Overview of m_W measurements: past, present and future

Outline

- → Recently published legacy measurement from CDF (at TeVatron)
  https://www.science.org/doi/pdf/10.1126/science.abk1781
  https://www.science.org/action/downloadSupplement?doi=10.1126%2Fscience.abk1781&file=science.abk1781_sm.pdf

- → A quick chronological overview and perspective : from UA2 to FCCee

- → What is likely to happen in the near future at the LHC?

Recent very precise CDF m_W measurement

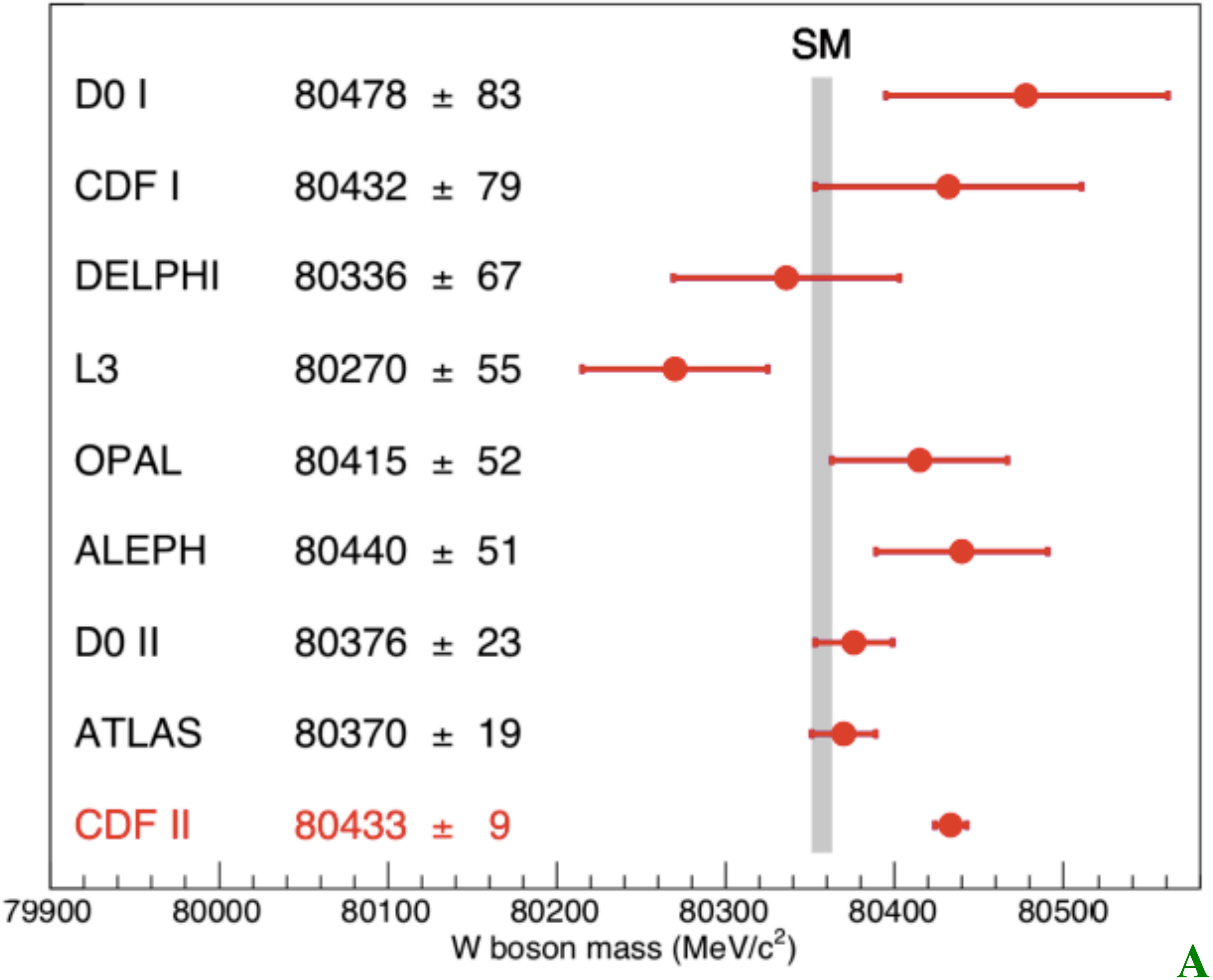


Fig. 5

A. Kotwal

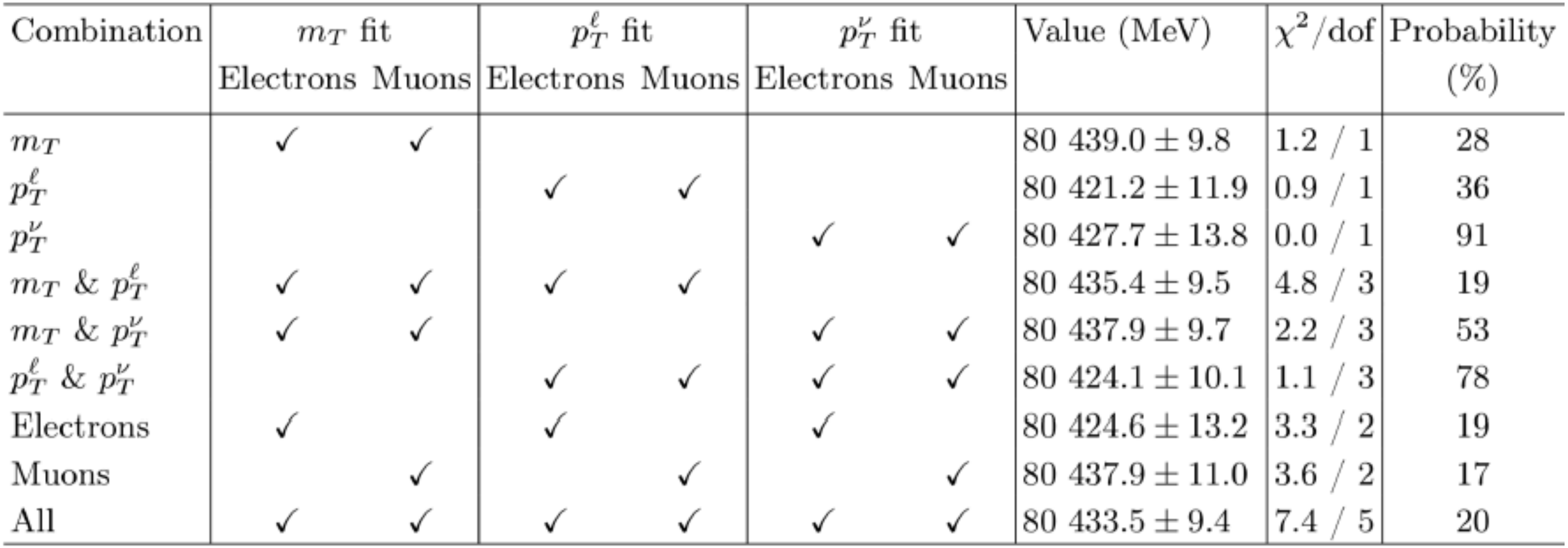
A. Kotwal

SM expectation: $M_W = 80{,}357 \pm 4_{\text{inputs}} \pm 4_{\text{theory}}$ (PDG 2020)

LHCb measurement : $M_W = 80{,}354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}$ [*JHEP* **2022**, 36 (2022)]

A few points about legacy CDF m_W measurement

Combinations of Fit Results



Combination	m_T fit		p_T^ℓ fit		p_T^ν fit		Value (MeV)	χ^2/dof	Probability (%)
	Electrons	Muons	Electrons	Muons	Electrons	Muons			
m_T	✓	✓					$80\,439.0 \pm 9.8$	1.2 / 1	28
p_T^ℓ			✓	✓			$80\,421.2 \pm 11.9$	0.9 / 1	36
p_T^ν					✓	✓	$80\,427.7 \pm 13.8$	0.0 / 1	91
m_T & p_T^ℓ	✓	✓	✓	✓			$80\,435.4 \pm 9.5$	4.8 / 3	19
m_T & p_T^ν	✓	✓			✓	✓	$80\,437.9 \pm 9.7$	2.2 / 3	53
p_T^ℓ & p_T^ν			✓	✓	✓	✓	$80\,424.1 \pm 10.1$	1.1 / 3	78
Electrons	✓		✓		✓		$80\,424.6 \pm 13.2$	3.3 / 2	19
Muons		✓		✓		✓	$80\,437.9 \pm 11.0$	3.6 / 2	17
All	✓	✓	✓	✓	✓	✓	$80\,433.5 \pm 9.4$	7.4 / 5	20

Table S9

- Combined electrons (3 fits): $M_W = 80424.6 \pm 13.2$ MeV, $P(\chi^2) = 19\%$

- Combined muons (3 fits): $M_W = 80437.9 \pm 11.0$ MeV, $P(\chi^2) = 17\%$

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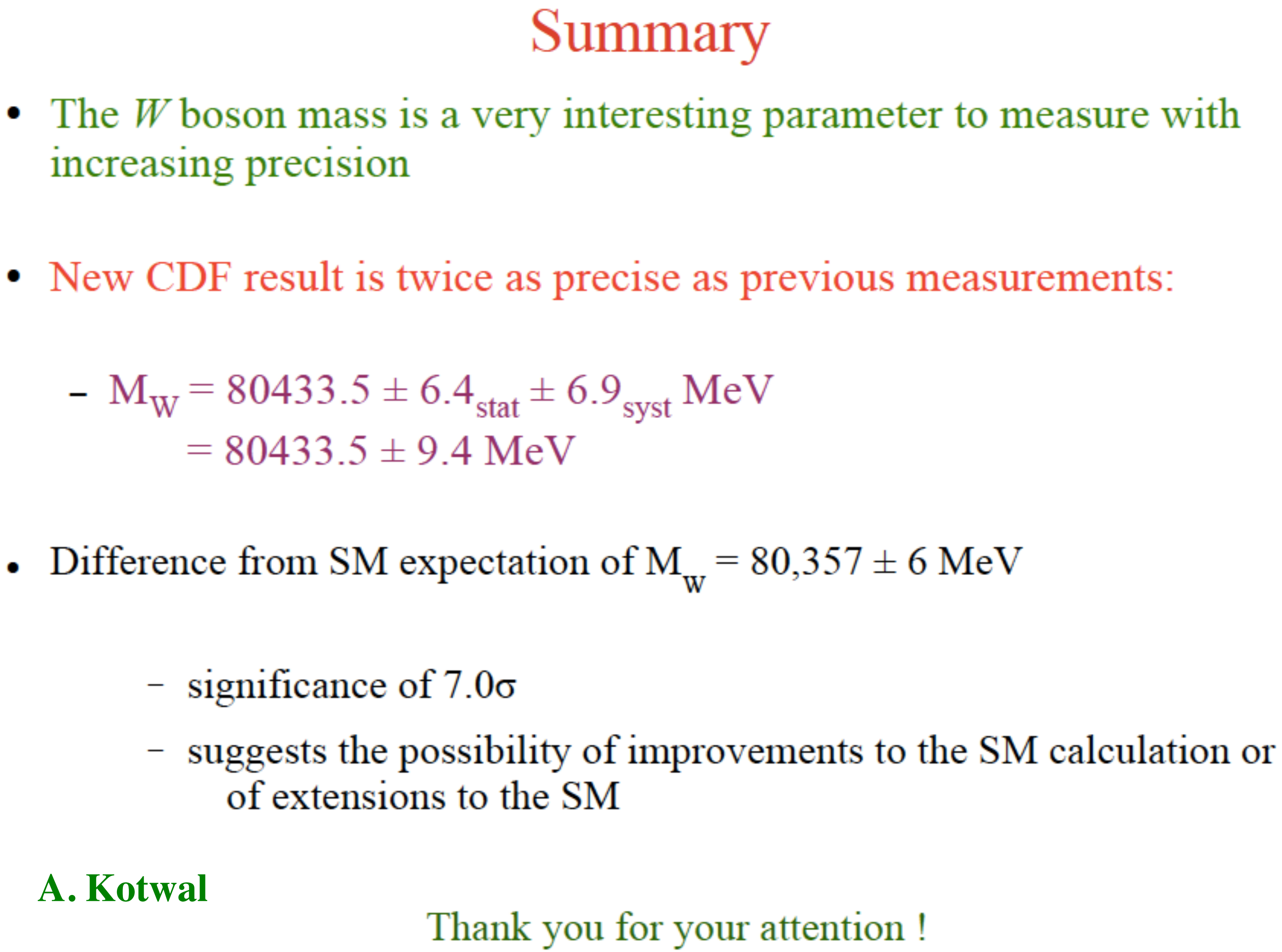
- All combined (6 fits): $M_W = 80433.5 \pm 9.4$ MeV, $P(\chi^2) = 20\%$

A few points about legacy CDF m_W measurement



Summary

- The *W* boson mass is a very interesting parameter to measure with increasing precision

- New CDF result is twice as precise as previous measurements:
  - $M_W = 80433.5 \pm 6.4_{stat} \pm 6.9_{syst}$ MeV
    $= 80433.5 \pm 9.4$ MeV

- Difference from SM expectation of $M_W = 80{,}357 \pm 6$ MeV
  - significance of 7.0σ
  - suggests the possibility of improvements to the SM calculation or of extensions to the SM

A. Kotwal

Thank you for your attention !

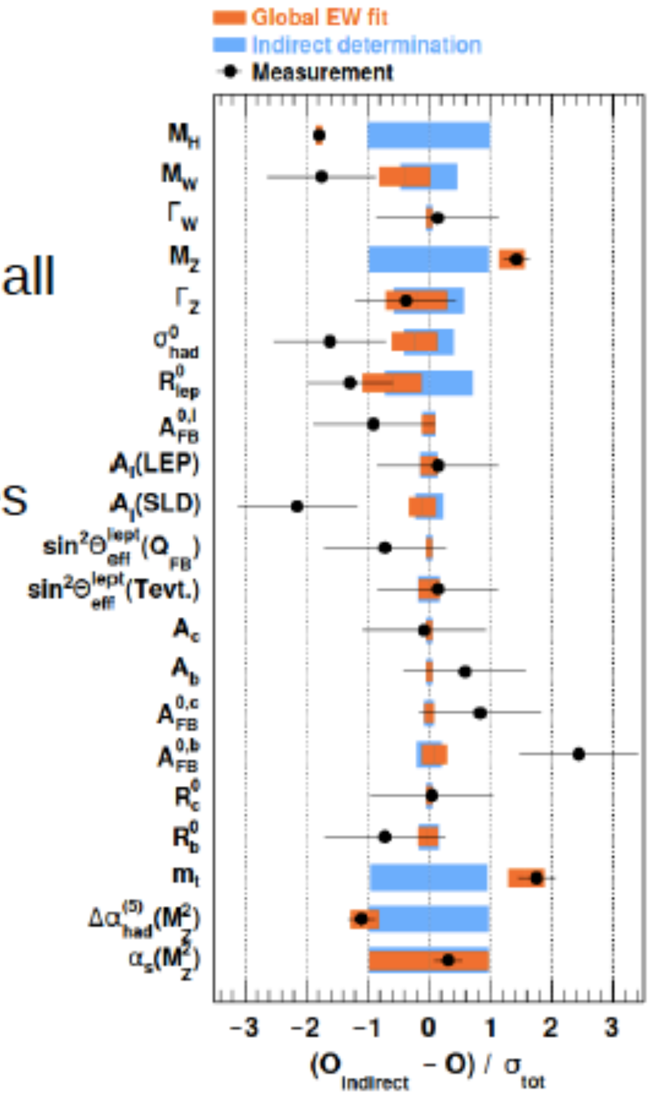
Overview of m_W measurements: past, present and future

In the recent past, the global electroweak fit was able to predict the masses of the top quark and Higgs boson before their discovery

- After the measurement of the Higgs mass, all the free parameters of the Standard Model are known
- Relations between electroweak observables can be predicted at 2-loop level

Precise measurements of the electroweak parameters allow

- Stringent test of the self consistency of the SM
- Looking for hints of physics beyond the SM



Eur. Phys. J. C78, 675 (2018)

Overview of m_W measurements: past, present and future

The electroweak gauge sector of the Standard Model is constrained by three precisely measured parameters

$$\begin{aligned} \alpha &= 1/137.035999139(31) \\ G_F &= 1.1663787(6) \times 10^{-5}\ \mathrm{GeV}^{-2} \\ m_Z &= 91.1876(21)\ \mathrm{GeV} \end{aligned}$$

At tree level, other EW parameters can be expressed as

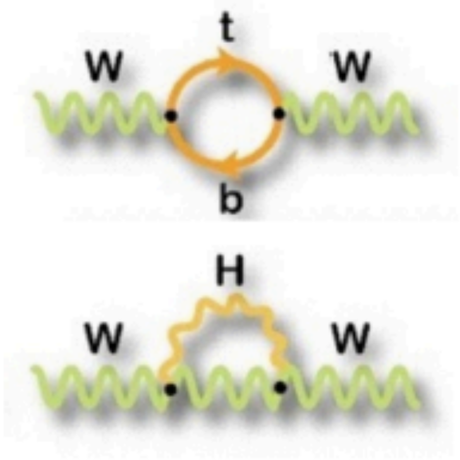
$$\left\{ \begin{aligned} m_W^2 &= \frac{\pi\alpha}{\sqrt{2}G_F\,(1 - m_W^2/m_Z^2)}\,(1-\Delta r) \\ \sin^2_{\mathrm{eff}}\theta_W &= \left(1 - \frac{m_W^2}{m_Z^2}\right)\kappa \\ \Gamma_W &= \frac{3G_F m_W^3}{2\sqrt{2}\pi}\rho \end{aligned} \right.$$

Higher order corrections modify these relations, and determine sensitivity to other particle masses and couplings

Overview of m_W measurements: past, present and future

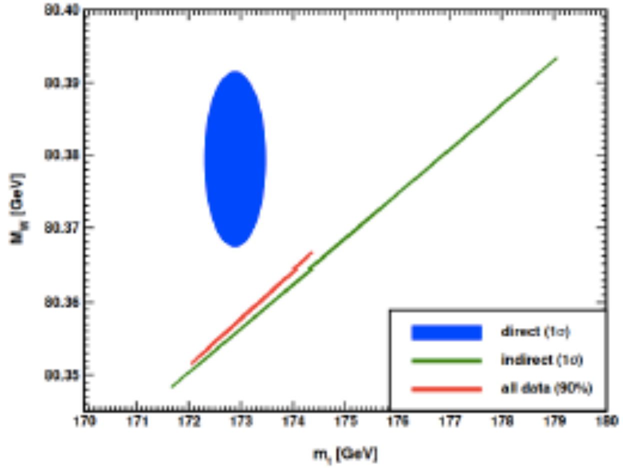
Radiative corrections Δr to mW are dominated by top-quark and Higgs loops

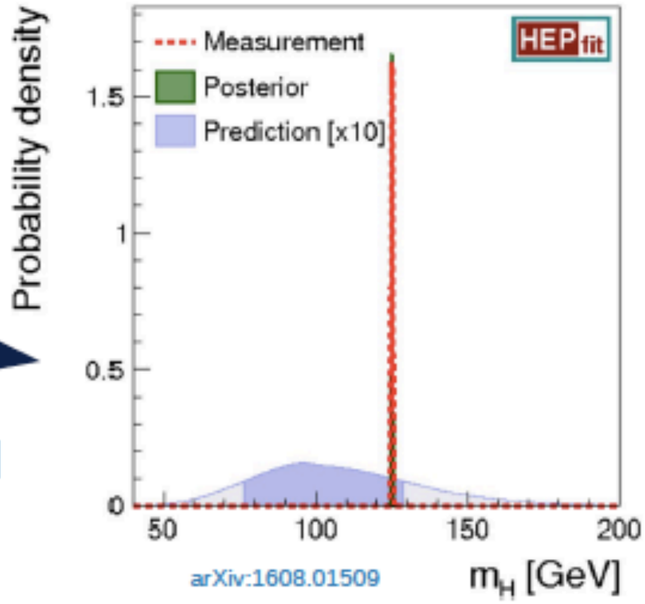
$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F\left(1 - m_W^2/m_Z^2\right)\left(1 - \boxed{\Delta r}\right)}$$



- The relation between m_t, m_H and m_W provides a stringent test of the SM

Prog. Theor. Exp. Phys. 2020, 083C01 (2020)



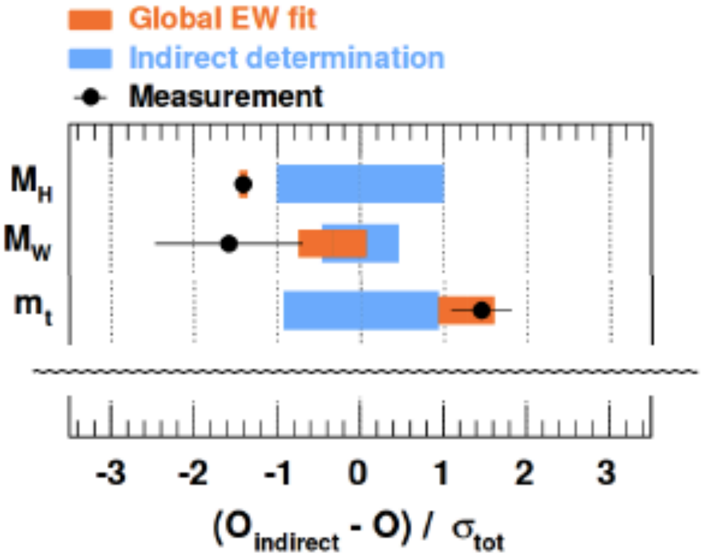


arXiv:1608.01509

- The comparison between the measured m_H and the predicted m_H is sensitive to new physics

Overview of m_W measurements: past, present and future

The global fit of the electroweak observables is dominated by the measurement of m_W



	Measurement	SM Prediction (*)
m_H	125.09 ± 0.24	100.6 ± 23.6
m_t	173.1 ± 0.6	176.1 ± 2.2
m_W	80.379 ± 0.012	80.360 ± 0.007

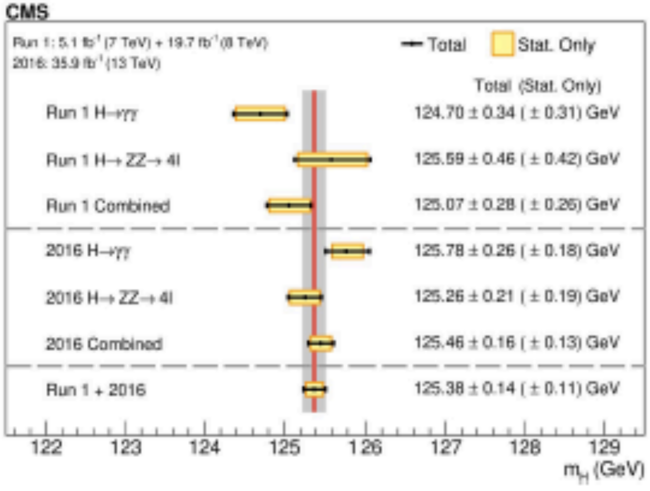
(*) arXiv:1710.05402

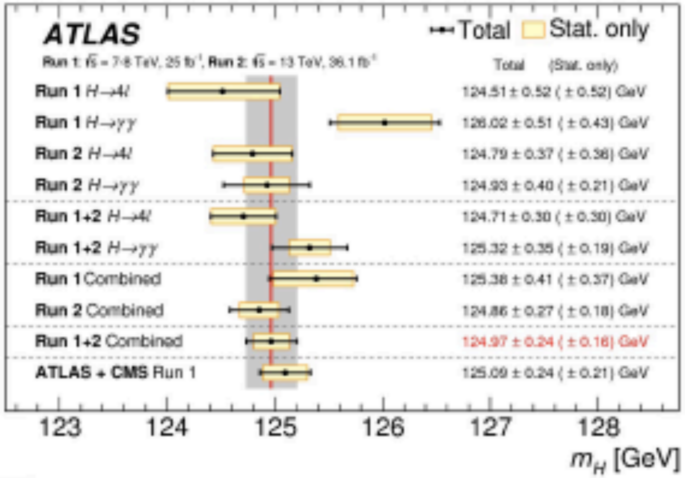
The measurements of the Higgs and top-quark masses are currently more precise than their indirect determination from the global fit of the electroweak observables → Improving precision will not increase sensitivity to new physics

Indirect determination of m_W (±7 MeV) is more precise than the experimental measurement → Call for $\delta m_W^{exp} \sim 5$ MeV

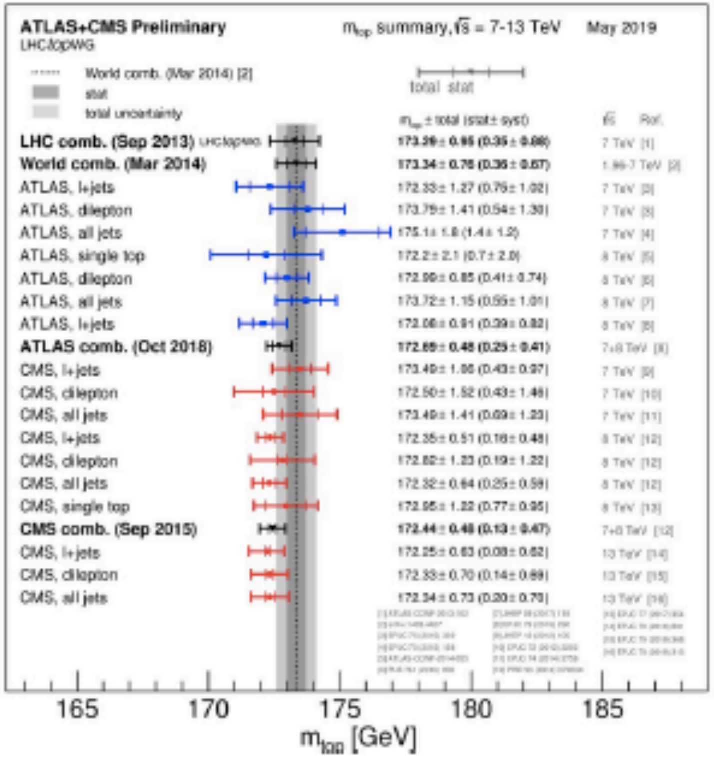
The W mass is nowadays the crucial measurement to improve the sensitivity of the global EW fits to new physics

Overview of m_W measurements: past, present and future





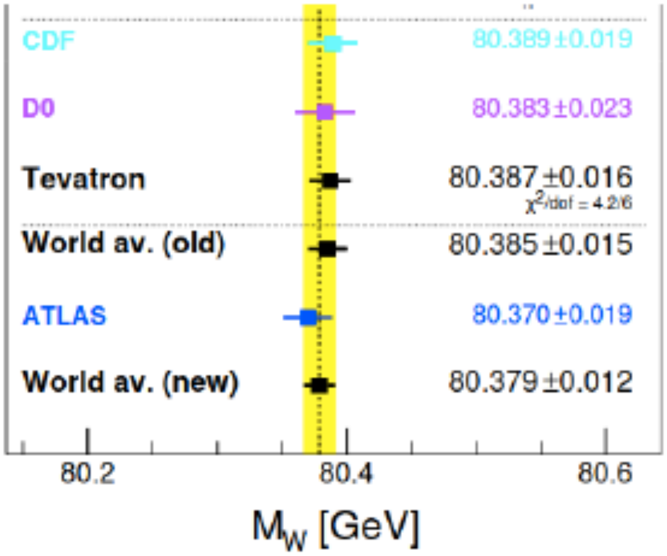
m_H 2012 – 2020



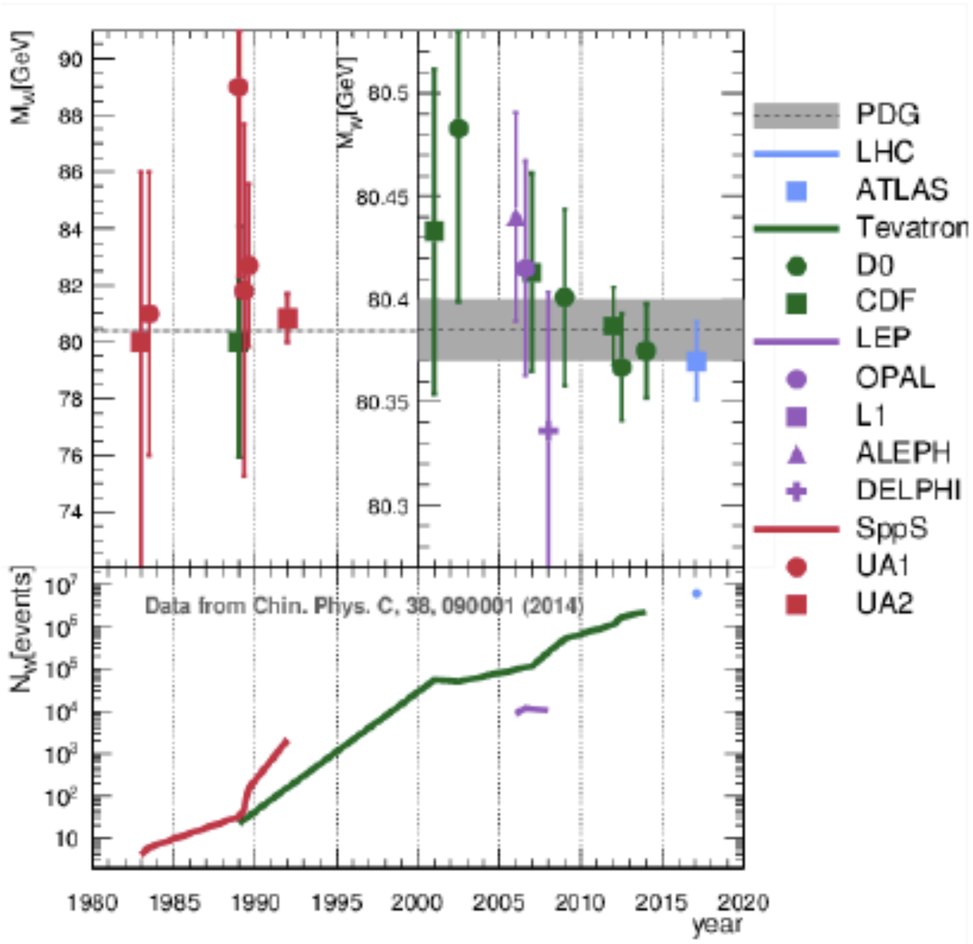
m_t 2013 – 2019

Many more m_t and m_H measurements in recent years than m_W

$m_W \geq$ 2012



History of W-boson mass measurements



Data from Chin. Phys. C, 38, 090001 (2014)

- 1983 CERN SPS – W discovery
- 1983 – UA1

  $m_W = 81 \pm 5$ GeV
- 1992 – UA2 (with m_Z from LEP)

  $m_W = 80.35 \pm 0.37$ GeV
- 2013 – LEP combined

  $m_W = 80.376 \pm 0.033$ GeV
- 2013 – Tevatron combined

  $m_W = 80.387 \pm 0.016$ GeV
- 2017 – LHC (ATLAS)

  $m_W = 80.370 \pm 0.019$ GeV

- Only four W-boson mass measurements in the last 10 years

→ Complex measurements which require O(5-7) years

S. Camarda

History of W-boson mass measurements

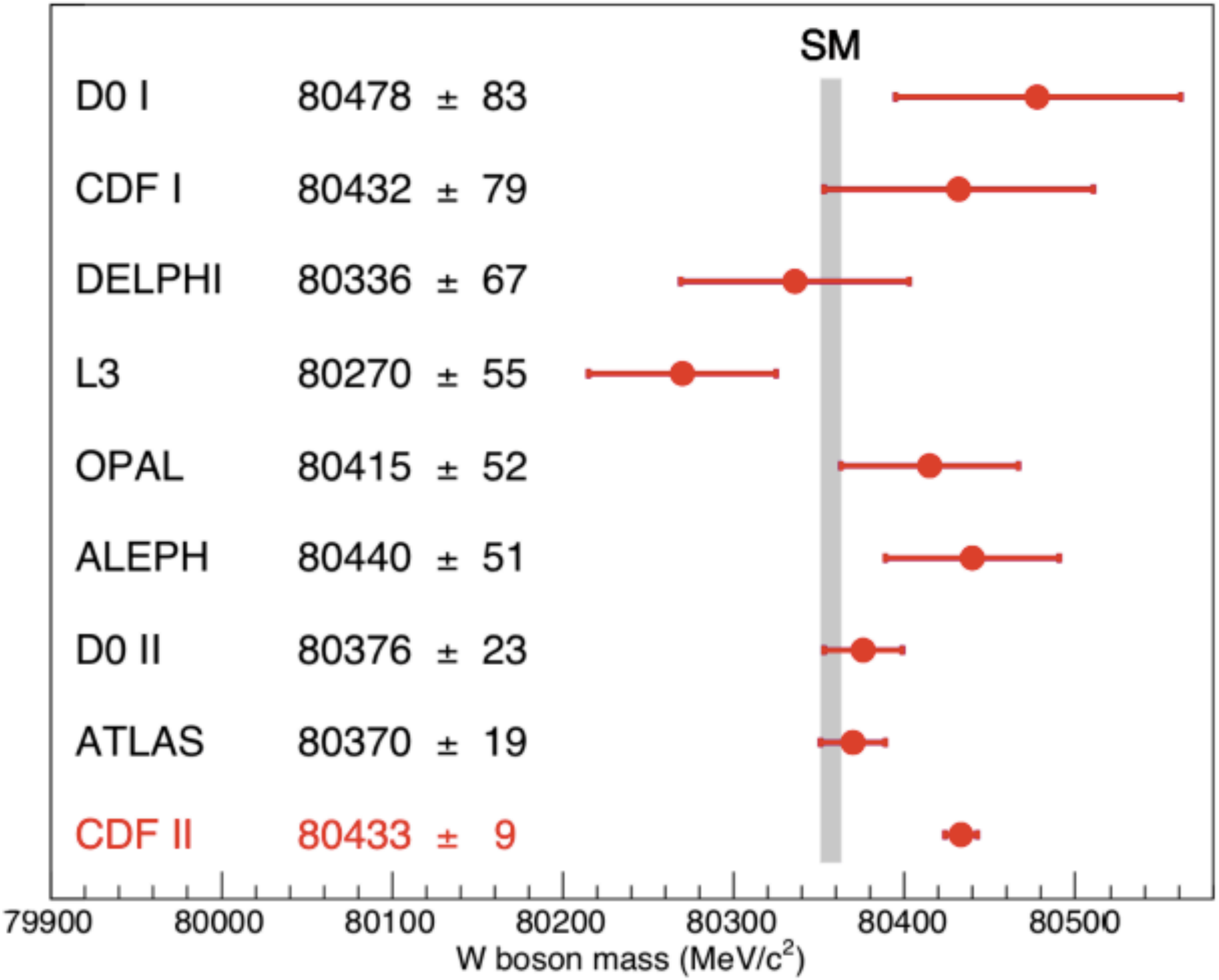


Fig. 5

A. Kotwal

SM expectation: $M_W = 80{,}357 \pm 4_{\text{inputs}} \pm 4_{\text{theory}}$ (PDG 2020)

LHCb measurement : $M_W = 80{,}354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}$ *[JHEP* **2022**, 36 (2022)]

Methodology of W-boson mass measurements

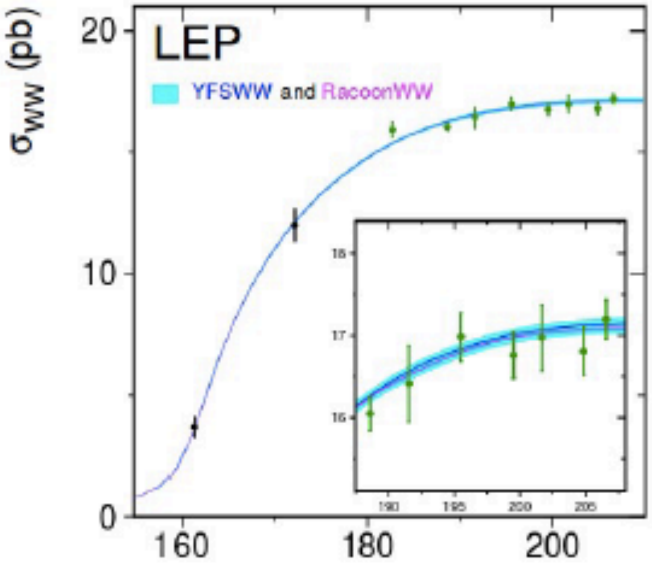
The W-boson mass can be measured from:

- Kinematic properties of decay leptons in the final state in pp → W → lν processes (hadron colliders)
- Direct reconstruction from the final state in ee → WW → qqqq/qqlν (e+e- colliders)
- W-pair production at thresholds (e+e- colliders)

SPS, Tevatron, LHC

LEP best measurements

Limited by stats at LEP, but best prospect at FCC$_{ee}$ where better than 1 MeV might be reached



Intermezzo

Historical perspective: the 80's in UA1/UA2 at the SppS

From the beginning, with the observation of two-jet dominance and of 4 W → eν and 8 Z → e^+e^- decays

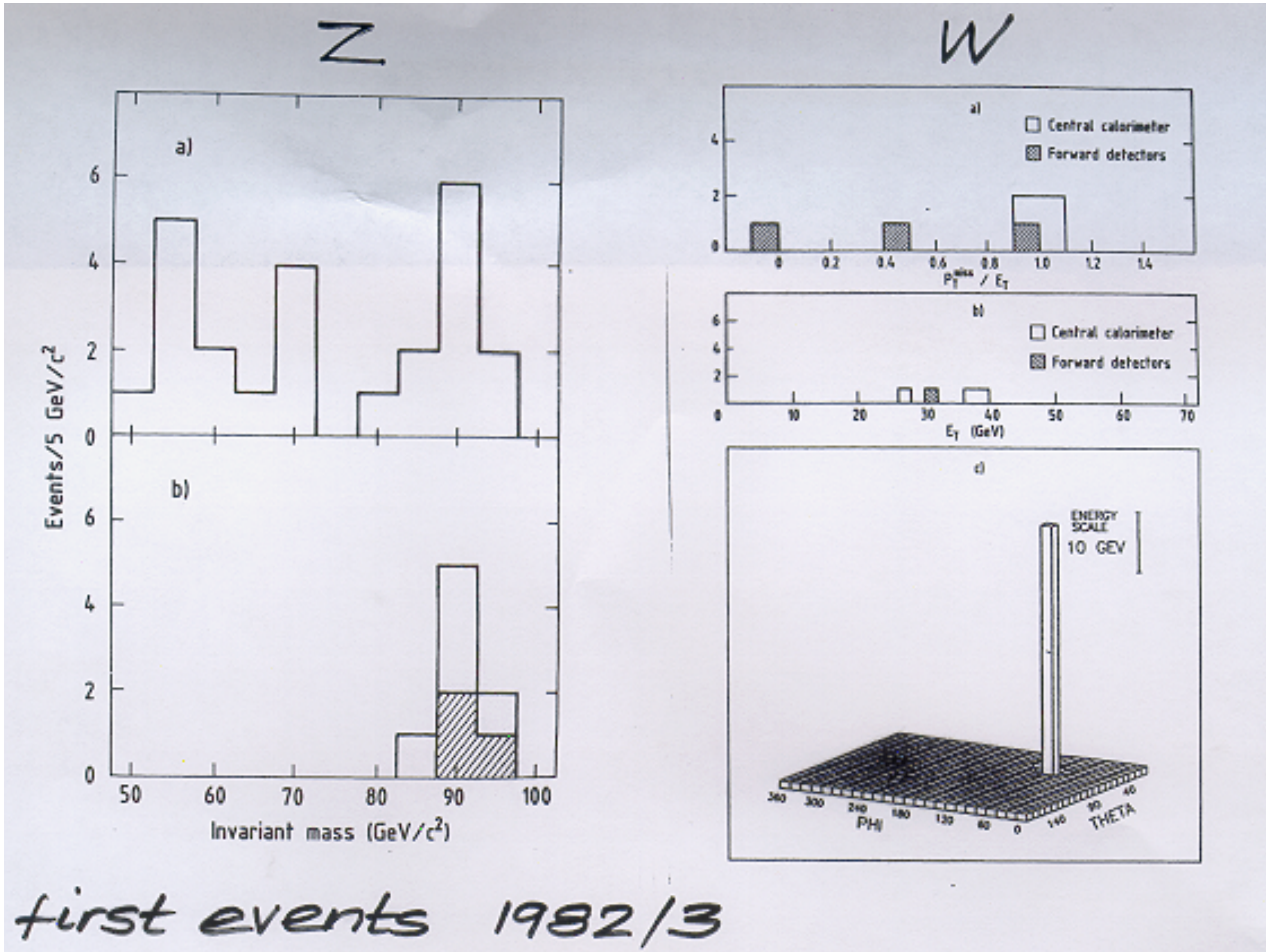
$\sqrt{s}$ = 546 GeV, L ~ 10^{29} cm^{-2}s^{-1}

UA2 was perceived as large at the time:

- ♥ 10-12 institutes
- ♥ from 50 to 100 authors
- ♥ cost ~ 10 MCHF
- ♥ duration 1980 to 1990

Physics analysis was organised in two groups:

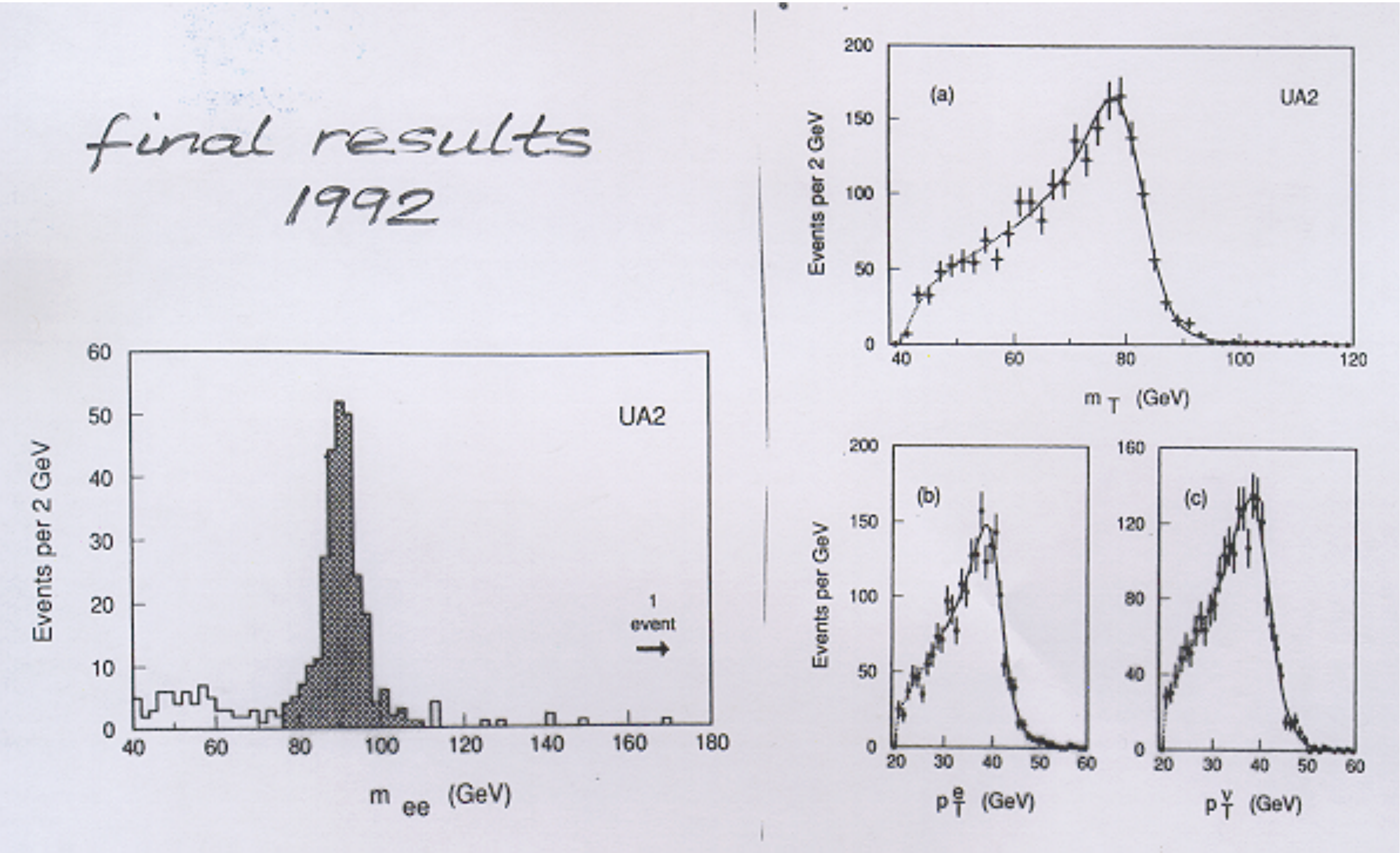
1. Electrons → electroweak
2. Jets → QCD



first events 1982/3

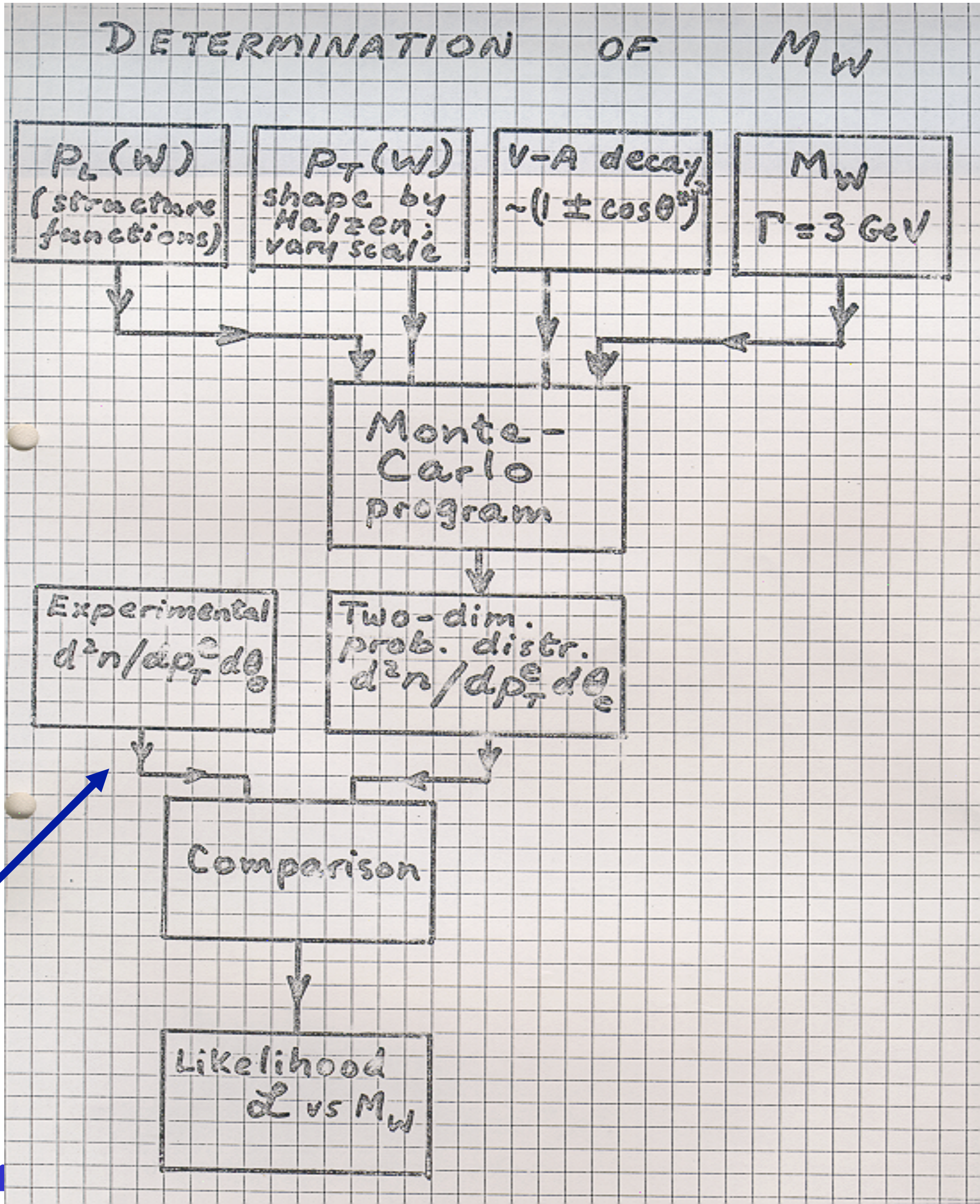
Historical perspective: the 80's in UA1/UA2 at the SppS

To the end, with first accurate measurements of the W/Z masses and the search for the top quark and for supersymmetry



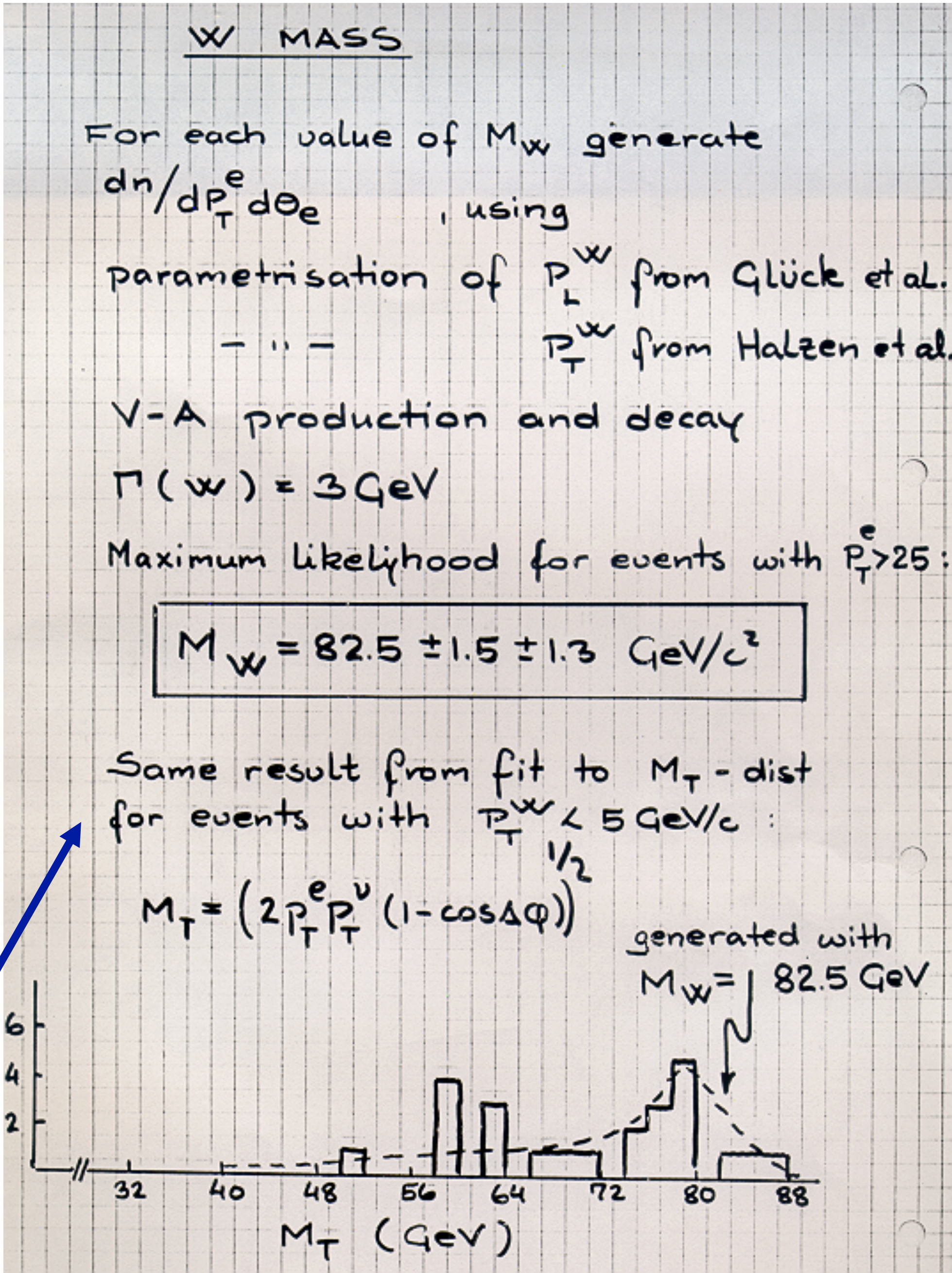
final results
1992

Historical perspective: the 80's in UA1/UA2 at the SppS



Software design in UA2

Historical perspective: the 80’s in UA1/UA2 at the SppS



W MASS

For each value of M_W generate
$dn/dP_T^e d\Theta_e$, using
parametrisation of P_L^W from Glück et al.
— " — P_T^W from Halzen et al.
V-A production and decay
$\Gamma(W) = 3$ GeV
Maximum likelihood for events with $P_T^e > 25$:

$$\boxed{M_W = 82.5 \pm 1.5 \pm 1.3 \text{ GeV}/c^2}$$

Same result from fit to M_T - dist
for events with $P_T^W < 5$ GeV/c :

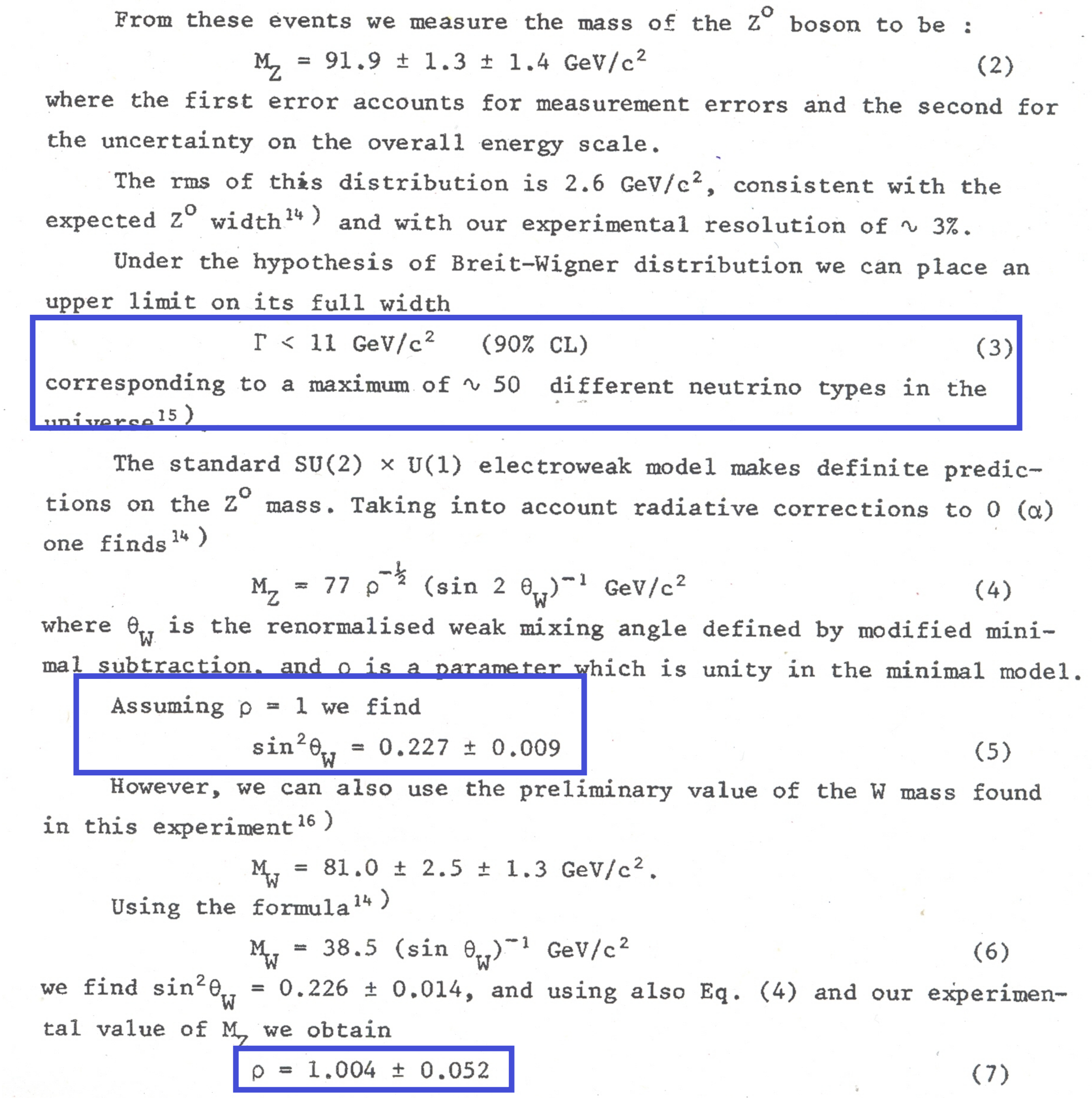
$$M_T = \left(2 P_T^e P_T^\nu (1-\cos\Delta\varphi)\right)^{1/2}$$

generated with M_W = 82.5 GeV

Analysis support note in UA2

Historical perspective: the 80's in UA1/UA2 at the SppS

First ever EW fits in UA2 before LEP turned on



From these events we measure the mass of the Z^o boson to be :

$$M_Z = 91.9 \pm 1.3 \pm 1.4 \text{ GeV/c}^2 \qquad (2)$$

where the first error accounts for measurement errors and the second for the uncertainty on the overall energy scale.

The rms of this distribution is 2.6 GeV/c², consistent with the expected Z^o width[14] and with our experimental resolution of ∿ 3%.

Under the hypothesis of Breit-Wigner distribution we can place an upper limit on its full width

$$\Gamma < 11 \text{ GeV/c}^2 \quad (90\% \text{ CL}) \qquad (3)$$

corresponding to a maximum of ∿ 50 different neutrino types in the universe[15]

The standard SU(2) × U(1) electroweak model makes definite predictions on the Z^o mass. Taking into account radiative corrections to $0(\alpha)$ one finds[14]

$$M_Z = 77\, \rho^{-\frac{1}{2}} (\sin 2\,\theta_W)^{-1} \text{ GeV/c}^2 \qquad (4)$$

where θ_W is the renormalised weak mixing angle defined by modified minimal subtraction, and ρ is a parameter which is unity in the minimal model.

Assuming $\rho = 1$ we find

$$\sin^2\theta_W = 0.227 \pm 0.009 \qquad (5)$$

However, we can also use the preliminary value of the W mass found in this experiment[16]

$$M_W = 81.0 \pm 2.5 \pm 1.3 \text{ GeV/c}^2.$$

Using the formula[14]

$$M_W = 38.5\, (\sin\theta_W)^{-1} \text{ GeV/c}^2 \qquad (6)$$

we find $\sin^2\theta_W = 0.226 \pm 0.014$, and using also Eq. (4) and our experimental value of M_Z we obtain

$$\rho = 1.004 \pm 0.052 \qquad (7)$$

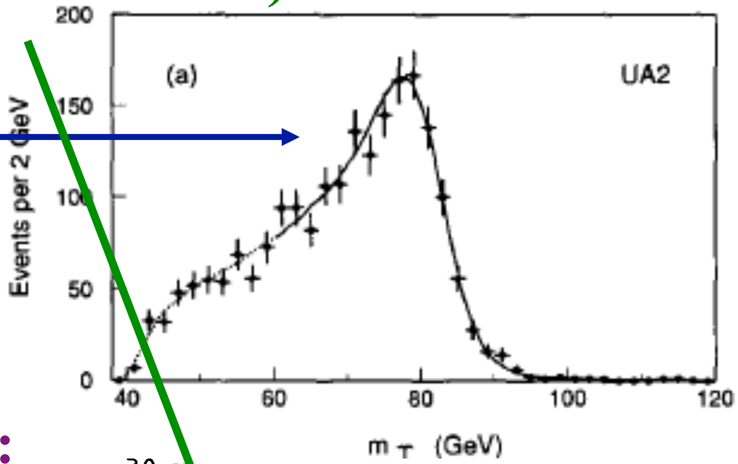
Historical perspective: the 80's in UA1/UA2 at the SppS

Most important results from 1987-1990 campaign with UA2:

precise measurement of m_W/m_Z

and direct limit on top-quark mass ($m_{top} < 60$ GeV)

Transverse mass distribution for electron-neutrino pairs



$$\frac{m_W}{m_Z} = 0.8813 \pm 0.0036 \pm 0.0019$$

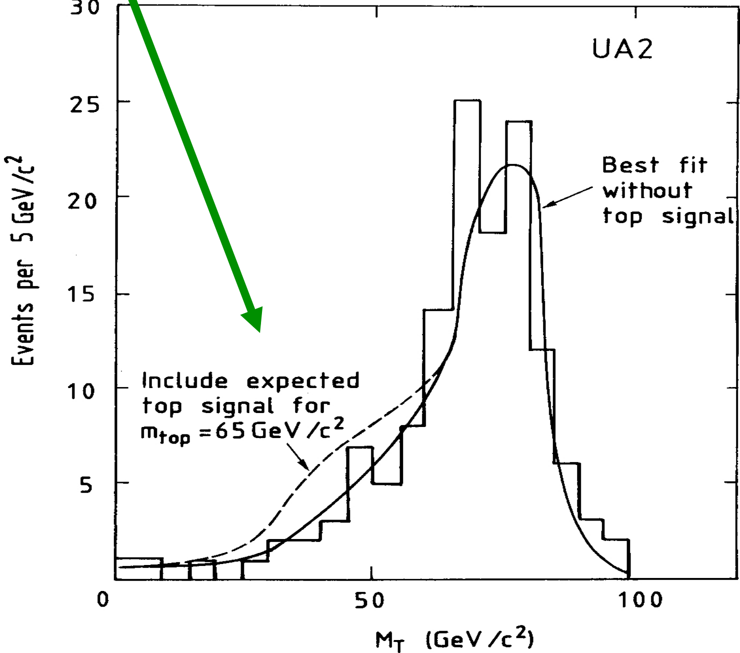
Using the precise measurement of m_Z (LEP):

$$m_W = 80.35 \pm 0.33 \pm 0.17 \text{ GeV}$$

Indirect limits on top-quark mass in the context of the Standard Model:

$$m_{top} = 160^{+50}_{-60} \text{ GeV}$$

(four years before the discovery of the top quark at Fermilab)



End of intermezzo

Discussion of CDF measurement

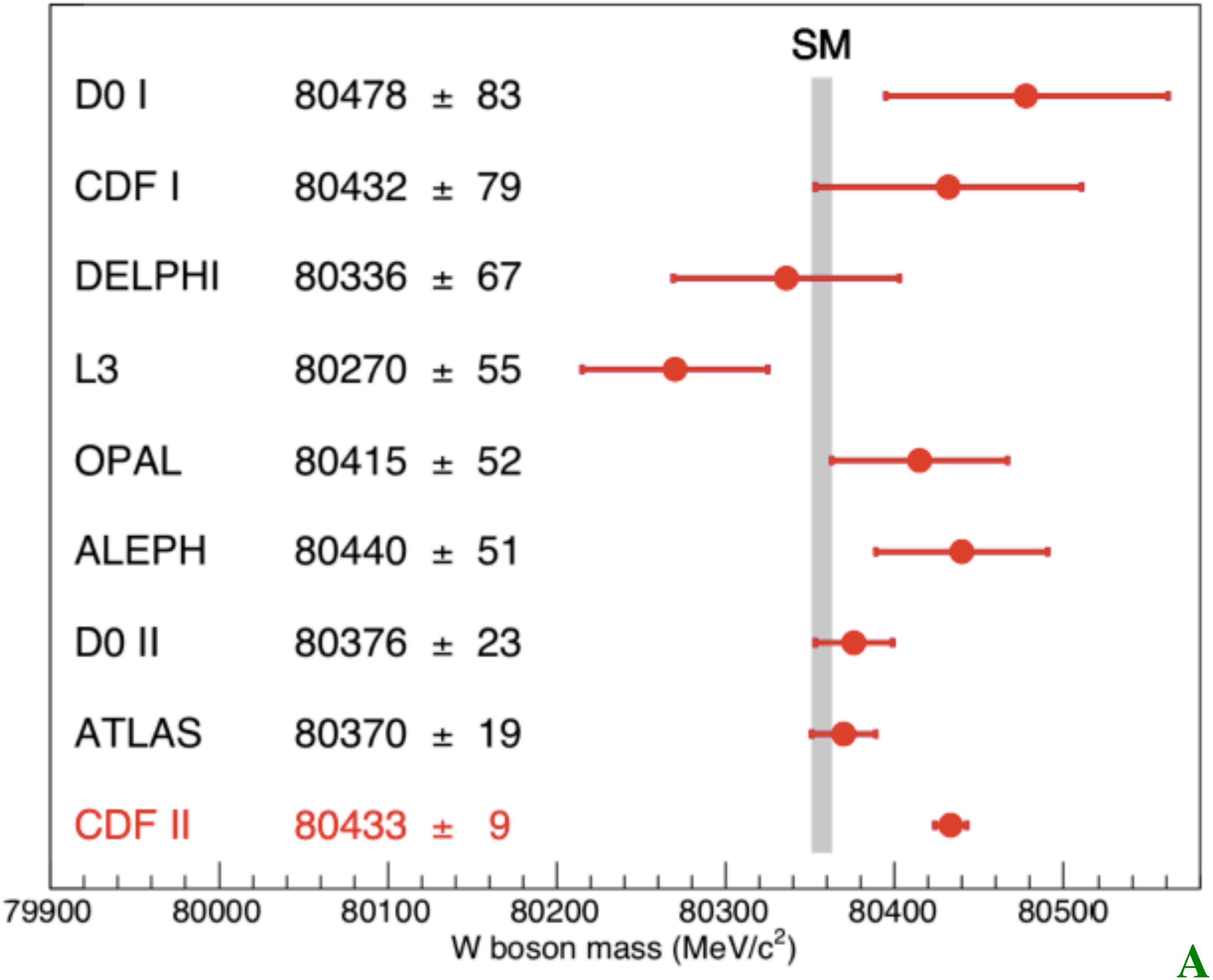


Fig. 5

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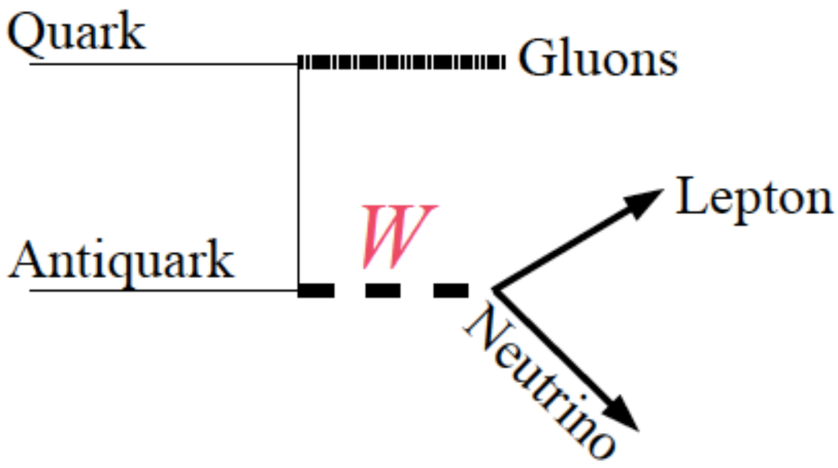
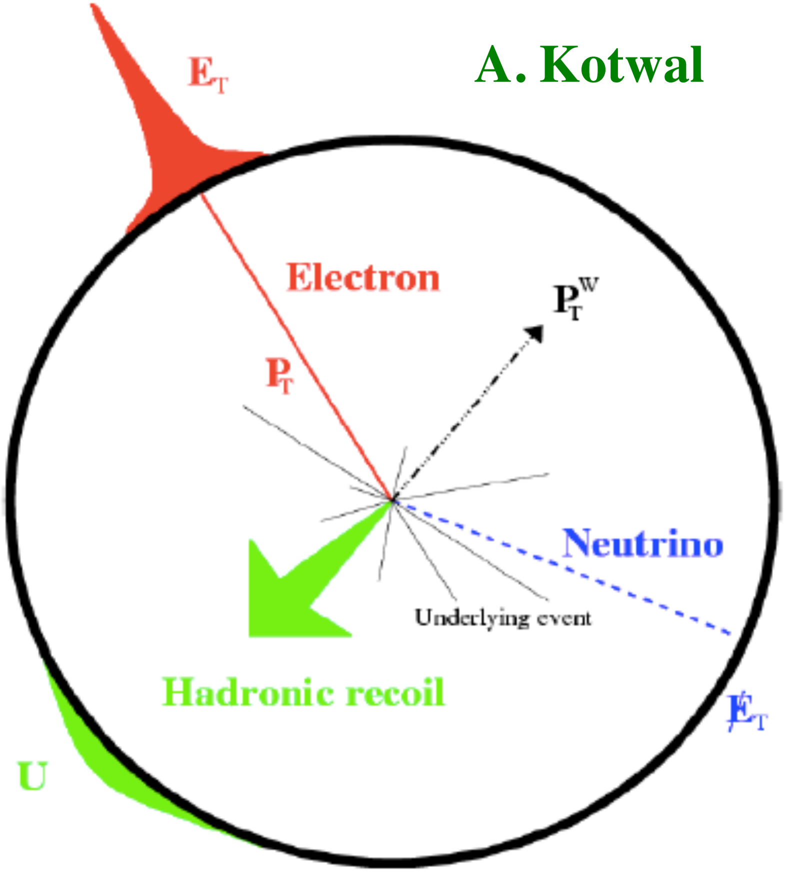
Discussion of CDF measurement

W Boson Production at the Tevatron

A. Kotwal





Quark-antiquark annihilation dominates (80%)

Lepton p_T carries most of W mass information, can be measured precisely (achieved 0.004%)

Initial state QCD radiation is O(10 GeV), measure as soft 'hadronic recoil' in calorimeter (calibrated to ~0.2%)
dilutes W mass information, fortunately $p_T(W) << M_W$

Discussion of CDF measurement

Information is scant: no ratio plots nor reference to m_W shift!

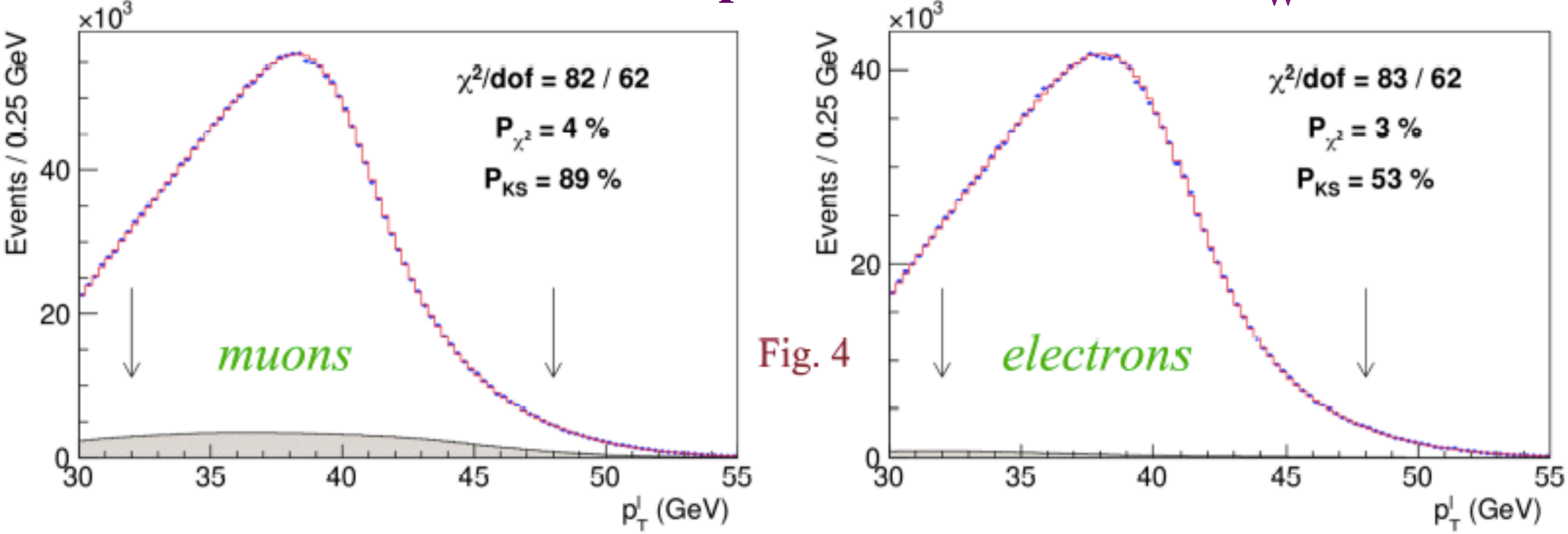


Fig. 4

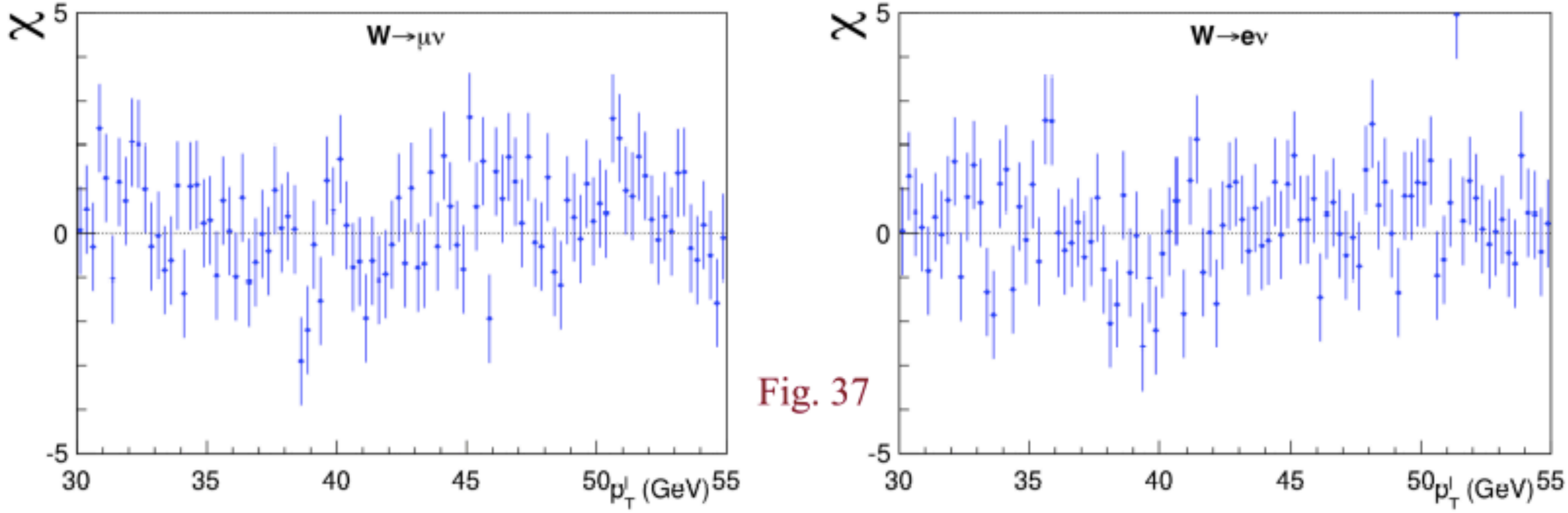
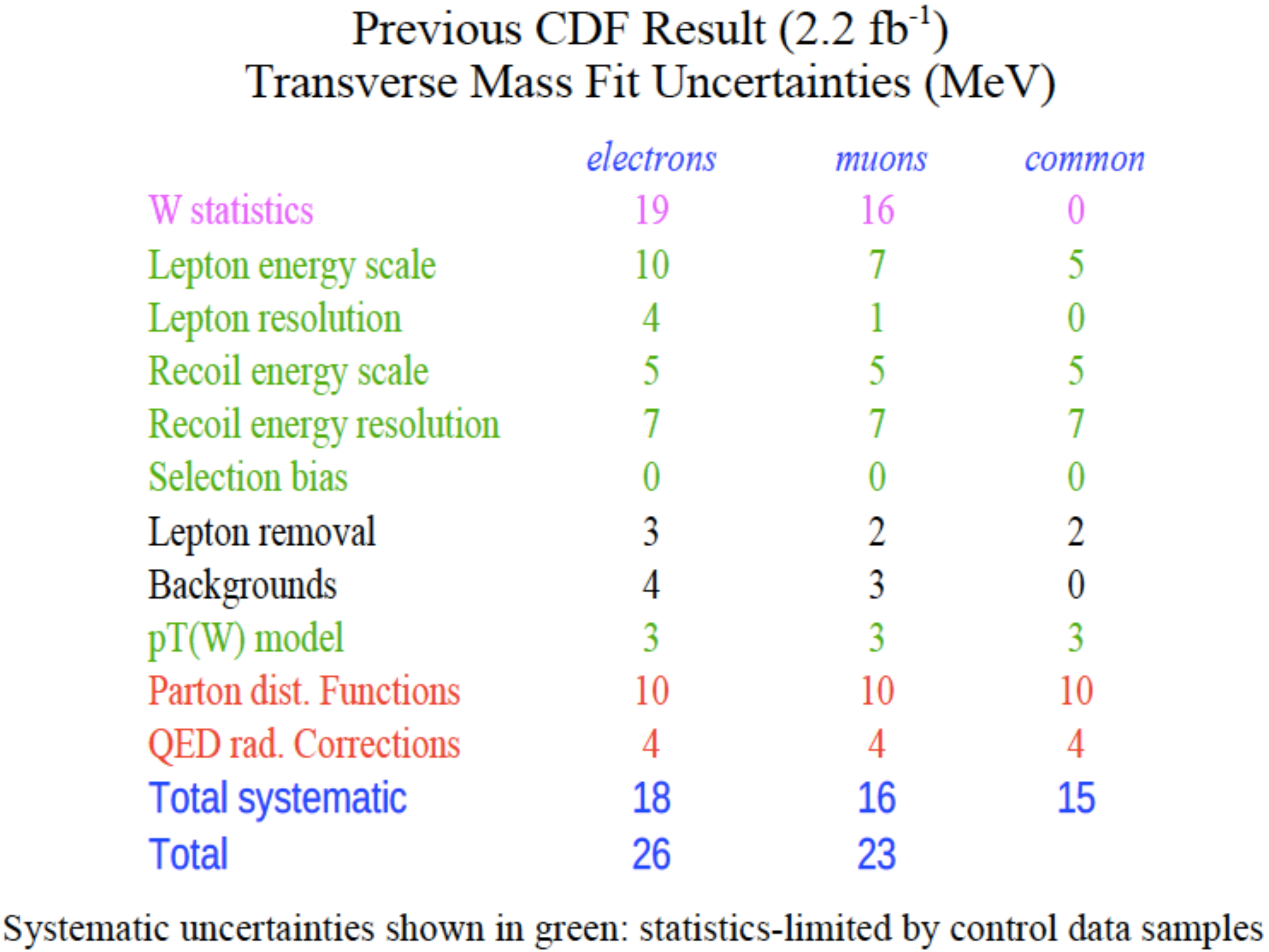


Fig. 37

Discussion of CDF measurement

Information is scant: hard to assess very small numbers below



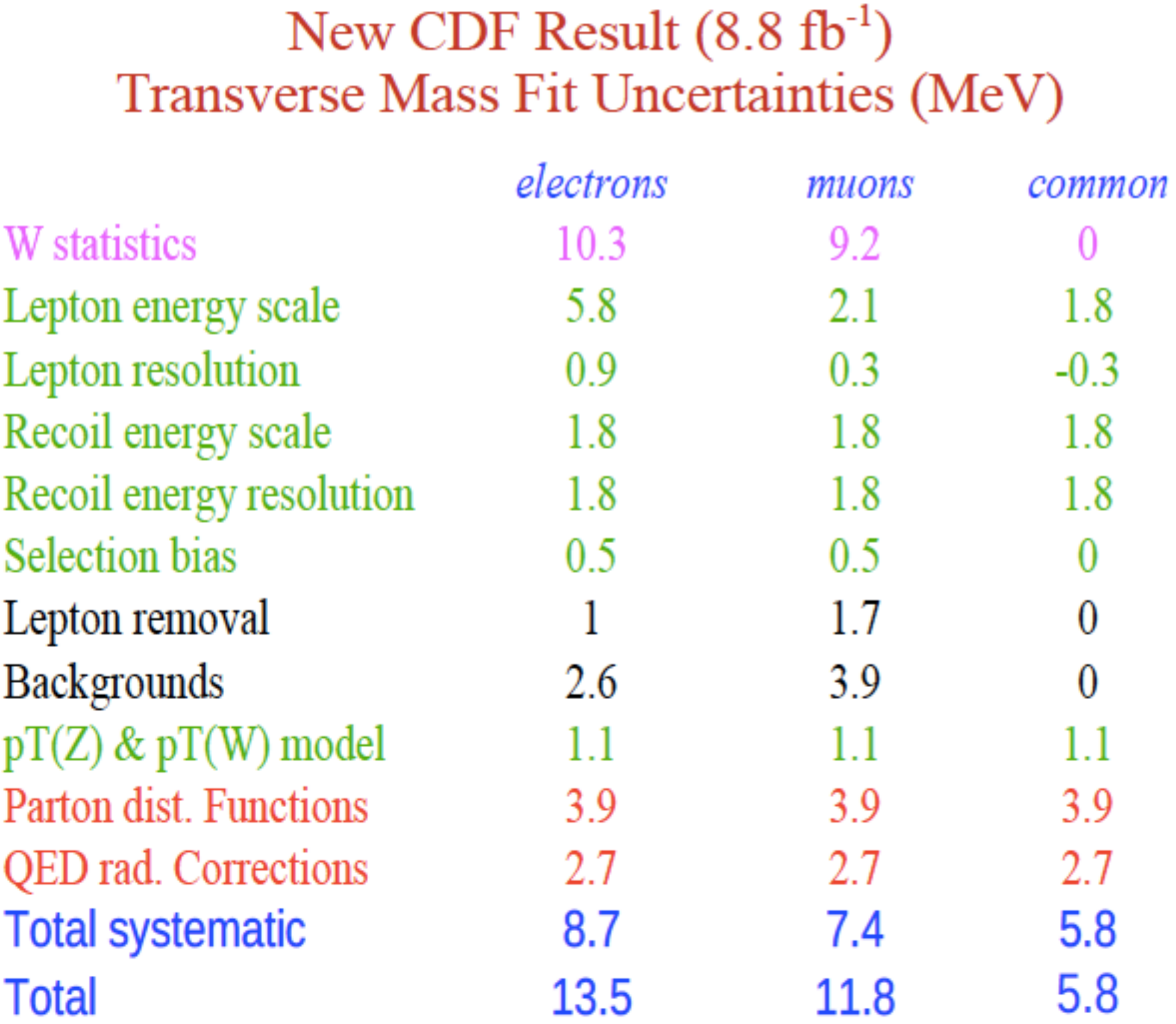
Previous CDF Result (2.2 fb^{-1})
Transverse Mass Fit Uncertainties (MeV)

	electrons	*muons*	*common*
W statistics	19	16	0
Lepton energy scale	10	7	5
Lepton resolution	4	1	0
Recoil energy scale	5	5	5
Recoil energy resolution	7	7	7
Selection bias	0	0	0
Lepton removal	3	2	2
Backgrounds	4	3	0
pT(W) model	3	3	3
Parton dist. Functions	10	10	10
QED rad. Corrections	4	4	4
Total systematic	18	16	15
Total	26	23	

Systematic uncertainties shown in green: statistics-limited by control data samples

Discussion of CDF measurement

Information is scant: hard to assess very small numbers below

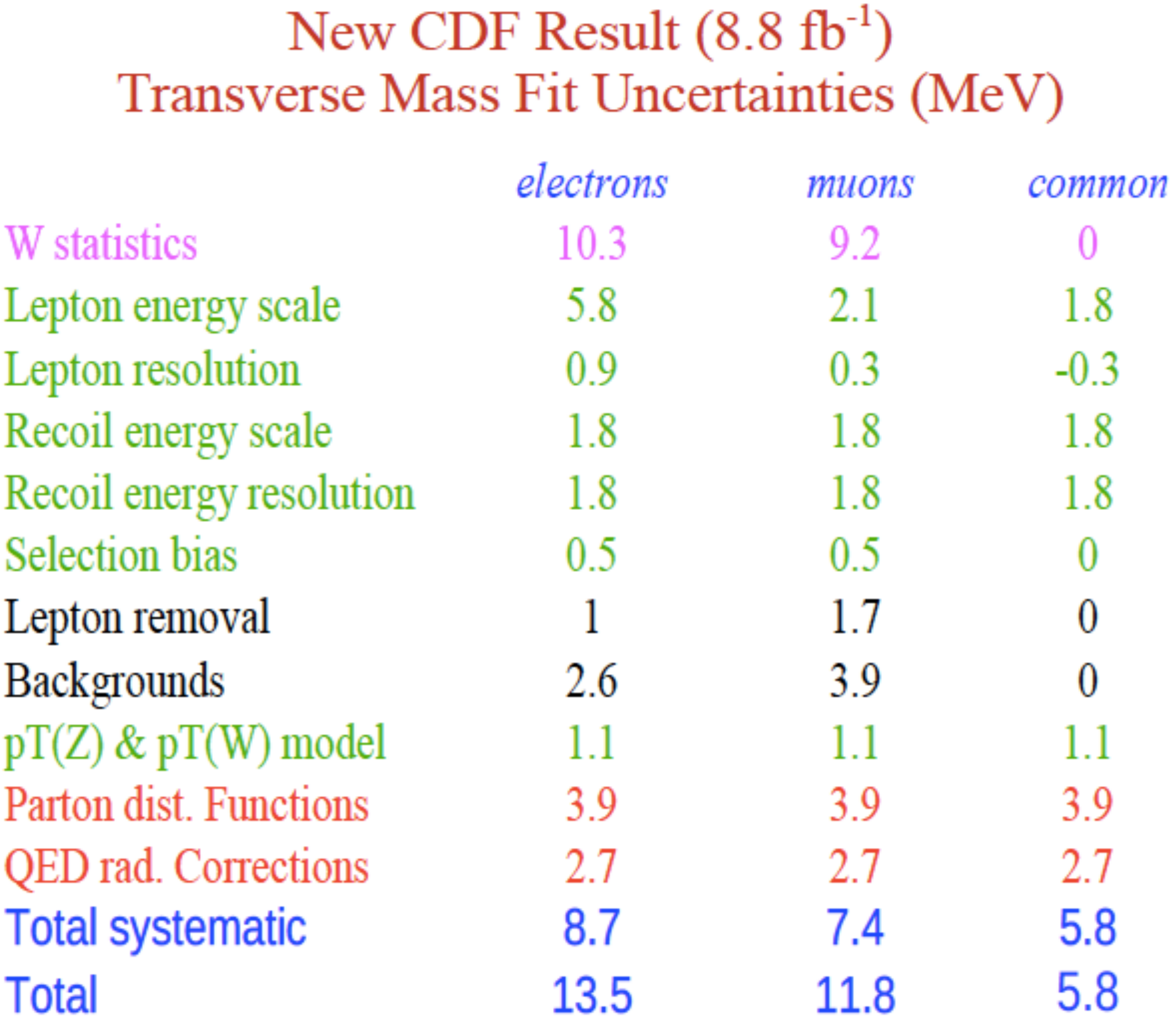


New CDF Result (8.8 fb^{-1})
Transverse Mass Fit Uncertainties (MeV)

	electrons	*muons*	*common*
W statistics	10.3	9.2	0
Lepton energy scale	5.8	2.1	1.8
Lepton resolution	0.9	0.3	-0.3
Recoil energy scale	1.8	1.8	1.8
Recoil energy resolution	1.8	1.8	1.8
Selection bias	0.5	0.5	0
Lepton removal	1	1.7	0
Backgrounds	2.6	3.9	0
pT(Z) & pT(W) model	1.1	1.1	1.1
Parton dist. Functions	3.9	3.9	3.9
QED rad. Corrections	2.7	2.7	2.7
Total systematic	8.7	7.4	5.8
Total	13.5	11.8	5.8

Discussion of CDF measurement

Information is scant: hard to assess very small numbers below



New CDF Result (8.8 fb^{-1})

Transverse Mass Fit Uncertainties (MeV)

	electrons	muons	common
W statistics	10.3	9.2	0
Lepton energy scale	5.8	2.1	1.8
Lepton resolution	0.9	0.3	-0.3
Recoil energy scale	1.8	1.8	1.8
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Total systematic	8.7	7.4	5.8
Total	13.5	11.8	5.8

Discussion of CDF measurement

- Final calibration using the J/ψ, ϒ and Z bosons for calibration
- Combined momentum scale correction :

$$\Delta p/p = (-1389 \pm 25_{syst}) \text{ parts per million}$$

  - Z mass consistent with PDG value (91188 MeV) (0.7σ statistical)
  - $M_Z = 91192.0 \pm 6.4_{stat} \pm 2.3_{momentum} \pm 3.1_{QED} \pm 1_{alignment}$ MeV

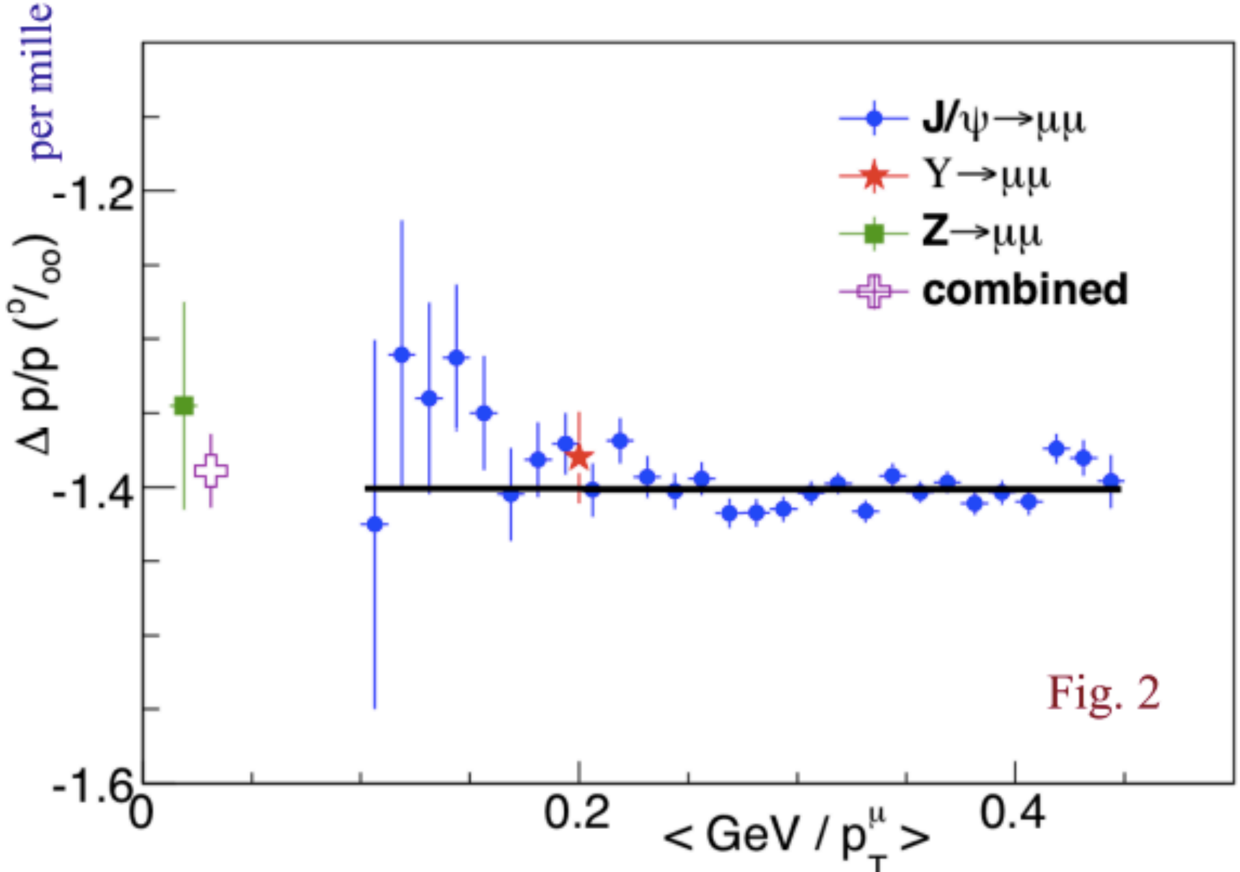


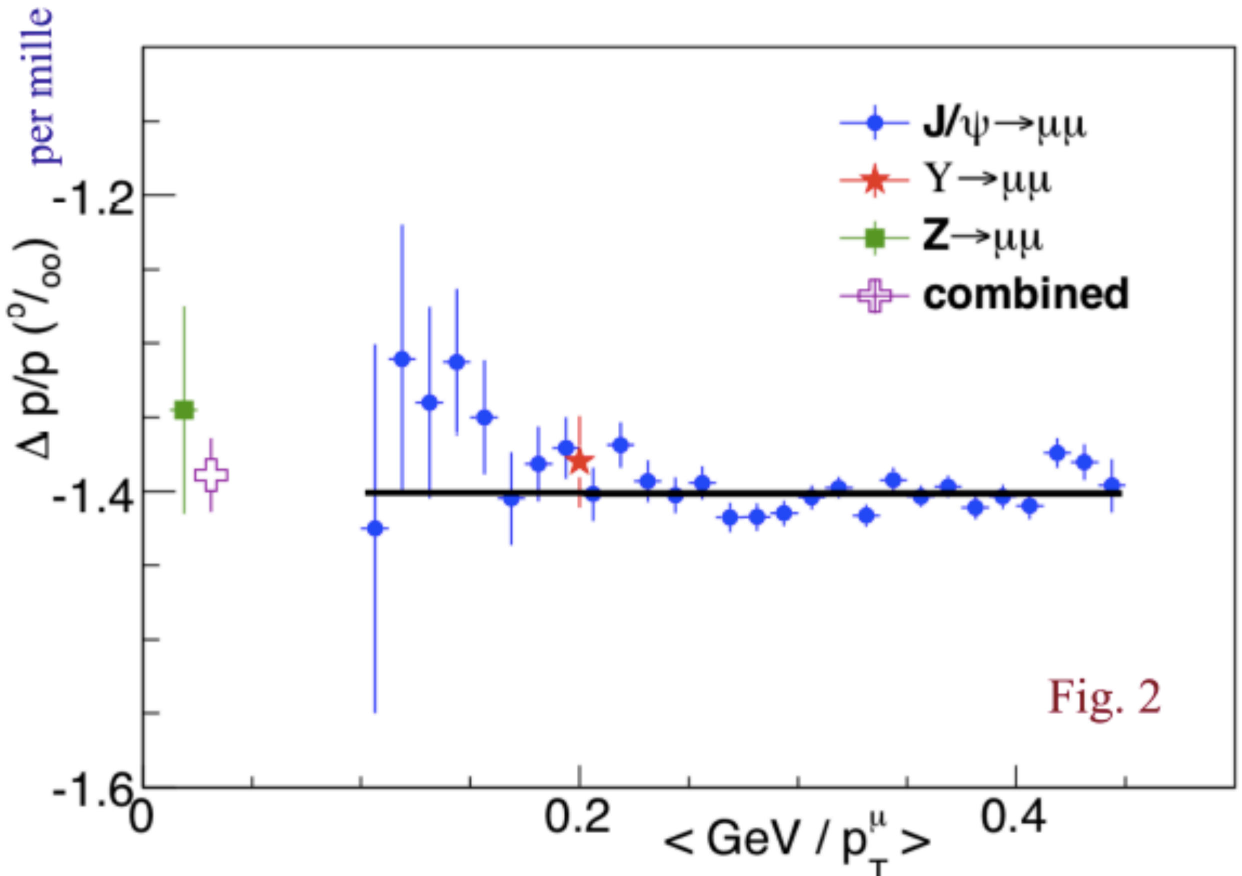
Fig. 2

A. Kotwal

Discussion of CDF measurement

Discussion:

1) **Very impressive work on muon momentum scale calibration**
2) **However overall shift of scale seen below, although compatible with being flat over whole spectrum correspons to > 100 MeV**
3) **A bit difficult to believe the overall 2 MeV systematic assigned**



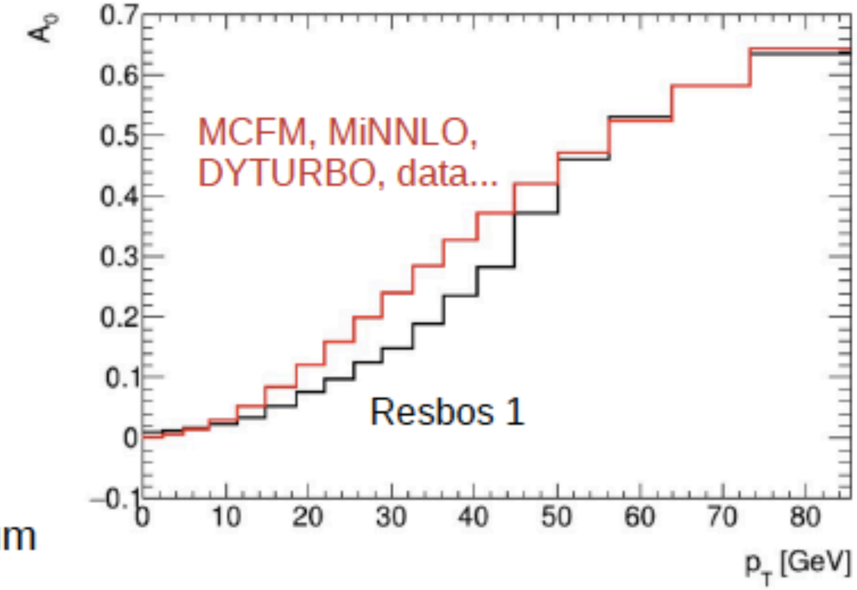
Discussion of CDF measurement

Effect below affects potentially central value but also uncertainty

Physics : QCD

- Scale variations found to have negligible impact (largely follows from fit procedure [normalized histograms] and tight uT cut)
- Spin correlations : problematic (and not mentioned)

$$\begin{aligned}\frac{d\sigma}{d\Omega} = \frac{d\sigma}{dm\,dp_T\,dy}\,[\,(1+\cos^2\theta) &+ \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi \\ &+ \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi \\ &+ A_4\cos\theta + A_5\sin^2\theta\sin 2\phi \\ &+ A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\,],\end{aligned}$$



biased A_0 → biased θ^* → biased p_T^l, m_T

Effect is typically to harden the predicted spectrum

Discussion of CDF measurement

Precision measurement of mW at hadron colliders is in deep trouble!

CDF M_W *vs* m_{top}

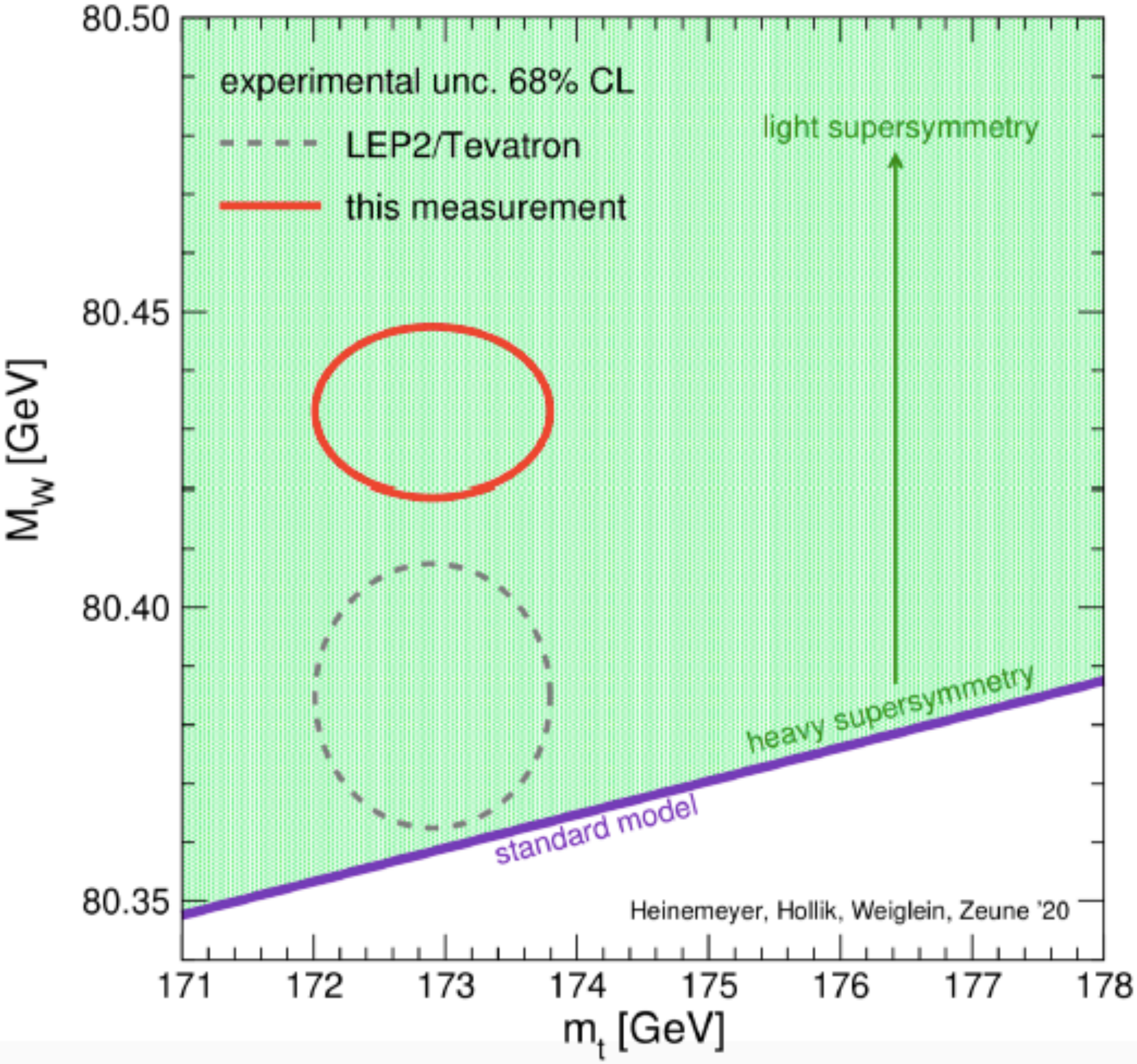


Fig. 1

Understanding Tevatron-LHC correlations and combination with ATLAS in progress

Back-up slides

Precision EW measurements: measure m_W to ~ 5 MeV: very difficult! What for??

- **Perhaps untangle whether possibly observed Higgs boson is SM or SUSY-like?**