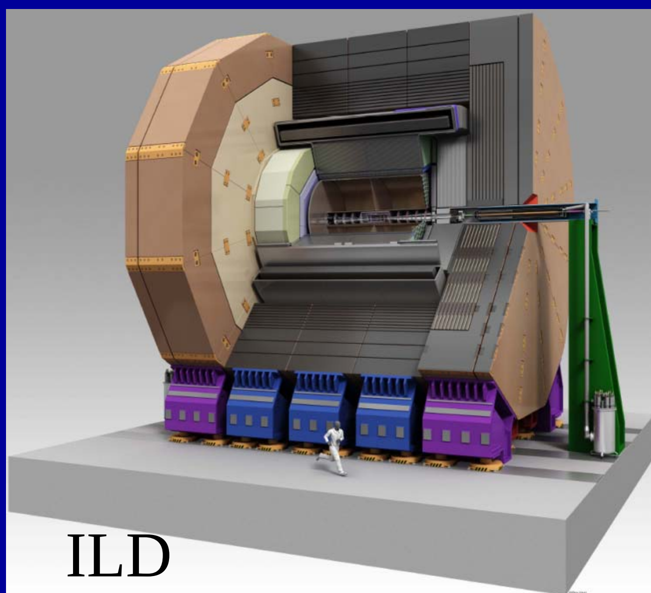
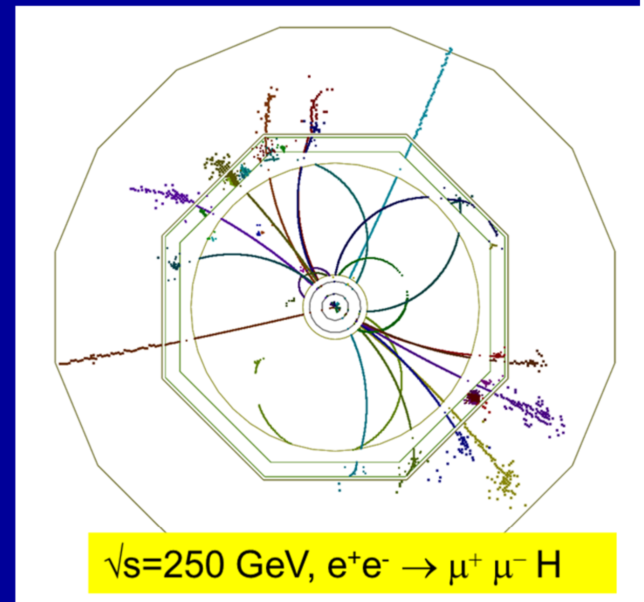
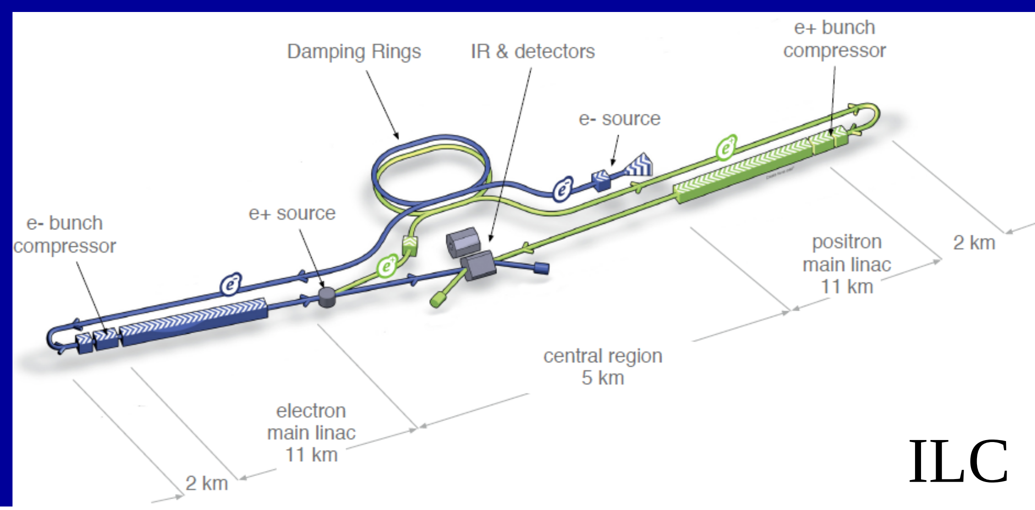
Revisiting W Mass Measurement from a Polarized Threshold Scan at ILC

aka $m_W^2 = E_{\mu\mu(\gamma)}^2 - P_{J/\psi}^2$







Graham W. Wilson

KU HEP Seminar

Feb 20th 2014

Context

- Work related to last year's Snowmass process – with contributions related to ILC and participation in the "Energy Frontier" electroweak group.
  - Put some of the claims on a firmer footing
- Ongoing "re-optimization" studies of the ILD detector.
  - In light of today's physics landscape
  - Examine what resolution is required
  - Is the high performance (and cost) justifiable ?

Outline

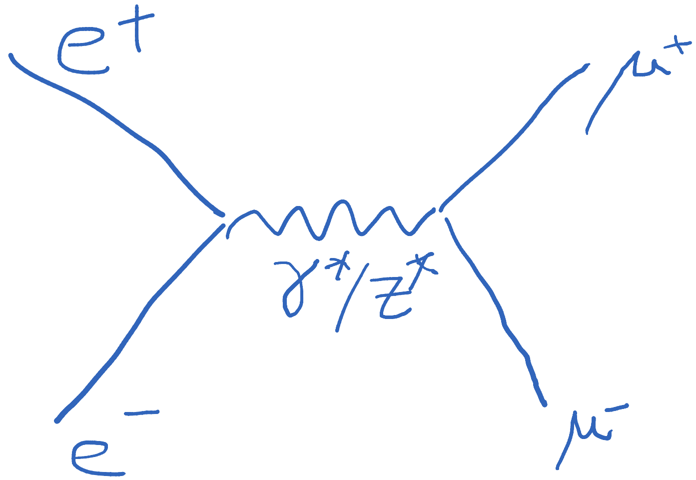
- I: m_W
- II: $\sqrt{s}$ measurement using $\mu\mu(\gamma)$
- III: J/psi based momentum calibration

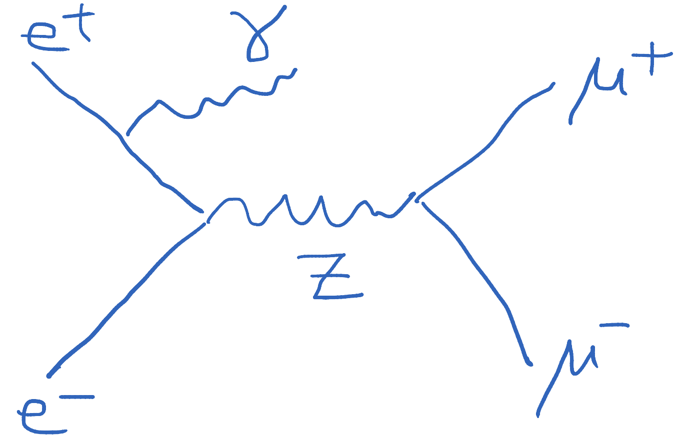
Why

aka $m_W^2 = E^2_{\mu\mu(\gamma)} - P^2_{J/\psi}$

- Measuring m_W precisely in e^+e^- collisions, usually means measuring the center-of-mass energy ($\sqrt{s}$) precisely.
- The center-of-mass energy may be measured from di-muon events (often with photons included)

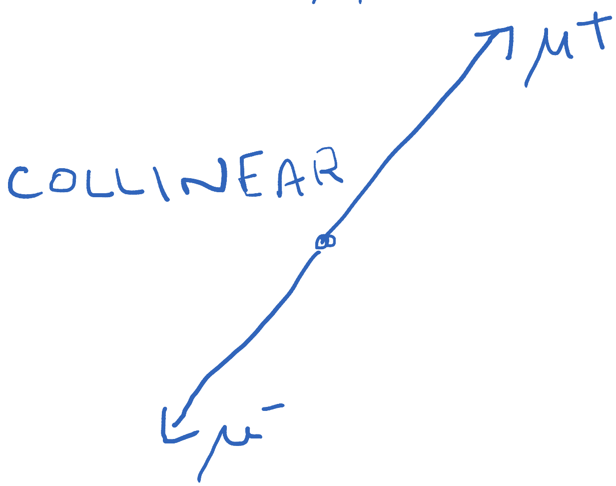
Di-muon topologies

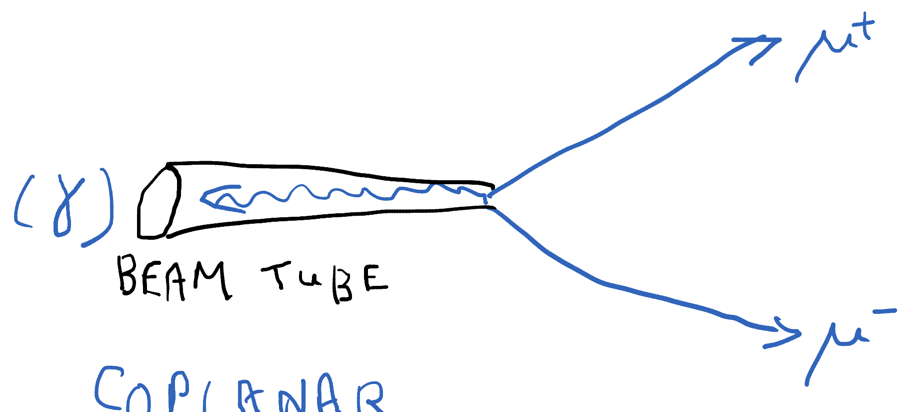




$M_{\mu\mu} \approx \sqrt{s}$

$M_{\mu\mu} \approx M_Z$





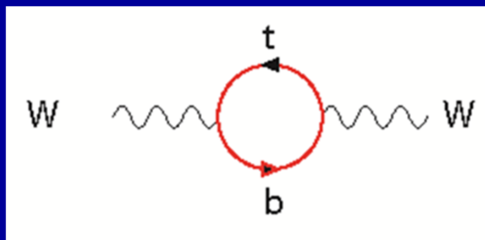
“radiative-return”

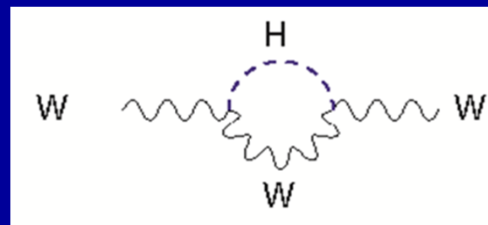
Why

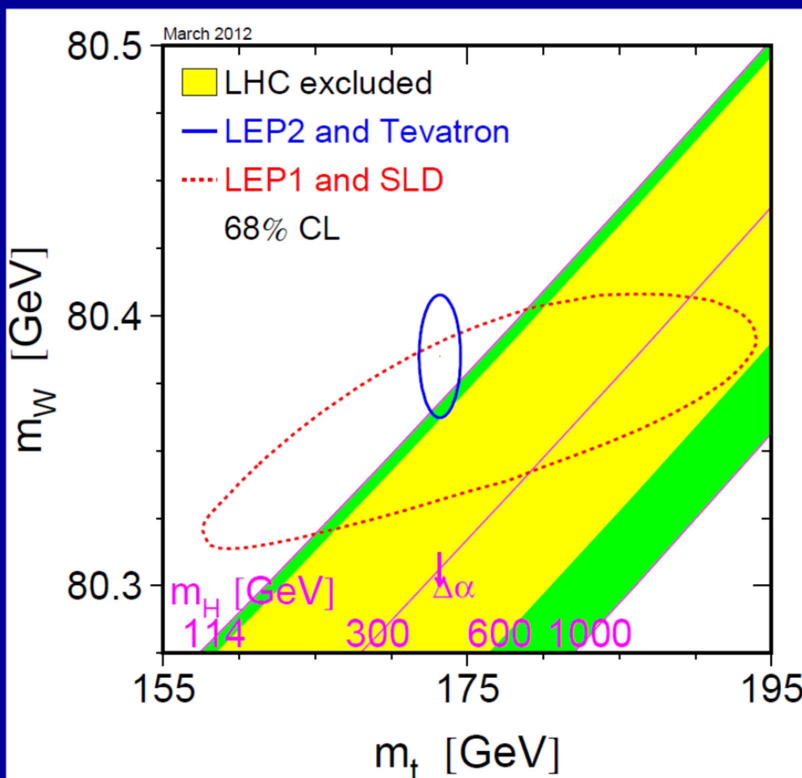
aka $m_W^2 = E^2_{\mu\mu(\gamma)} - P^2_{J/\psi}$

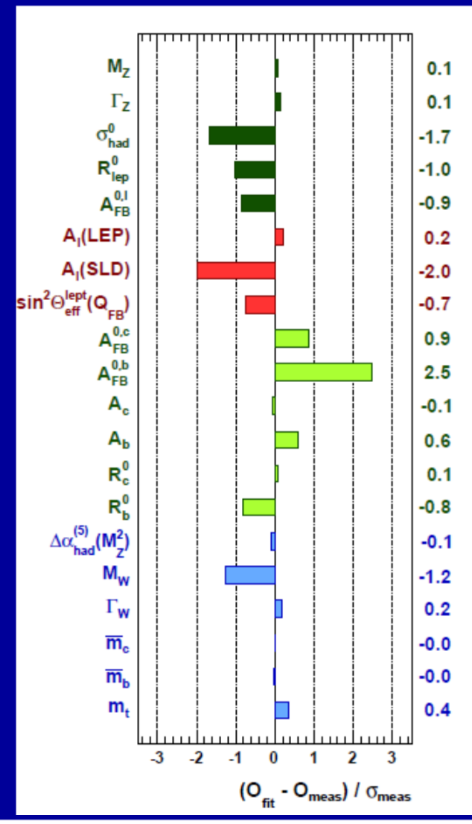
- Measuring m_W precisely in e^+e^- collisions, usually means measuring the center-of-mass energy ($\sqrt{s}$) precisely.
- The center-of-mass energy may be measured from di-muon events (often with photons included)
  - The di-muon momentum method requires an absolute momentum scale calibration
- The best way to do this appears to be using J/psi's.
  - (I made the claim that this could be done to 10 ppm)
  - Most prolific source is from $Z \rightarrow b\ b$
  - J/psi mass is known to 3.6 ppm

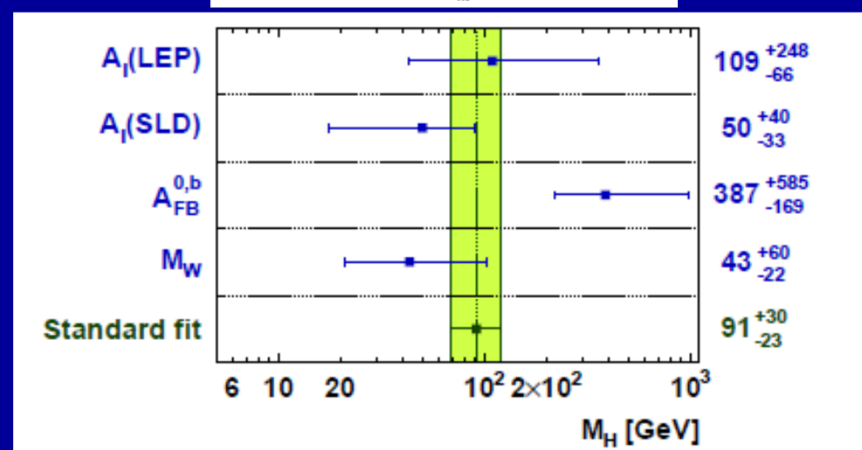
Precision Electroweak - 2011









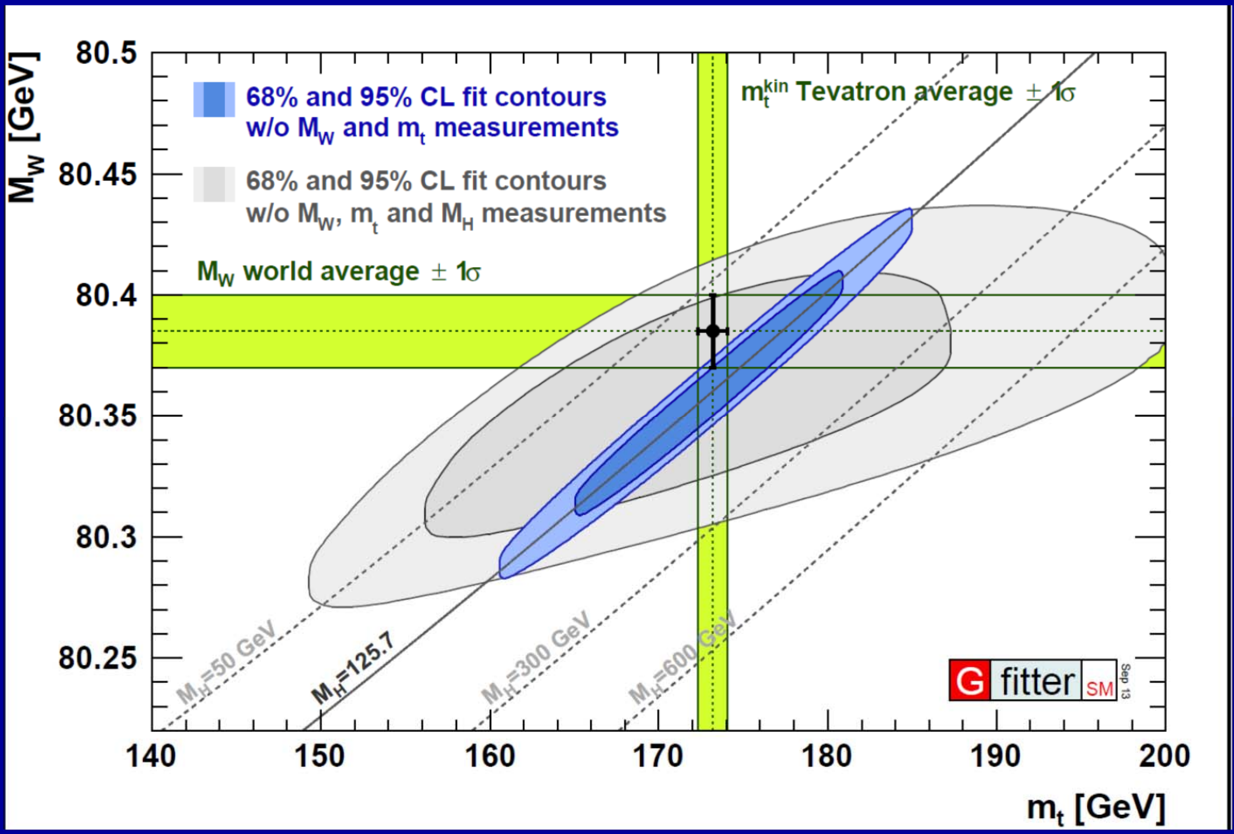


Data have been indicating a light Higgs for quite some time.

Precision Measurements

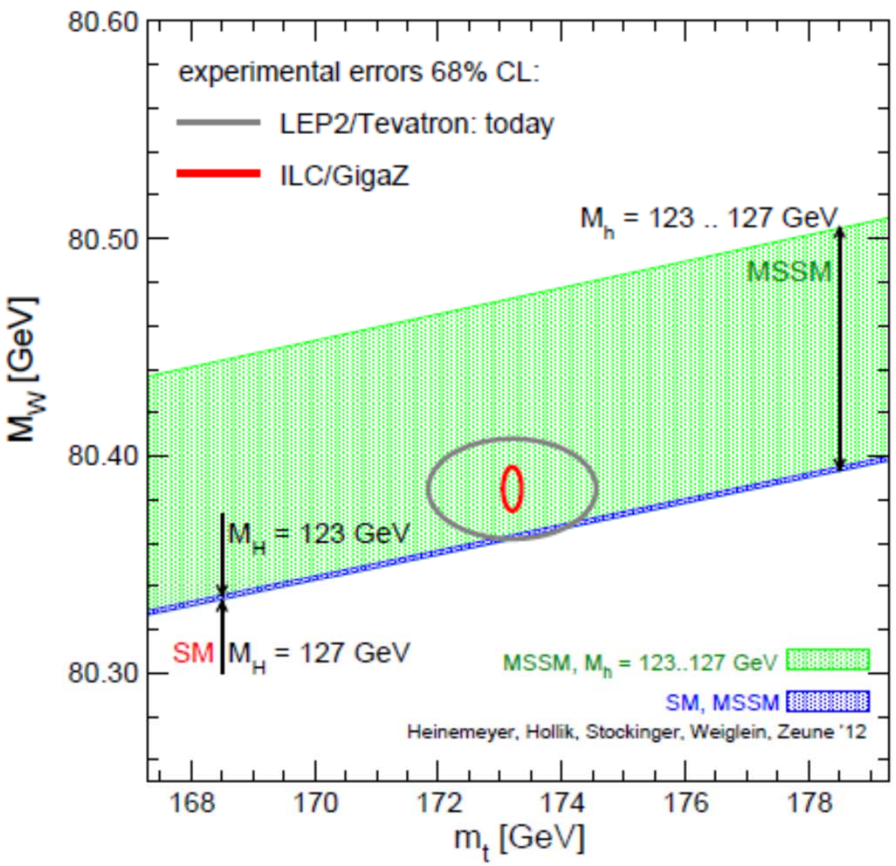
Testing Nature at ILC.

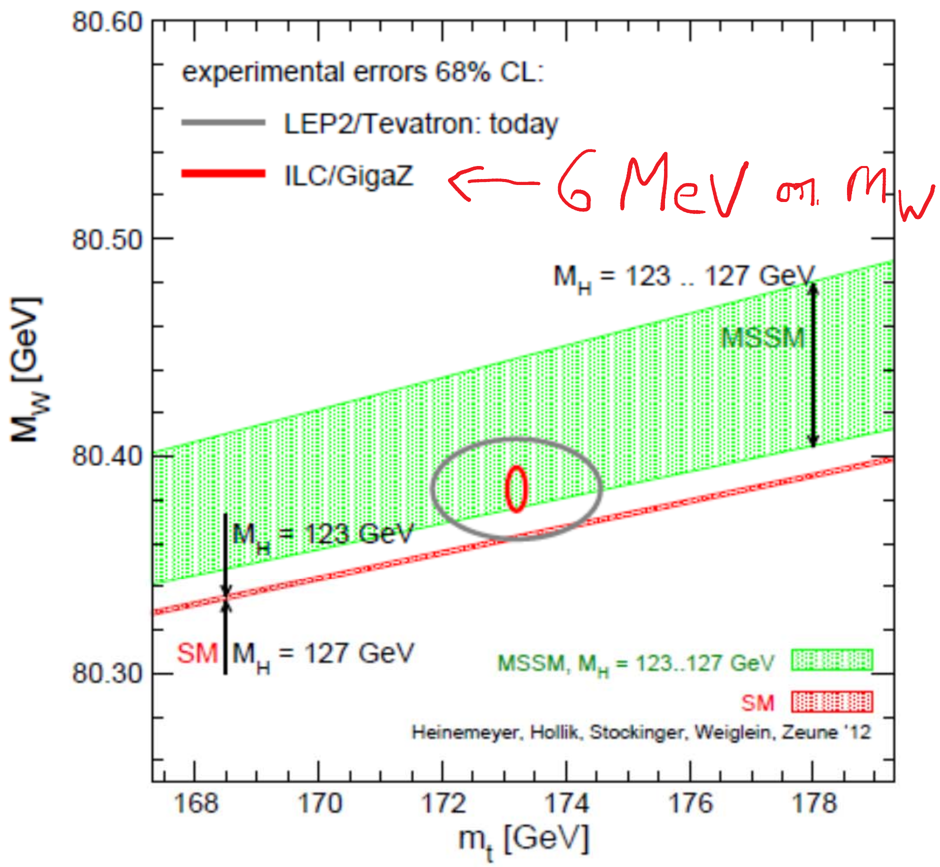
Can measure m_W, m_t, m_H, A_{LR}. m_Z? with unprecedented precision.



Now that m_H is measured directly, improvements in the green bands (m_t and especially m_W) and blue bands (A_{LR} etc) are directions which test the internal consistency of the SM, and may probe for new physics to high scales.

Would m_W 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 (in the MSSM).

Precision Measurements

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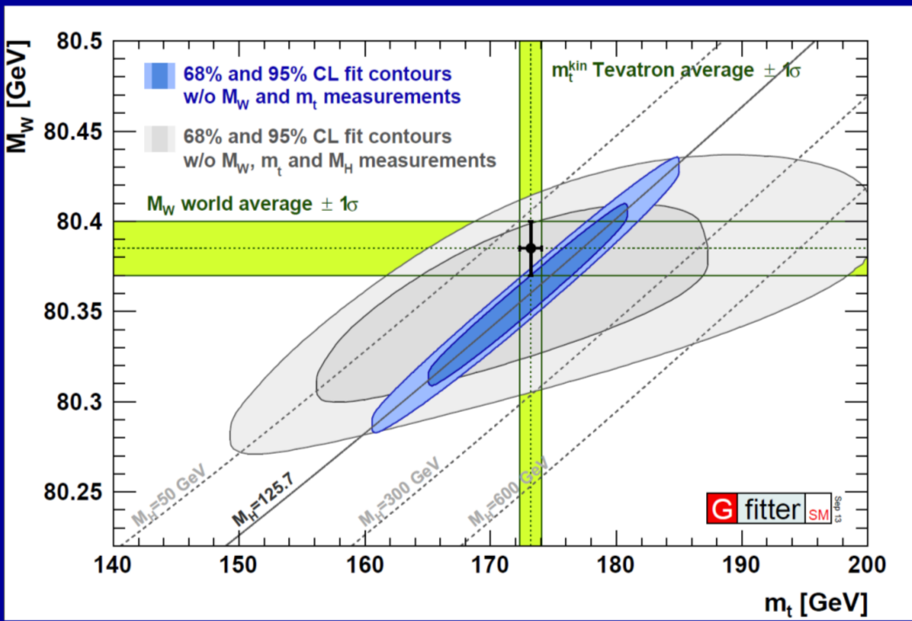
Can measure m_W, m_t, m_H, A_{LR}. m_Z? with unprecedented precision.



Experimental reach depends on ability to control systematics such as those associated with the beam energy measurement and detector energy scales. I've been working on these aspects.

arXiv: 1307.3962 and arXiv:1310.6780

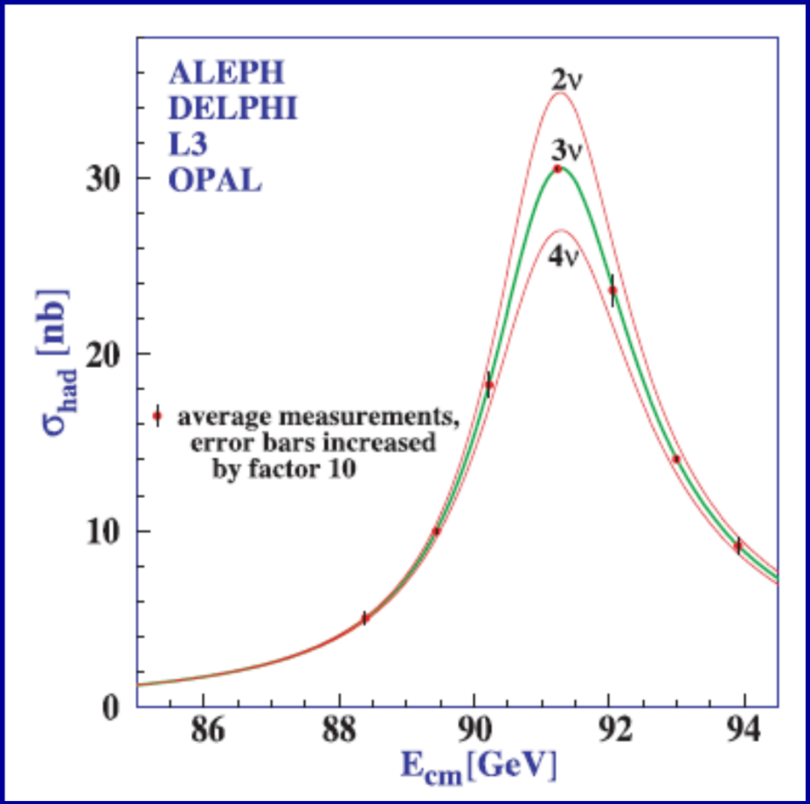
Exploring Quantum Physics at the ILC

(White Paper for the HEP decadal survey)

A. Freitas[1*], K. Hagiwara[2†], S. Heinemeyer[3‡], P. Langacker[4,5§], K. Moenig[6¶], M. Tanabashi[7,8‖] and G.W. Wilson[9**]

Study of Electroweak Interactions at the Energy Frontier

A bit of history



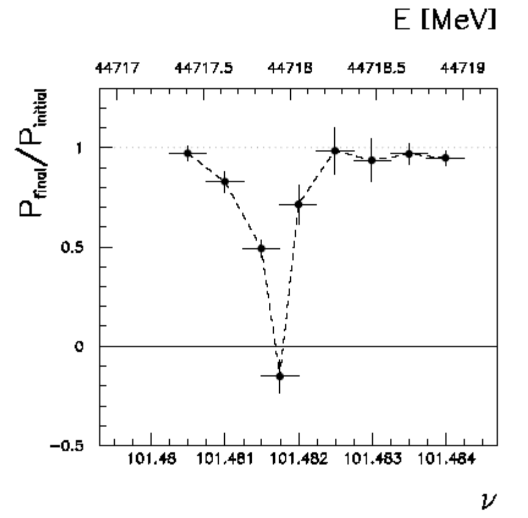
- The Z mass and width were measured at LEP (1989-1995) to very high precision from a line-shape scan
- $m_Z = 91187.6 \pm 2.1$ MeV
- $\Gamma_Z = 2495.2 \pm 2.3$ MeV
- A primary experimental issue was knowledge of the absolute center-of-mass energy scale

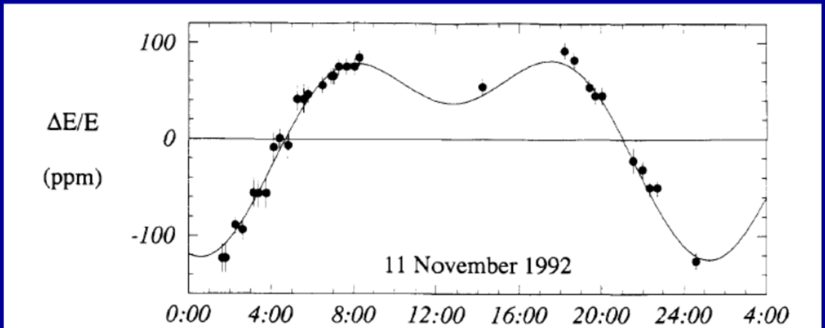
The beam energy could be measured precisely using resonant depolarization. (See eg. Assmann et al, EPJC6 (1999) 187-223)

What is resonant de-polarization (RDP)?

- 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 in principle measure E_b to 100 keV (2ppm)

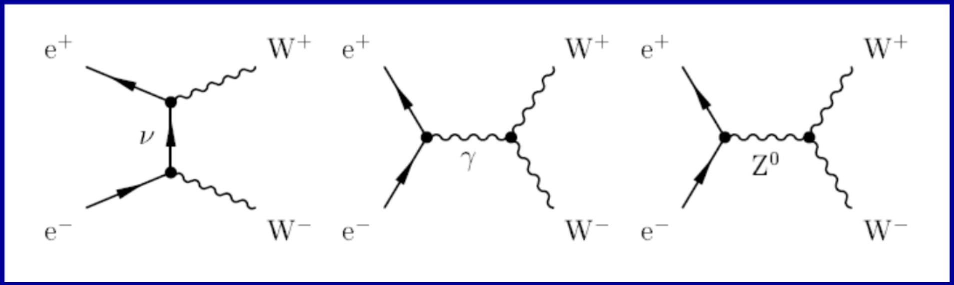
$$E_b = \frac{\nu_s \cdot m_e c^2}{(g_e - 2)/2} = \nu_s \cdot 440.6486(1)[\text{MeV}]$$

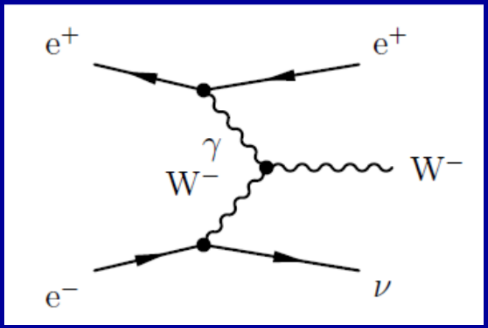




Feasible at LEP for beam energies up to 50-60 GeV. Beam energy spread at higher energies too large.
(Not an option for ILC)

W Production in e^+e^-

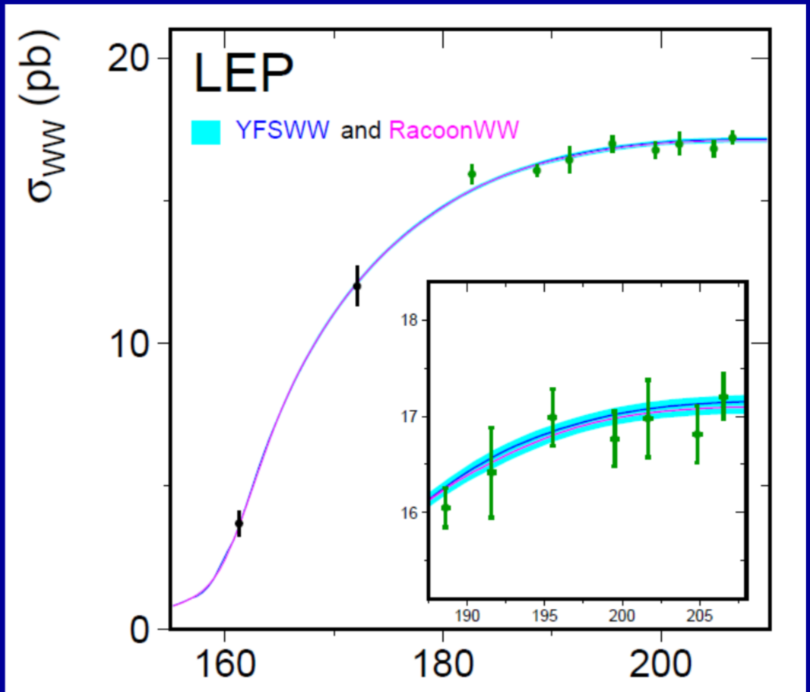


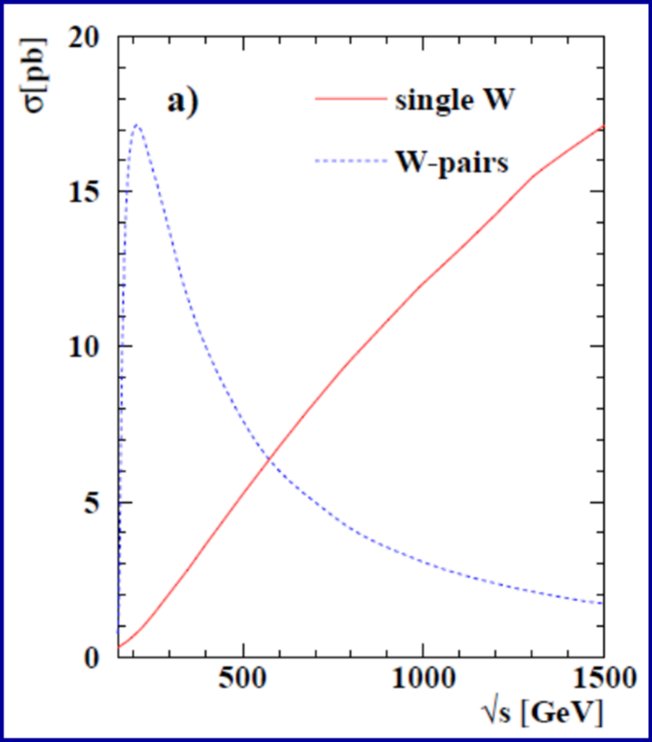


etc ..

$e^+e^- \to W^+W^-$

$e^+e^- \to W\, e\, \nu$

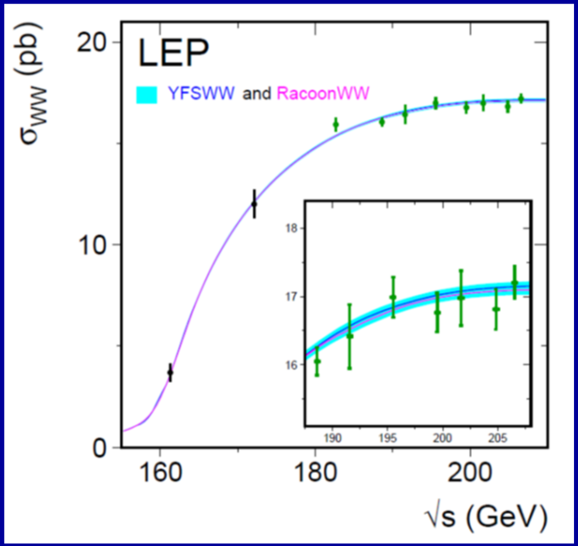


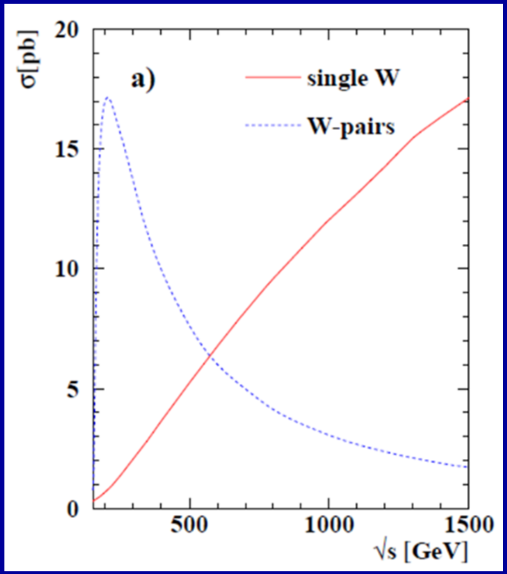


unpolarized cross-sections

W Mass Measurement Strategies

- W^+W^-
  - 1. Threshold Scan (σ ~ β/s)
    - Can use all WW decay modes
  - 2. Kinematic Reconstruction (qqeν and qqμν)
    - Apply kinematic constraints
- W e ν (+ WW)
  - 3. Directly measure the hadronic mass in W → q q' decays.
    - Can use WW → qqτν too



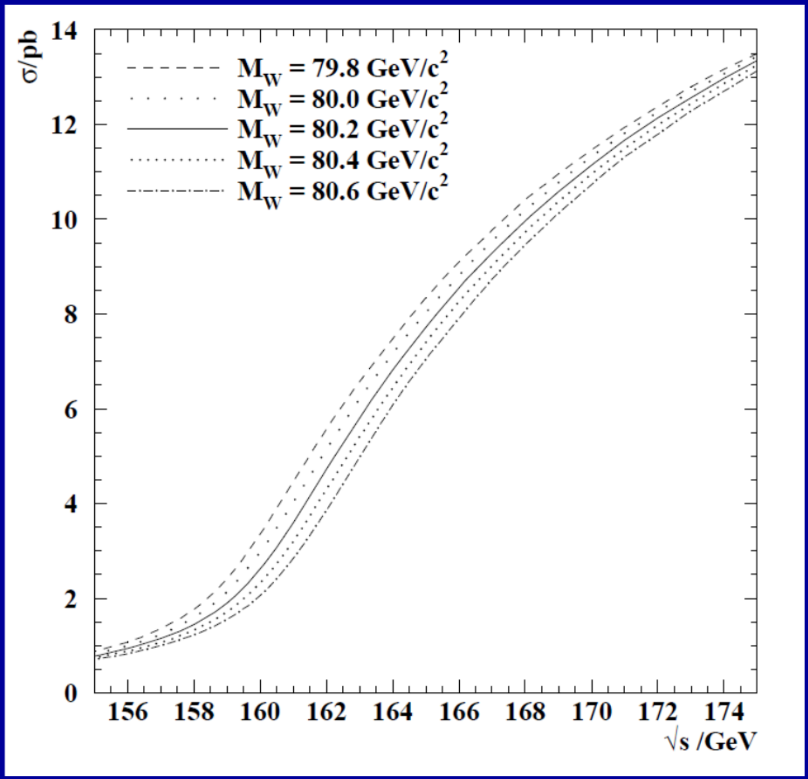


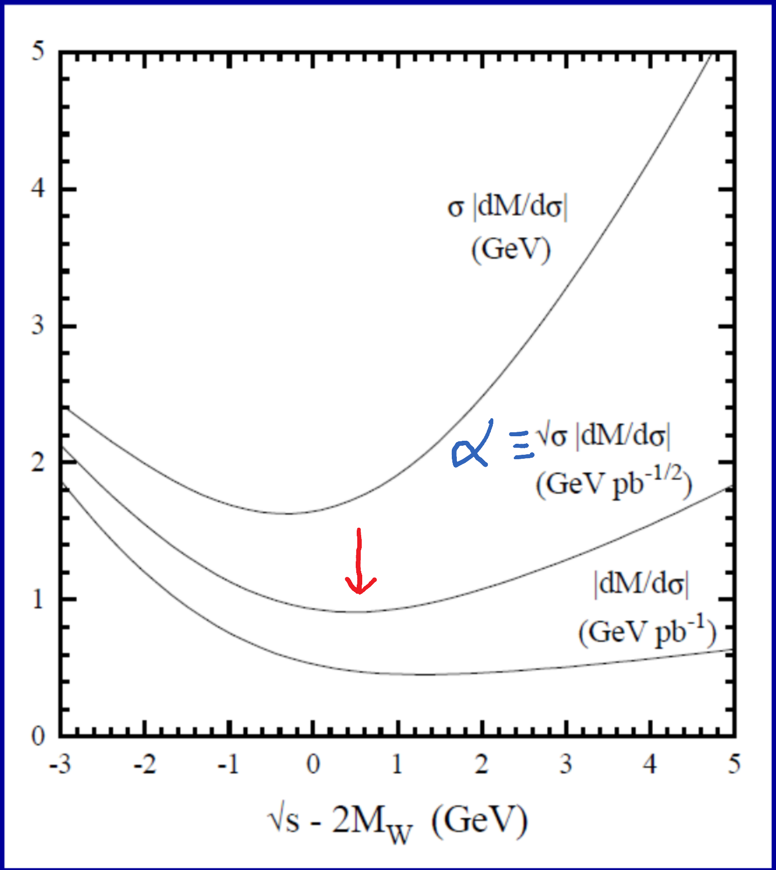
Methods 1 and 2 were used at LEP2. Both require good knowledge of the absolute beam energy.

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

LEP2 YR (hep-ph/9602352)

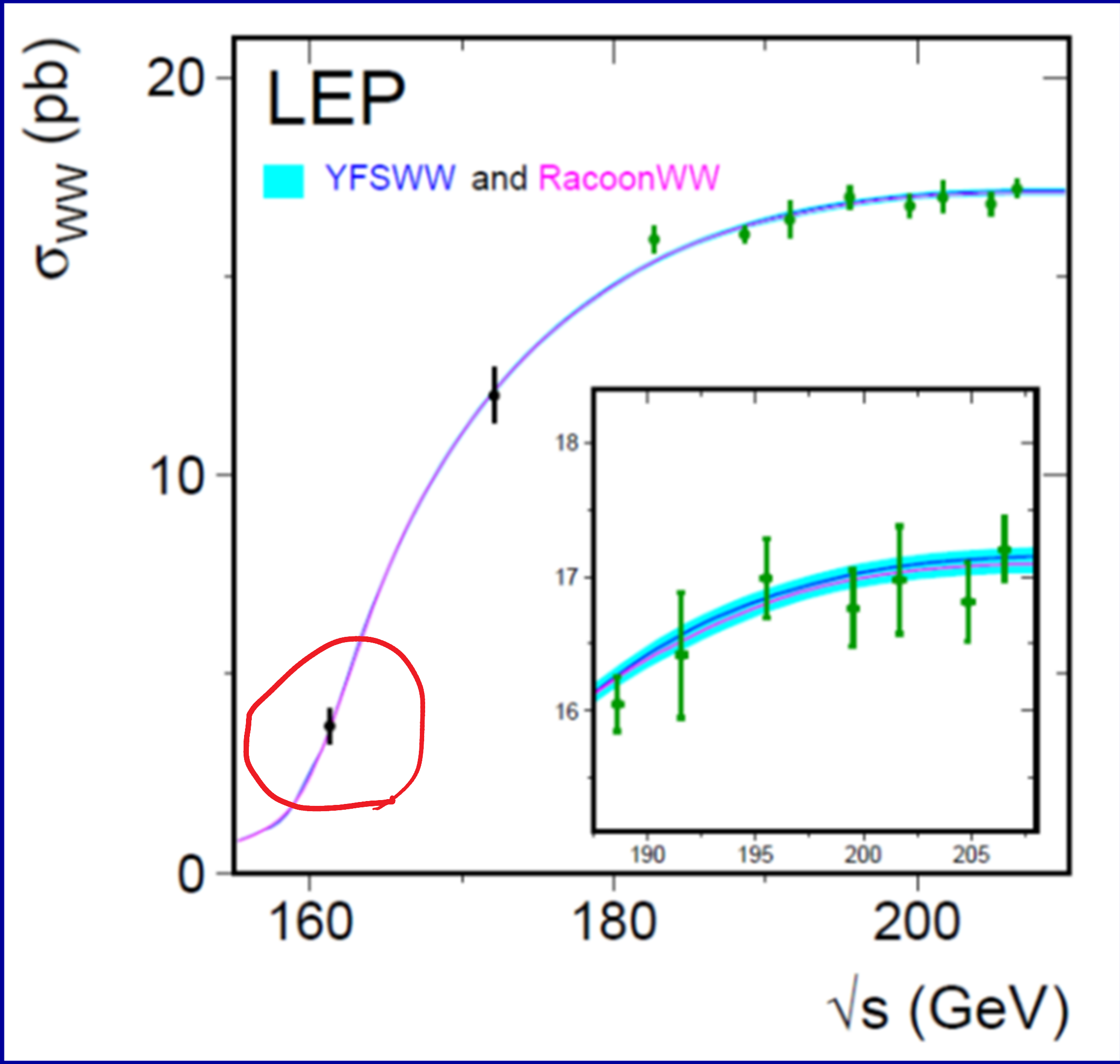
In 1996, m_W was already known to 160 MeV from the Tevatron





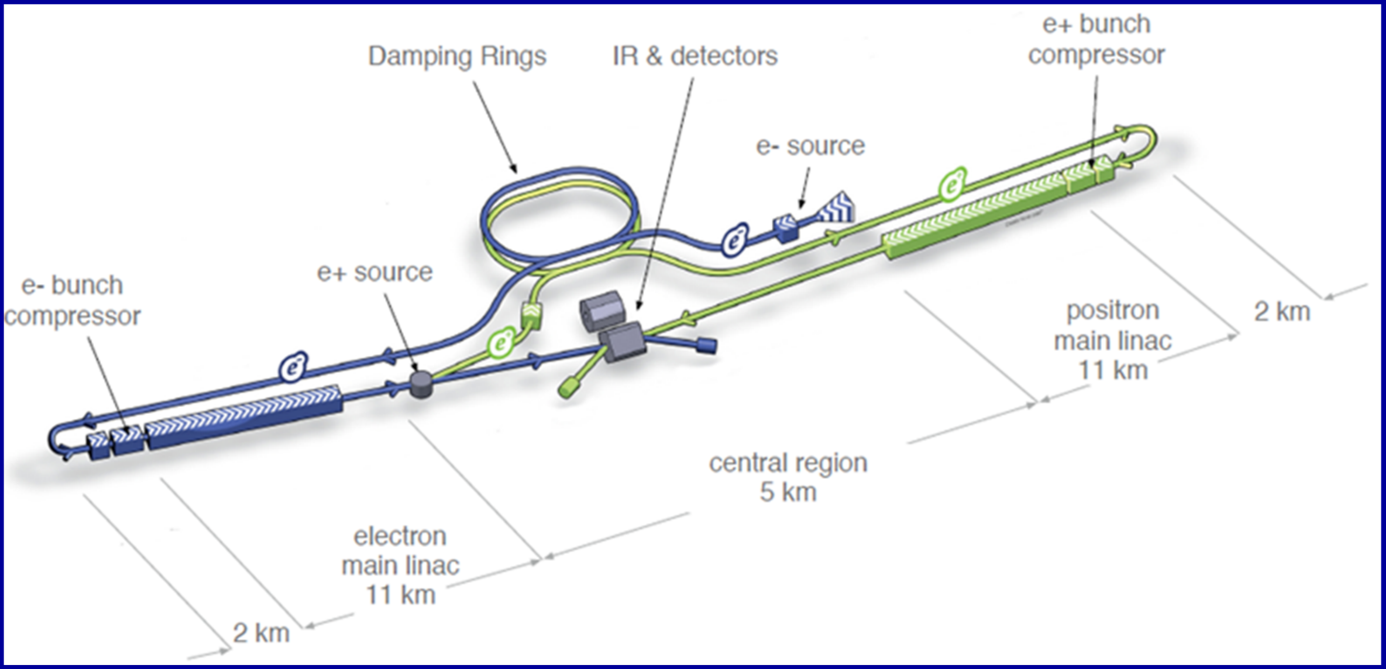
$$\Delta m_W^{stat} = \frac{\alpha}{\sqrt{\varepsilon \mathcal{L}}} \text{ with } \alpha_{opt} = 0.91$$

LEP2 Threshold Cross-Section Measurement



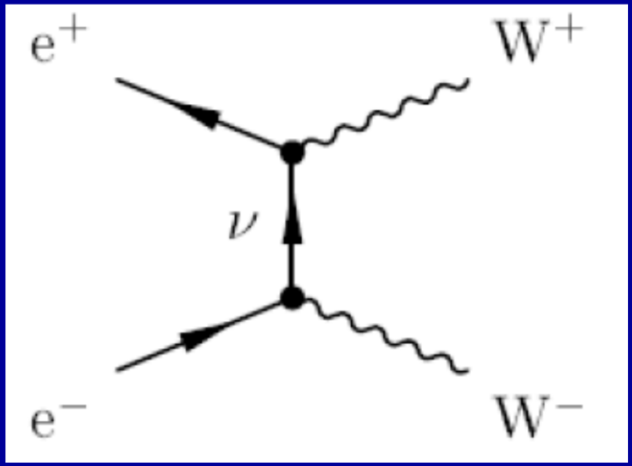
- 10 pb^{-1} per experiment was collected at **one** CME energy (161.3 GeV) in 1996
- 35 events produced per experiment

International Linear Collider (ILC)



O(100 fb^{-1}) per year near 161 GeV.
Polarized beams.
Beamstrahlung (BS)

Polarized Beams



- Near threshold W W cross-section almost entirely due to this diagram.
- Only couples to $e_L^- e_R^+$

$$\sigma(P_{e^-}, P_{e^+}) = \frac{1}{4}\{(1-P_{e^-})(1+P_{e^+})\sigma_{LR} + (1+P_{e^-})(1-P_{e^+})\sigma_{RL} + (1-P_{e^-})(1-P_{e^+})\sigma_{LL} + (1+P_{e^-})(1+P_{e^+})\sigma_{RR}\}$$

If one could collide fully polarized beams with the favorable helicities, the cross-section is quadrupled !
Colliding the wrong helicity combination => turn off WW production.
It appears feasible to flip the helicity of both beams.

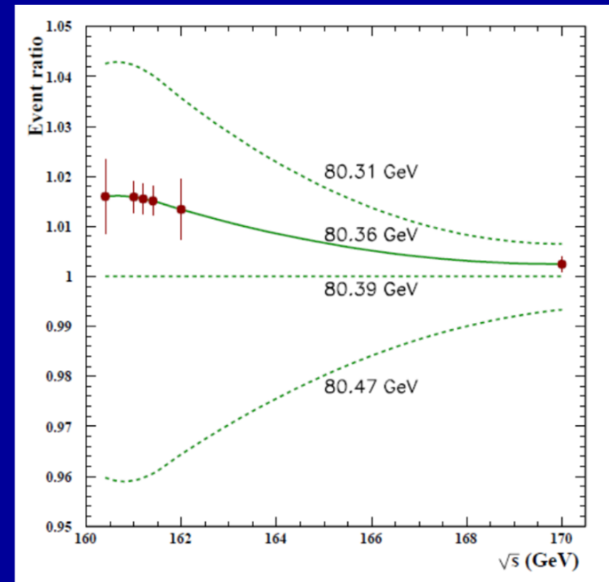
m_W Measurement Prospects Near Threshold

LCWS99 + TESLA TDR

PRECISION MEASUREMENT OF THE W MASS WITH A POLARISED THRESHOLD SCAN AT A LINEAR COLLIDER

Graham W. Wilson, LC-PHSM-2001-009, 21st February 2001
Department of Physics, Schuster Laboratory, The University, Manchester M13 9PL, UK

Threshold scans potentially offer the highest precision in the determination of the masses and widths of known and as yet undiscovered particles at linear colliders. Concentrating on the definite example of the WW threshold for determining the W mass (M_W), it is shown that the currently envisaged high luminosities and longitudinal polarisation for electrons **and positrons** allow M_W to be determined with an error of 6 MeV with an integrated luminosity of 100 fb^{-1} (One 10^7 s year with TESLA). The method using polarised beams is statistically powerful and experimentally robust; the efficiencies, backgrounds and luminosity normalisation may if needed be determined from the data. The uncertainties on the beam energy, the beamstrahlung sprectrum and the polarisation measurement are potentially large; required precisions are evaluated and methods to achieve them discussed.



LEP2 numbers

Channel (j)	Efficiency (%)	Unpolarised $\sigma_{\rm bkgd}$ (fb)	WW fraction (%)
$\ell\ell$	75	20	10.5
ℓh	75	80	44.0
h h	67	400	45.5

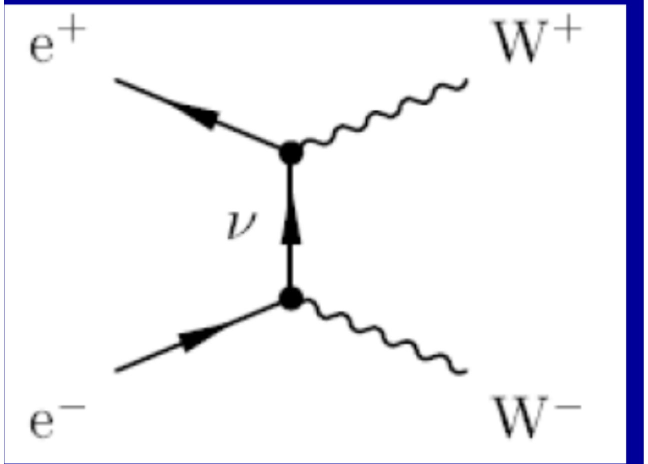
$\sqrt{s}$ (j)	Luminosity weight
160.4	0.2
161.0	1.0
161.2	1.0
161.4	1.0
162.0	0.2
170.0	1.2

Measure at 6 values of √s, in 3 channels, and with up to 9 different helicity combinations.

Estimate error of 6 MeV (includes E_b error of 2.5 MeV from Z γ) per 100 fb^{-1} polarized scan (assumed 80%/60% e^-/e^+ polarization)

Used RR (100 pb) cross-section to control polarization

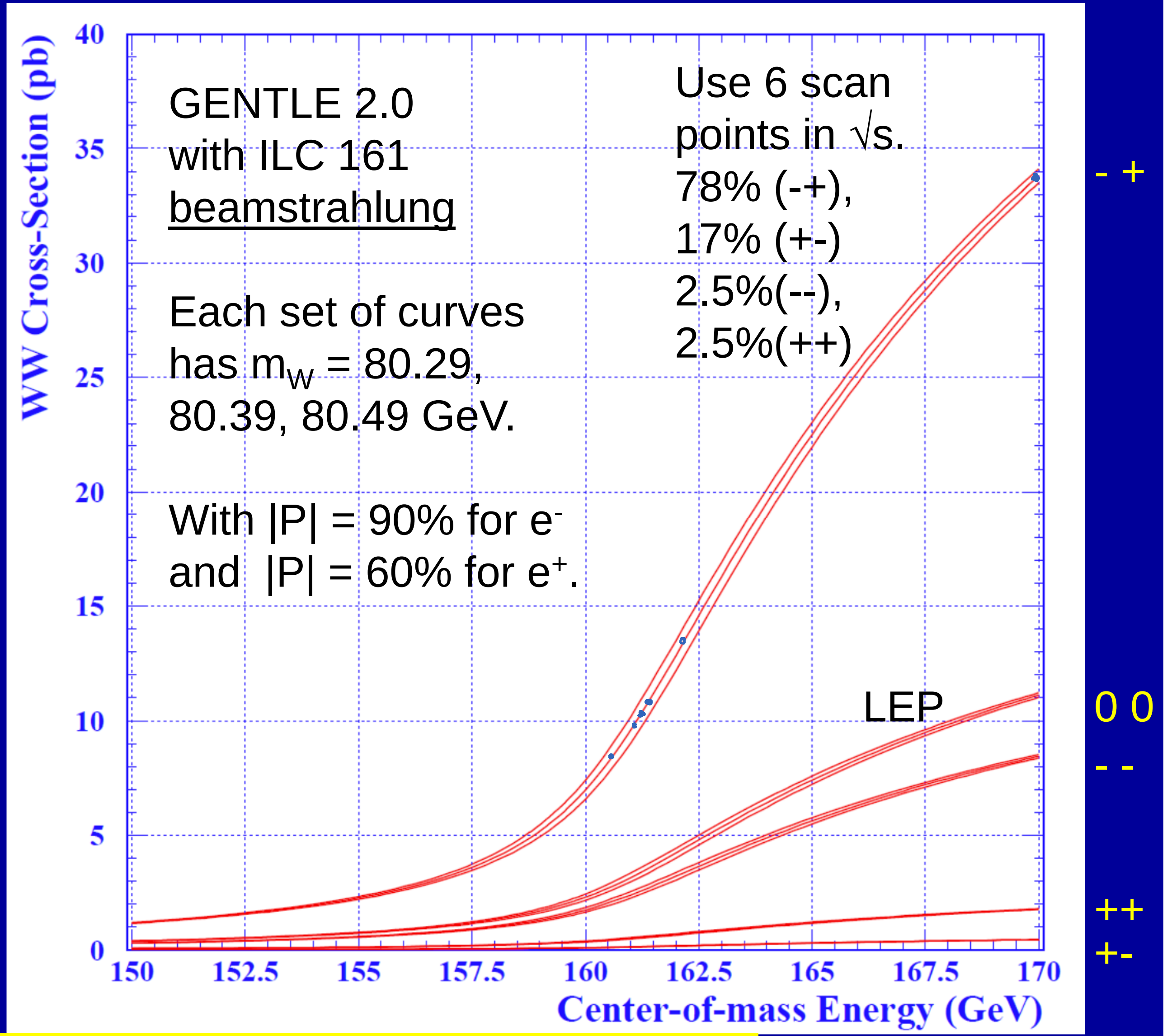
Polarized Threshold Scan



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

ILC Accelerator Features

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

$P \sim f_c N$ $\delta E \sim (N^2 \gamma)/(\varepsilon_x,N \beta_x \sigma_z) U_1 (\Psi_{av})$

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 MUCH better than an e^+e^- ring

Scope for improving luminosity performance.

1. Increase number of bunches (f_c)
2. Decrease vertical emittance (ε_y)
3. Increase 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.

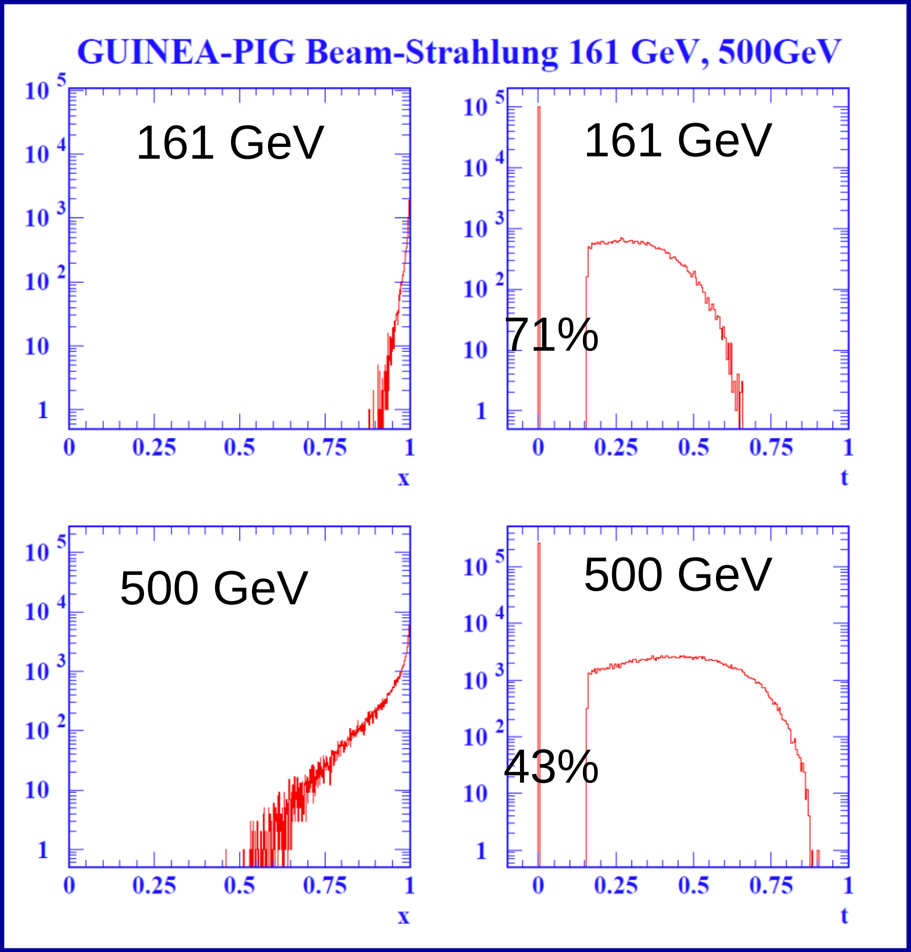
Average energy loss of colliding beams is factor of 2 smaller.

Median energy loss per beam from beamstrahlung typically ZERO.

Parametrized with CIRCE functions.

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

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

t=0.25 => x = 0.999

Fit

- Fit observed event counts in each channel at each √s and helicity combination.
- Channels: 4 (ll,lh,hh,rr)
- Center-of-mass energies: 6
- Helicity combinations: 4
- 12 parameter fit
  - m_W
  - Backgrounds (ll,lh,hh)
  - Normalization factor (f_{lumi})
  - Relative efficiencies (ll,lh,hh)
  - "Blondel scheme" polarization variables (P^-,P^+,σ,A_{LR}) from RR
- 4x6x4=96 measurements (84 d.o.f)

MINUIT TASK: FIT W MASS TO NUMBER OF EVENTS in EACH CHANNEL

FCN= 91.53745 FROM MINOS STATUS=SUCCESSFUL 1104 CALLS
EDM= 0.12E-10 STRATEGY= 1 ERROR MATRIX ACCURATI

EXT PARAMETER NO.	NAME	VALUE	PARABOLIC ERROR	MINOS ERRORS NEGATIVE	MINOS ERRORS POSITIVE
1	WMASS	80.385	0.38496E-02	-0.38489E-02	0.38504E-02
2	BKGLL	0.89168E-02	0.94955E-03	-0.94950E-03	0.94961E-03
3	BKGLQ	0.39487E-01	0.24830E-02	-0.24825E-02	0.24835E-02
4	BKGQQ	0.20030	0.38214E-02	-0.38210E-02	0.38218E-02
5	FLUMI	0.99962	0.87207E-03	-0.87203E-03	0.87212E-03
6	REFFLL	0.99971	0.95758E-03	-0.95757E-03	0.95759E-03
7	REFFLQ	0.99961	0.89928E-03	-0.89923E-03	0.89933E-03
8	REFFQQ	1.0003	0.91607E-03	-0.91605E-03	0.91610E-03
9	ALPHAS	0.12000	constant		
10	ALRLL	0.15000	constant		
11	ALRLQ	0.30000	constant		
12	ALRQQ	0.48000	constant		
13	ALRMZ	0.18966	0.30827E-03	-0.30821E-03	0.30833E-03
14	PELL	0.90201	0.15343E-02	-0.15332E-02	0.15353E-02
15	PELR	0.90000	constant		
16	PELZ	0.0000	constant		
17	PPOSL	0.59864	0.11664E-02	-0.11652E-02	0.11675E-02
18	PPOSR	0.60000	constant		
19	PPOSZ	0.0000	constant		
20	XSRR	150.06	0.63953E-01	-0.63952E-01	0.63953E-01

constrained nuisance parameters (0.1%)

Polarized Threshold Scan Errors

- conservative – viewed from + 14 years ....
- Non-Ebeam experimental error (stat + syst)
  - 5.2 MeV

	Scenario 0	**Scenario 1**	**Scenario 2**	**Scenario 3**
L (fb^{-1})	100	160*3	100	100
Pol. (e^-/e^+)	80/60	90/60	90/60	90/60
Inefficiency	LEP2	0.5*LEP2	0.5*LEP2	0.5*LEP2
Background	LEP2	0.5*LEP2	0.5*LEP2	0.5*LEP2
Effy/L syst.	0.25%	0.1%	0.25%	0.1%
Δm_W(MeV)	5.2	1.9	4.3	3.9

W Mass Measurement from Polarized Threshold Scan

Polarized Threshold Scan

Statistics limited.

Systematics are measured.

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	4.1	2.3

remainder of talk → ⇒ justify $\lesssim$ 10 ppm on E_b

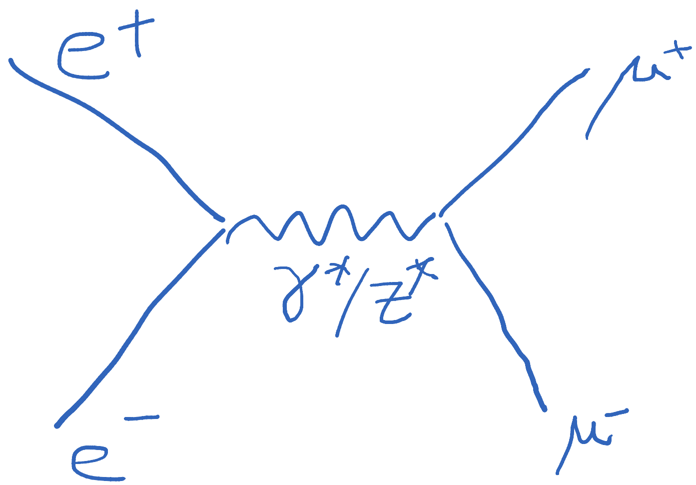
II: CME Measurement

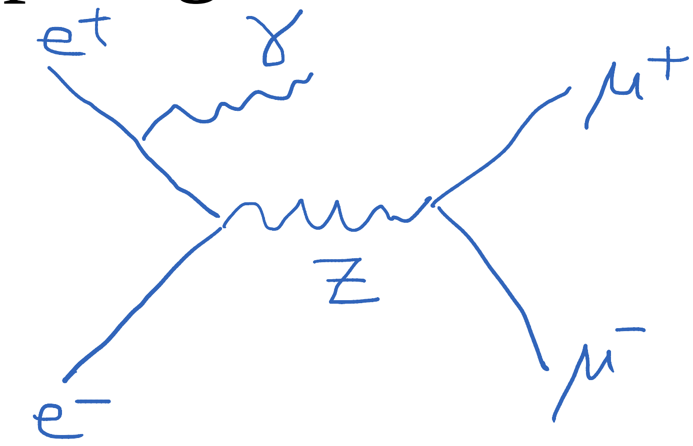
In-Situ √s Determination with μμ(γ)

- ILC physics capabilities will benefit from a well understood center-of-mass energy
  - Preferably determined from collision events.
- Measure precisely W, top, Higgs masses. (and Z ?)
- Two methods using μ μ (γ) events have been discussed:
  - Method A: Angle-Based Measurement
  - Method P: Momentum-Based Measurement

See my talk at ECFA LC2013 Hamburg for more details of recent studies on Method P.

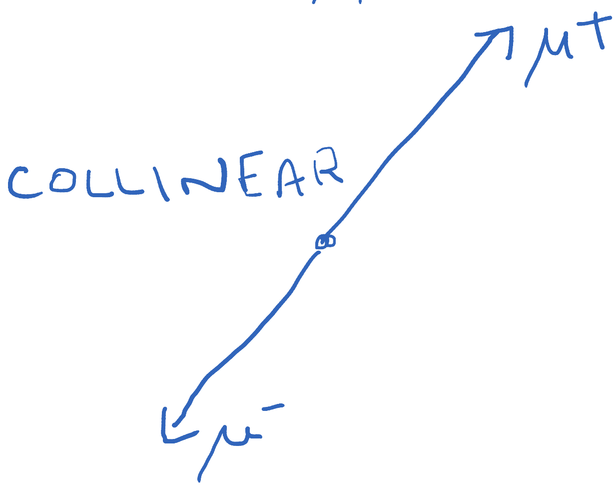
Di-muon topologies

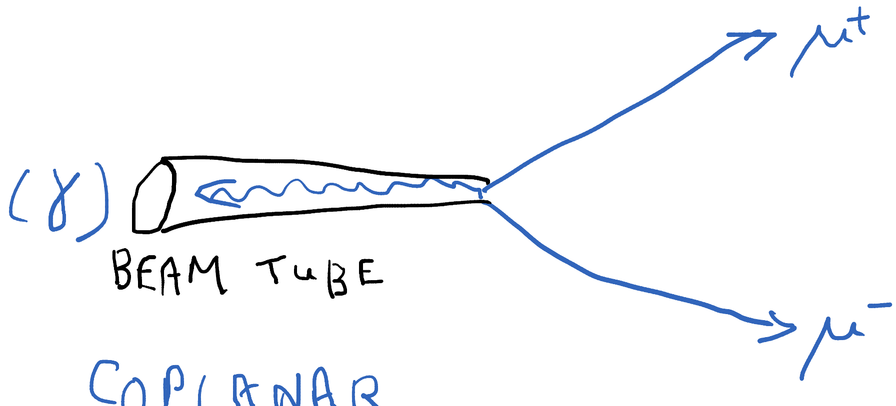




$$M_{\mu\mu} \simeq \sqrt{s}$$

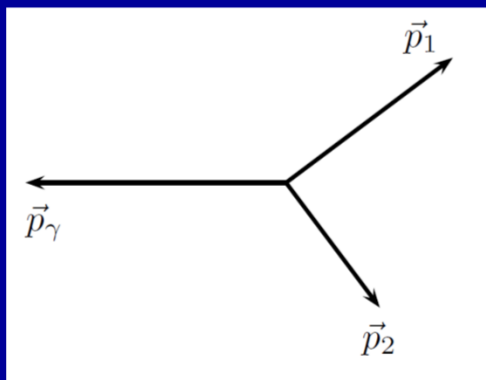
$$M_{\mu\mu} \simeq M_Z$$





“radiative-return”

3-body Kinematics



Define $x_i = 2E_i/\sqrt{s}$

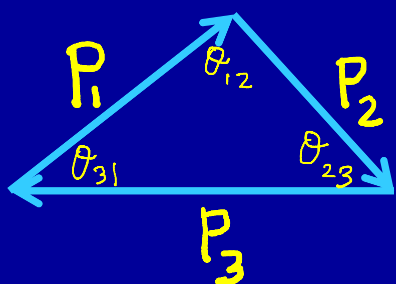
$$(E_{12}, \vec{p}_{12}) = (\sqrt{s} - E_\gamma, -\vec{p}_\gamma)$$

$$m_{12}^2 = s - 2E_\gamma\sqrt{s} = s(1 - x_\gamma)$$

$$\vec{p}_1 + \vec{p}_2 + \vec{p}_\gamma = 0$$

$$E_1 \simeq p_1, \quad E_2 \simeq p_2, \quad E_3 = p_3$$

$$\sqrt{s} = E_1 + E_2 + E_3 \approx r(s_{12} + s_{23} + s_{31})$$



$$x_i = \frac{2E_i}{\sqrt{s}} = \frac{2 s_{jk}}{s_{12} + s_{23} + s_{31}}$$

Sine Rule:

$$\frac{P_1}{\sin\theta_{23}} = \frac{P_2}{\sin\theta_{31}} = \frac{P_3}{\sin\theta_{12}} \equiv r$$

=> Measure x_γ from angles only

Method A)
Use angles only in Z(γ) events to, measure m_{12} /√s. Use known m_Z to reconstruct √s.

(proposed initially by GWW) Used at LEP2.

Hinze & Moenig

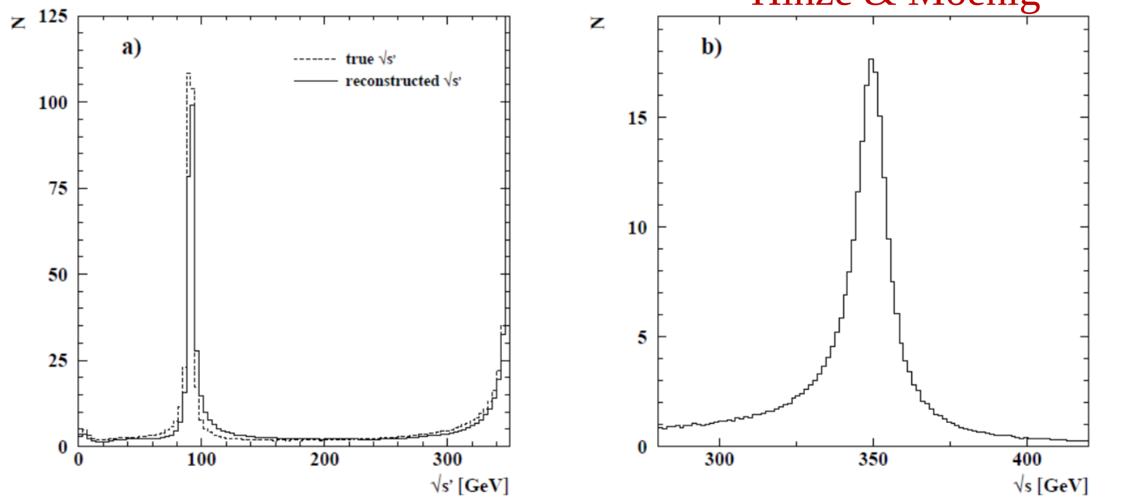


Figure 2: True and reconstructed $\sqrt{s'}$ (a) and reconstructed $\sqrt{s}$ for $e^+e^- \to Z\gamma \to \mu^+\mu^-\gamma$ at $\sqrt{s} = 350$ GeV

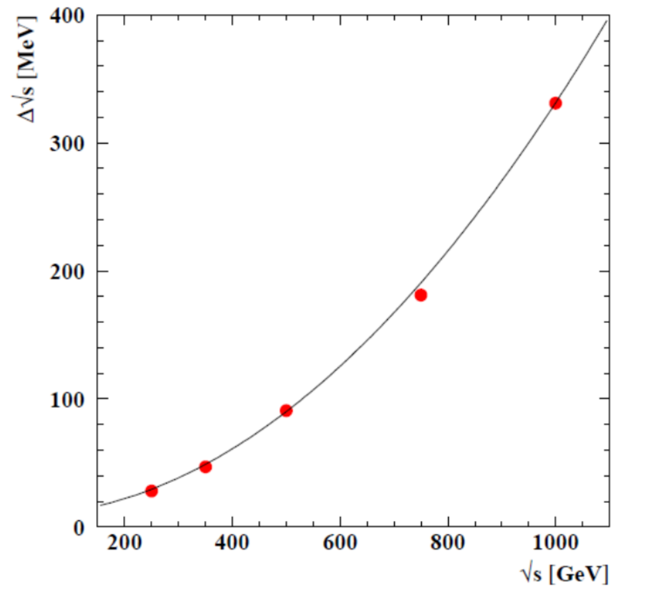


Figure 3: Energy dependence of $\Delta\sqrt{s}$ for $\mathcal{L} = 100\ \mathrm{fb}^{-1}$.

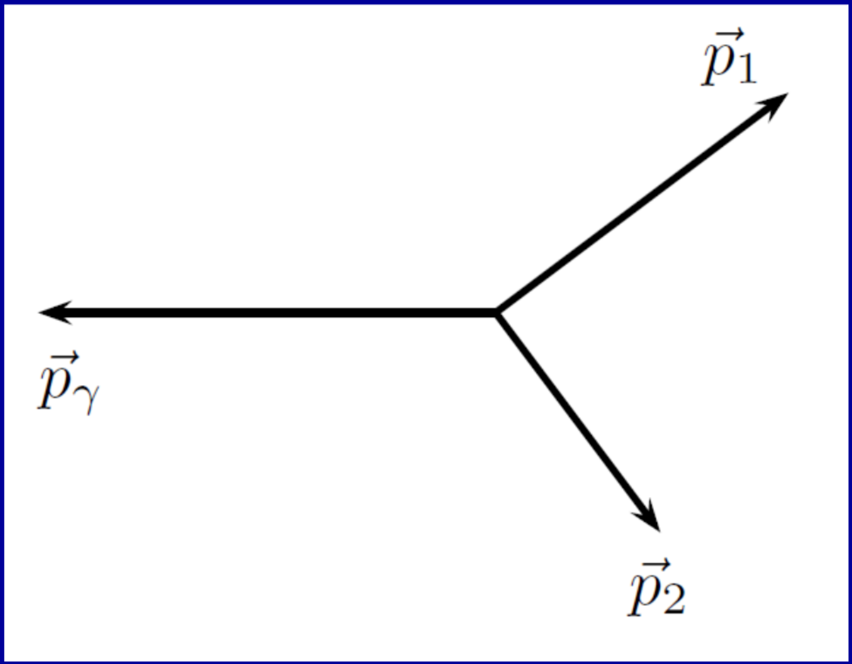
$$\sqrt{s} = m_Z \sqrt{\frac{\sin\theta_1 + \sin\theta_2 - \sin(\theta_1+\theta_2)}{\sin\theta_1 + \sin\theta_2 + \sin(\theta_1+\theta_2)}}$$

1. Statistical error per event of order Γ/M = 2.7%
2. Error degrades fast with √s.

(Note. At 161 GeV my error estimate (ee,μμ) on √s is 5 MeV: 31 ppm)

Method P
Use muon momenta. Measure $E_1 + E_2 + |p_{12}|$.

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 the center-of-mass energy 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, the expression is particularly straightforward. It is well approximated by

$$\sqrt{s}_P = p_T \left(\frac{1+\cos\theta_1}{\sin\theta_1} + \frac{1+\cos\theta_2}{\sin\theta_2} \right)$$

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

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

Very simplified 3-body MC with $m_{12} \approx m_Z$ to show the potential)

Method A (Angles)

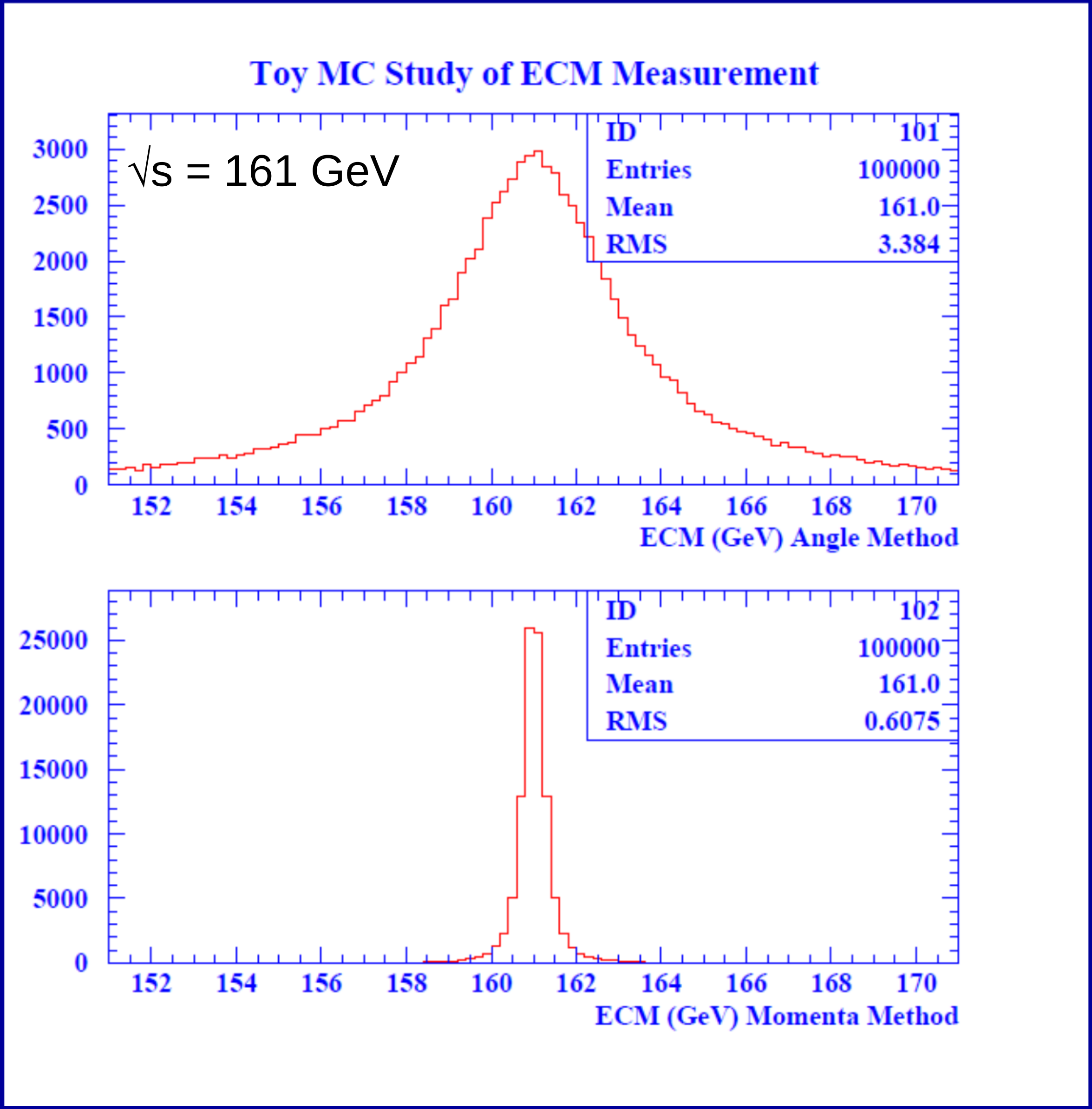
(Absolute scale driven by m_Z – known very well)

Method P (Momenta)

(Absolute scale driven by tracker momentum scale).

Momenta smeared.

Resolution is effectively 10 times better !



Error on $\sqrt{s_P}$

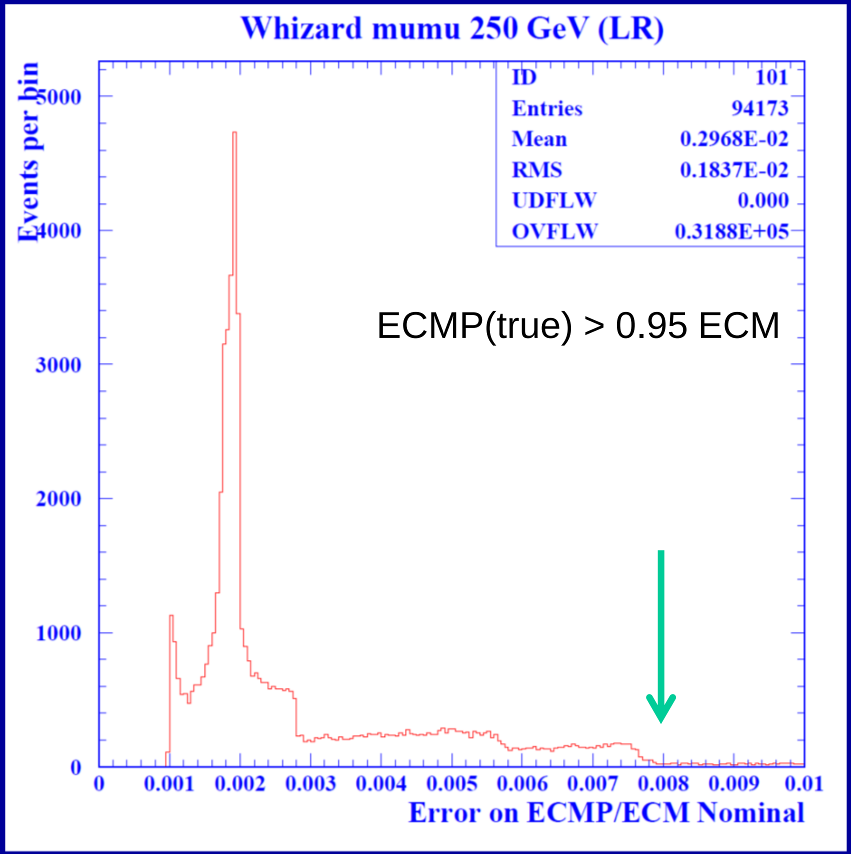
- Can write

  $$\sqrt{s_P} = E_1 + E_2 + |\mathbf{p}_{12}|$$
  $$= \sqrt{(p_1^2 + m^2)} + \sqrt{(p_2^2 + m^2)}$$
  $$+ \sqrt{(p_1^2 + p_2^2 + 2p_1p_2\cos\psi_{12})}$$

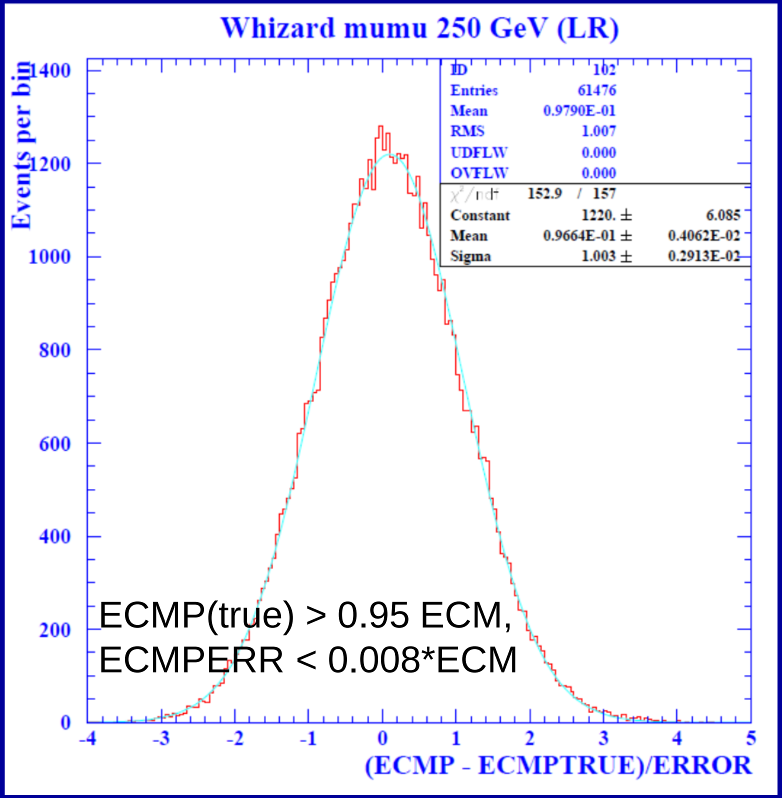
- Write $p_1 = \csc\theta_1/\kappa_1$ with $\kappa_1 = 1/pT_1$ and similarly for p_2. Use errors on κ from ILD.
- Do error propagation (neglecting angle errors).

Error on $\sqrt{s_P}$ estimator from momentum resolution

- Using general expression with error propagation. Does not use zero p_T approximation. Assumes angle errors negligible.

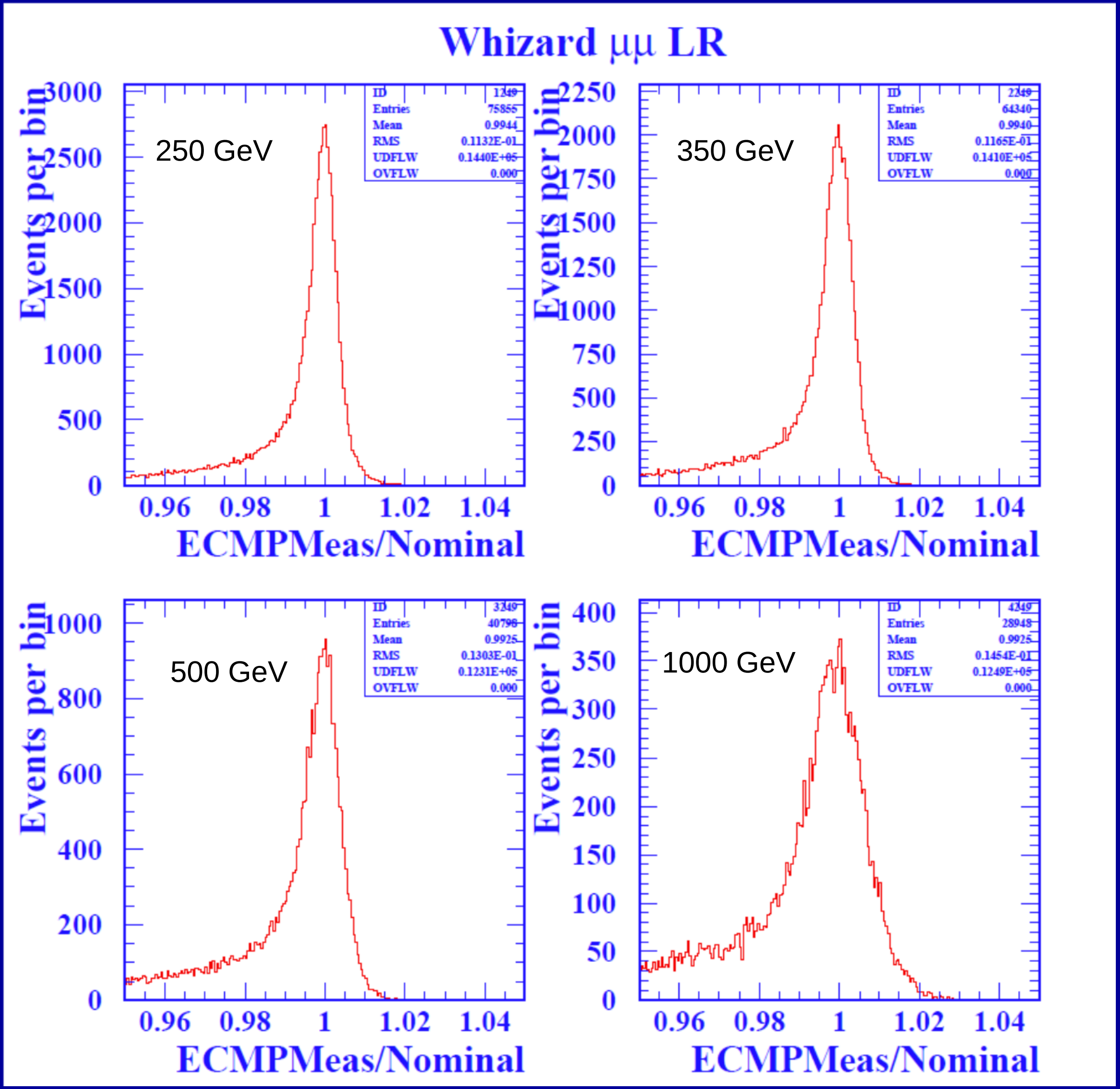


Error distribution is complicated. Reflects the kinematics, beamstrahlung, ISR, FSR, polar angles and p resolution.



Pull distribution has correct width. 10% +ve bias presumably due to errors being Gaussian in curvature ($1/p_T$) not in p.

ECMP Distributions (error<0.8%)



Momentum Resolution

Use the standard parametrization fitted to single muons from the ILD DBD.

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

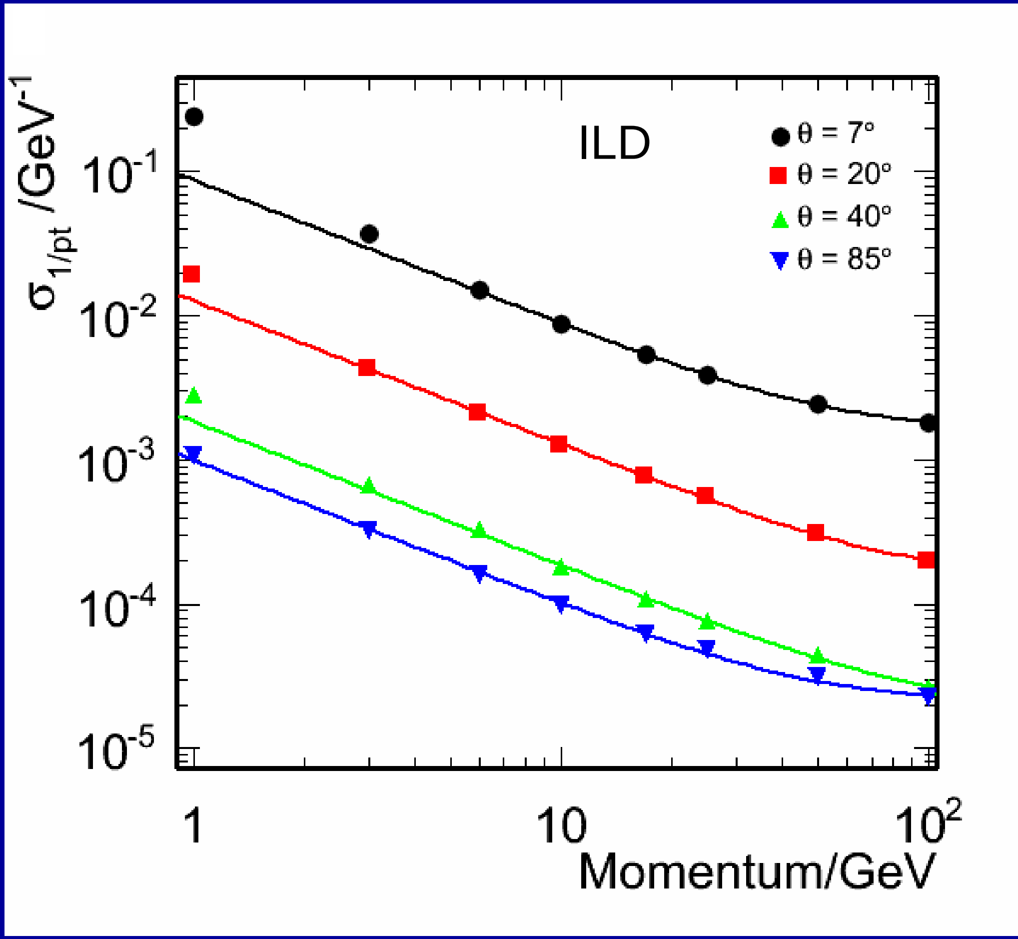
Where typically

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

for the full TPC coverage ($\theta > 37°$)

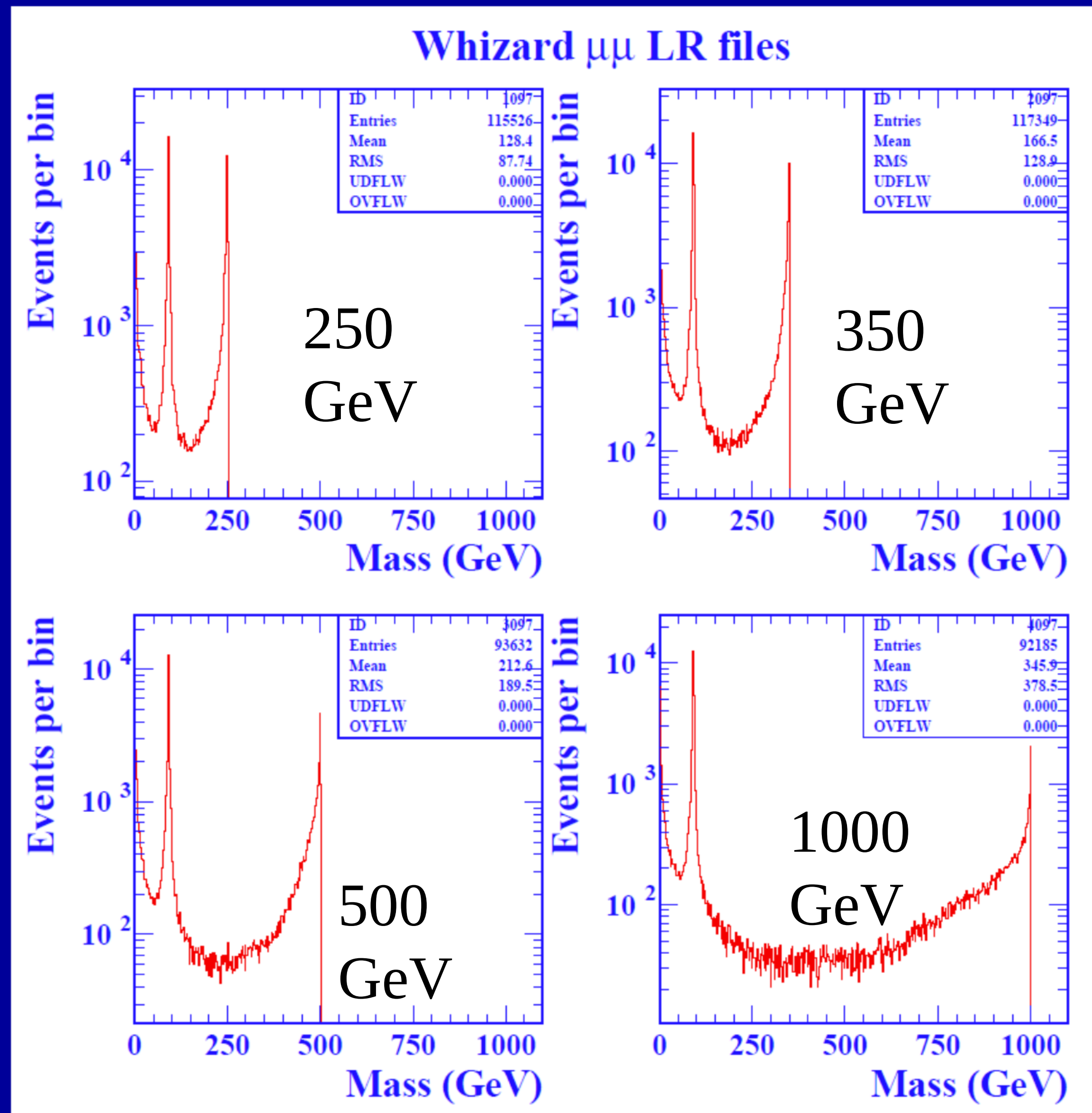
Fit momentum resolution in the p≥10 GeV range.
Superimposed curves are fits for the a,b parameters at 4 polar angles.
Maximum deviation from fit with this simple parametric form is 6%.
Interpolate between polar angles in endcap (use R^2 scaling for the a term).

(more explanation of this later)

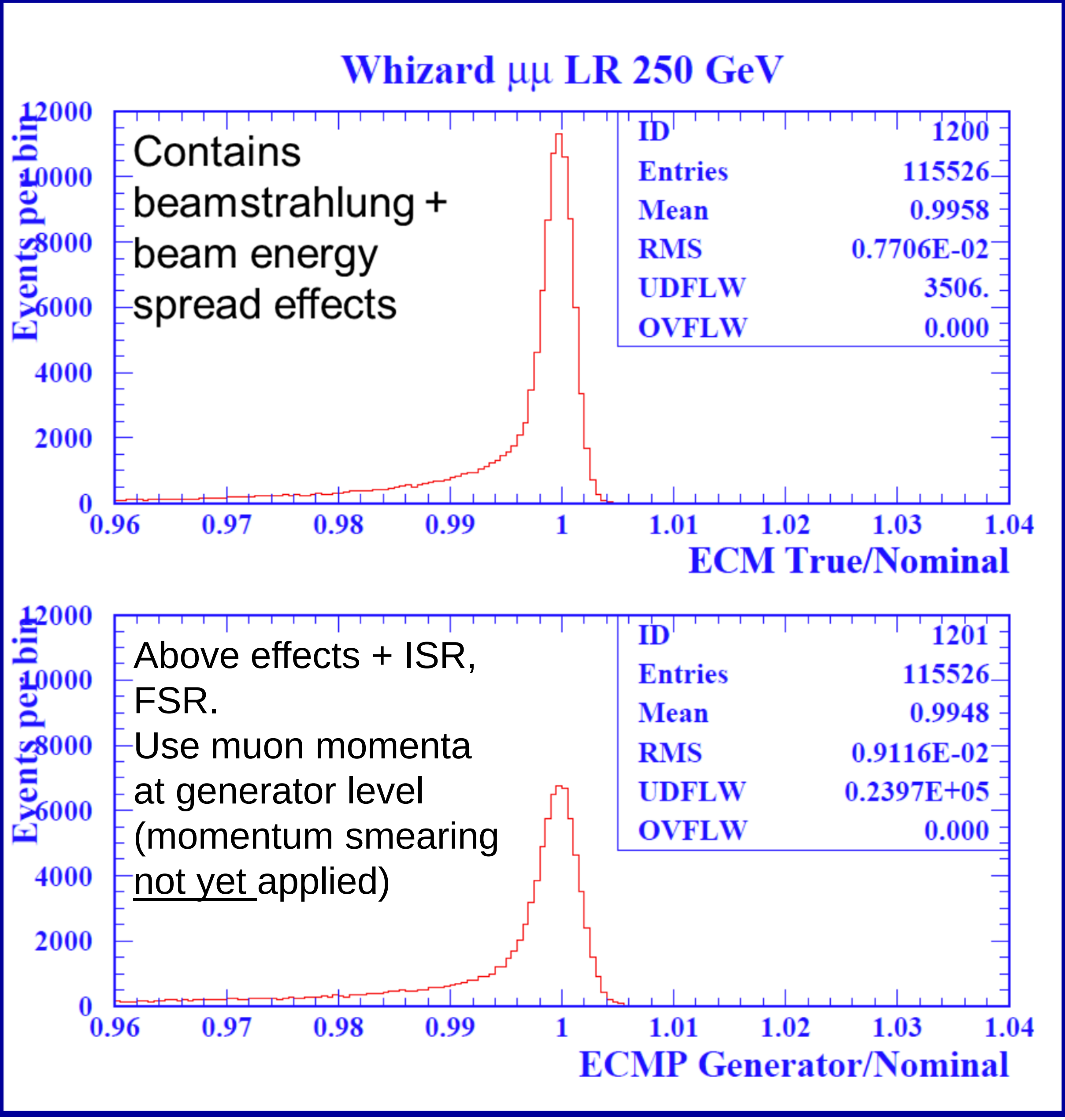


Generator Data-sets

- Use Whizard 4-vector files.
- At ECM=250, 350, 500, 1000 GeV.
- Use 1 stdhep file per energy. (e^-_L, e^+_R).
- Lumis are 10.4, 20.1, 32.2, 109 fb^{-1}.
- Events of interest have a wide range of di-muon mass values.



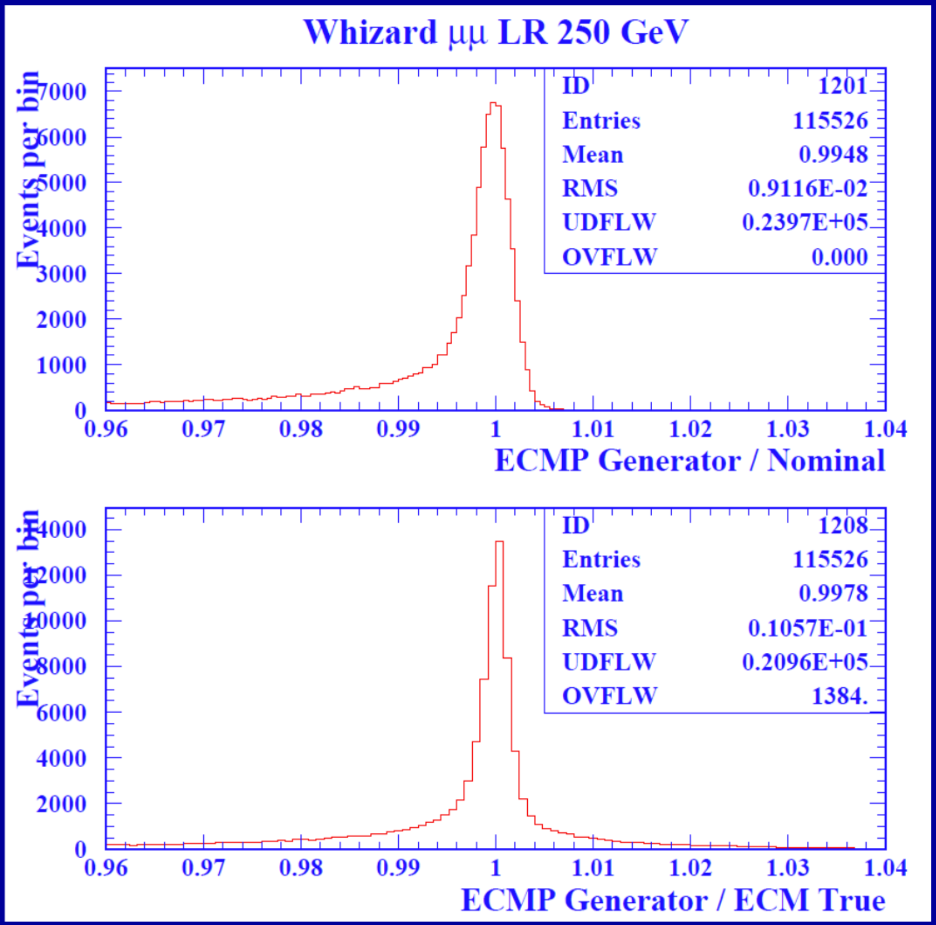
ECMP as an estimator of ECM

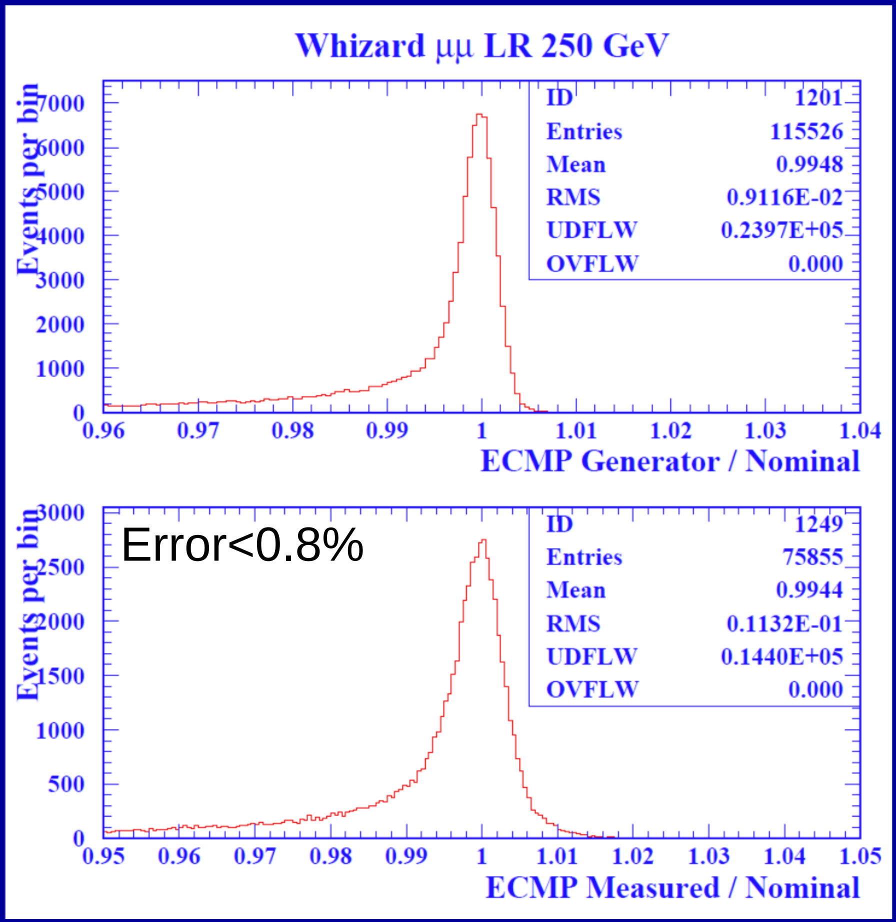


Full energy peak is wider – but still contains a lot of information on the absolute center-of-mass energy.

Opposite-beam double ISR off-stage left.

ECMP as an estimator of ECM





ECMP often is very well correlated with ECM. But long tails : eg hard ISR from BOTH beams

ECMP measured has additional effects from momentum resolution

Summary Table

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 …)

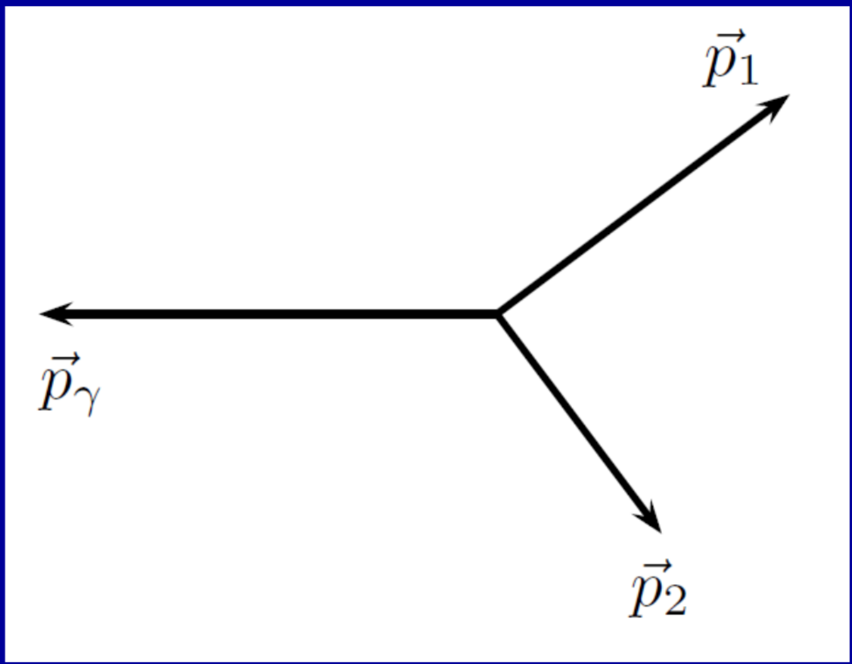
ECM (GeV)	L (fb^{-1})	$\Delta(\sqrt{s})/\sqrt{s}$ Angles (ppm)	$\Delta(\sqrt{s})/\sqrt{s}$ Momenta (ppm)	Ratio
161	161	-	4.3	
250	250	64	4.0	16
350	350	65	5.7	11.3
500	500	70	10.2	6.9
1000	1000	93	26	3.6

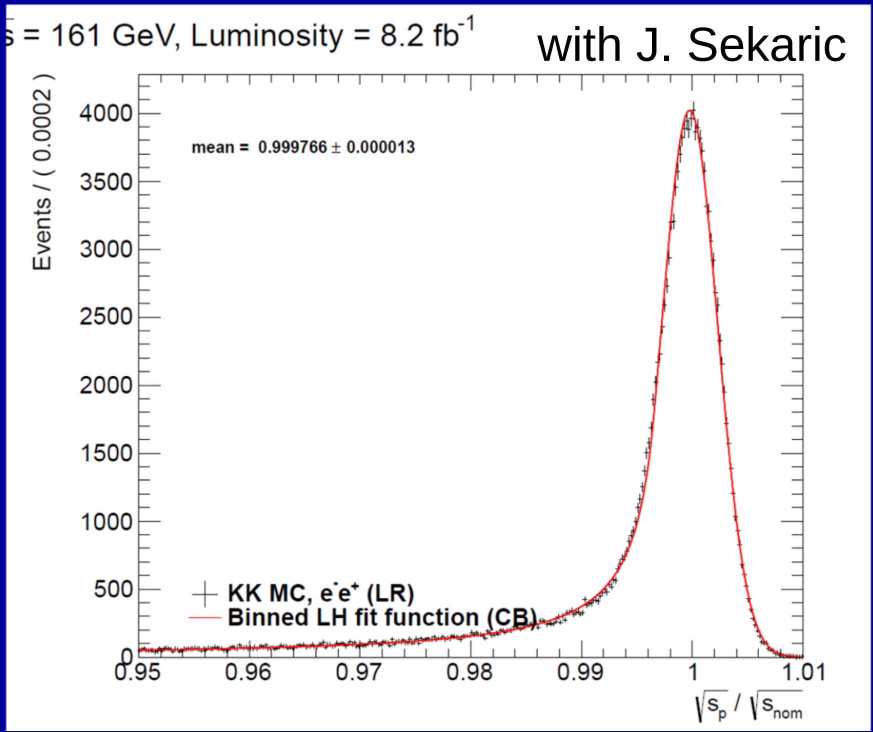
< 10 ppm for 150 – 500 GeV CoM energy

161 GeV estimate using KKMC.

"New" In-Situ Beam Energy Method

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



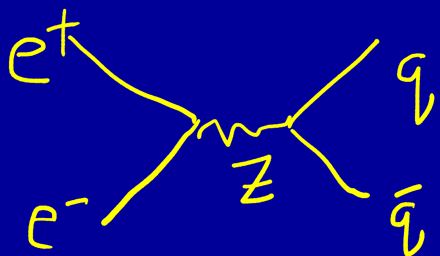


Use muon momenta. Measure $E_1 + E_2 + |\mathbf{p}_{12}|$ as an estimator of $\sqrt{s}$

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 m_W. (J/psi)

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

III: ILD Tracking and J/psi Based Momentum Calibration



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

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

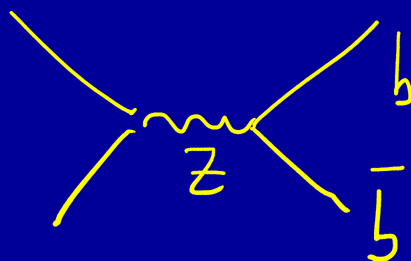
Most $Z \to J/\psi\, X$ believed to be from $B_{hadron} \to J/\psi\, X$

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

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

J/psi's from Z

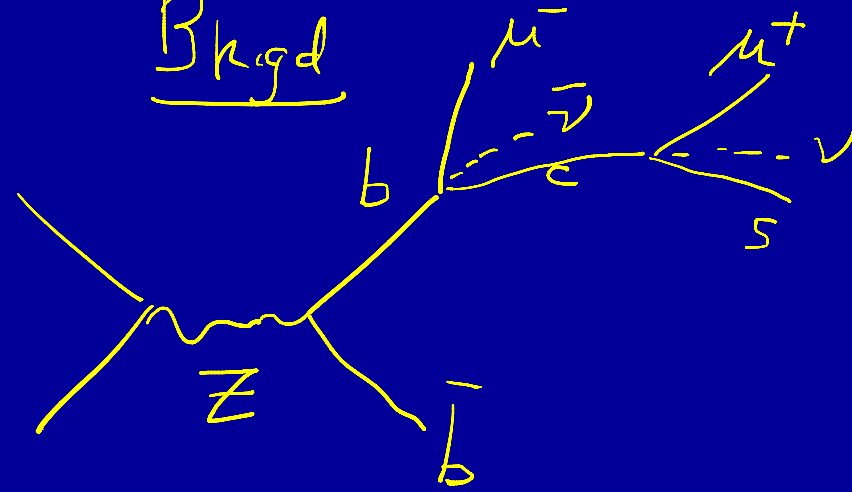
Signal



$b \rightarrow J/\psi\, X$

$\hookrightarrow \mu^+\mu^-$

Bkgd

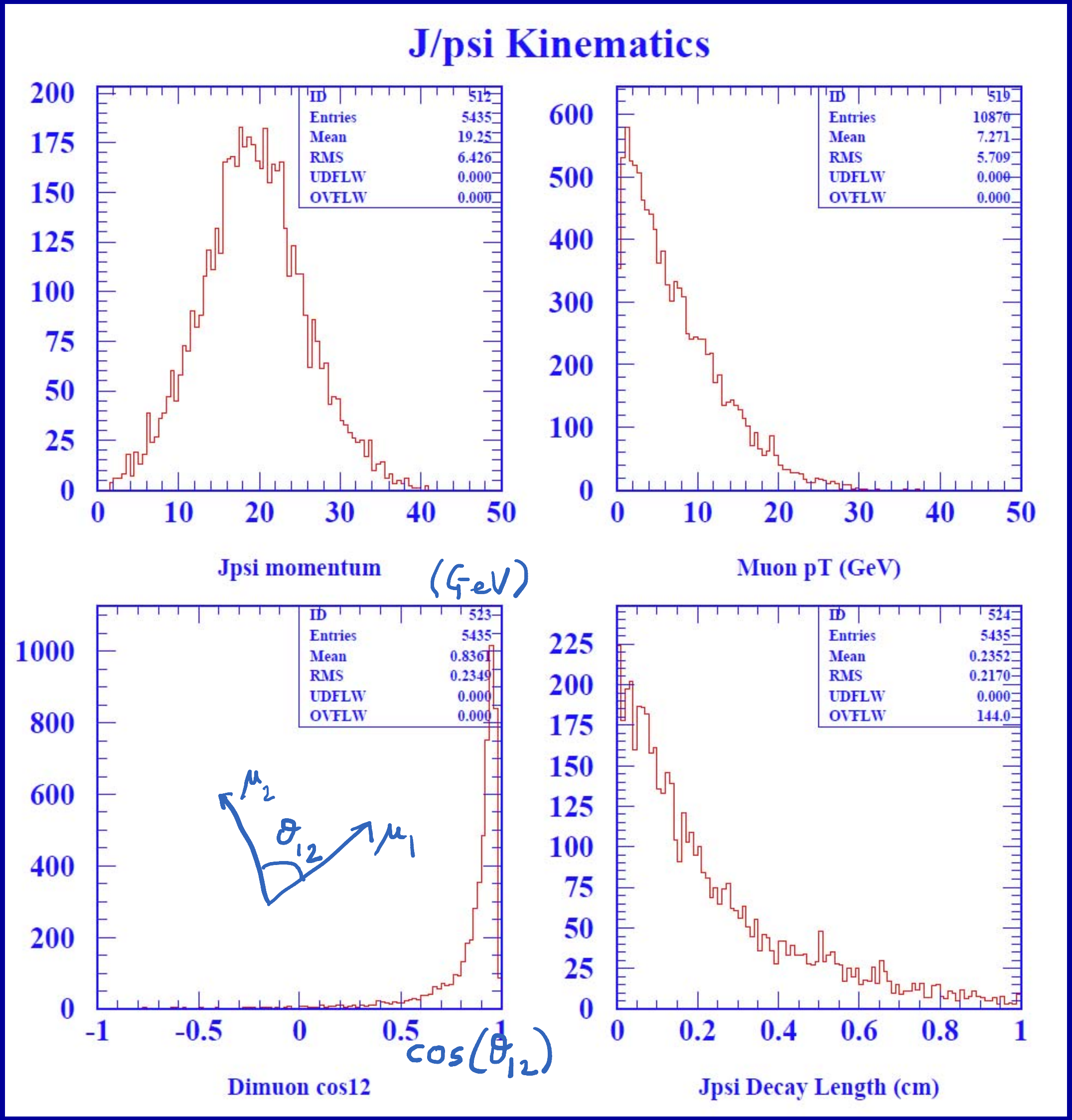


semi-leptonic cascades

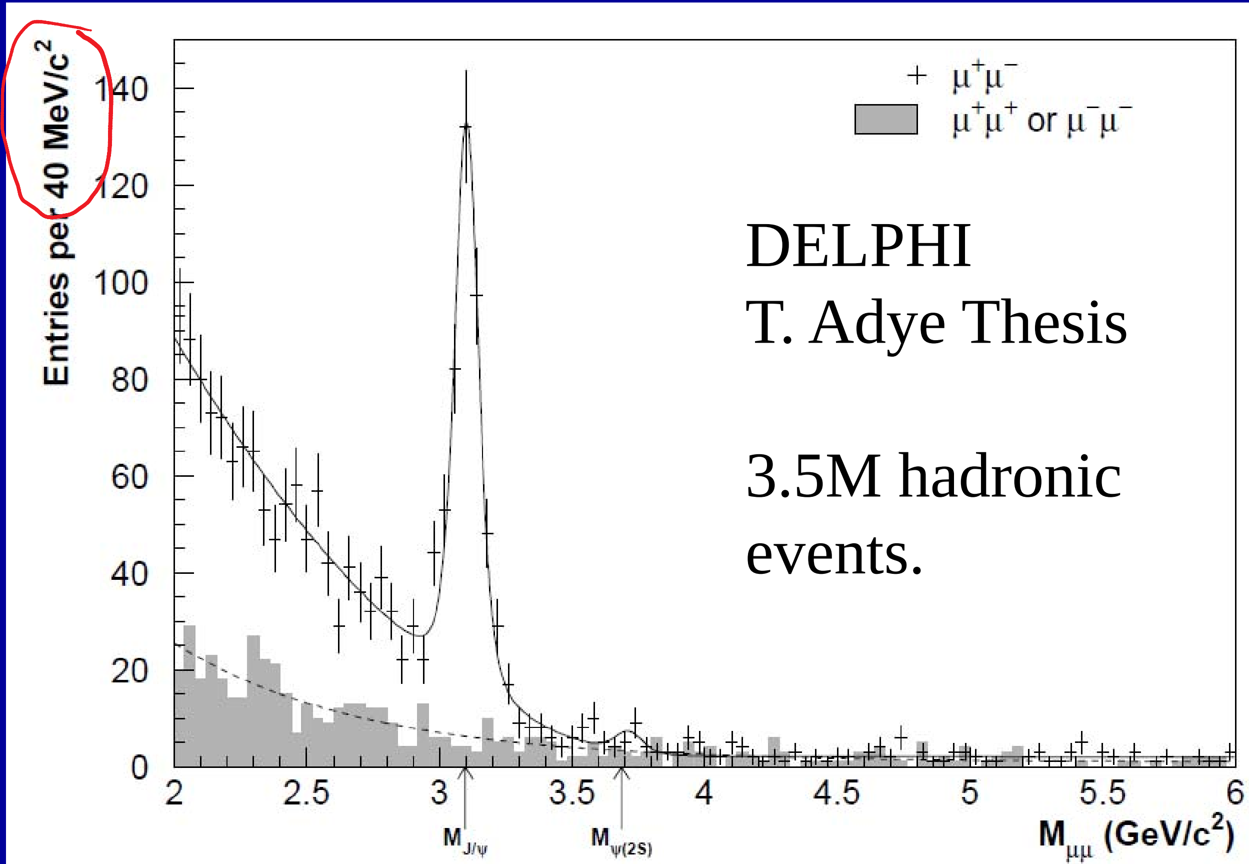
$b \rightarrow c\, l\, \nu$

$\hookrightarrow s\, l\, \nu$

J/psi Kinematics from Z→bb



Example LEP data



Opposite-sign fit (1941 candidates; 495 in $2.95 \leq M_{\mu\mu} < 3.25$ GeV/c^2 window)

J/ψ fraction in window	$f_{J/\psi} =$	(73.3±2.1)	%
hemiparabola fraction	$P_N =$	(69.9±1.6)	%
total ψ(2S)s	$N_{\psi(2S)} =$	16.7±6.6	
J/ψ mass	$M_{J/\psi} =$	(3102.3±3.4)	MeV/c^2

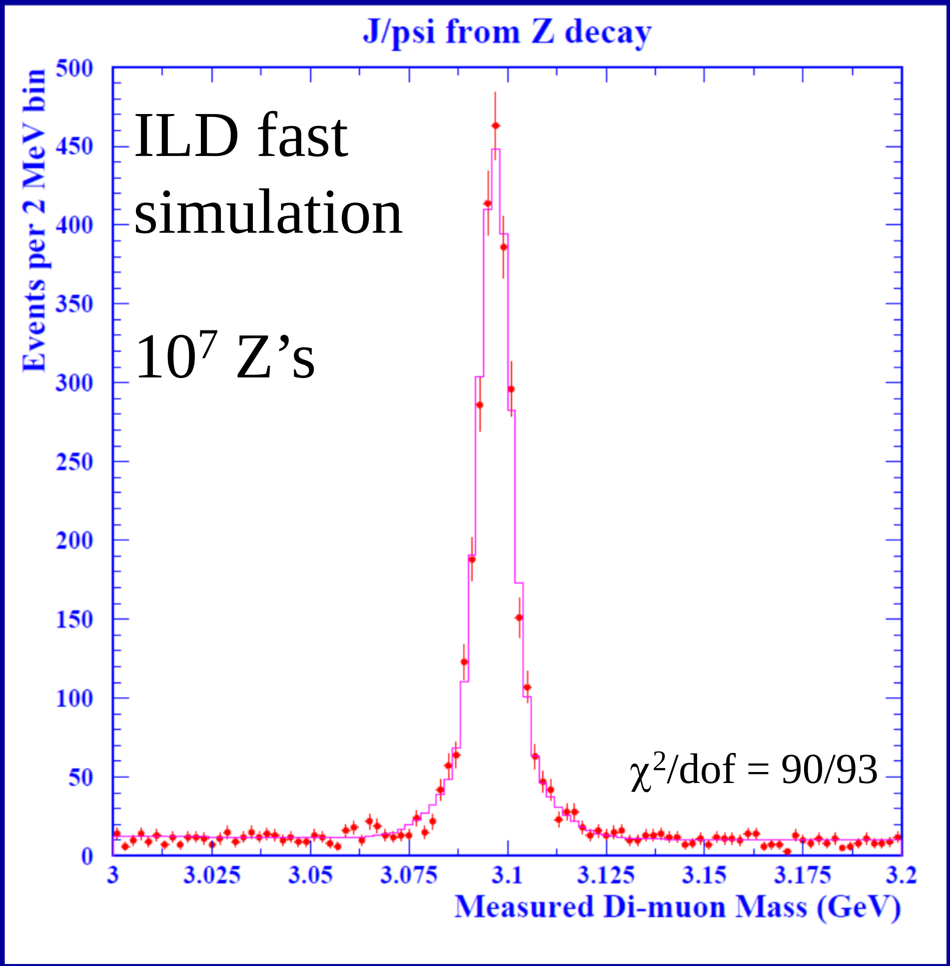
Momentum Scale with J/psi

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

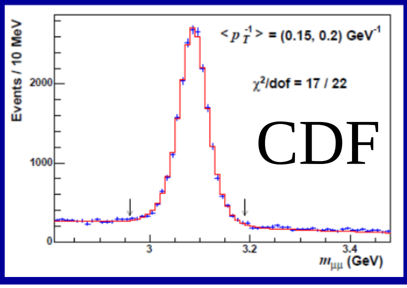
Most of the J/psi's are from B decays.

J/psi mass is known to 3.6 ppm.

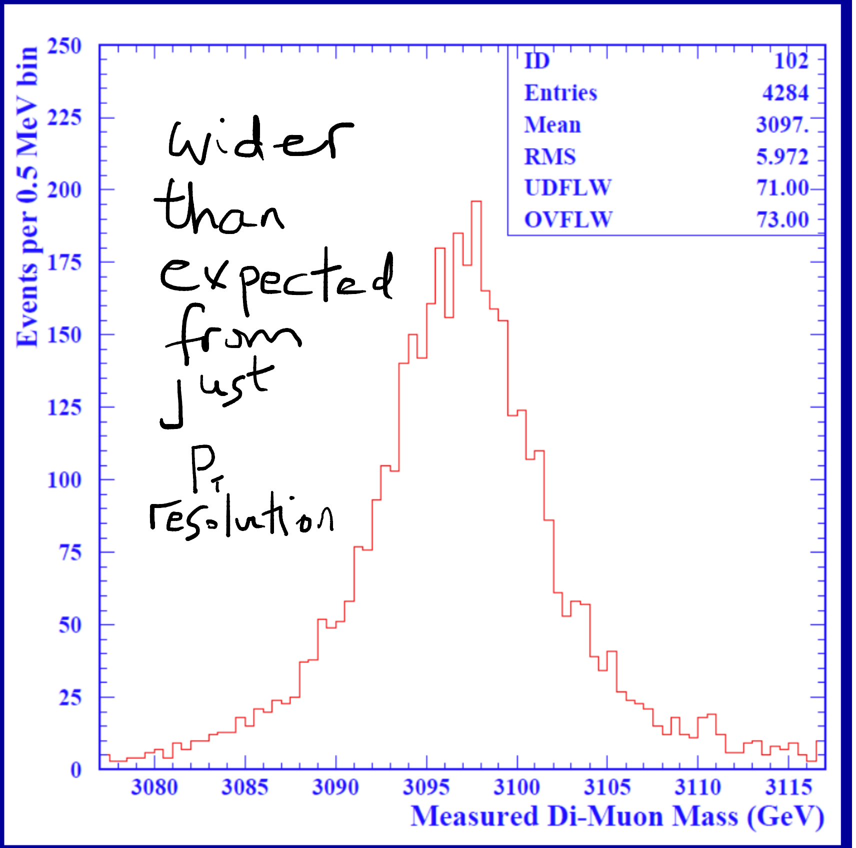
Can envisage also improving on the measurement of the Z mass (23 ppm error)

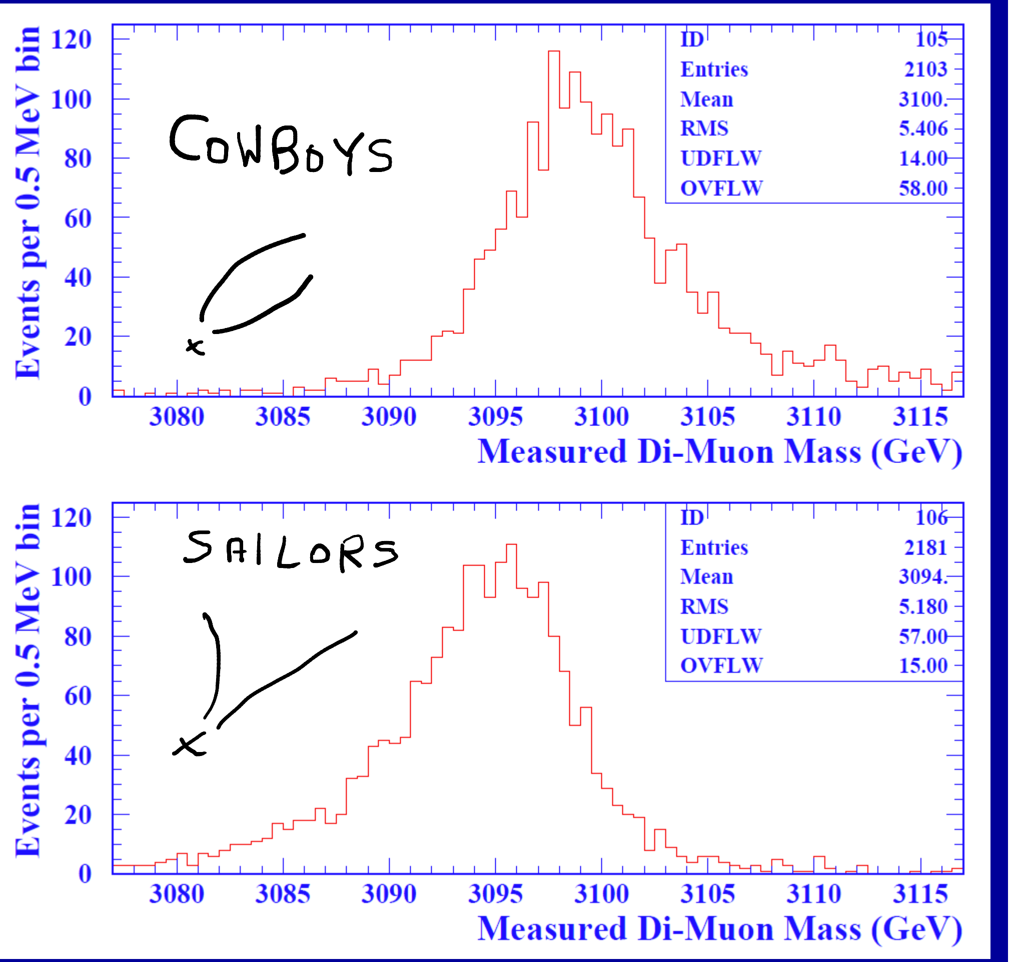


Double-Gaussian + Linear Fit



Is the mass resolution as expected?

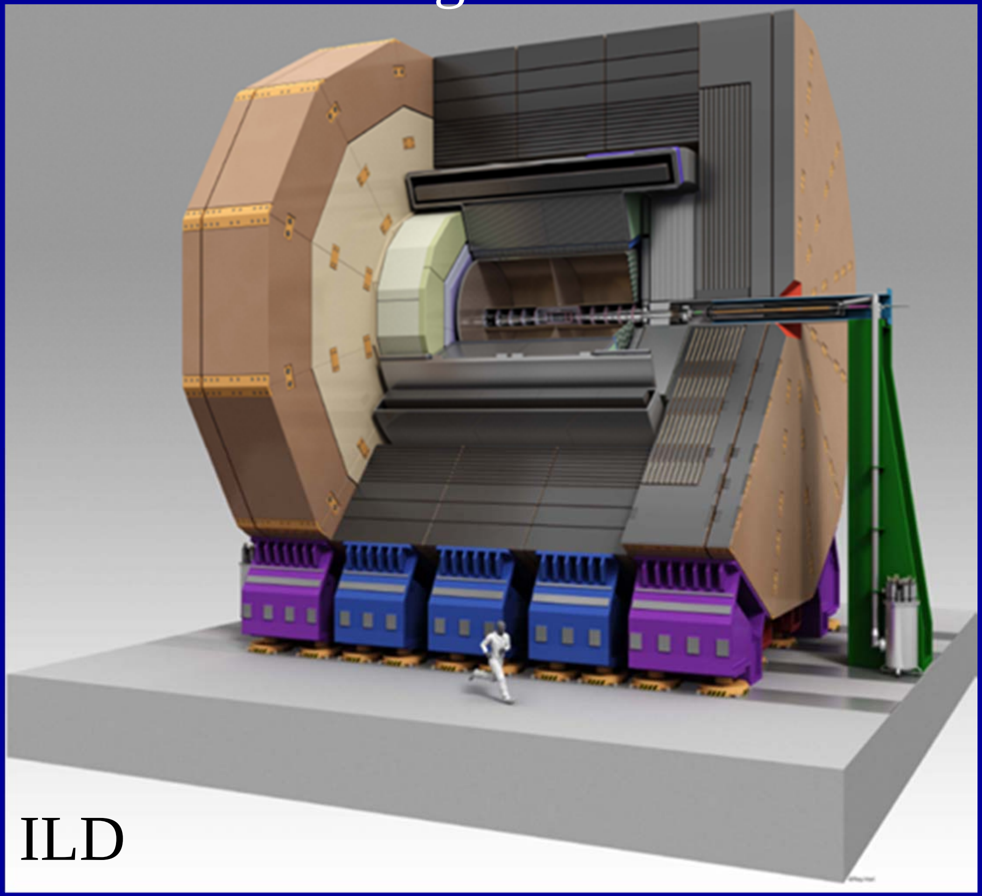




=> Need to calculate mass using the track parameters at the di-muon vertex.

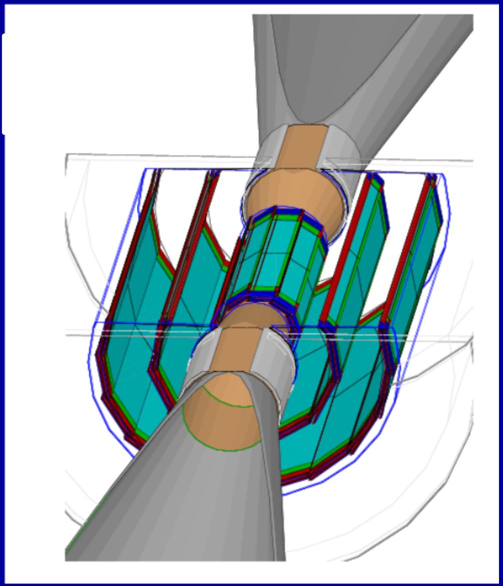
What is ILD ?

International Large Detector



A modern detector designed for ILC. Similar size to CMS.
ILC: higher energy (x 5), higher luminosity (x 500), much better detector.

Vertex Detector

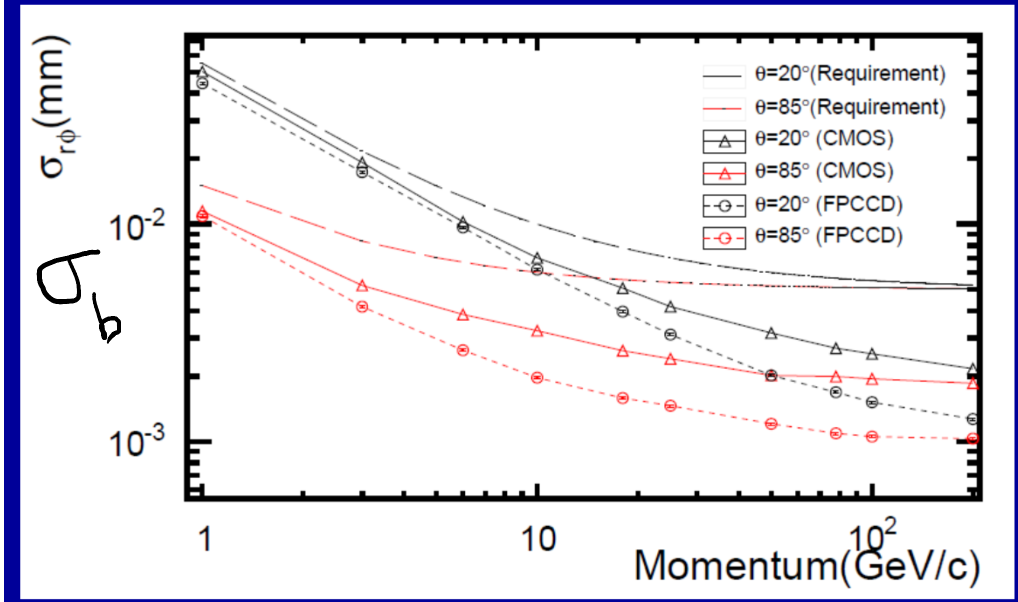


Several different technologies: pixel sensors, readout scheme, material budget. CMOS, FPCCD, DEPFET.

Pairs background => Inner radius ~ $1/\sqrt{B}$

Baseline geometry: 3 double-layers.

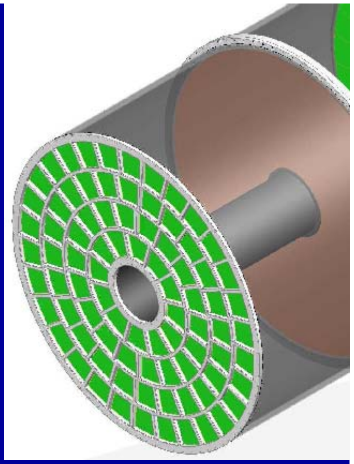
	R (mm)	$\|z\|$ (mm)	$\|\cos\theta\|$	σ (μm)	Readout time (μs)
Layer 1	16	62.5	0.97	2.8	50
Layer 2	18	62.5	0.96	6	10
Layer 3	37	125	0.96	4	100
Layer 4	39	125	0.95	4	100
Layer 5	58	125	0.91	4	100
Layer 6	60	125	0.9	4	100



CMOS and FPCCD solutions meet the design requirement of

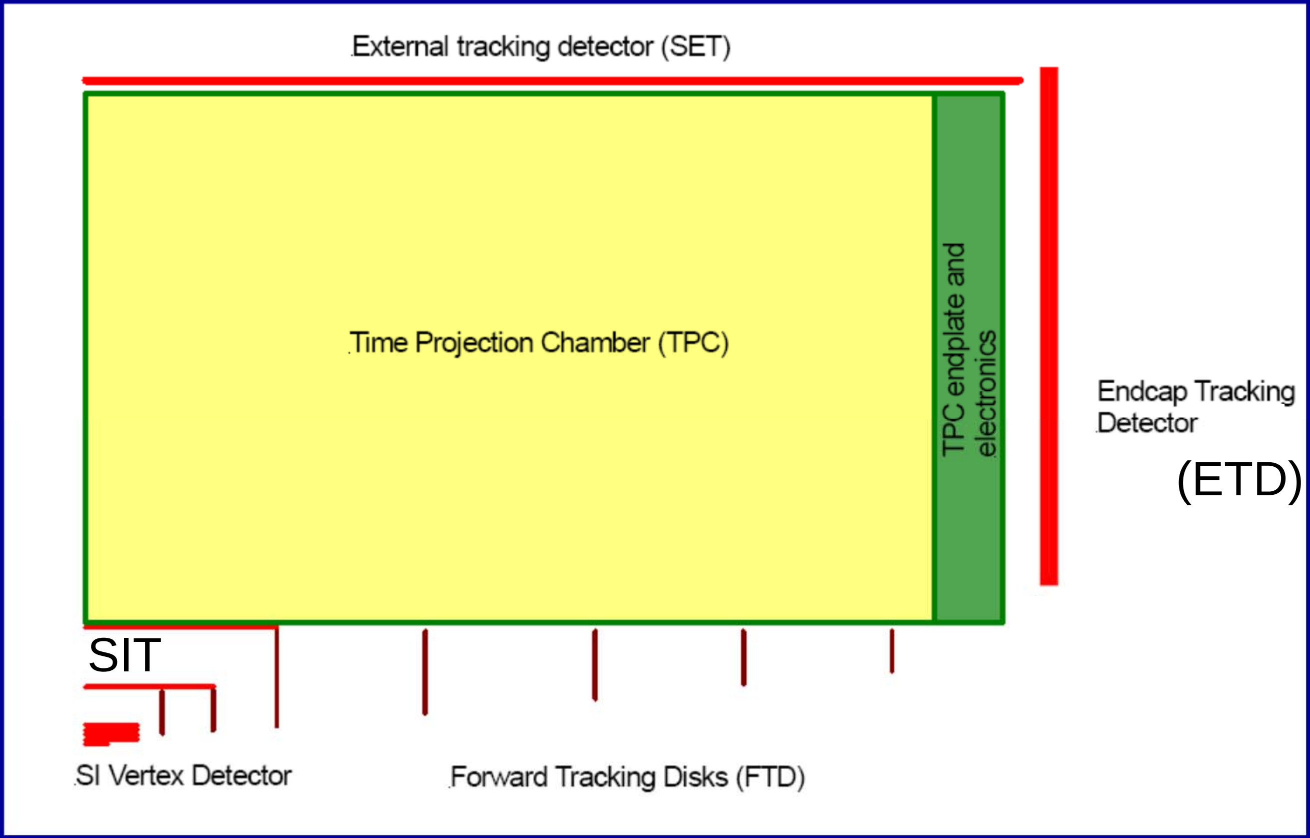
$$\sigma_b = 5 \oplus 10/(p\,\beta\,\sin^{3/2}\theta)\ \mu m$$

Main Tracker: Time Projection Chamber



Supplemented by stand-alone VTX tracking, SIT + Forward tracking disks.

SET and ETD provide precise external space-point.



$3\ 10^9$ volume pixels.

224 points per track.

Single-point resolution

50 - 100 μm r-ϕ,

400 μm r-z

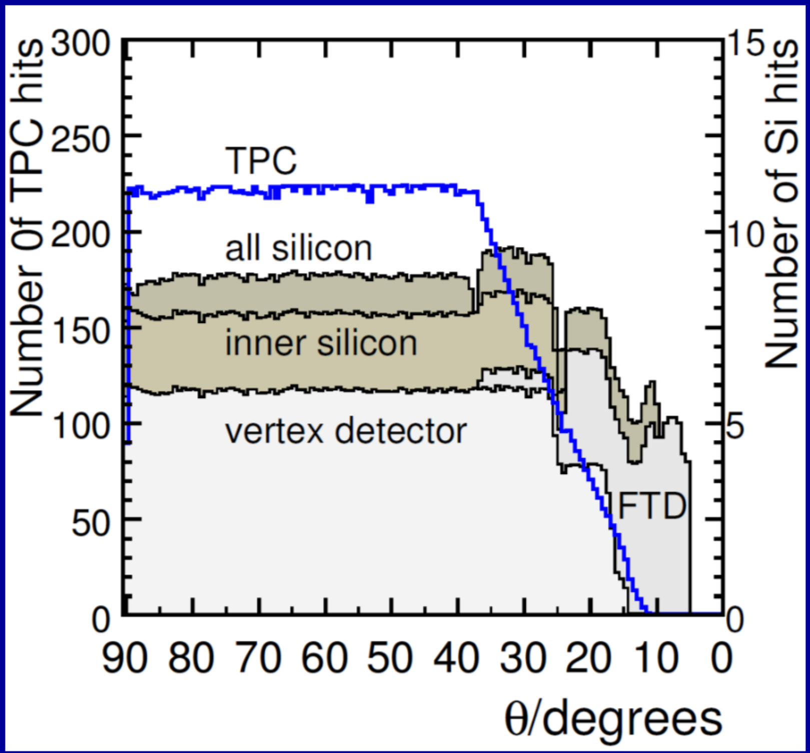
$|\cos\theta| < 0.985$ (TPC)

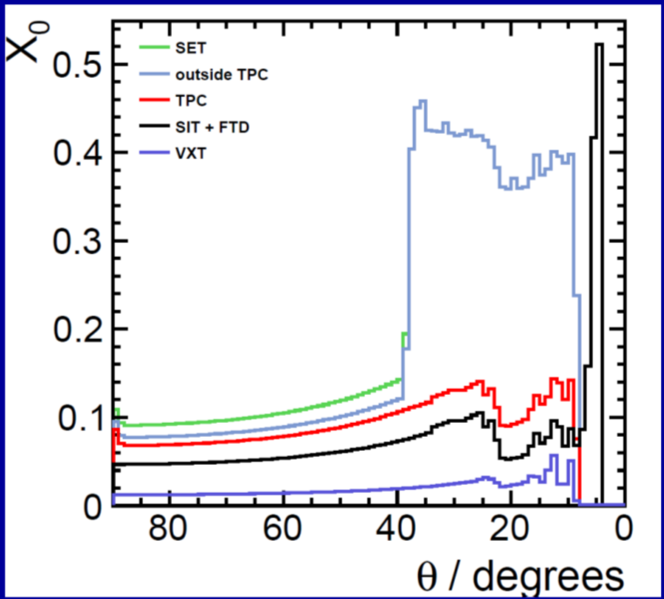
$|\cos\theta| < 0.996$ (FTD)

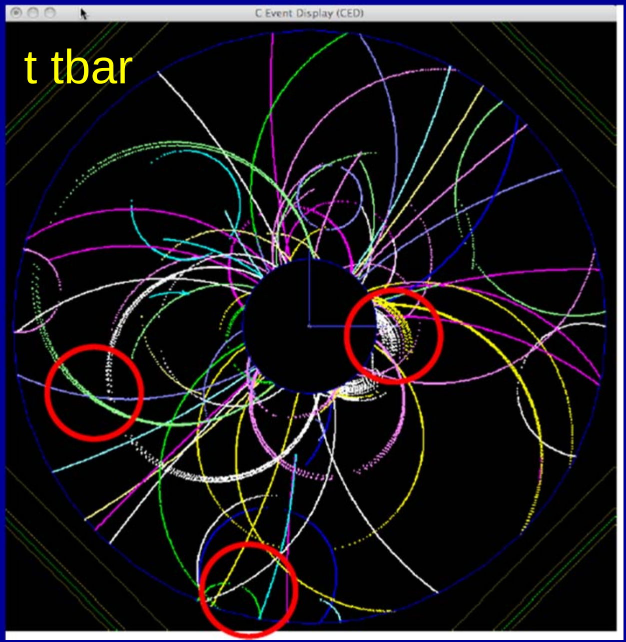
Readout options: GEM, Micromegas. Alternative: Si Pixel

SIT and FTD are essential elements of an integrated design.

Tracking System







Complete TPC coverage to 37°
VTX + SIT + FTD + SET + ETD =>
precision, redundancy and coverage to
$|\cos\theta| = 0.996$.

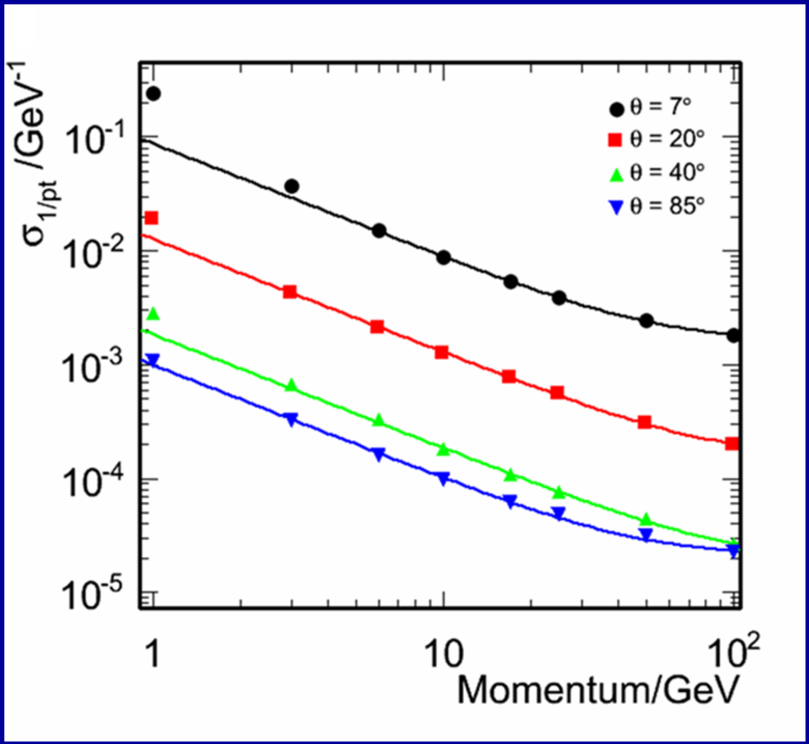
Momentum Resolution

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

Define track curvature

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

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



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

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

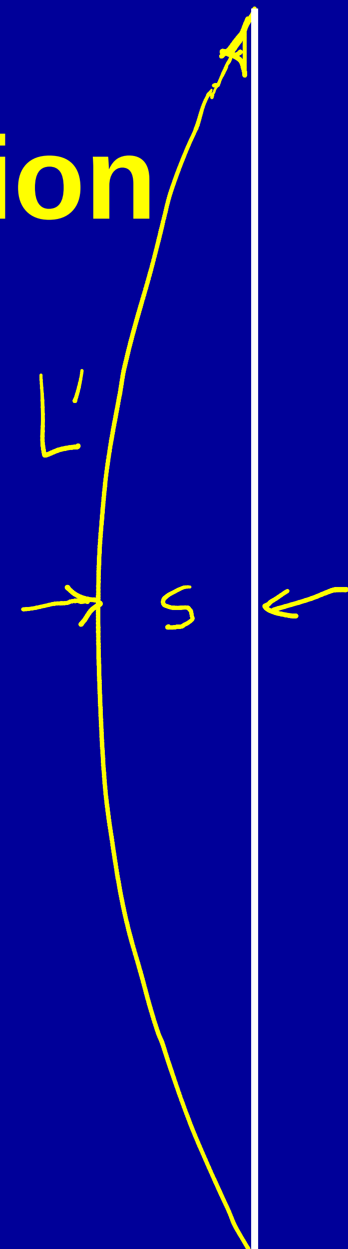
See PDG

Momentum Resolution

$$\Delta K_{res} = \sqrt{\frac{720}{N+4}}\,\frac{\epsilon}{L'^2}$$

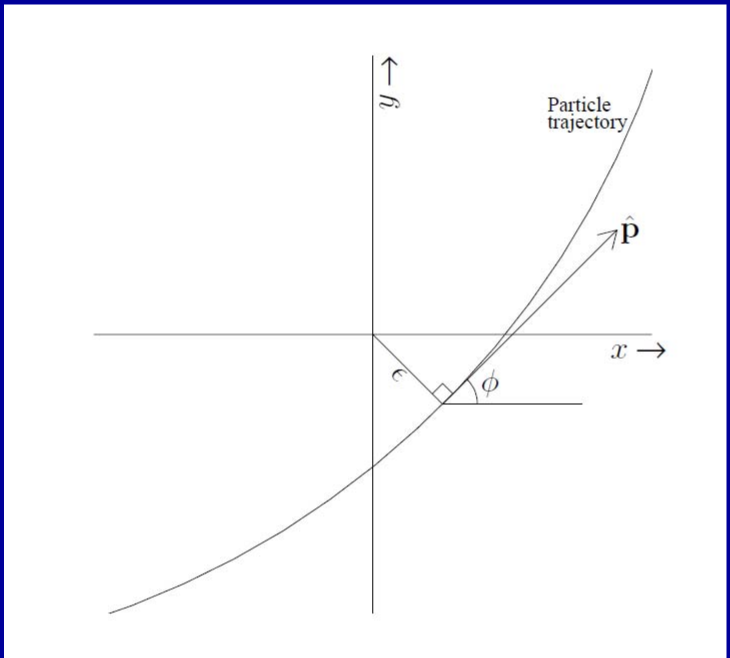
720 → 320 → 256 → 136

$$\Delta K_{MS} \approx \frac{0.016}{L\,p_T \sin\theta}\sqrt{\frac{L}{X_0}}$$



Resolution depends on number of points (N), track-lengths (L and L'), point-resolution (ε) and material thickness.

Track/Helix Parameterization



Track parameters

$$\vec{q} = \begin{pmatrix} \epsilon \\ z \\ \theta \\ \phi \\ K \end{pmatrix} \qquad \begin{matrix} d_0 \\ z_0 \\ \tan\lambda \\ \phi_0 \\ \rho \quad \frac{1}{R} \end{matrix}$$

Note: often impt.
Sign conventions.

Vertex Fit

Idea.

$\vec{q}_1, V_1$

$\vec{q}_2, V_2$

10 measurements

V_1, V_2 independent.

Adjust $\vec{q}_1, \vec{q}_2$ subject to the constraint that they originate from a common point in 3-d.

Fit parameters (9)

$\vec{r}_v = (x_v, y_v, z_v)$

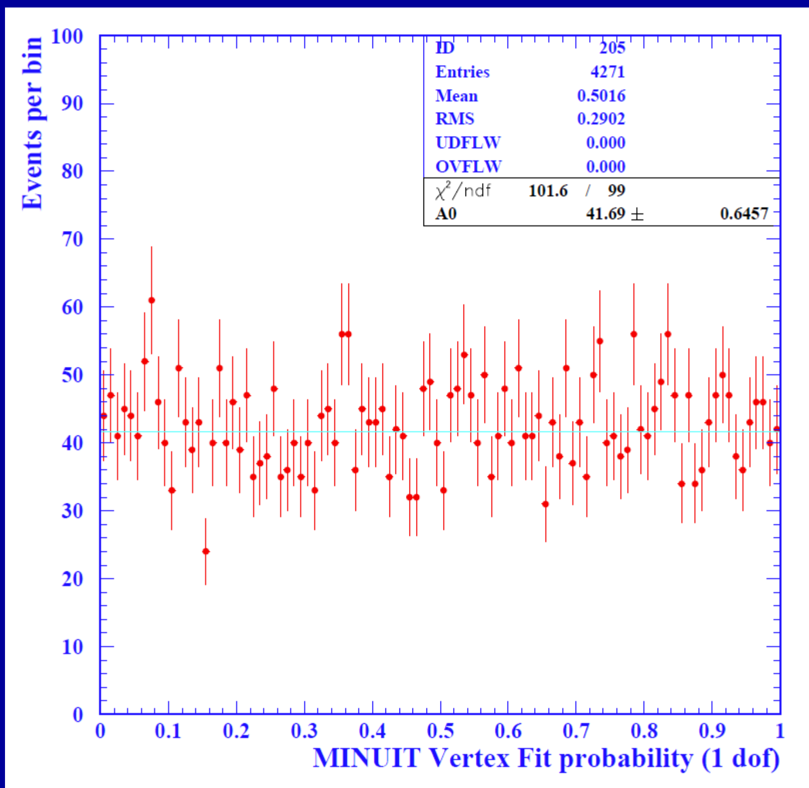
$\vec{p}_1 \quad (K_1, \theta_1, \phi_1)$

$\vec{p}_2 \quad (K_2, \theta_2, \phi_2)$

$\Rightarrow \chi^2_{fit}, \quad \vec{q}_{12}' = (\vec{r}_v, \vec{p}_1, \vec{p}_2), \quad V_{12}$

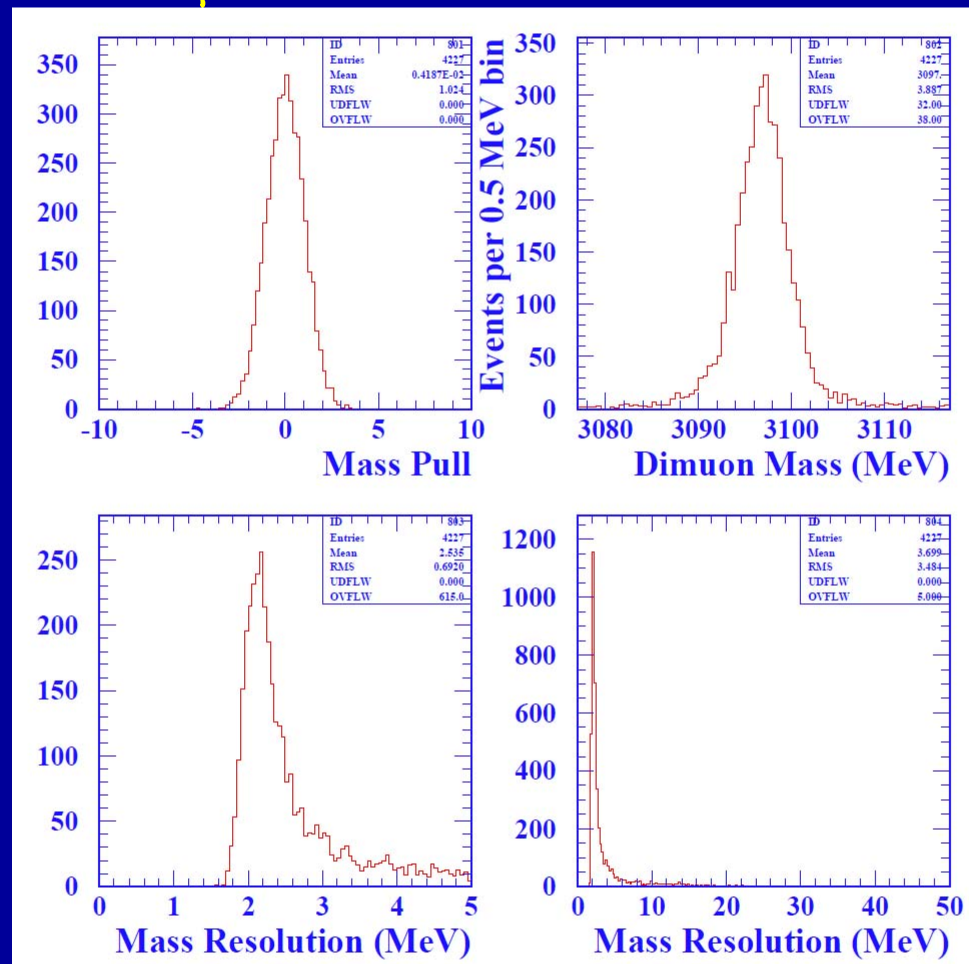
Vertex Fit Results

Implemented in MINUIT by me.
(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



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

Bottom-line

- Without vertex fit and using simple mass fit, expect **statistical** error on J/psi mass of 3.4 ppm from 10^9 hadronic Z's.
- With vertex fit => 2.0 ppm
- With vertex fit and per-event errors => 1.7 ppm.
- (Note background currently neglected. (S:B) in ± 10 MeV range is about 135:1 wrt semi-leptonic dimuons background from Z->bb, and can be reduced further if required)
- Neglected issues likely of some eventual importance :
  - J/psi FSR, Energy loss.
  - Backgrounds from hadrons misID'd as muons
  - Alignment, field homogeneity etc ..

Improving on the Z Mass and Width etc?

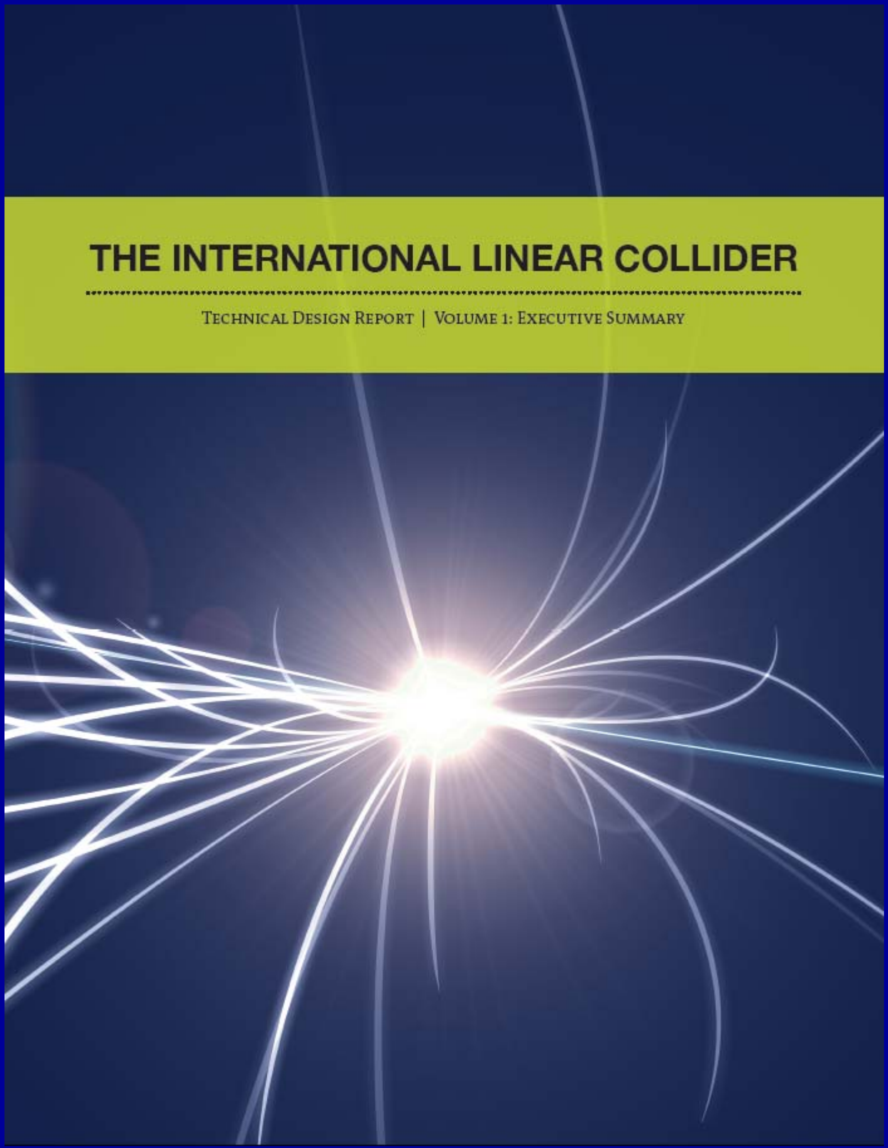
- Now that we have the prospect of controlling the center-of-mass energy at the few ppm level, ILC can also target much improved Z line-shape parameters too.

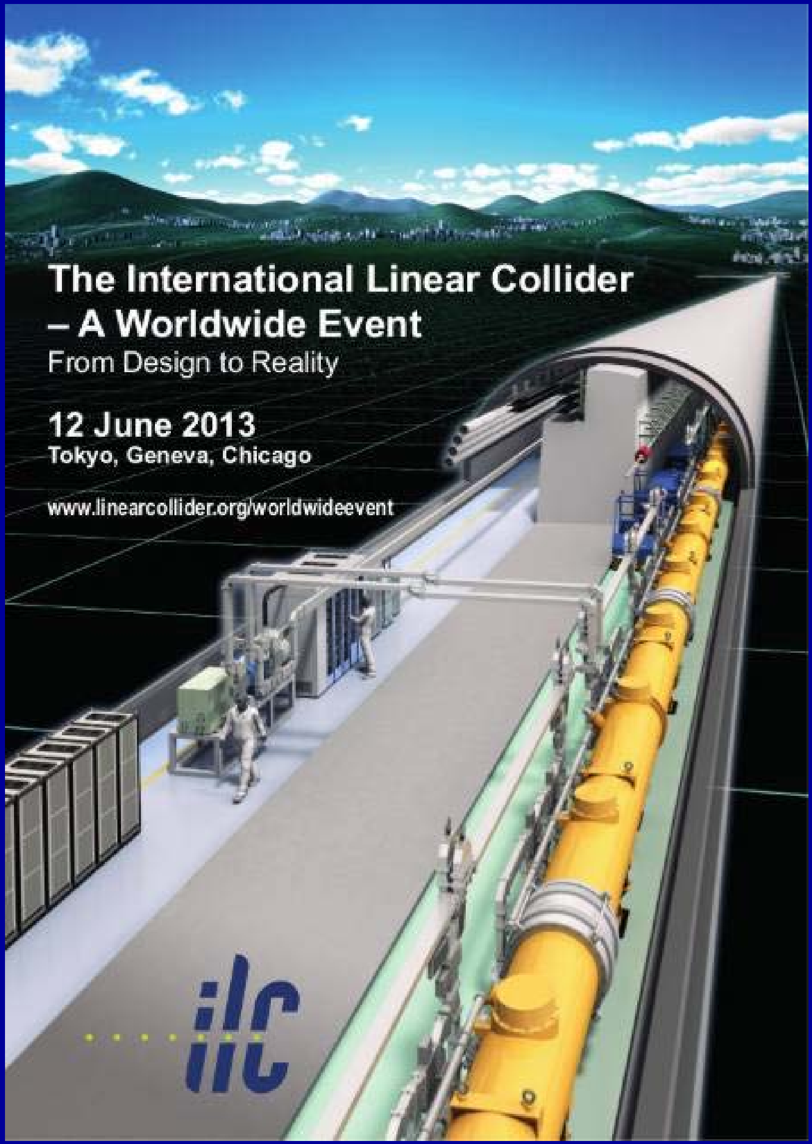
Summary

- m_W can potentially be measured to 2 MeV at ILC from a polarized threshold scan.
- Needs beam energy controlled to 10 ppm
  - Di-muon momentum-based method has sufficient statistics ($\sqrt{s}$=161 GeV)
  - Associated systematics from momentum scale can be controlled with good statistics using J/psi's collected at $\sqrt{s}$=91 GeV
    - Statistics from J/psi in situ at $\sqrt{s}$=161 GeV is an issue. Sizable prompt cross-section from two-photon production (45 pb) in addition to b's.

Backups

25-years of Development

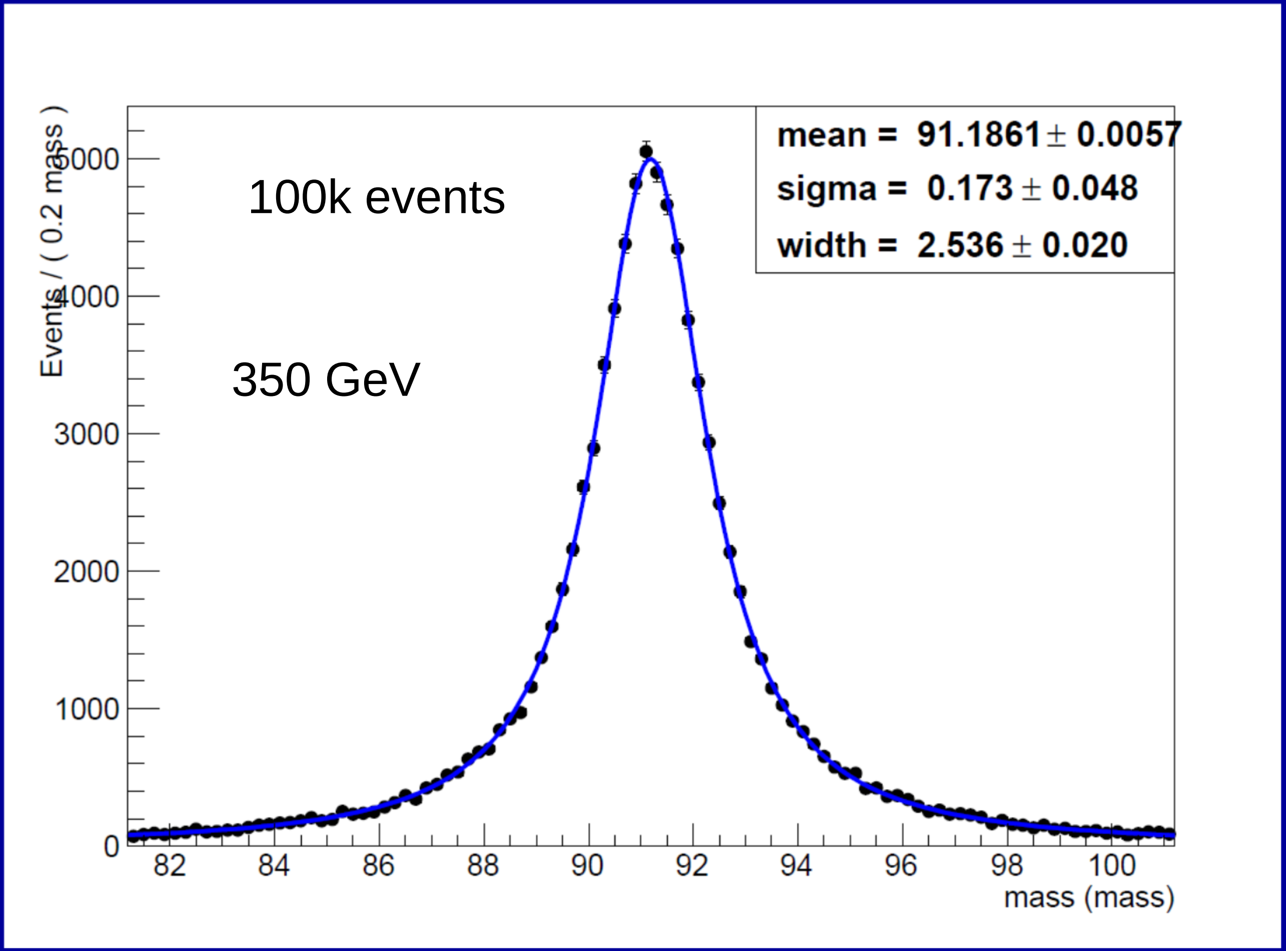




ILC Baseline Parameters

Centre-of-mass energy	E_{CM}	GeV	200	230	250	350	500
Luminosity pulse repetition rate		Hz	5	5	5	5	5
Positron production mode			10 Hz	10 Hz	10 Hz	nom.	nom.
Estimated AC power	P_{AC}	MW	114	119	122	121	163
Bunch population	N	$\times 10^{10}$	2	2	2	2	2
Number of bunches	n_b		1312	1312	1312	1312	1312
Linac bunch interval	Δt_b	ns	554	554	554	554	554
RMS bunch length	σ_z	µm	300	300	300	300	300
Normalized horizontal emittance at IP	$\gamma\epsilon_x$	µm	10	10	10	10	10
Normalized vertical emittance at IP	$\gamma\epsilon_y$	nm	35	35	35	35	35
Horizontal beta function at IP	β_x^*	mm	16	14	13	16	11
Vertical beta function at IP	β_y^*	mm	0.34	0.38	0.41	0.34	0.48
RMS horizontal beam size at IP	σ_x^*	nm	904	789	729	684	474
RMS vertical beam size at IP	σ_y^*	nm	7.8	7.7	7.7	5.9	5.9
Vertical disruption parameter	D_y		24.3	24.5	24.5	24.3	24.6
Fractional RMS energy loss to beamstrahlung	δ_{BS}	%	0.65	0.83	0.97	1.9	4.5
Luminosity	L	$\times 10^{34}$ cm^{-2} s^{-1}	0.56	0.67	0.75	1.0	1.8
Fraction of L in top 1% E_{CM}	$L_{0.01}$	%	91	89	87	77	58
Electron polarisation	P_-	%	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	30	30
Electron relative energy spread at IP	$\Delta p/p$	%	0.20	0.19	0.19	0.16	0.13
Positron relative energy spread at IP	$\Delta p/p$	%	0.19	0.17	0.15	0.10	0.07

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