ICHEP Summary: (A few) Selected Tevatron results

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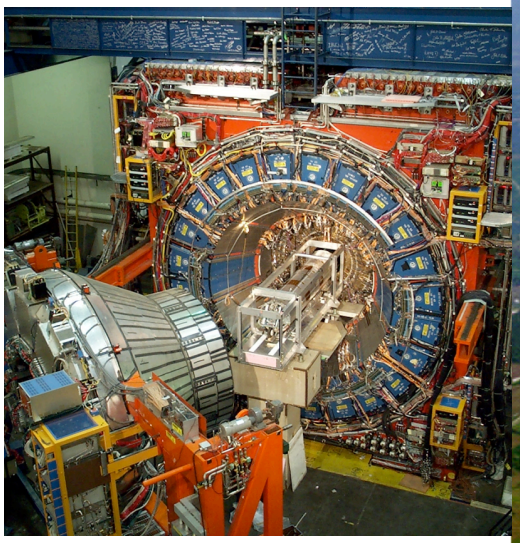
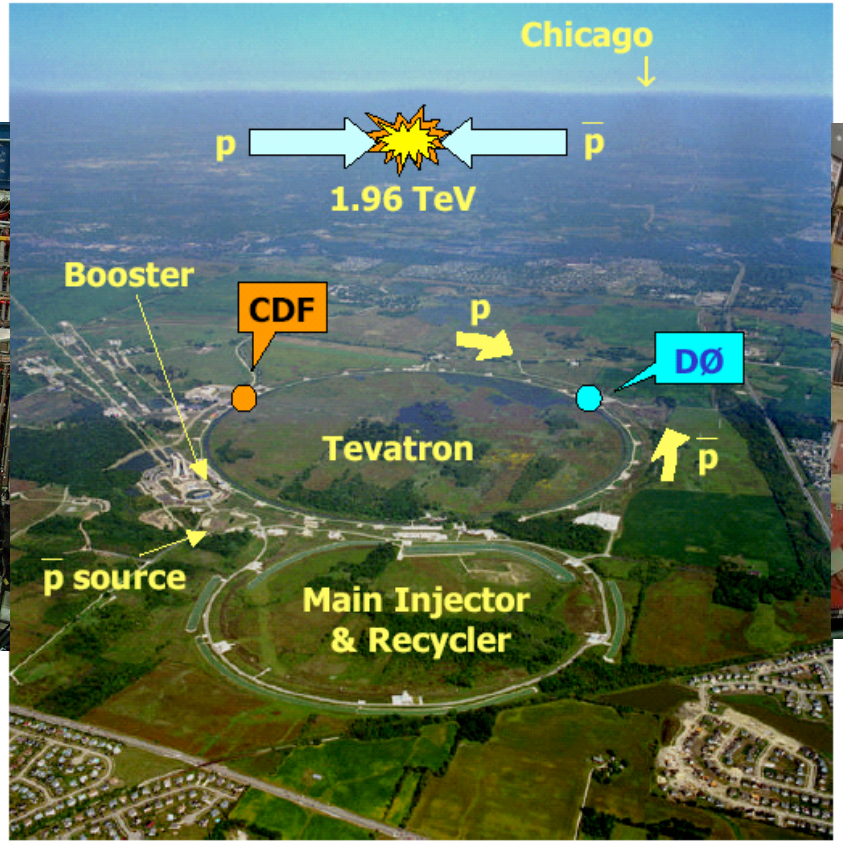
BNL

Sep 18, 2008

The Tevatron at Fermilab

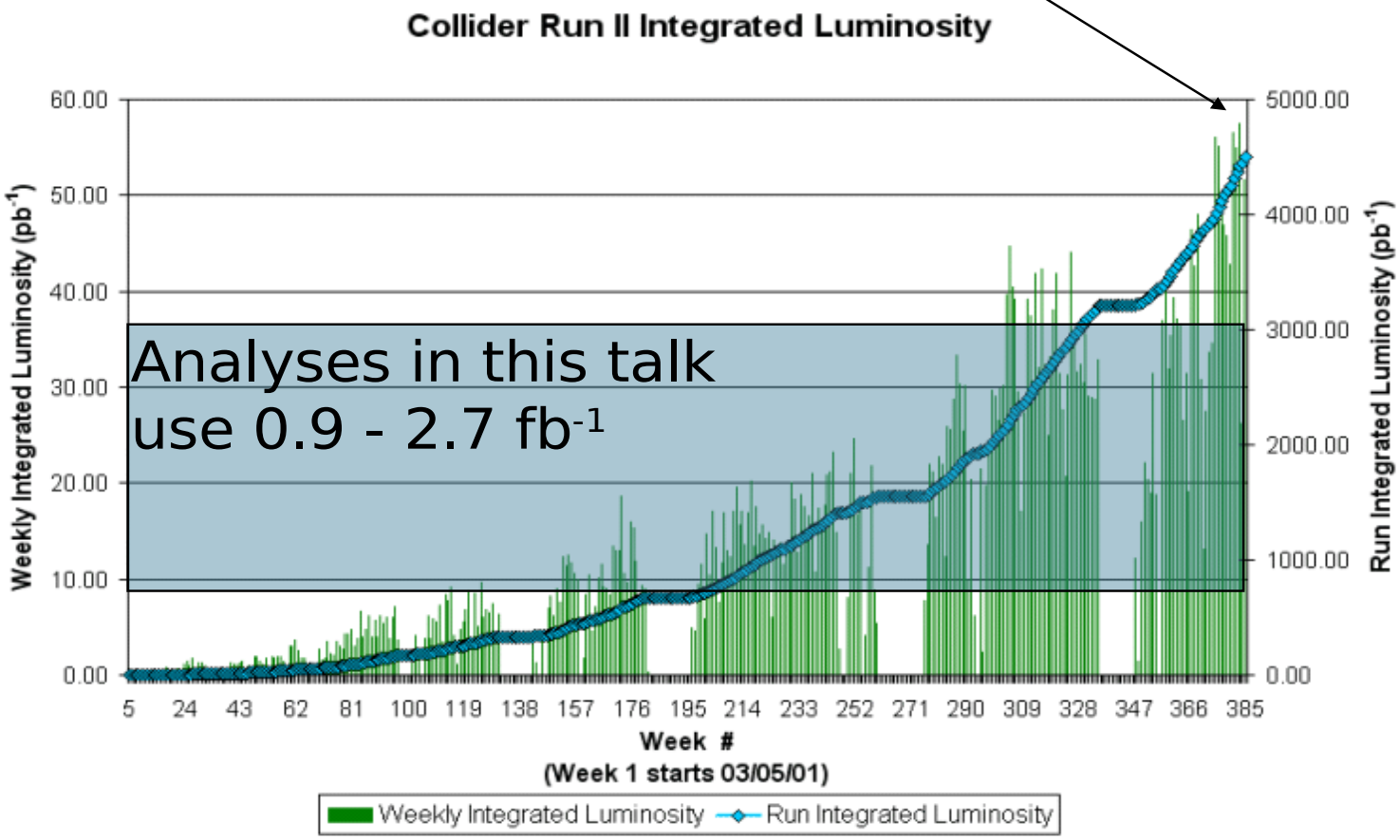




- $p\bar{p}$ collider at Fermilab $\sqrt{s} = 1.96\text{TeV}$
- Average initial: >280 x 10^{31} cm^{-2} s^{-1}
- 40+ pb^{-1} per week
- Recorded in total $\int\mathcal{L}$ ~4 fb^{-1} per experiment

Tevatron Integrated Luminosity

- Tevatron is performing extremely well ~58 pb^{-1} / week!



- Expect 6-8 fb^{-1} datasets by end of 2009 (possibly run in 2010)

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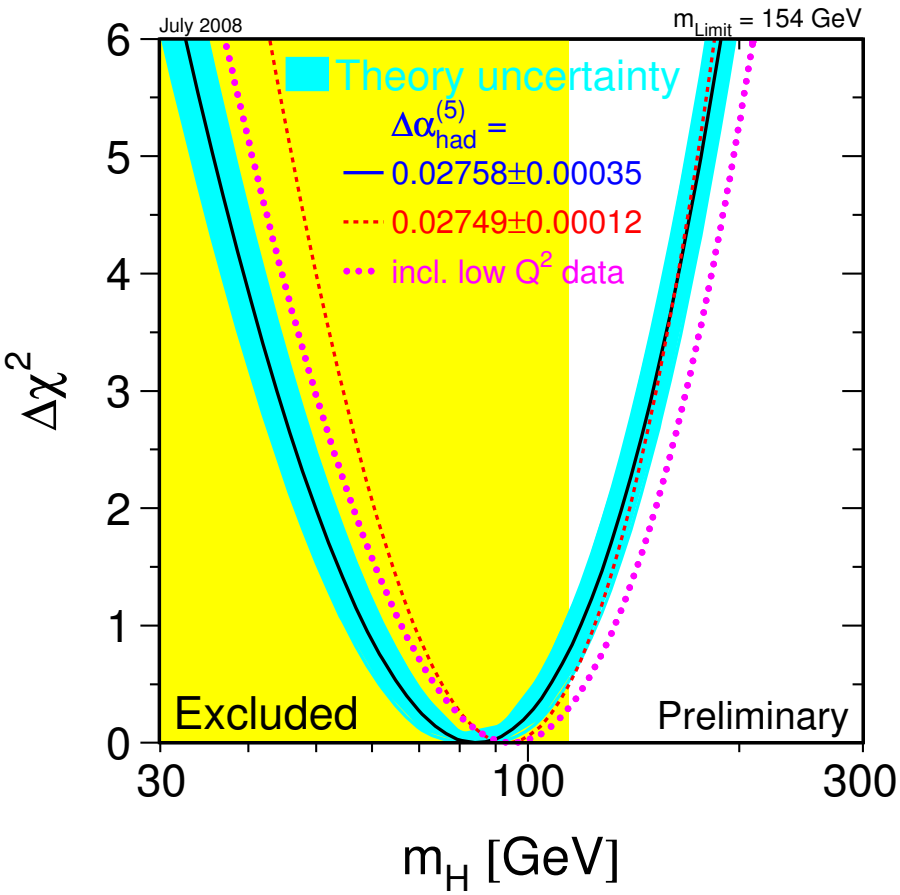
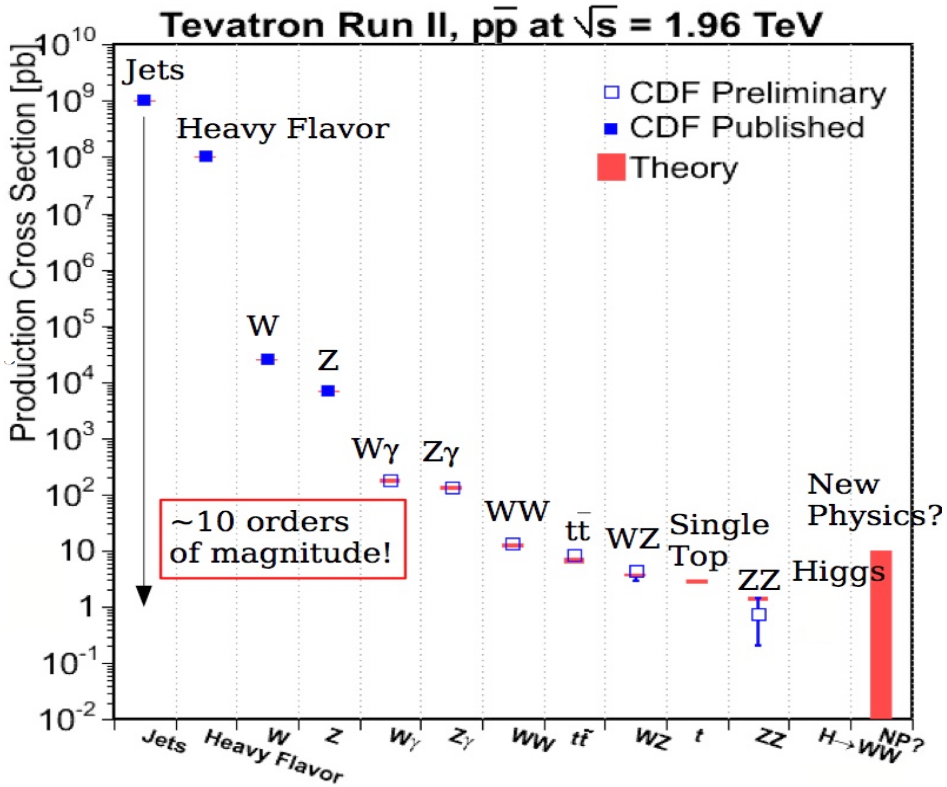
(B. Stelzer)

SM Higgs

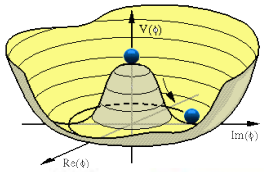




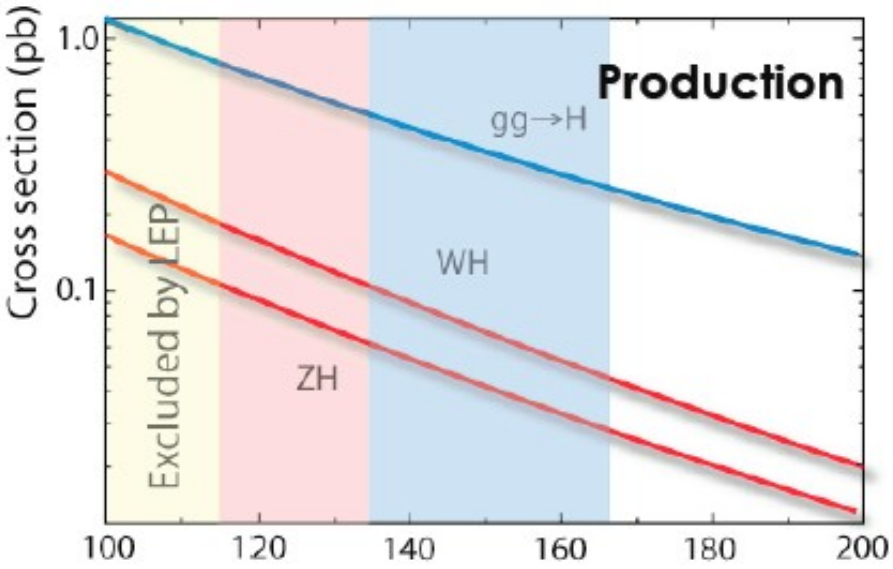
Current limits:

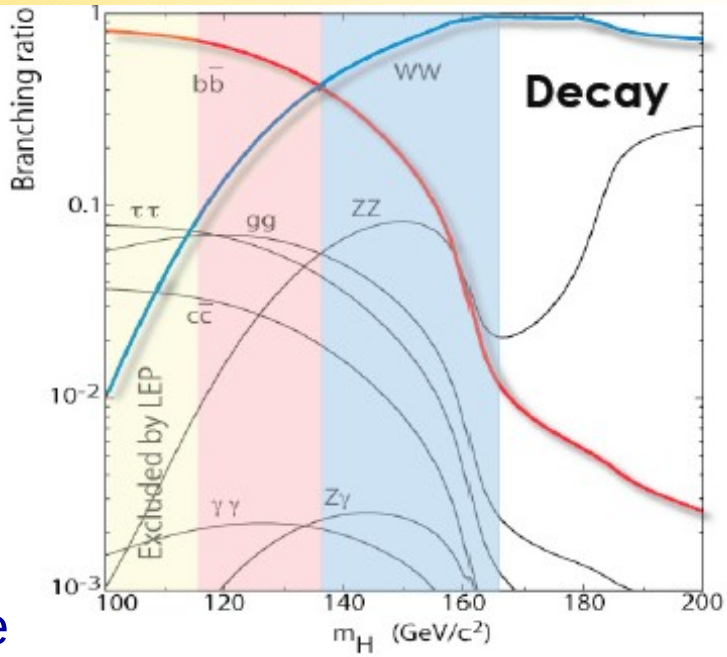
- $m_H > 114$ GeV (LEP direct)
- $m_H < 154$ GeV (indirect)
- $m_H < 185$ GeV (indirect + LEP)

- A very rare process!
- Lepton ID, $\not{E}_T$.
- b-tagging.
- Careful background estimation.
- Extensive use of multivariate discriminants (NN, BDT, ME).



SM Higgs Production and Decay





- High mass: H→WW→lνlν decay available
  - Take advantage of large gg→H production cross section
- Low Mass: H→bb, QCD bb background overwhelming
  - Use associated production with W or Z for background discrimination
  - WH→lνbb, ZH→ννbb (MET+bb), ZH→llbb
  - Also: VBF Production, VH→qqbb, H→ττ(with 2jets), H→γγ, WH->WWW, ttH

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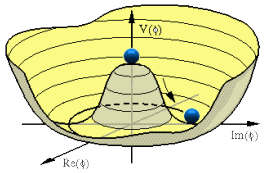
A few statistics

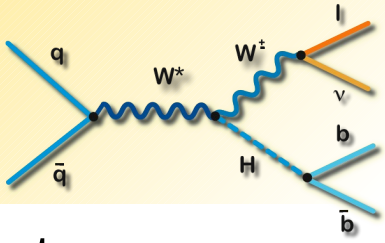
- Many different decay channels to consider.
- Must combine *all* channels across *both* experiments for full significance.
- Total of 77 input channels:

$WH \to \ell\nu bb$	$WH \to \tau\nu bb$	$WH \to WWW$	
$ZH \to \ell\ell bb$	$VH \to \not{E}_T bb$	$VH \to qqbb$	
$H \to WW$	$H \to \tau\tau$	$H \to \gamma\gamma$	ttH

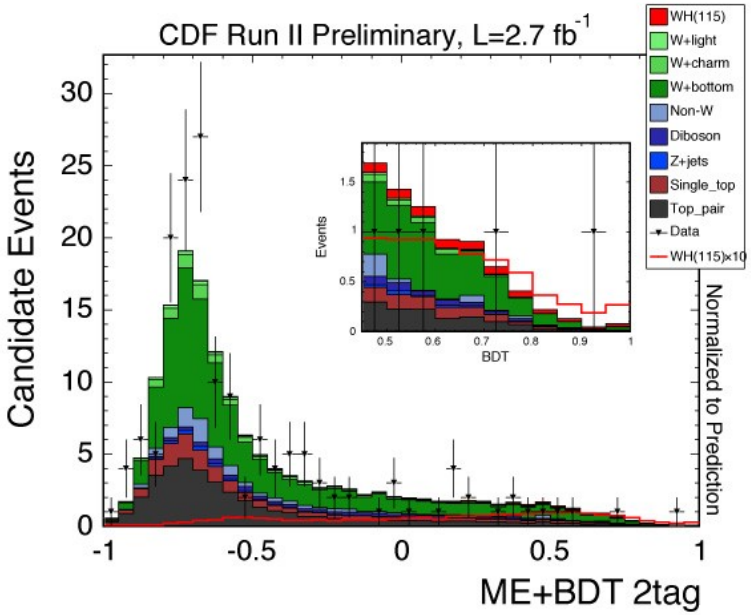
- At $m_H = 115\,\text{GeV}$
  - 10827 Background events predicted
  - 37 SM Higgs signal events predicted
  - 10746 Events observed in data
- At $m_H = 160\,\text{GeV}$
  - 2622 Background events predicted
  - 34 SM Higgs signal events predicted
  - 2578 Events observed in data



SM Higgs: WH→lνbb



- WH→lνbb - signature: high pT lepton, MET and b jets
  - Backgrounds: W+bb, W+qq(mistagged), single top, Non W(QCD)
  - Key issue: estimating W+bb background
    - Shape from MC with normalization from data control regions
  - Innovations: CDF: 20% acceptance from isolated tracks, ME with NN jet corrections
    DØ : 20% acceptance from forward leptons, use 3 jet events



Results at mH = 115GeV: 95%CL Limits/SM

Analysis	Lum (fb^{-1})	Higgs Events	Exp. Limit	Obs. Limit
CDF NN	2.7	8.3	5.8	5.0
CDF ME+BDT	2.7	7.8	5.6	5.7
DØ NN	1.7	7.5	8.5	9.3

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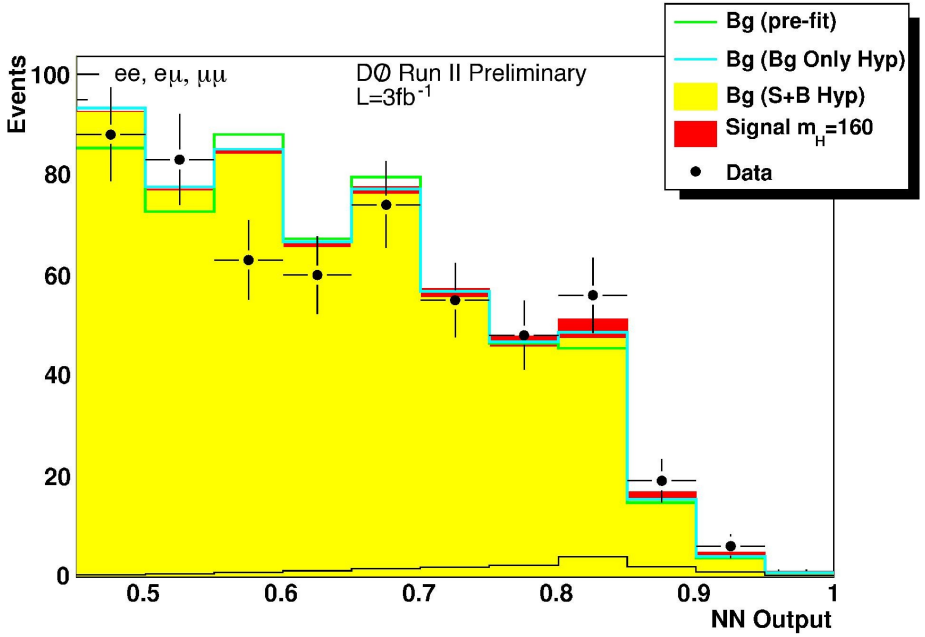
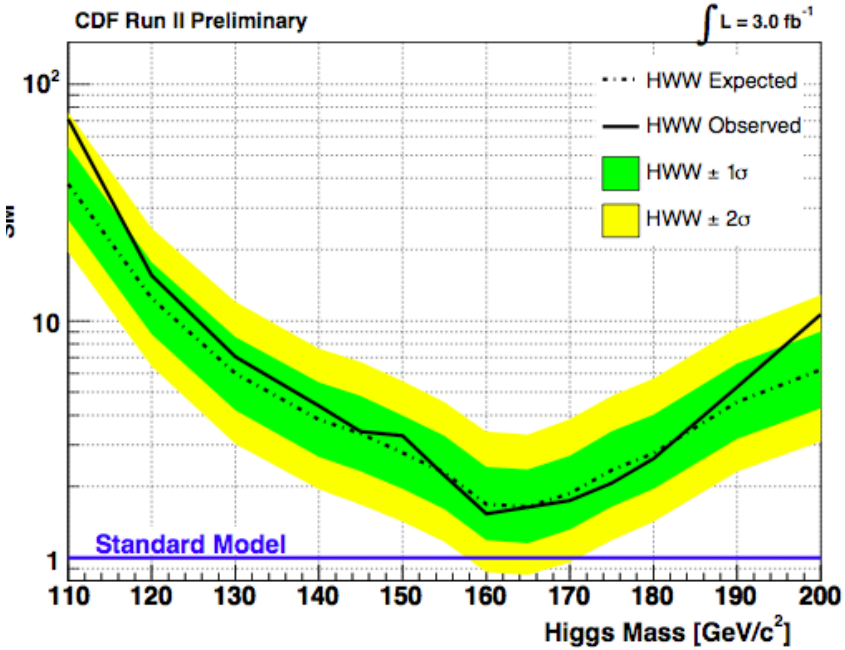
SM Higgs: H→WW

- Most sensitive Higgs search channel at the Tevatron





Results at mH = 165GeV : 95%CL Limits/SM

Analysis	Lum (fb^{-1})	Higgs Events	Exp. Limit	Obs. Limit
CDF ME+NN	3.0	17.2	1.6	1.6
DØ NN	3.0	15.6	1.9	2.0

Both experiments Approaching SM sensitivity!

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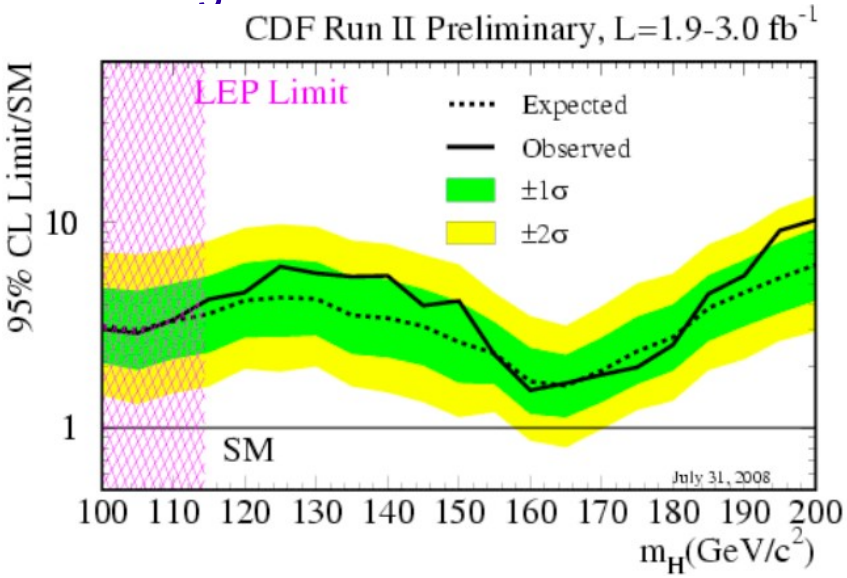
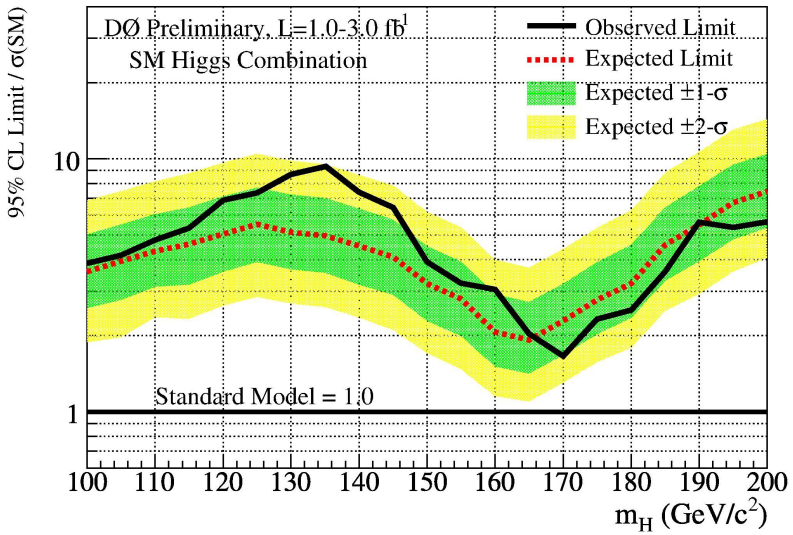
SM Higgs Combined Limits

- Limits calculating and combination
  - Using Bayesian and CLs methodologies.
  - Incorporate systematic uncertainties using pseudo-experiments (shape and rate included) (correlations taken into account between experiments)
  - Backgrounds can be constrained in the fit

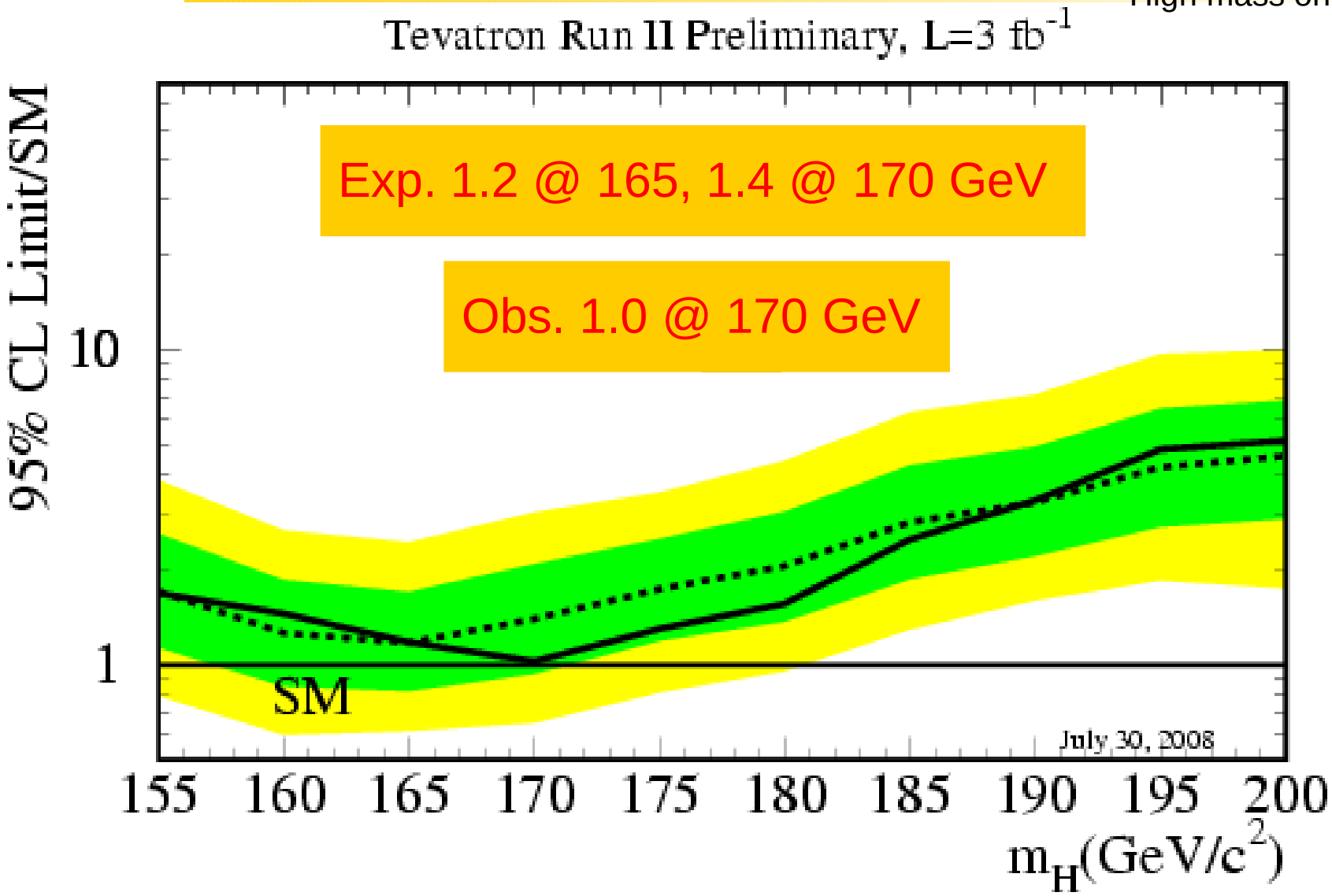




- Low mass combination difficult due to ~70 channels
  - Expected sensitivity of CDF/DØ combined: <3.0xSM @ 115GeV

SM Higgs Combination

High mass only

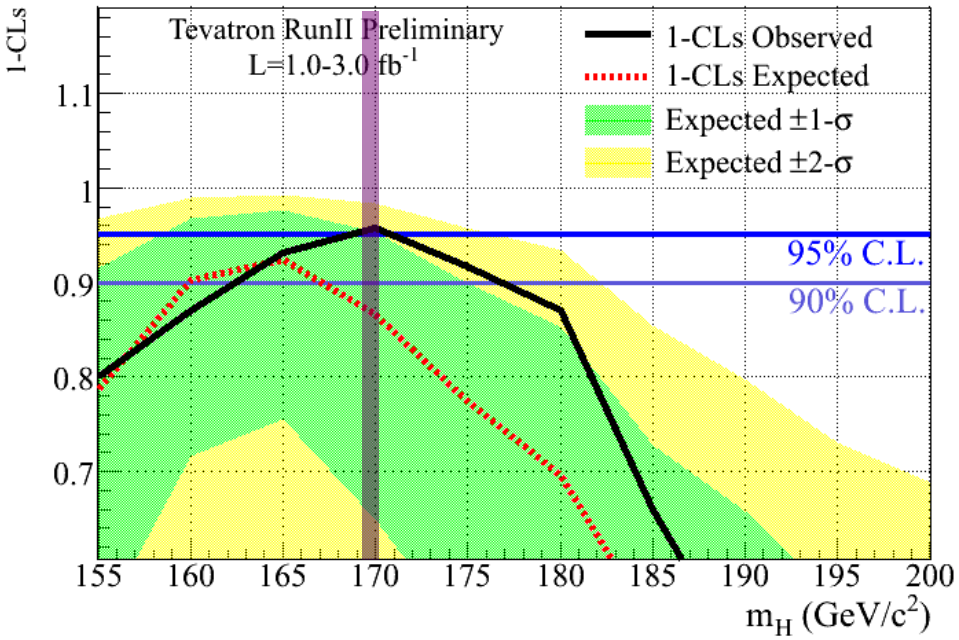


Exp. 1.2 @ 165, 1.4 @ 170 GeV

Obs. 1.0 @ 170 GeV

SM Higgs Combination

- Result verified using two independent methods(Bayesian/CLs)



95%CL Limits/SM

M Higgs(GeV)	160	165	**170**	175
Method 1: Exp	1.3	1.2	1.4	1.7
Method 1: Obs	1.4	1.2	**1.0**	1.3
Method 2: Exp	1.2	1.1	1.3	1.7
Method 2: Obs	1.3	1.1	**0.95**	1.2

SM Higgs Excluded: m_H = 170 GeV

- We exclude at 95% C.L. the production of a SM Higgs boson of 170 GeV

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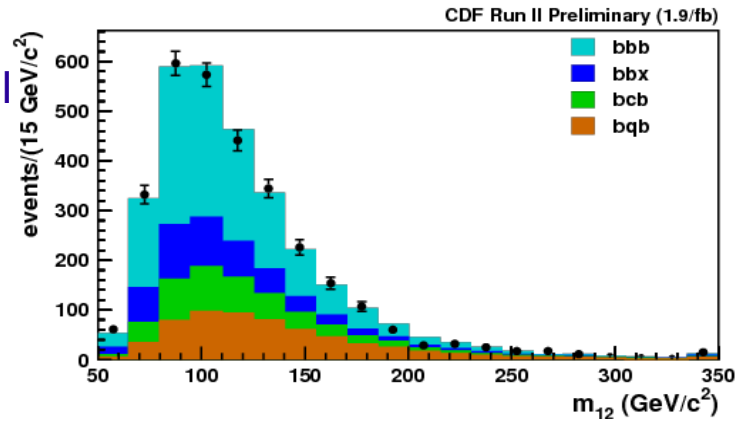
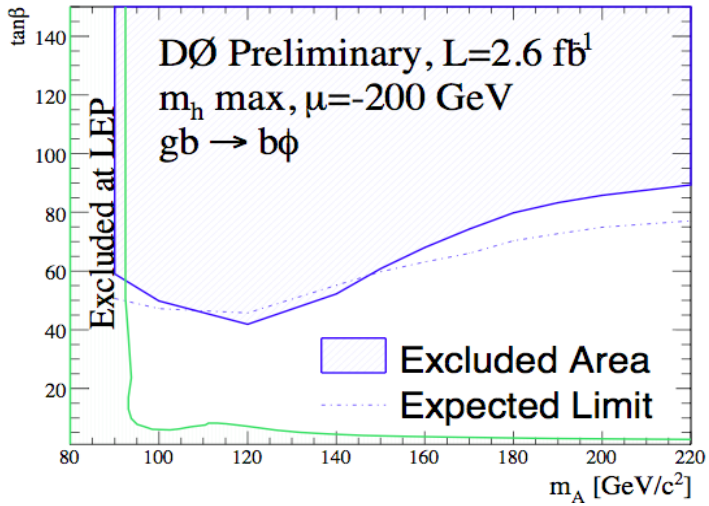
BSM Higgs: $\phi \rightarrow bb$

- CDF and DØ 3b channel: $b\phi \rightarrow bbb$.
  - Di-b-jet background too large in $\phi \rightarrow bb$ channel
  - Search for peak in di-b-jet mass distribution of leading jets
- Key issue: understanding the quark content of the 3 jets
  - CDF: Secondary vertex tagger and vertex mass
  - D0: NN tagger using multiple operating points
  - Simulation/data driven studies of background
- No Evidence for Higgs:
  - Limits $\tan\beta$ vs m_A
  - 3b search very sensitive with certain SUSY parameter choices





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Other BSM modes: $\phi \rightarrow \tau\tau$, $WH \rightarrow WWW$, $H \rightarrow \gamma\gamma$.

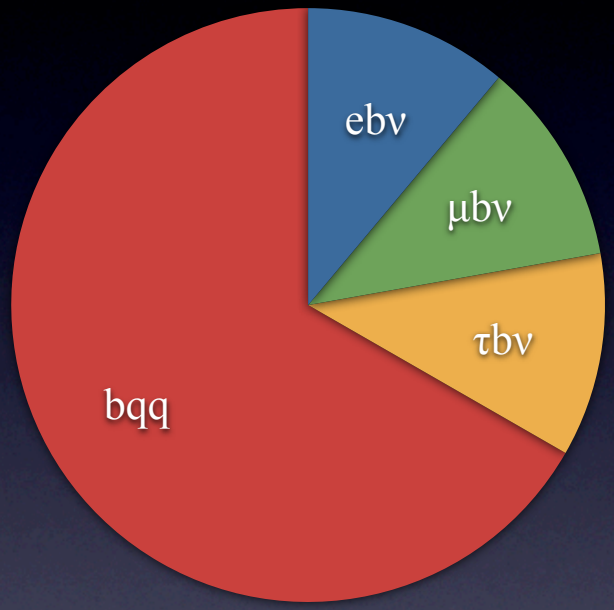
What We Can Learn From the Top Quark

- Questions
  - What is the Higgs boson mass?
  - Do we understand heavy flavor production in QCD?
  - Are there more than three fermion generations?
  - Are there new massive particles?
  - Do all quarks have the expected couplings?
- Measurements in this talk
  - Single top cross section
  - Constraints on Wtb couplings
  - Searches for $H^+ \to tb$, $t \to H^+ b$
  - Search for FCNC
  - Top quark pair cross section
  - Top quark mass
  - Forward-backward charge asymmetry
  - M_{tt} distribution
  - Search for t' quark
  - W boson helicity
  - Top quark branching fractions

Top Quark Signatures

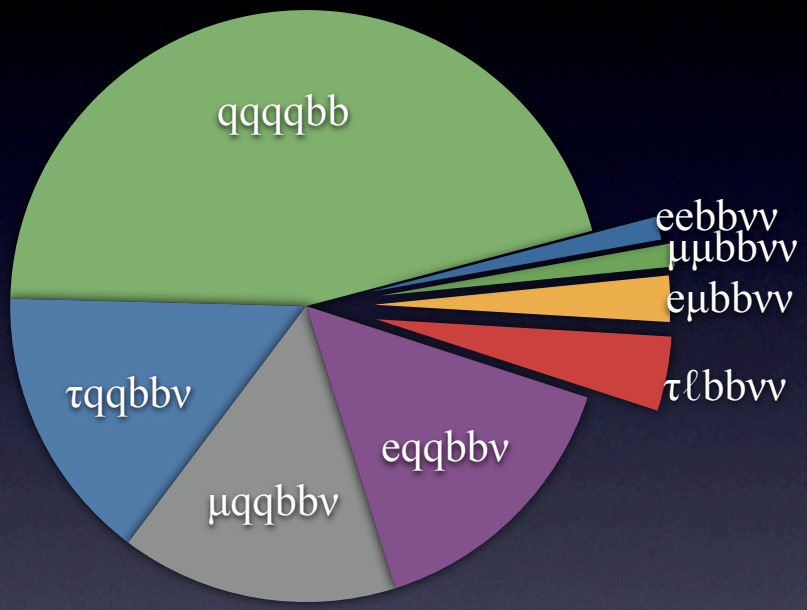
- Single top quark:

Tevatron cross section: ~3 pb



- Top quark pair:

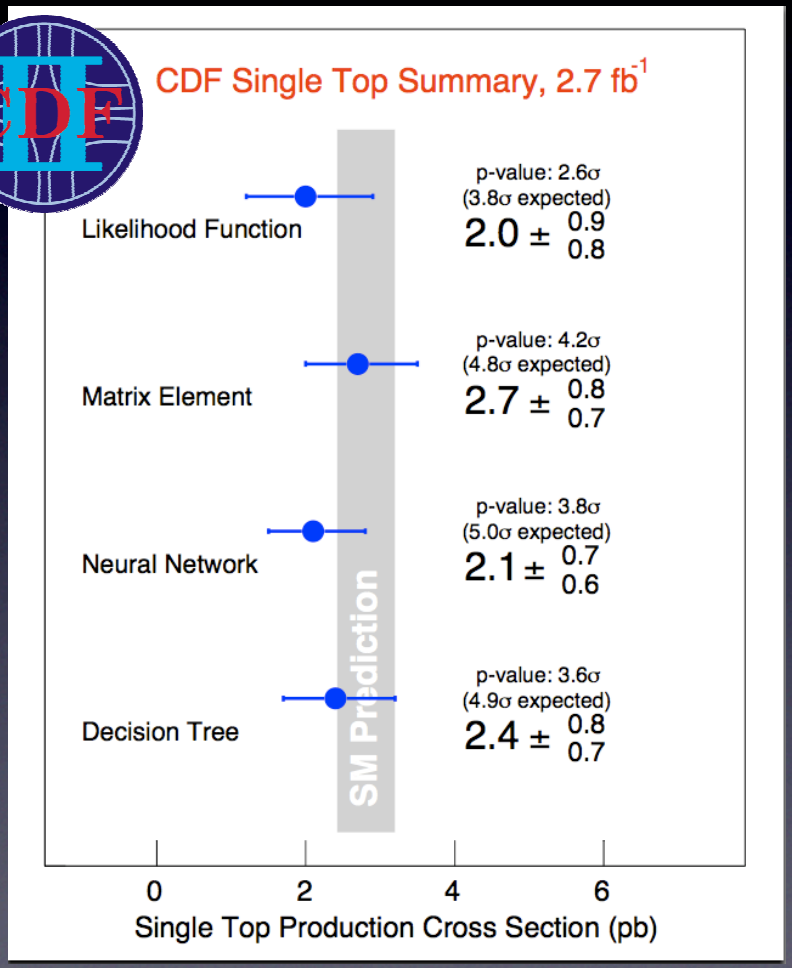
Tevatron cross section: ~7 pb

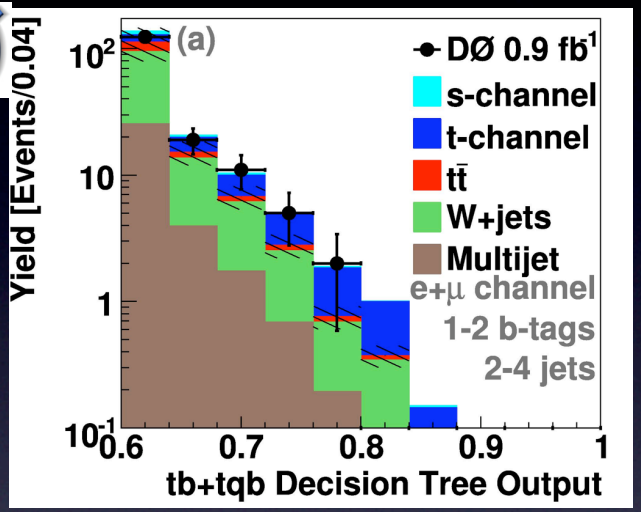


- Dominant backgrounds arise from vector boson + jet production
  - Good *b* jet and lepton ID, missing E_T resolution help in finding top quarks

Single Top Cross Section

- Both CDF and DØ use several multivariate discriminants to find single top candidates:



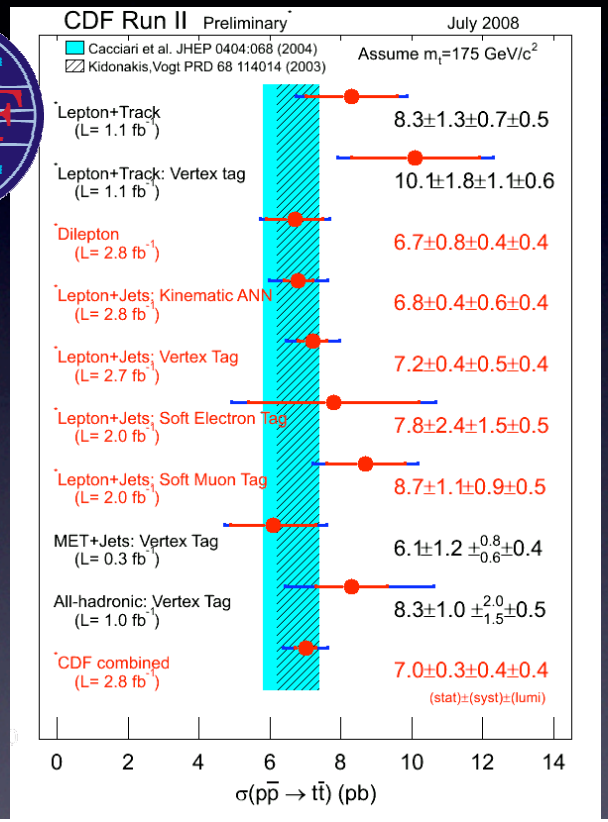


- Combining methods:

DØ: $\sigma = 4.7 \pm 1.3$ pb
3.6σ significance (obs)
2.3σ significance (exp)
$|V_{tb}| > 0.68$ @ 95% C.L.

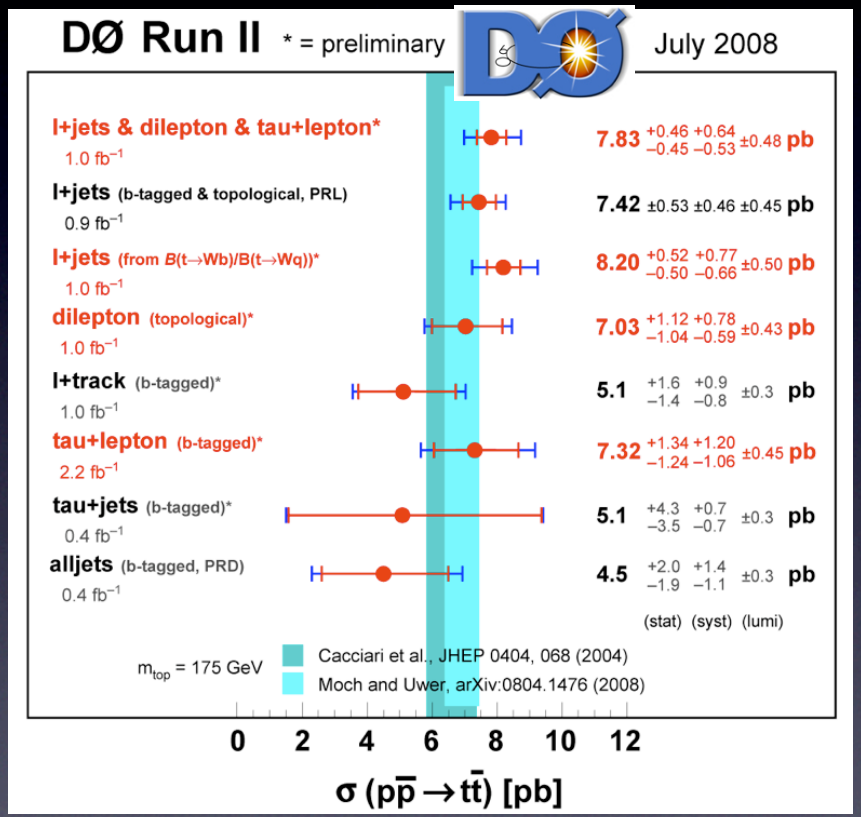
Production Cross Section

- The $t\bar{t}$ cross section has been measured in many final states
  - new physics may impact final states differently



$$\sigma(p\bar{p} \to t\bar{t}) = 7.0 \pm 0.3 \pm 0.4 \pm 0.4 \text{ pb}$$

stat. syst. lum.

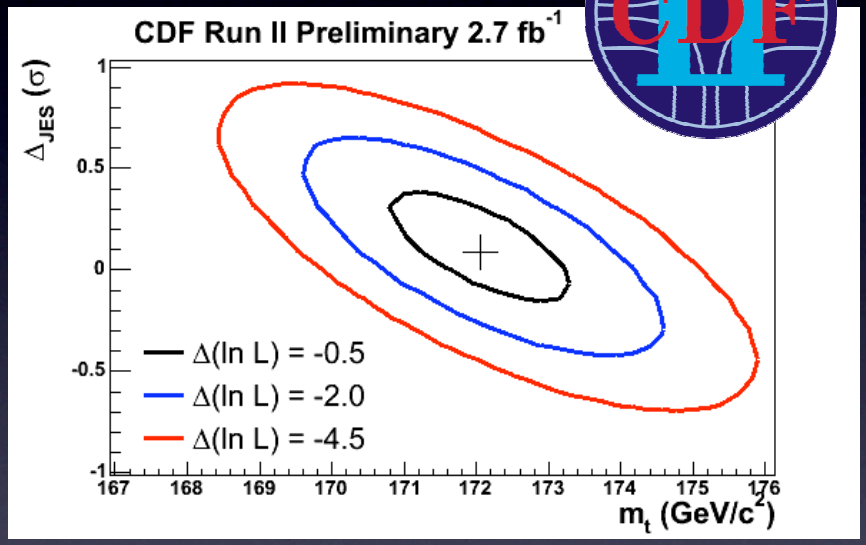


$$\sigma(p\bar{p} \to t\bar{t}) = 7.8 \pm 0.5 \pm 0.6 \pm 0.5 \text{ pb}$$

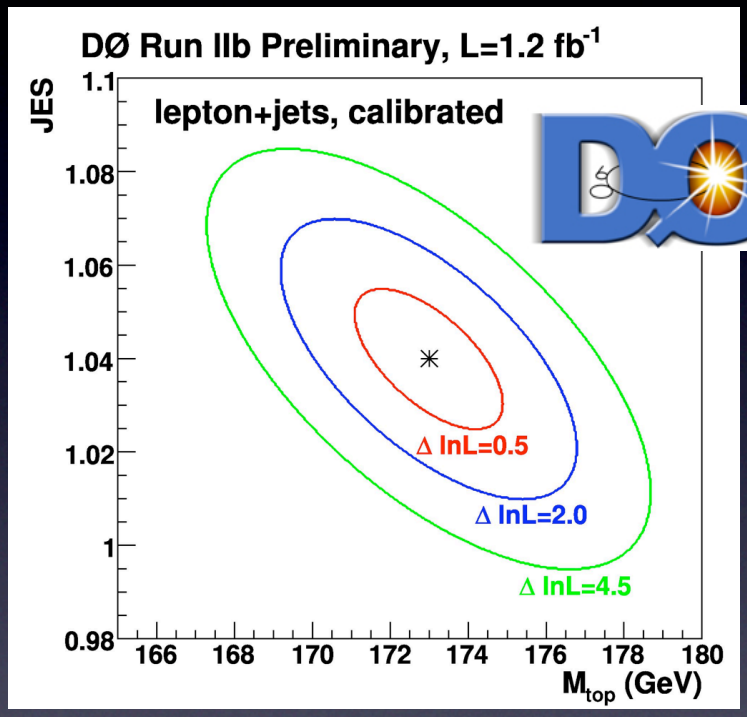
stat. syst. lum.

Top Quark Mass (ℓ +jets)

- Results:



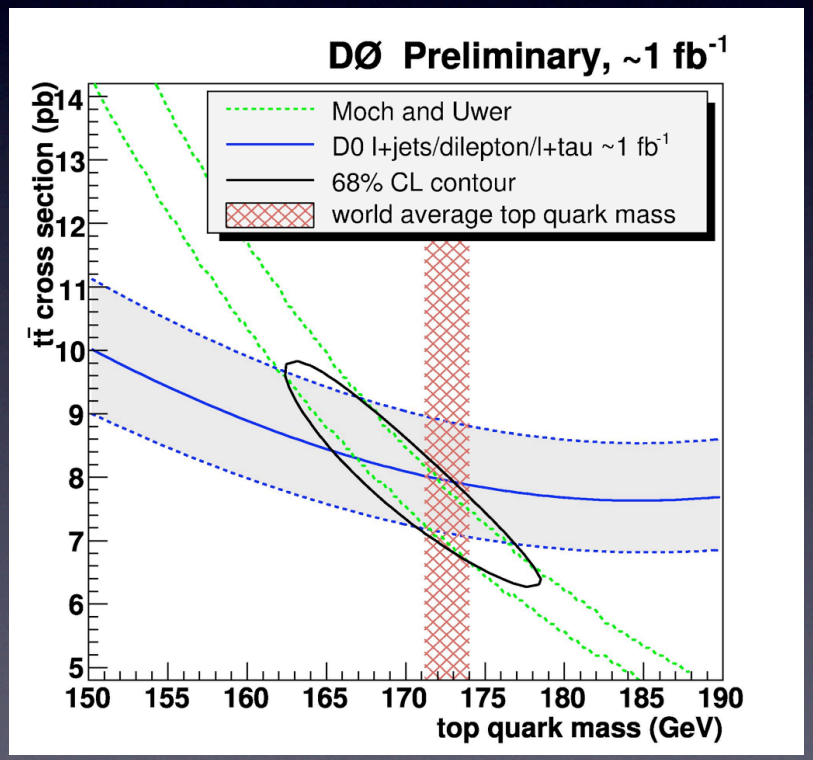
$m_t = 172.2 \pm 1.0 \pm 1.3$ GeV



DØ Run II combined (2.2 fb^{-1}):
$m_t = 172.2 \pm 1.0 \pm 1.4$ GeV

Mass Measurement from Cross Sections

- Assuming that production is governed by SM, can compare measured to calculated cross sections to extract top mass
  - mass is measured in a well-defined renormalization scheme
  - systematics largely uncorrelated with other methods



NLO+NLL cross section:

M. Cacciari *et al.* (2008)

$m_t = 167.8 \pm 5.7$ GeV

Approx NNLO cross section:

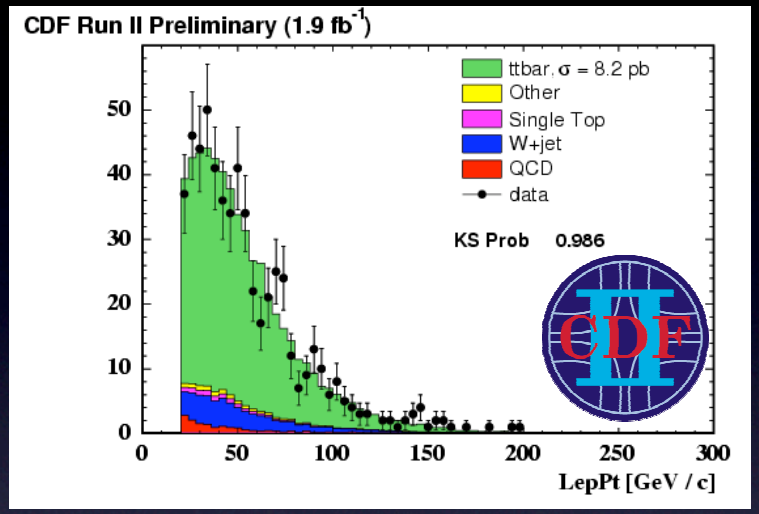
S. Moch and P. Uwer (2008)

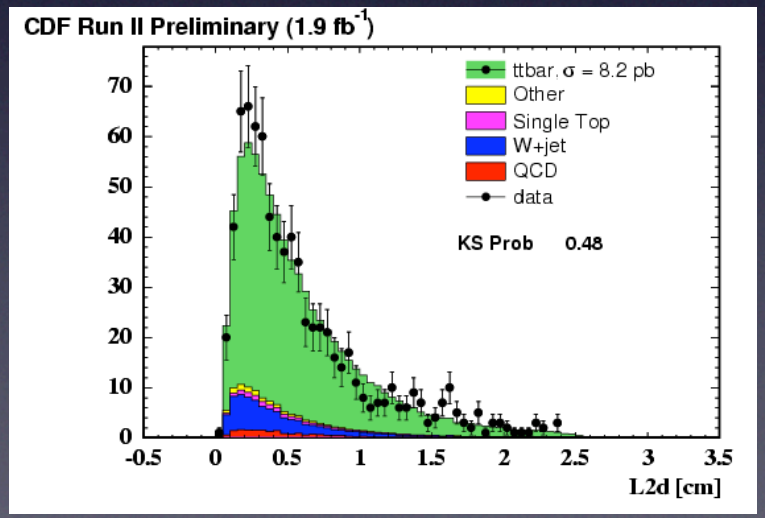
$m_t = 169.6 \pm 5.4$ GeV

Top Quark Mass without Jet Energy

- Use observables that vary with top mass but have no first-order dependence on jet response
  - lepton p_T
  - b decay length in xy plane

$$m_t = 175.3 \pm 6.2 \pm 3.0 \text{ GeV}$$



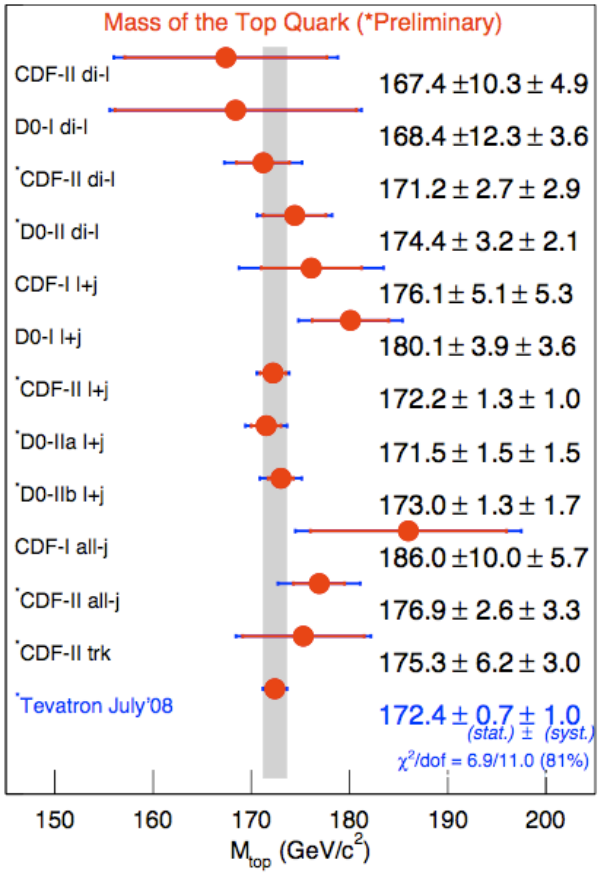


Systematics largely orthogonal to other measurements

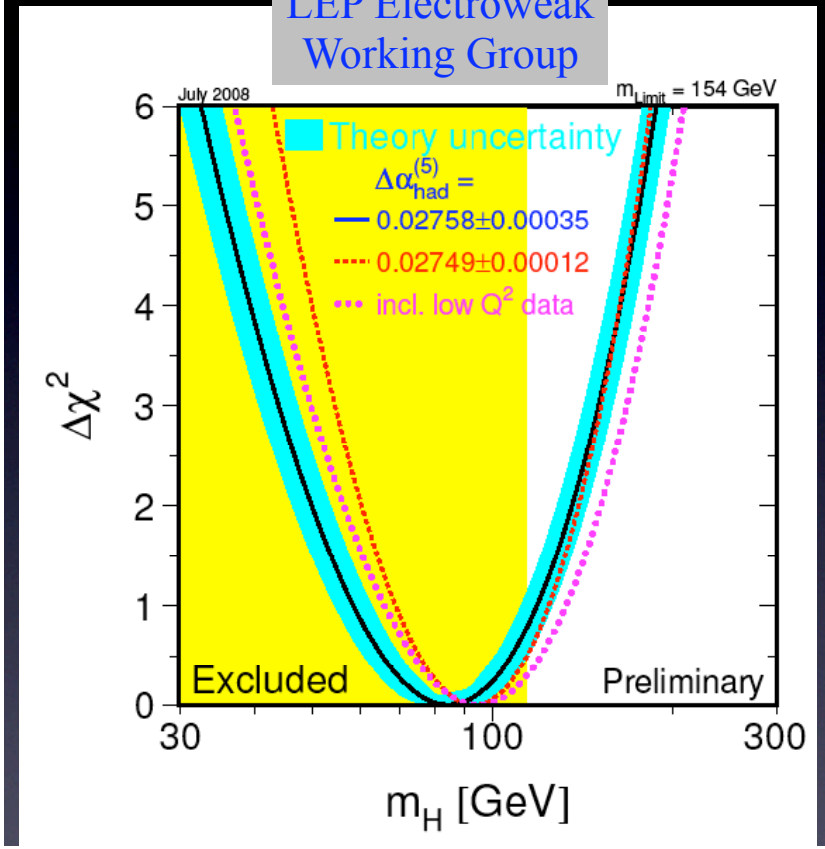
Currently statistics-limited, but will be an important technique at the LHC

World Average Top Quark Mass

Tevatron Electroweak Working Group



LEP Electroweak Working Group



$m_t = 172.4 \pm 0.7 \pm 1.0$ GeV

0.7 % precision

$m_H < 154$ GeV @ 95% C.L.

< 185 GeV

with LEP2 limit

Search for Invisible Decays

- Measure absolute rate (rather than fraction) of events with 2 b-tagged jets to determine $B(t \rightarrow X)$
  - sensitive to invisible top decays

X is any state with different acceptance than Wb

Top Cross Section: Double Loose SECVTX Tag ($\int \mathscr{L} dt = 1.9\,\mathrm{fb}^{-1}$)				
Sample	**2 Jets**	**3 Jets**	**4 Jets**	**≥ 5 Jets**
WW	0.5±0.1	0.5±0.1	0.2±0.0	0.1±0.0
WZ	2.6±0.3	0.8±0.1	0.2±0.0	0.0±0.0
ZZ	0.1±0.0	0.0±0.0	0.0±0.0	0.0±0.0
Single Top (s)	8.4±1.2	2.8±0.4	0.7±0.1	0.1±0.0
Single Top (t)	2.0±0.3	1.8±0.2	0.5±0.1	0.1±0.0
Z+LF	1.1±0.2	0.7±0.1	0.2±0.0	0.1±0.0
$Wb\bar{b}$	33.9±13.3	10.6±4.3	2.0±0.9	0.5±0.2
$Wc\bar{c}/Wc$	6.1±2.5	2.7±1.1	0.7±0.3	0.2±0.1
Mistags	4.3±1.0	2.6±0.7	0.7±0.2	0.2±0.1
Non-W	2.7±1.9	0.8±1.5	0.5±1.5	0.2±1.5
Total Background	61.6±16.6	23.4±7.3	5.7±3.3	1.4±1.7
SM $t\bar{t}$ (8.8pb)	32.9±5.2	90.2±14.1	113.7±17.6	41.1±6.3
Total Prediction	94.5±17.4	113.6±15.9	119.4±17.9	42.5±6.5
Observed	107.0	118.0	115.0	44.0

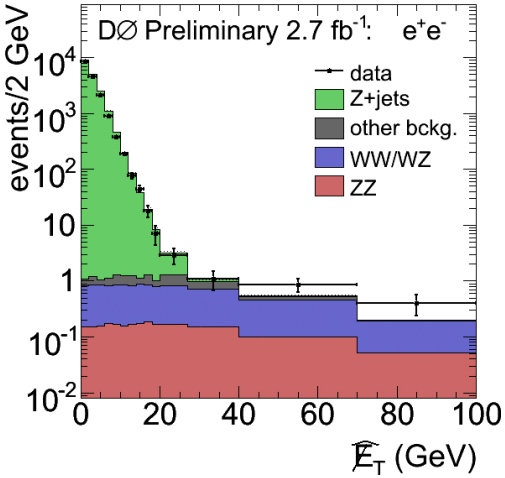
$$B(t \rightarrow Zc) < 13\%$$
$$B(t \rightarrow \text{invisible}) < 9\%$$

Z Pair Production @ DØ (1.7-2.7 fb^{-1})

ZZ→llνν channel: new missing E_T estimator, likelihood to separate WW background (S/B=0.25)

ZZ→llll: no candidate in first 1 fb-1, then 3 candidates in 1.7 fb^{-1}

Result $\sigma=(1.48\pm0.59^{+0.17}_{-0.19})$ pb (stat+syst)

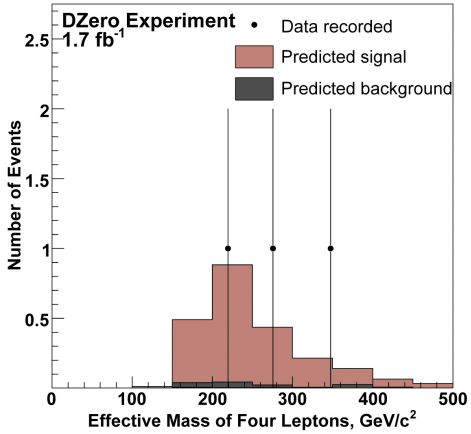


Observation

Channel	ZZ→llνν	ZZ→llll*	Combined
Observed Results			
p-value	$4.0*10^{-3}$	$4.3*10^{-8}$	
significance	2.7σ	5.3σ	5.7σ

* 1.7fb^{-1}

Expected significance 4.8σ



Hopefully not last diboson process to be observed at Tevatron

available on arxiv this week

CDF observes *ZZ* too!

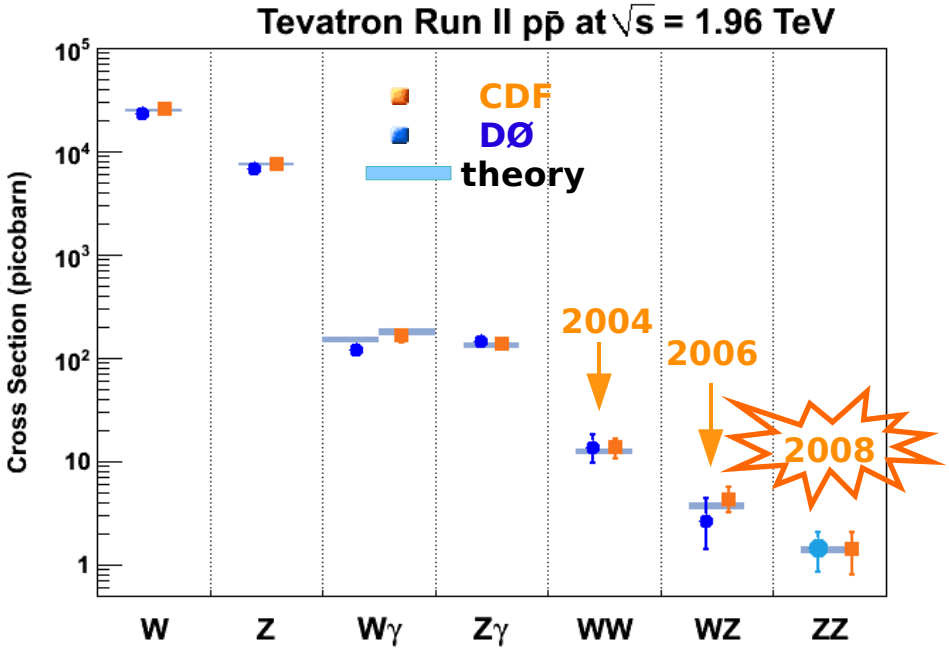
Cross Sections Summary

All diboson processes involving W/Z/γ observed at Tevatron .....

..... but only in the fully leptonic decay channels

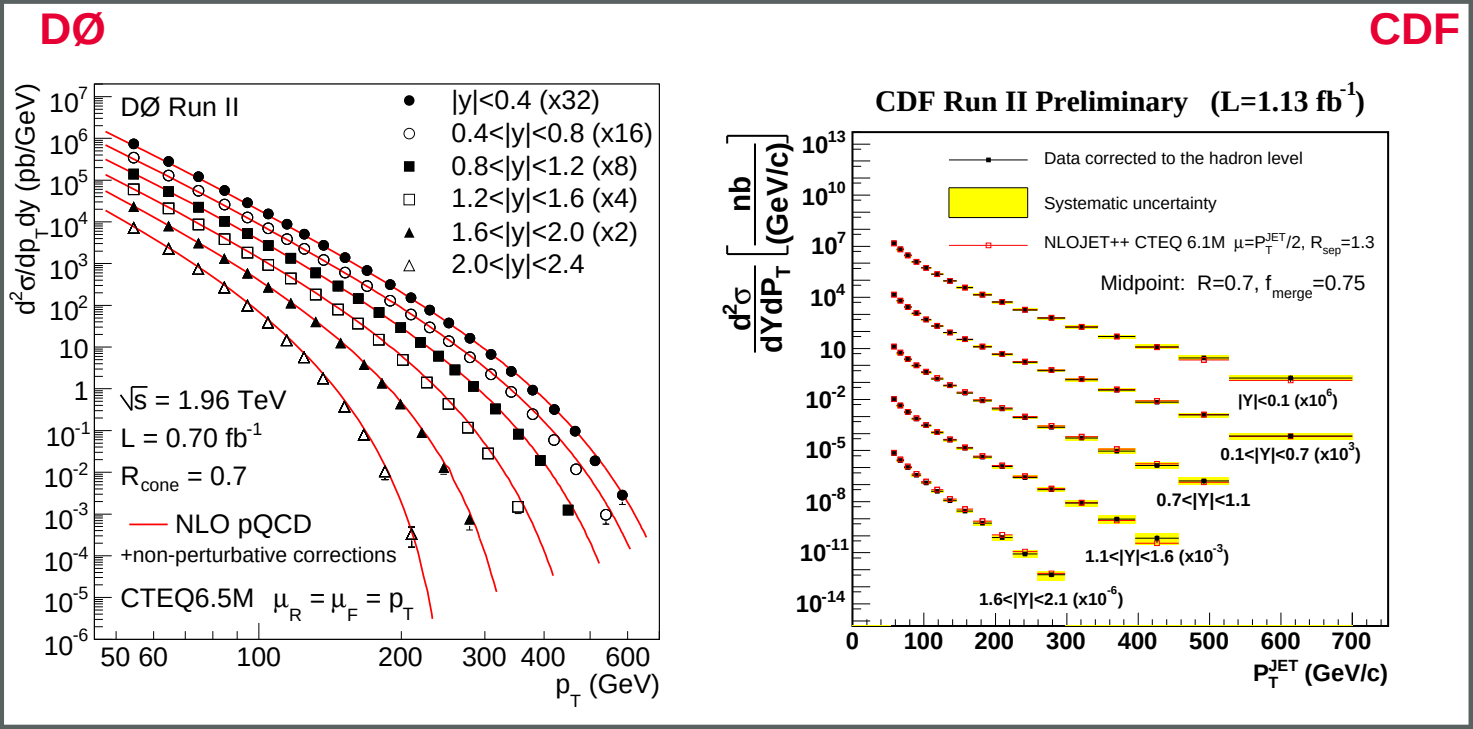
Both experiments working on selecting diboson processes with W/Z→jets, large W/Z+jets background

Proving ground for analysis techniques for Higgs searches and theory calculations / Montecarlos



Jet cross sections at TevaTron

- **Inclusive-jet cross sections in $p\bar{p}$ collisions: high precision measurements at high $E_T^{\rm jet}$, where new physics might show up (and sensitive to g PDF at high x)**



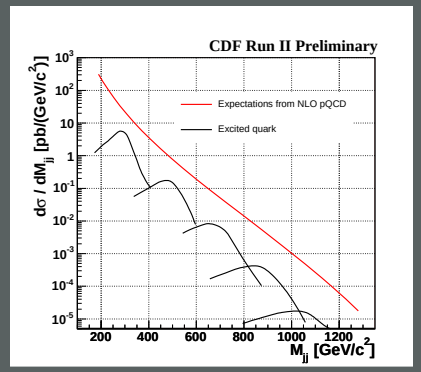
→ **Good description of data by NLO QCD calculations**

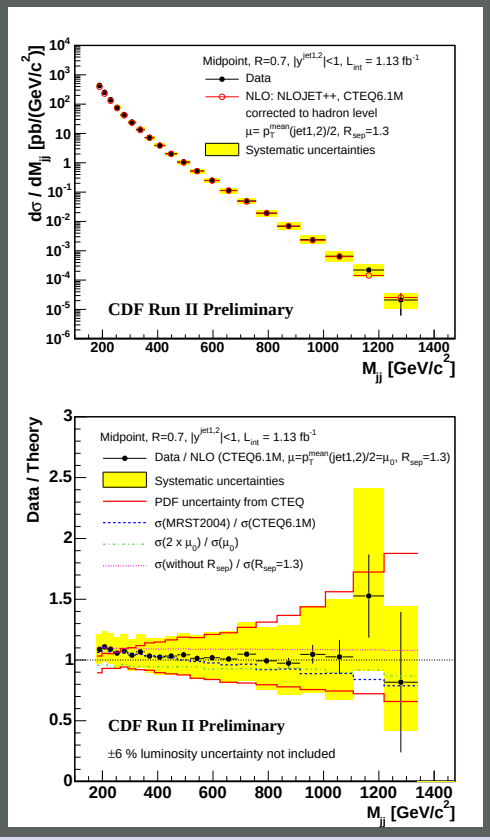
→ **These measurements constitute the most stringent test of pQCD at highest available energies**

DØ, abstract 506, hep-ex/0802.2400 CDF, abstract 452, CDF/DOC/JET/PUBLIC/8928

Jet cross sections at TevaTron

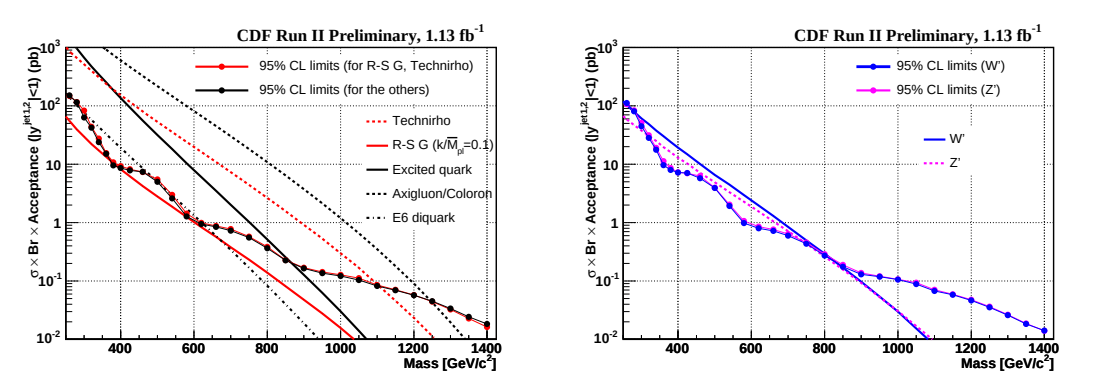
- Jet production dominant at hadron colliders → highest reach in energy and probe of hard interactions at shortest distances
  → dijet production ideal to test SM and search for new physics (narrow resonances in dijet mass spectrum)





→ Good description of data by NLO QCD over whole $M^{\rm jj}$ range ($0.2 < M^{\rm jj} < 1.4$ TeV)

→ Set limits on new physics: excited quarks, W', Z' and gravitons

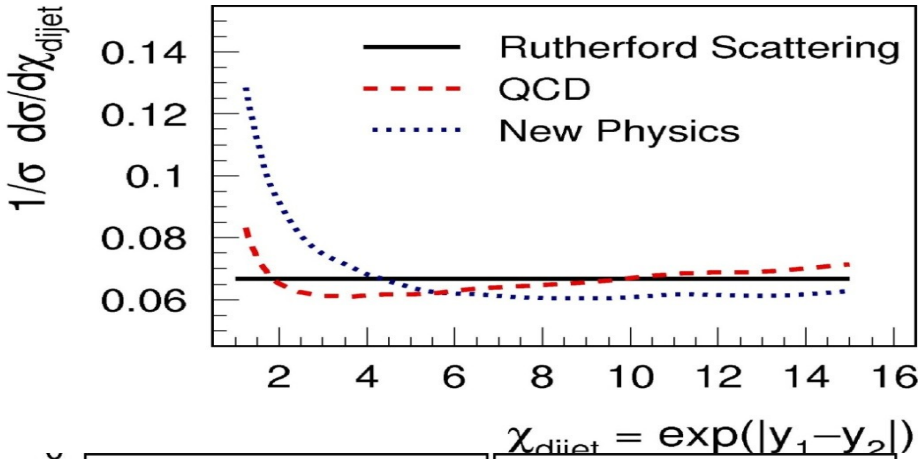


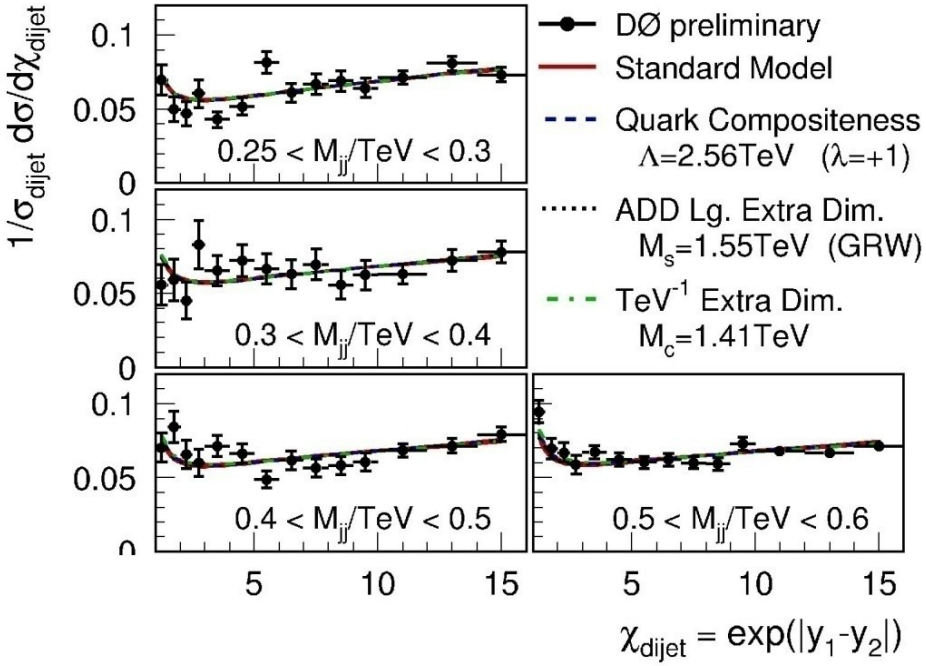
CDF, abstract 452, CDF/9246

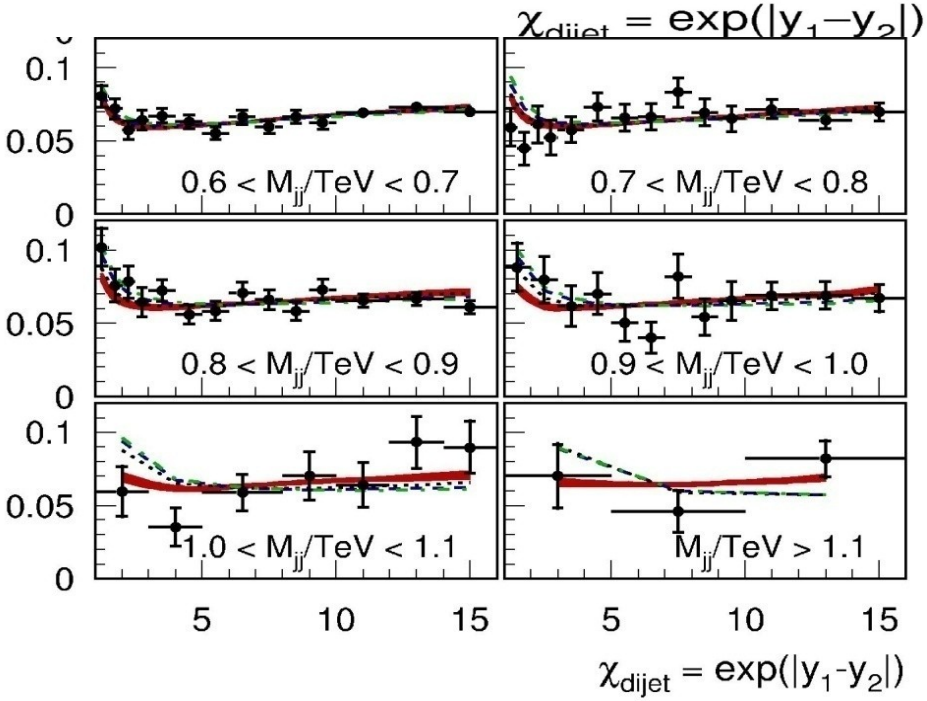
Dijet angular distributions

Variable $\chi_{\rm dijet} = \exp(|y_1 - y_2|)$

- Flat for Rutherford scattering
- Slightly shaped for pQCD
- New physics enhances low end



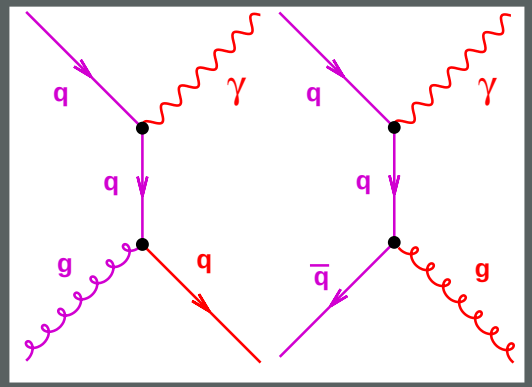




Compositeness ($\lambda = +1$): $\Lambda > 2.6$ TeV;
ADD extra dim ($n = 4$): $M_s > 1.6$ TeV; TeV^{-1} extra dim: $M_c > 1.4$ TeV.

Prompt photons + jets at TevaTron

- **Production of isolated photons in association with jets:** $p\bar{p} \to \gamma + \mathrm{jet} + \mathrm{X}$

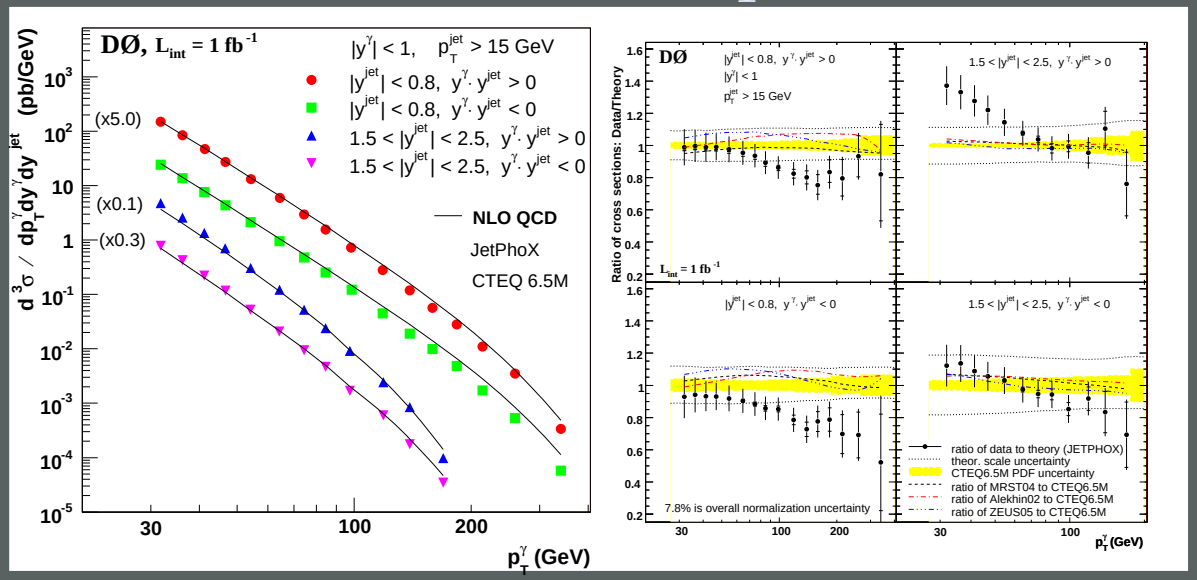


→ **probe of dynamics of hard QCD interactions**

– **different angular configurations test different x and Q^2 regions → constrain on PDFs**

$0.007 \lesssim x \lesssim 0.8,\ 900 \leq Q^2 \equiv (p_T^\gamma)^2 \leq 1.6 \cdot 10^5$ **GeV^2**

- **Measurements as a function of p_T^γ for different photon and jet rapidities →**

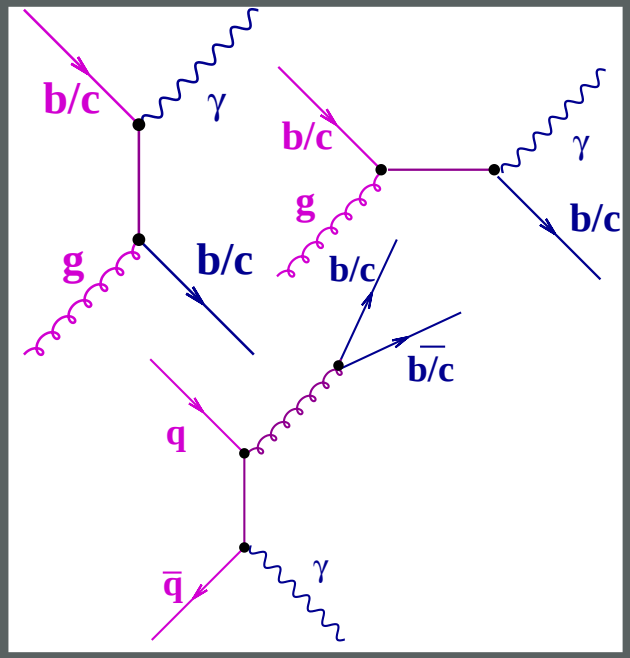


→ **NLO predictions with various PDF sets do not describe shape of cross section over entire measured range simultaneously**

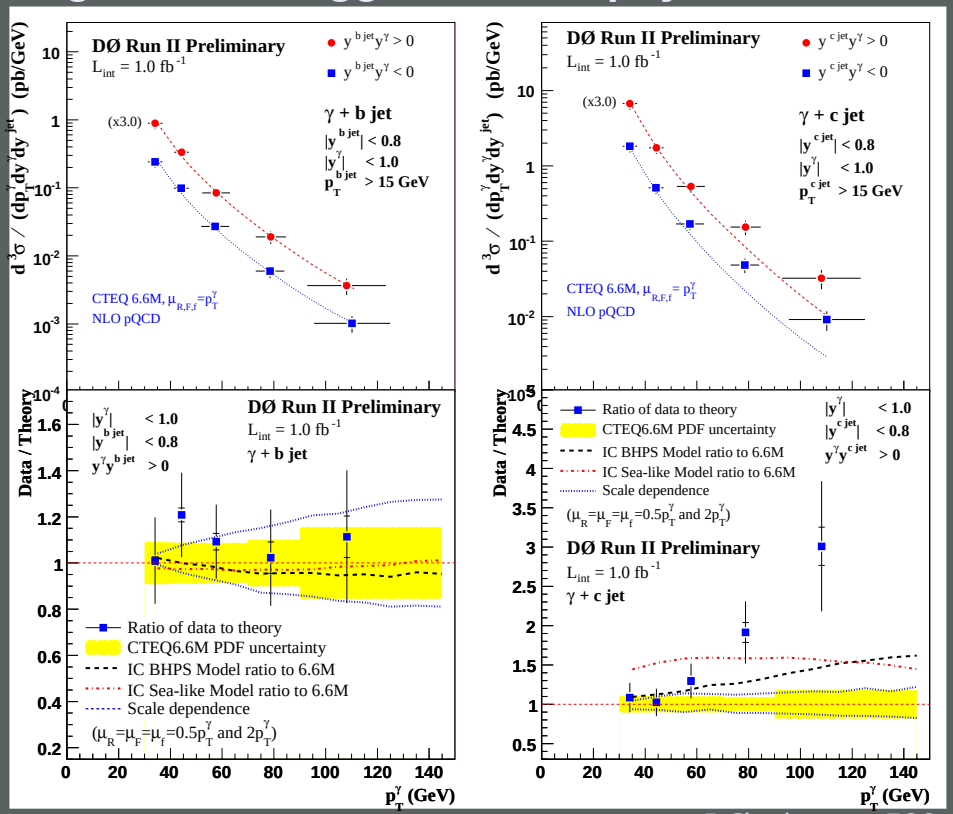
→ **an improved theoretical description of $\gamma + \mathrm{jet}$ production is needed**

DØ, abstract 509, hep-ex/0804.1107

$\gamma + b/c - \text{jets}$ at TevaTron



- **Production of γ in association with b/c-jets**
  - $\longrightarrow$ tests of pQCD
  - $\longrightarrow$ sensitive to b/c pPDFs
  - $\longrightarrow$ background to Higgs and new physics



- **Comparison with NLO predictions:**
  - $\longrightarrow$ good agreement for $\gamma + b(c)$ in all p_T^γ ($p_T^\gamma < 50$ GeV)
  - $\longrightarrow$ difference for $\gamma + c$ grows with increasing $p_T^\gamma \longrightarrow$ can be attributed to intrinsic charm, uncertainties in $g \longrightarrow Q\bar{Q}$, ...

DØ, abstract 526

There's lots more...

- Heavy flavor:
  - New measurements of B_s^0, B_c, Λ_b, Σ_b, Ξ_b.
  - CP violation in B_s^0.
  - V_{td}/V_{ts} from B_d, B_s mixing.
- Beyond Standard Model:
  - SUSY/leptoquark limits.
  - Charged massive stable particle search.
  - Monojet/monophoton searches, Z'.
- SUSY Higgs searches.
- Top physics:
  - Wtb coupling, $B(t \to Wb)/B(t \to Wq)$, $F(gg)$.
  - Forward/backward asymmetry, W helicity.
  - $m(t\bar{t})$, t', FCNC limits.
- Electroweak:
  - Z p_T form factor.
  - A_{FB}
- QCD
  - Underlying event.
  - W/Z + jets and heavy flavor.