Weighing the Weak Force at Fermilab

A precision determination of the mass of the W Boson

Outline

- **from Heisenberg to Weinberg - *why***
- **status of M_W measurements**
- **the experiment**
- **DO results**
- **future**

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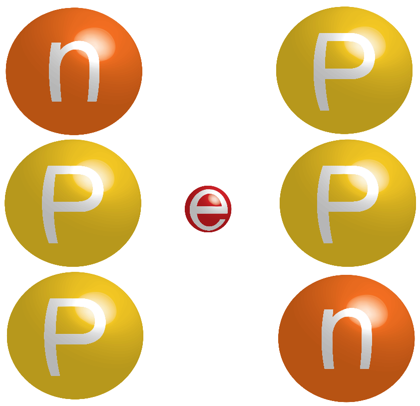
background to (perhaps) the

l o n g e s t

“discovery moment” in history

after the discovery of the neutron, Heisenberg attempted an explanation of how it stays in the nucleus by proposing *an exchange force*

- **a series of 3 papers in 1932/33**
  - **he proposed a new force, acting at short range between protons and neutrons in the nucleus**
  - **protons exchanged electrons - a *Platzwechsel*, or "migration"**
  - **tied nuclear forces and beta-decay together**
    - **a source of the electron!**



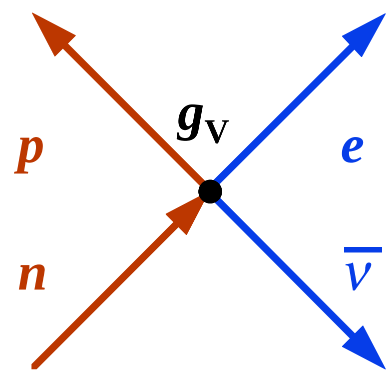
- **by 1936...**
  - **there were 3 other p-n exchange force models**

"...the general idea of a connection between beta-emission and nuclear forces is so attractive that one would be very reluctant to give it up." Bethe and Bacher, 1936

- **However, the plausibility of Fermi's model was the crucial stimulus to furthering this notion**

4 very new ideas/tools came together in Fermi's model for β decay (1933)

- Dirac's relativistic quantum mechanics - direct analogy with QED
- the neutron as a fundamental particle
- Heisenberg's idea of n $\leftrightarrow$ p
- Pauli's neutrino



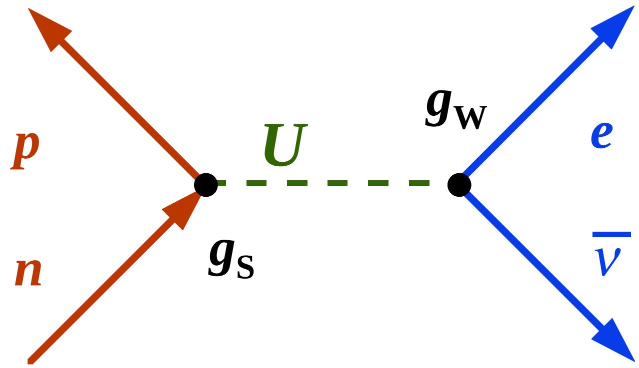
$g_V \approx 4 \times 10^{-50}$ erg cm^3

(dimension-full coupling)

- it worked and spawned an industry of determining the Lorentz character of the interaction term, V, A, S, T, or P

  all forms had experimental support within the growing collection of apparently related weak interactions - Feynman and Gell Mann set that straight in 1958 in the remarkable "V - A" paper

- **Heisenberg tried again, with an exchange of ν - e pair...but flawed**
- **Yukawa took Heisenberg's exchange metaphor and promoted it to a postulate about physical reality**
  - **He proposed a new force, mediated by a new quantum, *U*.**
  - ***U* would couple differently to the neutron and proton, than to the electron and neutrino.**



Yukawa explicitly separated the weak and the strong interactions for the 1st time

- **the "rest of the story" is well known... the pion and cosmic rays**

By the 1960's

- **Following the Feynman-Gell Mann article, the way was clear for a single vector quantum exchange of indeterminant parity**
- **every textbook had a chapter on the "Intermediate Vector Boson Hypothesis"**
- **one can find in the literature numerous references to: the "weakon", "intermediate meson", the "V", the "Z", and the "W" which would have:** ***spin 1, electrical charge, and mass*** $>M_K$

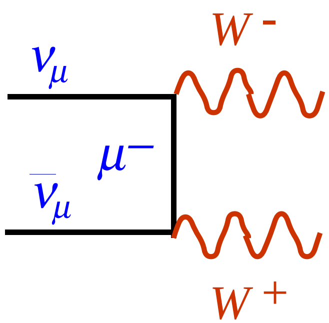
Everyone knew that it had to exist

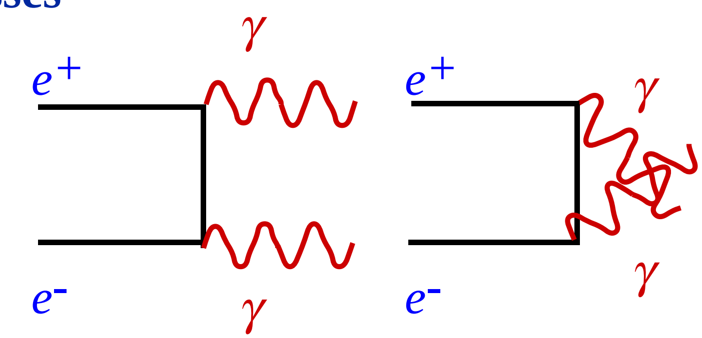
- **all of the experimental evidence was unhelpful - adjustments to ρ , neutrino cross section, precise measurements of τ_μ ...none were precise enough**
- **Yet, if found, it would have rendered the field theory unusable and cast doubt on even the presumed understanding of QED**

the classical *W* is impossible

While the idea was appealing and the connections with QED's photon were understood

- **it became apparent in the '50's that the massive *W* was impossible**
  - **the <u>mass</u>, necessary for the short range, ruined the theory by causing infinities to occur in various processes**





the badly behaved term is the longitudinal degree of freedom, harmless in the QED calculation

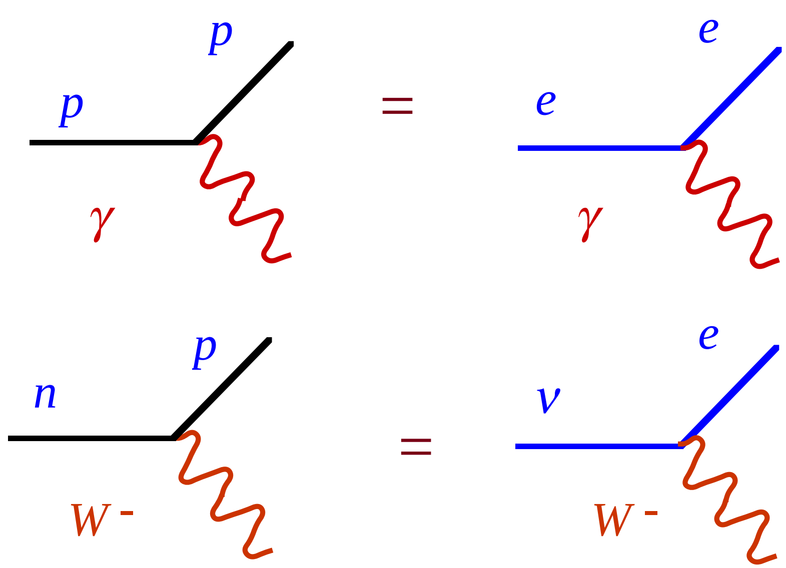
- **strenuous theoretical efforts were expended to rid the theory of this plague *and***

- **all experimental efforts through the 1960's and late 1970's to produce the *W* in neutrino collisions failed:by 1978, $M_W > 10$ GeV from the linearity of the neutrino cross section...**

However, the kinship with electromagnetism, begun by Fermi, continued to be pursued

- **Fermi's original ideas stole directly from QED**
- **More surprisingly, there were formal similarities:**

Good behavior in QED was imagined for the weak interactions because of the renormalized coupling constant in both theories

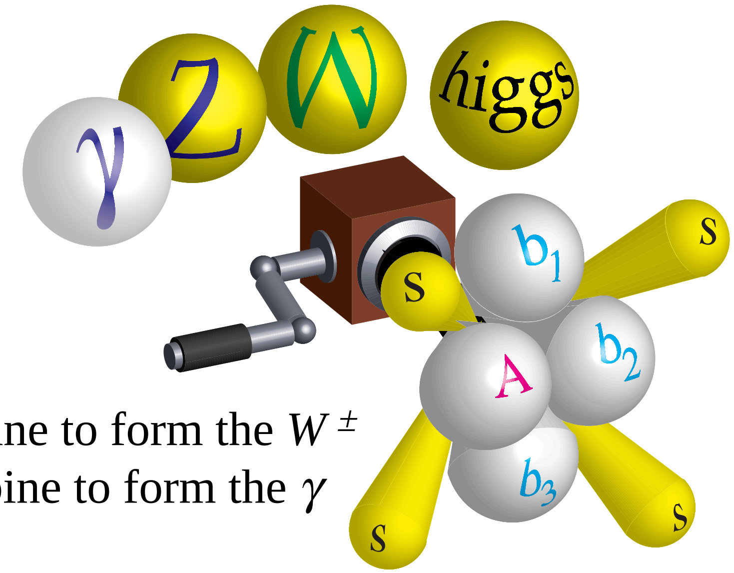


In 1967, Weinberg, following incomplete ideas of Schwinger, Glashow, and Salam, put it all together into a single theory - now called Standard

the zoological ingredients of the SM

The ideas in the SM borrow directly from other branches of physics - notably many-body physics and the Ginzburg-Landau theory of phase transitions.

The early situation includes:
1) an SU(2) triplet of massless spin 1 bosons (***b***)
2) a massless spin 1 singlet, *A, and*
3) four scalar fields, *s with unusual self couplings*.



something happens (phase transition?),
a crank turns,
and

a) two of the *b*'s mix, absorb two of the *s*, and combine to form the $W^{\pm}$
b) the other *b* and the *A* **mix**, absorb one *s*, and combine to form the γ and the *Z*

θ_W, the "Weinberg angle"

the remaining scalar becomes the left-over Higgs Particle - it is the Cooper Pair: macroscopic, filling the ground state (vacuum?), screening the W and Z, and providing their apparent mass

The masses of the *W* and the *Z* are intimately related to mass generation.

the longest discovery-moment in history

predictions - *2.5 page unnoticed 1967 letter*

$$M_{W^\pm} = \frac{1}{\sin\theta_W}\sqrt{\frac{\pi\alpha}{G_F\sqrt{2}}}$$

- **Weinberg could make a set of predictions:**

  circa 1980, from neutrino experiments,

$$\sin^2\theta_W = 0.231 \pm 0.010$$

so, $M_W = 77.6 \pm 1.6$ GeV/c ^{2} - 2% prediction.

- **Another prediction was** $M_Z = \frac{M_W}{\cos\theta_W}$ $\Rightarrow$ **M_Z = ~ 89 GeV/c ^{2}**

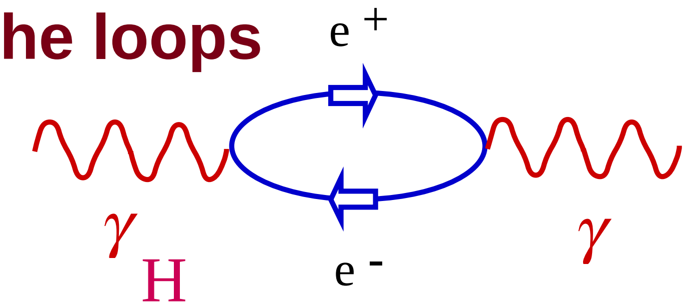
an accelerator was needed, so CERN built one - to discover the *W* and hopefully the *Z*

- **The CERN $p\bar{p}$ collider was built, UA1 and UA2 found both at the expected masses in 1983.**

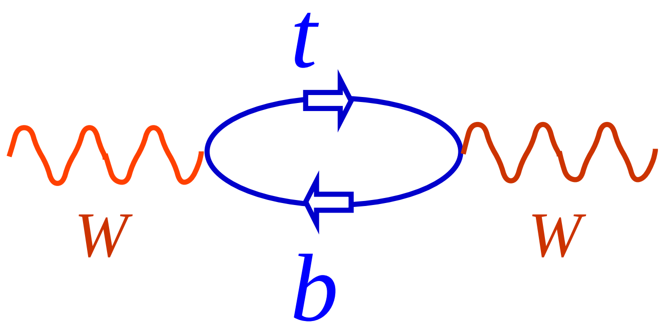
after 1/2 century, the *W* was loose, inaugurating two decades of physics

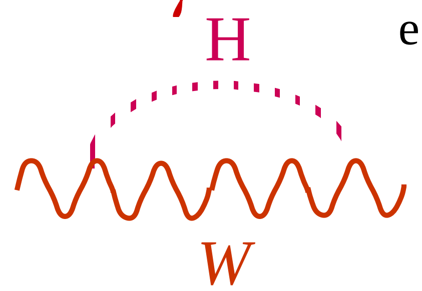
the fundamental concentration is <u>mass</u>

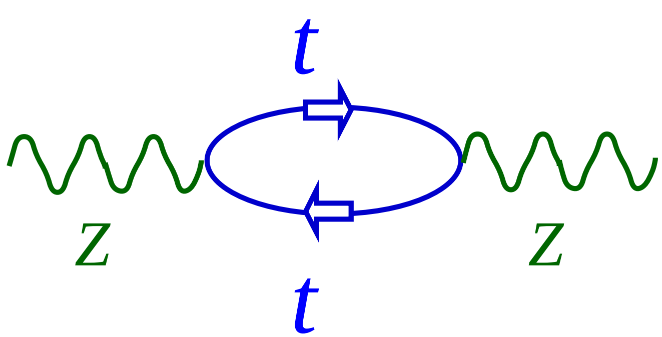
this continuing importance is in the loops

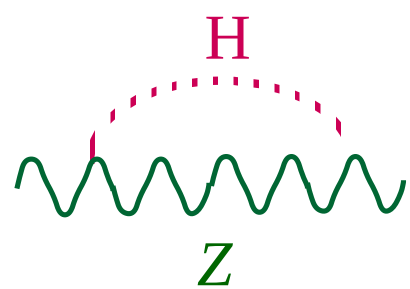


just like in QED - observable consquences result
from the uncertainty principle and the field theory









modification of the “propagator” affects the “mass”. The field theory is unforgiving and the relationships among M_T, M_W, M_Z, and M_H are <u>specified.</u>

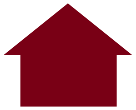
the stakes for the Standard Model are very high

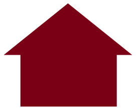
one common language is to bury all high-order corrections into a single term, "Δr"

- **Now, the three input parameters to the model are**
  - **fine structure constant,** $\alpha^{-1}_{EM} = 137.0359895(61)$ **0.045ppm**
  - **Fermi constant,** $G_F = 1.6639(2) \times 10^{-5}\ \mathrm{GeV}^{-2}$ **20 ppm**
  - ***Z* mass** $M_Z = 91.1884 \pm 0.0022\ \mathrm{GeV/c^2}$ **24 ppm**

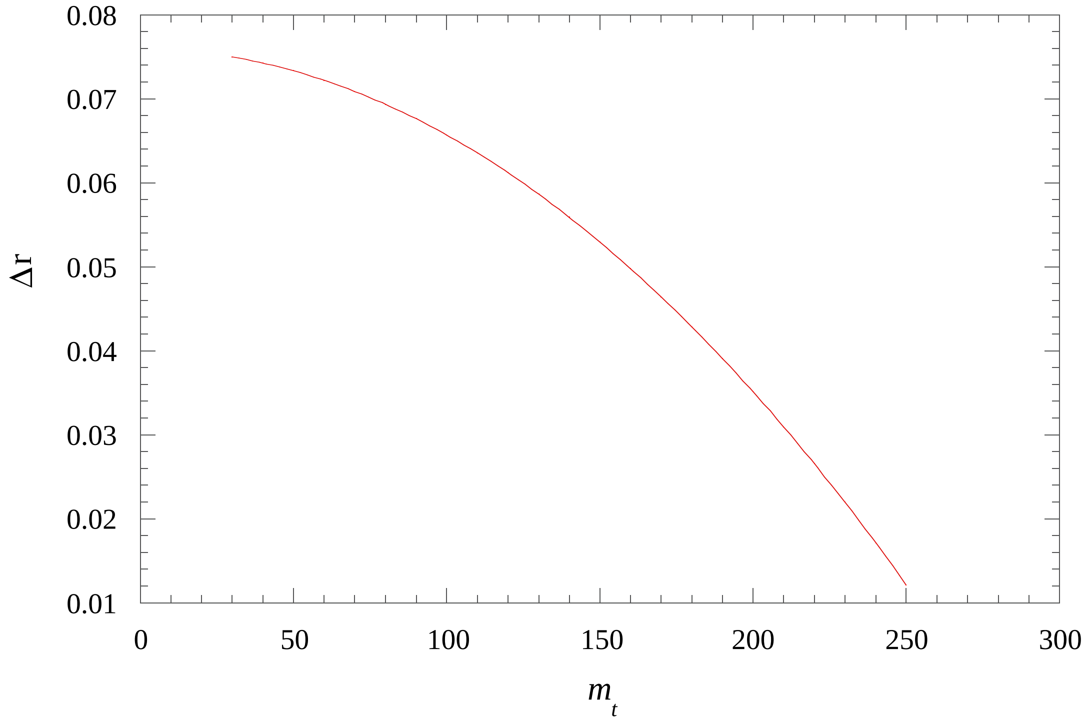
- **Then,** $M_W = \frac{M_Z}{\sqrt{2}}\sqrt{1+\sqrt{1-\frac{4A^2}{M_Z^{\ 2}}}}$ **where** $A \equiv \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}}\frac{1}{(1-\Delta r)^{\frac{1}{2}}}$
  - the dominant contributions are due to QED [~7%], heavy quarks (Top), and the Higgs mass

$$\Delta r = \Delta\alpha \ - \ \text{const.} \bullet (m_{top} / M_W)^2 + \text{another const.} \bullet \ln(m_{Higgs} / M_W)$$



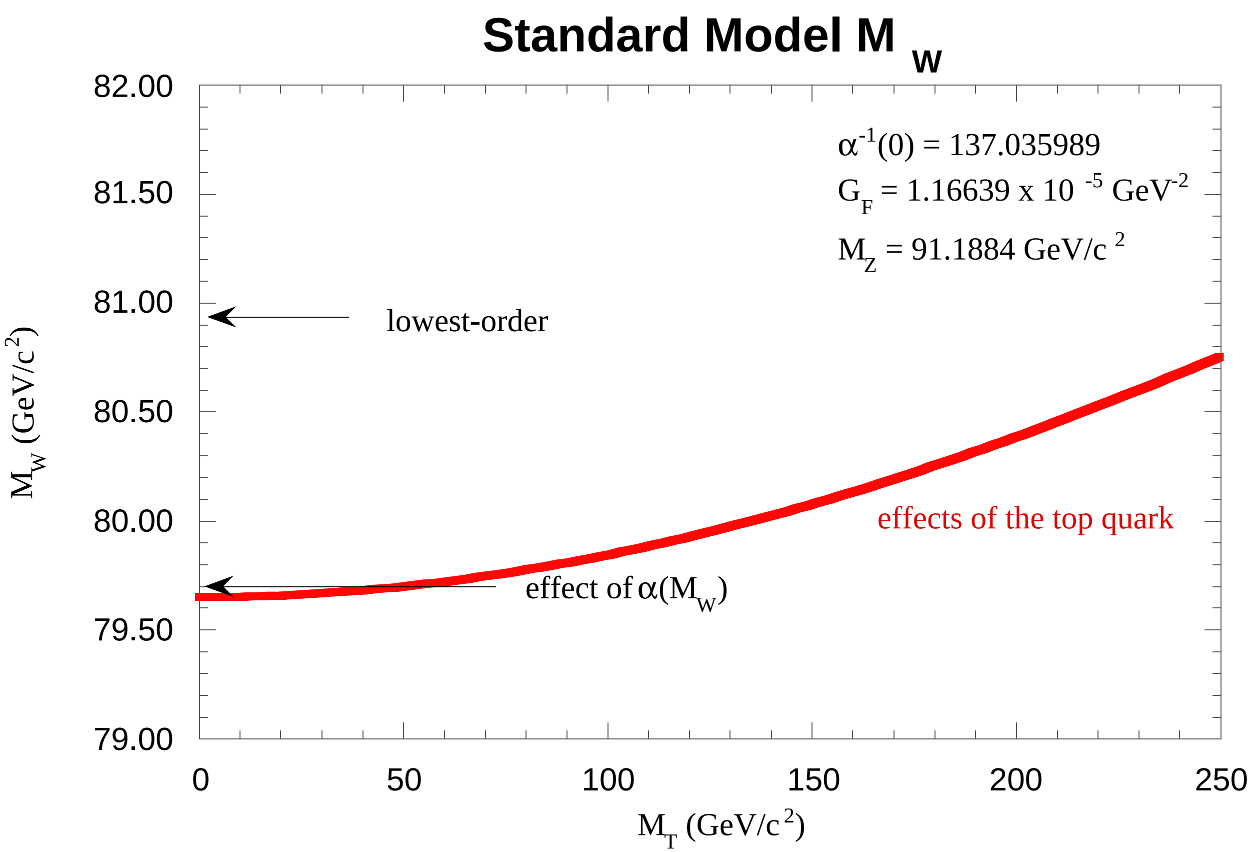


the quadratic top mass effect is striking...



(for 500 GeV/c^2 higgs boson)

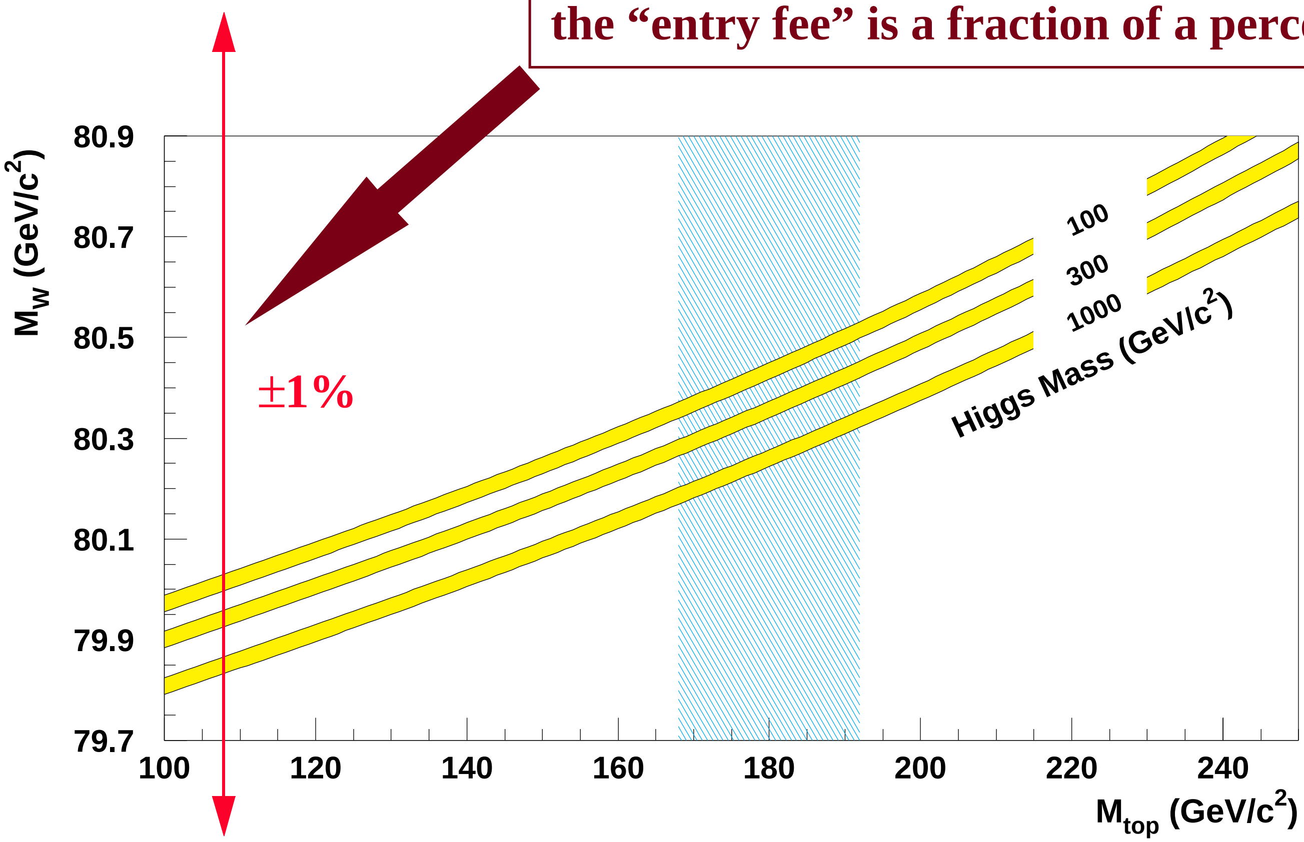
calculated effect on M_W



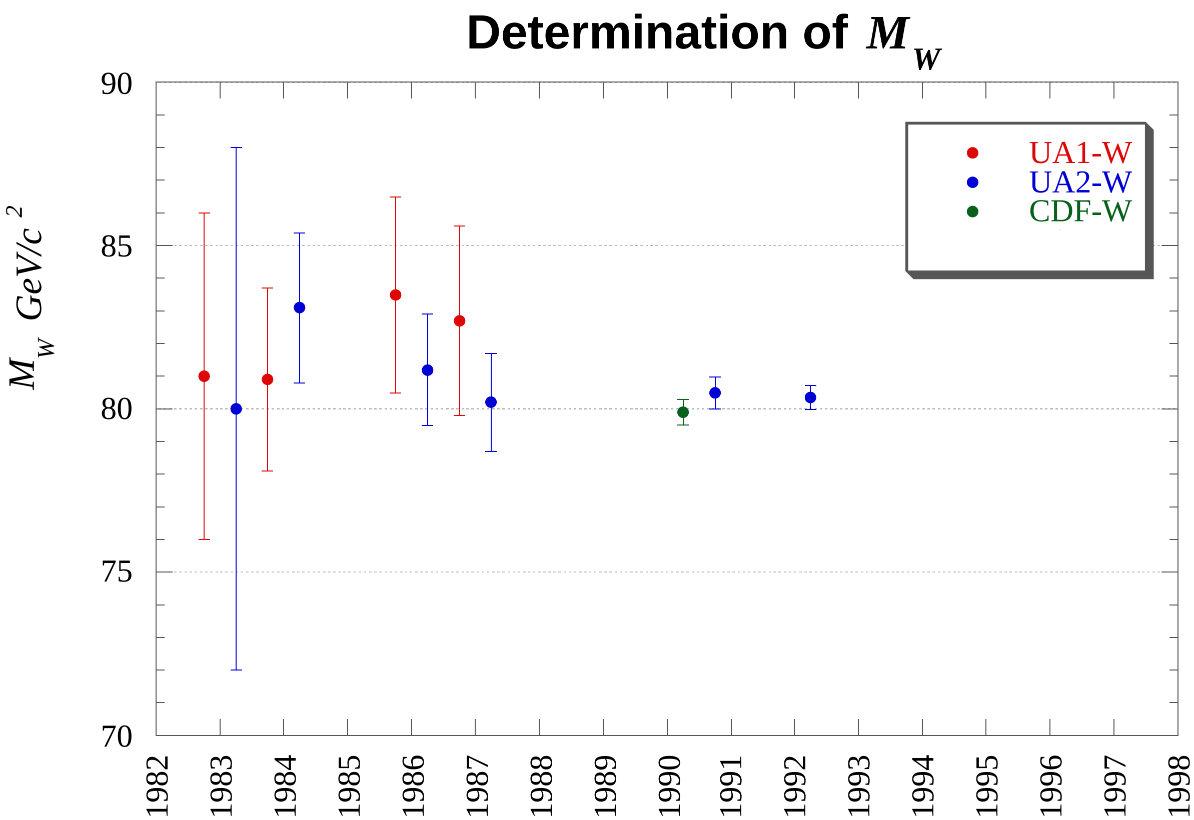
the precision of *W* and top should keep pace with one another...

- **a little while to get the central value - years to understand the errors**

the "entry fee" is a fraction of a percent precision!

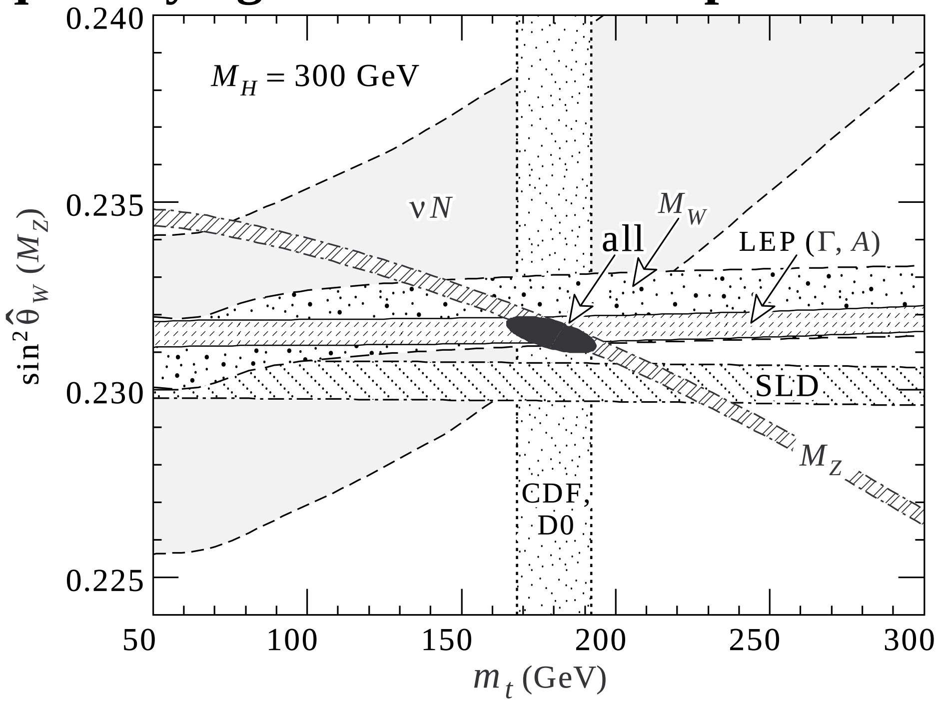


precision is indeed improving with each era



professionals calculate huge, global fits

- **combining all data**
- **quantifying the effects of anticipated new electroweak physics**



The Plan: stress the SM and search for new physics in the high-order effects - $\delta m_{Top} \approx$ few GeV/ c^2 ,

$\delta M_W \approx$ 50 MeV/ c^2 by 2002

Measuring M_W at a hadron collider

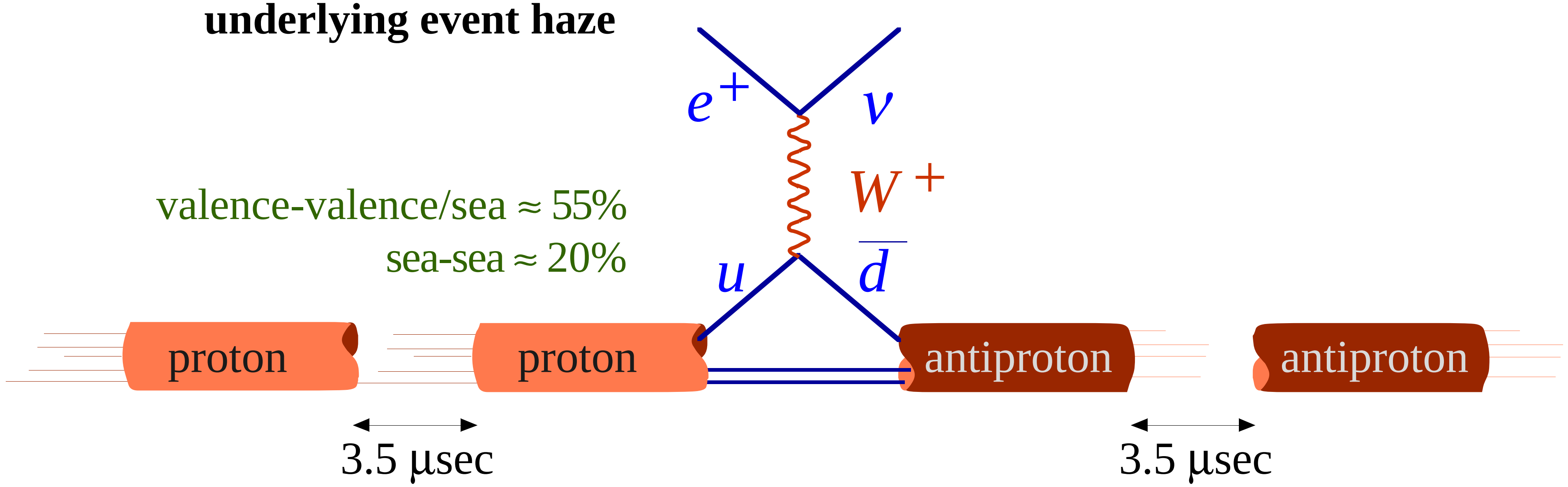
Drell-Yan-Lederman-Pope mechanism

- **quark-antiquark pairs annihilate - the “naive” version**

note that other proton bunches are preceeding and following

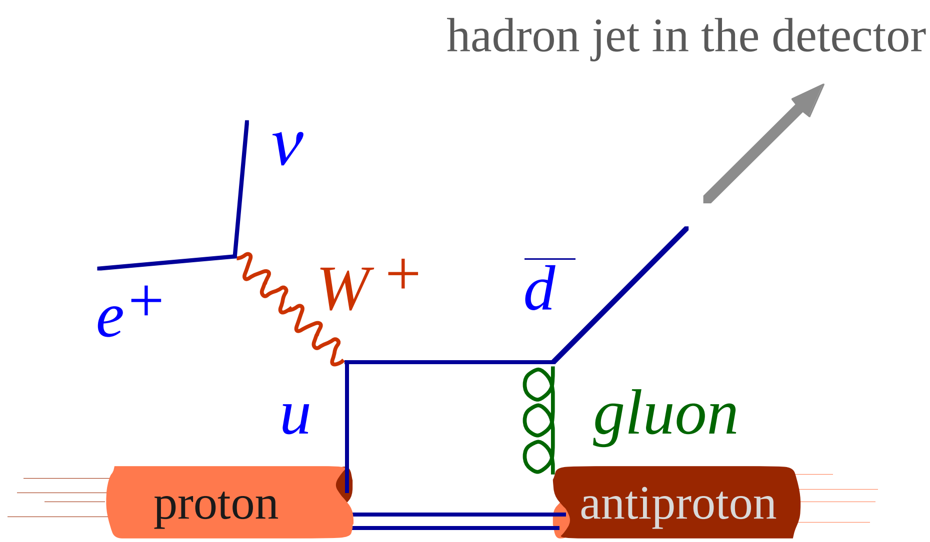
- **with sufficient bunch population, pileup is a problem**
- **good occupancy is $N_p(N_{antip})$ / bunch = 2 x 10^{11}(6 x 10^{10})**
- **at L = 6 x 10^{30}/cm^2/s the event rate is 1 interaction per crossing**

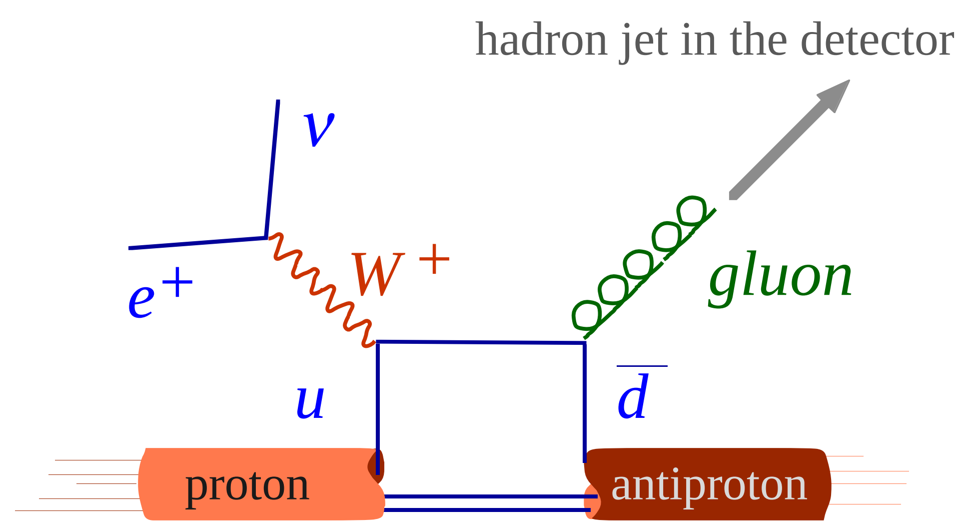
spectator quarks (and gluons) do provide a “minimum bias” underlying event haze



more realistic production

gluon radiation & q - $\bar{q}$ pair-production will always dominate





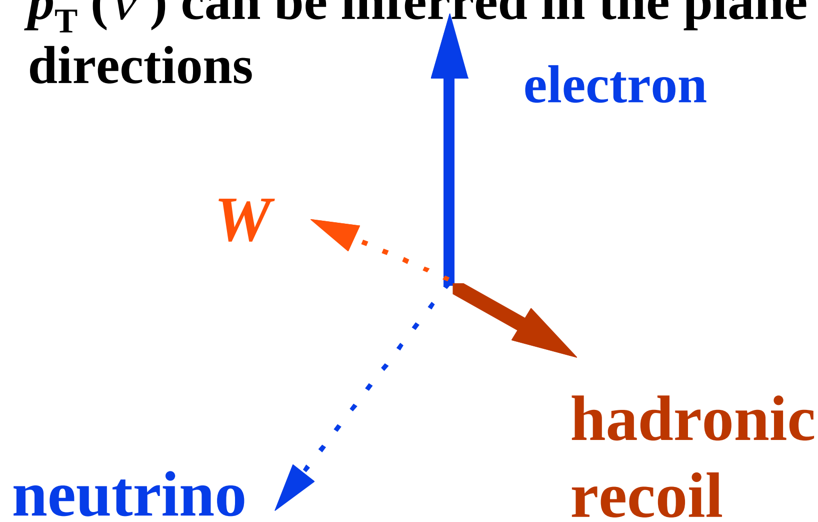
- **jets may occur, but *W* production is dominated by soft, multiple emissions which "gently" shove the W to small transverse momenta, p_T - peaks at only 5 GeV/c**
- **need a model of this production**
  - **Collins, Soper, Sterman, Yuan, Ladinsky**

$W \rightarrow e\,\nu$

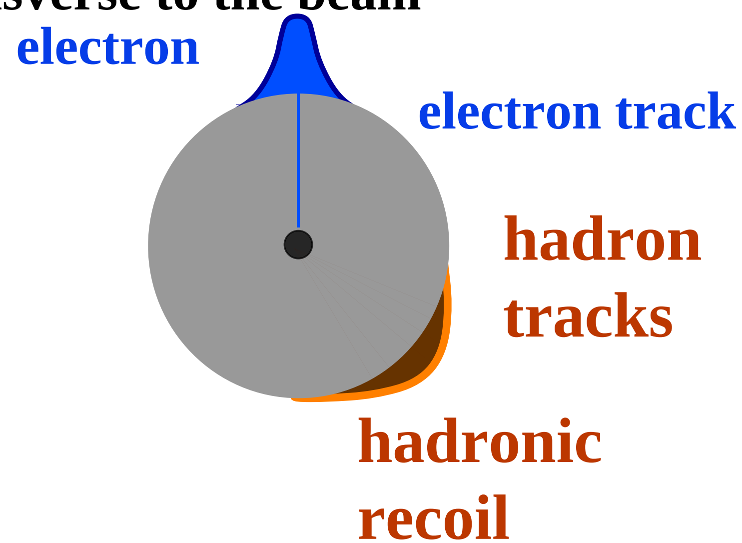
- two body $\Rightarrow$ useful kinematical constraints
- measurables are: electron p_T, the hadronic debris, $\sum_i p_T(h_i)$, and the relative angles
- the neutrino is invisible

  $p_L(\nu)$ <u>un</u> measurable

  $p_T(\nu)$ can be inferred in the plane transverse to the beam directions



momentum “picture”



what the detector provides

mass determination

exploiting the two body kinematics

- **can use $p_T(e)$, using the sharp edge at $M_W/2$**

  actually... $p_T(W)$ makes the edge less sharp

$$\frac{d\sigma}{dp_T^{\,2}(e)} \propto \frac{\left(1-2\frac{p_T^{\,2}}{s}\right)}{\sqrt{1-4\frac{p_T^{\,2}}{s}}}$$

- **Rather, use the "transverse mass"...**

  an invariant mass calculated in the transverse plane

$$m_T^{\,2} = 2\,p_T(e)\,p_T(\nu)[1-\cos\phi(e-\nu)]$$ **where**

$$p_T(\nu) = \vec{p}_T(W) - \vec{p}_T(e) = -\vec{p}_T(recoil) - \vec{p}_T(e)$$ **and** $$\vec{p}_T(recoil) \equiv \sum_{i=cells} E_i \hat{n}(cell)$$

which shows

$$\frac{d\sigma'}{dm_T^{\,2}} = \frac{|V_{q\bar{q}'}|}{4\pi}\left(\frac{G_F M_W^{\,2}}{\sqrt{2}}\right)^2 \left[\frac{1}{\left(s-M_W^{\,2}\right)^2+\left(\Gamma_W M_W\right)^2}\right]\frac{2-\frac{m_T^{\,2}}{s'}}{\sqrt{1-\frac{m_T^{\,2}}{s'}}}$$

the job is to determine m_T and infer M_W with maximum likelihood fitting

The DØ experiment at Fermilab

The DØ experiment at Fermilab

permanent staff:	**Abolins, Brock, Edmunds, Linnemann, Pope, Weerts**
research associates:	**Geld, Owens, Varelas**
graduate students:	**Di Loreto, Flattum, Frame, Genik, Jerger, Landry, McKinley, Rockwell**

plus:

414 other physicists from 45 other institutions in the US and 5 other countries

the DØ experiment

electromagnetic calorimeter (U LAr)

- **4 EM longitudinal read-outs**

  (2,2,7,10 X_0 thick)

  5000 signals

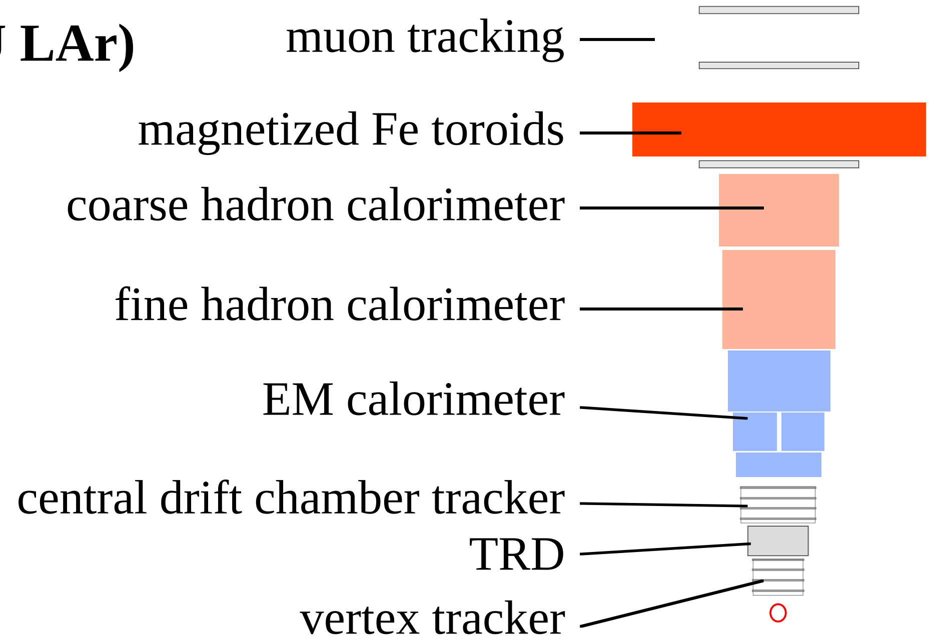
- **transverse segmentation**

  $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$

  at shower max,

  $\Delta\eta \times \Delta\varphi = 0.05 \times 0.05$

  10,400 signals



hadronic calorimeter (U/Cu/Fe LAr)

- **4-5 longitudinal segments**
- ***e* id $|\eta| < 1.2$ & $1.5 < |\eta| < 2.5$**
- **cal coverage $|\eta| < 4.2$**

general

- **asym. pedestal from U noise**

  zero suppression corrections

tracking resolutions:

- **60 μm, VTX**
- **150 μm, CDC**
- **200 μm, FDC**
- **e/π rejection 1:10, TRD**

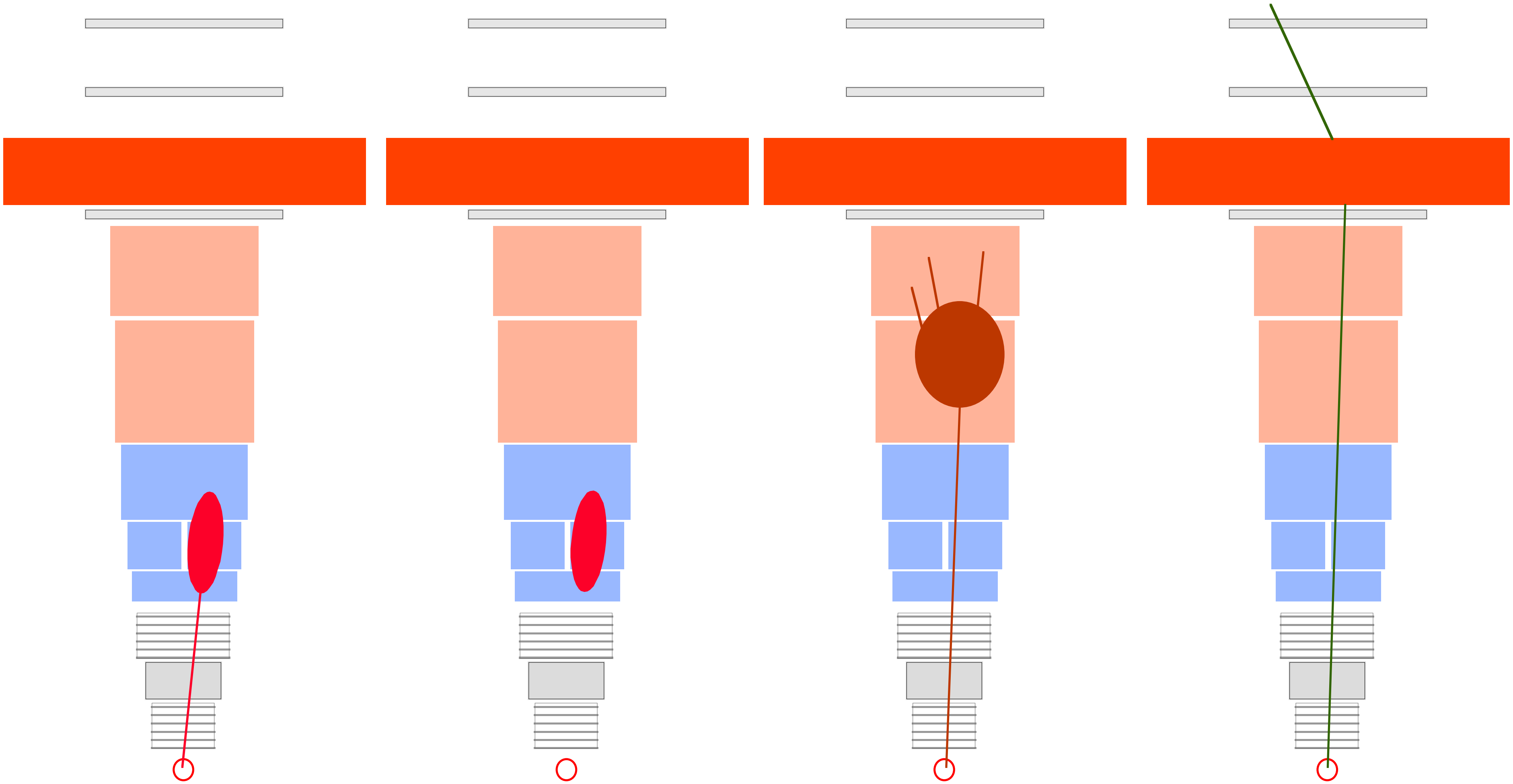
hermetic muon detection

- **$\Delta p / p \approx 20 - 50\%$**

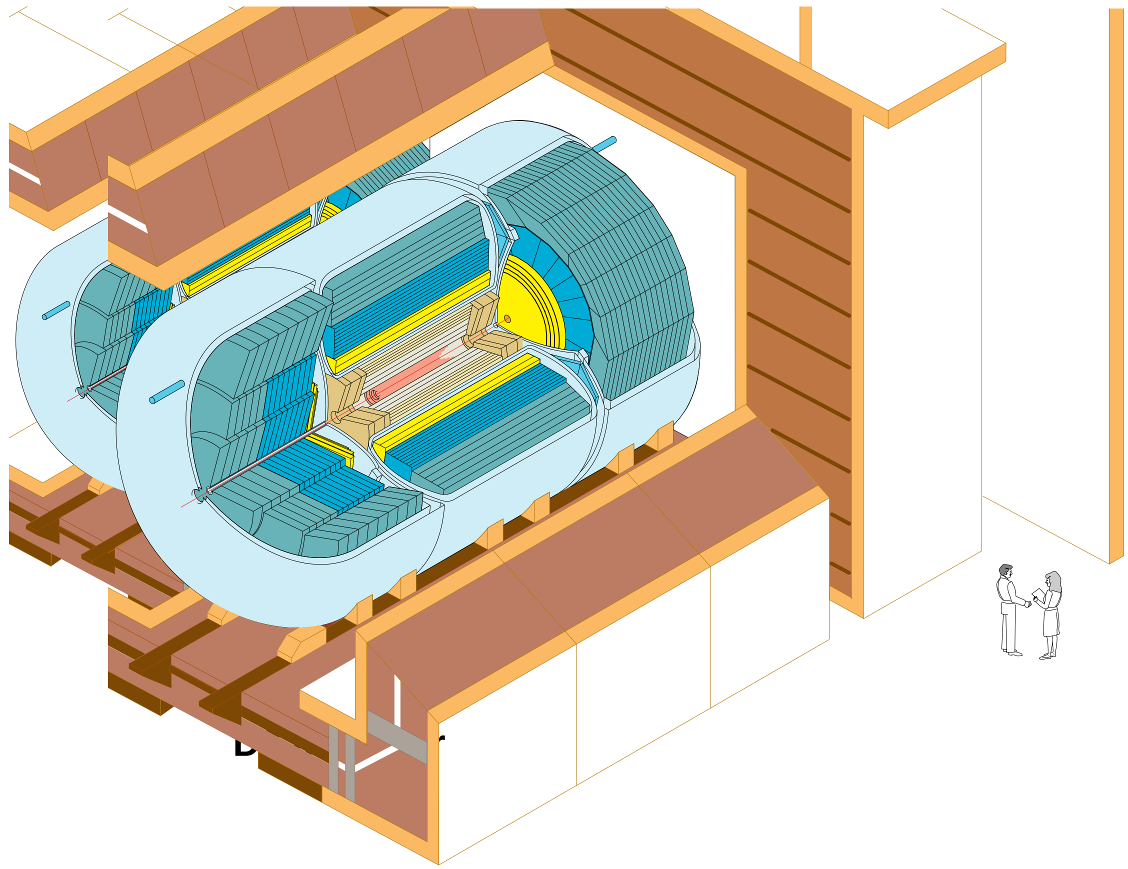
the players:

- **electrons & photons**
  - **electrons only will dE/dx and leave a track in low-ρ materials**
  - **gammas will pair-produce electrons and electrons will ionize and radiate, in denser, high Z materials $\rightarrow$ "electromagnetic shower"**
  - **well- columnated...characteristic length is X_0 (= 6 gm/cm^2 for U)**
- **hadrons (protons, neutrons, pions, kaons, protons)**
  - **will ionize and leave a track in low-ρ materials**
  - **will interact and produce many hadrons, sucessively with the nuclei of high density materials $\rightarrow$ "hadronic shower"**
  - **broad & "tracky"...characterstic length λ_I (= 199 gm/cm^2 for U)**
  - **n, K, etc. will interact hadronically**
  - **π^0 will decay $\gamma\gamma$, lending an EM component to hadronic showers**
- **muons**
  - **will leave a track, not shower, and will penetrate deeply**
- **neutrinos**
  - **do nothing - but *appear* to imbalance momentum**

a particle's eye-view



electron photon hadron muon



DØ Detector

(photographs)

collider kinematics sets the geography

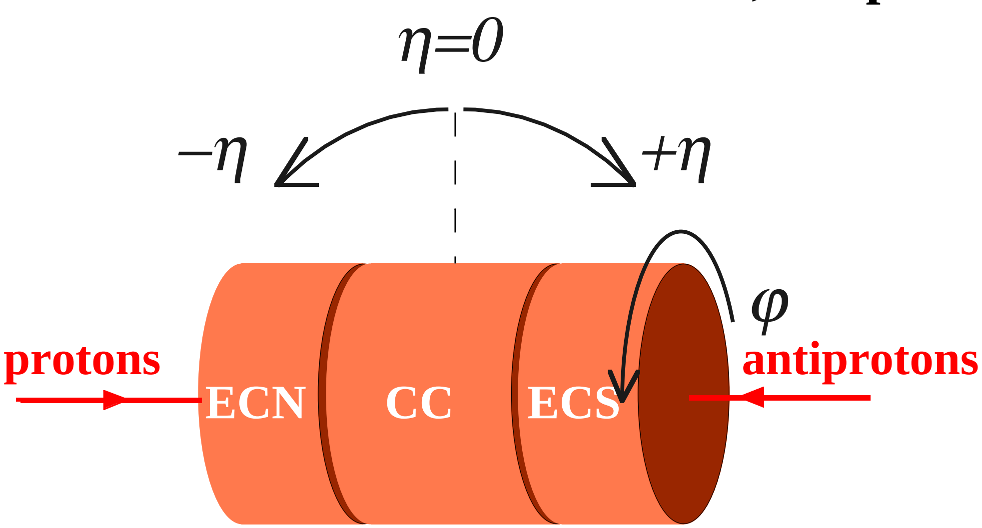
- **azimuthal angle, around the beam**
- **instead of a polar angle, "pseudo rapidity" is commonly used**

rapidity: $y = \frac{1}{2}\ln\left(\frac{E+p_{\parallel}}{E-p_{\parallel}}\right)$ **which has a max** $y_{\max} = \ln\left(\frac{\sqrt{s}}{M}\right)$

for W @ s = 1.82 TeV $y_{\max} = 3.11$

when masses don't matter, use pseudorapidity, η

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$



detectors are segmented in chunks of $\Delta\eta$ x $\Delta\varphi$

the measurement

the measurement

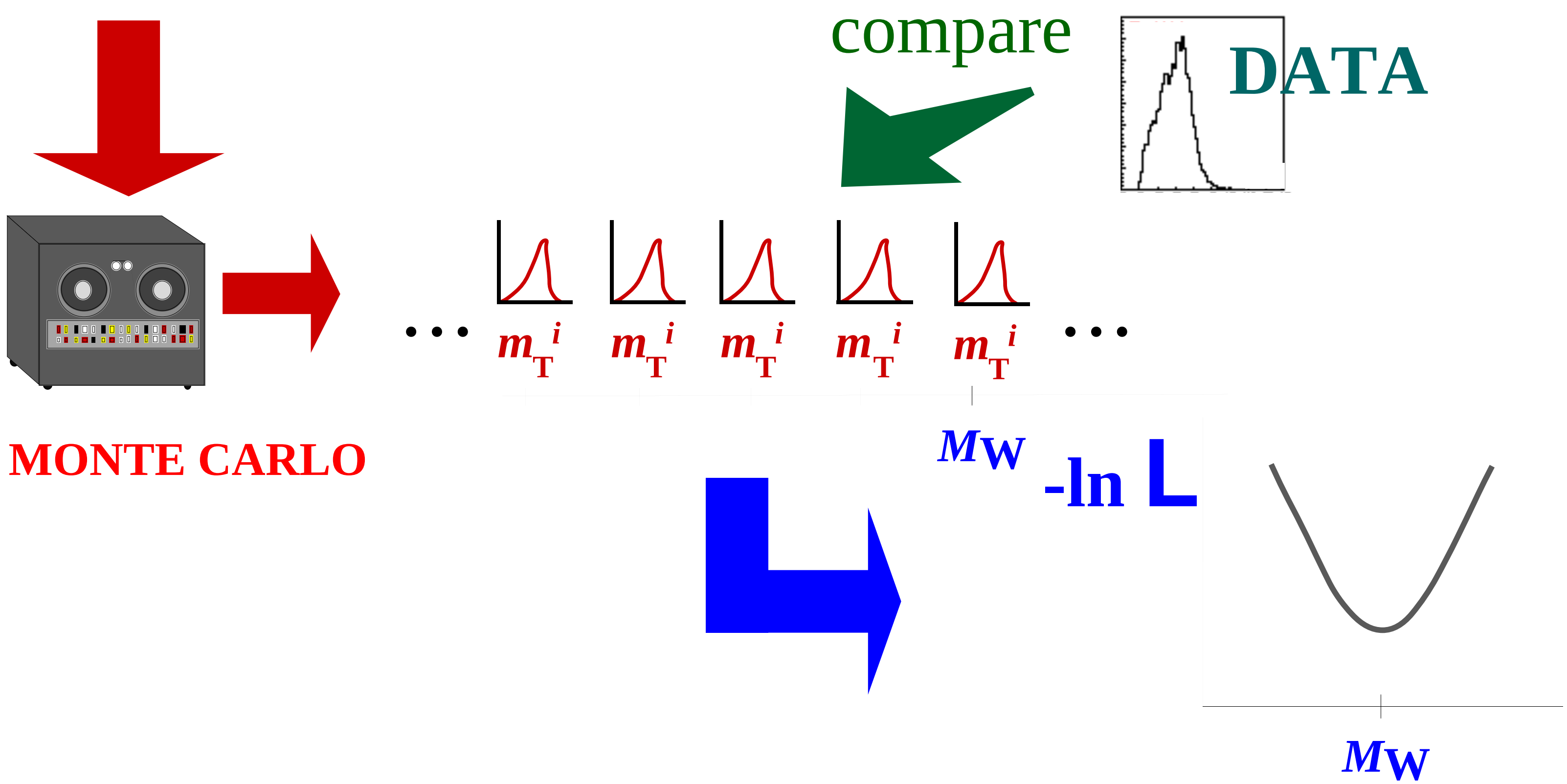
Ian Adam, Columbia; Chip Brock, MSU; Marcel Demarteau, FNAL/MSU; Eric Flattum, MSU; FNAL; Norman Graf, BNL; Uli Heintz, FNAL; John Sculli, NYU; Kathy Streets, NYU; Srini Rajagopalan, Stony Brook; Q. Zhu, NYU

the plan

MODEL of PHYSICS

+

MODEL of DETECTOR



the running

The two important reactions are:

$p\bar{p} \rightarrow W + X \rightarrow e + \nu + X$ BR($W \rightarrow e + \nu$) = 10%

$p\bar{p} \rightarrow Z + X \rightarrow e + e + X$ BR($Z \rightarrow e + e$) = 3%

These data were taken at Fermilab's proton-antiproton collider during 1992 & 1993

- s = (1800 GeV)^2
- **total accumulated luminosity, ≈ 13 pb^{-1}**
- **This was the first running of DO...and the price of entry into the M_W sweepstakes was 0.3% precision**

σ (W)•BR($W \rightarrow e + \nu$) = 2.4 nb

effective cross section ª 0.3• σ (W)•BR ⇒ about 10k events

σ (Z)•BR($Z \rightarrow e + e$) = 0.22 nb

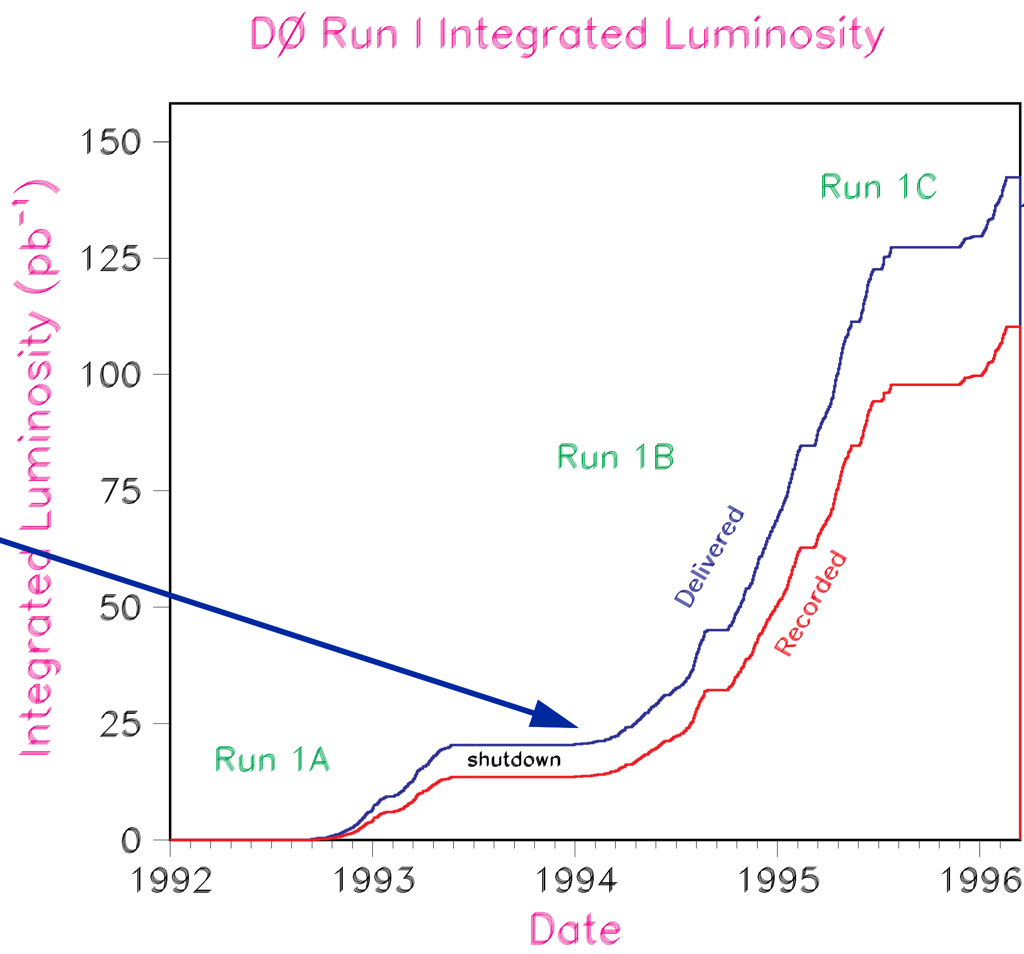
effective cross section ª 0.3• σ (W)•BR ⇒ about 1000 events

Z's will turn out to be very important

accumulated running in first, 3 year exposure!

Eric's thesis

this analysis



3 levels of triggering, overall rate reduction 10^{-5}

- **Level 0 (scint. counters) → ≈ 150 kHz (at L = 5 x 10^{30} /cm/s)**
  - **signify inelastic collision...fully efficient**
- **Level 1 (hardware) → ≈ 100 Hz**

  256 inputs to 32 separate triggers...some reserved for high-p_T electrons

  W-trigger (coverage for $|\eta| \leq 3.2$)

  - **one $E_T^{EM} >$ 10, (or 12, or 14) GeV in calorimeter towers (0.2 x 0.2)**

  Z-trigger (coverage for $|\eta| \leq 3.2$)

  - **two towers with $E_T^{EM} >$ 7 GeV**
- **Level 2 (software) → ≈ 2-3 Hz, to tape**

  128 filters, computed in a farm of 48 VAX 4000/m60's

  W-filter

  1 EM cluster w/ $E_T^{EM} >$ 20 GeV, $\not{E}_T >$ 20 GeV, loose electron shower topologies, isolation on electron candidates

  Z-filter

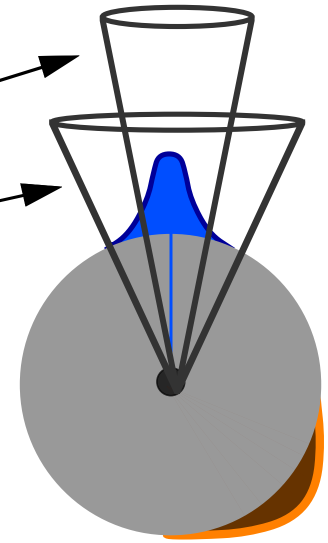
  2 EM clusters w/ $E_T^{EM} >$ 10 GeV, isolation

electron isolation inefficiency

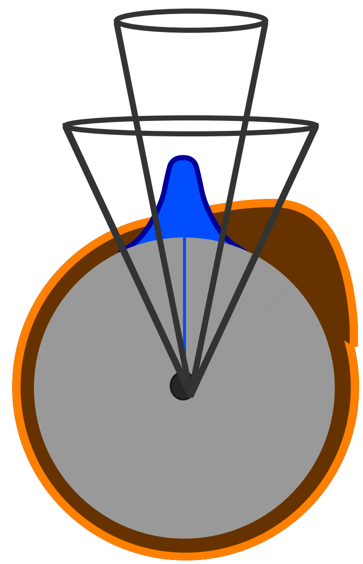
“isolation” implies determining that a cluster has electron like characteristics

- **dense, compact energy deposition**

  compare deposition inside
  a cone of a specific size
  with that in a larger cone



- **However, can lose electrons...**
  - **- recoil can be near e**
  - **- general hadron haze can be bothersome**



electron quality selection:

- EM cluster energy fraction > 90%; isolation; 20 cells or more in a cluster; general topological characteristics of “electron”...11x11 matrix; minimal leakage; module edge cuts; high quality track match, track projection - calorimeter position

W candidates

- $E_T(e) > 25$ GeV
- $\not{E}_T > 25$ GeV
- $p_T(W) < 30$ GeV/c
- $m_T < 110$ GeV

W event sample		
ECN	CC	ECS
1838	7234	1681

central electrons used int this analysis

Z candidates

- $E_T(e) > 25$ GeV, each
- small variations on above

Z event sample				
ECN-ECN	ECN-CC	CC-CC	CC-ECS	ECS-ECS
48	147	366	134	39

(event pictures)

a variety of measurements are extracted from data, for precision and accuracy

- **calibration**
  - **EM and hadron calorimeter**
    - **EM calorimetric scale determined in a test beam and secondarily using collider data: π^0 , J/ψ , Z**
    - **hadronic calorimeter scale tied to EM**
  - **module to module calorimetric uniformity from special runs..known to 0.5% per module**
  - **polar angle for the electron is determined using a bias-corrected determination of the cog of the cluster in the 3rd EM layer and the cog of the CDC track**
    - **multiple interactions compromise a precision use of the vertex position**
- **EM energy resolution**
  - **test beam + Z width**

EM scale calibration; $\delta M_W^{\text{EM scale}} = 160$ MeV/c²

- **we determine ratio** $$M_W(extracted) = \left(\frac{M_W(measured)}{M_Z(measured)}\right) \bullet M_Z(LEP)$$
- **we presume a linear response:** $E(measured) = \alpha E(true) + \delta$

  nonlinearities are determined and reflected in an error on δ
- **one can show that:** $m(measured) = \alpha\, m(true) + \delta\, f$

  where *f* is a kinematical factor depending on the decay

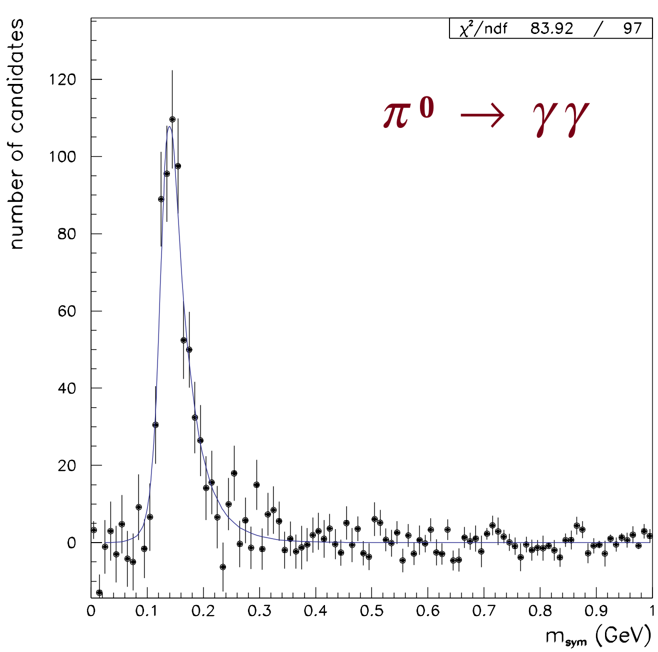
$$f = \frac{2(E_1 + E_2)}{m} \sin^2\left(\theta/2\right)$$

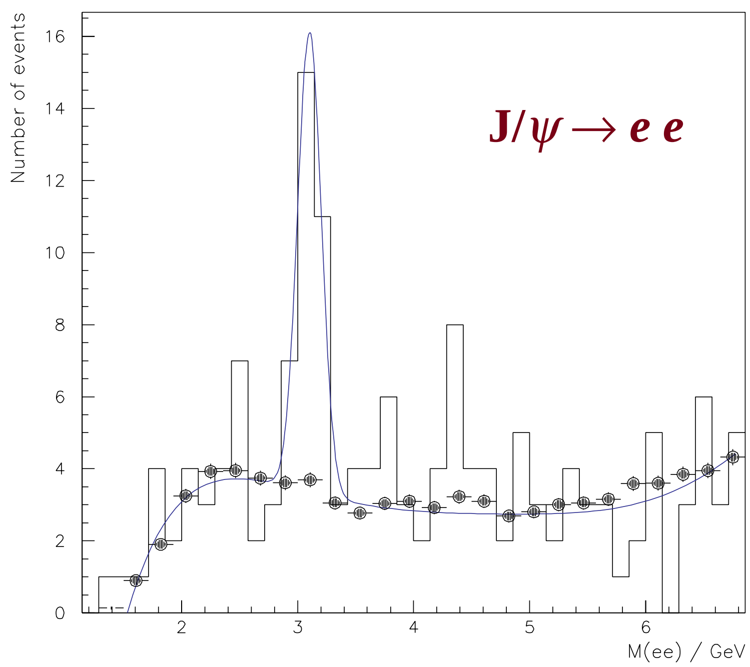
samples with different sensitivities to α **and** δ **are used**

the mass ratio can then be determined from:

$$\left(\frac{M_W}{M_Z}\right)_{TRUE} = \left(\frac{M_W(measured)}{M_Z(measured)}\right)\left[1 + \frac{f\,\delta}{\alpha} \bullet \frac{(M_Z - M_W)}{M_Z M_W}\right]^{-1}$$

derivative, gives systematic scale uncertainty



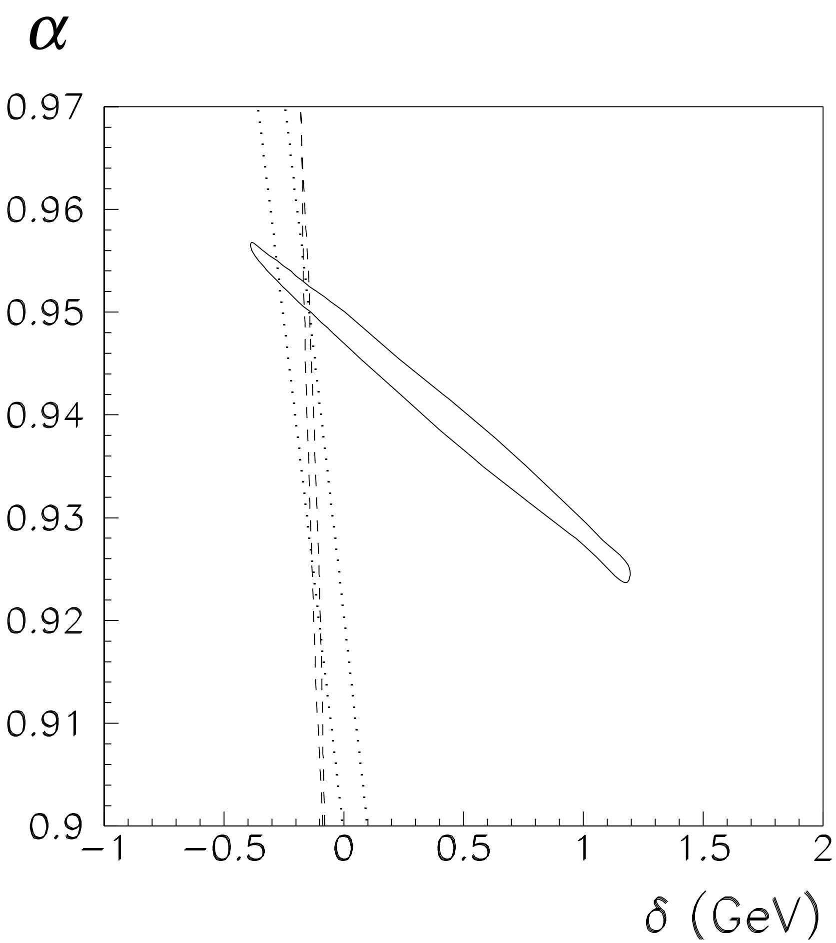


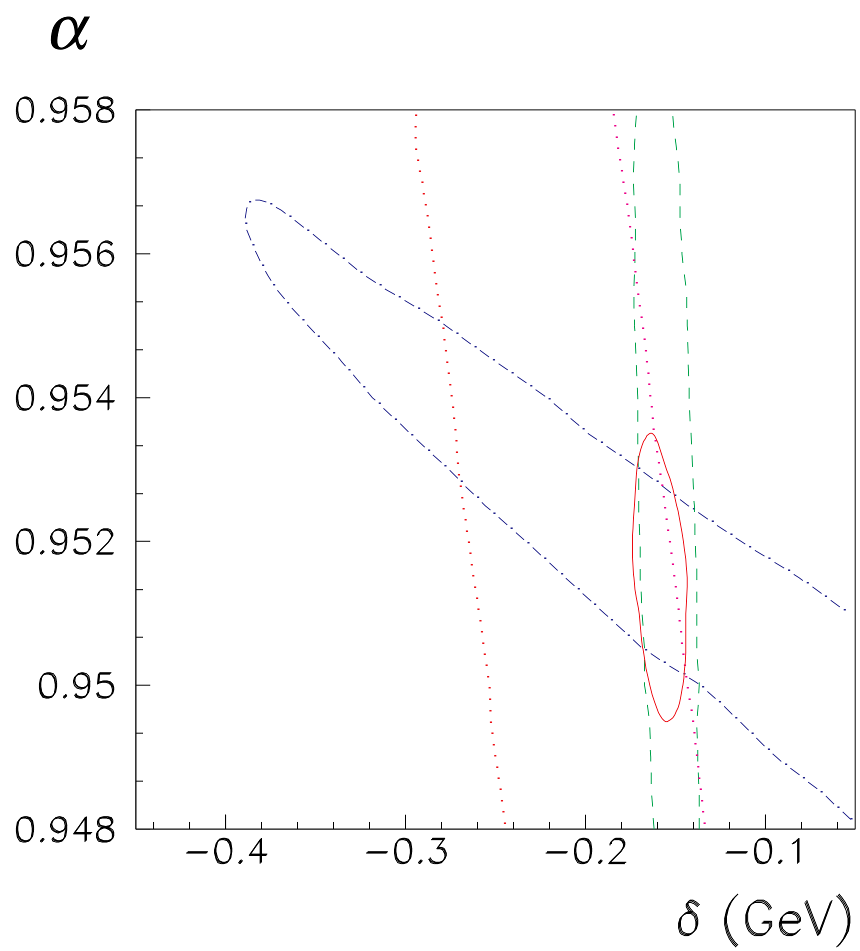
$\pi^0 \to \gamma\gamma$

$J/\psi \to e\, e$

- one EM cluster with 2 doubly ionizing tracks
- "symmetric mass" calculated $m_{sym} = E_{cluster} \sin\theta/2$ which is greater than the invariant mass

α and δ determination





$$\alpha = 0.9514 \pm 0.0018 \text{ and } \delta = -0.158 \pm 0.015 ^{+0.03}_{-0.21}$$

The MC is deweighted for the scale.

EM resolution; $\delta M_W^{\text{EM resolution}} = 70\ \text{MeV}/c^2$

the observed width of the Z is resolution dominated

- **natural width is $\Gamma_Z = 2.493 \pm 0.004$ GeV**

  Γ_Z is convoluted with a dielectron mass $\sigma(m)$ in a Breit Wigner, which in turn is correlated with the constant term in detector resolution

$$\frac{\sigma_E}{E} = C^2 \oplus \left(\frac{S}{\sqrt{E_T}}\right)^2 \oplus \left(\frac{N}{E}\right)^2$$

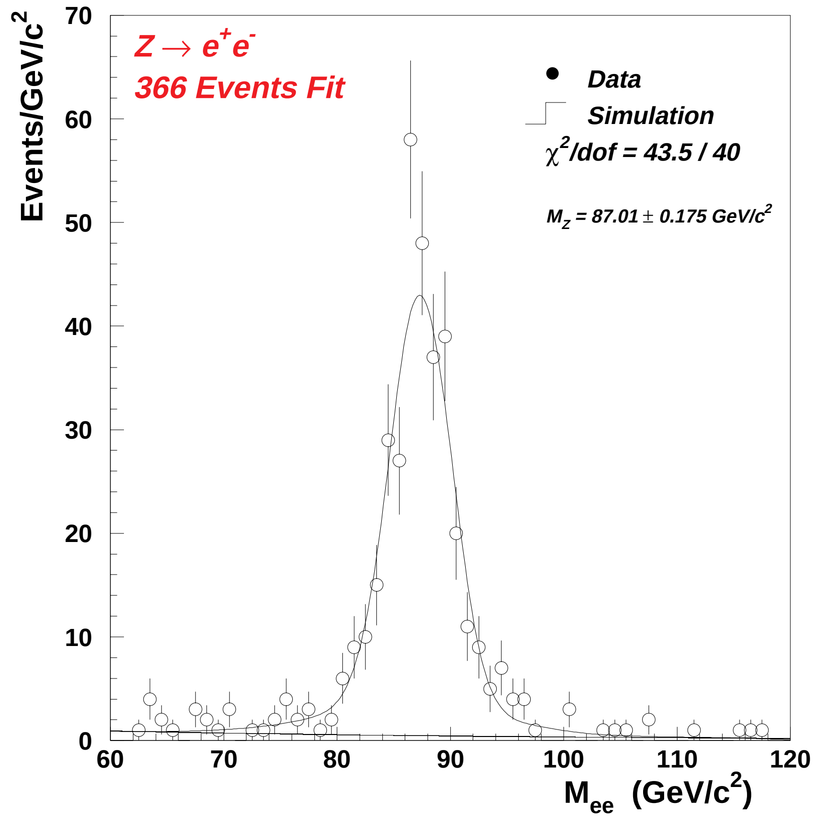
from test beam:

$S = 0.13\ \text{GeV}^{0.5}$ sampling

N = 0.4 GeV noise

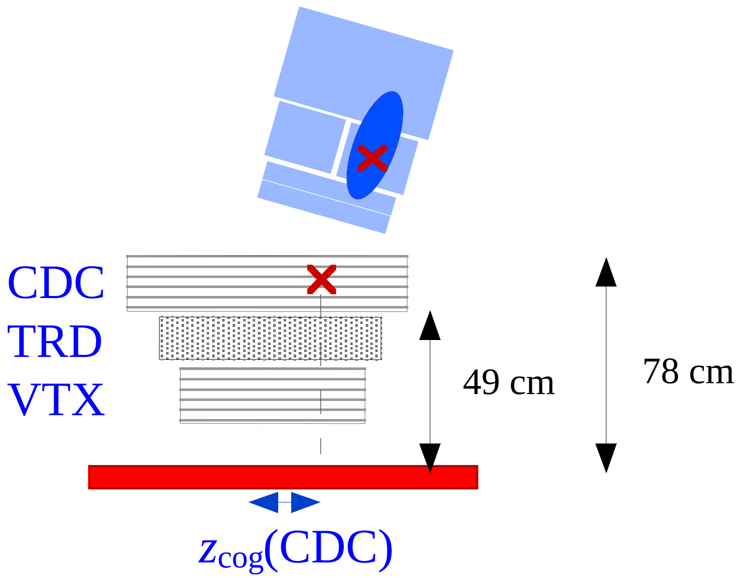
Fit:

$C = 1.5^{+0.6}_{-1.5}$ %



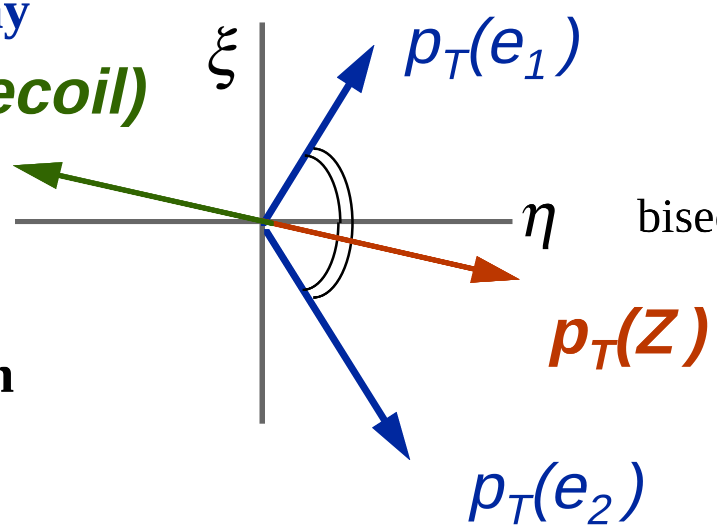
the measurement of θ directly affects $p_T(e)$

- determination of the vertex position is compromised by multiple interactions
  beam spot has $\sigma(z) \approx$ 30cm
- cog of CDC and COG of
  calorimeter cluster position
- there is a known bias in the CDC
  z position - modeled well



there are two helpful coordinate systems

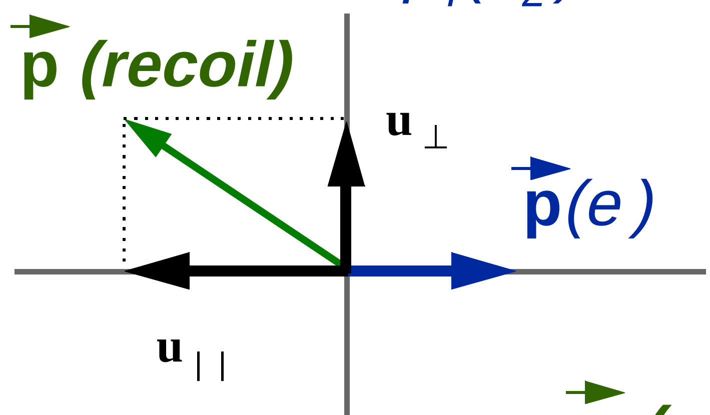
- **“$\eta - \xi$” axes: Z decay**



bisector of dielectron angles

insensitive to resolution

- **“$u_{||}$ - $u_{\perp}$” axes**

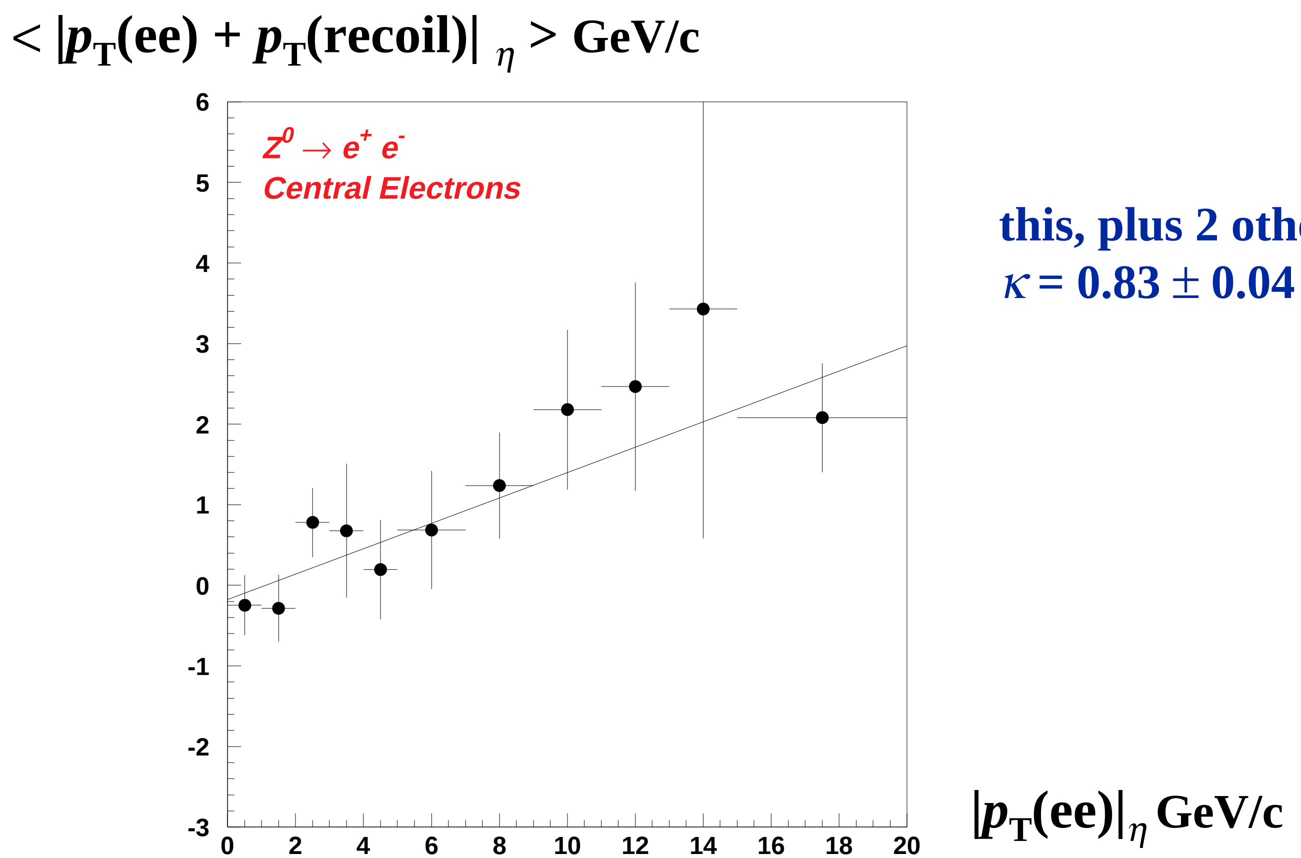


$$u_{||} = \vec{p}\,(recoil) \bullet \vec{p}(e)$$

sensitive to electron-recoil overlap

3 methods are used with over-constrained Z system...

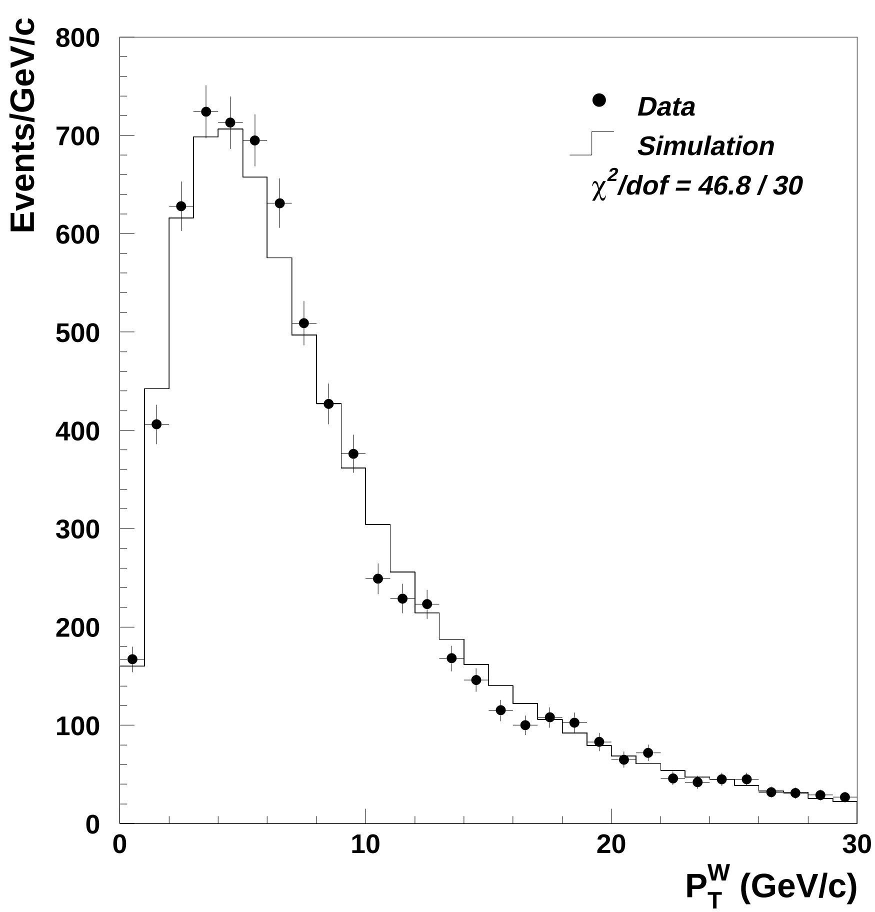
- **measure pT(Z) with electrons and compaire to recoil determination... ultimately to measure κ in $|p_T(\text{recoil})| = \kappa\ |p_T(\text{ee})|$**

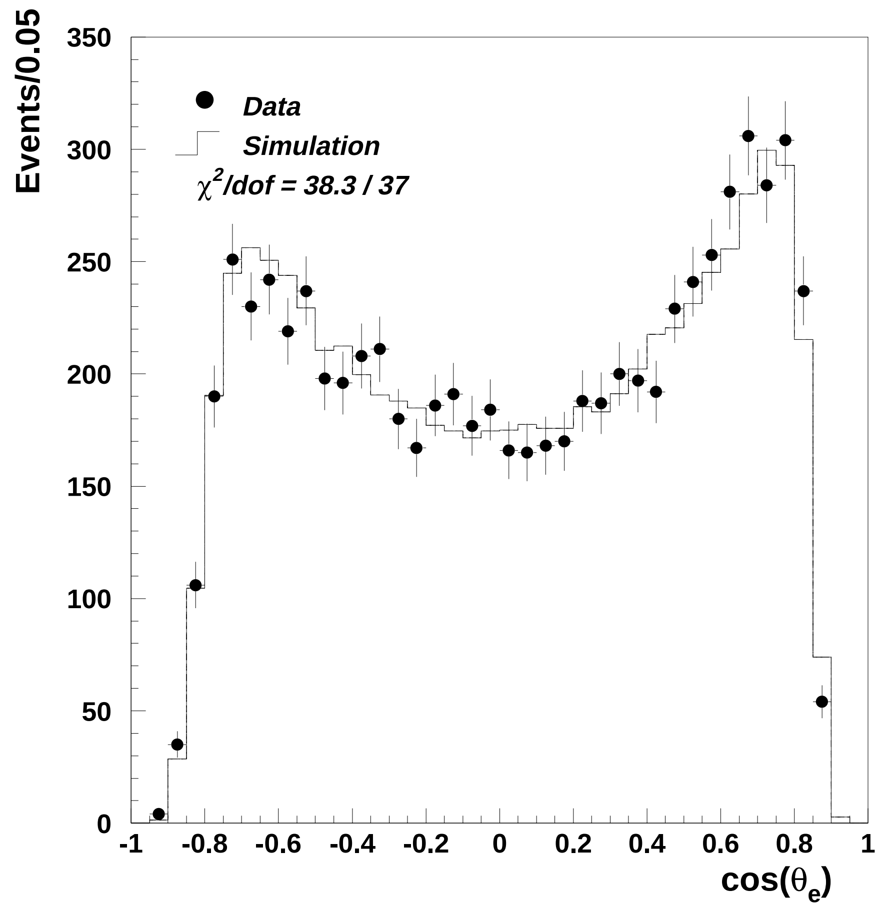


this, plus 2 other methods give $\kappa = 0.83 \pm 0.04$

The trio of measurables

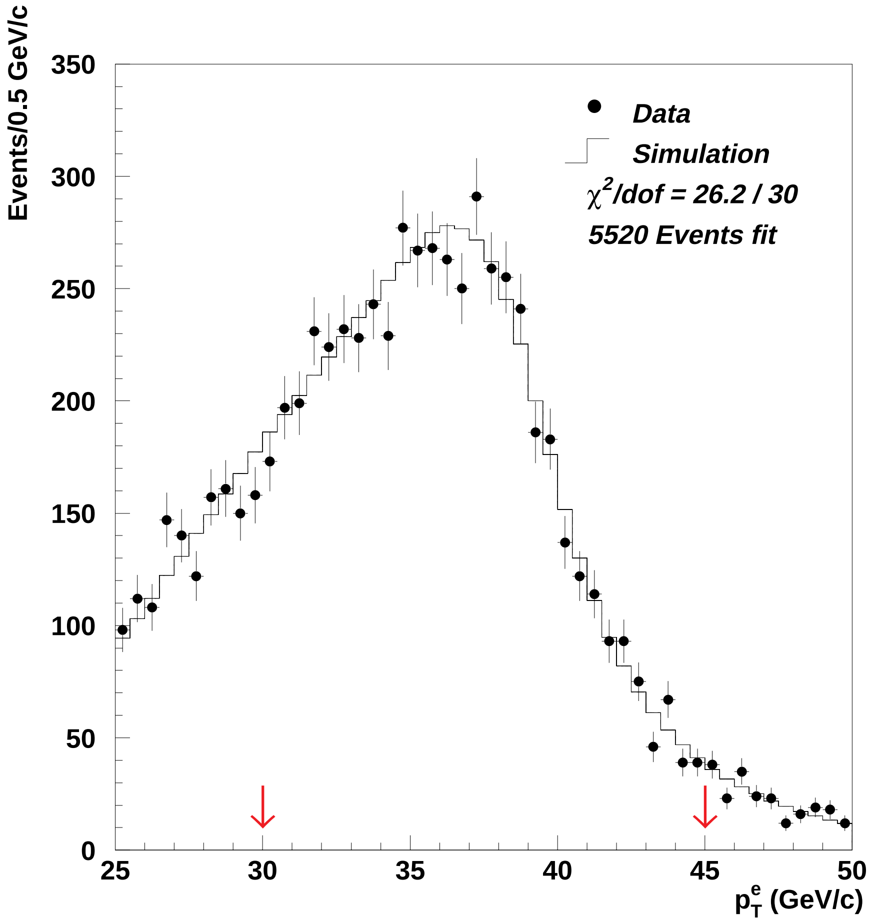
the primary ingredients to m_T:

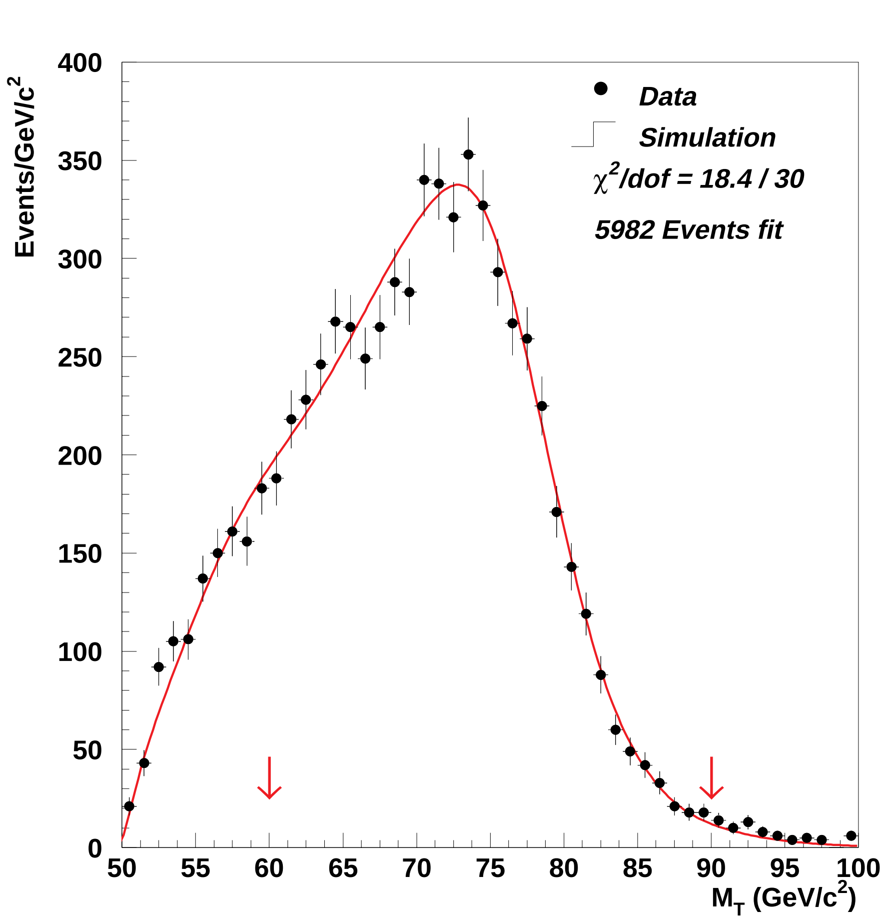




$p_T(W) = - p_T(\text{recoil})$ + $\cos(\theta_e)$ +

trio, cont.

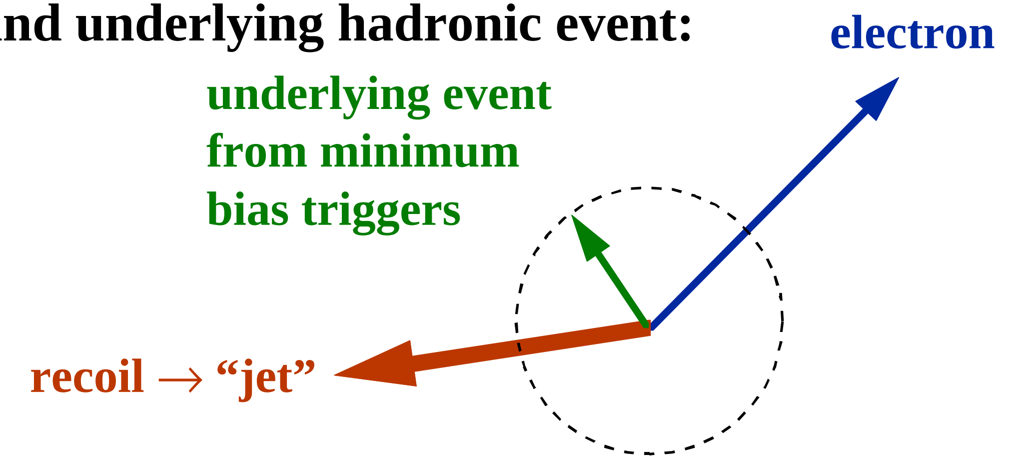




electron p_T = m_T

model for the physics

- grids of $p_T(W)$ vs y (W) are generated $$\frac{d\sigma(p\bar{p} \to W)}{dp_T dy}$$
  resummed, non perturbative model + perturbative contribution
  density matrix handled correctly
  - varied for parton distribution model
  - varied for parameters for nonperturbative production model
  - 12.8k points generated for each of 40 models
- decay performed according to *W* helicity and boosted
- recoil and underlying hadronic event:



model for the detector - must be *fast* ... 10's of millions of events required at a time

- **trigger efficiencies, kinematical cuts, tracking resolutions, EM and hadronic energy scale, energy resolutions**
- **electron identification efficiency modeled**
- **backgrounds included**

  $\mathbf{W} \rightarrow \tau\, \nu \rightarrow e\, \nu\, \nu\, \nu$

  "QCD" fake events (hadronic events in which a jet fluctuates into a large electromagnetic component) $\approx$ 1.6 $\pm$ 0.8 %

  $Z \rightarrow e\, e$ **(with an electron lost) $\approx$ 0.45 $\pm$ 0.05 %**

- **radiative decays**

  complicated, as close to electron and upsetting standard id parameters and cone algorithm for isolation

  modelled in two independent monte carlos, including full-plate GEANT simulation

underlying hadron event; $\delta M_W^{\text{min bias}}$ = 60 MeV/c^2

presumed to have character of minumum bias triggers

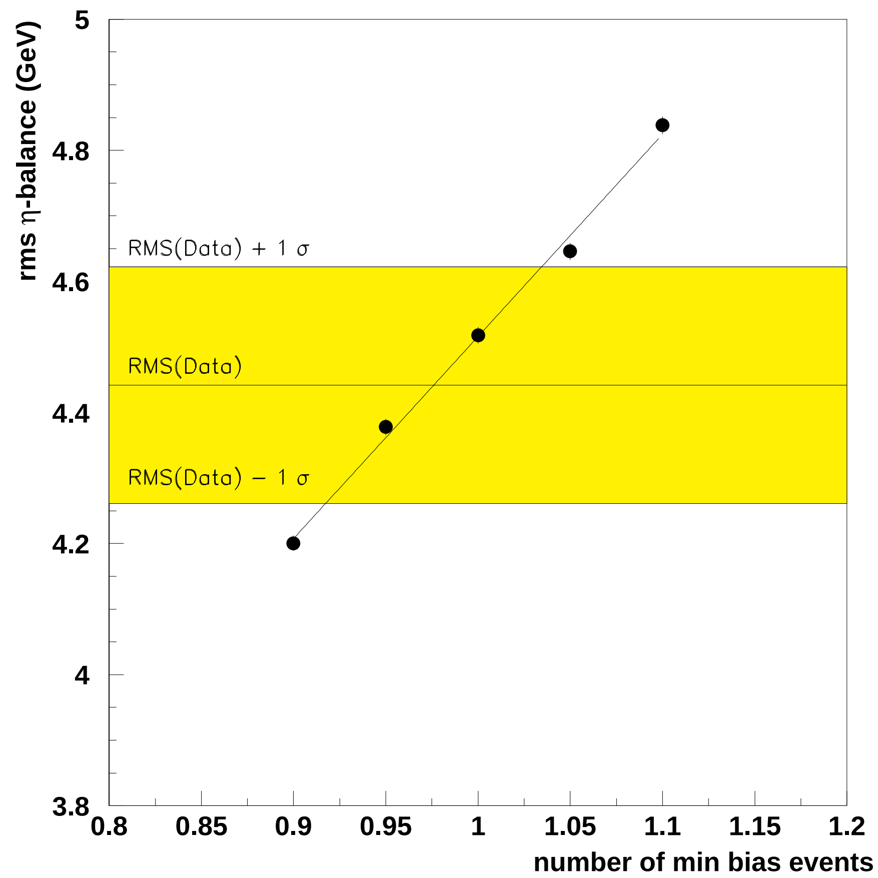
- magnitude of underlying event vector is similar to $p_T(W) \approx$ few GeV

  sensitive to width of overall η balance distribution

- conclude

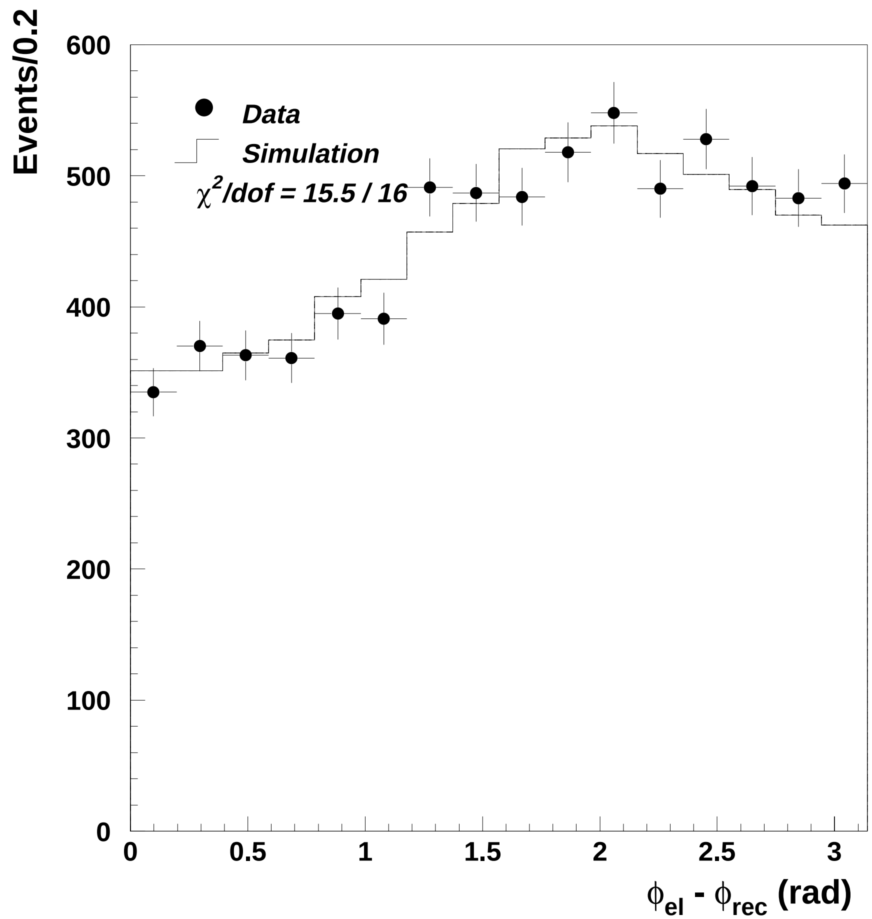
  $<$ #min bias $>$ = 0.98 ± 0.06

- min bias library created at different values of the instantaneous luminosity experienced in the run



recall $u_{||}$,

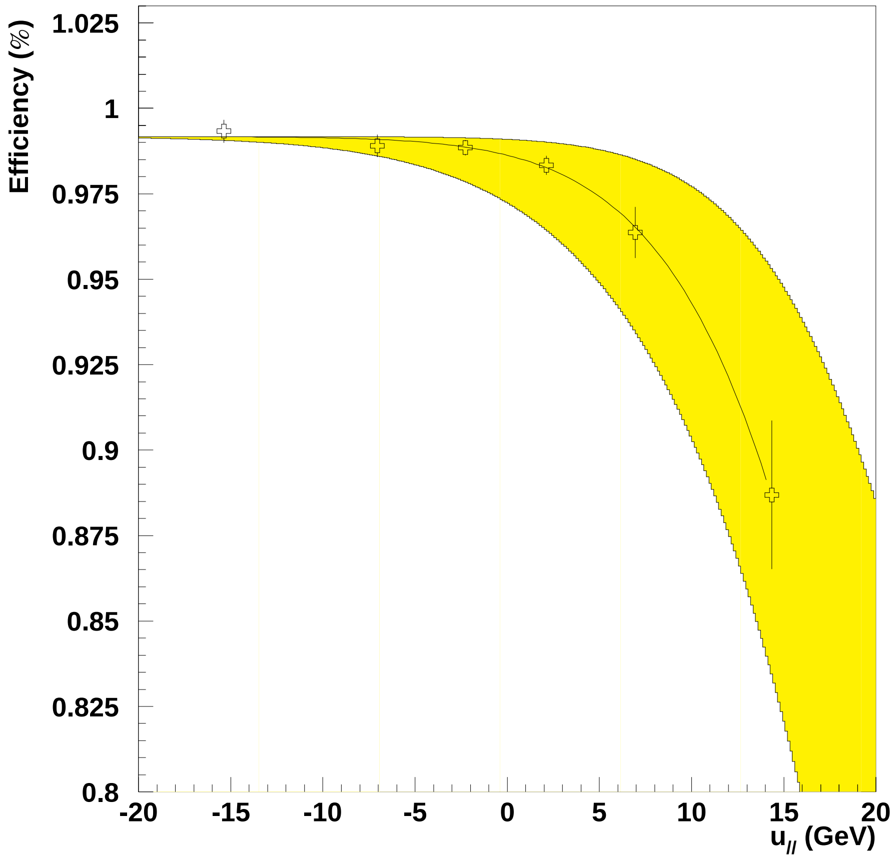
- the projection of the resultant hadron momentum vector onto the electron direction
- creates an inefficiency with isolation algorithm efficiency must be measured and included in simulation



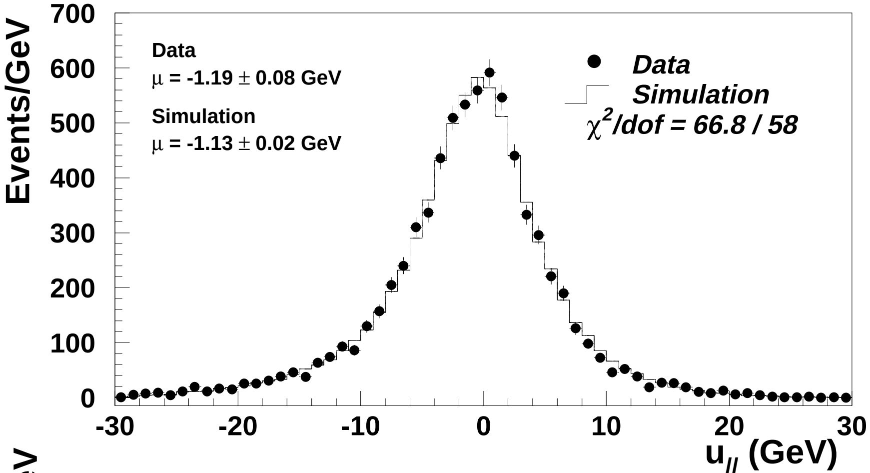
$u_{||}$ efficiency; $\delta M_W{}^{u_{||}\ \mathrm{parameterzation}} = 20\ \mathrm{MeV}/c^2$

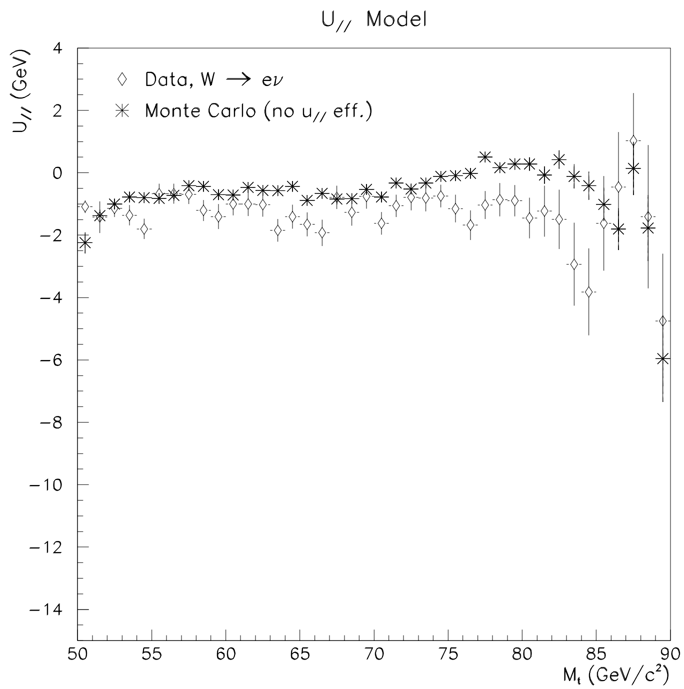
unbiased data set used to determine efficiency

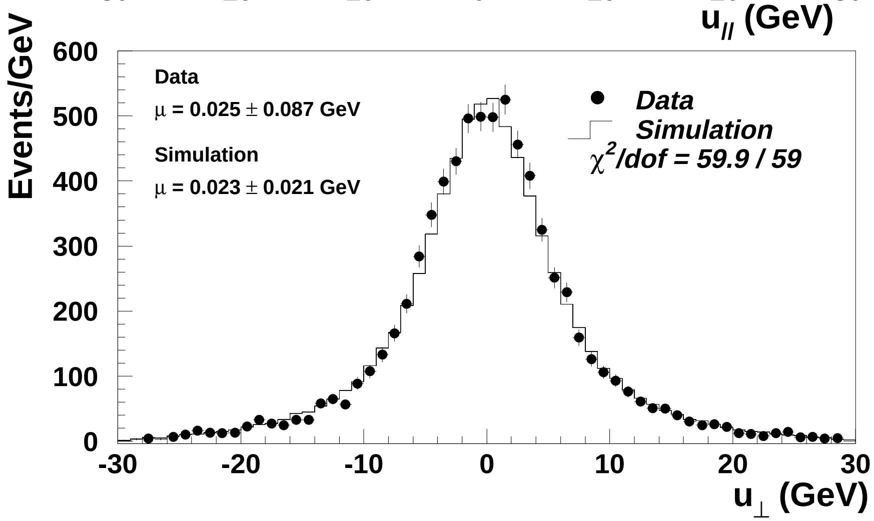
- **isolation distribution is measured for electrons in W events which are rotated away from their real position**

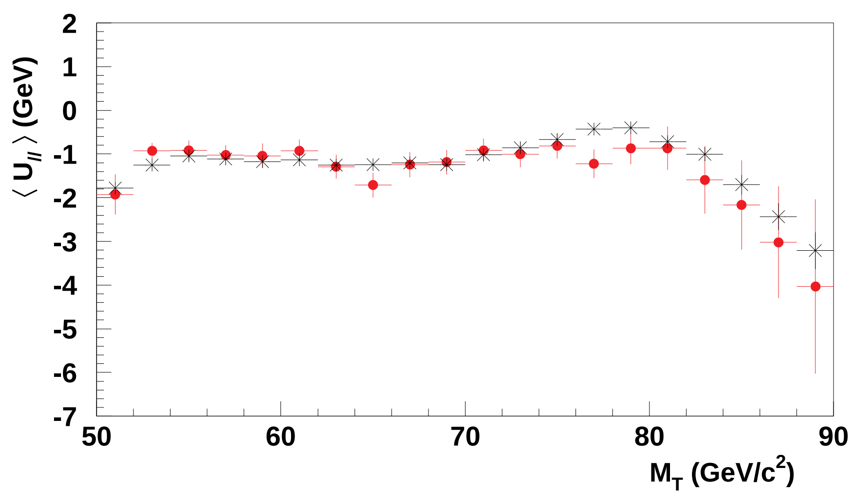


monte carlo simulates $u_{||}$ distribution well





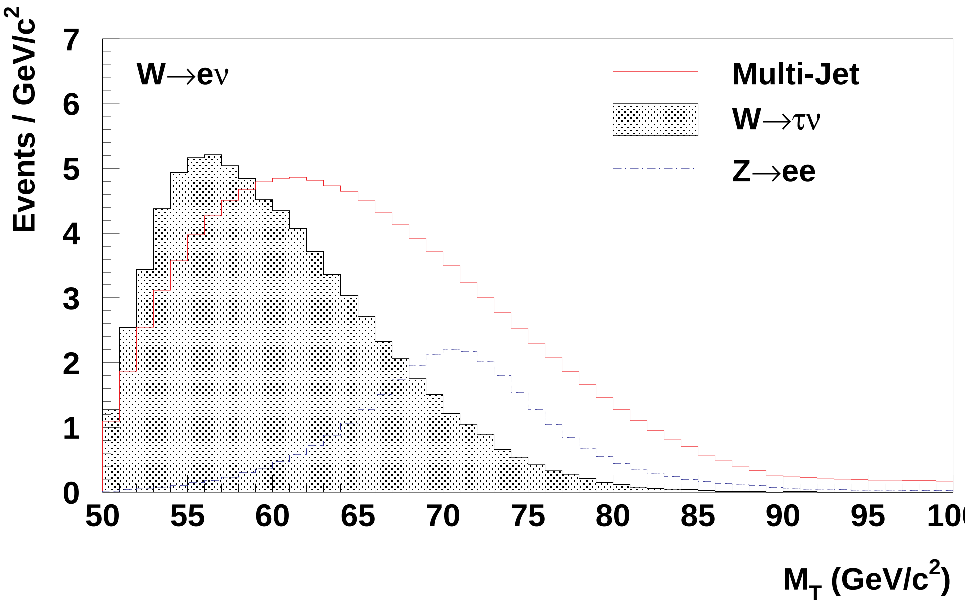


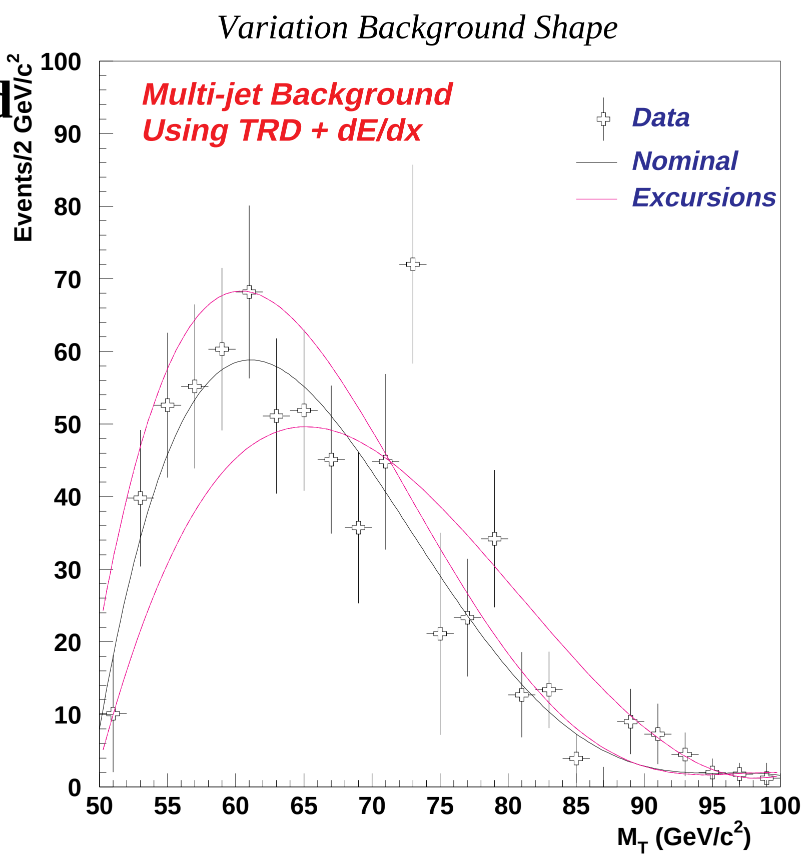


backgrounds ; $\delta M_W^{backgrounds} = 30(QCD) \oplus 20(Z)$ MeV/c²

backgrounds are understood from data

- effects on m_T
- include TRD analysis in QCD bckgnd



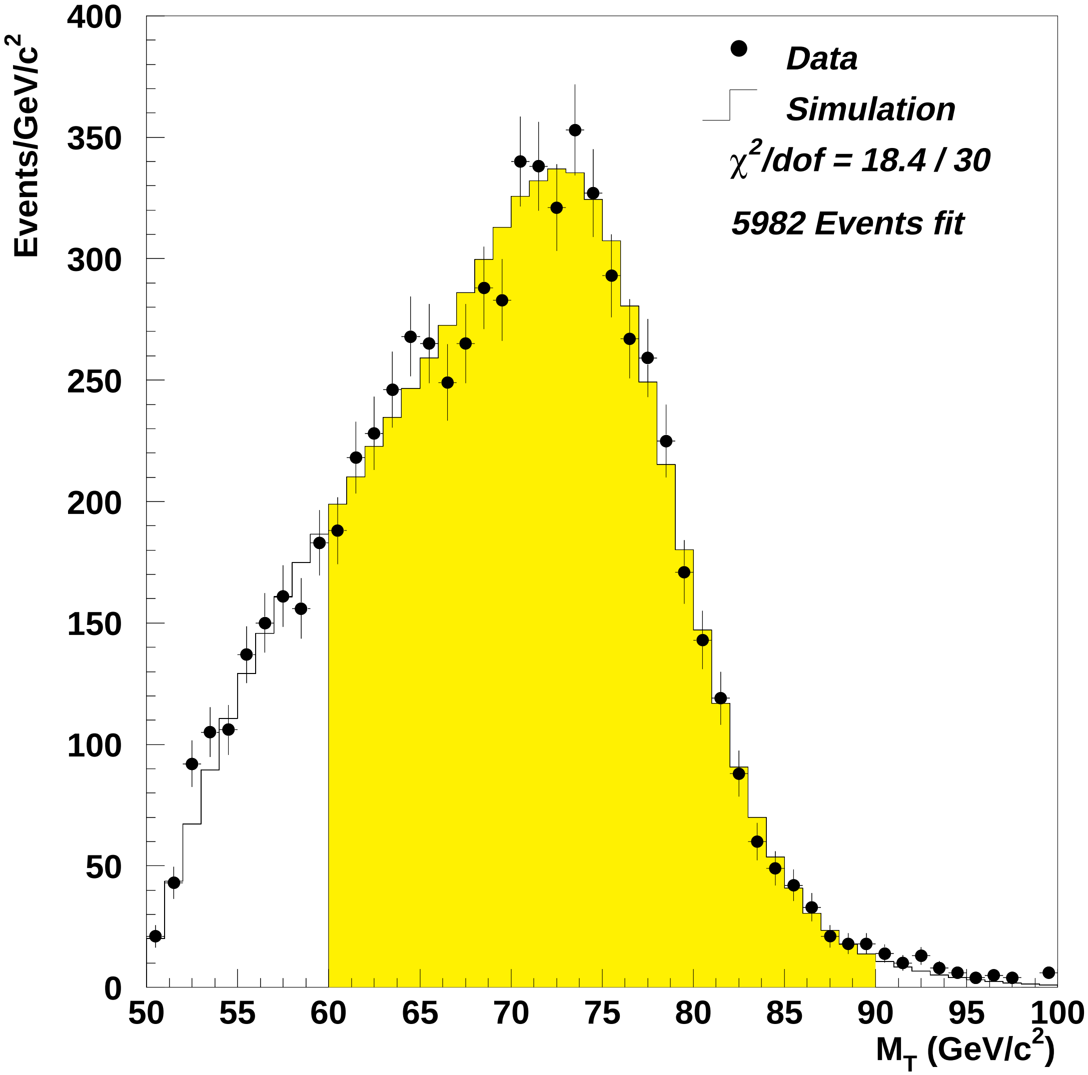


cuts on m_T instituted to minimize the effects:

$$60 < m_T < 90 \text{ GeV/c}^2$$

the results

transverse mass fit



$M_W = 80.33 \pm 0.140$ (stat) GeV/c^2

DØ final result

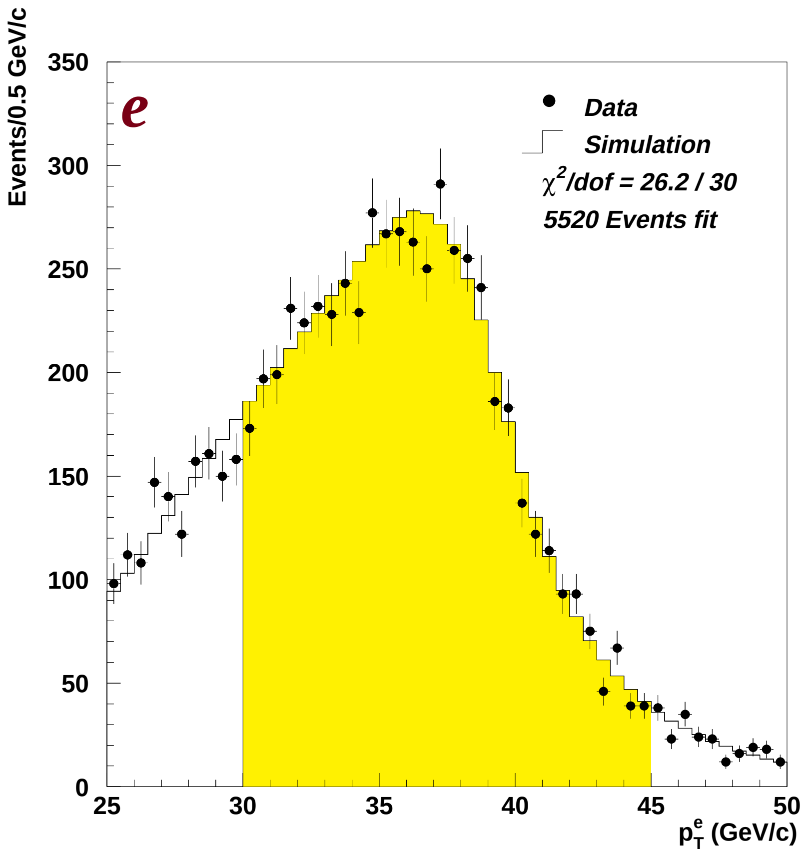
source	parameter, **P**, range	sensitivity $\partial M_W / \partial \mathbf{P}$	$\sigma(M_W)$ MeV
EM resolution	C = 1.5+0.6/-1.5 %	-112 MeV/c^2 /%	70
CDC z-scale	$\alpha = 0.988 \pm 0.002$	+25.0 MeV/c^2 / 0.001	50
had resolution	$S_{had} = 0.8 \pm 0.2$	-31.5 MeV/c^2 / 10%	65
underlying event	E_T (tower) = 16.8 ± 1.5 MeV	-	35
W-width	$\Gamma_W = 2.1 \pm 0.1$ GeV	+40.0 MeV/c^2 / GeV	10
had scale	$\alpha_{had} = 0.83 \pm 0.04$	+12.1MeV/c^2 / 0.01	50
# min bias	1.0 ± 0.05	-31.5 MeV/c^2 / %	60
bkgnd, QCD	1.6 ± 0.8 %	-	30
bkgnd, $Z \rightarrow ee$	0.43 ± 0.05 %	-	20
u|| efficiency	parameterization	-	20
rad. decays	E_{min}, $R_{e\gamma}$, χ^2	-	20
$p_T(W)$, pdf	$p_T(W)$, g_2 fit, varied 2σ MRSA - CTEQ3M difference	-	65
trigger efficiencies	efficiency spread	-	20
non-uniformity	test beam	-	10
fitting error	-	-	10
TOTAL syst.			165
TOTAL scale			160
TOTAL stat			140

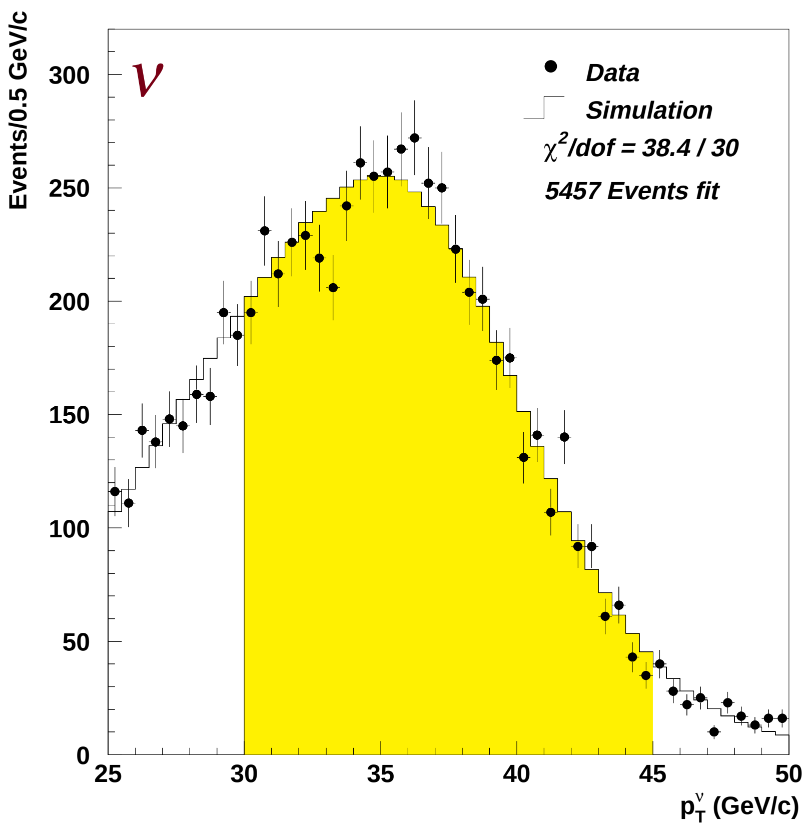
$$M_W = 80.33 \pm 0.140 \pm 0.165 \pm 0.160 \text{ GeV}/c^2$$

many checks

- **vary fitting window**
  - **variation consistent within statistical uncertainty**
  - **confirmed by MC**
- **specific subsamples**
  - **only one vertex** $\Delta M_W = -76 \pm 76$ MeV/c^2
  - $u_{||} < 10$ GeV $\Delta M_W = -16 \pm 30$ MeV/c^2
  - $p_T(W) < 10$ GeV $\Delta M_W = -160 \pm 90$ MeV/c^2
  - $|\eta| < 0.6$ $\Delta M_W = +80 \pm 150$ MeV/c^2
- **lepton p_T fits**
- **2 d fitting**
  - M_W **vs EM resolution const. term,** C $\Delta M_W = +26$ MeV/c^2
  - M_W **vs hadron energy scale,** κ $\Delta M_W = -7$ MeV/c^2

separate p_T fits to electron and neutrino

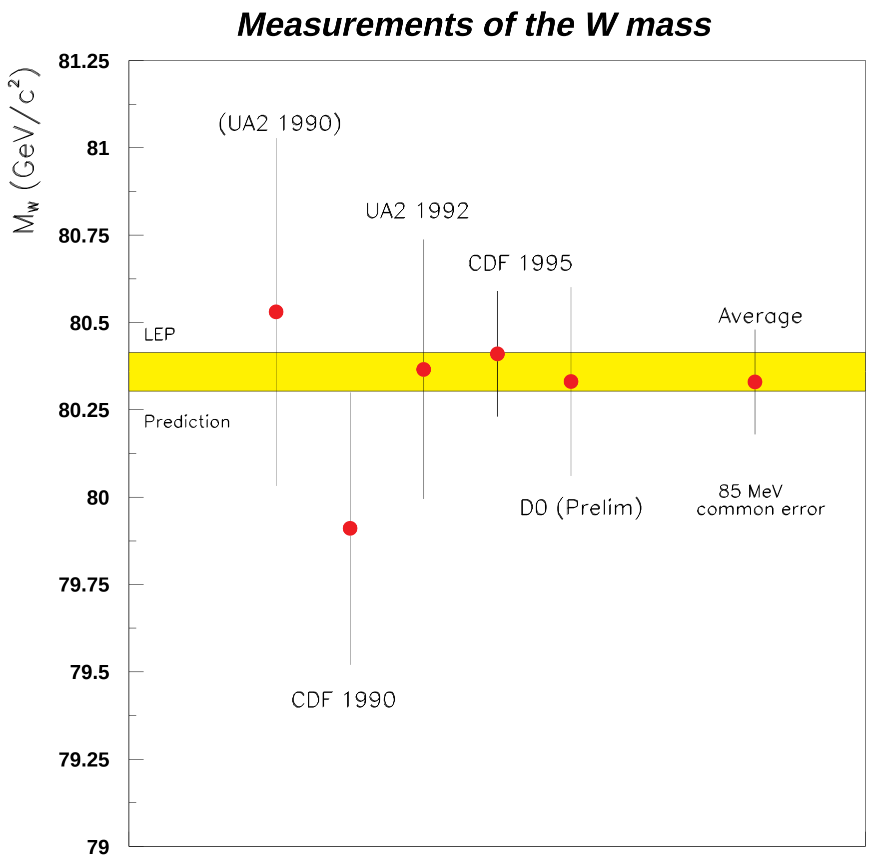




$M_W(e) = 80.280 \pm 0.190 \pm 0.315$ GeV/c²

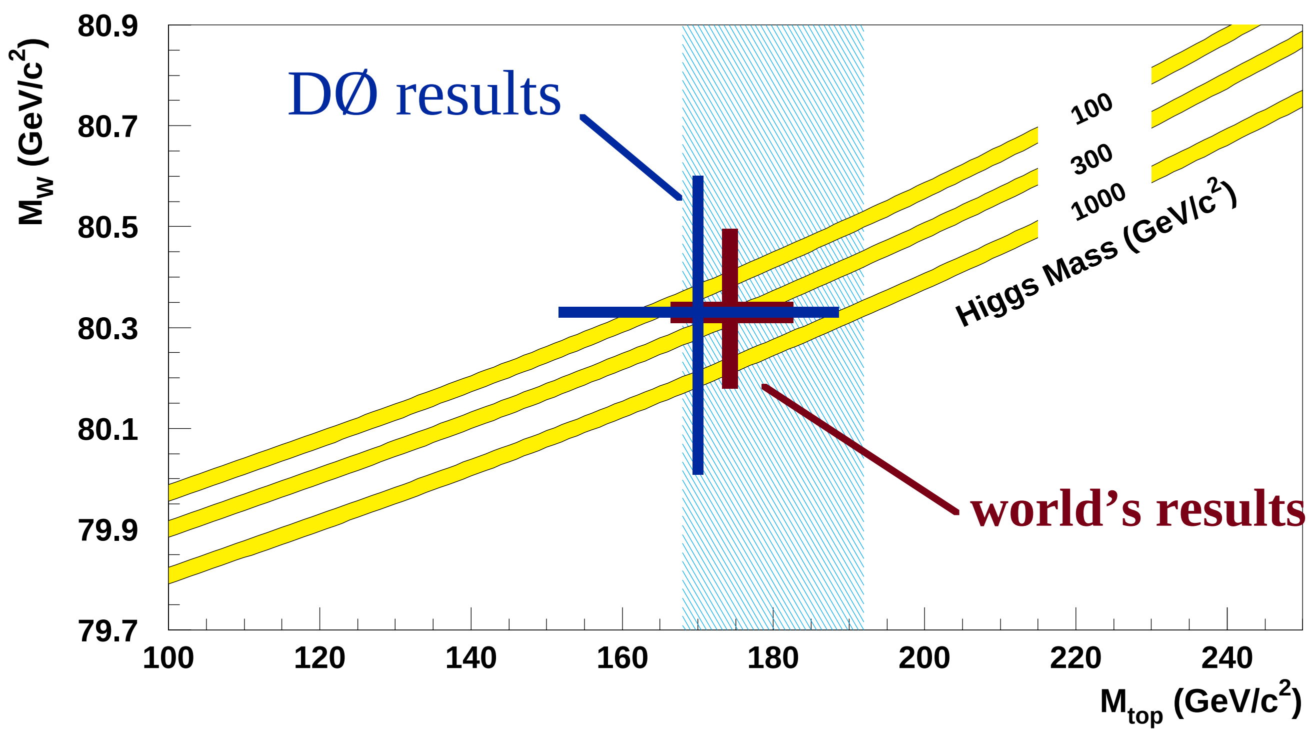
$M_W(\nu) = 80.040 \pm 0.260 \pm 0.435$ GeV/c²

world's accumulation of M_W



... but we're only partway there. Much more to come with an effort consistent with the stakes.

fermilab measurables, *redux*



Fermilab

- **completion of run 1, with the b and c cycles**
  - **probably an overall δM_W reduction by 1/2 ... ± 110 - 120 MeV /c^2**
  - **Eric and Co. now nearly at ≈ ± 120**
  - **δM_W(syst and scale) dominated by Z statistics**
- **run II, after significant accelerator and detector upgrades**
  - **1999-2000 running period, anticpate ±50 MeV /c^2 or so**
- **attempting to keep up with m_{Top} which will continue to be reduced to the few GeV/c^2 stage**

CERN

- **LEP II**
  - **running at $s = (2\ M_W)^2$ in a couple of years**
  - **targeting ± 50 MeV/c^2**