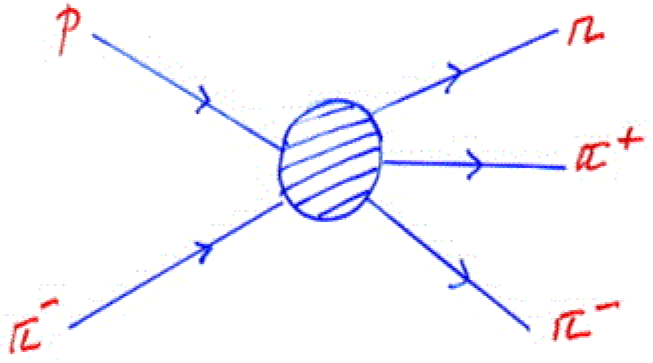
Is it a Real Signal?

Bob Orr

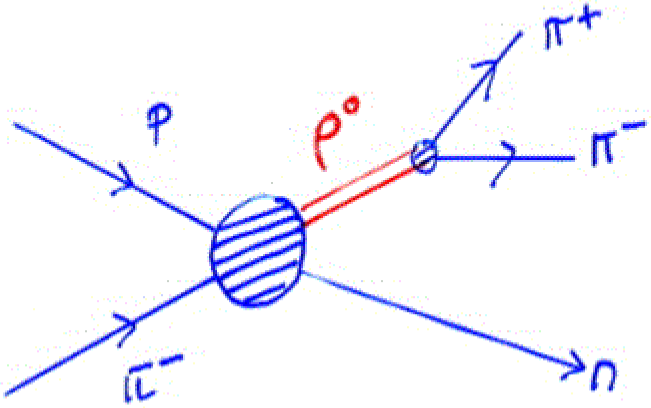
- Some real signals that established the Standard Model
- A Famous Fake
- What is “Look Elsewhere”?



NO INTERMEDIATE STATE

ENERGY + MOMENTUM SHARED BETWEEN $\pi^+ \pi^- n$ IN RANDOM STATISTICAL FASHION

"PHASE SPACE"



IF INTERMEDIATE STATE

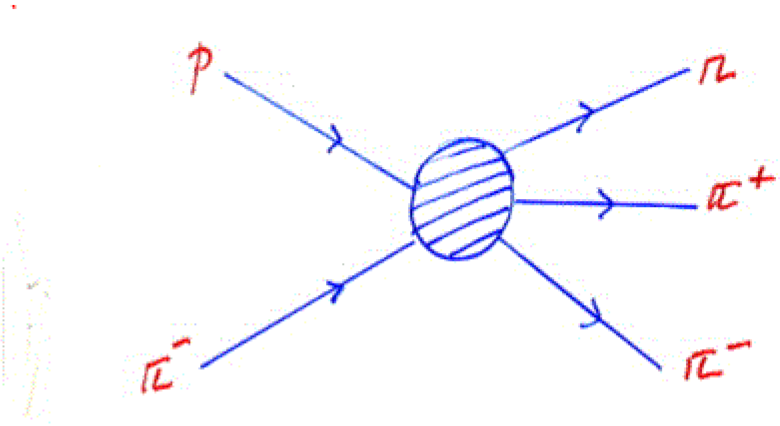
$$E_\rho = E_{\pi^+} + E_{\pi^-}$$

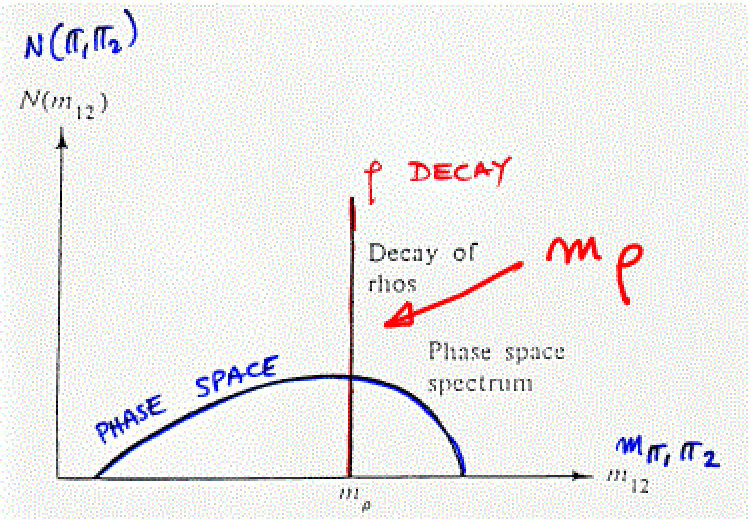
$$\bar{p}_\rho = \bar{p}_{\pi^+} + \bar{p}_{\pi^-}$$

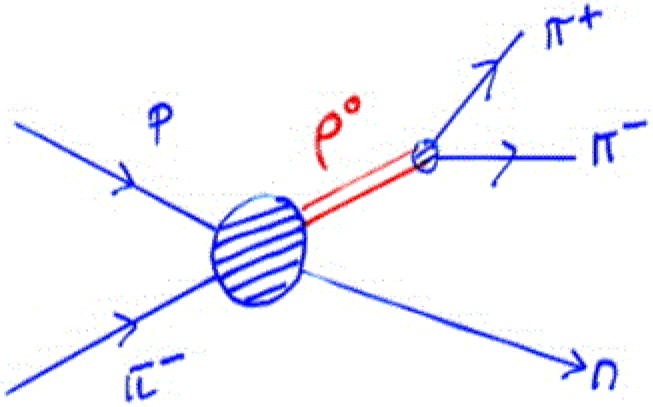
$$m_\rho^2 = \left[E_\rho^2 - \bar{p}_\rho^2\right]$$

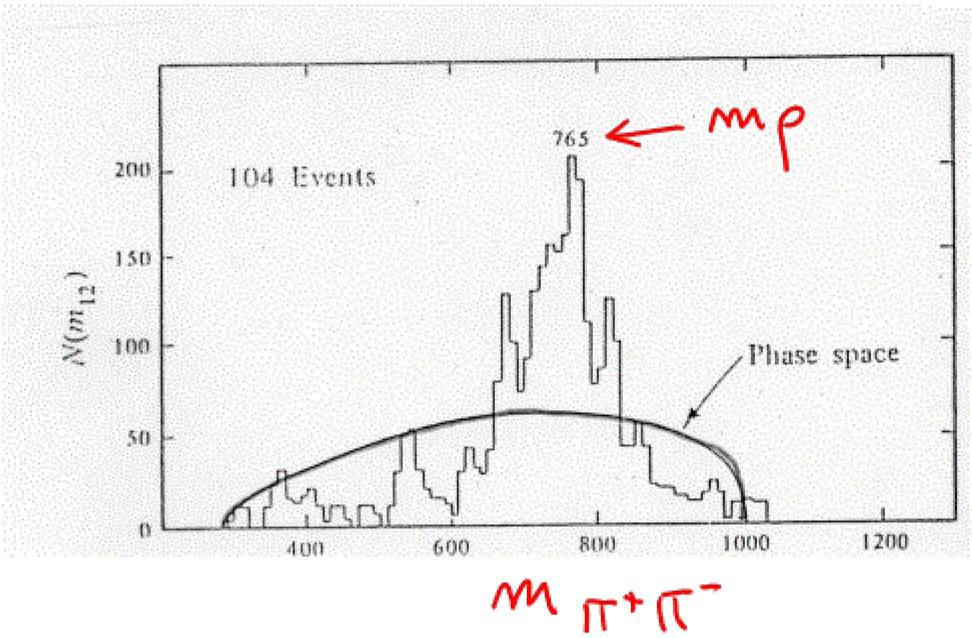
$$= \left[(E_{\pi^+} + E_{\pi^-})^2 - (\bar{p}_{\pi^+} + \bar{p}_{\pi^-})^2\right]$$

MASS OF ρ^0 = INVARIANT MASS OF DAUGHTER π PAIR


p
π−
n
π+
π−

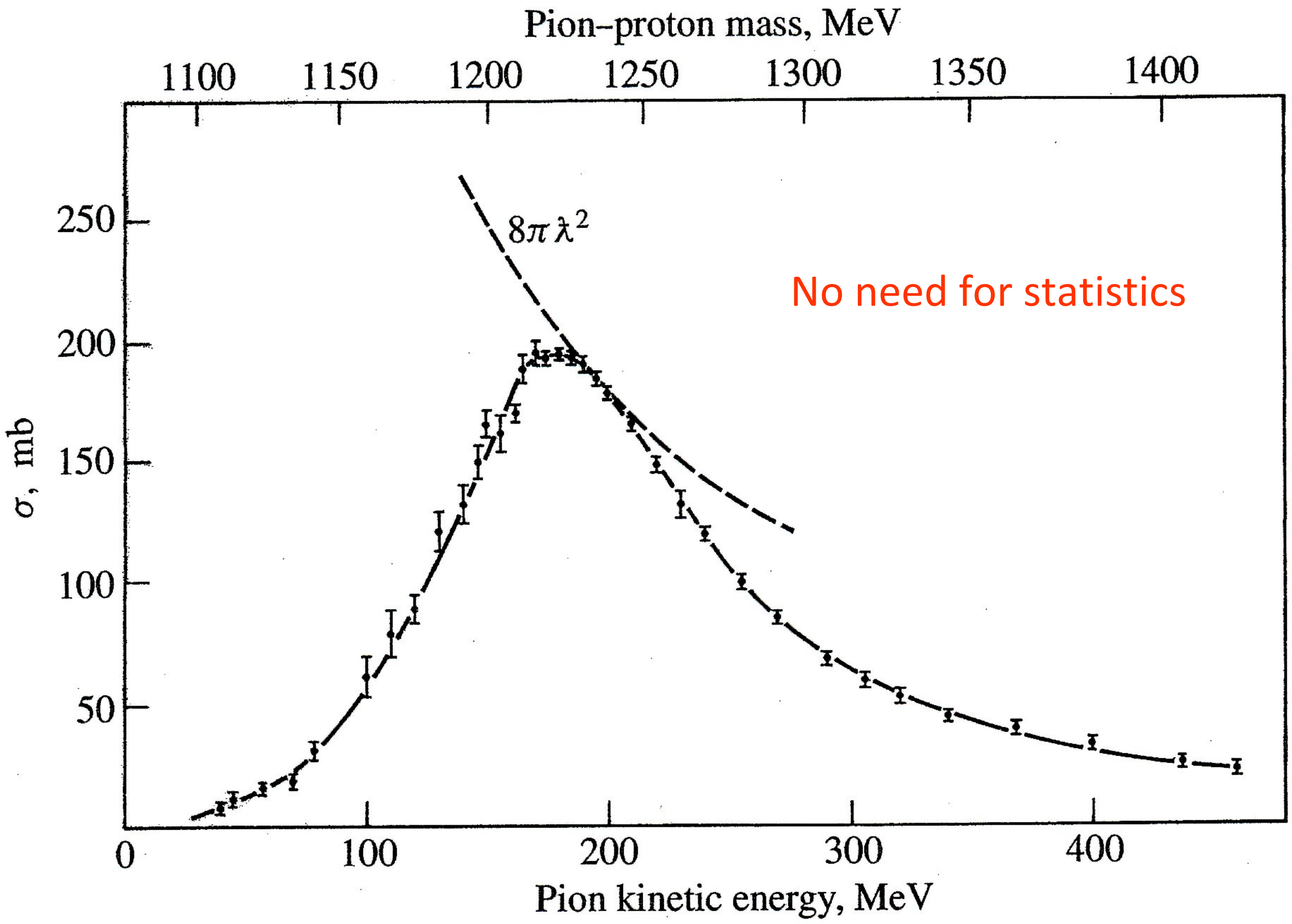

N(π1,π2)
N(m12)
ρ DECAY
Decay of rhos
mρ
Phase space spectrum
PHASE SPACE
mπ1π2
m12
mρ


p
ρ°
π+
π−
π−
n


765
mρ
104 Events
200
150
100
50
0
N(m12)
Phase space
400
600
800
1000
1200
mπ+π−

Fermi Discovers the Quark Model

$$\Delta^{++} = (uuu)$$



No need for statistics

EVIDENCE FOR A π-π RESONANCE IN THE $I=1$, $J=1$ STATE*

A. R. Erwin, R. March, W. D. Walker, and E. West
Brookhaven National Laboratory, Upton, New York and University of Wisconsin, Madison, Wisconsin
(Received May 11, 1961)

Quark Model

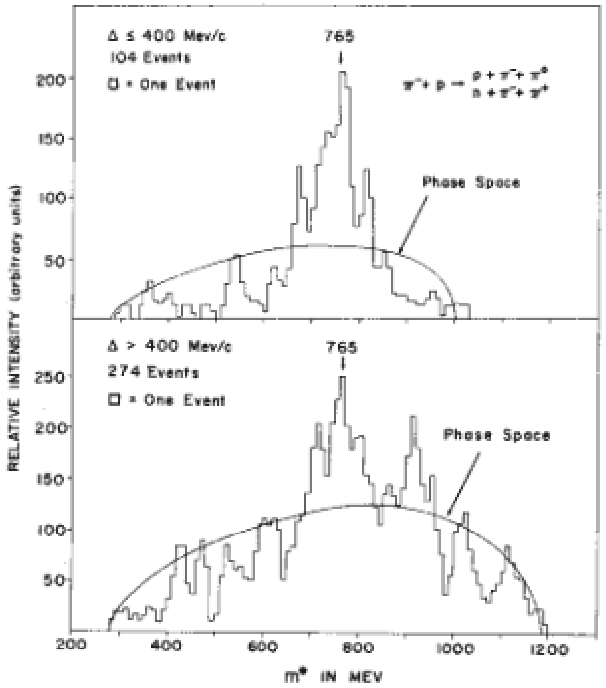


FIG. 2. The combined mass spectrum for the $\pi^-\pi^0$ and $\pi^-\pi^+$ system. The smooth curve is phase space as modified for the included momentum transfer and normalized to the number of events plotted. Events used in the upper distribution are not contained in the lower distribution.

$$\rho^- = (d\bar{u})$$

No need for statistics

$$\rho^0 = (u\bar{u})$$

Quark Model

EVIDENCE FOR A $T = 0$ THREE-PION RESONANCE*

B. C. Maglić, L. W. Alvarez, A. H. Rosenfeld, and M. L. Stevenson
Lawrence Radiation Laboratory and Department of Physics, University of California, Berkeley, California

(Received August 14, 1961)

The existence of a heavy neutral meson with $T = 0$ and $J = 1^-$ was predicted by Nambu[1] in an attempt to explain the electromagnetic form factors of the proton and neutron. Chew[2] has pointed out

$$|Q| = 0: \ \pi^+\pi^-\pi^0 \ (800\times 4 \text{ combinations}), \qquad (4)$$

$$|Q| = 1: \ \pi^\pm\pi^\pm\pi^\pm \ (800\times 4 \text{ combinations}), \qquad (4')$$

and

The χ^2 distribution of the events in the "peak region" was compared with the χ^2 distribution of the events in the adjacent "control region," ranging from $M_3 \geq 820$ to $M_3 < 900$ Mev. These distributions agree with each other, which indicates that the events in the peak are genuine, rather

No need for statistics

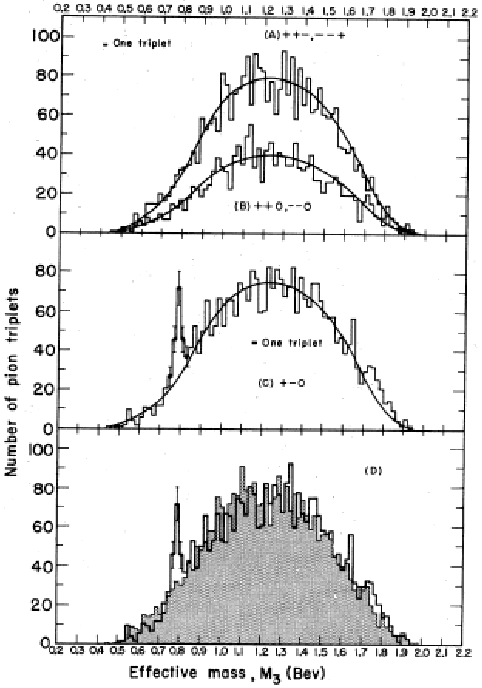


FIG. 1. Number of pion triplets versus effective mass (M_3) of the triplets for reaction $\bar{p}+p \rightarrow 2\pi^+ + 2\pi^- + \pi^0$. (A) is the distribution for the combination (4′), $|Q| = 1$; (B) is for the combination (4″), $|Q| = 2$; and (C) for (4), $Q = 0$, with 3200, 1600, and 3200 triplets, respectively. Full width of one interval is 20 Mev. In (D), the combined distributions (A) and (B) (shaded area) are contrasted with distribution (C) (heavy line).

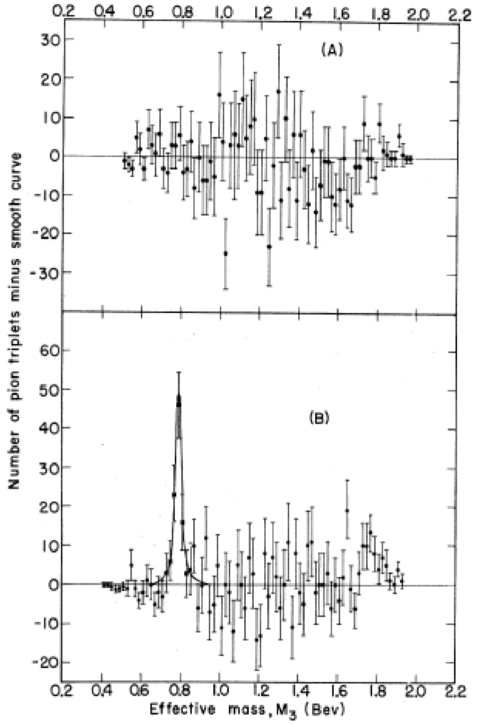


FIG. 2. (A) M_3 spectrum of the pion triplets in the combined distributions 1(A) and 1(B), with the smooth curve subtracted. (B) M_3 spectrum of the neutral pion triplets in distribution 1(C), again with the smooth background subtracted; a resonance curve is drawn through the peak at 787 Mev with $\Gamma/2 = 15$ Mev. The error flags are $\sqrt{N}$, where N is the total number of triplets per 20-Mev interval before subtraction of the smooth background curve.

Volume 33, Number 23 PHYSICAL REVIEW LETTERS 2 December 1974

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhage
J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technolc
Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

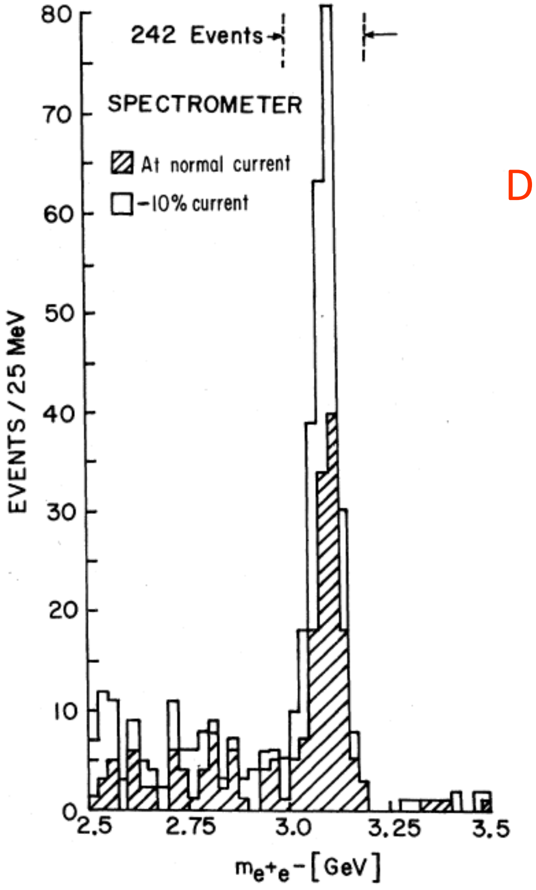


FIG. 2. Mass spectrum showing the existence of J. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

Discovery of Charm Quark

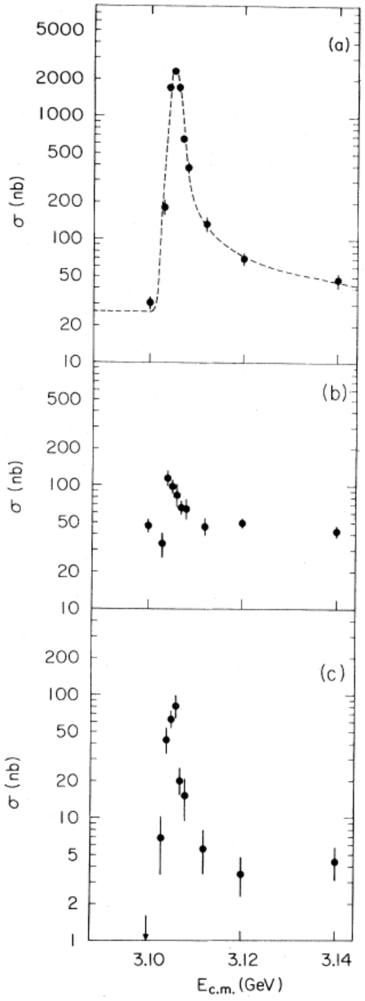
$$J/\psi = (c\bar{c})$$

No need for statistics

Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman,
G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth,
H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl,
B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum,
and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

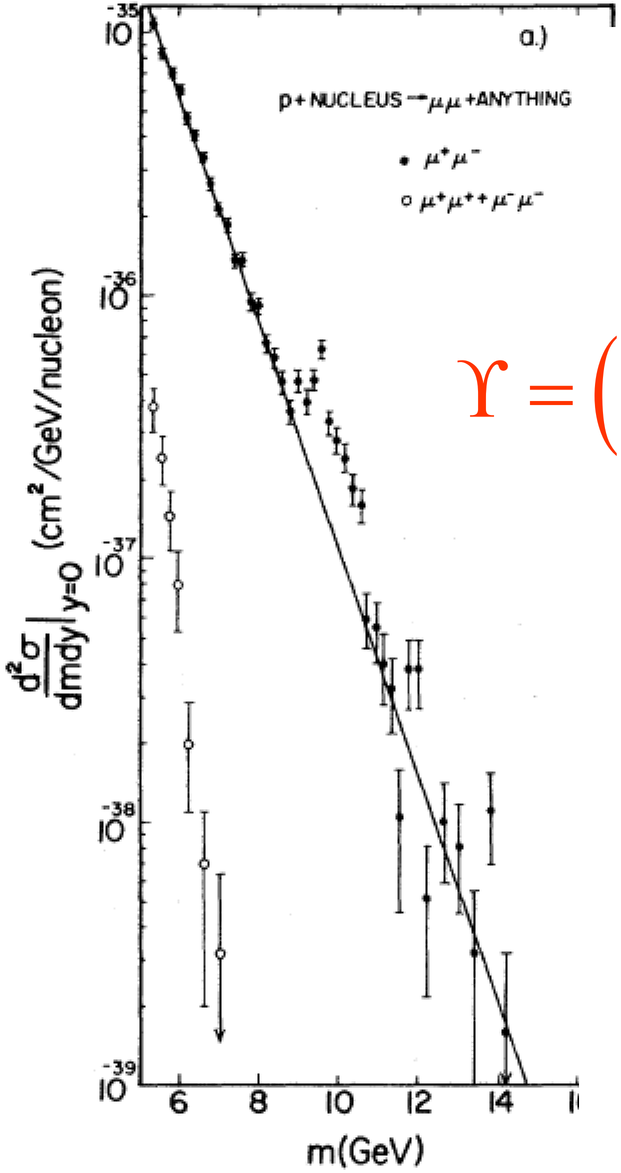
G. S. Abrams, D. Briggs, W. Chinowsky, C
J. A. Kadyk, B. Lulu, F. Pierr
J. Wiss, a
Lawrence Berkeley Laboratory and Department of Phy
(Received 13



IG. 1. Cross section versus energy for (a) multi-
ron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$,
$^-$, and K^+K^- final states. The curve in (a) is the ex-
ted shape of a δ-function resonance folded with the
ssian energy spread of the beams and including

Discovery of Bottom Quark

(1) A statistically significant enhancement is observed at 9.5-GeV $\mu^+\mu^-$ mass.



$$\Upsilon = \left(b\bar{b}\right)$$

What do they mean by significant?

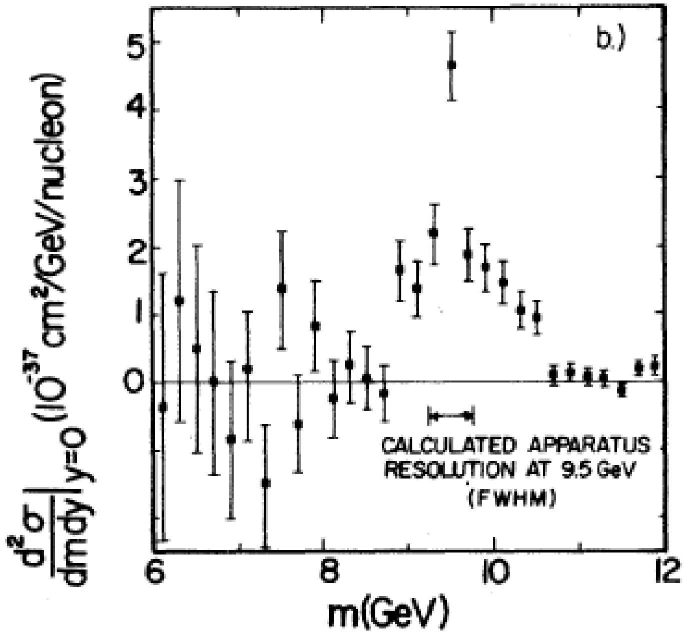


FIG. 3. (a) Measured dimuon production cross sections as a function of the invariant mass of the muon pair. The solid line is the continuum fit outlined in the text. The equal-sign–dimuon cross section is also shown. (b) The same cross sections as in (a) with the smooth exponential continuum fit subtracted in order to reveal the 9–10-GeV region in more detail.

Observation of Top Quark Production in $\bar{p}p$ Collisions with the Collider Detector at Fermilab

proximately 30% $t\bar{t}$ signal and 70% W + jets background. The Monte Carlo background shape agrees well with that meaured in a limited-statistics sample of Z + 4-jet events

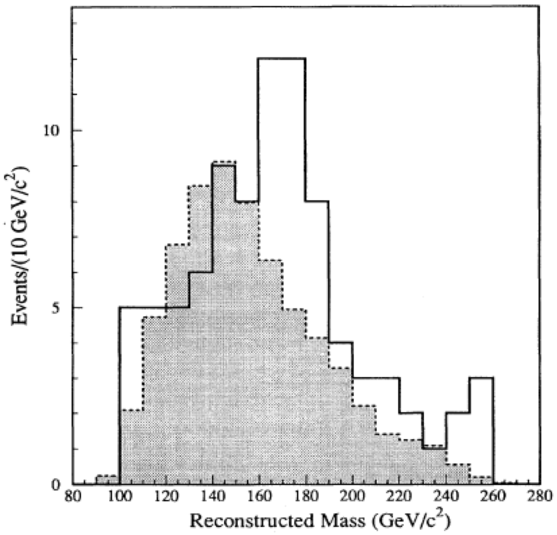


FIG. 2. Reconstructed mass distribution for the $W+ \geq 4$-jet sample prior to b tagging (solid). Also shown is the background distribution (shaded) with the normalization constrained to the calculated value.

distribution. After including systematic effects in the predicted background shape, we find a 2×10^{-2} probability that the observed mass distribution is consistent with the background (Kolmogorov-Smirnov test). This is a con-

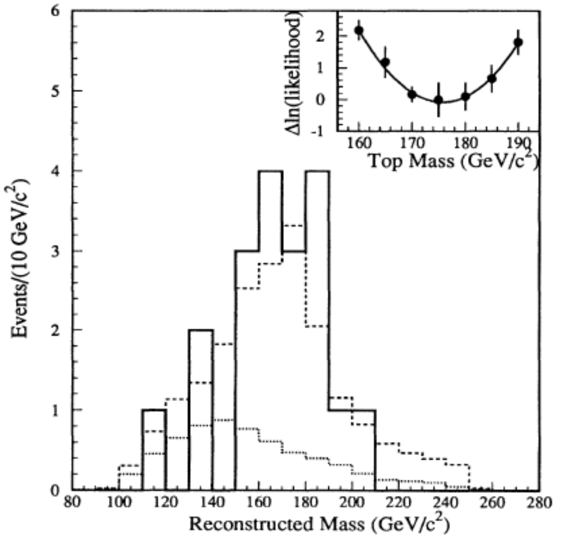


FIG. 3. Reconstructed mass distribution for the b-tagged $W+ \geq 4$-jet events (solid). Also shown are the background shape (dotted) and the sum of background plus $t\bar{t}$ Monte Carlo simulations for $M_{\text{top}} = 175\ \text{GeV}/c^2$ (dashed), with the background constrained to the calculated value, $6.9^{+2.5}_{-1.9}$ events. The inset shows the likelihood fit used to determine the top mass.

evidence presented in Ref. [1]. There is now a large excess in the signal that is inconsistent with the background prediction by 4.8σ, and a mass distribution with a 2×10^{-2} probability of being consistent with the background shape. When combined, the signal size and mass distribution have a 3.7×10^{-7} probability of satisfying the background hypothesis (5.0σ). In addition, a substantial fraction of the jets in the dilepton events are b tagged. This establishes the existence of the top quark. The

Discovery of W

EXPERIMENTAL OBSERVATION OF ISOLATED LARGE TRANSVERSE ENERGY ELECTRONS WITH ASSOCIATED MISSING ENERGY AT $\sqrt{s}$ = 540 GeV

UA1 Collaboration, CERN, Geneva, Switzerland

In conclusion, we have been unable to find a background process capable of simulating the observed high-energy electrons. Thus we are led to the conclusion that they are electrons. Likewise we have searched for backgrounds capable of simulating large-E_T neutrino events. Again, none of the processes considered appear to be even near to becoming competitive.

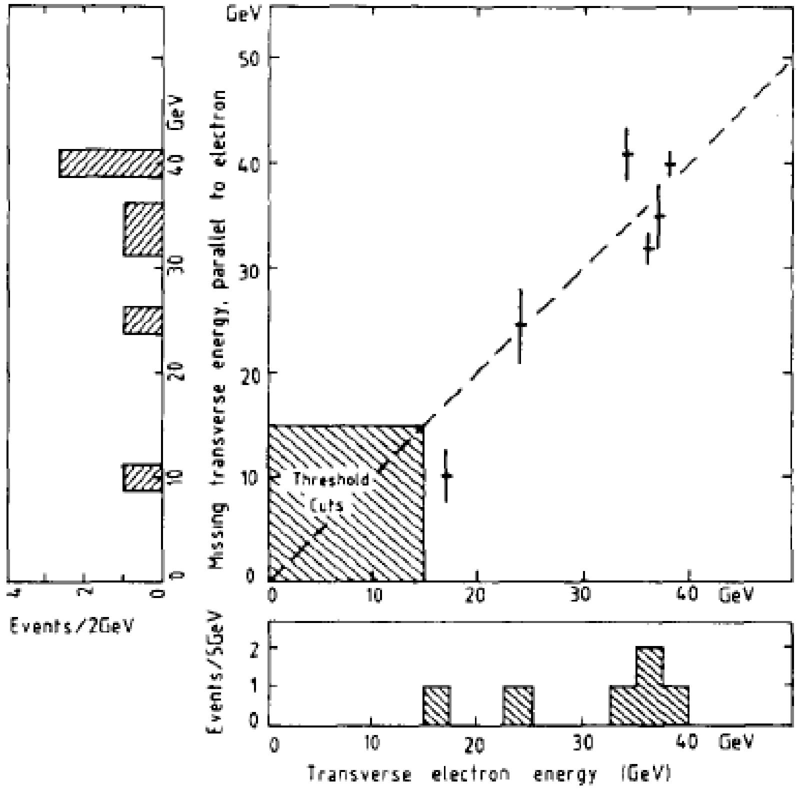
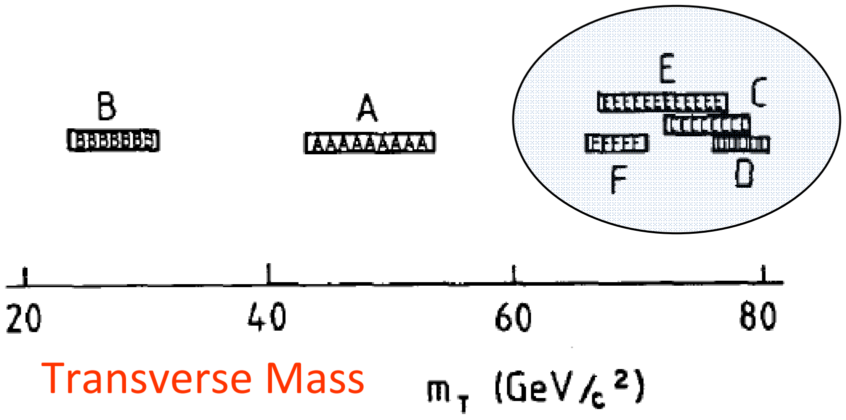


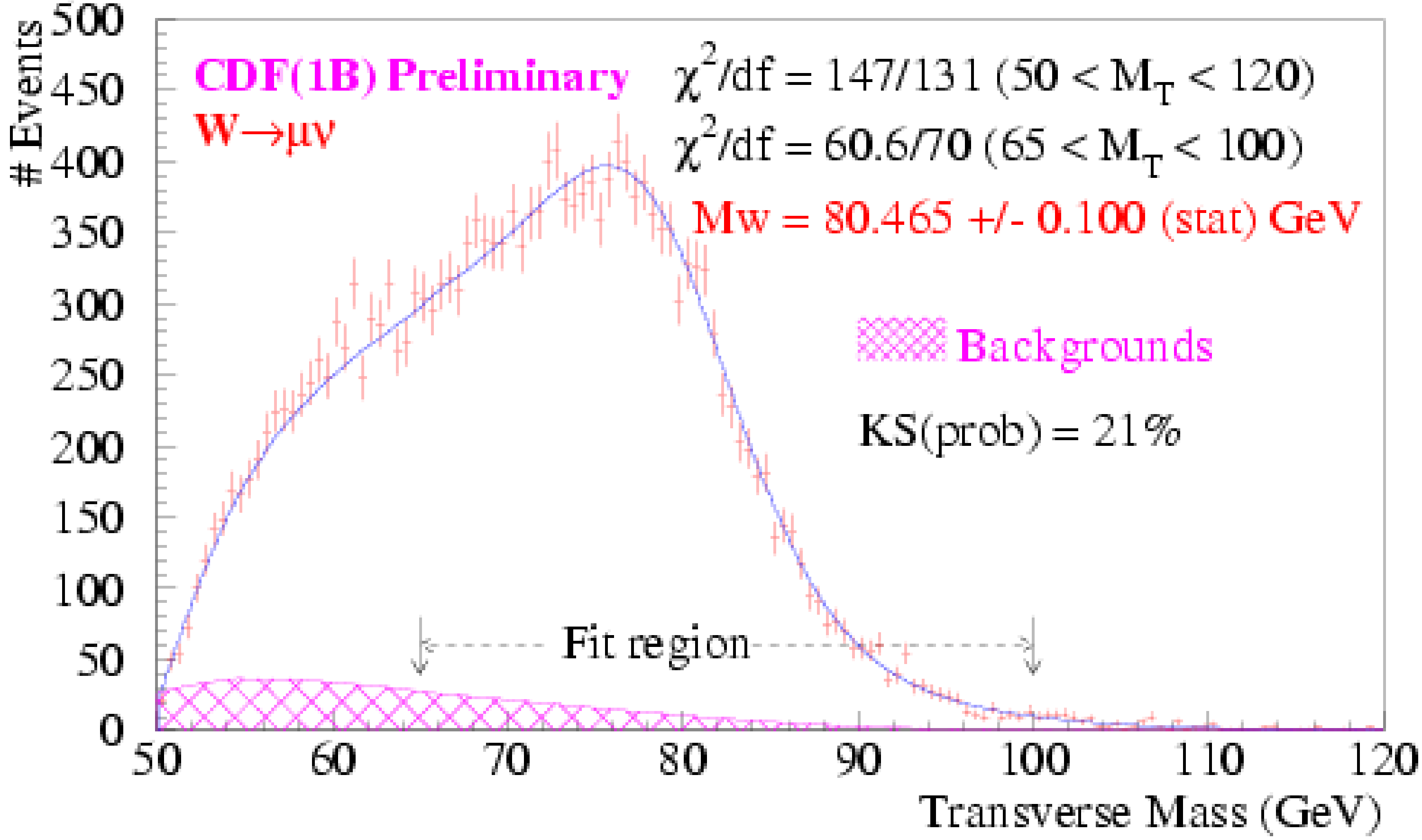
Fig. 8. The missing transverse energy component parallel to the electron, plotted versus the transverse electron energy for the final six electron events without jets (5 gondolas, 1 bouchon)

Volume 122B, number 1 PHYSICS LI



Transverse Mass

Fig. 9. The distribution of the transverse mass derived from the measured electron and neutrino vectors of the six electron events.


CDF(1B) Preliminary
W→μν
χ²/df = 147/131 (50 < M_T < 120)
χ²/df = 60.6/70 (65 < M_T < 100)
Mw = 80.465 +/- 0.100 (stat) GeV
Backgrounds
KS(prob) = 21%
Fit region
Events
500
450
400
350
300
250
200
150
100
50
0
50
60
70
80
90
100
110
120
Transverse Mass (GeV)

EXPERIMENTAL OBSERVATION OF LEPTON PAIRS OF INVARIANT MASS AROUND 95 GeV/c^2 AT THE CERN SPS COLLIDER

UA1 Collaboration, CERN, Geneva, Switzerland

Discovery of Z

of the events is their common value of the invariant mass (fig. 8); values agree within a few percent and with expectations from experimental resolution. Detection efficiency is determined by the energy thresholds in the track selection, 15 GeV/c for $e^{\pm}$ and 7 GeV/c for $\mu^{\pm}$. Most "trivial" sources of background are not expected to exhibit such a clustering at high masses.

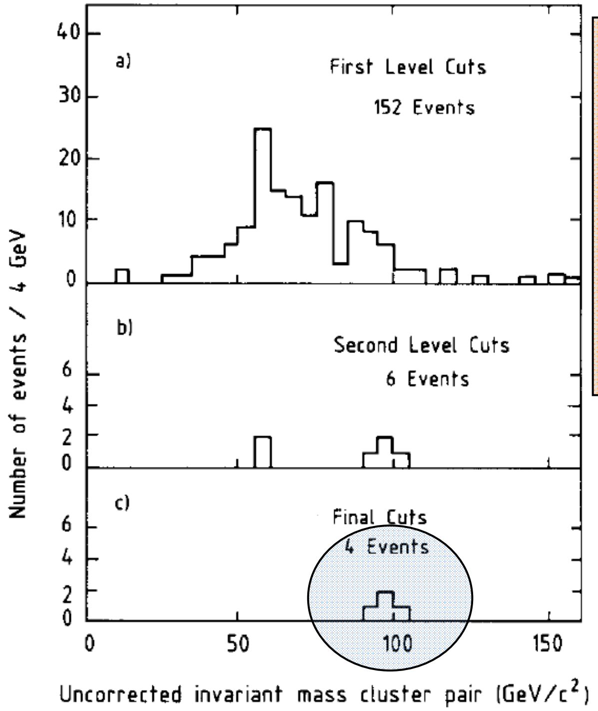


Fig. 1. Invariant mass distribution (uncorrected) of two electromagnetic clusters: (a) with $E_T > 25$ GeV; (b) as above and a track with $p_T > 7$ GeV/c and projected length >40 cm pointing to the cluster. In addition, a small energy deposition in the hadron calorimeters immediately behind (<0.8 GeV) ensures the electron signature. Isolation is required with $\Sigma\, p_T < 3$ GeV/c for all other tracks pointing to the cluster. (c) The second cluster also has an isolated track.

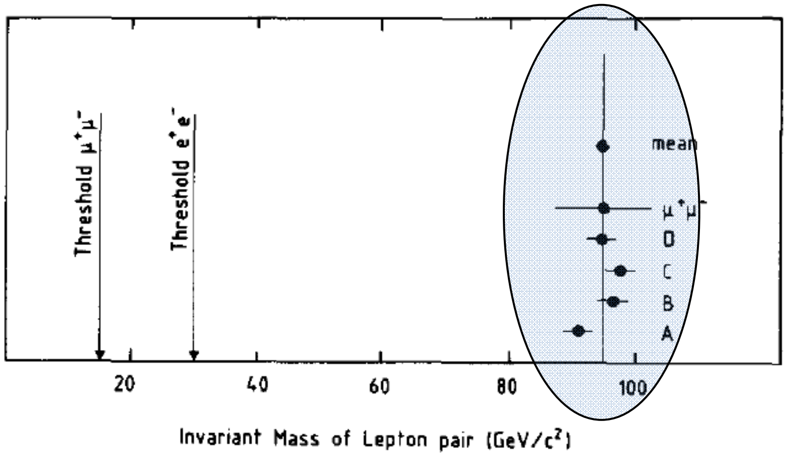
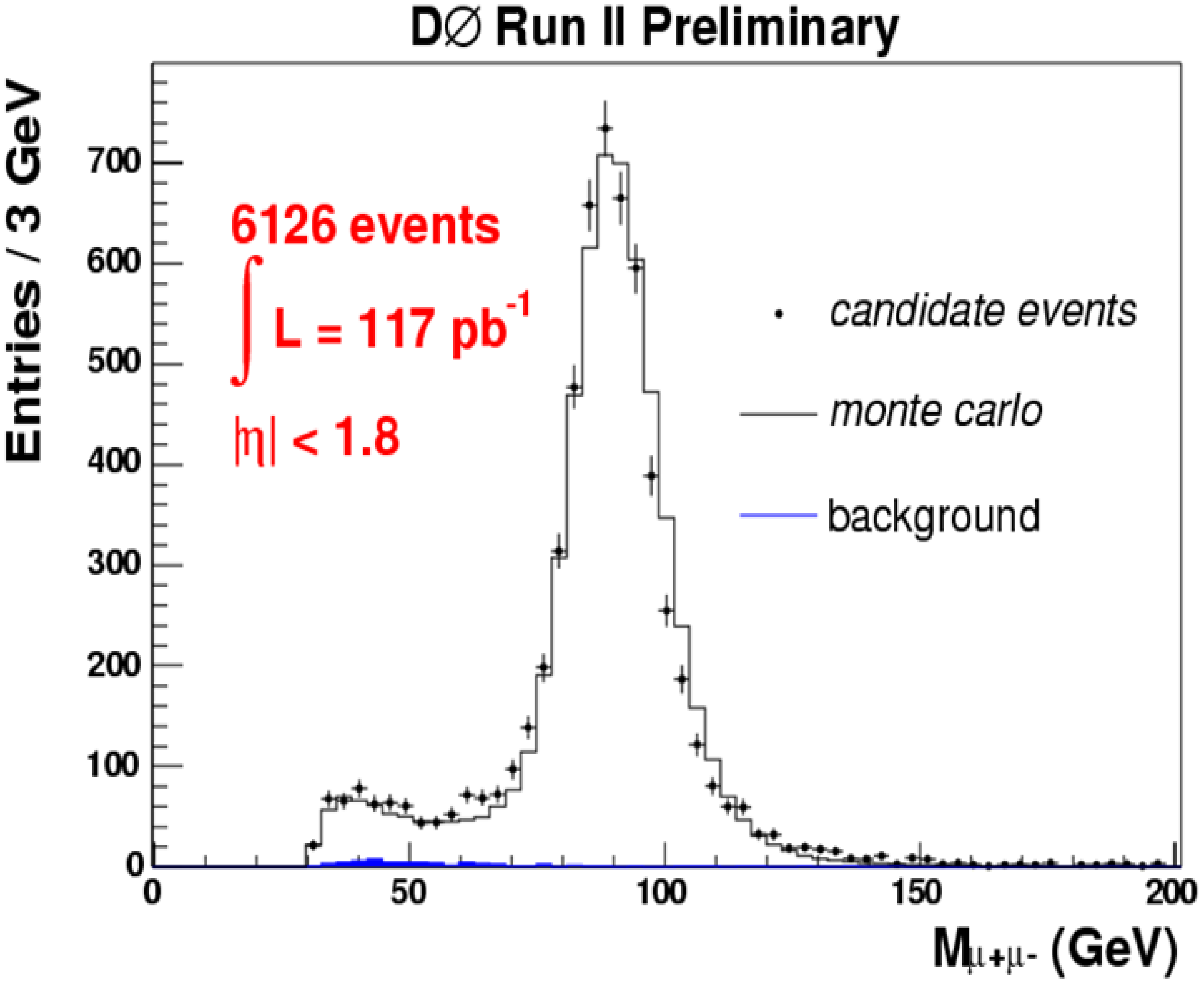
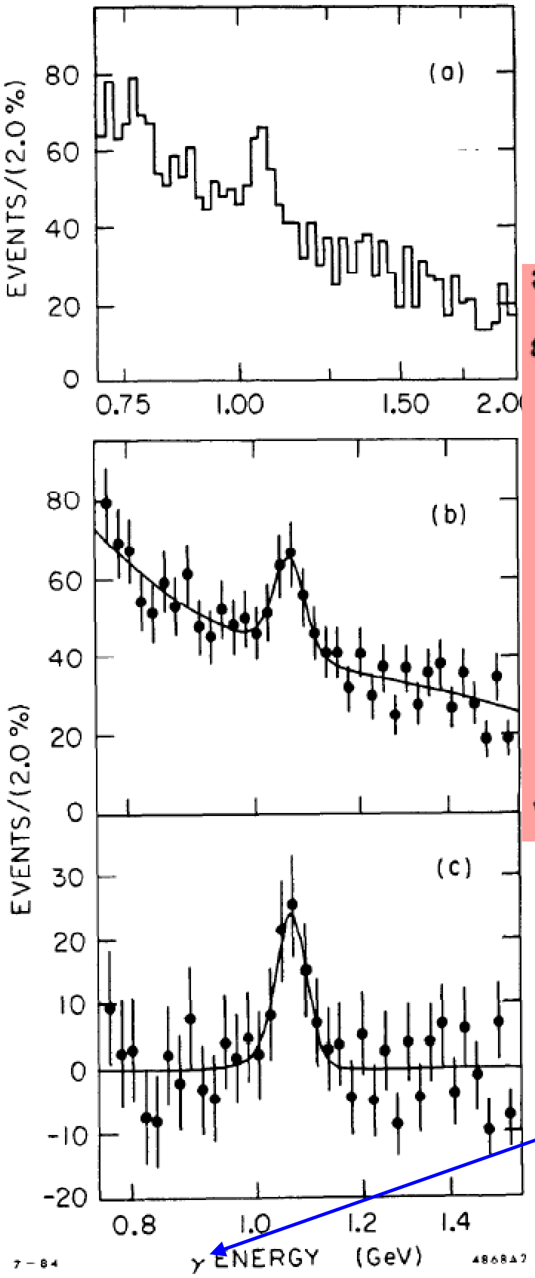


Fig. 8. Invariant masses of lepton pairs.

DØ Run II Preliminary
Entries / 3 GeV
0
100
200
300
400
500
600
700
0
50
100
150
200
$M_{\mu+\mu-}$ (GeV)
6126 events
$\int L = 117\ pb^{-1}$
$|\eta| < 1.8$
candidate events
monte carlo
background



Evidence for a Narrow Massive State in the Radiative Decays of the Upsilon* July 1984 (T/E)

Crystal Ball Collaboration

above (see Fig. 2b) now yields a significance of 4.2 standard deviations for the signal. The signal-parameters become

$$E_\gamma = (1072 \pm 8 \pm 21)\ \mathrm{MeV}$$
$$M = (8319 \pm 10 \pm 24)\ \mathrm{MeV}$$
$$\text{Counts} = 87.1 \pm 20.5 \tag{1}$$
$$\chi^2 = 24.8 \text{ for 32 degrees of freedom,}$$

where the first error in E_γ or M is systematical and the second is systematic.(6)

$$\Upsilon(1S) \rightarrow \gamma H^0$$

Is the Higgs mass 8.3 GeV ???

At 4.2 sigma???

Volume 154B, number 5,6 PHYSICS LETTERS 9 May 1985

SEARCH FOR NARROW STATES COUPLING TO τ PAIRS IN RADIATIVE Υ DECAYS

The ARGUS Collaboration

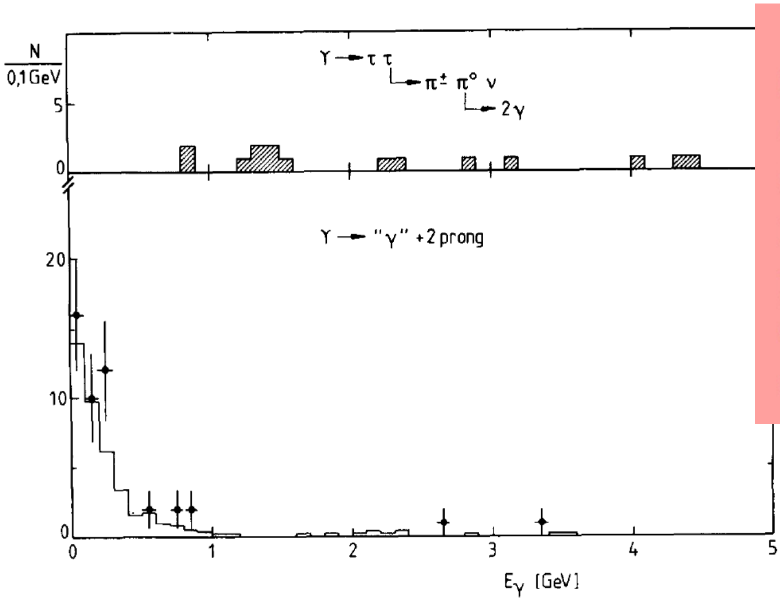


Fig. 3. Photon spectrum from the decay $\Upsilon \to \gamma$ + two prongs used in search for the decay $\Upsilon \to \gamma X$, $X \to \tau^+\tau^-$. The hatched histogram shows the observed contribution from the decay $\Upsilon \to \tau^+\tau^-$ with one τ decaying into $\rho\nu$, the open histogram shows expected background contributions from other sources as described in the text.

In summary, we have observed no indication for narrow objects produced in radiative Υ decays and decaying into a τ pair. The present sensitivity is an order of magnitude to small to check the predictions from the standard model, if only one scalar Higgs particle is assumed. However, the result puts improved constraints on models with a more complicated Higgs structure.

Is the Higgs mass 8.3 GeV ???
At 4.2 sigma???

No, it isn't!

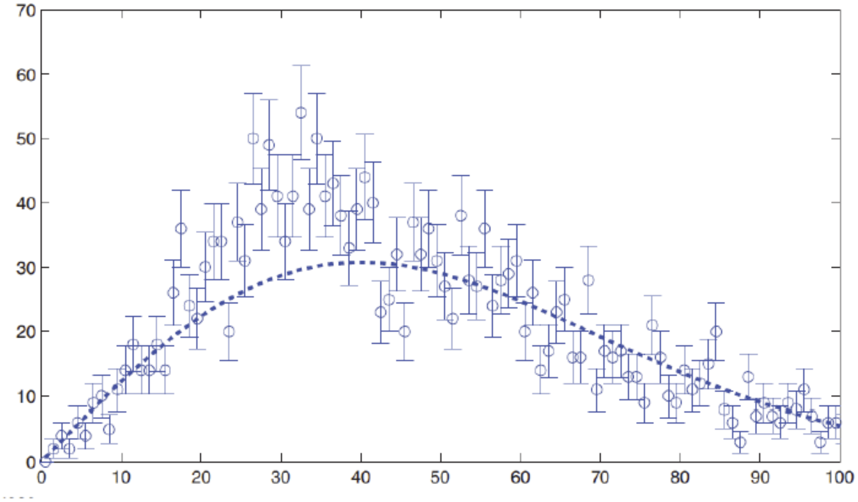
the observation of new phenomena is usually expressed using a *p-value*, that is, the probability that a similar or more extreme effect would be seen when the signal does not exist (a situation usually referred to as the null or background-only hypothesis). It is often the case that one does not *a priori* know where the signal will

When searching for a new resonance somewhere in a possible mass range, the significance of observing a local excess of events must take into account the probability of observing such an excess *anywhere* in the range. This is the so called "look elsewhere effect". The effect can be quantified in terms of a trial factor, which is the ratio between the probability of observing the excess at some fixed mass point, to the probability of observing it anywhere in the range. and fast

based on

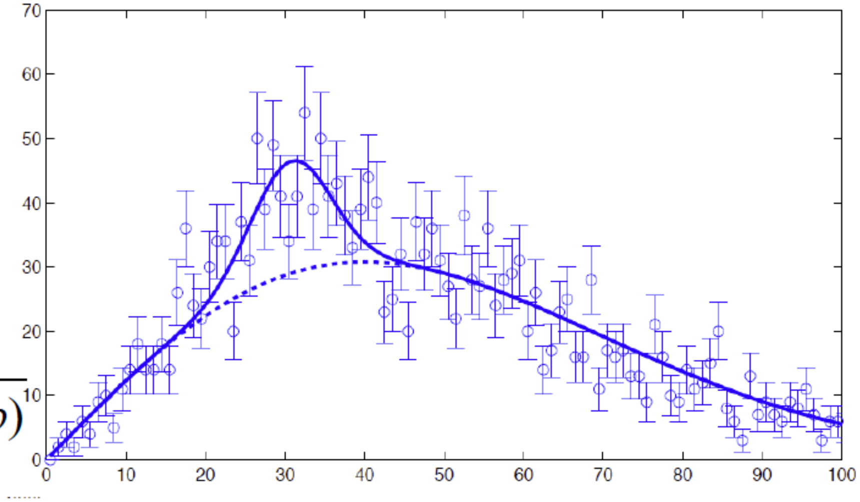
Look Elsewhere Effect

- Is there a signal here?



- Obviously @ m=30
- What is its significance?
- What is your test statistic?

$$t_{fix,obs} = -2\ln\frac{L(b)}{L(\hat{\mu}s(m=30)+b)}$$

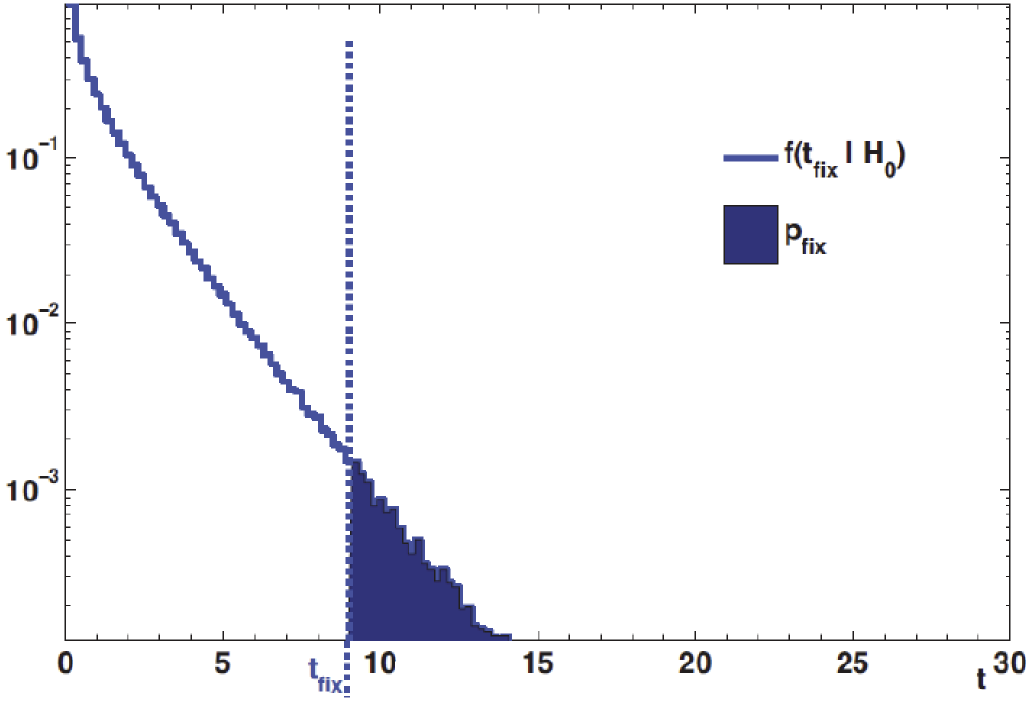


- Test statistic

$$t_{fix\ obs} = -2\ln\frac{L(b)}{L(\hat{\mu}s(m=30)+b)}$$

- What is the p-value?
- generate the PDF

$$f(t_{fix} | H_0)$$



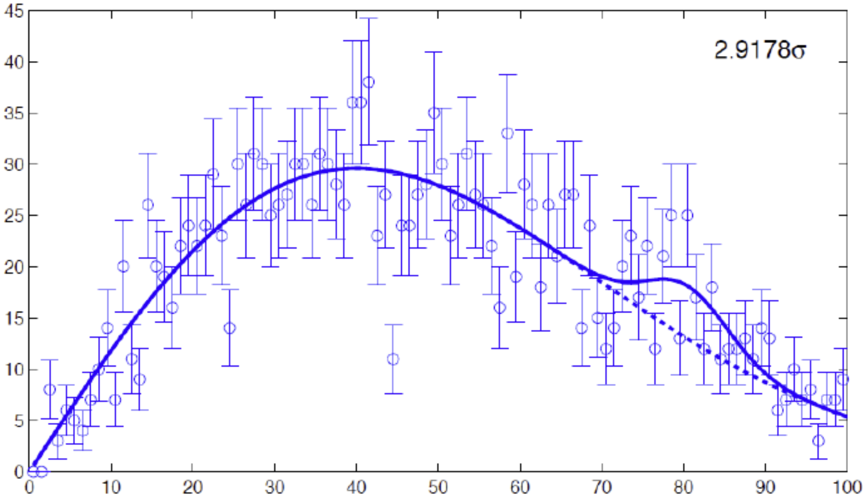
and find the **p-value**

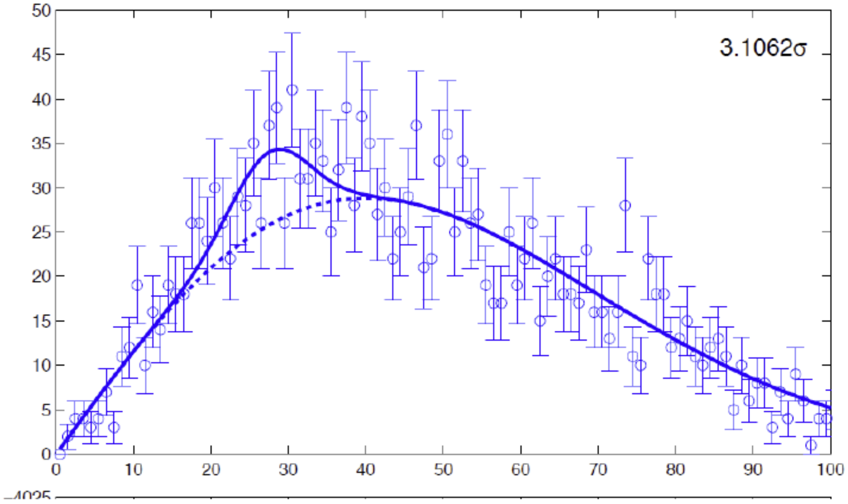
Wilks theorem:

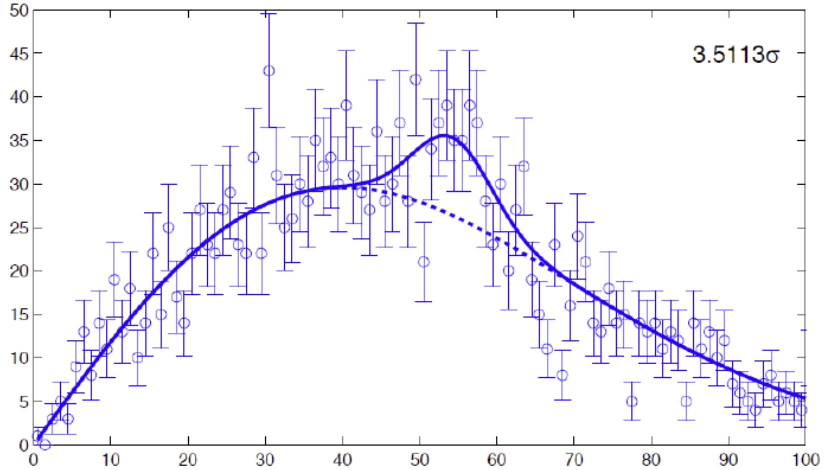
$$f(t_{fix} | H_0) \sim \chi^2_1$$

$$p_{fix} = \int_{t_{fix,obs}} f(t_{fix}|H_0)dt_{fix}$$

- Would you ignore this signal, had you seen it?



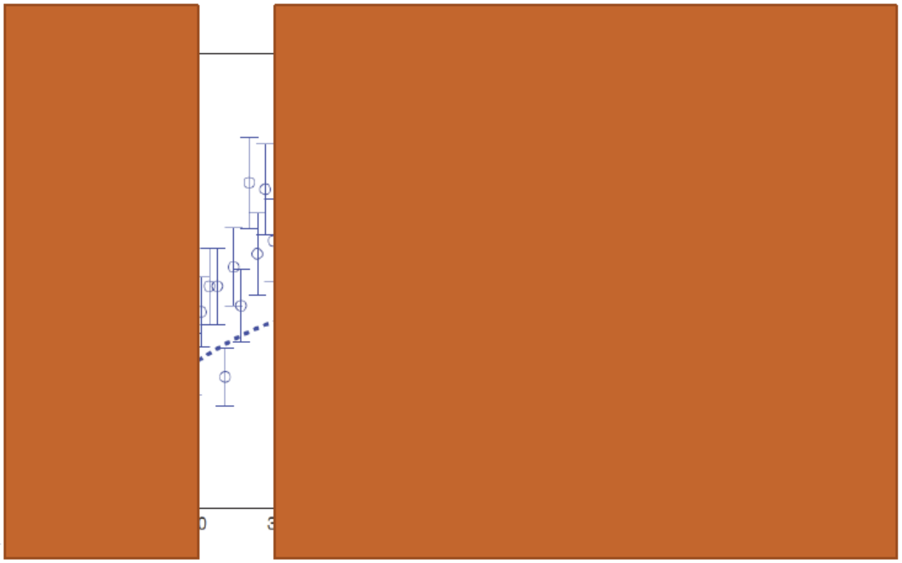




- ALL THESE "SIGNALS" ARE BG FLUCTUATIONS

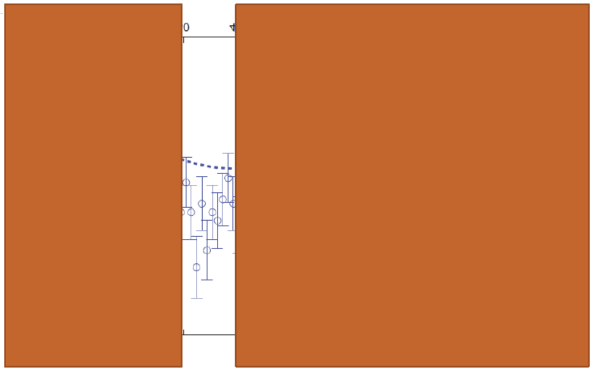
- Having no idea where the signal might be there are two options
- **OPTION I:**

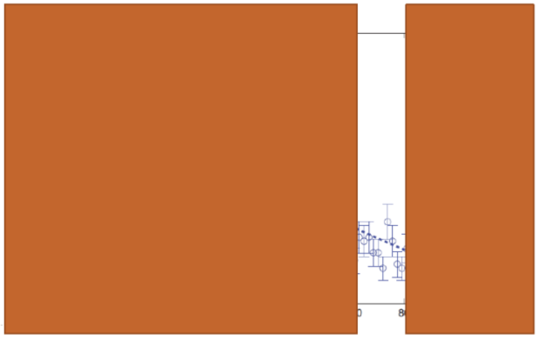
scan the mass range in pre-defined steps and test any disturbing fluctuations



- Perform a fixed mass analysis at each point

$$t_{fix\;obs}(\hat{\mu}) = -2\ln\frac{L(b)}{L(\hat{\mu}s(m)+b)}$$



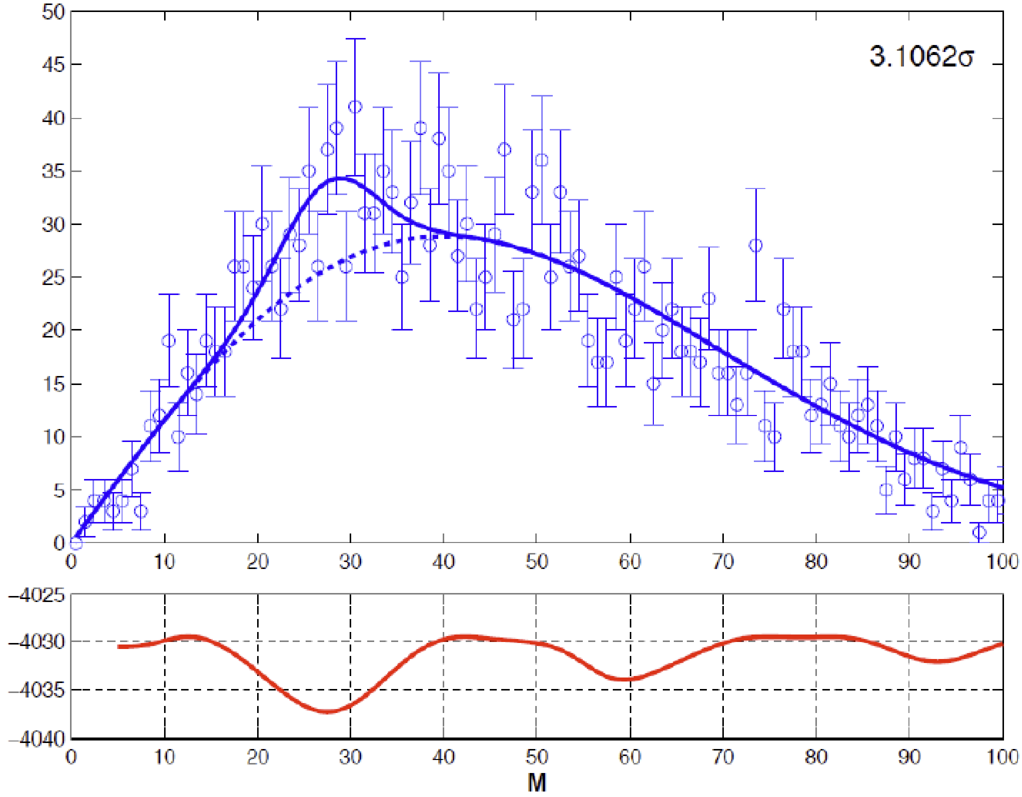


Look Elsewhere Effect: Floating Mass

- Having no idea where the signal might be you would allow the signal to be anywhere in the **search range** and use a modified test statistic

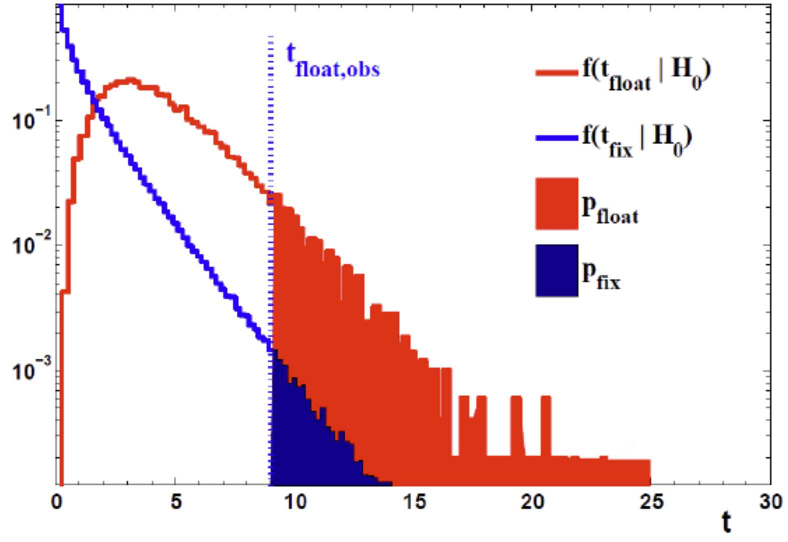
$$t_{float,\ obs}(\hat{\mu},\hat{m}) = -2\ln\frac{L(b)}{L(\hat{\mu}s(\hat{m})+b)}$$

- The p-value increases because more possibilities are opened



- We can now ask the question: Assume the Higgs is observed at some mass $\hat{m}$ what is the probability for the background to fluctuate locally at the observed level (or more) $@ m_H = \hat{m}$

$$t_{fix\ obs} = t_{float\ obs} = -2\ln\frac{L(b)}{L(\hat{\mu}s(\hat{m}=m=30)+b)}$$



- We can calculate the following p-value

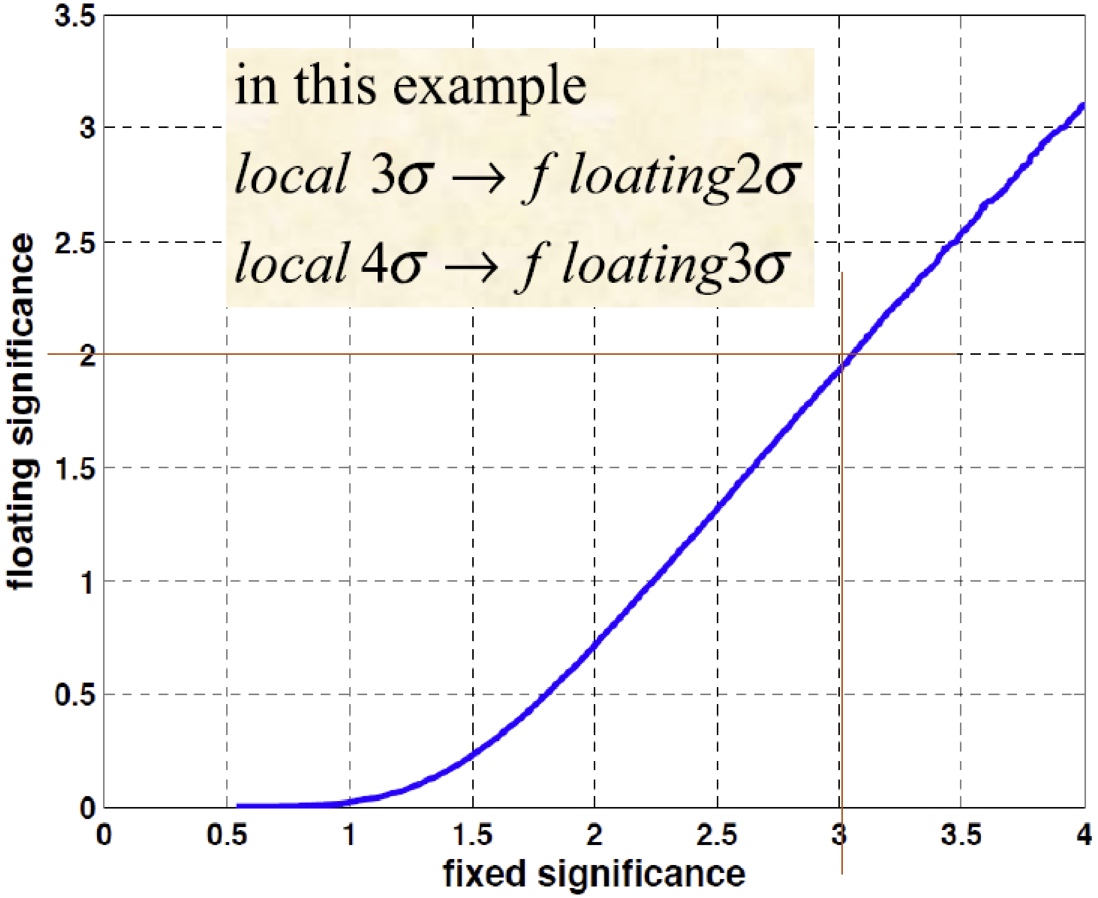
$$p_{fix} = \int_{t_{obs}} f(t_{fix} | H_0)\,dt_{fix} < p_{float} = \int_{t_{obs}} f(t_{float} | H_0)\,dt_{f}$$

Look Elsewhere Effect

- The Look Elsewhere Effect reduces the apparent significance

- It addresses the alternate hypothesis:
  - A Higgs at some mass in the search-range

$$p_{float} = \int_{t_{float}} f(t_{float} | H_0) dt_{floa}$$



in this example

$local\ 3\sigma \rightarrow floating\ 2\sigma$

$local\ 4\sigma \rightarrow floating\ 3\sigma$

$$p_{fix} = \int_{t_{fix}} f(t_{fix} | H_0) dt_{fi}$$