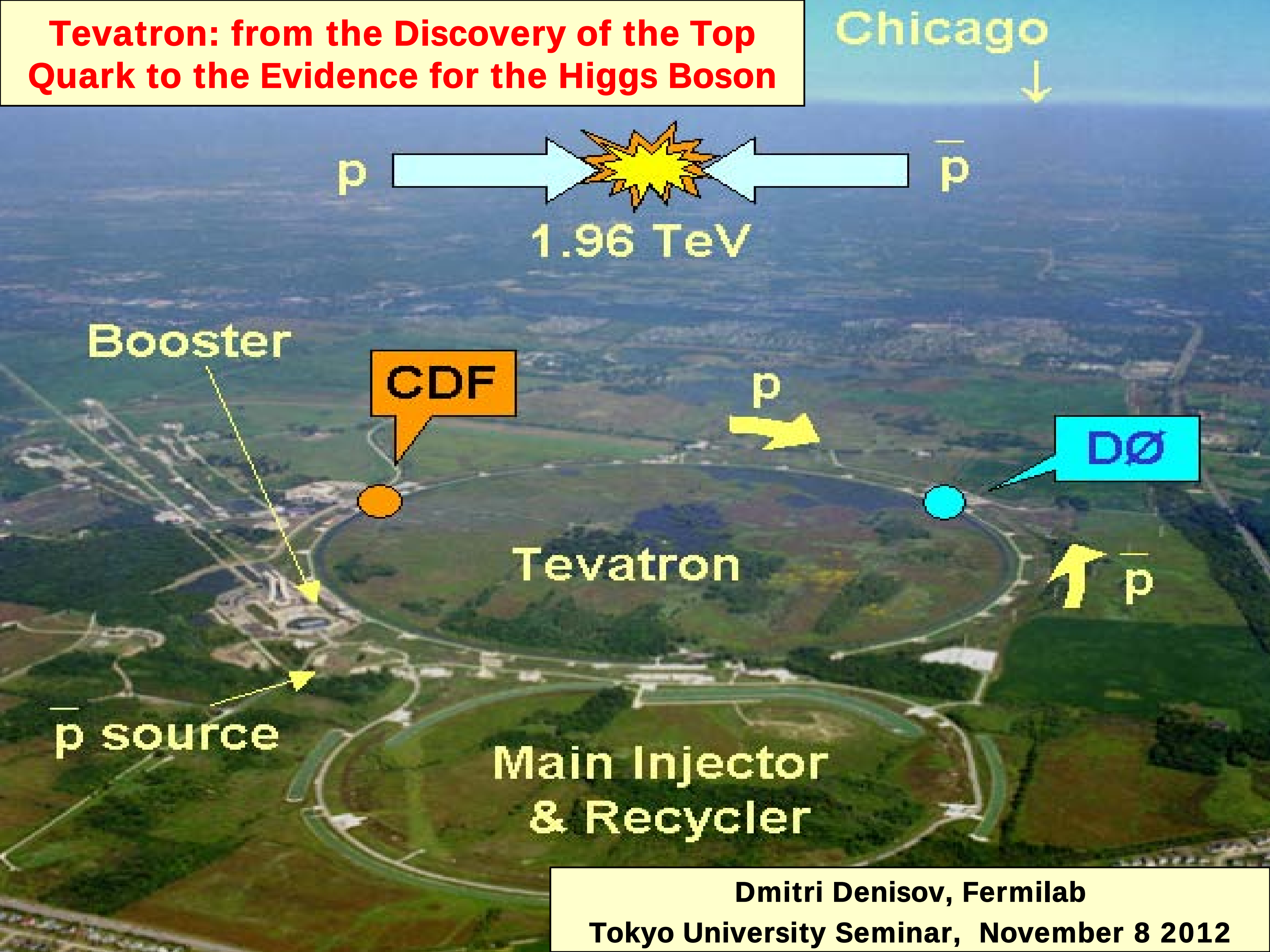
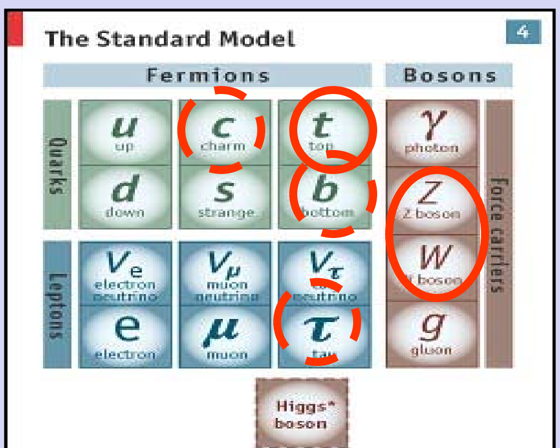
Tevatron: from the Discovery of the Top Quark to the Evidence for the Higgs Boson



Dmitri Denisov, Fermilab

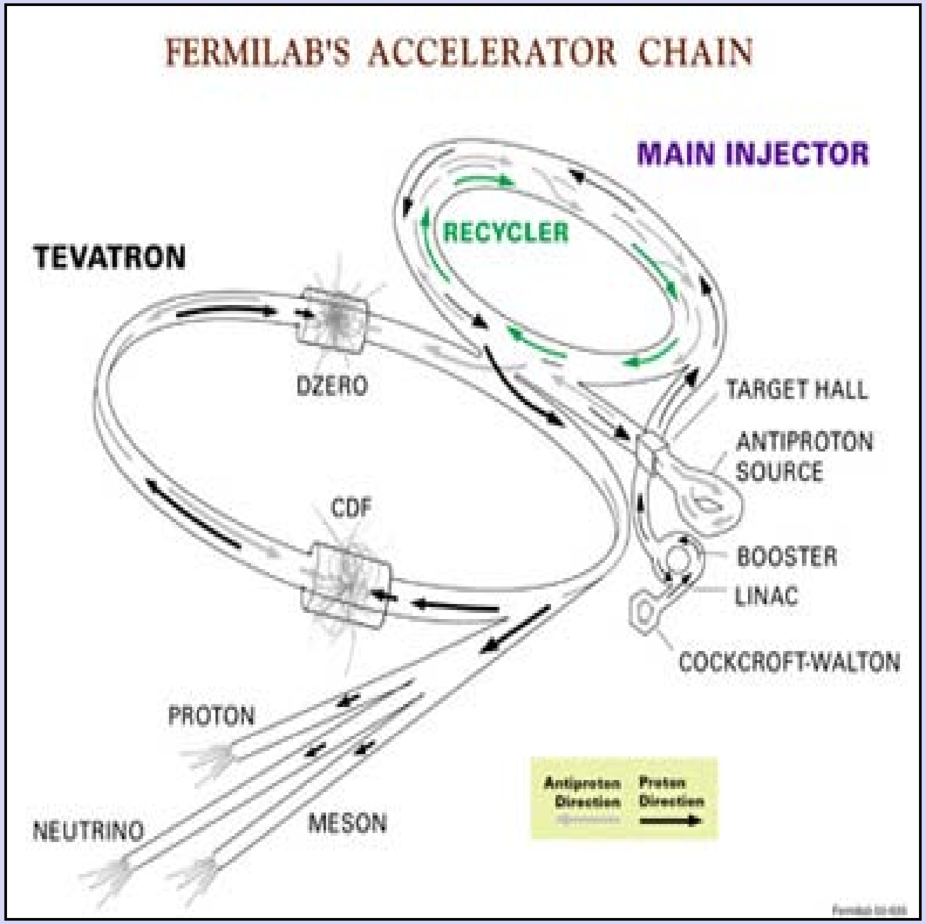
Tokyo University Seminar, November 8 2012

From Fixed Target to Colliders



- **In late 1970's the hunt for heavier and heavier elementary particles continued**
  - **Fixed target E_{cms} ~ √2mE : for 100 GeV particle ~5 TeV accelerator is required**
- **Brilliant idea: use existing proton accelerators and circulate antiprotons in the same beam pipe to collide**
- **Main challenge was to make enough antiprotons to have dense particle beams**
  - **SppS and Tevatron were born**

Tevatron: Proton-antiproton Collider

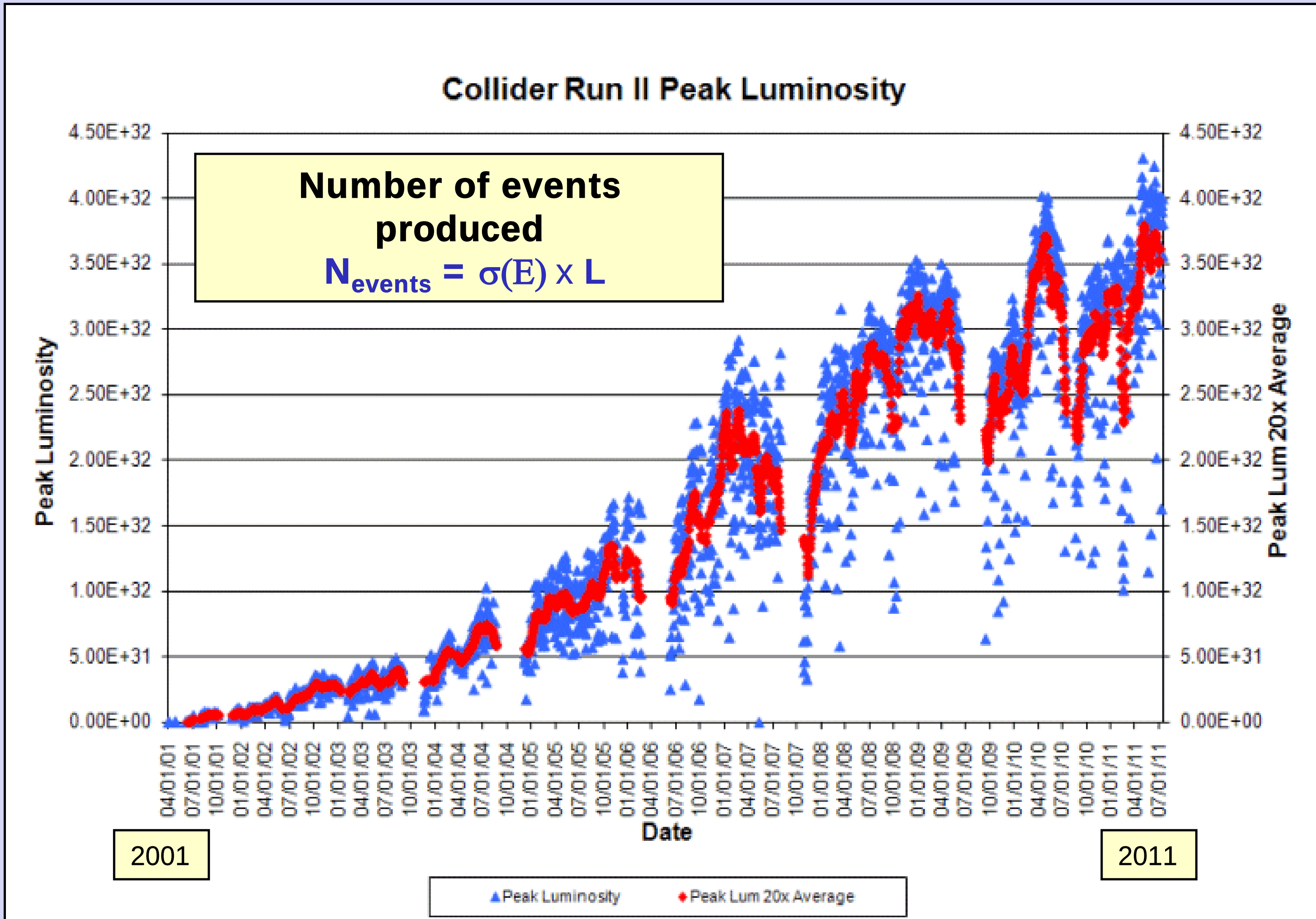


	Run I 1992-1996	Run IIa 2001-2006	Run IIb 2006-2011
Bunches in Turn	6 × 6	36 × 36	36 ×36
√s (TeV)	1.8	1.96	1.96
Typical L ($cm^{-2}s^{-1}$)	1.6×10^{30}	9×10^{31}	3×10^{32}
∫Ldt (pb^{-1}/week)	3	17	50
Bunch crossing (ns)	3500	396	396
Interactions/crossing	2.5	2.3	8

Run I → Run IIa → Run IIb
0.1 fb^{-1} ~1 fb^{-1} ~12 fb^{-1}

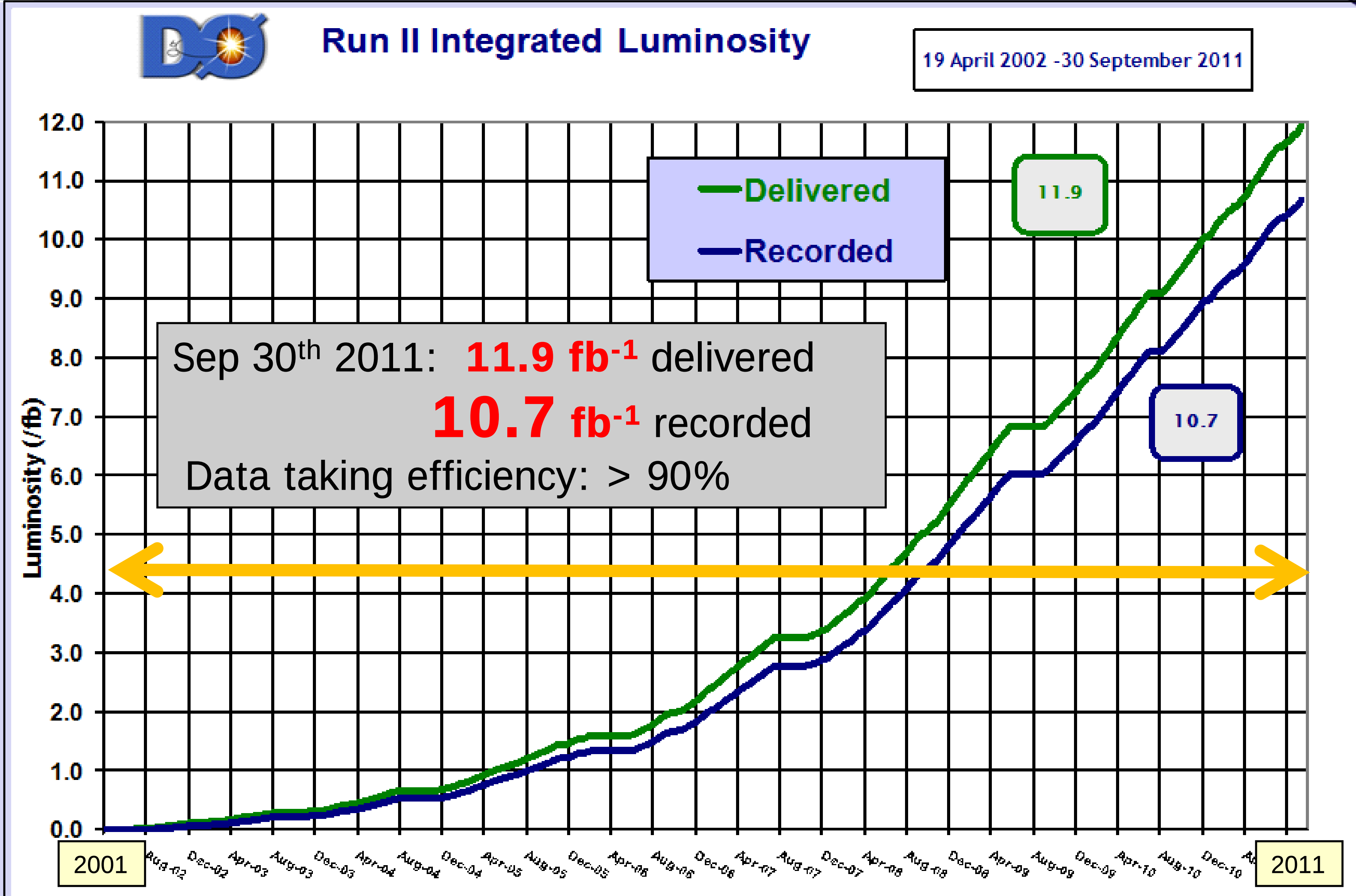
- Chain of six accelerators to get to 1 TeV per beam energy
- Single magnet ring – protons and antiprotons circulate in the opposite directions
- Elaborate source of antiprotons – main driver of the Tevatron luminosity
  - Use of electron cooling of antiproton beam
- Collision particles wavelength is ~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

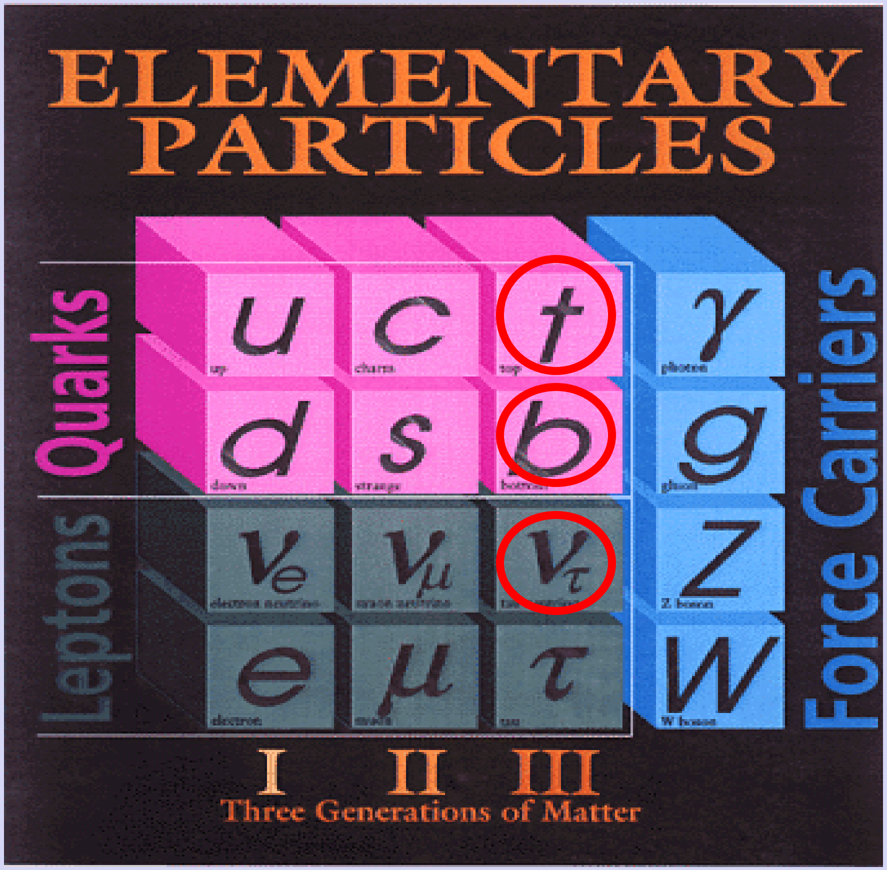


- **Total data set is ~5 times above original Tevatron Run II goal**
- **Detectors and accelerator components operated well till last store on September 30, 2011**

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...



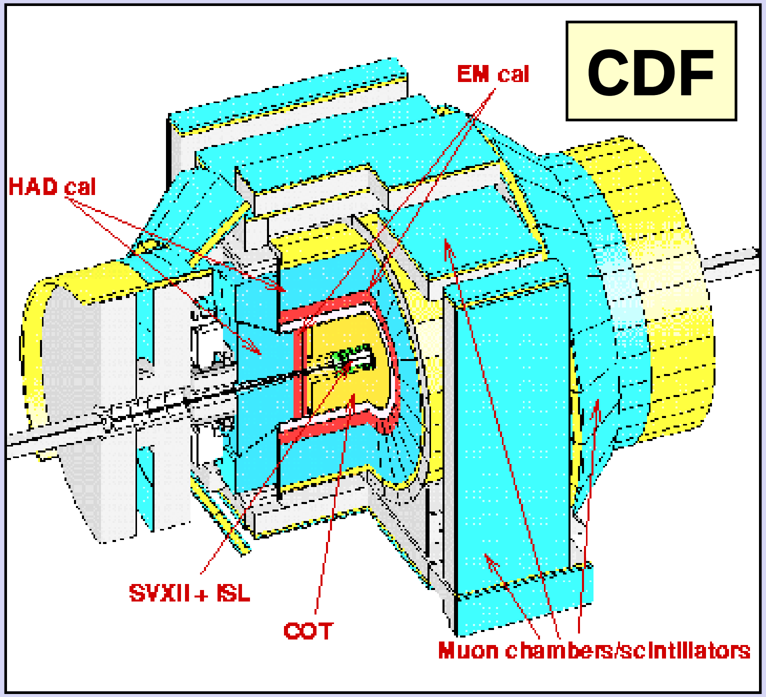
Fundamental Questions

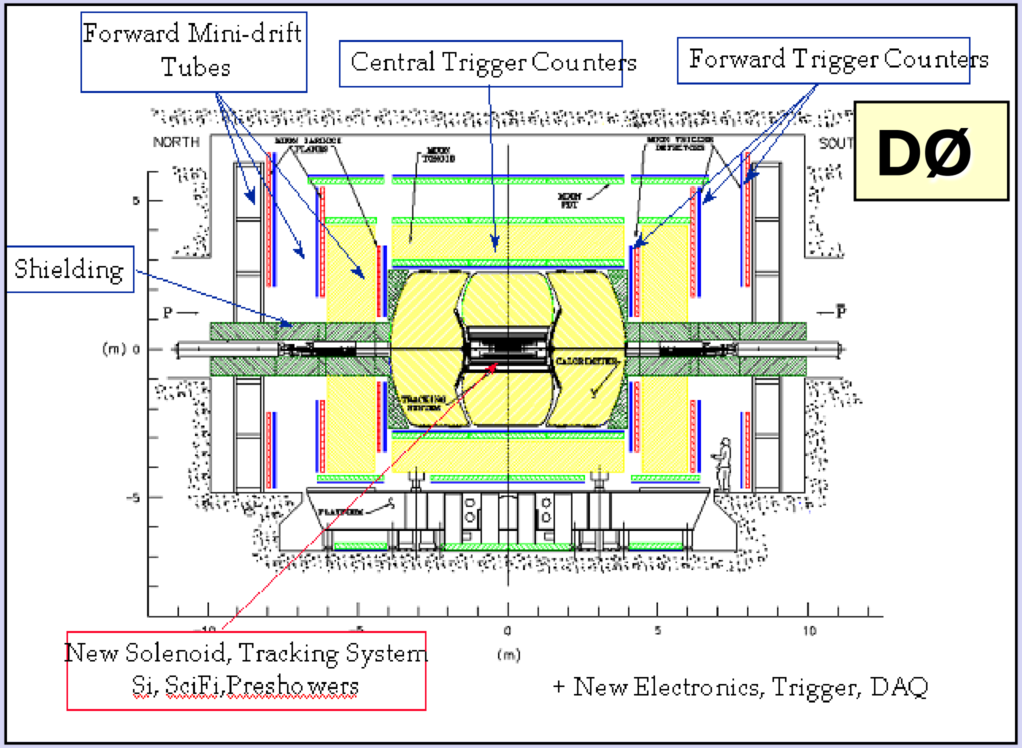
- ✓ Quark sub-structure?
- ✓ Origin of mass? Higgs?
- ✓ Matter-antimatter asymmetry?
- ✓ What is cosmic dark matter?
  SUSY?
- ✓ What is space-time structure?
  Extra dimensions?...

The CDF and DZero Collaborations

Tevatron collaborations are ~1000 scientists from 26 countries

CDF and DØ Detectors





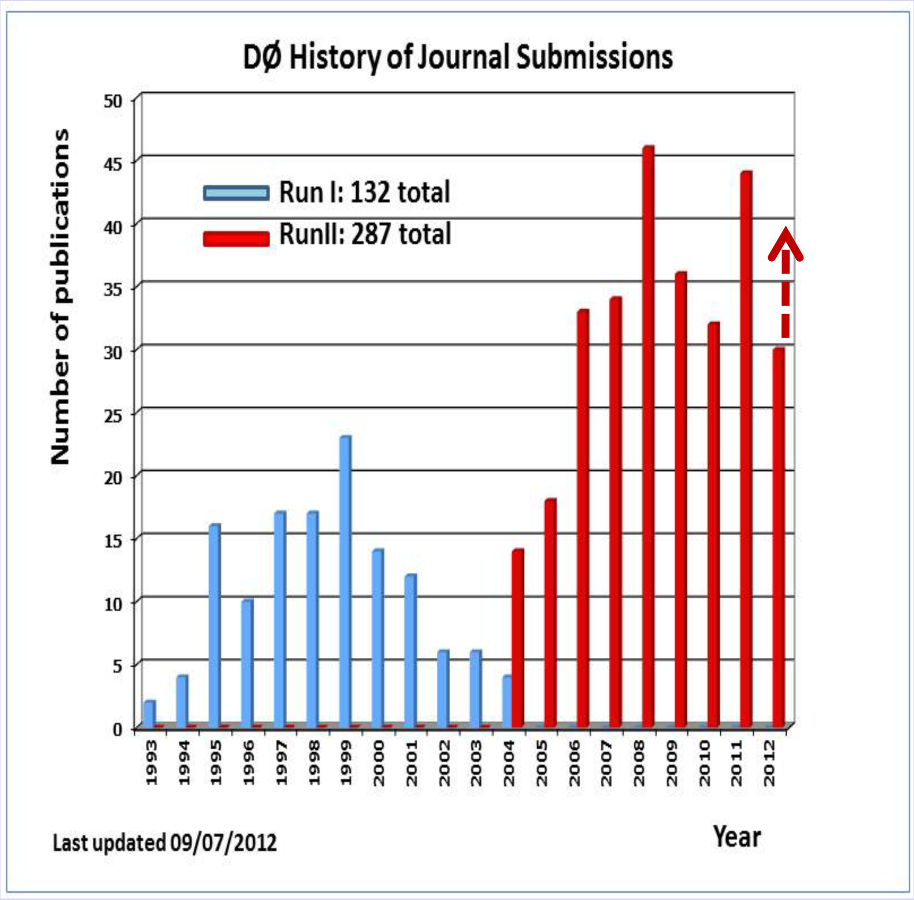
Silicon Detector
Central Drift Chamber
Calorimetry
Extended muon coverage
Fast electronics

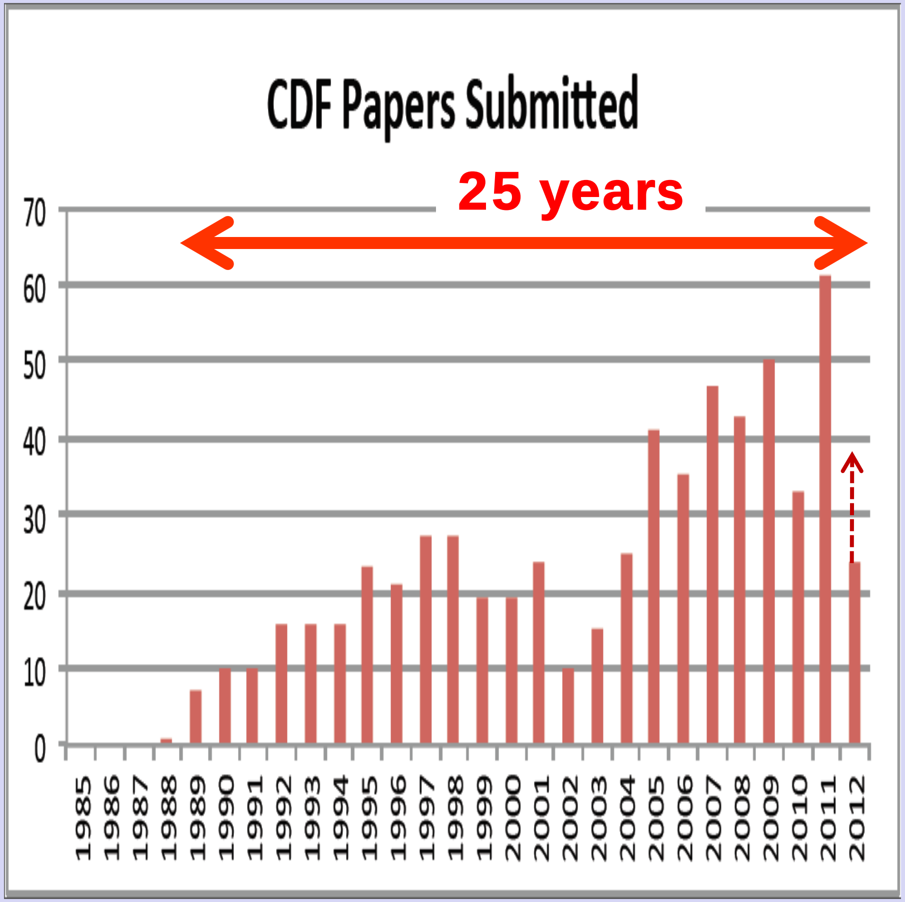
Silicon Detector
2 T solenoid and central fiber tracker
Large coverage muon system
Fast electronics

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

Layout of the hadron collider detectors have been finalized at the Tevatron

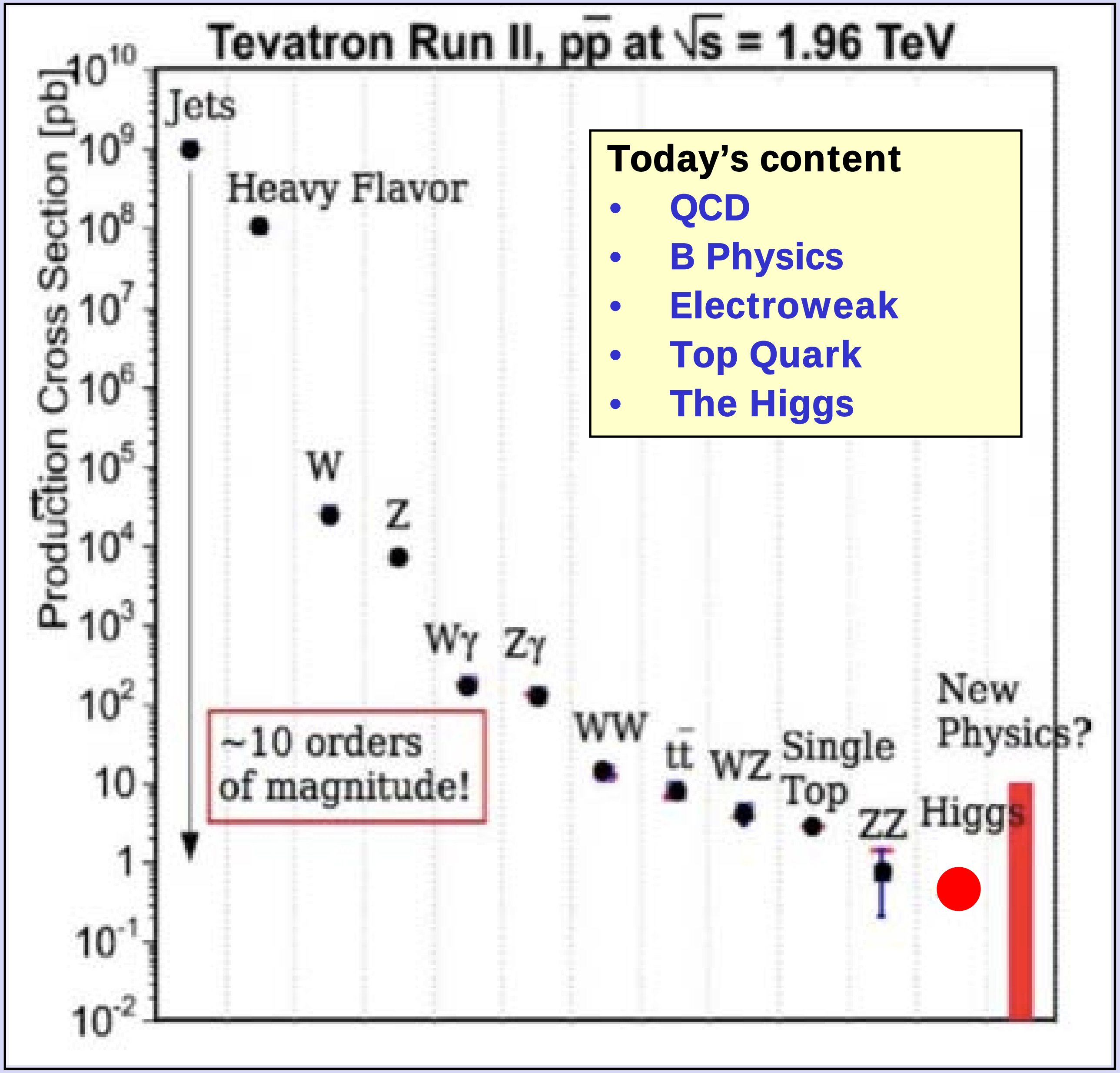
Tevatron Results





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

Tevatron Cross Sections



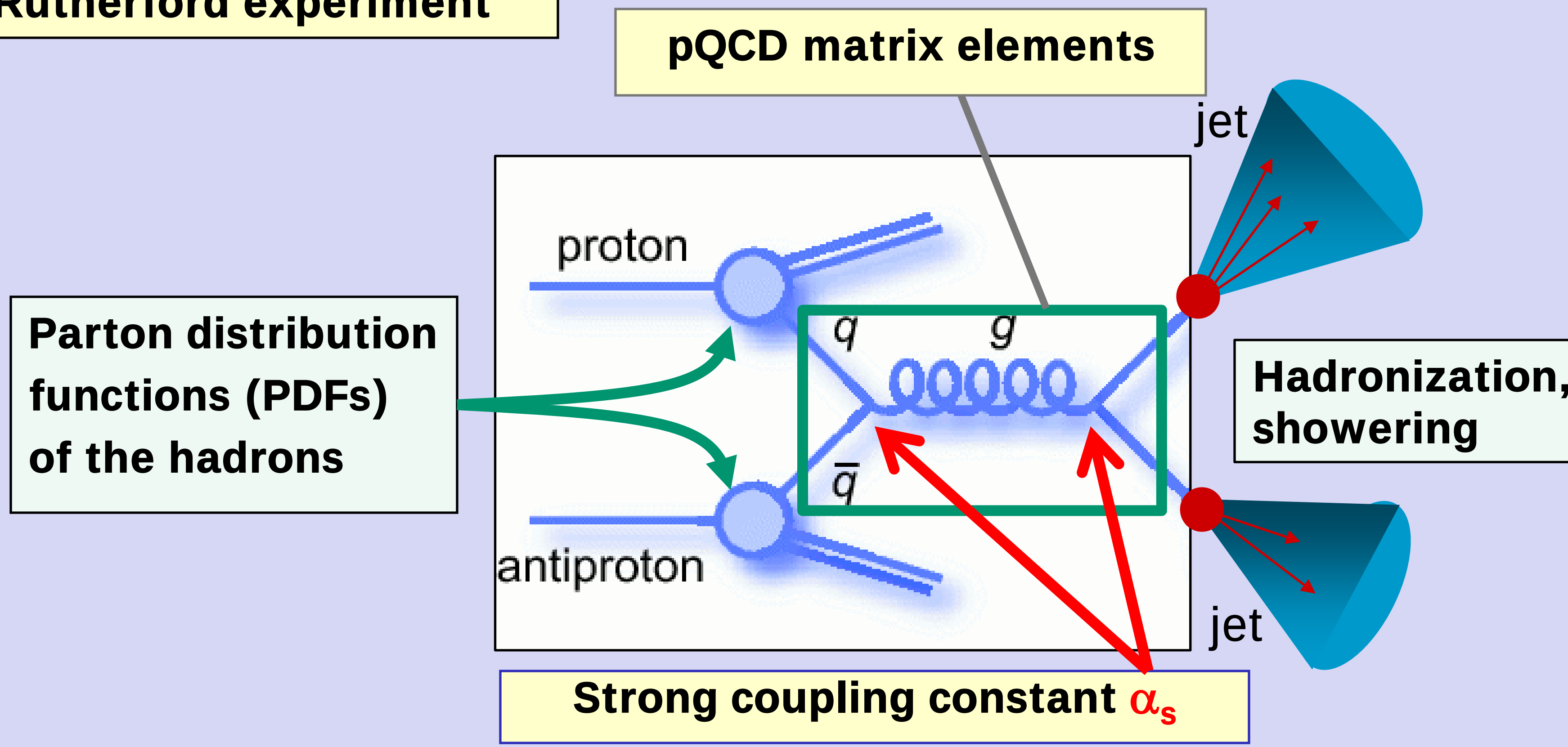
Today's content

- QCD
- B Physics
- Electroweak
- Top Quark
- The Higgs

Studies of Quantum Chromo Dynamics – QCD

The most copious physics process at hadron colliders

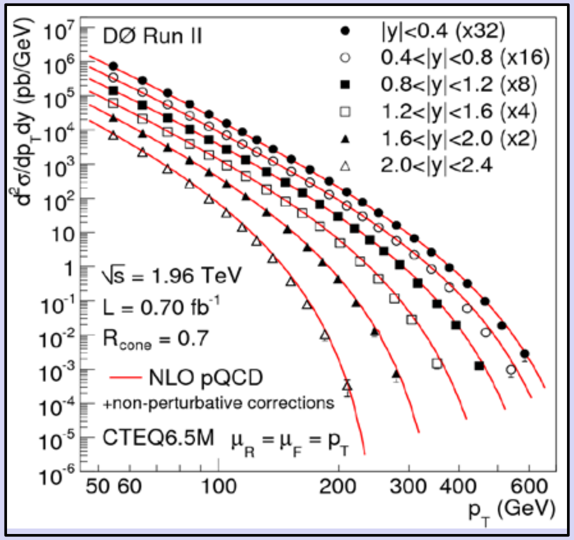
"Rutherford experiment"



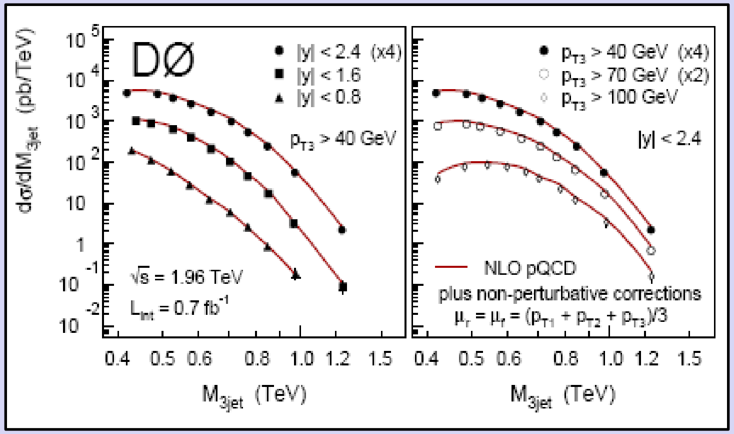
- **PDFs, higher order corrections, α_s measurements, production of vector bosons and jets, direct photons, double parton interactions and many others**
- **Understand how strong force works and to be able to predict backgrounds for processes with much lower cross sections**

Various QCD Measurements

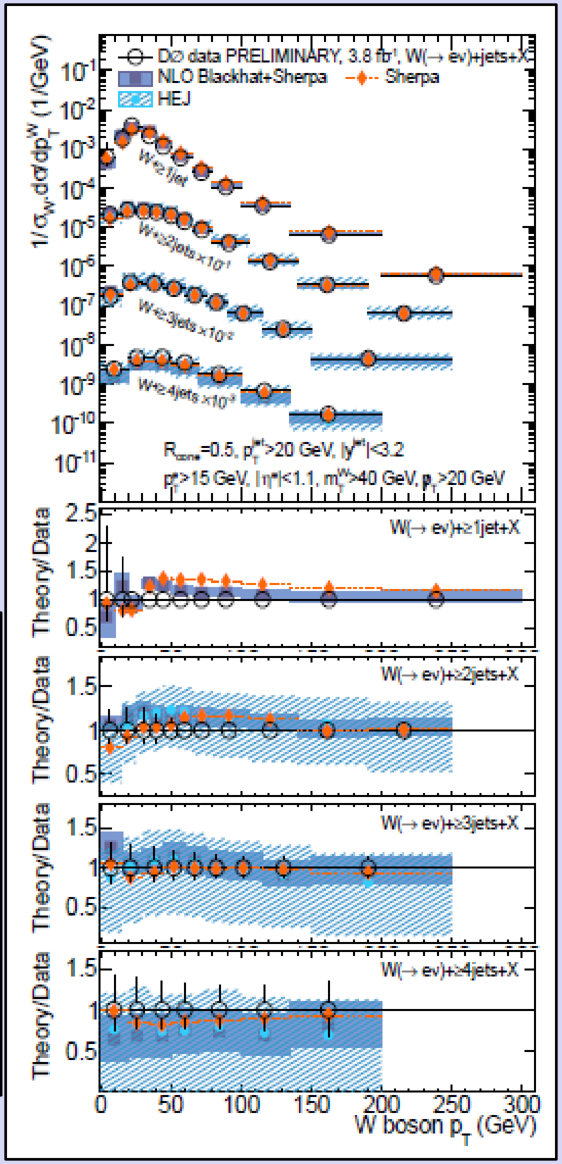
Inclusive Jets



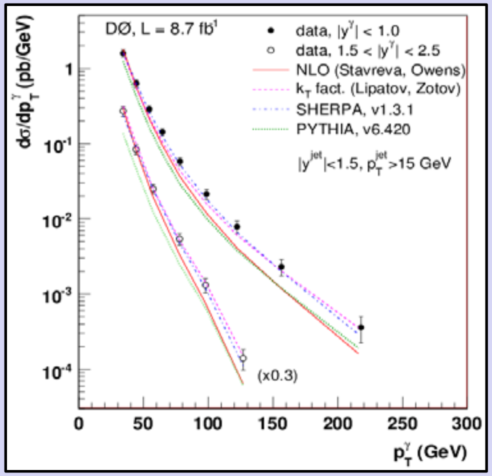
3 jets distributions



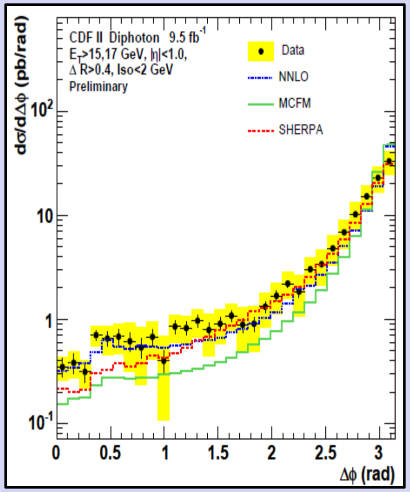
W + jets

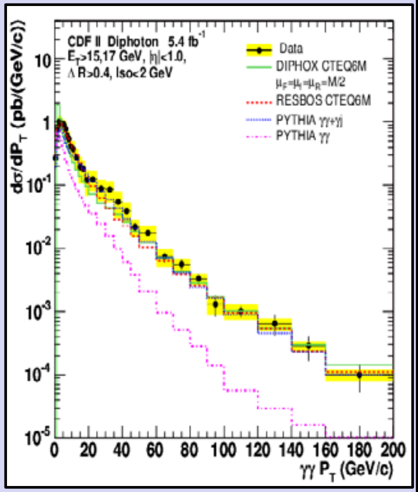


γ + b-jets



Di-photons



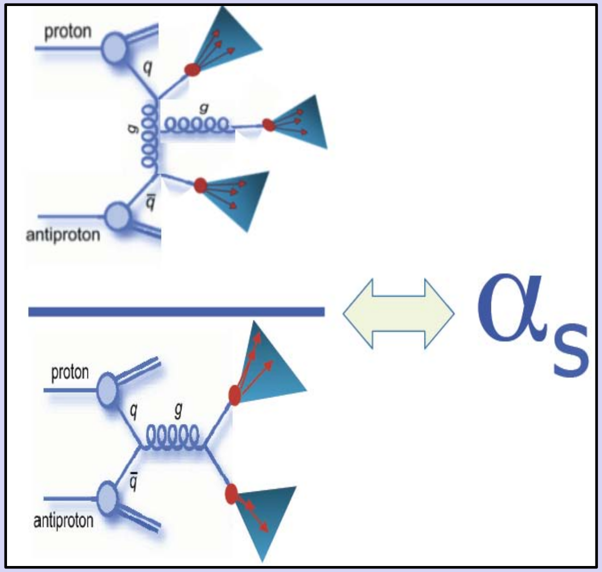


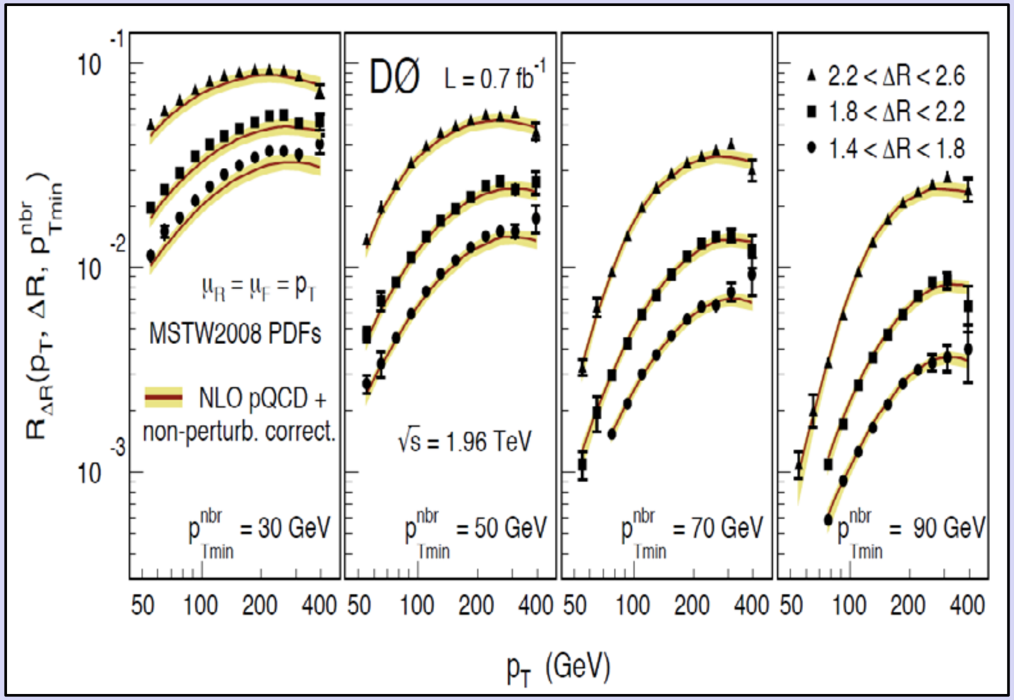
Many important results including generators testing

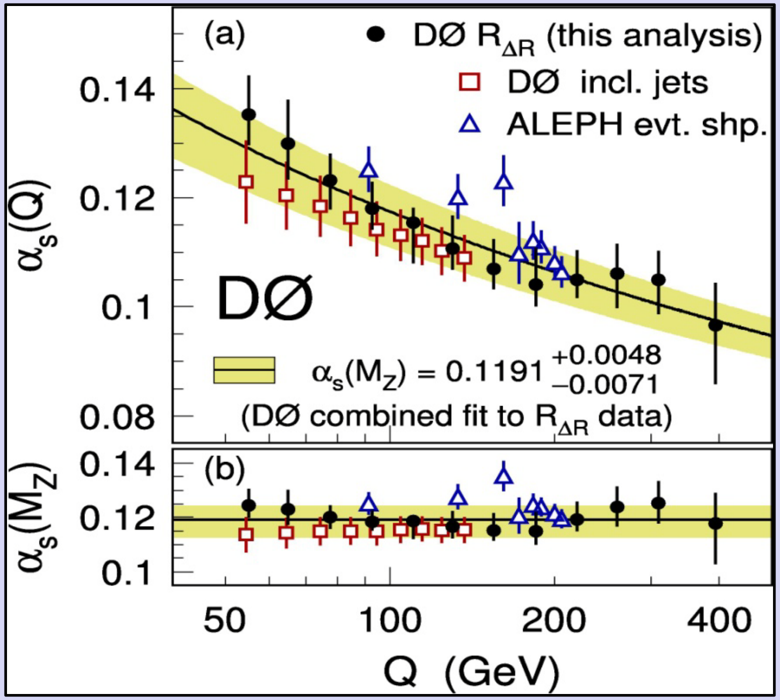
α_s Running at Untested Scale > 208 GeV

- $R_{3/2} = \sigma_{3Jet} / \sigma_{2Jet}$
- **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

b-quark Studies

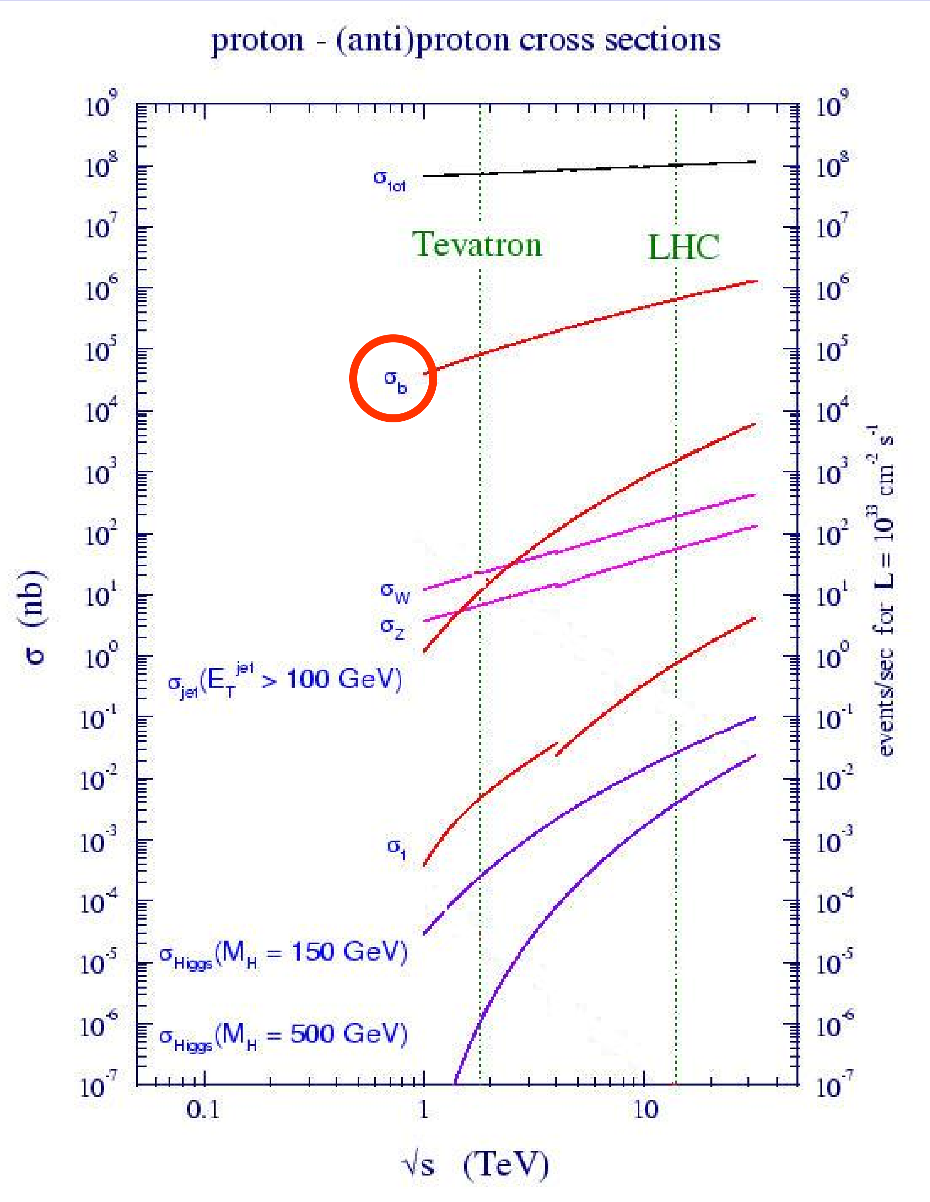
High b quark cross section at Tevatron

~10^{-3} σ_{tot}

~10^4 b's per second produced!

Large data samples of particles with b-quarks provide

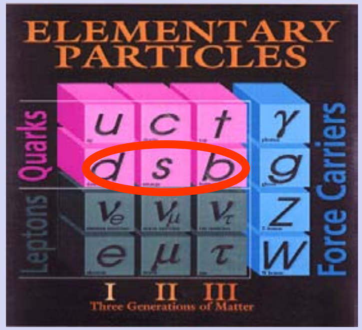
- **B mesons lifetime studies**
- **Mass spectroscopy (B_c, etc.)**
- **Studies of B_s oscillations**
- **CP violation studies**
- **Search for new b hadrons**
- **Search for rear decays**

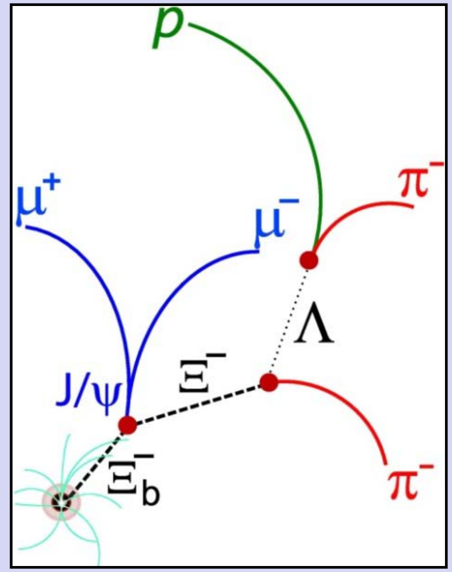


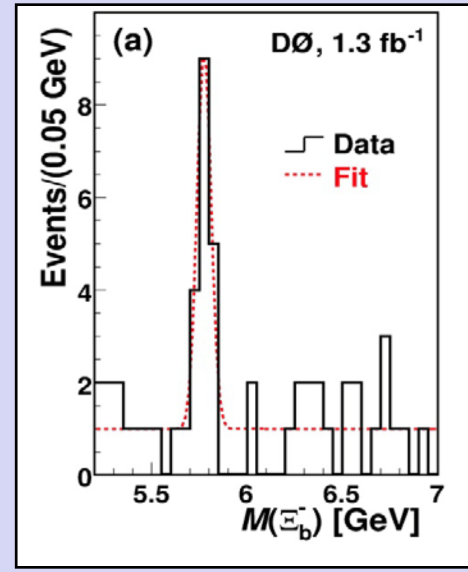
Discoveries of b-Baryons

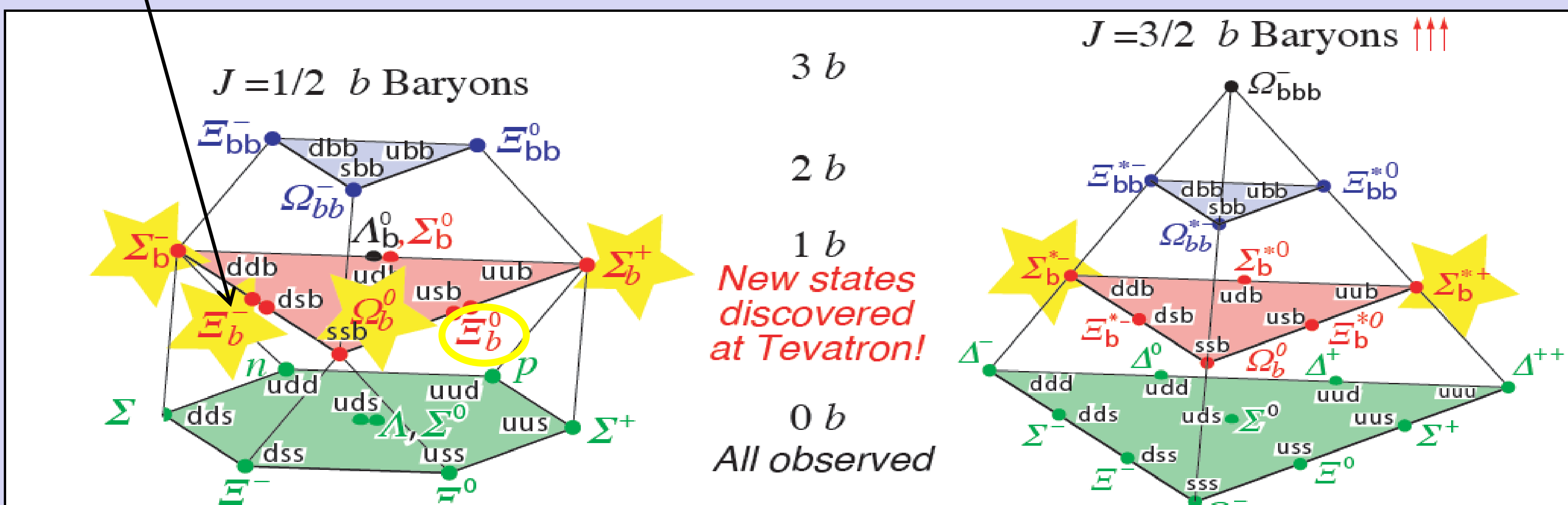
All b quark containing species are produced: $B^{\pm}$, B^0, B_s, B_c, Λ_b …and many new heavy baryons!

First baryon with quarks from all three generations observed!





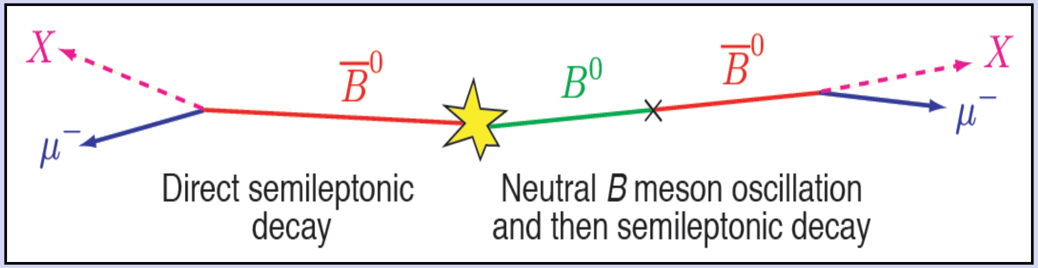


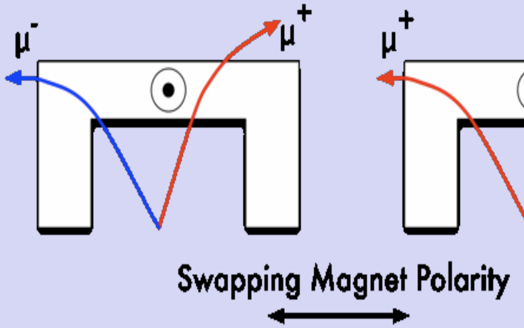


Until Tevatron, ground state Λ_b was the only directly observed b baryon

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

DØ di-muon Charge Asymmetry





- **Di-muon charge asymmetry**

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

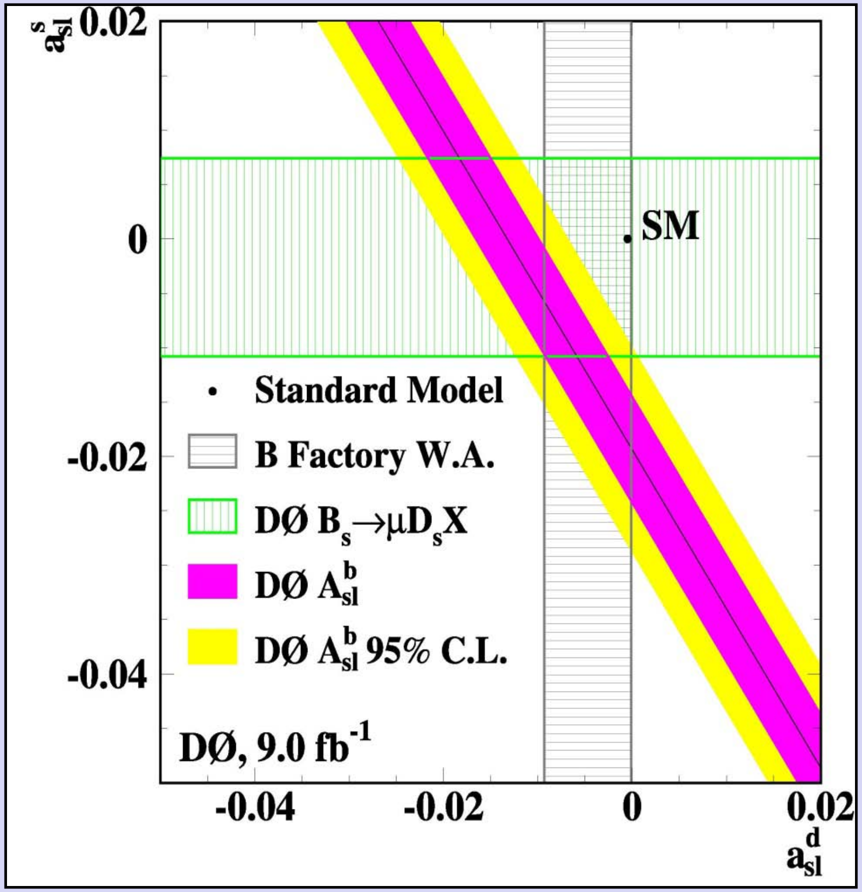
for events coming from decays of mesons containing b quarks undergoing mixing

- **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:

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

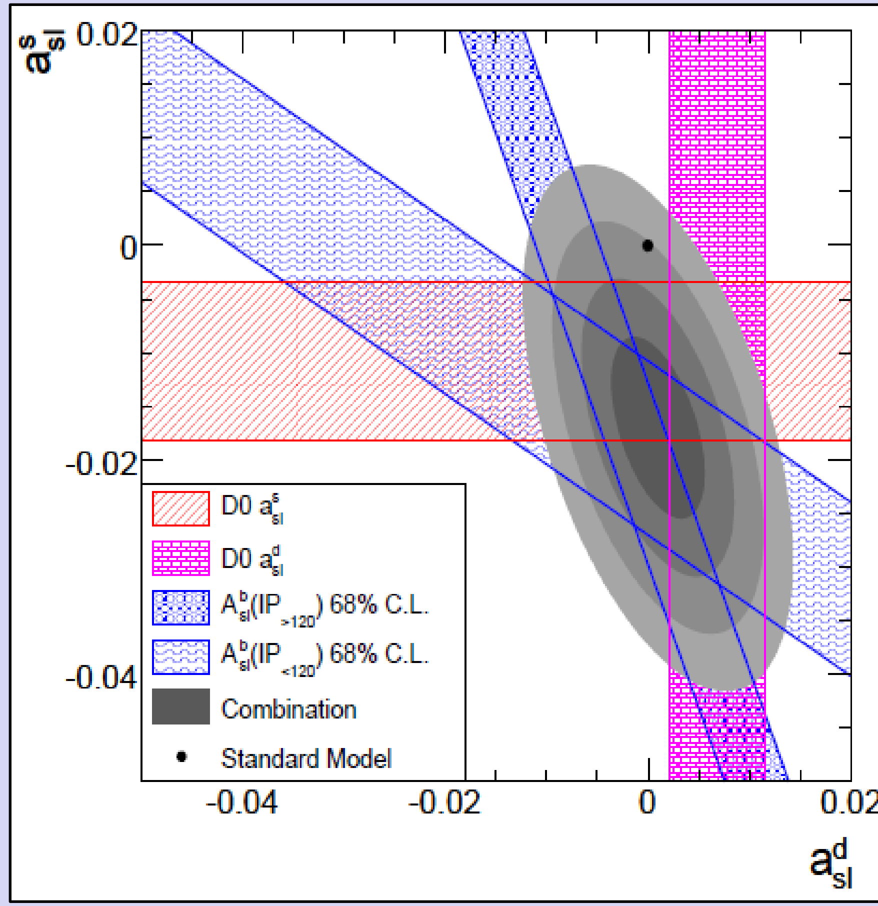
$$a_{sl}^s = [-1.08 \pm 0.72\,(\mathrm{stat}) \pm 0.17\,(\mathrm{syst})]\,\%$$

Decay channels for B^0:

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

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

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



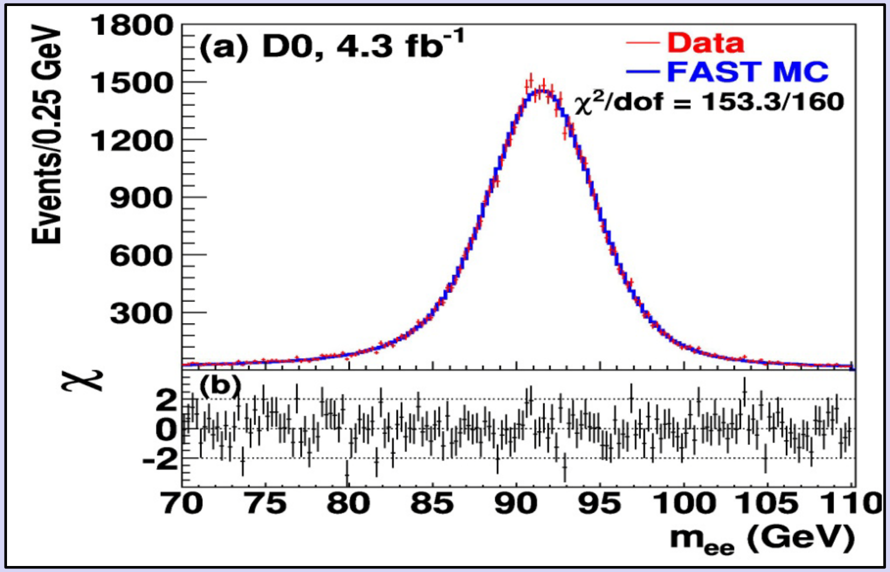
- **Combined DØ result**
  - **Deviation is ~2.9 σ from the SM**
- **Reasons**
  - **New physics?**
  - **Un-known systematic?**
  - **Di-muon asymmetry is not related to B mesons oscillations?**

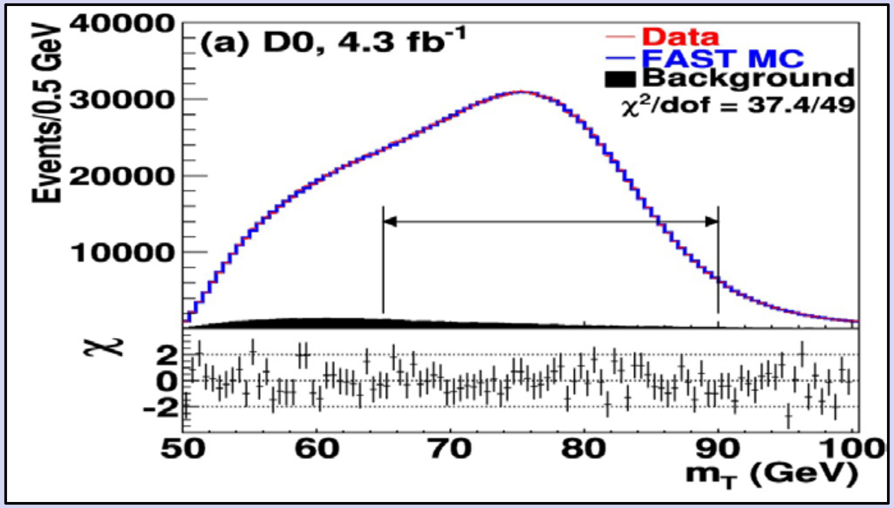
LHCb : $a_{sl}^s = (-0.24 \pm 0.54 \pm 0.33)\%$

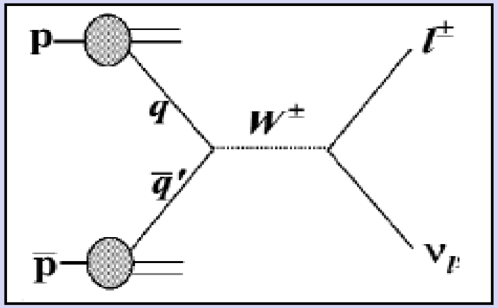
B-Factories : $a_{sl}^d = (-0.05 \pm 0.56)\%$

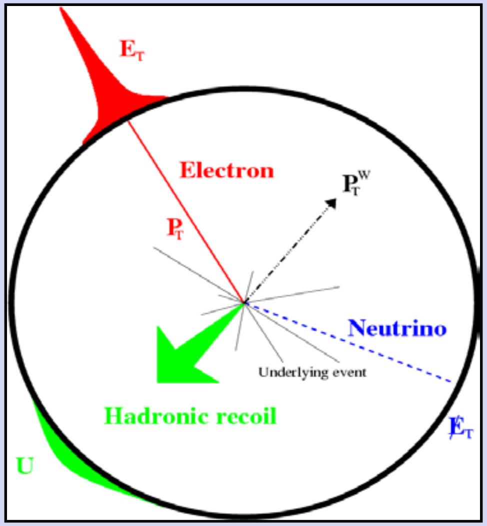
Electroweak: W Boson Mass Measurement

Single and pair W/Z production, asymmetries, weak mixing angle…





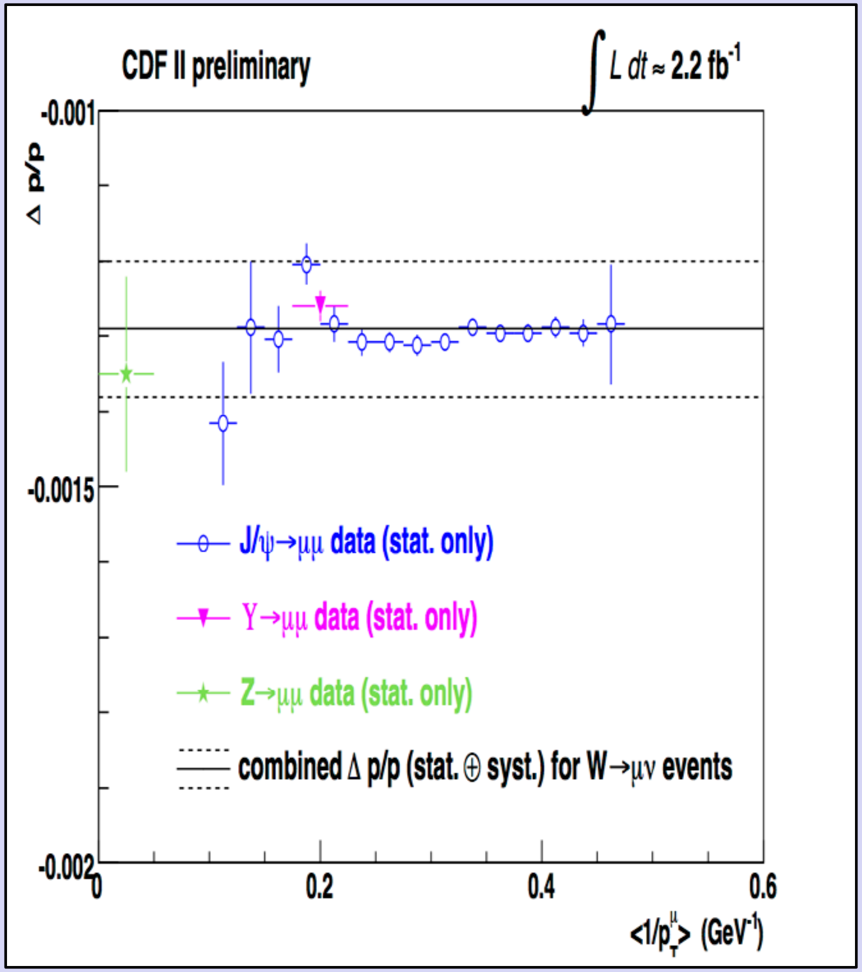


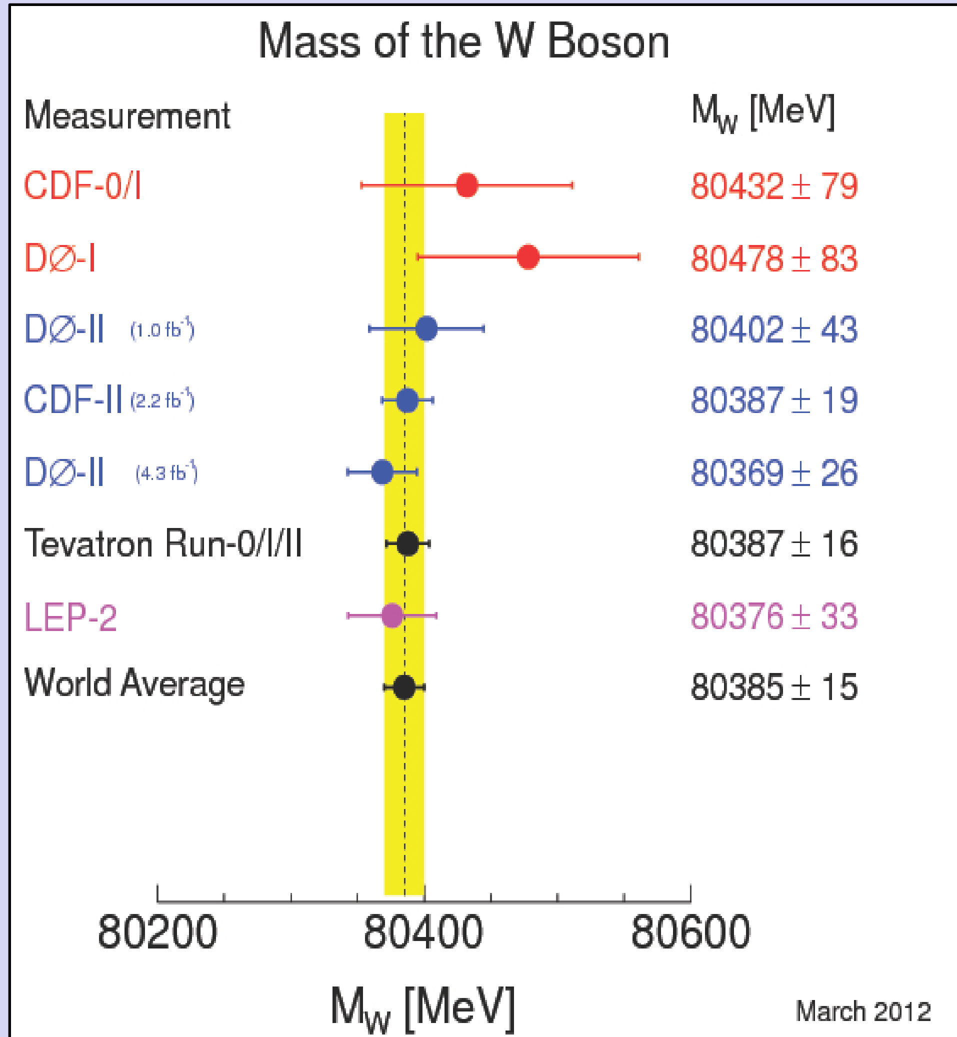


M_W = 80,375   23MeV
0.03% accuracy

- **W boson mass is measured using decay products: electron and neutrino**
- **DØ : 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%)

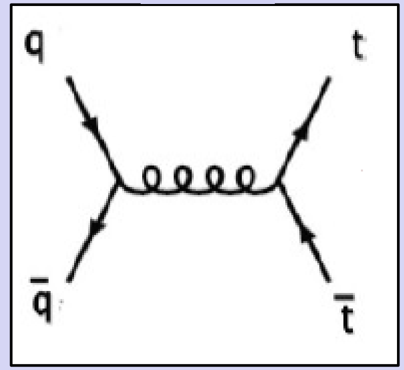
Top Quark Studies

Heaviest known elementary particle: ~173 GeV

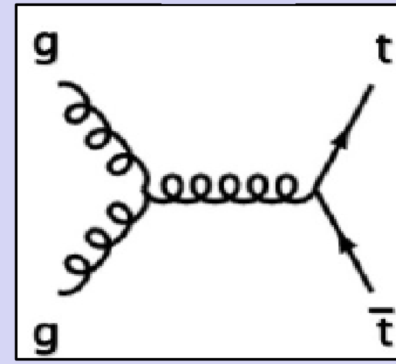
→Measure properties of the least known quark
- **mass, charge, decay modes, etc.**
- **data sets of 1000's of top quarks exist**

→ Short life time: probe bare quark

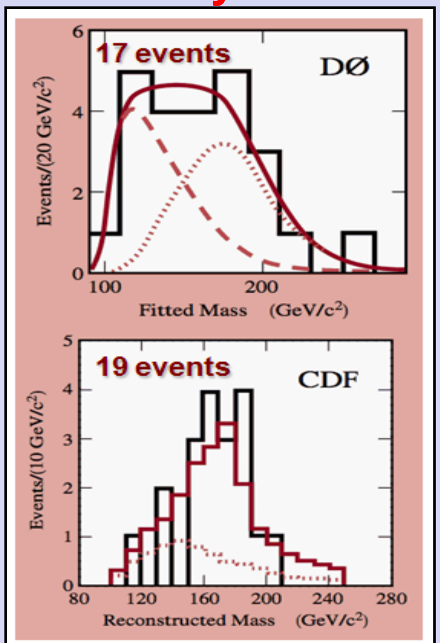
85 %



15 %

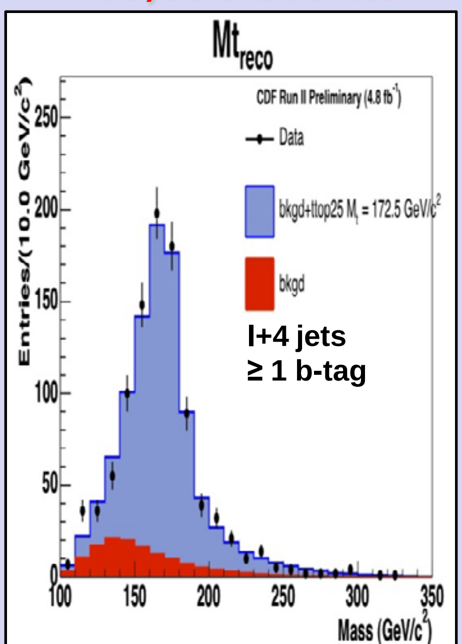


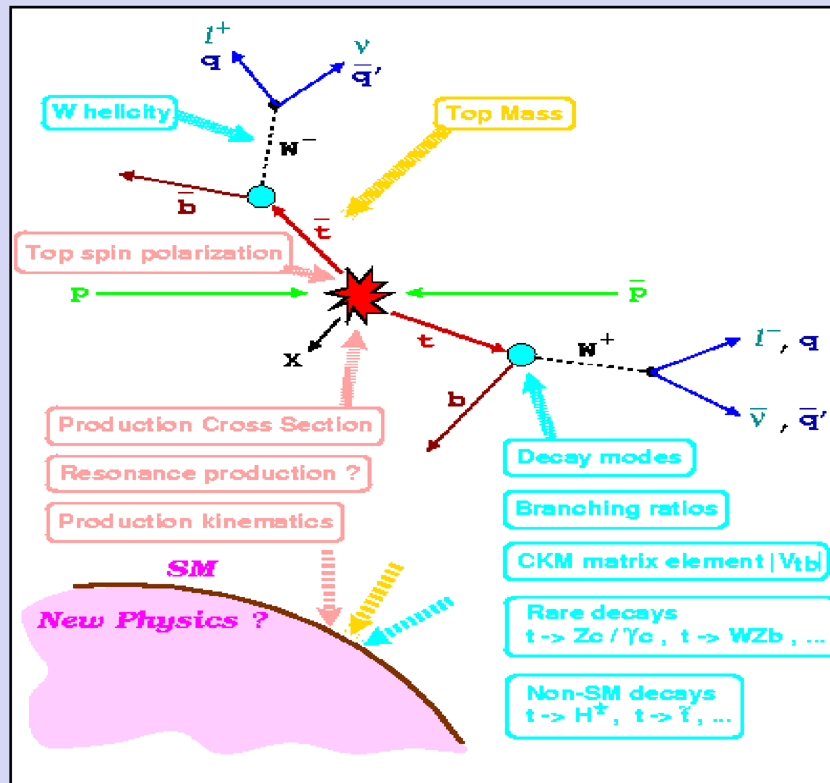
Discovery in 1995



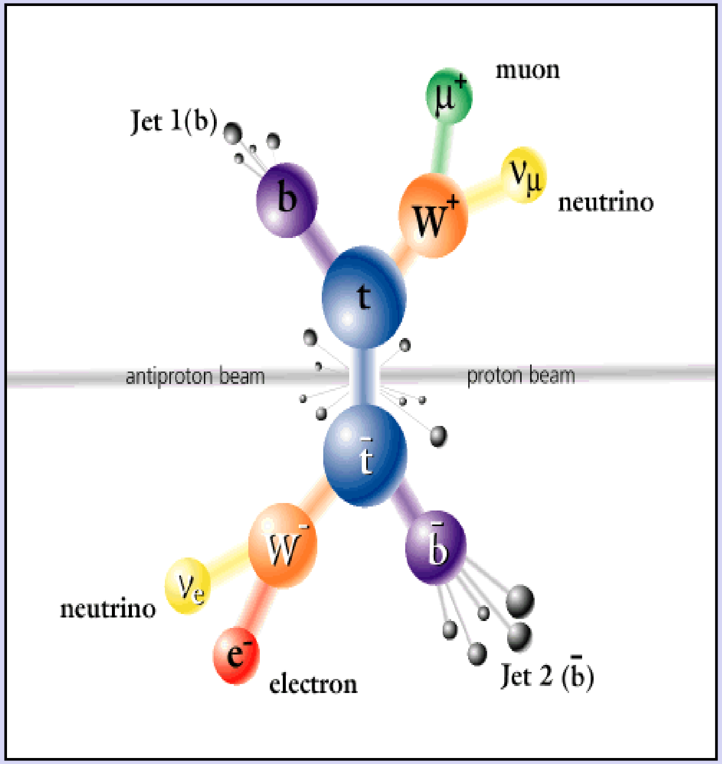
1995, CDF and DØ experiments, Fermilab

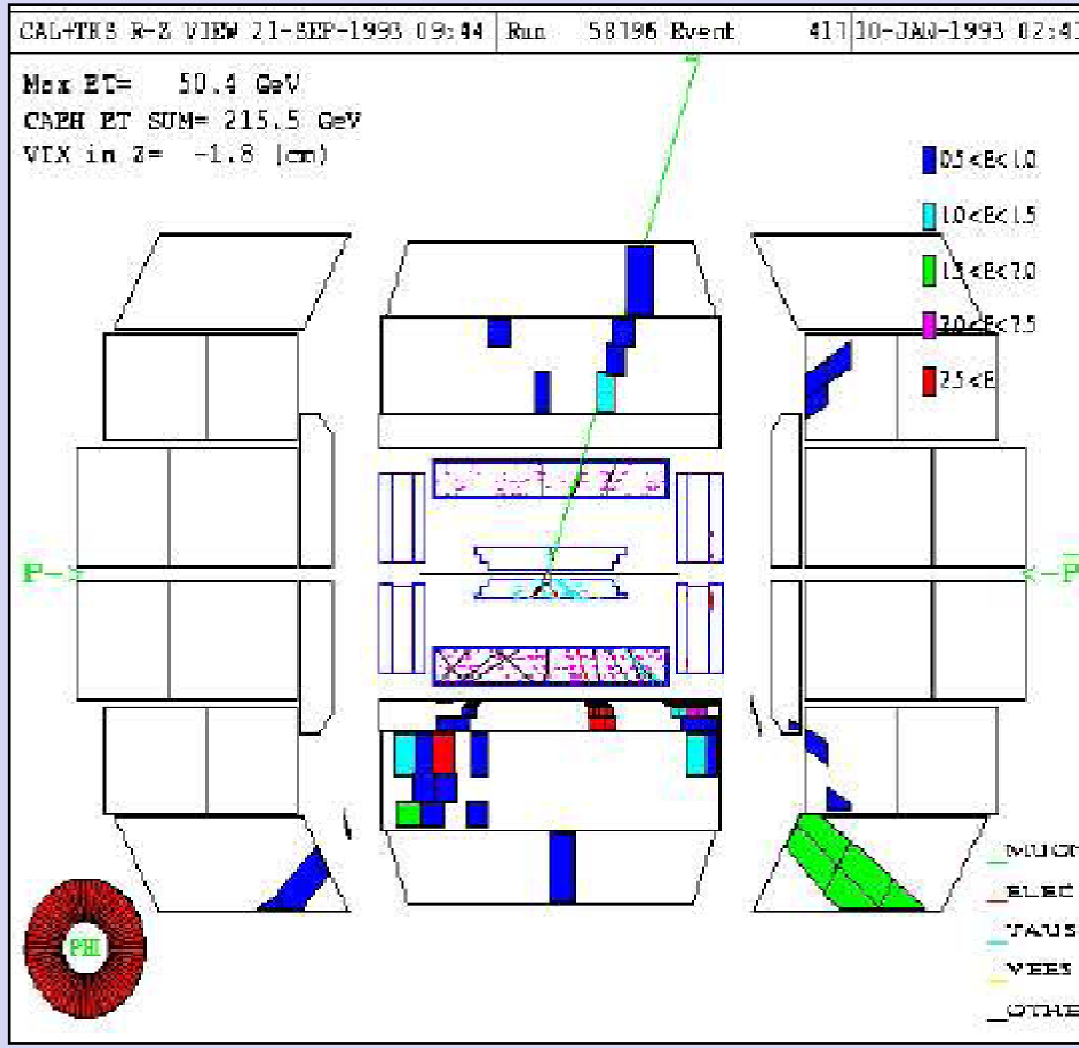
Today ~10,000 events





Discovery of the Top Quark

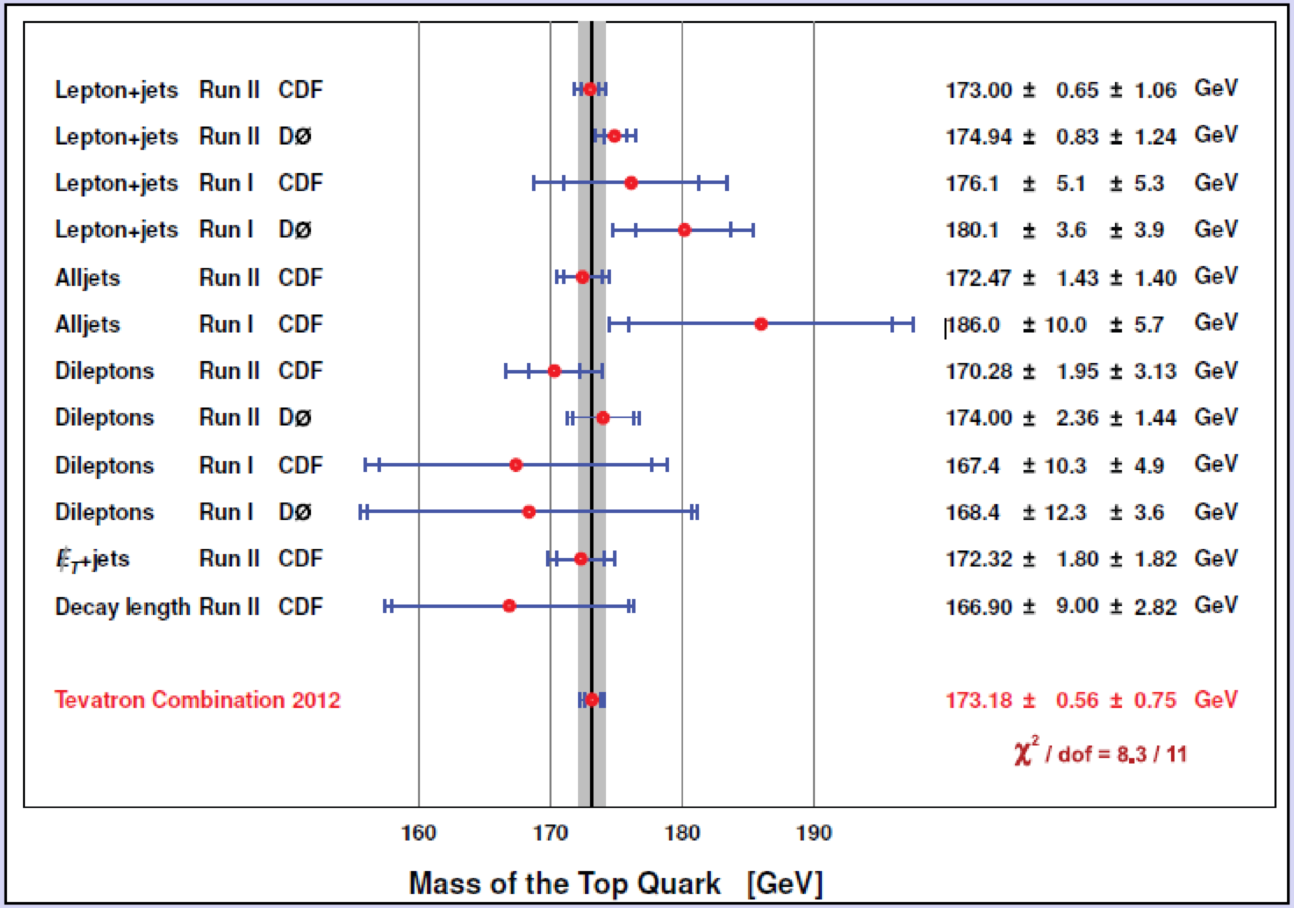


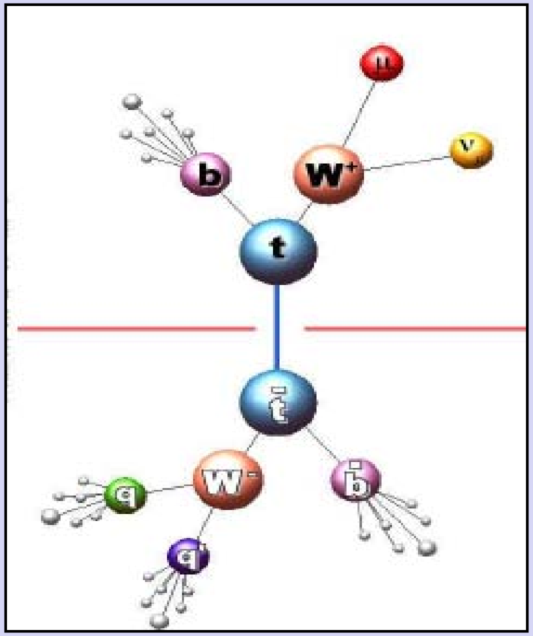


Due to relatively low backgrounds (high top quark mass, pair production) "a few" candidates only required for the discovery

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



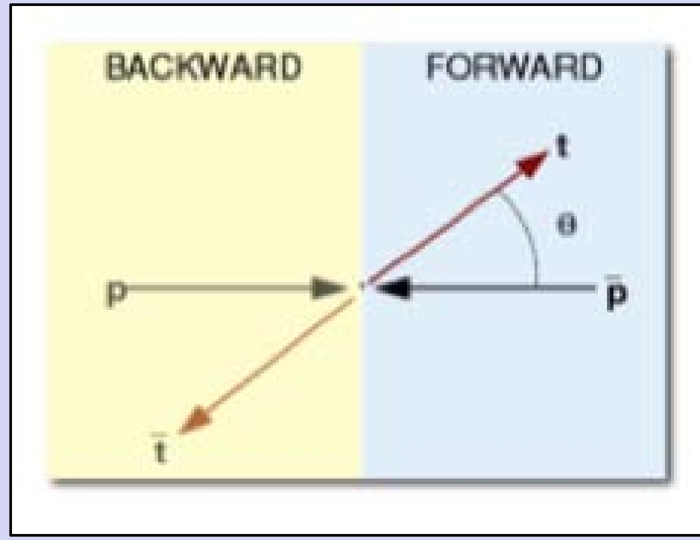


DØ and CDF combined top mass result
m_t = 173.2±0.9 GeV
0.5% accuracy
Best (of any) quark mass measurement!

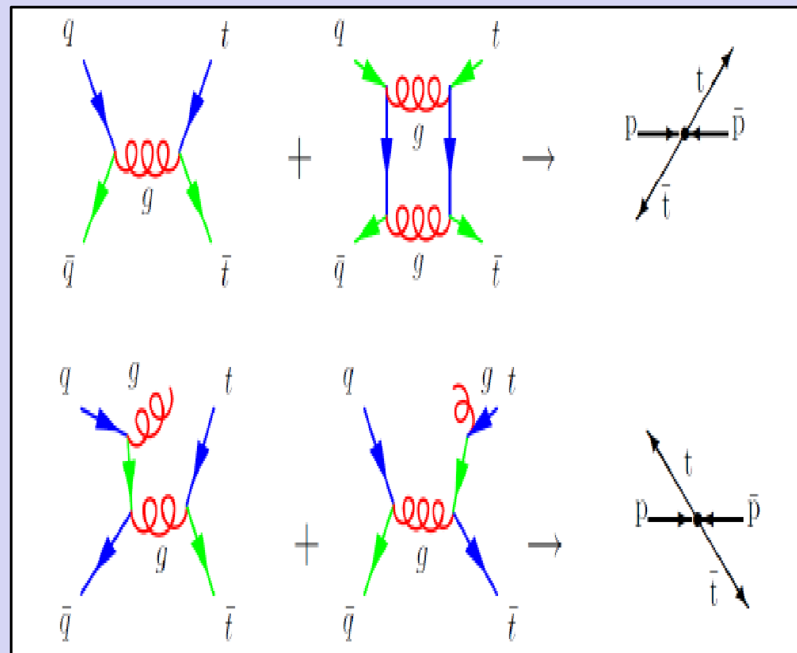
Anomaly in Top Quark Studies

Tevatron

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



- **In Standard Model, there is no asymmetry in leading order, but next to leading order predicts asymmetry**
  - **Positive asymmetry from box diagrams**
  - **Negative asymmetry from ISR and FSR**
- **Forward backward asymmetry**
  - **Enhanced in some beyond standard models scenarious**

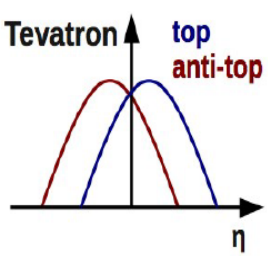


Tevatron

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

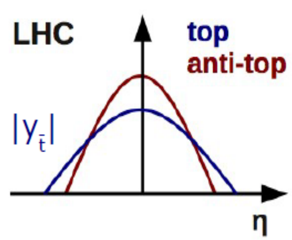
LHC

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



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

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

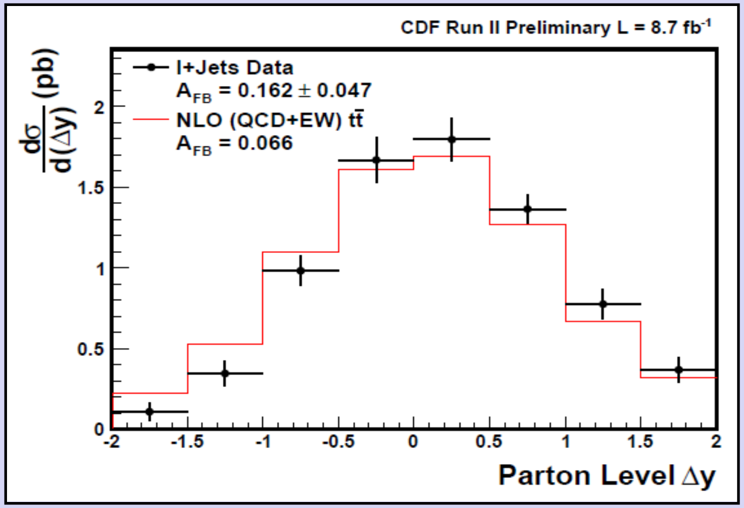


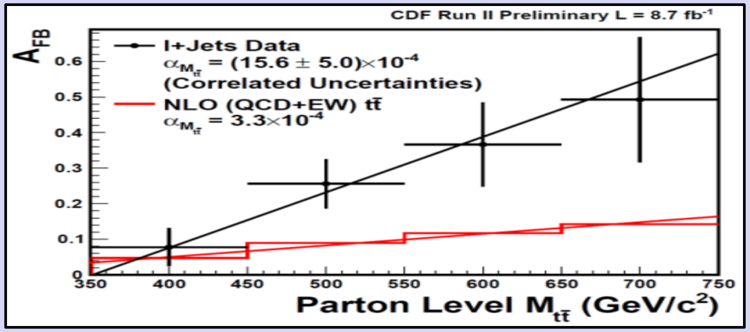
Top Quark Forward-Backward Asymmetry

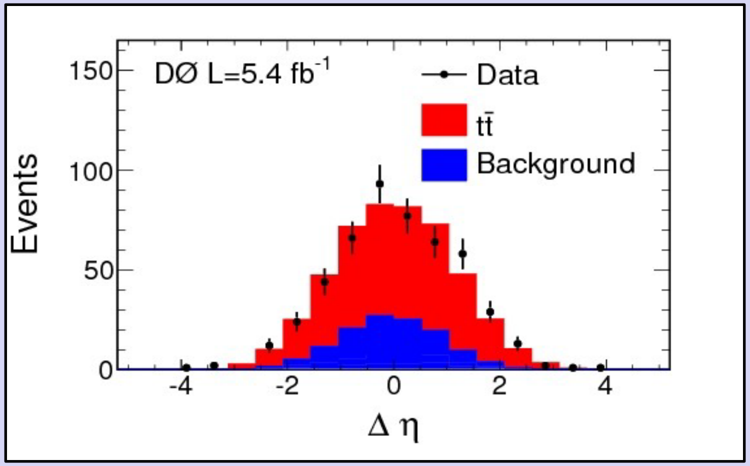
- **CDF l+jets (8.7 fb^{-1})**
  A_{FB} = (16.2 ± 4.7) %
  Theory prediction: 6.6 %
  ~2 σ deviation from NLO
  Slope of $A_{FB}(M_{tt})$
  (15.6 ± 5.0) ×10^{-4}

- **DØ results (5.4 fb^{-1})**
  l+jets : A_{FB} = 15.2 ± 4.0 %
  dileptons : A_{FB} = 5.8 ± 5.1 ± 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?**







Main Top Quark Properties Measured at the Tevatron

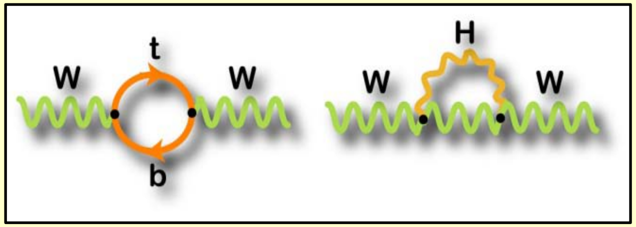
- Top quark mass: m_t = 173.2±0.9 GeV (0.5% accuracy)
- Are top and antitop masses the same? Test of CPT
  Δm=0.8± 1.9 GeV (equal to 1%)
- Top quark lifetime
  Γ_t=1.99(+0.69/-0.55) GeV agrees with SM
- Top charge |q|=2/3e to 95% C.L.
- W helicity in top decay expect 70% longitudinal, 30% left-handed
  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
  $<2\times10^{-4}$ ($t\rightarrow gu$); $<4\times10^{-3}$ ($t \rightarrow gc$)
- 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
- 4^{th} 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!

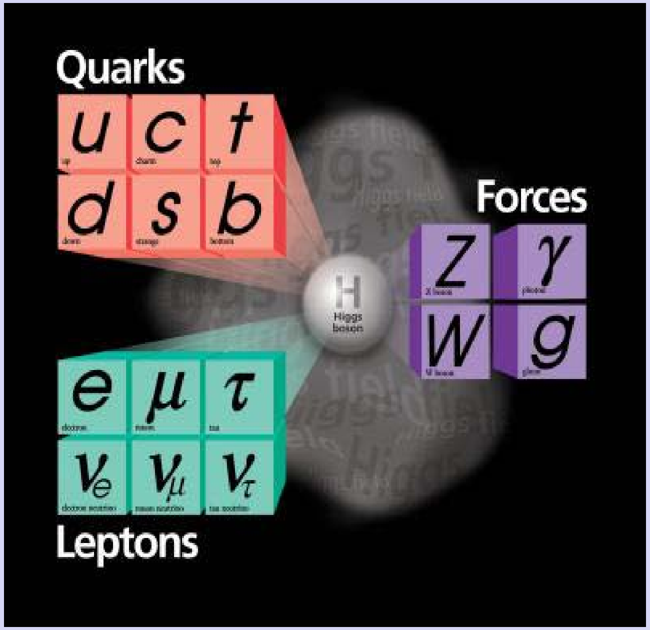
Higgs Searches – Indirect Limits

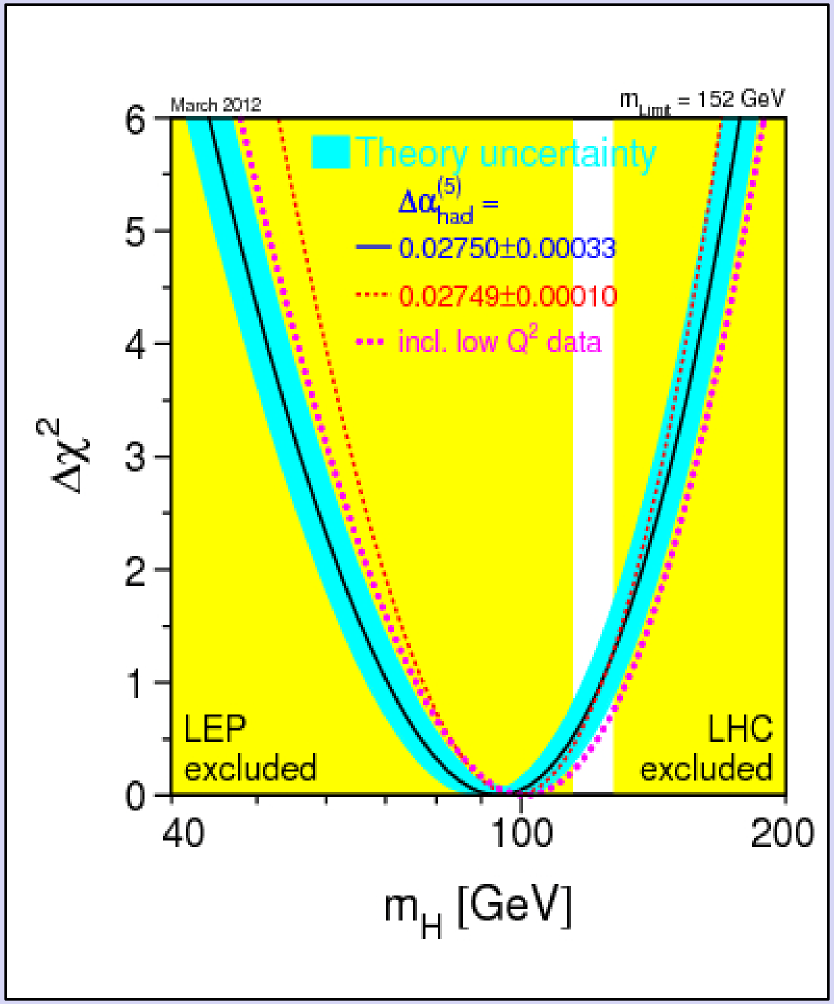
Indirect experimental limits

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



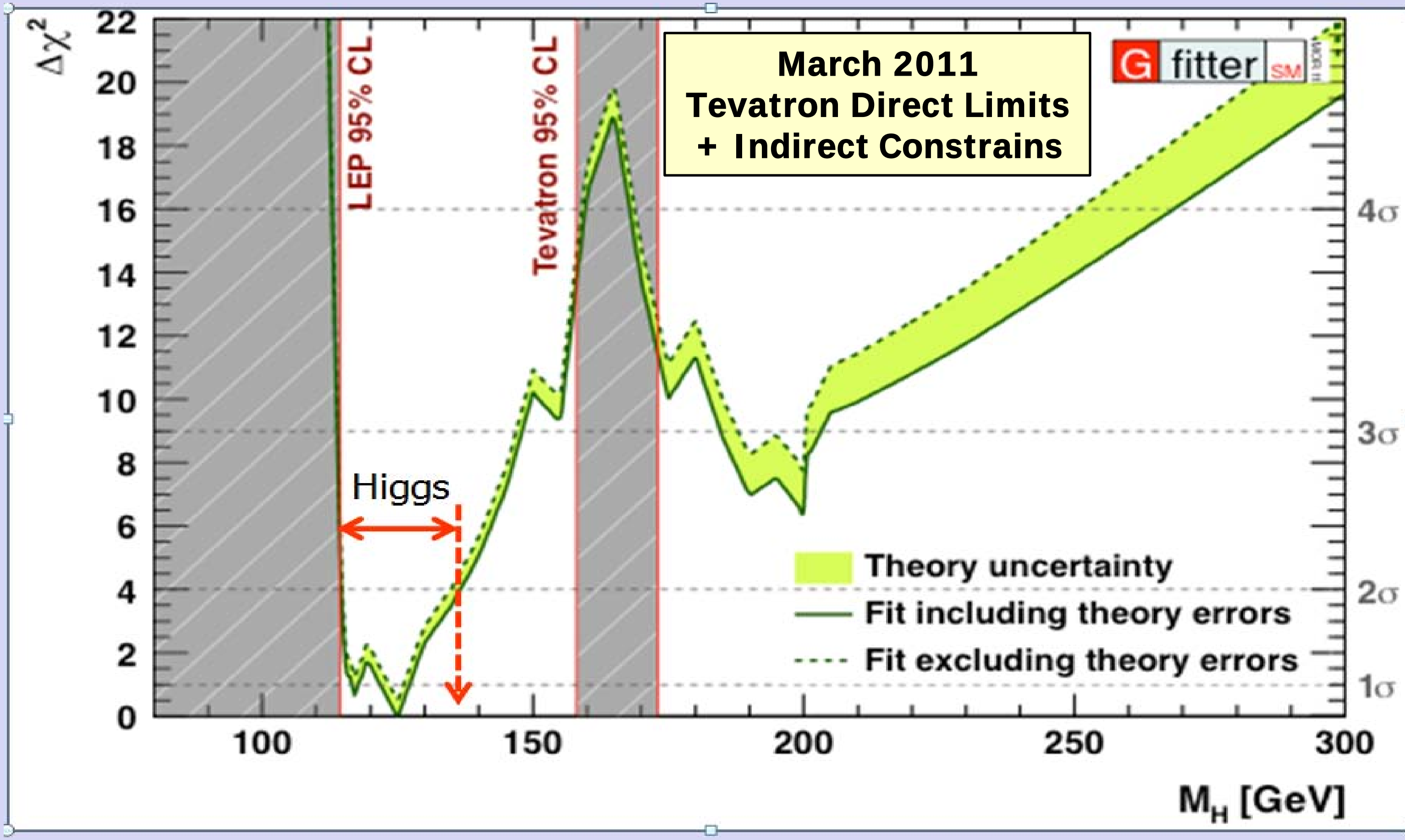
M_H< 152 GeV at 95% CL





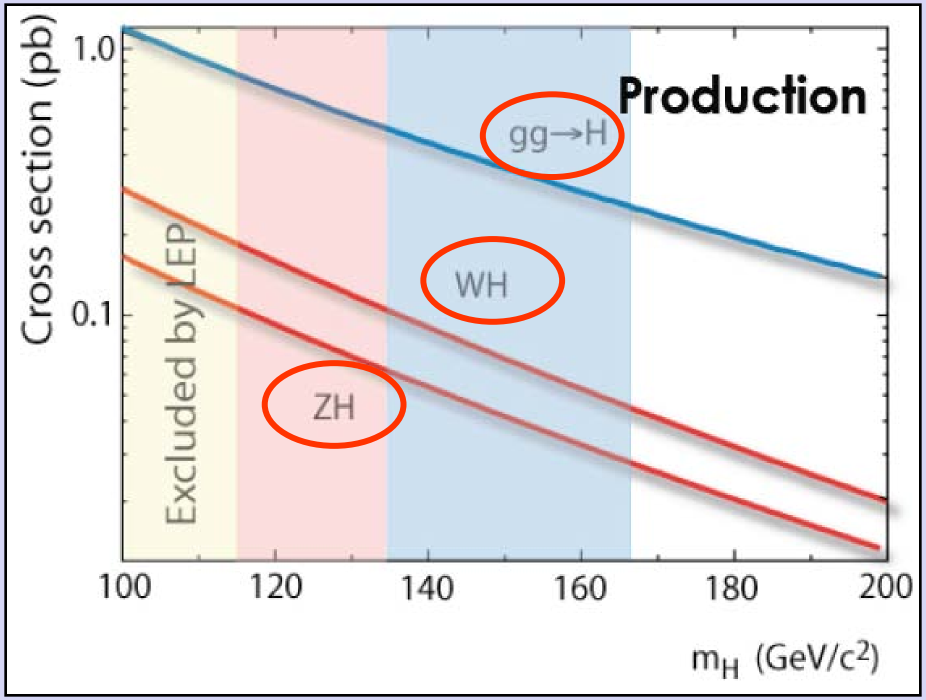
Higgs Searches Status: ~1.5 Years Ago

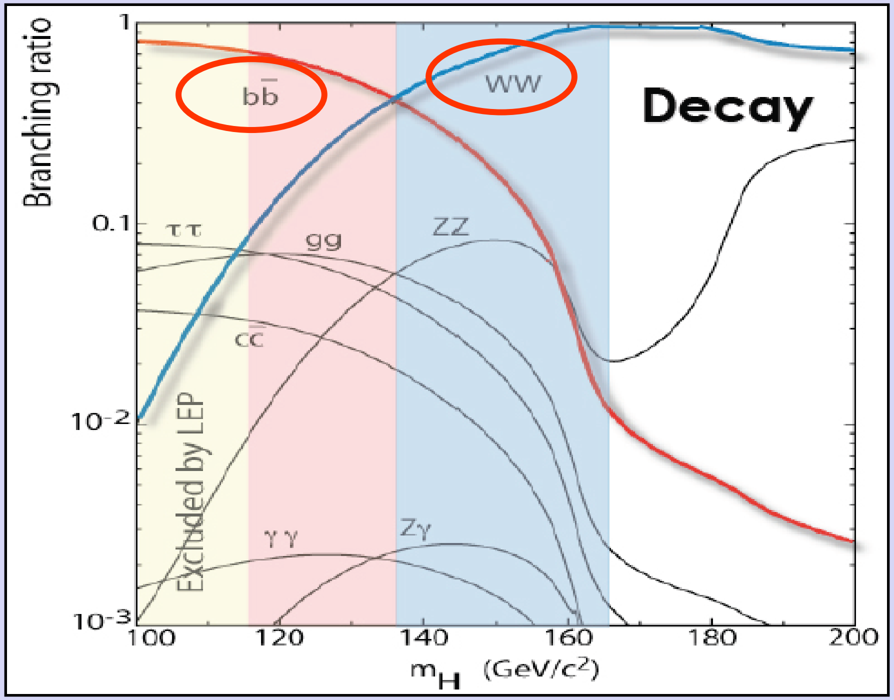
- Higgs masses 158-173 GeV are excluded by the Tevatron
- Precision measurements point to Higgs masses below ~150 GeV
- LEP results indicate Higgs mass is above ~114 GeV



- 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

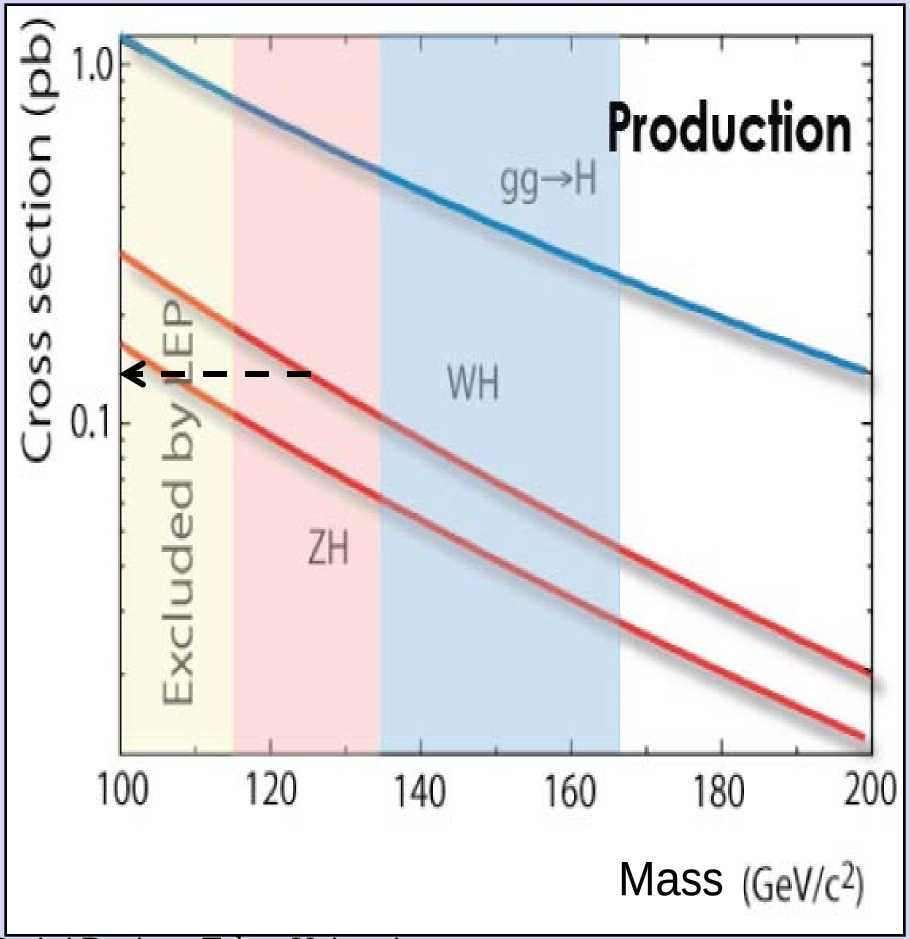
Experimental Challenges

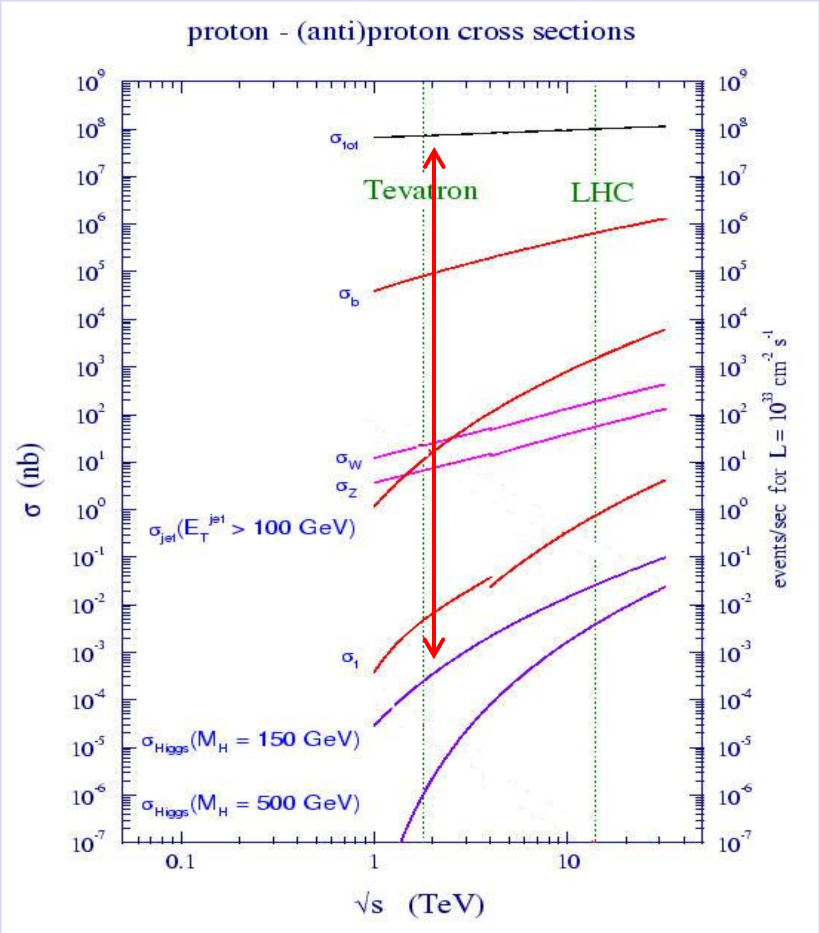
- Probability of producing Higgs is low

$$N_{events} = L \times \sigma$$

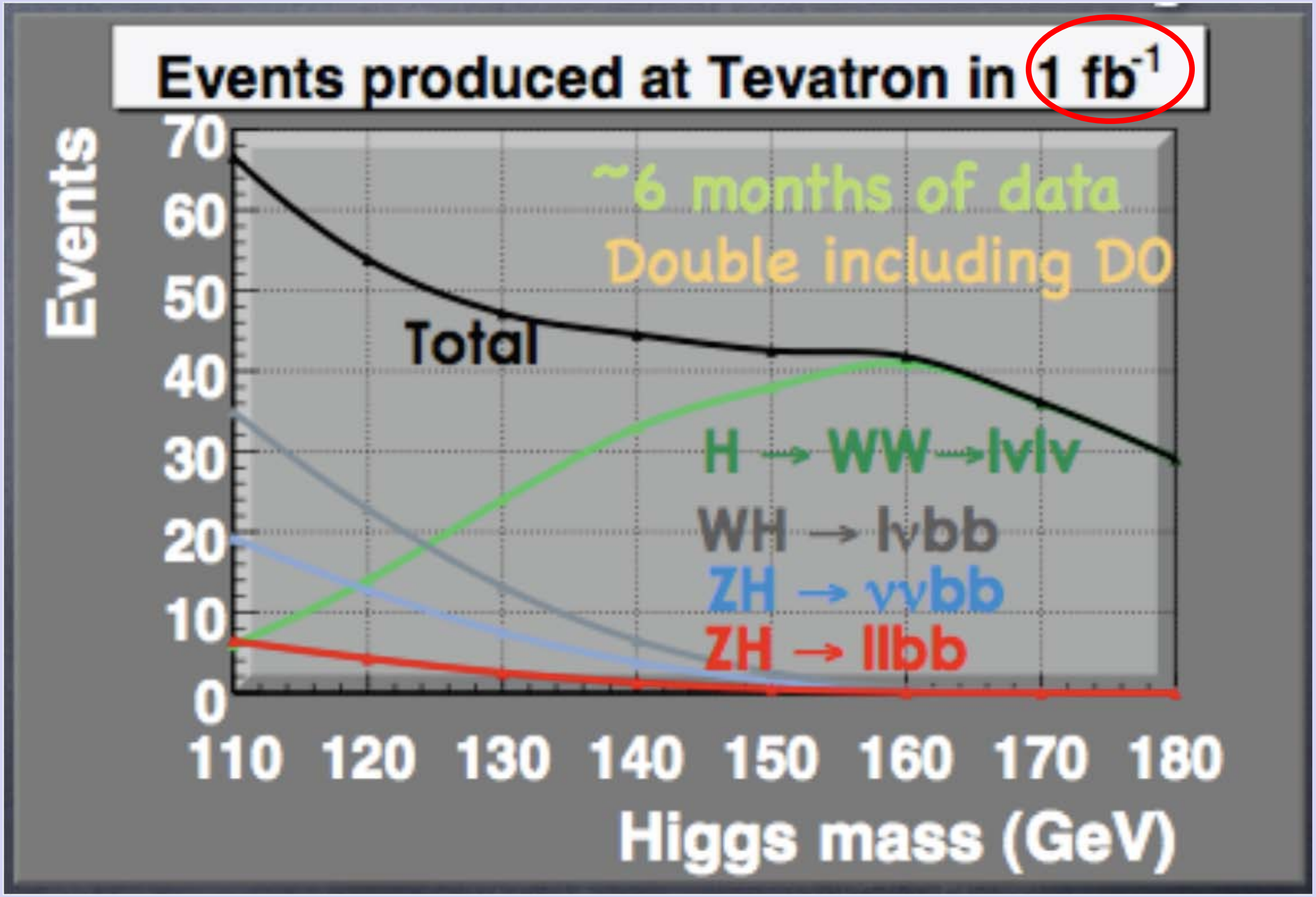
- High luminosity is important!

- Backgrounds from Standard Model processes are high
  - Only one out of ~10^{12} collisions might contain Higgs
- Separation of backgrounds is one of the main challenges in hunt for the Higgs



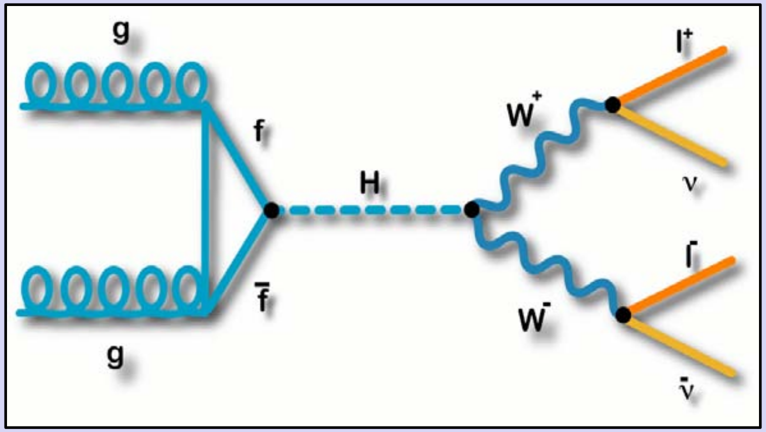


Number of Higgs Events

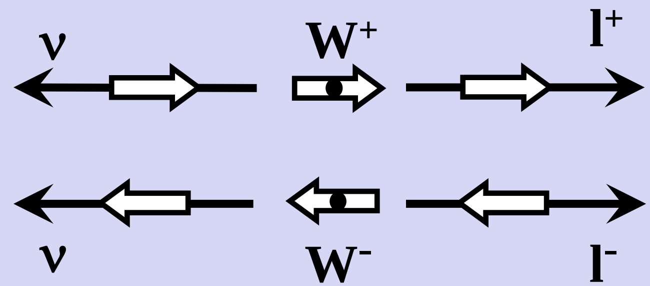


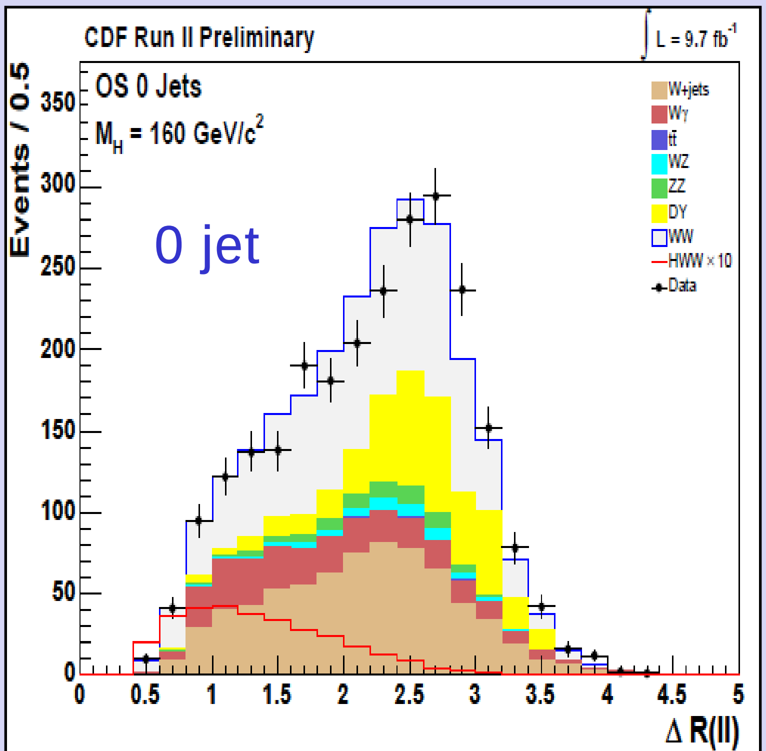
- Number of Higgs events available to CDF+DØ with the full Tevatron Run II data set of 10 fb^{-1} at 125 GeV is ~10^3
- Reconstruction/selection efficiencies
  - ~10% in H→bb channels and ~25% in H→WW channels

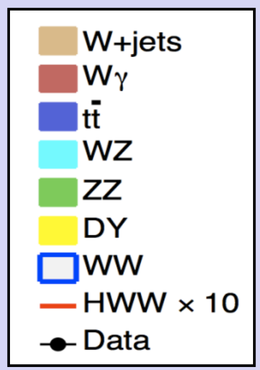
Higgs Search: H → WW → lνlν (M_H >130 GeV)

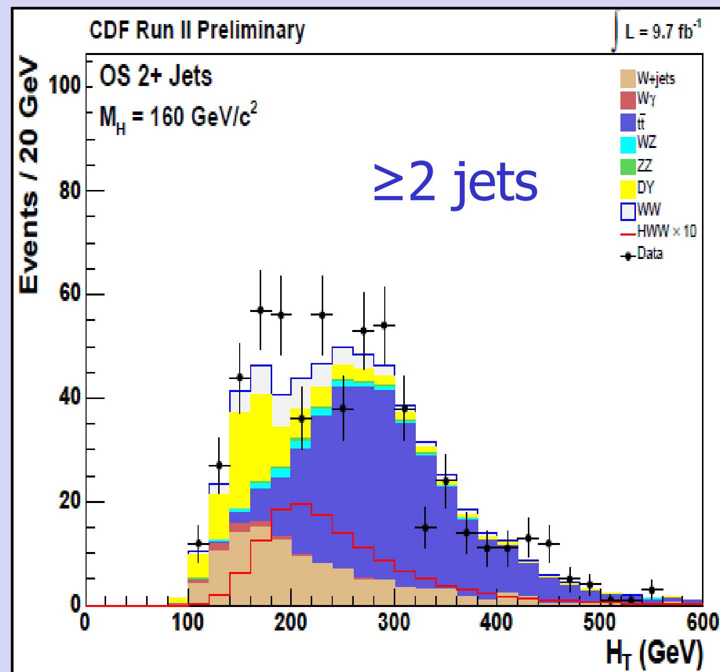


Search strategy:
→ 2 high P_t leptons and missing E_t
→ WW pair comes from spin 0 Higgs: leptons prefer to point in the same direction



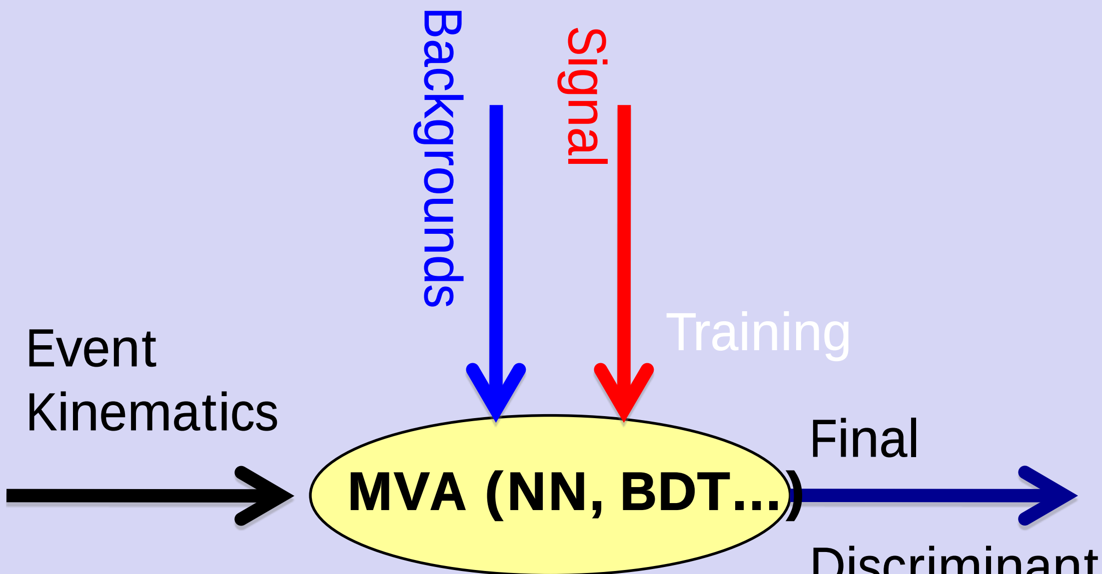




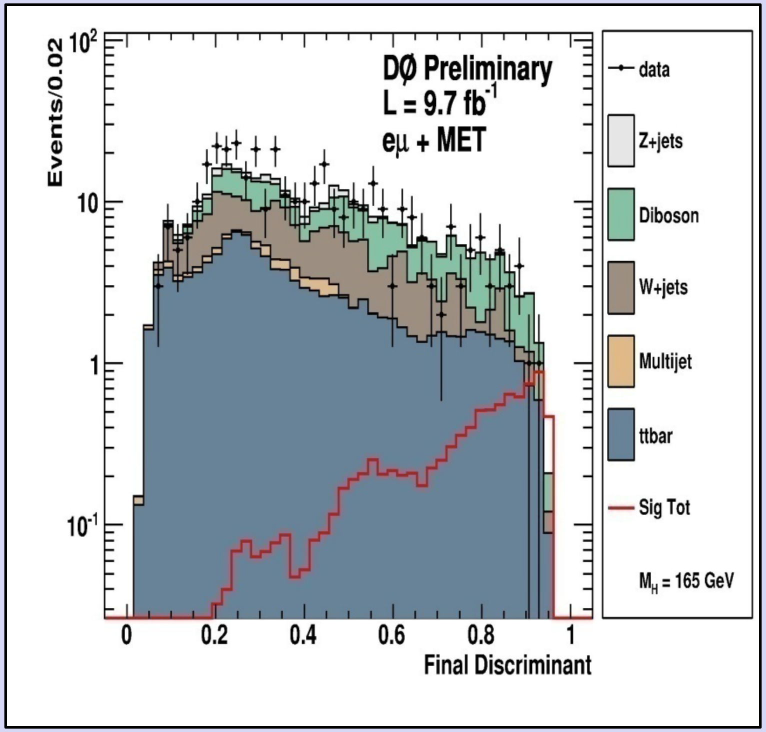


Final Selection Discriminants

Multivariate Analyses (neural networks, boosted decision trees, etc.) are used to provide a gain sensitivity beyond that obtained from optimized, cut-based analysis

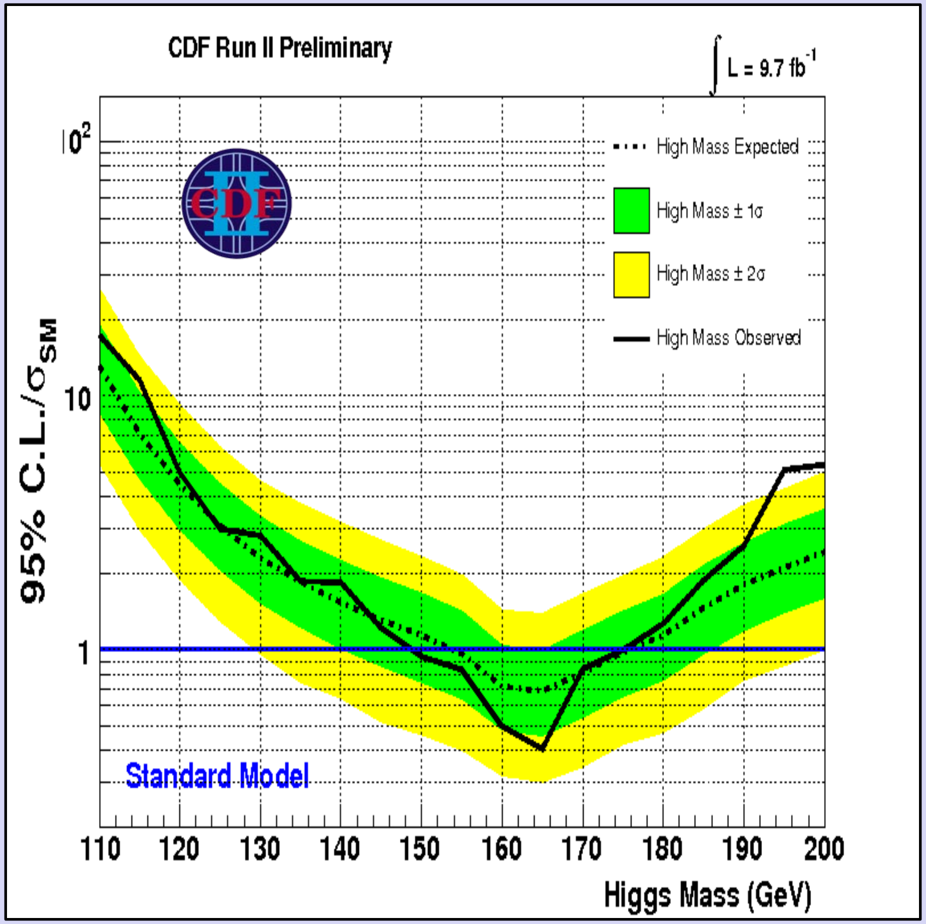


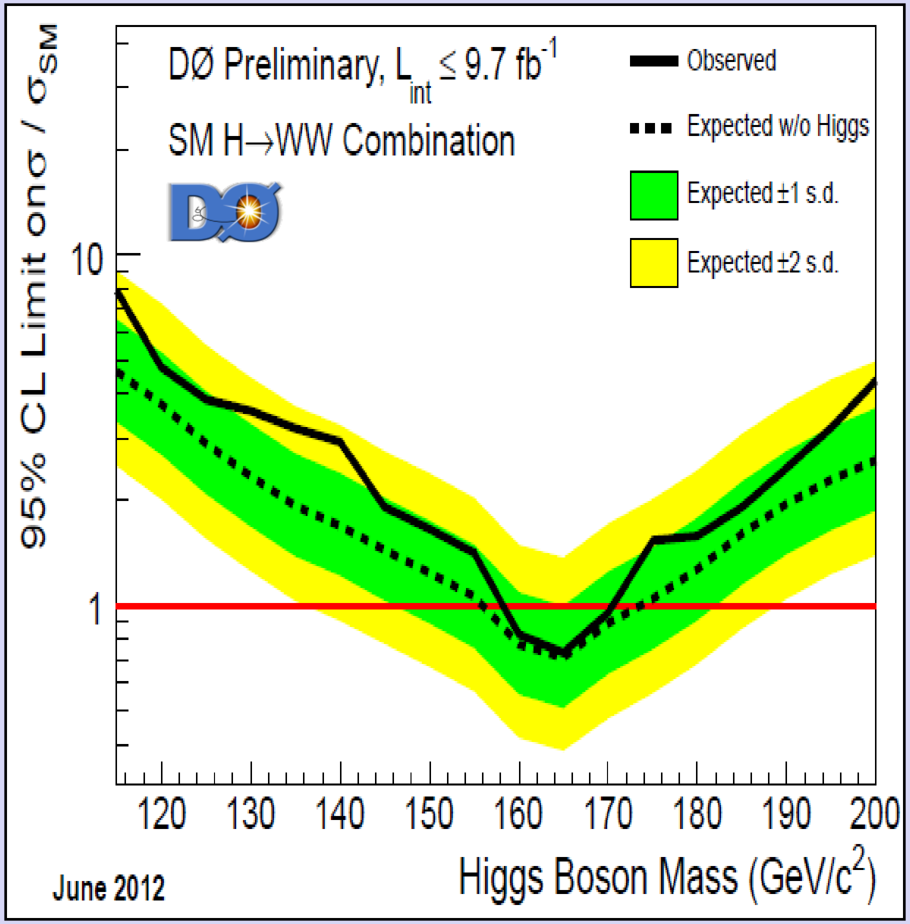
Training ➔correlate multiple input variables



Even for a single channel reach S/B ~1 in high discriminant region!

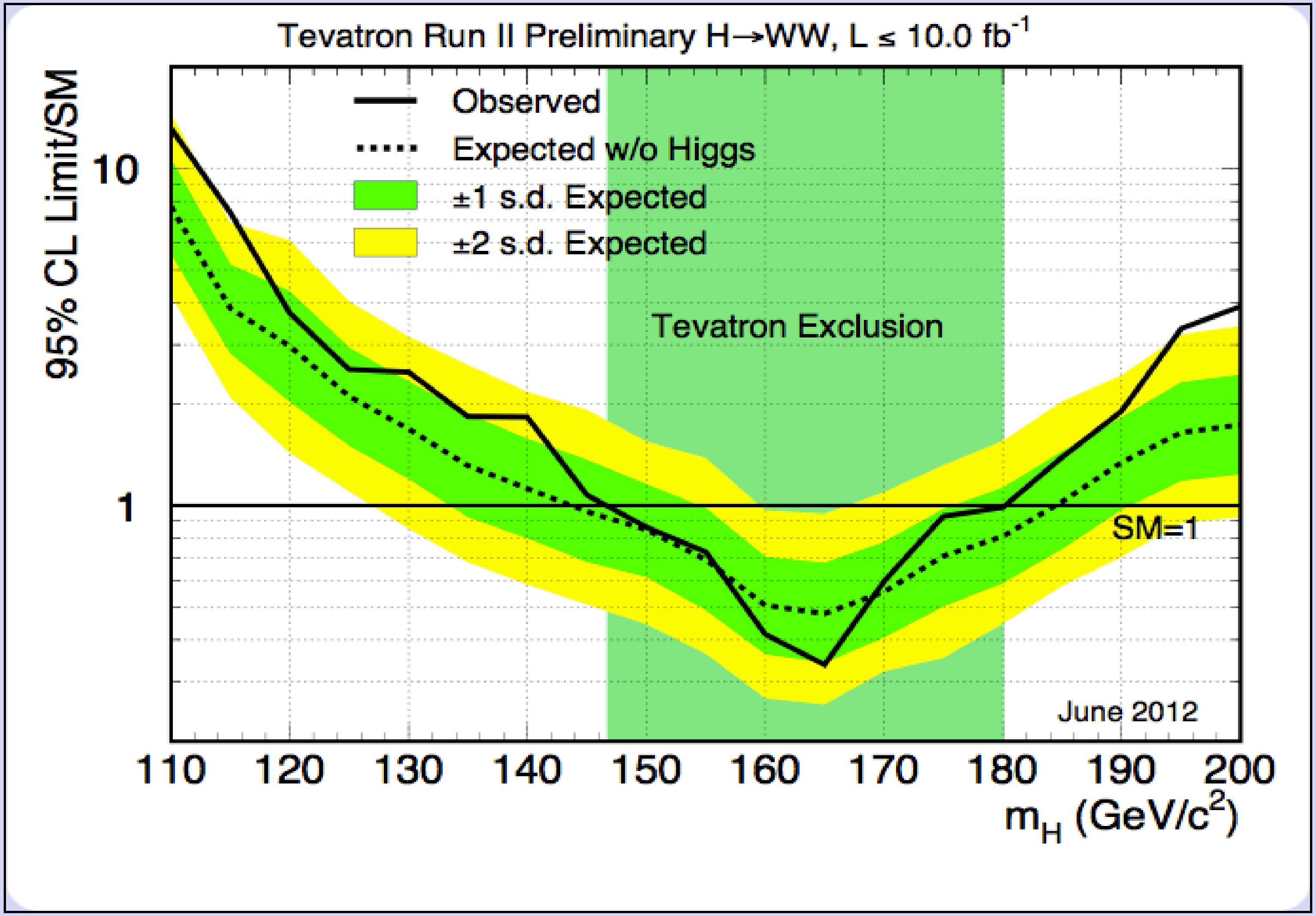
CDF / D0 H→WW→lνlν Limits





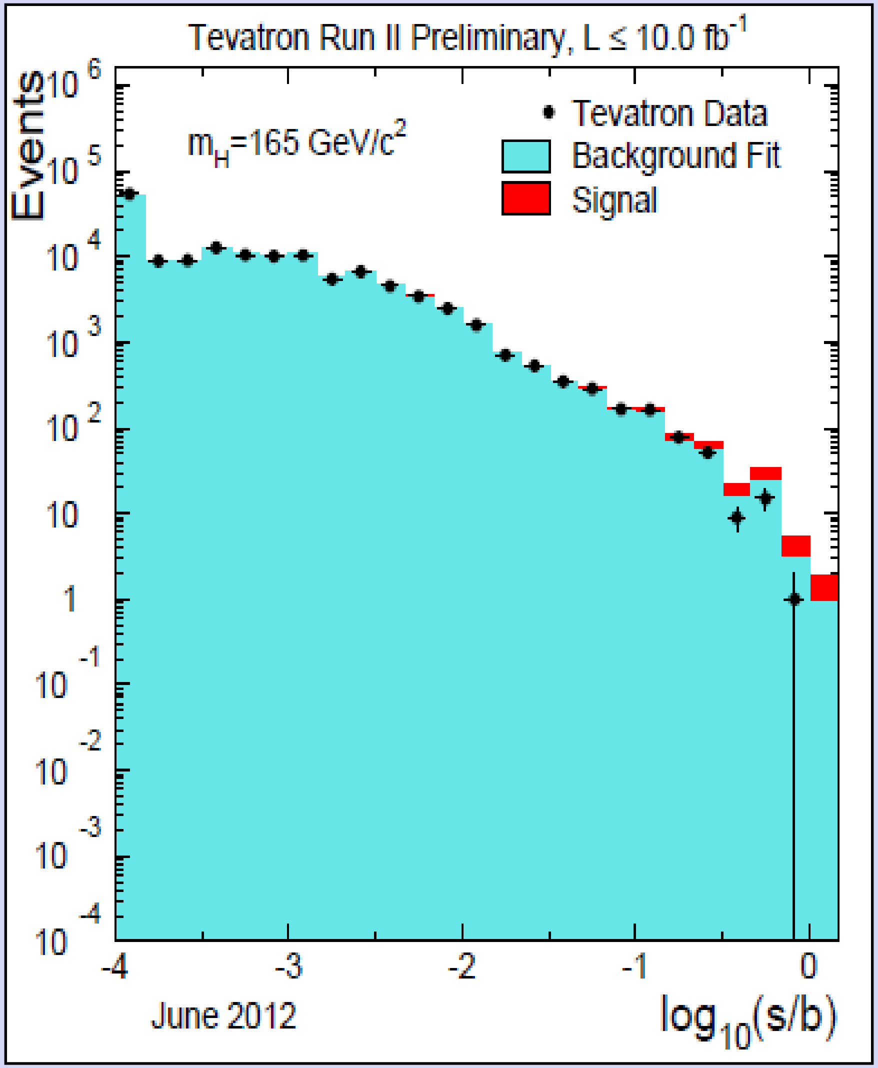
Limits are presented as ration to Standard Model predictions
Both experiments exclude Standard Model Higgs boson around 165 GeV

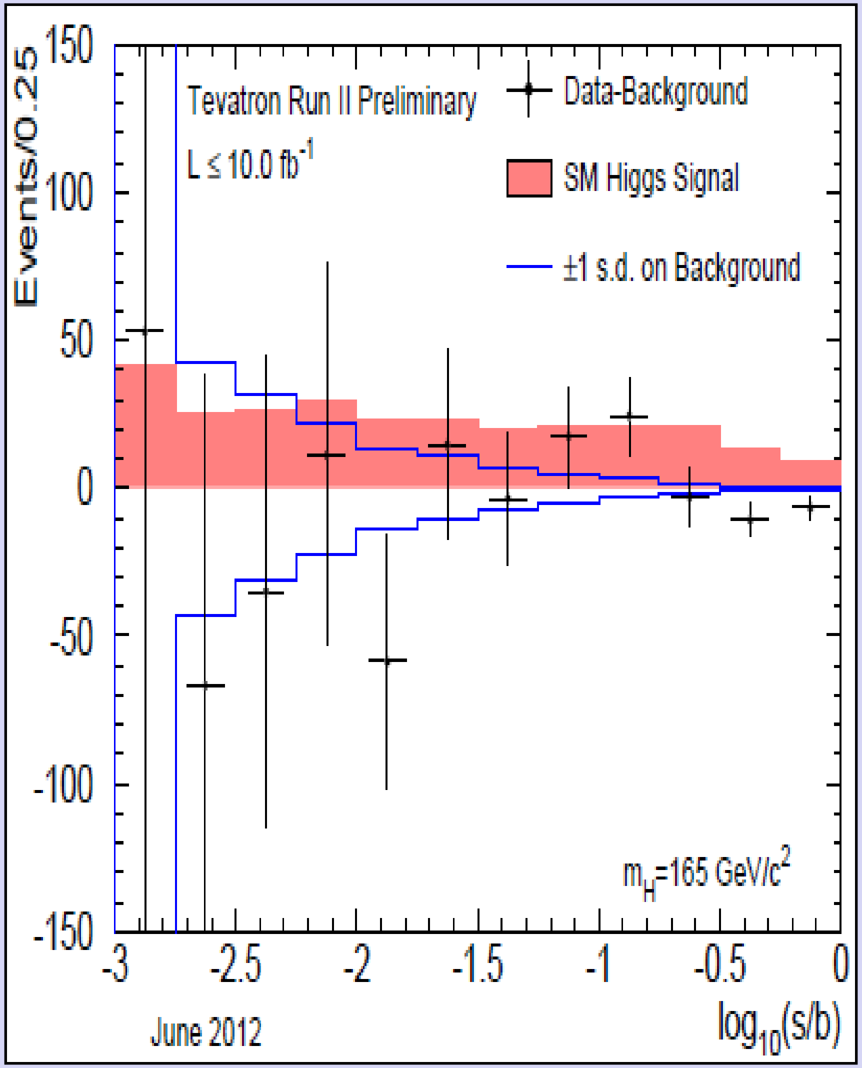
$H \rightarrow W^+W^-$ Tevatron Combination



Exclude 147 < M_H < 180 GeV at 95 % CL

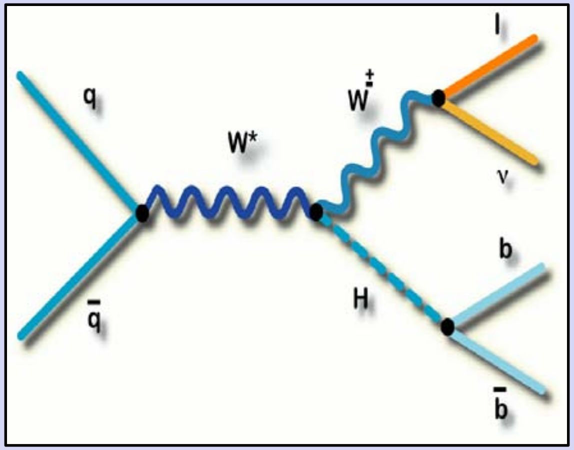
165 GeV Mass - Number of Events



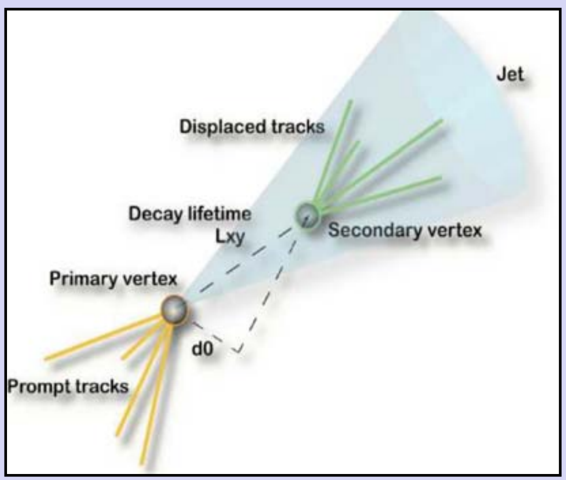


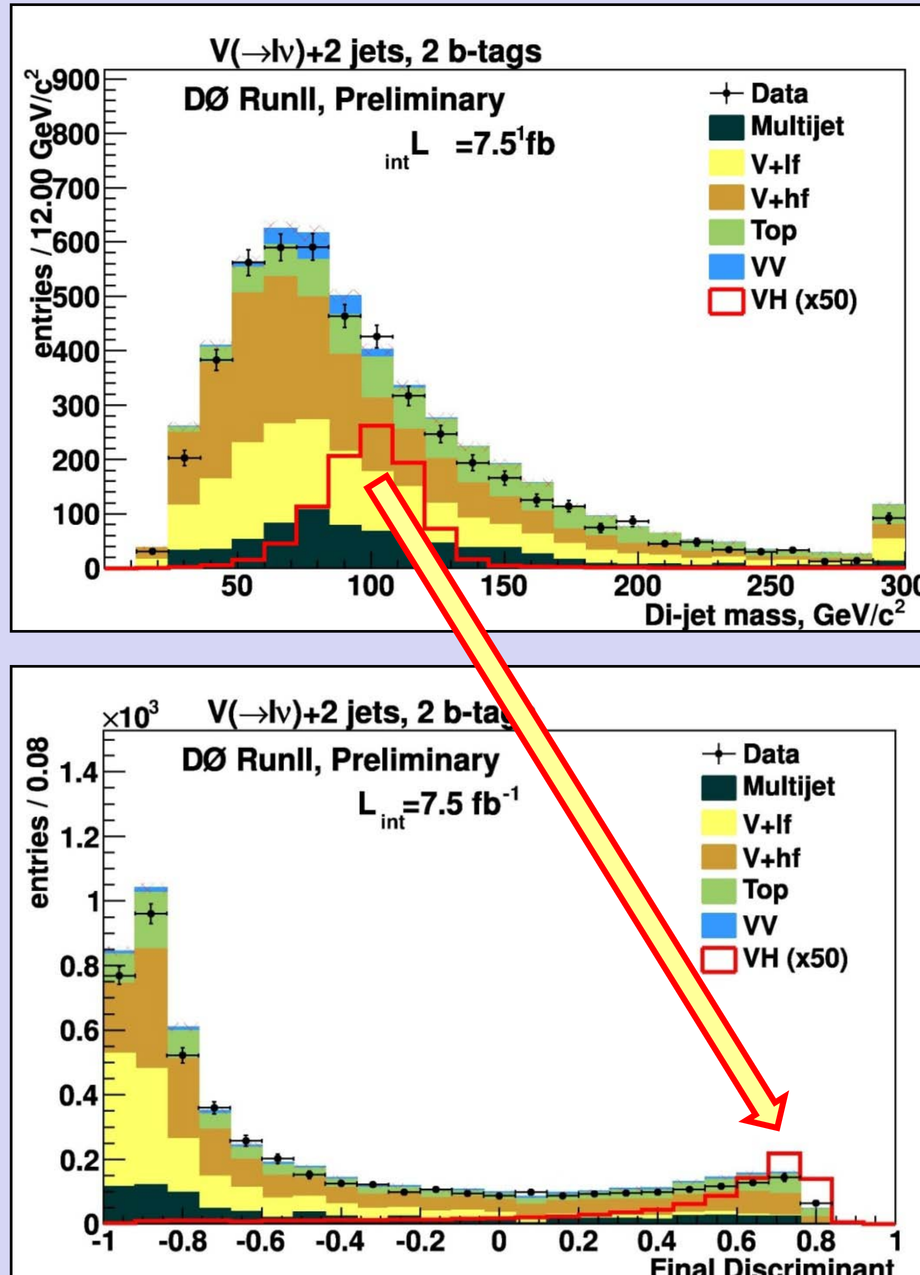
Events in all channels are sorted based on signal / background ratio
No excess observed

Low Mass Higgs Channels



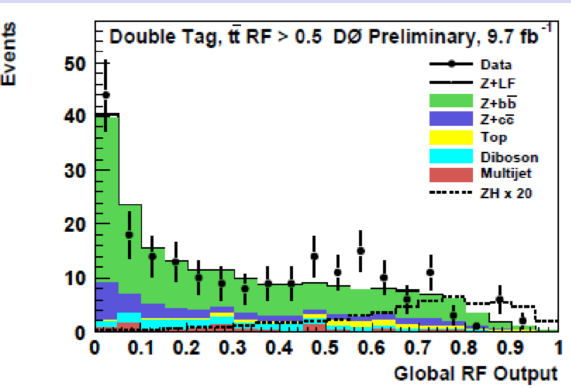
- Main discriminant is di-jet mass from b-quarks pair
- Elaborate b-tagging of jets
- Multivariate analyses help to extract full information about event kinematic

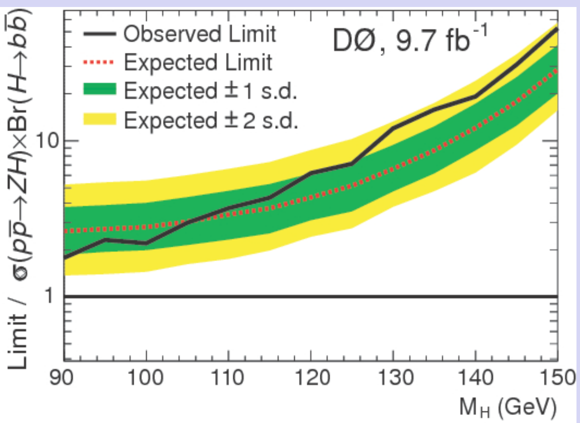




Results from DØ

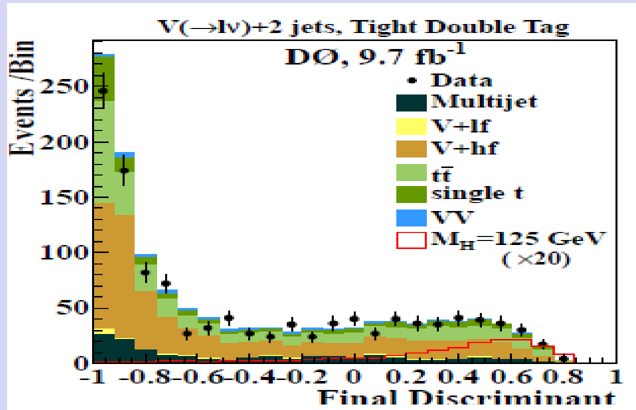
ZH→llbb ∫Ldt=**9.7**fb^{-1}

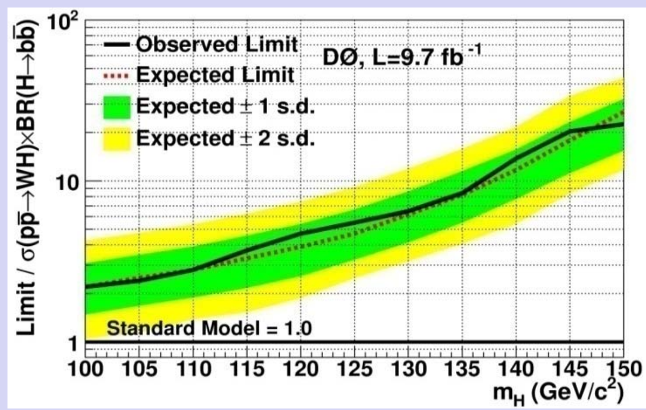




95% CL Exp (obs)
Limit **3.7** (**4.3**) x SM
@ MH=115 GeV

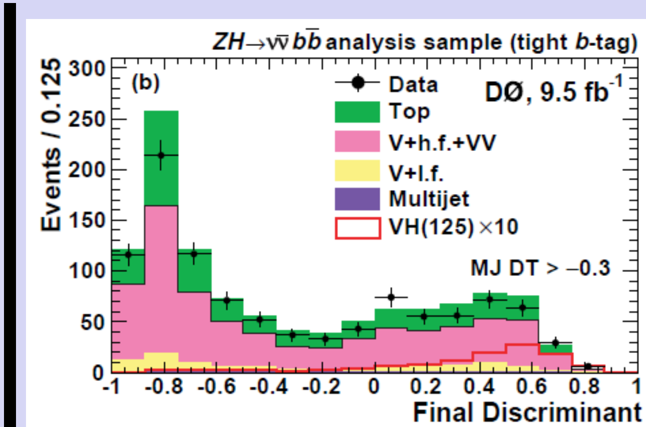
WH→lνbb ∫Ldt=**9.7** fb^{-1}

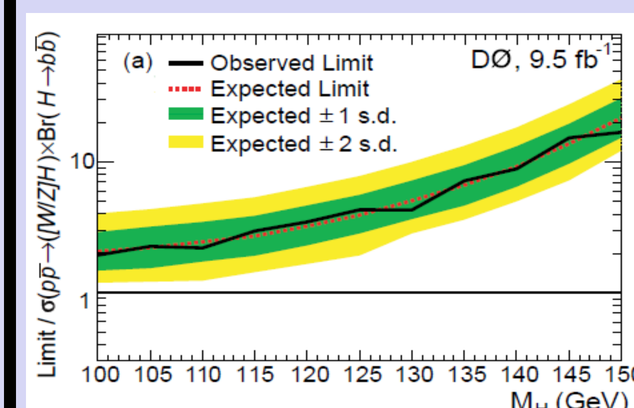




95% CL Exp (obs)
Limit **3.2** (**3.7**) x SM
@ MH=115 GeV

ZH→ννbb ∫Ldt=**9.5** fb^{-1}



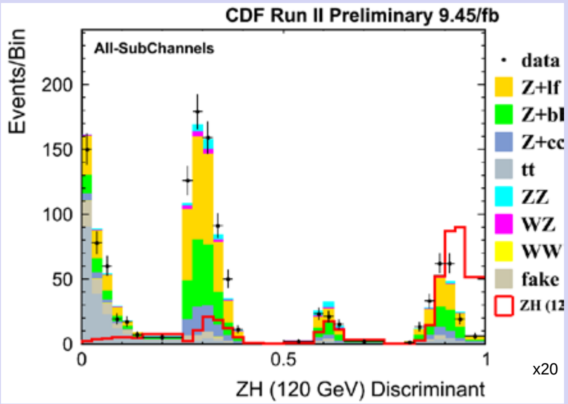


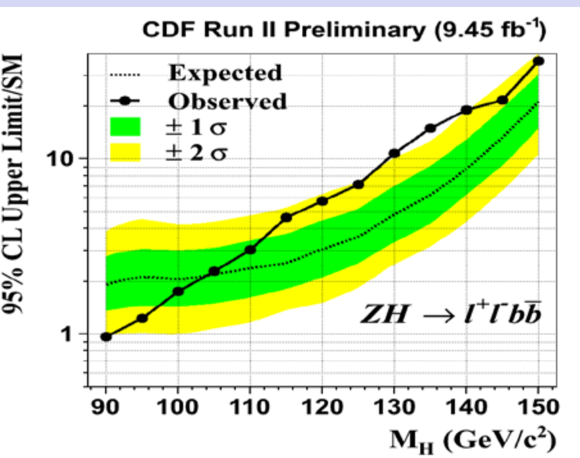
95% CL Exp (obs)
Limit **3.0** (**2.7**) x SM
@ MH=115 GeV

All channels are consistent and demonstrate sensitivity to the Higgs

Results from CDF

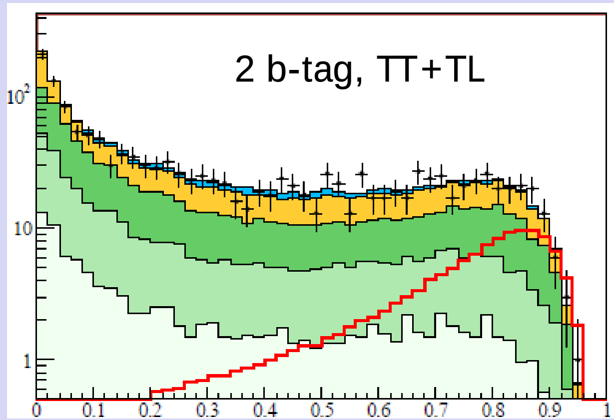
ZH→llbb ∫Ldt=9.5 fb^{-1}

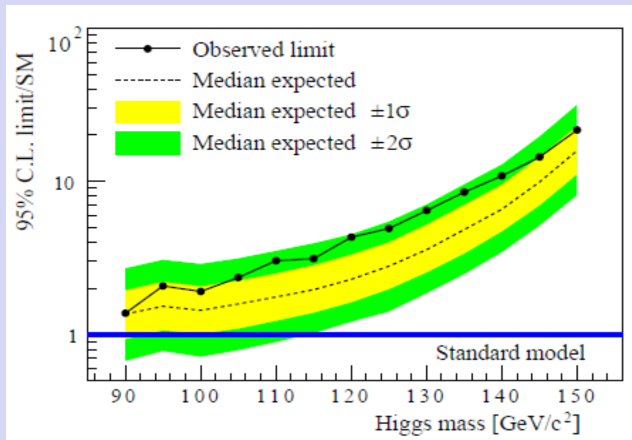




95% CL Exp (obs)
Limit 2.6 (4.7) x SM
@ MH=115 GeV

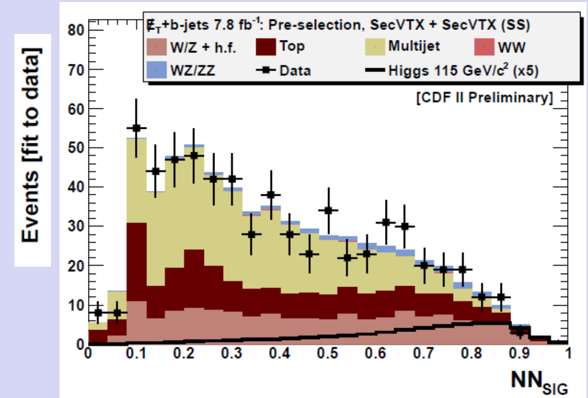
WH→lvbb ∫Ldt=9.5 fb^{-1}

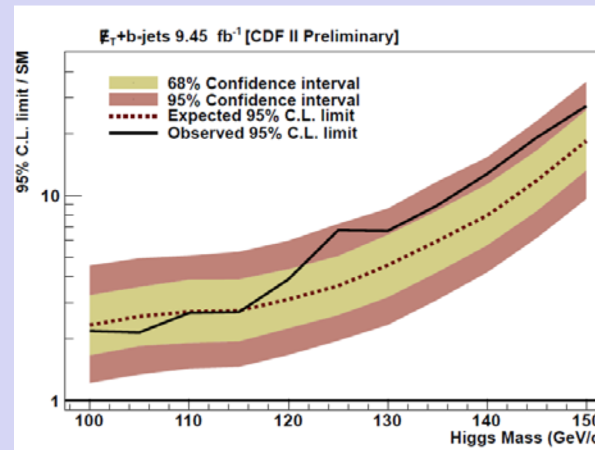




95% CL Exp (obs)
Limit 2.0 (3.1) x SM
@ MH=115 GeV

ZH→vvbb ∫Ldt=9.5 fb^{-1}





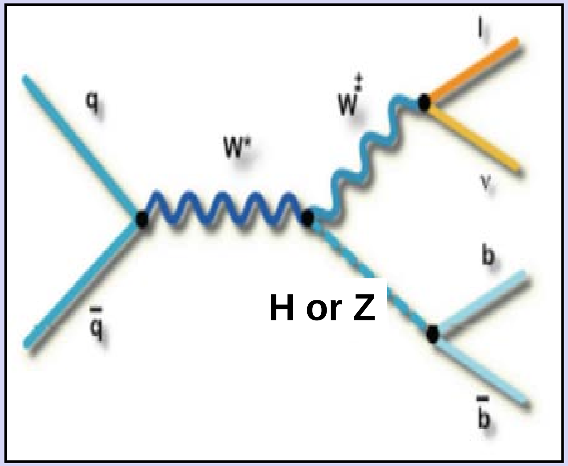
95% CL Exp (obs)
Limit 2.7 (2.7) x SM
@ MH=115 GeV

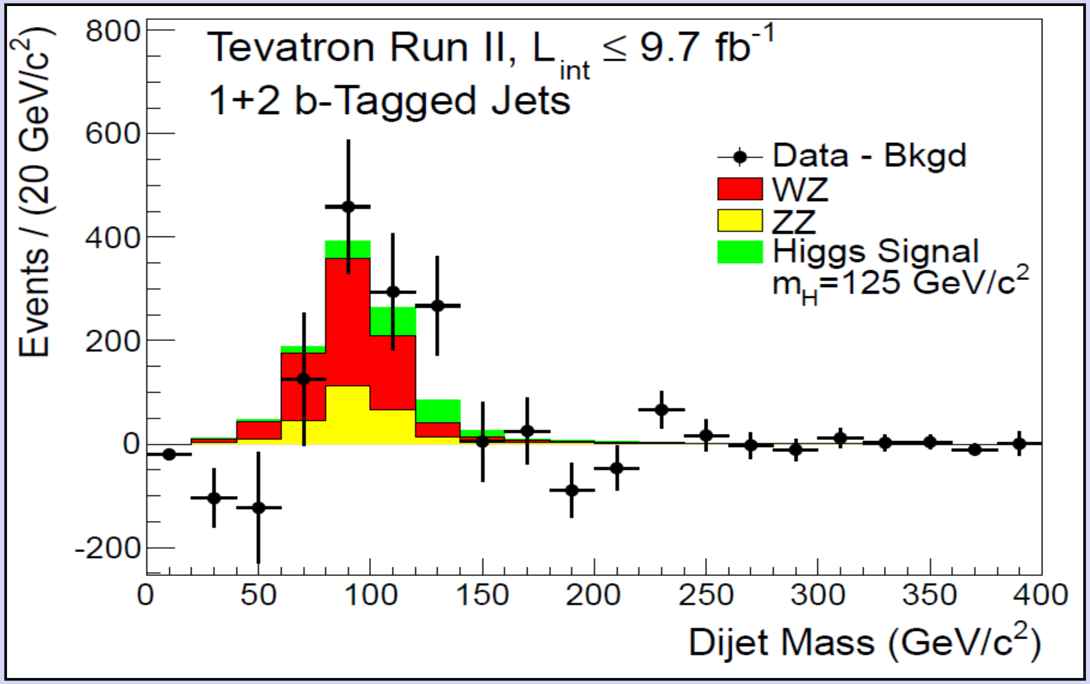
Pattern of an excess is starting to appear…

Cross Check on Di-boson 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 searches

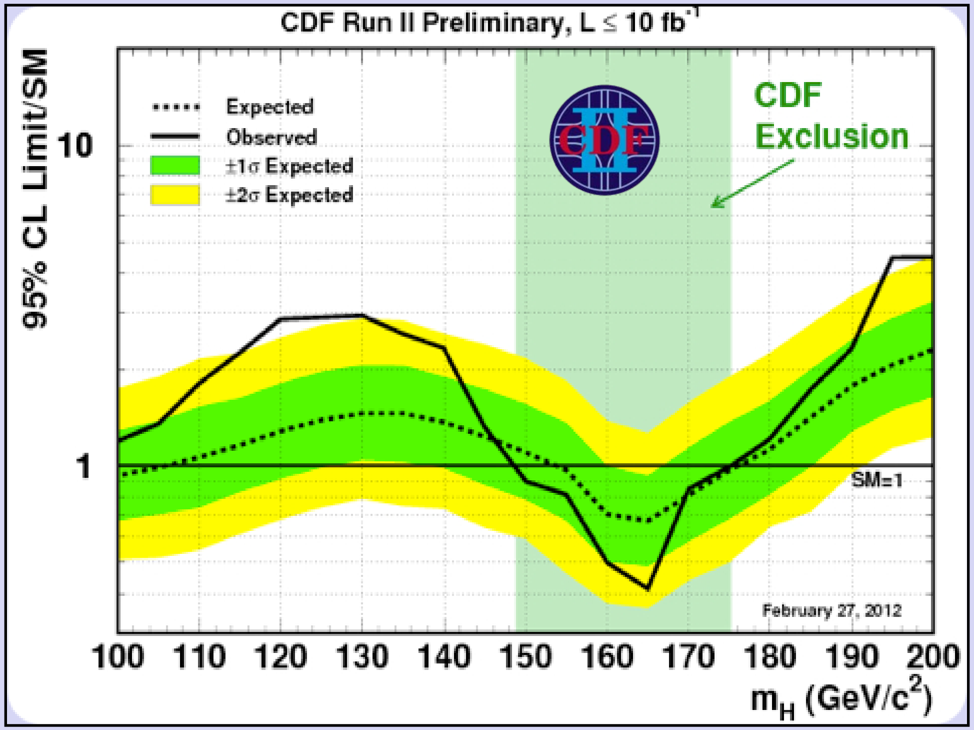
CDF+DØ combination cross-section: 3.9 +/- 0.9 pb

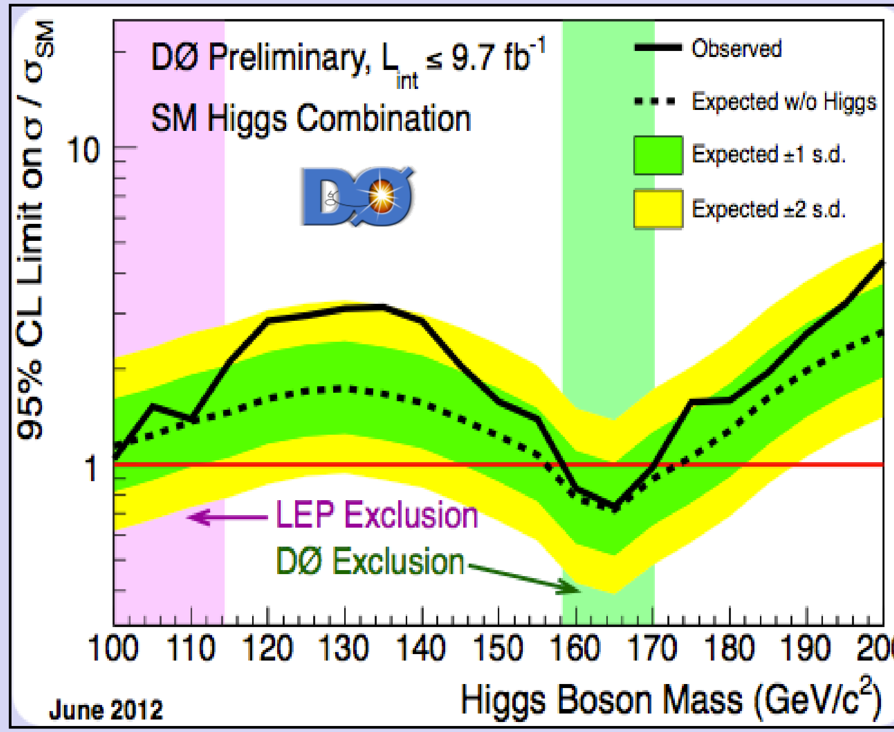
Standard Model prediction: 4.4 +/- 0.3 pb

4.5 σ significance

CDF and DØ Higgs Search Results

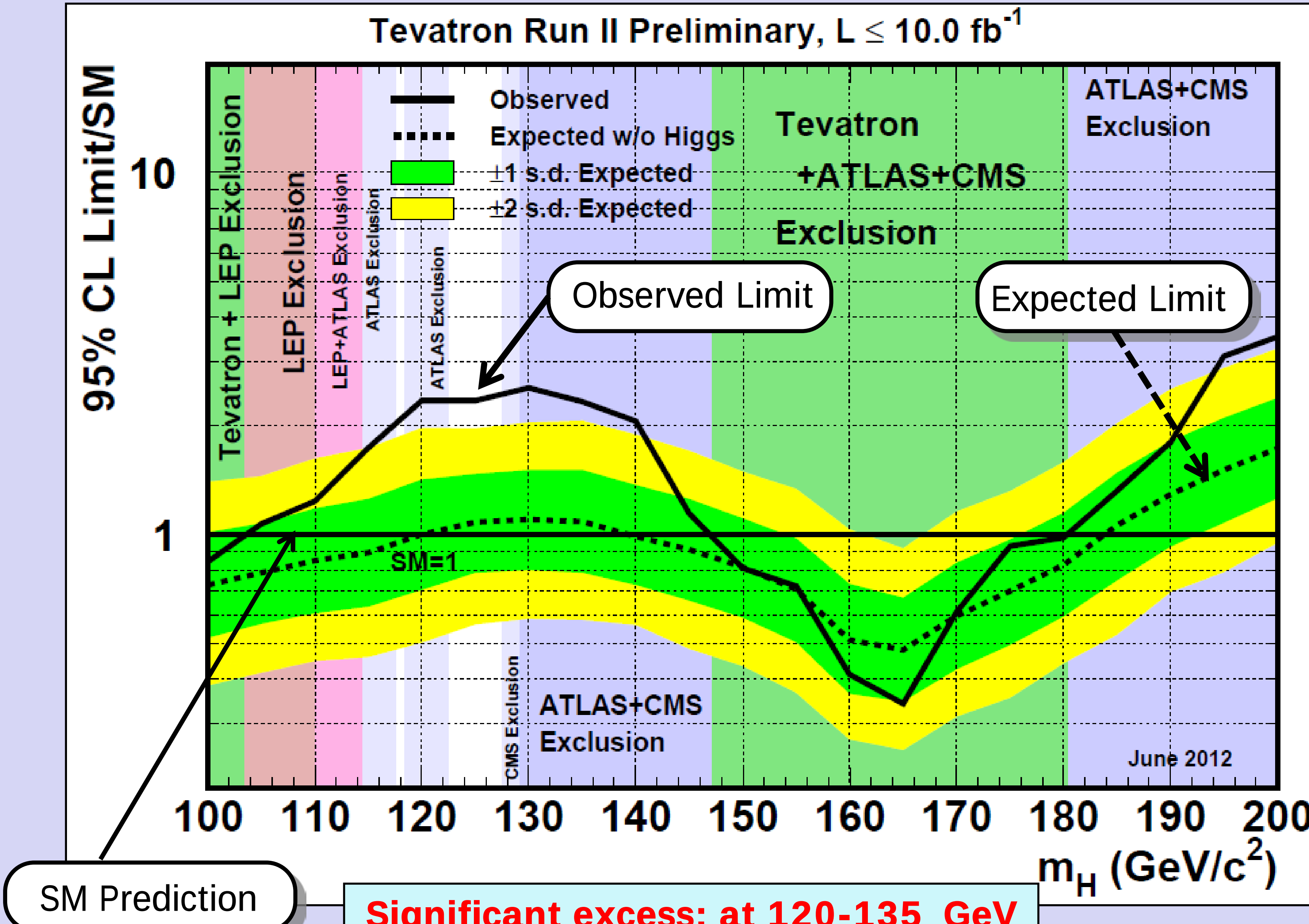
CDF and DØ combinations of all Higgs search channels:
H→WW, H→bb, H→γγ + other modes





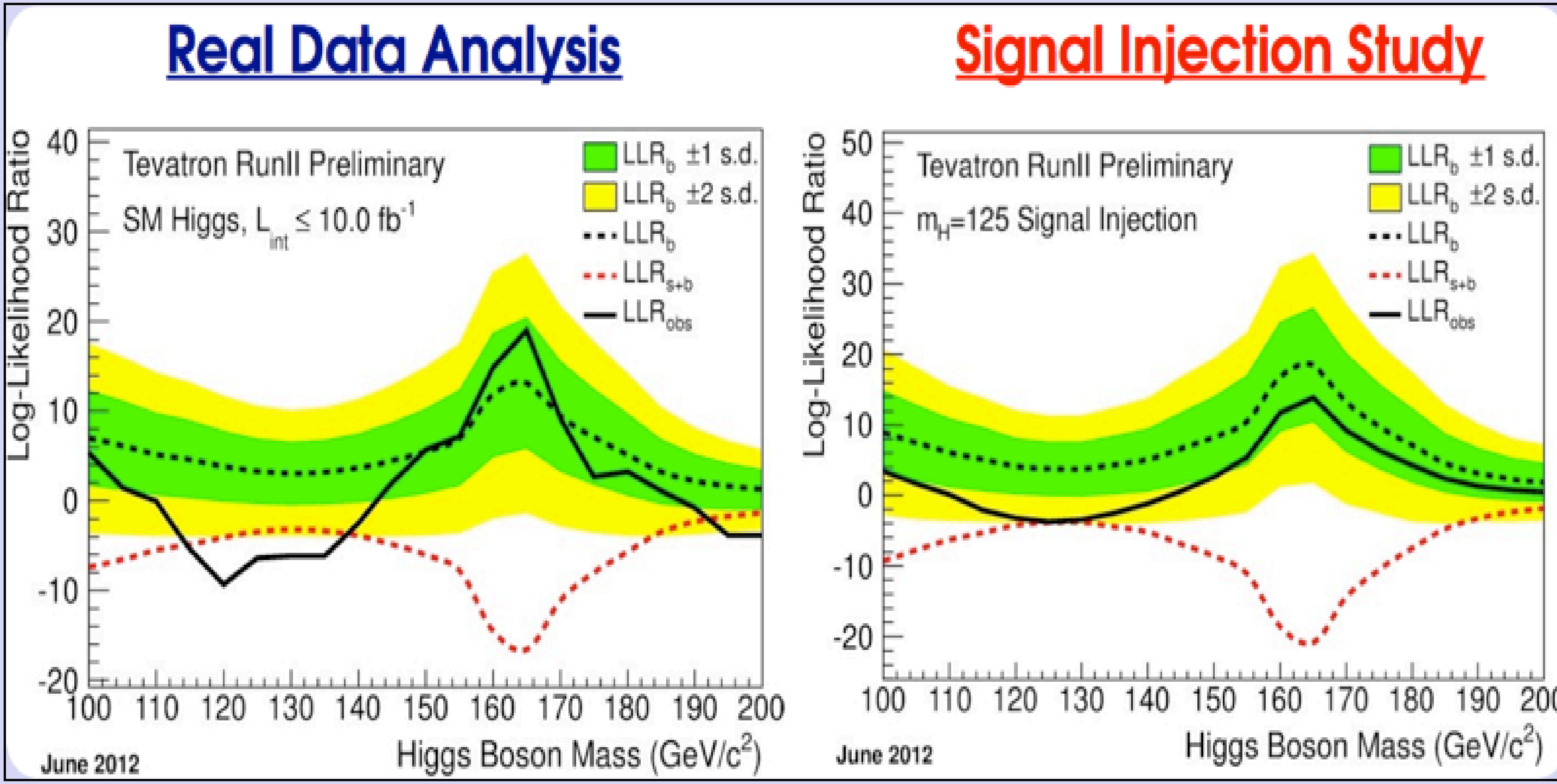
Remarkably similar shapes: **no excess below ~110 GeV**
broad excess around ~120-140 GeV
exclusion around ~165 GeV

June 2012 Tevatron Combination



Significant excess: at 120-135 GeV

Excess Shape Comparable with Higgs – Yes!

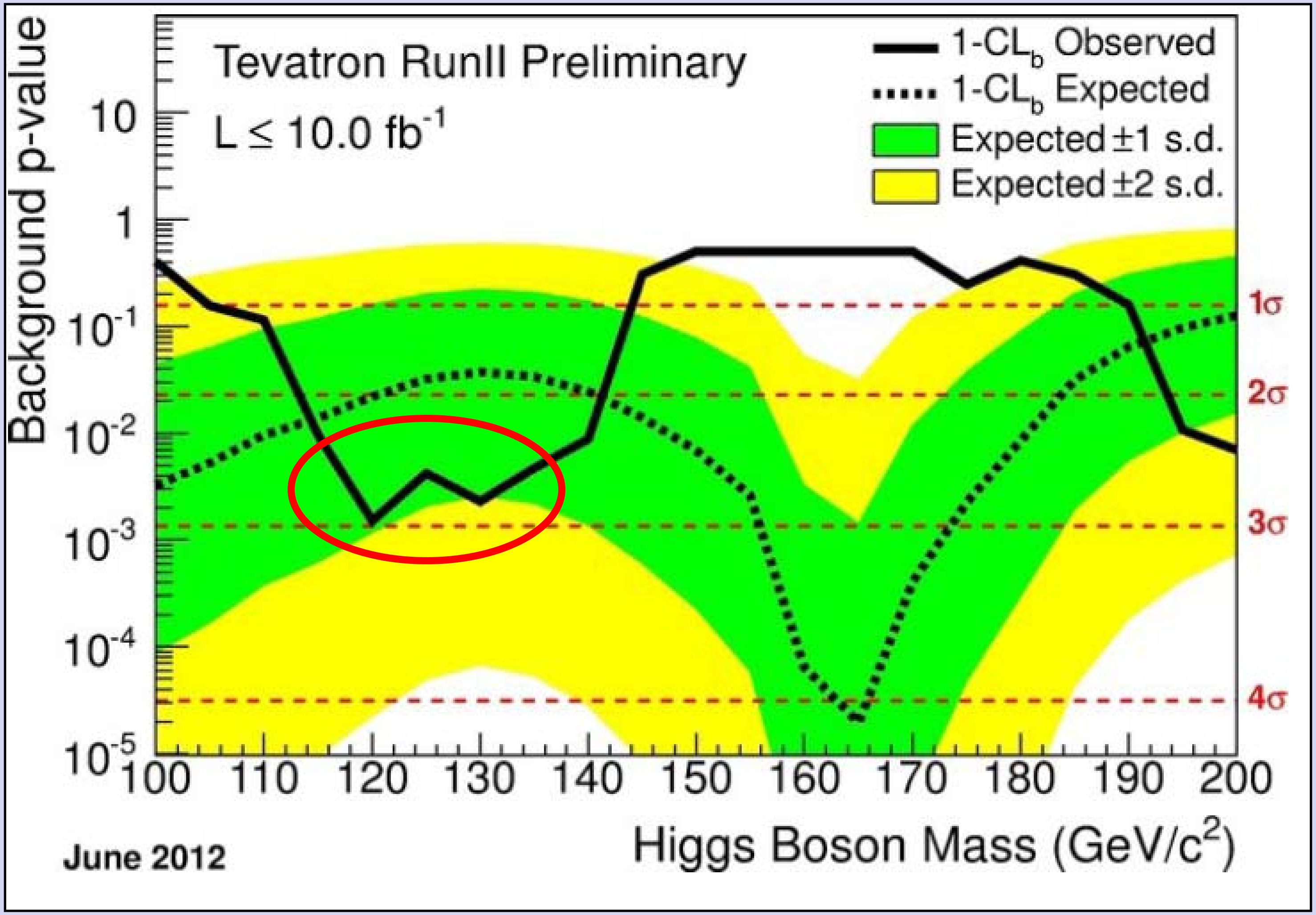


Injection of Standard Model Higgs signal at 125 GeV provides very similar to the observed behavior

"background like" shape above ~140 GeV

"signal like" shape in 115-140 GeV region

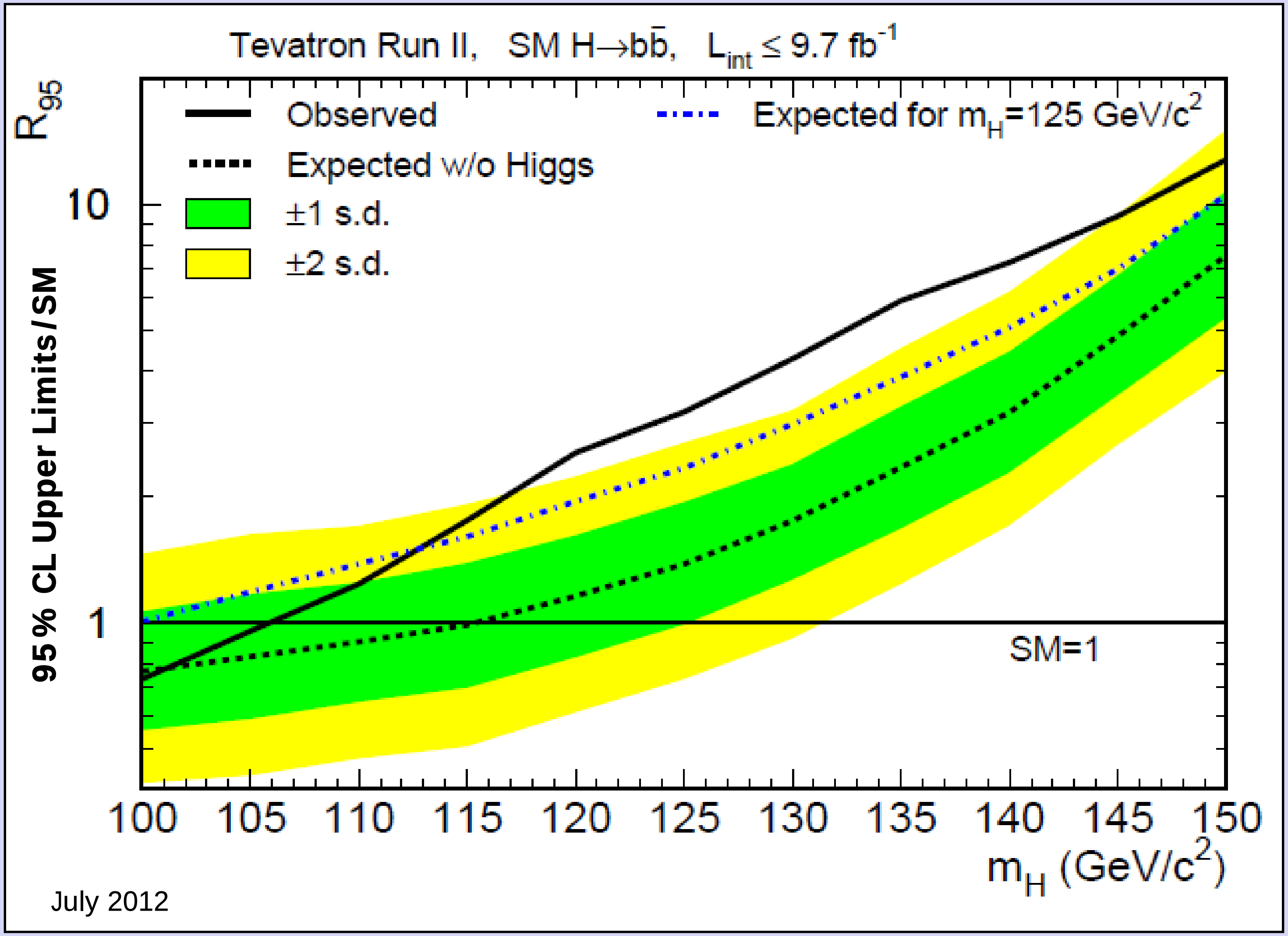
Probability of Background to Mimic Signal



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

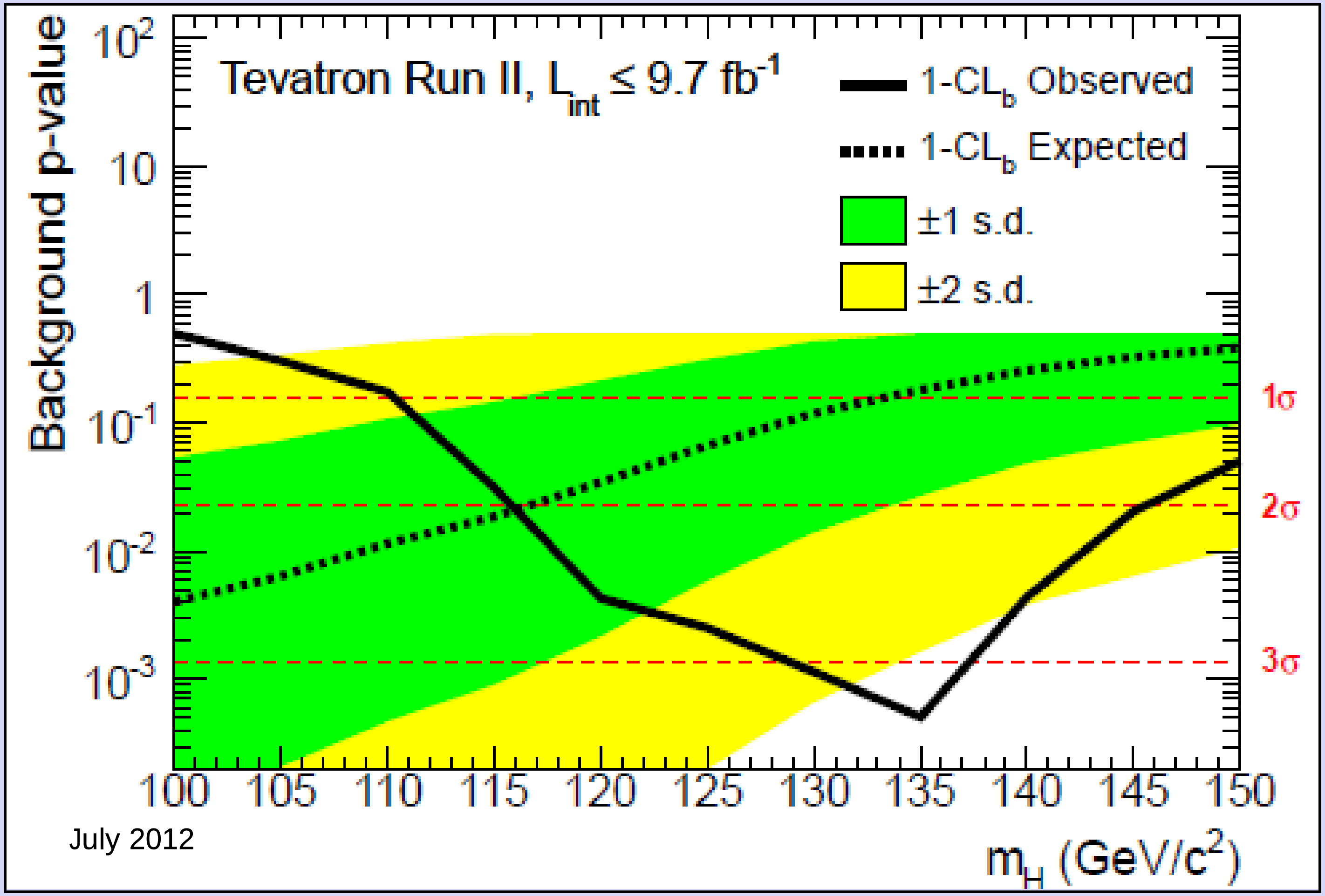
Tevatron H→bb Combination



Broad excess, maximum between 120 and 140 GeV

Width consistent with di-jet mass resolution

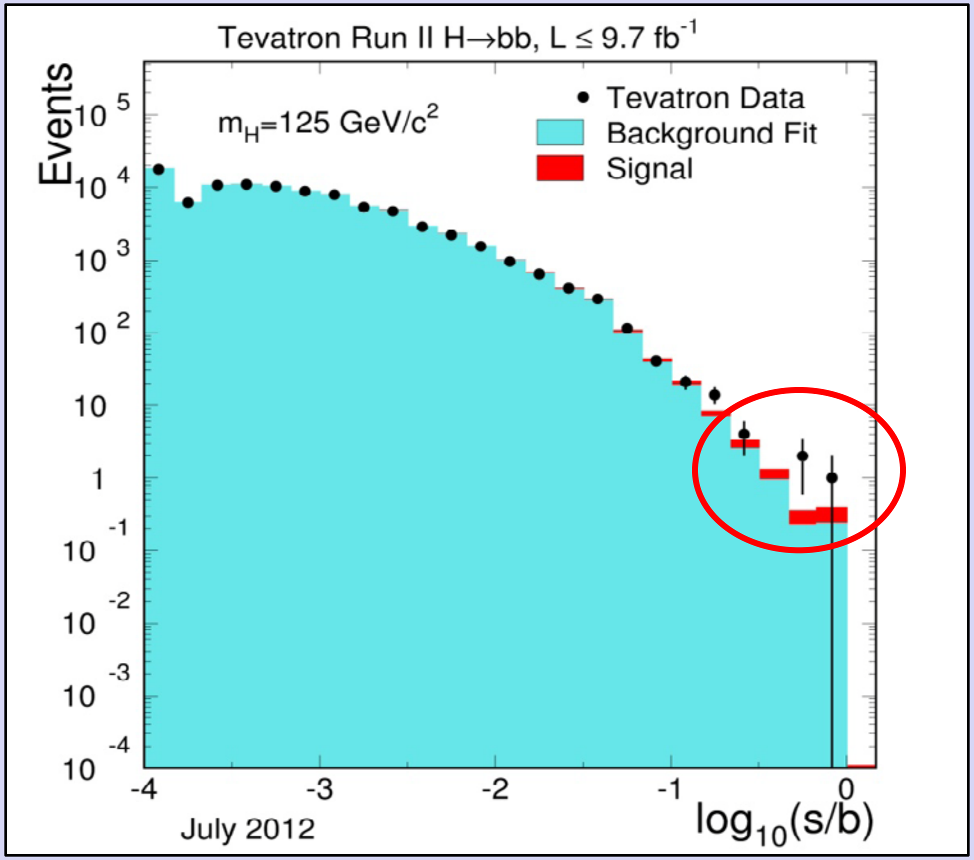
H→bb, Probability of Background to Mimic Signal

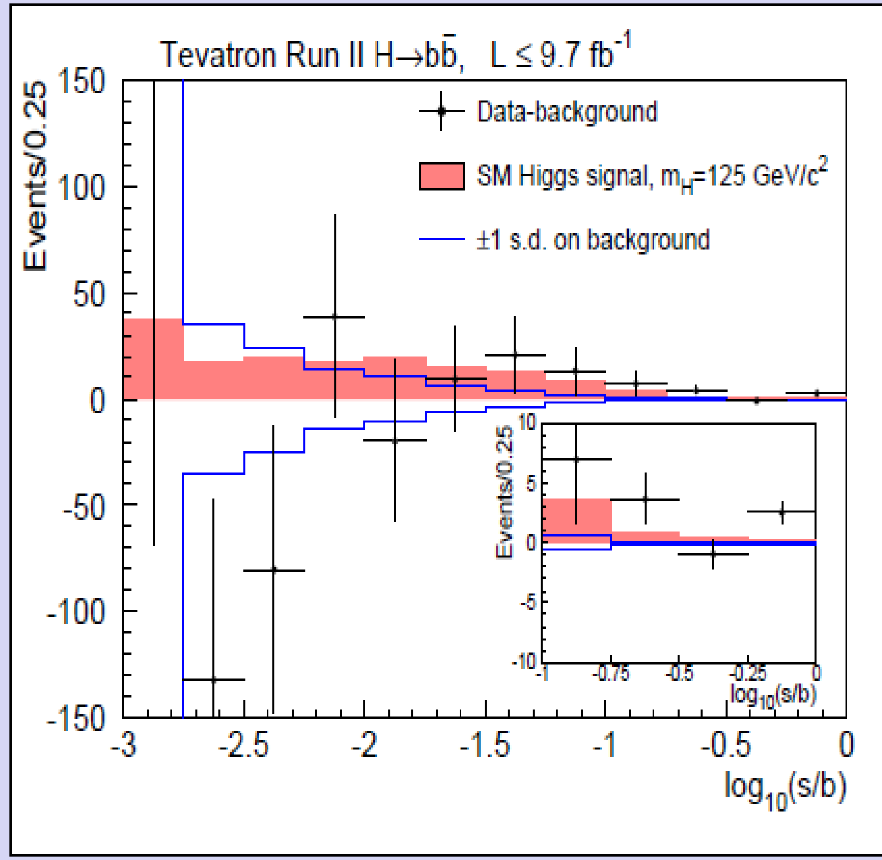


Significance of observed excess

Channels	Local	Global
H→bb	3.3 σ	3.1 σ Evidence!

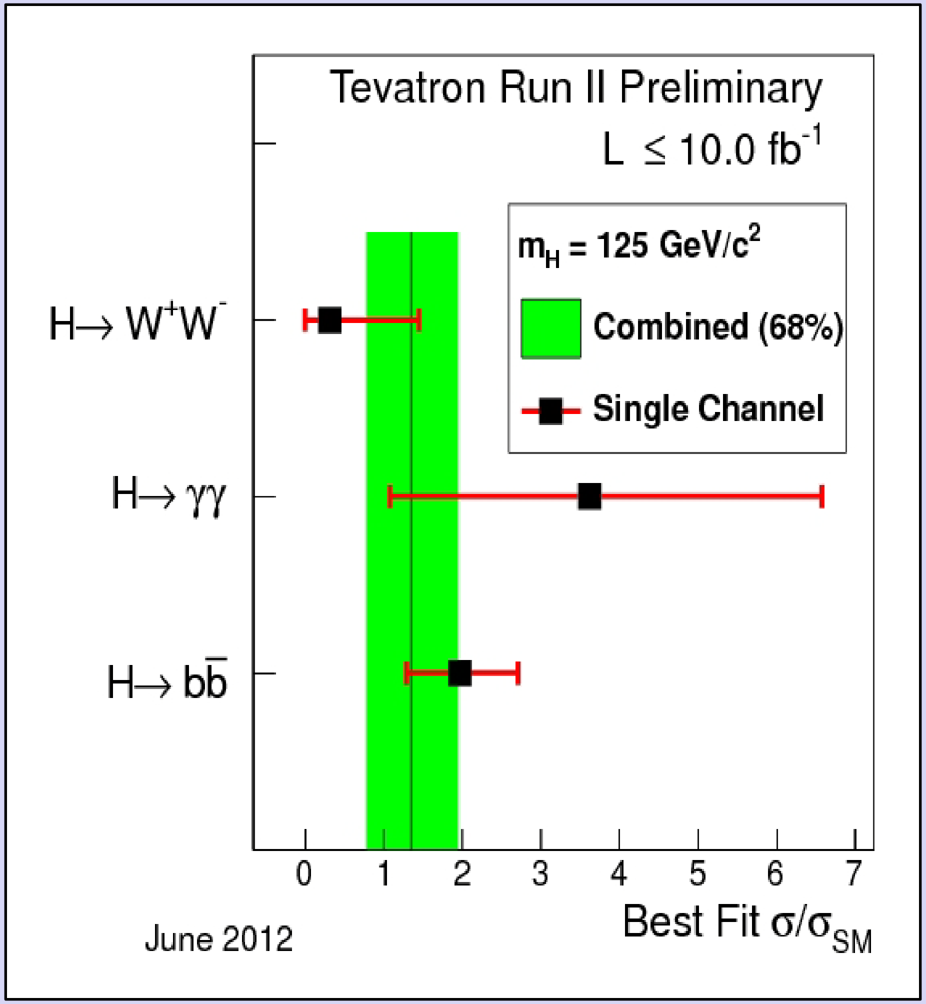
Events Count for 125 GeV Higgs Search

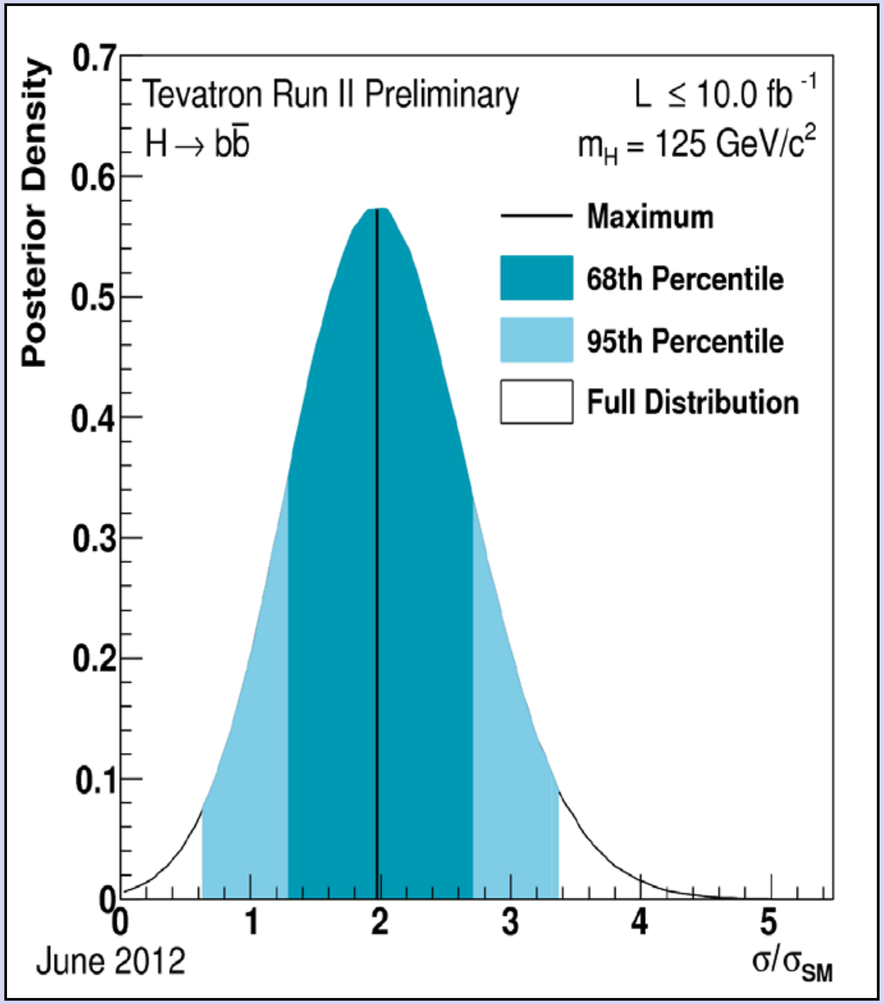




Clear excess in the high Signal / Background region

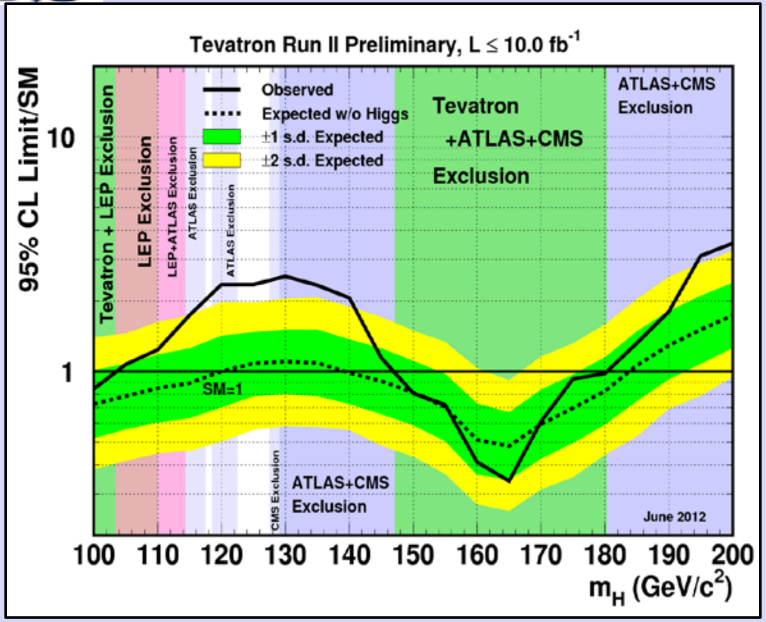
Best Fit Cross Sections

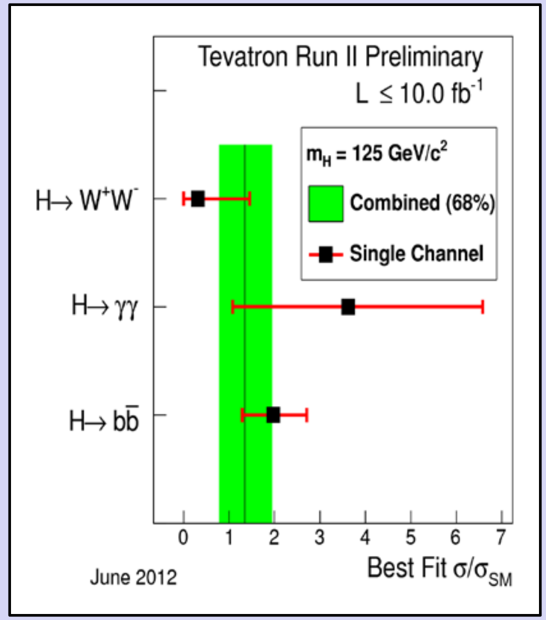


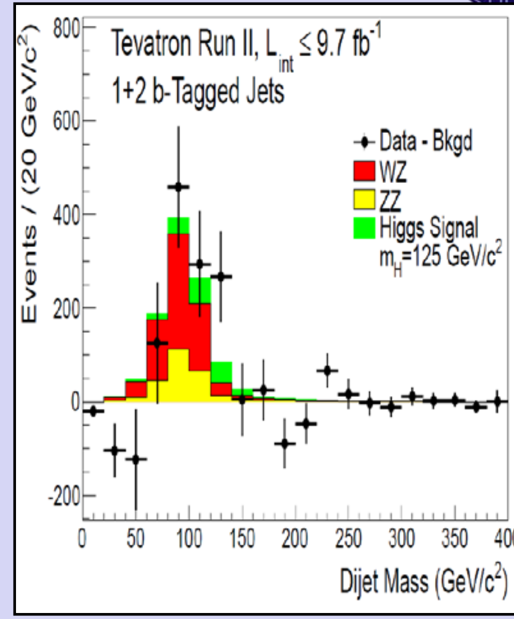


- Using data we extract σ x Br for H → bb, H → WW and H → γγ values normalized by the Standard Model predictions
- All data are compatible with predictions for the Standard Model Higgs boson

Evidence for the Higgs Boson with Full Tevatron Data Set





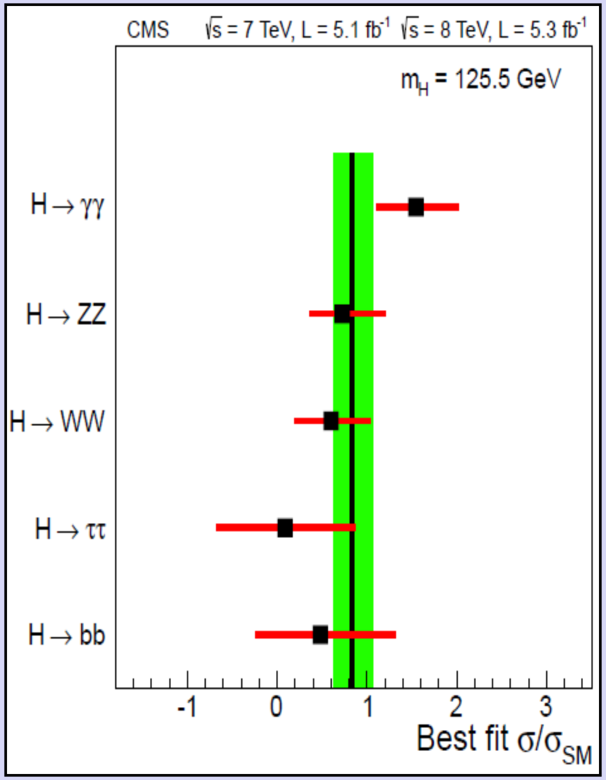


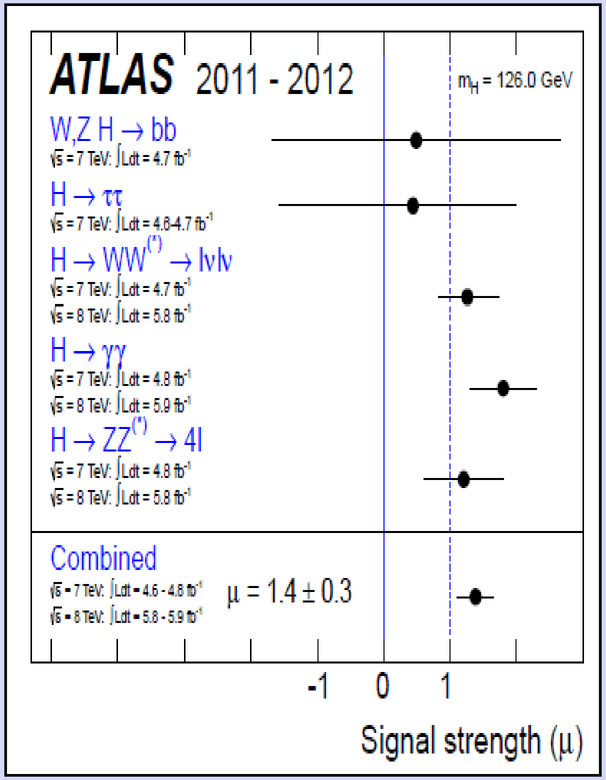
- **Tevatron Higgs search data are incompatible with background only hypothesis**
  - **For Higgs to bb channel p-value is 3.1σ**
- **Tevatron data are compatible with Standard Model Higgs boson production in the mass range**
  - **115 GeV < M_H < 135 GeV in all studied channels including H → bb, H → WW and H → γγ**
  - $(\sigma_{WH} + \sigma_{ZH}) \times \mathcal{B}(H \to b\bar{b}) = 0.23^{+0.09}_{-0.08}\ (\mathrm{stat} + \mathrm{syst})\ \mathrm{pb}$
- **Based on Tevatron results, including precision W boson and top quark mass measurements, new particle has properties predicted for the Higgs in the Standard Model and couples to fermions**

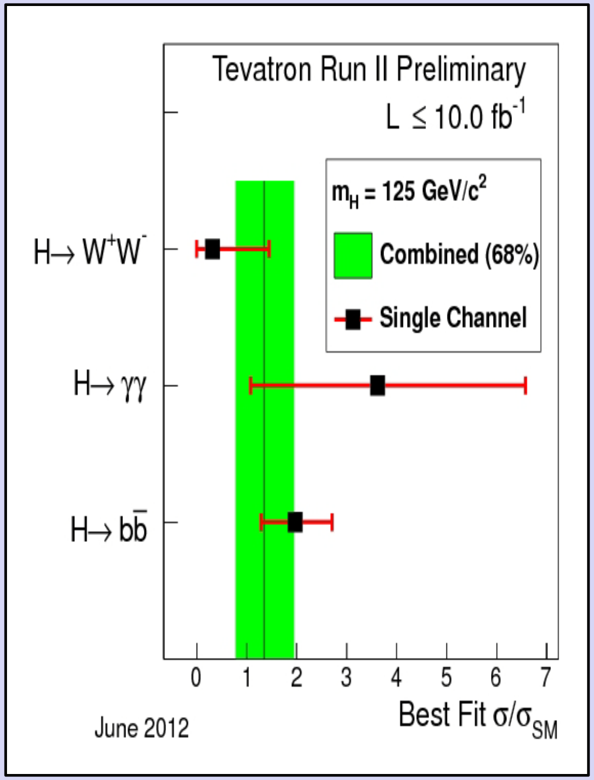
- **All of the above is interpreted as**
  - **Evidence for the Higgs boson production at the Tevatron**

Current Status of Higgs "Searches"

- **LHC provides large samples of Higgs bosons (x100 Tevatron cross section)**
  - **Rare and clean decay modes, like $\gamma\gamma$ can be used for searches – discovery this summer!**
- **Tevatron, due to proton-antiproton collisions, provides unique opportunity to study most probable at 125 GeV decay mode: pair of b quarks and indicate coupling to fermions**

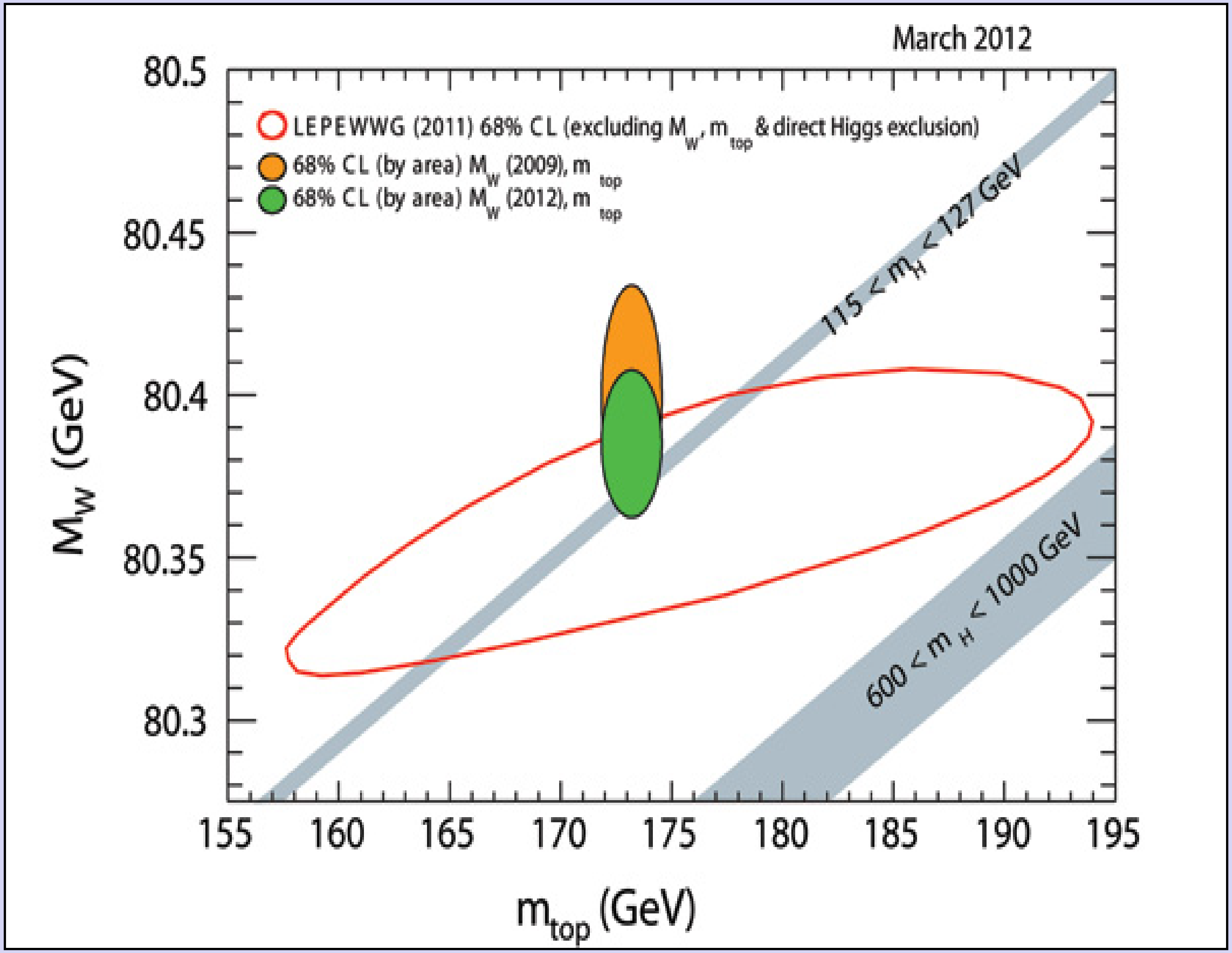






Careful analysis of all available data, including cross sections at vastly different collision energies, demonstrates good agreement between properties of the observed particle and predicted in the Standard Model Higgs boson

Self-consistency of the Standard Model



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

Looking Ahead - Higgs

- **Tevatron**
  - **Improved analysis will gain another ~10% in sensitivity**
    - **HCP, Kyoto next week**
  - **Using mass constrain of 125 GeV will improve measurements of branching fraction to a pair of b-quarks**
  - **Measurement of Higgs couplings**

- **LHC**
  - **More data coming: ~30 fb^{-1} by later this year before ~2 years shutdown**
  - **Sensitivity over 3 σ for majority decay modes, including fermions**
  - **Measurement of Higgs spin using large data sets**
  - **Measurement of Higgs couplings**

- **Higgs factory**
  - **As Higgs mass is relatively low**
    - **Medium energy lepton collider will suffice**
  - **High luminosity is required for reasonable number of Higgs bosons**
  - **Exciting option widely discussed**

Tevatron Highlights Summary

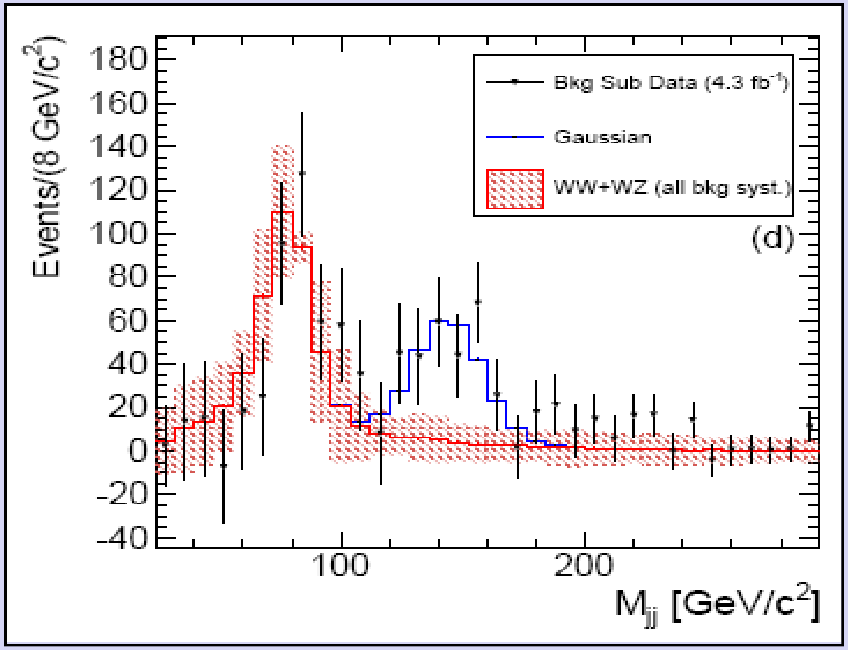
- Tevatron experiments published over 1000 fundamental results
  - From the discovery of the top quark to the evidence of the Higgs boson production and decay to fermions
- Many extremely precise measurements of the Standard Model parameters
- 100's of searches for physics beyond Standard Model with 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 ~150 papers in 2012 and 2013
- Large number of analyses in all physics areas continue including
  - Unique for proton-antiproton collider measurements
  - Top quark mass to ~0.6 GeV accuracy and W boson mass to ~10 MeV accuracy

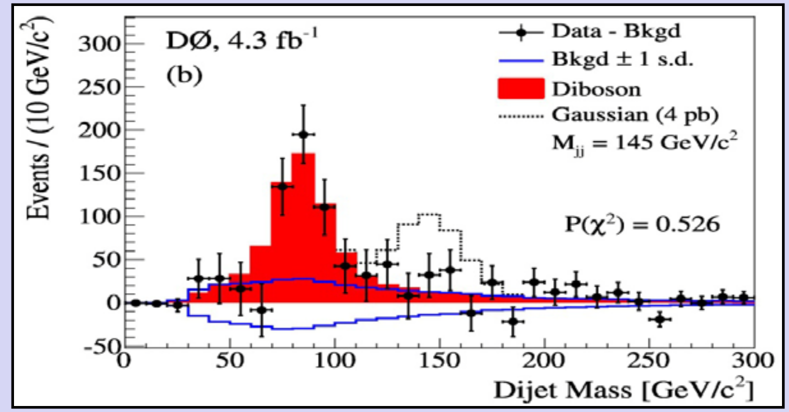
Thank you for the invitation to visit Tokyo University and present an exciting summary of recent Tevatron results!

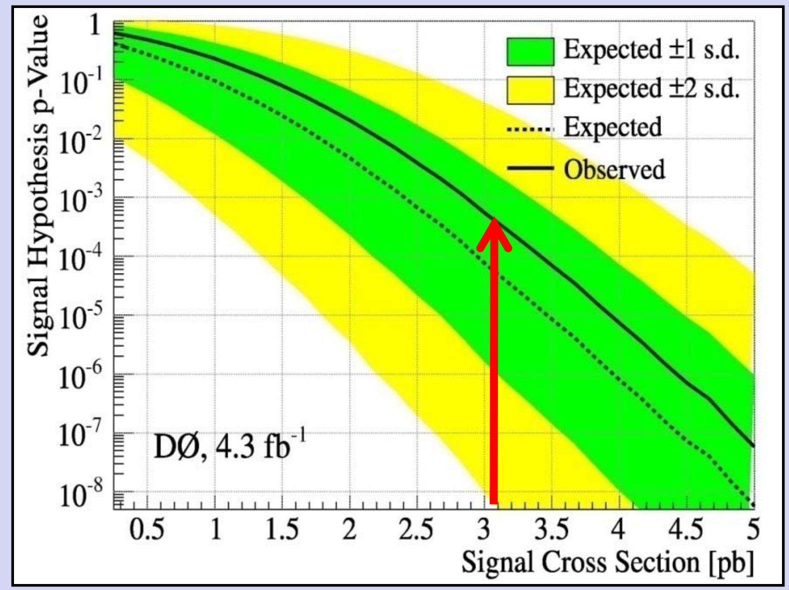
ありがとうございます。

Backup Slides

Wjj Puzzle at the Tevatron







- **CDF: 3.2σ peak in di-jet mass spectrum**
- **Cross section 3.1 + / - 0.8 pb**
- **Mass 144 + / - 5 GeV**
- **Width consistent with detector resolution**

- **ATLAS / CMS (pp) do not see "the bump"**
- **Waiting for updated CDF analysis addressing uncovered concerns**

- **DZero: good agreement with Standard Model**
- **Exclude 3.1 pb cross section at $5 \cdot 10^{-4}$**
- **95 % CL exclusion at 1.9 pb**

Particle Experiments Tools - Accelerators

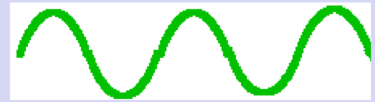
- **Accelerators are giant microscopes to study extremely small objects**

$$\text{Wavelength} = h / E_{beam}$$

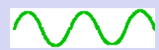
- **Accelerators are "converters" of energy into mass**

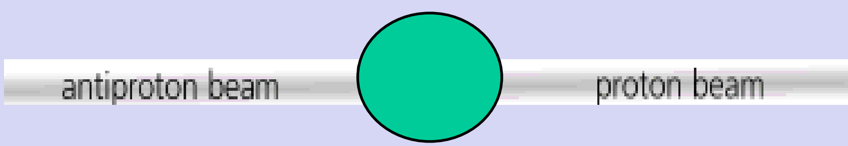
$$E = mc^2$$

Objects with masses up to
$\text{Mass} = 2E_{beam} / c^2$ could be created



Cell

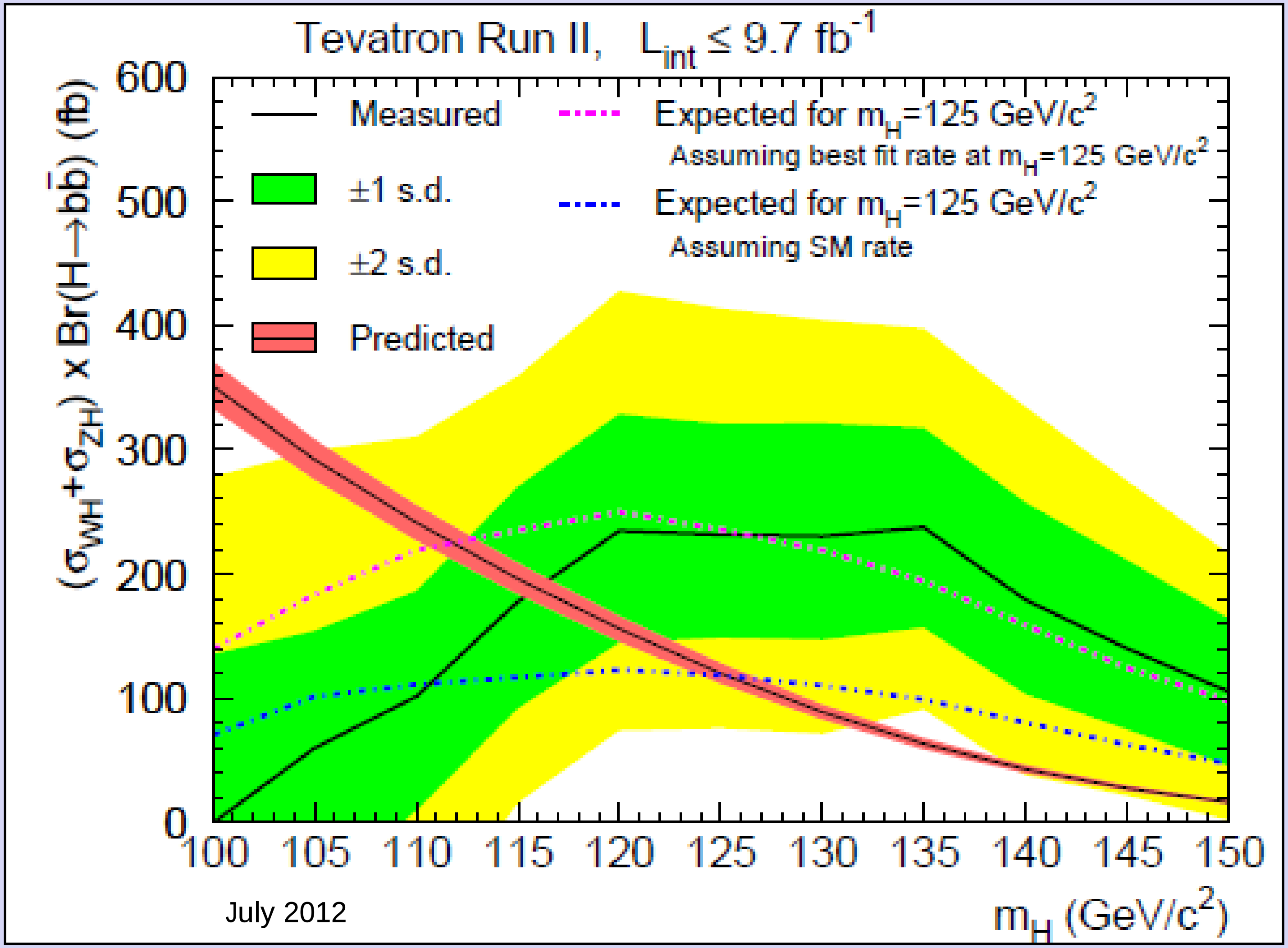




E_{beam} Mass E_{beam}

Tevatron center of mass energy is 2000 GeV
Protons wavelength is ~10^{-16} cm

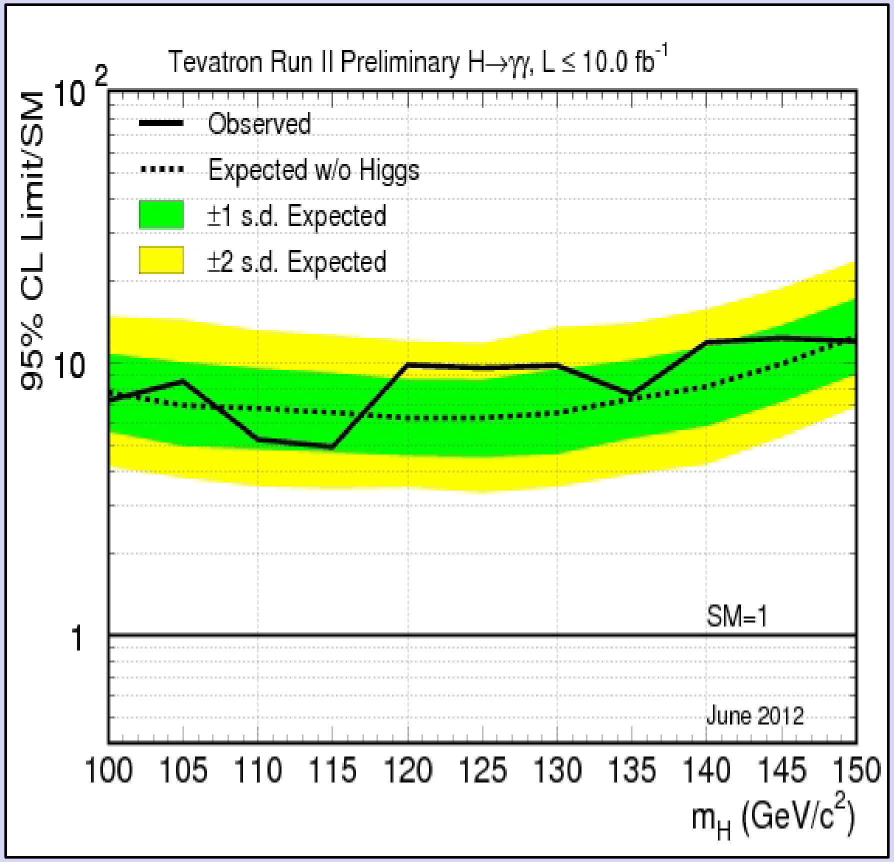
Cross Section * BR Measurement

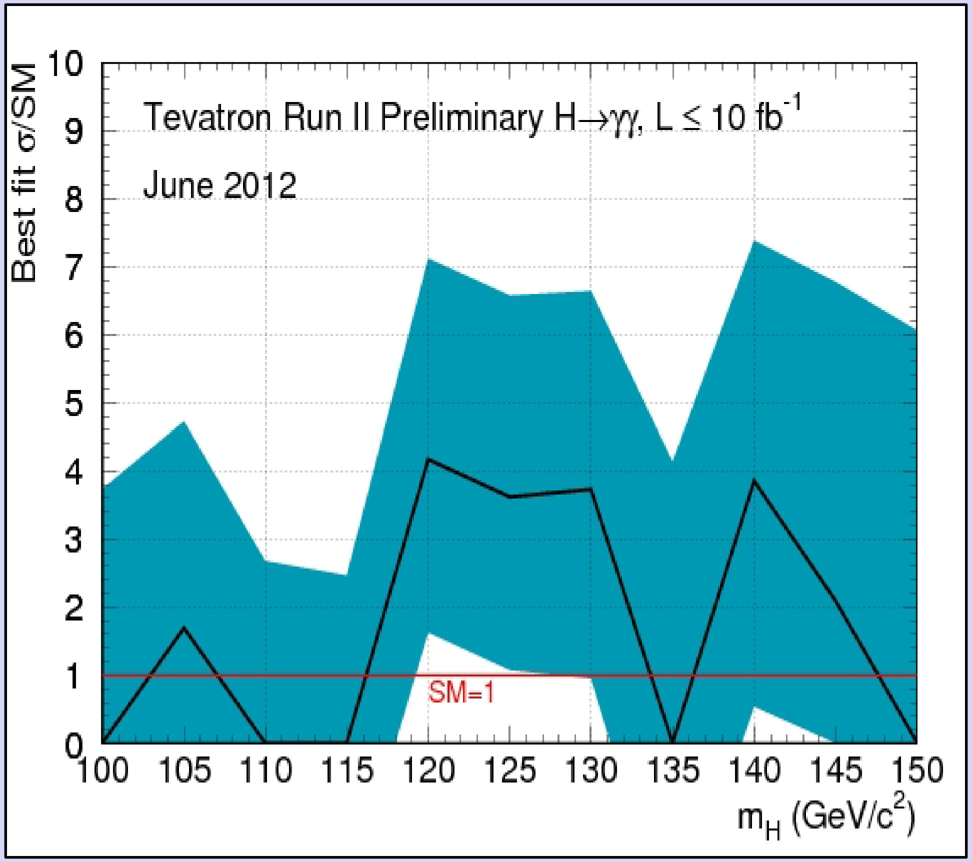


$$(\sigma_{WH} + \sigma_{ZH}) \times \mathcal{B}(H \rightarrow b\bar{b}) = 0.23^{+0.09}_{-0.08}\ (\mathrm{stat + syst})\ \mathrm{pb}$$

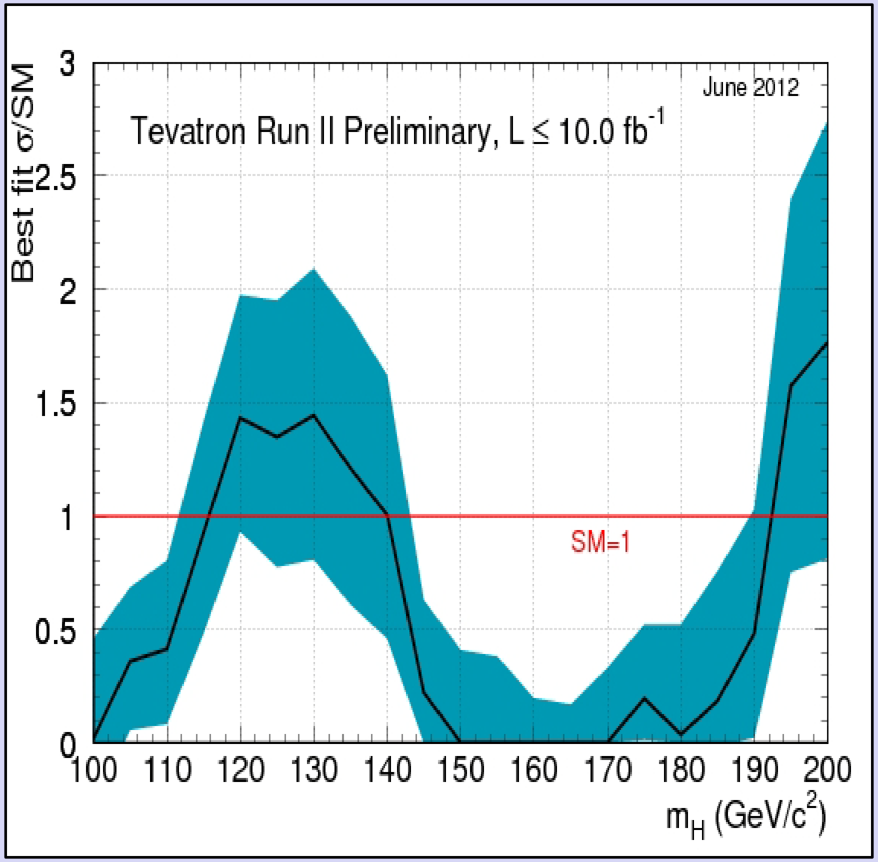
SM Higgs @ 125 GeV: 0.12 ± 0.01 pb

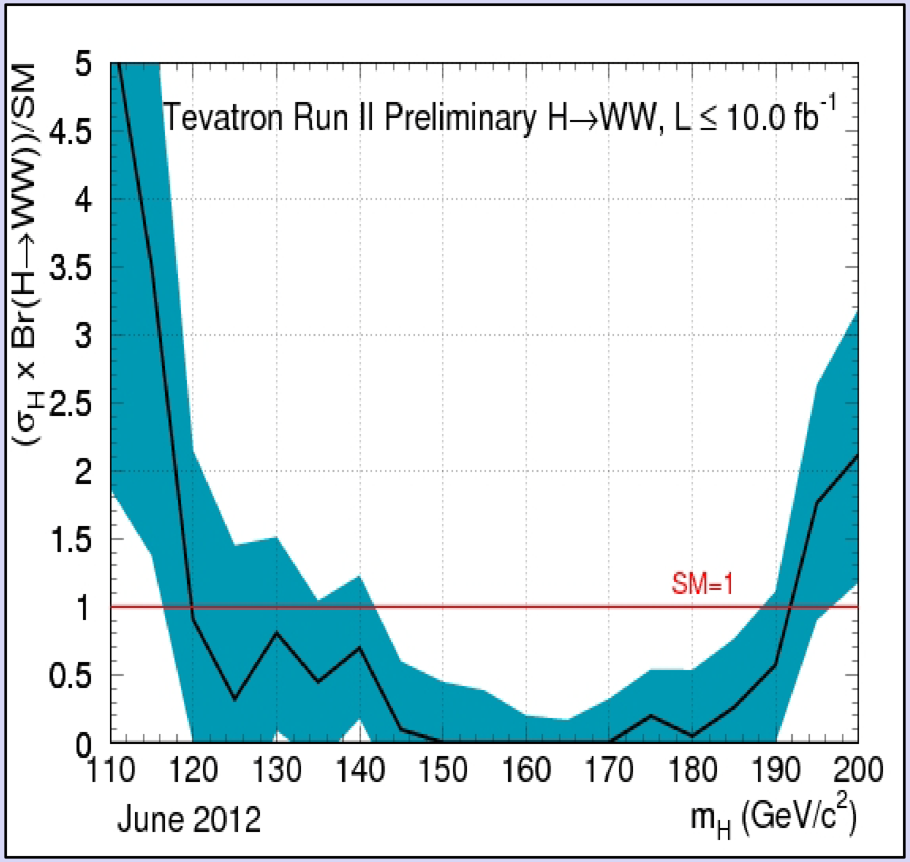
Higgs to $\gamma\gamma$



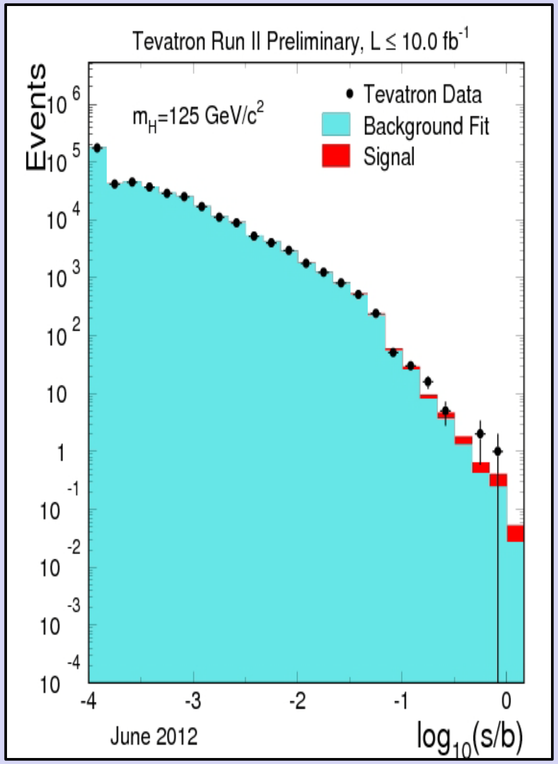


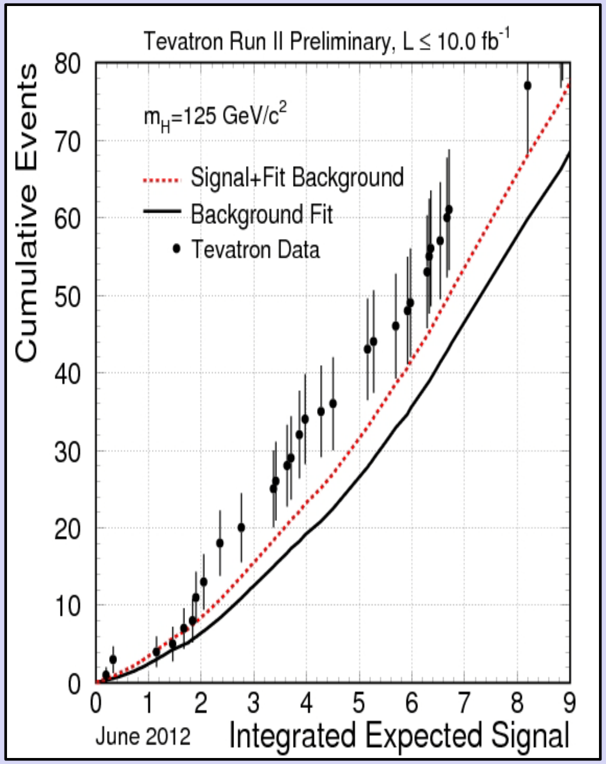
Best Fit Cross Sections

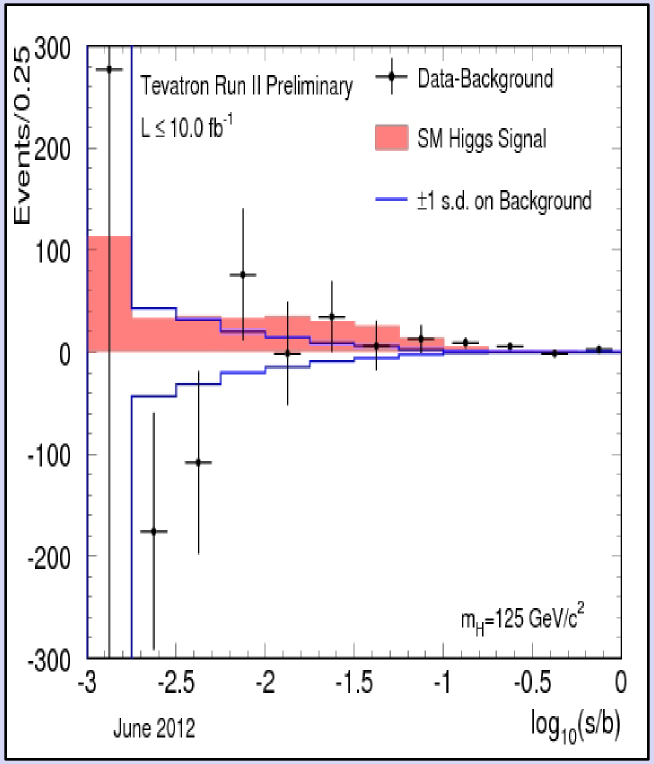




Full Combination Events Count







H to bb Combination Events Count