High Energy Polarimetry of Positron Beams

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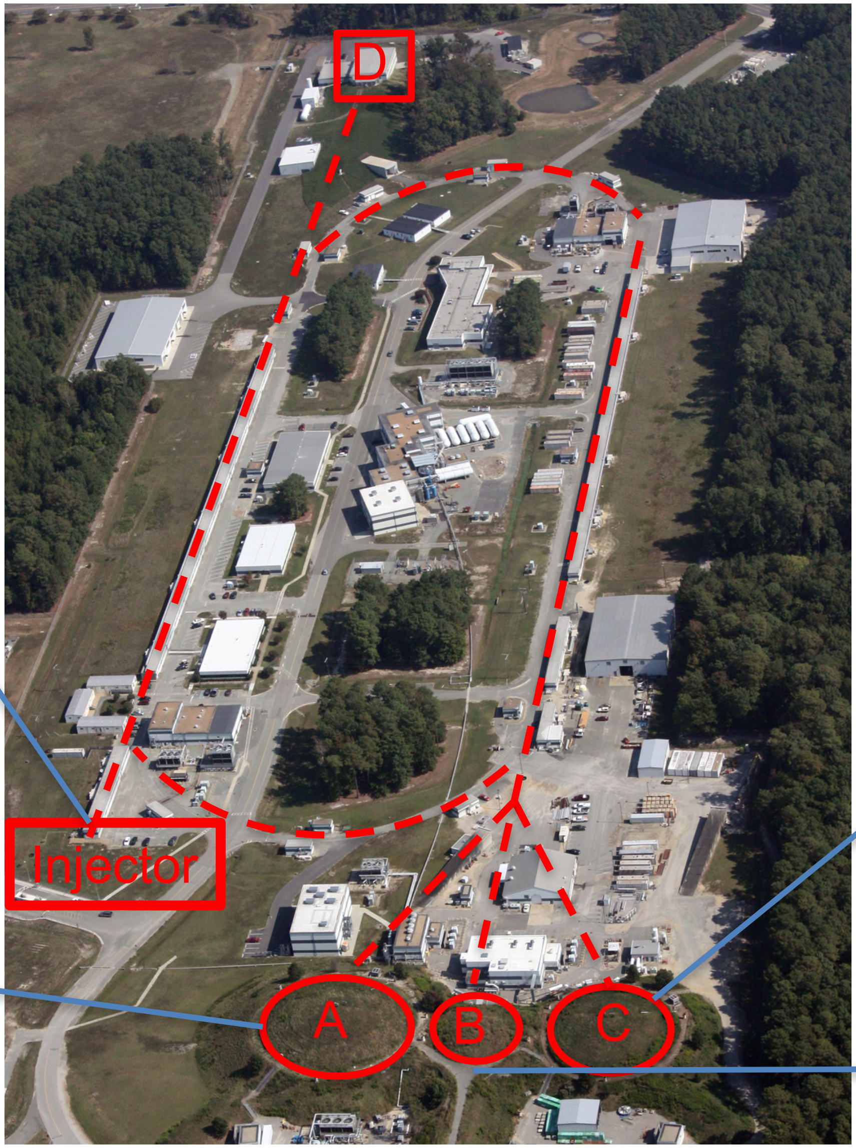
1. Electron polarimetry at High Energies and at JLab
    - Techniques
    - Overview of devices
2. Application of electron techniques and devices for positron beams

JLab Polarimetry Techniques

- Three different processes used to measure electron beam polarization at JLab
  - Møller scattering: $\vec{e}+\vec{e}\rightarrow e+e$, atomic electrons in Fe (or Fe-alloy) polarized using external magnetic field
  - Compton scattering: $\vec{e}+\vec{\gamma}\rightarrow e+\gamma$, laser photons scatter from electron beam
  - Mott scattering: $\vec{e}+Z\rightarrow e$, spin-orbit coupling of electron spin with (large Z) target nucleus
- Each has advantages and disadvantages in JLab environment

Method	Advantage	Disadvantage
Compton	Non-destructive, precise	Can be time consuming, systematics energy dependent
Møller	Rapid, precise measurements	Destructive, low current only
Mott	Rapid, precise measurements	Does not measure polarization at the experiment

Geography of JLab Polarimeters



Injector

5 MeV Mott Polarimeter

Hall A

Compton Polarimeter
- IR → Green laser

Møller Polarimeter
- In plane, low field target → out of plane saturated iron foil

Hall C

Compton Polarimeter
- Installed 2010 (Q-Weak)

Møller Polarimeter
- Out of plane saturated iron foil

Hall B

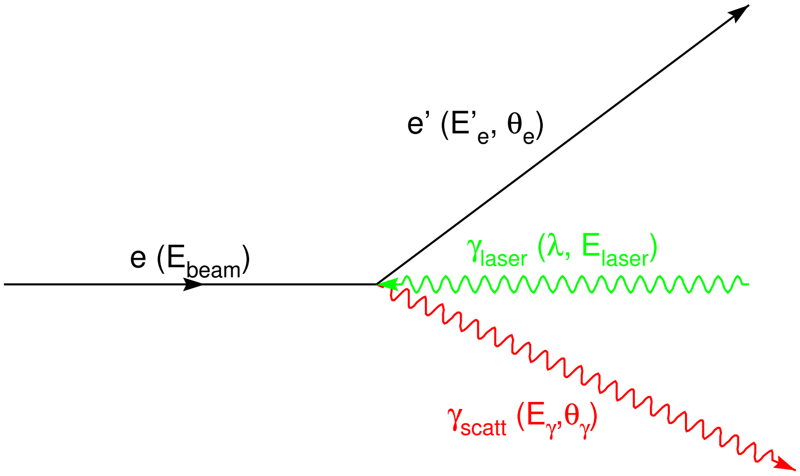
Møller Polarimeter
- In plane, low field target

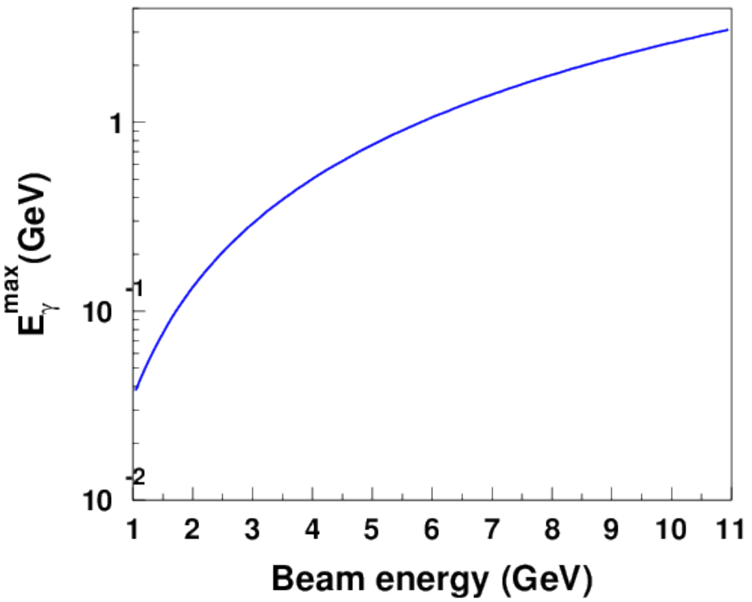
Compton Scattering - Kinematics

Laser beam colliding with electron beam nearly head-on

$$E_\gamma \approx E_{\text{laser}} \frac{4a\gamma^2}{1 + a\theta_\gamma^2\gamma^2}$$

$$a = \frac{1}{1 + 4\gamma E_{\text{laser}}/m_e}$$





Maximum backscattered photon energy at θ=0 degrees (180 degree scattering)

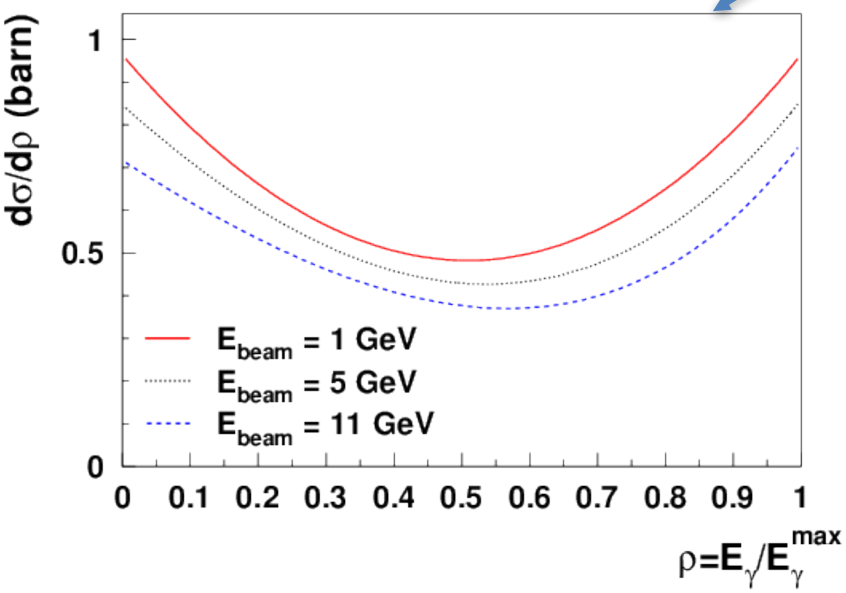
For green laser (532 nm):

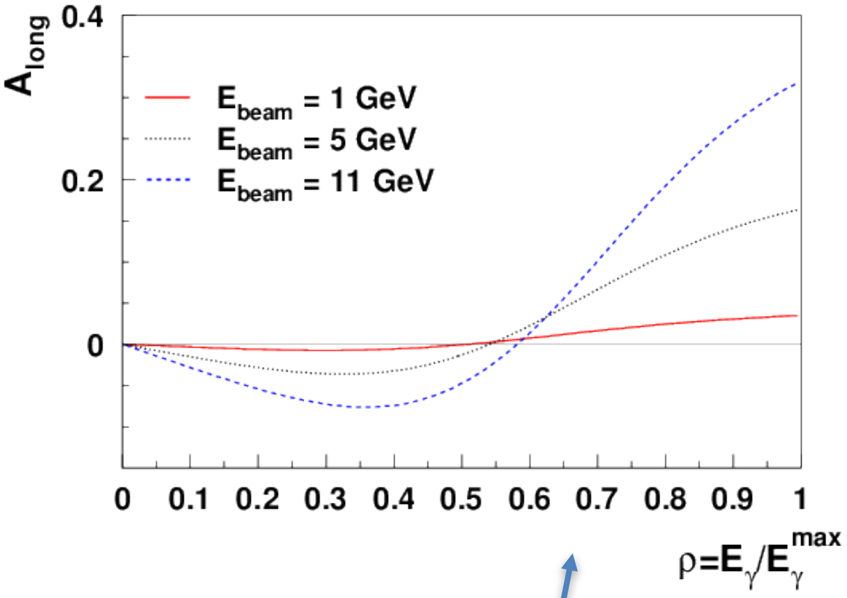
→ E_γ^{max} ~ 34.5 MeV at E_{beam}=1 GeV

→ E_γ^{max} = 3.1 GeV at E_{beam}=11 GeV

Compton Scattering – Cross Section and Asymmetry

$$\rho = \frac{E_\gamma}{E_\gamma^{\max}} \Rightarrow \frac{d\sigma}{d\rho} = 2\pi r_o^2 a \left[\frac{\rho^2(1-a)^2}{1-\rho(1-a)} + 1 + \left(\frac{1-\rho(1+a)}{1-\rho(1-a)} \right)^2 \right]$$





$$A_{\text{long}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)} (1-\rho(1+a)) \left[1 - \frac{1}{(1-\rho(1-a))^2} \right]$$

Compton Polarimetry at JLab

- Compton polarimetry routinely used at colliders/storage rings before use at JLab

- Several challenges for use at JLab
  - Low beam currents (~100 μA) compared to colliders
    - Measurements can take on the order of hours
    - Makes systematic studies difficult

  - At lower energies, relatively small asymmetries
    - Smaller asymmetries lead to harder-to-control systematics

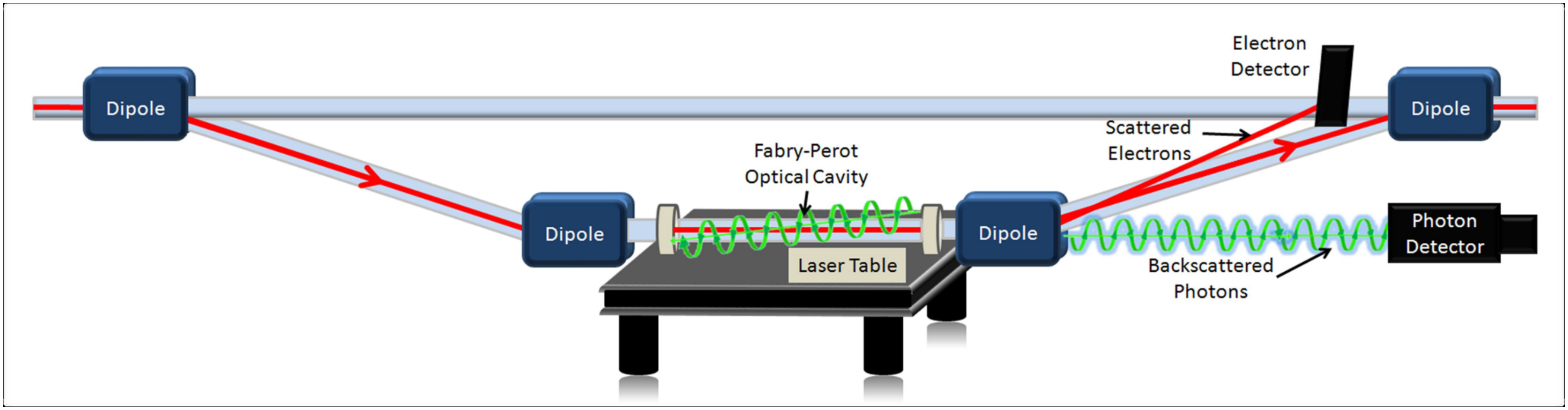
- Strong dependence of asymmetry on E_γ leads to non-trivial determination of analyzing power
  - Understanding the detector response crucial

JLab Compton Polarimeters

Hall A and C have similar (although not identical) Compton polarimeters

Components:

1. 4-dipole chicane: Deflect electron beam vertically
    - 6 GeV configuration: Hall A → 30 cm, Hall C → 57 cm
    - 12 GeV configuration: Hall A → 21.5 cm, Hall C → 13 cm
2. Laser system: Fabry-Perot cavity pumped by CW laser resulting in few kW of stored laser power
3. Photon detector: PbWO4 or GSO – operated in integrating mode
4. Electron detector: segmented strip detector



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Compton Polarimetry for Positrons at JLab

- Compton polarimetry can be almost trivially applied to positron beams
  - Cross sections, analyzing power identical
  - Polarimeter layout (dipole chicane, detectors, etc.) needs no modifications → just need to flip polarity of dipoles in chicane
- The only significant challenge is the relatively low rates
- Deploying Compton polarimeter in Hall B would be difficult (real estate and cost) → might be limited to using existing Comptons in Halls A and C

Polarization Measurement Times

Luminosity for Compton scattering at non-zero crossing angle:

$$\mathcal{L} = \frac{(1+\cos\alpha_c)}{\sqrt{2\pi}} \frac{I_e}{e} \frac{P_L \lambda}{hc^2} \frac{1}{\sqrt{\sigma_e^2 + \sigma_\gamma^2}} \frac{1}{\sin\alpha_c}$$

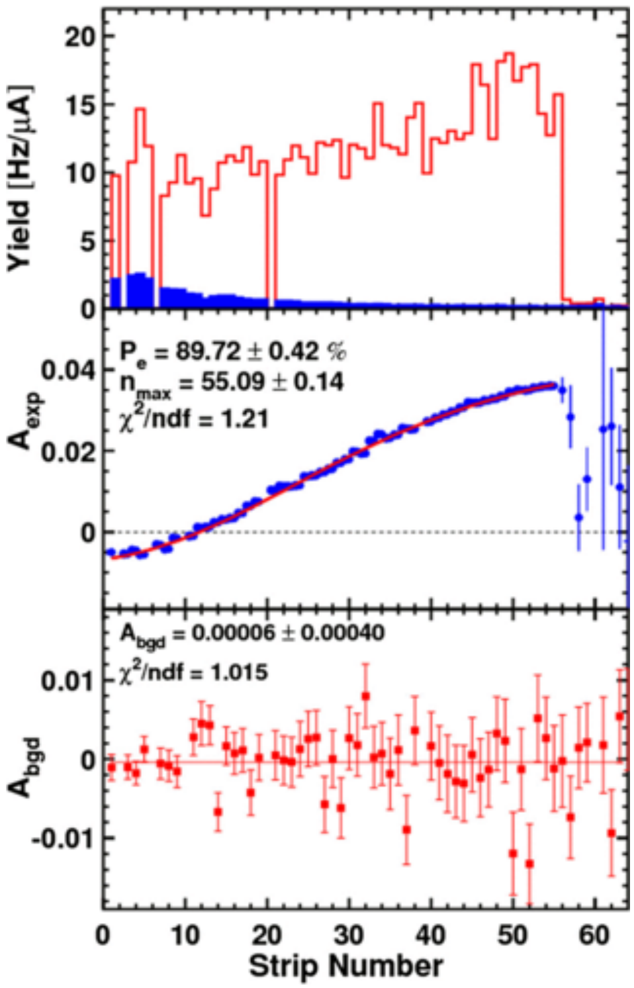
Positron beam size at interaction point with laser dictates luminosity (for given beam current and laser/electron beam crossing angle)

Time for measurement of precision ΔP/P:

$$t^{-1} \approx \mathcal{L}\sigma \left(\frac{\Delta P}{P}\right)^2 P_e^2 < A^2 >$$

This expression is a little too simple – ignores fit uncertainties, additional degrees of freedom

Polarization Measurement Times



Use Q-Weak experience to deduce realistic measurement times for “positron Compton”

Q-Weak:
E_{beam} = 1.16 GeV, P~ 89%, P_{Laser}=1.7 kW,
I_{beam} = 180 uA:
→ Rate ~ 150 kHz,
→ dP/P = 0.47% in 1 hour run
(laser off half the time for background measurements)

Assume comparable beam size for 11 GeV positrons, P~ 60%, 100 nA, higher power laser (5 kW)

→ Rate ~ 185 Hz
→ dP/P ~ 3% for 1 hour run

dP/P = 1% would require ~ 9 hours
→ This is “best case” scenario. Lower polarization, energy, beam current all lead to longer measurement times

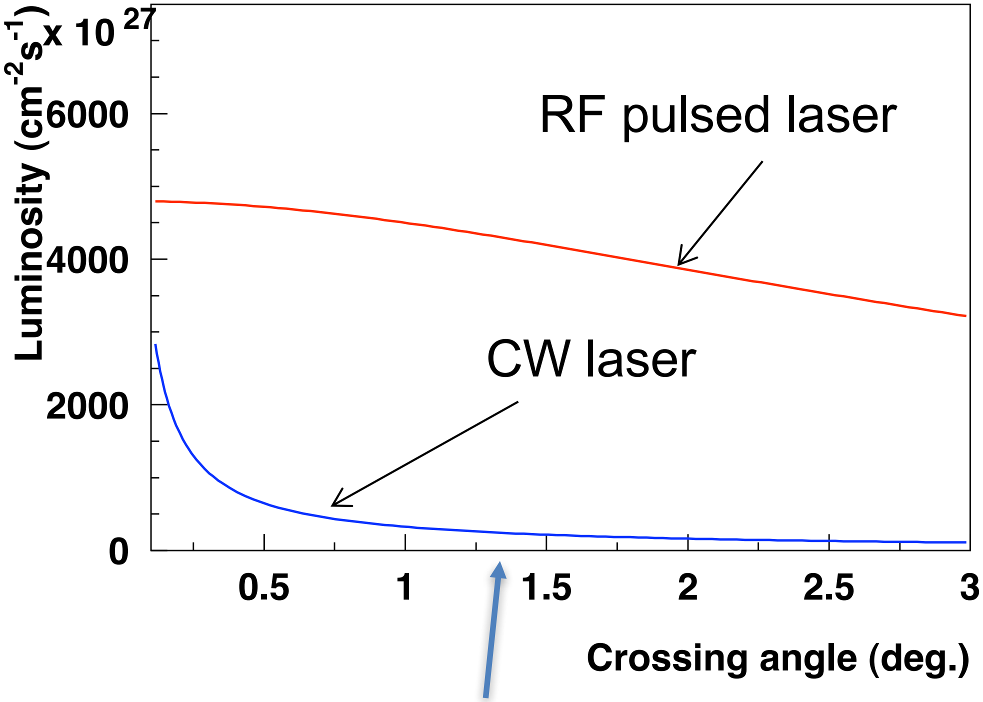
Compton Polarimetry for Positrons

- Compton polarimeters in Halls A and C can in principle be used for positrons with no modifications → change polarity of dipole string
- Measurements times are significant – Compton polarimeters envisioned for use with beam currents > 1 μA
  - Shorter measurement times would require higher power laser system
  - 10 kW FP cavities have been achieved at JLab – not routine
  - Alternate laser system with mode-locked laser locked to FP cavity could provide higher luminosity

RF pulsed FP Cavity

$$\frac{L_{pulsed}}{L_{CW}} \approx \frac{c}{f\sqrt{2\pi}}\left(\sqrt{\sigma^2_{c\tau,laser}+\sigma^2_{c\tau,e}+\frac{1}{\sin^2(\alpha/2)}\left(\sigma_e^2+\sigma_{laser}^2\right)}\right)^{-1}$$

JLab beam → 499 MHz, Δτ~0.5 ps



Hall A/C lasers

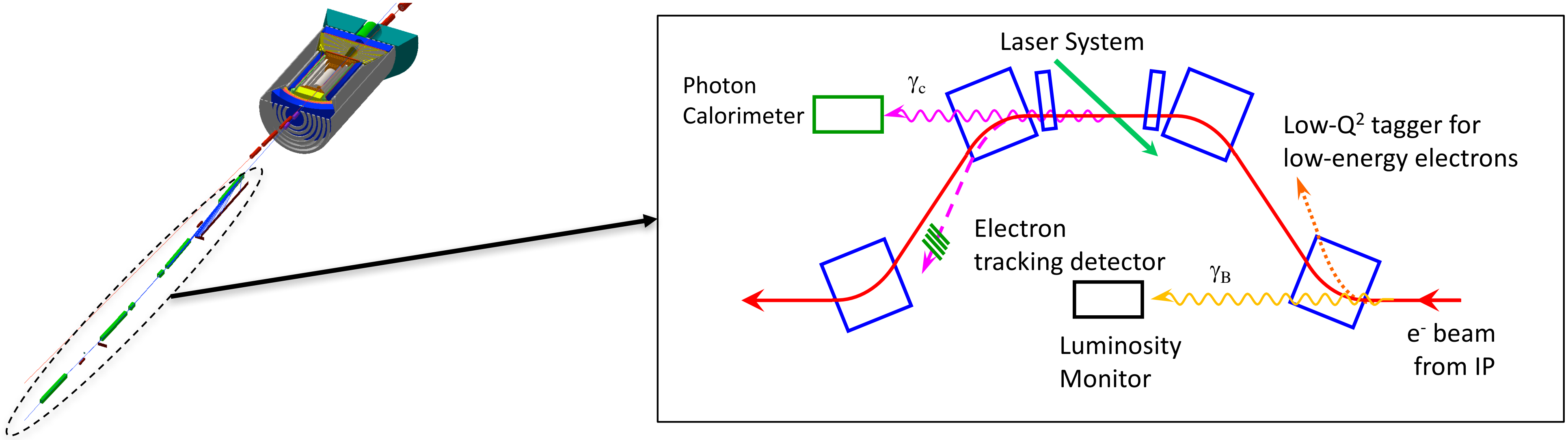
Luminosity from pulsed laser drops more slowly with crossing angle than CW laser

→ FP cavity pumped by mode-locked laser at beam frequency could yield significantly higher luminosity

→ More complicated system – R&D required

RF pulsed cavities have been built – this is a technology under development for ILC among other applications

Compton Polarimetry at JLEIC



Compton polarimeter concept exists for JLEIC → integrated with chicane that will be used for forward electron tagging and luminosity monitor

→ Expected positron currents/polarizations lower than electrons, but luminosity still very high so measurement times remain short

Energy	$I_{electron}$	Electrons		$I_{positron}$	Positrons	
(GeV)	(A)	Rate (MHz)	Time (1%)	(A)	Rate (MHz)	Time (1%)
3 GeV	3	26.8	161 ms	0.2	1.79	5.8 s
5 GeV	3	16.4	106 ms	0.2	1.09	3.9 s
10 GeV	0.72	1.8	312 ms	0.2	0.49	2.7 s

Møller Polarimetry

Electron beam scatters from (polarized) atomic electrons in atom (typically iron or similar)

Longitudinally polarized electrons/target:

$$\frac{d\sigma}{d\Omega^*} = \frac{\alpha^2}{s}\frac{(3+\cos^2\theta^*)^2}{\sin^4\theta^*}\left[1 + P_e P_t A_{\parallel}(\theta^*)\right]$$

$$A_{\parallel} = \frac{-(7+\cos^2\theta^*)\sin^2\theta^*}{(3+\cos^2\theta^*)^2}$$

→ At θ^*=90 deg. → -7/9

Transversely polarized electrons/target

$$A_{\perp} = \frac{-\sin^4\theta^*}{(3+\cos^2\theta^*)^2}$$

→ At θ^*=90 deg. → -1/9

Maximum asymmetry independent of beam energy

Møller Polarimetry at JLab

Møller polarimetry benefits from large longitudinal asymmetry → -7/9

→ Asymmetry independent of energy

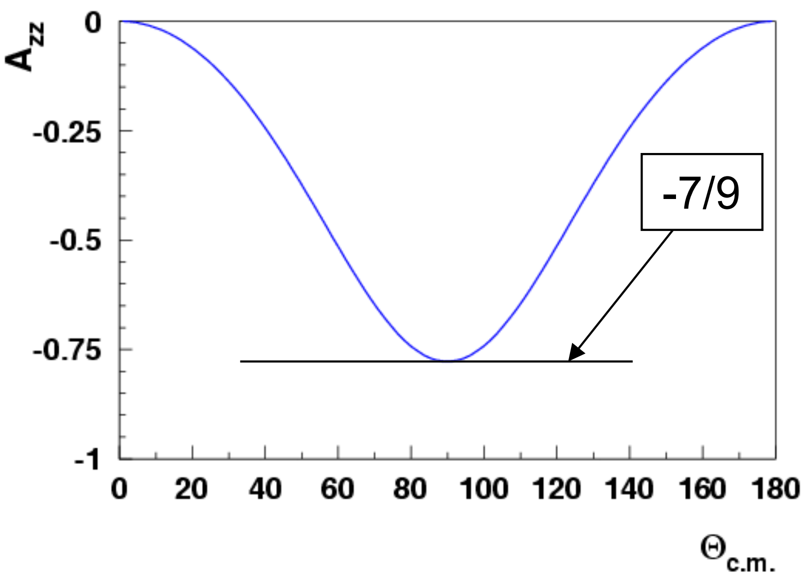
→ Relatively slowly varying near θ_{cm}=90°

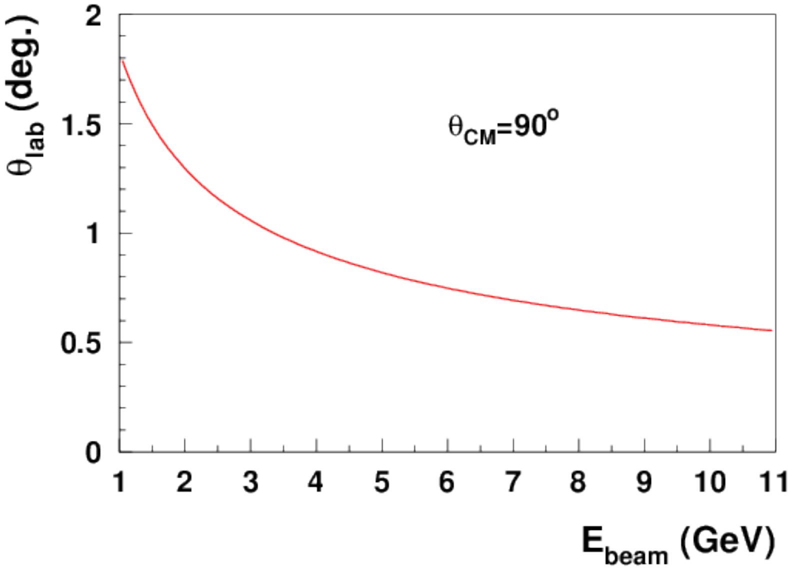
→ Large asymmetry diluted by need to use iron foils to create polarized electrons → P_e ~ 8%

Large boost results in Møller events near θ_{cm}=90° having small lab angle

→ Magnets/spectrometer required so that detectors can be adequate distance from beam

Dominant backgrounds from Mott scattering – totally suppressed via coincidence detection of scattered and recoiling electrons





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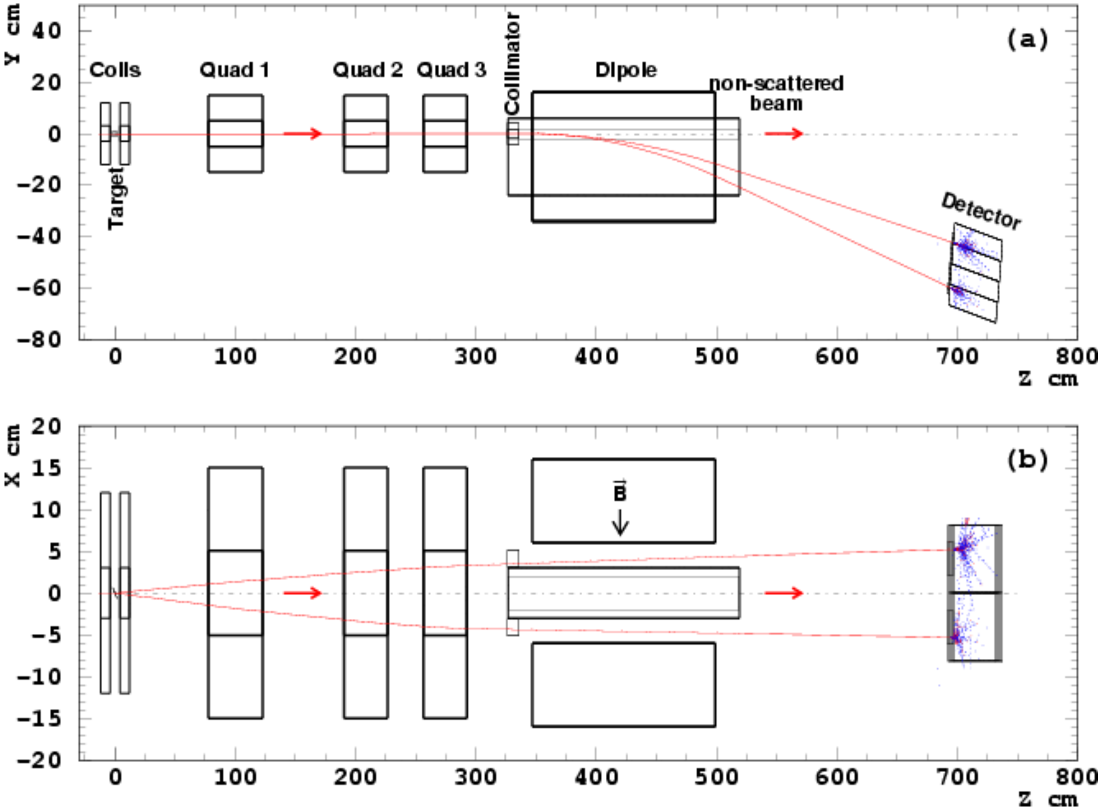
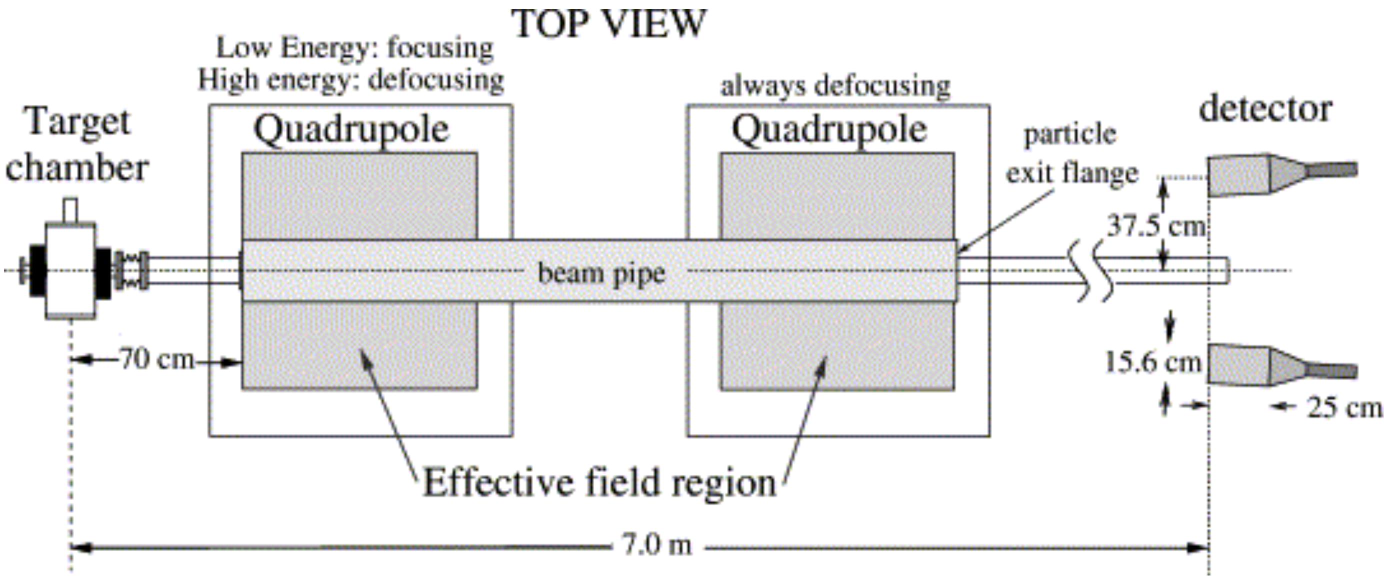
Hall A Møller Polarimeter

- Two target systems available
  - Supermendeur foil, polarized in-plane, low applied field
  - Pure iron foil, polarized out of plan, 3-4 T applies field
- Large acceptance of detectors mitigates potentially large systematic unc. from Levchuk effect (atomic Fermi motion of bound electrons)
- Large acceptance also leads to large rates - dead time corrections cannot be ignored, but are tractable



Hall B Møller Polarimeter

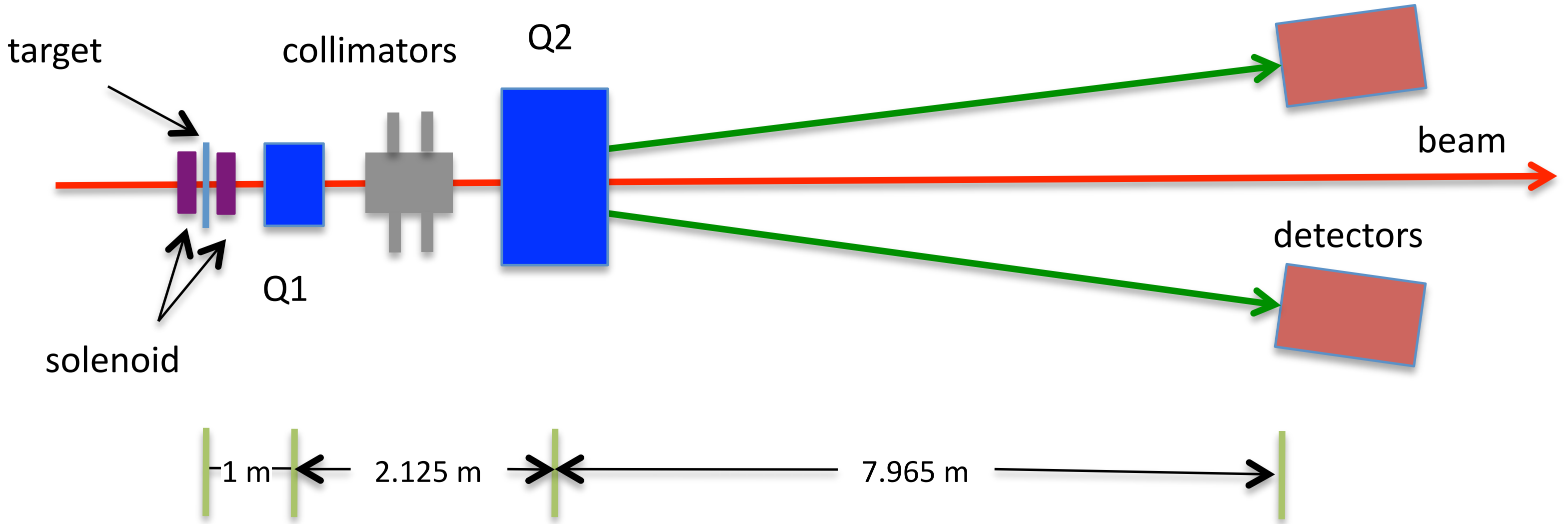
- Hall B Møller uses similar target design as (old) Hall A target → Fe alloy in weak magnetic field
- Two-quadrupole system rather than QQQD
- Detector acceptance not as large – Levchuk effect corrections important
- Dominant systematics *[NIM A 503 (2003) 513]*
  - Target polarization ~ ***1.4%***
  - Levchuk effect ~ ***0.8%***



6 GeV configuration

Hall C Møller Polarimeter

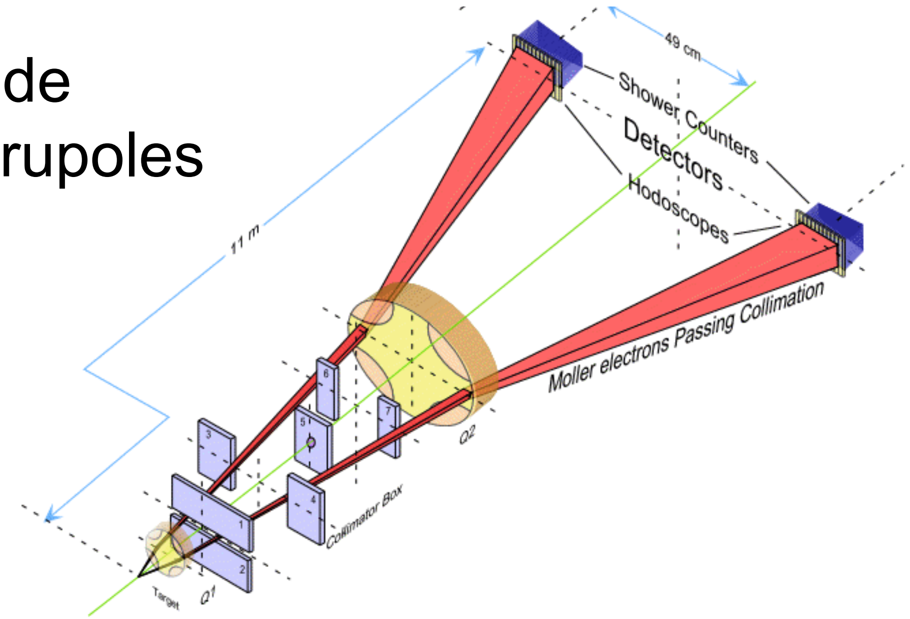
- 2 quadrupole optics maintains constant tune at detector plane
- "Moderate" acceptance mitigates Levchuk effect → still a non-trivial source of uncertainty
- Target = pure Fe foil, brute-force polarized out of plane with 3-4 T superconducting magnet
- Target polarization uncertainty = ***0.25%*** *[NIM A 462 (2001) 382]*



Møller Polarimeter Optics and Positrons

- All JLab Møller polarimeters use quadrupoles to focus and steer scattered and recoiling electrons simultaneously
  - This cannot be done with positron beams – scattered and recoiling particles have opposite charge

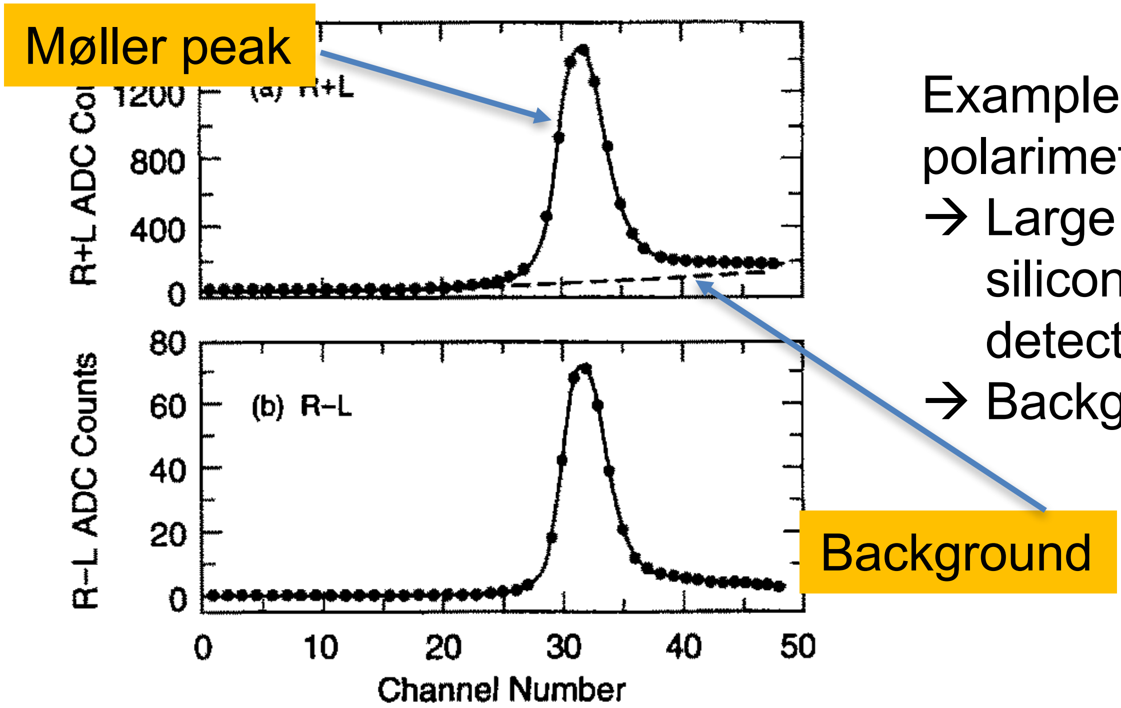
- Two options for operation with positron beams at JLab
  - Operate in “single arm” mode
  - Replace one or more quadrupoles with dipoles



Single-arm Møller Polarimetry

All three JLab Møller polarimeters designed to suppress Mott backgrounds via coincidence electron detection

Single-arm Møller polarimetery requires:
→ Optics that enable measurements of Møller lineshape (energy spectrum)
→ Coordinate detector with sensitivity in relevant direction



Example: SLAC E-154 Møller polarimeter
→ Large aperture dipole used with silicon detectors for coordinate detection
→ Background determined via fit

H.R. Band et al, Nucl.Instrum.Meth. A400 (1997) 24-33

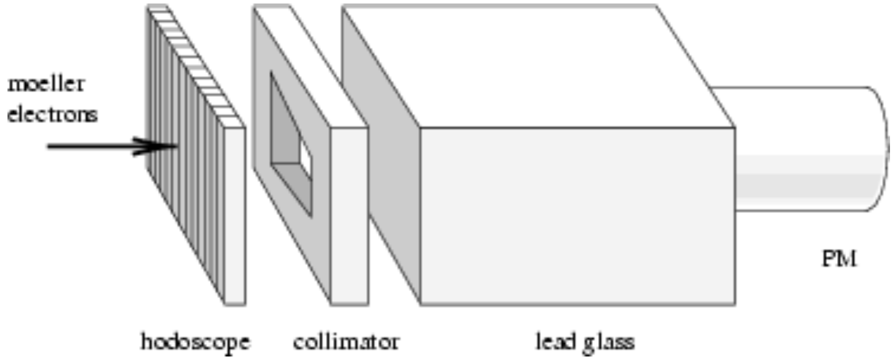
Single-arm Møller Polarimetry at JLab

JLab polarimeters use total energy deposition calorimeters as primary detectors for polarization measurements
→ Coordinate detectors are also used, but mainly to verify optics

In general, optics not designed for measurement of Møller lineshape
→ No easy way to disentangle angle/momentum

Single-arm Møller measurements may be most easily accomplished in Hall A
→ quads + dipole system can act as conventional spectrometer

In any JLab Møller polarimeter, will need modified or optimized coordinate detectors



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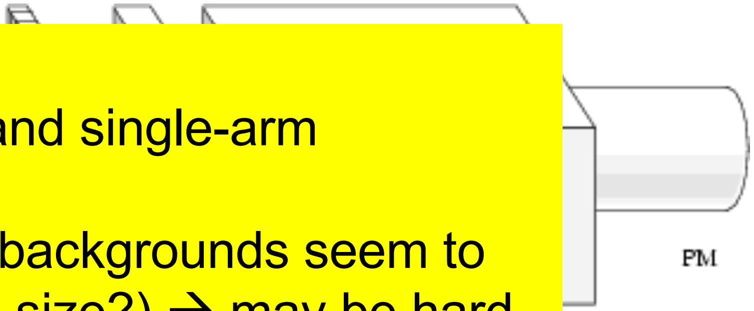
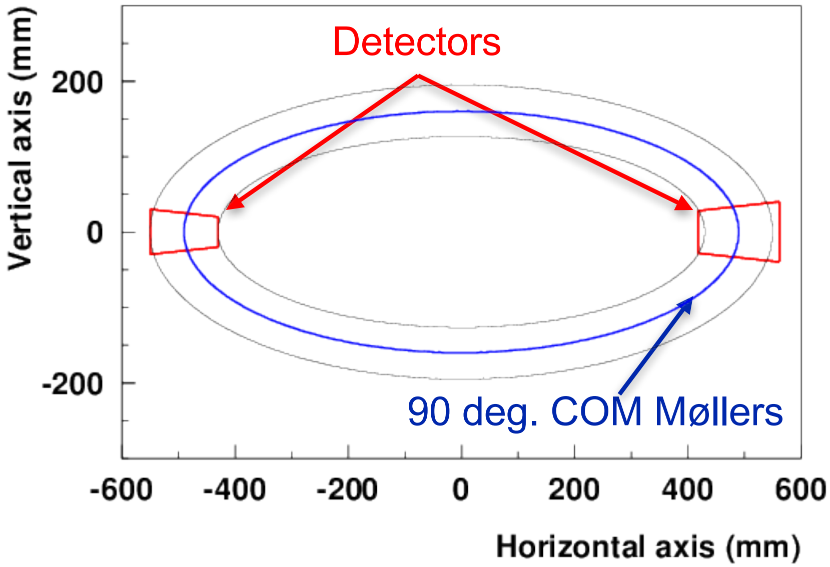


Alternate "brute force" method:
→ Direct cross-calibration of coincidence and single-arm analyzing power using electrons
→ Drawback: single-arm analyzing power/backgrounds seem to be pretty sensitive to beam position (beam size?) → may be hard to maintain identical beam conditions between electron and positron beams

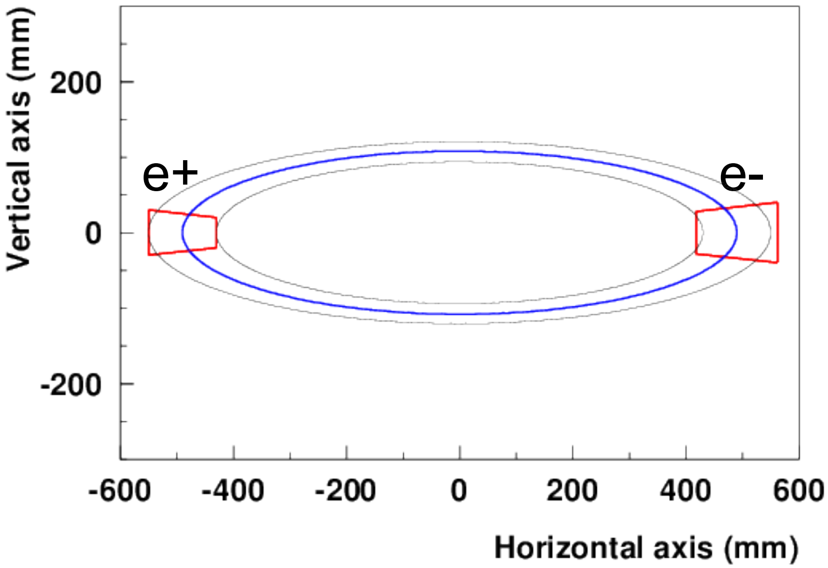
Møller Polarimetry with e+/e- coincidences

Detection of scattered and recoiling electrons in JLab polarimeters makes measurement virtually background free
→ Quadrupoles used to steer like-charged particles away (or toward) the beamline
→ Can control both vertical and horizontal focusing – fixed optics for all beam energies

Hall C: 2-Quad optics



Hall C: 1-Dipole optics @ 11 GeV



Coincidence detection could be achieved for scattered e+ and recoiling e- using a large gap (~3.5 inches) dipole (~ 1 T-m)

- → No control over particle envelope in non-dispersive direction
- → Tune/optics will change with beam energy

Summary

- Compton polarimetry can be used in Halls A and C with the existing devices virtually unmodified
  - Measurement times will be long with existing laser system
  - New laser system (FP cavity pumped by mode-locked laser) could significantly improve luminosity → R&D would be required
- Møller polarimetry is possible, but some modifications would be required
  - Operation in single arm (scattered particle only) mode would require investigation into optimized background suppression → new optics and/or detector system
  - Operation in coincidence mode (scattered e+ and recoil e-) would require new magnet → replace one or more quads with dipole