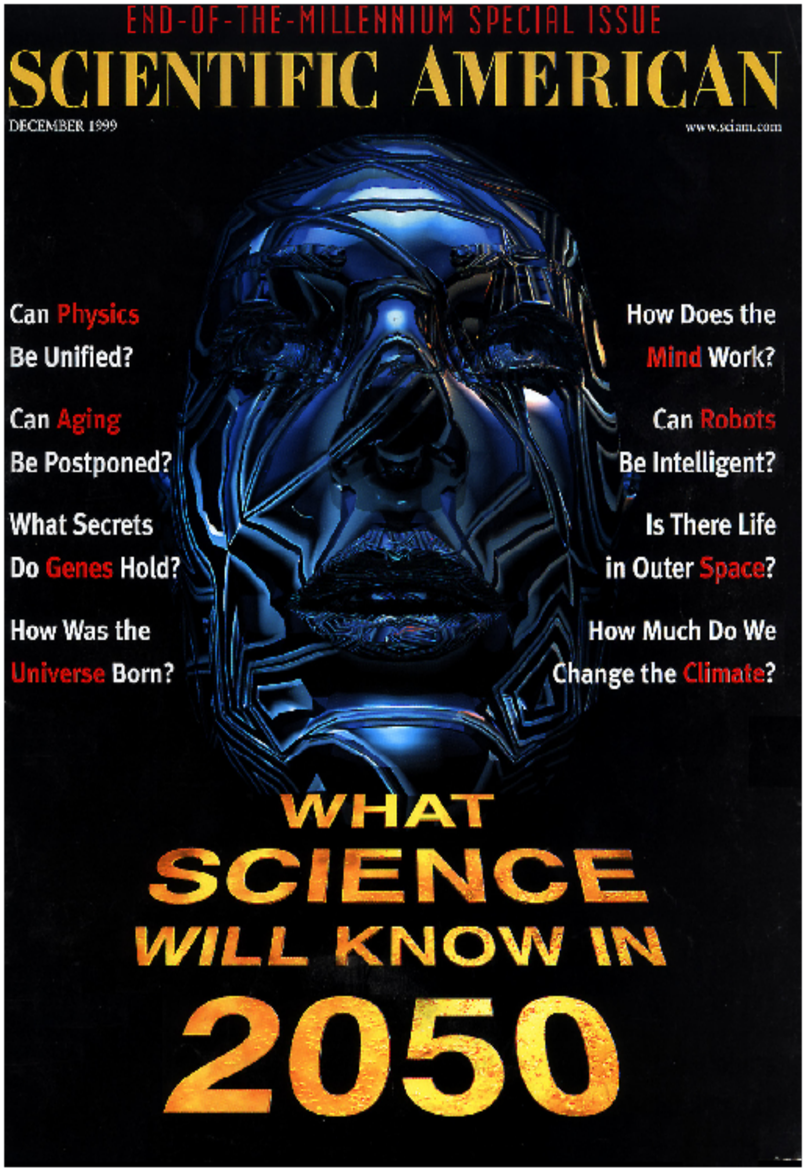
The Big Questions

Can Physics
Be Unified ?

Can Aging
Be Postponed ?

What Secrets
Do Genes Hold ?

How Was the
Universe Born ?



How Does the
Mind Work ?

Can Robots
Be Intelligent ?

Is There Life
In Outer Space?

How Much Do We
Change the Climate?

The Big Questions

Can we combine QM and G. Relativity?

Dark energy?
Cosmological constant?

Unification of forces?

Arrow of time

Correct interpretation of QM?

Dark matter?

Where is antimatter?

Black hole information paradox?

Why three generations of matter?

Extra dimensions?

Magnetic monopoles?

Inflation?

Are there many universes?

Mechanism of symmetry breaking, Higgs, origin of mass, mecanism for meutrino masses?

End of universe?

Locality in QM (Quantum entanglement)?

Clues from P-P(Pbar) Collisions?

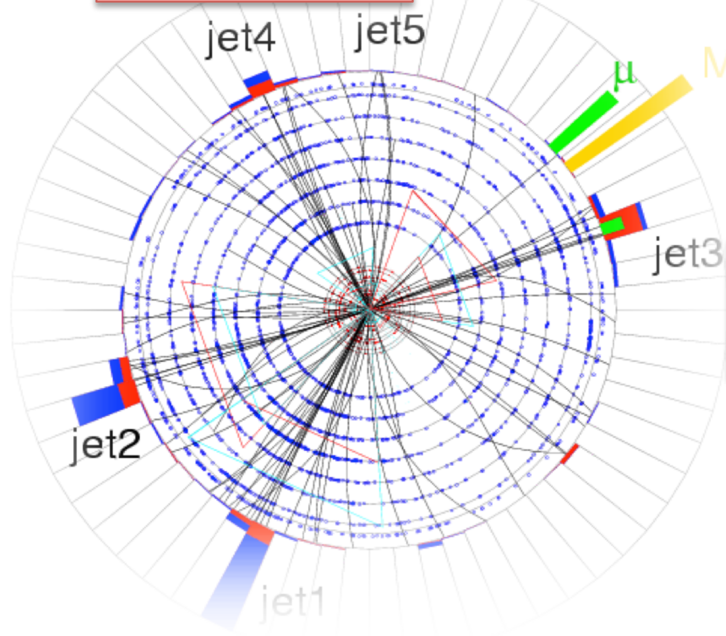
Unification of forces?

Arrow of time

Higgs

Correct interpretation of QM?

Dark matter?



Where is antimatter?

Why three generations of matter?

Can we combine QM and G. Relativity?

Mechanism of symmetry breaking, origin of mass

Extra dimensions?

QCD	B Physics	Electroweak	Top Quark	Higgs	New Phenomenon

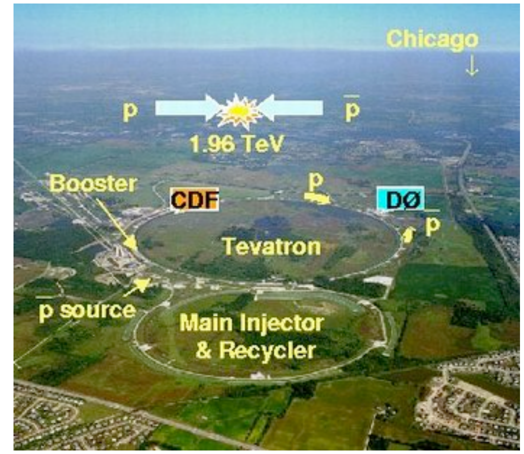
The Tevatron

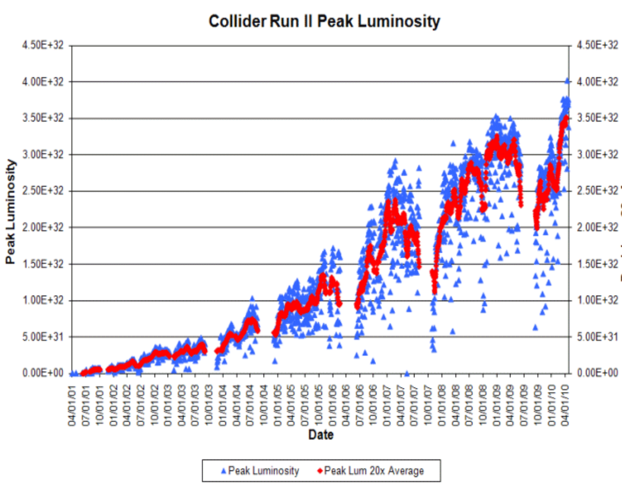
25years ago, first Tevatron collisions in 1985

Expected Tevatron luminosity ~3×10^{30} cm^{-2}s^{-1}

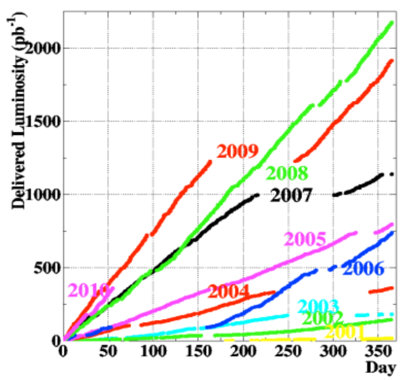
Now running at 3×10^{32} cm^{-2}s^{-1} routinely !

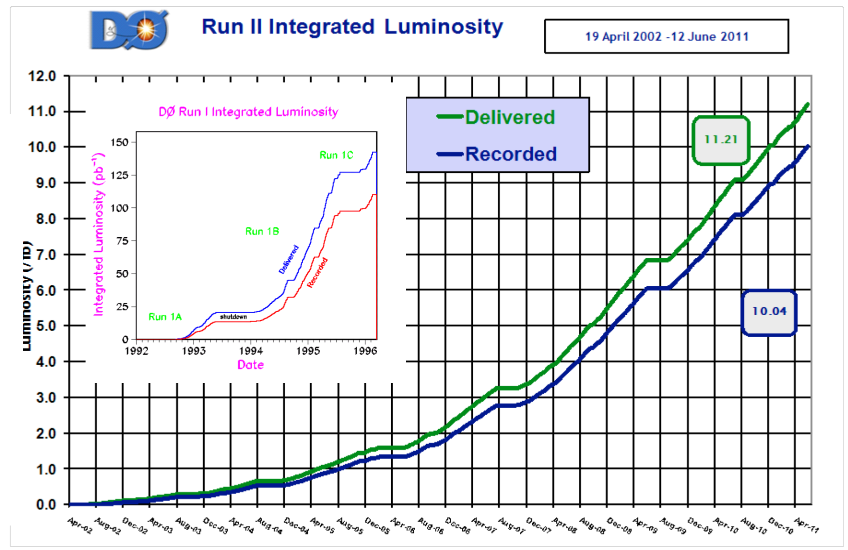
…and this is not the only time when a Tevatron team exceeded its own expectations and projections





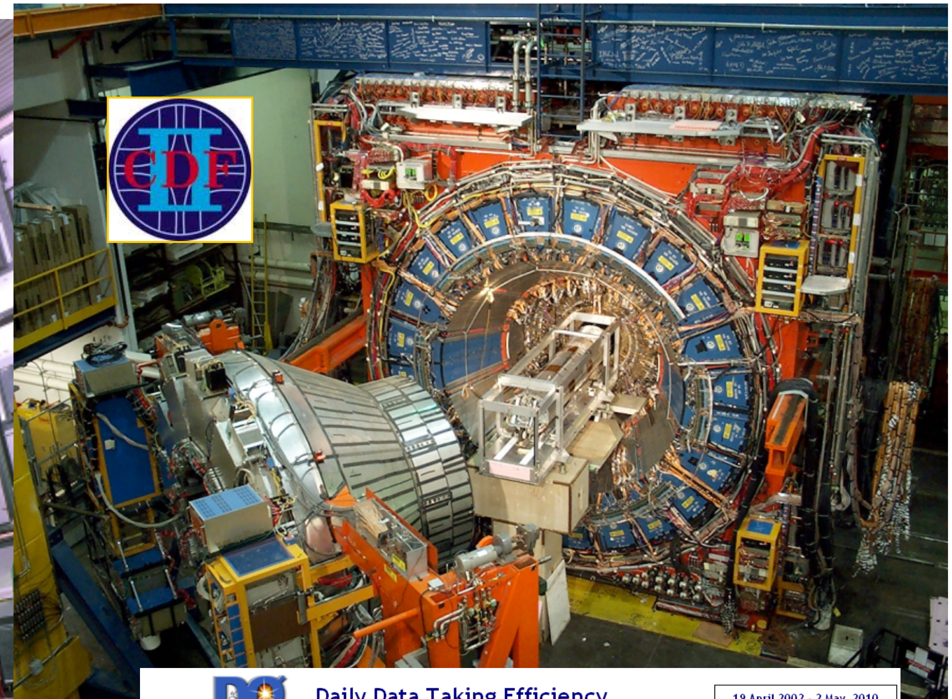
Luminosity Delivered per Calendar Year (*CDF Exp*)

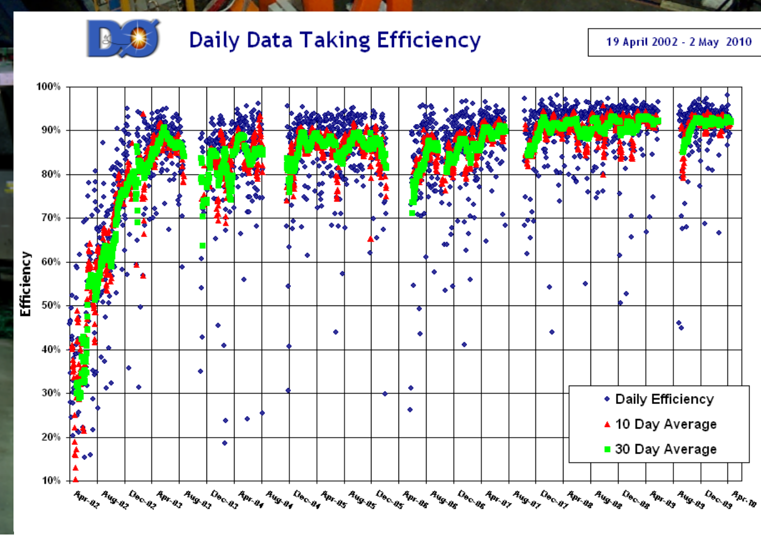




For 25 years, the Tevatron has been the only machine at the frontier… and we have learned much.

CDF and D0 Detectors





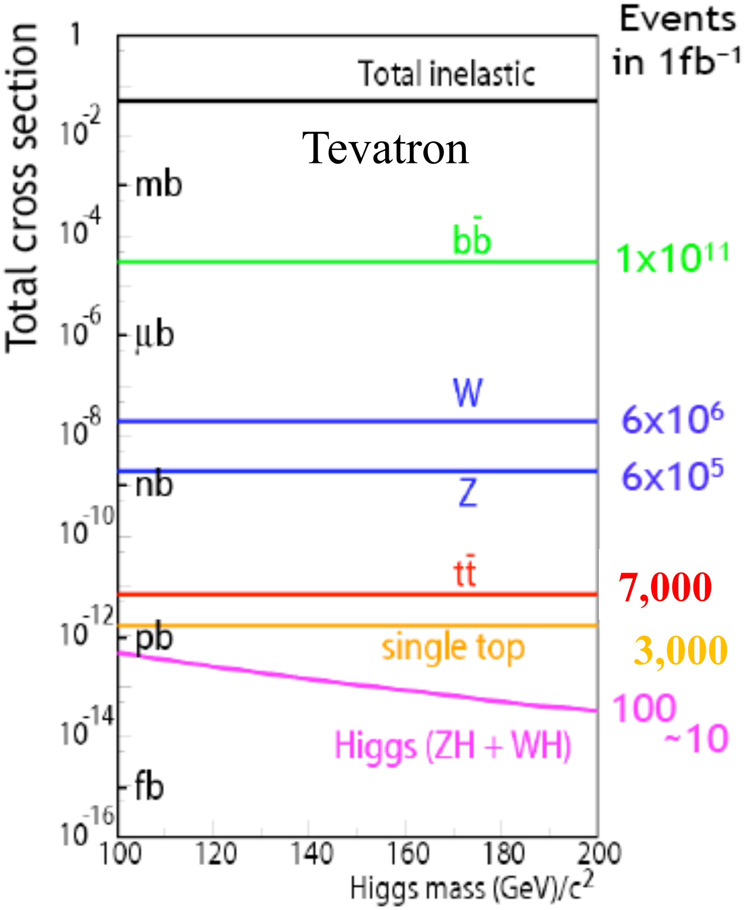
- Multipurpose detectors
- Good resolution for track momenta, vertex, calorimeter
- 85-90% avg. data taking effeiciency for both detectors

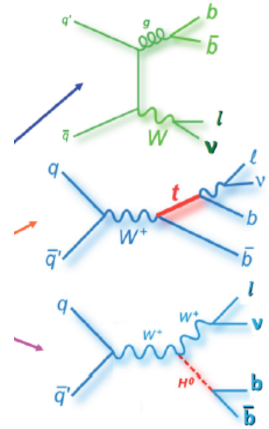
Production of Fundamental Particles

- Cross section:
  Total inelastic cross section is huge
  ~60 trillion events in 1 fb^{-1}
  ~ 2 MHz interaction rate

- Translate it into rates
  bb: 42 kHz
  Jets with ET>40 GeV: 300 Hz
  W: 3 Hz
  Top: 2-3 eventst /hour

- Trigger needs to select the interesting





The key is trigger – that is rejecting as much as we can while keeping as many interesting events as possible on tape

Tevatron's Research Program

Competitiveness

Single top production
EW processes and couplings
High XT gluons

Higgs

Complementarity

ttbar spin corelations
ttbar FB asymmetry
W asymmetry

Hints& Excesses

t', Z' searches
Ttbar FB asymmetry
CP violation in Bs

Legacy

Top quark mass
Top quark properties
W mass

Outline of This Talk

Competitiveness

Single top production

Higgs

Complementarity

ttbar spin corelations

ttbar FB asymmetry

Hints& Excesses

t', Z' searches

ttbar FB asymmetry

Legacy

Top quark mass

Top quark properties

Why Look at The Top Quark?

- **Was discovered at Fermilab in1995**

- The heaviest known fundamental particle
  - m_t = 173.3 ±1.1 GeV (<1% precision)

    Close to a gold atom

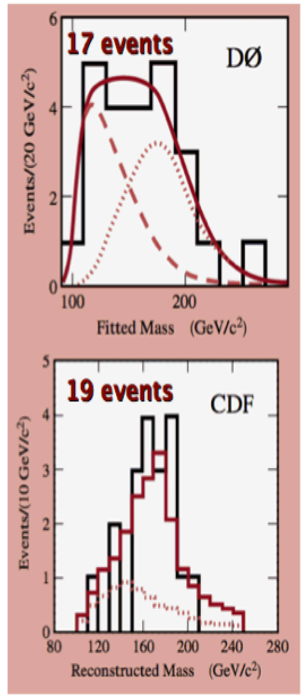
  $\tau = 5\times10^{-25}$ s $<< \Lambda_{QCD}^{-1}$

  Decays before hadronization

- Mass close to scale of electroweak symmetry breaking
  - Only quark for which coupling to Higgs is significant
  - May shed light on EWSB mechanism
- Top quark plays special role in many of the new physics models

discovery

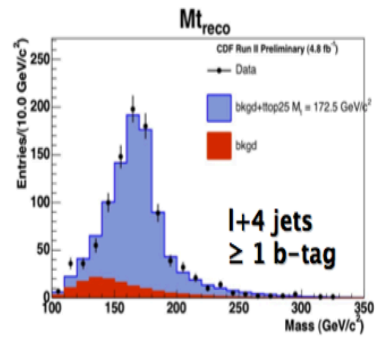
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



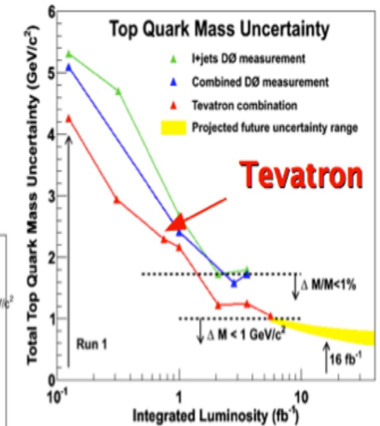
1995, CDF and DØ experiments, Fermilab

today

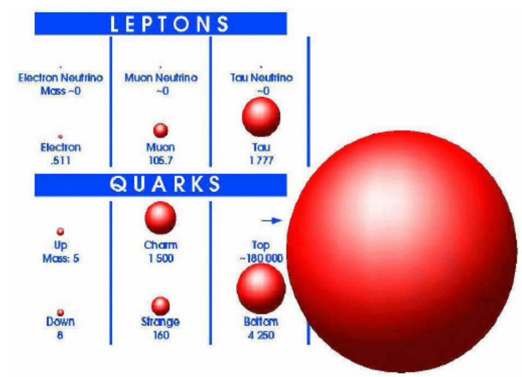
~1000 events



precision



searches



Why we Love to Talk about Top?

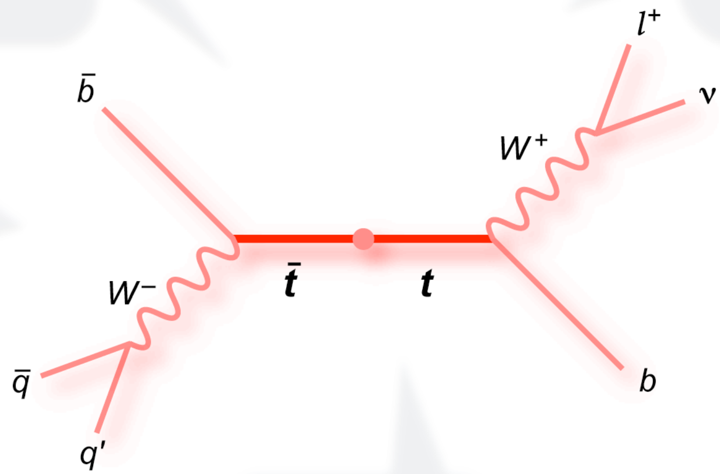
Top Mass
Width
Charge
Spin

W helicity
Anomalous couplings
CP violation
FCNC
$|V_{tb}|$

Production Cross-section

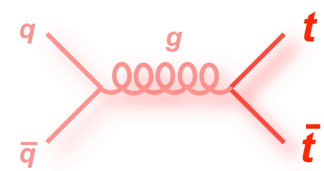
Resonant production

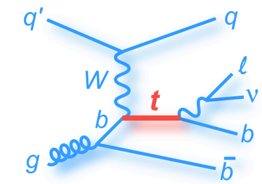
Charge asymmetry

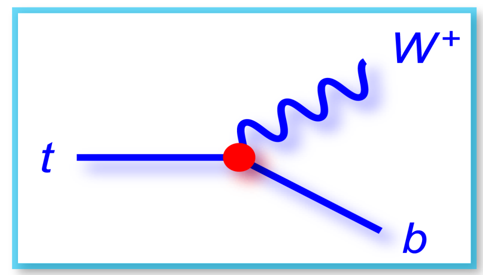


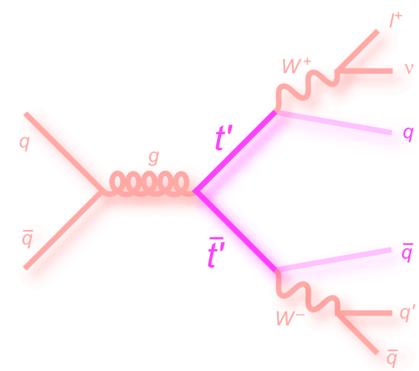
Branching Ratios
Rare/non SM decays

- **New physics in properties**
  - Cross section
  - Mass
  - Width
  - Spin
  - Forward backward asymmetry
- **New physics in couplings**
  - Wtb couplings
  - W helicity
- **New Physics in the form of new particles**
  - ttbar resonances
  - 4^{th} generation? (looking for t')
  - Color flow

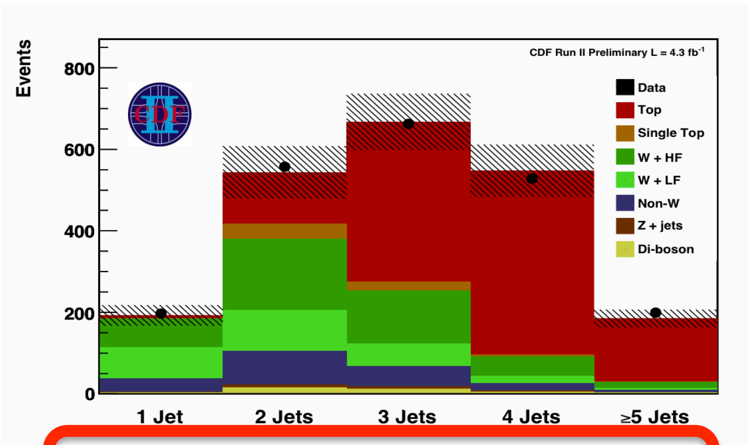




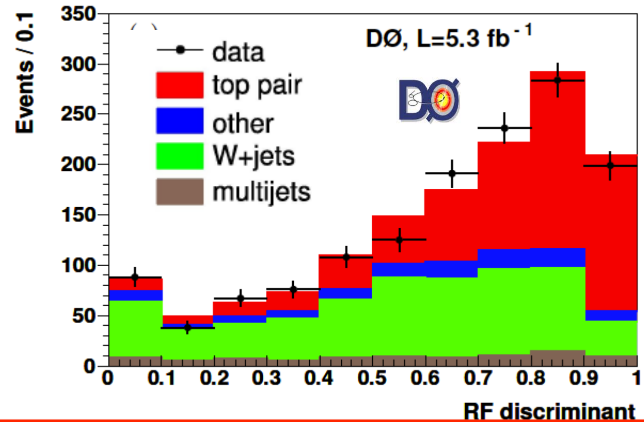




Top Pair Cross Section

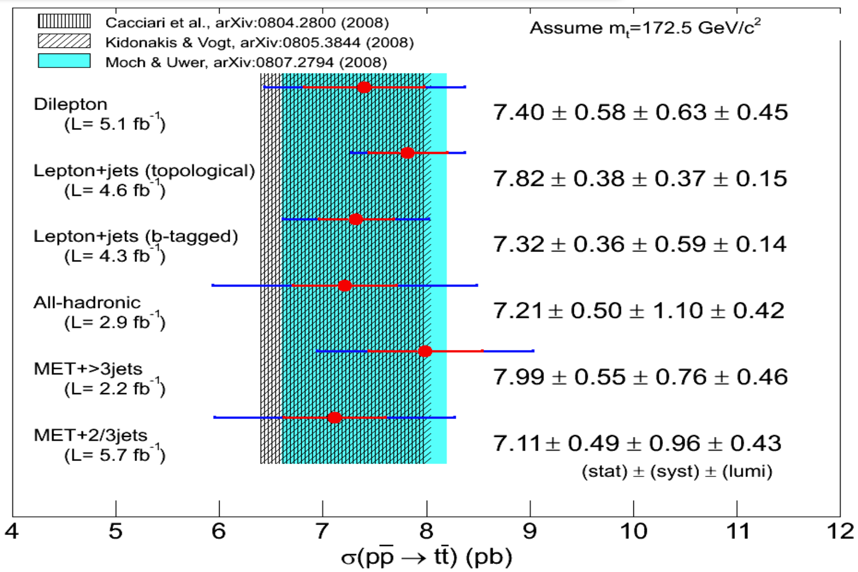


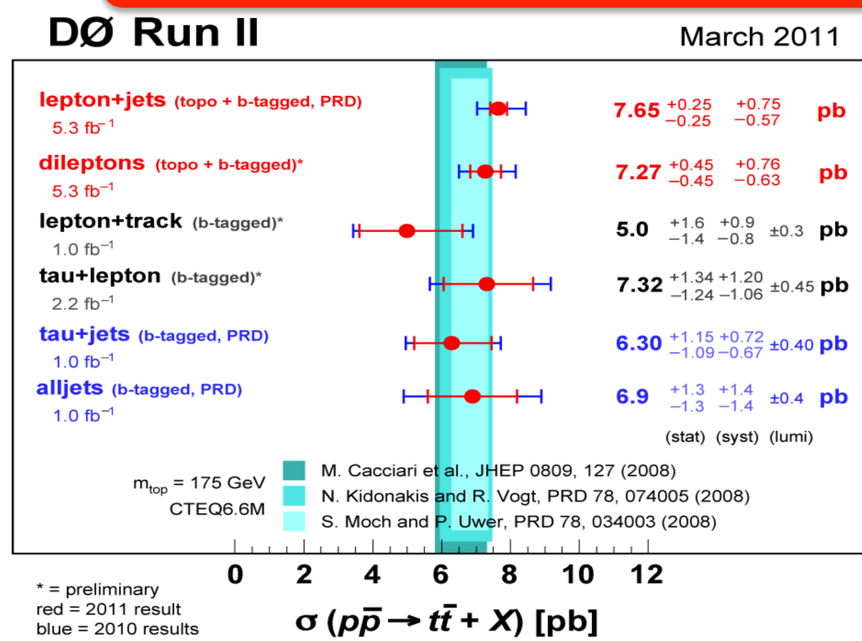
$$\sigma_{t\bar{t}} = \frac{N_{data} - N_{bck}}{\varepsilon . L . A}$$



$\sigma_{t\bar{t}} = 7.70 \pm 0.52 (\text{stat+sys})$ pb

$\sigma_{t\bar{t}} = 7.78^{+0.77}_{-0.64} (\text{stat} + \text{syst} + \text{lumi})$ pb,

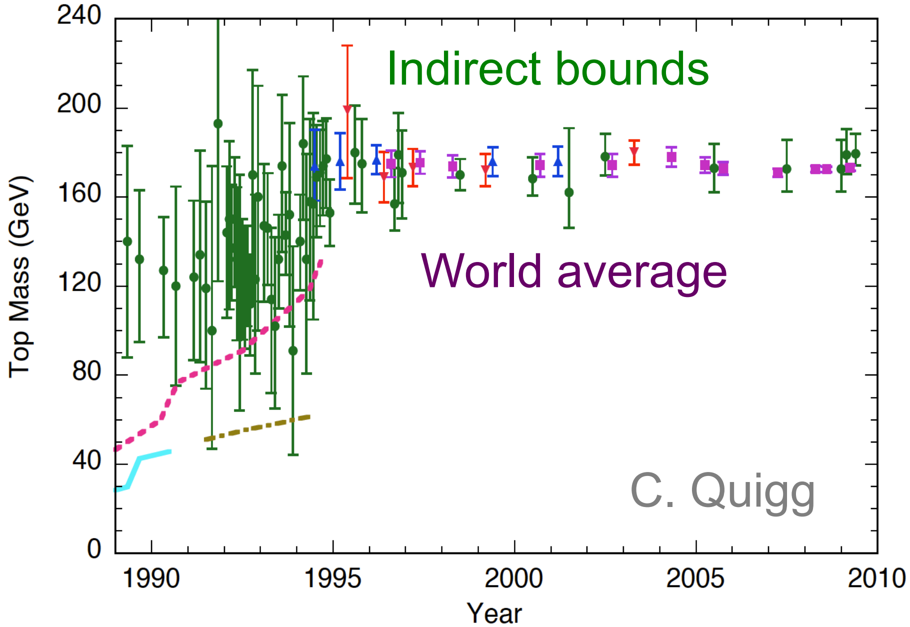


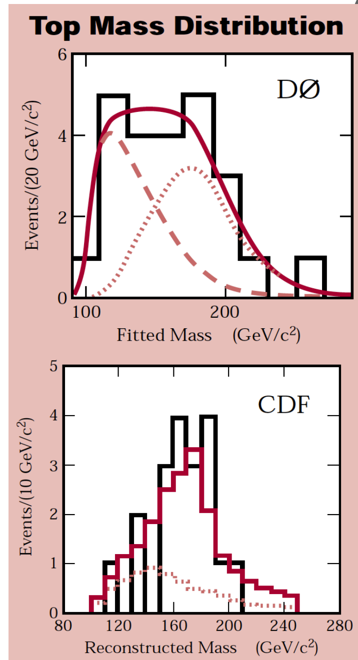


arXiv.org:1101.0124

Top Quark Mass

… a very long tale



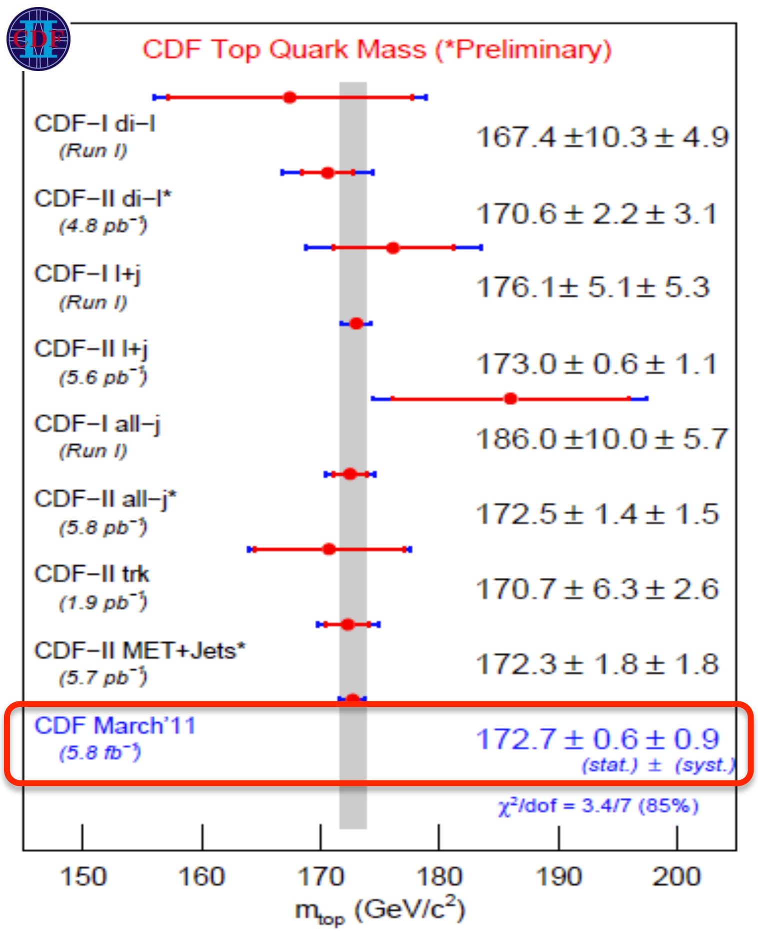


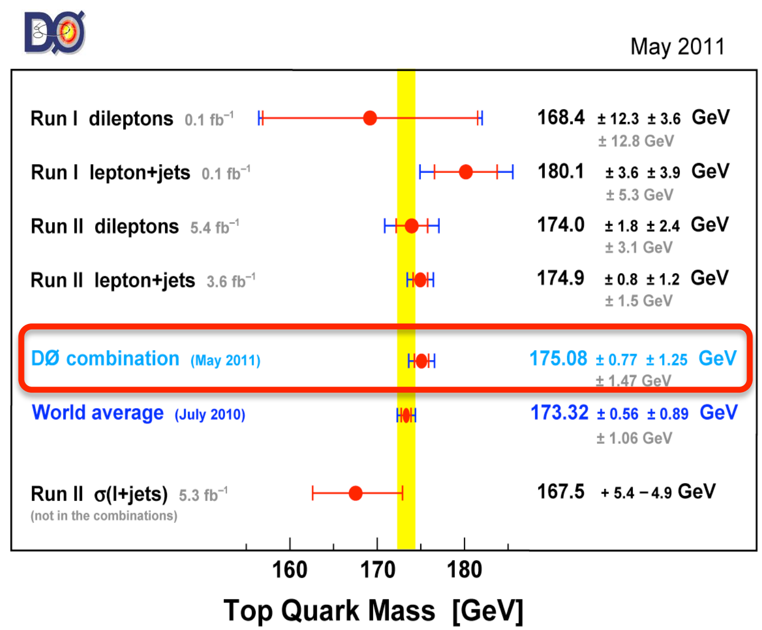

NEWS AND VIEWS

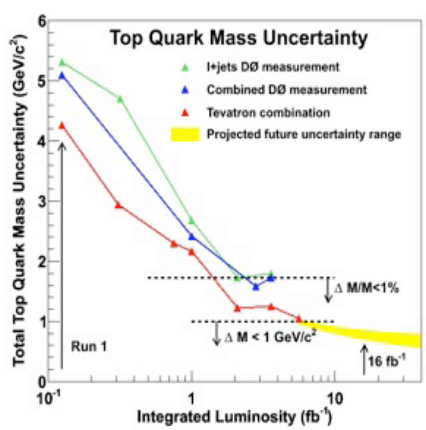
CERN comes out again on top

Top Quark Mass

- Top quark mass is measured directly in different channels using a variety of techniques by both CDF and DØ
- Both experiments are in agreement





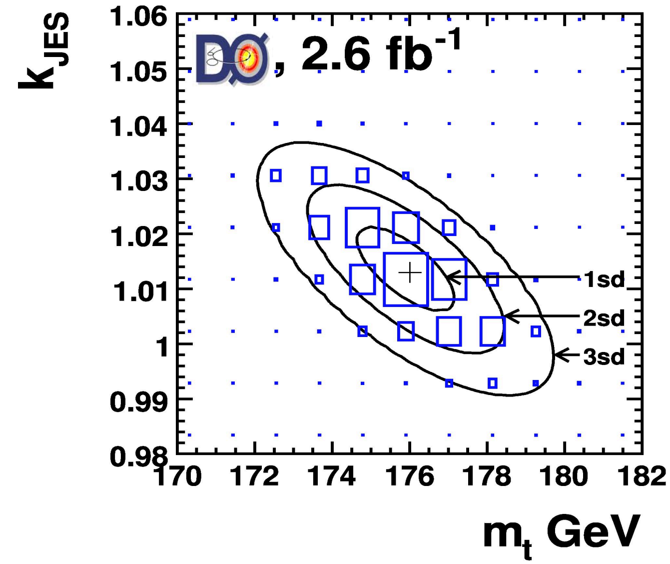


Measured top mass = 173.3±1.1 GeV

We have long exceeded the Tevatron goal of δM=2 GeV

…but we are not done yet

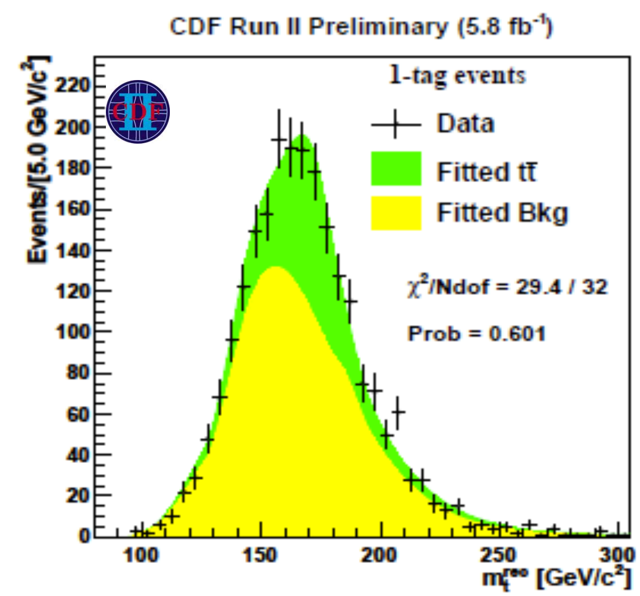
Lot of work on reduction of sytematic uncertainties for final legacy measurement



D0 Matrix Element in ℓ+jets (3.6 fb-1)

- Detailed study of b/light jet response
- Used ϒ+jets Data/MC corrections

0.9% relative uncertainty



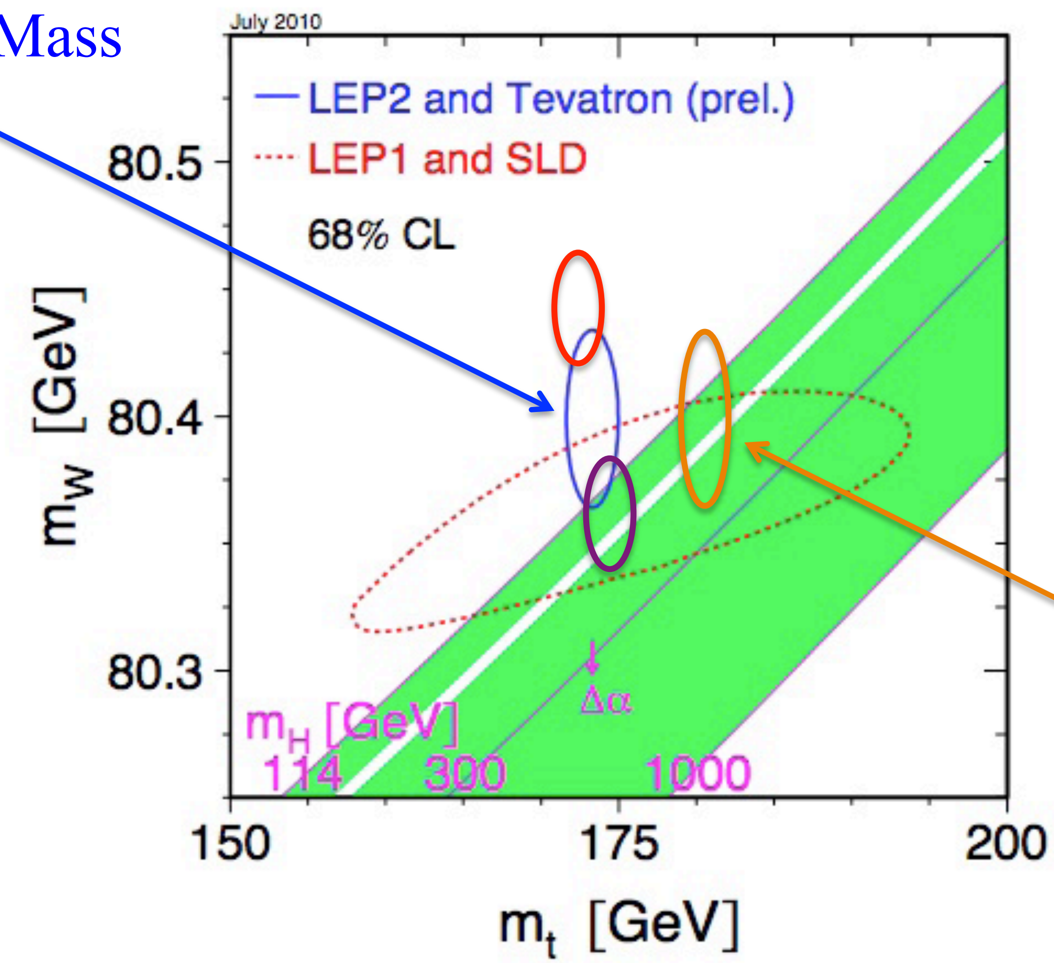
CDF templates in all hadronic (5.8 fb-1)

- Derive background from data
- Cut on NN discriminant to separate QCD
- chi^2 fit with m_W and m_t templates

1.2% relative uncertainty

But Which Mass do we Measure?

Pole Mass



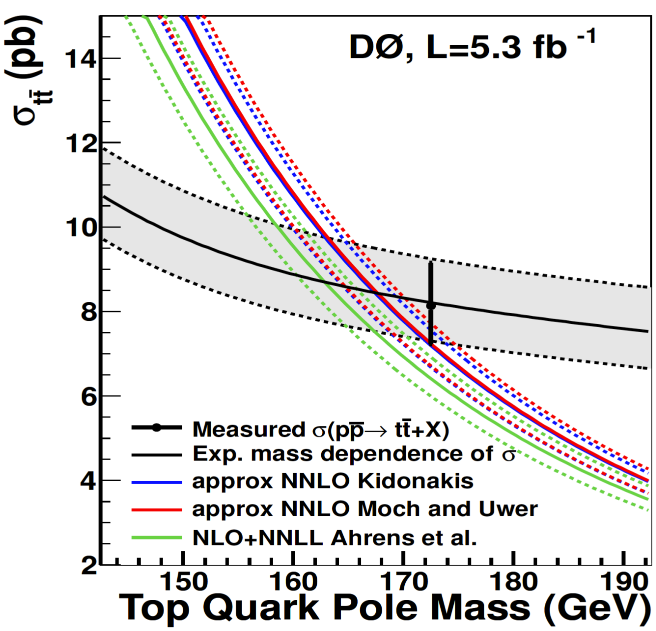
With Tevatron 10 fb^{-1}:
W mass uncertainty = 15 MeV
Top mass uncertainty =1 GeV

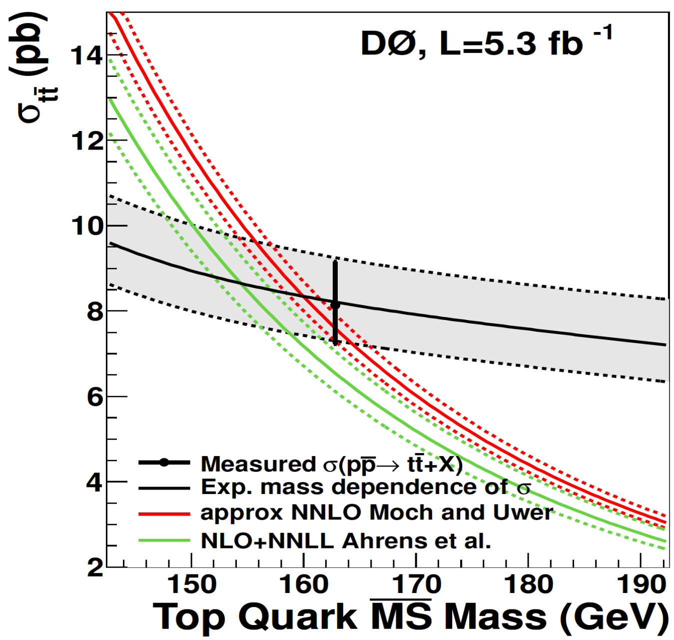
World average interpreted as $\overline{\text{MS}}$ mass

The top mass depends on M_H through loop diagrams ($M_t \sim \log M_H$).

Top Quark Mass from Cross Section

- Compare the experimental value for cross-section as function of top mass with theoretical calculations in pole and MS-bar schemes
- Extract the most probable top quark mass values in pole and MS-bar schemes and corresponding 68% CL bands



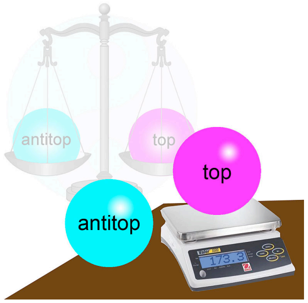


NNLO approx Moch and Uwer
NLO+NNLL Ahrens et al.

Theoretical Calculation	Measured Mass	
	Pole mass	MS-bar mass
NLO+NNLL	163.0+5.4 -4.9	154.4+5.2-4.5
Approx. NNLO	167.5+5.4-4.9	159.9+5.1-4.4

Directly measured top quark mass = 173.3±1.1 GeV

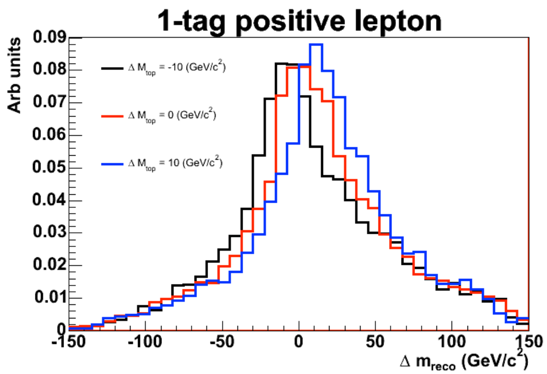
Top and Antitop Mass difference



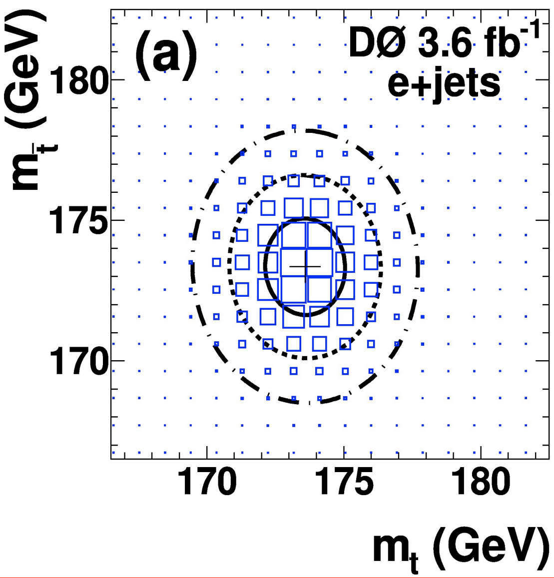
Probe CPT

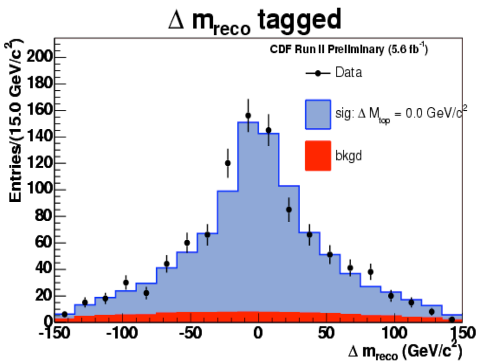
Template method

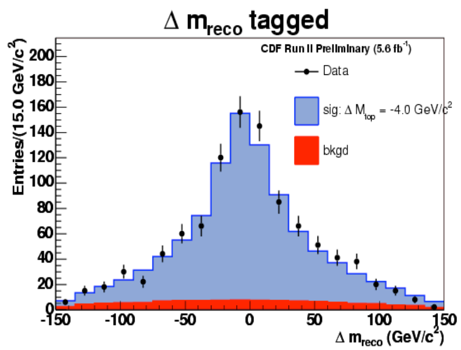
Compare 2D distribution (Δm_{reco}, $\Delta m_{reco(2)}$) in data with MC



Extension of mass analysis with insitu JES calibration - mt, JES → mt, mt







ΔMtop = -3.3± 1.4±1.0 (stat+syst)GeV

ΔMtop = 0.8 ± 1.8 ± 0.5 (stat+syst) GeV

Top Quark Width

SM predicts ~1.5 GeV (Mt = 175 GeV)

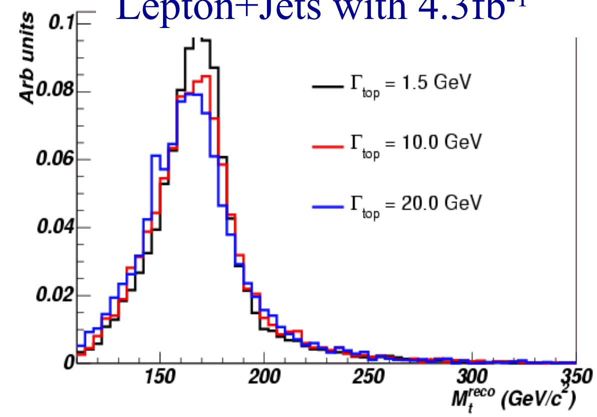
CDF Template based top width measurement

limit placed on top width

$0.4\ \text{GeV} < \Gamma_{top} < 4.4\ \text{GeV}$ @ 68% CL

$\Gamma_{top} < 7.5\ \text{GeV}$ @ 95% CL

Lepton+Jets with 4.3fb^{-1}



Use t-channel single top quark production and top decay branching ratio measurements

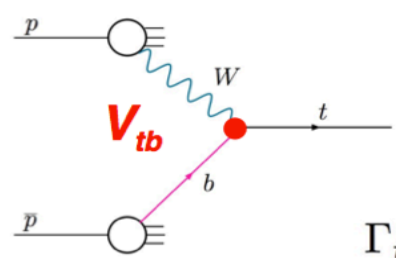
$$\sigma(t\text{-channel})\,\mathcal{B}(t \to Wb) = 3.14^{+0.94}_{-0.80}\ \text{pb}$$

$$\mathcal{B}(t \to Wb) = 0.962^{+0.068}_{-0.066}(\text{stat})\ ^{+0.064}_{-0.052}(\text{syst})$$

$$\Gamma(t \to Wb) = \sigma(t\text{-channel})\,\frac{\Gamma(t \to Wb)_{SM}}{\sigma(t\text{-channel})_{SM}}$$

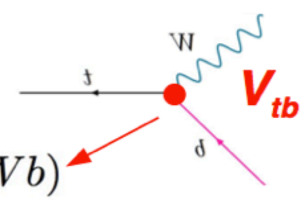
t-channel cross section:

σ(t-channel) = 2.14 ± 0.18 pb
NLO, m_t = 170 GeV



partial decay width:

Γ(t→Wb) = 1.26 GeV
NLO, m_t = 170 GeV



$$\Gamma_t = \frac{\Gamma(t \to Wb)}{\mathcal{B}(t \to Wb)}$$

$t\bar{t}$ production

assume that coupling in top production and decay is the same

$$\Gamma_t = 1.99^{+0.69}_{-0.55}\ \text{GeV}$$

$$\tau_t = (3.2^{+1.3}_{-0.9}) \times 10^{-25}\ \text{s}$$

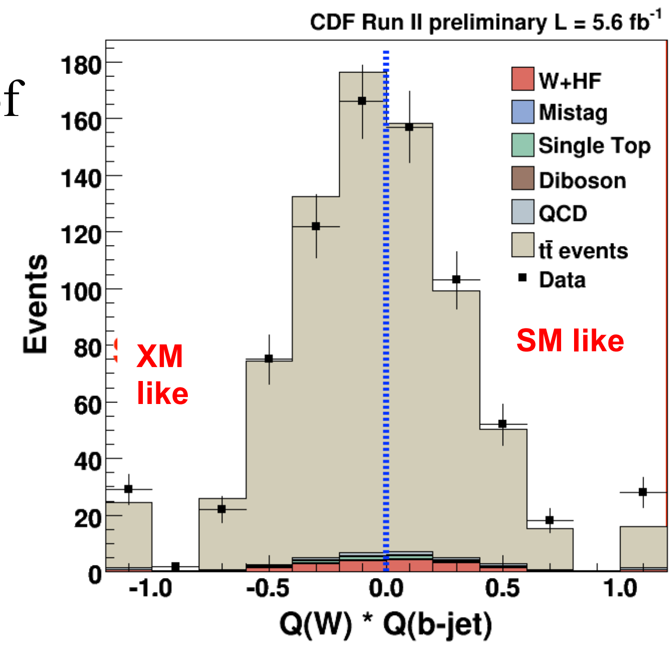
⇒ **most precise determination**

Top Quark Charge

- In l+jets top-antitop events (5.6 fb^{-1})
- Determine charge of the W boson using the charge of the lepton)
- Identify b-jets and find b jet charge using tracks

$$Q_{b-jet} = \frac{\sum_i q_i \cdot (\vec{p}_i \cdot \hat{a})^x}{\sum_i (\vec{p}_i \cdot \hat{a})^x}$$

x = weighting factor
$\hat{a}$ = jet axis
$\vec{p}_i$ = track momentum



- Calibration of jet charge using dijet events in data
- Pairing the W boson with the b jet to reconstruct top
- Use $Q_w x Q_b$ to build likelihood for SM hypothesis (+2/3) and Exotic model hypotheis (-4/3)

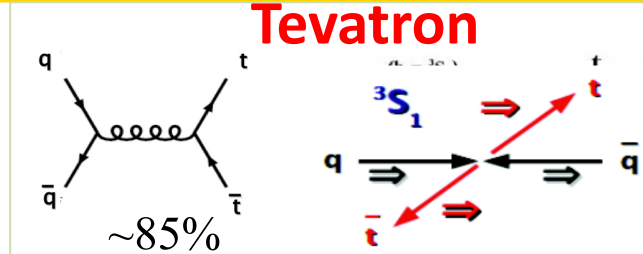
Exclude -4/3e at 95% CL

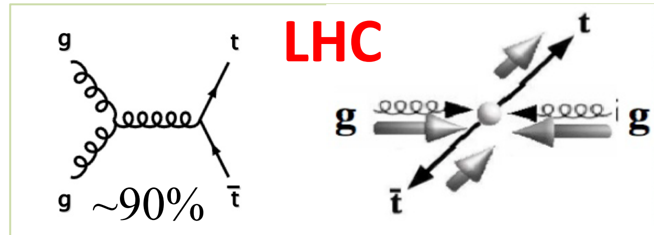
Spin Correlation in ttbar Events

- In top pair production at hadron colliders, their spins are expected to be correlated
- Observation of spin correlation will place upper limit on top quark life time
- Scenarios beyond the standard model can effect spin correlation
- Complementary to LHC
- Choosing the beam momentum vector as the quantization axis

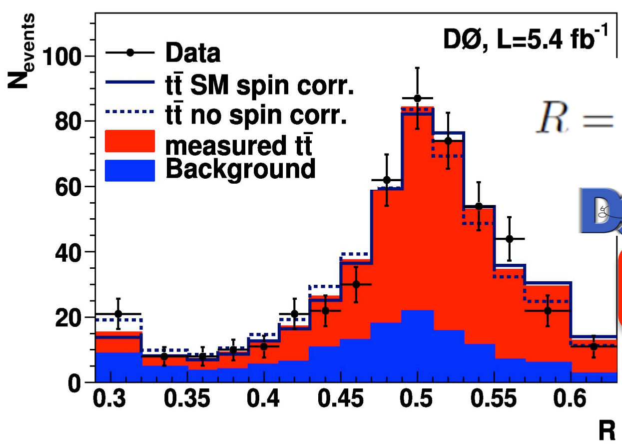
The NLO QCD prediction

C = 0.777+0.027-0.042





Using matrix element spin of the top

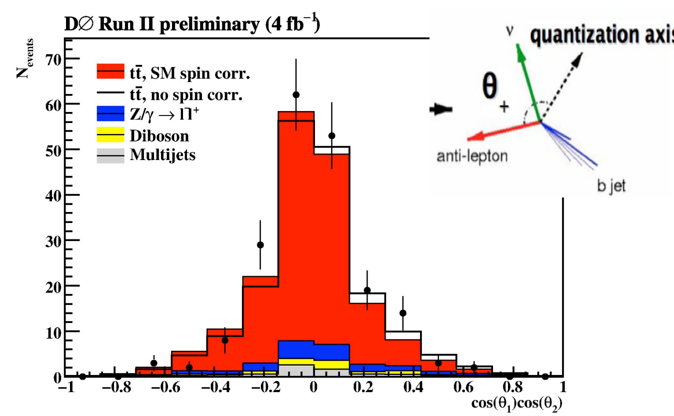


$$R = \frac{P_{\rm sgn}(H=c)}{P_{\rm sgn}(H=u) + P_{\rm sgn}(H=c)}$$

C = 0.6±0.3

Excludes uncorrelated case at 97.7%CL

Using templates

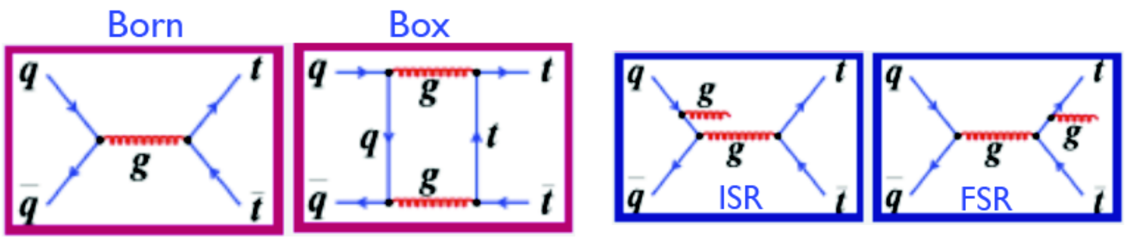


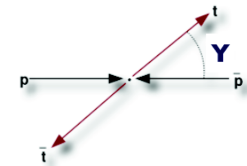
C = 0.1±0.5 (DØ)

C = 0.7 ± 0.7 (CDF)

Color Charge Forward-Backward Asymmetry

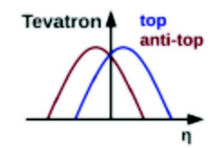
- SM predicts no asymmetry in LO in QCD
- NLO prediction is ~5%





$\Delta y = y_t - y_{\bar{t}}$

$$A_{fb} = \frac{N^{\Delta y>0} - N^{\Delta y<0}}{N^{\Delta y>0} + N^{\Delta y<0}}$$

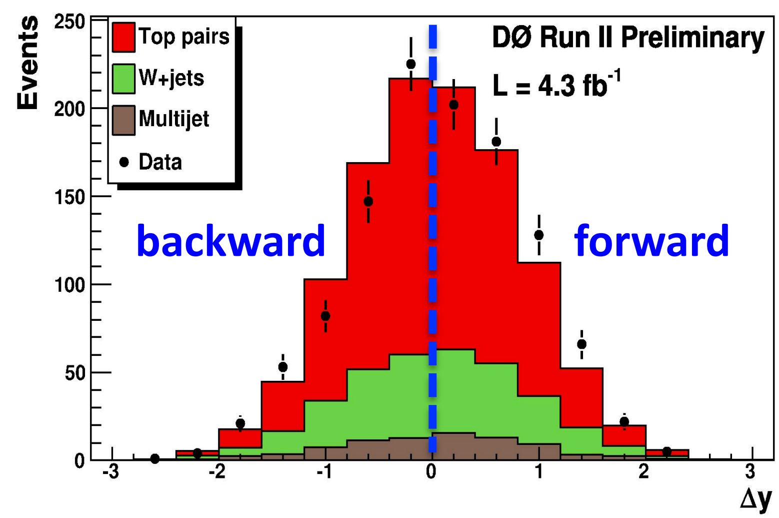


- Large measured asymmetry would indicate new physicsThe
- Tevatron A_{fb} measurements are complimentary to the LHC

Analysis in ℓ+jets 4.3 fb^{-1}

Measure unfolded (uncorrected for detector effect) forward backward asymmetry in top pair events

Measured A_{fb} = 8±4 %
Predicted A_{fb} SM = 1±2 %



~2 sigma discrepancy

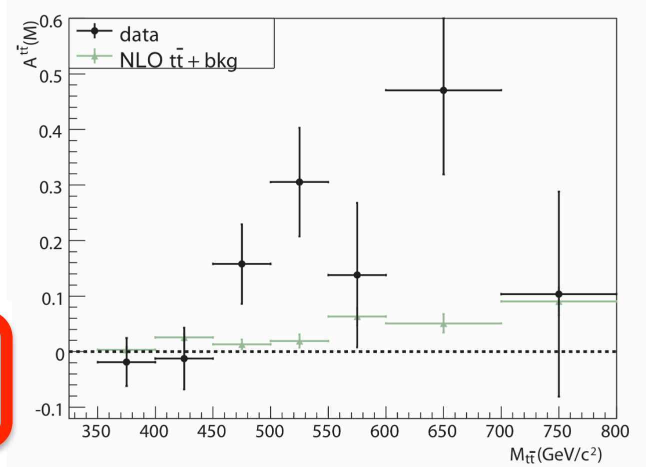
Color Charge Forward-Backward Asymmetry

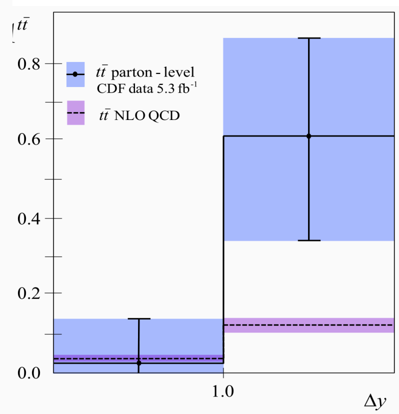
ℓ+jets sample with 5.3 fb^{-1}

MCFM predictions of 0.039 ±0.006

$$A^{t\bar{t}}(|\Delta y| < 1.0) = 0.026 \pm 0.118$$
$$A^{t\bar{t}}(|\Delta y| \geq 1.0) = 0.611 \pm 0.256$$

$$A^{t\bar{t}}(M_{t\bar{t}} < 450\ \mathrm{GeV}/c^2) = -0.116 \pm 0.153$$
$$A^{t\bar{t}}(M_{t\bar{t}} \geq 450\ \mathrm{GeV}/c^2) = 0.475 \pm 0.114$$

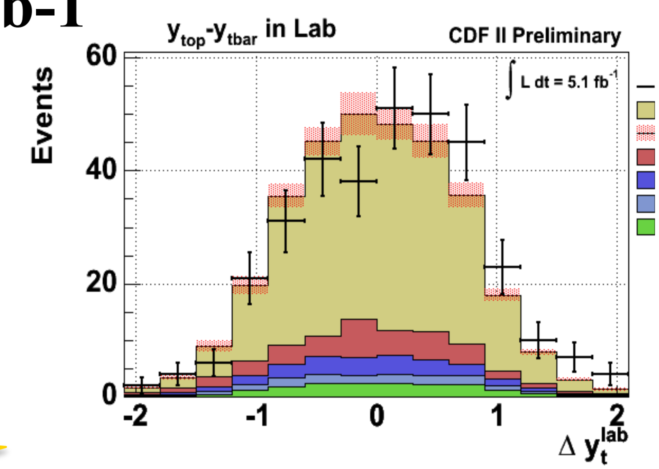


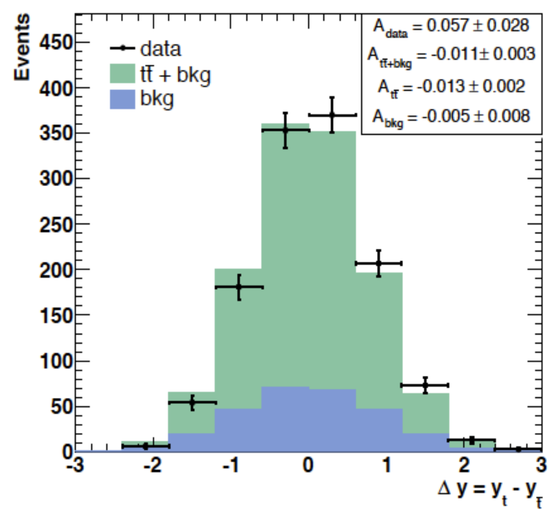


dilepton sample 5.1 fb-1

MCFM prediction = 6±1 %

$$A^{tt}_{ll} = 42 \pm 16\%$$



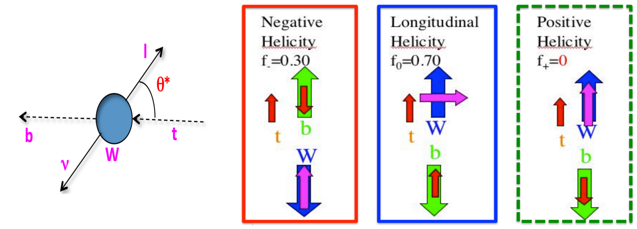


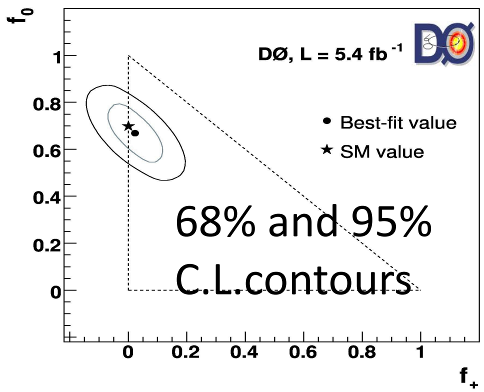
Hint of new physics beyond SM?

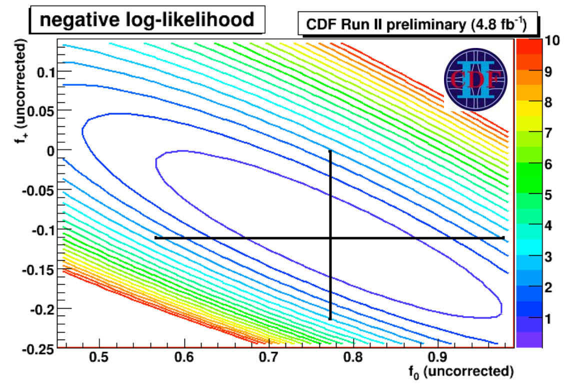
Check MC predictions in more detail especially top-antitop p_T

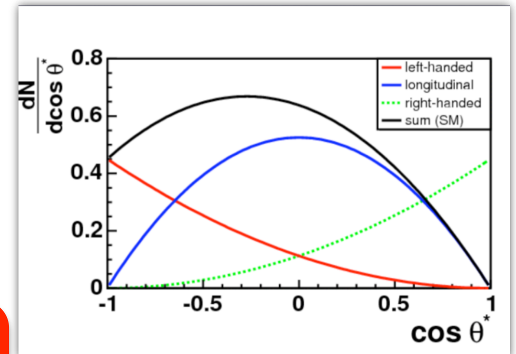
W Helicity and Wtb Couplings

In the SM, the top quark decays via the V −A charged current interaction, almost always to a W boson and a b quark









$$f_0 = 0.490 \pm 0.106\ (\text{stat.}) \pm 0.085\ (\text{syst.})$$
$$f_+ = 0.110 \pm 0.059\ (\text{stat.}) \pm 0.052\ (\text{syst.})$$

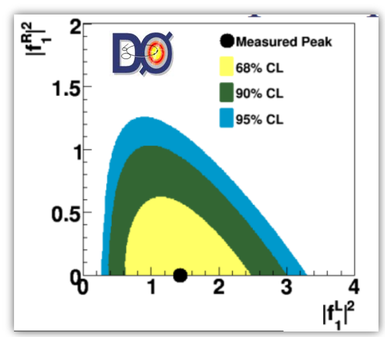
$$f_0 = 0.78^{+0.19}_{-0.20}(stat.) \pm 0.06(syst.)$$
$$f_+ = -0.12^{+0.11}_{-0.10}(stat.) \pm 0.04(syst.)$$

General Analysis of Single Top Production and W Helicity in Top Decay

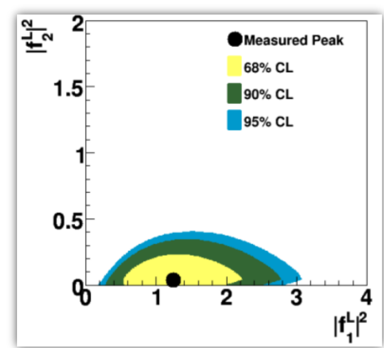
Ren, Larios, and C. P. Yuan (PLB 631, 126 (2005))

$$L_{tWb} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu \left(f_1^L P_L + f_1^R P_R\right) t - \frac{g}{\sqrt{2} M_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} \left(f_2^L P_L + f_2^R P_R\right) t + h.c.$$

where, in the SM $f_1^L \approx 1,\ f_2^L = f_1^R = f_2^R = 0$



$|f_1^R|^2 < 1.0$



$|f_2^L|^2 < 0.3$

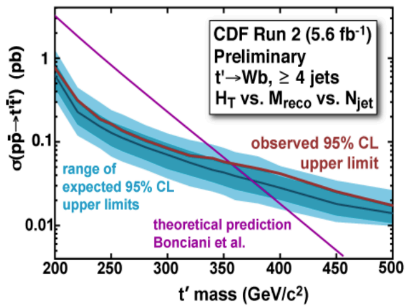
t’, b’ and Z’

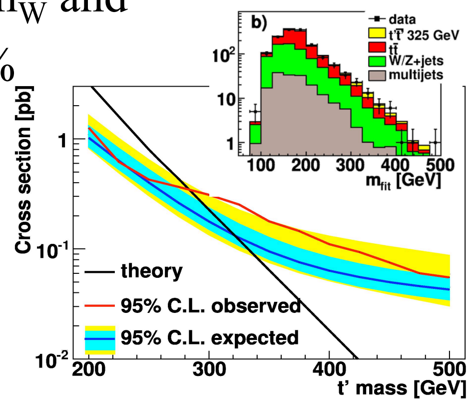
Search for fourth generation quark, t’

– More massive than top quark

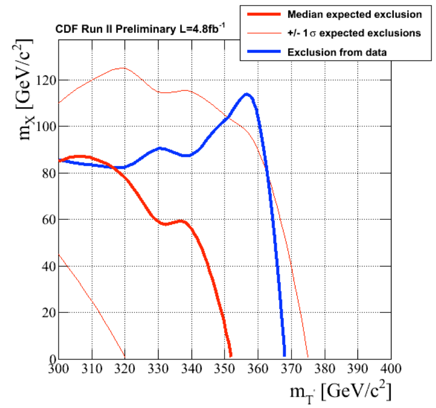
– assume $m_{t'} - m_{b'} < m_W$ and

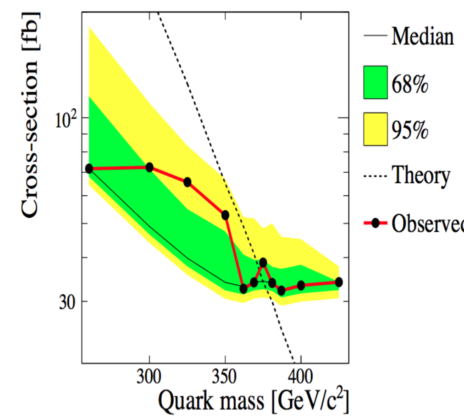
B(t’→Wb) = 100%





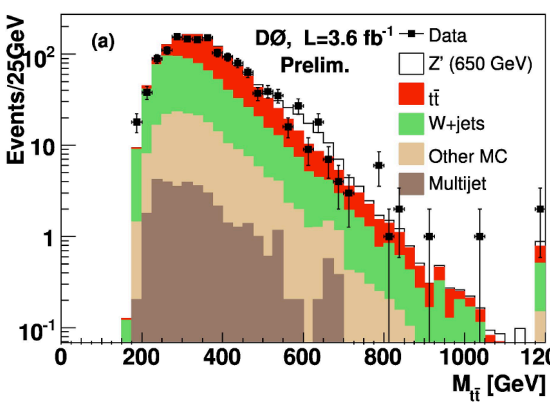
Search for fourth gen. quark, b’

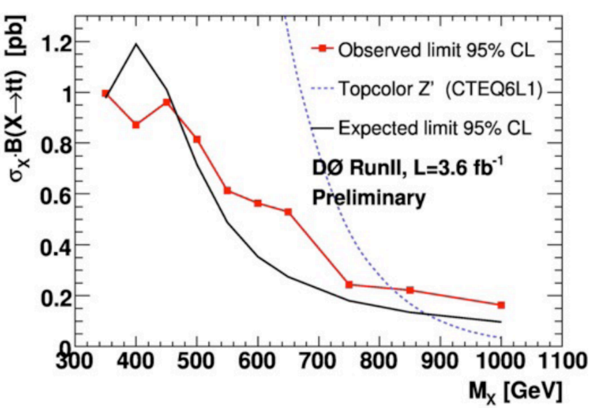


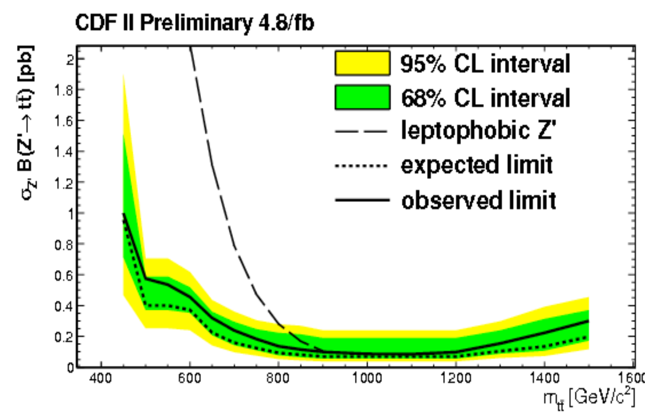


Serch for top-antitop resonance

- Search for excess in ttbar invariant mass distributions from Z’ boson

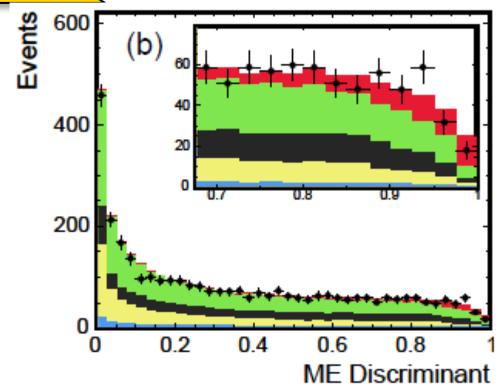


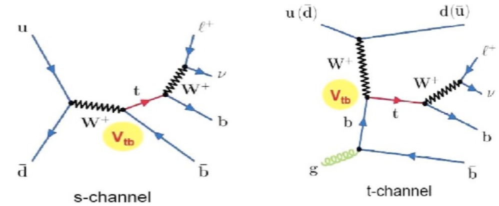


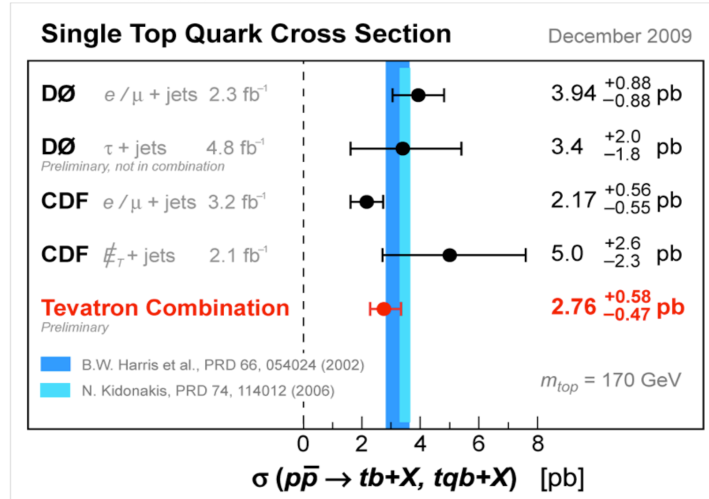


Single Top Cross Section

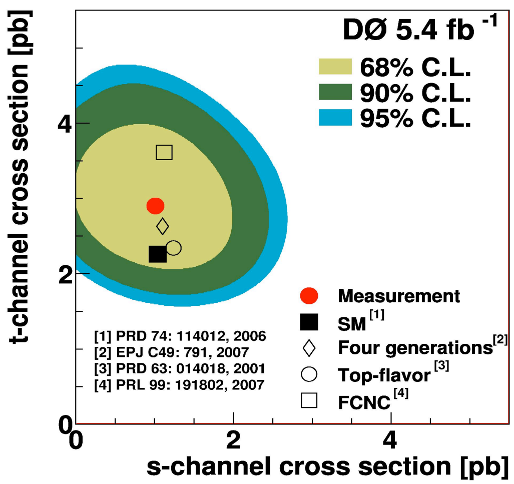
Observation in 2009

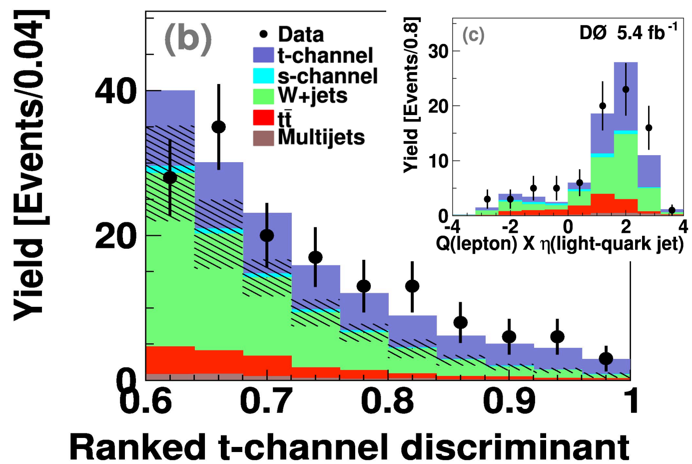






t- channel observation



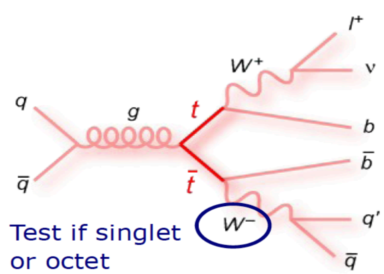


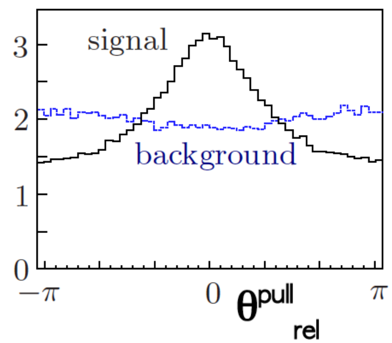
$$\sigma_{tqb} = 2.90 \pm 0.59 \text{ pb (5.5 std. dev.)}$$

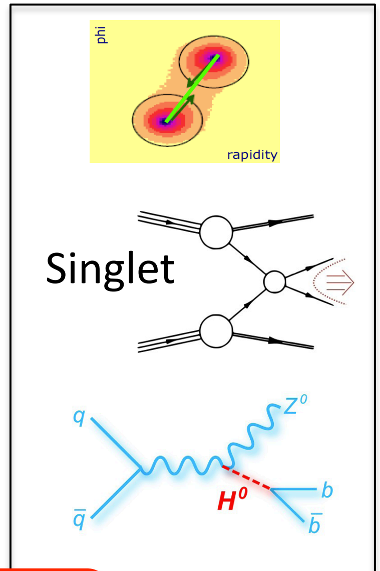
Color Flow

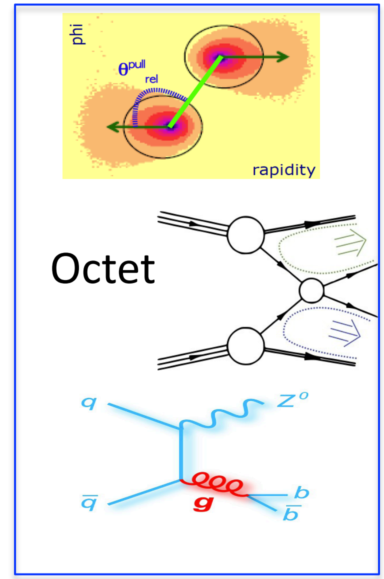
Gallicchio,Schwartz, PRL 105, 02200(2010)

- Jet shape influenced by color flow
- Shape influenced by direction of color flow!
  - Distinguish processes with same final state





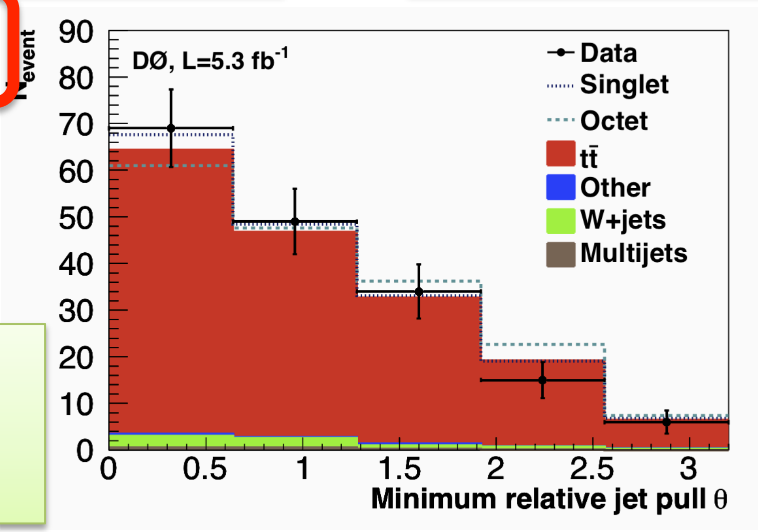




Fraction of singlet=0.56±0.38(stat+syst)±0.19(MC stat)

Expected: Exclude octet "W" @ 99%C.L.

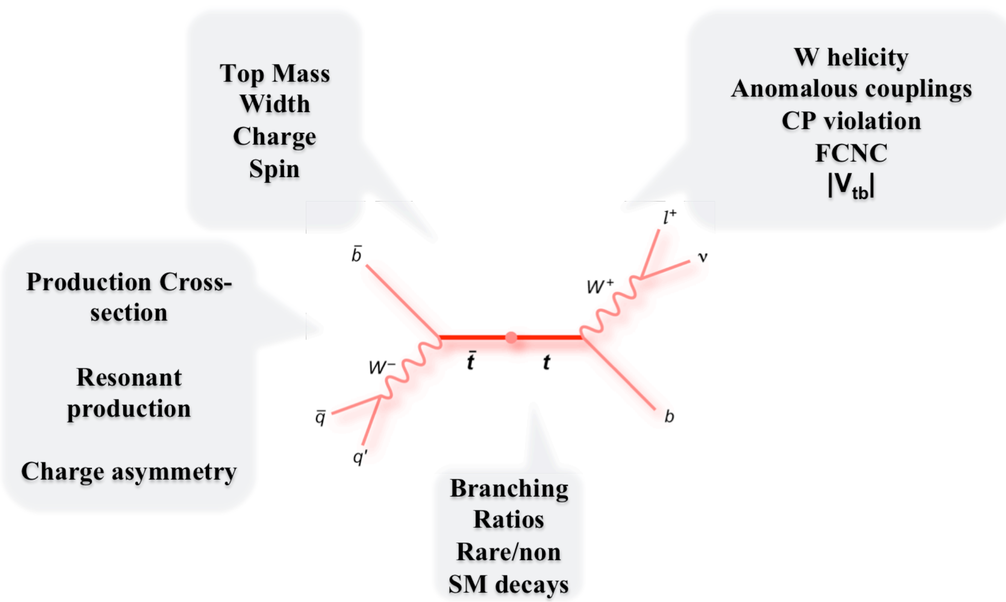
Expect $f_{Singlet}$=1 in SM

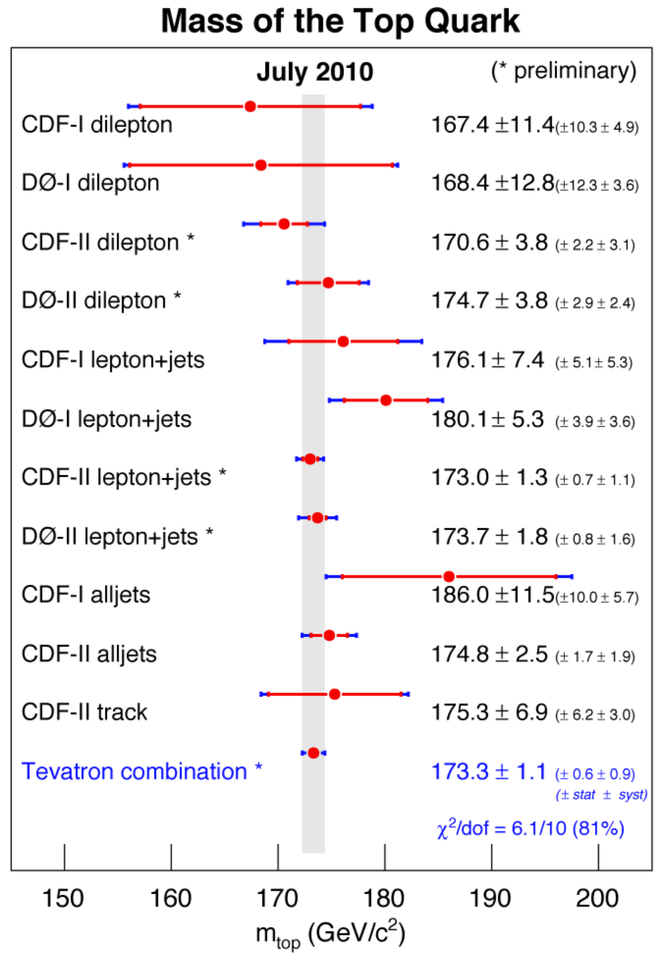


First study of color flow in tt events
First extraction of $f_{Singlet}$
(using only color flow information)

After 16 Years of Studying Top Quark

An impressive list of measurements

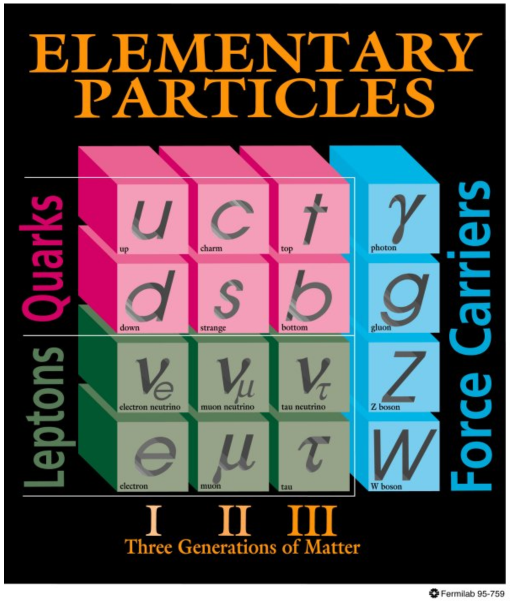




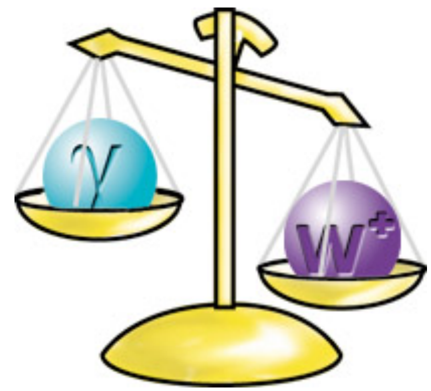
http://wwwcdf.fnal.gov/physics/new/top/top.html
http://wwwd0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html

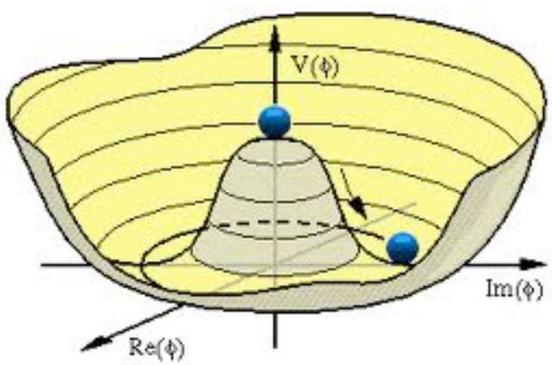
The Higgs Boson

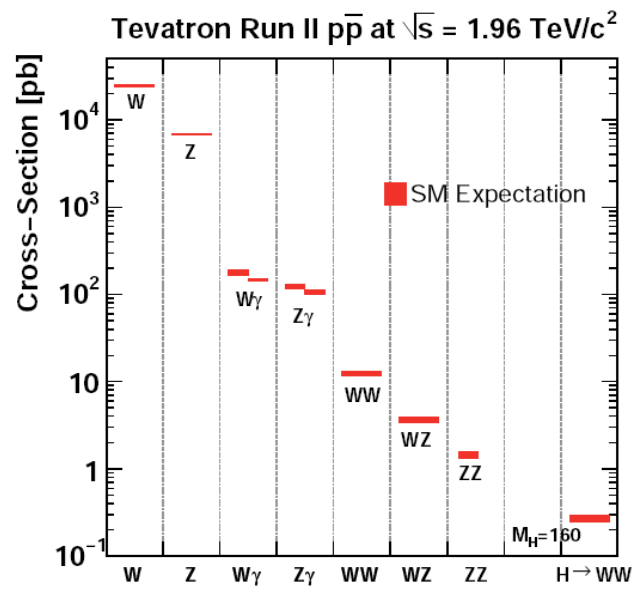
OR Eglert-Brout-Higgs-Guralnik-Hagen-Kibble Boson



What is the origin of the particle masses?





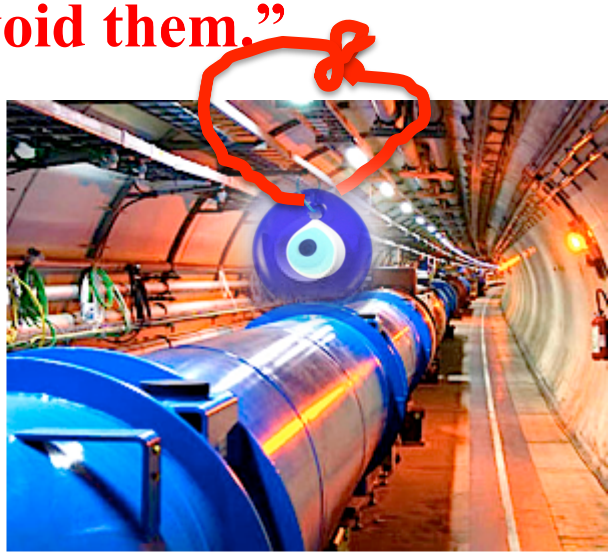


note: this is σ, not $\sigma \times$BR

"God" Particle or "God Damned" Particle

The New York Times

"It must be our prediction **that all Higgs producing machines shall have bad luck,"** Dr. Nielsen said in an e-mail message. In an unpublished essay, Dr. Nielson said of the theory, "Well, one could even almost say that we have a model for God." It is their guess, he went on, **"that He rather hates Higgs particles, and attempts to avoid them."**



Did anyone ever think of hanging Turkish Evil eye on LHC?

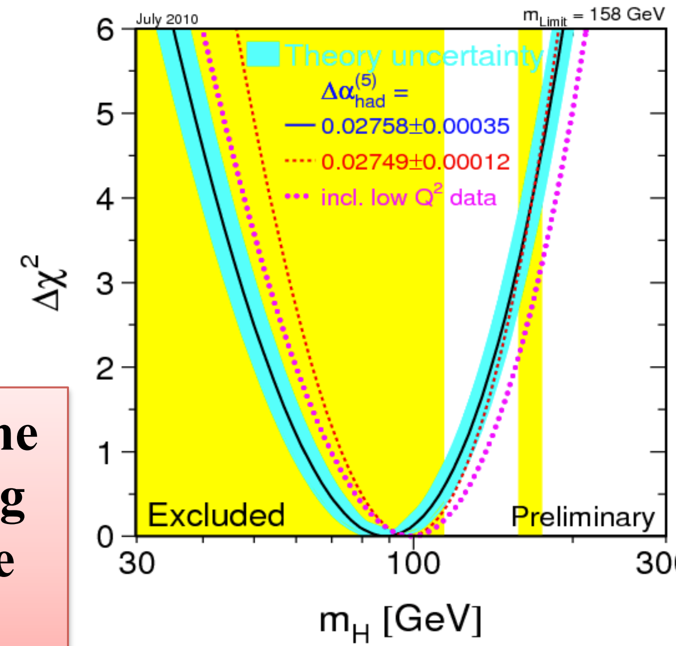
(We can use as much help as possible from any possible sources)

Higgs Physics at the Tevatron

Direct searches for a Standard Model Higgs boson:

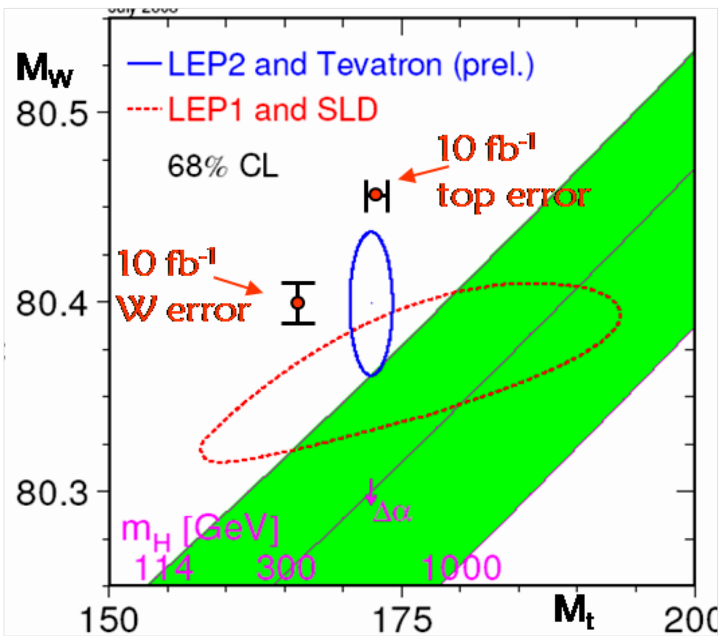
- LEP result: MH > 114.4 GeV/c2 at 95% C.L.
- Tevatron Summer '10 combination 95% C.L.
  158 < MH < 175 GeV/c2.

Indirect SM constraints and global EWK fits seem to prefer a light Higgs boson:
MH < 158 GeV/c2 at 95% C.L.



Minimum at 89 +35-26 GeV

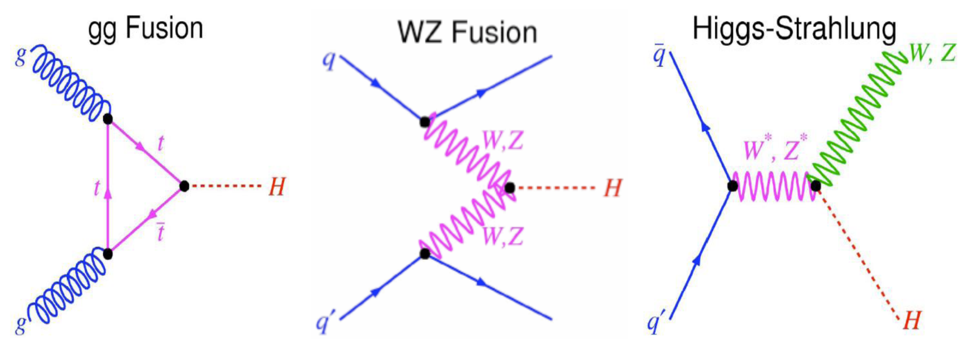
Higgs mass is the single remaining unknown in the SM.



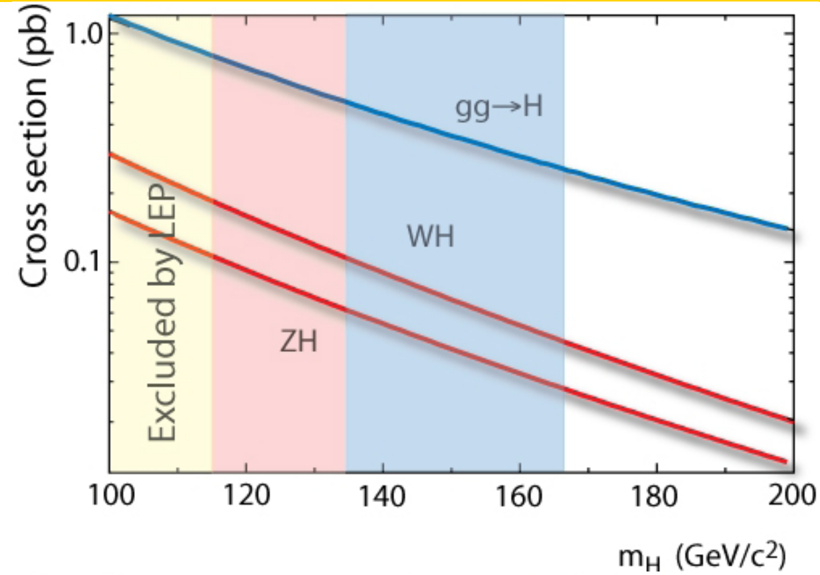
At the Tevatron, ~100 individual analyses with different final states, selections are searched and combined

Higgs at The Tevatron

Production

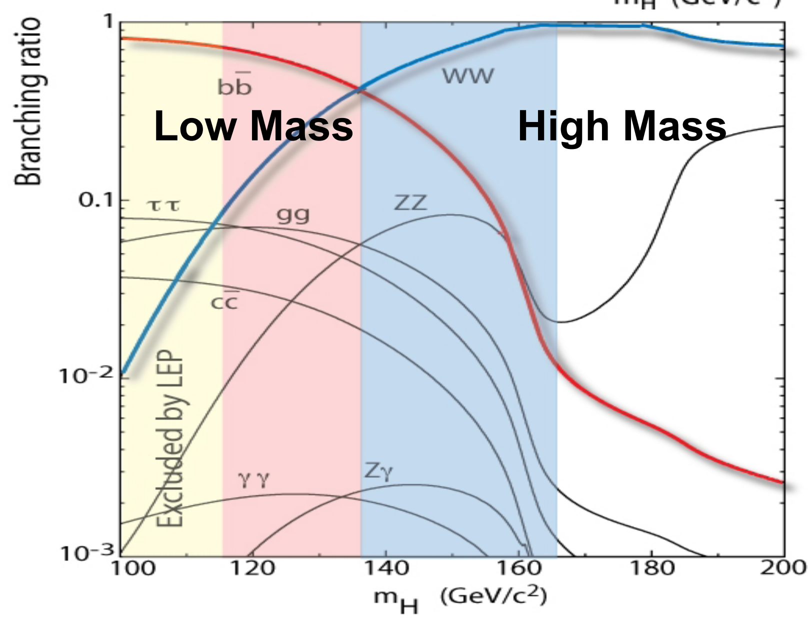


1.8 –0.2 pb 0.1 –0.02 pb 0.5 –0.03 pb



Decay

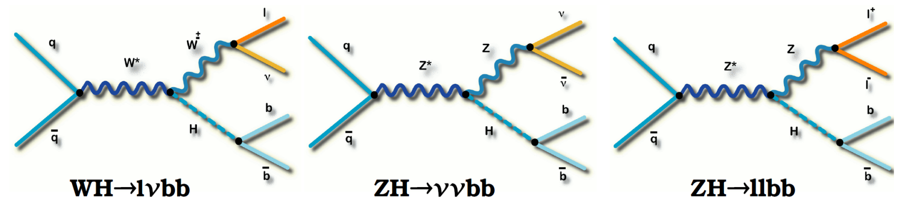
- **Lowmass Higgs (MH<135 GeV)**
  - Prefers to decay to bottom quark pairs
  - Need efficient identification of bottom quarks to reduce backgrounds
- **High mass (MH>135 GeV)**
  - Search for H→WW*
  - Potential for an offshell W boson allows nonresonant production

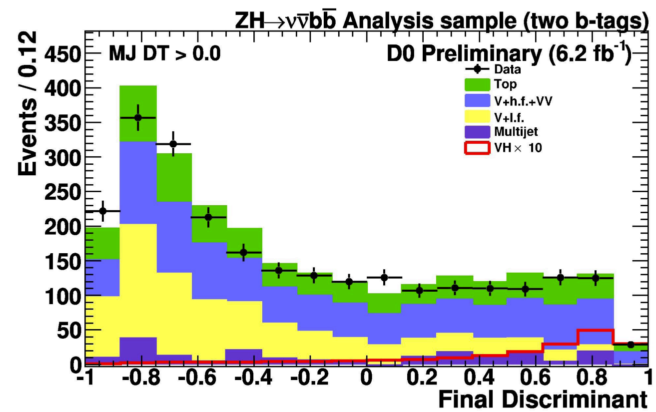


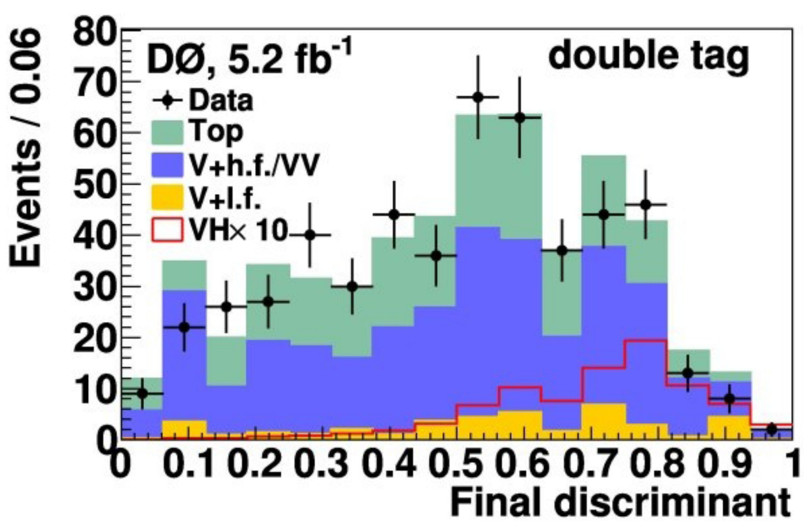
Low Mass Higgs

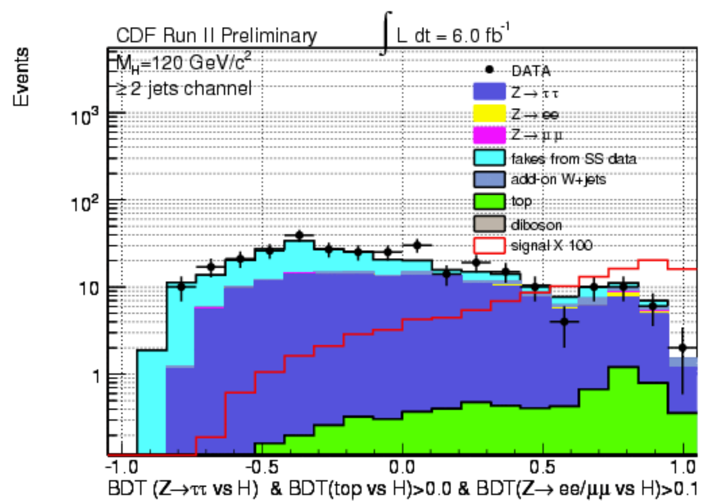
- Background reduction via the identification of displaced jet decay vertices
- Multivariate techniques are used to improve signal to background ratios
- Typical S/B of ~1/10 - 1/50

Associated Production: Low mass only, 3 dominant final states



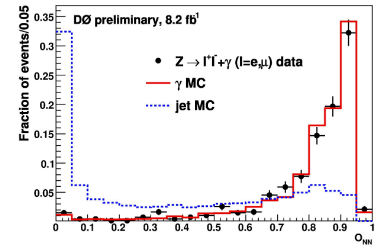


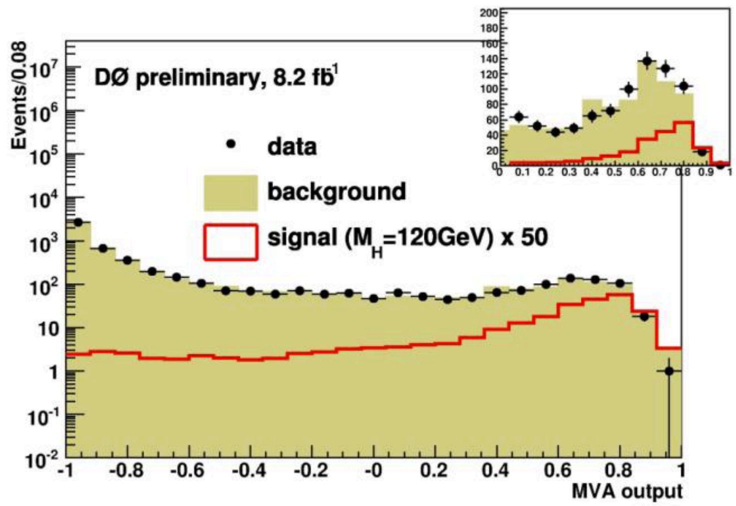


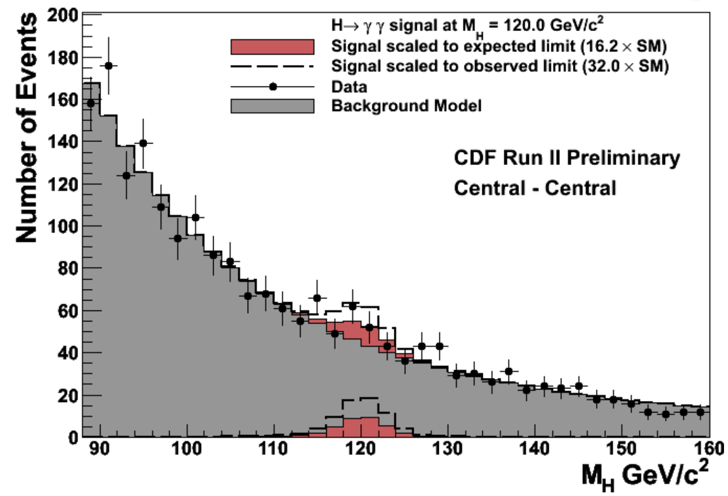


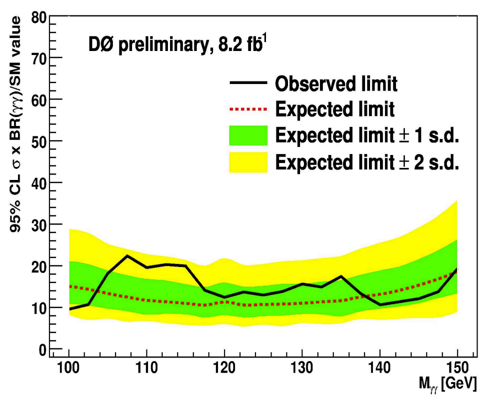
Low Mass Higgs: H→ γγ

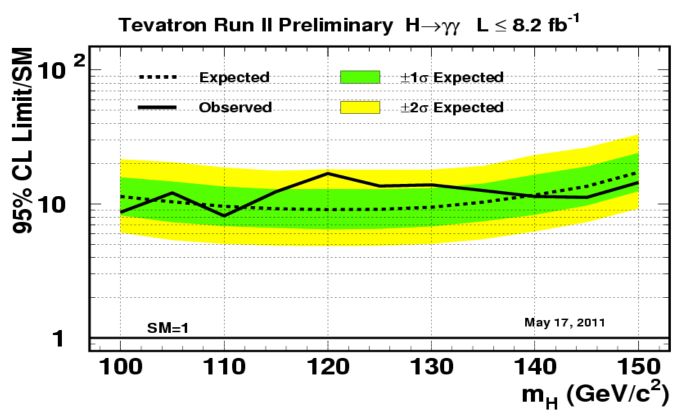
- **Calorimeter resolution : up to 2%**
- **Photon identification: improved by a NN selection**

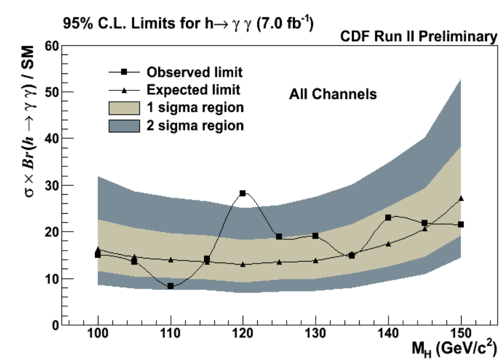






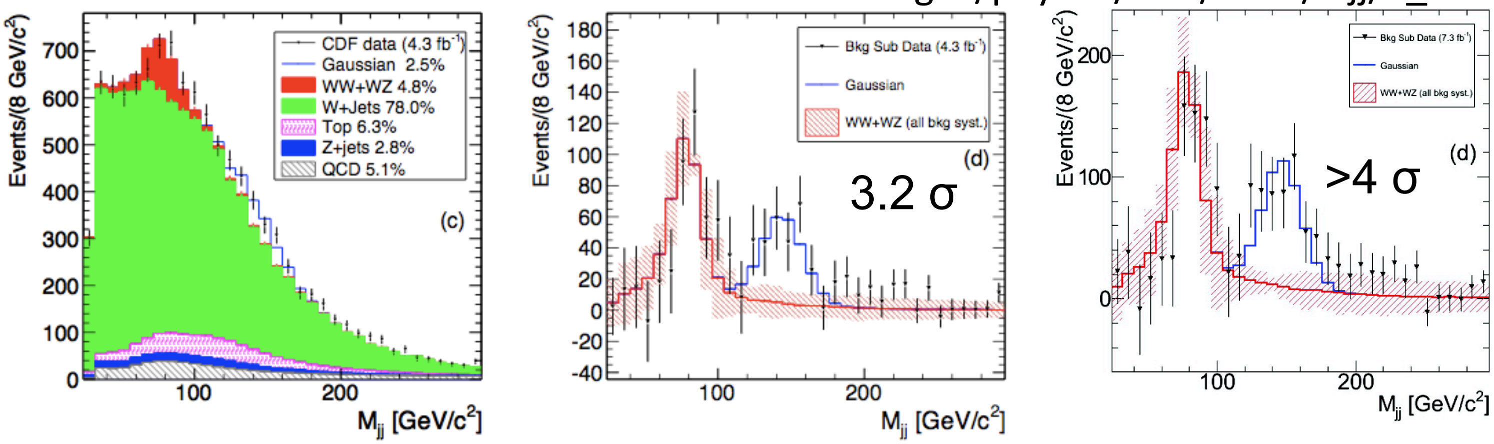


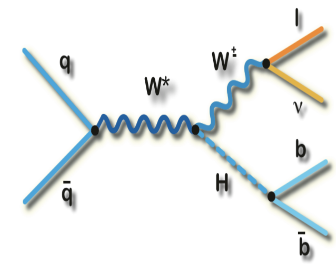




The CDF lν+jj "bump"

www-cdf.fnal.gov/physics/ewk/2011/wjj/7_3.html

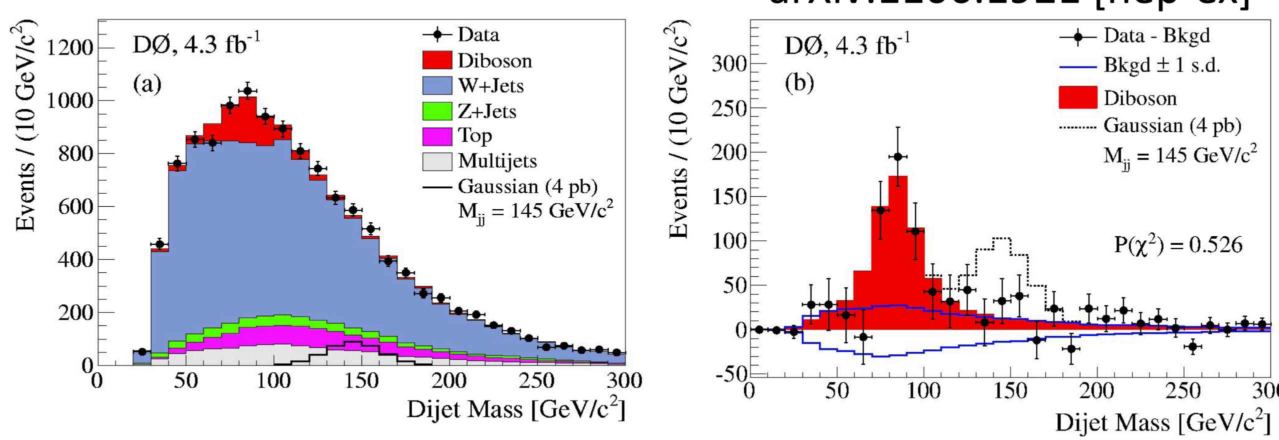




- CDF reports an excess in the dijet mass for W+2 jet events above the W mass
- Not consistent with SM Higgs, not seen in Z+jets
- If this is a resonance from some new particle, X, then σ(pp→WX) ≈ 4 pb
- D0 analysis excludes 4 pb resonance at 99.999% CL

arXiv:1106.1921 [hep-ex]

The D0 data are consistent with the SM prediction

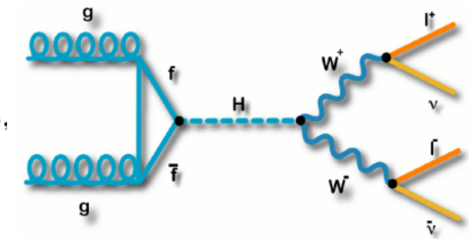


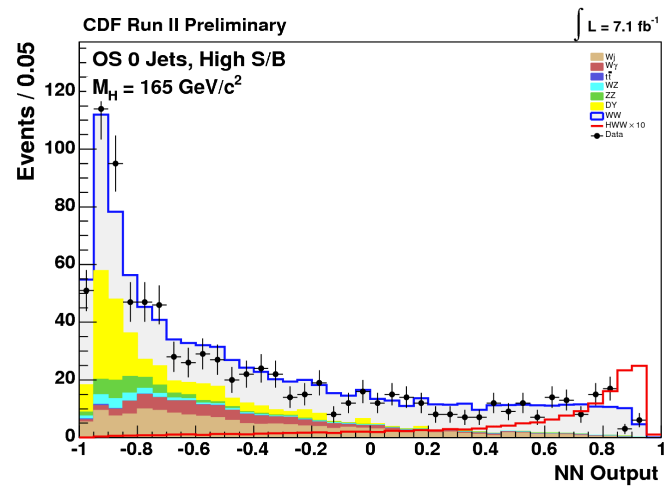
High Mass Higgs

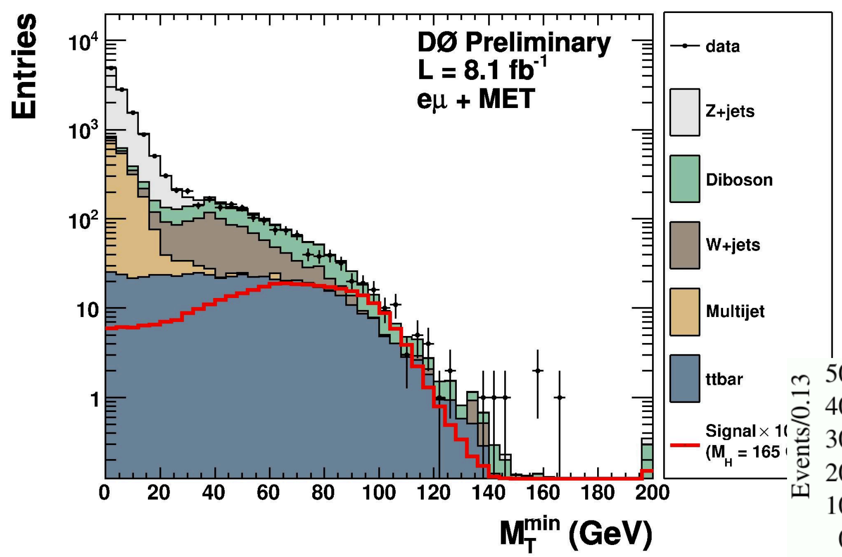
- Signature: two leptons + *MET*
- Exploit kinematic differences (lepton mass, spin correlation)
- Backgrounds: W+jets, WW/WZ production

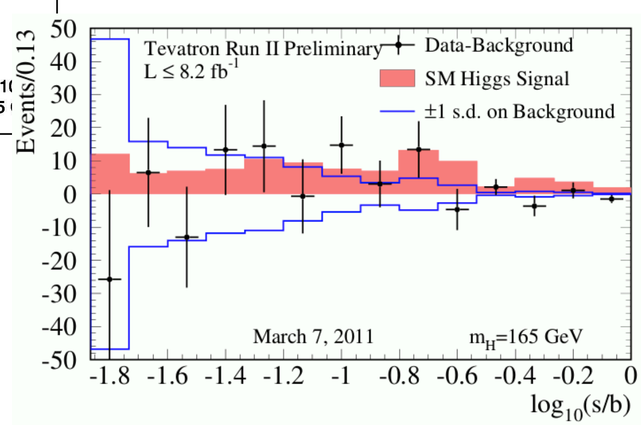
Gluon Fusion Production:

Maximum sensitivity at high mass, also useful at low mass

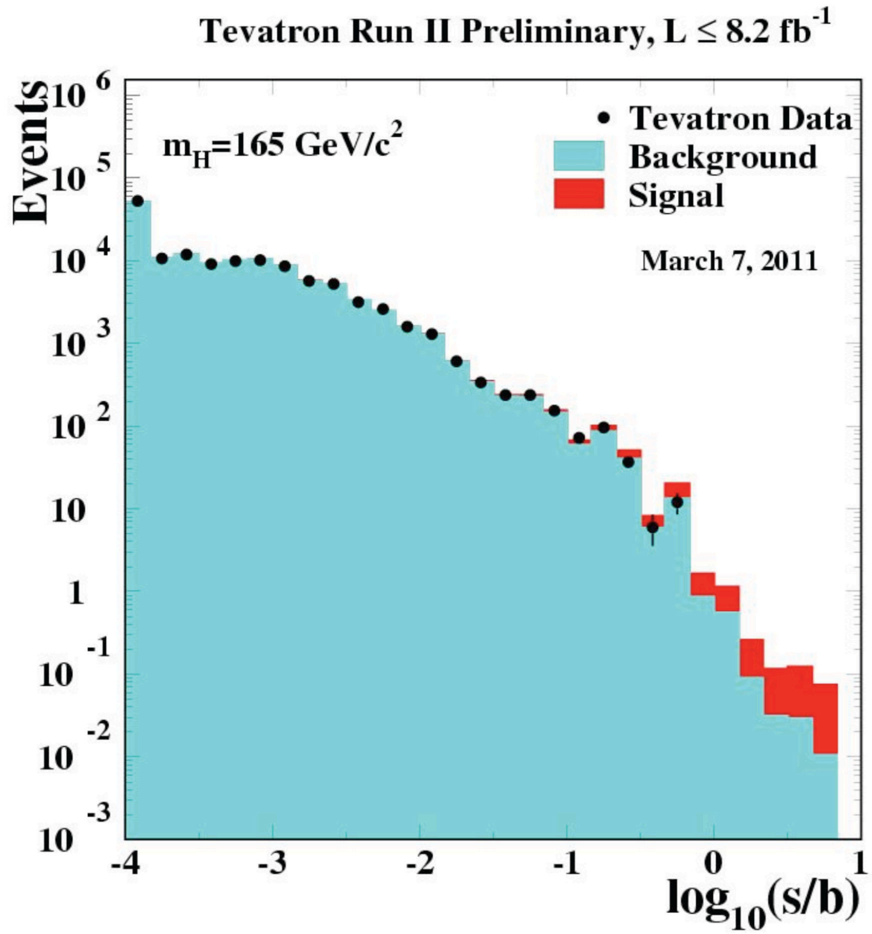




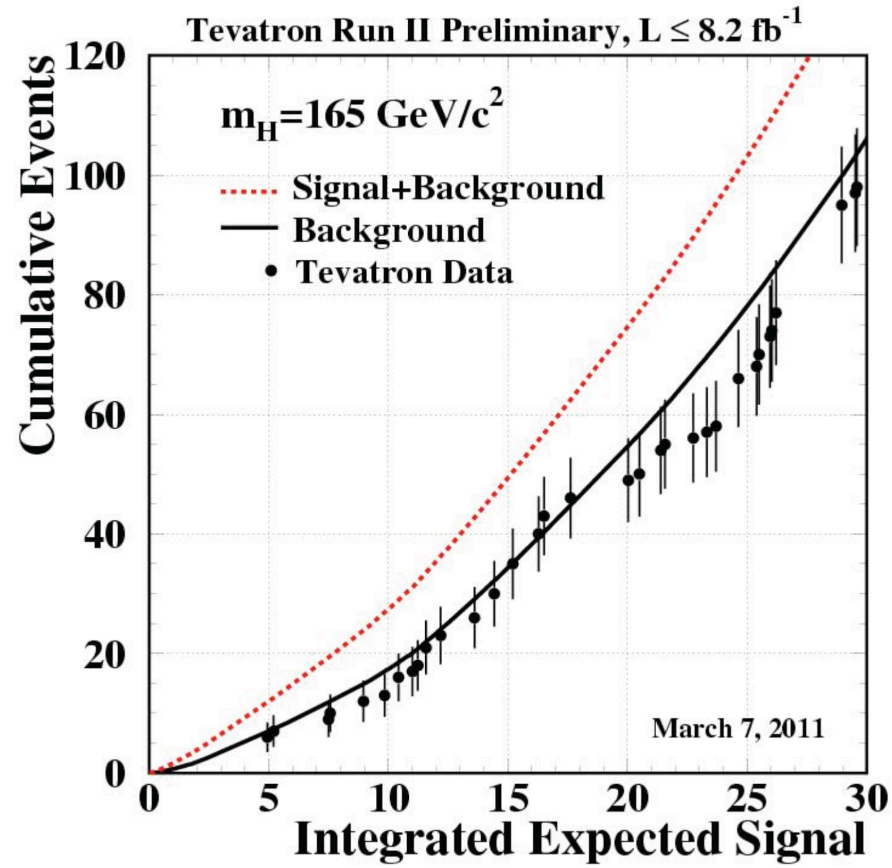




Bkg uncertainty does not wash out signal



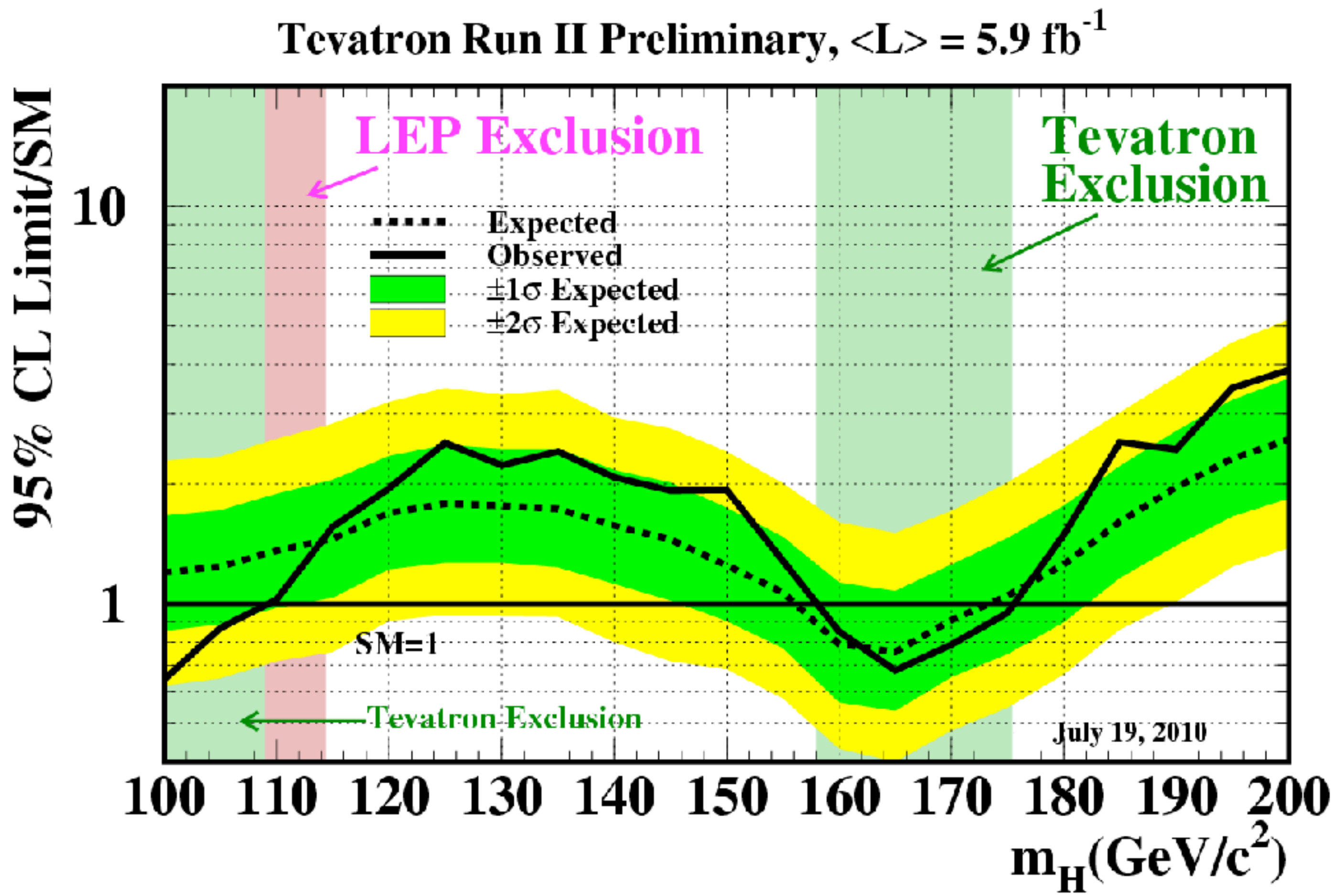
Tevatron Run II Preliminary, L ≤ 8.2 fb-1
Events
mH=165 GeV/c2
Tevatron Data
Background
Signal
March 7, 2011
log10(s/b)



Tevatron Run II Preliminary, L ≤ 8.2 fb-1
Cumulative Events
mH=165 GeV/c2
Signal+Background
Background
Tevatron Data
March 7, 2011
Integrated Expected Signal

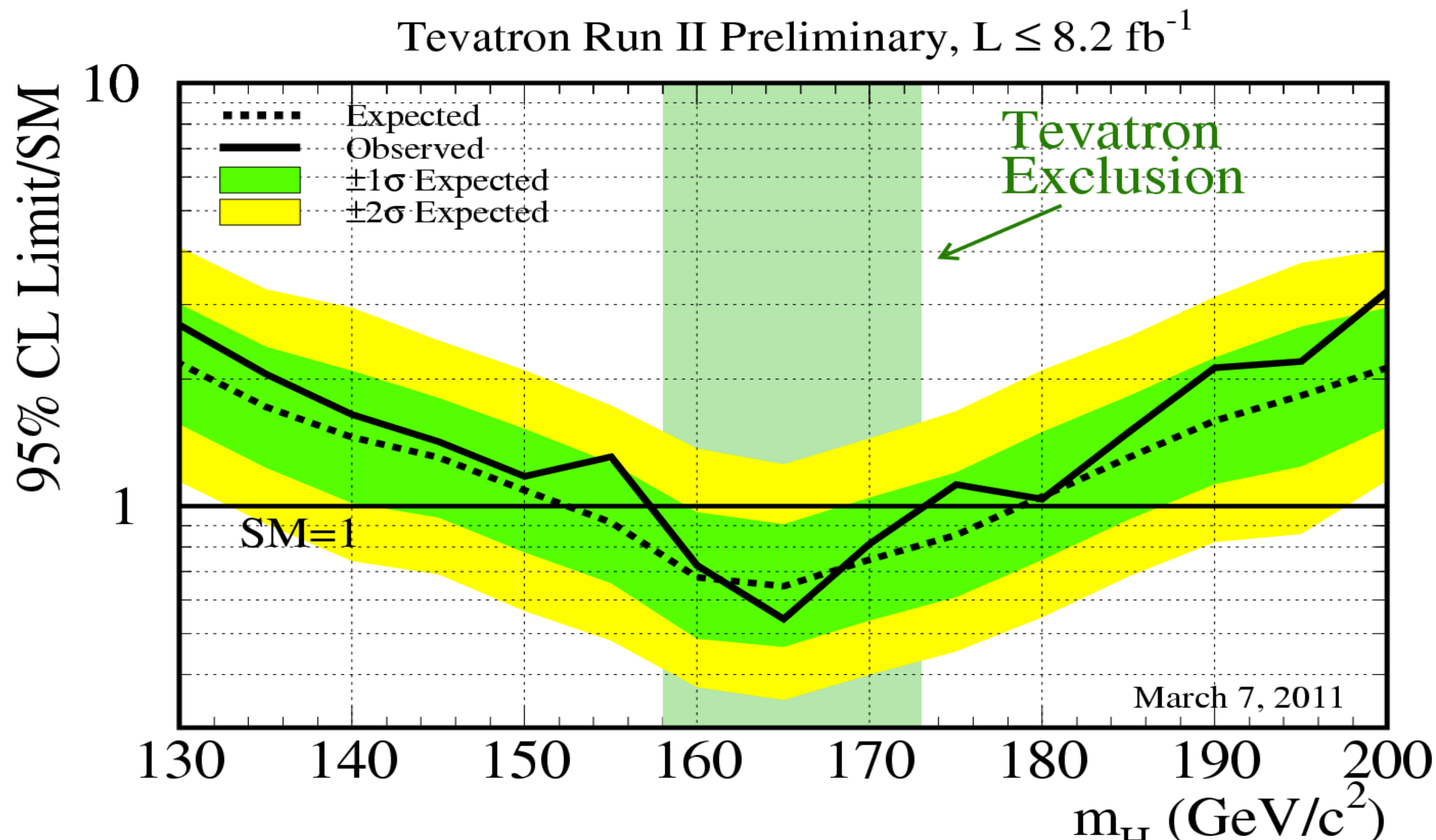
Tevatron Higgs Limits

2010 Tevatron combination



Tevatron Higgs Limits

Winter '11 Tevatron high mass combination



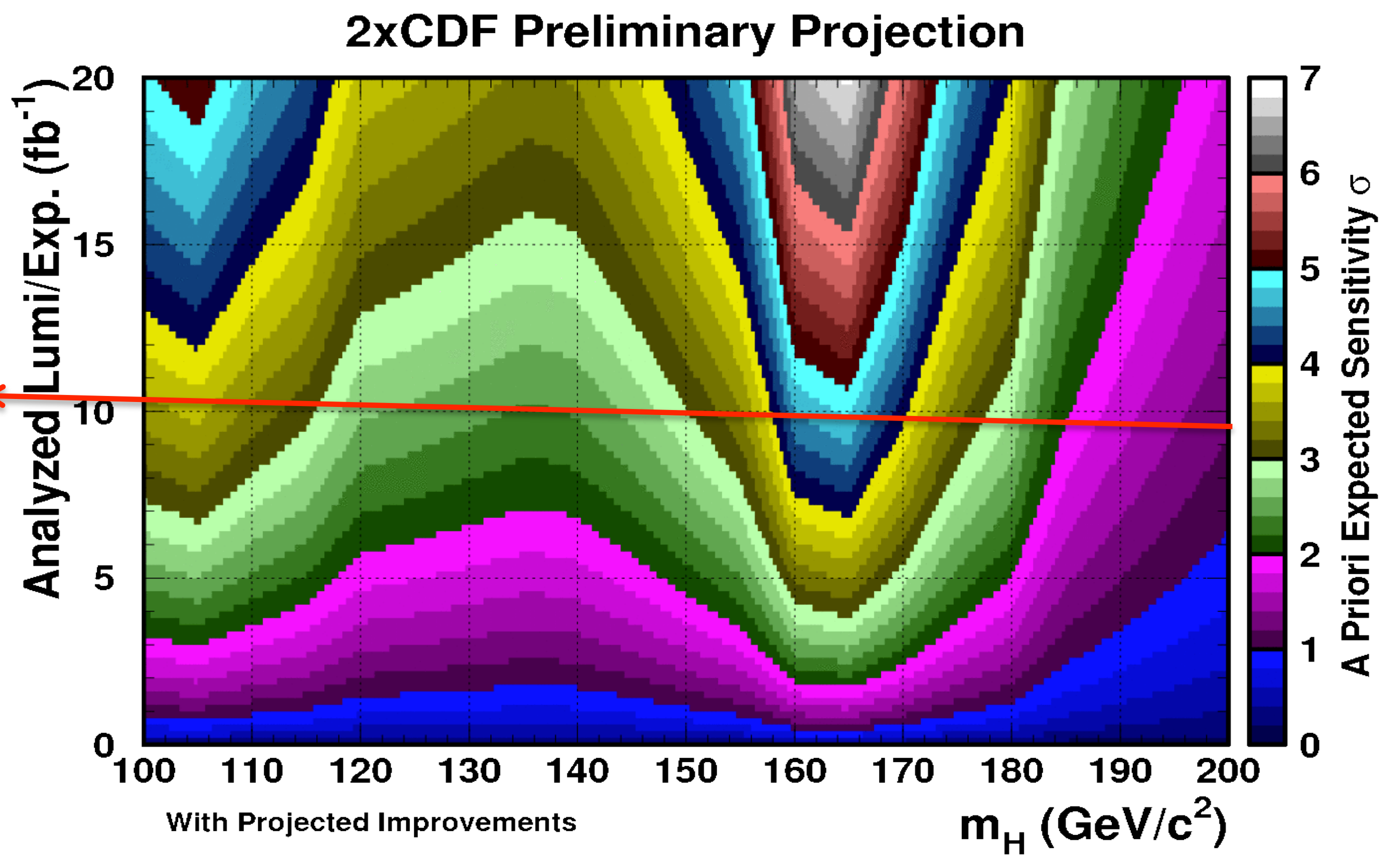
95% C.L. exclusion of the mass range 158< MH <173 GeV

Tevatron Projections

Tevatron will run through Sep. 2011

~12 fb^{-1} delivered per experiment translates to ~10 fb^{-1} available for analysis.

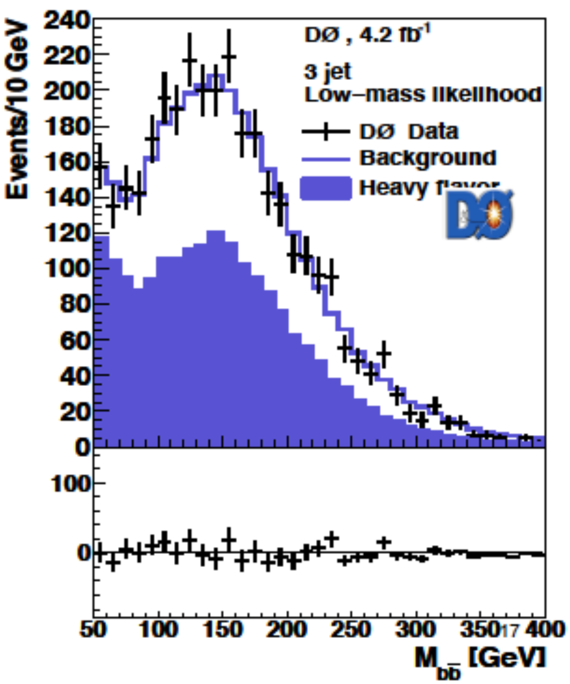
expect better than 2.4 σ sensitivity up to 180 GeV/c2

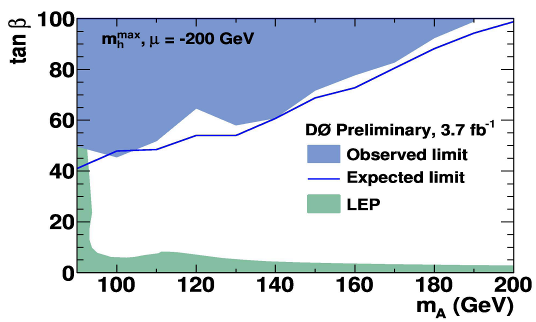


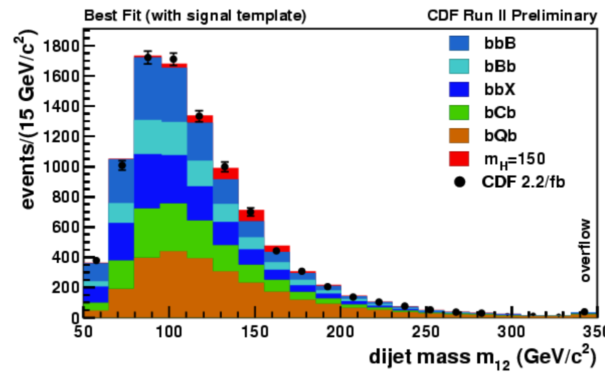
SM Higgs could be excluded by the Tevaron over the entire mass range favored by the EW fits

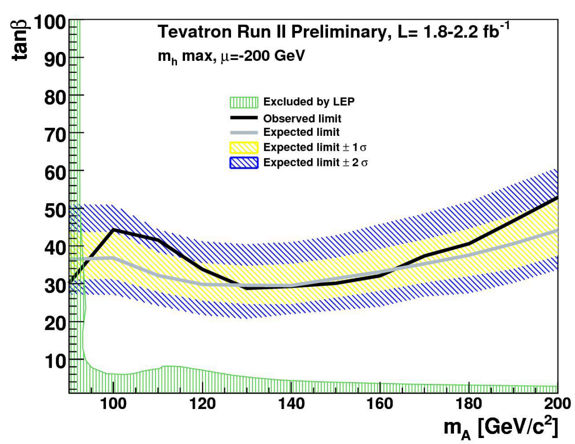
Higgs Beyond SM

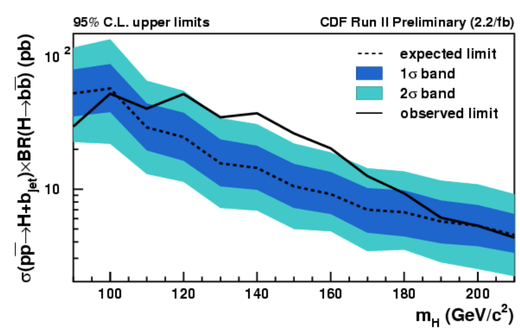
- Looking for Higgs bosons in a variety of models beyond the standard model
- **MSSM**: sensitive to tanβ ~30. Full dataset, combined results could be sensitive to tanβ ~20
- **4th Generation** excluded: 131-204 GeV .
- **Fermiophobic** Higgs: D0 Mhf>112 GeV/; CDF Mhf>106 GeV/
- **Hidden Valley** explored but nothing seen yet











Summary

- Tevatron has taken us far in understanding the SM
- The degree of sophistication of object algorithms, analysis techniques and tools developed at the Tevatron will used by next generations. These advances will of course migrate to the LHC experiments.
- The legacy of the Tevatron will be in its discovery and elucidation of the top quark, W & Z physics and perturbative QCD.
- While LHC will be able to test most of the top quark properties in detail, the legacy mass measurement and complimentary measurements at the Tevatron will still be relevant
- Tevatron still has a critical role to play in the Higgs story

  could exclude or discover Higgs in the entire mass range favored by the electroweak fit
- May be some hint of new physics?

Only part of data delivered has been analyzed yet!