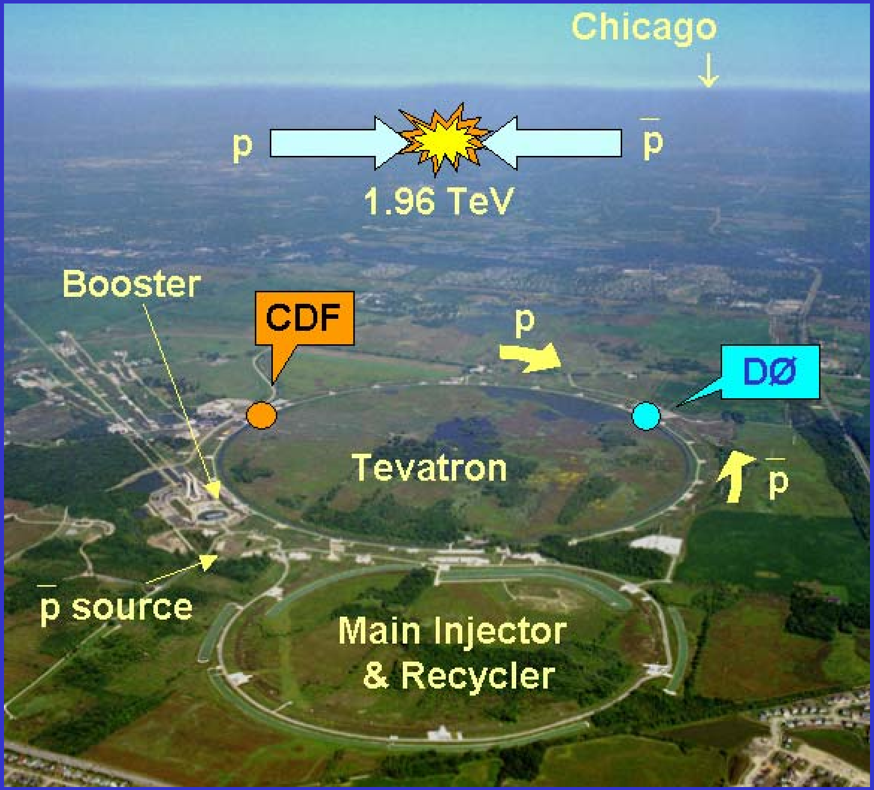
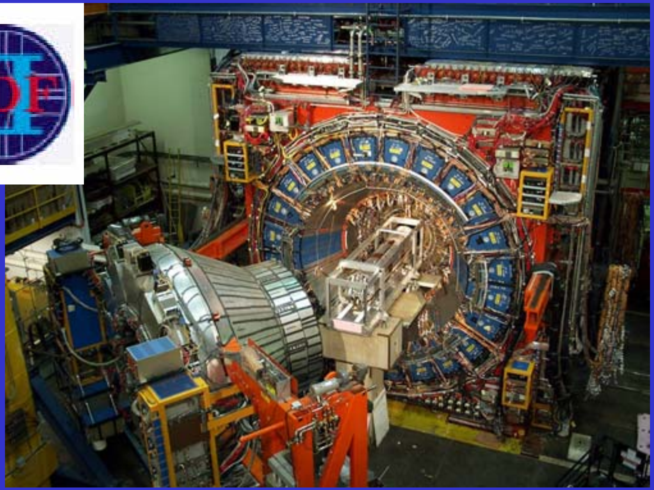
Top and Electroweak Physics at the Tevatron





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University of Kansas

for the CDF and DØ Collaborations

April APS 2008, St. Louis, MO. April 12th 2008

Outline

- **Introduction**
- **Top Physics**
  - Overview
  - Cross-section
  - **Top Mass**

(see E. Brubaker talk for single-top)

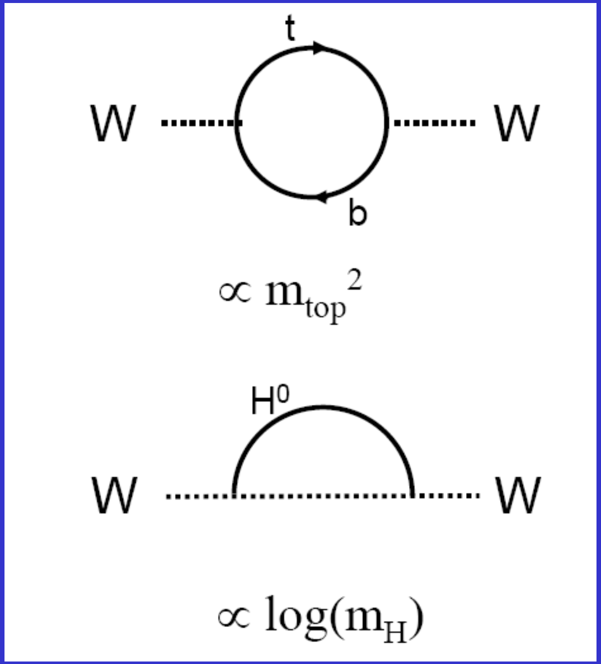
- **Electroweak Physics**
  - W's and Z's at hadron colliders
  - **W Mass**
  - Di-Bosons

(see B. Winer talk for direct Higgs search)

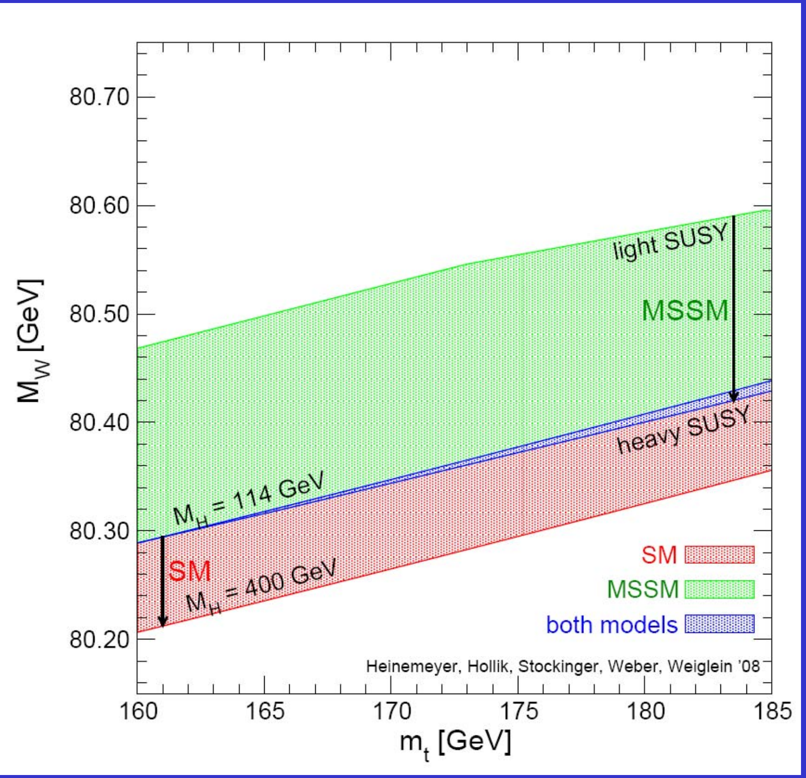
- **Higgs Constraints**
- **Summary**

m_t and $m_W \rightarrow m_{Higgs}$

Heavy particles talk to each other through virtual particle loops



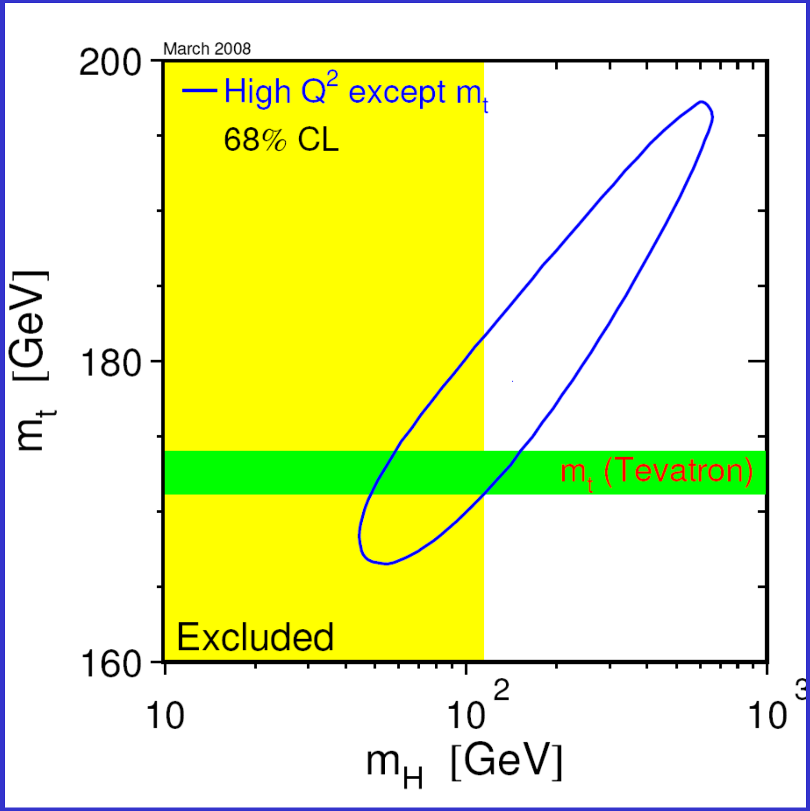
+ similar diagrams for Z, t

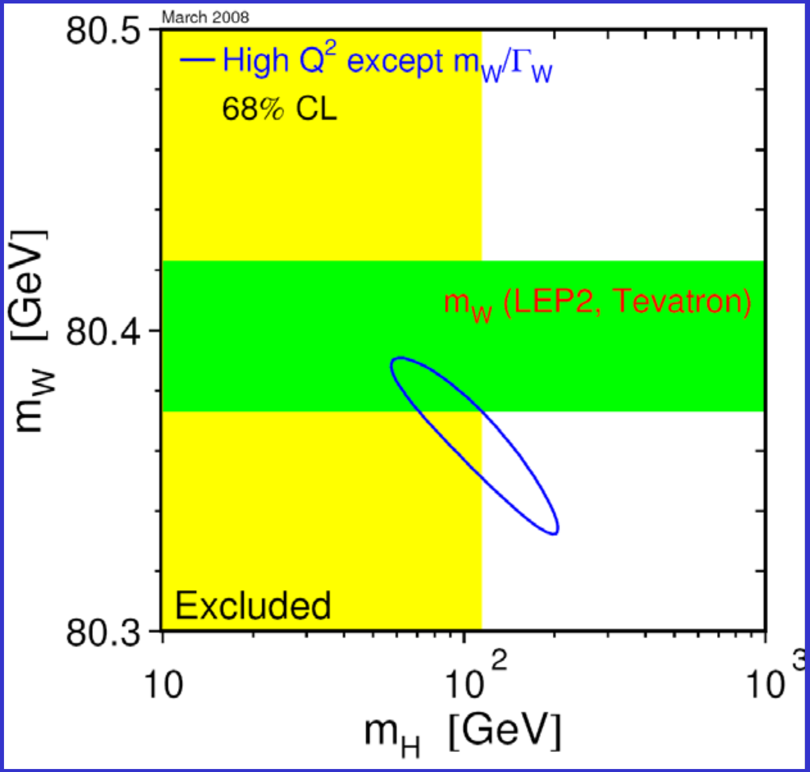


Well-defined predictions for the inter-relationships in both the Standard Model and BSM

Direct determination of m_t, m_W

LEP/SLD/Tevatron measurements
consistent with blue ellipses

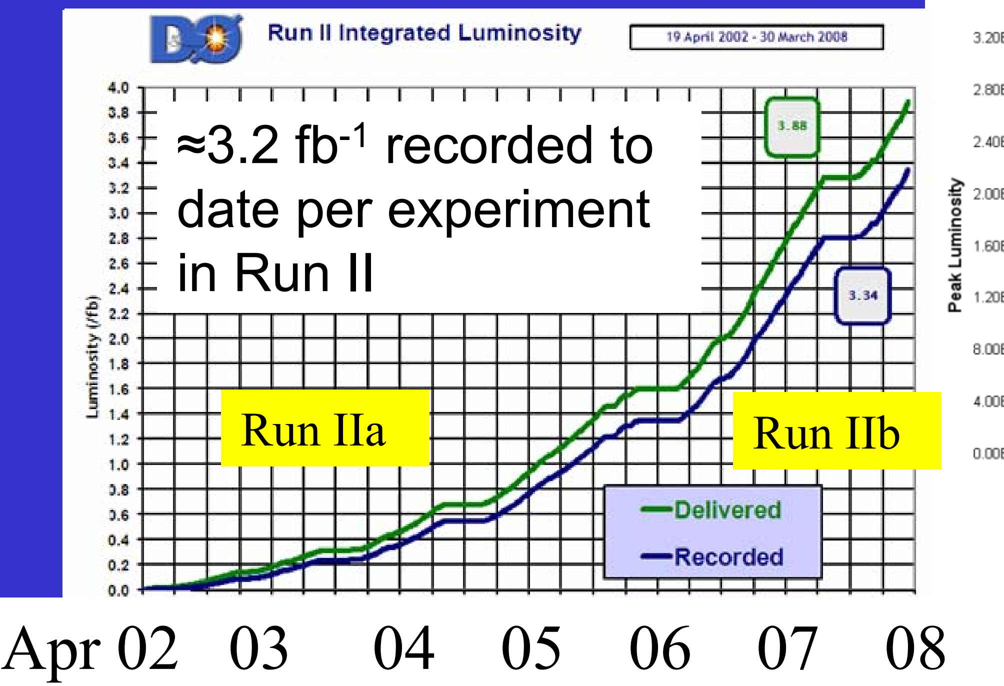


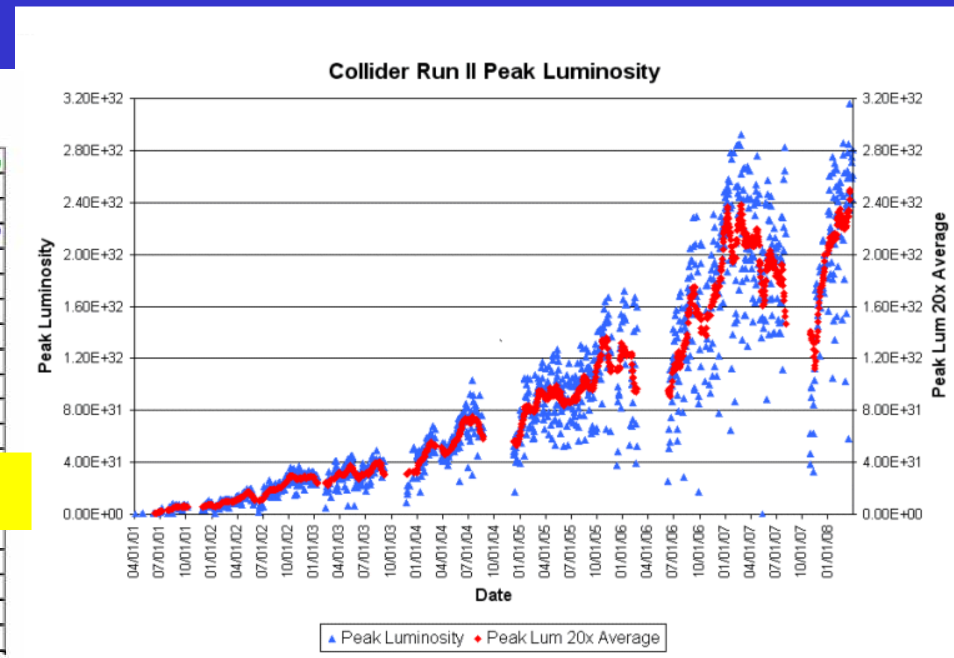


Direct measurements of m_t and m_W improve considerably over indirect measurements and favor light Higgs

Further improvement in m_t and especially m_W is important for testing m_H

Tevatron Luminosity





(RunI data-set: 0.1 fb^{-1} t-quark discovery)

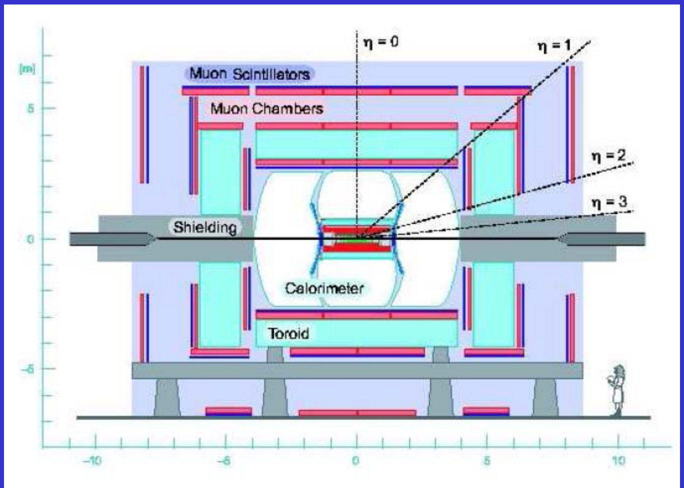
RunIIa data-set: 1.0 fb^{-1}

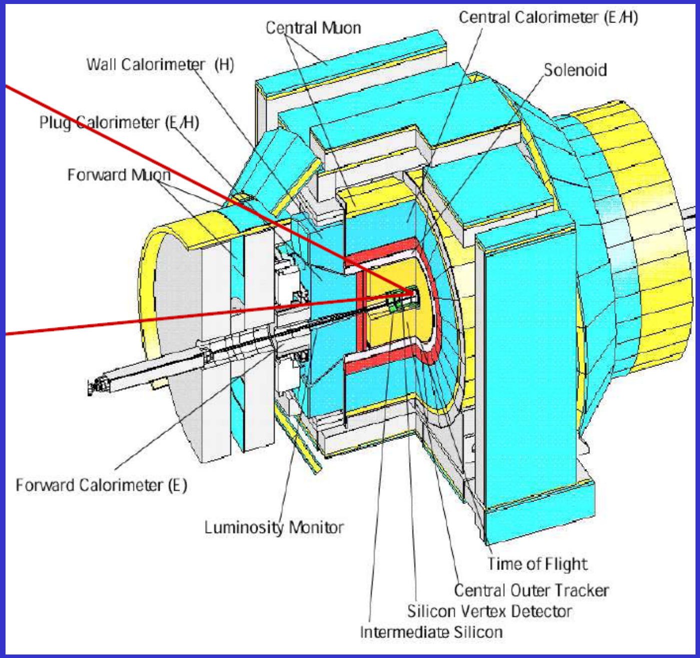
Analyzed RunII data-set: up to 2.8 fb^{-1}

Recent all-time records:
peak luminosity of 3.2×10^{32} $cm^{-2}s^{-1}$,
50 pb^{-1}/week

On track to collect 8 fb^{-1} through 2010

Detectors





D∅: calorimetry and μ coverage

- 2T Solenoid
- tracker to R = 52 cm
- RunIIb: Layer 0 Silicon. Upgrades to trigger

CDF: general purpose

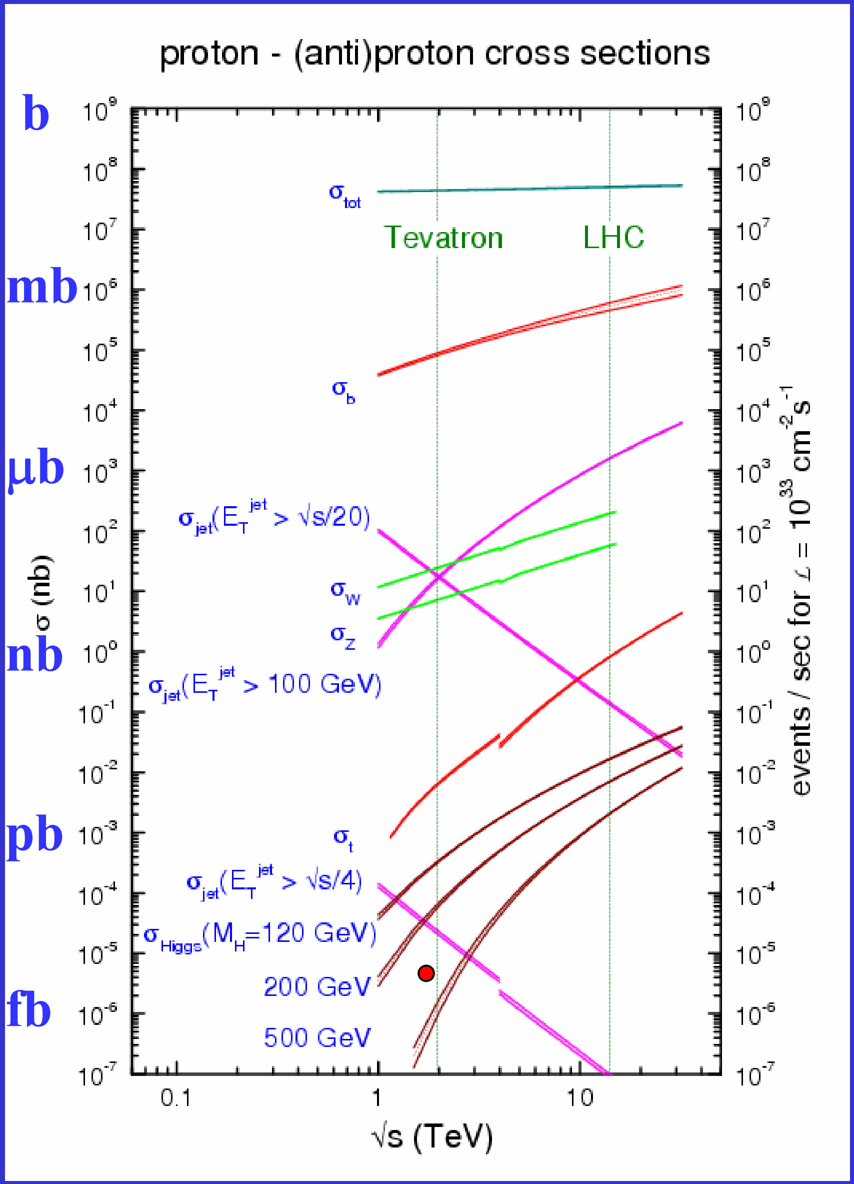
- 1.4T Solenoid
- High precision tracker (R = 1.4m)

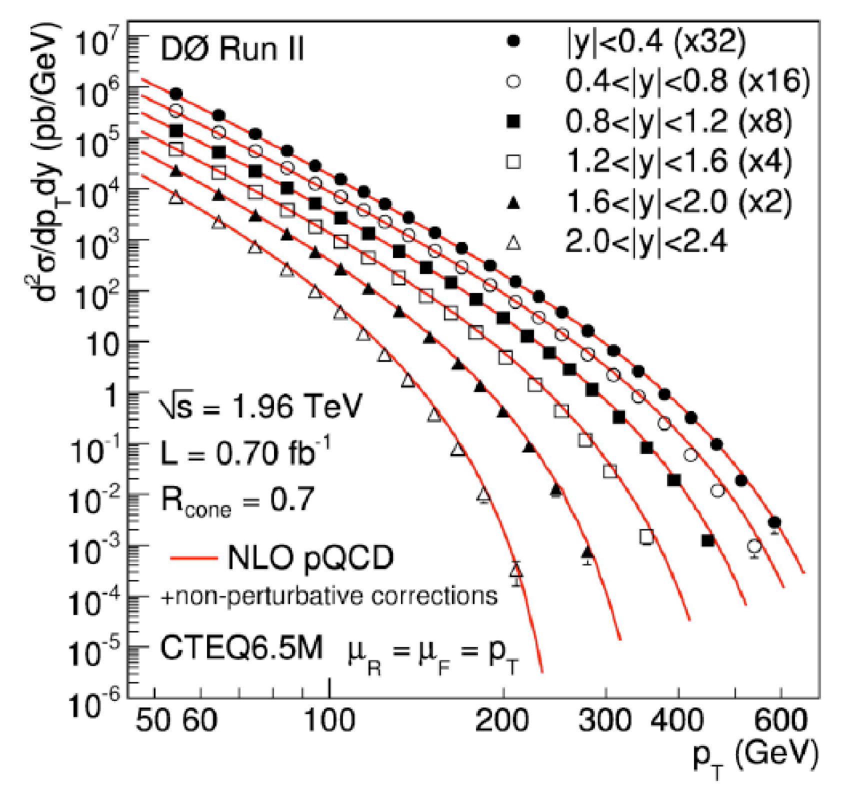
Both detectors have Si VTX detectors optimized for b-tagging

Tevatron: 1.7 MHz BX frequency

$\langle n_{int} \rangle$ on average ≈ 3 (store start ≈ 10)

Hadron Collider Physics



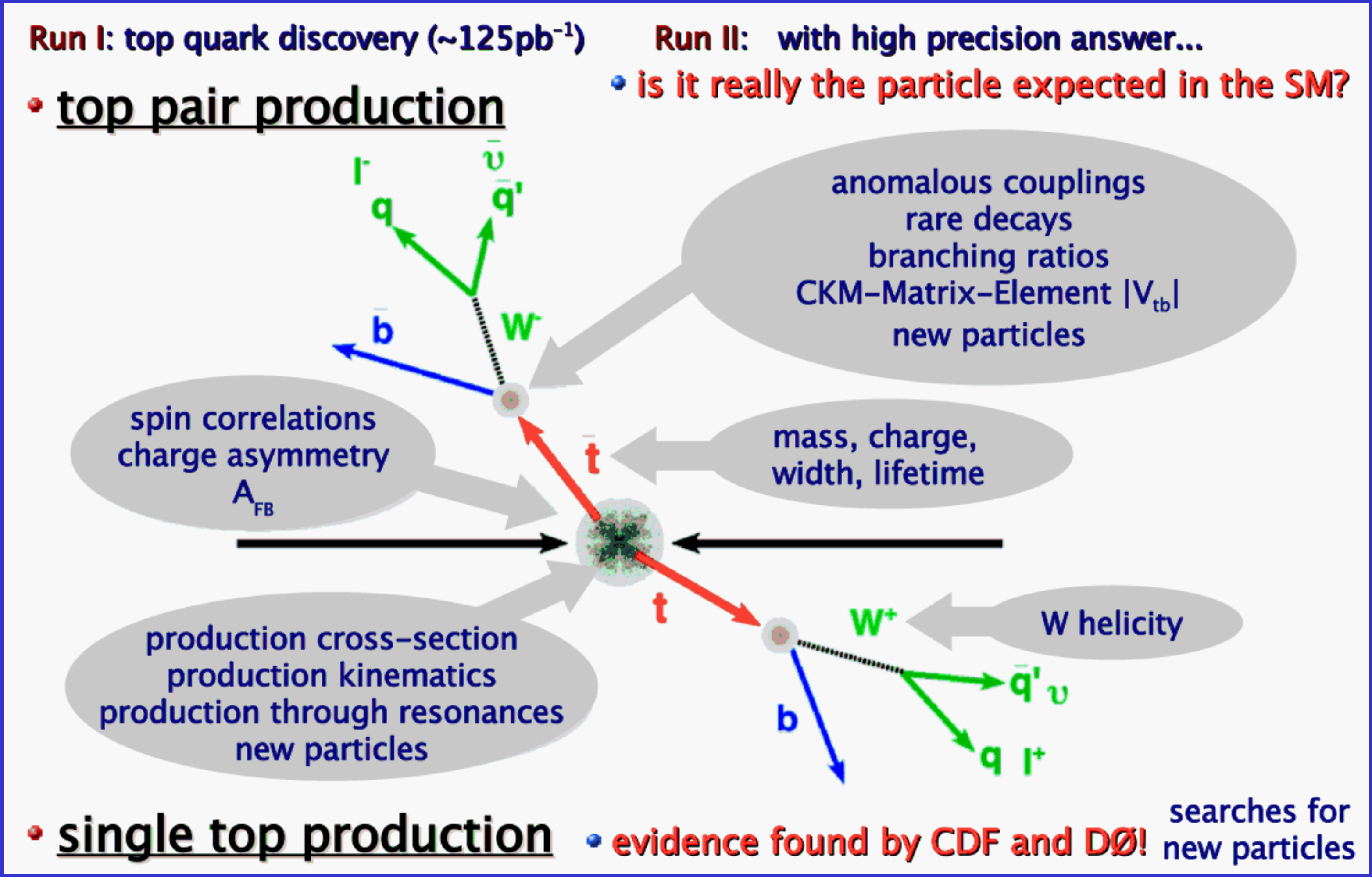


Physics program depends on being able to reconstruct jets reliably and requiring leptons to reduce QCD bkgds ($\sigma.B < \sigma$). Control lepton-id and trigger efficiencies using $Z \rightarrow l\,l$ samples.

All measured cross-sections have 6% normalization uncertainty

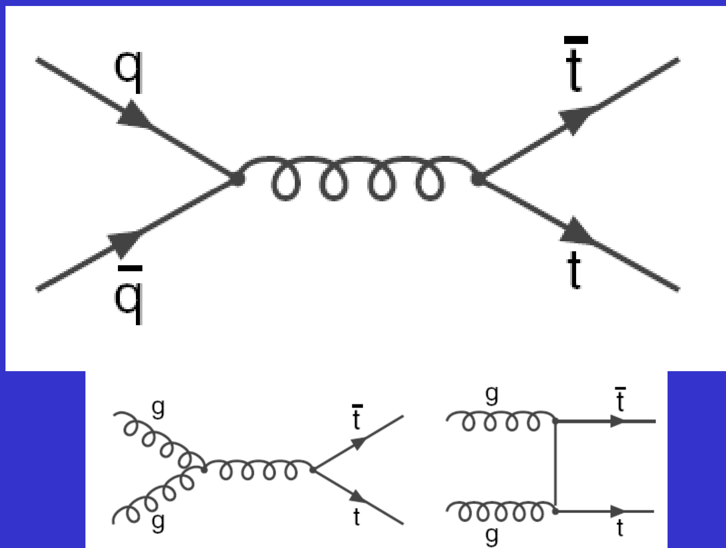
Top Over-view

Rich and unique system

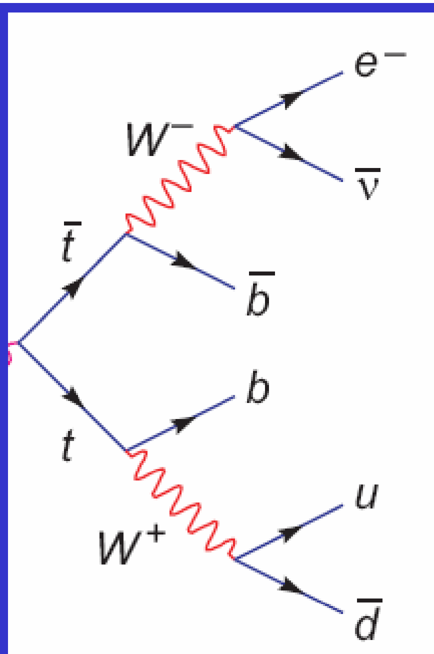


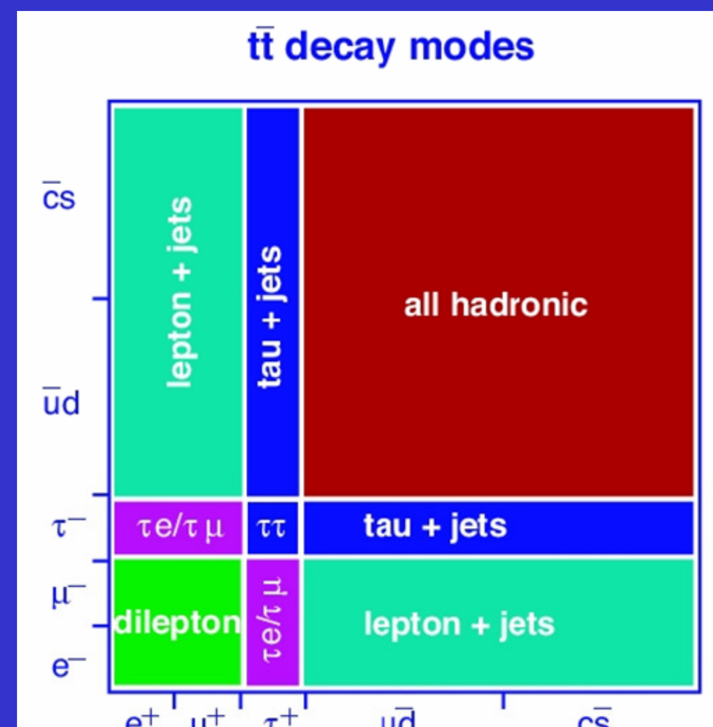
Many physics analyses. See 3 TOP parallel sessions (J12, M12, X11)

Top Pair Production & Decay

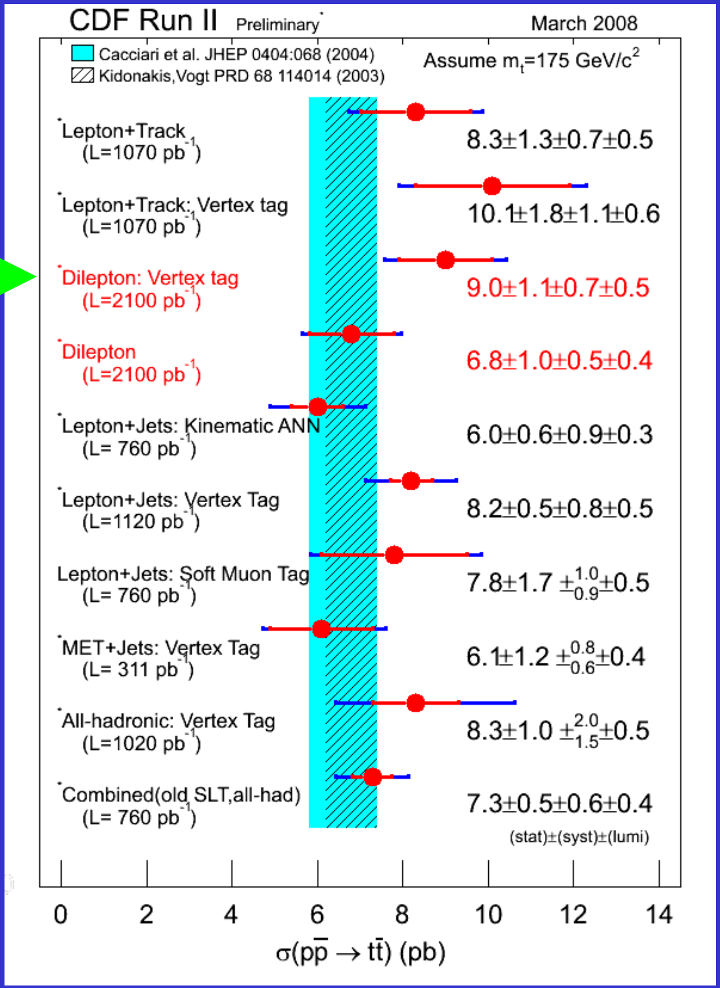


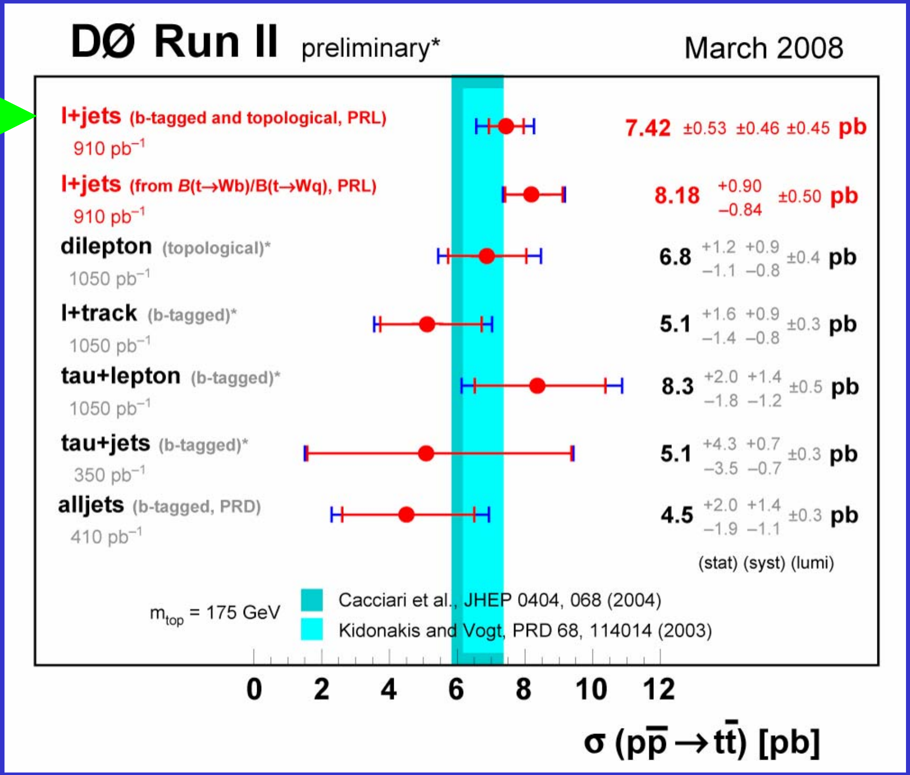
$|V_{tb}| = 0.9991$ in 3 gen unitary CKM matrix.
So expect BR($t \rightarrow W\, b$) ≈ 1.
Decay channels are defined by known W BRs.





Top Cross-Section



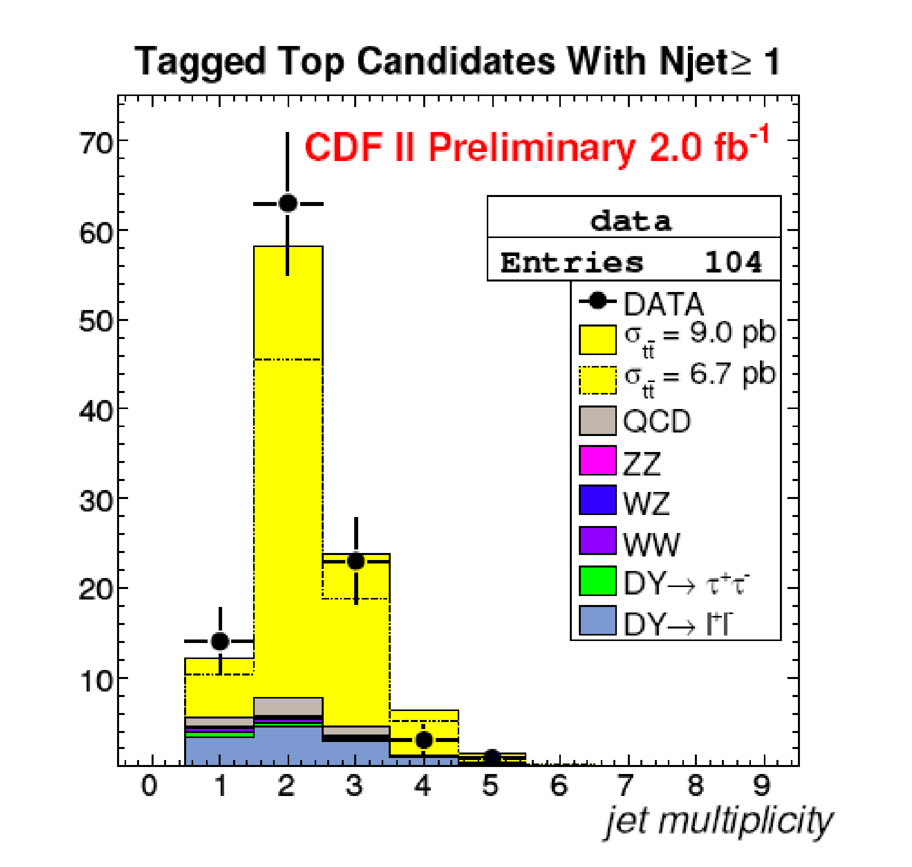


Measurements in many channels with different techniques by both experiments

Top Cross-Section

$$t\bar{t} \rightarrow \bar{b}\ell^{-}\overline{\nu}_{\ell}b\ell'^{+}\nu'_{\ell}$$

New di-lepton measurement with secondary vertex tag:

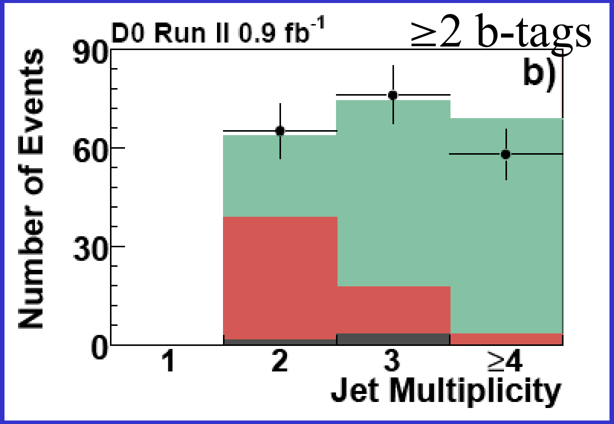


σ_{tt} = 9.0±1.1(stat.)±0.7(syst.)±0.5(lumi.) pb

Top Cross-Section

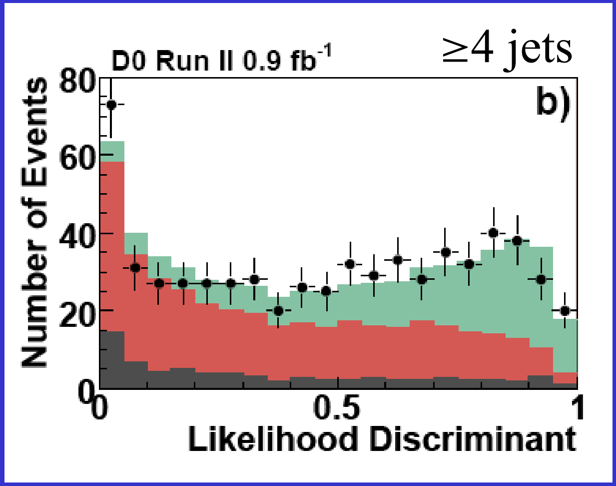
Lepton + jets

b-tag



8.05 ± 0.54 ± 0.70 ± 0.49 pb

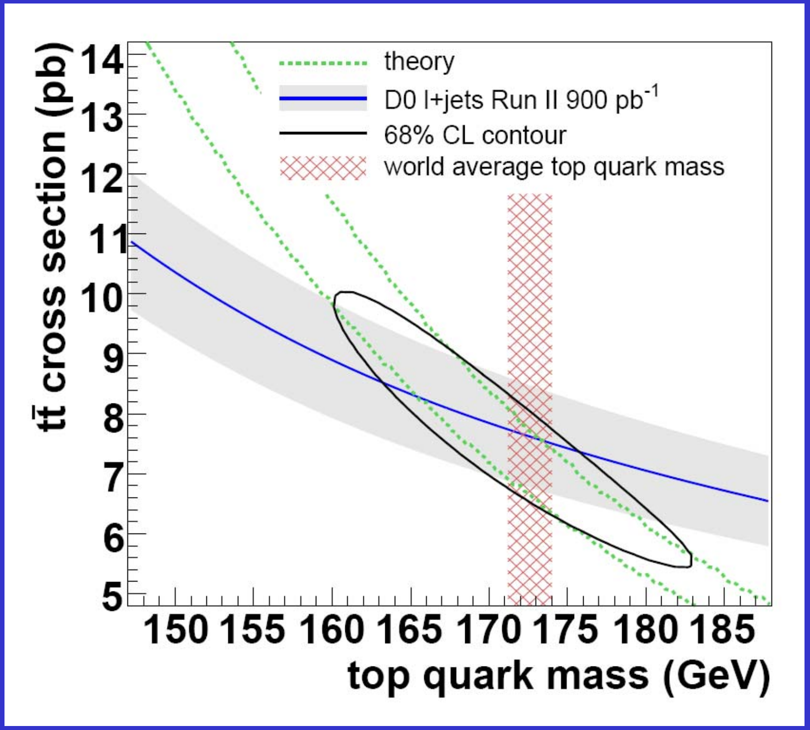
Kinematic likelihood



6.62 ± 0.78 ± 0.36 ± 0.40 pb

Combined result (m_t=175 GeV):

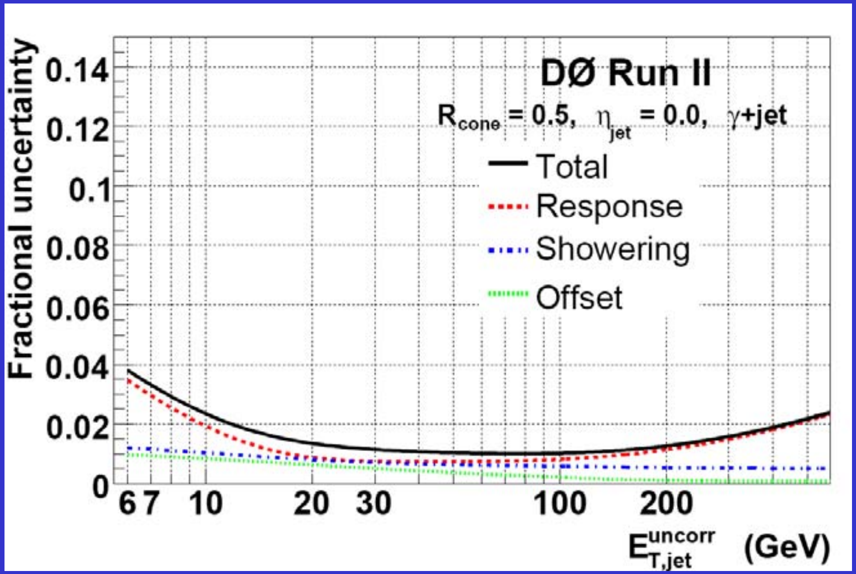
7.42 ± 0.53 ± 0.46 ± 0.45 pb
stat. syst. lumi



Infer, m_t = 170 ± 7 GeV

Top Mass

Critical to understand the jet energy scale (JES)



Years of careful work by CDF and D∅

Many measurements in progress.

Different channels, different techniques, different experiments.

Much attention to understanding statistical and systematic correlations amongst analyses so that they can be combined

Have selected the 3 most precise analyses which currently enter the Tevatron top mass combination. All are 2 fb^{-1} RunII measurements

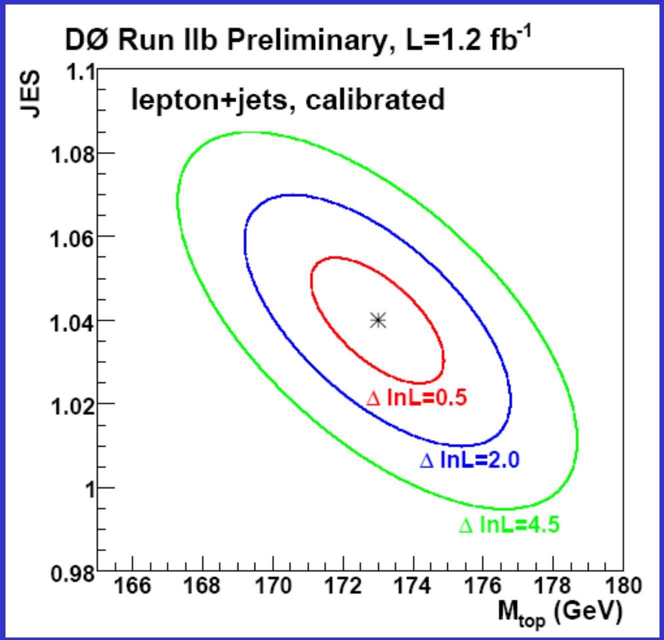
D∅ l+jets,
CDF l+jets
CDF di-lepton

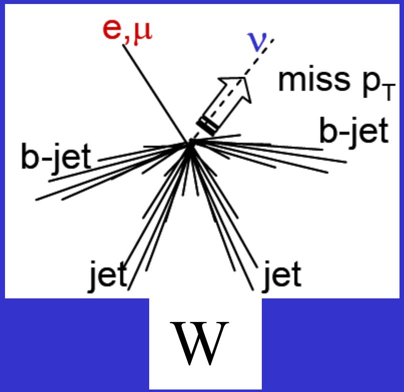
Lepton+jets

Matrix element method first applied in Nature 429 (2004) 638

PRD74 (2006) 092005 for more details

$$P_{sig}(x; m_{\text{top}}, JES) = \frac{1}{\sigma_{\text{obs}}(p\bar{p} \to t\bar{t}; m_{\text{top}}, JES)} \times \sum_{\text{perm}} w_i \int_{q_1,q_2,y} \sum_{\text{flavors}} dq_1 dq_2 f(q_1) f(q_2) \frac{(2\pi)^4 \left|\mathcal{M}(q\bar{q} \to t\bar{t} \to y)\right|^2}{2 q_1 q_2 s} d\Phi_6 W(x, y; JES)$$





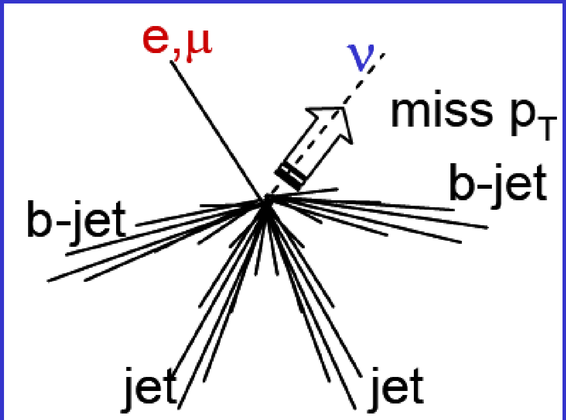
Use m_W constraint for $W \to jj$ in the l+jets ttbar event for *in situ* JES calibration

Most precise to date

2.1 fb^{-1} combined result:

$m_t = 172.2 \pm 1.1(\text{stat}) \pm 1.6\ (\text{syst})$ GeV

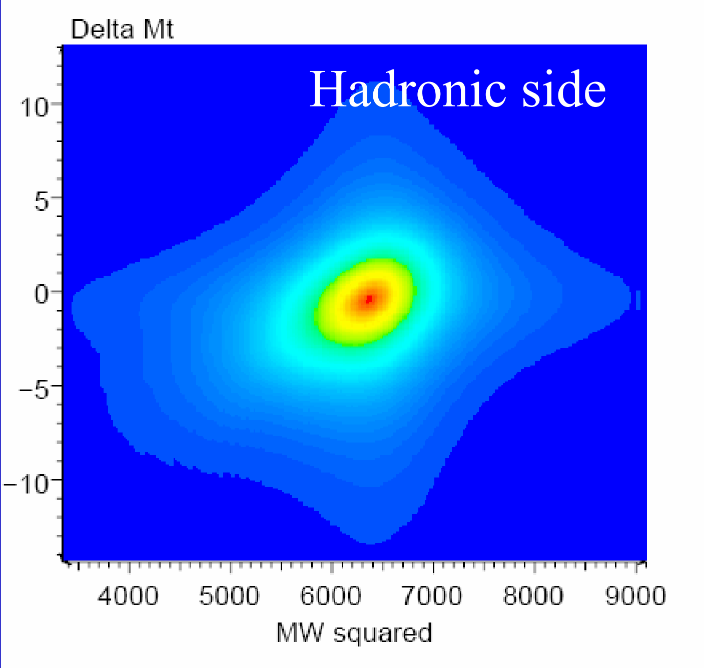
Lepton+jets

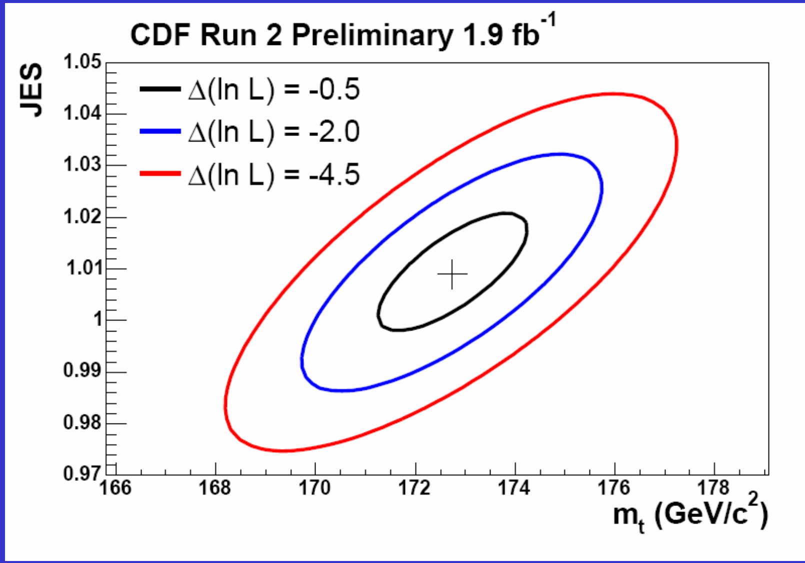


Modified matrix element method

$$L = \frac{1}{N(m_t)} \frac{1}{A(m_t, \mathrm{JES})} \sum_{i=1}^{24} w_i \int \frac{f(z_1) f(z_2)}{FF} \, \mathrm{TF}(\vec{y} \cdot \mathrm{JES} \mid \vec{x}) \, |M_{\mathrm{eff}}(m_t, \vec{x})|^2 \, d\Phi(\vec{x})$$

Integrate over the expected distributions in m_t^2, m_W^2 adjusting for simplifying assumptions which alter original BW form.





$m_t = 172.7 \pm 1.2(\mathrm{stat}) \pm 1.3\ (\mathrm{JES}) \pm 1.2\ (\mathrm{syst})$ GeV

(very recently updated CDF result will be shown in parallel session)

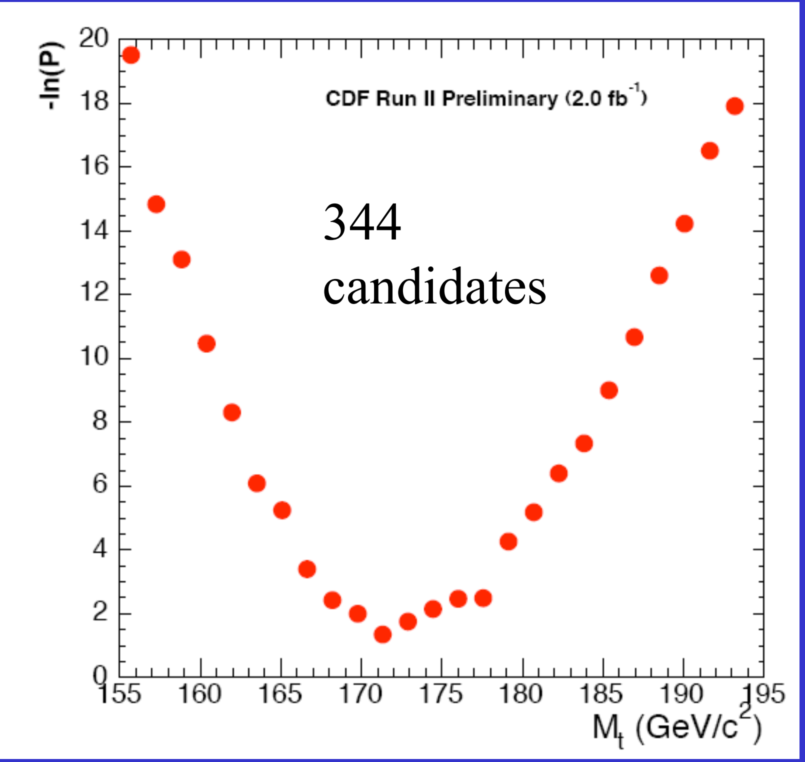
Di-leptons

$$t\bar{t} \longrightarrow \bar{b}\ell^-\bar{\nu}_\ell b\ell'^+\nu'_\ell$$

$$P(\mathbf{x}|M_t) = \frac{1}{N}\int d\Phi_8 |\mathcal{M}_{t\bar{t}}(p;M_t)|^2 \prod_{jets} W(p,j) f_{PDF}(q_1) f_{PDF}(q_2)$$

- Event selection with evolutionary neural network with 6 input variables optimized for mass resolution.
- Use t tbar production matrix element, jet-parton transfer functions and PDFs.
- Maximize posterior probability density
- Main systematic:

  Jet Energy Scale (2.5 GeV)



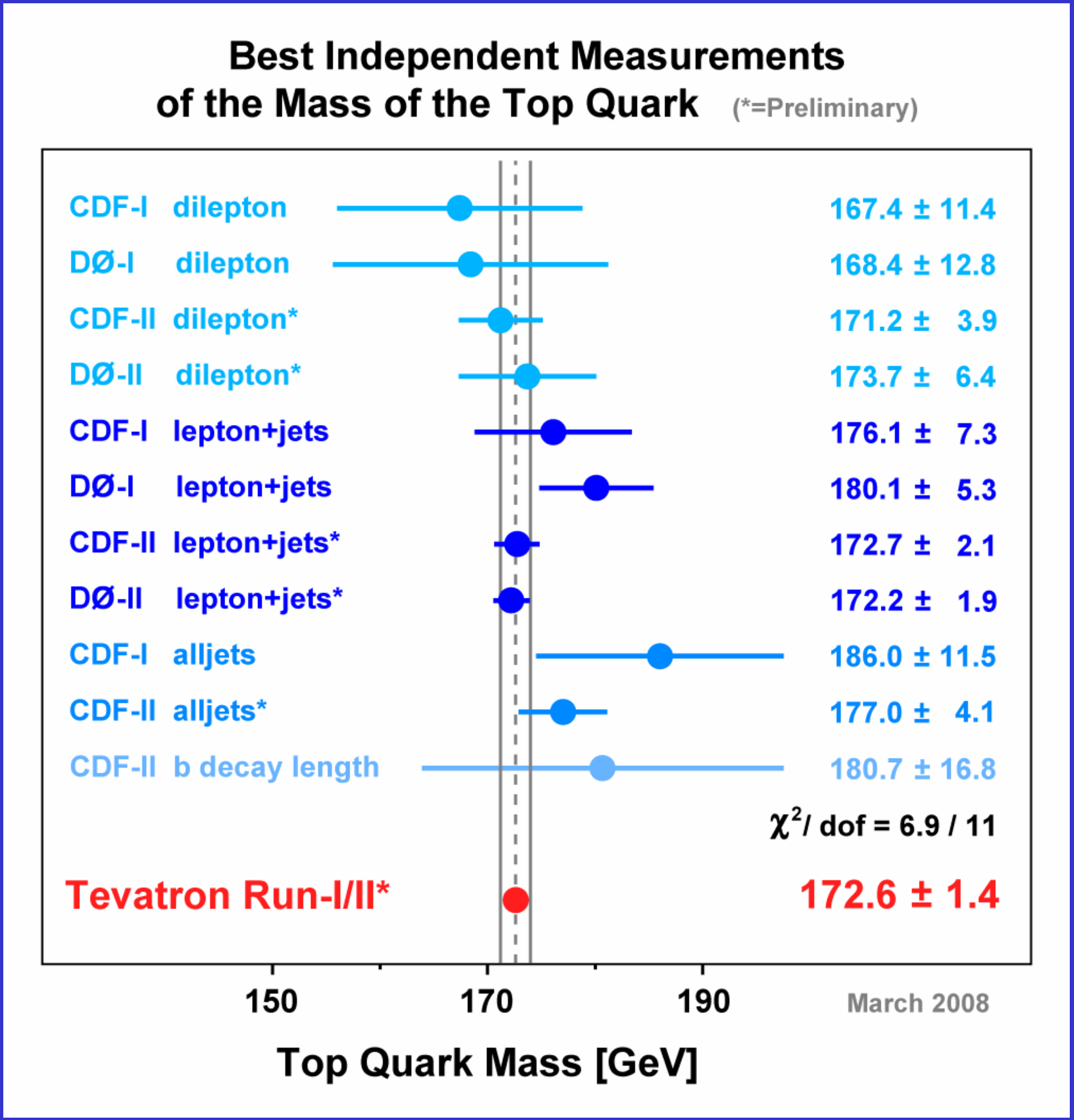
$m_t = 171.2 \pm 2.7 \pm 2.9$ GeV

Top Mass Uncertainties

Run II Measurement	CDF di-l	D0 di-l	CDF l+j	D0 l+j	CDF all-j	CDF lxy	world average
∫Ldt (fb^{-1})	2.0	1.1	1.9	2.1	1.9	0.7	
Result	171.2	173.7	172.7	172.2	177.0	180.7	172.6
Jet Energy Scale	2.5	3.1	1.5	1.3	2.0	0.3	0.9
Signal	0.7	0.8	0.6	0.7	0.6	1.4	0.5
Background	0.4	0.6	0.6	0.4	1.0	7.2	0.4
Fit	0.6	0.9	0.2	0.1	0.6	4.2	0.1
MC	0.7	0.2	0.4	0.0	0.3	0.7	0.2
Systematic	2.8	3.4	1.7	1.6	2.4	8.5	1.1
Statistical	2.7	5.4	1.2	1.1	3.3	14.5	0.8
Total Uncertainty	3.9	6.4	2.1	1.9	4.1	16.8	1.4

Note: Dominant JES uncertainties scale with statistics in l+j, all-j channels

Top Mass Summary



169.8 ± 3.1 GeV

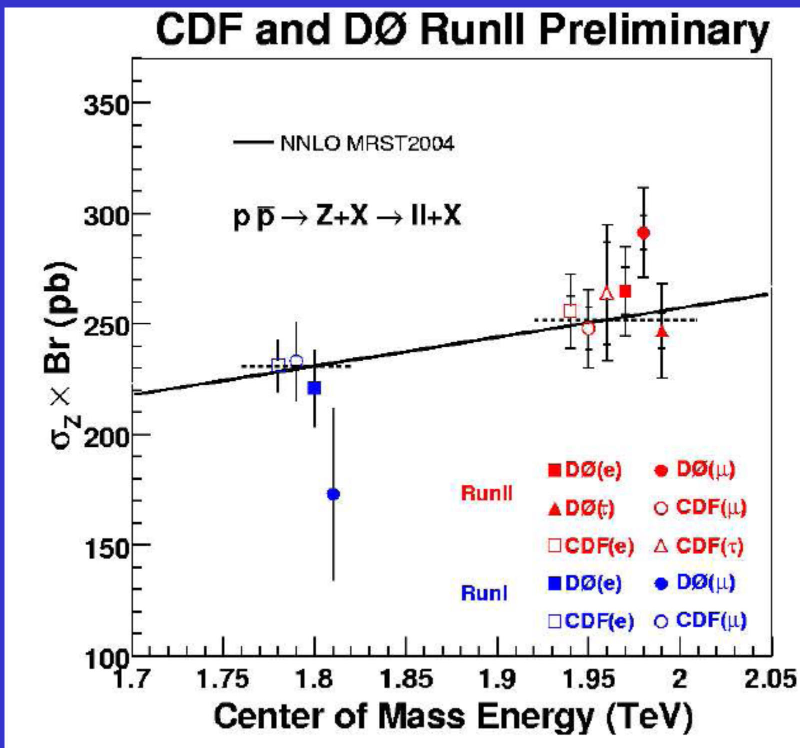
172.4 ± 1.5 GeV

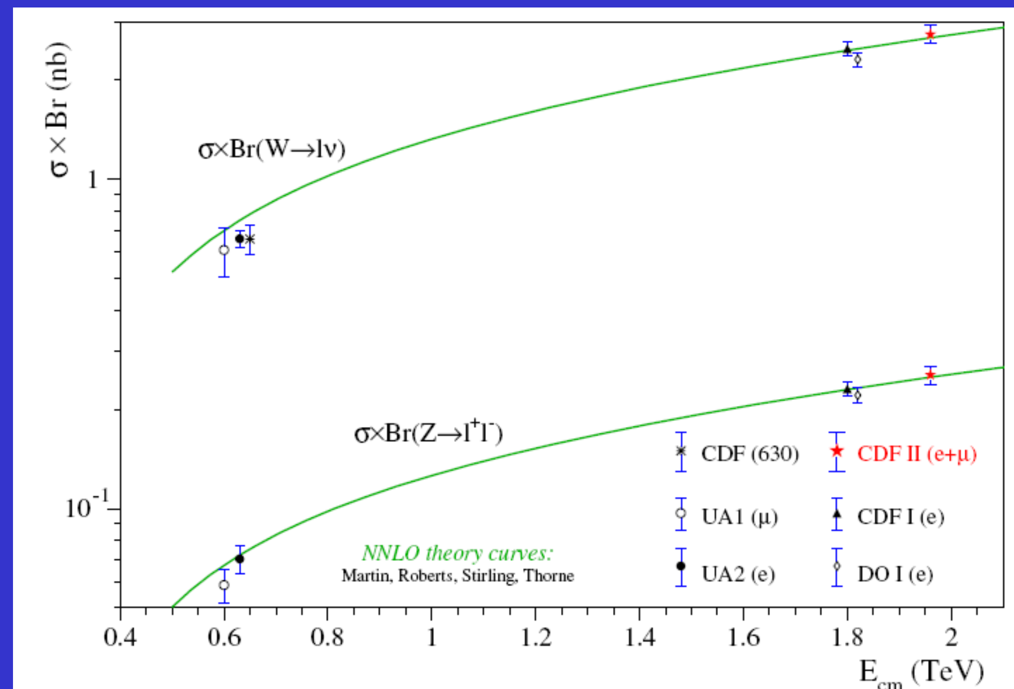
177.3 ± 3.9 GeV

0.8% uncertainty

$172.6 \pm 0.8 \pm 1.1$ GeV

W, Z Cross-Sections





CDF(e+μ): $\sigma_W . B = 2.749 \pm 0.010 \pm 0.053 \pm 0.165$ nb

stat. syst. lumi.

$\sigma_Z . B = 254.9 \pm 3.3 \pm 4.6 \pm 15.2$ pb

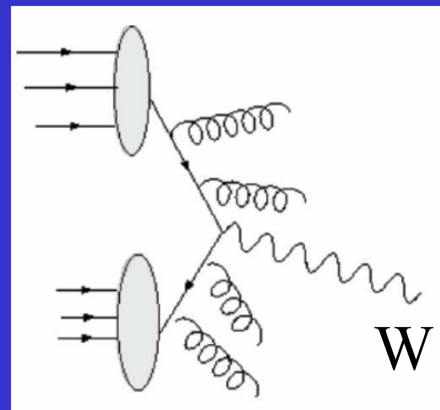
$R = 10.84 \pm 0.15 \pm 0.14$

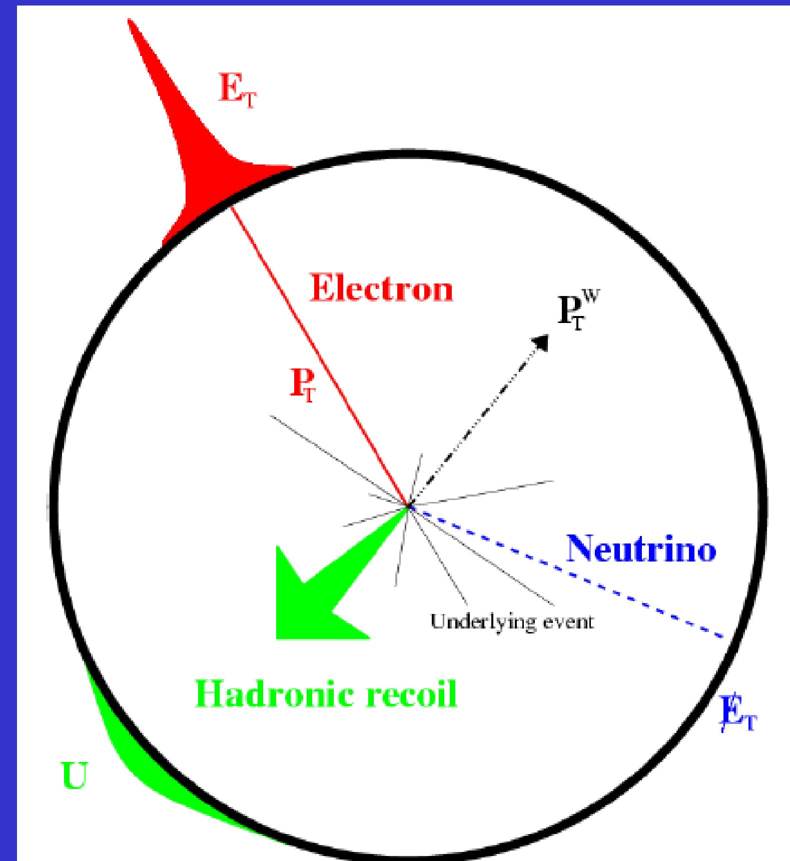
W, Z samples used extensively to understand detector and trigger efficiencies and investigate parton distribution functions and soft-gluon effects.

W mass measurement

Challenging measurement.
May not get any easier at LHC.

Goal around 0.3‰ precision.





+ additional hadronic interactions

Use leptonic decays.

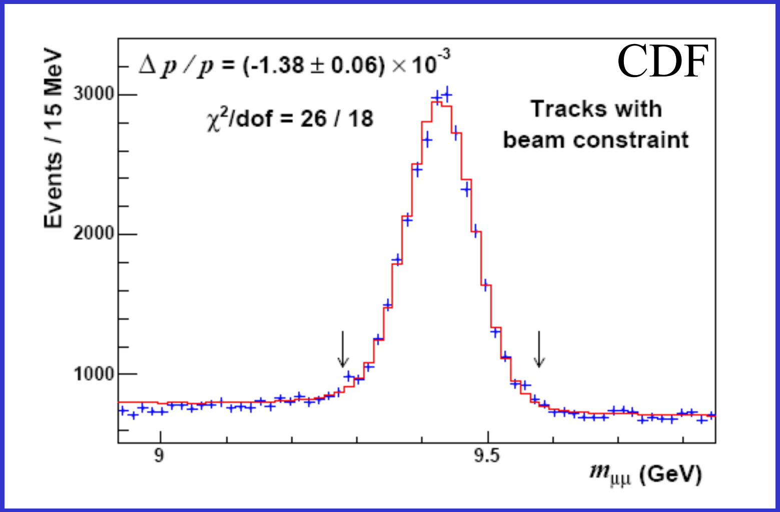
Longitudinal momentum fractions of initial partons not known event-by-event.
=> Work in transverse plane.

3 observables sensitive to m_W:
p_T(lepton), p_T(neutrino), m_T
where

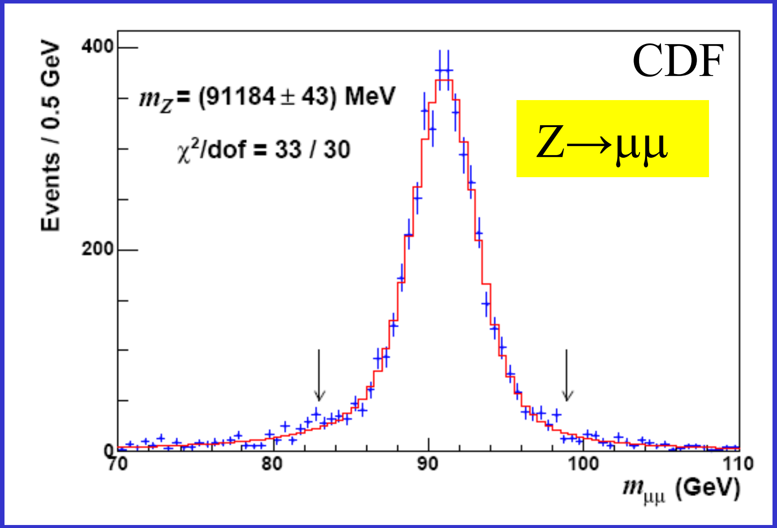
$$m_T = \sqrt{2 p_T^l \not{p}_T \, (1 - \cos \Delta\phi)}$$

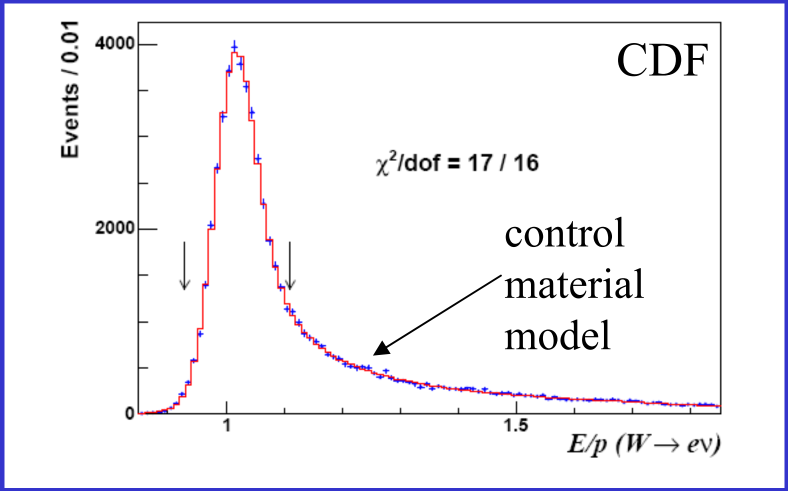
Need superb control of momentum and energy scales, and cross-checks on production, decay and recoil models

W mass measurement

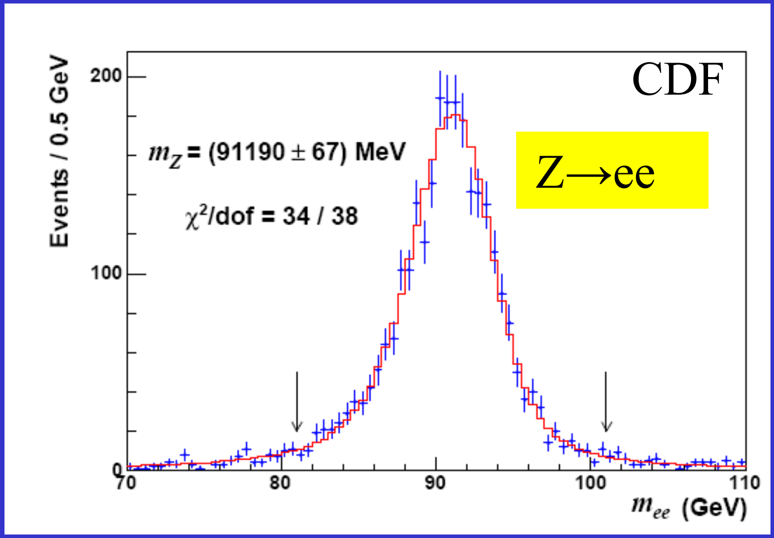


Calibrate p-scale of tracker with J/ψ and upsilon (ΔM_W = 17 MeV)



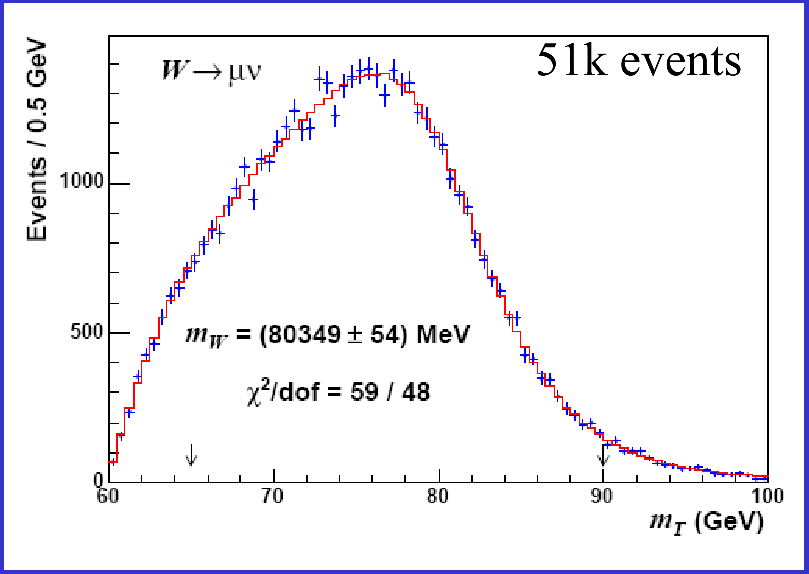


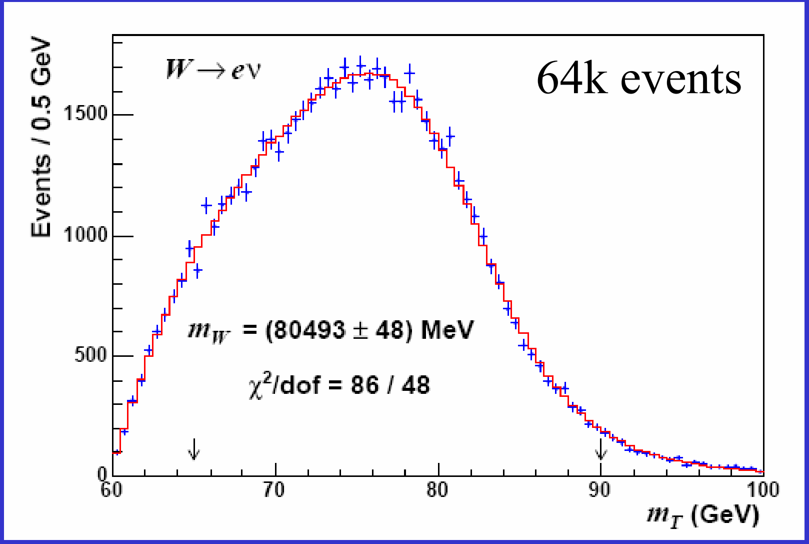
Transfer to calorimeter using E/p for electrons



Check scale and recoil modelling with Z samples

W mass measurement





CDF 0.2 fb^{-1}

m_T Fit Uncertainties

Source	$W \to \mu\nu$	$W \to e\nu$	Correlation
Tracker Momentum Scale	17	17	100%
Calorimeter Energy Scale	0	25	0%
Lepton Resolution	3	9	0%
Lepton Efficiency	1	3	0%
Lepton Tower Removal	5	8	100%
Recoil Scale	9	9	100%
Recoil Resolution	7	7	100%
Backgrounds	9	8	0%
PDFs	11	11	100%
W Boson p_T	3	3	100%
Photon Radiation	12	11	100%
Statistical	54	48	0%
Total	60	62	-

Many systematics scale with statistics

W Mass Result

0.2 fb^{-1} only

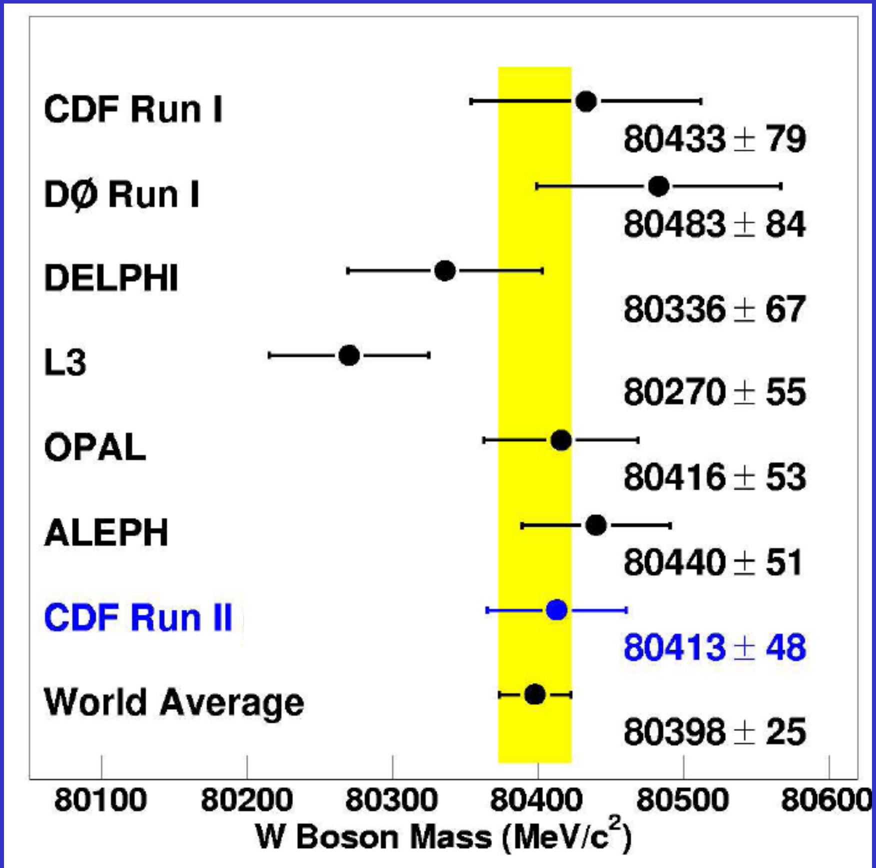
Distribution	m_W (GeV)	χ^2/dof
$m_T(e,\nu)$	$80.493 \pm 0.048 \pm 0.039$	$86/48$
$p_T(e)$	$80.451 \pm 0.058 \pm 0.045$	$63/62$
$\not{p}_T$ (e)	$80.473 \pm 0.057 \pm 0.054$	$63/62$
$m_T(\mu,\nu)$	$80.349 \pm 0.054 \pm 0.027$	$59/48$
$p_T(\mu)$	$80.321 \pm 0.066 \pm 0.040$	$72/62$
$\not{p}_T$ (μ)	$80.396 \pm 0.066 \pm 0.046$	$44/62$

CDF RunII Combined: $80.413 \pm 0.034 \pm 0.034$ GeV

CDF and D∅ results on 1-2 fb^{-1} data-sets in progress

W Mass Summary

0.2 fb^{-1} only



0.03% uncertainty

($1/26^{th}$ of $\delta m_t/m_t$)

CDF Run II Result is world's most precise single measurement

W Charge Asymmetry

PDF constraint unique to p pbar !

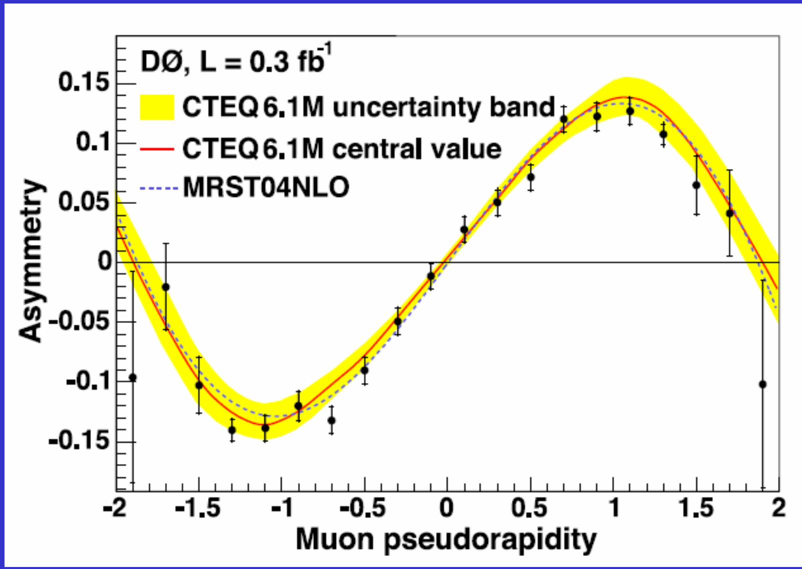
Measures tendency for u valence quarks to carry more fractional momentum than d valence quarks.

u dbar → W^+ follows p direction

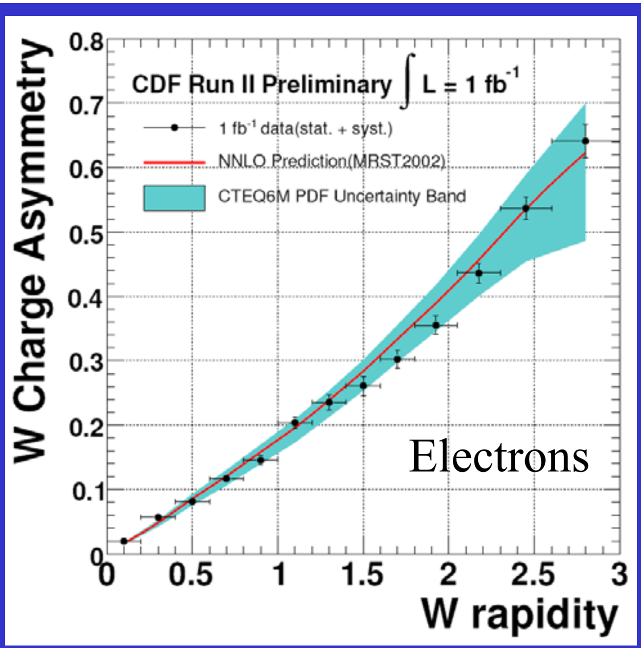
ubar d → W^- follows pbar

Defining η = -ln[tan(θ/2)]

$$A(\eta) = \frac{N_{\mu^+}(\eta) - k(\eta)N_{\mu^-}(\eta)}{N_{\mu^+}(\eta) + k(\eta)N_{\mu^-}(\eta)}$$



CDF: solve using m_W for the W rapidity (2 solutions)

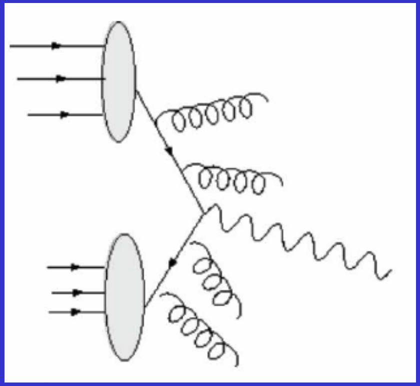


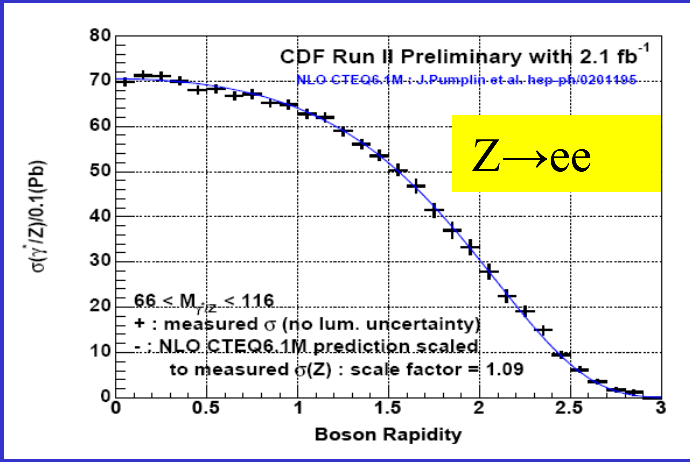
Statistics limited measurements with experimental uncertainties smaller than CTEQ uncertainty sets

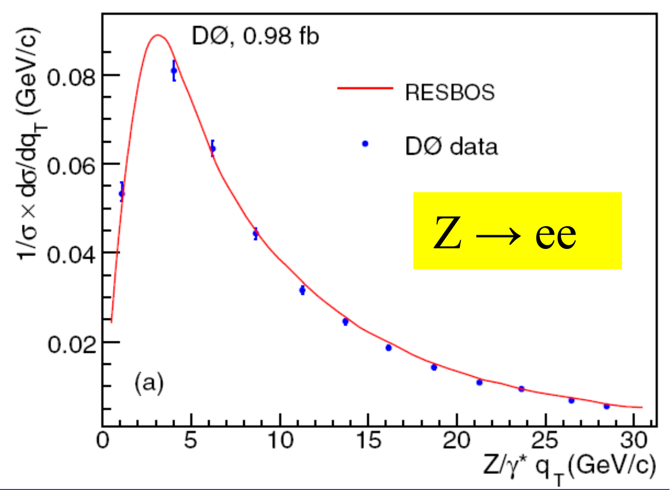
Z p_T and rapidity distributions

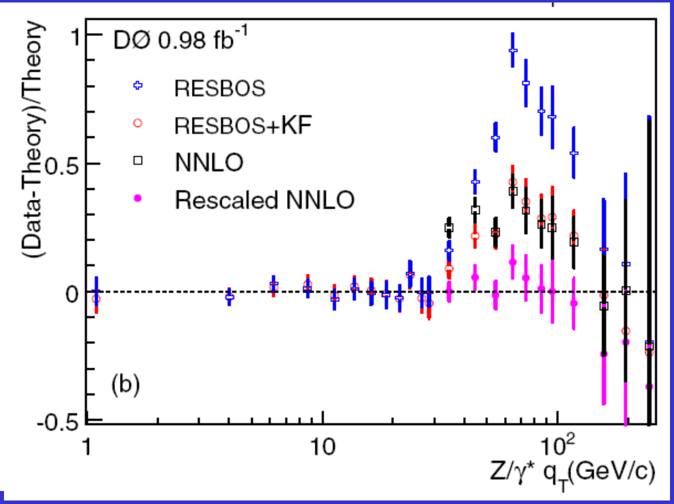
Soft gluons lead to sizeable transverse momentum of W, Z.

Non-perturbative effect. Need good phenomenological description of several QCD issues to do precision physics.







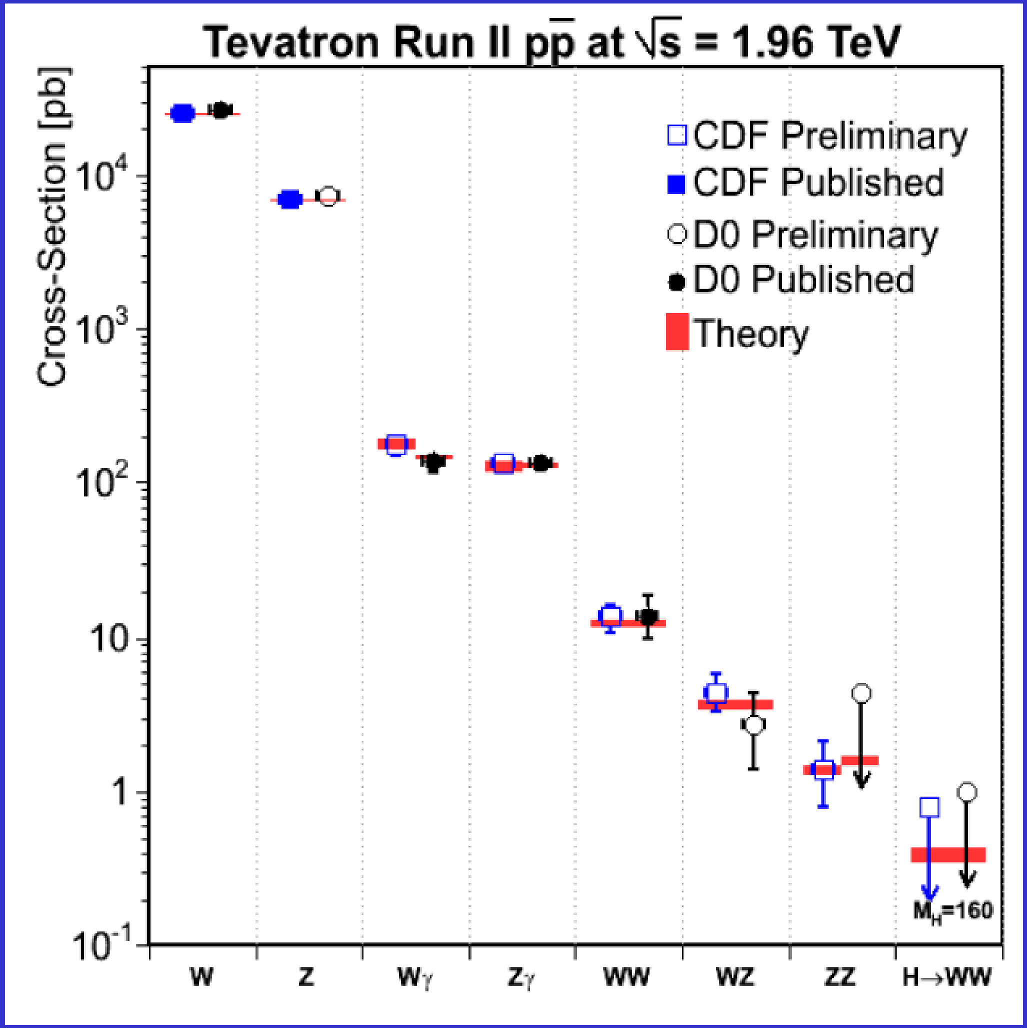


Use boson rapidity distribution to explore PDFs

Gluon resummation calculation (RESBOS) works well for $p_T < 30$ GeV

NNLO calculations needed to describe shape for $p_T > 30$ GeV

Di-Bosons



Measurement of WZ and ZZ at the Tevatron => confidence in capability to find signals in channels like WH, ZH and tri-leptons

WZ production now established.

ZZ is on the cutting edge.

σ_{ZZ} (SM) = 1.5 pb

Including leptonic branching ratios,

Eg. BR(ZZ → 4l) = 0.5%

=> σ.B = 7fb

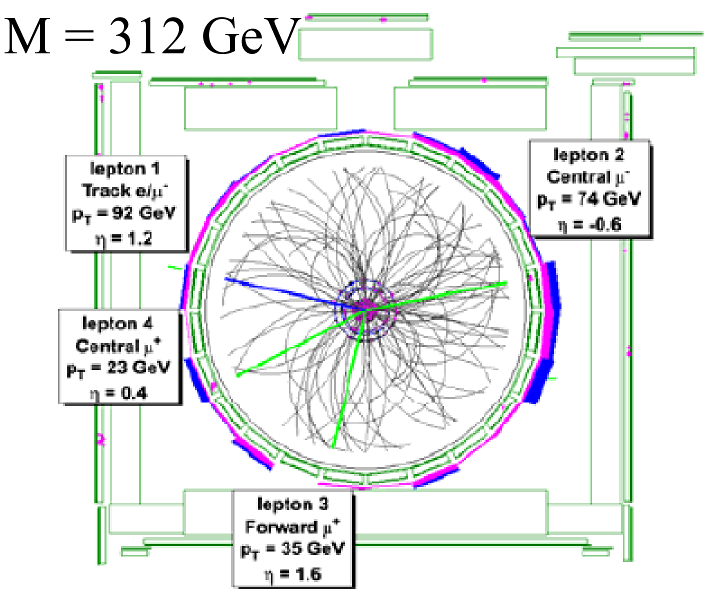
ZZ

CDF 4l: 3 events (0.1 bkgd)

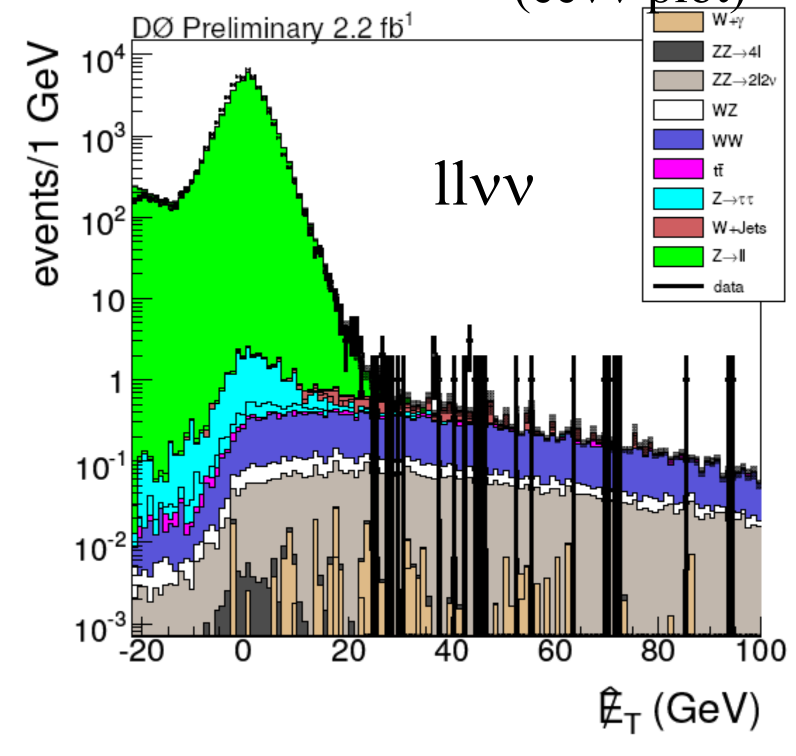
Category	Candidates without a trackless electron	Candidates with a trackless electron
ZZ	$1.990 \pm 0.013 \pm 0.210$	$0.278 \pm 0.005 \pm 0.029$
Z+jets	$0.014^{+0.010}_{-0.007} \pm 0.003$	$0.082^{+0.089}_{-0.060} \pm 0.016$
Total	$2.004^{+0.016}_{-0.015} \pm 0.210$	$0.360^{+0.089}_{-0.060} \pm 0.033$
Observed	2	1

+4.2 σ significance

M = 312 GeV



(eeνν plot)



ee, μμ: +2.4 σ (+1.8 σ expected)

$4l + ll\nu\nu \rightarrow +4.4\ \sigma$ significance

DØ: $\sigma^{ZZ} = 2.1 \pm 1.1(stat.) \pm 0.4(sys.)$ pb

CDF: $\sigma_{ZZ} = 1.4 + 0.7 - 0.6$ pb

Both consistent with SM expectation (1.5 pb)

More Electroweak Results

- Radiation Amplitude Zero in W γ
- $ZZ\gamma$, $Z\gamma\gamma$ neutral TGCs
- Z invisible width
- WZ
- Z rapidity

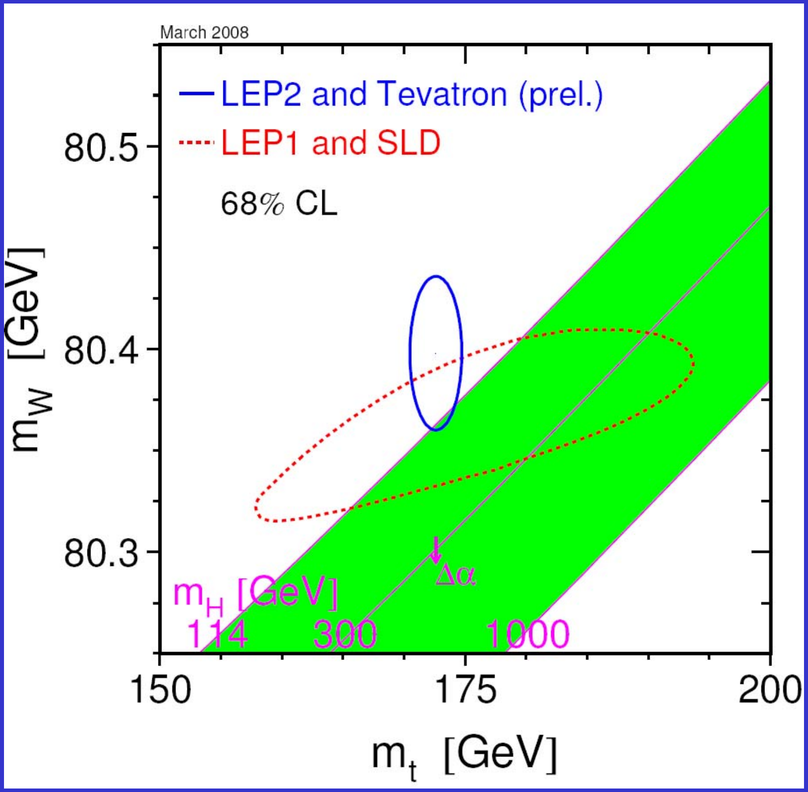
See parallel sessions E11, R12

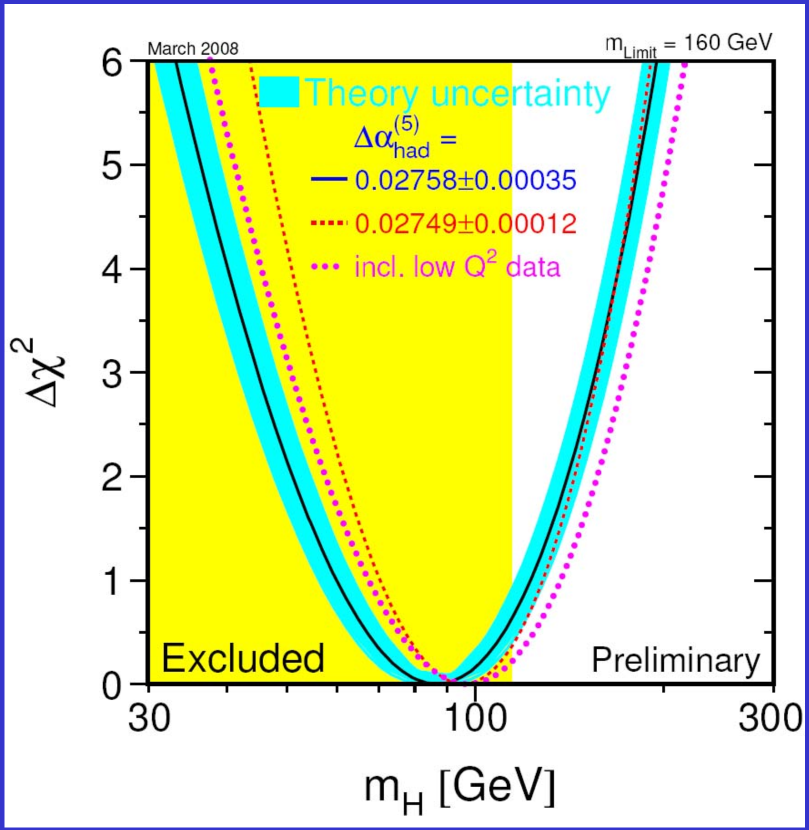
Global Electroweak Fit

Fit to many precision observables.

Main new recent input data is Tevatron m_t, m_W.

Consistent with SM (χ^2/dof =17.2/13)



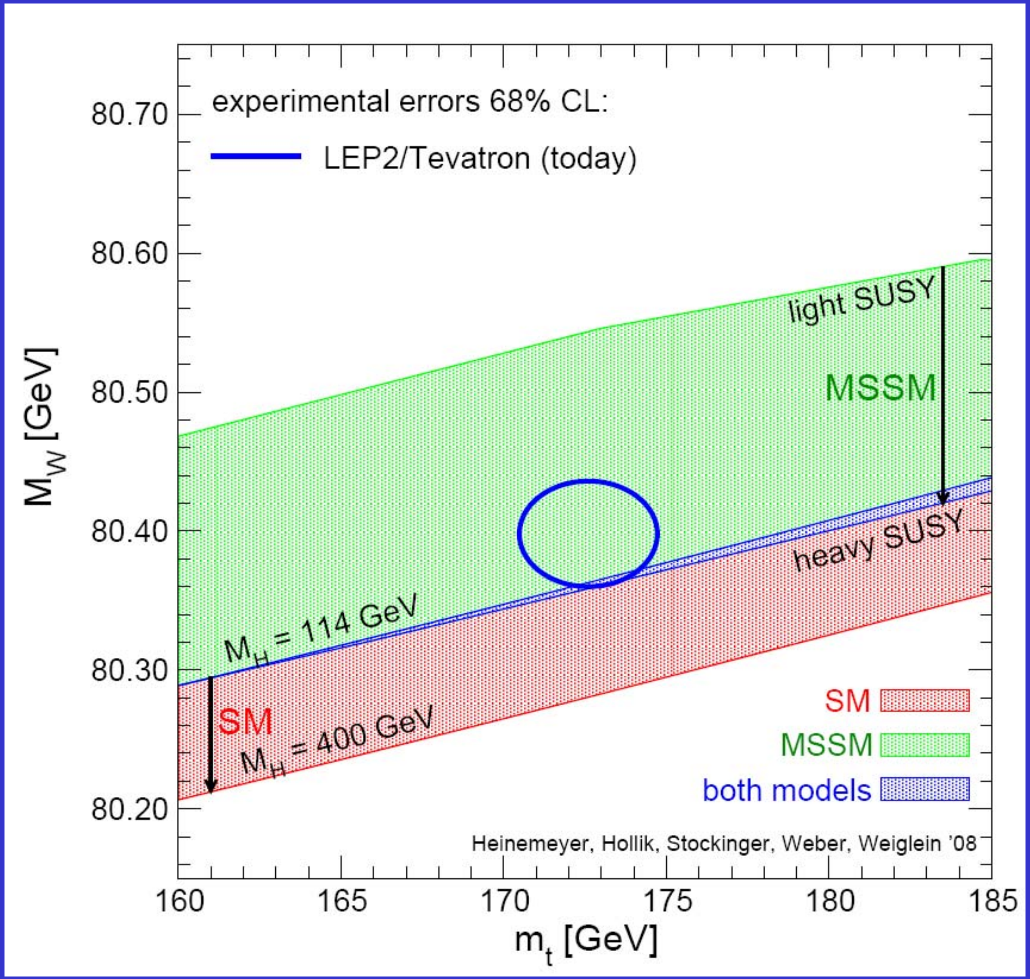


m_H = 87 + 36 – 27 GeV

m_H < 160 GeV @ 95% CL

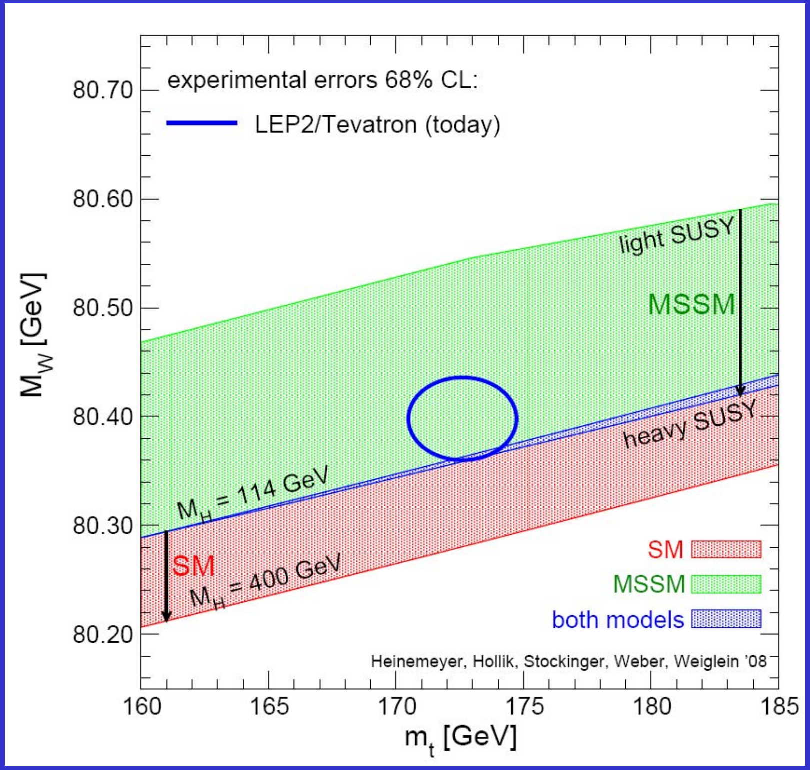
(< 190 GeV including LEP2 Higgs limit)

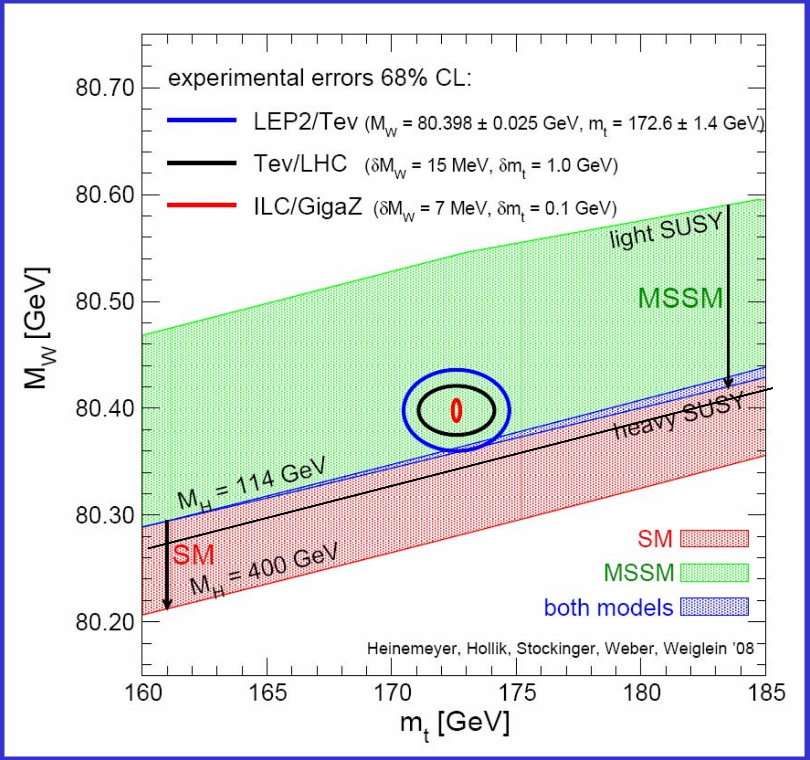
Electroweak precision measurements and Higgs tests



Understanding how the upcoming Higgs results at Tevatron/LHC fit into our SM or MSSM? world will benefit greatly from precision m_t, m_W measurements

Outlook





Tevatron with understood detectors and much larger data-sets is setting a bar for precision EW measurements.

Will continue to be highly competitive and relevant in the LHC era...

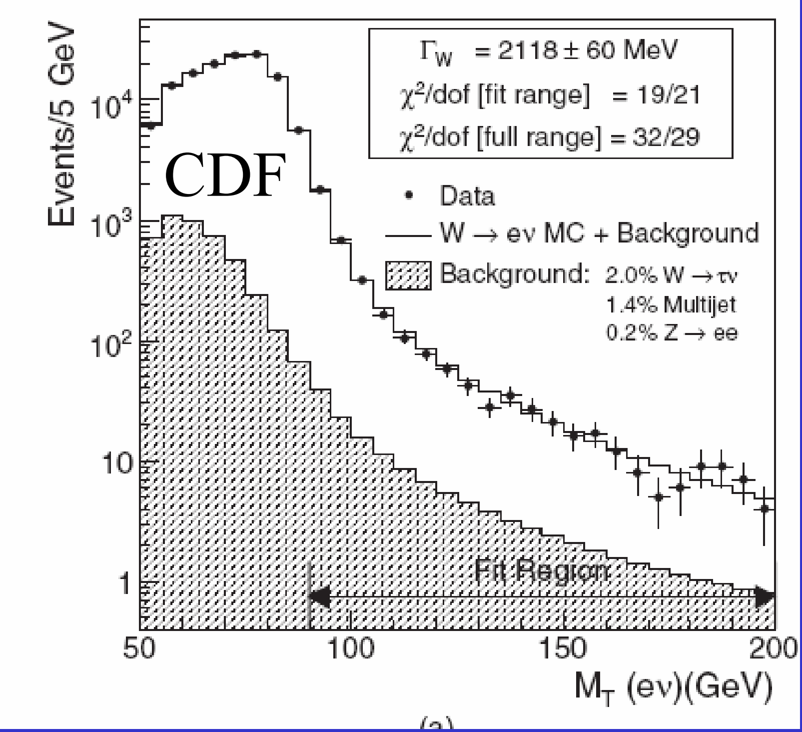
Let's make the most of the current opportunities...

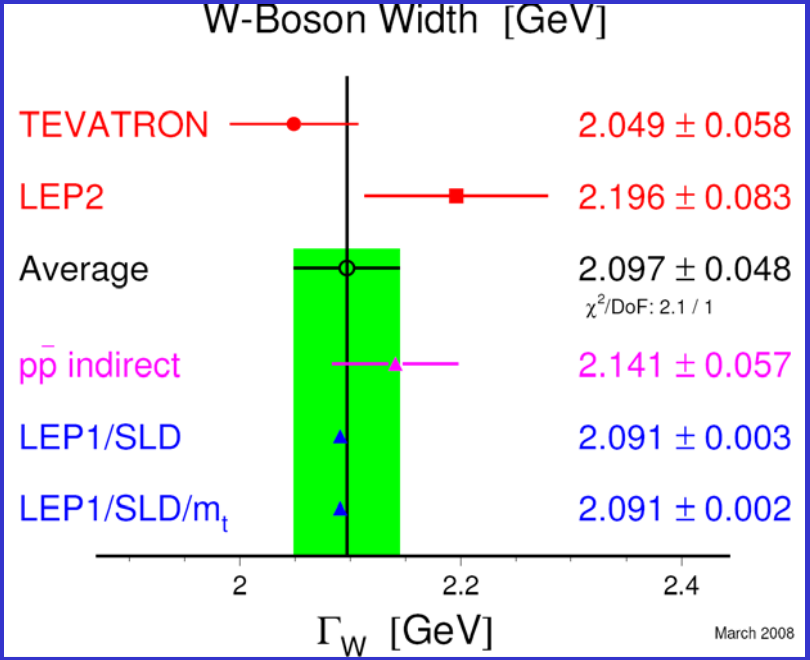
Summary

- Tevatron RunII is in scientific prime-time ($\sqrt{s}$=1.96 TeV)
  - More details, updates and other results see:
  - http://www-cdf.fnal.gov/physics/physics.html
  - http://www-d0.fnal.gov/results/index.html
- Top sector is under heavy scrutiny
- High precision measurements of the top mass and W mass
- Evidence for ZZ production
- Strong indirect constraints on the Higgs
- Many parallel session talks with Tevatron results:
  - Top (J12, M12, X11)
  - Electroweak (E11, R12)

Backup Slides

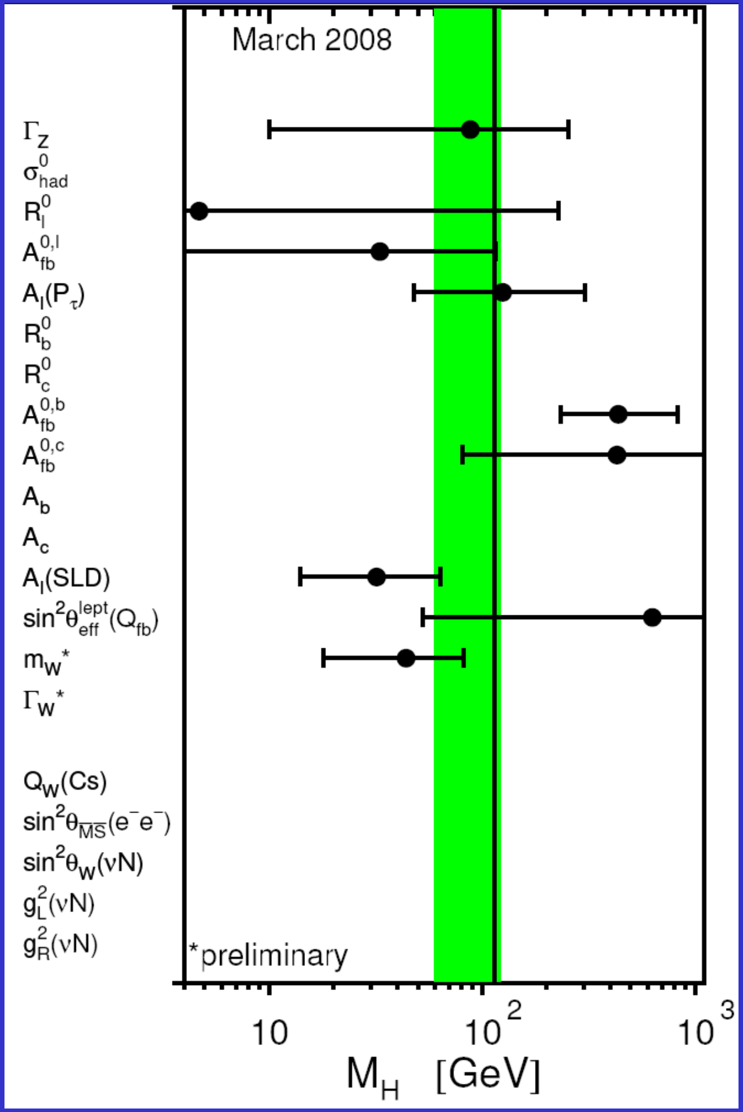
W width





$\Gamma_w = 2032 \pm 45 \pm 57$ MeV

Higgs Sensitivity Backup Slide



Pointer to parallel session talks

- Electroweak Sessions R12, E11
- Top Sessions J12, M12, X11

W Charge Asymmetry

PDF constraint unique to p pbar !

Measures tendency for u valence quarks to carry more fractional momentum than d valence quarks.

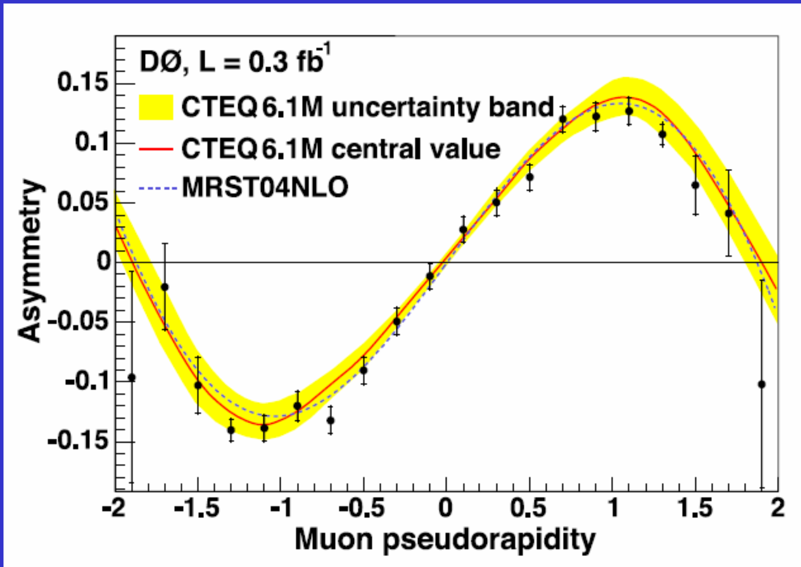
u dbar → W^+ follows p direction

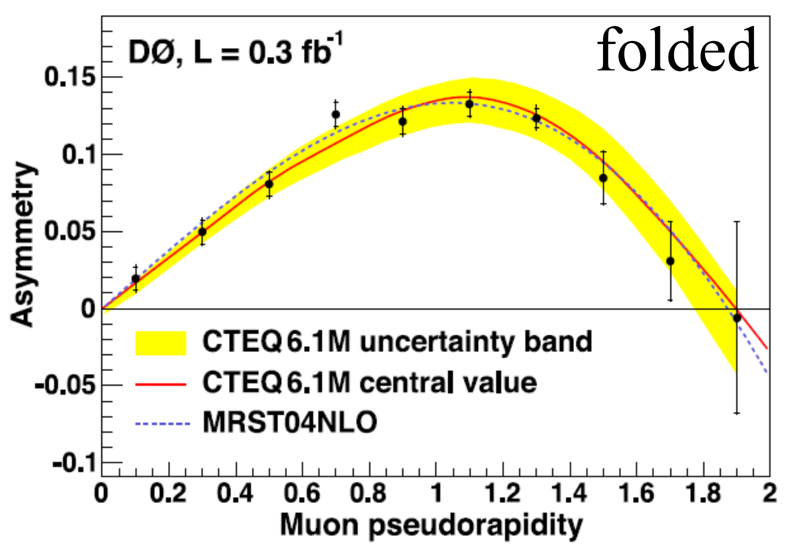
ubar d → W^- follows pbar

Defining η = -ln[tan(θ/2)]

$$A(\eta) = \frac{N_{\mu^+}(\eta) - k(\eta)N_{\mu^-}(\eta)}{N_{\mu^+}(\eta) + k(\eta)N_{\mu^-}(\eta)}$$

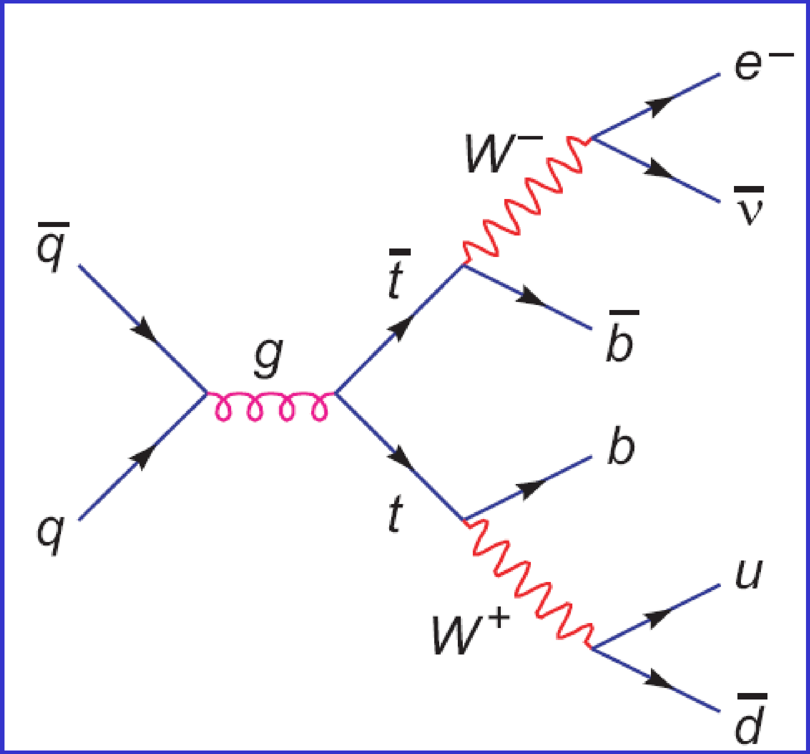
Statistics limited measurement with experimental uncertainties smaller than CTEQ uncertainty sets





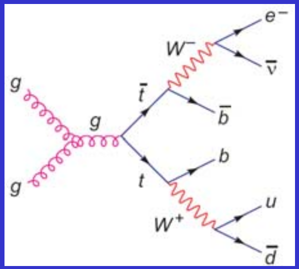
Include a slide on WZ ?

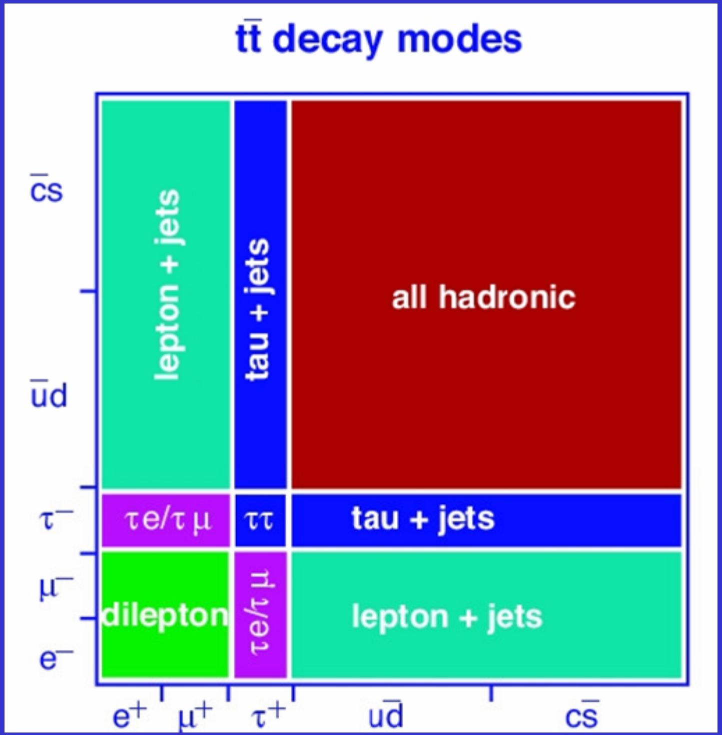
Top Pair Production & Decay



$|V_{tb}| = 0.9991$ in 3 gen unitary CKM matrix.

So expect $t \to W\, b$, with channels defined by known W BRs





ZZ

CDF llll: 3 events (0.1 bkgd)

Category	Candidates without a trackless electron	Candidates with a trackless electron
ZZ	$1.990 \pm 0.013 \pm 0.210$	$0.278 \pm 0.005 \pm 0.029$
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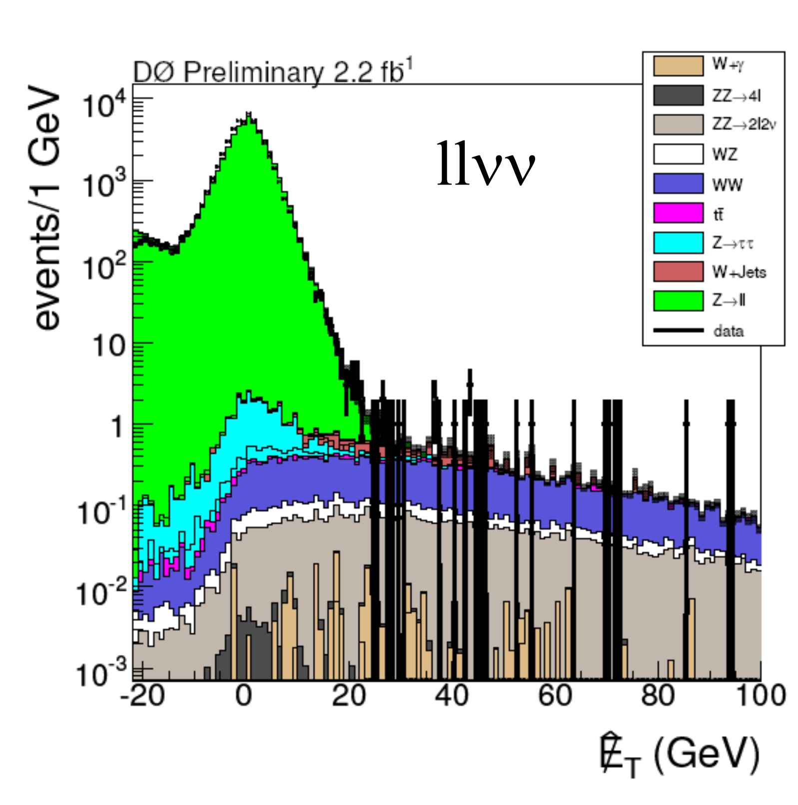
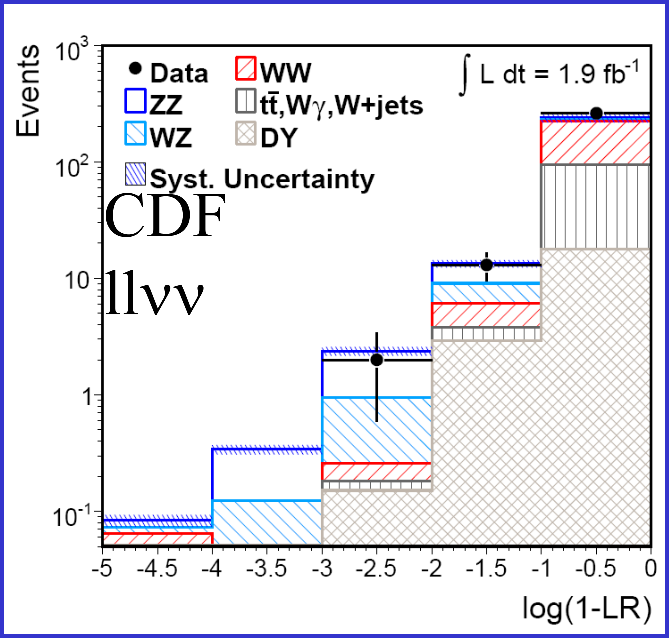
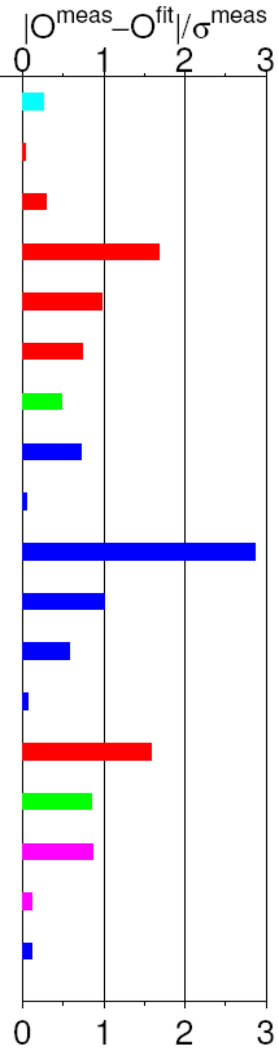




$$\sigma_{PDF\pm} = \frac{1}{1.6}\left(\sum_{i=1}^{n}\left[\Delta M_W\left(S_i^{\pm}\right)\right]^2\right)^{\frac{1}{2}}$$

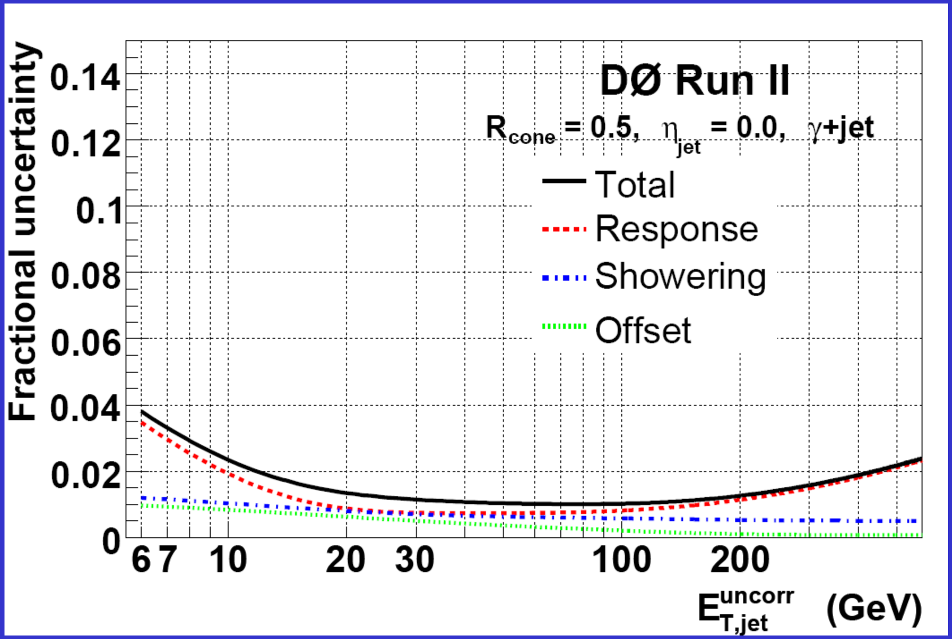
Conversion to1σ

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.743
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21581
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.377
Γ_W [GeV]	2.097 ± 0.048	2.092
m_t [GeV]	172.6 ± 1.4	172.8



March 2008

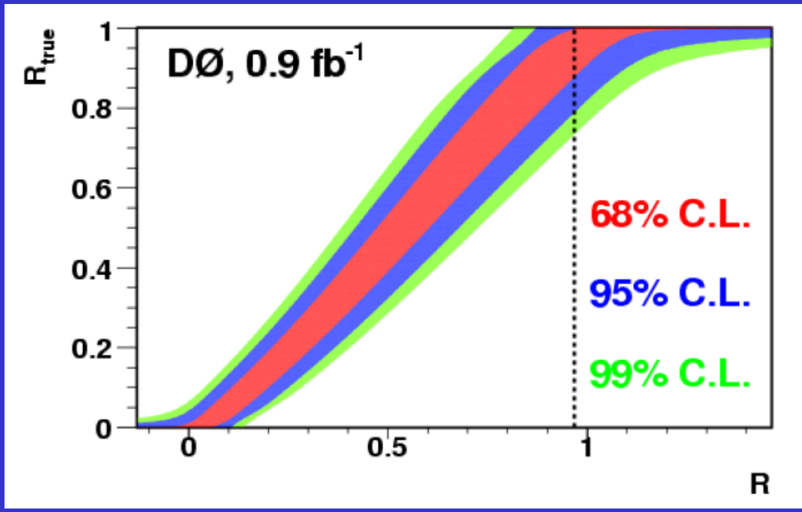
chi2/dof = 17.2/13


DØ Run II
R_{cone} = 0.5, η_{jet} = 0.0, γ+jet
Total
Response
Showering
Offset
Fractional uncertainty
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
6 7 10 20 30 100 200
$E_{T,jet}^{uncorr}$ (GeV)

New top decay modes ?

- $BR(t \to Z\,q)$
  $< 3.7\%$ @ 95% CL (CDF Prel.)

- $R = BR(t \to W\,b) / BR(t \to Wq)$



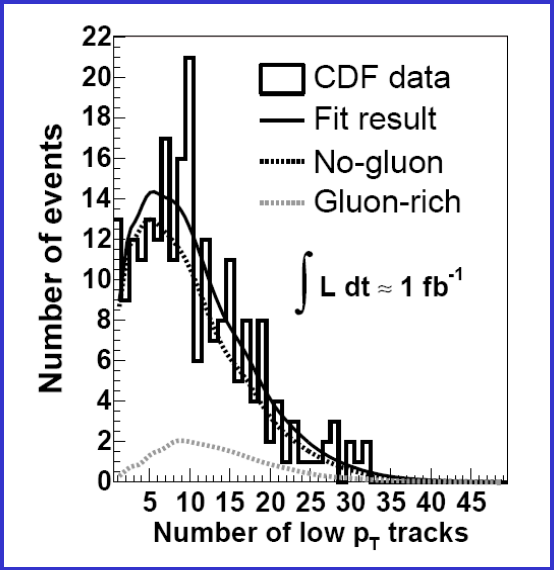
$R = 0.97 \pm 0.09$

> 0.79 @ 95% CL

- $BR(t \to H^{+}\,b)$

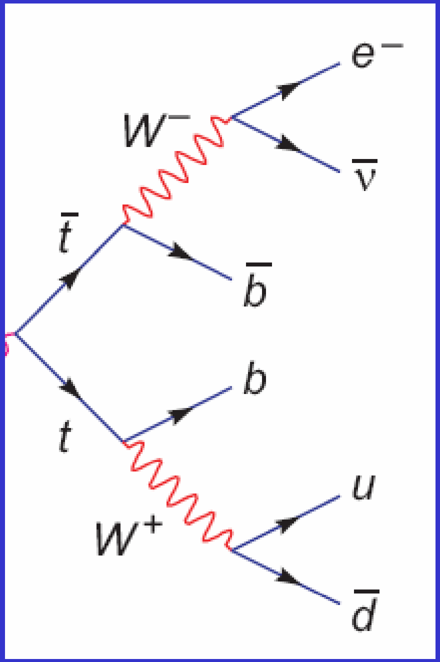
Top Properties

- Width
- Lifetime
- Charge
- Production (gg fraction): 0.07±0.14 ±0.07
- Charge asymmetry
- W helicity



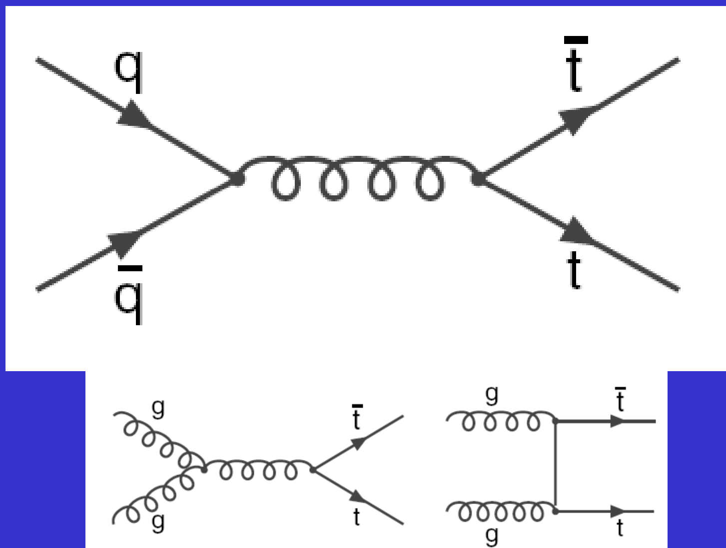
Discriminate $gg \rightarrow t\bar{t}$ and $q\bar{q} \rightarrow t\bar{t}$ using higher probability for gluons to radiate low-momentum gluon.

Calibrate low p_T track rate of gluon induced processes with W+n-jet and di-jet events



e^-
W^-
$\bar{\nu}$
$\bar{t}$
$\bar{b}$
b
t
u
W^+
$\bar{d}$

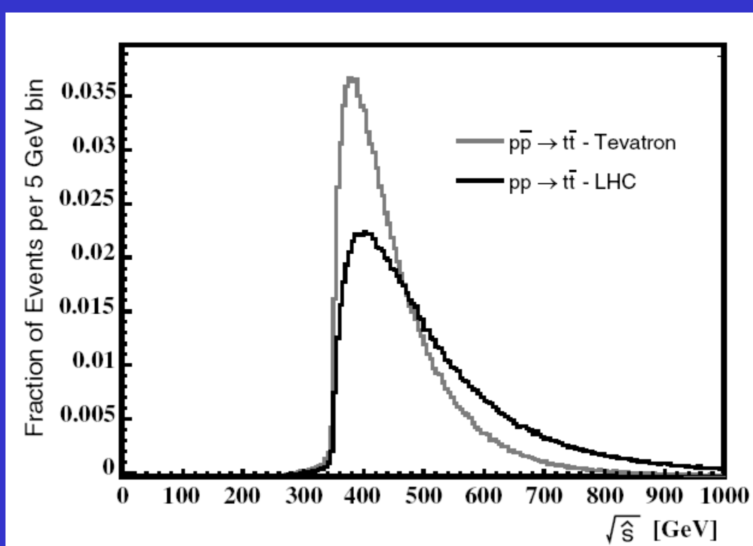
Top Pair Production & Decay

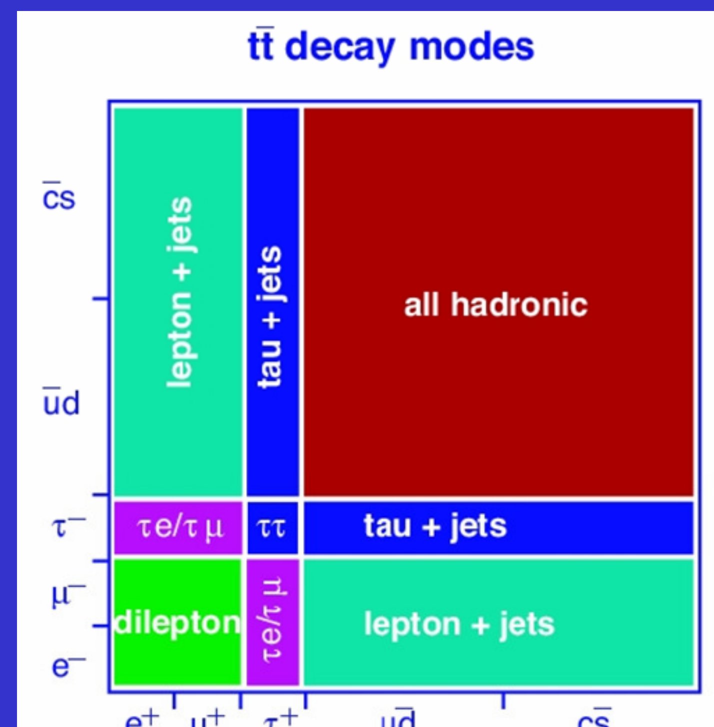


$|V_{tb}| = 0.9991$ in 3 gen unitary CKM matrix.

So expect BR($t \rightarrow W\, b$) ≈ 1.

Decay channels are defined by known W BRs.



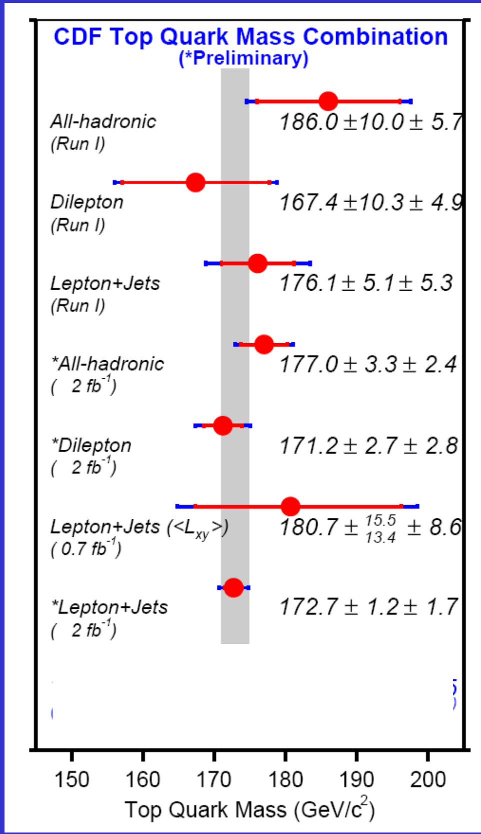


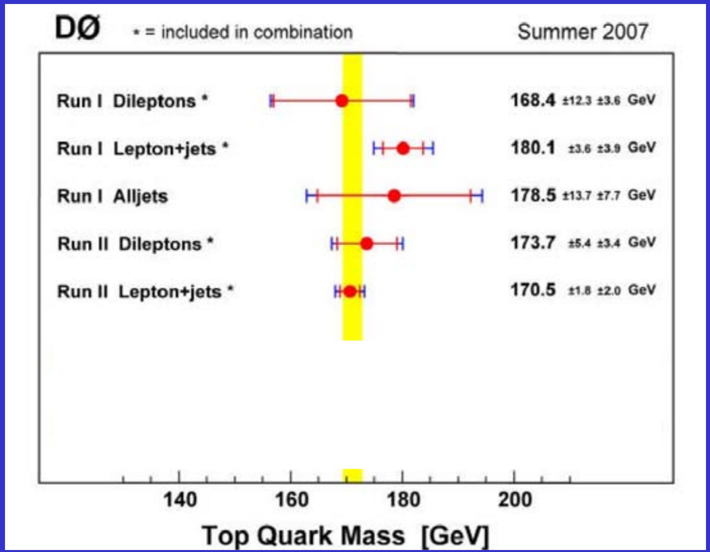
Which top mass measurements?

Many measurements in progress.

Different channels, different techniques, different experiments.

Much attention to understanding statistical and systematic correlations amongst analyses so that they can be combined





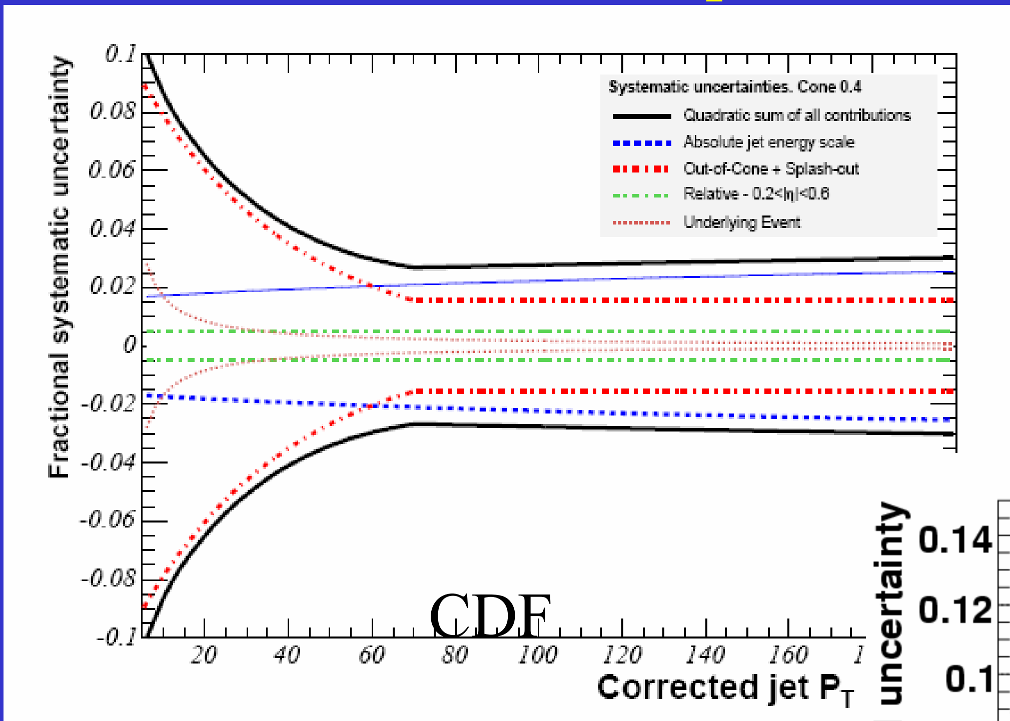
Have selected the 3 most precise analyses which currently enter the Tevatron top mass combination. All are 2 fb^{-1} RunII measurements

DØ l+jets

CDF l+jets

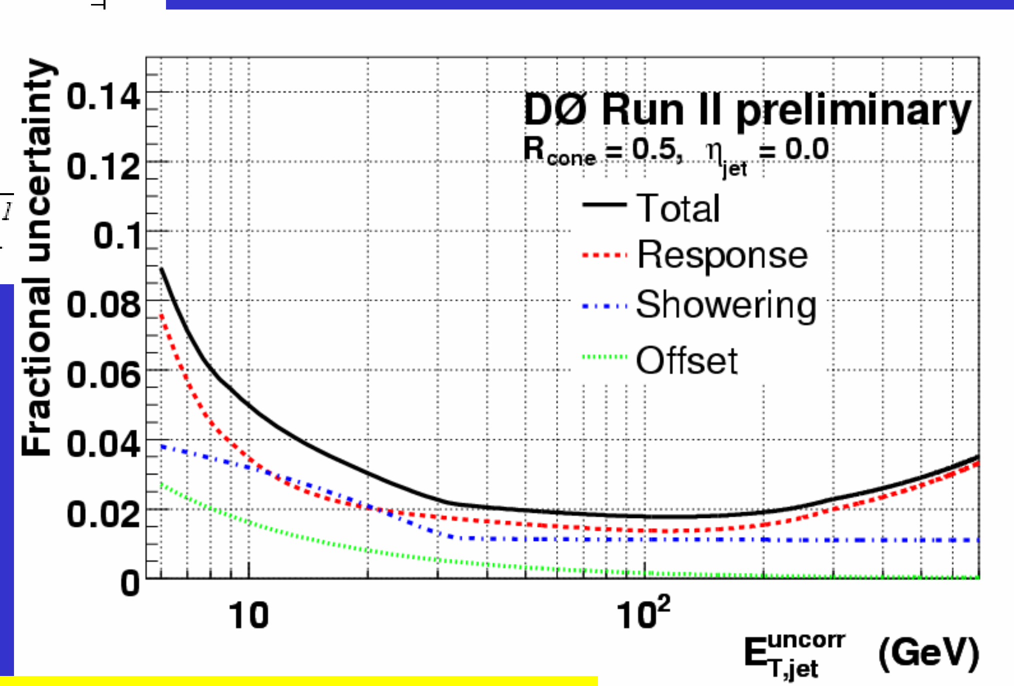
CDF di-lepton

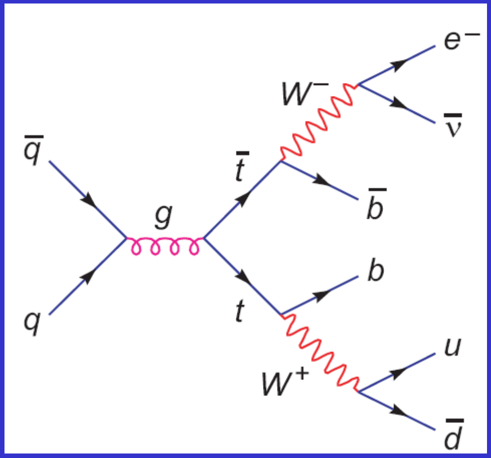
Top Mass



Need to understand jet energy scale (JES)

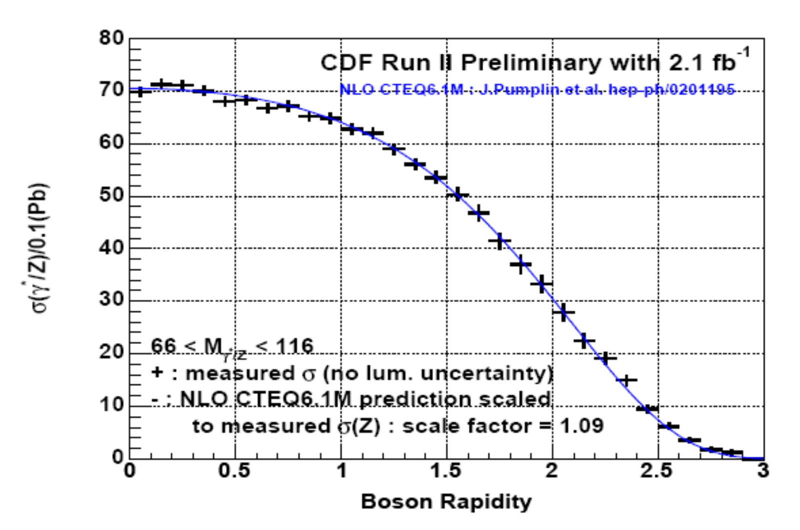
Years of careful work …

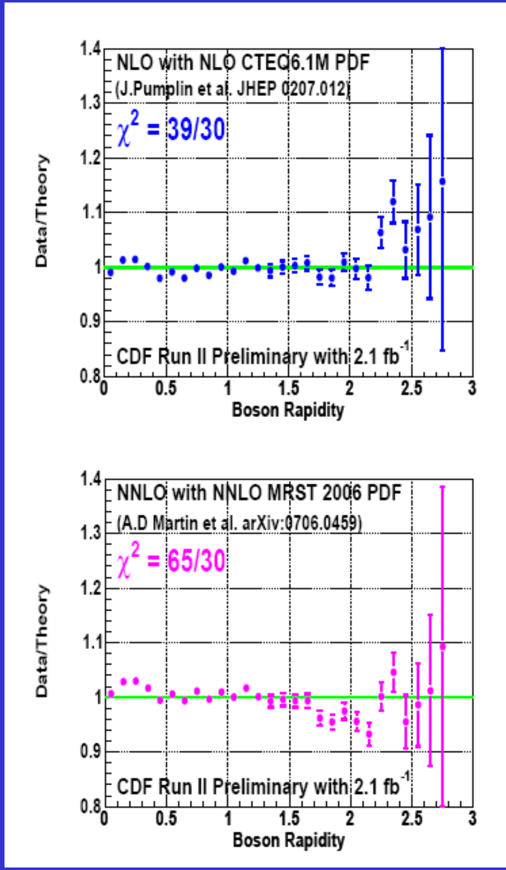




Use W → jj in l+jets ttbar event itself for in situ JES calibration

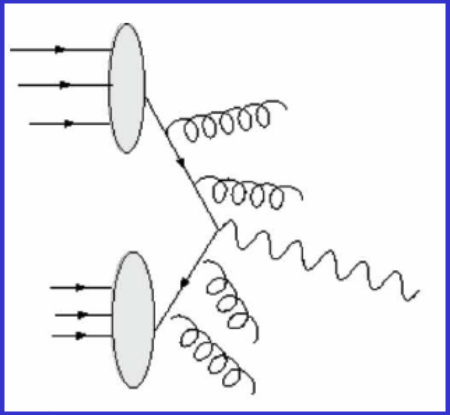
Z rapidity


CDF Run II Preliminary with 2.1 fb^{-1}
NLO CTEQ6.1M : J.Pumplin et al. hep-ph/0201195
66 < $M_{\gamma/Z}$ < 116
+ : measured σ (no lum. uncertainty)
- : NLO CTEQ6.1M prediction scaled
to measured σ(Z) : scale factor = 1.09
σ(γ*/Z)/0.1(Pb)
Boson Rapidity

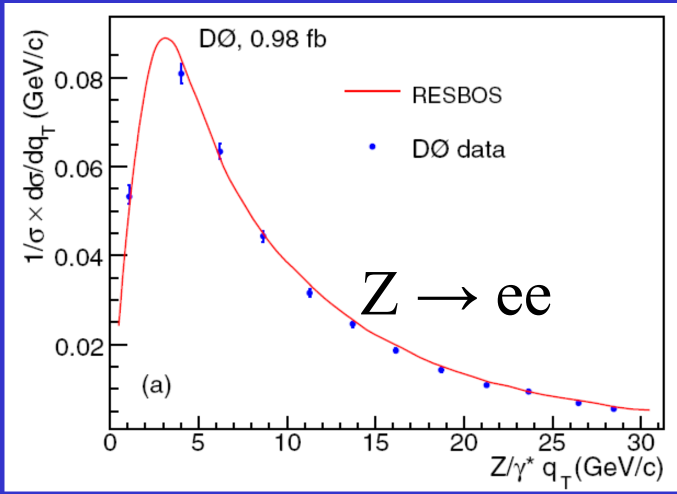

NLO with NLO CTEQ6.1M PDF
(J.Pumplin et al. JHEP 0207.012)
χ^2 = 39/30
CDF Run II Preliminary with 2.1 fb^{-1}
Data/Theory
Boson Rapidity
NNLO with NNLO MRST 2006 PDF
(A.D Martin et al. arXiv:0706.0459)
χ^2 = 65/30
CDF Run II Preliminary with 2.1 fb^{-1}
Data/Theory
Boson Rapidity

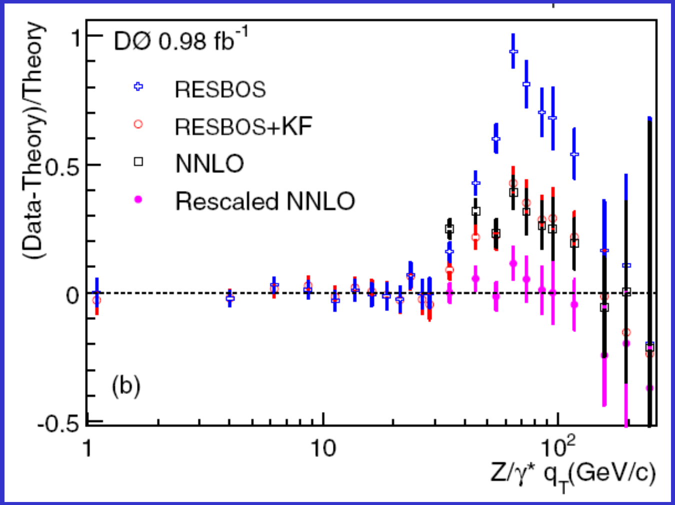
Z p_T Distribution

Soft gluons lead to sizeable transverse momentum of W, Z.



Non-perturbative effect. Need good phenomenological description of several QCD issues to do precision physics





Gluon resummation calculation (RESBOS) works well for p_T < 30 GeV

NNLO calculations needed to describe shape for p_T > 30 GeV