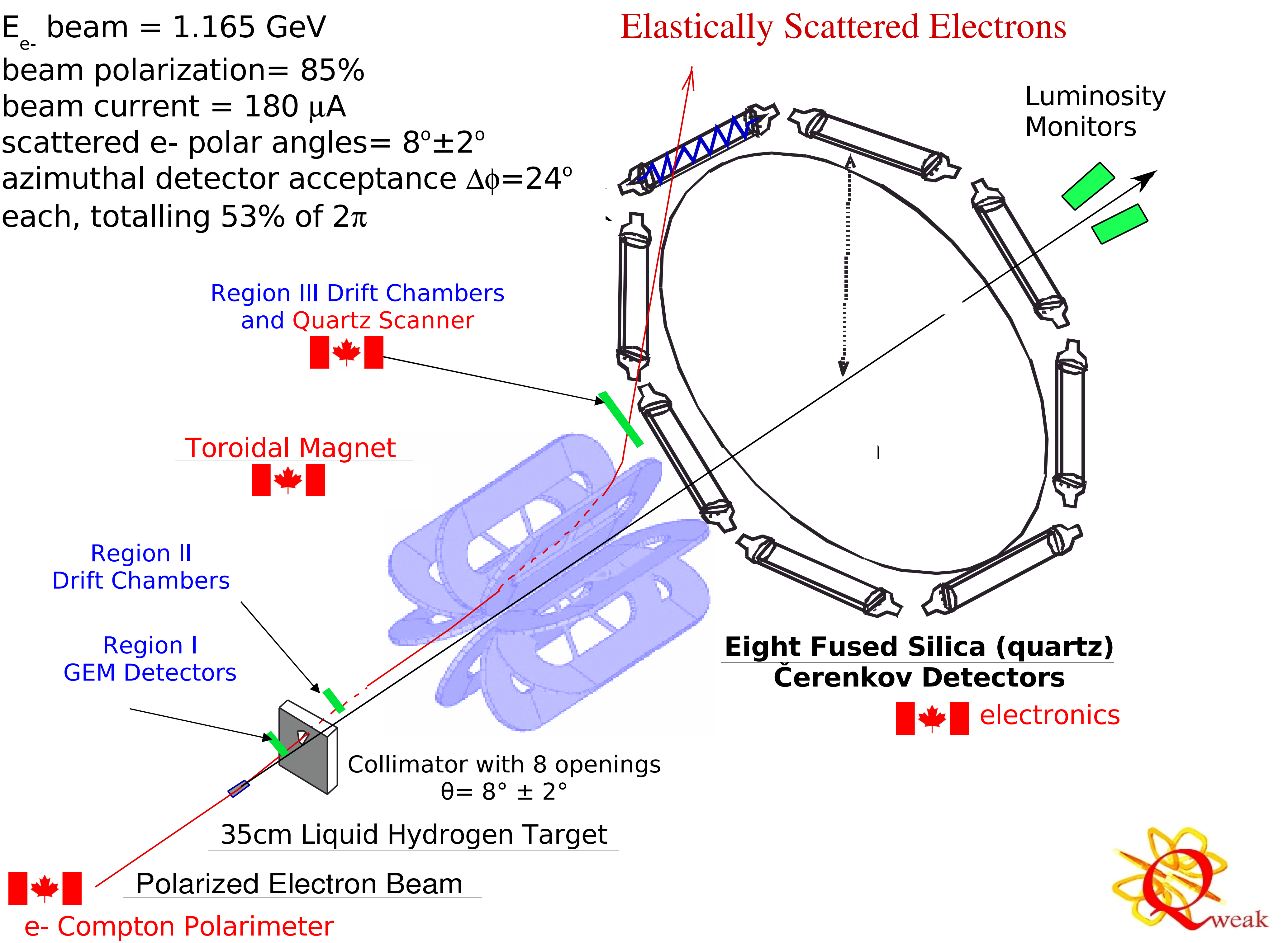
27 institutions (USA, **Canada**, Mexico, Armenia)

20% manpower from Canada:
TRIUMF,
University of Manitoba,
University of Winnipeg,
University of Northern British Columbia

The Experiment will be performed in 2010 at the Thomas Jefferson National Accelerator Facility in Newport News, Virginia

CEBAF: CW electron accelerator, energies upto 6 GeV

E_{e-} beam = 1.165 GeV
beam polarization= 85%
beam current = 180 μA
scattered e- polar angles= 8°±2°
azimuthal detector acceptance $\Delta\phi$=24°
each, totalling 53% of 2π

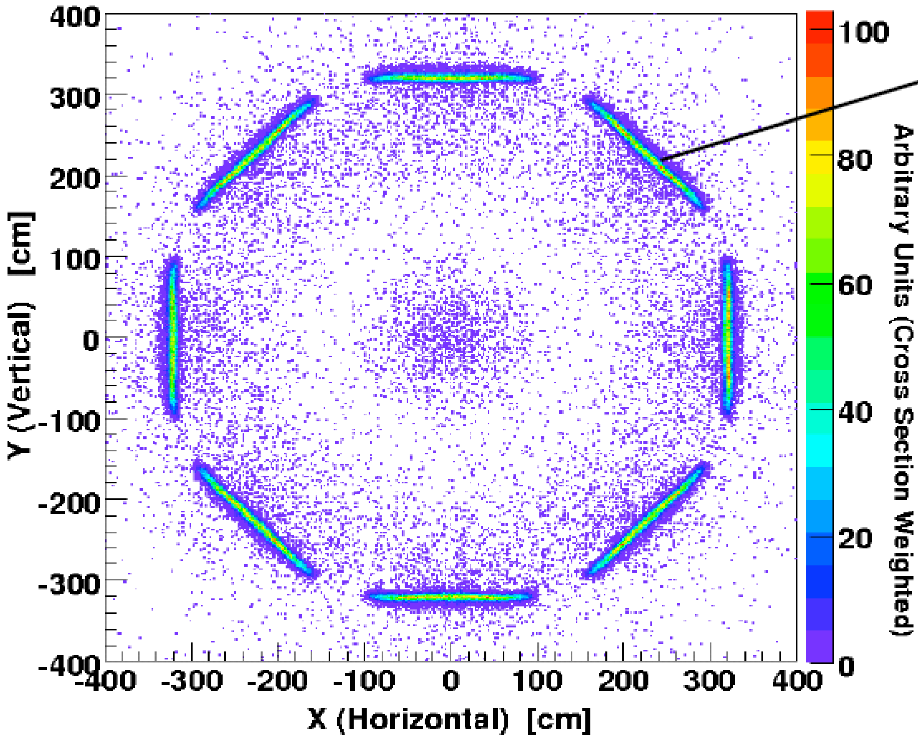


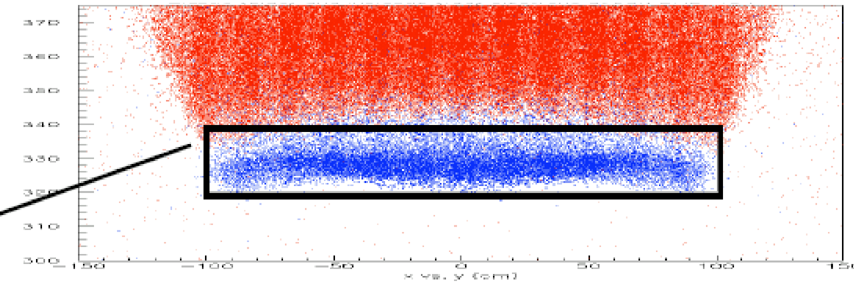
Good separation of elastic scattering events for Q^2=0.03GeV

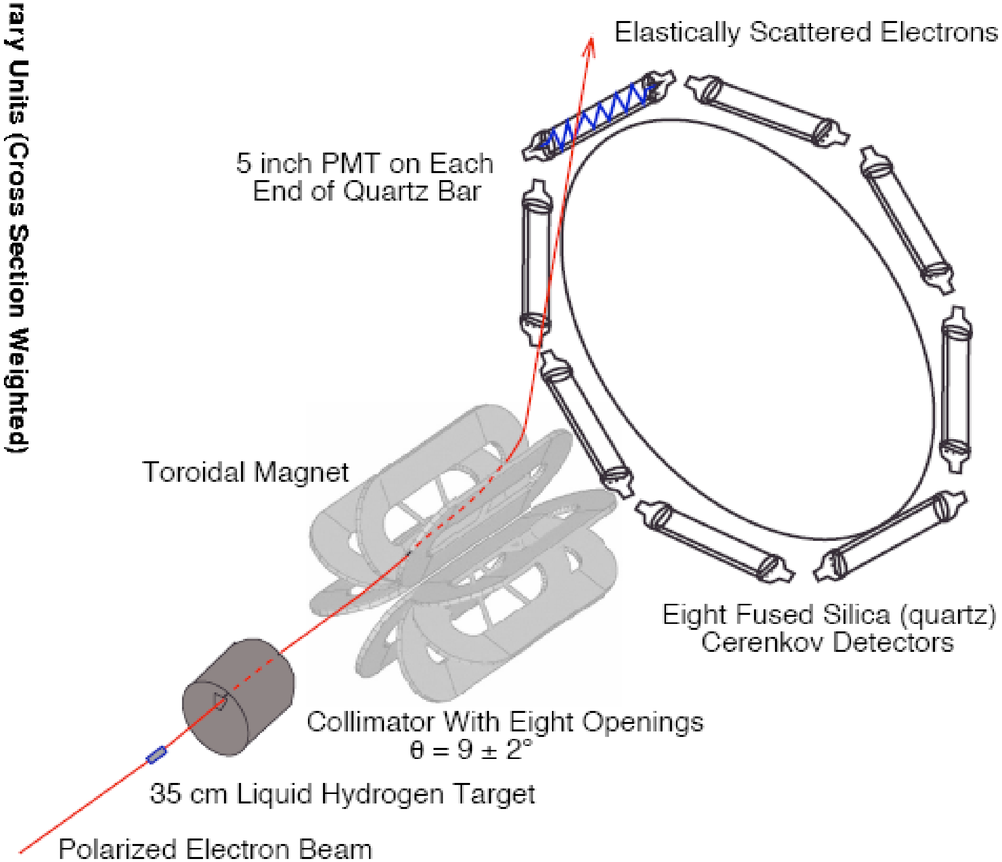
View Along Beamline of Q_{Weak} Apparatus - Simulated Events

8 fused silica radiators

200cm x 18cm x 1.25cm





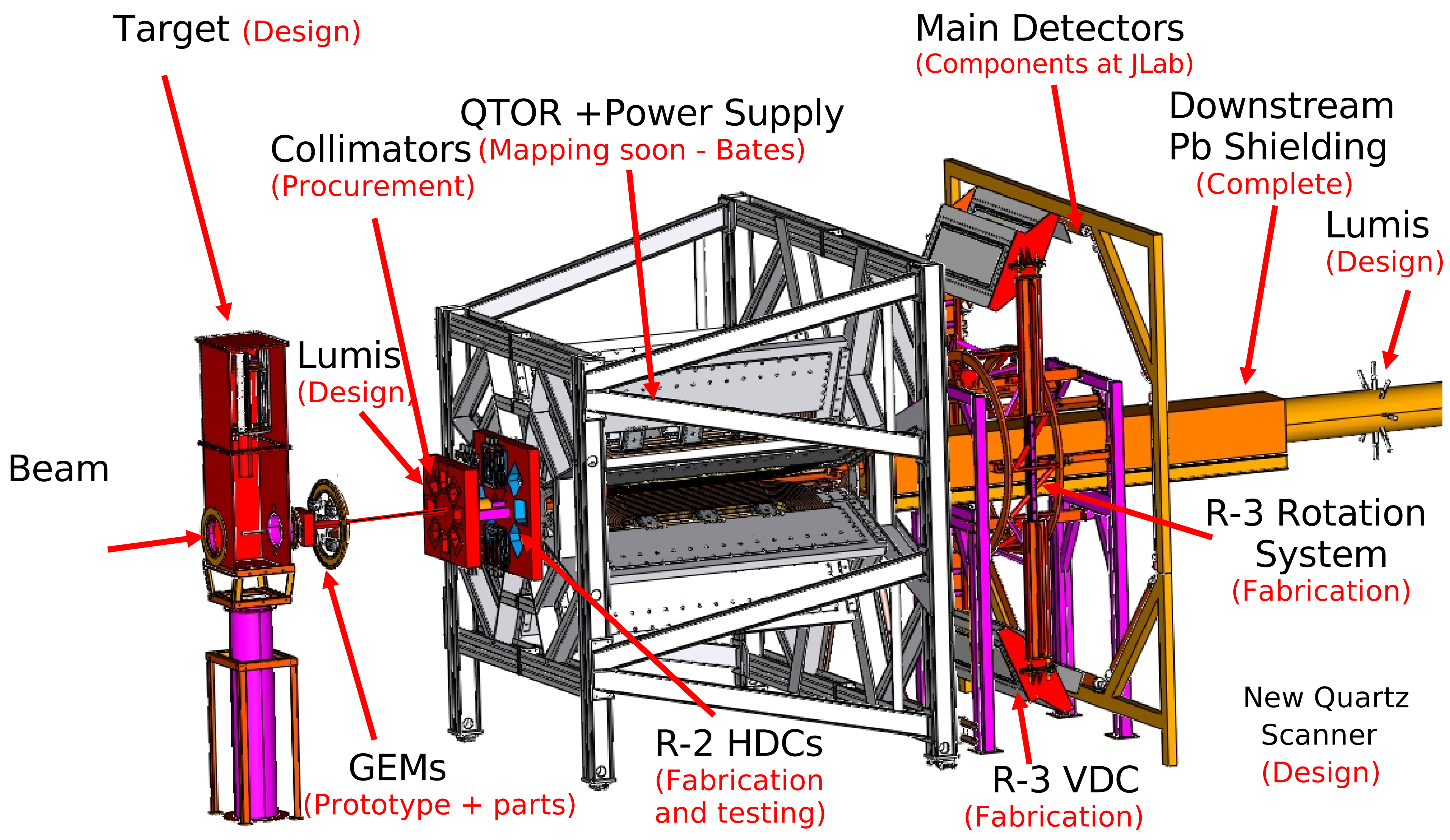


Central scattering angle:	~8° ± 2°
Phi Acceptance:	~50% of 2π
Average Q^2:	0.026 GeV^2
Acceptance averaged asymmetry:	–0.234 ppm
Integrated Rate (per detector):	~810 MHz
Inelastic/Elastic ratio:	~0.4%

Very clean elastic separation!

How this will look like in the nature:

Experiment Component & Status



What we should be worry about:

Anticipated Q^p_{Weak} Uncertainties

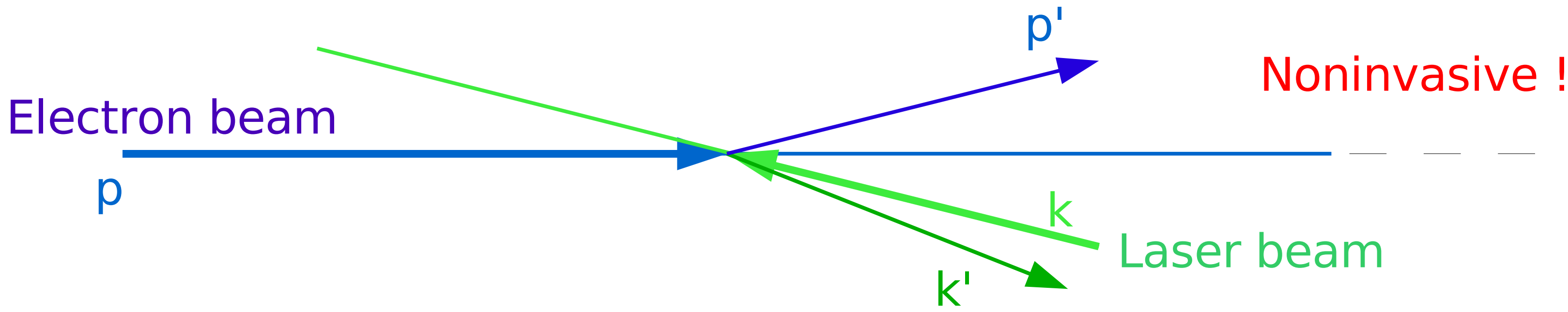
	$\Delta A_{phys}/A_{phys}$	$\Delta Q^p_{weak}/Q^p_{weak}$
Statistical (2200 hours production)	2.1%	3.2%
Systematic:		
Hadronic structure uncertainties	--	1.5%
Beam polarimetry	1.0%	1.5%
Absolute Q^2 determination	0.5%	1.0%
Backgrounds	0.5%	0.7%
Helicity-correlated Beam Properties	0.5%	0.7%
Total	**2.5%**	**4.1%**

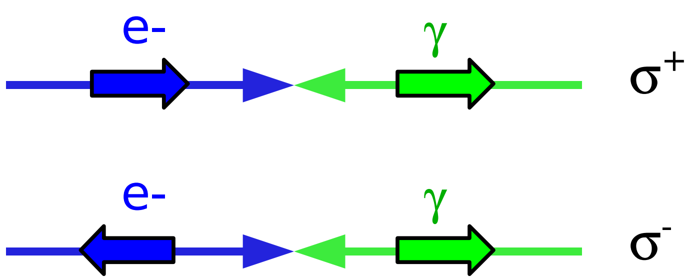
Experimental sensitivity: $$Q_W^p = (1 - 4\sin^2\theta_W) \cong 0.0713$$

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

Expected value: $A(Q^2 = 0.026\ \mathrm{GeV}^2) = -0.234$ ppm !!!

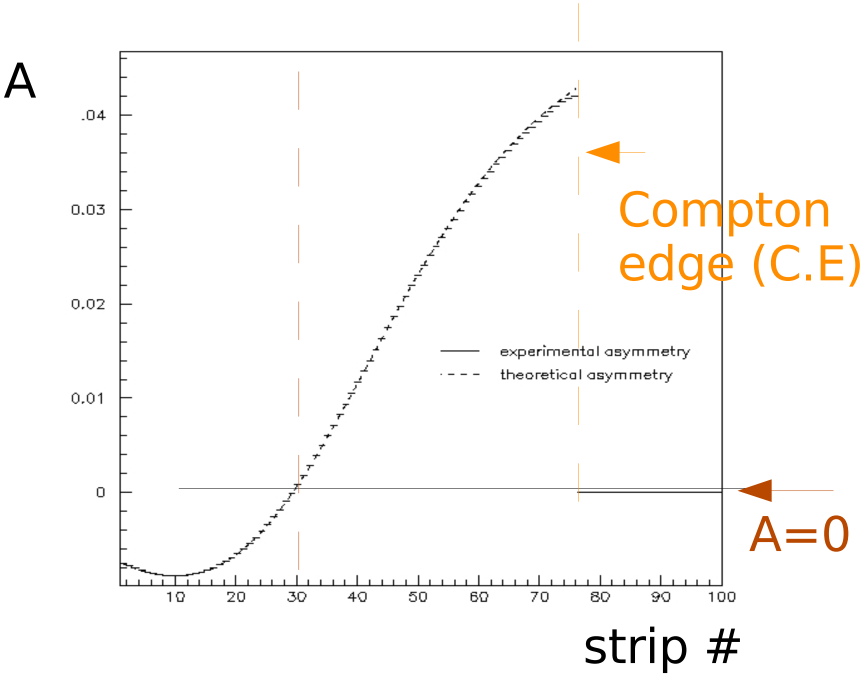
Electron Compton polarimetry





$$A_l = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

$$A_{exp} = \frac{n^+ - n^-}{n^+ + n^-} = P_e P_\gamma A_l$$

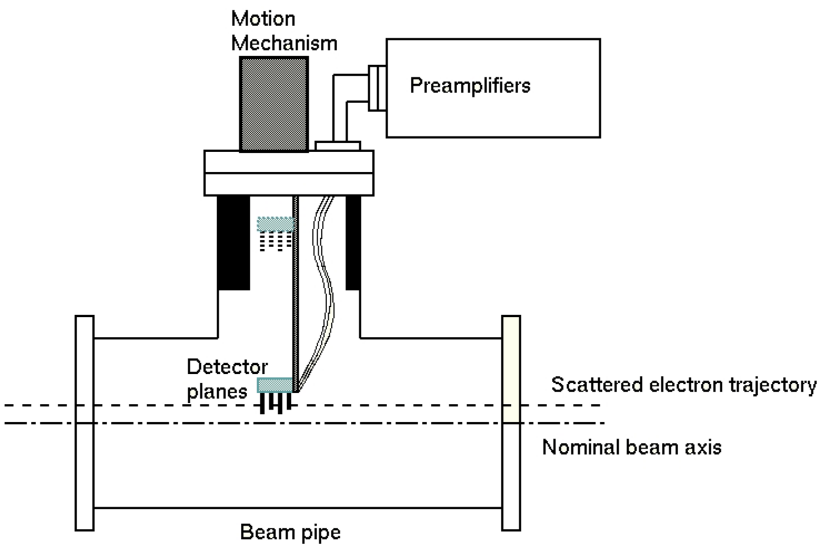


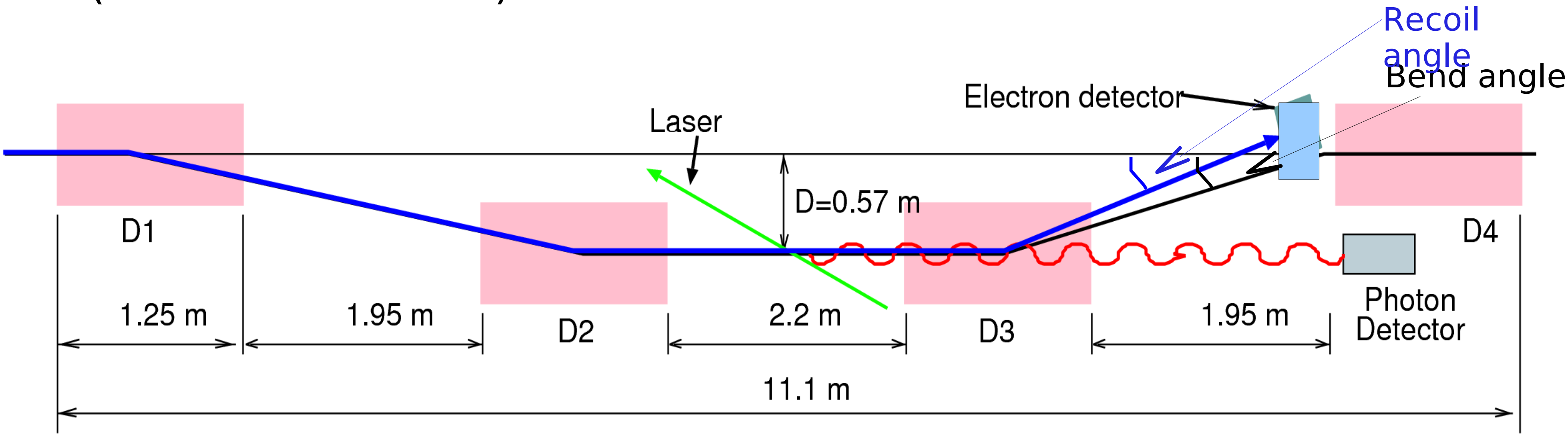
Parameter	Symbol	Value
Beam Energy	E_{beam}	1.165 GeV
Laser wavelength	λ	532 nm
γ Compton edge	k'_{max}	46.4 MeV
Max. asymmetry	A_{max}	0.041
Chicane bend angle	θ_{bend}	10 deg
e- free drift distance	d_{drift}	3.3 m
e- displacement at C.E.	X_{max}	23 mm

Major design goal at low beam energy is to maximize Compton edge

Electron Compton polarimetry

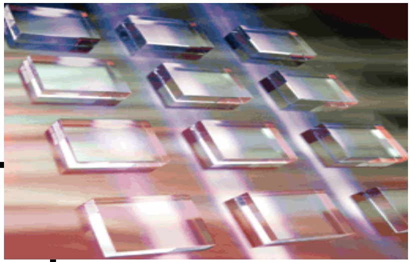
- Continuous, noninvasive, independent single-arm measurement of polarization
- Complementary to Moller (which is periodic and invasive)
- Systemematic uncertainty to be similar to Moller (<1%)
- Position resolution gives momentum of scattered electron (4x100 strips – for momentum analysis)
- Calibration of photon detector (coincidence mode)





side view of dipole chicane

PC-CVD diamond properties



	Silicon	Diamond
Band Gap (eV)	1.12	5.45
Electron/Hole mobility (cm^2/Vs)	1450/500	2200/1600
Saturation velocity (cm/s)	0.8×10^7	2×10^7
Breakdown field (V/m)	3×10^5	2.2×10^7
Dielectric Constant	11.9	5.7
Displacement energy (eV)	13-20	43
e-h creation energy (eV)	3.6	13
Av. e-h pairs per MIP per micron	89	36
Charge collection distance (micron)	full	~250

Low leakage current, shot noise

Fast signal collection

Low capacitance, noise

Rad hardness

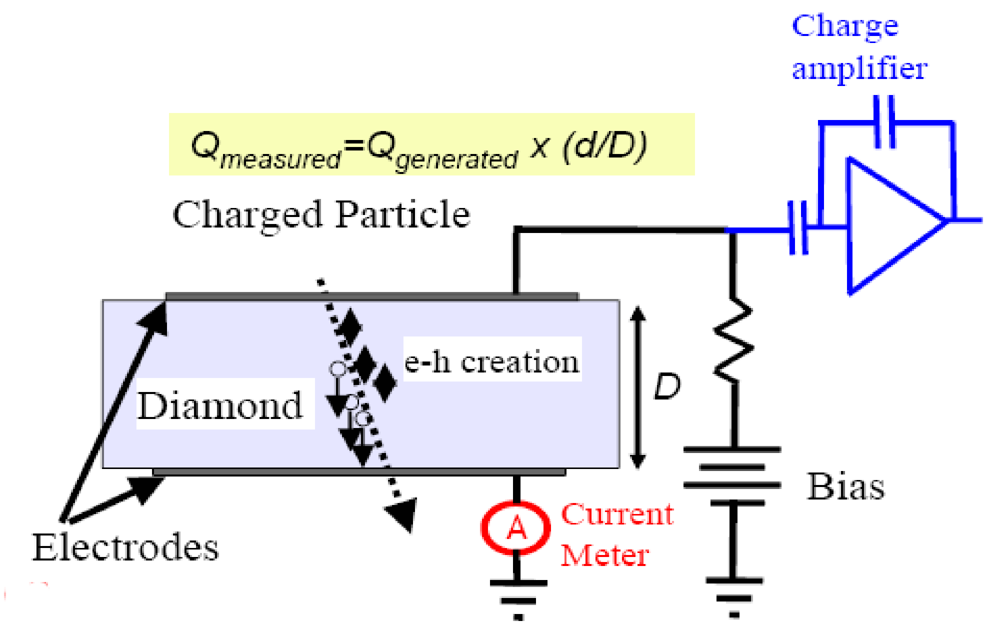
Smaller signal

sc (single crystal) diamonds are available in sizes up to 8 x 8 x 0.5 mm^3
pc (polycrystalline) diamonds are available in huge wafers

- we will use a 20 x 20 x 0.5 mm^3 square pc-CVD diamond

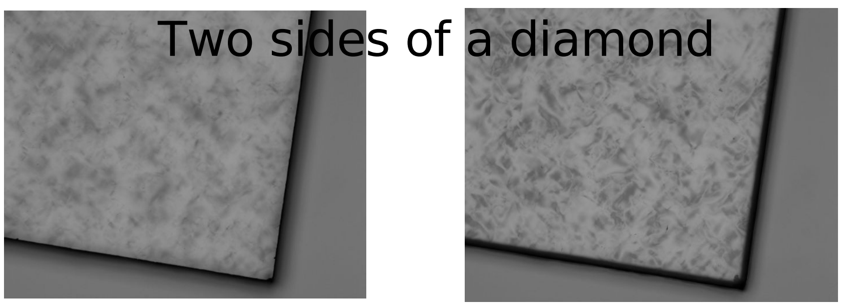
Strip trackers have been developed by CERN RD-42 and others using that thickness, available from Element Six

How a diamond detector works

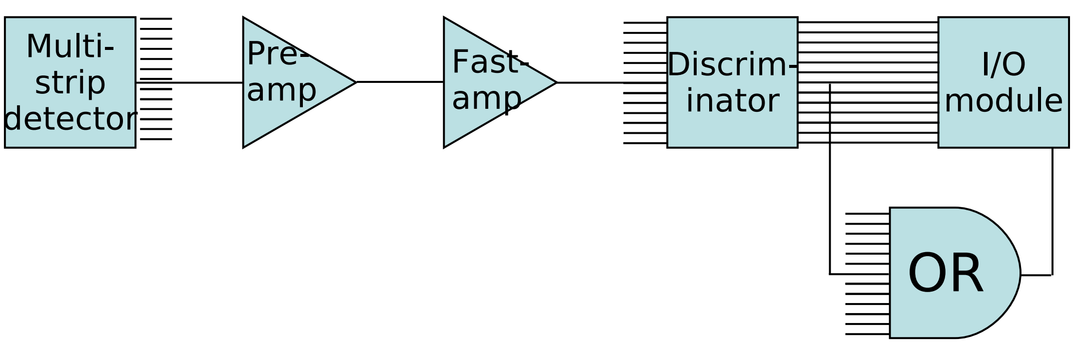


- Signal limited by impurities and grain boundaries
- Increases with E-field up to ~1-2 V/μm
- CCD (“charge collection distance”) ~ 250 μm

Two sides of a diamond



e- detector electronics:



- 4 x 100 strips
- Fast – high rates (~100kHz) expected from Compton Scattering + background
- High Amplification – small signal in diamond ~1/4 Silicon

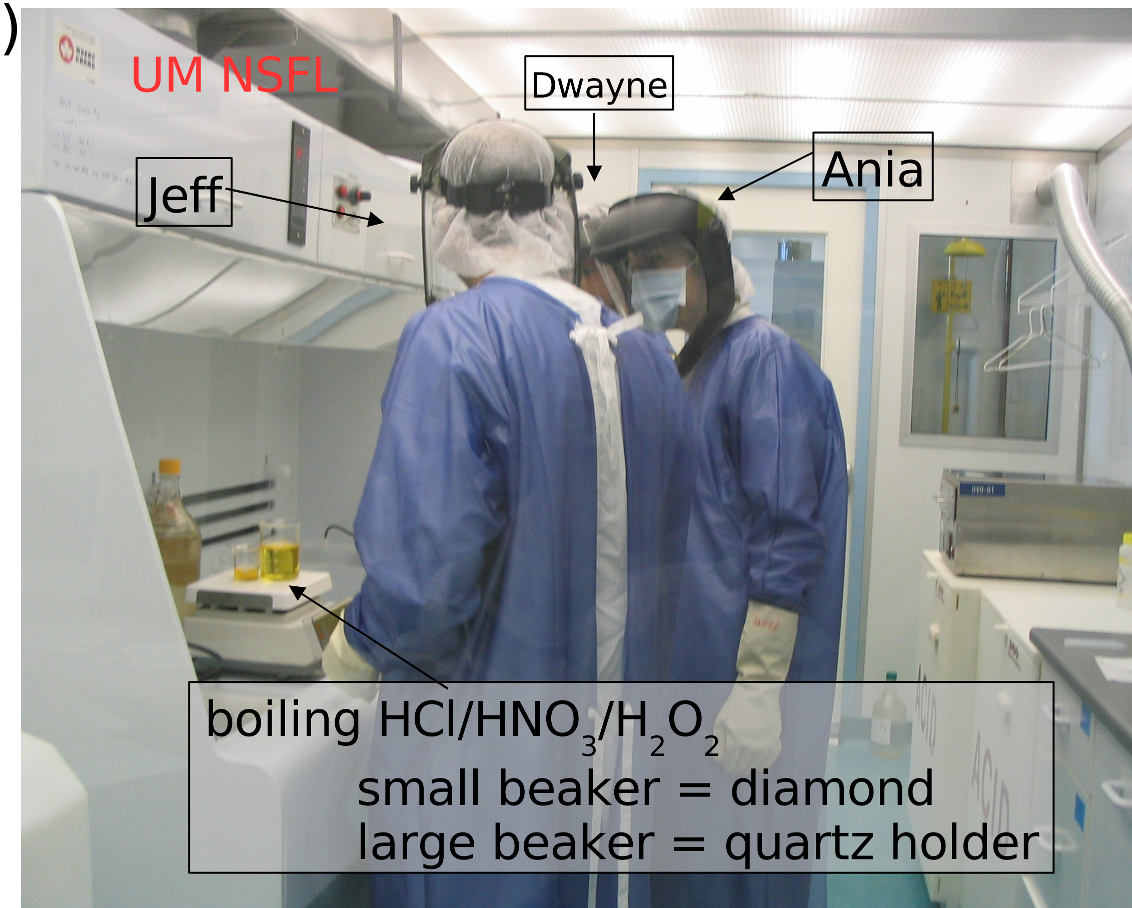
Diamond fabrication process

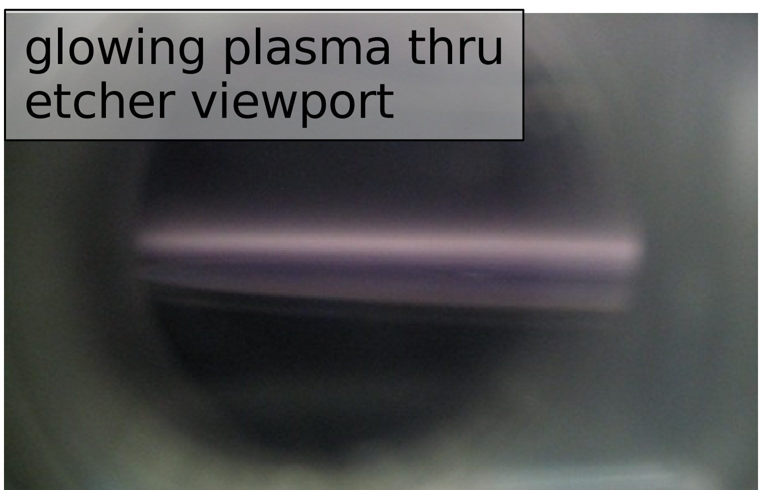
Step1: Purchase 'CERN grade" diamond from elementsix ADVANCING DIAMOND

(10 x 10 x 0.5 mm^3) PC-CVD

Step2: Boil in various acids/bases.

- cleans off the surface
- attempt to replace H-terminated surface with O-terminated (oxidizing agents like H_2O_2)
- follow with low-power plasma etch in O_2 environment

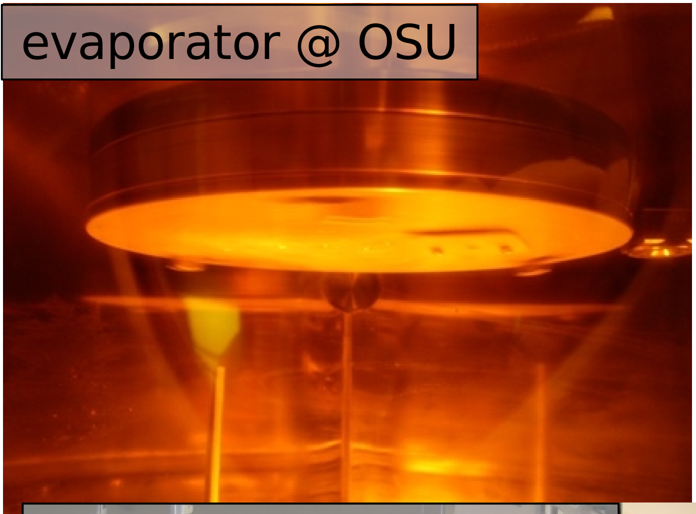


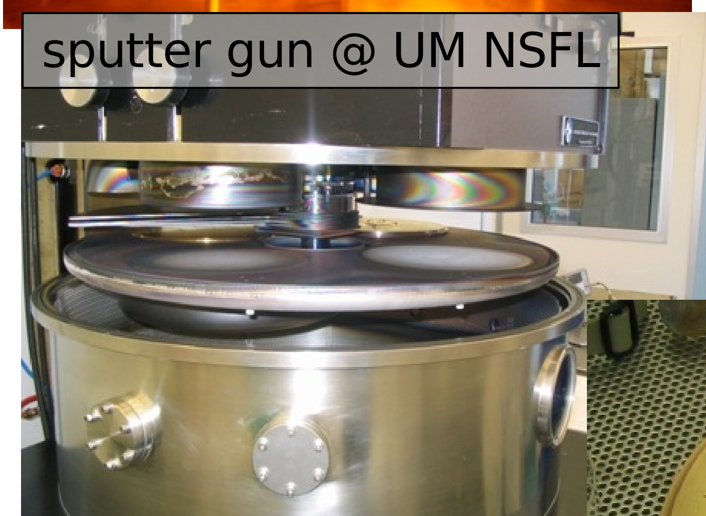


Diamond fabrication process

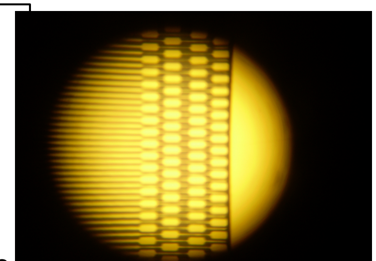
Step3: Lay down metal

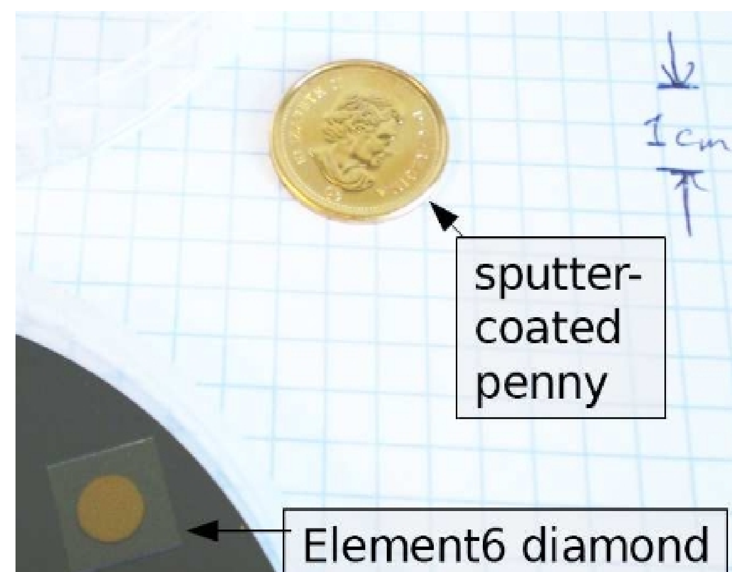
- sputter or evaporate
- test detectors usually done with Cr (50 nm) / Au (200 nm)
- shadow mask used for “dots”
- photolithography (“lift-off”) used for strips.
- OSU procedure: dots, then strips, for <u>every</u> diamond.





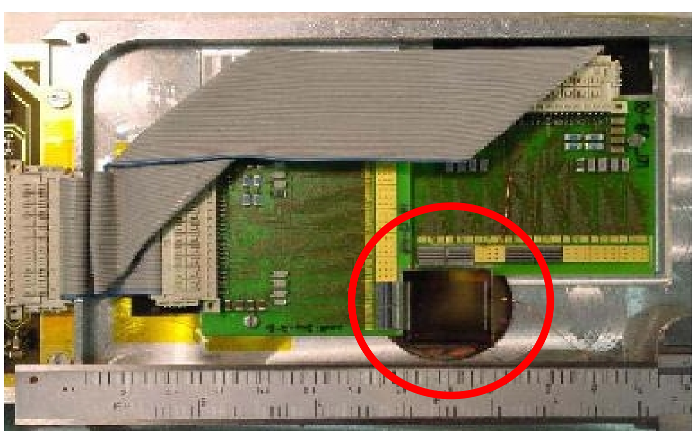
strips on glass @ OSU 50 um pitch





Diamond fabrication process

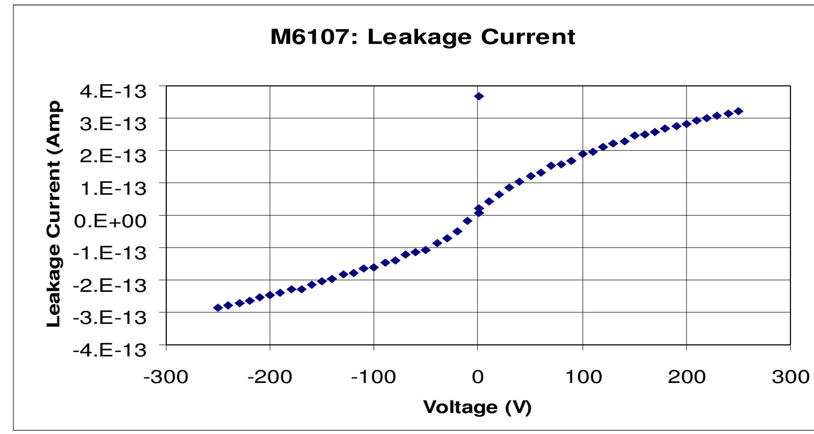
Step4: Mount in a package



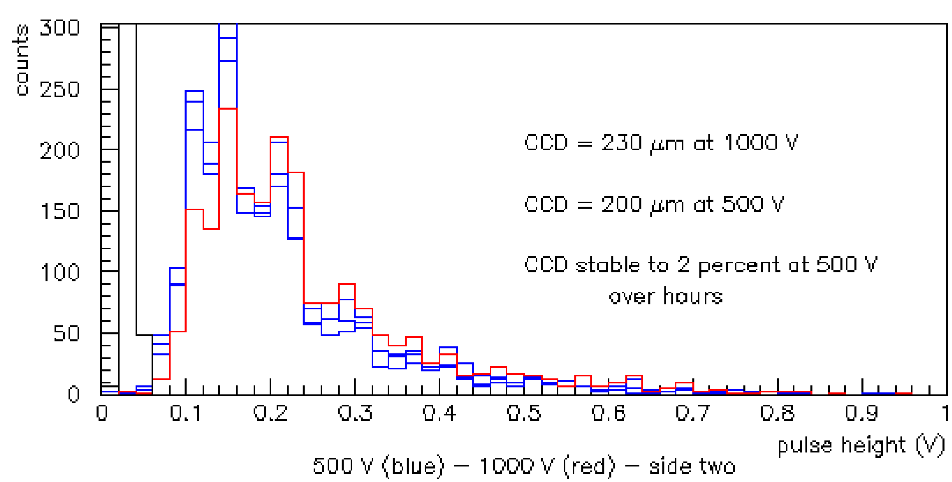
RD42-owned diamond strip tracker with seven planes, 50 um strip pitch.

Step5: Tests

- **Tape**: see if metal comes off with tape
- **I-V curve**: apply Voltage and measure leakage current; typ 1pA for 1000V for 6 mm Φ dots



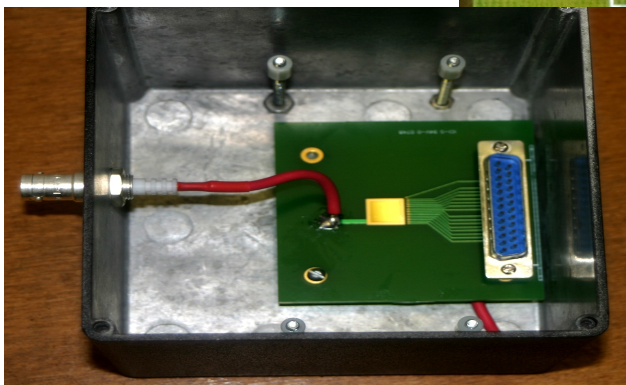
- **CCD measurement**: use ^{90}Sr to find the "charge collection distance" - distance you can pull apart an e-h pair before they are lost to recombination.



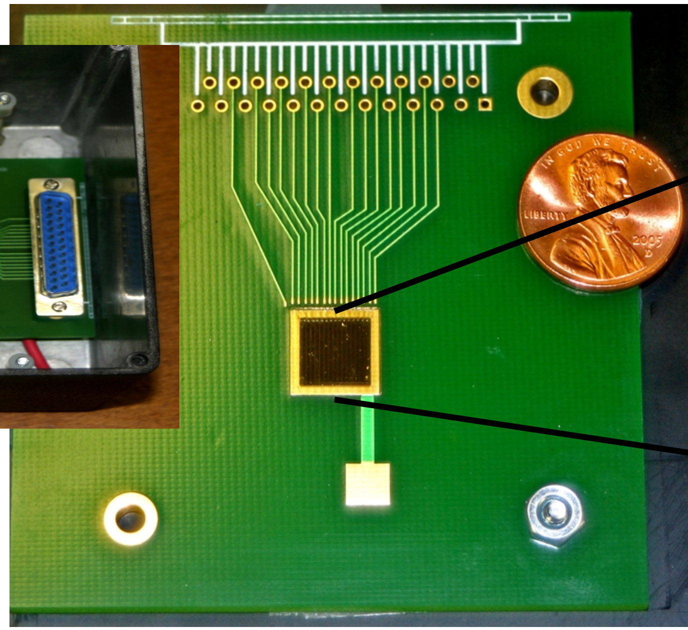
A Prototype Diamond Strip Detector - (MSU)

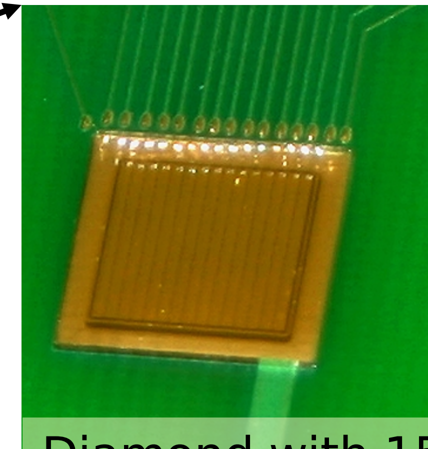
10 x 10 x 0.5 mm³ pc-CVD from Element6

Metalization and Lithography: 15 strips (450μm wide) fabricated at Ohio State University (thanks to Prof. Harris Kagan).

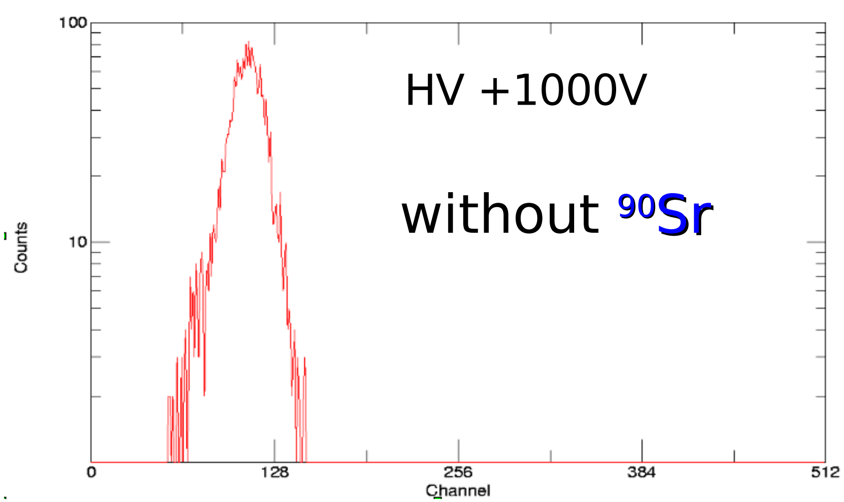


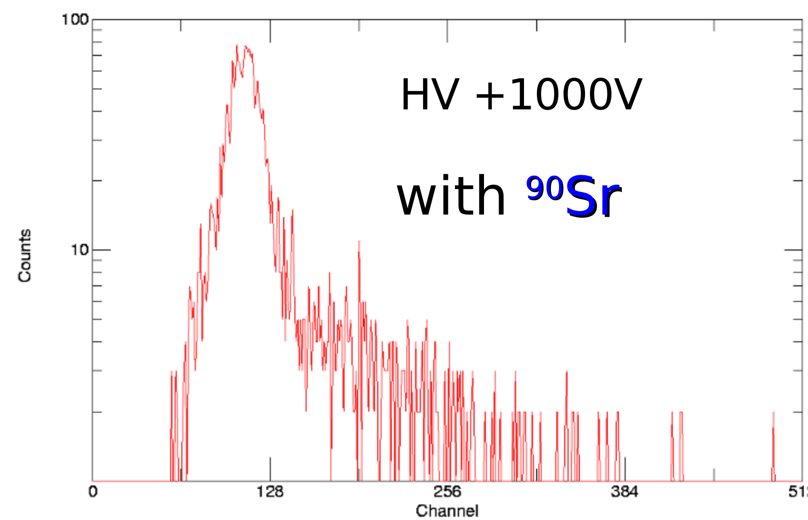
Detector enclosure





Diamond with 15 strips
~450μm strip pitch

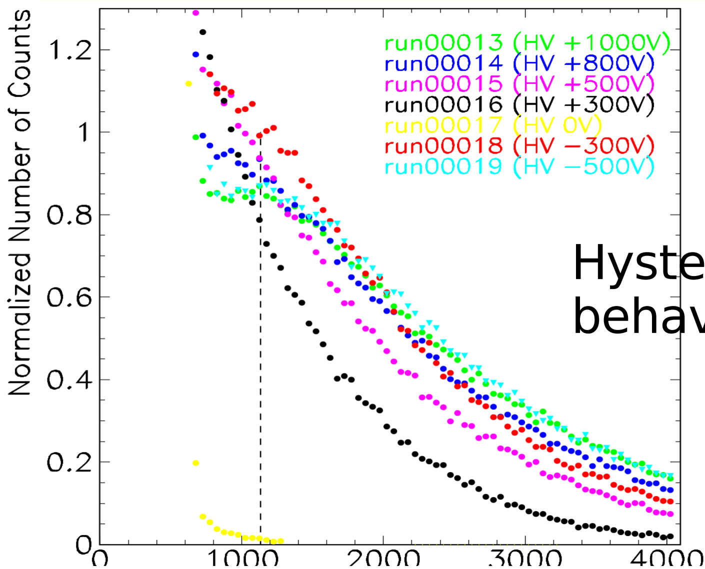




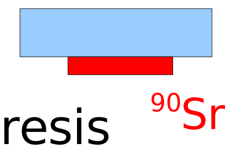
A Prototype Diamond dot Detector - (UW)

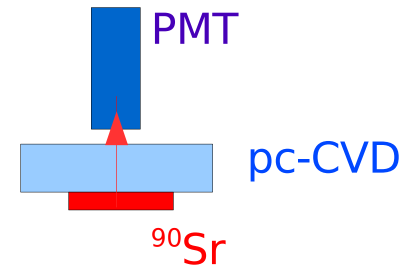
Test results with ^{90}Sr source

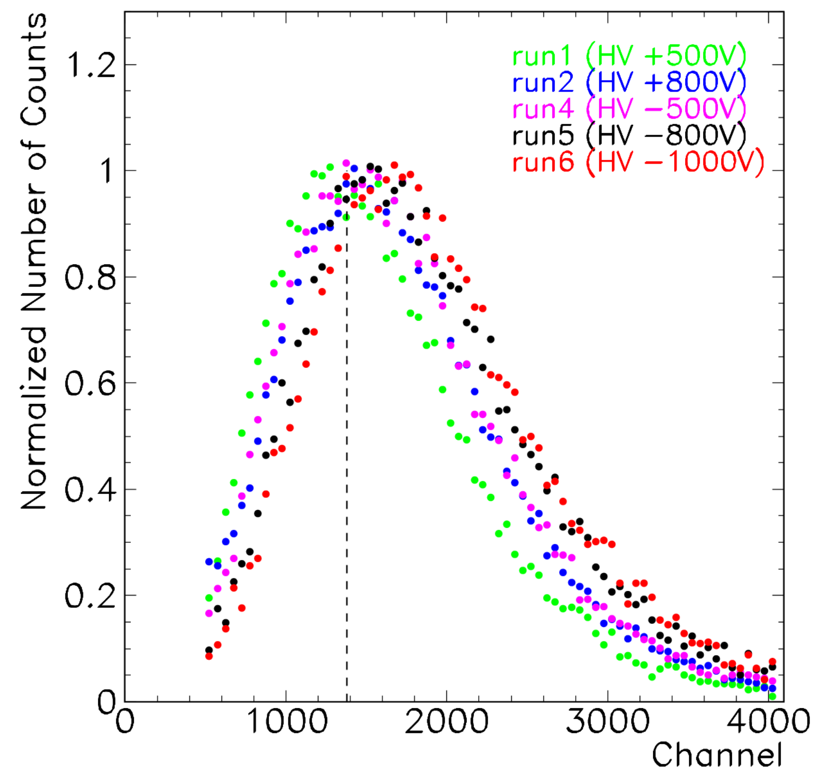
Cr/Au 6 mm dot on both sides of diamond fabricated in Winnipeg at NSFL

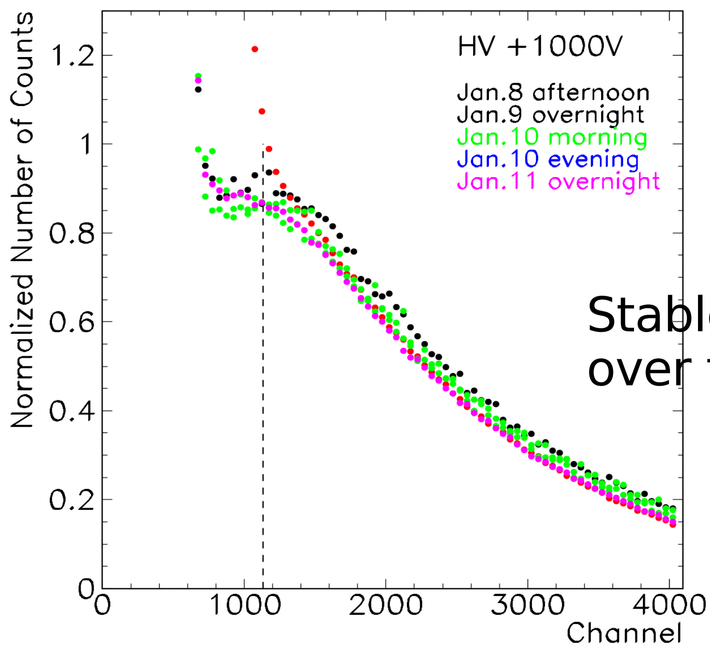


Hysteresis behavior









Stable operation over few days

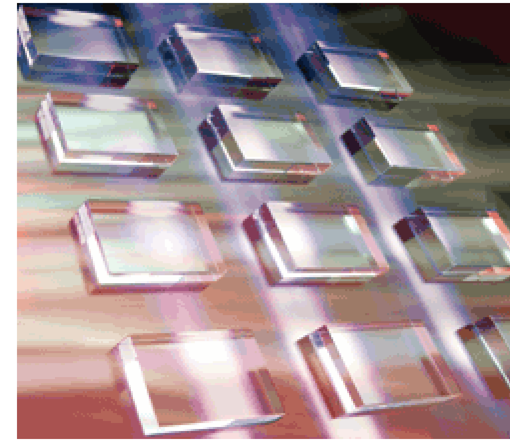
Summary

- Qweak –> PV e+p -> e+p would be:
  - the first measurement of the Q^{p}_{weak}
  - Fundamental measurement of the running of $\sin^2\theta_W$ at low energy
  - A sensitive search for new physics at the TeV Scale
  - To achieve 4% precision of Q^{p}_{weak} (0.3% $\sin^2\theta_W$) systematic needs to be under control
- Measurement of e- beam polarization on a 1 % level
  - Momentum analyzing e- multistrip detector
  - Lower noises and radiation hardness offered by diamond (pCVDD)
  - We learned multi-strip detector fabrication and test procedures (CCD measurement, I-V curve)
  - We successfully fabricated our first working detector
  - Tests of diamond response to e- undergoing
  - Fabrication of multistrip detector at UW undergoing

Extra

Bought "CERN grade diamonds from

elementsix
ADVANCING DIAMOND



Chemical Vapour Deposition (CVD) - method of diamond synthesis that can be compared to frost forming on a window – only the process uses carbon rather than water. A mixture of gases is heated to very high temperatures to produce carbon atoms in the form of a plasma. Out of the gases the diamond crystals can grow on complex, 3D shapes – such as tweeter domes

We bought 10.0 x 10.0 x 0.5 mm CVD diamond

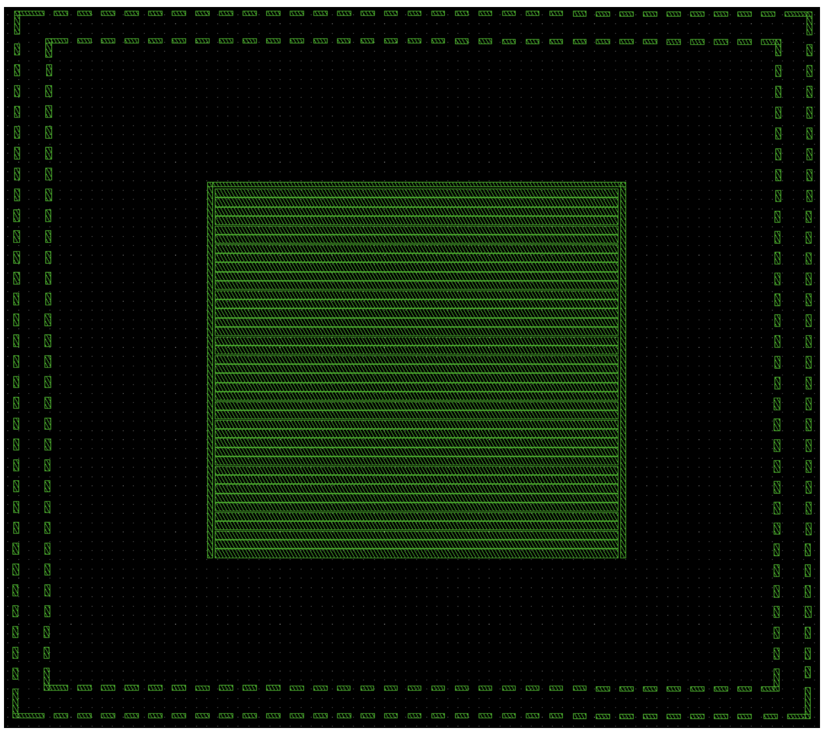
1 for MSU and 1 for Winnipeg

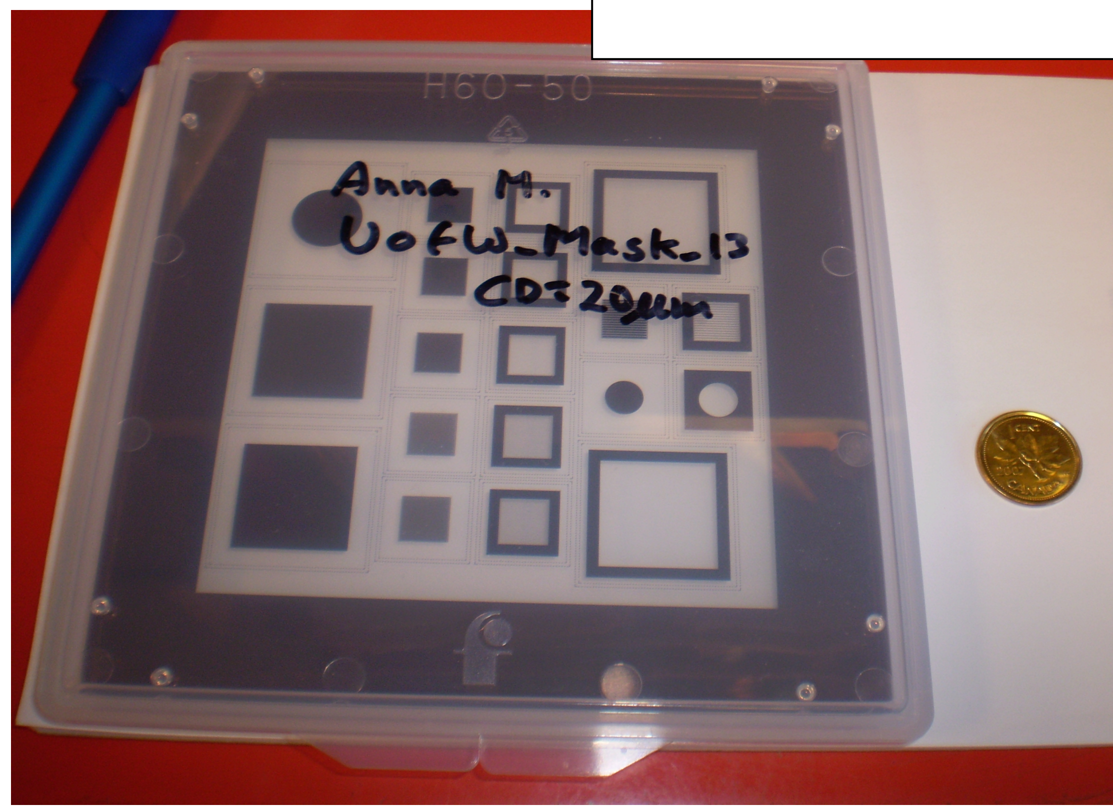
UW Mask design for “lift-off”

Mask 4 x 4 inch^2, drawing made using 'Layout' software

Has positive and negative images with patterns for 10 x 10 mm^2 test diamond sample and for 21 x 21 mm^2 sample

Fabricated at the University of Alberta,





Strip pitch :200um,
Strip width: 180 (150) um

Sensitivity to TeV Scale

- Parameterize New Physics contributions in electron-quark Lagrangian

$$\mathcal{L}^{PV}_{e\text{-}q} = \mathcal{L}^{PV}_{SM} + \mathcal{L}^{PV}_{NEW} = -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e \sum_q C_{1q}\bar{q}\gamma^\mu q + \frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

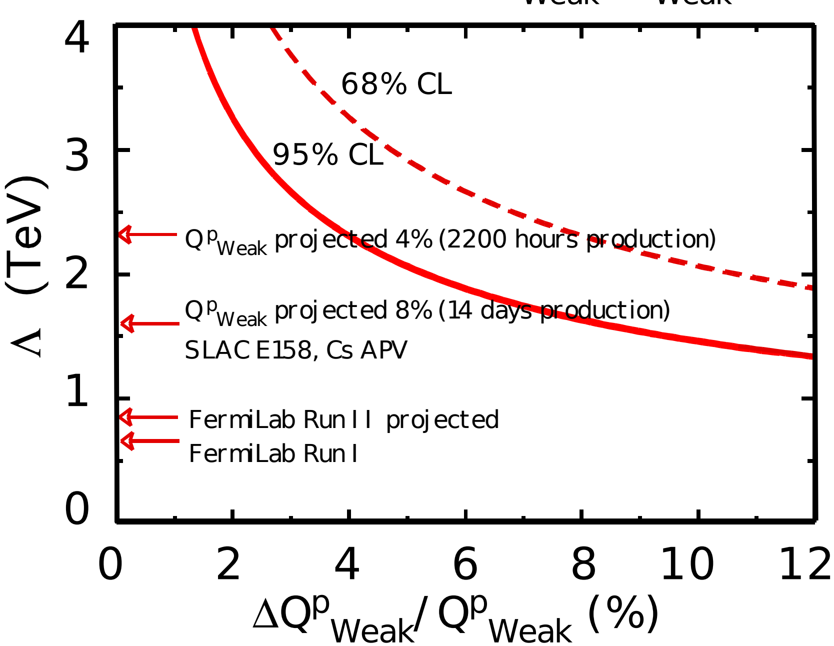
g: coupling constant, Λ: mass scale

- A 4% Q^p_{Weak} measurement probes with 95% confidence level for new physics at energy scales to:

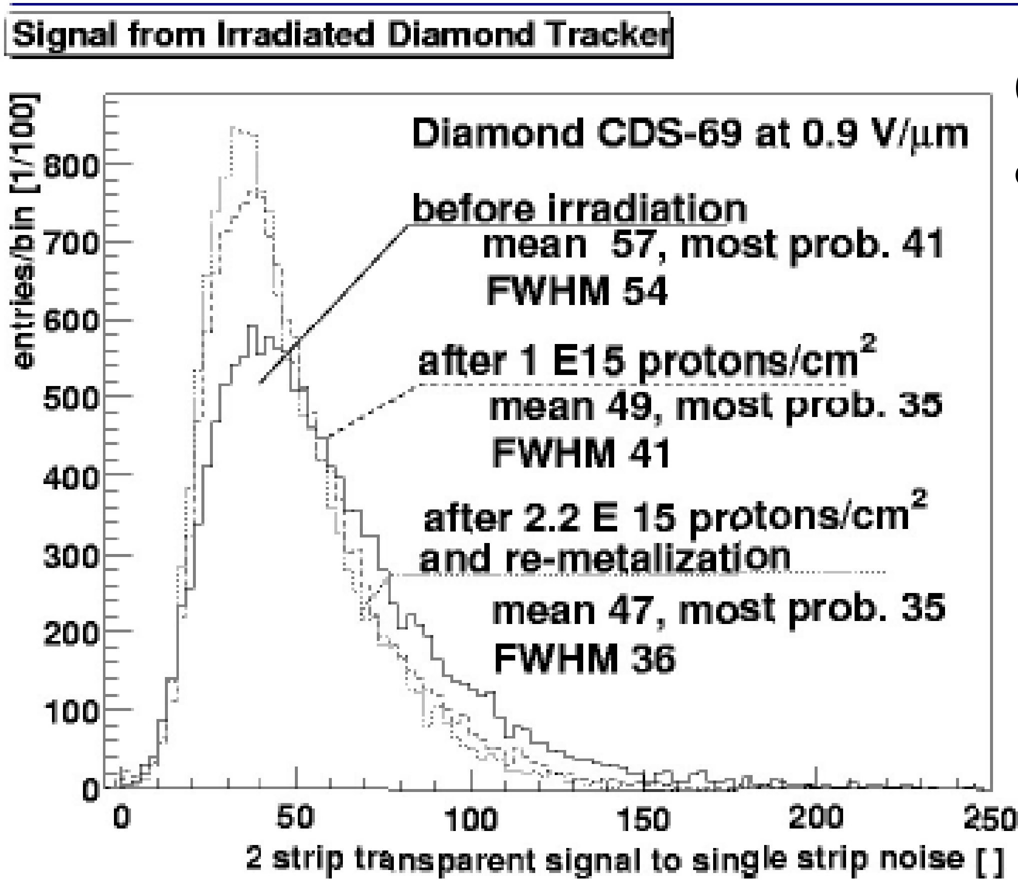
$$\frac{\Lambda}{g} \sim \frac{1}{2\sqrt{\sqrt{2}G_F\left|\Delta Q^p_W\right|}} \approx \boxed{2.3\ \text{TeV}}$$

- If LHC uncovers new physics, then precision low Q^2 measurements will be needed to determine charges, coupling constants, etc.

Mass Sensitivity vs $\Delta Q^p_{Weak}/Q^p_{Weak}$



Radiation Hardness of Diamond Detectors



CERN R&D: Performance after irradiation with protons

- **Little change in S/N after exposure of ~5 Mrad**
- **15% change in S/N after an exposure of ~50 Mrad**

Si 50% change in S/N after exposure of ~3 Mrad.

Thanks R. Wallny (UCLA)

Estimate for Qweak alone: 3 Mrad

Design Goals

- $\left(\Delta \mathrm{P/P}\right)_{\mathrm{statistical}} < 1\%$ per hour
  - high laser power
  - high laser energy (green) increases Compton asym.
  - large acceptance for detectors (in energy)
- $\left(\Delta \mathrm{P/P}\right)_{\mathrm{systematic}} < 1\%$
  - stable beam, small spot in interaction region
  - low backgrounds
  - good energy resolution in detectors
  - high laser energy increases Compton edge

Design Goals Cont'd

- Operable for a variety of beam energies from 1.165 GeV – 11.0 GeV
  - chicane
  - must fit in Hall C

Most design studies currently focused on achieving 1% for Qweak experiment: 1.165 GeV @ 180 uA

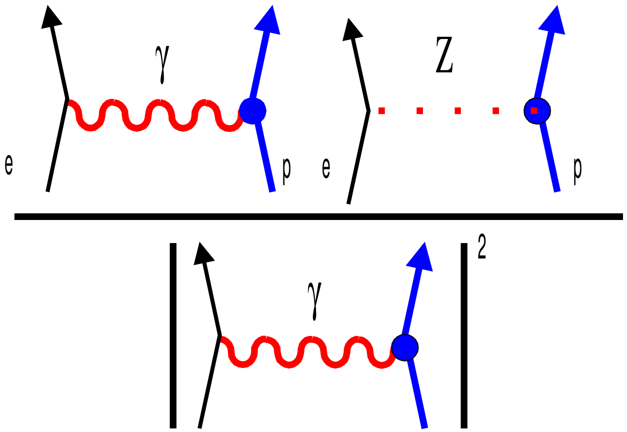
Summary of PV Electron Scattering Experiments

Lab/Expt	target	Q^2 GeV^2	A_{phys} ppm	Sensitivity	Status
MIT-Bates					
- SAMPLE	H_2	0.10	8.0	$\mu_s + 0.4 G_A^Z$	published
- SAMPLE-II	D_2	0.10	8.0	$\mu_s + 2.0 G_A^Z$	published
- SAMPLE-III	D_2	0.04	3.0	$\mu_s + 3.0 G_A^Z$	published
JLab Hall A					
-HAPPEX	H_2	0.47	15.0	$G_E^s + 0.39 G_M^s$	published
-HAPPEXII	H_2	0.11	1.5	$\rho_s + \mu_p \mu_s$	publishing,
-Helium-4	^4He	0.11	10.0	ρ_s	running
-Helium-4	^4He	0.60	50.0	G_E^s	running
-Lead-208	^{208}Pb	0.01	0.5	neutron skin	2006
Mainz					
- A4	H_2, D_2	0.1-0.25	1.0-10.0	G_E^s , G_M^s	published x2, running
Jlab Hall C					
- G0	H_2, D_2	0.1-1.0	1.0-30.0	G_E^s , G_M^s	publishing,
- Qweak	H_2	0.03	0.3	Qw	2008
SLAC					
- E158	H_2	0.02	0.2	Qw	published

K. Kumar

Parity Violating Asymmetry

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right] \frac{A_E + A_M + A_A}{\varepsilon(G_E^p)^2 + \tau(G_M^p)^2}$$



Where:

$$A_E = \varepsilon(\theta) G_E^Z(Q^2) G_E^\gamma(Q^2) \longrightarrow G_E^s \quad \textbf{forward ep}$$

$$A_M = \tau(Q^2) G_M^Z(Q^2) G_M^\gamma(Q^2) \longrightarrow G_M^s \quad \textbf{backward ep}$$

$$A_A = -(1 - 4\sin^2\theta_W)\varepsilon' G_A^e(Q^2) G_M^\gamma(Q^2) \longrightarrow G_A^e \quad \textbf{backward ed}$$

$$\tau = \frac{Q^2}{4M^2}$$

$$\varepsilon = \left[1 + 2(1+\tau)\tan^2\left(\tfrac{\theta}{2}\right)\right]^{-1}$$

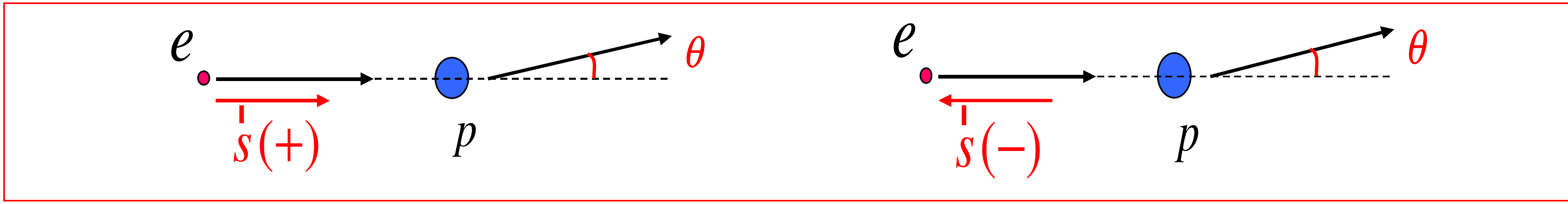
$$\varepsilon' = \sqrt{(1-\varepsilon^2)\tau(1+\tau)}$$

kinematical factors

Note: Asymmetry is of order ppm

Q^p_{weak}: Parity-Violating in elastic electron-proton scattering

Scatter longitudinally polarized electrons on unpolarized protons



$$A_{LR}(\vec{e},p) \quad = \quad \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R} = k(A_{Q^p_W} + A_{H,V} + A_{H,A})$$

Quantity of interest = -0.288 ppm

$$A_{Q^p_W} \quad = \quad Q^2 Q^p_W$$

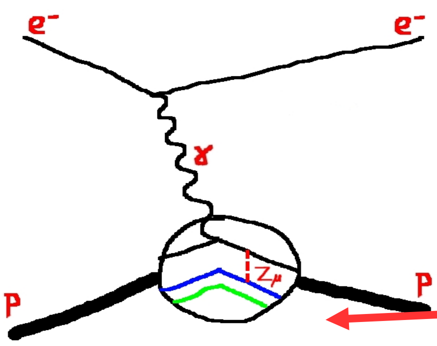
$$A_{H,V} \quad = \quad Q^n_W \frac{\epsilon G_E^{p,\gamma} G_E^{n,\gamma} + \tau G_M^{p,\gamma} G_M^{n,\gamma}}{\epsilon \left(G_E^{p,\gamma}\right)^2 + \tau \left(G_M^{p,\gamma}\right)^2} + Q^s_W \frac{\epsilon G_E^{p,\gamma} G_E^{s} + \tau G_M^{p,\gamma} G_M^{s}}{\epsilon \left(G_E^{p,\gamma}\right)^2 + \tau \left(G_M^{p,\gamma}\right)^2}$$

$$A_{H,A} \quad = \quad Q^e_W \frac{\epsilon' G_A^{p,Z} G_M^{p,\gamma}}{\epsilon \left(G_E^{p,\gamma}\right)^2 + \tau \left(G_M^{p,\gamma}\right)^2}$$

Well constraint from world data: HAPPEX, G0, A4, and many others

***$A_{H,V}$* ~ -0.101 ppm**

***$A_{H,A}$* ~ -0.012 ppm**



$$G_A^{p,Z}$$

Axial form factor

due to

q-q weak interaction

Electron Compton polarimetry

- Position resolution gives momentum of scattered electron (4x100 strips – for momentum analysis)
- Independent single-arm measurement of polarization
- Calibration of photon detector (coincidence mode)
- Design for 1% polarization determination for BOTH detectors

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