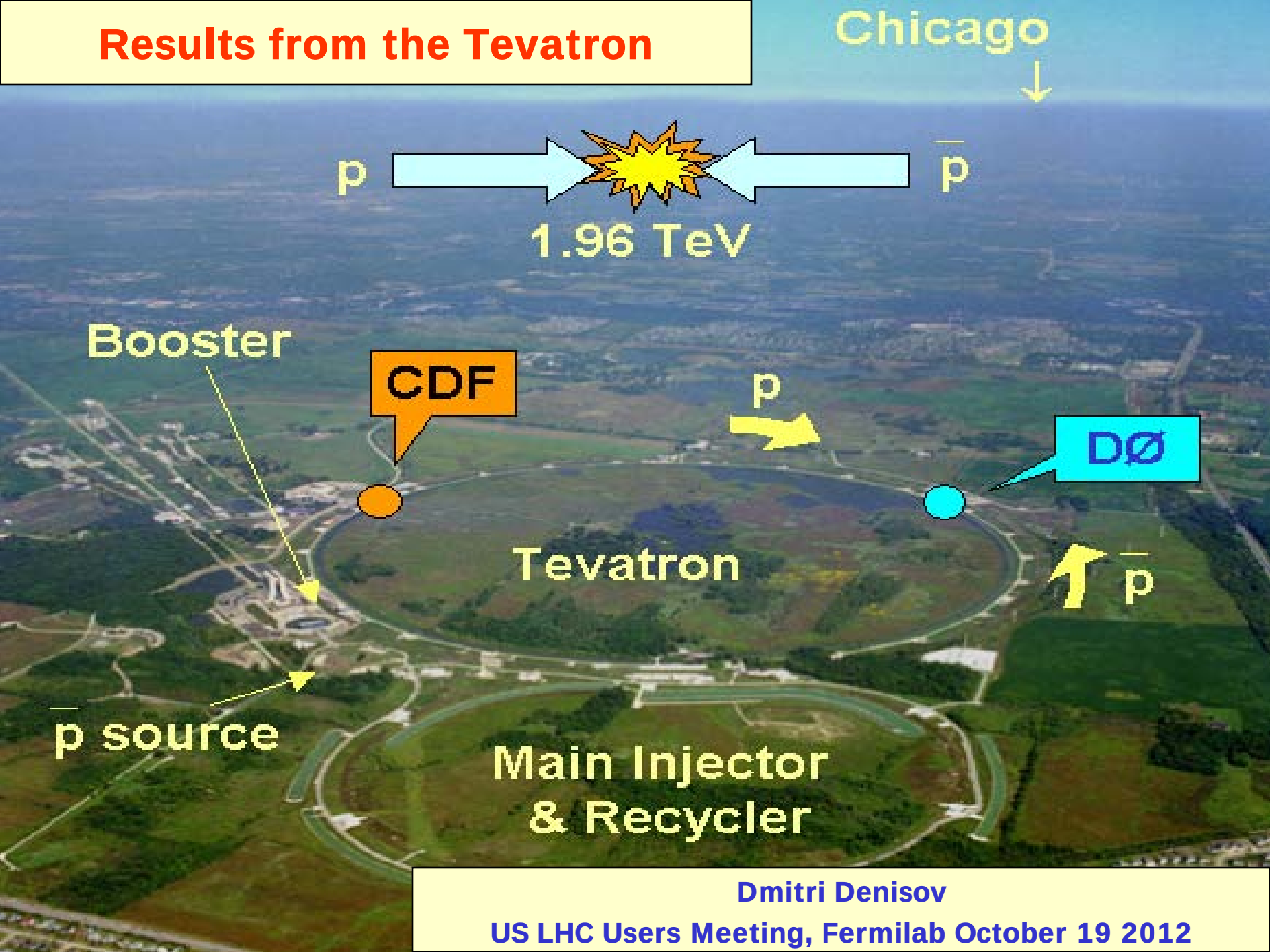
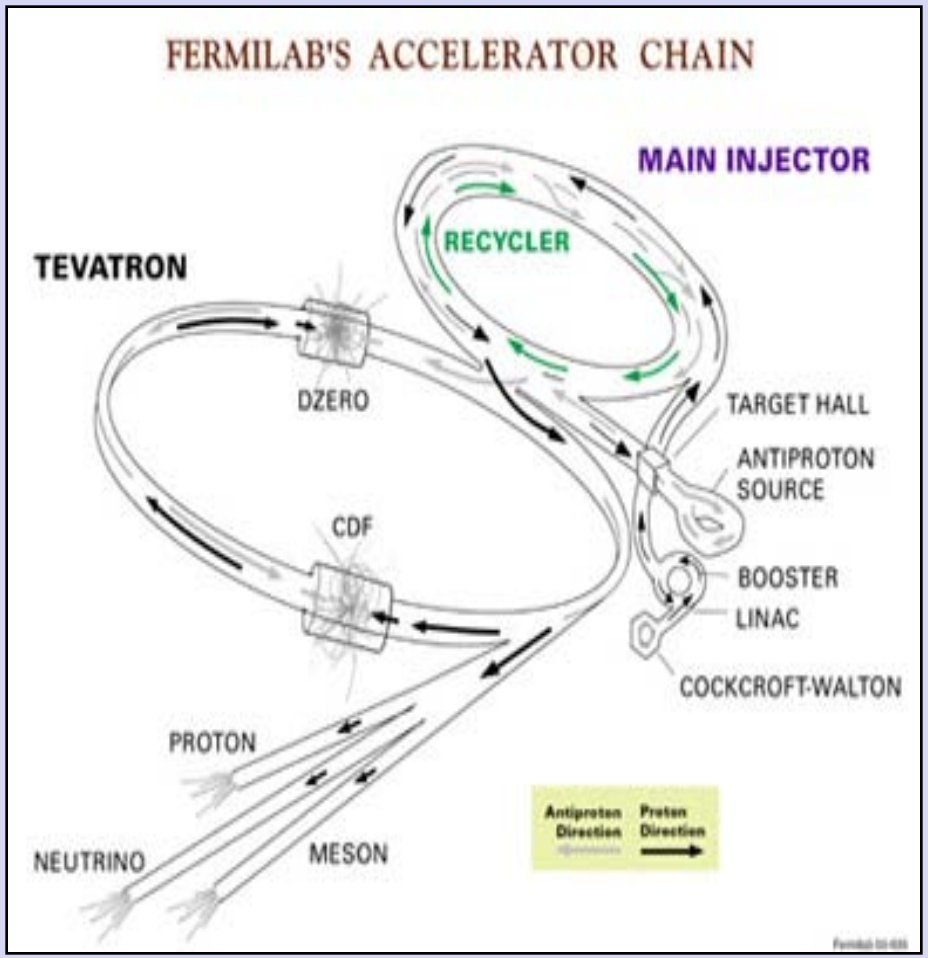
Results from the Tevatron



Dmitri Denisov

US LHC Users Meeting, Fermilab October 19 2012

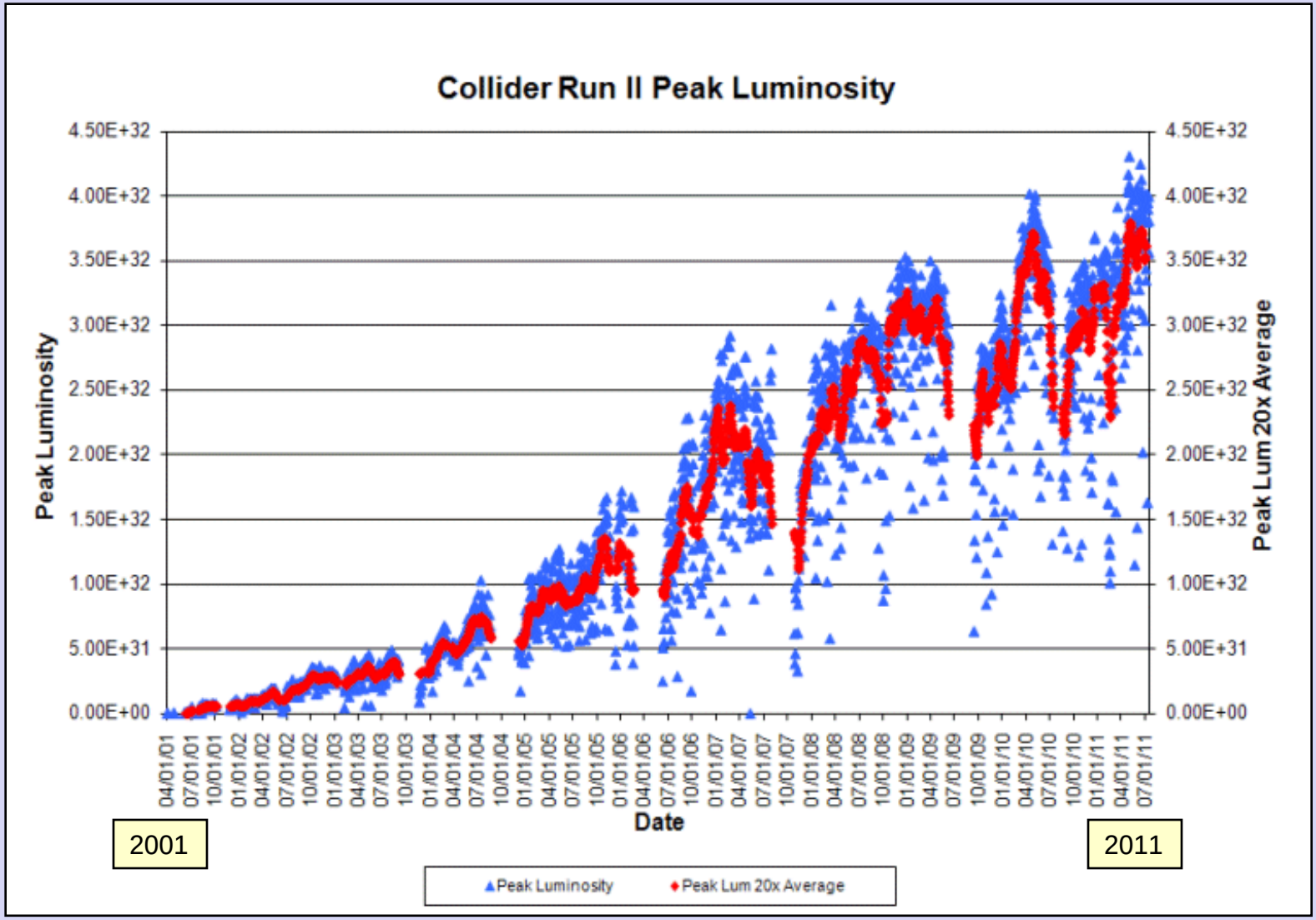
Tevatron: Proton-antiproton Collider



	Run I 1992-1996	Run IIa 2001-2006	Run IIb 2006-2011
Bunches in Turn	6 x 6	36 x 36	36 x36
√s (TeV)	1.8	1.96	1.96
Typical L ($cm^{-2}s^{-1}$)	1.6×10^{30}	9×10^{31}	3×10^{32}
∫ Ldt (pb^{-1}/week)	3	17	50
Bunch crossing (ns)	3500	396	396
Interactions/crossing	2.5	2.3	8
	Run I → 0.1 fb^{-1}	Run IIa → ~1 fb^{-1}	Run IIb ~12 fb^{-1}

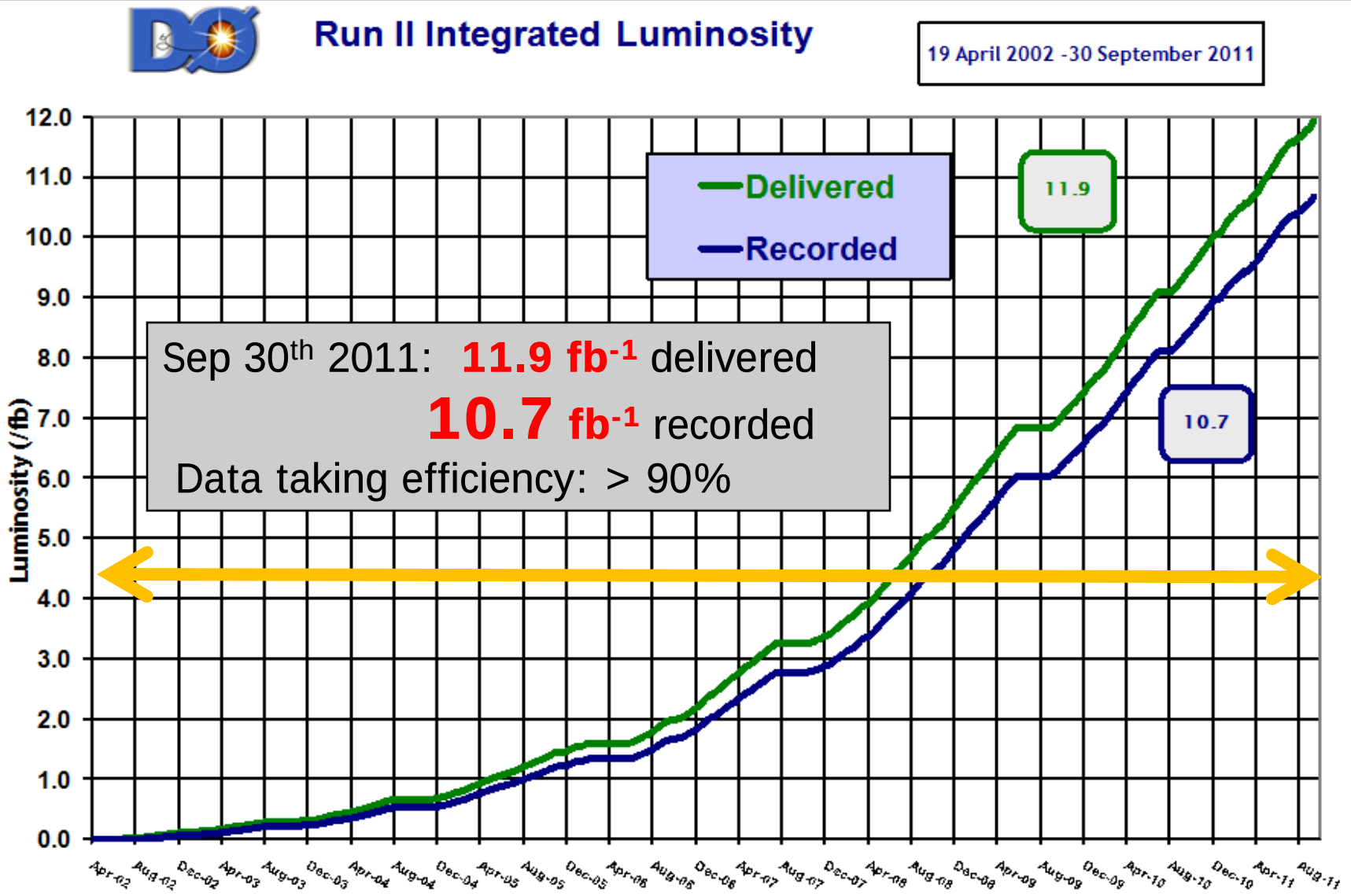
- **Chain of six accelerators to get to 1 TeV per beam energy**
- **Single magnet ring – protons and antiprotons circulate in the opposite directions**
- **Elaborate source of antiprotons – main driver of the Tevatron luminosity**
- **Beam particles wavelength of ~10^{-16} cm**

Peak Luminosity vs Time



- **Improvements to antiproton production and cooling increased Tevatron peak luminosity**
- **Very high reliability: ~80% of ~24 hours stores were ended by planned termination**
- **Average number of interactions per crossing is ~12 peak and ~6 average in 2011**

Tevatron Data Set



- **Total data set is ~5 times above original Tevatron Run II goal**
- **Detectors and accelerator components operated well till last store on September 30, 2011**

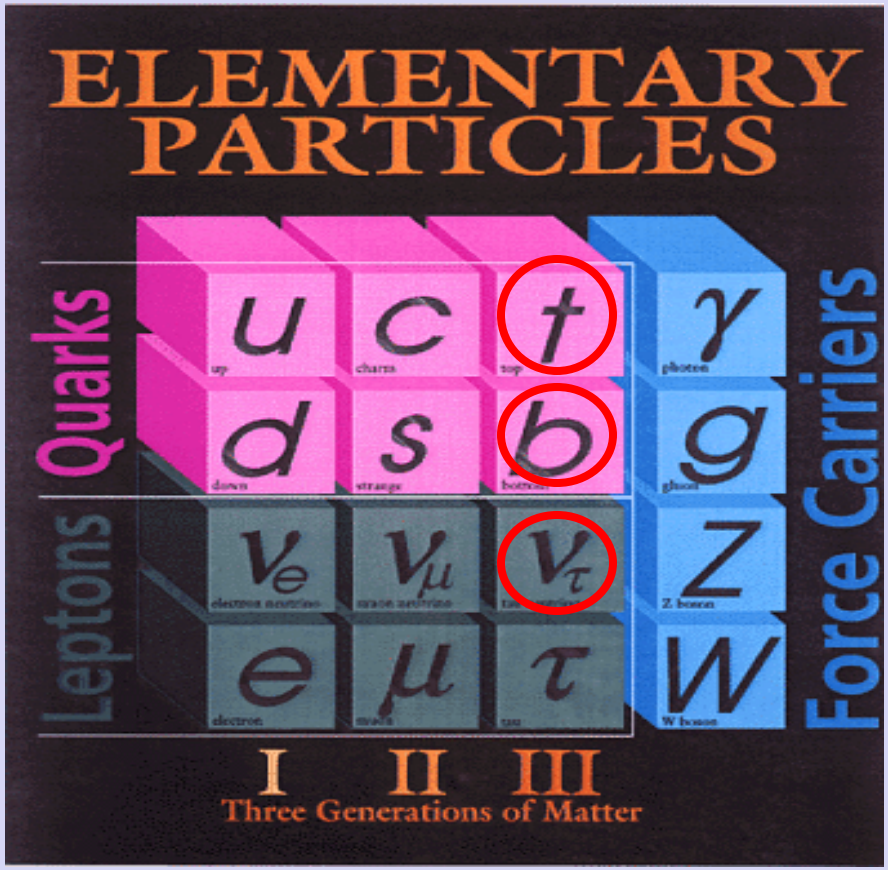
Tevatron Physics Program

Precision tests of the Standard Model

- Weak bosons, top quark, QCD, B-physics…

Search for particles and forces beyond those known

- Higgs, supersymmetry, extra dimensions…



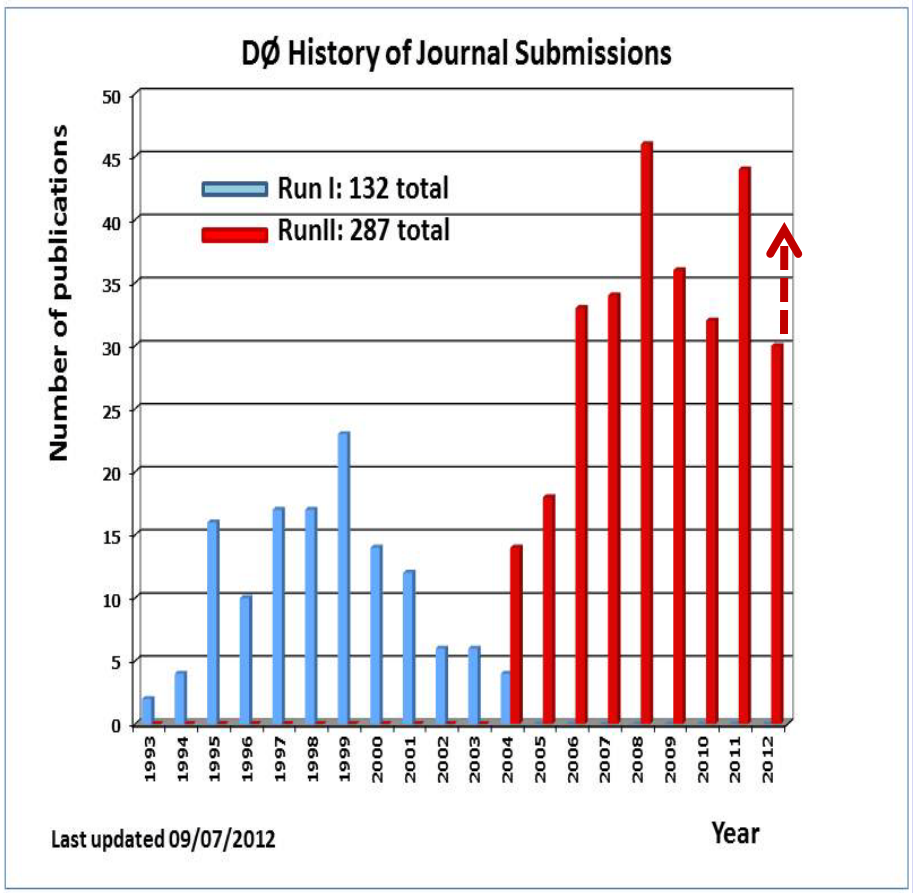
Fundamental Questions

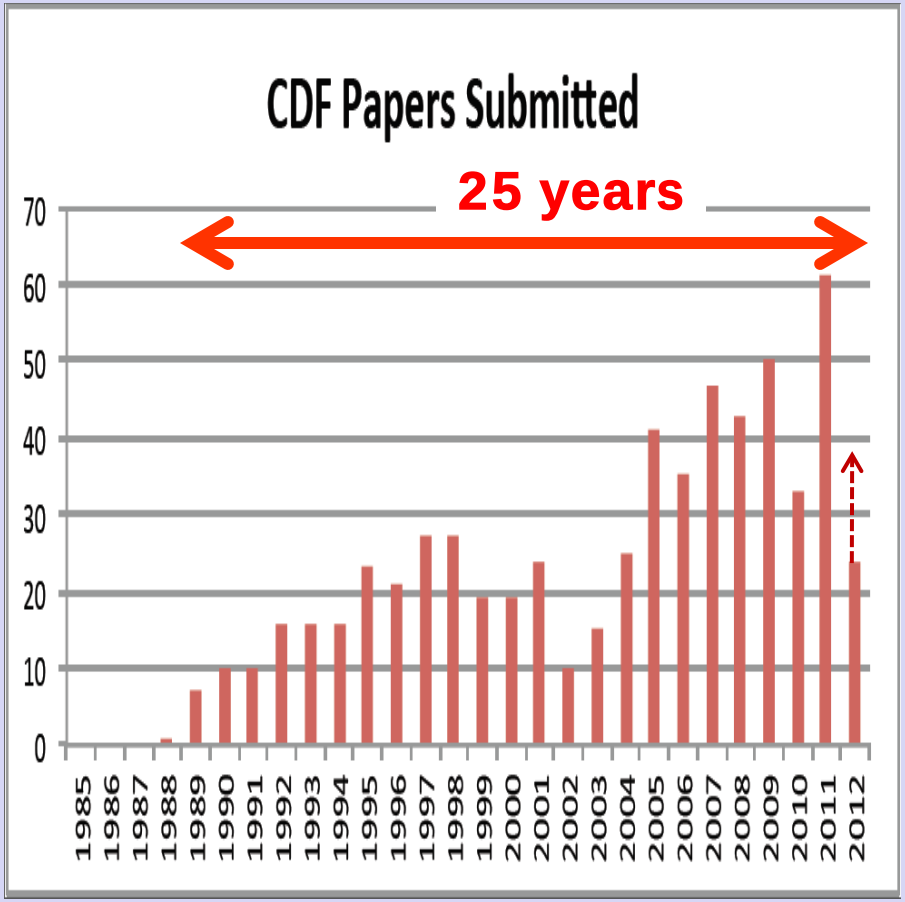
- ✓ Quark sub-structure?
- ✓ Origin of mass? Higgs?
- ✓ Matter-antimatter asymmetry?
- ✓ What is cosmic dark matter?
  SUSY?
- ✓ What is space-time structure?
  Extra dimensions?…

The CDF and DZero Collaborations

Tevatron collaborations are ~1000 scientists from 26 countries

Tevatron Results

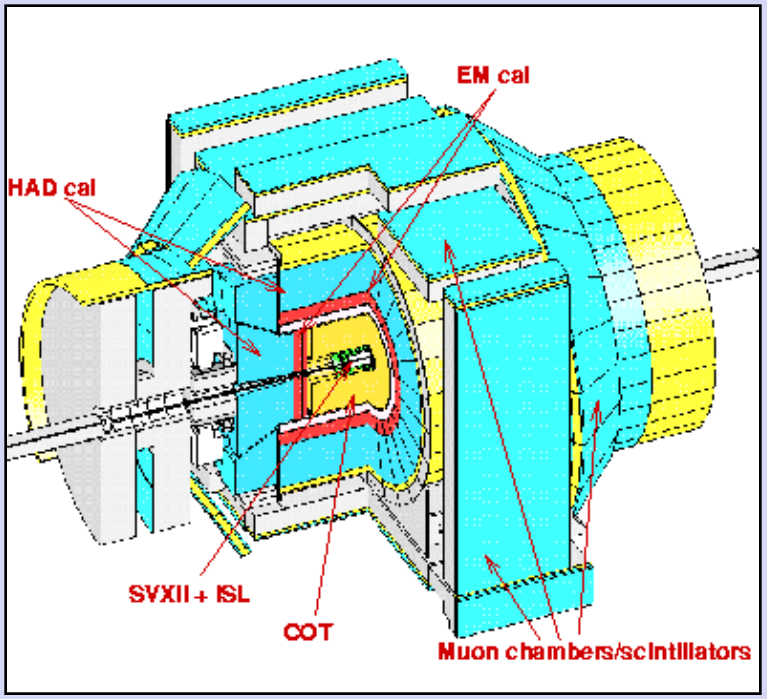




- Over 1000 publications in referenced journals from CDF and DØ
- From discoveries of top quark, new mesons and baryons to extremely precise measurements and searches for new phenomena
- ~100 new results over last year – visit CDF and DZero Web pages
  - Only few highlights in this talk

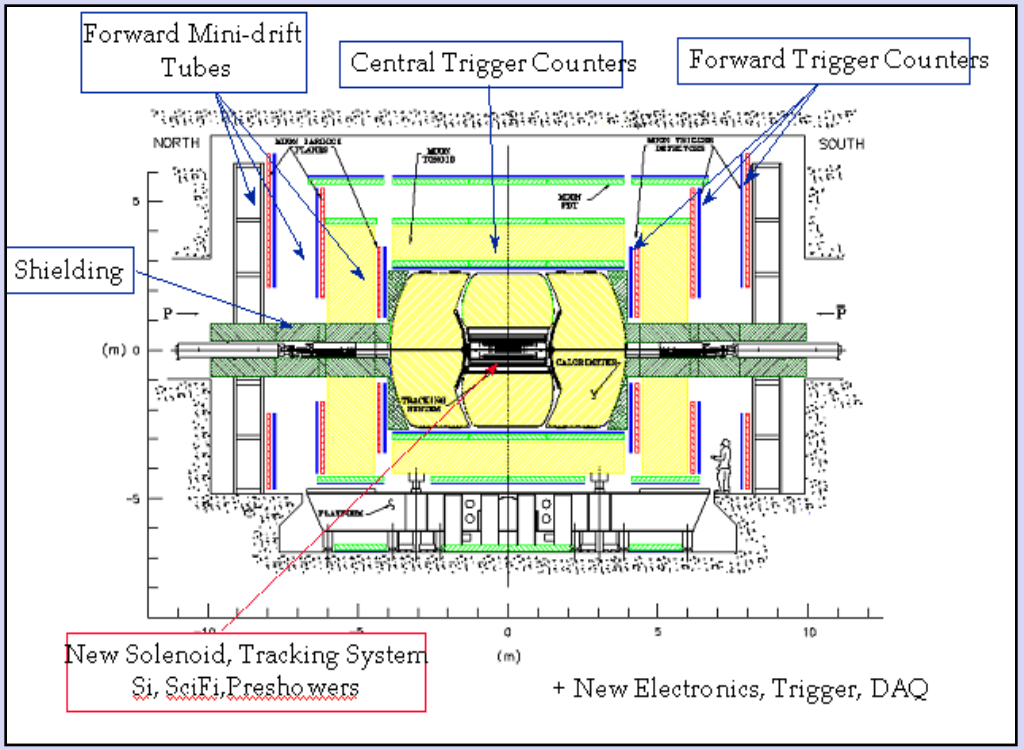
CDF and DØ Detectors

CDF



Silicon Detector
Central Drift Chamber
Calorimetry
Extended muon coverage
Fast electronics

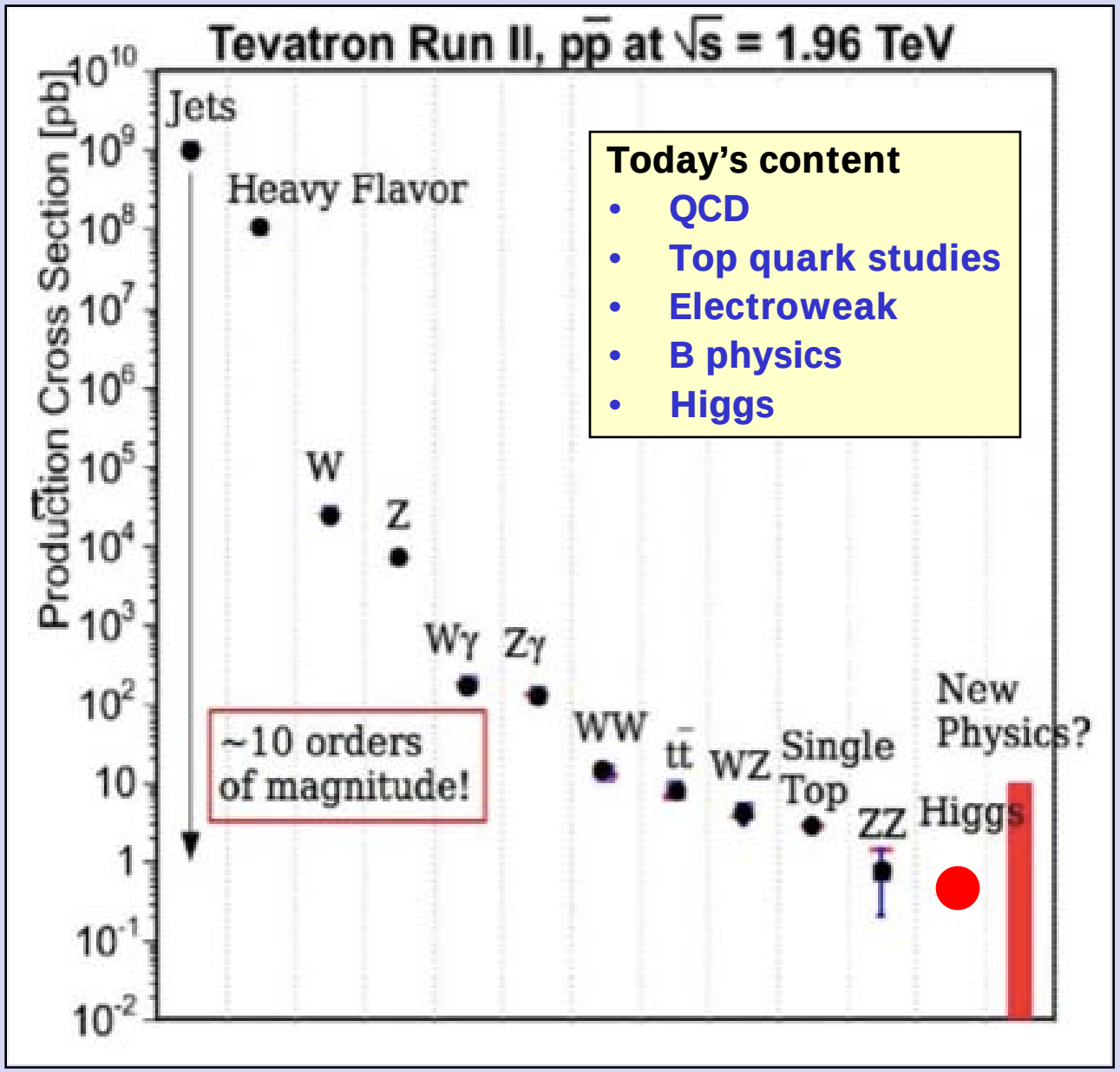
DØ



Silicon Detector
2 T solenoid and central fiber tracker
Large coverage muon system
Fast electronics

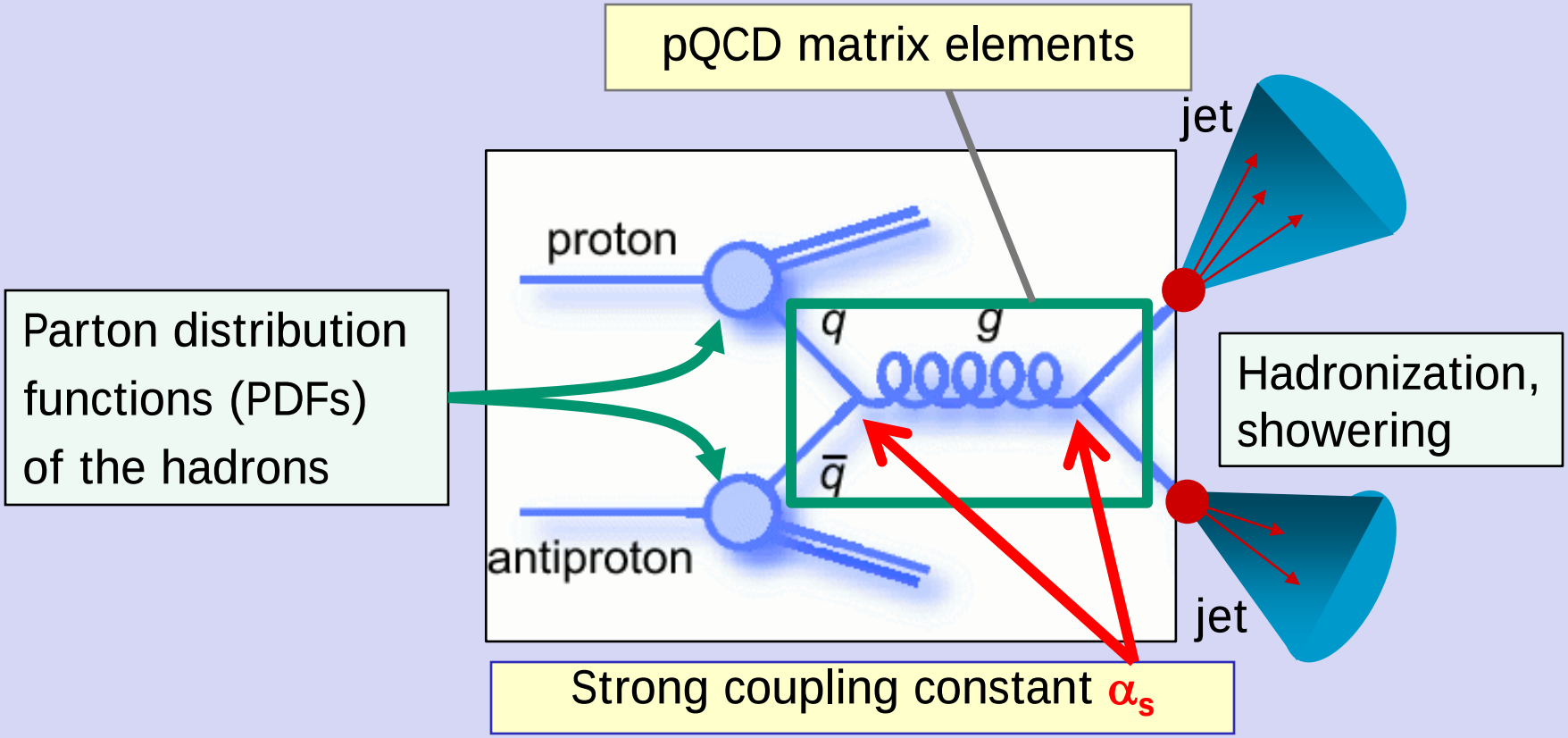
Driven by physics goals detectors are rather "similar":
silicon, central magnetic field, hermetic calorimetry and muon systems

Tevatron Cross Sections



QCD physics

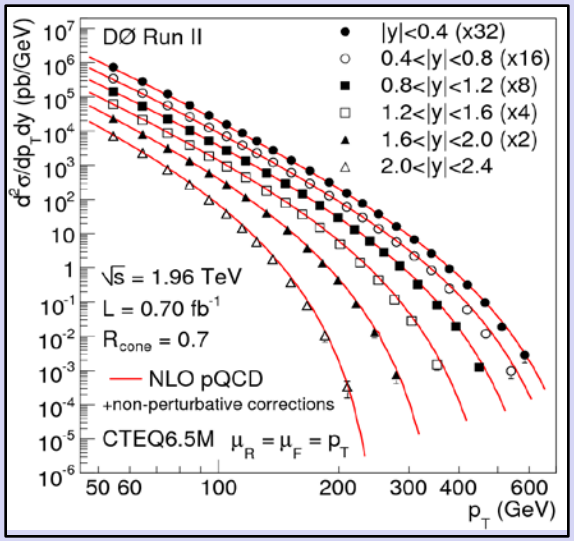
The most copious physics process at hadron colliders



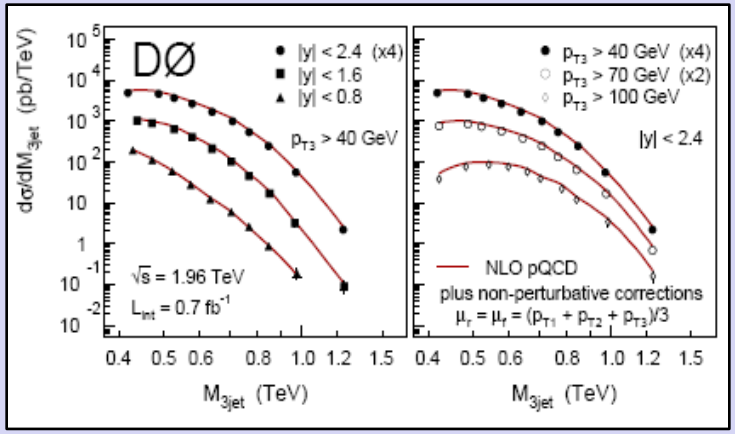
- **PDFs, higher order corrections, α_s measurements, production of vector bosons and jets, direct photons, double parton interactions and many others**
- **Understand how QCD works and to be able to predict backgrounds for processes with much lower cross sections**

Various QCD Measurements

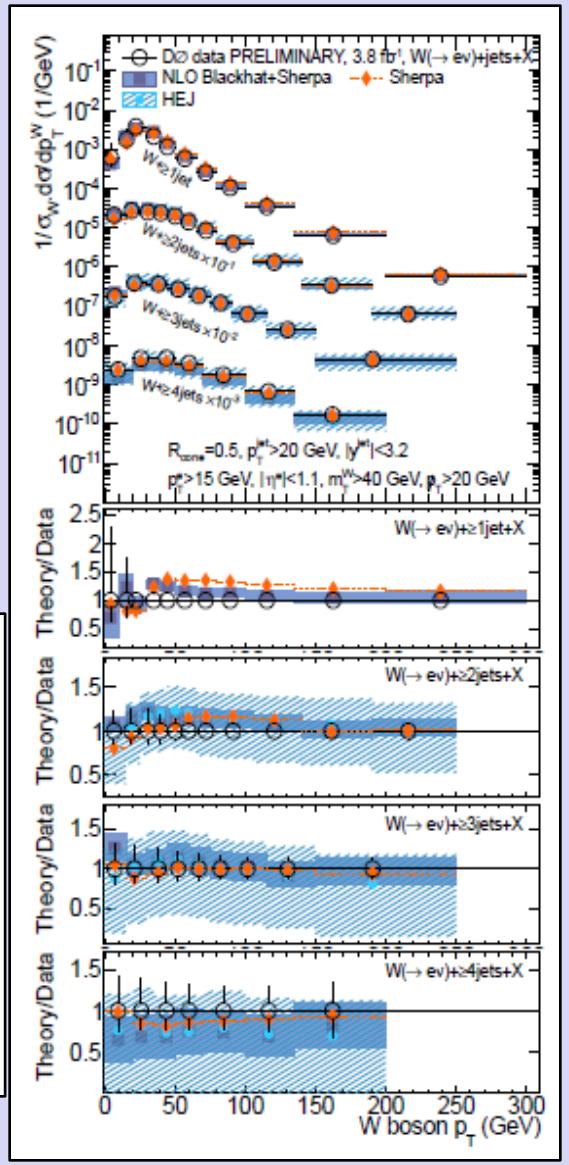
Inclusive Jets



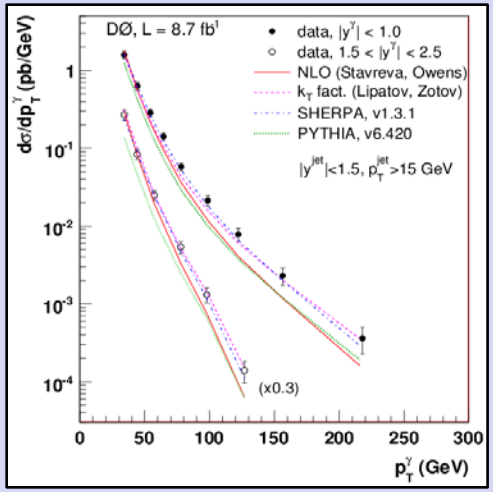
3 jets distributions



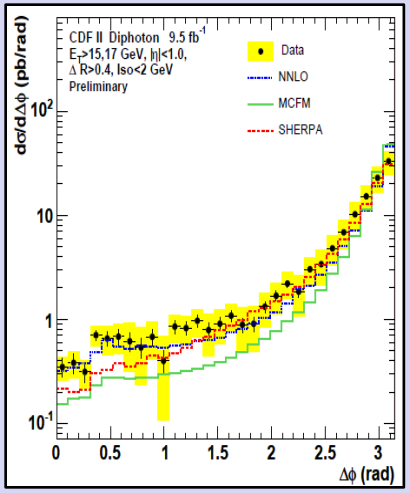
W + jets

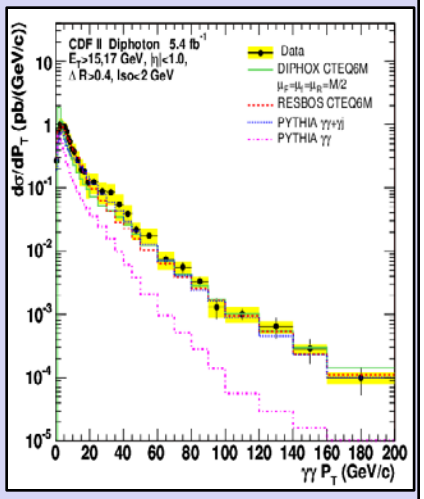


γ + b-jets



Di-photons



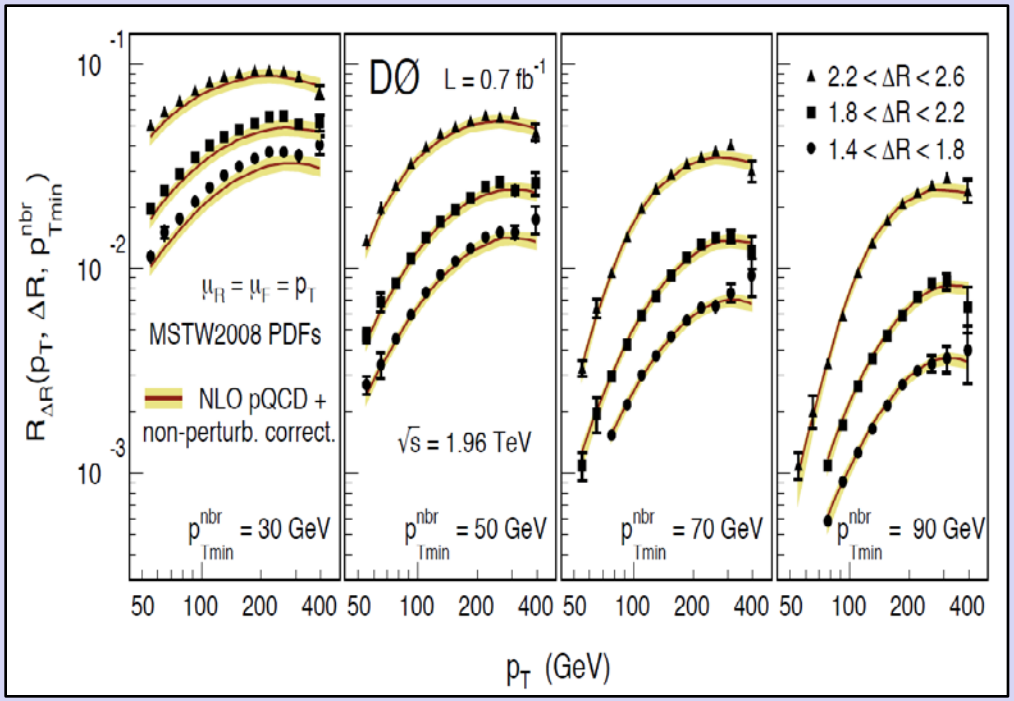


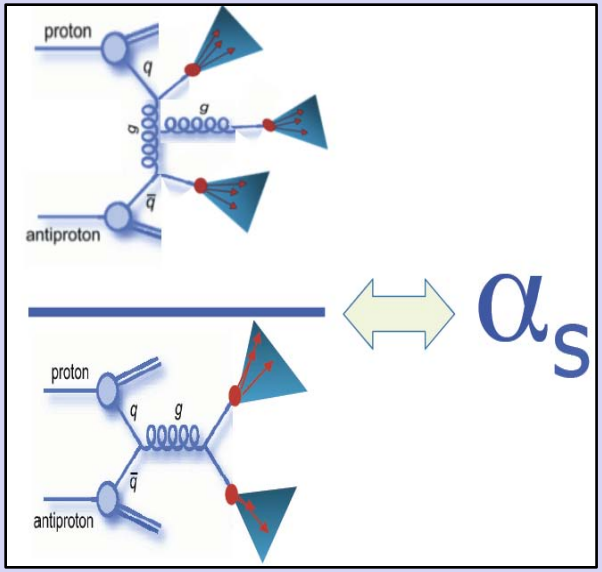
Many important results including models testing

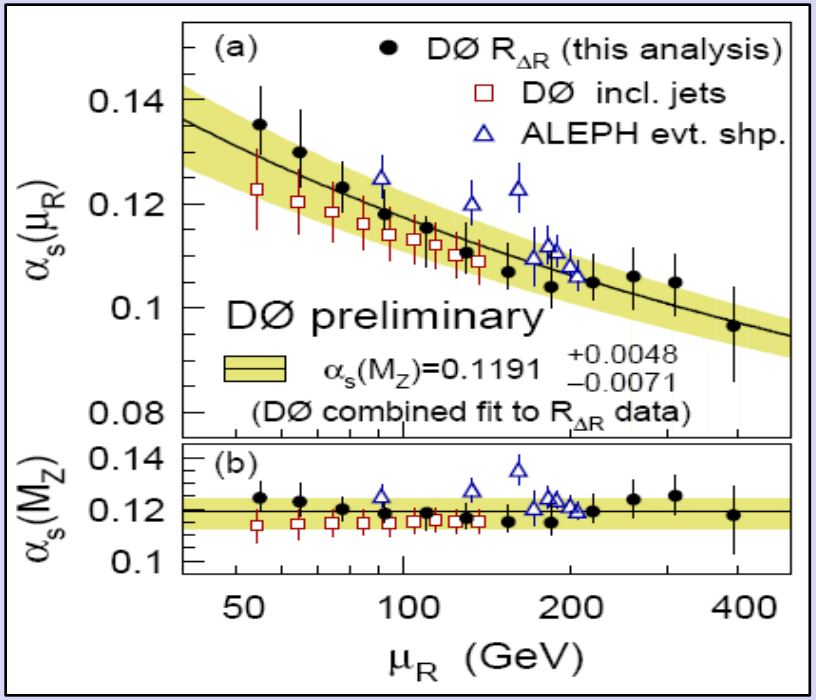
α_s Running at Untested Scale > 208 GeV

- $R_{3/2} = \sigma_{3Jet} / \sigma_{2Jet}$
- **Observable: average number of neighboring jets in ΔR (Δy - $\Delta\phi$ space) region less than π**

$$R_{\Delta R} = N_{jets}(\Delta R) / N_{jets}(all)$$







Confirm strong coupling constant running up to 400 GeV

Top Quark Studies

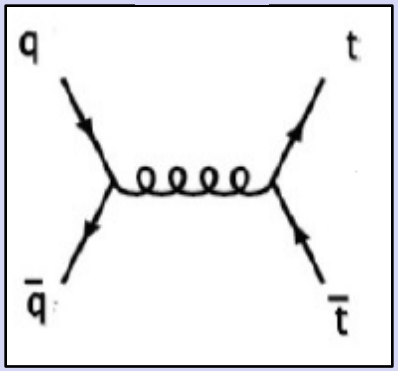
Heaviest known elementary particle: ~173 GeV

→Measure properties of the least known quark

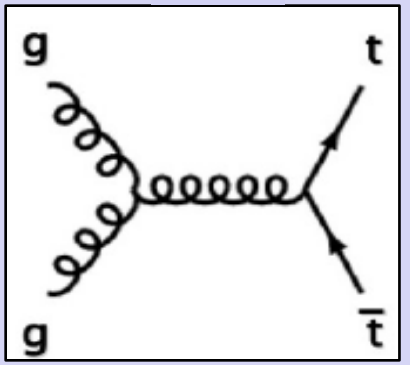
- **mass, charge, decay modes, etc.**
- **data sets of 1000's of top quarks exist**

→ Short life time: probe bare quark

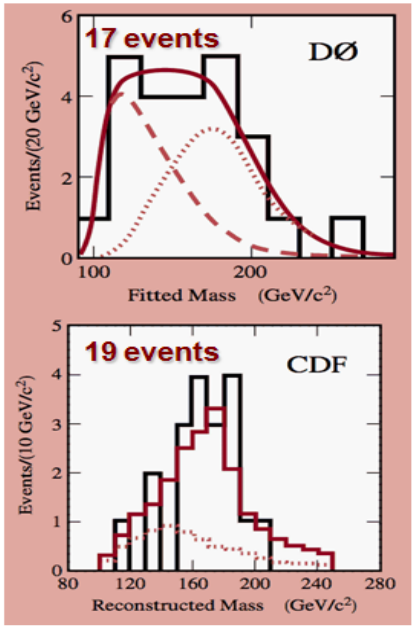
85 %



15 %

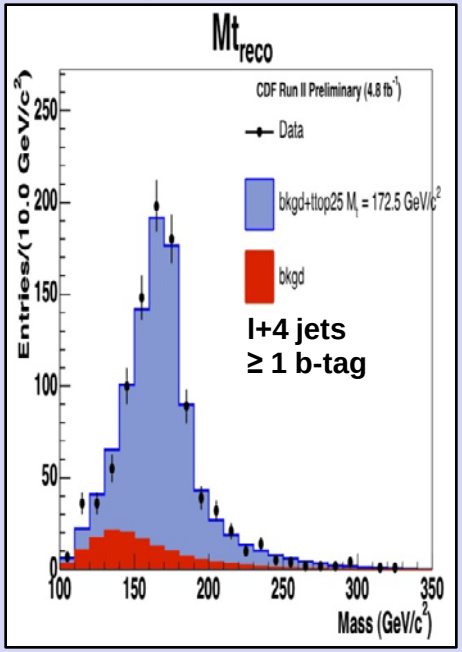


Discovery in 1995

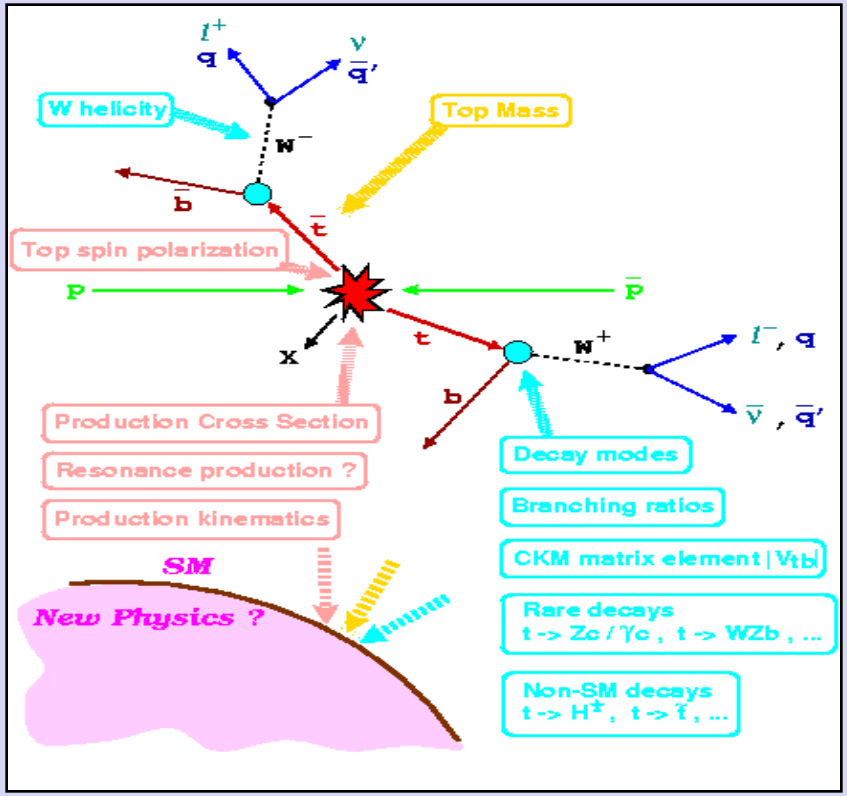


1995, CDF and DØ experiments, Fermilab

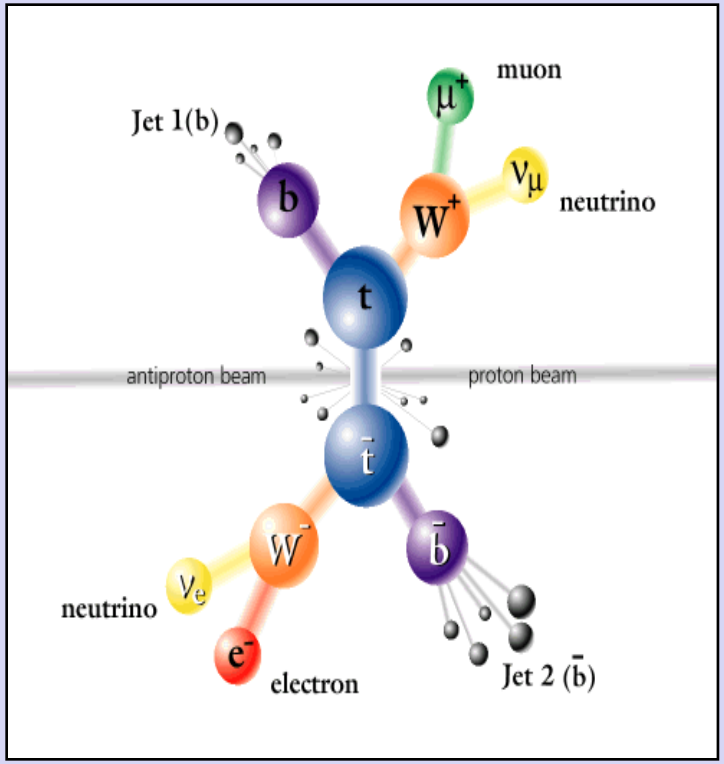
Today
~10,000 events

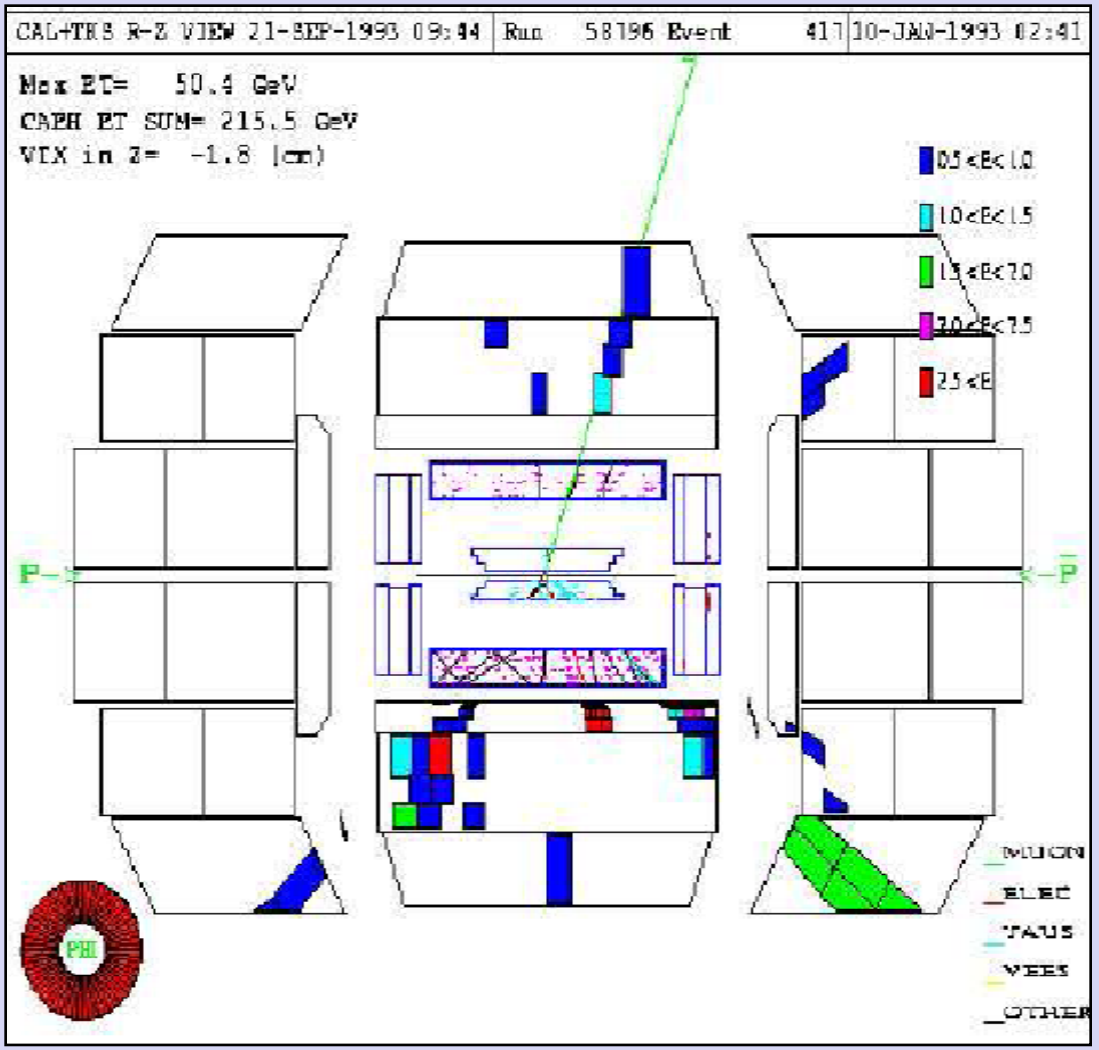


l+4 jets
≥ 1 b-tag



Example: Discovery of the Top Quark





Due to relatively low backgrounds (high top quark mass, pair production) "a few" candidates only required for the discovery

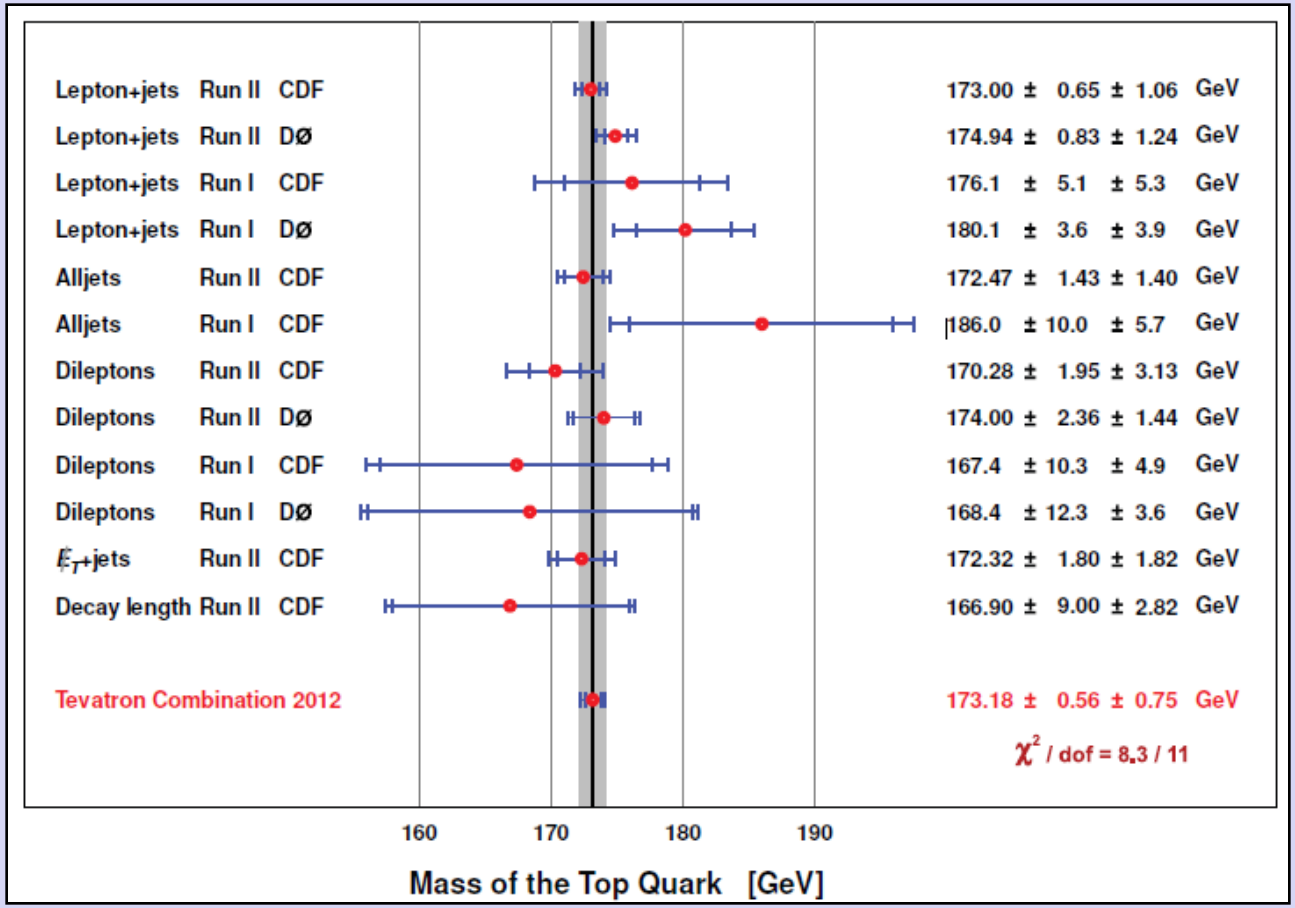
Main Top Quark Properties Measured at the Tevatron

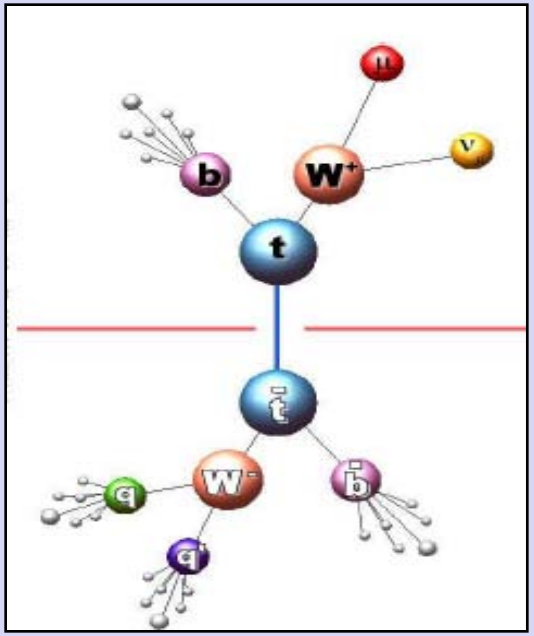
- Top quark mass: m_t = 173.2±0.9 GeV (0.5% accuracy)
- Are top and antitop masses the same? Test of CPT
  $\Delta m = 0.8 \pm 1.9$ GeV (equal to 1%)
- Top quark lifetime
  $\Gamma_t = 1.99(+0.69/-0.55)$ GeV agrees with SM
- Top charge $|q| = 2/3e$ to 95% C.L.
- W helicity in top decay expect 70% longitudinal, 30% left-handed
  SM looks good
- Asymmetry of top quark in p vs pbar direction expected to be a few %
  Anomalous asymmetry of ~15% - requires theory improvements?
- Correlations of spins of top and anti-top are consistent with SM
- No flavor changing neutral currents
  $< 2 \times 10^{-4}$ ($t \rightarrow gu$); $< 4 \times 10^{-3}$ ($t \rightarrow gc$)
- No evidence for SUSY $H^{\pm}$ in top decays
- Anomalous top vector/tensor couplings?
  Combination of W helicity & single top is in good agreement with SM V-A
- 4th generation t'? None below ~450 GeV
- tt resonances? None below ~800 GeV
- Is W in t decay color singlet? Singlet preferred
- Electroweak single top quark production observed: $|V_{tb}| > 0.77$ @ 95% C.L.

Very well know quark by now!

Top Quark Mass Measurement

- Top quark mass is measured using decay products in many different channels
- Lepton+jets channel with two jets coming from W boson is the most precise



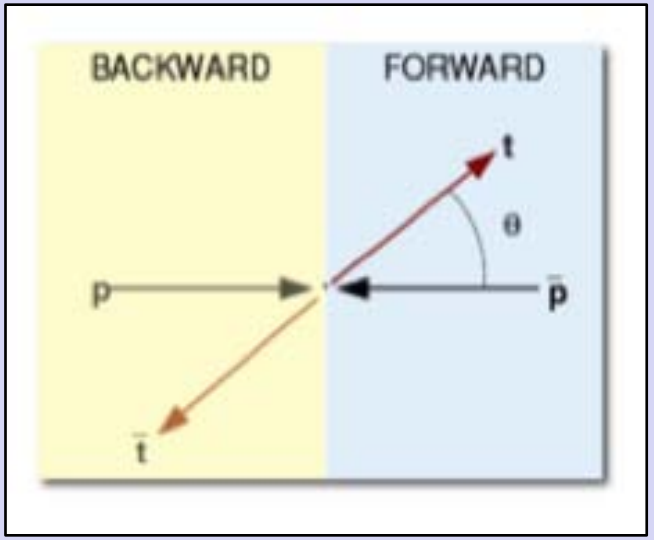


DØ and CDF combined top mass result
m_t = 173.2±0.9 GeV
0.5% accuracy
Best (of any) quark mass measurement!

Anomaly in Top Quark Studies

Tevatron

$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y>0) - N(\Delta y<0)}{N(\Delta y>0) + N(\Delta y<0)}$$



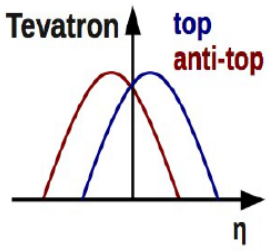
- In SM, there is no asymmetry in LO, but NLO predicts asymmetry
  - Positive asymmetry from box diagrams
  - Negative asymmetry from ISR and FSR
- Forward backward asymmetry
  - Enhanced in some BSM models

Tevatron

$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y>0) - N(\Delta y<0)}{N(\Delta y>0) + N(\Delta y<0)}$$

LHC

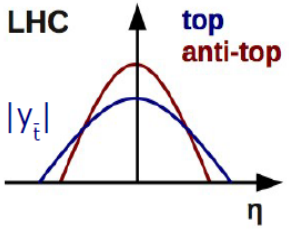
$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$

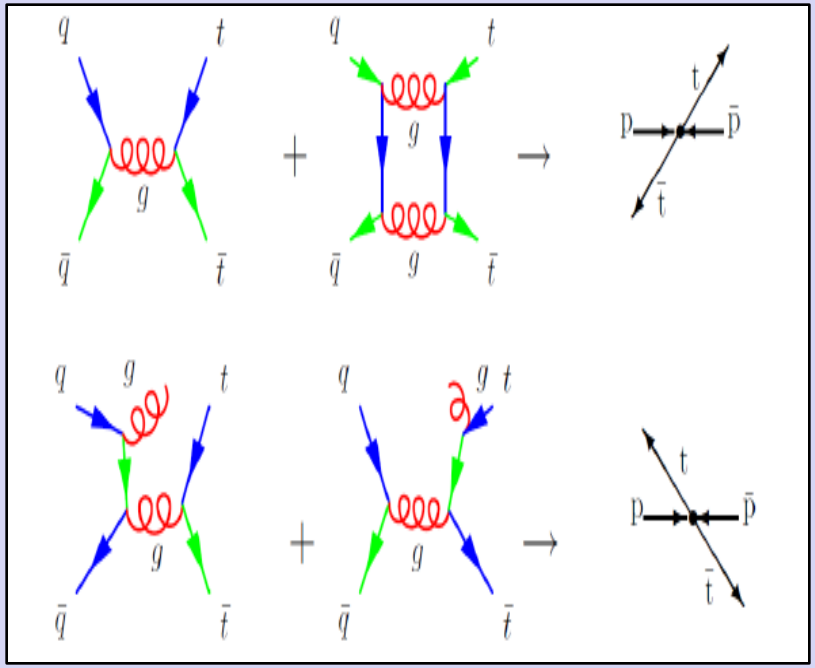


$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

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

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



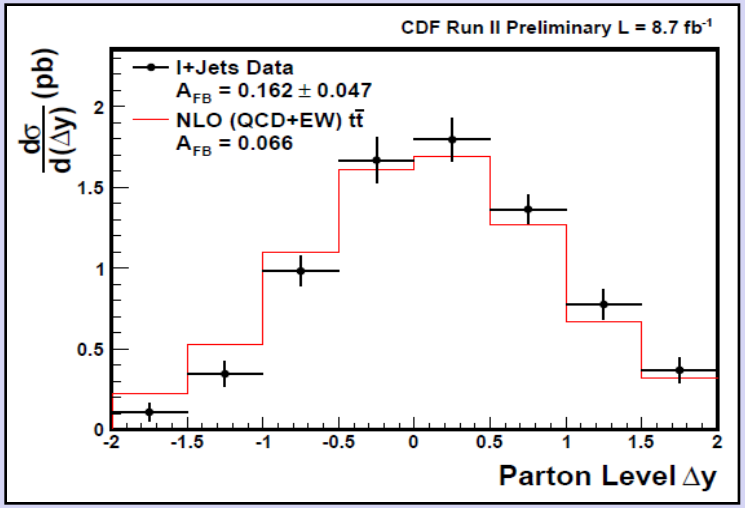


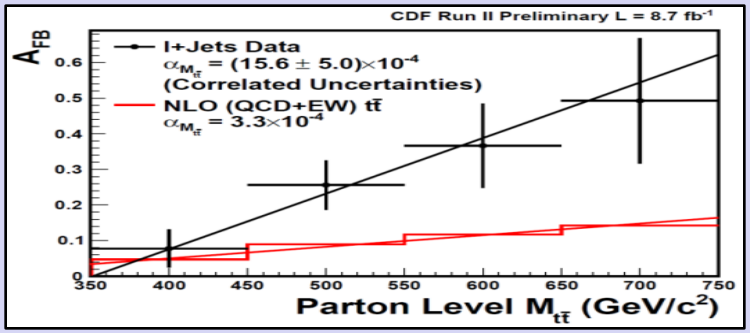
Top Forward-Backward Asymmetry

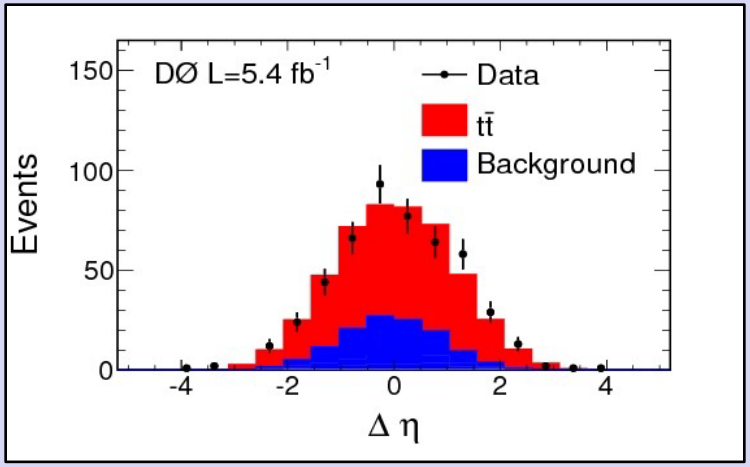
- **CDF lepton+Jets (8.7 fb^{-1})**
  - $A_{FB} = (16.2 \pm 4.7)$ %
  - SM prediction : 6.6 %
    - ~2 σ deviation from NLO
  - Slope of $A_{FB}(M_{tt})$
    - $(15.6 \pm 5.0) \times 10^{-4}$

- **D0 Result (5.4 fb^{-1})**
  - l+Jets : $A_{FB} = 15.2 \pm 4.0$ %
  - Dileptons : $A_{FB} = 5.8 \pm 5.1 \pm 1.3$ %
    - (stat.) (syst.)
  - Combined result : 11.8 ± 3.2 %
  - SM prediction : 4.7 %
    - ~2 σ deviation from NLO

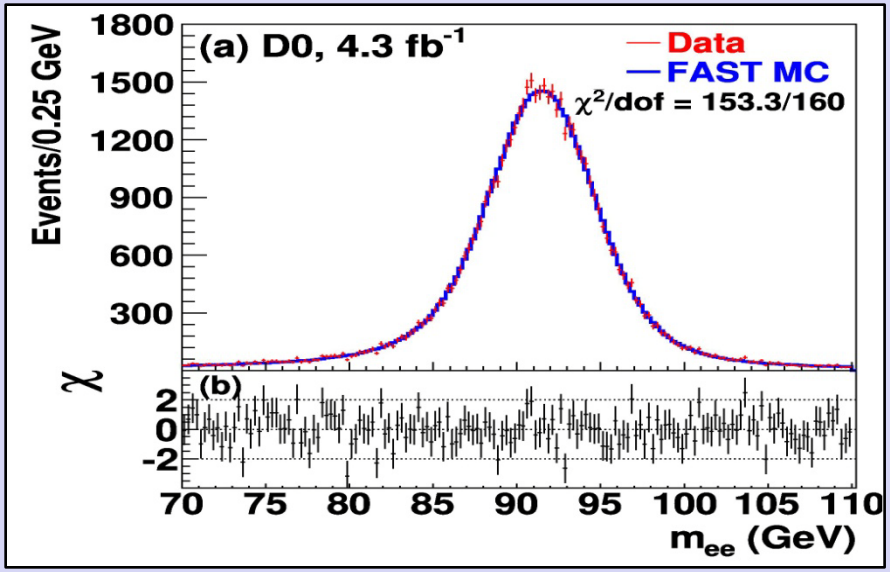
- **Options**
  - Statistics? Not accurate enough QCD predictions? New Physics?
- **Results from LHC are compatible with SM**
  - Not exactly the same quantity
  - SM predictions are below 1% at LHC
  - Current LHC accuracy ~1-2%

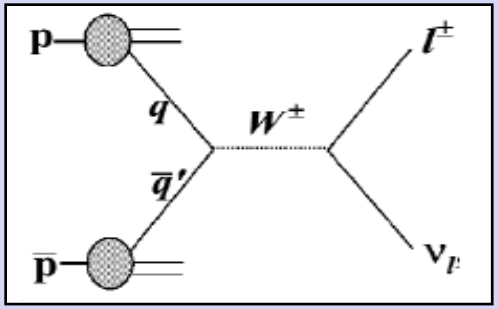


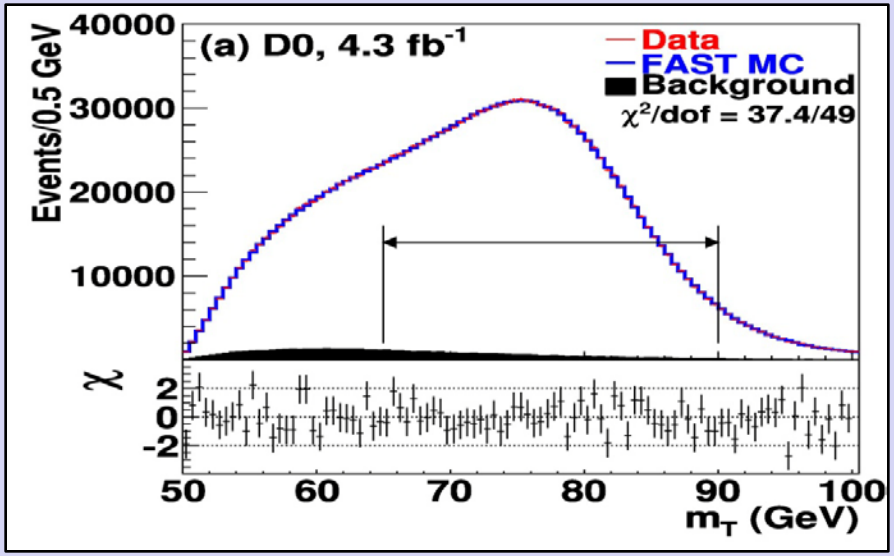


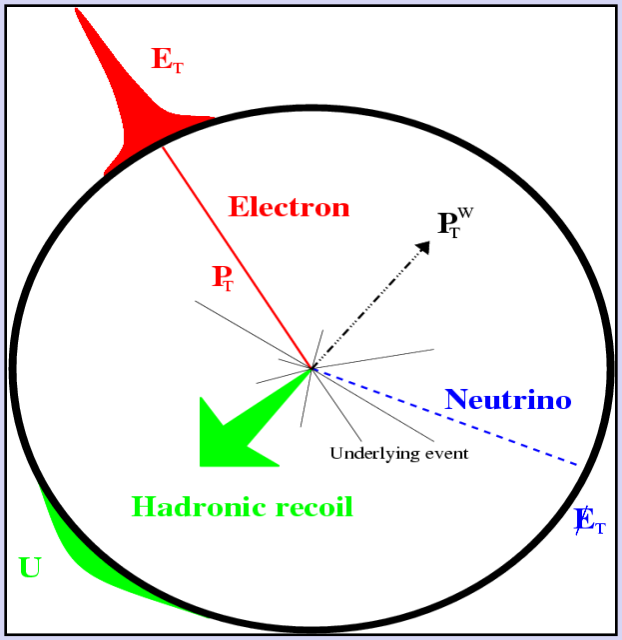


Electroweak: W Boson Mass Measurement





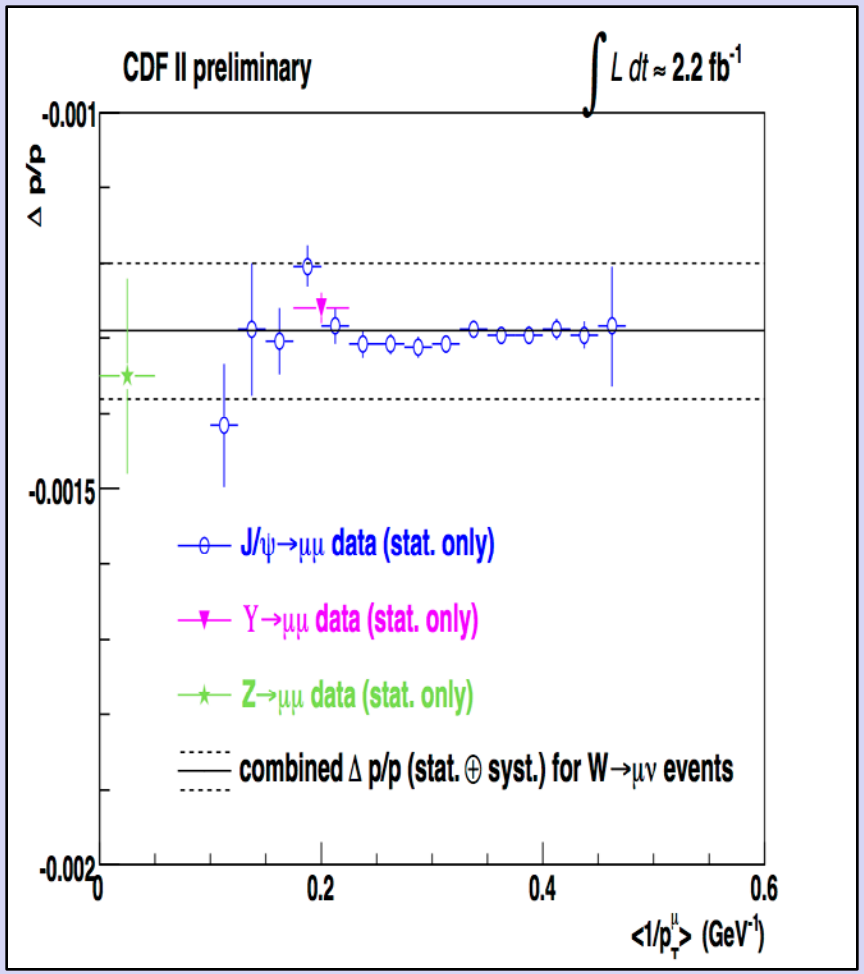


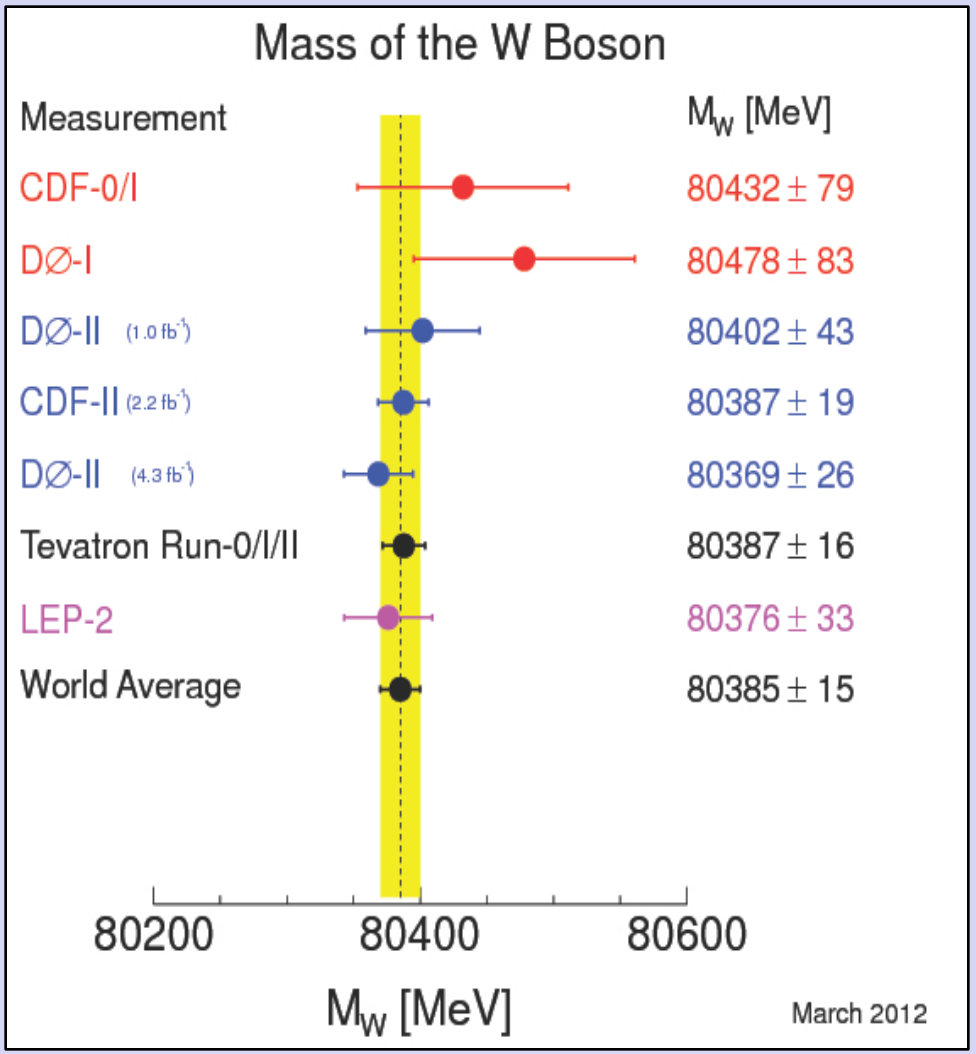


M_W = 80,375 23MeV
0.03% accuracy

- **W boson mass is measured using decay products: electron and neutrino**
- **DZero: calibration of energy scale is performed using Z boson mass**

World Average W boson Mass





CDF: tracker based lepton momentum measurement

M_W = 80,387 19 MeV

0.03% accuracy

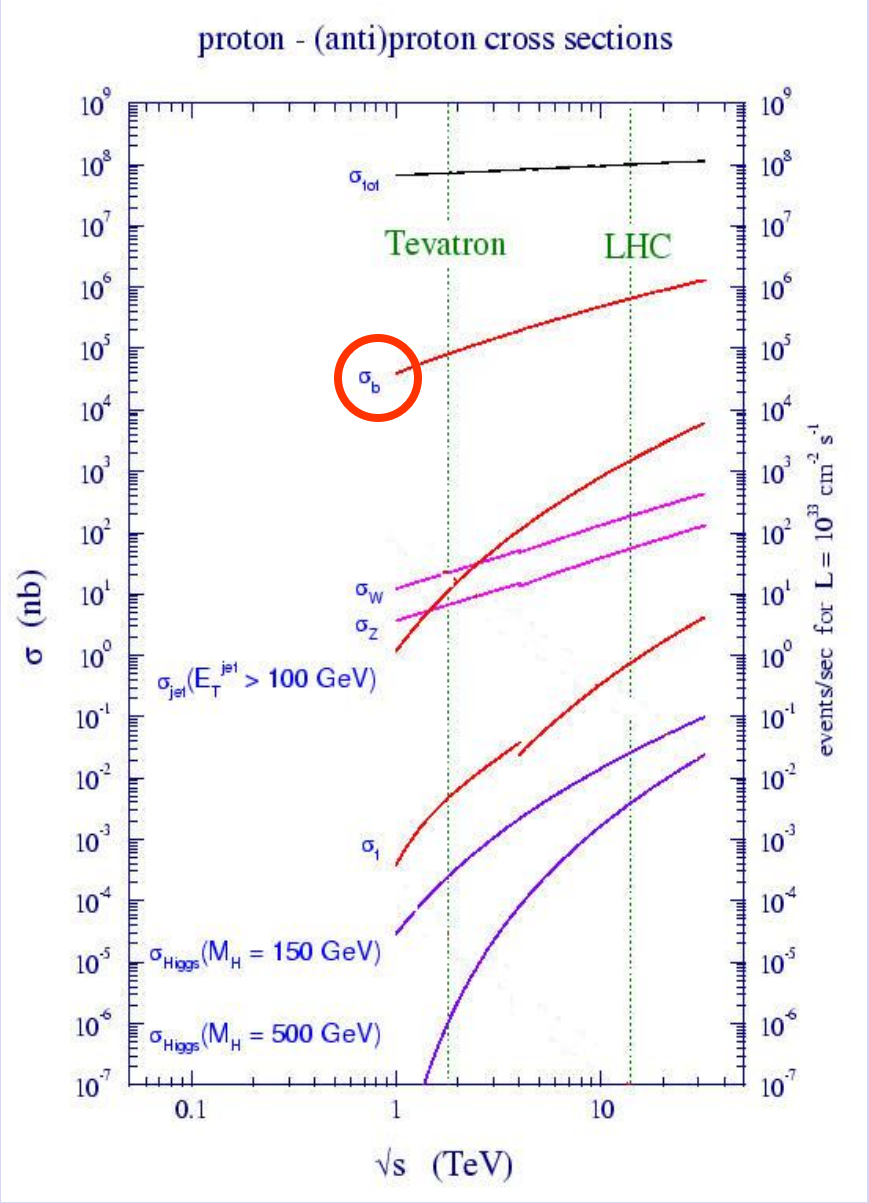
W mass world average is now 80,385 15 MeV (0.02%)

b-quark Studies

High b quark cross section: ~10^{-3} σ_{tot}
~10^4 b's per second produced!

Large data samples of particles with b-quarks provide

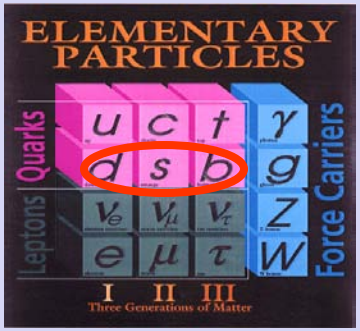
- **B mesons lifetime studies**
- **Mass spectroscopy (B_c, etc.)**
- **Studies of B_s oscillations**
- **CP violation studies**
- **Search for new b hadrons**
- **Search for rear decays**

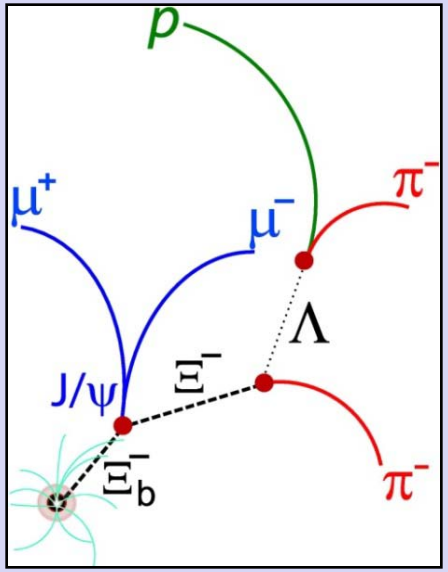


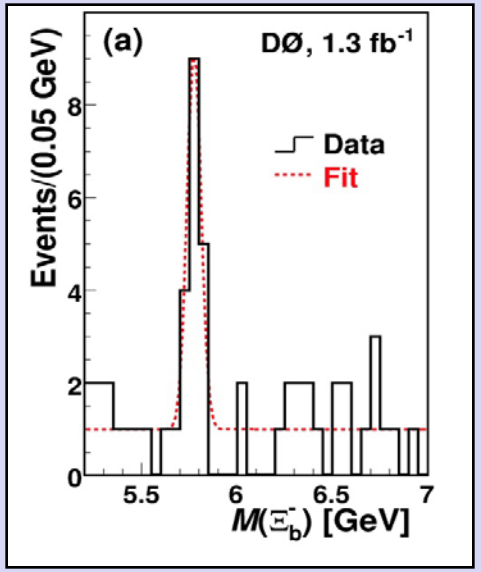
Discoveries of b-Baryons

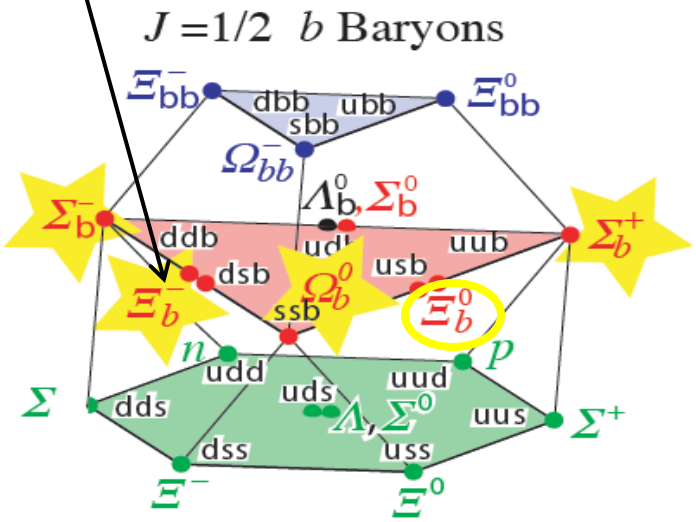
All b quark containing species are produced: $B^{\pm}$, B^0, B_s, B_c, Λ_b …and many new heavy baryons!

First baryon with quarks from all three generations observed!









3 *b*

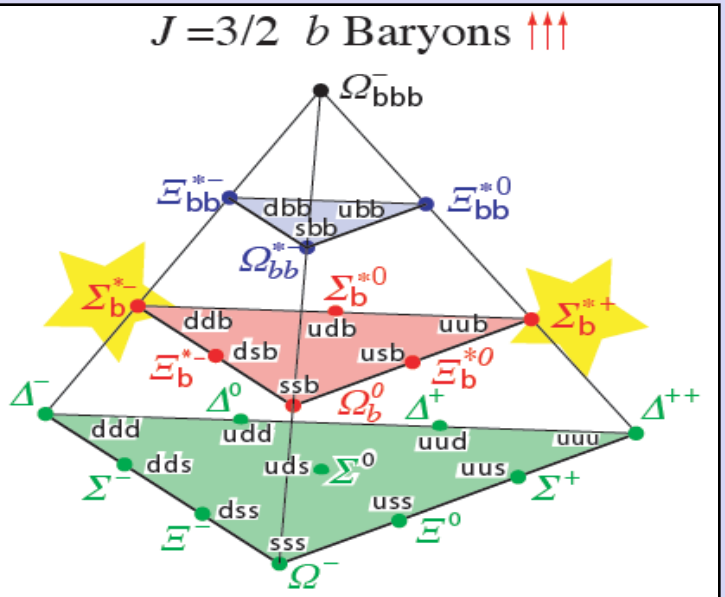
2 *b*

1 *b*

New states discovered at Tevatron!

0 *b*

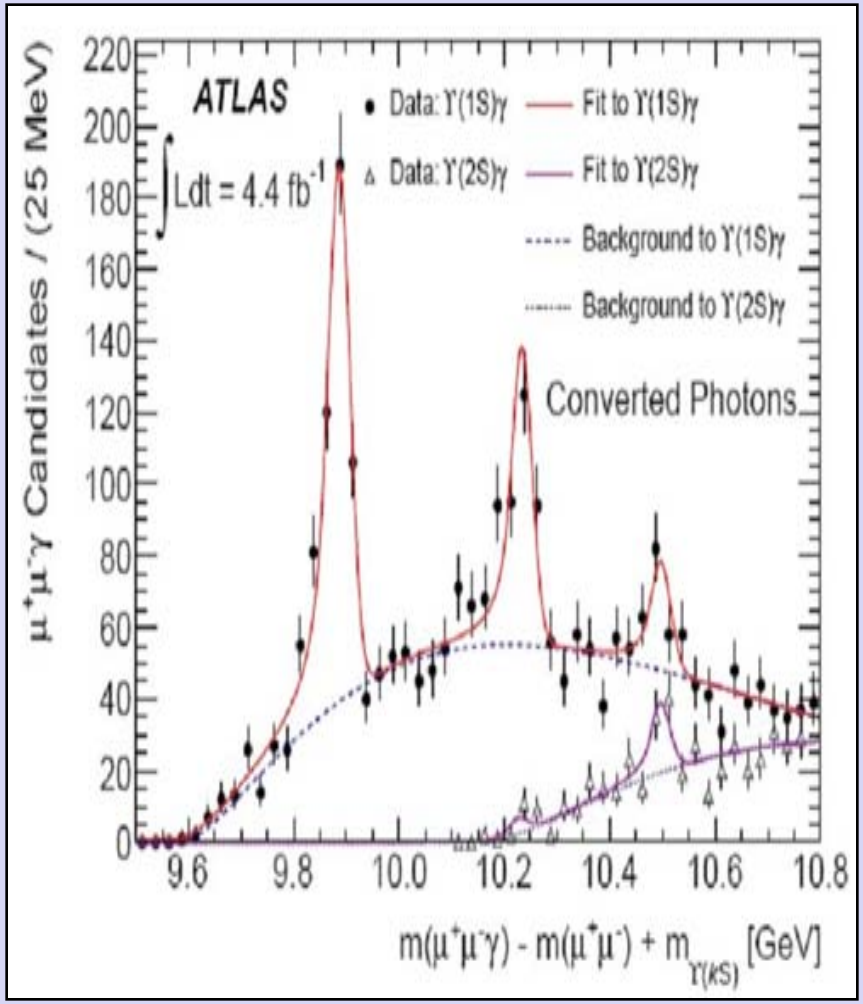
All observed

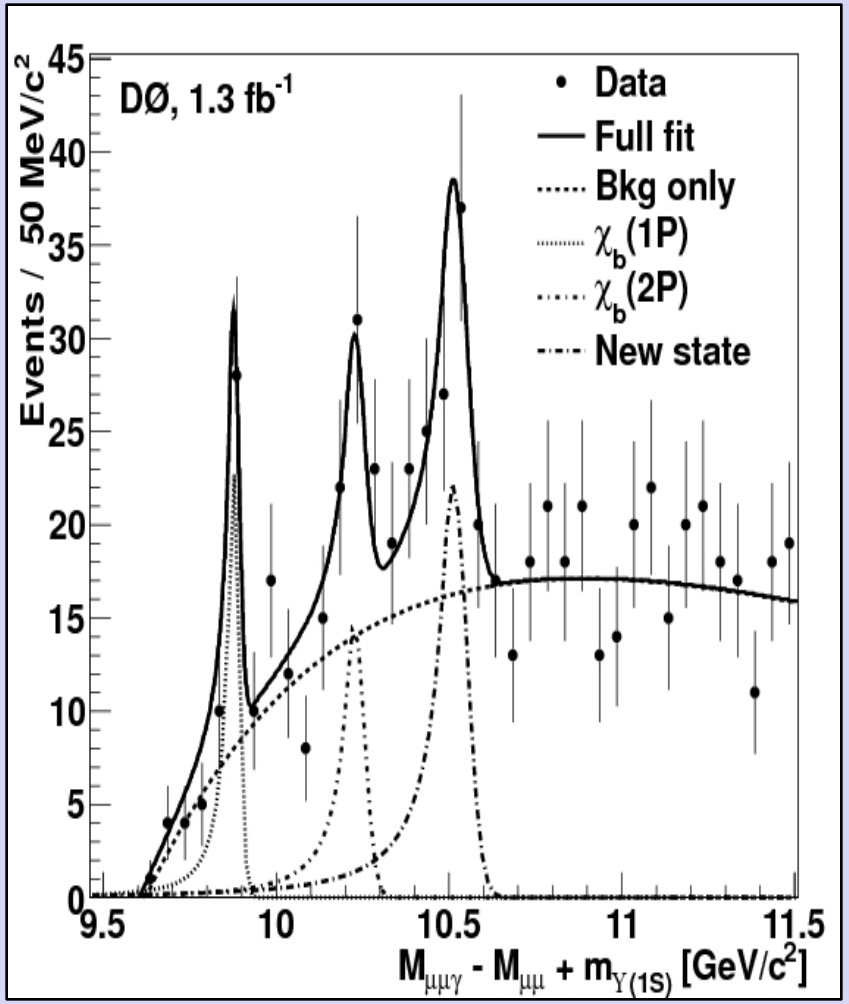


- Until Tevatron, ground state Λ_b was the only directly observed *b* baryon

$\Lambda_b^0 = |bud\rangle$ LEP, DØ, CDF

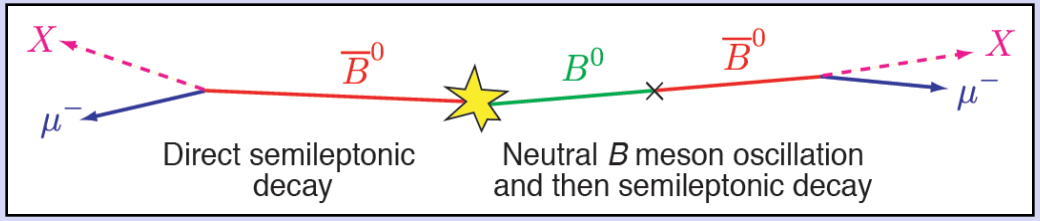
Confirmation of Chi-b(3P) State

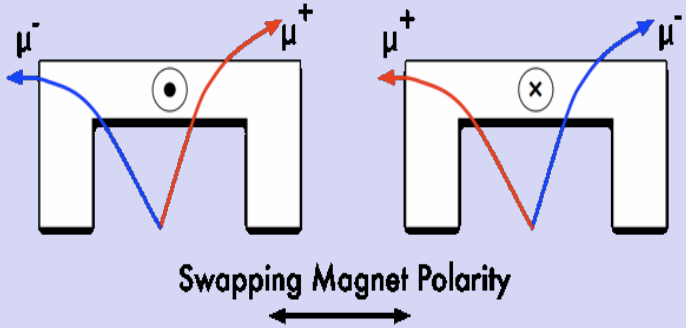




- **Late 2011 ATLAS reports observation of Chi-b(3P) state**
- **Within ~2 months DZero confirms observation with over 5 σ significance**

DØ di-muon Charge Asymmetry





- **Di-muon charge asymmetry**

$$A_{sl}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

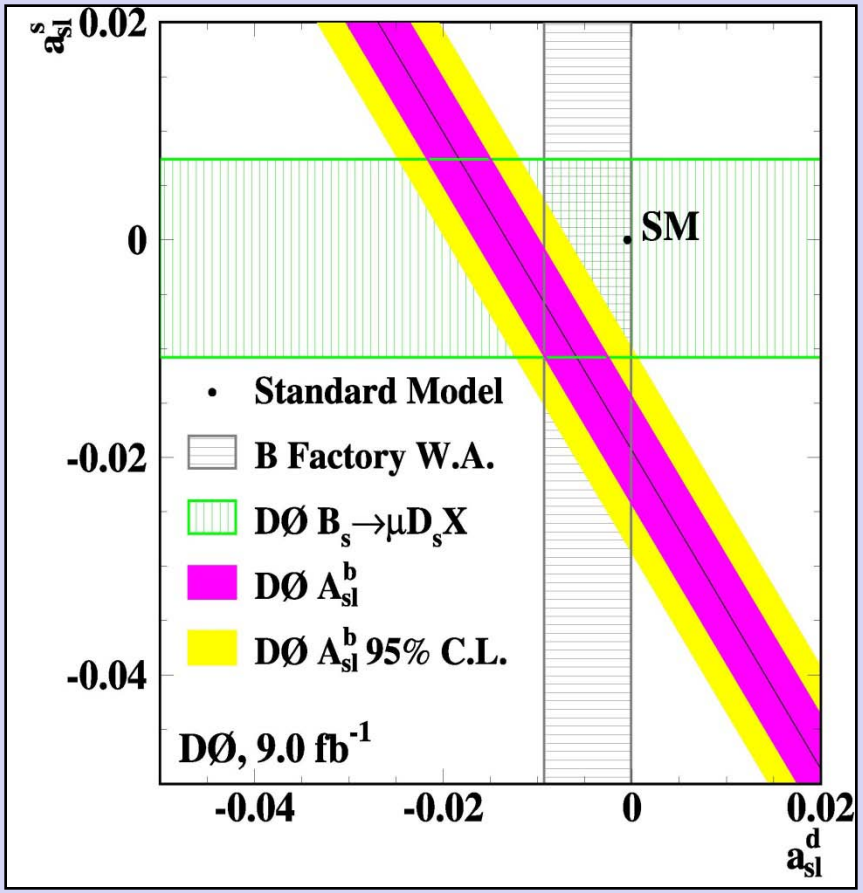
for events coming from decays of mesons containing b quarks undergoing mixing

- **Standard Model predicts this asymmetry to be very small**

$$A_{sl}^b = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$$

- **Any substantial deviation of this asymmetry from zero will be indication of new source of CP violation**
- **Measured value is 3.9σ from prediction**

$$A_{sl}^b = (-0.787 \pm 0.172\ (\text{stat}) \pm 0.093\ (\text{syst}))\ \%$$



Di-muon Asymmetry Anomaly

Decay channel for B_s^0:

$B_s^0 \rightarrow \mu^+ \nu D_s^- X$

$D_s^- \rightarrow \varphi \pi^-$

$\varphi \rightarrow K^+ K^-$

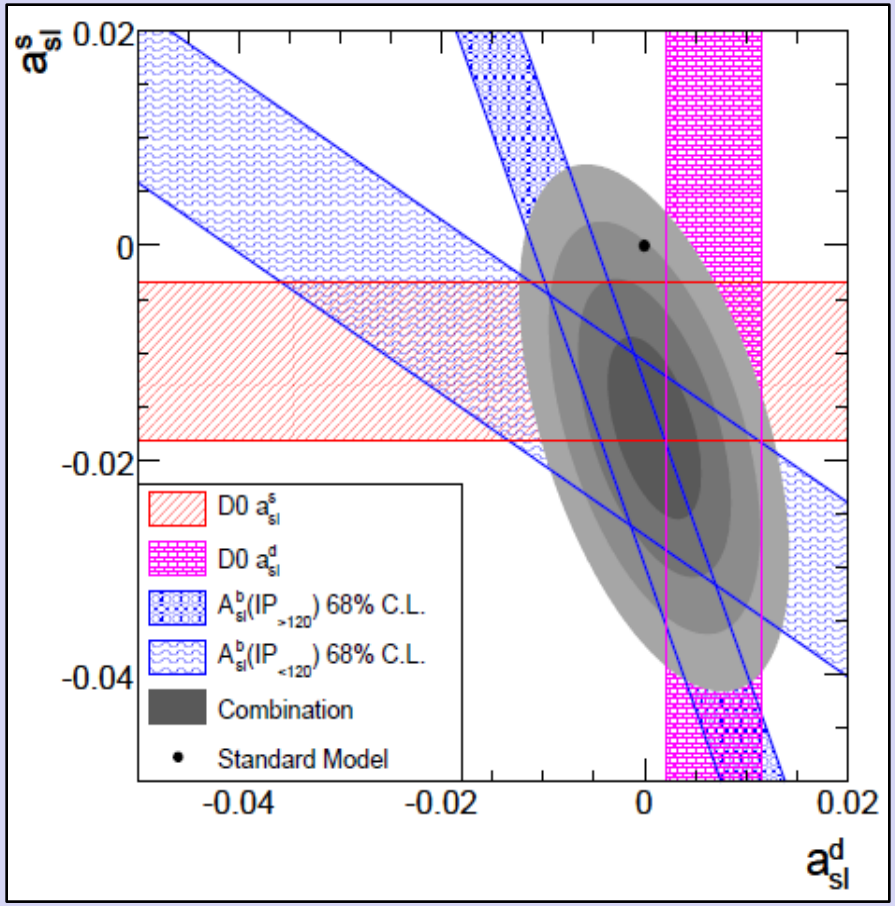
$$a_{sl}^s = [-1.08 \pm 0.72\,(\text{stat}) \pm 0.17\,(\text{syst})]\,\%$$

Decay channels for B^0:

1) $B^0 \rightarrow \mu^+ \nu D^- X$

$D^- \rightarrow K^+ \pi^- \pi^-$

$$a_{sl}^d = [0.68 \pm 0.45\,(\text{stat.}) \pm 0.14\,(\text{syst.})]\,\%$$



- **Combined DZero result**
  - **Deviation is 2.9 σ from the SM**
- **Reasons**
  - **New physics?**
  - **Un-known systematic?**
  - **Di-muon asymmetry is not related to B mesons?**

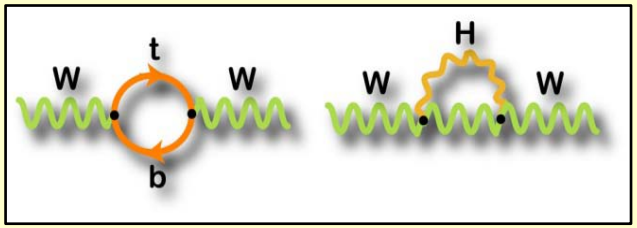
LHCb : $a_{sl}^s = (-0.24 \pm 0.54 \pm 0.33)\%$

B-Factories : $a_{sl}^d = (-0.05 \pm 0.56)\%$

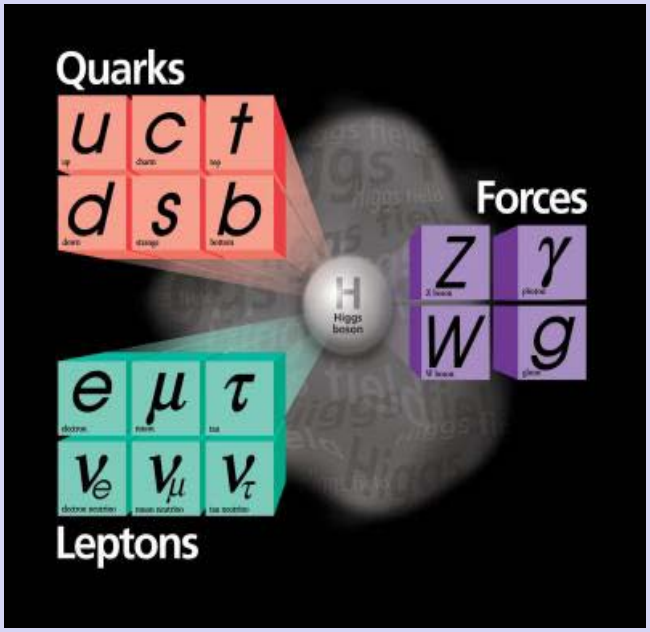
Higgs Searches – Indirect Limits

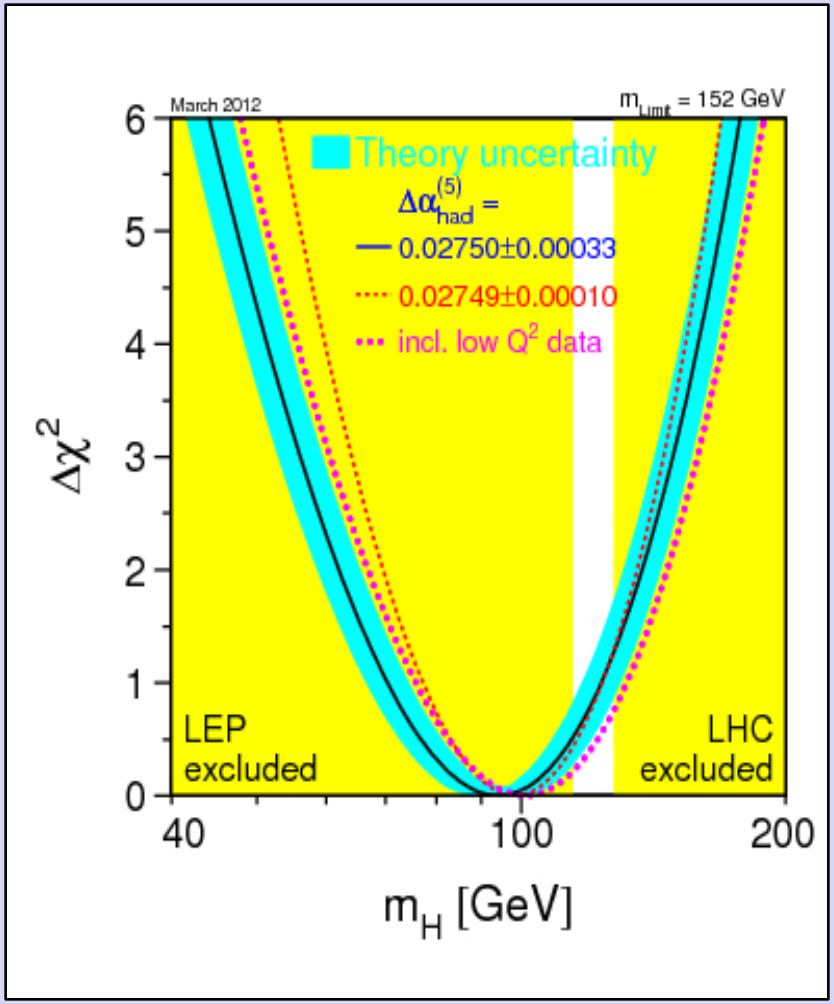
Indirect experimental limits

→ Precision theory fits including W boson mass and top quark mass



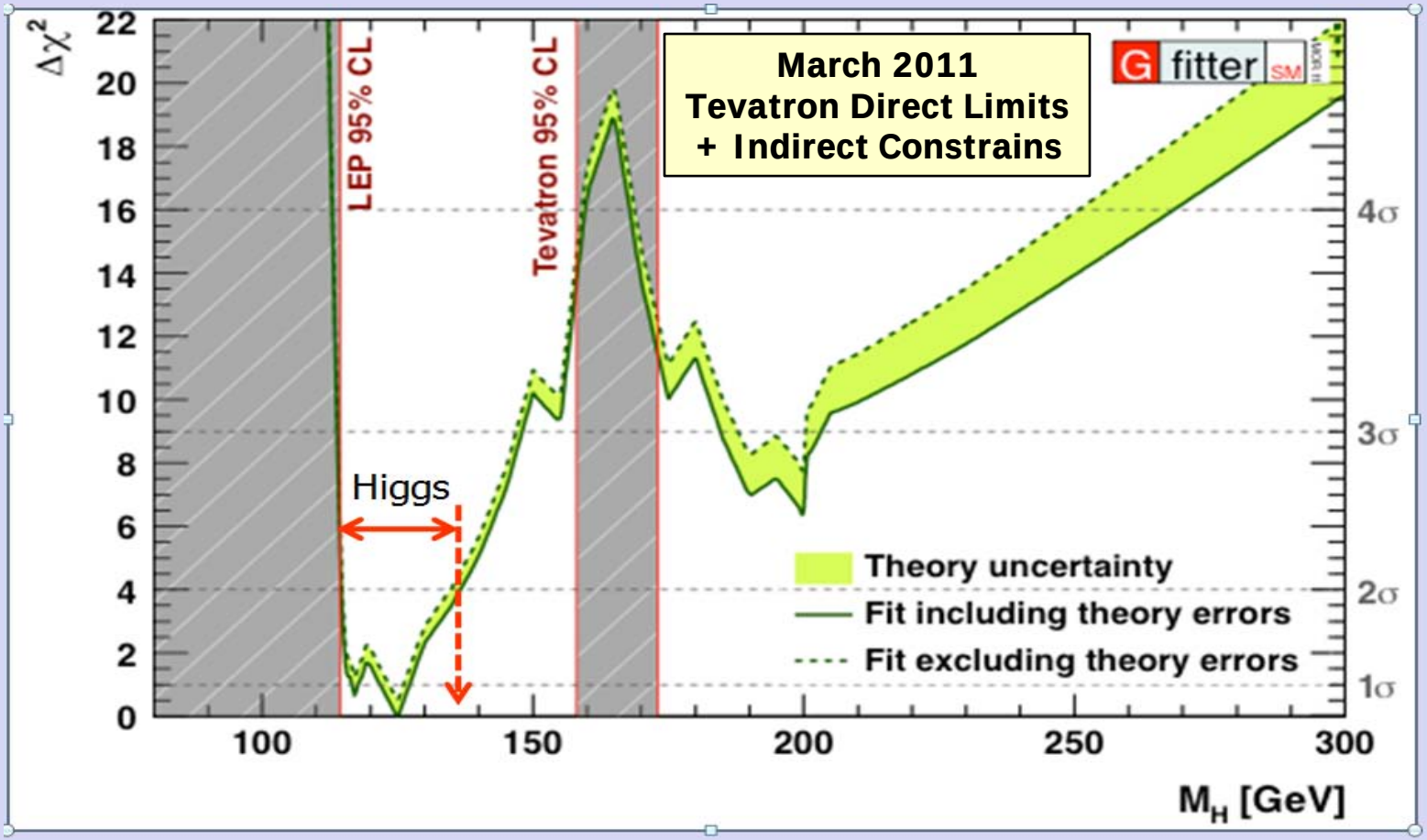
M_H < 152 GeV at 95% CL





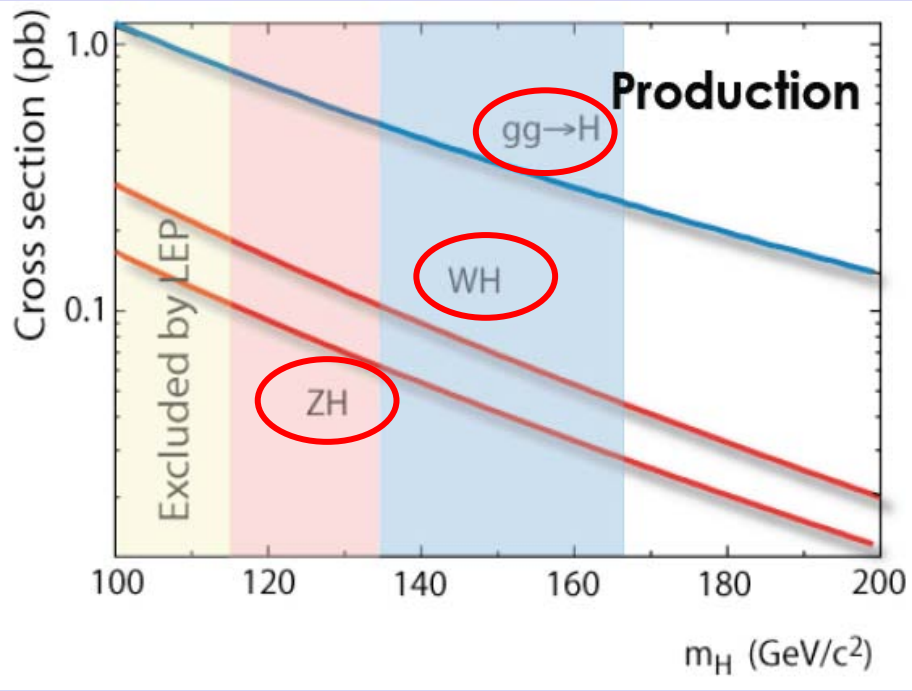
Higgs Searches Status: 1.5 Years Ago

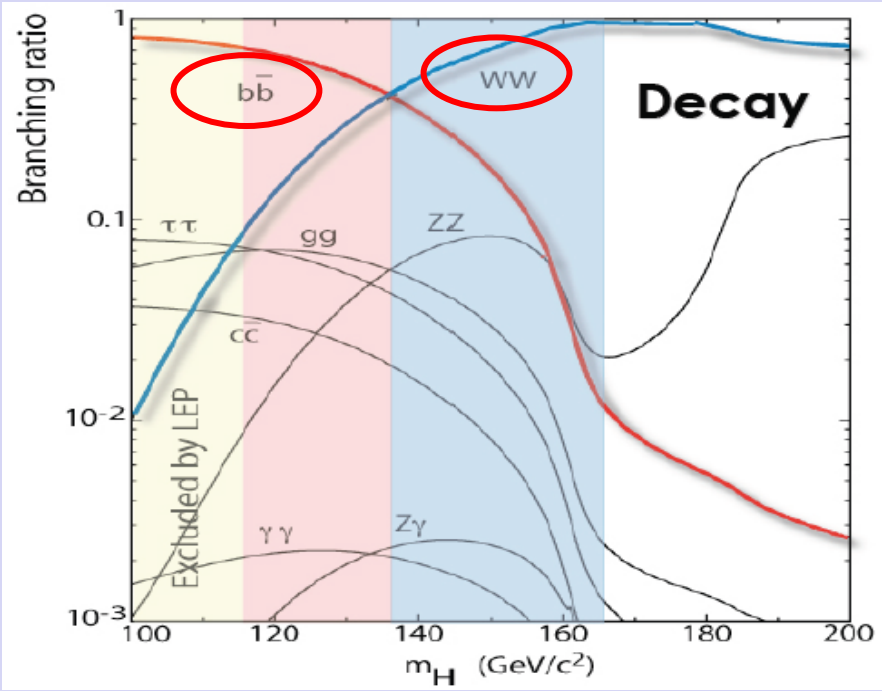
- Higgs masses ~160-175 GeV are excluded by the Tevatron
- Precision measurements point to Higgs masses below ~150 GeV
- LEP results indicate Higgs mass is above ~114 GeV



- Higgs mass was limited to 114 to 137 GeV window at 95% CL
- Most probable value was… 125 GeV

Higgs Production and Decays at the Tevatron



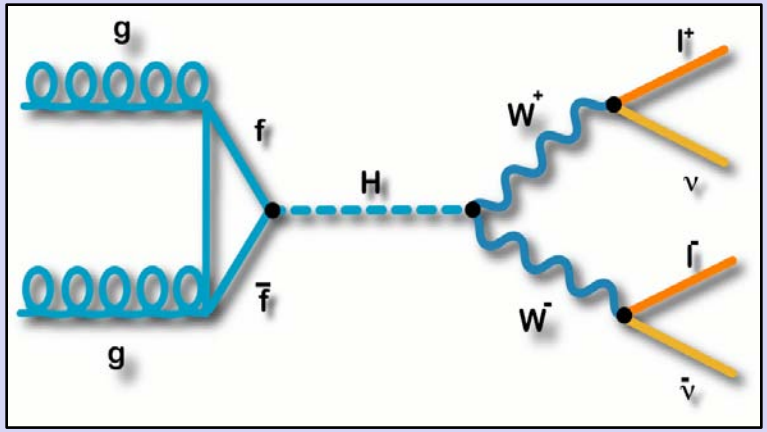


Production cross sections
→ in the 1 pb range for gg → H
→ in the 0.1 pb range for associated vector boson production

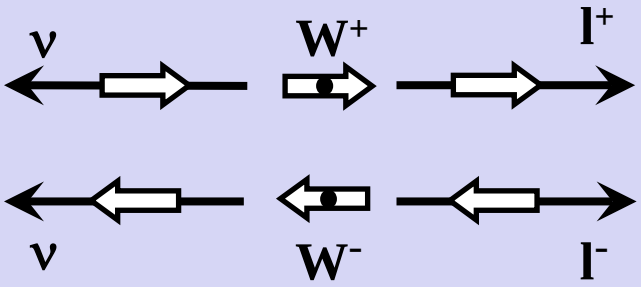
Decays
→ bb for M_H < 135 GeV
→ WW for M_H > 135 GeV

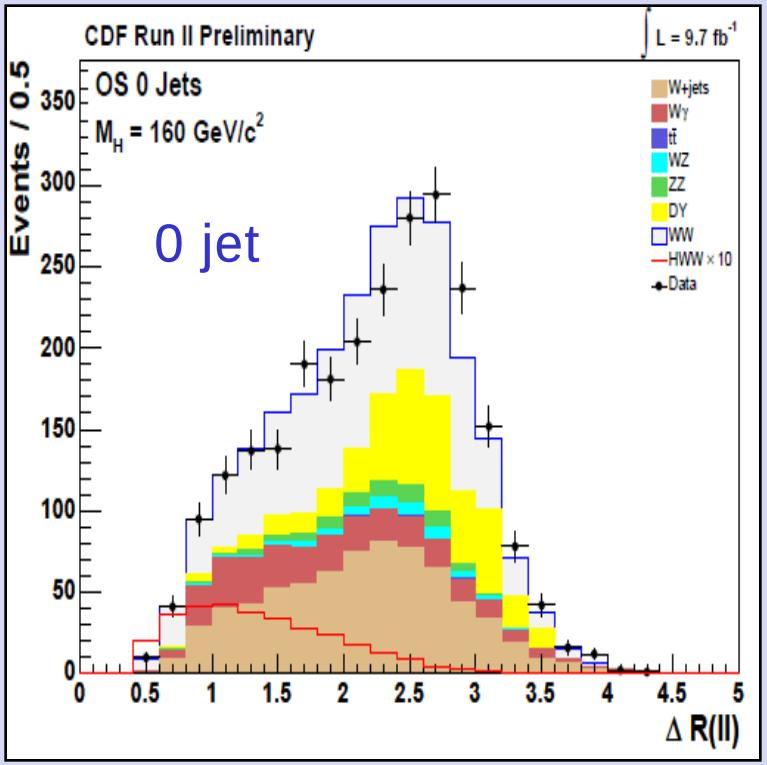
Search strategy:
M_H <135 GeV associated production and bb decay W(Z)H → lν(ll/νν) bb
Main backgrounds: top, Wbb, Zbb
M_H >135 GeV gg → H production with decay to WW
Main background: electroweak WW production

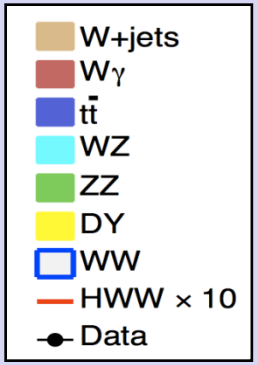
Higgs Search: H → WW → lνlν (M_H >130 GeV)

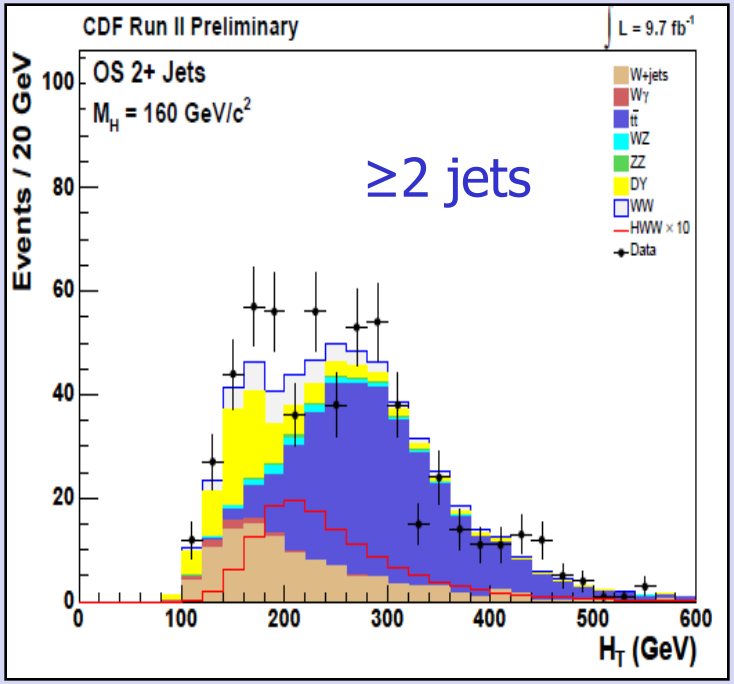


Search strategy:
→ 2 high P_t leptons and missing E_t
→ WW pair comes from spin 0 Higgs: leptons prefer to point in the same direction

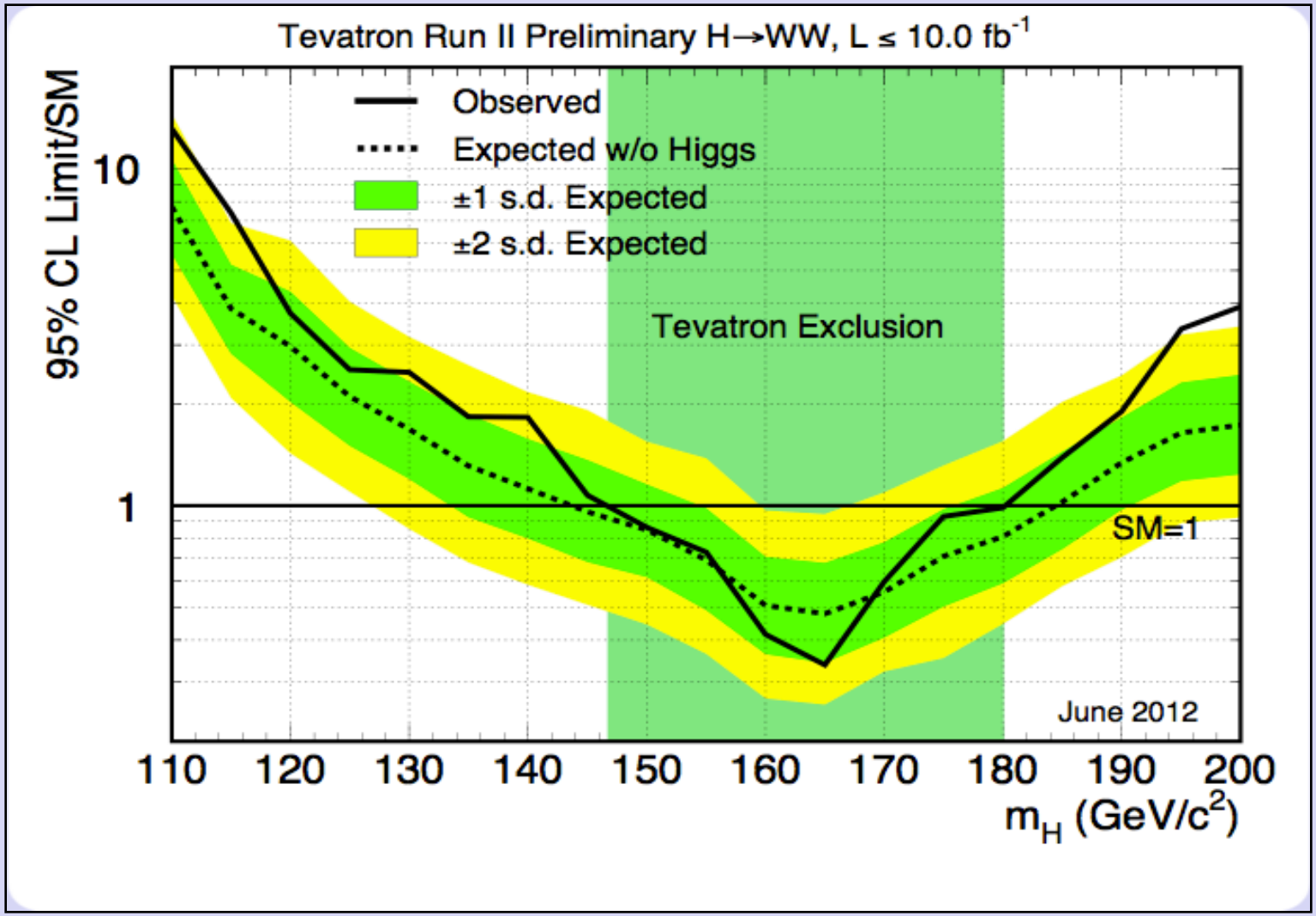






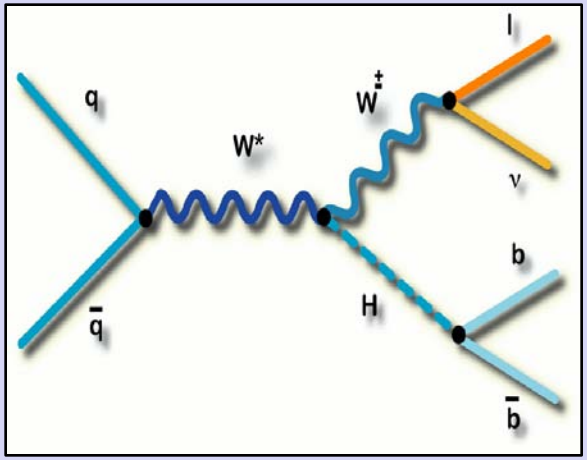


$H \rightarrow W^+W^-$ Tevatron Combination

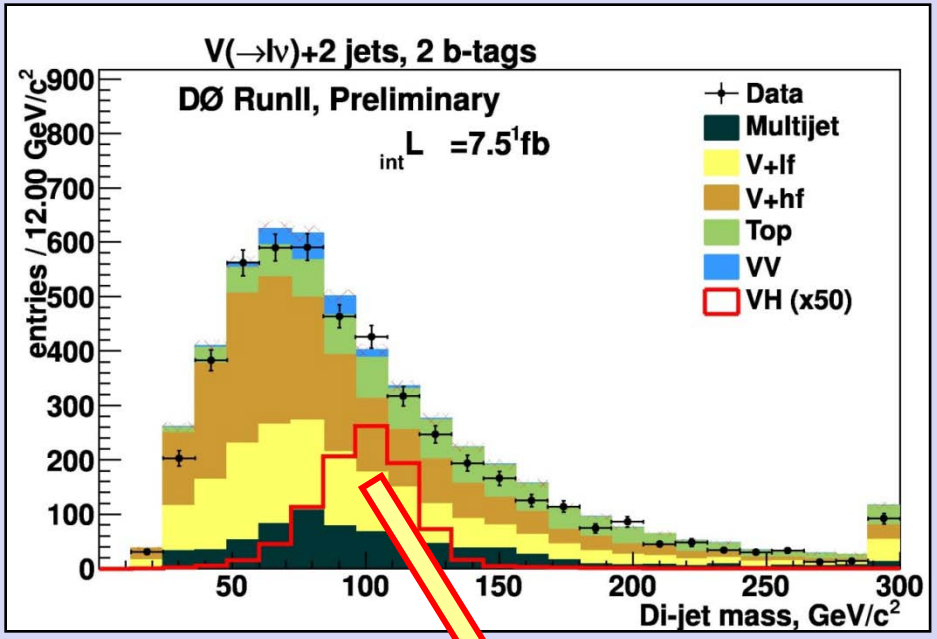


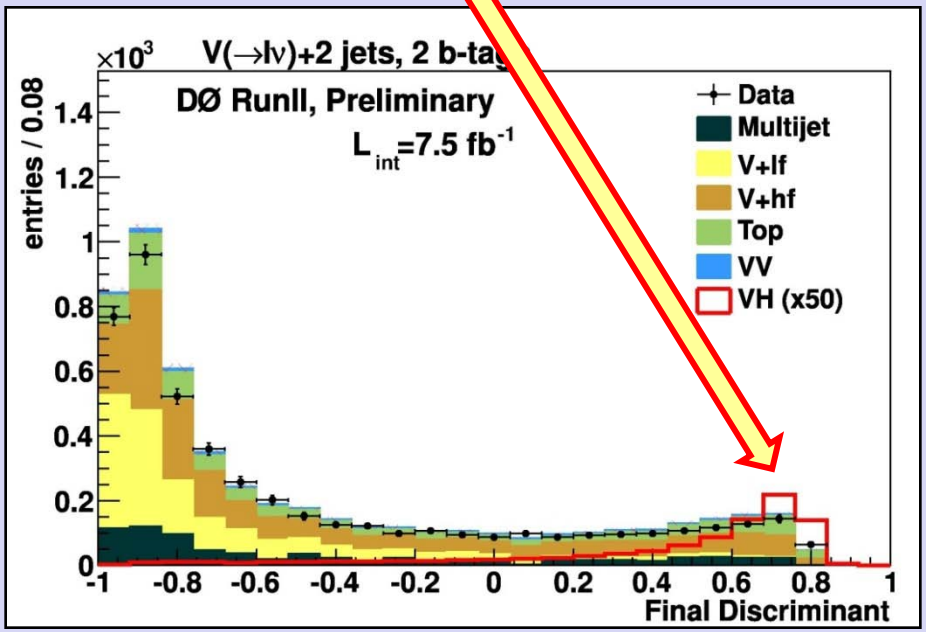
Exclude $147 < M_H < 180$ GeV at 95% CL

Low Mass Higgs Channels



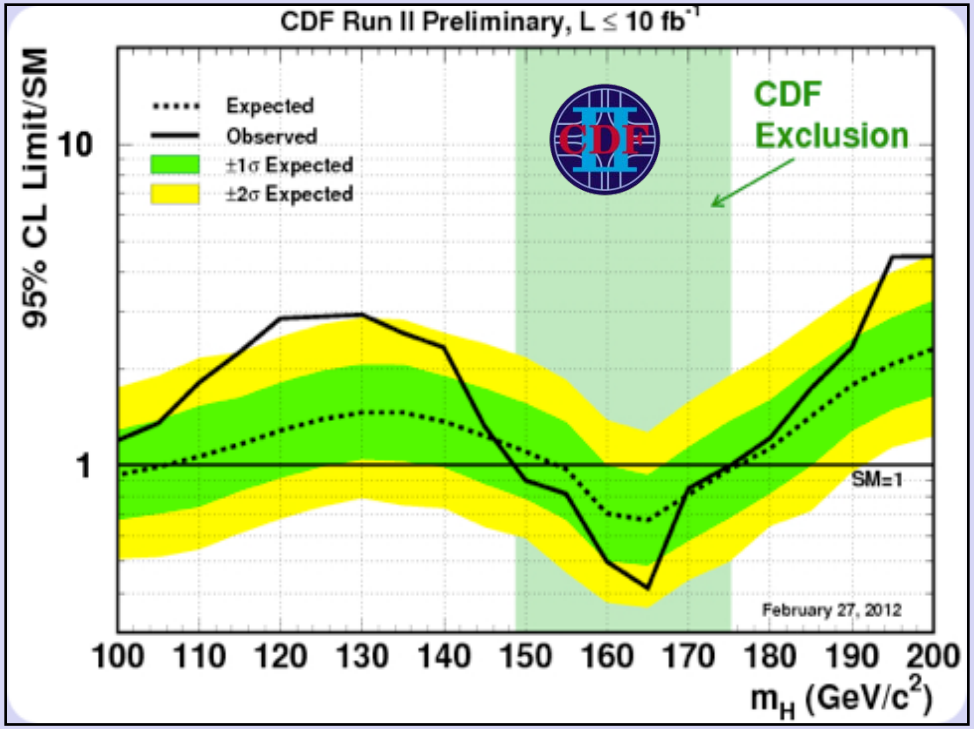
- **Main discriminant is di-jet mass from b-quarks pair**
- **Elaborate b-tagging**
- **Multivariate analyses help to extract full information about event kinematic**

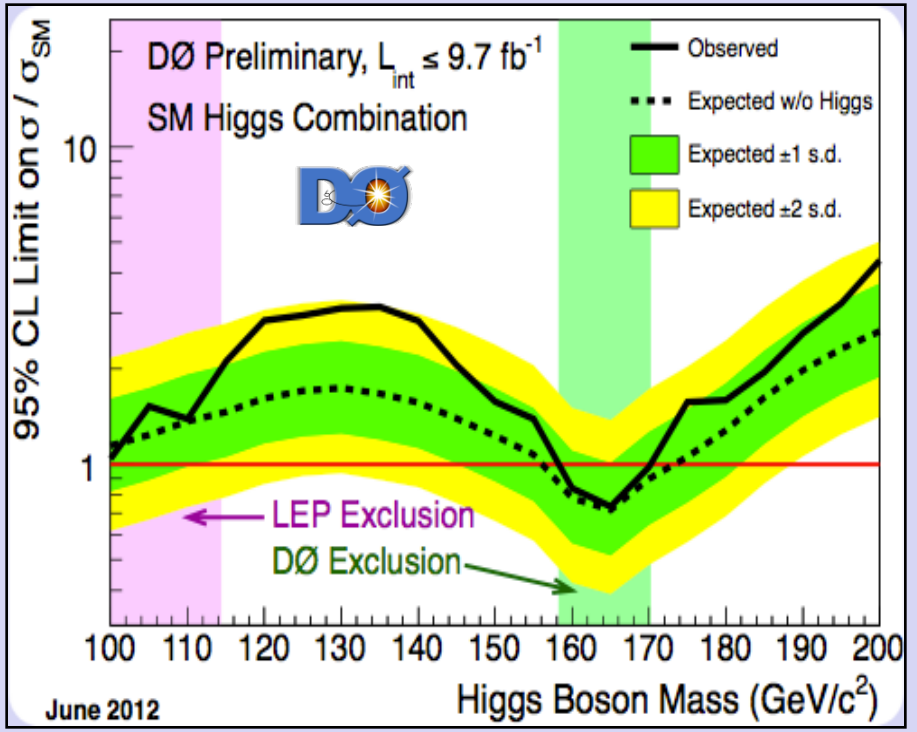




CDF and DØ Higgs Search Results

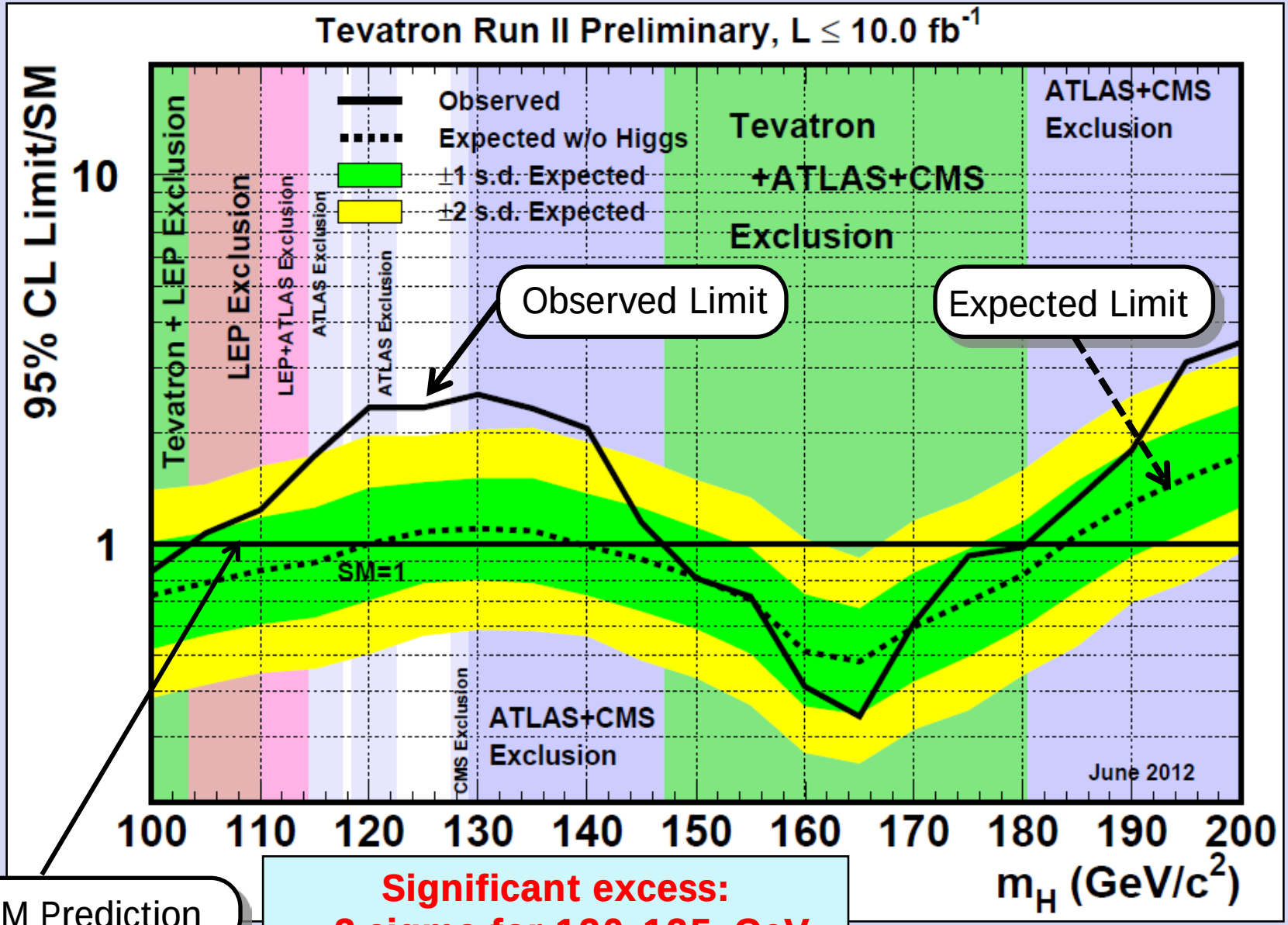
CDF and DØ single-experiment combinations of all Higgs search channels: H→WW, H→bb, H→γγ + other modes





Remarkably similar shapes: no excess below ~110 GeV
broad excess around ~120-140 GeV
exclusion around ~165 GeV

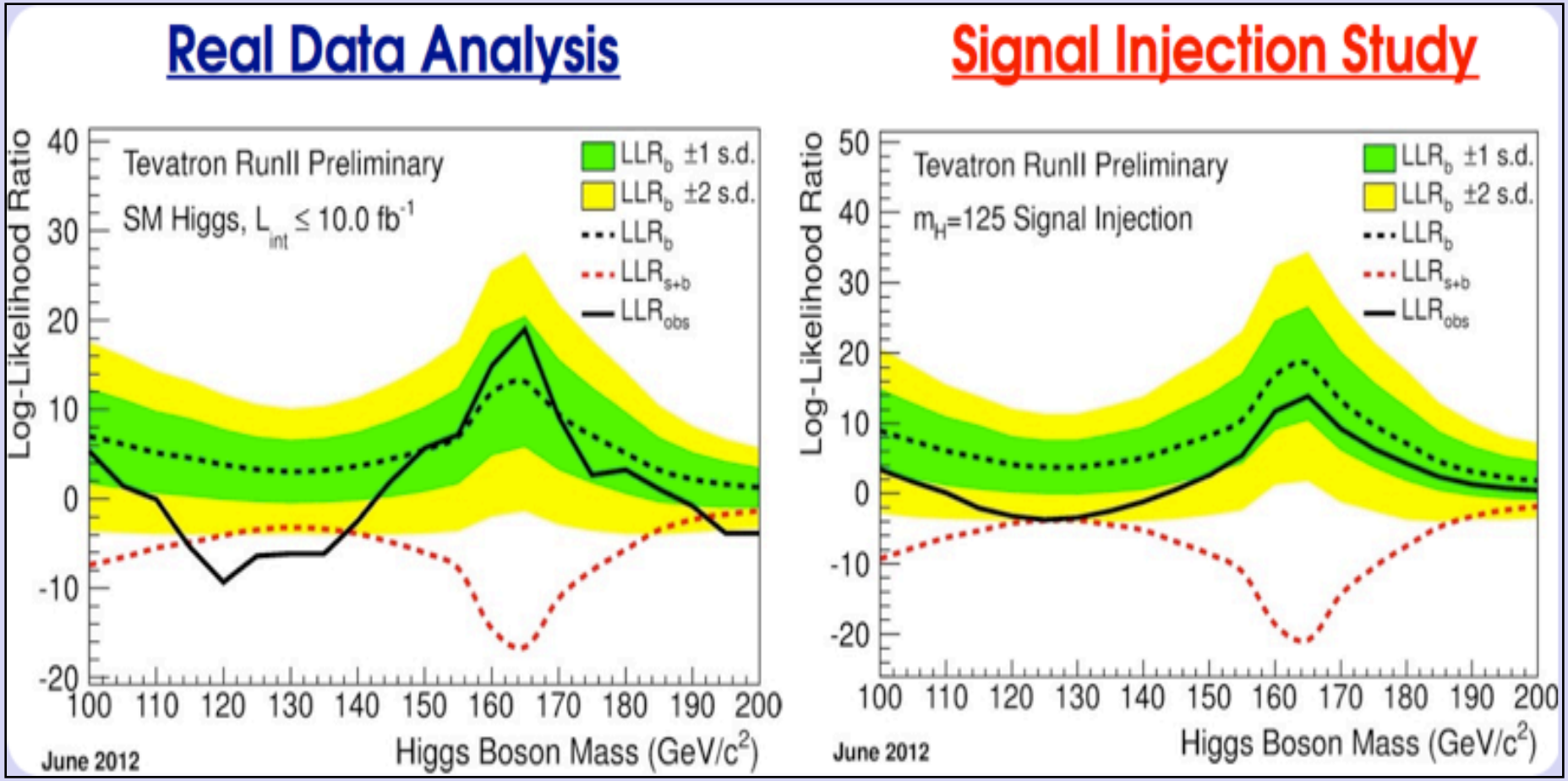
Summer 2012 Tevatron Combination



SM Prediction

Significant excess:
~3 sigma for 120-135 GeV

LLR test: Excess Shape Comparable with Higgs?

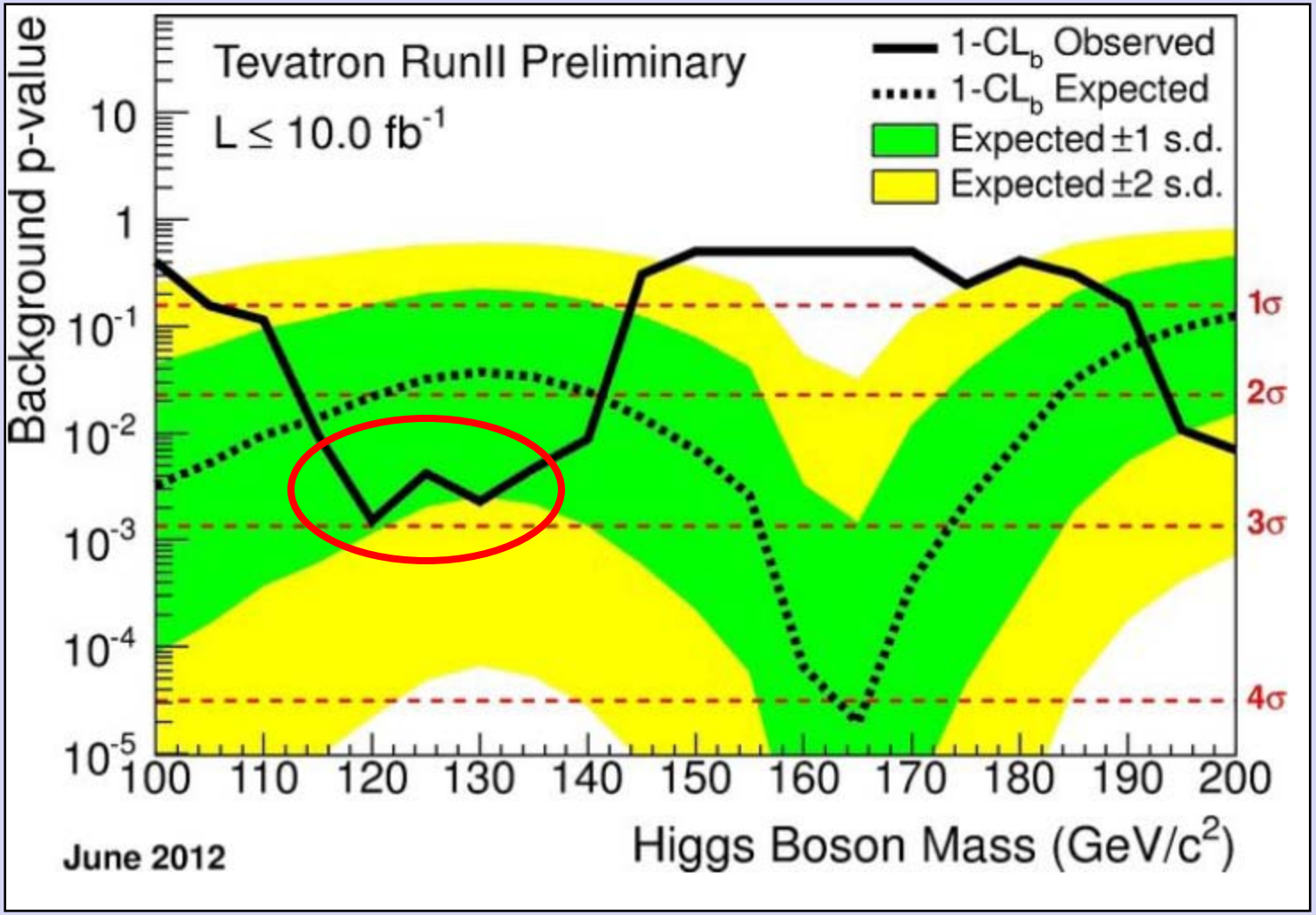


Injection of Standard Model Higgs signal at 125 GeV provides very similar to the observed behavior

"background like" shape above ~140 GeV

"signal like" shape in 115-140 GeV region

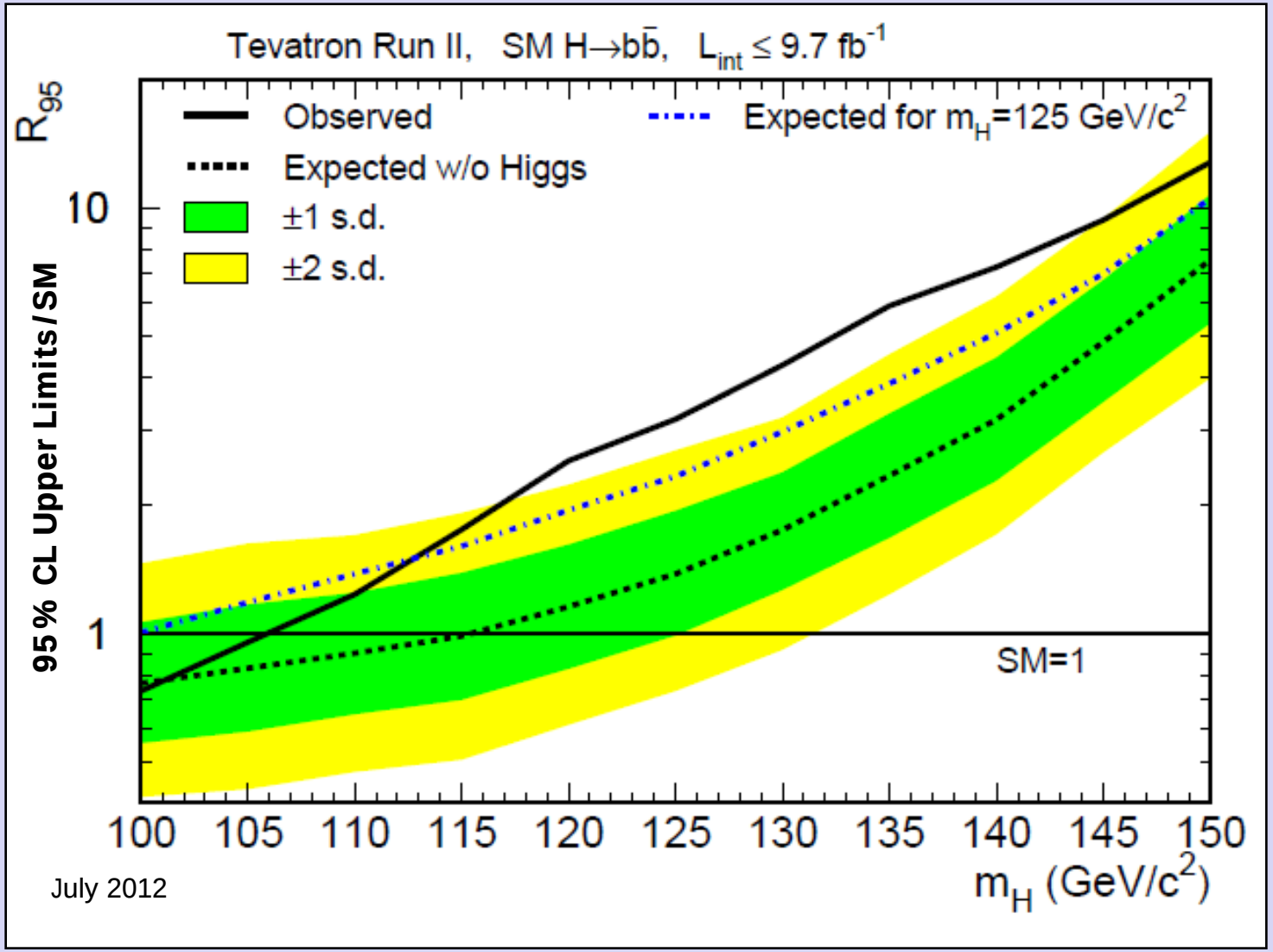
Probability of Background to Mimic Signal



3.0σ local excess at 120 GeV

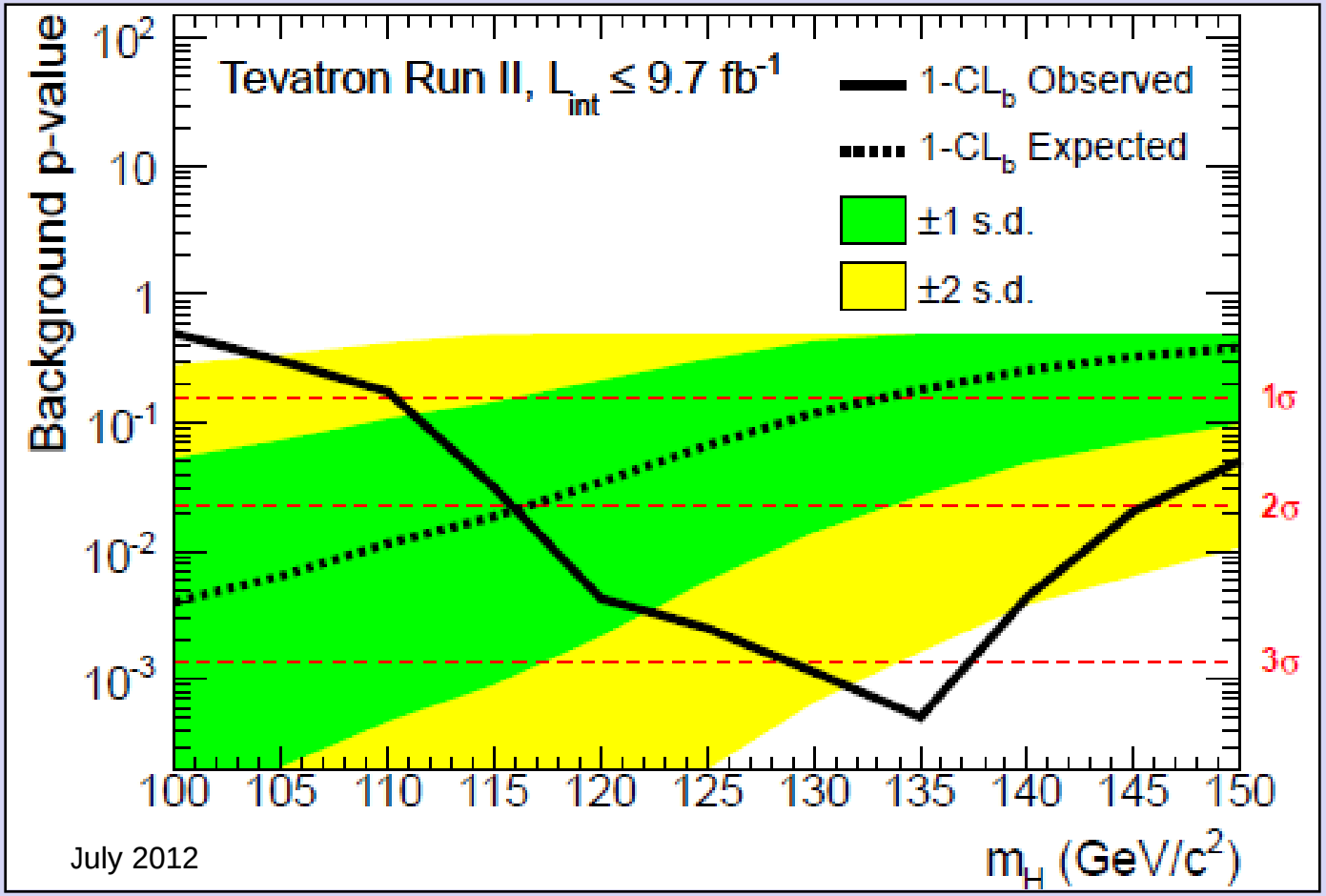
2.5σ global excess taking into account "look elsewhere effect" as we perform studies at many data points

Tevatron H→bb Combination



Broad excess, maximum between 120 and 140 GeV

H→bb, Probability of Background to Mimic Signal



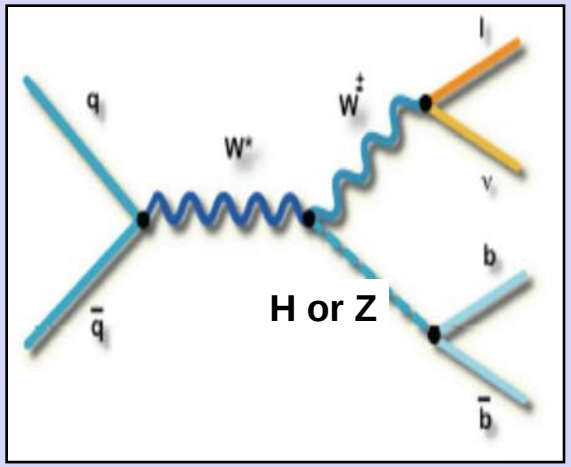
Significance of observed excess

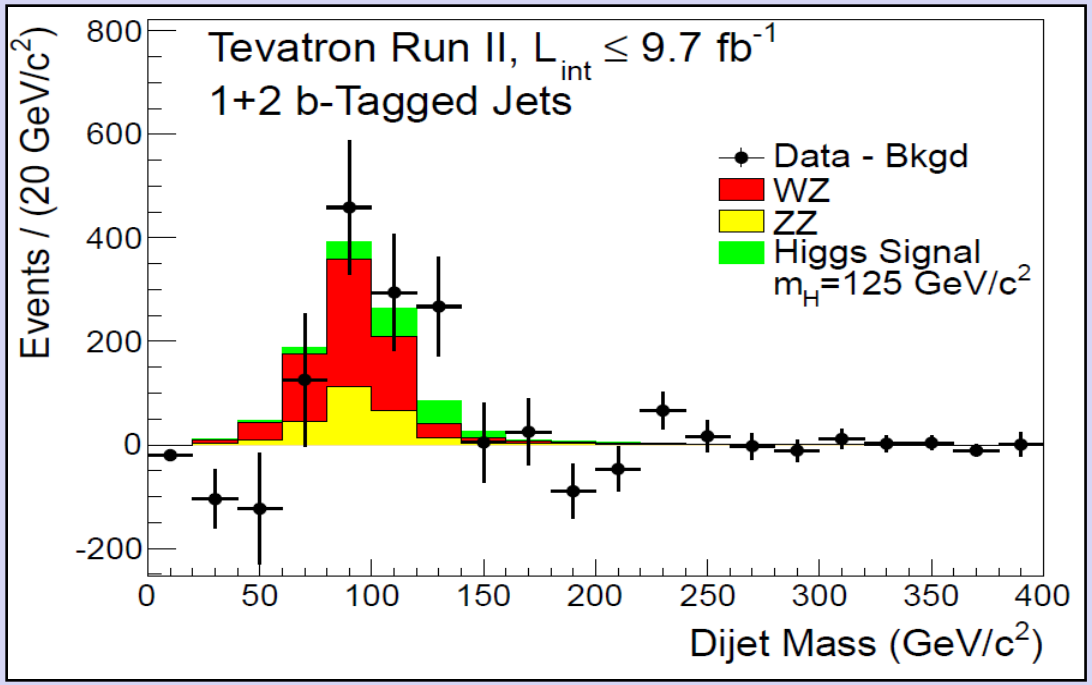
Channels	Local	Global
H→bb	3.3 σ	3.1 σ Evidence

Cross Check on Diboson Processes

Benchmark for H→bb searches using well known process

WZ, ZZ with W or Z decaying to leptons and Z decaying to heavy flavor jets





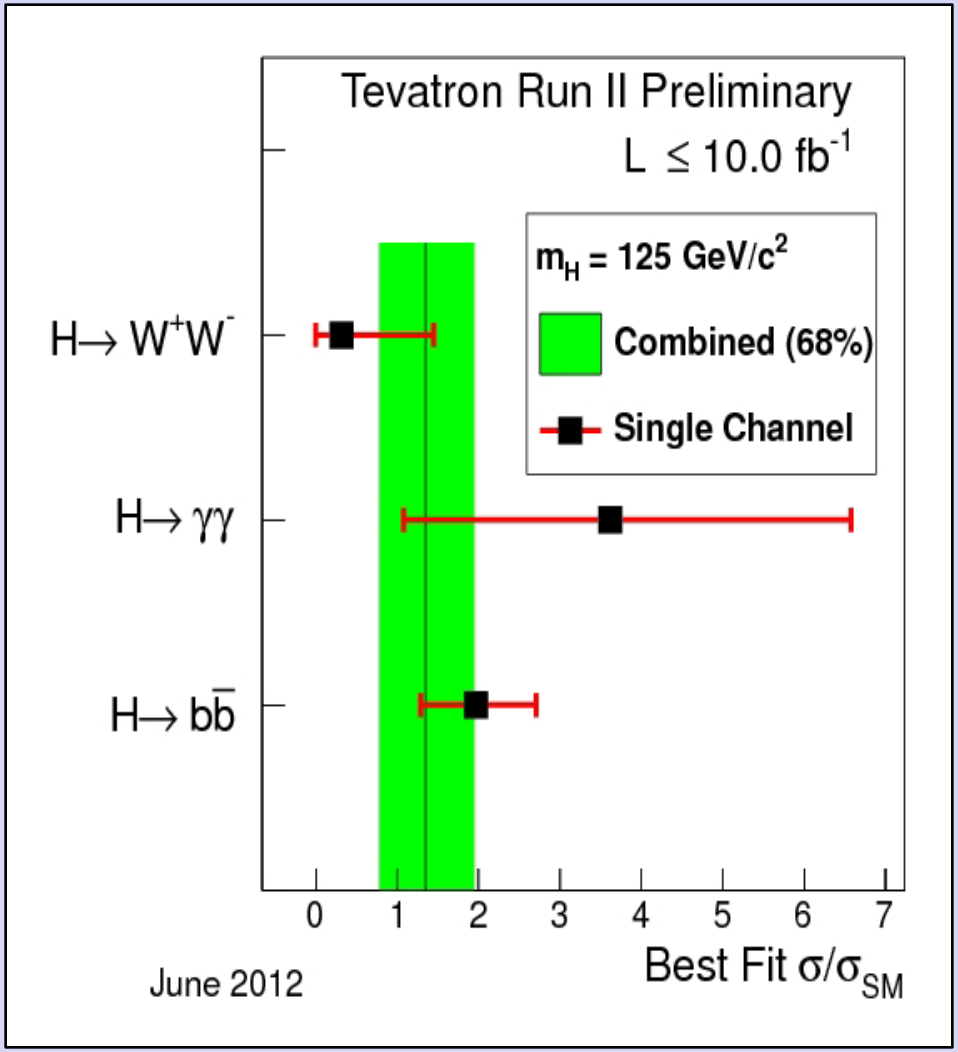
Apply exactly the same selections and multivariate analysis as for WH/ZH

CDF+DØ combination cross-section: 3.9 +/- 0.9 pb

SM prediction: 4.4 +/- 0.3 pb

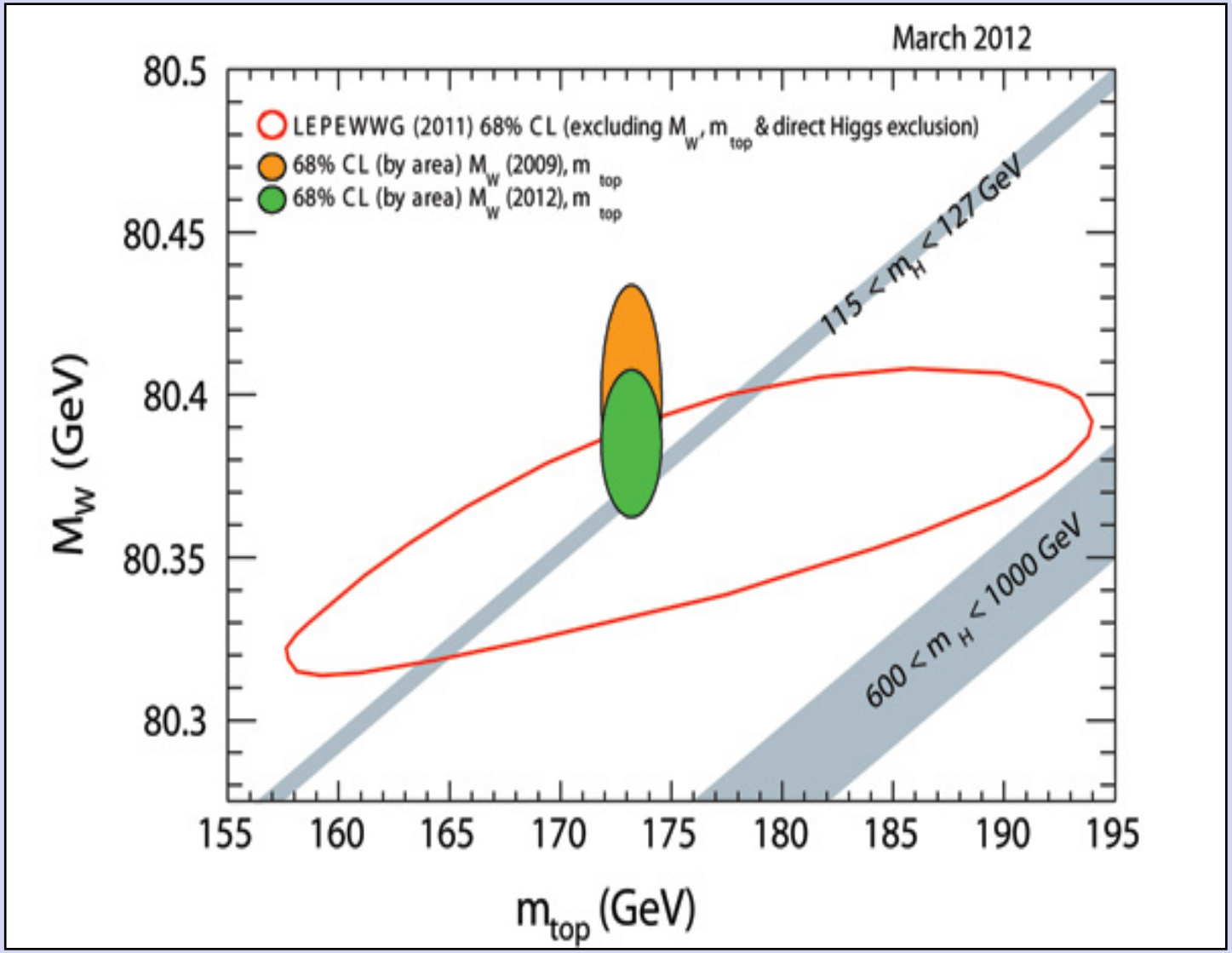
4.5 σ significance

Best Fit Cross Sections



Within errors data are compatible with predictions for Standard Model Higgs

Self-consistency of the Standard Model



Precision measurements of Standard Model parameters and Higgs mass of ~125 GeV are in perfect agreement

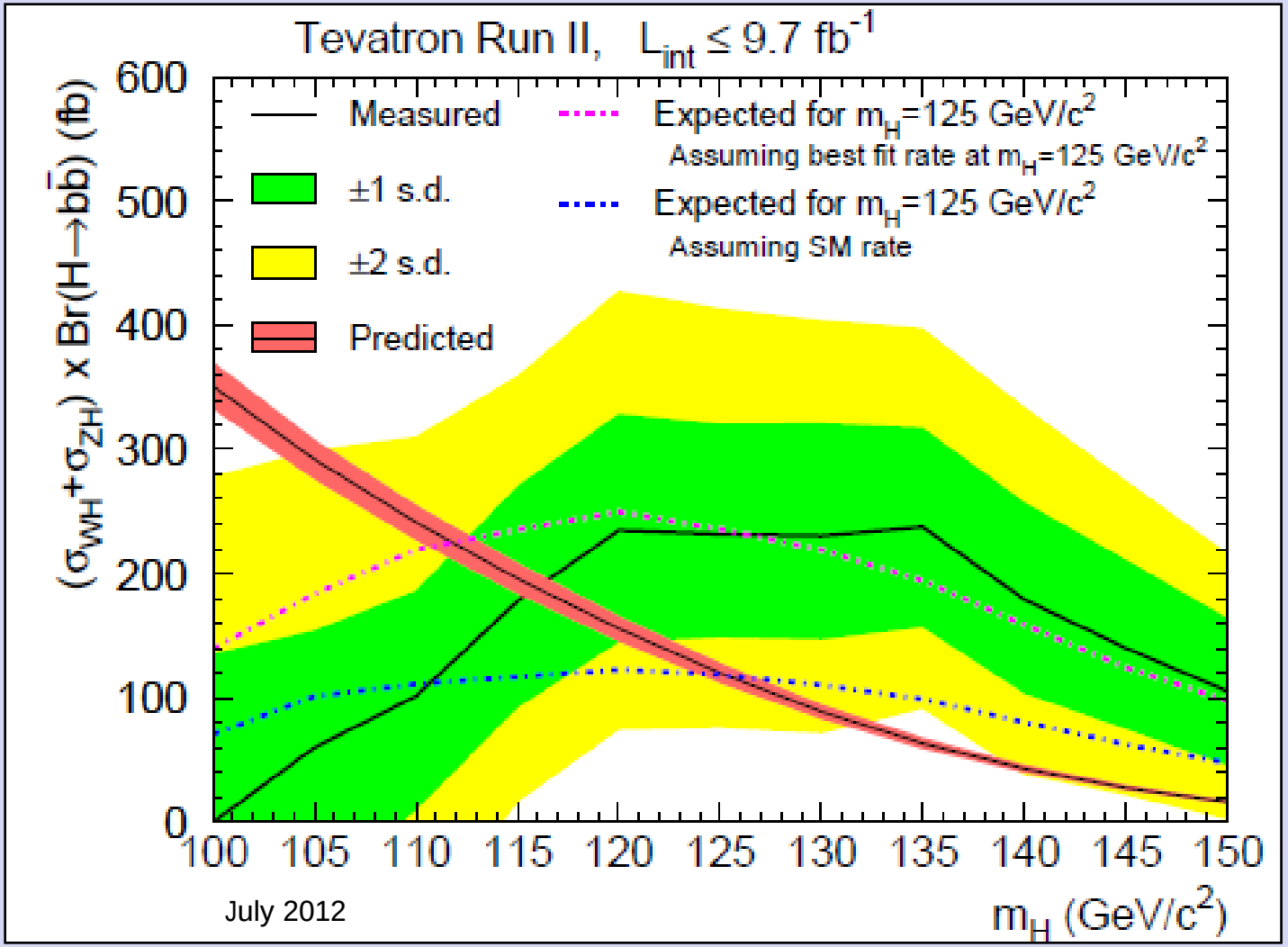
Tevatron Highlights Summary

- Tevatron experiments published over 1000 fundamental results
  - From the discovery of the top quark to the evidence of the Higgs boson production and decay to fermions
- Many extremely precise measurements of the Standard Model parameters
- 100's of searches for physics beyond Standard Model with two "clouds" remaining
  - Top quark forward-backward asymmetry
  - Anomalous di-muon asymmetry
- 10 fb^{-1} unique proton-antiproton collisions 1.96 TeV data set is accumulated
- Tevatron collaborations will publish ~100 papers in 2012
- Large number of analyses in all physics groups continues including
  - Top quark mass to ~0.6 GeV accuracy and W boson mass to ~10 MeV accuracy

Congratulations to our LHC colleagues with Higgs discovery and good luck!

Backup Slides

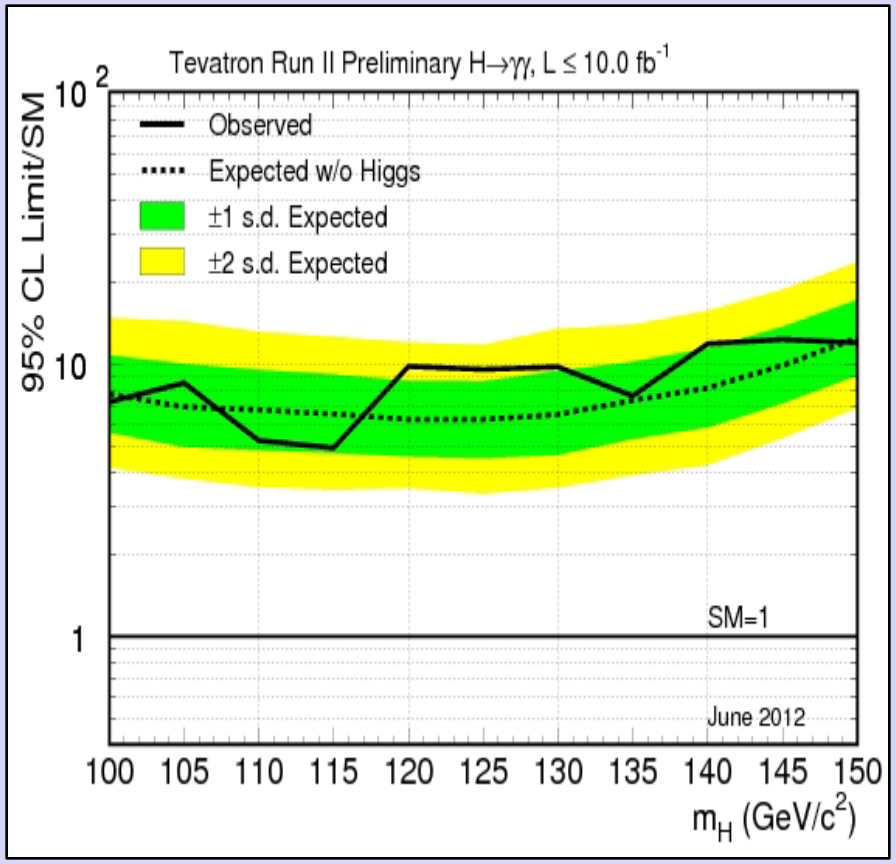
Cross Section * BR Measurement

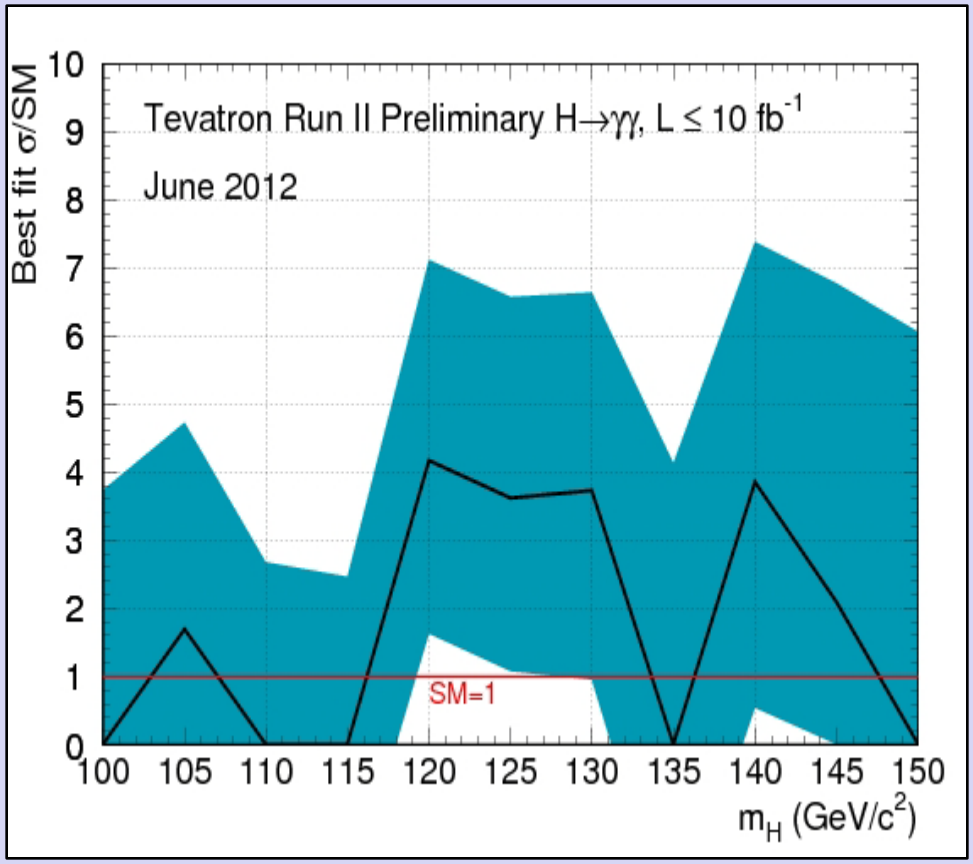


$$(\sigma_{WH} + \sigma_{ZH}) \times \mathcal{B}(H \to b\bar{b}) = 0.23^{+0.09}_{-0.08}\ (\text{stat} + \text{syst})\ \text{pb}$$

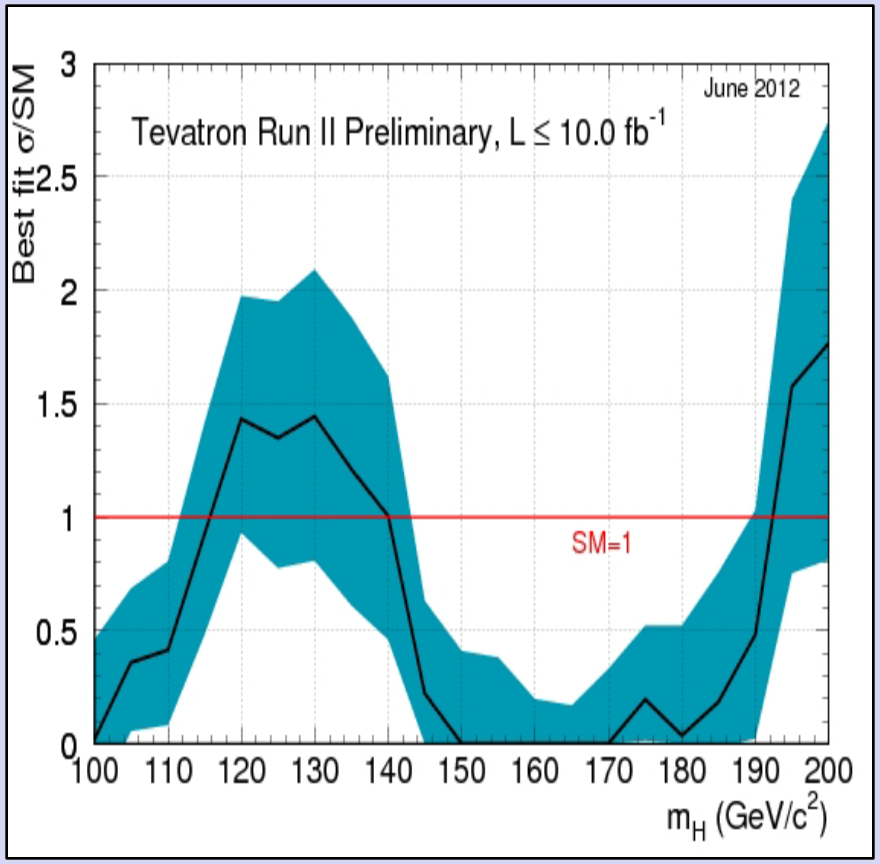
SM Higgs @ 125 GeV: 0.12 ± 0.01 pb

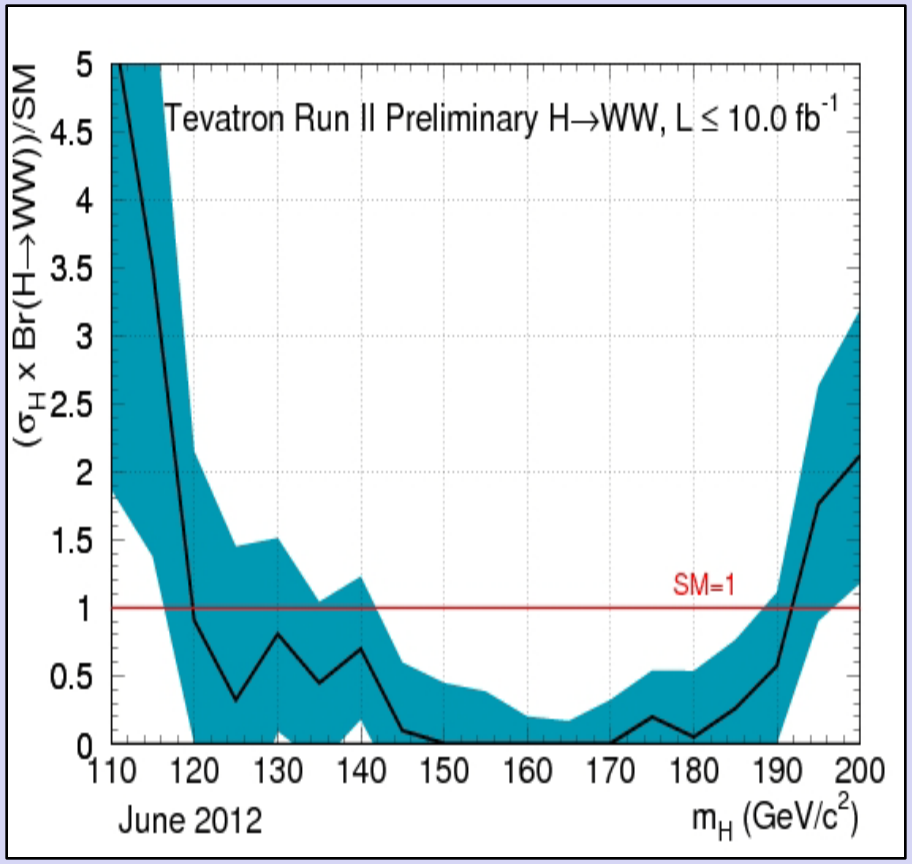
Higgs to γγ


Tevatron Run II Preliminary H→γγ, L ≤ 10.0 fb-1
95% CL Limit/SM
Observed
Expected w/o Higgs
±1 s.d. Expected
±2 s.d. Expected
SM=1
June 2012
mH (GeV/c2)

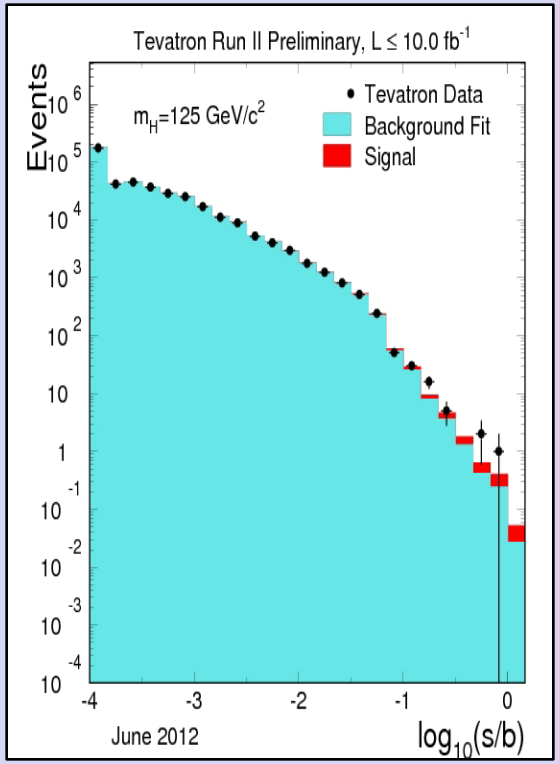

Tevatron Run II Preliminary H→γγ, L ≤ 10 fb-1
June 2012
Best fit σ/SM
SM=1
mH (GeV/c2)

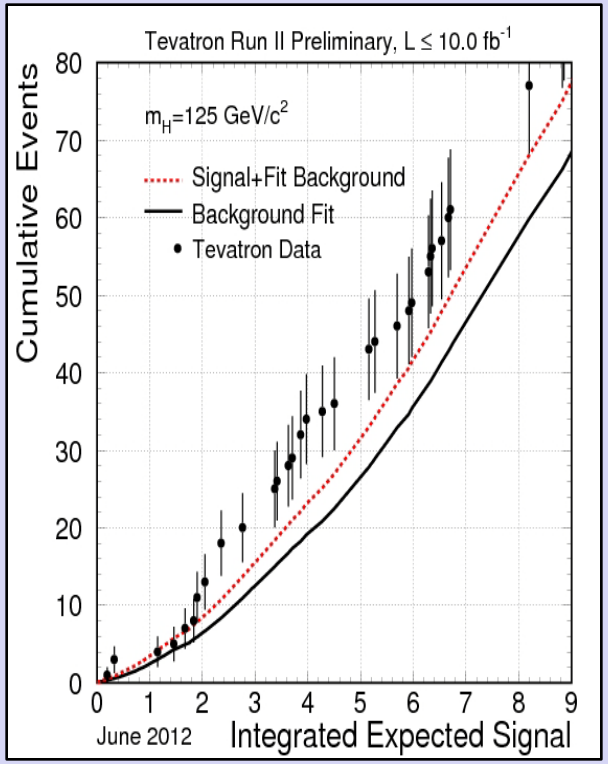
Best Fit Cross Sections

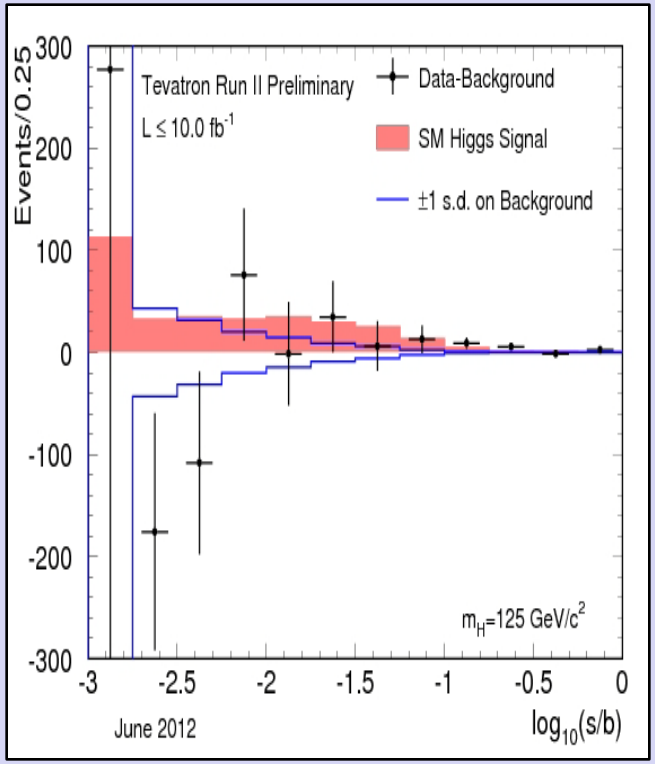




Full Combination Events Count







H to bb Combination Events Count