Physics at the LEP Collider – A Sampling

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Physics Department Colloquium

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Outline

- Refresher: Standard Model and e^+e^- Collisions
- LEP Accelerator
- L3 Detector and the Michigan Group
- Overview of LEP I Physics:
  - List of measurements / searches
  - Example: Z lineshape + measuring the invisible
- Selected ongoing Michigan Ph.D. thesis topics:
  - LEP I: Tau neutrino chirality (R. Moore)
  - LEP II: W pair production / mass (A. Button)
- Future of High Energy e^+e^- Collisions:
  - LEP II
  - Next Linear Collider (NLC)

Standard Model

Leptons:

ν_e	ν_μ	ν_τ
e^-	μ^-	τ^-

Quarks:

u	c	t
d	s	b

Gauge Bosons (force mediators)

γ	Electromagnetic
Z	Neutral weak
$W^\pm$	Charged weak
g	Strong
G	Gravitational

Last but not least...

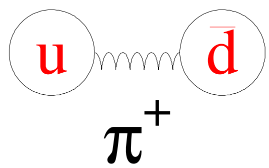
Higgs Boson – Imparts mass to other particles

(a.k.a. "God-Particle" – Leon Lederman)

Anti-Social Particles

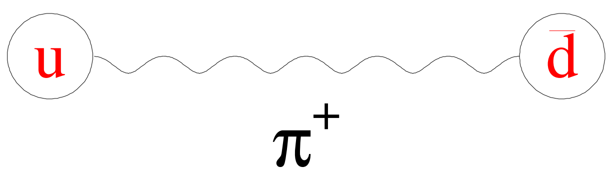
<u>Why we never observe quarks</u>

Start with π^+ meson: (bound state of $u\bar{d}$)



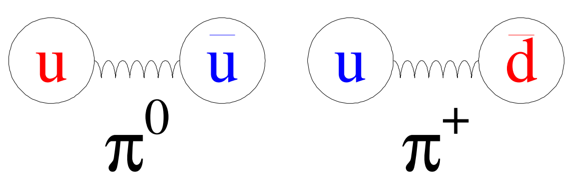
Slowly pull quark and anti-quark apart:

(enormous energy required)



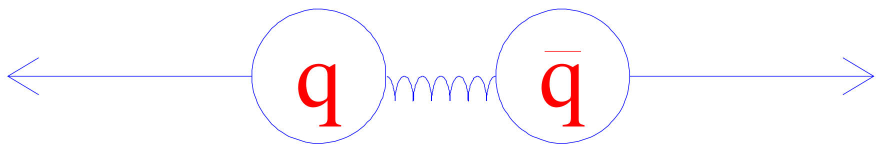
If enough energy to pop new $q\bar{q}$ pair from vacuum,

$\Longrightarrow$ End up with <u>two</u> mesons:

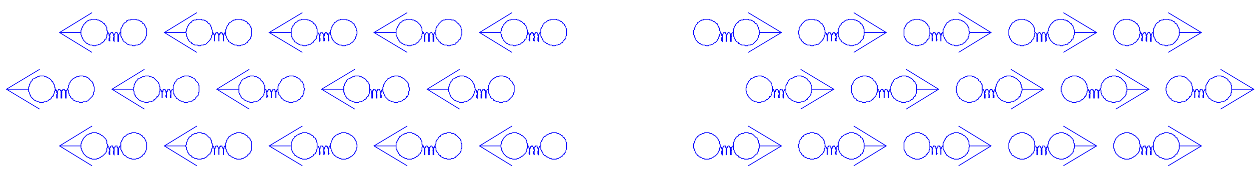


Quarks $\Rightarrow$ Jets

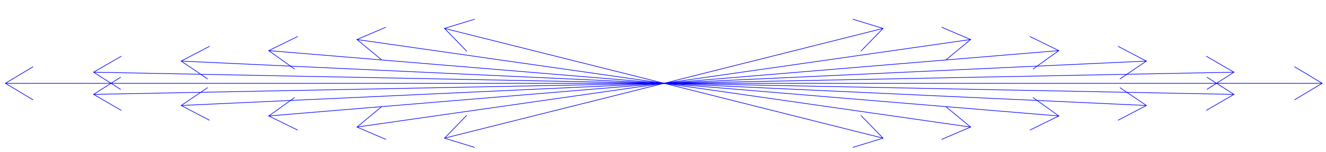
In Z decay, $q\bar{q}$ pair ejected in opposite directions with $p \approx 45$ GeV each:



$\Rightarrow$ Lots of energy to create new hadrons (≈ 30):

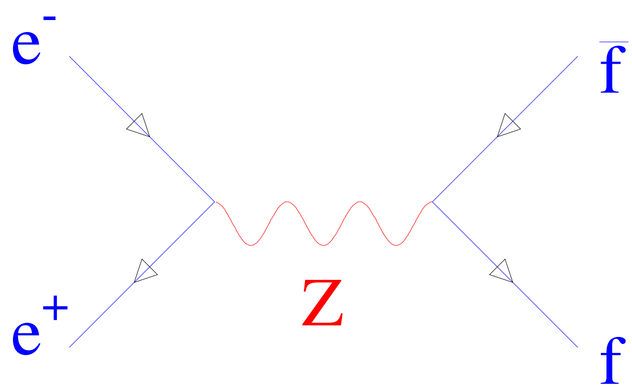


How resulting "jets" look in charged-particle detector:



Z Production and Decay

Feynman Diagram:



Possible fermions:

$$f \quad \equiv \quad \nu_e, \nu_\mu, \nu_\tau, \quad e^-, \mu^-, \tau^-, \quad u, d, s, c, b$$

Branching ratios depend on electroweak couplings:

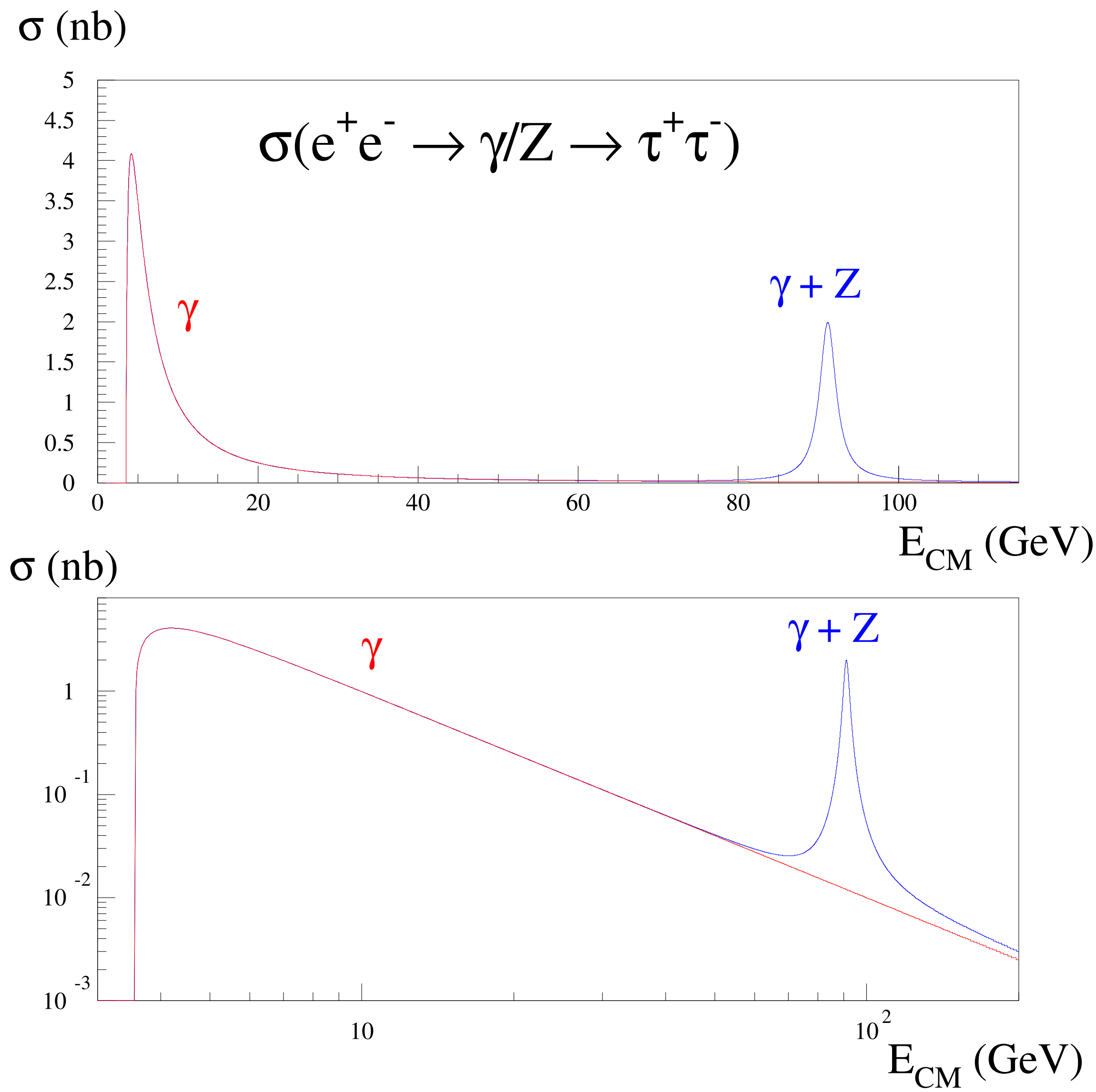
$\mathrm{f\bar{f}}$	$\mathrm{B}(Z \to \mathrm{f\bar{f}})$	Sum
$\nu_e\bar{\nu}_e$, $\nu_\mu\bar{\nu}_\mu$, $\nu_\tau\bar{\nu}_\tau^+$	6.7%	20% (invisible)
e^-e^+, $\mu^-\mu^+$, $\tau^-\tau^+$	3.4%	10%
$u\bar{u}$, $c\bar{c}$	11.9%	24%
$d\bar{d}$, $s\bar{s}$	15.4%	31%
$b\bar{b}$	15.1%	15%

To a good approximation: That's All!

And it's easy to separate e^-e^+ $\mu^-\mu^+$ $\tau^-\tau^+$ $q\bar{q}$

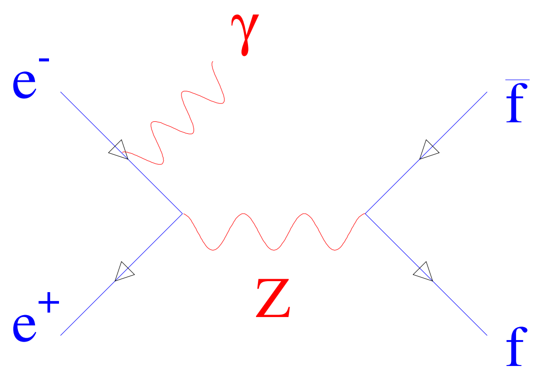
Z Production

Production of $\tau^+\tau^-$ pairs vs c.m. energy (Born level)



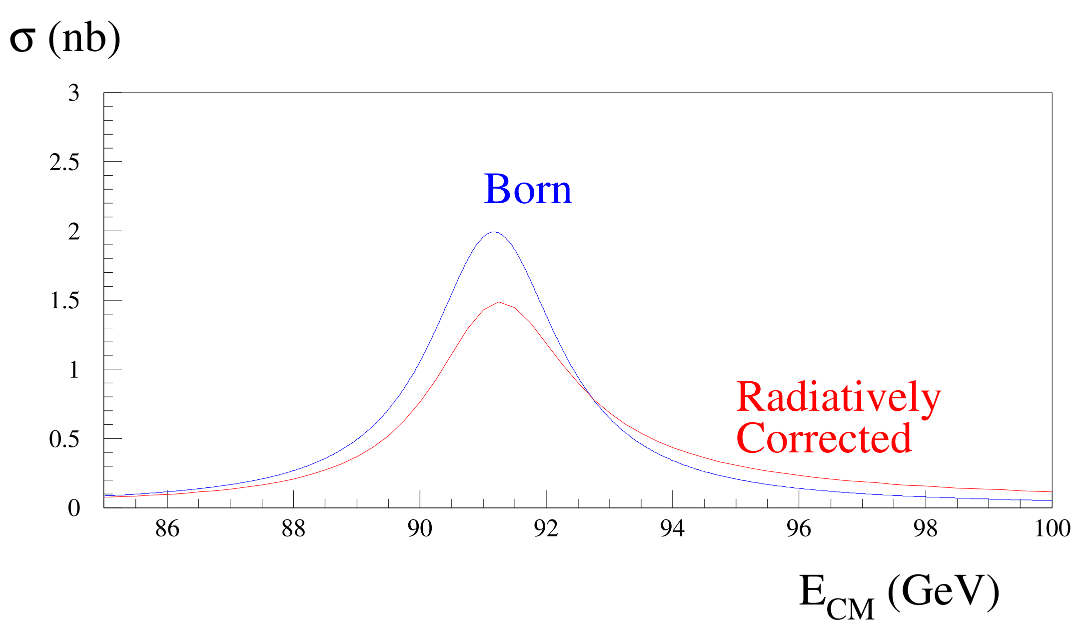
Radiative Effects

Probability of photon emission significant:



⇒ Lowers effective c.m. energy of e^+e^- collision

⇒ Distorts lineshape:

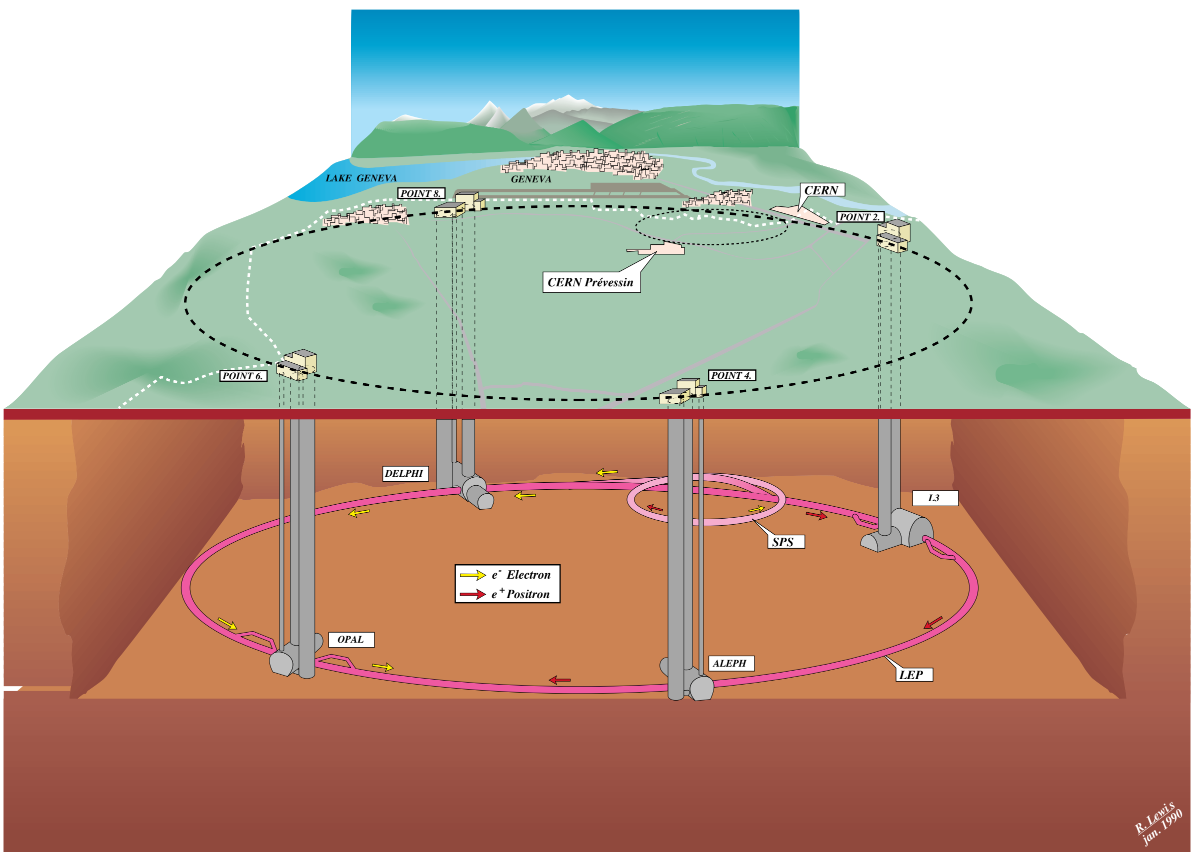


Photon radiation also perturbs event kinematics

LEP Accelerator

Physical Description:

- Electron-positron synchrotron near Geneva
- 27-km circumference
- Four to eight bunches of e^+ and e^- counter-circulate
- Four major detectors: ALEPH, DELPHI, L3, OPAL
- Ring magnets permit $\sqrt{s} \approx 240$ GeV
- RF cavities / power (\$) = real limitations
  $\Longrightarrow \sqrt{s} \leq 195$ GeV



LEP Accelerator

History:

- Turned on in 1989
- Ran at 91 $\pm$ 3 GeV 1989-1995
- Provided millions of Z's / experiment
- Short run at 130–140 GeV in November 1995
- Short run at 161 GeV in Summer 1996
  $\Longrightarrow W$ pairs observed

Future:

- Fall 1996 – Short run at $\sqrt{s} \approx 171$ GeV
- 1997–1999 – Raise $\sqrt{s}$ in steps to ≈ 195 GeV
- Higher energy unlikely (\$) unless hints of new physics appear (at CERN or FNAL)
- End 1999 – Turn off LEP to prepare tunnel for Large Hadron Collider (LHC)

L3 Detector

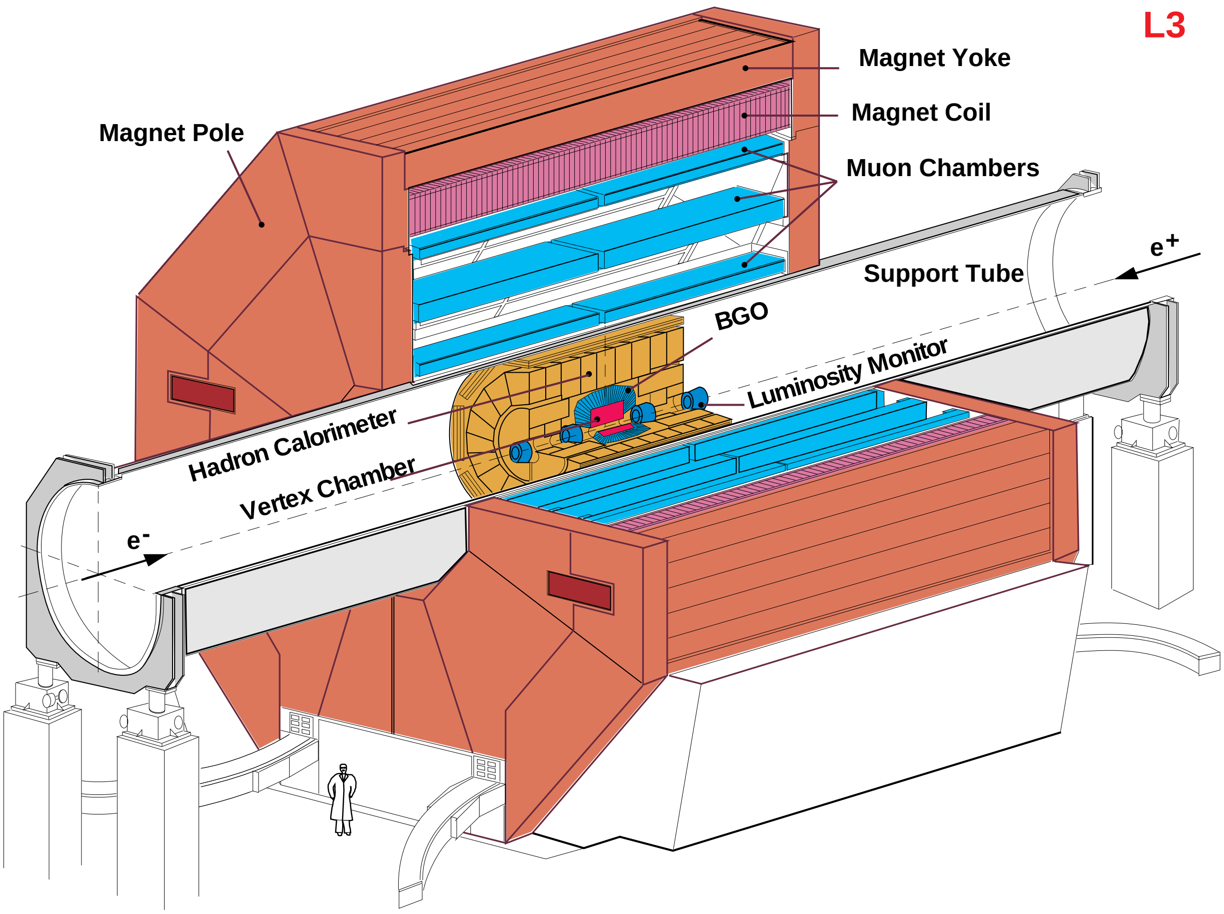
- General-Purpose Particle Detector in LEP Ring

- Strength: Measuring Photons / Electrons / Muons

- Weakness: Measuring Charged Hadrons

- Built / Operated by International Collaboration:
  - 450 Physicists
  - 51 Laboratories
  - 16 Nations

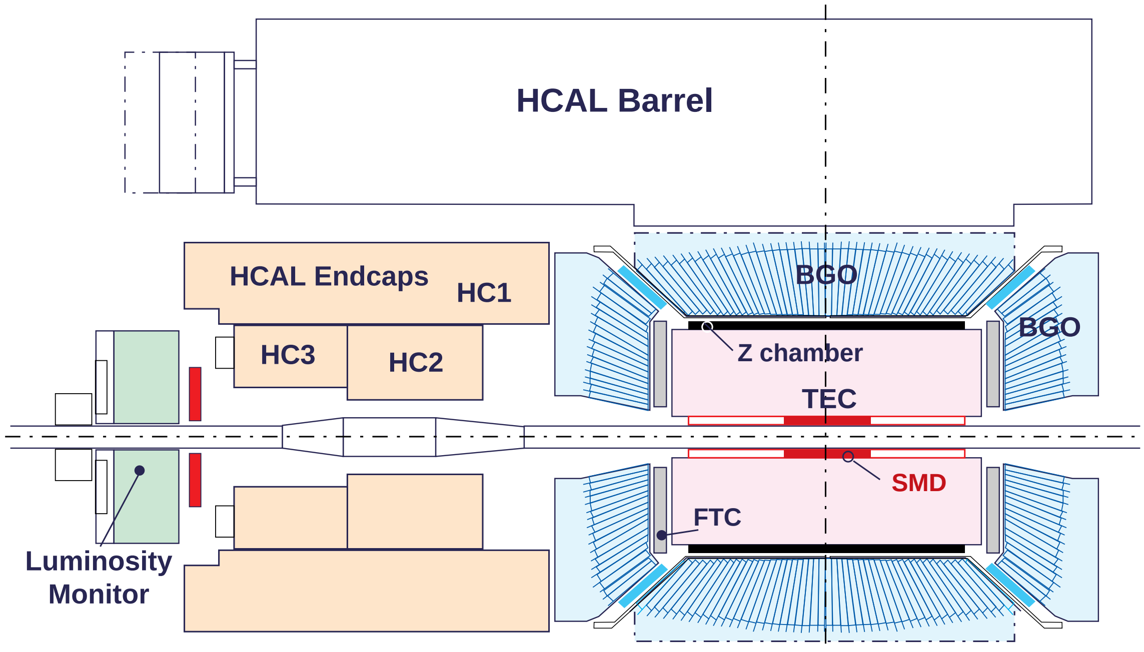
L3 Detector

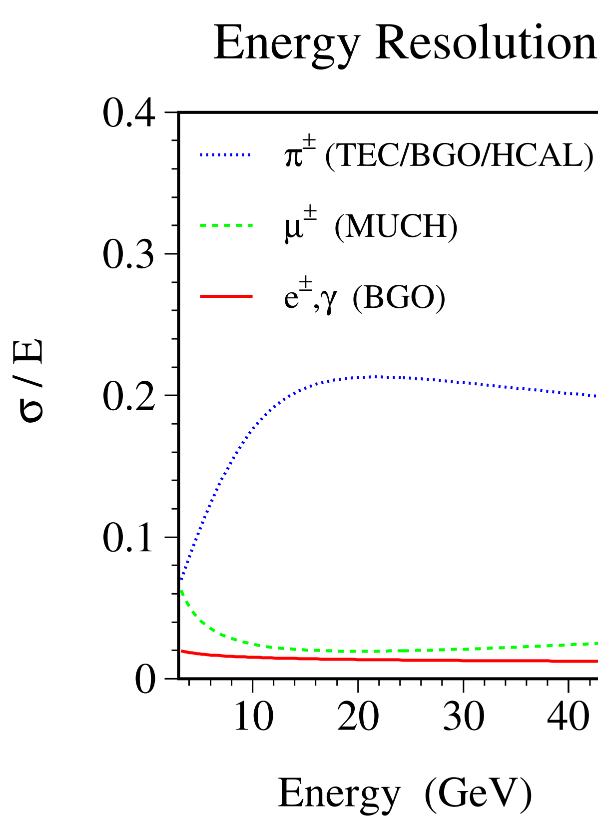


From outside to inside:

- Solenoid Magnet (12-m diameter) $\Longrightarrow$ 0.5 Tesla B-field $\parallel$ beam axis
- Muon Spectrometer: Precise Multiwire Drift Chambers
- Hadronic Calorimeter: Uranium / wire chamber sandwich
- Electromagnetic calorimeter: 12000 Bismuth Germanate (BGO) crystals
- Charged Particle Tracking:
  - Time Expansion Chamber
  - "Z" Chamber
  - Silicon Microstrip Detector

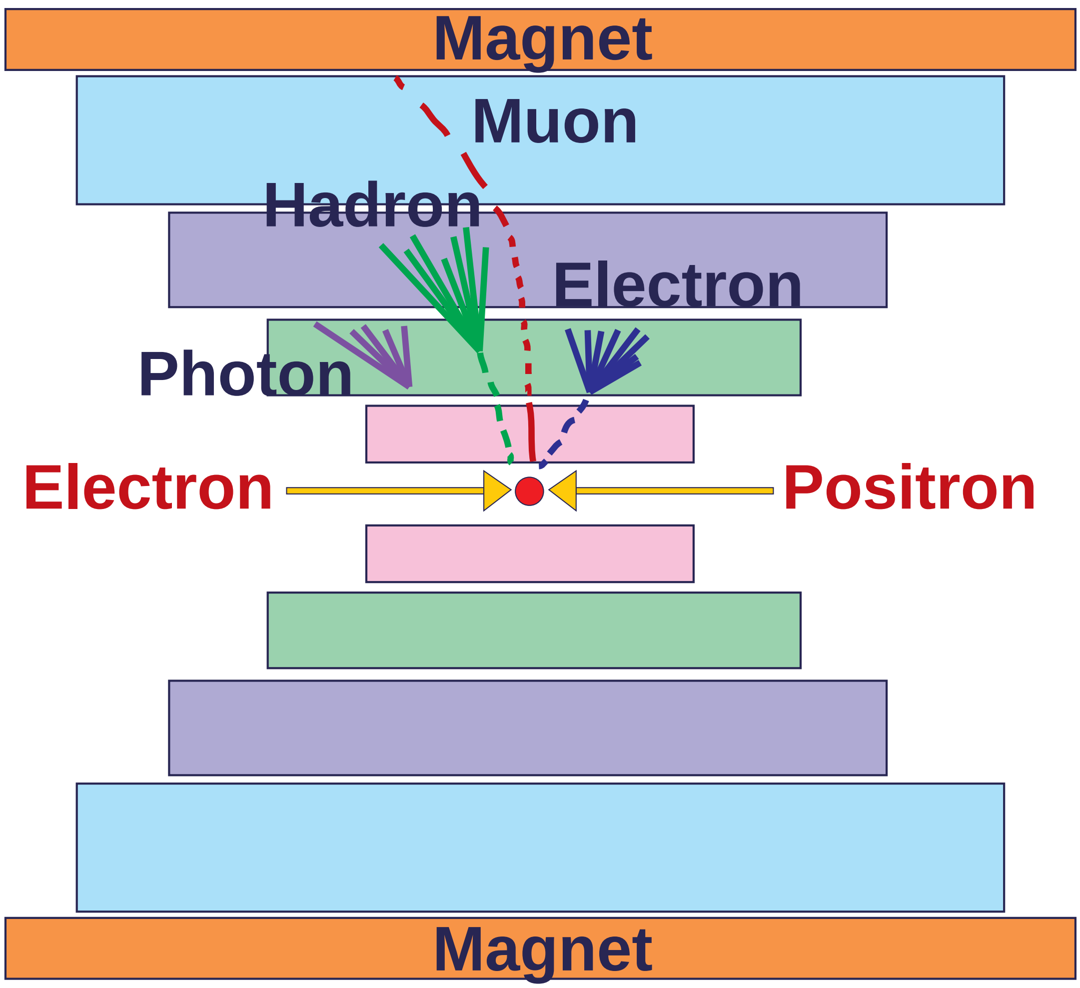
L3 Detector


HCAL Barrel
HCAL Endcaps
HC1
HC3
HC2
BGO
BGO
Z chamber
TEC
SMD
FTC
Luminosity
Monitor


Energy Resolution
0.4
0.3
0.2
0.1
0
10
20
30
40
σ / E
Energy (GeV)
π± (TEC/BGO/HCAL)
μ± (MUCH)
e±,γ (BGO)

L3 Detector

PARTICLE IDENTIFICATION:



Michigan L3 Group

Faculty and Research Scientists:

Tofigh Azemoon*
Bob Ball
Larry Jones
Keith Riles
Byron Roe

Graduate Students / Ph.D. Topics:

Alan Button*	Measurement of the W Boson Mass
Charles Leggett	Measurement of $\Gamma(Z \to b\bar{b})$
Ron Moore*	Measurement of the Tau Neutrino Chirality
Ofer Rind	Measurement of the $e^+e^- \to q\bar{q}\gamma$ Process
Yuan Zhou	Measurement of Time-Dependent B_d^0 Mixing

GraduateD Students / Ph.D. Topics:

Mei-Li Chen	Measurement of the $e^+e^- \to \gamma\gamma$ Process
Steve Goldfarb	Determination of the Number of Neutrinos
Dongning Mao	Search for the Higgs Boson

*Now resident at CERN

LEP I Physics Overview

Topics of Study at LEP (not exhaustive)

Electroweak Parameters

- M_Z, Γ_Z, $\Gamma_{e\bar{e}}$, $\Gamma_{\mu\bar{\mu}}$, $\Gamma_{\tau\bar{\tau}}$, $\Gamma_{q\bar{q}}$, $\Gamma_{b\bar{b}}$, $\Gamma_{c\bar{c}}$, σ_{had}, $N_{\nu\bar{\nu}}$
- $A^{\mathrm{FB}}_{e\bar{e}}$, $A^{\mathrm{FB}}_{\mu\bar{\mu}}$, $A^{\mathrm{FB}}_{\tau\bar{\tau}}$, $A^{\mathrm{FB}}_{b\bar{b}}$
- P_τ, A^{FB}_{τ}, $\sin^2\theta_W$

Heavy Quark Production / Decay

- B^*, B^{**} production, b fragmentation
- $B\bar{B}$ mixing ($\Delta m_{B^0_d}$, $\bar{\chi}$)
- $\mathrm{B}(B\rightarrow[e/\mu/\tau]X)$, $\mathrm{B}(B\rightarrow J/\psi X)$
- B lifetime, charmonium production

Tau Decays

- τ lifetime, Michel parameters, limits on m_{ν_τ}
- $\mathrm{B}(\tau\rightarrow e\bar{\nu}_e\nu_\tau)$, $\mathrm{B}(\tau\rightarrow \mu\bar{\nu}_\mu\nu_\tau)$
- $\mathrm{B}(\tau\rightarrow\pi\nu_\tau)$, $\mathrm{B}(\tau\rightarrow\rho\nu_\tau)$, $\mathrm{B}(\tau\rightarrow a_1\nu_\tau)$, $\mathrm{B}(\tau\rightarrow K^*\nu_\tau)$
- Decay correlations, ν_τ chirality

*Blue topics studied by Michigan physicists

e^- ⇒ ✷ ⇐ e^+

LEP I Physics Overview

Tests of Quantum Electrodynamics (QED)

- $e^+e^- \to \gamma\gamma$, $e^+e^- \to \gamma\gamma\gamma$, $e^+e^- \to \gamma\gamma\gamma\gamma$
- $e^+e^- \to q\bar{q}\gamma$, $e^+e^- \to \ell\ell\gamma$, $e^+e^- \to \ell\ell\gamma\gamma$, $e^+e^- \to \nu\bar{\nu}\gamma$

Tests of Quantum Chromodynamics (QCD)

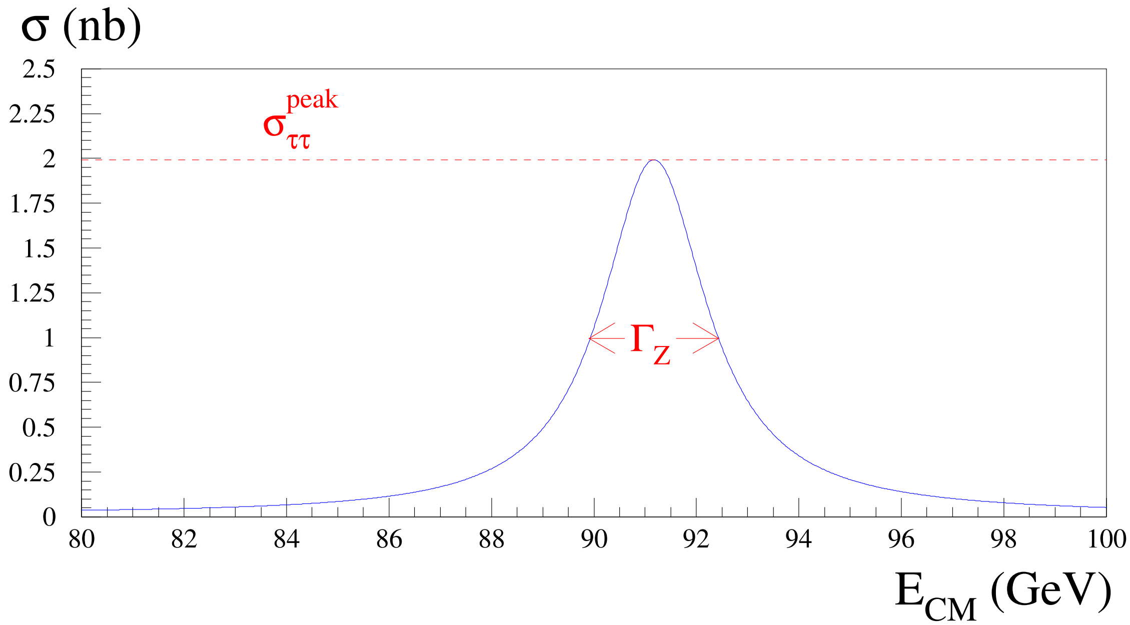
- Event shapes, jet rates
- Gluon- *vs* quark-jet properties, gluon interference

Searches for New Physics

- Higgs boson (MSM, MSSM)
- Supersymmetric particles (χ_i^0, $\chi_i^\pm$, $\tilde{\ell}^\pm$, $\tilde{\nu}$, $\tilde{q}$)
- Heavy leptons, quarks
- Excited leptons, quarks
- Lepton flavor violation, CP violation
- Anomalous τ, ν_τ magnetic moments
- Heavy weak boson (Z')

Z Lineshape

$$\sigma(e^+e^- \to f\bar{f}) \quad \propto \quad \frac{1}{(E_{\rm CM}^2 - M_Z^2)^2 + M_Z^2\,\Gamma_Z^2}$$



$\Longrightarrow$ "Q" of resonance $\approx \frac{M_Z}{\Gamma_Z} \approx 36$

- Γ_Z measures total rate of Z decay
- $\Gamma_{f\bar{f}}$ measures rate of decay to $f\bar{f}$
- $\Gamma_{e\bar{e}}$ also measures rate of Z production:

$$\sigma_{f\bar{f}}^{\rm peak} \quad = \quad \frac{\Gamma_{e\bar{e}}\,\Gamma_{f\bar{f}}}{\Gamma_Z^2}\,\frac{12\pi}{M_Z^2}$$

Z Lineshape

Testing the Standard Model

Measure M_Z, Γ_Z from lineshapes ($\sigma_{f\bar{f}}$ *vs* E_{CM})

Measure $\sigma_{q\bar{q}}^{\mathrm{peak}}$, $\sigma_{e\bar{e}}^{\mathrm{peak}}$, $\sigma_{\mu\bar{\mu}}^{\mathrm{peak}}$, $\sigma_{\tau\bar{\tau}}^{\mathrm{peak}}$

$\Longrightarrow$ Determine $\Gamma_{q\bar{q}}$, $\Gamma_{e\bar{e}}$, $\Gamma_{\mu\bar{\mu}}$, $\Gamma_{\tau\bar{\tau}}$

Given measured M_Z, S.M. predicts all other quantities

$\Longrightarrow$ Powerful consistency test

Z Lineshape

Wait! There's More!

- Can't observe $e^+e^- \to Z \to \nu\bar{\nu}$ directly
- BUT (in S.M.)

$$\Gamma_Z \quad = \quad \Gamma_{q\bar{q}} + \Gamma_{e\bar{e}} + \Gamma_{\mu\bar{\mu}} + \Gamma_{\tau\bar{\tau}} + \Gamma_{\nu\bar{\nu}}$$

Define $\quad \Gamma_{\text{invis}} \quad \equiv \quad \Gamma_Z \quad - \quad (\Gamma_{q\bar{q}} + \Gamma_{e\bar{e}} + \Gamma_{\mu\bar{\mu}} + \Gamma_{\tau\bar{\tau}})$

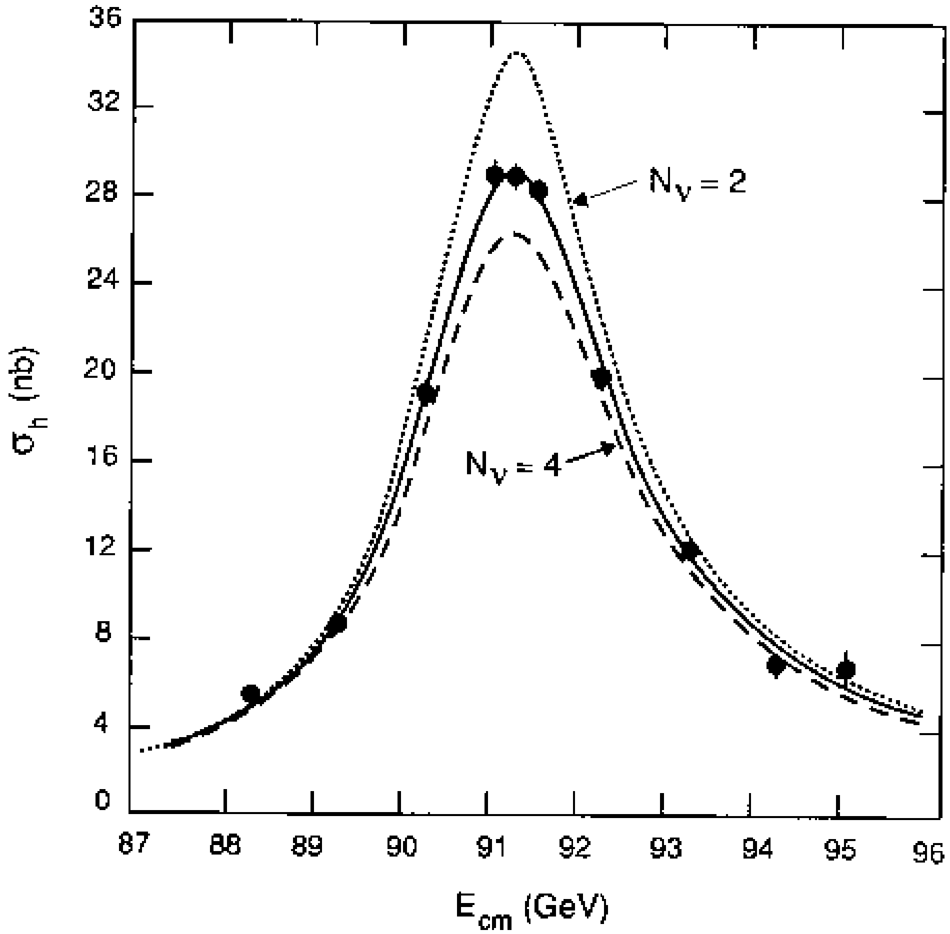
$\Longrightarrow$ Determine number of light neutrino species:

$$N_{\nu\bar{\nu}} \quad = \quad \frac{\Gamma_{\text{invis}}}{\Gamma_{\nu\bar{\nu}}^{\text{SM}}}$$

- We expect three species
- What do we observe?

Z Lineshape

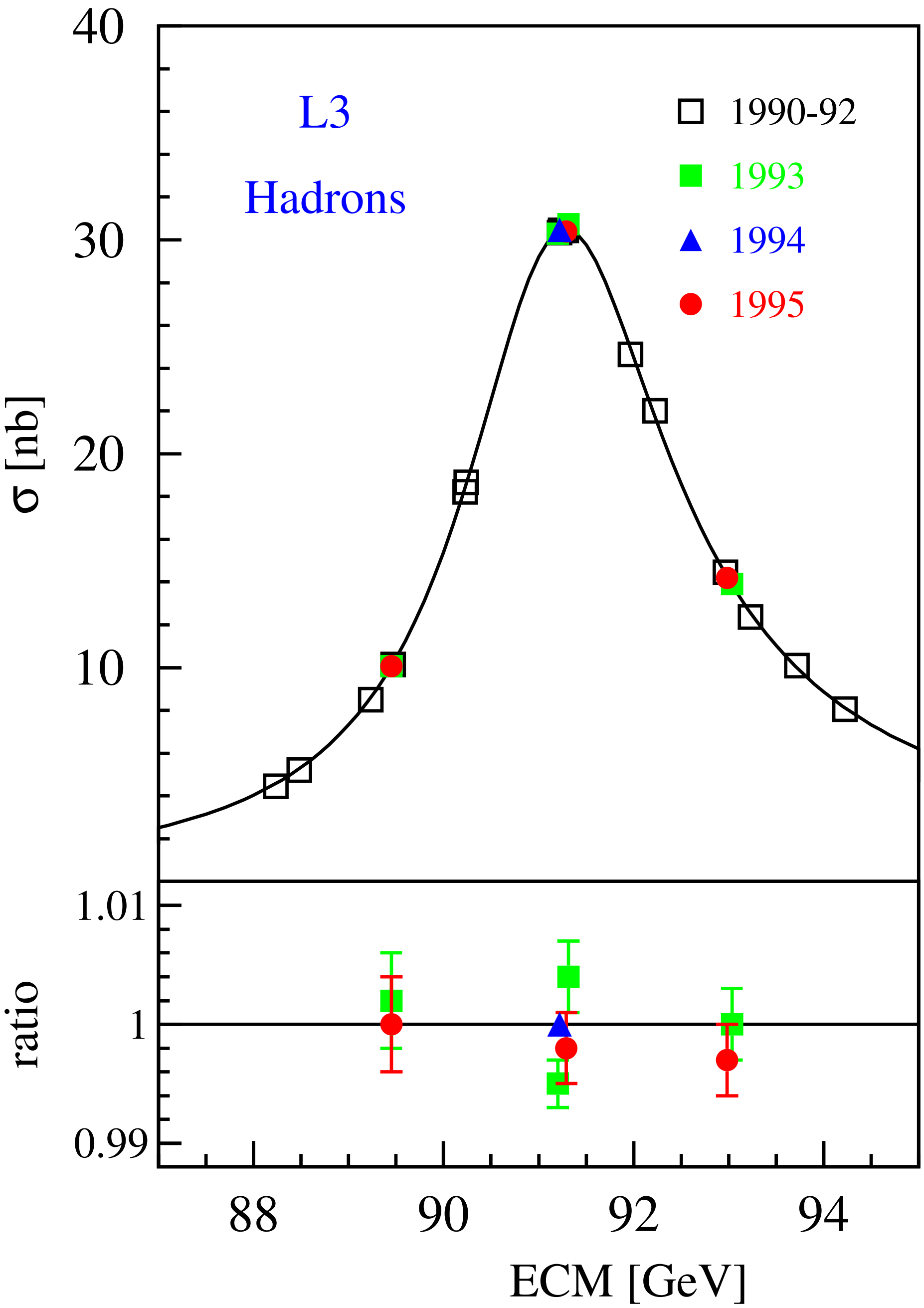
What we observed in 1989: ($\approx$ 15K Z's)



$$\Longrightarrow \qquad \boxed{N_{\nu\bar{\nu}} \quad = \quad 3.29 \pm 0.17}$$

Z Lineshape

What we have observed since 1989: ($\approx$ 4M Z's)



$$\Longrightarrow \qquad \boxed{N_{\nu\bar{\nu}} \quad = \quad 3.00 \pm 0.02}$$

Z Lineshape

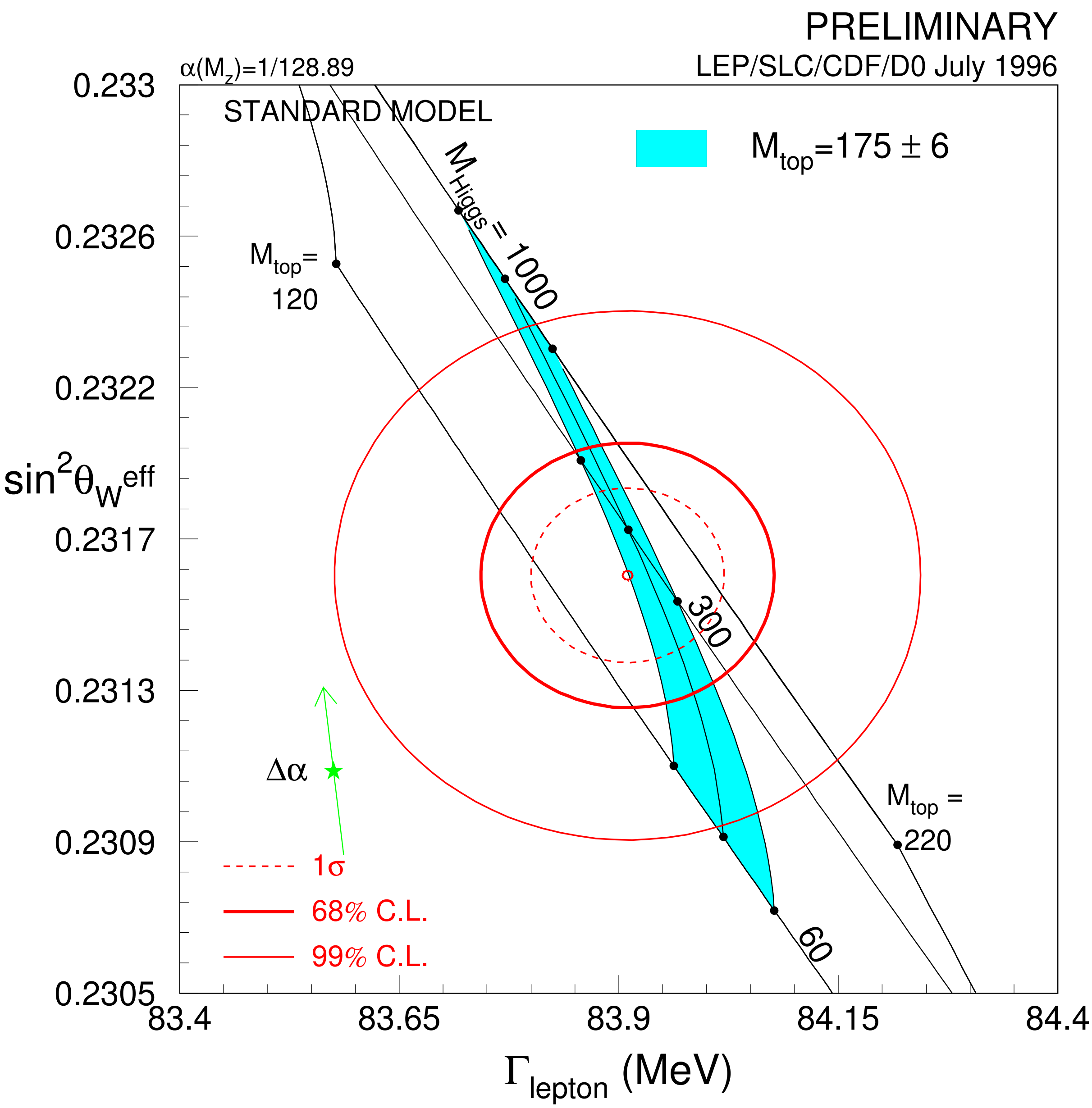
Many more measurements available:

- Forward / backward charge asymmetries
- Tau polarization
- A_{LR} (from SLAC SLD experiment)
- m_t, m_W (from Tevatron CDF, D0 experiments)
- Low-energy ν–N scattering

Combine into global fit:

- Rigorously test S.M. self consistency
- Probe unknown Higgs boson mass

Putting it all together (from LEP Electroweak W.G.)



Tau Neutrino Chirality

Ph.D. topic of Ron Moore

Main τ lepton decays: ($m_\tau \approx 1.8$ GeV, $\tau_\tau \approx 300$ fs)

$\tau^- \to e^- \bar{\nu}_e \nu_\tau$	18%
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$	18%
$\tau^- \to \rho^- \nu_\tau$	25%
$\tau^- \to \pi^- \nu_\tau$	12%
$\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$	8%
$\tau^- \to \pi^- \pi^0 \pi^0 \nu_\tau$	10%

Given variety of decay signatures, seems hard to identify $e^+e^- \to \tau^+\tau^-$ events with simple algorithm

But in fact at LEP it's easy!

Tau Neutrino Chirality

Why τ's are Easy to Identify

- 99.9% of τ decays produce 1 or 3 charged particles
  $\Longrightarrow$ Expect 2–6 charged particles from $e^+e^- \to \tau^+\tau^-$

- Lorentz boost of each τ is $\gamma \approx 45/1.8 = 25$
  $\Longrightarrow$ Decay products nearly back to back

- Only four potential backgrounds:

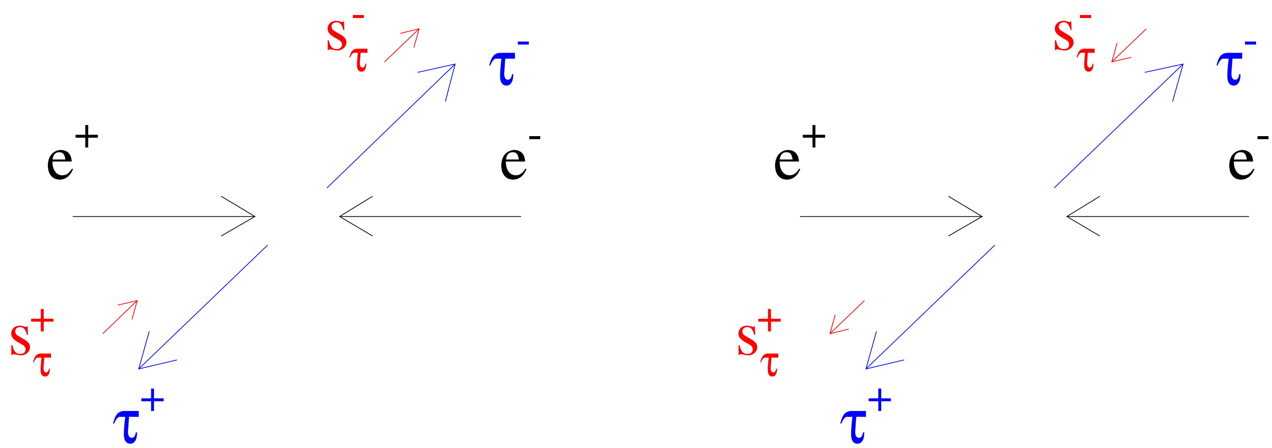
Channel	Signature
$e^+e^- \to e^+e^-$	Two electrons with $E = E_{\mathrm{BEAM}}$
$e^+e^- \to \mu^+\mu^-$	Two muons with $E = E_{\mathrm{BEAM}}$
$e^+e^- \to q\bar{q}$	Many charged particles (average = 20)
$e^+e^- \to e^+e^-X$	Very low visible energy, particles not produced back to back

$\Longrightarrow$ All simple to veto

Tau Neutrino Chirality

TAU POLARIZATION

Only two possible spin states (excellent approximation):



Quantize along $\tau^+\tau^-$ axis:

$$\text{Helicity}: \quad \frac{\vec{s}_\tau \cdot \hat{p}_\tau}{\hbar} \quad = \quad \pm\frac{1}{2}$$

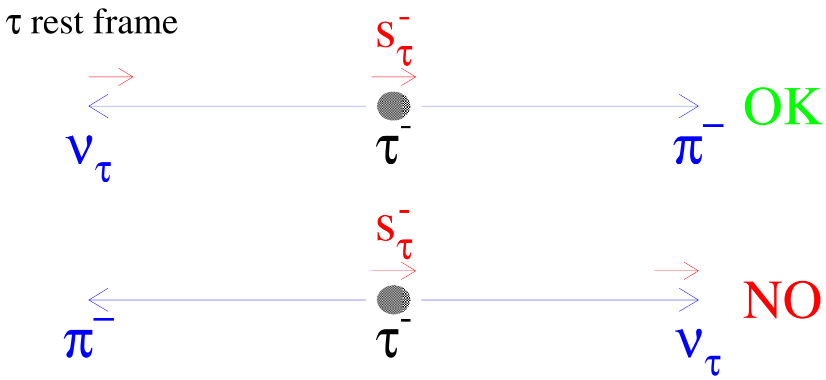
$-\frac{1}{2}$ – Left-handed $\qquad$ $+\frac{1}{2}$ – Right-handed

Expect small excess (14%) of left-handed over right-handed τ^- in Z decay

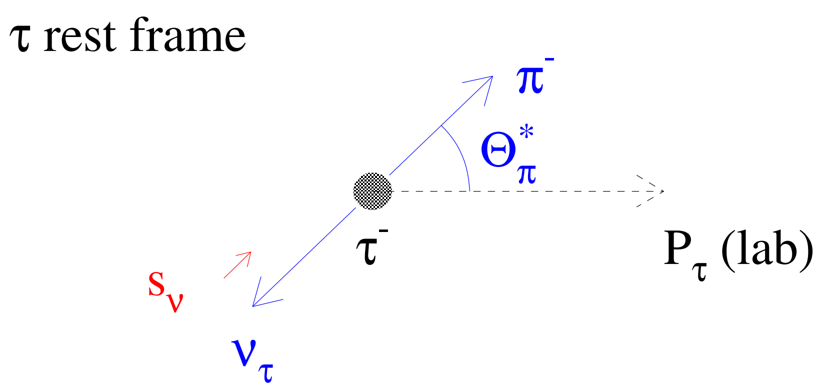
Note: If τ^- left-handed, then τ^+ right-handed

Tau Neutrino Chirality

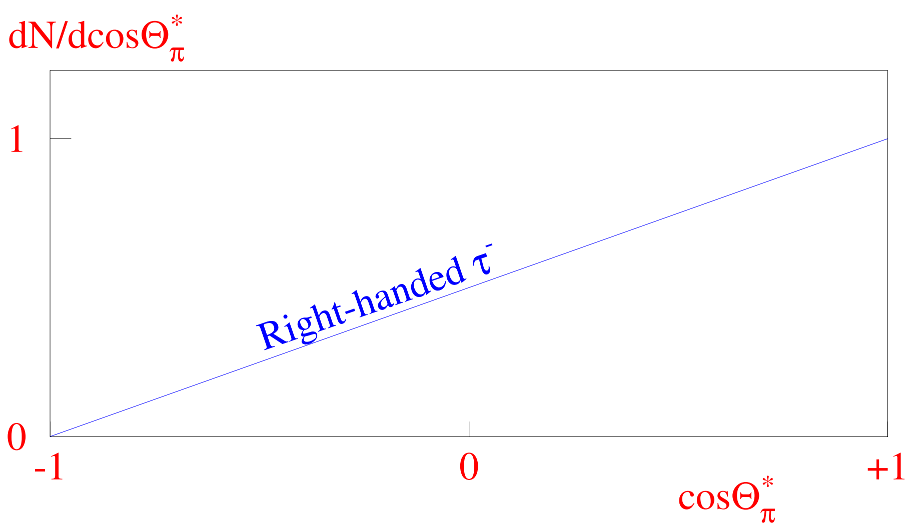
What happens when right-handed τ^- decays to $\pi^-\nu_\tau$?



General case involves rest-frame angle θ^*_π:



Right-handed τ^- prefers $\cos\theta^*_\pi > 0$:

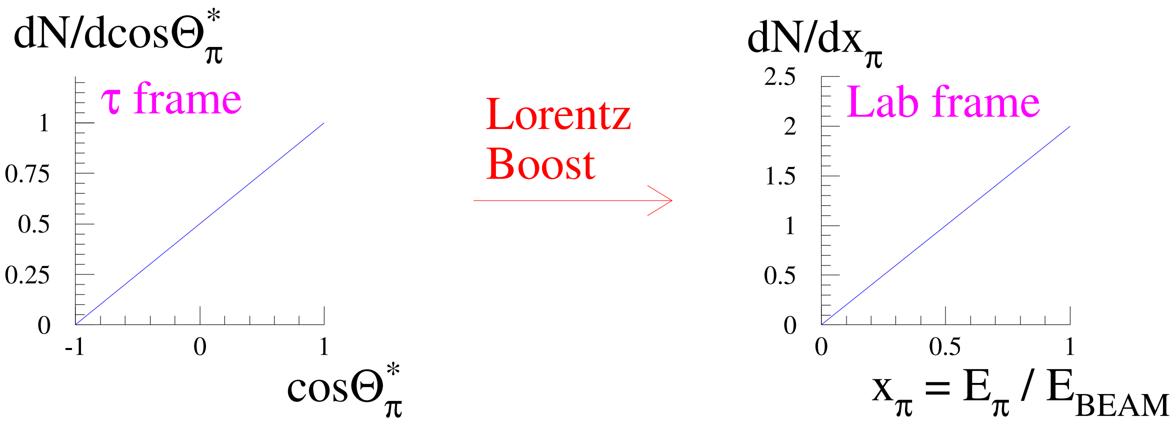


Now go back to lab frame:

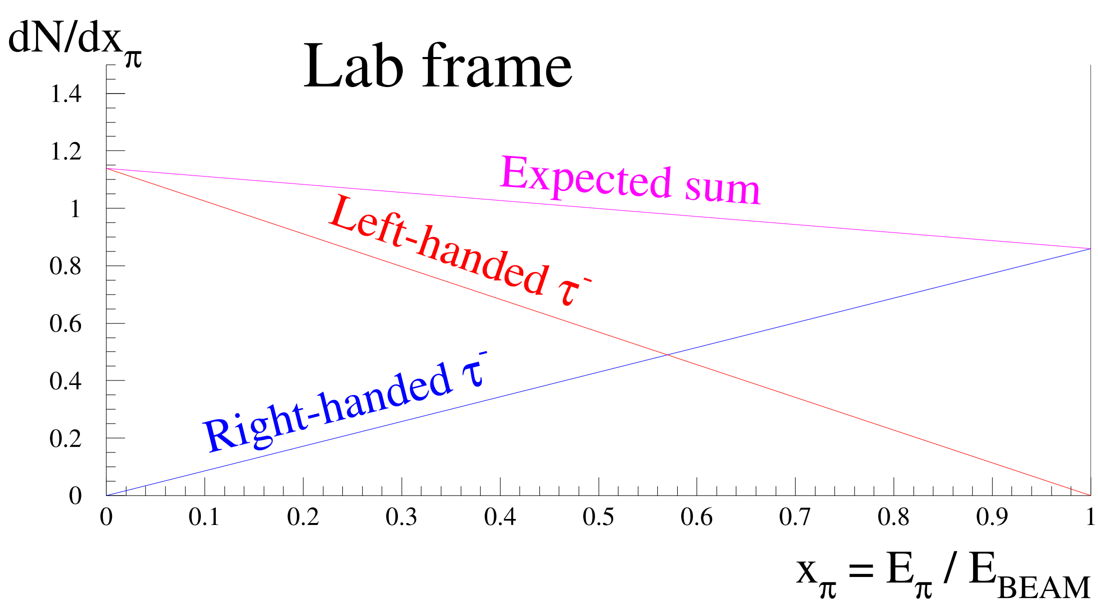
$$E_\pi^{\mathrm{LAB}} \quad = \quad \gamma_\tau \left(E_\pi^* + \beta_\tau p_\pi^* \cos\theta_\pi^* \right)$$

Positive $\cos\theta_\pi^*$ $\Longrightarrow$ Large measured lab energy

Negative $\cos\theta_\pi^*$ $\Longrightarrow$ Small measured lab energy



For $P_\tau = -14\%$ (left-handed excess):



Tau Neutrino Chirality

BUT

Preceding analysis assumed ν_τ helicity always $-\frac{1}{2}$ (always left-handed)

- Not proven!
- ν_τ not even directly seen (yet)

Define:

$$\xi_\pi \equiv 2 \cdot \text{average } \nu_\tau \text{ helicity in } \tau \to \pi\nu_\tau \text{ decay}$$

$$x_\pi \equiv E_\pi^{\mathrm{LAB}} \;/\; E_\tau \qquad (\approx E_\pi^{\mathrm{LAB}}/E_{BEAM})$$

Then

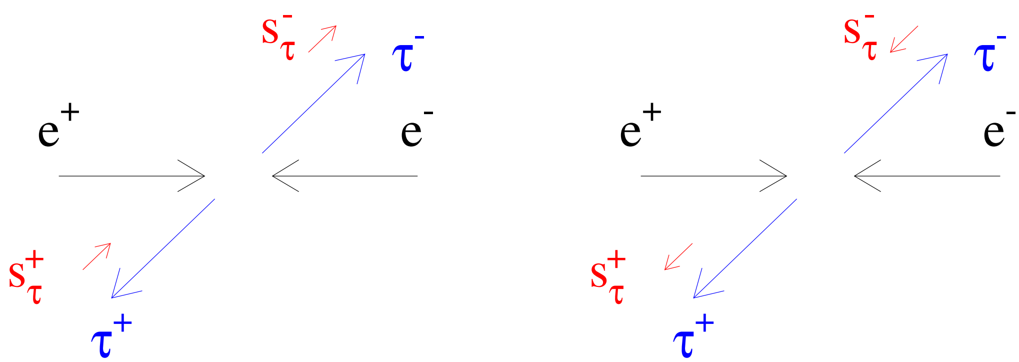
$$\frac{1}{N}\frac{dN}{dx_\pi} = 1 - P_\tau \xi_\pi \,(2\,x_\pi - 1)$$

What we have really measured is product $P_\tau \xi_\pi$

Can we separate the product?

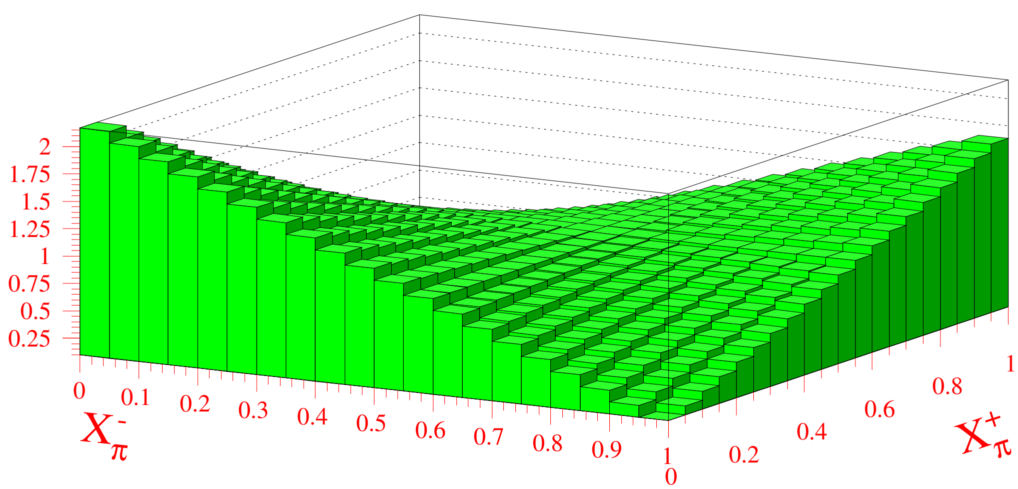
Tau Neutrino Chirality

YES!   Exploit correlations



Joint energy distribution for $e^+e^- \to \tau^+\tau^- \to \pi^+\bar{\nu}_\tau\pi^-\nu_\tau$

$$\frac{1}{N}\frac{d^2N}{dx_\pi^- dx_\pi^+} = 1 + \xi_\pi^2\,(2\,x_\pi^- - 1)(2\,x_\pi^+ - 1) - P_\tau\xi_\pi\,2(x_\pi^- + x_\pi^+ - 1)$$

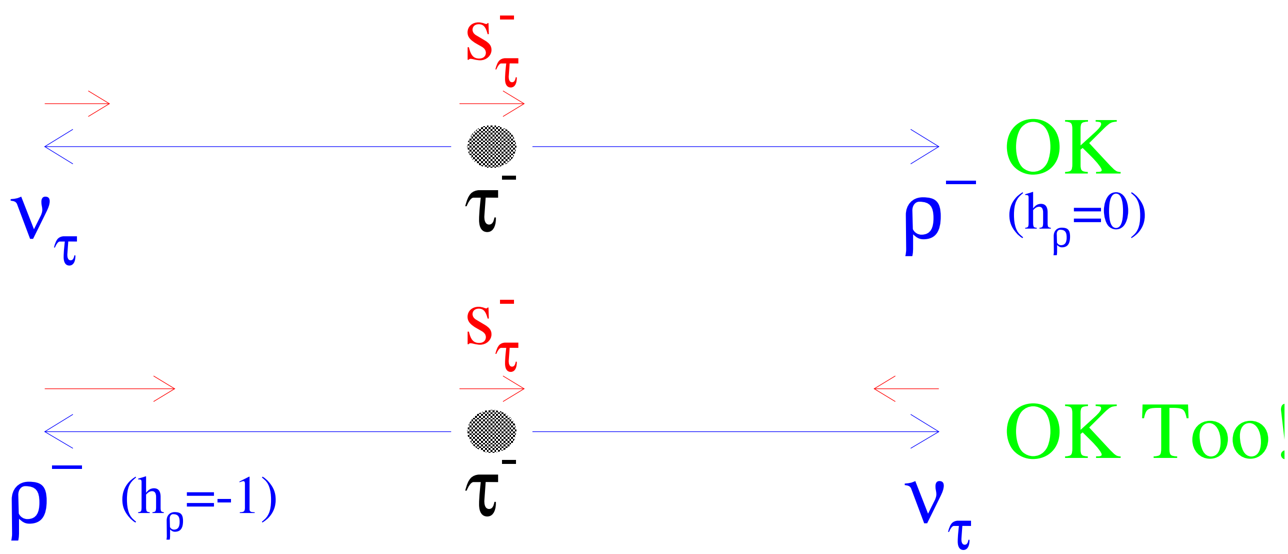


Can now separate $|\xi_\pi|$ from $P_\tau\xi_\pi$

Tau Neutrino Chirality

Can also use $\tau \to \rho\nu_\tau$

- Advantage: Higher B.R. (25% *vs* 12%)
- Disadvantage: More complicated because $J_\rho = 1$



Can disentangle different ρ^- helicities via $\rho^- \to \pi^-\pi^0$

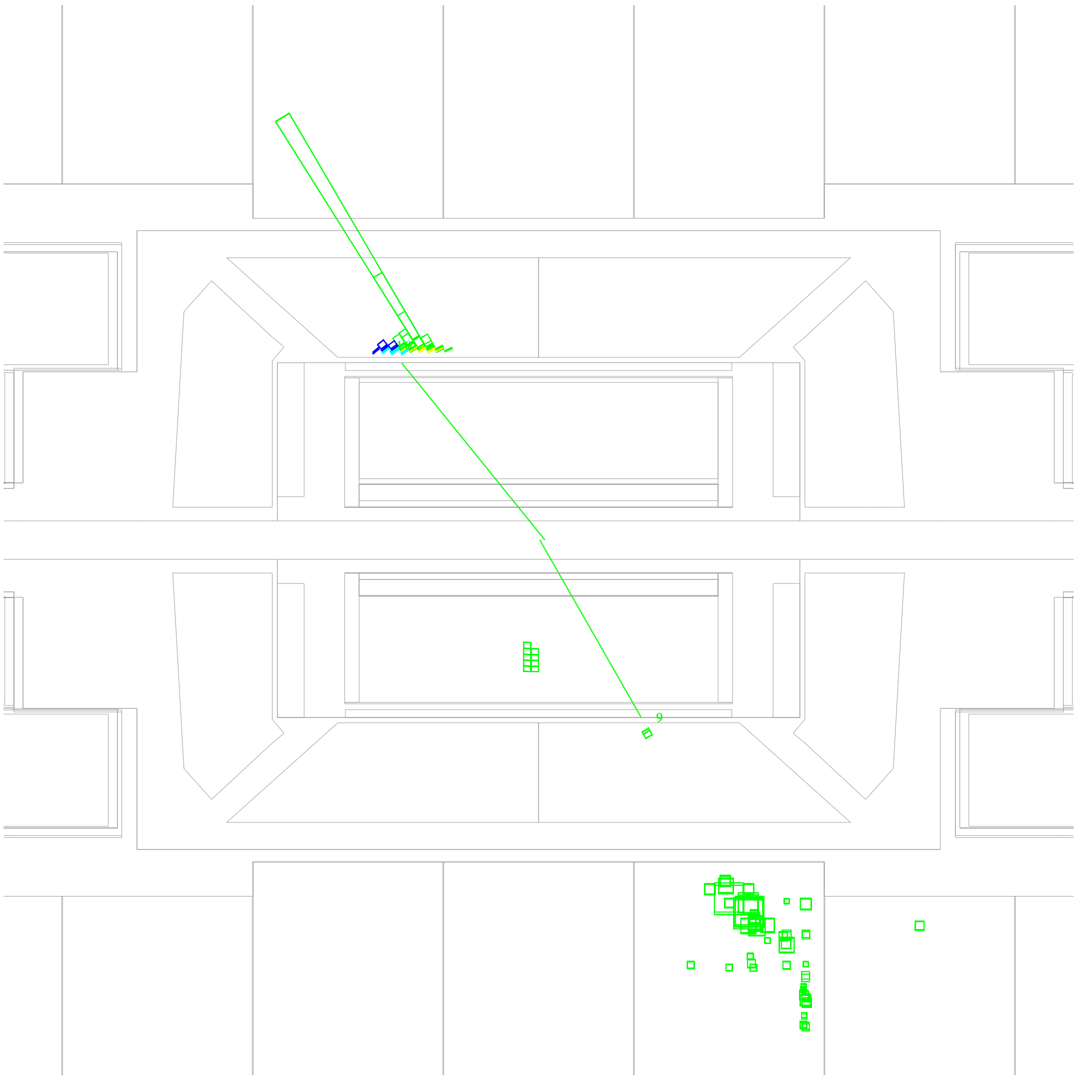
Construct optimized variable ω using:

- Measured energies E_{π^-}, E_{π^0}
- Measured opening angle $\theta_{\pi^-\pi^0}$

Tau Neutrino Chirality

Event with $\tau \rightarrow \rho\nu$ and $\tau \rightarrow \pi\nu$

Run # **359206** **Event #** **3586** Total Energy : 40.22 GeV

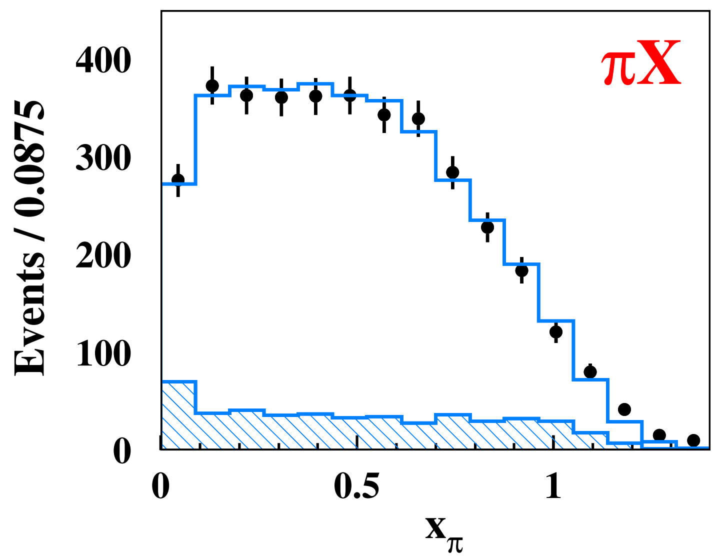


Transverse Imbalance :	.1578		**Longitudinal Imbalance :**	-.0699	
Thrust : .9985		**Major :** .0277		**Minor :** .0093	
Event DAQ Time :	*911029 220051*				

Tau Neutrino Chirality

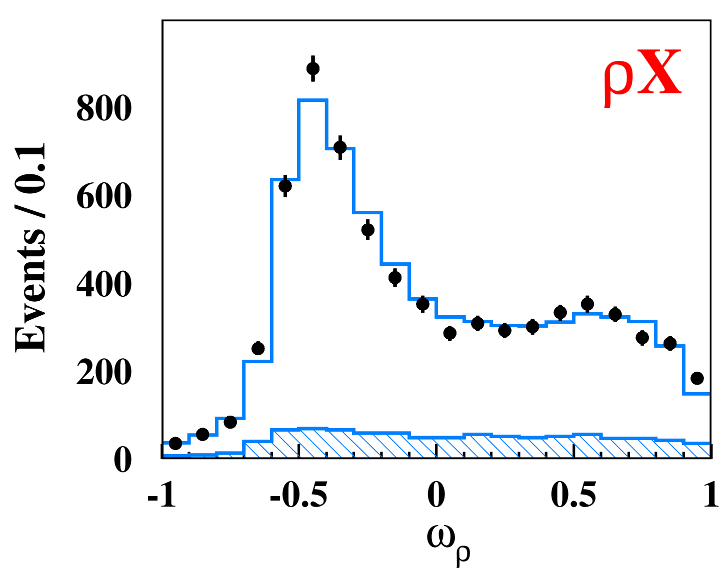
What do the data look like?

Distribution in x_π for $\tau \to \pi\nu_\tau$



● Data Fit Bkgd

Distribution in ω_ρ for $\tau \to \rho\nu_\tau$



Tau Neutrino Chirality

Must correct for detector resolution / efficiency

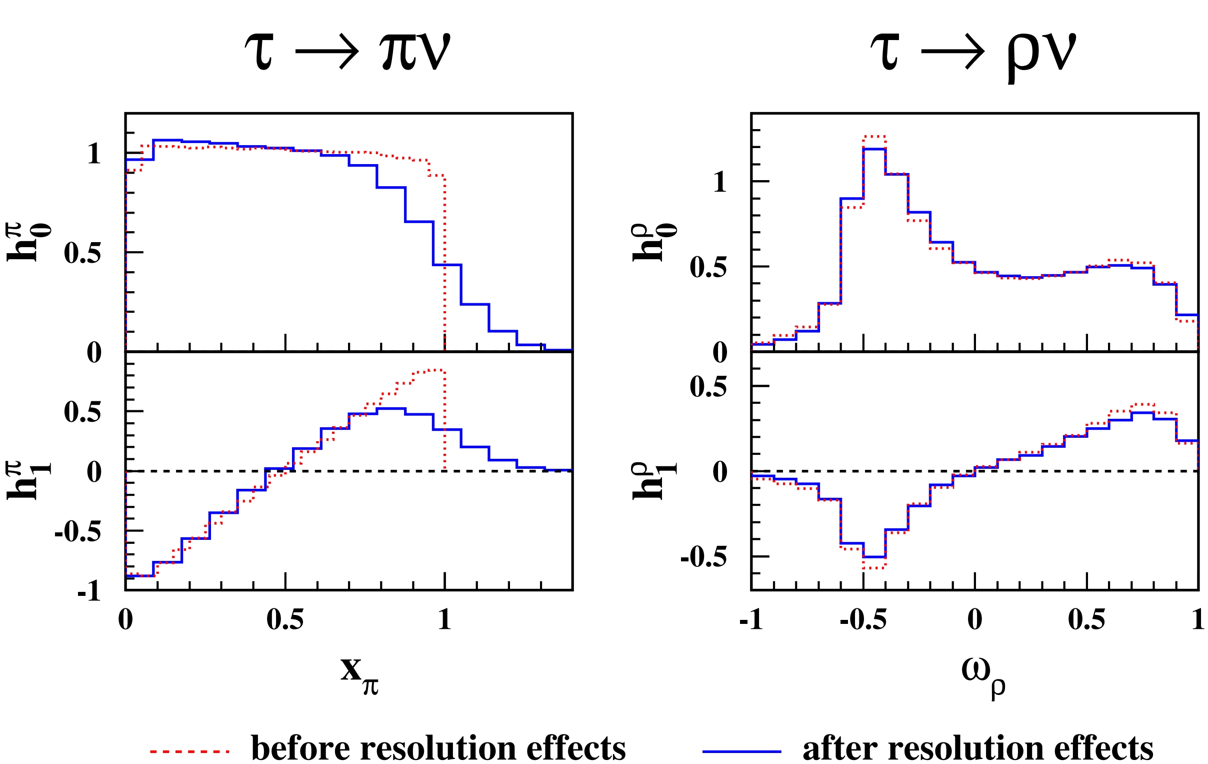
$\Longrightarrow$ Requires detailed Monte Carlo simulation

Parametrize measurable single-sided distributions with h functions:

$$\frac{1}{N}\frac{dN}{dx_h} \quad = \quad h_0(x_h) - P_\tau\, \xi_h\, h_1(x_h)$$

where

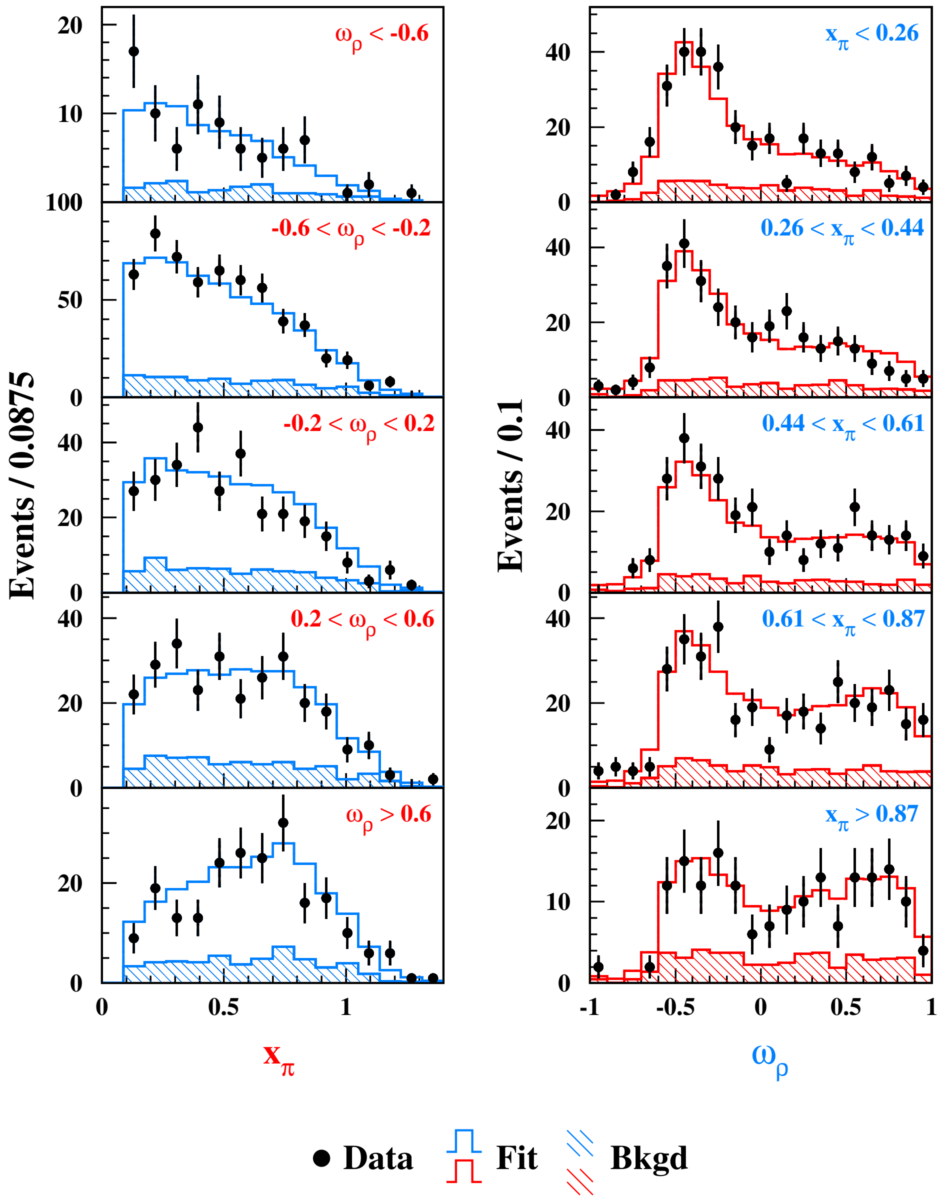
$$x_\pi \; = \; E_\pi^- / E_{\mathrm{BEAM}}$$
$$x_\rho \; = \; \omega(E_\pi^-, E_\pi^0, \theta_{\pi^- - \pi^0})$$



Tau Neutrino Chirality

Examples of π–ρ kinematic correlations

$$Z \rightarrow \tau^+\tau^- \rightarrow (\pi\nu)(\rho\nu)$$



Tau Neutrino Chirality

Results (Published 1991-1993 Data)

$$\xi_h = -0.970 \pm 0.053\,(\mathrm{stat}) \pm 0.011\,(\mathrm{syst})$$
$$P_\tau = -0.154 \pm 0.018\,(\mathrm{stat}) \pm 0.014\,(\mathrm{syst})$$

$\Longrightarrow$ Consistent with purely left-handed neutrinos in $\tau^- \to h^- \nu_\tau$

$\boxed{\text{No evidence for new physics}}$

Analysis of 1994-95 data underway:

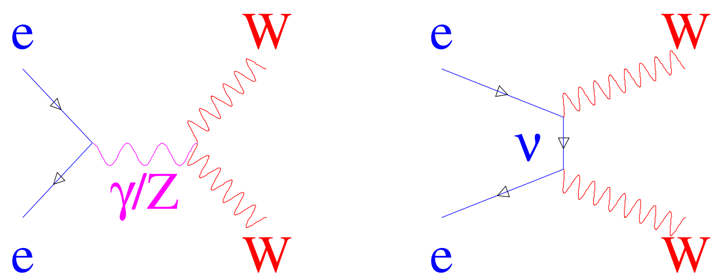
- Improved statistical precision
- Improved systematic precision

Expect final publication early 1997

W^+W^- Production

Ph.D. topic of Alan Button

In 1996 started producing W pairs:

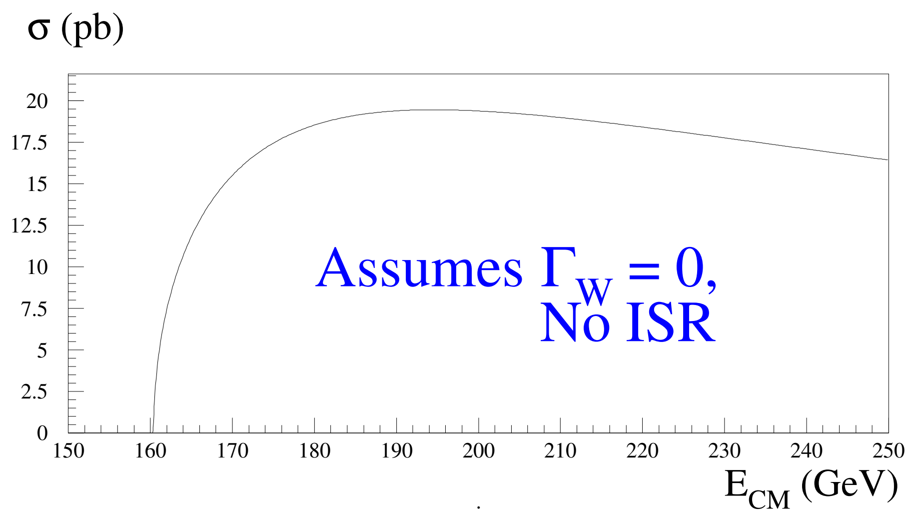


Goal: precise measurement of W mass

- M_W predicted by S.M., given other LEP measurements
- Important self-consistency check
- Helps pin down Higgs boson mass

We already know $M_W \approx 80$ GeV

$\Longrightarrow$ Need $E_{\mathrm{CM}} \geq 160$ GeV to observe $e^+e^- \rightarrow W^+W^-$



W^+W^- Production

Two main methods to measure M_W:

- Lineshape
  - Best near threshold ($\approx$ 161 GeV)   BUT
  - Low σ hurts other W measurements
  - Interferes with searches for new particles

- Direct Reconstruction (using kinematic constraints)
  - Needs higher E_{CM} for higher σ
  - Requires precise understanding of ISR
  - Non-trivial theoretical uncertainties in dynamics of most copious channel: $WW \rightarrow qqqq$

W^+W^- Production

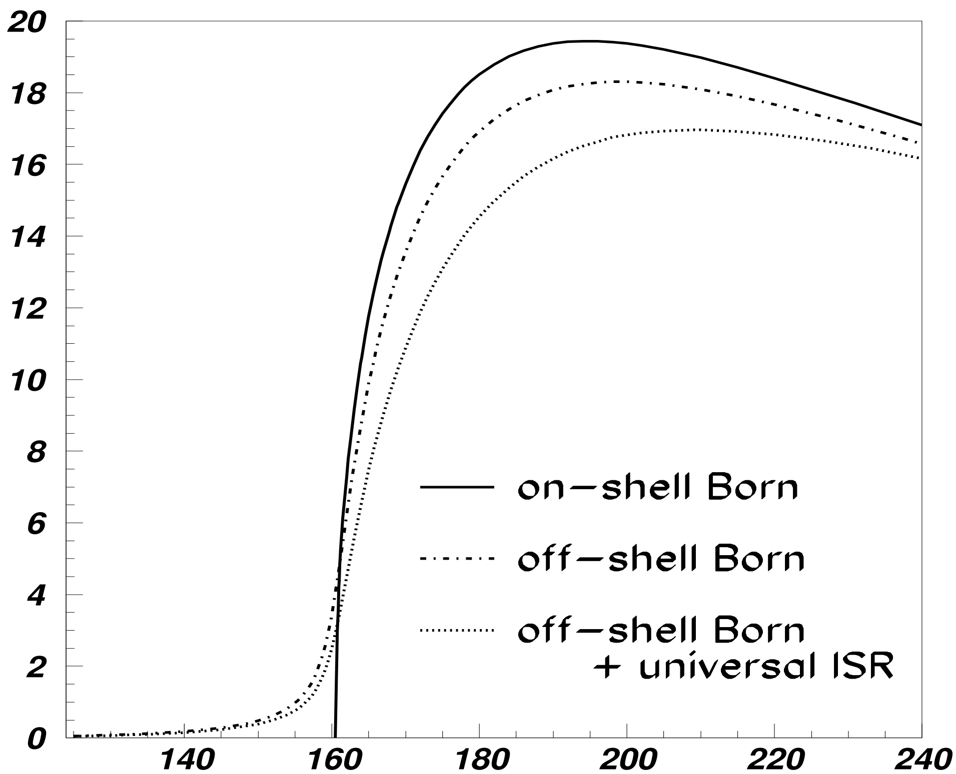
For now we have only near-threshold data

($E_{\mathrm{CM}} = 161.3$ GeV)

Complications

- Non-zero Γ_W smears sharp turn-on
- Phase space suppression: $<M_W> \; < \; 80$ GeV
- Initial state radiation reduces σ_{WW}
- Beam energy spread (negligible for now)

Realistic σ_{WW} vs E_{CM}:



W^+W^- Production

LEP I $\neq$ LEP II $\Longrightarrow$ Many New Challenges

LEP II now in infancy:

- Luminosity (beam intensity) still low
- C.M. energy barely above WW threshold
- Beam energy calibration still uncertain
- Beam backgrounds serious (synch. γ's, "halo")
- Accelerator unstable in general

Above problems should improve with experience

More fundamental problems:

- $\sigma_{WW}^{\max} \approx 15$ pb $\quad (\sigma_Z^{\max} \approx 40$ nb)

  $\Longrightarrow$ Poor signal statistics

  $\Longrightarrow$ $e^+e^- \to e^+e^-X$ background relatively high

- New backgrounds:

$$e^+e^- \to Z(\gamma)$$
$$e^+e^- \to ZZ$$
$$e^+e^- \to f\bar{f}f'\bar{f}'$$

W^+W^- Production

Expected W Properties

Naive expectation for relative partial widths:

$$
\begin{array}{ccccccccccc}
W^- \rightarrow & \bar{u}d & : & \bar{c}s & : & e^-\bar{\nu}_e & : & \mu^-\bar{\nu}_\mu & : & \tau^-\bar{\nu}_\tau \\
 & 3 & : & 3 & : & 1 & : & 1 & : & 1
\end{array}
$$

Resulting BR's before / after QCD / EW corrections:

Channel	Naive	Accurate
$W^- \rightarrow \bar{q}q'$	0.667	0.675
$W^- \rightarrow \ell^-\bar{\nu}_\ell$	0.333	0.325

Event topologies determined by BR products:

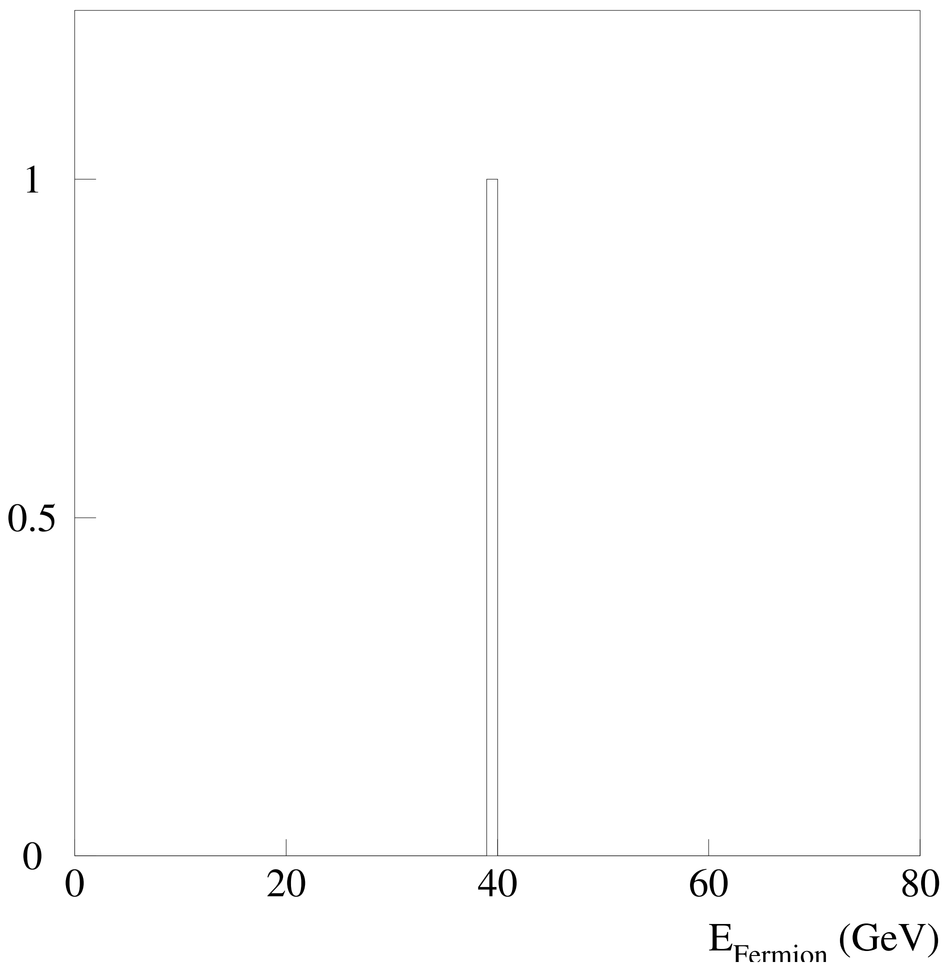
Topology	B.R. Product	Remarks
$WW \rightarrow qqqq$	0.456	Plentiful but high bkgd.
$WW \rightarrow qqe\nu$	0.146	Scarce but clean
$WW \rightarrow qq\mu\nu$	0.146	Scarce but clean
$WW \rightarrow qq\tau\nu$	0.146	Scarce and tricky
$WW \rightarrow \ell\bar{\nu}\ell\nu$	0.105	Scarce but clean, uncertain kinematics

Will concentrate on $WW \rightarrow qq\mu\bar{\nu}_\mu$ channel (A. Button)

W^+W^- Production

Naive expectation at threshold

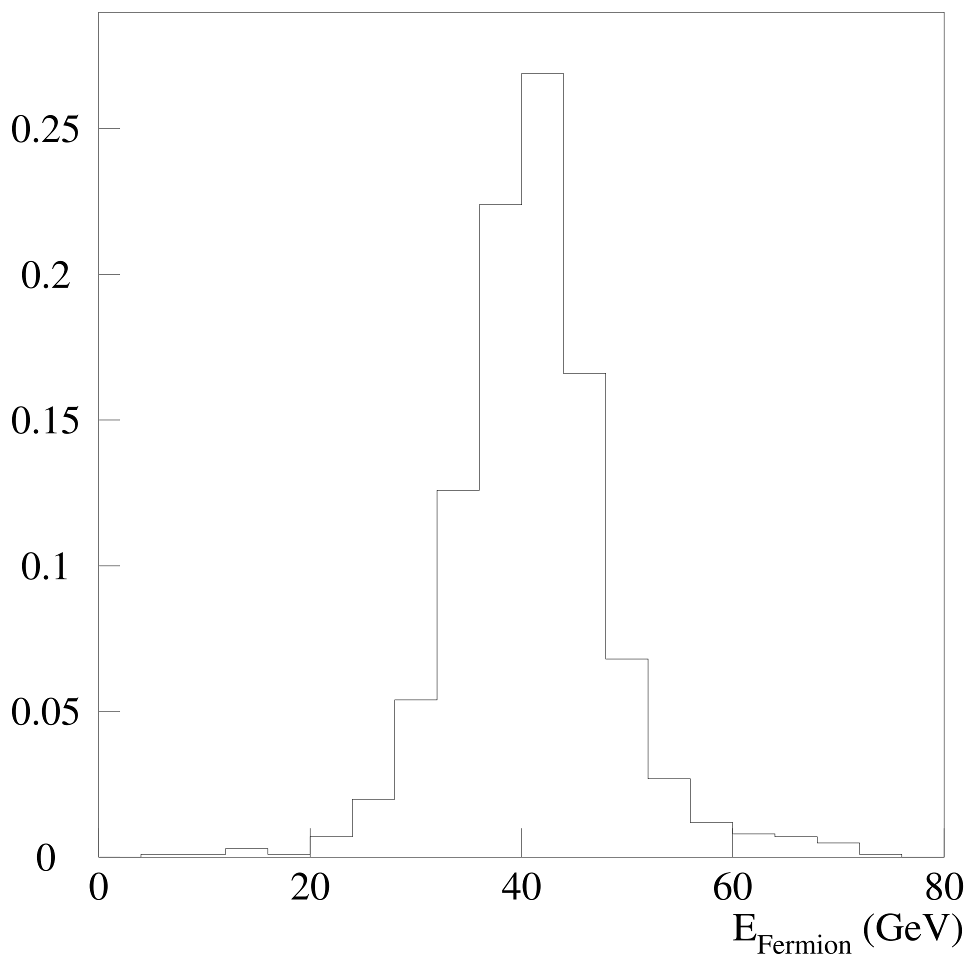
- Two W's produced at rest
- Each W decays to two fermions
- Each fermion has energy $E_f = E_{\mathrm{BEAM}}/2 \approx 40$ GeV:



W^+W^- Production

Reality

- $\Gamma_W \neq 0 \quad \Longrightarrow \quad M_W \neq 80$ GeV
- Phase space suppression distorts M_W distribution
- Hadronic W decays produce quarks and gluons
- Resulting fermion energy not at all monochromatic:



W^+W^- Production

Selecting $e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}'\mu\nu$ Candidates

Require:

- Isolated high-energy muon
- Two hadronic jets with large jet-jet invariant mass
- Missing energy/momentum (not along beam axis)
- Large $\mu - \nu$ invariant mass

$\Longrightarrow$ Efficiency $\approx 75\%$

$\Longrightarrow$ Background $\approx 5\%$

For summer 1996 run, expected 4.4 events

(M_W = 80.3 GeV)

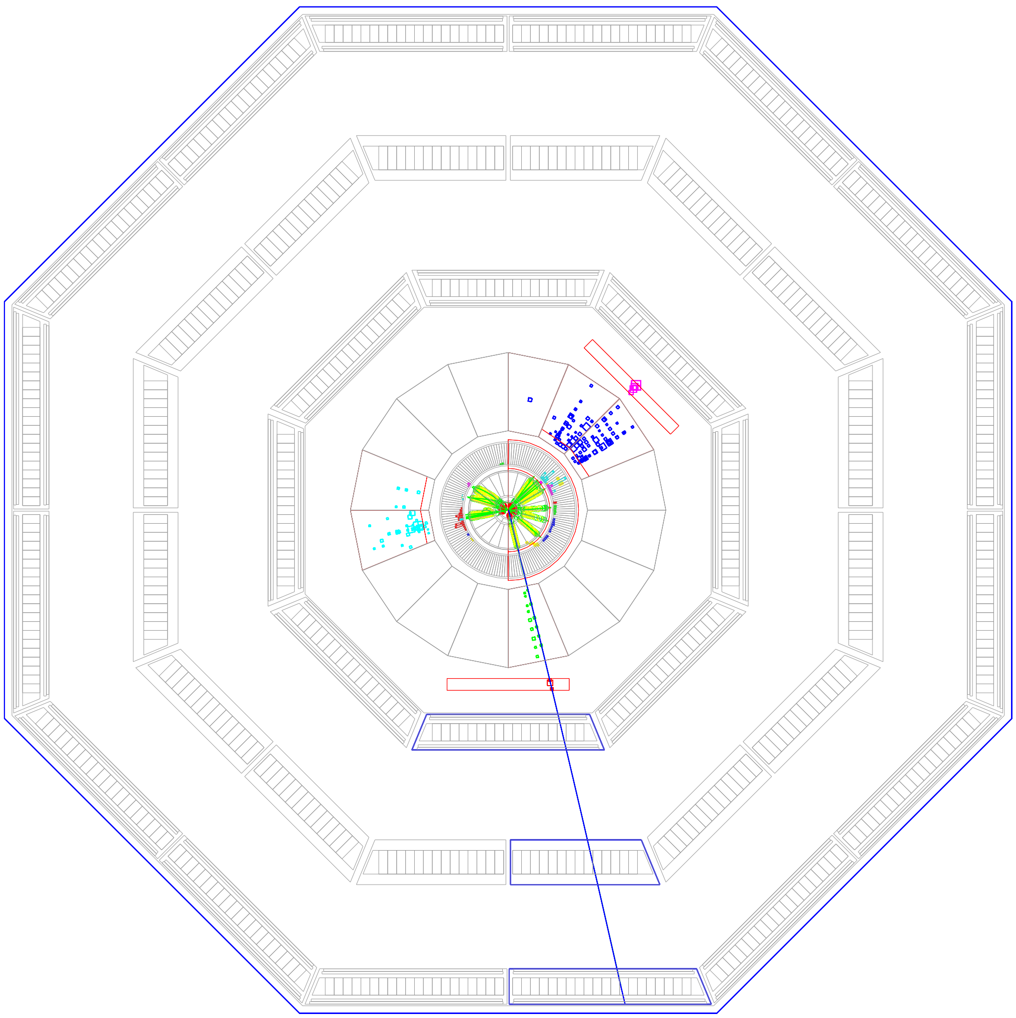
$\boxed{\text{Observed 4 candidates}}$

W^+W^- Production

CANDIDATE EVENT

The Big Picture:

Run # **660808** **Event #** **5034** Total Energy : 135.88 GeV

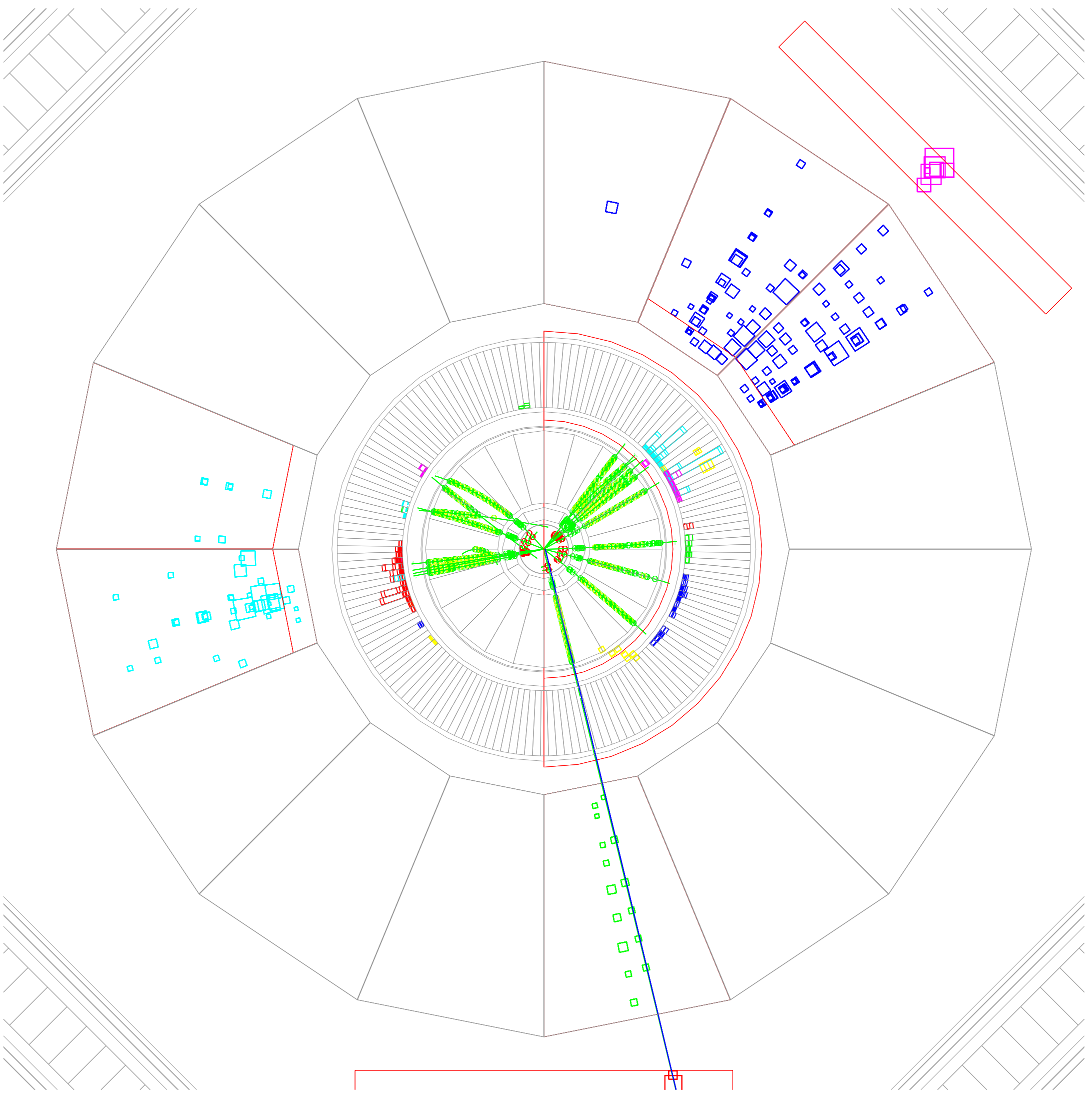


Transverse Imbalance :	.2433		**Longitudinal Imbalance :**	-.1338	
Thrust :	.7510	**Major :**	.5850	**Minor :**	.0467
Event DAQ Time :	*960810 20747*				

CANDIDATE EVENT

Zooming In:

Run # **660808** **Event #** **5034** Total Energy : 135.88 GeV



Transverse Imbalance :	.2433	**Longitudinal Imbalance :**	-.1338

Thrust :	.7510	**Major :**	.5850	**Minor :**	.0467
Event DAQ Time :	*960810 20747*				

e- ⇒ ✸ ⇐ e+

W^+W^- Production

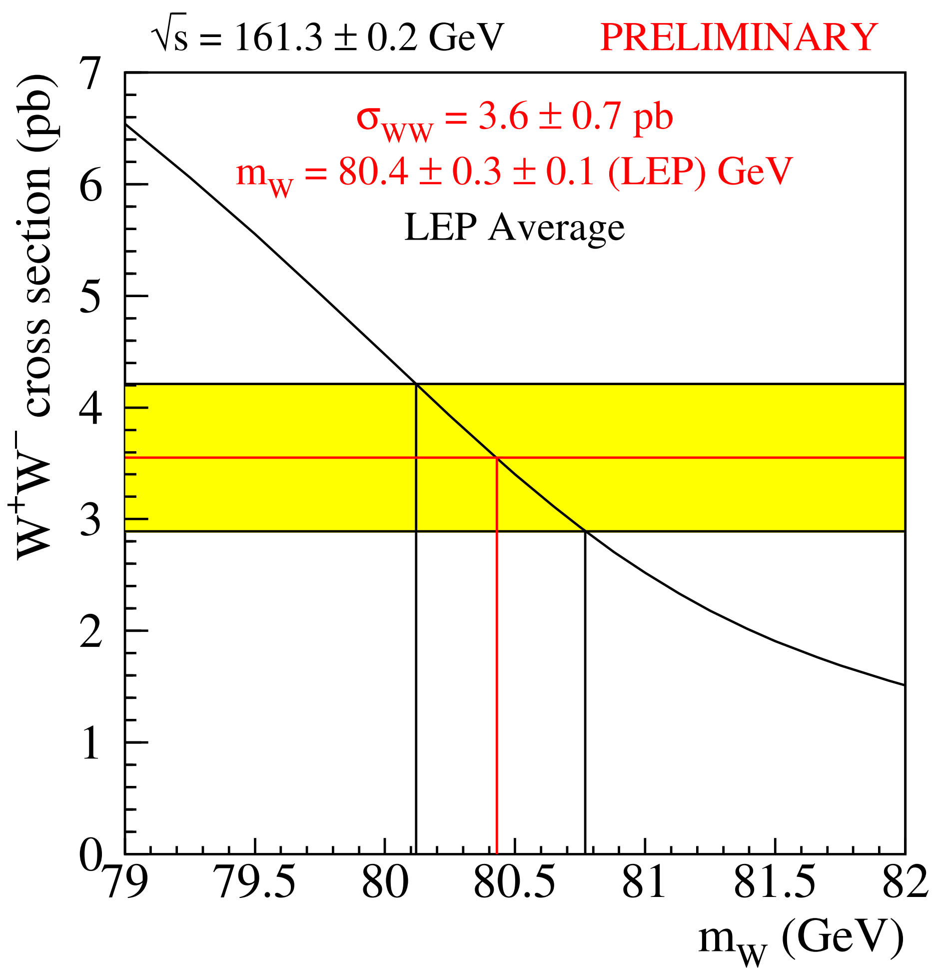
Analysis of other WW channels not quite final

$\Longrightarrow$ Not yet allowed to quote latest numbers

But CAN show preliminary results released for summer conferences (smaller data sample)

$$\sigma_{WW}^{\text{L3}} = 2.9 \pm 1.1 \text{ pb}$$

Combining with other LEP experiments:



$\mathbf{W^+W^-}$ Production

The Future

Rest of this year

- Finalize + publish summer measurements
- Run in the fall at 172 GeV
  - Higher $\sigma_{WW} \quad \Longrightarrow \quad$ More W events
  - First test of W lineshape consistency
  - Can start direct M_W reconstruction

Through end of 1999

- Expect 500 pb^{-1} at $E_{\mathrm{CM}} \leq 195$ GeV
- Hope to reach $\Delta M_W \approx 50$ MeV

Future of e^+e^- Collisions

LEP II

- Steady reduction of ΔM_W
- Measure $WWZ/WW\gamma$ couplings to $O(10\%)$
- Measure fundamental cross sections:

$e^+e^- \to q\bar{q}$	$e^+e^- \to \ell^+\ell^-$
$e^+e^- \to \nu\bar{\nu}(\gamma)$	$e^+e^- \to ZZ$
$e^+e^- \to \gamma\gamma$	$e^+e^- \to Z\gamma$
$e^+e^- \to f_1\bar{f}_2 f_3\bar{f}_4$	

- QCD tests – Measure α_s
- Search for new physics:
  - Higgs (MSM, MSSM)
  - Supersymmetry
  - New heavy fermions
  - New gauge bosons

Future of e^+e^- Collisions

Next Linear Collider (NLC)

Planning underway for very high energy e^+e^- collider

$$E_{\mathrm{CM}} \quad \geq \quad 500 \text{ GeV}$$

Competing (but also collaborative) efforts in

U.S.A.

Japan

Germany

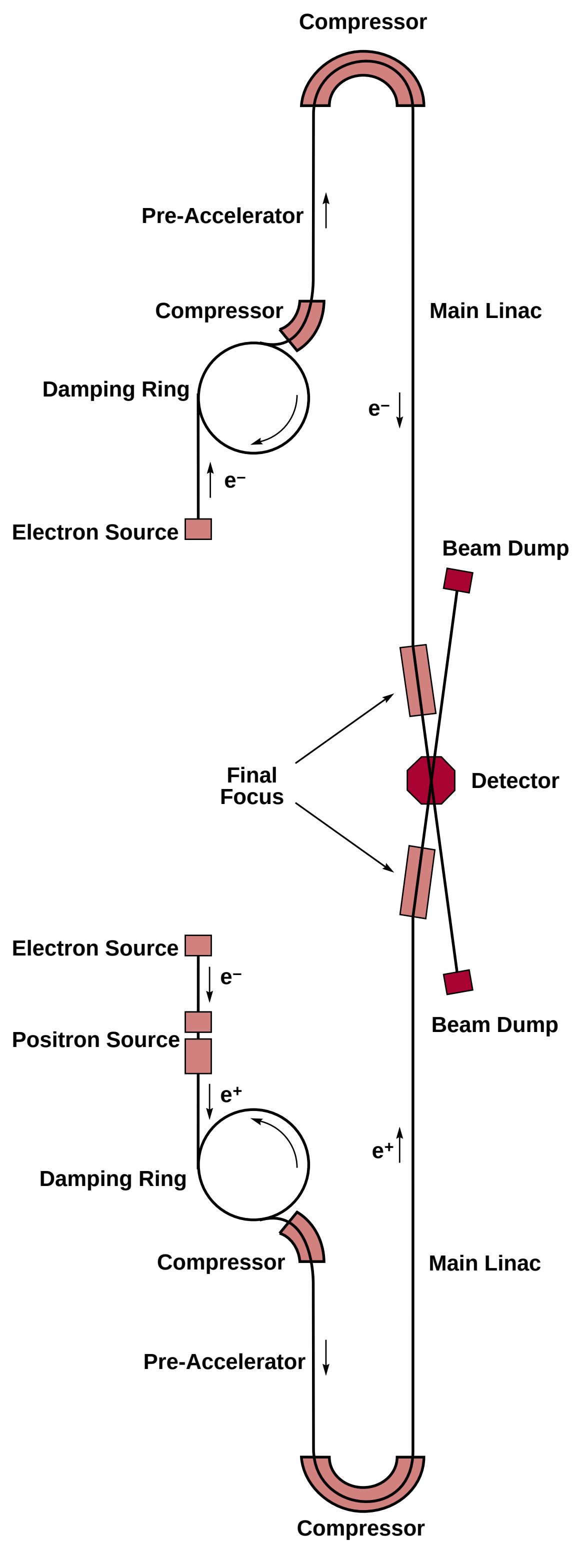
Switzerland

Russia

U.S. R & D effort centered at SLAC

- Three-stage concept:
  - Turn on with $\sqrt{s} = 500$ GeV
  - Increase $\sqrt{s}$ "adiabatically" to 1 TeV (more/better klystrons)
  - Lengthen machine to achieve 1.5 TeV

Layout of NLC



Future of e^+e^- Collisions

Physics at the NLC – A Sampling

Higgs

- Find it (if still missing)
- Measure Higgs properties with precision
- Distinguish SM Higgs from Supersymmetric Higgs (SUSY guarantees $\geq$1 Higgs visible at NLC)

Supersymmetry

- Gauginos / sleptons very likely visible
- Squarks also possible
- Can disentangle sparticle masses / couplings

Future of e^+e^- Collisions

Physics at the NLC

Top Quark

- $\approx$10K very clean $t\bar{t}$ events / year
- Precise M_t, Γ_t measurements
- Precise neutral-current, Yukawa couplings

W Physics

- Precise M_W
- Precise anomalous non-Abelian couplings
- Strong WW scattering
  $\Longrightarrow$ Probes Electroweak Unification
  $\Longrightarrow$ Higgs or no Higgs

NLC would be a wonderful machine!

Who will build it?