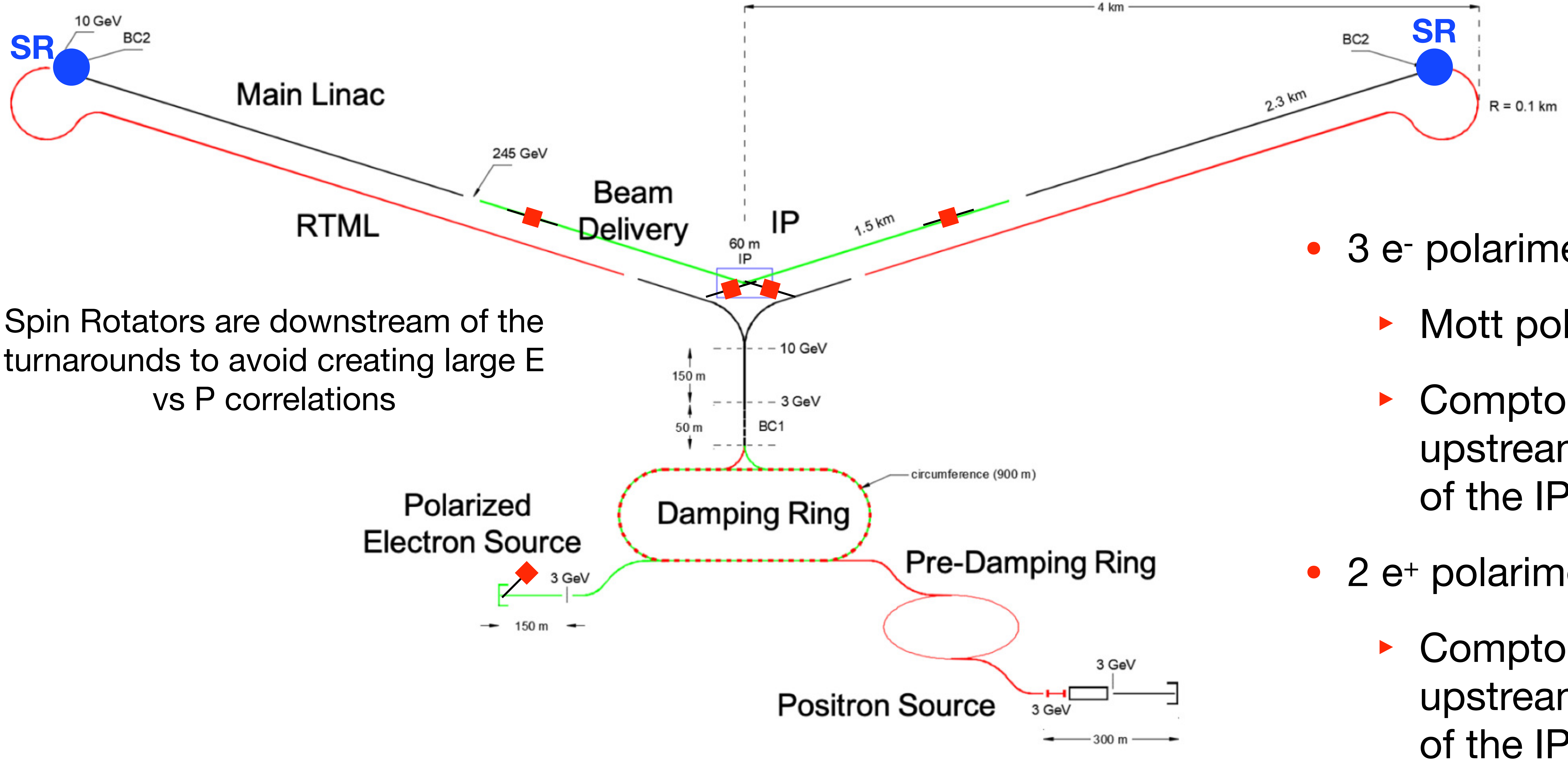
Polarimetry at C^3

M. Swartz

Polarimetry at C^3

There is literature about beam polarization and related techniques at the ILC [I haven't seen anything about C^3]. I'll assume that many of the ILC ideas are "in play" for C^3.



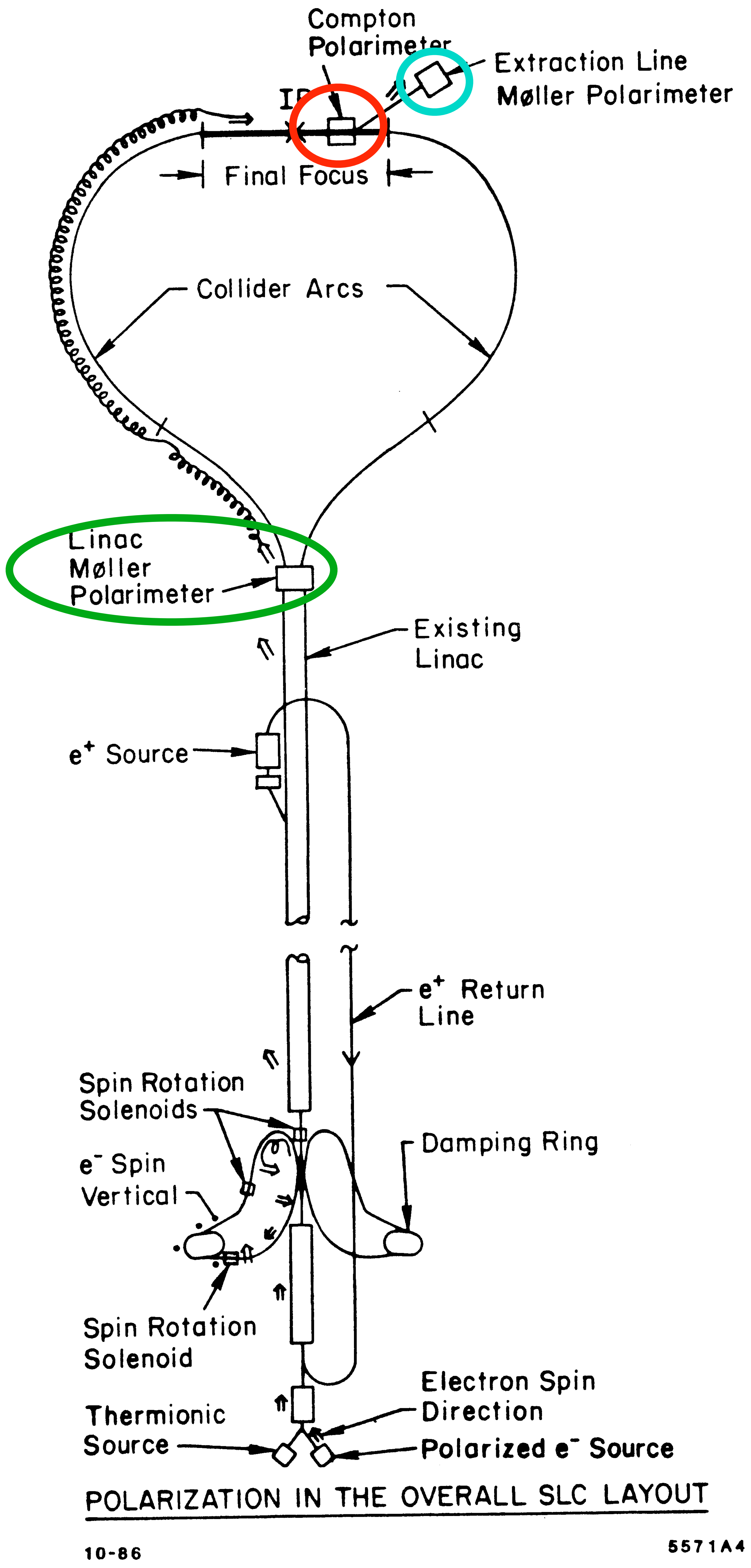
Spin Rotators are downstream of the turnarounds to avoid creating large E vs P correlations

- 3 e^- polarimeters
  - Mott polarimeter at source
  - Compton polarimeters upstream and downstream of the IP: $\delta P_{syst} = 0.25\%$
- 2 e^+ polarimeters
  - Compton polarimeters upstream and downstream of the IP: $\delta P_{syst} = 0.25\%$

SLC Experience

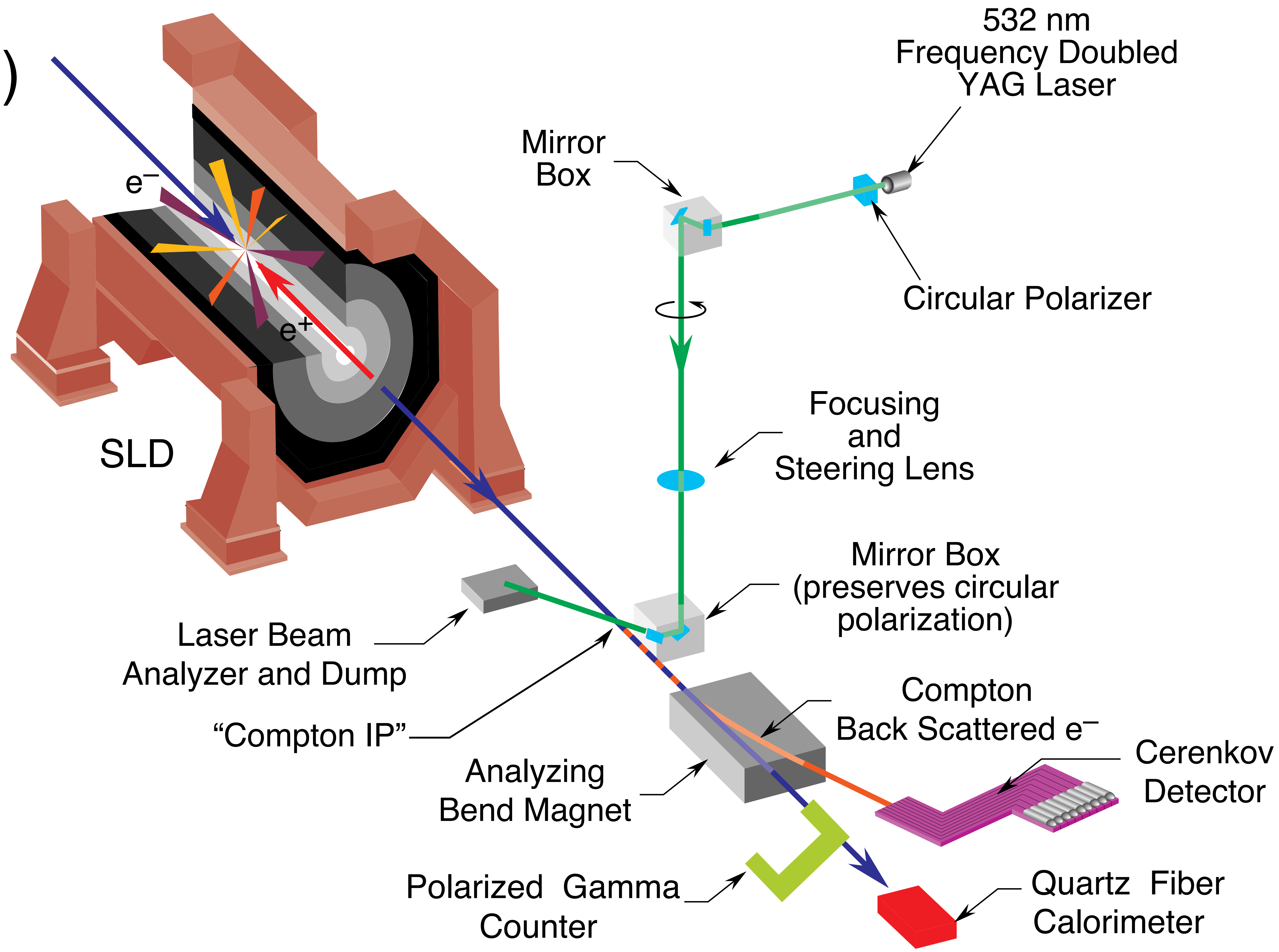
There has been only one polarized e^+e^- collider. The original design had a system of 3 polarimeters.

- No low energy Mott Polarimeter at the source
  - it would have been useful on day 1, probably not at all after that [photoemission sources are quite stable]
  - we measured the polarization and the spin rotation matrix to the Compton polarimeter with a “3-state measurement”
- Linac Møller Polarimeter - we learned a lot about magnetized targets and Moller polarimetry … not so much about anything else
- Compton Polarimeter - immediately downstream of the e+ final focus quads, measured the relevant information needed to do the experiment: $\delta P_{syst} = 0.5\%$
- Extraction Line Møller Polarimeter - compromised by extraction line energy spectrometer, never worked



SLC Compton Polarimeter

- best technique for polarimetry
  - large QED asymmetry (“easily” understood)
  - target has known quantum state of large polarization
  - no intrinsic background
  - machine backgrounds are directly measurable
  - expensive/complex
- laser/optical transport built by SLAC/LBL
- 9-channel e- detector by LBL Group
- photon X-check detectors added later by U-Tenn Group



SLC Experience

- Downstream polarimeter was separated from the interaction point by final focus quadrupoles
  - same P direction at the e^+e^- interaction point and the Compton Interaction Point
    - polarization optimization techniques at CIP optimize P_z at the e^+e^- IP
  - exposed the polarimeter to beamstrahlung
    - low critical energy was strongly suppressed by careful detector design
    - inner Cerenkov detector channels [low analyzing power] near beamline not useful during high luminosity operation due to high backgrounds
  - (very small) collision-induced depolarization directly measured by dumpering e+
    - small effect is measured in one polarimeter [uncertainties cancel]
  - small (10^{-3}) corrections for beam divergence and lum-weighted energy spread needed
    - in a true linear collider [no arcs], the energy spread [chromaticity] effect would be very small
  - backscattered photon cross checks only possible in e- only operation

Compton Scattering

The backscattering of high energy e± [E$_b$]with optical photons [k] has a large polarization dependent asymmetry. Defining lab frame variables y and x:

$$E_{\rm min} = yE_b \qquad K_{\rm max} = (1-y)E_b$$

$$y = \frac{1}{1+2E_b k(1+\cos\theta_{e\gamma})/m_e^2}$$

$\theta_{e\gamma}$ is the acollinearity angle

The scattered photon energy K and electron energy E are given by x

$$K = xK_{\rm max} \quad E = E_b - K = E_b - xK_{\rm max} = E_b\left[1-x(1-y)\right]$$

The cross section for longitudinally polarized electrons and circularly polarized photons is

$$\frac{d\sigma}{dx} = \sigma_u(x)\left[1 - P_e P_\gamma A_z(x)\right] \qquad \sigma_u(x) = 2\pi r_0^2 y\left\{\frac{x^2(1-y)^2}{1-x(1-y)} + 1 + \left[\frac{1-x(1+y)}{1-x(1-y)}\right]^2\right\}$$

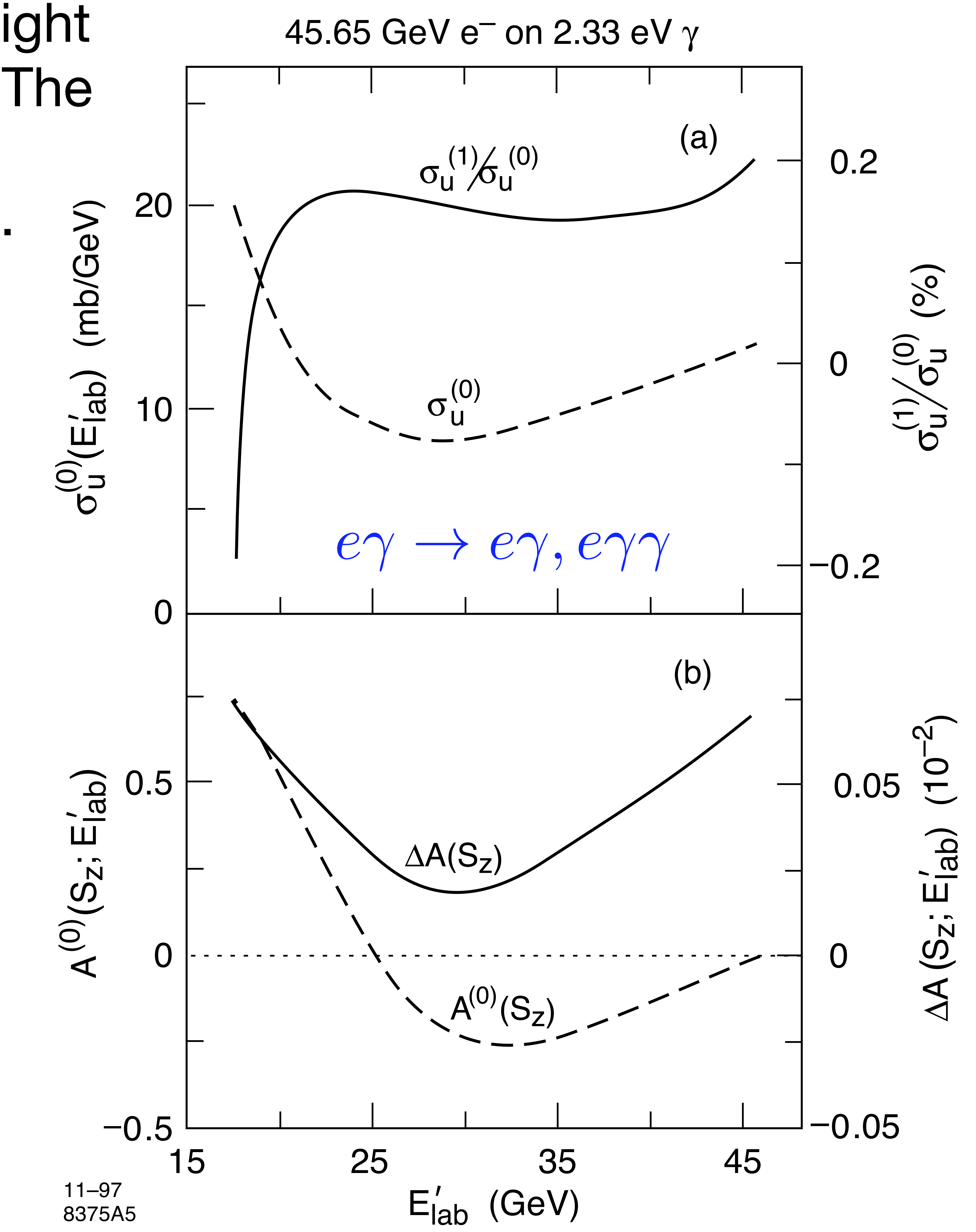
where $A_z(x) = 2\pi r_0^2 y\left[1-x(1+y)\right]\left\{1 - \frac{1}{[1-x(1-y)]^2}\right\}\sigma_u^{-1}(x)$

- The largest cross section and asymmetry occur near x = 1 [Compton edge]
    - lowest energy electrons/positrons and highest energy photons

The LO cross section and asymmetry are shown at the right for the SLC case with the (very small) NLO corrections. The asymmetry is a strong function of E/K. Detect e± (not γ) because a spectrometer can measure many events vs E. The y parameter does not scale with beam energy:

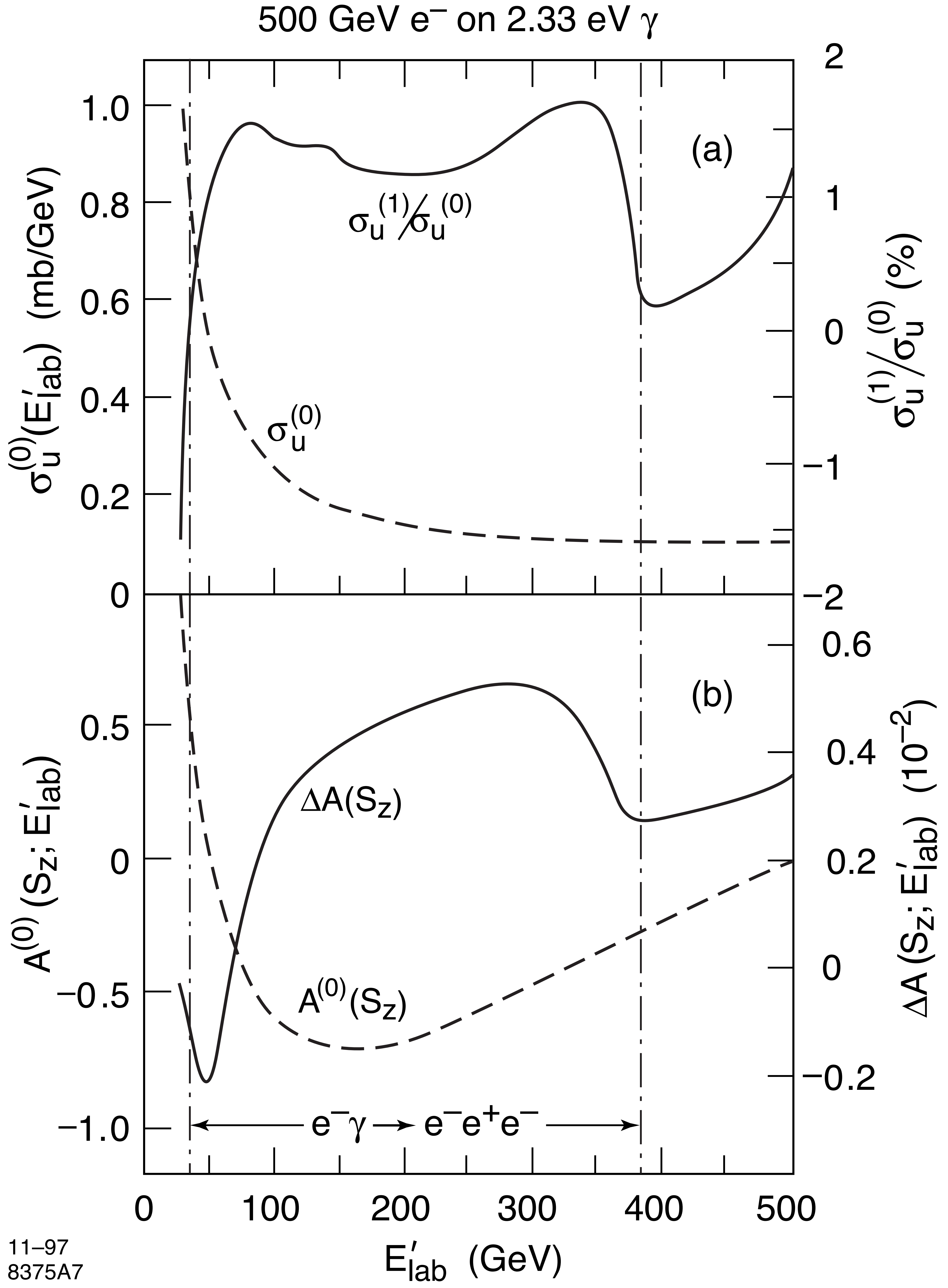
Collider	E_b (GeV)	k(eV)	y	E_{min} (GeV)	σ_u (mb)	$A_z(x=1)$
SLC	45.65	2.331	0.381	17.35	289	0.747
C^3	125	2.331	0.183	22.88	195	0.935
C^3	125	1.165	0.309	38.69	270	0.825
C^3	275	2.331	0.092	25.42	128	0.983
C^3	275	1.165	0.169	46.54	188	0.944
C^3	500	2.331	0.053	26.53	89.7	0.994
C^3	500	1.165	0.101	50.38	136	0.980

Small y means large separation between E_{min} e± and beam (and beamstrahlung) but possibly with aperture problems. Choose 125GeV+2.331eV and 275GeV+1.165eV to keep y similar?


45.65 GeV e⁻ on 2.33 eV γ

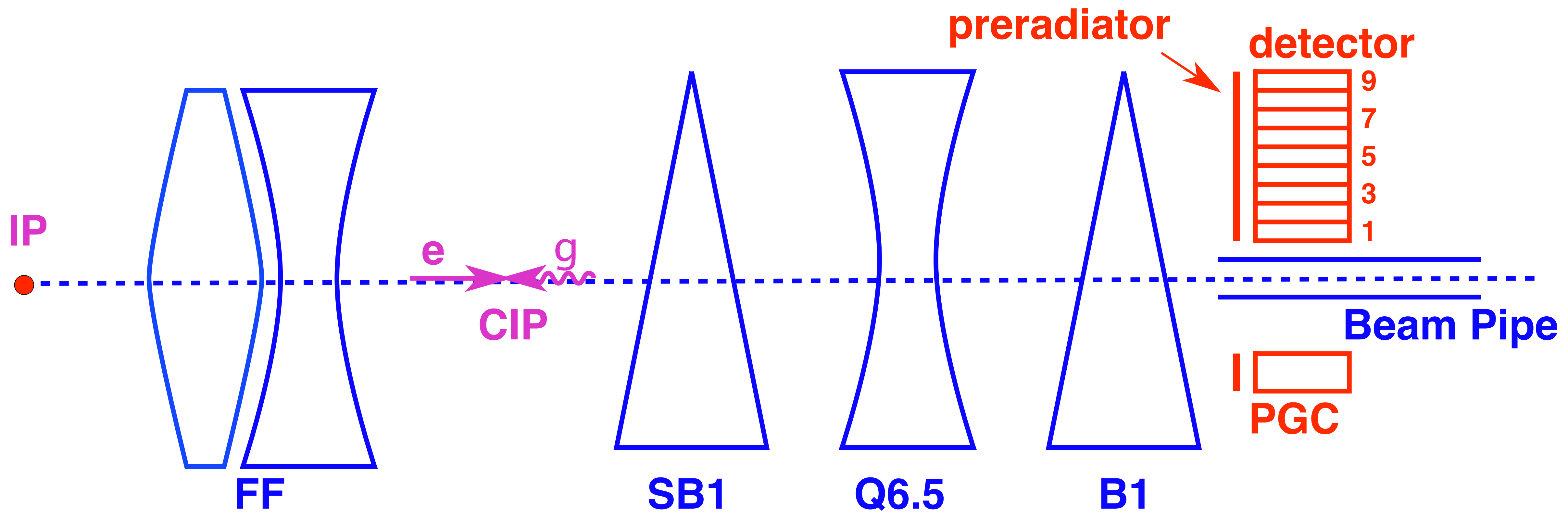
An IR laser also suppresses the process e±γ -> e±e-e+ at high beam energies. They become an issue at the largest energies where they affect the asymmetry close to the Compton edge.

The threshold beam energy for e±e-e+ is 224 GeV for 2.331 eV photons and 448 GeV for 1.165 eV photons.



Because there was no spin rotation between the SLC IP and the Compton IP, the one axis SLC polarimeter directly measured one row of the spin rotation matrix from the Spin Rotation System to the SLC IP/CIP

$$\begin{pmatrix} \mathcal{P}_x \\ \mathcal{P}_y \\ \mathcal{P}_{\mathbf{z}} \end{pmatrix}_{IP} = \begin{pmatrix} R_{xx} & R_{xy} & R_{xz} \\ R_{yx} & R_{yy} & R_{zy} \\ \mathbf{R_{zx}} & \mathbf{R_{zy}} & \mathbf{R_{zz}} \end{pmatrix} \cdot \begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix}_{SR}$$



Launching the polarization along the x,y,z axes separately measures the needed info

$$\mathcal{P}_{tot} = \sqrt{\mathcal{P}_z^2(\hat{x}) + \mathcal{P}_z^2(\hat{y}) + \mathcal{P}_z^2(\hat{z})} \quad R_{zx} = \frac{\mathcal{P}_z(\hat{x})}{\mathcal{P}_{tot}} \quad R_{zy} = \frac{\mathcal{P}_z(\hat{y})}{\mathcal{P}_{tot}} \quad R_{zz} = \frac{\mathcal{P}_z(\hat{z})}{\mathcal{P}_{tot}}$$

The optimum launch direction from the SR system to yield longitudinal P at the IP is

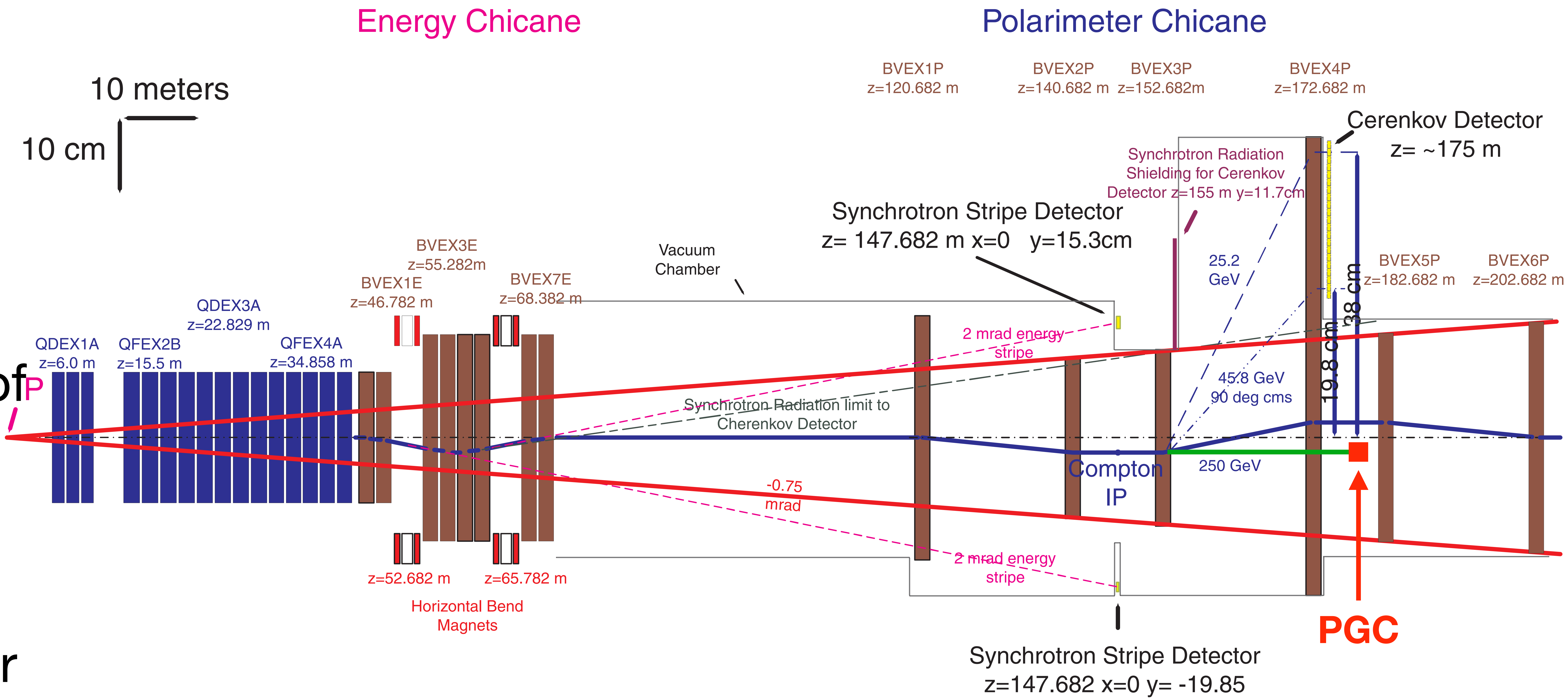
$$\hat{n} = \begin{pmatrix} R_{zx} \\ R_{zy} \\ R_{zz} \end{pmatrix}_{SR}$$

Note that this technique fails if there is any spin rotation between the IP and the CIP. Note also that the **technique does not determine the full rotation matrix** [only 2 of 3 parameters in a 3x3 orthogonal matrix]. In actual (flat beam) running, the SLC arc was used to rotate spins.

Downstream ILC Polarimetry

In the Reference Design Report, the extraction line instrumentation is ordered “unintuitively”

- The energy spectrometer [bends alternately in 2 planes] is upstream of the polarimeter?
  - causes spin rotation?
  - locate it downstream of the polarimeter
    - beamstrahlung cone is smaller at the Compton polarimeter

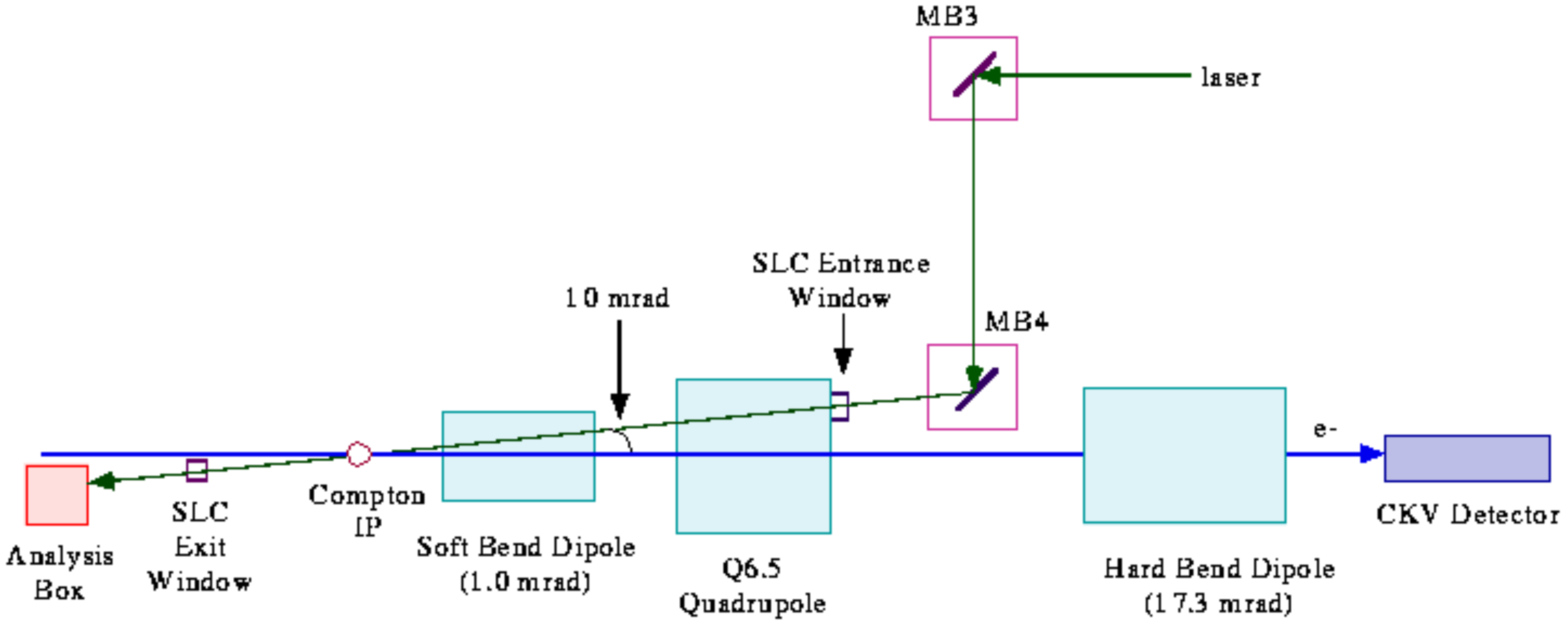


- The polarimeter chicane moves the Compton IP out of line with the ∞ momentum beam axis
  - can measure backscattered photons without beamstrahlung background from collisions
    - use them to cross check the backscattered e± measurements [PGC] if backgrounds are tractable?

SLC vs C^3 CIP

The 7ns SLC laser pulse was focused to a transverse size of ~0.5mm and crossed the 1 bunch train at an angle of 1 mRad: luminous region was ~0.5m in length ℓ producing backscattered e- for about 1.7ns. C^3(250) would have a train of 133 bunches in 700ns.

- YAG lasers can have pulse lengths of ~500ns from multipass cavities
  - could sample most or all of a train
  - 1.7ns/5.26ns(bunch spacing) = 32% of laser pulse length used for collisions
  - how much laser energy needed to produce the same number of scatters per bunch train as the SLC?
  - for same N_C/e, multiply by 33 [5J]
- Can order off-the-shelf 10 Hz Nd:YAG lasers having $E_{\rm pulse}$ ~ 20J w/ short pulses



$$N_C = N_{\rm bun} N_e [\rho_\gamma] \ell \sigma_{e\gamma} = N_{\rm bun} N_e \left[A \frac{E_{\rm pulse}}{T} \right] \ell \sigma_{e\gamma}$$

$$\underbrace{133 \cdot (10^{10}) \left[\frac{E_{\rm pulse}}{700\ \text{ns}} \right]}_{\text{C}^3} = \underbrace{1 \cdot (4 \times 10^{10}) \left[\frac{50\ \text{mJ}}{7\ \text{ns}} \right]}_{\text{SLC}}$$

$$\rightarrow E_{\rm pulse} = 150\ \text{mJ}$$

Long Pulse Polarimetry

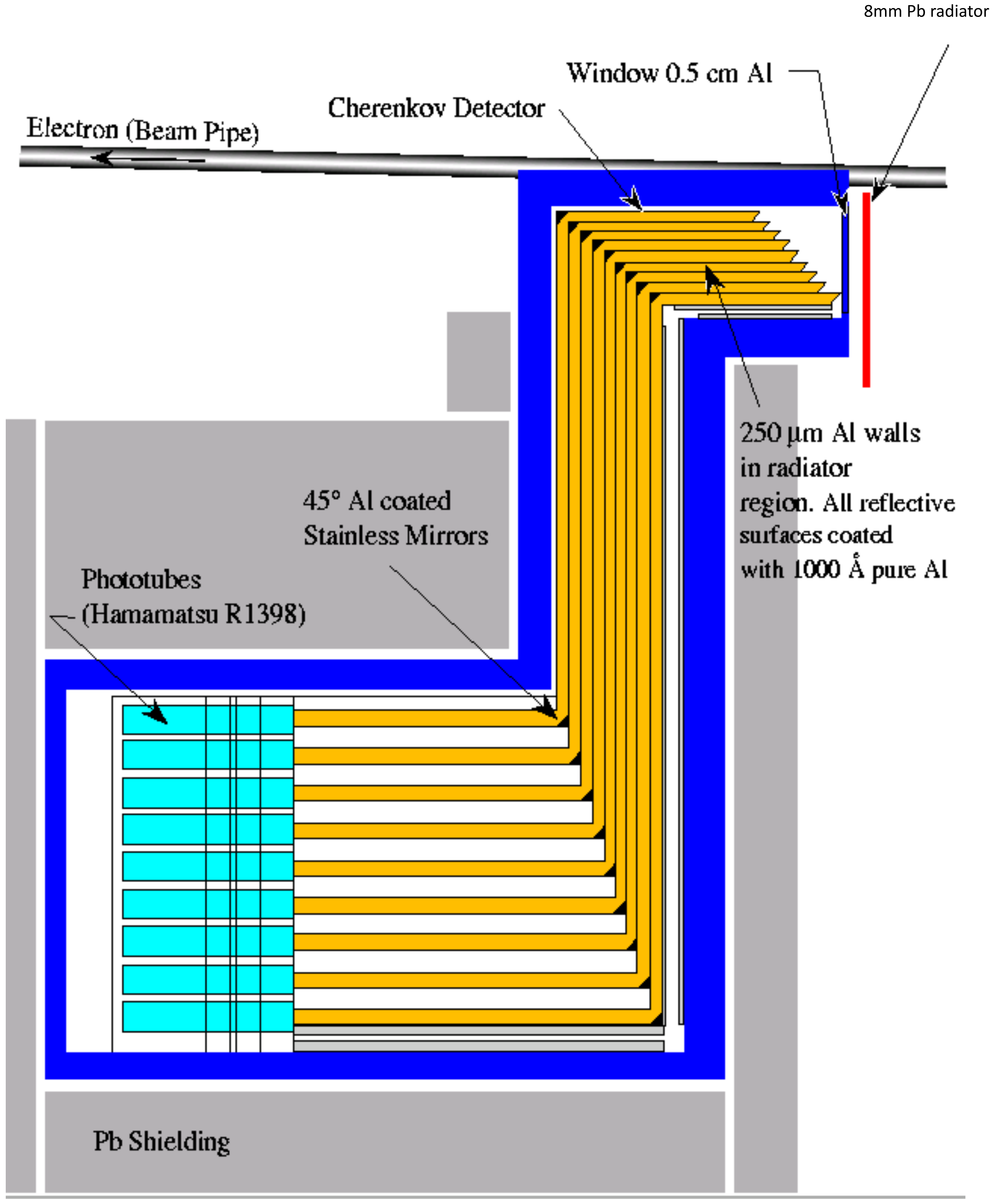
The ILC literature seems to focus on short pulses at high rep rates to probe individual bunches. That might be a useful diagnostic? The physics cares about the average polarization of the whole beam.

- long pulse laser could still study early/late bunches in the train by shifting the laser firing time
    - can shorten the pulse too.
- long integration times for signals [low noise?]
- suppresses laser induced damage to optical system [scales as (instaneous power)$^{1/2}$?]
- power supplies, laser monitoring, and detector readout electronics would be somewhat different from SLC case

Cerenkov Detector

Nine channel detector filled with 1 atm of propane

- non-scintillating gas with 11 MeV Cerenkov threshold to suppress low energy backgrounds
  - critical energy and flux of C^3 beamstrahlung increase significantly [2.5×10^{12} 3 GeV γ/train?]
- mounted on a moving table to scan the position of the Compton edge
  - crucial for calibration
- Quartz window PMTs buried in lead shielding
  - **future iterations should transport the light out of the bend plane of the spectrometer** [and bury the photosensitive detectors in shielding]
- many new photon detection technologies that are smaller, cheaper, and could have improved linearity



Gas is propane at 1atm; 11 MeV threshold

Upstream vs Downstream

- Upstream polarimeter
  - no beamstrahlung or other IP related radiation
    - smaller detector backgrounds
    - narrower beam energy distribution
  - redundancy
    - if the downstream polarimeter doesn’t work due to intractable background problems
    - if long pulse laser in downstream, use short pulses here?
- Downstream polarimeter
  - IP related backgrounds much worse than the SLC case: need chicanes, small y, good detector design
  - in-situ measurement of the depolarization by dumpering e+ beam
    - need to correct beam energy for beamstrahlung losses [ILC: 5% shift, measured by E spectrometer, would shift analyzing power by 0.5% … C^3?]

Polarization Corrections

Polarimeters do not measure exactly what we want to know. They measure the average polarization of a beam with some emittance and energy spread at some β_x/β_y that is not at the IP of the collider. Furthermore, correlations between the parameters during the collision process can be non-negligible yielding physics measurements that depend upon the luminosity weighted average beam polarizations.

- All of the corrections are predicted to be units of 10^{-3}
  - most of the uses of beam polarization are to modulate various physics and background processes
    - calculated corrections are more than good enough
    - Giga-Z samples are an exception: the Z vector coupling provides loop level information and A_{LR} measurements would be limited by δP
- If we have e+ polarization, the “Blondel Scheme” uses the extinction of the J_z=1 cross section in J_z=0 initial states to provide information about the luminosity-weighted polarizations

Luminosity Weighted Polarization

Let's assume that the luminosity weighted average polarization of each beam is proportional to the polarization measured by the polarimeters:

$$\text{lum weighted } \bar{P}_{e\pm} = (1+\varepsilon)P_{e\pm} \text{ measured}$$

where ε can be positive or negative. Using only e^+e^- → f-fbar and e^+e^- → W^+W^- events [no e^+e^- → e^+e^- or e^+e^- → e^+e^-X events], we measure the ratio of J_z=0 and J_z=1 events

$$R = \frac{\sigma(J_z=0)}{\sigma(J_z=1)} = \frac{\sigma_{RR}+\sigma_{LL}}{\sigma_{LR}+\sigma_{RL}} = \frac{1-|\bar{P}_{e+}||\bar{P}_{e-}|}{1+|\bar{P}_{e+}||\bar{P}_{e-}|} \simeq \frac{1-|P_{e+}||P_{e-}|}{1+|P_{e+}||P_{e-}|}\left[1-\frac{4\varepsilon|P_{e+}||P_{e-}|}{1-|P_{e+}|^2|P_{e-}|^2}\right]$$

- Using the measured ratio of (RR+LL)/(LR+RL) events and the measured beam polarizations, we can extract the correction for lum-weighted polarizations [assumed to be common to both beams]
  - "model independent"
  - uses most of the total cross section
  - lots of running in the unproductive (RR+LL) configuration
- This is probably very difficult because the size of the effect is comparable to the systematic errors on the polarization measurements and it needs lots of collision statistics

Summary

I've been away from Linear Collider stuff for more than 20 years … hope it doesn't show too much. Most of my comments apply to ILC ideas [if there are different C^3 ones, sorry]

- Mott Polarimetry at the source - not parasitic, can't be used during machine operation
  - was not needed in SLC [source came late, everything else already existed]
  - useful for standalone commissioning of the source
- Upstream Compton Polarimetry - less risky than downstream polarimetry
- Downstream Compton Polarimetry - move it as close to the FF as possible [put the energy spectrometer behind it]
- Either or Both
  - long laser pulses to measure bunch trains?
  - chicane-based design makes detection of backscattered photons much cleaner [X-check]
- Positron Polarization - useful in very high luminosity scenarios where some can be "wasted" in LL+RR operation.