# Direct Measurement of the W Width

… or, How Fast Does the Weak Force Decay ?

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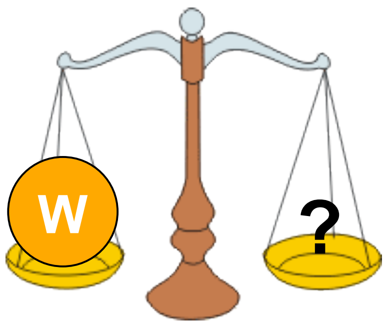
# Two Closely Related Precision Measurements from CDF

W&C
1/5/07

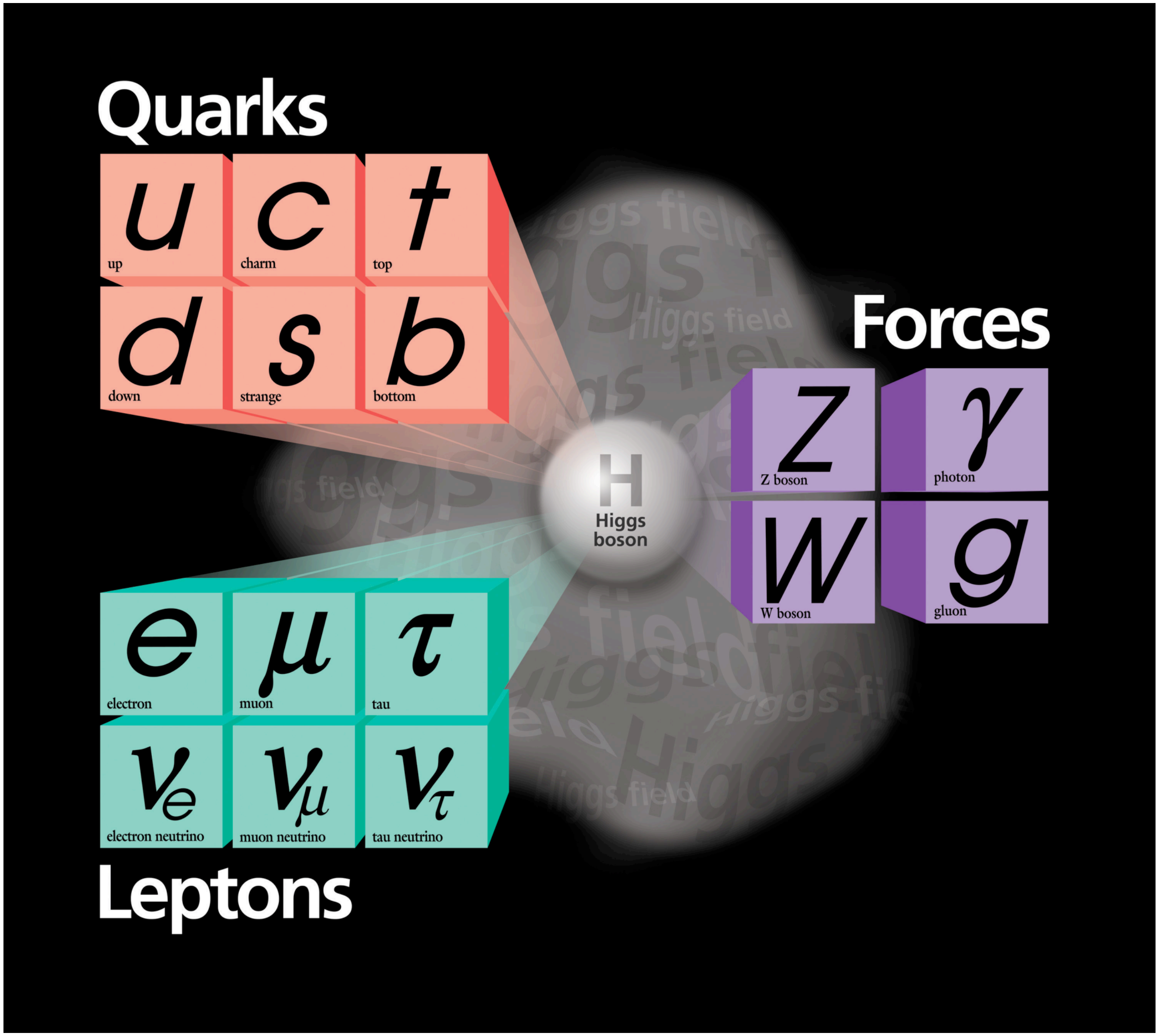


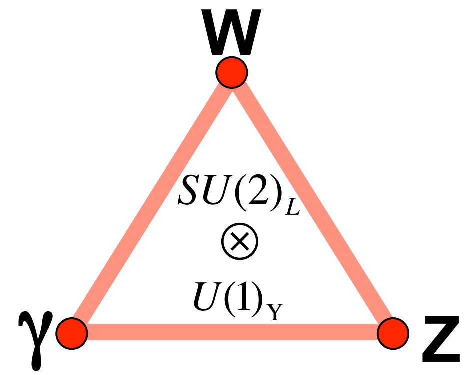

**W Boson Mass**

NEW !


**W Boson Width**

# How Well Do We Know Our Forces ?




We want to measure the properties of all the Gauge Bosons in order to confirm this basic picture.


# How Well Do We Know Our Forces ?

| Force | Carrier | Mass | Lifetime |
|---|---|---|---|
| EM | Photon | $< 10^{-16}$ eV | stable |
| Strong | Gluon | < few MeV | stable |
| Weak NC | $Z^0$ | 91.1876 ± 0.0021 GeV | $1/\tau$ = 2.4952 ± 0.0023 GeV |
| Weak CC | $W^\pm$ | 80.398 ± 0.025 GeV | $1/\tau$ = 2.137 ± 0.060 GeV **(directly measured)** |

$$\frac{\Delta M_W}{M_W} \Big/ \frac{\Delta M_Z}{M_Z} \approx 14 \qquad \frac{\Delta \Gamma_W}{\Gamma_W} \Big/ \frac{\Delta \Gamma_Z}{\Gamma_Z} \approx 30$$

# $\Gamma_W$ : Testing W Decay

- The Standard Model precisely predicts the W boson width, assuming unitarity and no non-SM decay modes.
- Radiative corrections are small when the width is expressed in terms of other precisely measured quantities (on-shell scheme) :

$$G_F = 1.16637(1) \times 10^{-5} \ \mathrm{GeV}^{-2}$$

assuming $\sum_{|\text{no top}|} |V_{qq'}|^2 = 2$

$\approx -0.35\%$ $\approx 2.5\%$

$$\Gamma_W = \frac{3 G_F M_W^3}{\sqrt{8\pi}} \left(1 + \delta_{EW}\right)\left(1 + \delta_{QCD}\right)$$

$$\Gamma_W = 2091 \pm 2 \ \ \mathrm{MeV}$$

Mainly due to uncertainty on $M_W$

▸ We aim to test this precise prediction of the Standard Model.

# Direct & Indirect $\Gamma_W$ Determinations

- An important goal is compare ***direct*** and ***indirect*** width measurements.

**DIRECT**

Literally measure the Breit-Wigner width :

$$\frac{d\sigma}{dM} \sim \frac{1}{(\hat{s} - M_W^2)^2 + (\hat{s}\Gamma_W / M_W)^2}$$

▶A measurement of far off-shell W's

**INDIRECT**

Really measurements of the W leptonic branching ratio, either directly (LEP-II) or indirectly (Tevatron) :

$$R_{\mathrm{TeV}} = \frac{\sigma_W \cdot BR(W \to l\nu)}{\sigma_Z \cdot BR(Z \to l^+ l^-)}$$

Then :

$$\Gamma_W = \Gamma^{SM}(W \to l\nu) / BR(W \to l\nu)$$

Use to test unitarity, extract $|V_{cs}|$ etc.

▶A measurement of on-shell W's

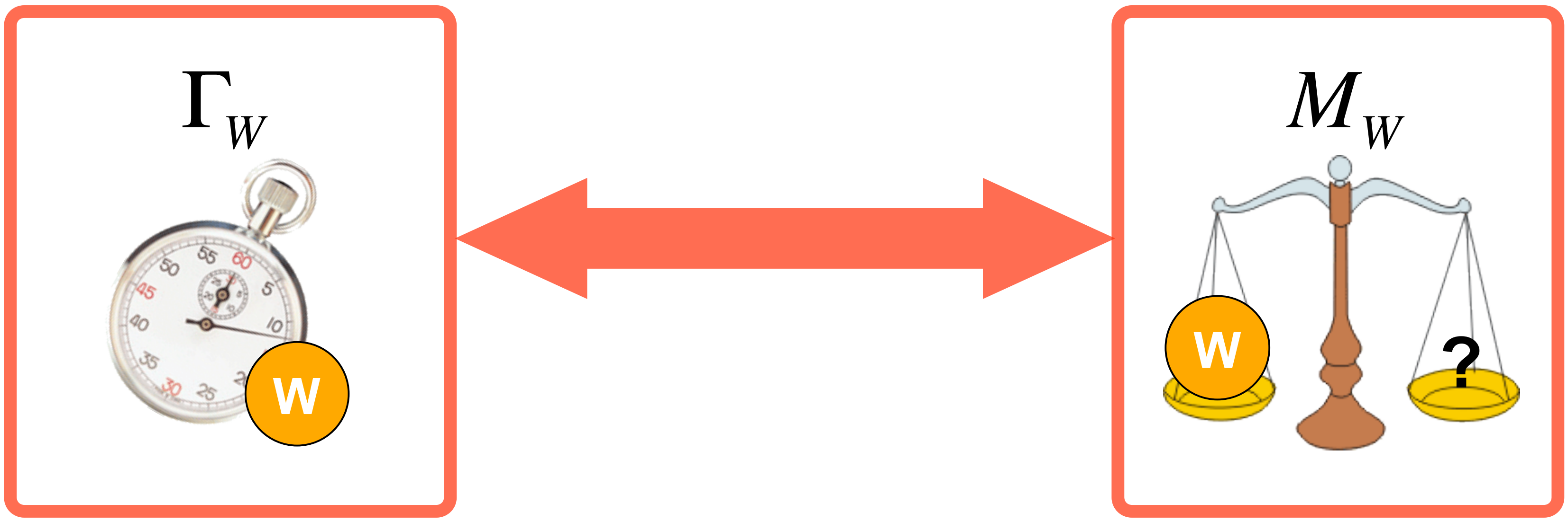
Same answer ???

# $\Gamma_W \Leftrightarrow M_W$

- Width measurement can be converted into a mass measurement :

$$\Gamma_W \propto M_W^3 \;\Rightarrow\; \frac{\Delta M_W}{M_W} = \frac{1}{3} \times \frac{\Delta \Gamma_W}{\Gamma_W}$$

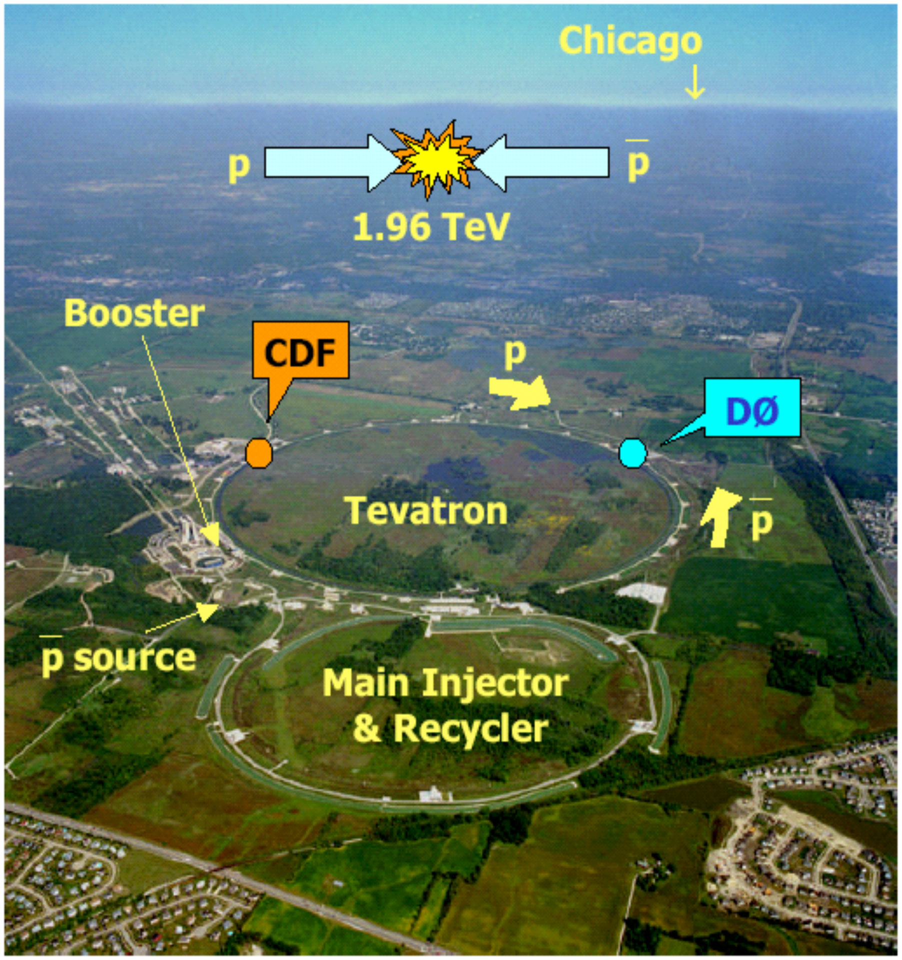
**Equivalent to a ~500 MeV $M_W$ determination (!)**




- Mass measurement depends on assumed width :

$$\frac{dM_W\,(\text{measured})}{d\Gamma_W\,(\text{assumed})} \sim 0.15$$

# The Tevatron




**W & Z Factory**

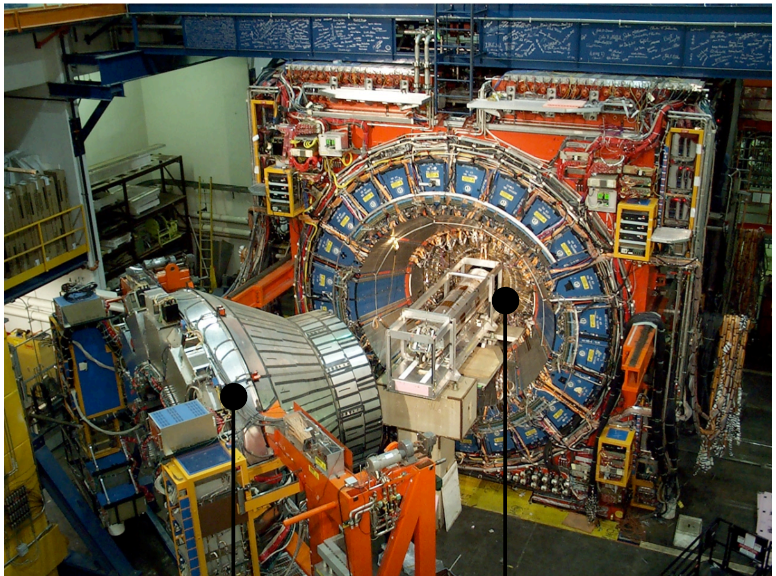
| Mode | Events/Week/Exp. (before trigger & cuts) |
|---|---|
| $W \to e\nu$ | ~50,000 |
| $Z \to ee$ | ~5,000 |
| $t\bar{t}$ | ~150 |
| $gg \to H$ $(M_H = 115\ \text{GeV})$ | ~18 |

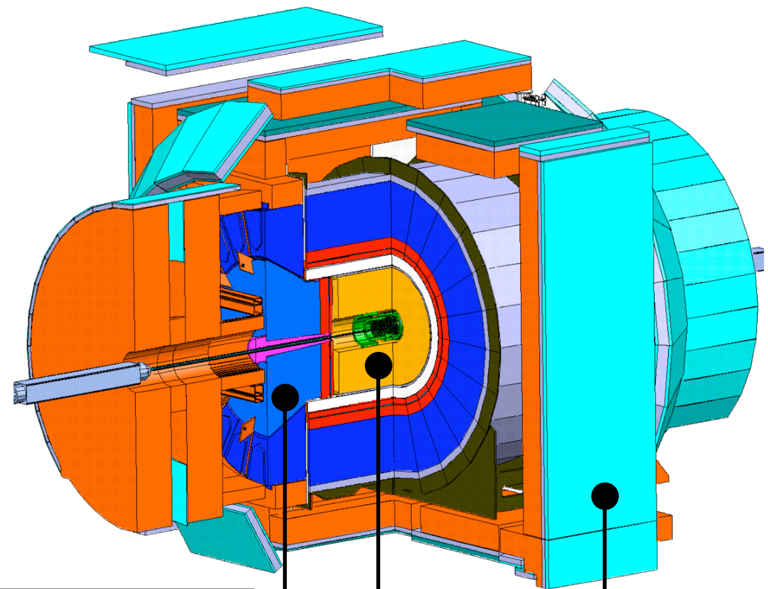
- This talk's superlative : we are approaching a $W \to l\nu$ production rate of ~1 Hz at our highest luminosity.

Now operating in precision regime:

$$N(Z \to ee)_{\text{Tevatron}} >> N(W)_{\text{LEP}}$$

# The CDF Detector





**Drift chamber outer tracker :**

$\delta p_T / p_T \approx 0.0005 \times p_T$ [GeV/c; beam constrained]; $|\eta| < 1$

**Silicon vertex detector :**

tracking coverage out to $|\eta| < 2.8$

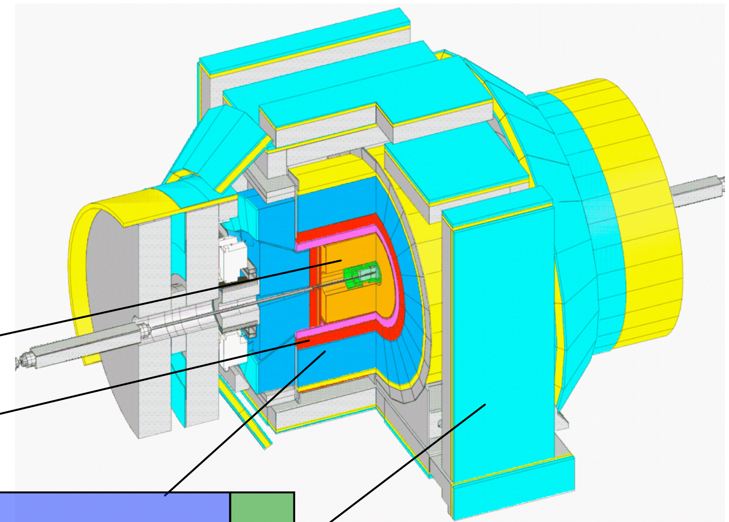
**Central calorimeter :** $\delta E_T / E_T \approx 13.5\% / \sqrt{E_T} \oplus 1\%$ $|\eta| < 1.1$

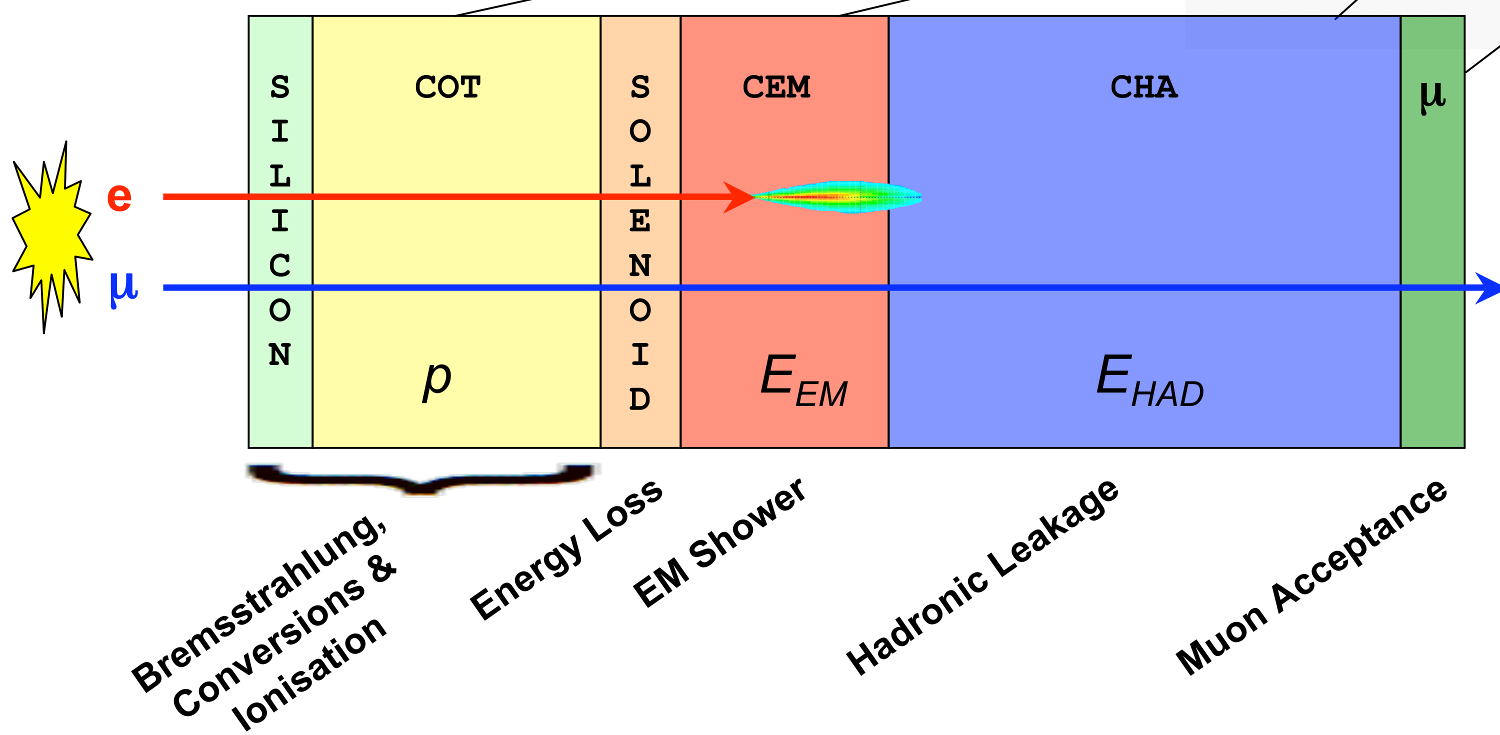
**Plug calorimeter :** coverage out to $|\eta| < 3.0$

**Muon chambers :** coverage out to $|\eta| < 1.0$

# Our Simulated Detector

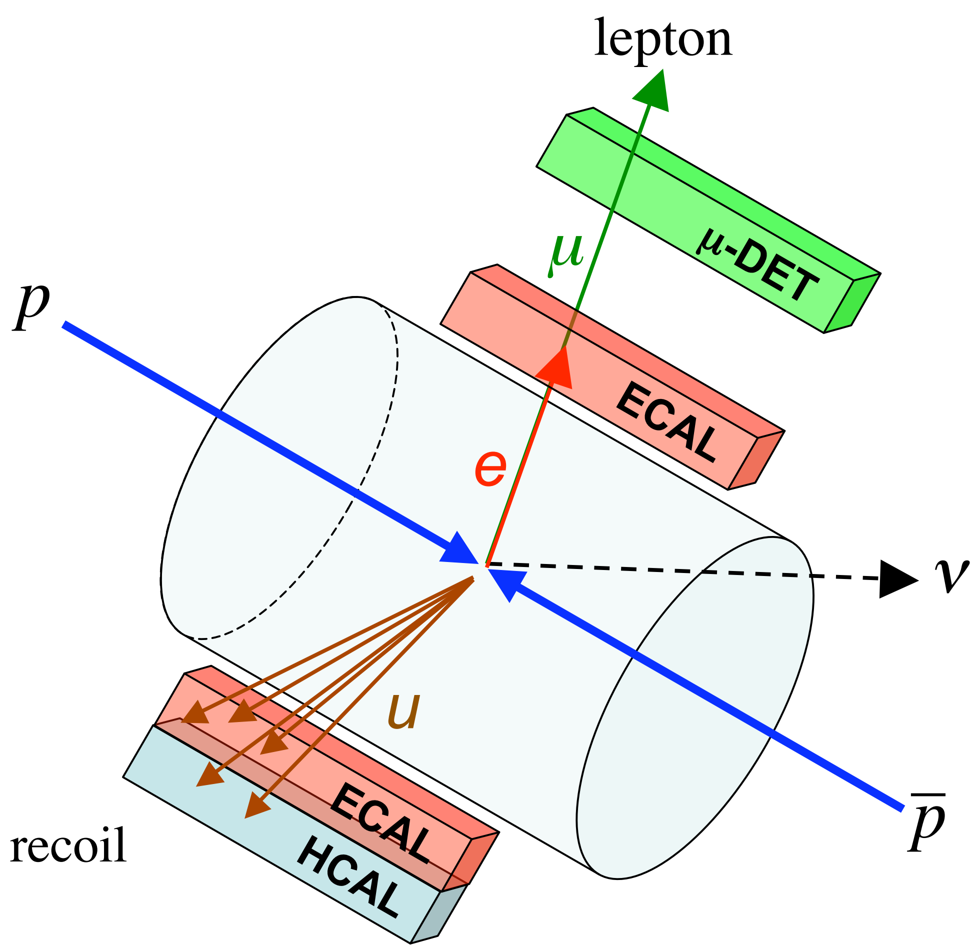
- We have developed a detailed "first principles" detector simulation : fast & easily configurable.
- Extract shower shapes from **GEANT** based full detector simulation.
- Geometry from **GEANT** & data.





# Measurement Strategy

$$p\bar{p} \to W(\to l\nu) + X$$




**Lepton :**
Measure 4-vector as precisely as possible.

**Recoil :**
Measure in transverse plane only

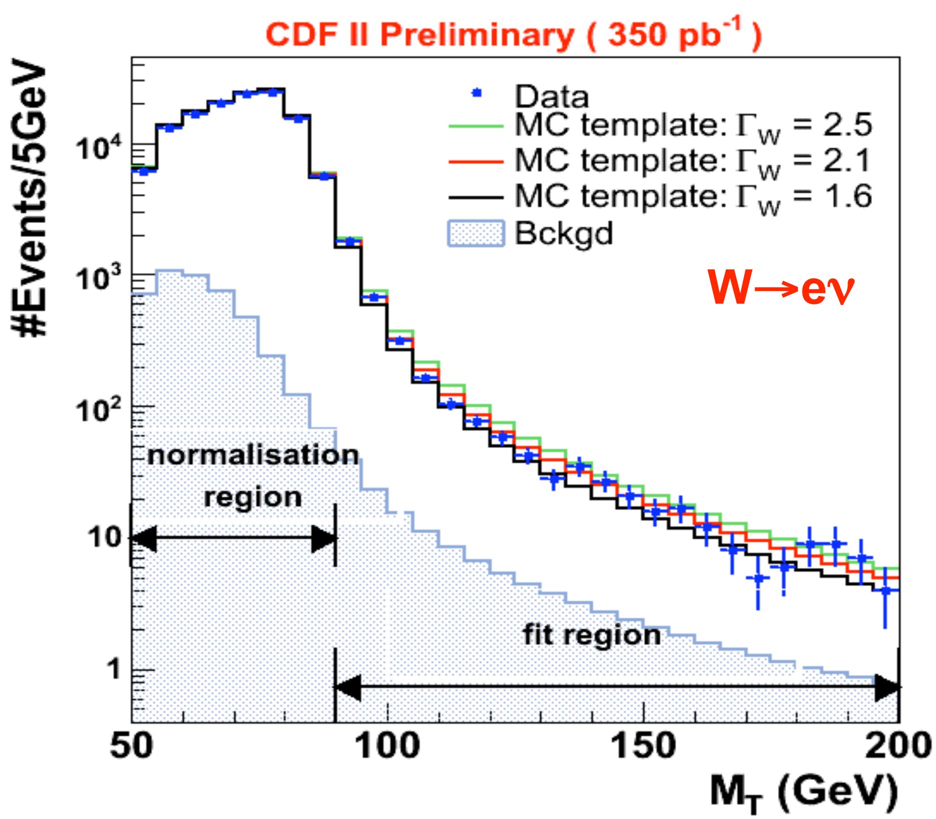
$$\vec{u} = \{u_x, u_y\}$$

**Neutrino :**
Infer transverse momentum :

$$\vec{p}_T^{\,\nu} = -(\vec{p}_T^{\,l} + \vec{u})$$

# Measurement Strategy

- Direct width measurement by "comparing the signal for real and virtual W bosons" first proposed in 1994 (**Rosner, Worah, Takeuchi, Frisch, Saltzberg**) and used by CDF and DØ in Run I.




Fit to transverse mass :

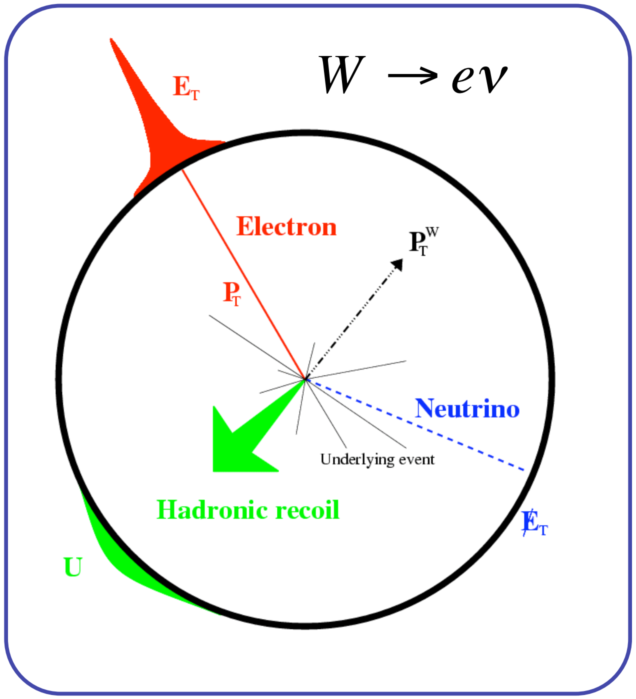
$$M_T = \sqrt{2 p_T^l p_T^\nu (1 - \cos(\Delta\phi^{l\nu}))}$$

- Fit to $M_T$ tail [90-200] GeV - **optimised**
- Normalise in peak region.
- Focus on :
  - Resolutions (especially non-Gaus.)
  - Backgrounds
  - Energy & momentum scales
  - W production modeling

# Measurement Steps

I. **Event Selection**
II. W & Z Production Modeling
III. Determine Momentum & Energy Scales
IV. Determine Resolutions
V. Measure Backgrounds
VI. Fit for the Width

# Selecting Events




<u>1 (2) leptons for W(Z) :</u>

$p_T$ > 25 GeV

<u>For W's :</u>

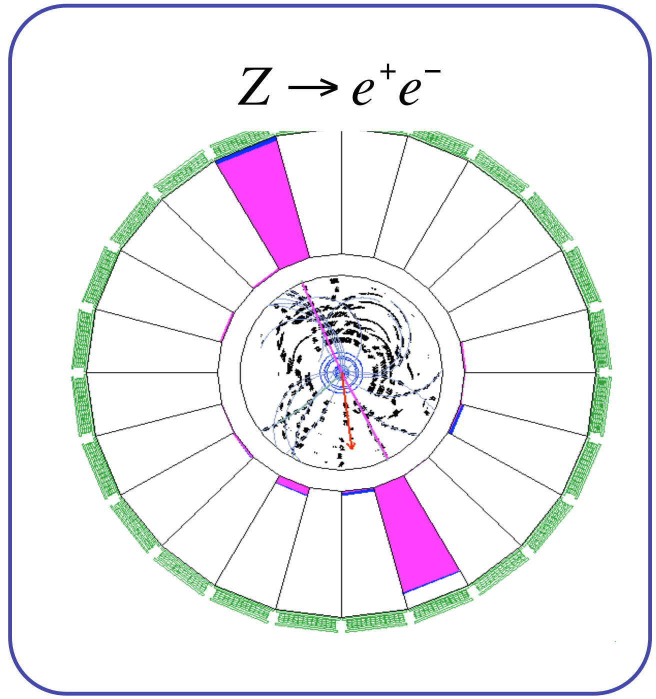
$\not{E}_T$ > 25 GeV

|U|<20 GeV

<u>Yields :</u> (350 $pb^{-1}$)

127(109)k W→**e**(μ)ν

2.9(6.3)k Z→**ee**(μμ)




- Careful choice of lepton identification cuts :
  - Minimal kinematic bias
  - Straightforward to simulate
  - Tighter cuts for the ***width*** than the ***mass*** since backgrounds are more problematic.

# Measurement Steps

I. Event Selection

II. **W & Z Production Modeling**

III. Determine Momentum & Energy Scales

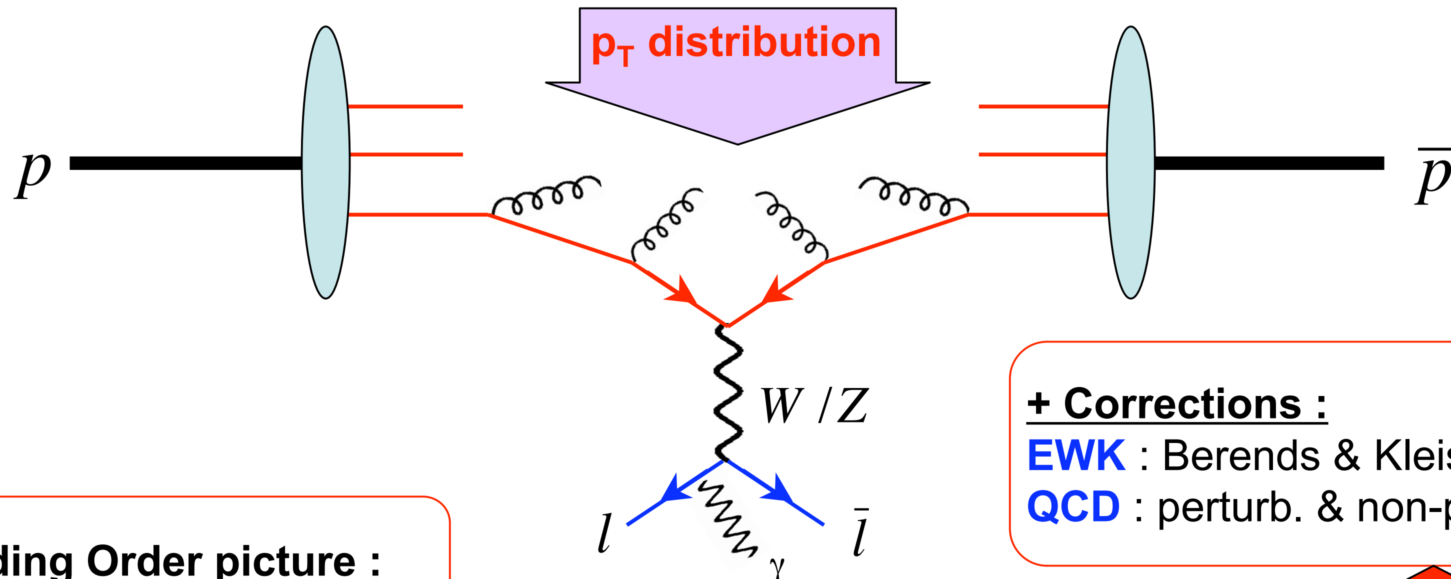
IV. Determine Resolutions

V. Measure Backgrounds

VI. Fit For the Width

**Goals** : construct as accurate a model of W production as possible. Determine systematic uncertainties.

# W/Z Production & Decay Modeling




**+ Corrections :**
**EWK** : Berends & Kleiss, PHOTOS
**QCD** : perturb. & non-perturbative

**Leading Order picture :**

$$d\sigma_{p\bar{p}\to W/Z\to l\bar{l}} = \int \sum_{i,j=u,d,s,(c,b)} [f_i^q(x_p) f_j^{\bar{q}}(x_{\bar{p}}) + f_i^{\bar{q}}(x_p) f_j^q(x_{\bar{p}})] \times d\sigma_{q\bar{q}\to W/Z\to l\bar{l}} \; dx_p dx_{\bar{p}}$$

**rapidity distribution**

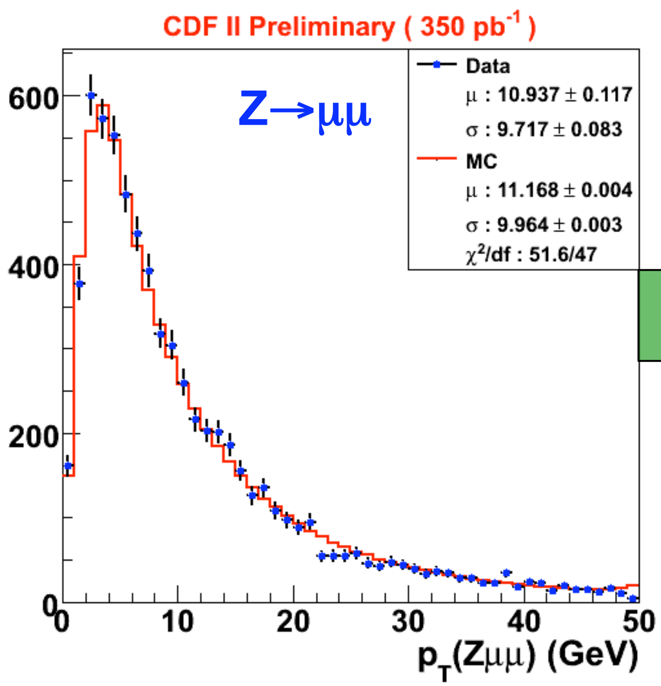
**angular & mass distributions :**

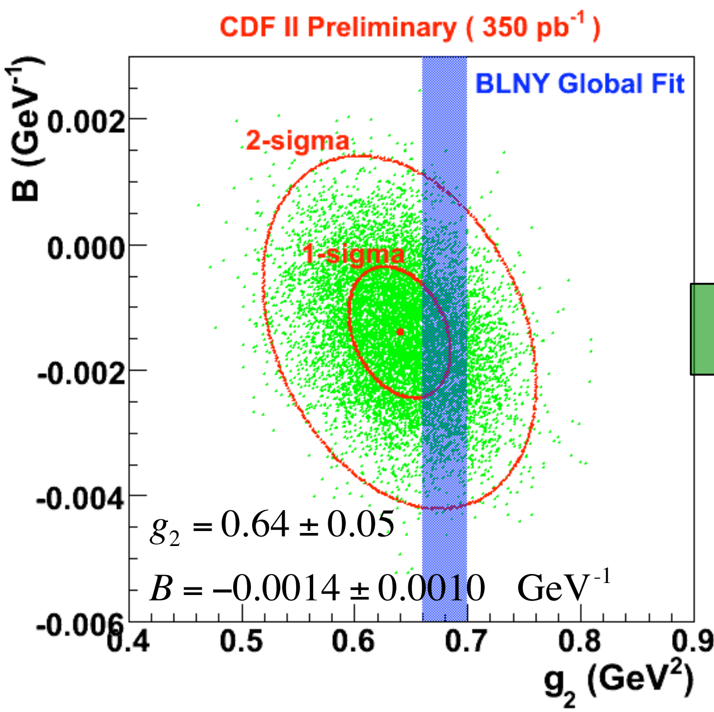
$$d\sigma_{q\bar{q}\to W/Z\to l\bar{l}}(\hat{s},\theta_l,\phi_l) \propto \text{couplings} \times \left[\frac{1}{(\hat{s} - M_{W/Z}^2)^2 + (\Gamma_{W/Z}\hat{s}/M_{W/Z})^2}\right]$$

# W Production Modeling : $p_T$

- Use the best theoretical model on the market :
  - NLO QCD + resummation + non-perturbative. **Brock, Landry, Nadolsky & Yuan (2003)**
- But, we don't trust it blindly ! We constrain BLNY parameters and lineshape using *our own Z data* :

$$\frac{d\sigma}{dp_T^Z} \sim (1 + B \cdot p_T^Z) \times f(g_1, g_2, g_3)_{\mathrm{BLNY}}$$

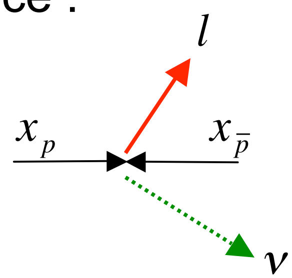


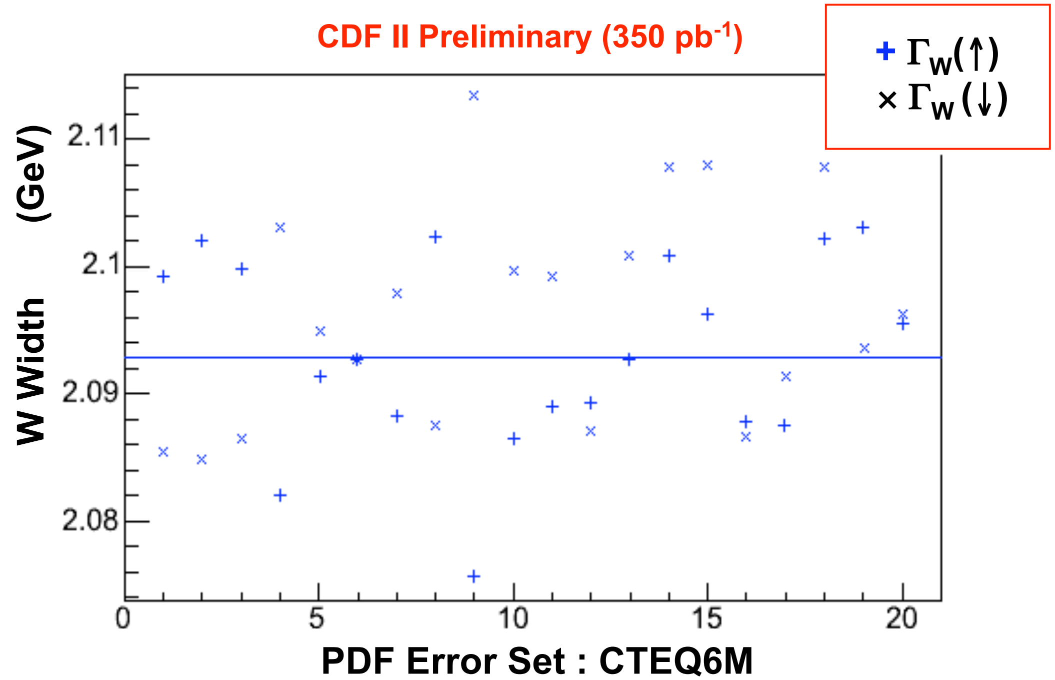

$\Delta\Gamma_W$ **(e,μ): 7 MeV**

# W Production Modeling : $p_Z$

- Different PDF's result in slightly different spectra & experimental acceptance :




- Generate reweighted event ensembles using **CTEQ6M** "error sets" obtained by fits to world data.




$$\Delta O = \frac{1}{2}\sqrt{\sum_i (\Delta O^i_+ - \Delta O^i_-)^2}\,/1.6 \quad ; \quad O = \Gamma_W$$

**$\Delta\Gamma_W$ (e,$\mu$): 17 MeV**

▶ Tevatron PDF constraints (e.g. from W charge asymmetry) may be useful in future.

# Measurement Steps

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III. **Determine Momentum & Energy Scales**

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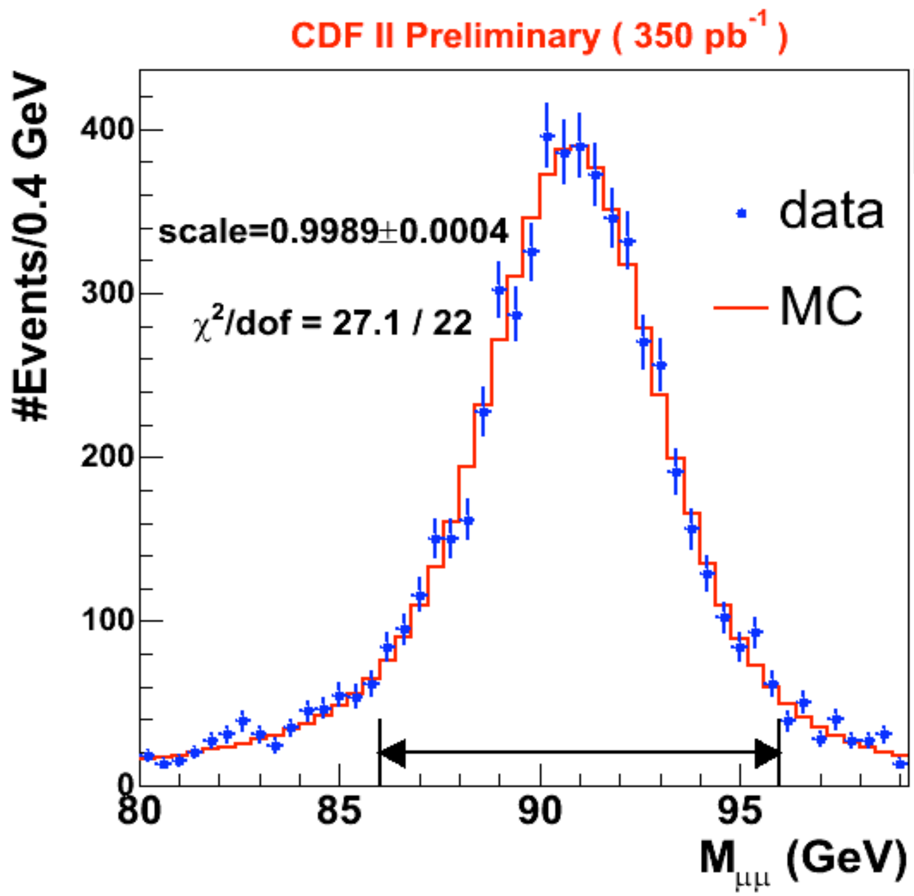
**Goals** : measure the momentum scale of the tracker and the energy scale of the calorimeter to a few parts per 10,000.

# Momentum Scale : W→μν

- Use the Z resonance : find the momentum scale for simulated **Z→μμ** events @ 91.187 GeV that best fits the data.




**Δp/p = 0.04% : $\Delta\Gamma_W(\mu)$= 17 MeV**

<u>Aside :</u>

- We don't need to use the low mass resonances J/ψ and Υ since the scale uncertainty is sub-leading for the width.
- There is essentially zero extrapolation from Z's to W's in curvature space, in contrast to J/ψ's :

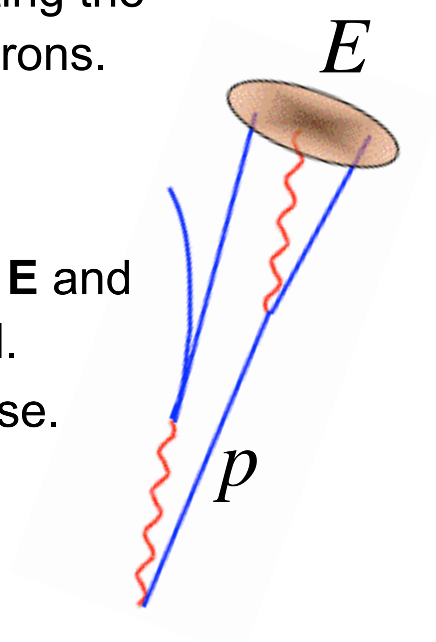
$$\Delta(1/p_T)[W,J/\psi] \sim 200 \times \Delta(1/p_T)[W,Z]$$

# Electron Energy Scale

- How do we precisely determine the electromagnetic calorimeter energy scale ?

[1] Transfer the precise momentum scale to the calorimeter by fitting the ratio ***E/p*** for electrons.

- Hard ! Need to understand reconstruction of **E** and ***p*** in minute detail.
- Statistically precise.

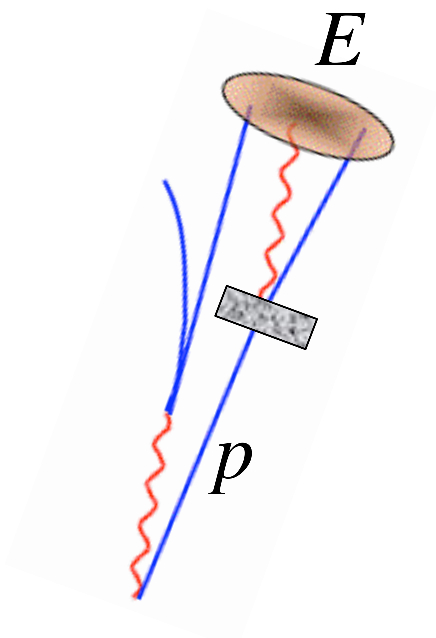



[2] Extract directly by fitting to precisely known **Z→ee** resonance.

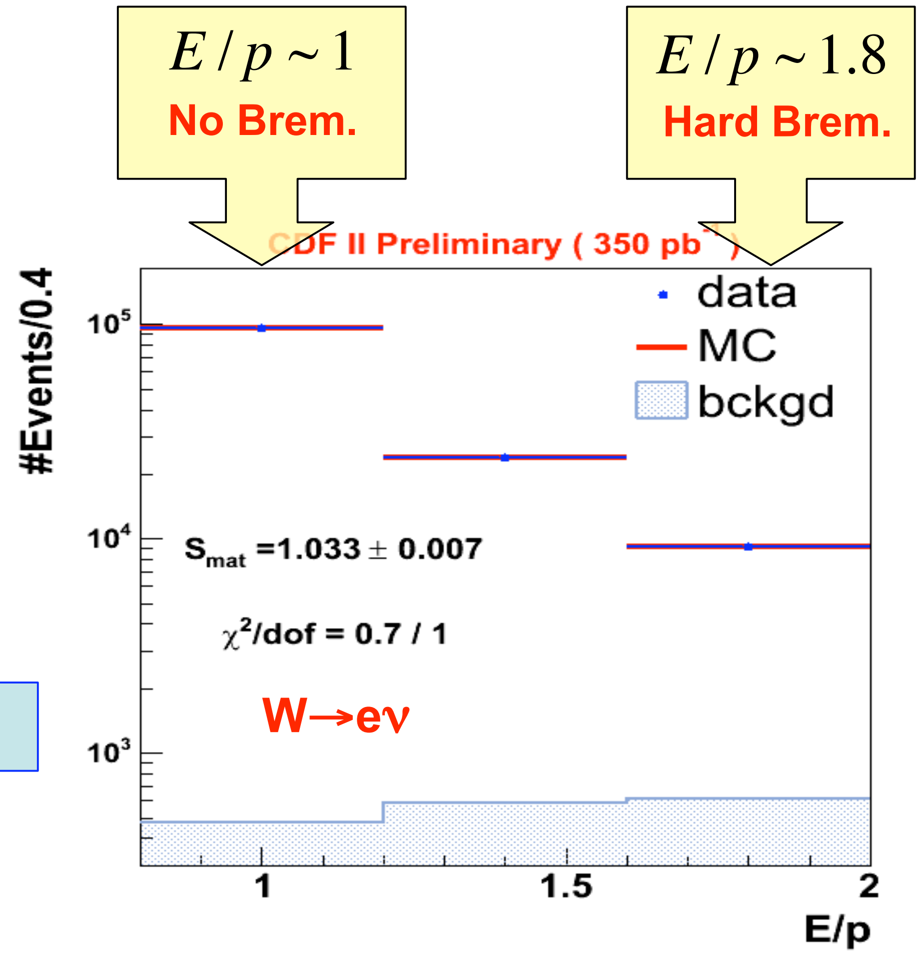
- Relatively easy. No tracking.
- Statistically poorer.

- Do the 2 methods agree ?
- ▸ A very powerful cross-check .
- ▸ Run I 3.9σ discrepancy never resolved.

# Simulating Electrons (I) : Material



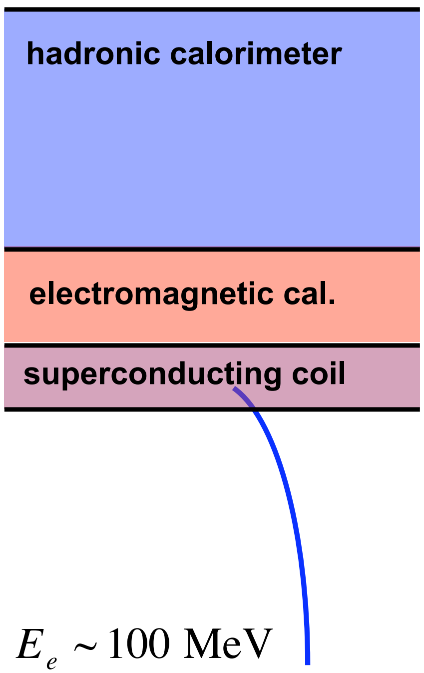

- Start from a detailed, tuned material map.
- Very detailed Brem. & energy loss treatment.
- Compare E/P tails in data and simulation :

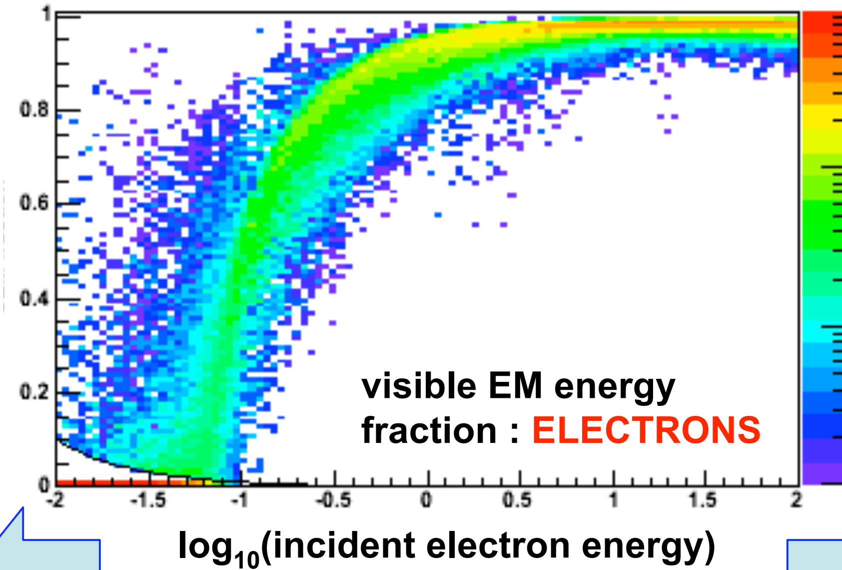


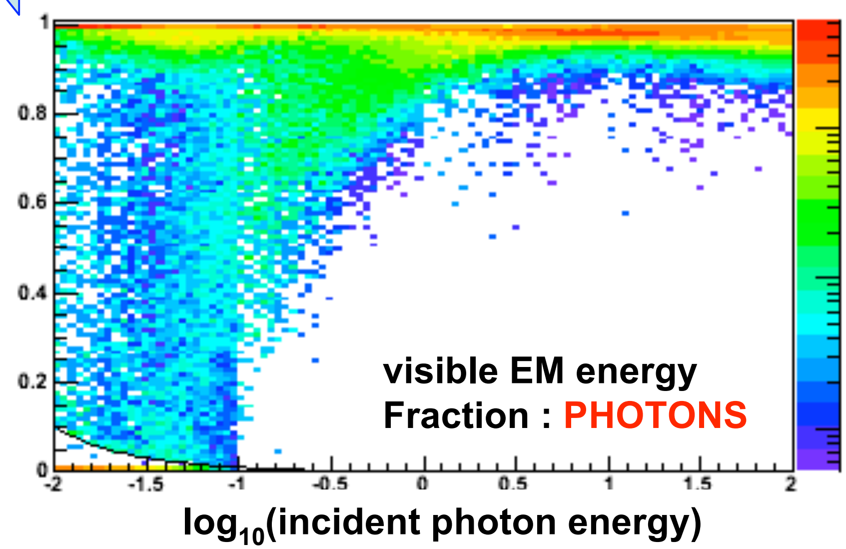

Determine amount of radiating material to better than 1%

# Simulating Electrons (II) : CAL

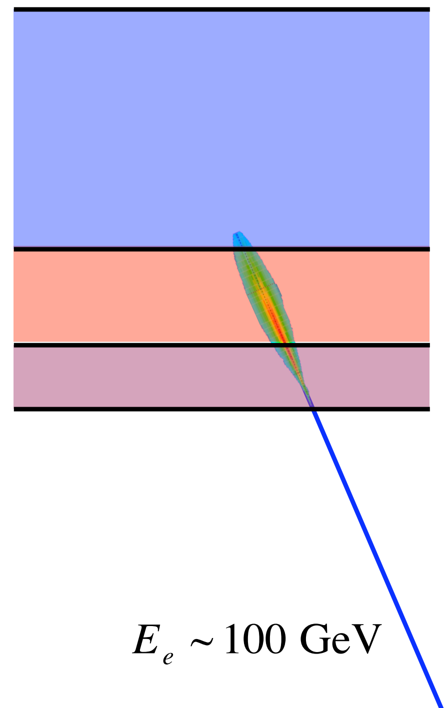
Soft electrons and photons suffer absorption in the coil



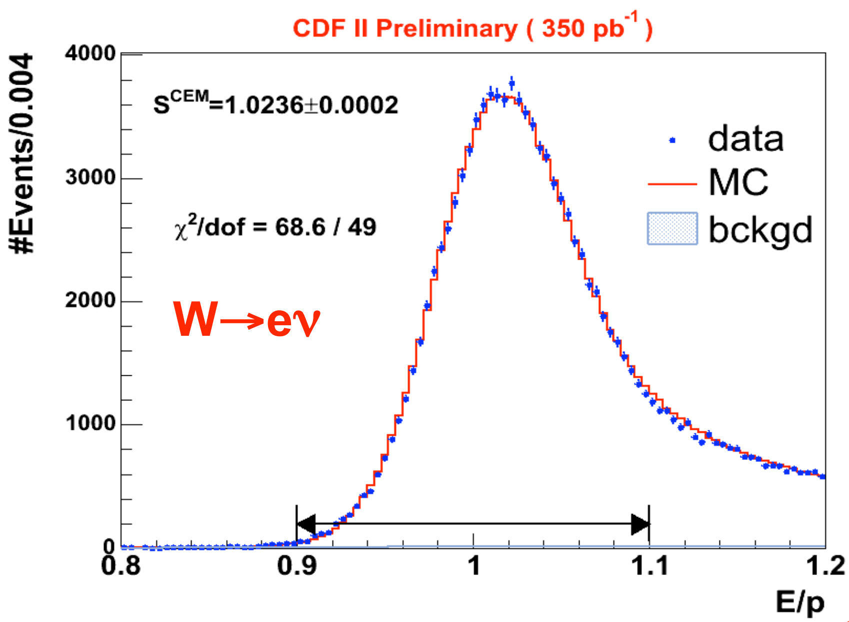

Energetic electrons and photons leak into the hadronic compartment



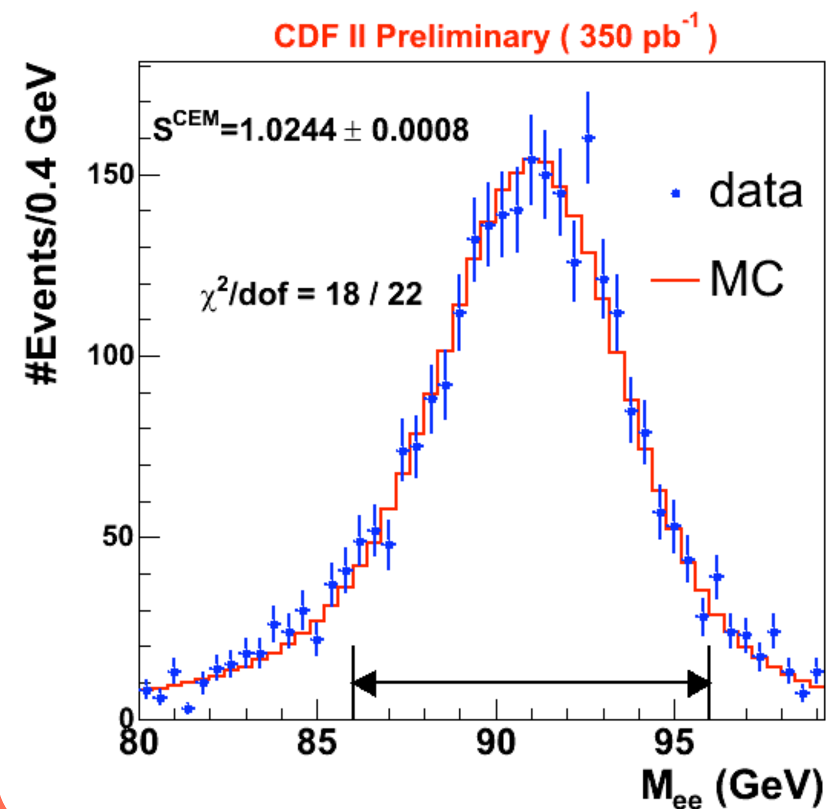
# Electron Energy Scale

- The results of doing all this …

[1] Take scale from E/p fit :




[2] Take scale from **Z→ee** fit :

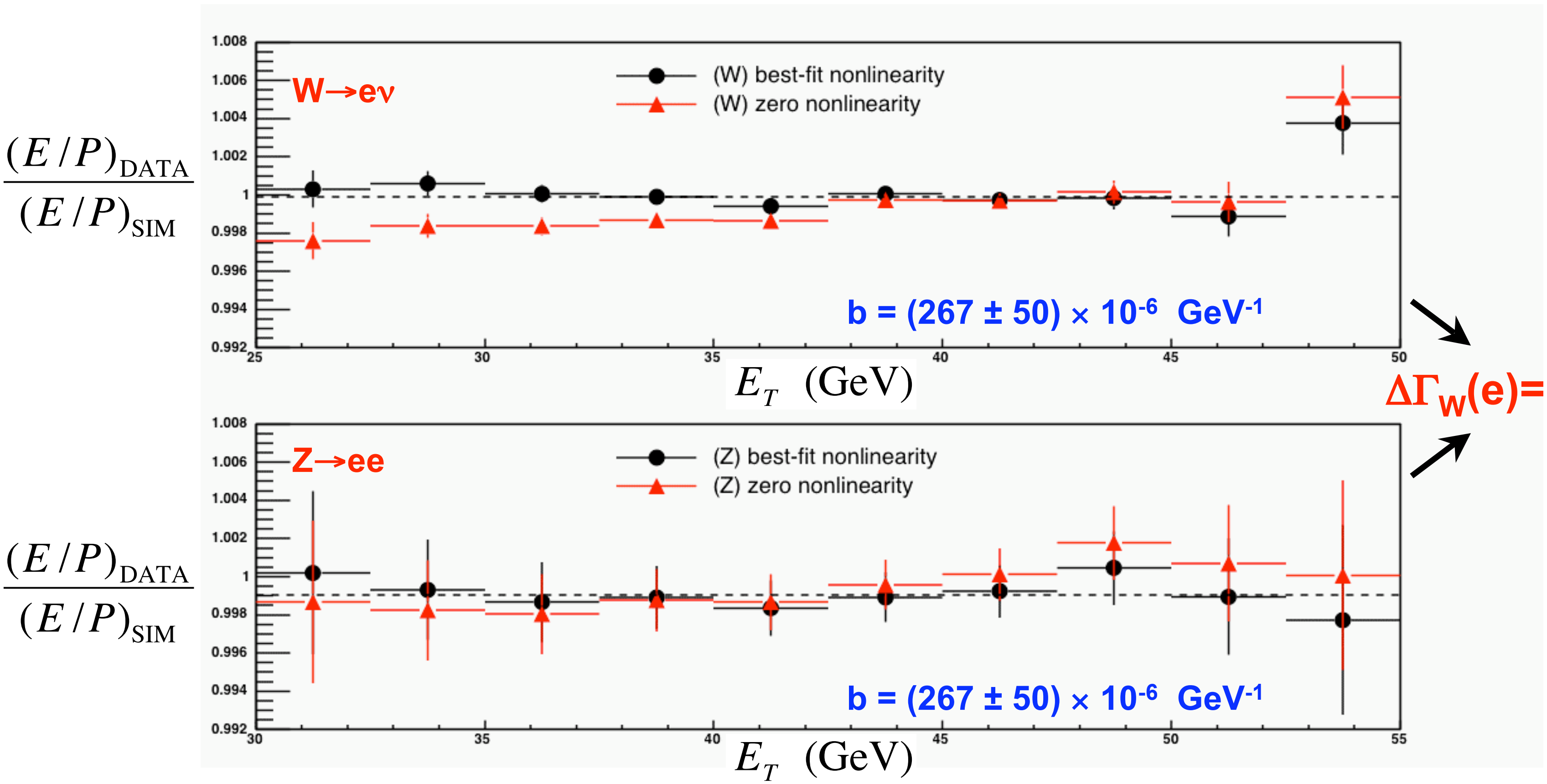



- Same ? Yes!
- Combine both scale determinations :
- **$\Delta S/S$ = 0.04 % : $\Delta\Gamma_W(e)$= 17 MeV**

# EM Scale Nonlinearity

- No sample of $J/\psi \rightarrow e^+e^-$ decays to determine the EM scale over a large lever-arm.
- We constrain any non-linearity *within* the W and Z samples.

**measured cluster $E_T$** ⟸ $$E_T = \sum \left(a + b \times E_T^i\right) \cdot E_T^i$$ ⟹ **constituent particle $E_T$'s**




$\Delta\Gamma_W(e)$=12 MeV

# Recoil Model

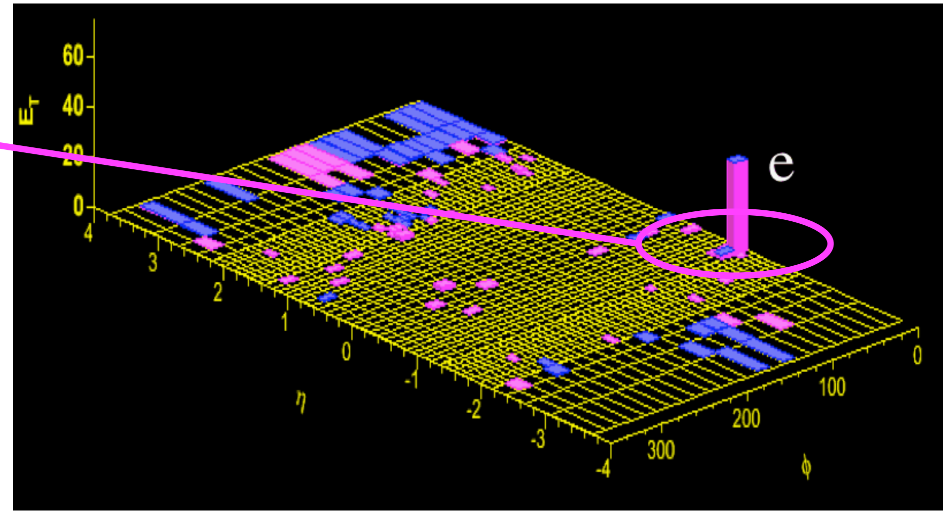
- Sum over energy in all calorimeter towers excluding the lepton(s) :

$$\vec{u} = (u_x, u_y) = \sum_{towers} E \sin\theta(\cos\phi, \sin\phi)$$

- Then our neutrino $\boldsymbol{p_T}$ estimate is :

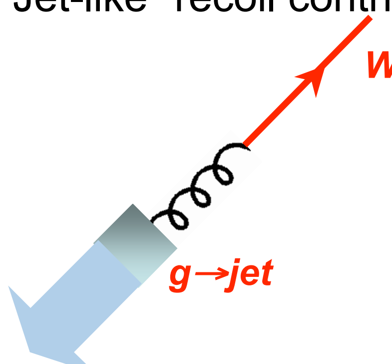
$$\vec{p}_T^{\,\nu} = -\left(\vec{p}_T^{\,l} + \vec{u}\right)$$

- There are 3 contributions to the recoil :




**Hard emission**

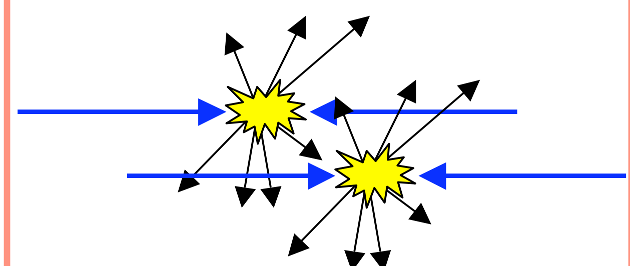
"Jet-like" recoil contribution.




parameterise $\sim f\left(p_T^{W/Z}\right)$

**Underlying Event**

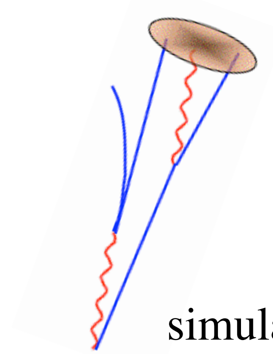
From W(Z) collision & overlapping $p\bar{p}$ interactions



parameterise $\sim f\left(\Sigma E_T\right)$

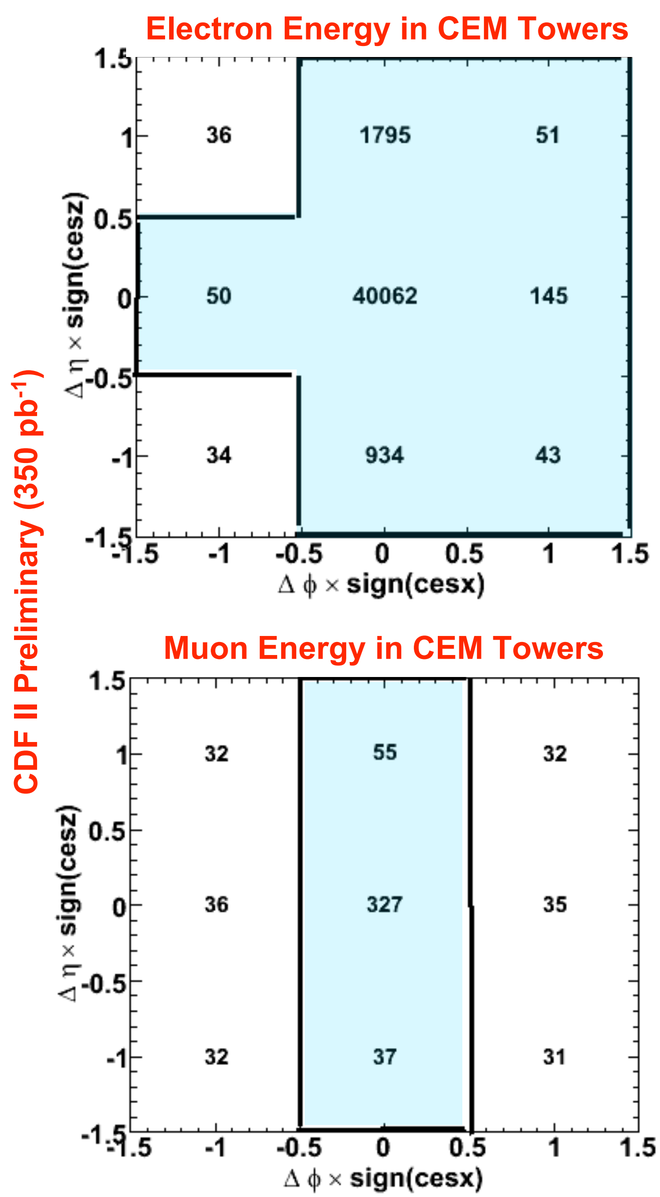
**Lepton E-Loss**

Energy leaving the lepton towers (e.g. wide ∠ Brem.)

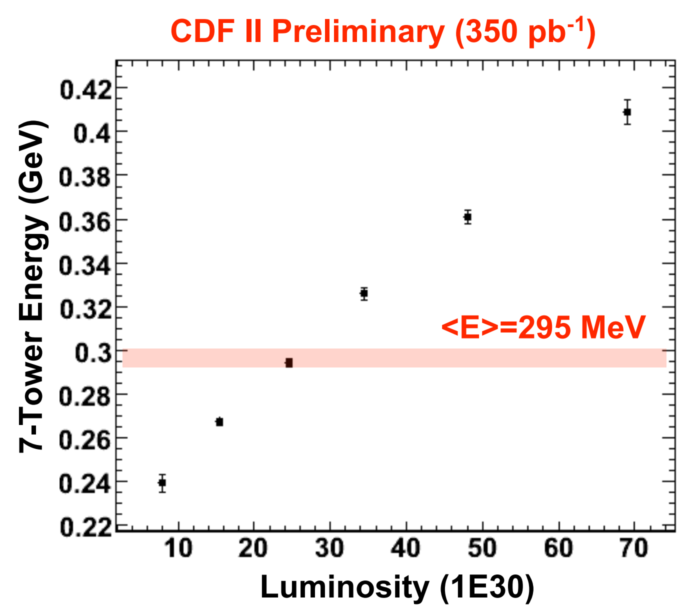


simulate

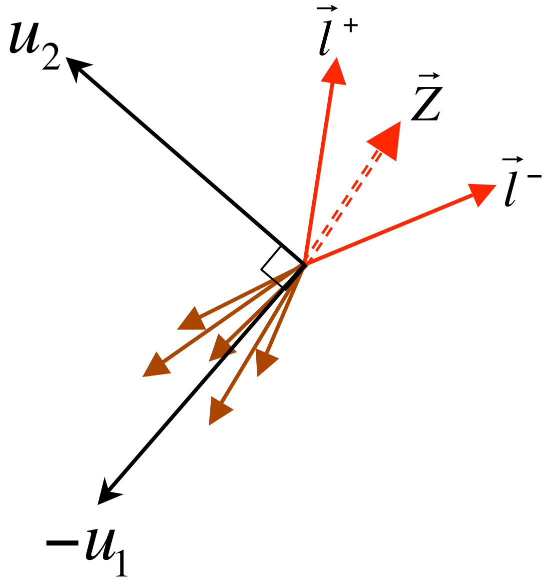
# Recoil Corrections




- The recoil energy falling on or near the lepton direction is not separable from the lepton energy.
- Remove **7**(**3**) towers surrounding the **e**(μ).
- Put *back in* the average recoil we would expect in that area of the detector, measured orthogonal to the lepton direction.
- This correction is luminosity dependence - we are seeing the effect of pileup :



# Recoil Response



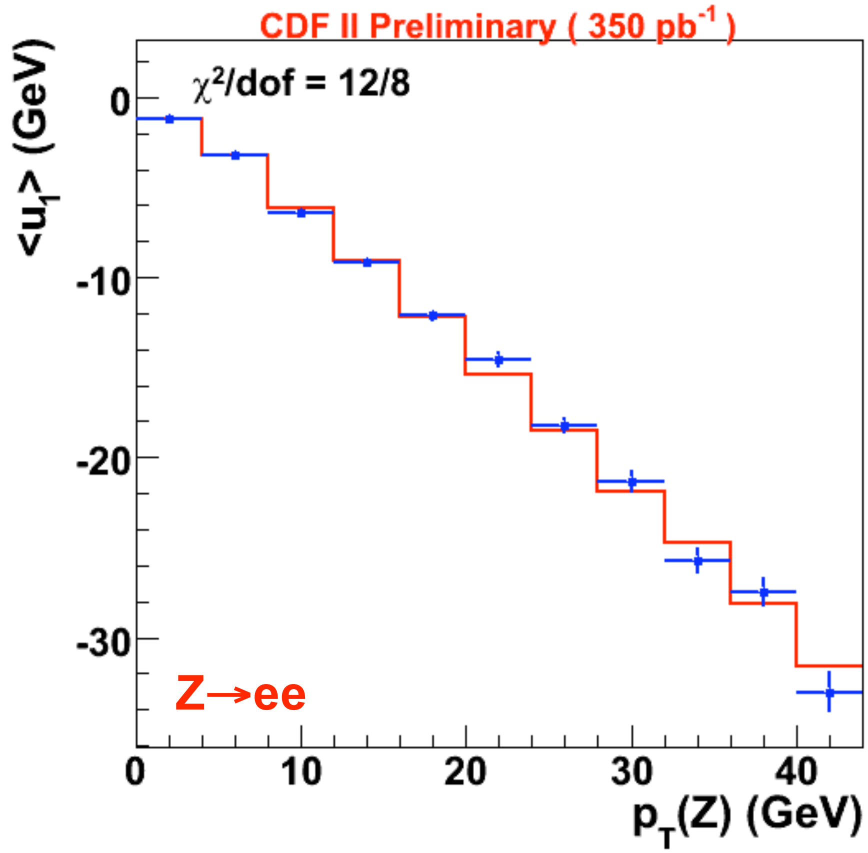

$$\langle u_2 \rangle = 0$$ → **momentum conservation**

$$\langle u_1 \rangle = (A + B \cdot p_T^Z) \times (1 - e^{-C \cdot p_T^Z})$$

↓ **linear calorimeter response** ↓ **low $p_T$ suppression**

**$\Delta\Gamma_W(e) \approx 44$ MeV; $\Delta\Gamma_W(\mu) \approx 33$ MeV**

- Calibrate the detector response to the hadrons recoiling from the well measured $p_T(Z)$.



# Measurement Steps

I. Event Selection

II. W & Z Production Modeling

III. Determine Momentum & Energy Scales

IV. **Determine Resolutions**

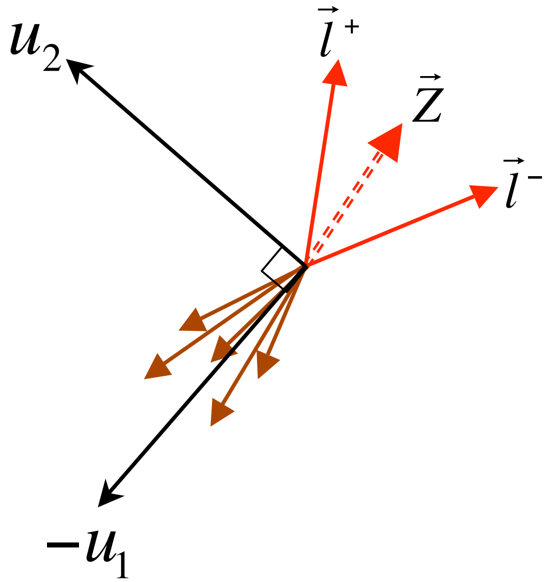
V. Measure Backgrounds

VI. Fit For the Width

**Goals** : determine momentum & energy resolutions as accurately as possible. Non-Gaussian tails are especially important for the width measurement.

# Recoil Resolution

- Cannot directly take **PYTHIA/HERWIG** + full simulation. Use ad-hoc parameterisation.
- Tune on both Z and Minimum-Bias data samples.




- **Function of $\Sigma E_T$ derived from Minimum-Bias data.**
- **Parameterises the "underlying event" contribution.**
- **Is implicitly luminosity dependent.**

$$\sigma(u_1) = \sigma_{MB}\left(D + E \cdot p_T^Z\right)$$

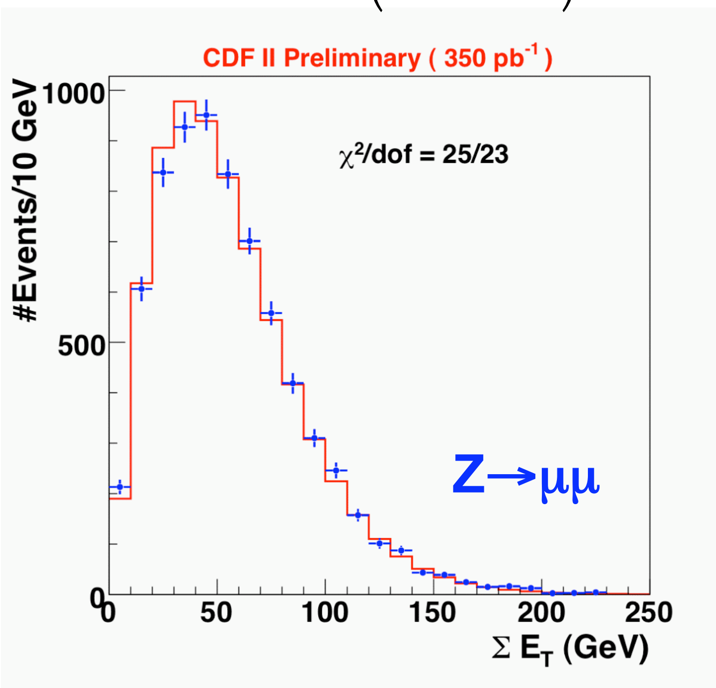
$$\sigma(u_2) = \sigma_{MB}\left(F + G \cdot p_T^Z\right)$$

- **Represents the "hard" contribution to the recoil resolution.**
- **Should be ~0 for $u_2$**

# Recoil Resolution

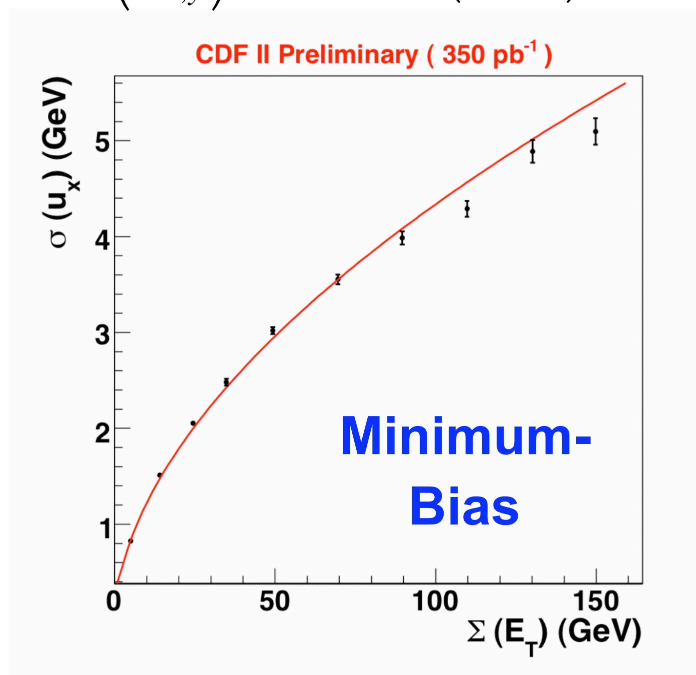
- Leading component of the resolution function depends on the event $\Sigma E_T$ :

$$\Sigma E_T = f\left(Q_{1-4}, p_T^Z\right)$$




Larger $p_T$ or more underlying event activity

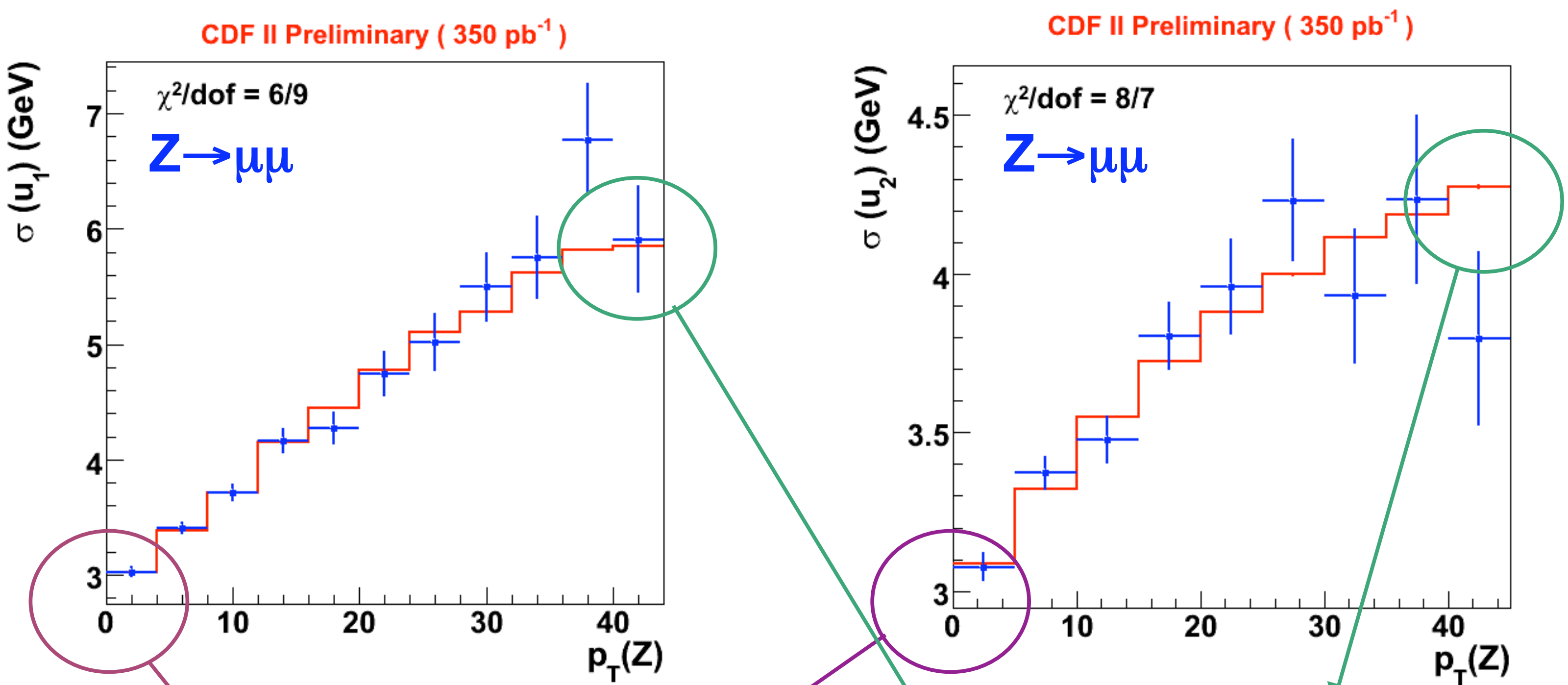
$$\sigma_{MB}\left(u_{x,y}\right) = 0.3384\left(\Sigma E_T\right)^{0.5589}$$




Harder or more overlapping events

# Recoil Resolution

- … then fit the remaining model parameters directly in the Z sample :



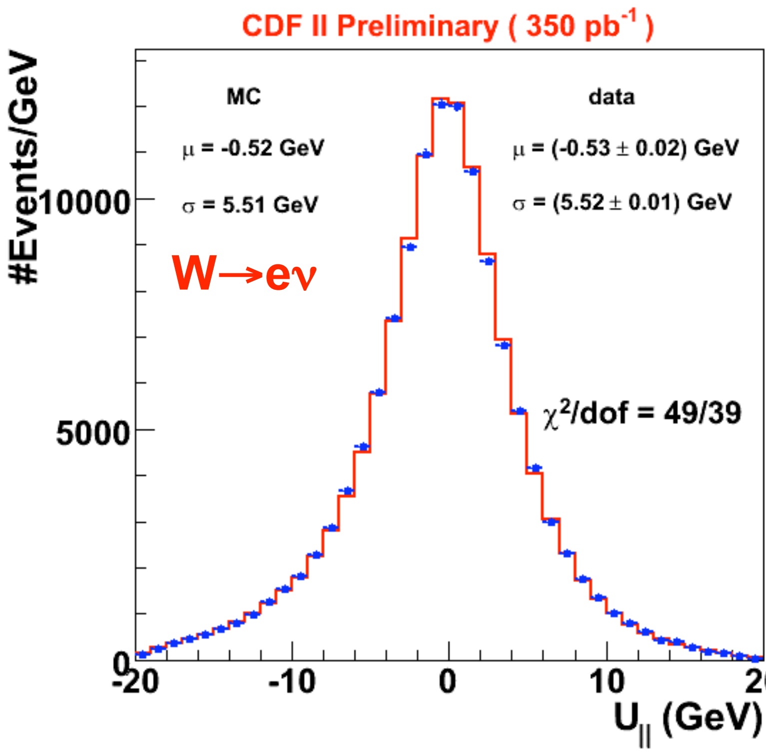

$$p_T^Z \approx 0 \Rightarrow \ \sigma(u_1) \approx \sigma(u_2) \approx \sigma_{MB}$$

$$\text{Large } p_T^Z \ \Rightarrow \ \sigma(u_1) > \sigma(u_2)$$
due to "jet" component

Overall systematic from recoil resolution : **$\Delta\Gamma_W(e) \approx 38$ MeV**; **$\Delta\Gamma_W(\mu) \approx 28$ MeV**

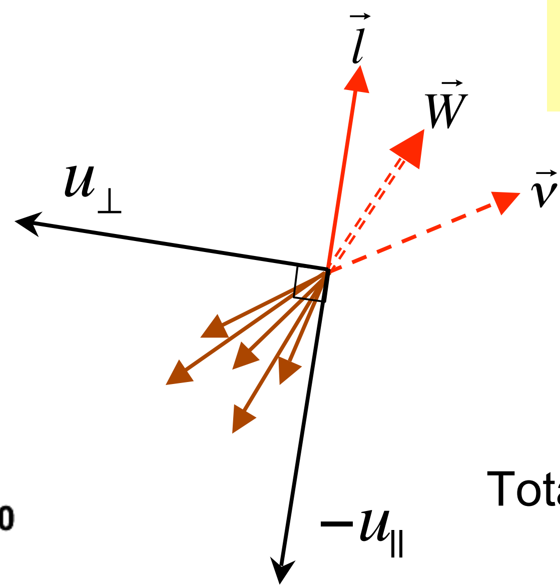
# Recoil Resolution

- The acid test : can we describe the W data with the model tuned on Z's ?




Good agreement !

$$M_T \sim 2p_T^l + u_{||}$$




Total recoil systematic :

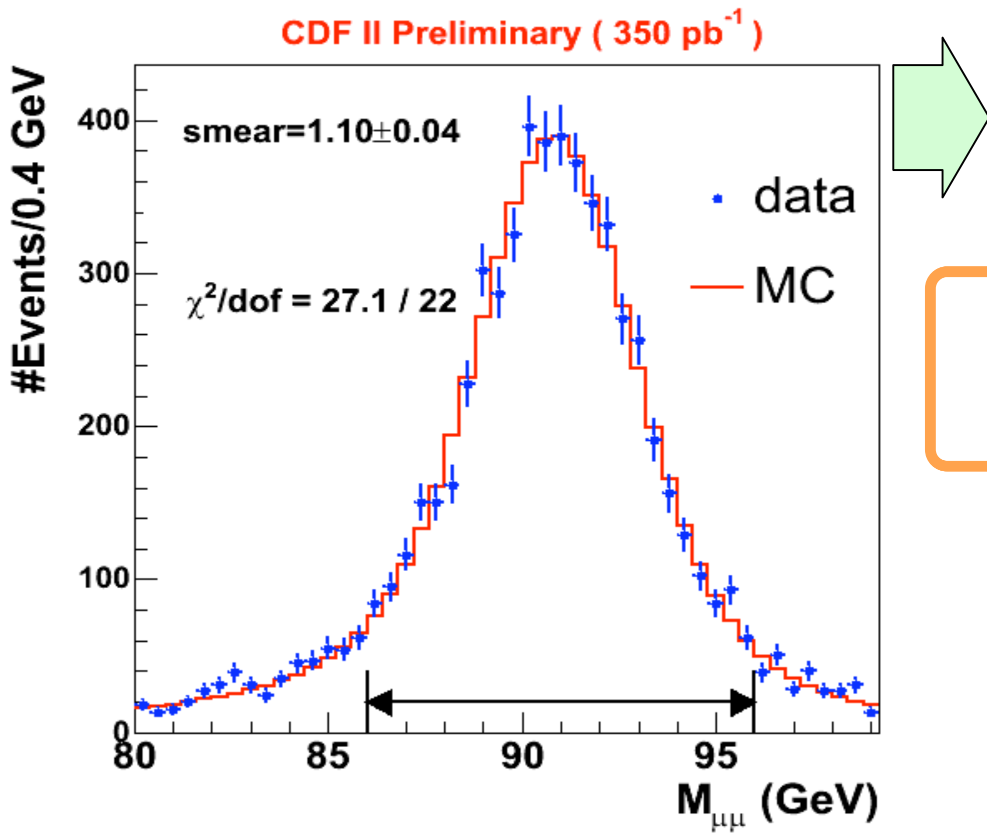
$\Delta\Gamma_W(e)$=54 MeV

$\Delta\Gamma_W(\mu)$=49 MeV

# Momentum Resolution

- Take resolution function from full simulation, reweighted to hit-content of data tracks.
- The same fit to the **Z→μμ** peak yielding the momentum scale also yields a resolution scale factor :

$$\delta(q/p_T)_{FAST-SIM} = S_{RES} \times \delta(q/p_T)_{GEANT}$$

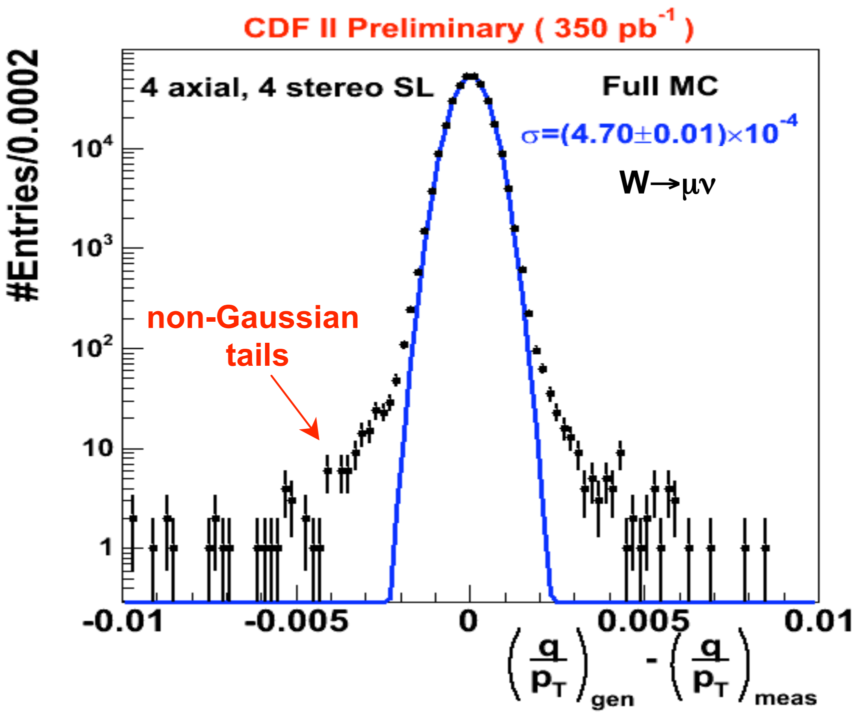


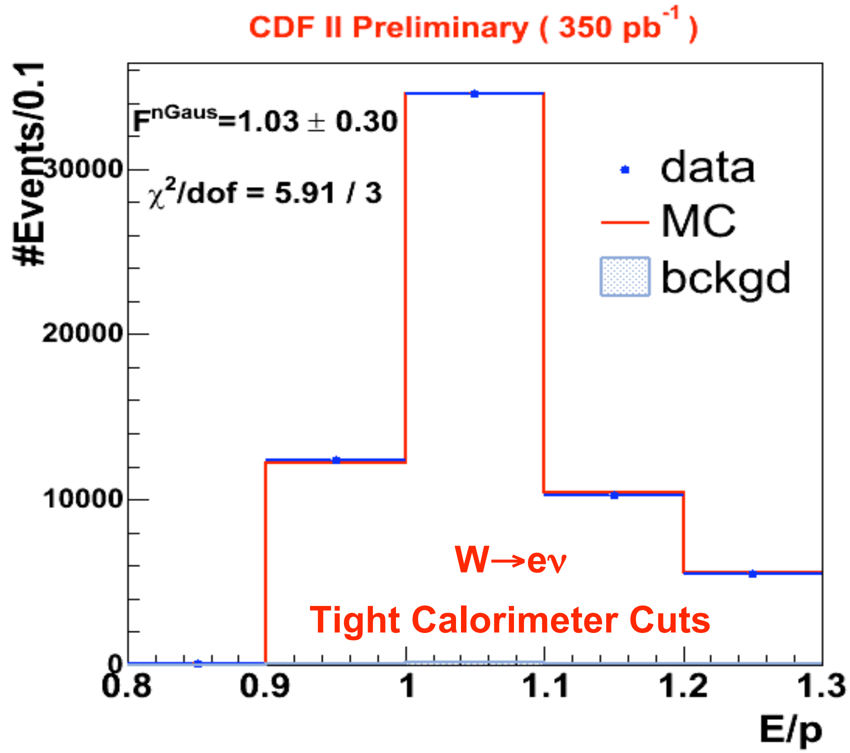

**$S_{RES}$=1.10±0.04 : $\Delta\Gamma_W$ (μ)= 21 MeV**

- Data needs 10±4% more smearing than detailed simulation.

# What About the Tails ?

- Width measurement is also sensitive to the presence of non-Gaussian tails :




- Tail fraction correct ?
- Fit E/P distribution with cuts designed to reduce resolution on "E".

$$F_{\text{NON-GAUSS}} = 1.03 \pm 0.45_{\text{STAT+SYST}}$$

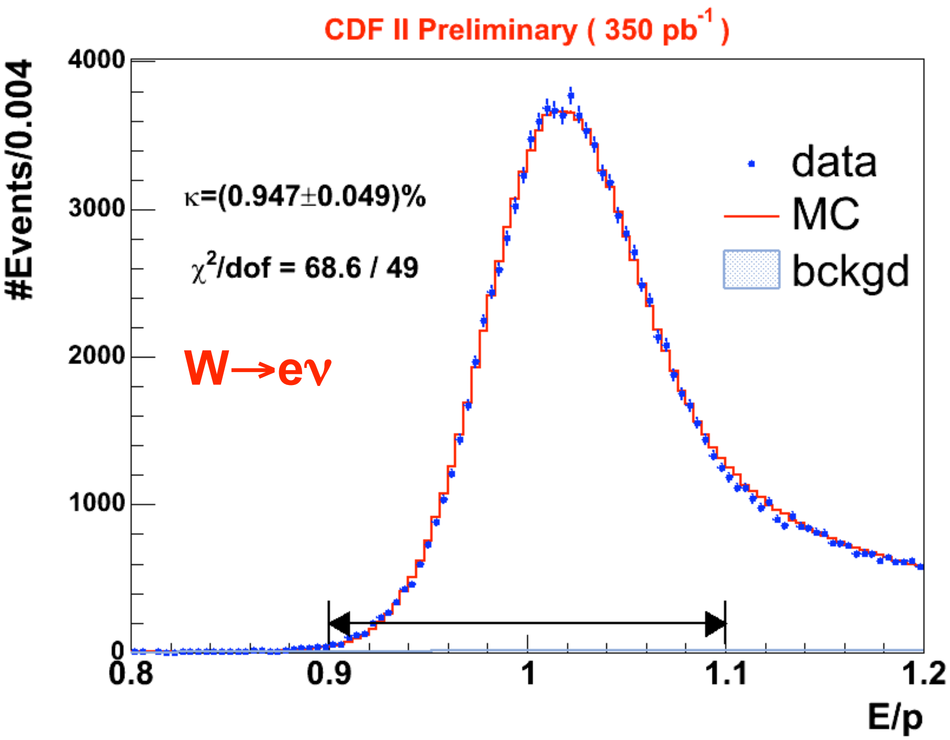
**$\Delta\Gamma_W$ (μ): 16 MeV**

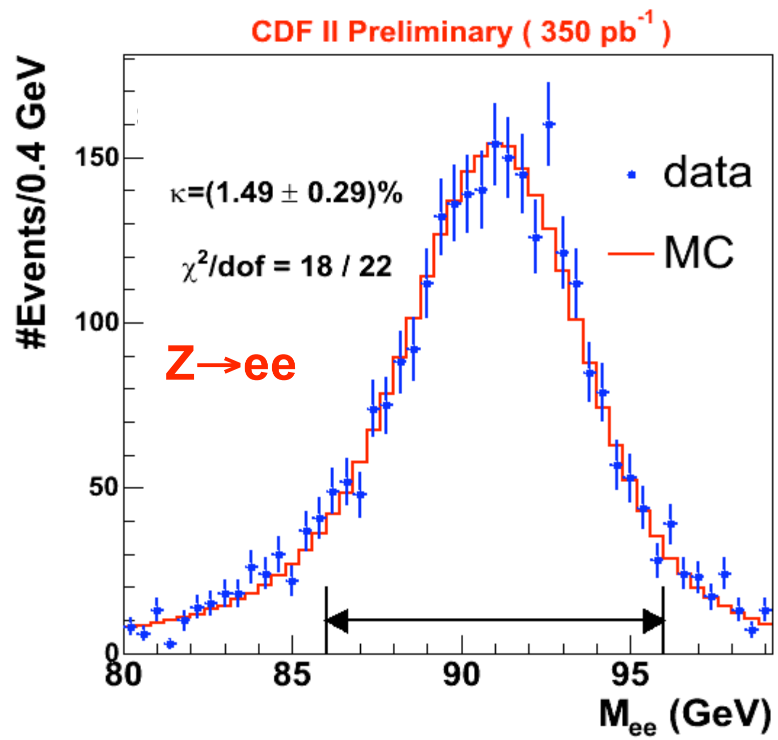
# Electron Energy Resolution

$$\sigma(E_T)/E_T = \text{stochastic} \oplus \text{constant} = 13.5\%/\sqrt{E_T} \oplus \kappa$$

→ determine κ

- Once again : do we measure the same value in W's and Z's ?
- But, careful, … there are correlations between Z electrons (calibrations, luminosity)




▶ Consistent. But vary κ fit over wide range to absorb any non-Gaussian tails.

$\kappa = 1.1 \pm 0.4\ \%$ **$\Delta\Gamma_W$ (e): 31 MeV**


# Measurement Steps

I. Event Selection

II. W & Z Production Modeling

III. Determine Momentum & Energy Scales

IV. Determine Resolutions

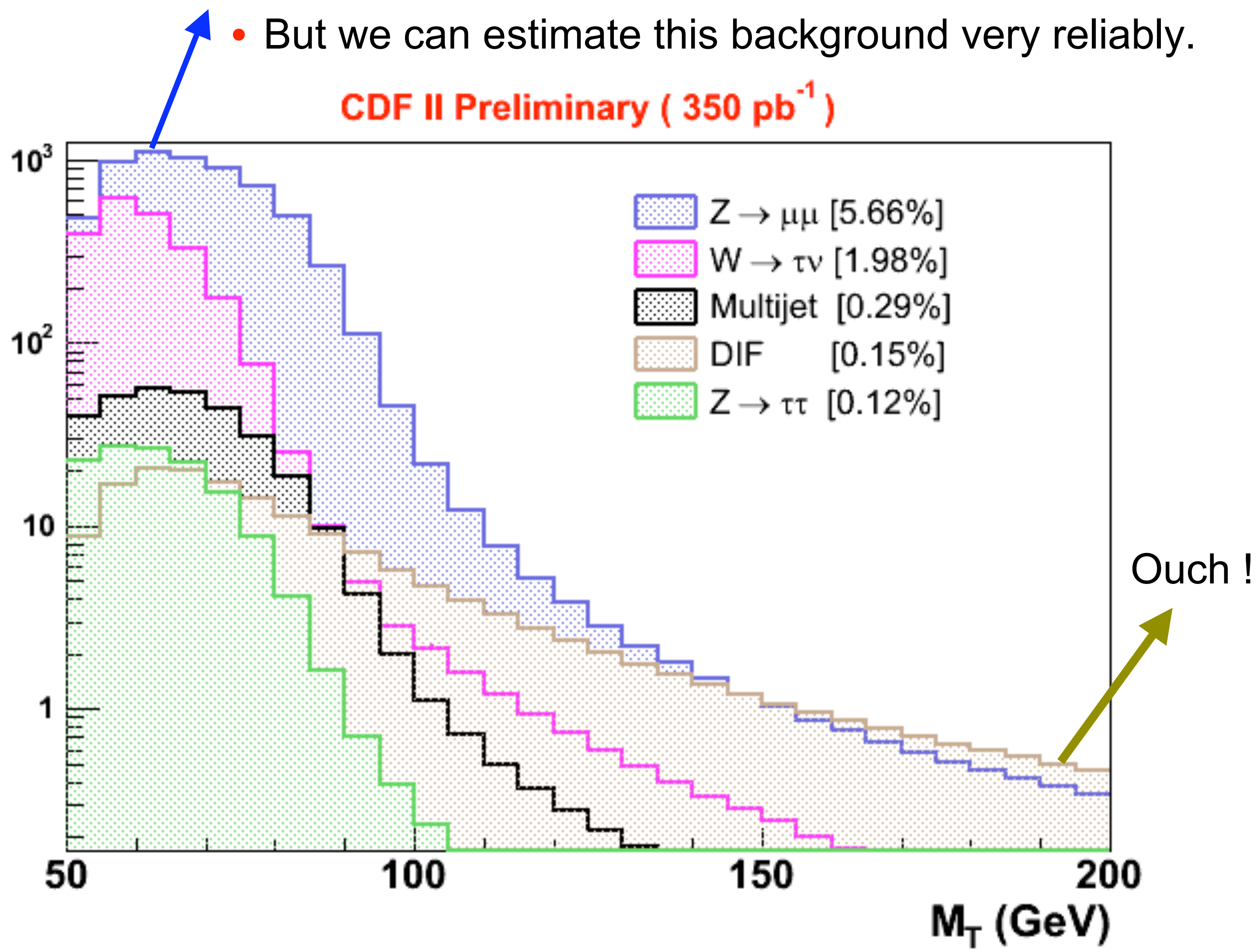
V. **Measure Backgrounds**

VI. Fit For the Width

**Goals** : measure amount of contamination from backgrounds.
Need to know background shapes too.

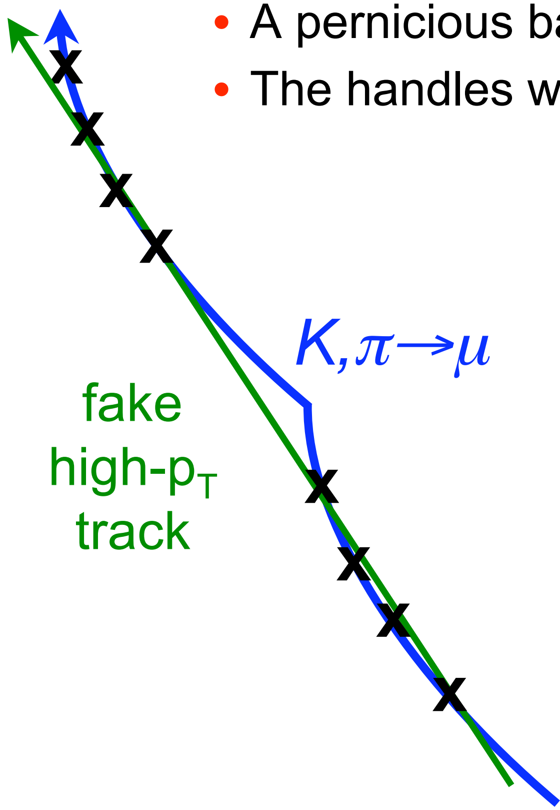
# Muon Channel Backgrounds

- It's easy to lose a leg …
- But we can estimate this background very reliably.



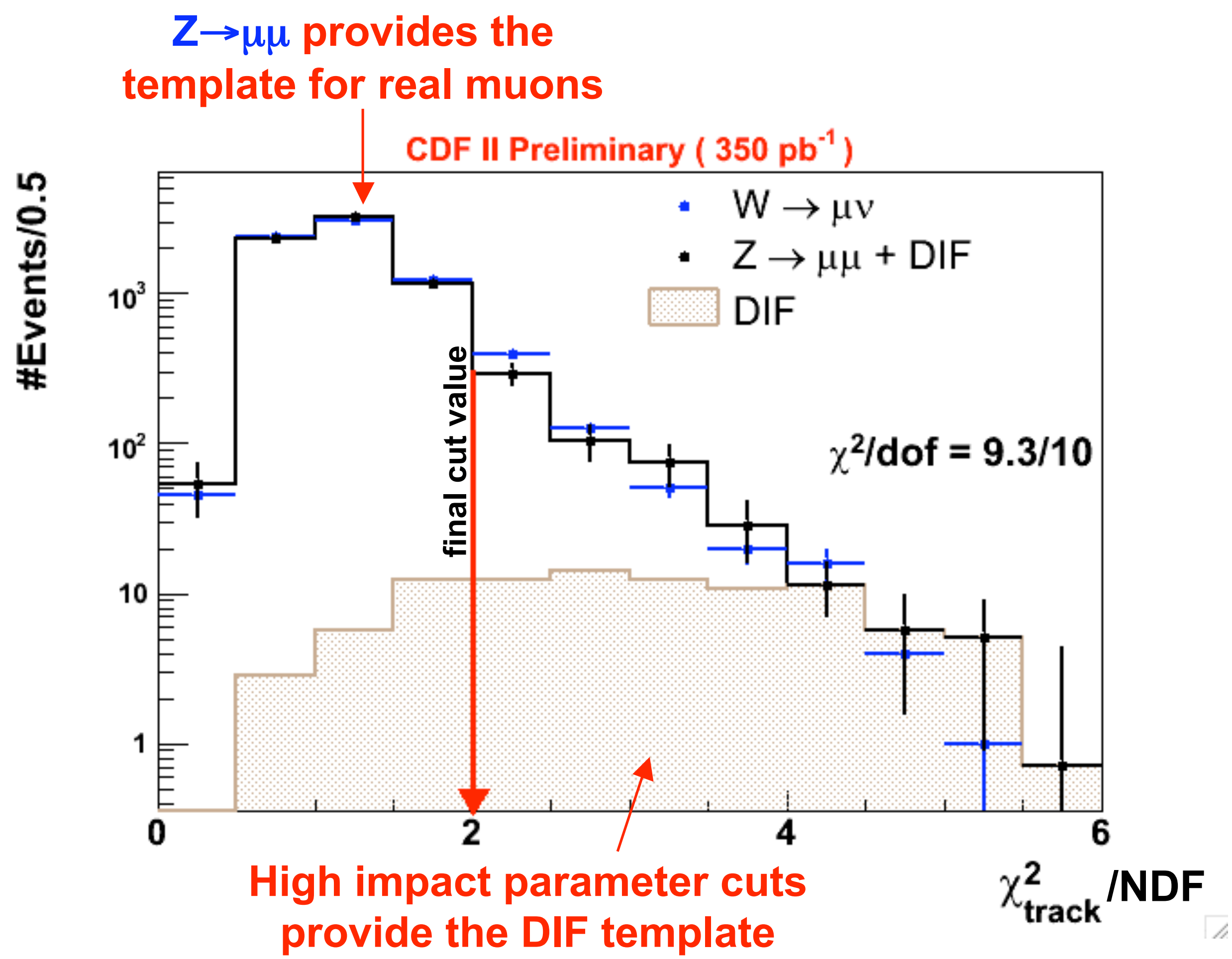
# Decay In Flight Background

- A pernicious background : very flat in transverse mass.
- The handles we have are on track quality : $\chi^2$ and $d_0$

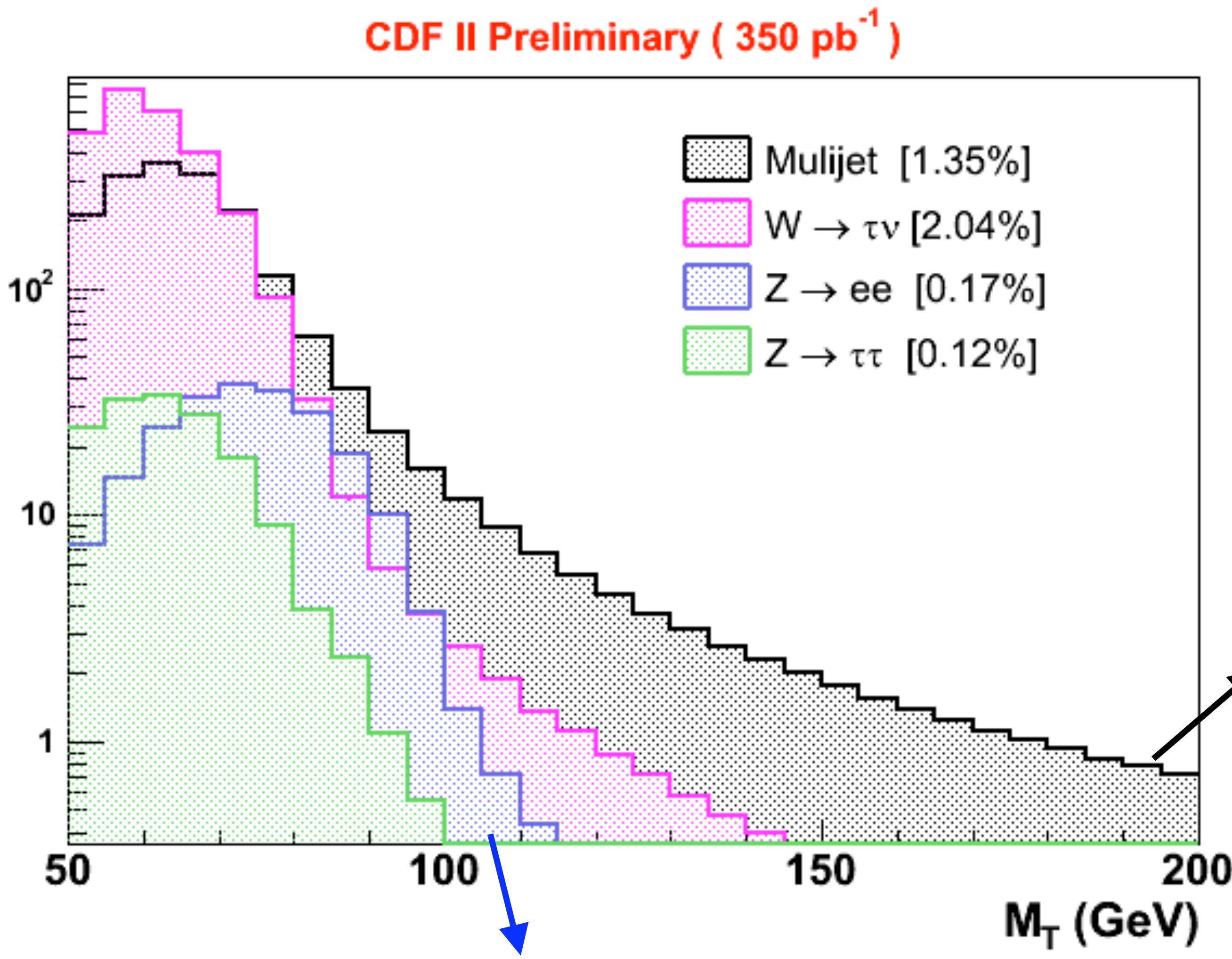



Vary normalization & shape :

**$\Delta\Gamma_W$ (μ): 27 MeV**



# Electron Channel Backgrounds

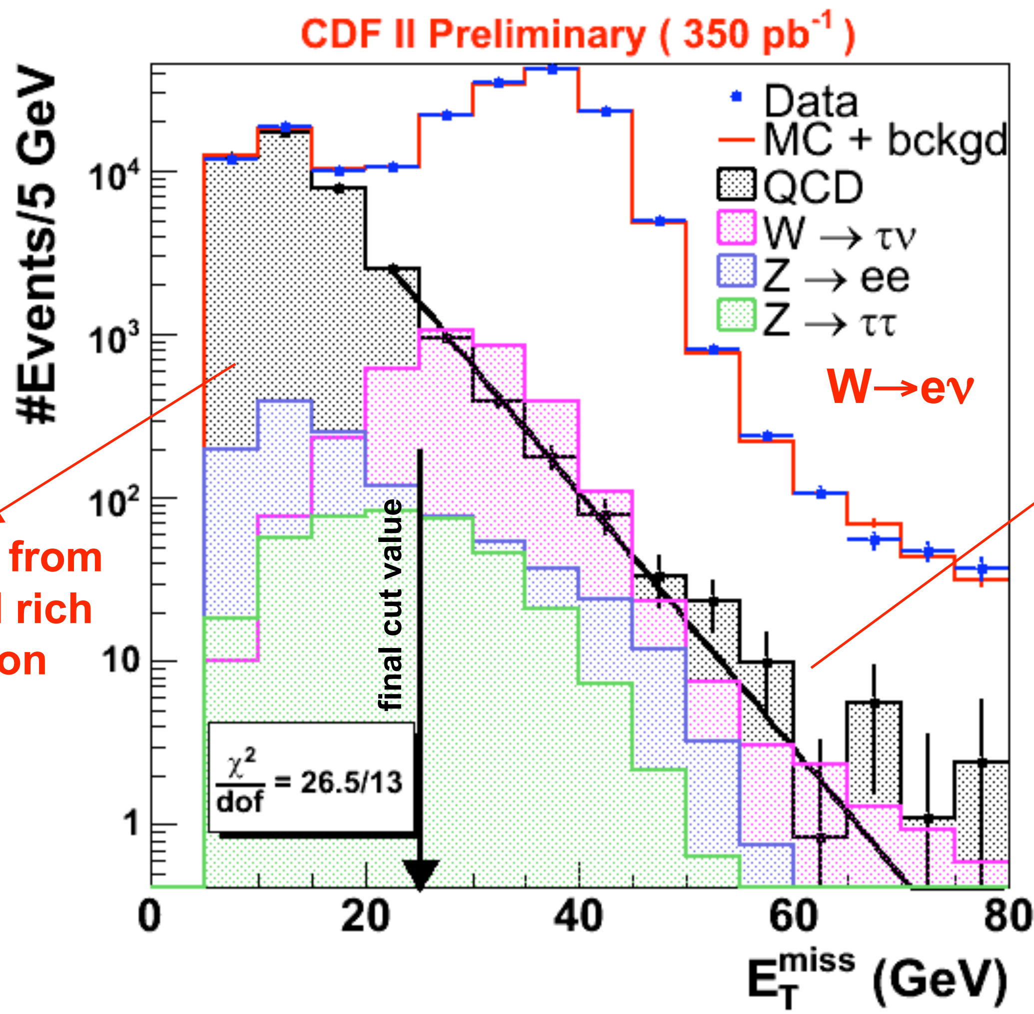



QCD background is the problem

Z's almost negligible

# QCD Background

- Multijet events [ **large cross-section ⊗ fake(jet→lepton) ⊗ fake(jet→$\not{E}_T$)** ]




**QCD template from a background rich "anti-electron sample"**

Vary normalization & shape :

**$\Delta\Gamma_W(e)$ : 32 MeV**

**$\Delta\Gamma_W(\mu)$ : 12 MeV**

# Measurement Steps

I. Event Selection

II. W & Z Production Modelling

III. Determine Momentum & Energy Scales

IV. Determine Resolutions

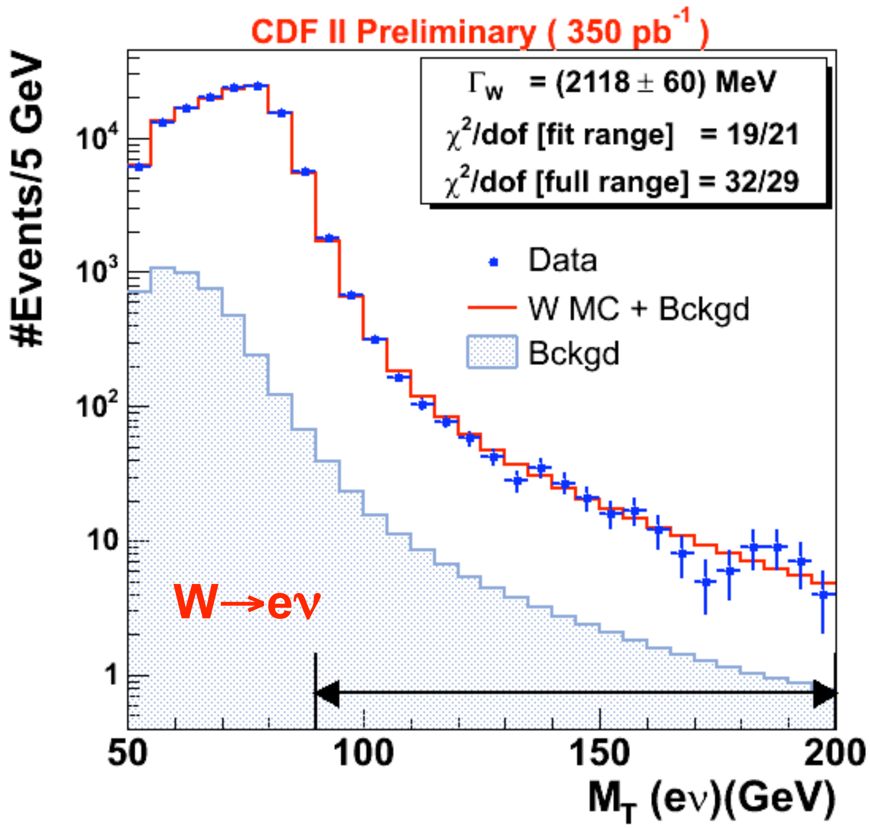
V. Measure Backgrounds

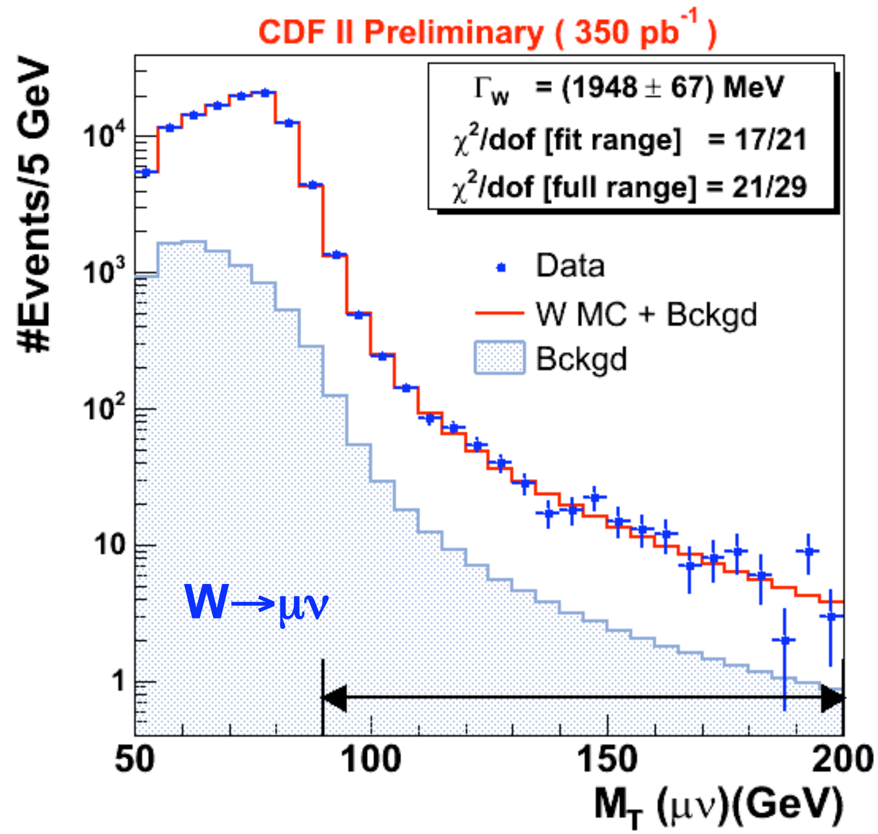
VI. **Fit For the Width**

**Finally !**

# Results : Width Fits

- Transverse mass fits :



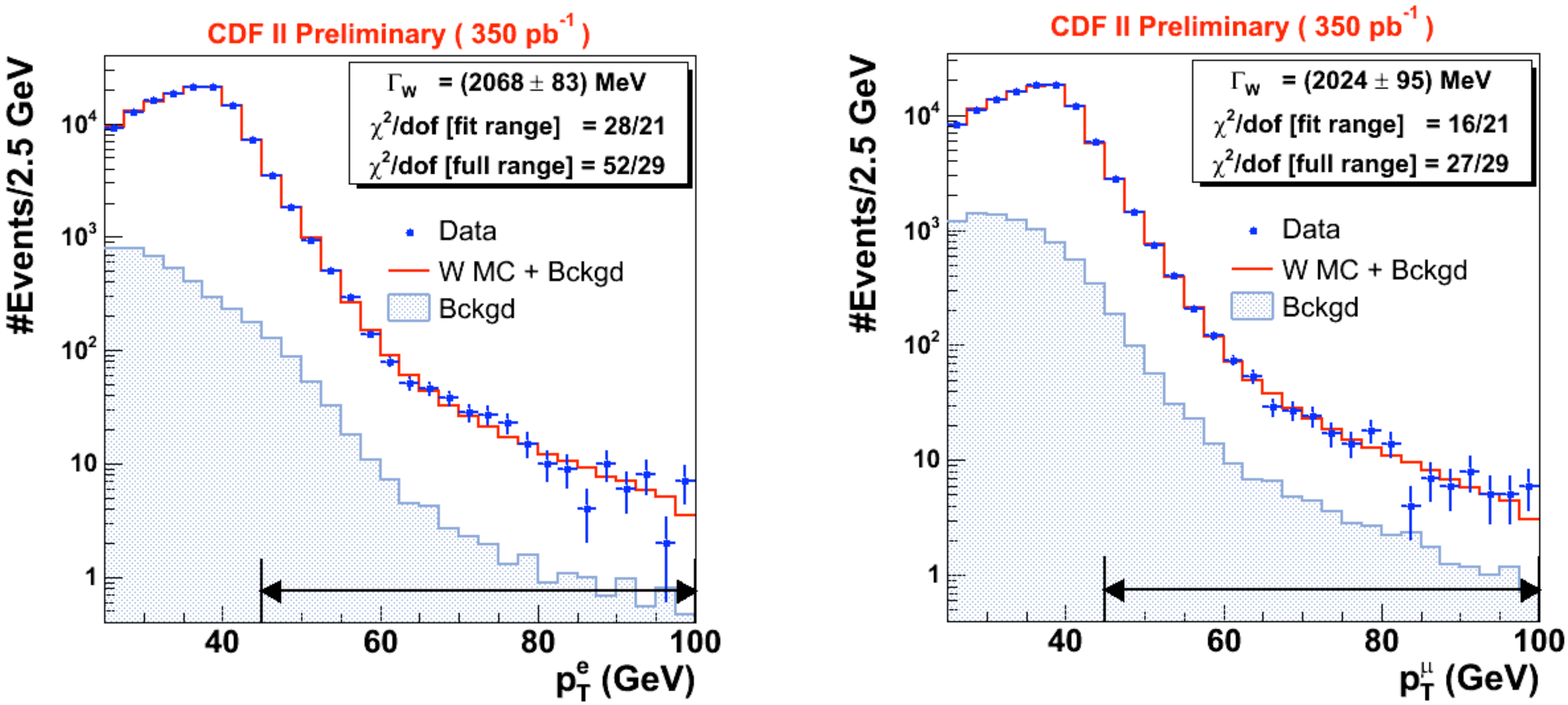




**$\Gamma_W$ = 2032 ± 71 MeV (stat. + syst.)**

**[ $\chi^2$=1.62; p=20%]**

# Cross Checks

- Fit the lepton $p_T$ spectra :
  - Statistically poorer
  - Subject to different systematics




- Use pseudo-experiment ensembles to account for $M_T \Leftrightarrow p_T$ correlations
  - Differences $< 1\sigma$

# Cross Checks

- <u>Vary the fit range</u> from [80,200]→[110,200] :
  - Largest discrepancy in 12 comparisons is **2.1σ**

- <u>Charge splits</u> : sensitive to (for example) large residual false curvature.

| | | | |
|---|---|---|---|
| **electron** | **(+ve):** | **2.107 ± 0.086 GeV** | **0.2σ** |
| | **(-ve):** | **2.130 ± 0.086 GeV** | |
| **muon** | **(+ve):** | **1.989 ± 0.097 GeV** | **0.6σ** |
| | **(-ve):** | **1.910 ± 0.093 GeV** | |

- Can we <u>measure the W mass</u> ?
  - Yes! Good agreement with current World Average **80.389 ± 0.025 GeV**

# Systematic Uncertainties

CDF Run II Preliminary (350 $pb^{-1}$)

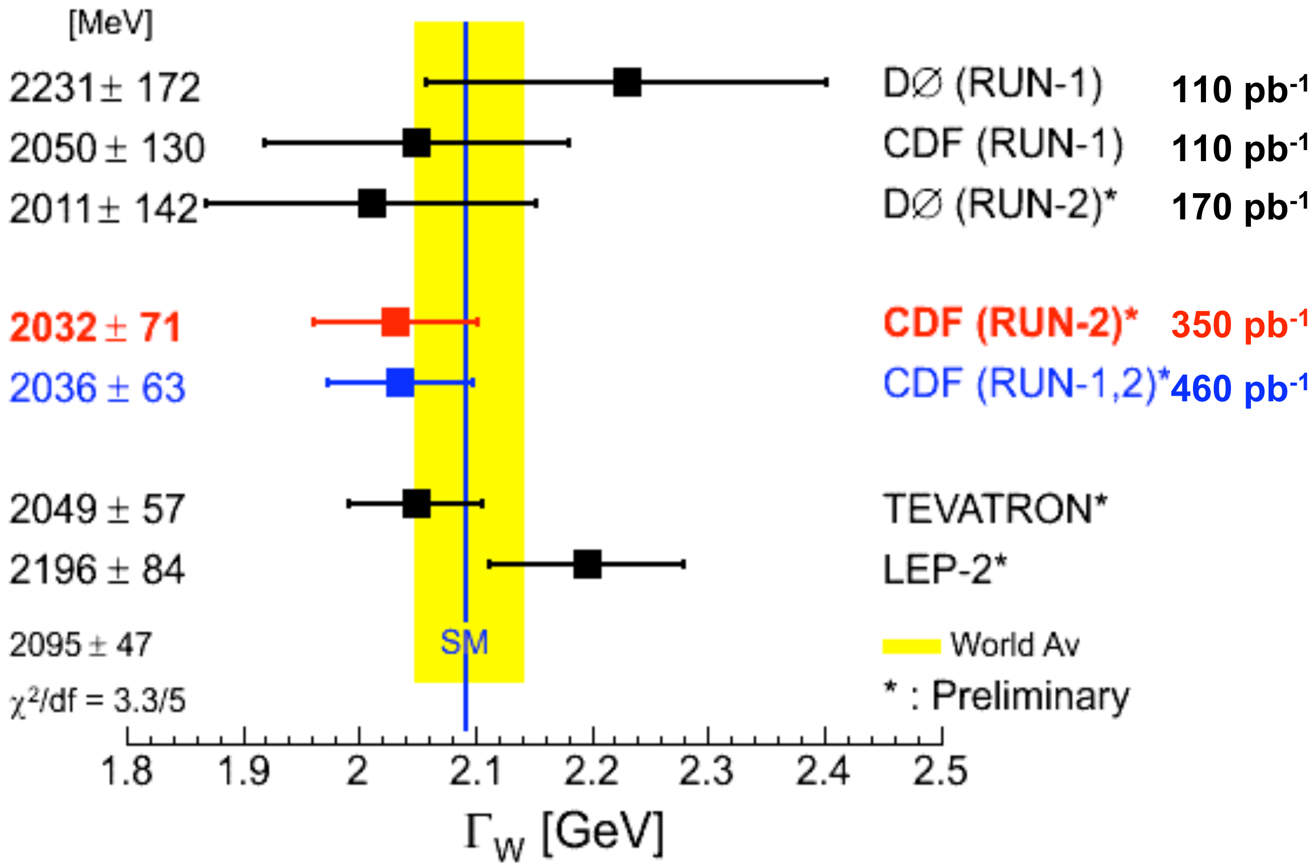
| | $\Delta\Gamma_W$ [MeV] | | |
|---|---|---|---|
| | Electrons | Muons | Common |
| Lepton Scale | 21 | 17 | 12 |
| Lepton Resolution | 31 | 26 | 0 |
| Simulation | 13 | 0 | 0 |
| Recoil | 54 | 49 | 0 |
| Lepton ID | 10 | 7 | 0 |
| Backgrounds | 32 | 33 | 0 |
| $p_T(W)$ | 7 | 7 | 7 |
| PDF | 16 | 17 | 16 |
| QED | 8 | 1 | 1 |
| W mass | 9 | 9 | 9 |
| Total systematic | 78 | 70 | 23 |
| Statistical | 60 | 67 | 0 |
| Total | 98 | 97 | 23 |

scaling statistically

fixed ?

The measurement is still "statistics" dominated

# Comparison with World Data




World's most precise single measurement !

World Average central value lower by 44 MeV: **2139 → 2095 MeV**

World Average uncertainty reduced by 22% : **60 → 47 MeV**

# Comparison with World Data

New World Average **DIRECT**

$\Gamma_W$ **= 2095 ± 47 MeV**

**STANDARD MODEL**

$\Gamma_W$ **= 2091 ± 2 MeV**

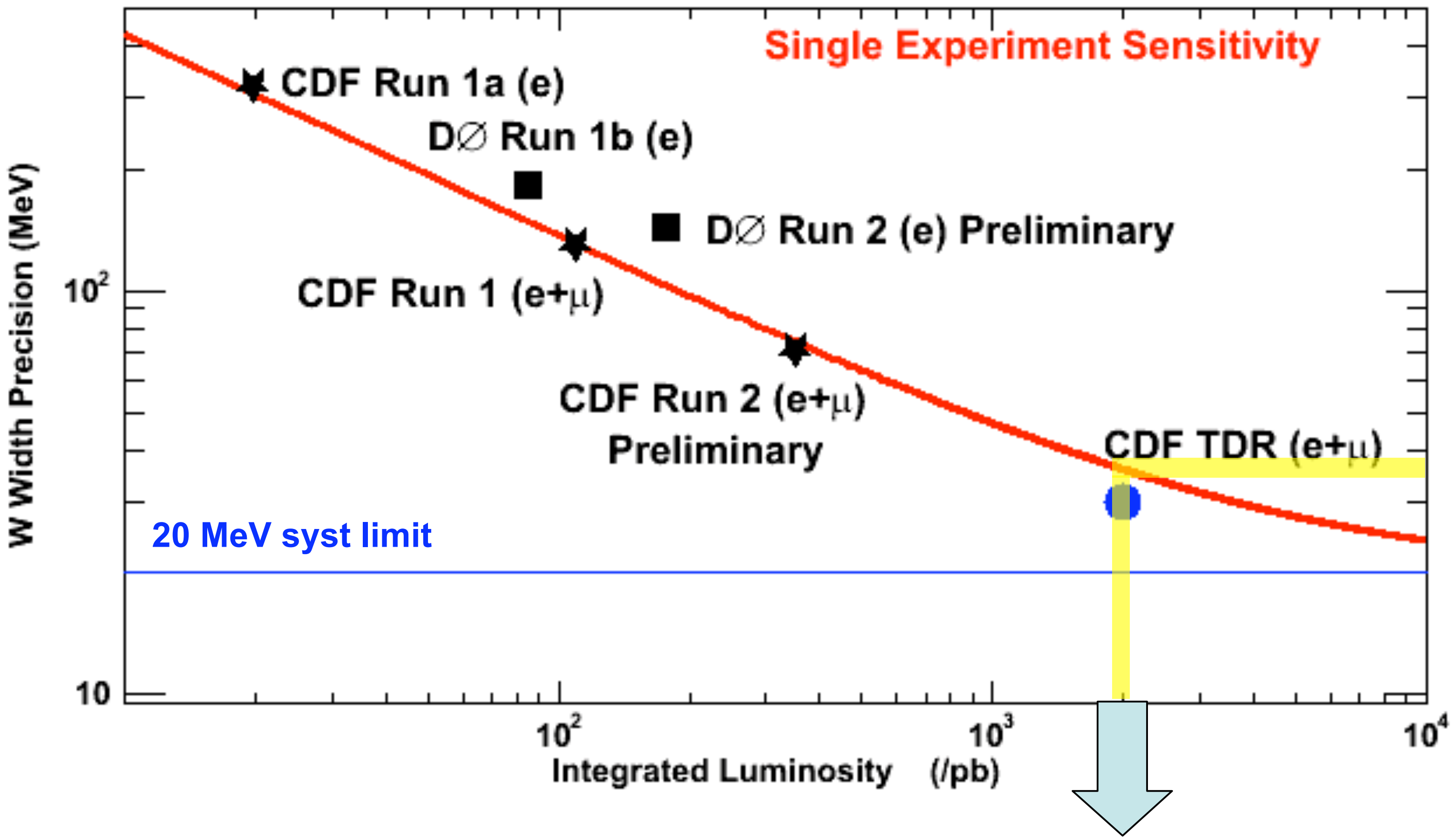
CDF Run 2 **INDIRECT**

$\Gamma_W$ **= 2092 ± 42 MeV**

**[ PRL 94, 091803 (2005) ]**

N.B. PDG World Average is a mixture of direct & indirect

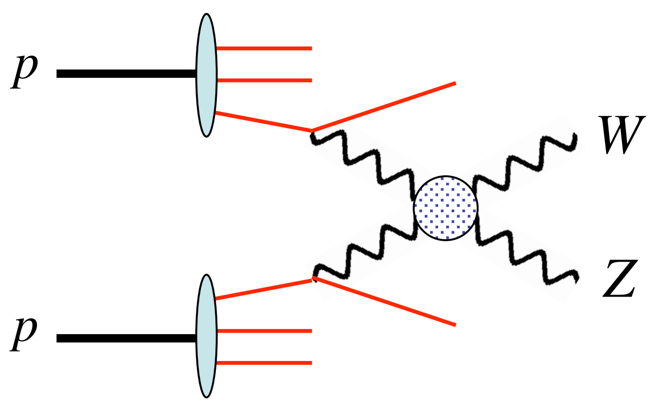
# Prospects




**40 MeV $\Gamma_W$** measurement
with data already in the can ?

# Longer Term Prospects

- Direct W width measurement at the LHC ?
  - Beating the Tevatron W mass will already be hard …
  - … beating the Tevatron W width may be even harder → backgrounds.
  - Tevatron may be the best place to directly measure $\Gamma_W$ before the ILC.
- Precision measurements of new physics @ LHC will be more interesting :
  - New dilepton resonances ?
  - New diboson resonances ?



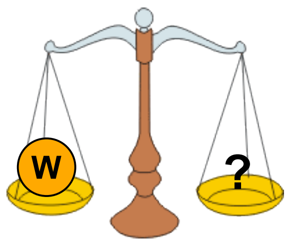

**In some models it may be necessary to measure the *mass* and *width* of WZ resonances with high precision to aid the physics interpretation**

**Birkedal et al., hep-ph/0412278**

- A lot of knowledge can be transferred from precision measurements TeV→LHC


# Summary

- Two new world beating precision measurements from CDF :




**$M_W$ (CDF II) = 80413 ± 48 MeV**

**$M_W$ (WA) = 80398 ± 25 MeV**

**15% increase in precision**


**$\Gamma_W$ (CDF II) = 2032 ± 71 MeV**

**$\Gamma_W$ (WA) = 2095 ± 47 MeV**

**22% increase in precision**

- We know our weak force quite a bit better than we did 3 months ago.
- The prospects are excellent for further refining these measurements @ Tevatron.