The 6th KEK Topical Conference:
Frontiers in Particle Physics and Cosmology

Tevatron results on *Electroweak, Top and Higgs*

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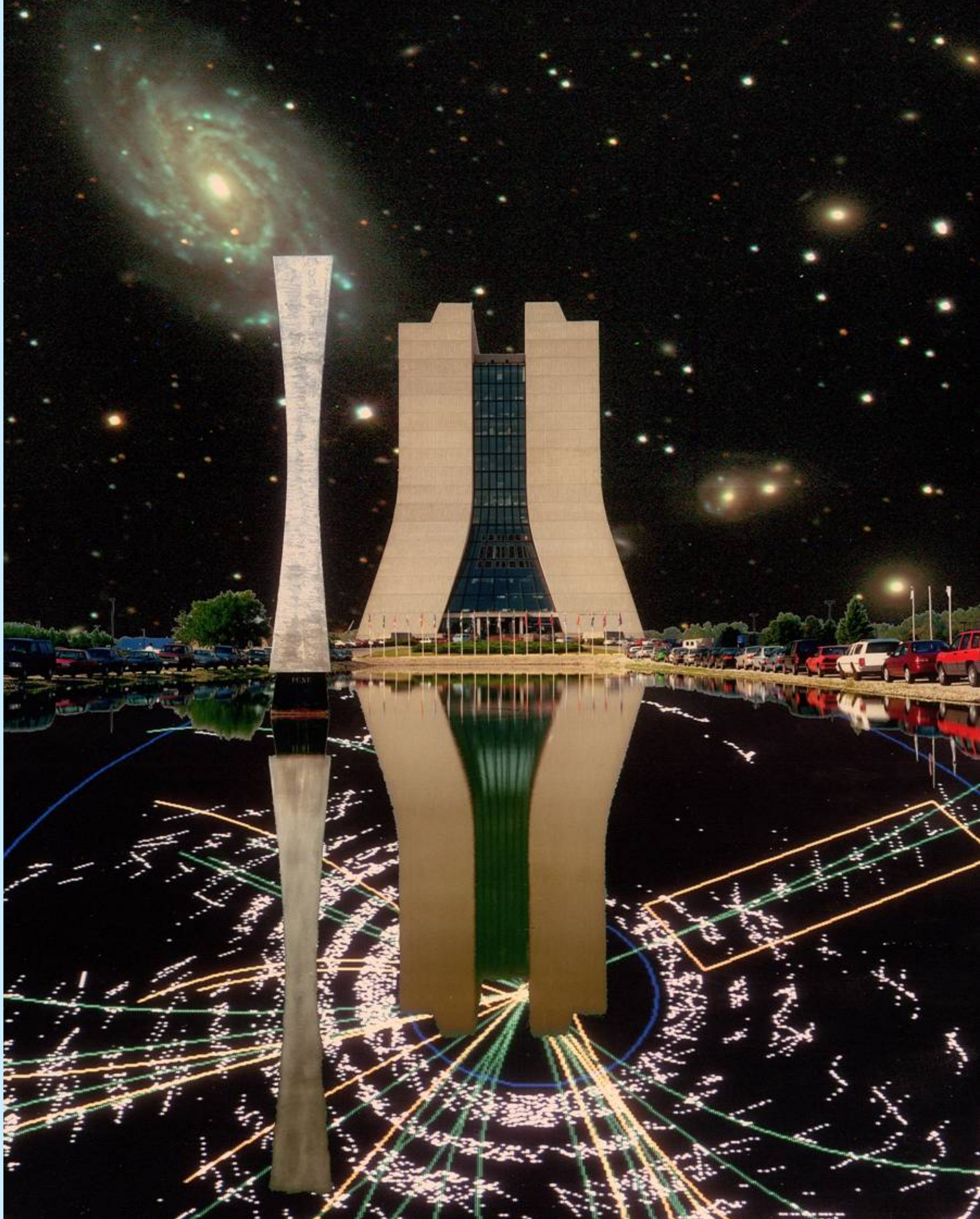
KEK, Tsukuba, Japan

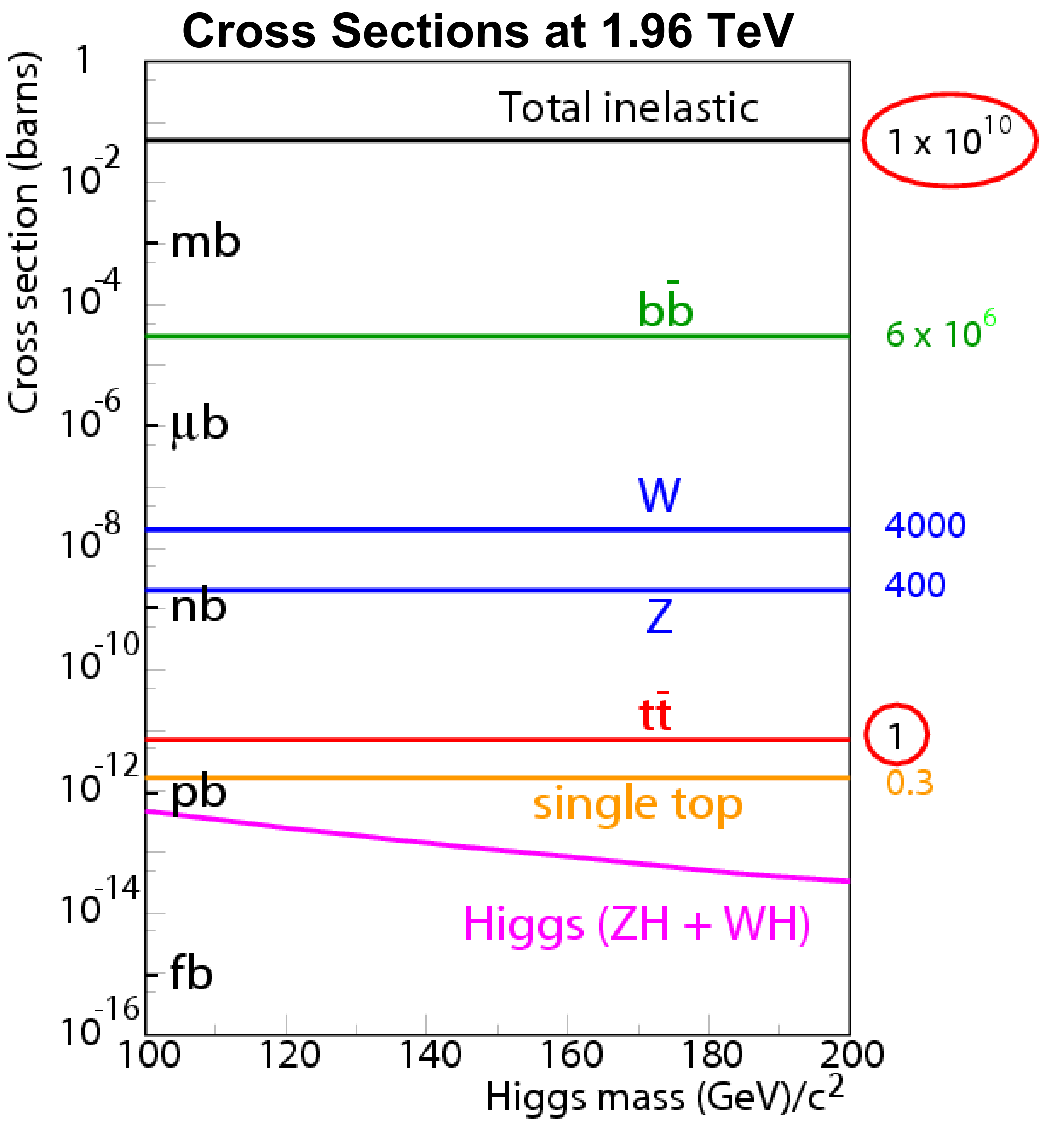
February 2007

Outline

- **Introduction**
  - Tevatron, CDF and DØ
- **Electroweak measurements**
  - W and Z properties
  - Di-boson production
- **Top physics**
  - Cross section, mass, charge
  - Single top
- **Higgs searches**
  - The SM
    - ZH → $\nu\nu$bb
    - WH → eνbb
    - H → WW* → $\ell^+\ell^-\nu\nu$
  - SUSY
    - bh/bbh(→bb)
    - h → $\tau\tau$
- **Summary**



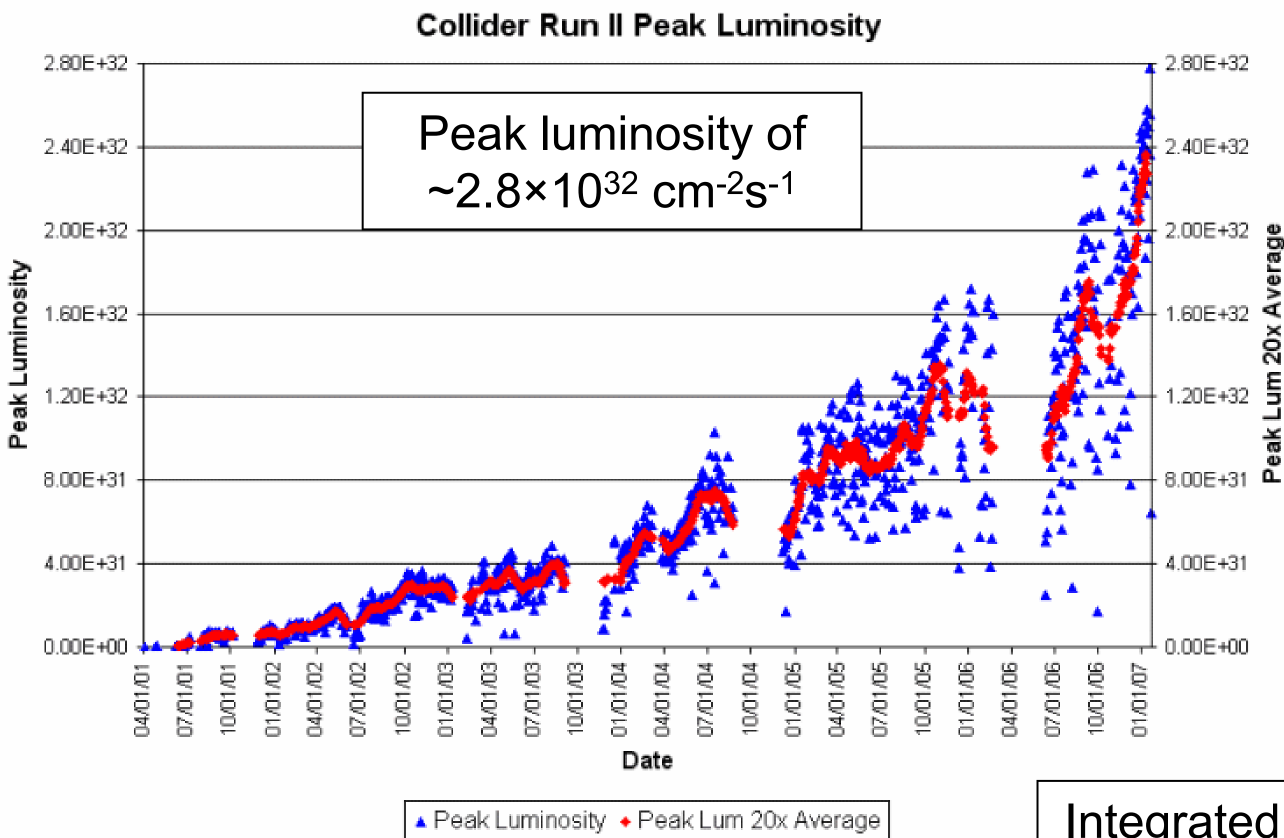
W, Z, top, Higgs boson production rates at the Tevatron



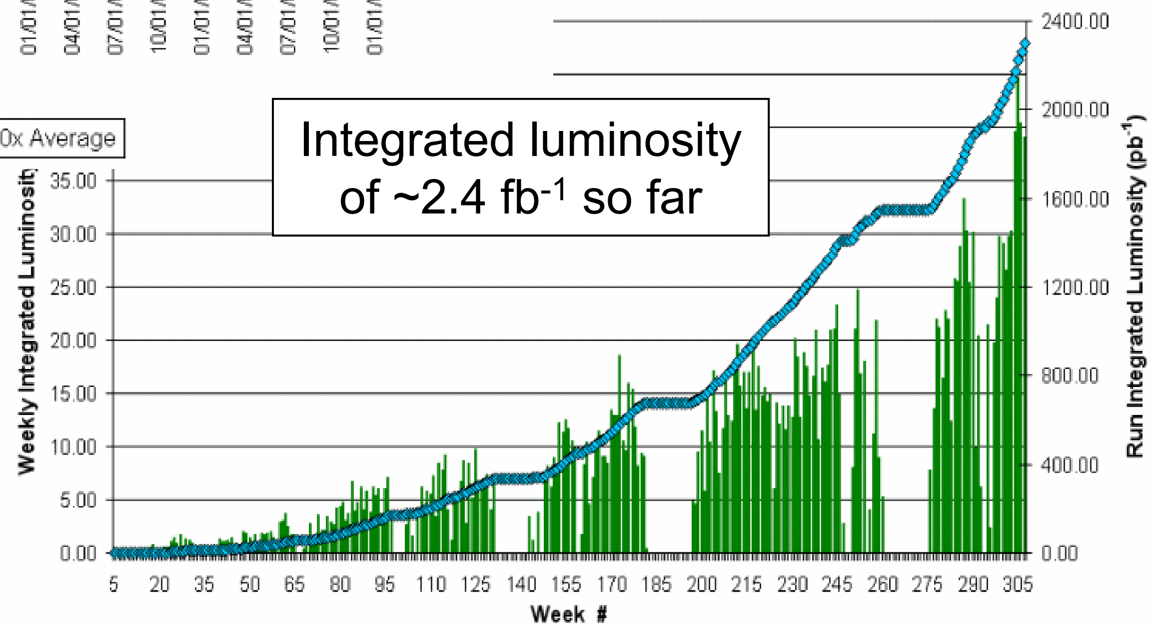
- Cross sections for interesting processes are very small
  - Especially so when clean final states with low decay branching fractions are considered
- For example, an event with top production occurs just once in 10,000,000,000 interactions
- Multi-level trigger is the key in managing the huge rate of QCD background processes
- Capabilities to identify b-jets are essential to extract the top, Higgs, and other events with b-quarks in final states

Accumulate luminosity as much as possible

Tevatron peak and integrated luminosities, Jan '07



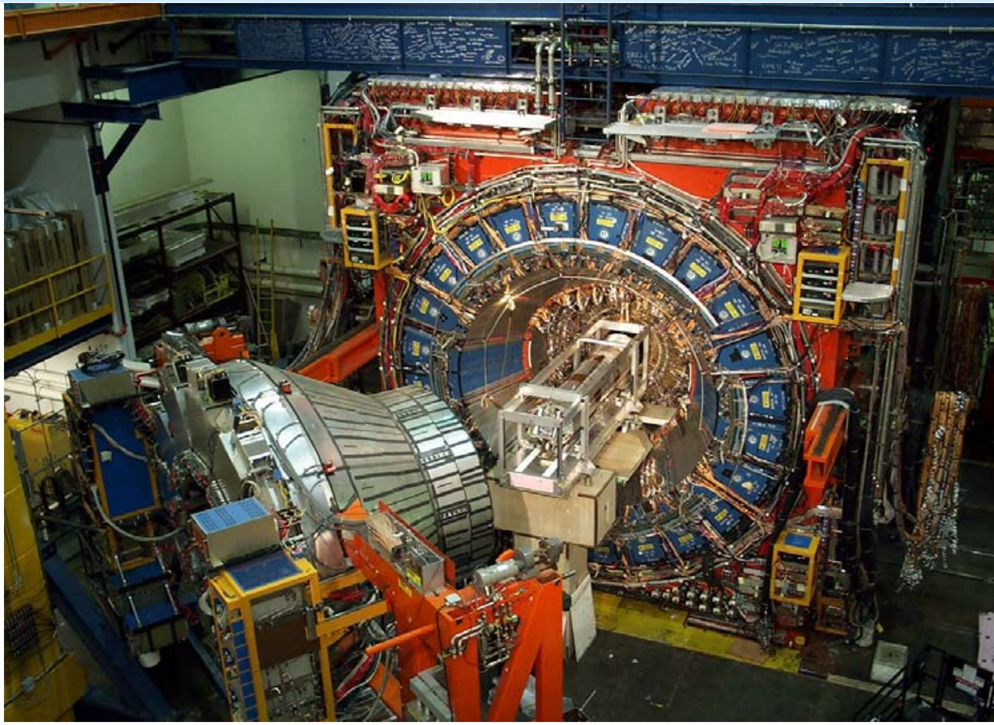
- Delivered integrated luminosity ~2.4 fb^{-1}
- Data set has doubled every year
- Expect 4 – 8 fb^{-1} by the end of 2009

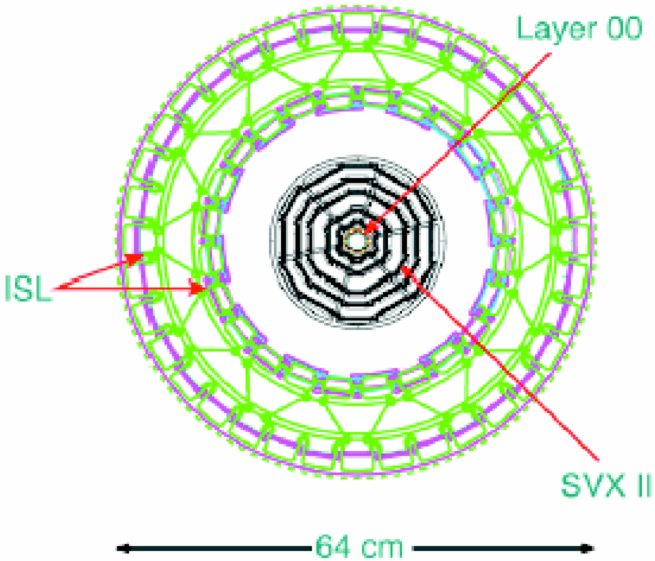


- CDF/DØ operate at ~85% efficiency
- Results in the following are based on 0.2 – 1 fb^{-1} of data

The upgraded CDF II

- Major upgrades for Run II:
  - Drift chamber: COT
  - Silicon: SVX, ISL, L00 at r ~ 1.5 cm
    - 8 layers
    - 700 k readout channels
    - 6 m^2
    - material:15% X_0
  - Forward calorimeters
  - Forward muon system
    - Improved central muon system
  - Time-of-flight
  - Preshower detector
  - Timing in EM calorimeter
  - Trigger and DAQ



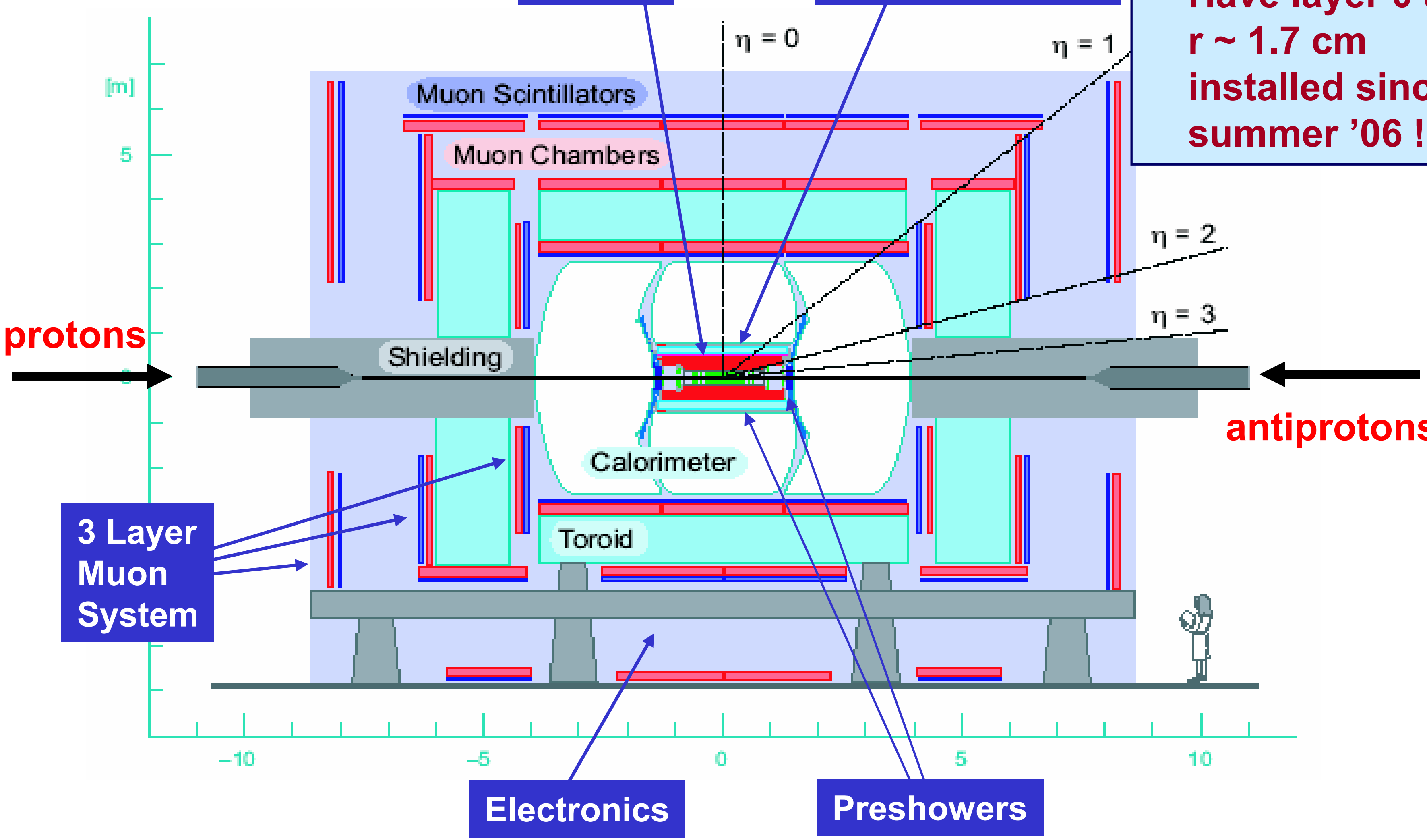


The upgraded DØ detector in Run II

- Upgraded
  - Muon system, cal. electronics
  - DAQ, (track) trigger system
  - Displaced-vtx trigger

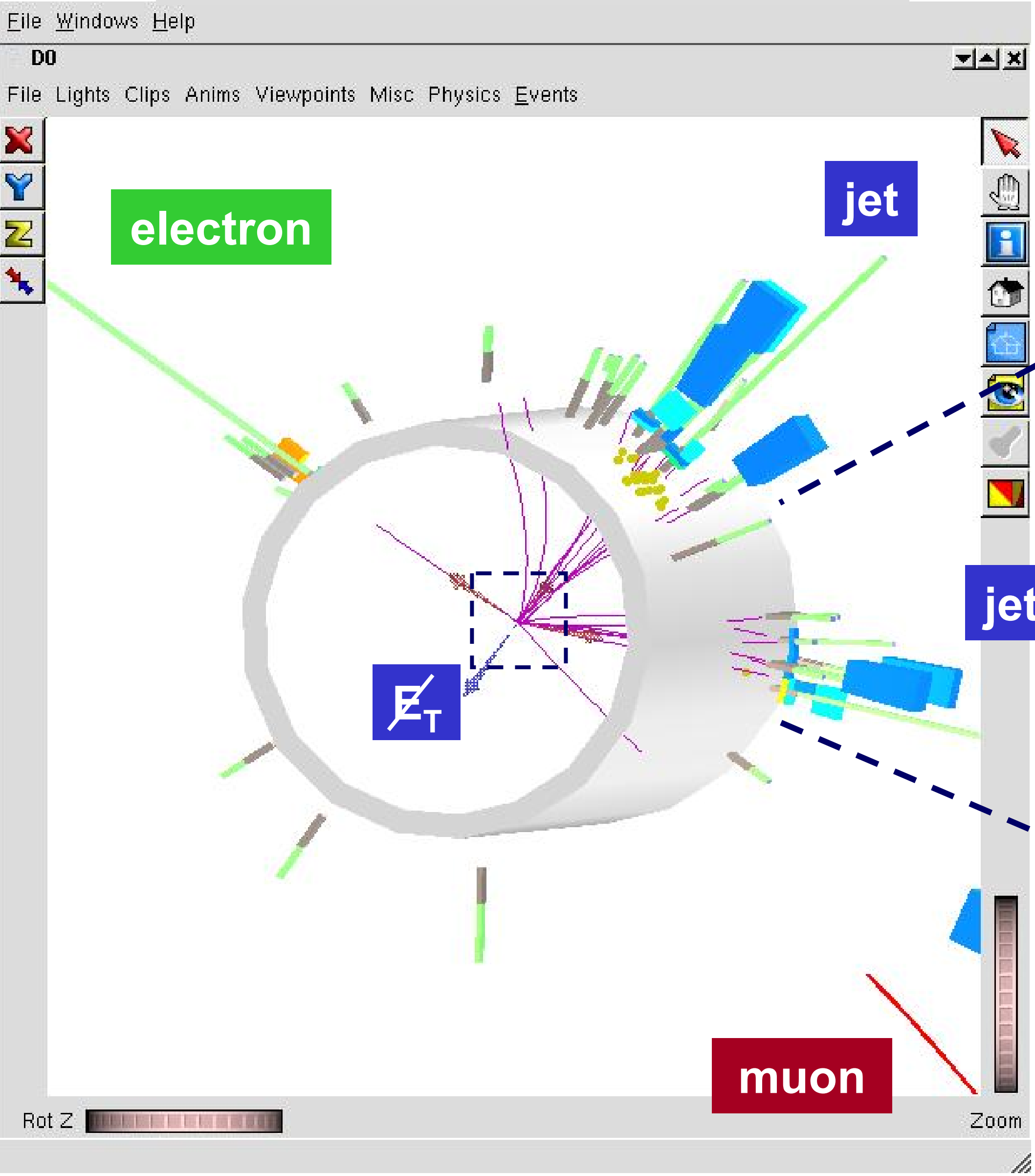
- New (tracking in B-field)
  - Silicon detector
  - Fiber tracker

- **Have layer 0 at r ~ 1.7 cm installed since summer '06 !**

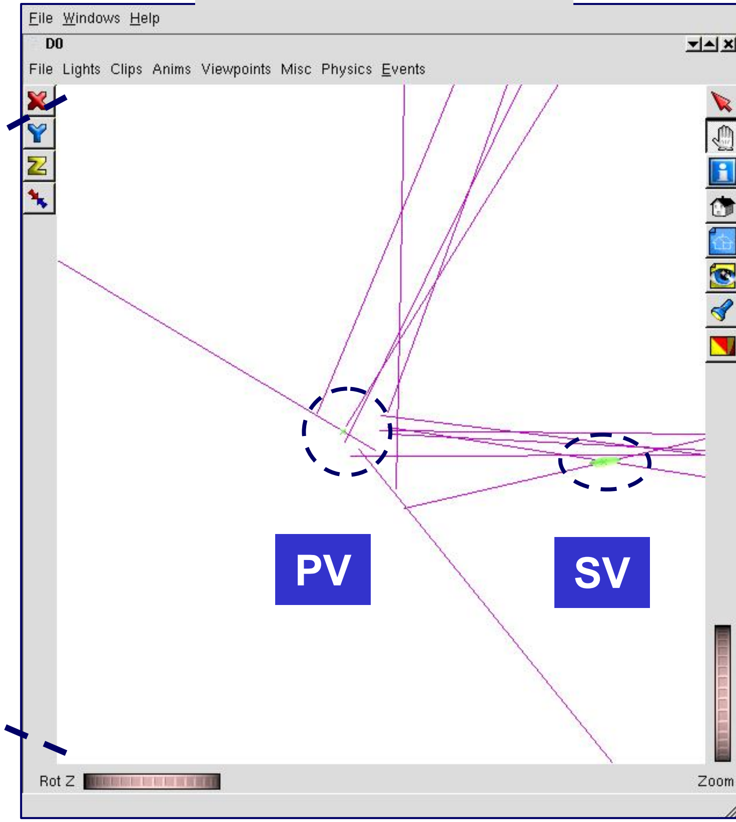


… and how it works

Run / event: 169261 / 6854840



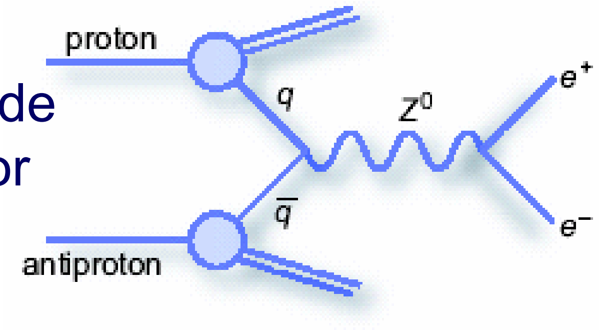
Two b-tagged jets

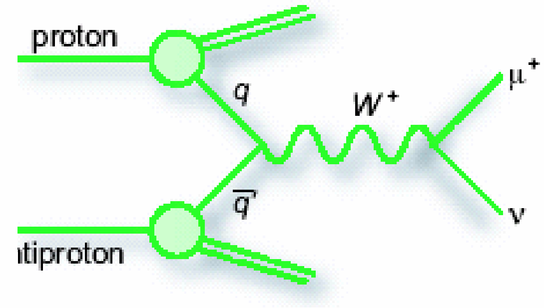


Electroweak measurements

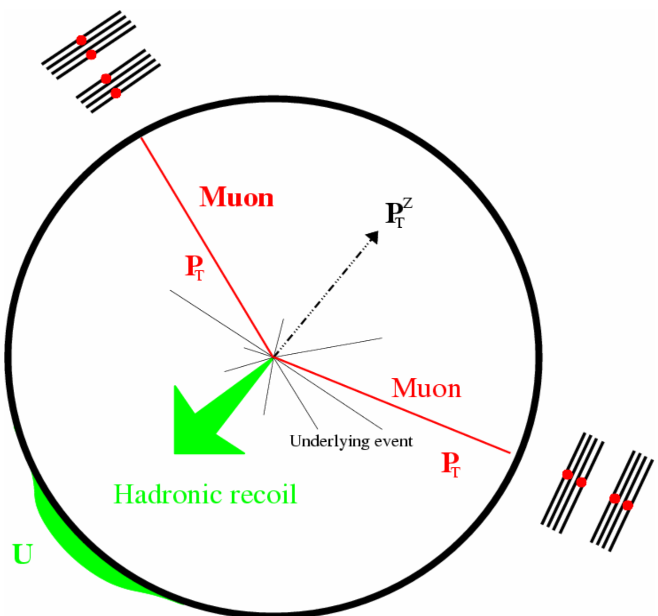
W and Z bosons

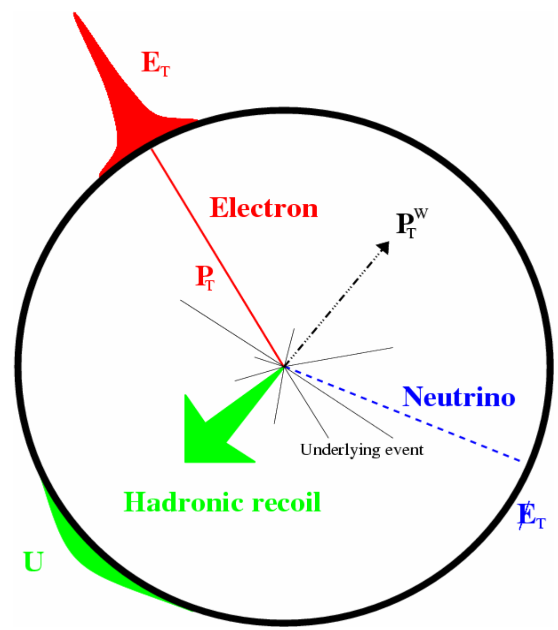
- Along with many interesting physics topics, W and Z provide excellent calibration signals for
  - Electron energy scale
  - Track momentum scale
  - Lepton ID & trigger efficiencies
  - Missing E_T resolution
  - Luminosity





- Z selection
  - Two isolated leptons with $E_T > 20$ GeV
  - Electron, muon, tau

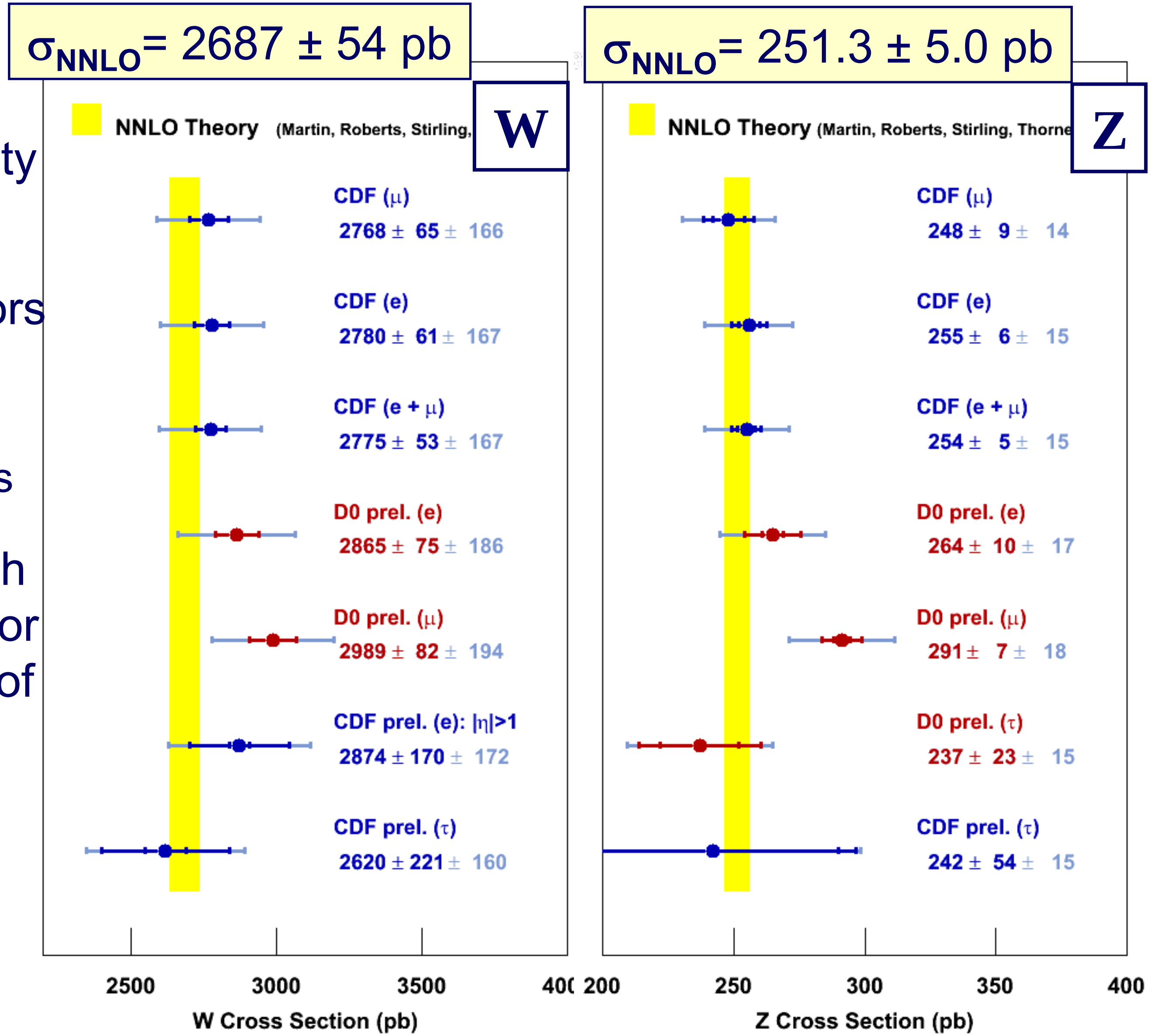




- W selection
  - One isolated lepton with $E_T > 20$ GeV
  - Large missing E_T>20 GeV due to escaping neutrinos

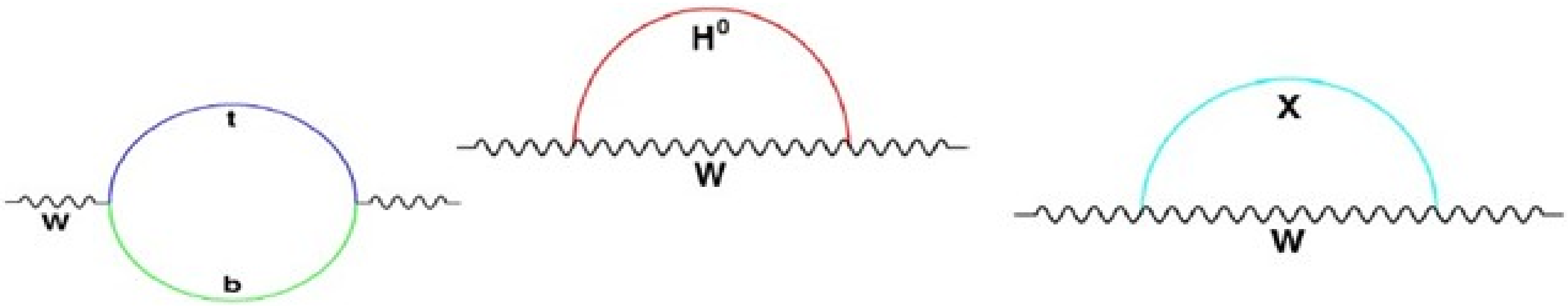
W and Z production cross section

- Uncertainty on luminosity ~ 6% is dominant
- Other experimental errors ~ 2%
  - Comparable in size to theoretical calculations
- Is theory reliable enough to use W/Z production for absolute normalization of luminosity ?



W mass measurement: motivation

- m_W is a parameter of the SM – must be measured as precisely as possible
- Higher order corrections due to heavy quark, Higgs and new particles



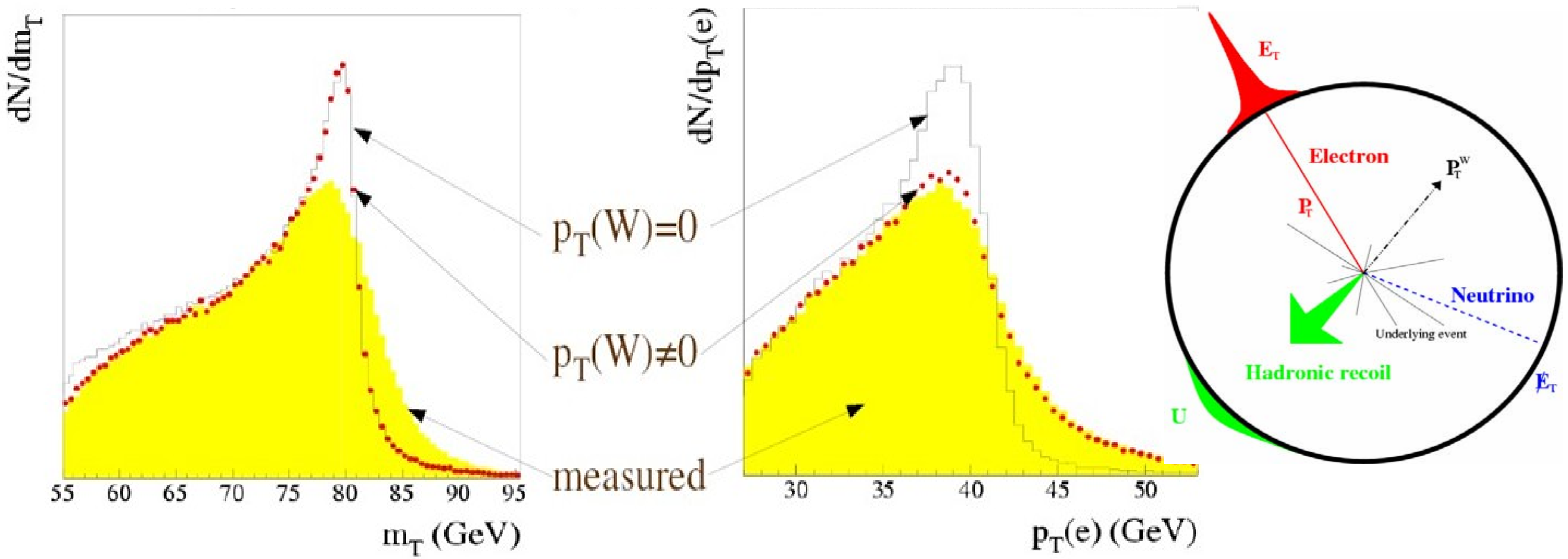
$$\rho = \frac{m_W^2}{m_Z^2(1-\sin^2\theta_W)} \equiv 1 + \Delta r$$

$$\Delta r = \frac{3G_F}{8\pi^2\sqrt{2}} m_t^2 + \frac{\sqrt{2}G_F}{16\pi^2} m_W^2 \left[\frac{11}{3}\ln\left(\frac{m_H^2}{m_W^2}\right) + \ldots\right] + \ldots$$

- Along with the top mass, m_W constrains the mass of the Higgs boson

W mass measurement techniques at the Tevatron

- W mass is related to the location of Jacobian edge



1. W transverese mass

$$m_T = \sqrt{2\, p_T^{\ell}\, p_T^{\nu} \left(1 - \cos\phi_{\ell\nu}\right)}$$

Insensitive to $p_T(W)$ to 1st order

Reconstruction of $p_T(\nu)$ is sensitive to hadronic response and multiply interactions

2. $p_T(\ell)$ fit: needs theoretical model for $p_T(W)$; provides cross-check of production model

3. $p_T(\nu)$ fit provides cross-check of hadronic recoil model

CDF: W mass systematic uncertainties and results

$L_{int} \sim 200\ pb^{-1}$

Transverse Mass Fit Uncertainties (MeV)

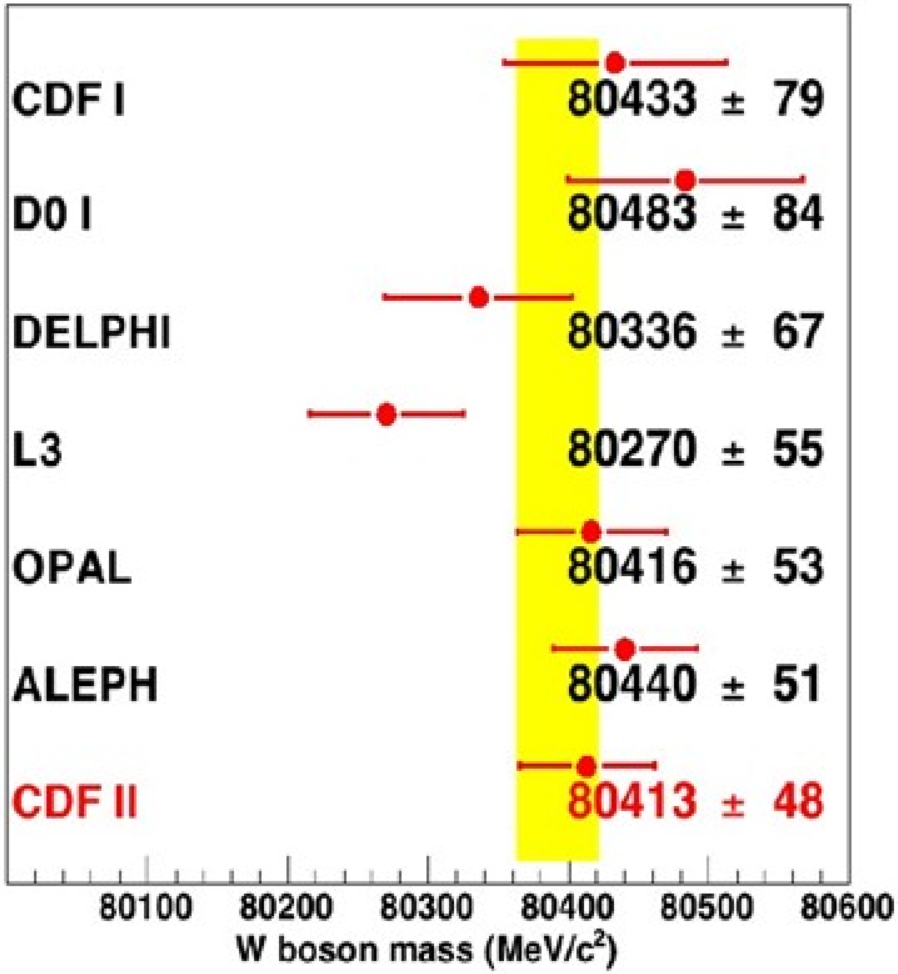
	electrons	*muons*	*common*
W statistics	48	54	0
Lepton energy scale	30	17	17
Lepton resolution	9	3	-3
Recoil energy scale	9	9	9
Recoil energy resolution	7	7	7
Selection bias	3	1	0
Lepton removal	8	5	5
Backgrounds	8	9	0
pT(W) model (g2,g3)	3	3	3
Parton dist. Functions	11	11	11
QED rad. Corrections	11	12	11
Total systematic	39	27	26
Total	62	60	

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

- Combined electrons (3 fits): M_W = 80477 ± 62 MeV, $P(\chi^2)$ = 49%
- Combined muons (3 fits): M_W = 80352 ± 60 MeV, $P(\chi^2)$ = 69%
- All combined (6 fits): M_W = 80413 ± 48 MeV, $P(\chi^2)$ = 44%

W mass: new world average

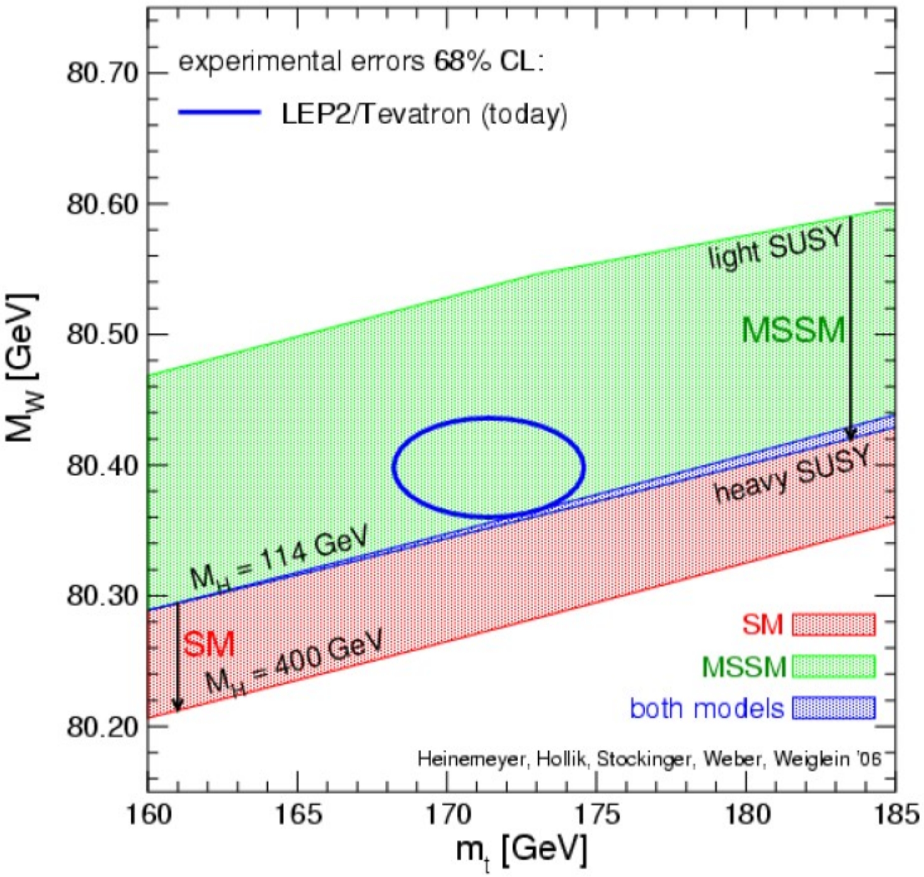
	W mass (MeV)
DELPHI	80336 ± 67
L3	80270 ± 55
OPAL	80416 ± 53
ALEPH	80440 ± 51
CDF-I	80433 ± 79
D0-I	80483 ± 84
LEP Average	80376 ± 33
Tevatron-I Average	80454 ± 59
Previous World Average	80392 ± 29
CDF-II (preliminary)	80413 ± 48
New Tevatron Average	80429 ± 39
New World Average	80398 ± 25

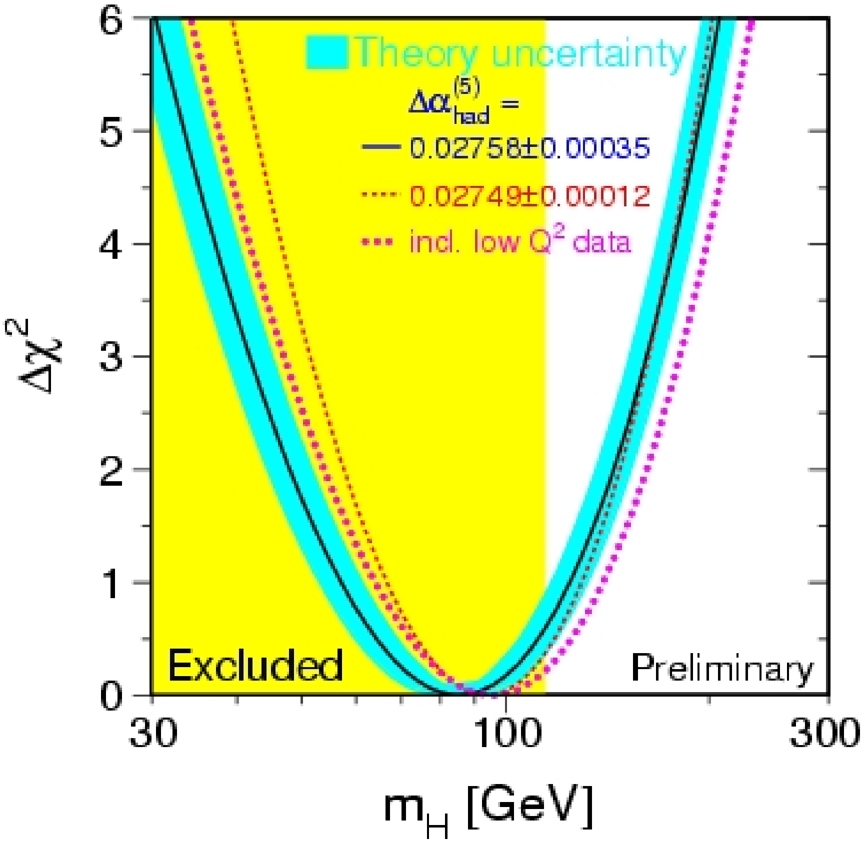


- The CDF Run II result is the most precise measurement to date

Impact on Higgs boson mass

Updated M_W *vs* M_{top}





- To match the current top mass precision of 2.1 GeV need the W mass accuracy of 15 MeV

Central value for m_H changed from

85^{+39}_{-28} GeV to 80^{+36}_{-26} GeV

(LEP EWWG preliminary)

Other electroweak measurements

- W/Z p_T and rapidity spectra, W charge asymmetry
  - Constrain PDFs in particular
- $Z \rightarrow \ell^+\ell^-$ forward-backward asymmetry, $Z \rightarrow \tau\tau$ (a reference for $h \rightarrow \tau\tau$ search)
- Di-boson production: $W\gamma$, $Z\gamma$, WW, WZ
  - Probe non-Abelian nature of $SU(2)_L \otimes U(1)_Y$ gauge boson self-interactions
- CDF: recent measurement of WZ cross section in $3\ell + \cancel{E}_T$ final states

Final data sample composition, $L_{int} = 1.1\ fb^{-1}$

Source	Expectation ± Stat ± Syst ± Lumi
Z+jets	$1.22 \pm 0.27 \pm 0.28 \pm$ -
ZZ	$0.89 \pm 0.01 \pm 0.09 \pm 0.05$
$Z\gamma$	$0.48 \pm 0.06 \pm 0.15 \pm 0.03$
$t\bar{t}$	$0.12 \pm 0.01 \pm 0.01 \pm 0.01$
WZ	$9.79 \pm 0.03 \pm 0.31 \pm 0.59$
Total Background	$2.70 \pm 0.28 \pm 0.33 \pm 0.09$
Total Expected	$12.50 \pm 0.28 \pm 0.46 \pm 0.68$
Observed	**16**

Result:

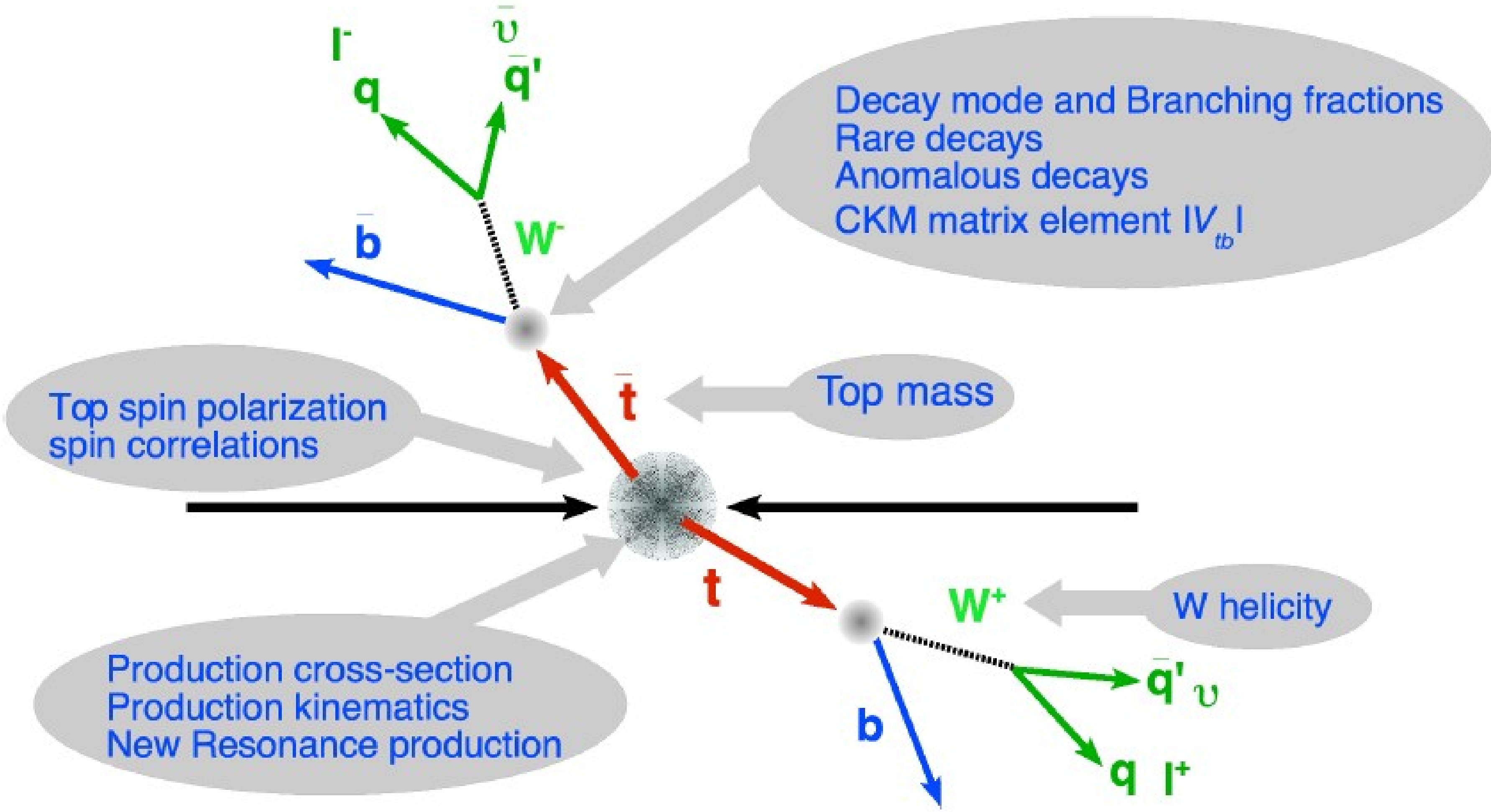
$$\sigma(WZ) = 5.0^{+1.8}_{-1.6}\ (\mathrm{stat.} + \mathrm{syst.})\ \mathrm{pb}$$

Consistent with the NLO prediction of 3.7±0.3 pb

Top physics

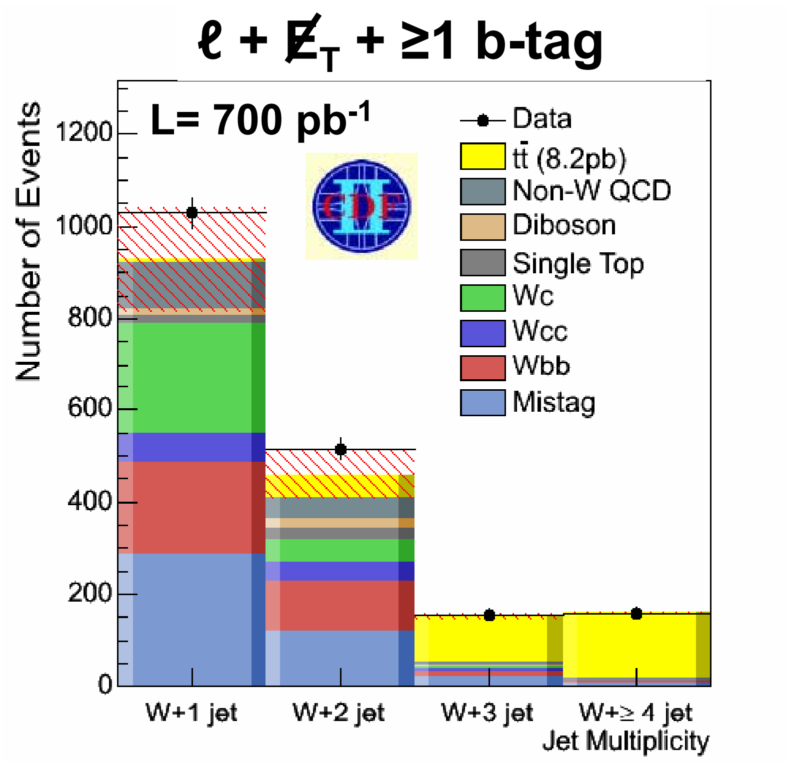
Motivation

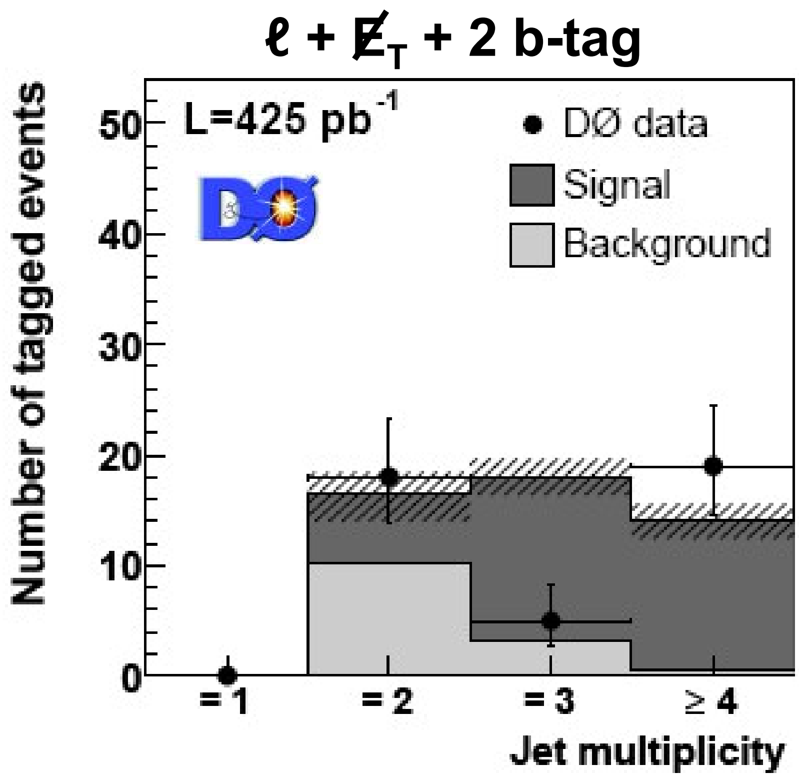
- Heaviest elementary particle – may hold a key for EW symmetry braking
- Unique opportunity to study bare quark since decays before hadronization



Lepton+jets cross section

- Golden channel due to high yield and relative purity (after b-tag)
- Events with a lepton (e/μ), missing E_T, ≥ 3 jets and with at least 1 b-tagged jet are used for the cross section measurement



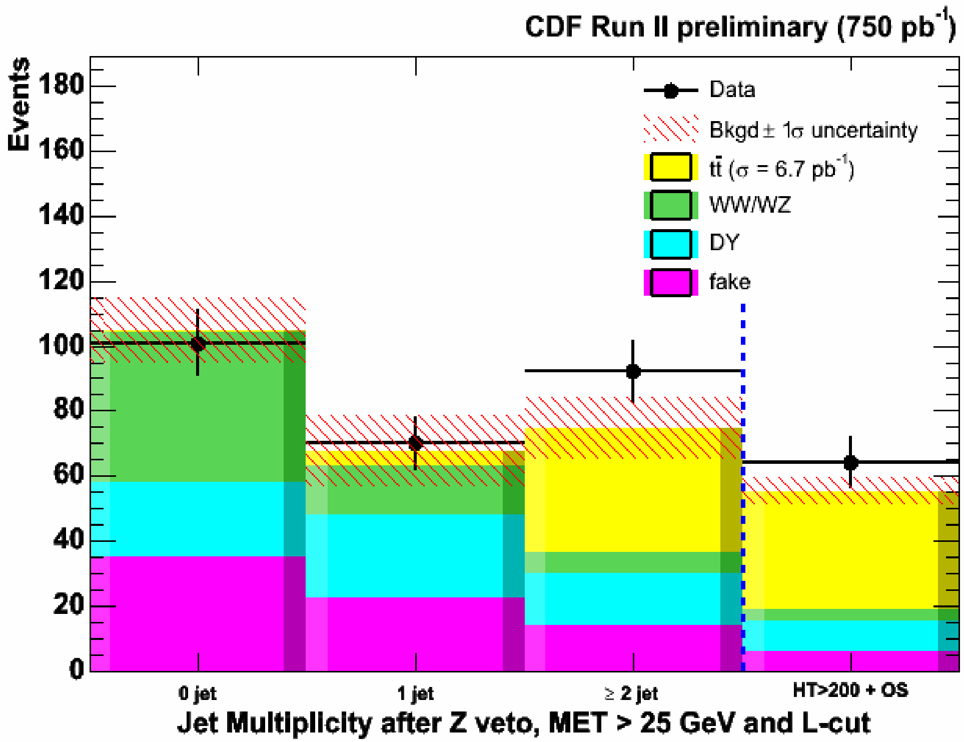


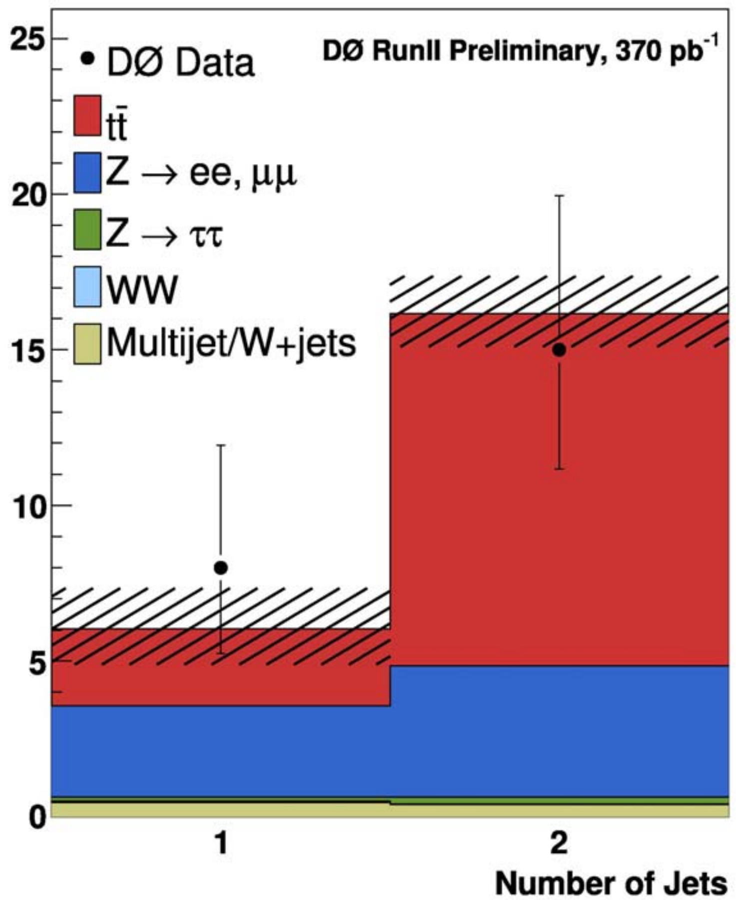
$$\sigma(t\bar{t}) = 8.2 \pm 0.6\,(\text{stat}) \pm 1.0\,(\text{syst})\,\text{pb}$$

$$\sigma(t\bar{t}) = 6.6 \pm 0.9\,(\text{stat}+\text{syst}) \pm 0.4\,(\text{lum})\,\text{pb}$$

Di-lepton final states

- Signal to background ratio already good enough with ℓ + MET + ≥2 jets
- Even more pure sample with b-tagging

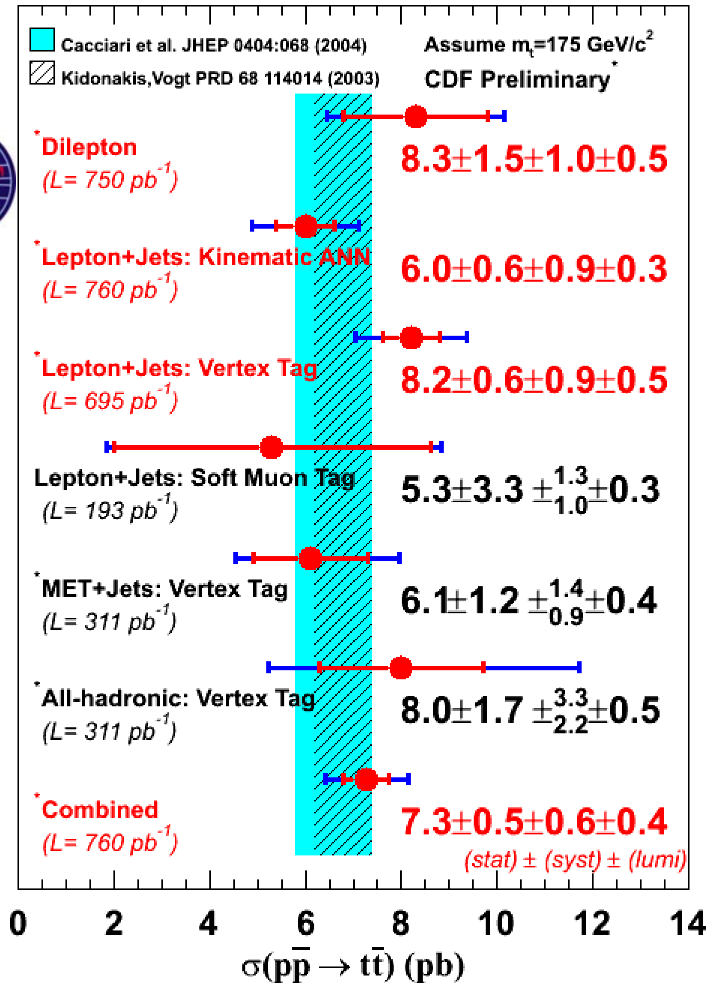


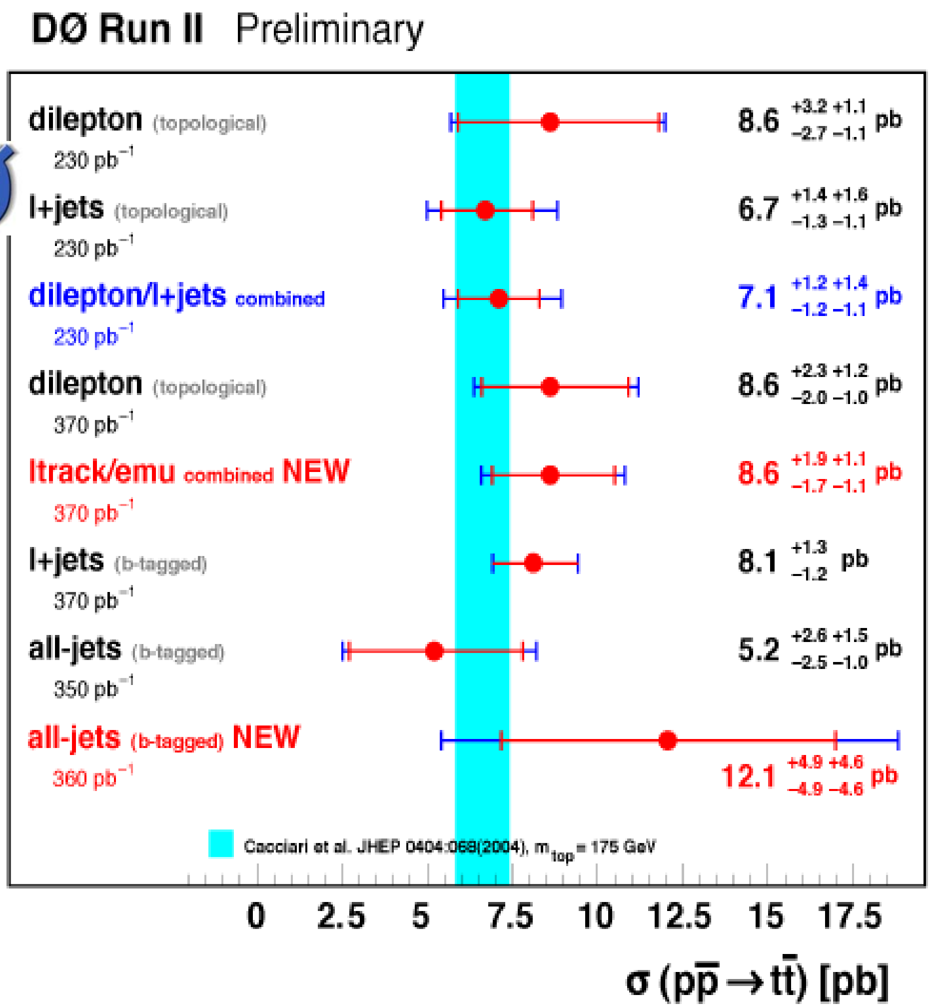


$$\sigma_{t\bar{t}}(\text{notag}) = 8.3 \pm 1.5_{stat} \pm 1.0_{syst} \pm 0.5_{lumi}\ \text{pb}$$

$$\sigma(t\bar{t}) = 8.6^{+1.9}_{-1.7}(\text{stat}) \pm 1.3(\text{syst})\text{pb}$$

$t\bar{t}$ cross section summary (few channels not up-to-date)



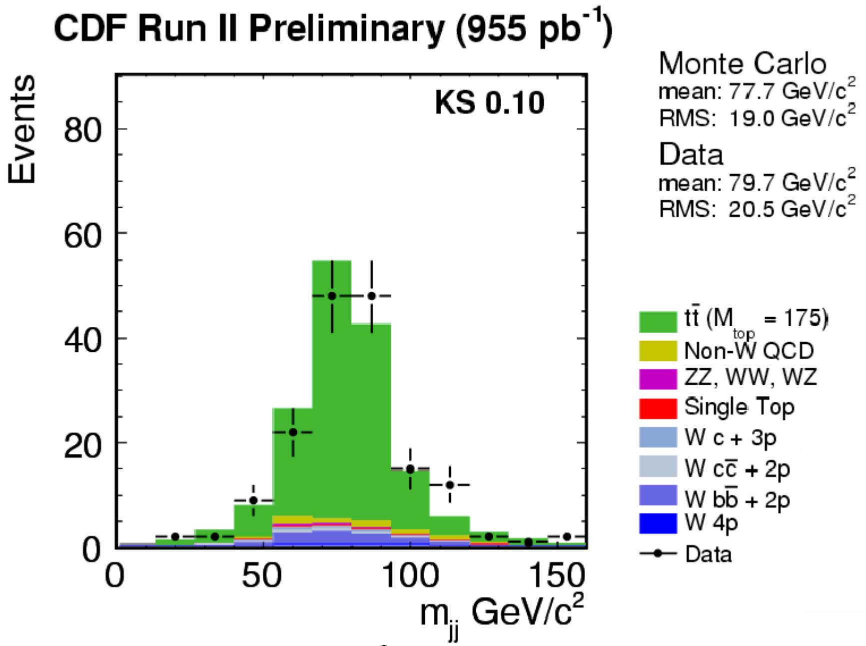


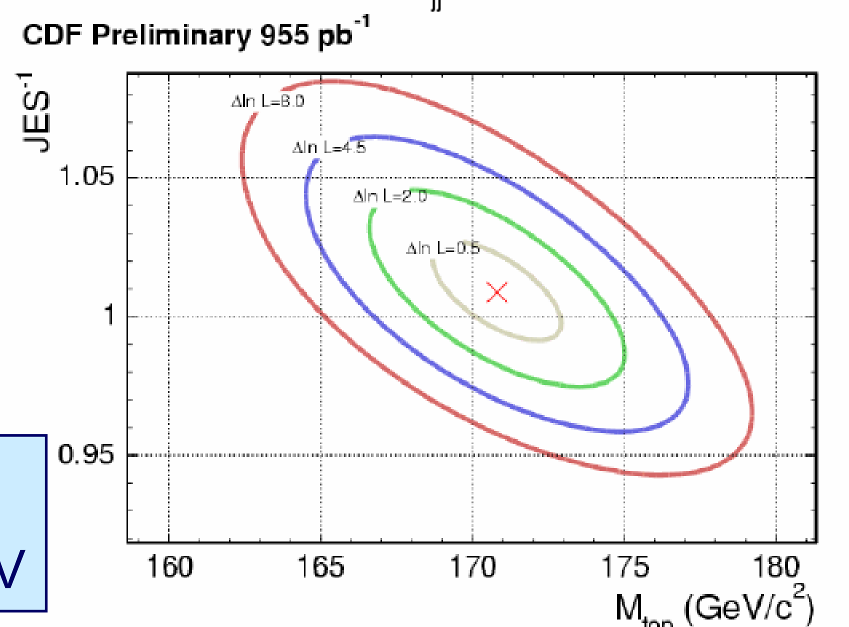
- Different channels and techniques all in agreement
- Precision at 14%. No CDF+DØ combined result as of yet

Tevatron goal: 10% uncertainty/experiment with 2 fb^{-1}

CDF: top mass in ℓ+jets channel using ME method

- Matrix Element method
  - Calculate likelihood for each event using LO ME for tt and W+jets diff. cross section and parameterized parton showering
- Select events with ≥1 b-tag
  - Signal/Background = 4/1
- One unknown, three constraints
  - Overconstrained
- Add jet energy scale as the 2nd unknown and fit for it
  - Obtain ΔJES = 0.99 ± 0.02
  - Consistent with a priori knowledge
  - Uncertainty only 2% !



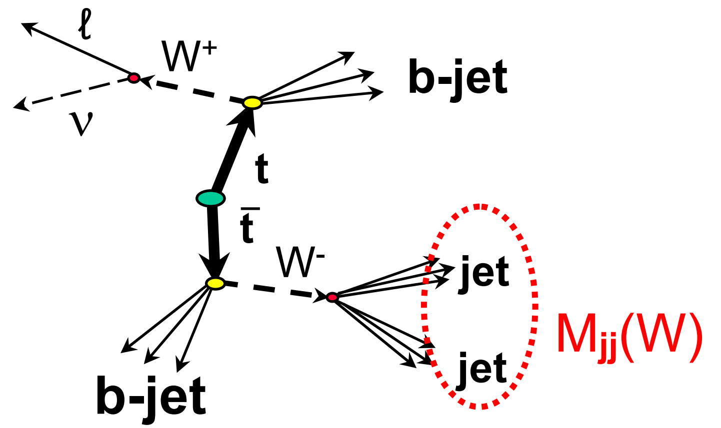


Single most precise measurement:

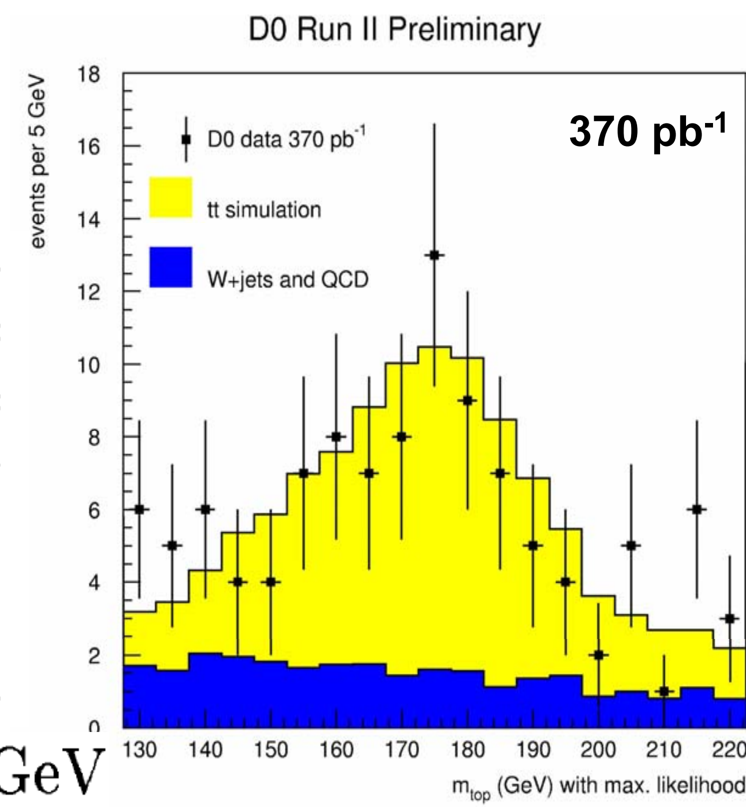
m_{top} = 170.9 ± 2.2 (stat+JES) ± 1.4 (sys) GeV

DØ: top mass in ℓ+jets channel using ideogram method

- Method
  - Calculate a likelihood for each event based on kinematic fit that includes all possible jet assignments and probability that an event is signal or background
- Use b-tag information when available
- In situ calibration of JES using jets from W
- Selections
  - Lepton $p_T > 20$ GeV, MET > 20 GeV, ≥4jets with $p_T > 20$ GeV and $|\eta| < 2.5$



	electron+jets	muon+jets
no. of events observed in data	116	114
estimated sample composition:		
$t\bar{t}$	61.5 ± 8	45.6 ± 8
W+jets	35.6 ± 5	63.0 ± 8
QCD	18.9 ± 3	5.4 ± 1



$$m_t = 173.7 \pm 4.4\ (\text{stat} + \text{JES})^{+2.1}_{-2.0}\ (\text{syst})\ \text{GeV}$$

Top mass in di-lepton final states

- Underconstrained system
  - 2 neutrinos, 18 kinematic quantities
  - 14 measured + 3 constraints

Both experiments use (among others)

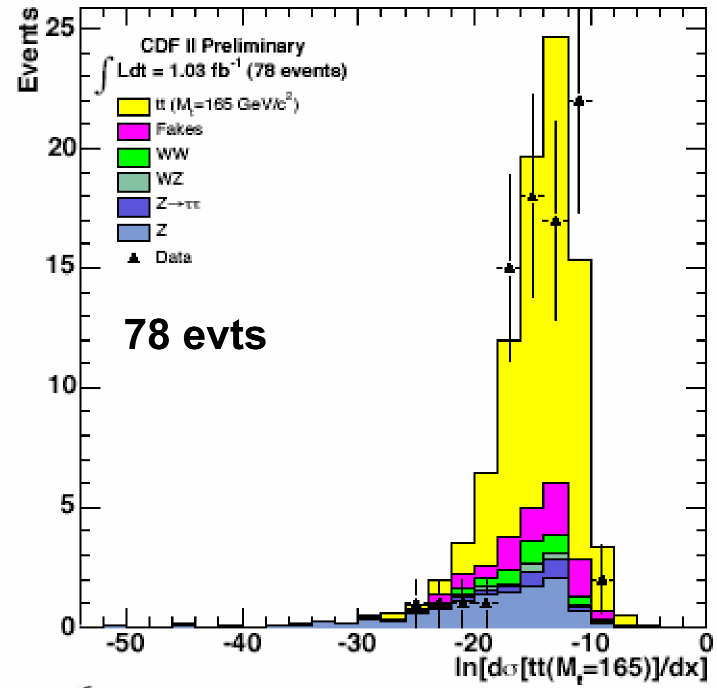
- ME technique
  - Calculate event-by-event signal probability curve (rather than single m_{rec}) using decay matrix element and transfer functions
- Neutrino weighting technique
  - Start by ignoring observed missing E_T, assume top mass and η for each ν and extract ν 4-momenta. Weight each solution

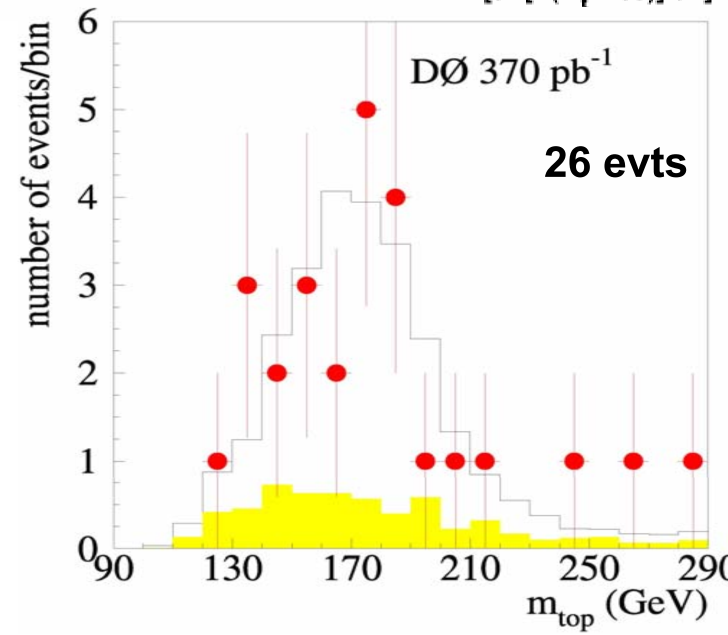
CDF's best result with ee, eμ and $\mu\mu$:

m_{top}=164.5±3.9 (stat) ±3.9 (sys) GeV

DØ's resent with ee, eμ, $\mu\mu$ and ℓ+track:

m_{top}= 178.1±6.7 (stat) ±4.8 (sys) GeV





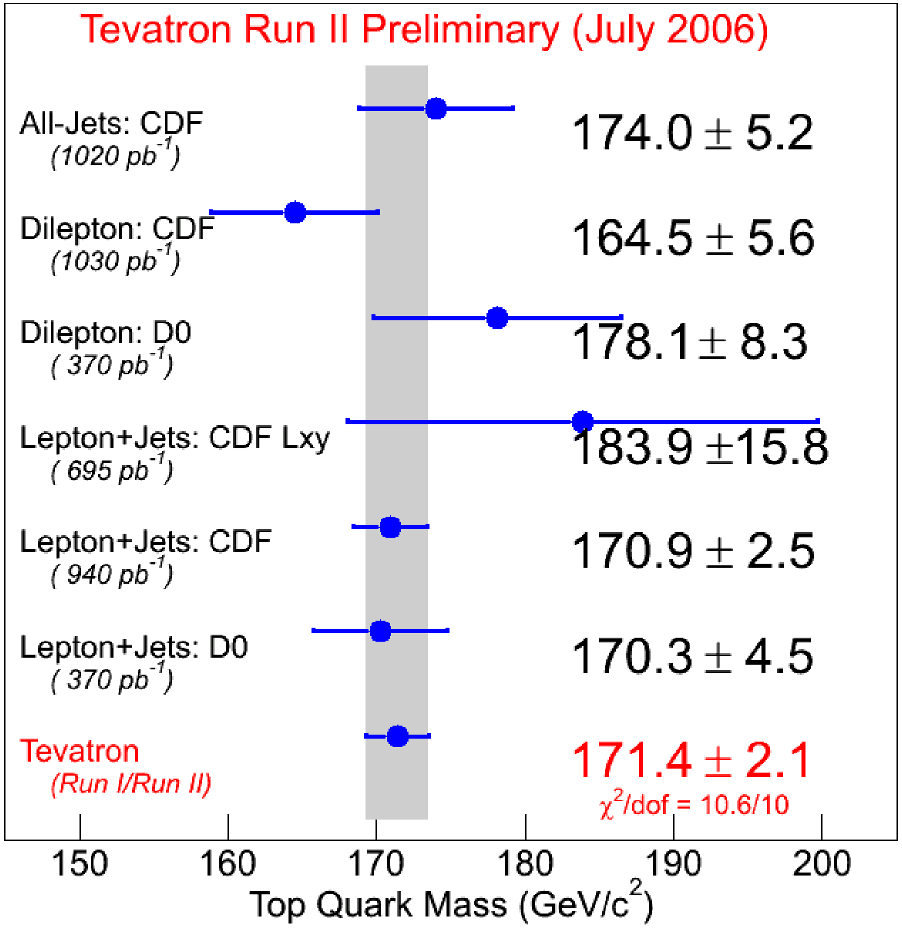
Top mass summary (July 2006)

- Excellent results in each channel
- Combine CDF + D0, Run I + Run II
- Account for all correlations
- m_{top} = 171.4 + 2.1 GeV
- Uncertainty:

  δm_{top}(stat) = $\pm$1.2 GeV

  δm_{top}(JES) = $\pm$1.4 GeV

  δm_{top}(syst) = $\pm$1.0 GeV

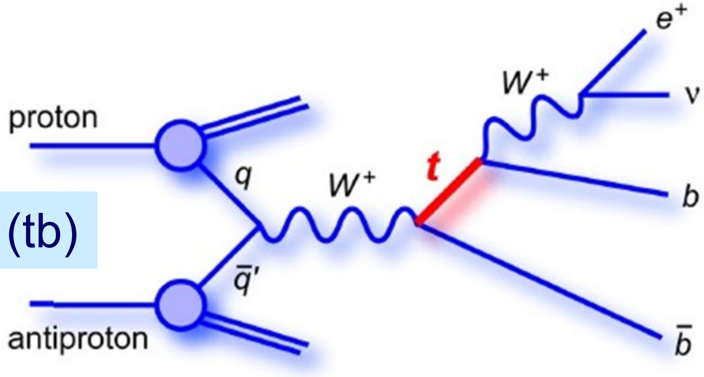


- Contributing factors
  - ISR, FSR, bkgd evaluation, PDF, NLO effects, b-tagging
- Jet Energy Scale is the leading systematic in all channels

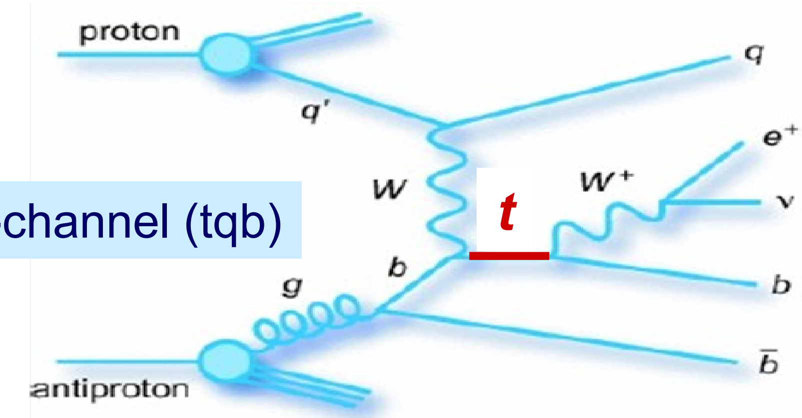
m_{top} determined to 1.2% !

Single top production: motivation

s-channel (tb)



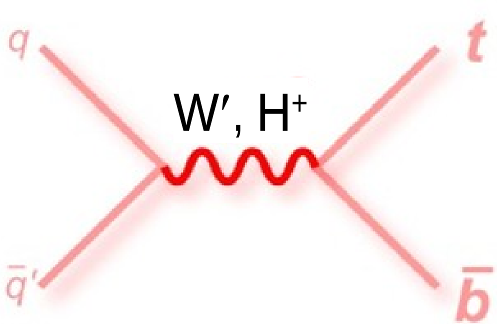
t-channel (tqb)

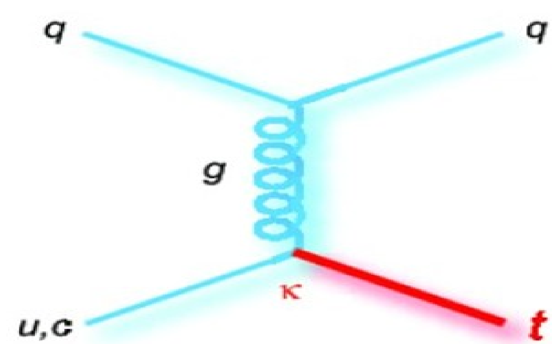


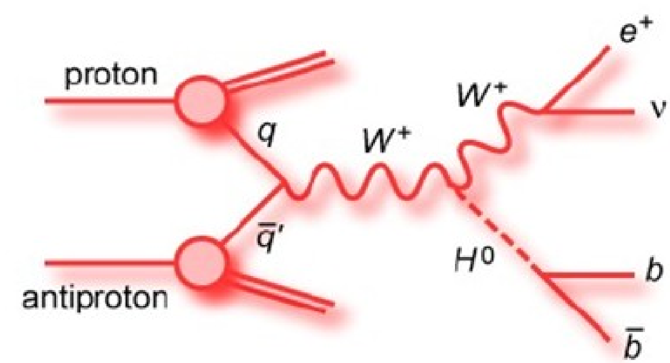
$\sigma_{NLO} \approx 0.9$ pb

$\sigma_{NLO} \approx 2$ pb

- Directly measure V_{tb}: $\sigma_{\text{single top}} \sim (V_{tb})^2$
- Cross section sensitive to new physics
  - Heavy *W′* boson, charged Higgs boson, etc.
  - Flavor changing neutral currents: *t-Z/γ/g-c* couplings
- Source of ~100% polarized top quarks
- Important background to the SM Higgs searches







DØ: single top event selection

- Select events with isolated leptons, large missing E_T and jets

Signal acceptance and S/B ratio in lepton + jets sample

Percentage of single top *tb+tqb* selected events and S:B ratio (white squares = no plans to analyze)

Electron + Muon	1 jet	2 jets	3 jets	4 jets	≥ 5 jets
0 tags	10% 1 : 3,200	25% 1 : 390	12% 1 : 300	3% 1 : 270	1% 1 : 230
1 tag	6% 1 : 100	21% 1 : 20	11% 1 : 25	3% 1 : 40	1% 1 : 53
2 tags		3% 1 : 11	2% 1 : 15	1% 1 : 38	0% 1 : 43

DØ: single top analysis strategy

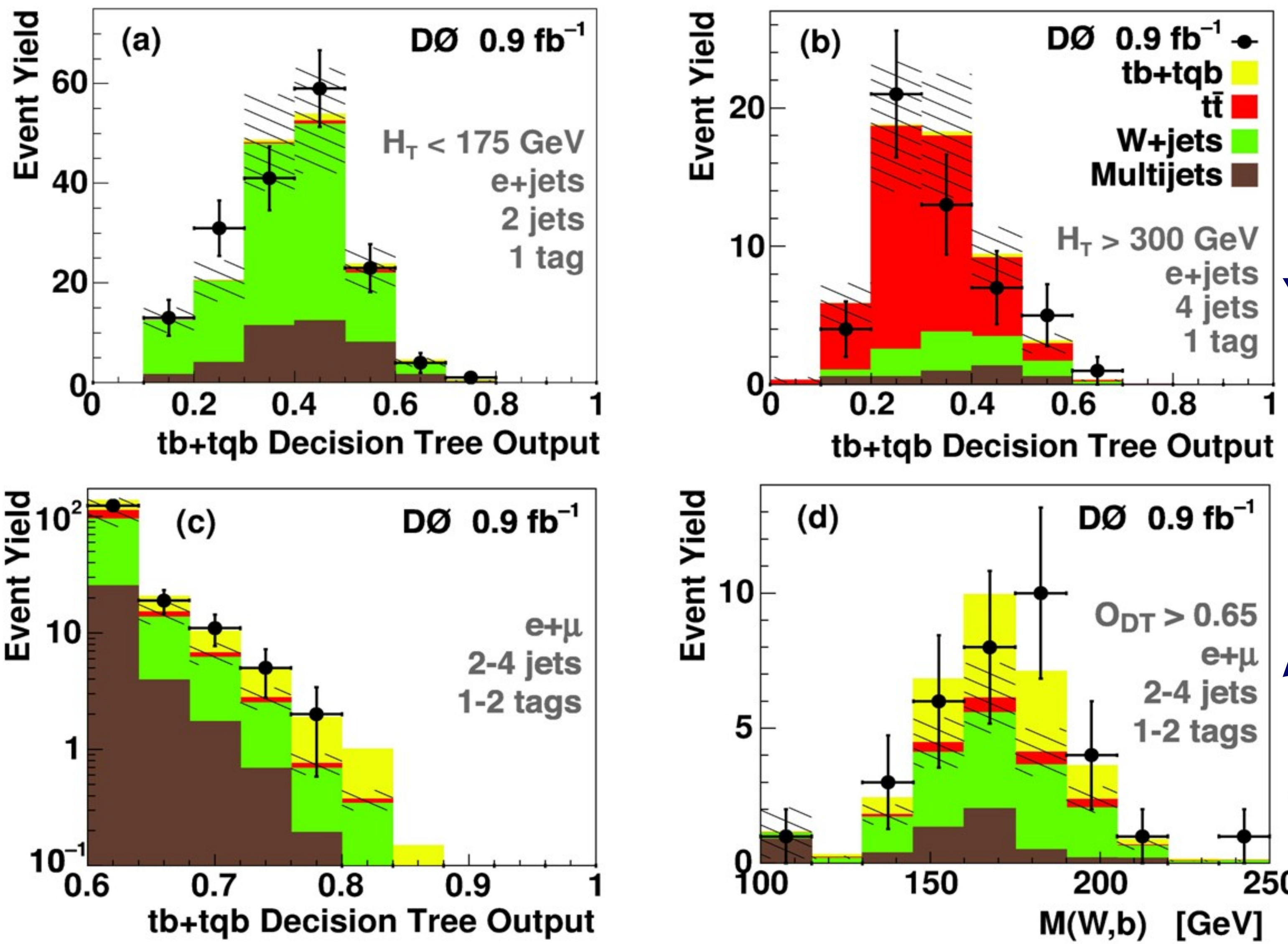
Composition of lepton + jets sample with 1 or 2 b-tags

Source	Event Yields in 0.9 fb^{-1} Data Electron+muon, 1tag+2tags combined 2 jets	3 jets	4 jets
tb	16 ± 3	8 ± 2	2 ± 1
tqb	20 ± 4	12 ± 3	4 ± 1
$t\bar{t} \to ll$	39 ± 9	32 ± 7	11 ± 3
$t\bar{t} \to l$+jets	20 ± 5	103 ± 25	143 ± 33
$W+b\bar{b}$	261 ± 55	120 ± 24	35 ± 7
$W+c\bar{c}$	151 ± 31	85 ± 17	23 ± 5
$W+jj$	119 ± 25	43 ± 9	12 ± 2
Multijets	95 ± 19	77 ± 15	29 ± 6
Total background	686 ± 131	460 ± 75	253 ± 42
Data	697	455	246

- Employ several multivariate analysis techniques to extract the signal
  - Decision Trees, Matrix Elements method, Bayesian Neural Network

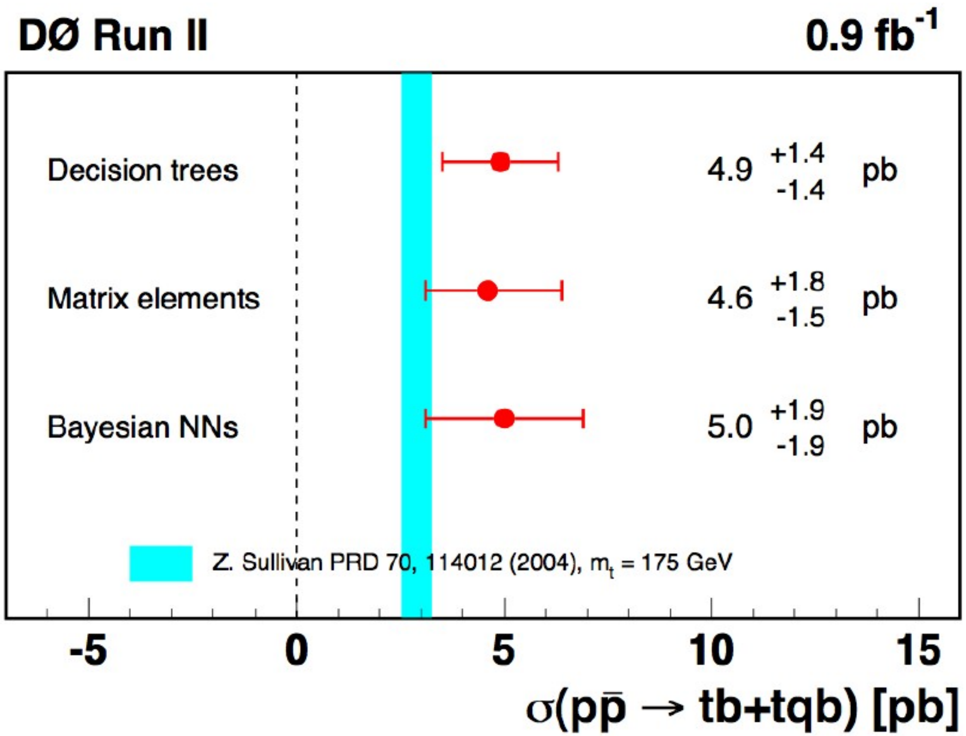
DØ: single top analysis (II)

Example: Decision Tree discriminant output (a-c) and the top mass spectrum (d)



Signal and background enriched samples

DØ: single top results



- All three techniques are in good agreement
- Evidence for the single top production with a significance of 3.4 standard deviations; the cross section

  4.9 ± 1.4 pb
- This measurement is used to directly constrain (without assumption on CKM matrix unitarity) the $|V_{tb}|$:

  $0.68 < |V_{tb}| \leq 1.0$ at 95% C.L.

DØ: top quark charge

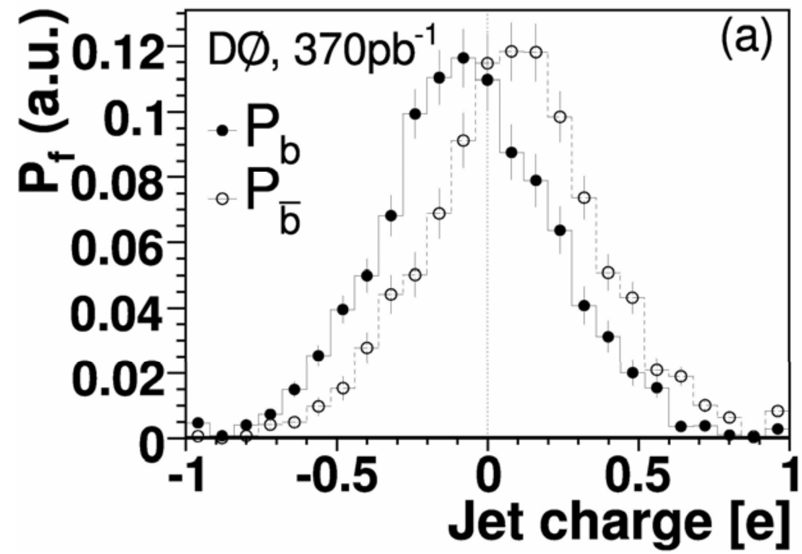
- t → Wb could mean top has charge – 4/3
- Jet charge estimator

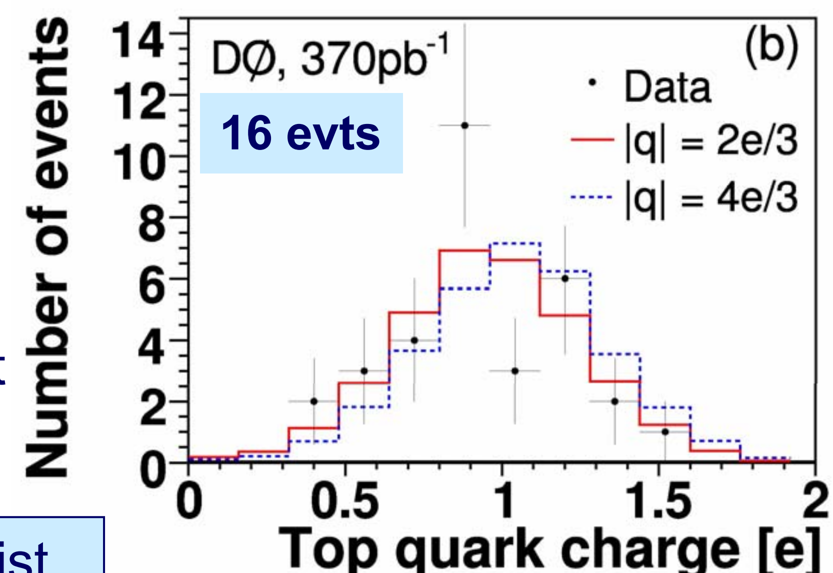
$$q_{\text{jet}} = \frac{\sum q_{\text{track}} * p_T^{0.6}}{\sum p_T^{0.6}}$$

- b/c jet charge distributions derived from data → use them in simulations
- ℓ+jet sample of double b-tag tt candidates
  - Use kinematic/mass constraint fit to pair lepton with the correct b jet
- Have two entries per event:

$\boldsymbol{Q_1 = |q_\ell + q_{b\ell}|}$ ← leptonic side of the evt

$\boldsymbol{Q_2 = |-q_\ell + q_{bh}|}$ ← hadronic side of the evt

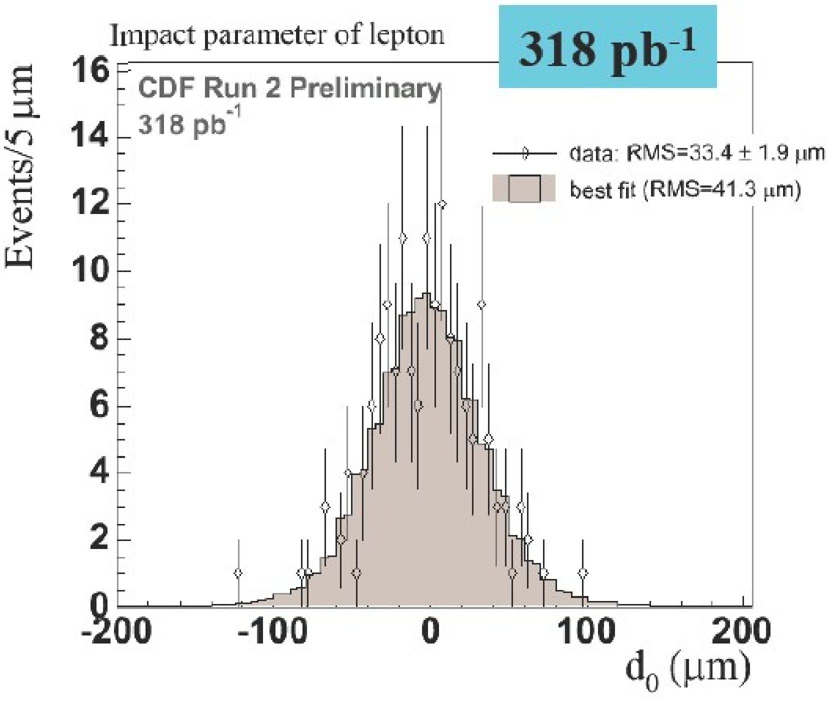




Exclude at 92% CL that the sample consist of only QQ pairs with charge |q| = 4e/3

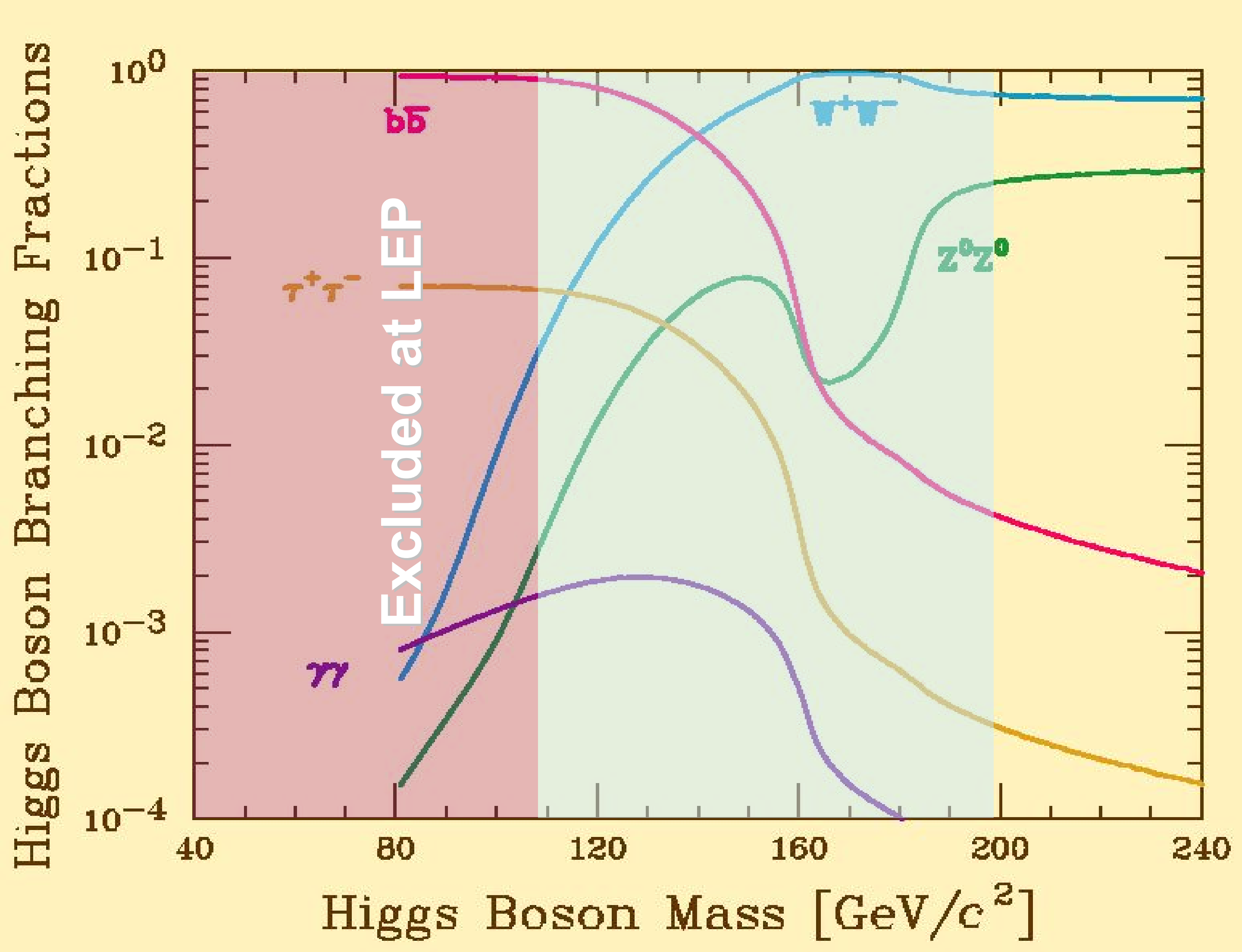
Other active top topics (not discussed here)

- W helicity in top decays
  - SM: longitudinal fraction f_0 = 0.7, right-handed fraction $f_+ = 3.6\times10^{-4}$
  - Several methods: lepton p_T, M_{lb}^2, $\cos\theta^*$
  - Results consistent with the SM prediction; still stat. limited
- BR(t→Wb) / BR(W→Wq)
  - $1.03^{+0.19}_{-0.17}$
- Top quark lifetime
  - $c\tau < 52.5\ \mu m$ ($\sim1.8\times10^{-13}$ s) at 95% CL
- Search for tt resonances
  - m(X) > 725 GeV at 95% CL
- 4th generator t‘ quark
  - m(t‘) > 258 GeV at 95% CL
- Search for W’ → tb decays
  - $m(W'_L/W'_R)$ > 610/630 GeV at 95% CL



Higgs searches

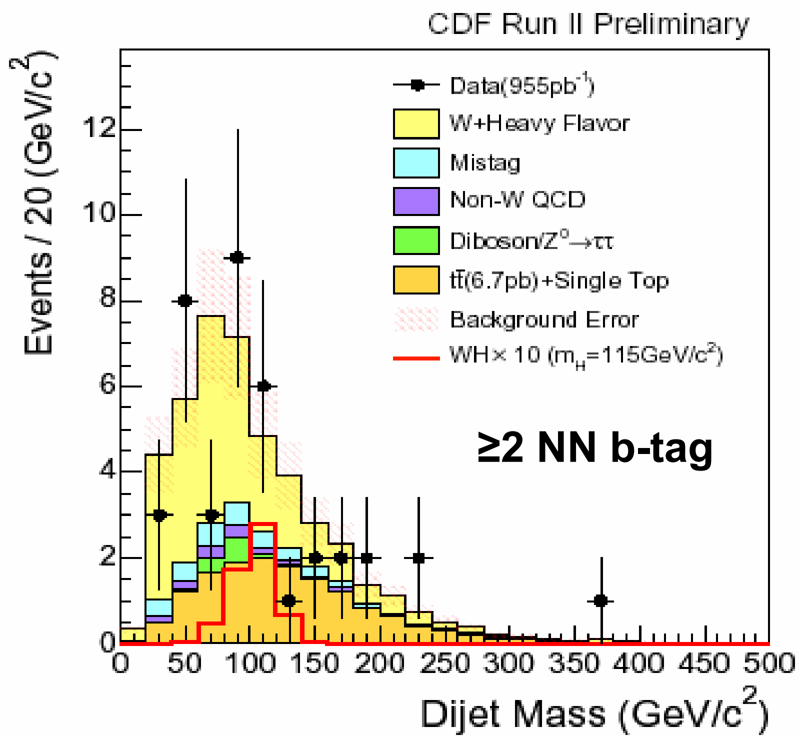
The SM Higgs boson decays

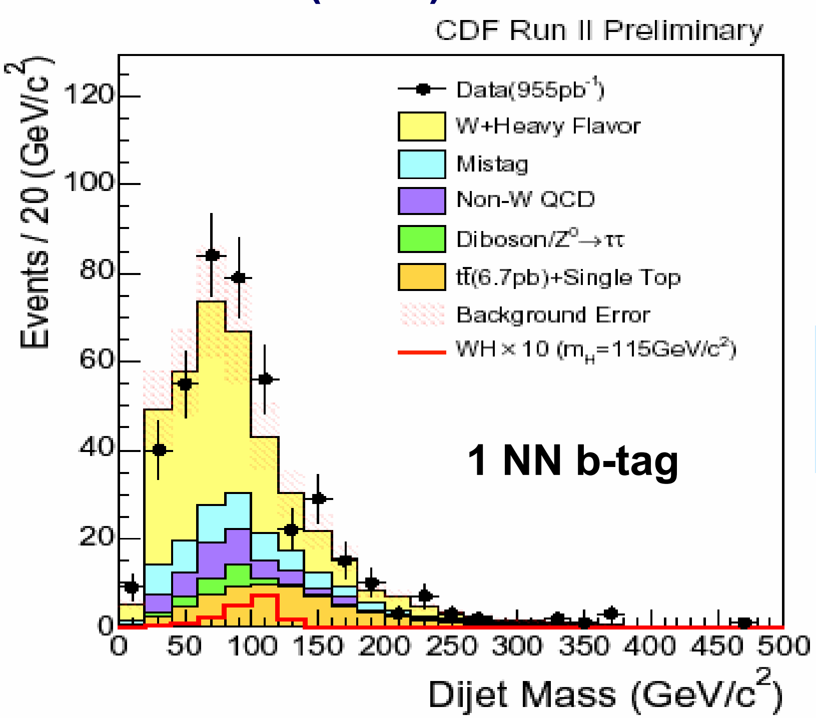


Tevatron can explore bb and WW decay modes

CDF: WH → ℓνbb channel

- Lepton, missing E_T and 2 jets
  - One or two b-tags
- New since last year
  - NN b-tagger
  - Include double-tag
  - Include full 1 fb^{-1} dataset
  - Luminosity equivalent gain
    - **$(S/\sqrt{B})^2=1.25^2=1.6$**





σ_{WH} < 3.9 - 1.3 pb for m_H= 110 - 150 GeV
Measured limit/SM rate = 23 (m_H=115 GeV)

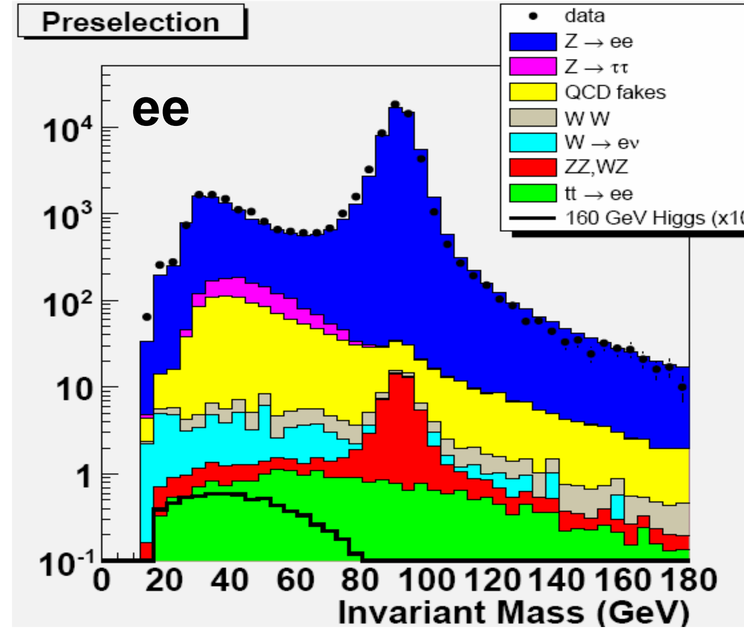
DØ: H → WW* → $\ell^+\ell^-\nu\nu$ decays; ℓ = e, μ (1)

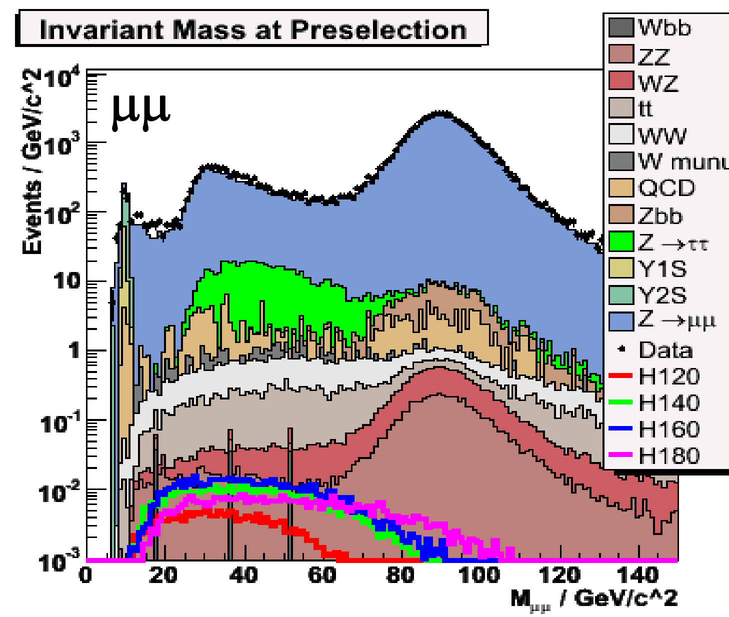
- Event selection include
  - Isolated lepton
    - $p_T(\ell_1) > 15$ GeV, $p_T(\ell_2) > 10$ GeV
  - Missing E_T > 20 GeV
  - Scaled missing E_T > 15 (suppress evts. with mismeasured jet energy)

$$\not{E}_T^{\mathrm{Sc}} = \frac{\not{E}_T}{\sqrt{\sum_{\mathrm{jets}}\left(\Delta E^{\mathrm{jet}} \cdot \sin\theta^{\mathrm{jet}} \cdot \cos\Delta\phi\left(\mathrm{jet}, \not{E}_T\right)\right)^2}}$$

  - Veto on
    - Z resonance
    - Energetic jets

Data vs MC after evt. preselection

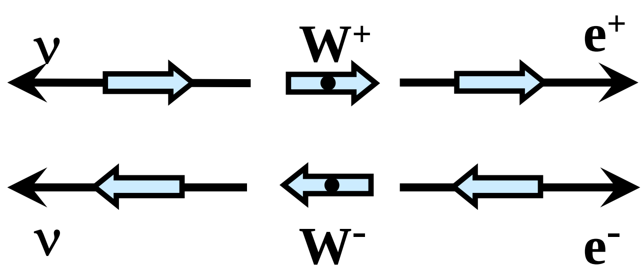




- Data correspond to integrated lumi. of 950-930 pb^{-1} depending on the final states

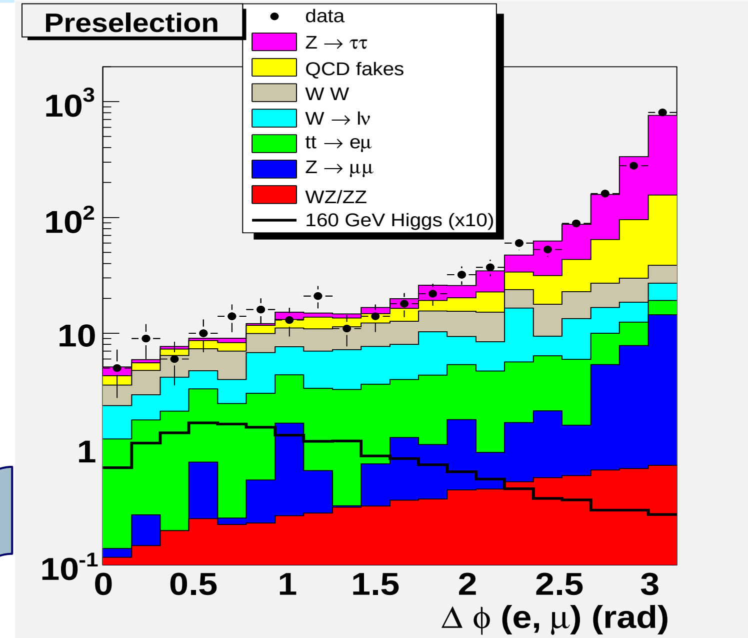
DØ: $H \rightarrow WW^* \rightarrow \ell^+\ell^-\nu\nu$ decays (2)

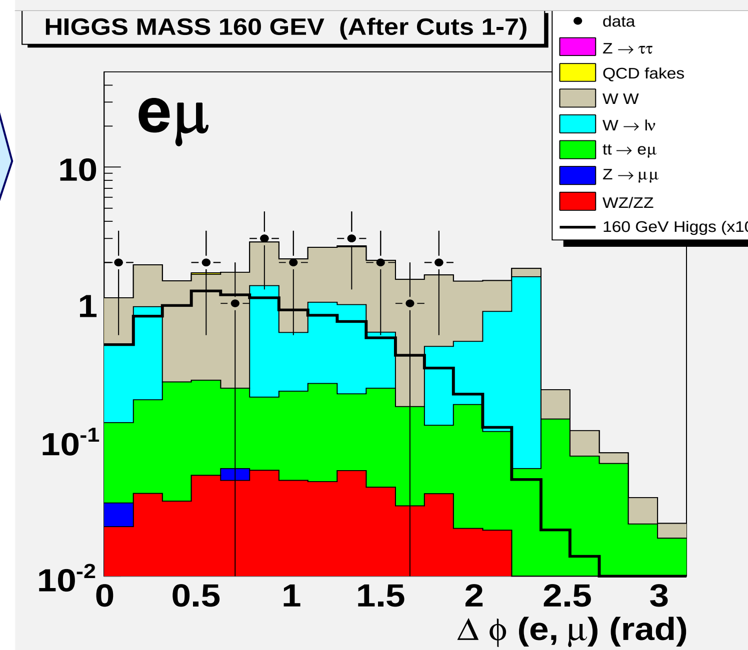
- Higgs mass reconstruction not possible due to two neutrions
- Employ spin correlations to suppress the bkgd.
  - $\Delta\phi(\ell\ell)$ variable is particularly useful



- Leptons from Higgs tend to be collinear

Good agreement between data and MC after all selections and in all final states

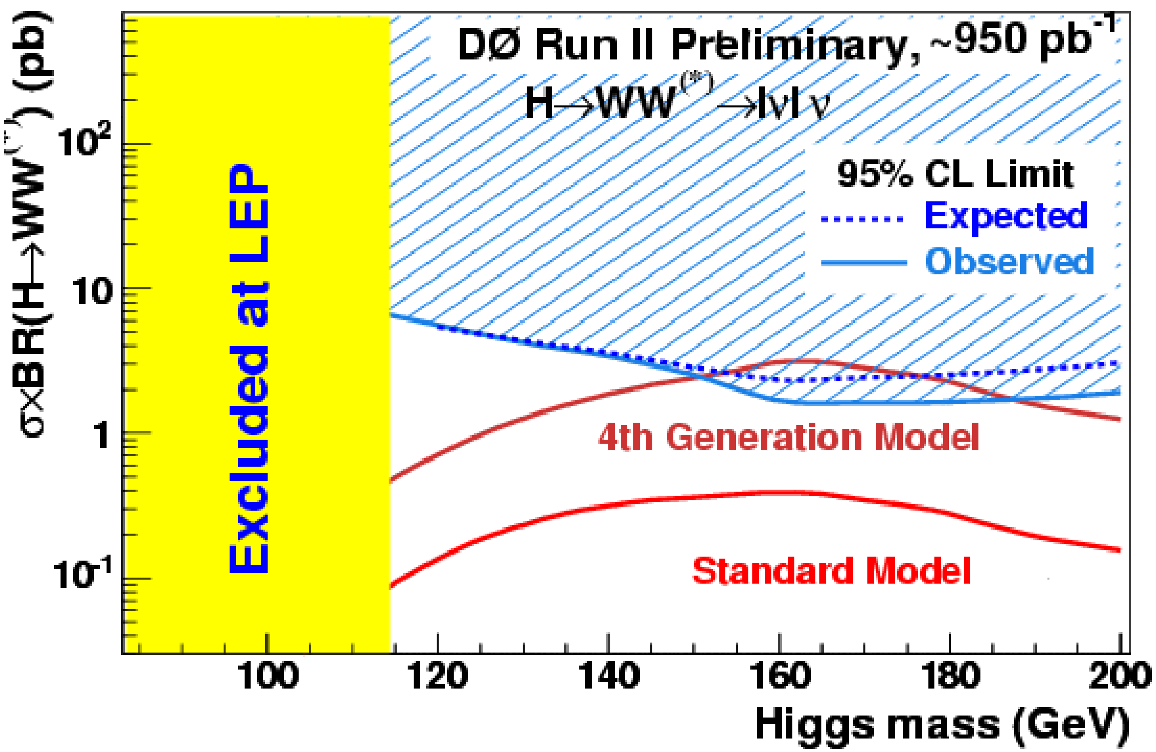




DØ: results on H → WW*

Expected/Observed # of events for m_H = 160 GeV (L ~ 950 pb^{-1})

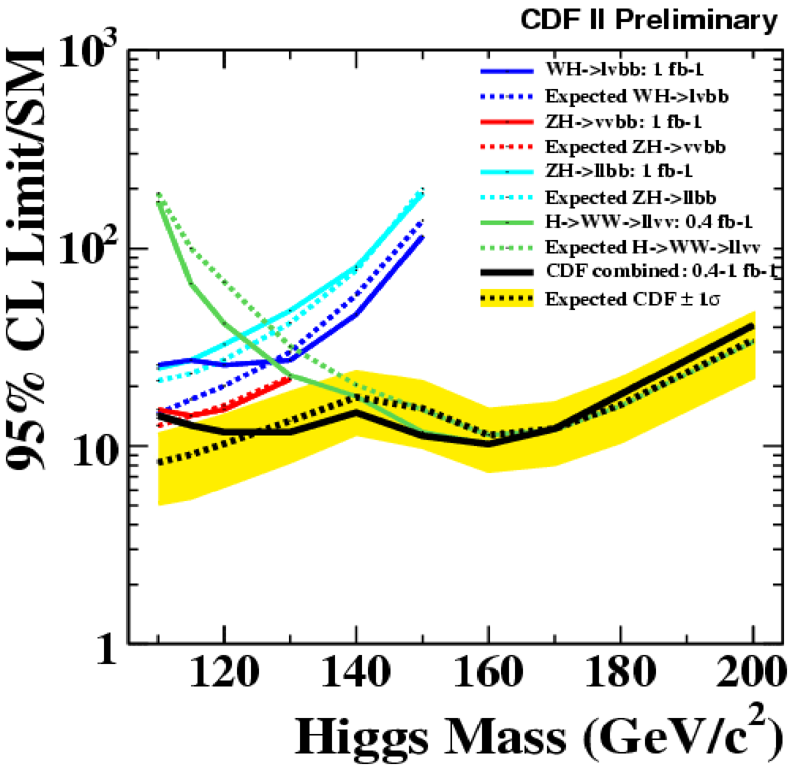
	Data	Sum BGND	WW	W+jet/γ	Z/γ *	tt(bar)	WZ / ZZ	QCD	H--> WW*
e e	10	10.3 ± 0.6	7.0 ± 0.2	1.4 ± 0.6	0.0 ± 0.0	1.1 ± 0.1	0.8 ± 0.1	0.06 ± 0.02	0.415
e μ	18	24.4 ± 1.5	16.4 ± 0.1	5.3 ± 1.5	0.02 ± 0.01	2.1 ± 0.1	0.6 ± 0.1	0.1 ± 0.05	0.97
μμ	9	9.8±0.8	6.6±0.1	1.0±0.4	0.6±0.4	0.5±0.1	0.5±0.1	0.6±0.6	0.35

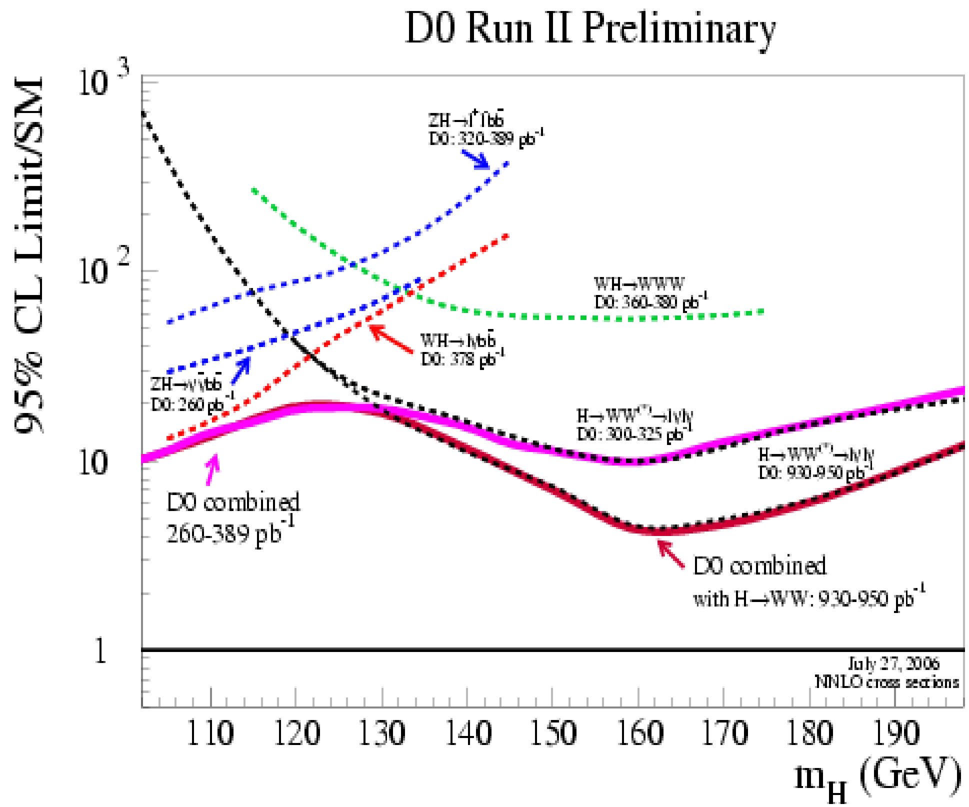


- If m_H= 160 GeV then might have a couple of Higgses in our sample already !

- SM only a factor 4 away
- 4^{th} generation models with m_H=150-185 GeV excluded

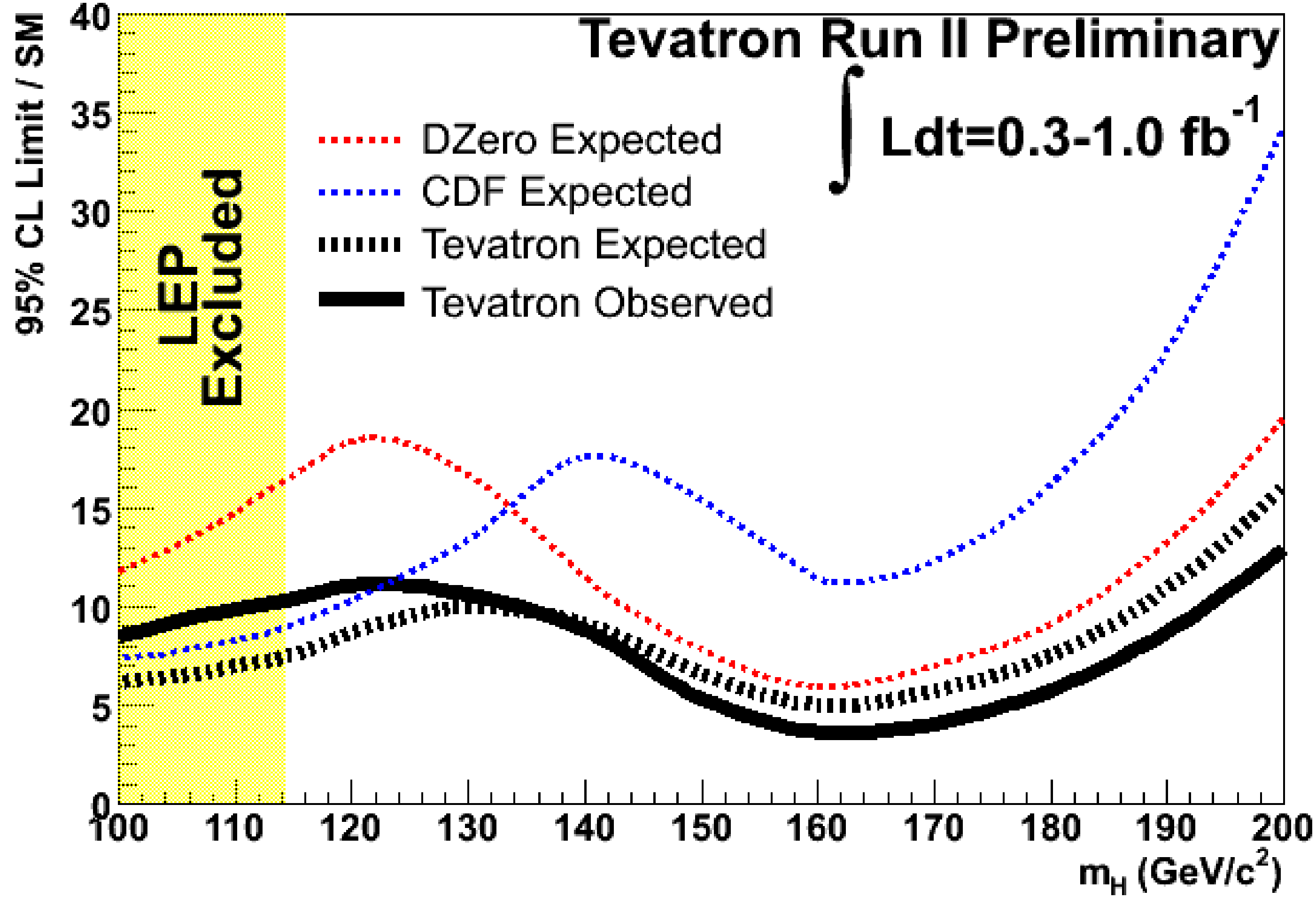
Limits from CDF and DØ





Analysis	**CDF**, M_H = 115 GeV (factor above SM)	**DØ**, M_H = 115 GeV (factor above SM)
ZH → ννbb	Includes WH w/ miss ℓ (14)	3.4 pb (41)
WH → ℓνbb	3.4 pb (23)	2.4 pb (16)
ZH → ℓℓbb	2.2 pb (27)	6.1 pb (75)

Limits from CDF and DØ combined



Searches for SUSY Higgs bosons

- In MSSM have two Higgs doublet fields
  - H_u (H_d) couple to up- (down-) type fermions
  - The ratio of their VEV's

    $\tan\beta = \langle H_u\rangle / \langle H_d\rangle$
  - 5 Higgs particles after EWSB

    h, H, A, H^+, H^-
  - h is "guaranteed" to be light

    m_h <~ 130-140 GeV

- At large $\tan\beta$, coupling to down-type quarks, i.e. b's, is enhanced wrt SM
  - At tree level ~ $\tan\beta$ → production cross section rise as $\tan\beta^2$

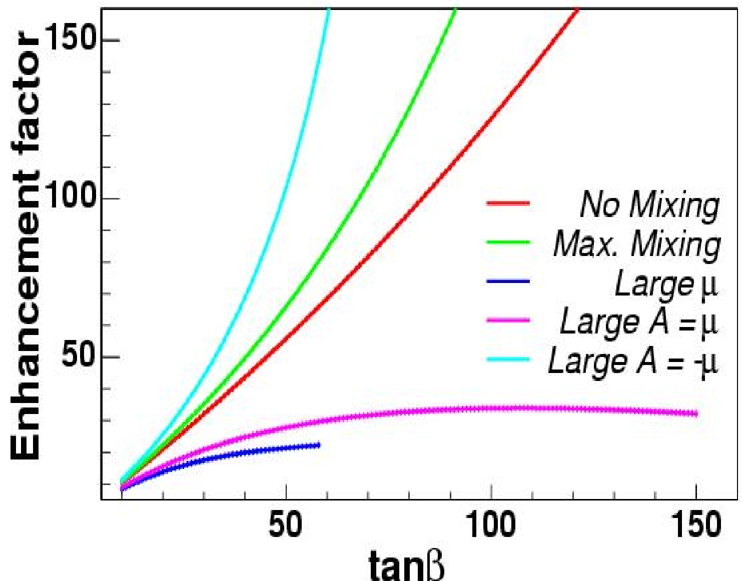
- CP conservation is assumed in the following analyses

Loop level corrections to x-section and BR

$$\sigma \times BR_{SUSY} = 2 \times \sigma_{SM} \times \frac{\tan\beta^2}{(1+\Delta_b)^2} \times \frac{9}{[9+(1+\Delta_b)^2]}$$

with $$\Delta_b = \frac{\Delta h_b}{h_b} \times \tan\beta$$

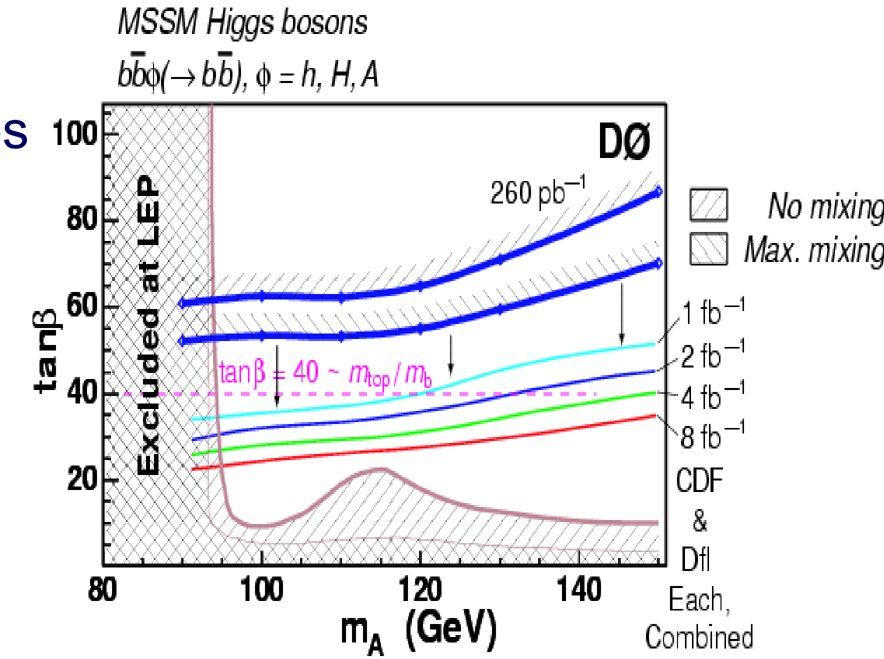
Function of various SM/SUSY parameters: $X_t = A_t - \mu\cot\beta$, μ, M_g, M_q, etc.



MSSM higgs searches: CDF and DØ published results

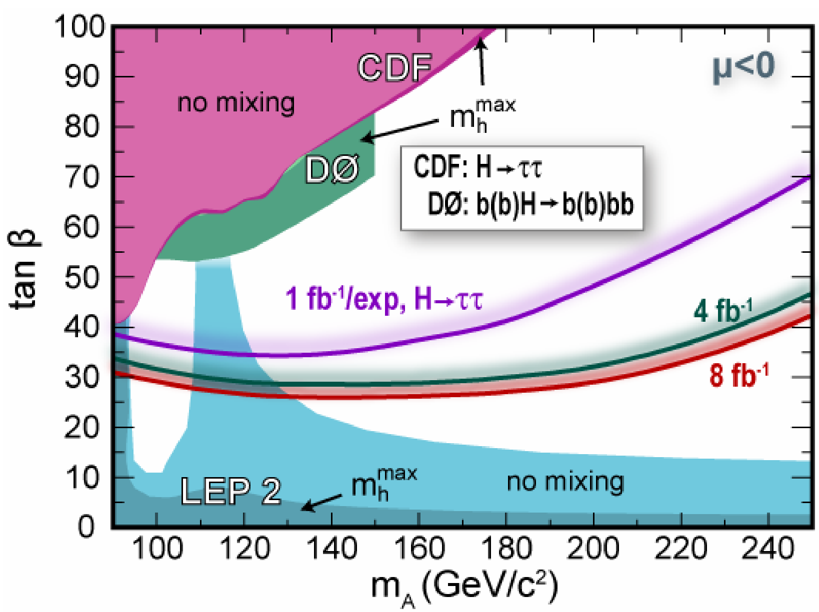
Associated production with b quarks

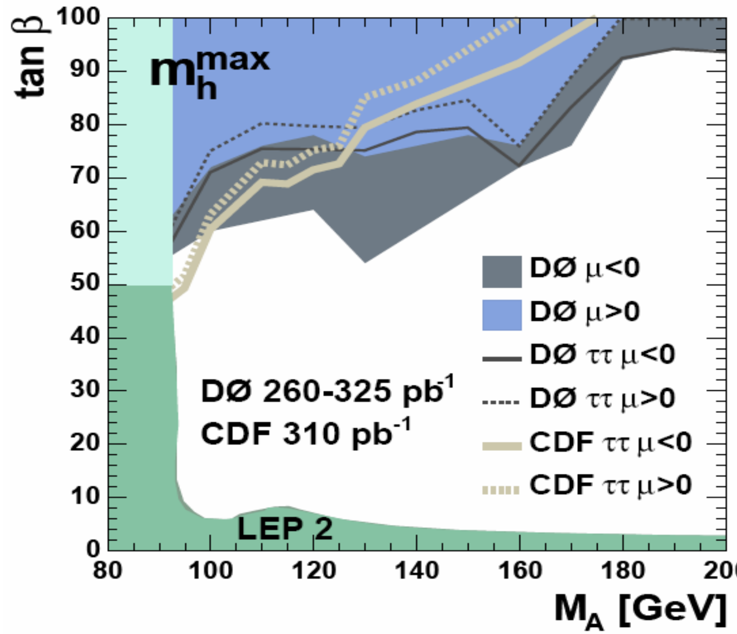
- DØ: bh/bbh(→bb) → 3/4 b's in final states
  - Require ≥ 3 b-tagged jets
  - Background evaluated from data
  - Look for excess in di-jet mass window



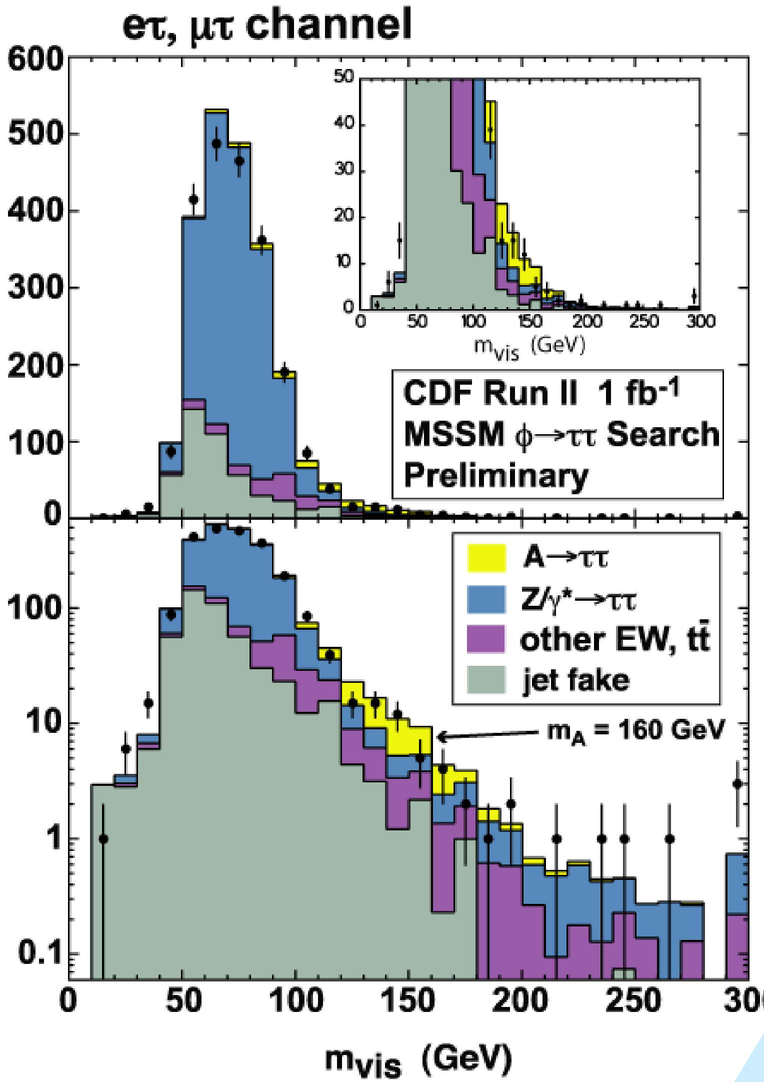
Inclusive production

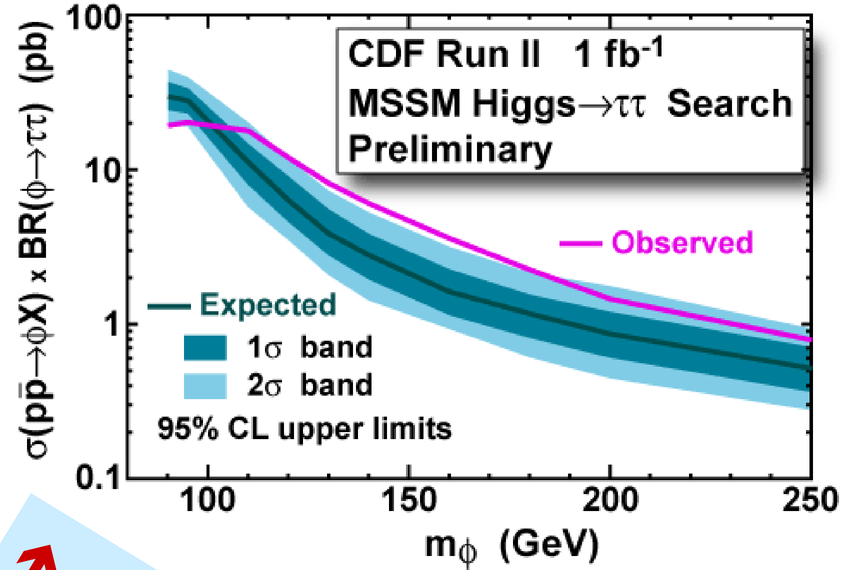
- CDF and DØ: h → ττ → $e\tau_h$, $\mu\tau_h$, or eμ
  - Look for excess in m_{vis} (= mass of visible τ decay products and missing E_T) spectrum

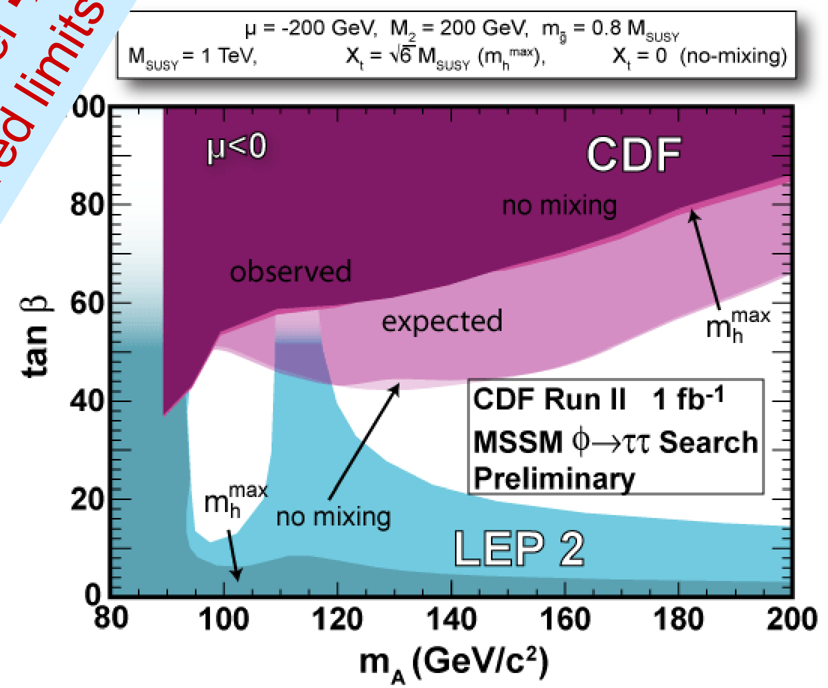




h → ττ: CDF preliminary with 1 fb^{-1}







"Discrepancy" at ~2σ level
no claims, but impaired limits

- eμ channel agrees with data (not shown here)

Summary

- Upgraded for Run II Tevatron, CDF and DØ are performing well and contribute to world class physics at the energy frontier

- Most of Run I Electroweak measurements are improved and new processes are established, such as di-boson production
  - Good agreement with the SM so far

- Both experiments are in the era of precision top quark measurements
  - Many results are now systematics limited that will improve with more data

- In coming years, the CDF and DØ concerted efforts will offer a real opportunity to find the SM, or non-SM, Higgs boson or exclude a very interesting low-mass region

- Tevatron will bring more order to many scenarios before the LHC start up !