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# *Jet Reconstruction Experience and Physics Applications at LEP2*

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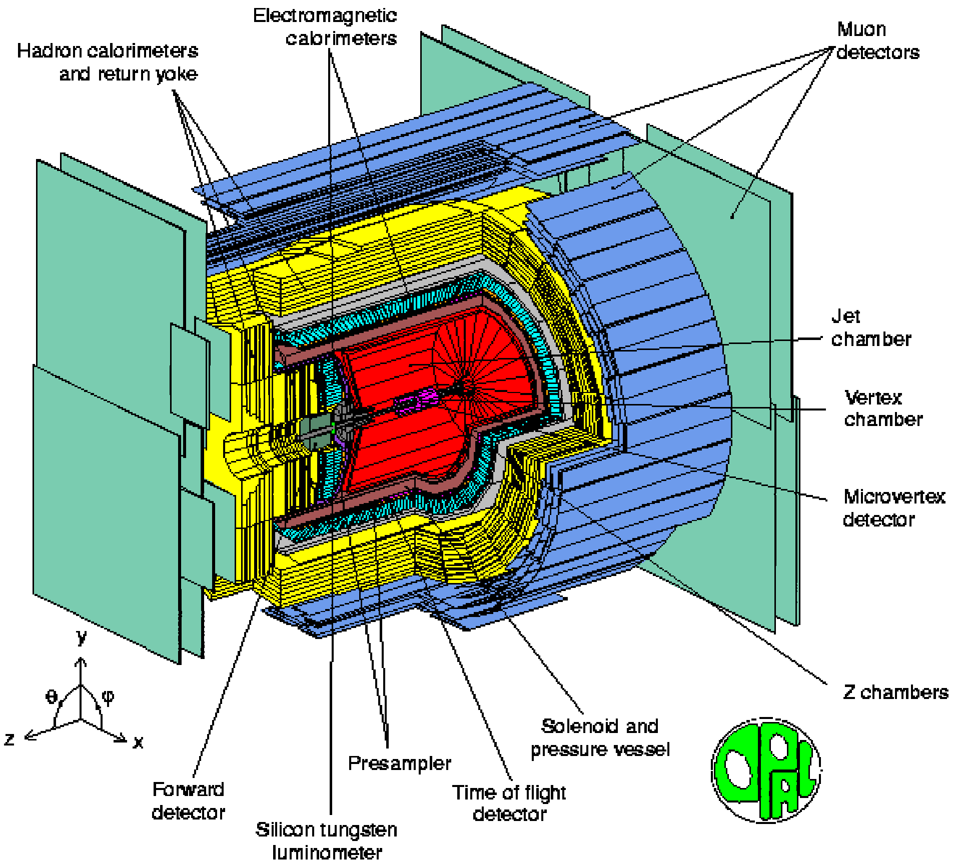
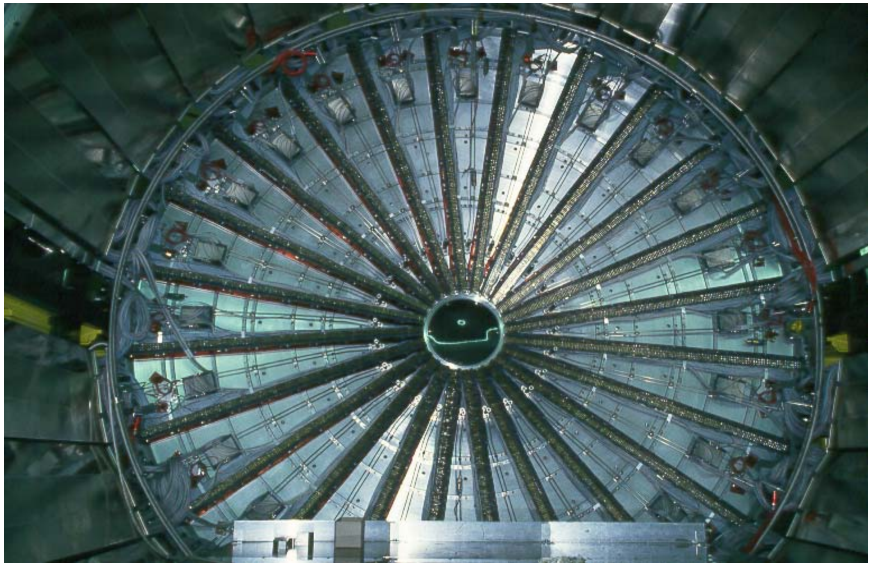
- A Typical LEP detector
- Reconstructing Jet energies
- Error parameterization
- Physics Applications using jets and beam constraints
    - W mass measurements
    - Higgs boson searches

# *A “Typical” LEP detector*



- Optimized for $Z^0$ pole physics
- Worked fine at LEP2 energies, but some lessons learned along the way.
- ALEPH, DELPHI, L3 – some better features, others not as good.

# *A "Typical" LEP detector*



- Tracking chambers:
  1.85 meter radius jet chamber
  159 axial sense wires per jet cell
  4 bar of gas – Ar Ethane (good d$E$/d$x$)
  **B** = 0.435 T
  poor z resolution  (5 cm)
  -- improved by outer Z chambers,
  inner stereo+
  silicon+PV constraint;
  endpoint constraint

$$\Delta P / P^2 = 1.9\times10^{-3}\,/\,\mathrm{GeV}$$

$1.6\times10^{-3}$ with silicon; better at LEP1

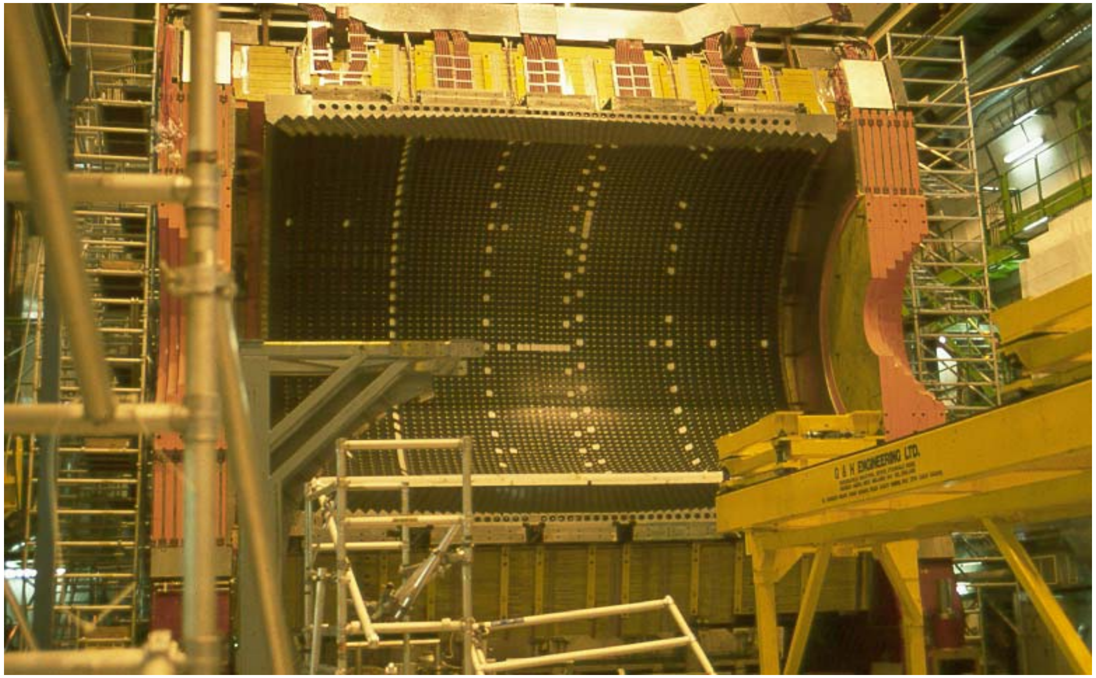
- Presampler
  - 3 cm thick, two layers of limited streamer mode tubes – axial wires + stereo cathode strips
  - Mounted outside the magnet coil (1.5 rad lengths thick) and before EM calorimeter
  - Aids in electron ID

- Calorimetry
  - EM calorimeter: Barrel: 9440 lead-glass blocks with PMT's outside of coil+presampler.

    24.6 radiation lengths at normal incidence

    Projective, but not towards the IP
    (reduces effects of cracks).

EM segmentation:
1 layer thick, blocks ~2 degrees on a side.
99.97% of solid angle covered (with endcap, gamma-catcher and luminoisity monitor)



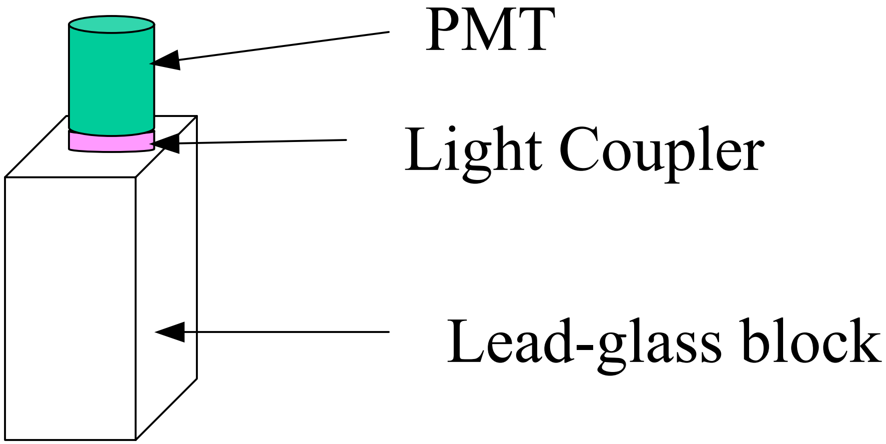
During installation – showing barrel EM and hadron calorimeters.
Inner radius of Barrel EM: about 2.5 meters.

Intrinsic resolution: $0.2\% \oplus 6\% / \sqrt{E[\mathrm{GeV}]}$

With material in front, normal incidence: $15\% / \sqrt{E[\mathrm{GeV}]}$

worse at higher cosθ (more material)
and in the barrel/endcap overlap

# EM calorimetry and increasing $E_{CM}$



Higher-energetic EM showers at LEP2 are longer. Some spilled into the plastic light coupler, scintillating (normal light is Cherenkov light from the lead glass).

→ nonlinearity for high-energy showers

# Hadron Calorimetry

- 80 cm of iron (4.8 interaction lengths) with 9 layers of streamer tubes. Pad and strip readout.

- 2.2 interaction lengths of material in front -- use both EM and HCAL for measuring hadrons.

$$\Delta E / E \approx 120\% / \sqrt{E[\mathrm{GeV}]}$$

For individual hadrons
(approx. intrinsic resolution from beam tests, and also achieved with the help of the EM calorimeter in use).

# A bit of Experience with Stray Material

- Make sure all material is in the MC – electronics, cables, cooling, pipes, supports, misc. Nobody ever really gets this fully right (except maybe KTeV)
- $e^+e^- \to \gamma\gamma$ energy dip near readout cards.
- 1996: OPAL had an event with large missing $P_T$. There was an energetic photon visible in the ECAL but nowhere near enough to balance $P_T$. It had lost energy in a steel support wheel for the jet chamber.

  The good news: it was in the MC simulation. The bad news: no background events in the relevant MC had a photon hitting the wheel.

  Effect characterized with LEP1 Bhabhas – very clear what was going on. -- Need lots of calibration data at the $Z^0$!

# *Jet Reconstruction*

- Would like to use tracking chamber for measuring charged-particle energy and calorimetry for neutrals.

  Exception: electrons – often clustered with their FSR and bremsstrahlung photons

- Can naively use tracks + unassociated clusters, but problems with overlapping showers.

  EM showers: narrow. Fine segmentation should help quite a lot; improves $\pi^0$ reconstruction too. Hadron showers: much broader

  Can try to separate particles more with a high B field – showers at different angles then.

# *OPAL's Approach: Matching Algorithm*

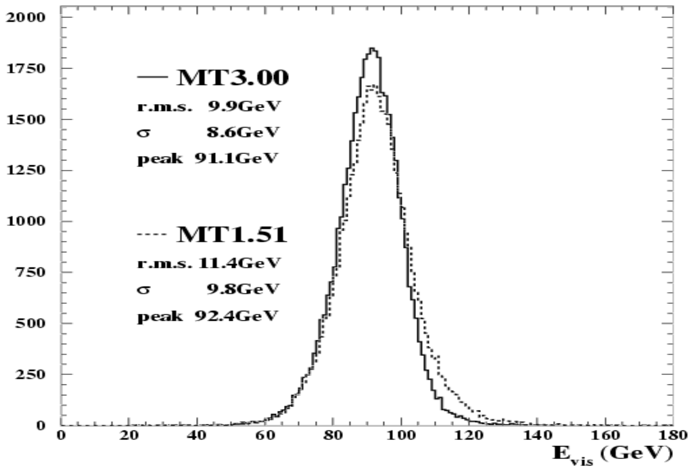
- Similar to ALEPH, DELPHI, L3: -- in papers the result is referred to as "energy-flow objects"
- The steps:
    - Associate tracks and clusters
    - Identify electrons (also from photon conversions) and muons.
        - muons: subtract MIP energy from associated ECAL and HCAL clusters
        - electrons: subtract track energy fro assoc. ECAL cluster
    - Apply energy compensation to remaining clusters (cosθ and energy dependent) – tuneable!
    - Subtract track energy from HCAL clusters. (Don't go negative). If that's not enough,
    - Subtract remainder from associated ECAL cluster.

# *Performance*

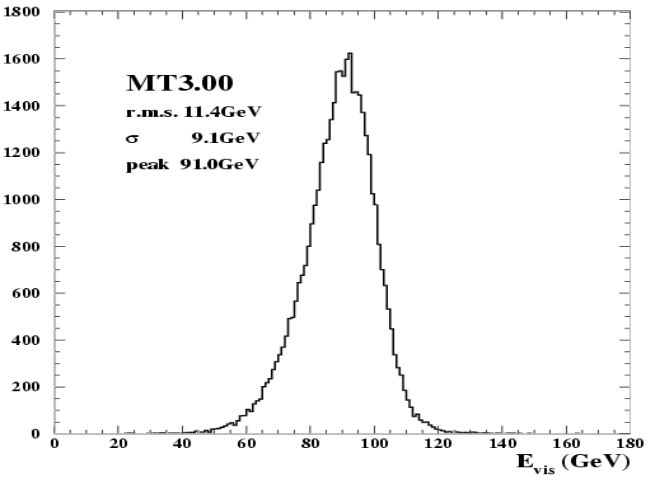
Measured at the $Z^0$: Jets in HZ at LEP2 are similar to Z jets at LEP1.

Total energy resolution: 8.7 GeV out of 91.2 GeV – 9.5% for the event. (~14% per jet)

Without HCAL: (re-optimized cluster compensation):
10.6% resolution, but low Evis tail.



With HCAL



Without HCAL

# *Jet Resolutions*

- Angular resolution for a jet in $\phi$=22 mrad (1.3°)

-- estimated from acoplanarity angle distribution at the $Z^0$ in two-jet events

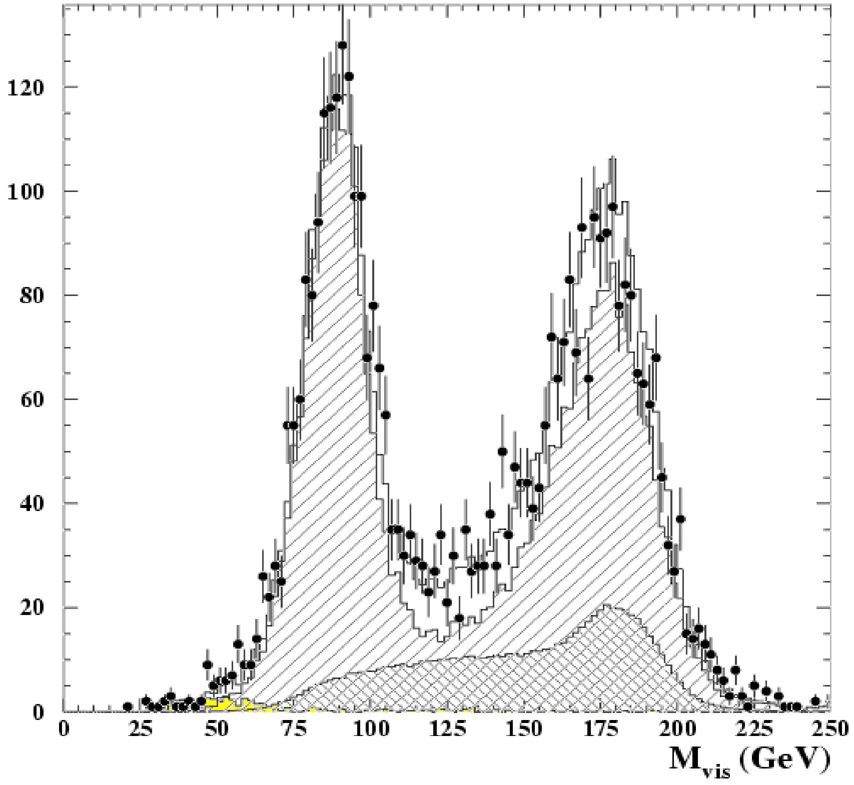
- Angular resolution for a jet in $\theta$ is 34 mrad (2°)

Angular resolutions are more important for mass fits than energy resolutions after beam constraints are applied (assuming no ISR).

# *Hadronic Events at LEP2*

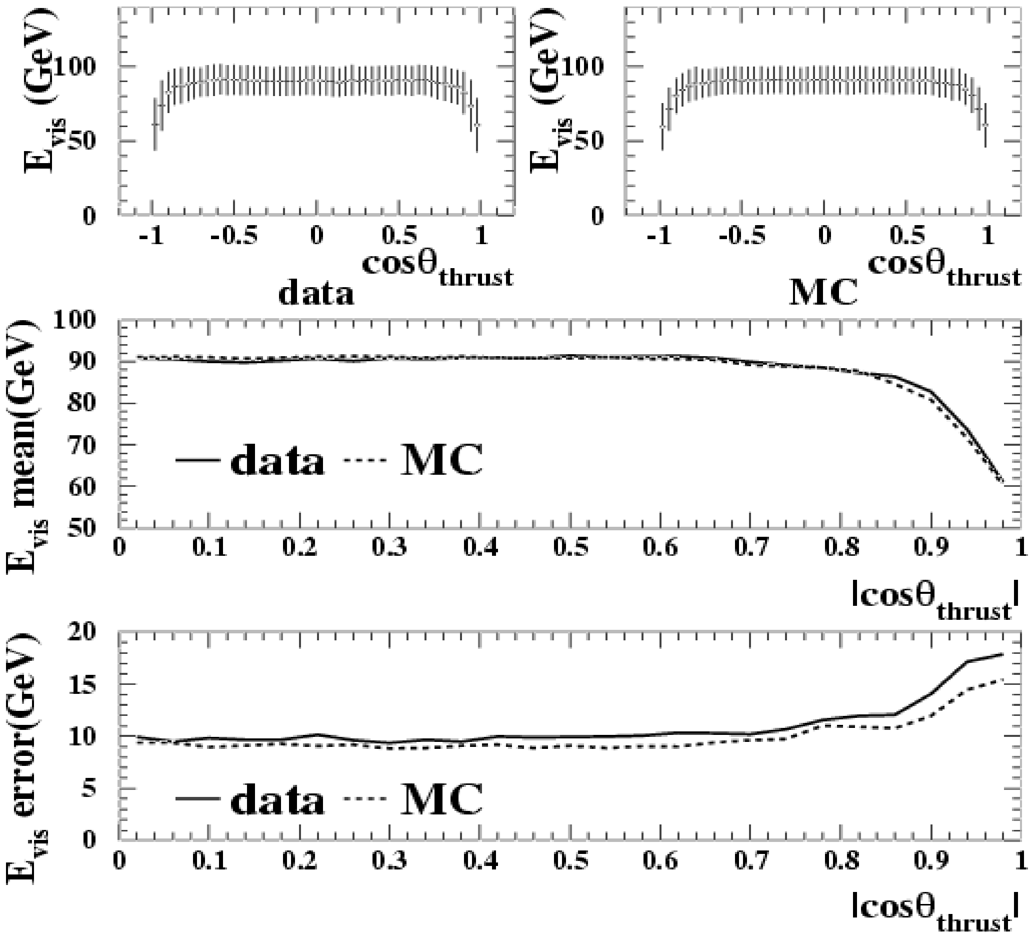
A large fraction are “radiative return” events to the $Z^0$. ISR photons mainly go down the beam pipe but some are detected.

Other events: WW, full-energy qqbar, two-photon processes, ZZ



$M_{vis}$ distribution for ECM=183 GeV with qqbar, WW and two-photon portions indicated.

# *Jet Error Parameterization*



Choose variables so errors
are minimally correlated)

The usual: p, cotθ, and ϕ
But: variations.
p, 1/p or log(p)
θ instead of cotθ Errors
depend on θ: (example: energy)

Jet energies are corrected vs. costheta before kinematic fitting for more generality. (not all analyses want the same corrections. e.g., tau, bhabha, photons).

# *Kinematic Fits in Hadronic Events*

- Depends on what kind of analysis you're doing!

- Taking advantage of the clean $e^+e^-$ environment:

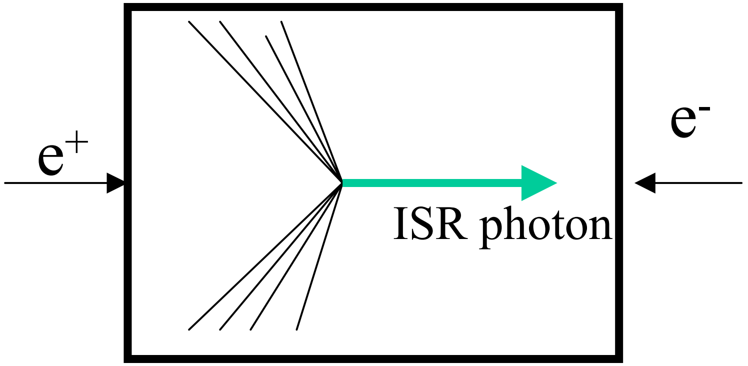
**"4C" fits – constrain $E = 2E_{beam}$ $p_x=0$, $p_y=0$, $p_z=0$**

and use the jet errors to readjust the jet 4-vectors. Jets can have measured masses or can be constrained to be massless. (ALEPH: use the measured jet β)

- In 4-jet events, $m_{12}+m_{34}$ measured ~4x better than $m_{12}-m_{34}$ due to total energy constraint (configuration-dependent!)

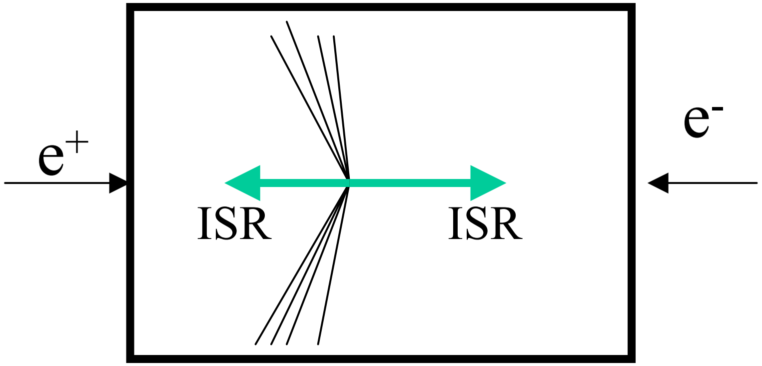
- Then again, you may not want the constraints.
  -- Initial State Radiation

# *Kinematic Fits and ISR*



Radiative Return to the $Z^0$

Very common at LEP2.
Can be found with kin.
fit + beam constraint if the
photon is not detected.



Double ISR.

Less common (for energetic photons)

Can fake Emis signatures (event may pass $p_z$ cuts).

Can bias $m_{rec}$ distibs upwards.

# *More Kinds of Kinematic Fits*

- “5C” fits: Beam energy and momentum plus another constraint.
  - **4-jet $e^+e^- \rightarrow W^+W^-$ candidates:** constrain $m_{12}=m_{34}$ -- dijet pair mass equality.
    - Three combinations
    - Can use fit $\chi^2$ to help pick the right combination (other variables help too).
    - Not correct because W’s can be off shell, but this procedure gives the best resolution for a distribution.
    - Can also use for $Z^0Z^0$ events, or can constrain one dijet to $m_Z$.
  - **4-Jet $e^+e^- \rightarrow H^0Z^0$ candidates:** Constrain two jets to $m_Z$, and fit for $m_H$ using E and p conservation, pick pairing with help of fit $\chi^2$
    - Resolution: approx. 3 GeV
- Jet angles are more constraining than energies.

# *More Kinds of Kinematic Fits*

- $W^+W^-\rightarrow qql\nu$: Missing $p_x$, $p_y$, $p_z$ of the neutrino. "Two" constraints left of the five. Most information from the jet angles -- less from the lepton energy.

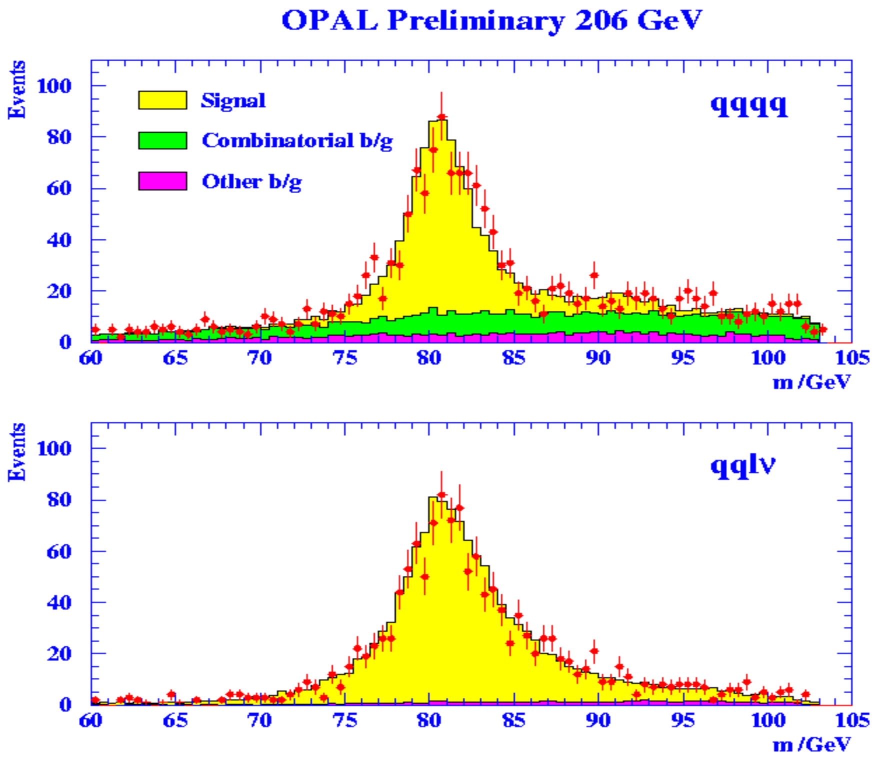
- $W^+W^-\rightarrow qq\tau\nu$: Poor tau momentum measurement. "1.5" constraint fit

- Can constrain both dijets to $m_W$: "6C" fit.
  - no $m_{rec}$ left, just $\chi^2$. (often that's better).

- Higgs search: Can constrain events to both $m_Z$ for two jets and $m_H$ for the other two. Pairing and fit quality depend on the $m_H$ you are looking for.

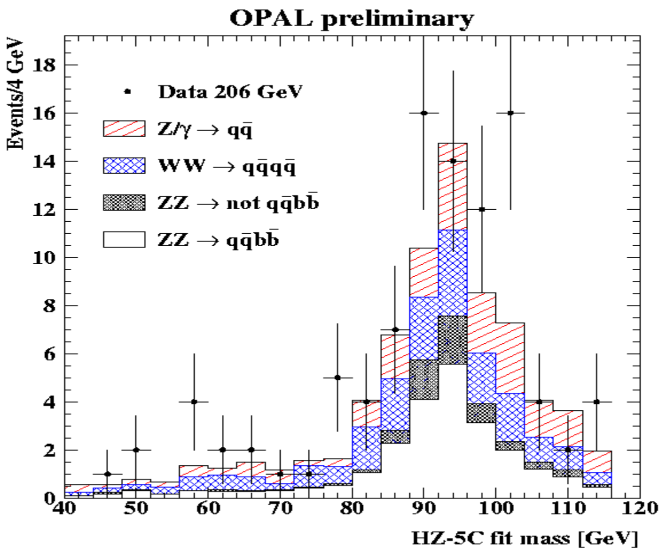
Advantages: takes optimal account of jet error matrix.

# *W and Z mass reconstruction at ECM=206 GeV*



"5C": equal mass constraint.

ISR gives high tail on $m_{rec}$



"5C": constrain one dijet to $m_Z$, fit for the other.

B jets often have energetic neutrinos

# *Extracting $M_W$*

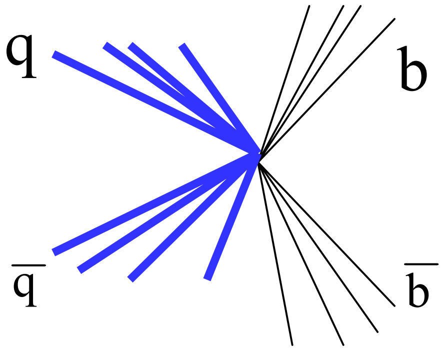
- "Breit-Wigner" fit -- fit the $m_{rec}$ distrib. to a B-W. Biased by ISR + other things.

- "Reweighting Fit" -- Run MC at different $M_W$ and find which sample fits the data the best. Interpolate by reweighting.

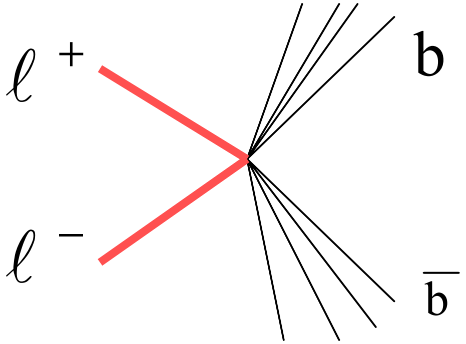
- "Convolution Fit" Construct a likelihood curve for each event as a function of $m_W$.

- Other techniques:
  - Treat 5-jet events separately
    - More combinatorics in this subsample
    - Bigger errors for these evens
  - Treat events with large uncertainty in $m_{rec}$ separately.

# *Higgsstrahlung Signatures*

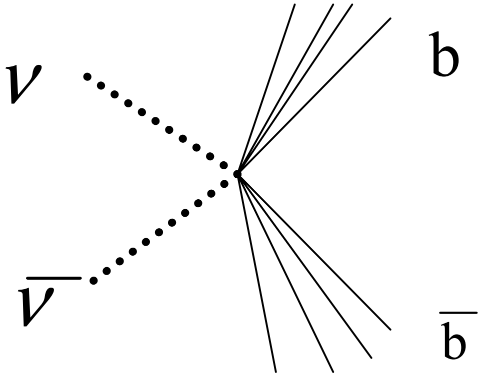


$$e^+e^- \to Z^0H^0 \to q\bar{q}b\bar{b}$$

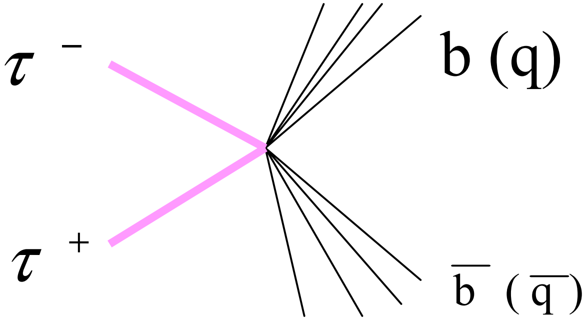


$$e^+e^- \to Z^0H^0 \to \mu^+\mu^-b\bar{b}$$

$$e^+e^- \to Z^0H^0 \to e^+e^-b\bar{b}$$



$$e^+e^- \to Z^0H^0 \to \nu\bar{\nu}b\bar{b}$$

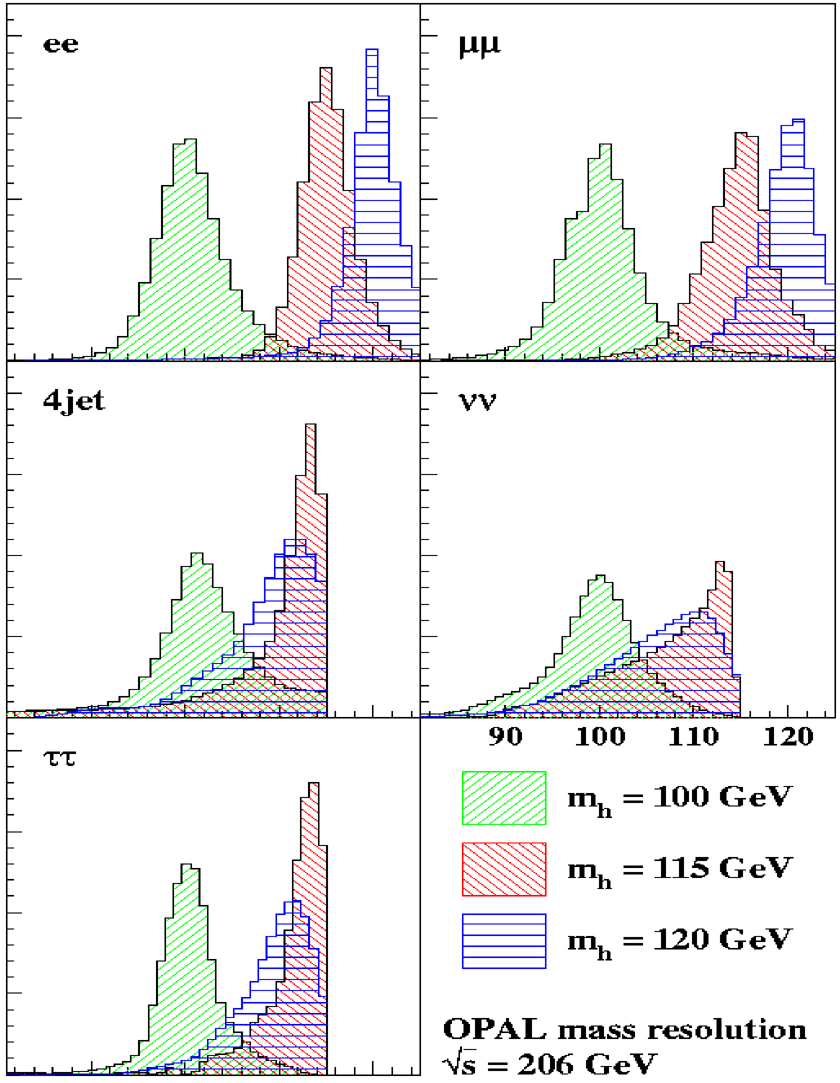


$$e^+e^- \to Z^0H^0 \to \tau^+\tau^-b\bar{b}$$

$$e^+e^- \to Z^0H^0 \to q\bar{q}\tau^+\tau^-$$

# *Resolutions of Reconstructed Higgs Mass*

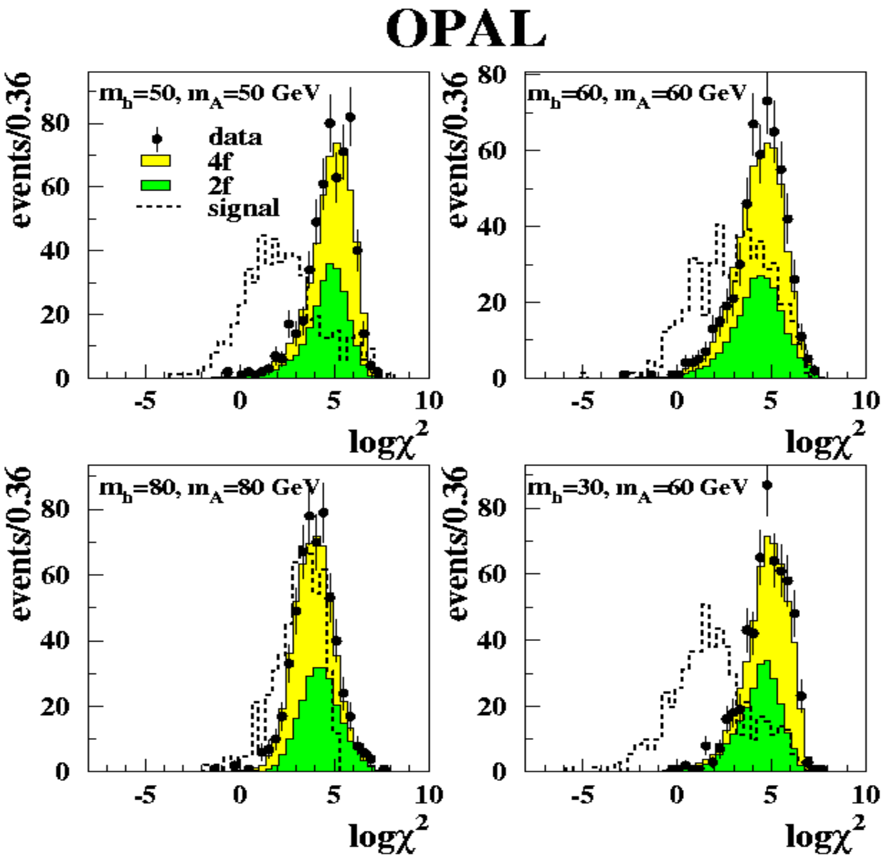
Depends on channel and $\sqrt{s} - m_Z - m_H$



From
A. Quadt

# *Complicated:* $e^+e^- \rightarrow h^0A^0$

- Six pairings possible in 4-jet events, all equally good.
- Two reconstructed masses
- The strategy: Do a 4C fit (E, P) and get two $m_{rec}$'s plus errors for each combination.
- For each test $m_h$, $m_A$ pair, re-constrain to a "6C" fit using the recon. masses and errors.
- Use the smallest of six $\chi^2$'s to pick the pairing.
- Can compare with WW (ZZ) 6C $\chi^2$



# *Summary*

- Matching tracks and clusters is necessary.
- Fine segmentation helps, but unclear how much it can pay off with HCAL -- benefit of HCAL is not much on OPAL to begin with.
- Beam constraints are very powerful.
  - Jet angles are most constraining -- energy measurements less so. Of course a better energy msmnt may switch the roles.
  - ISR can bias measurements when using a beam constraint. ISR is a bigger effect with increasing ECM. Be sure to cover polar angles close to the beam. Sitting on a resonance helps!
  - Jet assignment makes a big difference.
- Take lots of calibration data. Test beams don’t tell you everything.
- Analyzers will be clever.