Tevatron results and the consolidation of the Standard Model

Tevatron day

Padova, 20/12/2011

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SM determined by a fixed set of parameters:

3 • **gauge couplings: α_{em} , α_s , $\sin\theta_W$** — $g=e/\sin\theta_W \Rightarrow$ coupling of weak interactions

+ 11 • **masses: m_W, m_{quarks}, $m_{leptons}$, m_{Higgs}** — $M_Z = M_W / \cos\theta_W$

+ 4 • **CKM mixings and CP-odd phase**

+ 1 • **Higgs selfcoupling λ_H**

= 19

Everything else:

- Triple gauge boson couplings
- Michel parameters
- $BR(B_S \to \mu^+\mu^-)$, etc.
- PDFs
- $\sigma(W)$, $\sigma(ttbar)$, ...

follows from the above inputs and from the SM dynamics

The Tevatron programme of "SM measurements" addressed:

1. discovery of yet unknown particles (top and Higgs), and the measurement of their properties

2. improved determination of known ones: m_Z, m_W, $\sin\theta_W$, CKM, and ensuing validity tests of the SM

3. Challenging the SM: searches, etc

4. Challenging our ability to describe SM dynamics:

   4.1. to assess and improve the quality of theoretical calculations

   4.2. to constrain or detect BSM physics, through the study of deviations from the expected SM behaviour

   4.3. to learn about non-perturbative aspects of QCD, still incalculable from first principles (PDF, MB, diffraction, ...)

At the time of the Tevatron turn-on, the following parameters had not been *directly* measured

- m_{top}
- V_{tb}
- V_{td} , V_{ts}
- m_H, λ_H

The following parameters were known with limited accuracy, or indirectly (e.g. assuming 3 generations)

- $m_Z = 93 \pm 3$ GeV
- $m_W = 83 \pm 3$ GeV
- $V_{tb/d/s}$

From the point of view of dynamics, the only process known to NLO was Drell-Yan (W and Z production), tested with limited accuracy because of

- Large statistical uncertainty
- Large PDF uncertainties (only LO PDFs were available until 1989)

mZ and mW

At tree level,

$$g_V^e = -1/2 + 2\sin^2\theta_W$$

$$g_A^e = -1/2$$

$$m_W/m_Z = \cos\theta_W$$

vector and axial coupling to Z boson, measured e.g. in $e^+e^- \to Z \to \mu^+\mu^-$ angular distributions

At one loop and beyond, these relation receive corrections proportional to

m_t^2 and **$\log m_H$**

The mismatch between $\cos\theta_W$ determined from m_W/m_Z and from the measurement of couplings provides therefore an indirect determination of m_{top} and m_H

mZ, up to LEP

1989	UA1	93.1 ± 1 ± 3	24 events
1989	CDF	90.0 ±0.3 ±0.2	188 events
1989	Mk2	91.14 ± 0.12	480 events
2000	LEP	91.1876 ± 0.0021	~20M events

mW, the beginning

1983	UA1	81±5	6 events
1989	UA1	82.7 ± 1 ± 2.7	150 events
1989	CDF	80.0 ± 3.3 ± 2.4	22 events
1990	UA2	80.79 ± 0.31 ± 0.84	2065 events
1990	CDF	79.91 ± 0.39 (40/30/30% stat/syst/scale)	$4pb^{-1}$ (e/mu 88/89 run)

UA2+CDF+ LEP(mZ):

mW/mZ = cosθ_W **(so-called on-shell ren scheme)**

⇒ $\sin^2\theta_W = 0.227 \pm 0.006$

⇒ $m_{top} < 220$ GeV for m_H below 1 TeV

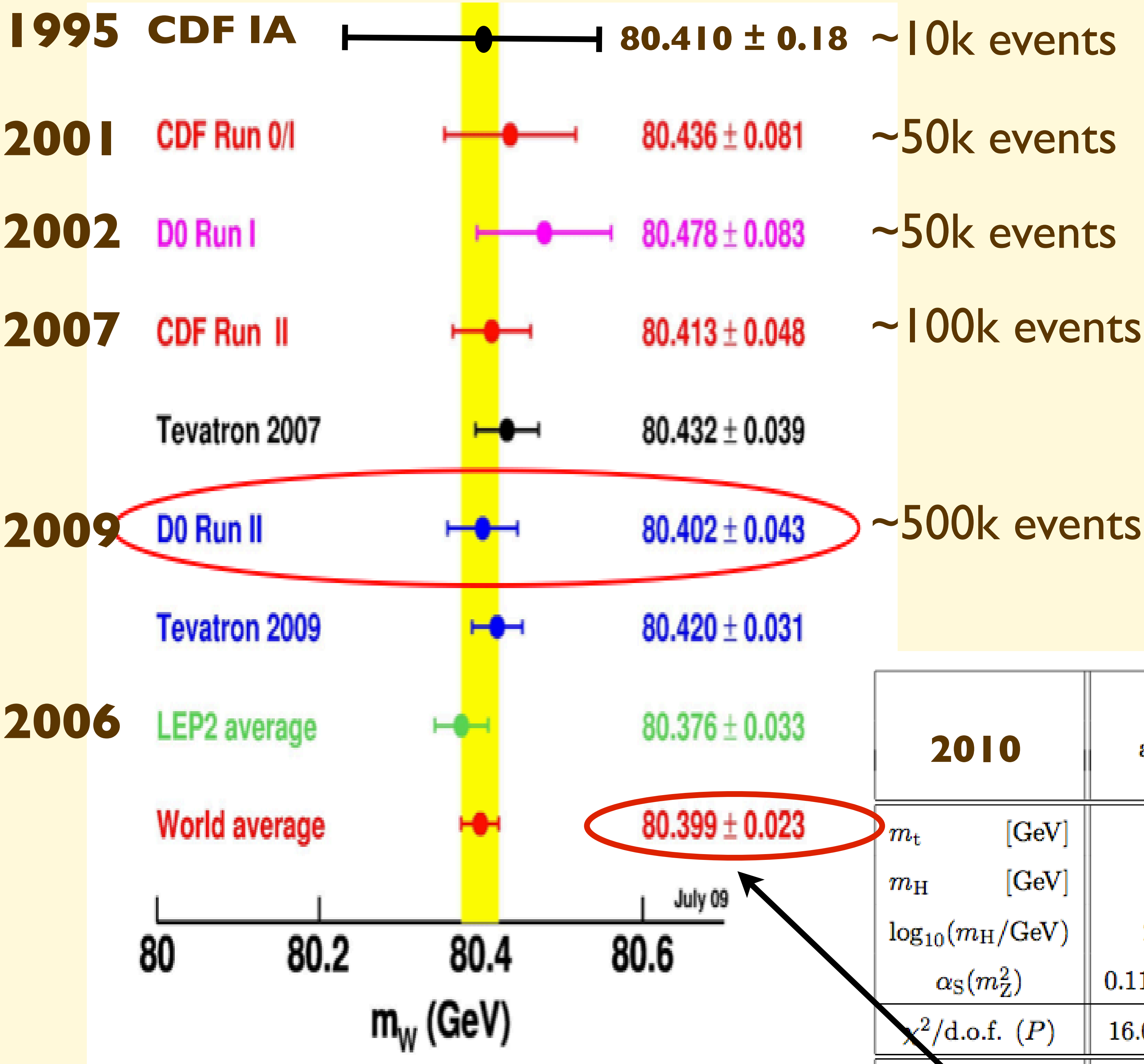
By 1994 a new challenge starts, due to precision EW measurements

1995 LEP EW WG

	LEP	LEP + SLD
m_t (GeV)	$170 \pm 10\ ^{+17}_{-19}$	$180\ ^{+8}_{-9}\ ^{+17}_{-20}$
$\alpha_s(m_Z^2)$	$0.125 \pm 0.004\ \pm 0.002$	$0.123 \pm 0.004\ \pm 0.002$
χ^2/d.o.f.	$18/9$	$28/12$
$\sin^2\theta_{eff}^{lept}$	$0.23206 \pm 0.00028\ ^{+0.00008}_{-0.00017}$	$0.23166 \pm 0.00025\ ^{+0.00006}_{-0.00013}$
$1 - m_W^2/m_Z^2$	$0.2247 \pm 0.0010\ ^{+0.0004}_{-0.0002}$	$0.2234 \pm 0.0009\ ^{+0.0005}_{-0.0002}$
m_W (GeV)	$80.295 \pm 0.057\ ^{+0.011}_{-0.019}$	$80.359 \pm 0.051\ ^{+0.013}_{-0.024}$

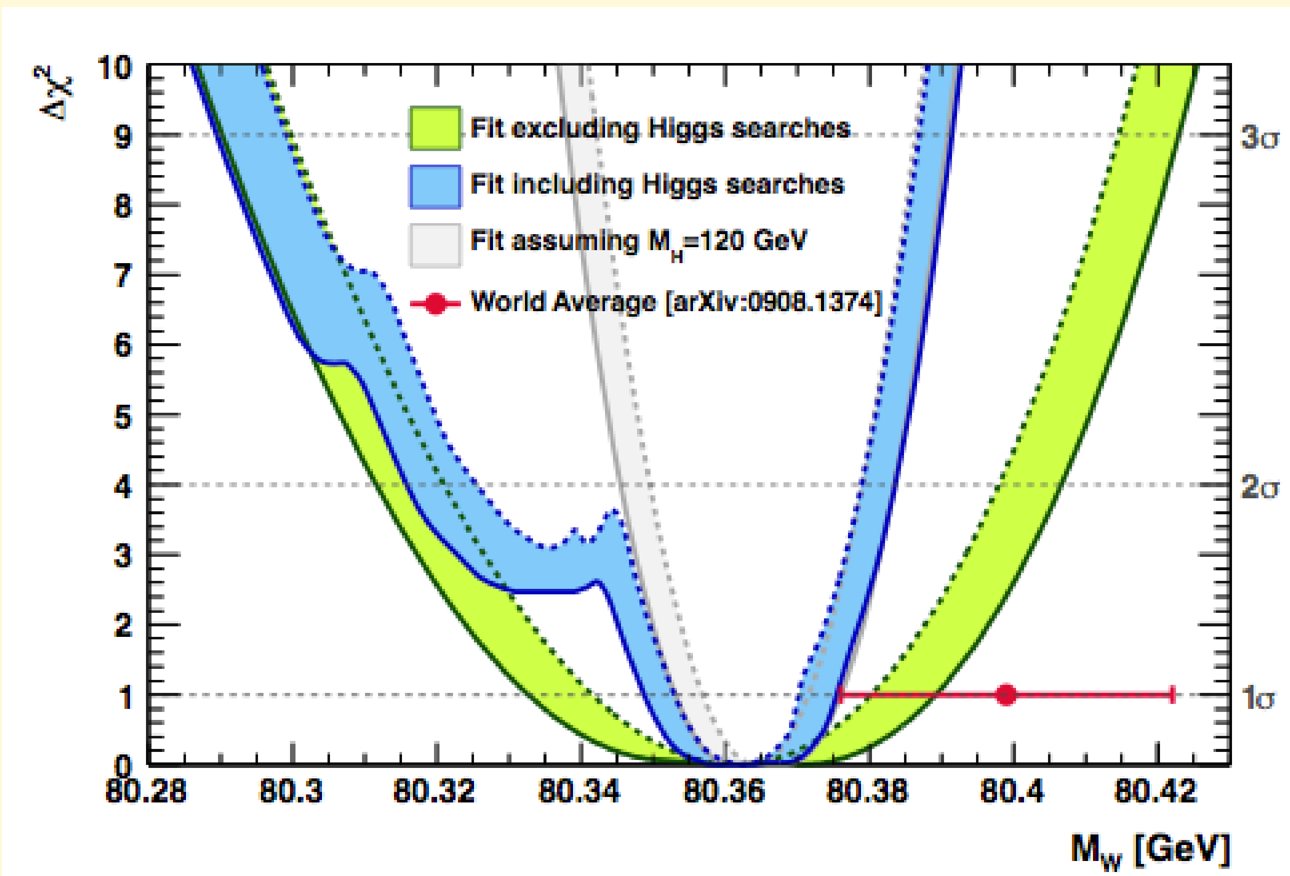
1995 CDF IA **M_W= 80.410 ± 0.18** ~10k events

mW, pushing further



2010	- 1 - all Z-pole data	- 2 - all Z-pole data plus m_t	- 3 - all Z-pole data plus m_W, Γ_W	- 4 - all Z-pole data plus m_t, m_W, Γ_W
m_t [GeV]	173^{+13}_{-10}	$173.3^{+1.1}_{-1.1}$	179^{+12}_{-9}	$173.4^{+1.1}_{-1.1}$
m_H [GeV]	111^{+190}_{-60}	117^{+58}_{-40}	146^{+241}_{-81}	89^{+35}_{-26}
$\log_{10}(m_H/\mathrm{GeV})$	$2.05^{+0.43}_{-0.34}$	$2.07^{+0.18}_{-0.19}$	$2.16^{+0.42}_{-0.35}$	$1.95^{+0.14}_{-0.15}$
$\alpha_S(m_Z^2)$	0.1190 ± 0.0027	0.1190 ± 0.0027	0.1190 ± 0.0028	0.1185 ± 0.0026
χ^2/d.o.f. (P)	16.0/10 (9.9%)	16.0/11 (14%)	16.9/12 (15%)	17.3/13 (19%)
$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$	0.23149 ± 0.00016	0.23149 ± 0.00016	0.23143 ± 0.00014	0.23138 ± 0.00013
$\sin^2\theta_W$	0.22331 ± 0.00062	0.22328 ± 0.00040	0.22287 ± 0.00036	0.22301 ± 0.00028
m_W [GeV]	80.363 ± 0.032	80.365 ± 0.020	80.386 ± 0.018	80.379 ± 0.015

Implications of current mW measurements



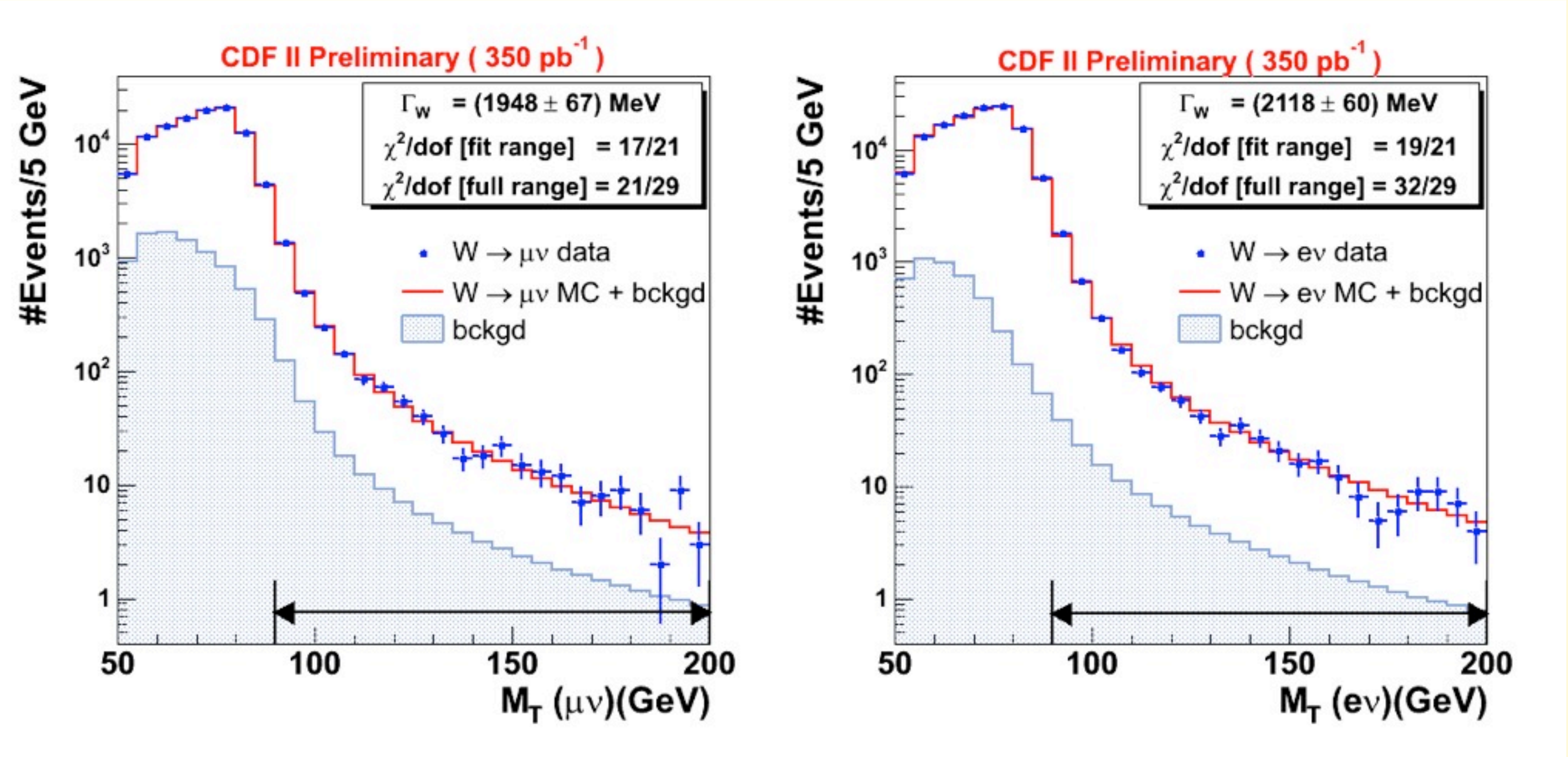
The Gfitter Group arXiv:1107.0975v1

M. Baak[a], M. Goebel[b,c], J. Haller[c,d], A. Hoecker[a], D. Ludwig[b,c], K. Mönig[b], M. Schott[a], J. Stelzer[e]

From the EW fit,
$M_{W,\,fit}$ = 80.362 ± 0.013 GeV
1.6σ lower than direct measurement,
M_W^{direct} = 80.399 ± 0.023 GeV

Notice that LEP2 only would be ~OK, with 80.376 ± 0.033

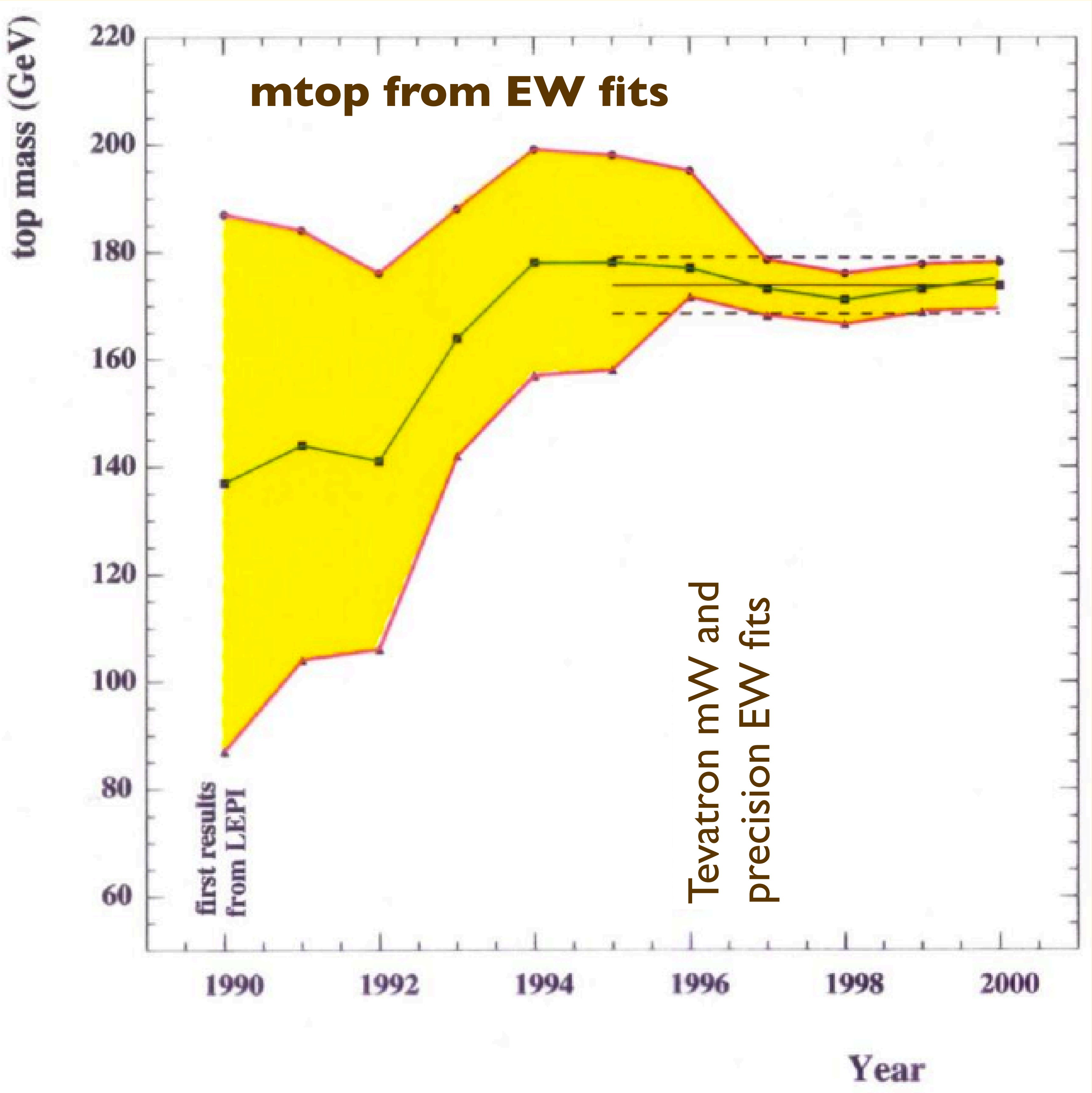
W width



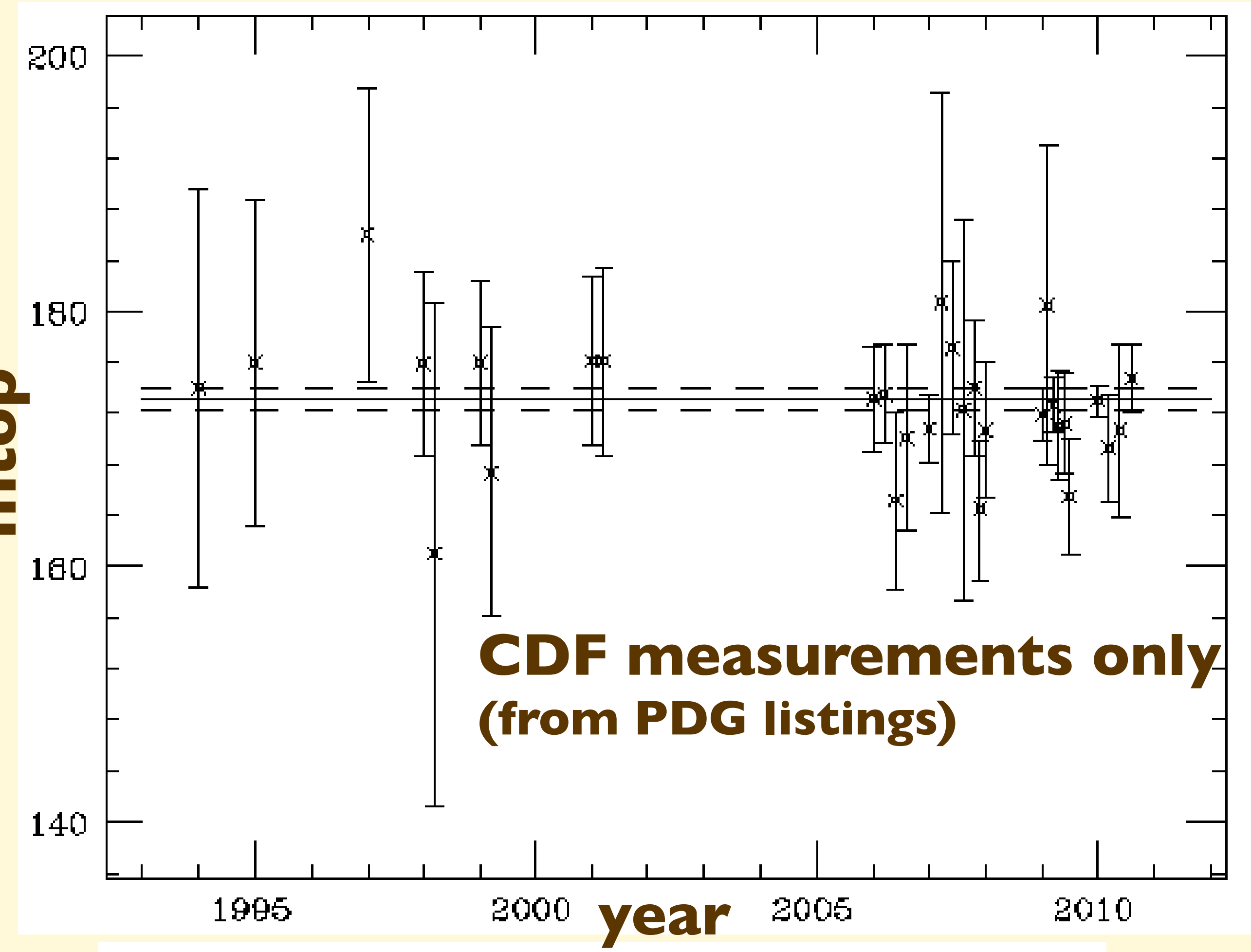
$\Gamma_W = 2032 \pm 73$ MeV/c^2

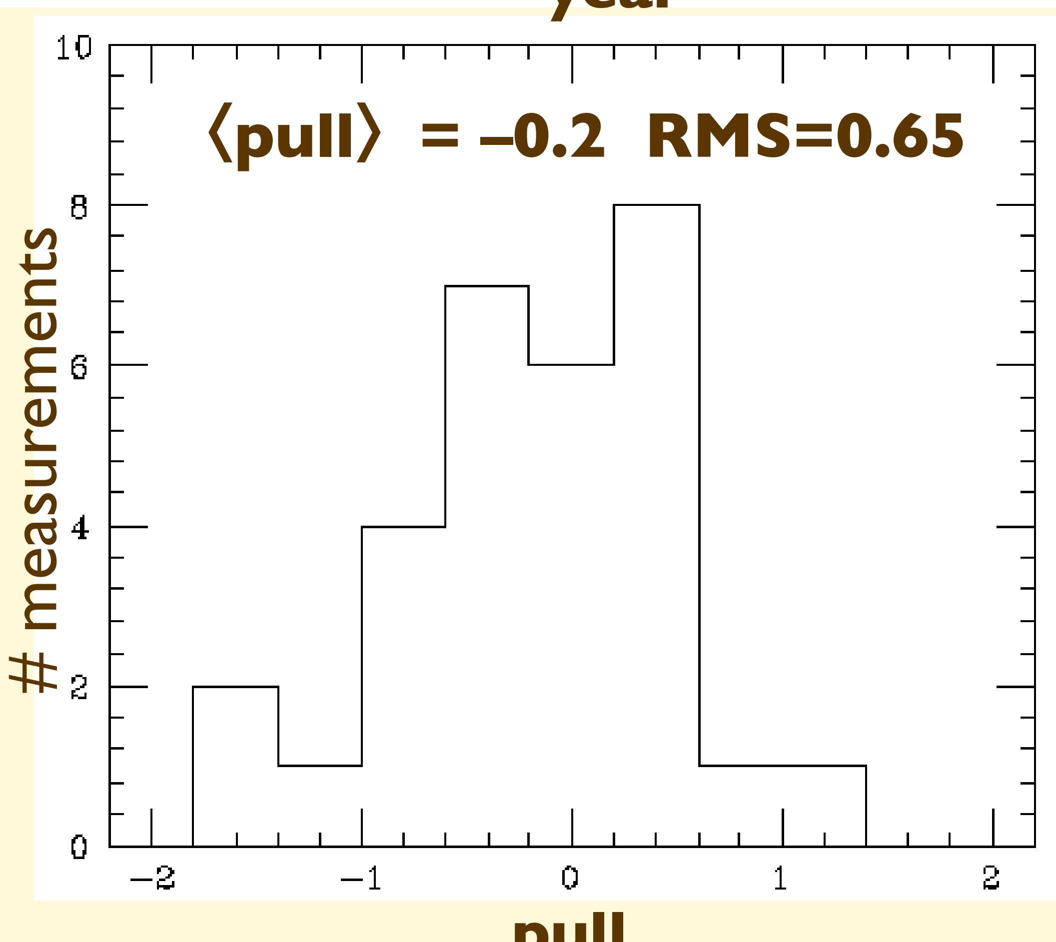
The most precise direct measurement of the W width

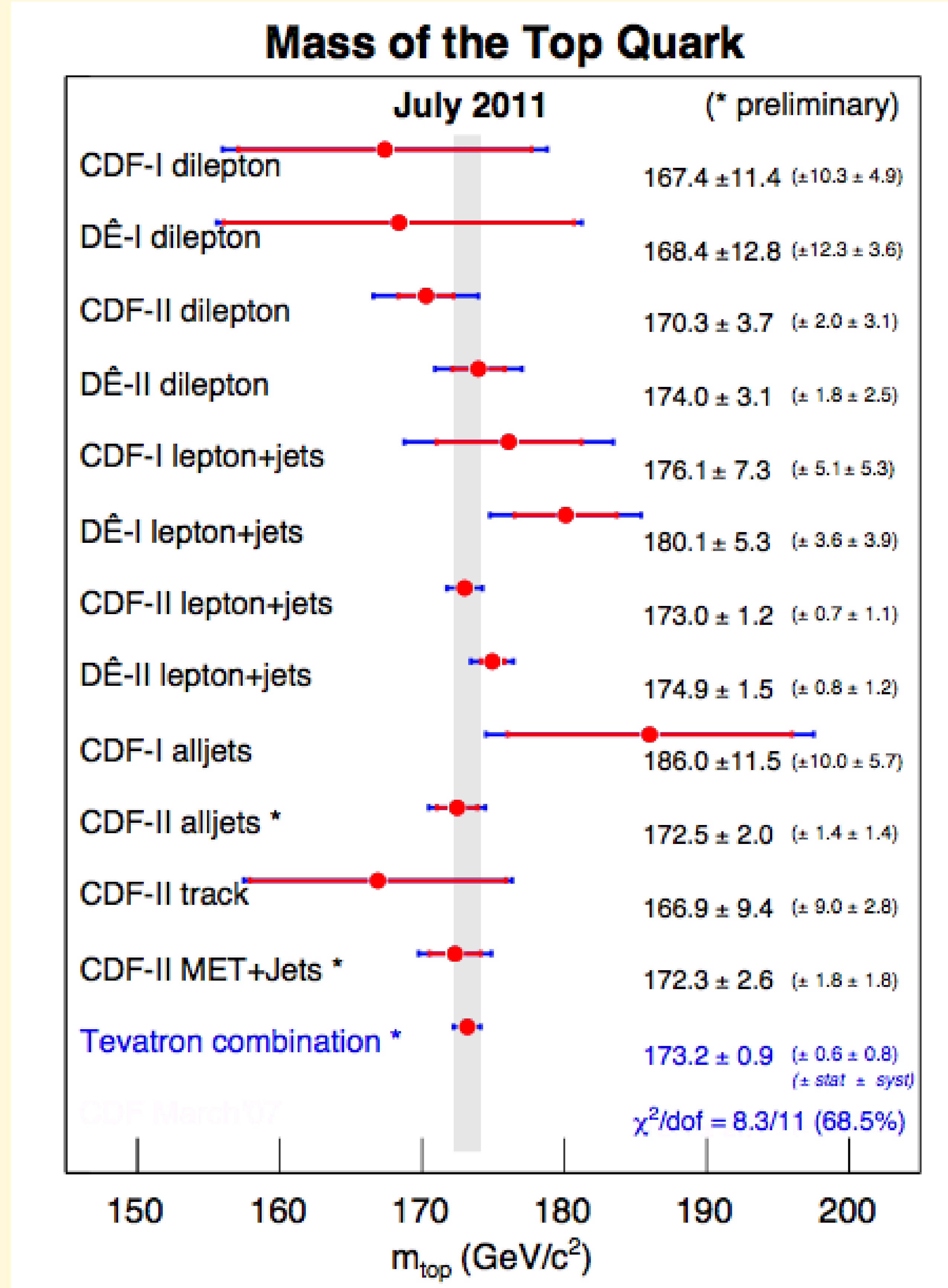
The role of mtop



CDF history of mtop measurements







The role of mtop

Table 10.5: Values of $\hat{s}^2_Z$ and s^2_W (in parentheses), α_s, and m_t for various combinations of observables. The central values are for $M_H = 300$ GeV, and the second set of errors is for $M_H \to 1000(+), 60(-)$.

Data	$\hat{s}^2_Z$ (s^2_W)	α_s (M_Z)	m_t (GeV)
Indirect + CDF + DØ	0.2315(2)(3) (0.2236 ± 0.0008)	0.123(4)(2)	$180 \pm 7^{+12}_{-13}$
All indirect	0.2315(2)(2) (0.2236 ± 0.0009)	0.123(4)(2)	$179 \pm 8^{+17}_{-20}$
All LEP	0.2318(3)(2) (0.2246 ± 0.0011)	0.124(4)(2)	$171 \pm 10^{+18}_{-20}$
SLD + M_Z	0.2302(5)(0) (0.2184 ± 0.0020)	—	220^{+14+19}_{-15-24}
Z pole (LEP + SLD)	0.2314(3)(1) (0.2234 ± 0.0010)	0.123(4)(2)	181^{+8+18}_{-9-20}

PDG 1996

1995	LEP	LEP + SLD
m_t (GeV)	$170 \pm 10\ ^{+17}_{-19}$	$180\ ^{+8}_{-9}\ ^{+17}_{-20}$
$\alpha_s(m_Z^2)$	$0.125 \pm 0.004\ \pm 0.002$	$0.123 \pm 0.004\ \pm 0.002$
χ^2/d.o.f.	18/9	28/12
$\sin^2\theta_{eff}^{lept}$	$0.23206 \pm 0.00028\ ^{+0.00008}_{-0.00017}$	$0.23166 \pm 0.00025\ ^{+0.00006}_{-0.00013}$
$1 - m_W^2/m_Z^2$	$0.2247 \pm 0.0010\ ^{+0.0004}_{-0.0002}$	$0.2234 \pm 0.0009\ ^{+0.0005}_{-0.0002}$
m_W (GeV)	$80.295 \pm 0.057\ ^{+0.011}_{-0.019}$	$80.359 \pm 0.051\ ^{+0.013}_{-0.024}$

2002	- 1 - LEP including LEP-II m_W, Γ_W	- 2 - all Z-pole data	- 3 - all Z-pole data plus m_t	- 4 - all Z-pole data plus m_W, Γ_W	- 5 - all data except NuTeV	- 6 - all data
m_t [GeV]	184^{+13}_{-11}	171^{+11}_{-9}	$173.6^{+4.7}_{-4.6}$	180^{+11}_{-9}	$175.4^{+4.3}_{-4.2}$	$174.3^{+4.5}_{-4.3}$
m_H [GeV]	228^{+367}_{-136}	81^{+107}_{-40}	99^{+64}_{-40}	117^{+161}_{-63}	78^{+48}_{-31}	81^{+52}_{-33}
$\log(m_H/\mathrm{GeV})$	$2.36^{+0.42}_{-0.39}$	$1.91^{+0.37}_{-0.30}$	$1.99^{+0.22}_{-0.23}$	$2.07^{+0.38}_{-0.33}$	$1.89^{+0.21}_{-0.22}$	$1.91^{+0.22}_{-0.23}$
$\alpha_S(m_Z^2)$	0.1199 ± 0.0030	0.1186 ± 0.0027	0.1187 ± 0.0027	0.1185 ± 0.0027	0.1181 ± 0.0027	0.1183 ± 0.0027
χ^2/d.o.f. (P)	13.3/9 (15%)	14.8/10 (14%)	14.9/11 (19%)	17.9/12 (12%)	20.5/14 (11%)	29.7/15 (1.3%)
$\sin^2\theta_{eff}^{lept}$	0.23160 ± 0.00018	0.23145 ± 0.00016	0.23145 ± 0.00016	0.23135 ± 0.00015	0.23131 ± 0.00015	0.23136 ± 0.00015
$\sin^2\theta_W$	0.22284 ± 0.00053	0.22313 ± 0.00063	0.22299 ± 0.00045	0.22240 ± 0.00045	0.22255 ± 0.00036	0.22272 ± 0.00036
m_W [GeV]	80.388 ± 0.027	80.373 ± 0.032	80.380 ± 0.023	80.410 ± 0.023	80.403 ± 0.019	80.394 ± 0.019

2006	- 1 - all Z-pole data	- 2 - all Z-pole data plus m_t	- 3 - all Z-pole data plus m_W, Γ_W	- 4 - all Z-pole data plus m_t, m_W, Γ_W
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m_H [GeV]	111^{+190}_{-60}	103^{+54}_{-37}	137^{+228}_{-76}	85^{+39}_{-28}
$\log(m_H/\mathrm{GeV})$	$2.05^{+0.43}_{-0.34}$	$2.01^{+0.18}_{-0.19}$	$2.14^{+0.43}_{-0.35}$	$1.93^{+0.16}_{-0.17}$
$\alpha_S(m_Z^2)$	0.1190 ± 0.0027	0.1190 ± 0.0027	0.1190 ± 0.0028	0.1186 ± 0.0027
χ^2/d.o.f. (P)	16.0/10 (9.9%)	16.0/11 (14%)	17.4/12 (14%)	17.8/13 (17%)
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$\sin^2\theta_W$	0.22331 ± 0.00062	0.22336 ± 0.00039	0.22298 ± 0.00041	0.22316 ± 0.00031
m_W [GeV]	80.363 ± 0.032	80.361 ± 0.020	80.380 ± 0.021	80.371 ± 0.016

2008	- 1 - all Z-pole data	- 2 - all Z-pole data plus m_t	- 3 - all Z-pole data plus m_W, Γ_W	- 4 - all Z-pole data plus m_t, m_W, Γ_W
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m_W [GeV]	80.363 ± 0.032	80.363 ± 0.020	80.385 ± 0.020	80.376 ± 0.015

Tension between mtop and mW

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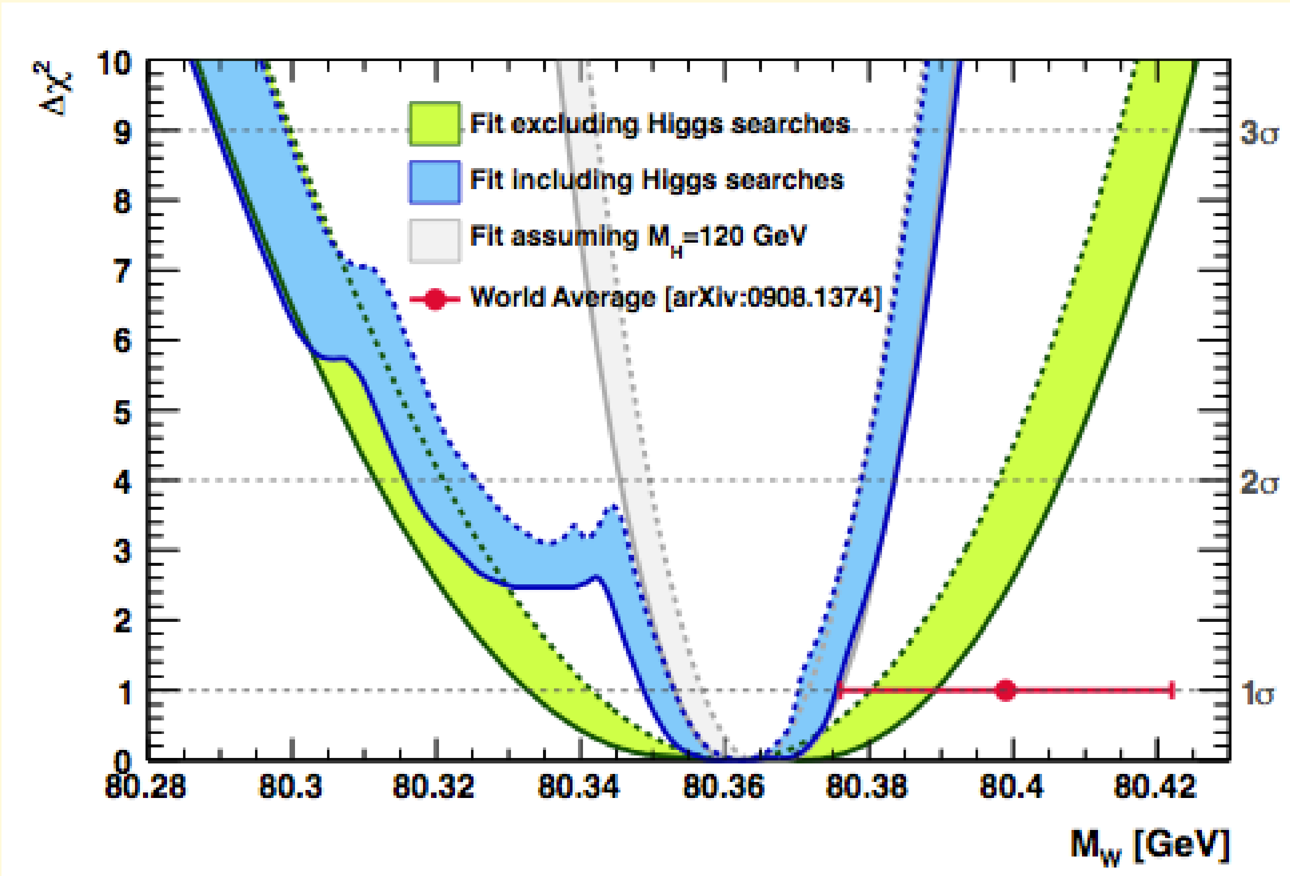
Implications of current mW measurements



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From the EW fit,
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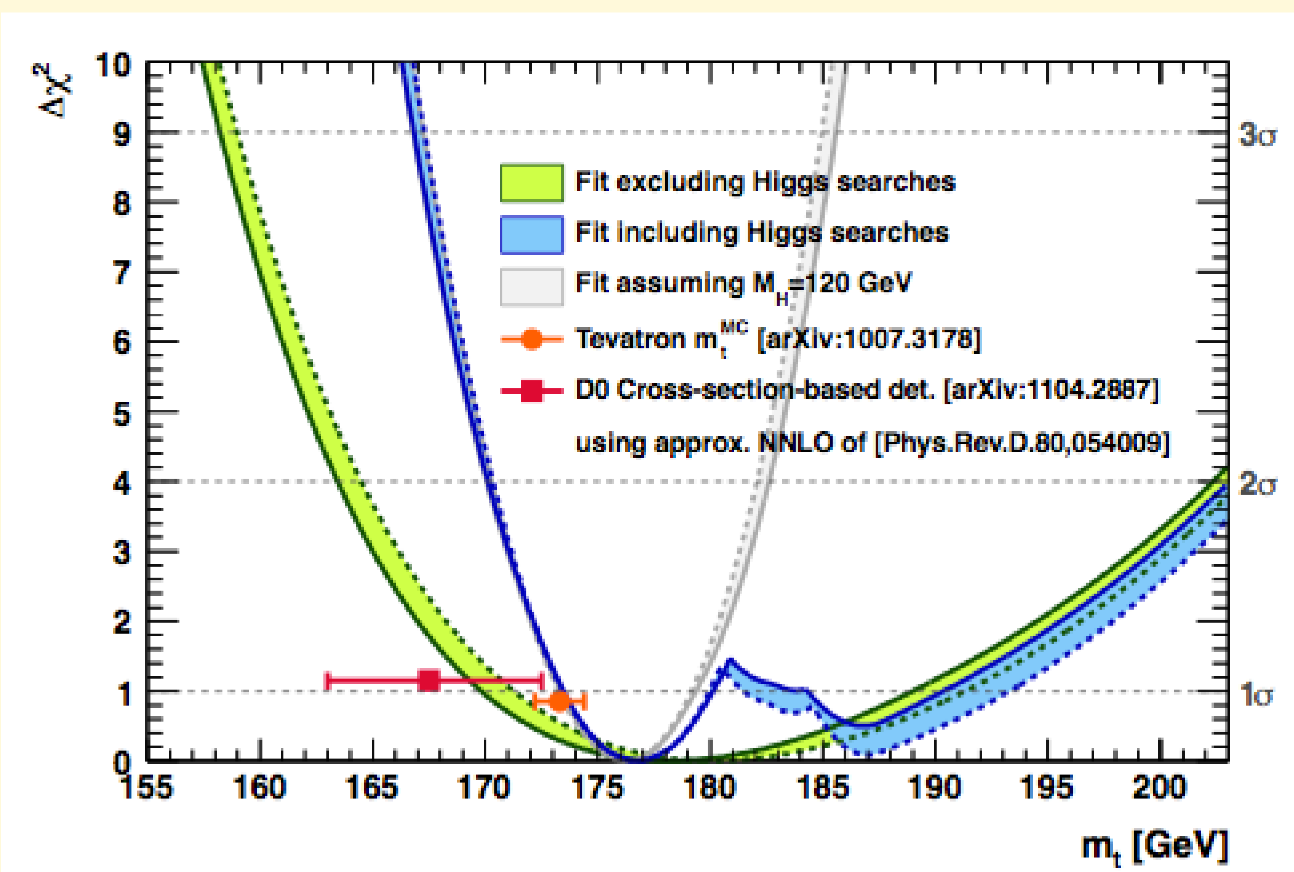
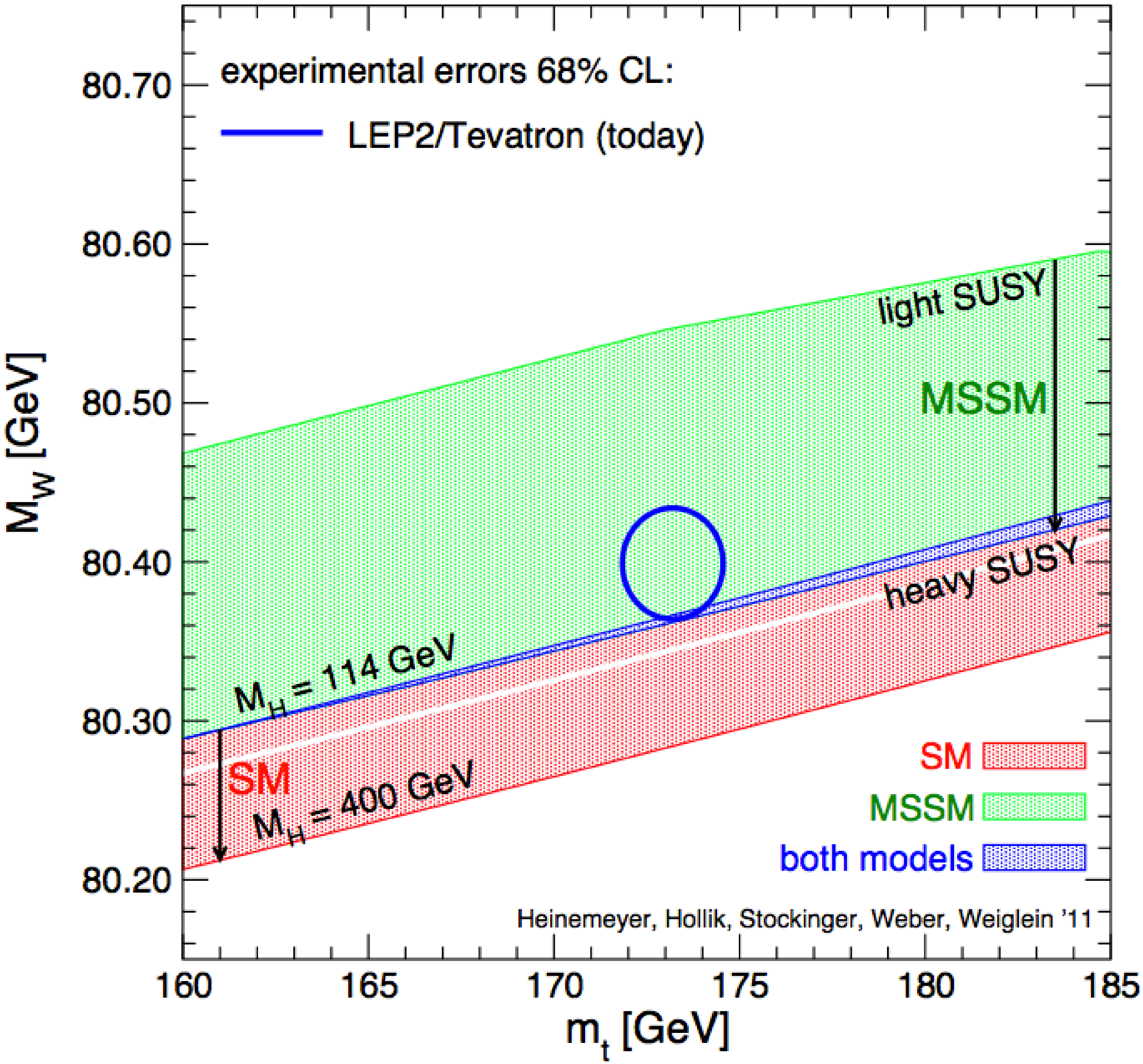


No significant tension, instead, between the "direct" and "fit" values of m_{top}

Putting all together



For equal contribution to the Higgs mass uncertainty need:

$\Delta M_W \approx 0.006\ \Delta M_t$.

Current Tevatron average:

$\Delta M_t = 0.9$ GeV

$\Rightarrow$ would need: ΔM_W = 5 MeV

Currently have: ΔM_W = 23 MeV

At this point, *i.e.* after all the precise top mass measurements from the Tevatron, the limiting factor here is ΔM_W, not ΔM_t .

Remarks

- δm_{top} from EW fits ~ ± 10 GeV
- δm_W from EW fits ~ ± 20 MeV
- What's really important is not **just** how accurately we can infer $m_{top,W}$ from EW fits, but how accurately we can test these predictions! Without the direct measurements we couldn't tell whether the SM is consistent, and we'd have no clue on mH
- m_{top} is known today with accuracy greatly exceeding the immediate needs. Further progress should come from improvements in m_W
- The same remarks apply to observables in the flavour sector, namely CKM entries ...

Contributions to CKM studies. An example

$$A_{CP} = \frac{N(\overline{B}^0 \to J/\psi K_S^0) - N(B^0 \to J/\psi K_S^0)}{N(\overline{B}^0 \to J/\psi K_S^0) + N(B^0 \to J/\psi K_S^0)}$$ = sin 2β

1999: SM prediction: $0.59 \lesssim \sin 2\beta \lesssim 0.82.$

CDF, 1999: first observation of CP violation in the B system:

$$\sin 2\beta = 0.79^{+0.41}_{-0.44}(\text{stat} + \text{syst})$$

=> spot on SM value!

July 2000: first results from B factories:

BaBar: $a_{\psi K_S} = 0.12 \pm 0.38.$!!!

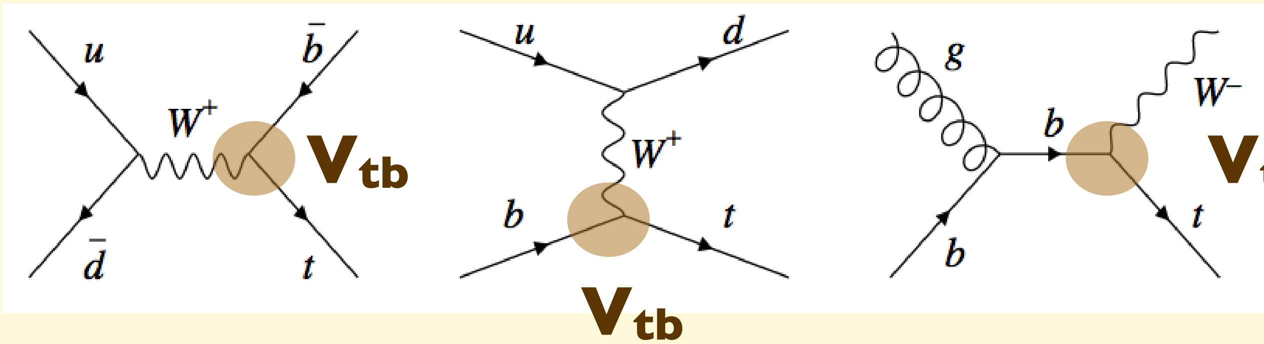
Babar, Belle, CDF average: $a_{\psi K_S} = 0.42 \pm 0.24,$

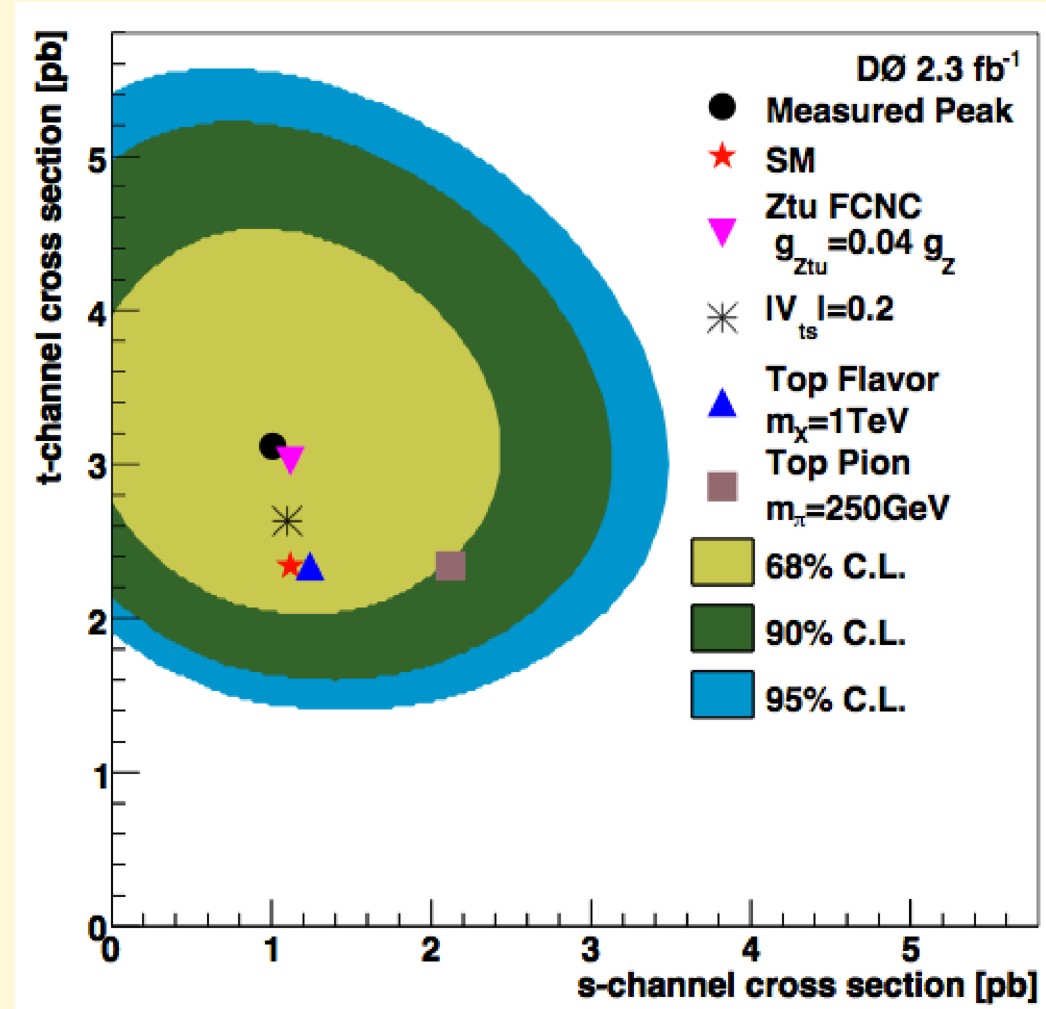
=> flourishing of BSM speculations

Current world average:

$$\sin 2\beta = 0.673 \pm 0.023 .$$

Top EW couplings





http://arxiv.org/pdf/1010.2999

Table 2: Measurements of $|V_{tb}|$ from CDF and DØ single-top results.

$|V_{tb}|$ or $|V_{tb}f_1^L|$	Source		$\int \mathcal{L}dt$ (fb^{-1})	Ref.
$|V_{tb}f_1^L| = 1.07 \pm 0.12$	DØ	Run II	2.3	[14]
$|V_{tb}| > 0.78$	DØ	Run II	2.3	[14]
$|V_{tb}| = 0.91 \pm 0.13$	CDF	Run II	3.2	[15]
$|V_{tb}| = 0.88 \pm 0.07$	CDF + DØ	Run II	3.2	[55]
$|V_{tb}| > 0.77$	CDF + DØ	Run II	3.2	[55]

Top decay width

t→bW

$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}}\left(1-\frac{M_W^2}{m_t^2}\right)^2\left(1+2\frac{M_W^2}{m_t^2}\right)\left[1-\frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3}-\frac{5}{2}\right)\right]$$

2) Γ_{top} ~ 1.34 GeV > T_{had}^{-1} ~ Λ_{QCD}

t-quark DECAY WIDTH

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
$1.99^{+0.69}_{-0.55}$		[1] ABAZOV	11B	D0	$\Gamma(t \to Wb)/B(t \to Wb)$

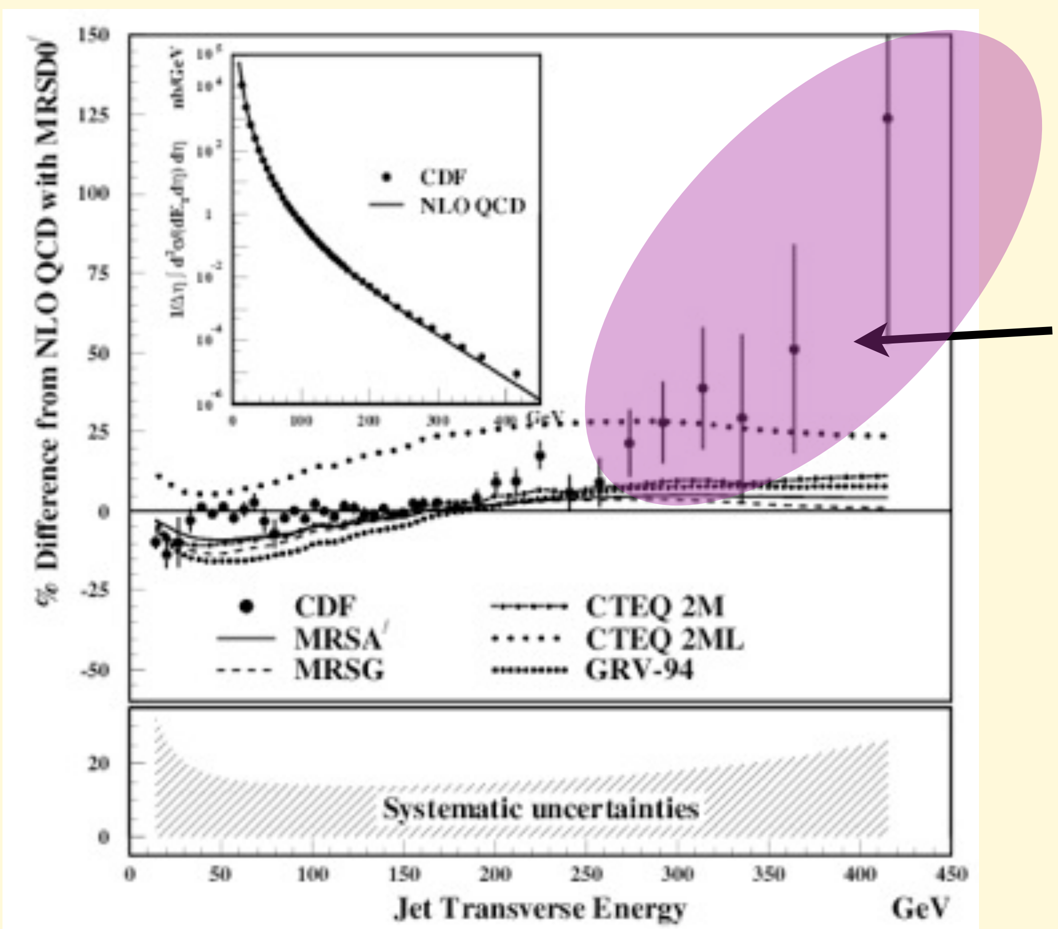
[1] Based on 2.3 fb^{-1} in $p\overline{p}$ collisions at $\sqrt{s}$ = 1.96 TeV. ABAZOV 11B extracted Γ_t from the partial width $\Gamma(t \to Wb) = 1.92^{+0.58}_{-0.51}$ GeV measured using the t-channel single top production cross section, and the branching fraction brt $\to Wb$ = $0.962^{+0.068}_{-0.066}$(stat)$^{+0.064}_{-0.052}$(syst). The $\Gamma(t \to Wb)$ measurement gives the 95% CL lowerbound of $\Gamma(t \to Wb)$ and hence that of Γ_t.

⇒Top quark decays before hadronizing: there are no top-hadrons

Exploring the quark structure: how pointlike is it?

Analysis of large-ET jet production at the Tevatron

[QCDNLO / data – 1] (%)

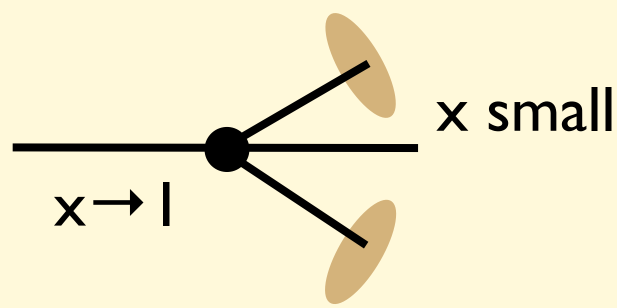


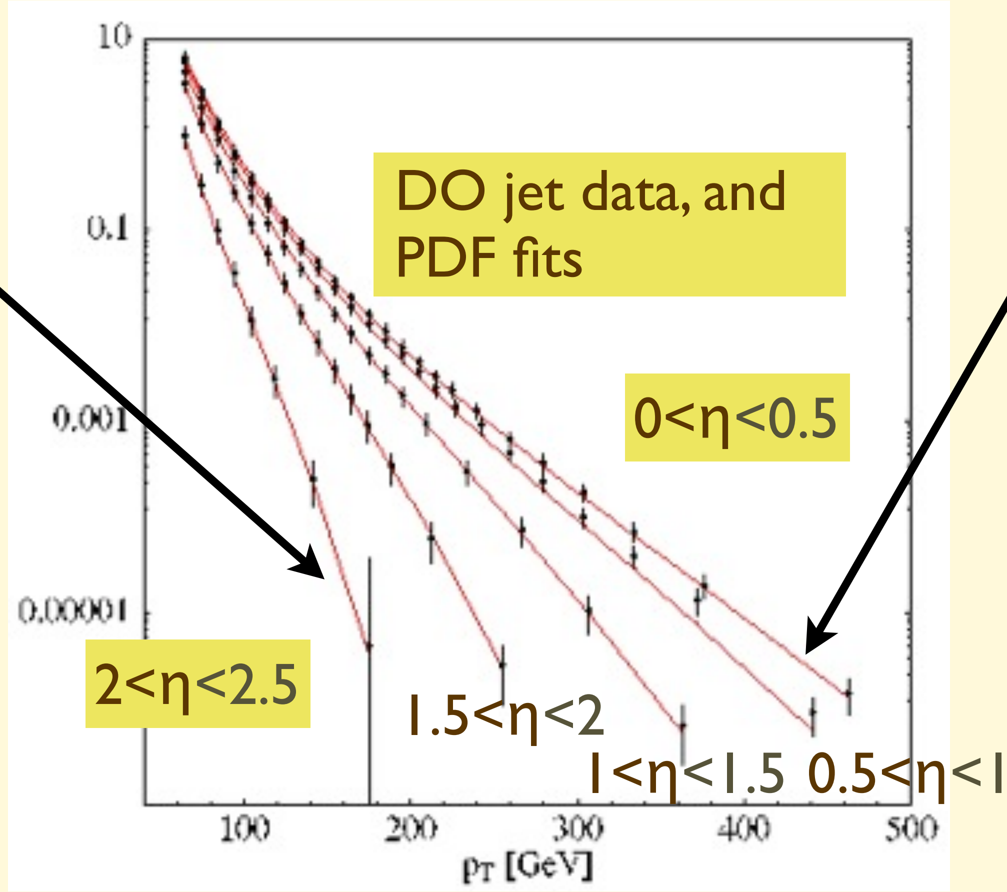
Large excess ⇒ **quark substructure** ??

Effect later understood as poor knowledge/ parameterization of the gluon density of the proton at $x \to 1$, using asymmetric, low-ET final states:

Control region

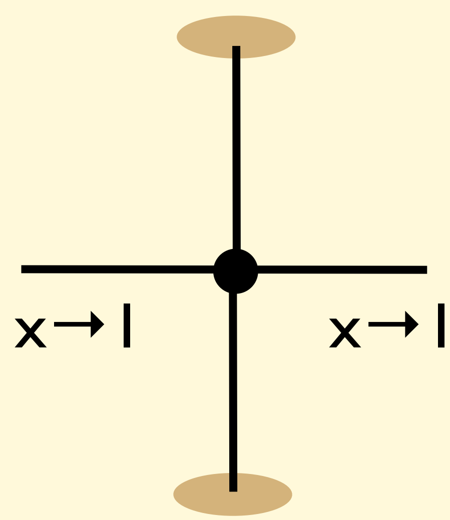
fwd jets - low ET, small $\sqrt{s}$, no BSM "contamination", extract large-x PDF





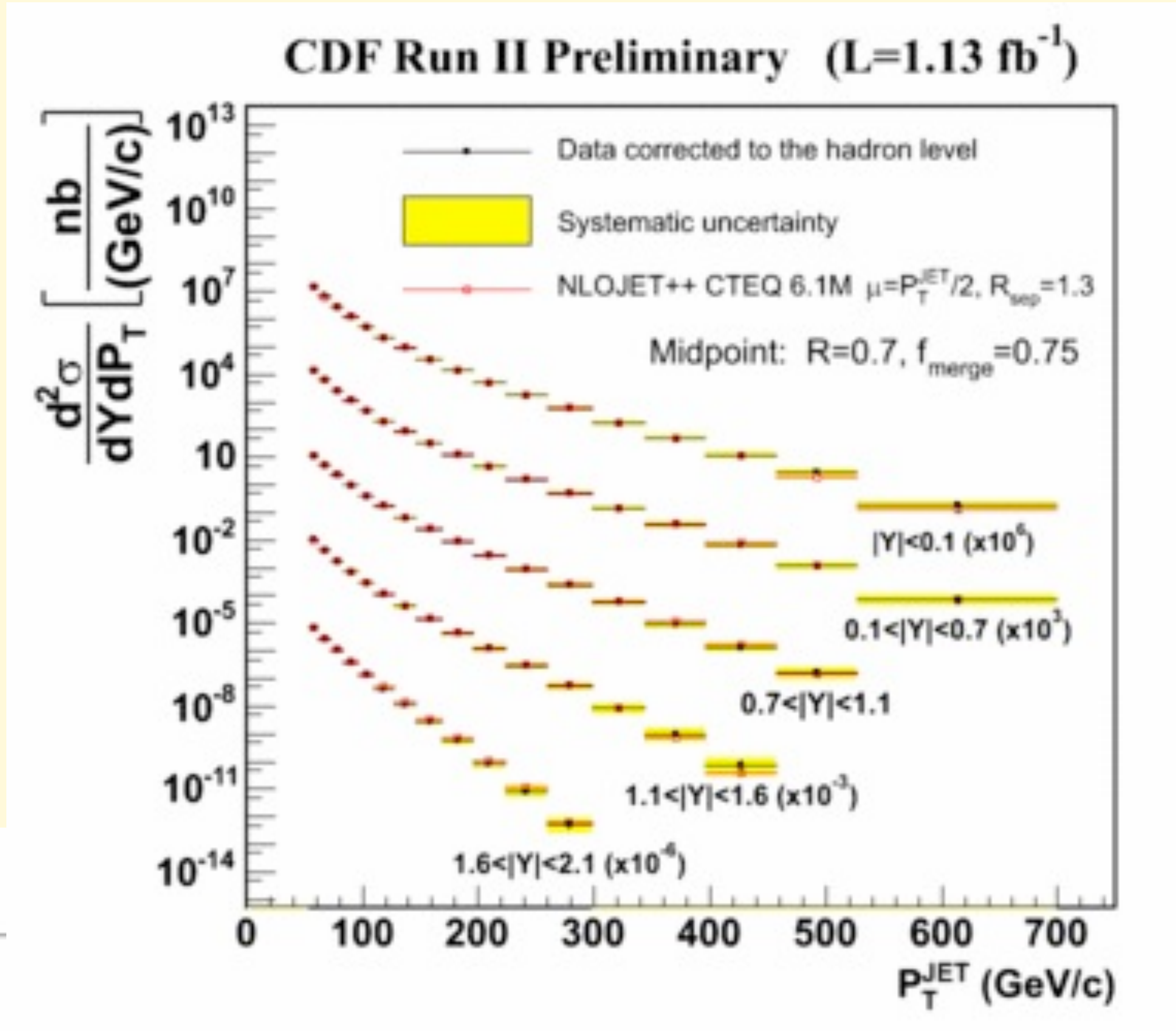
Signal region

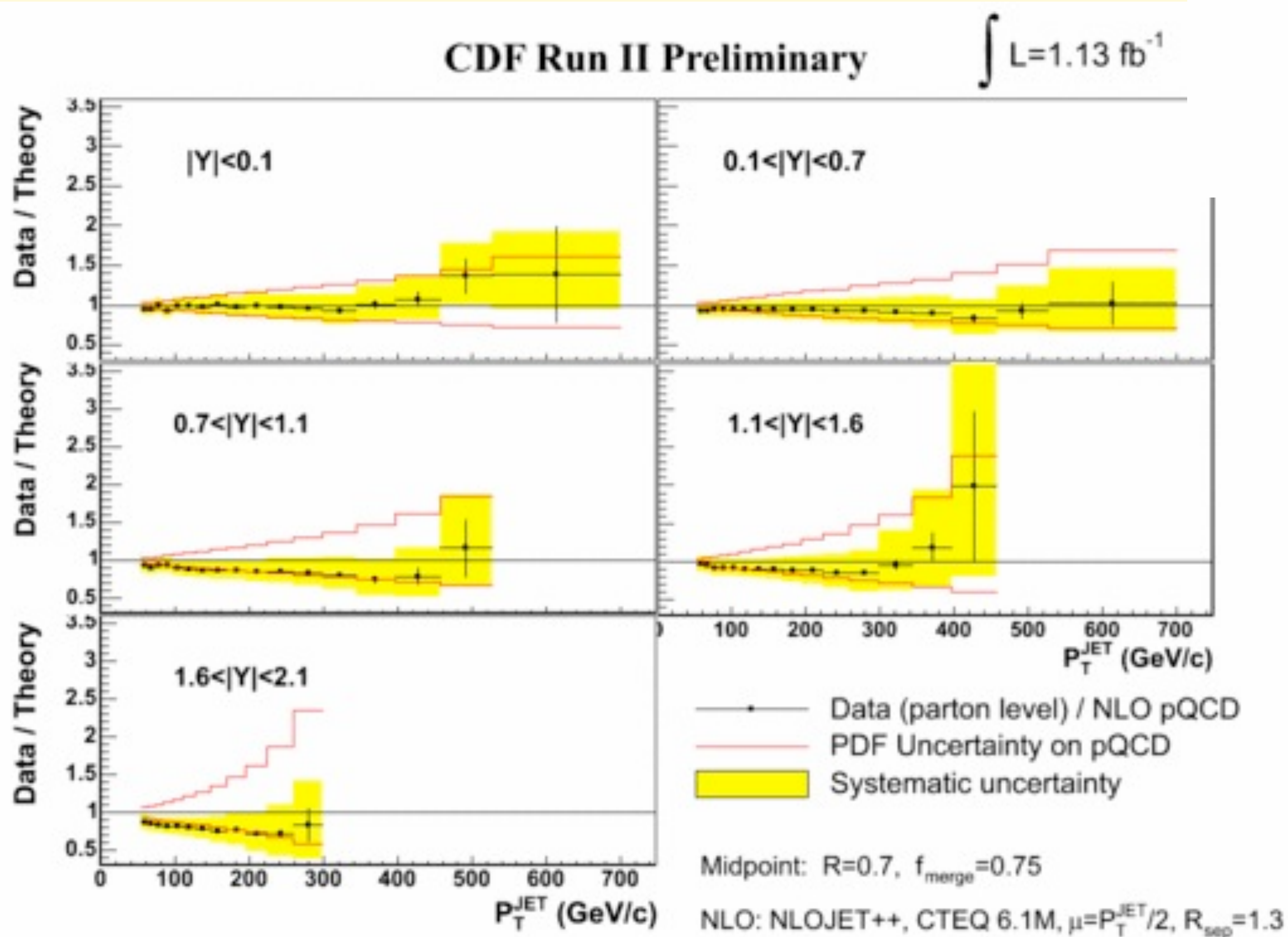
central jets - high ET, large $\sqrt{s}$, explore quark substructure



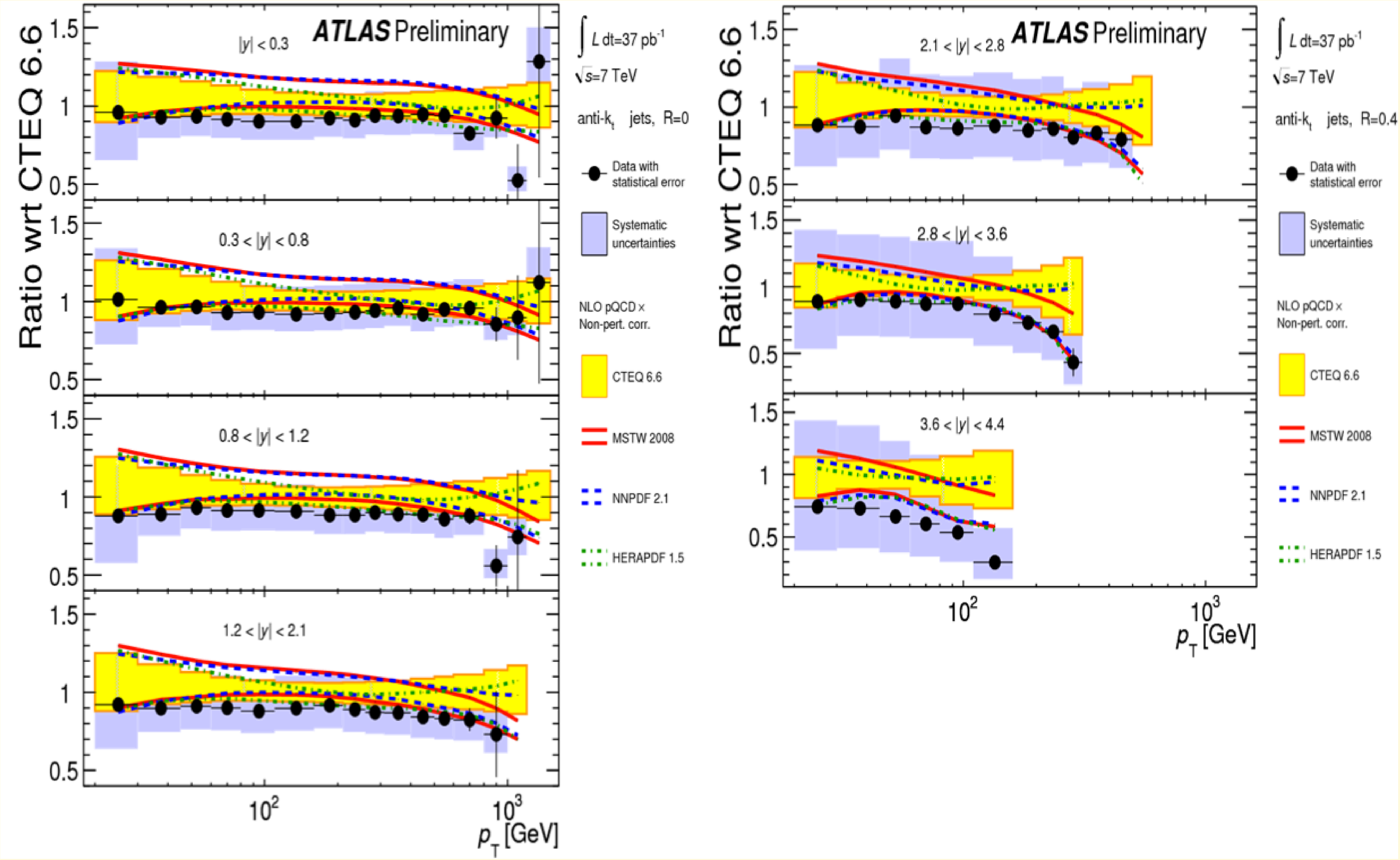
A prototype for self-consistent, robust and credible bg determination ...

Tevatron, Run 2 results





Strategy carried over to the LHC ....

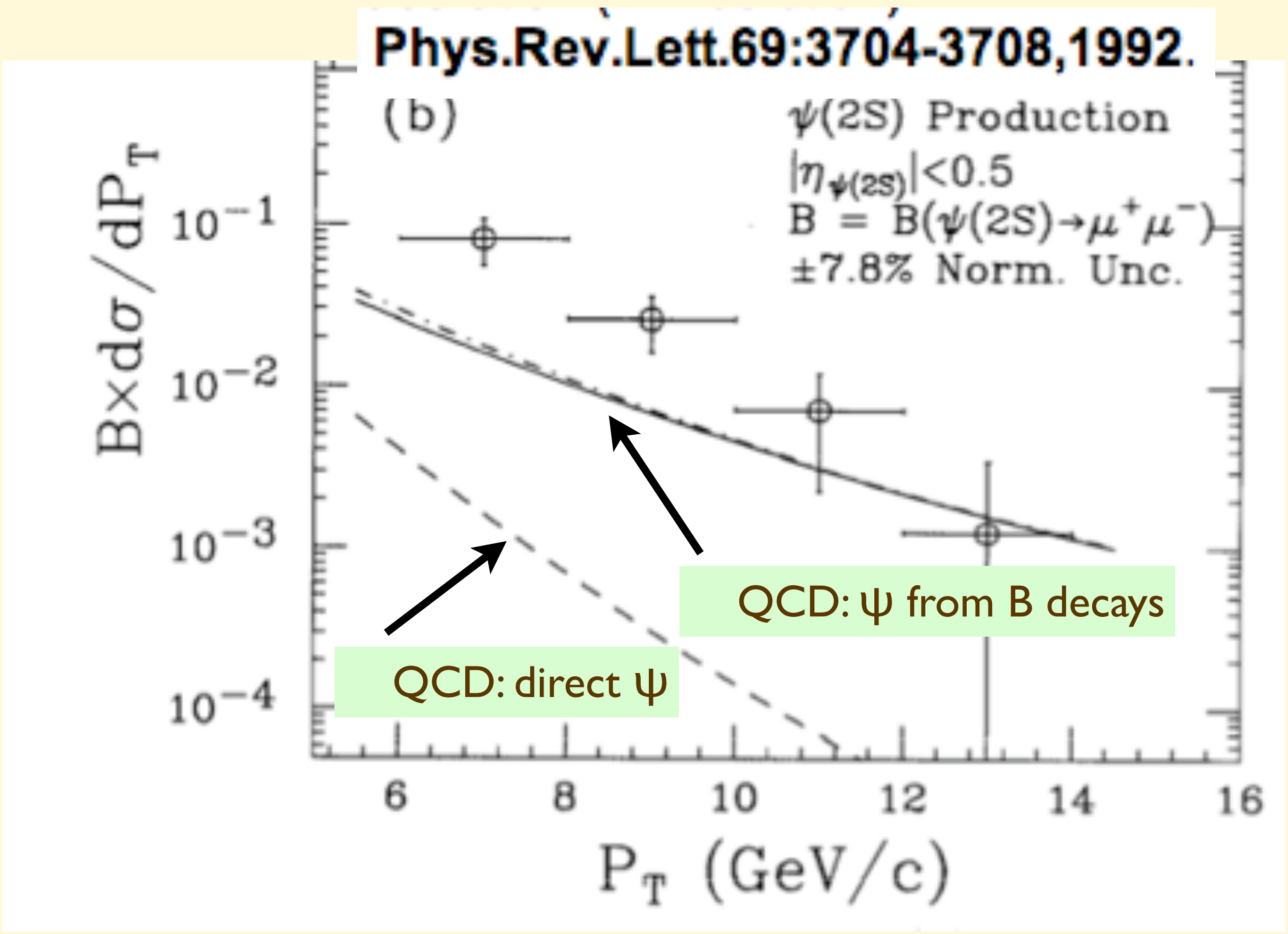


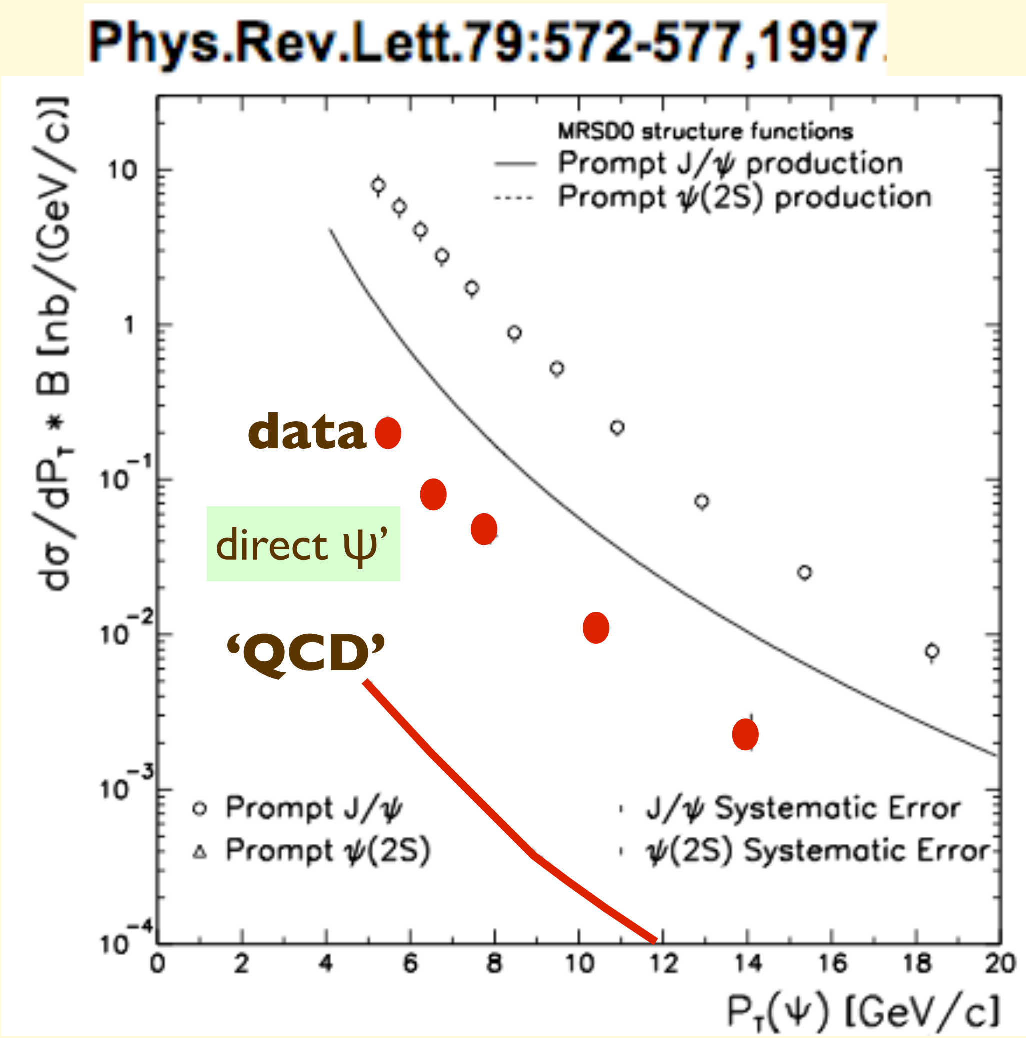
SCALE LIMITS for Contact Interactions: $\Lambda(qqqq)$

Limits are for $\Lambda^{\pm}_{LL}$ with color-singlet isoscalar exchanges among u_L's and d_L's only, unless otherwise noted. See EICHTEN 84 for details.

VALUE (TeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>4.0	95	[31] KHACHATRY...	10A	CMS	pp; dijet centrality. Λ^{+}_{LL}
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>2.96	95	[32] ABAZOV	09AE	D0	$p\overline{p} \rightarrow$ dijet, angl. Λ^{+}_{LL}
>2.0	95	[33] ABBOTT	00E	D0	H_T distribution; Λ^{+}_{LL}
>2.7	95	[34] ABBOTT	99C	D0	$p\overline{p} \rightarrow$ dijet mass. Λ^{+}_{LL}
>2.1	95	[35] ABBOTT	98G	D0	$p\overline{p} \rightarrow$ dijet angl. Λ^{+}_{LL}
		[36] BERTRAM	98	RVUE	$p\overline{p} \rightarrow$ dijet mass

J/ψ production at the Tevatron, the biggest surprise among the studies of production dynamics



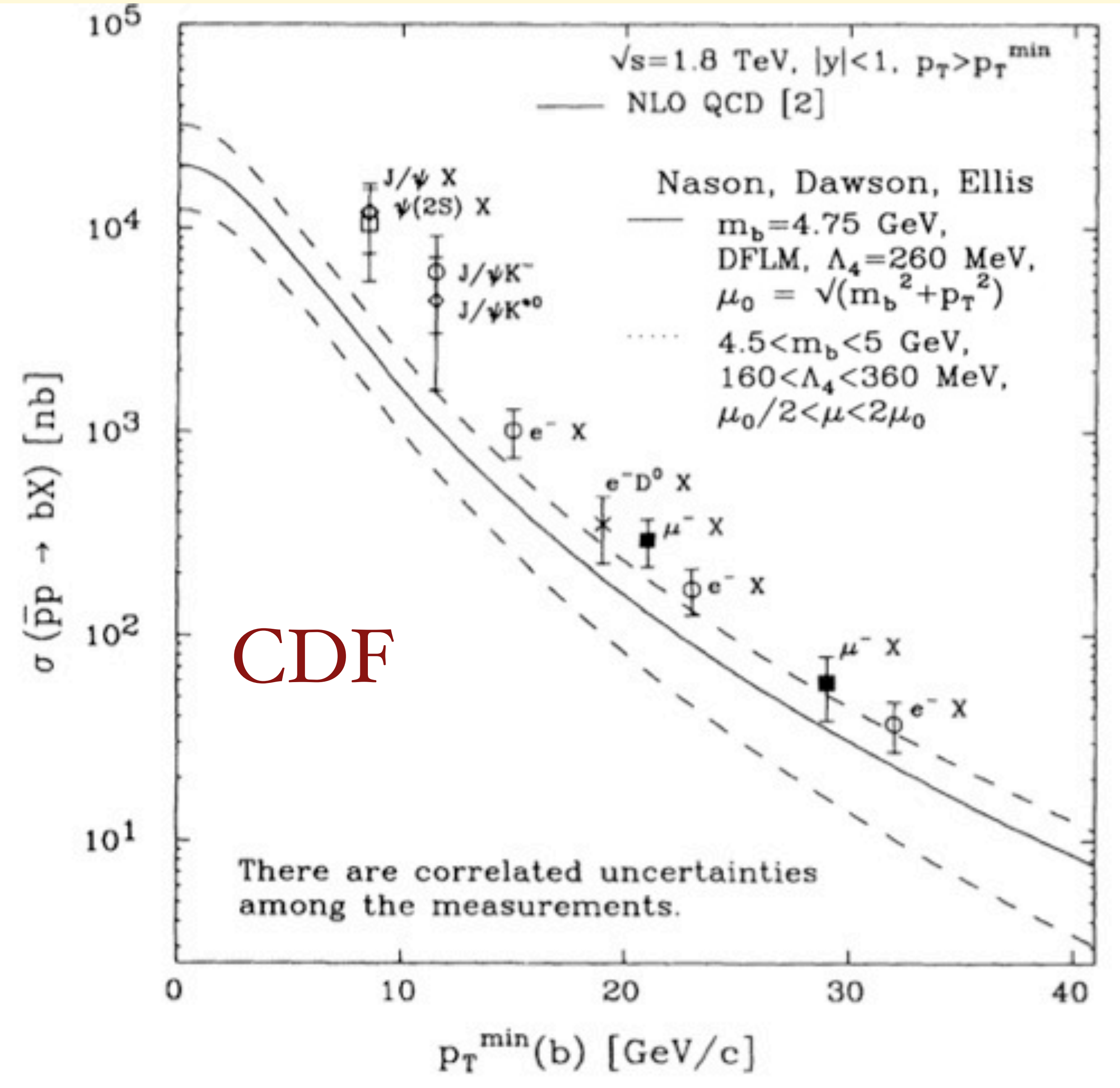


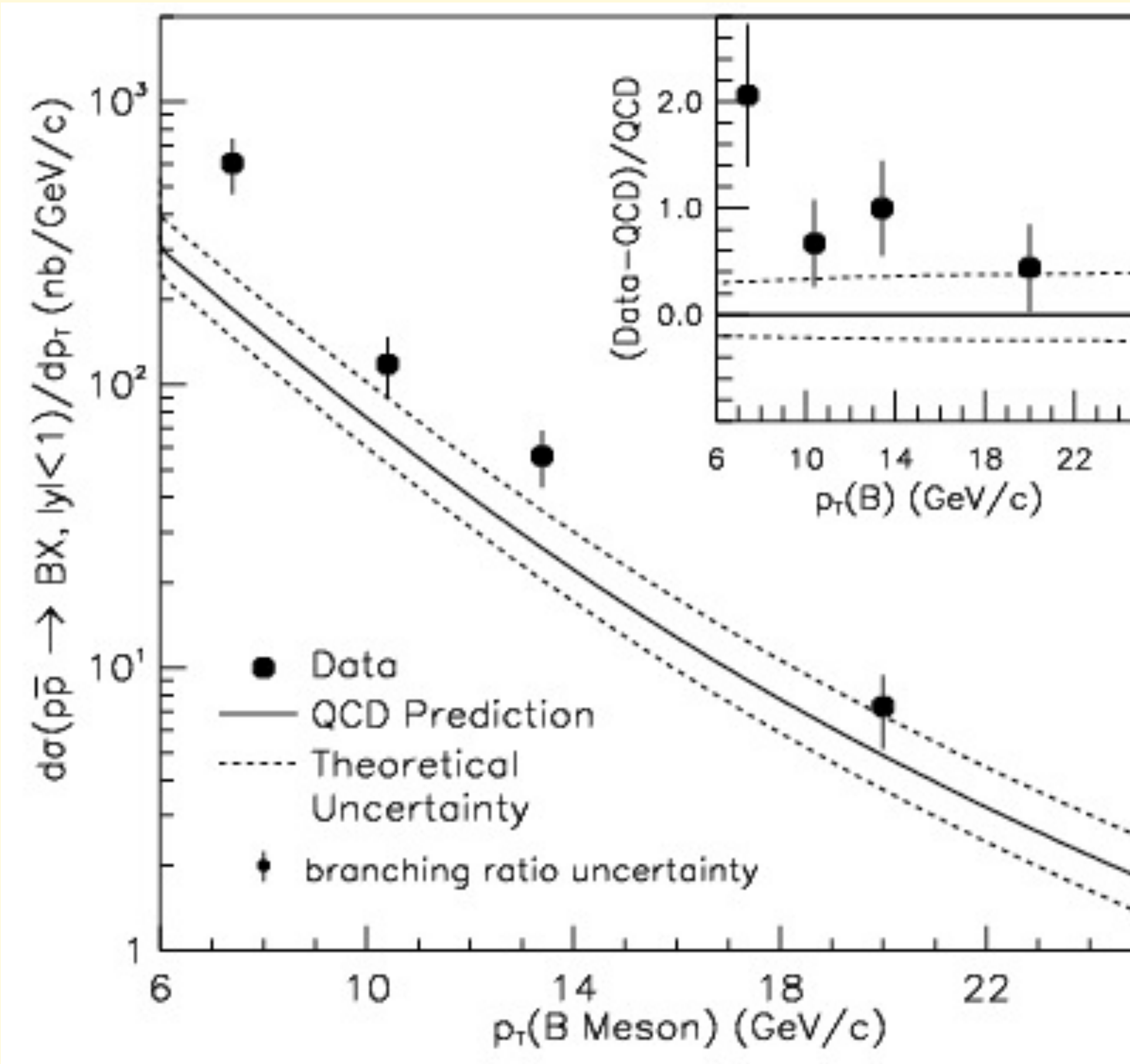
Things don't appear so bad if one cannot separate ψ's from B decays and direct ones ......

... but the disagreement grows to a factor of 50 if we can separate out the directly produced ψ's !

... Later solved by realizing the role of neglected color-octet production processes

The b-quark production rate, a tough challenge





July 1993:
CDF, PRL 71 (1993) 500

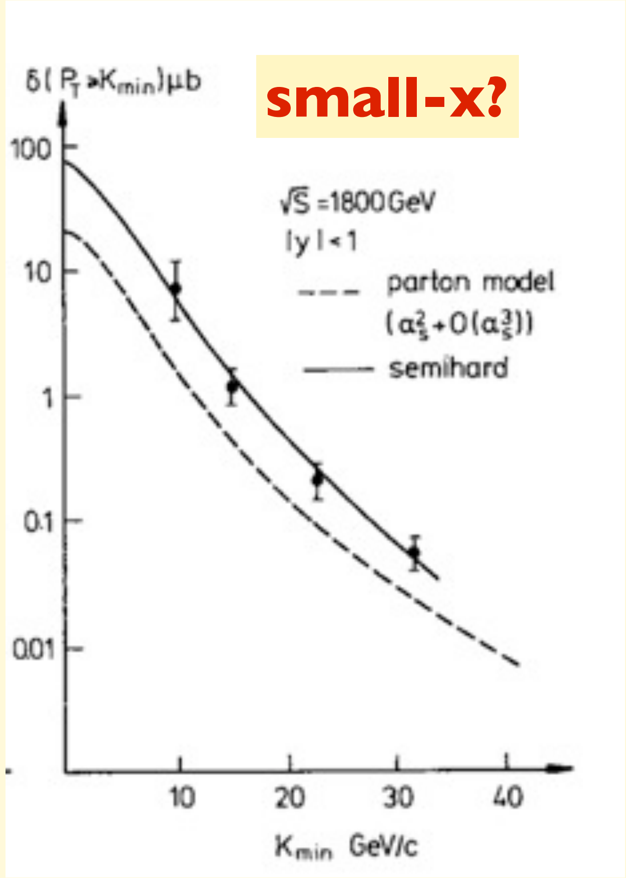
Oct 1993:
CDF, PRL 71 (1993) 2396

Oct 1994:
CDF, PR D50 (1994) 4252

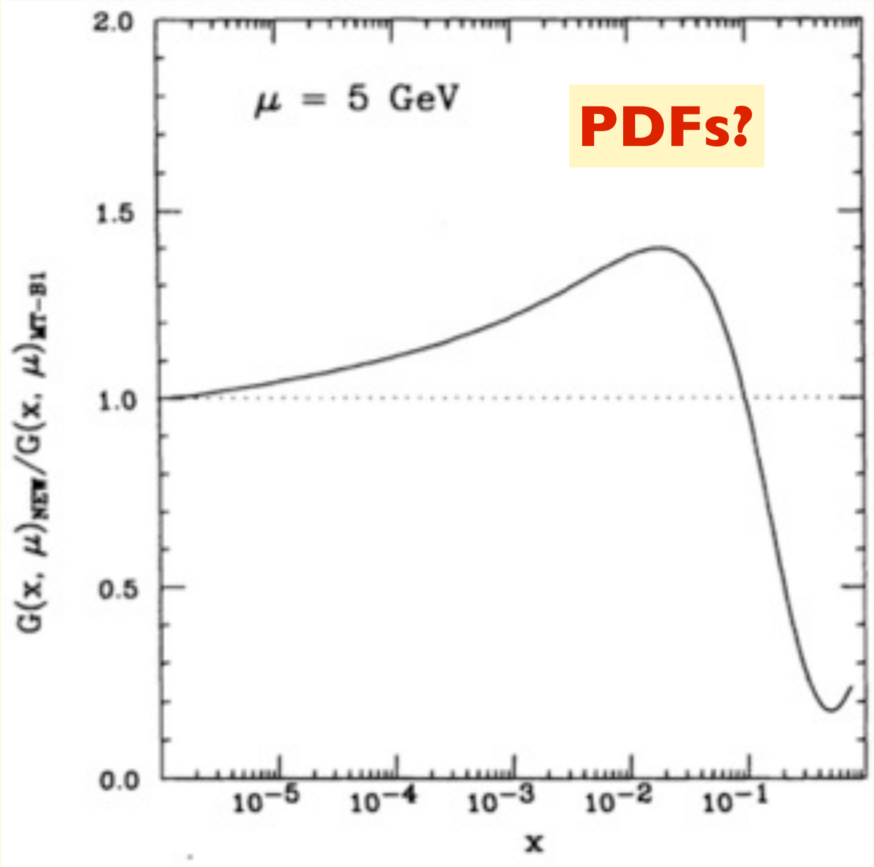
σ(PT>11.5 GeV, |y|<1):

CDF = 3.7±2.2 μb
theory = 1.1±0.5 μb

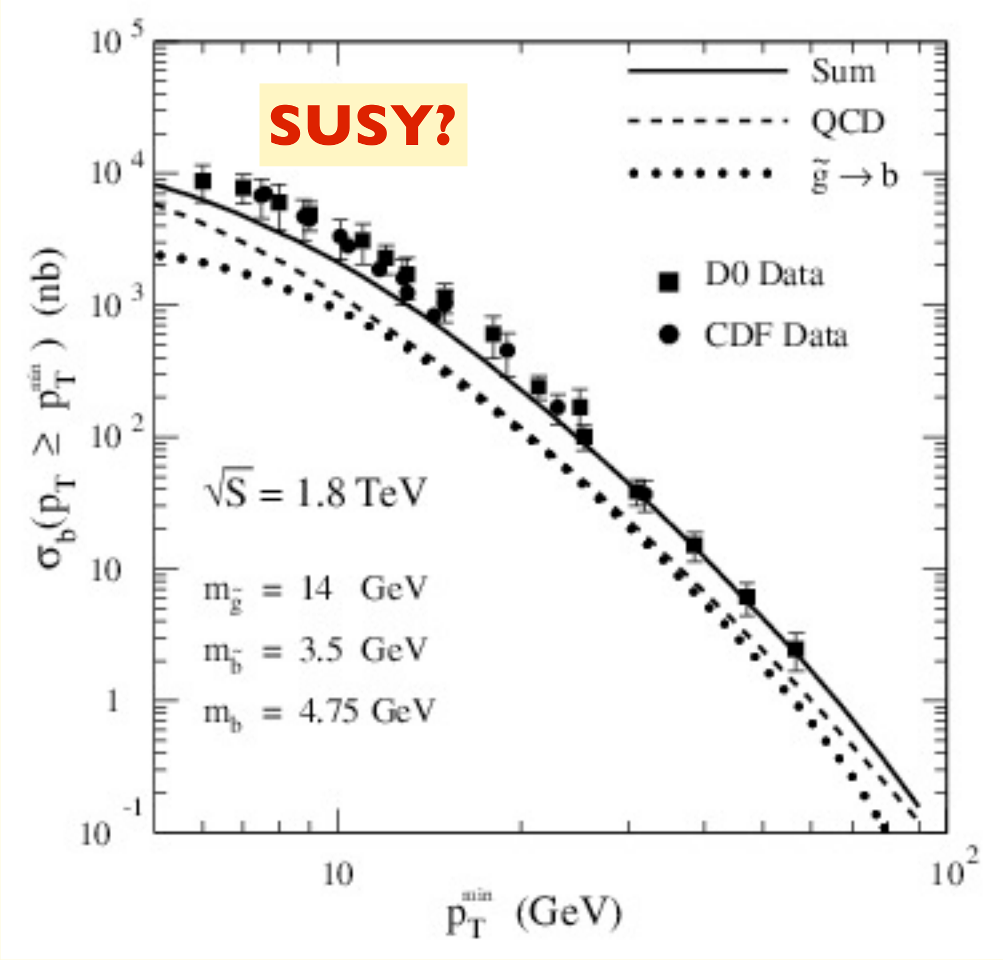
March 1995:
CDF, *PRL, 75 (1995) 1451*



Levin, Ryskin, Shabelski, Phys.Lett.B260: 429-432,1991

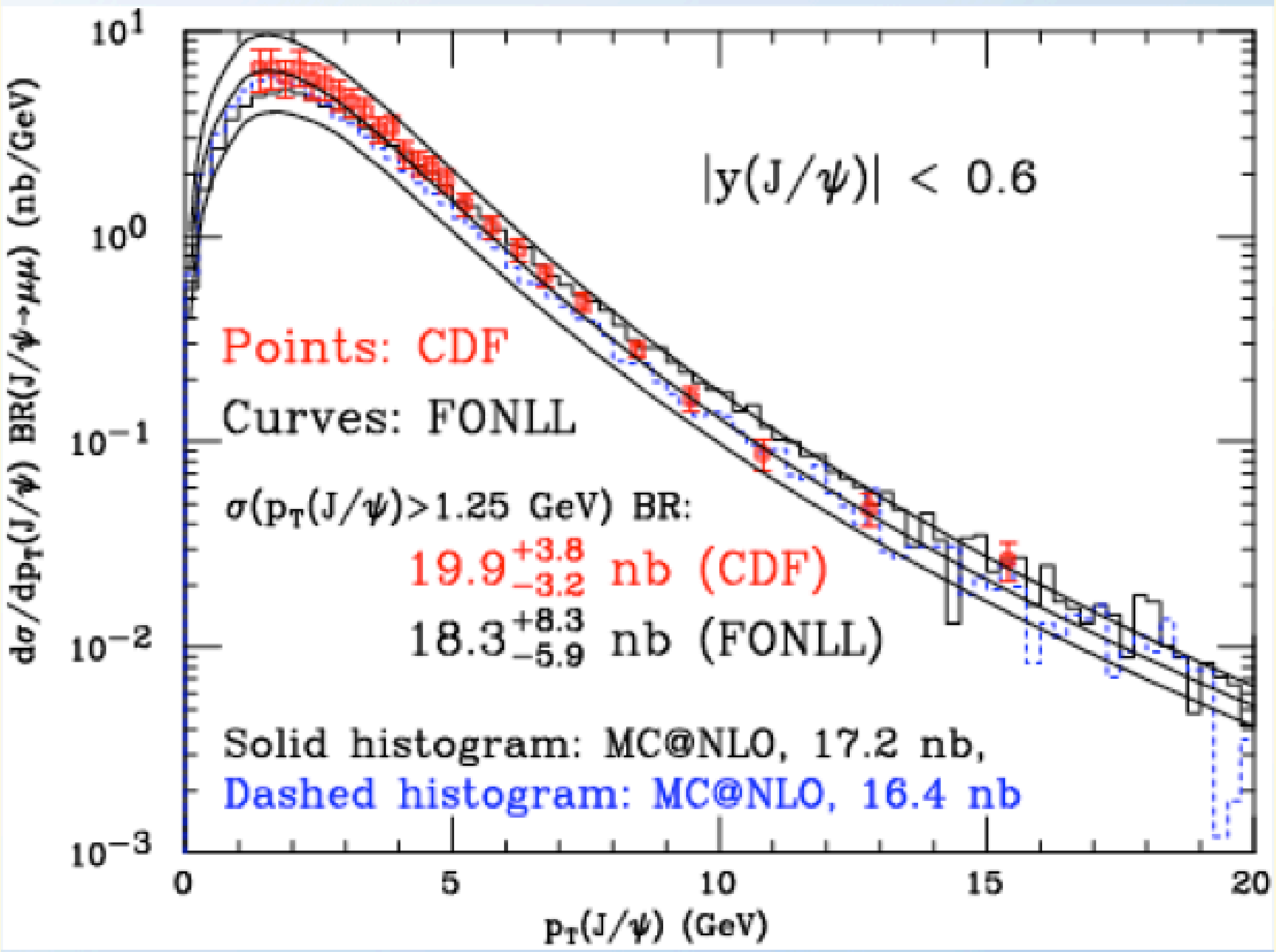


Berger, Meng, Tung, PR D46 (1992) R1895



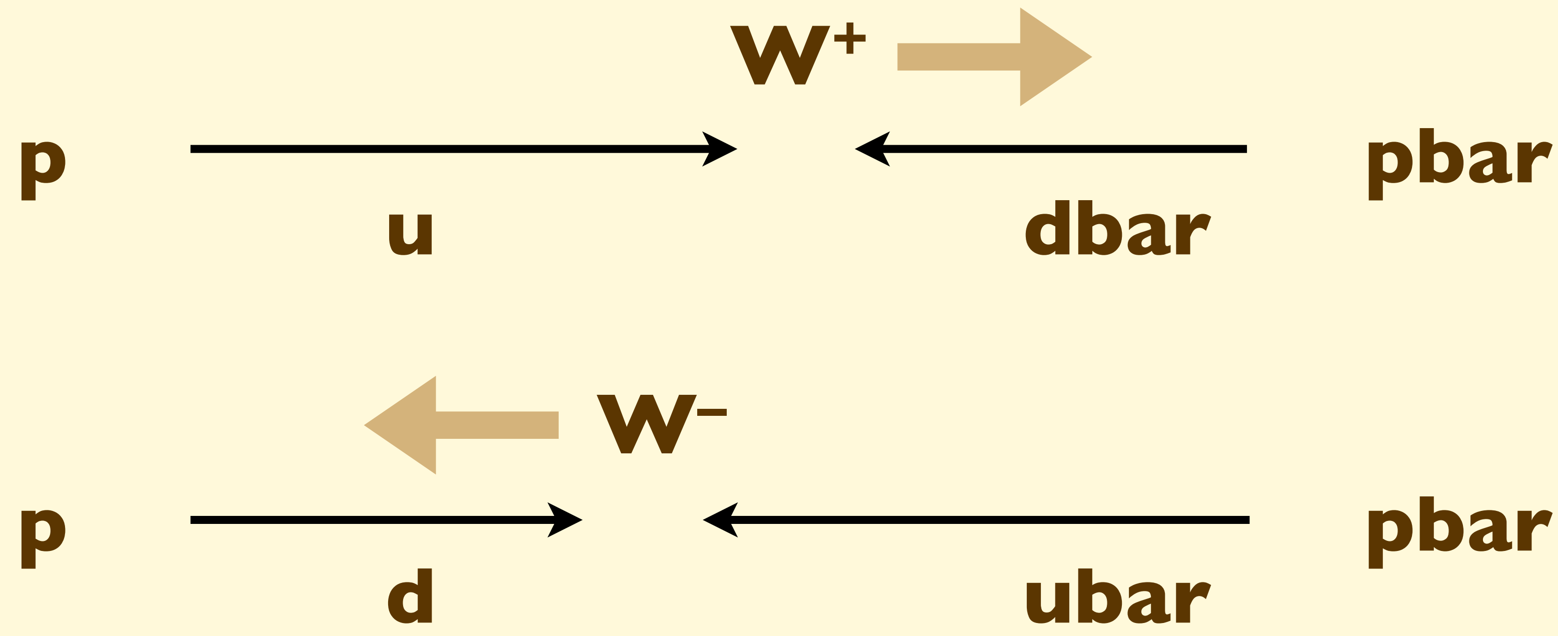
Berger, Harris, Kaplan, Sullivan, Tait, Wagner, PRL 86 (2001) 4231

Finally, none of the above .....



Cacciari, Frixione, Mangano, Nason, Ridolfi, hep-ph/0312132
hep-ph/0411020

Exploitation of dynamical understanding of production processes: W rapidity asymmetry and PDF fits



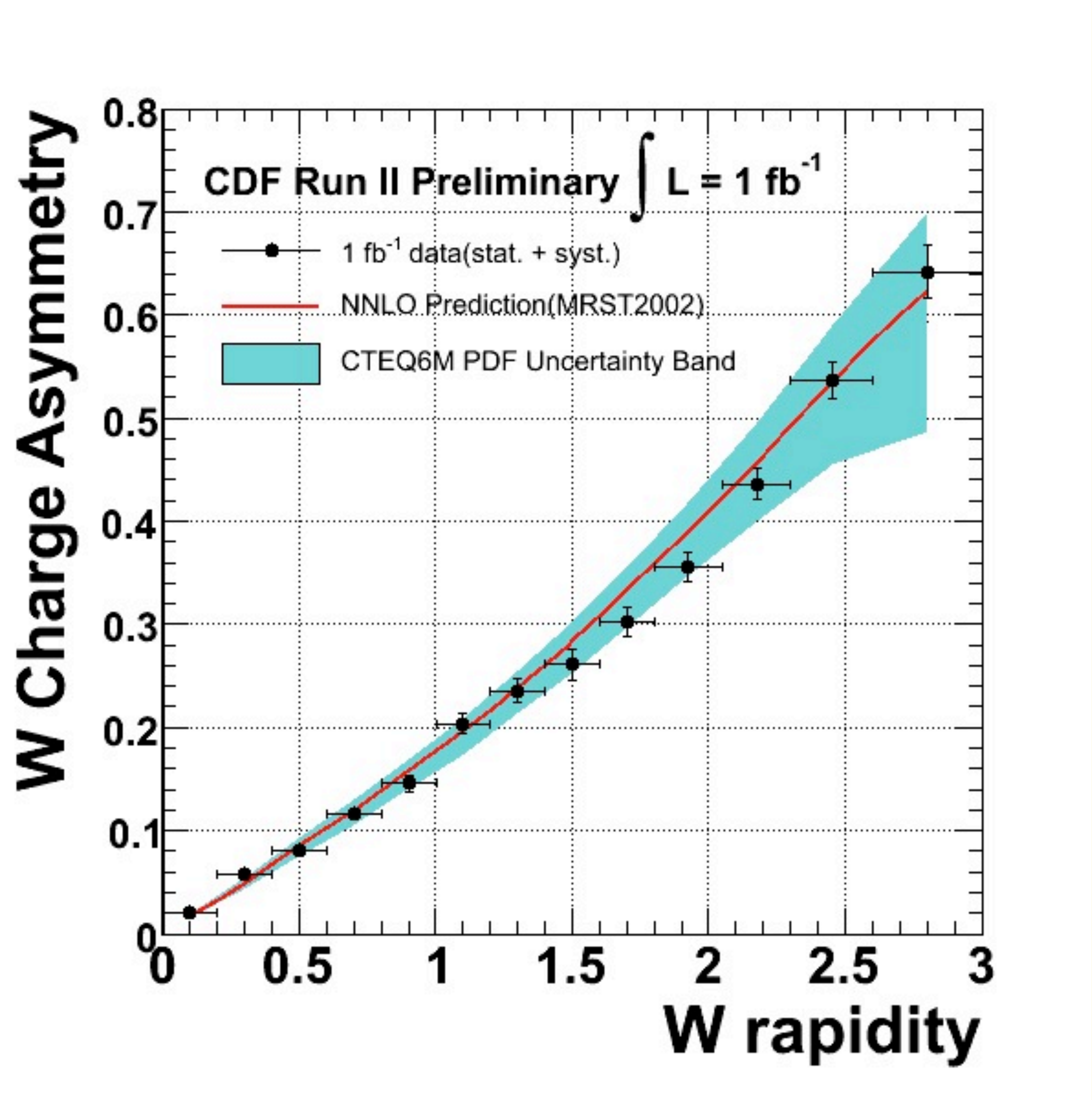
$$\frac{d\sigma_{W^+}}{dy} \propto f_u^p(x_1)\ f_{\bar{d}}^{\bar{p}}(x_2) + f_{\bar{d}}^p(x_1) f_u^{\bar{p}}(x_2)$$

$$\frac{d\sigma_{W^-}}{dy} \propto f_{\bar{u}}^p(x_1)\ f_d^{\bar{p}}(x_2) + f_d^p(x_1) f_{\bar{u}}^{\bar{p}}(x_2)$$

(Assuming dominance of valence contributions)

$$f_d(x) = f_u(x)\ R(x)$$

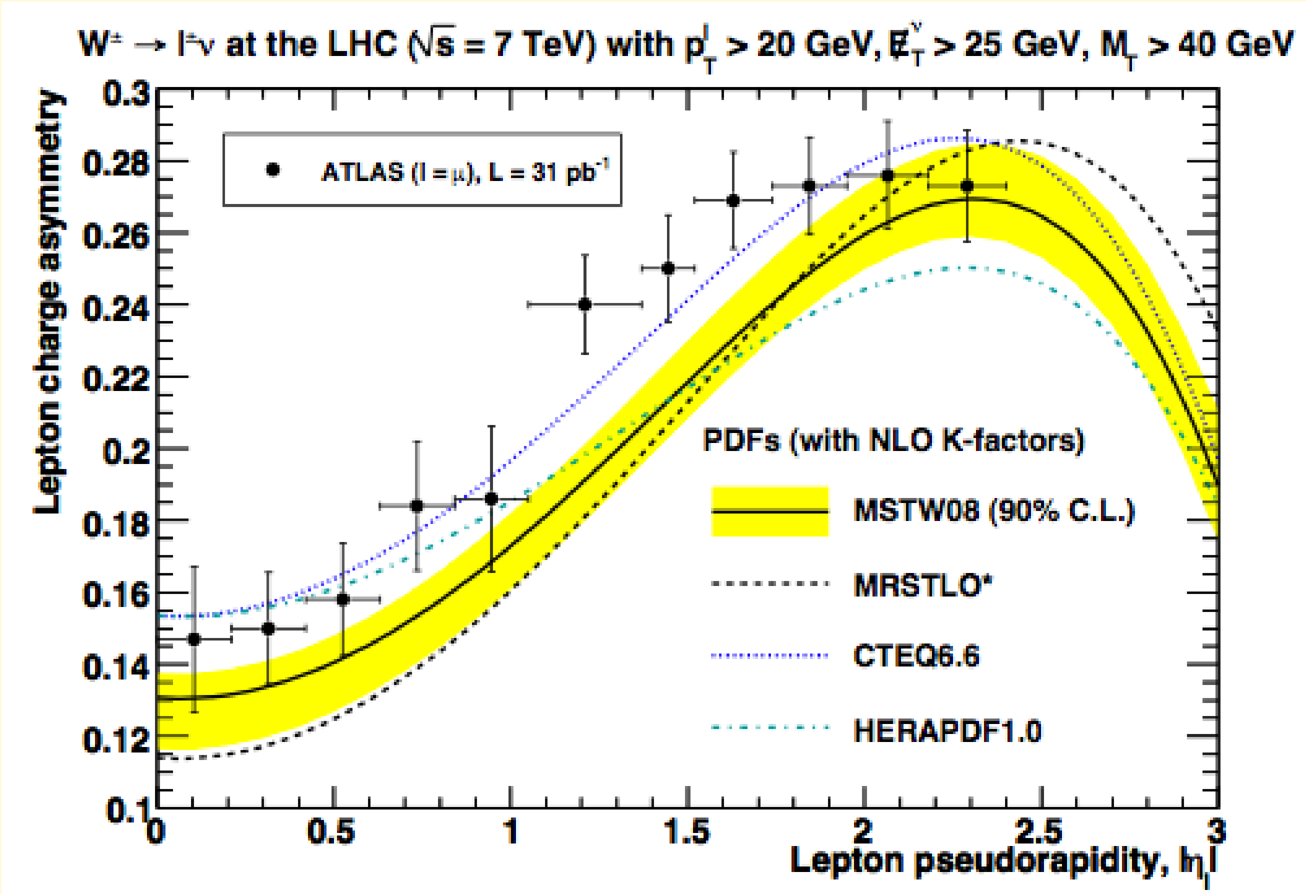
$$A(y) = \frac{\frac{d\sigma_{W^+}}{dy} - \frac{d\sigma_{W^-}}{dy}}{\frac{d\sigma_{W^+}}{dy} + \frac{d\sigma_{W^-}}{dy}} = \frac{f_u^p(x_1)\ f_d^p(x_2) - f_d^p(x_1)\ f_u^p(x_2)}{f_u^p(x_1)\ f_d^p(x_2) + f_d^p(x_1)\ f_u^p(x_2)} = \frac{R(x_2) - R(x_1)}{R(x_2) + R(x_1)}$$

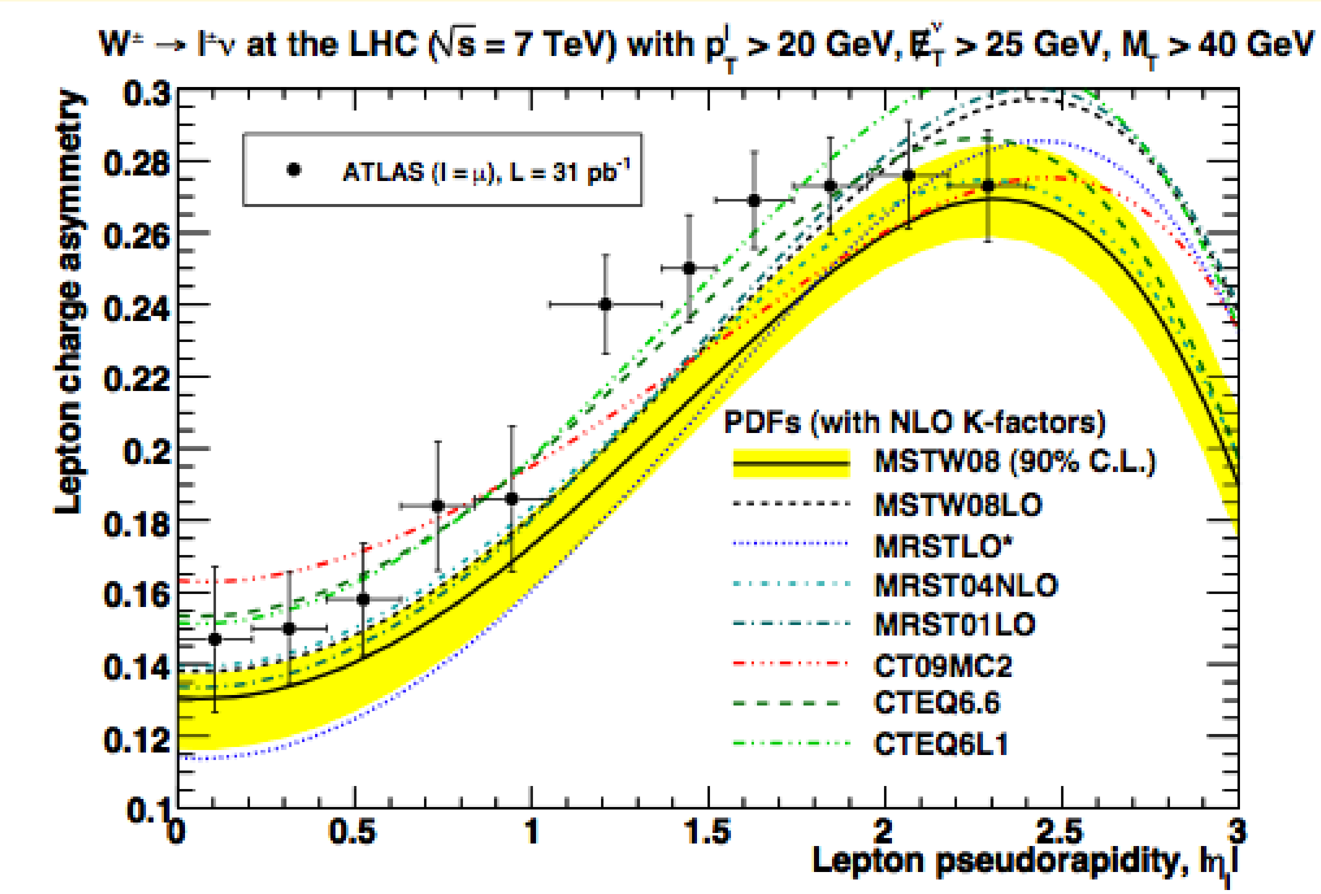


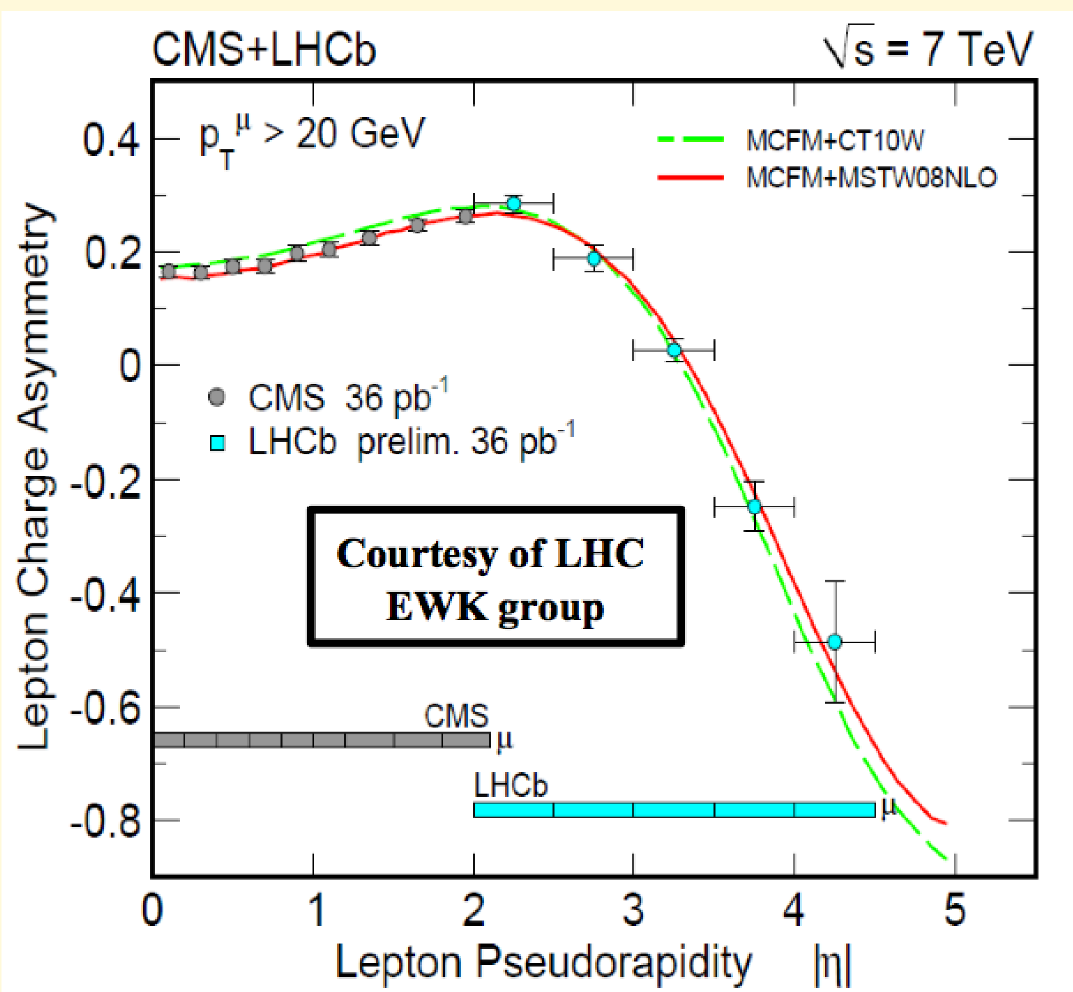
Run II comparison of W charge asymmetry with current PDF parameterizations

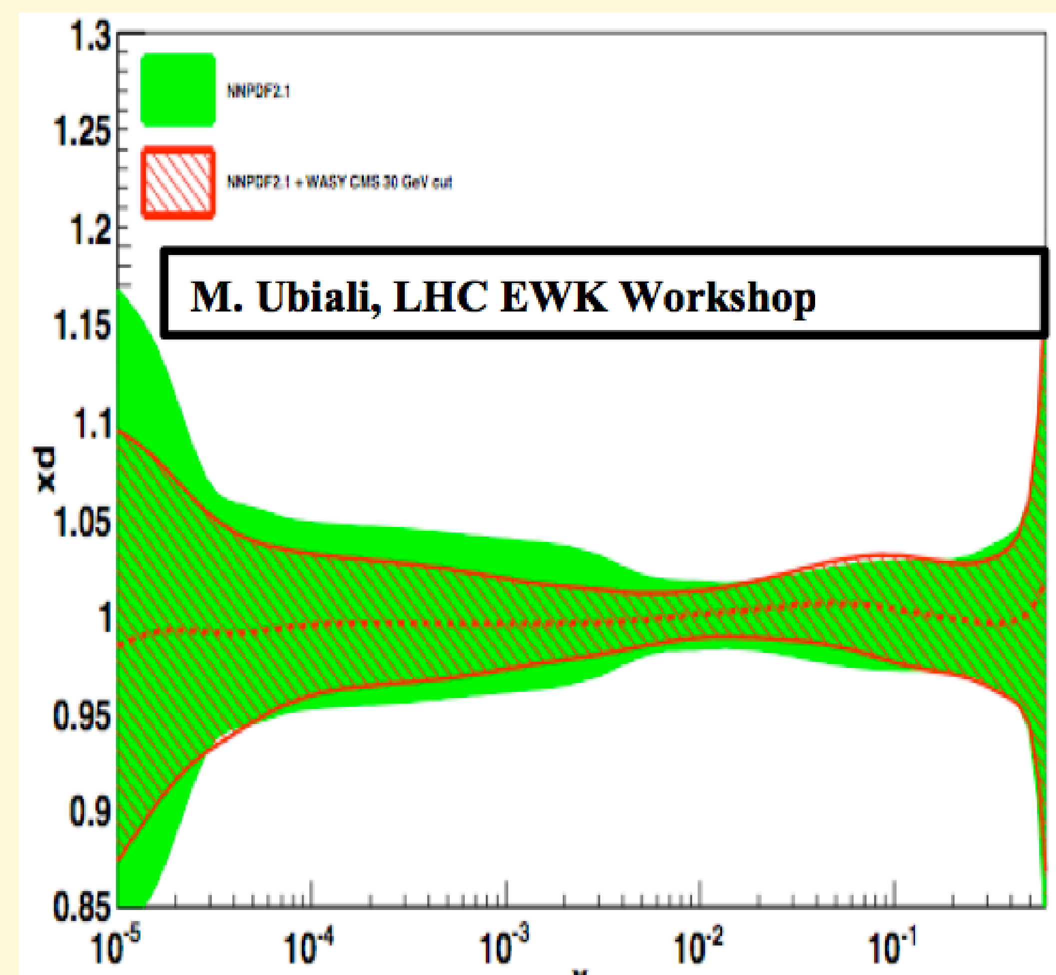
Lepton charge asymmetry in W production

G.Watt, http://arXiv.org/pdf/1106.5788









A personal top-list of CDF achievements

1. Top discovery and m_{top}
2. B_S oscillations
3. m_W
4. CPV in $B \to \psi K_S$
5. ... and much much more:
    1. BSM and Higgs limits
    2. QCD dynamics

What's missing?

1. Higgs
2. $B_S \to \mu^+ \mu^-$