Enabling Precision W and Z Physics at ILC with In-Situ Center-of-Mass Energy Measurements

(plus some comments related to accelerator design at low energy)

ILC@DESY General Project Meeting

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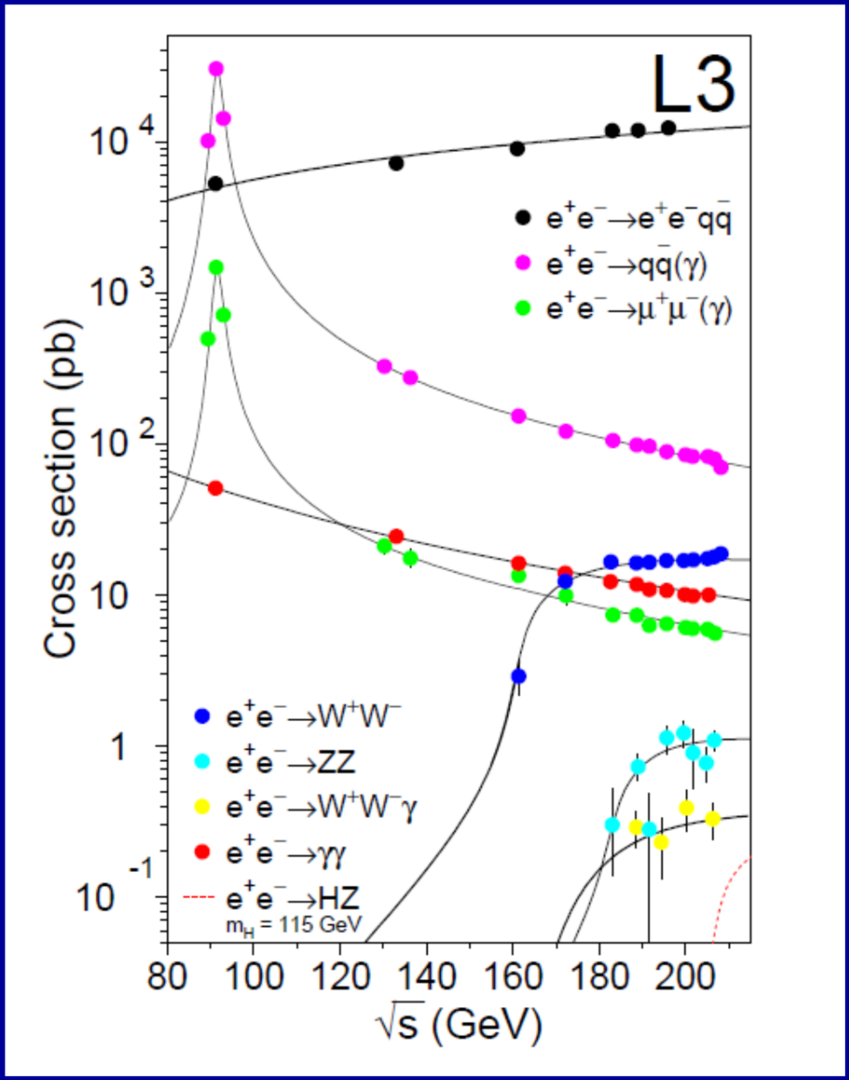
Outline

- Introduction
  - e^+e^- landscape
  - Center-of-Mass Energy Measurements Intro
  - W mass measurement prospects
- In-situ Center-of-Mass Energy Measurement
  1. $e^+e^- \rightarrow \mu\mu(\gamma)$ study
  2. momentum-scale study with $Z \rightarrow J/psi\ X$, $J/psi \rightarrow \mu\mu$

Conclusions

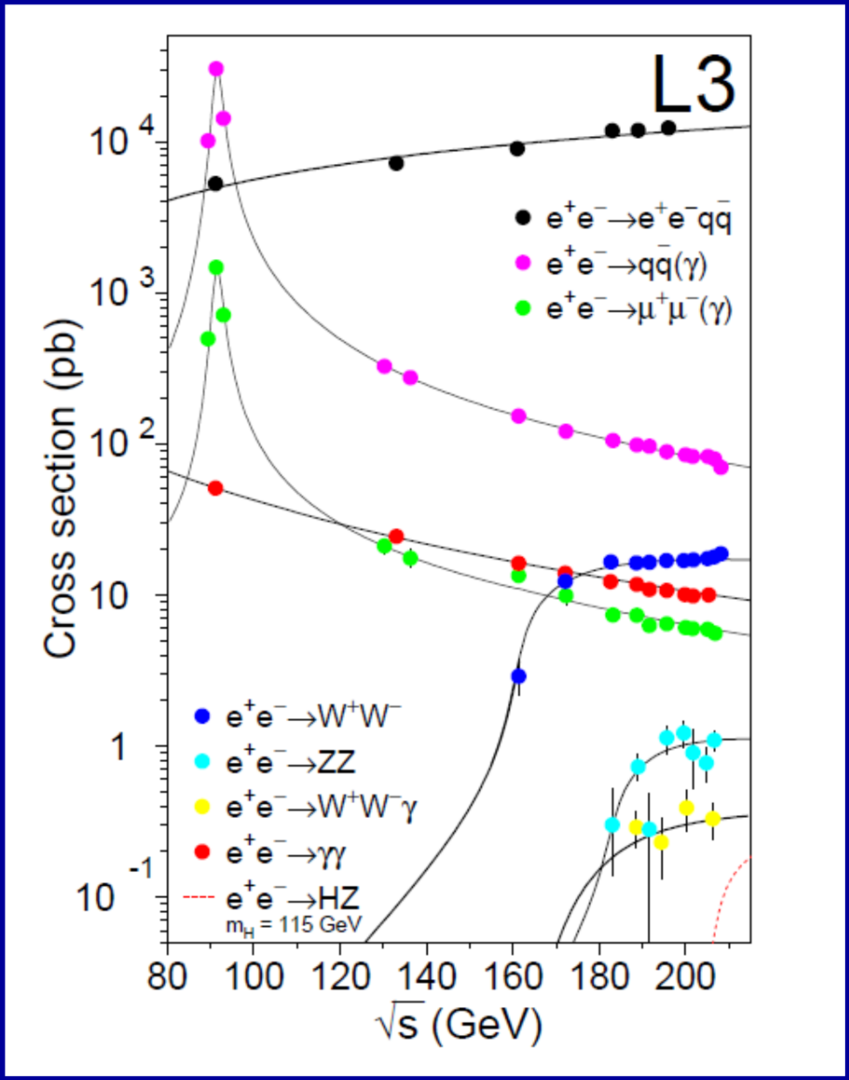
e^+e^- Collisions

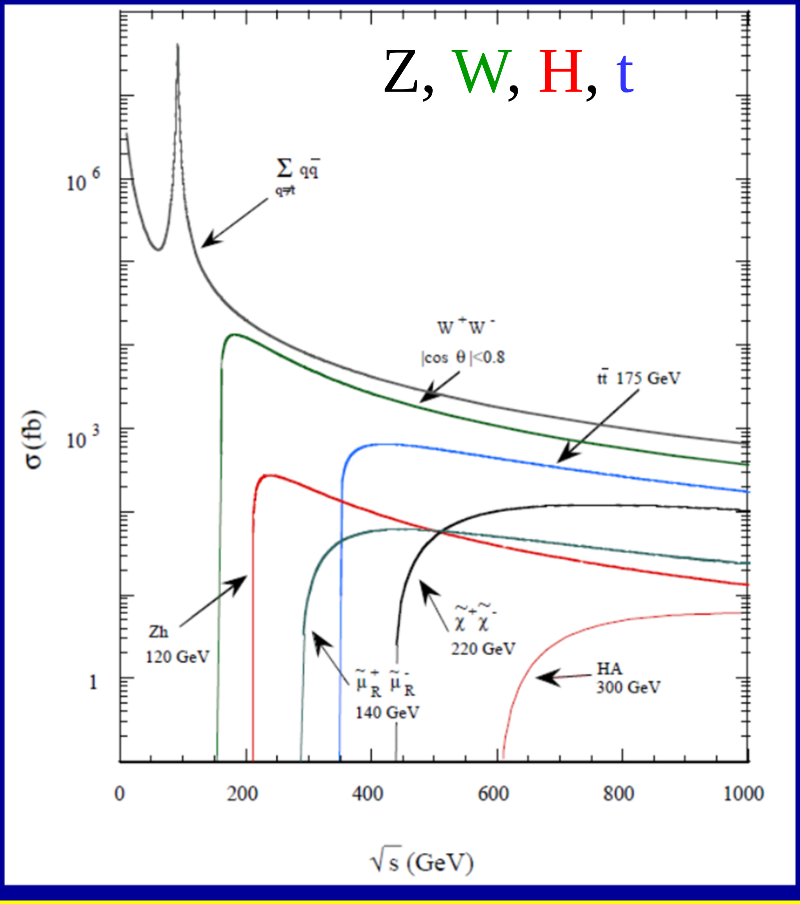


LEP

What is out here ??

e^+e^- Collisions

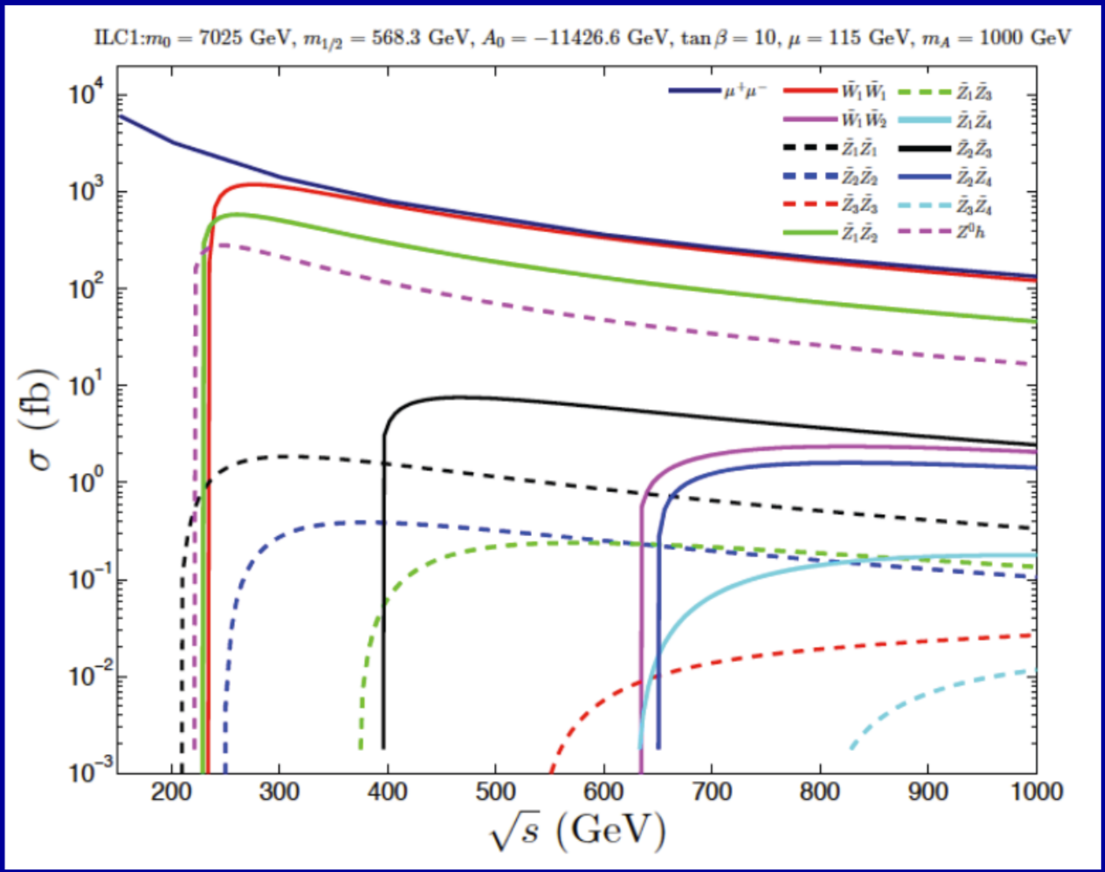




Expected new processes: Zh, tt, tth, Zhh,ννhh. And measure known processes in new regime.

LEP ----------------------------------→ ILC

The ILC Higgsino Factory



H. Baer et al.

10-15 GeV mass differences no problem for ILC.

Model is still allowed and “natural” after LHC results.

Comprehensively test new physics models

My take on the ILC run plan

- Explore the Higgs
- Look for completely new phenomena to highest possible energy
- Precision measurement of top
- Especially if no new phenomena observed, precision measurements of W and Z will be very compelling.

The e^+e^- Advantage

- The physics scope of e^+e^- colliders is fundamentally tied to the ability to precisely characterize the initial conditions
  - Luminosity, Energy, Polarization
- A precise knowledge of the **center-of-mass energy** is key.
  - (eg. mass from threshold scans)
  - Examples: m_t, m_W, m_H, $m_{Z,}$ m(chargino)

Center-of-Mass Energy Measurements

- At LEP (C=27km), resonant spin depolarization (RSD) was used routinely to measure the average beam energy (E_b) up to 55 GeV.
  - Resonant spin depolarization is unique to circular machines – and gets very difficult at higher energies even with a large ring.
- For ILC – need other approaches.
  - Especially in-situ methods sensitive to the collision energy.
- For a ring, naïve scaling with energy spread ($E_b^2/\sqrt{\rho}$) suggests RSD calibration at $\sqrt{s}$ = 161 GeV is only guaranteed for C = 124 km. For $\sqrt{s}$=240 GeV, need C = 612 km.
  - So rings also need other methods to take advantage of the higher possible energies for a given circumference as was evident at LEP2.
- In this talk, I'm focussed on in-situ studies targeted at ILC. They can also likely be applied to rings and CLIC.

ILC Beam Energy Measurement Strategy

- Upstream BPM-based spectrometers (LEP2 like)
- In-situ measurements with physics
  - ➔ Sensitive to collision absolute center-of-mass energy scale
  - Sensitive to collision luminosity spectrum (dL/dx_1dx_2)
    - See Andre Sailer's diploma thesis (ILC)
- Downstream synchrotron imaging detectors (SLC like)
  - Also measures the energy spectrum of the disrupted beam down to x=0.5.
- See http://arxiv.org/abs/0904.0122 for details on beam delivery system energy (and polarisation) diagnostics.
  - Target precision of fast beam-based methods: 100 ppm.

2006 updated ILC parameters document

- "Options":
  - Positron polarization above 50%
  - Z running with L = several 10^{33} for a year.
  - WW threshold running, L = several 10^{33} for a year
    - Beam energy calibration required with accuracy of few 10^{-5} (still to be demonstrated by experimental community)

(a few things in this document are inaccurate)

High Statistics Z Running

- See eg. TESLA TDR for more details.
- Lots of physics can be done.
- "Lumi upgrade" has L=3.0e34 at 250 GeV
- So could think about L =1.1e34 at 91 GeV – and up to 10^{10} Z's in 3 years.
  - 1000 times the LEP statistics
  - With detectors in many aspects 10 times better.
- It would be advisable to have a good design in hand for this opportunity

	LEP/SLC/Tev [19]	TESLA
$\sin^2\theta^\ell_{\rm eff}$	0.23146 ± 0.00017	± 0.000013
lineshape observables:		
M_Z	91.1875 ± 0.0021 GeV	± 0.0021 GeV
$\alpha_s(M_Z^2)$	0.1183 ± 0.0027	± 0.0009
$\Delta\rho_\ell$	$(0.55 \pm 0.10) \cdot 10^{-2}$	$\pm 0.05 \cdot 10^{-2}$
N_ν	2.984 ± 0.008	± 0.004
heavy flavours:		
$\mathcal{A}_b$	0.898 ± 0.015	± 0.001
R_b^0	0.21653 ± 0.00069	± 0.00014
M_W	80.436 ± 0.036 GeV	± 0.006 GeV

Assumed 10^9 Z's and 100 fb^{-1} at 161

Current Status of m_W and m_Z

VALUE (GeV)	EVTS	DOCUMENT ID		TECN	COMMENT
80.385 ± 0.015 OUR FIT					
80.387 ± 0.019	1095k	[1] AALTONEN	12E	CDF	$E^{p\bar{p}}_{cm}$ = 1.96 TeV
80.367 ± 0.026	1677k	[2] ABAZOV	12F	D0	$E^{p\bar{p}}_{cm}$ = 1.96 TeV
80.401 ± 0.043	500k	[3] ABAZOV	09AB	D0	$E^{p\bar{p}}_{cm}$ = 1.96 TeV
80.336 ± 0.055 ± 0.039	10.3k	[4] ABDALLAH	08A	DLPH	E^{ee}_{cm} = 161–209 GeV
80.415 ± 0.042 ± 0.031	11830	[5] ABBIENDI	06	OPAL	E^{ee}_{cm} = 170–209 GeV
80.270 ± 0.046 ± 0.031	9909	[6] ACHARD	06	L3	E^{ee}_{cm} = 161–209 GeV
80.440 ± 0.043 ± 0.027	8692	[7] SCHAEL	06	ALEP	E^{ee}_{cm} = 161–209 GeV
80.483 ± 0.084	49247	[8] ABAZOV	02D	D0	$E^{p\bar{p}}_{cm}$ = 1.8 TeV
80.433 ± 0.079	53841	[9] AFFOLDER	01E	CDF	$E^{p\bar{p}}_{cm}$ = 1.8 TeV

$\Delta M/M = 1.9\times10^{-4}$

LEP2: 3 fb $^{-1}$

VALUE (GeV)	EVTS	DOCUMENT ID		TECN	COMMENT
91.1876 ± 0.0021 OUR FIT					
91.1852 ± 0.0030	4.57M	[1] ABBIENDI	01A	OPAL	E^{ee}_{cm} = 88–94 GeV
91.1863 ± 0.0028	4.08M	[2] ABREU	00F	DLPH	E^{ee}_{cm} = 88–94 GeV
91.1898 ± 0.0031	3.96M	[3] ACCIARRI	00C	L3	E^{ee}_{cm} = 88–94 GeV
91.1885 ± 0.0031	4.57M	[4] BARATE	00C	ALEP	E^{ee}_{cm} = 88–94 GeV

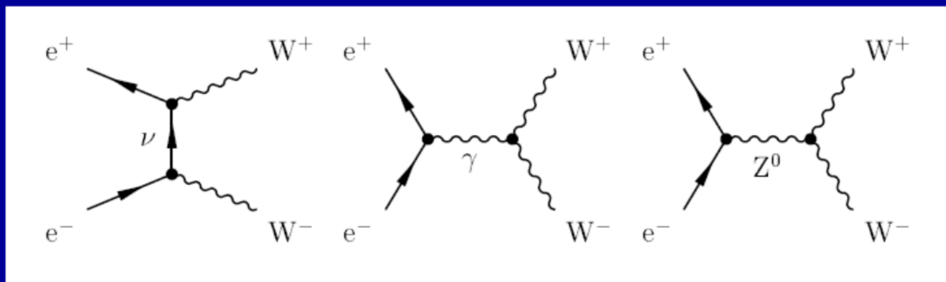
$\Delta M/M = 2.3\times10^{-5}$

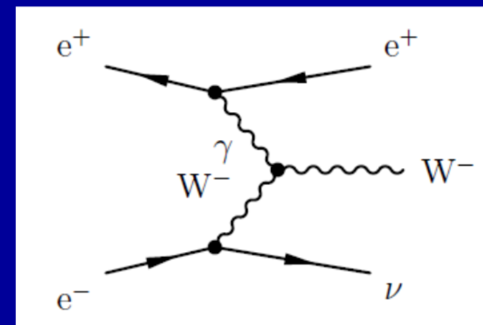
LEP: 0.8 fb $^{-1}$

m_W is currently a factor of 8 less precise than m_Z

Note: LHC has still to make a competitive measurement of m_W.

W Production in e^+e^-

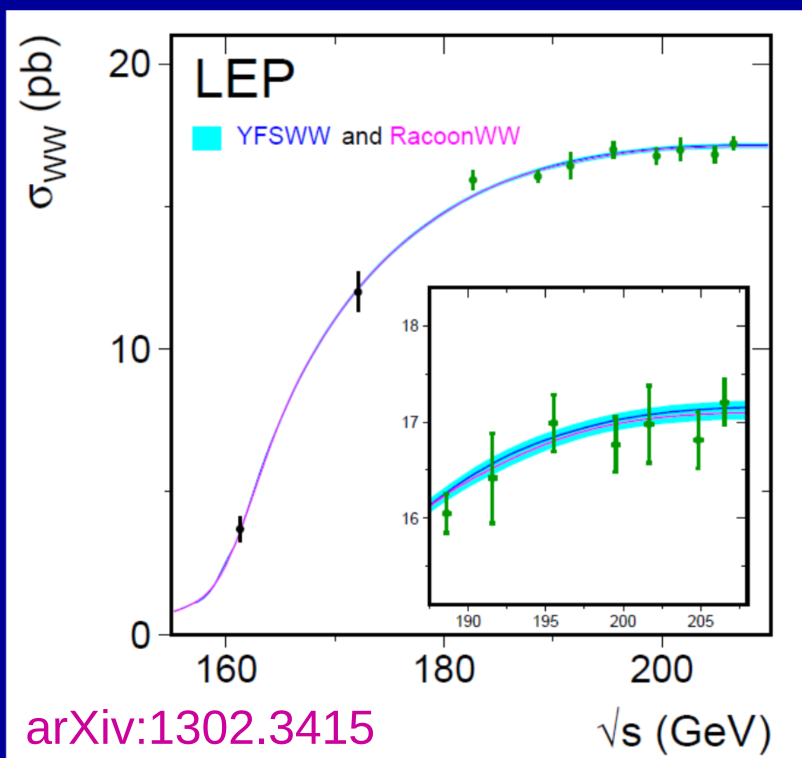


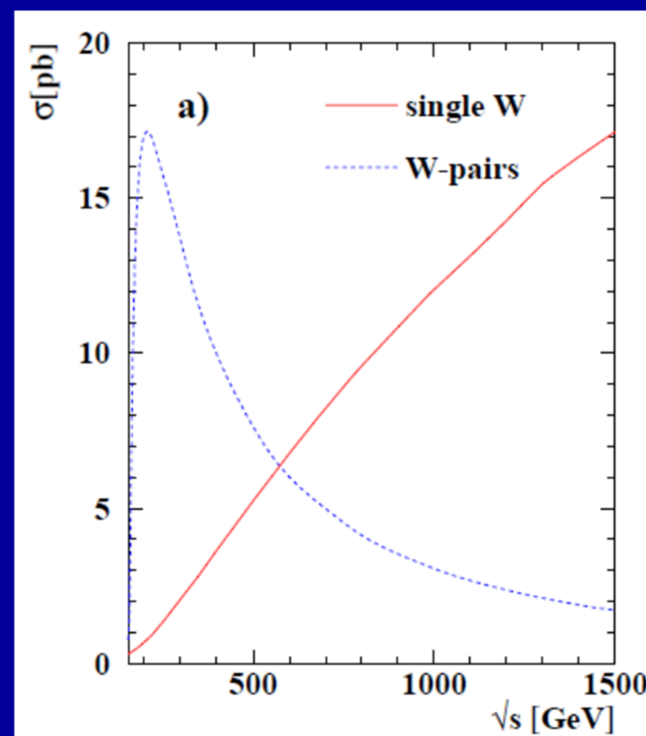


etc ..

e+e- → W+W-

e+e- → W e ν





unpolarized cross-sections

Primary Methods

- 1. Polarized Threshold Scan
  - All decay modes
  - Polarization => Increase signal / control backgrounds
- 2. Kinematic Reconstruction using (E,**p**) constraints
  - q q l v (l = e, μ)
- 3. Direct Hadronic Mass Measurement
  - In q q τ v events and

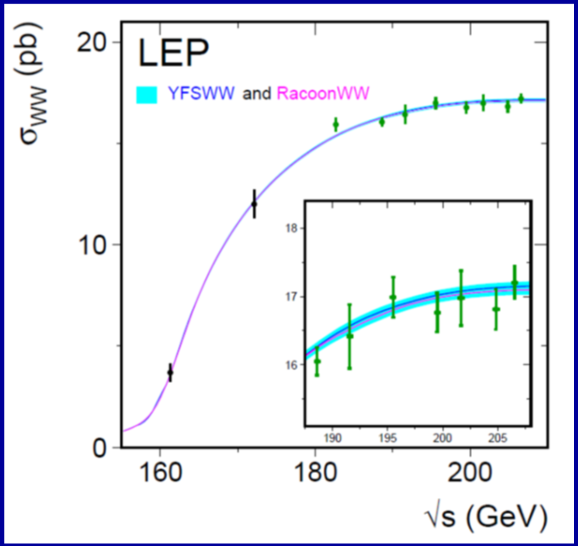
    hadronic single-W events (e usually not detected)

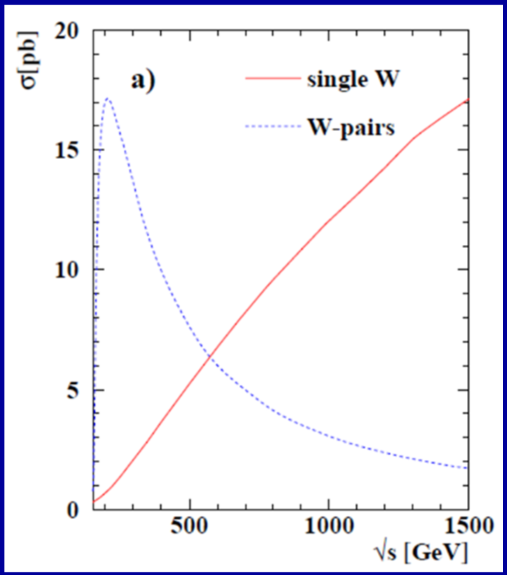
ILC may contribute to W mass measurements over a wide range of energies.
ILC250, ILC350, ILC500, ILC1000, ILC161 …

Threshold scan is the best worked out.

W Mass Measurement Strategies

- W^+W^-
  - 1. Threshold Scan ($\sigma \sim \beta/s$)
    - Can use all WW decay modes
  - 2. Kinematic Reconstruction
    - Apply kinematic constraints
- W e ν (and WW → qqτν)
  - 3. Directly measure the hadronic mass in W → q q' decays.
    - e usually not detectable





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.

ILC

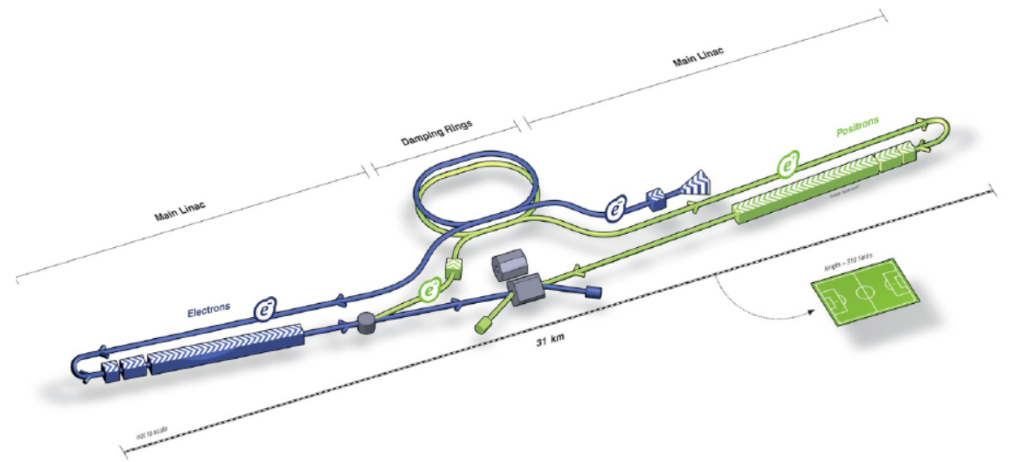


Figure 2: Layout of the ILC accelerator systems.

√s (GeV)	L (fb-1)	Physics
91	100	Z
161	160	WW
250	250	Zh, NP
350	350	t tbar, NP
500	1000	tth, Zhh, NP
1000	2000	ννh, ννhh,VBS, NP

My take on a possible run-plan factoring in L capabilities at each √s.

Can polarize both the e^- and e^+ beam.
Electron: 80% …. 90%?
Positron 20, 30 … 60%.

In contrast to circular machines this is not supposed to be in exchange for less luminosity

ILC Accelerator Features

$L \sim (P/E_{CM}) \sqrt{(\delta_E / \varepsilon_{y,N})}\, H_D$

$P \sim f_c\, N$ $\delta_E \sim (N^2 \gamma^2)/(\varepsilon_{x,N}\, \beta_x\, \sigma_z)\, U_1\, (\Psi_{av})$

Machine design has focused on 500 GeV baseline

$\sqrt{s}$	$\mathcal{L}[10^{34}]$	dE [%]	(dp/p)(+) [%]	(dp/p)(-) [%]
200	0.56	0.65	0.190	0.206
250	0.75	0.97	0.152	0.190
350	1.0	1.9	0.100	0.158
500	1.8/3.6	4.5	0.070	0.124
1000	4.9	10.5	0.047	0.085

dp/p same as LEP2 at 200 GeV

dp/p typically better than an e^+e^- ring which worsens linearly with $\sqrt{s}$

Scope for improving luminosity performance.

1. Increase number of bunches (f_c)
2. Decrease vertical emittance (ε_y)
3. Increase bunch charge (N)
4. Decrease σ_z
5. Decrease β_x

3,4,5 => L, BS trade-off
Can trade more BS for more L or lower L for lower BS.

Beamstrahlung

Average energy loss of beams is not what matters for physics.

Average energy loss of colliding beams is factor of 2 smaller.

Median energy loss per beam from beamstrahlung typically tiny compared to beam energy spread.

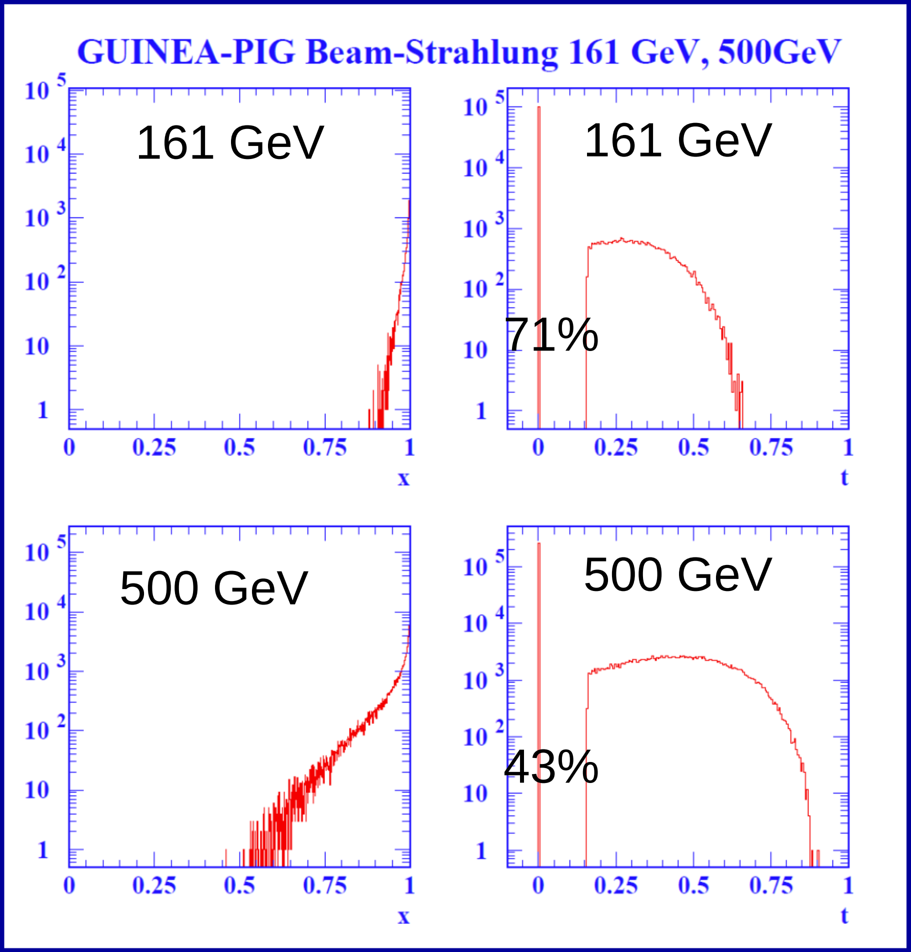
Parametrized with CIRCE functions.

f $\delta(1\text{-}x) + (1\text{-}f)\,\mathrm{Beta}(a_2,a_3)$

Define $t = (1 - x)^{1/5}$

In general beamstrahlung is a less important issue than ISR. Worse BS could be tolerated in the WW threshold scan

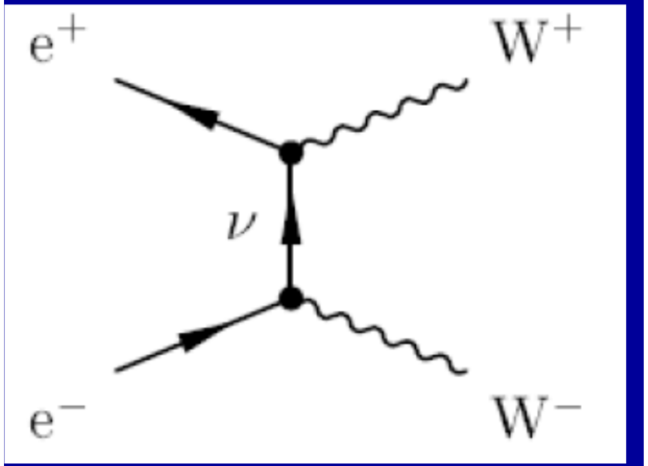
Scaled energy of colliding beams



$t=0.25 \Rightarrow x = 0.999$

$x > 0.9999$ in first bin

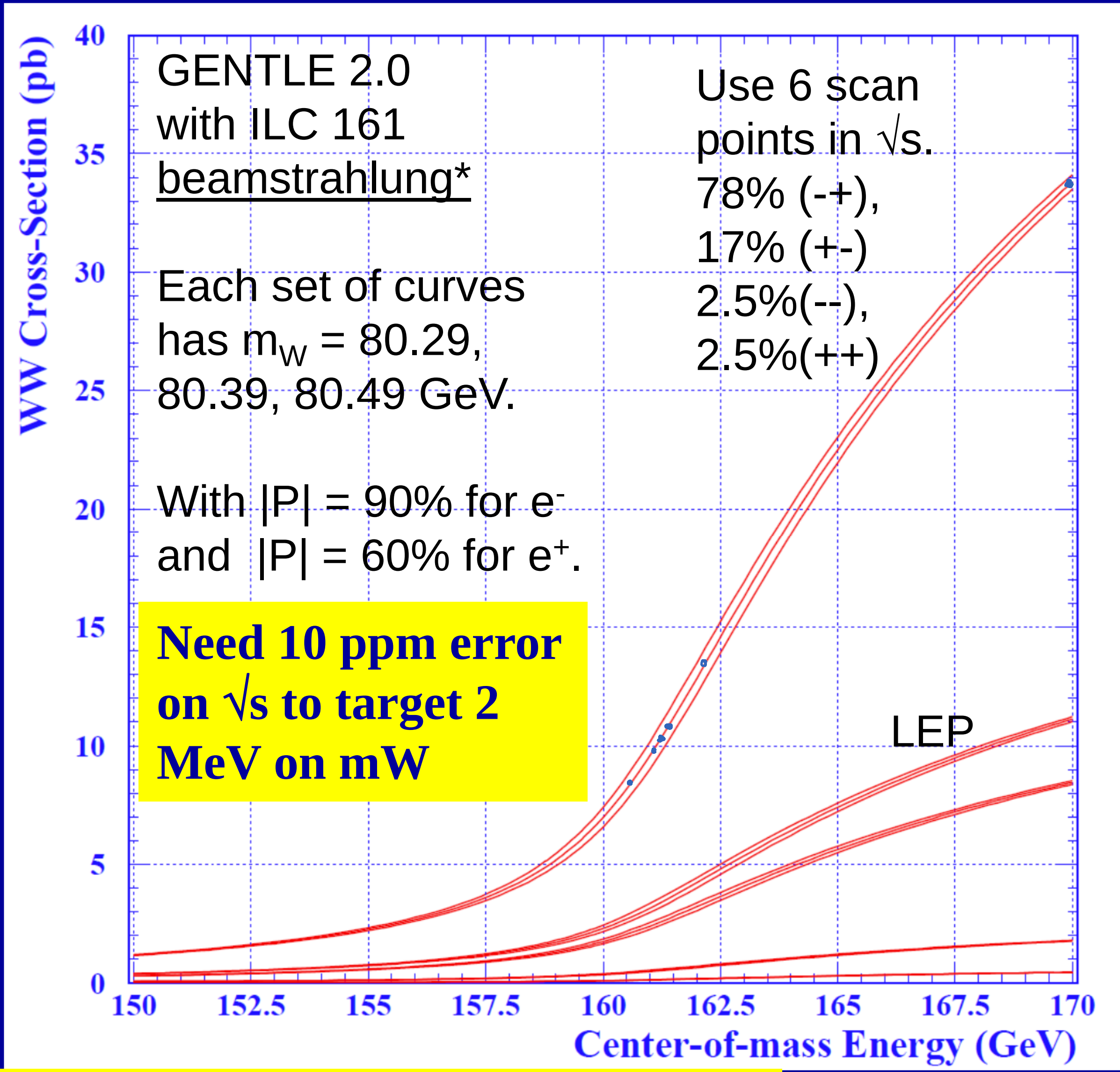
ILC Polarized Threshold Scan



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

m_W Prospects

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

ΔM_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	4.0	2.1

2

ΔM_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

ΔM_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

See attached document for more detailed discussion

In-situ Physics Based Beam Energy Measurements

- Potential Mass-Scale References for Energy Calibration

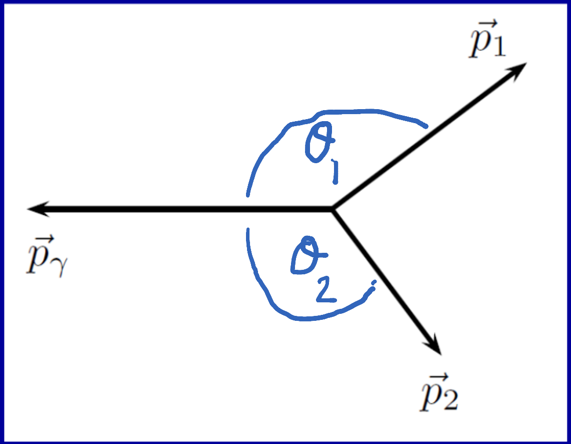
Particle	ΔM/M (PDG) (ppm)
J/psi	3.6
Upsilon	27
Z	23
W	190
H	2400

Conventional wisdom has been to use Z's, but with ILC detector designs J/psi's look attractive.

Prefer not to use something that one plans to measure better or something that will limit the precision.

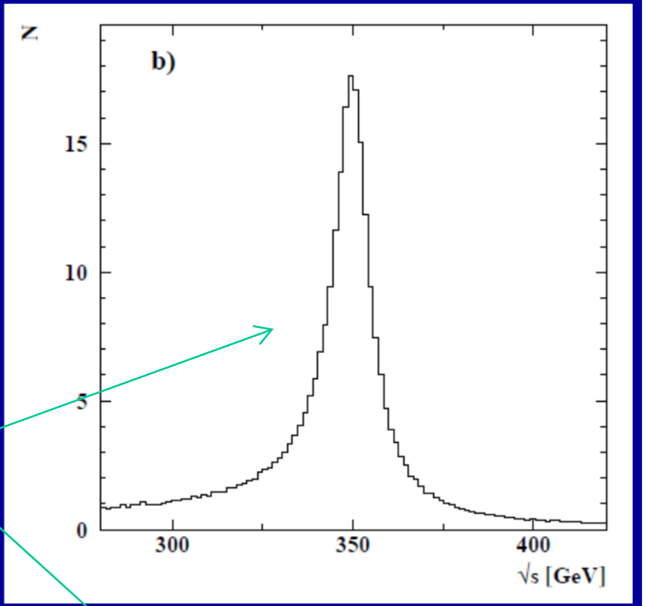
"Old" In-Situ Beam Energy Method

$e^+ e^- \to Z(\gamma) \to \mu^+\mu^-(\gamma)$



GWW – MPI 96
LEP Collabs.

Hinze & Moenig



Photon often not detected.
Use muon angles to (photon/beam-axis).
Requires precision polar angle.

$$\sqrt{s} = m_Z \sqrt{\frac{\sin\theta_1 + \sin\theta_2 - \sin(\theta_1+\theta_2)}{\sin\theta_1 + \sin\theta_2 + \sin(\theta_1+\theta_2)}}$$

Statistical error per event of order Γ/M = 2.7%

Acceptance degrades quickly at high √s

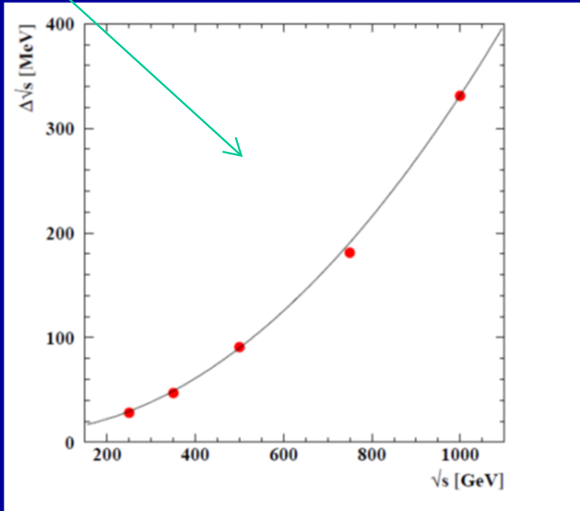
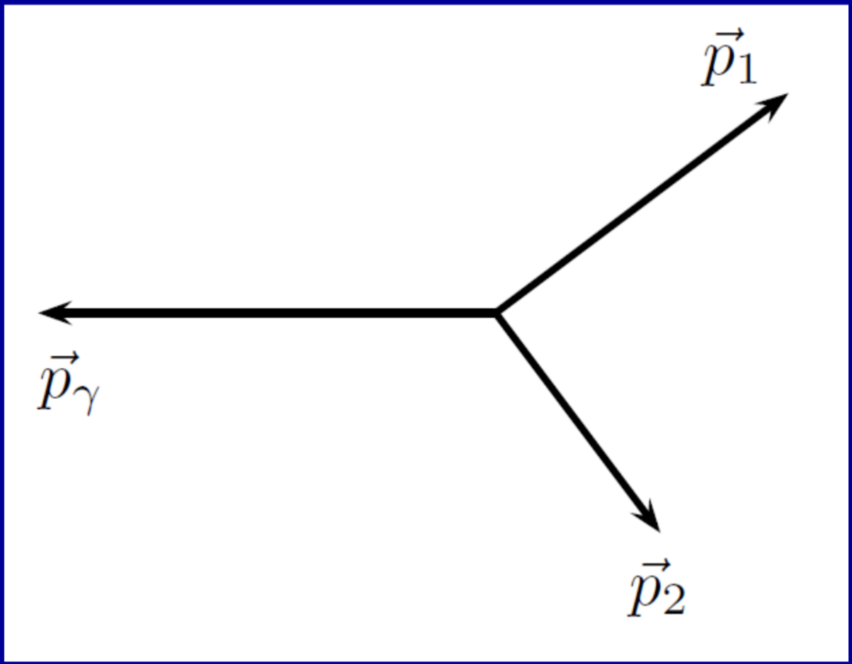


Figure 3: Energy dependence of $\Delta\sqrt{s}$ for $\mathcal{L} = 100$ fb^{-1}.

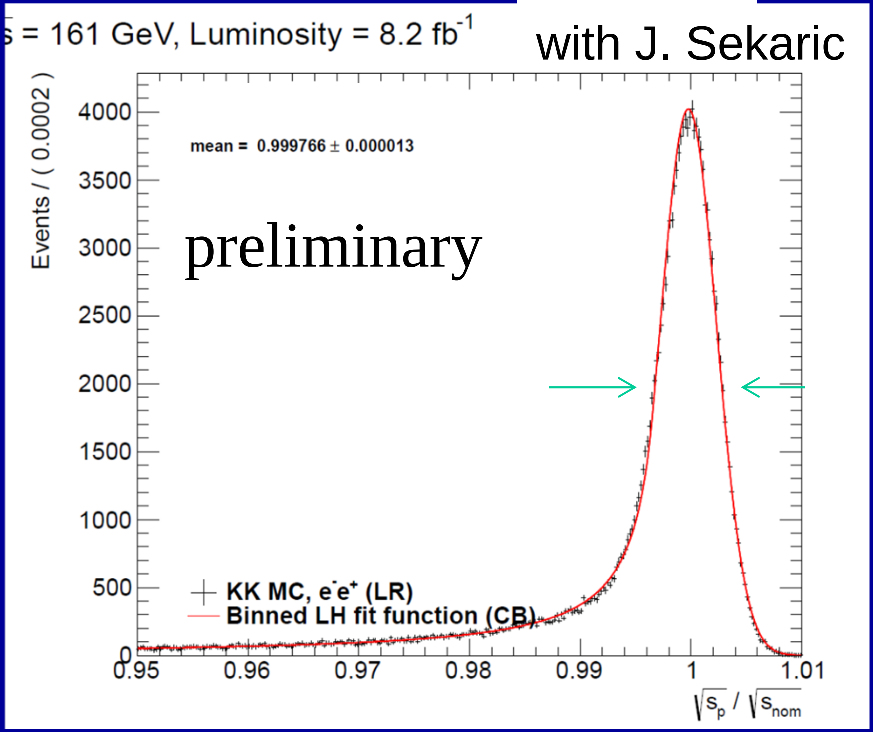
"New" In-Situ Beam Energy Method

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



Use muon momenta.
Measure $E_1 + E_2 + |\mathbf{p}_{12}|$ as an estimator of $\sqrt{s}$
(no assumption that $m_{12} \approx m_Z$)

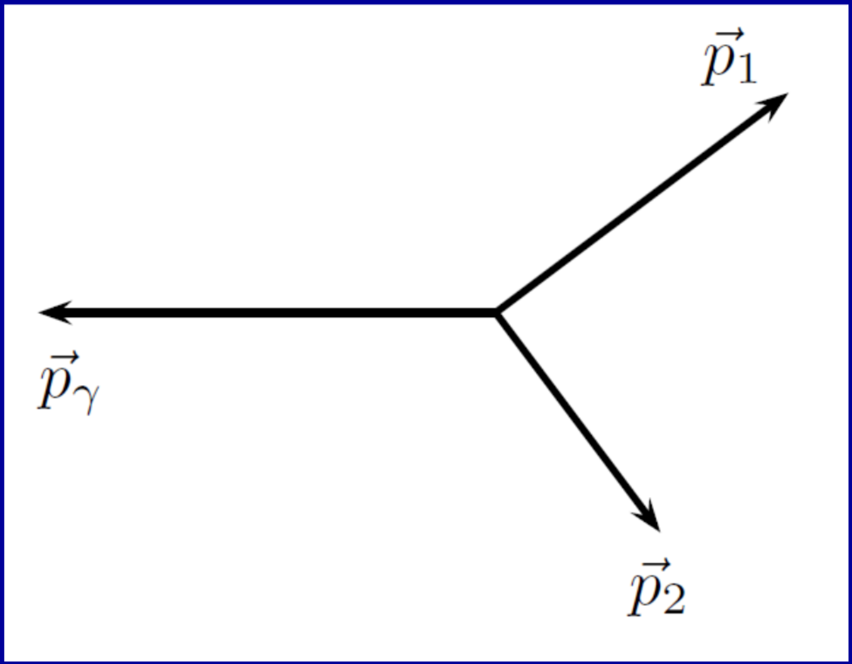
GWW
with J. Sekaric



ILC detector momentum resolution (0.15%) plus beam energy spread gives beam energy to about 5 ppm statistical for 150 < $\sqrt{s}$ < 350 GeV

Method explained in more detail. Use muon momenta. Measure $E_1 + E_2 + |\mathbf{p}_{12}|$.

Proposed and studied initially by T. Barklow



Under the assumption of a massless photonic system balancing the measured di-muon, the momentum (and energy) of this photonic system is given simply by the momentum of the di-muon system.

So $\sqrt{s}$ can be estimated from the sum of the energies of the two muons and the inferred photonic energy.

$(\sqrt{s})_P = E_1 + E_2 + |\mathbf{p}_1 + \mathbf{p}_2|$

In the specific case, where the photonic system has zero p_T, it is well approximated by this

$$\sqrt{s}_\mathrm{P} \approx (p_\mathrm{T})_1 \left(\frac{1+\cos\theta_1}{\sin\theta_1}\right) + (p_\mathrm{T})_2 \left(\frac{1+\cos\theta_2}{\sin\theta_2}\right)$$

Assuming excellent resolution on angles, the resolution on $(\sqrt{s})_P$ is determined by the θ dependent p_T resolution.

Method also uses non radiative-return events with $m_{12} \gg m_Z$

Beam Energy Spread

- Current ILC Design.
- Not a big issue especially at high $\sqrt{s}$

IP RMS Energy spreads (%)

Centre of mass energy (GeV)		200	230	250	350	500	1000 A1	1000 B1B
							0,250	0,225
Damping ring @ 5GeV	e+	0,137	0,137	0,137	0,11	0,11	0,109	0,109
	e-	0,12	0,12	0,12	0,12	0,12		
RTML @ 15 GeV	e+	1,23	1,23	1,23	1,13	1,13	1,36	1,51
(assume no z-correlation)	e-	1,17	1,17	1,17	1,13	1,13		
Main linac	e+	0,185	0,160	0,148	0,097	0,068	0,041	0,045
	e-	0,176	0,153	0,140	0,097	0,068	0,014	0,014
Long. wakefield contribution		0,046	0,039	0,036	0,026	0,018		
Positron undulator contribution	e-	0,098	0,113	0,123	0,122	0,103	0,071	0,071
IP value	**e+**	**0,190**	**0,165**	**0,152**	**0,100**	**0,070**	**0,043**	**0,047**
	e-	**0,206**	**0,194**	**0,190**	**0,158**	**0,124**	**0,083**	**0,085**

LEP2 was 0.19% per beam at 200 GeV.

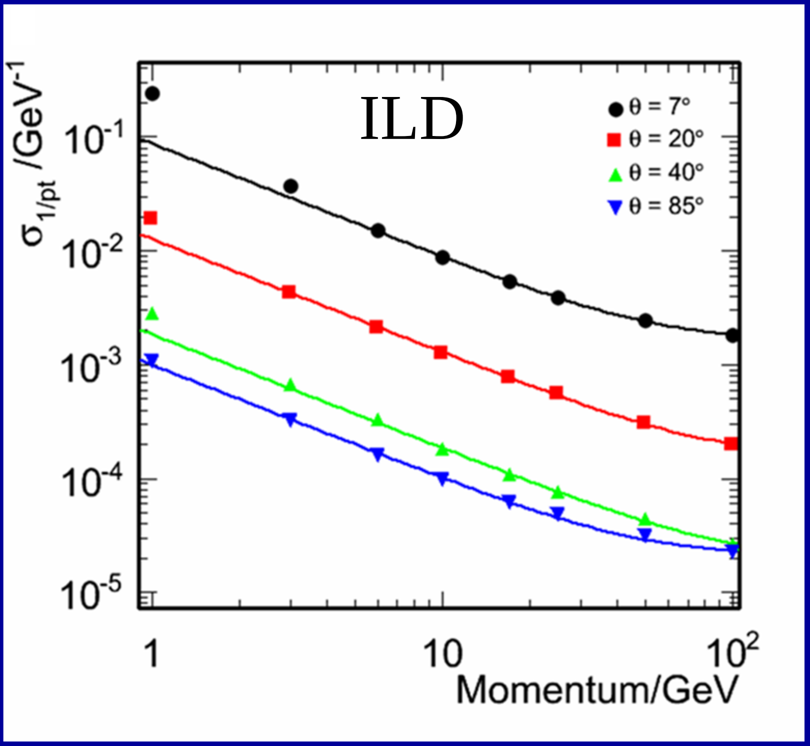
Momentum Resolution

$$P_T(\mathrm{GeV}/c) = 0.3\, z\, B(T) R(m)$$

Define track curvature

$$\kappa \equiv \frac{1}{R} \sim \frac{1}{P_T}$$

$$(\Delta\kappa)^2 = (\Delta\kappa_{res})^2 + (\Delta\kappa_{MS})^2$$



μμ(γ) studies in this talk model momentum resolution using the plotted parameterization. J/psi studies are done with the ILD fast and full simulations

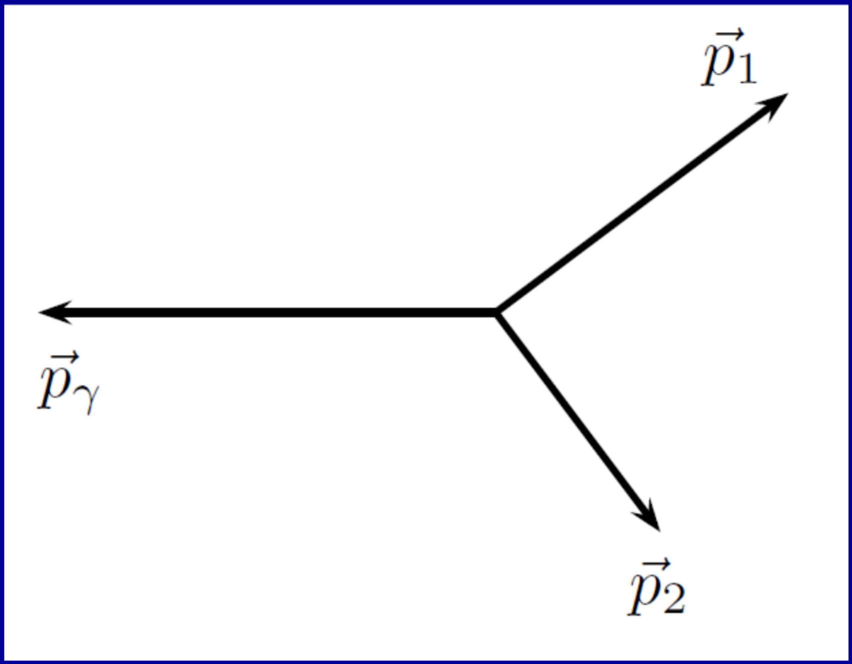
$$\sigma_{1/p_T} = a \oplus b/(p_T \sin\theta)$$

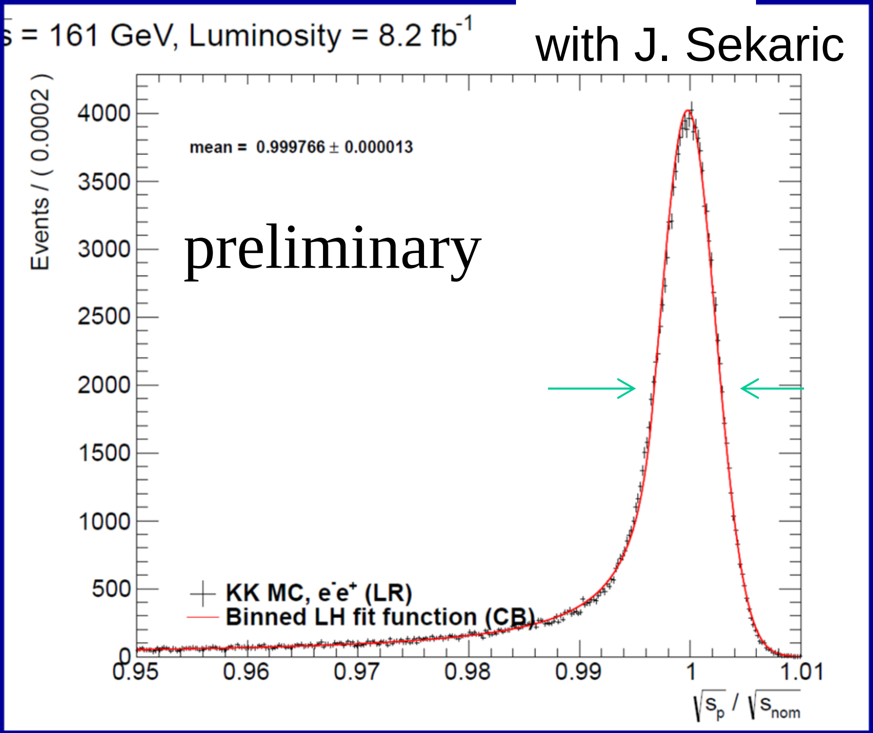
$$a = 2 \times 10^{-5}\,\mathrm{GeV}^{-1} \text{ and } b = 1 \times 10^{-3}$$

"New" In-Situ Beam Energy Method

GWW
with J. Sekaric

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





Use muon momenta.
Measure $E_1 + E_2 + |\mathbf{p}_{12}|$ as an estimator of $\sqrt{s}$
(no assumption that $m_{12} \approx m_Z$)

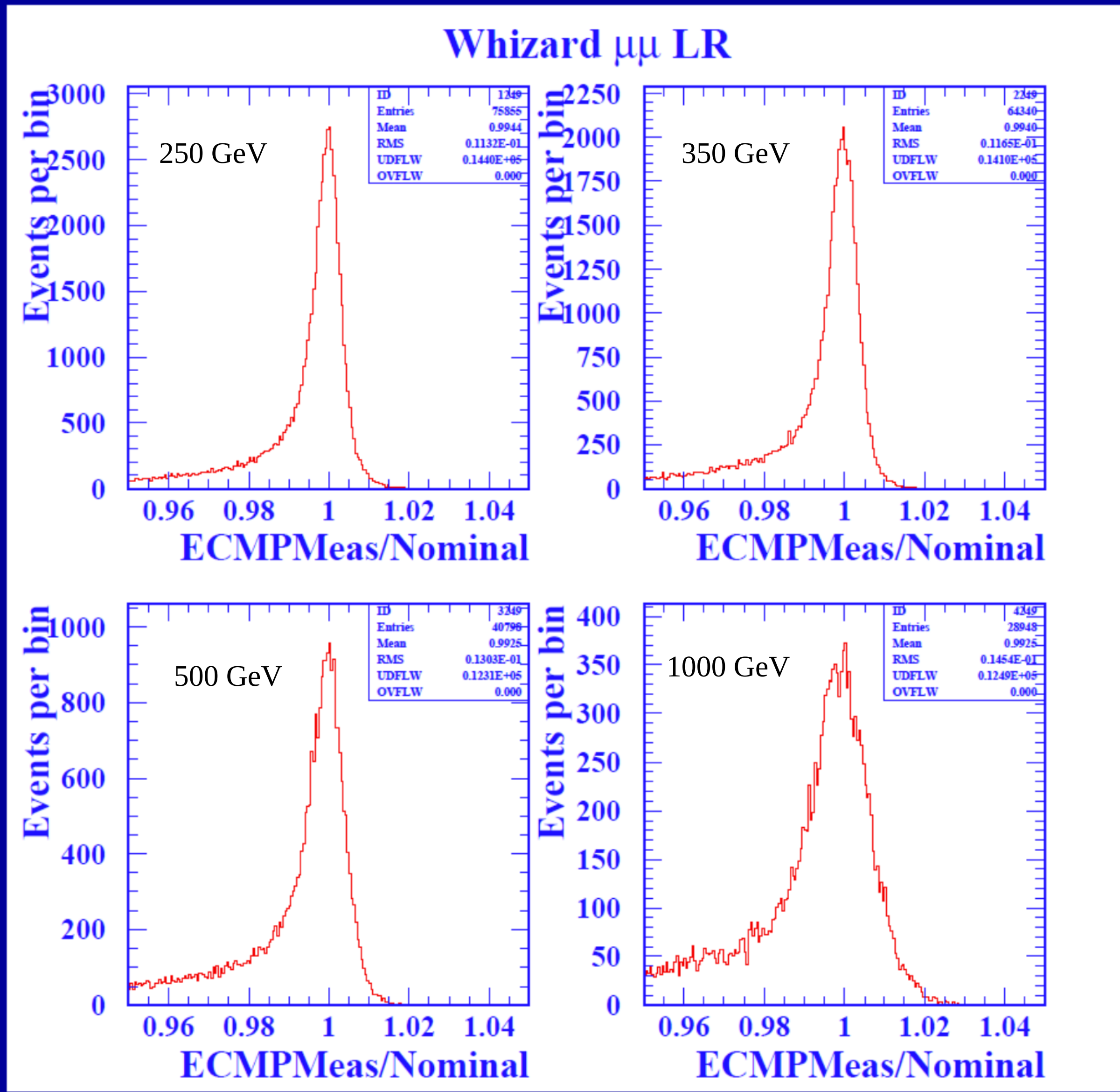
ILC detector momentum resolution (0.15%), gives beam energy to better than 5 ppm statistical. Momentum scale to 10 ppm => 0.8 MeV beam energy error projected on m_W (J/psi)

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

$\sqrt{s_P}$ Distributions (error<0.8%)

Using DBD Whizard generator files for each ECM

At 1000 GeV, error on peak position dominated by detector momentum resolution



Projected Errors

See talk at LC2013 for more details.

ECMP errors based on estimates from weighted averages from various error bins up to 2.0%. Assumes (80,30) polarized beams, equal fractions of +- and -+.

Preliminary

(Statistical errors only)

ECM (GeV)	**L (fb^{-1})**	**$\Delta(\sqrt{s})/\sqrt{s}$ Angles (ppm)**	**$\Delta(\sqrt{s})/\sqrt{s}$ Momenta (ppm)**	**Ratio**
161	161	-	4.3	
250	250	64	4.0	16
350	350	65	5.7	11.3
500	500	70	10.2	6.9
1000	1000	93	26	3.6

< 10 ppm for 150 – 500 GeV CoM energy

161 GeV estimate using KKMC.

NB. Need a strategy to establish and maintain the momentum scale calibration ..

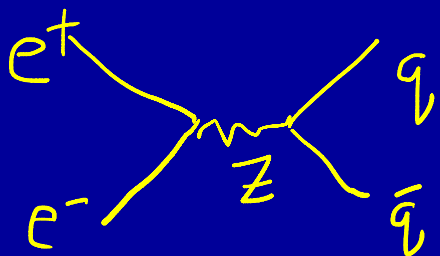
Systematics

$$\sqrt{s}_{\mathrm{P}} \approx (p_{\mathrm{T}})_1 \left(\frac{1+\cos\theta_1}{\sin\theta_1}\right) + (p_{\mathrm{T}})_2 \left(\frac{1+\cos\theta_2}{\sin\theta_2}\right)$$

- New method depends on p_T scale and angles.
- Momentum scale assumed to be dominant experimental systematic error.
- Best prospect appears to be to use J/psi from Z decay, assuming substantial running at the Z.
  - Can also use $Z \rightarrow \mu\mu$ without need for Z running - but 23 ppm PDG error would be a limiting factor - and Γ_Z is big.
- Next slides discuss an initial J/psi based momentum scale study. See recent talk at AWLC14 for more details.

J/ψ Based Momentum Scale Calibration

$\sqrt{s}=m_Z$



$\sigma_{had} = 30\,nb$ at $\sqrt{s} \simeq m_Z$

$f_{b\bar{b}} \equiv R_b = 22\%$

Most $Z \to J/\psi\, X$ believed to be from $B_{hadron} \to J/\psi\, X$

$B(Z_{had} \to J/\psi\, X) \cdot B(J/\psi \to \mu^+\mu^-) \approx 3.0 \times 10^{-4}$

$\Rightarrow$ Expect 300,000 events with 10^9 hadronic Z's

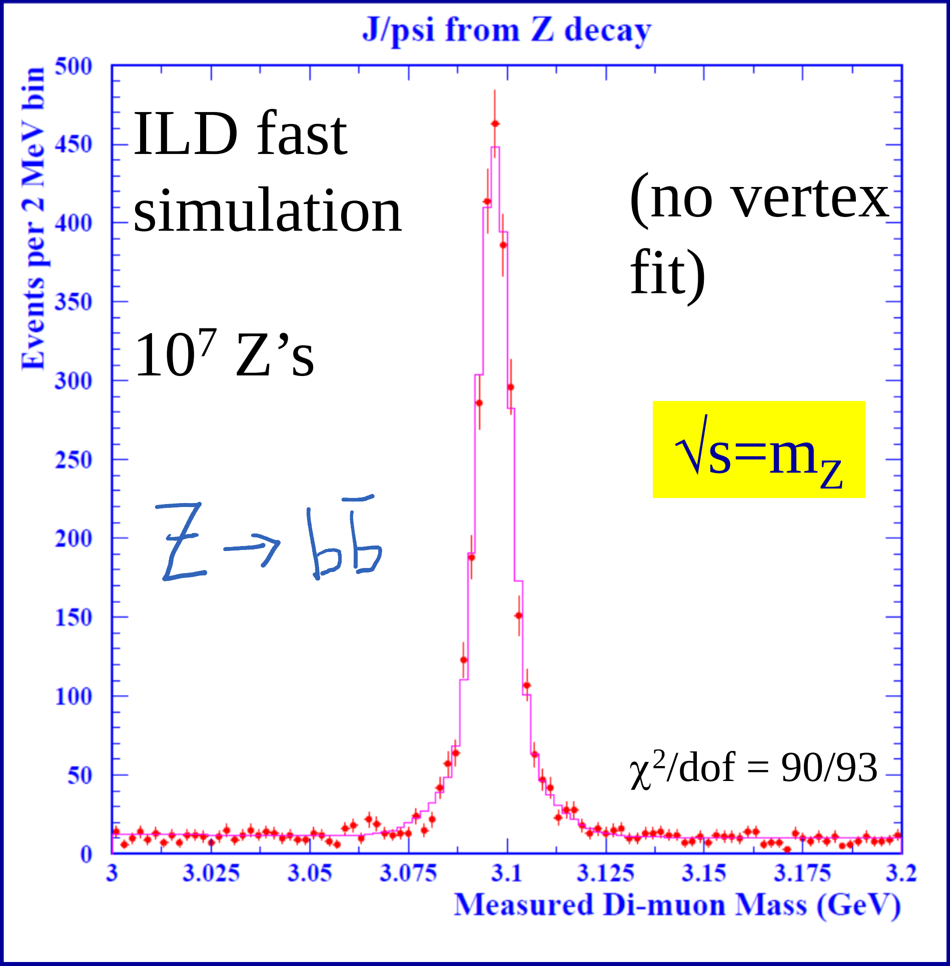
Mean J/psi energy of 20 GeV. Vertex displaced on average 2.5mm.

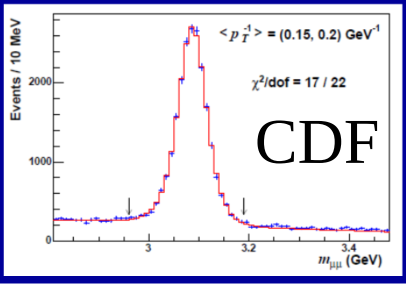
Momentum Scale with J/psi

With 10^9 Z's expect statistical error on mass scale of 1.7 ppm given ILD momentum resolution and vertexing based on fast simulation.

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)



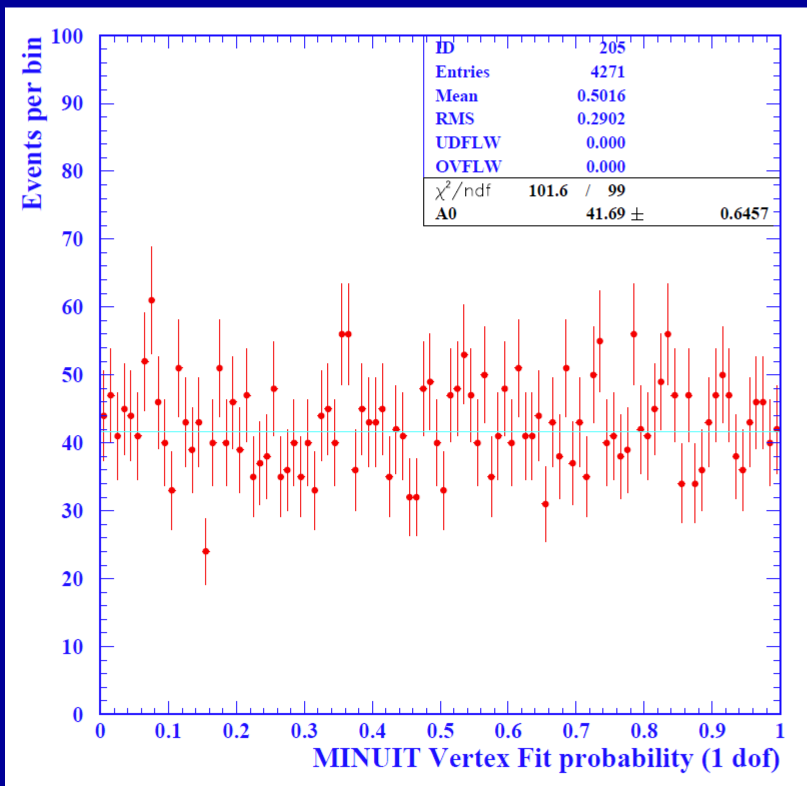


Double-Gaussian + Linear Fit

J/Psi (from Z) Vertex Fit Results

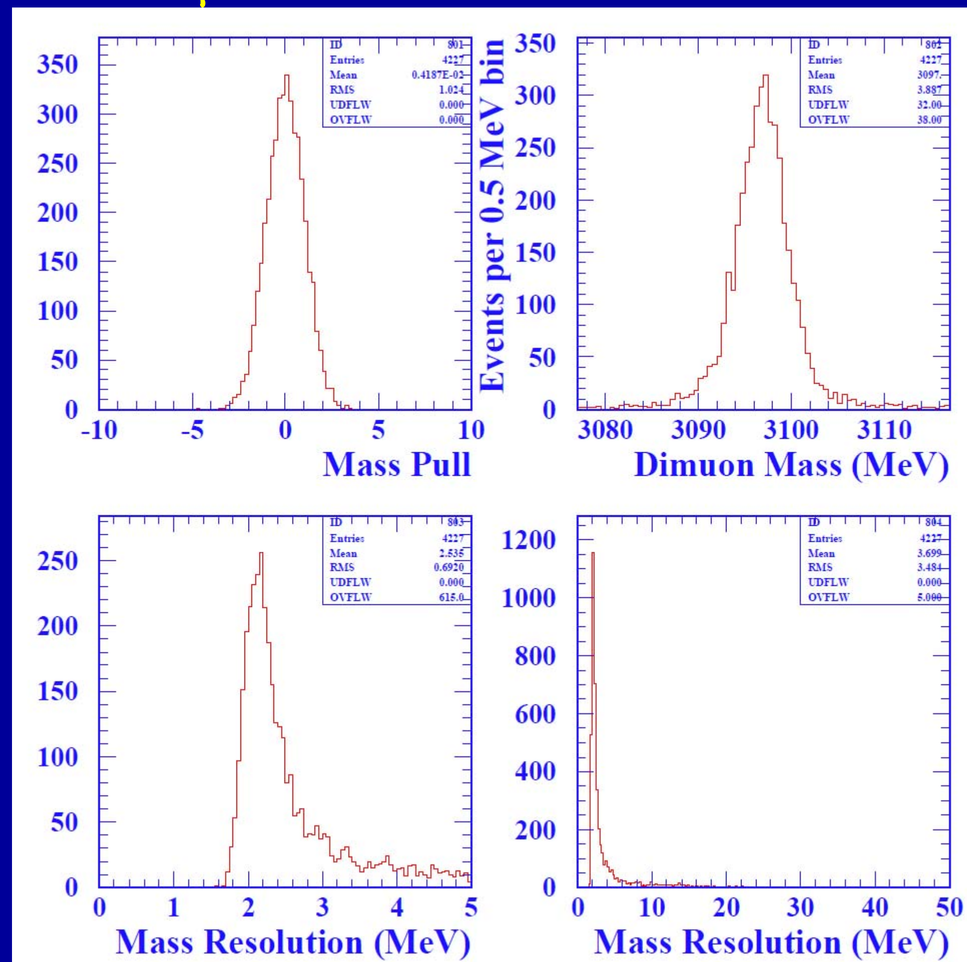
$\sqrt{s}=m_Z$

Implemented in MINUIT.
(tried OPAL and DELPHI fitters – but some issues)



Mass errors calculated from V_{12}, cross-checked with mass-dependent fit parameterization

With $P_{fit} > 1\%$ cut



$$\text{pull} \equiv \frac{m_{fit} - m_{gen}}{\Delta m_{fit}}$$

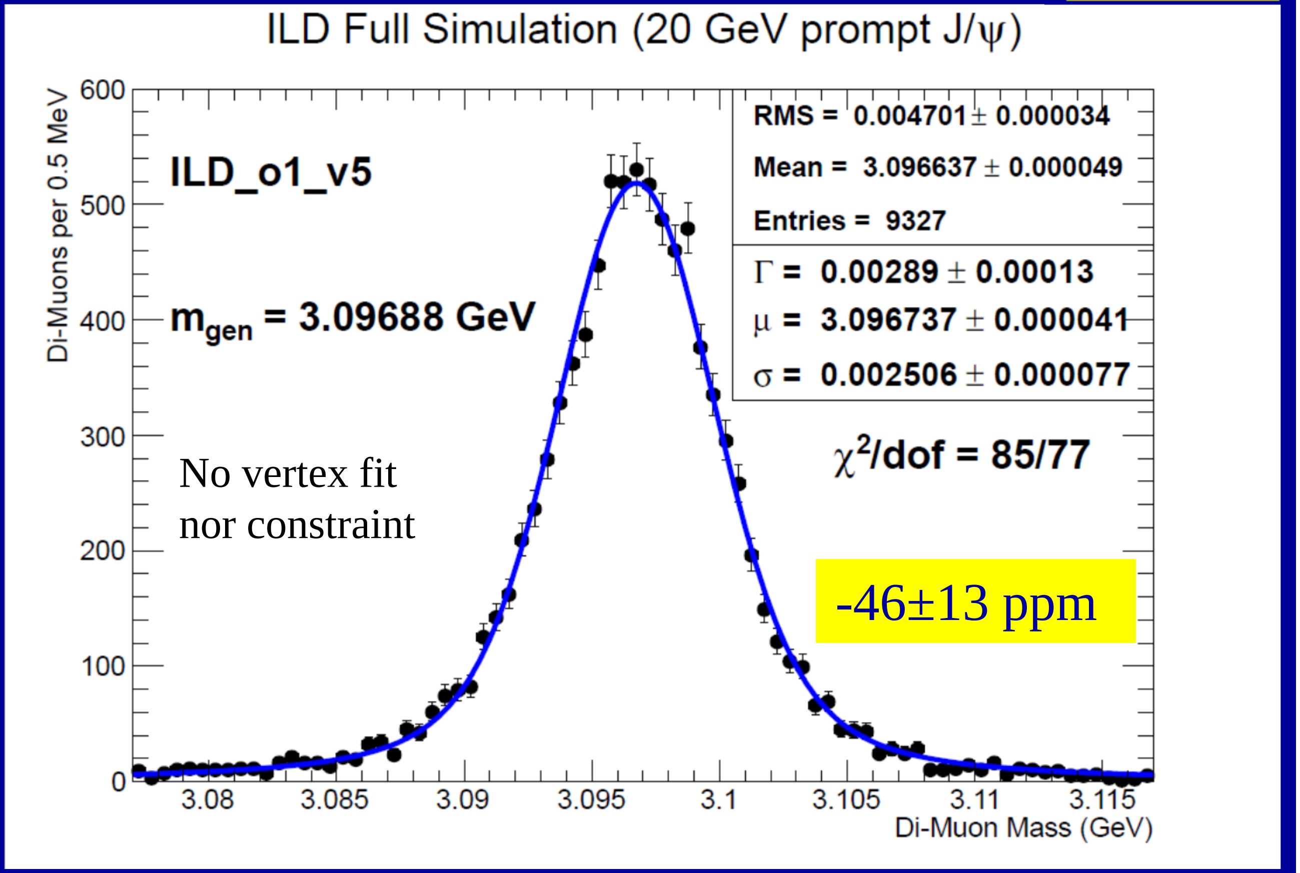
Full Simulation + Kalman Filter

10k “single particle events”

$\sqrt{s}=m_Z$

Work in progress – likely need to pay attention to issues like energy loss model and FSR.

Preliminary statistical precision similar.
More realistic material, energy loss and multiple scattering.



Empirical Voigtian fit.

Prospects at higher √s for establishing and maintaining momentum-scale calibration

J/psi:
- b $\bar{b}$ cross-section comparison

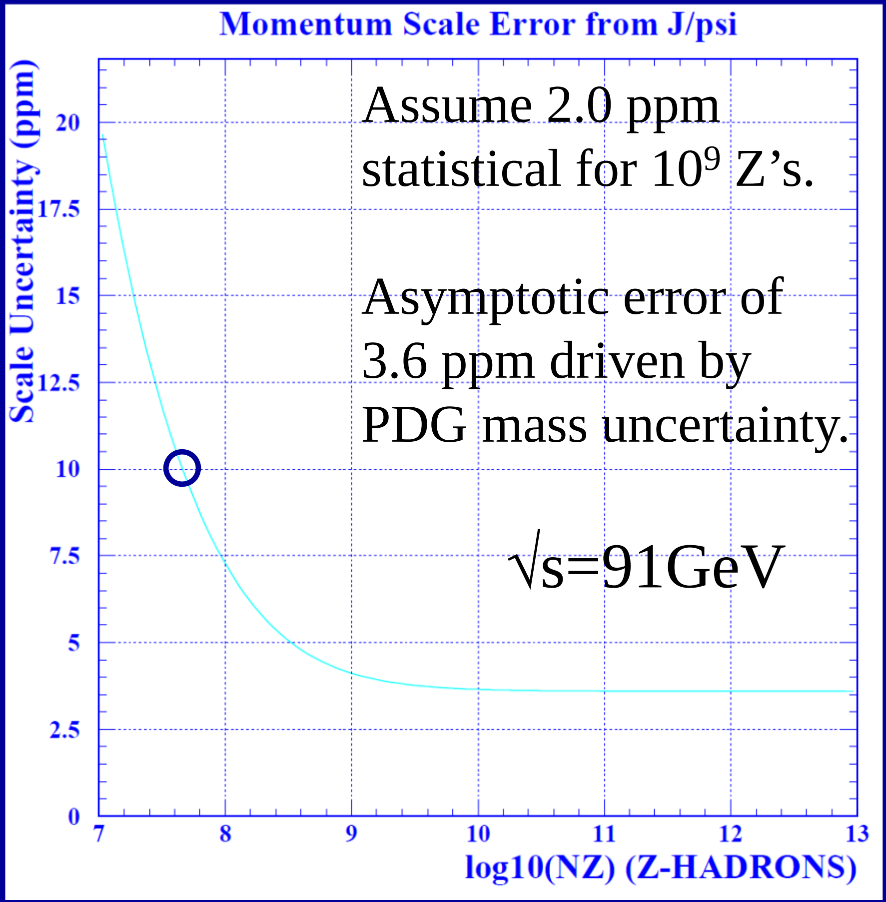
$\sqrt{s}$ (GeV)	91	161	250	350	500	1000
$\sigma_{b\bar{b}}$ (pb)	6600	25	9.9	4.9	2.5	0.7

Table 3: Unpolarized $e^+e^- \to b\bar{b}$ cross-sections

- Other modes: H X, t $\bar{t}$
- (prompt) J/psi production from γγ collisions (DELPHI: 45 pb @ LEP2)
- Also $\gamma\gamma \to$ b $\bar{b}$ leading to J/psi
- Best may be to use J/psi at Z to establish momentum scale, improve absolute measurements of particle masses (eg. D^0, K^0_S). (see backup slide)
  - Then use D^0, K^0_S, for more modest precision at high energy (example top mass application)

"Calibration" Run at $\sqrt{s}=m_Z$ for detector p-scale calibration

If detector is stable and not pushed, pulled and shaken, one could hope that such a calibration could be maintained long term at high energy.



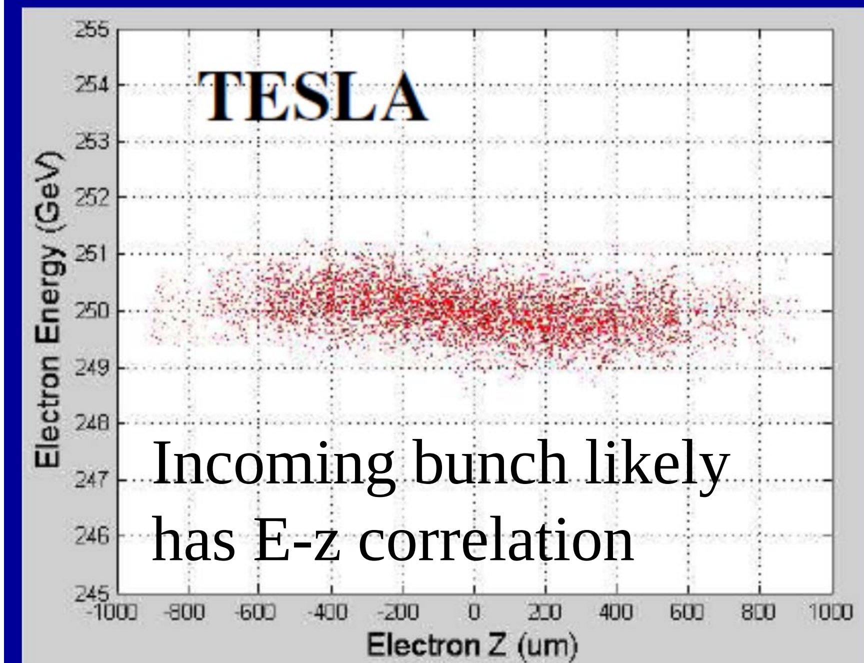
Plot assumes negligible systematics from tracking modeling …

⇒ Need at least 40 M hadronic Z's for 10 ppm

⇒ Corresponds to ≥ 1.3 fb^{-1} ($L \geq 1.3 \times 10^{33}$ for 10^6s) assuming unpolarized beams

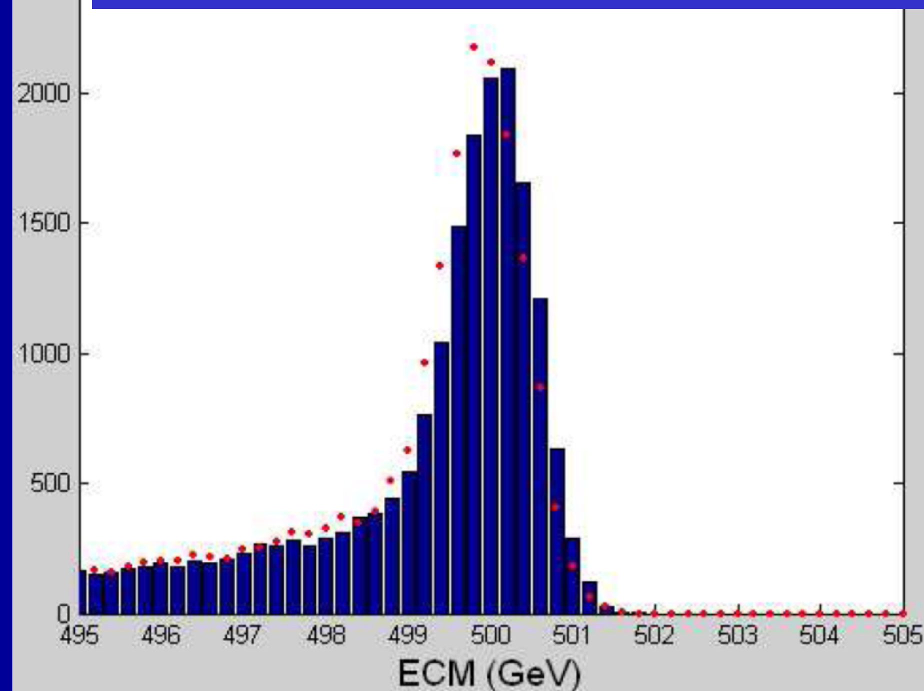
CoM Energy Measurement Systematics

An example of why an upstream spectrometer will not be good enough.



See Florimonte, Woods (IPBI TN-2005-01)

Histogram: with E-z correlation.
Red dots: no correlation



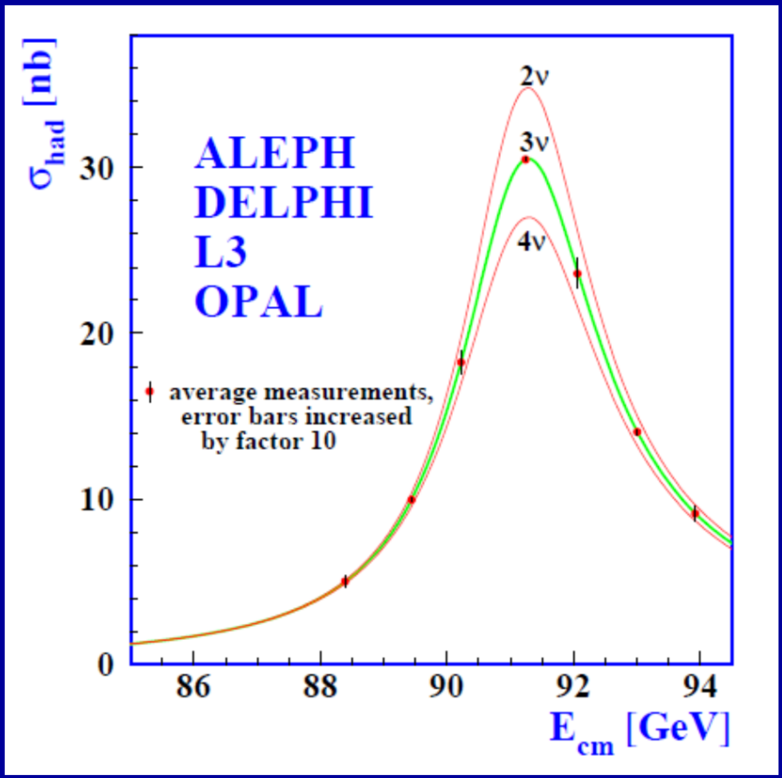
The incoming E-z correlation + the collision effects (disruption and beamstrahlung) leads to the actual luminosity spectrum being sensitive to the E-z correlation.
The $\sqrt{s_P}$ method should help resolve this issue.

Higher Precision Enables more Physics

- With the prospect of controlling $\sqrt{s}$ at the few ppm level, ILC can also consider targeting much improved Z line-shape parameters.
- The “Giga-Z” studies appear conservative in their assumptions on beam energy control - was the dominant systematic in many of the observables.
  - It was not believed that it was feasible to have an absolute $\sqrt{s}$ scale independent of the LEP1 Z mass measurement.
- Controlling the $\sqrt{s}$ systematics will also extend the scope for improvement on m_W using kinematic constraints at energies like 250 GeV and 350 GeV using $qql\nu$ in tandem with the Higgs and top program.

Z-lineshape: Measuring the Centre-of-Mass Energy at $\sqrt{s} \approx m_Z$

- The same $\sqrt{s_P}$ method with $\mu\mu(\gamma)$ should work
- Pros:
  - Cross-section much higher cf 161 GeV
  - Factor of 100.
  - Less beamstrahlung
  - p-scale calibration in place
- Cons:
  - Intrinsic fractional resolution worse
    E_b spread of 200 MeV (0.44%)



Prelim.Estimate: statistical error of 10 ppm on $\sqrt{s}$ with lumi corresponding to 30 M hadronic Z’s.

Conclusions 0

- The $\mu\mu(\gamma)$ channel using the $\sqrt{s_P}$ method is a very powerful $\sqrt{s}$ calibration method for a wide range of $\sqrt{s}$.
  - Running at the Z with high statistics is highly desirable to take advantage of J/psi statistics for the momentum scale calibration
    - Also obvious physics opportunities.
  - Need an excellent low material tracker, B-field map, alignment …
  - $\mu\mu(\gamma)$ should also be able to constrain the luminosity spectrum….
- While running at high $\sqrt{s}$, maintenance of the momentum scale would be very important and/or finding an independent method with similar power.

Concluding Remarks I

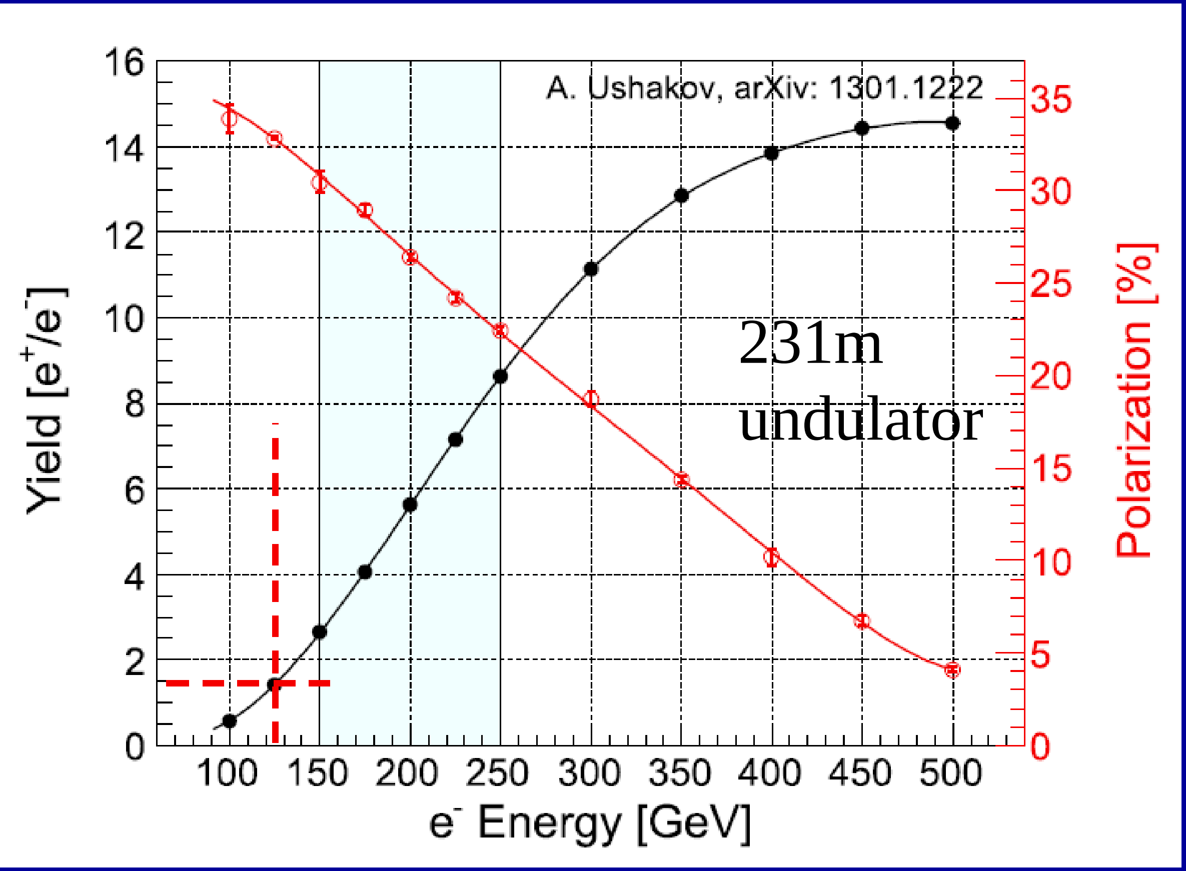
- In-situ precision C-o-M energy calibration using the $\sqrt{s_P}$ method with $\mu\mu(\gamma)$ events looks achievable at the 10's of ppm level for the 200-500 GeV program.
  - Requires excellent momentum resolution especially at high $\sqrt{s}$
  - Beware detector de-scoping ….
- Requires precision absolute calibration of detector momentum-scale and stability.
  - Calibration looks feasible with 100 M Z's using J/psi's.
    - (driven by momentum resolution in the multiple scattering regime)
  - Calibration challenging at high $\sqrt{s}$ – need further investigation
  - Stability – may also be challenging.
- 10 ppm error on $\sqrt{s}$, enables one to target even more precise m_W, and perhaps m_Z

Concluding Remarks II

- The ILC physics program will be even stronger with low energy running ($\sqrt{s}$<200GeV)
  - Need reasonable machine parameters for studies and a feasible machine design.
  - Adequate e^+ source essential.
- Beam energy spread is a major statistical limitation for the $\sqrt{s_P}$ method.
  - Especially for low $\sqrt{s}$.
- "Calibration runs" at the Z are interesting if the luminosity is not too low.
  - Recommend including relatively high L performance capability at the Z from the start given likely implications for C-o-M energy determination **at all $\sqrt{s}$**
- Running at 161 GeV (threshold) for m_W should be kept open.
  - Will be most time effective if done with highest possible beam polarizations (e^- and e^+) and luminosity. (e^- polarization level also very important!)
  - Methods for measuring m_W at 250 GeV, 350 GeV are more synergistic with the overall physics program.
    - But they still need to be fully demonstrated and shown to be ultimately competitive with the threshold method.

Backup Slides

Positron Source



For √s ≪ 250 GeV, still need a high energy e^- beam for adequate e^+ production.

Candidate Decay Modes for Momentum-Scale Calibration

Particle	$n_{Z\,\mathrm{had}}$	Decay	BR (%)	$n_{Z\,\mathrm{had}} \cdot$ BR	Γ/M	PDG $(\Delta M/M)$
J/ψ	0.0052	$\mu^-\mu^+$	5.93	0.00031	3.0×10^{-5}	3.6×10^{-6}
K^0_S	1.02	$\pi^-\pi^+$	69.2	0.71	1.5×10^{-14}	4.8×10^{-5}
Λ	0.39	π^-p	63.9	0.25	2.2×10^{-15}	5.4×10^{-6}
D^0	0.45	$K^-\pi^+$	3.88	0.0175	8.6×10^{-13}	7.0×10^{-5}

Table 1: Candidate standard candles for momentum scale calibration and abundances in Z decay.

Particle	Decay	Sensitivity	σ_M/M	Stat. Error (10^7 Z)	Stat. Error (10^9 Z)	PDG limit
J/ψ	$\mu^-\mu^+$	0.99	1.2×10^{-3}	22 ppm	2.2 ppm	3.6 ppm
K^0_S	$\pi^-\pi^+$	0.55	2.3×10^{-3}	1.6 ppm	0.16 ppm	87 ppm
Λ	π^-p	0.044	3.8×10^{-4}	5.5 ppm	0.55 ppm	123 ppm
D^0	$K^-\pi^+$	0.77	1.2×10^{-3}	3.7 ppm	0.37 ppm	91 ppm

Table 2: Estimated momentum scale statistical errors assuming 100% acceptance.

ILC Detector Concepts

Large international effort.
See Letters of Intent from 2009. Currently Detailed Baseline
(See ILC TDR)

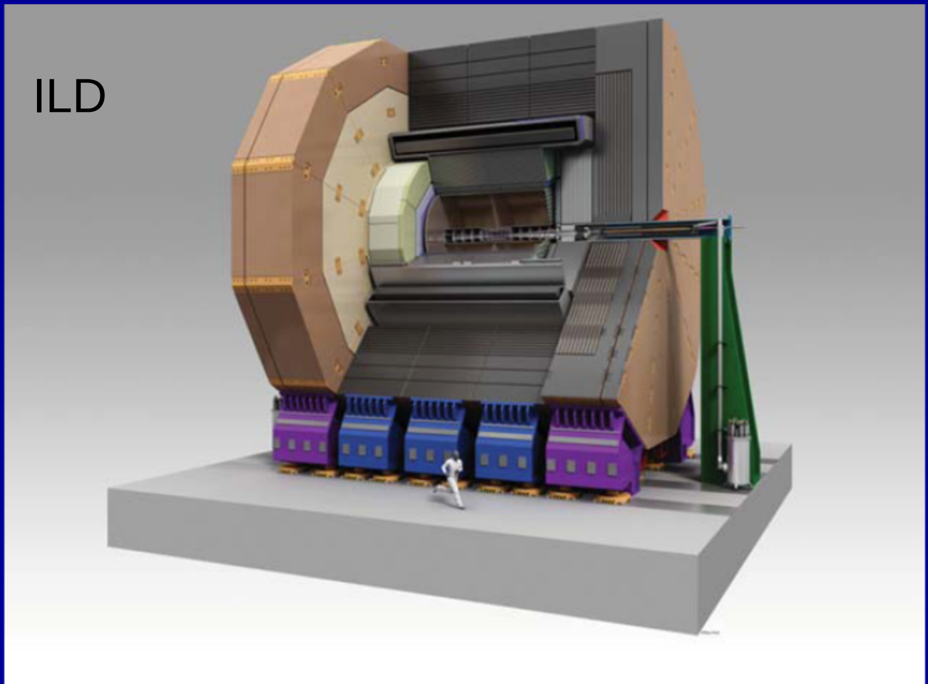
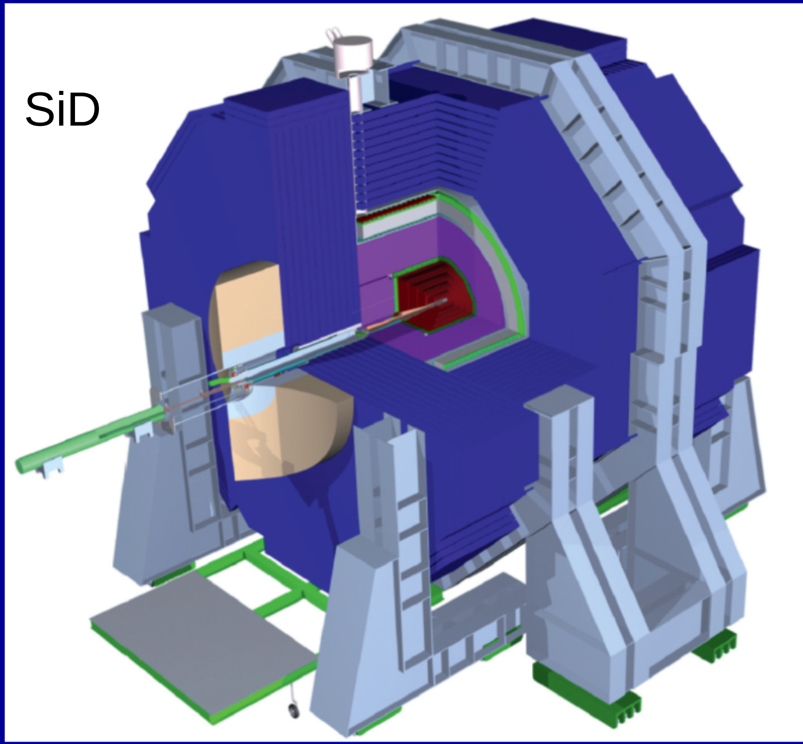


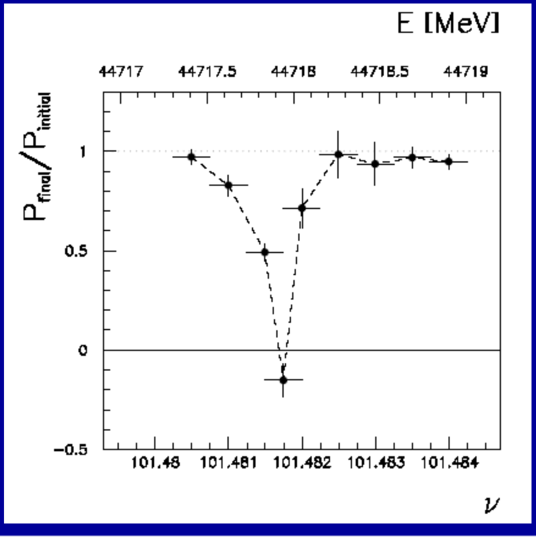
Figure 1.1.1: View of the ILD detector concept.

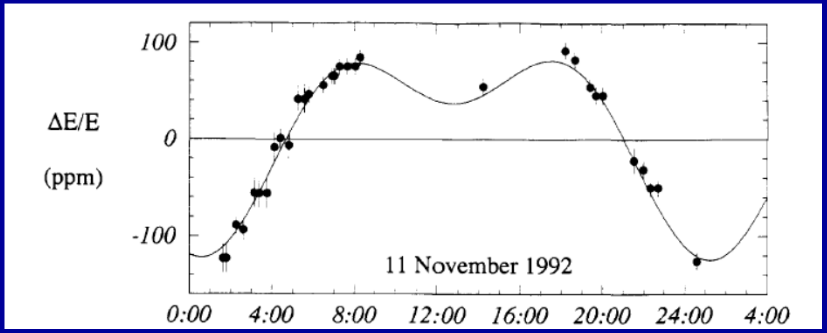


Detailed designs with engineering realism. Full simulations with backgrounds. Advanced reconstruction algorithms. Performance in many respects (not all) much better than the LHC experiments. Central theme: particle-flow based jet reconstruction. New people welcome !

Resonant spin depolarization

- In a synchroton, transverse polarization of the beam builds up via the Sokolov-Ternov effect.
- By exciting the beam with an oscillating magnetic field, the transverse polarization can be destroyed when the excitation frequency matches the spin precession frequency.
- Once the frequency is shifted off-resonance the transverse polarization builds up again.
- Can measure E_b to 100 keV or less





$$E_b = \frac{\nu_s \cdot m_e c^2}{(g_e - 2)/2} = \nu_s \cdot 440.6486(1)[\mathrm{MeV}]$$

Feasible at LEP for beam energies up to 50-60 GeV. Beam energy spread at higher energies too large.
(Not an option for ILC)

ILC Accelerator Parameters

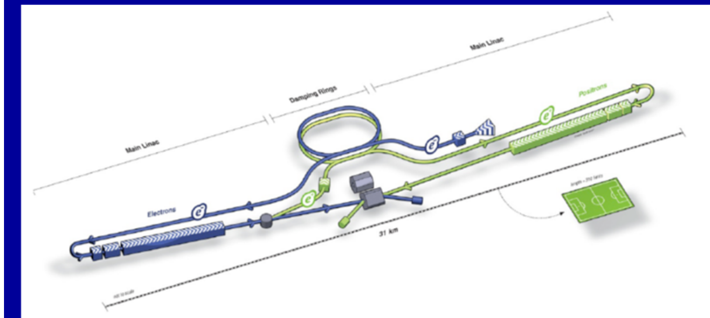


Figure 2: Layout of the ILC accelerator systems.

Parameters of interest for precision measurements:

Beam energy spread,
Bunch separation,
Bunch length,
e^- Polarization / e^+ Polarization,
dL/d√s ,
Average energy loss,
Pair backgrounds,
Beamstrahlung characteristics,

and of course **luminosity**.

								L Upgrade	E_{cm} Upgrade	
Centre-of-mass energy	E_{cm}	GeV	**200**	**230**	**250**	**350**	**500**	**500**	**1000**	**1000**
									A1	B1b
Beam energy	E_{beam}	GeV	100	115	125	175	250	500	500	500
Lorentz factor			#######	#######	#######	#######	#######	#######	9,78E+05	9,78E+05
Collision rate	f_{rep}	Hz	5	5	5	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	10	10	10	5	5	5	4	4
Number of bunches	n_b		1312	1312	1312	1312	1312	2625	2450	2450
Electron bunch population	N_-	$\times 10^{10}$	2,0	2,0	2,0	2,0	2,0	2,0	1,74	1,74
Positron bunch population	N_+	$\times 10^{10}$	2,0	2,0	2,0	2,0	2,0	2,0	1,74	1,74
Bunch separation	t_b	ns	554	554	554	554	554	366	366	366
Bunch separation $\times f_{RF}$	$t_b f_{RF}$		720	720	720	720	720	476	476	476
Pulse current	I_{beam}	mA	5,8	5,8	5,8	5,8	5,79	8,75	7,6	7,6
RMS bunch length	$_z$	mm	0,3	0,3	0,3	0,3	0,3	0,3	0,250	0,225
Electron RMS energy spread	p/p	%	0,206	0,194	0,190	0,158	0,124	0,124	0,083	0,085
Positron RMS energy spread	p/p	%	0,190	0,165	0,152	0,100	0,070	0,070	0,043	0,047
Electron polarisation	P_-	%	80	80	80	80	80	80	80	80
Positron polarisation	P_+	%	31	31	30	30	30	30	20	20
Horizontal emittance	$_x$	m	10	10	10	10	10	10	10	10
Vertical emittance	$_y$	nm	35	35	35	35	35	35	30	30
IP horizontal beta function	$_x^*$	mm	16,0	14,0	13,0	16,0	11,0	11,0	22,6	11,0
IP vertical beta function (no TF)	$_y^*$	mm	0,34	0,38	0,41	0,34	0,48	0,48	0,25	0,23
IP RMS horizontal beam size	$_x^*$	nm	904	789	729	684	474	474	481	335
IP RMS veritcal beam size (no TF)	$_y^*$	nm	7,8	7,7	7,7	5,9	5,9	5,9	2,8	2,7
Horizontal distruption parameter	D_x		0,2	0,2	0,3	0,2	0,3	0,3	0,1	0,2
Vertical disruption parameter	D_y		24,3	24,5	24,5	24,3	24,6	24,6	18,7	25,1
Horizontal enhancement factor	H_{Dx}		1,0	1,1	1,1	1,0	1,1	1,1	1,0	1,0
Vertical enhancement factor	H_{Dy}		4,5	5,0	5,4	4,5	6,1	6,1	3,5	4,1
Total enhancement factor	H_D		1,7	1,8	1,8	1,7	2,0	2,0	1,5	1,6
Geometric luminosity	L_{geom}	$\times 10^{34}$ cm^{-2}s^{-1}	0,30	0,34	0,37	0,52	0,75	1,50	1,77	2,64
Luminosity	**L**	$\times 10^{34}$ cm^{-2}s^{-1}	**0,50**	**0,61**	**0,68**	**0,88**	**1,47**	**2,94**	**2,71**	**4,32**
Average beamstrahlung parameter	$_{av}$		0,013	0,017	0,020	0,030	0,062	0,062	0,127	0,203
Maximum beamstrahlung paramete	$_{max}$		0,031	0,041	0,048	0,072	0,146	0,146	0,305	0,483
Average number of photons / partic	n		0,95	1,08	1,16	1,23	1,72	1,72	1,43	1,97
Average energy loss	E_{BS}	%	0,51	0,75	0,93	1,42	3,65	3,65	5,33	10,20
Luminosity	L	$\times 10^{34}$ cm^{-2}s^{-1}	0,498	0,607	0,681	0,878	1,50	3,00	3,23	4,31
Coherent waist shift	W_y	m	250	250	250	250	250	250	190	190
Luminosity (inc. waist shift)	**L**	$\times 10^{34}$ cm^{-2}s^{-1}	**0,56**	**0,67**	**0,75**	**1,0**	**1,8**	**3,6**	**3,6**	**4,9**
Fraction of luminosity in top 1%	$L_{0.01}/L$		91,3%	88,6%	87,1%	77,4%	58,3%	58,3%	59,2%	44,5%
Average energy loss	E_{BS}		0,65%	0,83%	0,97%	1,9%	4,5%	4,5%	5,6%	10,5%
Number of pairs per bunch crossing	N_{pairs}	$\times 10^3$	44,7	55,6	62,4	93,6	139,0	139,0	200,5	382,6