Revisiting EW Constraints at a Linear Collider

Work done by

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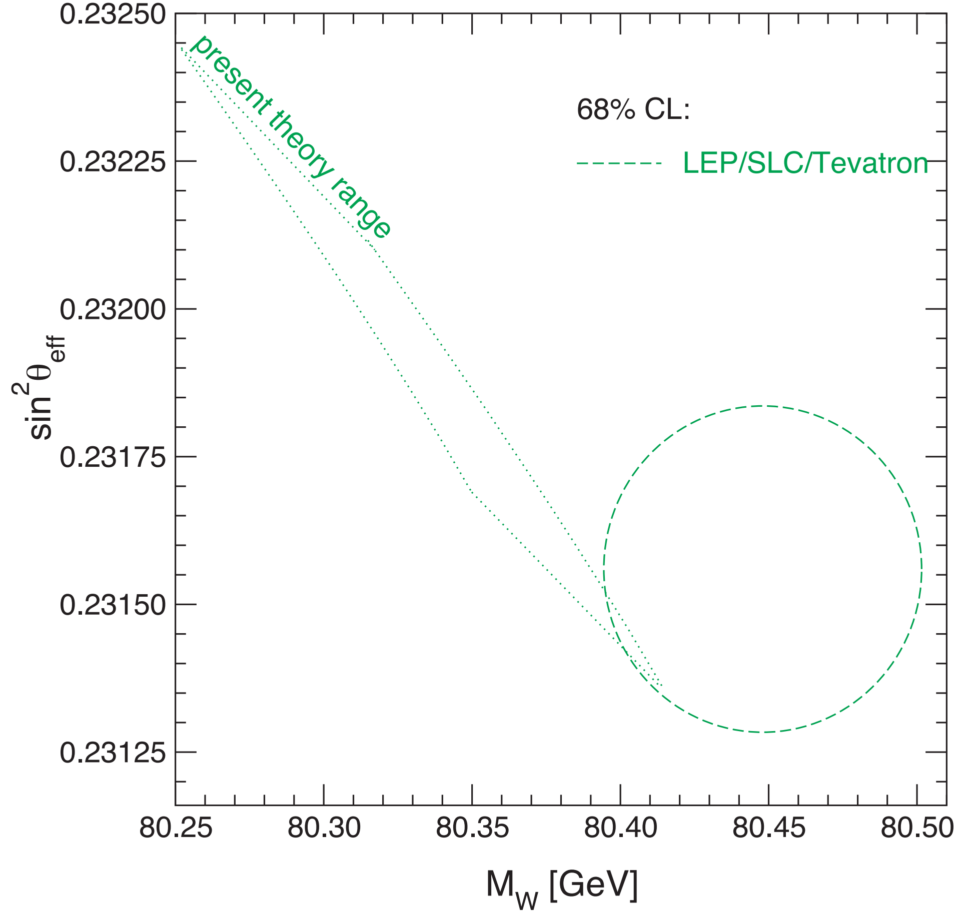
Why improve EW parameters?


S. Heinemeyer (LC Physics Resource Book)

- Dominant theory limitations
  - M_t
  - $\Delta\alpha = \alpha_{QED}(M_Z)-\alpha_{QED}(0)$
- Three key measurements
  - tt threshold: M_t
  - Z pole: $\sin^2\theta_{eff}$
  - W^+W^- threshold: M_W

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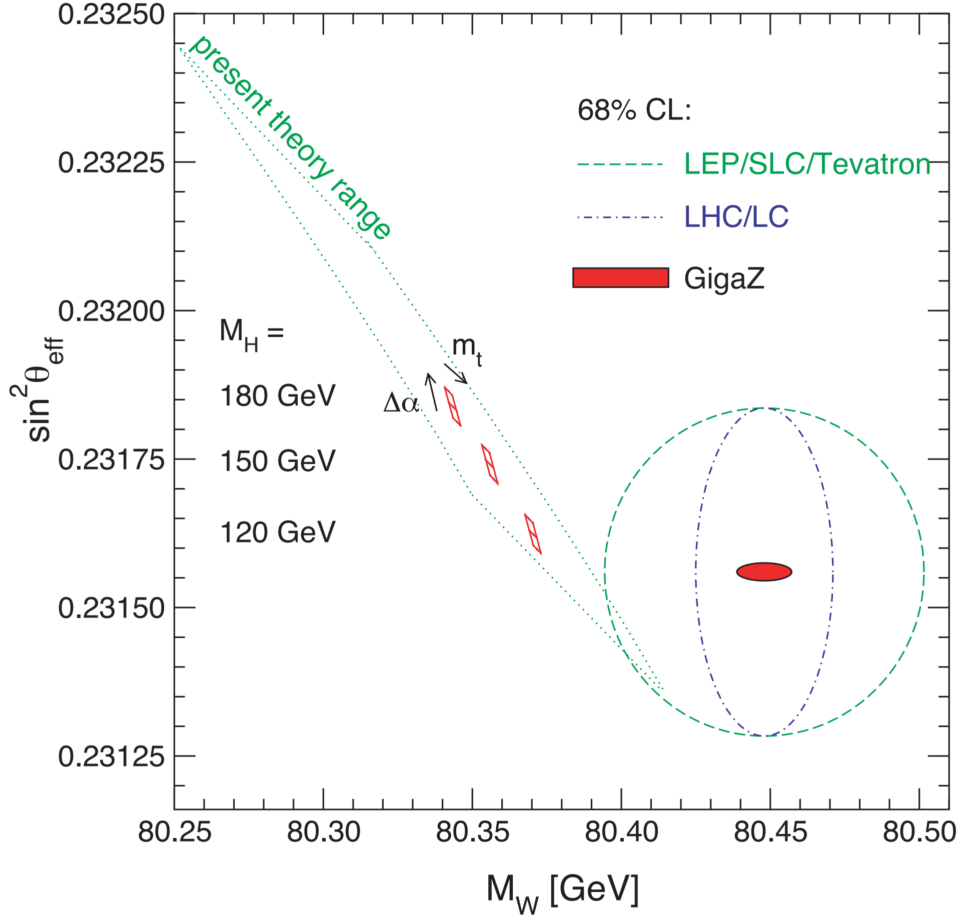
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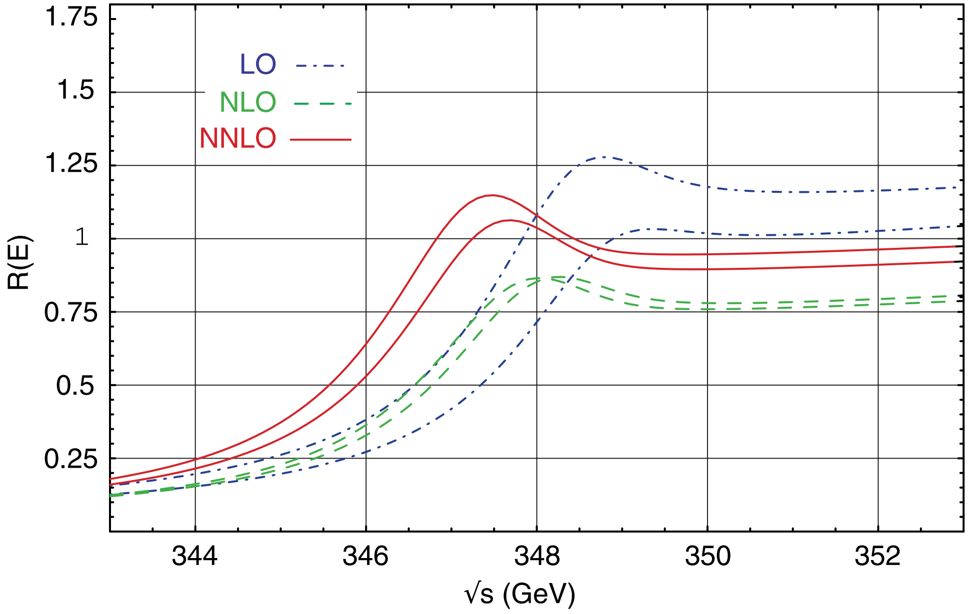
  - W^+W^- threshold: M_W
- Indirect prediction power
  - M_W to ±4 MeV
  - M_H to +- 8%
- Caveat: must improve $\Delta\alpha$

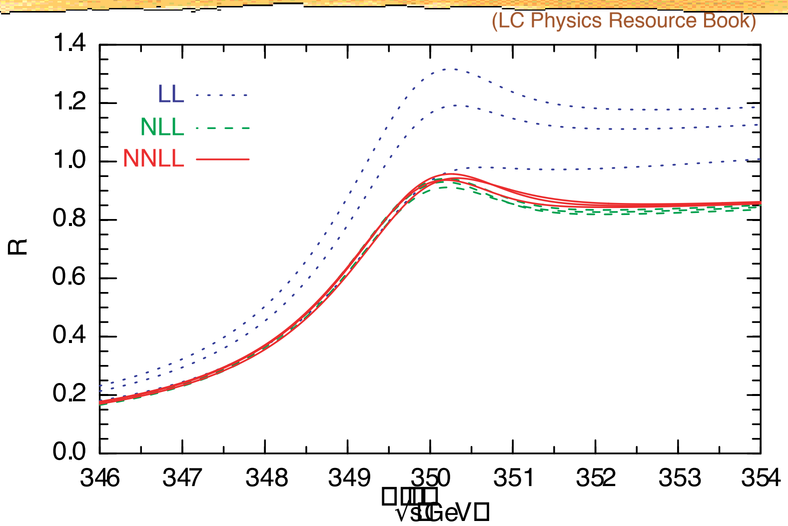
tt threshold: M_t

- Kinematic reconstruction
  - Hadronic machines systematics limited
    - M_t to ~ ±2-3 GeV
  - Measures ~ pole mass
- Pole mass ill-defined in QCD
  - Nonperturbative ambiguity of $\mathcal{O}(\Lambda_{QCD})$ in definition
  - Eg., poorly-behaved perturbation series for threshold cross-section
- Want short-distance mass, eg. $\overline{M}_t(M_t)$
  - EW constraints, ΔM_B, …

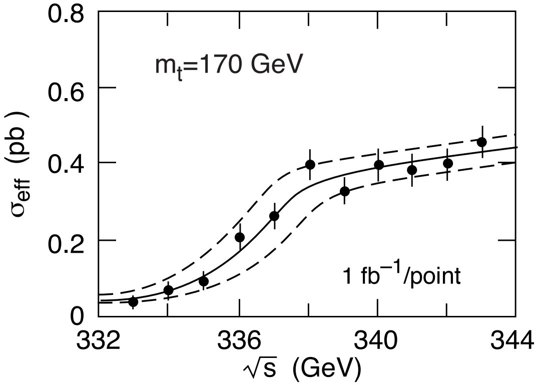


O. Yakovlev (LC Physics Resource Book)

tt threshold: M_t


(LC Physics Resource Book)

- Large Γ_t (~1.4 GeV) a boon
  - $\Gamma_t >> \Lambda_{QCD} \Rightarrow$ no narrow resonances, smooth line shape
  - Allows calc. in pert. QCD
    - infrared cutoff, smearing



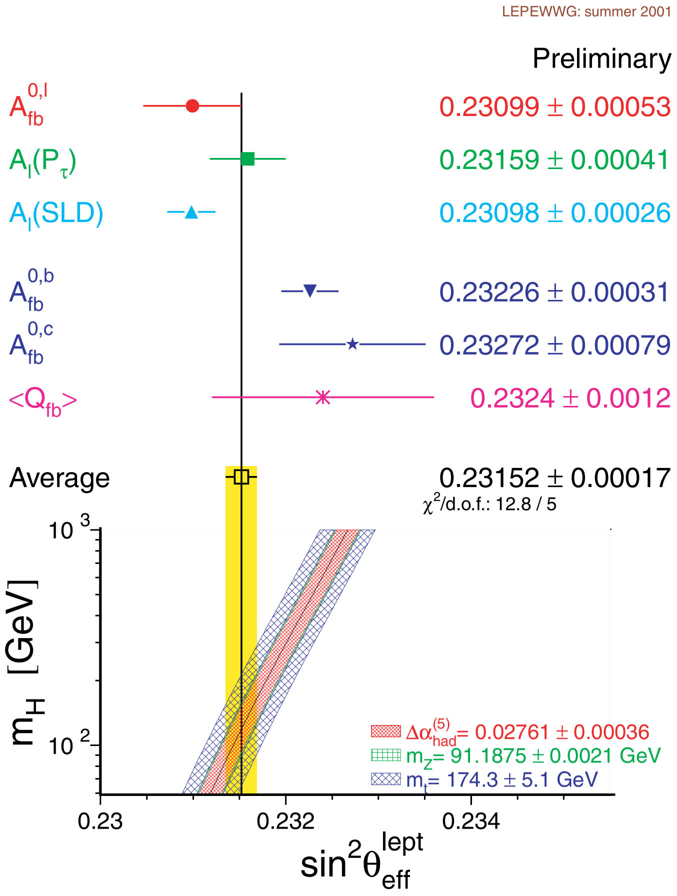
- A few short-distance mass def's near threshold
  - 1S peak position stable to ~200-300 MeV
  - Masses related to $\overline{MS}$ mass via pert. QCD series
- Modest luminosity required
  - 10 fb^{-1} → ±40 MeV stat. uncertainty

M_t to ±200 MeV

Other top measurements

- Threshold
  - Total top width
    - Peak $\sigma \sim 1/\Gamma_t$
    - 100 $fb^{-1} \rightarrow$ ~2% uncertainty
  - Yukawa coupling
    - 115 GeV Higgs → 5-8% increase in threshold σ
    - 2-3% uncertainty in predicted cross section
      - 14-20% on Yukawa coupling
    - Sensitivity drops for increasing Higgs mass
- High energy
  - Yukawa coupling
    - $e^+e^- \rightarrow tth \rightarrow W^+W^-bbbb$
    - 800 GeV (1000 fb^{-1}): ~5.5%
    - 500 GeV: ~4x worse
  - All neutral and charged current couplings
    - Measure/limit mostform factors at 1% level
      - 500 GeV, 100-200 fb^{-1}
    - ttZ couplings unique to LC
      - production polarization asymm.
  - Test QCD, EW radiative corr.
    - $\sigma(e^+e^- \rightarrow tt \rightarrow l\nu jjbb)$ to < 1%

$\sin^2\theta_W$ status



- At Z pole: dominated by
  - LEP b quark A^b_{FB}
  - SLD A_{LR}
  - A^b_{FB}: not in best agreement w/ SM
- Lower energy scales
  - Recent NUTEV result
    - "3σ high"
  - atomic parity violation
    - ~2 σ low

Giga-Z

- Revisit Z pole with a linear collider
  - Expect $\mathcal{L} \sim 5 \times 10^{33}$ cm^{-2}s^{-1}
  - 10^9 Z decays in ~ 10^7 s
    - Could contemplate interruption of high energy program
  - 10^{10} Z decays: 3-5 year program
    - Would need simultaneous low energy/high energy running
    - Mainly heavy flavor program benefits
  - Polarization
    - 80% electron polarization a given
    - positron polarization an enormous boon: achievable?
      - 60% polarization desirable

Z pole scan

- Measured
  - M_Z
  - Γ_Z
  - $\sigma_0 \propto \Gamma_{had}\Gamma_{ll} / \Gamma_Z^2$
  - $R_l = \Gamma_{had}/\Gamma_{ll}$

→

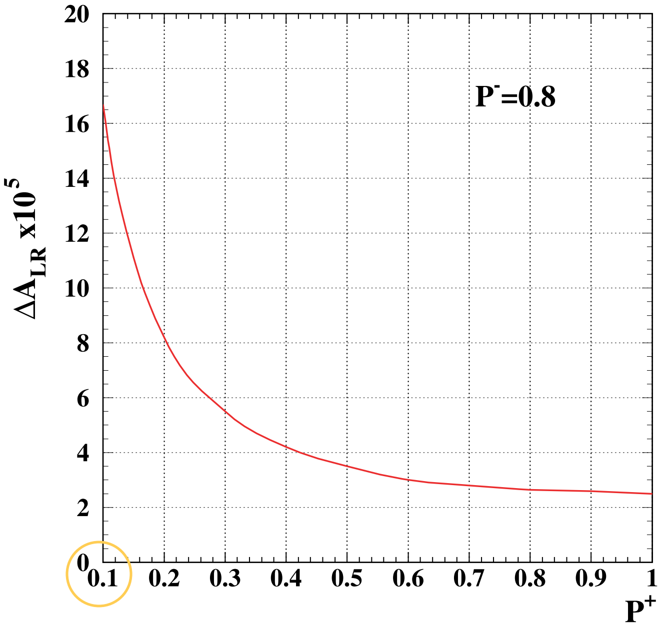
- Extracted
  - M_Z: ±2 MeV → LC E scale
  - $\alpha_S(M_Z^2)$: ±0.0027 → ±0.0009
  - ρ_l: ±0.001 → ±0.0005
  - N_ν: ±0.008 → ±0.0004
- Current measurements systematics limited
  - 2x improvement on eff. syst. (no th'y improvement for $\mathcal{L}$)
    - 4x R_l, 30% σ_0 improvements
  - $\delta E_{beam}/ E_{beam}$: potentially 10^{-5} w/ Moller spectrometer?
    - 2x Γ_Z improvement
  - Energy spread: beamstrahlung to $\mathcal{O}(2\%)$: further study needed
    - Γ_Z, ρ_l limited otherwise
    - monitor with Bhabha acolinearity? 5 point scan?

$A_{LR} \rightarrow \sin^2\theta_W$

- A_{LR} the most sensitive variable to $\sin^2\theta_W$

$$A_{LR} = \frac{1}{P_-}\frac{N_L - N_R}{N_L + N_R} = A_e = 2\frac{1-4\sin^2\theta_W^{eff}}{1+\left(1-4\sin^2\theta_W^{eff}\right)^2}$$

  - GigaZ = 2000x SLD
    - SLD: A_{LR}=0.1514±0.0022
- e^+ polarization:
  - None: $\delta P_-/P_-$ dominates uncertainty: 0.25% (optimistically) feasible
    - ΔA_{LR} to 4×10^{-4}
  - With: use Blondel scheme (combine N_{LL},N_{RR},N_{LR},N_{RL})
    - 60% $P_+ \leftrightarrow$ effective 95% polarization, don't need absolute polarization
    - $\Rightarrow \Delta A_{LR}$ to 10^{-4}



$A_{LR} \rightarrow \sin^2\theta_W$: experimental issues

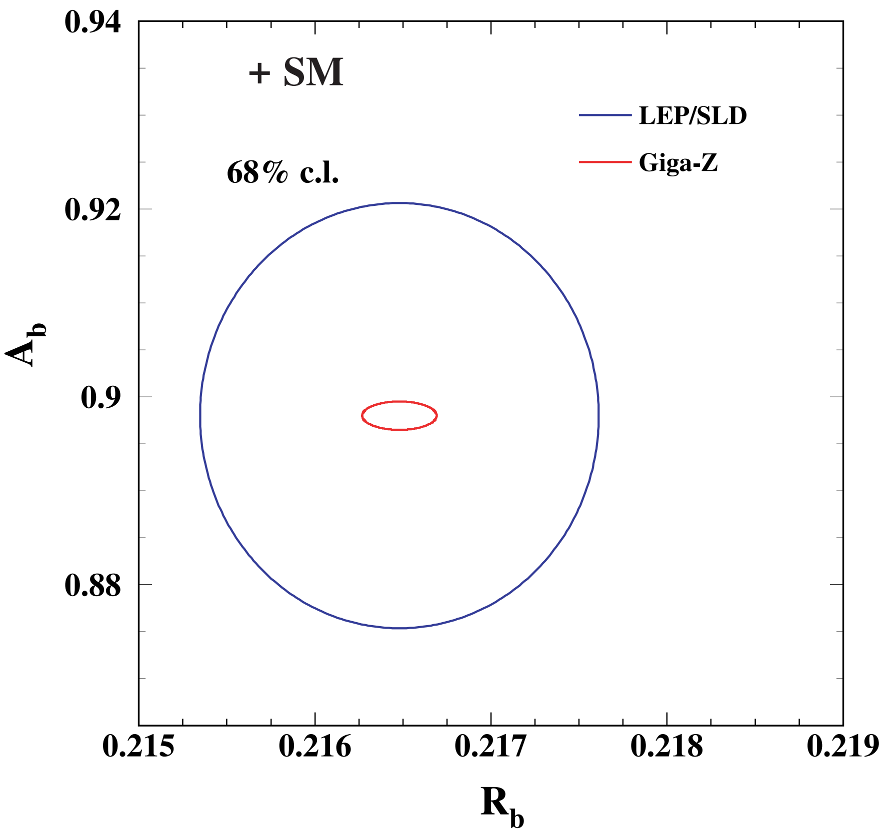
- polarization
  - Blondel scheme: need *relative* L,R polarizations to 10^{-4}
    - Appears feasible
  - Systematics: polarimeters after IP?
    - Difficult w/o crossing angle
  - Can positron helicity be switched rapidly enough relative to beam stability?
    - What is the relevant time scale?

$A_{LR} \rightarrow \sin^2\theta_W$: experimental issues

- Z-γ interference: A_{LR} changes rapidly away from pole
  - Control $\delta E/E$ to 10^{-5}
  - Control of beamstrahlung (effective $\sqrt{s}$ shift)
    - Ignore: A_{LR} shift of 9×10^{-4} at TESLA, much worse at NLC
    - E scale from Z pole scan + LEP M_Z. Same beam parameters?
    - Trade $\mathcal{L}$ for reduced beamstrahlung
      - NLC:125→18 MeV E shift for factor 5 $\mathcal{L}$ penalty
- If beam issues controlled:

$\sin^2\theta_W$ to ±0.000013

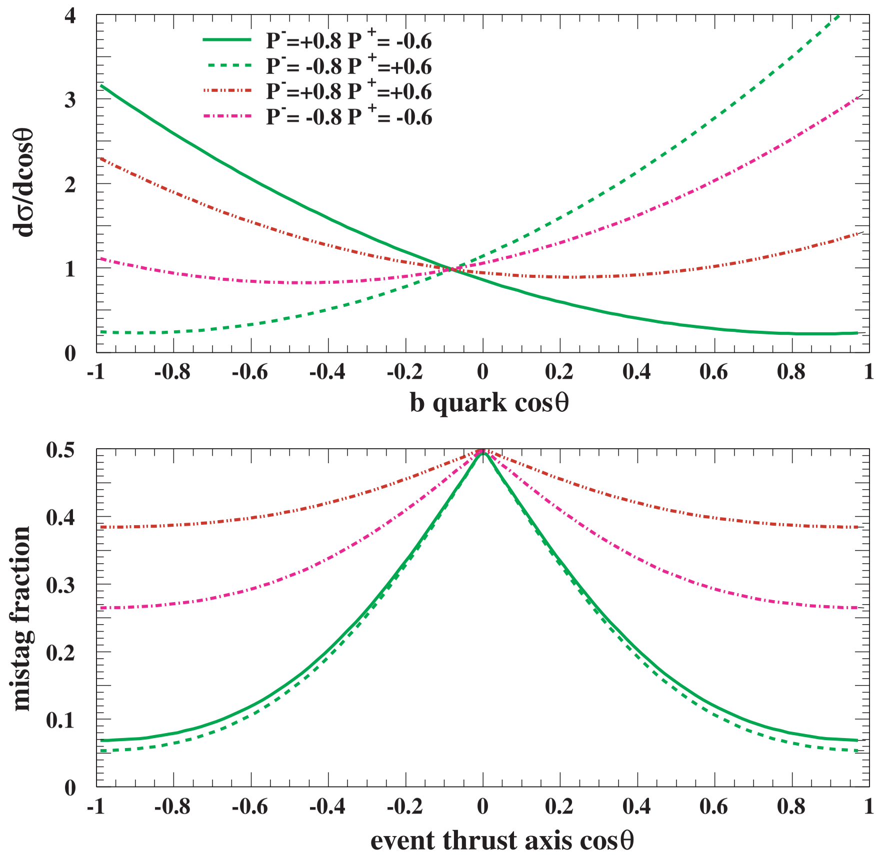
Zbb vertex



- A_b: 2.5–3.5 σ discrepancy w/ SM persists
  - Stat's dominated measurement
- Complementary sensitivity to "new physics" than S,T,U
- $R_b = \Gamma_{bb} / \Gamma_{had}$
  - Measure corrections to Zbb vtx
    - EW prop., QCD corr. cancel
  - 5x improvement from b-tagging
- $A_b (=3/4\ A_{FB,LR})$
  - $P^+ = 60\%$: 15x improvement
  - $P^+ = 0$: 6x improvement

b physics at Giga-Z?

- Great potential
  - Production flavor tagging
    - εD^2~0.6 vs 0.1-0.25
    - D=1-2P(mistag)
  - Large boost
    - b's well-separated
    - Excellent b tagging
  - Well-defined initial state:
    - "ν-reconstruction"
- Stiff competition
  - Mainly cross checks others on "standards"
    - CKM unitarity angles
    - Δm_s



Some unique b physics

- $B_s \rightarrow Xl\nu$ rate
  - Constrain uncontrolled uncertainty in OPE from quark-hadron duality violations
- Polarized Λ_b decays (G. Hiller)
  - Probe $b_R \rightarrow q_L\gamma$ (SM) vs $b_L \rightarrow q_R\gamma$ (new physics)
    - 10^9 Z's gives interesting reach in $\theta(\mathrm{spin}, p_\gamma)$ asymmetry
- $B \rightarrow X_s\nu\nu$
  - Emiss constraints + well-separated b decays allow access
  - Non-SM physics affects $X_s\nu\nu$, $X_s l^+ l^-$ differently
  - reach? $B \rightarrow \tau\nu$ bkg?
- Production flavor tagged $B \rightarrow \pi^0\pi^0$

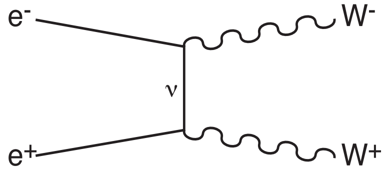
W^+W^- threshold: M_W

- Potential indirect precision: $\delta M_W \sim \pm 4$ MeV
  - Tevatron/LHC: expect 15-20 MeV precision (syst. limited)
- EW constraints: can LC approach indirect precision?
  - E_{beam}, beamstrahlung appear to be most serious issues
    - high energies: direct reconstruction needs E_{beam} constraint
      - E scale likely to be pinned via M_Z
      - Beamstrahlung scales as $(E_{beam})^2$

        ⇒ explore threshold region
  - Threshold needs:
    - E_{beam} to 10^{-5}: potentially $e^+e^- \to \gamma Z$, $Z \to \mu\mu, ee$?
      - Stat's for √s vs time?
    - Beamstrahlung: control shape distortion to 0.12%↔±2 MeV
      - Bhabha acolinearity?
    - Theory: cross section shape to 0.12%

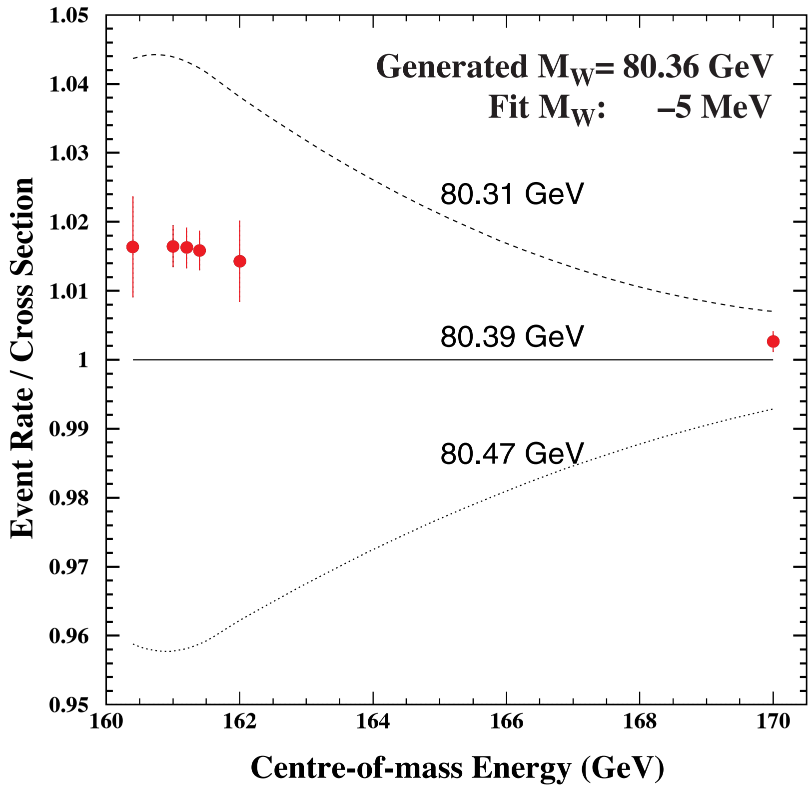
W^+W^- threshold: M_W

- 100 fb^{-1} → ±5 MeV (stat)
  - 60% e^+ polarization
  - ~10^7 sec
- Strategy: t-channel dominates



  - 75% $e^+_R e^-_L$
  - 15% $e^+_L e^-_R$ (~ no W^+W^-)
  - 10% other
- Polarization
  - 0.25% absolute or $e^+e^- \rightarrow \gamma Z$ + Blondel scheme
  - P_+=0: doubles $\mathcal{L}$ required

G. Wilson



M_W to ±7 MeV

EW reach summary

(U. Baer *et al*, hep-ph/0111314)

	now	Tev. Run IIA	Run IIB	Run IIB*	LHC	LC	GigaZ
$\delta \sin^2\theta_{\rm eff}\,(\times 10^5)$	17	78	29	20	14–20	(6)	1.3
δM_W [MeV]	33	27	16	12	15	10	7
δm_t [GeV]	5.1	2.7	1.4	1.3	1.0	0.2	0.13
δM_H [MeV]	—	—	$\mathcal{O}(2000)$		100	50	50

Run IIB: 15 fb^{-1}

Run IIB*: 30 fb^{-1}

LC improvement in $\sin^2\theta_{eff}$:

dedicated fixed target Moller scattering exp.

GigaZ improvement in M_t:

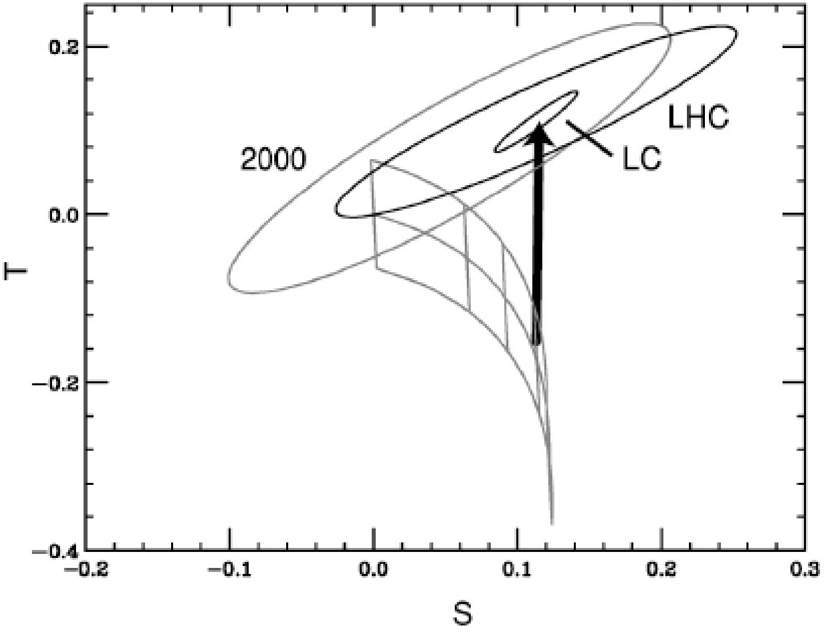
from improved α_s (Z pole scan)

$\delta M_H/M_H$ *from:*	M_W	$\sin^2\theta_{\rm eff}$	all
now	106 %	60 %	58 %
Tevatron Run IIA	72 %	39 %	35 %
Tevatron Run IIB	37 %	33 %	25 %
Tevatron Run IIB*	30 %	29 %	23 %
LHC	22 %	25 %	18 %
LC	15 %	24 %	14 %
GigaZ	12 %	8 %	8 %

Constraint potential: S,T,U

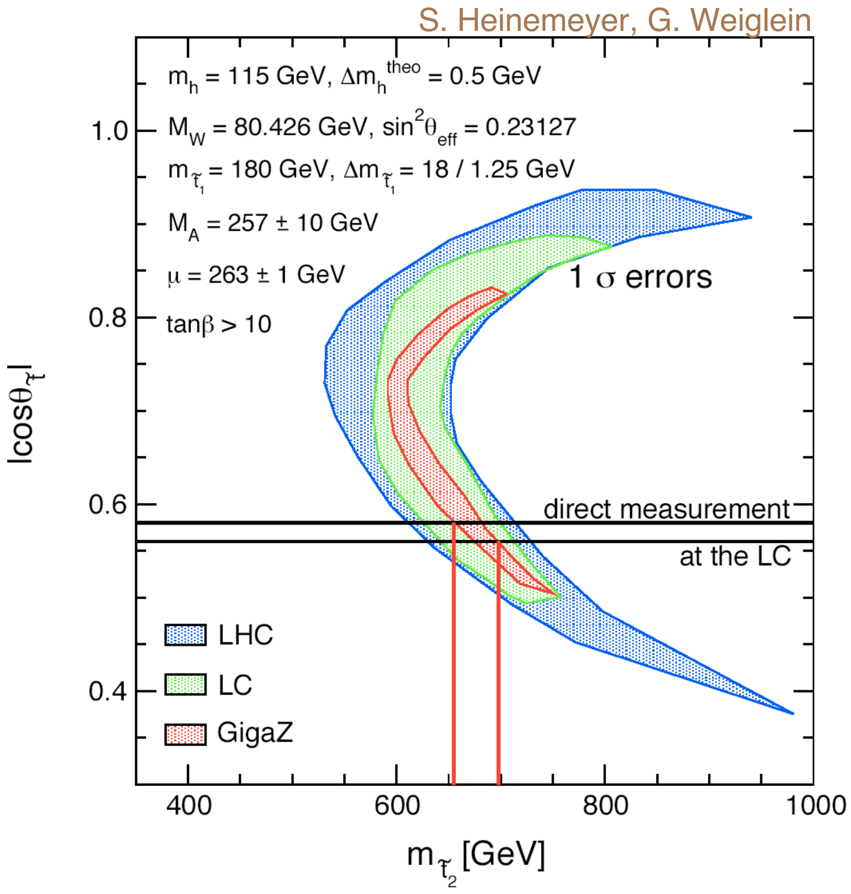
- S,T,U
  - Parameterize effect of new physics on W, Z vacuum pol.
  - EW variables linear fcn's of STU
- Sensitivity (now→LC/GigaZ)
  - S: ±0.11 → ±0.05 (±0.02 w/ U=0)
  - T: ±0.14 → ±0.06 (±0.02 w/ U=0)
  - U: ±0.15 → ±0.04
- Peskin,Wells (PRD 64, 093003)
  - Survey models w/ heavy Higgs:
    - Significant dev's in S,T from SM observable w/ GigaZ

M. Peskin, J. Wells



- eg. technicolor
  - S, T > ~0.1
  - 5σ deviation from SM

Constraint potential: SUSY



- MSSM Higgs, light scalar top seen at Tevatron/LHC/LC
  - $e^+e^- \to \tilde{t}_1\tilde{t}_1^*$ at LC yields
    - $\tilde{t}_1$ mass, stop-sector mixing to 1%
- Various MSSM constraints
  - $\sin^2\theta_W$ vs M_W predicted vs. measured
  - M_h predicted vs measured
  - Constraint on mass of heavy scalar top

Conclusion

- Low energy program adds great value to the overall LC and general HEP program
  - Powerful constraints provide
    - Self-consistency checks for interpretation of new particles
    - Extension of effective mass reach
  - Unique flavor physics contributions a bonus
- Beam energy and polarization issues need further study
  - Solutions will involve monitoring instrumentation that must be allowed for in baseline designs