An Ultra-precise Measurement of the Weak Mixing Angle in Møller Scattering with a 11 GeV Beam at Jefferson Laboratory

Krishna Kumar, UMass Amherst

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Outline

- *Beyond the Standard Model at Low Energy*
- *Parity-Violating Møller Scattering*
- *SLAC E158 Result*
- *A New Ultra-Precise Measurement proposed at Jefferson Laboratory after the Upgrade*

Worldwide Experimental Thrust in the 2010s: New Physics Searches

Compelling arguments for "New Dynamics" at the TeV Scale

A comprehensive search for clues requires:

Large Hadron Collider ***as well as*** **Low Energy: $Q^2 \ll M_Z^2$**

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- ***Neutrino mass and mixing*** $0\nu\beta\beta$ *decay*, θ_{13}, β *decay, long baseline neutrino expts*
- ***Rare or Forbidden Processes*** *EDMs, charged LFV,* $0\nu\beta\beta$ *decay*
- ***Dark Matter Searches***
- ***Low Energy Precision Electroweak Measurements:***

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Complementary signatures to decipher LHC new physics signals

- ***Neutrons:*** *Lifetime, Asymmetries (LANSCE, NIST, SNS...)*
- ***Muons:*** *Lifetime, Michel parameters, g-2 (BNL, PSI, TRIUMF, FNAL, J-PARC...)*
- ***Parity-Violating Electron Scattering*** *Low energy weak neutral current couplings, precision weak mixing angle (SLAC, JLab)*

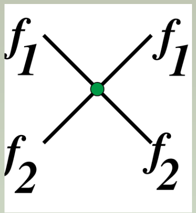
Comprehensive Search for New Neutral Current Interactions

Important component of indirect signatures of "new physics"

Many new physics models give rise to neutral 'contact' (4-Fermi) interactions:
Heavy Z's, compositeness, extra dimensions…

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

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



Λ's for all $f_1 f_2$ combinations and L,R combinations

Eichten, Lane and Peskin, PRL50 (1983)

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

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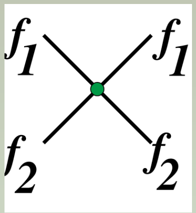

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LEPII, Tevatron access scales Λ's ~ 10 TeV

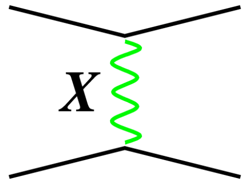
e.g. Tevatron dilepton spectra, fermion pair production at LEPII

- L,R combinations accessed are parity-conserving

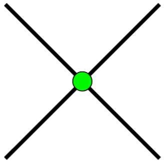
LEPI, SLC, LEPII & HERA accessed some parity-violating combinations but precision dominated by Z resonance measurements

Colliders vs Low Q^2

consider



$$A_X \propto \frac{1}{Q^2 - M_X^2} \longrightarrow$$



Contact interaction

$$\sim \frac{4\pi}{\Lambda^2}$$

$Q^2 \sim M_Z^2$ on resonance: A_Z imaginary $\longrightarrow A_Z^2 \left[1 + \frac{A_X^2}{A_Z^2}\right]$

no interference!

Consider known weak neutral current interactions mediated by Z Bosons

$$\frac{\delta A_Z}{A_Z} \propto \frac{\pi/\Lambda^2}{g\, G_F} \longrightarrow$$

$\delta(g)/g \sim 0.1$

$\Lambda \sim 10$ TeV

$$\frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \lesssim 0.01$$

Window of opportunity for weak neutral current measurements at $Q^2 << M_Z^2$

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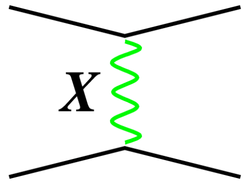

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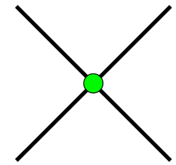

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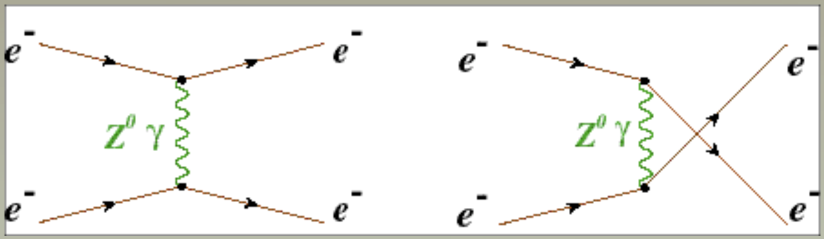
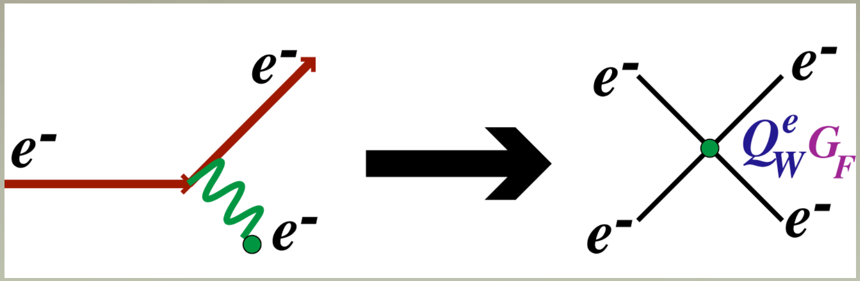
Processes with potential sensitivity:

- *neutrino-nucleon deep inelastic scattering* — *NuTeV at Fermilab*
- *Atomic parity violation (APV)* — *^{133}Cs at Boulder*
- *parity-violating electron scattering* — *E158, Qweak, PVDIS*

Møller Scattering





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Purely leptonic reaction

$$A_{PV} = -mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{2y(1-y)}{1+y^4+(1-y)^4}Q_W^e$$

Derman and Marciano (1978)

$$A_{PV} \propto m_e E_{lab}(1-4\sin^2\vartheta_W)$$

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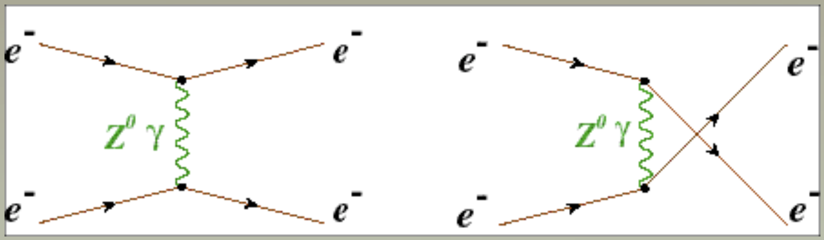

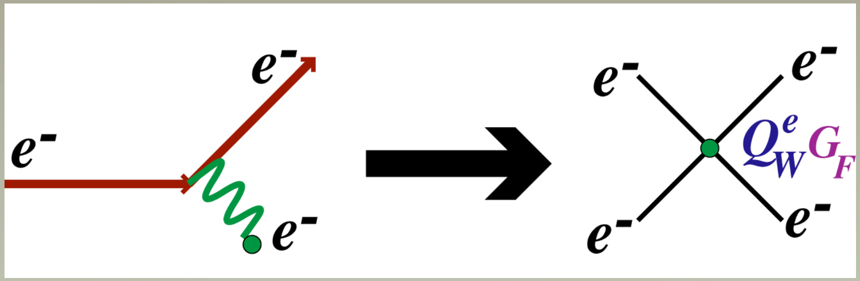

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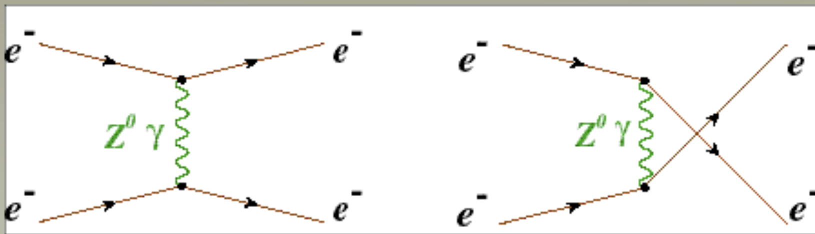

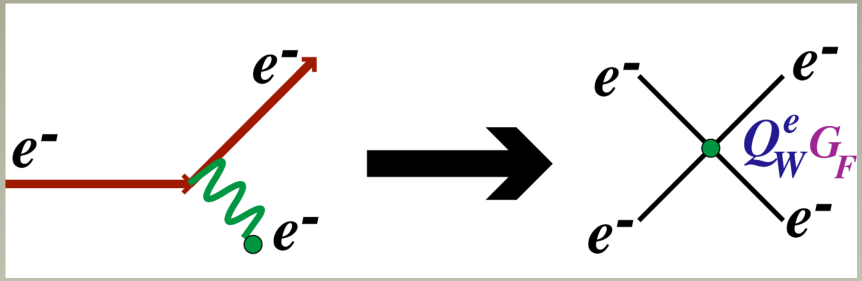

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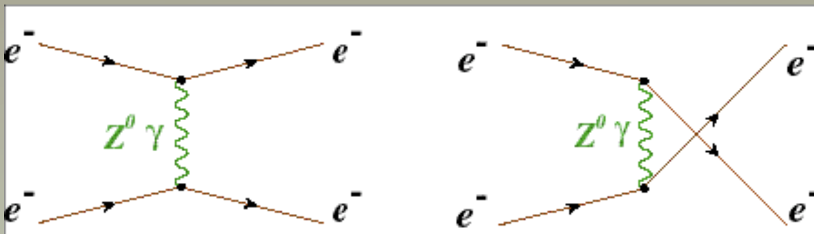

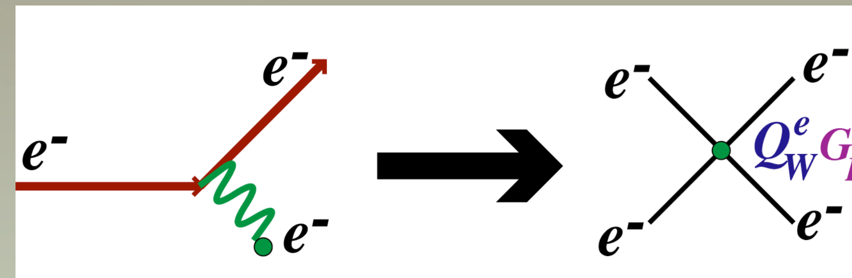

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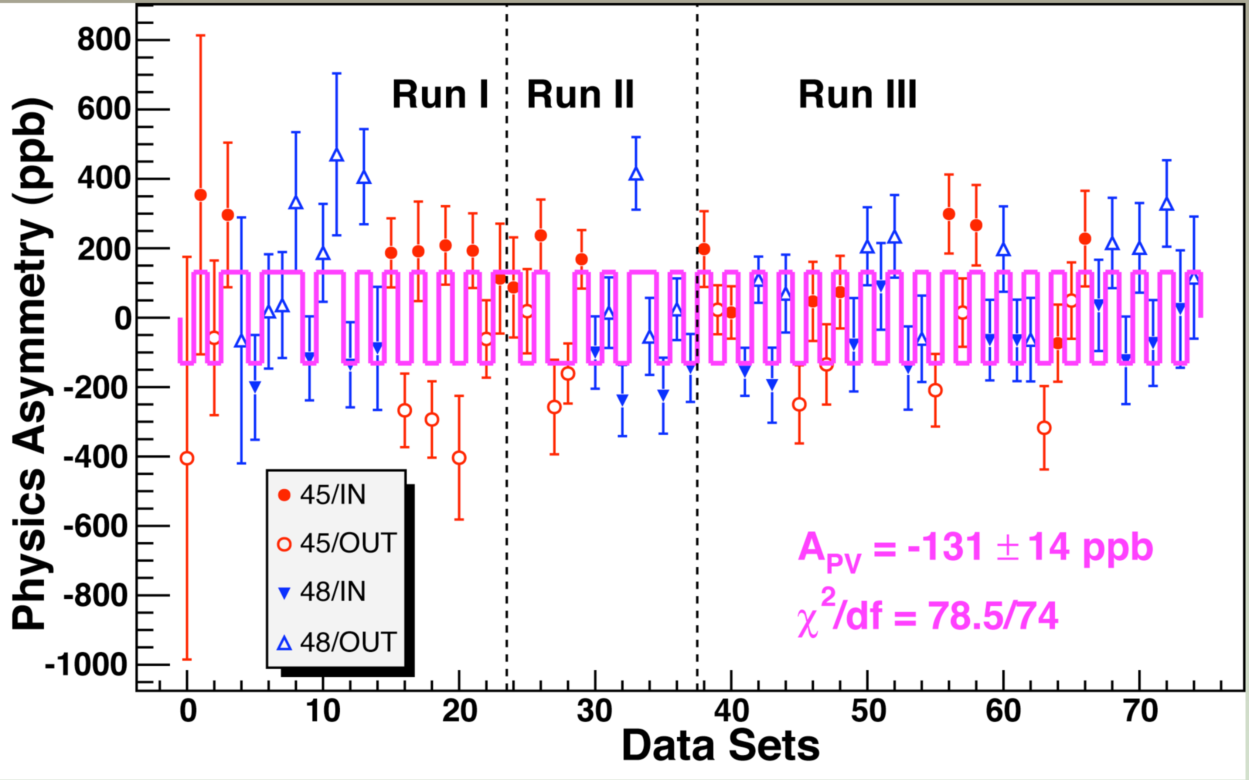
SLAC: Highest beam energy with moderate polarized luminosity

JLab 11 GeV: Moderate beam energy with LARGE polarized luminosity

SLAC E158 Result



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

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

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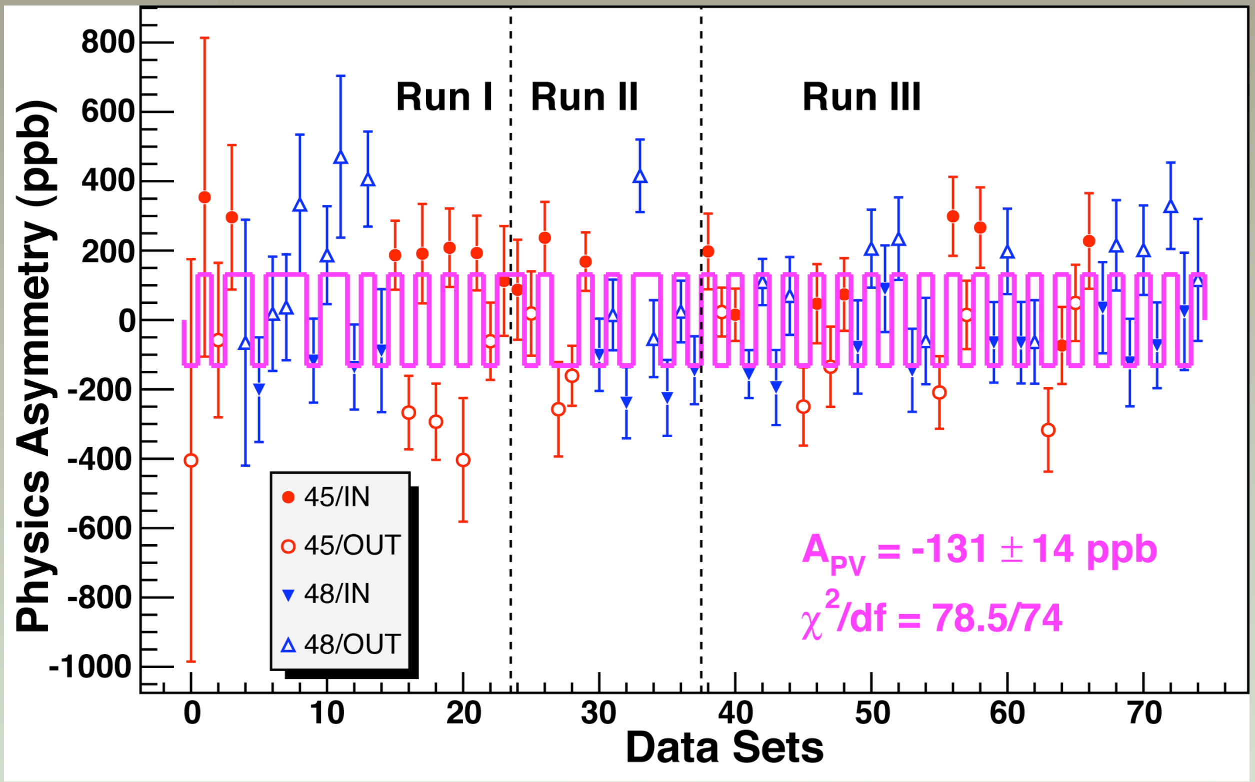

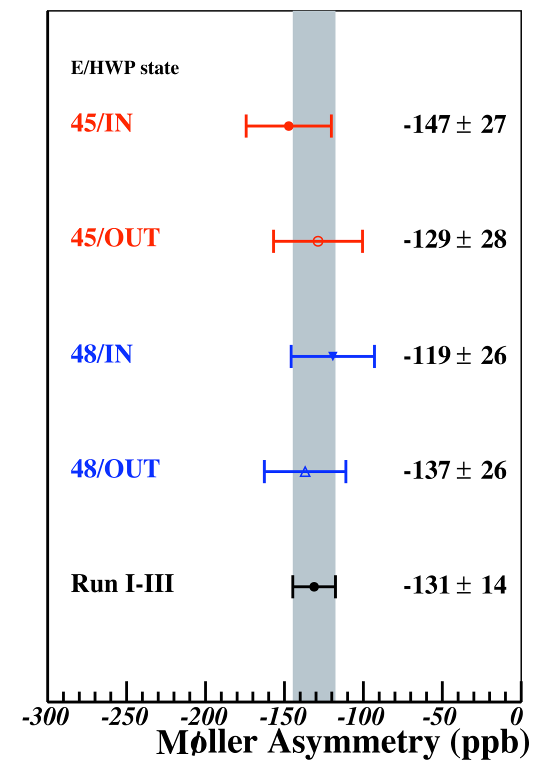

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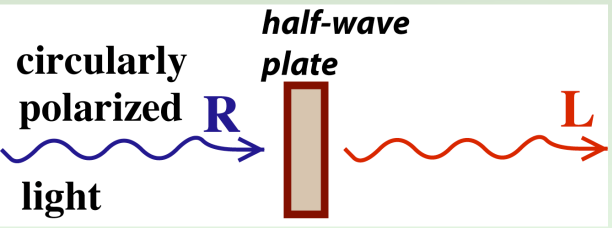
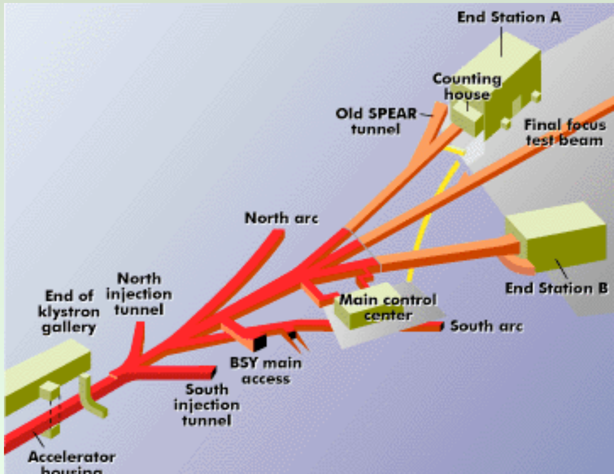


g-2 spin precession

45 GeV: 14.0 revs

48 GeV: 14.5 revs



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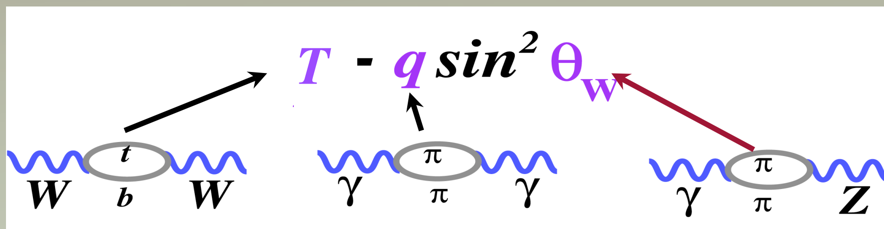
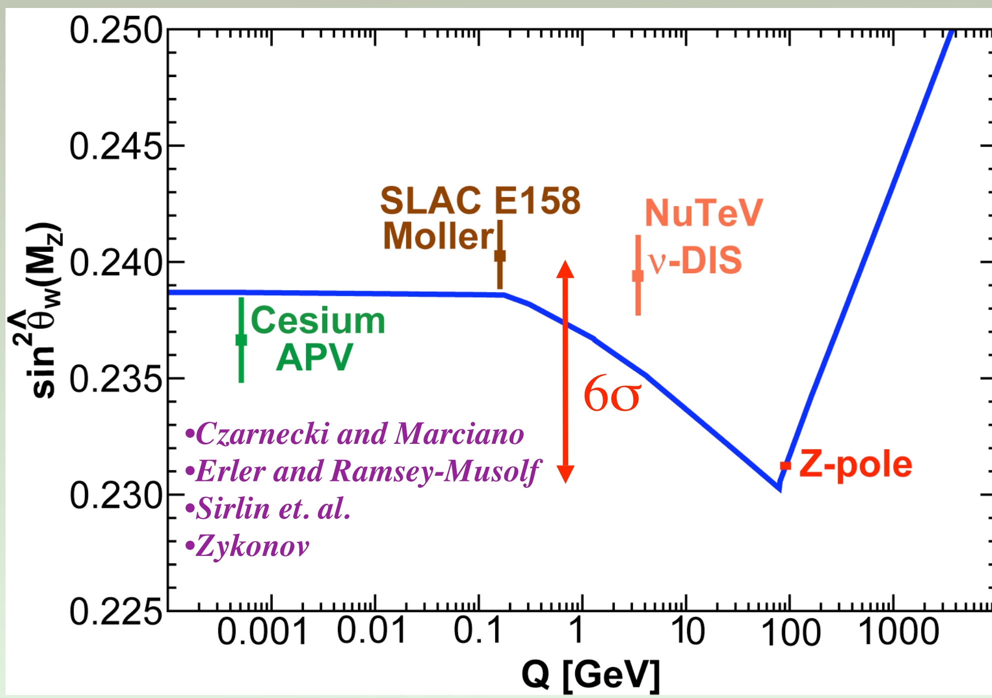
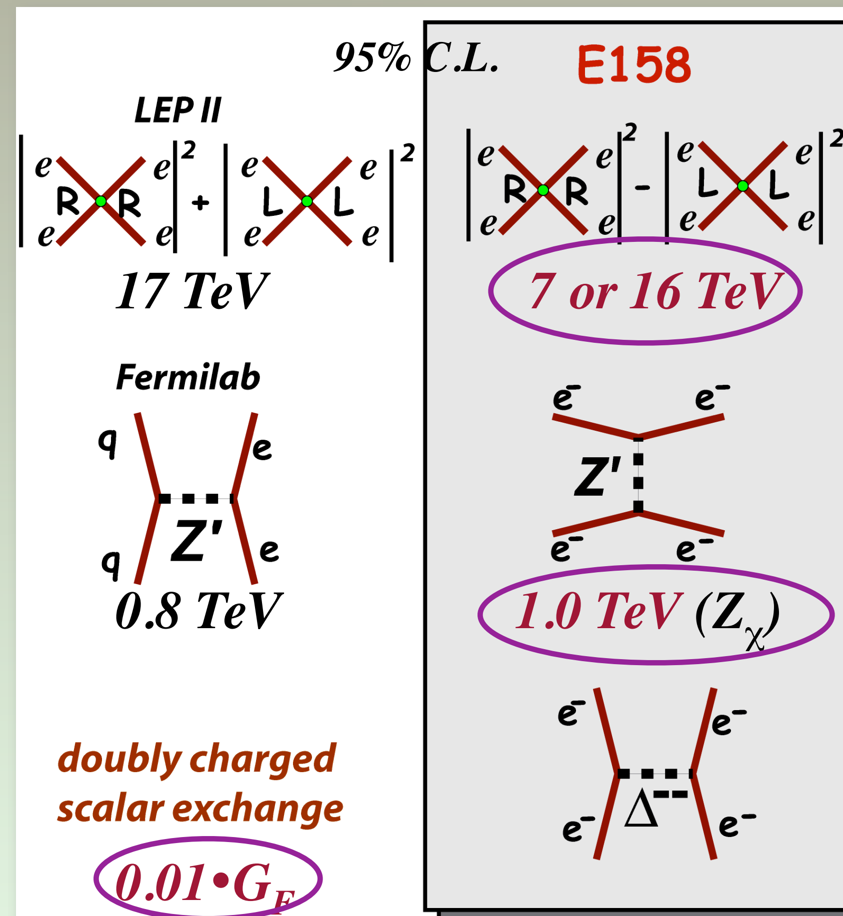
SLAC E158 Implications

Running of $\sin^2\theta_W$ established to 6σ





Limits on "New" Physics



New Opportunity

A new proposal at Jefferson Laboratory after the 12 GeV Upgrade

~ 100 authors from ~ 30 institutions

experienced from challenging, ongoing PV program

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Let us build the parity dream team!

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E_{beam} = 11 GeV   75 μA   80% polarized → ~ 38 weeks (~ 2 yrs) → $\delta(A_{PV})$ = 0.73 ppb

A_{PV} = 35.6 ppb → $\delta(Q^e_W) = \pm\ 2.1$ (stat.) ± 1.0 (syst.) %

$\delta(\sin^2\theta_W) = \pm\ 0.00026$ (stat.) ± 0.00012 (syst.) → ~ 0.1%

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Compelling opportunity with the Jefferson Lab Energy Upgrade:

- Comparable to the two best measurements at colliders
- Unmatched by any other project in the foreseeable future
- At this level, one-loop effects from "heavy" physics

Unprecedented 4-Lepton Sensitivity

The moment one adds "new physics", $\sin^2\theta_W$ becomes process-dependent (initial and final state fermion type)

Further, with contact interactions, one needs several measurements of different processes off the Z resonance

$$\mathcal{L}_{e_1e_2} = \sum_{\mathbf{i,j=L,R}} \frac{\mathbf{g_{ij}^2}}{\mathbf{2\Lambda^2}} \bar{\mathbf{e}}_\mathbf{i}\gamma_\mu \mathbf{e_i}\bar{\mathbf{e}}_\mathbf{j}\gamma^\mu \mathbf{e_j} \quad \xrightarrow{A_{PV}} \quad \frac{\mathbf{\Lambda}}{\sqrt{|\mathbf{g_{RR}^2 - g_{LL}^2}|}} = \mathbf{7.5}\ \mathrm{TeV}$$

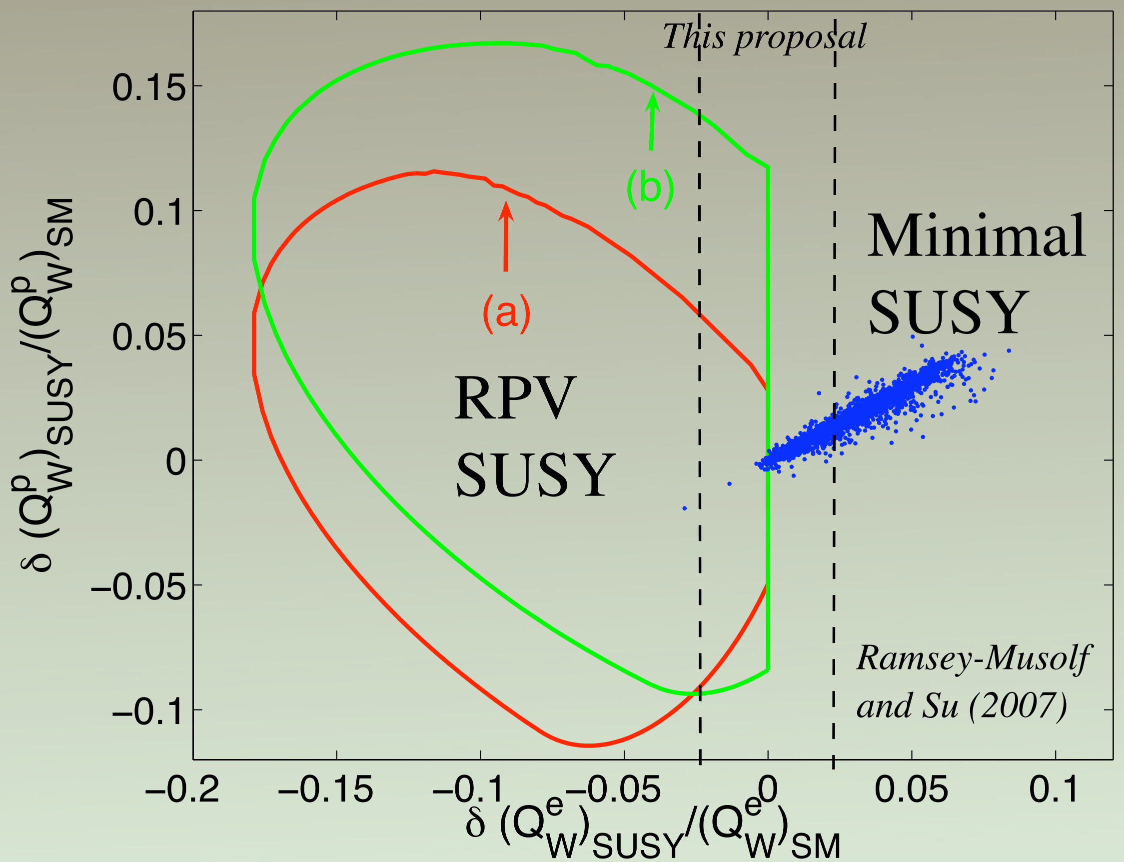
Best current limits on 4-electron contact interactions: LEPII at 200 GeV

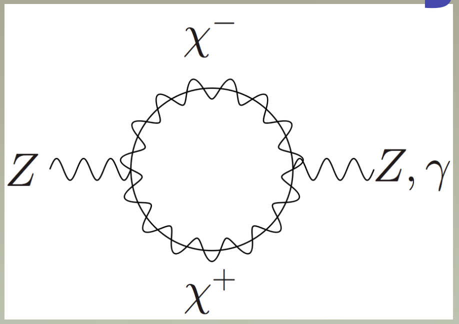
(Average of all 4 LEP experiments)

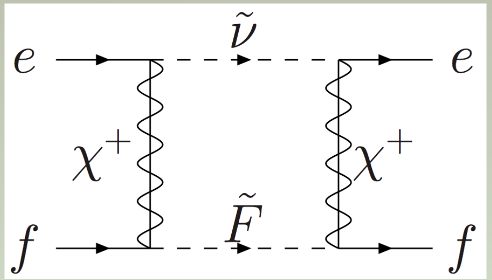
$$\frac{\mathbf{\Lambda}}{\sqrt{|\mathbf{g_{RR}^2 + g_{LL}^2}|}} = \mathbf{4.4}\ \mathrm{TeV} \quad \text{OR} \quad \frac{\mathbf{\Lambda}}{\mathbf{g_{RL}}} = \mathbf{5.2}\ \mathrm{TeV}$$

insensitive to $|\mathbf{g_{RR}^2 - g_{LL}^2}|$

Example I: Supersymmetry







MSSM sensitivity if light super-partners, large tanβ

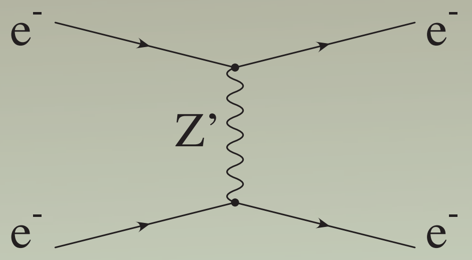
$$P_R = (-1)^{3(B-L)+2s}$$

Does Supersymmetry provide a candidate for dark matter?

- B and/or L need not be conserved (RPV): neutralino decay
  - neutralino then no longer viable dark matter candidate
- Qweak and PVDIS are additional complementary measurements

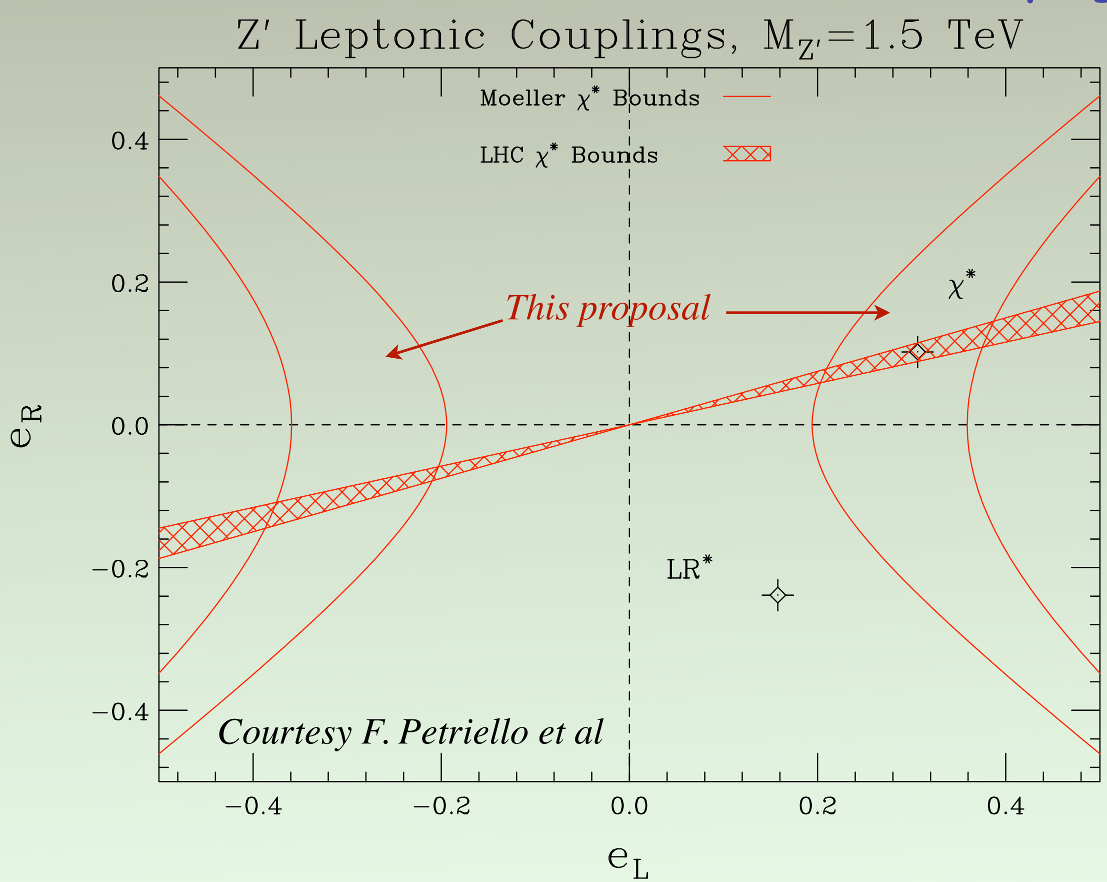
Example II: Heavy Z

- *Virtually all GUT models predict new Z's: LHC reach ~ 5 TeV*
- *With high luminosity at LHC, 1-2 TeV Z' properties can be extracted*
- *A_{PV} can help separate left- and right-handed couplings*



Suppose a 1 to 2 TeV heavy Z' is discovered at the LHC

- What are its vector- and axial-vector coupling?



$$\sqrt{2}G_F\delta(Q_W^e) = \frac{1}{(7.5\ \mathrm{TeV})^2}$$

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

LHC data can extract the mass, width and $A_{FB}(s)$

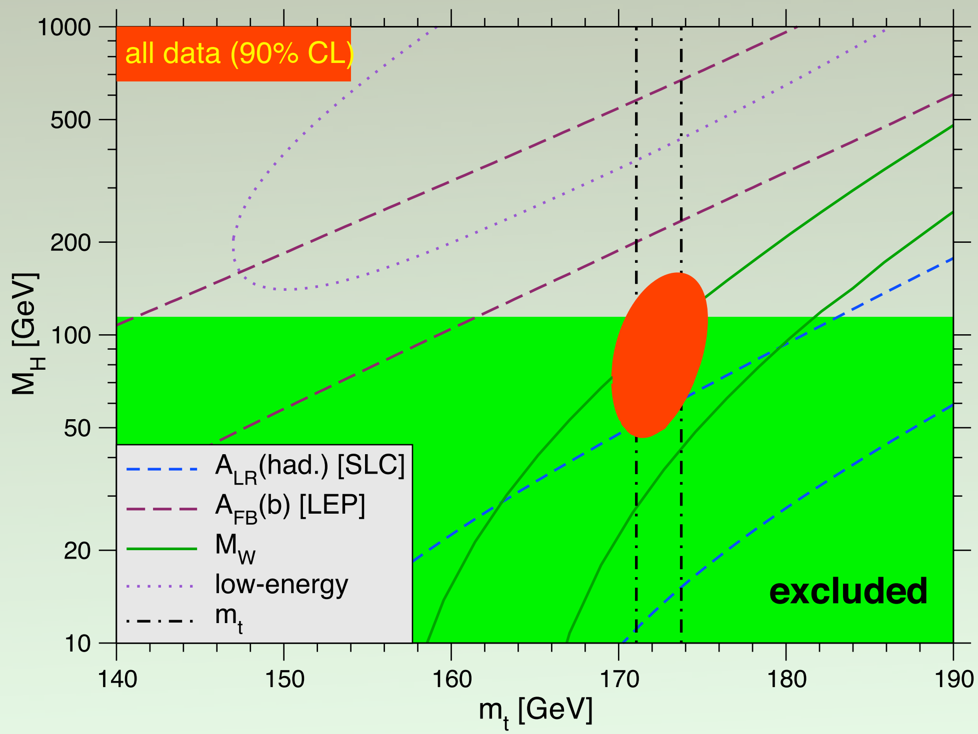
⇨ ***constraint on e_R/e_L***

EW Physics at One-Loop

Three 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



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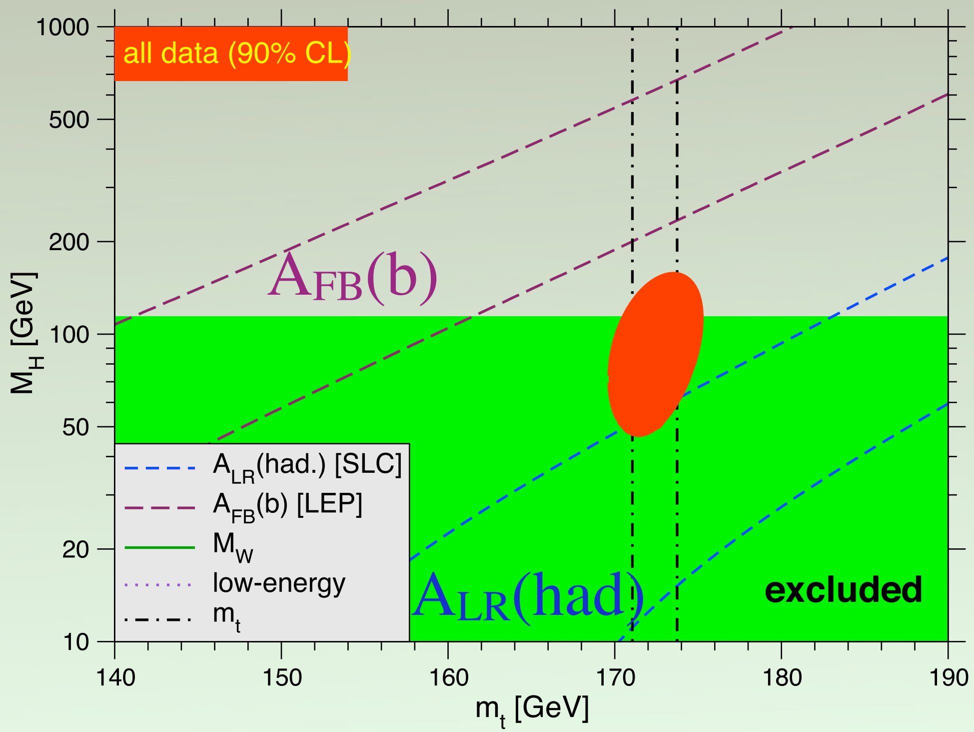

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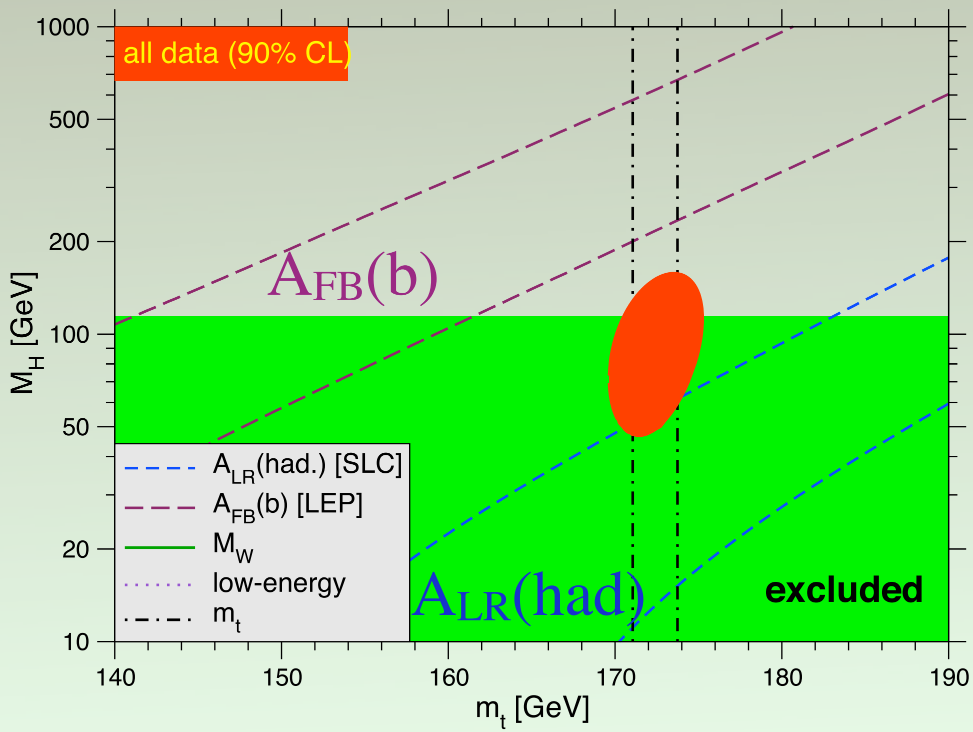

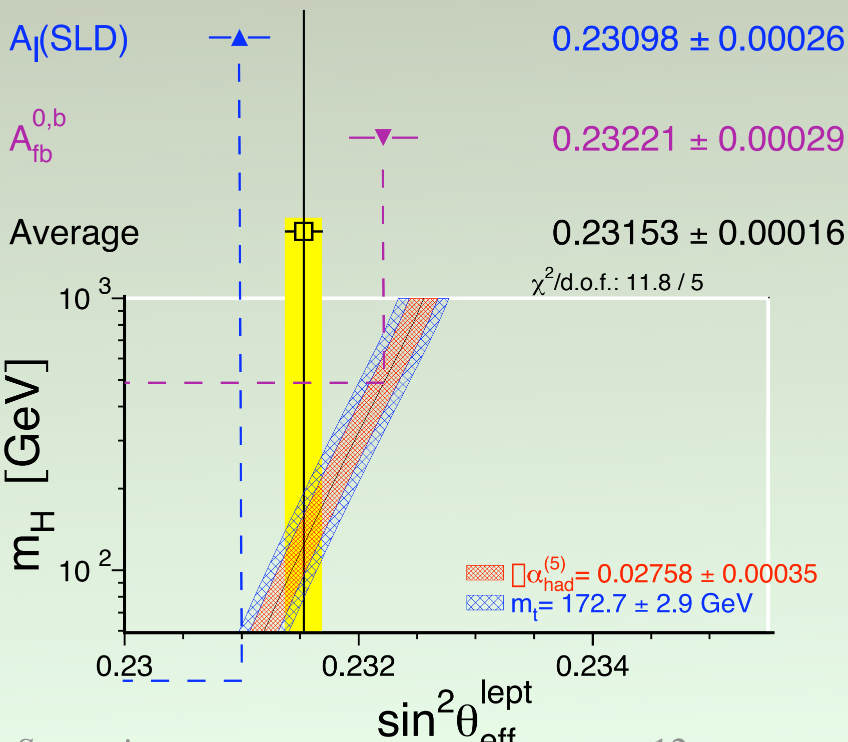

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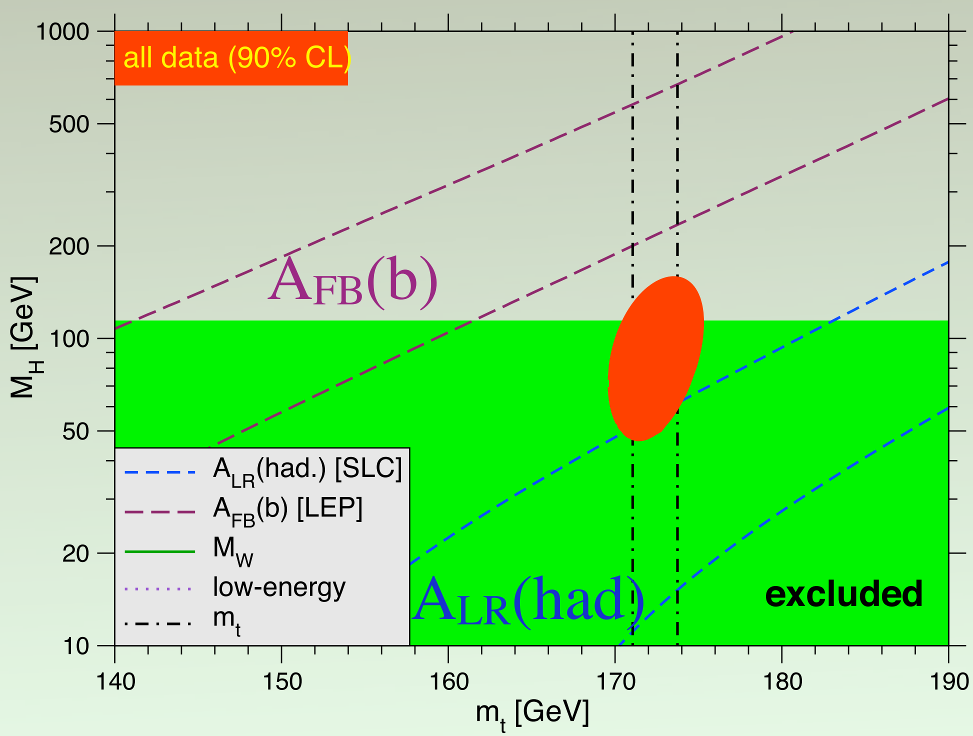
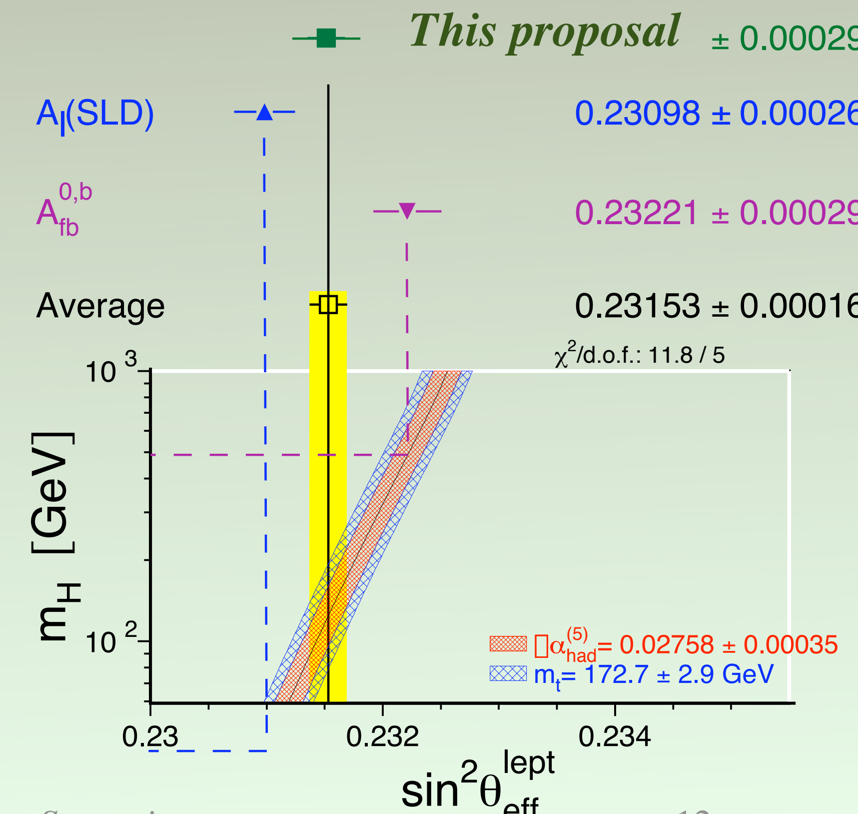
A_{LR}(had) measures purely the e-Z couplings



Proposed A_{PV} measures purely the e-Z couplings at a different energy scale



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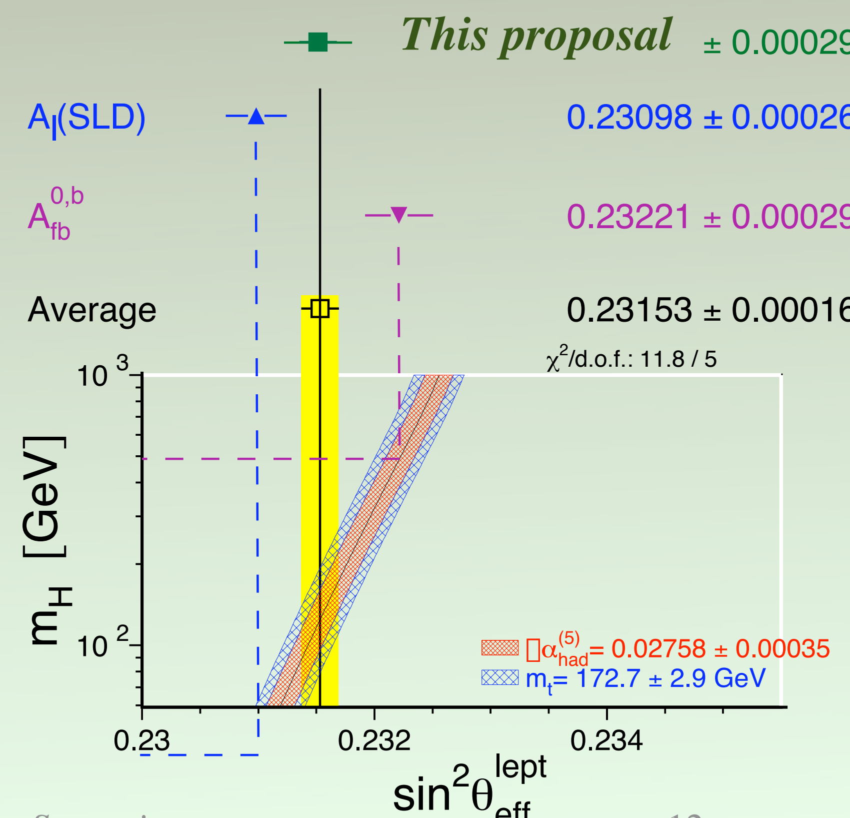
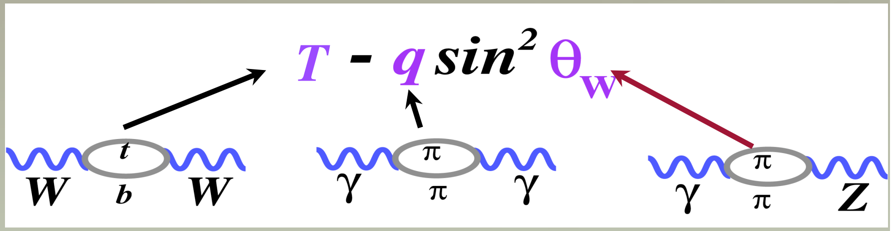


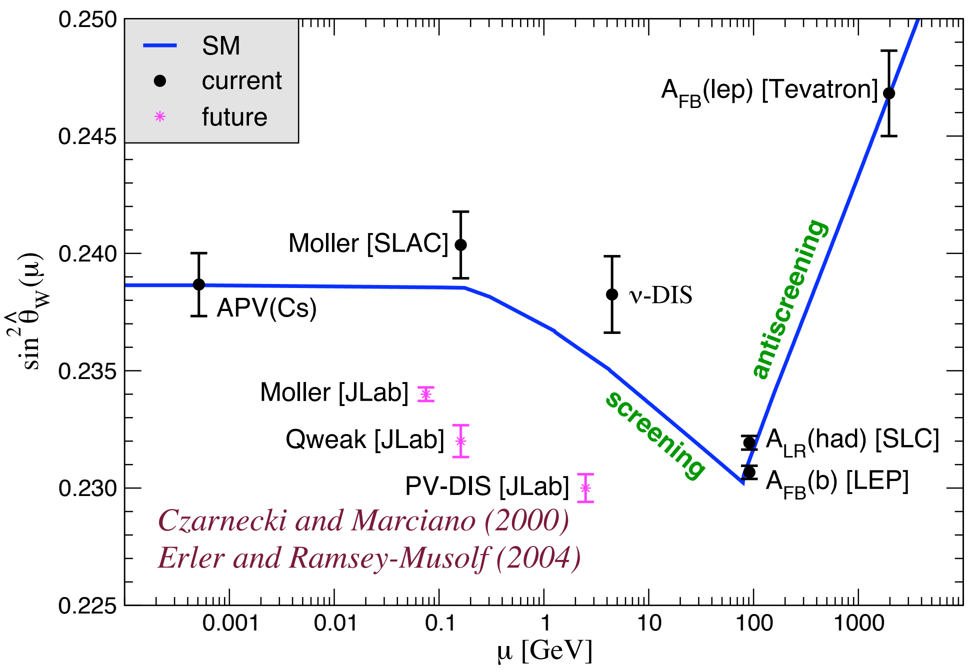
the proposed measurement is precise enough to affect the central value of the $\sin^2\theta_W$ and its implications for m_H

Running of θ_W

Bookkeeping for off-resonance measurements

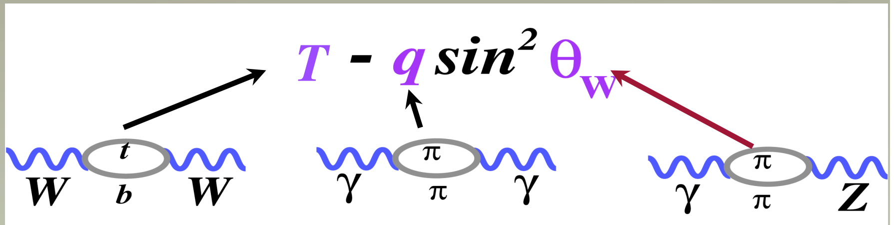


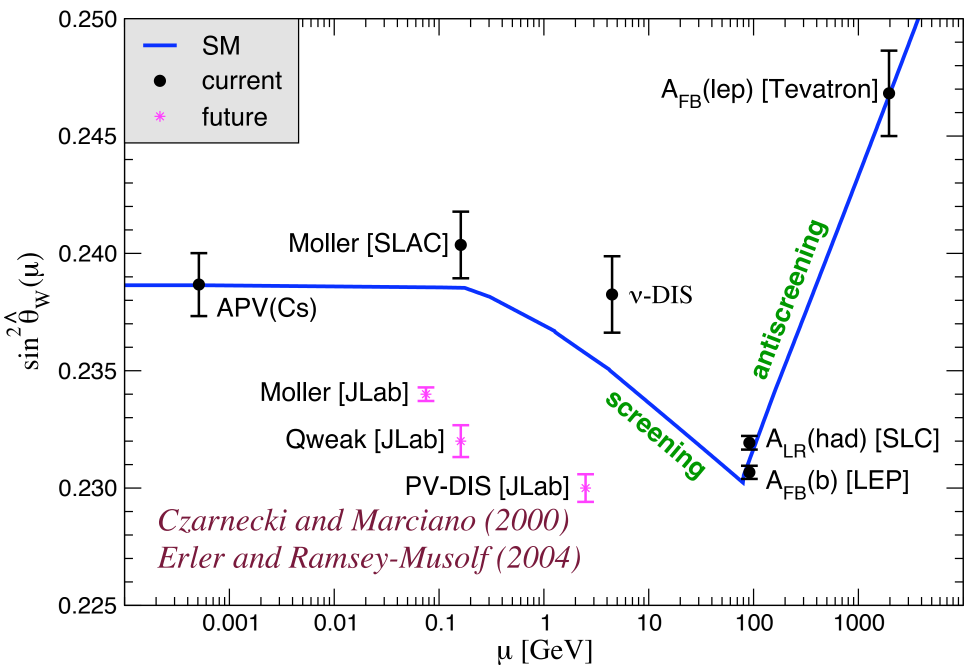
- *γ-γ loop is the running of α_{EM}*
- *W-W loop provides indirect m_t*
- *γ-Z loop is the running of $\sin^2\theta_W$*



Running of θ_W

Bookkeeping for off-resonance measurements





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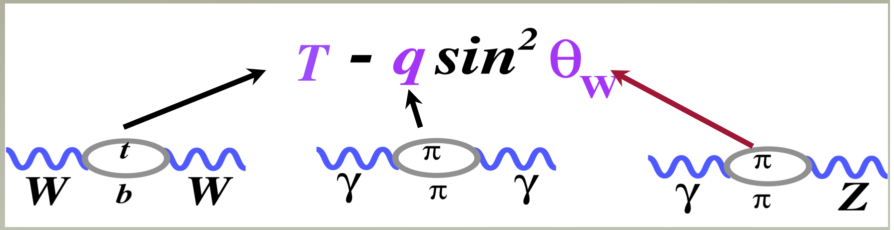
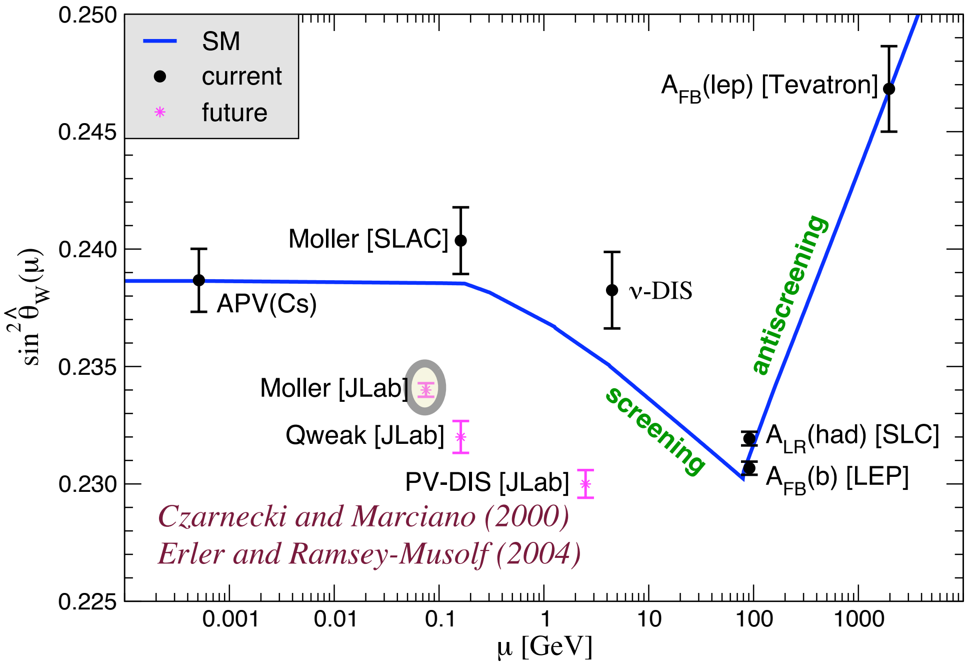
  - Semi-leptonic: APV (e-q) & NuTeV (ν -q)

Running of θ_W

Bookkeeping for off-resonance measurements





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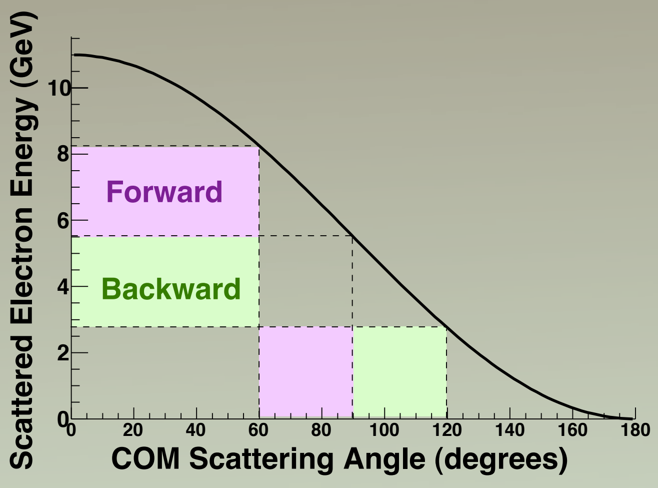
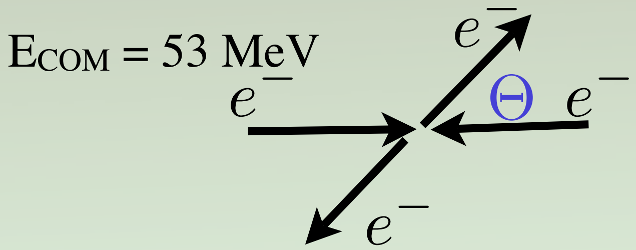
- *Published measurements*
  - Purely leptonic: SLAC E158 (e-e)
  - Semi-leptonic: APV (e-q) & NuTeV (ν -q)
- *Future measurements search for new contact interactions*
  - Qweak (e-q), PVDIS (e-q) and this proposal (e-e)

New Challenges

- *~ 150 GHz scattered electron rate*
  - Plan to flip Pockels cell ~ 2 kHz
  - 80 ppm pulse-to-pulse statistical fluctuations
    - *Electronic noise and density fluctuations < 10^{-5}*
    - *Pulse-to-pulse beam jitter ~ 10s of microns at 1 kHz*
    - *Pulse-to-pulse beam monitoring resolution ~ few micron at 1 kHz*
- *1 nm control of beam centroid on target*
  - Modest improvement on control of polarized source laser transport elements
  - Improved methods of "slow helicity reversal" to combat second order effects
- *> 10 gm/cm^2 target needed to achieve desired luminosity*
  - 1.5 meter Liquid Hydrogen target: ~ 5 kW @ 85 μA
- *Full Azimuthal acceptance with θ_{lab} ~ 5 mrad*
  - novel two-toroid spectrometer
  - radiation hard integrating detectors
- *Robust and Redundant 0.4% beam polarimetry*
  - Plan to pursue both Compton and Atomic Hydrogen techniques

100% Azimuthal Acceptance with Toroids





identical particles!

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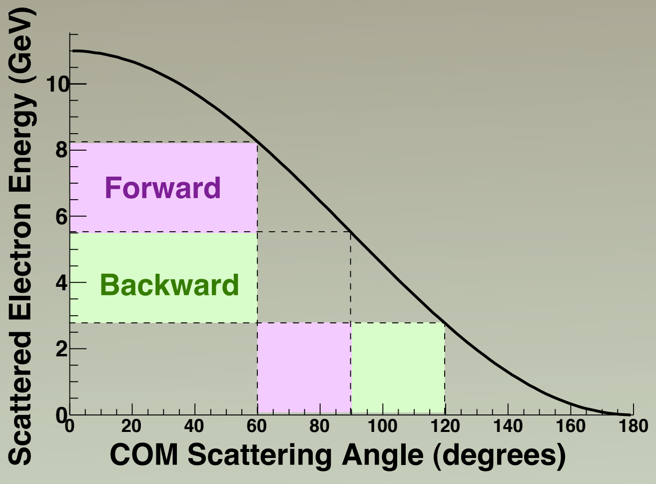
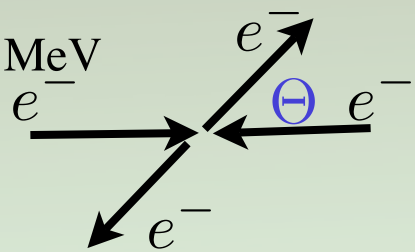


highly boosted laboratory frame

E_{COM} = 53 MeV



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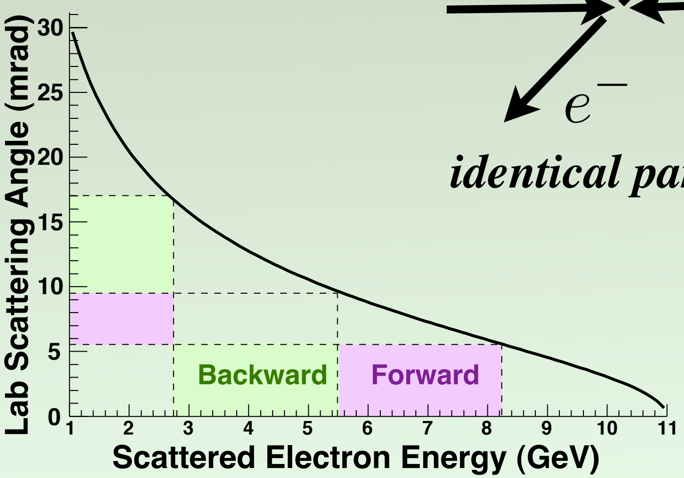

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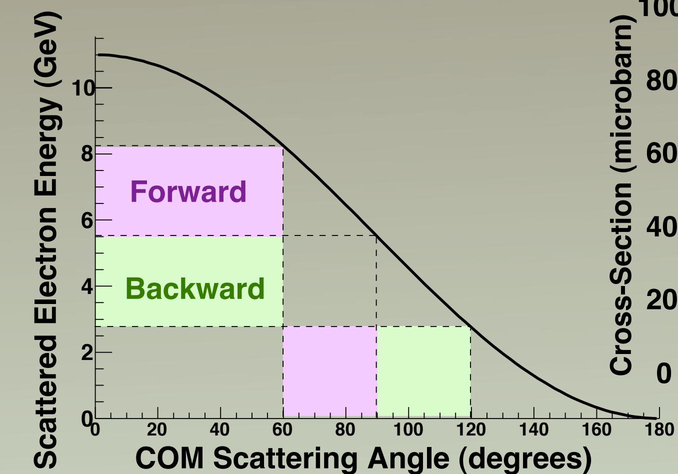

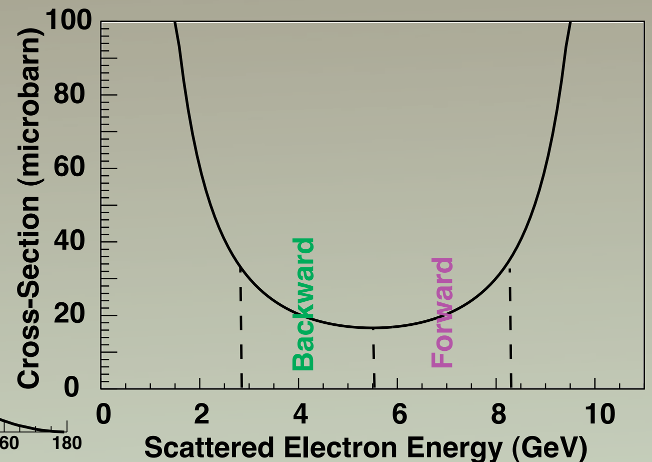

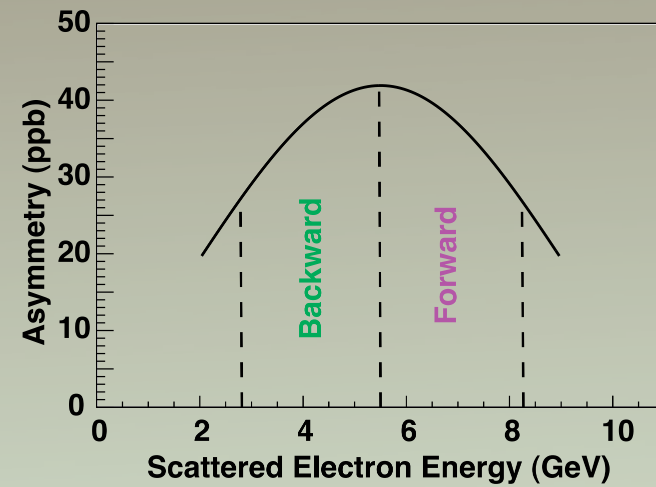

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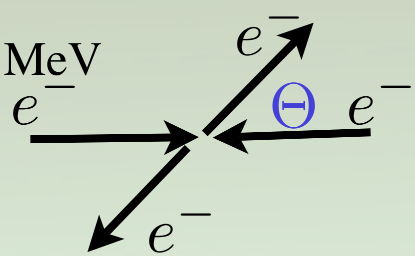

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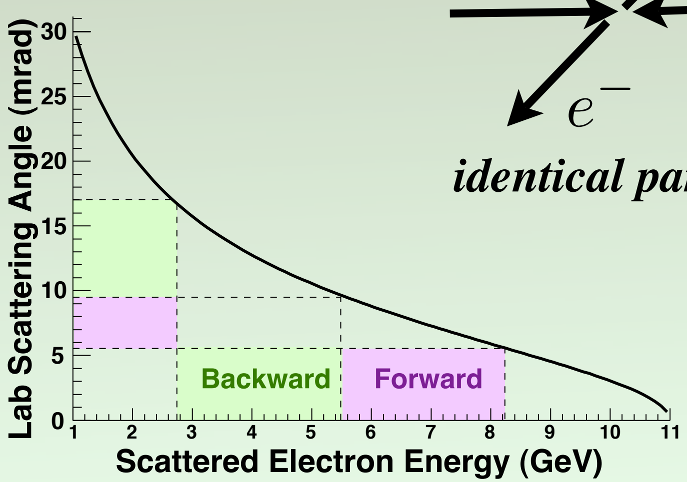

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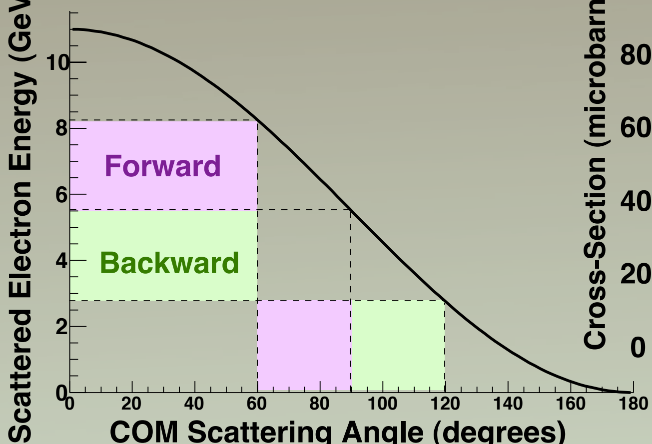

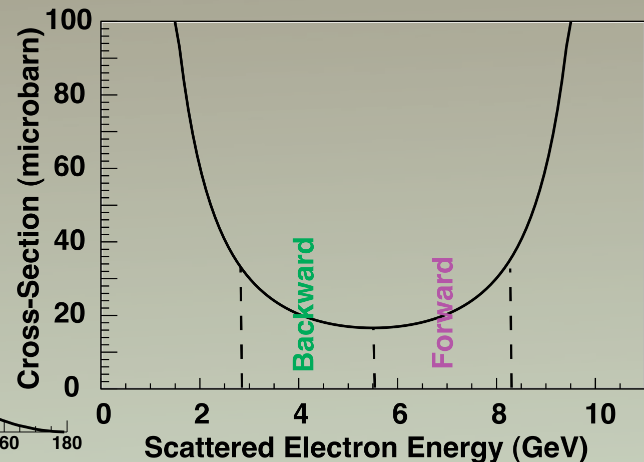

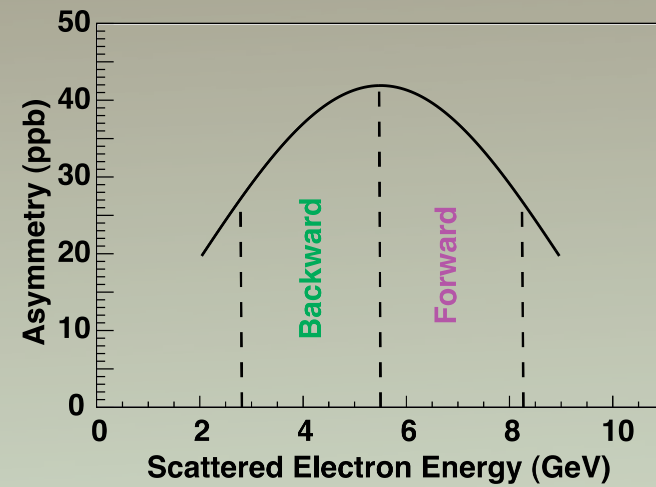

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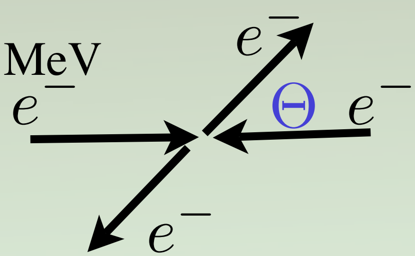

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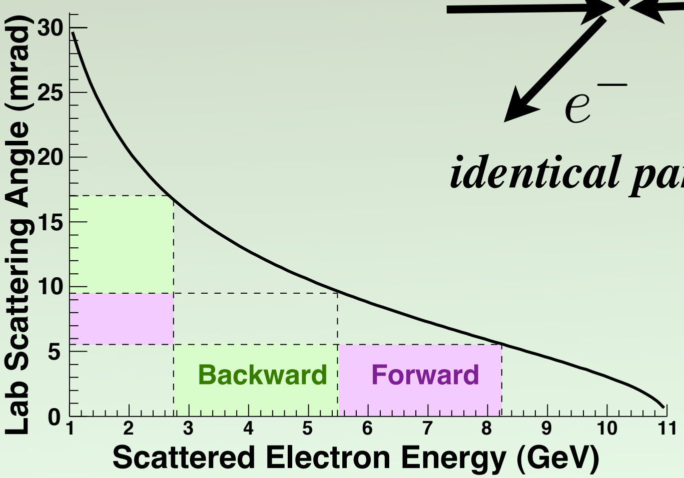

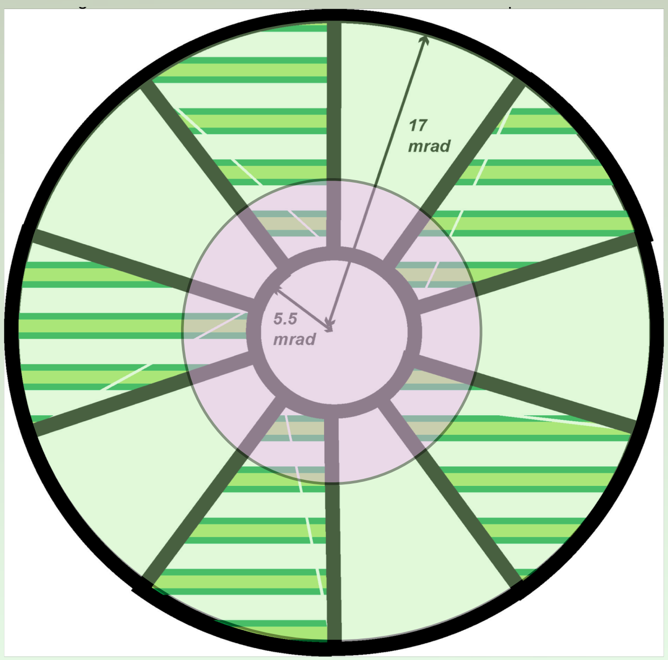

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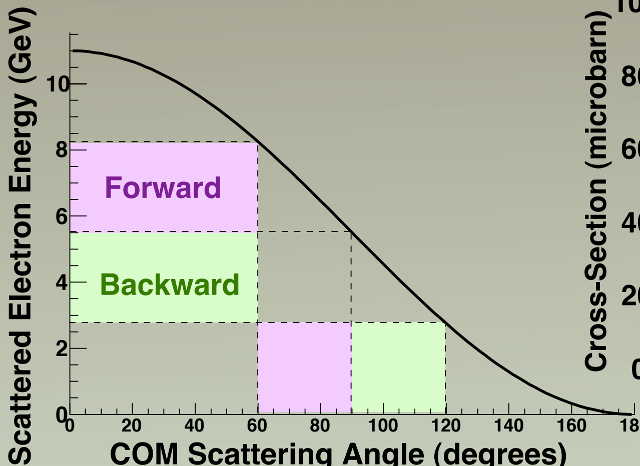

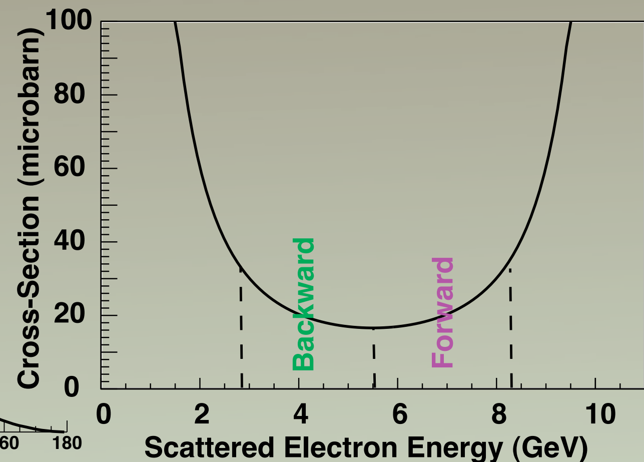

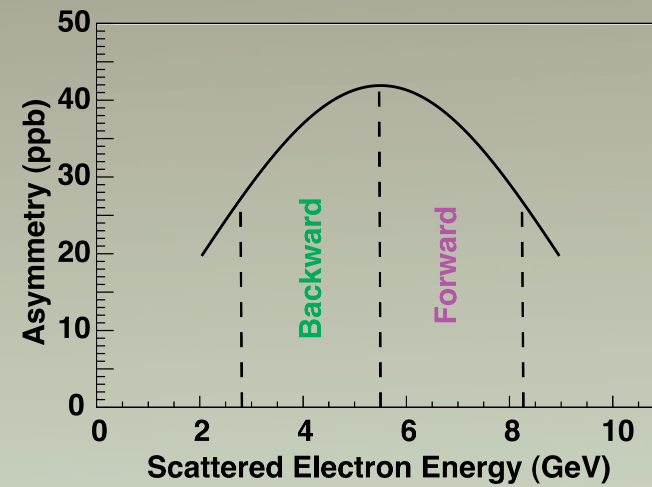

All of those rays of θ_{CM}=[90,120] that you don't get here...

highly boosted laboratory frame

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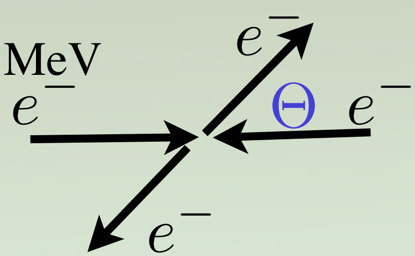

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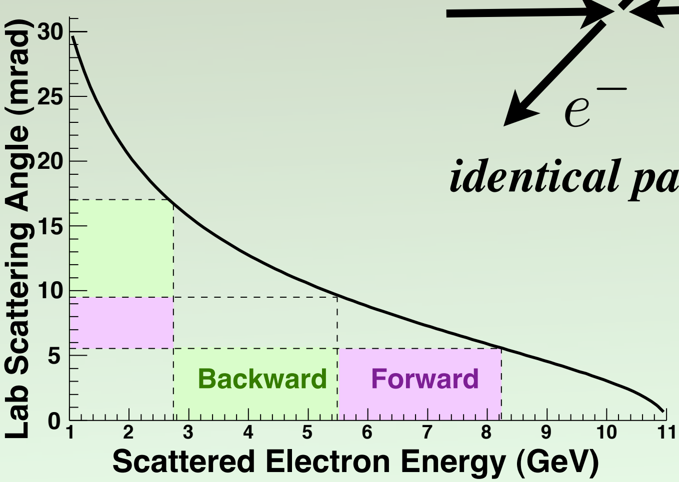
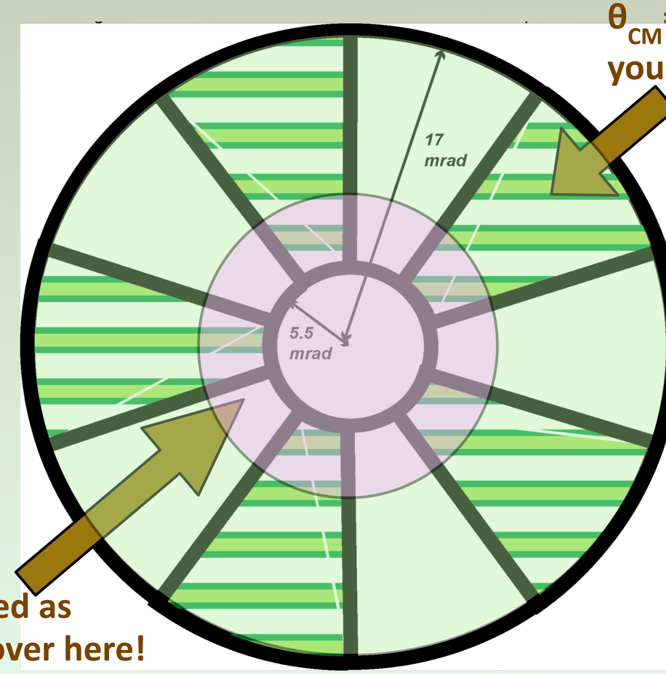
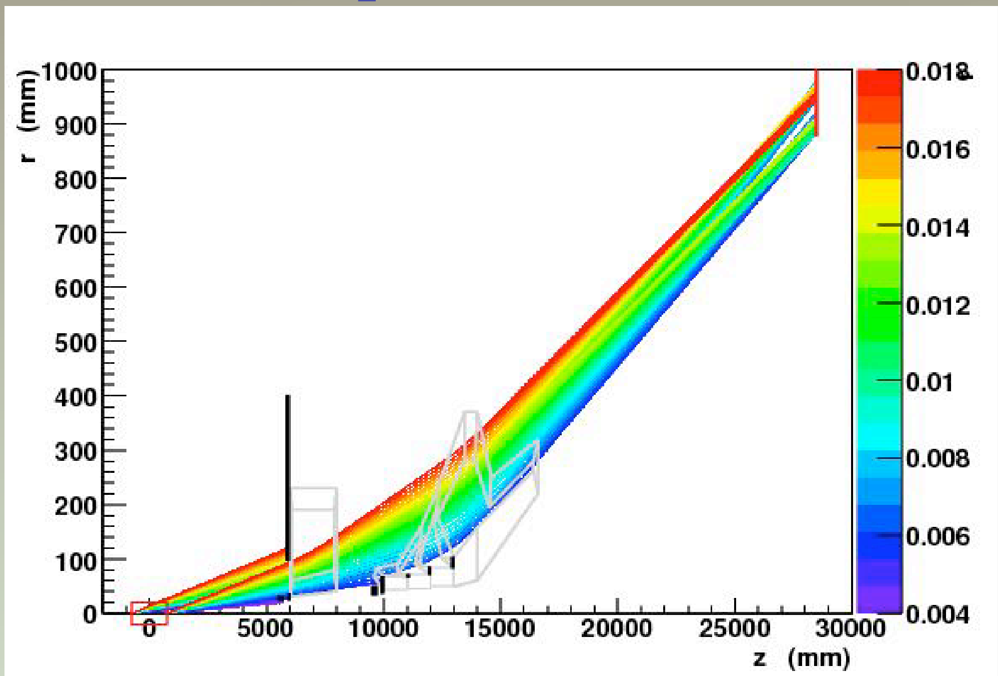
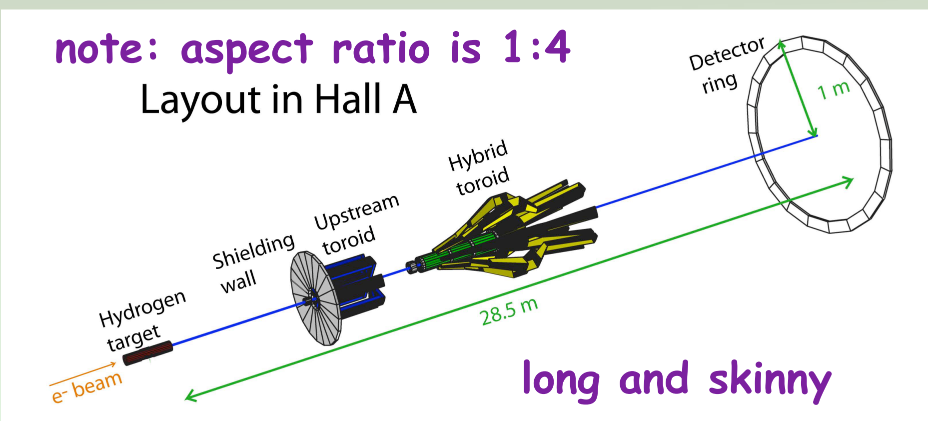


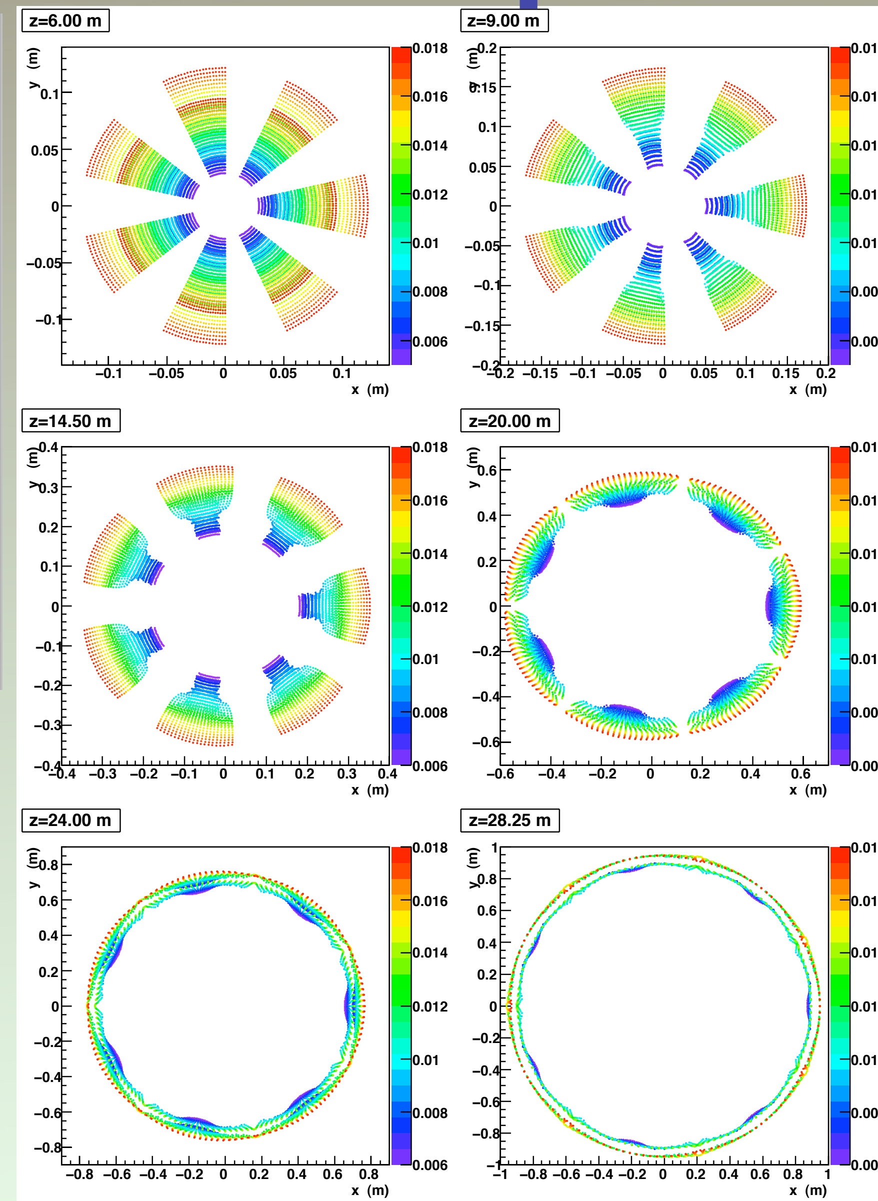


... are collected as θ_{CM}=[60,90] over here!

Spectrometer Concept







- ***Radial focus ~ 1 m, @ z ~ 28 m***
- ***Defocusing results in population of full azimuth***

Signal & Backgrounds

parameter	*value*
cross-section	***45.1 μBarn***
Rate @ 75 μA	***135 GHz***
pair stat. width (1 kHz)	***82.9 ppm***
$\delta(A_{raw})$ (6448 hrs)	***0.544 ppb***
$\delta(A_{stat})/A$ (80% pol.)	***2.1%***
$\delta(\sin^2\theta_W)_{stat}$	***0.00026***

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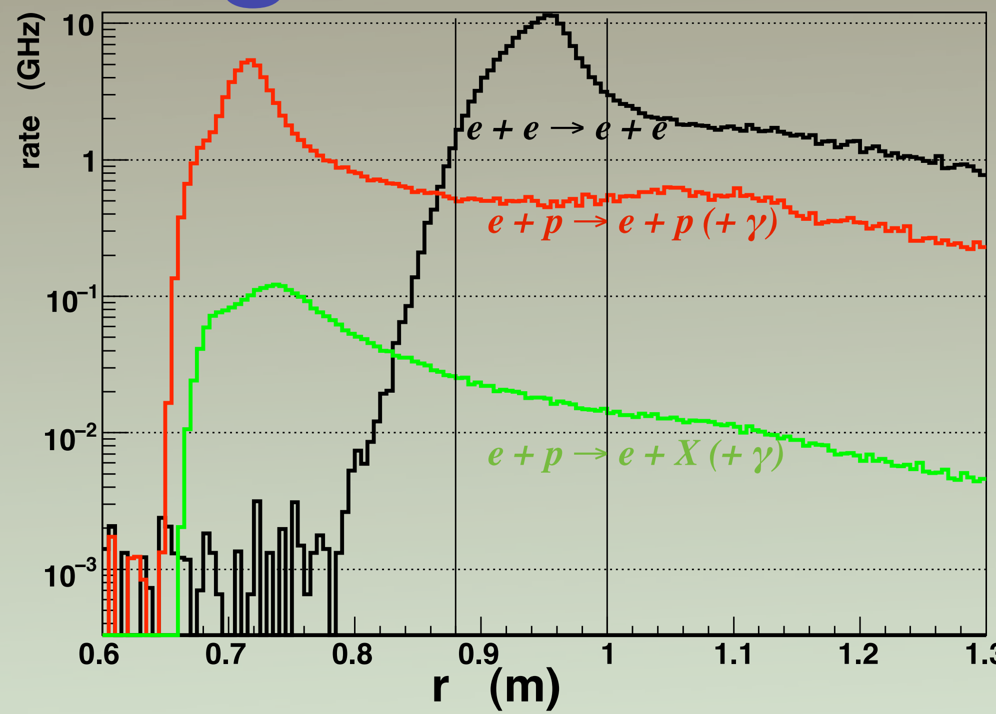

- ***Elastic e-p scattering***
  - well-understood and testable with data
  - 8% dilution, 7.5±0.4% correction
- ***Inelastic e-p scattering***
  - sub-1% dilution
  - large EW coupling, 4±0.4% correction
  - variation of A_{PV} with r and ϕ

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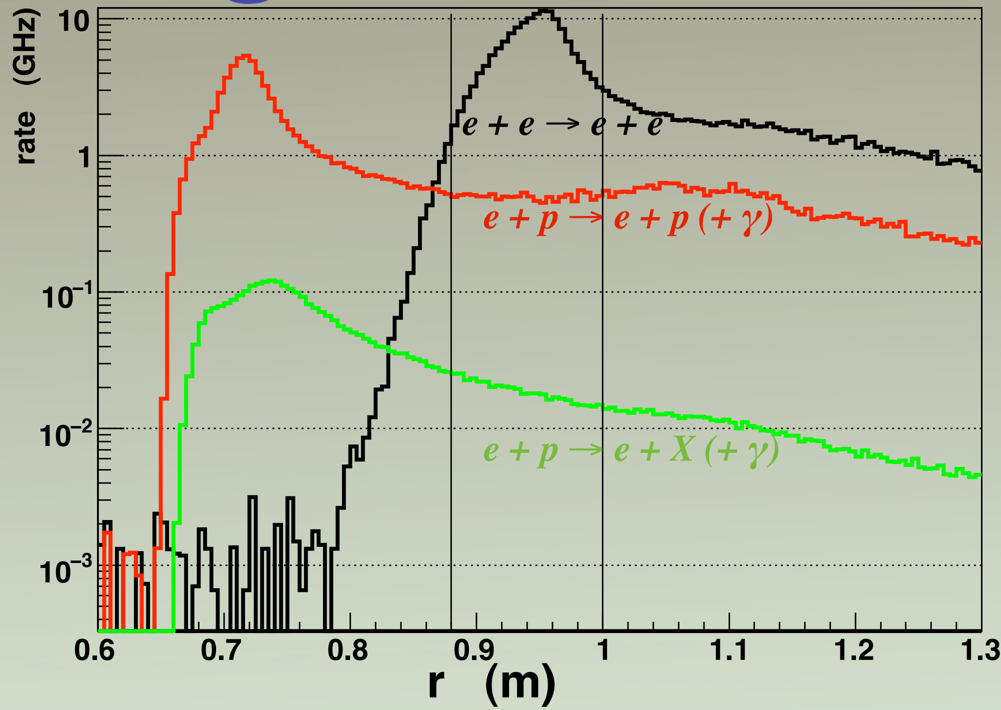

- ***photons and neutrons***
  - mostly 2-bounce collimation system
  - dedicated runs to measure "blinded" response
- ***pions and muons***
  - real and virtual photo-production and DIS
  - prepare for continuous parasitic measurement
  - estimate 0.5 ppm asymmetry @ 0.1% dilution
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  - well-understood and testable with data
  - 8% dilution, 7.5±0.4% correction
- ***Inelastic e-p scattering***
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  - large EW coupling, 4±0.4% correction
  - variation of A_{PV} with r and ϕ

Systematic Errors

source of error	*% error*
absolute value of Q^2	*0.5*
beam second order	*0.4*
longitudinal beam polarization	*0.4*
inelastic e-p scattering	*0.4*
elastic e-p scattering	*0.3*
beam first order	*0.3*
pions and muons	*0.3*
transverse polarization	*0.2*
photons and neutrons	*0.1*
Total	***1.0***

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Total	**1.0**

- **longitudinal beam polarization**
  - strive for redundant, continuous monitoring
  - pursue both Compton and Atomic Hydrogen
- **transverse beam polarization**
  - kinematic separation allows online monitoring
  - slow feedback using Wien filter
  - **Absolute value of Q^2**
  - dedicated tracking and scanning detectors
  - experience with HAPPEXII & Qweak
  - easier than elastic e-p scattering

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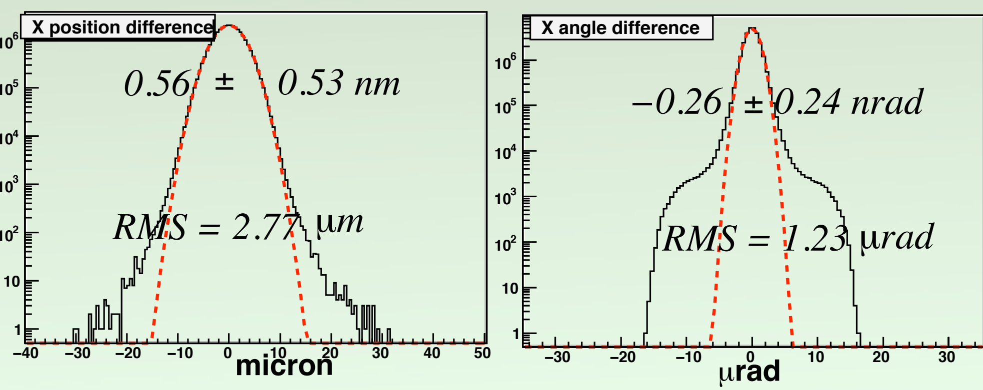
- **I order beam helicity correlations**
  - position to 0.5 nm, angle to 0.05 nrad
  - active intensity, position and angle feedback
- **II order beam helicity correlations**
  - control laser spotsize fluctuations to 10^{-4}
  - slow flips with Wien filter and g-2 energy flip

HAPPEXII



Slow Reversals Downstream of Photocathode

A comprehensive "data-based" strategy to cancel second-order beam helicity correlations is unrealistic

g-2 spin sign flip is available with ~100 MeV energy shift;
perhaps even smaller with asymmetric linacs?

→ *Near ideal cancellation of 2nd order beam systematics...*

but machine tuning requirements mean long time scale for reversal

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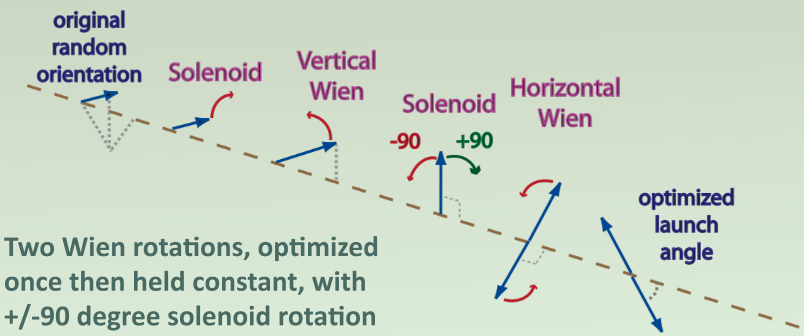
Wein Spin Rotator



Two Wien rotations, optimized once then held constant, with +/-90 degree solenoid rotation

Wein upgrade project now underway at JLab to support the 2010 experiments

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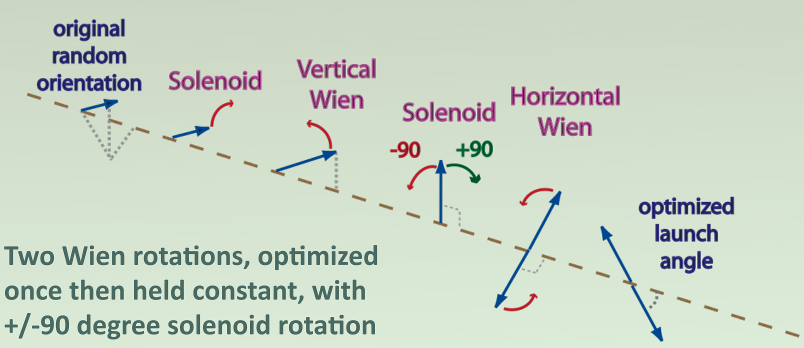

Two Wien rotations, optimized once then held constant, with +/-90 degree solenoid rotation

Possible Helicity-Correlated Spot Size:

- Sensitivity ~ 120 ppm x $\delta\sigma/\sigma$
- Should be bound to $<10^{-4}$ in laser optics
- g-2 & Wien flips: factor of 10

Final contribution: 0.1 ppb

Wein upgrade project now underway at JLab to support the 2010 experiments

Collaboration, Funding...

sub-system	*Institutions*
polarized source	*UVa, JLab, Miss. St.*
Target	*JLab, VaTech, Miss. St.*
Spectrometer	*Canada, ANL, MIT, UVa*
Integrating Detectors	*Syracuse, Canada, JLab*
Luminosity Monitors	*VaTech, Ohio U.*
Pion Detectors	*UMass/Smith, LATech*
Tracking Detectors	*William & Mary, Canada, UMass/Smith*
Electronics	*Canada, JLab*
Beam Monitoring	*UMass, JLab*
Polarimetry	*UVa, Syracuse, JLab, CMU, ANL, Miss. St., Claremont-Ferrand*
Data Acquisition	*Ohio U., Rutgers U.*
Simulations	*LATech, UMass/Smith, UC Berkeley*

- ***Strong Collaboration being formed***
  - Expertise from PREX, Qweak and E158
  - 4th generation JLab parity experiment
  - Major interest and commitment to development of apparatus given funding
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- **Immediate Plans**
  - Use calendar 2009 to develop a conceptual design of spectrometer, and a cost range
  - viability and cost range to be reviewed by early 2010 via a Jefferson Lab Director’s Review
- **Funding**
  - Cost is roughly in the 10+ M$ range
  - Must seek DoE, NSF and foreign funding
  - lobbying to enter the CD-n process @ DoE
  - collaboration committed to construction project
- **Potential Schedule**
  - target for funding to begin early 2012
  - target for installation in 2015
- **Possible Beam Time Allocation**
  - Run I: 4 months (6 wks setup + 10 wks data)
  - Run II: 2 full “JLab” years (60% efficiency)

Summary

- **Projected Result from an A_{PV} measurement in Møller Scattering**

A_{PV} = 35.6 ppb $\delta(A_{PV})$ = 0.73 ppb $\delta(Q^e_W)$ = ± 2.1 (stat.) ± 1.0 (syst.) %

$\delta(\sin^2\theta_W)$ = ± 0.00026 (stat.) ± 0.00012 (syst.) ⇨ ~ 0.1%

- **Opportunity with high visibility and large potential payoff**
  - The weak mixing angle is a fundamental parameter of EW physics
  - HEP has tried to come up with a cost-effective project for years
    - *expensive ideas reach perhaps 0.2% (reactor or accelerator ν's, LHC Z production...)*
    - *sub-0.1% requires a new machine (e.g. Z- or ν-factory, linear collider....)*
  - physics impact on nuclear physics, particle physics and cosmology
    - *pin down parameter for other precision low energy measurements*
    - *help decipher potential LHC anomalies at the TeV scale*
    - *shed light on feasibility of SUSY dark matter via search for R-Parity violation*
- **US NSAC Long Range Plan strongly endorsed the physics**
  - part of fundamental symmetries initiative to tune of 25M$
- **11 GeV JLab beam is a unique instrument that makes this feasible**

Backups

J. Benesch, P. Brindza, R.D. Carlini, J-P. Chen, E. Chudakov, S. Covrig, C.W. de Jager,
A Deur, D. Gaskell, J. Gomez, D. Higinbotham, J. LeRose, D. Mack, R. Michaels,
S. Nanda, G.R. Smith, R. Suleiman, V. Sulkosky, B. Wojtsekhowski
Jefferson Lab

H. Baghdasaryan, G. Cates, D. Crabb, D. Day, M. Dalton, N. Kalantarians, N. Liyanage,V.V. Nelyubin
B. Norum, K. Paschke, S. Riordan, M. Shabestari, J. Singh, A. Tobias, K. Wang, X. Zheng
University of Virginia

J. Birchall, M.T.W. Gericke, W.R. Falk, L. Lee, W.D. Ramsay, S.A. Page, W.T.H. van Oers
University of Manitoba

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Rutgers

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Argonne National Lab

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W. Deconinck, S. Kowalski, B. Moffit
MIT

P. Decowski
Smith College

R. Holmes, P. Souder
Syracuse University

N. Morgan, M. Pitt
Virginia Tech

P.M. King, J. Roche
Ohio University

Yu.G. Kolomensky
U.C. Berkeley

J.A. Dunne, D. Dutta
Mississippi State

C.A. Davis
TRIUMF

A. Ahmidouch, S. Danagoulian
North Carolina A&T State

J. Erler
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M.J. Ramsey-Musolf
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Cal. State U.(LA)

J.W. Martin
U. Winnipeg

E. Korkmaz
U. Northern B.C.

T. Holmstrom
Longwood U.

S.F. Pate
New Mexico State

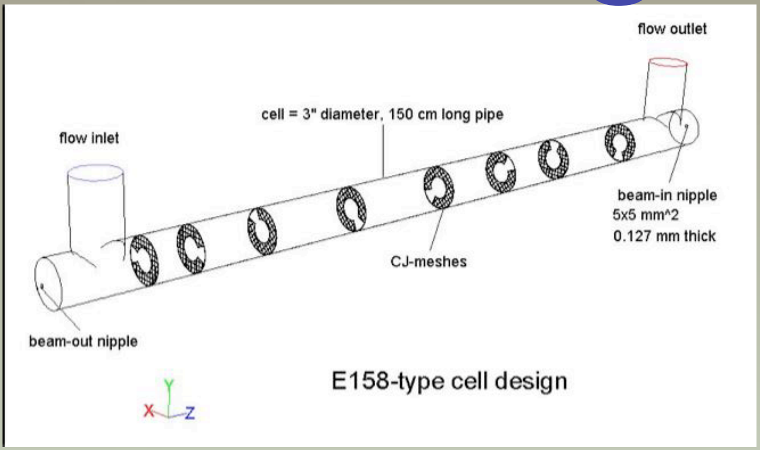
G. Ron
Tel Aviv U.

P. Markowitz
Florida International U.

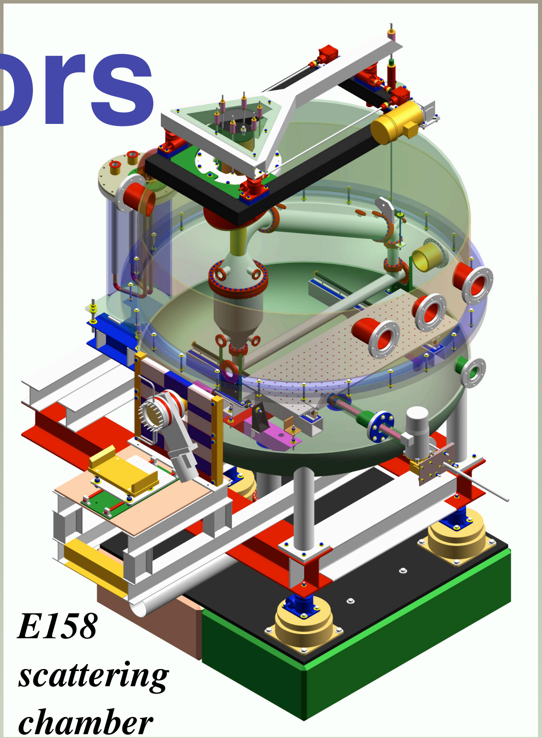
~ 100 authors
~ 30 institutions

expertise from HAPPEX, PREX, G0, Qweak and E158

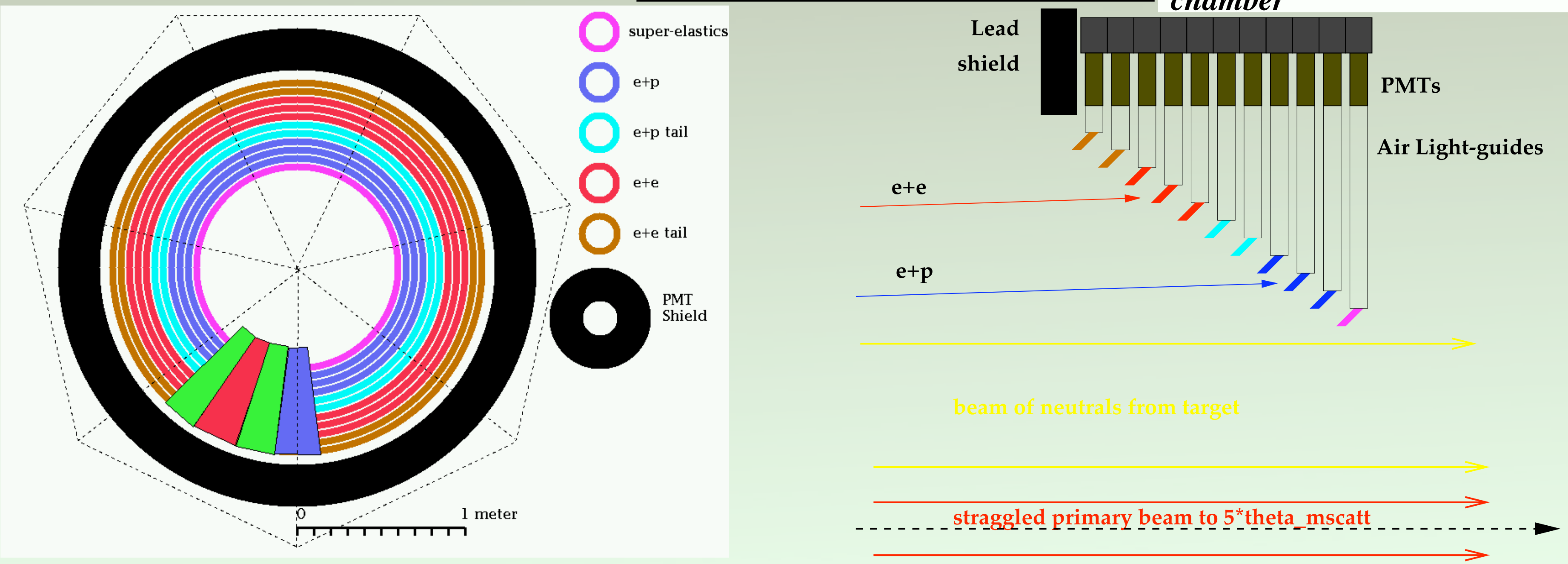
Target & Detectors



parameter	value
length	150 cm
thickness	10.7 gm/cm^2
X_0	17.5%
p,T	35 psia, 20K
power	5000 W

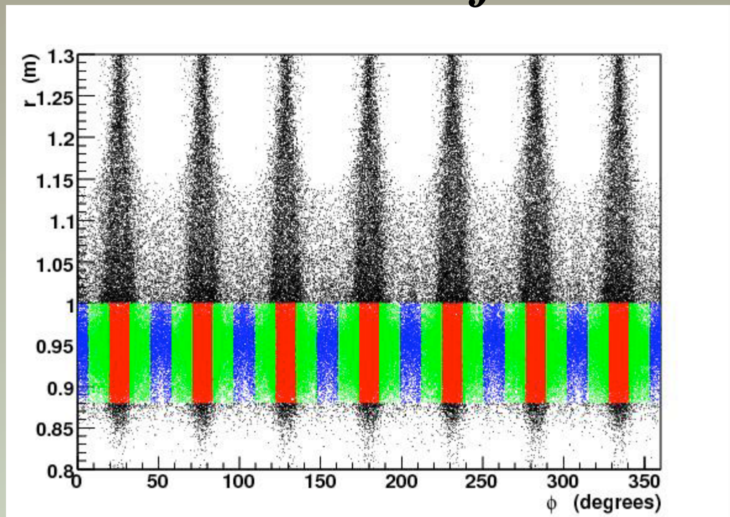


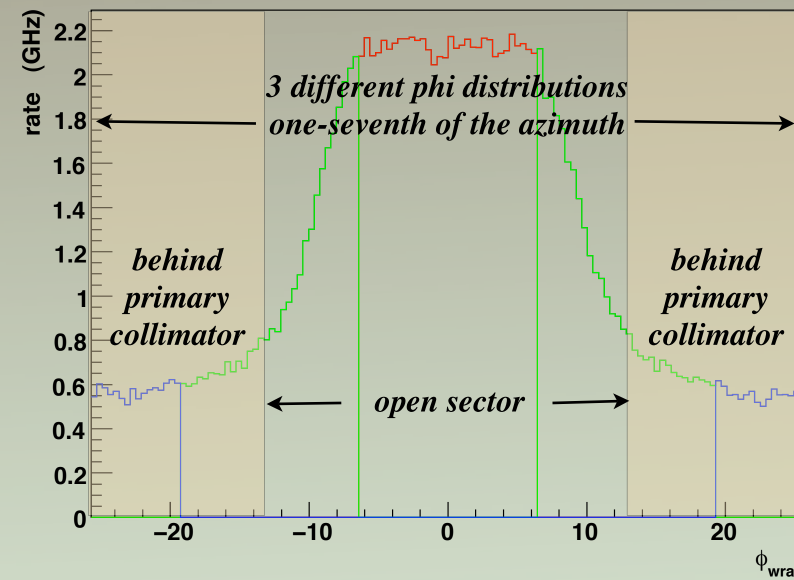
E158 scattering chamber

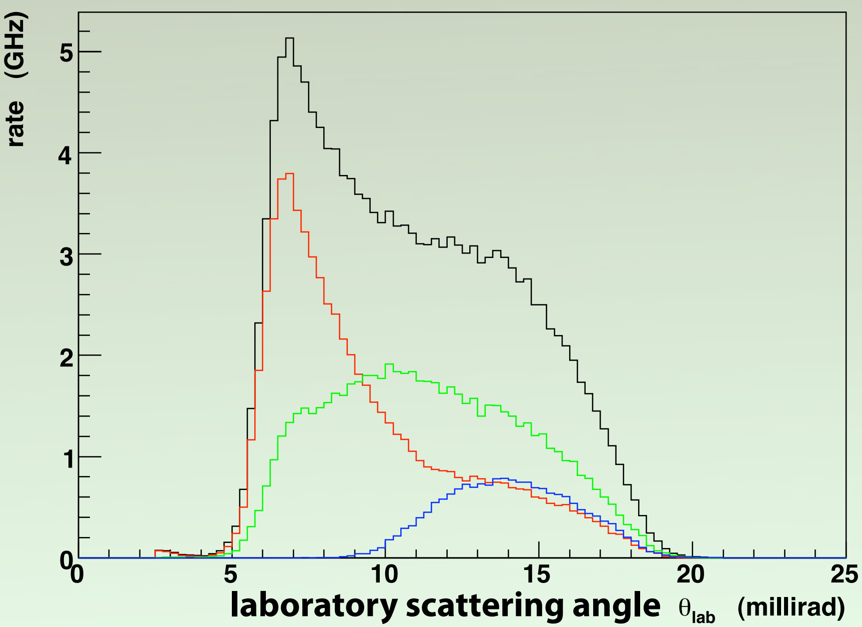


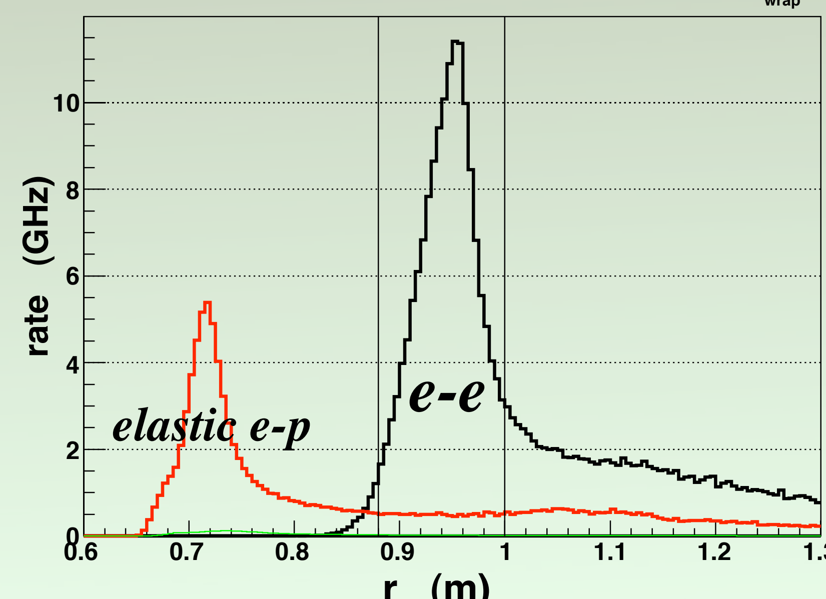
Simulations

Initial and final state radiation effects in target









leptonic forward backward asymmetry

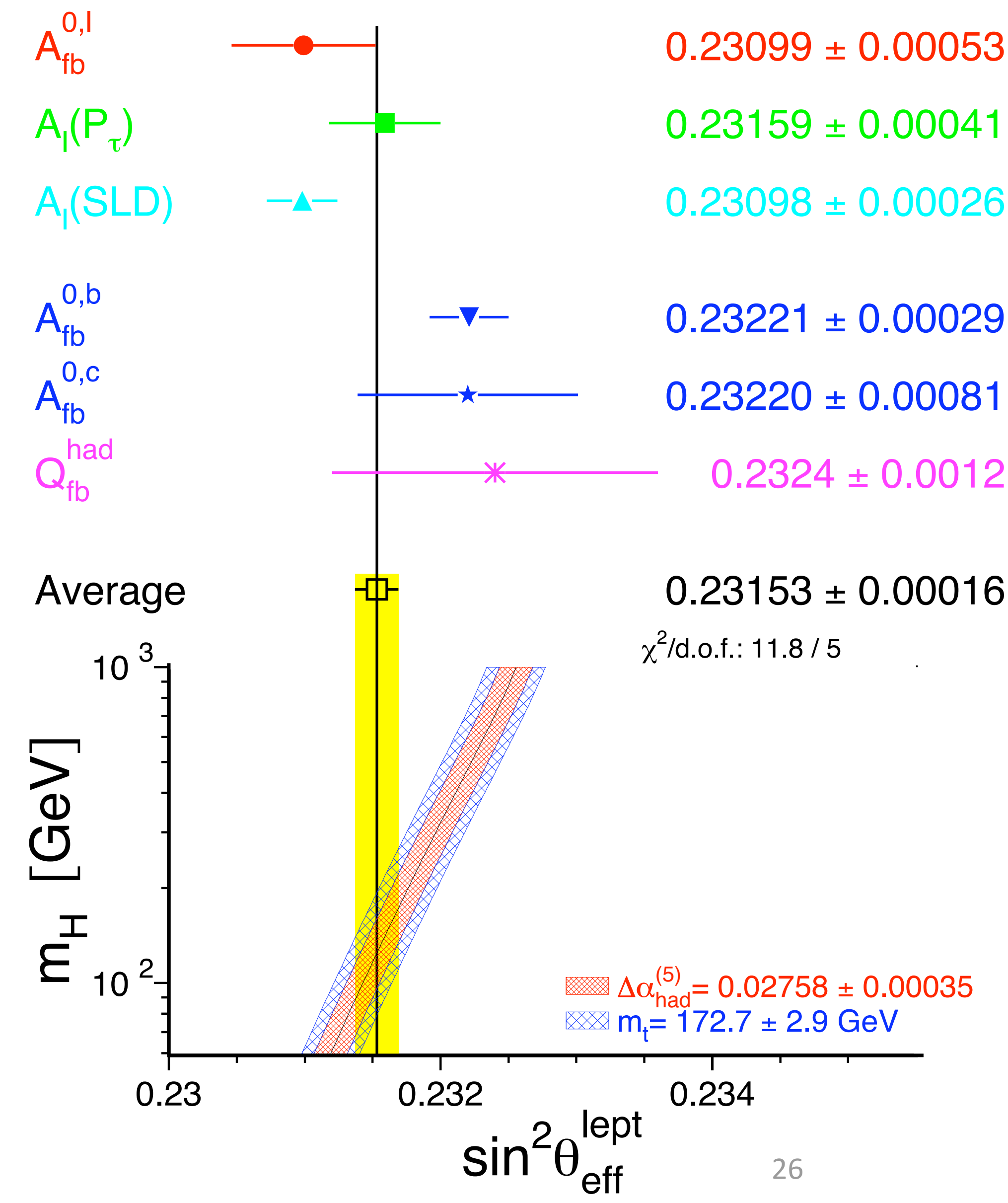
tau polarization asymmetry

left-right asymmetry

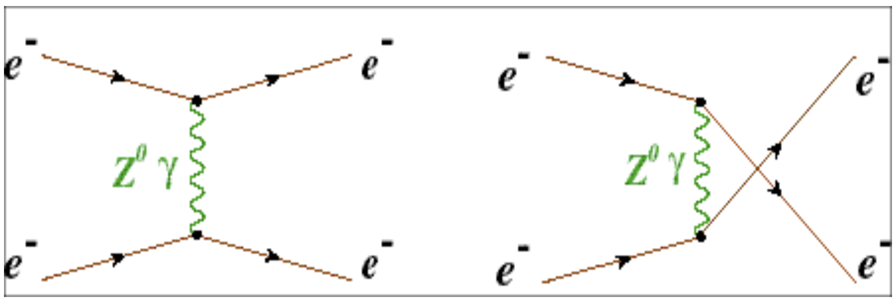
b-quark forward backward asymmetry

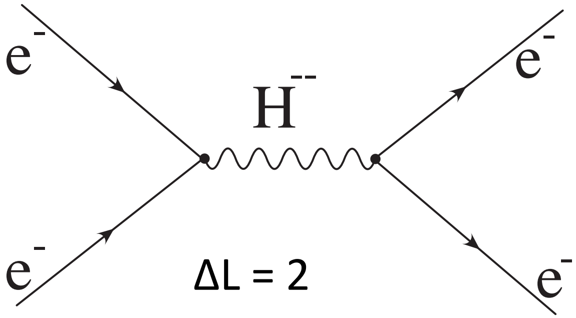
c-quark forward backward asymmetry

hadronic charge asymmetry



Doubly Charged Scalars





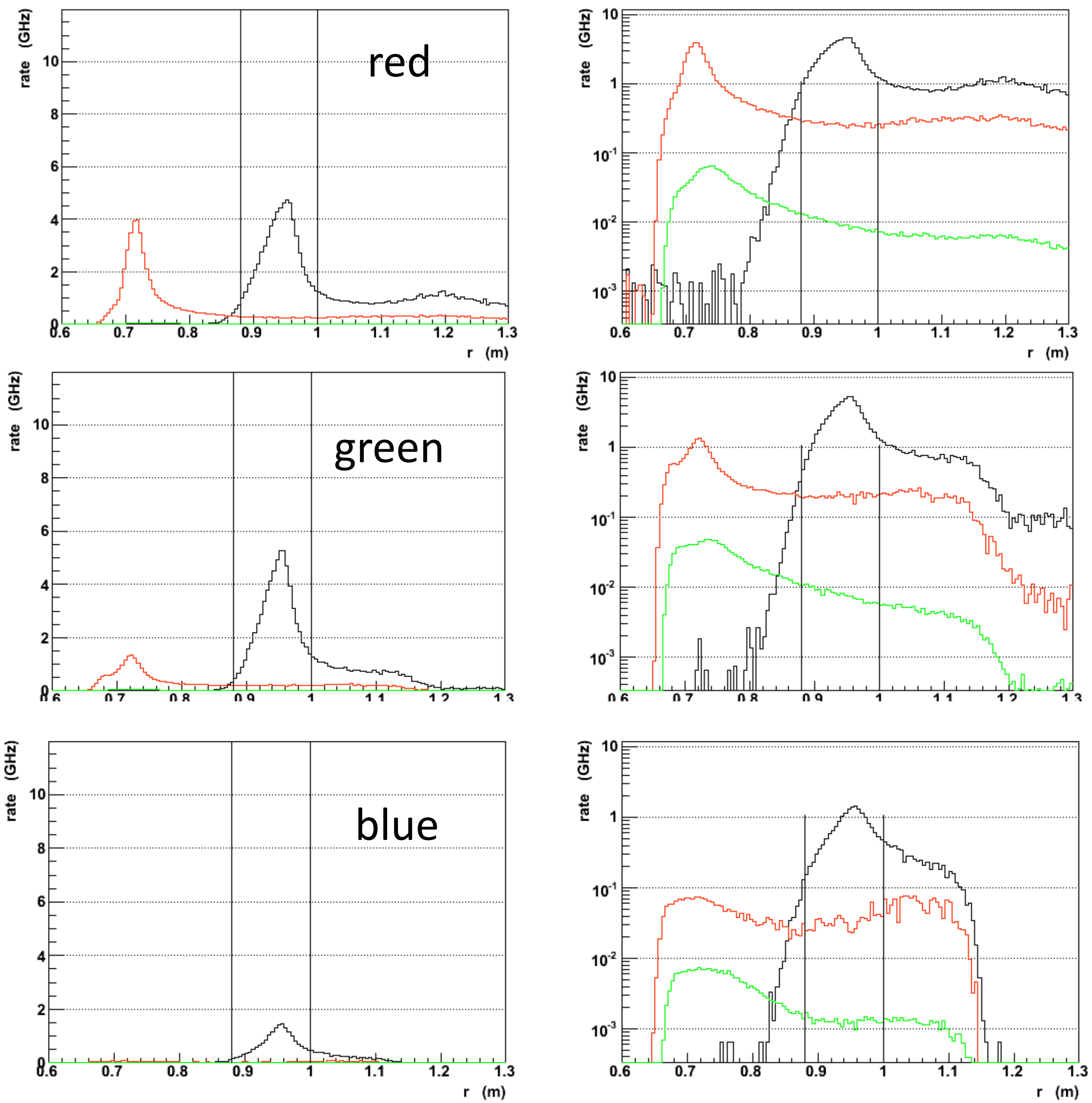
$$\sqrt{2}\mathbf{G_F}\delta(\mathbf{Q_W^e}) = \frac{\mathbf{1}}{(\mathbf{7.5}\ \mathrm{TeV})^{\mathbf{2}}}$$

$$\mathcal{M}^{\mathrm{PV}} \sim \frac{|h_{L,R}^{ee}|^2}{2M_{\delta_L}^2}\bar{e_L}\gamma_\mu e_L \bar{e_L}\gamma^\mu e_L$$

$$\frac{M_{\delta_L}}{|h_L^{ee}|} \sim 5.3\ \mathrm{TeV}$$

Sensitivity better than LEP200

e-p inelastic background



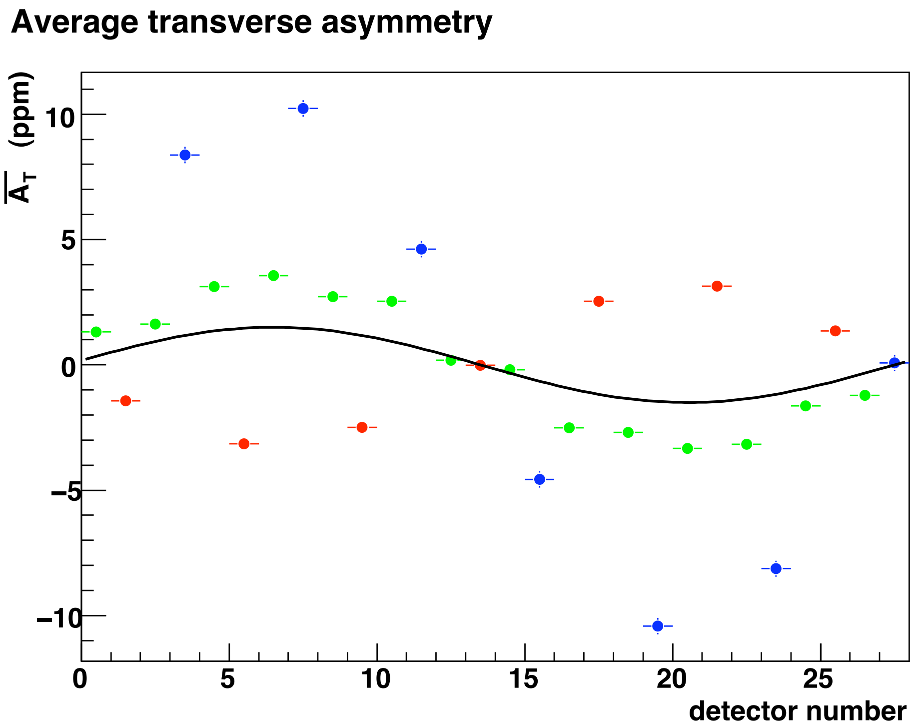
inelastic p-Z coupling unknown at diffractive kinematics

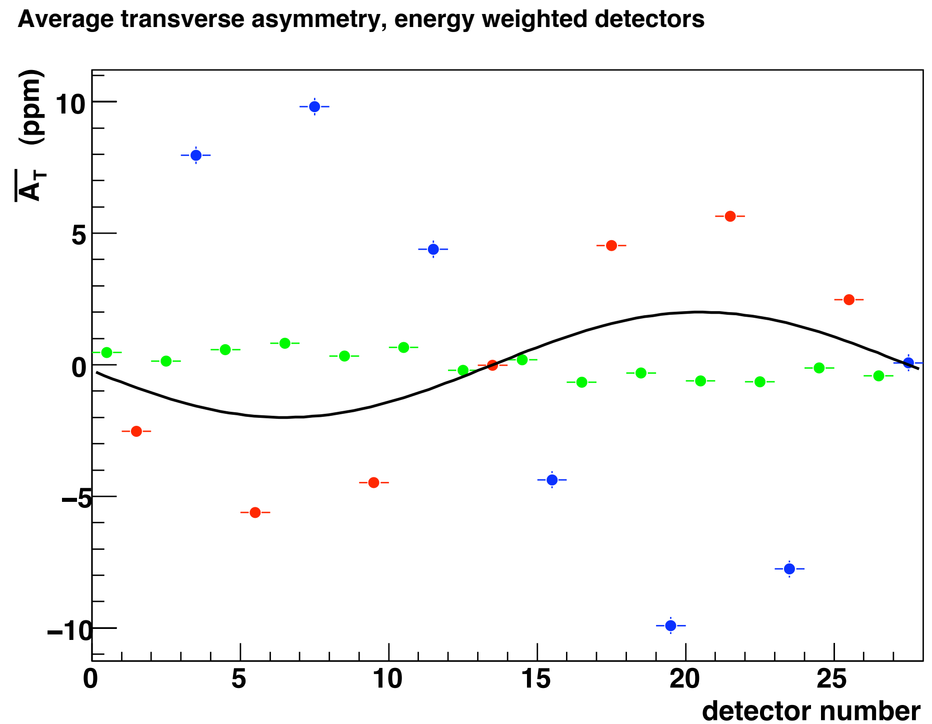
E158 measured $10^{-4} \times Q^2$

A_{PV} as function of r & ϕ

4% correction, 0.4 % error

Transverse Polarization





Initial beam setup ~ 1 degree

50 ppb error in 4 hours: 0.5 degree precision

Feedback 25 times in ~ 1 week

Grand average: 0.04 degrees + azimuthal cancellation

Dependence of A_{pv} on E and θ

The kinematic dependence of A_{pv} in e+e→e+e is very different than that in e+p→e+p. The very light e+e mass causes a large θ_{CM} bite around 90 degrees (where the asymmetry peaks) to boost into a small θ_{LAB} bite.

We can't calculate dA/dE and dA/dθ analytically in one line: acceptance-integrated simulations are essential!

Ebeam: For a 0.05% beam energy measurement:

dA/A(energy) = (dA/A)/(dE/E) x dE/E = 0.9 x 0.05% = **0.045%**

(the coefficient 0.9 is a factor of 2 more favorable than an equivalent e+p experiment)

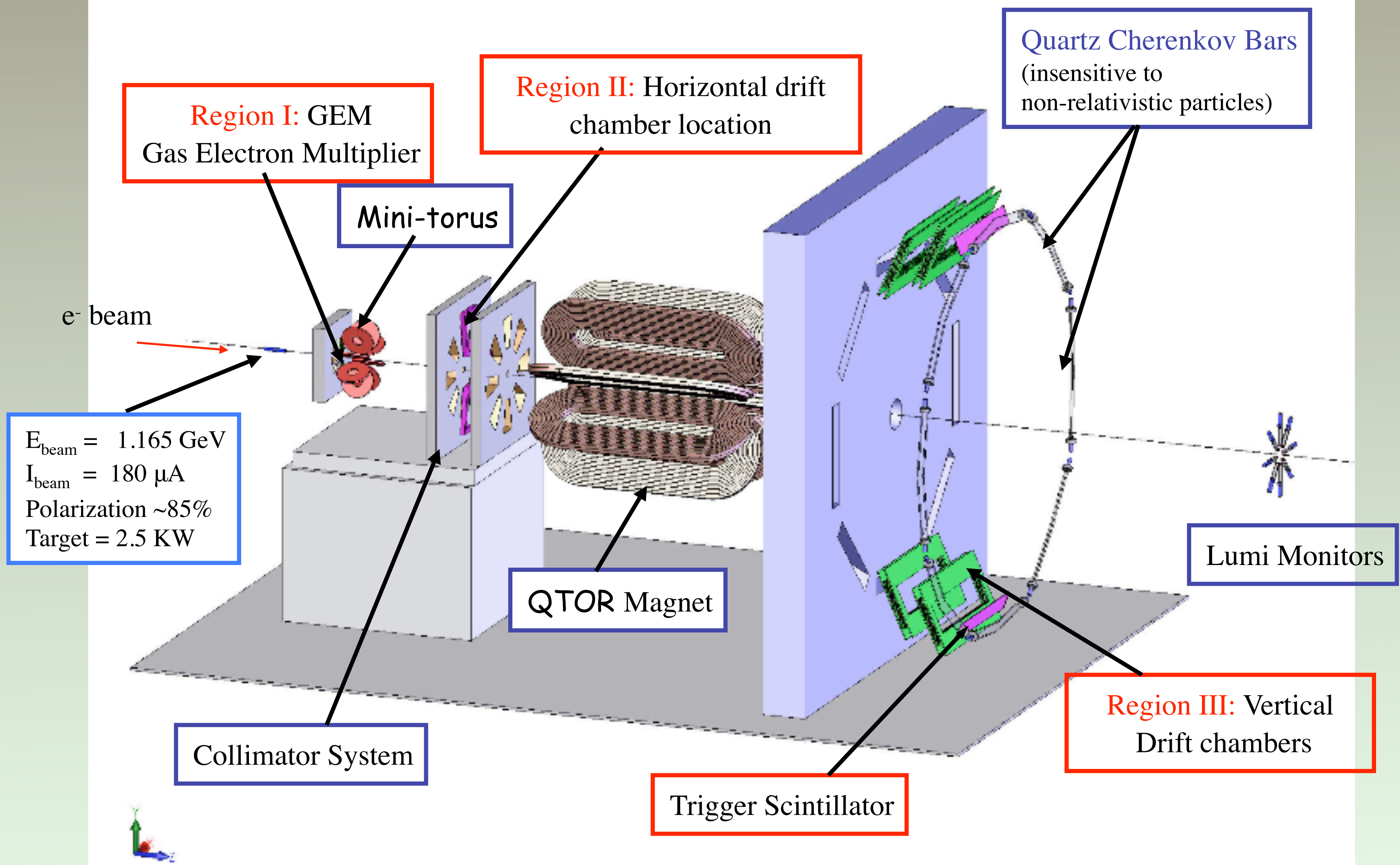
Angle: For a 0.37% error on the inner collimator angle
(corresponding to dR = 0.25 mm on R_{inner} = 67mm, or dL = 25 mm on L = 9.9 m):

dA/A(angle) = (dA/A)/(dθ/θ) x dθ/θ = 0.3 x 0.37% = **0.11%.**

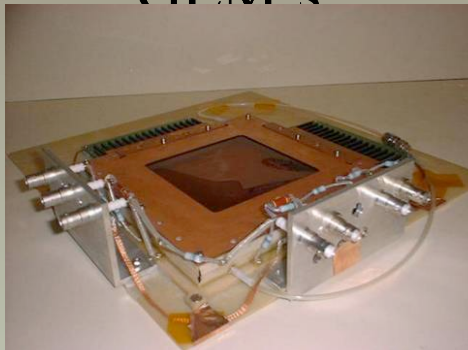
(the coefficient 0.3 is a factor of 8 more favorable than an equivalent e+p experiment)

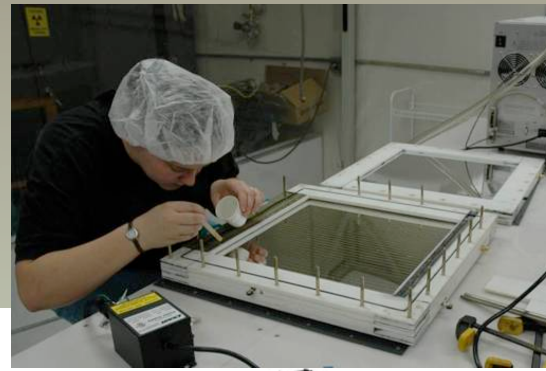
More careful study is needed, but Moeller kinematics are forgiving.
We have a lot of reserve!

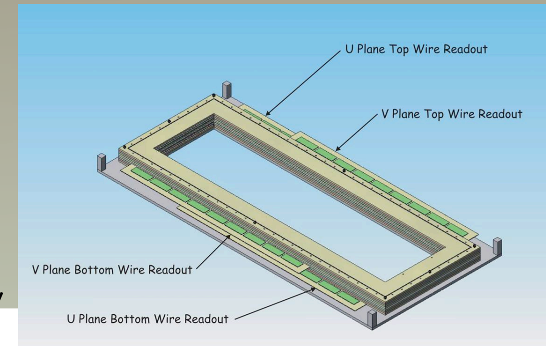
The Q^p_{Weak} Apparatus

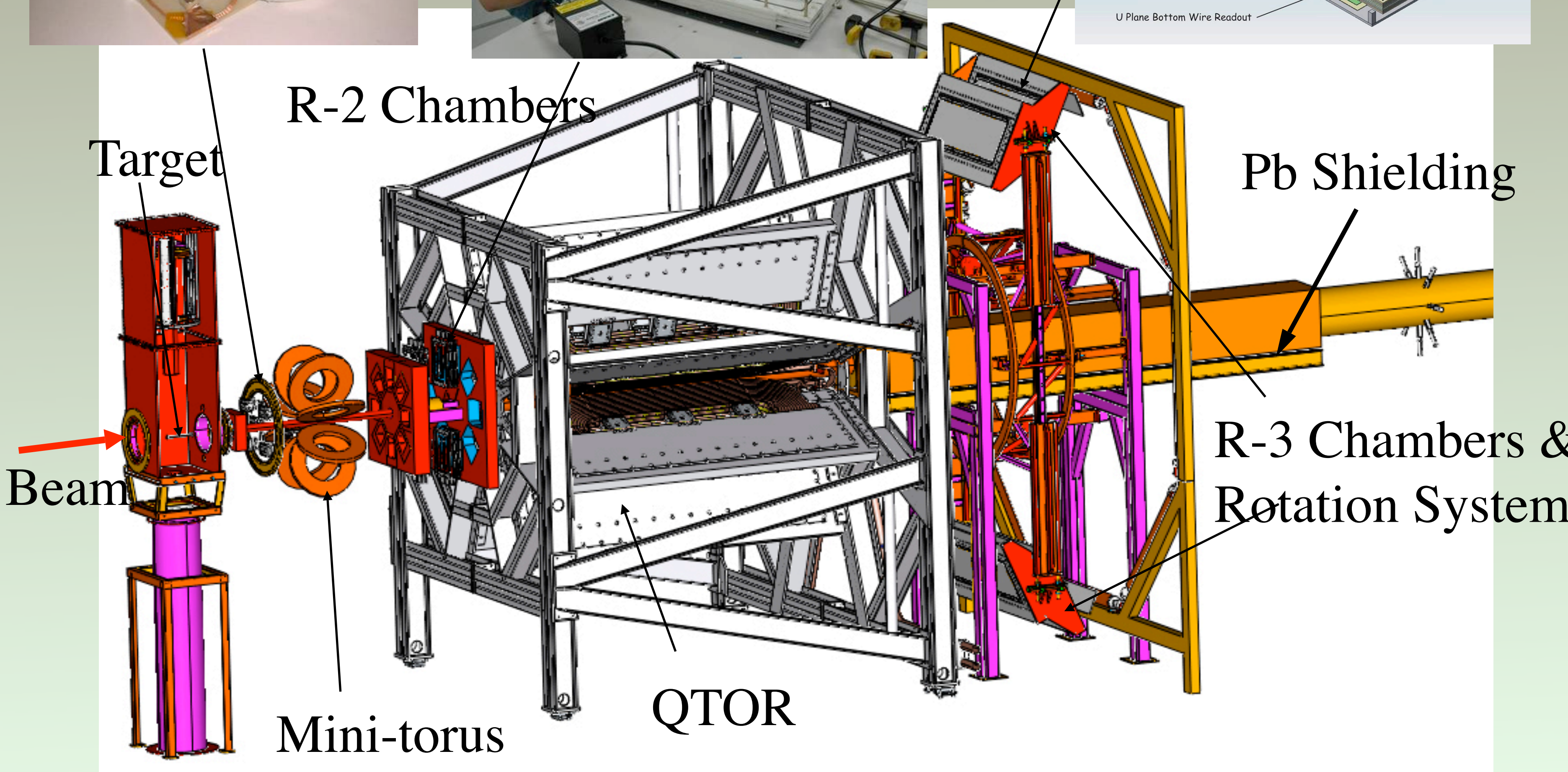


Tracking Systems (counting mode)









Overview of the Møller LH_2 Target System

Requirements: high luminosity (thick target), high cooling power, very low noise

• beam conditions: helicity flip 2000 Hz, 85 μA, 11 GeV e^- beam rastered 5x5 mm^2

→ deposits 4546 W in LH_2, total target power 5000 W (including overhead)

• LH_2 conditions: 20 K, 35 psia (2.4 atm), 1 kg/s (3.7 K sub-cooled liquid)

• closed re-circulating cryogenic loop for LH_2 with 150 cm (10.7 g/cm^2, 17.5 % rl) Al cell

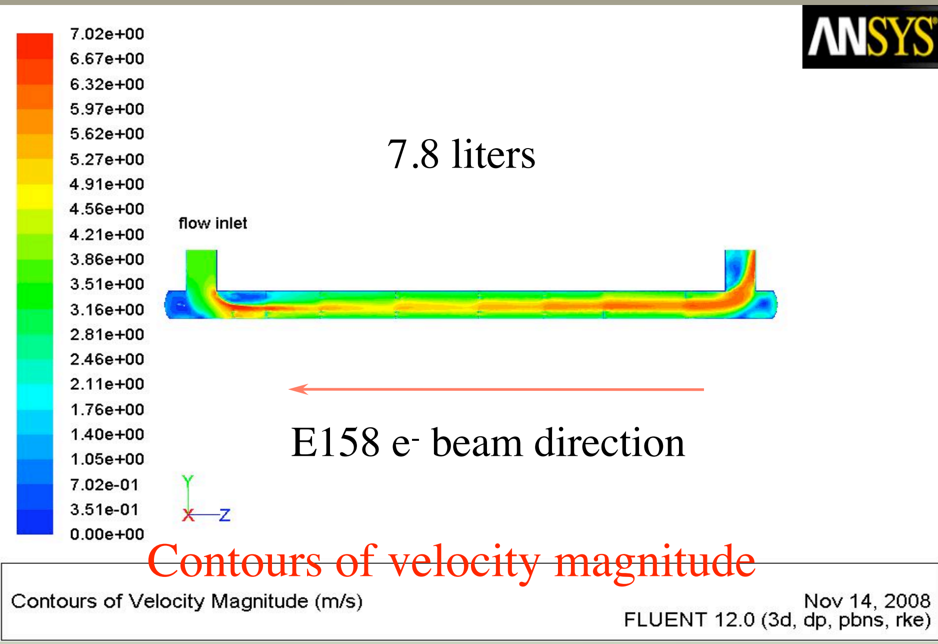
• noise scaling from G0 target measurements (238 ppm@30 Hz) would indicate ~26 ppm@2000 Hz for the Møller target, a 5 % increase to the counting statistical width of 77.3 ppm/pair

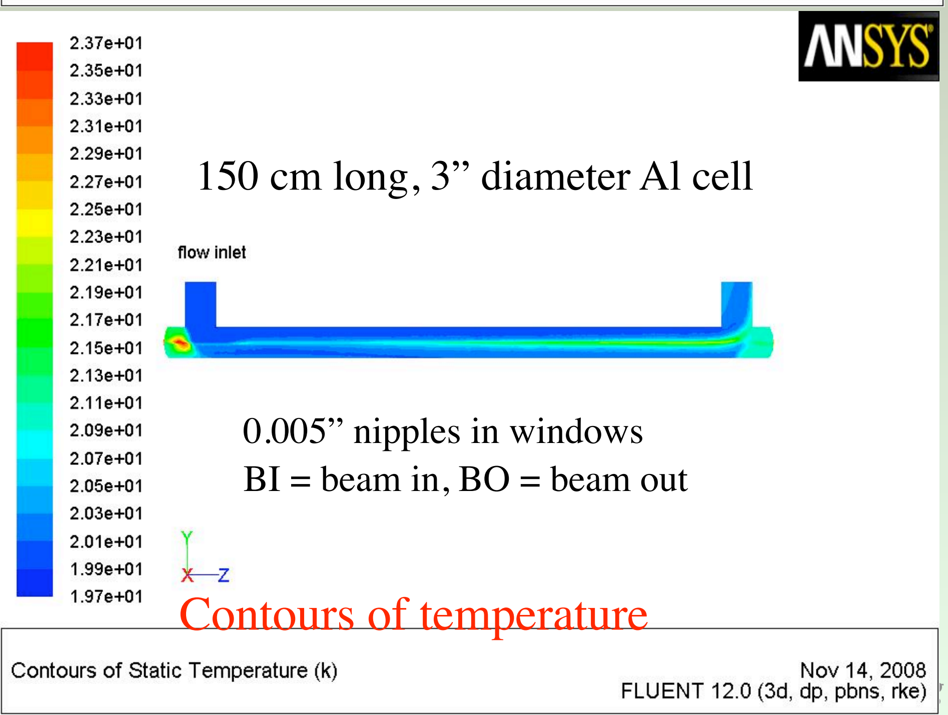
• the 2500 W Q_{weak} target is a critical precursor to the Møller target

• computational fluid dynamics (CFD) simulations are essential to the design of the Møller target components as well as any safety assessment

This is the highest power LH_2 target in the world

CFD simulations with FLUENT





Our starting geometry was the SLAC E158-style target cell.

Preliminary FLUENT results:

- ΔT (LH_2 in beam) = 1.23K,
  $\Delta\varrho/\varrho = 2\%$

- $\Delta P = 0.5$ psi @ 1.2 kg/s

- Flow in E158 cell was somewhat stagnant in the endcaps, but would not have boiled in a CW beam at the Al windows.

- This cell is indeed a good starting point. Improvements will be straightforward.

Scaling arguments for target noise

The measured detector asymmetry width

$$\sigma_m^2 = \sigma_0^2 + \sigma_b^2$$

where σ_m = measured, σ_0 = statistics (77.3 ppm/helicity pair), and σ_b is the LH_2 noise at 2000 Hz.

The target noise scales like

$$\sigma_b \propto \frac{P_{beam}}{A_{raster} \times \dot{m} \times f_{helicity}^{0.4}}$$

where P_{beam} is beam power, A_{raster} is the rastered area, mdot is the mass flow rate, and $f_{helicity}$ is the helicity reversal rate.

Scaling from the measured G0 target noise:

$$\sigma_b^{M\phi ller} = 238 \frac{4546}{320} \frac{4}{25} \frac{0.25}{1} \left(\frac{30}{2000} \right)^{0.4} \approx 26\, ppm$$

Possible He refrigeration solution for a 5000 W target

The “12 GeV” CHL may have no excess capacity

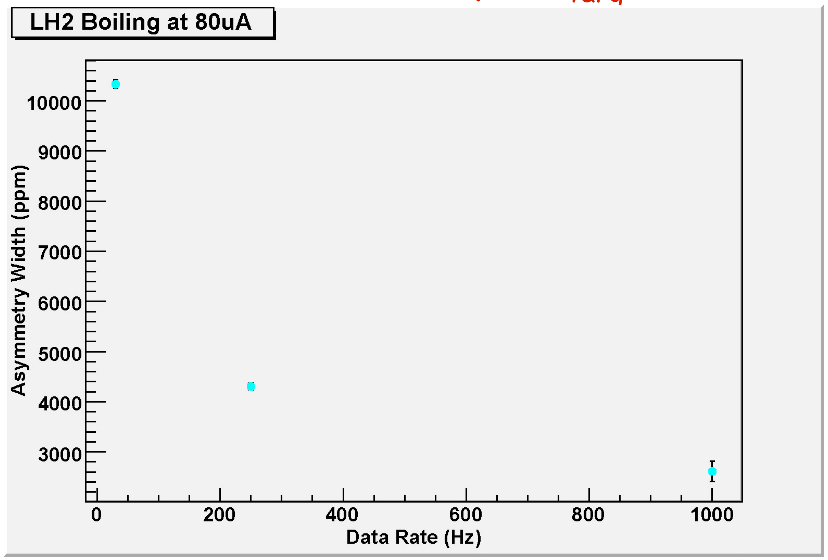
but

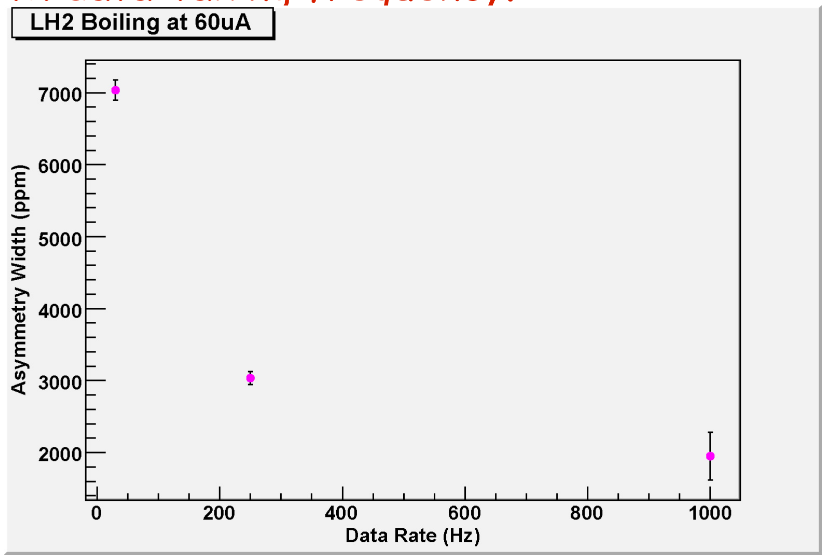
there is a 4kW-4K He cold box on site that can be converted into a 6kW-15K He cold box that will become ESRII.

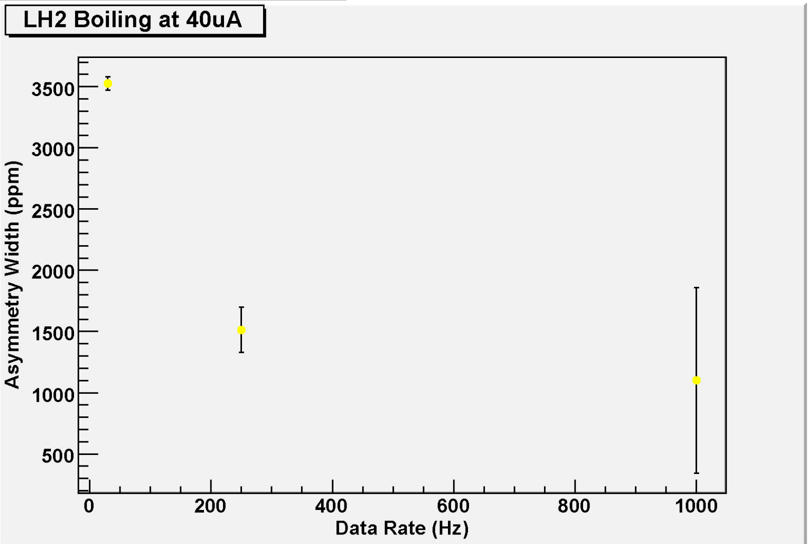
Time frame for changeover 2-3 years from the start of 12 GeV beam.

Dependence of Target "Boiling" Width on Data-Taking Rate

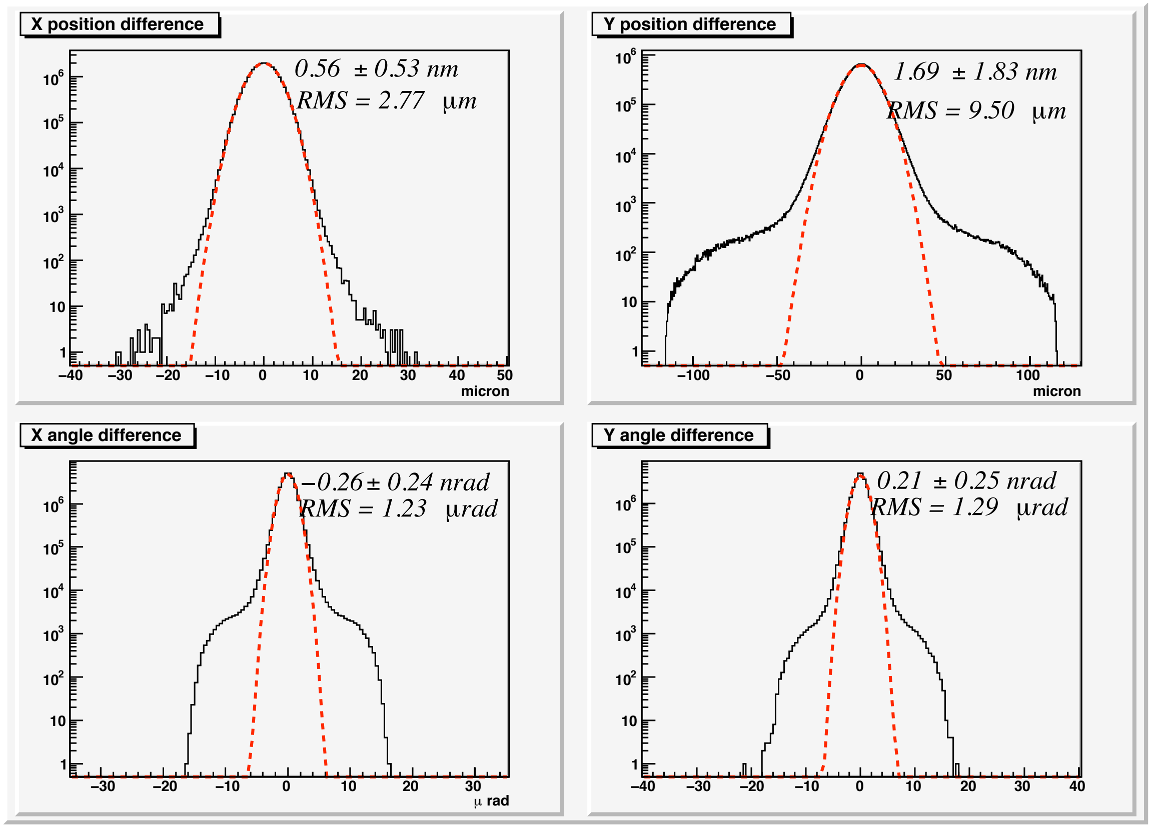
Studies were done with a 20 cm LH_2 target. Scattered particles were measured with luminosity monitors and target density fluctuation widths were extracted after other random noise effects were corrected for with a carbon target. At 40, 60, 80 μA the target boiling width is well-described by a $\Gamma_{targ} \sim f^{-0.4}$ scaling law with data-taking frequency.







HAPPEX-II beam corrections



1 month runtime : random jitter dominates

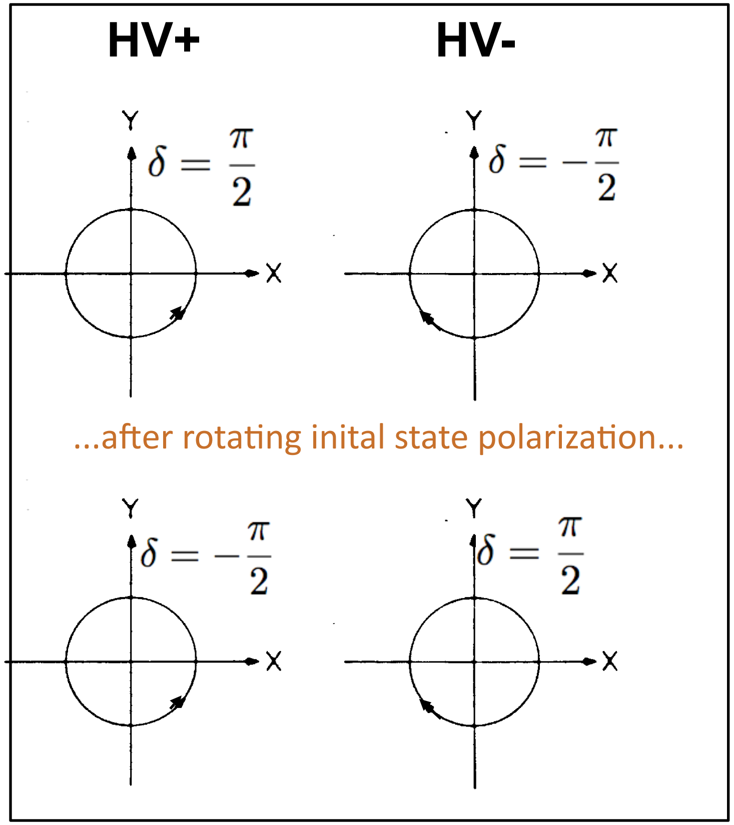
position < 2nm
angle < 0.25 nrad

Position feedback will likely be required to speed convergence ~ factor of 5

1st order beam corrections

Property	Sensitivity	precision	required helcity-correlation	Systematic contribution
Charge Asymmetry	1 ppb / ppb	~1%	<10 ppb	~0.1 ppb
energy	-1.4 ppb/ppb	~10%	<0.3 ppb	~0.05 ppb
position (on target)	0.85 ppb/ nm	~10%	<0.5 nm	~0.05 ppb
angle	8.5 ppb/nrad	~10%	<0.05 nrad	~0.05 ppb

Insertable Half-wave plate



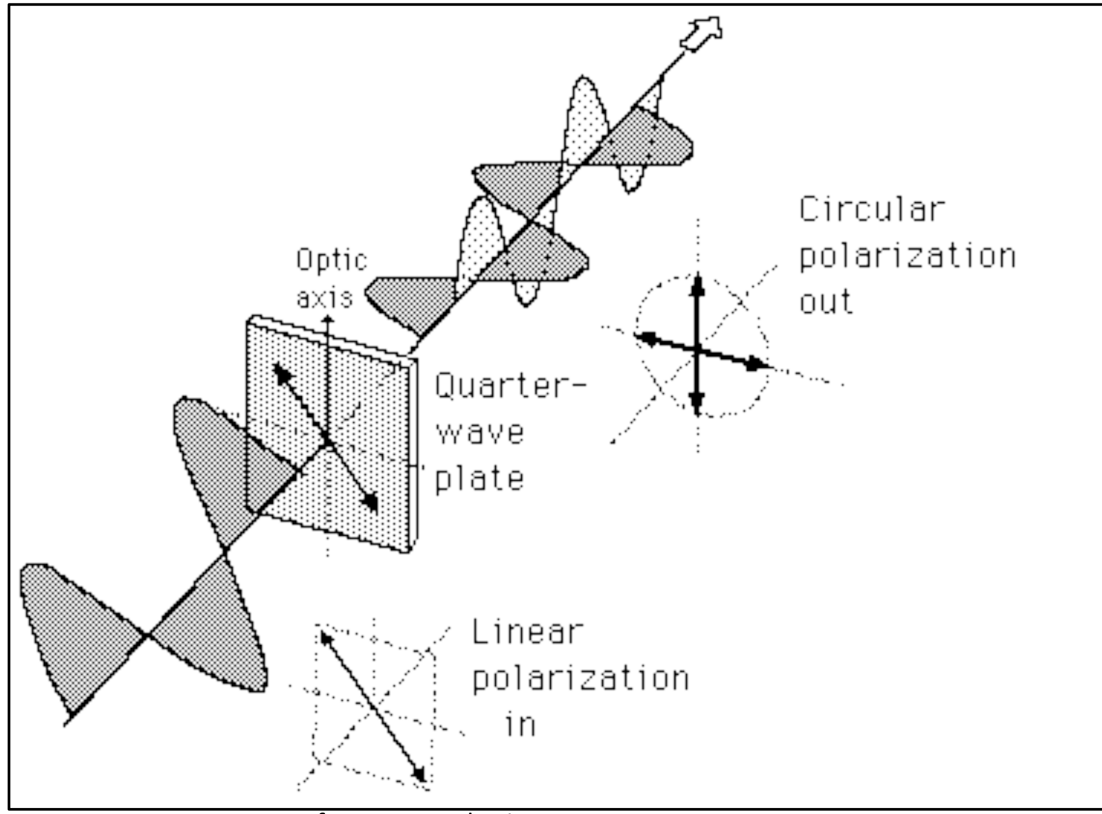


Image from HyperPhysics:
http://hyperphysics.phy-astr.gsu.edu/Hbase/hph.html

IHWP flips sign of cathode analyzing power with respect to Pockels cell voltage, but also:

- all analyzing power with respect to Pockels cell, and
- all birefringence downstream of Pockels cell

Most beam asymmetries ARE NOT cancelled by the IHWP

2nd order beam corrections: spot size

Spot Size

- Sensitivity ~ 120 ppm x $\delta\sigma/\sigma$
- Should be bound to $<10^{-4}$ in laser optics
- g-2 slow reversal : factor of 10

Final contribution: 0.1 ppb

Helicity Sequence

60Hz line noise must cancel to avoid conflating electronics noise with sensitivity to beam dynamics

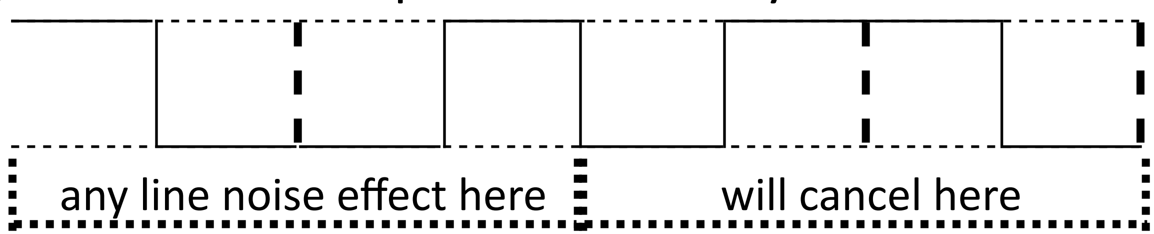
Present scheme (30 Hz) automatically handles this, as each window is ~2 60Hz cycles long.

Best Solution: form pulse-pair groups to combine high-frequency noise suppression with 60 Hz line noise averaging

Example: at 240 Hz reversal, 4 windows completes a 60 Hz cycle.

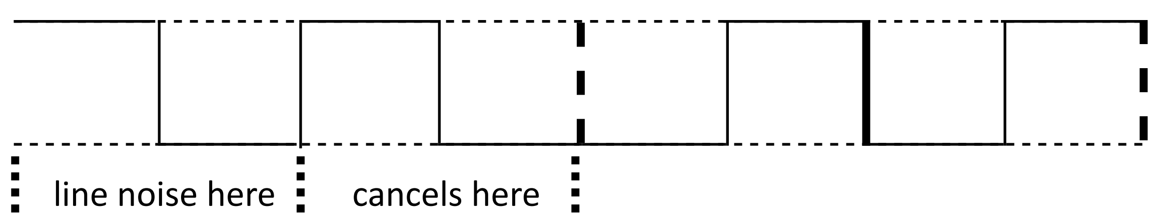
Option 1: Choose 2 pairs, force complementary two pairs to follow

Analyze each "macropulse" of 8 windows together



Option 2: Choose 1 pair followed by the same pair, every time.

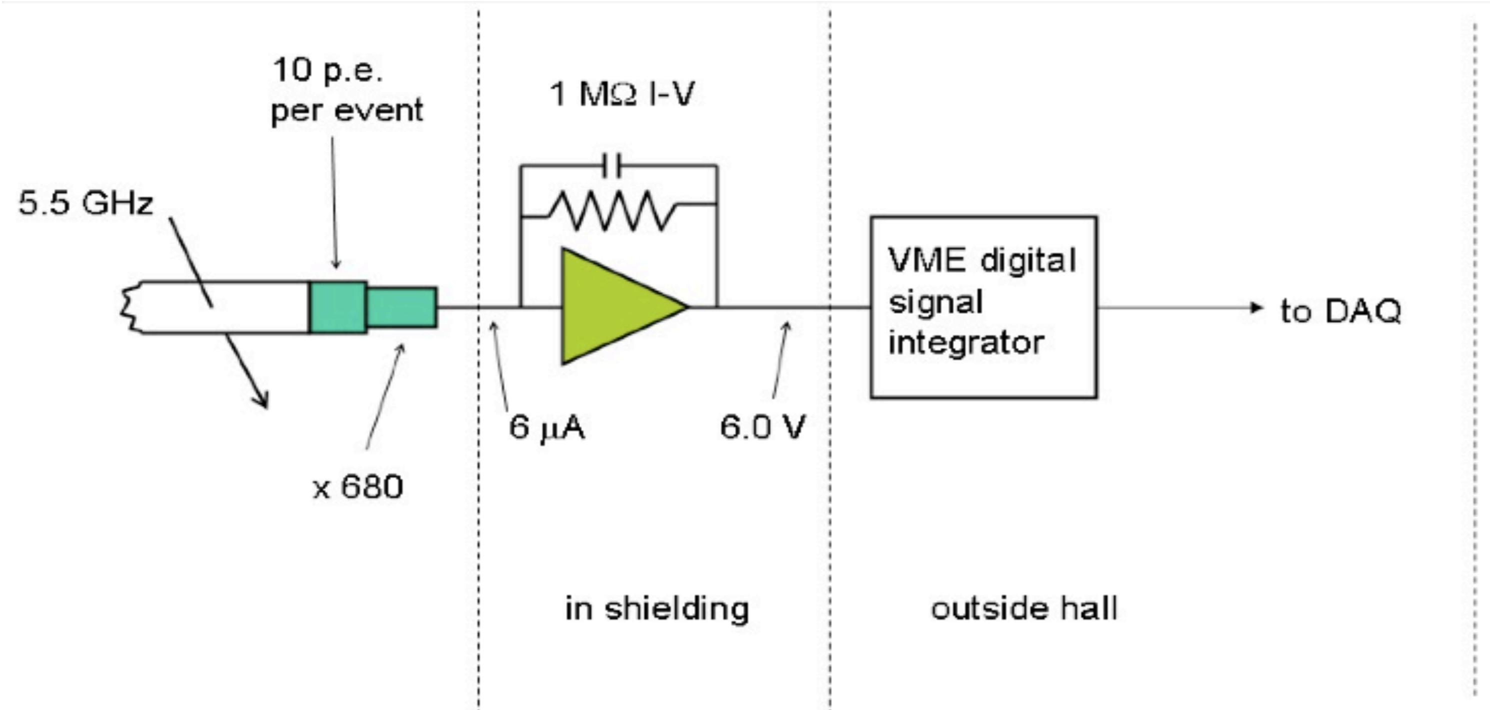
Analyze each "macropulse" of 4 windows together



Potential drawback is additional sensitivity to low frequency electronics noise

Signal Path

Current signals from the detector are first converted to large voltage signals using nearby, low-noise preamplifiers. The amplified signals are then sent outside the hall to precision digital integrators.

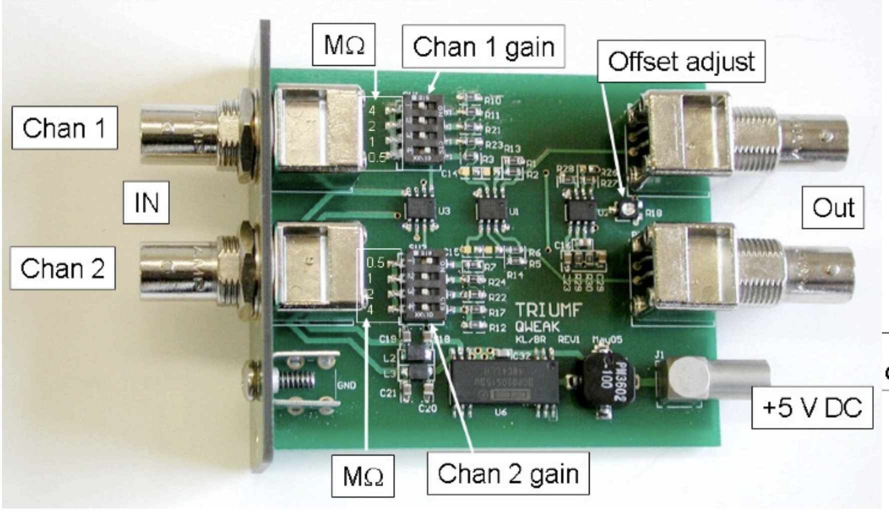


Low-Noise Electronics

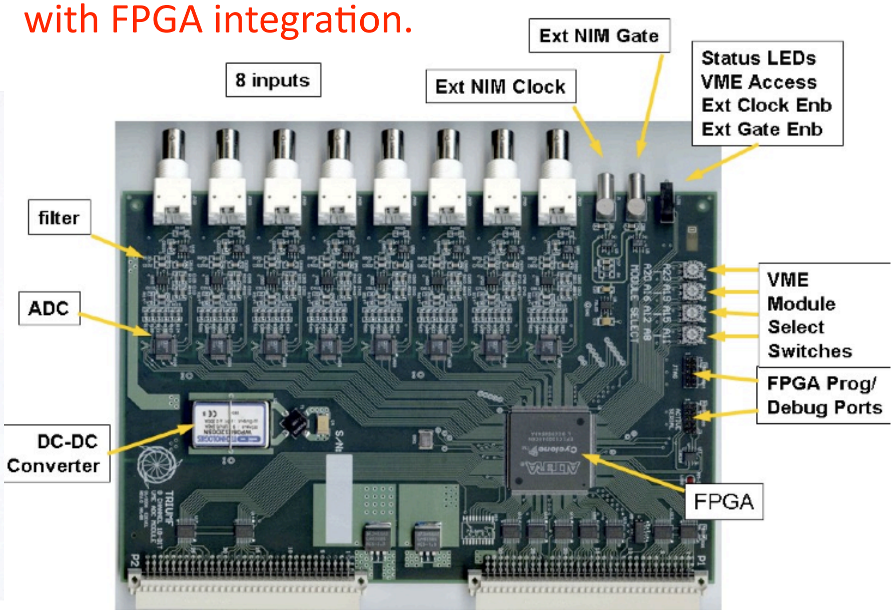
Our TRIUMF collaborators originally developed low-noise electronics for their own parity program. They have built custom versions for the Qweak experiment.

The same or similar electronics would be used in this experiment.

TRIUMF low-noise preamplifier (I-to-V) with RF shield removed.



TRIUMF 18-bit, 500 KHz sampling ADC with FPGA integration.



Electronic Noise, Counting Statistics, and Isolation Tests

In the table below, the electronic noise from the pre-amp and digital integrator are negligible compared to the noise from the counting statistics of electron tracks, 1/√N.

This is critical to preserving our statistical error bar.

Noise Source	charge quantization at pre-amp input	Noise density $\mu V/\sqrt{Hz}$	RMS Noise in 500 Hz Bandwidth (1 ms integral)
electron track counting statistics	6800e	114	2560 μV
LED test shot noise	680e	36	800 μV
battery test shot noise	1e	1.4	31 μV
pre-amp	—	0.5	11 μV
digital integrator	—	1.3	29 μV

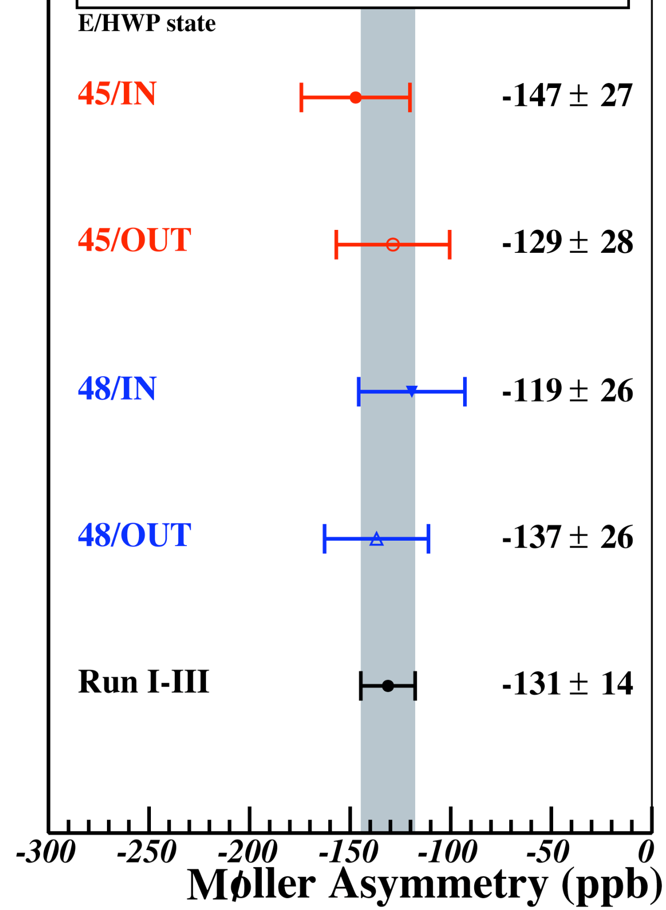
Furthermore, because each electron track yields a packet of 6800 electrons at the preamplifier input , (10 pe's/track x PMT gain of 680), the noise in a *battery* test will be 1/√6800 times smaller.

A low noise battery test will permit a < 1 ppb null test in a day, warning us of a potential false asymmetry due to electronic pickup.

Slow Helicity Reversal

"slow" helicity reversals are an important component of a comprehensive strategy to control HCBA

SLAC E158 used an energy change to create a g-2 spin flip into End Station A



Why use slow reversal:

- Comparison to two data sets rules out gross problems, at the level of ~4σ of final error bars
- Addition of two data sets implies cancellation of subtle problems (at least those susceptible to cancellation under the reversal)

Why use more than one:

- Effectiveness relies on flipping helicity without changing systematic effect... you need the right flip for the specific possible systematic effect

g-2 and Injector Spin Manipulation

g-2 spin rotation is available with 100 MeV energy shift

Near ideal cancellation for 1st and higher order beam systematics... but machine tuning requirements mean long time scale for reversal

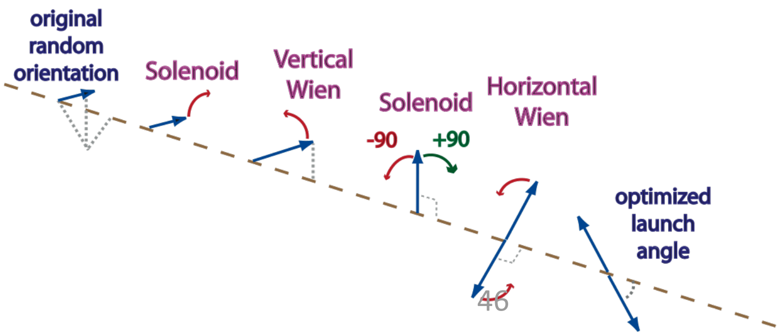
Injector Spin Rotation

Wein Spin Rotator

• Crossed E/B fields intrinsically focus the beam. 180^o spin flip from Wein will <u>not</u> perserve the beam properties!

• Solution: incorporate Wein with solenoids, and accomplish spin flip with +/-90 degree solenoid rotation. Solenoids focus as B^2, so this minimally changes beam transport properties.

Two Wien rotations, optimized once then held constant, with +/-90 degree solenoid rotation

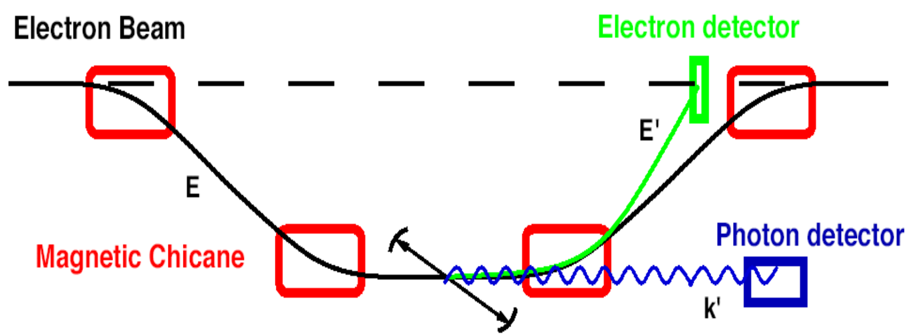


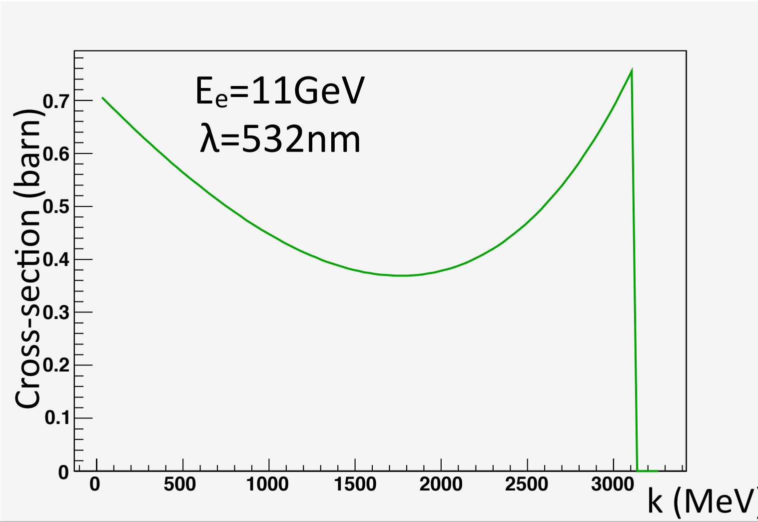
Wein upgrade project now underway at JLab to support the 2010 experiments

Polarimetry

Need major effort to establish unimpeachable credibility for 0.4% polarimetry
= two separate measurements, with separate techniques, which can be cross-checked.

Compton Polarimetry



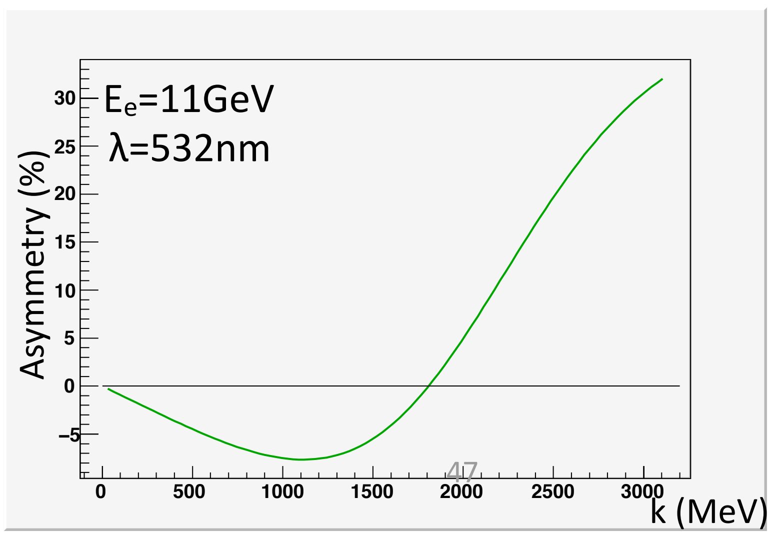


For scattered electrons in chicane:
two Points of well-defined energy!

- Asymmetry zero crossing
- Compton Edge

Integrate between to minimize error on analyzing power!

"independent" Photon analysis also normalizable at ~0.5%



High Precision Compton

At high energies, SLD achieved 0.5%.

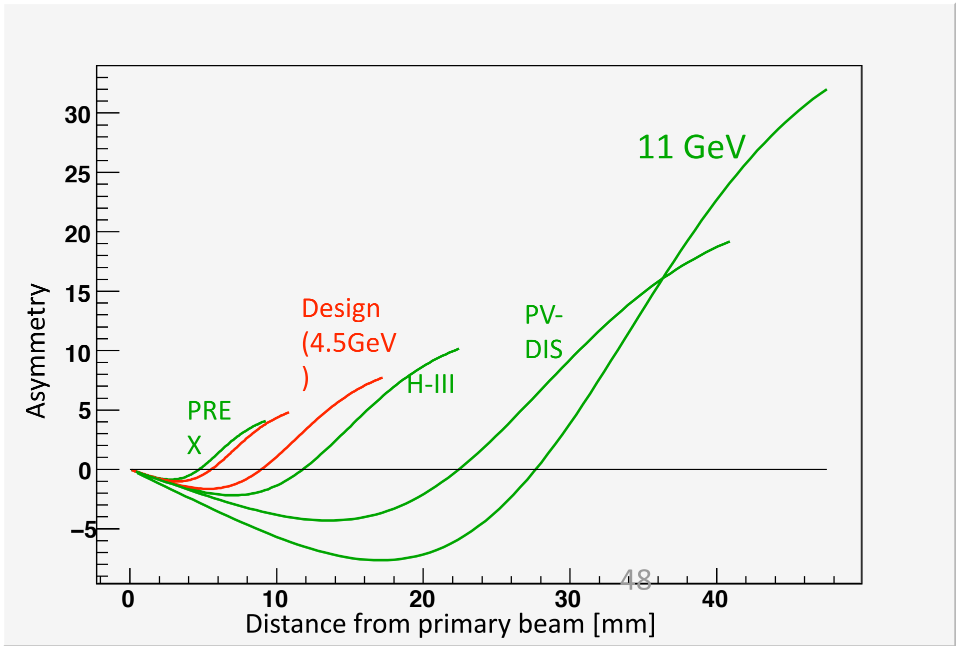
Why do we think we can do better?

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

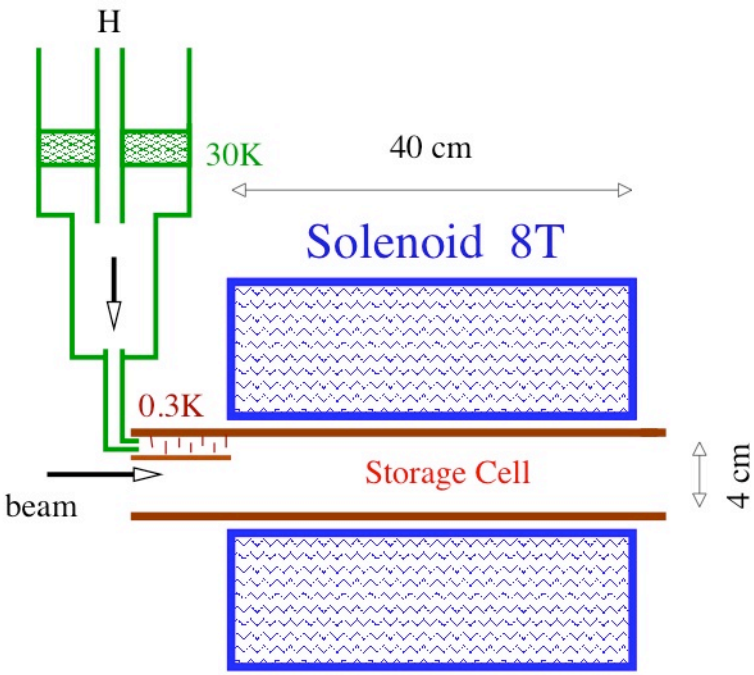
> Its a major effort and a full time job, but there is no obvious *fundamental* show-stopper

So why haven't we done better before?

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



Atomic Hydrogen For Moller Target



10 cm, ρ = $3\times10^{15}/cm^3$
in B = 7 T at T=300 mK

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

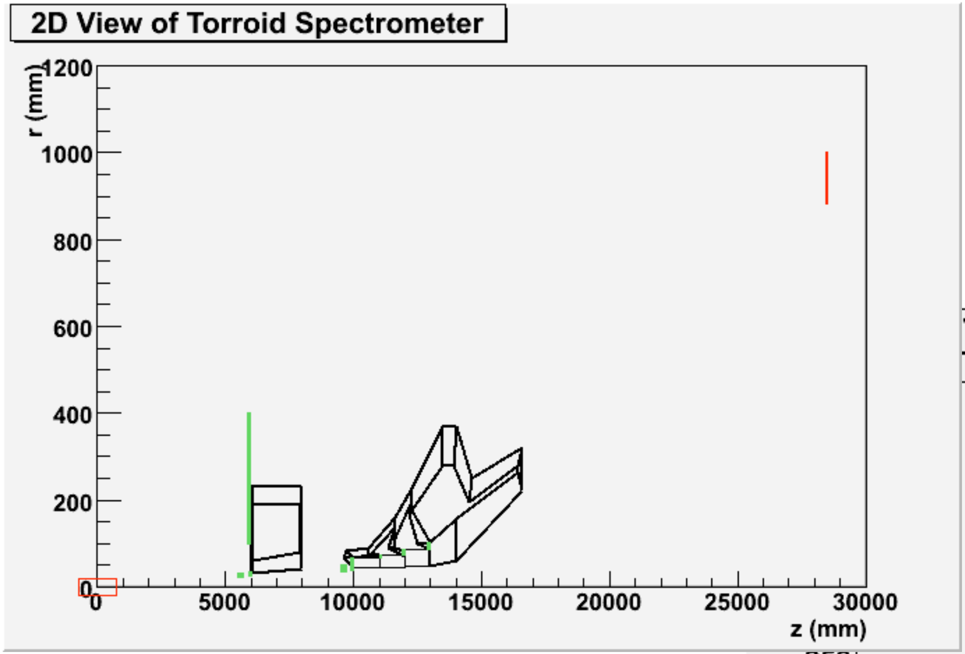
Brute force polarization

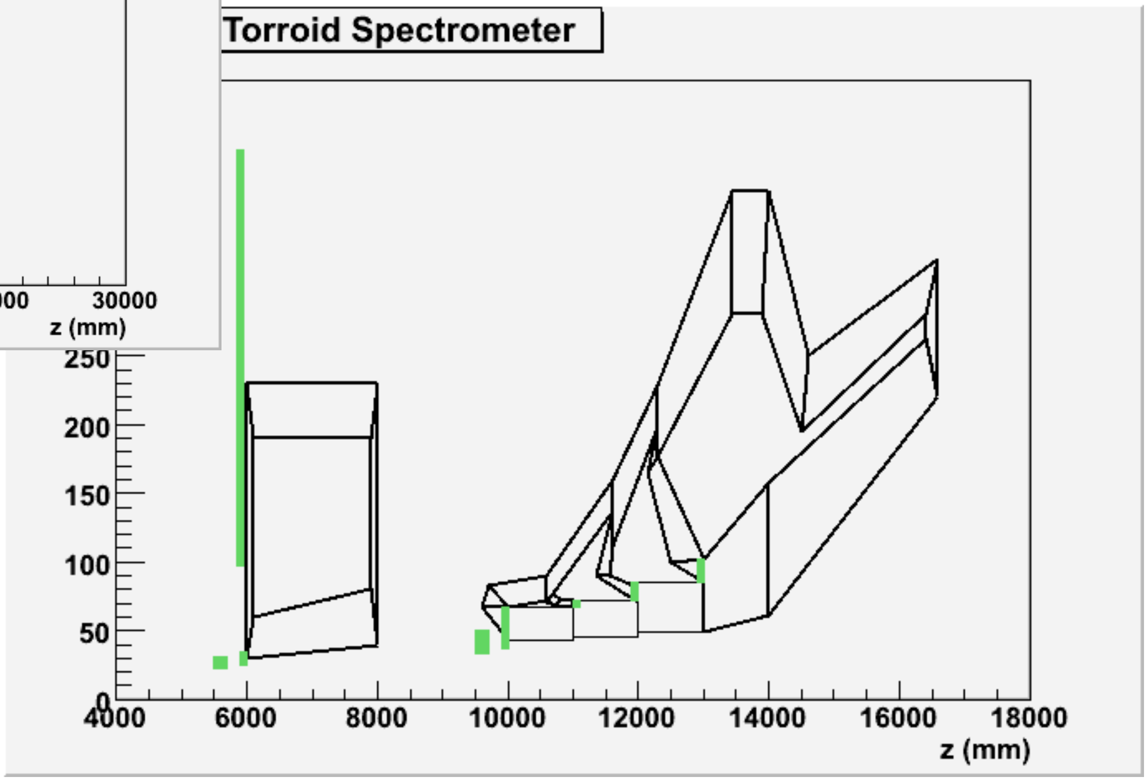
Moller polarimetry from polarized atomic hydrogen gas, stored in an ultra-cold magnetic trap

- 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

Collimation





Main Detector Requirements

•Full coverage of e+e→e+e locus

•Good coverage of e+p→e+p including radiative tail

•Rad-hard

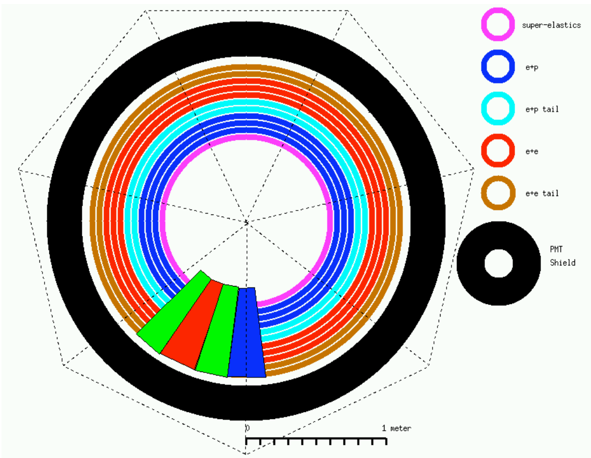
•Low excess noise (i.e., shower and electronic noise should be negligible)

•Radial segmentation for systematics (backgrounds)

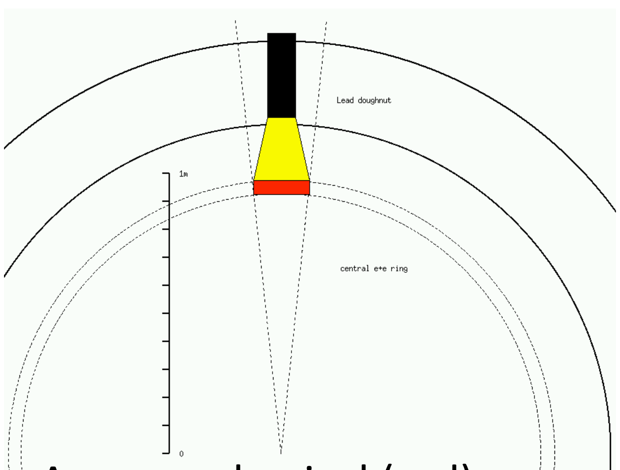
•Azimuthal segmentation for systematics (e.g., parity-conserving cos(Φ) asymmetries, azimuthal defocusing, beam sensitivities, backgrounds, etc.)

Our collaboration will investigate several straightforward detector technologies which are consistent with our proposed budget . We will then choose the best option(s).

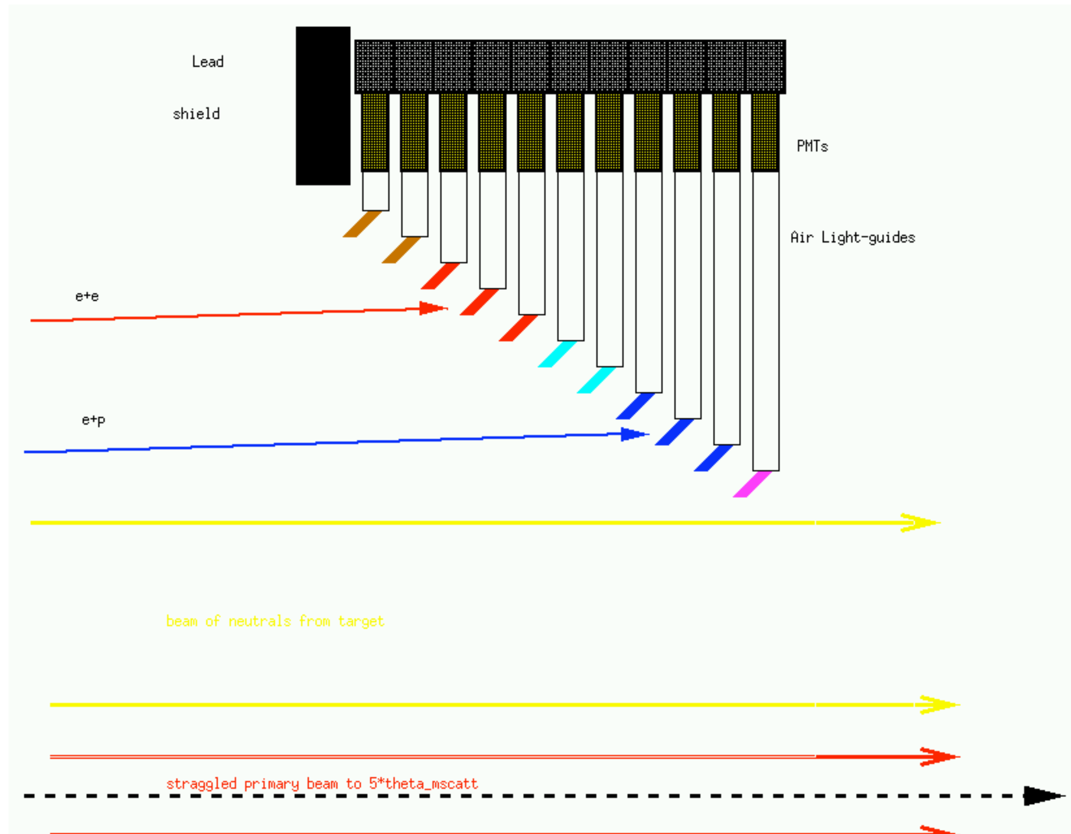
Main Detector Reference Design



Front view



An example pixel (red) with lightguide (yellow)



Side view

Main Detector Dimensions

Table 1: *Miscellaneous detector parameters.*

Parameter	Value
radiator shape	rectangular (e+p region)
	rhomboidal (e+e region)
radiator size	5 cm (H) x 2 cm (T), length 11-25 cm (increases with radius)
radiator material	artificial fused silica (Spectrosil 2000 or JGS1-UV)
radiator position	Z = 28.5m downstream of the target center)
	(for central $e + e \rightarrow e + e$ detector)
	R = 57.5-62.5 cm (super-elastic region)
	R = 62.5-77.5 cm (e+p events)
	R = 77.5-87.5 cm (e+p tail)
	R = 87.5-102.5 cm (e+e events)
	R = 102.5-112.5 cm (e+e tail)
Lead doughnut dimensions	10 cm (thick) x 117.5cm (inner radius) x 147.5cm (outer radius)
Lead doughnut weight	7000 lbs

Main Detector Signals

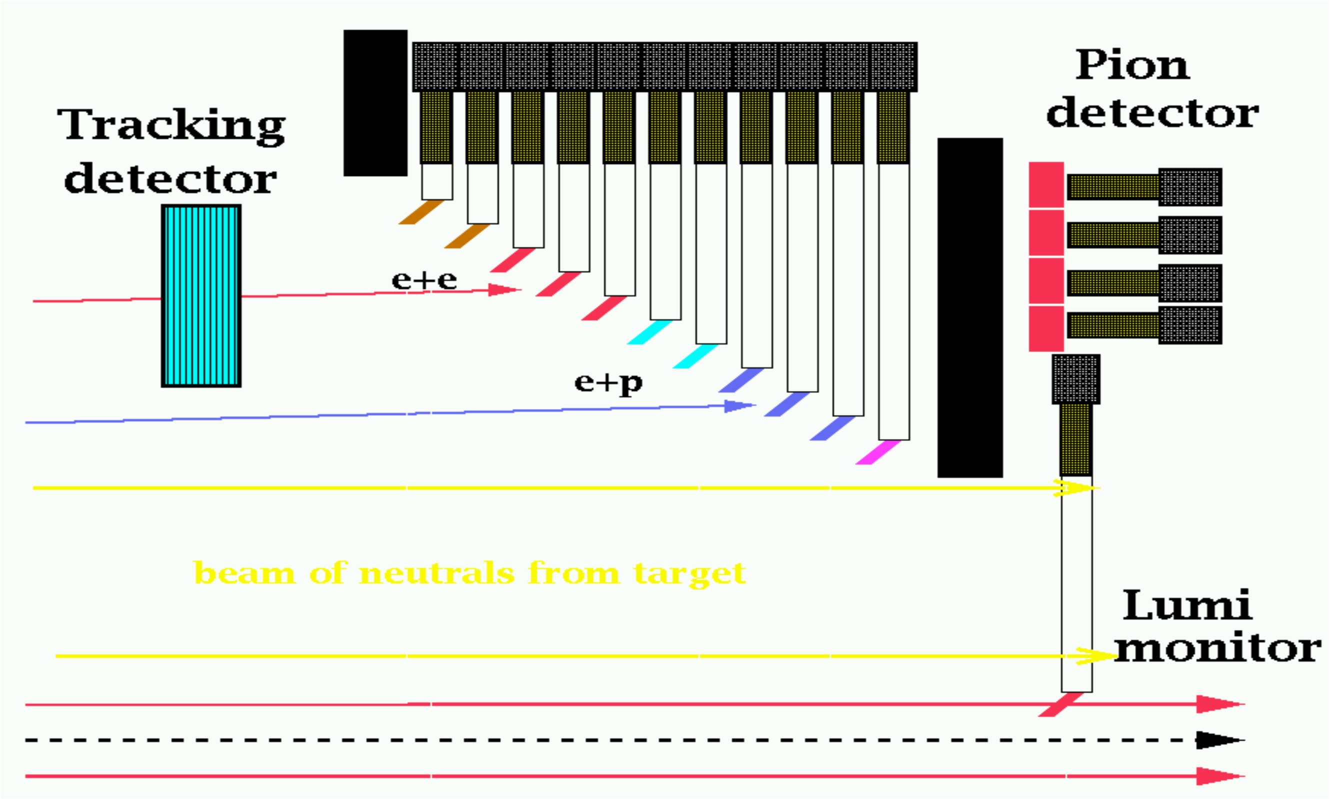
Table 2: *Parameters for the PMT signals in an average azimuthal bin for* $e + e \rightarrow e + e$*. A single radial bin has been assumed.*

Parameter	**Value**
Total PMTs	308 (28 azimuthal bins x 11 radial bins)
current mode:	
$I_{cathode}$	9 nA
gain	675
I_{anode}	6 μA
non-linearity (goal)	5×10^{-3}
pulsed mode:	
$I_{cathode}$	0.16 pA at 100 KHz
gain	1×10^{7}
I_{anode}	1.6 μA
V_{signal} (no amp.)	8 mV for 1 pe; 80 mV for 10 pe
non-linearity (goal)	$< 10^{-2}$

Ancillary Detectors

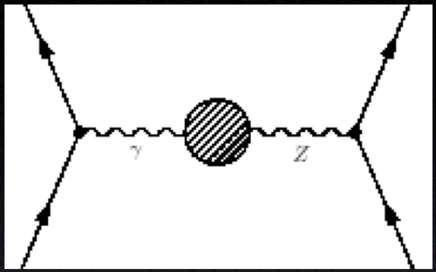
Tracking detector – event mode detector which operates only at low luminosity to measure the detector response, search for backgrounds, etc.

Pion detector – integrating detector which operates at high luminosity to measure the PV asymmetry of muons and charged pions after EM shower products are ranged out by lead shielding.



Luminosity monitor – integrating detector at small angles

application to $\sin^2 \hat{\theta}_W(\mu)$



- rigorous (same spectral and kernel functions) once a set of quark masses have been accepted.
- $\sin^2 \hat{\theta}_W(0)$ important input for low energy observables, like APV, E158, Qweak, 12 GeV Møller, ...

source	uncertainty
s quarks	0.00005
OZI rule	0.00003
isospin	0.00001
non-param.	0.00006
data/OPE	0.00003
α_s	0.00004
m_c, m_b	0.00004
sub-total	0.00009
$\sin^2 \hat{\theta}_W(M_Z)$	0.00015
TOTAL	0.00016

Future improvements

- s quarks: currently very conservative. In future use τ spectral functions? 0.00005 → 0.00003
- e+e- data already improved, and will continue to improve: 0.00003 → 0.00002
- strong coupling will incrementally improve in the future: 0.00004 → 0.00002
- sum rule error on charm quark mass currently inflated; expect 0.00004 → 0.00003
- in total: ±0.00009 → ±0.00006