Searches for a Light Higgs Boson at the Tevatron

Artur Apresyan
Purdue University
On behalf of the CDF and DØ Collaborations

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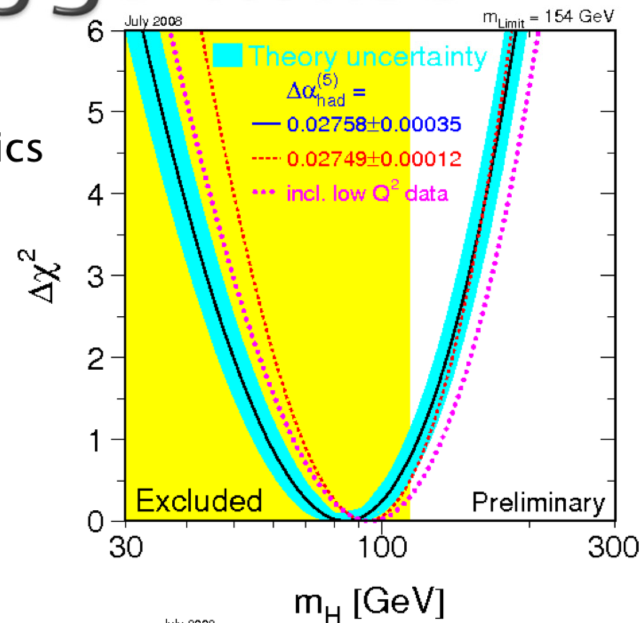
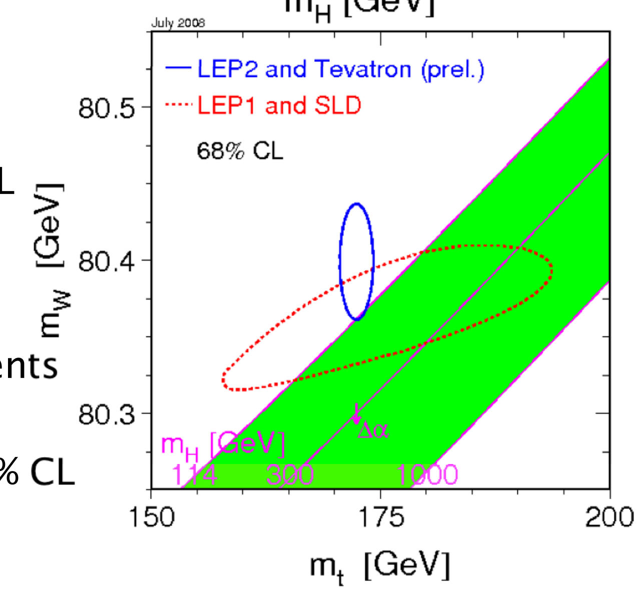
Constraints on the Higgs mass

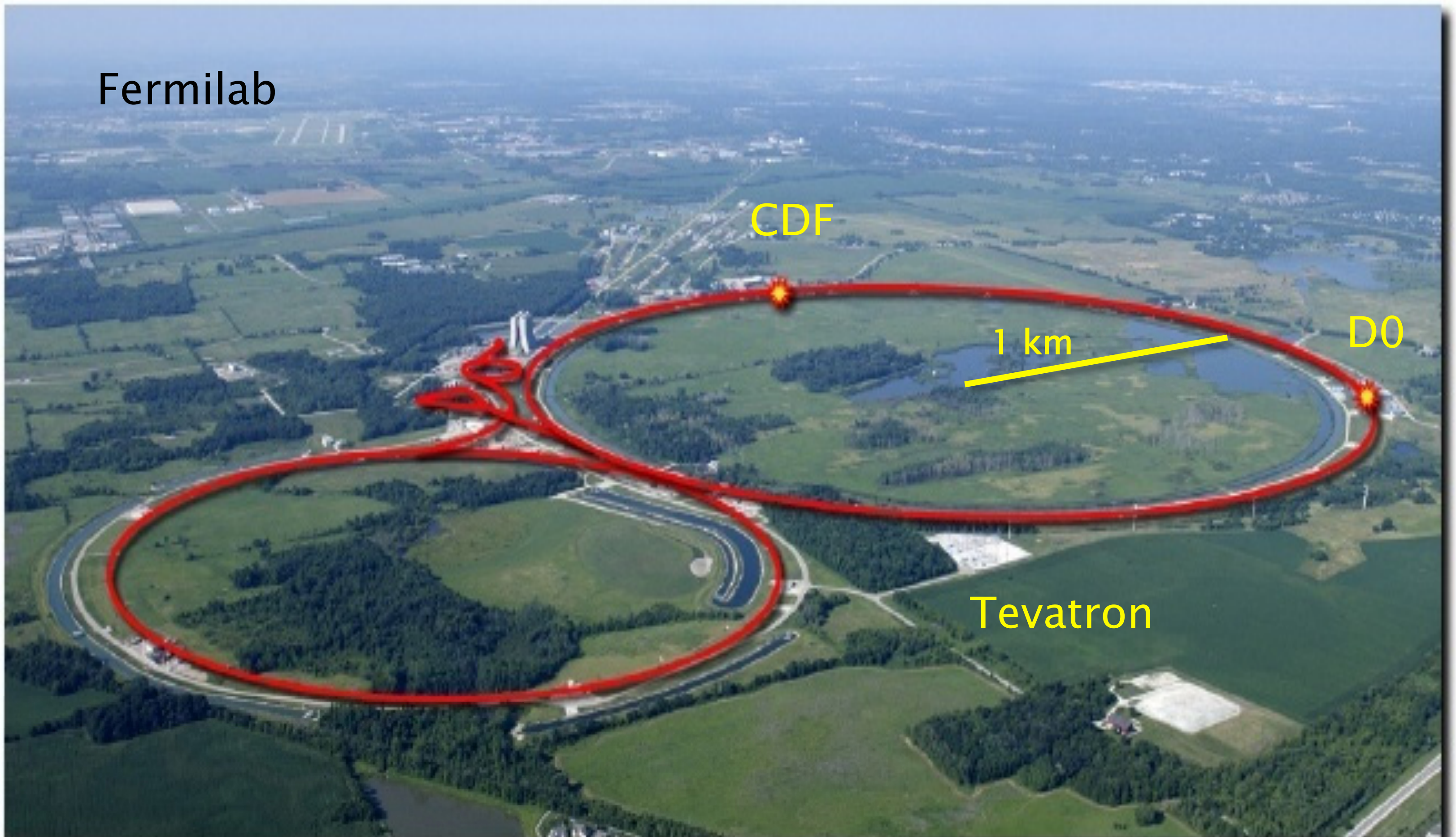
- Standard Model: a very successful theory
  - Explains most of known phenomenology of particle physics
- Last missing piece: the Higgs boson, has yet to be detected
  - In a sense, the fact that ($W^{\pm}$, Z) are massive is a *testament* of Higgs-like mechanism at work
- The SM does not predict the mass of Higgs boson
  - Need to be determined from experiment
- Direct observation of Higgs boson is needed
  - LEP excluded SM Higgs boson with $M_H < 114.4$ GeV/c^2 at 95%CL
- Higgs boson enters into radiative corrections
  - Constrain the mass of Higgs boson from precision measurements
  - Logarithmic dependence causes only weak constraints
  - With latest top/W mass from Tevatron: $M_H < 154$ GeV/c^2 at 95% CL





Tevatron Experiments

- The only machine currently capable to directly probe the Higgs sector above LEP limit
  - Proton-antiproton collisions at 1.96 TeV center-of-mass energy
  - Two-multipurpose detectors: **CDF** and **D0,** stable operations



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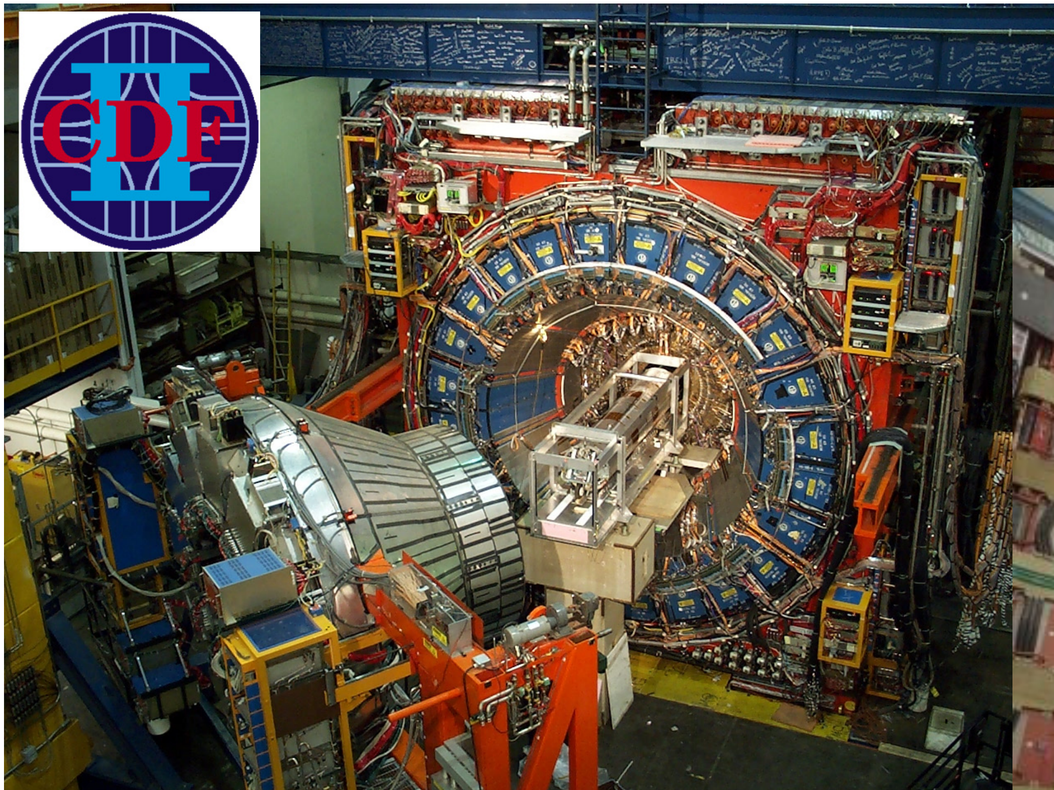

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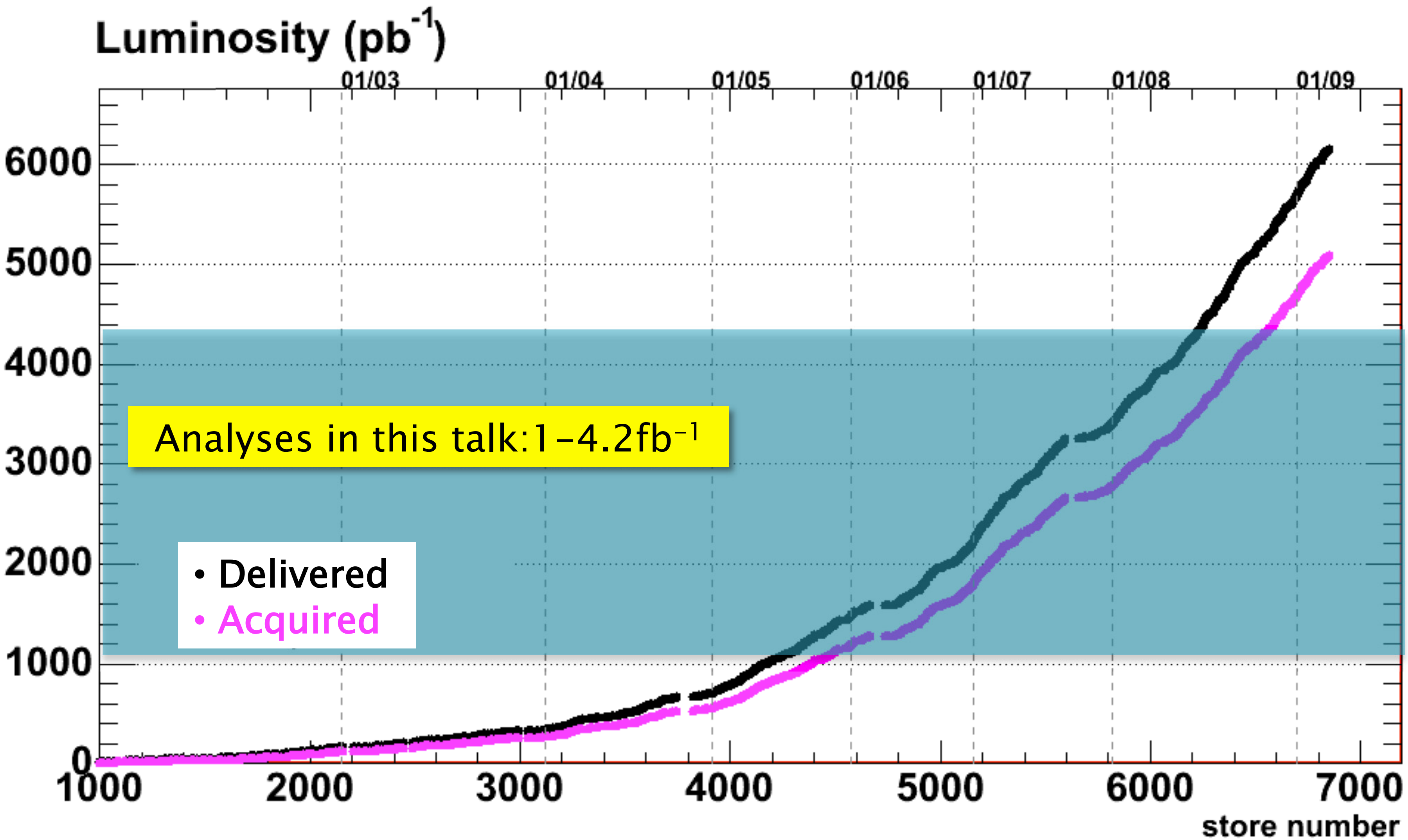
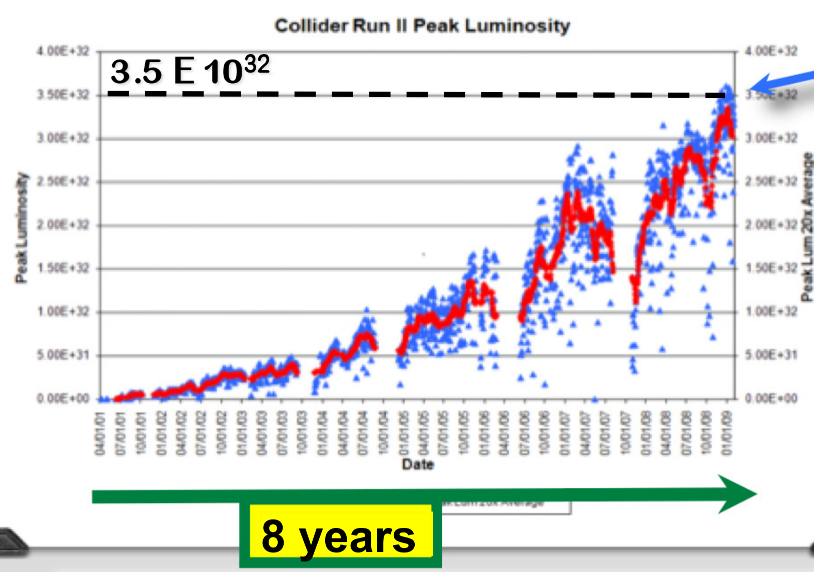


Tevatron Luminosity Progress



Record peak inst. luminosity

3.6 E 10^{32} cm^{-2} s^{-1}

Record luminosity/week

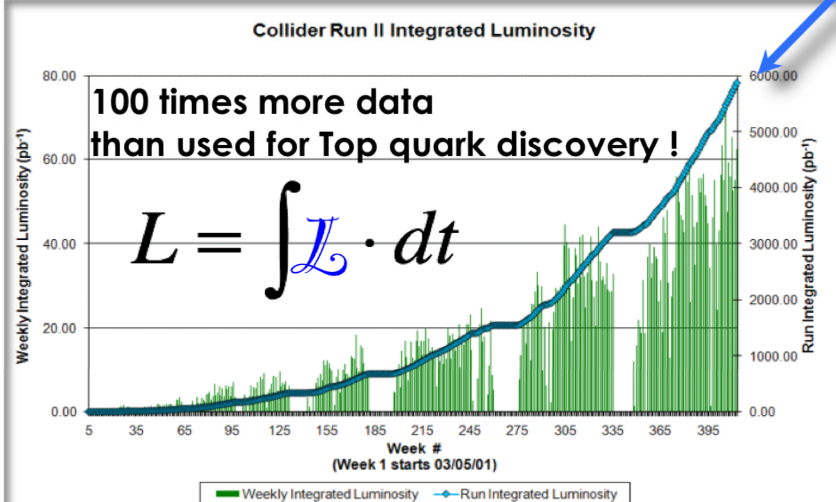
74 pb^{-1}

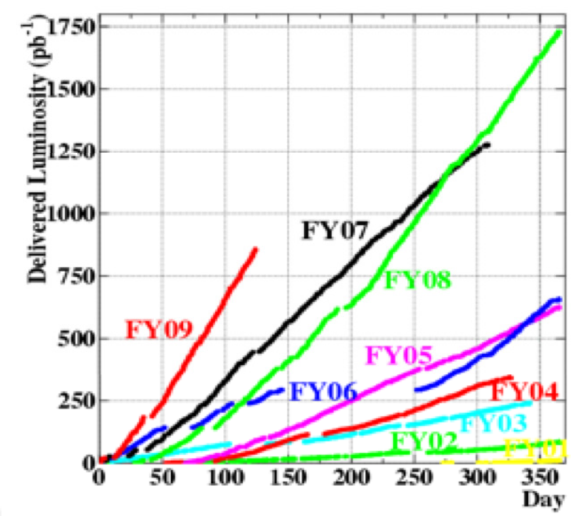
Record luminosity/month

263 pb^{-1}

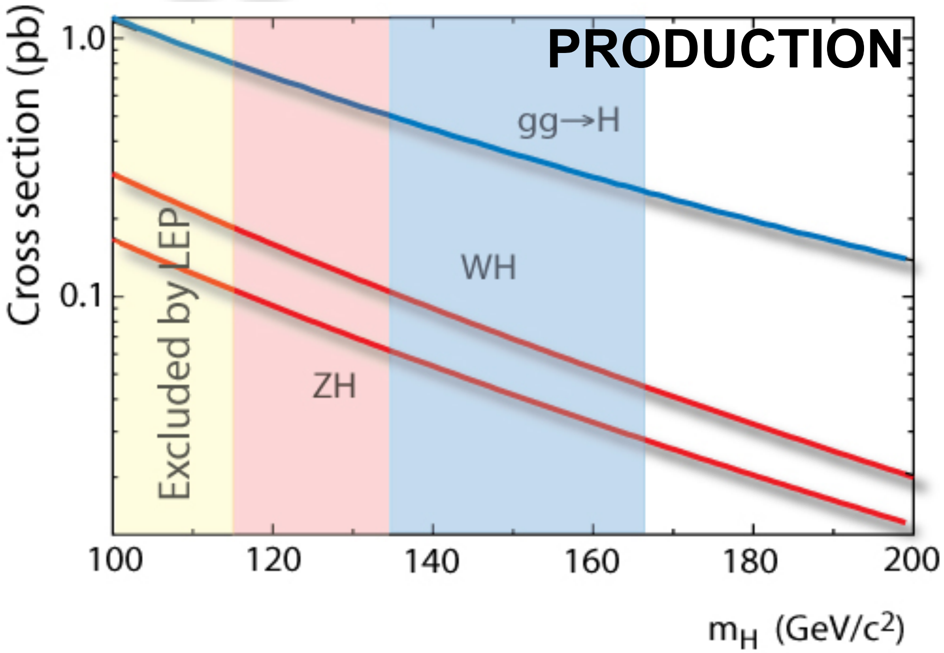
Total Luminosity delivered

6 fb^{-1}

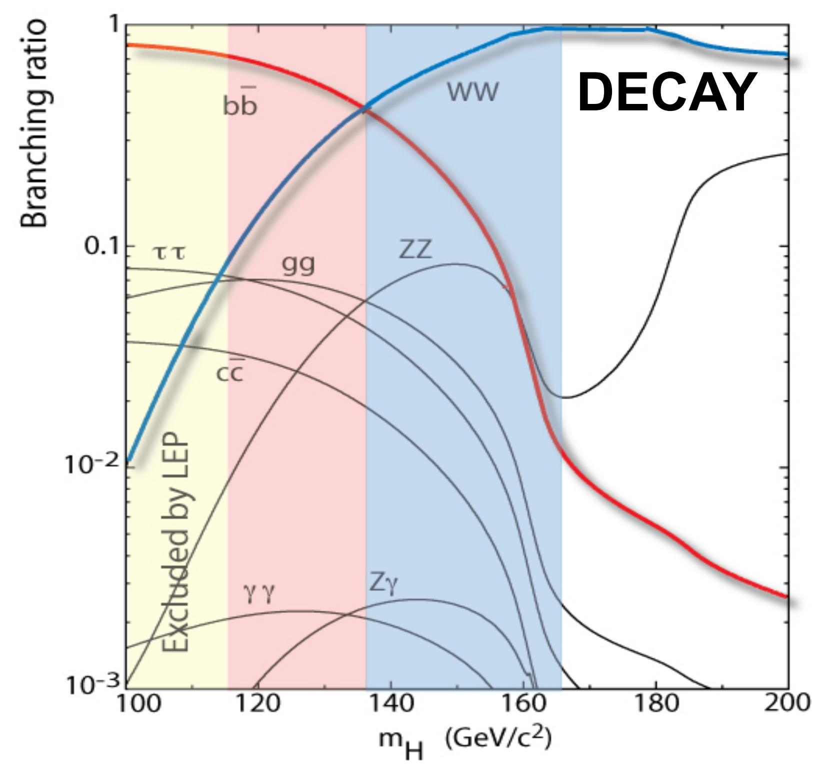




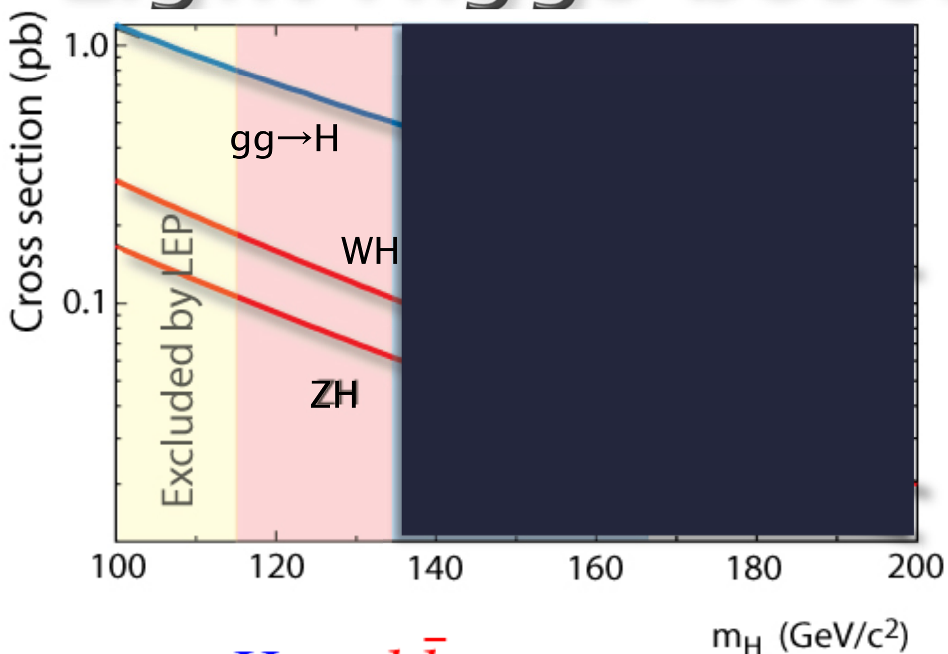
Higgs boson at the Tevatron



- The gluon fusion is the dominant production mode: σ ~1.1–0.1 pb
- W/Z associated production next most frequent mode: σ ~0.2–0.01 pb



Light Higgs boson at the Tevatron



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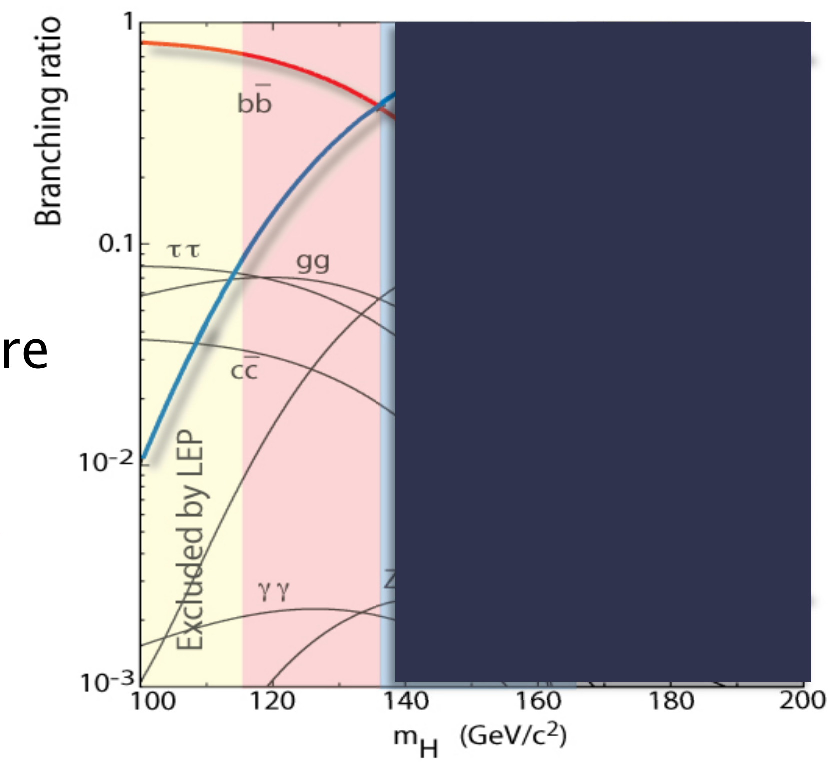
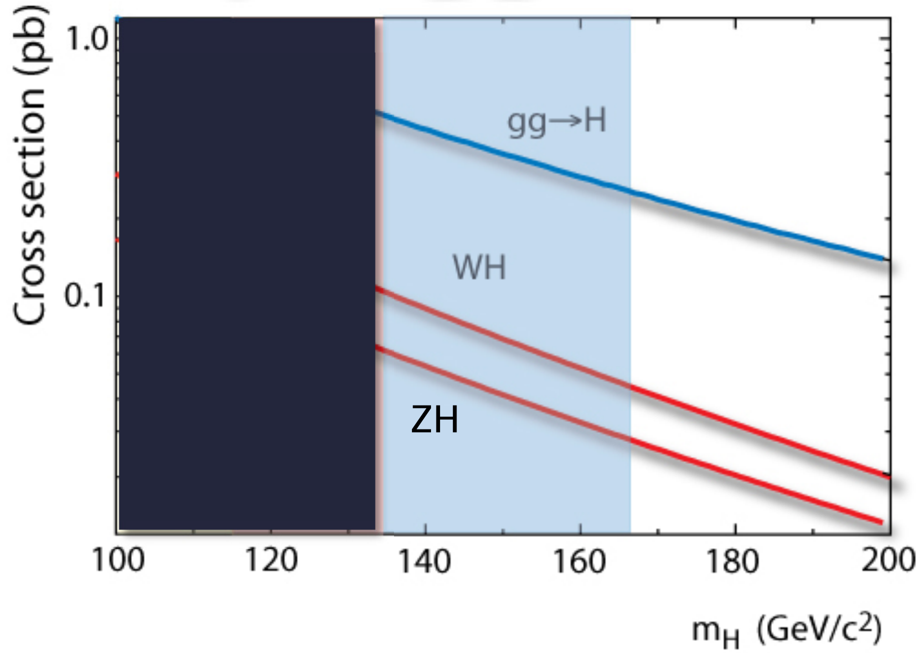


- $gg \to H \to b\bar{b}$: dominates
  - Not feasible, swamped by QCD
- Rely on **VH**: W/Z decays provide signature to increase S/B
- Additional modes, *e.g.* VBF, ttH, H→ γ γ

Heavy Higgs boson at the Tevatron



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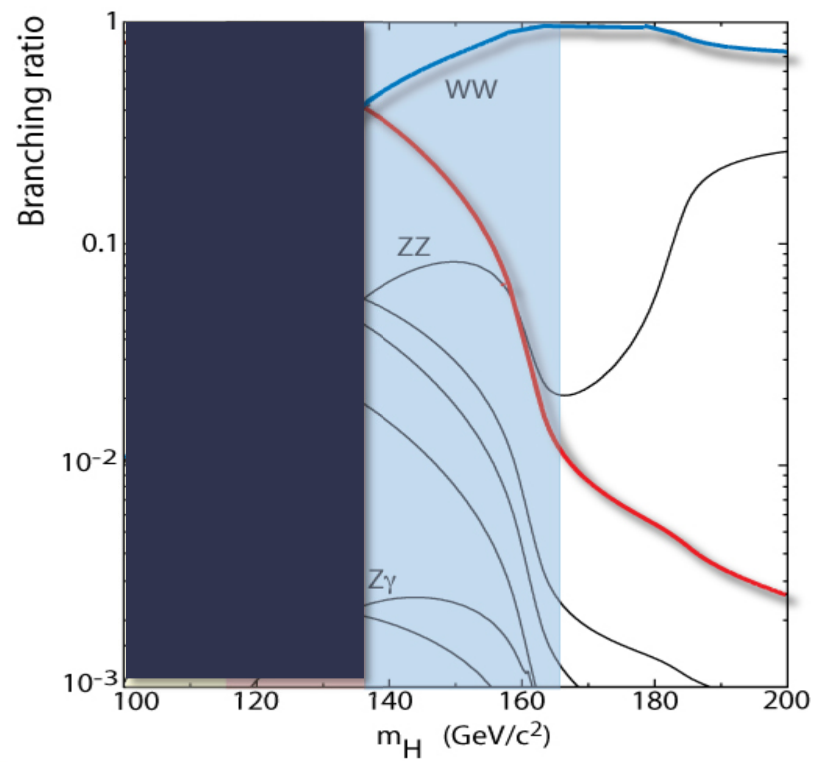
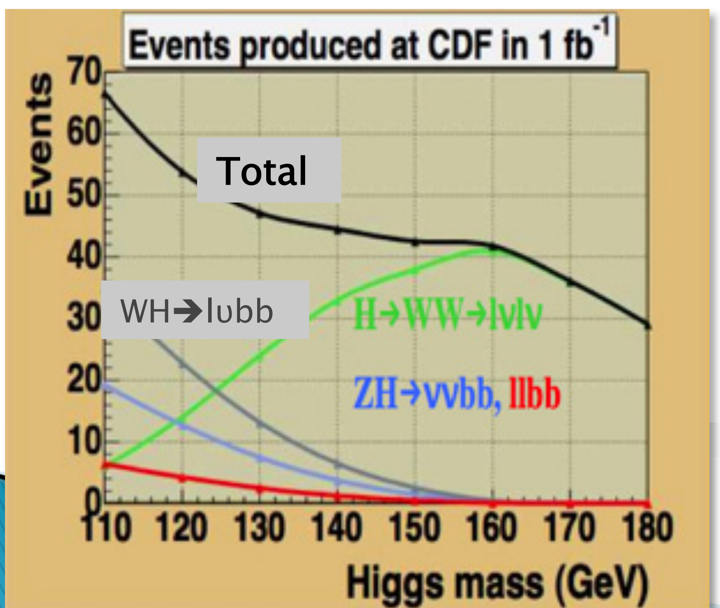
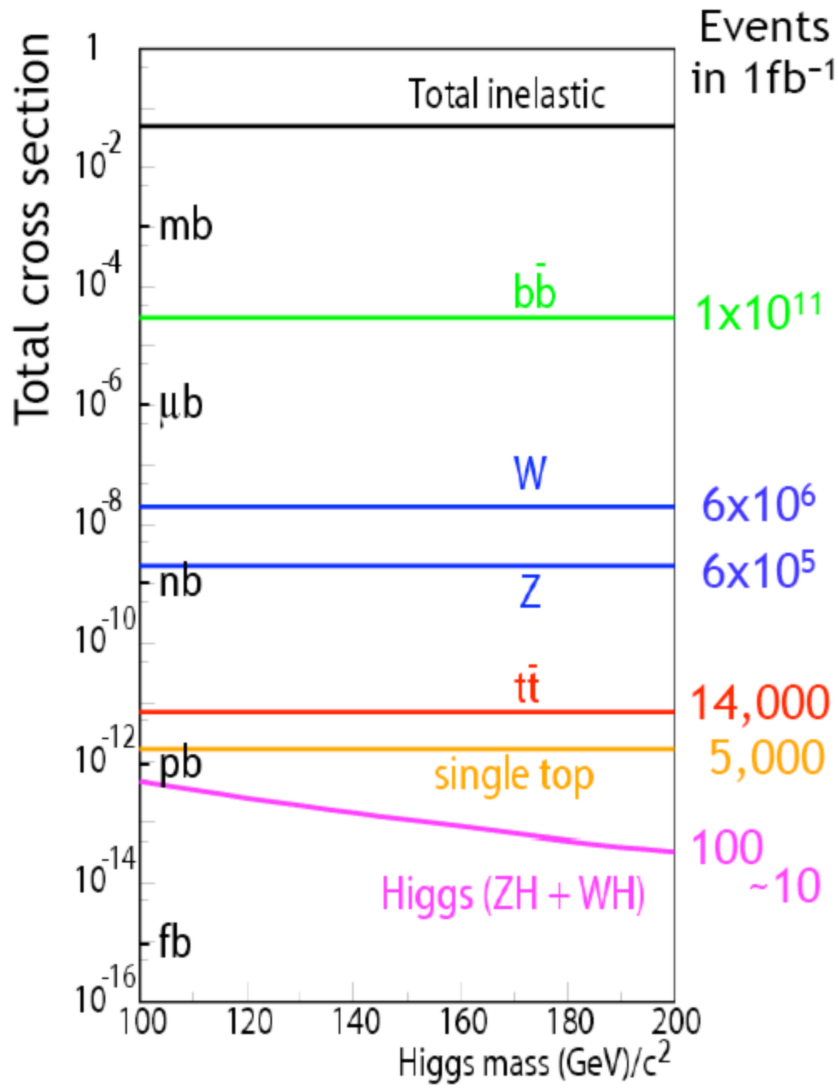


- **High Mass**: $M_H \gtrsim 135 GeV/c^2$
  - $gg \to H \to W^+W^-$ dominates
  - Leptonic decays of the W's help to suppress backgrounds
  - Associated modes also contribute
  - See next talk by H.Greenlee!

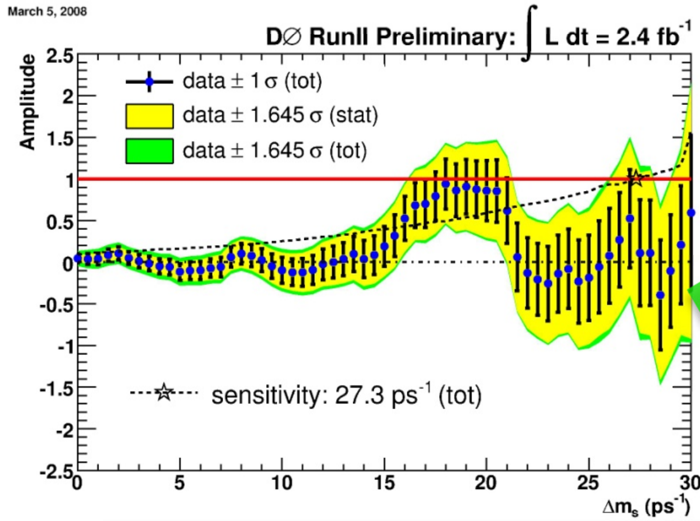
The challenges of the Higgs searches

- Hadron colliders: most promising for discovery
  - Challenging experimental environment
  - QCD production: orders of magnitude higher than signals
- Many background processes are not yet well-measured/understood
  - Continuously reaching new landmarks
  - Single top evidence.
  - Observations of diboson production: WW, WZ, ZZ
  - Production of h.f. jets in association with W/Z
- Higgs boson production is **very rare**!

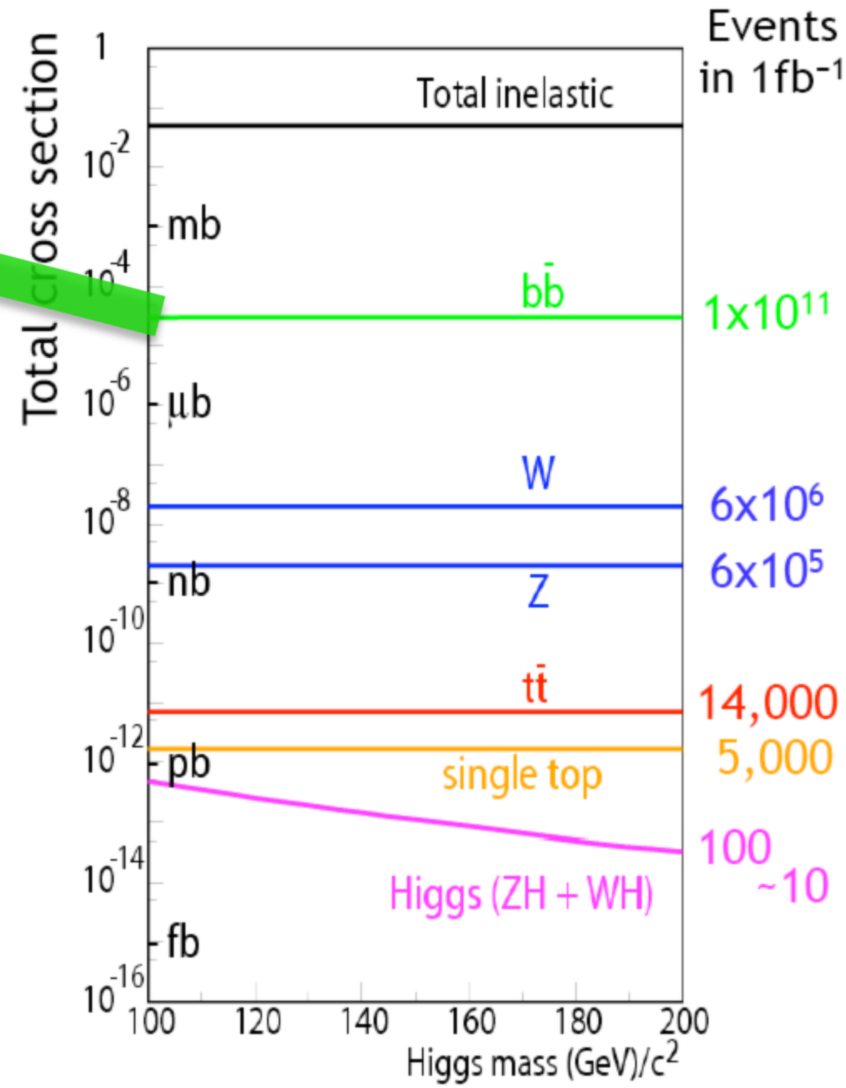




Measuring small signals at Tevatron



B^0_S oscillation frequency



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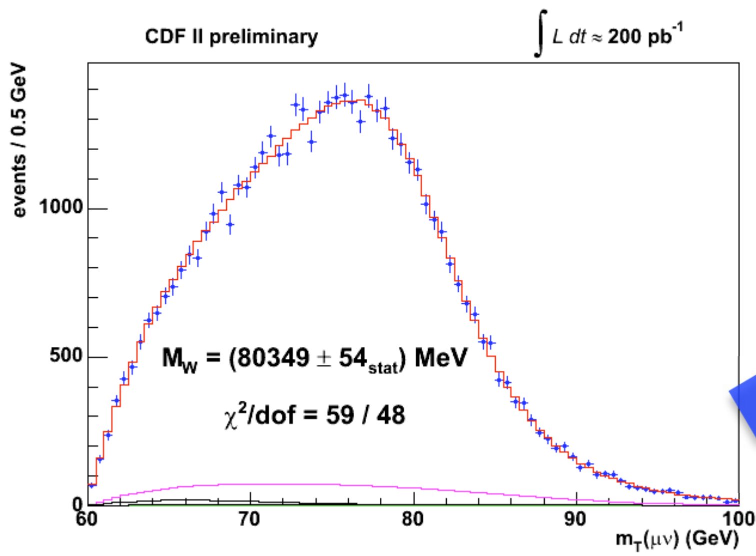
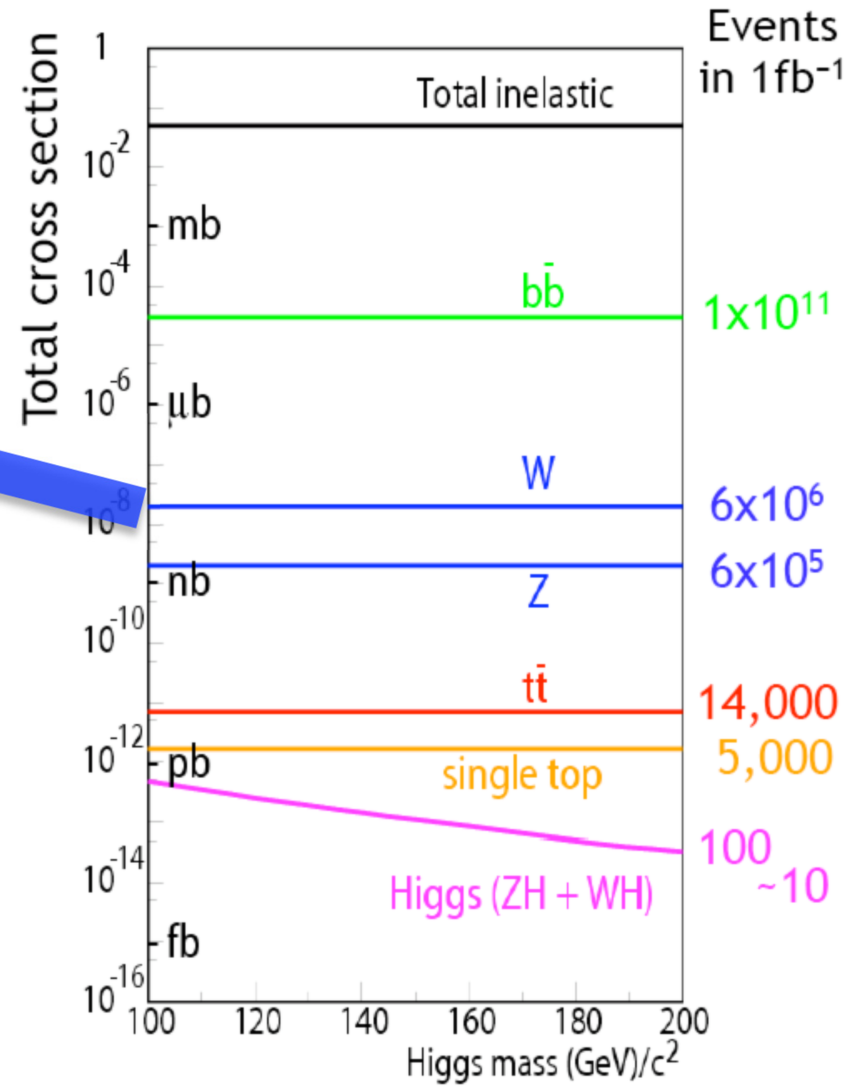


W boson mass



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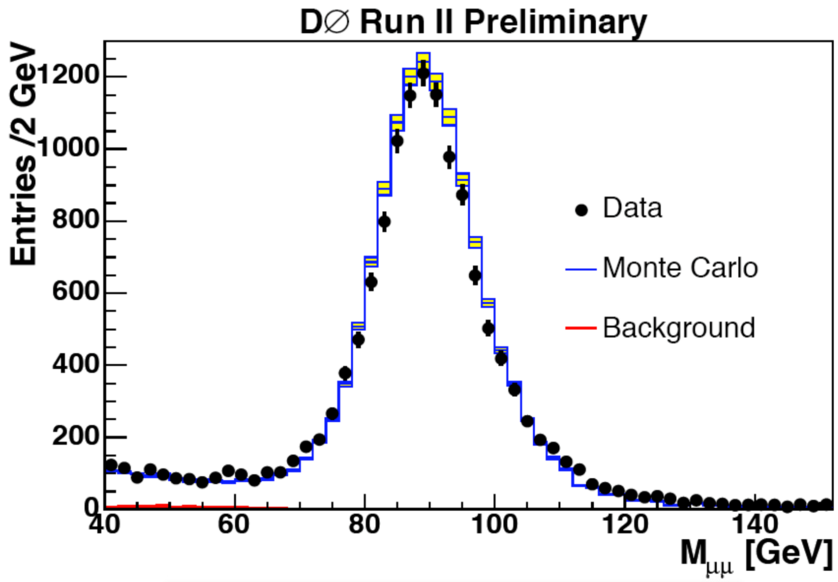
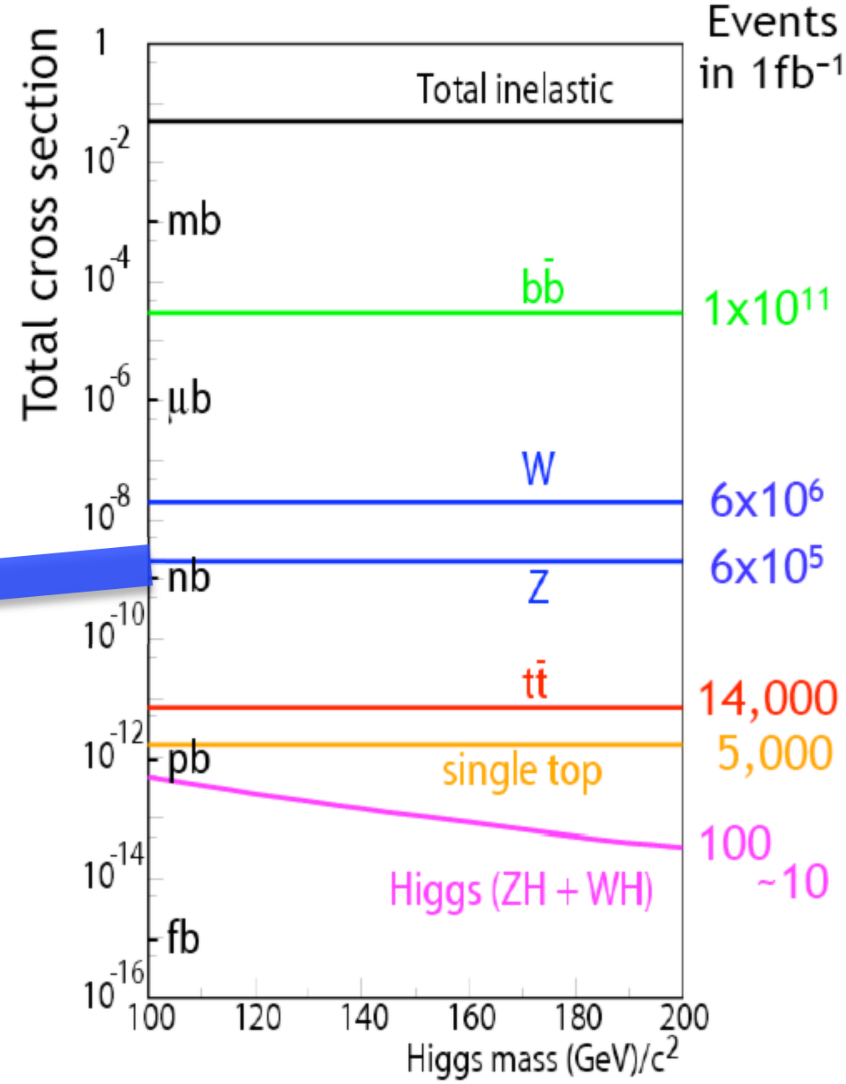


Z➔μμ cross-section



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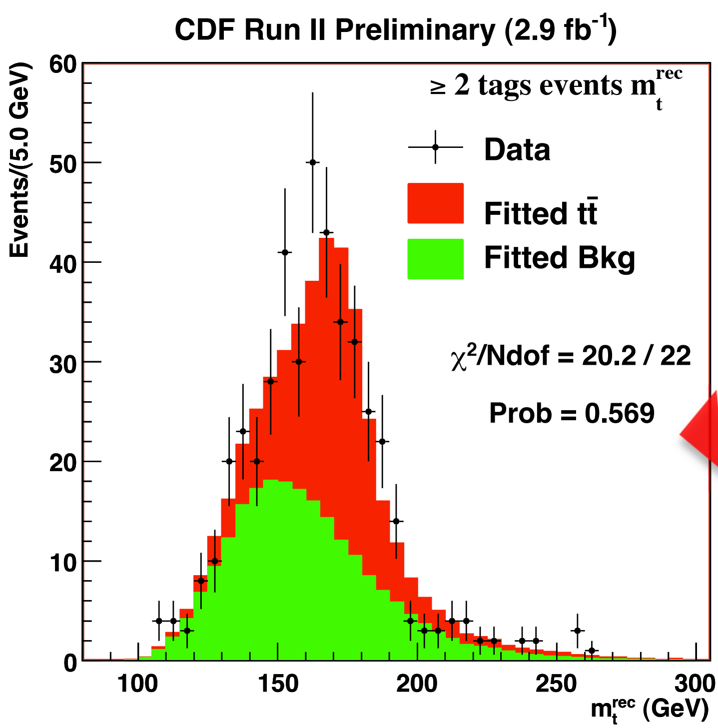
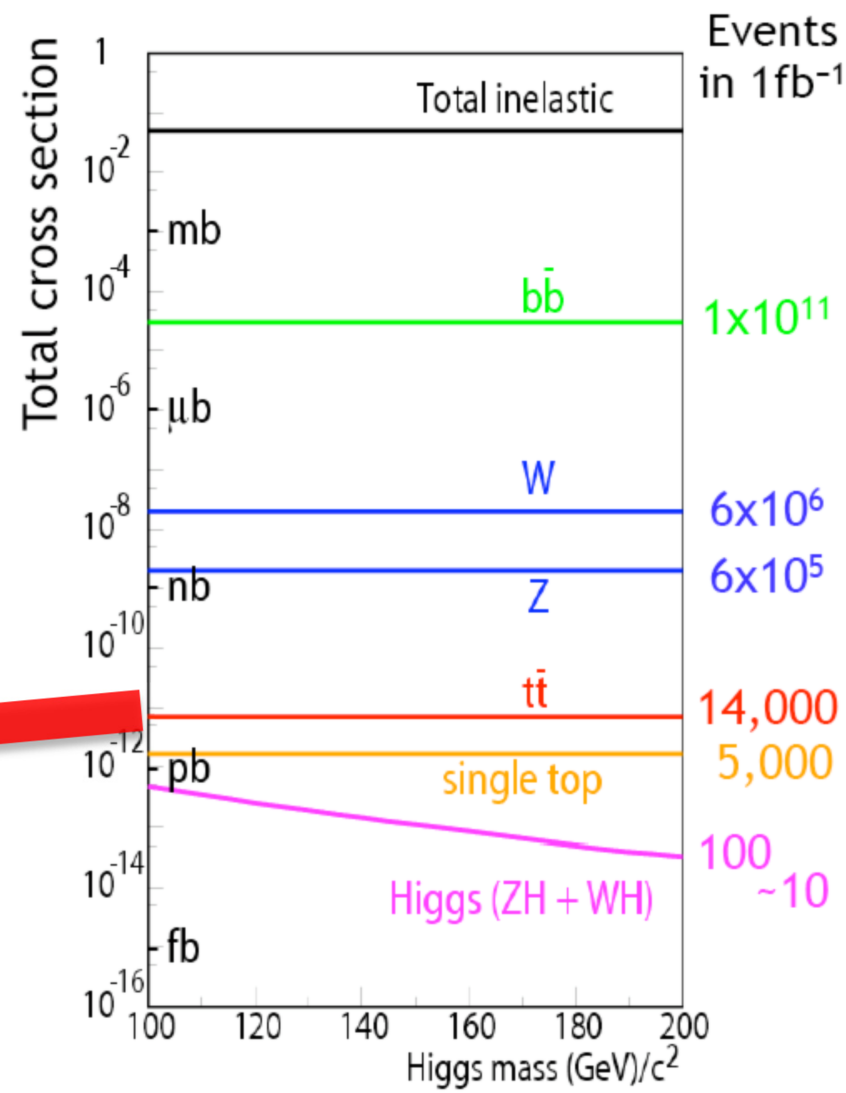


top quark mass



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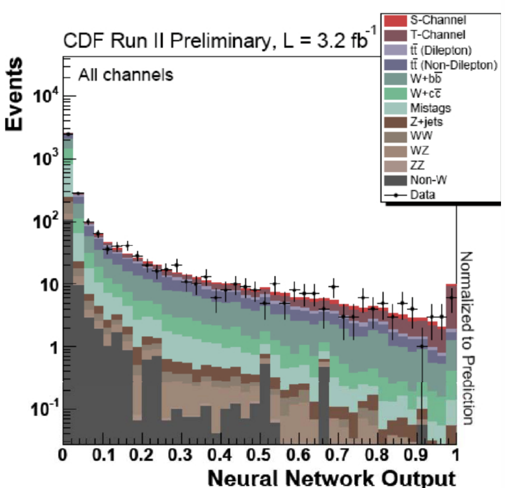
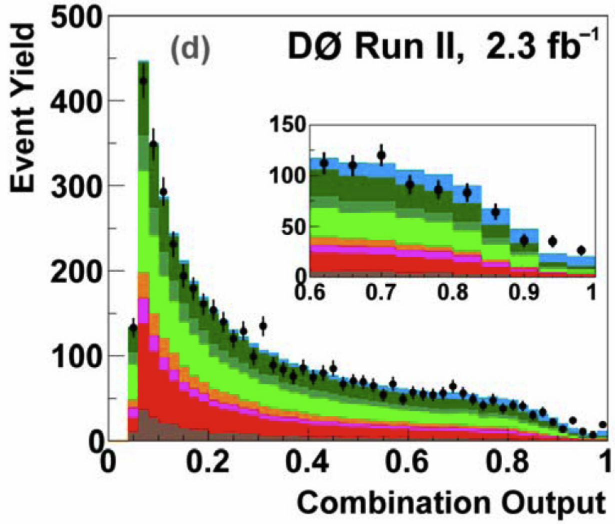
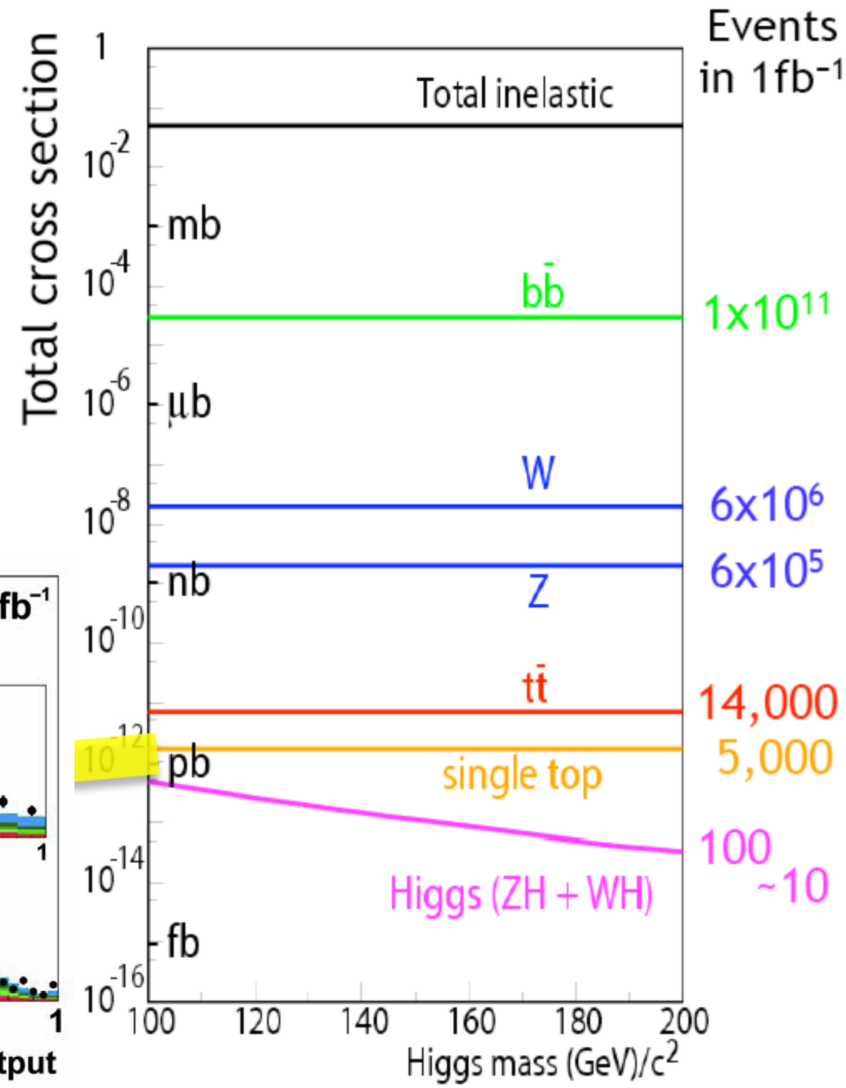


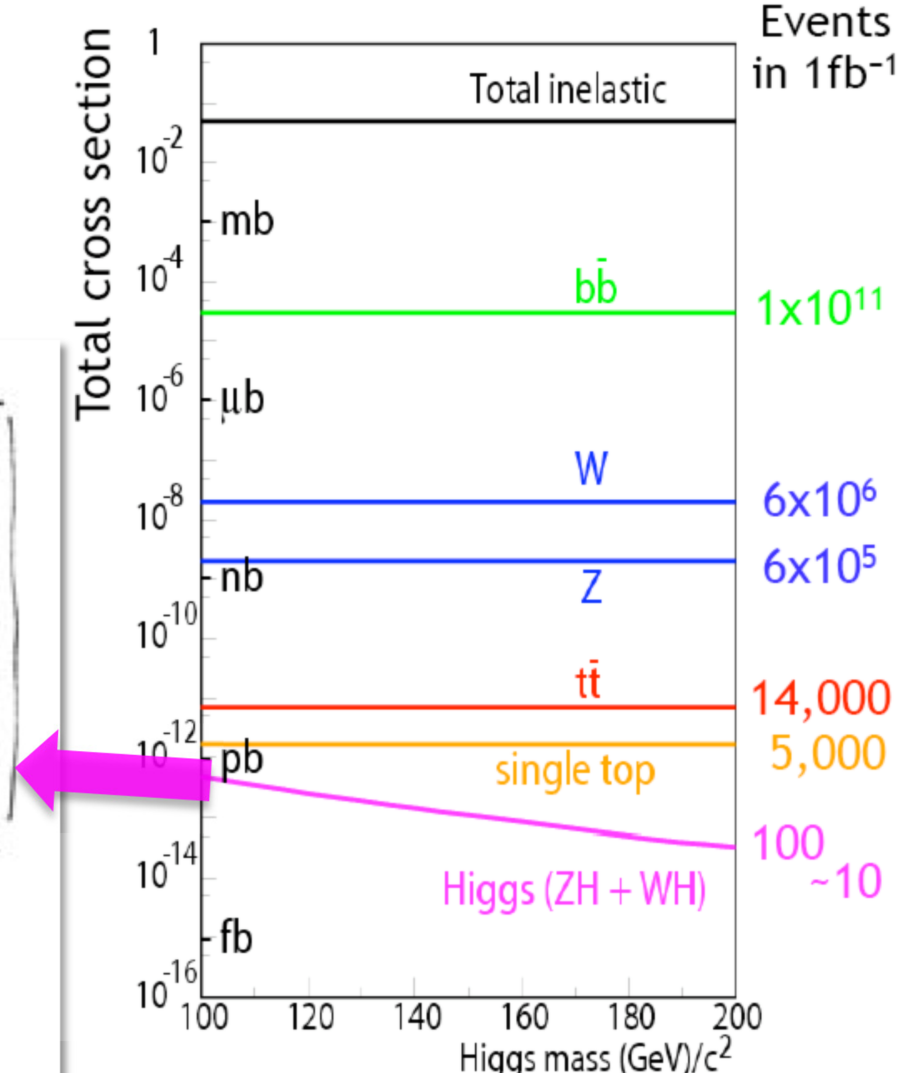




EW production of single top quarks

Measuring small signals at Tevatron

"Well, either we've found the Higgs boson, or Fred's just put the kettle on"



The Higgs search strategy

- Efficient triggers to keep most of potential Higgs candidates
  - **High P_T charged leptons**: ***e*** or ***μ*** to select leptonic decays of the W/Z
  - **MET+Jets**: to select $ZH \to \nu\nu b\bar{b}$ or $WH \to \not{\ell}\nu b\bar{b}$ (*the lepton is not identified*)
  - **Lepton+Track** for ***τ τ*** -modes or **MET+Jets** for $WH \to \tau\nu b\bar{b}$

- Increase signal yields:
  - Improve lepton acceptance by improving the ***e*** / ***μ*** ID
  - More efficient *b*-tagging algorithms: crucial for low-mass Higgs: $H \to b\bar{b}$ dijet mass resonance
  - Better understand the calorimeter response: Dijet mass resolution

Events per fb^{-1}	ZH->llbb	WH->lnbb	ZH->ννbb
Signal produced	5	30	15
Signal accepted	~1	~3	~2
Signal/Background	~1/200	~1/280	~1/400

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- Looking for a resonance in Dijet mass
  - Backgrounds are large in size, with large uncertainties
  - Use multivariate techniques to maximally separate signal from backgrounds
  - *Neural Networks, Matrix Element, Boosted Decision Tree*, etc…

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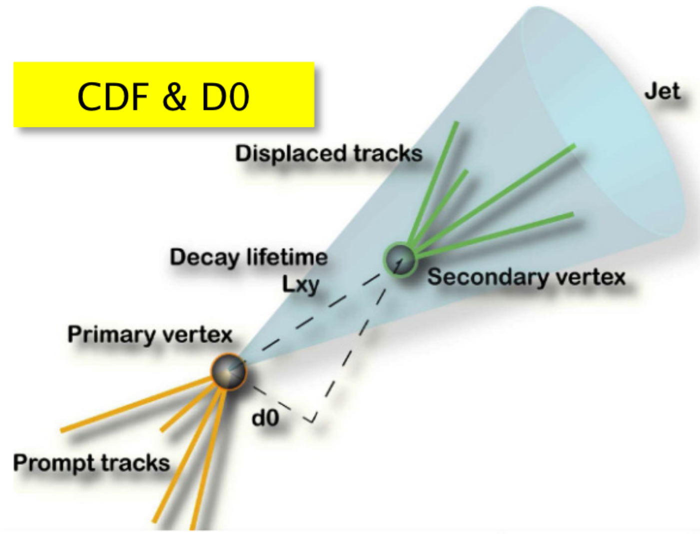
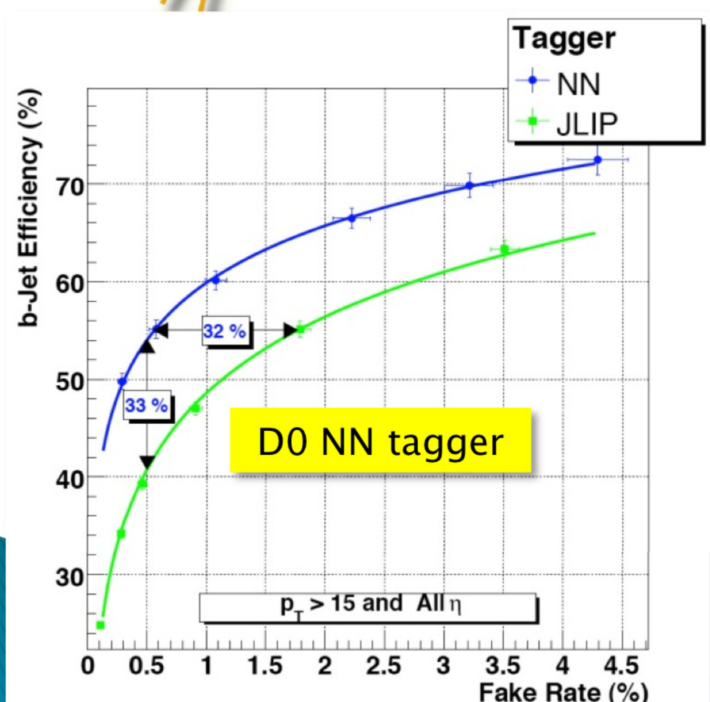
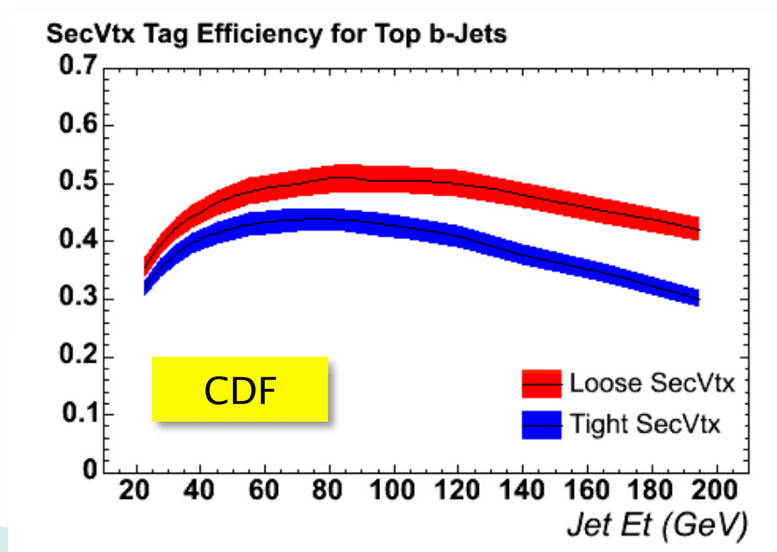
- The statistical significance of single channels is not enough
  - Combine all the channels within CDF and D0, and combine CDF and D0
  - Collect as much data as possible: improve triggers, data-taking efficiency

Analysis tools: *b*–jet identification



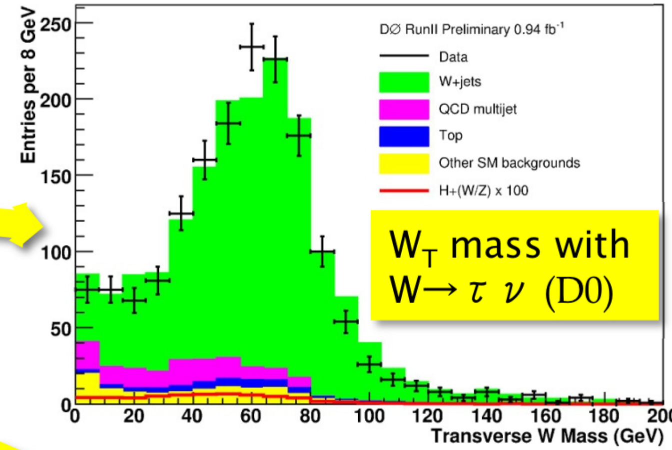


- Dijet Invariant Mass: resonance from H→bb
- Exploit long lifetime of B-mesons: *b*-tagging
  - Identify signal with jets from ***b***-quarks
  - Suppress light flavor backgrounds (*u, d, s or g*)
  - Improves S/B to from 1:1000 to ~1/50-1:100
- Various algorithms used by CDF and D0
  - Identify the displaced vertex from the decay of B
  - Exploit multiple features of b-jets: NN tagging
  - Probability that the tracks come from prime vtx: JetProb
  - High ***b***-tagging efficiency: 40-70%

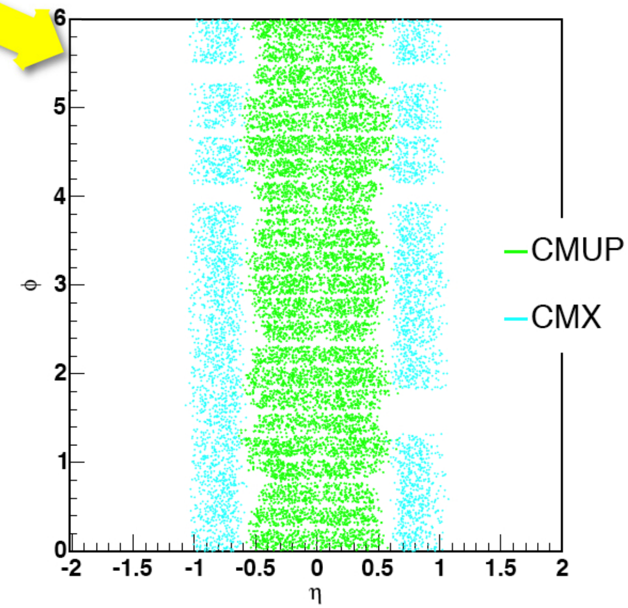


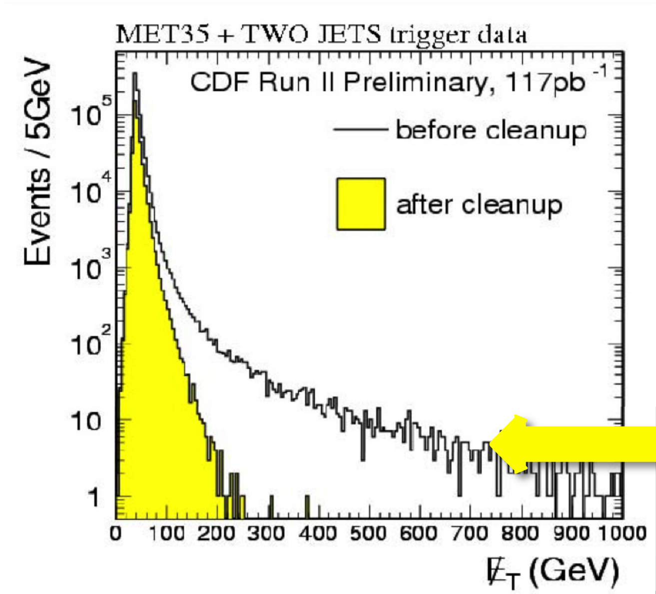
Analysis tools: lepton identification

- Identify the decays of the W/Z
  - Electrons: tracks matched to shower max in ECAL
  - Taus: tracks matched to a calorimeter cluster
  - Muons: tracks matched to muon chambers



- Expand the lepton coverage
  - Interplay between sub-detectors: cover the "holes"
  - Include forward detectors to extend coverage





- Excellent MET triggers:
  - Select events with neutrinos and charged leptons that failed to ID
  - Good understanding of the detector
  - Efficiently remove events with fake MET

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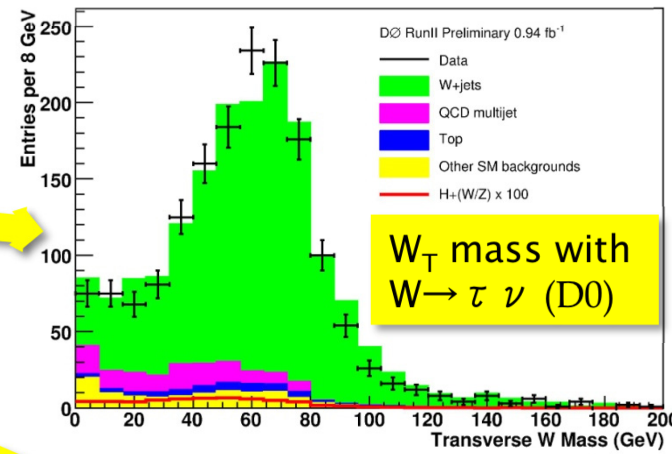

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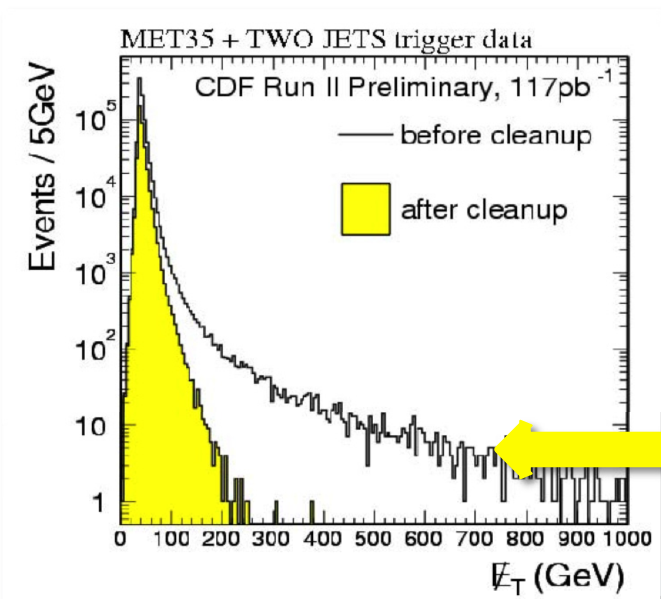

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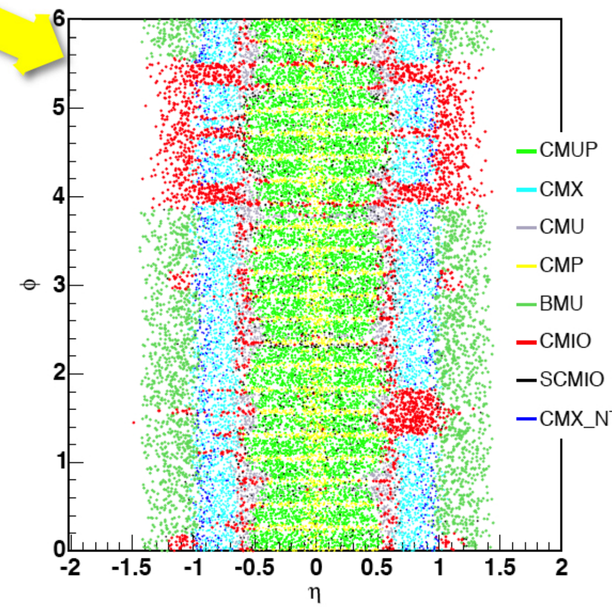


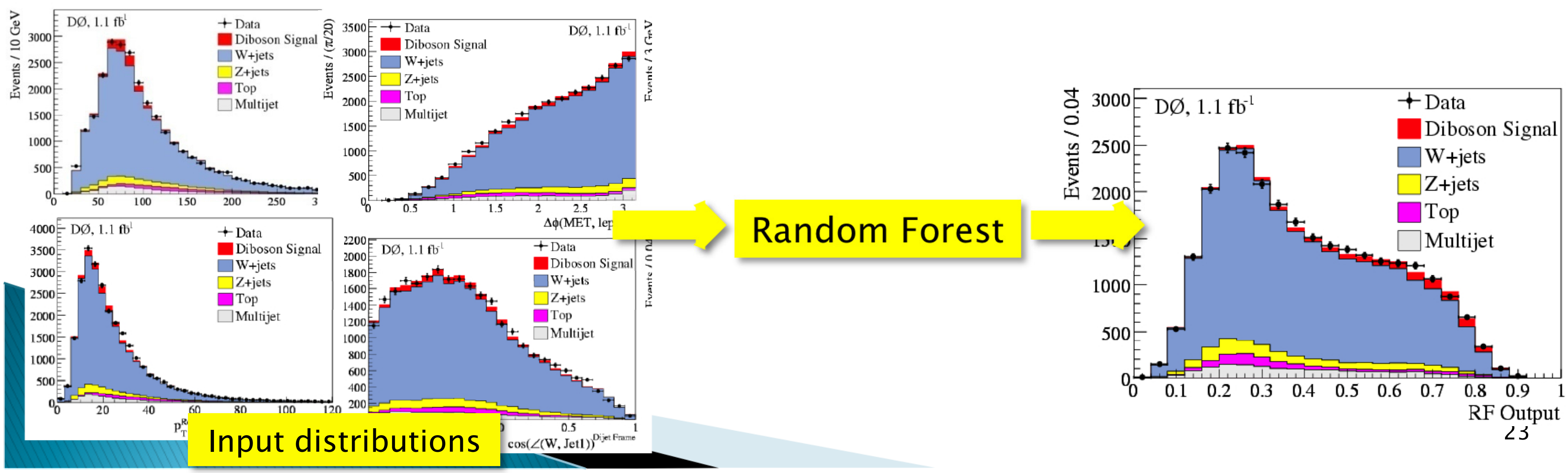
Extended muon coverage at CDF

Analysis tools: multivariate techniques

- Maximize discriminating power: global kinematics of signal & backgrounds
  - Machine learning techniques: Neural Networks (NN), Boosted Decision Trees (BDT), etc.
  - Calculate the probabilities for event to come from signal from LO matrix element (ME)

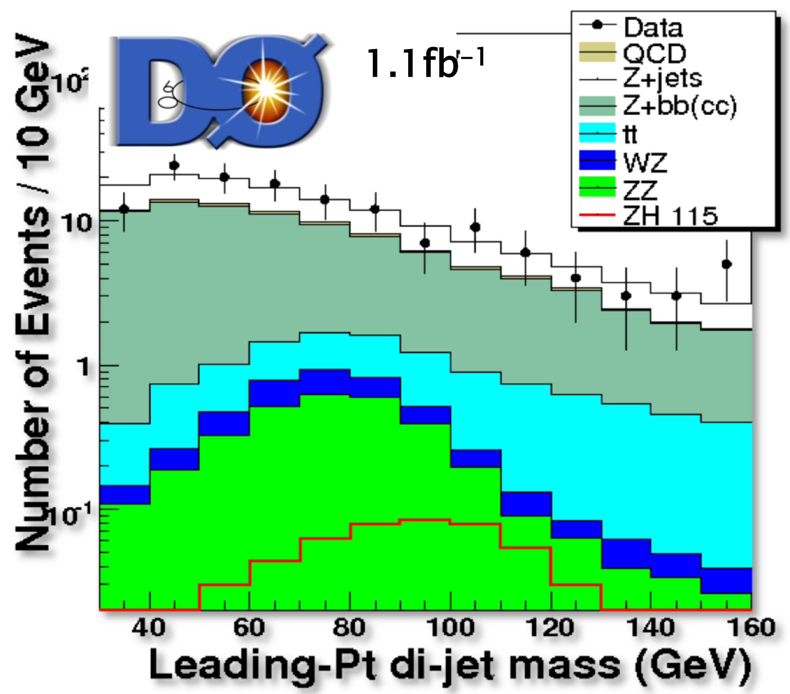
- Multivariate techniques help to improve the sensitivity
  - Remove large, uncertain backgrounds to reduce large systematic effects
  - Increase the significance of signal
  - Test these methods in well-known processes: e.g. ttbar

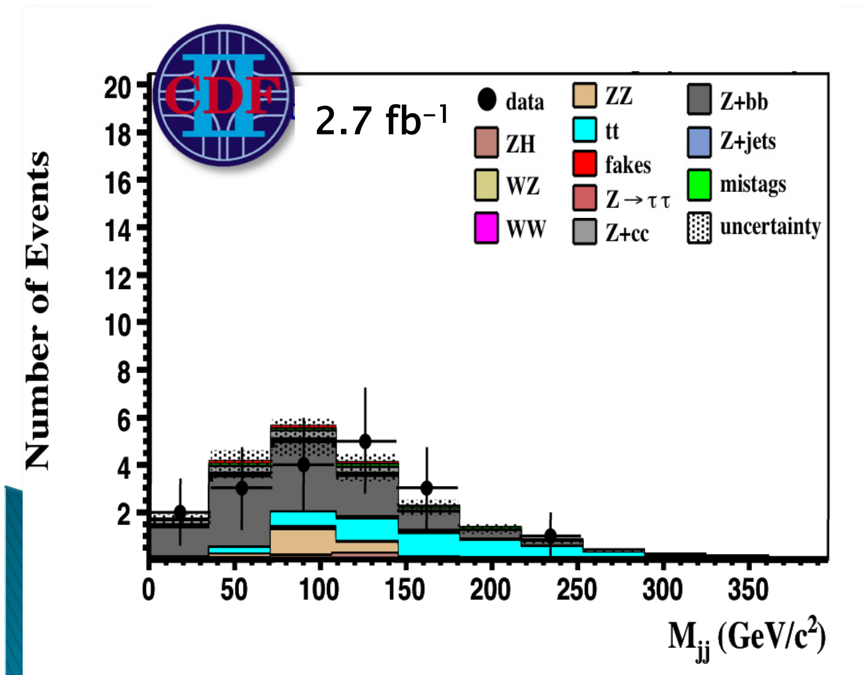
- Evidence for semi-leptonic WW/WZ at D0: Random Forest (RF) technique
  - Dijet mass scan yields 2.9s.d. (expected), output of RF improves sensitivity to 3.6s.d.
  - Observed signal significance 4.4s.d.: σ^{meas}=20.2±4.5 pb *(σ^{theory}=16.1±0.1 pb)*



Two charged leptons: $ZH \to \ell^+\ell^- b\bar{b},\ \ell = e,\mu$

- Fully reconstructed final state
  - Two resonances: H→bb and Z →ll
  - The dilepton mass cut $M_{ll} \approx M_Z$
- Dominant backgrounds:
  - Z+jets (irreducible Z+bb), top, dibosons
- Small σ×Br: ~1 event/fb^{-1}
  - Acceptance is crucial: employ loose *b*–tagging
  - Analyze events with at least one *b*–jet

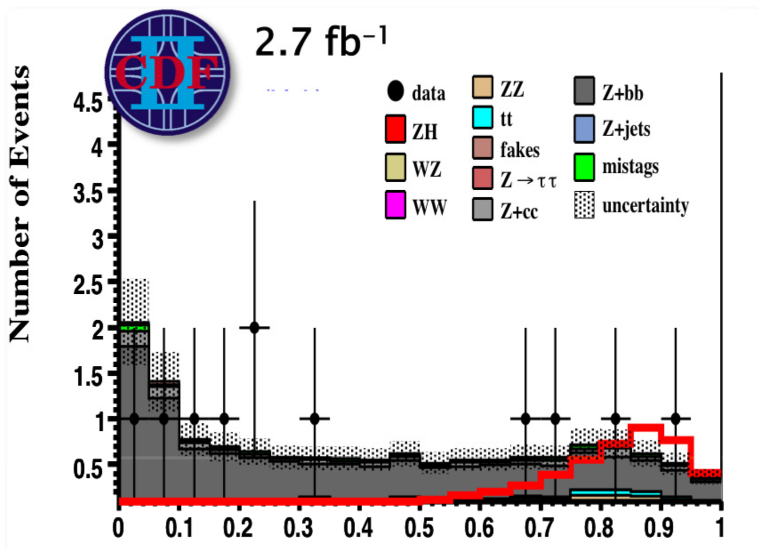




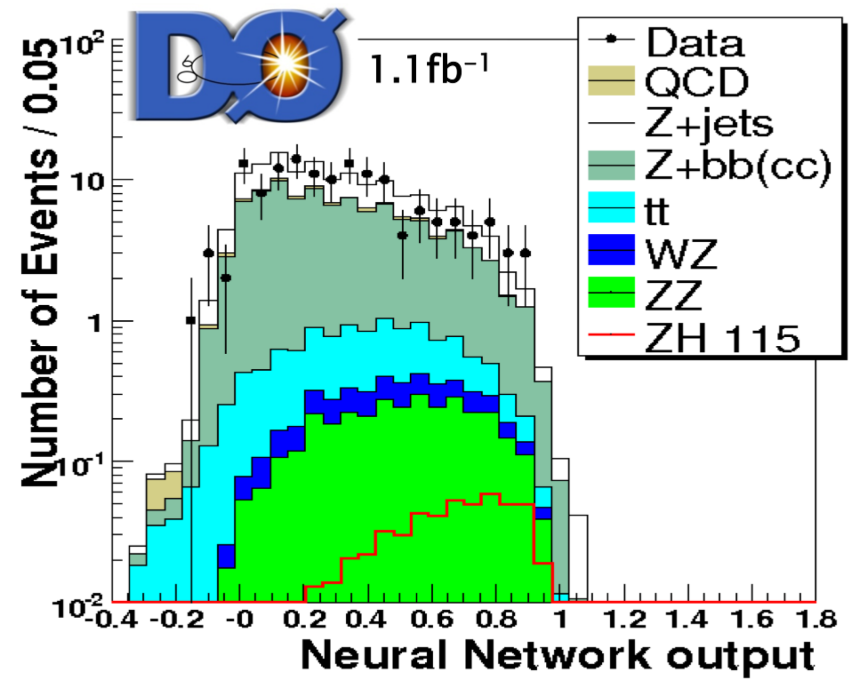
- Special techniques:
  - Correct jet E_T's using MET=> JER improves from 18% to 11%
  - Lepton coverage: stubless μ's, forward e's: improve limit by 10%

Two charged leptons: $ZH \to \ell^+\ell^- b\bar{b},\ \ell = e, \mu$

- Improve analysis sensitivity:
  - CDF: Matrix Element and 2D NN
  - DØ: NN for *ee* and BDT for *μμ* channels



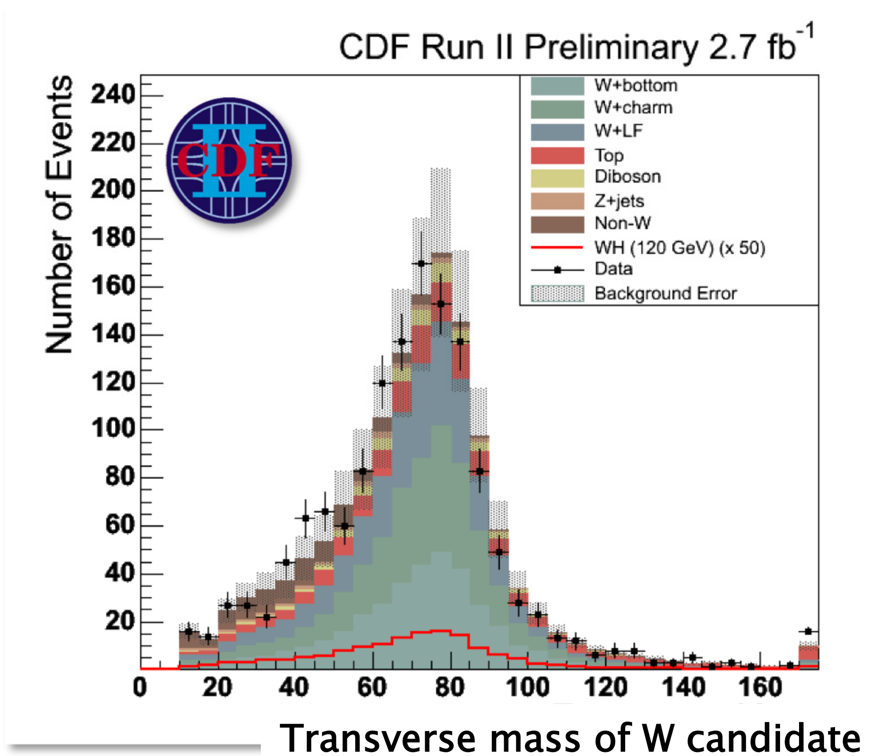
ZH Neural Network

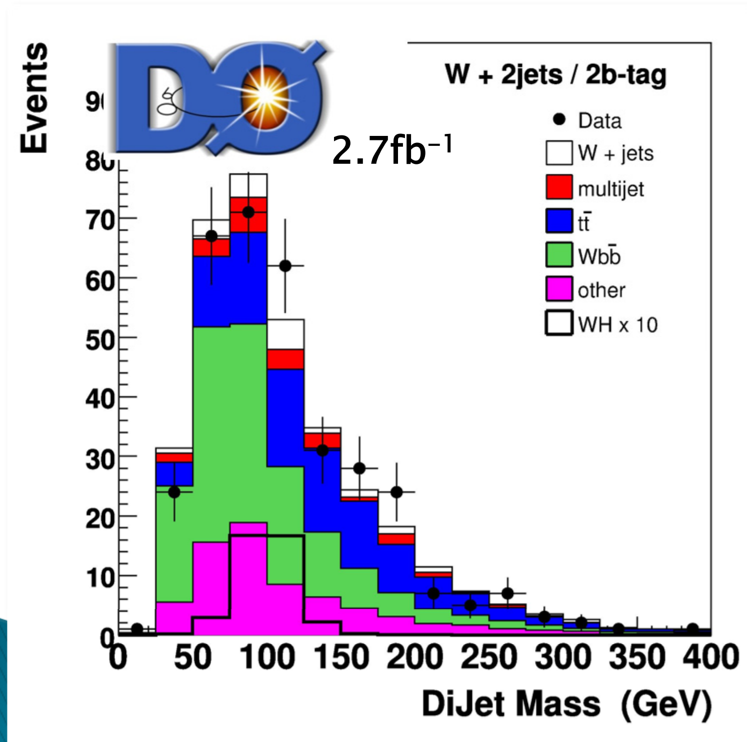


Analysis M_H=115	Lumi (fb^{-1})	Signal Evts	Exp limit	Obs limit
CDF ME (M_H=120)	2.1	1.4	15	14.2
CDF NN	2.7	2.1	9.9	7.1
DØ BDT	2.3	2.1	12.3	11.0

One charged lepton: $WH \to \ell\nu b\bar{b},\ \ell = e, \mu$

- *"Large"* $\sigma\times$Br, clean signature
  - Acceptance to about 3-4 events/fb^{-1}
  - High P_T leptons, MET and $\geq$2 jets
- Dominant backgrounds:
  - W+bb, top, diboson, QCD multi-jet

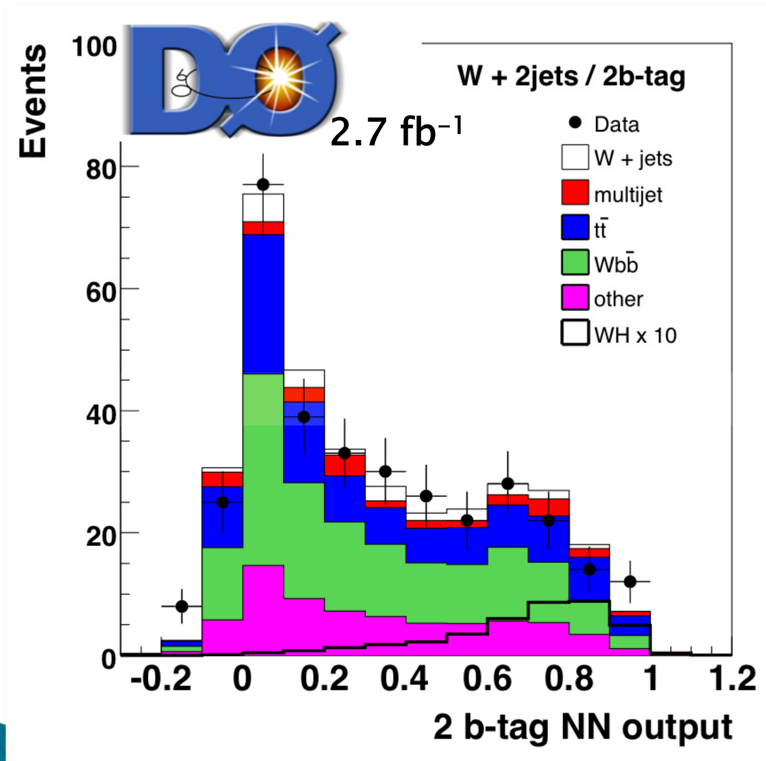


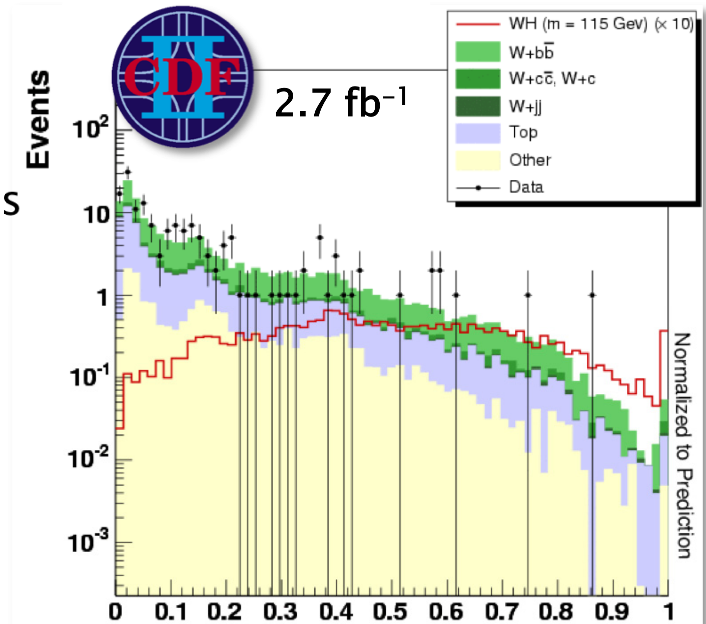


- Special techniques:
  - CDF/DØ: at least 1 b-tag, loose double-tag
  - CDF/DØ: ME to discriminate signal from bckg
  - CDF: loose muons, NN-based jet correction
  - DØ: forward electrons, events with 3 jets

One charged lepton: $WH \to \ell\nu b\bar{b},\ \ell = e, \mu$

- Improve analysis sensitivity:
  - CDF: BDT+NN → SuperDiscriminant using NEAT
  - DØ: NN for events with 2 jets, Dijet Mass for 3-jets



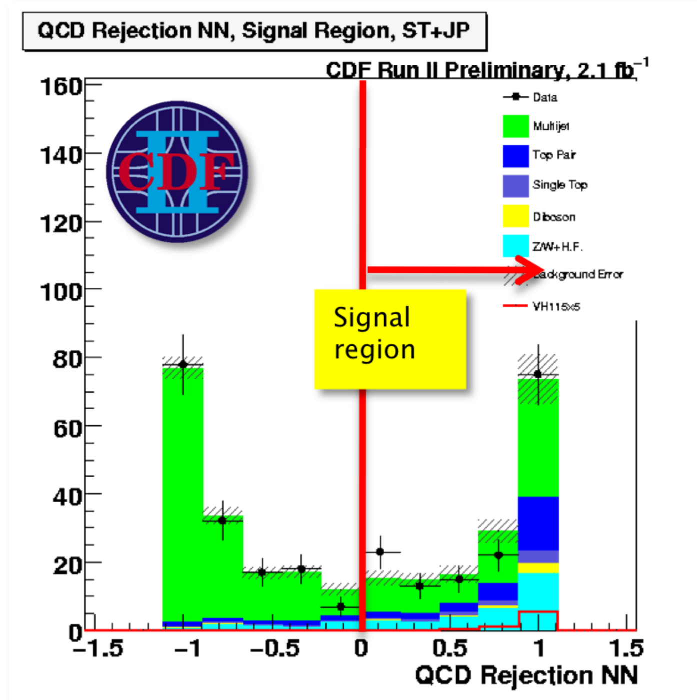


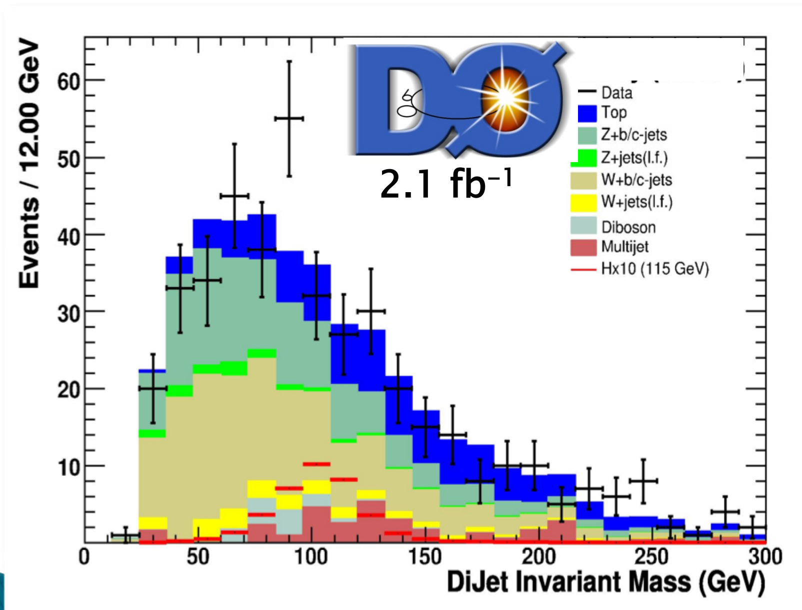
SuperDiscriminant NN

Analysis M_H=115	Lumi (fb^{-1})	Signal Evts	Exp limit	Obs limit
CDF NEAT	2.7	8.3	4.8	5.6
DØ NN	2.7	13.3	6.4	6.7

Zero charged leptons: $VH \rightarrow \not{E}_T b\bar{b}$

- Large signal acceptance: $ZH \rightarrow \nu\nu b\bar{b}$ / $WH \rightarrow \not{\ell}\nu b\bar{b}$
  - Acceptance to about 3-4 events/fb^{-1}
  - Large MET and $\geq$2 jets
  - Information of W/Z missed: no strong constraints
- Dominant backgrounds:
  - QCD with fake MET, W/Z+jets, top, diboson

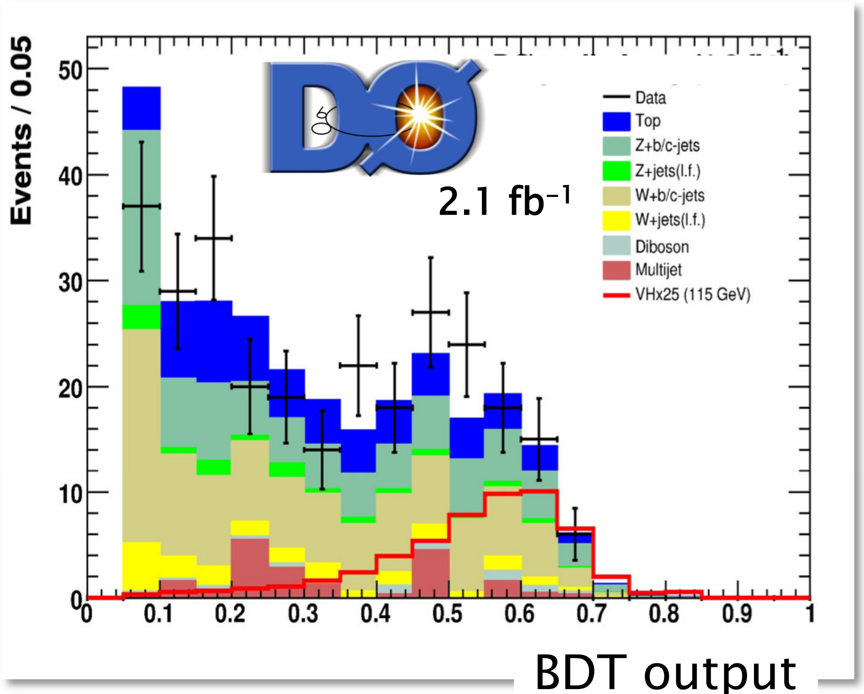


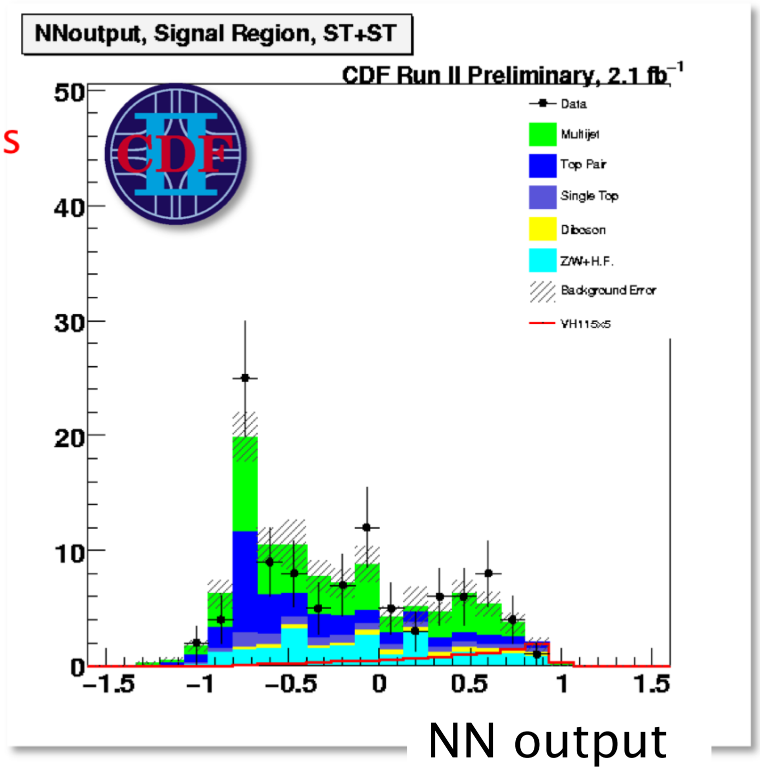


- Special techniques:
  - CDF/DØ: data-driven QCD model, track MP$_T$
  - CDF: at least 1 *b*-tag, 3 tagging channels, NN-based event selection *(QCD rejection NN)*, track-based jet corrections
  - CDF: accept $WH \rightarrow \tau\nu b\bar{b}$ with hadronic τ

Zero charged leptons: $VH \rightarrow \not{E}_T b\bar{b}$

- Improve analysis sensitivity:
  - CDF: NN with separate training for 2 and 3 jets
  - DØ: BDT for double tagged sample

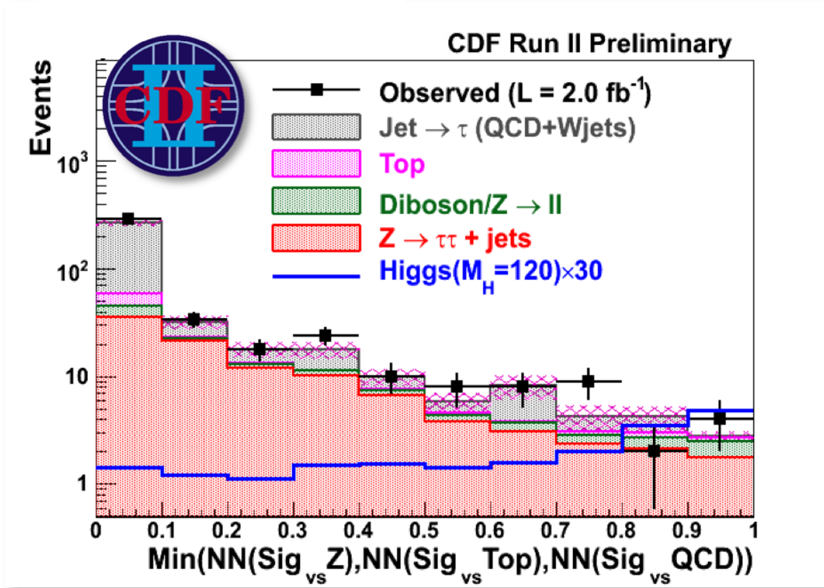


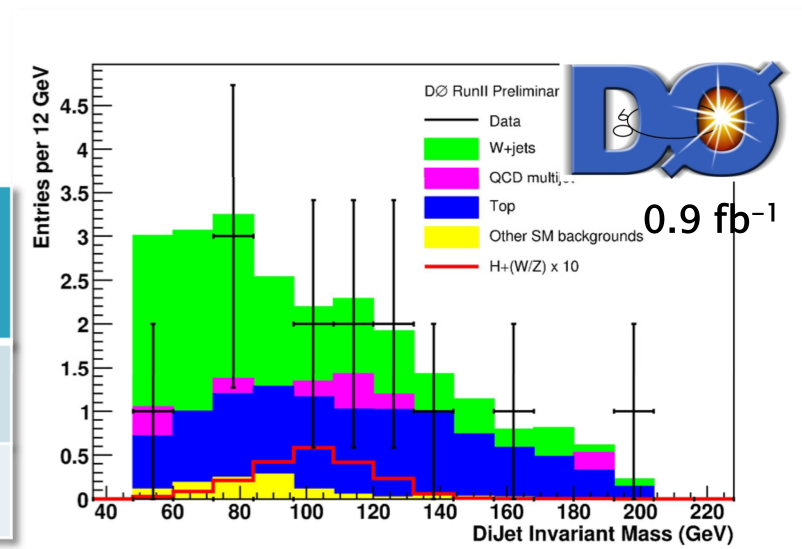


Analysis M_H=115	Lumi (fb^{-1})	Signal Evts	Exp limit	Obs limit
CDF NN	2.1	7.5	5.6	6.9
DØ BDT	2.1	3.7	8.4	7.5

Other channels: $H \to \tau\tau + 2\ jets,\ WH \to \tau\nu b\bar{b}$

- Analyze all feasible channels
  - Additional sensitivity in combination
- CDF: H−> $\tau\tau$+2 jets
  - Largest backgrounds: QCD fakes, Z➔ττ+jets
  - Sensitivity to WH/ZH, VBF, ggH
  - Train 3 NN targeting specific backgrounds
- DØ: WH−> $\tau\upsilon bb$: hadronic τ+MET+b−jets
  - Largest backgrounds: W+jets, top, multijet
  - Require 2 b-tagged jets
  - Scan the Dijet Mass distribution



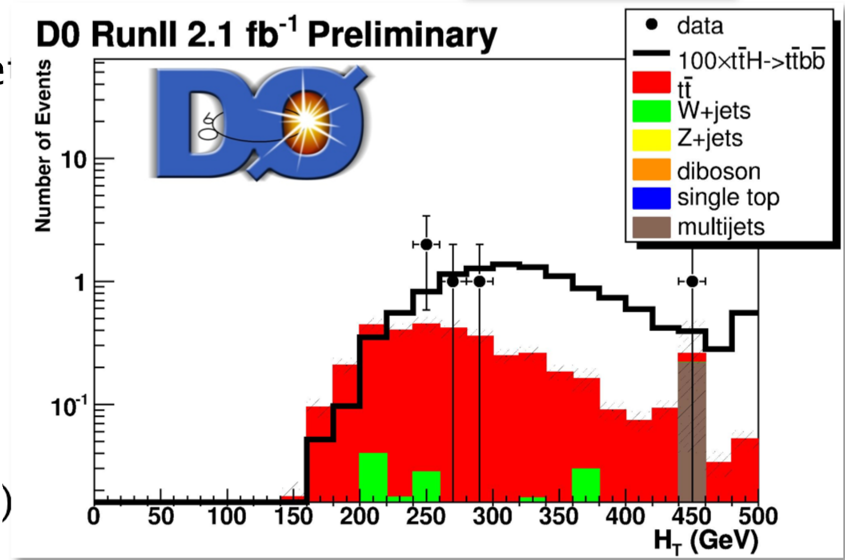


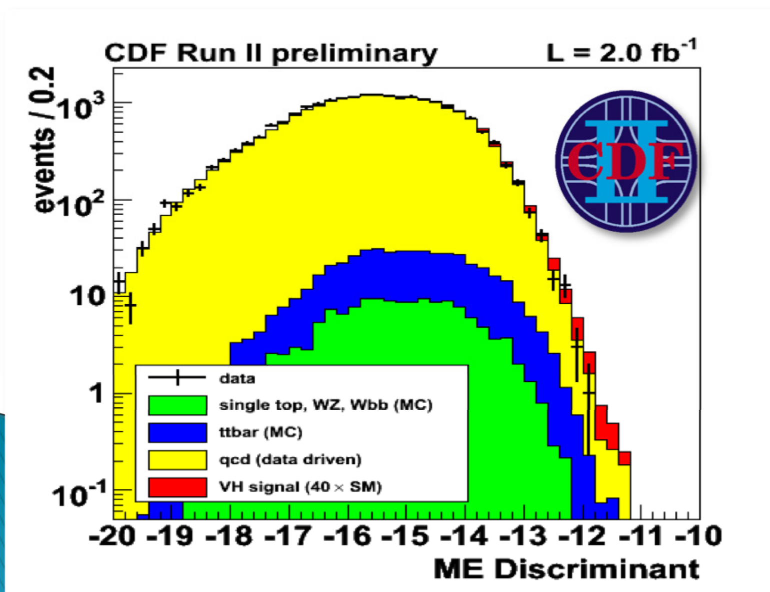
Analysis M_H=115	Lumi (fb^{-1})	Signal Evts	Exp limit	Obs limit
CDF $\tau\tau$+2jets	2.0	5.3	24.8	30.5
DØ WH−> $\tau\upsilon bb$	1.0	0.2	42.1	35.4

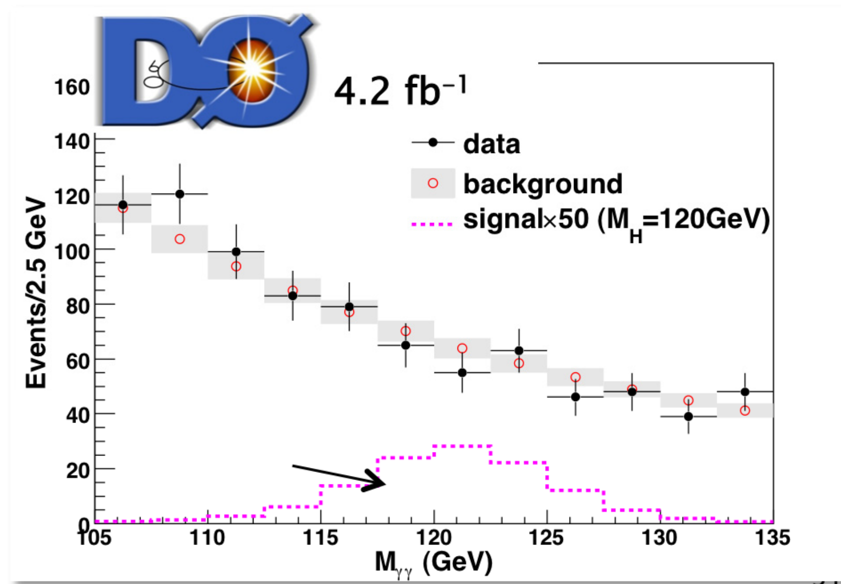
Additional channels

All limits on this page at MH=115

- DØ: ttH->*lνbbbbqq* ($2.1 fb^{-1}$)
  - Scan the distribution of H_T: scalar sum of je
  - 4 or 5 jets, 1-3 *b*-tagged jets
  - Exp (Obs) Limit: 45.3 (63.9)*SM
- DØ: H->γγ ($4.2 fb^{-1}$)
  - Scan the Diphoton mass
  - Exp (Obs) Limit: 18.5 (15.8)*SM
- CDF: VH->*qqbb* ($2.0 fb^{-1}$)
  - Good signal acceptance: large BR(W/Z->qq)
  - Employ ME technique, 2 *b*-tagged jets
  - Exp (Obs) Limit 37 (38)*SM

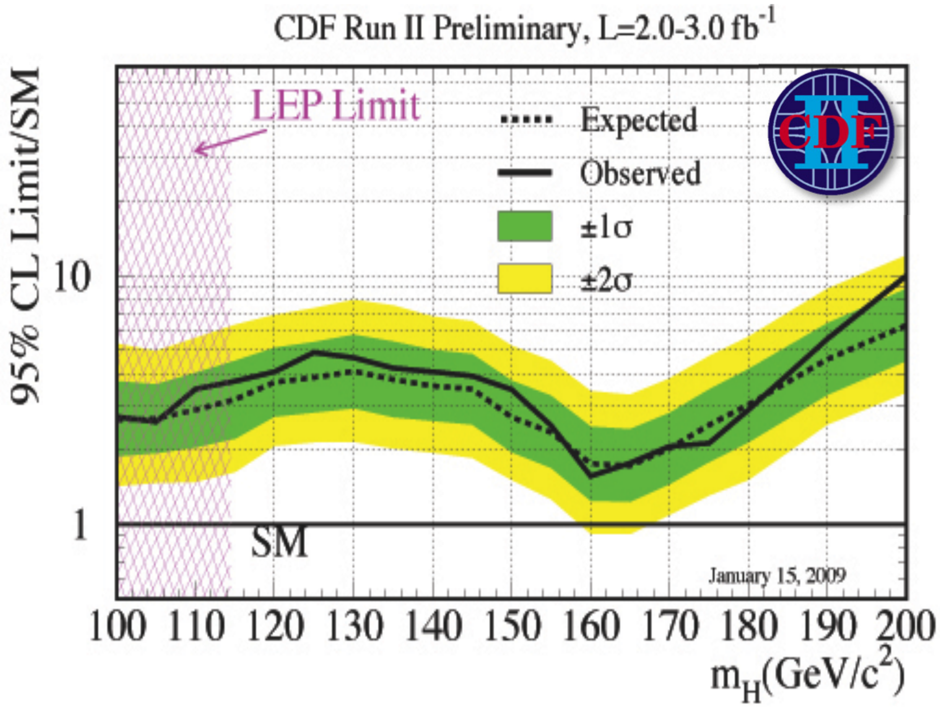


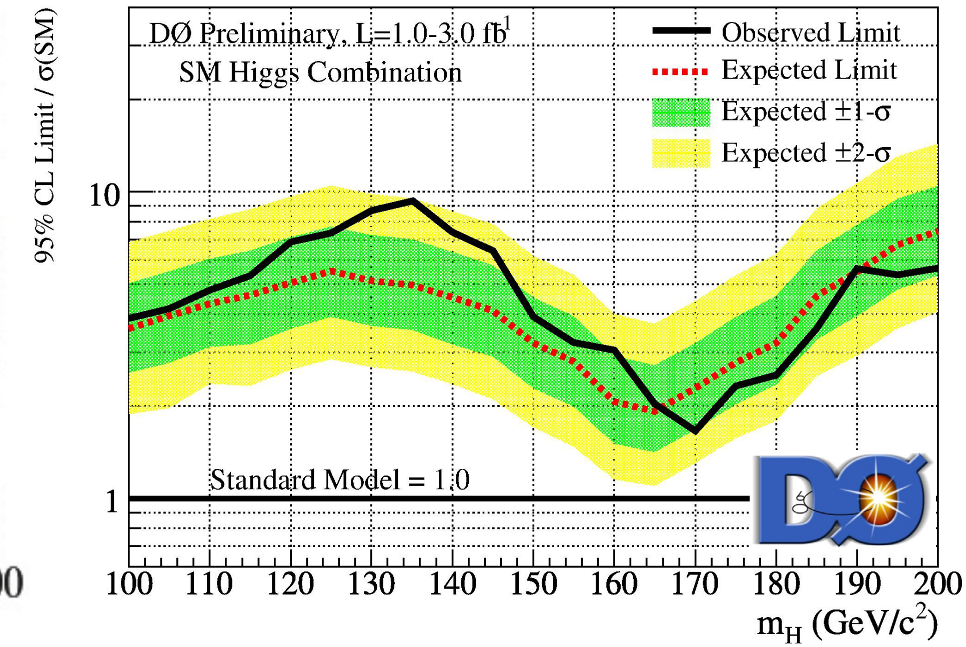




CDF and DØ combined limits

- Increase the Tevatron reach: statistically combine all search channels
  - Effectively double the analyzed luminosity
  - Systematic uncertainties: nuisance parameters with truncated Gaussian constraints
  - Set 95% C.L. upper limits on the Higgs boson production cross-section





at M_H=115 GeV/c^2	Exp limit	Obs limit
CDF	3.2	3.8
DØ	4.6	5.3

CDF and DØ combined limits

- Increase the Tevatron reach: statistically combine all search channels
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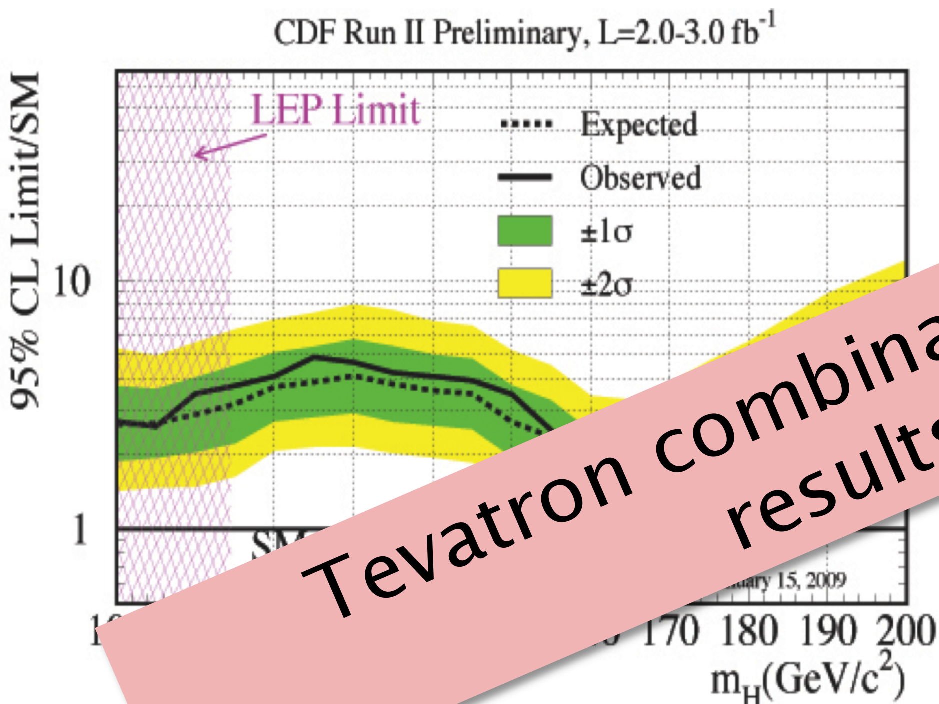
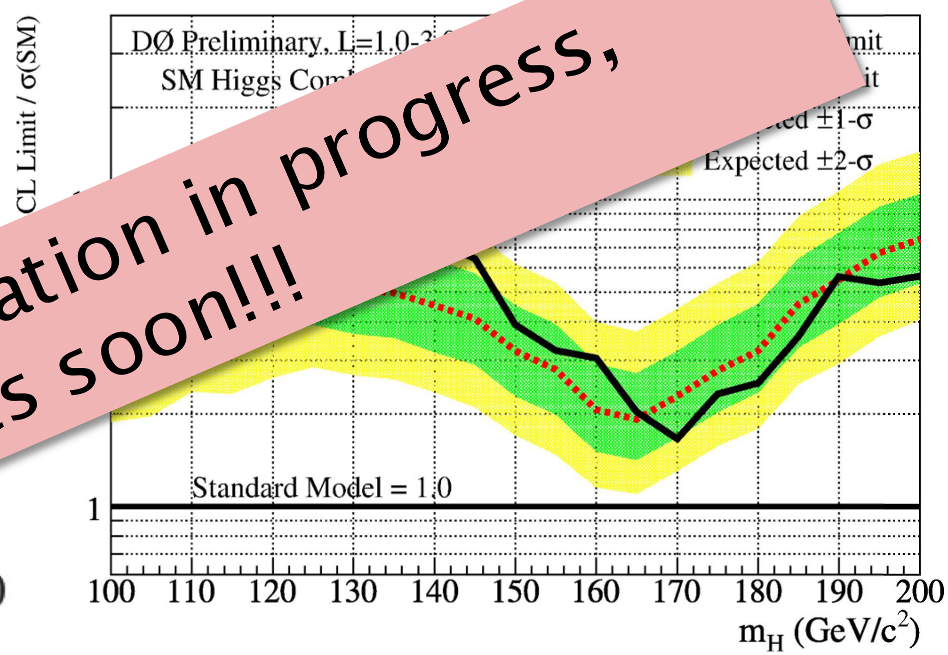
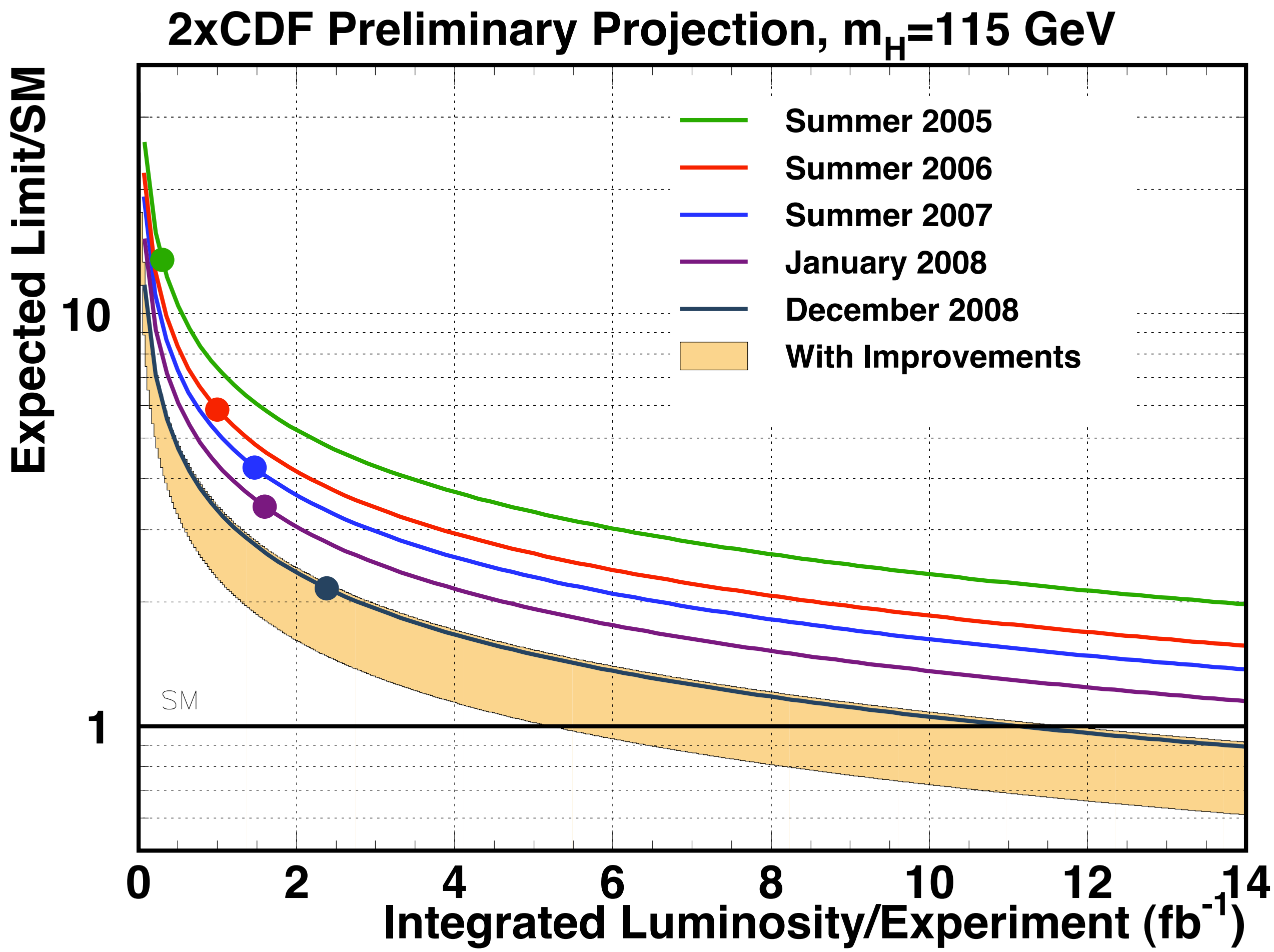




Tevatron combination in progress, results soon!!!

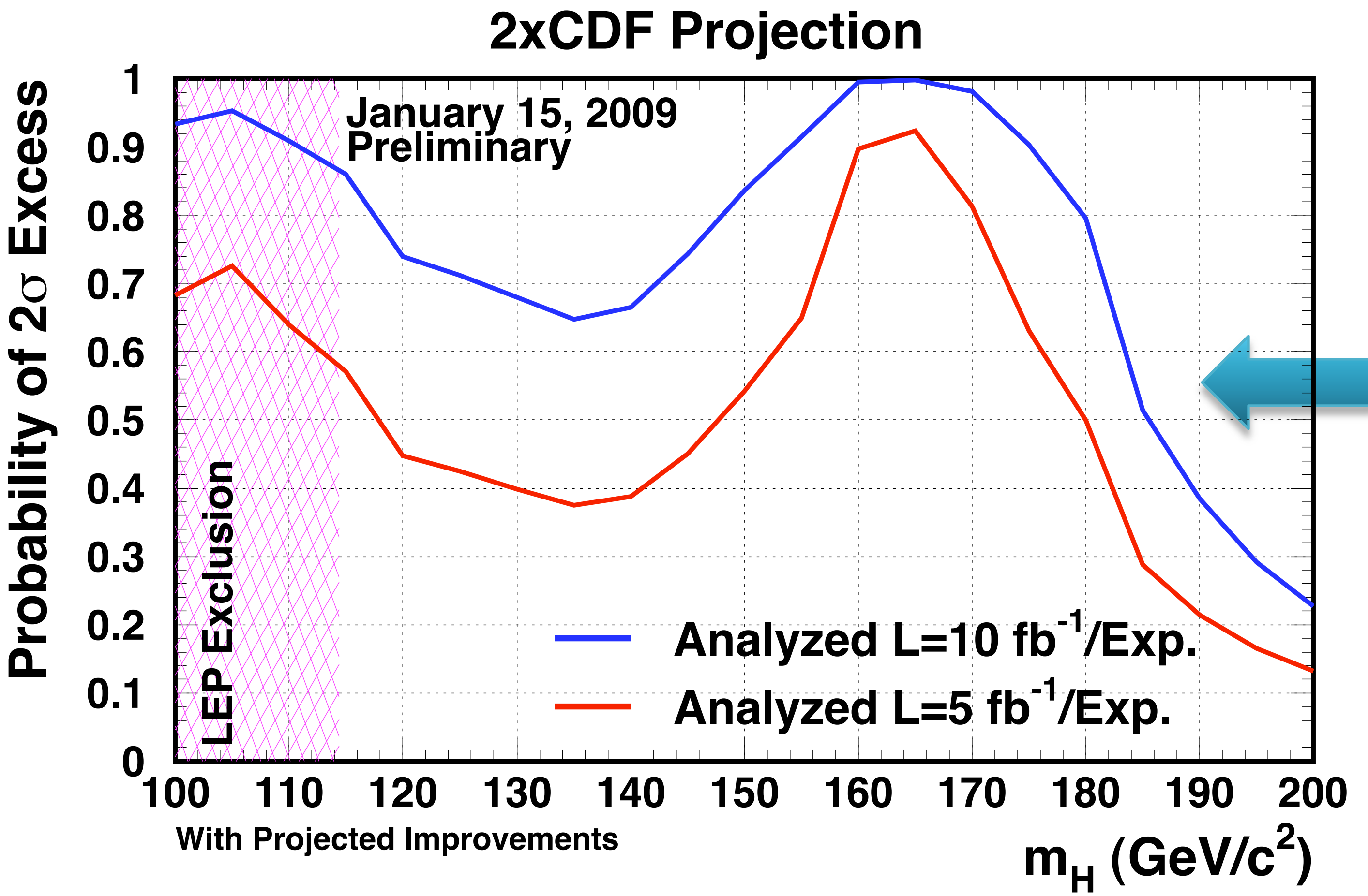
at M_H=115 GeV/c^2	Exp limit	Obs limit
CDF	3.2	3.8
DØ	4.6	5.3

Tevatron: future prospects



- Experiments are continuously improving analysis technique:
  - Progress much faster than only from additional data
  - Sensitivity increased factor of 1.5 w.r.t last year: equivalent of more than double luminosity
  - Should be able to probe SM cross-sections with full Tevatron luminosity

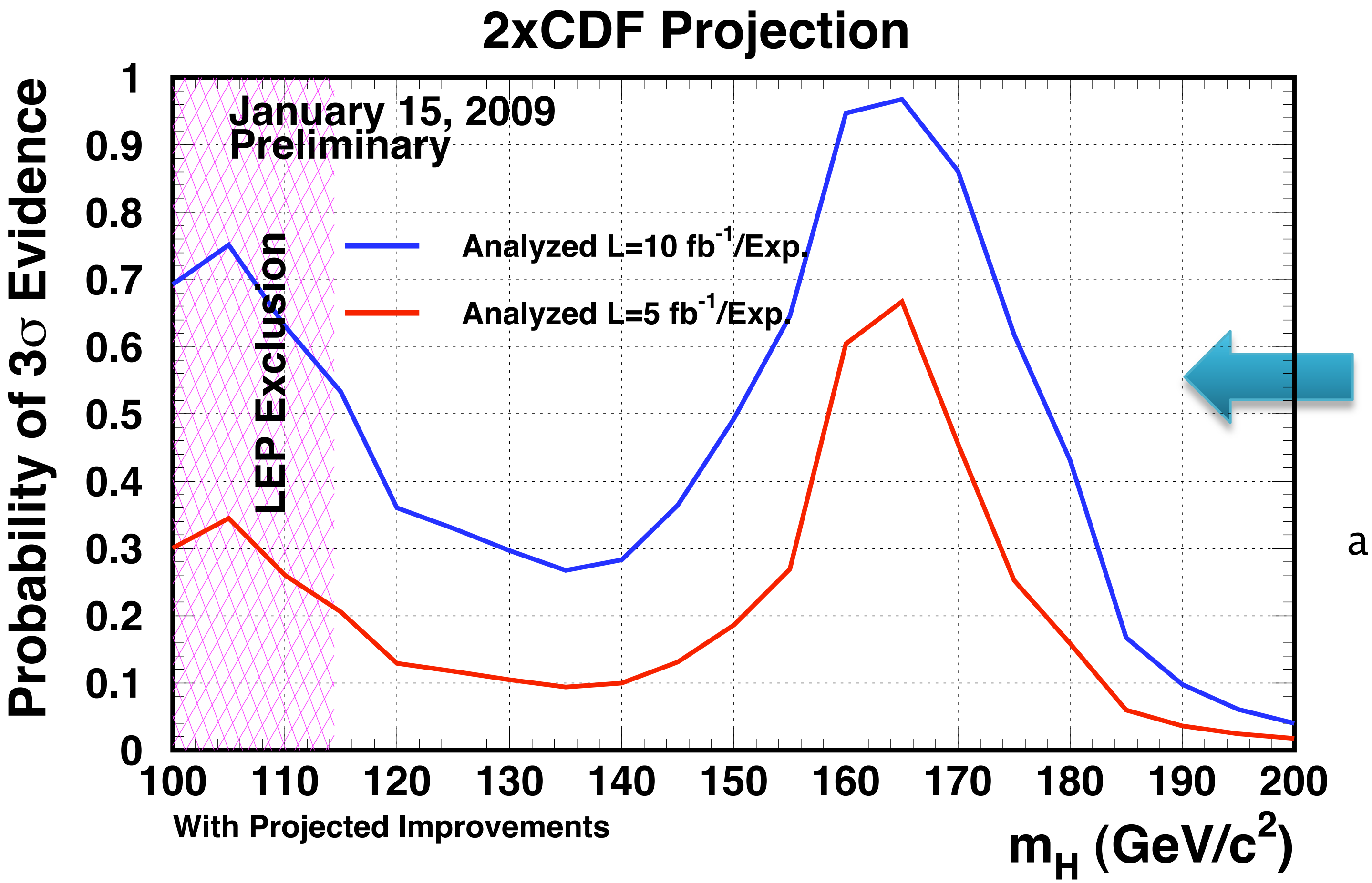
Tevatron sensitivity for 2σ



With additional factor 1.5 improvement in analysis technique

- Experiments are continuously improving analysis technique:
  - Progress much faster than only from additional data
  - Sensitivity increased factor of 1.5 last year: equivalent of more than double luminosity
  - Should be able to probe SM cross-sections with full Tevatron luminosity

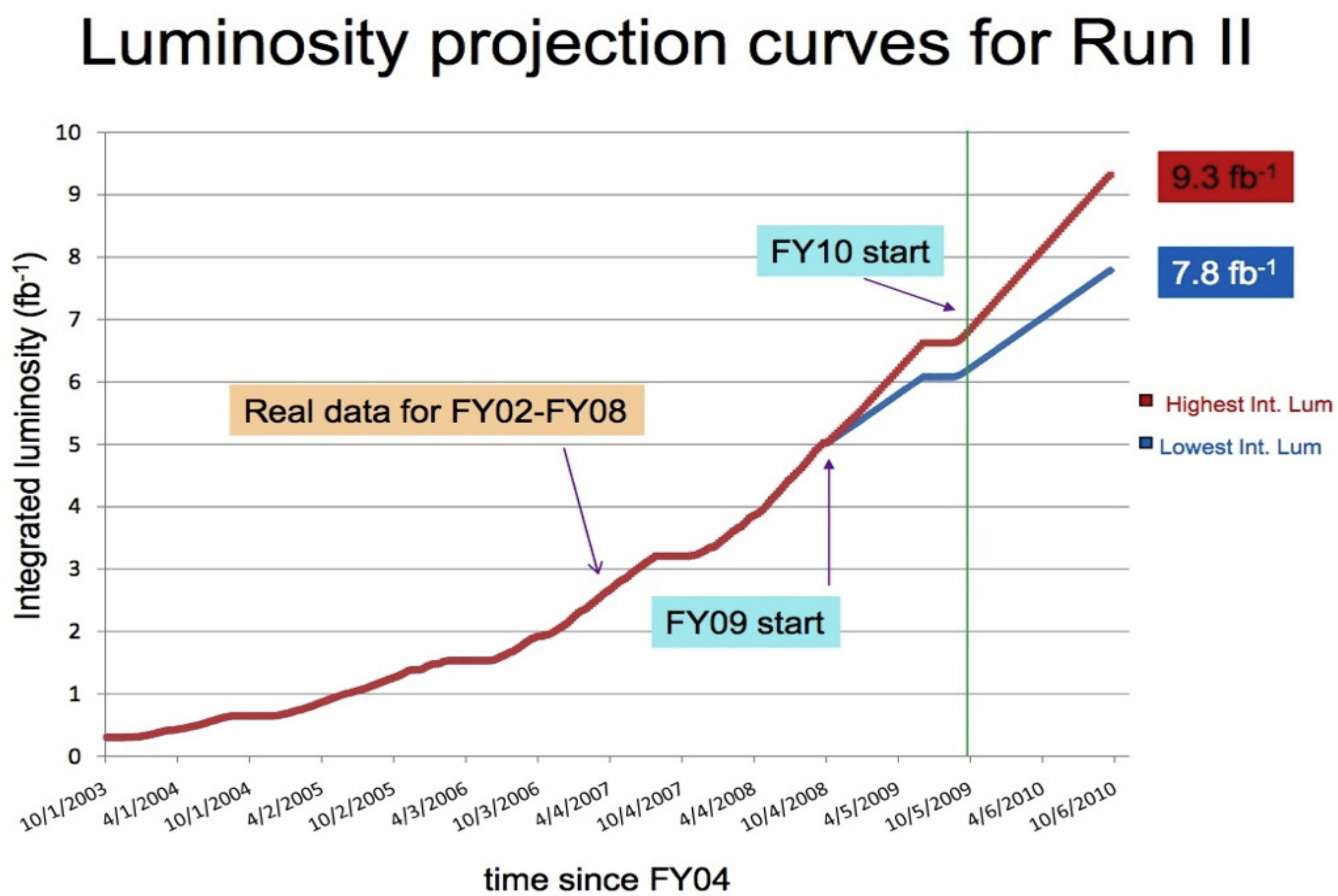
Tevatron sensitivity for 3σ



With additional factor 1.5 improvement in analysis technique

- Experiments are continuously improving analysis technique:
  - Progress much faster than only from additional data
  - Sensitivity increased factor of 1.5 last year: equivalent of more than double luminosity
  - Should be able to probe SM cross-sections with full Tevatron luminosity

Tevatron: luminosity prospects



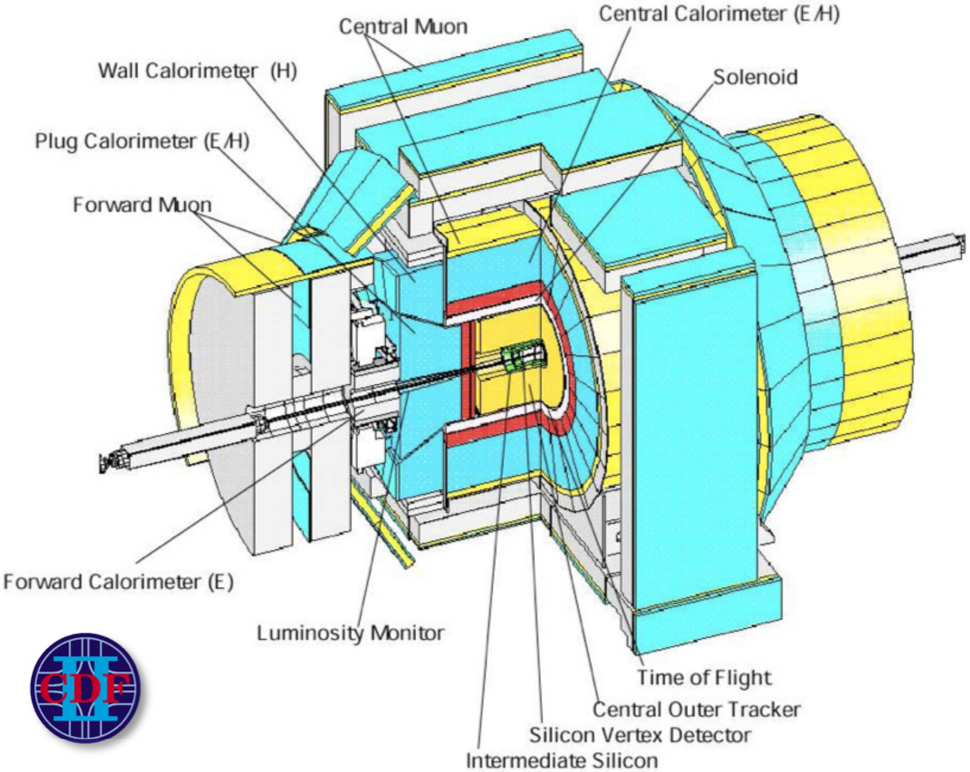
- Tevatron running very well
  - Expect to have > 7.8 fb^{-1}/exper by the end of 2010
  - More than 6.6 fb^{-1}/experiment of good data

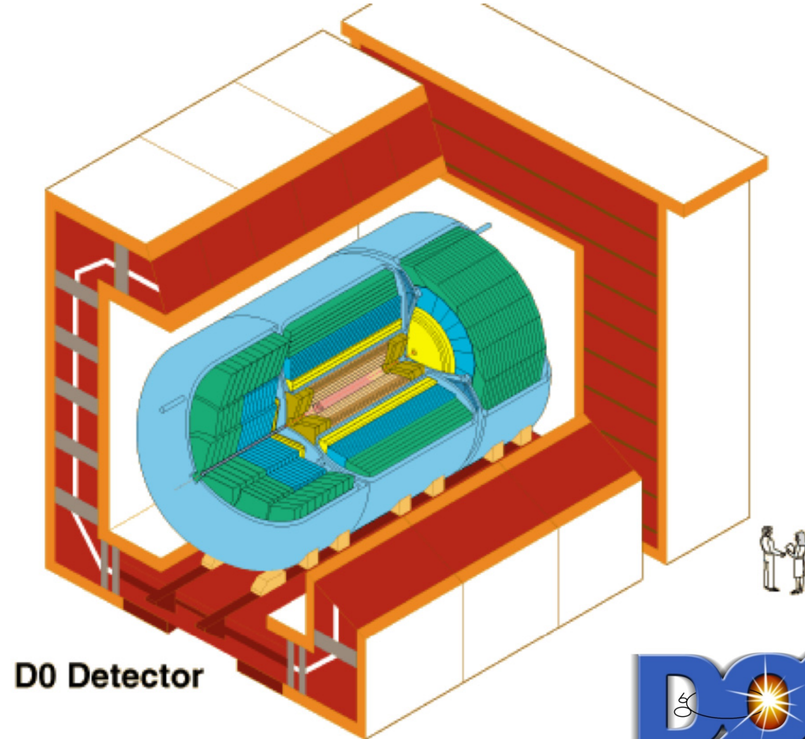
Summary

- Accelerator and the experiments performing very well
- Broad program of Higgs physics
  - Search for signal in all feasible channels
  - Quick turn-around to analyze additional accumulated data
- Combined Tevatron sensitivity below 3*SM *(for MH=115GeV)*
  - Steadily getting close to being able to probe Standard Model Higgs production
- Analysis improvements in progress:
  - Enhanced *b*-tagging efficiency, new triggers, additional lepton categories
  - Additional tools to increase statistical sensitivity: optimize multivariate tools
  - Reduce background uncertainties: systematics will start to be limiting
- The Tevatron does have a chance to find an evidence of Higgs
  - A flow of improvements and close collaboration between CDF and DØ are crucial

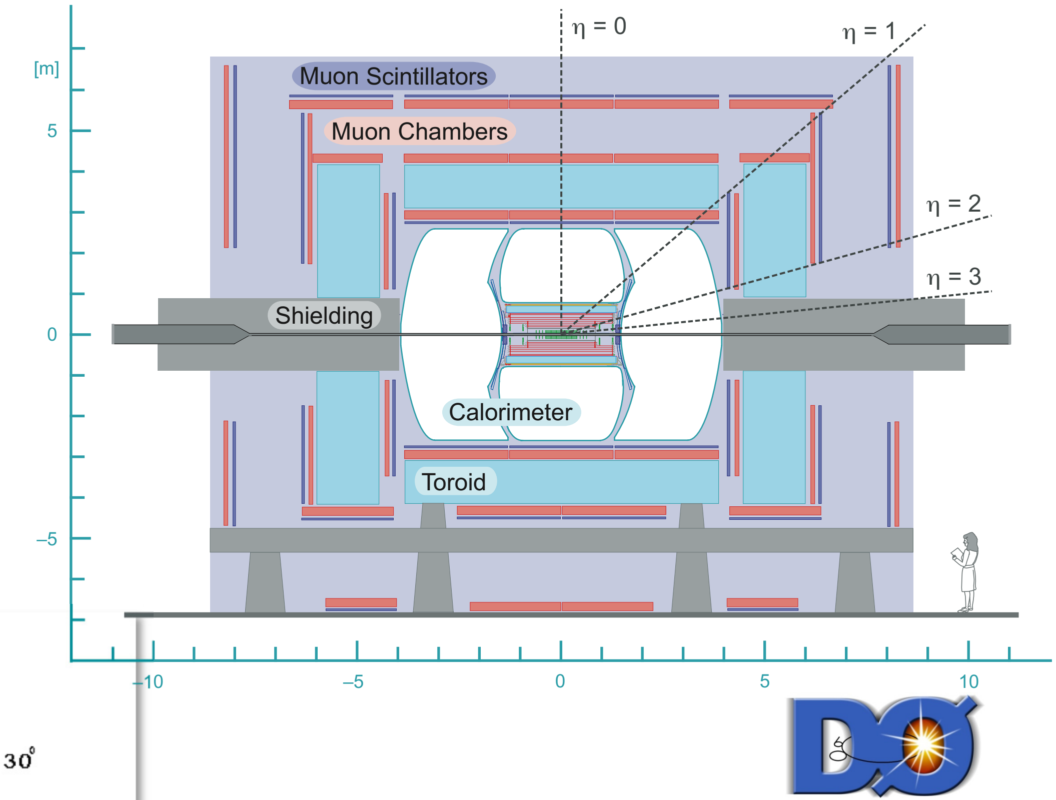
Backup

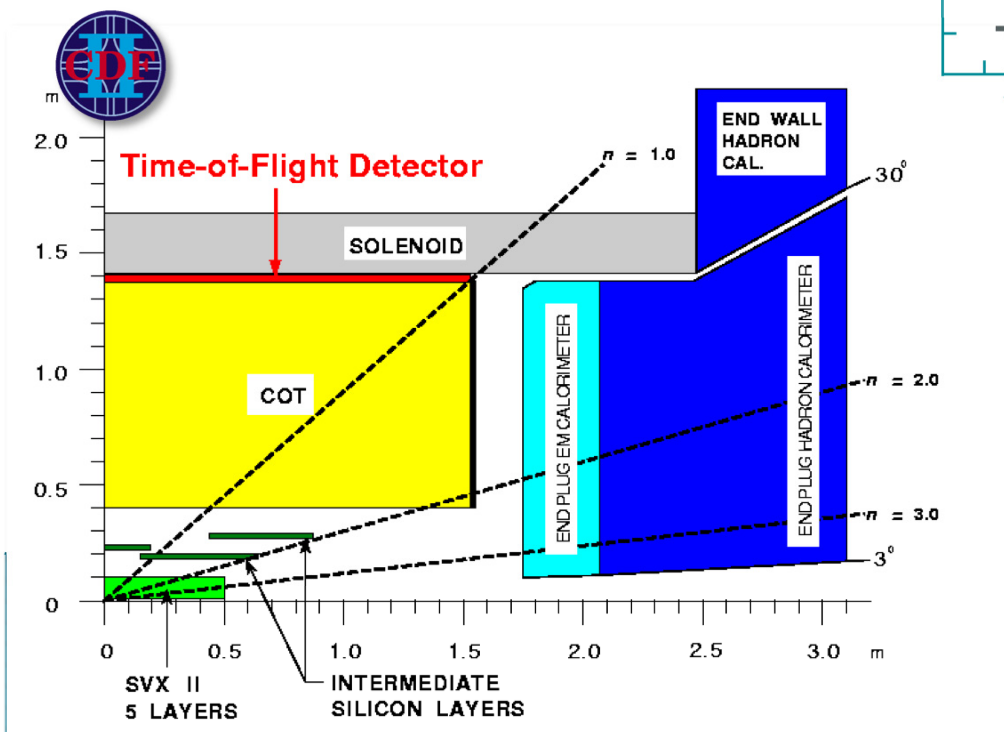
The CDF and D0 detectors



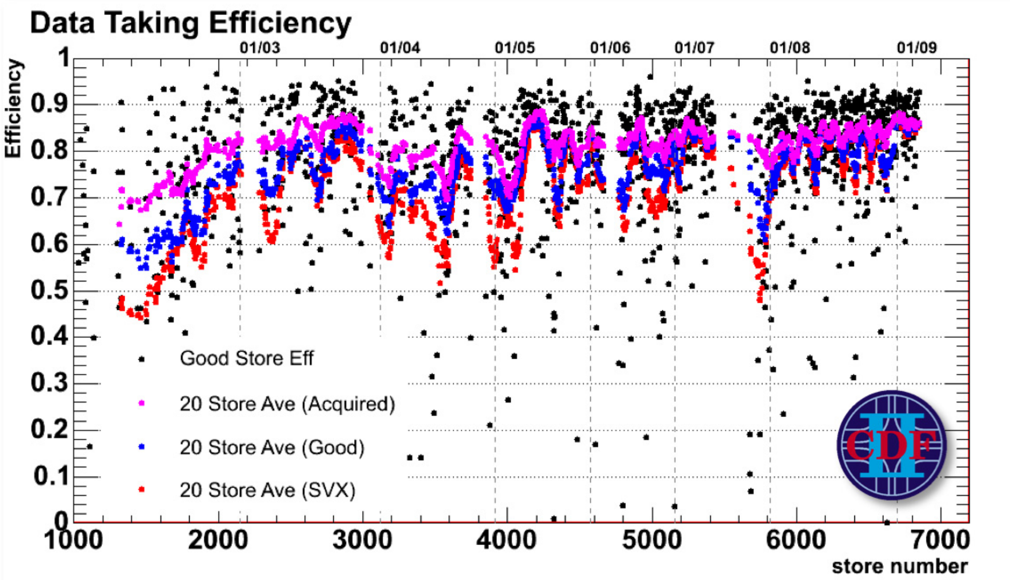


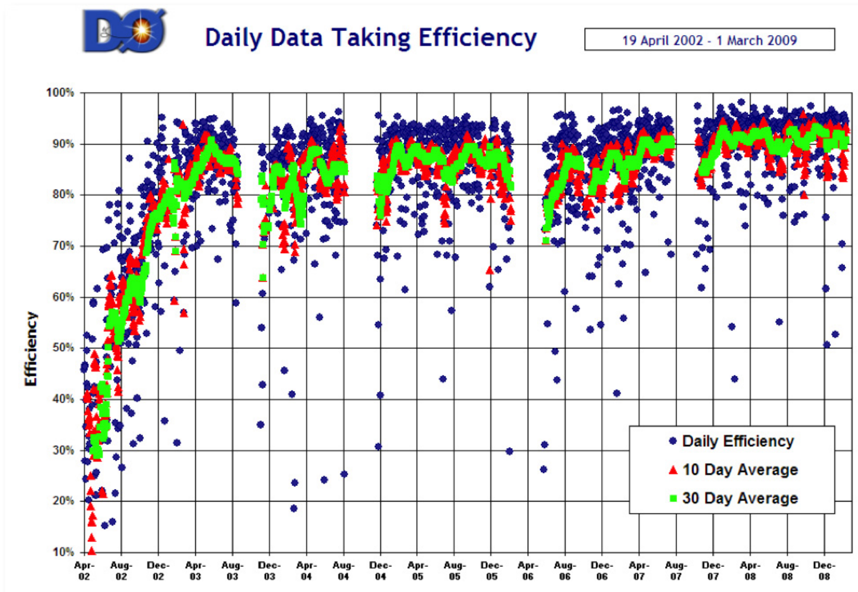
- ✓ Tracking: silicon tracker + drift chamber
  - ✓CDF $|\eta|<2$ scint
  - ✓D0 $|\eta|<3$
- ✓ Calorimeters: central, wall, plug coverage:
  - ✓ CDF $|\eta|<3.6$
  - ✓ DO$|\eta|<4.2$
- ✓ Muon coverage $|\eta|<2$


η = 0
η = 1
η = 2
η = 3
[m]
5
0
–5
Muon Scintillators
Muon Chambers
Shielding
Calorimeter
Toroid
–10
–5
0
5
10


Time-of-Flight Detector
SOLENOID
END WALL HADRON CAL.
30°
η = 1.0
COT
END PLUG EM CALORIMETER
END PLUG HADRON CALORIMETER
η = 2.0
η = 3.0
3°
m
2.0
1.5
1.0
0.5
0
0
0.5
1.0
1.5
2.0
2.5
3.0
m
SVX II
5 LAYERS
INTERMEDIATE
SILICON LAYERS

Experiments' performance





- Data taking efficiency ~85-90%
  - ~5% due to trigger dead time
  - ~5% from beam conditions
  - ~5% occasional detector related downtime

The searches for the Higgs boson

- The Higgs mechanism is testable in experiments
  - Direct observation of the Higgs boson is needed
  - The interactions of the Higgs boson are predicted by theory, but not its mass

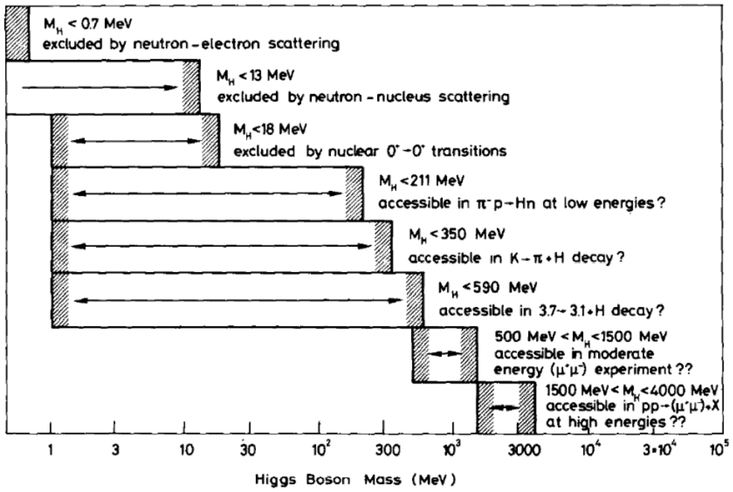
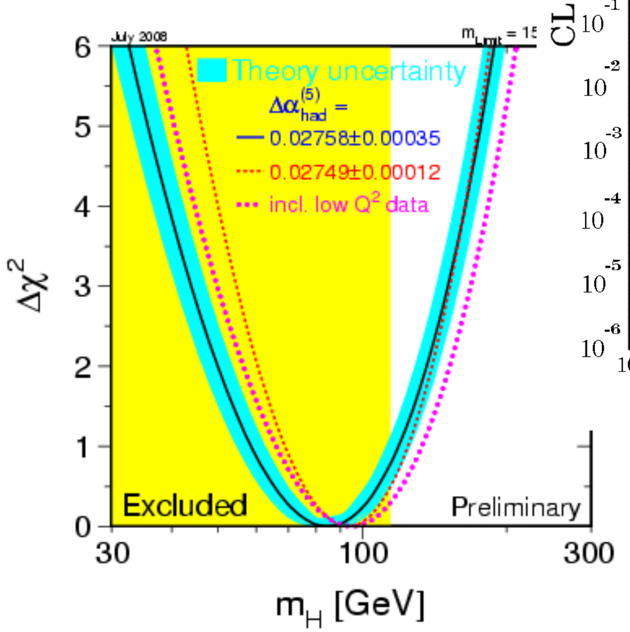
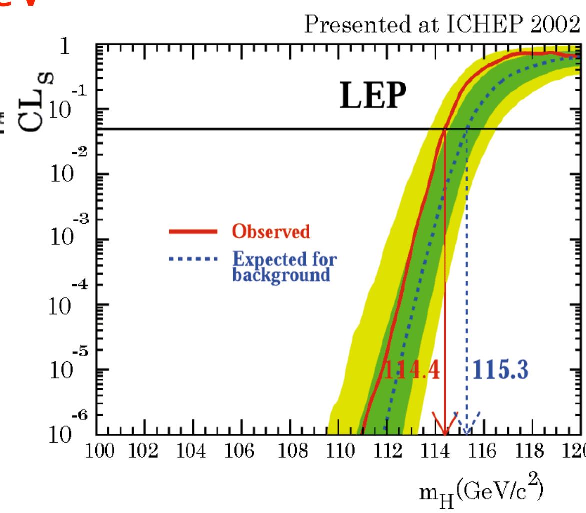


Fig. 3. Present and possible future limits on the Higgs boson mass.

- Searches for the Higgs boson in 70's–80's
  - Before the LEP era searches were sensitive to $M_H \lesssim 5$GeV
- LEP provided the most stringent bounds for SM Higgs: $M_H > 114.4$GeV

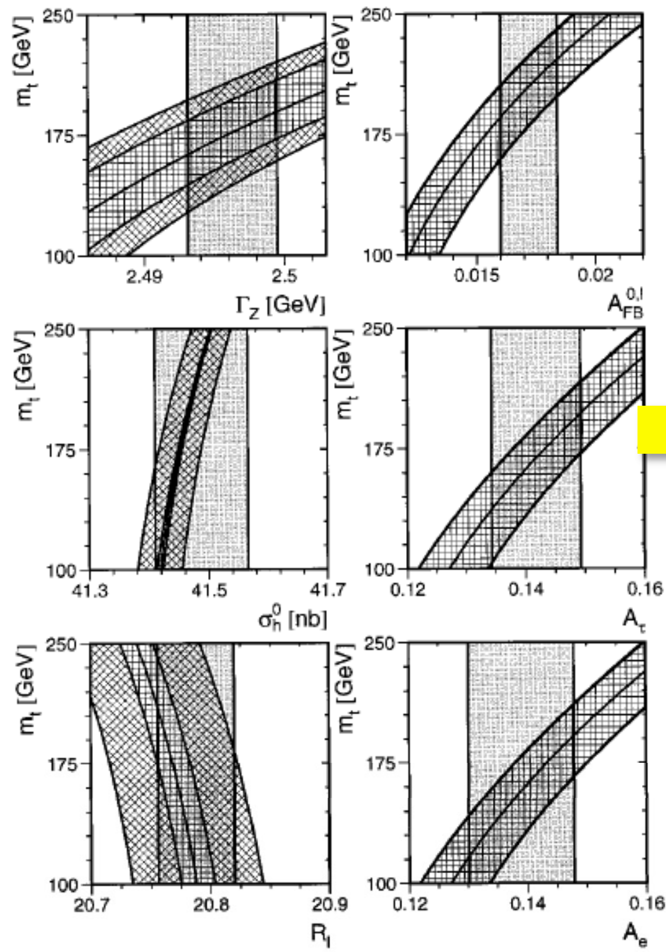


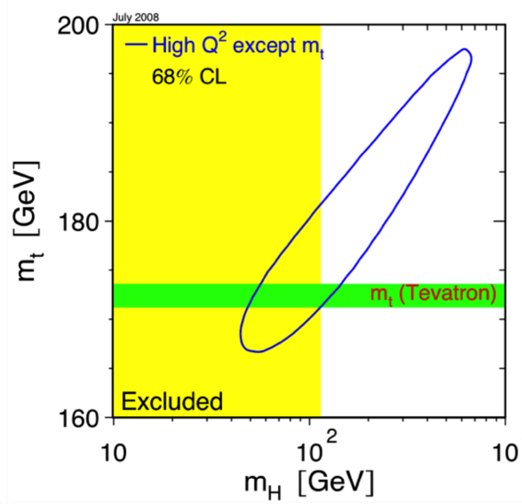


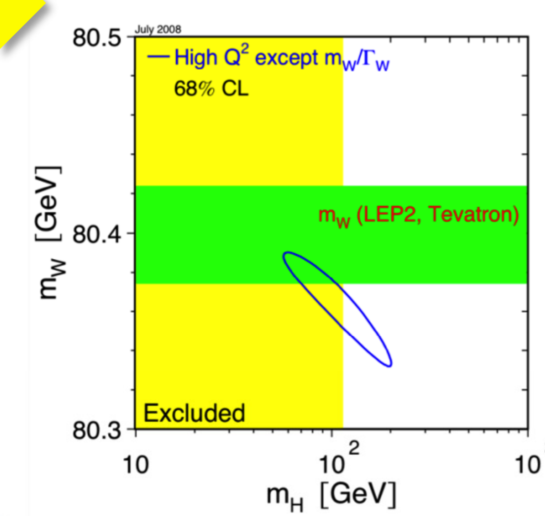
- Indirect searches:
  - Constraints from fitting EW data
  - $M_H = 84^{+34}_{-26}$ GeV
  - $M_H < 154$GeV at 95%CL
- Indirect constraints provided first hints of top mass **before** discovery
  - Predicted to be 180 ± 12GeV

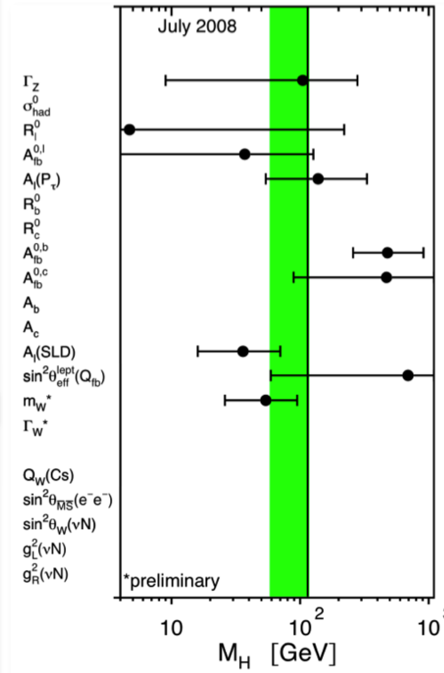
Electroweak fits

- Indirect constrains from EW parameter fits provided first hints of top quark mass
  - Will this repeat for Higgs?









Setting the limit

- Use Bayesian and frequentist approach:
  - Bayesian $L(R,\vec{s},\vec{b}|\vec{n},\vec{\theta})=\prod_{i=1}^{Nc}\prod_{j=1}^{Nbins}\mu_{ij}^{nij}e^{-\mu_{ij}}/n_{ij}!\times\prod_{k=1}^{n}e^{-\theta_k^2/2}$
  - Frequentist(CL_s) $LLR_n=2\sum_{i=1}^{N}(s_i-n_i Log(1+\frac{s_i}{b_i}))$

- If the excess is significant after combination, do more checks to make sure not statistic fluctuation.
- If no excess, set 95% CL upper limit vs mH