The Moller Project at Jefferson Laboratory

Krishna S. Kumar
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A Global Strategy

Direct and Indirect Searches for Physics Beyond the Standard Model

Compelling arguments for "New Dynamics" at the TeV Scale

A comprehensive search for clues requires:

Large Hadron Collider ***as well as*** **Lower Energy: $Q^2 << M_Z^2$**

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Nuclear/Atomic systems address several topics; complement the LHC:

- *Neutrino Masses and Mixing*
  - *$0\nu\beta\beta$ decay, reactor θ_{13}, long baseline experiments*
- *Rare or Forbidden Processes*
  - *EDMs, other CP & T-Violation, Charged Lepton Flavor Violation*
- *Dark Matter Searches*
- *Precision Electroweak Measurements*
  - *weak neutral currents at low energy, muon g-2, weak decays*

OUTLINE

- **Physics Motivation**
  - *Weak Neutral Current Interactions at Low Energy*
    - Parity-Violating Electron Scattering
  - *Møller Scattering*
    - The MOLLER Project at Jefferson Laboratory
- **Experimental Technique**
  - *Main Components of the Apparatus*
  - *Statistical & Systematic Errors*
- **Status and Plans**

Physics Motivation

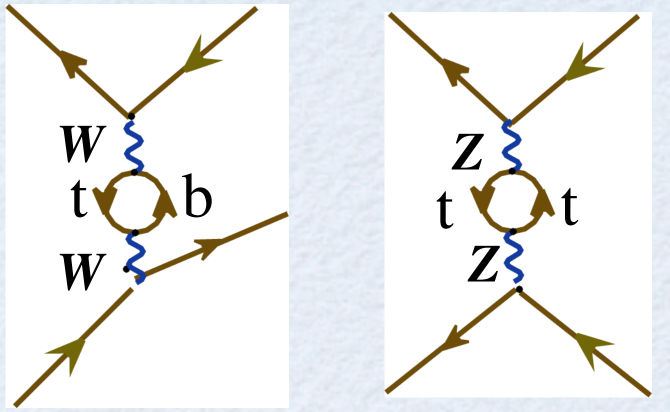
Precision EW Physics

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

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

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

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



Muon decay *Z production*

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

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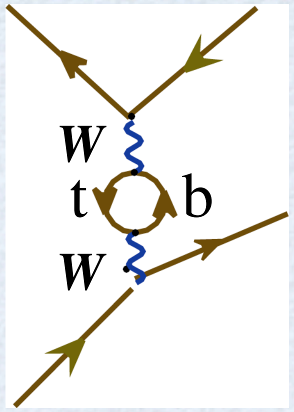

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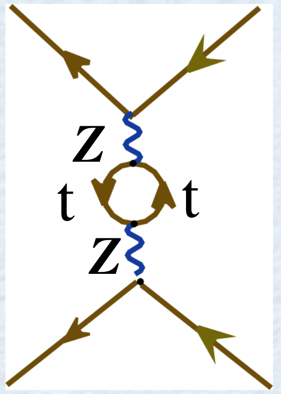

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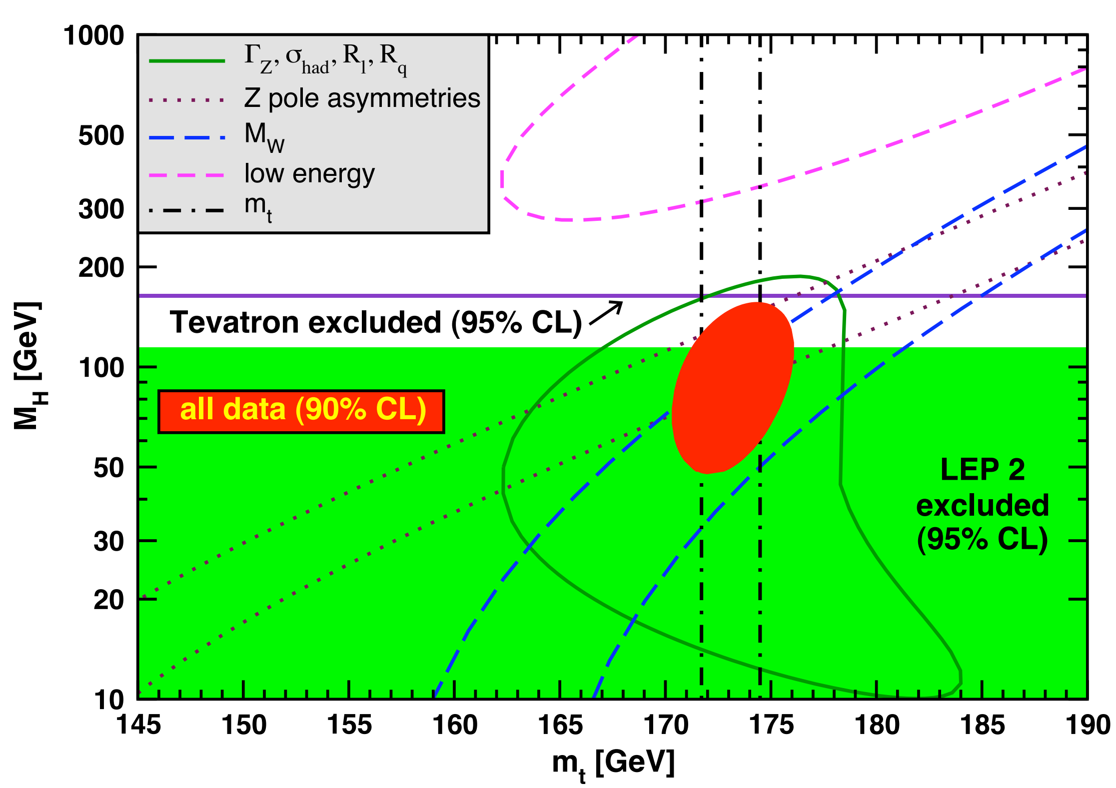

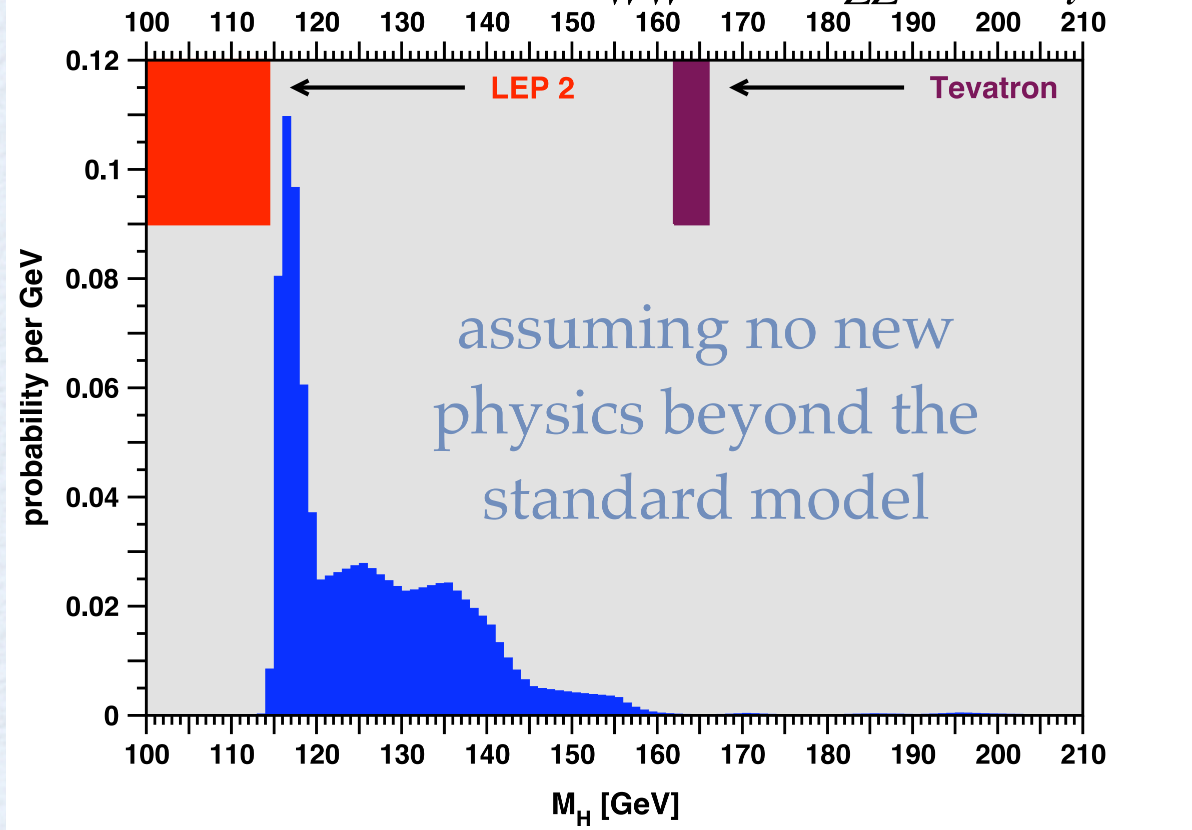

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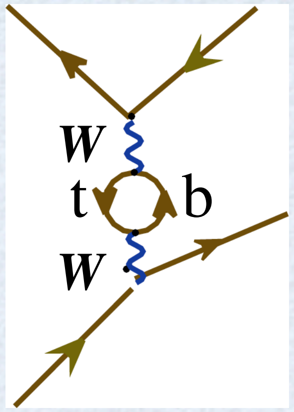

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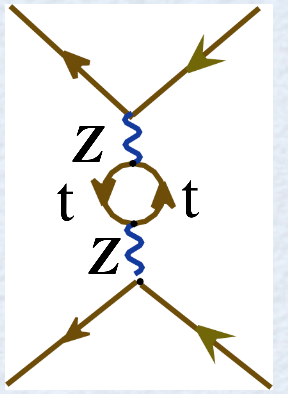

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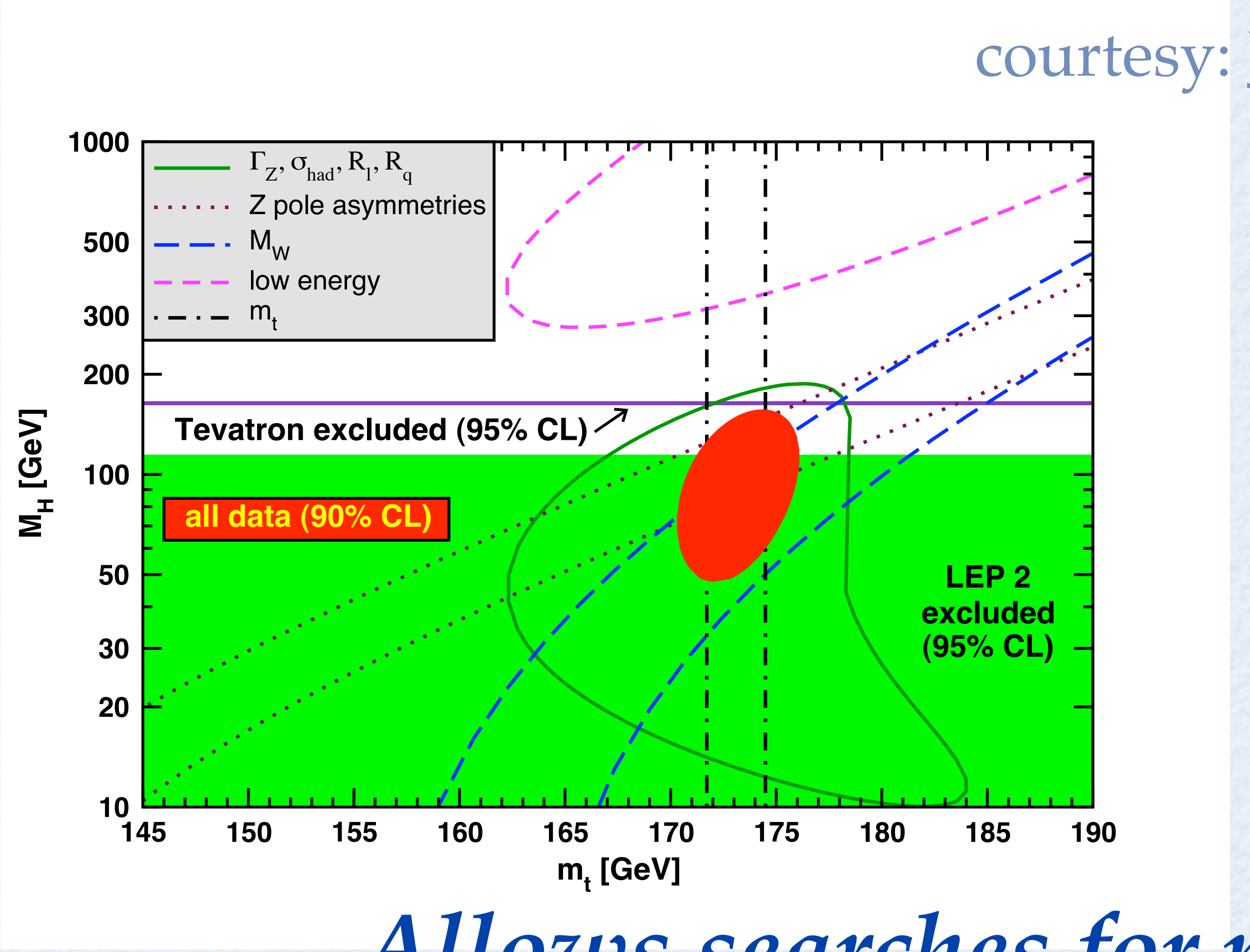
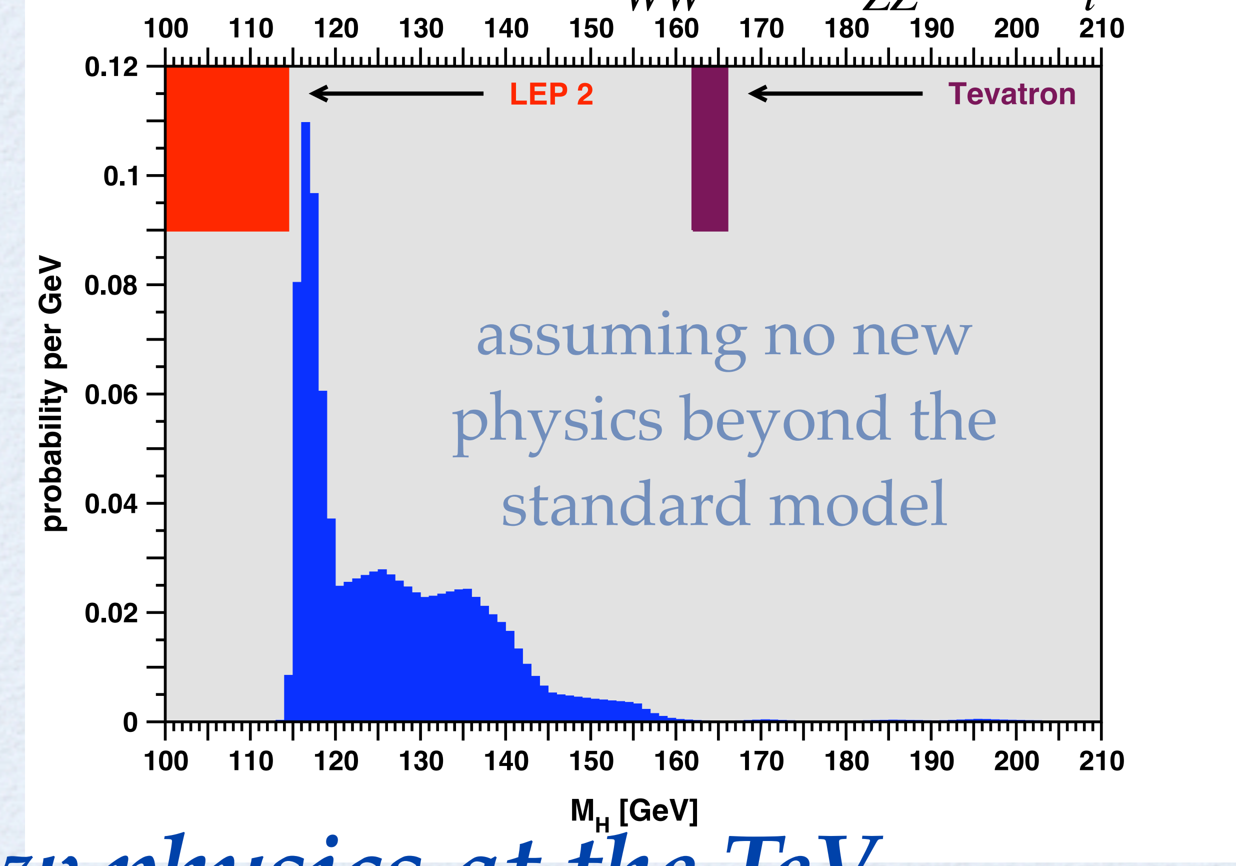
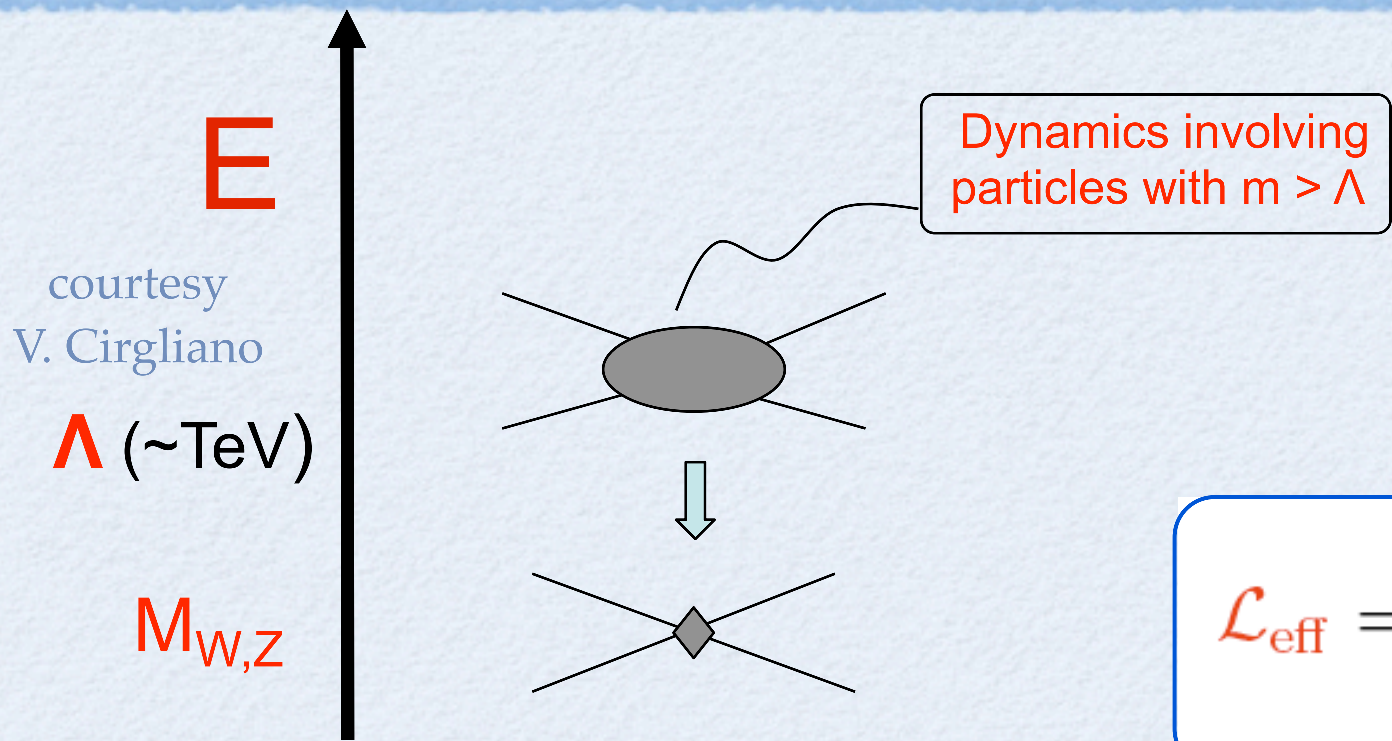




Allows searches for new physics at the TeV scale via small measurement deviations

Comprehensive Search

Neutral Current Interactions at Low AND High Energy



Many theories predict new forces that disappeared when the universe cooled

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

$$\Downarrow$$

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

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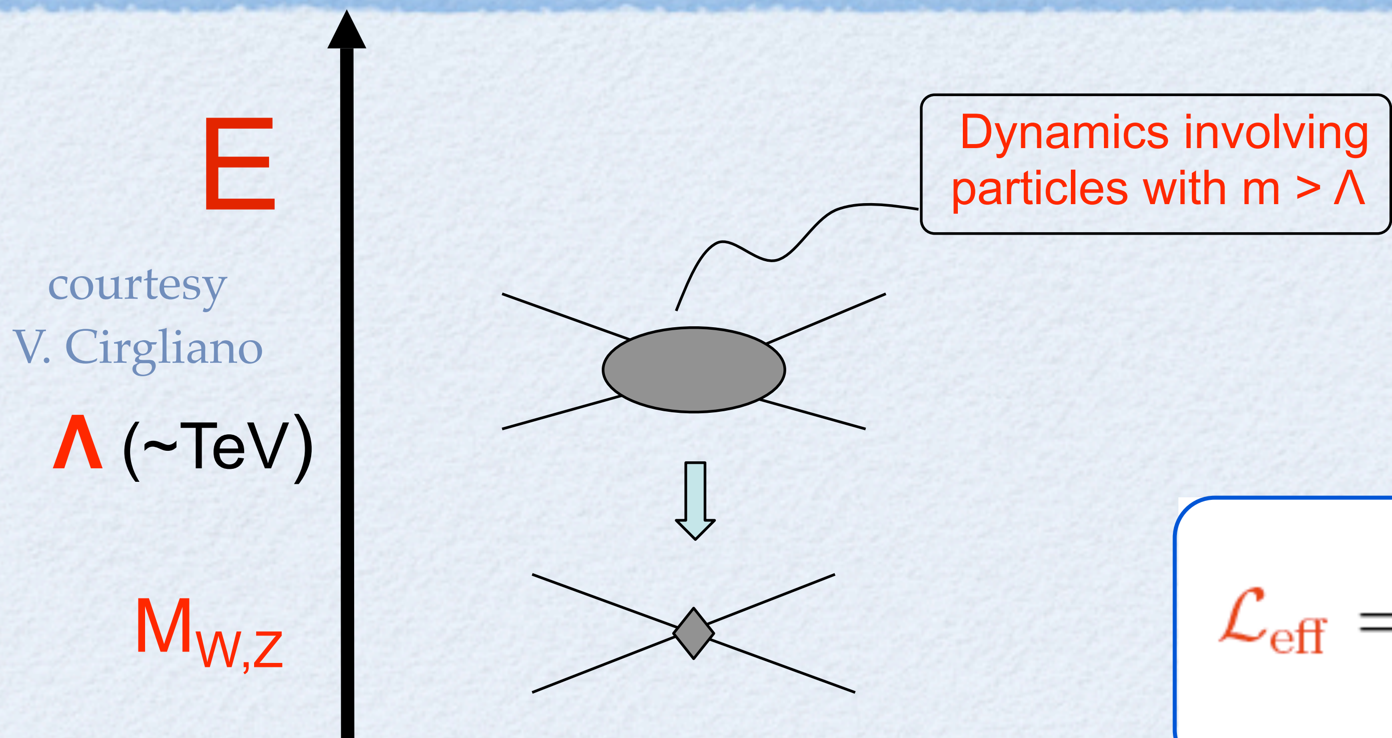

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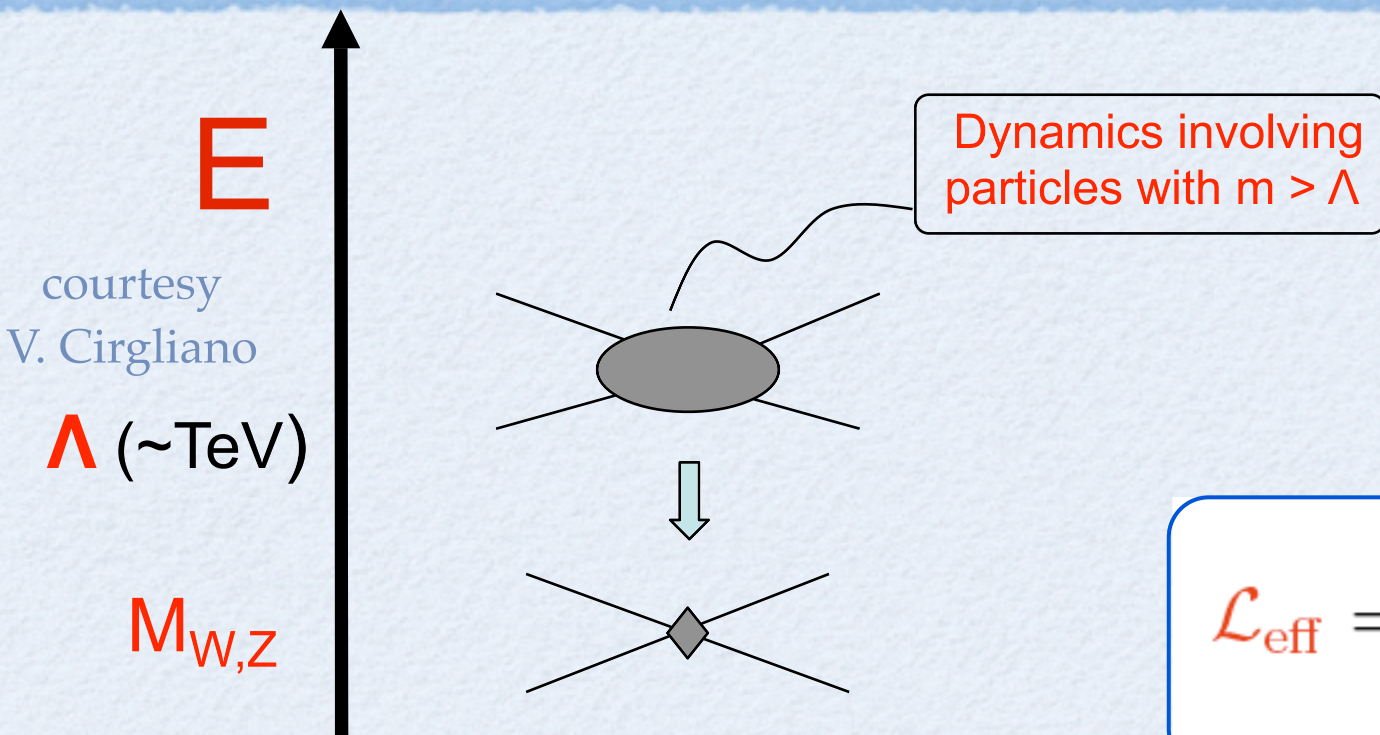

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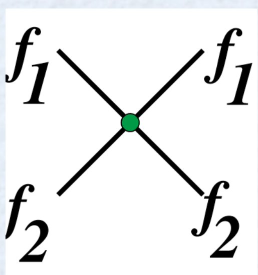
Flavor Diagonal Interactions

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

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



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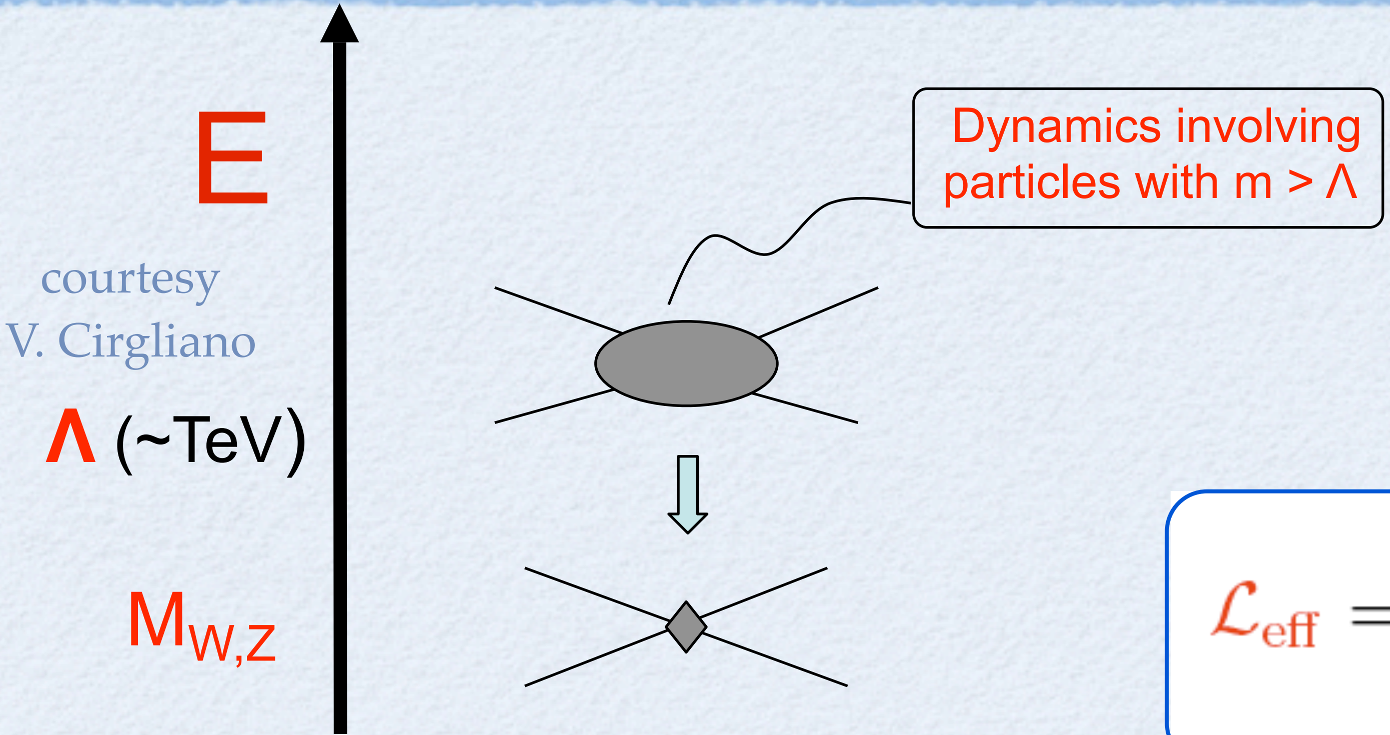

courtesy V. Cirgliano

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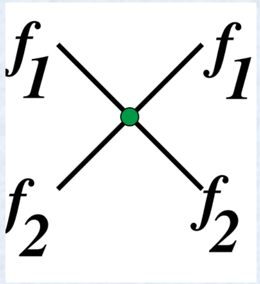

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One goal of neutral current measurements at low energy AND colliders: Access Λ > 10 TeV for as many f_1f_2 and L,R combinations as possible

Colliders vs Fixed Target

Weak-Electromagnetic Interference

Colliders access scales Λ's ~ 10 TeV

Tevatron, LEP, SLC, LEP200, HERA

- L,R combinations accessed are mostly parity-conserving

Z boson production accessed some parity-violating combinations but…

on resonance:

A_Z imaginary

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

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parity-violating electron scattering

Electromagnetic amplitude interferes with Z-exchange as well as any new physics

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

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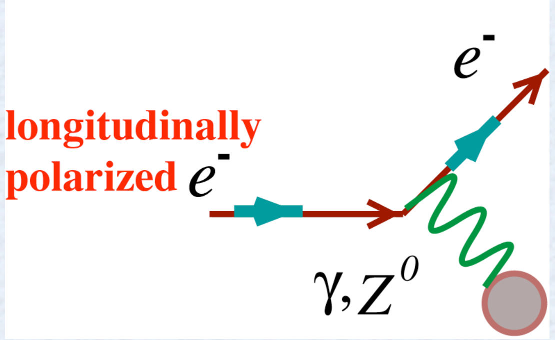

$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{\rm weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha}\left(g_A^e g_V^T + \beta\, g_V^e g_A^T\right)$$

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

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

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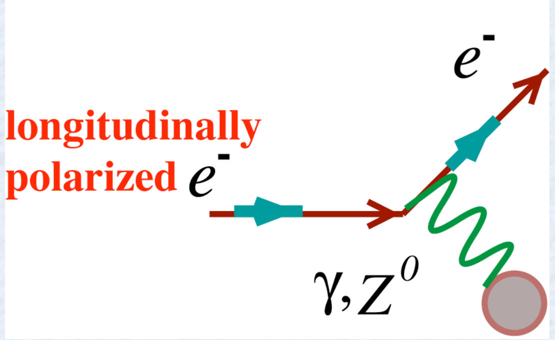

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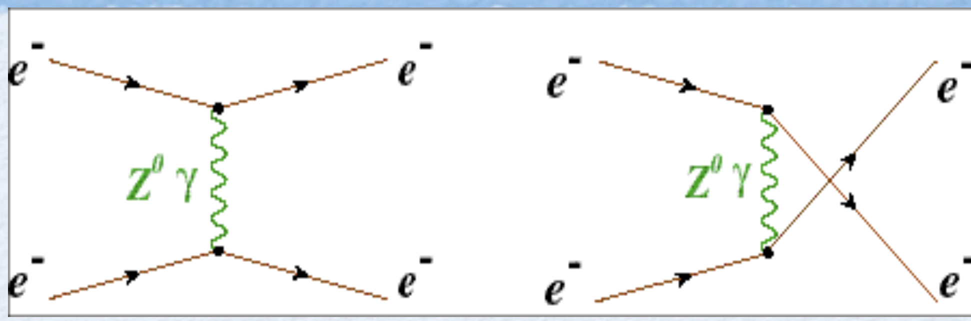
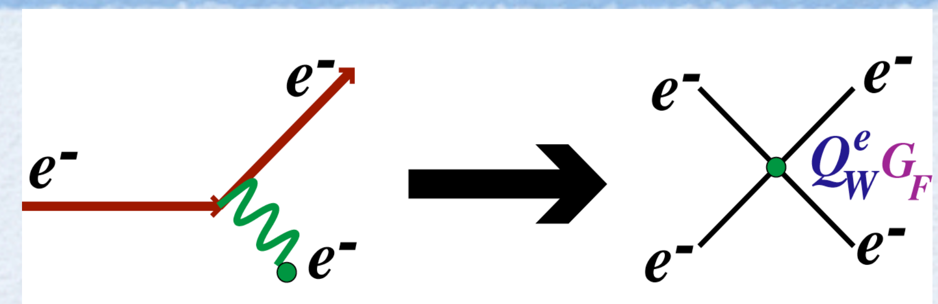
At very forward angles, $A_{PV} \propto g_V^T$, the target vector coupling, called the weak charge Q_W

Thumb rule: measure $\delta(\sin^2\theta_W) \lesssim \mathbf{0.002}$ ***or better to access the multi-TeV scale***

Electron Weak Charge

Parity-Violating Electron-Electron (Møller) Scattering





Purely leptonic reaction

Derman and Marciano (1978)

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

50 GeV at SLAC: ~ 150 ppb!

E158 at SLAC *Major technical challenges*

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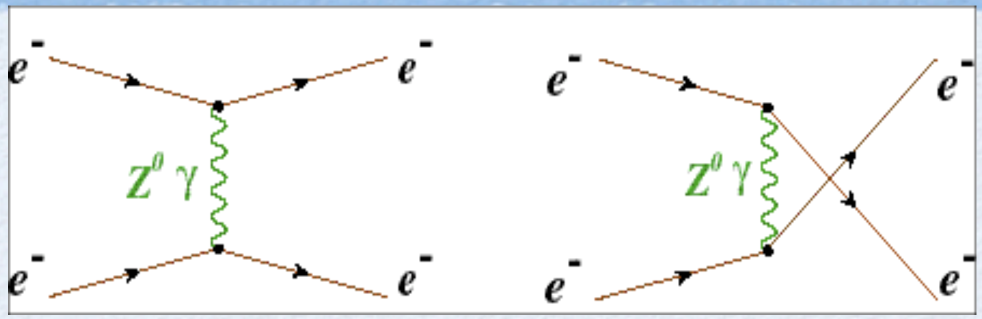

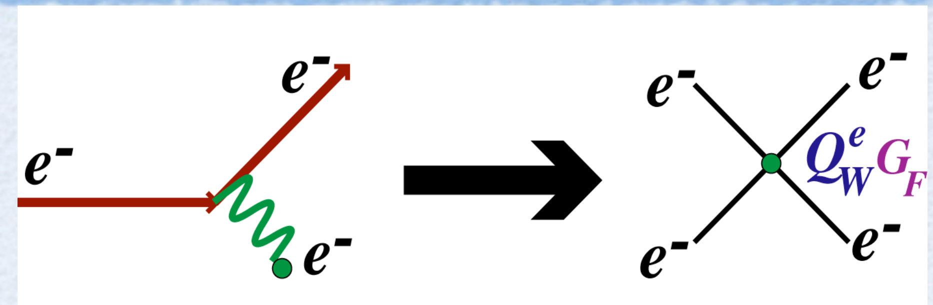

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E158 at SLAC   *Major technical challenges*

Final Result:

A_{PV} = (-131 ± 14 ± 10) x 10^{-9}

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

ELECTRON WEAK CHARGE

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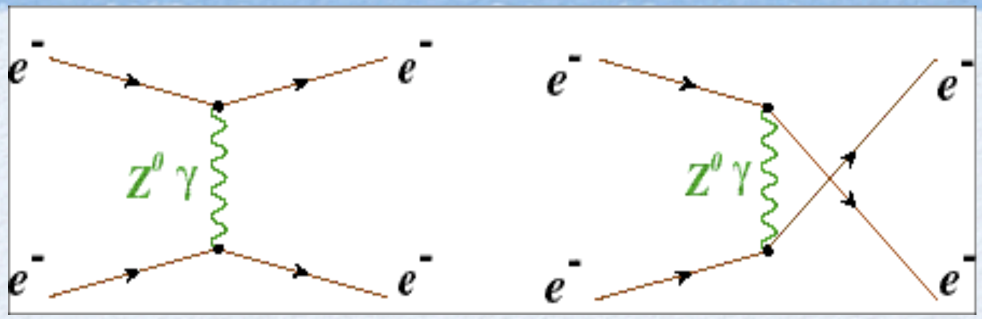

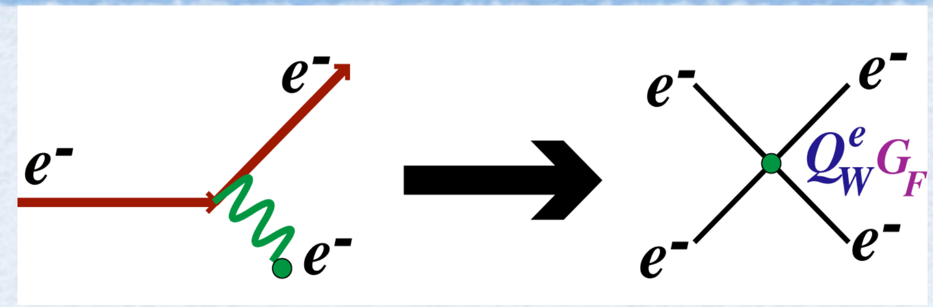

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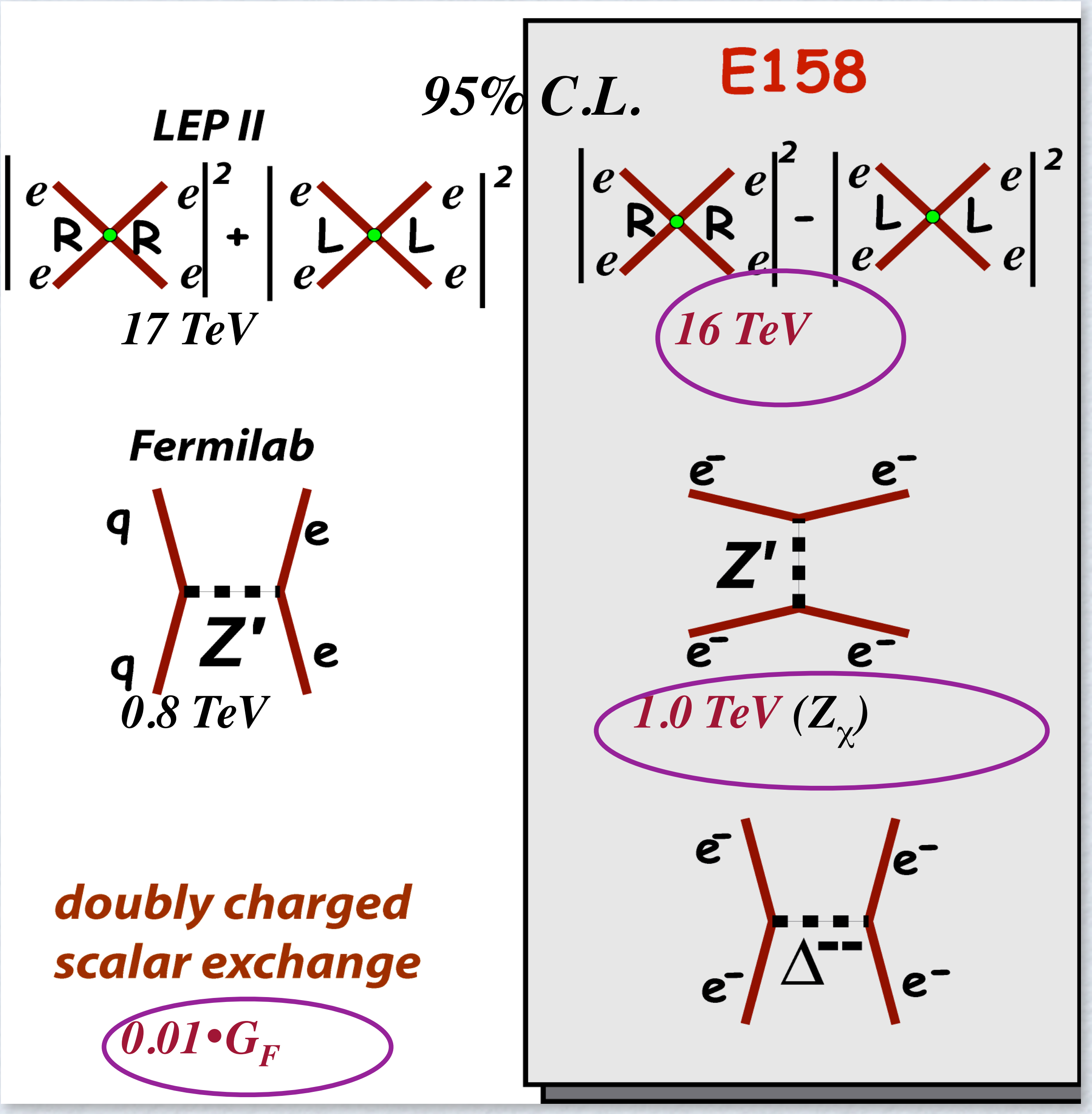

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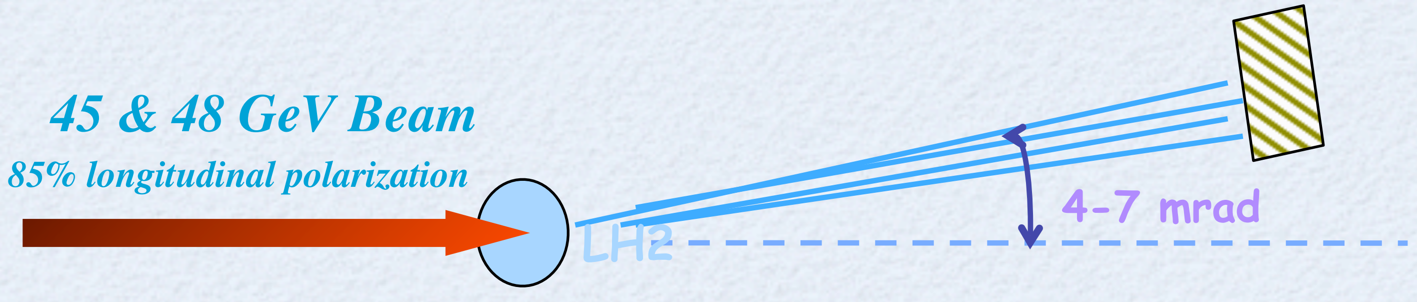

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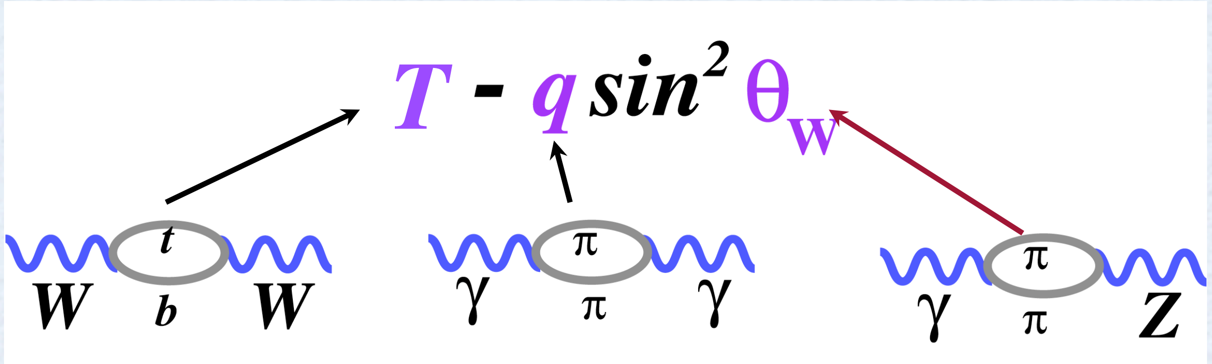
The Weak Mixing Angle

Running of θ_W: Bookkeeping for off-resonance measurements



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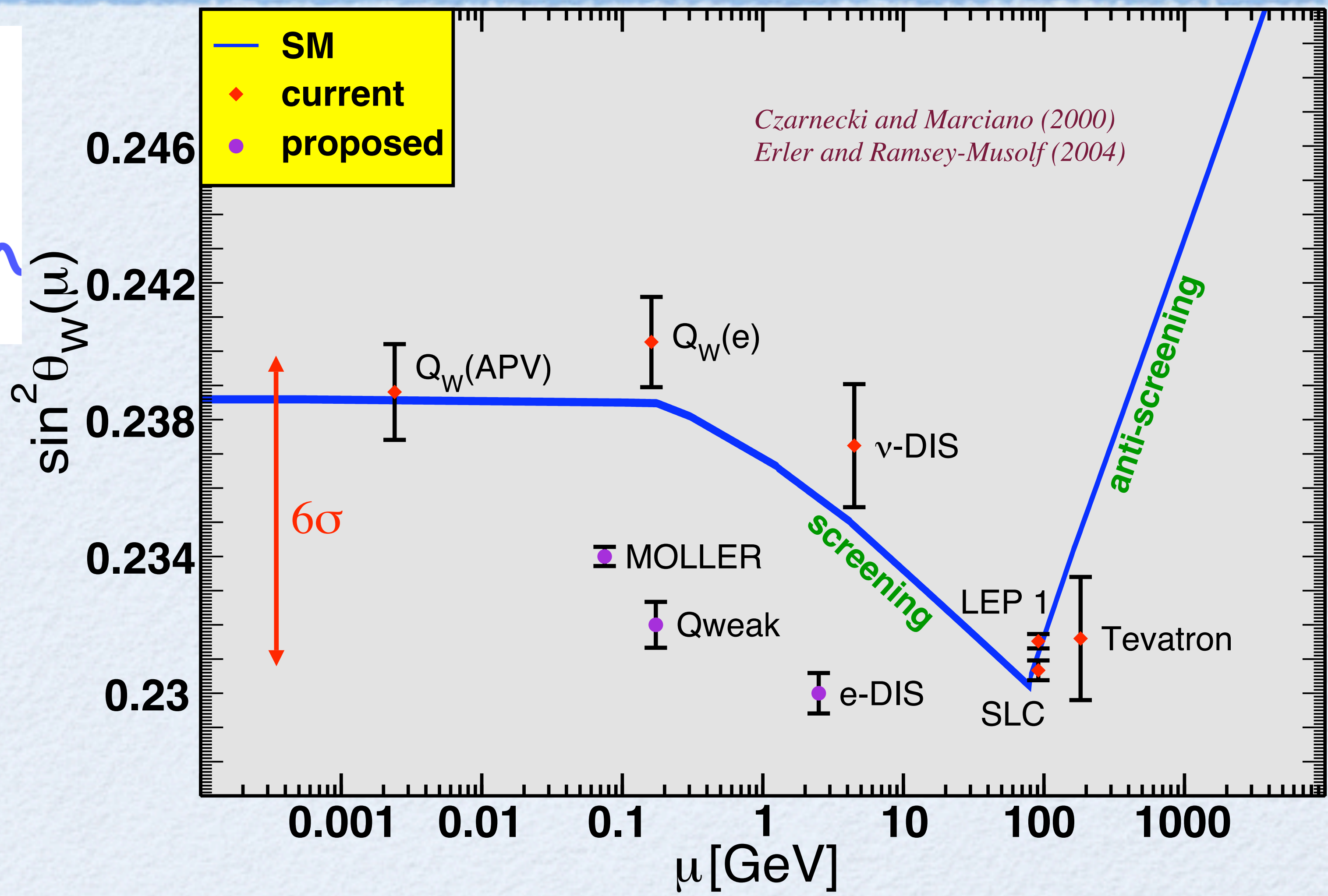
- *W-W loop provides indirect m_t*
- *γ-Z loop is the running of $\sin^2\theta_W$*



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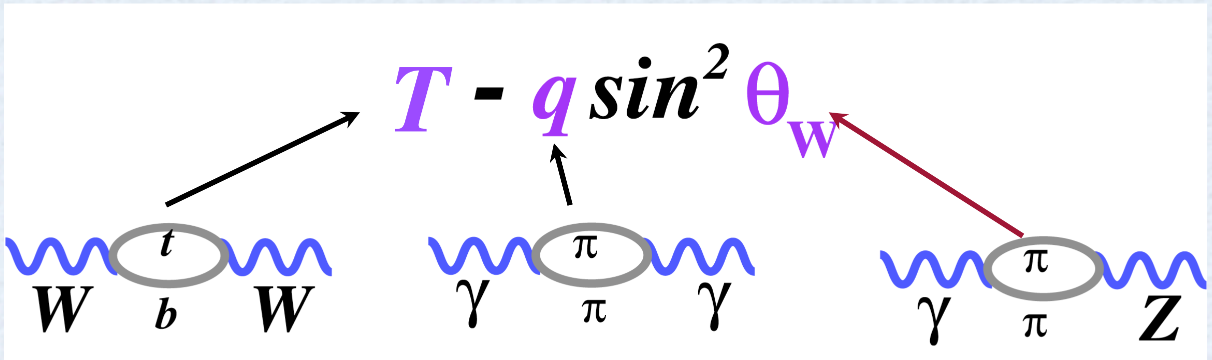

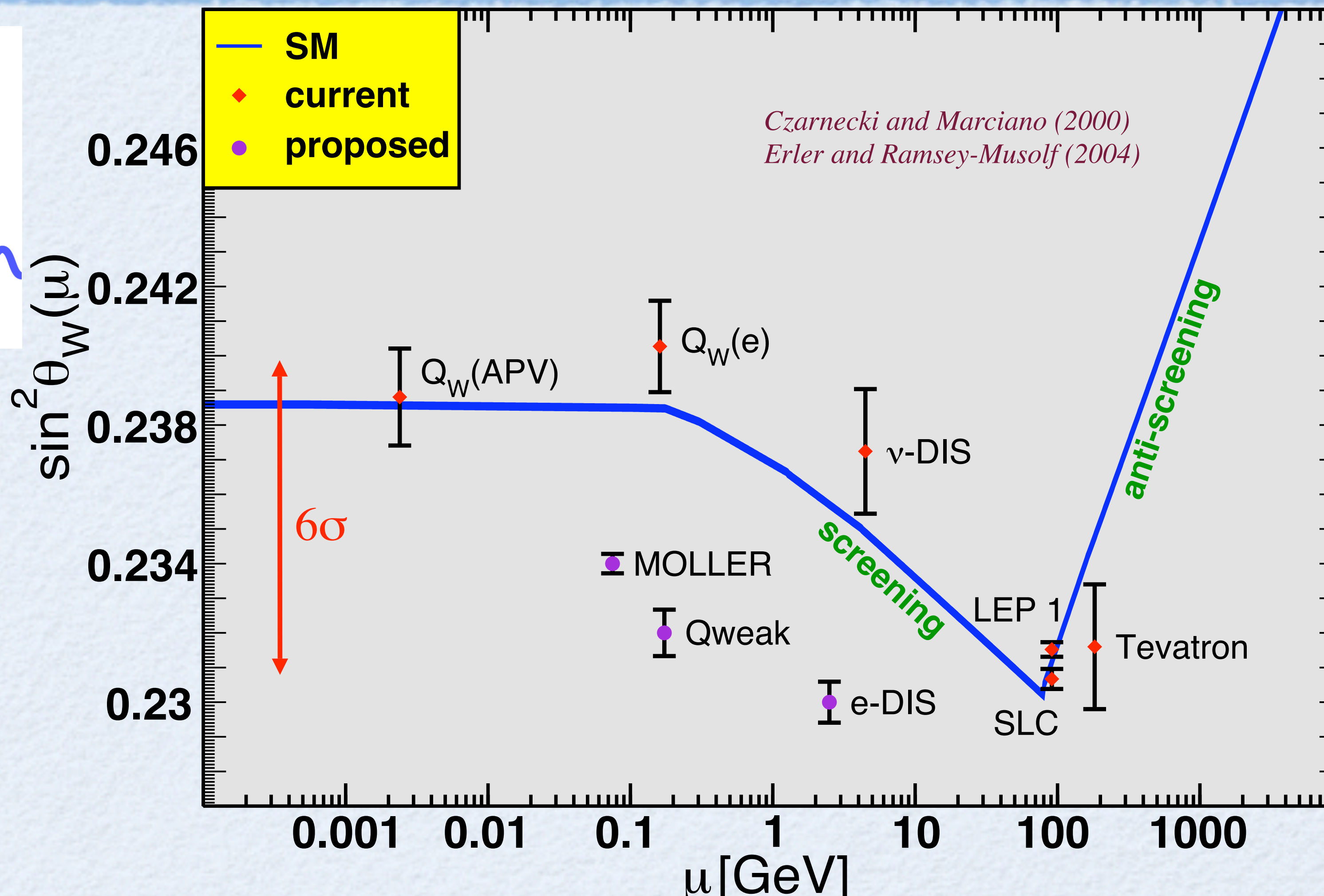

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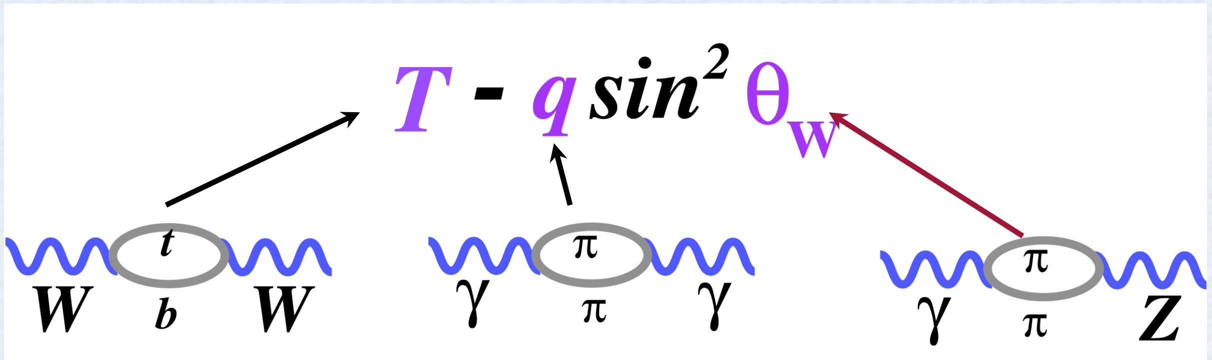

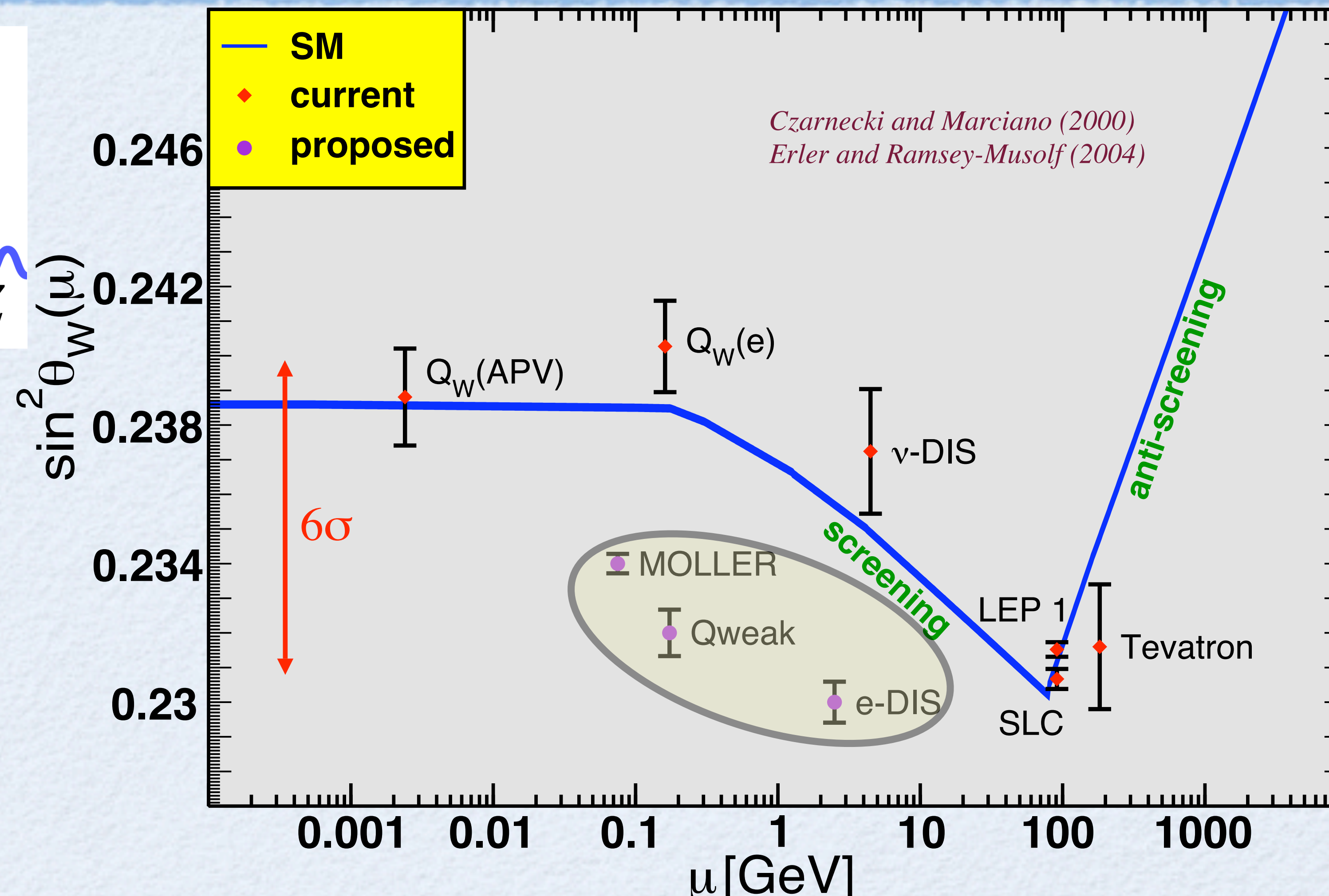

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- ***Future Electron Scattering Measurements***
  - *e-q measurements: QWeak (running) and DIS (Paul Souder talk)*
  - *Improved on E158 by a factor of 5: MOLLER at 12 GeV JLab*

MOLLER at JLab

Measurement of Lepton-Lepton Electroweak Reaction

$$\mathbf{A_{PV} \propto m_e E_{lab} Q^e_W \propto (1 - 4\sin^2\Theta_W)}$$

$$\frac{\delta(\sin^2\vartheta_W)}{\sin^2\vartheta_W} \cong 0.05\,\frac{\delta(A_{PV})}{A_{PV}}$$

A_{PV} = 35.6 ppb → *38 weeks* → *$\delta(A_{PV})$ = 0.73 ppb* → ***$\delta(Q^e_W)$ = ± 2.1 (stat.) ± 1.0 (syst.) %***

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

best contact interaction reach at low Q^2

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Current limits on 4-electron contact interactions:

LEPII at 200 GeV

(Average of all 4 LEP experiments)

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

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

MOLLER AT JLAB

Measurement of Lepton-Lepton Electroweak Reaction

$$\mathbf{A_{PV}} \propto \mathbf{m_e E_{lab} Q^e_W} \propto (\mathbf{1} - \mathbf{4}\sin^{\mathbf{2}} \mathbf{\Theta_W})$$

$$\Rightarrow \quad \frac{\delta(\sin^2\vartheta_W)}{\sin^2\vartheta_W} \cong 0.05 \frac{\delta(A_{PV})}{A_{PV}}$$

A_{PV} = 35.6 ppb ⇒ *38 weeks* ⇒ $\delta(A_{PV})$ = 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%*

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

best contact interaction reach at low Q^2

Current limits on 4-electron contact interactions:

LEPII at 200 GeV

(Average of all 4 LEP experiments)

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

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

Compositeness scale:

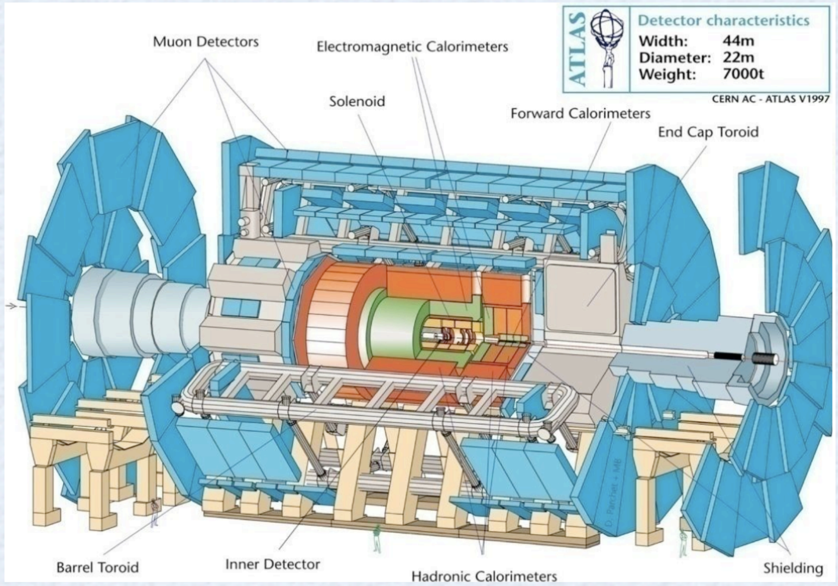
$$\sqrt{|\mathbf{g^2_{RR}} - \mathbf{g^2_{LL}}|} = \mathbf{2}\pi$$

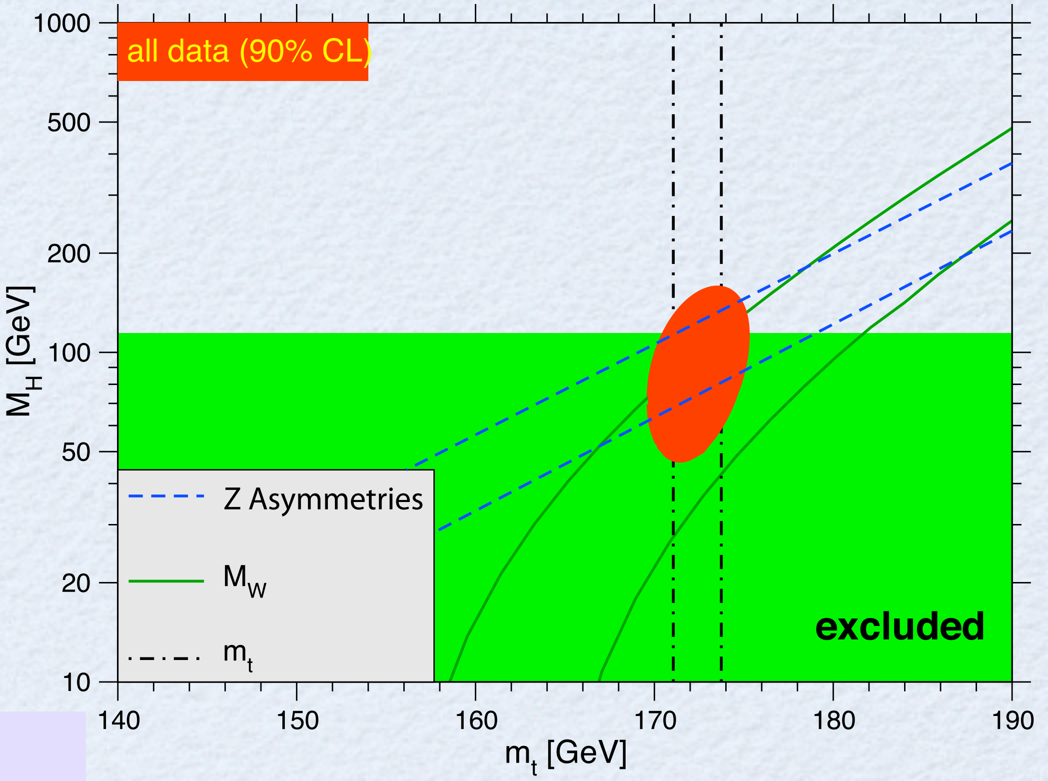
$$\Rightarrow \quad \mathbf{\Lambda} = \mathbf{47}\ \mathrm{TeV}$$

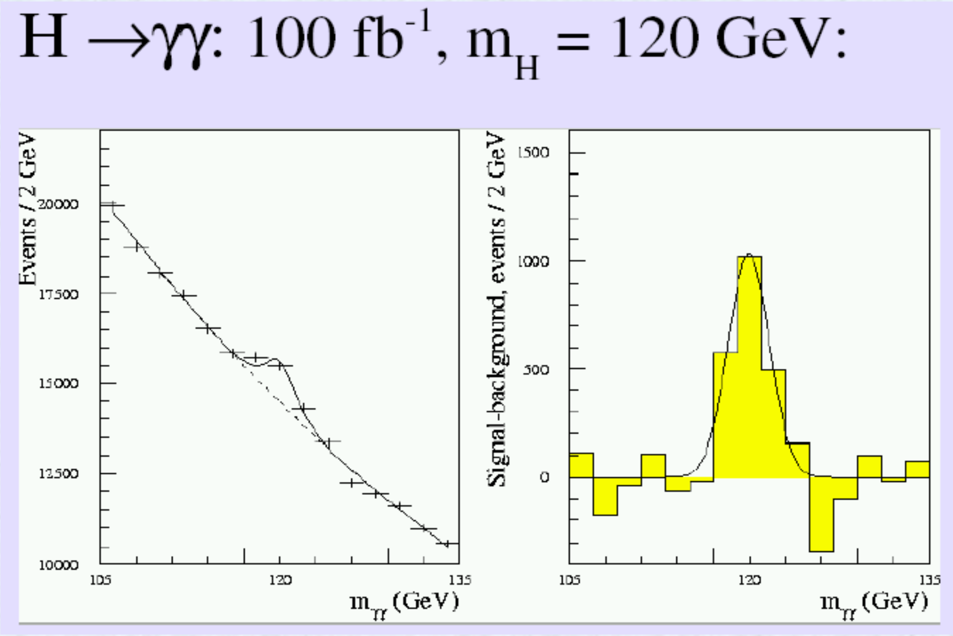
Length scale probed: $\mathbf{4} \times \mathbf{10^{-21}}\ \mathrm{m}$

SM Higgs at LHC

MOLLER has discovery reach independent of LHC but...







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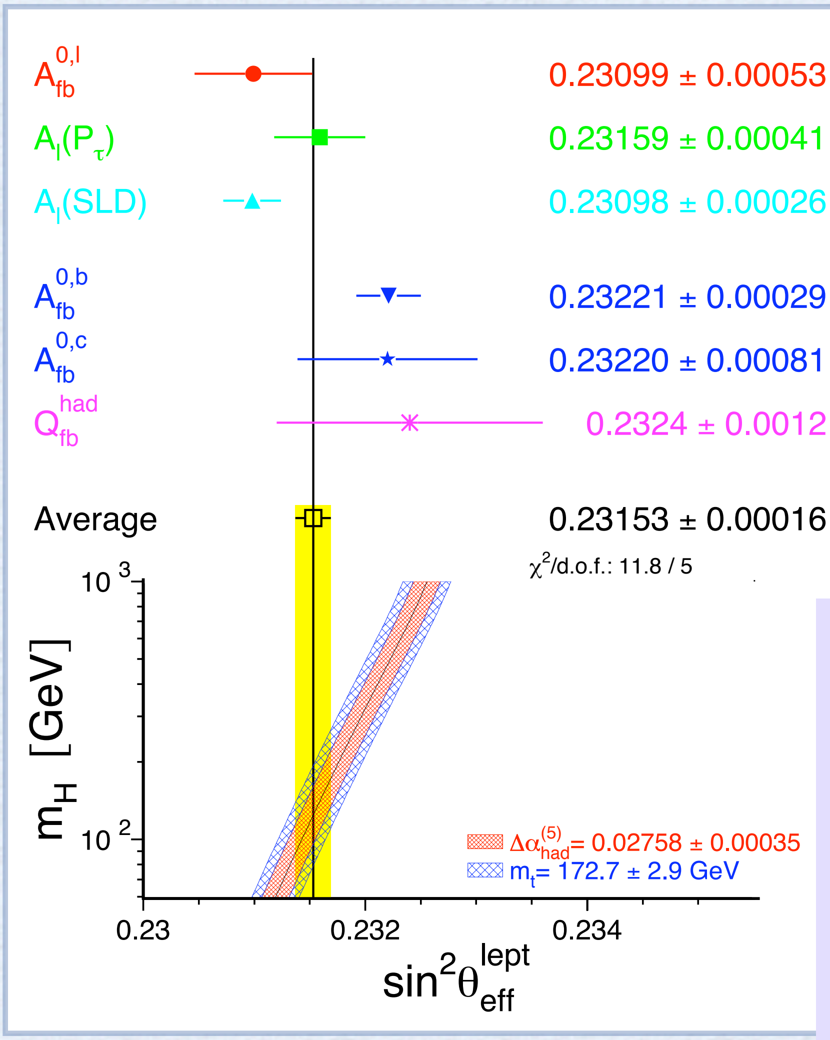
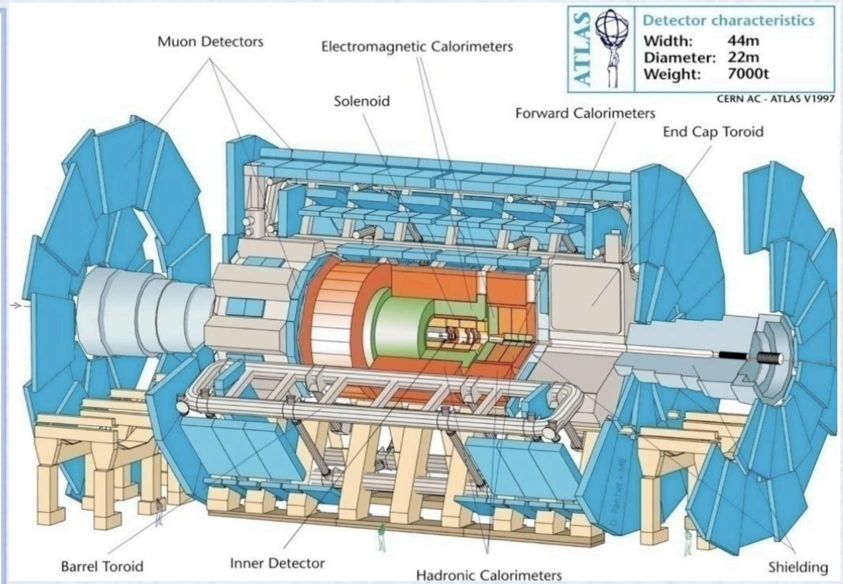
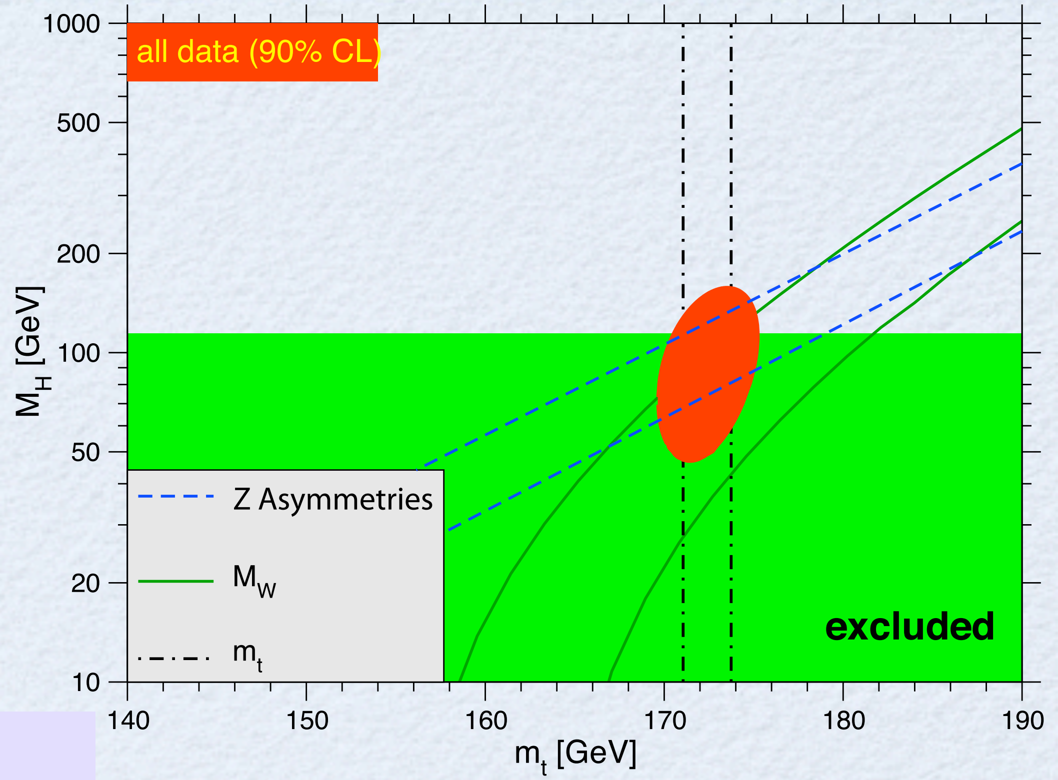
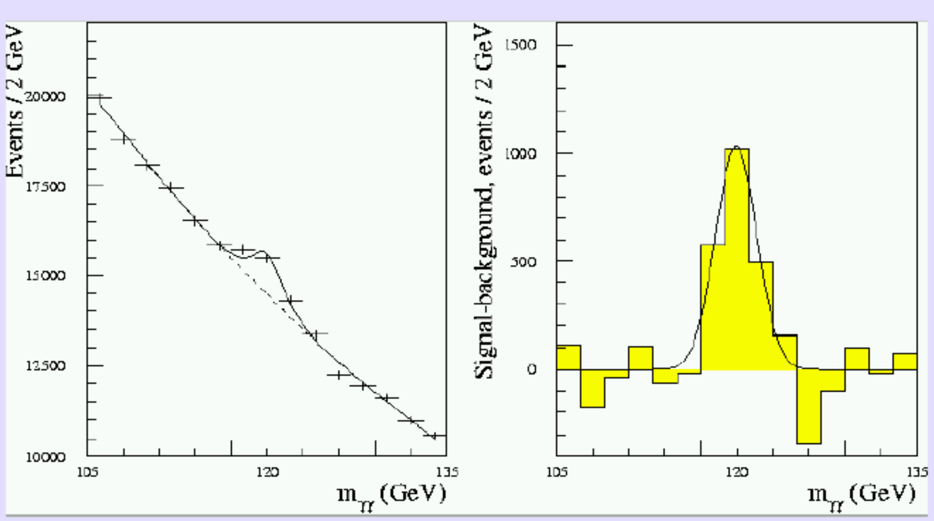






$H \rightarrow \gamma\gamma$: 100 fb^{-1}, m_H = 120 GeV:



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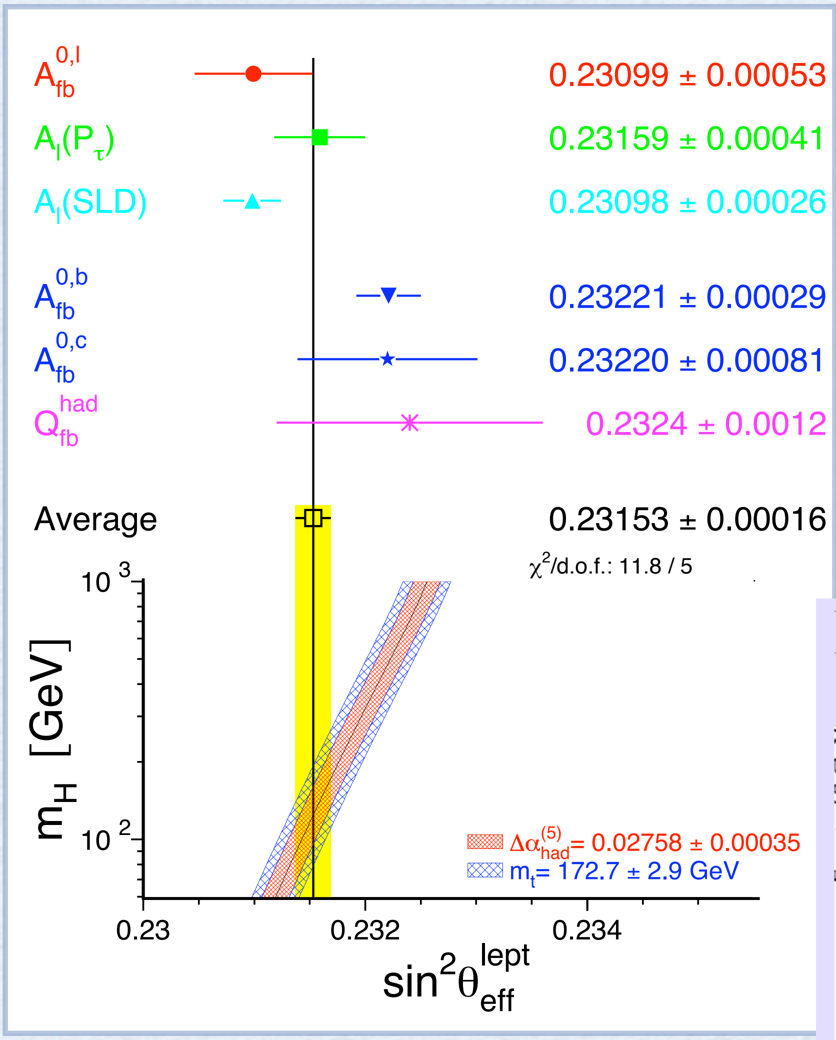

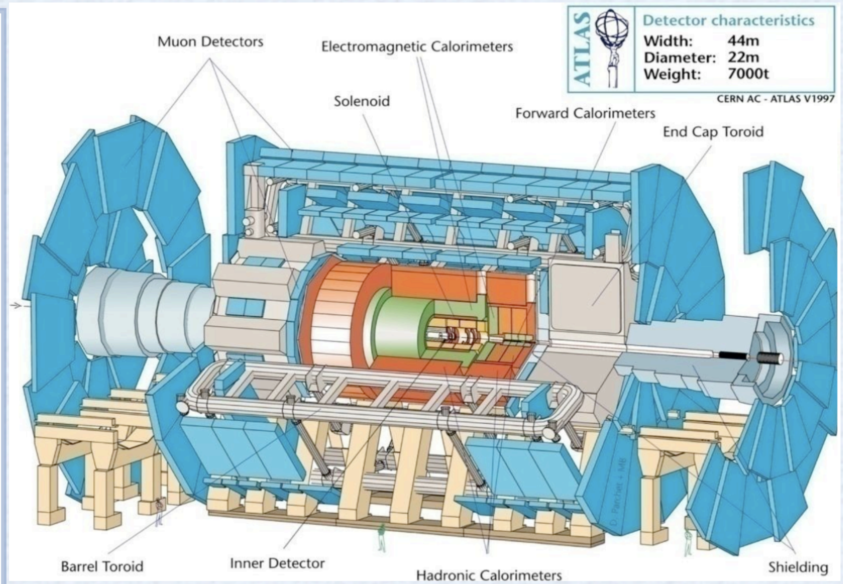

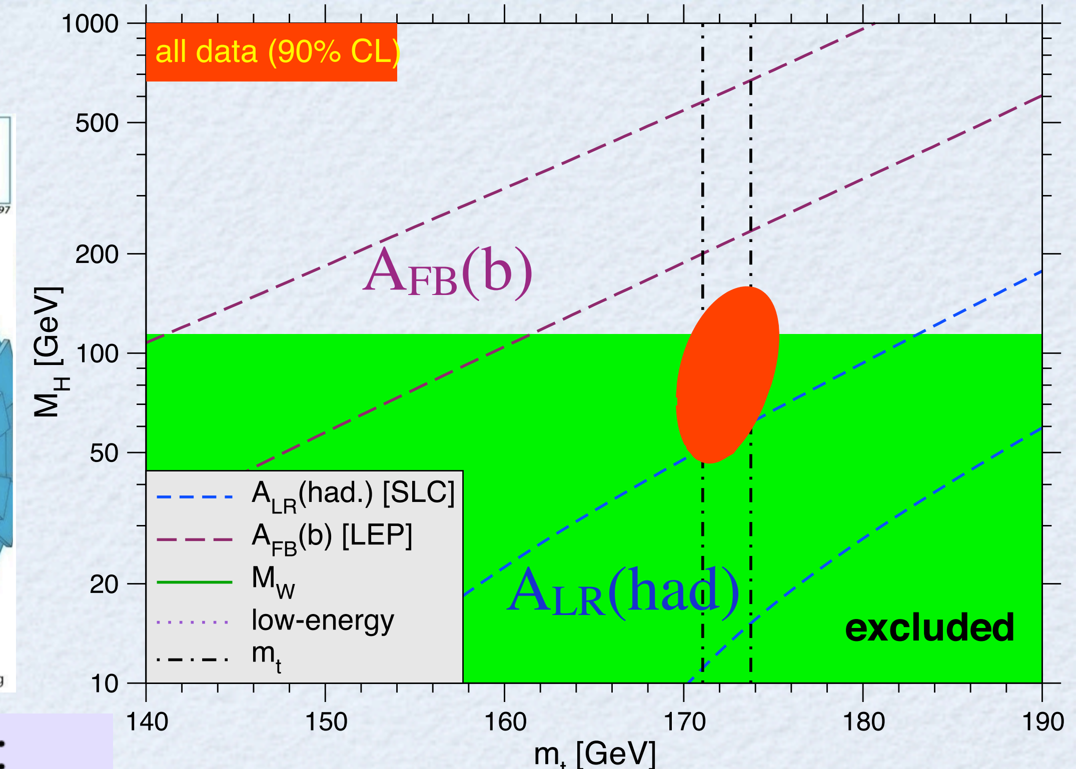

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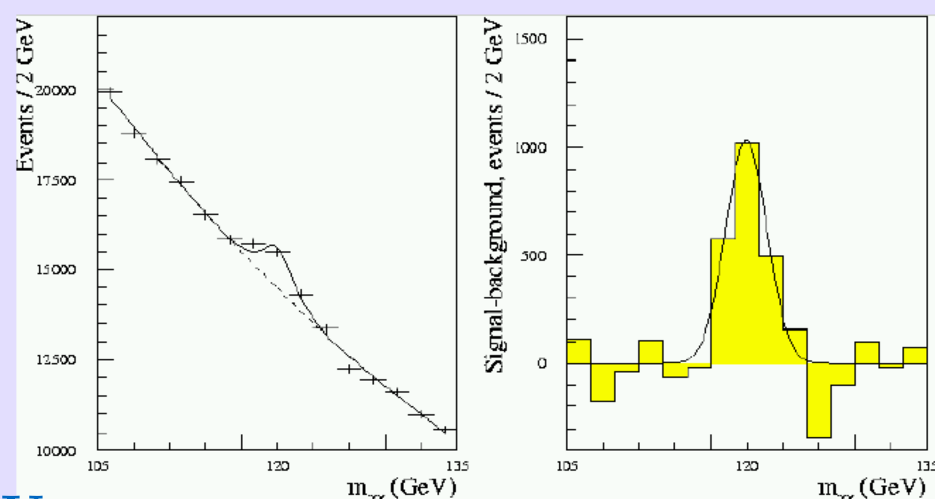

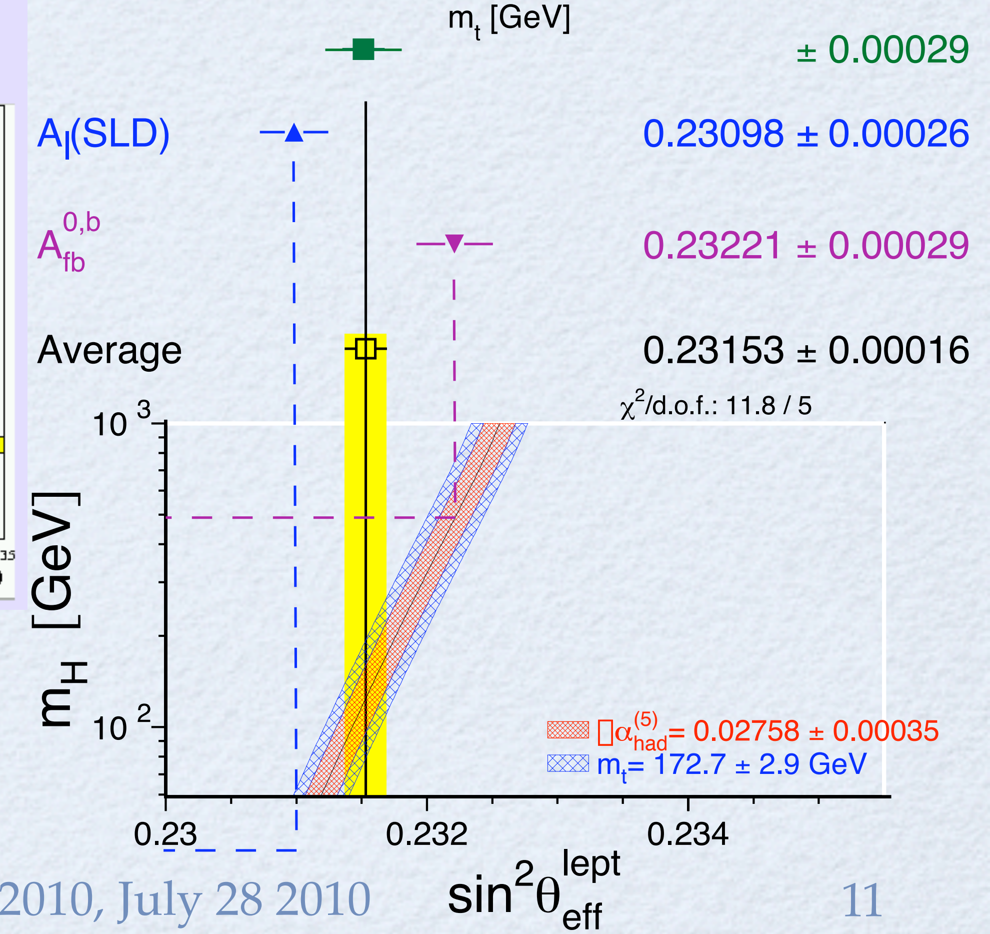

Bill Marciano:

We forgot to nail $\sin^2\theta_W$

SM HIGGS AT LHC

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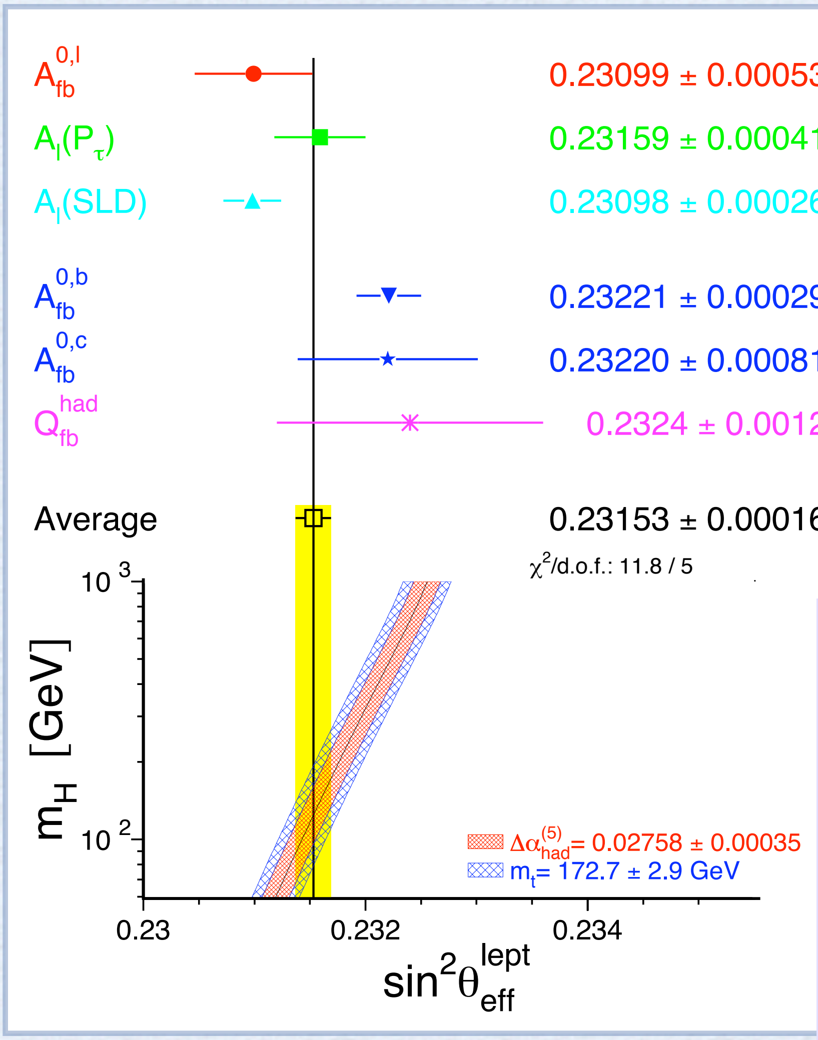

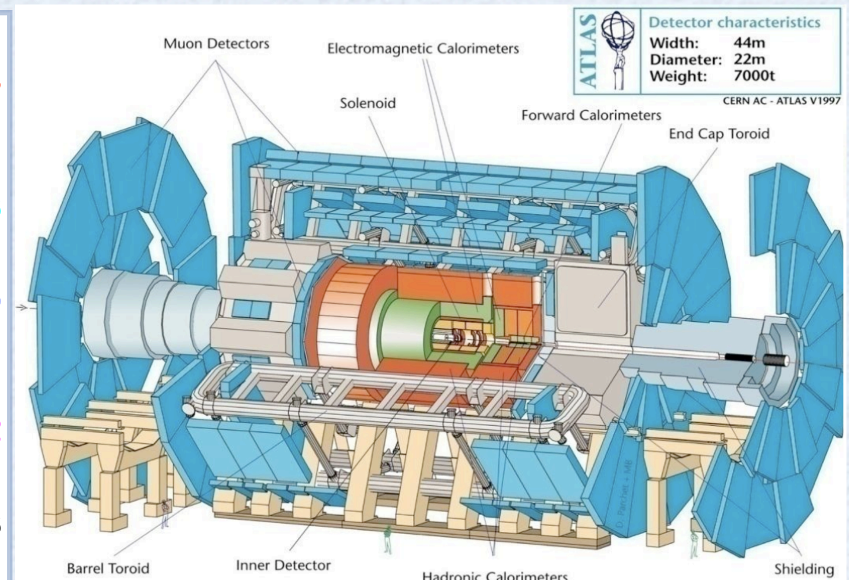

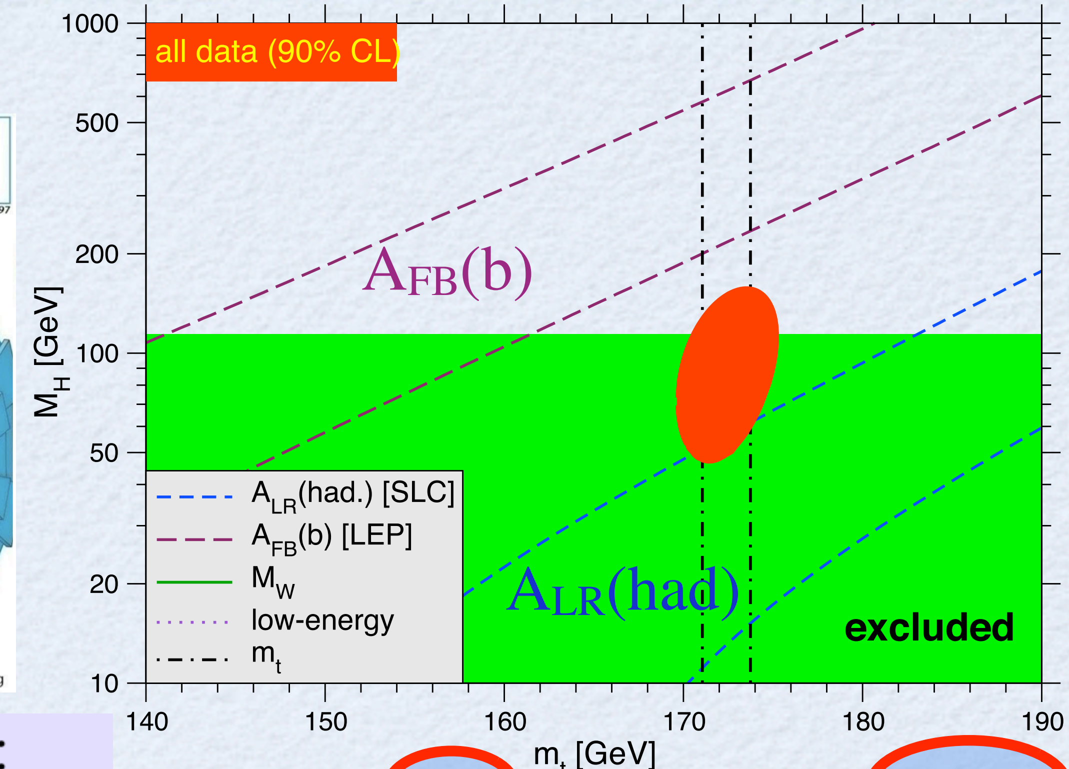

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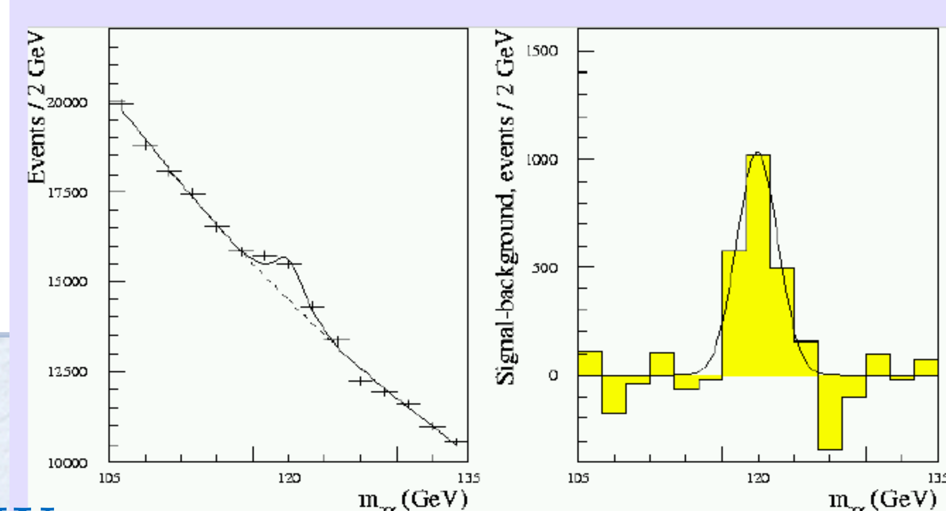
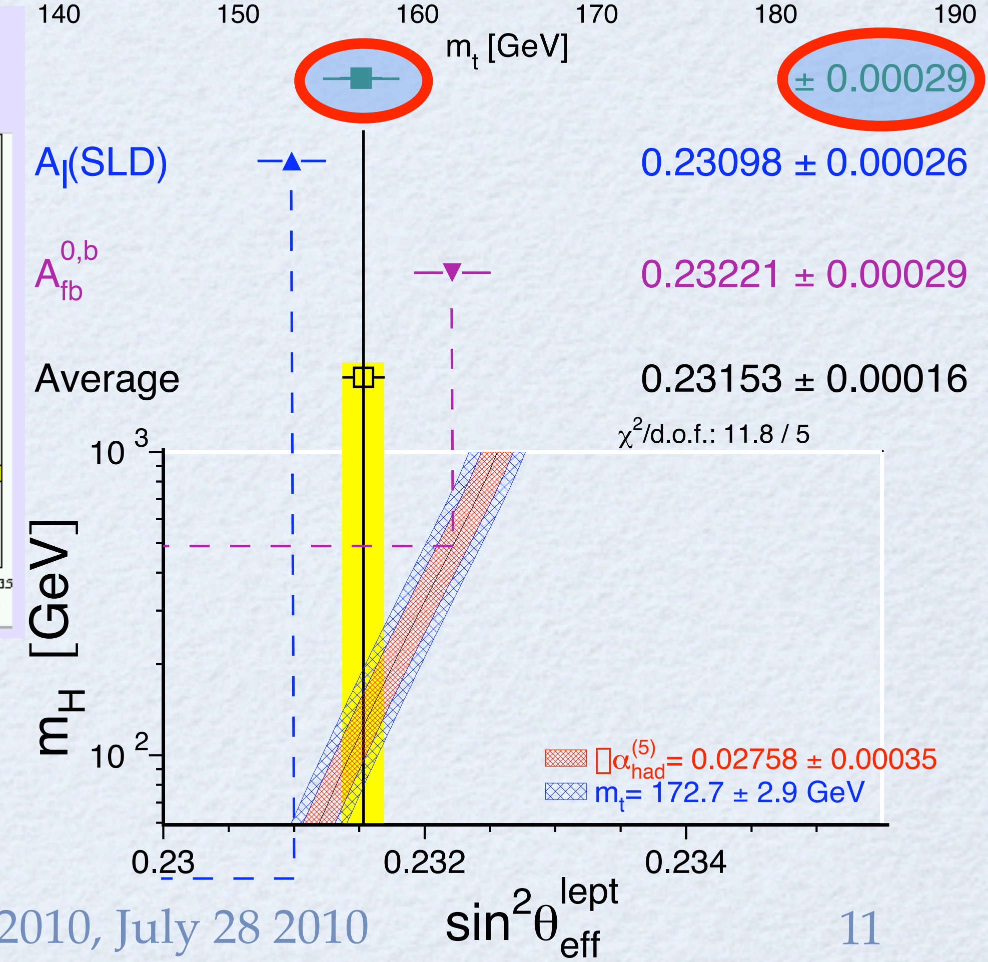




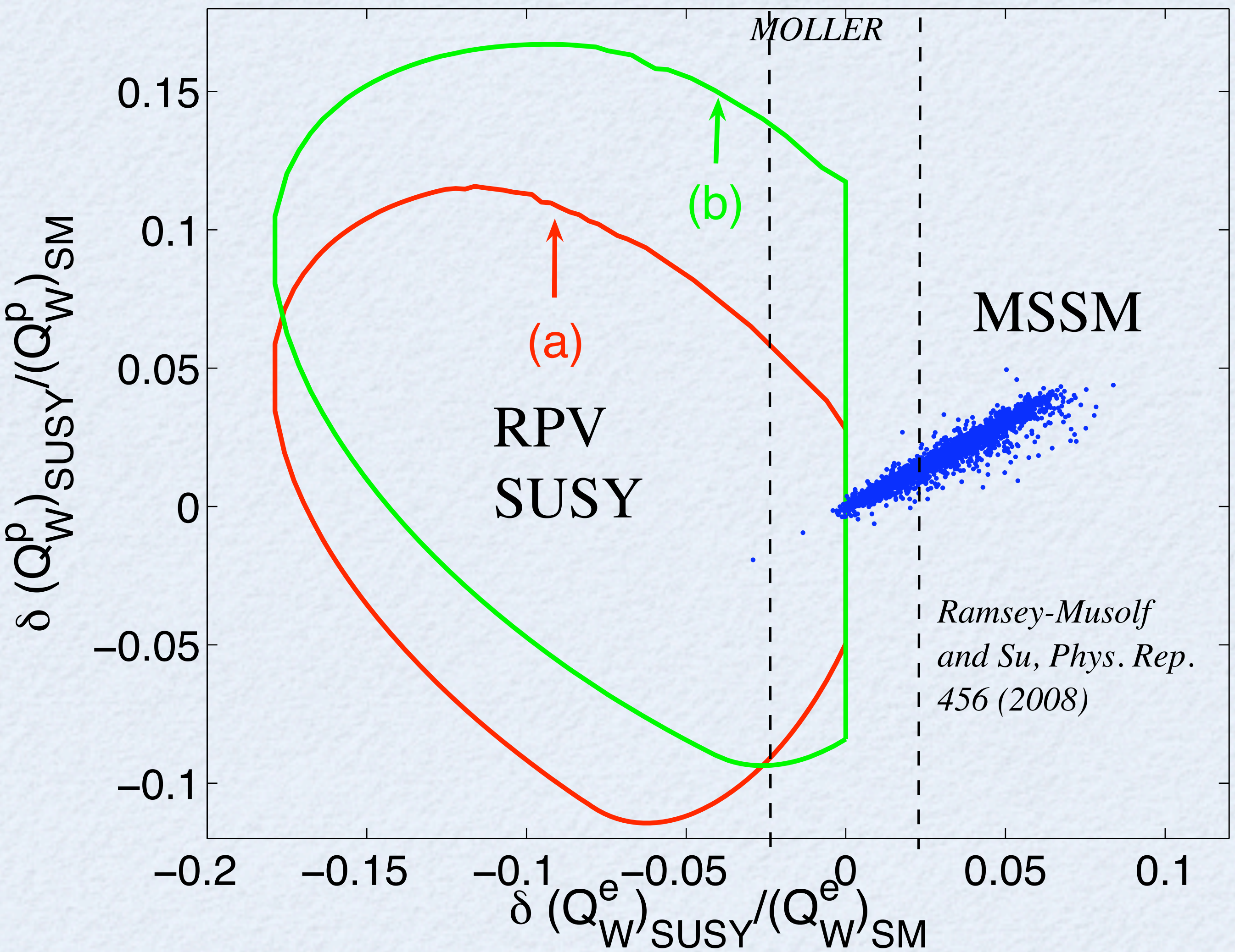
Bill Marciano:

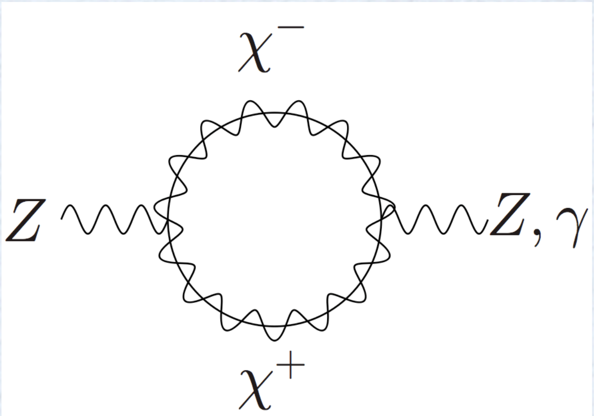
We forgot to nail $\sin^2\theta_W$

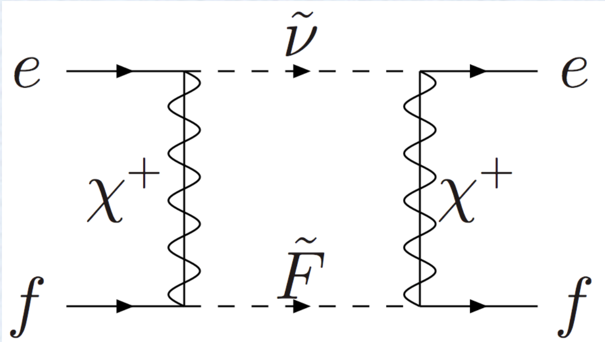
Proposed MOLLER error bar is precise enough to affect the central value of the world average

New Physics at LHC (I)

Assume there is a SUSY signal discovered







MSSM sensitivity if light super-partners, large tanβ

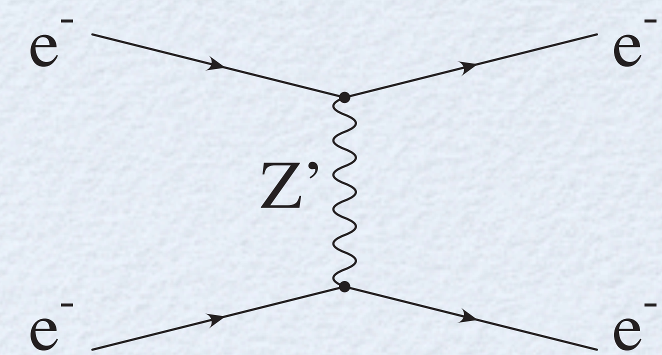
$$P_R = (-1)^{3(B-L)+2s}$$

Does Supersymmetry provide a candidate for dark matter?

- B and/or L need not be conserved (RPV): neutralino decay
  - neutralino then unlikely to be a dark matter candidate
  - neutrinos are Majorana

New Physics at LHC (2)

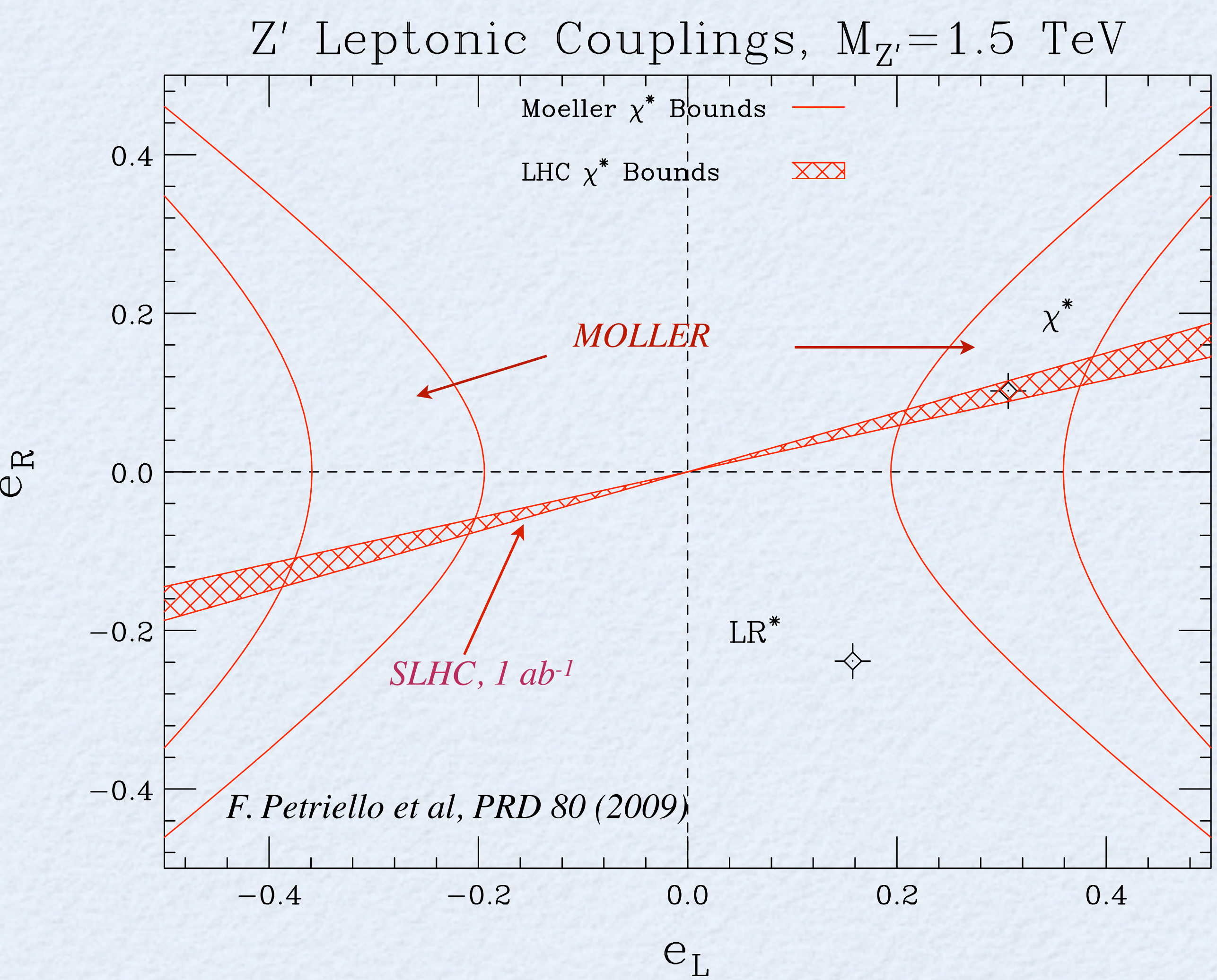
Assume a new, heavy vector boson is discovered



- *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 couplings?**



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

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

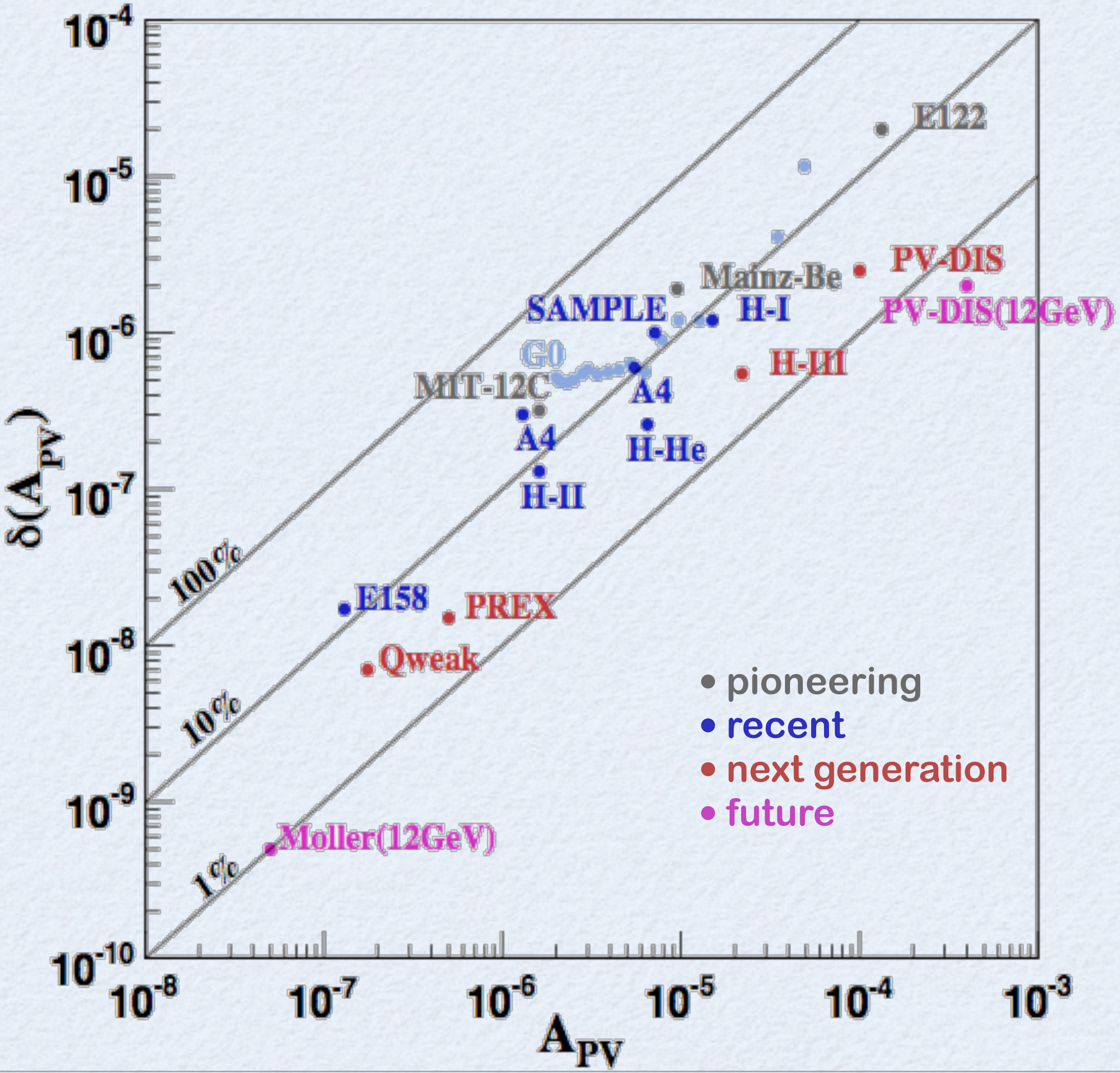
LHC data can extract the mass, width and A_{FB}(s)

⇒ *constraint on e_R/e_L*

Experimental Design

Progress over 3 Decades

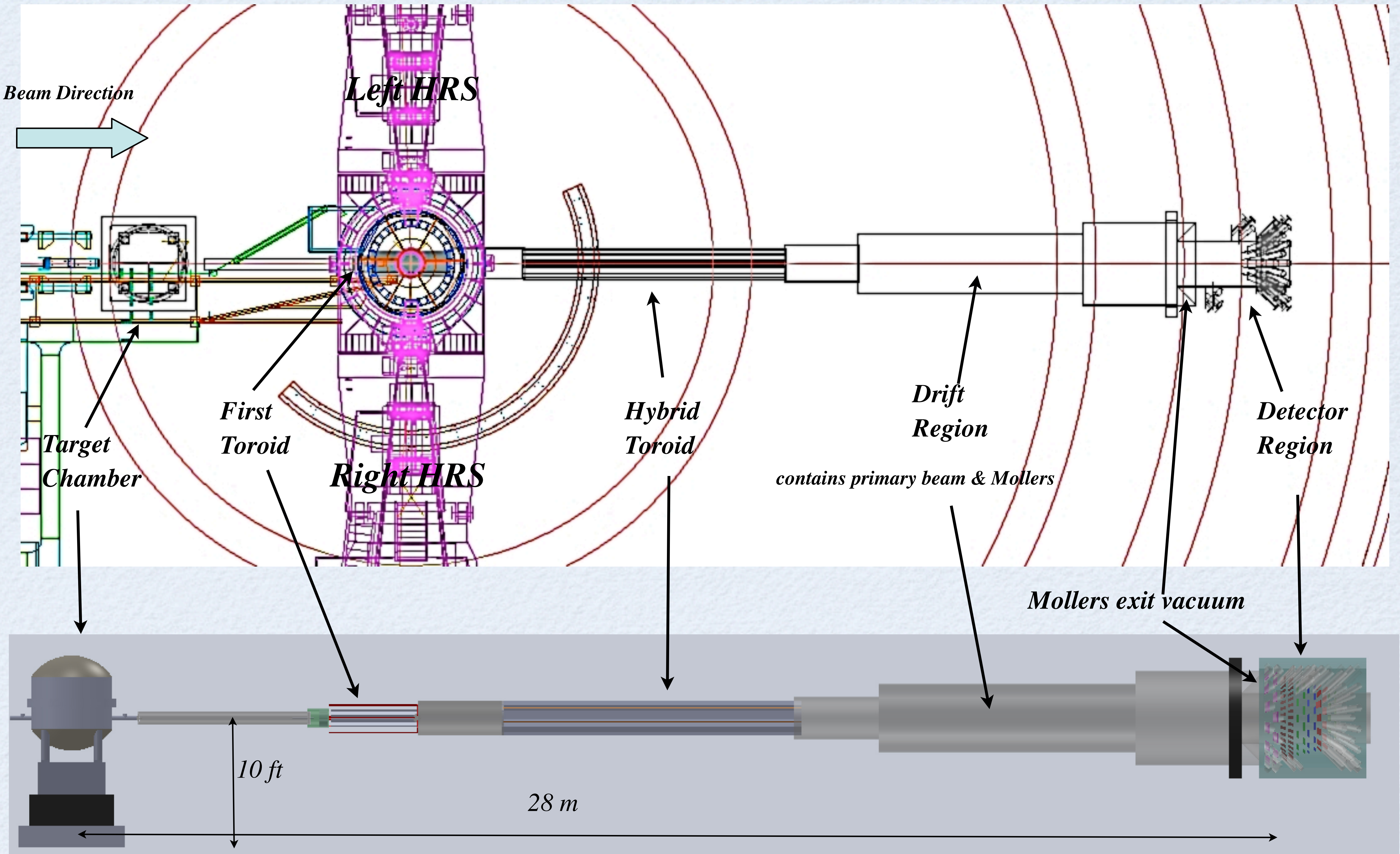
Parity-violating electron scattering has become a precision tool



Steady progress in technology towards:

- ***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***

Moller Hall Layout

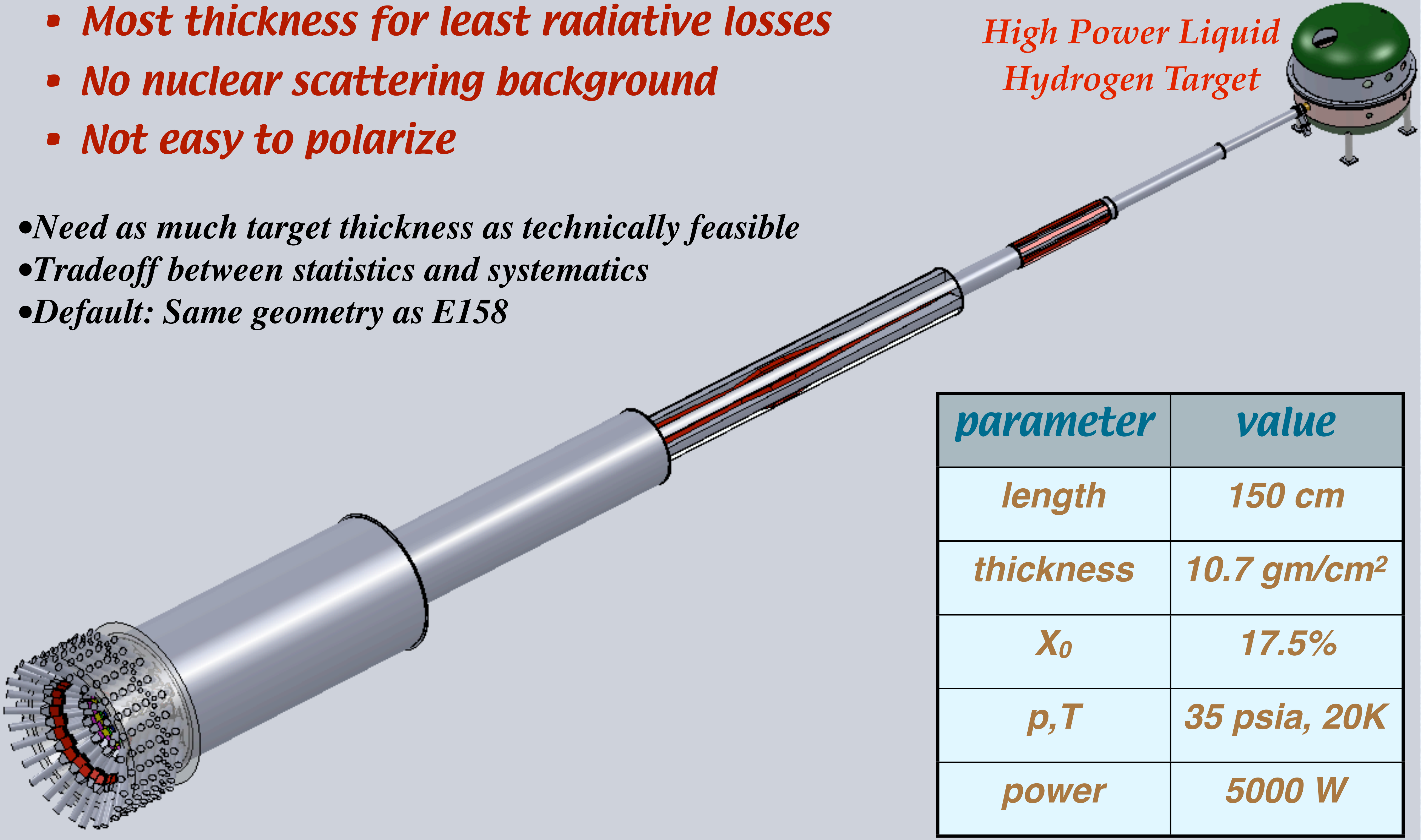


Moller Apparatus
Target, spectrometer, detectors

- ***Most thickness for least radiative losses***
- ***No nuclear scattering background***
- ***Not easy to polarize***

High Power Liquid Hydrogen Target

- *Need as much target thickness as technically feasible*
- *Tradeoff between statistics and systematics*
- *Default: Same geometry as E158*



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

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Target, spectrometer, detectors

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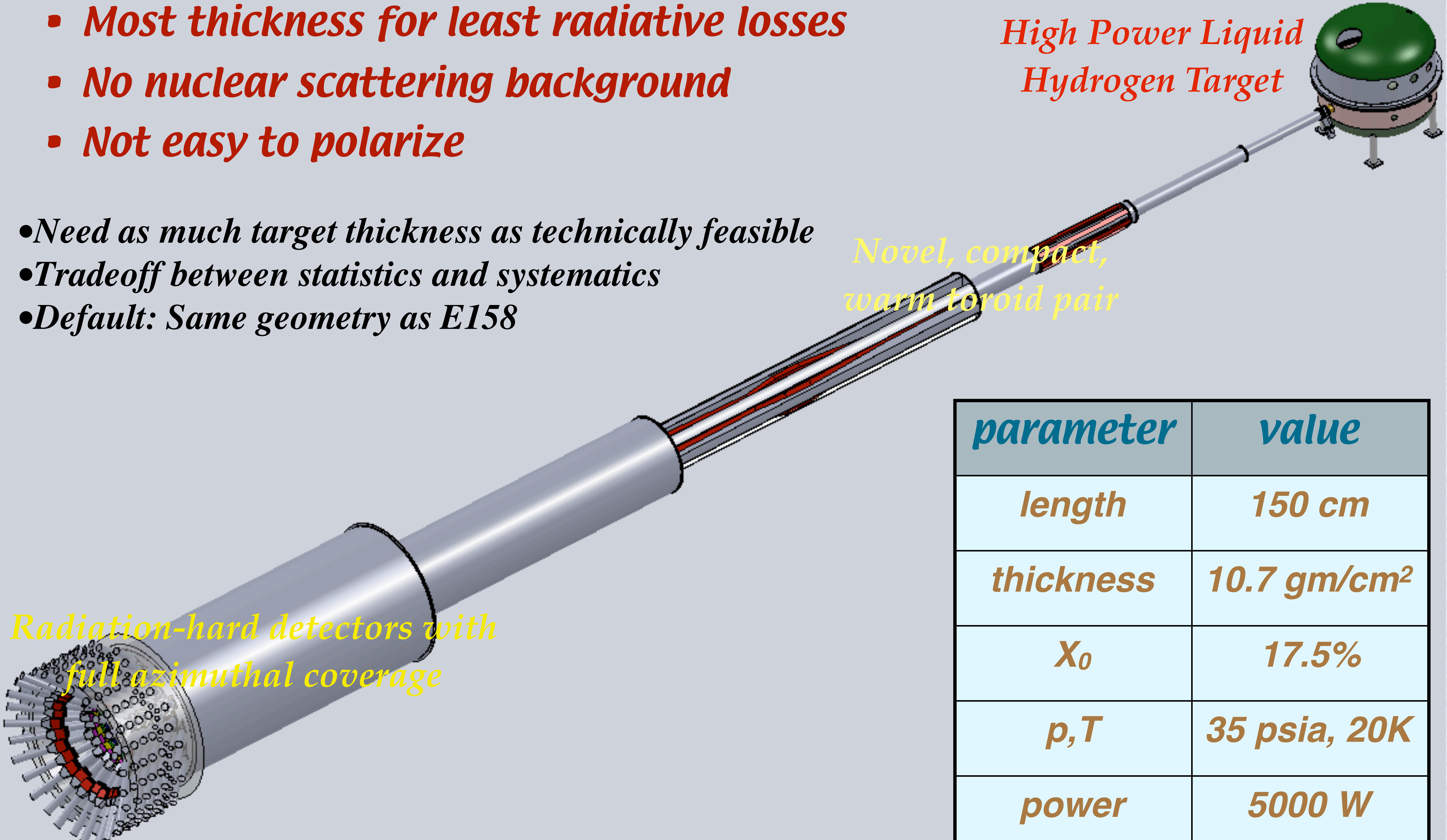

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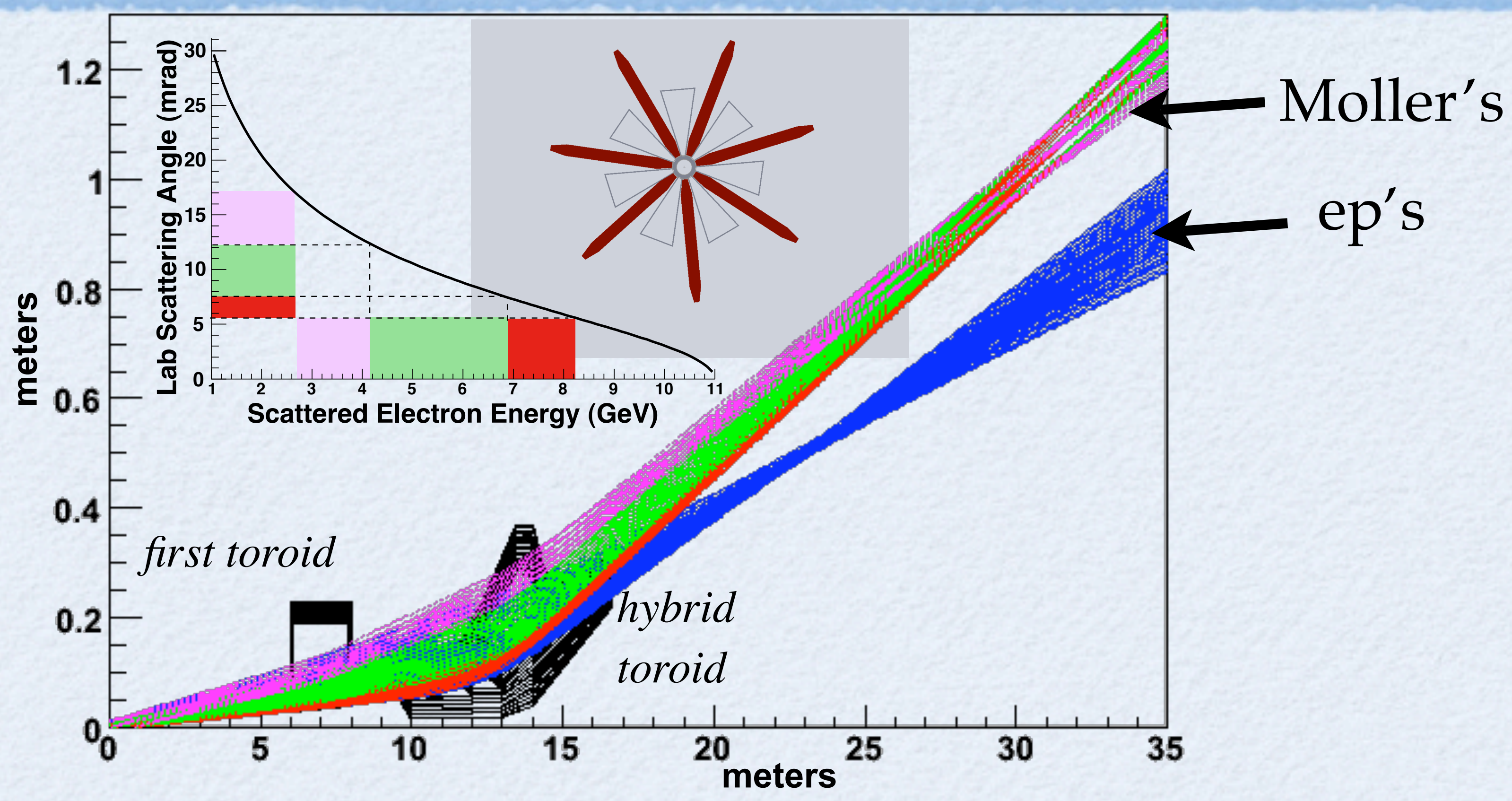
Spectrometer concept



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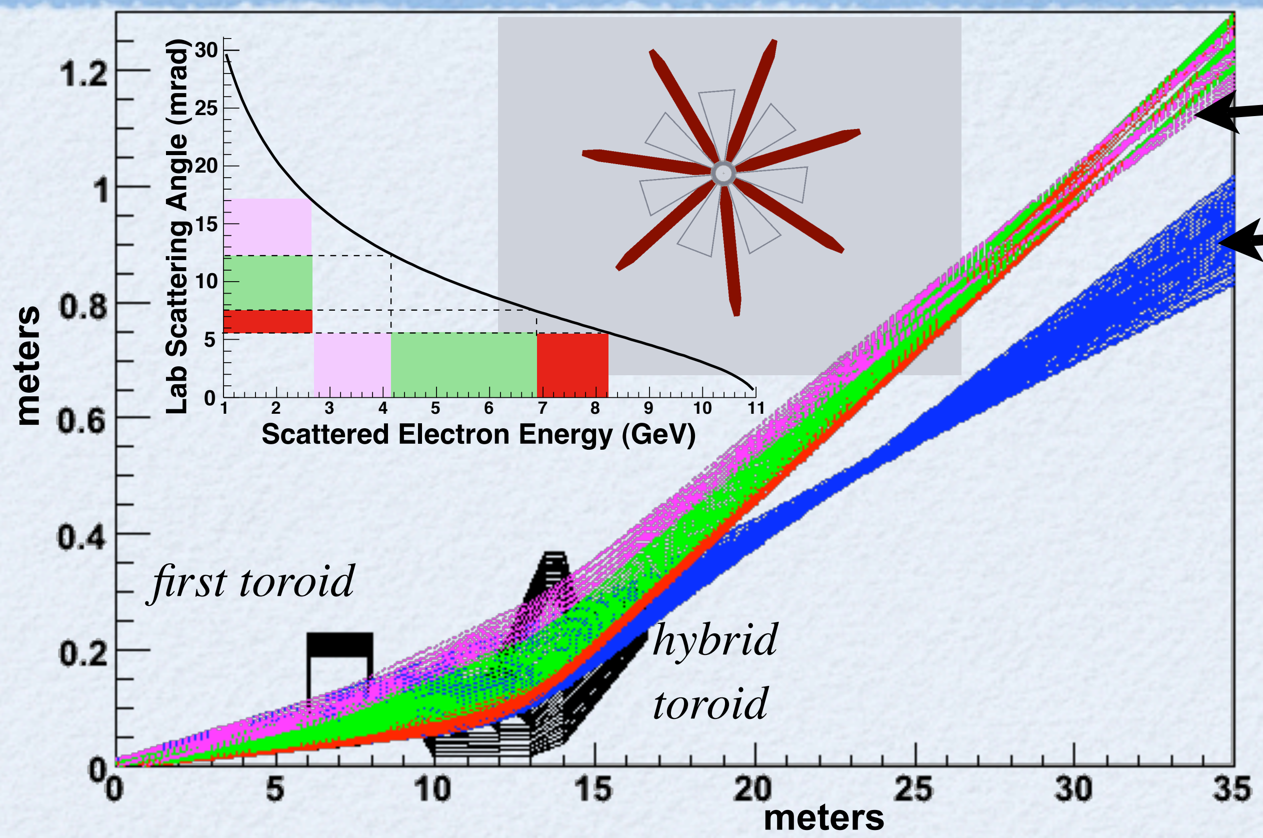

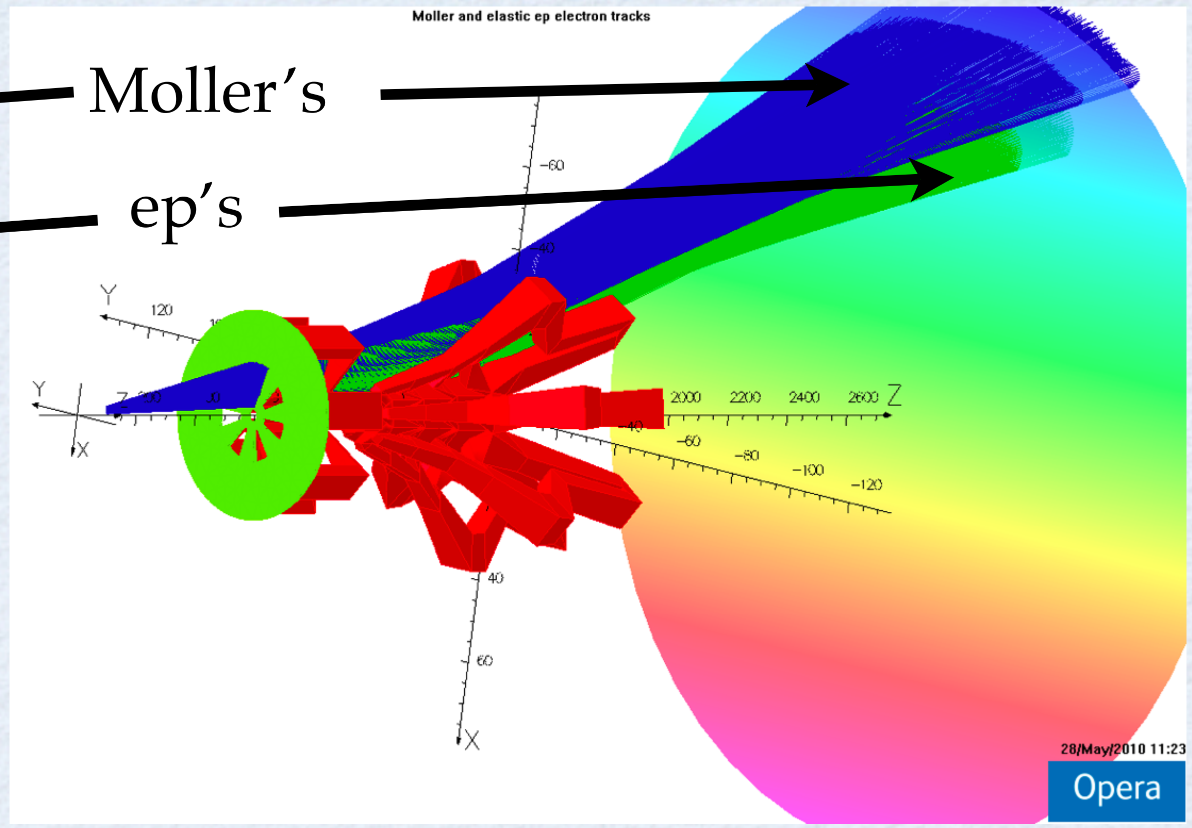

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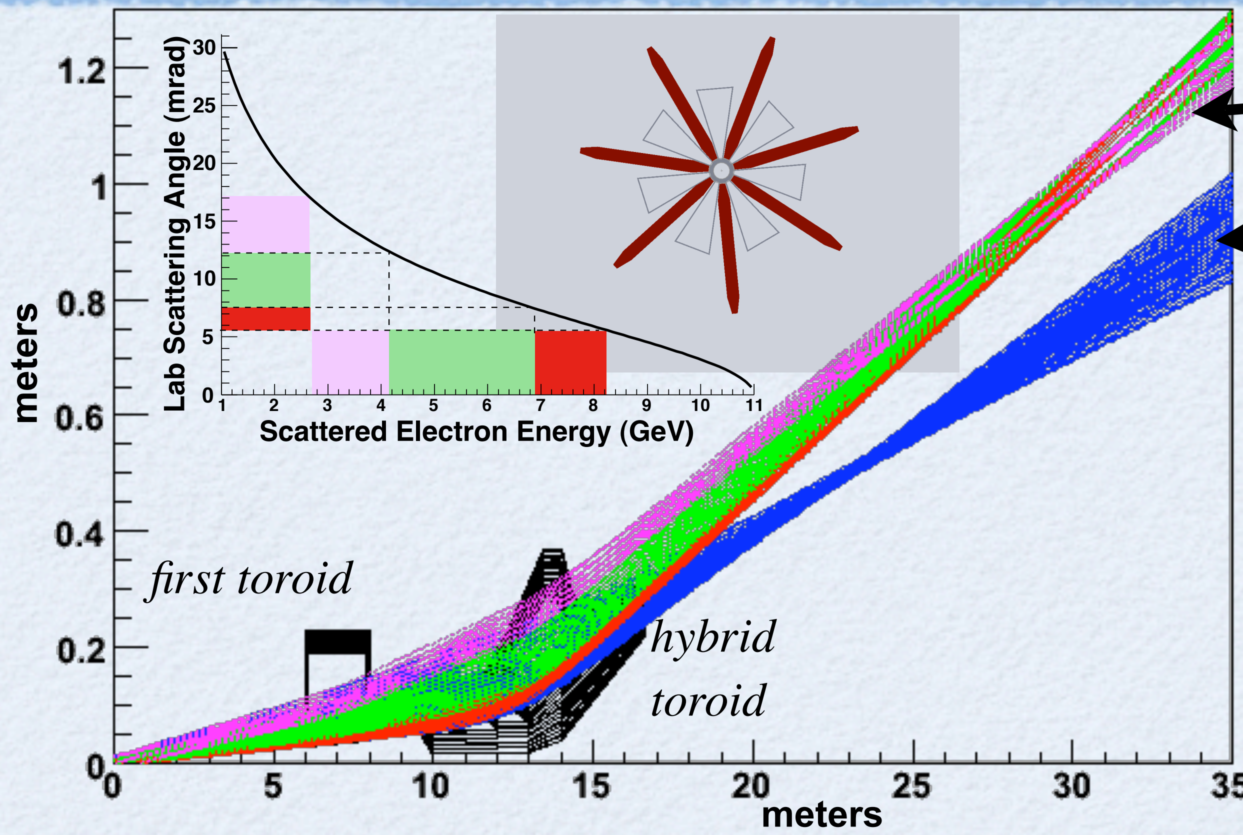

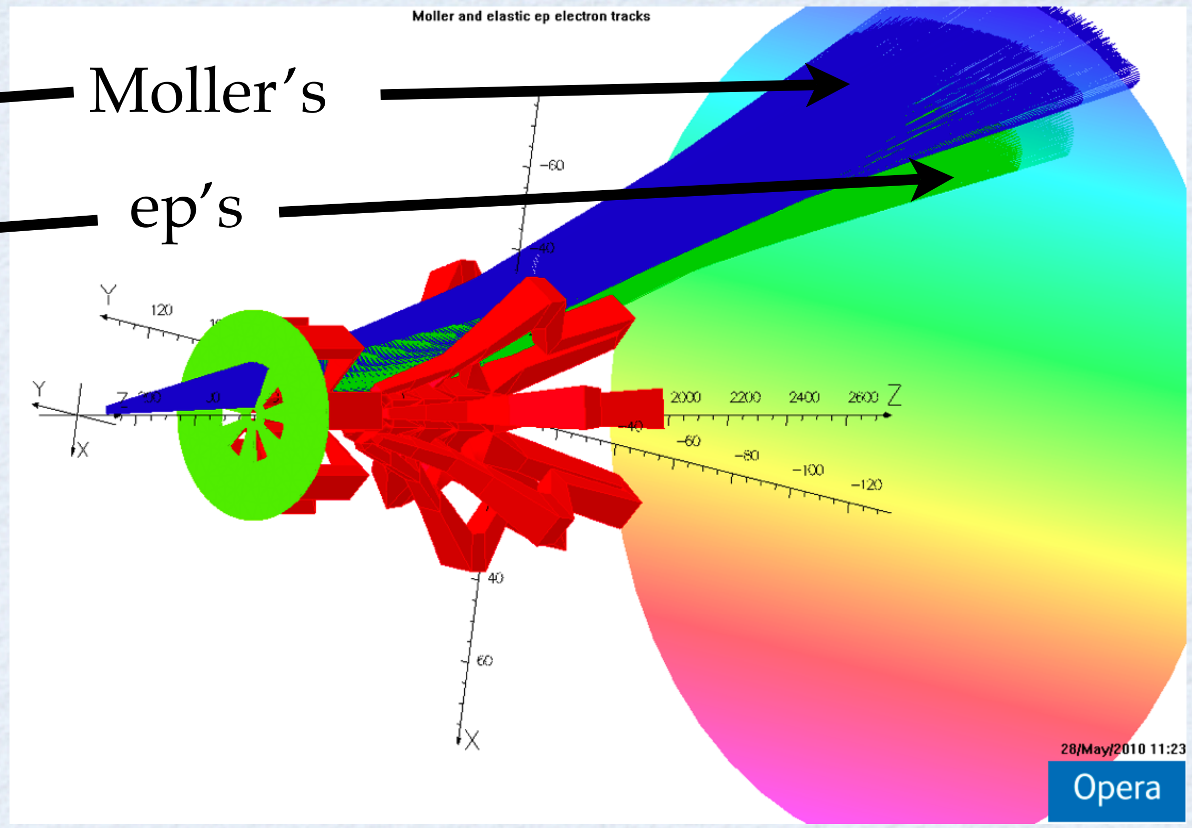

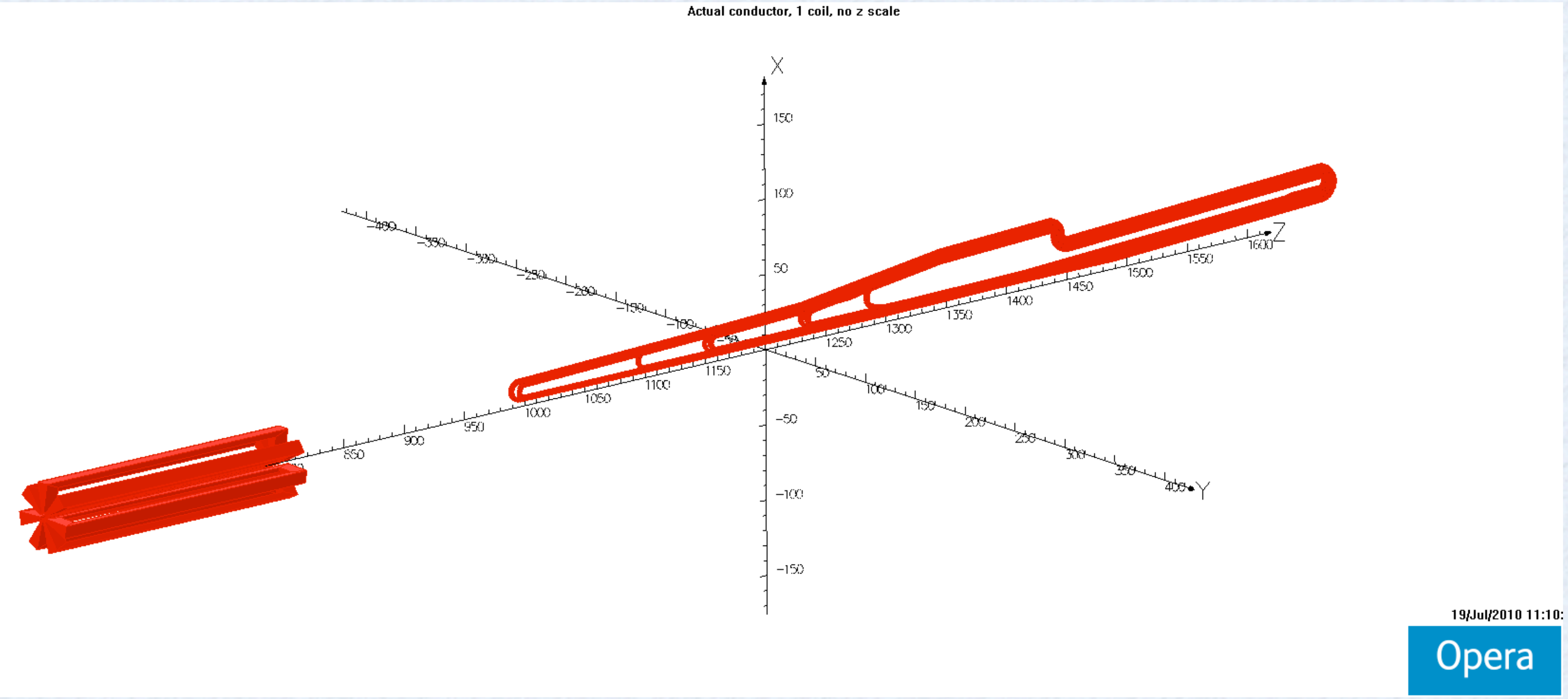

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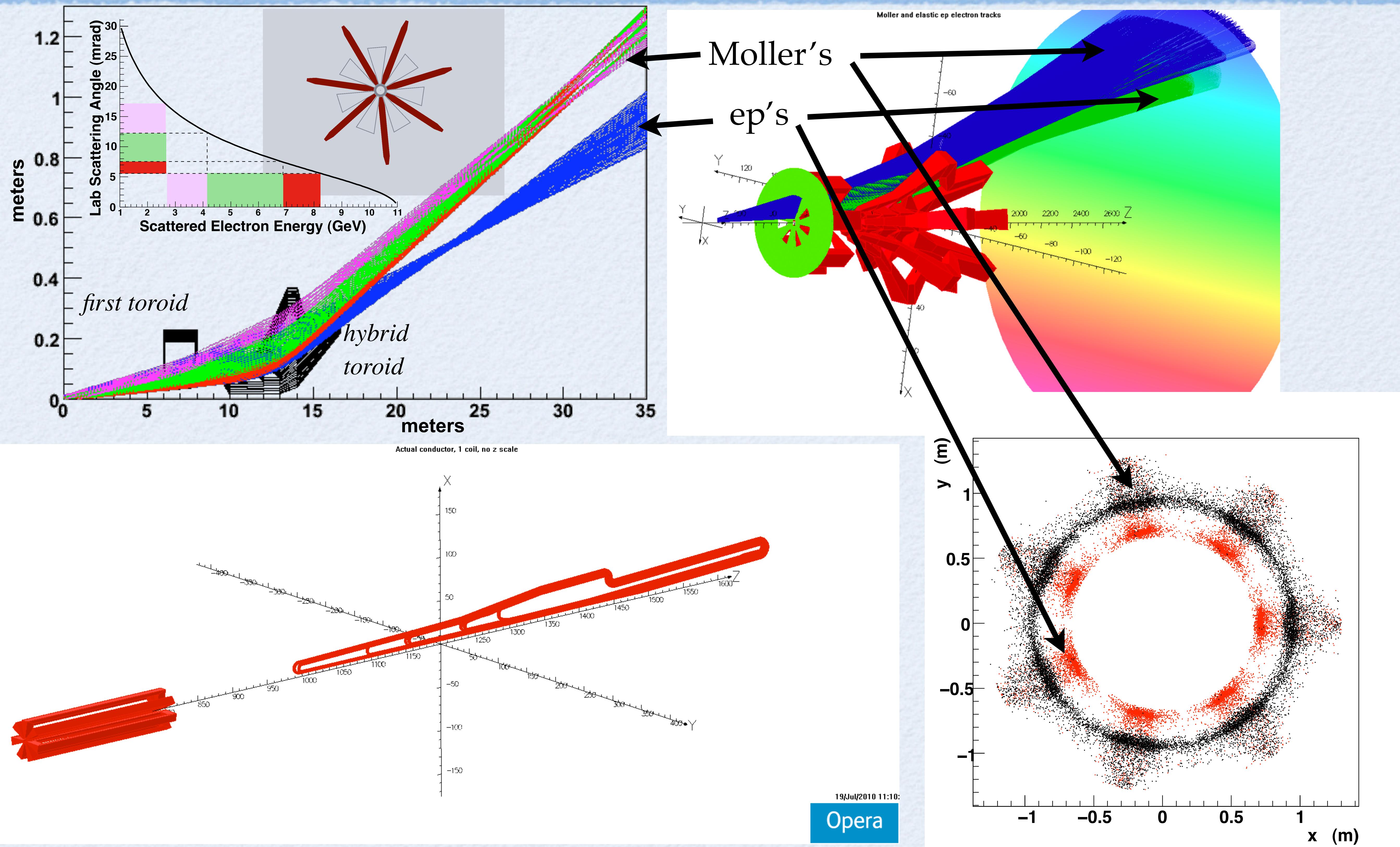

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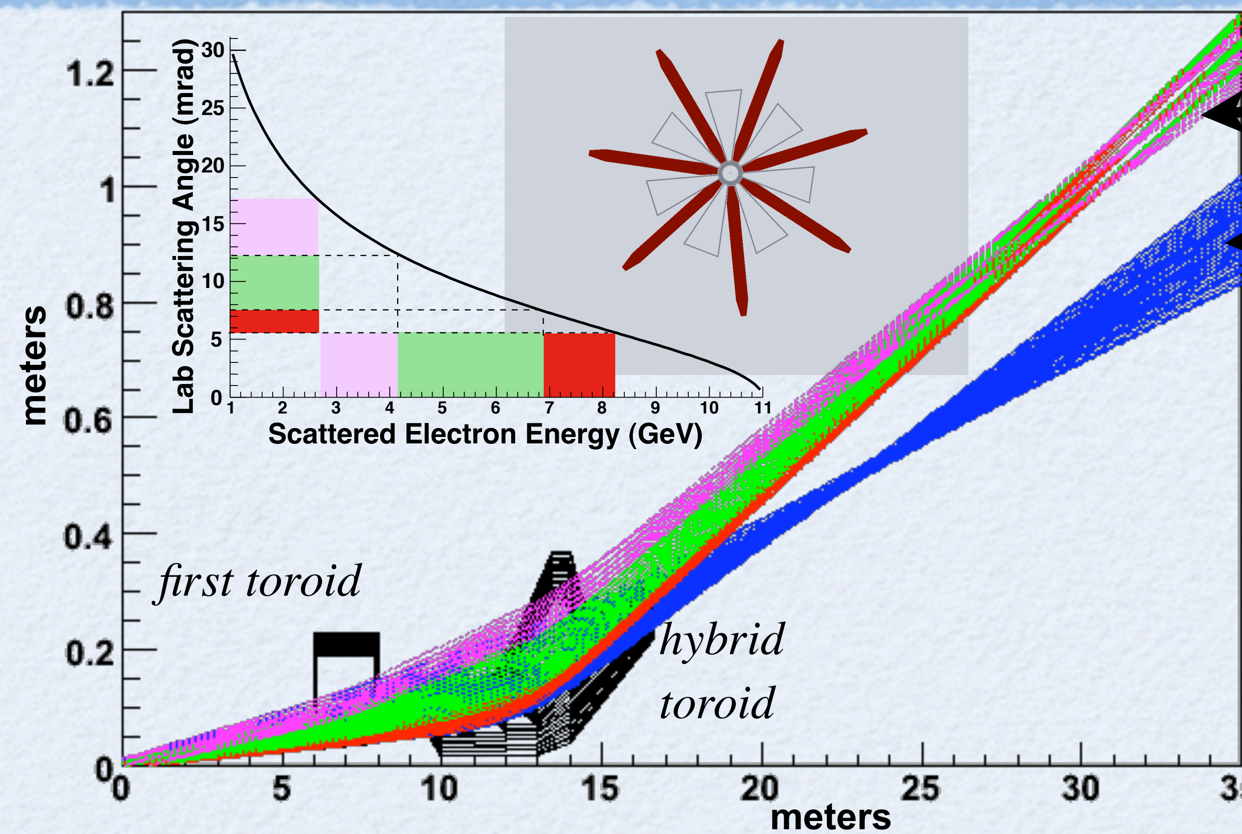
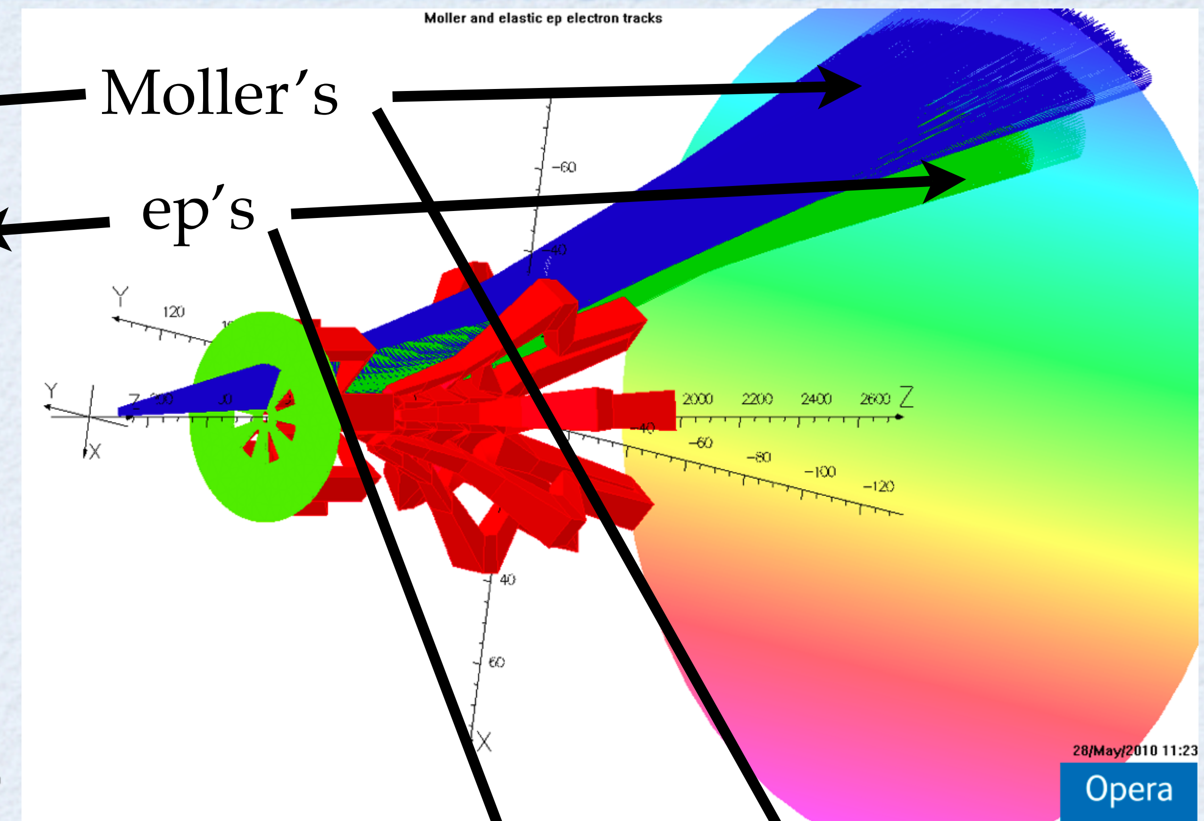
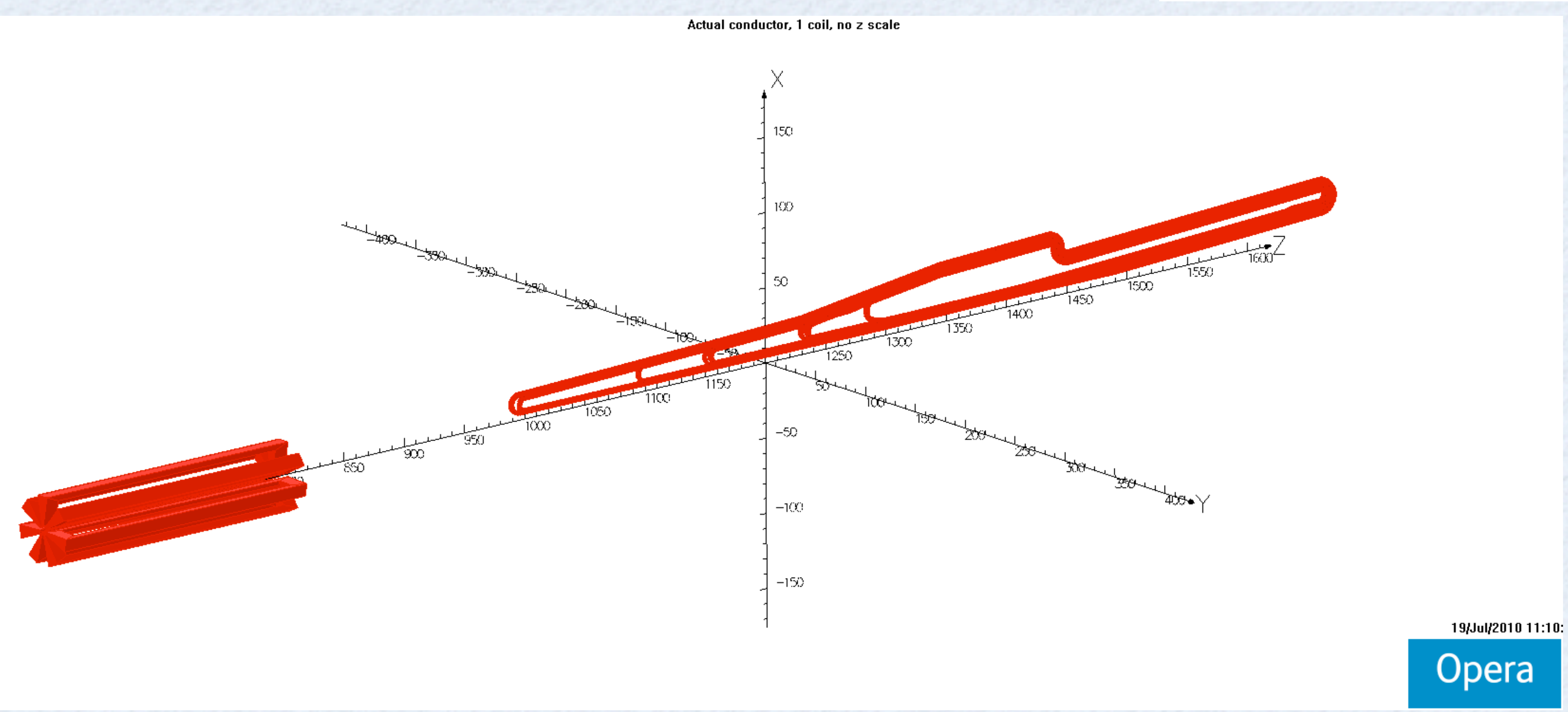
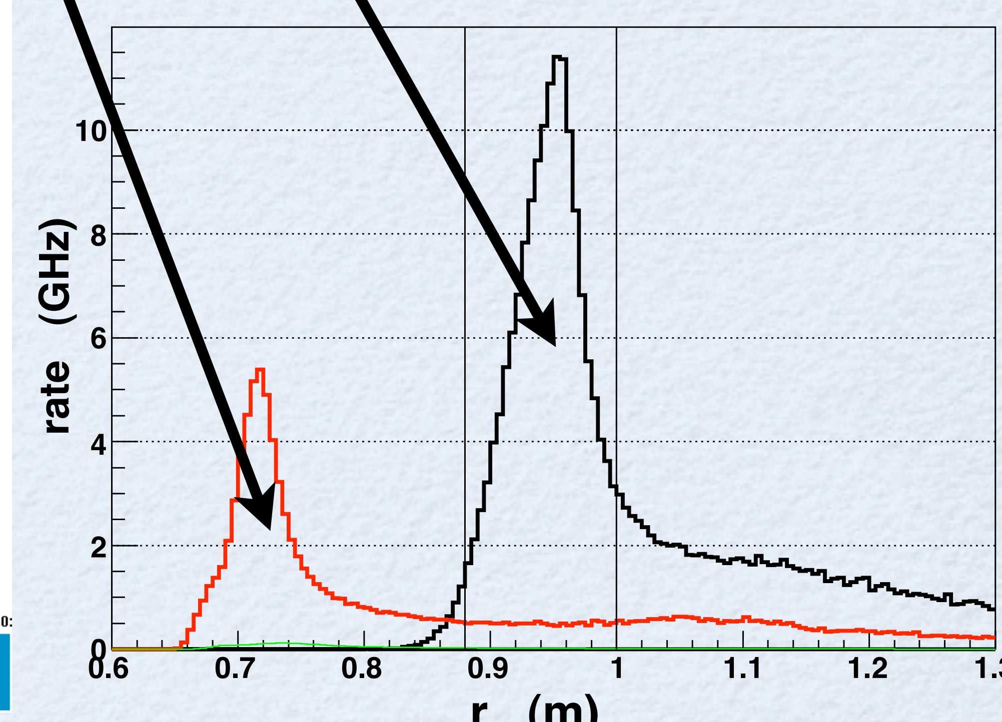
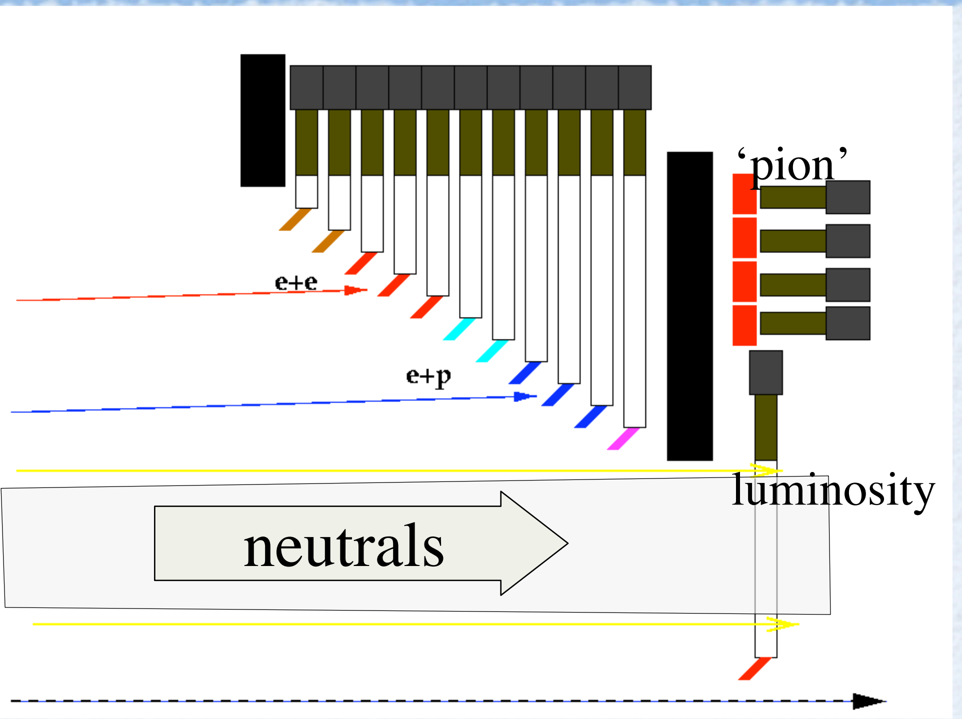






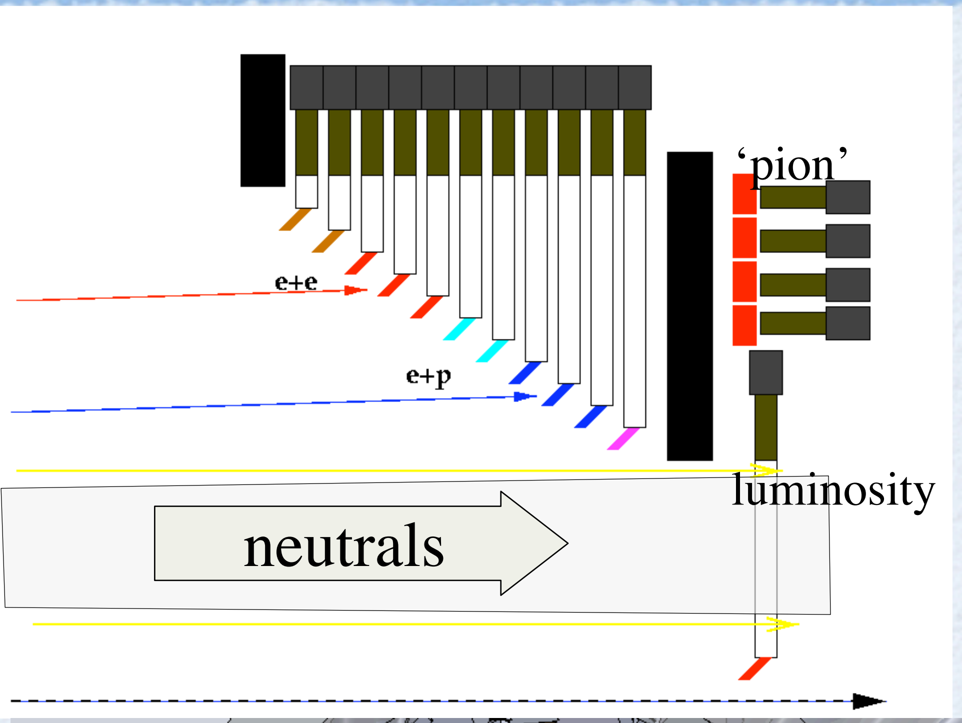


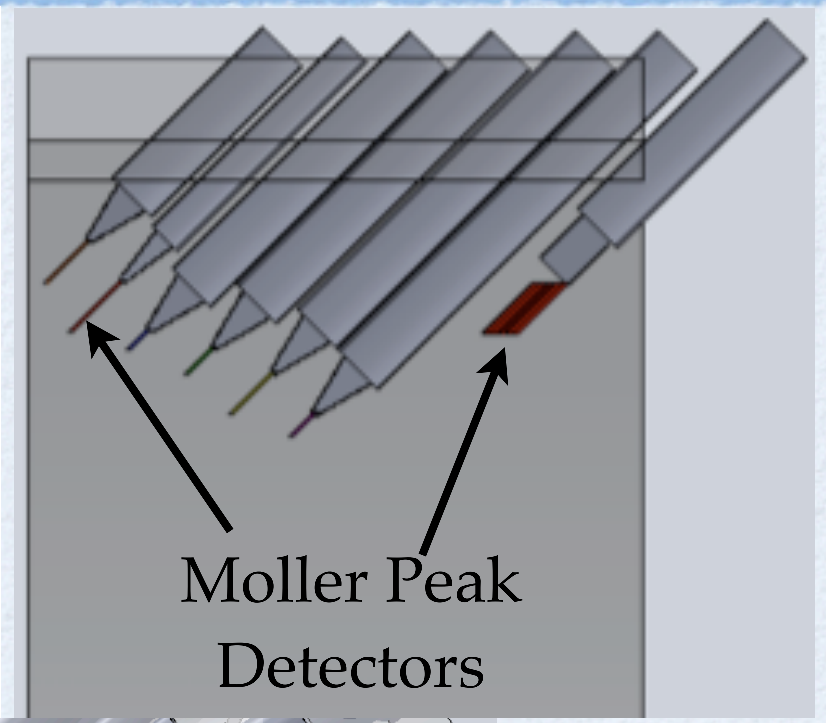
Detector Systems

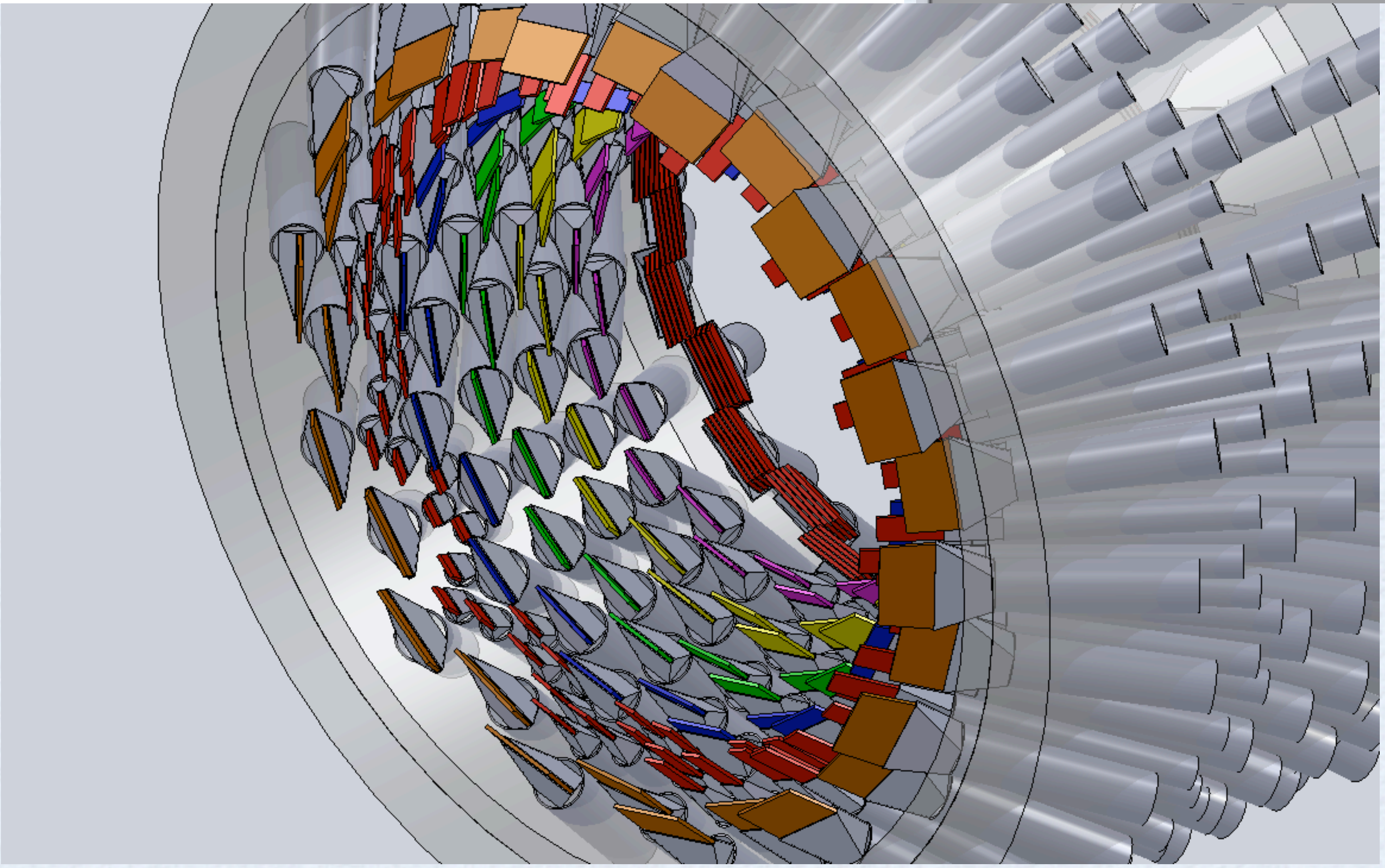


- ***Integrating Detectors:***
  - **Moller and e-p Electrons:**
    - *radial and azimuthal segmentation*
    - *quartz with air lightguides & PMTs*
  - **pions and muons:**
    - *quartz sandwich behind shielding*
  - **luminosity monitors**
    - *beam & target density fluctuations*

Detector Systems







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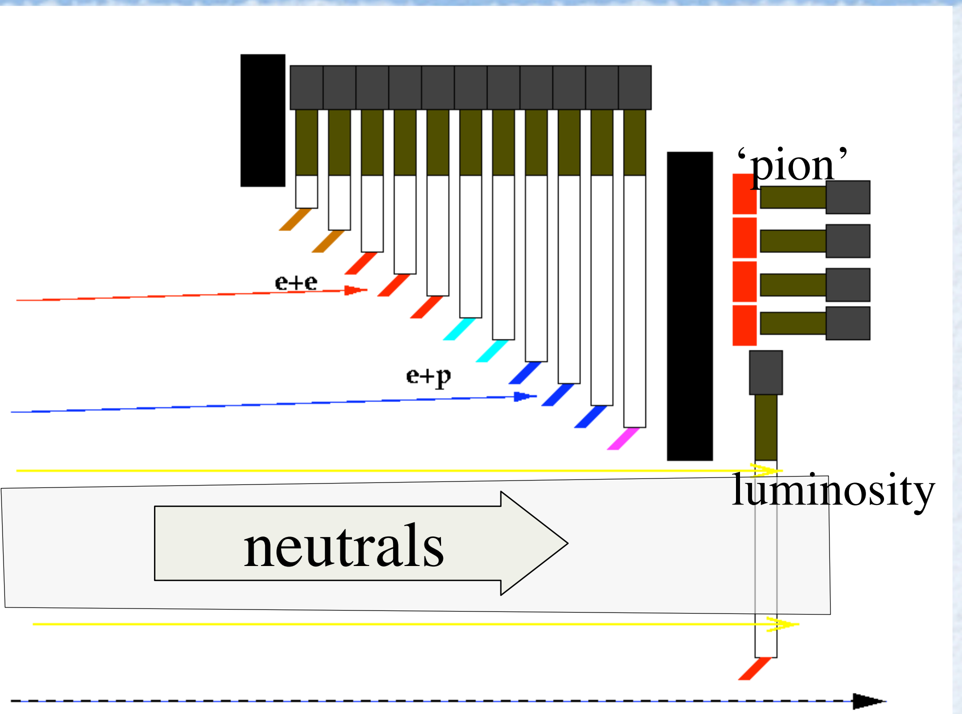
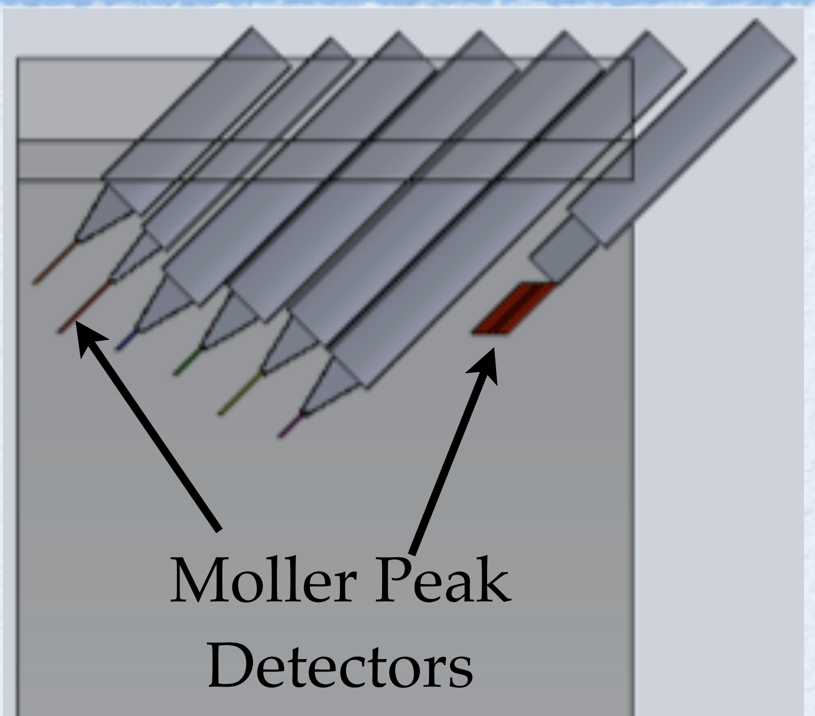
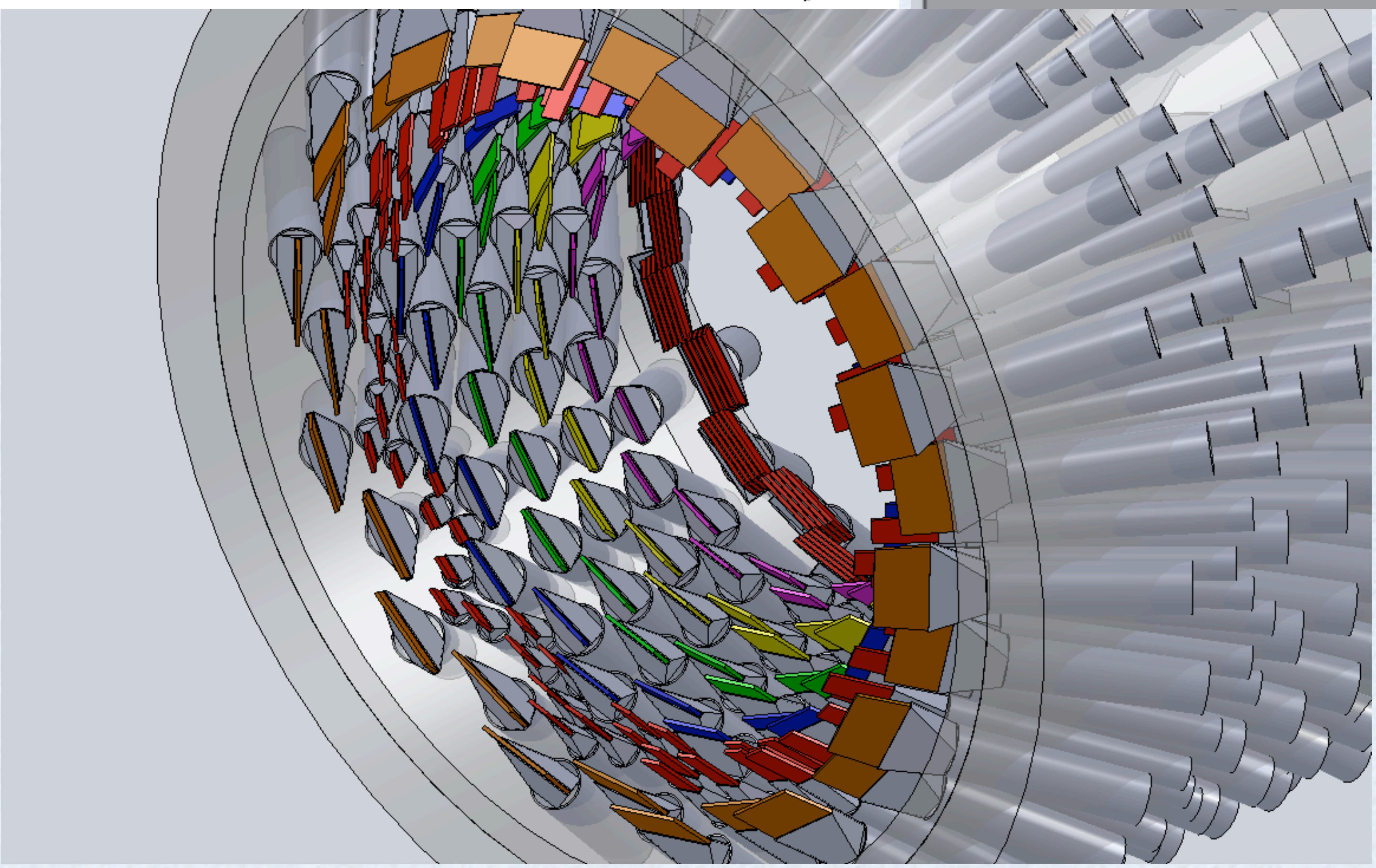




- ***Other Detectors***
  - Tracking detectors
    - *3 planes of GEMs/Straws*
    - *Critical for systematics/ calibration/debugging*
  - Integrating Scanners
    - *quick checks on stability*



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Statistics & Systematics

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

Irreducible Backgrounds:

- *Elastic e-p scattering*
  - well-understood and testable with data
  - 8% dilution, 7.5±0.4% correction
- *Inelastic e-p scattering*
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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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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**

Technical Challenges

- ~ 150 GHz scattered electron rate
  - Design 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 ~ 10 ppm and few microns 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"
- > 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, highly segmented integrating detectors
- Robust and Redundant 0.4% beam polarimetry
  - Plan to pursue both Compton and Atomic Hydrogen techniques

Status and Plans

- Project received PAC approval: Jan '09
- Director's review of physics goals and concept: Jan '10
- Aim to develop project funding (US + foreign): 2011-12
- Aim to install at JLab after 12 GeV upgrade: late 2015

- *Steering Committee:*
  - D.Armstrong, R.Carlini, G.Cates, K.de Jager, Y.Kolomensky, K.Kumar (chair), F.Maas, D.Mack, K.Paschke, M.Pitt, G.Smith, P.Souder, W.van Oers
- *Working Groups & Conveners*
  - Polarized Source *G. Cates*
  - Beam & Beam Instrumentation *M. Pitt*
  - Target *G. Smith*
  - Spectrometer *K. Kumar*
  - Integrating Detectors *D. Mack*
  - Tracking Detectors *D. Armstrong*
  - Polarimetry *K. Paschke*
  - Electronics/DAQ *R. Michaels*
  - Simulations *N. Simicevic / K. Grimm*

Need to expand collaboration further!

expression of interest: not yet finalized

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

(Canada: UBC, Manitoba, Winnipeg, TRIUMF)

Summary

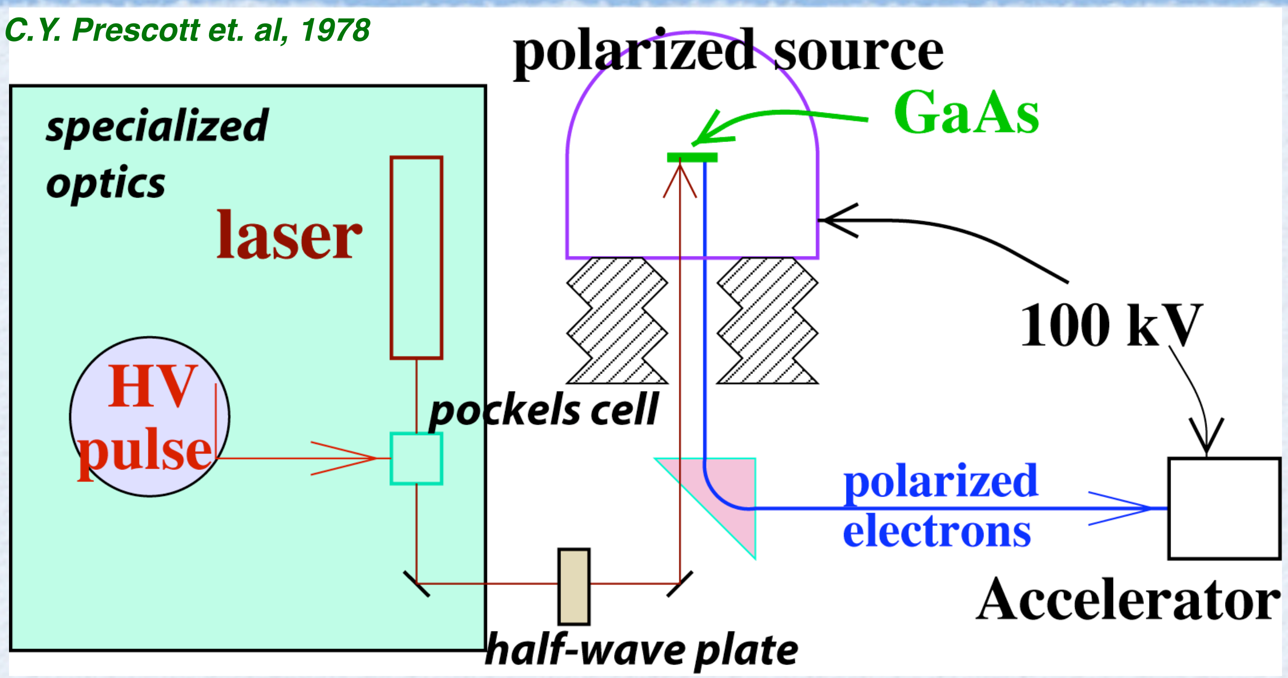
- **Projected Result from an A_{PV} measurement in Møller Scattering**

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

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

- **Opportunity with high visibility and large potential payoff**
  - The weak mixing angle is a fundamental parameter of EW physics
  - A cost-effective project has been elusive until now
    - *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*
- **NSAC Long Range Plan strongly endorsed the physics**
  - part of fundamental symmetries initiative to tune of 25M$
  - will need significant foreign participation to succeed
- **11 GeV JLab beam is a unique instrument that makes this feasible**

OPTICAL PUMPING



- Optical pumping of a GaAs wafer
- Rapid helicity reversal: change sign of longitudinal polarization ~ kHz to minimize drifts (like a lockin amplifier)
- Control helicity-correlated beam motion: under sign flip, keep beam stable at the sub-micron level

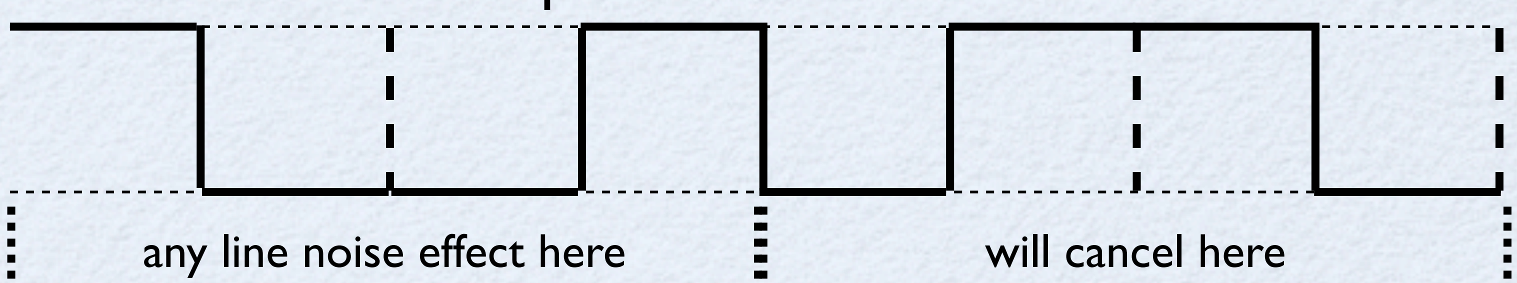
✧ **Beam helicity is chosen pseudo-randomly at multiple of 60 Hz**

- *sequence of "window multiplets"*

Example: at 240 Hz reversal

Choose 2 pairs pseudo-randomly, force complementary two pairs to follow

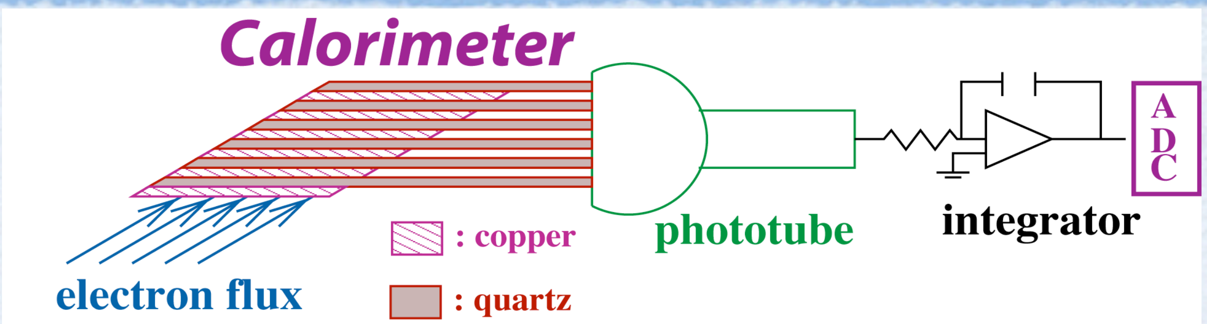
Analyze each "macropulse" of 8 windows together



MOLLER will plan to use ~ 2 kHz reversal; subtleties in details of timing

Noise characteristics have been unimportant in past experiments: Not so for PREX, Qweak and MOLLER....

FLUX INTEGRATION



"Flux Integration": very high rates

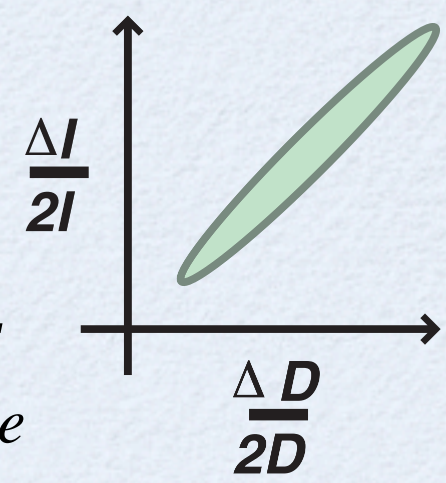
direct scattered flux to background-free region

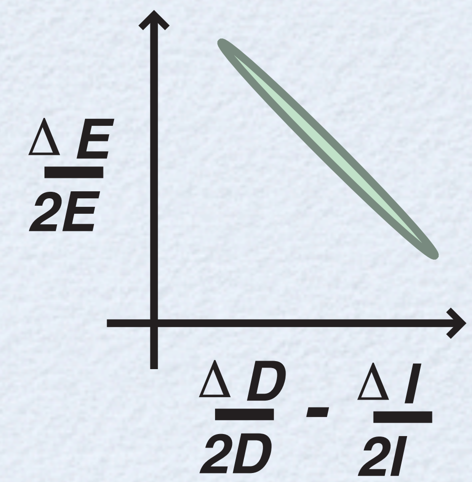
Detector D, Current I: F = D/I

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

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

I order: $x, y, \theta_x, \theta_y, E$
II order: e.g. spot-size

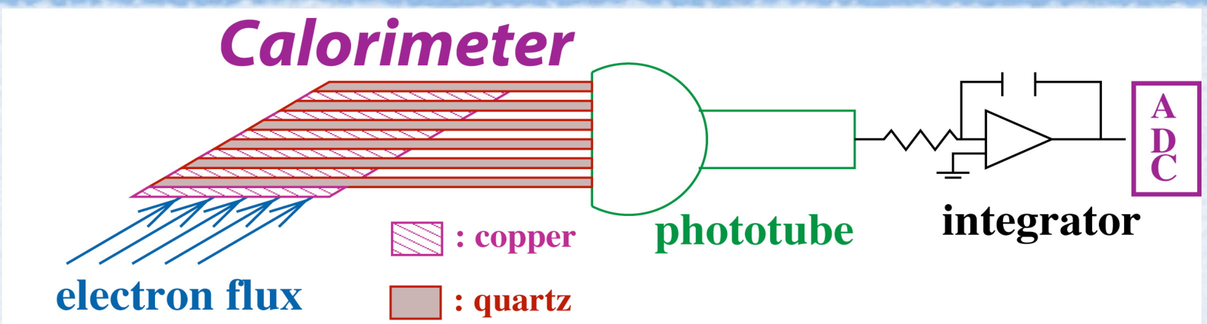




After corrections, variance of A_{pair} must get as close to counting statistics as possible: ~ 80 ppm (2kHz); central value then reflects A_{phys}

Experimental Challenge & Systematic Control

FLUX INTEGRATION



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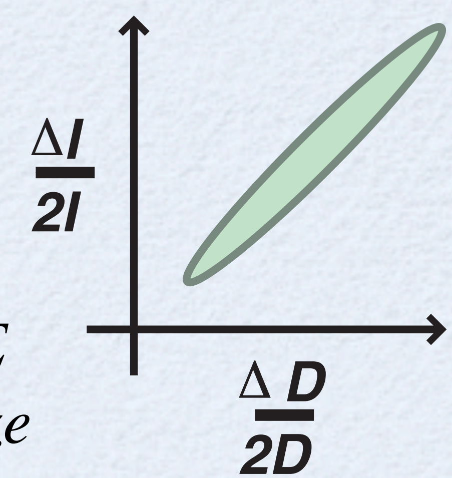

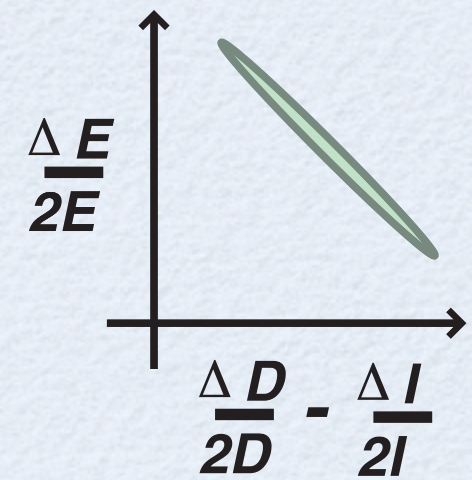

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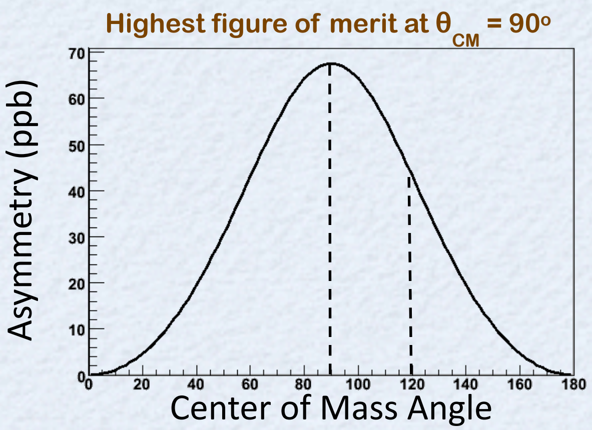
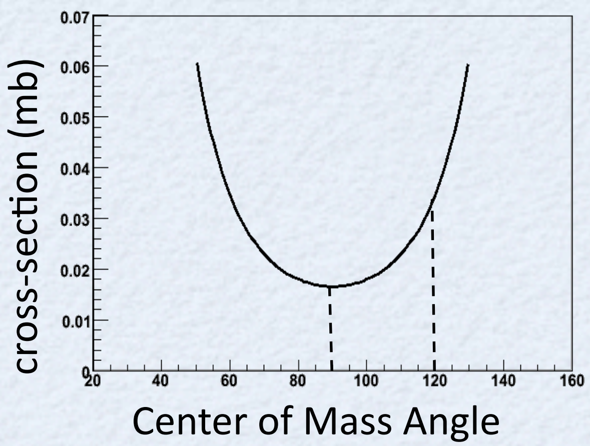
After corrections, variance of A_{pair} must get as close to counting statistics as possible: ~ 80 ppm (2kHz); central value then reflects A_{phys}

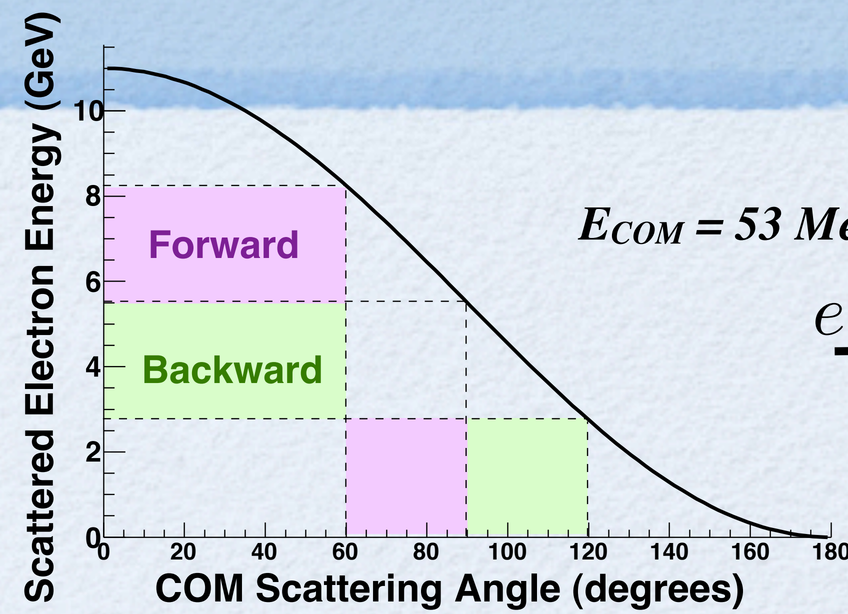
Experimental Challenge & Systematic Control

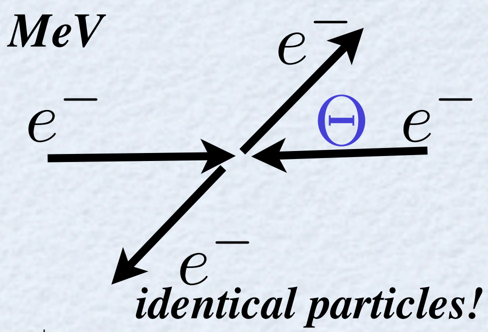
- ***Must minimize both random and helicity-correlated fluctuations in the integrated window-pair monitor response of electron beam trajectory, energy and spot-size.***

Spectrometer choice



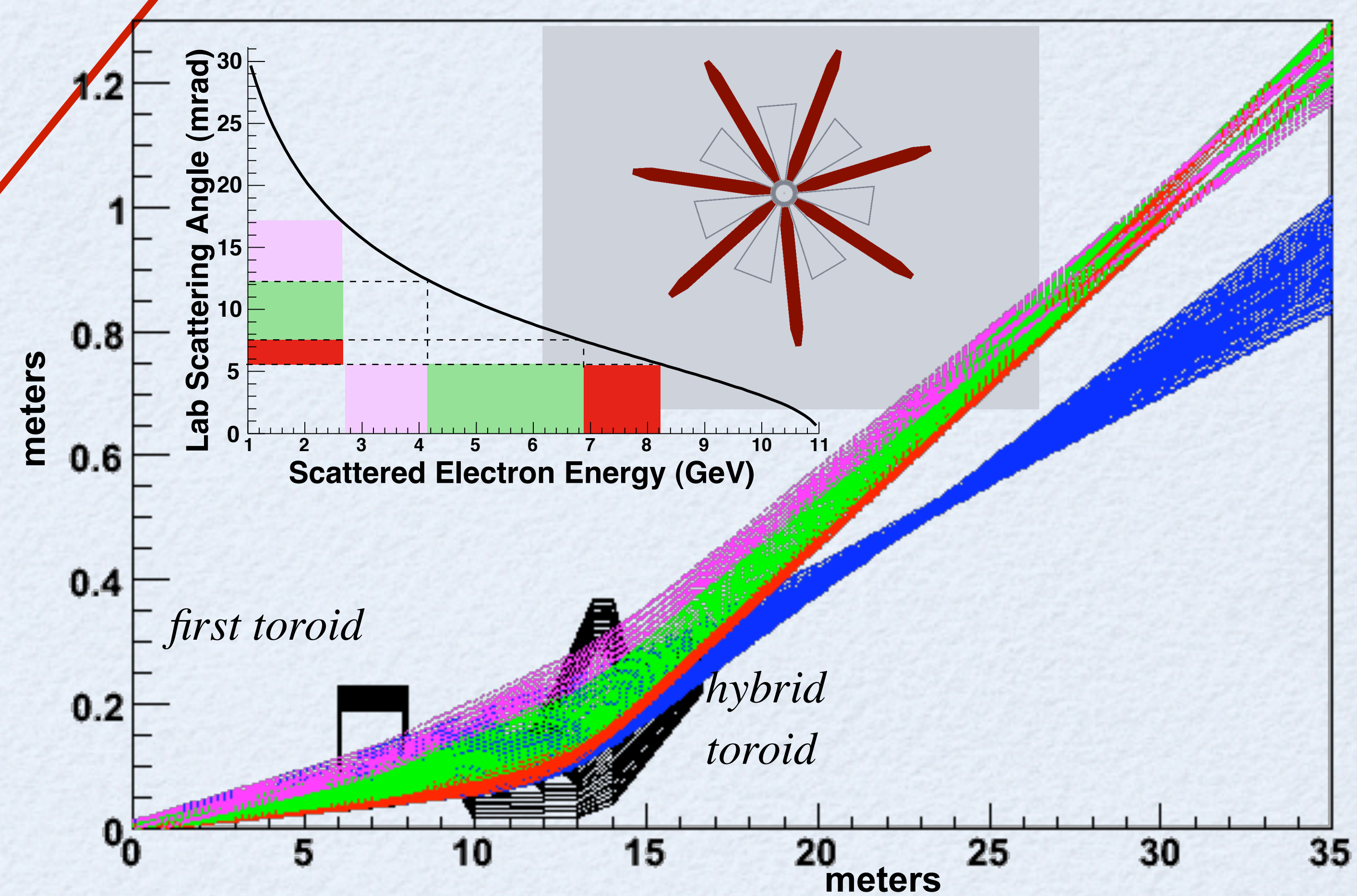




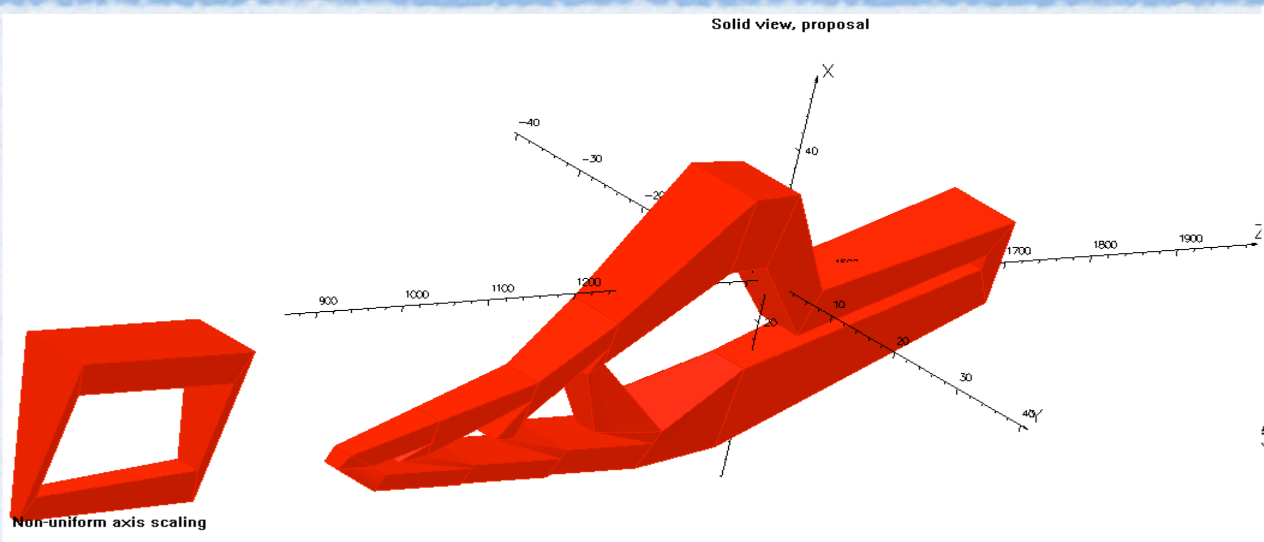


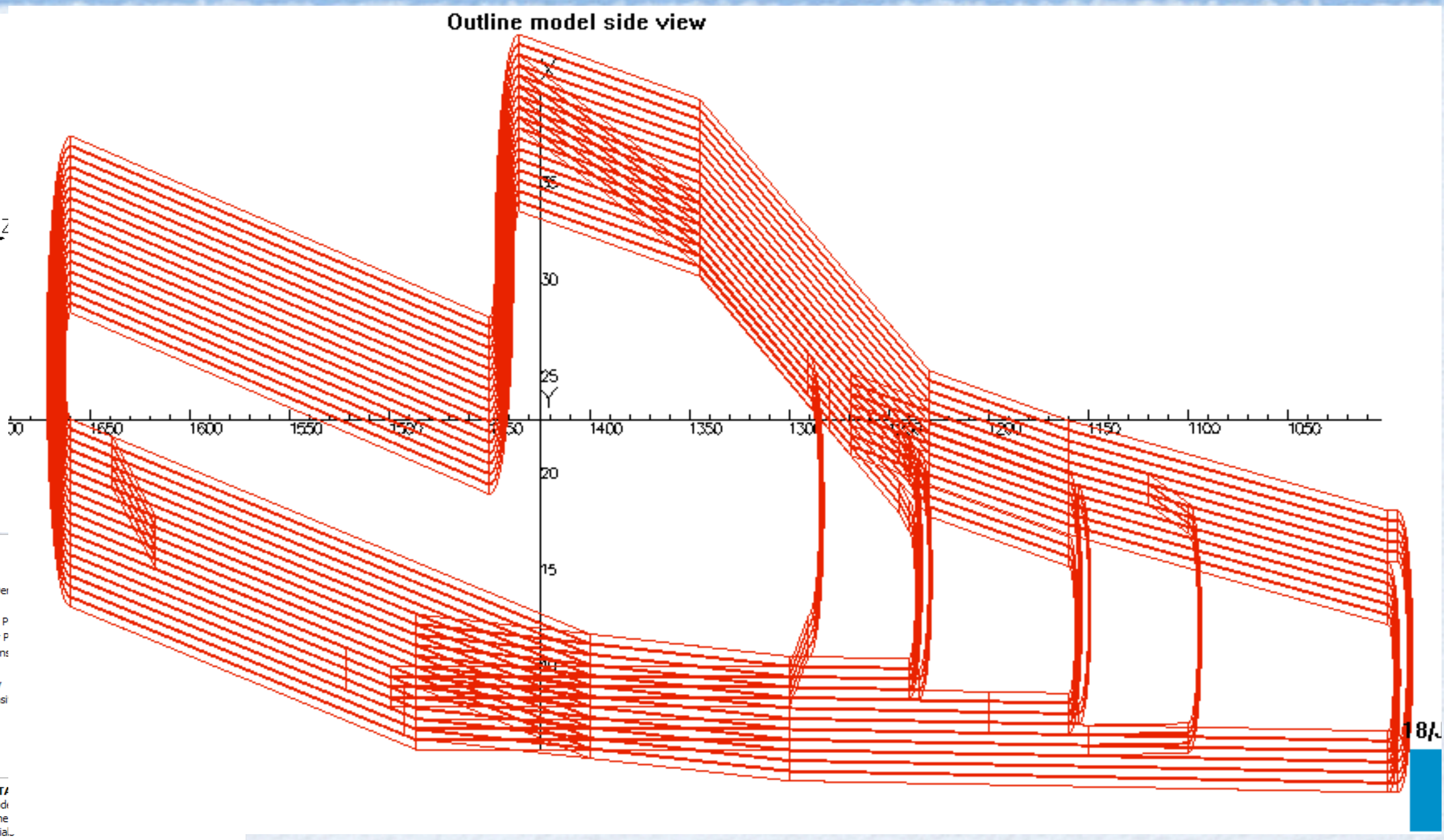
Odd number of coils: both forward & backward Mollers in same phi-bite

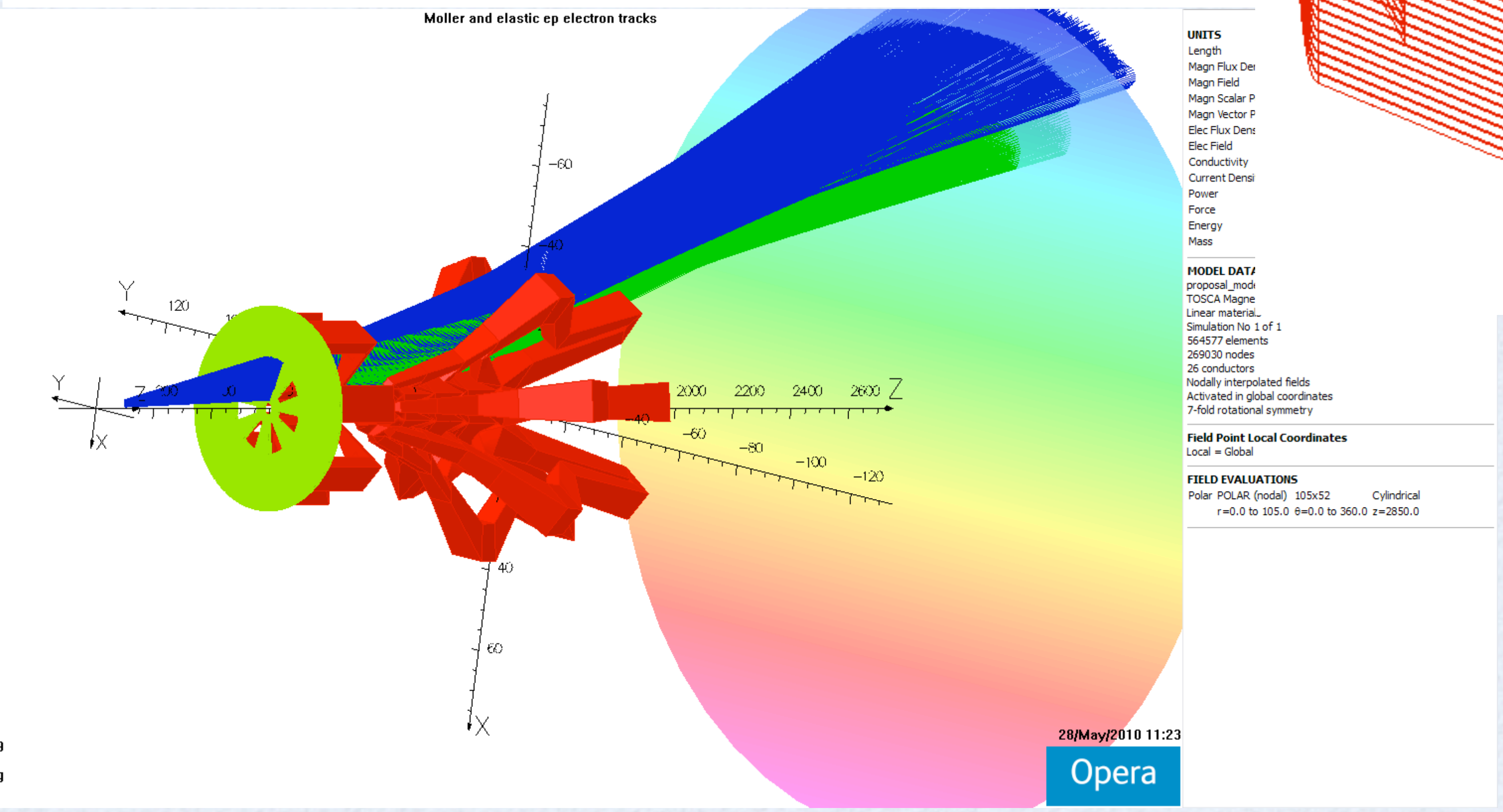
- ***Avoid superconductors***
  - ~150 kW of photons from target
  - Collimation extremely challenging
- ***Quadrupoles a la E158***
  - high field dipole chicane
  - poor separation from background
  - ~ 20-30% azimuthal acceptance loss
- ***Two Warm Toroids***
  - 100% azimuthal acceptance
  - better separation from background



Spectrometer Layout







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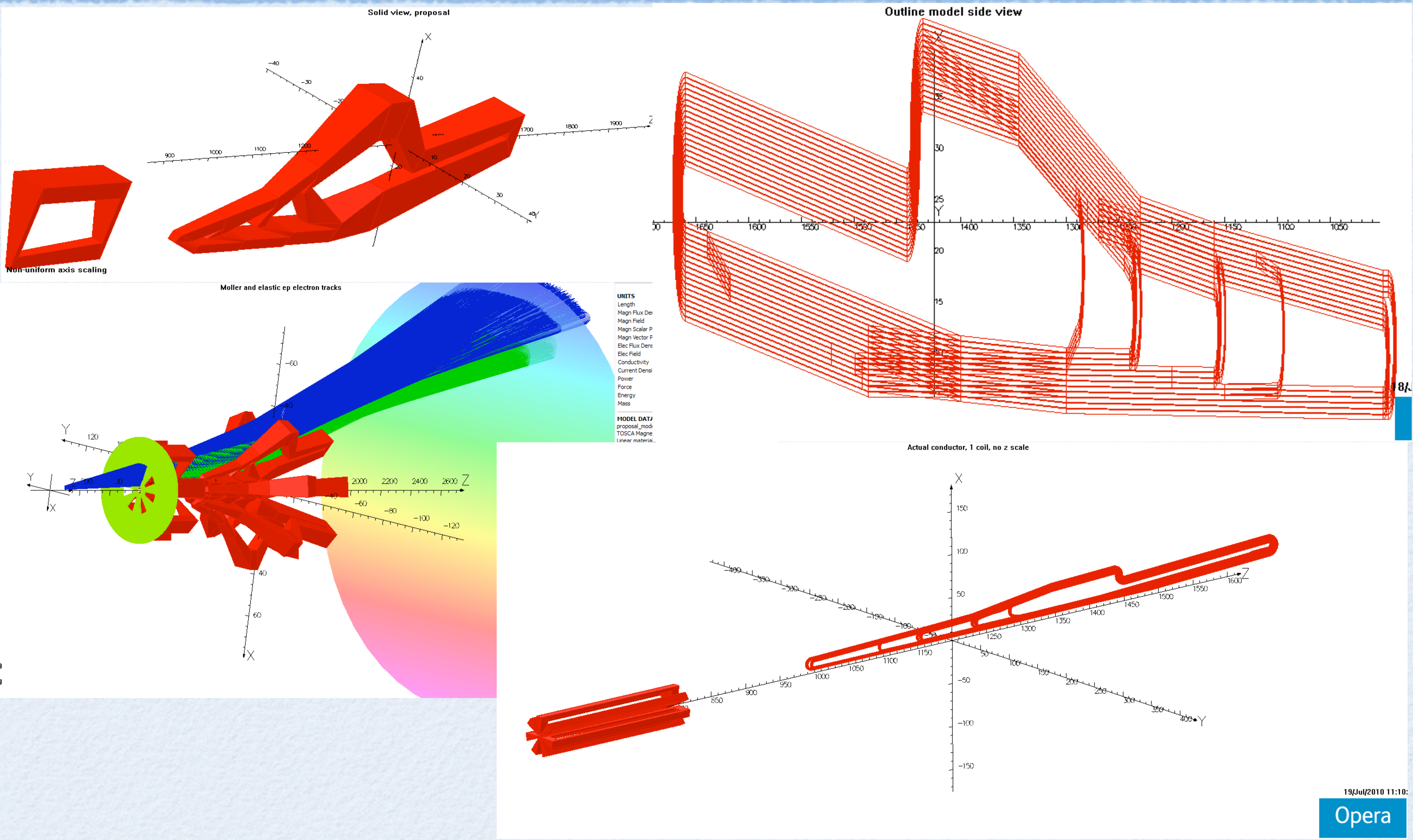

Signal & Backgrounds

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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- *Statistical Error*
  - 83 ppm 1 kHz pulse-pair width @ 75 μA
  - table assumes 80% polarization & no degradation of statistics from other sources
  - realistic goal ~ 90 ppm
  - potential for recovering running time with higher Pe, higher efficiency, better spectrometer focus....

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Backgrounds:

- ***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
- ***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

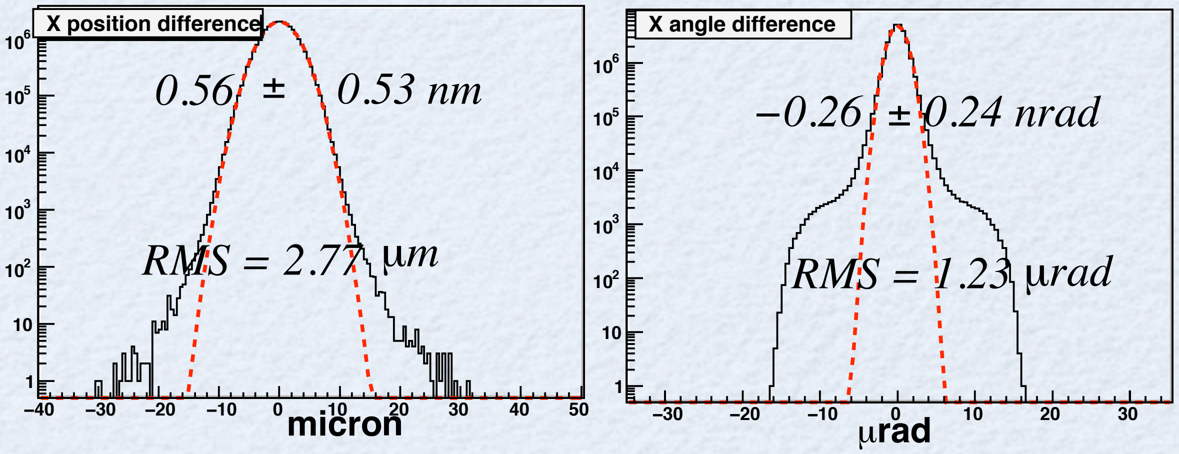
Systematics overview

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**

- *longitudinal beam polarization*
  - Goal: redundant, continuous monitoring with Compton & Atomic Hydrogen Moller
  - Redundancy backup plan: High field Moller
- *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

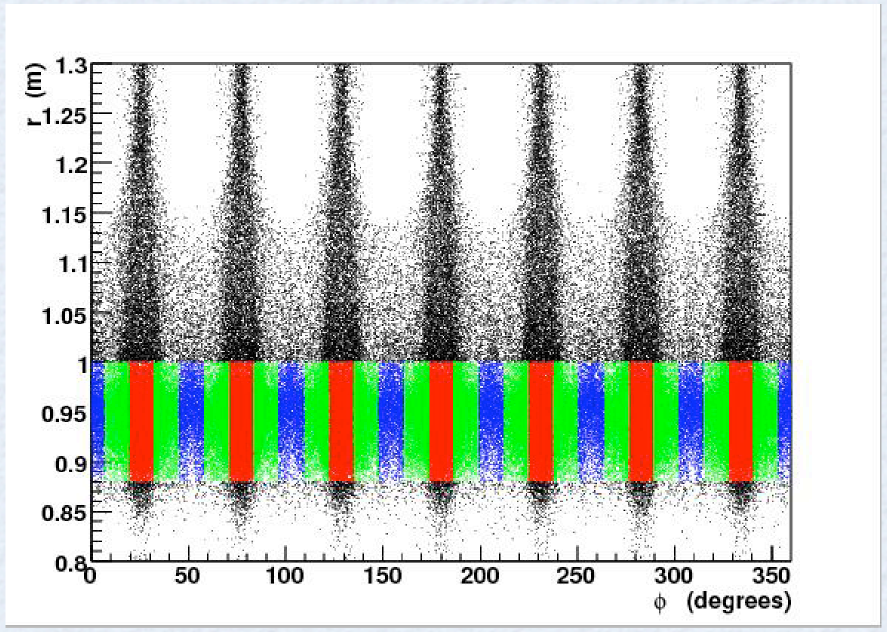
- *I order beam helicity correlations*
  - position to 0.5 nm, angle to 0.05 nrad
  - active intensity, position and angle feedback
- *II order beam helicity correlations*
  - control laser spotsize fluctuations to 10^{-4}
  - slow flips with Wien filter and g-2 energy flip

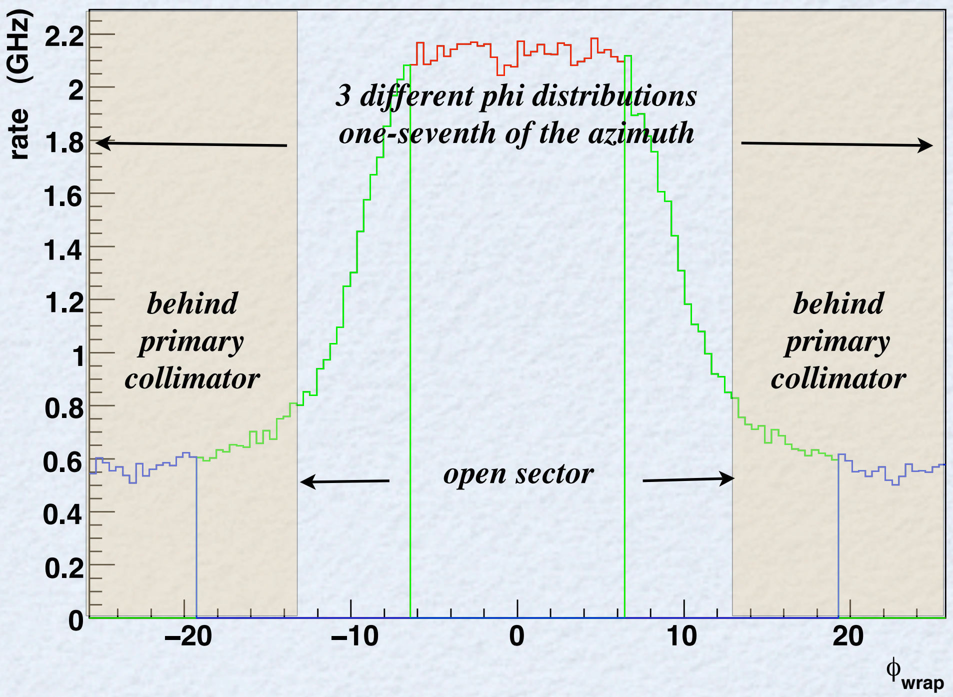
HAPPEXII

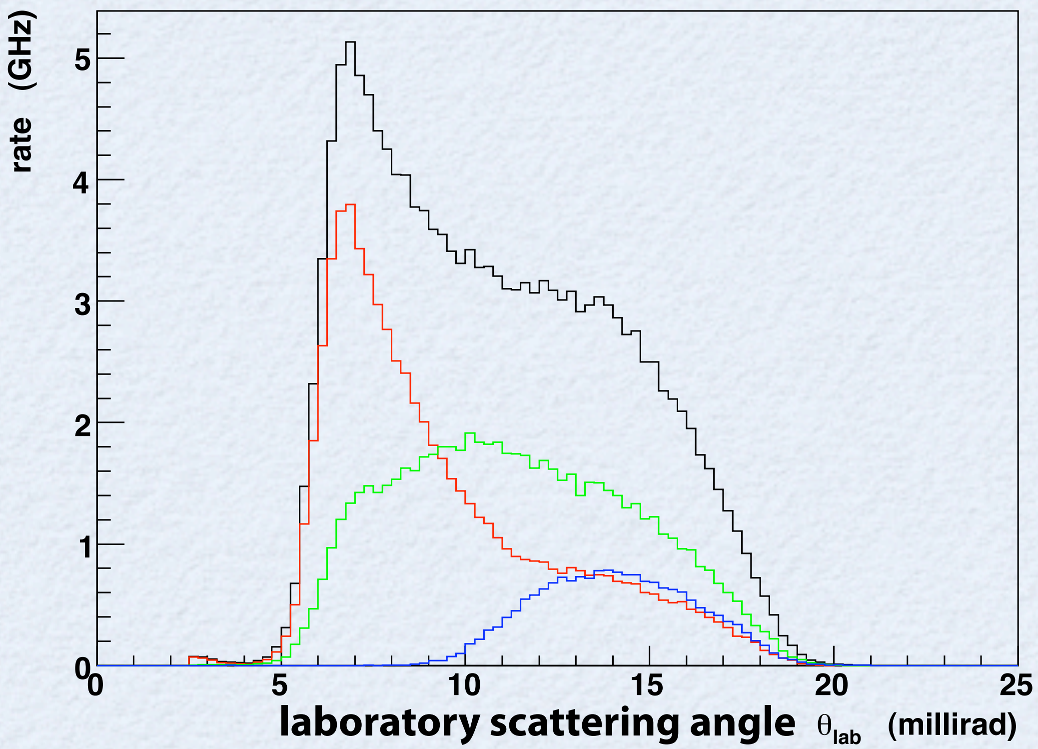


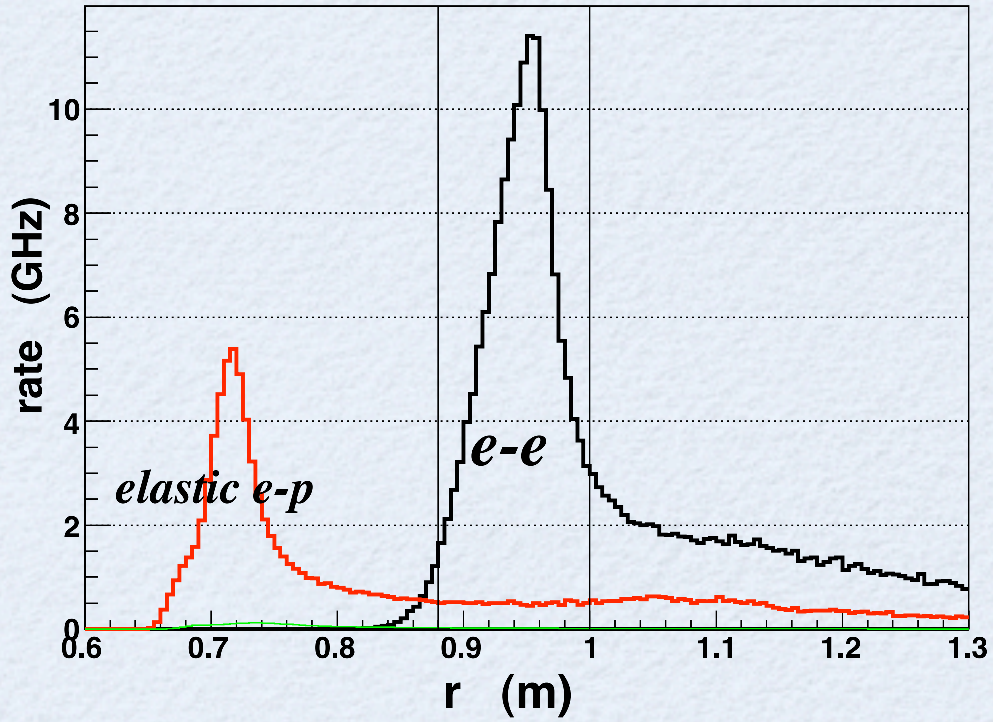
Scattered Flux

Initial and final state radiation effects in target

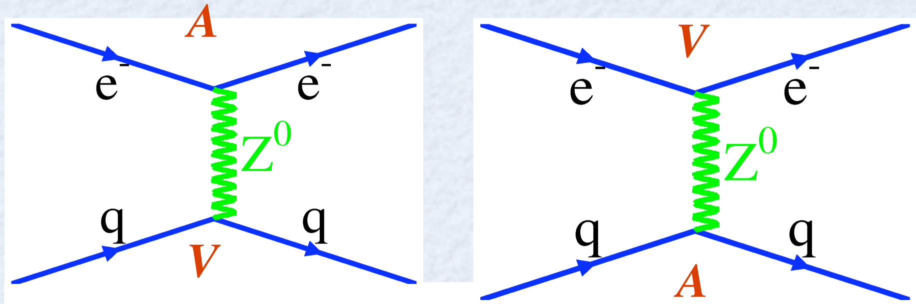








Quark Weak Charges



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

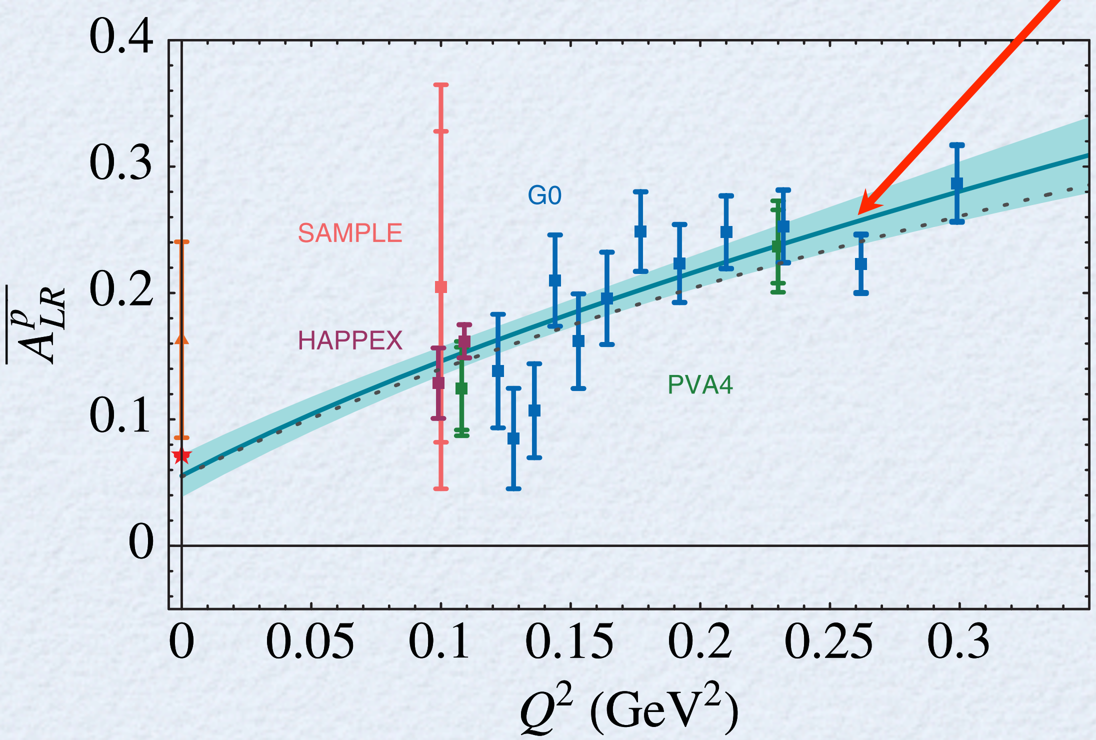
$\delta(C_{1q}) \propto (+\eta_{RL}^{eq} + \eta_{RR}^{eq} - \eta_{LL}^{eq} - \eta_{LR}^{eq})$ ⇒ *PV elastic e-p, APV*

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

A_{PV} in elastic e-p scattering:

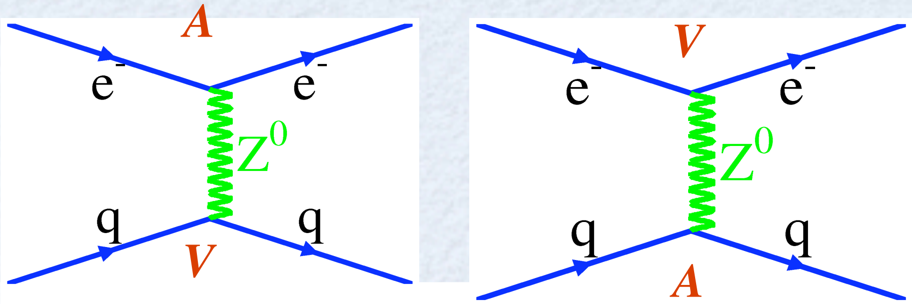
$$A(Q^2 \to 0) = -\frac{G_F}{4\pi\alpha\sqrt{2}}\left[Q^2\, Q^p_{weak} + Q^4 B\left(Q^2\right)\right]$$

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



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

Quark Weak Charges



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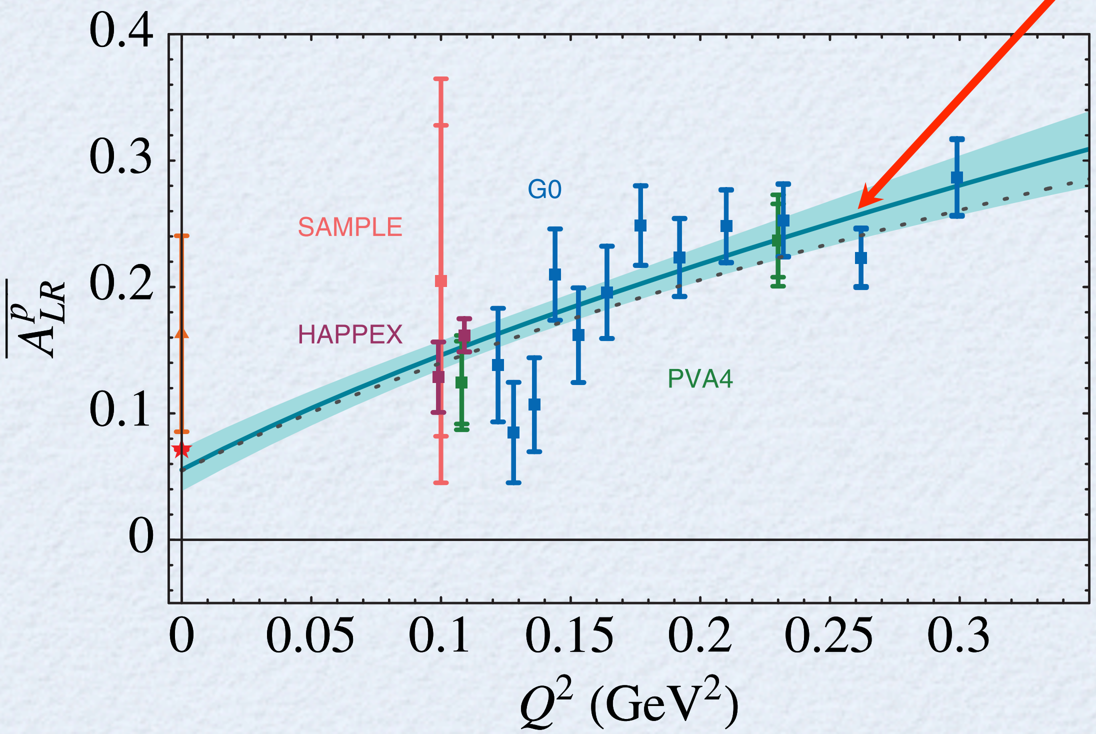

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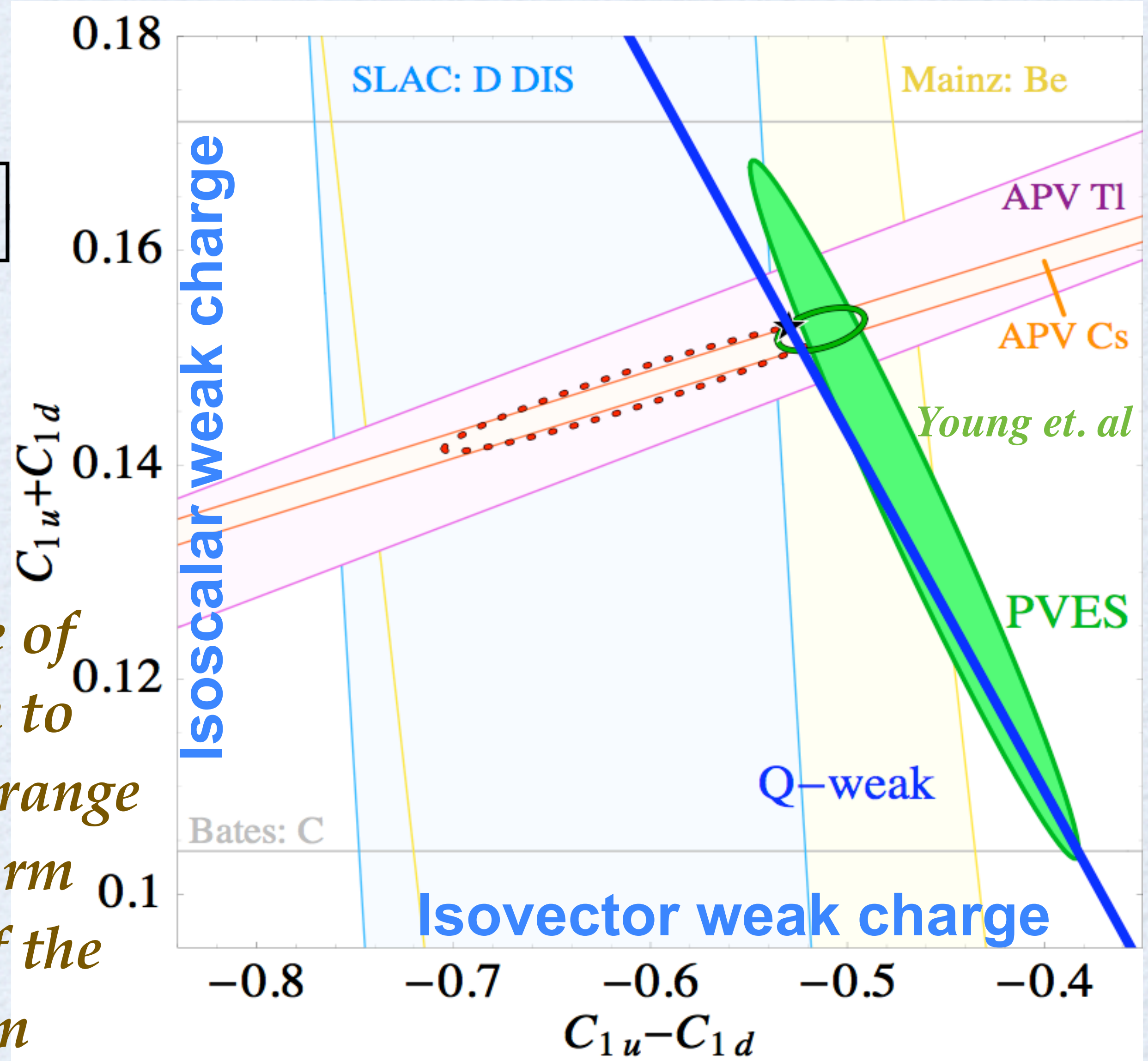
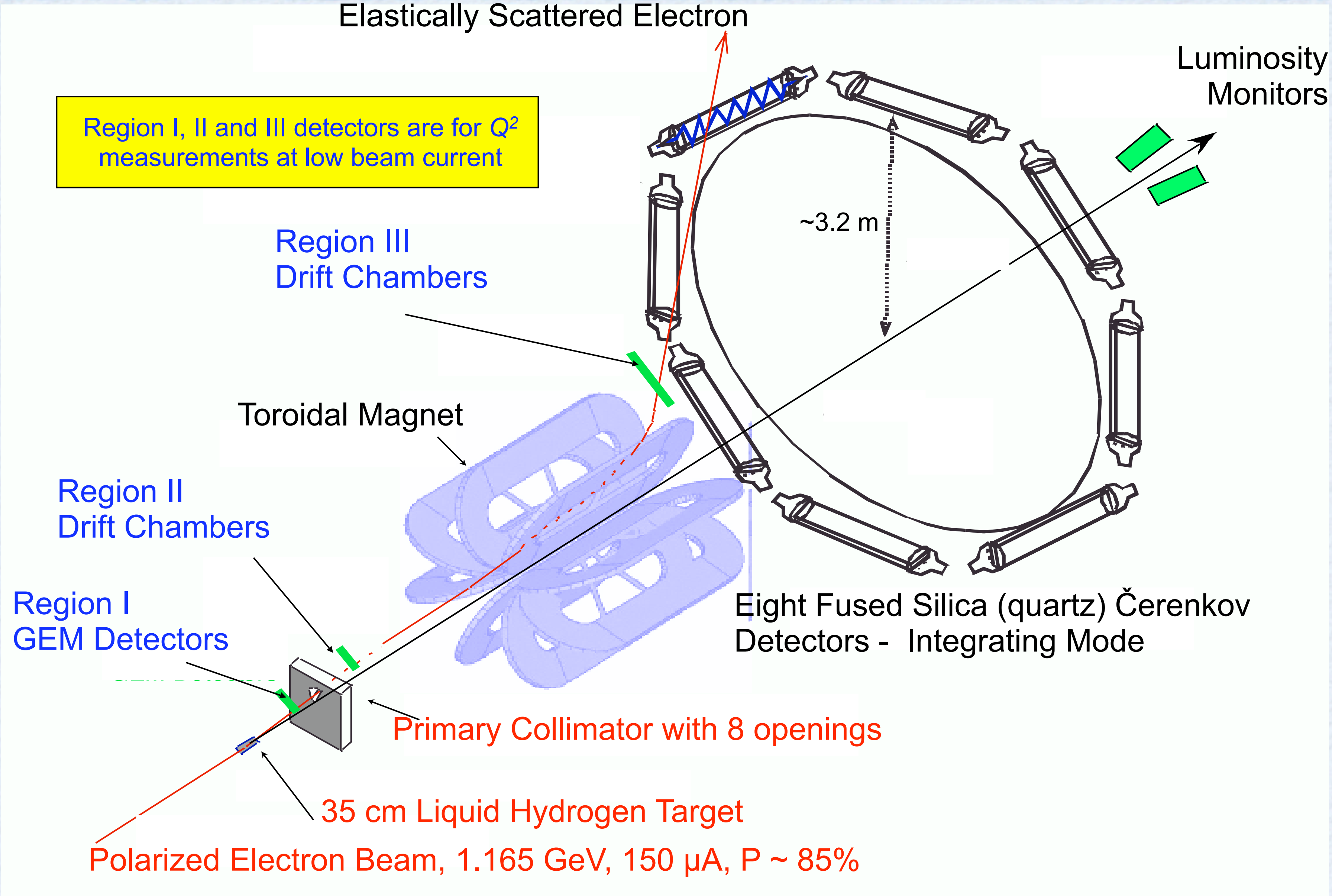
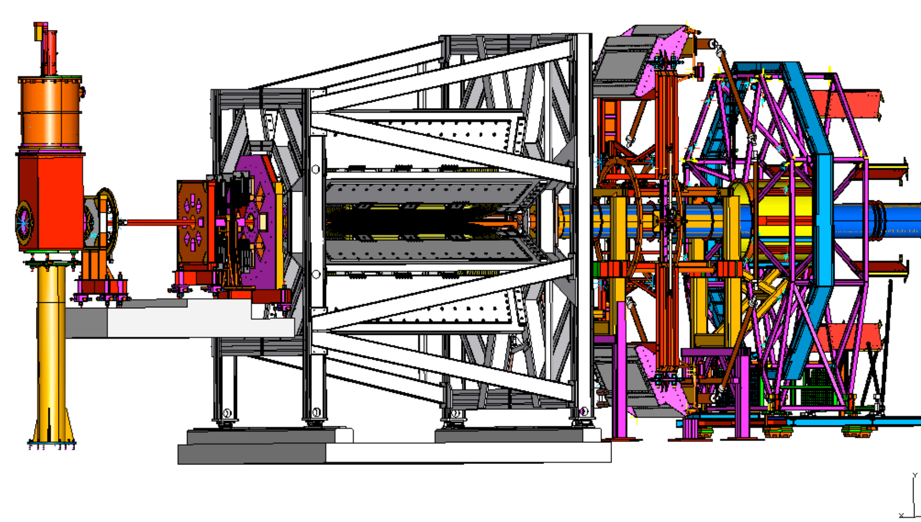
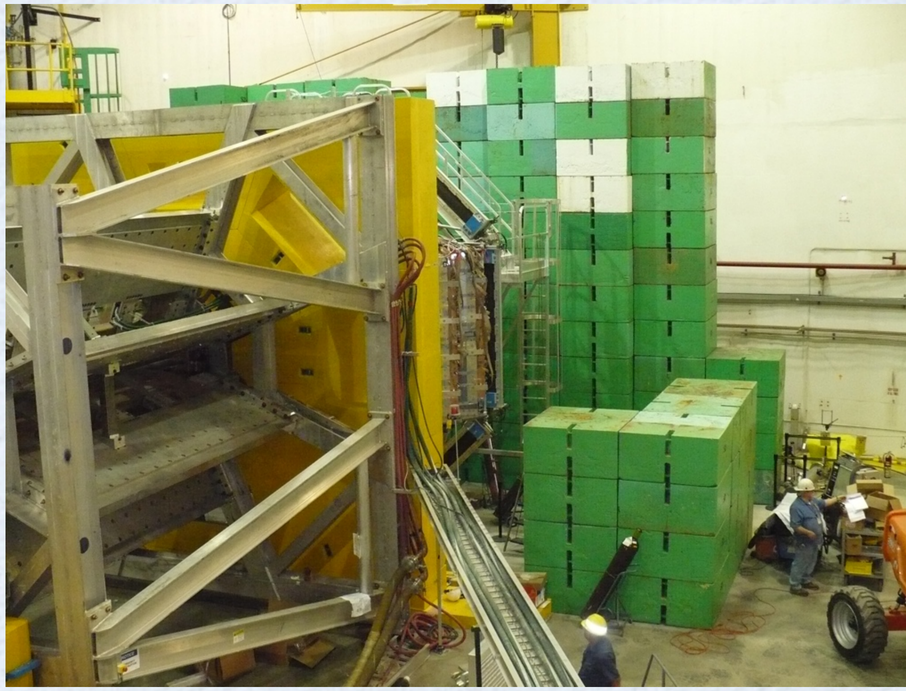


Qweak @ Jefferson Lab

Precision Measurement of the Proton's Weak Charge





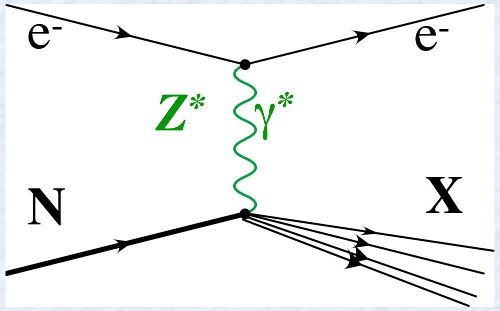


- Design and construction over past several years
- Installation nearly complete
- Pilot beams a few days ago!
- Commissioning: next few weeks
- Data ~ 2010 thru mid-2012

New, complementary constraints on lepton-quark interactions at the TeV scale

Deep Inelastic Scattering

With Qweak and APV, C_{1i}'s measured, but C_{2i}'s still unconstrained



A_{PV} in Electron-Nucleon DIS:

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

$Q^2 >> 1$ GeV^2 , $W^2 >> 4$ GeV^2

$$a(x) = \frac{3}{10}\left[(2C_{1u} - C_{1d})\right] + \cdots$$

$$\boxed{b(x) = \frac{3}{10}\left[(2C_{2u} - C_{2d})\frac{u_v(x) + d_v(x)}{u(x) + d(x)}\right] + \cdots}$$

For a ^{2}H target, assuming charge symmetry, structure functions largely cancel in the ratio

Must measure A_{PV} sub-1% fractional accuracy! ⇨ ***luminosity > 10^{38}/cm^2/s at JLab***

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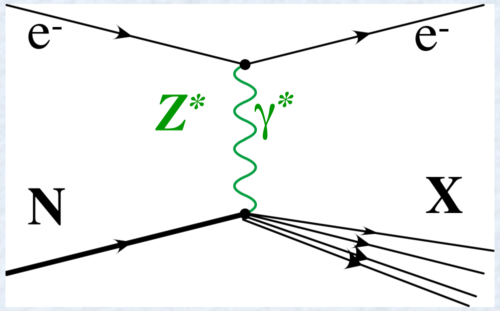

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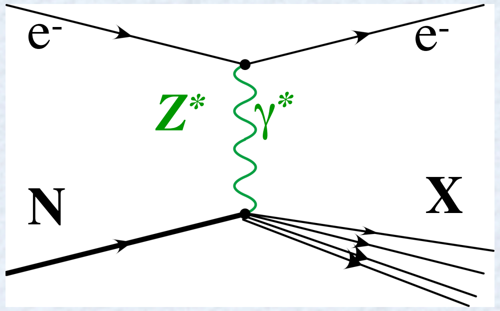

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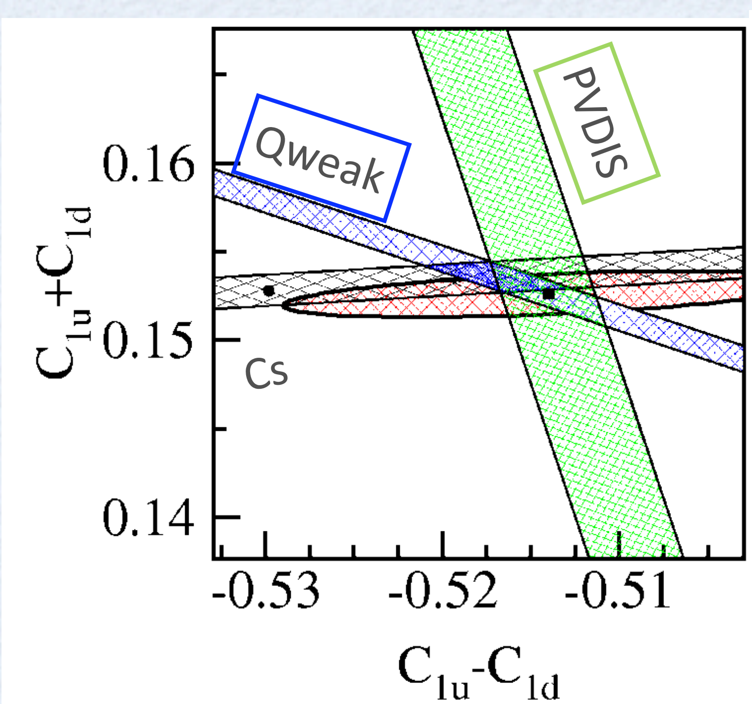
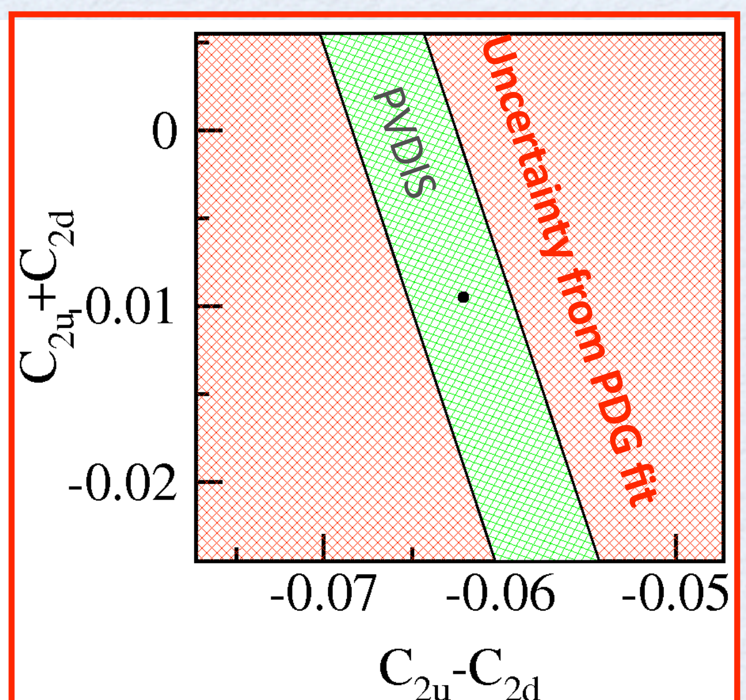
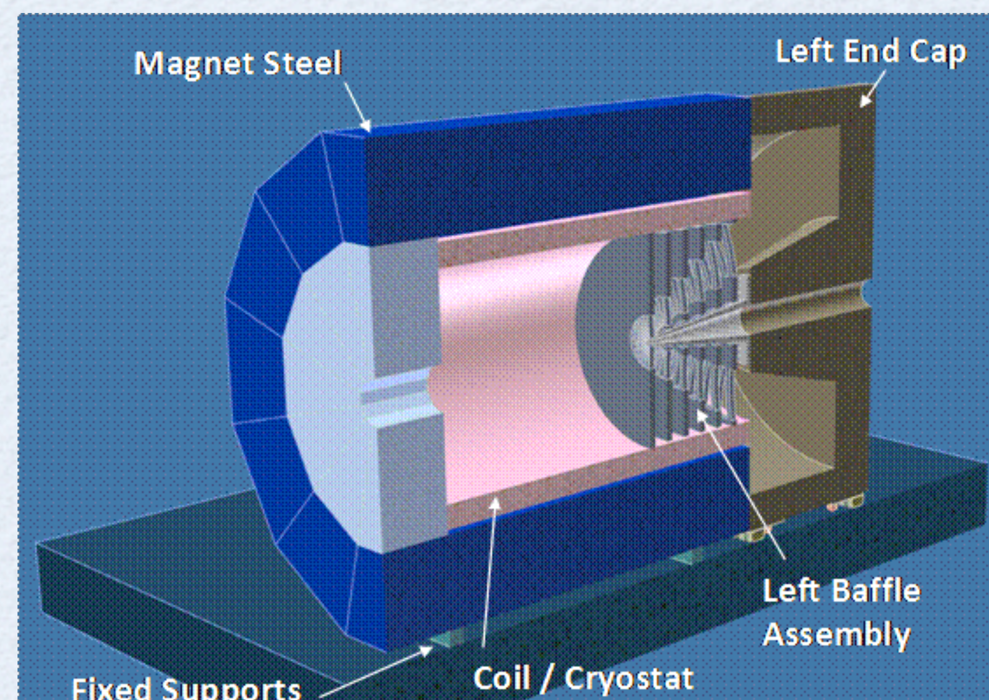
Precision Data

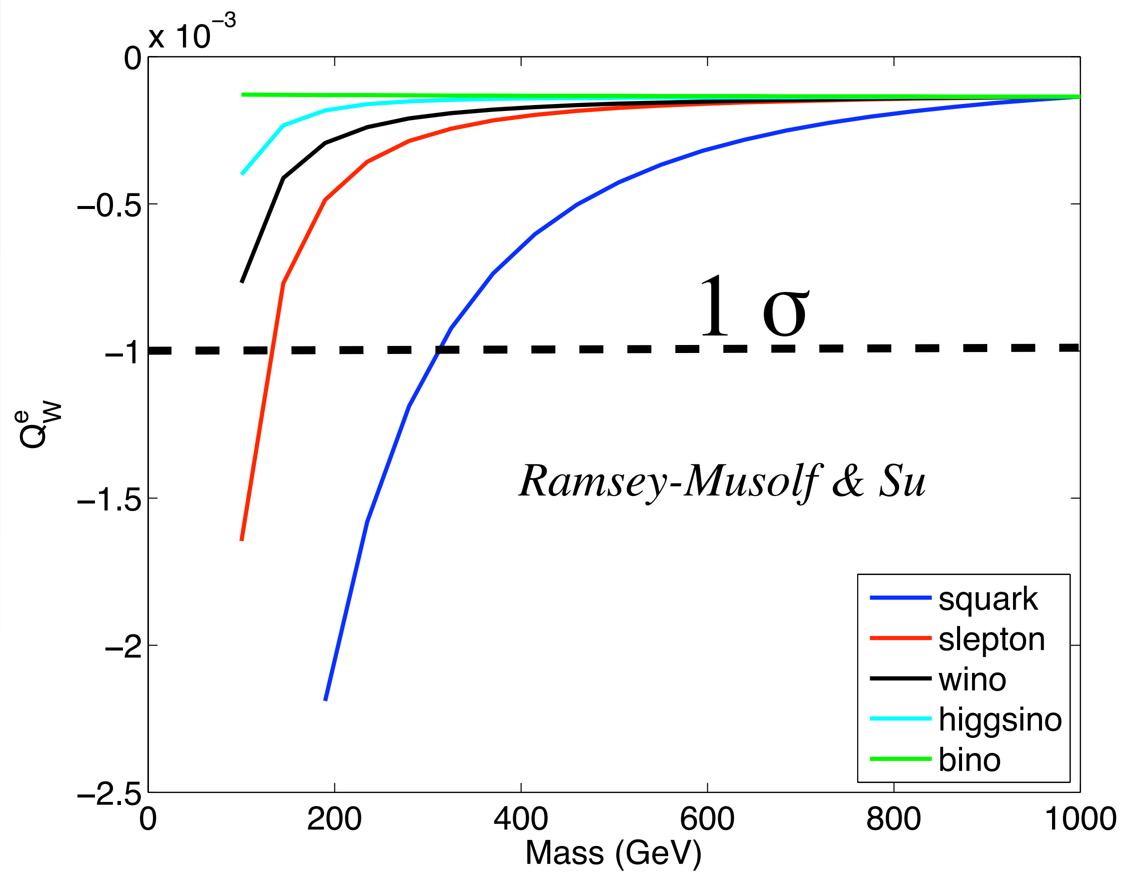


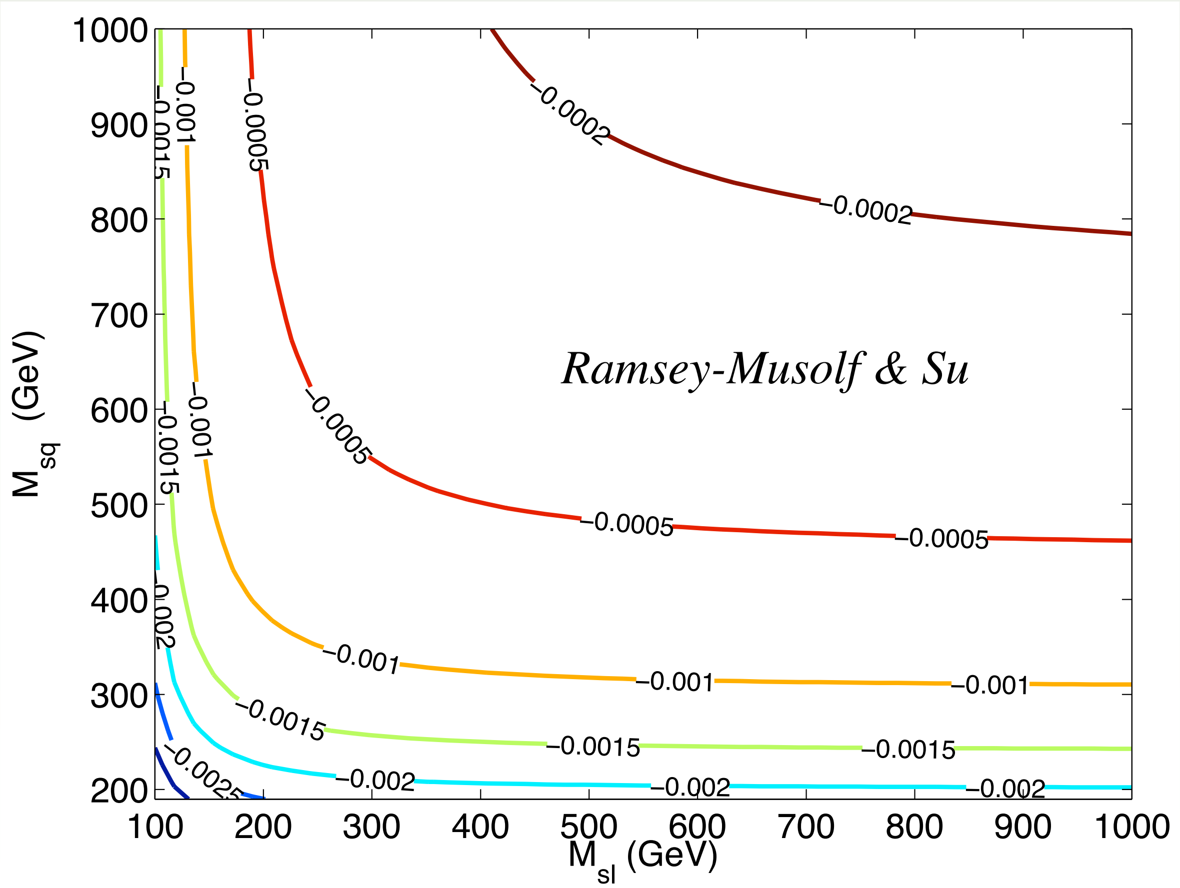


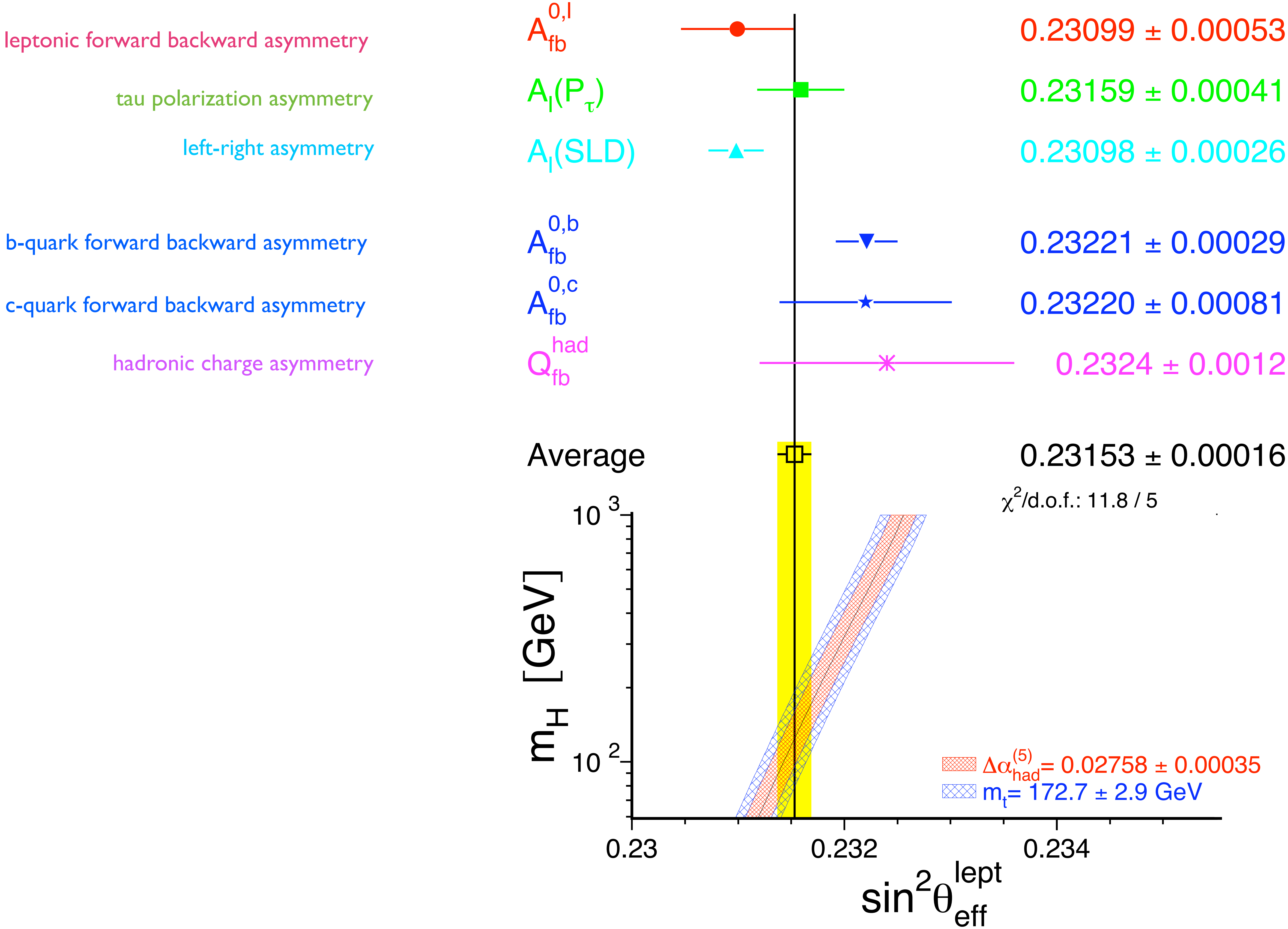


MSSM Sensitivity

- *If ~ 200 GeV sparticles; useful benchmark*
  - What are the scenarios for LHC SUSY searches that allows interesting discovery phase space for MOLLER?
  - If LHC discovers light squarks, expect greater than 2 sigma deviation in MOLLER
  - If LHC doesnt find squarks, then they are heavy. If winos are relatively light, then MOLLER sensitive to light sleptons

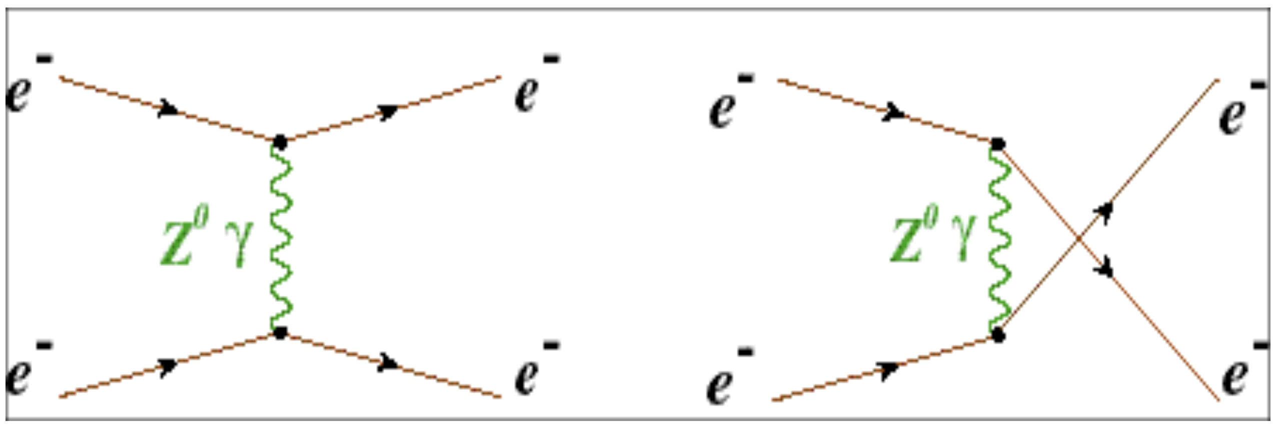


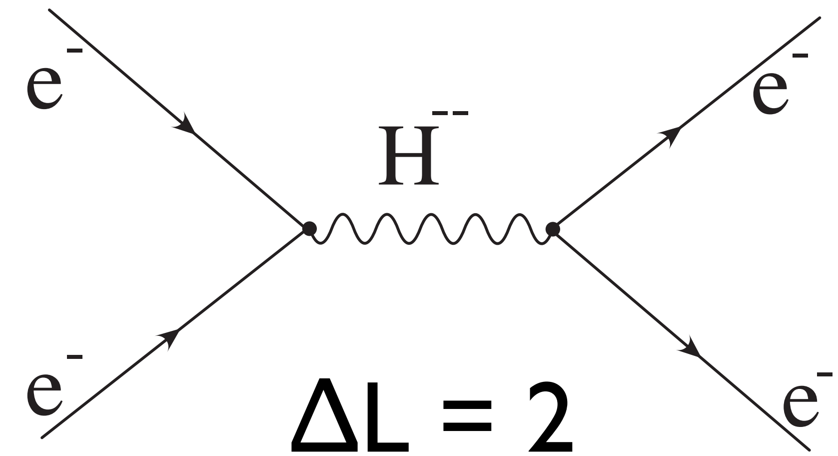




leptonic forward backward asymmetry
$A_{fb}^{0,l}$
0.23099 ± 0.00053
tau polarization asymmetry
$A_l(P_\tau)$
0.23159 ± 0.00041
left-right asymmetry
$A_l(SLD)$
0.23098 ± 0.00026
b-quark forward backward asymmetry
$A_{fb}^{0,b}$
0.23221 ± 0.00029
c-quark forward backward asymmetry
$A_{fb}^{0,c}$
0.23220 ± 0.00081
hadronic charge asymmetry
Q_{fb}^{had}
0.2324 ± 0.0012
Average
0.23153 ± 0.00016
χ^2/d.o.f.: 11.8 / 5
10^3
10^2
m_H [GeV]
$\Delta\alpha_{had}^{(5)}$= 0.02758 ± 0.00035
m_t= 172.7 ± 2.9 GeV
0.23
0.232
0.234
$\sin^2\theta_{eff}^{lept}$

Doubly Charged Scalars





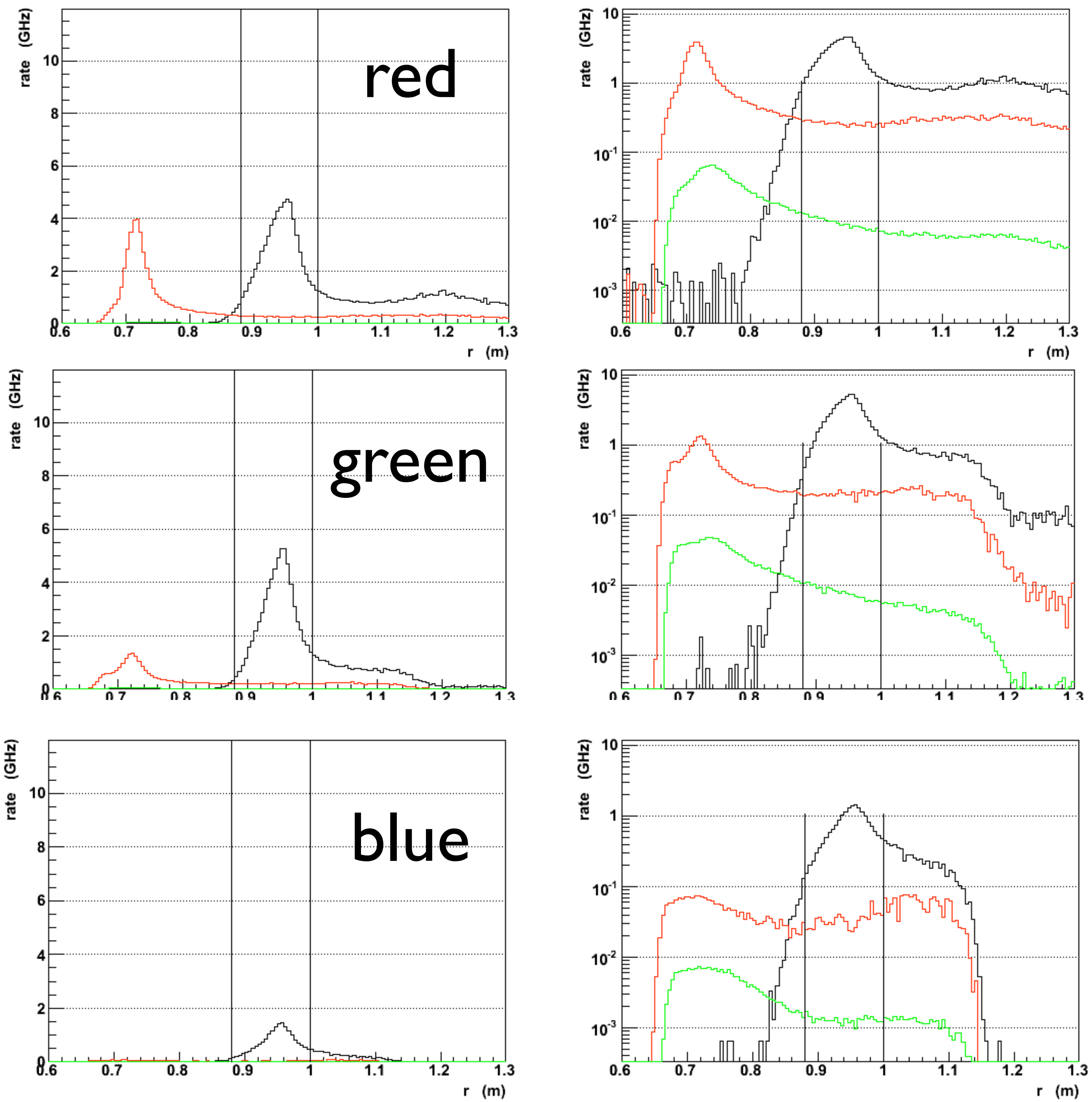
$$\sqrt{2}\mathbf{G_F}\delta(\mathbf{Q_W^e}) = \frac{\mathbf{1}}{(\mathbf{7.5}\ \mathrm{TeV})^{\mathbf{2}}}$$

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

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

Sensitivity better than LEP200

e-p inelastic background



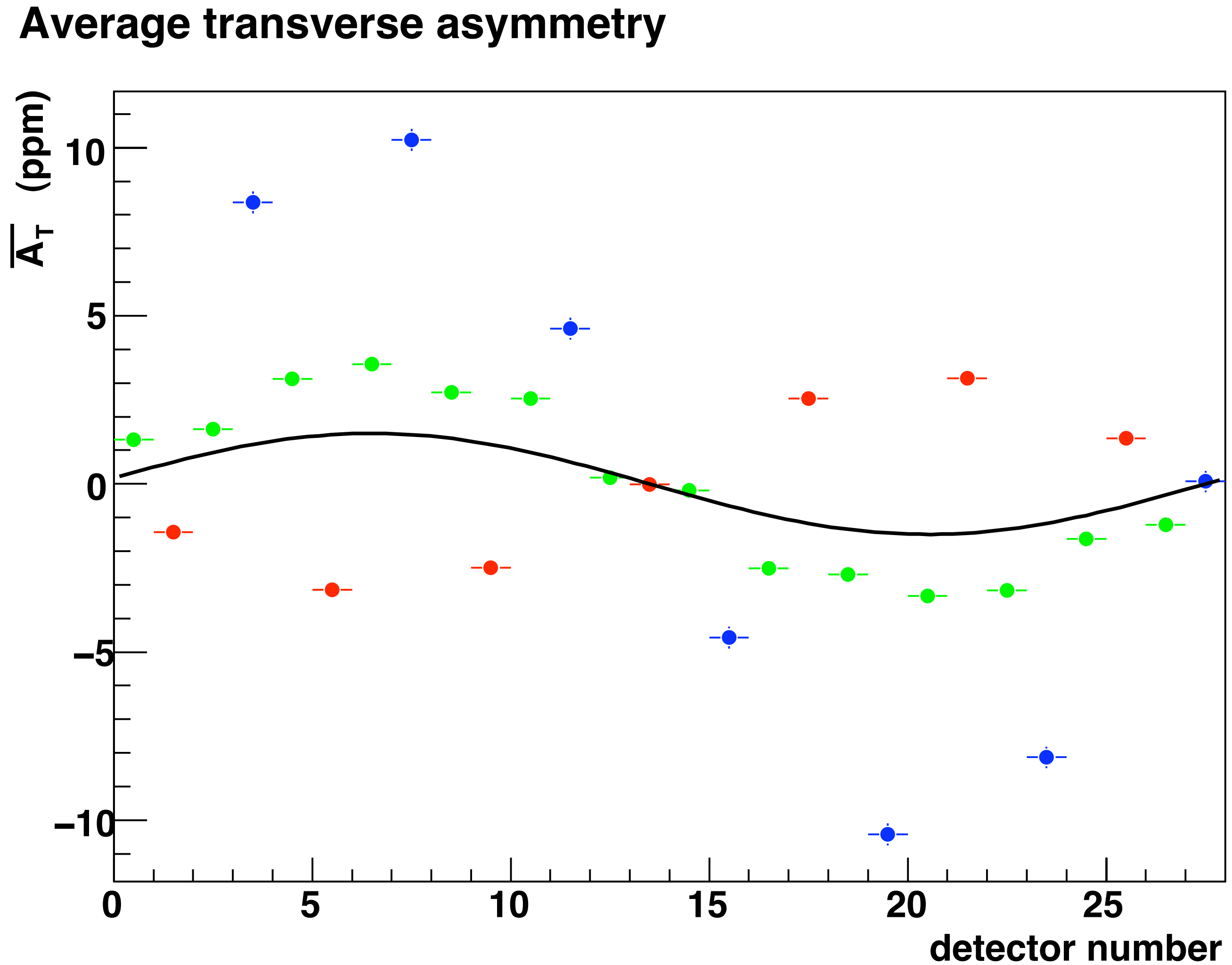
inelastic p-Z coupling unknown at diffractive kinematics

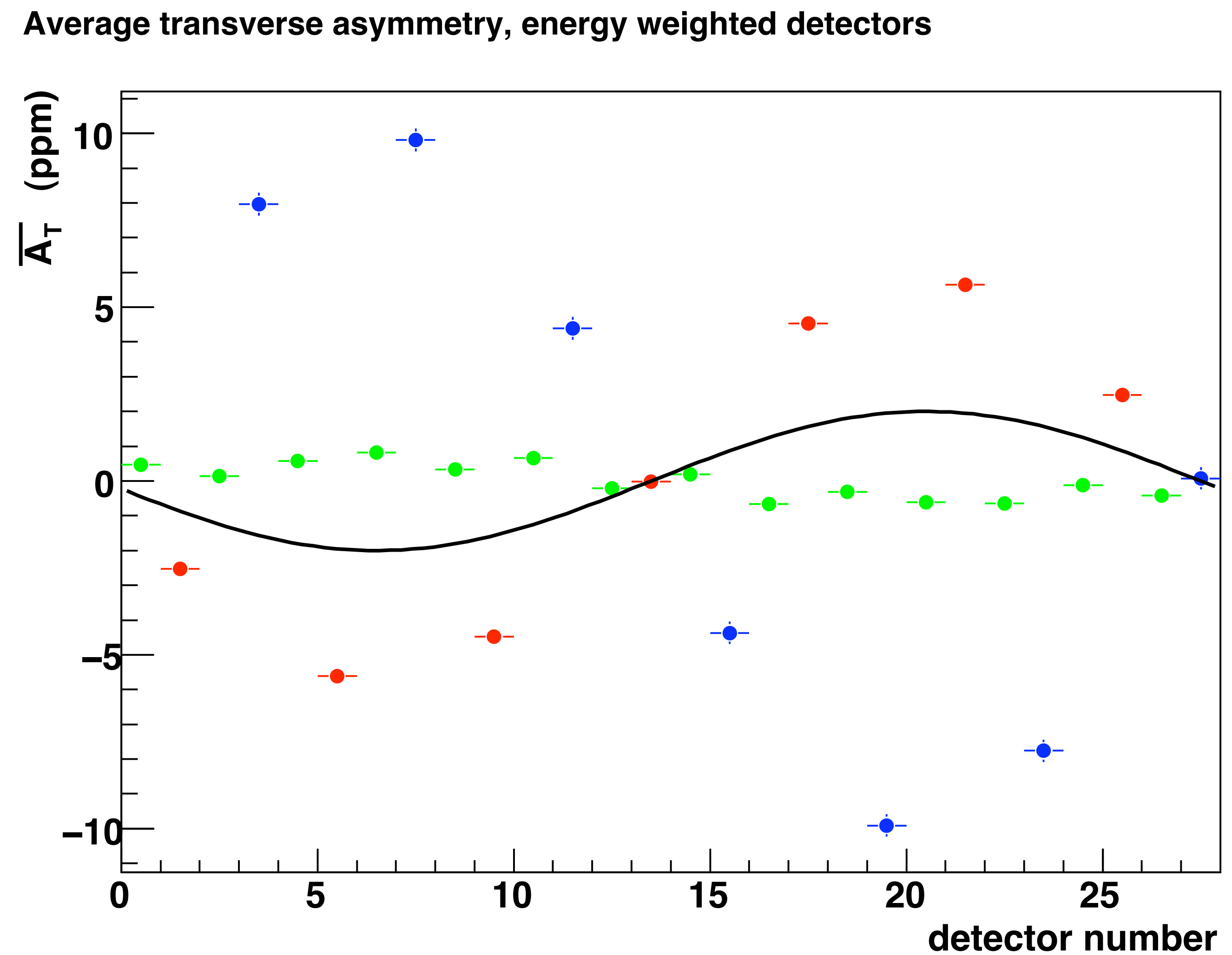
E158 measured
$10^{-4} \times Q^2$

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

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

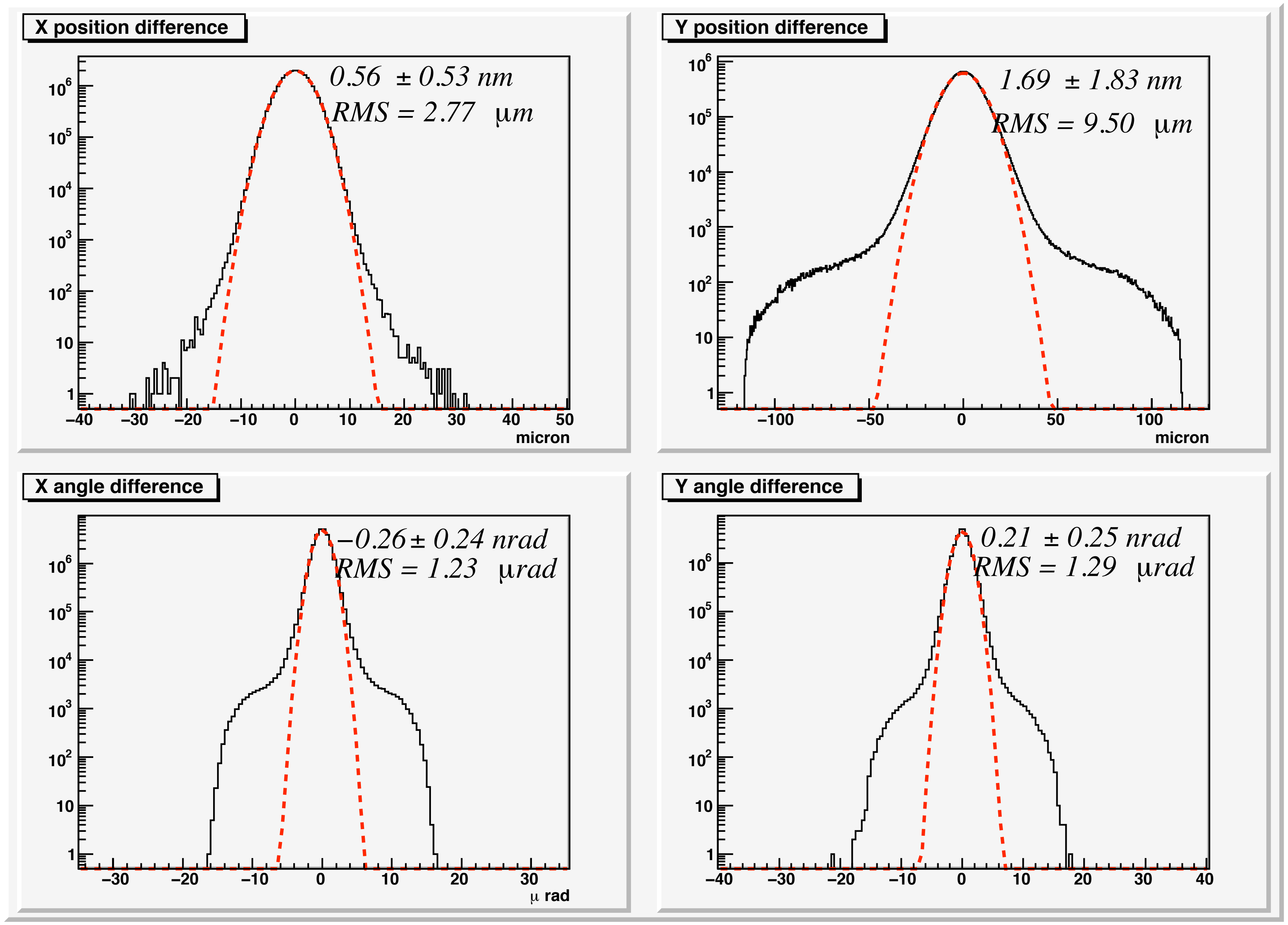
• noise scaling from G0 target measurements (238 ppm@30 Hz) would indicate ~26 ppm@2000 Hz for the Møller target, a 5 % increase to the counting statistical width of 77.3 ppm/pair

• 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

HAPPEX-II beam corrections



1 month runtime : random jitter dominates

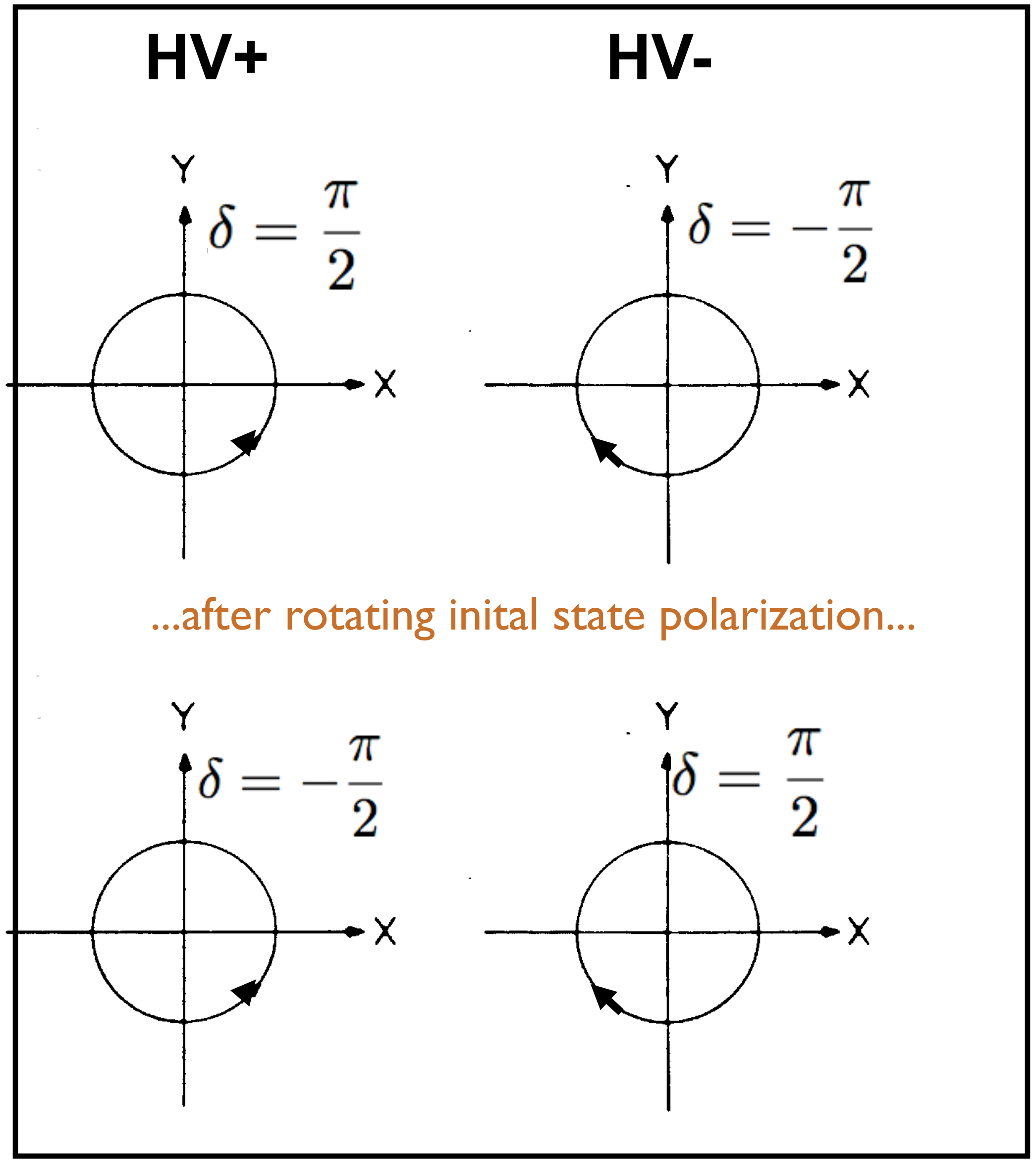
position < 2nm
angle < 0.25 nrad

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



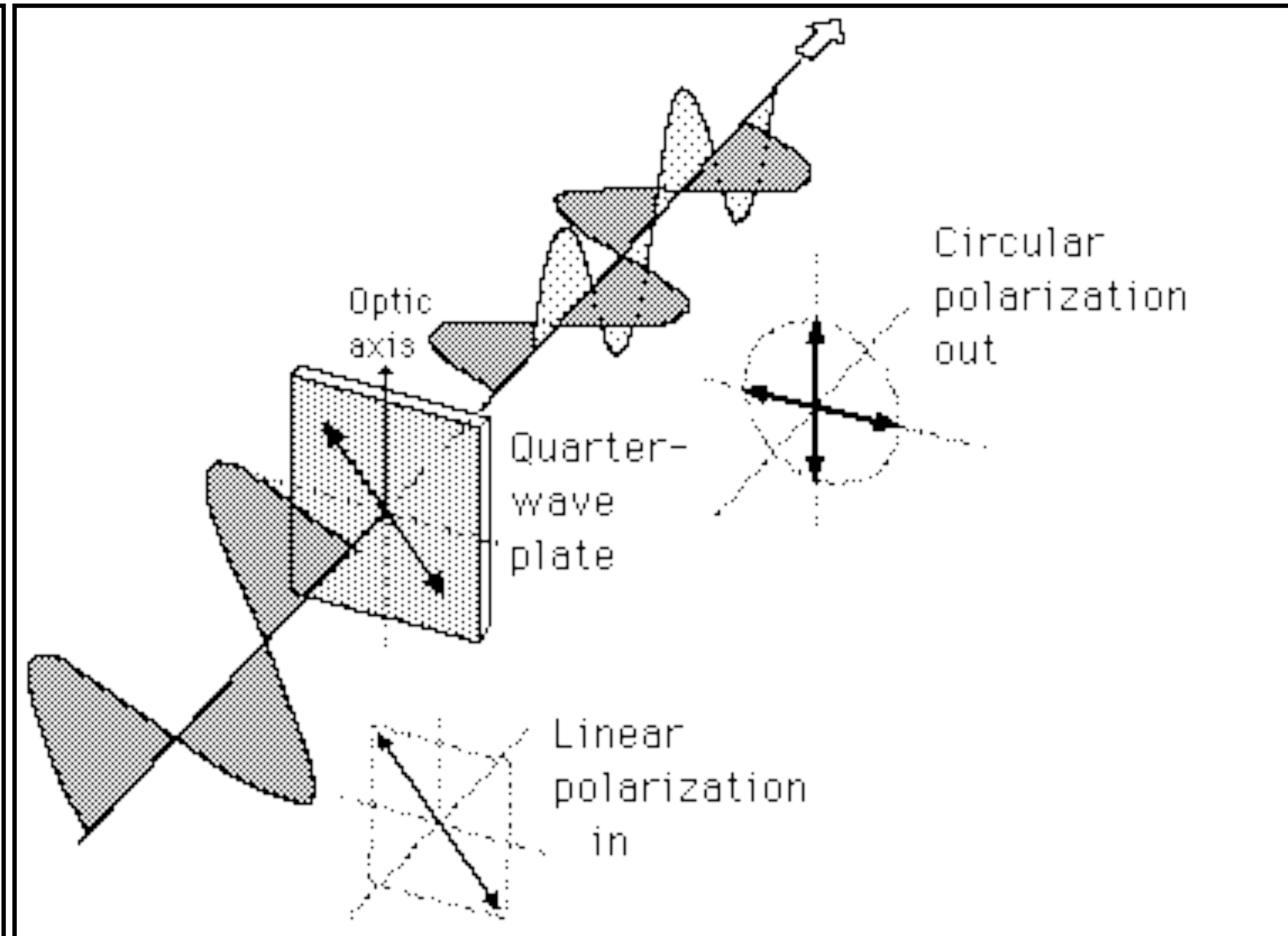


Image from HyperPhysics:
http://hyperphysics.phy-astr.gsu.edu/Hbase/hph.html

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

Helicity Sequence

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

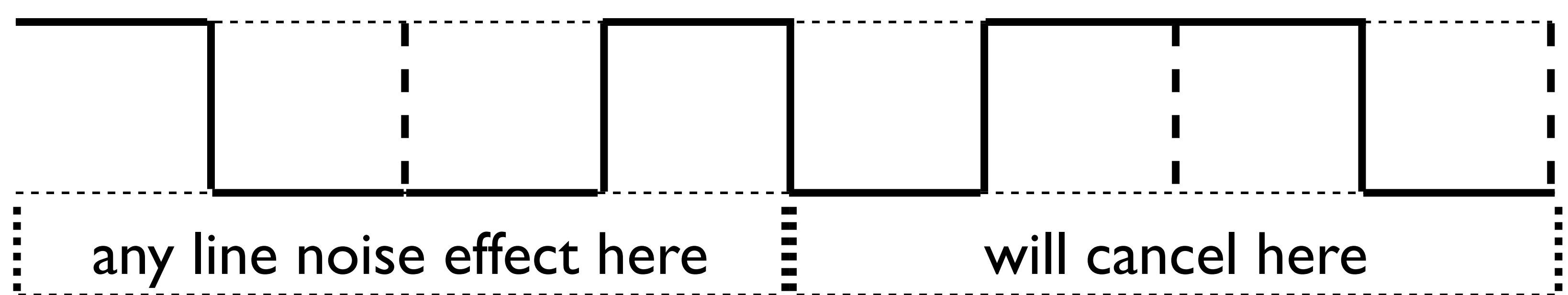
Present scheme (30 Hz) automatically handles this, as each window is ~2 60Hz cycles long.

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.

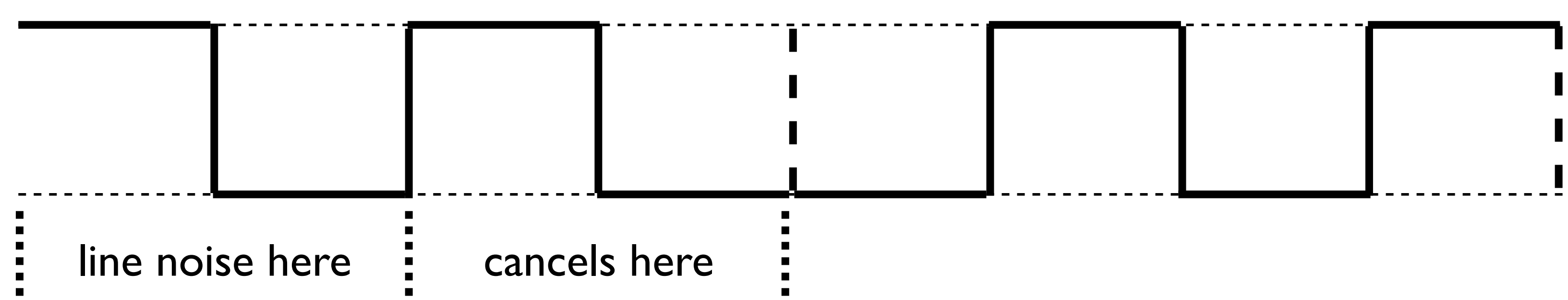
Option 1: Choose 2 pairs, force complementary two pairs to follow

Analyze each "macropulse" of 8 windows together



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

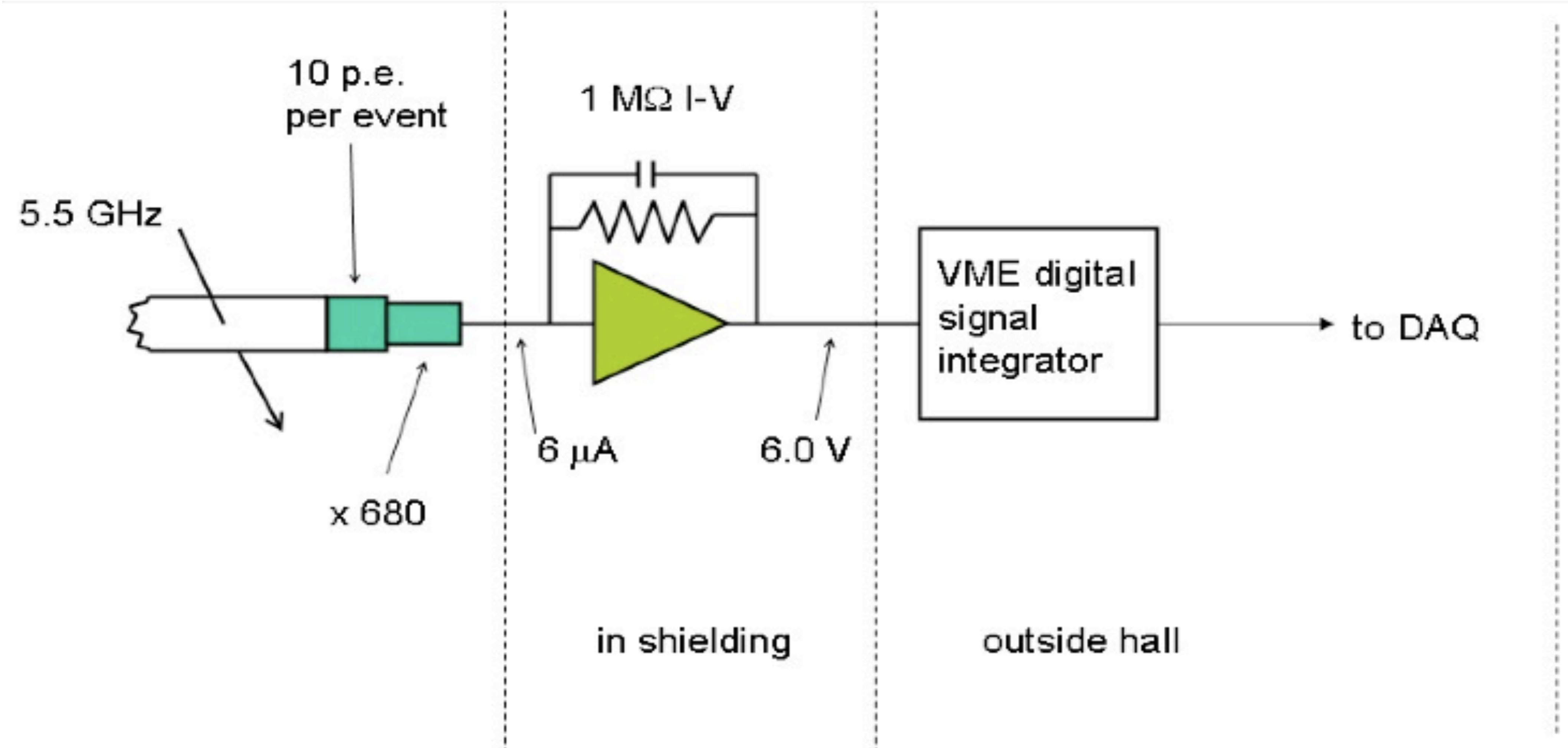
Analyze each "macropulse" of 4 windows together



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.

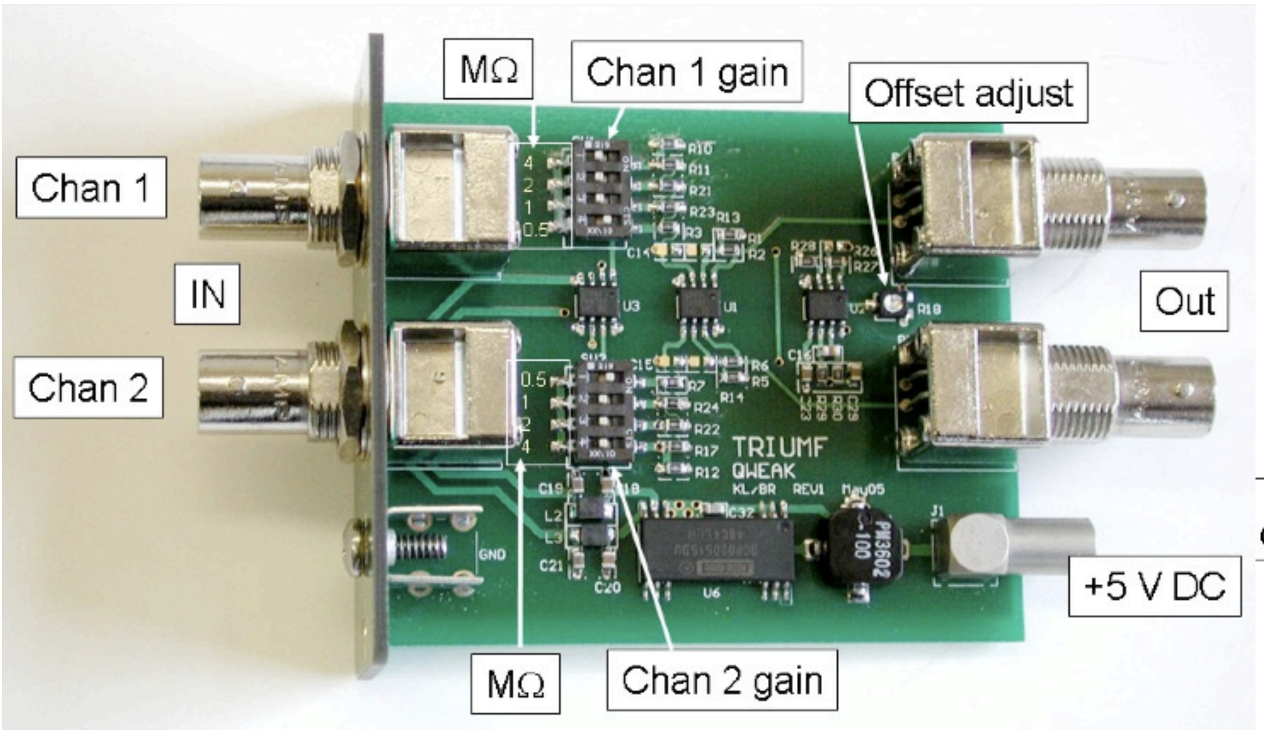


Low-Noise Electronics

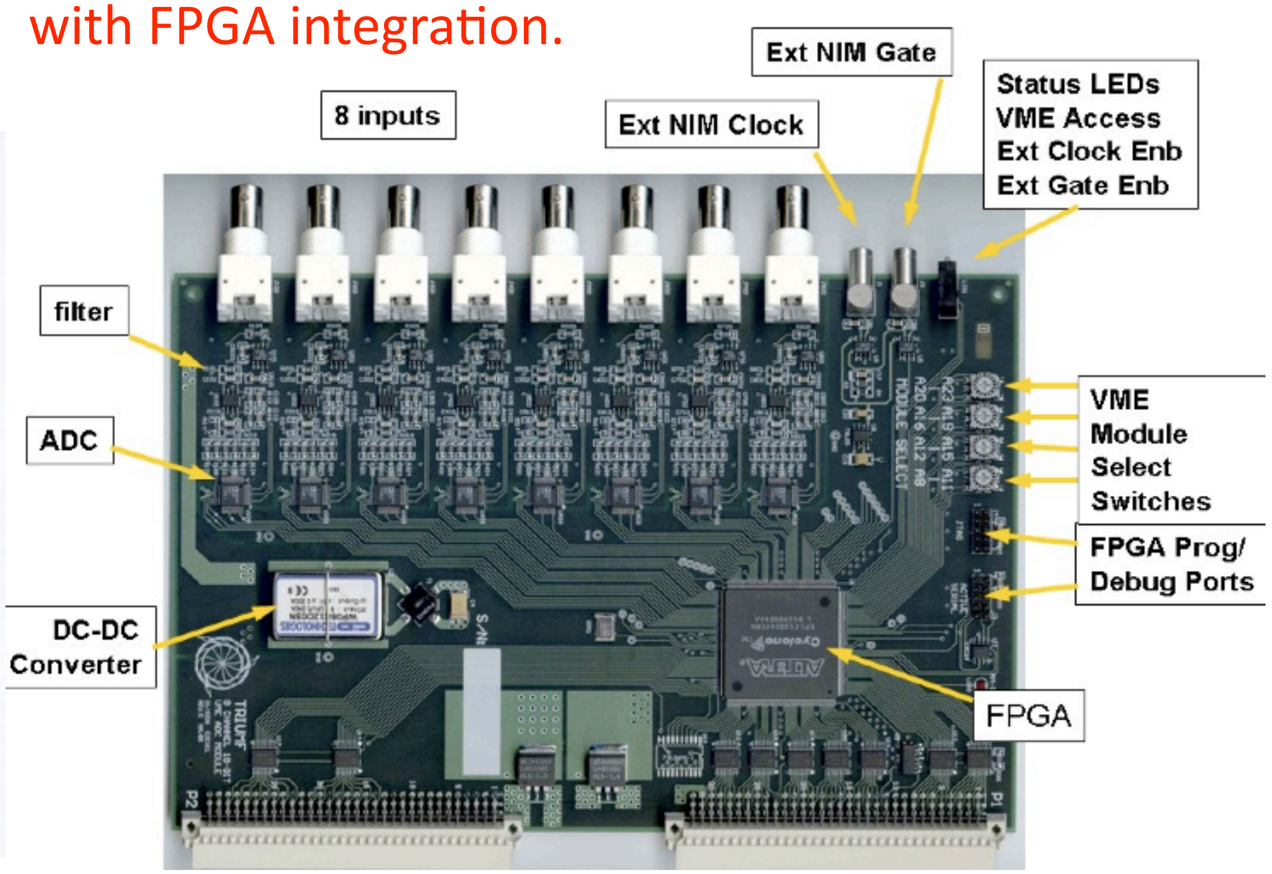
Our TRIUMF collaborators originally developed low-noise electronics for their own parity program. They have built custom versions for the Qweak experiment.

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.



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

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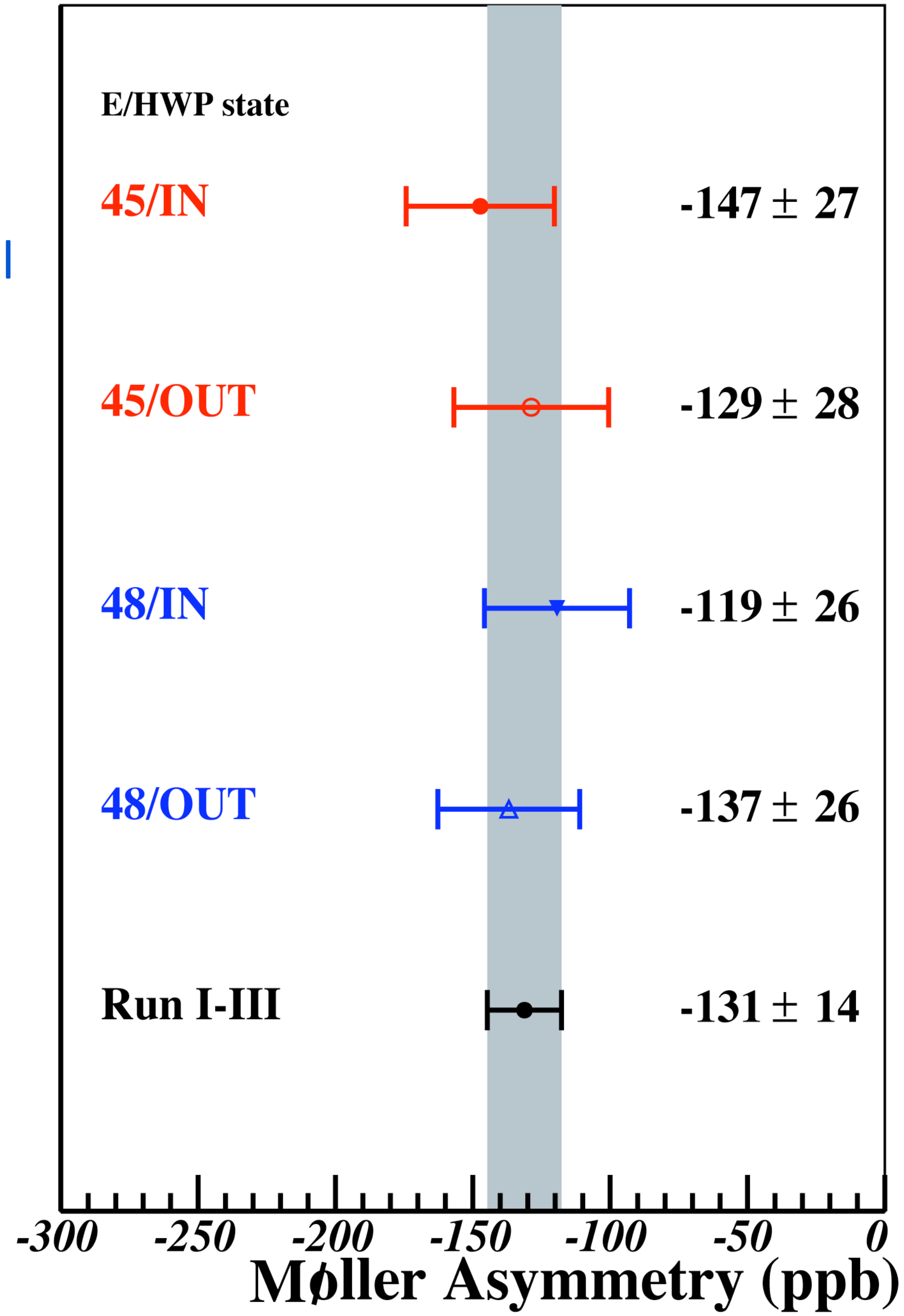


g-2 and Injector Spin Manipulation

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

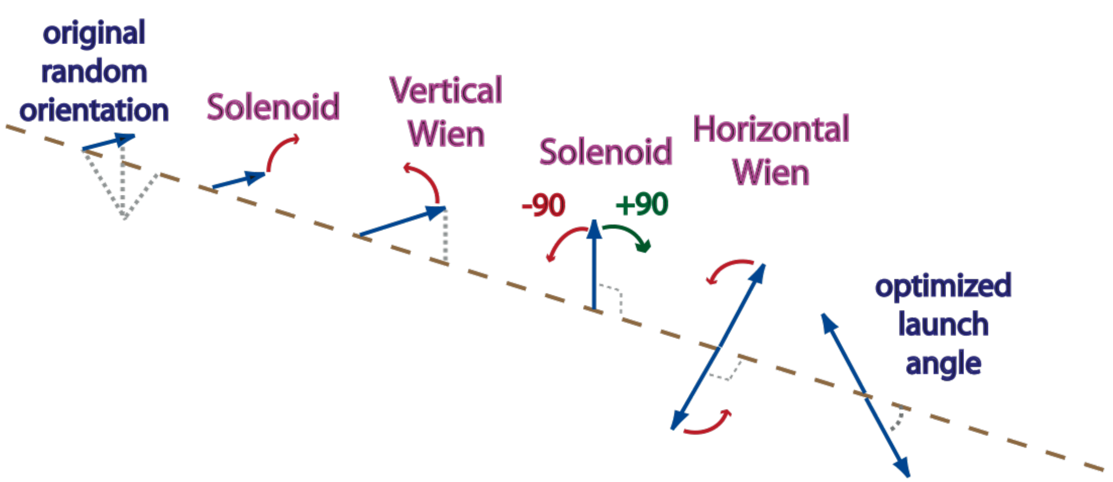
<u>Injector Spin Rotation</u>

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

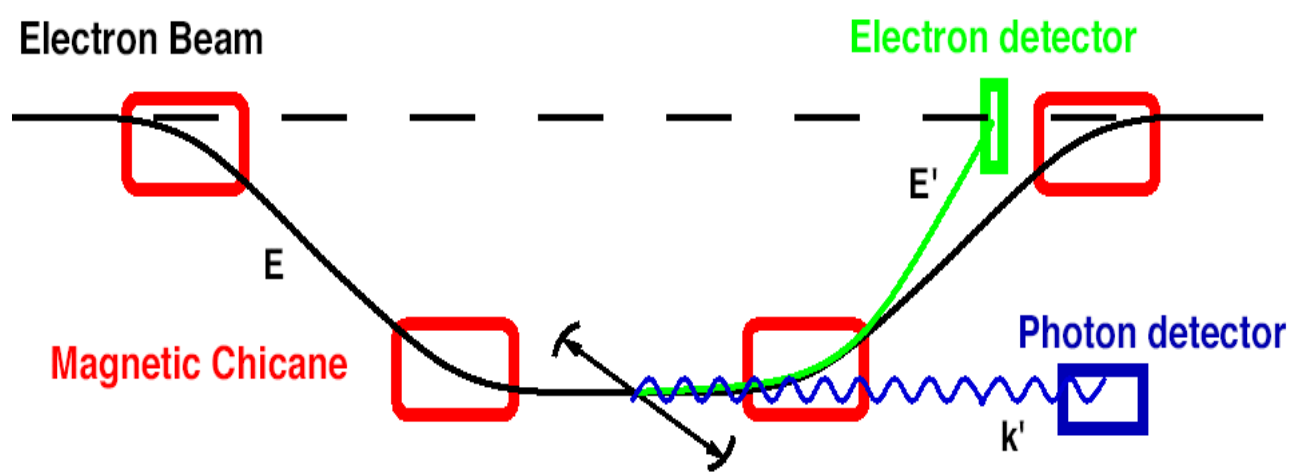


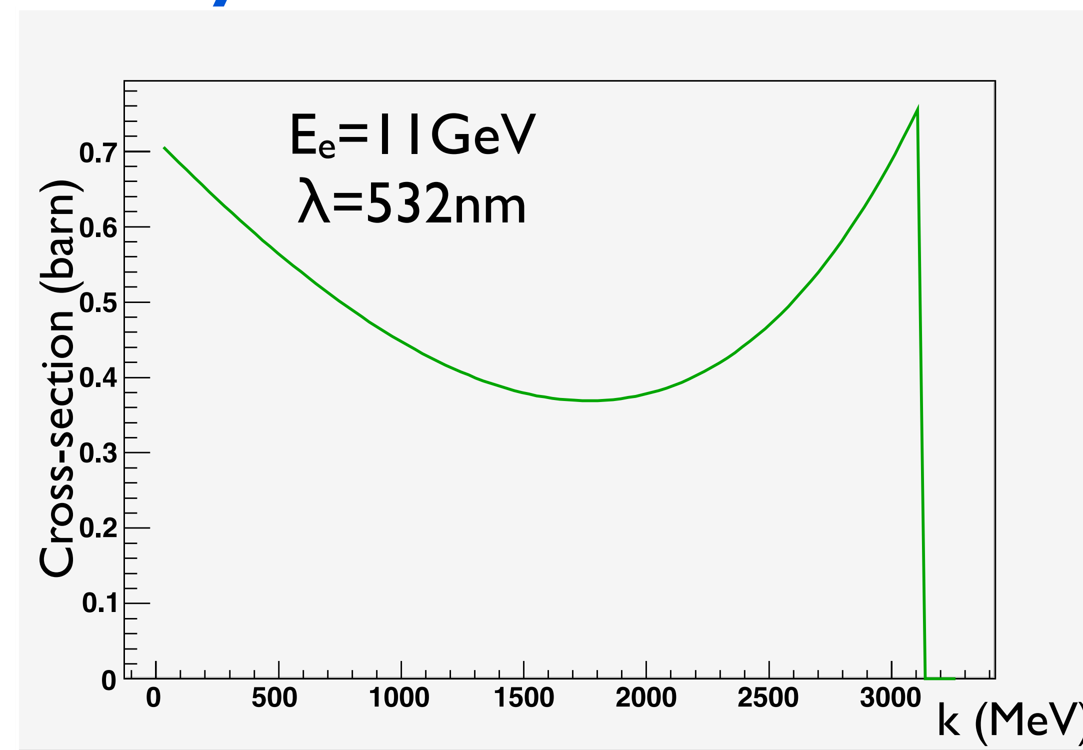
Wein upgrade project now underway at JLab to support the 2010 experiments

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



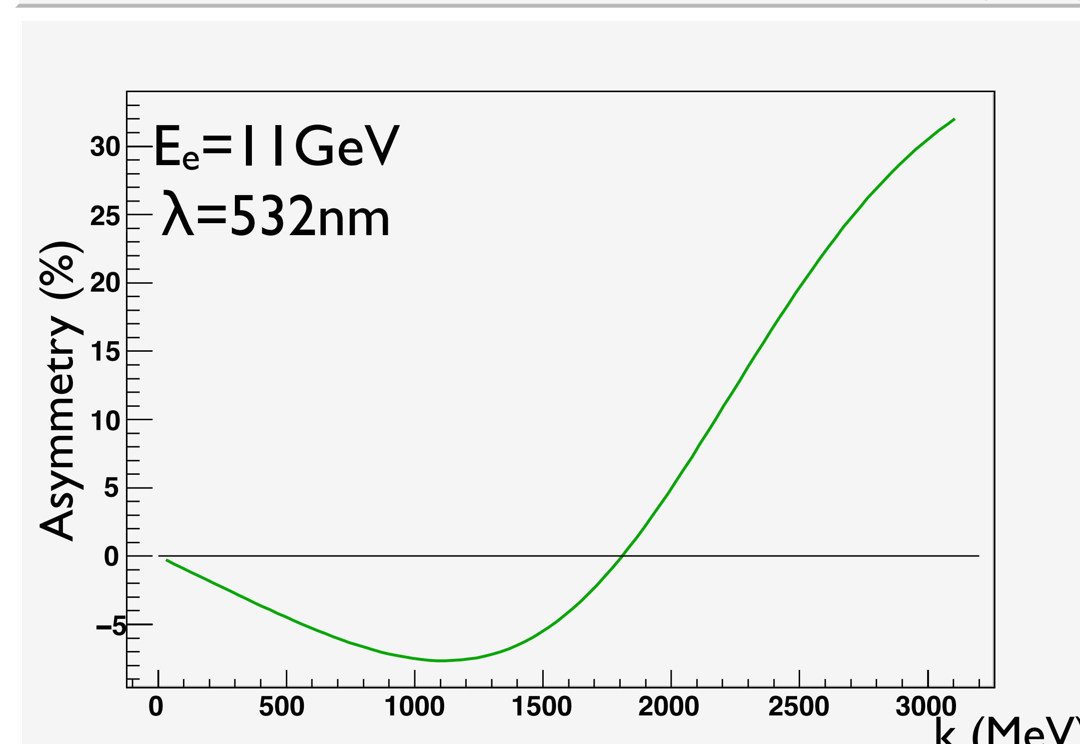


For scattered electrons in chicane:
two Points of well-defined energy!

- Asymmetry zero crossing
- Compton Edge

Integrate between to minimize error on analyzing power!

"independent" Photon analysis also normalizable at ~0.5%



High Precision Compton

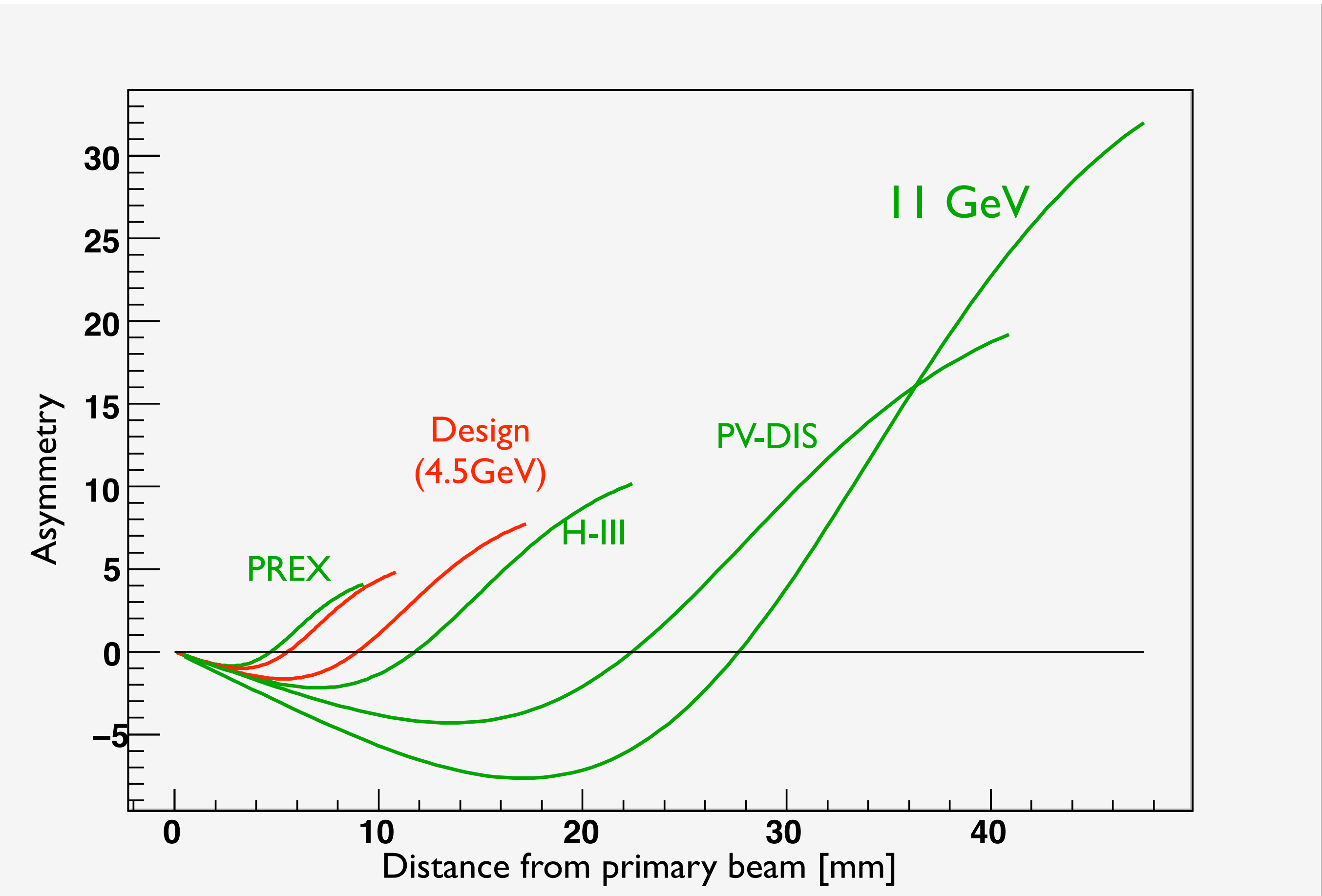
At high energies, SLD achieved 0.5%.

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

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



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

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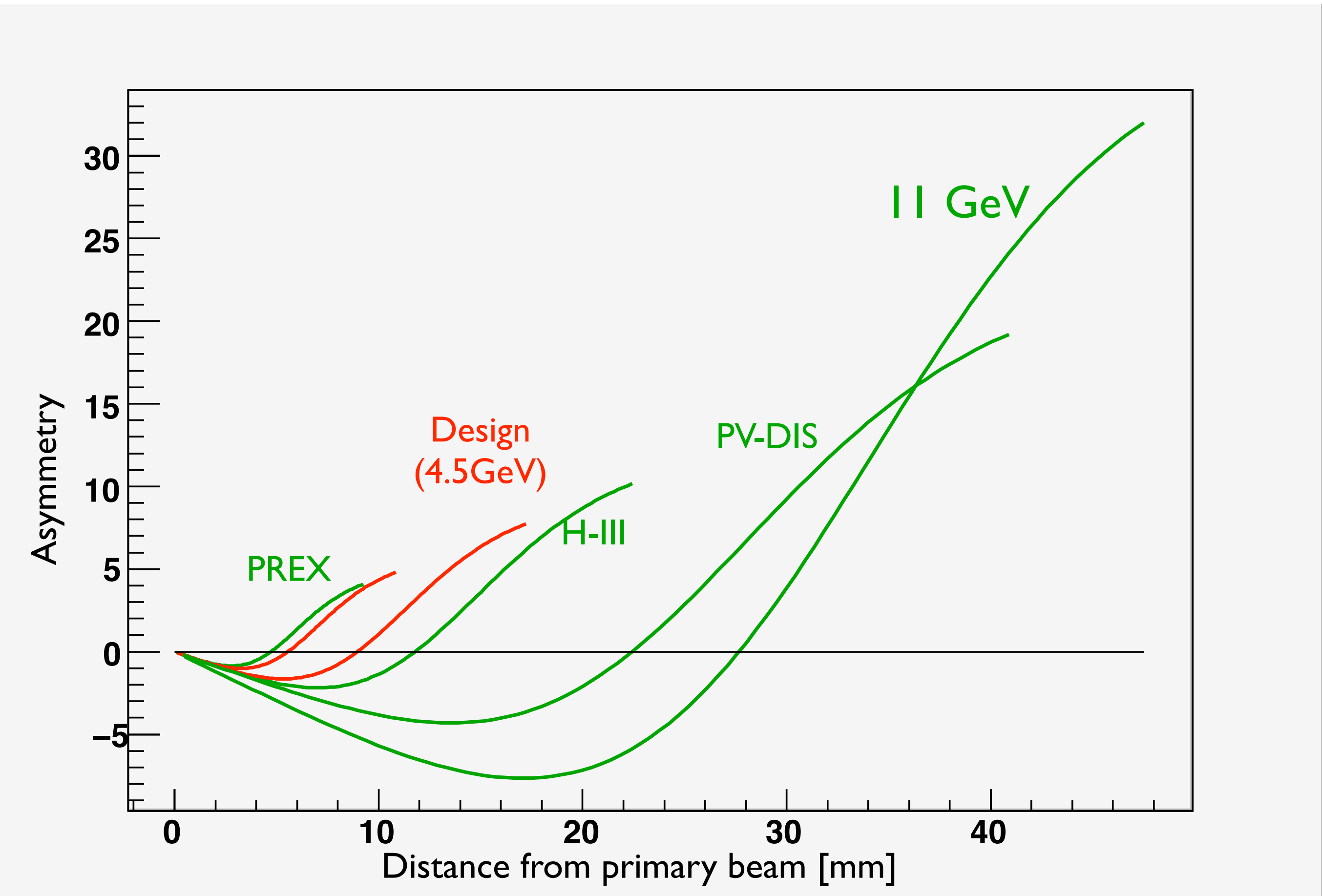
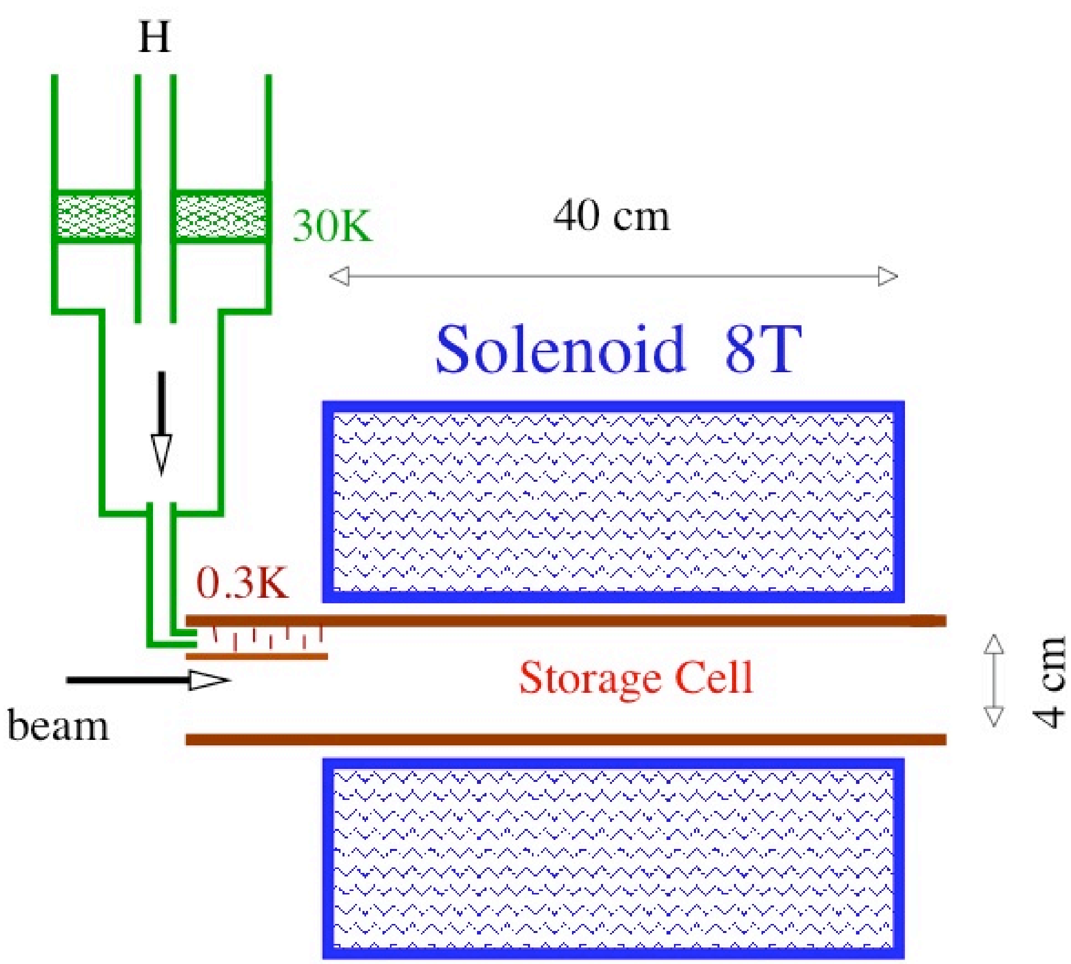


Atomic Hydrogen For Moller Target



10 cm, ρ = 3x10^{15}/cm^3
in B = 7 T at T=300 mK

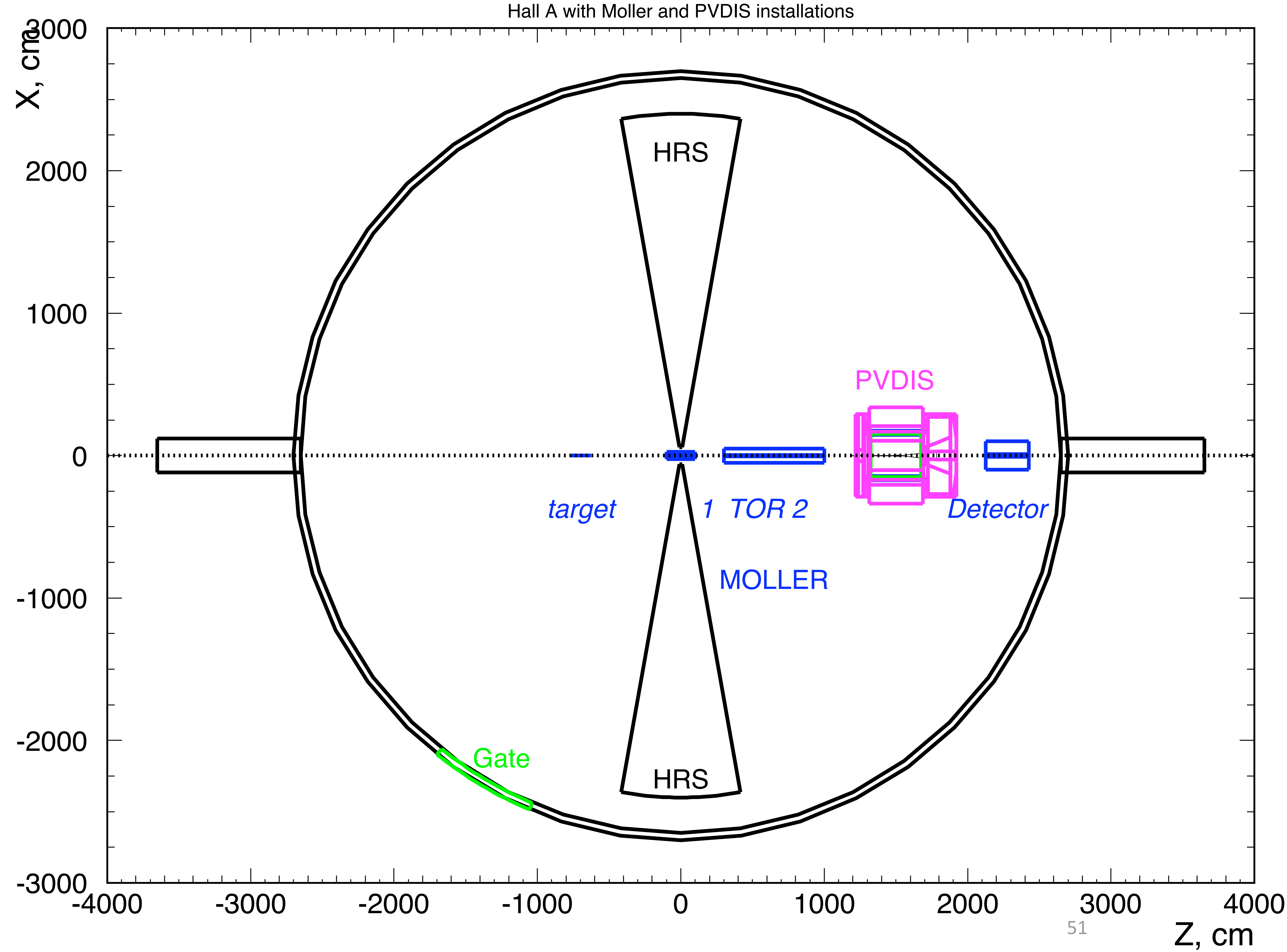
$$\boxed{\frac{n_+}{n_-} = e^{-2\mu B/kT} \approx 10^{-14}}$$

Brute force polarization

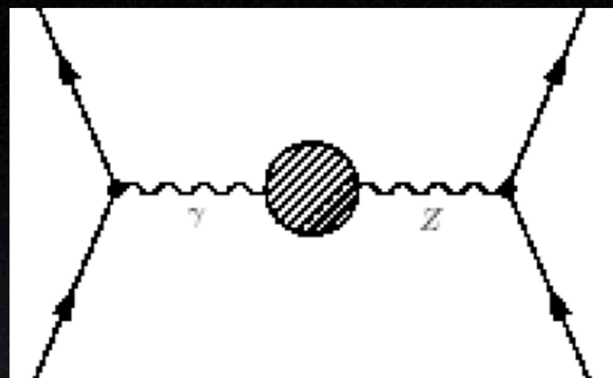
Moller polarimetry from polarized atomic hydrogen gas, stored in an ultra-cold magnetic trap

- 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


Hall A with Moller and PVDIS installations
X, cm
Z, cm
HRS
HRS
PVDIS
target
1 TOR 2
Detector
MOLLER
Gate
3000
2000
1000
0
-1000
-2000
-3000
-4000
-3000
-2000
-1000
0
1000
2000
3000
4000

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

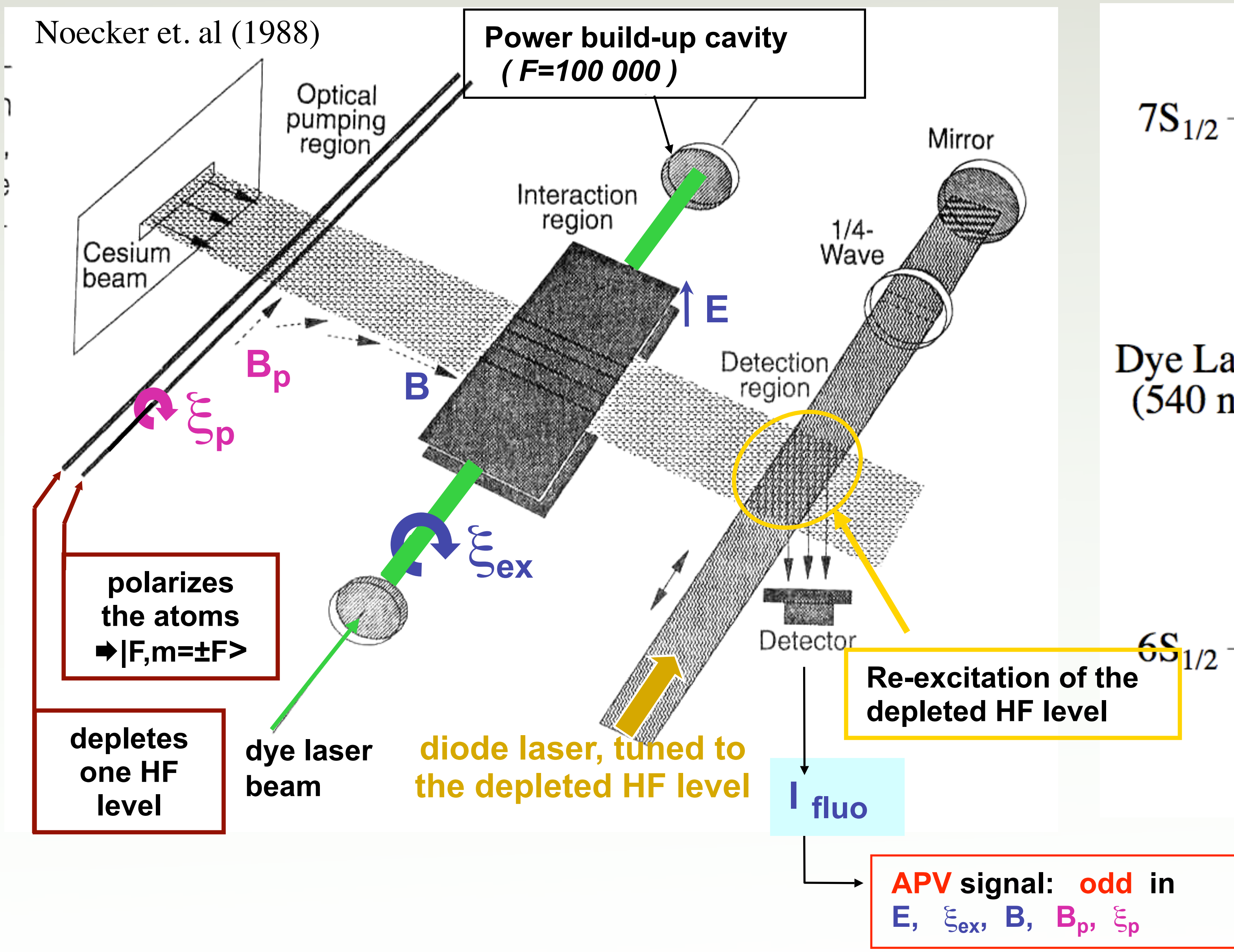
Future improvements

- 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

Atomic Parity Violation

- 6S → 7S transition in ^{133}Cs is forbidden within QED
- Parity Violation introduces small opposite parity admixtures
- Induce an E1 Stark transition, measure E1-PV interference
- 5 sign reversals to isolate APV signal and suppress systematics
- Signal is ~ 6 ppm, measured to 40 ppb

Boulder Experiment



Partial Level Structure of Cesium