Measurement of the W mass at LHC

- Motivation
- The Tevatron experience
- ATLAS : <u>preliminary study</u>
  → more results in TDR

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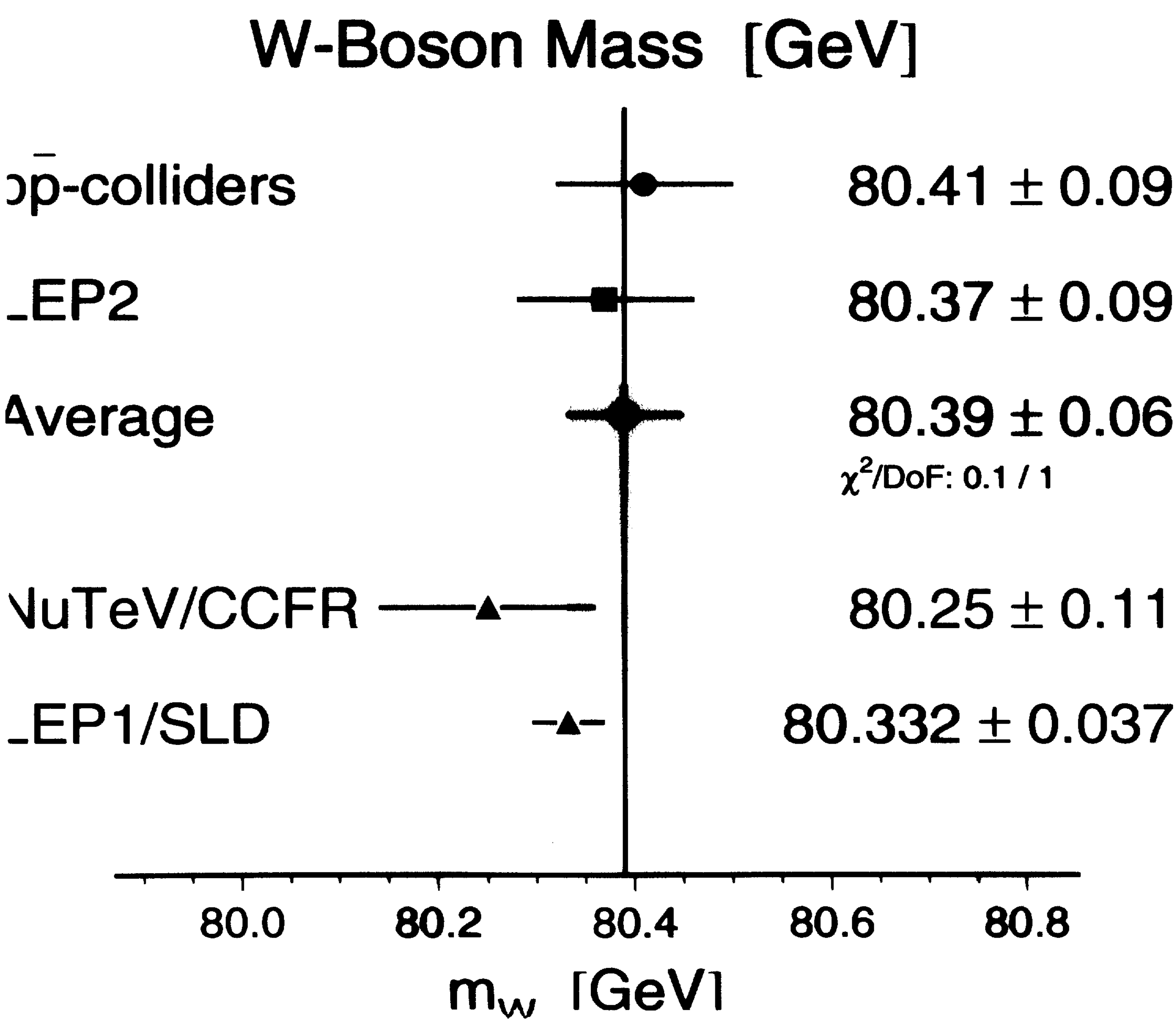
" If anyone wants to measure the W mass at LHC with high precision, better he commits suicide ..."

G. Altarelli
LHCC 4/3/'98

Year 2005 : $\Delta m_W \approx 30$ MeV

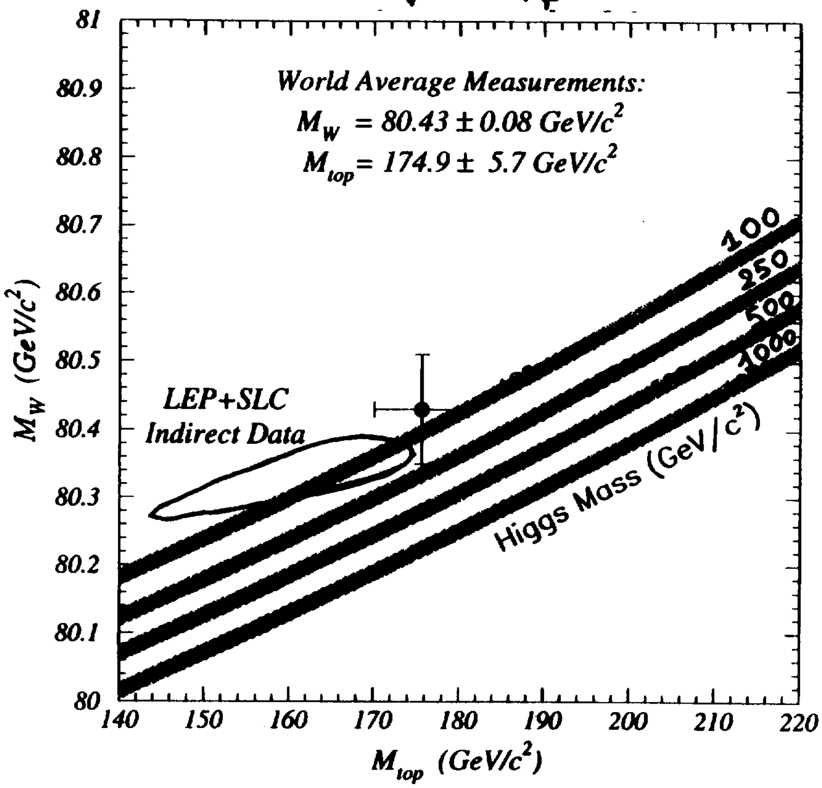


Motivations

$$m_W = \left(\frac{\pi \, \alpha(m_Z^2)}{\sqrt{2} \, G_F} \right)^{1/2} \frac{1}{\sin\vartheta_W \sqrt{1 - \Delta\rho}}$$

$\Delta\rho \approx 4\%$

$\uparrow f(m_t^2, \lg m_H^2)$



Jerusalem '97

"Gold rule": $\Delta m_W \sim 0.7 \times 10^{-2} \, \Delta m_t$ to get equivalent errors

$\hookrightarrow$ $\Delta m_t \approx 2$ GeV LHC

requires $\Delta m_W \approx 15$ MeV beyond sensitivity of LEP2 / Tev2000 (~ 30 MeV)

$\boxed{\text{Can LHC measure } m_W \text{ to } \lesssim 20 \text{ MeV ?}}$ $\leftarrow$ no complete study exists

- constrain m_H to $\approx 30\%$
- allow test of SM if Higgs found

m_W : <u>first precision measurement</u> at hadron Colliders ($S\bar{p}pS$, Tevatron)

Difficult ! – not enough kinematic constraints ($W \to \ell\nu$)

– underlying event
– background
– etc. .

⊕ subject to subtle effects difficult to predict before experiment starts

However

Determine LHC potential based on Tevatron experience + expected detector performance and physics at LHC

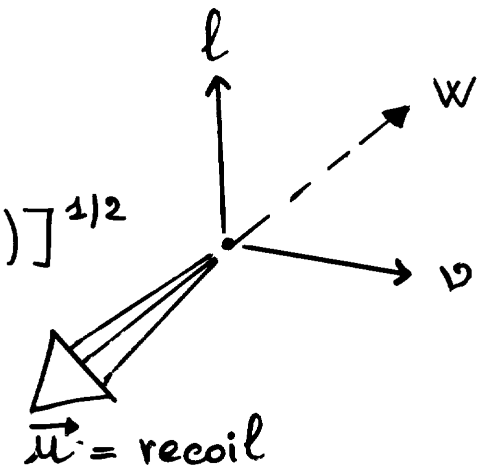
⬇

1) get idea of total error and dominant uncertainties

2) extract relevant lessons : needed detector performance, theoretical inputs, etc.

Method: pioneered by UA2

$\perp$ plane



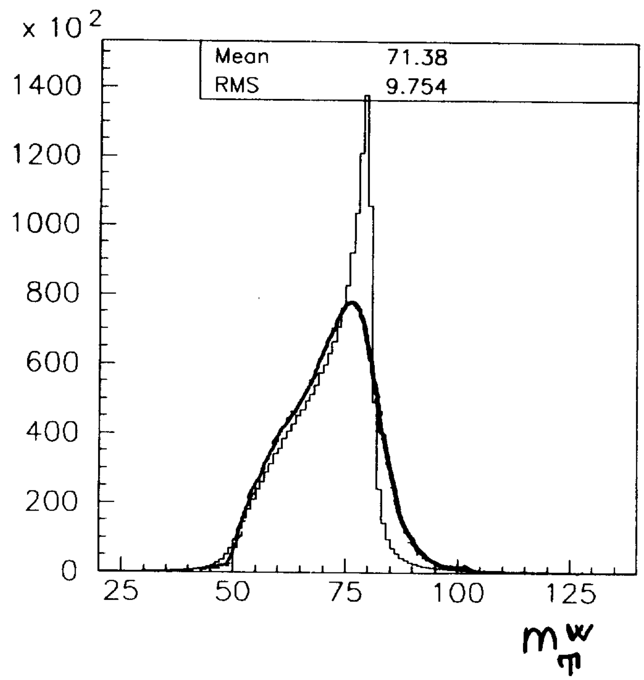
- Reconstruct m_T^W :

$$m_T^W = \left[2\, p_T^\ell\, p_T^\nu \left(1 - \cos\Delta\varphi_{e\nu}\right)\right]^{1/2}$$

$$p_T^\nu = -\left|\vec{p}_T^{\,\ell} + \vec{u}\right| = \not{p}_T$$

Edge of m_T^W distribution sensitive to m_W

$\downarrow$



—— particle level

—— include detector resolution (ATLAS)

Fit m_T^W from data with MC samples generated with various m_W $\longrightarrow$ get m_W which gives the best fit

Uncertainties on m_W

Come mainly from uncertainties on MC input ingredients

- **From detector performance :**
  - E, p scale
  - E, p resolution
  - Recoil modelling
  - Selection biasses

- **From physics :**
  - p_T^W, ϑ_W (higher-order)
  - structure functions
  - Γ_W
  - radiative decays
  - background

Constrained "in situ" by physics samples:

$W \to \ell\nu$

$Z \to \ell^+\ell^-$

$J/\psi \to \ell^+\ell^-$ etc.

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

Advantages of LHC

- **Physics** (statistics):

$\sigma(pp \to W + X) \simeq 30$ nb $\quad \sqrt{s} = 14$ TeV

$\quad\quad\quad\quad \hookrightarrow \ell\nu \quad\quad \ell = e, \mu$

$\hookrightarrow$ 300×10^6 events / year / expt at low $\mathcal{L}$

NB: $\sigma \approx 3$ nb $\quad \sqrt{s} = 1.8$ TeV

After typical selections:

1 isolated ℓ $\quad p_T^\ell > 25$ GeV $\quad |\eta_\ell| < 2.4$

$\not{p}_T > 25$ GeV , $|\vec{u}| < 20$ GeV

No jets $p_T > 30$ GeV

$$\hookrightarrow \varepsilon = \underset{\text{kinematic cuts}}{25\%} \times \underset{\ell\ \text{reconstruction}}{90\%} \times \underset{\ell\ \text{ID}}{80\%} \approx 20\%$$

$\hookrightarrow$ $\boxed{\sim 60\ \text{M}W / \text{year} / \text{expt at } 10^{33}}$

Tevatron Run I : ~ 35000 $W \to \ell\nu$ / expt

Tevatron Run II : $< 600\cdot000$ $W \to \ell\nu$ / expt

Furthermore :

High - statistics "control sample" close to m_W : $Z \to \ell^+ \ell^-$

Used to :

- understand detector performance (E, p scale , etc.)
- model detector response in MC (recoil, E/p resolution , etc.)
- model physics (p_T^W, etc.)

$$\sigma\,(pp \to \underset{\hookrightarrow \ell^+\ell^-}{Z + X}) \approx 3\ \text{nb} \qquad \ell = e, \mu$$

$\hookrightarrow$ $\boxed{\begin{array}{l} 1\ Z \to e^+e^-,\ 1\ Z \to \mu^+\mu^- \\ \text{per second at } 10^{33} \\ \\ 6\ \text{M}Z\ /\ \text{year}\ /\ \text{expt at } 10^{33} \\ \text{after all cuts} \end{array}}$

Tevatron Run I : ~ 3500 $Z \to \ell^+ \ell^-$

Tevatron Run II : $\lesssim 60\cdot000$ $Z \to \ell^+ \ell^-$

- **Detectors**:

ATLAS / CMS are potentially better detectors than CDF / DØ:

- E, p resolution (EM calo, μ system)
  → lepton measurement

- granularity (EM CALO):

DØ	$\Delta\varphi \times \Delta\eta = .1 \times .1$
CDF	$= .25 \times .1$
ATLAS	$= .025 \times .025$ + strips

→ electron ID, radiative decays, underlying event, etc.

- coverage:

$\lvert\eta\rvert < 2.4$	precision physics	LHC
$\lvert\eta\rvert < 1$	" "	Tevatron Run 1
$\lvert\eta\rvert < 5$	calorimetry coverage	LHC

→ acceptance, $\not{p}_T$ measurement

Disadvantages of LHC

- **Detector complexity**
  ↳ need time to understand performance to required level

- Environment (pile-up) if $\mathcal{L}$ goes up fast.

For $\mathcal{L} = 10^{33}\ cm^{-2}\ sec^{-1}$:

2 interactions / x-ing ⟶ "quiet environment"

Note : Tevatron Run 1B
~ 2.5 interactions / x-ing

For $\mathcal{L} = 10^{34}\ cm^{-2}\ sec^{-1}$:

20 interactions / x-ing ⟶ m_T^W edge spoiled

↳ m_W is most likely a low $\mathcal{L}$ measurement

Method :

PYTHIA + ATLFAST

- Produce m_T^W plot for "reference" mass ($m_W = 80.300$ GeV)
- Consider all uncertainties from Tevatron → extrapolate to LHC

TABLE. I. Summary of uncertainties (in MeV/c^2) in the W mass measurement.

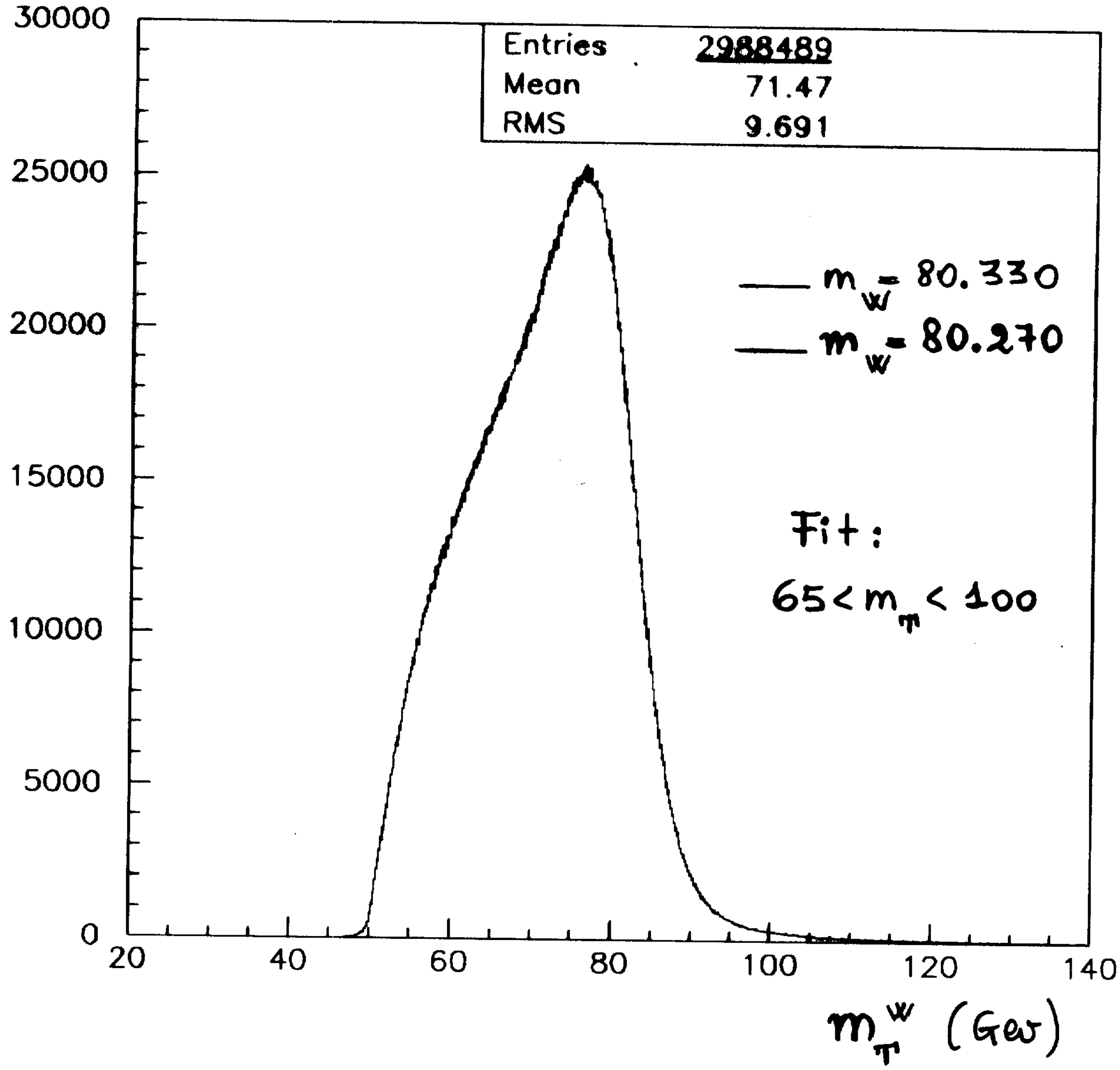
Uncertainty	ΔM_W^e	ΔM_W^μ	Common
Statistical	145	205	...
Energy scale	120	50	50
Scale from J/ψ	50	50	50
CTC alignment	15	15	15
Calorimeter	110	...	...
Other systematics	130	120	90
e or μ resolution	80	60	...
Input p_T^W	45	45	25
Recoil modeling	60	60	60
Parton dist. functions	50	50	50
e or μ ID and removal	25	10	5
Trigger bias	0	25	...
Radiative corrections	20	20	20
W width	20	20	20
Higher-order corrections	20	20	20
Backgrounds	10	25	...
Fitting	10	10	...
Total uncertainty	230	240	100

CDF
Run 1A

PRD, 52, 1995, 4784.

- Change simulation ingredients (p_T^W, e/μ resolution, etc.)
  ↳ new m_T^W spectra
- Compare new m_T^W spectra with "reference" spectrum (Kolmogorov test)
  ↳ Δm_W

Total $\Delta m_W \lesssim 20$ MeV $\longrightarrow$
single uncertainties $\ll 10$ MeV
$\longrightarrow$ need large statistics



3 M of events after cuts $\longleftarrow$ 5% of
$\approx$ 12 M of events generated : LHC statistics!
(one year)

$\Delta m_W = 60$ MeV $\longleftrightarrow$ 7.5 σ

$\hookrightarrow$ sensitive to $\approx$ 8 MeV

ℓ energy / momentum scale

Largest uncertainty at Tevatron :

CDF (1A)	:	120	MeV	$W \to e\nu$	(1.5 ‰)
		50	MeV	$W \to \mu\nu$	(0.6 ‰)
DØ (1 A+B)	:	70	MeV	$W \to e\nu$	(0.9 ‰)

Most likely dominant error also at LHC :

$\Delta m_W \lesssim 20$ MeV $\to$ $\Delta E \lesssim 0.2$ ‰

(15 MeV error on m_W)

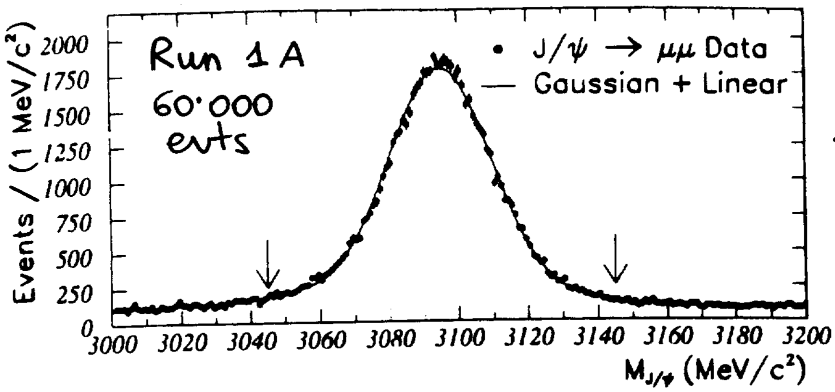
$\longrightarrow$ **! ?**

Note :

- up to now ATLAS goal : 1 ‰
  ($H \to \gamma\gamma$ mass, $\chi^0_2 \to \ell\ell\,\chi^0_1$ edge, etc.)
  $\to$ not enough to measure m_W
- TeV 2000 : $\Delta m_W \lesssim 40$ MeV $\to$ $\Delta E \approx 0.4$ ‰

CDF:

- p scale in tracker determined with $J/\psi \to \mu^+ \mu^-$

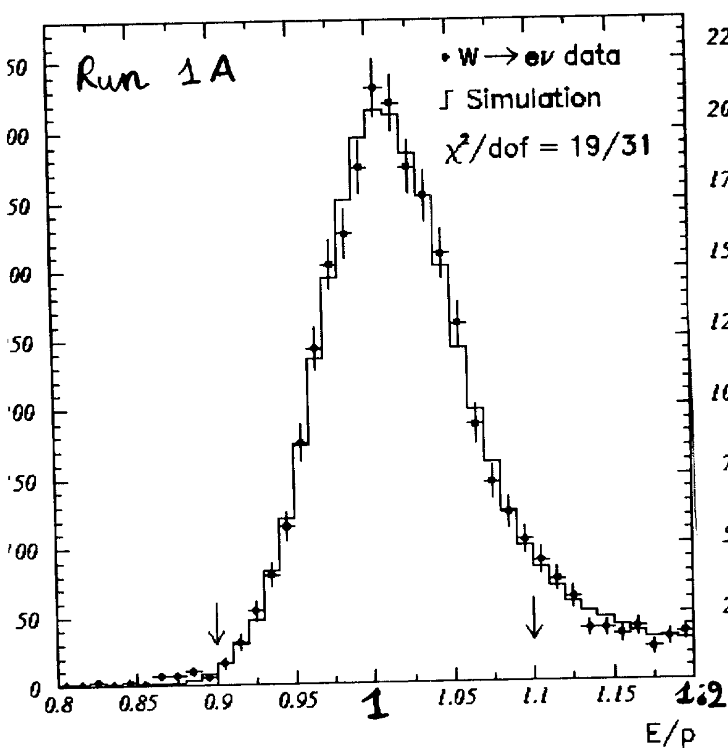


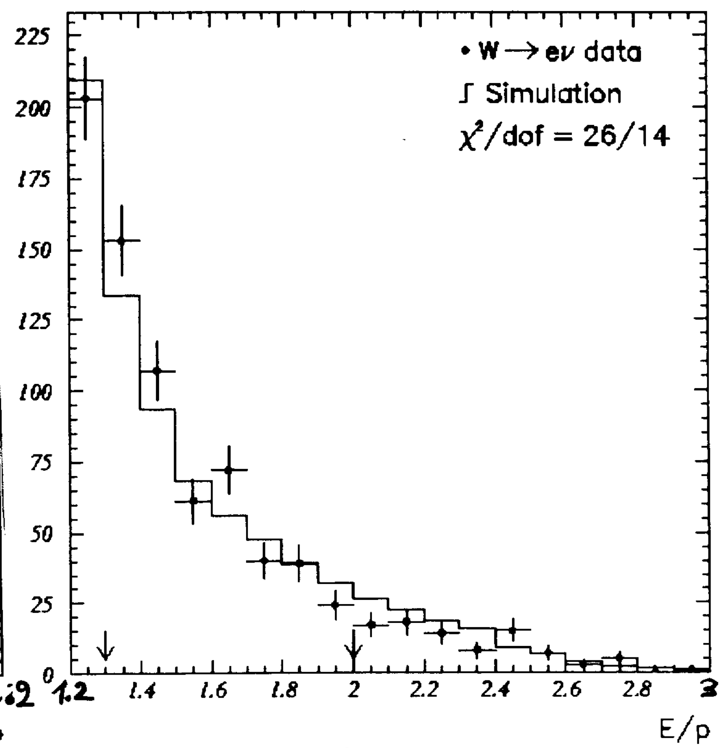
$\to$ 0.6 ‰

$\Delta m_W \approx 50$ MeV

- E scale in calorimeter transferred from tracker using E/p for $e^\pm$ from W decays

↑ from MC (Bremsstrahlung)

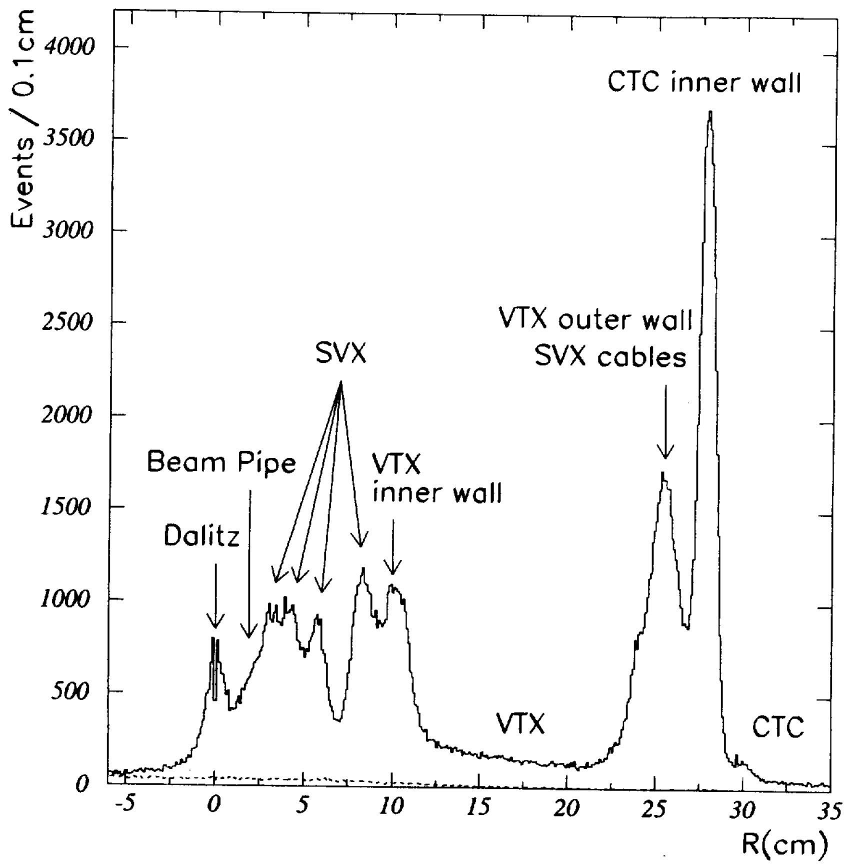


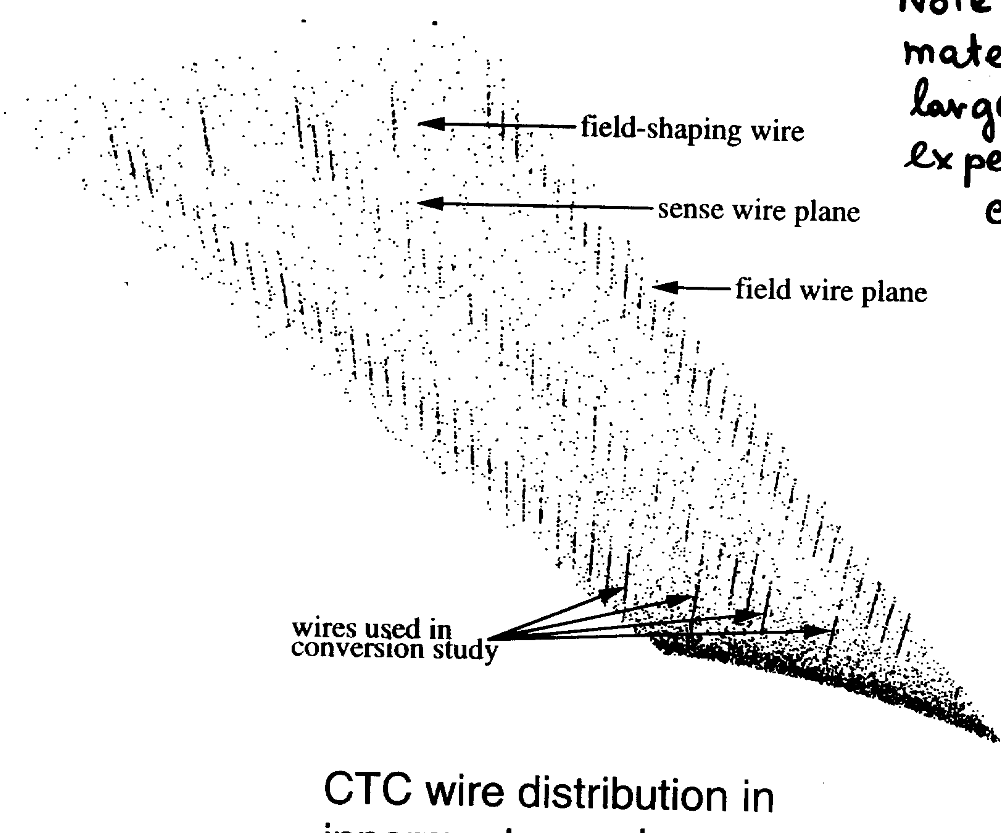


from peak get the scale

from tails (+ $\gamma \to e^+ e^-$) get tracker material

Material checked with $\gamma \rightarrow e^+e^-$





CTC wire distribution in innermost superlayer

Note: measured material ~ 1.4 larger than expected from construction

CDF error on $\mu^\pm$ scale

from $J/\psi \to \mu^+\mu^-$ (60·000 evts)

Effect	Uncertainty (MeV/c^2)	ATLAS ($Z \to \mu^+\mu^-$)
Statistics	0.1	/
Muon energy loss before tracking	1.3	.04
Beam constraint	0.3	/
Opening polar angle effect	—	/
Residual field nonuniformity	0.6	< 0.6 ?
Background	0.1	/
Time variation	0.5	/
Radiative decay	0.2	.1
Uncertainty in world-average $M_{J/\psi}$	0.1	.05
Subtotal	1.6	
Extrapolation from $M_{J/\psi}$ to M_W	0.9	.04
$\boxed{\text{Total}}$	.6‰ 1.8	< .6 MeV $\boxed{.2‰}$

→ $\Delta m_W \approx 50$ MeV $\Delta m_W \approx 15$ MeV

CDF error on $e^\pm$ scale

TABLE XIII. Uncertainties incurred setting the energy scale from the momentum scale.

Effect	Uncertainty (%)	ΔM_W^e (MeV/c^2)	ATLAS (E/p)
Statistics in E/p peak	0.08	65	/
Material scale	0.09	70	8 MeV (*)
Electron resolution	0.06	50	5
Fitting	0.02	15	/
Total	0.136	110	
+ μ scale	.06	50	15 MeV
$\boxed{\text{Total}}$	.15	$\boxed{120}$	18 MeV (.2‰)

⊕ <u>$Z \to ee$</u>

(*) require knowing iD material to ≈ %

↳ <u>Hard to get .2‰ but not impossible</u>
(to be studied with full simulation)

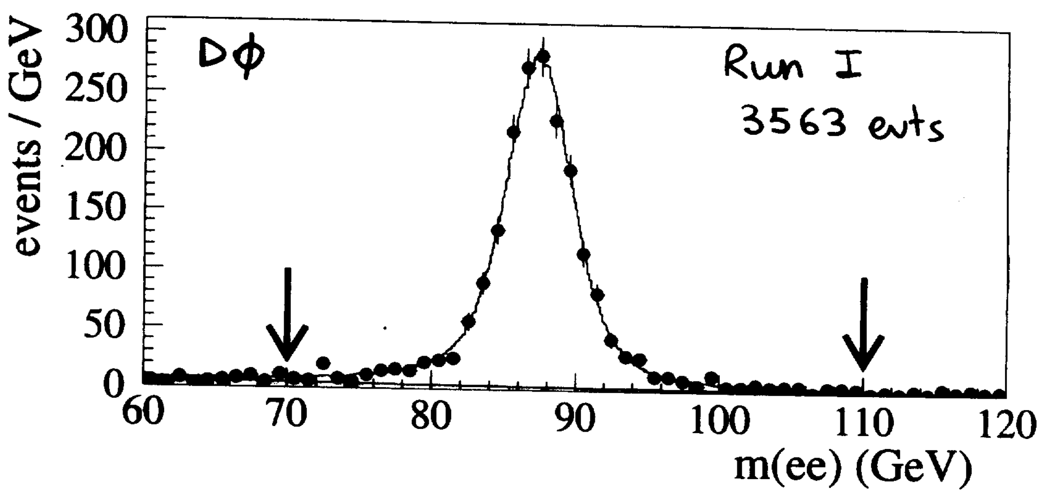
DØ : no B-field → use $Z \to e^+e^-$ to calibrate EM calo

$$E_{TRUE} = \alpha \, E_{MEAS.} + \delta$$

material, linearity, etc.

α, δ obtained constraining $Z \to e^+e^-$, $\pi^0 \to \gamma\gamma \to e^+e^-$ peaks
$\hookrightarrow e^+e^-$

uncorrected mass is 5% too low



→ $\Delta m_W \approx 70$ MeV from uncertainty (mainly statistics) on α, δ

Note: Uncorrected absolute scale is ~ 5% too low

ℓ energy / momentum resolution

CDF : 80 MeV $W \to e\nu$
60 MeV $W \to \mu\nu$

σ / p_T^2 and σ / E determined from
$Z \to \ell^+ \ell^-$ width

Ex. $\dfrac{\sigma(\mu)}{p_T^2} = 0.000810 \underbrace{\pm 0.000085}_{\text{statistics}}^{10\%} \underbrace{\pm 0.00001}_{\text{systematics}}^{1\%} \ \mathrm{GeV}^{-1}$

LHC : 20% uncertainty on
e/μ resolution $\to \Delta m_W \approx 120$ MeV

similar to CDF

↳ to have $\Delta m_W < 10$ MeV
need to know ℓ
resolution to $\lesssim 1.5\%$

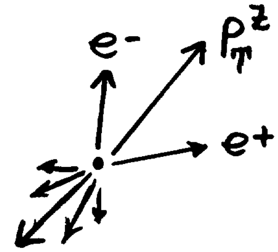
Large samples of $Z \to \ell^+ \ell^-$: 5.7 M Z / year
after all cuts
(CDF : ~ 900 Z's)

↳ Dominated by systematic error ($<1.5\%$ CDF)

↳ $\boxed{\Delta m_W < 10 \text{ MeV}}$ to be confirmed by full simulation

Recoil modelling (*)

For a given p_T^W recoil taken from $Z \to \ell^+ \ell^-$ data with $p_T^Z \approx p_T^W$



CDF : 60 MeV $W \to e\nu$
60 MeV $W \to \mu\nu$

dominated by $Z \to \ell^+ \ell^-$ statistics

$\Downarrow$

LHC : $\boxed{\Delta m_W \ll 10 \text{ MeV}}$

Note : recoil includes (small) pile-up at low $\mathcal{L}$

(*) $m_T^2 = 2\, p_T^\ell \not{p}_T \, (1 - \cos\Delta\varphi)$

$\hookrightarrow \quad \vec{\not{p}}_T = -(\vec{u} + \vec{p}_T^{\,\ell})$

DΦ (Run 1) : $\Delta m_W \approx 30$ MeV

Uncertainty on p_T^W ← ≈ 12 GeV $\sqrt{s}=14$ TeV

Predicted p_T^W : "large" theoretical uncertainties — non-perturbative region (soft gluons)

Measured p_T^W : large experimental uncertainties — low-p_T particles

↓

- since $p_T^W \approx p_T^Z$, measure p_T^Z $(Z \to \ell^+\ell^-)$ and use it as initial guess for p_T^W
- tune "p_T^W" until

$u_{\parallel}, u_{\perp}$ ← recoil MC ≈ recoil W data

CDF : 45 MeV $W \to e\nu$; 45 MeV $W \to \mu\nu$ } mainly from statistics of W/Z samples

—— LHC
—— Tevatron

PYTHIA

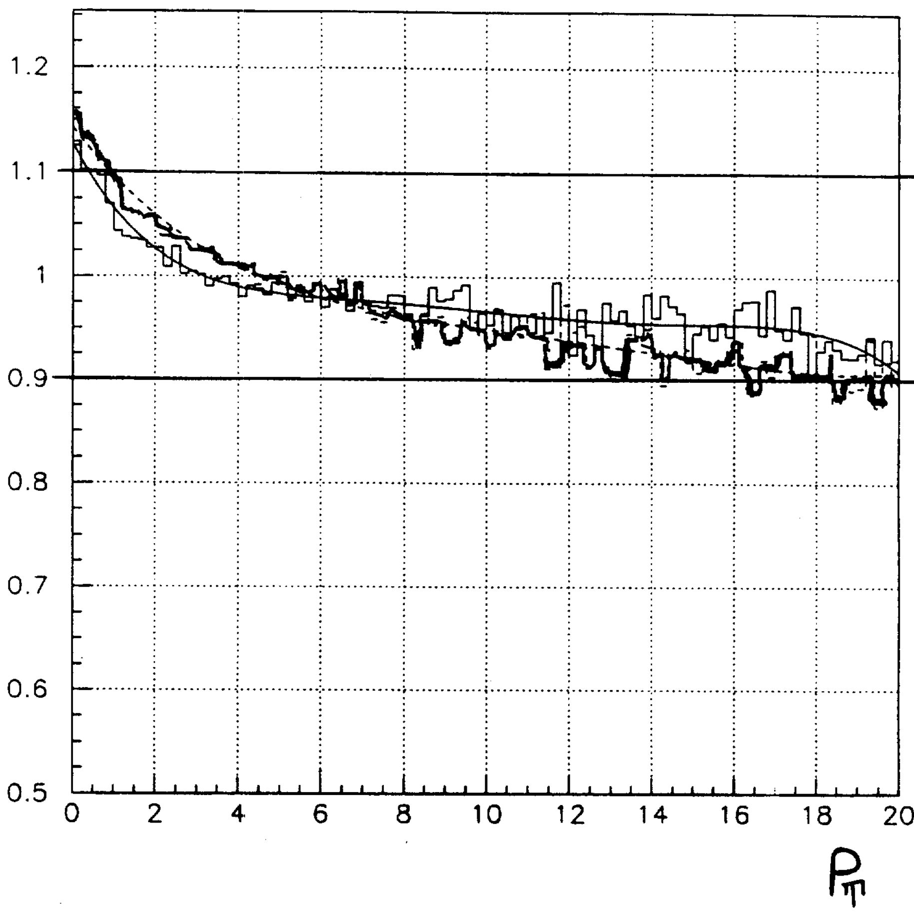
$\langle \rangle \approx 12$ GeV

$\downarrow$

$\dfrac{p_T^W}{p_T^Z}$

$\uparrow$

$\langle \rangle \approx 14$ GeV



+ 10 %

− 10 %

difference increases for $p_T > 20$ GeV $\rightarrow$ justifies $|\vec{u}| < 20$ GeV

LHC : large statistics of $Z \to \ell^+ \ell^-$
↳ accurate measurement of p_T^Z

Replacing p_T^W with p_T^Z in the simulation:

$\underline{\Delta m_W \simeq 10 \text{ MeV}}$	fit $65 < m_T^W < 100$ GeV
$\simeq 60$ MeV	fit full spectrum
$\simeq 200$ MeV	fit to p_T^ℓ spectrum

No further tuning done

↳ $\boxed{\Delta m_W < 10 \text{ MeV}}$

W width

CDF : 20 MeV $W \to q\nu$; 20 MeV $W \to \mu\nu$ $\Big\}$ $\Gamma_W = 2.064 \pm .085$ GeV

measured by CDF

Tevatron : Γ_W measured from:

– fit to high-E tails of m_T^W

$\longrightarrow \Delta\Gamma_W \approx 320$ MeV

– $R = \dfrac{\sigma_W}{\sigma_Z} \cdot \dfrac{BR(W \to \ell\nu)}{BR(Z \to \ell^+\ell^-)}$ ← LEP

measured (R) ; theory (σ_W/σ_Z)

↳ deduce $BR(W \to \ell\nu) \to \Gamma_W$

$\Delta\Gamma_W = .085$ GeV

2005 : LEP2 : $\Delta\Gamma_W \approx 200$ MeV ?

Tev 2000 : $\Delta\Gamma_W \ll 30$ MeV

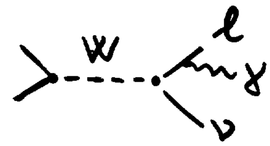
↳ Using $\Delta\Gamma_W = 30$ MeV and CDF error on m_W:

$$\boxed{\Delta m_W < 7 \text{ MeV}}$$

Γ_W at LHC : need to know $\dfrac{\sigma_W}{\sigma_Z}$ at $\ll 1\%$

$\longrightarrow$ theoretical input

Radiative corrections



$W \to \ell\nu\gamma$ decays produce shift in $m_T^W \longrightarrow$ corrected. Error from theoretical uncertainties $\longleftarrow$ today $O(\alpha)$ calculations

CDF : 20 MeV $W \to e\nu$
20 MeV $W \to \mu\nu$

LHC :

- improved theoretical calculations already available (Baur et al., Phys. Rev. D56, 140 (1997))
- granularity of ATLAS calo much finer than CDF $\longrightarrow$ study in more detail distribution of radiated γ's
- large statistics of $Z \to \ell^+\ell^-\gamma$

$$\downarrow$$

$$\Delta m_W \ll 20 \text{ MeV}$$

Assume : $\boxed{\Delta m_W \approx 10 \text{ MeV}}$ $\longleftarrow$ to be confirmed by full sim.

DØ (Run 1) : $\Delta m_W = 15$ MeV

Background

Can distort m_T^W shape

CDF : 10 MeV $W \to e\nu$ } from background
25 MeV $W \to \mu\nu$ } uncertainty

Dominant backgrounds : $W \to \tau\nu$ e channel
$\hookrightarrow e\nu$ (.8%)

$Z \to \mu^+\mu^-$ μ channel
(3.6%)
↑
μ coverage
up to $|\eta|<1.7$

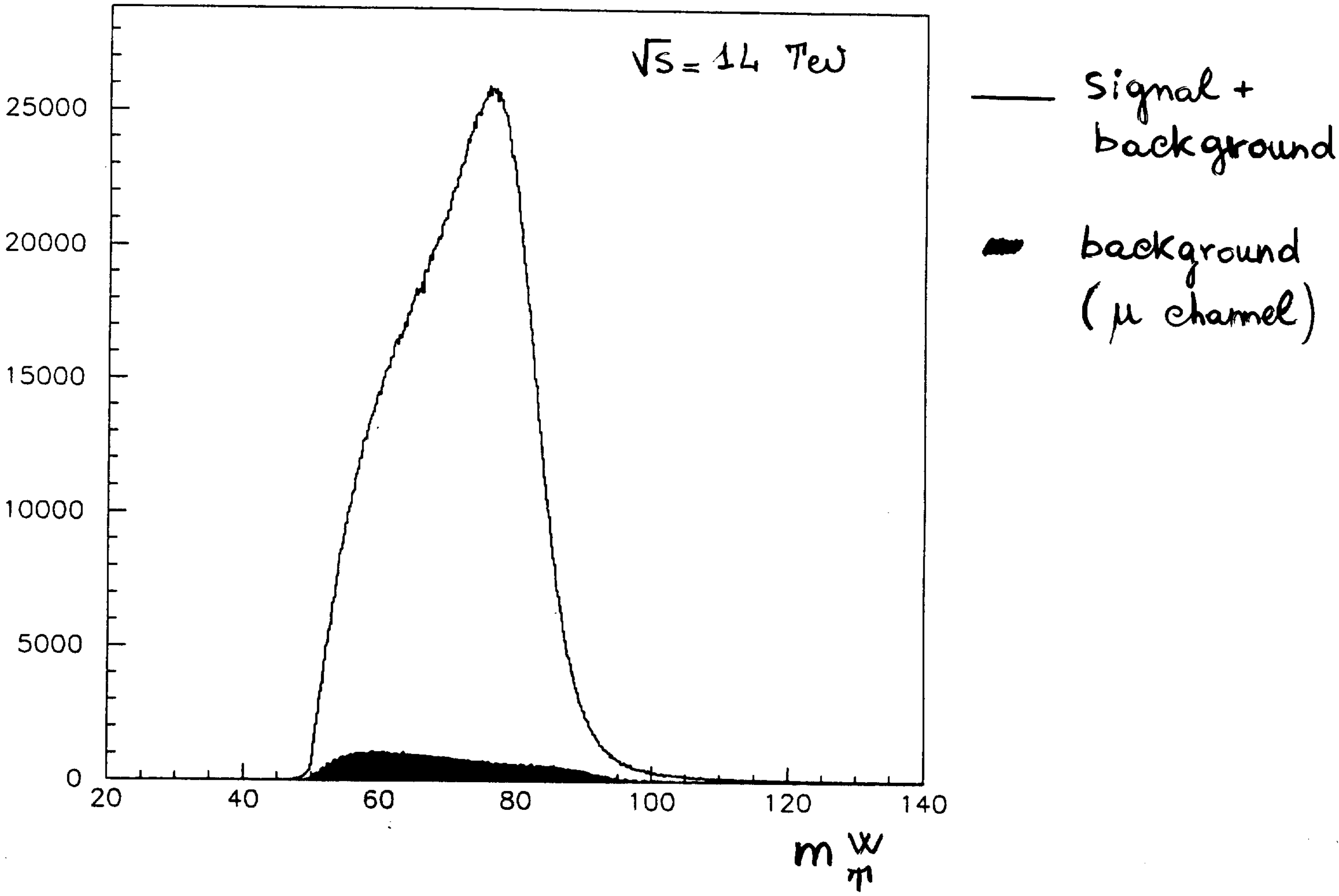
ATLAS :

$Z \to e^+e^-$: $\sim 10^{-4}$

$Z \to \mu^+\mu^-$: 4% (if $|\eta_\mu| > 2.7$ large p_T !)

$W \to \tau\nu$: 1.3%

$t\bar{t}$: 10^{-5}



$\langle m_T^W \rangle = 71.5$ GeV signal

$\simeq 69.7$ GeV background

If background is neglected:

$\Delta m_W \approx 30$ MeV $W \to e\nu$

140 MeV $W \to \mu\nu$

↳ to have $\Delta m_W < 10$ MeV need to know background to

$< 30\%$ $W \to e\nu$

$< 7\%$ $W \to \mu\nu$ ← dominated by $Z \to \mu\mu \to$ check with $Z \to ee$

CDF: background known to 15%

Total error on m_W

(a first provocative guess...)

SOURCE	Δm_W $(10^4 pb^{-1})$
Statistics	2 MeV
E-scale	15 MeV ←
e/μ resolution	5 MeV
P_T^W	5 MeV
recoil modelling	5 MeV
e/μ removal	3 MeV
e/μ ID	5 MeV
W width	5 MeV
Radiative corrections	10 MeV
Higher-order corrections	10 MeV
Structure functions	10 MeV ← ?
Background	5 MeV
Fitting	5 MeV
Others (unpredictable ...)	?
TOTAL	~ 25 MeV

↑ per channel / expt.

→ $\boxed{< 20 \text{ MeV}}$ combining e/μ per experiment

Note :

- Statistics is large but we will need to understand detector vs η / φ / E ....

- Need a lot of constraints (e.g. precise knowledge of $\underline{B}$ and iD material) to disentangle different contributions to detector behaviour → to determine systematics

- Use of p_T^ℓ ($\rightarrow \approx m_W/2$) under study (insensitive to p_T, less sensitive to pile-up, more sensitive to p_T^W than m_T^W)

- Use of m_T^Z will also be studied. However:
  - lose ~ 10 in statistics
  - different W / Z production (PDF, radiative decays, etc.)
  - $e^\pm$ identification bring bias

Eventually will use everything

Conclusions

- Measurement of m_W to ≈ 15 MeV important to constrain m_H and theory (SM, MSSM)

- Preliminary study : ATLAS can achieve

  $m_W < 20$ MeV from m_T^W (*)

  More study needed with p_T^ℓ, m_T^Z

- Full simulation needed to understand detector effects (E/p scale/resolution, bias from lepton iD, pile-up, etc.)

  ↳ lot of work

(*) Note: precision competitive with $\ell^+\ell^-$ LC where $\Delta m_W \approx 15$ MeV (not true for m_{top} !)

Theoretical challenges:

- p_T^W , ϑ_W
- radiative decays
- $\sigma_W / \sigma_Z \longrightarrow \Gamma_W$
.....

Experimental challenges :

- ℓ scale $\longrightarrow$ $\Delta \underline{B} \approx 1‰$
  $\Delta X_0 \approx \%$
  Alignement $\approx \mu$
- ℓ resolution
- bias from ℓ identification

ATLAS:
1 month
during
installation
devoted to
this