Standard Model Physics at the Tevatron

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On behalf of

CDF and D0

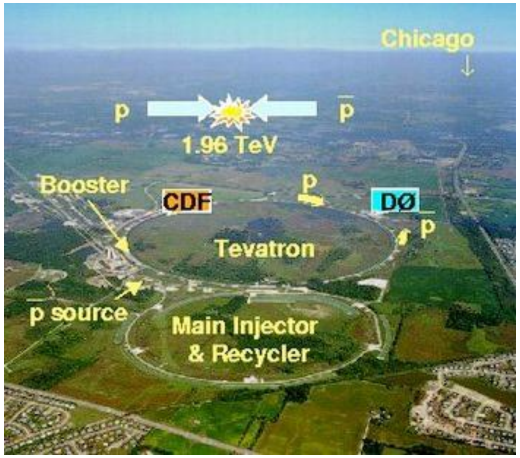
The Tevatron

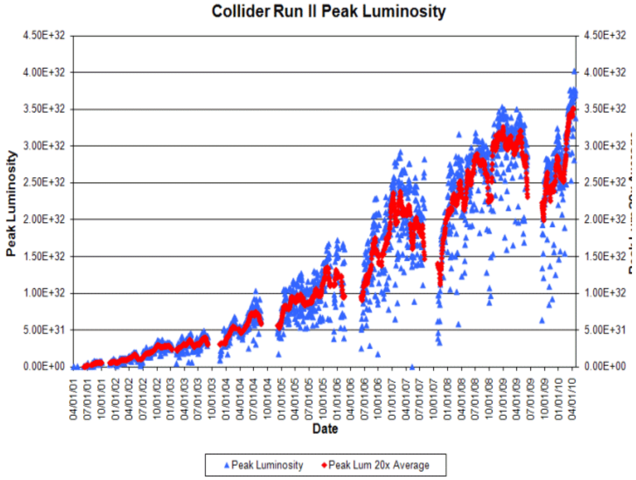
25years ago, first Tevatron collisions in 1985

[“Tevatron luminosity will not exceed 3×10^{30} cm^{-2}s^{-1}” J. Peoples then pbar project leader]

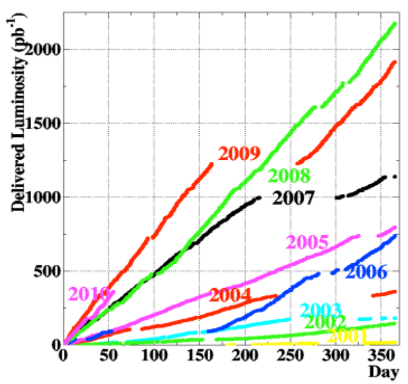
Now running at 3×10^{32} cm^{-2}s^{-1} almost routinely !

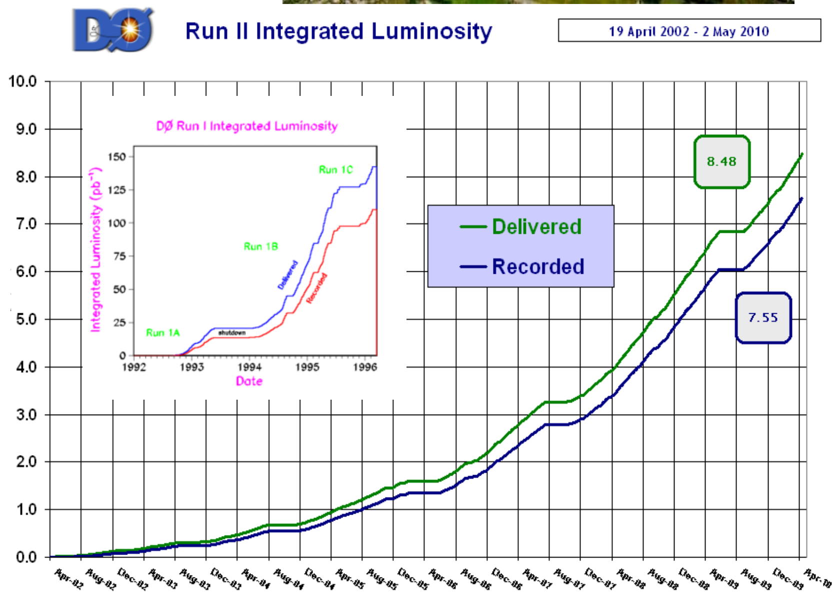
…and this is not the only time when a Tevatron team exceeded its own expectations and projections





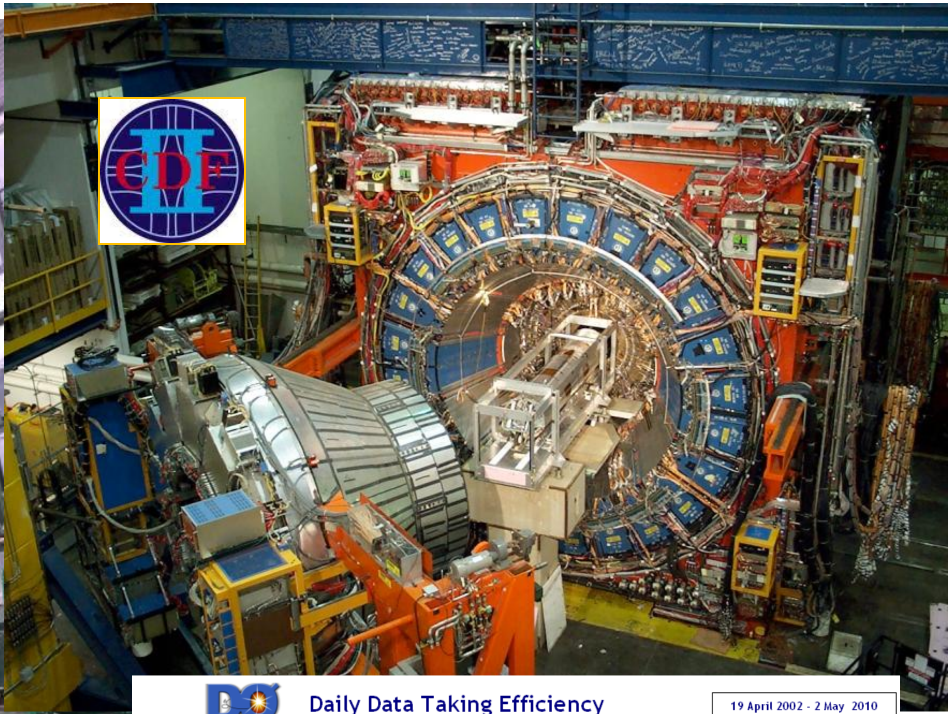
Luminosity Delivered per Calendar Year (*CDF Exp*)

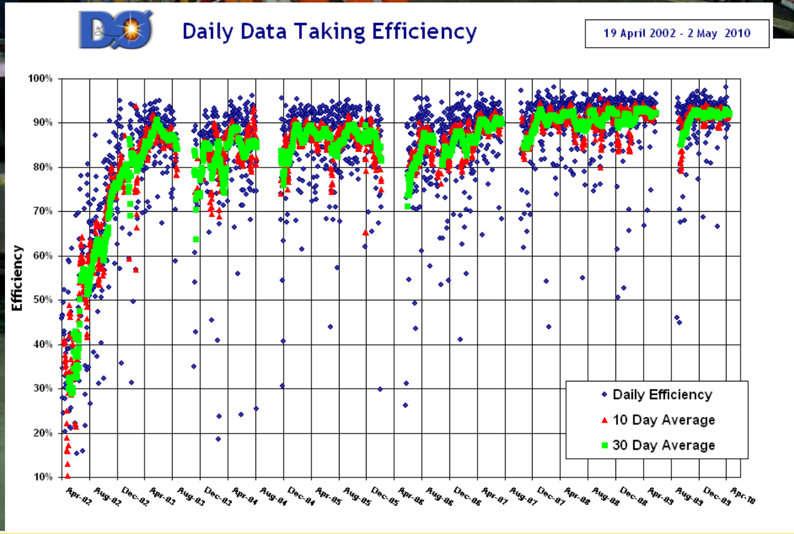




For 25 years, the Tevatron has been the only machine at the frontier… and we have learned much.

CDF and D0 Detectors

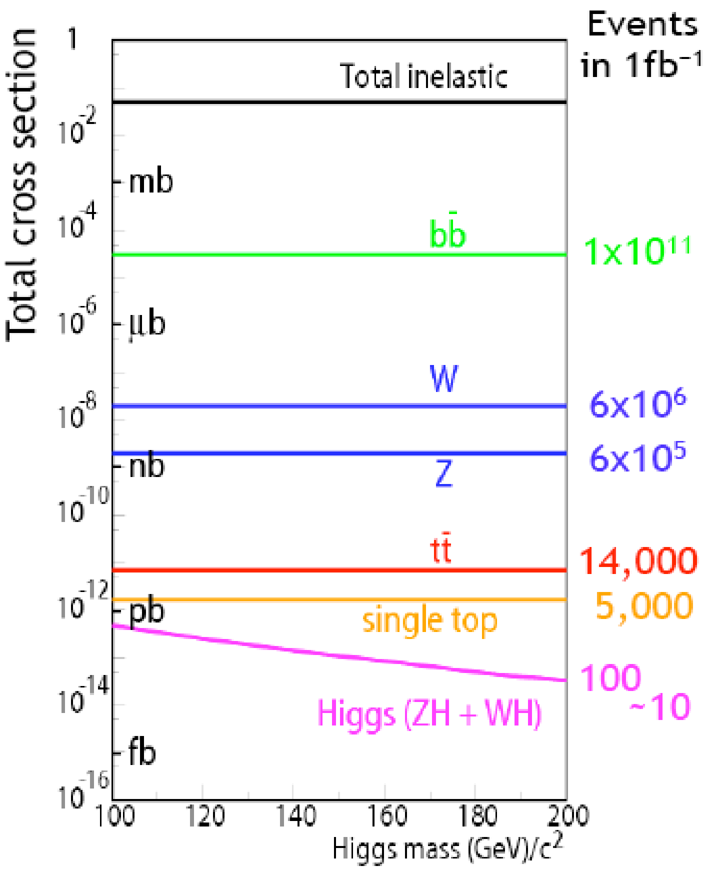




- Multipurpose detectors
- Good resolution for track momenta, vertex, calorimeter
- 85-90% avg. data taking effeiciency for both detectors

Production of Fundamental Particles

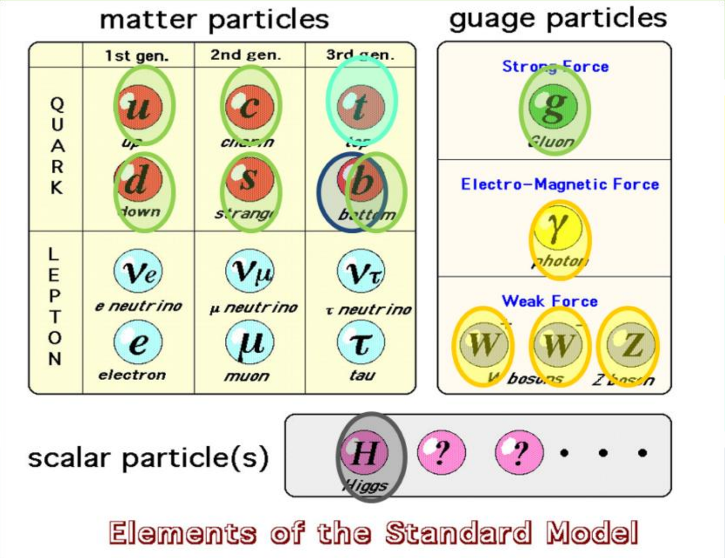
- Cross section:
  - Total inelastic cross section is huge
  - Used to measure luminosity
- Translate it into rates
  - Total ~10 Trilion events in 1 fb^{-1}
    - even with a hard cut of 20 GeV you go down only two orders of magnitude
  - bb: 42 kHz
  - Jets with ET>40 GeV: 300 Hz – 10^8 events
  - W: 3 Hz
  - Top:25 evt /hour
- Trigger needs to select the interesting events
  - Mostly fighting generic jets!



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

Outline of This Talk

- **QCD – quark and gluon physics**
  - Inclusivecross-section;di-jet;3-jet mass cross-section; Ratio 3-jet/2-jet; Asymmetries,W/Z+jets
- **Electroweak – W, Z, photon physics**
  - W boson mass and width;Diboson production
- **Top quark**
  - Top quark cross-section, mass, width; Single top quark production
- **Higgs Boson**
  - Low and high mass searches; Tevatron combination; Future projections



These are just a few selected results.

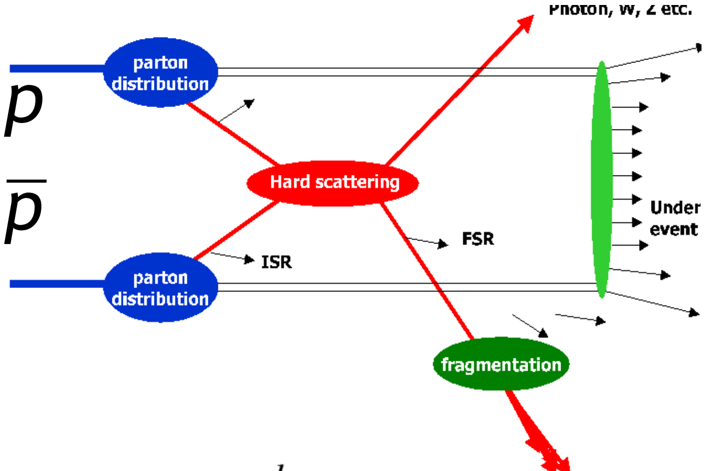
For a detailed picture of D0 and CDF physics program:

http://www-d0.fnal.gov/Run2Physics/W10D0Results.html

http://www-cdf.fnal.gov/physics/physics.html

QCD at the Tevatron

- **Inclusive jets and dijets**
  - α_s, PDFs, Physics beyond the Standard Model
- **Photons**
  - Photons: “direct” probes of hard scattering
  - Test perturbative QCD, PDFs
- **W/Z+jets**
  - Prerequisites for top, Higgs, SUSY, BSM
  - Test perturbative QCD calculations & Monte Carlo Models
- **Soft QCD and Exclusive Production**
  - Prerequisites for High Pt Physics Monte Carlo Tuning
  - Exclusive Higgs Production at the LHC

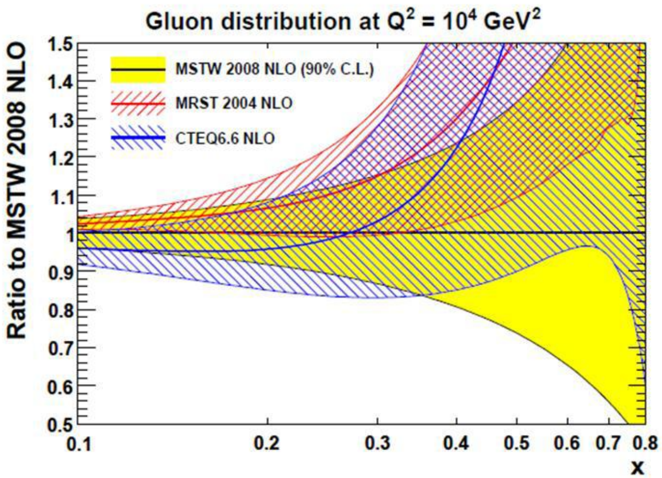


$$d\sigma_{jet} =$$

$$\text{PDFs} \left\{ \sum_a \sum_b f_{a/p}(x_1, \mu_F^2) f_{b/\bar{p}}(x_2, \mu_F^2) \right.$$

$$\text{Hard Scatter} \left\{ \otimes \hat{\sigma}_{a,b}(p_1, p_2, \alpha_s, Q^2/\mu_R^2, Q^2/\mu_F^2) \right.$$

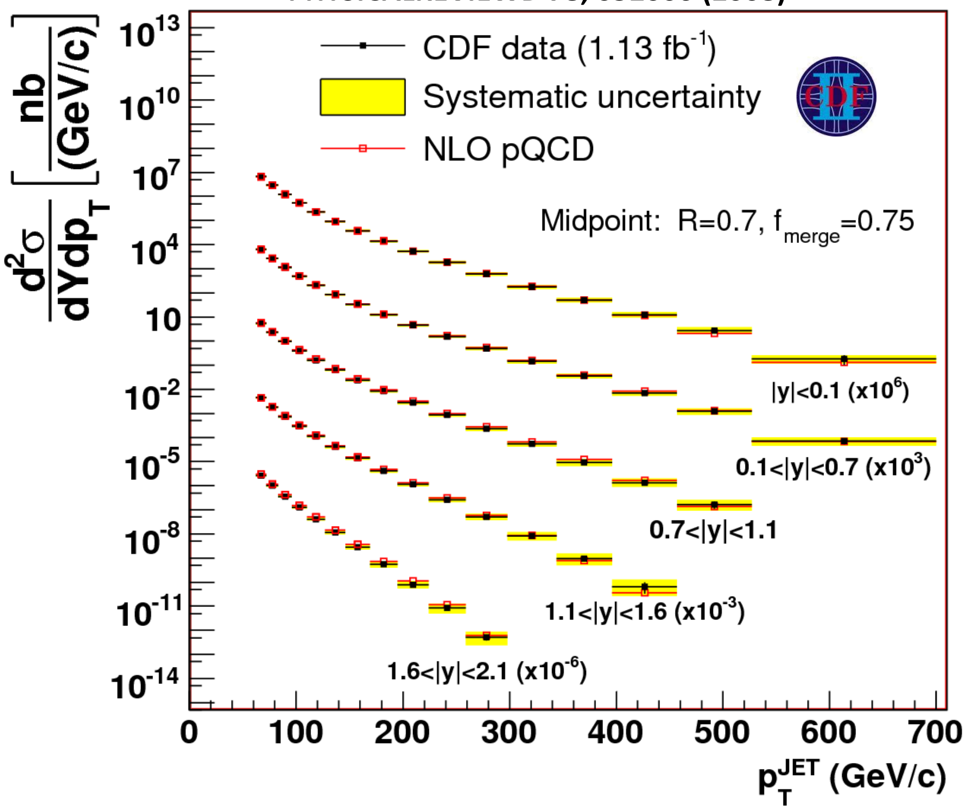
Testing and verifying QCD calculations is essential!



Inclusive Jet Production

- Inclusive jet measurements test pQCD over 9 orders of magnitude and up to p_{Tjet}>600 GeV
- Dominant systematic jet energy scale
- Both CDF and D0 measurements are in agreement with NLO predictions
- Experimental uncertainties smaller than PDF uncertainties

PHYSICALREVIEWD 78, 052006 (2008)



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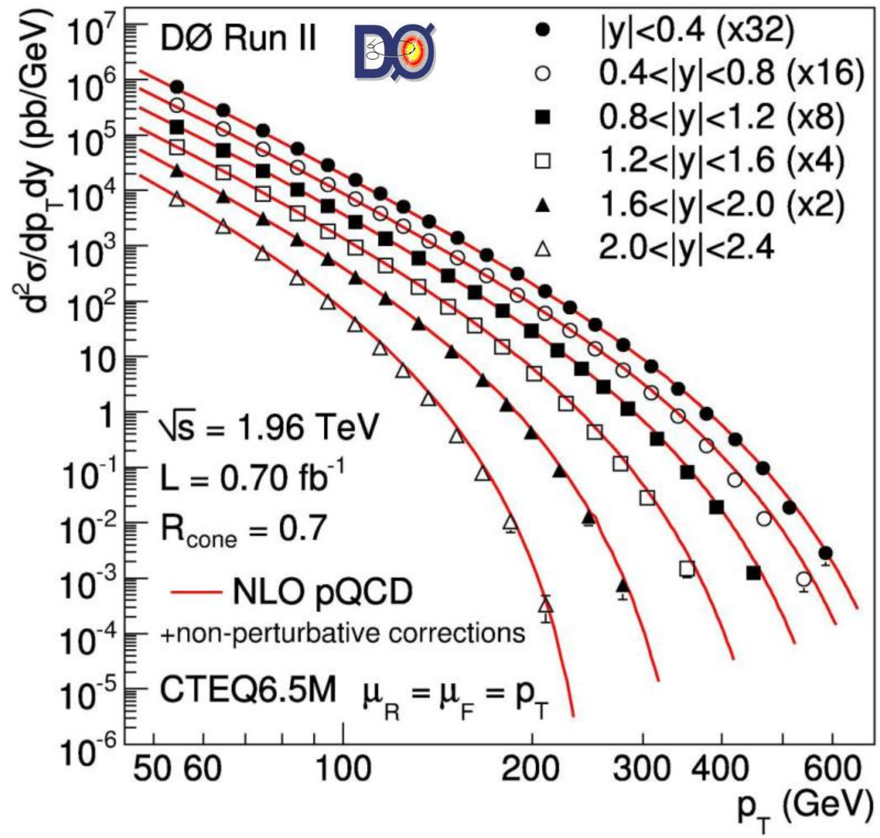
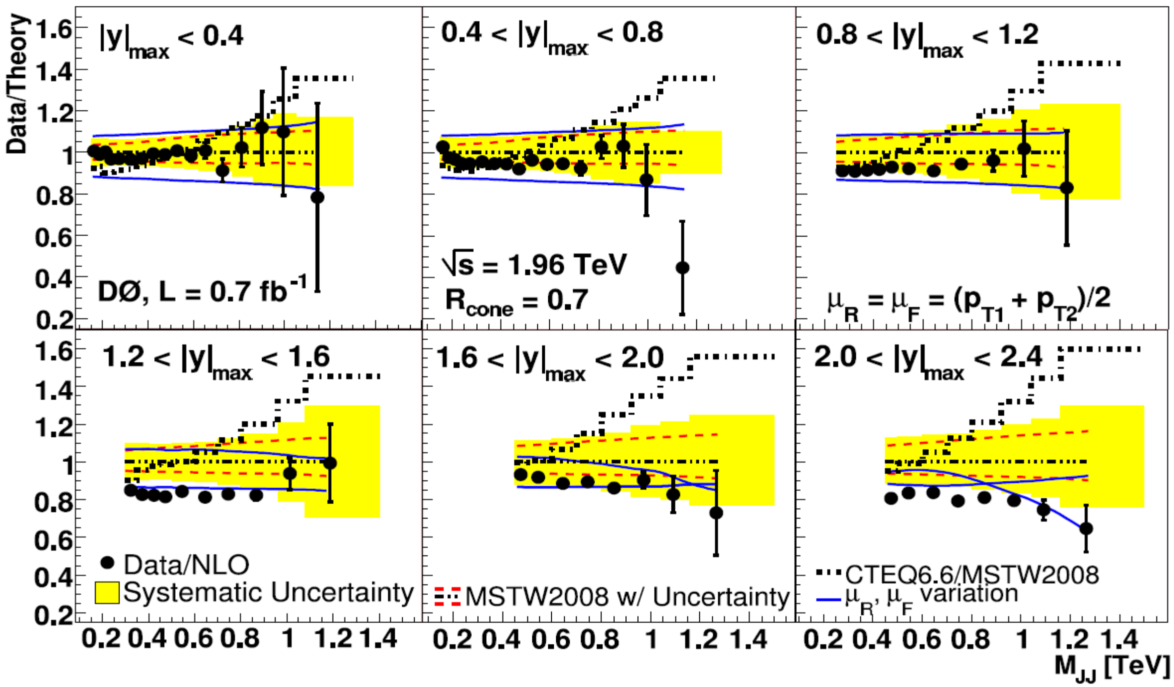
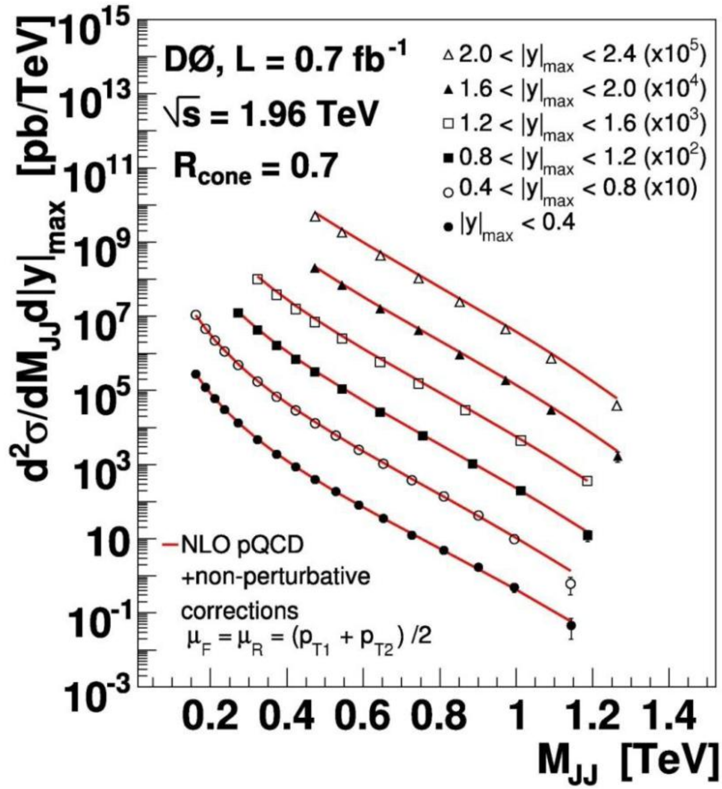


Dijet Mass

- Measurement of dijet mass in six rapidity bins
- Double-differential comparison to NLO pQCD with MSTW2008 NLO PDFs

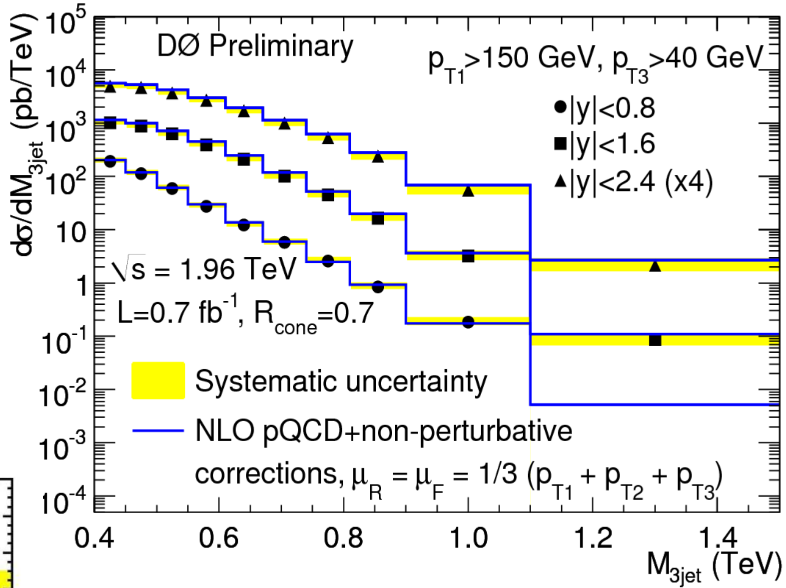


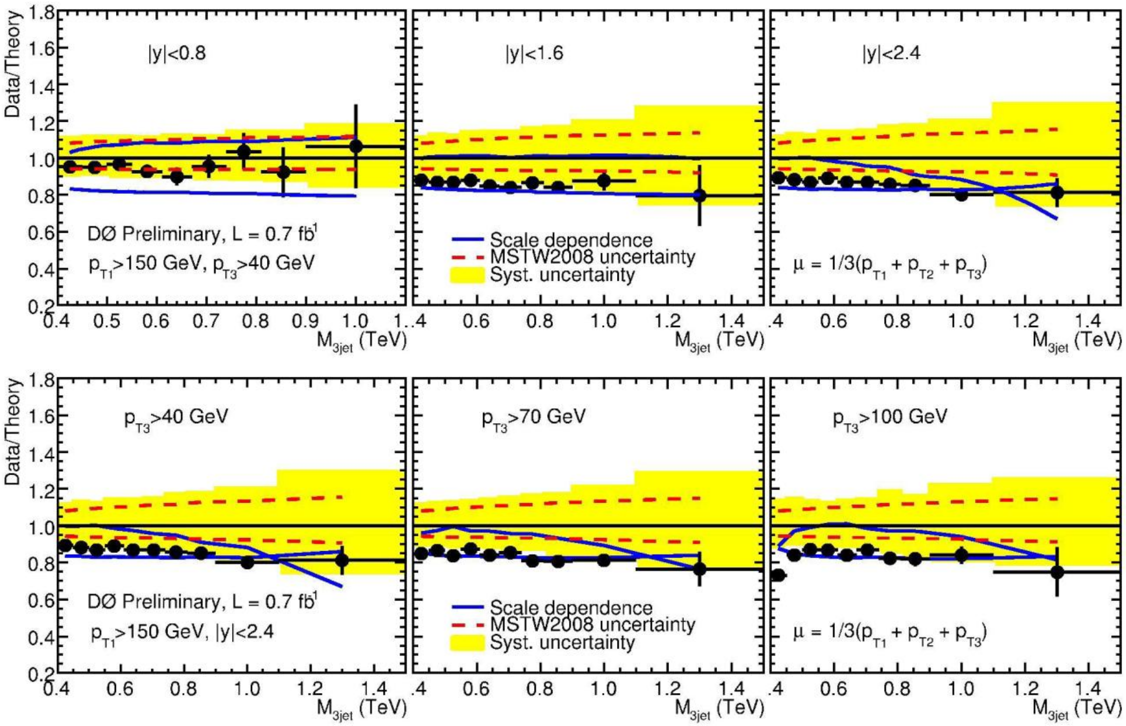


- **Data/QCD in good agreement in central region**
- **40—60% difference between PDFs (MSTW2008/CTEQ6.6) at highest mass**

Three-jet Mass

- Differential measurements of three-jet mass
- Three-jet calculation available @NLO Use NLOJET++ 4.1.2 with MSTW2008
- Invariant masses > 1 TeV
- Total systematic uncertainty:20—30% (dominated by JES, pT resolution and luminosity)

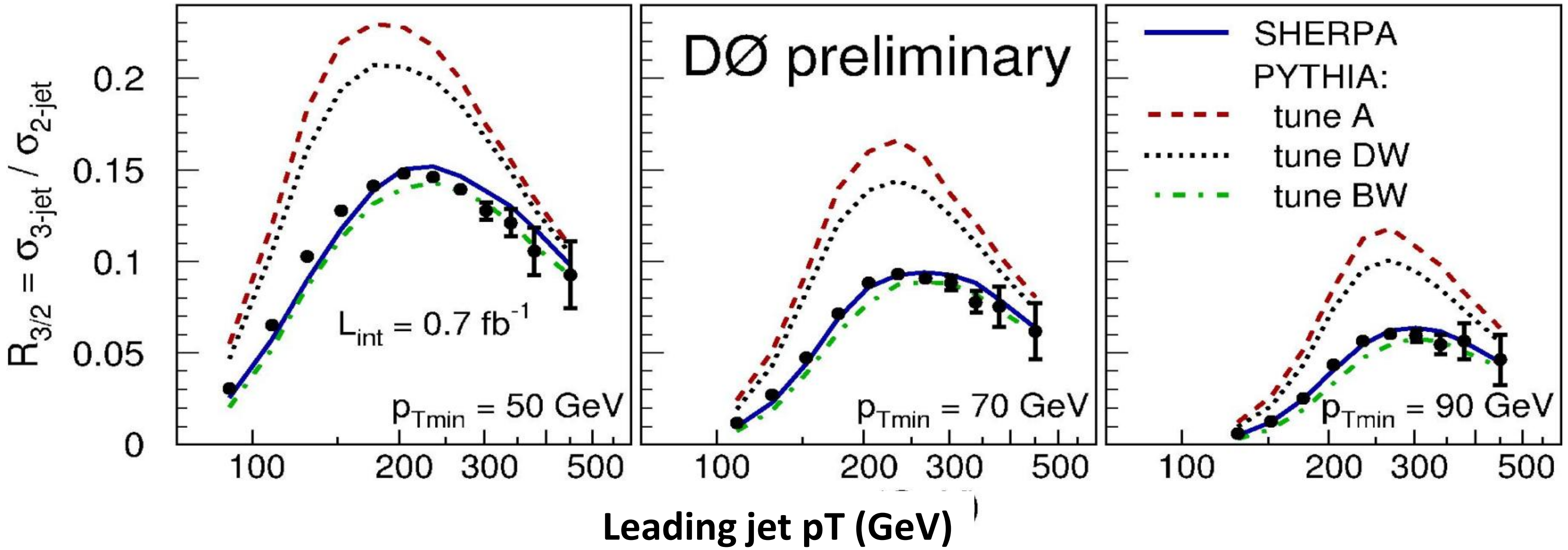




- Reasonable agreement seen between data and NLO
- More 3-jet variables can be studied in future with this dataset

Ratio of 3 to 2-jet cross-sections

- First measurement of ratios of multijet cross-sections at Tevatron
- Test of QCD independent of PDFs (small residual dependence because of 2/3-jet subprocess compositions). Many uncertainties also cancel in ratio
- Probes running of α_s up to p_T of 500 GeV
- Excellent agreement to Sherpa 1.1.3 (MSTW2008 LO)
- Future studies: NLO pQCD comparisons; extract α_s



Strong Coupling Constant α_s

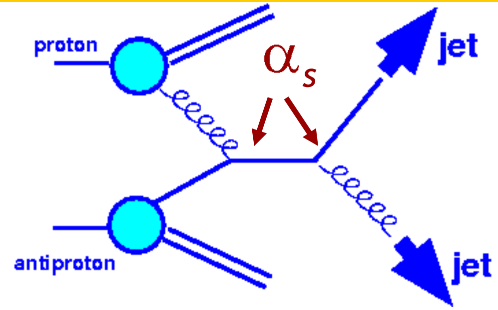
- Determined from DØ inclusive jet cross section
- NLO + 2-loop threshold corrections
- MSTW2008NNLO PDFs
- This is the most precise determination of the strong coupling constant from a hadron collider

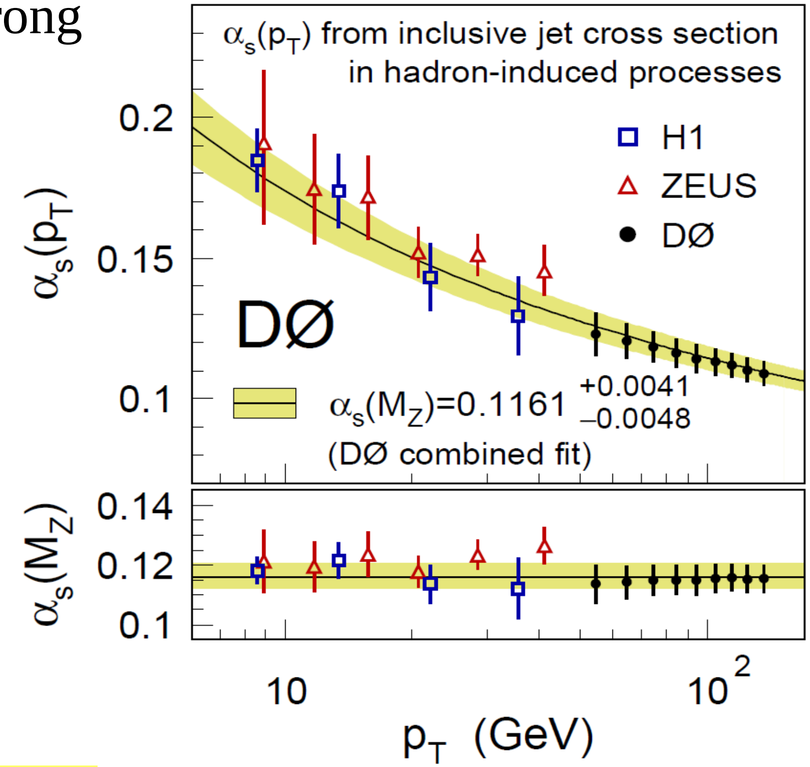
$$\alpha_s(M_Z) = 0.1173^{+0.0041}_{-0.0049}$$

3.5-4.2% precision

- Tevatron has extended the measurements of running α_S at high Q^2, beyond the HERA reach.
- Good agreement with NLO QCD

Hadron colliders can do precision physics!



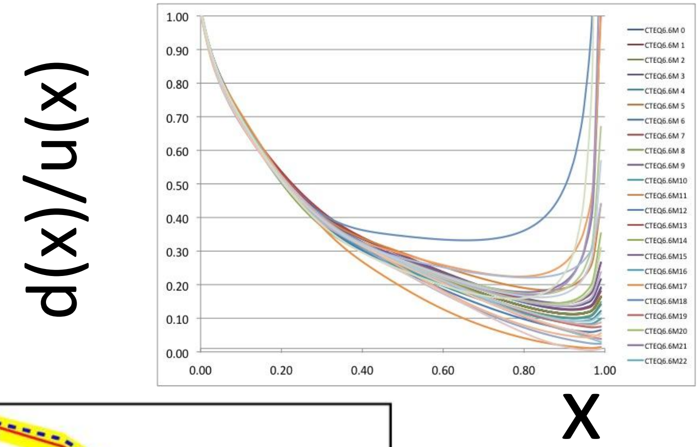


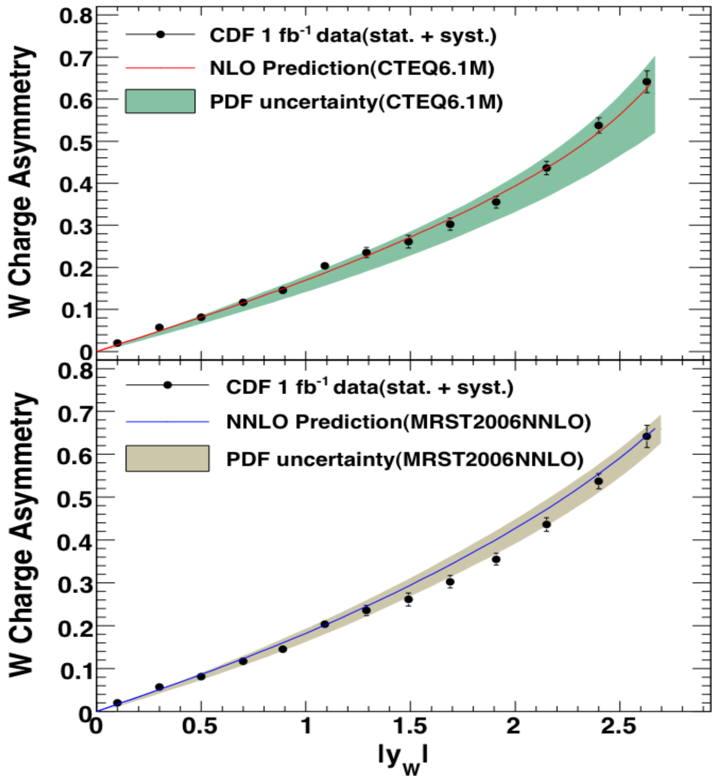
D0:Phys. Rev. D 80, 111107 (2009)

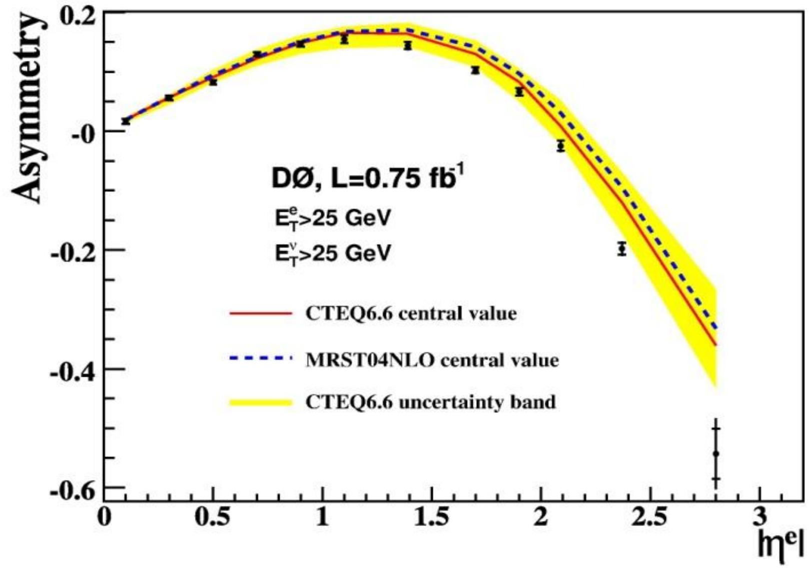
CDF: Phys. Rev. Lett. 88, 042001

d(x)/u(x) from W Asymmetry

- D0: Lepton asymmetry in W→μν
  - L = 4.9 fb^{-1}, 2.3 M reconstructed W decays!
  - Results compared to RESBOS+CTEQ6.6M
- CDF: W asymmetry
  - L= 1fb^{-1}
  - Use *W* mass constraint



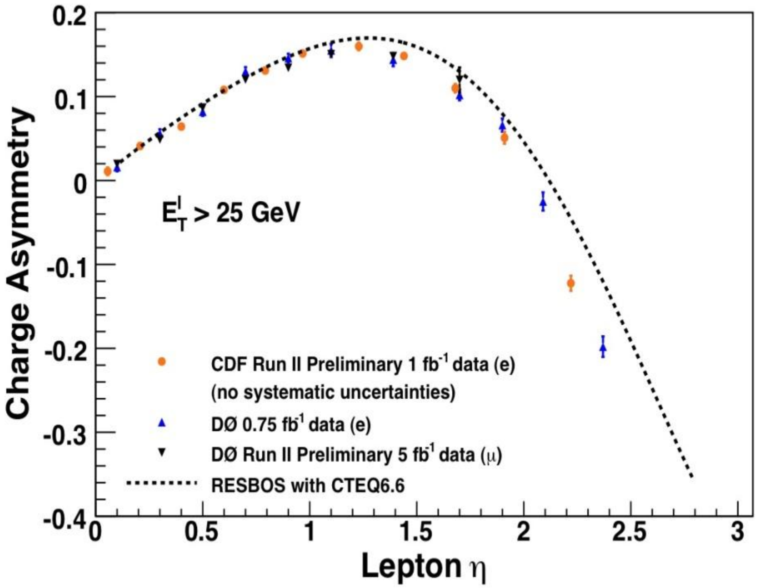


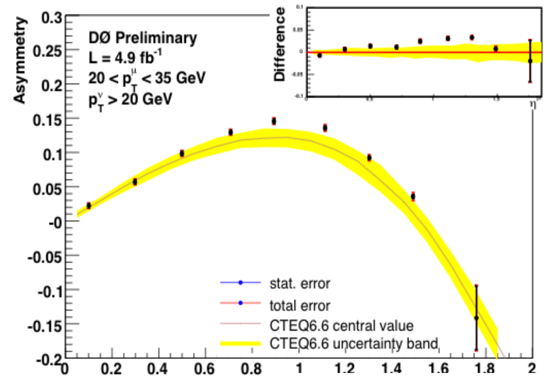


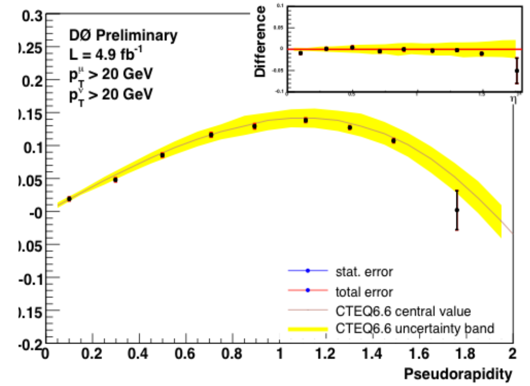
- Compare to NLO and NNLO PDFs and their uncertainties
- Experimental precision is *much* better than the theoretical error band!

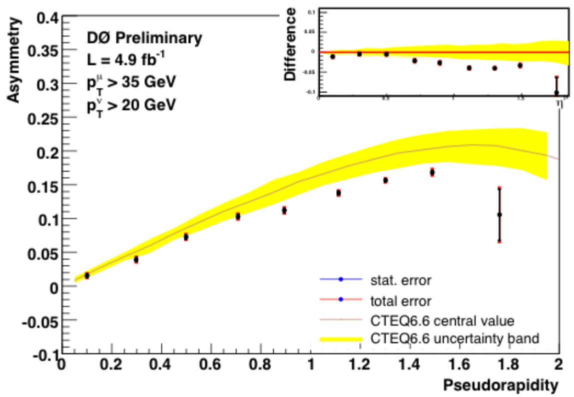
d(x)/u(x) from W Asymmetry

- CDF has measured the electron asymmetry from the same data sample as their W asymmetry. Compare with D0 muon and electron data





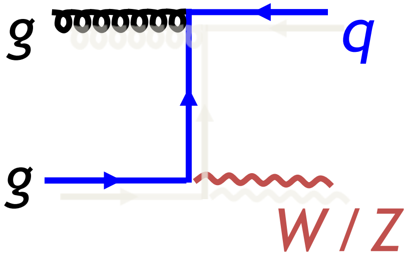


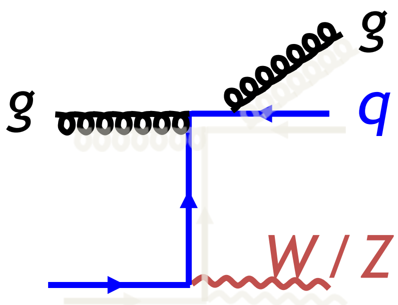


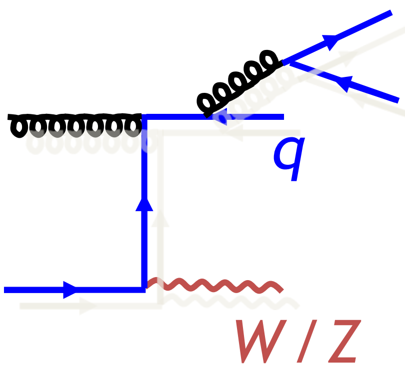
- The CDF W asymmetry agrees well with theoretical predictions.
- D0 and CDF lepton asymmetries disagree with theoretical predictions for binned lepton pt, but seem to agree with each other!

W/Z + Jets

- W/Z+jets are critical for physics at the Tevatron and LHC: top, Higgs, beyond Standard Model
- Many Monte Carlo tools are available
  - LO + Parton shower Monte Carlo (Pythia, Herwig)
  - MC based on tree level matrix element + parton showers, matched to remove double counting: Alpgen, Sharpa, …
  - These calculations and tools need "validation" by experimental measurements
- Tevatron is providing precise QCD measurements of W/Z+jets and W/Z+HF
  - W/Z+jets:
    - good agreement with NLO predictions
  - W/Z+HF:
    - First Z/W+HF measurements start challenging theoretical uncertainties
    - W+charm well described by recent NLO predictions
    - W+bottom does not agree well with predictions



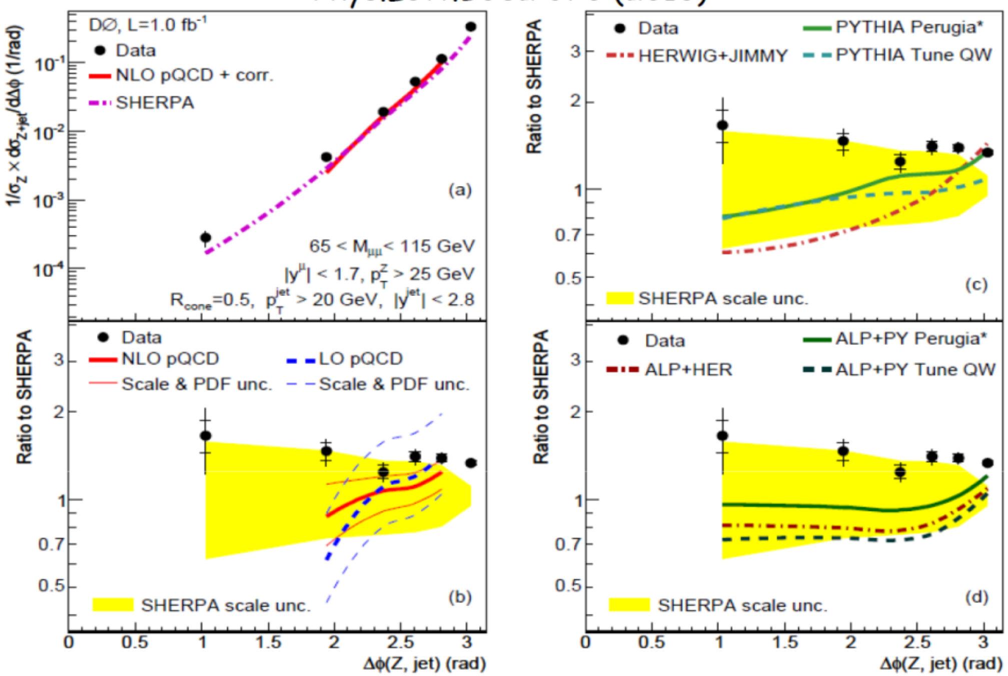


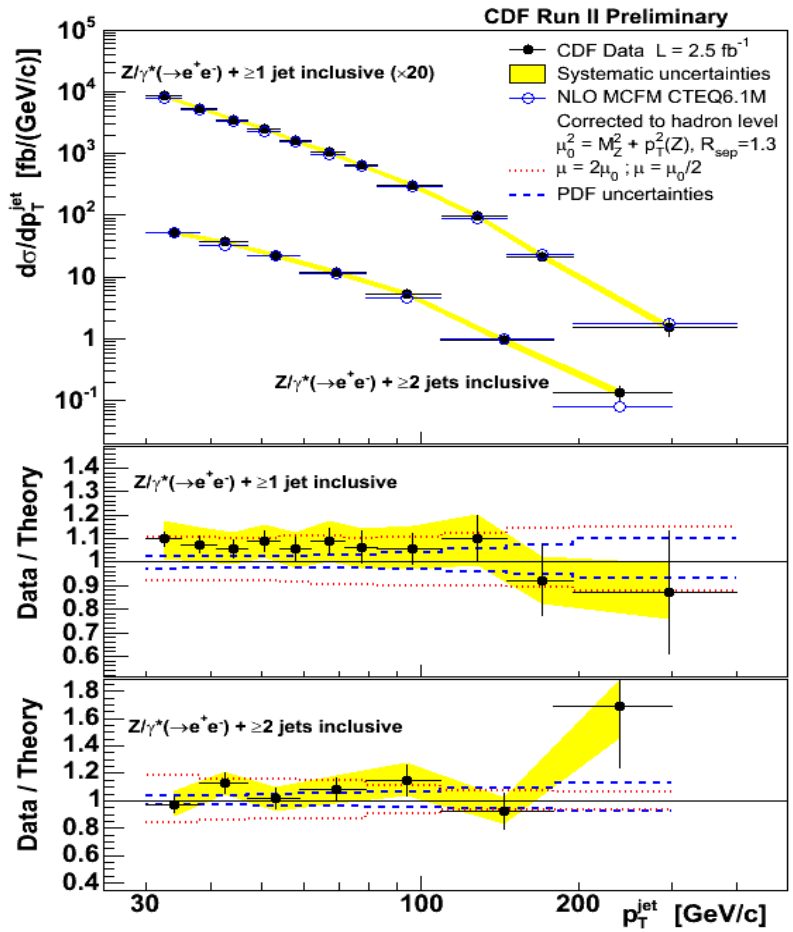


Z+jets

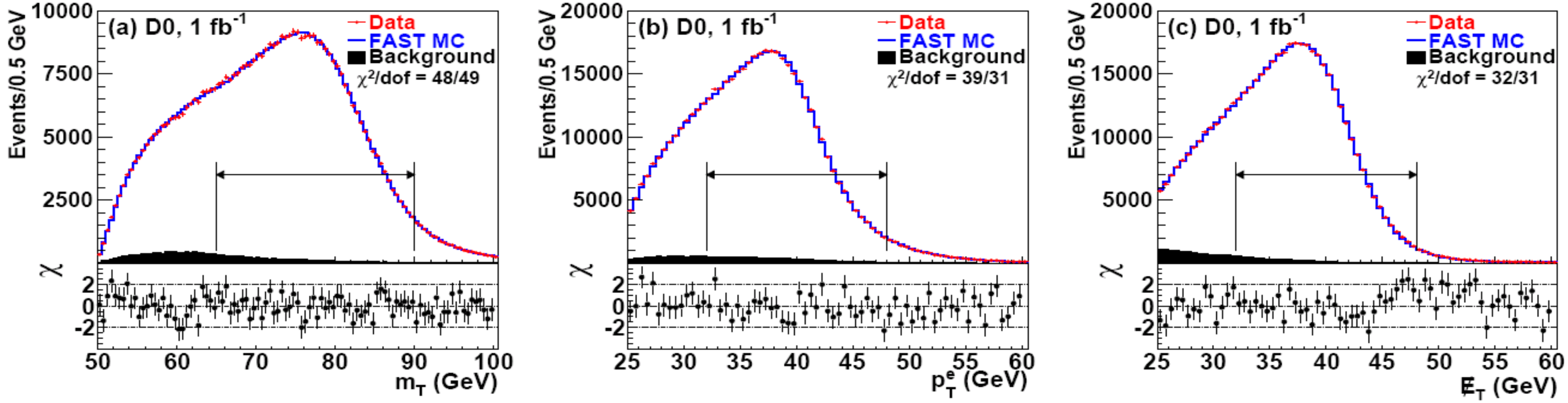
- Reasonable agreement between data and NLO
- Significant improvement of NLO compared to LO
- Event generators tend to have normalization and shape differences
- Alpgen + Pythia (Perugia) improves description
- Sherpa best describes the shape, but not normalization

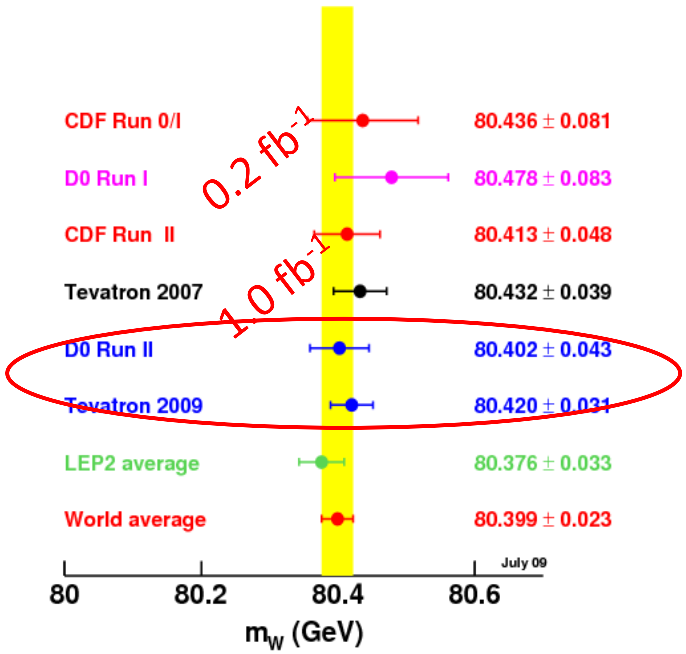
Phys.Lett.B682:370 (2010)





W Boson Mass





- W mass is a key parameter in the SM
- High precision measurement from Tevatron (0.05%) requires precision lepton momentum and recoil momentum calibration (driven by the Z→ll statistics)
- World best result from D0

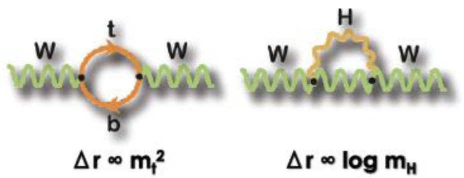
  [Phys. Rev. Lett. **103**, 141801 (2009)]
- Combining all measurements from Tevatron and LEP gives new world average

  M_W=80.399±0.023 GeV (<0.03%).

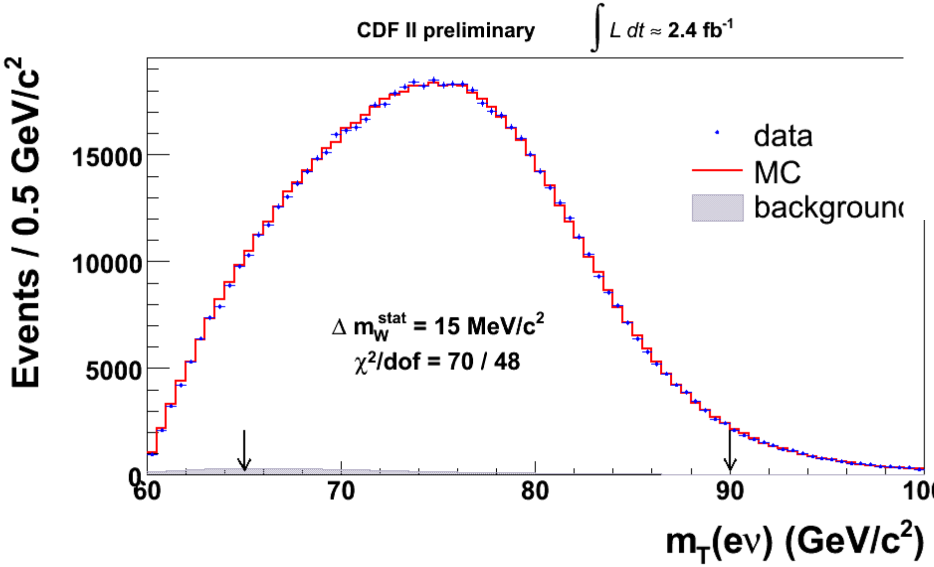
Tevatron is now better than LEP!!

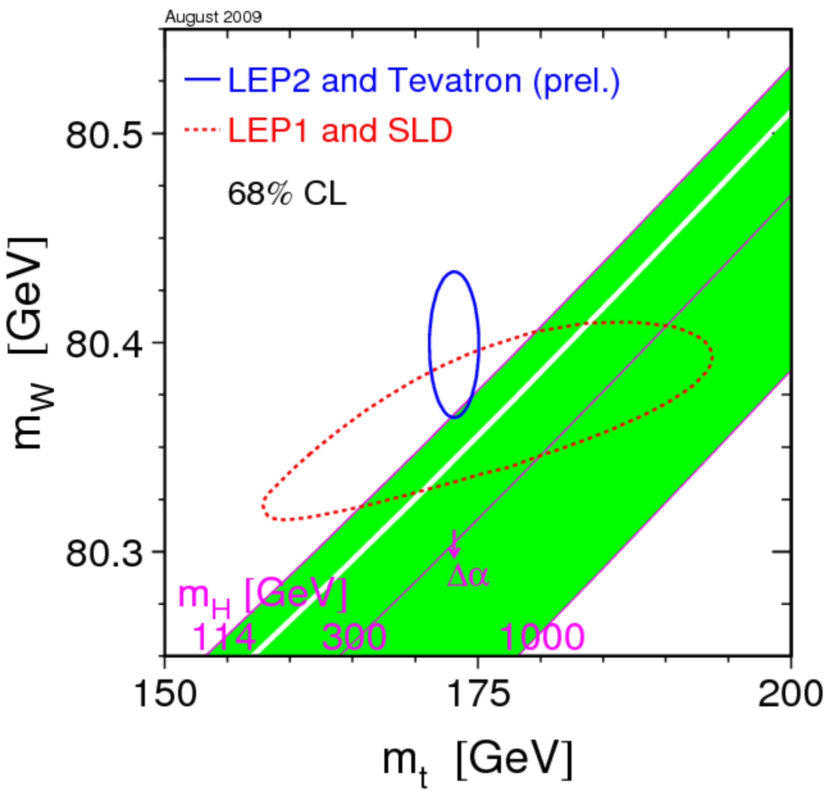
W Boson Mass

But we are not done yet…..



- M_W vs M_{top} + EWK precision observables favor low mass SM Higgs
- The indirect limit on the Higgs mass is dominated by the W mass uncertainty.
- Even smaller uncertainty in M_W highly desirable, could hint to New Physics

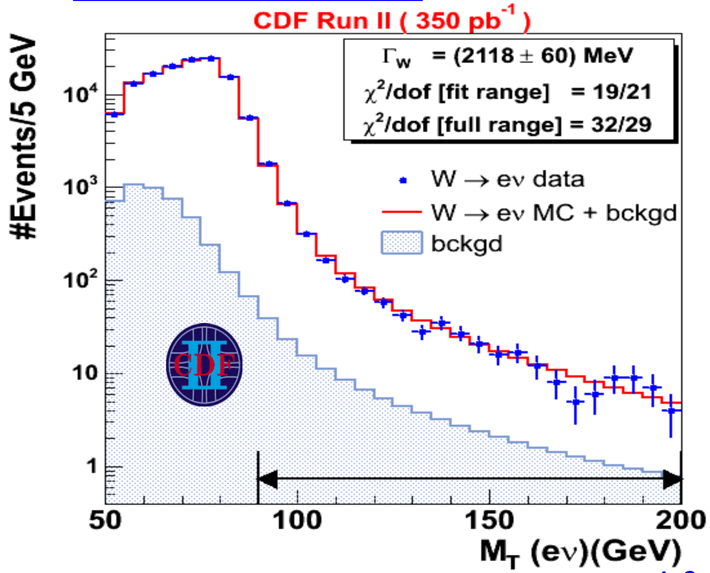




CDF: new results with 2.4 fb^{-1} expects ~ 15 MeV/c^2 statistical uncertainty per channel

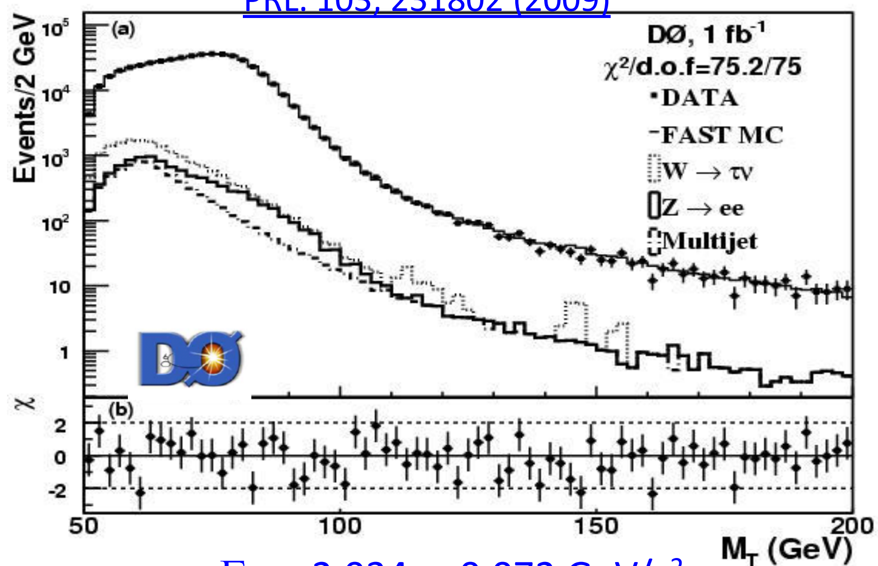
W Boson Width (Γ_W)

PRL 100, 071801(2008)

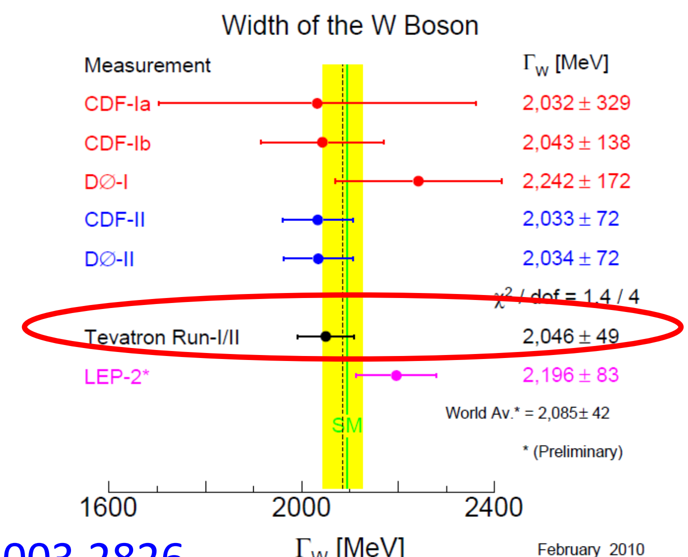


Γ_W = 2.033   0.072 GeV/c^2

PRL. 103, 231802 (2009)



Γ_W = 2.034   0.072 GeV/c^2



- Fit to the high-end tail of the transverse mass distribution
- Combined Tevatron value for W width:

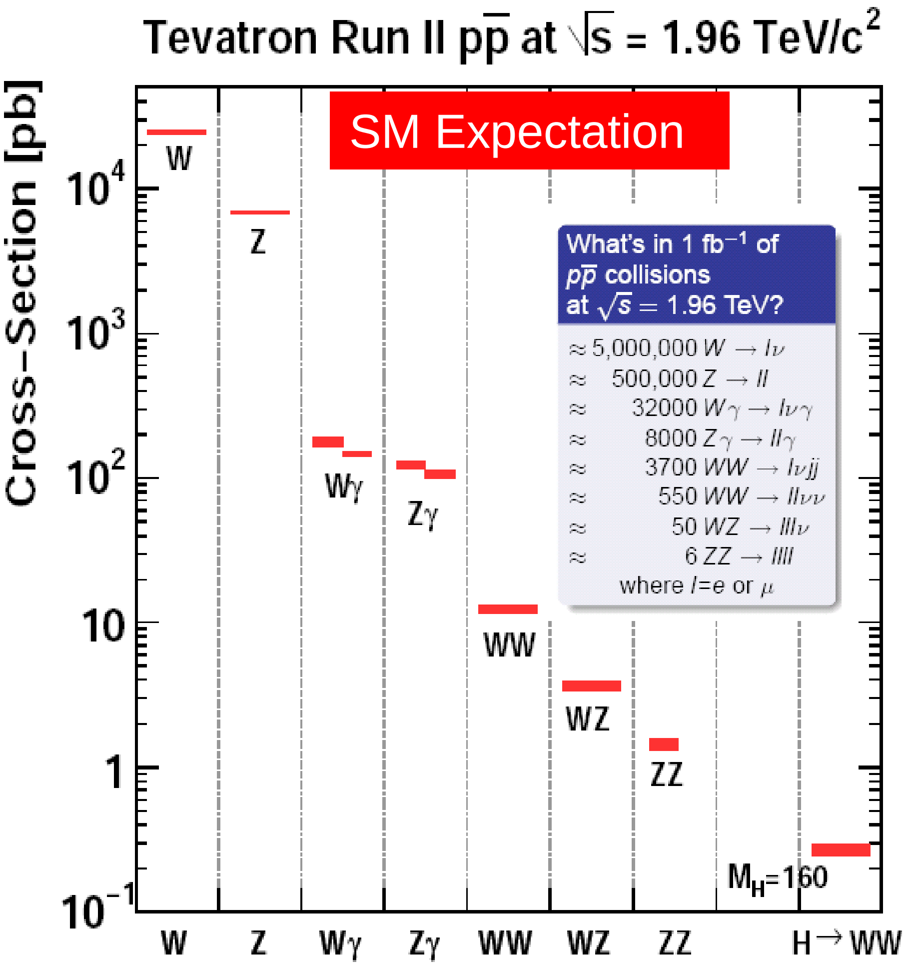
$$\Gamma_W = 2,046 \pm 49 \text{ MeV}$$

Tevatron is now better than LEP!!

arXiv:1003.2826

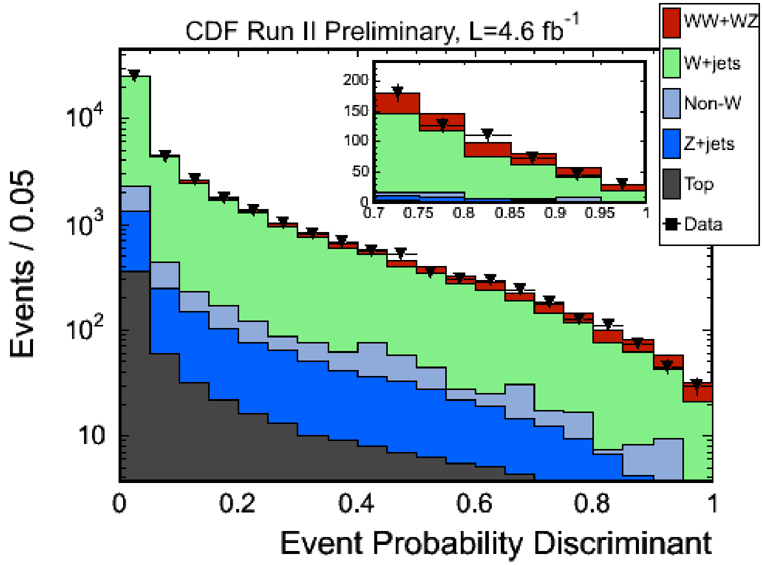
Diboson Production

- Production cross sections, kinematics, gauge boson self-interactions
- Diboson production is one of the least tested areas of the SM.
- Triple gauge vertices are sensitive to physics beyond the SM.
- Tevatron complementary to LEP: explores higher energies and different combinations of couplings.
- In the SM, diboson productions are important to understand: they share many characteristics and present backgrounds to Higgs and SUSY.

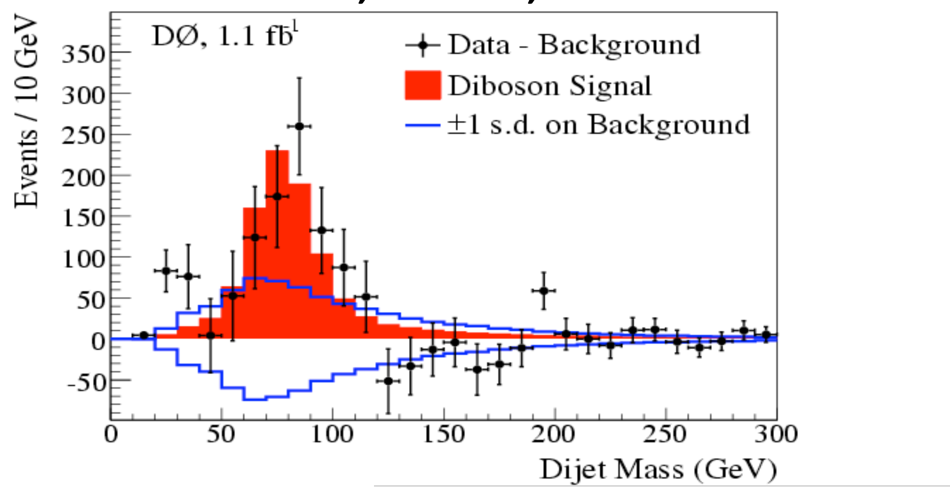


note: this is σ, not $\sigma \times$ BR

WW/WZ→lvjj Production



PRL 102, 161801, 2009



- WW+WZ

  D0: σ (WW+WZ) = 20.2   4.5 pb evidence at 4.4σ

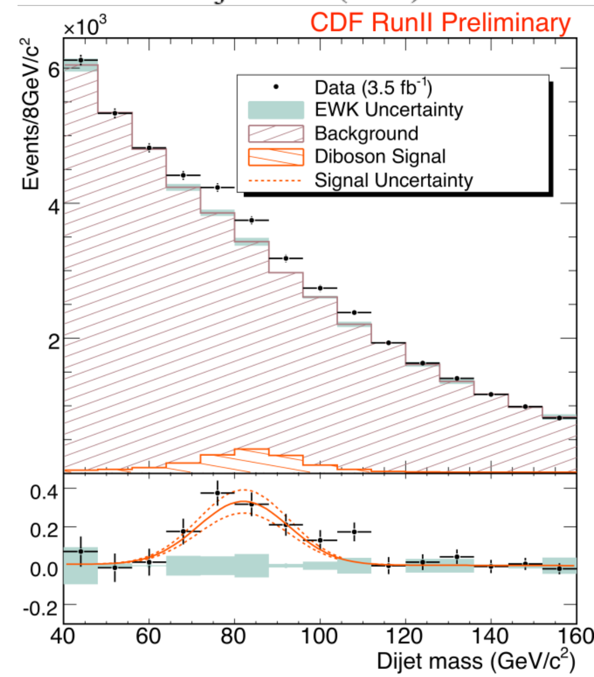
  CDF: σ (WW+WZ) = $16.5^{+3.3}_{-3.0}$ observation at 5.4σ

- WW+WZ+ZZ

  CDF: σ (WW + WZ+ ZZ) = 18.± 2.8(stat) ±2.4(sys) ±1.1(lum)pb

  SM prediction = 16.8 ± 0.5 pb (MCFM+CTEQ6M)

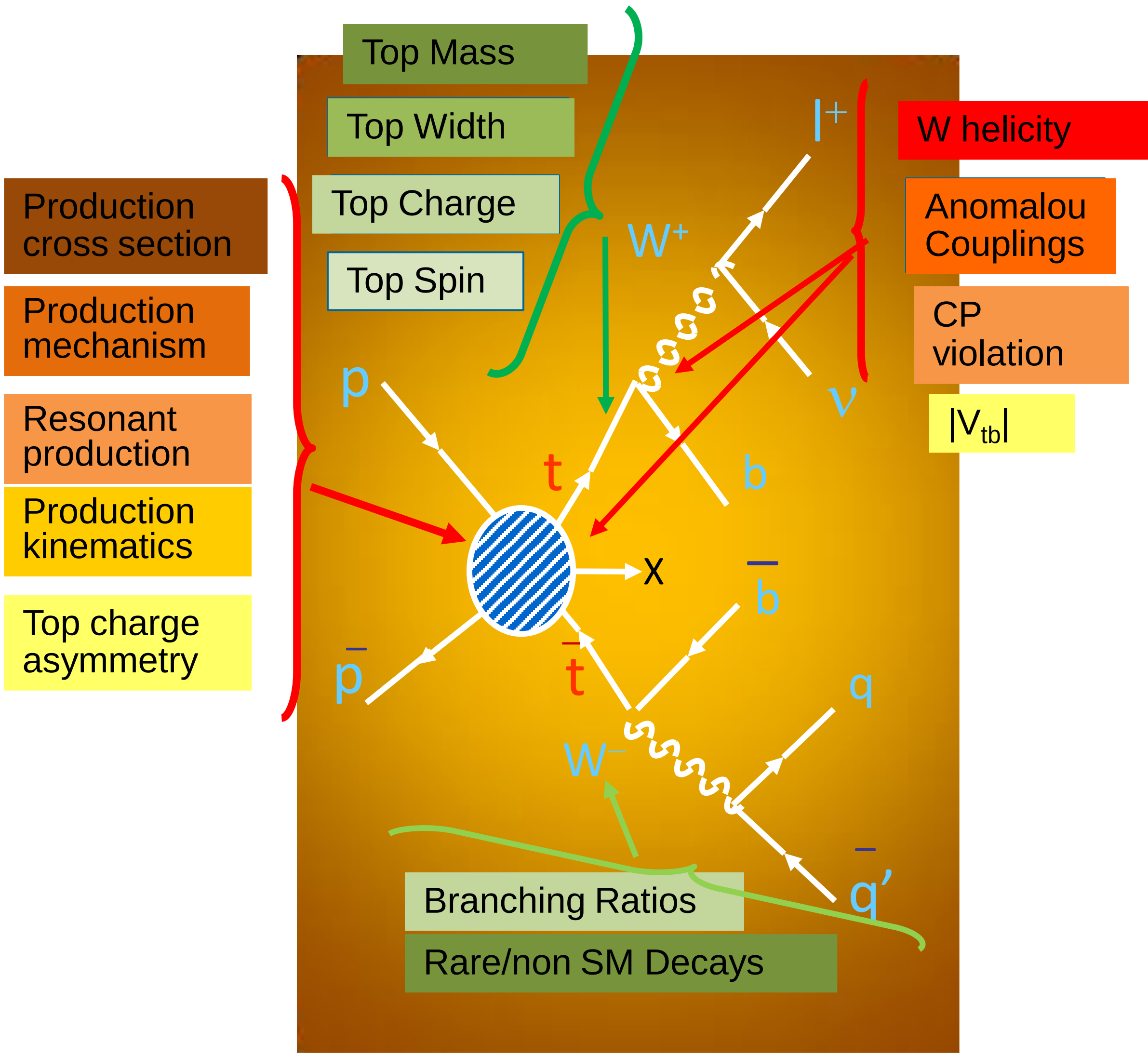
  observation at 5.3σ significance



- Top quark is the heaviest known elementary particle

Questions we can answer

- Higgs boson mass?
- More than three fermion generations?
- Charged Higgs bosons?
- New massive particles?
- Do all quarks have the expected couplings?
- Unknown unknowns??

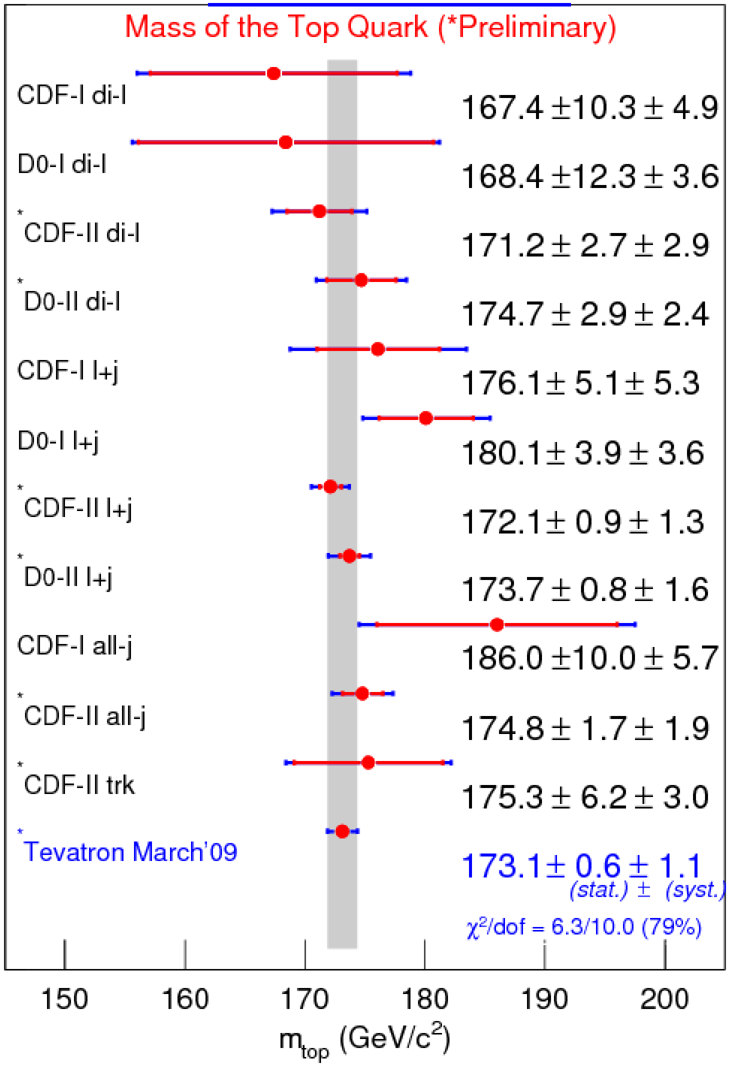


Top Quark Mass

- The large top quark mass means its coupling to Higgs is large.
- The top mass depends on M_H through loop diagrams ($M_t \sim \log M_H$).
- Mass measurements made in dilepton, lepton+jets, all jets channels using a variety of techniques by both CDF and DØ. They are in agreement:

Have now exceeded the Tevatron goal of δM=2 GeV

arXiv:0903.2503v1

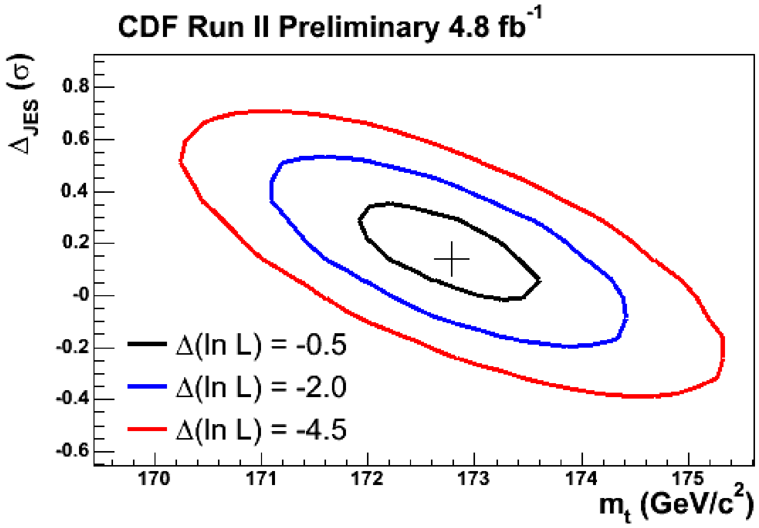


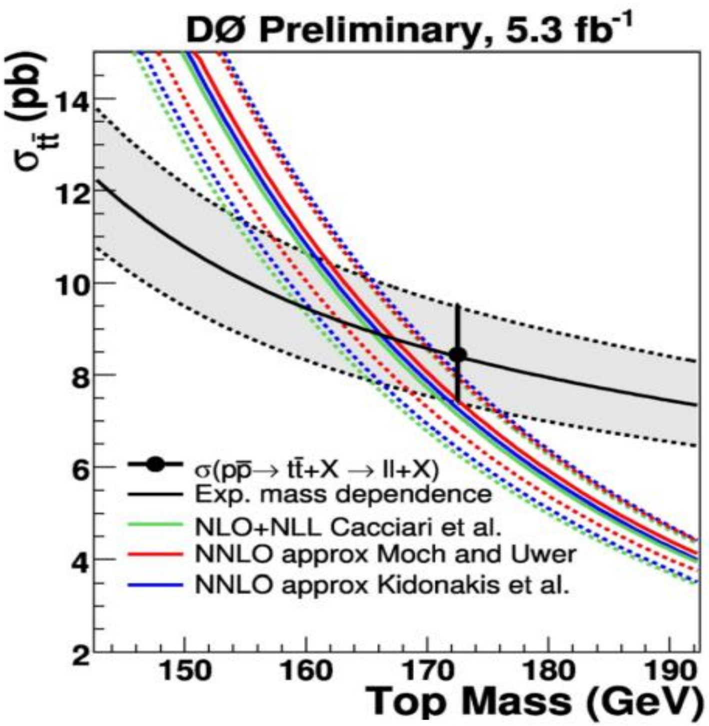
But we are not done yet…..

- New Matrix element based top mass measuremen Lepton+Jets with 4.8fb-1

$m_t = 172.8 \pm 1.3_{total}$ GeV 0.7_{stat}, 0.6_{JES}, 0.8_{sys}

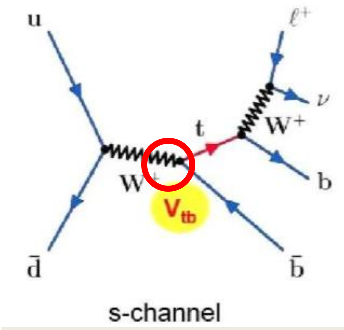
Expect 1GeV precision achievable

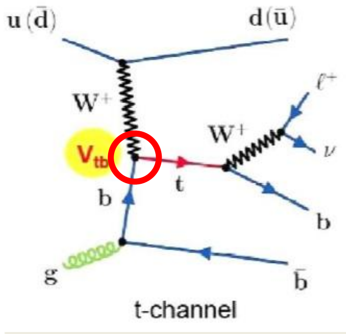




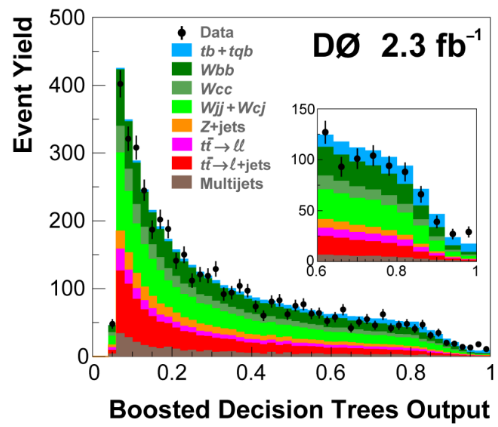
Top quark cross section measurement constraints top quark mass by taking into account theoretical calculation
PRD 80 (2009) 071102

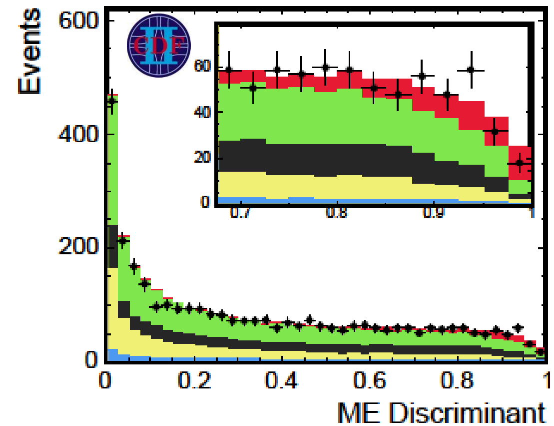
Single Top Production





- **Electroweak production: tb and tqb** $\sigma_t \sim 1/2\ \sigma_{tt}$
  - Measure directly W-t-b coupling (CKM)
  - Source of ~100% polarized quarks
  - New physics





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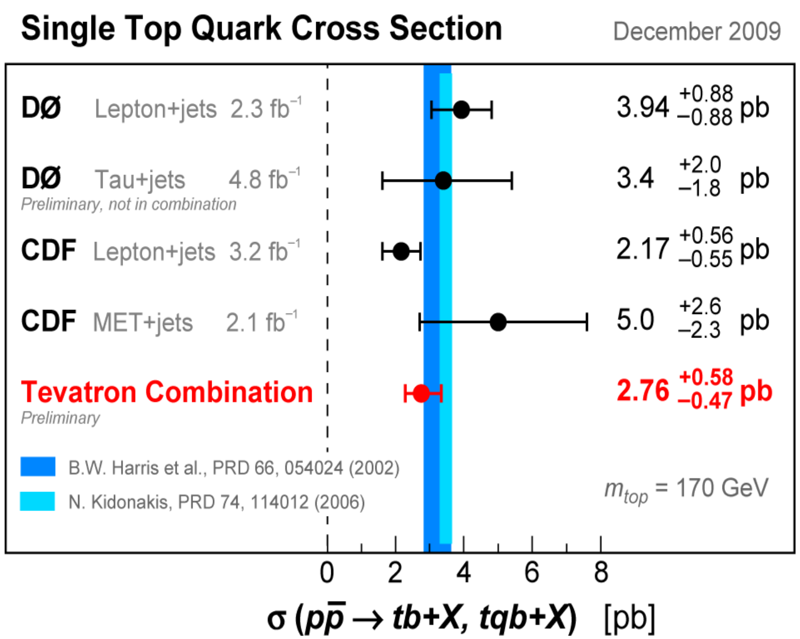


- CDF and DØ observe single top with 5 SD
- Compatible at 1.6 SD with each other
- Combined result (mt=170GeV):

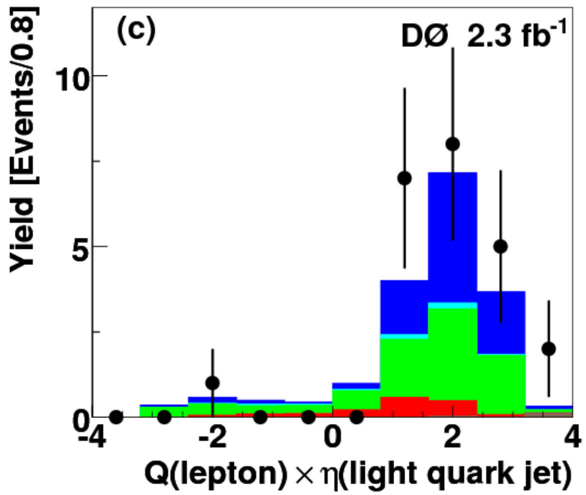
$$\sigma(s+t) = 2.8^{+0.6}_{-0.5}\ \text{pb}$$

Single Top Production

Evidence for t-channel only

$\sigma(t) = 3.14^{+0.94}_{-0.80}$ pb

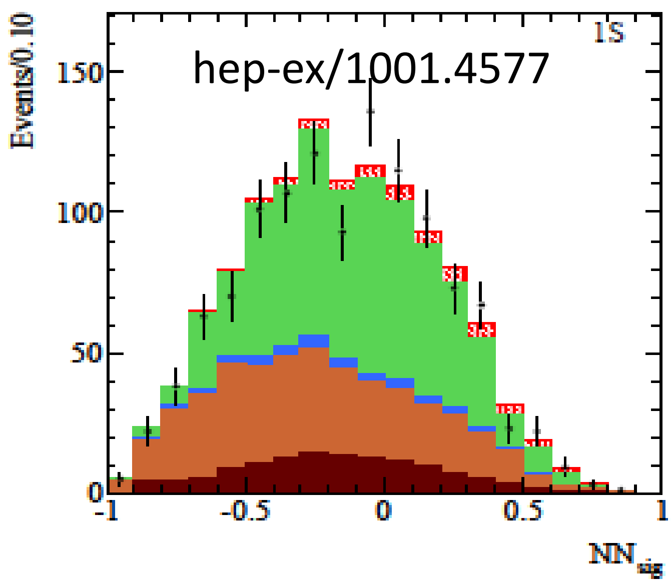
Exp/Obs significance: 3.7/4.8 SD

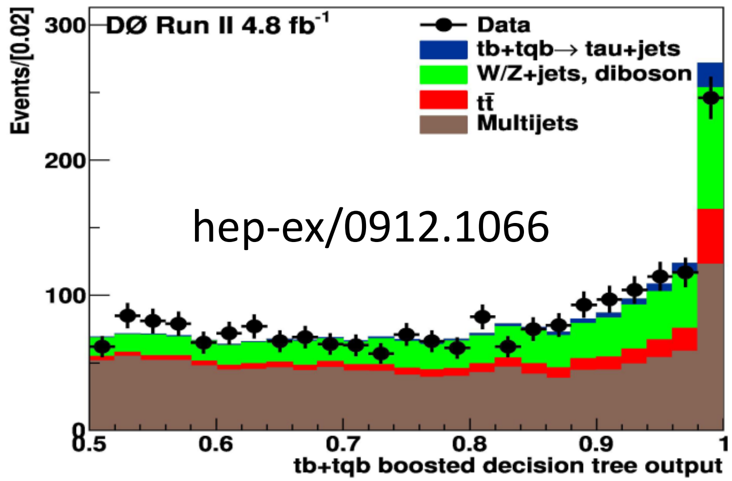


New Channels

- **Reconstructed tau decays (DØ 4.8 fb^{-1})**

$\sigma(s+t) = 3.4^{+2.0}_{-1.8}$ pb Exp/Obs sig: 1.8/1.9 SD





- **Taus from MET+jets sample (CDF 2.1 fb^{-1})**

$\sigma(s+t) = 4.9^{+2.5}_{-2.2}$ pb Exp/Obs sig: 1.4/2.1SD

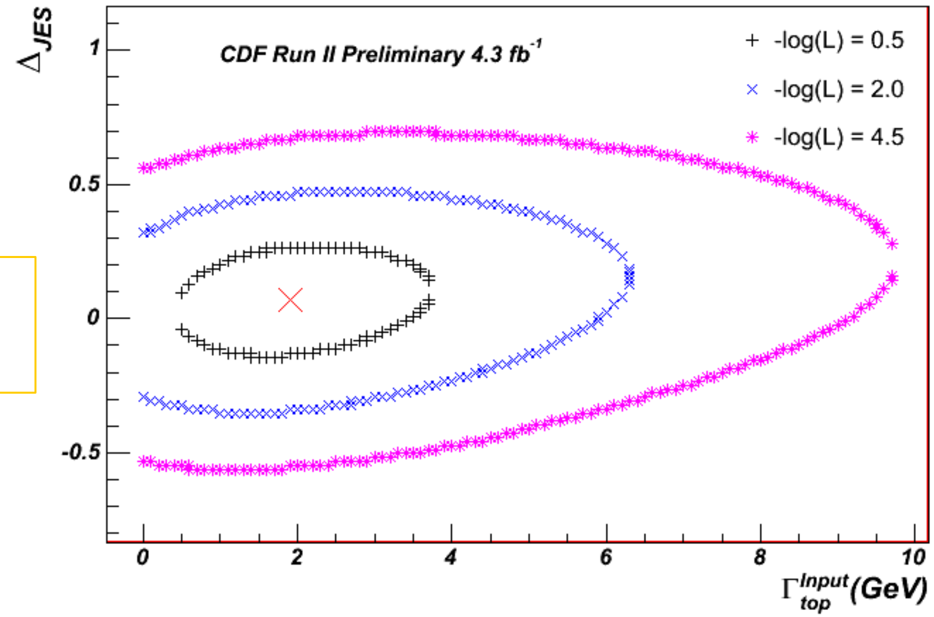
Top Quark Width

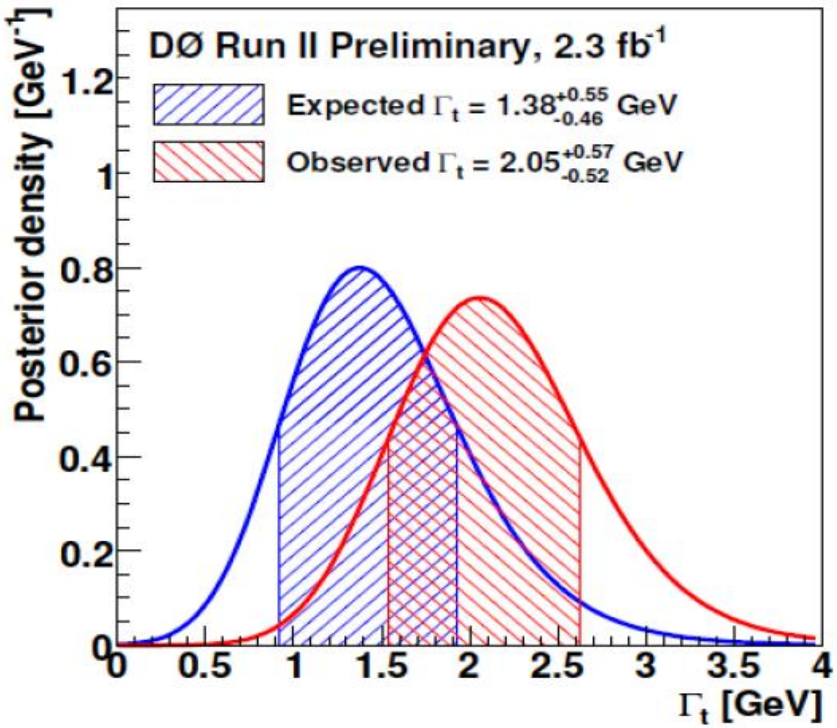
Template based top width measurement

- Lepton+Jets with 4.3fb^{-1}
- Upper limit placed on top width
- SM predicts ~1.5 GeV (Mt = 175 GeV/c

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

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





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

$$\Gamma_t = 2.05^{+0.57}_{-0.52} \text{ GeV}$$

$$\tau_t = (3.2^{+1.1}_{-0.7}) \times 10^{-25} \text{ s}$$

"God" Particle or "God Damned" Particle

"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."**

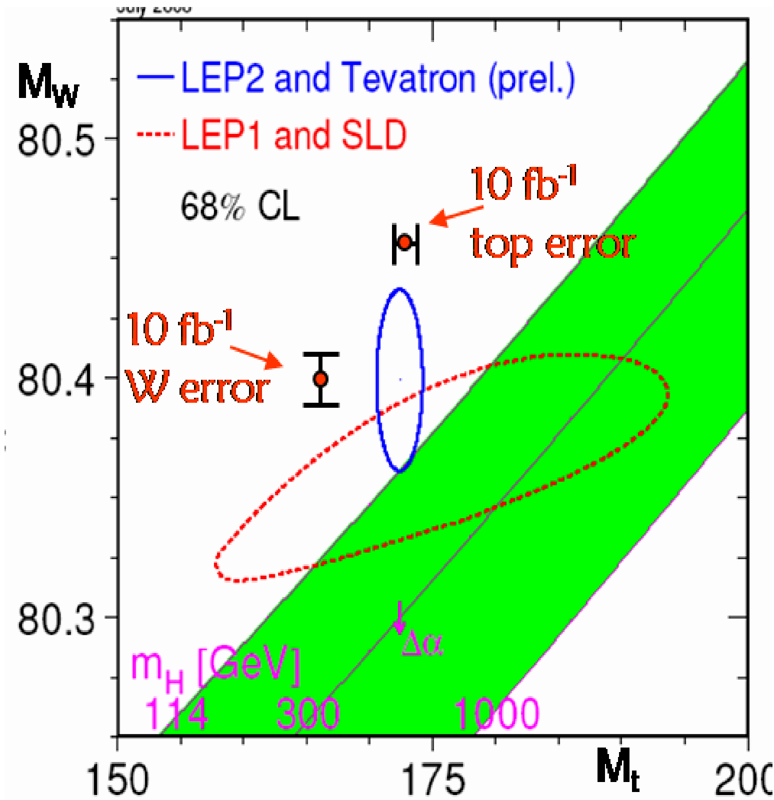
- In case you hadn’t noticed, we theorists have been going a bit crazy waiting for THE Higgs.

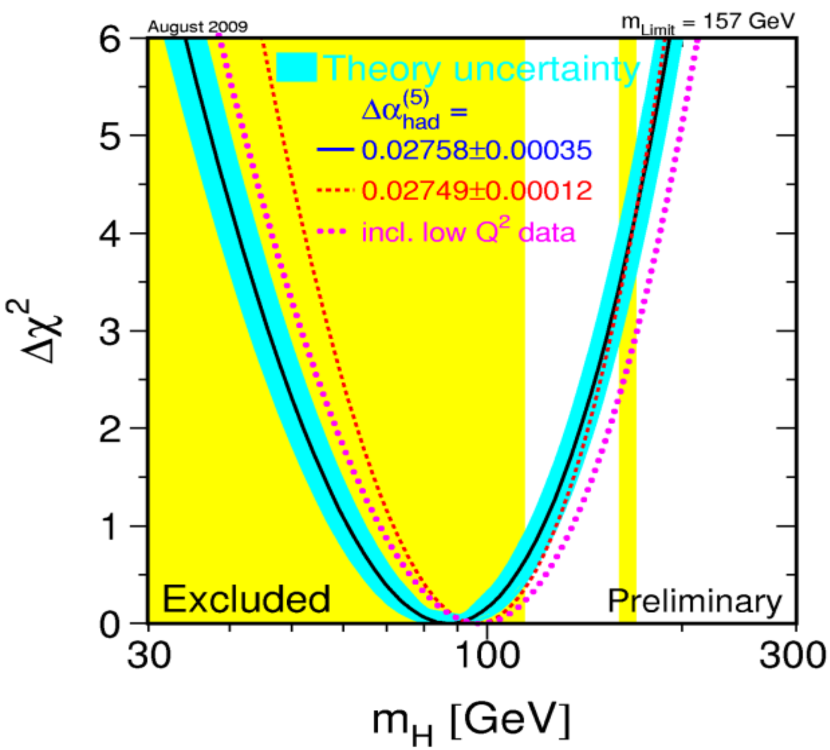
- ”Unfortunately”, a lot of the theories developed make sense, but I remain enamored of the NMSSM scenarios and hope for eventual verification that nature has chosen ”wisely”.

John Gunion

Higgs - Indirect Constraints

- The Higgs mass is the single remaining unknown in the SM.
- The mass of the SM Higgs boson is now restricted to a small range of values by the data
  - Constraints on Higgs mass: 114 GeV <H_{mass}< 185GeV



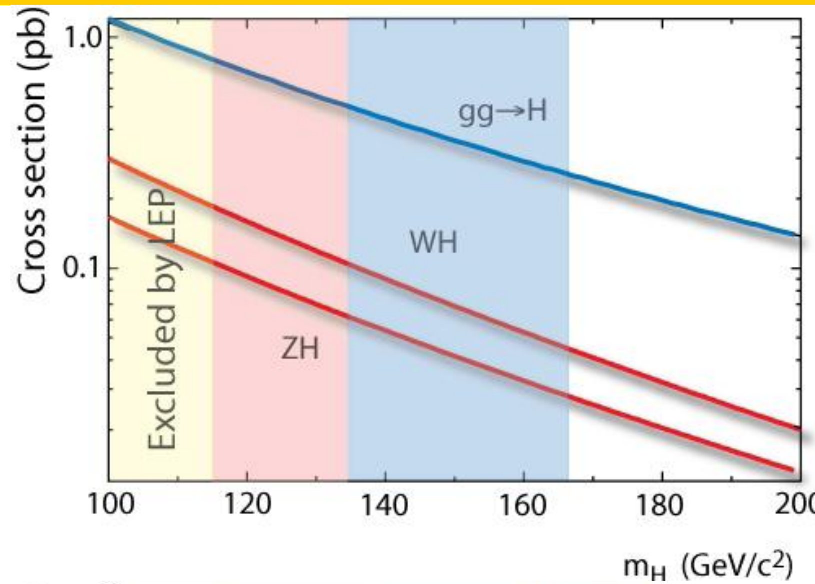


At the Tevatron, ~100 individual analyses with different final states, selections are searched and combined.

Higgs at The Tevatron

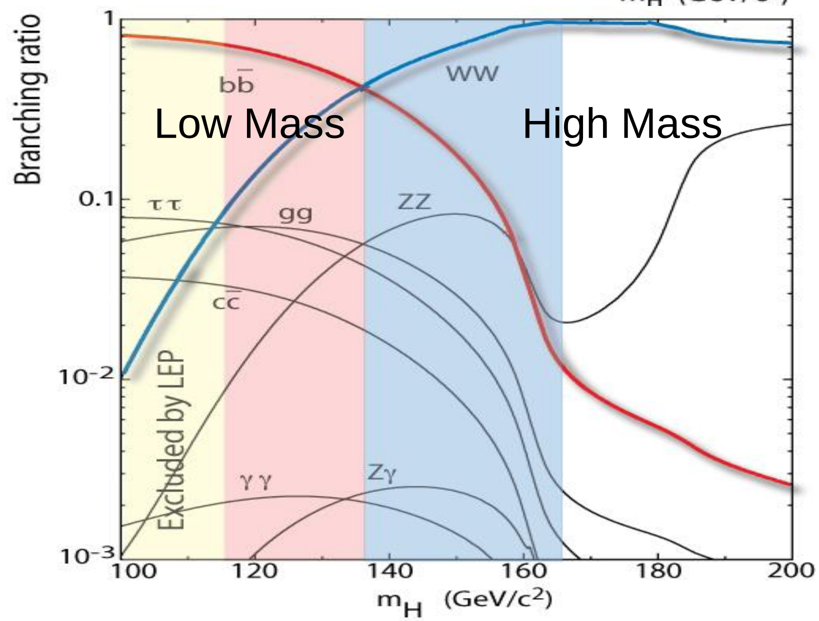
Production

- Higgs production via gluon fusion dominates at the Tevatron
- Large multijet background makes fully hadronic searches difficult
- Next largest rate is associated production of W/Z bosons + Higgs
- Leptonic decays of W/Z bosons provide a tag for triggering and analysis



Decay

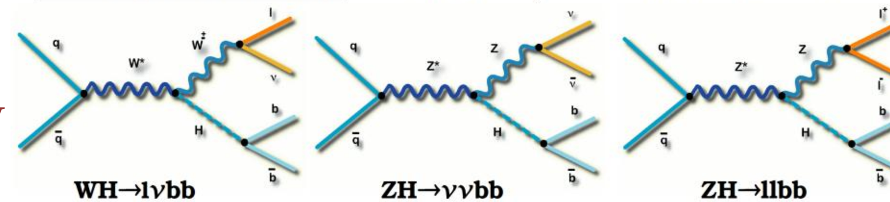
- Lowmass Higgs (MH<135 GeV)
  - Prefers to decay to bottom quark pairs
  - Need efficient identification of bottom quarks to reduce backgrounds
- High mass (MH>135 GeV)
  - Search for H→WW*
  - Potential for an offshell W boson allows nonresonant production

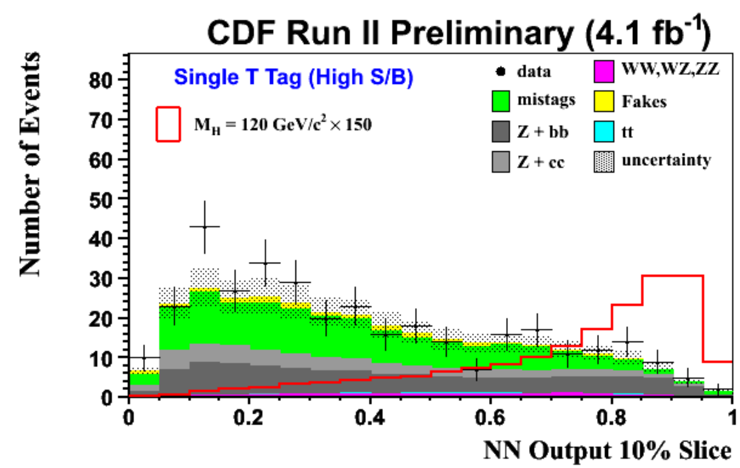


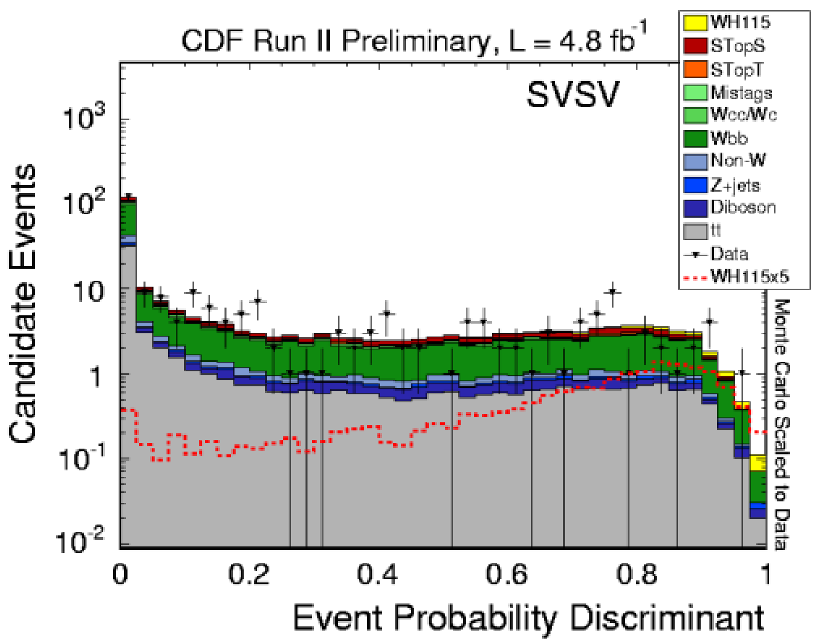
Low Mass Higgs

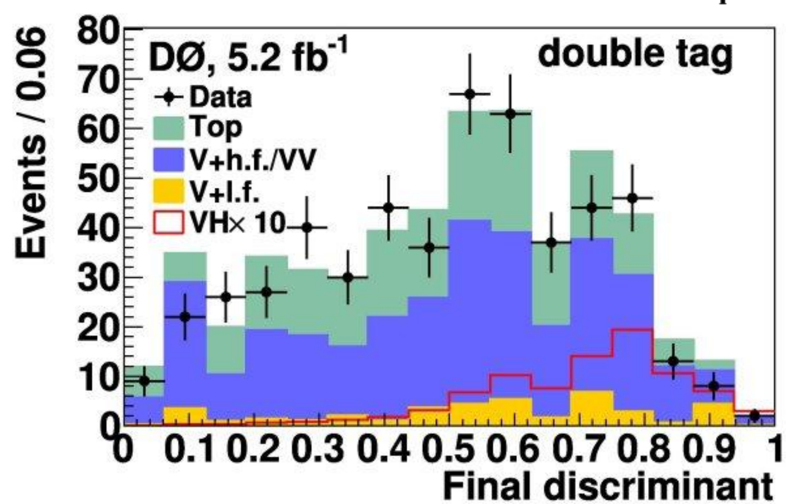
- Background reduction via the identification of displaced jet decay vertices
- Multivariate techniques are used to improve signal to background ratios
- Typical S/B of ~1/10 - 1/50

Associated Production: Low mass only, 3 dominant final states







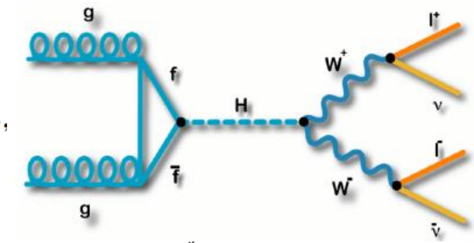


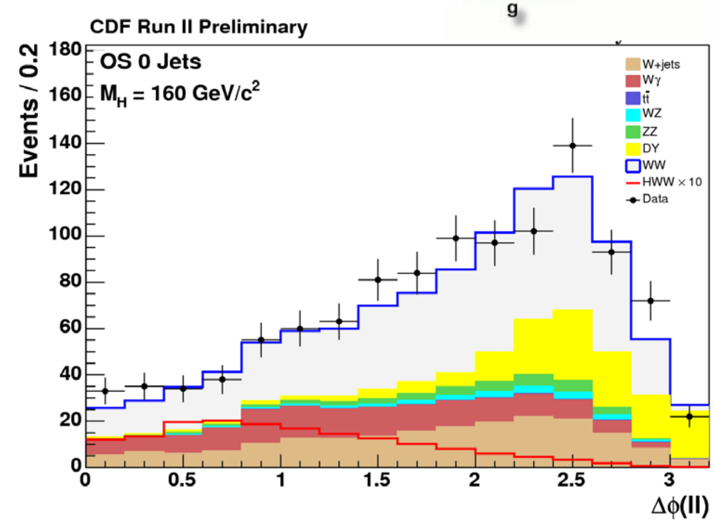
High Mass Higgs

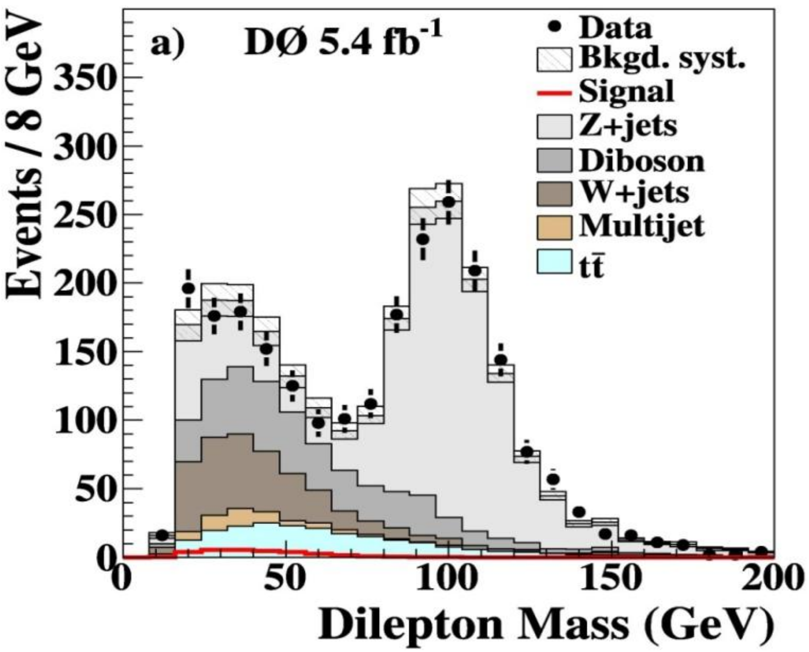
- Signature: two leptons + *MET*
- Exploit kinematic differences (lepton mass, spin correlation)
- Backgrounds: W+jets, WW/WZ production

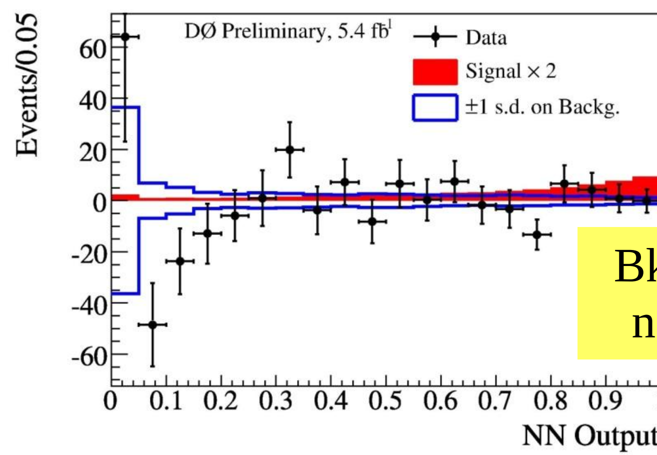
Gluon Fusion Production:

Maximum sensitivity at high mass, also useful at low mass



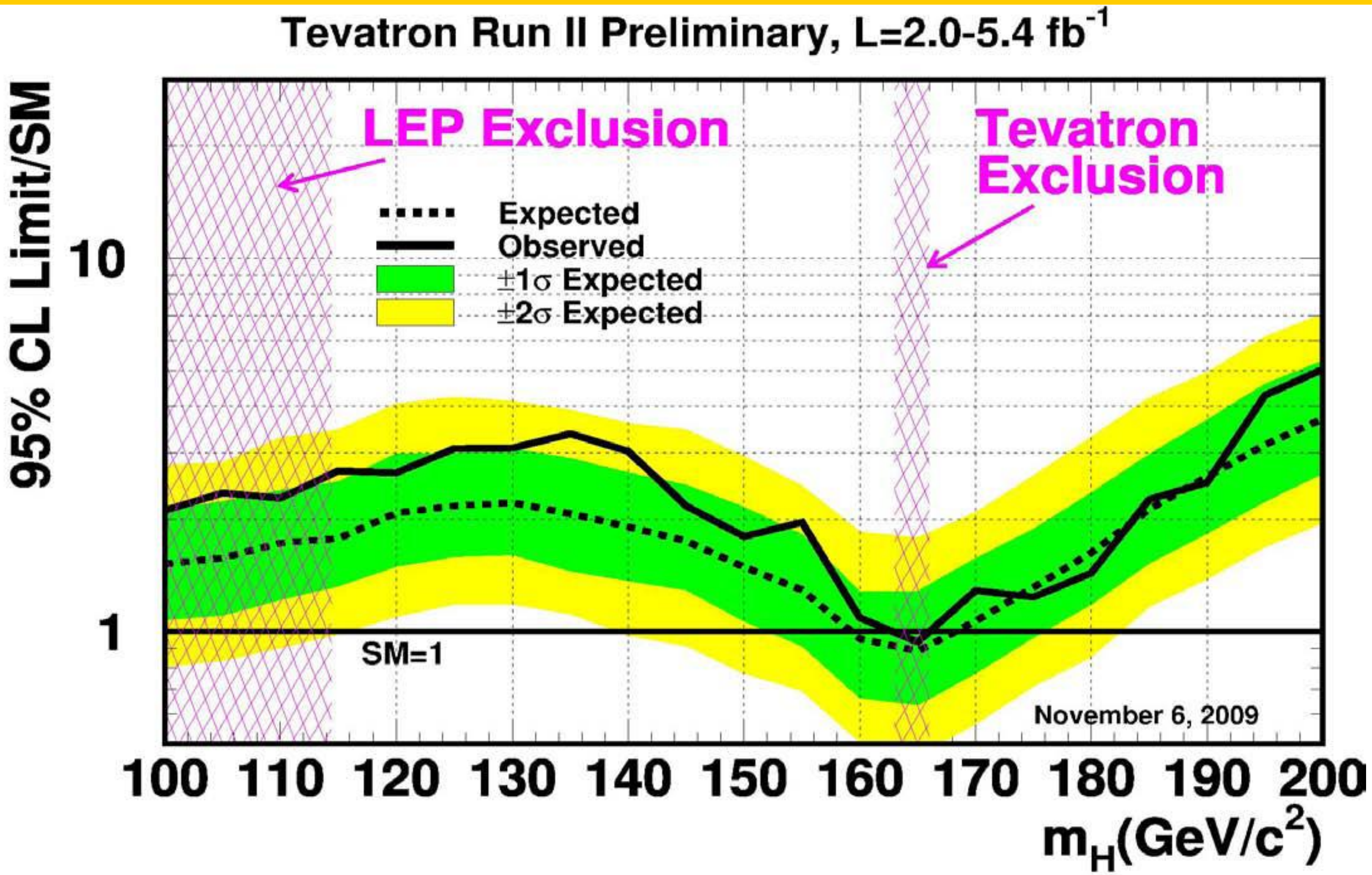






Bkg uncertainty does not wash out signal

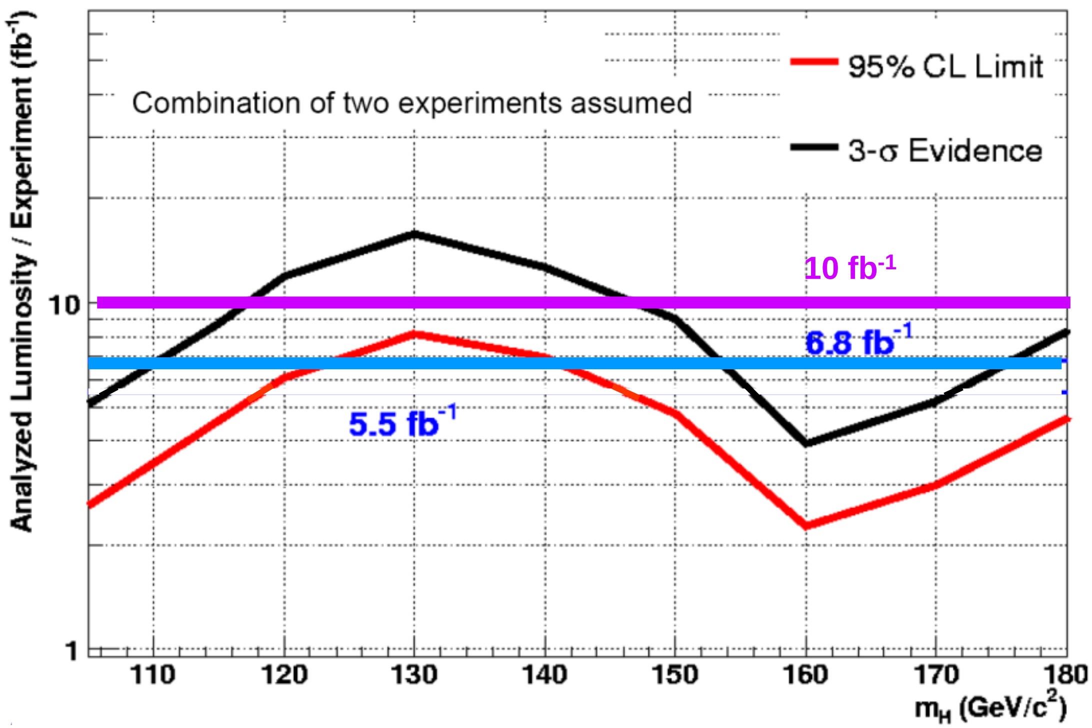
Tevatron Higgs Limits



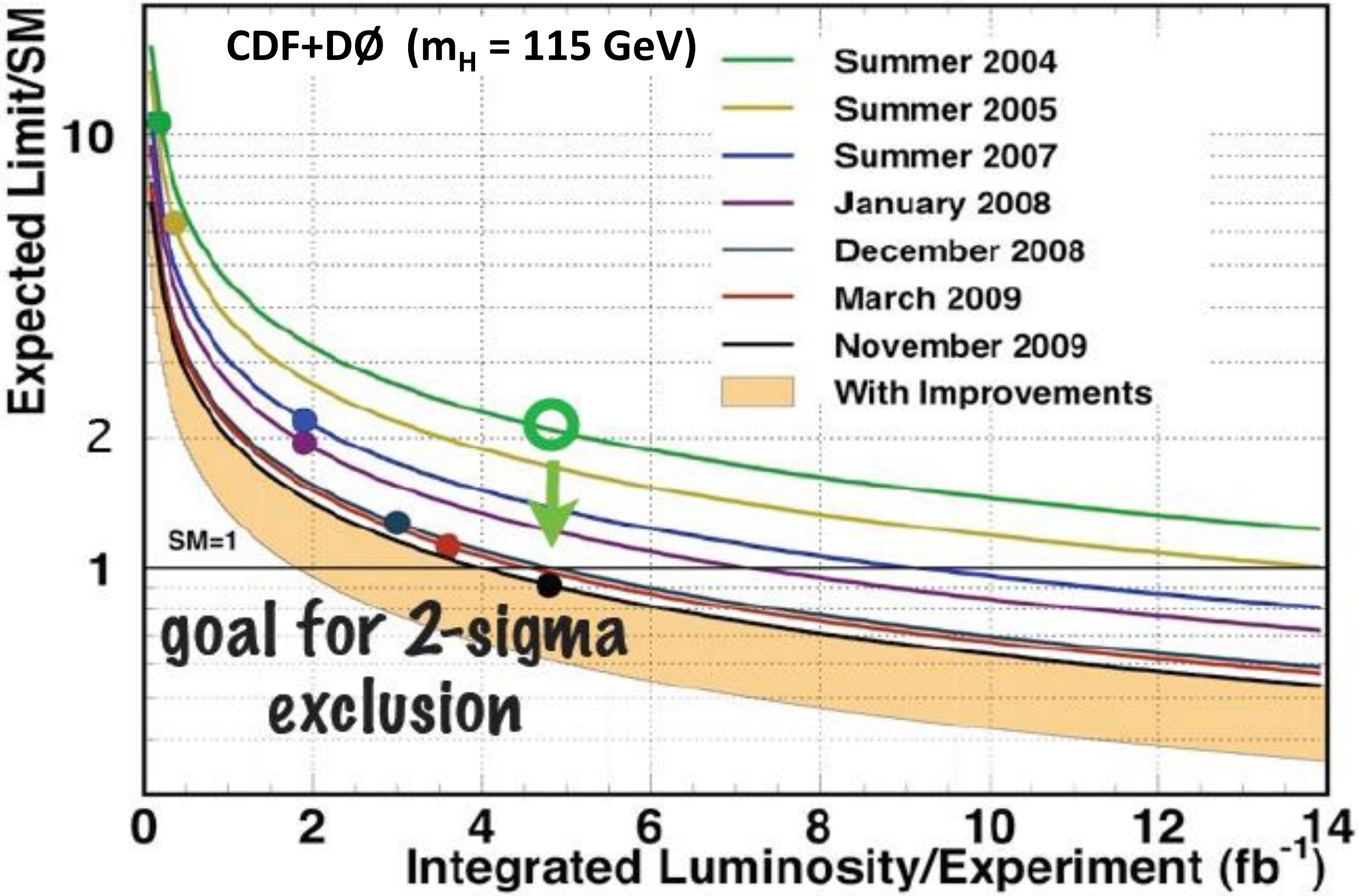
SM Higgs Excluded: m_H = 163-166 GeV

Tevatron Projections

- Tevatron will run through Sep.2011 (beyond 2011?)
  - 10-12 fb^{-1} delivered per experiment translates to ~ 10 fb^{-1} available for analysis. Additional ~2 fb^{-1} per extended year



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



…and we might do better than our projections!

Summary

- The 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. It still has a critical role to play in the Higgs story.

Tevatron could exclude or discover Higgs in the entire mass range favored by the electroweak fits

Tevatron has already shown how "almost impossible" can be made possible!

- May be some hint of new physics?(only part of data delivered has been analysed yet)

While I wish our friends at the LHC the best of luck and eagerly look forward to uncovering the greatest secrets of nature, I remind you that the Tevatron's legacy is still being written

- It is a great time to be a physicist
- We had two revolutions at the turn of last century – these revolutions changed the way we look at our universe
- There are again many questions unanswered and hints will come from experiments
- With Tevatron collecting data rapidly, LHC finally coming online and many other experiments from under ground to outer space are giving me hope that revolution is in the air

Good luck to us all!!!!