Bread and Butter Physics at the Tevatron

2004 Phenomenology Symposium
University of Wisconsin, Madison
Apr. 26, 2004

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Fermilab
For the CDF and D0 Collaborations

Dedication

This talk is dedicated to the memory of my friend and colleague Harry Melanson, who was originally supposed to have given this talk, but who passed away suddenly and unexpectedly on Apr. 17, 2004.

Tevatron Run II

The World's Highest Energy Accelerator.

Collision Energy

1.80 → 1.96 TeV

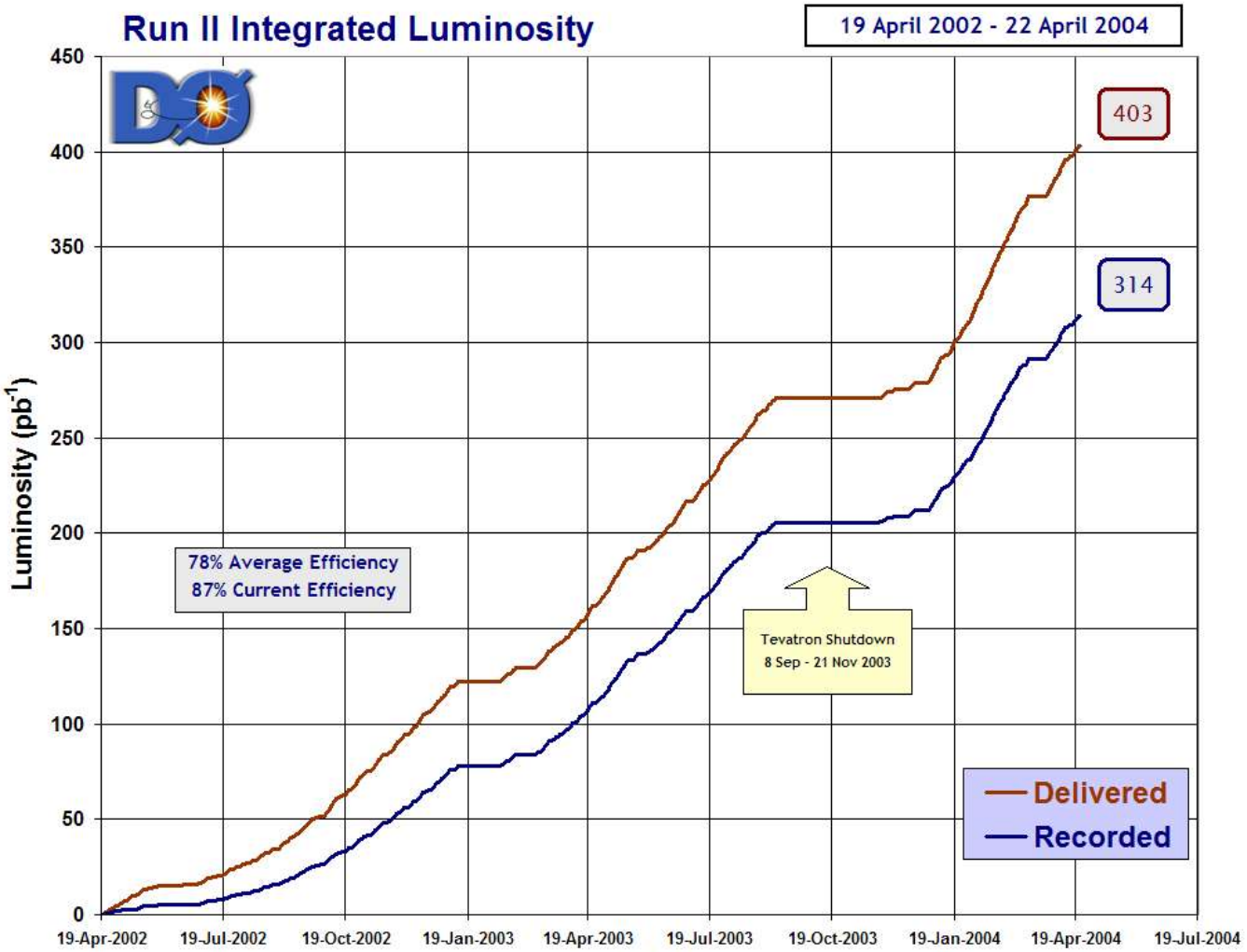
Luminosity

Run I: **~0.1 fb^{-1}**

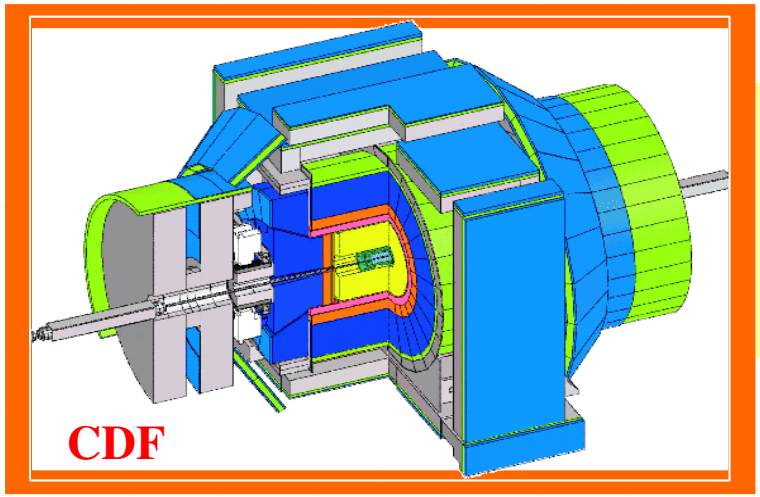
Run II: **4-9 fb^{-1}**

recorded so far: ~300pb^{-1}

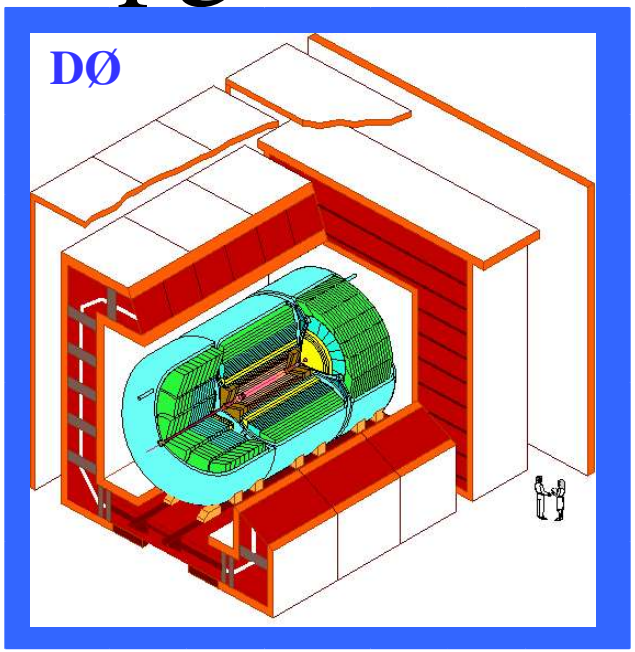
The Tevatron has been running well in 2004.



CDF & DØ Detector Upgrades



Upgrades enhance the ability to make sensitive searches



- New central drift chamber and silicon tracker
- New forward calorimeters ("plug") ($1<|\eta|<3$)
- New TOF, extended muon coverage
- improved tracking & secondnary vertex trigger

- New Silicon and Fiber tracker in 2T magnetic field
- Added preshower detector in front of calorimeter
- Improved muon system
- New DAQ and trigger system

The Tevatron Physics Program

- Higgs boson searches (SM and non-SM).
- New phenomena (SUSY and other non-SM physics).
- Top Quark.
- Electroweak (W and Z bosons).
- QCD.
- Heavy flavor physics (b and c quarks).

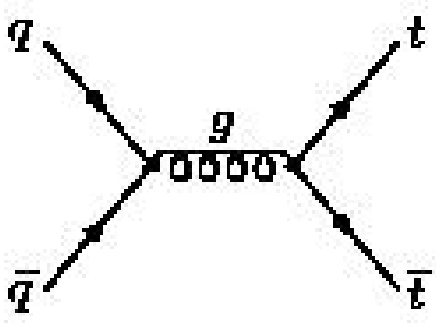
Last four covered in this talk.

Top Quarks at the Tevatron

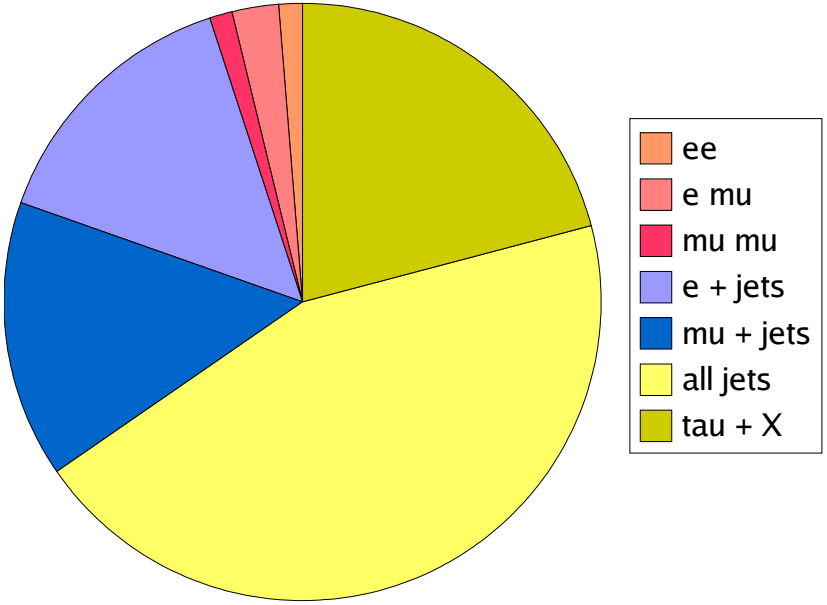
- Top quark pair production cross section.
- Single top quark production cross section.
- Top quark mass.
- Top quark properties.
  - *W* polarization.
  - Top polarization.
  - Spin correlation.

Top Quark Pair Production

- Top quarks are pair-produced by strong interaction.



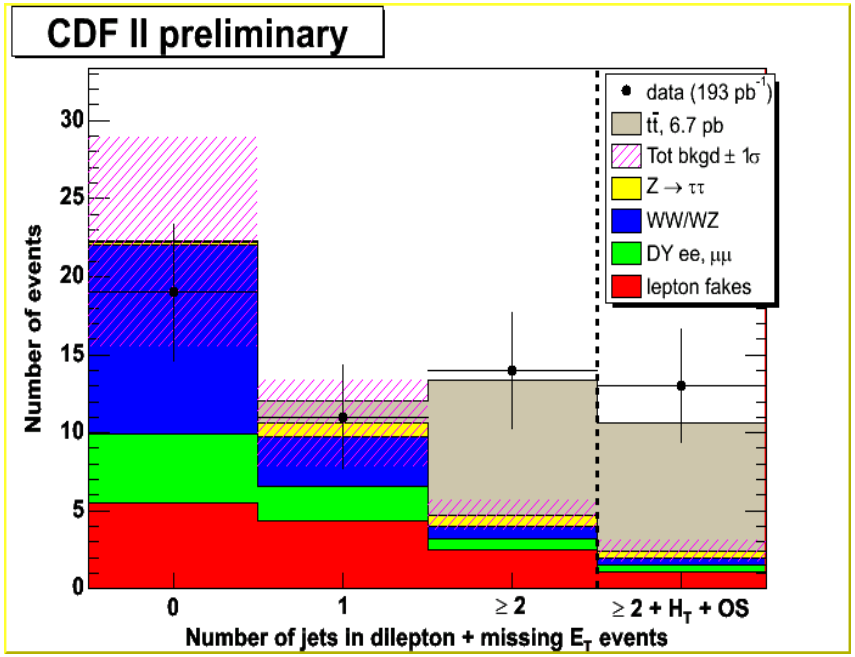
- Top quarks decay 100% to W + b quark.

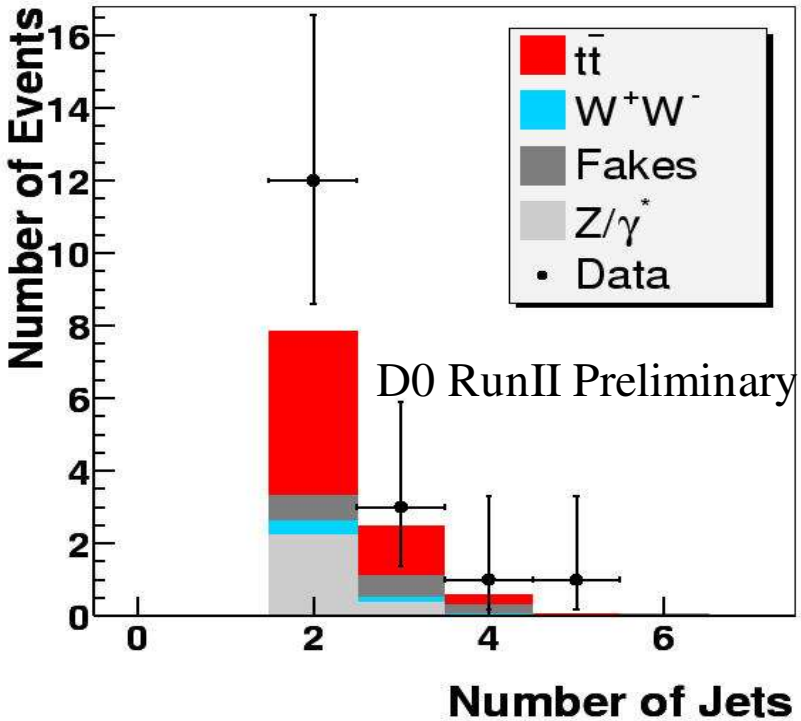


- Decay signatures:
  - Dilepton ee, $e\mu$, $\mu\mu$ (5%).
  - Lepton + jets (30%).
  - All jets (44%).
  - τ + lepton, τ + jets (21%).

Top to Dileptons

- Signature: 2 leptons + 2 b jets + missing E_T.
- Backgrounds: $Z(ee, \mu\mu, \tau\tau)$, WW, WZ, fakes.





CDF dilepton: $\sigma_{tt} = 8.7\ ^{+3.9}_{-2.6}$(stat.) ±1.4 (syst.) ± 0.5 (lum.) pb ($\mathscr{L}$=193 pb^{-1})

CDF l + iso track: $\sigma_{tt} = 6.9\ ^{+2.7}_{-2.4}$(stat.) ±1.2 (syst.) ± 0.4 (lum.) pb ($\mathscr{L}$=202 pb^{-1})

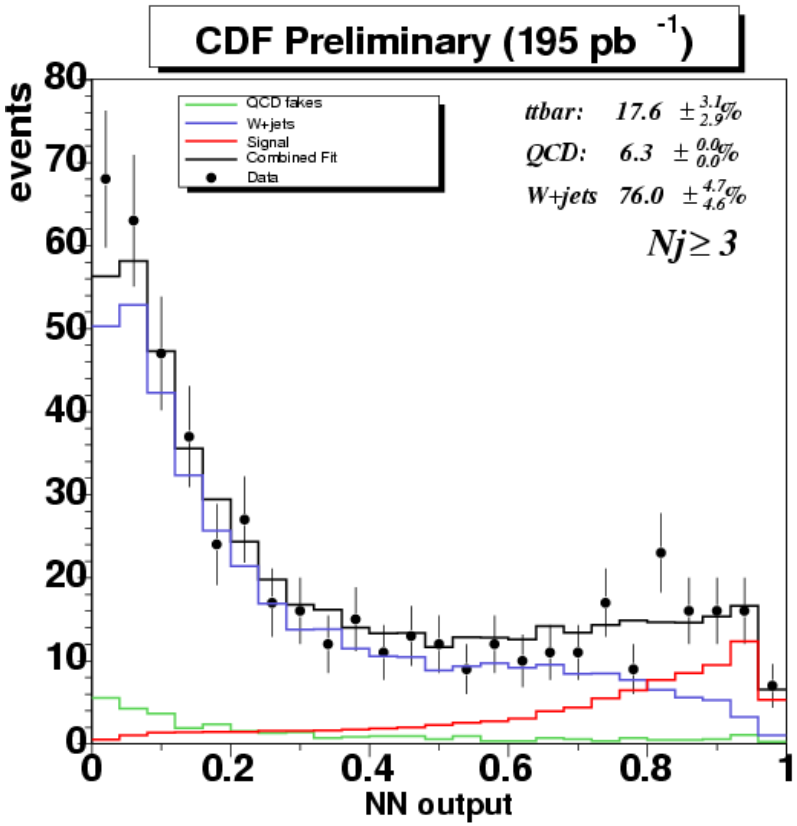
D0 dilepton: $\sigma_{tt} = 14.3\ ^{+5.1}_{-4.3}$(stat.) $^{+2.6}_{-1.9}$(syst.) ± 0.9 (lum.) pb ($\mathscr{L}$=140-156 pb^{-1})

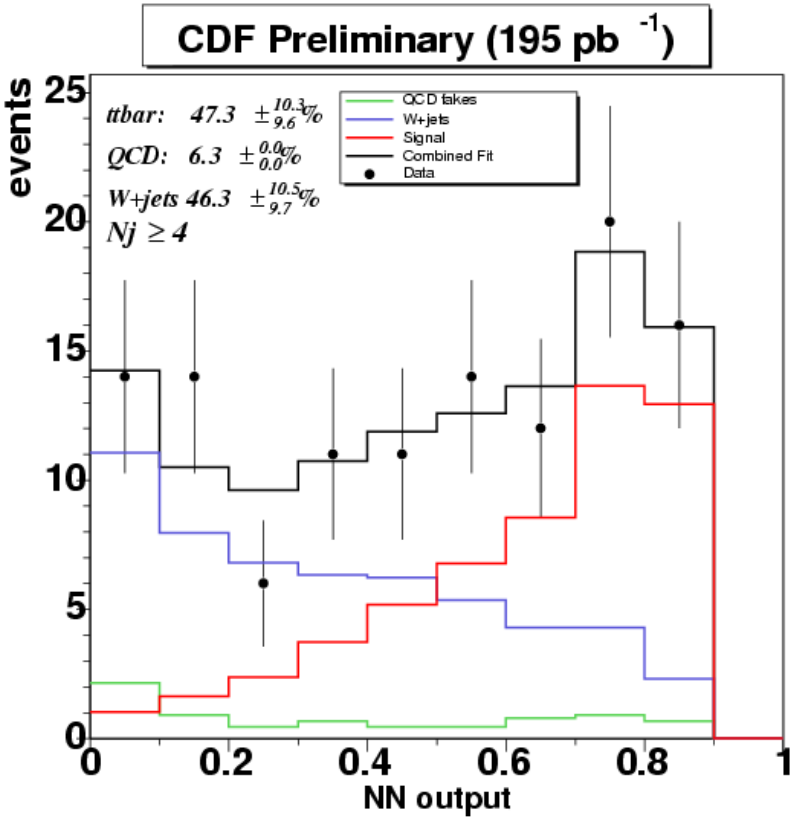
Top to Lepton + Jets

- Signature: 1 lepton + 4 jets (incl. $2b$) + missing E_T.
- Backgrounds: W+jets, fakes, WW, WZ.
- Lepton + jets (topological).
  - Analyze event shape (often using multivariate methods to combine several different event shape variables).
- Lepton + jets + b-tag.
  - Soft lepton tag.
  - Displaced vertex tag.

CDF Lepton + Jets (topol.)

- Seven kinemtic variables combined in neural network.

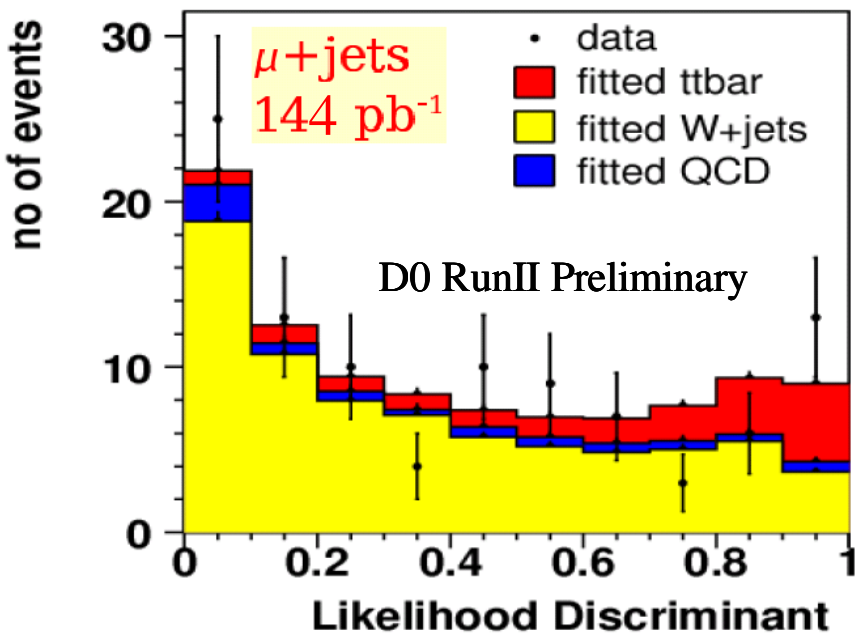


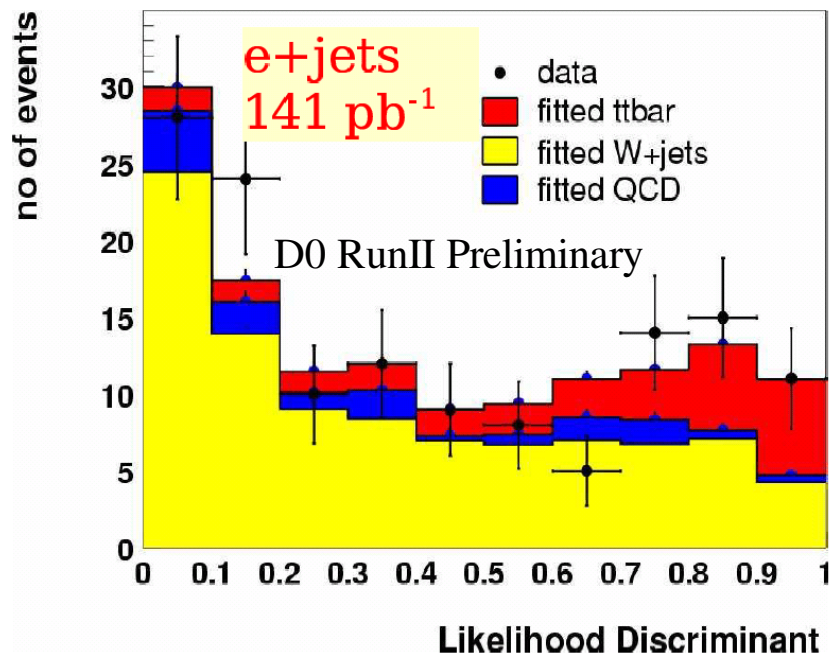


Sample	Observed Evts	$t\bar{t}$ fraction	$\sigma(t\bar{t})$
W+≥3 Jets	519	0.176 ± 0.030	$6.7 \pm 1.1 \pm 1.6$ pb
W+≥4 Jets	118	0.473 ± 0.100	$7.5 \pm 1.6 \pm 1.8$ pb

D0 Lepton + Jets (topol.)

- Four kinematic variables combined in likelihood disc.



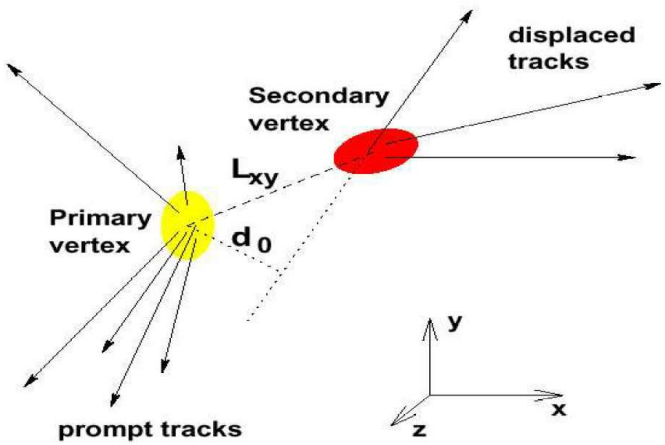


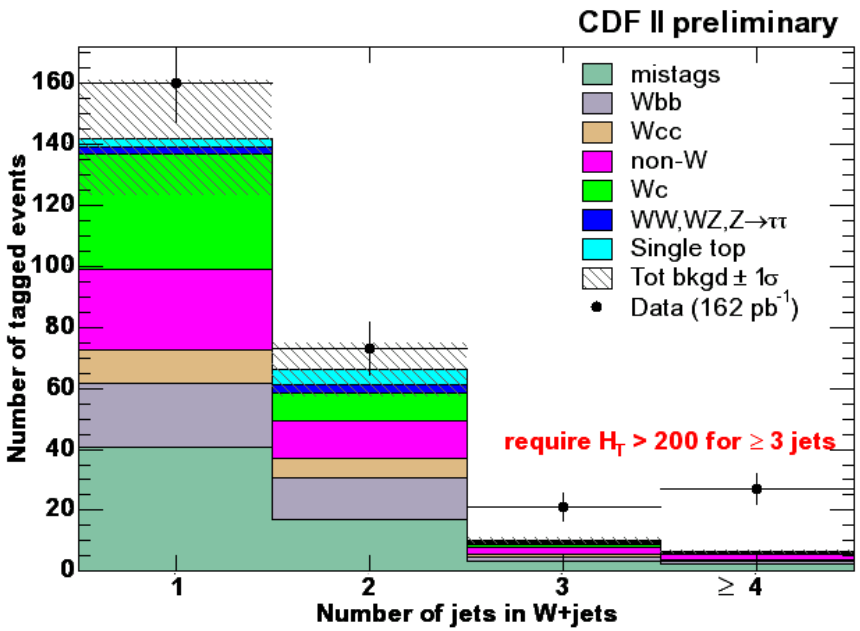
	muons	*electrons*
Nev	*100*	*136*
fitted N^W	*74.7 + 12.7 – 12.0*	*94.6 + 15.8 - 15.0*
fitted N^{QCD}	*7.1 + 0.9 – 0.9*	*14.1 + 1.2 - 1.2*
fitted N^{tt}	*17.8 + 9.9 – 8.7*	*27.5 + 12.7 - 11.7*

$$\sigma_{tt} = 7.2^{+2.6}_{-2.4}(\text{stat.})^{+1.6}_{-1.7}(\text{syst.})\pm 0.47(\text{lum.})\ \text{pb.}$$

CDF Lepton + Jets (SVX *b*-tag)

- SVX *b*-tagging efficiency (t-tbar) ~55%.
- Fake b-tag rate ~0.5%.





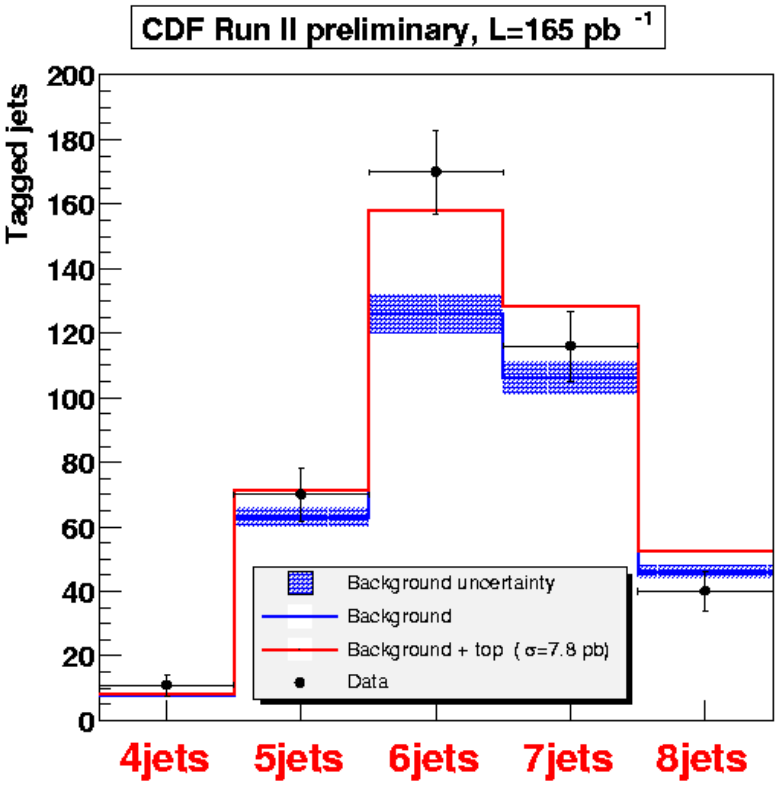
$$\sigma_{tt} = 5.6^{+1.2}_{-1.0}(\text{stat.})^{+1.0}_{-0.7}(\text{syst.})\ \text{pb.}$$

Top to All Jets

- Signature: 6 jets (incl. 2*b*).
- Backgrounds: QCD.
- Discrimination between signal and overwhelming background using:
  - Event shape (sphericity, aplanarity, centrality, jet E_Ts, etc.)
  - At least one *b*-tag.
  - Background estimation using background *b*-tag rate.

CDF Top to All Jets

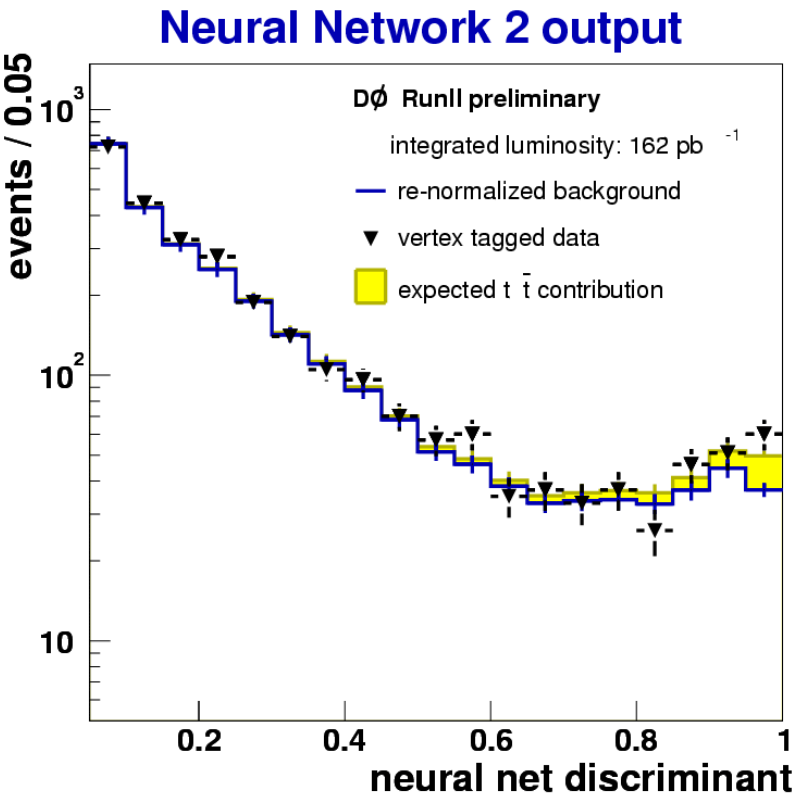
- Kinematic preselection to enhance top relative to qcd.
- Look for excess *b*-tags vs. number of jets (≥6 jets).



$$\sigma_{tt} = 7.8 \pm 2.5\ (\text{stat.})\ ^{+4.7}_{-2.3}\ (\text{syst.})\ \text{pb}$$

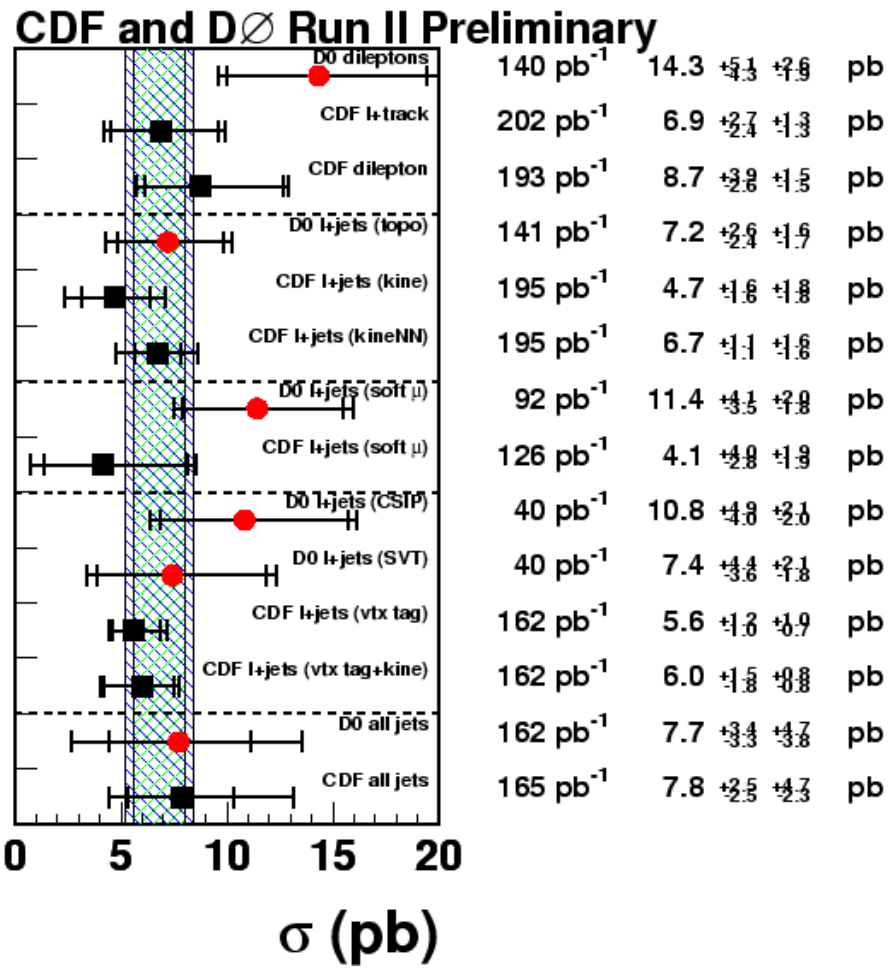
D0 Top to All Jets

- Require single *b*-tag.
- Neural network discriminator derived from kinematic variables. Fit to top and background templates.



$$\sigma_{tt} = 8.3 \pm 3.8\ (\text{stat.})\ ^{+2.3}_{-2.1}\ (\text{syst.}) \pm 0.5\ (\text{lum.})\ \text{pb}$$

Top Pair Production Summary



There is general consistency and agreement with theory.

Top Quark Mass

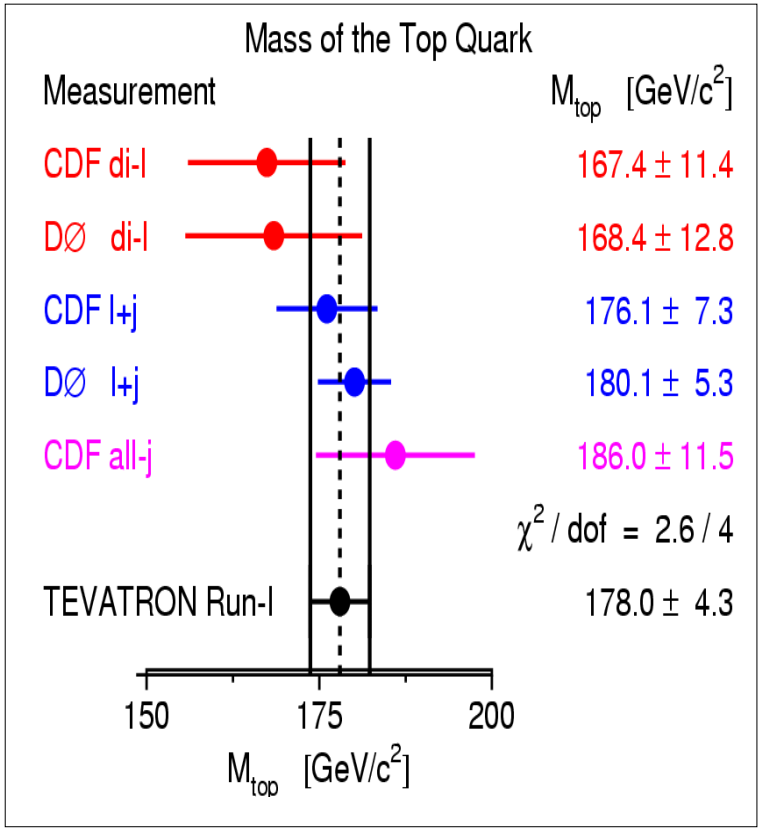
- All methods rely on templates for different top mass hypotheses and background (max likelihood fit of data to top + background).
- Templates predict distribution of any observable ("mass estimator") that depends on the top quark mass.
  - Estimator can be a single number, such as "reconstructed top mass" from kinematic fit.
    - Lepton + jets and all jets have traditionally used such estimators.
  - Estimator can also be a set of numbers or a continuous curve (matrix element method, dynamic likelihood method).
    - Often used for top dilepton mass analysis.
    - Multi-dimensional estimators always give smaller statistical errors than single number estimators. Amount of improvement depends on how much "top mass resolution" varies from event to event.

Top Quark Mass

- Current error on top quark mass is about equally from statistics and systematics. Main systematic errors are:
  - Jet energy scale.
  - Production model.
- Future improvements from Run II measurements will require reduced systematic errors.

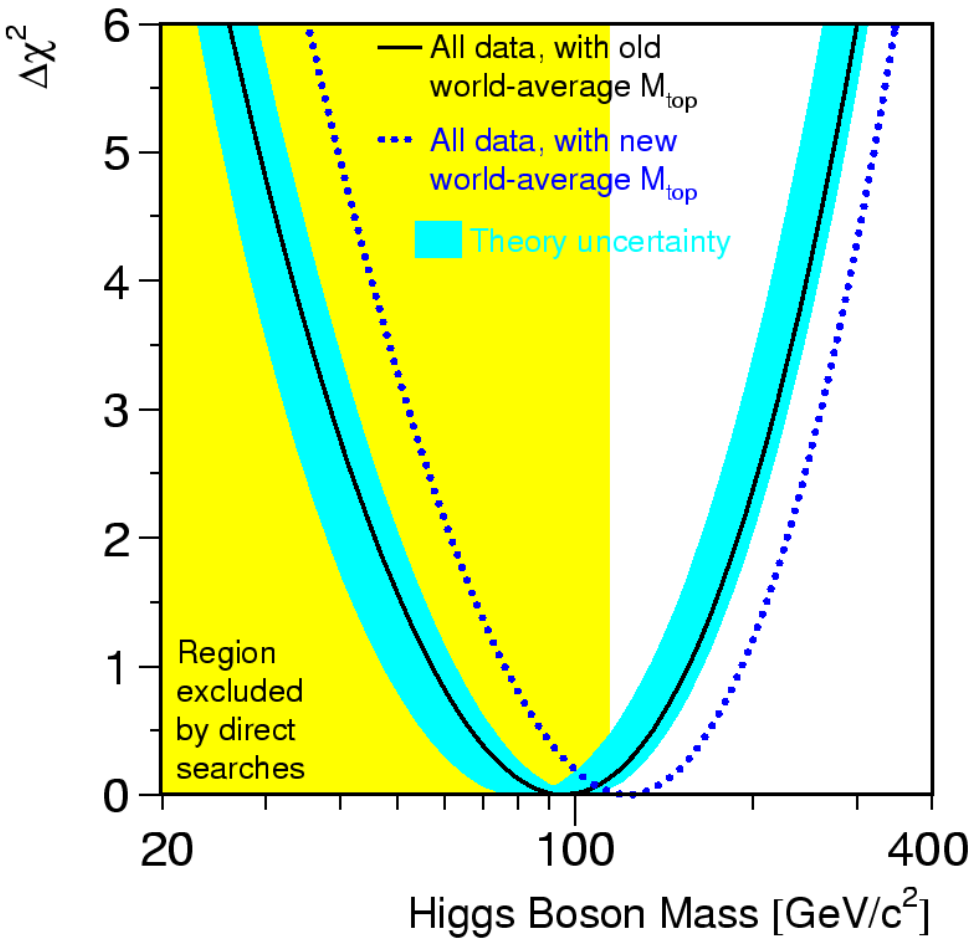
Top Quark Mass Status

- Improved D0 Run I lepton+jets top mass achieved by using multidimensional estimator.
  - Old Run I D0 l+jets: 173.3 ± 5.6 ± 5.5 GeV/c^2.
  - New Run I D0 l+jets: 180.1 ± 3.6 ± 3.3 GeV/c^2.
- New Tevatron average top mass (hep-ex/0404010, Apr. 8, 2004).
  - Old Run I Tev top mass: 174.3 ± 3.2 ± 4.0 GeV/c^2.
  - New Run I Tev top mass: 178.0 ± 2.7 ± 3.3 GeV/c^2.
- First competitive Run II top quark mass result from CDF (l+jets).
  - $m_t = 177.8\ ^{+4.5}_{-5.0}$ (stat.) ± 6.2(syst.) GeV/c^2.



Indirect Higgs Mass

- New top quark mass has affected indirect Higgs mass.



Old: $m_H = 96^{+60}_{-38}$ GeV/c^2

$m_H < 219$ GeV/c^2 @95% CL

New: $m_H = 117^{+67}_{-45}$ GeV/c^2

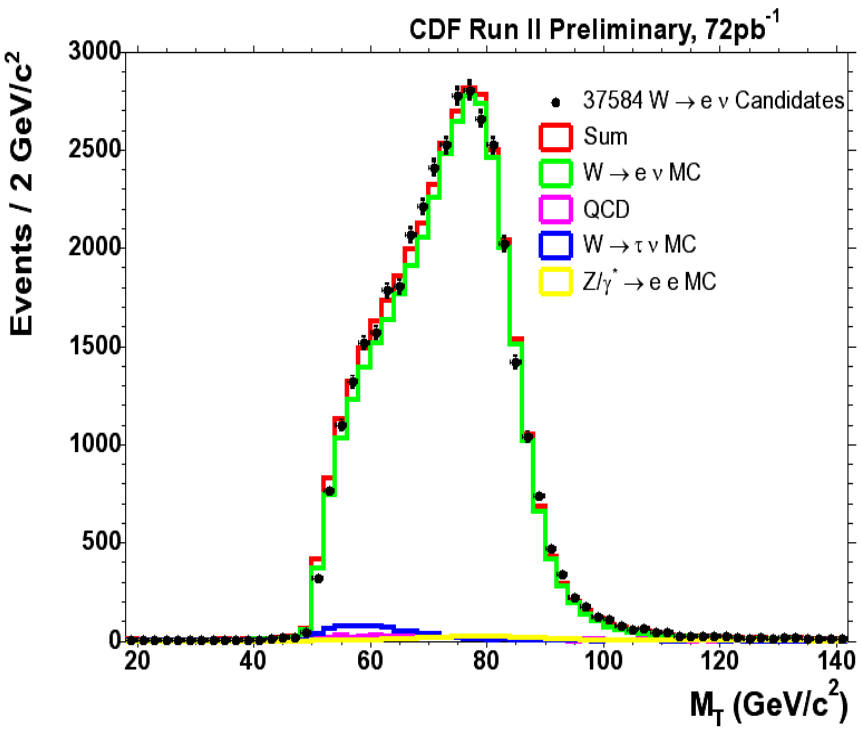
$m_H < 251$ GeV/c^2 @95% CL

Electroweak Physics at the Tevatron

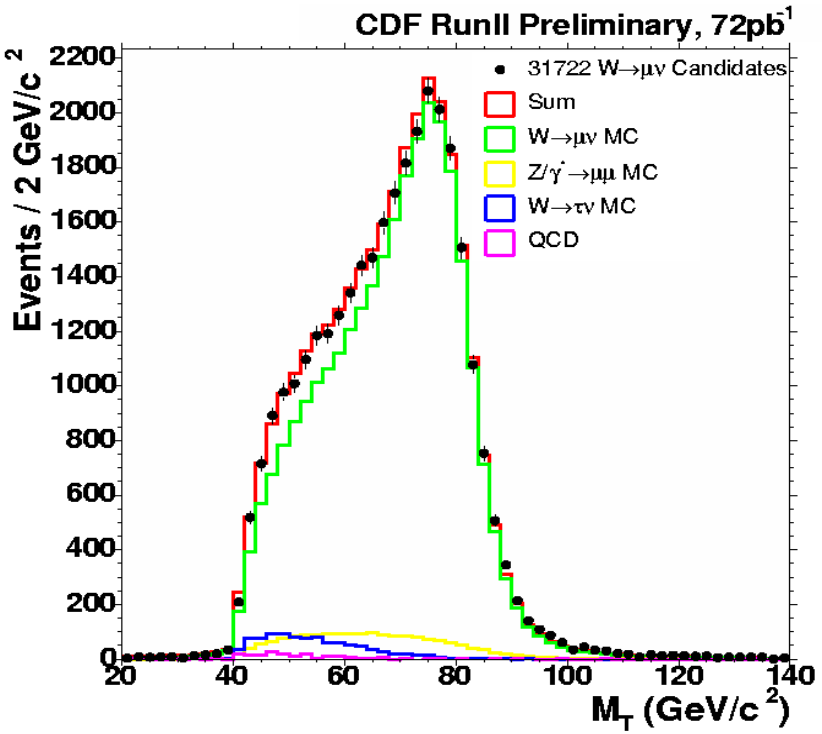
- The Tevatron is a W and Z factory.
- The Tevatron electroweak physics program.
  - W mass (no RunII results yet).
  - W and Z production.
  - Dibosons: WW, WZ, Wγ, Zγ (test SM trilinear gauge boson couplings).
  - W + jets, Z + jets, Wb, Zb (qcd crossover topic).

CDF *W* Cross Section

$W \to e\nu$ Tranverse Mass



$W \to \mu\nu$ Tranverse Mass

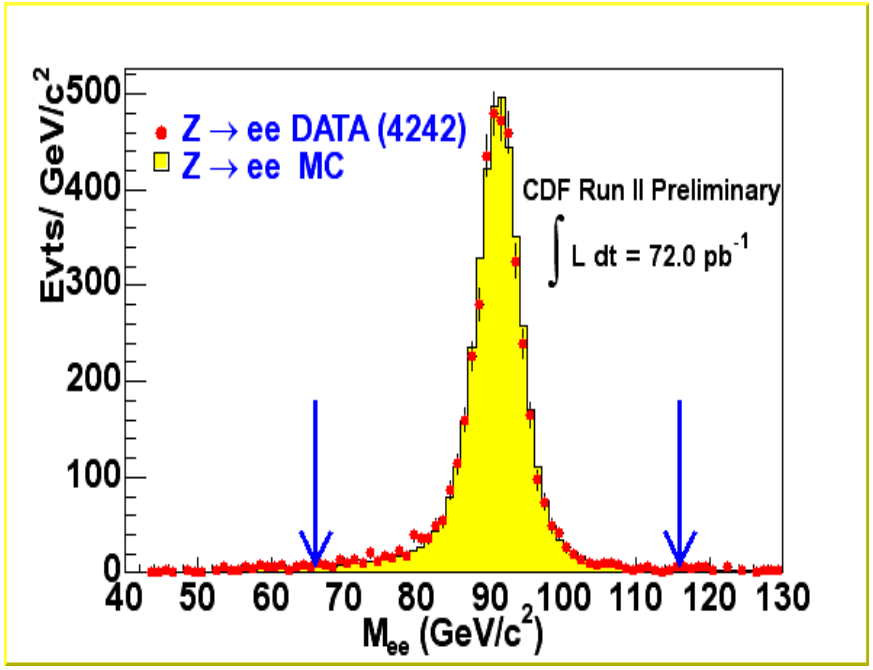


$$\sigma \bullet BR(W \to e\nu) = 2782 \pm 14\ (\text{stat.})\ ^{+61}_{-56}\ (\text{syst.}) \pm 167\ (\text{lum.})\ \text{pb}$$

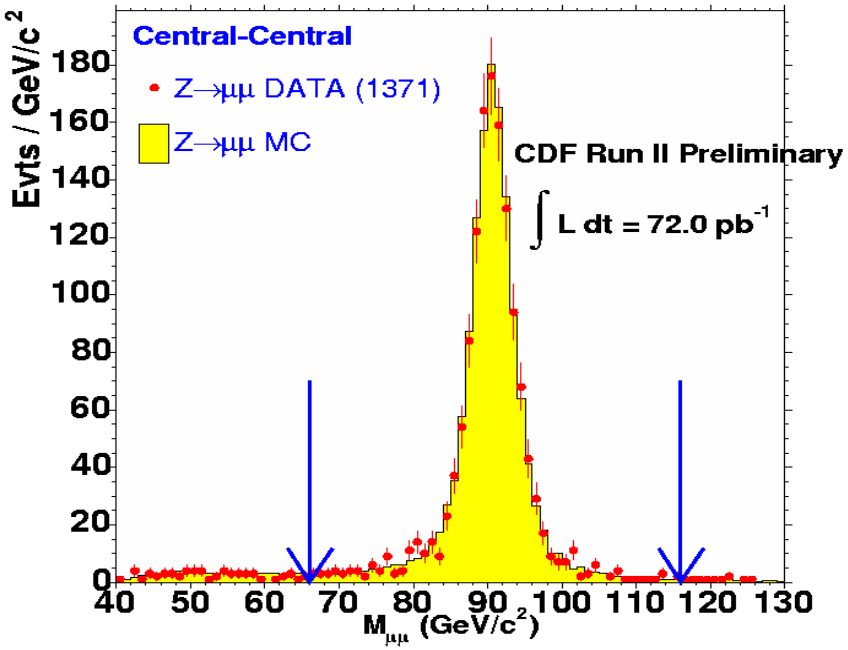
$$\sigma \bullet BR(W \to \mu\nu) = 2772 \pm 16\ (\text{stat.})\ ^{+64}_{-60}\ (\text{syst.}) \pm 166\ (\text{lum.})\ \text{pb}$$

CDF Z Cross Section

$Z \rightarrow ee$ Invariant Mass



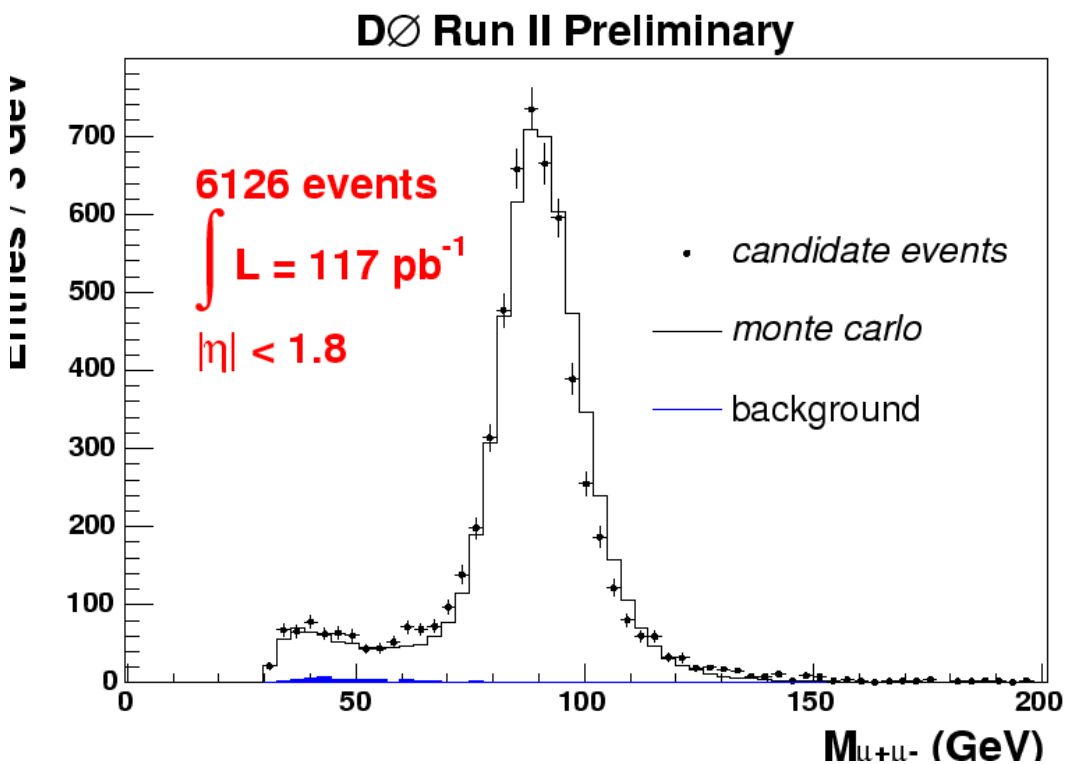
$Z \rightarrow \mu\mu$ Invariant Mass



$$\sigma \bullet BR(Z \rightarrow ee) = 255.2 \pm 3.9 \text{ (stat.)} \pm 5.5 \text{ (syst.)} \pm 15.3 \text{ (lum.) pb}$$

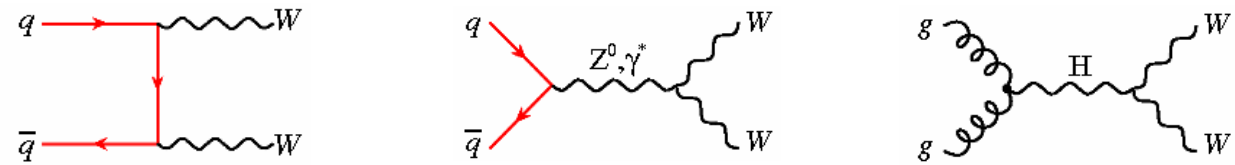
$$\sigma \bullet BR(Z \rightarrow \mu\mu) = 248.9 \pm 5.9 \text{ (stat.)} \, ^{+7.0}_{-6.2} \text{ (syst.)} \pm 14.9 \text{ (lum.) pb}$$

D0 Z Cross Section



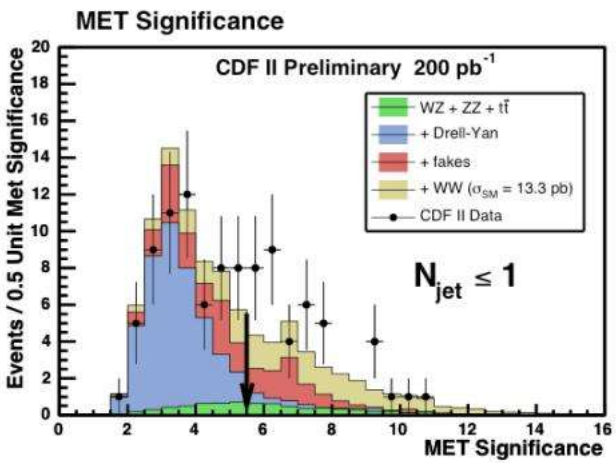
$\sigma \bullet BR(Z \rightarrow \mu\mu) = 261.8 \pm 5.0(\text{stat.}) \pm 8.9(\text{syst.}) \pm 26.2(\text{lum.})$ pb

CDF *WW*



- Signature: 2 leptons (e,μ + track) + missing E_T.

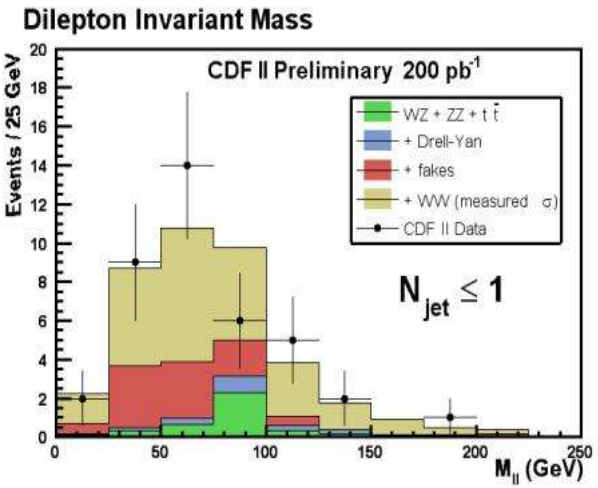
MET Significance



MET Significance = MET/SQRT(SumET)

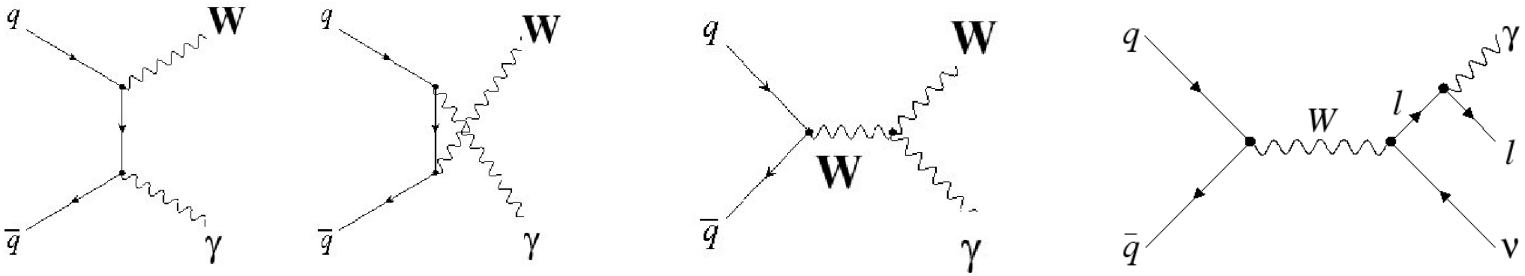
Distribution after all cuts, but MET Significance cut applied. The cut value is indicated by the arrow.

Dilepton Invariant Mass



$\sigma = 19.4 \pm 5.1$ (stat) ± 3.5 (sys) ± 1.2 (lumi) pb.

D0 $W\gamma$

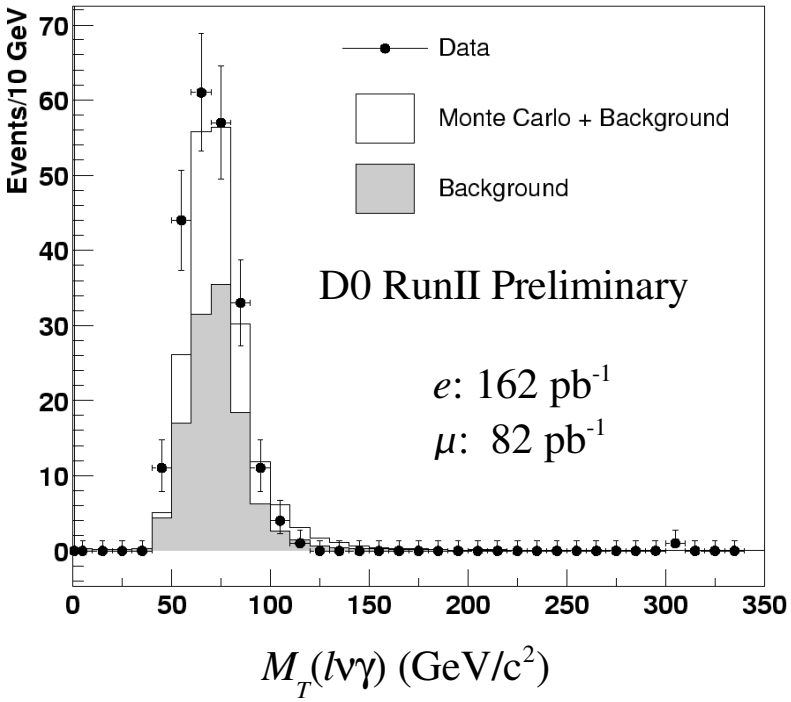


- Signature: 1 lepton (e,μ) + 1 photon + missing E_T.

$E_{T\gamma} > 8$ GeV

$\Delta R_{l\gamma} > 0.7$

$|\eta_\gamma| < 1.1$



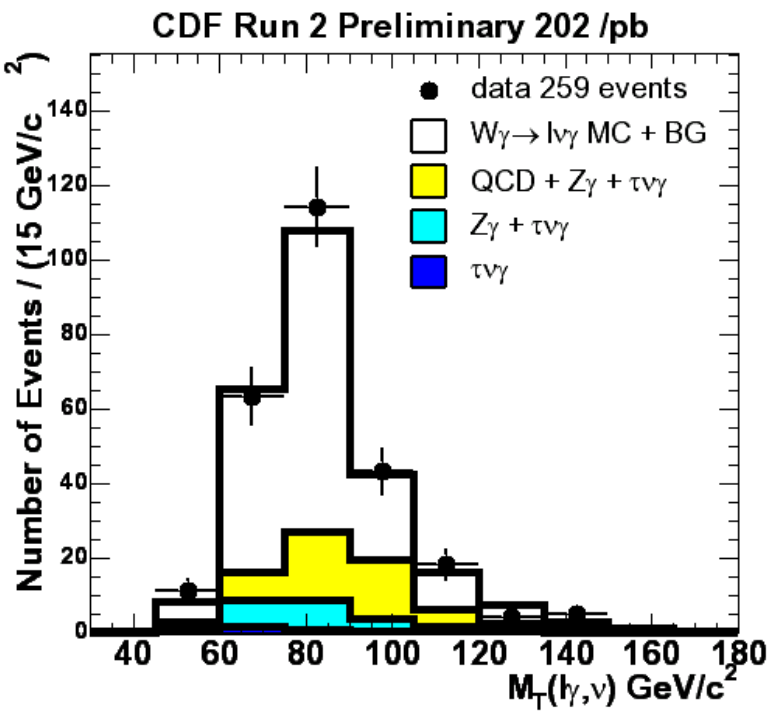
$\sigma \bullet BR = 19.3 \pm 6.7 \pm 1.2$ (lum.) pb

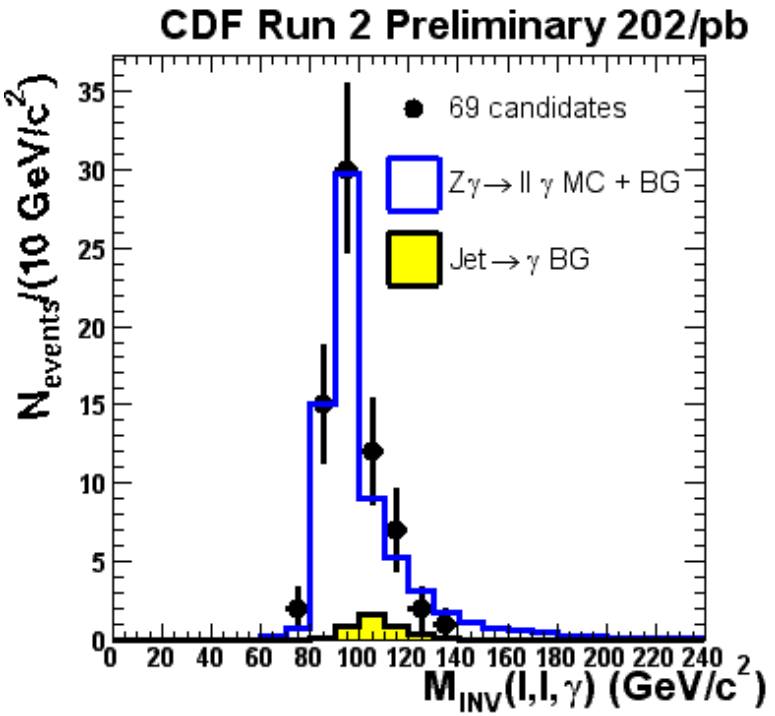
CDF $W\gamma$ and $Z\gamma$

$E_{T\gamma} > 7$ GeV

$\Delta R_{l\gamma} > 0.7$

$|\eta_\gamma| < 1.1$





$\sigma \bullet BR(W\gamma \rightarrow l\nu\gamma) = 19.7 \pm 1.7$ (stat.) ± 2.0 (syst.) ± 1.1 (lum.) pb

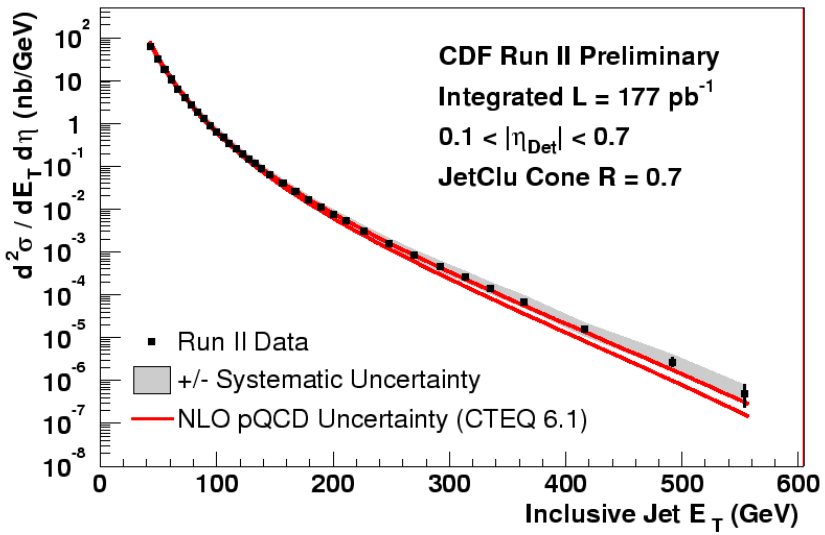
$\sigma \bullet BR(Z\gamma \rightarrow ll\gamma) = 5.3 \pm 0.6$ (stat.) ± 0.4 (syst.) ± 0.3 (lum.) pb

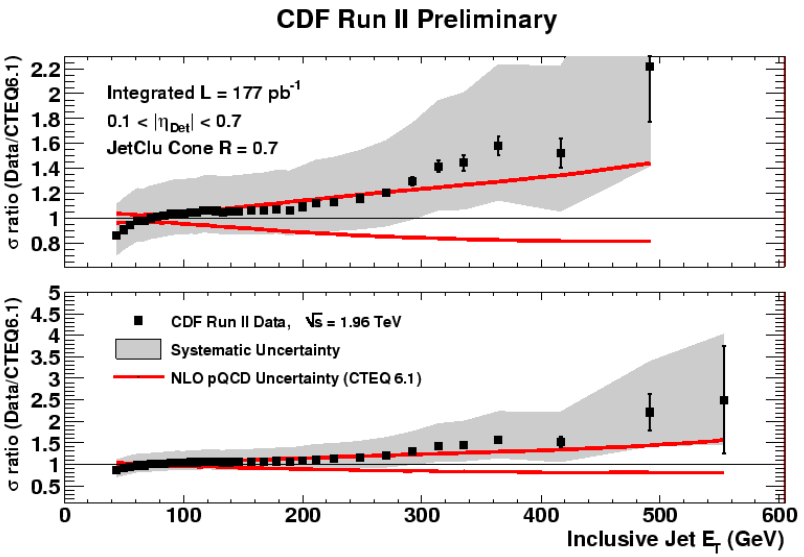
QCD Studies at the Tevatron

- At hadron colliders, all processes are "QCD processes."
- Measure fundamental parameters: PDFs.
- Test perturbative QCD. Deviation from pQCD at high E_T can signal new physics.
- Some specific reactions of interest.
  - High E_T jets: inclusive jets, dijets.
  - W,Z,γ + jets, multijets.
  - Heavy flavor quark production.
  - Diffraction, rapidity gaps.

CDF Inclusive Jets

- Jet cross section varies by eight orders of magnitude.



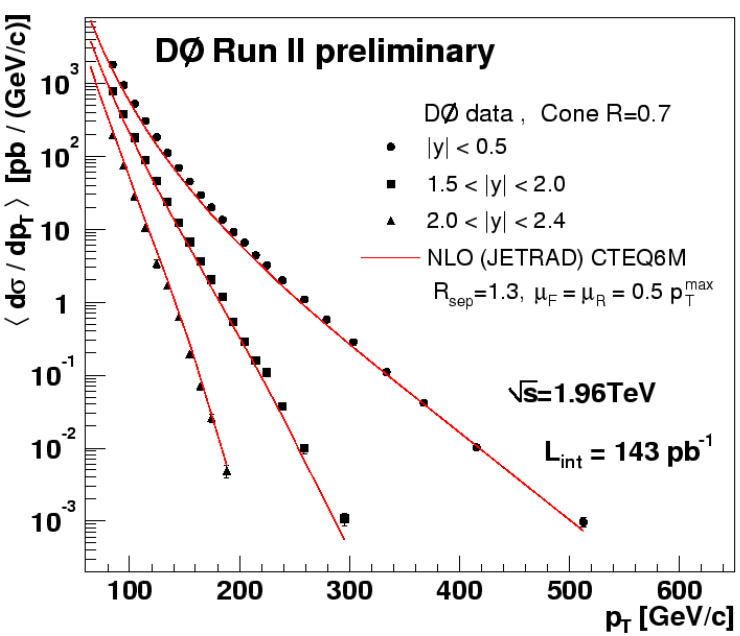


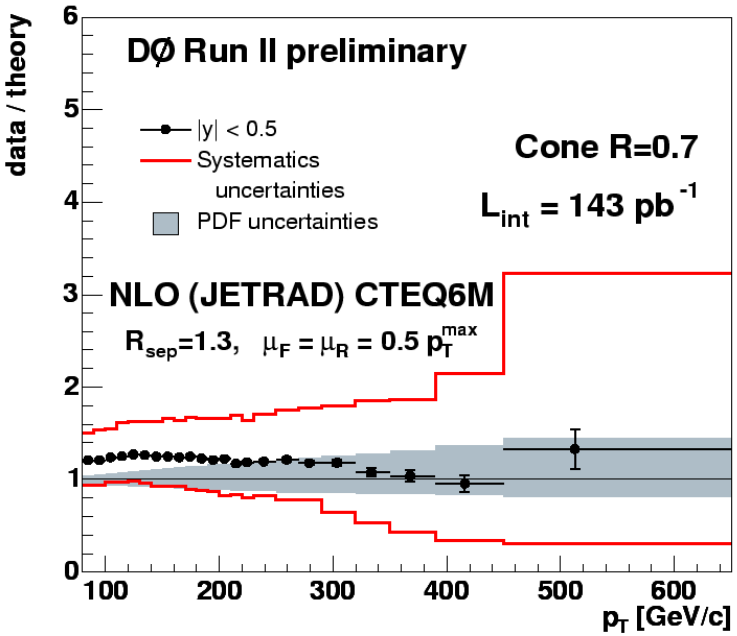
(Above: same plot, different scale)

- Major systematic uncertainties: Jet energy scale & theory (PDFs).

Data and theory are in agreement within errors.

D0 Inclusive Jets

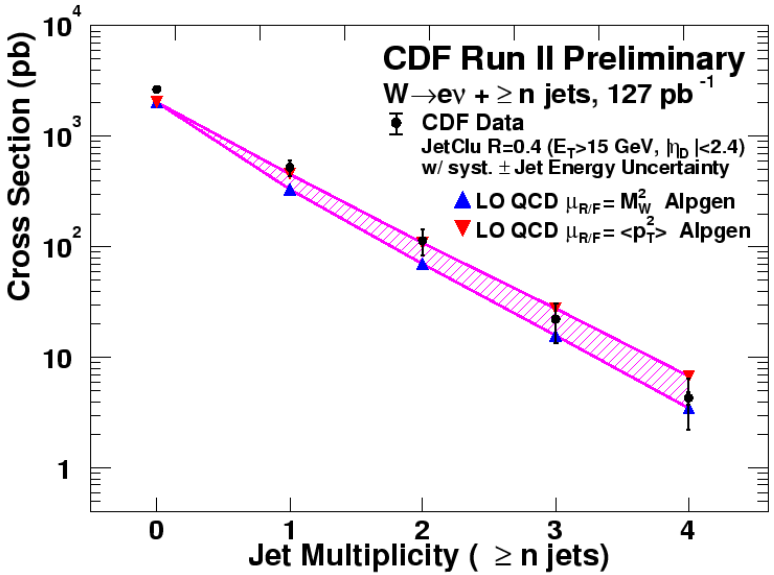


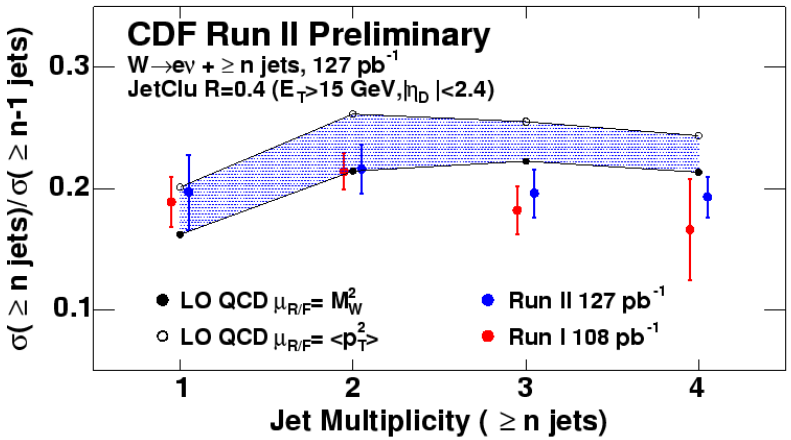


Data and theory are in agreement within errors.

CDF $W(e\nu)$+jets

- Signature: 1 electron + missing E_T + high E_T jets (≥15 GeV).
- Backgrounds: Fakes, top (4 jets).



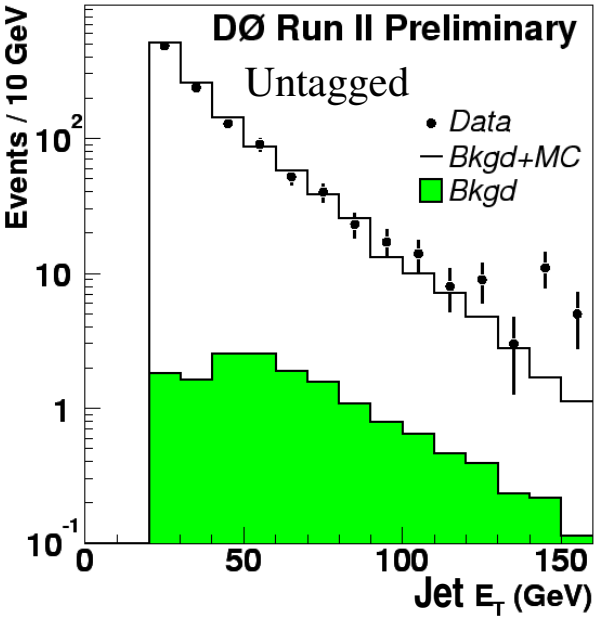


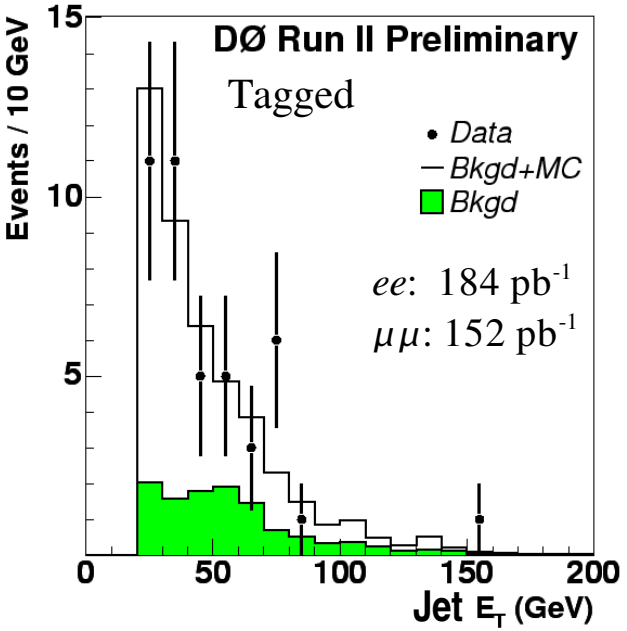
LO QCD provides reasonable account of jet multiplicity

D0 $\sigma(Z+b)/\sigma(Z+\text{jet})$

- Sensitive to b-quark PDF.
- Signature: 2 leptons (ee or $\mu\mu$) + jet ($E_T \geq 20$ GeV).
- Background: QCD fakes, Drell-Yan.
- B-tagging by secondary vertex algorithm.
  - Efficiency = 34%.
  - Mistag rate = 0.27%/jet.

$$\sigma(Z+b)/\sigma(Z+\text{jet}) = 0.024 \pm 0.007$$



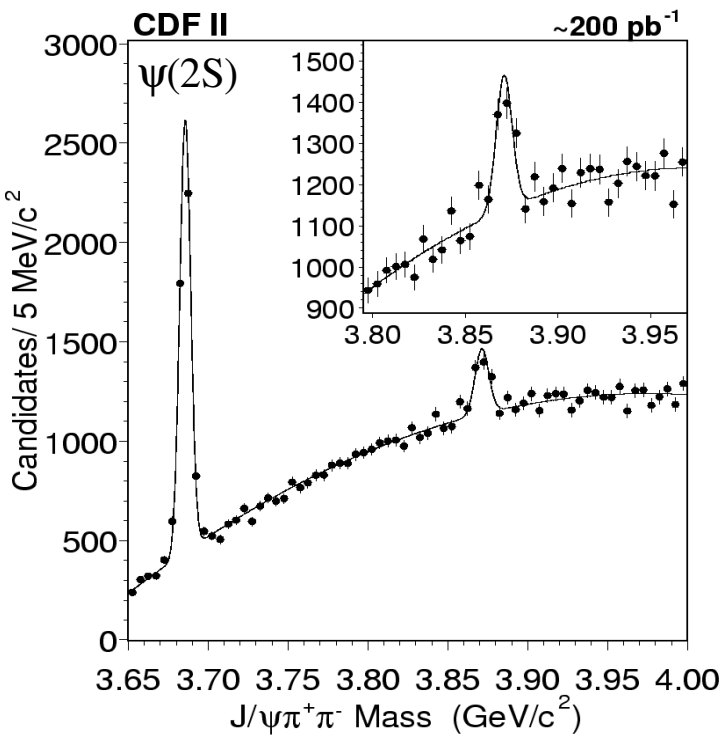


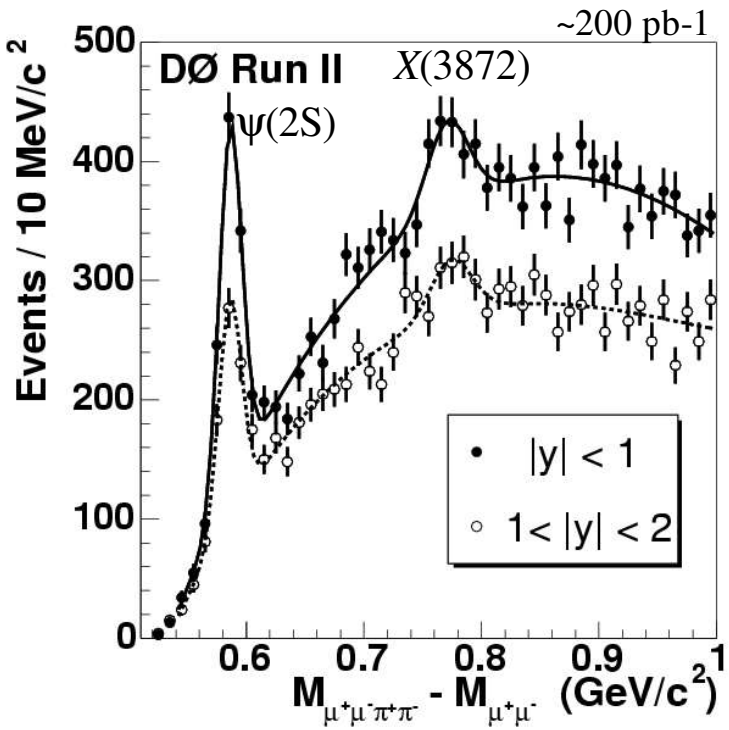
Heavy Flavor Physics at the Tevatron

- The Tevatron is a copious source of *b* and *c* quarks and hadrons.
- *b* quark production.
- B^0 & B_s mixing & CP violation.
- *B* hadron lifetimes.
- Spectroscopy (B_c, baryons, quarkonium).
- Rare decays ($B \to l^+ l^-$, $B \to K l^+ l^-$).

$X(3872)$

- $X(3872)$ recently observed by Belle in $X \rightarrow J/\psi \pi^+ \pi^-$.
  - Charmonium, D molecule?
- $X(3872)$ observed by CDF and D0.

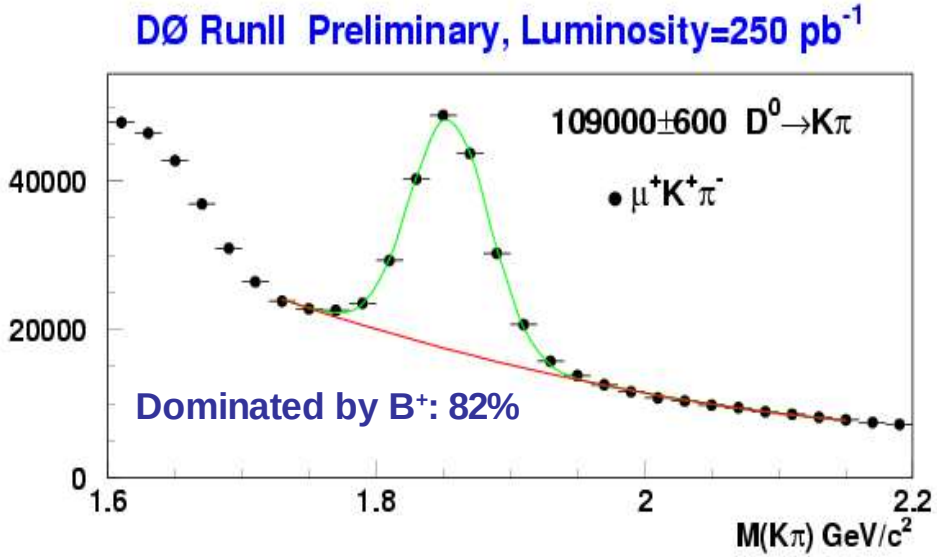




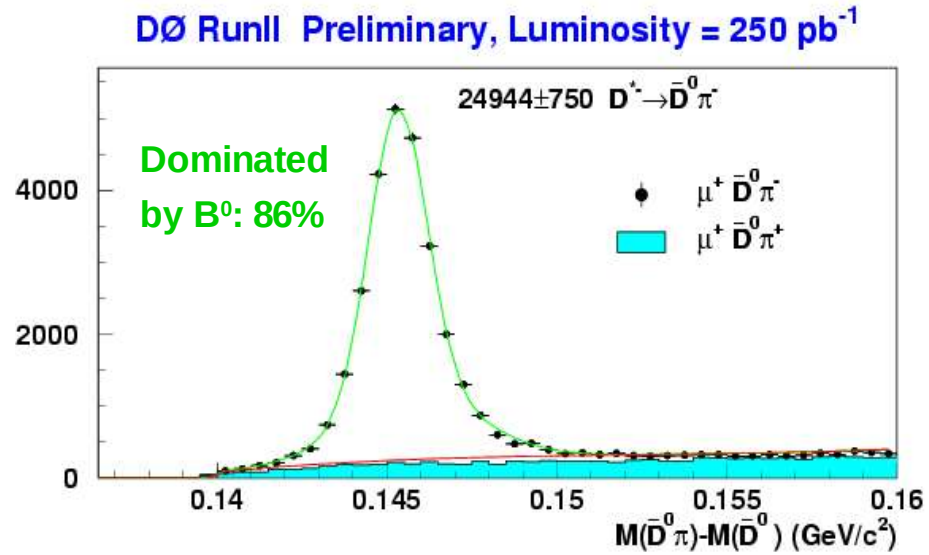
FERMILAB-PUB-03/393-E. Submitted to Phys. Rev. Lett.

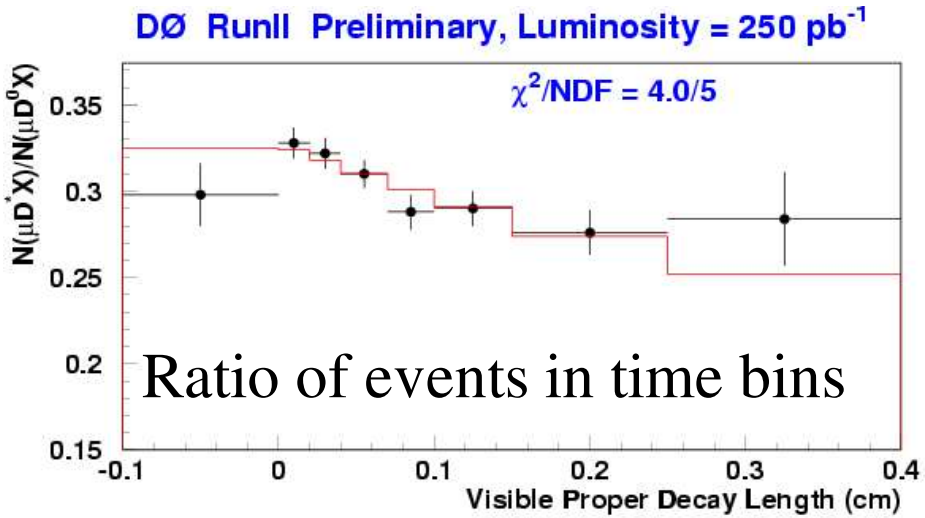
D0 $\tau(B^+)/\tau(B^0)$

$B^+ \to D^0 \mu^+ X$



$B^0 \to D^{*-} \mu^+ X$





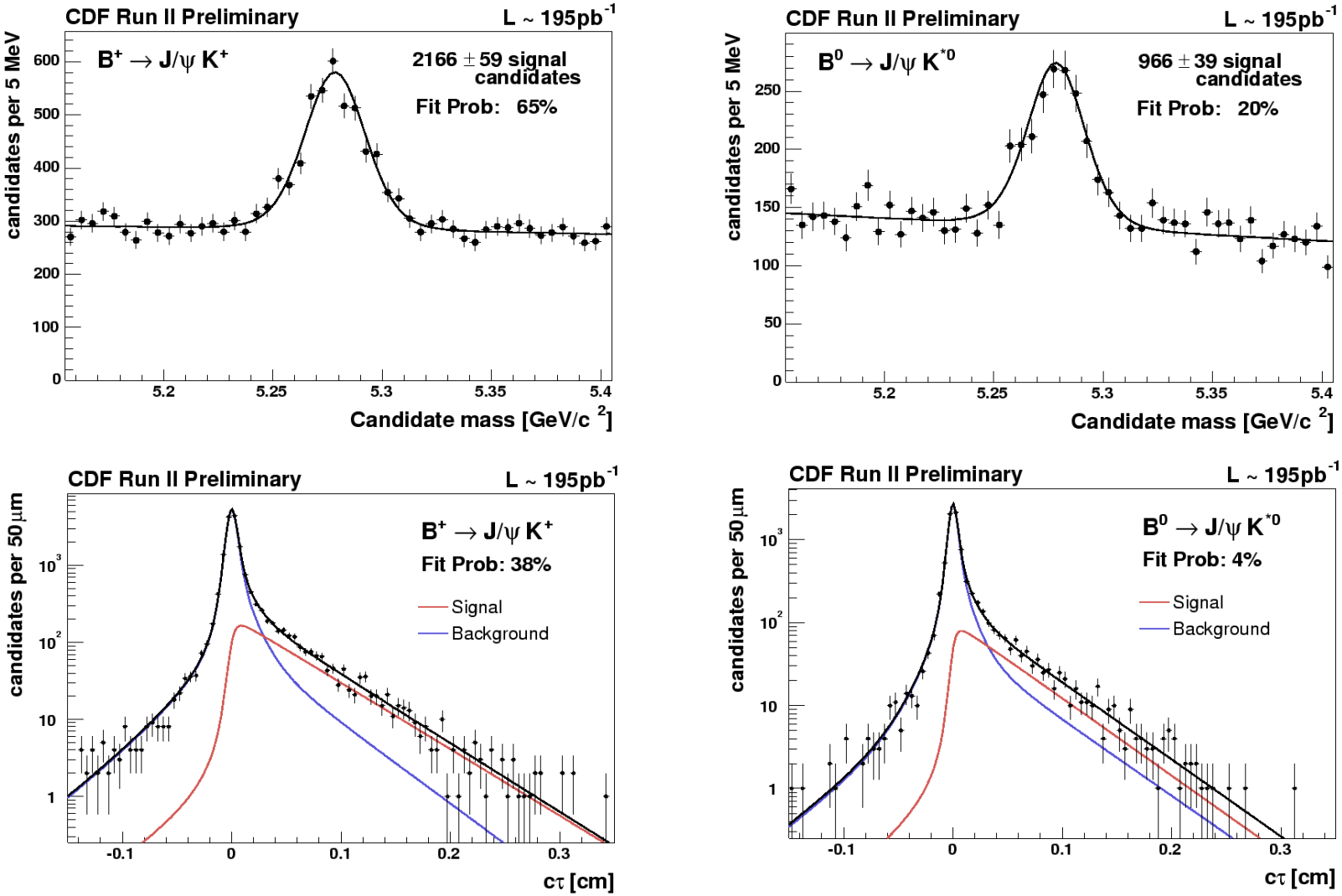
Ratio of events in time bins

Novel technique to measure $\tau(B^+)/\tau(B^0)$

- **Divide $B^+ \to D^0\mu X$ and $B^0 \to D^*\mu X$ each into 7 time intervals**
- **Measure ratio of events in time bins**

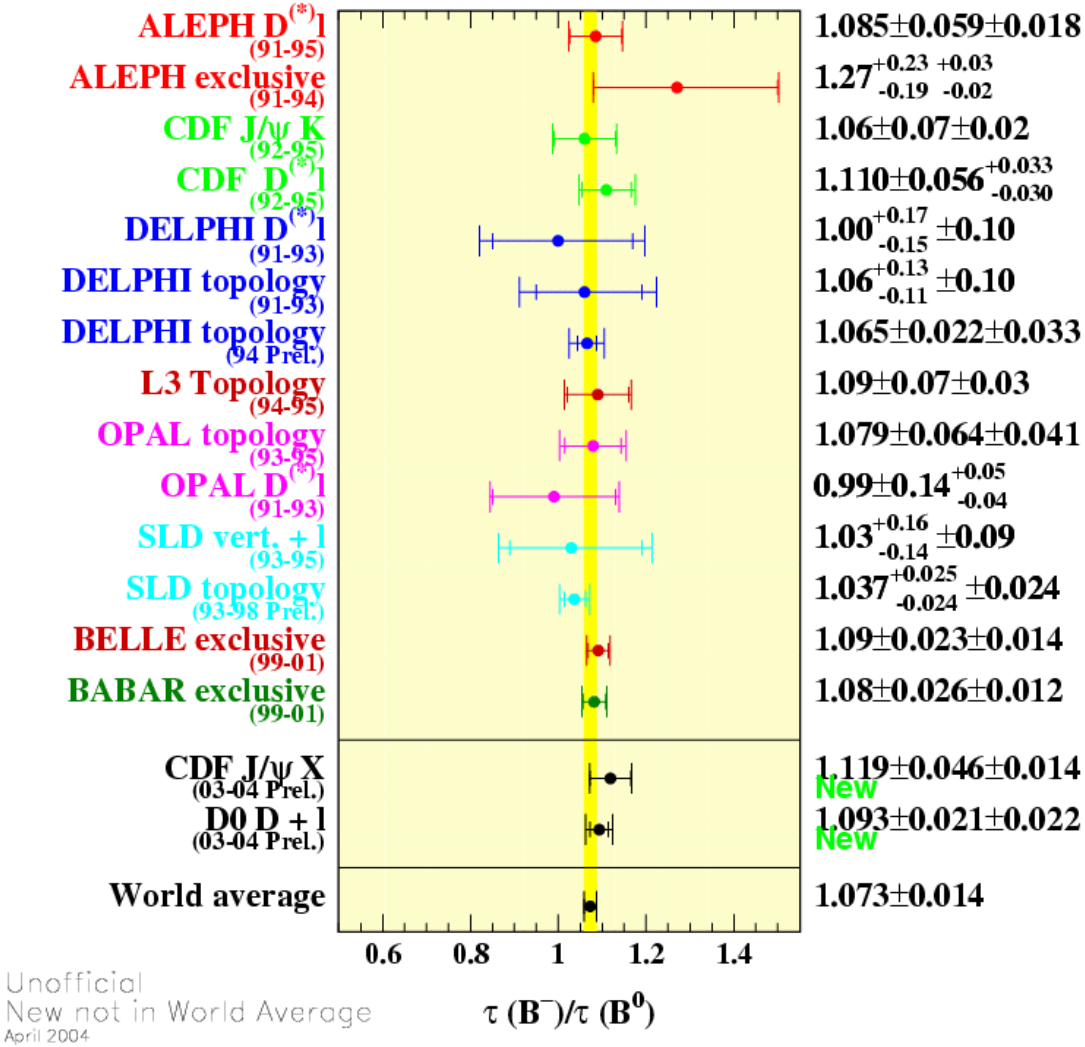
$$\tau^+/\tau^0 = 1.093 \pm 0.021 \pm 0.022$$

CDF $\tau(B^+)/\tau(B^0)$



$$\tau^+/\tau^0 = 1.119 \pm 0.046 \text{ (stat.)} \pm 0.014$$

$\tau(B^+)/\tau(B^0)$



Systematics dominated currently by:

- time dependence of slow pion reconstruction efficiency
- relative reconstruction efficiencies
- Branching ratios.
- K-factors
- decay length resolution differences: D^0 vs. D^*

Work in progress to decrease the error

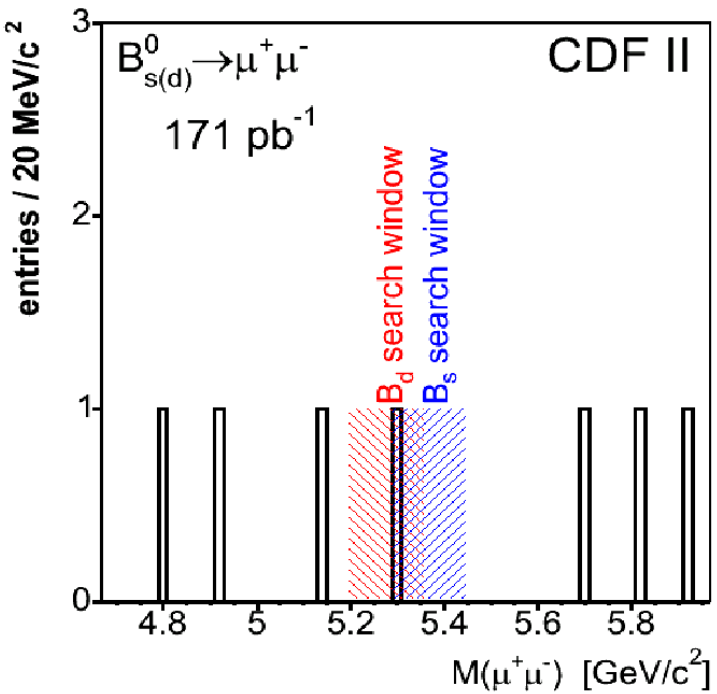
New DØ result

(average not updated, plot not official or approved by HFAG)

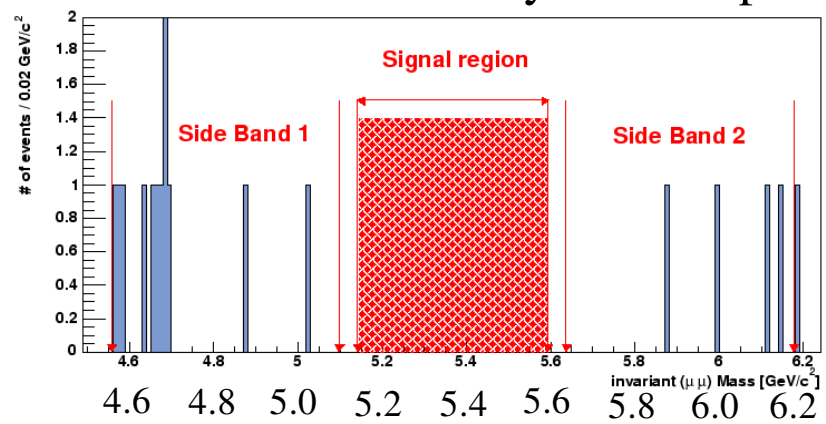
This is one of the most precise measurements to date

Rare Decays $B_{s(d)} \to \mu^+\mu^-$

- $B_s \to \mu\mu$ is rare in SM (BR=3.4×10^{-9}), but very sensitive to new physics (*e.g.* $BR \propto \tan^6\beta$ in MSSM).



D0 RunII Preliminary 180 pb^{-1}



Blind analysis (box not opened)

D0 $BR(B_s \to \mu\mu) < 1.0 \times 10^{-6}$ @95% CL (expected)

CDF $BR(B_s \to \mu\mu) < 5.8 \times 10^{-7}$ @90% CL

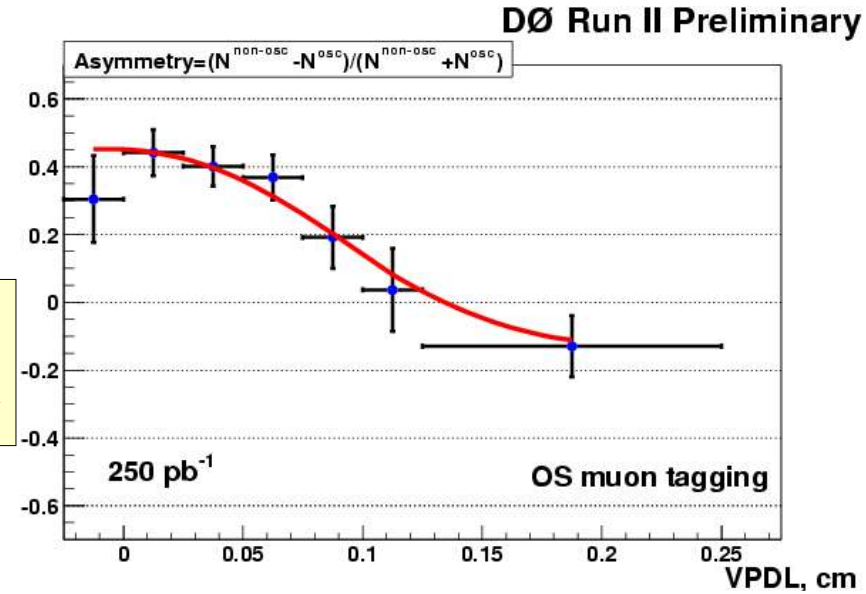
CDF $BR(B_d \to \mu\mu) < 1.5 \times 10^{-7}$ @90% CL

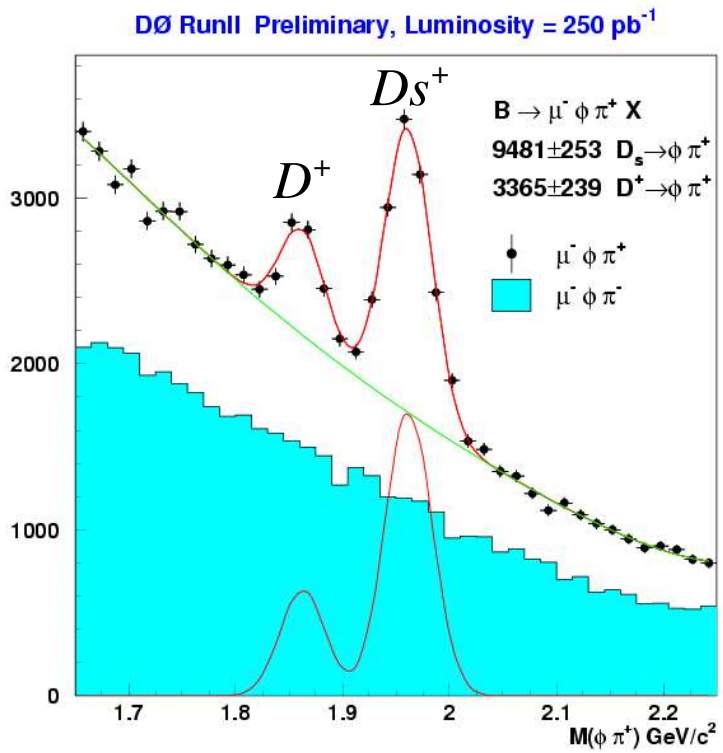
FERMILAB-PUB-04/036-E. Submitted to Phys. Rev. Lett.

B^0 and B_s Mixing

- B_d mixing from $B_d \to D^{*+}\mu^- X$ using visible proper decay length (VPDL=$L_{xy}\, m_B / p_{T\mathrm{vis}}$)

D0	$\Delta m = 0.506 \pm 0.055 \pm 0.049\ \mathrm{ps}^{-1}$
CDF I	$\Delta m = 0.500 \pm 0.052 \pm 0.043\ \mathrm{ps}^{-1}$





- B_s mixing from $B_s \to D_s^+\mu^- X$?
  - Semileptonic mode has larger yields than fully reconstructed modes, but poorer time resolution.

Conclusion

- The Tevatron is running well.
- CDF and D0 are collecting a lot of data, more on the way.
- New results coming out of CDF and D0 are beginning to surpass Run I. Too many new results to include in this talk.