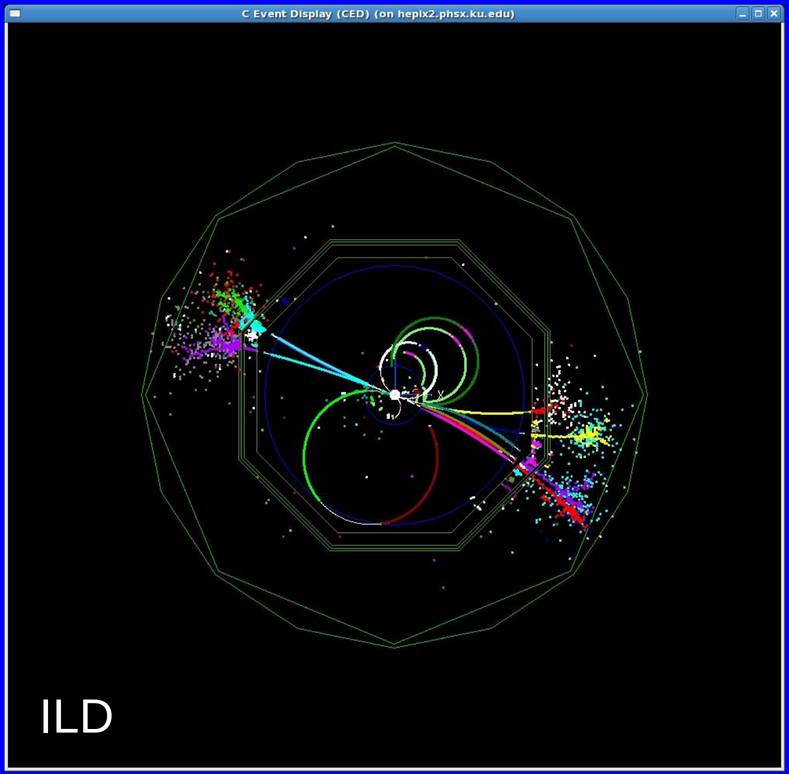
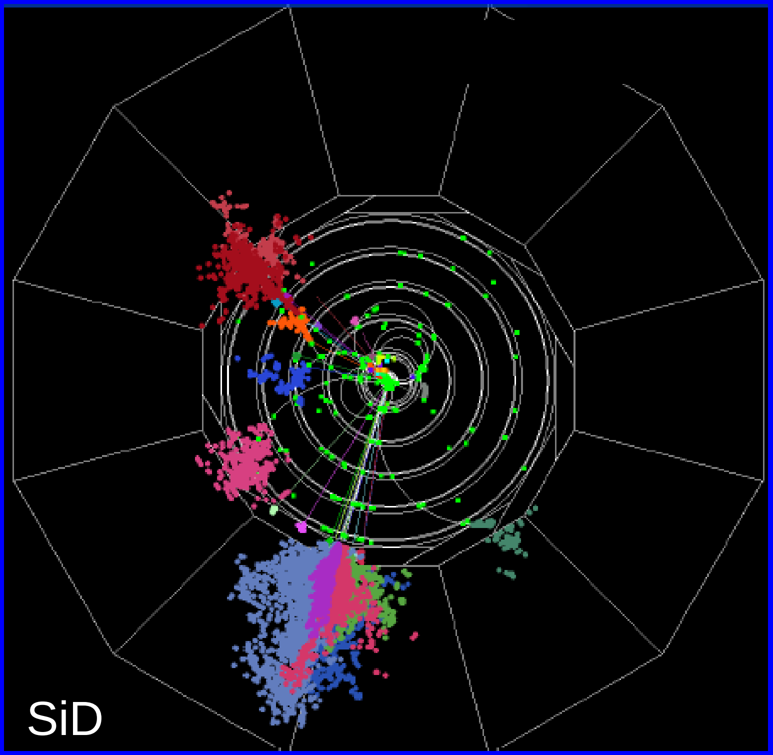
# Prospects for Precision $m_W$ Measurements at ILC



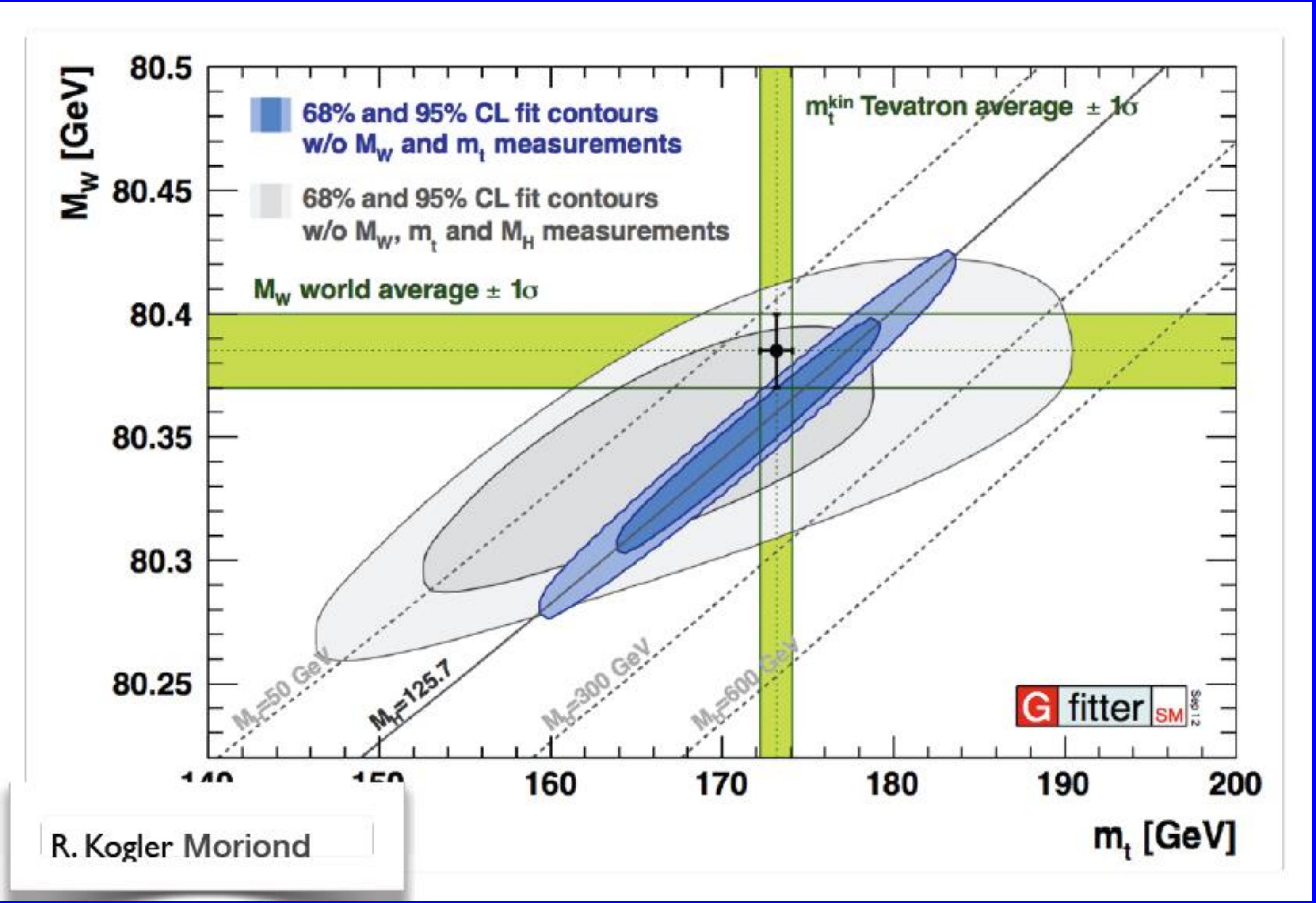




Graham W. Wilson, University of Kansas,
Snowmass EF Workshop, BNL, April 4th 2013

# Precision Measurements

Testing Nature at ILC.

Can measure mW, mt, mH, ALR. mZ? with unprecedented precision




R. Kogler Moriond

# Plan

- Brief Introduction to $m_W$ Measurement Basics
- Experimentation at Lepton Colliders with Emphasis on ILC.
  - => get appreciation of systematic issues
- Prospects for $m_W$ Measurement
  - Threshold
  - WW in continuum
  - Single-W in continuum
- Conclusion

# 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 |

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

3 fb $^{-1}$

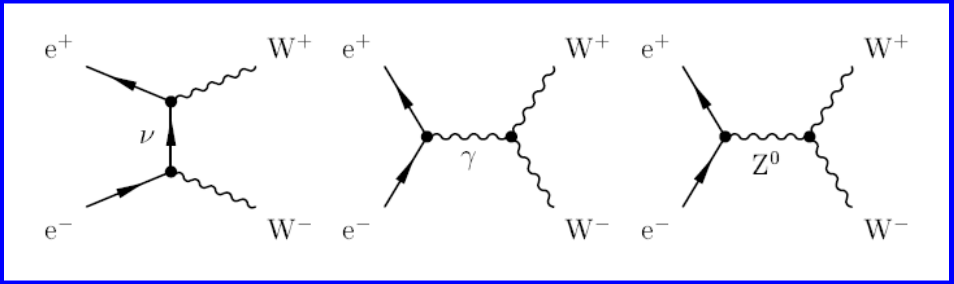
| VALUE (GeV) | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **91.1876 ± 0.0021 OUR FIT** | | | | | |
| 91.1852 ± 0.0030 | 4.57M | [1] ABBIENDI | 01A | OPAL | $E^{ee}_{cm}$ = 88–94 GeV |
| 91.1863 ± 0.0028 | 4.08M | [2] ABREU | 00F | DLPH | $E^{ee}_{cm}$ = 88–94 GeV |
| 91.1898 ± 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 |

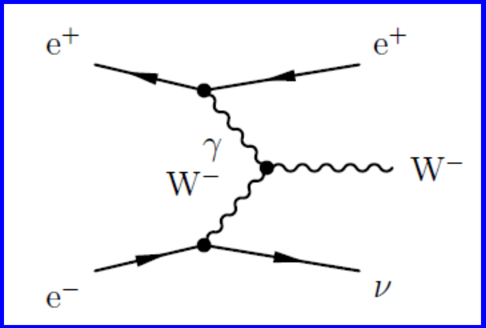
$\Delta M/M = 2.3\times10^{-5}$

0.4 fb $^{-1}$

$m_W$ is currently a factor of 8 less precise than $m_Z$

# W Production in $e^+e^-$

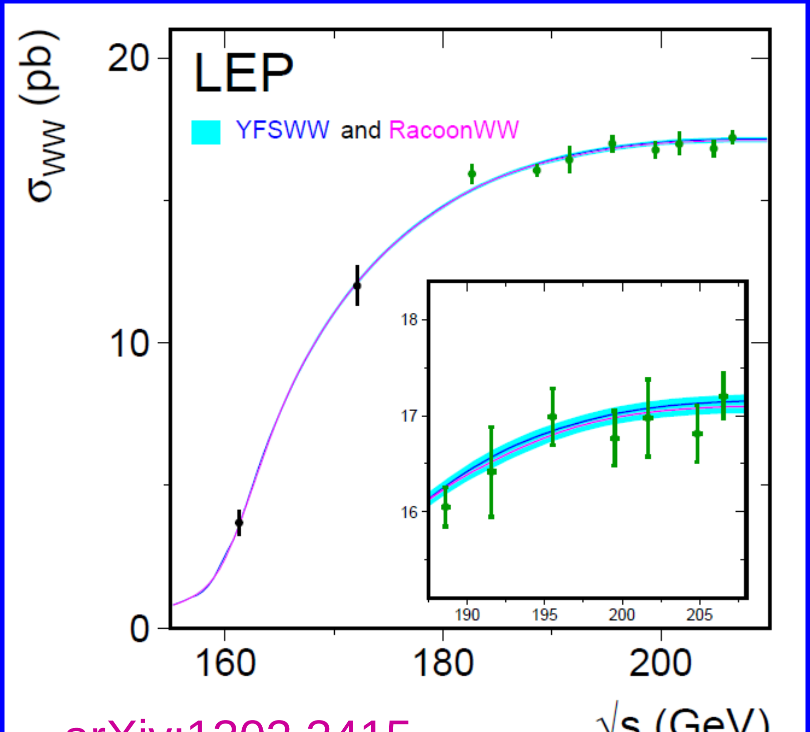


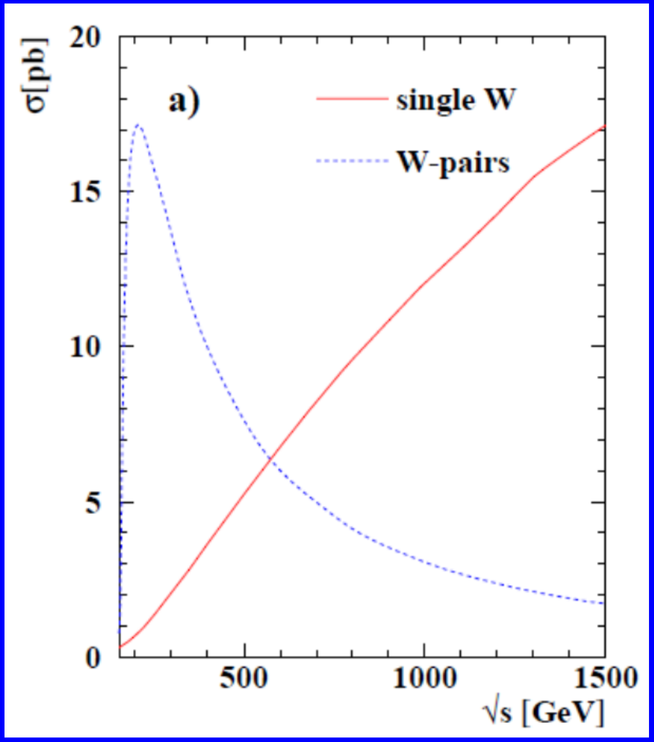




etc ..

e+e- $\rightarrow$ W+W-

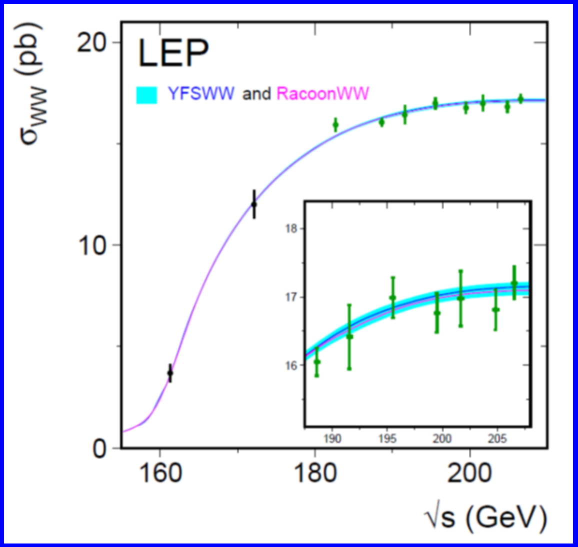
e+e- $\rightarrow$ W e $\nu$

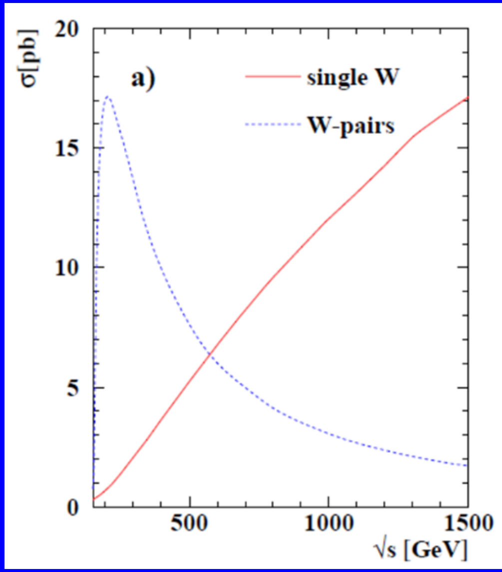


# W Mass Measurement Strategies

- $W^+W^-$
  - 1. Threshold Scan ( $\sigma \sim \beta/s$ )
    - Can use all WW decay modes
  - 2. Kinematic Reconstruction
    - Apply kinematic constraints
- W e ν
  - 3. Directly measure the hadronic mass in $W \to q\, q'$ decays.
    - e usually not detectable, so $W \to l\, \nu$ has 3 undetected particles and is not well suited to W mass measurement



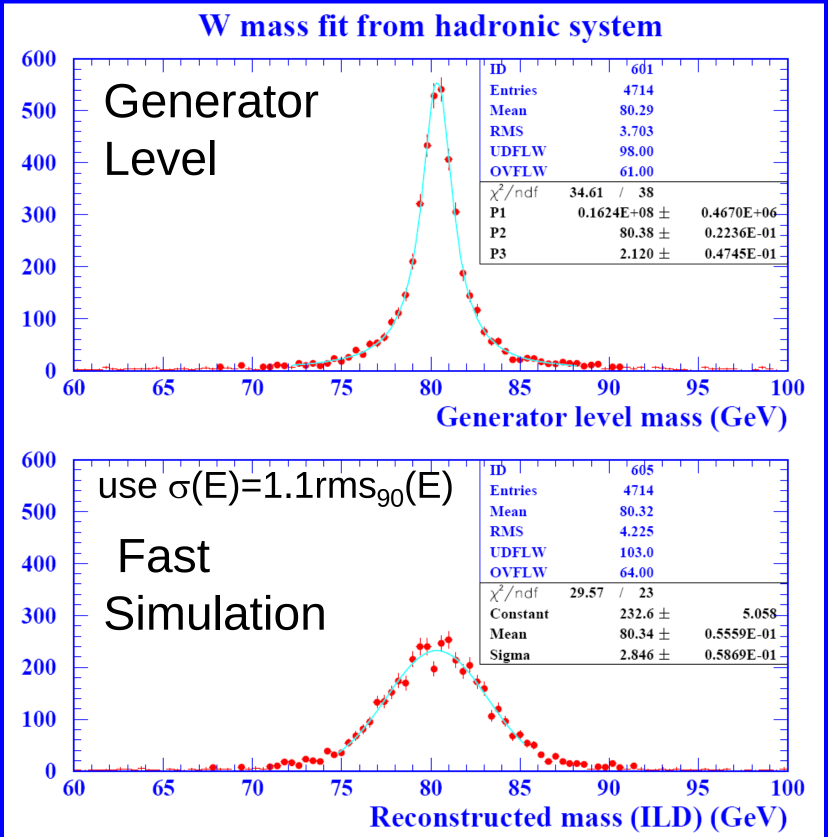

Methods 1 and 2 were used at LEP2. Both require good knowledge of the absolute beam energy.

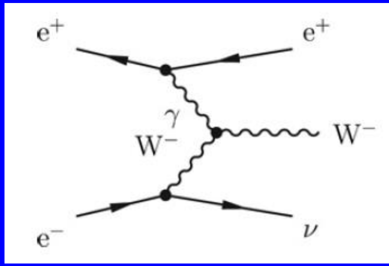
Method 3 is novel (and challenging), very complementary systematics to 1 and 2 if the experimental challenges can be met.

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

(and not get locked up ;-) )

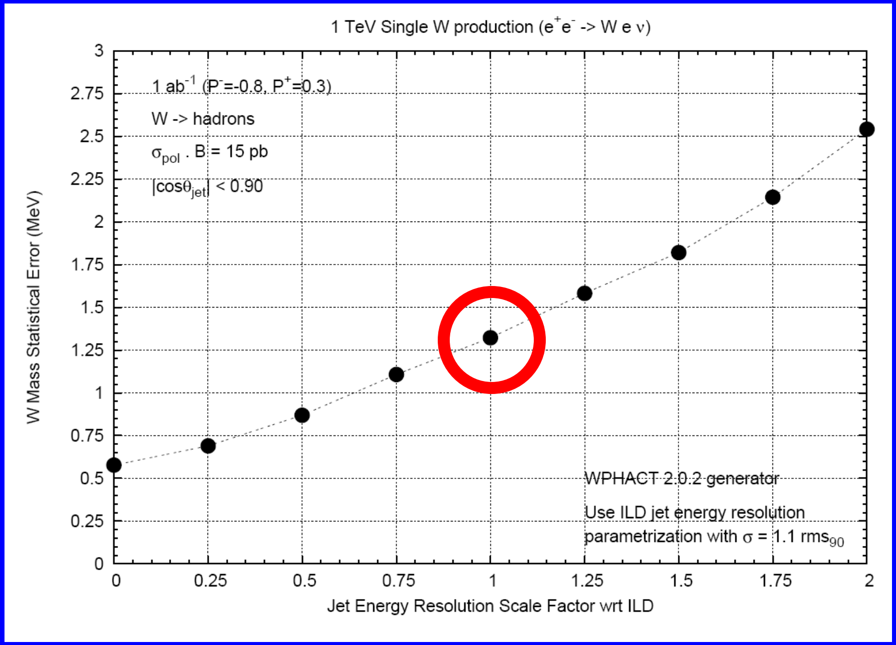
Single W study at $\sqrt{s}$ = 1TeV (e+e-)




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!)

# Experimentation at Lepton Colliders

- Facilities under discussion (some more or less seriously)
- ILC $e^+e^-$ : 91 – 1000 GeV
- CLIC $e^+e^-$ : 250 – 3000 GeV
- $e^+e^-$ ring colliders
- muon collider
- $e^+e^-$ (or $e^-e^-$ colliders) operated in either $e\gamma$ or $\gamma\gamma$ modes (or $e^-e^-$)

# ILC

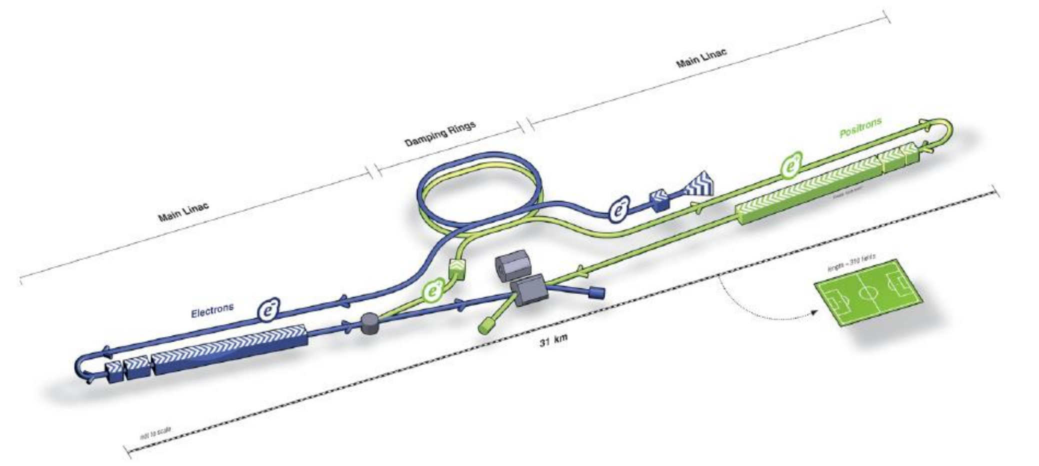



Figure 2: Layout of the ILC accelerator systems.

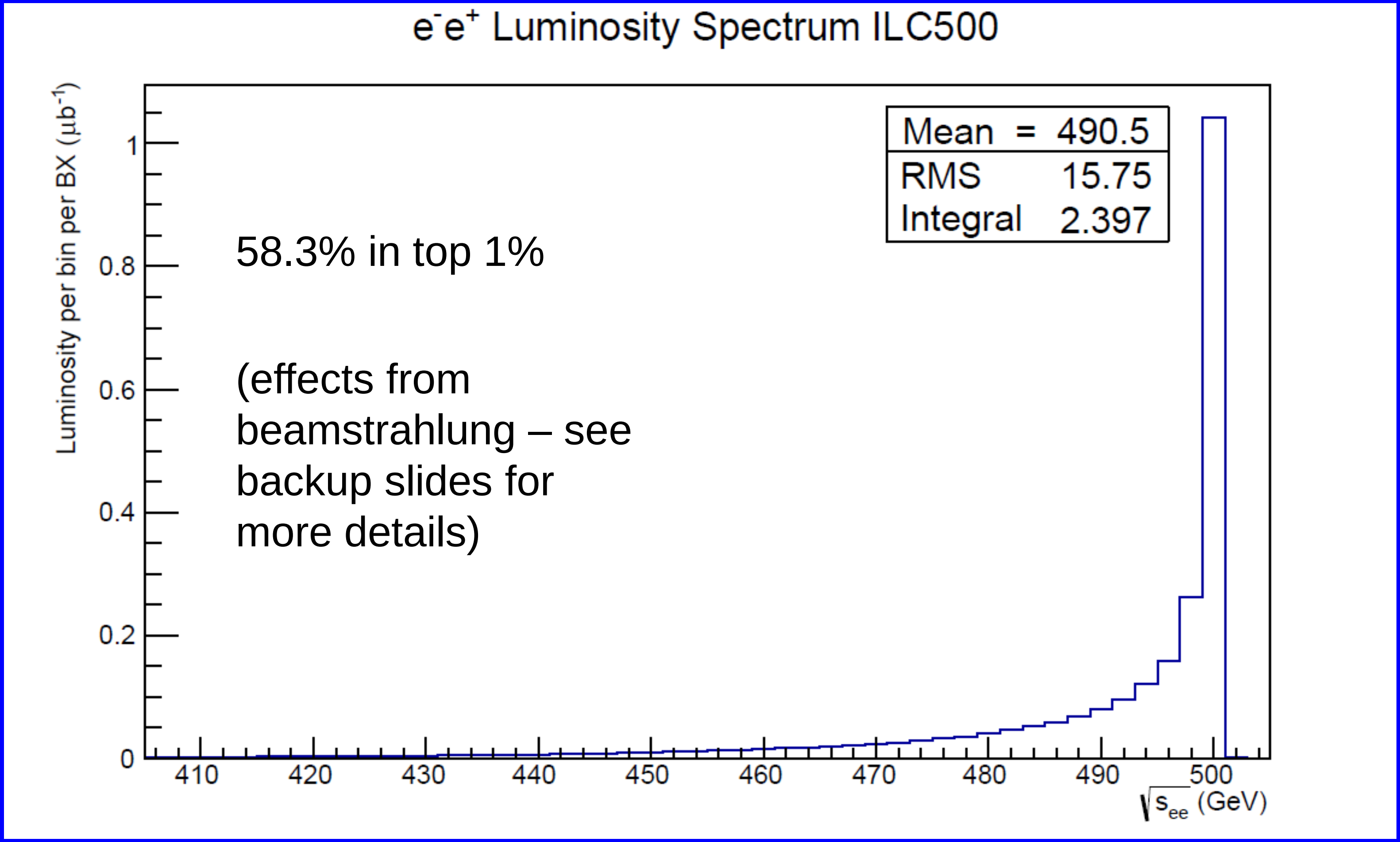
| √s (GeV) | L (fb-1) | Physics |
|---|---|---|
| 91 | 100 | Z |
| 161 | 160 | WW |
| 250 | 250 | Zh |
| 350 | 350 | t tbar |
| 500 | 1000 | tth, Zhh |
| 1000 | 2000 | vvh, VBS |

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

Can polarize both the electron and positron beam.
Electron: 80% …. 90%? Positron 20, 30 … 60%.

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

# Luminosity Spectrum

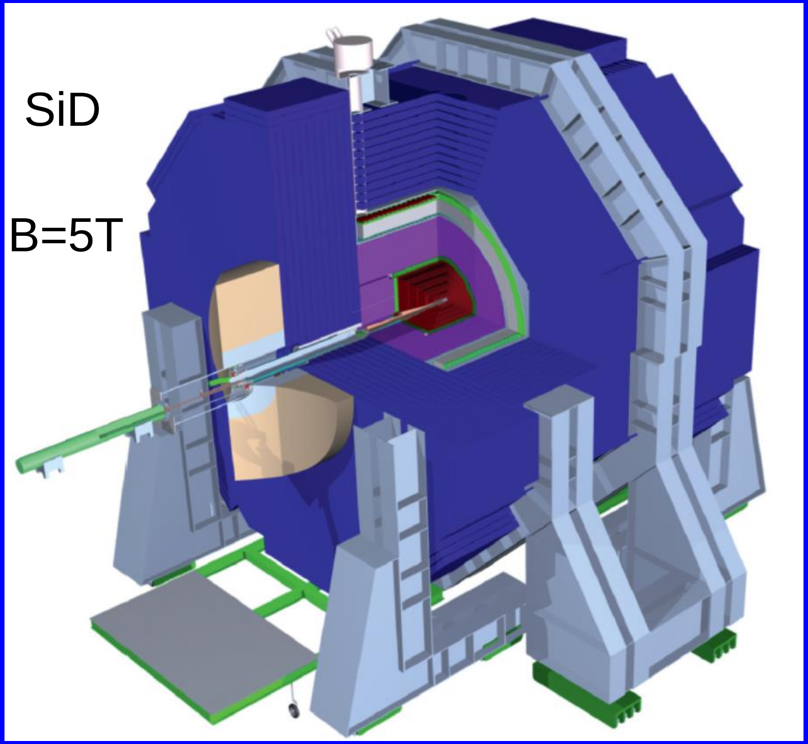



Note plot starts at 405 GeV

# ILC Detector Concepts

Large international effort.
See Letters of Intent from 2009. Currently Detailed Baseline Documents in finalization stage (part of ILC TDR)


Figure 1.1.1: View of the ILD detector concept.

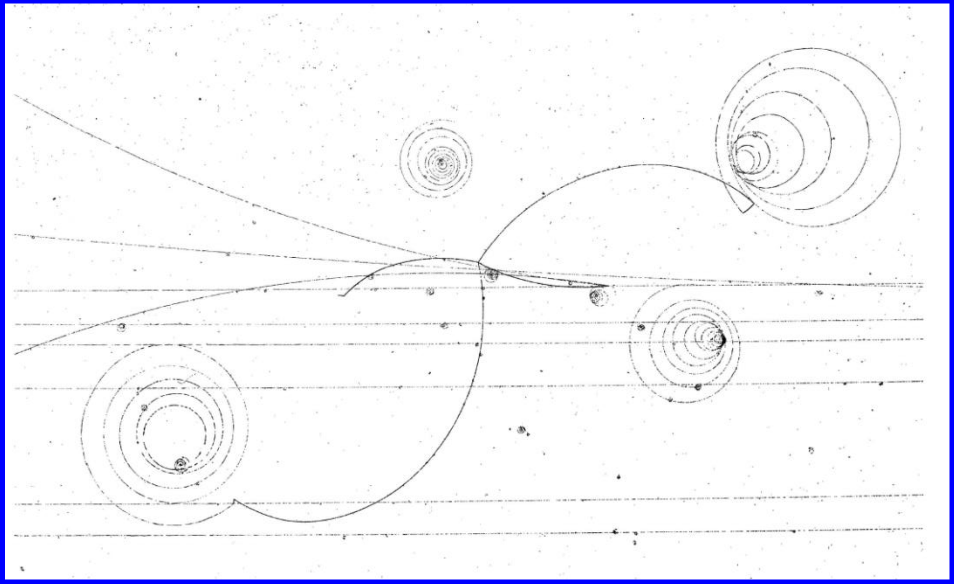


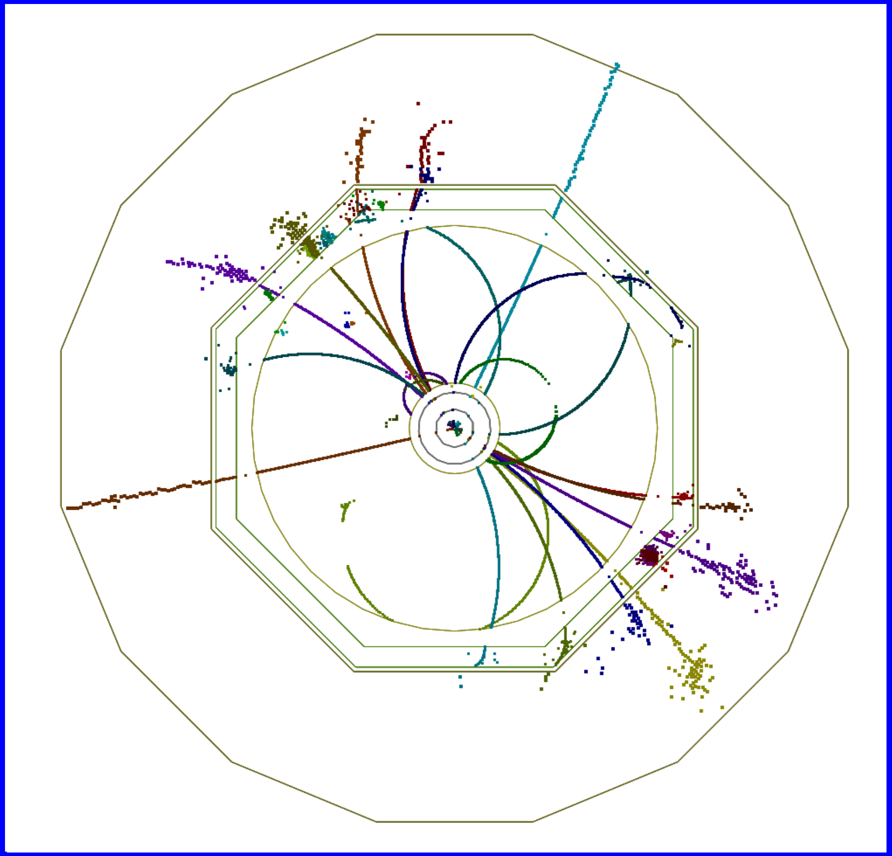

Detailed designs with engineering realism. Full simulations with backgrounds. Advanced reconstruction algorithms. Performance in many respects (not all) much better than the LHC experiments. Central theme: particle-flow based jet reconstruction. New people welcome !

# Bubble Chamber

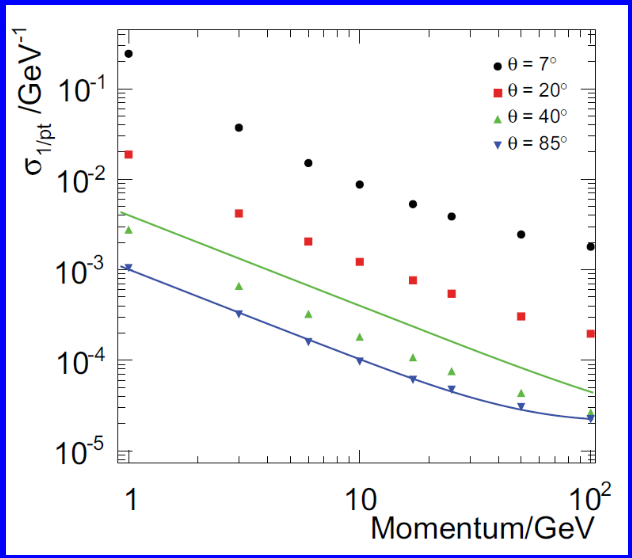
The vision is to do the best possible physics at the linear collider, by reconstructing as far as possible every single piece of each event.

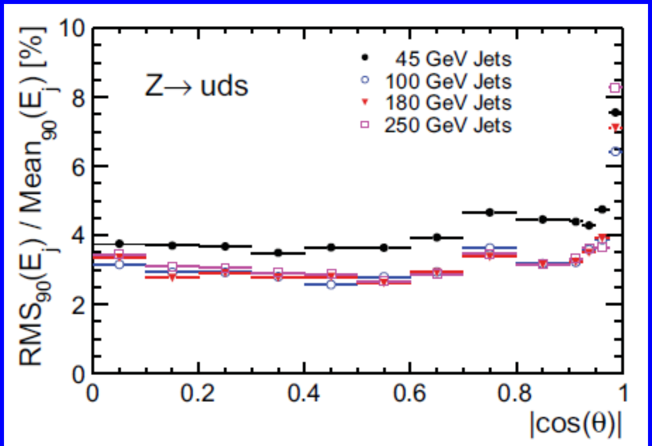
Very much in the spirit of bubble chamber reconstruction – but with full efficiency for photons and neutral hadrons, and in a high multiplicity environment at high luminosity.

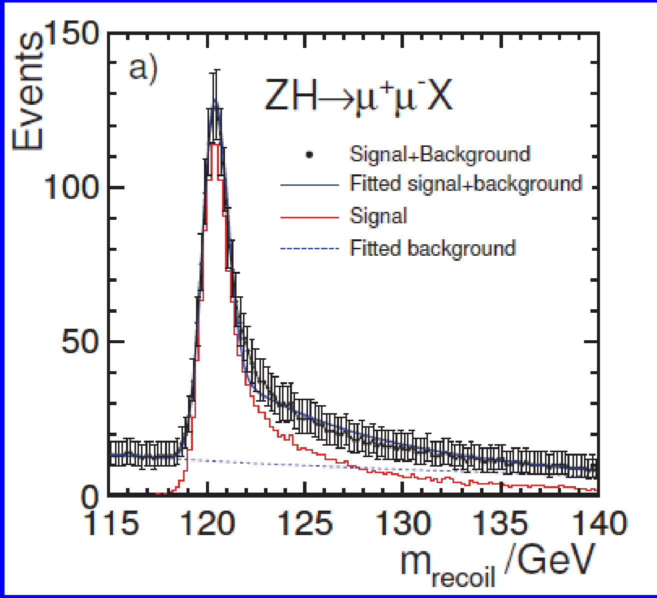




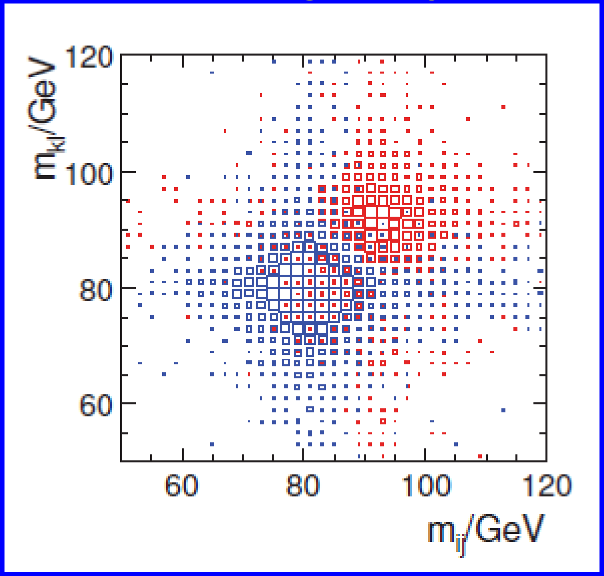
# Detector Performance




WW scattering to 4 jets




ννWW / ννZZ

# $m_W$ Measurement Prospects

- A crucial systematic common to the threshold measurement and kinematic reconstruction is the absolute beam energy knowledge.
- This is expected to worsen with $\sqrt{s}$. (statistics & BS).
- Direct $E_{beam}$ measurements target $10^{-4}$ precision.
- One way to control it - discussed by me in 1996 …is to use radiative return to the Z events using angular measurements in f f ($\gamma$) events.
  - Study by Hinze & Moenig, 2005
    - Confirms that the uncertainty worsens significantly with $\sqrt{s}$
  - Measured by OPAL, L3, DELPHI
  - This looks solid – but statistics limited.
    - Needs control of detector aspect ratio (for $\theta$ measurement).

# In-situ Beam-Energy Calibration

Hinze & Moenig

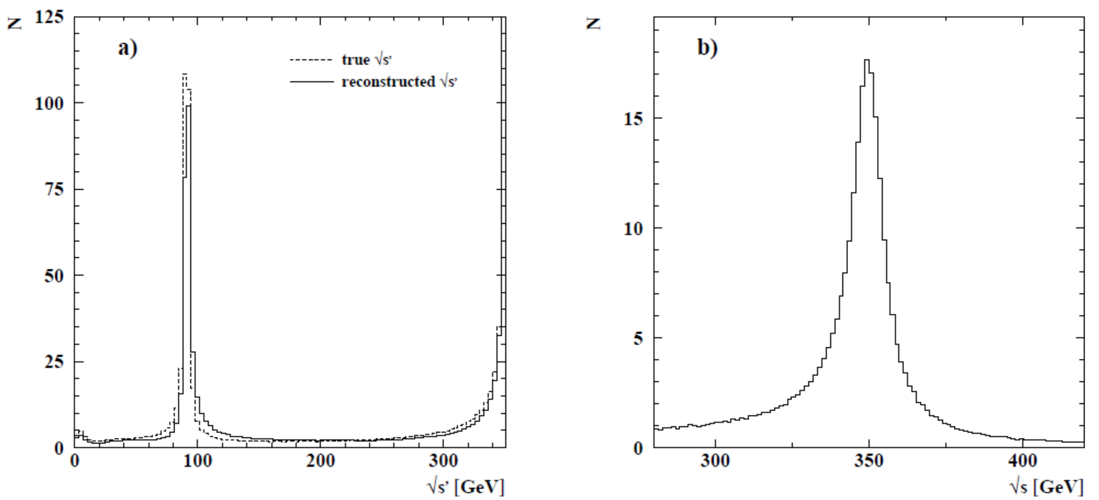



Figure 2: True and reconstructed $\sqrt{s'}$ (a) and reconstructed $\sqrt{s}$ for $e^+e^- \to Z\gamma \to \mu^+\mu^-\gamma$ at $\sqrt{s} = 350\,\mathrm{GeV}$

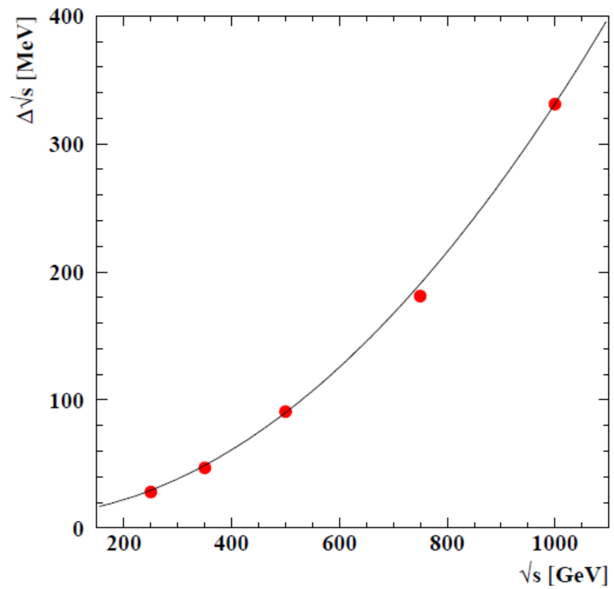



Figure 3: Energy dependence of $\Delta\sqrt{s}$ for $\mathcal{L} = 100\ \mathrm{fb}^{-1}$.

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

$$\Delta\sqrt{s} = \left(8.8 + 0.0026\sqrt{s}/\,\mathrm{GeV} + 0.0032 s/\,\mathrm{GeV}^2\right)\ \mathrm{MeV}.$$

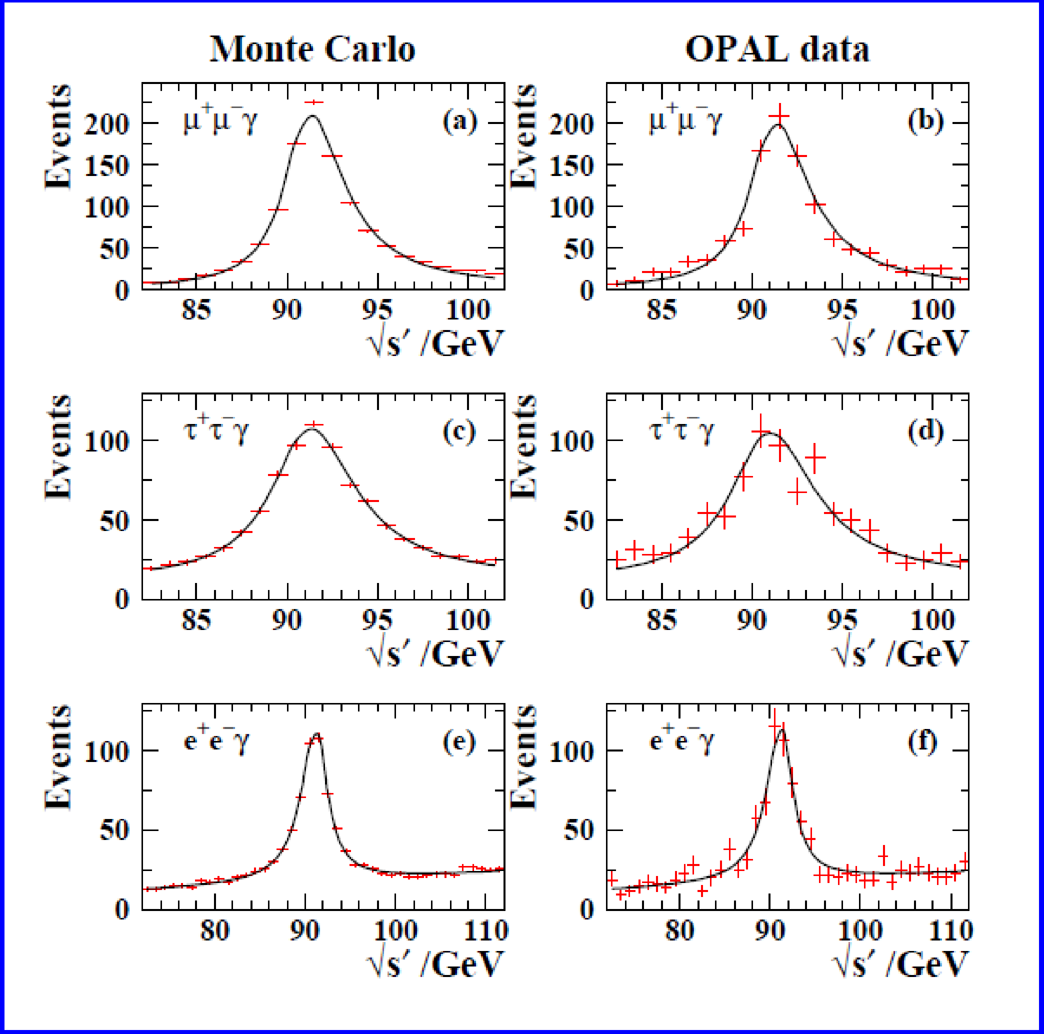
Suspect +ve linear term is in fact –ve.

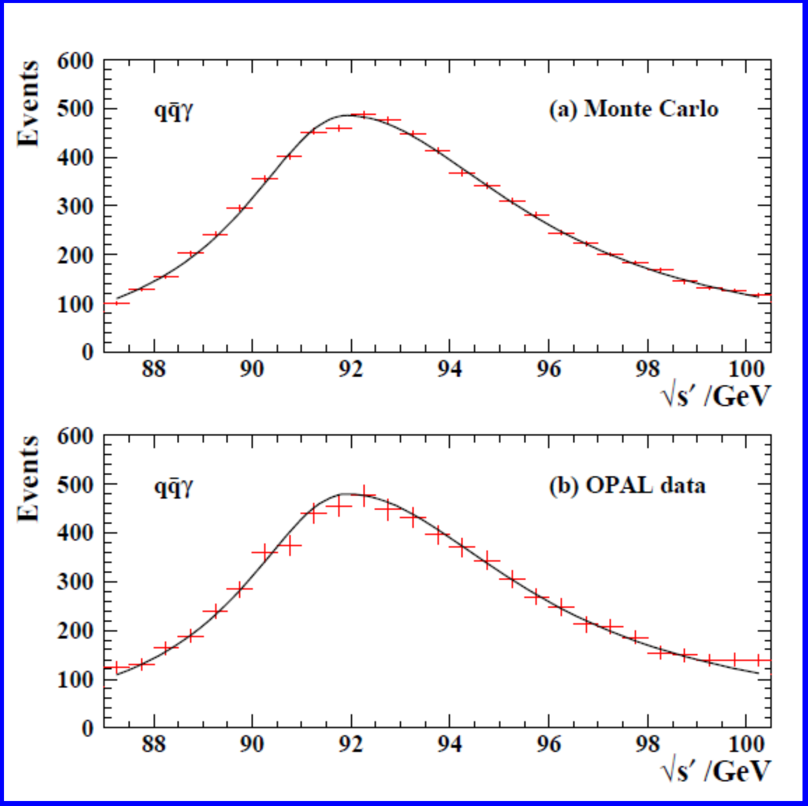
(Note. At 161 GeV my error estimate (ee,μμ) on √s is 5 MeV)

Studies (by T. Barklow) including p measurement indicate factors of 6-8 better precision at 350 GeV

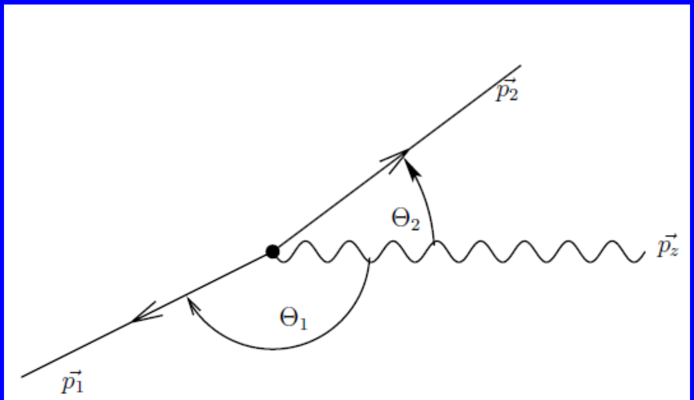
# Z γ Beam Energy Measurement (OPAL)

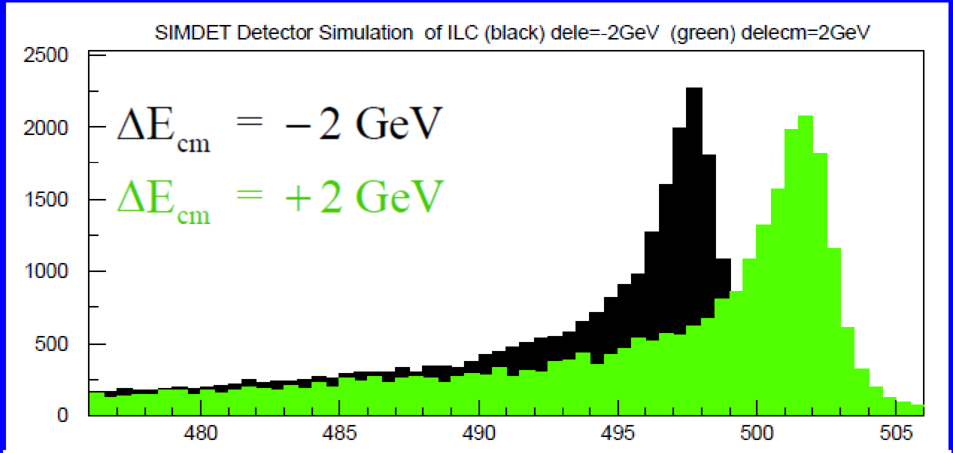
*PLB 604 (2004) 31-47*

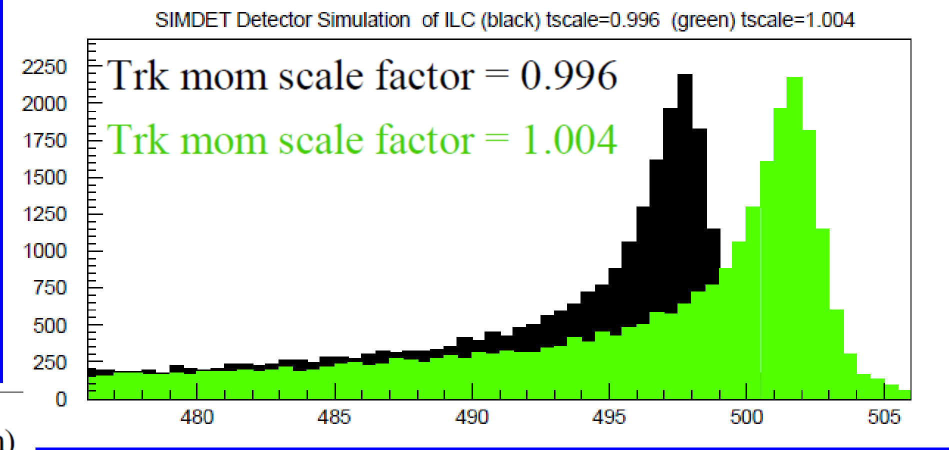


# Using Zγ for √s determination




Two methods:

1) Use angles only, measure $m_{12}$ /√s.
   Use known $m_Z$ to reconstruct √s.
2) Use muon momenta and angles.
   Measure $E_1 + E_2 + p_{12}$.

Tim Barklow study. (assume $dL/dx_1dx_2$ known)

ECM = 350 GeV 100 fb$^{-1}$

| measured var | fit var | $\Delta E_{cm}$ (GeV) | $\frac{\Delta E_{cm}}{E_{cm}}$ (ppm) |
|---|---|---|---|
| $E_{Z\gamma}$ using angles only | $E_{cm}$ | 0.0425 | 121 |
| $E_{Z\gamma}$ using momenta & angles | $E_{cm}$ | 0.0035 | 10 |
| $E_{Z\gamma}, M_Z$ using momenta & angles | $E_{cm}$ & t | 0.0045 | 13 |
| $E_{Z\gamma}$ using momenta & angles | $E_{cm}$ & t | 0.0048 | 14 |

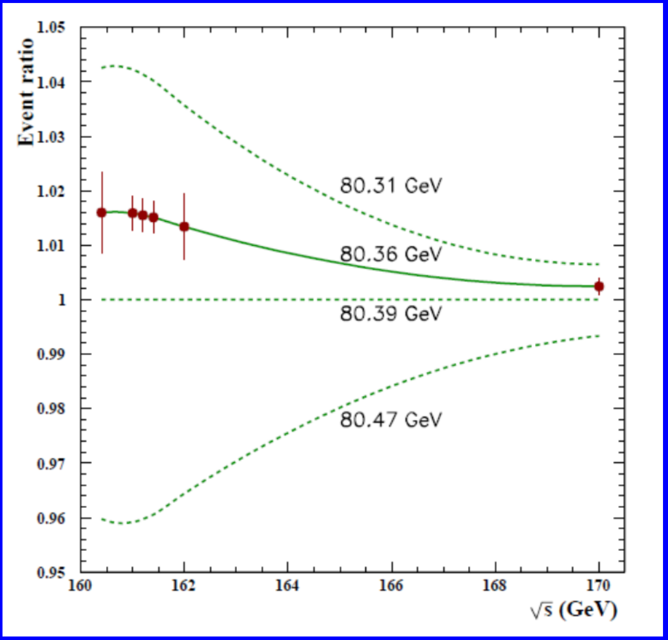
With detectors designed for 0.14% ΔpT/pT at 45 GeV, it is feasible to improve by an order of magnitude over the $\Gamma_Z$ dominated method. Should also scale better with √s ?

# $m_W$ Measurement Prospects Near Threshold

**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.




| Channel $(j)$ | Efficiency (%) | Unpolarised $\sigma_{\text{bkgd}}$ (fb) | WW fraction (%) |
|---|---|---|---|
| $\ell\ell$ | 75 | 20 | 10.5 |
| $\ell$h | 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 7 different helicity combinations.

Estimate error of 6 MeV (includes conservative Eb error from Z $\gamma$) per 100 fb$^{-1}$ polarized scan (assumed 60% e+ polarization)

# $m_W$ Measurement Near Threshold

- Requires dedicated running at an energy which is mostly only good for $m_W$ measurement.
- The envisaged Higgs and top producing next lepton collider may not spend much time if any near W threshold – especially if there are other ways to access $m_W$ with competitive precision.
- Could still be a very useful thing to do for a less ambitious regional machine (say a Z and WW factory).
- (Note that resonant depolarization measurement of beam energy (used for $m_Z$) was not possible above 60 GeV at LEP2)

# $m_W$ Prospects from Kinematic Reconstruction

- WW statistics are plentiful in envisaged run plan.
- Especially so using polarized beams compared with LEP2
- Detector performance much better than LEP detectors (helps also threshold cross-section).
- Can envisage samples with 1000 times more events than the 4 LEP experiments combined.
  - Statistical reasons to countenance error on the 1 MeV scale
  - But straightforward application of LEP2 techniques may not be the way to achieve this goal.

# $m_W$ from Kinematic Reconstruction

- qqlv Channel
- Apply (E, **p**) conservation constraint.
- 3 unknowns for v momentum.
- 1C fit.

Bottom-line.

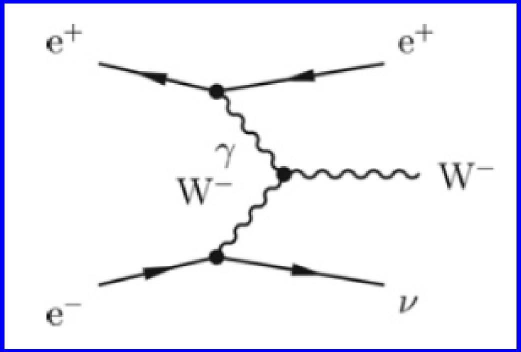
Need beam energy and beamstrahlung under control.

Latter is thought doable.

- qqqq
- Apply (E, **p**) conservation constraint
- 4C fit.
- Final LEP2 results suffered from "color reconnection" systematic.

- Also lvlv channel.
- Use lepton endpoints and pseudo-mass.

# $m_W$ from Hadronic Mass in Single W

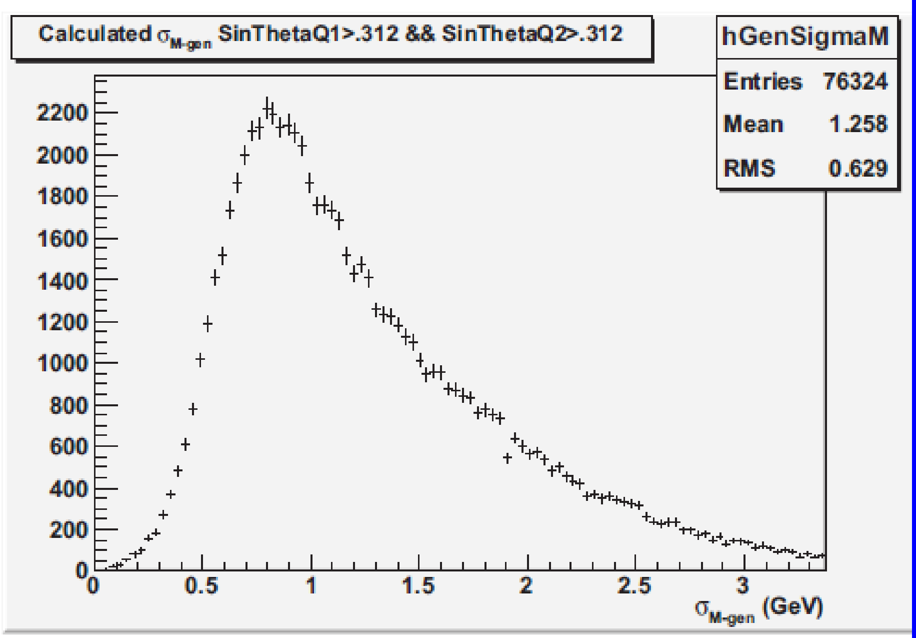


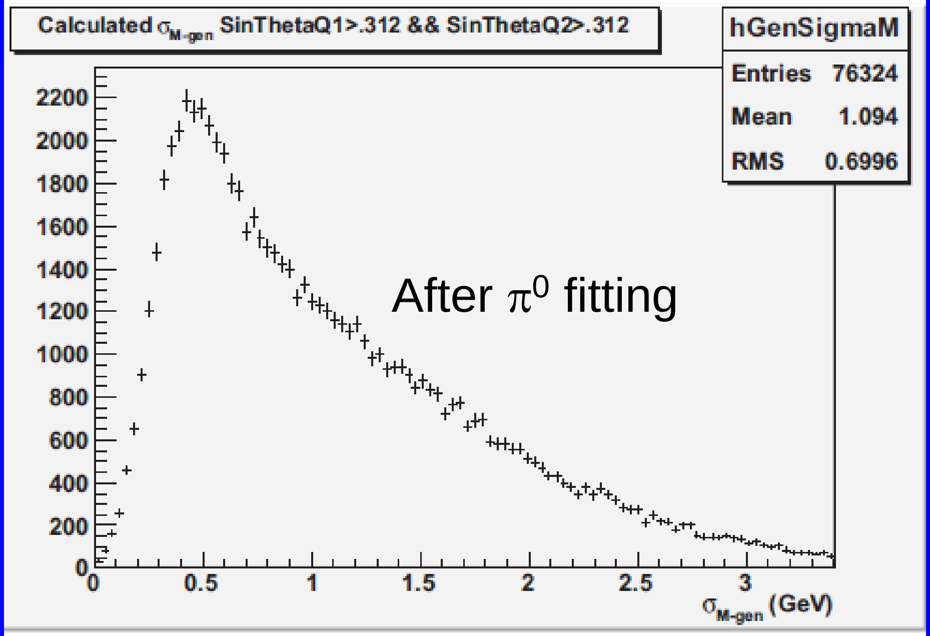

\+ ….

- Cross-section including eγ induced reactions with -80% (e-), +20% (e+) is 40 pb at 1 TeV.
- Per event mass resolution is the convolution of the intrinsic width, (2.08 GeV), and detector resolution.
- The latter varies significantly from event-to-event.
  - Depends a lot on the amount of neutral hadron energy.

# Event-Specific Hadronic Mass Resolution

B. van Doren (KU)




Assumes individual particles are reconstructed, resolved and measured with perfect efficiency, intrinsic detector resolutions and perfect mass assignments.
(Also no confusion: valid for low jet-energy and jet multiplicity environment)

Many experimental systematics need to be included: including effects like multiple interactions ($\gamma\gamma \rightarrow$ hadrons)

# Estimated Statistical Uncertainties

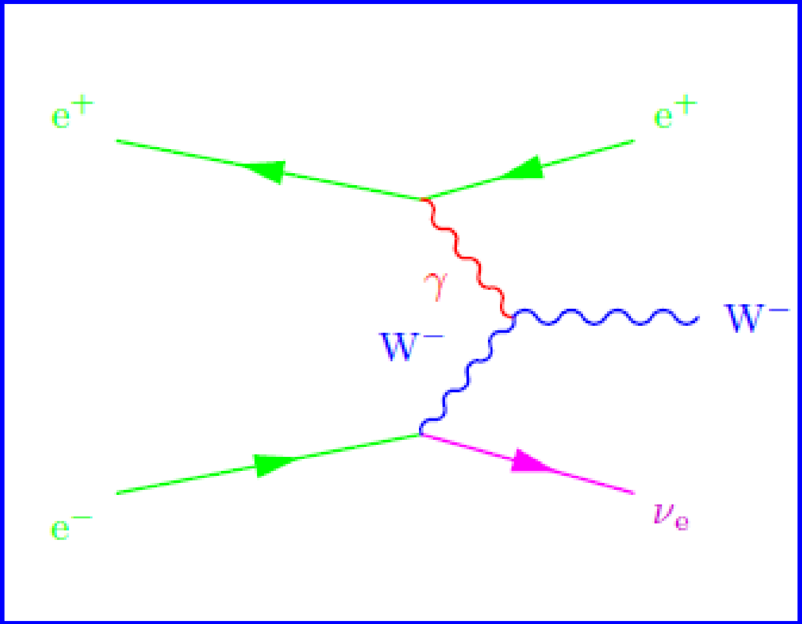
- 38 pb Single W $\rightarrow$ hadron cross-section
- Assumes 1000 $fb^{-1}$ at 1 TeV (80,20 polarization).
- Estimate 20 M accepted W-like events
  - ILD00 jet resolution model and simple Gaussian fit (see slide 7).
    - $\Delta M_W$ (stat) = 1.0 MeV
  - With toyMC assumptions and simple fit
    - $\Delta M_W$ (stat) = 0.68 MeV
  - With toyMC assumptions and convolution fit
    - $\Delta M_W$ (stat) = 0.52 MeV
  - With toyMC assumptions and convolution fit and $\pi 0$ fitting
    - $\Delta M_W$ (stat) = 0.46 MeV
  - With perfect resolution (intrinsic width limit)
    - $\Delta M_W$ (stat) = 0.34 MeV

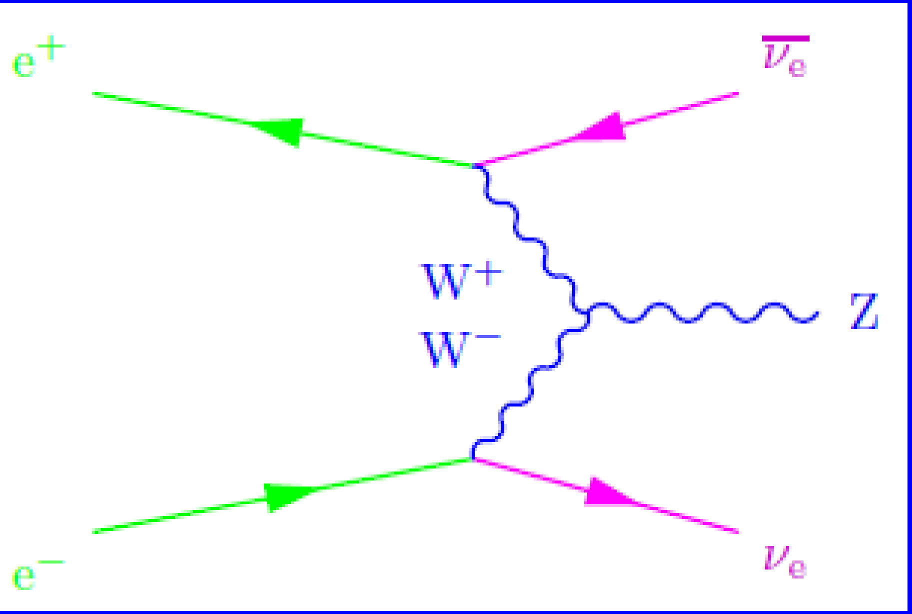
# Similar Exercise Done with $\nu\nu h$

with B. van Doren

- Require h decays hadronically.
- Require no secondary neutrinos (from b, c, b$\rightarrow$c, W, Z).
  - Likely a lepton veto in reality
- h (126 GeV) intrinsic width is very small. (4 MeV).
- For 1 TeV find following errors on $m_H$ from convolution fits ignoring the (tiny) width, background etc.
  - 6.6 MeV : standard
  - 4.8 MeV: with $\pi^0$ fitting
  - 8.7 MeV: standard + allow neutral hadron energy scale to float.

# Z Calibration Methods



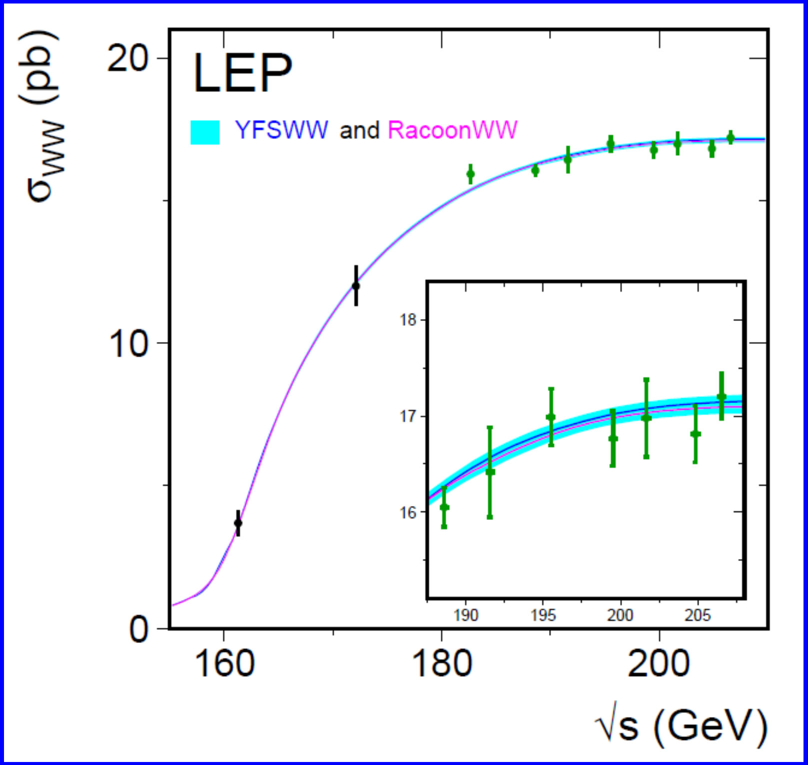



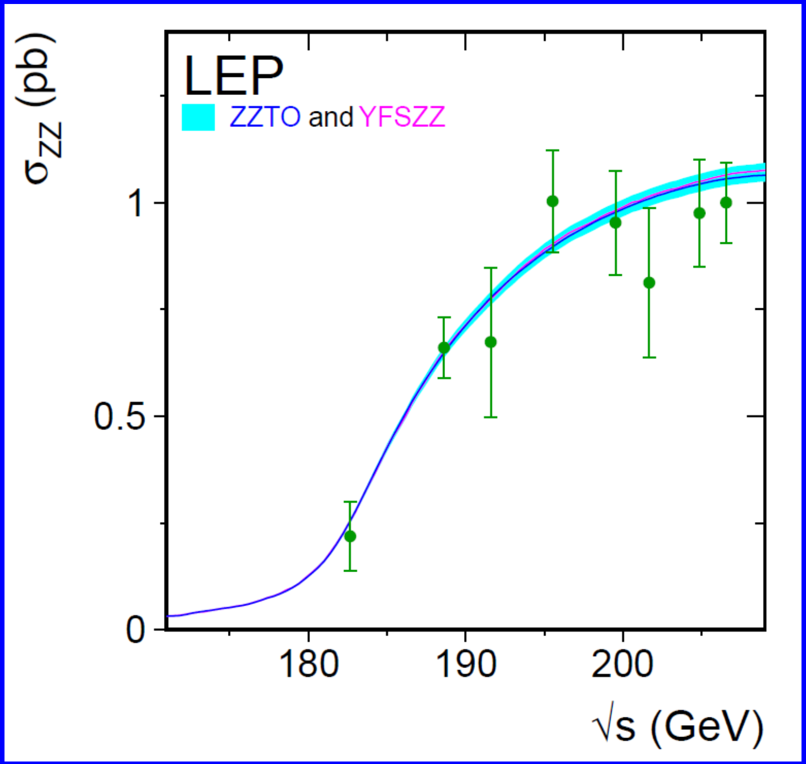

$$(\Delta M/M)_Z = 2.3\times10^{-5}$$

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.

# WW and ZZ



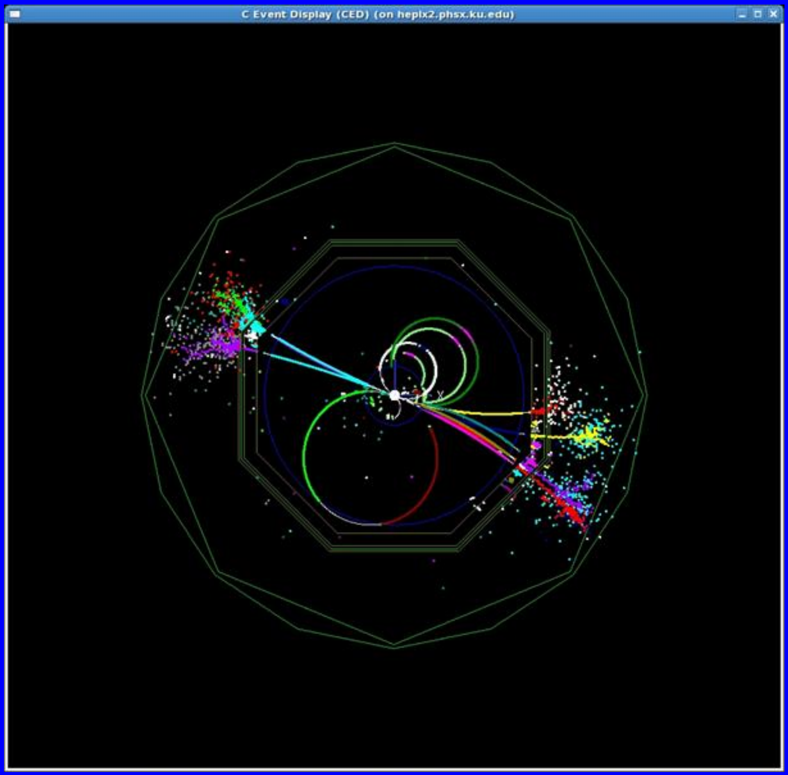

WW

ZZ

At ILC can potentially use ZZ to control beam energy systematics in WW production using PDG Z mass (LEP). ZZ cross-sections lower by factor of 25 (15 and up to 2 for polarization…)

# 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 masses: $\Lambda^0$, $\pi^0$, $\phi$, $\Sigma$.
- Also fragmentation errors ($K_L$, n)



# Conclusions

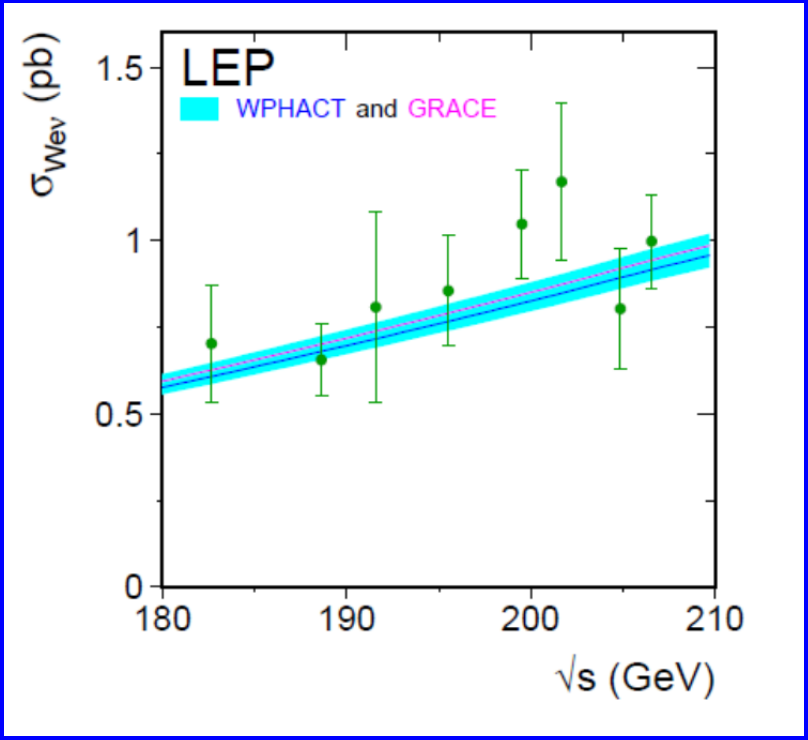
- Many ways to measure $m_W$ at a lepton collider like ILC with modern detectors.
- Statistics is not the issue.
  - Worth doing this well and with different methods
  - May not need dedicated threshold scan
- Established approaches to exploit 1 MeV statistical precision likely rely on the known $m_Z$
  - Setting an error scale of 2 MeV
- New – can plausibly measure Eb much more precisely without relying on mZ. (20 ppm seems feasible; need more study)
- Can also potentially measure the X(125) mass to the 10 MeV level at ILC with similar technique.
- A related question is whether we can do better on measuring $m_Z$ ?
- Bottom-line:
- A 5 MeV error on $m_W$ from ILC is achievable.
- It is not unreasonable to target a 2.5 MeV error – needs work!

# ILC References

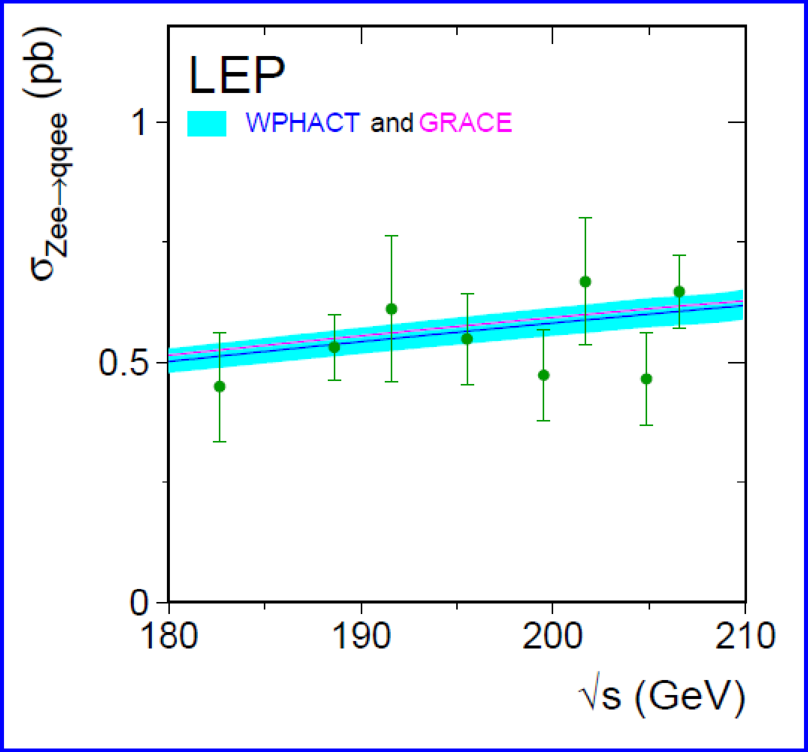
- http://www.linearcollider.org/physics-detectors/WWS
- ILC Reference Design Report 2007 has links to
  - i) Physics at the ILC (Vol II)
  - ii) Detectors (Vol IV).
- Detector Letters of Intent 2009. (ILD and SiD).
- Currently, ILC TDR report is being finalized with Documents (DBDs) for the detectors.
- Visit/subscribe to http://newsline.linearcollider.org/ to find out more and stay informed.

# Backup

# 4f processes with resonant W, Z




Wev

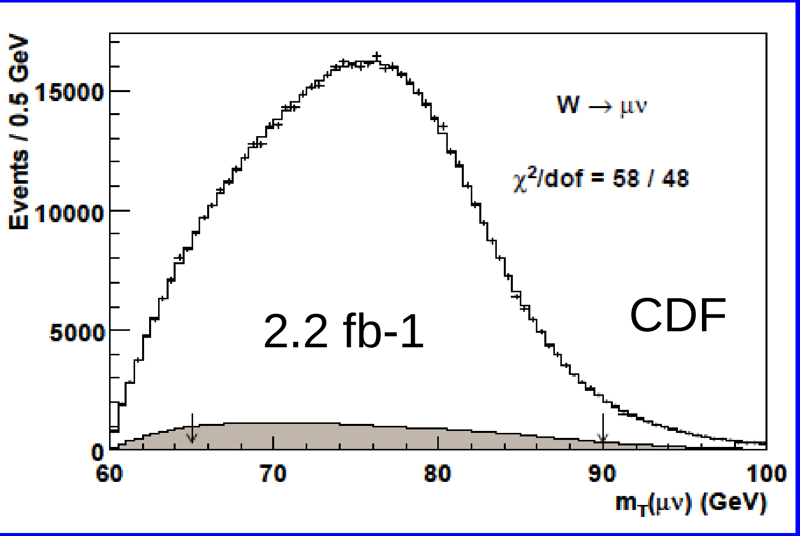


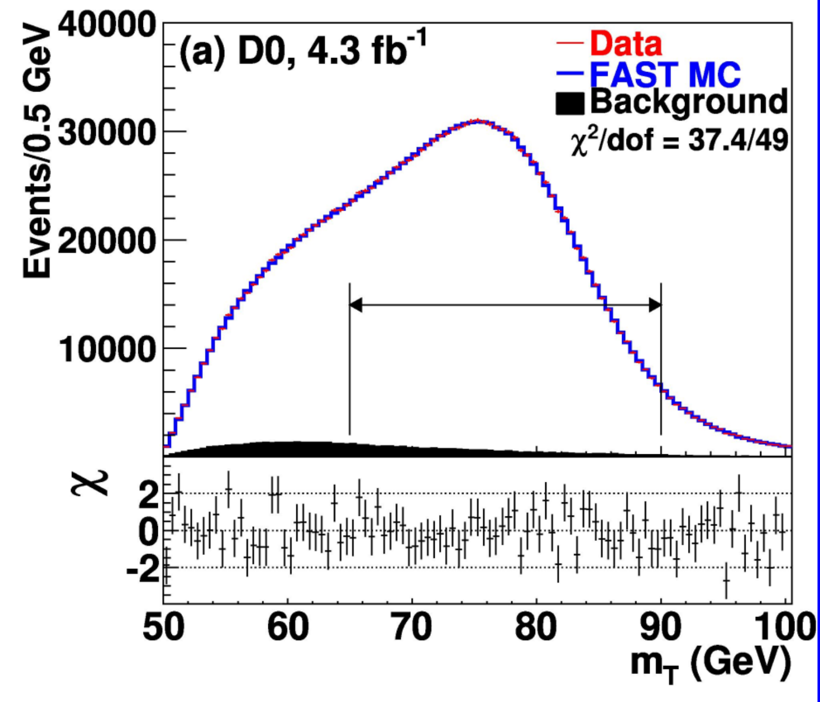

Zee

Experimentally feasible to get similar in-situ Z statistics to W.

# Hadron Collider $m_W$ Measurements

- Tevatron results on partial data-sets
- CDF (e,μ). D0 (e-only)
- Final Tevatron analyses will be challenging
- No results yet from LHC
  - Remember pp (not p-pbar)
  - Low pile-up datasets limited
- It remains to be proven that the LHC in pp mode can supersede the Tevatron.
  - Especially with the focus on HE and HL.



# ILC Accelerator Parameters

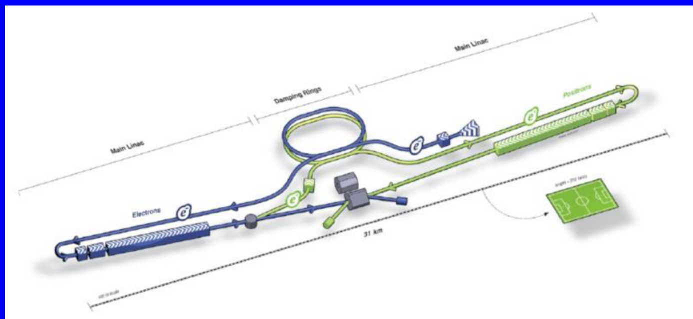


Figure 2: Layout of the ILC accelerator systems.

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 |

# Beamstrahlung

- Very strong magnetic field experienced by individual particles of beam during collision.
- Leads to quantum emission of hard photons of order 0.1 $E_{beam}$.
- See Yokoya and Chen.
- Distorts $e^+e^-$ lumi spectrum
- And in addition to $e^+e^-$ collisions, we also have collisions (with real $\gamma$'s).
- $e^- \gamma$, $\gamma\ e^+$, $\gamma\gamma$

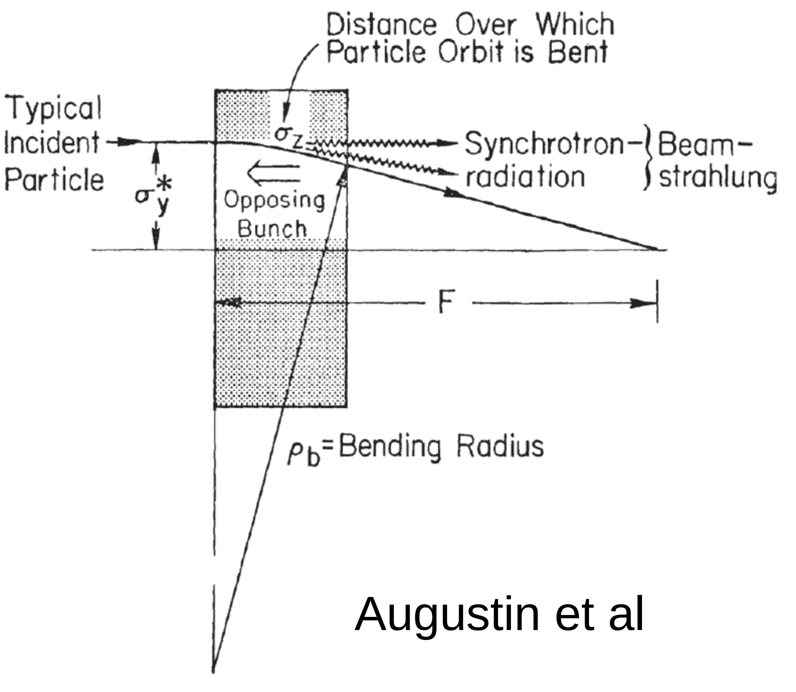
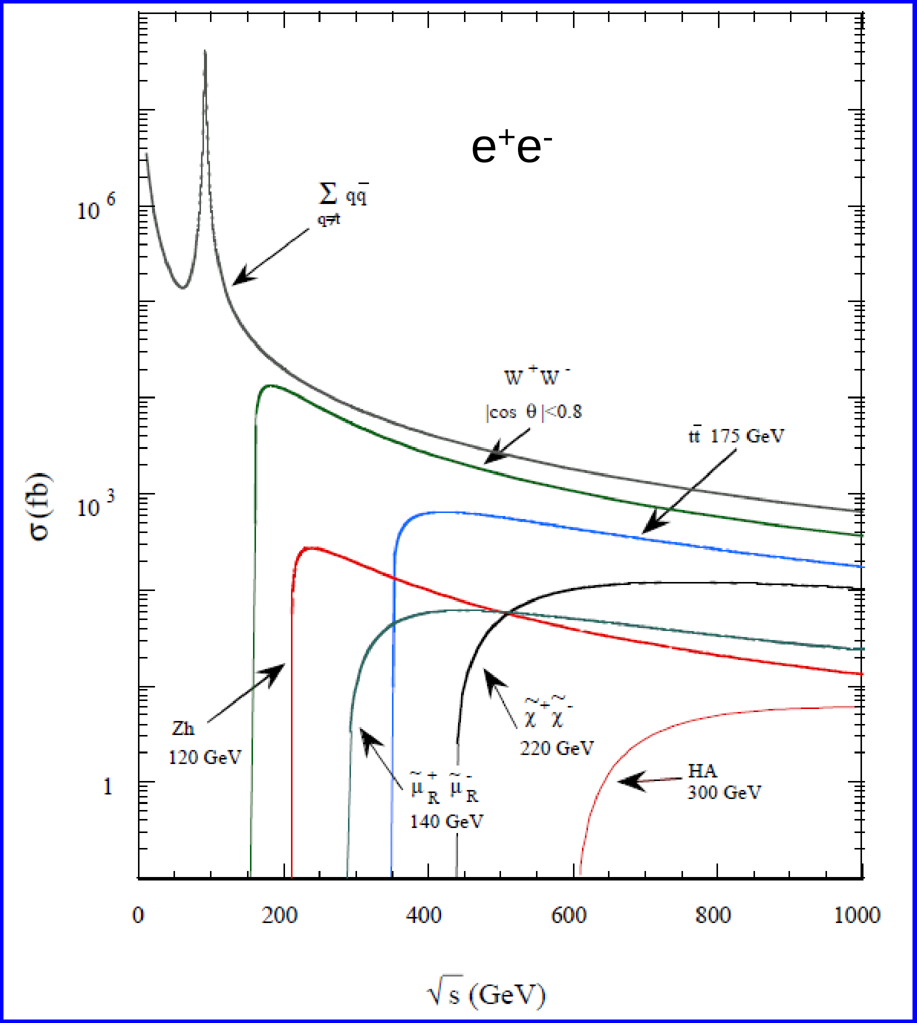
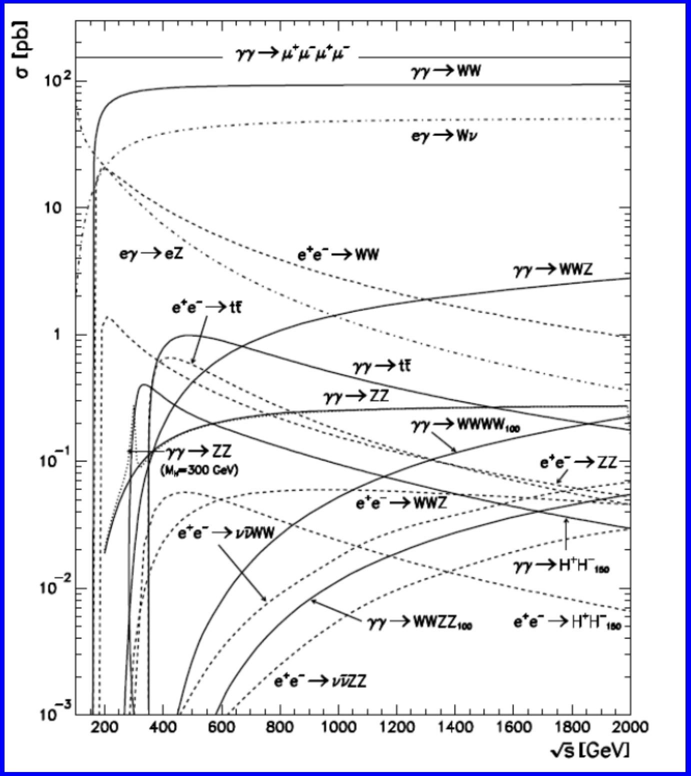



Fig. 1. Typical particle incident on an opposing bunch.

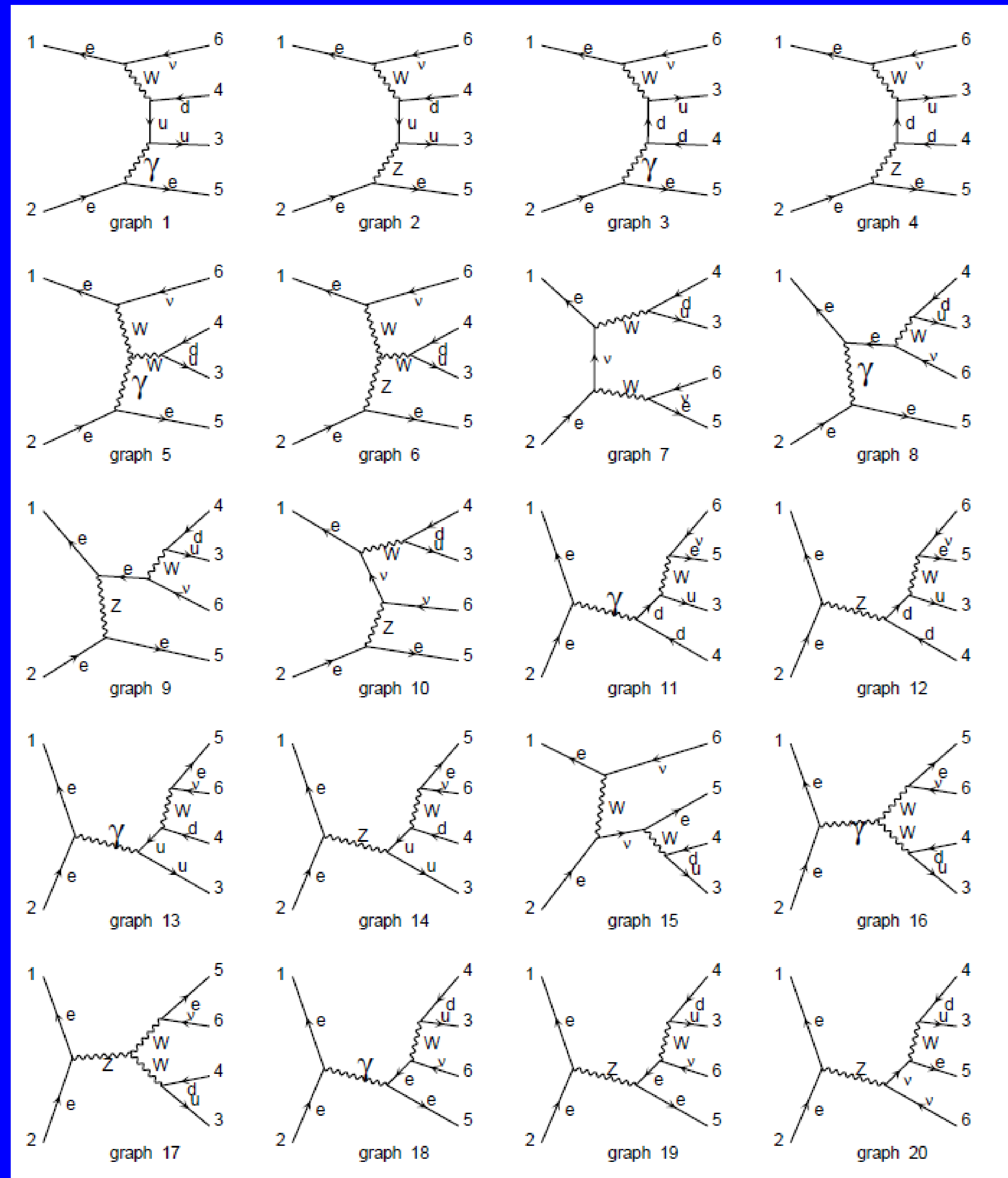
# $e^+e^-$ Cross-Sections (unpolarized)



# $e^+e^- \to u\bar{d}e^-\bar{\nu}_e$

- CC20
- 4 non-resonant
- 3 are doubly-resonant (WW)
- Graphs 5, 8, 15 particularly important.
- Graphs 11-14 have non-resonant $u\bar{d}$



# Convolution Fit

Perform event-by-event likelihood fit for proper weighting of events

- Convolution of physics and resolution functions

$$\mathcal{L}_i = R_i(m' \mid m, \sigma_i) \otimes P(m \mid m_W, \Gamma_W, f_B)$$

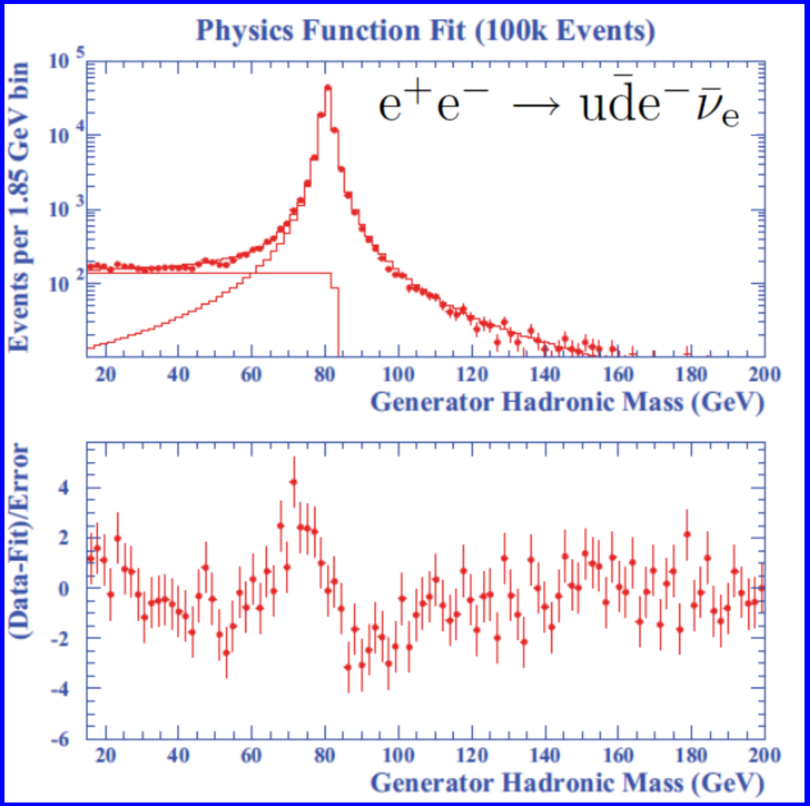
- Physics function is distribution of hadronic mass. Uses combination of signal and background functions

$$P(m \mid m_W, \Gamma_W, f_B) = (1 - f_B)P_S + f_B P_B$$

Can use the estimated hadronic mass resolution for each event (can be vastly different)

# Physics Function

- Ideally, parametrize the physics function ($d\sigma/dm\_had$) analytically ($M_W$, $\Gamma_W$ as parameters).
- Example: ECM = 500 GeV
- Plot for non doubly-resonant helicity configuration (LL) for illustration.
- Physics function needs the resonance, phase-space, non-resonant background, interference.
- With this in hand it would be fairly trivial to include detector resolution in a convolution fit.




What $M_W$? What $\Gamma_W$? s-dependent width? Phase-space? Theoretical input welcome !
May be a problem which naturally needs MC though …

# Why have longitudinally polarized beams?

## Advantages

- Measure polarized cross-sections and asymmetries to better understand new and old physics
- Improve statistical errors by preferentially selecting preferred beam helicities (best with high $|P|$)
- Reduce backgrounds in new physics searches

The expected event number, $\mu$, in a particular channel, $j$, with a particular configuration of signed beam polarizations, $(P_{\mathrm{e}^-}, P_{\mathrm{e}^+})$, exposed to an integrated luminosity $\mathcal{L}$ is

$$\mu = \sigma(P_{\mathrm{e}^-}, P_{\mathrm{e}^+})\,\mathcal{L}$$

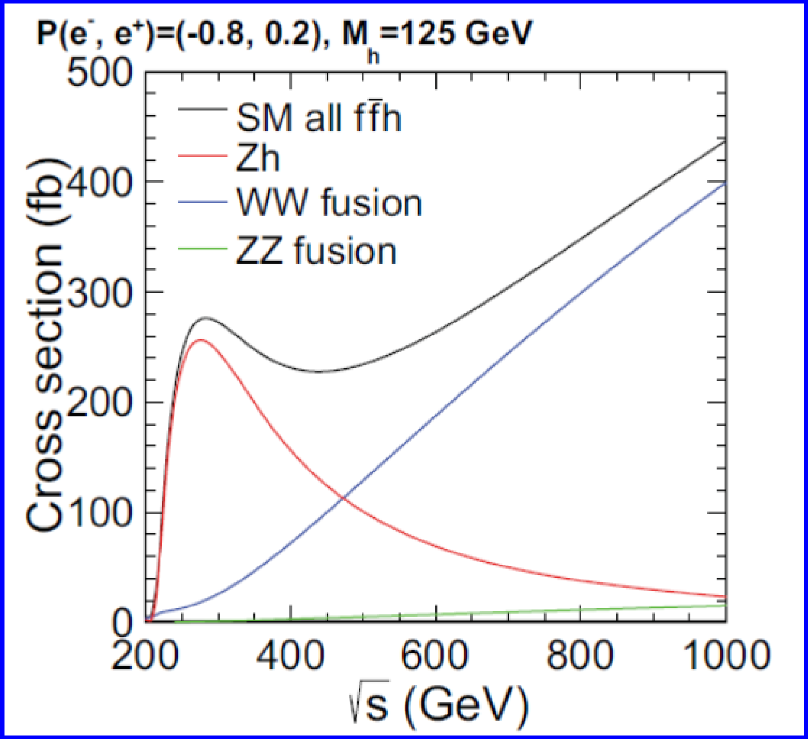
where

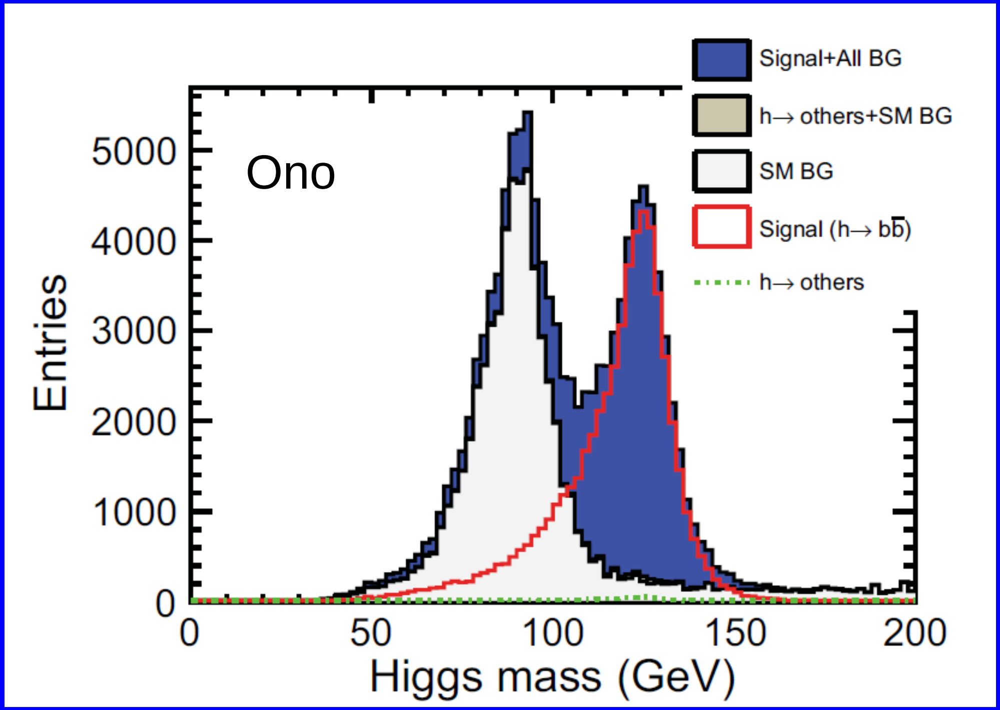
$$\begin{aligned}\sigma(P_{\mathrm{e}^-}, P_{\mathrm{e}^+}) &= \frac{1}{4}\{(1-P_{\mathrm{e}^-})(1+P_{\mathrm{e}^+})\sigma_{LR} + (1+P_{\mathrm{e}^-})(1-P_{\mathrm{e}^+})\sigma_{RL} + \\ &\quad (1-P_{\mathrm{e}^-})(1-P_{\mathrm{e}^+})\sigma_{LL} + (1+P_{\mathrm{e}^-})(1+P_{\mathrm{e}^+})\sigma_{RR}\}\end{aligned}$$

and $\sigma_k$ ($k$ = LR, RL, LL and RR) are the fully polarized cross-sections.

# ILD Full Simulation with Background

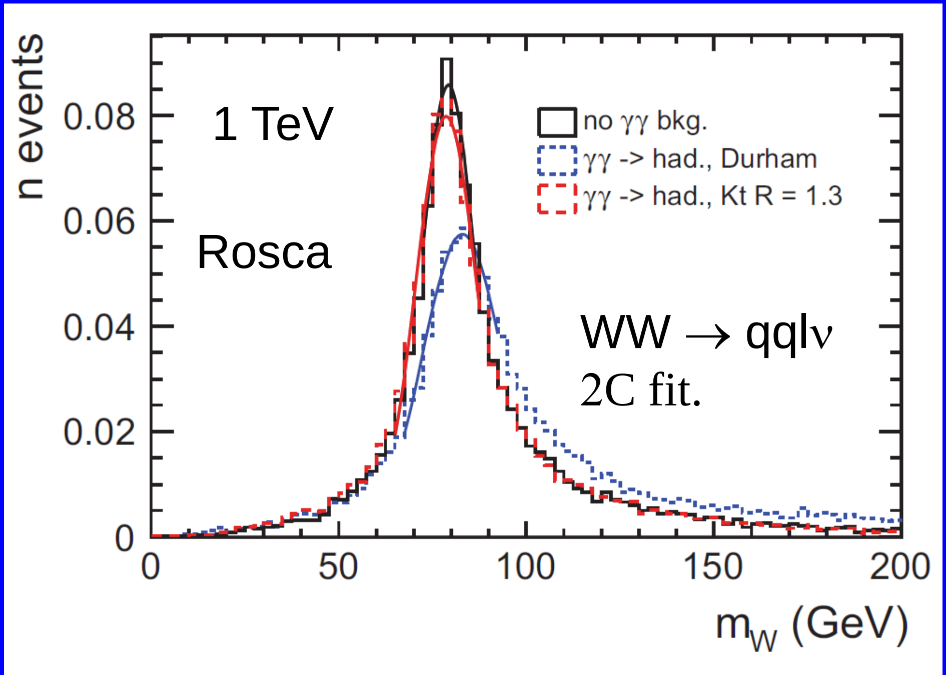
1 TeV. $e^+e^- \rightarrow \nu\,\nu\,h\,(125) \rightarrow \nu\,\nu\,b\,b$

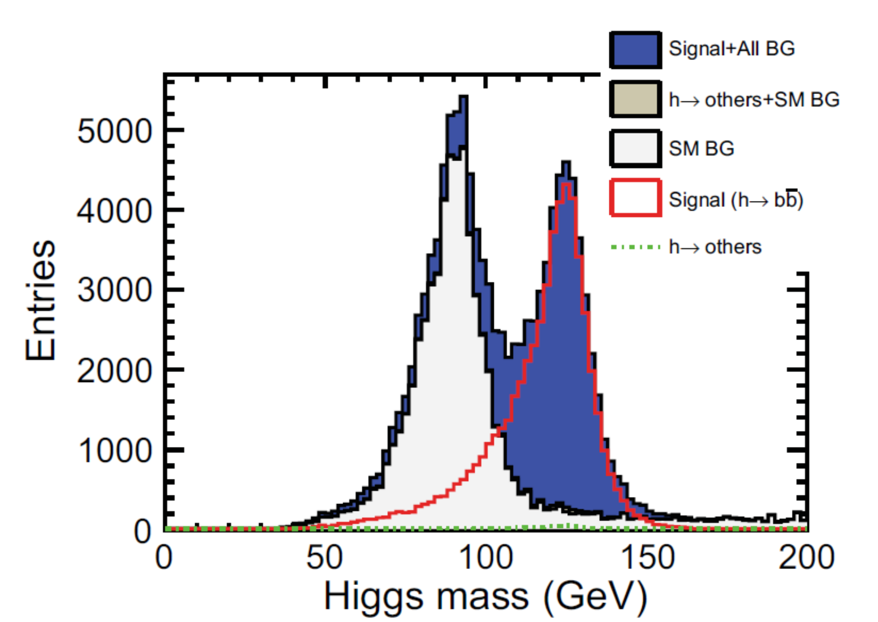


# ILD Full Simulation with Background

Inclusion of backgrounds associated with $\gamma\gamma$ interactions – although typically with low $\gamma\gamma$ mass – have necessitated changes to more HC-like jet finders – particularly for higher $\sqrt{s}$




You basically see in these two plots: W, Z, h reconstructed hadronically.

# Beam Energy Calibration

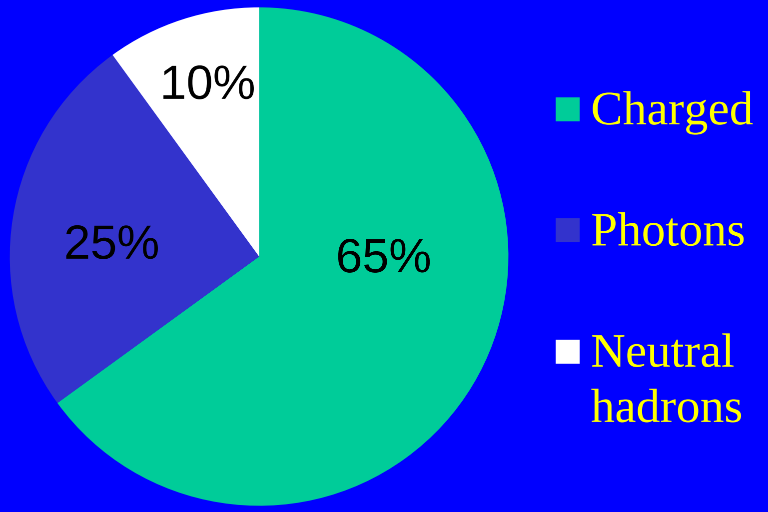
- Ideas of using a mini-scan at the Z to calibrate say a spectrometer – which can be extrapolated to higher energy.
- Even the calorimeter – potentially calibrated at the Z using Bhabhas can be used in a similar fashion ?? (although calorimeter non-linearities can be unfavorable…)

# Particle-Flow in a Nut-Shell

**E(jet) = E(charged) + E(photons) + E(neutral hadrons)**

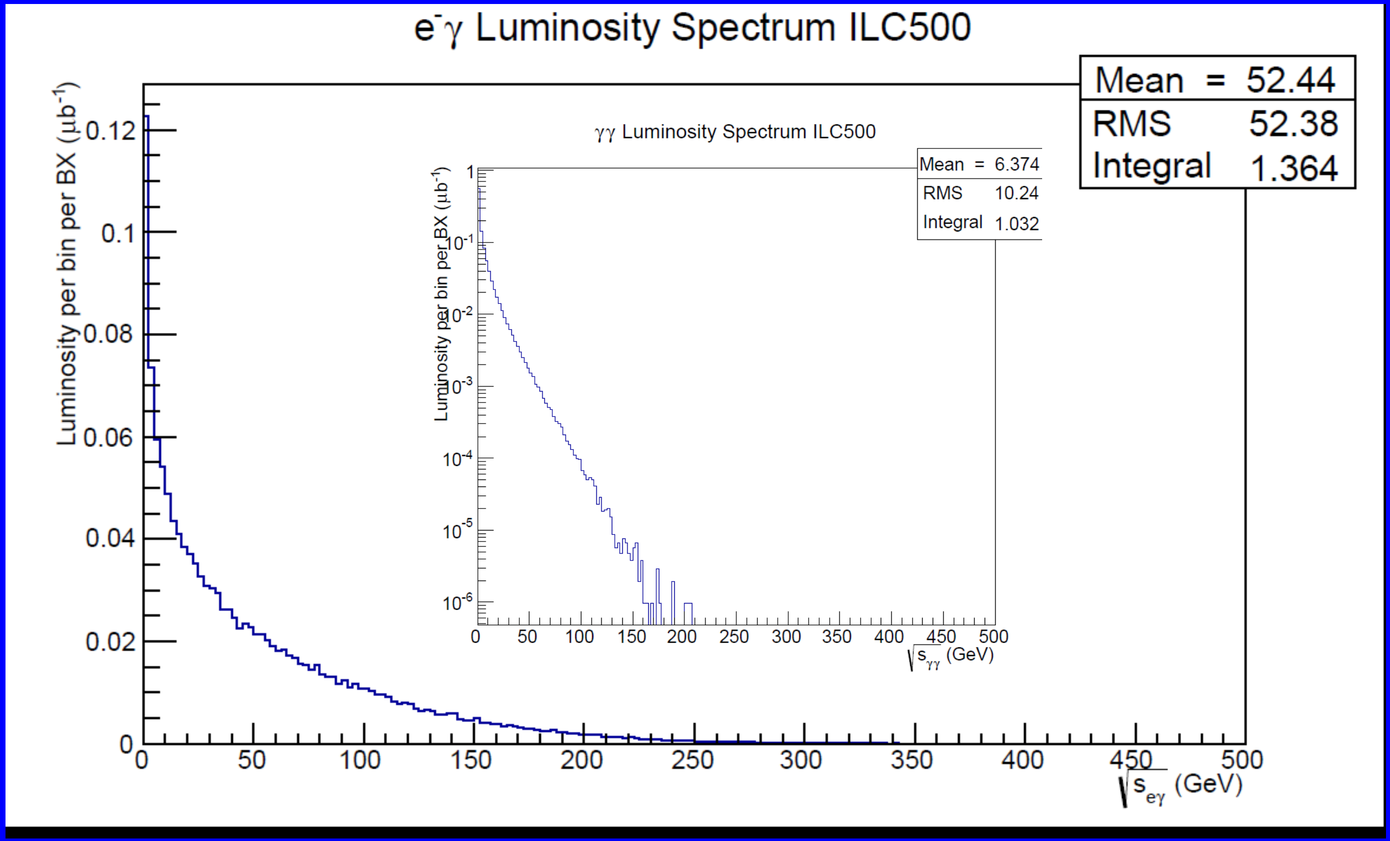
- Basics
  - Outsource **65%** of the event-energy measurement responsibility from the calorimeter to the tracker
    - Emphasize particle separability and tracking
    - Leading to better jet energy precision
  - Reduce importance of hadronic leakage
    - Now only 10% instead of 75% of the average jet energy is susceptible
    - Detector designs suited to wide energy range
  - Maximize event information
    - Aim for full reconstruction of each particle including V0s, kinks, $\pi^0$ etc.
    - Facilitates software compensation and application of multi-variate techniques

**Particle AVERAGEs**



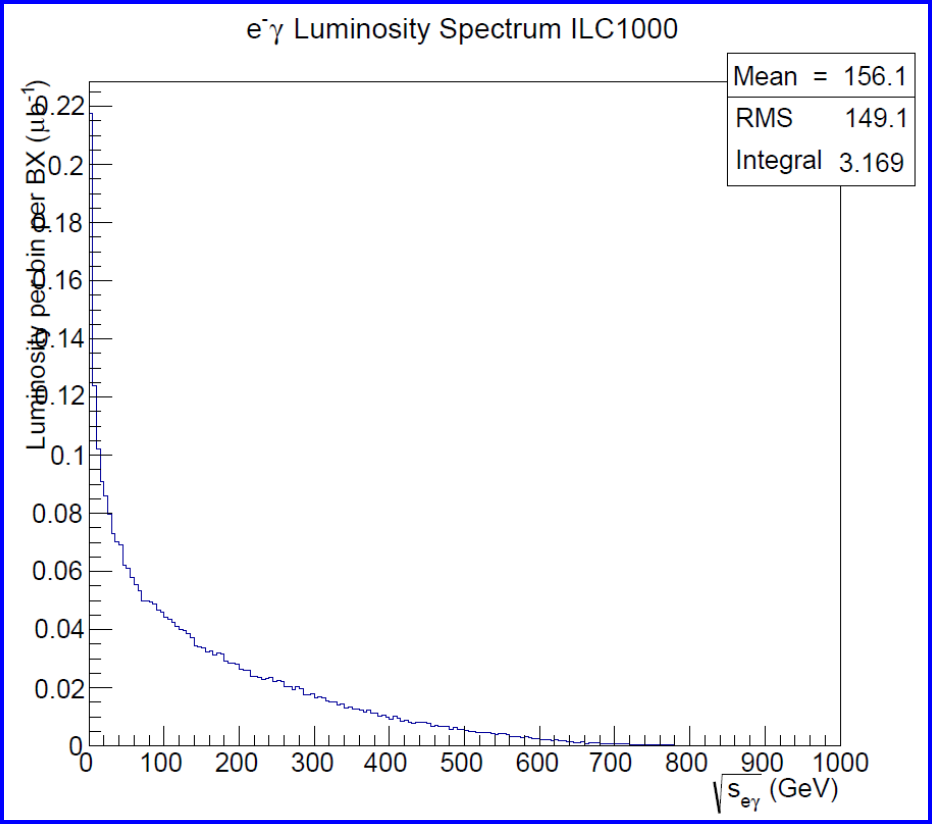

This used to be controversial – but already was well established at LEP. Now is widely applied at LHC in particular in CMS.

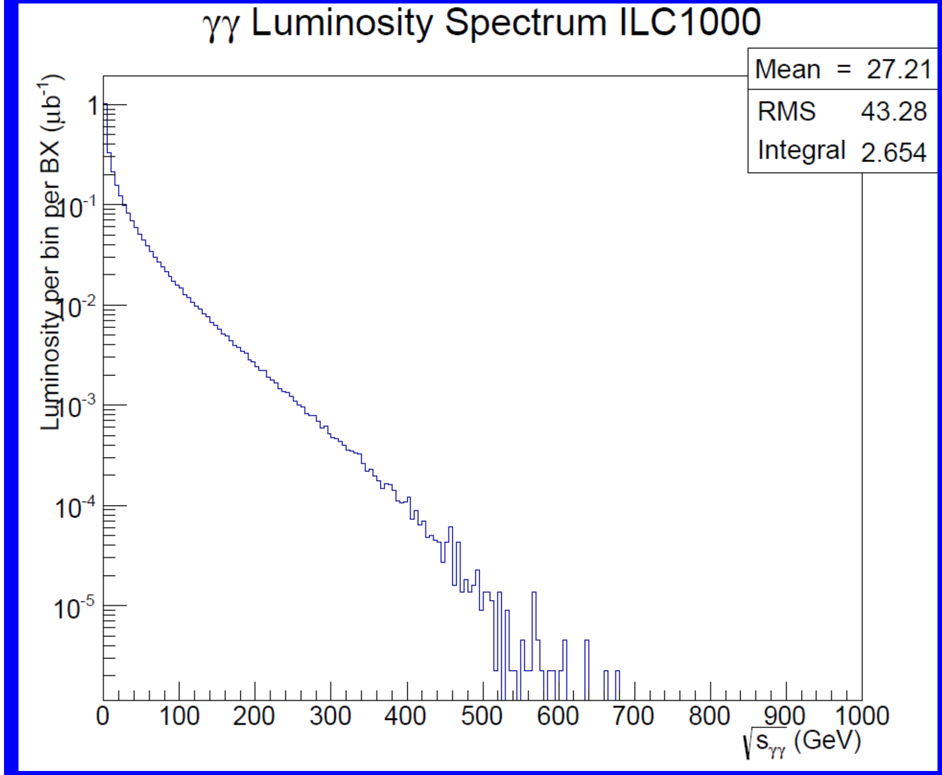
# Luminosity Spectrum




$\langle n(\gamma\gamma \rightarrow \text{had}) \rangle$ with W > 2 GeV = 0.5

# Luminosity Spectrum




<n($\gamma\gamma \rightarrow$ had)> with W > 2 GeV = 2.0

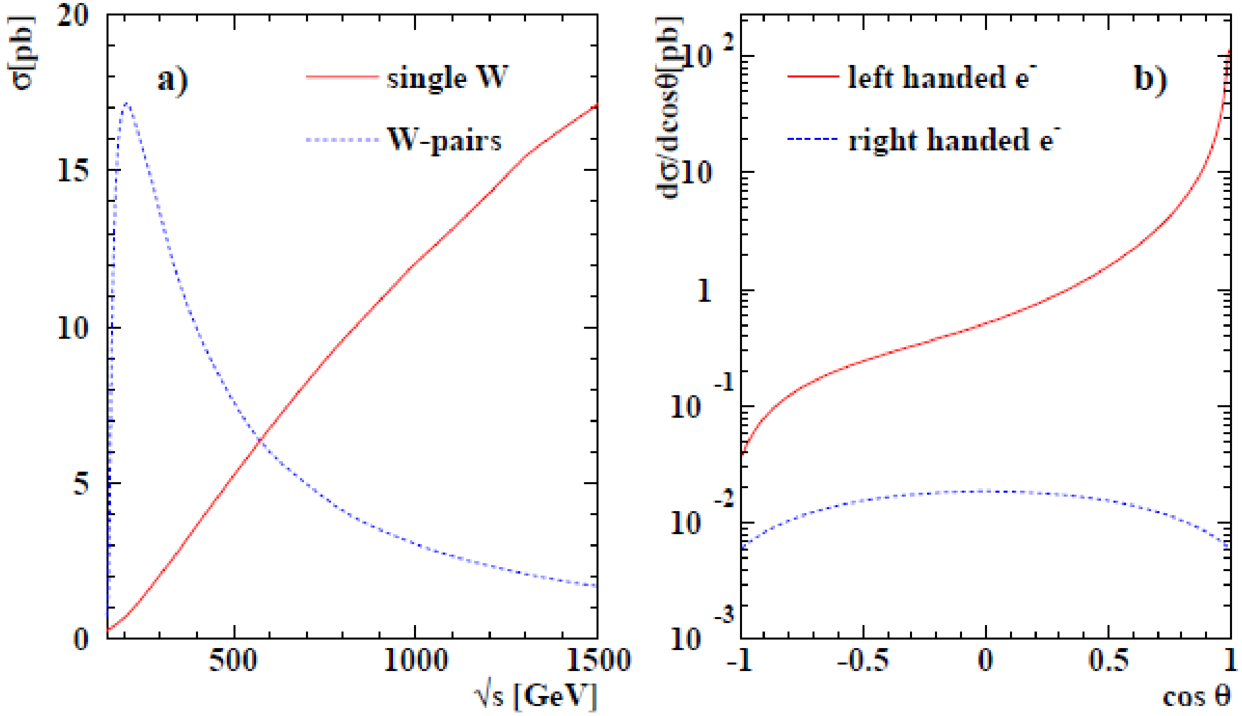



Figure 5.1.3: *a): Total cross section for single W [1] and W pair production [2] as a function of the centre of mass energy. b): Differential cross section for W-pair production for different beam polarisation.*

# W Mass from Di-lepton Events

*Eur.Phys.J.C.26 (2003) 321-330*

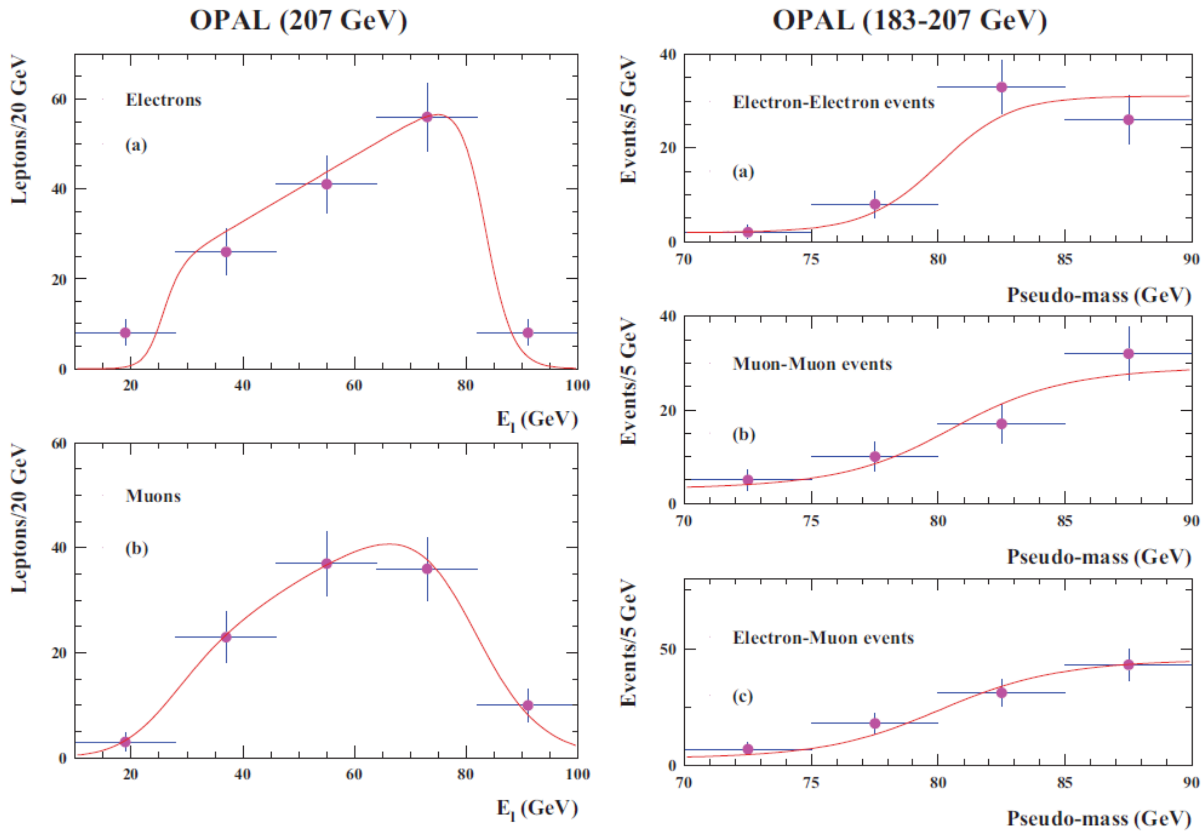
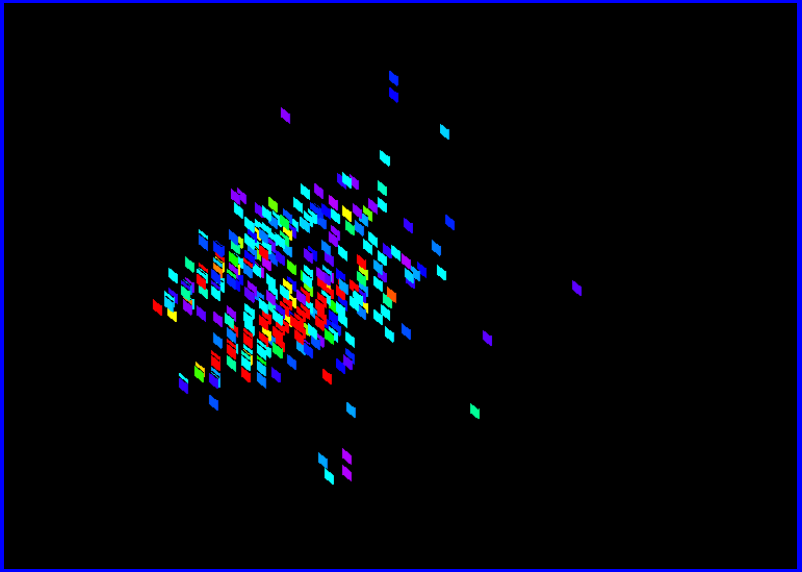


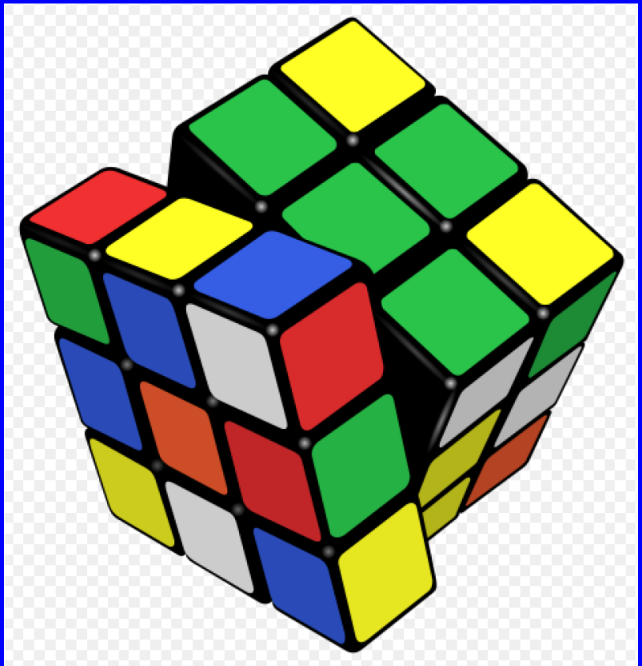

**Fig. 7a,b.** Comparison between the data and the fit functions for the leptonic energy at a center-of-mass energy of 207 GeV. **a** electrons. **b** muons

**Fig. 8a–c.** Comparison between the data and the fit function for the pseudo-mass at all center-of-mass energies. **a** electron-electron events. **b** muon-muon events. **c** electron-muon events

# Imaging Calorimeters



- Standard cell-sizes under discussion
- ECAL : 5mm X 5mm X 30 layers
  - 10,000 more channels than OPAL
- HCAL : 10 mm X 10 mm X 50 layers
- Immense amount of information.
- Potentially (E, time) for each volume pixel.



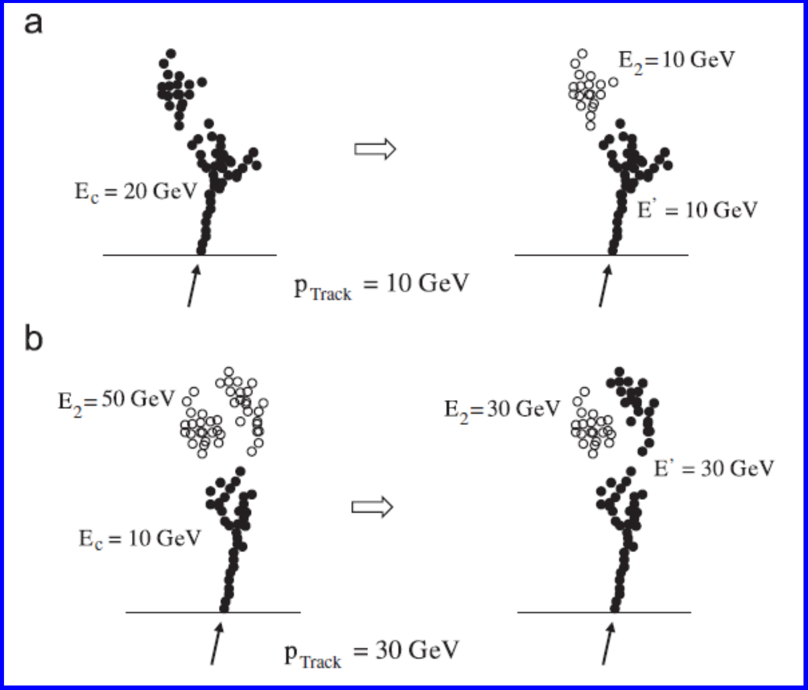
# Particle Flow Algorithms

M. Thomson, NIM A611 (2009) 25.

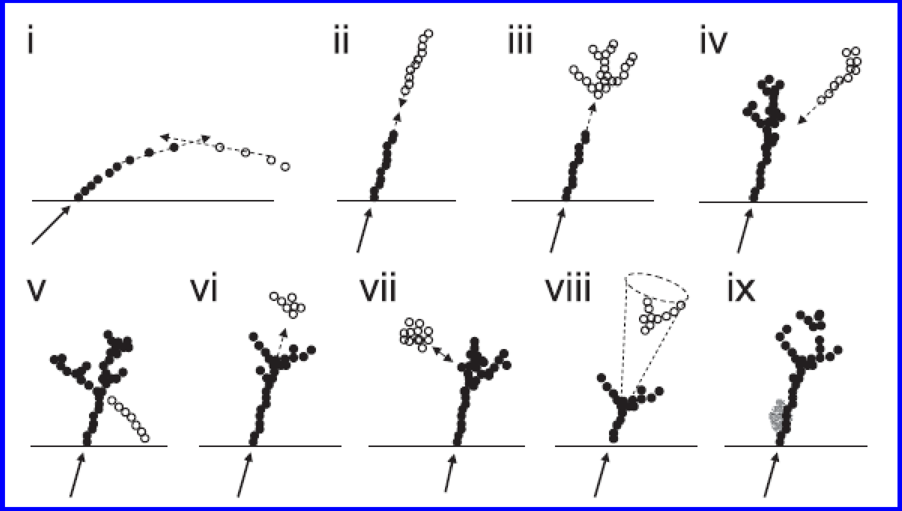
- Highly non-trivial.
  - Many groups have worked in this area
  - To date, PandoraPFA developed primarily by M. Thomson for ILD and using the Mokka/Marlin framework and now rewritten by J. Marshall has set the performance bar.

Depends at basic level on calorimeter clustering.

Reclustering




Use track-momentum – cluster-energy consistency to drive re-partitioning of energy.



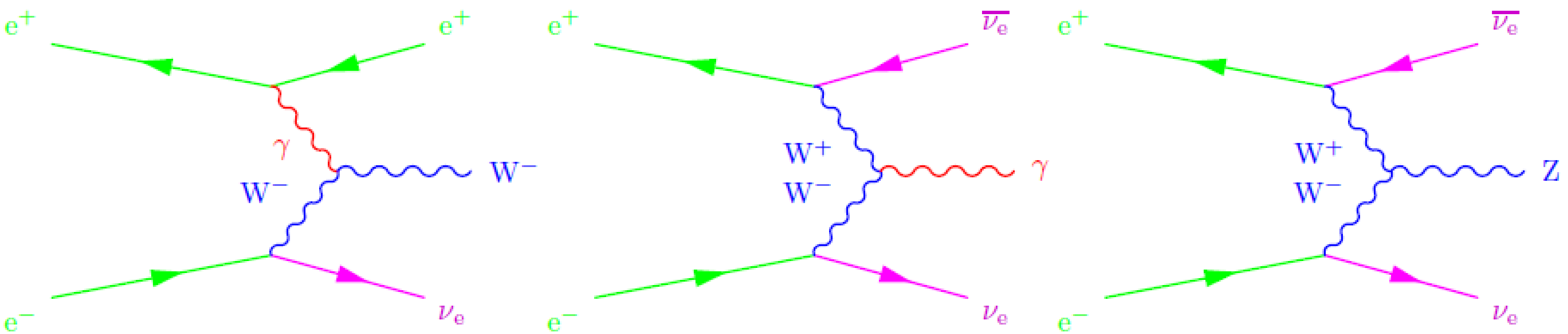

Topological clustering

# Beam Polarization Measurement Using Single Bosons with Missing Energy

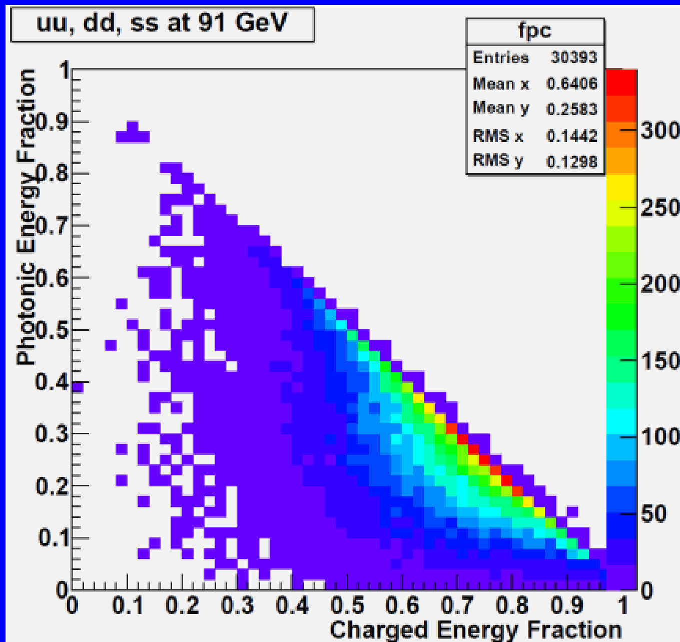
Graham W. Wilson

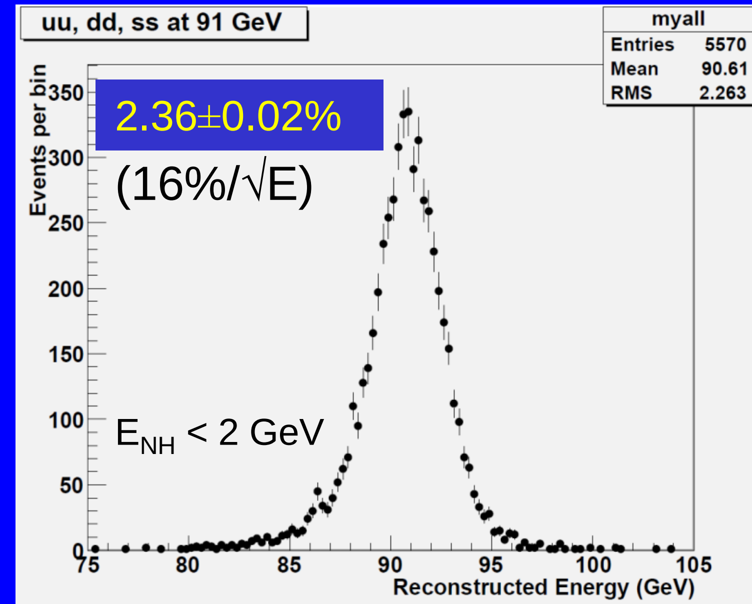
University of Kansas

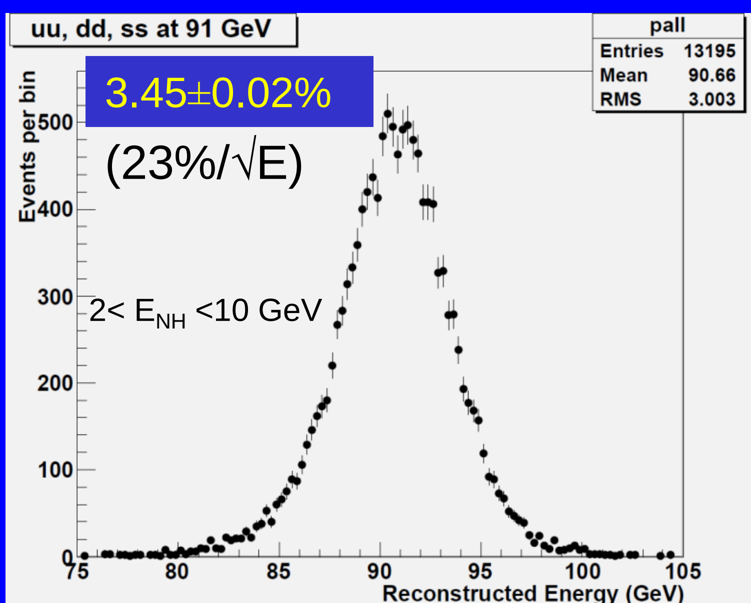
October 23rd 2012

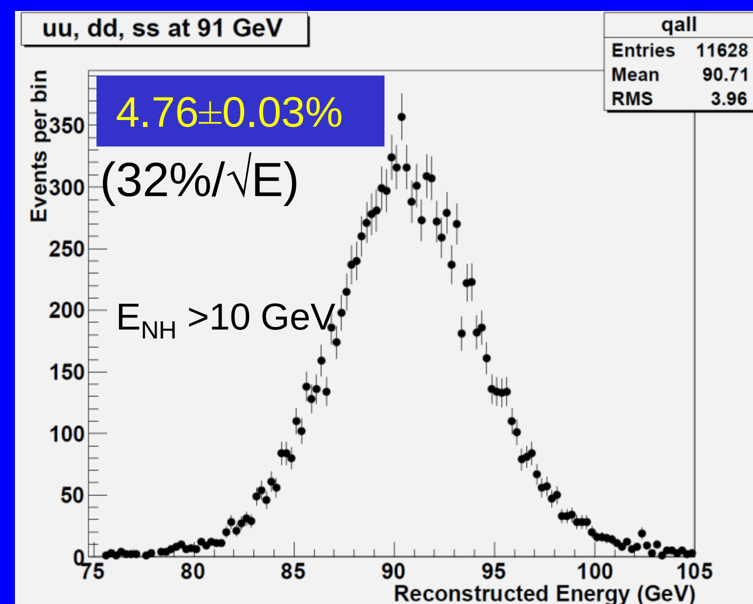


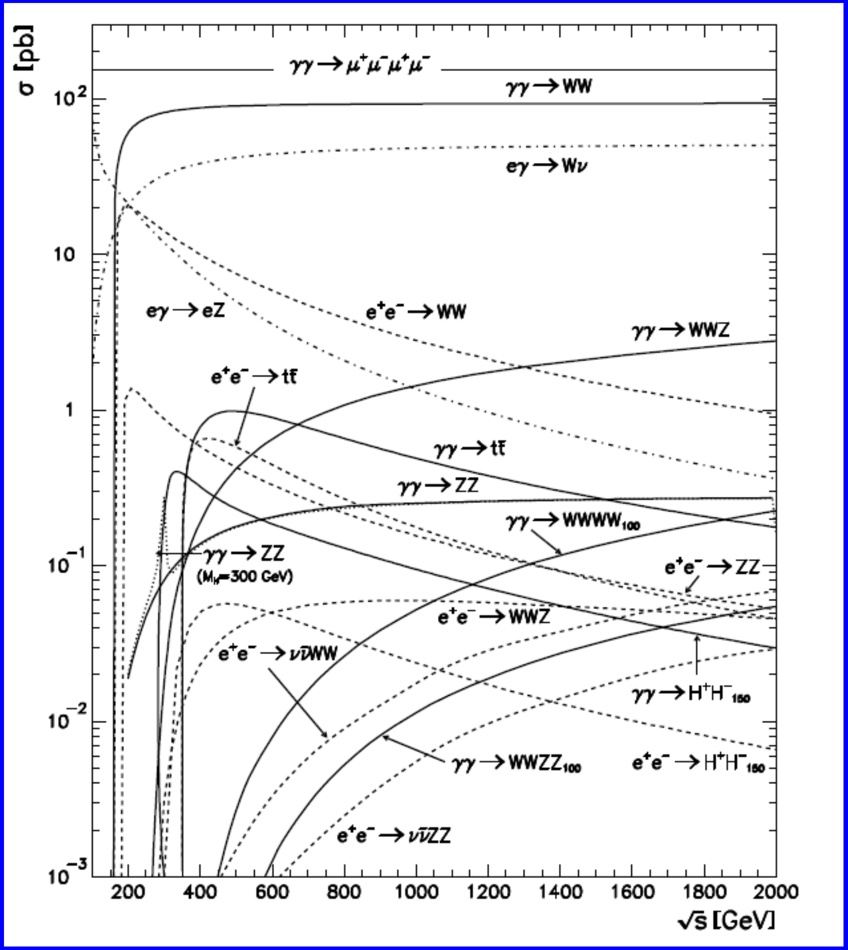
# Event-Specific Resolution




σ [pb]
$\sqrt{s}$ [GeV]
γγ → μ⁺μ⁻μ⁺μ⁻
γγ → WW
eγ → Wν
eγ → eZ
e⁺e⁻ → WW
γγ → WWZ
e⁺e⁻ → tt̄
γγ → tt̄
γγ → ZZ
γγ → WWWW₁₀₀
γγ → ZZ
(M_H=300 GeV)
e⁺e⁻ → ZZ
e⁺e⁻ → WWZ
e⁺e⁻ → νν̄WW
γγ → H⁺H⁻₁₅₀
γγ → WWZZ₁₀₀
e⁺e⁻ → H⁺H⁻₁₅₀
e⁺e⁻ → νν̄ZZ