# Detector and Accelerator Requirements from EW Precision Observables

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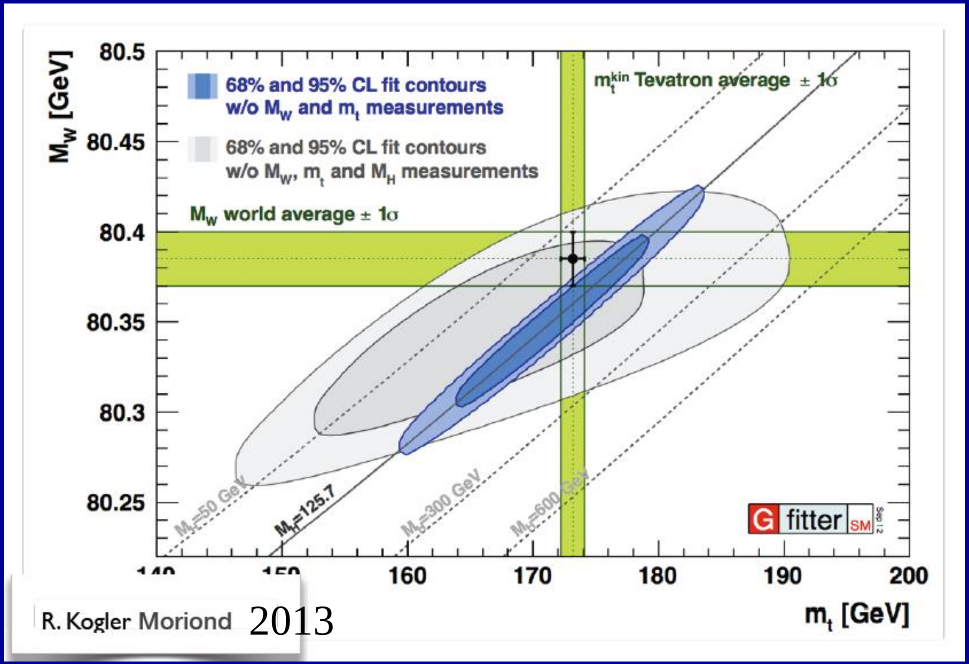
# Precision Measurements

Testing Nature at ILC.
Can measure mW, mt, mH, ALR. mZ? with unprecedented precision.




Experimental reach depends on ability to control systematics such as those associated with the beam energy measurement and detector energy scales.

See eg.arXiv:1307.3962

To get the most out of ILC in terms of precision, need to push on higher statistics + higher resolution (statistical errors) but also controlling systematics.
What use is precision, if we don’t understand measurement errors, and our detector is not accurate!

# Accelerator Requirements

- Much of the EWPO physics scope is predicated on understanding the absolute collision energy, luminosity spectrum, etc.
  - In practice at ILC these need to be determined by the detector.
- Physics running with high luminosity near 91 GeV is needed for improving on LEP1/SLC observables.
  - ALR only makes sense with polarized electrons and POSITRONs.
  - High statistics will need excellent control of beam systematics
- Physics running with high luminosity near WW threshold (161 GeV) with polarized beams is best for mW.
  - Higher energies may also play a role.
  - Likely need lots of Z's (almost certainly GigaZ) to take full advantage.

# Statistics

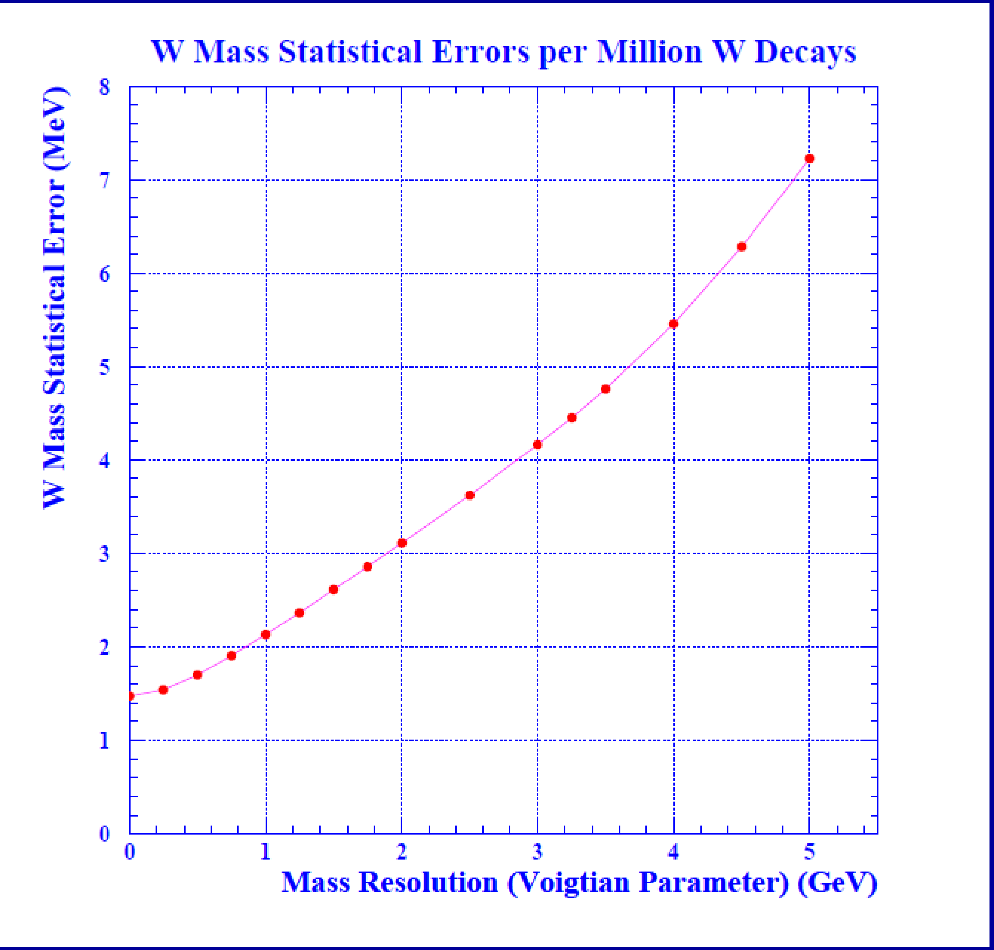
ILC will produce 10-100M W's

Polarization very helpful.

For statistical errors, W width leads to following error per million reconstructed W decays

Can envisage mass resolution in the 1-2 GeV range.

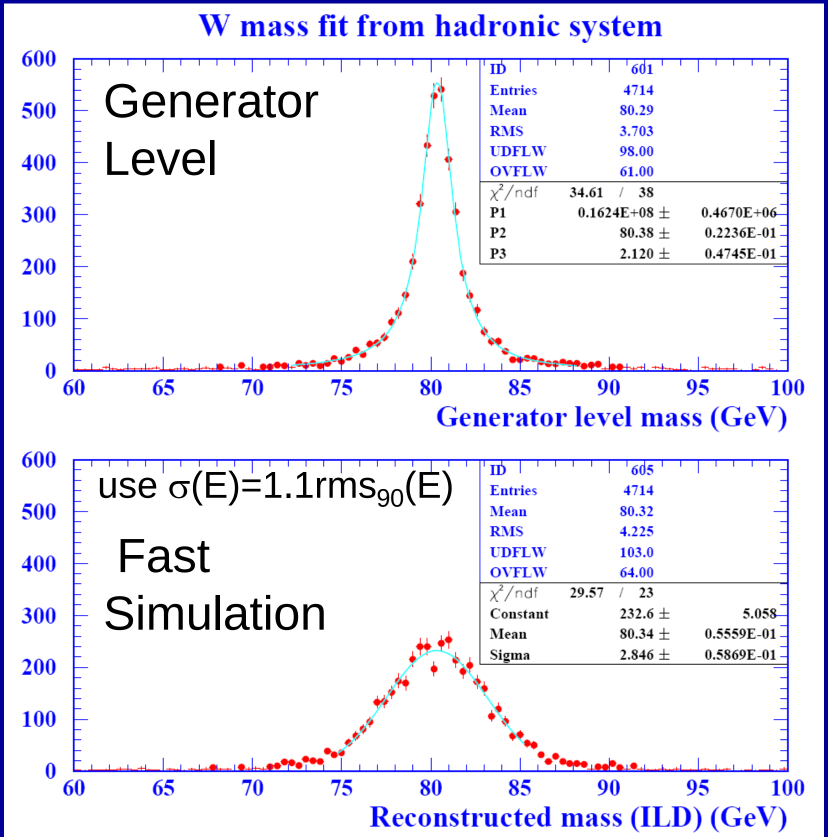
Statistics for below 1 MeV error.

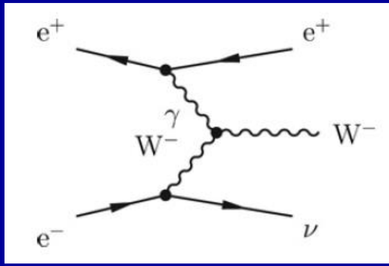


# Can one dream of measuring $m_W$ to 1 MeV ?

(and not get locked up ;-) )

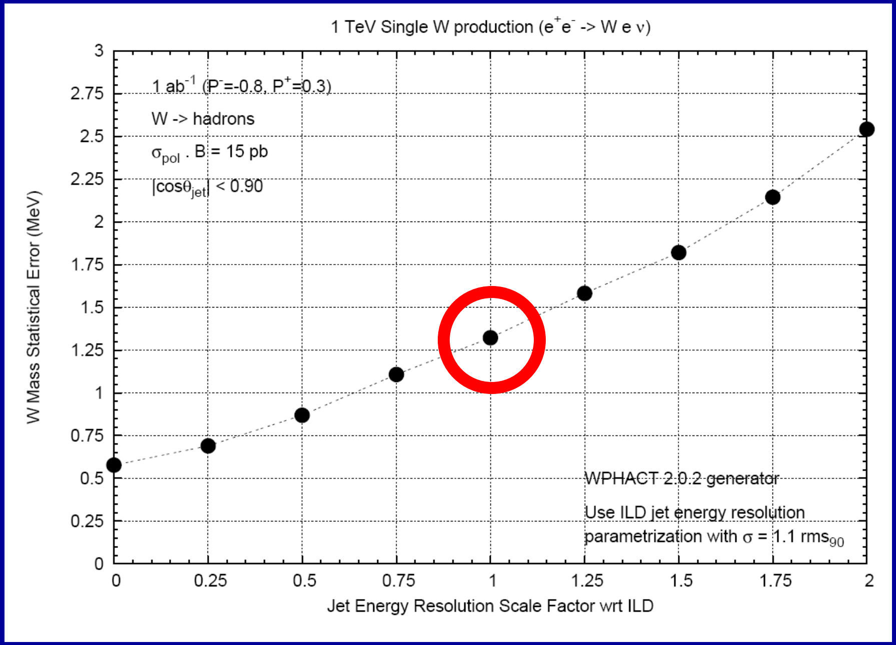
Single W study at √s = 1TeV (e+e-)




W → q q
(jets are not so energetic)

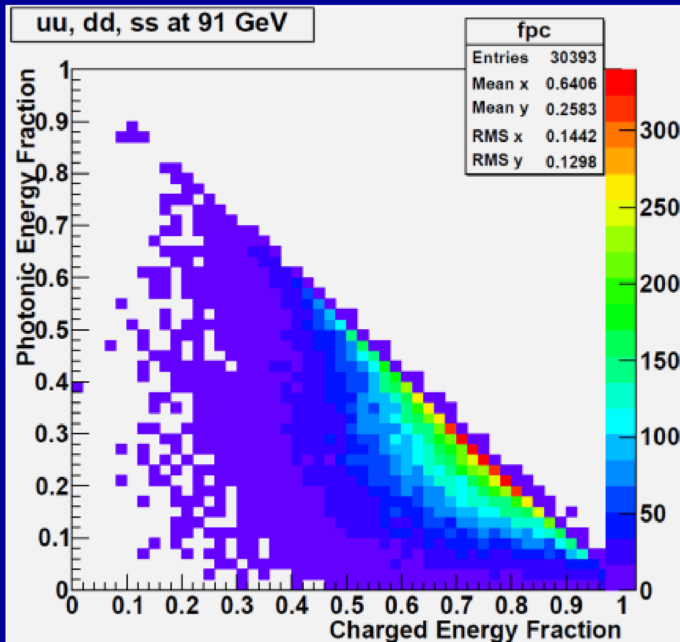
Is this useful for physics? Example $m_W$.

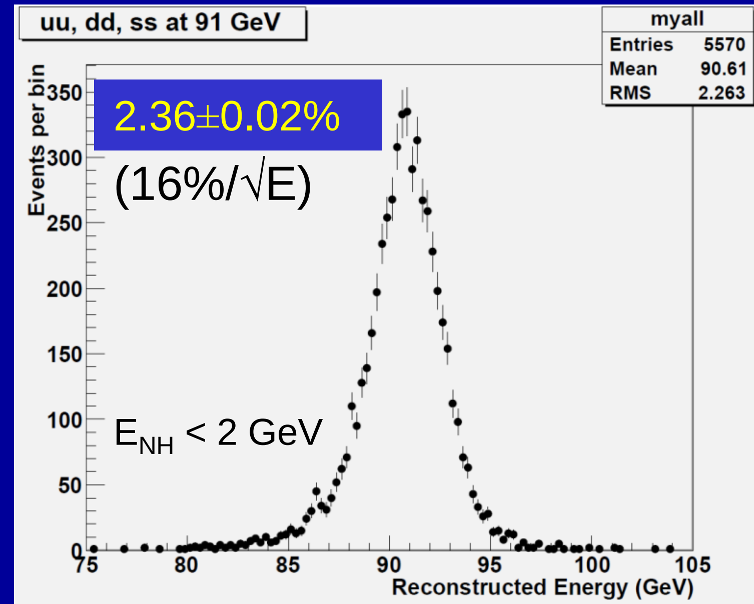


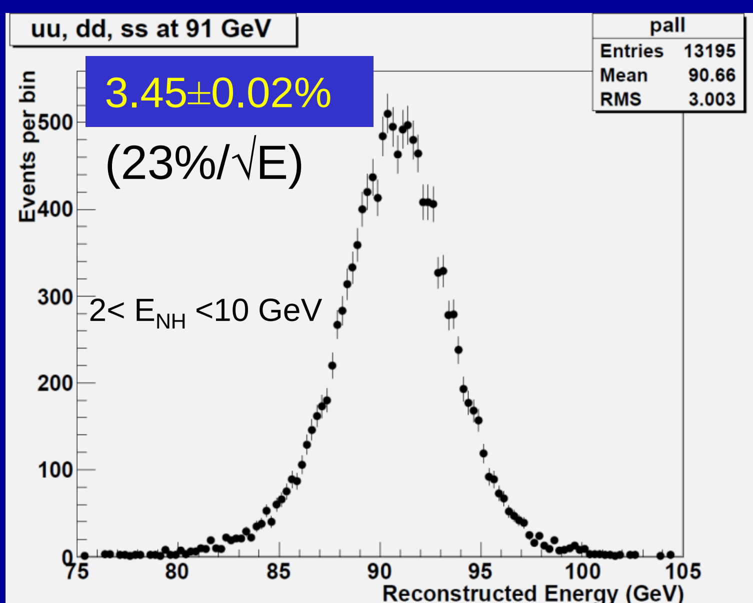

=> Further $E_{jet}$ resolution improvement very desirable

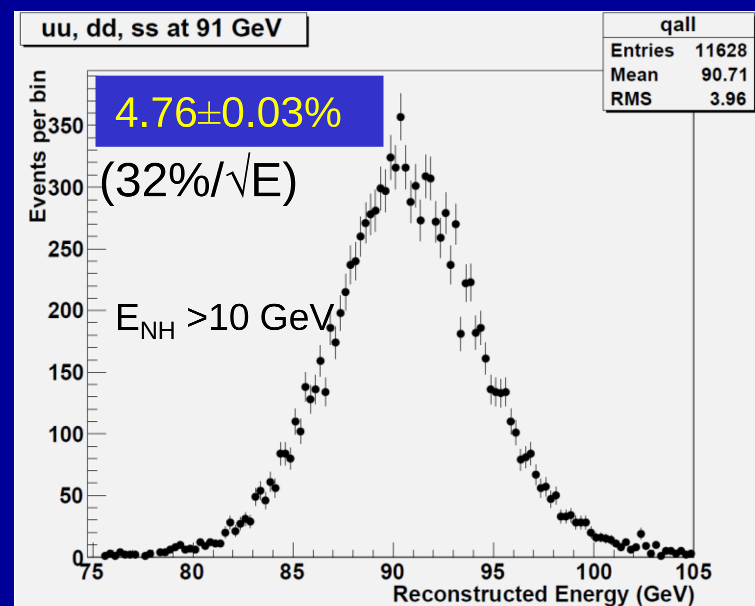
Potentially very useful! (Especially, if the really challenging requirements on jet energy scale and calibration can be met!)

# Event-Specific Resolution

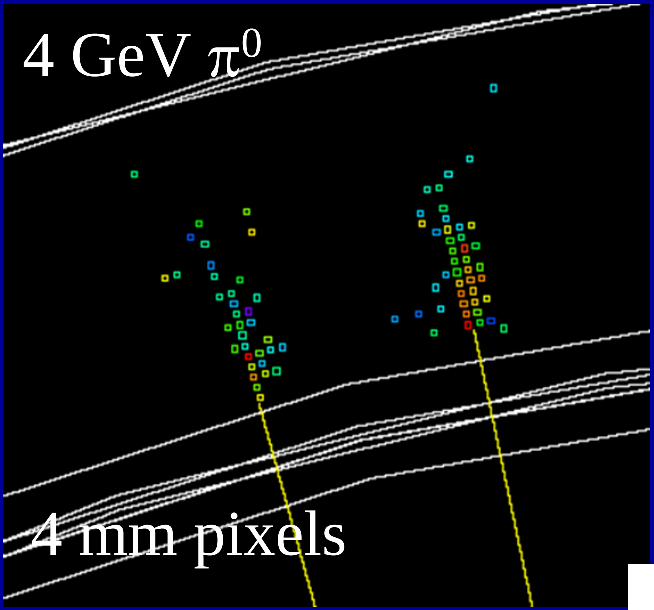


# Pi0 Fitting




GWW and Brian van Doren

$$\pi^0 \to \gamma_1 \gamma_2 \; (98.8\%)$$

$$m^2 = 2E_1 E_2 (1 - \cos\psi_{12})$$

We know m=134.9766 ± 0.0006 MeV

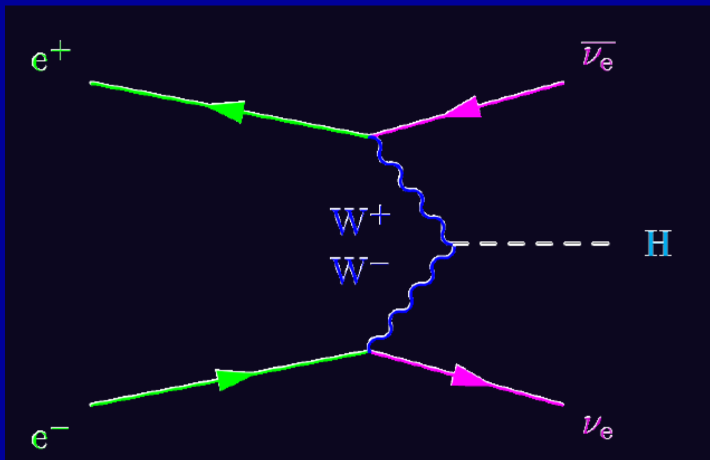
$$\chi^2(\mathbf{x}) = f(\mathbf{x}) = (\mathbf{x} - \mathbf{x}_M)^T \, \mathbf{V}_M{}^{-1} \, (\mathbf{x} - \mathbf{x}_M)$$

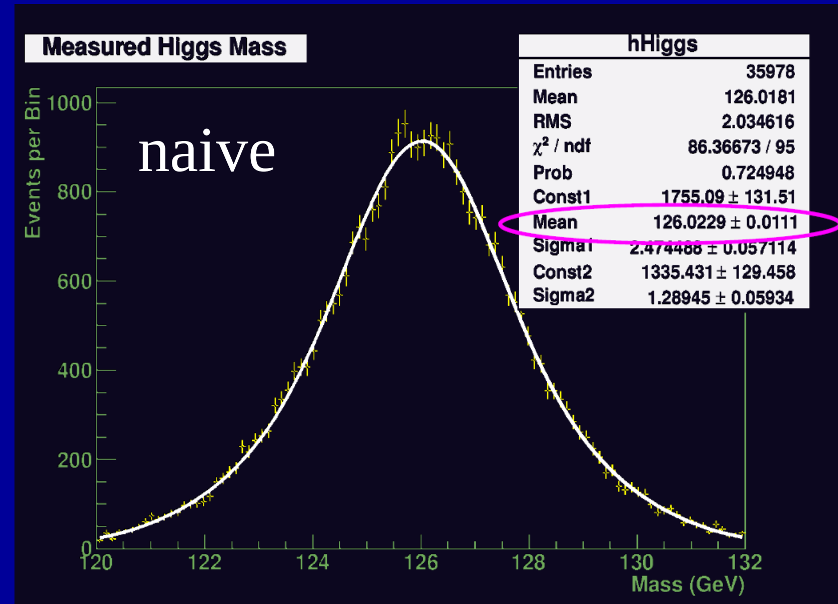
We can fit, minimizing the $\chi^2$ between the measurement vector ($\mathbf{x}_M$) and the fit vector ($\mathbf{x}$) subject to the mass constraint.

| Variable | Measured | 3-variable fit | 6-variable fit | Pull |
|---|---|---|---|---|
| $E_1$ | $2.468 \pm 0.253$ | $2.385 \pm 0.192$ | $2.385 \pm 0.192$ | -0.504 |
| $E_2$ | $1.679 \pm 0.196$ | $1.605 \pm 0.130$ | $1.605 \pm 0.130$ | -0.504 |
| $2(1-\cos\psi_{12})$ | $(4.765 \pm 0.0985) \times 10^{-3}$ | $(4.759 \pm 0.0977) \times 10^{-3}$ | | -0.504 |
| $\theta_1$ (mrad) | $1608.36 \pm 0.50$ | | $1608.37 \pm 0.50$ | 0.504 |
| $\theta_2$ (mrad) | $1619.11 \pm 0.50$ | | $1619.10 \pm 0.50$ | -0.504 |
| $\phi_1$ (mrad) | $2196.86 \pm 0.50$ | | $2196.84 \pm 0.50$ | -0.504 |
| $\phi_2$ (mrad) | $2128.60 \pm 0.50$ | | $2128.62 \pm 0.50$ | 0.504 |
| $m_{\pi^0}$ (MeV) | 140.5 | | | |
| $\rho_{E_1E_2}$ | | -0.9683 | -0.9683 | |
| $E_{\pi^0}$ | $4.147 \pm 0.320$ | $3.990 \pm 0.074$ | $3.990 \pm 0.074$ | |
| $\chi^2/\nu$ | | 0.2543/1 | | |
| $p_{\text{fit}}$ (%) | | 61.4 | | |

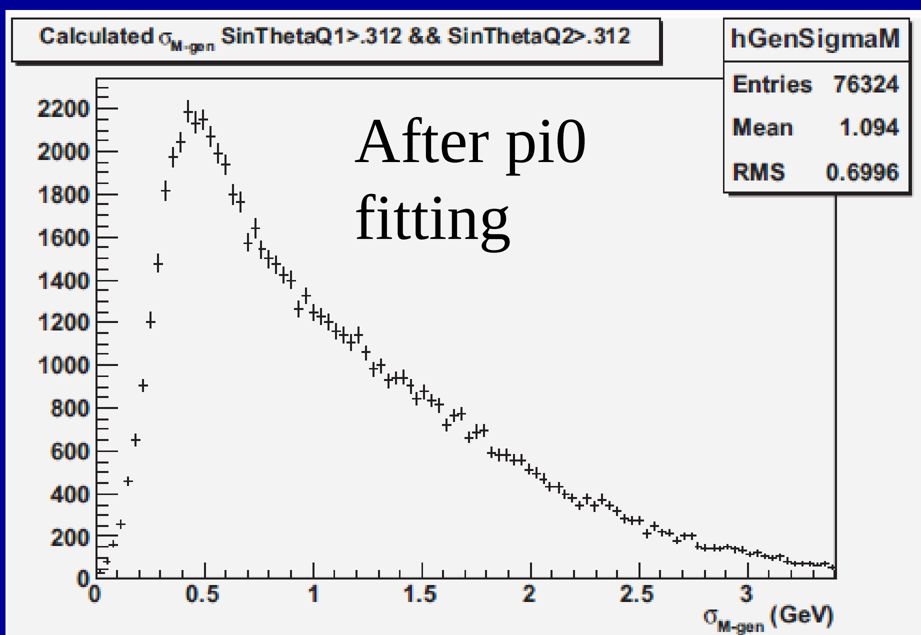
Can greatly improve E measurement error

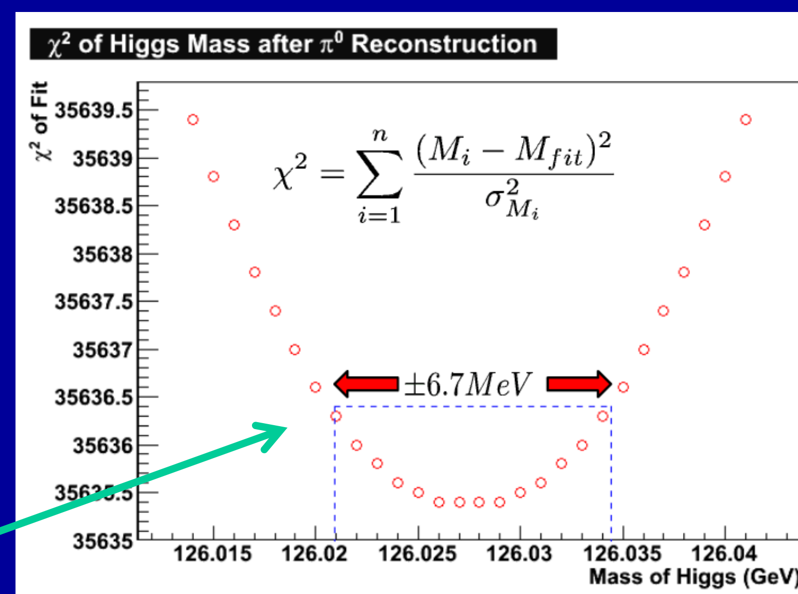
# Applying to Physics ( H → hadrons)




NH E-scale remark

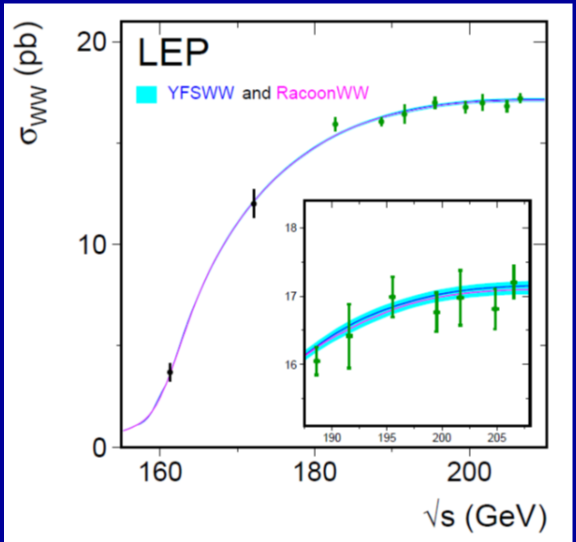


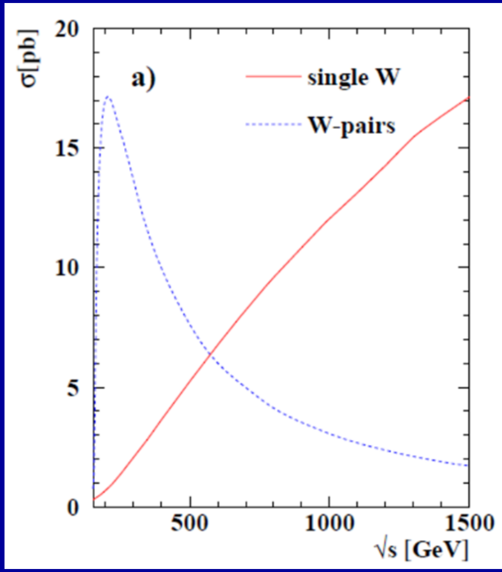




Using event-to-event error knowledge

# ILC W Mass Measurement Strategies

- $W^+W^-$
  - 1. Threshold Scan ( $\sigma \sim \beta/s$ )
    - Can use all WW decay modes
  - 2. Kinematic Reconstruction (qq e nu and qq mu nu)
    - Apply kinematic constraints
- W e ν (+ WW) - same issues as ννH discussed above
  - 3. Directly measure the hadronic mass in $W \rightarrow q\, q'$ decays.
    - Can use WW -> q q tau nu too

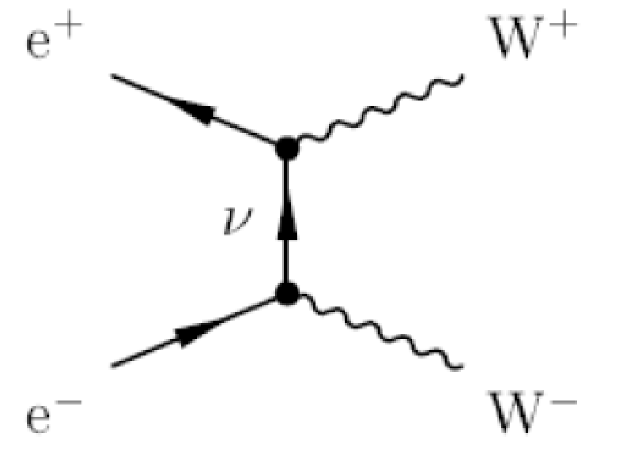



Methods 1 and 2 were used at LEP2. Both require good knowledge of the absolute beam energy.

Method 3 is novel (and challenging), very complementary systematics to 1 and 2 if the experimental challenges can be met.

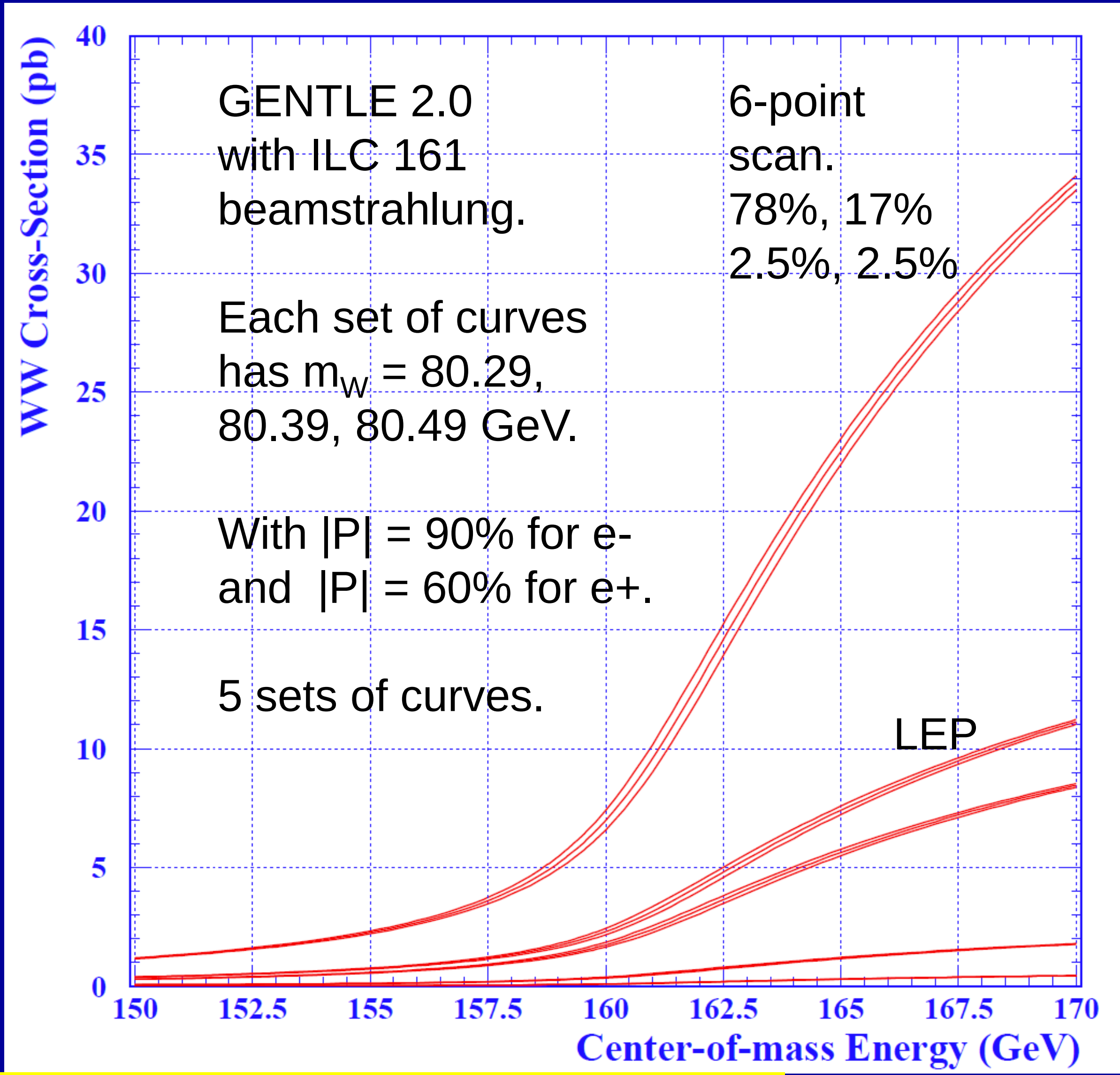
# Polarized Threshold Scan (GWW)




Use (-+) helicity combination of e- and e+ to enhance WW.

Use (+-) helicity to suppress WW and measure background.

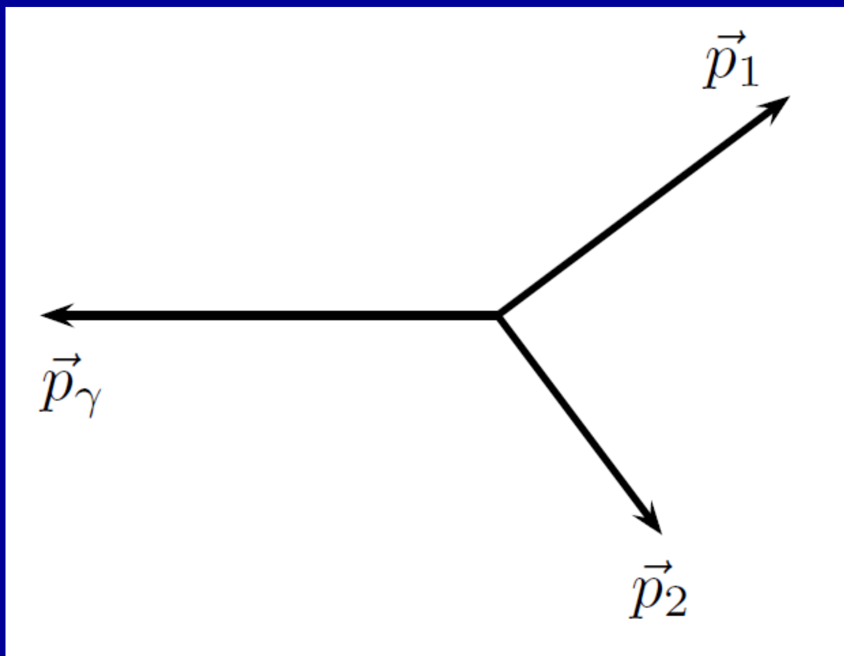
Use (--) and (++) to control polarization (also use 150 pb qq events)

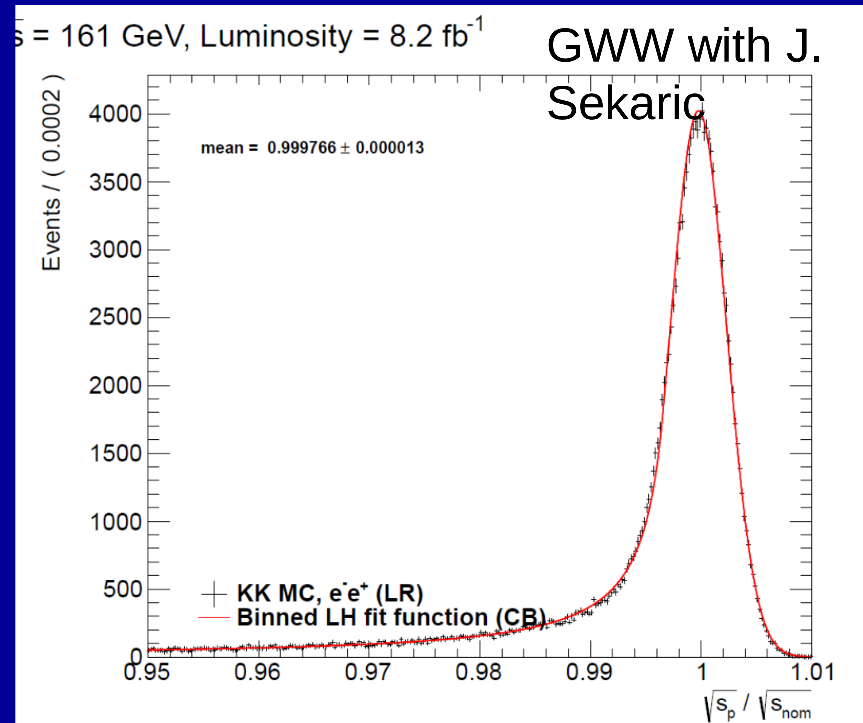



Experimentally very robust. Fit for eff, pol, bkg, lumi

# “New” In-Situ Beam Energy Method

$e^+e^- \rightarrow \mu^+\mu^-(\gamma)$



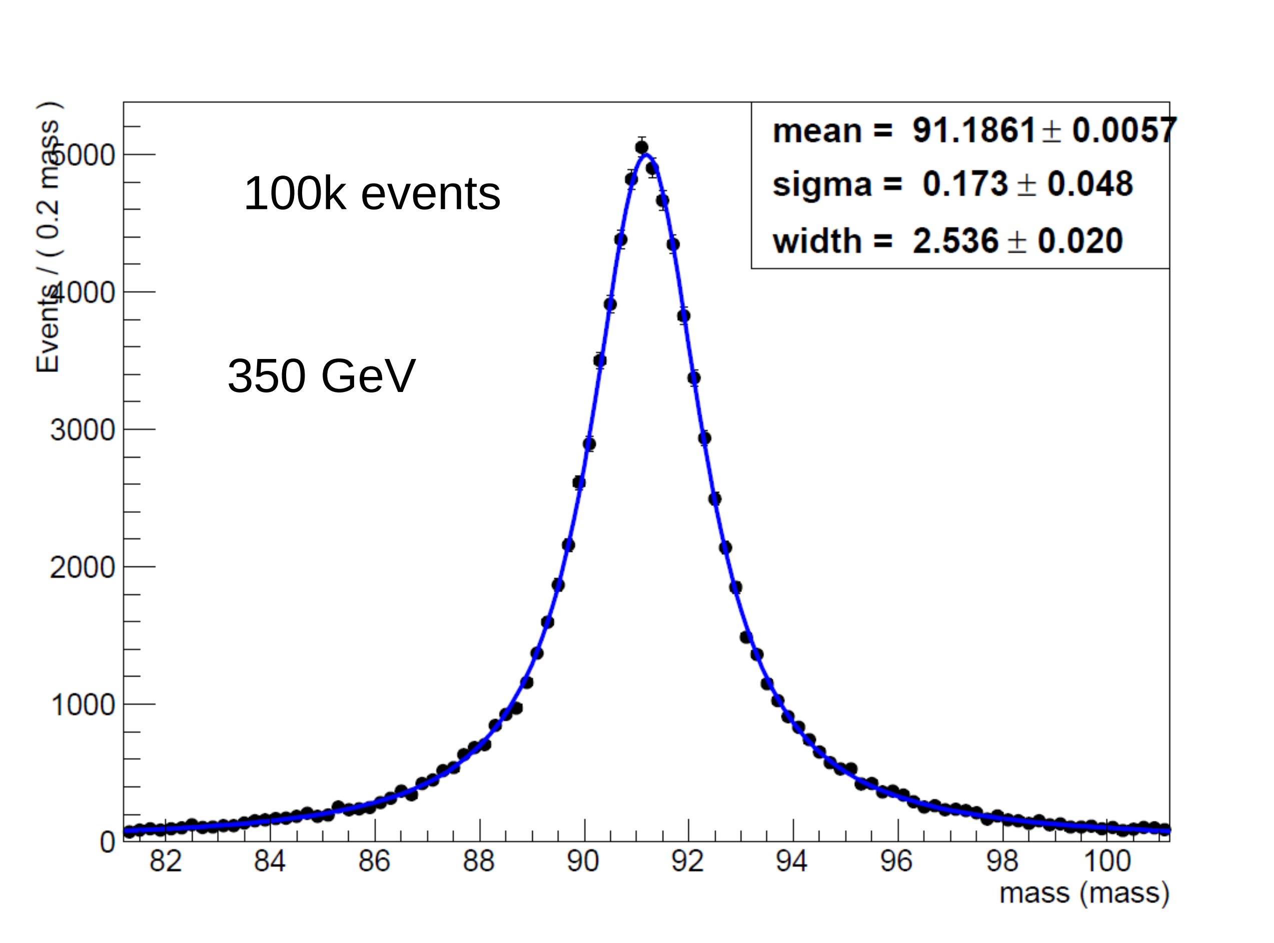




Use muon momenta. Measure $E_1 + E_2 + |\mathbf{p}_{12}|$ as an estimator of $\sqrt{s}$

ILC detector momentum resolution (0.15%), gives beam energy to better than 5 ppm statistical. Momentum scale to 10 ppm => 0.8 MeV beam energy error projected on mW. (J/psi)

**Beam Energy Uncertainty should be controlled for $\sqrt{s}$ <= 500 GeV**

# Can control momentum scale using measured di-lepton mass




This is about 100 $fb^{-1}$ at ECM=350 GeV.

Statistical sensitivity if one turns this into a Z mass measurement (if p-scale is determined by other means) is

1.8 MeV / √N

With N in millions.

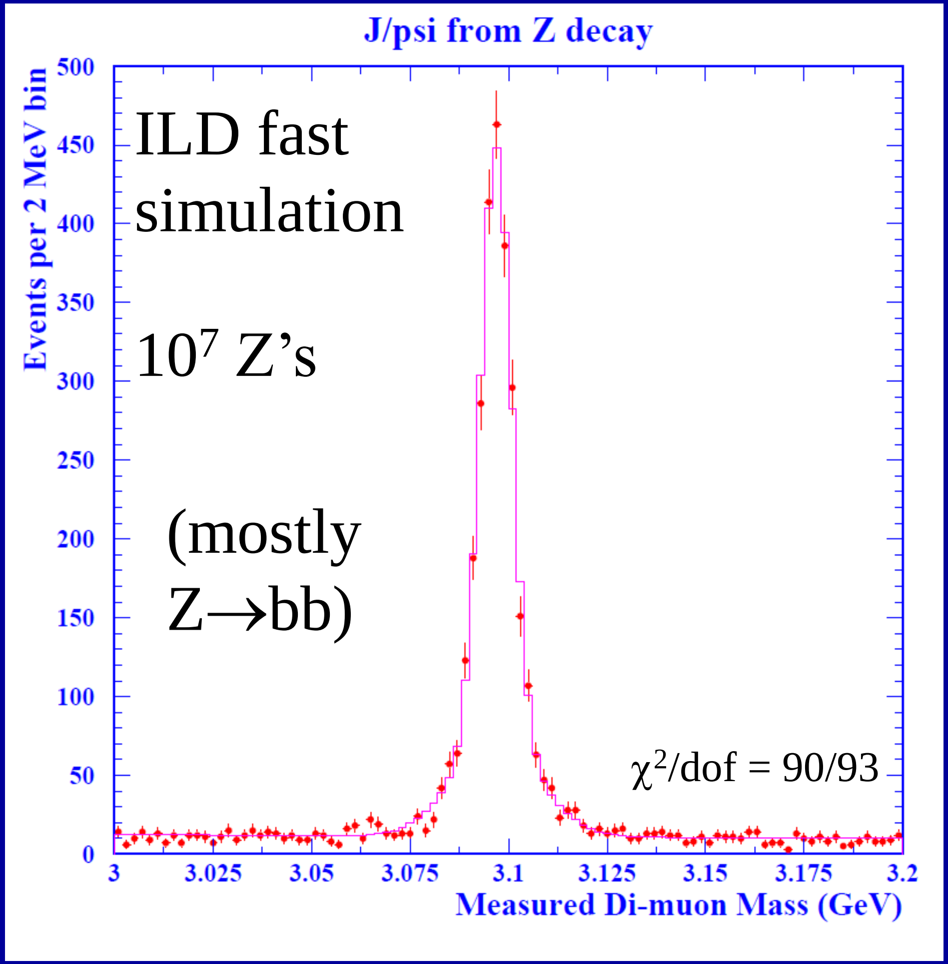
Alignment ?
B-field ?
Push-pull ?
Etc …
Note Z mass only known to 23 ppm

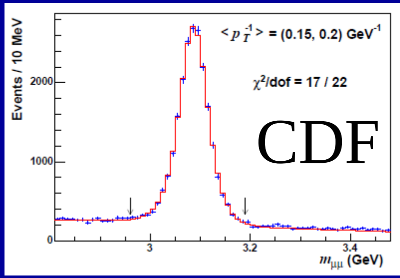
# Momentum Scale with J/psi

With $10^9$ hadronic Z's expect statistical error on mass scale of < 3.4 ppm given ILD momentum resolution.

Most of the J/psi's are from B decays.

J/psi mass is known to 3.6 ppm. Can envisage also improving on the measurement of the Z mass (23 ppm error)




Double-Gaussian + Linear Fit

# W Mass Measurements

GWW

1. Polarized Threshold Scan
2. Kinematic Reconstruction
3. Hadronic Mass

Method 1: Statistics limited.

Method 2: With up to 1000 the LEP statistics and much better detectors. Can target factor of 10 reduction in systematics.

Method 3: Depends on di-jet mass scale. Plenty Z's for 3 MeV.

1

| $\Delta M_W$ [MeV] | LEP2 | ILC | ILC |
|---|---|---|---|
| $\sqrt{s}$ [GeV] | 161 | 161 | 161 |
| $\mathcal{L}$ [fb$^{-1}$] | 0.040 | 100 | 480 |
| $P(e^-)$ [%] | 0 | 90 | 90 |
| $P(e^+)$ [%] | 0 | 60 | 60 |
| statistics | 200 | 2.4 | 1.1 |
| background | | 2.0 | 0.9 |
| efficiency | | 1.2 | 0.9 |
| luminosity | | 1.8 | 1.2 |
| polarization | | 0.9 | 0.4 |
| systematics | 70 | 3.0 | 1.6 |
| experimental total | 210 | 3.9 | 1.9 |
| beam energy | 13 | 0.8 | 0.8 |
| theory | - | (1.0) | (1.0) |
| total | 210 | 4.1 | 2.3 |

(2)

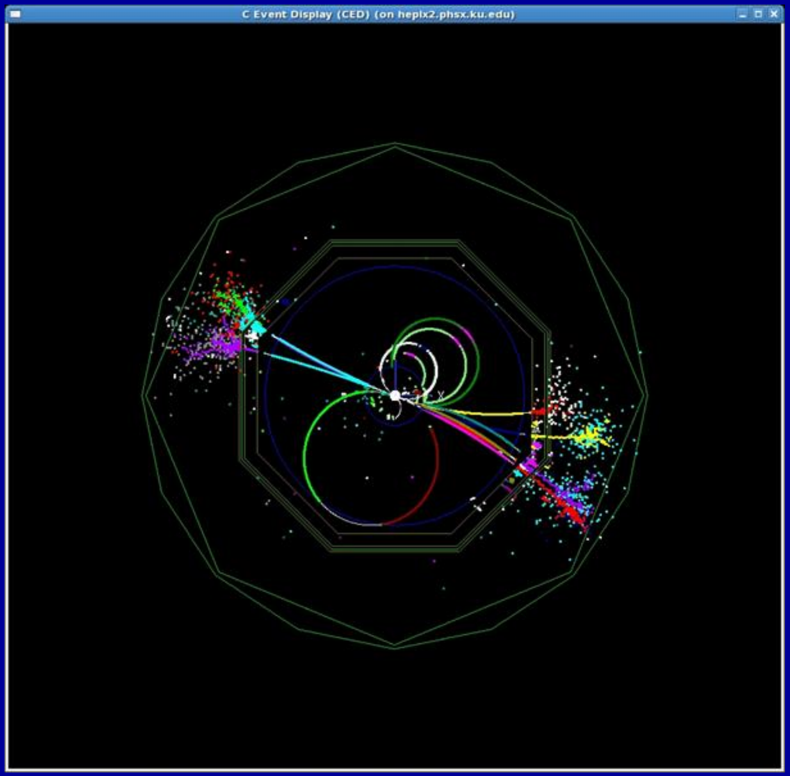
| $\Delta M_W$ [MeV] | LEP2 | ILC | ILC | ILC |
|---|---|---|---|---|
| $\sqrt{s}$ [GeV] | 172-209 | 250 | 350 | 500 |
| $\mathcal{L}$ [fb$^{-1}$] | 3.0 | 500 | 350 | 1000 |
| $P(e^-)$ [%] | 0 | 80 | 80 | 80 |
| $P(e^+)$ [%] | 0 | 30 | 30 | 30 |
| beam energy | 9 | 0.8 | 1.1 | 1.6 |
| luminosity spectrum | N/A | 1.0 | 1.4 | 2.0 |
| hadronization | 13 | 1.3 | 1.3 | 1.3 |
| radiative corrections | 8 | 1.2 | 1.5 | 1.8 |
| detector effects | 10 | 1.0 | 1.0 | 1.0 |
| other systematics | 3 | 0.3 | 0.3 | 0.3 |
| total systematics | 21 | 2.4 | 2.9 | 3.5 |
| statistical | 30 | 1.5 | 2.1 | 1.8 |
| total | 36 | 2.8 | 3.6 | 3.9 |

(3)

| $\Delta M_W$ [MeV] | ILC | ILC | ILC | ILC |
|---|---|---|---|---|
| $\sqrt{s}$ [GeV] | 250 | 350 | 500 | 1000 |
| $\mathcal{L}$ [fb$^{-1}$] | 500 | 350 | 1000 | 2000 |
| $P(e^-)$ [%] | 80 | 80 | 80 | 80 |
| $P(e^+)$ [%] | 30 | 30 | 30 | 30 |
| jet energy scale | 3.0 | 3.0 | 3.0 | 3.0 |
| hadronization | 1.5 | 1.5 | 1.5 | 1.5 |
| pileup | 0.5 | 0.7 | 1.0 | 2.0 |
| total systematics | 3.4 | 3.4 | 3.5 | 3.9 |
| statistical | 1.5 | 1.5 | 1.0 | 0.5 |
| total | 3.7 | 3.7 | 3.6 | 3.9 |

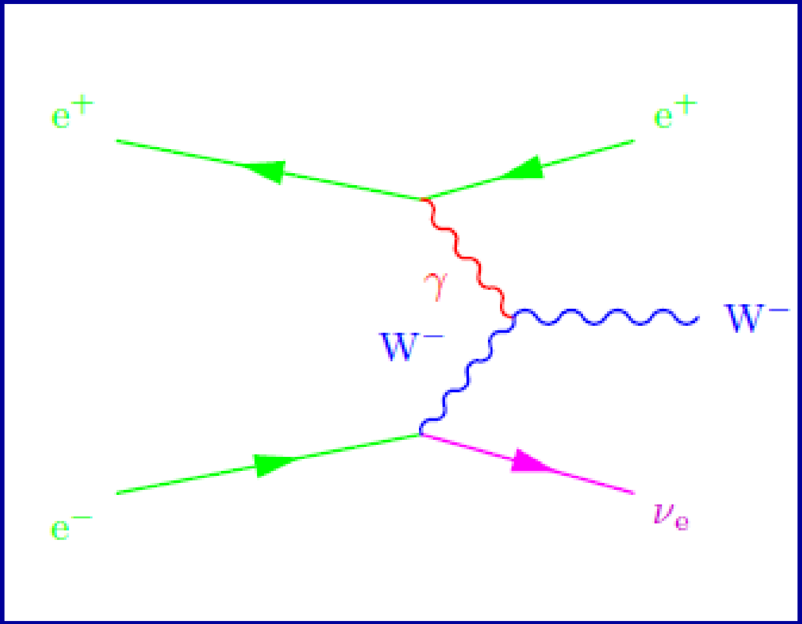
# Jet Energy Scale Particle-by-Particle

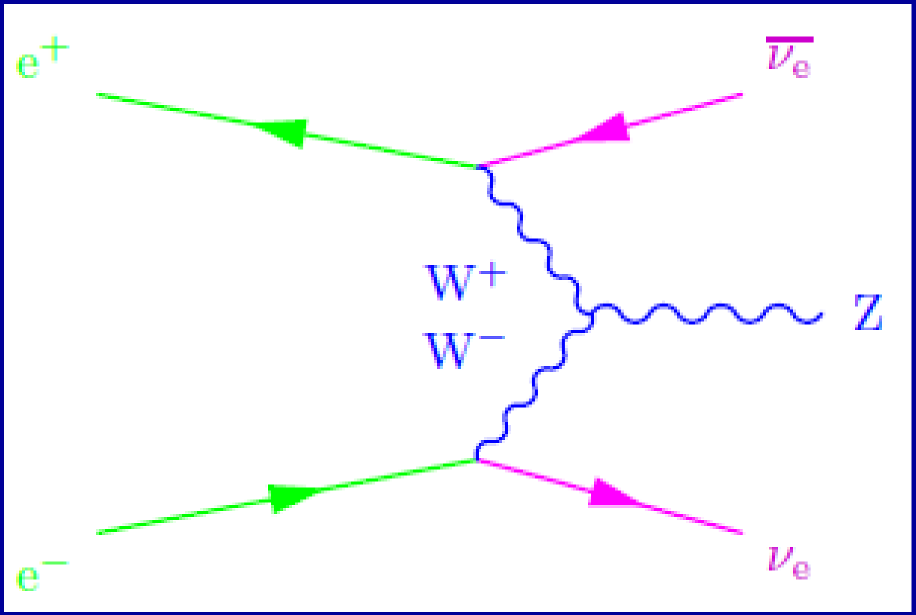
- One can also consider calibrating absolutely given the $m_Z$ uncertainty.
- Need
  - Tracker p-scale
  - EM Cal E-scale
  - Calorimeter neutral-hadron energy scale
- Can use precisely known particle scales: $\Lambda^0$, $\pi^0$, $\phi$, $\Sigma$.
- Also fragmentation errors ($K_L$, n)




Likely dominated by NH energy scale.

# High Energy Z Calibration Methods




$(\Delta M/M)_Z = 2.3\times10^{-5}$

Zνν.
Effective cross-section for final states with Z → hadrons are around 1.3 pb at 1 TeV.

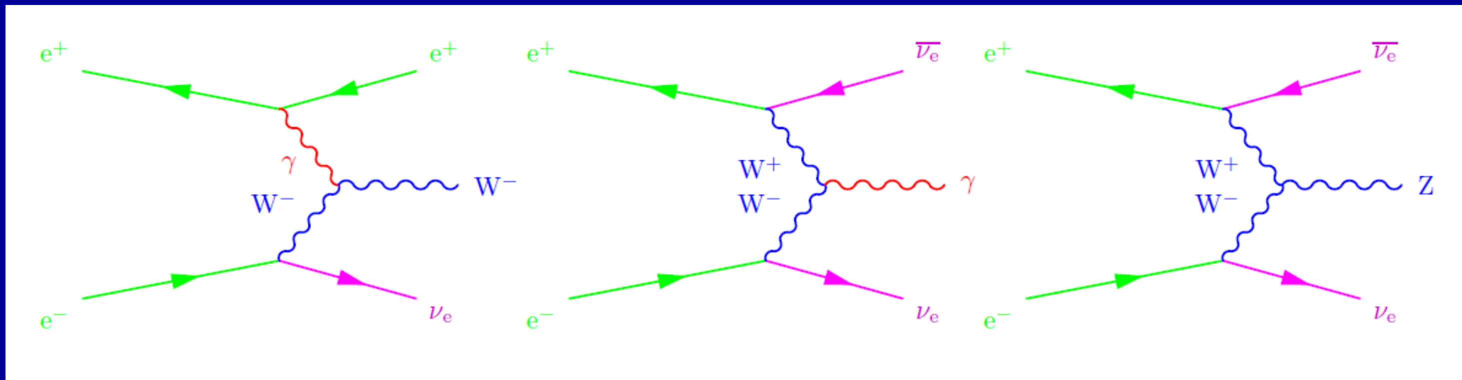
Also Zee. Cross-sections huge (20 pb) when including eγ -> eZ. Need to check acceptance.
And Z (γ).

# Conclusions

- While Higgs physics will drive the program, we should take full advantage of the data-samples that are factors of 100-1000 beyond LEP for W and Z physics.
  - Momentum resolution and scale appears key to controlling the beam energy systematic
  - Need a compatible accelerator design
- Detector design needs to be focussed on systematics not just resolution.
  - But lowering our goals on resolution is in general NOT a recipe for controlling systematics any better.
  - Push-pull and feather-like detectors make alignment challenging
  - Decreasing R to save money – increases confusion – increases systematics.

# Backup Slides

# New Beam Polarization Measurement Method




Use final states with photon or muon(s) with missing energy

Collect data with all 4 pairings.
(-+) (+-) (--) (++)
Count events in each of the 4 channels.

**7-parameter fit with 16 measurements**

2 ab$^{-1}$ distributed 40:40:10:10 amongst polarisation configurations 1-4.

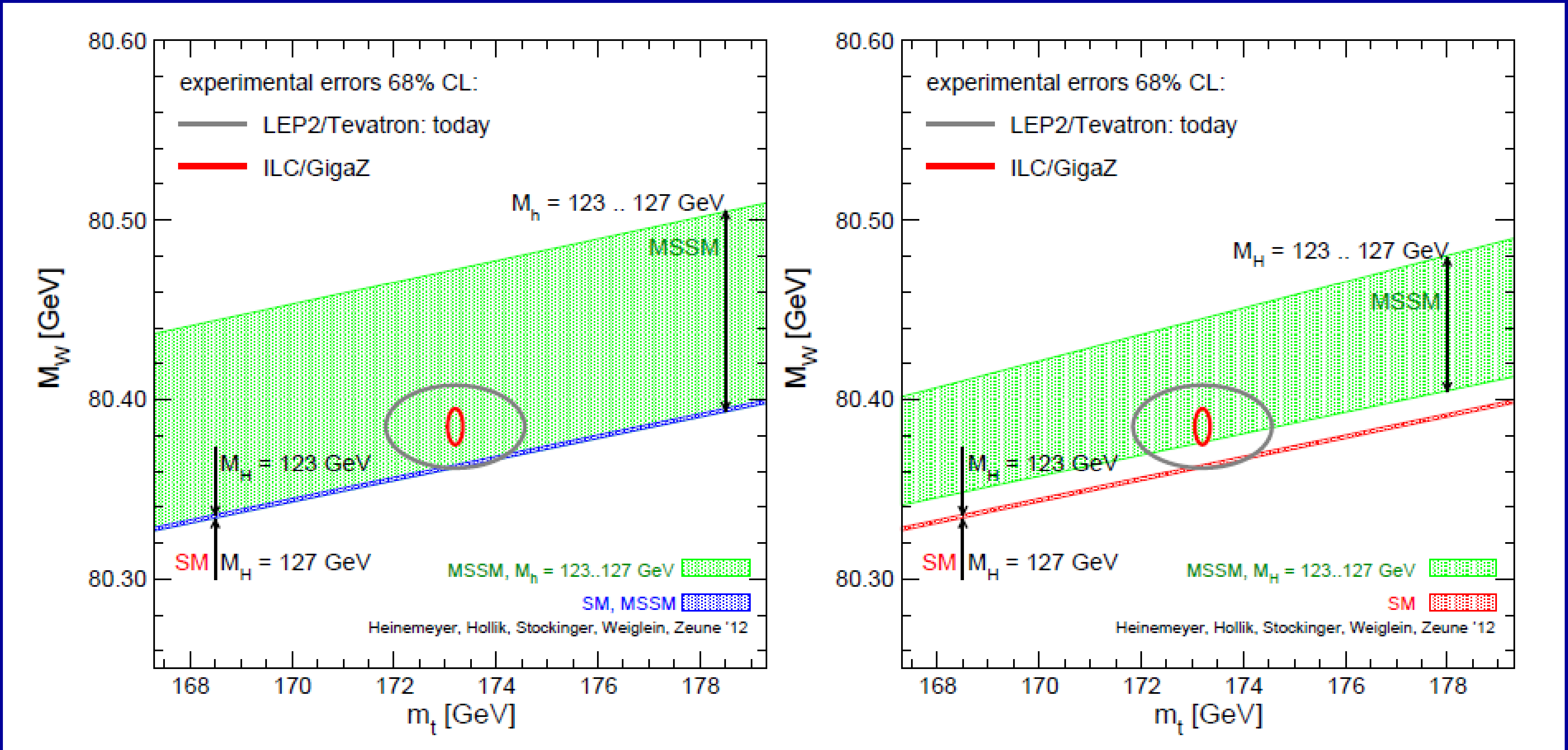
$\sqrt{s}$=3TeV study

| | |
|---|---|
| $\lvert P_{e^-}\rvert$ | $80.000 \pm 0.064\%$ |
| $\lvert P_{e^+}\rvert$ | $30.000 \pm 0.085\%$ |
| $\sigma^{\gamma}_{LR}$ | $3098.0 \pm 3.0$ fb |
| $\sigma^{\gamma}_{RL}$ | $25.3 \pm 1.0$ fb |
| $\sigma^{Z}_{LR}$ | $159.40 \pm 0.53$ fb |
| $\sigma^{\mu}_{LR}$ | $580.9 \pm 1.0$ fb |
| $\sigma^{\mu}_{SS}$ | $657.4 \pm 1.3$ fb |

Beam polarisation correlation:

$$\rho(\lvert P_{e^-}\rvert, \lvert P_{e^+}\rvert) = 10\%$$

# Would mW to 2 MeV be interesting ?




Can test whether W and top masses are consistent with the SM Higgs mass or MSSM with either the 126 GeV object being the light (left plot) or heavy (right plot) CP even Higgs