The Search For The Higgs Boson In The Complete Run II Dataset With CDF

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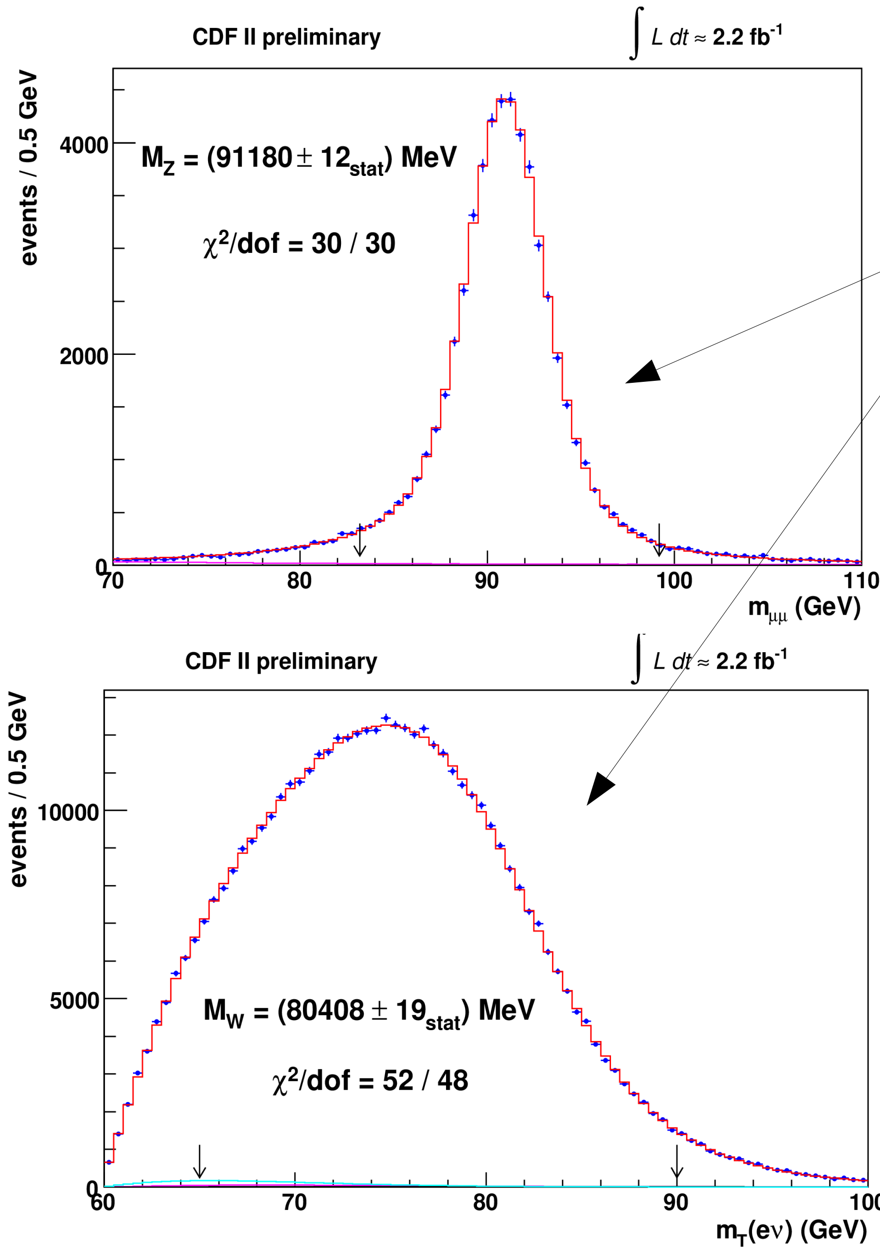
On Behalf of the CDF Collaboration

Les Rencontres de Physique de la Vallée d'Aoste
2 March 2012 La Thuile, Italy

Overview

- Goal: <u>Direct</u> Evidence for the SM Higgs Boson
- Motivation
- 2011 Search Status
- The Tevatron, CDF
- SM Higgs Production & Decay at the Tevatron
- Recent Advancements in Search Techniques
- Prospects for Full Dataset Results
- The Future

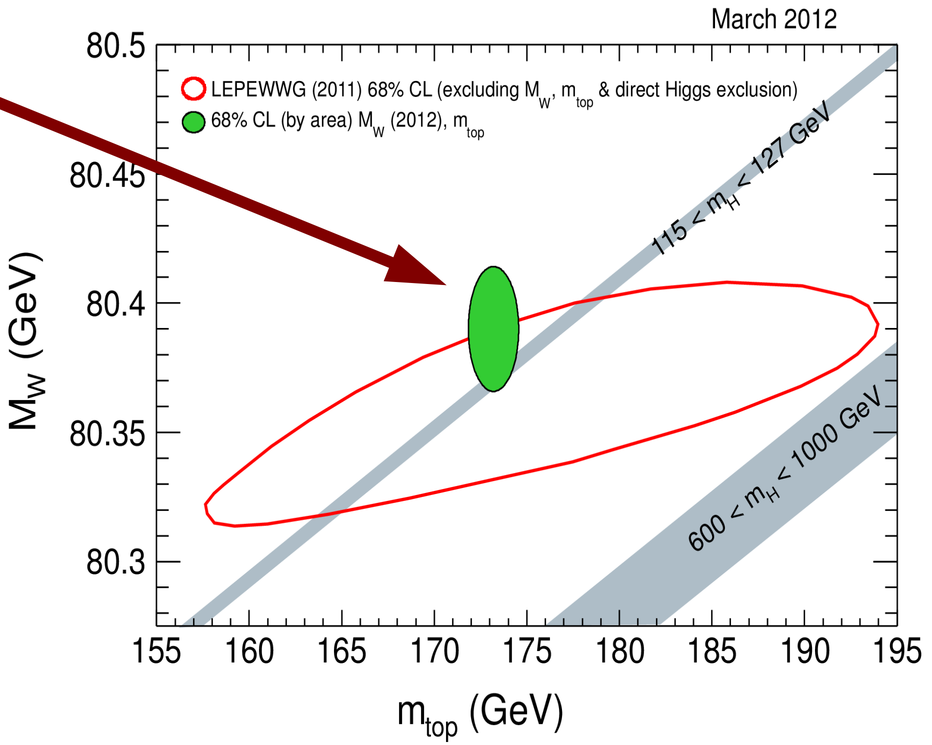
Theoretical Motivation



- Gauge invariance suggests massless W and Z bosons
  - W, Z observed to be massive
- In SM, W&Z observable mass via electroweak symmetry breaking
- Ground breaking work on EWSB:
  - F. Englert, R. Brout, PRL 13 (9): 321–323.
  - P.W. Higgs, PRL 13 (16): 508–509.
  - G.S. Guralnik, C.R. Hagen, T.W.B. Kibble, PRL 13 (20): 585–587.
- Proposed mechanism of EWSB **predicts** an additional **observable scalar particle.**

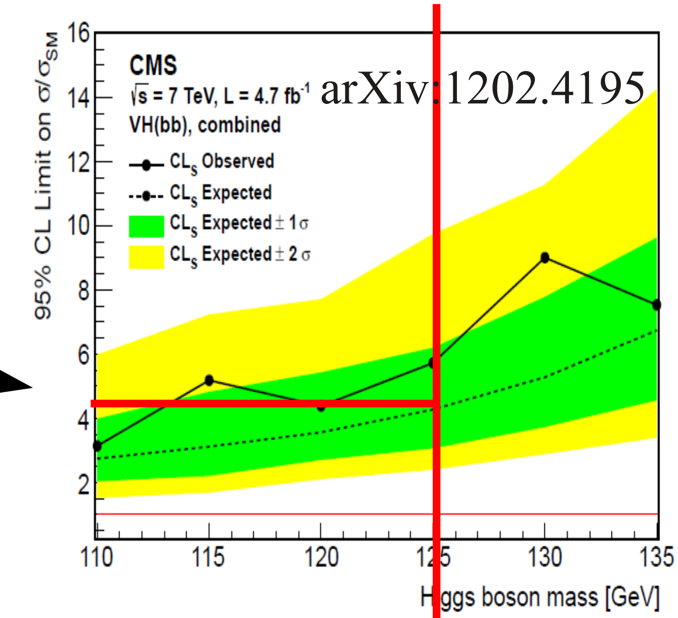
Experimental Status

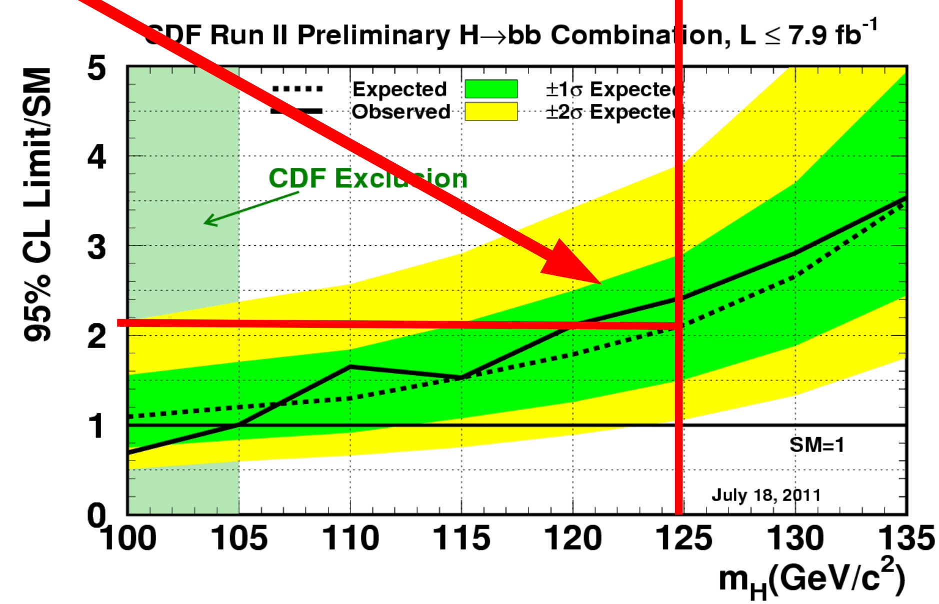
- Resulting boson mass is unpredicted by theory
  - Mass determines production and decay rates (next slide)
- Indirect constraints (MW, Mtop) prefer a "light" SM Higgs Boson
  - New CDF 2012 W mass! (B. Jayatilaka, La Thuile)
- Direct Searches: Exclusions of MH:
  - LEP < 114 GeV
    - arXiv:0602042v1
  - Tevatron [156,177] GeV
    - arXiv:1107.5518
  - LHC [~127, 600] GeV
    - arXiv:1202.1408 (ATLAS)
    - arXiv:1202.1488 (CMS)



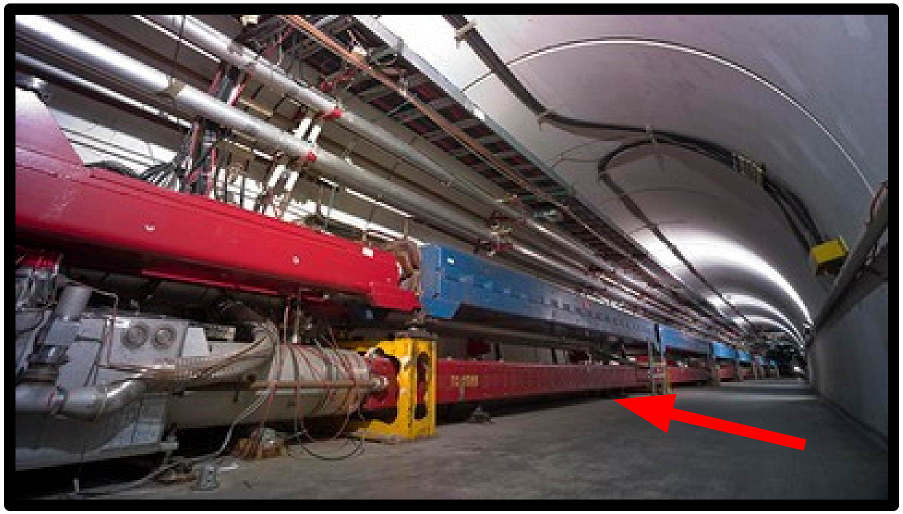
Tevatron: Powerful in H→bb

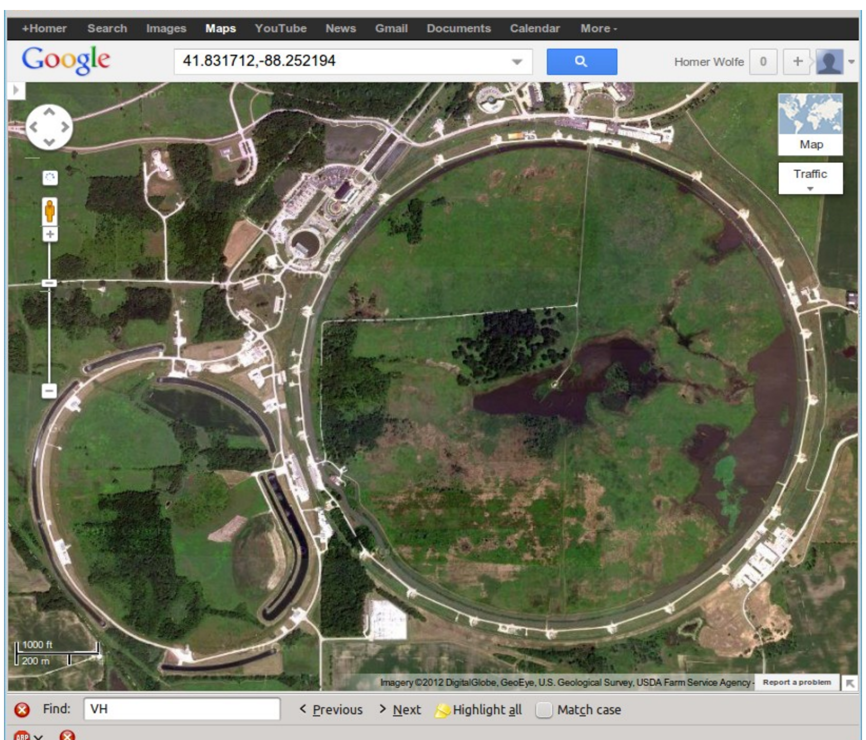
- Expected Sensitivities (January 2012, 125 GeV):
  - H→bb:
    - ATLAS,CMS: ~4.3xSM
    - CDF, D0: ~2xSM
  - H→γγ:
    - ATLAS,CMS: ~1.5-2xSM
    - CDF, D0: ~10-13xSM
  - H→WW:
    - ATLAS,CMS: ~1-2xSM
    - CDF, D0: ~3.5xSM
- Tevatron's strength in the light-SM-Higgs scenario is the branching fraction of H to bb!





The Tevatron, Batavia IL, USA

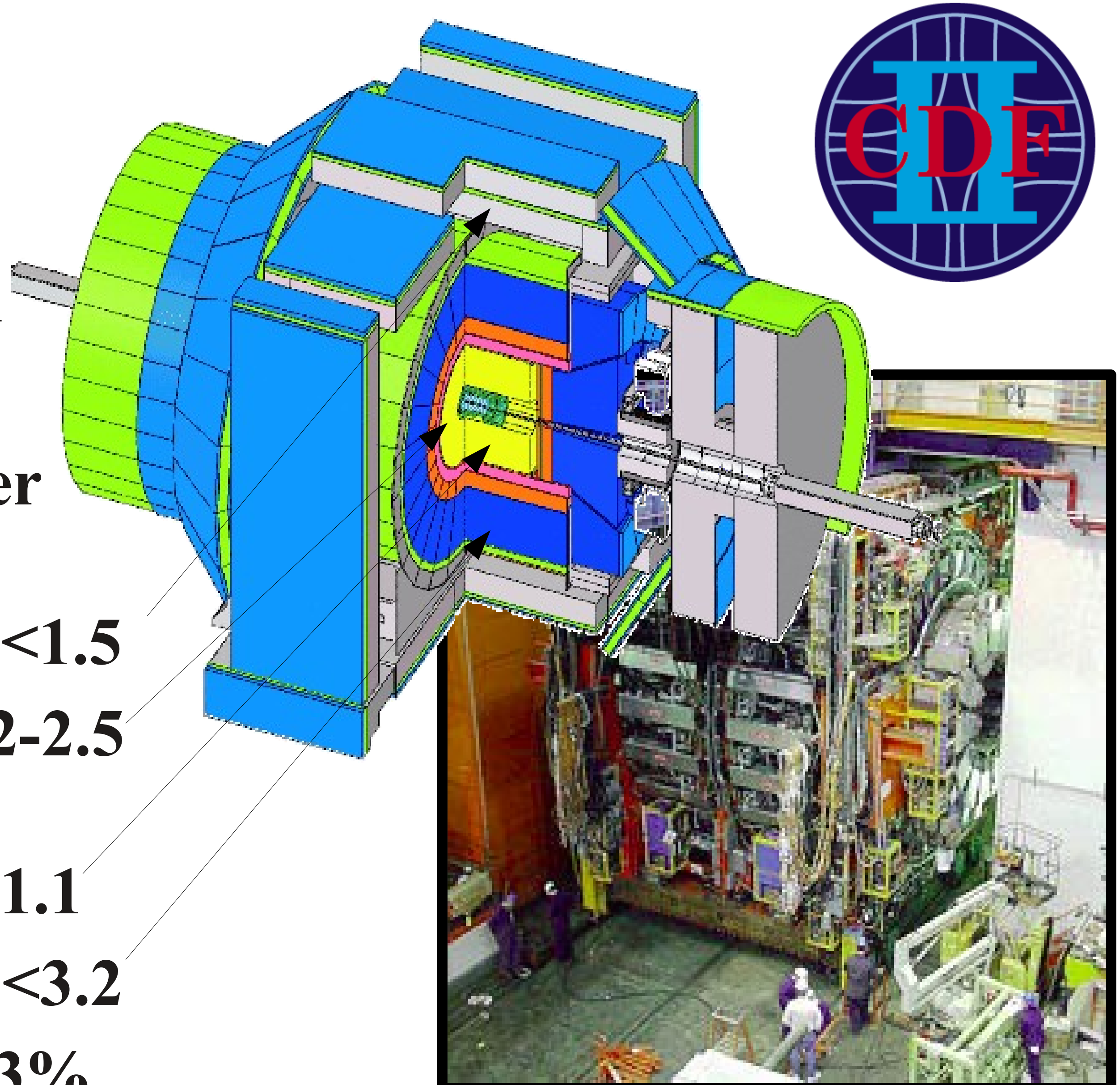




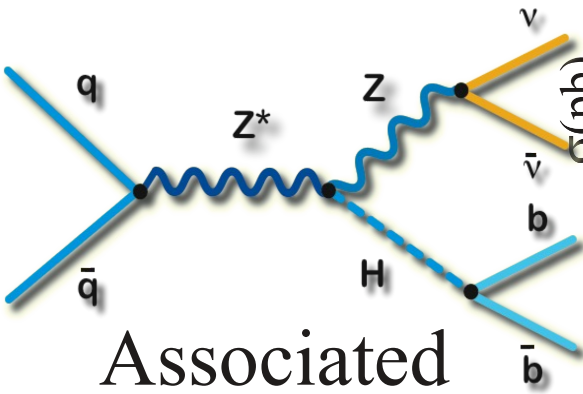
- Superconducting storage ring
  - 1 beampipe, 1 km radius
- Run II: Mar 2001-Sept 2011
- Provided $p\bar{p}$ collisions at 1.96 TeV to CDF/DØ
  - 36x36 bunches
  - ~E10-E11 particles per bunch
  - ~21μs per revolution
  - ~1.5 MJ beam energy
- Thanks to FNAL Beams Division!
  - Peak inst.: >4.2E32 cm^{-2}/s
  - ~70/pb delivered/week
  - ~12/fb delivered/exp.

CDFII: a Multipurpose Collider Detector

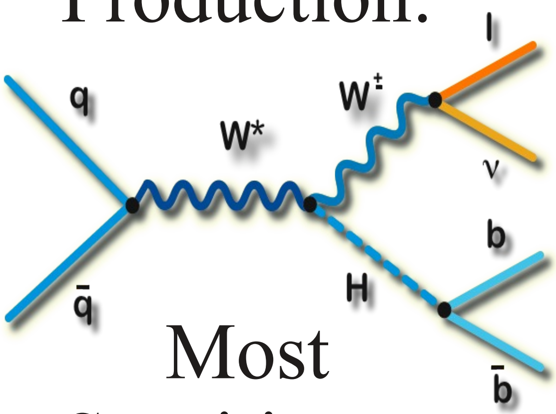
- ~5K tons
  (~2.5K central only)
- ~10 m each direction
- ~100 Hz readout
- ~720 K silicon tracker
  readout channels
- Muon chambers: $|\eta|<1.5$
- Silicon tracking $|\eta|<2\text{-}2.5$
- Drift cell tracker
  1.4 Tesla B field, $|\eta|<1.1$
- Pb/Cu/scint calor. $|\eta|<3.2$
  - JES uncertainty 2-3%



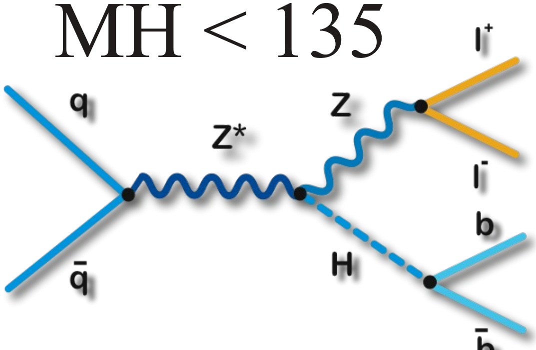
SM Higgs Production at The Tevatron

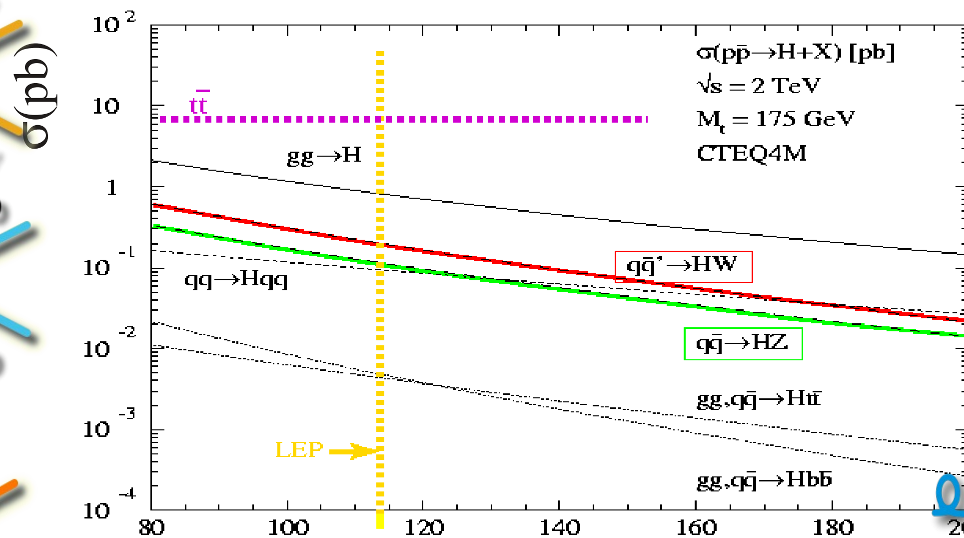


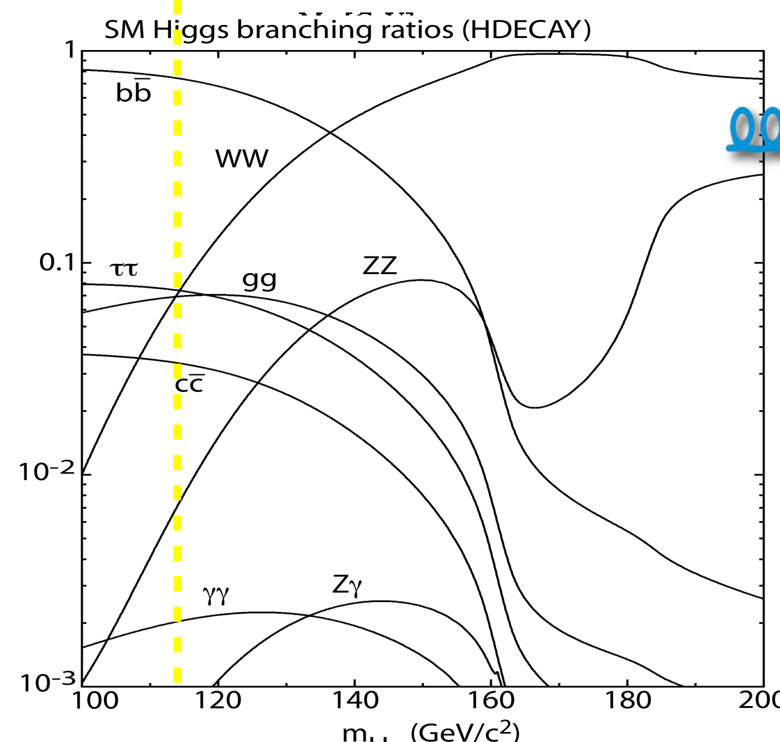
Associated Production:



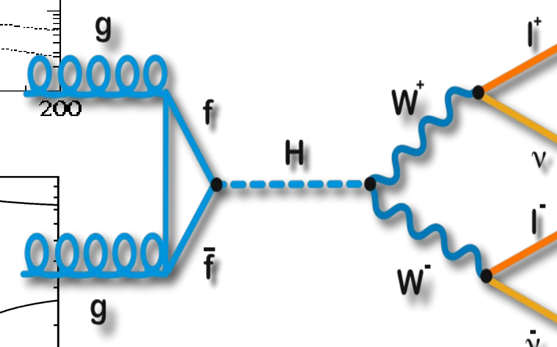
Most Sensitive at MH < 135





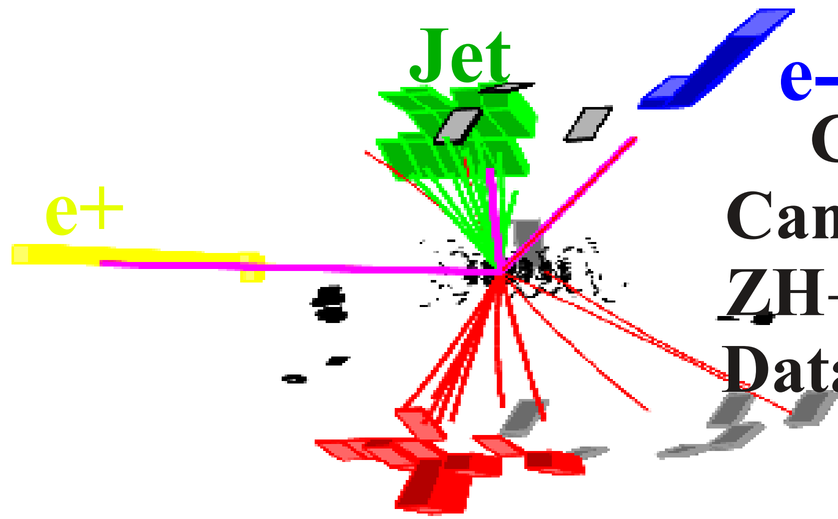


Direct Production:

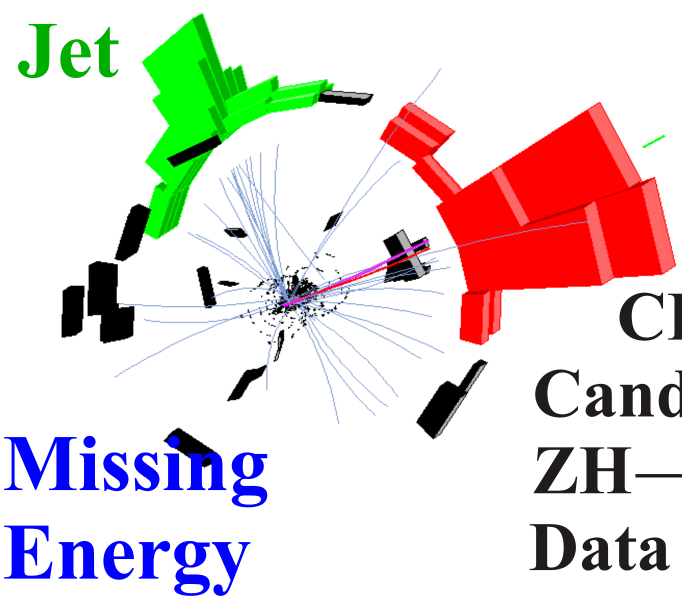


Most Sensitive at MH > 135

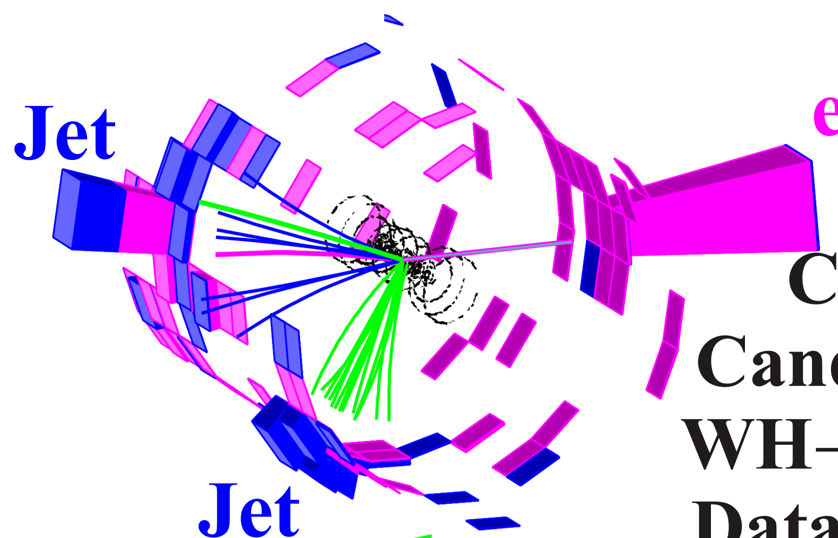
Some of the Many Final States in Associated Production



CDF
Candidate
ZH→eebb
Data Event



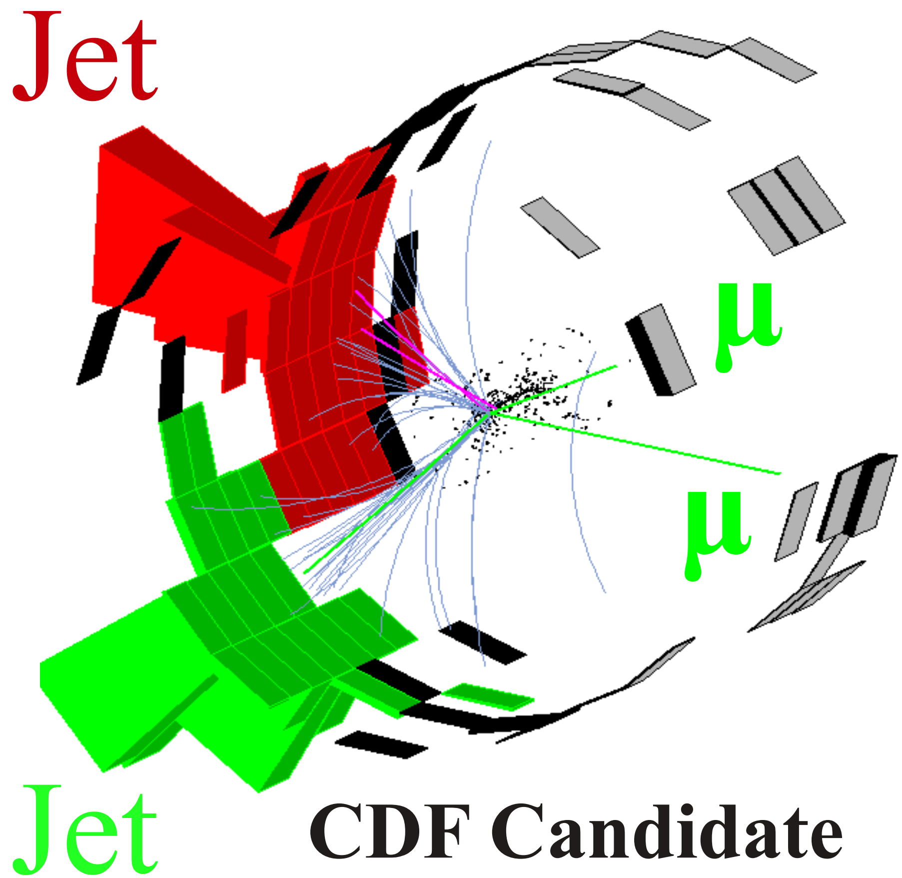
CDF
Candidate
ZH→ννbb
Data Event



CDF
Candidate
WH→eνbb
Data Event

1 SM Higgs, Many Decays

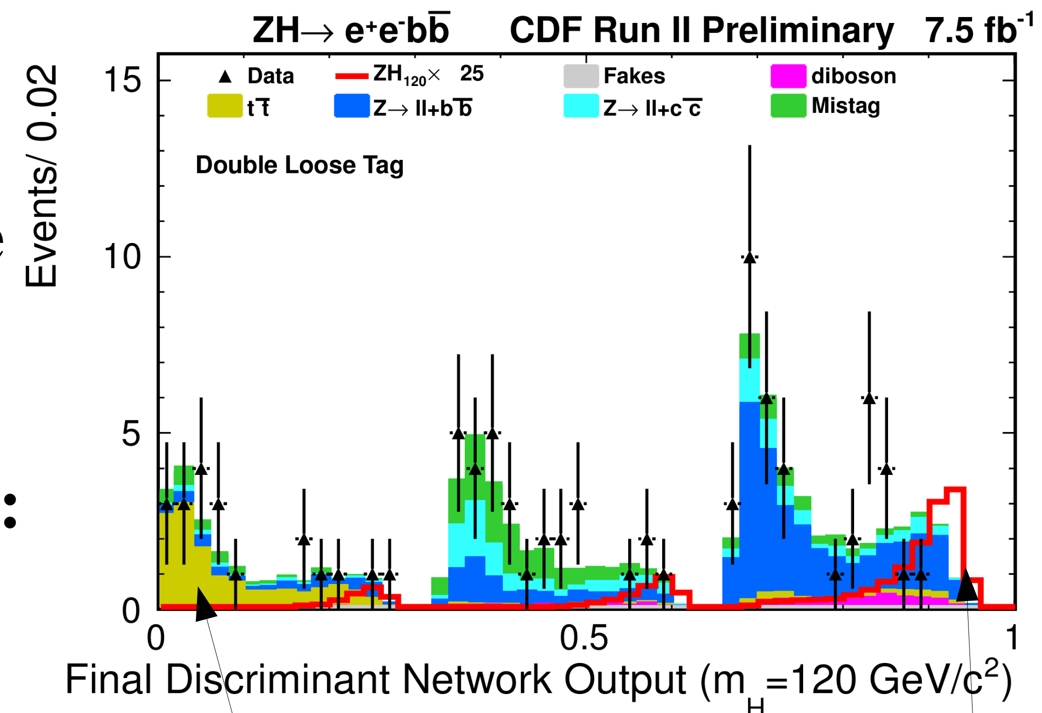
- For the 2012 CDF Winter results:
  - SM predicts ~167 Higgs (125 GeV) events *reconstructed and selected*
  - SM background of ~200K
- Partitioned over many final states
  - Low (<150 GeV) mass
    - WH, ZH, METbb, ttH, γγ,VBF→bbjj
  - High (>150 GeV) mass
    - WWW, WWZ, WW, ZZ, τ-decays, full/semi-leptonic...
- 16 CDF analyses:
  - 93 orthogonal sub-channels.
- Small signal on diverse background
  - Maximizing signal acceptance is key



CDF Candidate
ZH→μμbb
Data Event

Quantitative Statements About Small Signals

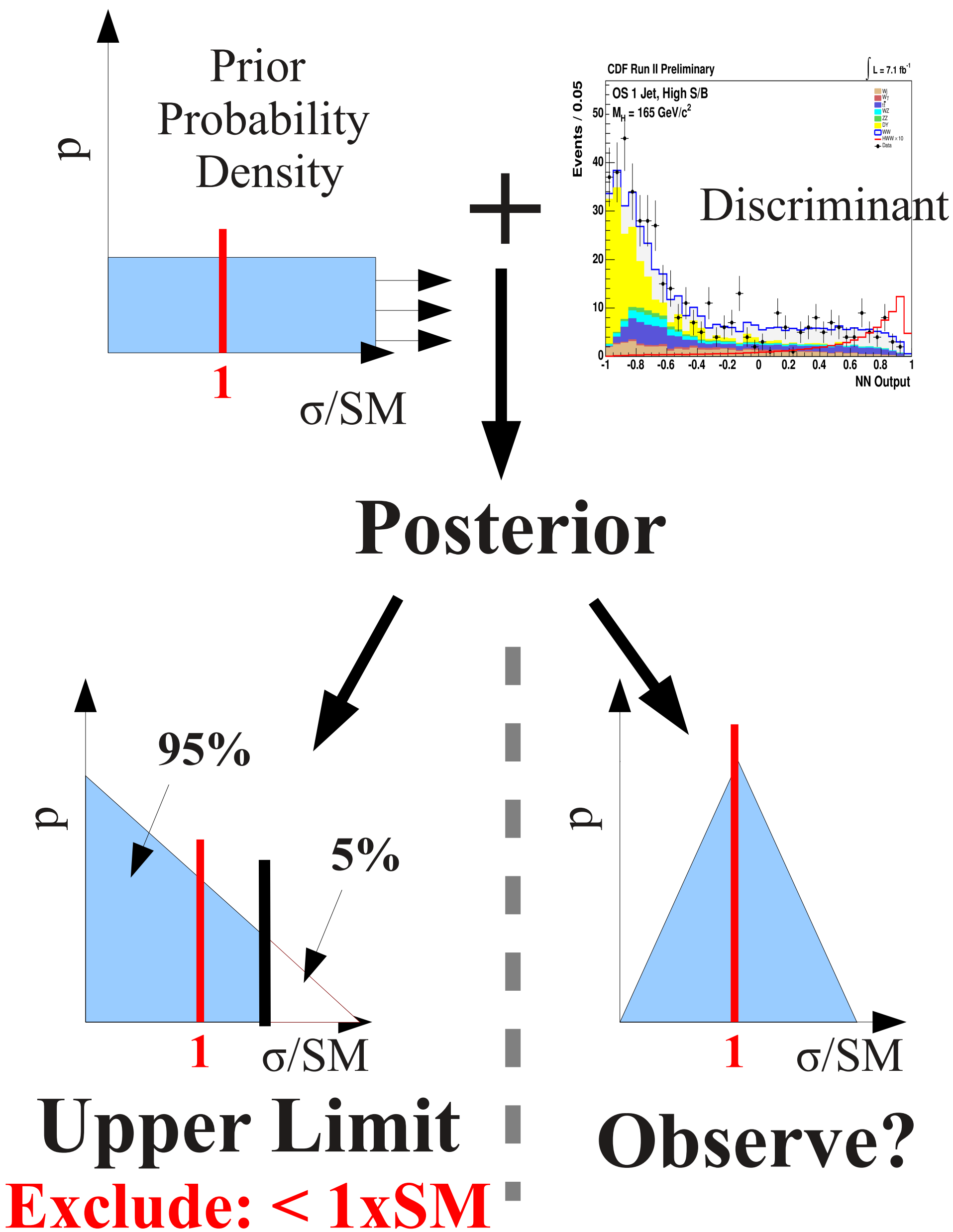
- Reconstruct, select events
  - Simulate background processes
- Optimize signal significance
  - Avoid cutting any signal events!
  - Discriminant distribution:
    - Dijet mass
    - Neural network, BDT, Matrix element probability
  - Background rich regions can be used to constrain backgrounds underneath signal, and constrain systematic uncertainties



S/B is *Really* Small

S/B is Small

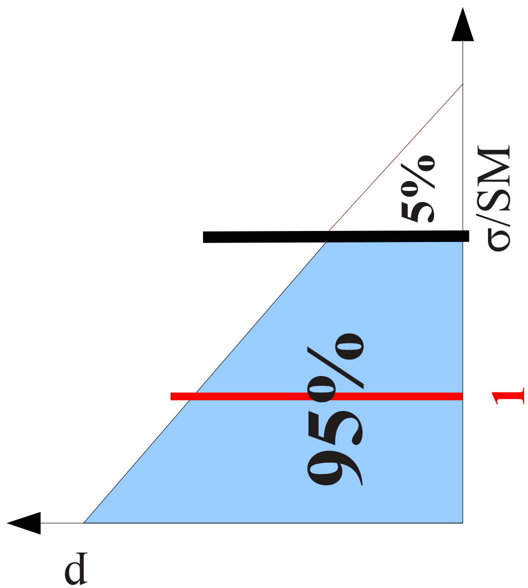
Quantitative Statements About Small Signals

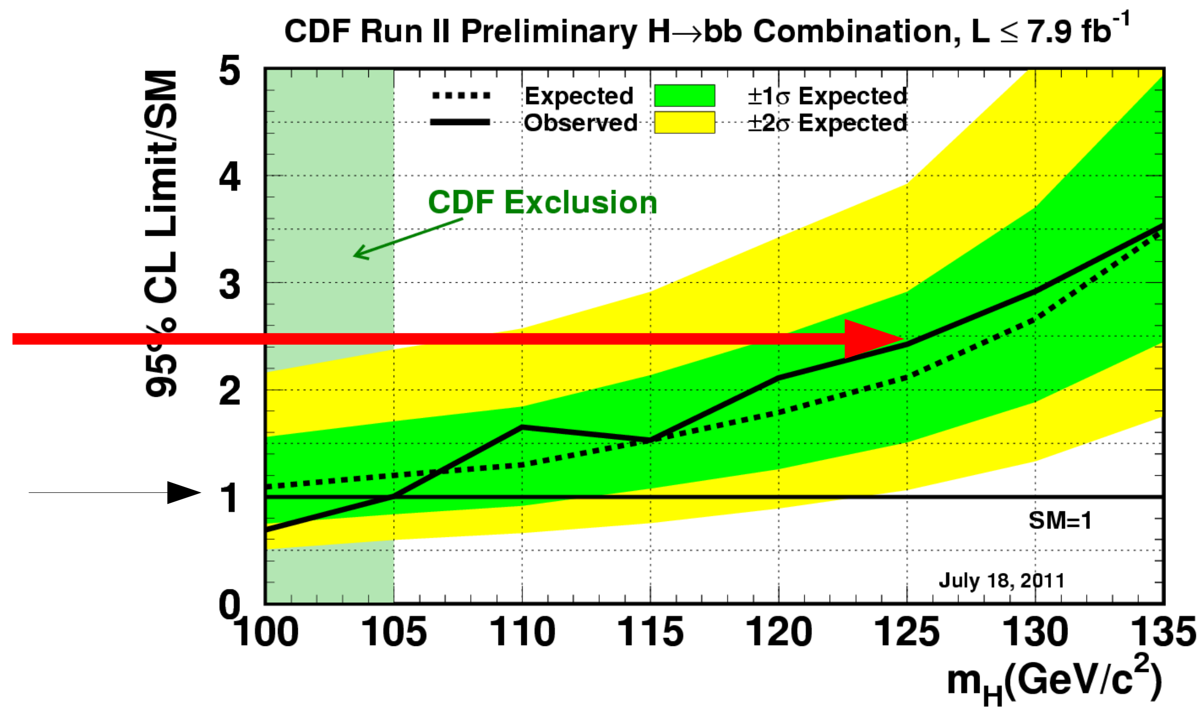


- **Bayesian Method:**
  - **Compare 2 models:**
    - **BG-only**
    - **BG+signal hypotheses**
  - **Compute Poisson Likelihood**
    - **Compatibility of data with each hypothesis**
  - **Compute posterior probability density:**
    - **Cross section scaling: R=σ/σ(SM)**
      - **Flat Prior: R=[0,Large #]**
    - **Nuisance parameters:**
      - **Detector response, background cross sections, PDFs, etc.**
  - **Integrate likelihood over nuisance parameters:**
    - **Produces posterior probability as function of R alone**

Quantitative Statements About Small Signals

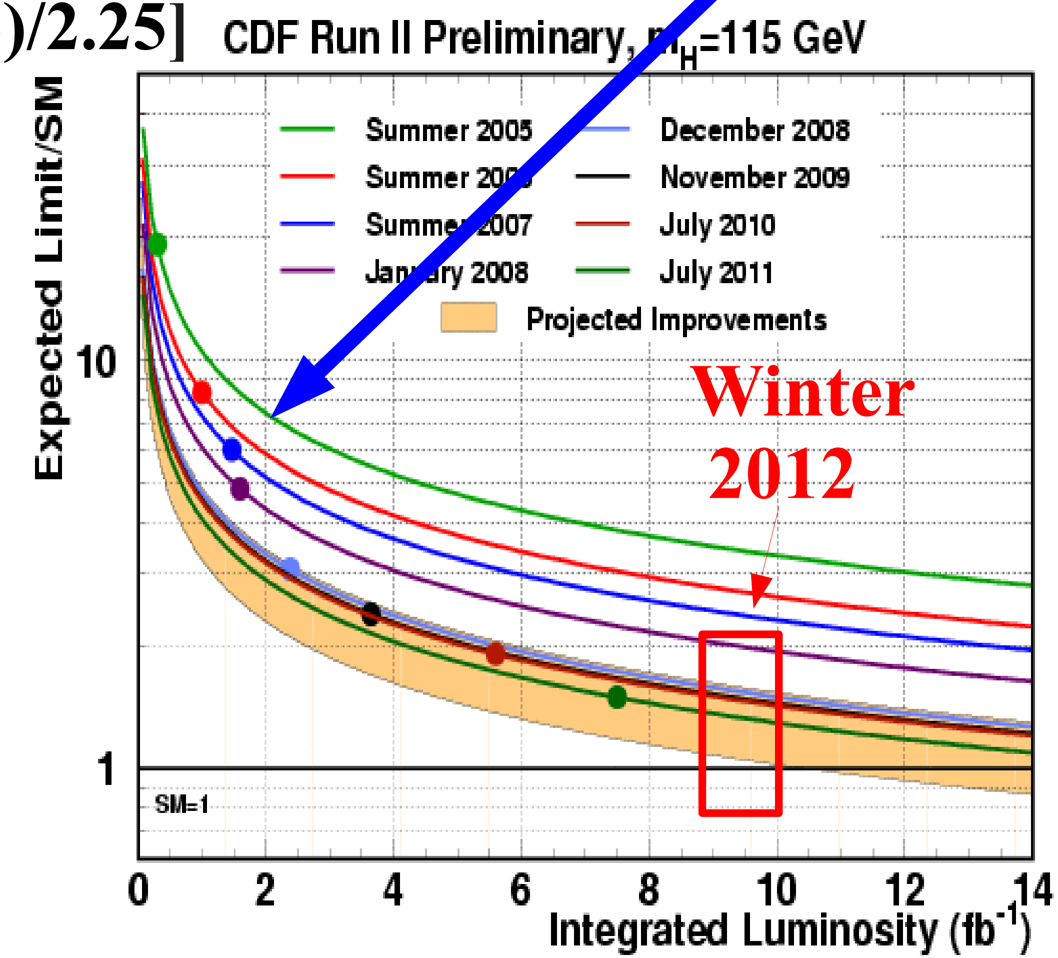
- Perform this analysis for each assumed Higgs Mass:
  - For data (Observed upper limit)
    - Construct ensemble of *background-only* pseudoexperiments (Expected sensitivity)
      - Each has same statistical uncertainty as data
    - Shaded bands show *background-like* statistical and systematic excursions



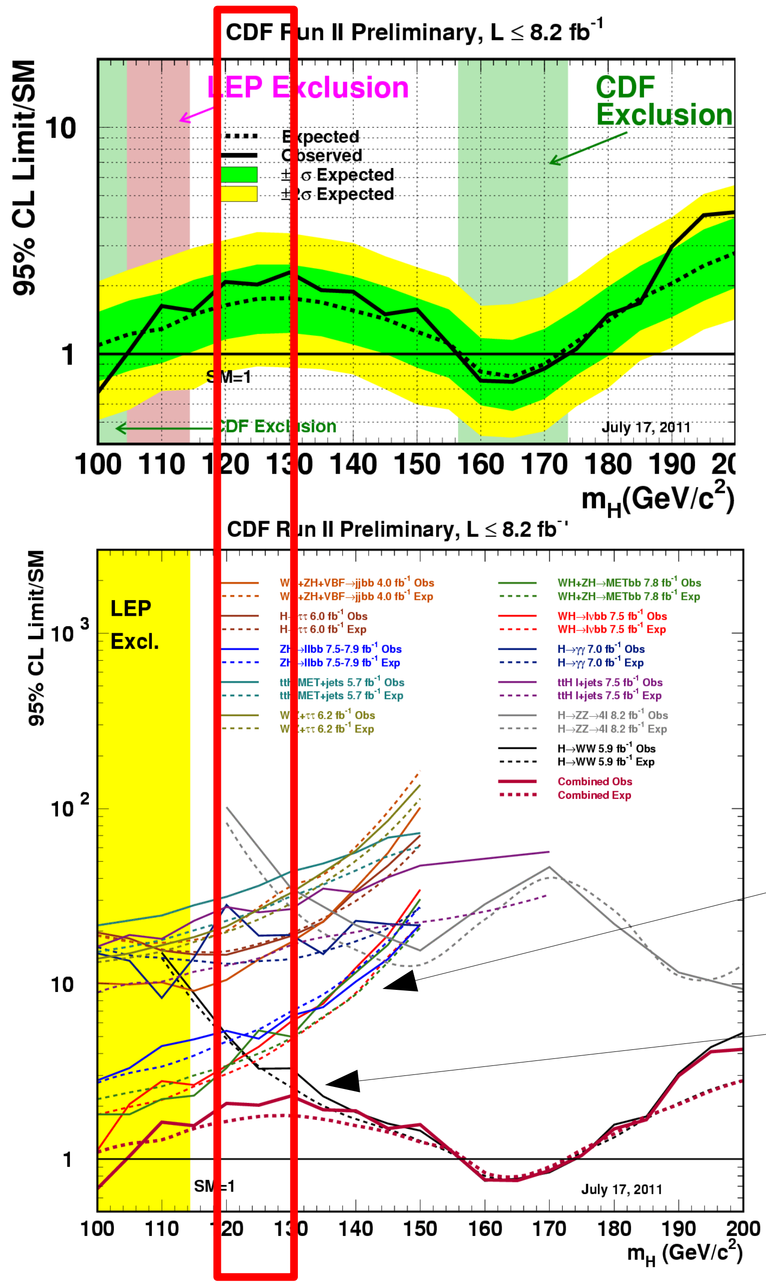


CDF: Relentless Pursuit

- CDF analyses improve **far beyond adding data.**
  - Improvements made are beyond those projected in 2007!
  - [(2007 Exp)/1.5, (2007 Exp)/2.25]
- Adding data alone to the 2007 analyses would have required >30/fb to reach SM MH=115 cross section sensitivity!



CDF Combined Higgs Search: 2011

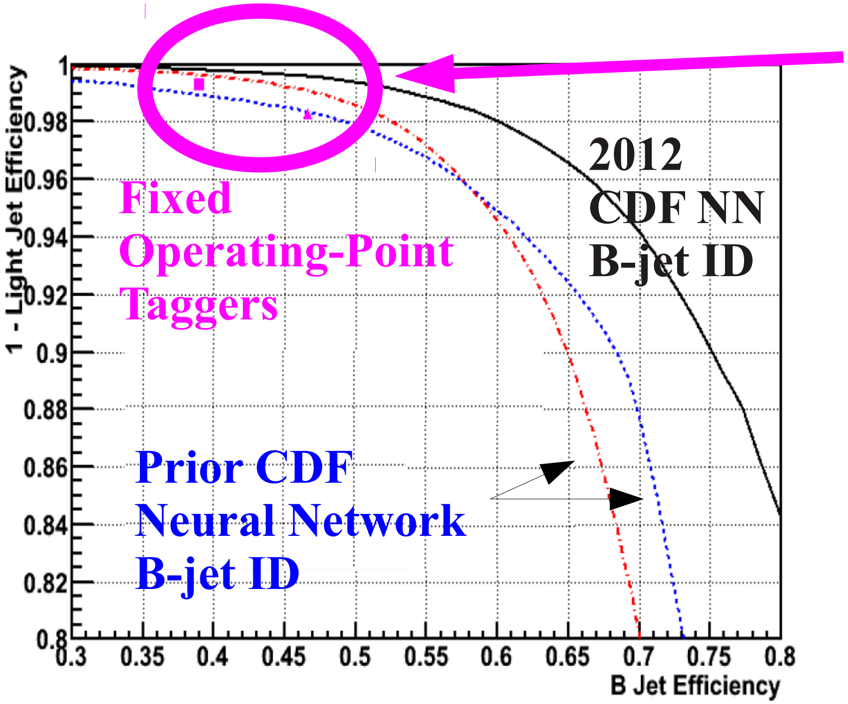


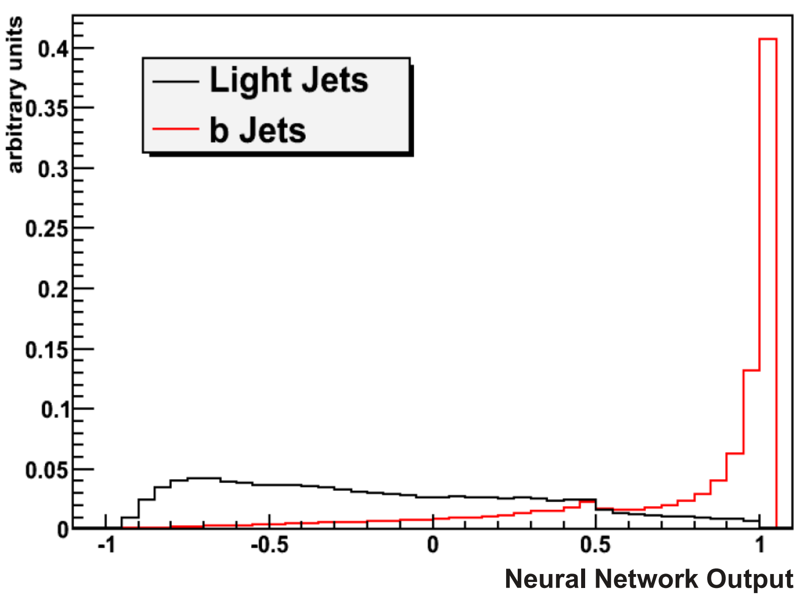
- Better than 2xSM over non-excluded range
  - Broad excess 100-150 GeV
    - Not significant (~0.5-σ)
    - Mjj resolution ~+/-15 GeV
  - Most sensitive searches at 125 GeV, ~equal:
    - WH→lυbb
    - ZH→llbb
    - WH+ZH→METbb
    - H→WW→lυlυ
- Sensitivities add roughly as inverse quadrature

New Major Improvements

- Summer 2011 results used 7.5-8/fb
  - Luminosity quoted depends on each final state
  - **Full CDF dataset** results (9.4-10/fb) presented here
- Improved b-jet identification:
  - **More acceptance: ~10-15% better sensitivity in WH, ZH**
  - less background
- Inclusive online selection
- More efficient offline selection
  - See H→WW presentation (R. St. Denis)
- Improved background discrimination

Identifying Jets from Hadronic Higgs Decays

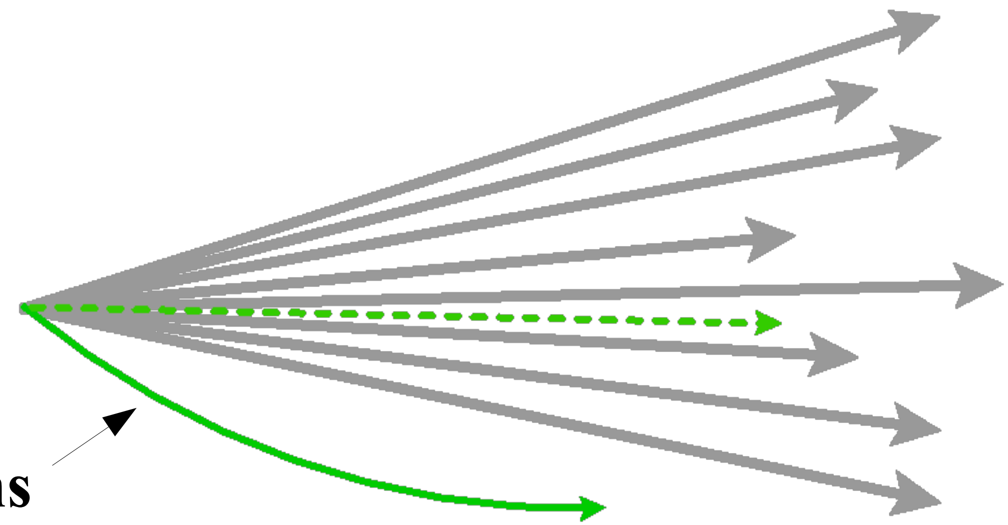


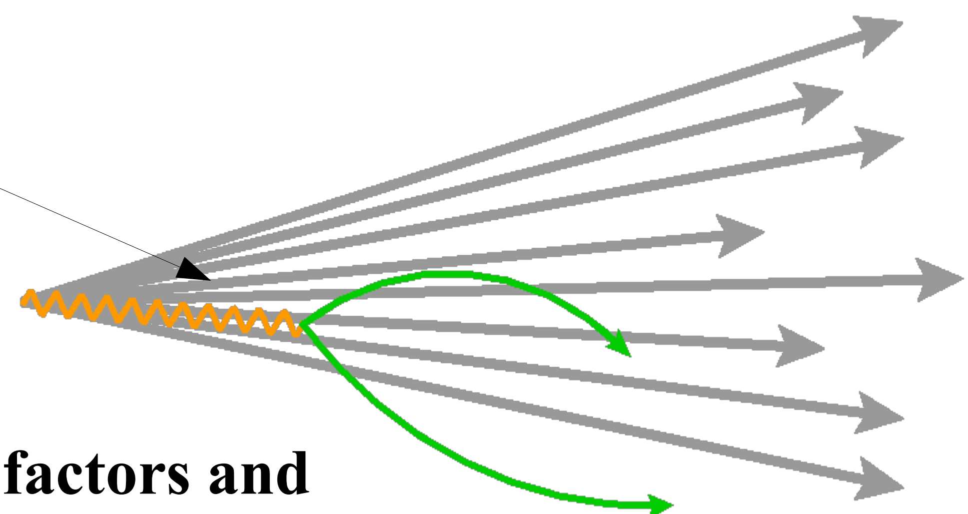


- 2011: CDF WH (ZH,VH) used 3 (2) different b-taggers in orthogonal series
- 2012: New CDF Neural Network b-tagger
  - Uses most sensitive variables from previous CDF taggers
    - Uses semileptonic b-decay muons, Jet tower mass, secondary vertex mass...
    - Can tag jets with only one charged particle track
  - Continuous variable output allows for analysis group to choose cuts:
    - optimize expected sensitivity
  - For identical false-positive rates of previous taggers, b-jet efficiency:
    - Tight: 38.6→53.6%
      - False Positive: 1.4%
    - Loose: 47.1→59.3%
      - False Positive: 2.8%

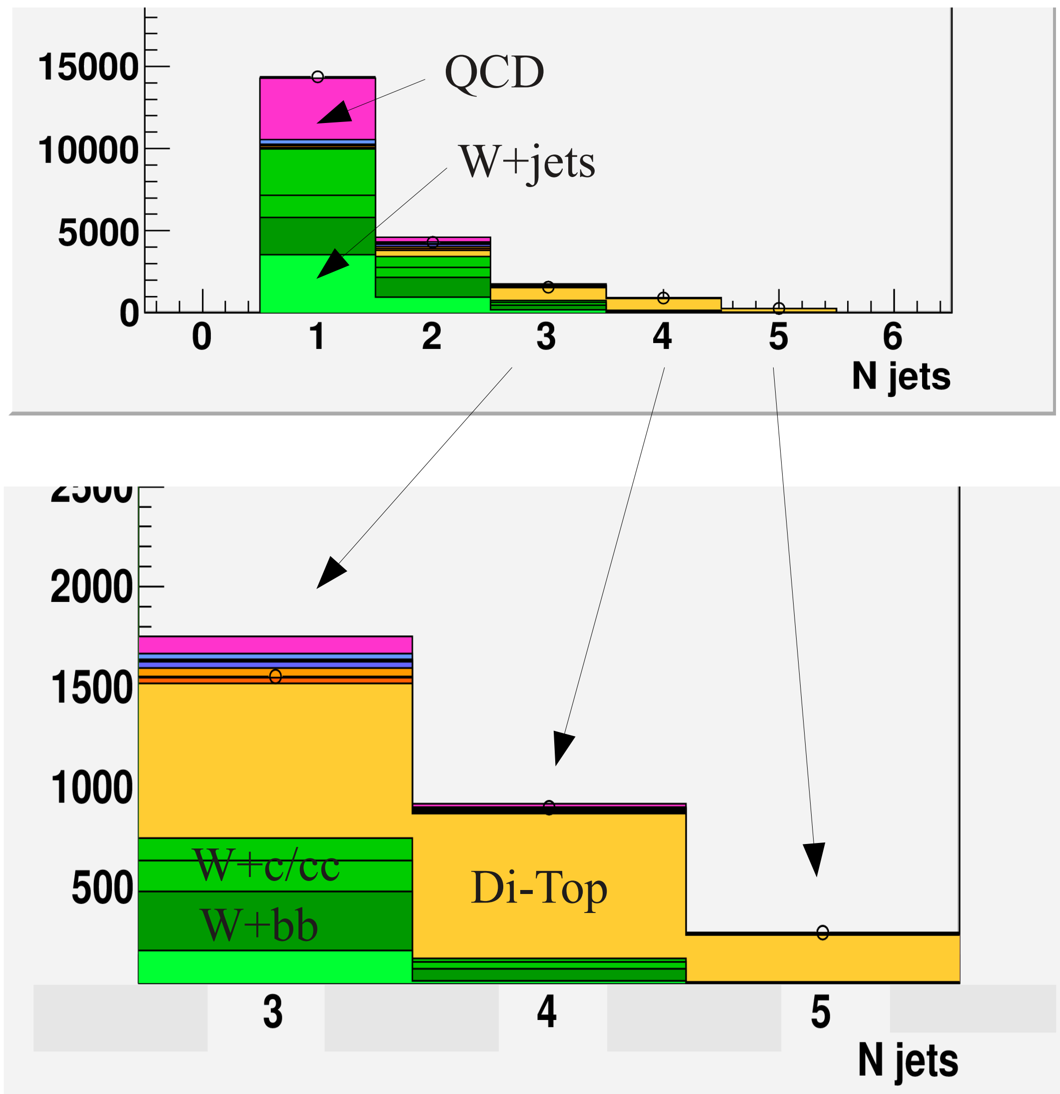
Calibration of 2012 b-Jet Tagger In Multiple Control Samples

- Calibration samples
  - Kinematic selection of W+4,5 jets events (di-top)
  - QCD dijets with low relative-pt electrons
    - Not an input to tagger
    - Semileptonic decay electrons
      - Enriched in b,c
    - Photon conversion electrons (New method)
      - Primarily u,d,s,c,g
    - Examine both e-jet and opposing side jets
- These samples produce correction factors and uncertainty estimates for simulated events
- Resulting b-jet tag-rate corrections: ~5%±4%





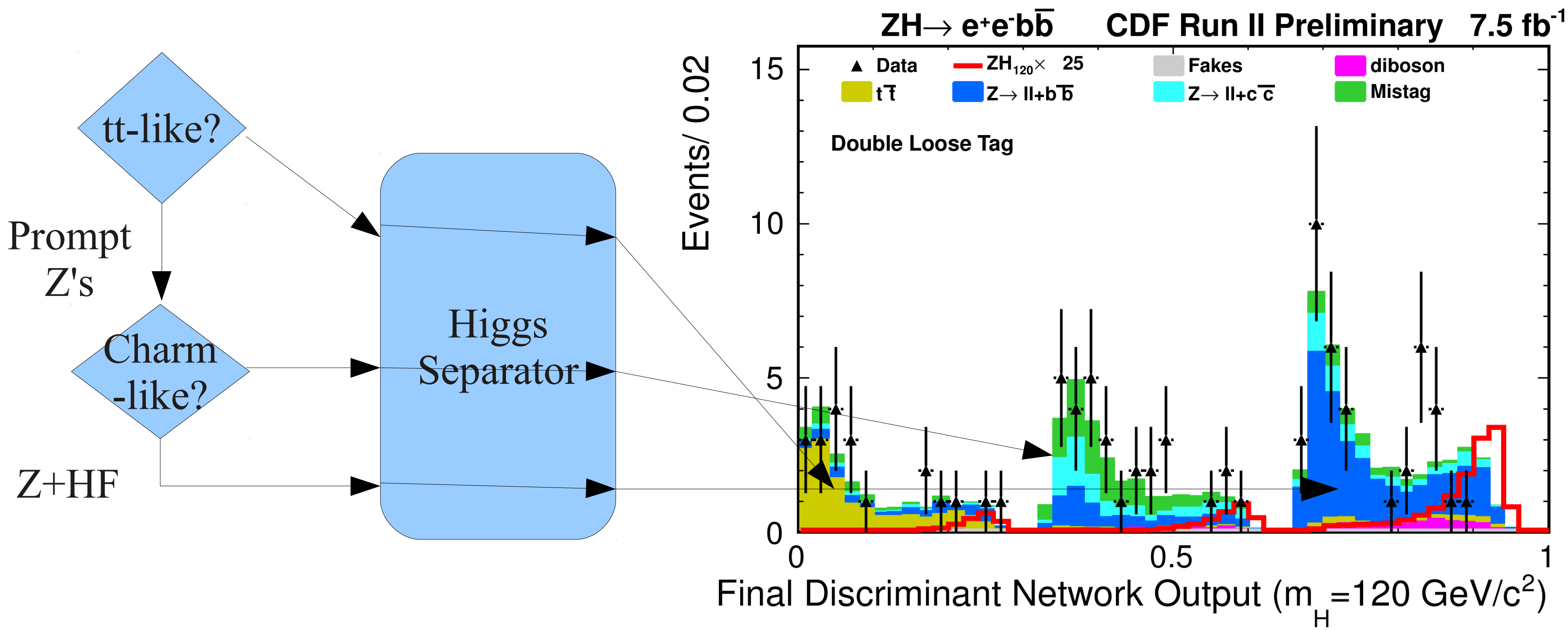
Deployment of 2012 NN b-jet ID



- After calibration of LF and b-jet responses
  - Examine data/MC yields in samples of W+jets
    - W+1jet: largely u,d,s,c,g
    - W+4,5 Jet: Di-Top
      - real b-jets
    - W+2,3: Mixture
  - Good agreement overall
    - ~40% K-factor uncertainties for W+jets

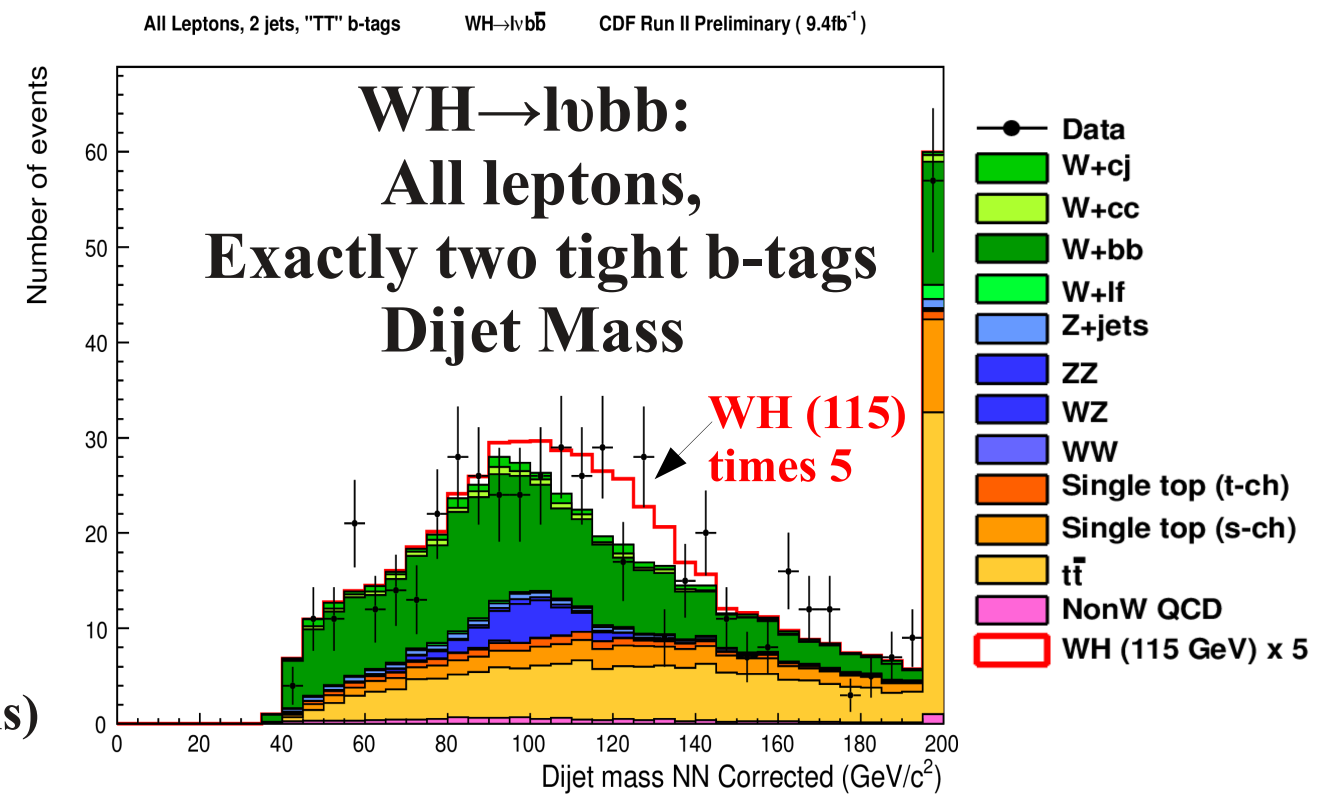
Improved Discrimination

- Both WH and ZH now performing Multi-stage discriminants:
- Gets background out from under signal
- Prevents the need for cuts
  - 4% gain in WH 3-jet bin (removing di-top)
  - ~7% gain in ZH by separating di-top and ZZ



WZ+ZZ: Validating Methods

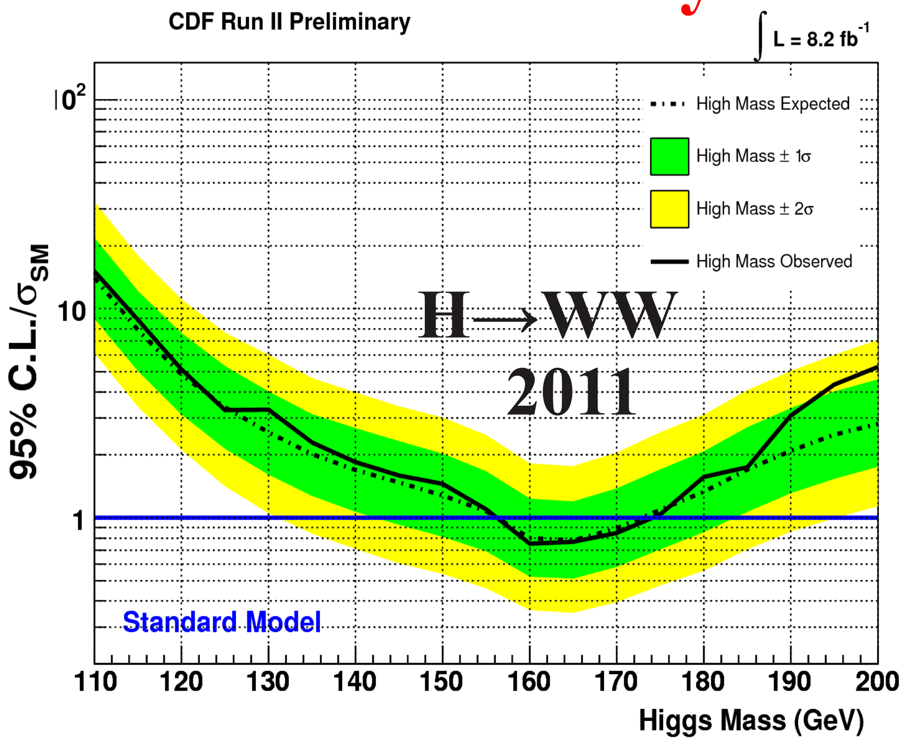
- **CDF detects SM-compatible semi-leptonic WZ and ZZ over a tagged background of dijets.**
  - llbb, lυbb, υυbb
  - Identical final state as a "90 GeV Higgs"
  - See upcoming talks at Moriond EWK and QCD by J. Vizan Garcia and J. Sekaric
- SM expected yields for WH,ZH,VH: (Summed over all subchannels)
  - ~215 WZ+ZZ
    ~591 H→bb (MH=90)
    ~84 H→bb (MH=125)

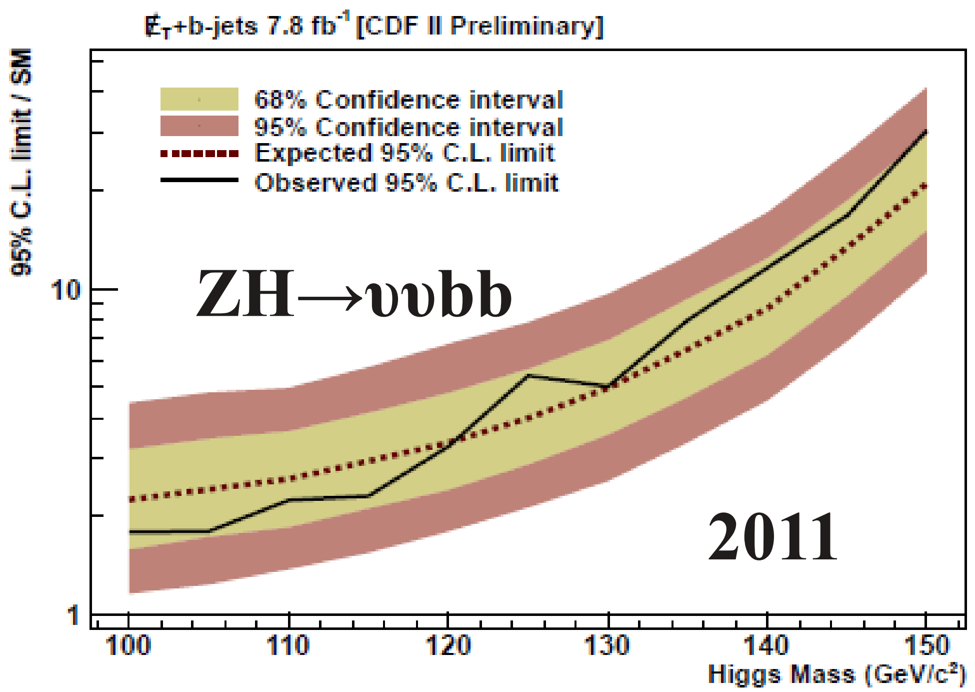


- Measured Cross Section to be released next week!
- Additionally, The newly generated 90 GeV Higgs signal MC will test our dijet modeling lower in Mjj than ever before.

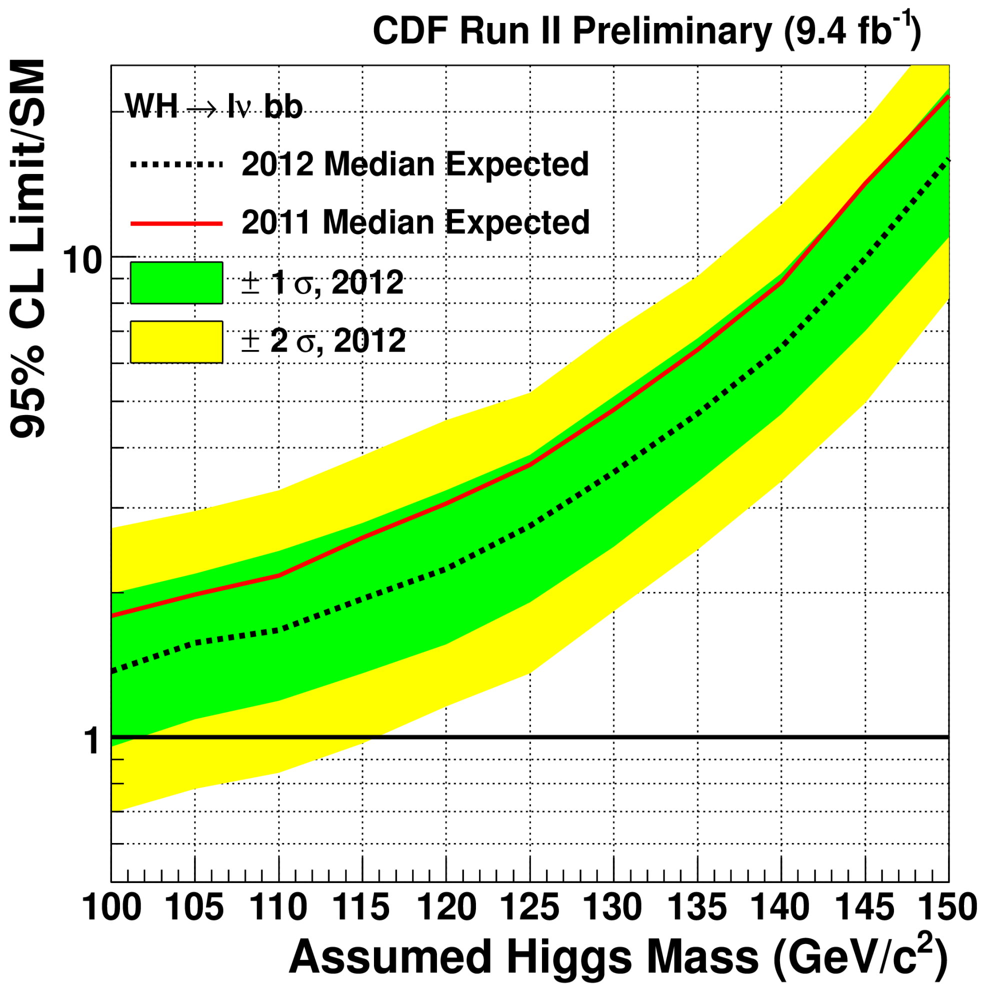
2011→2012 Limit Comparisons

- WW, METbb:
  - Biggest improvement is data update
    - ~11-12% sensitivity improvement everywhere
  - Overall behavior of limits should not dramatically change





2011→2012 WH Limit Comparisons



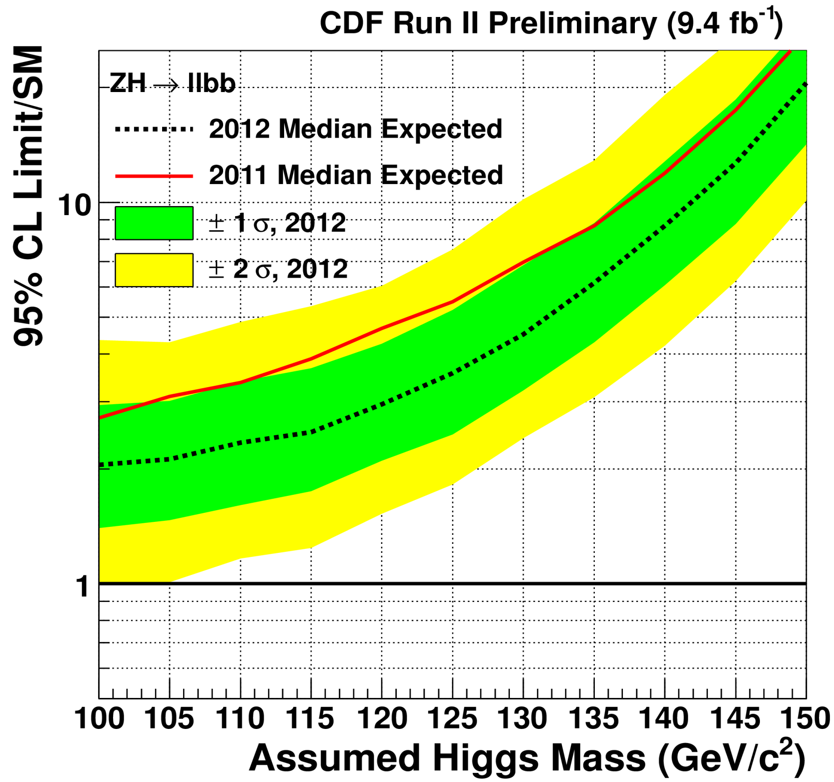
- Added data + improved tagging + new triggers + update of 3-jet bin:
  - 22.7→40.2 Expected Signal Events!!!
  - Roughly 30% stronger expected limits

ZH: Massive Improvements

- **ZH Analysis:**
  Total sensitivity improvement after systematics:
  58% @ MH=120
  - New Data: ~11%
  - Improved lepton Acceptance: ~8%
  - New b-tagger: ~12%
  - Other Improvements ~5-10 each%
    - Exclusive Z+2,3-jet categories
      - Previously had inclusive 2-jet category
    - Expert ZH, ZZ separator
    - Higher threshold on jets
    - Dijet mass resolution: 12%→9.6%
      - Improved MET calculation, less sensitive to underlying event

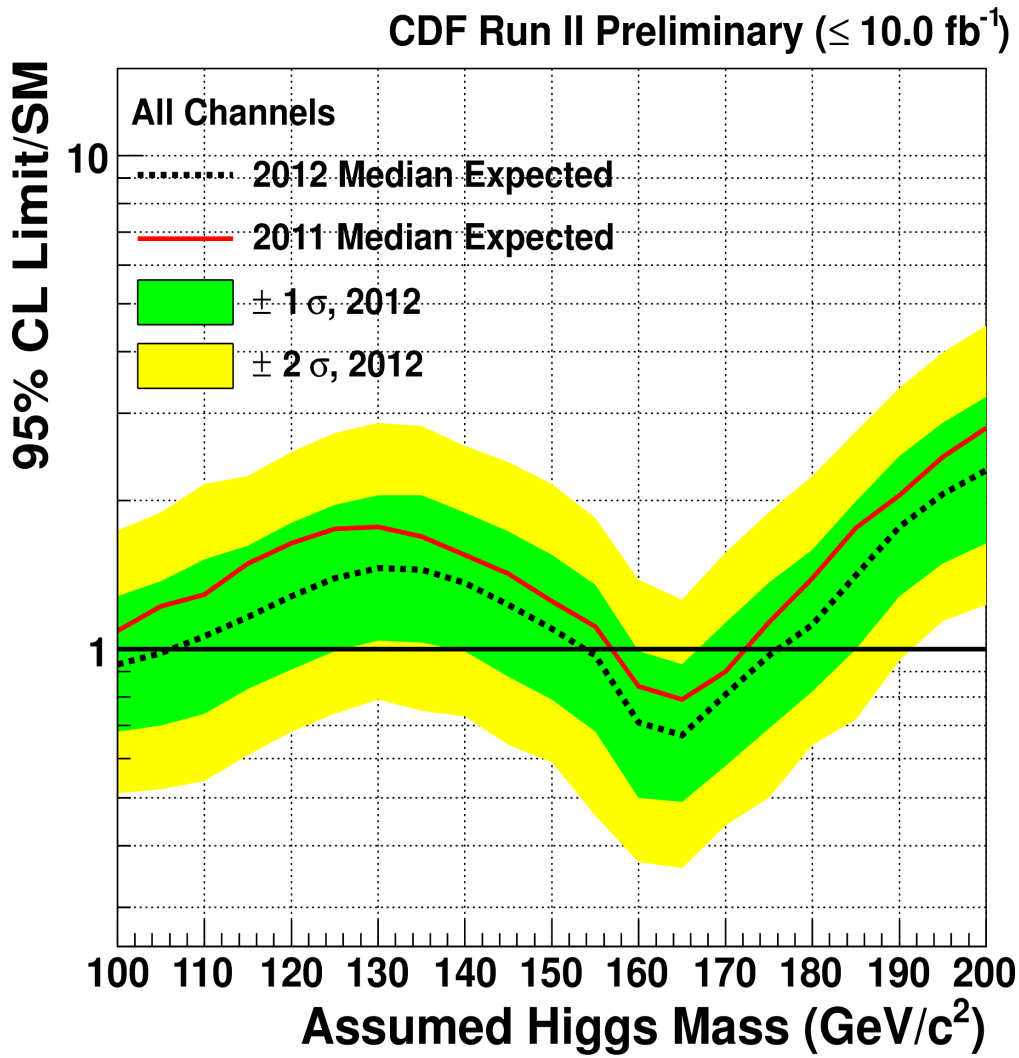
2011→2012 ZH Limit Comparisons

- Total Yield:
  - 5.3(1388)→7.2(1211) expected S(B) events.
    - Per-event Tagging Efficency was 60%, now is 69%
    - Better rejection of BG
  - Double integrated signal significance!
  - EPS 2011 Limit Median is at 2012 +1-σ!



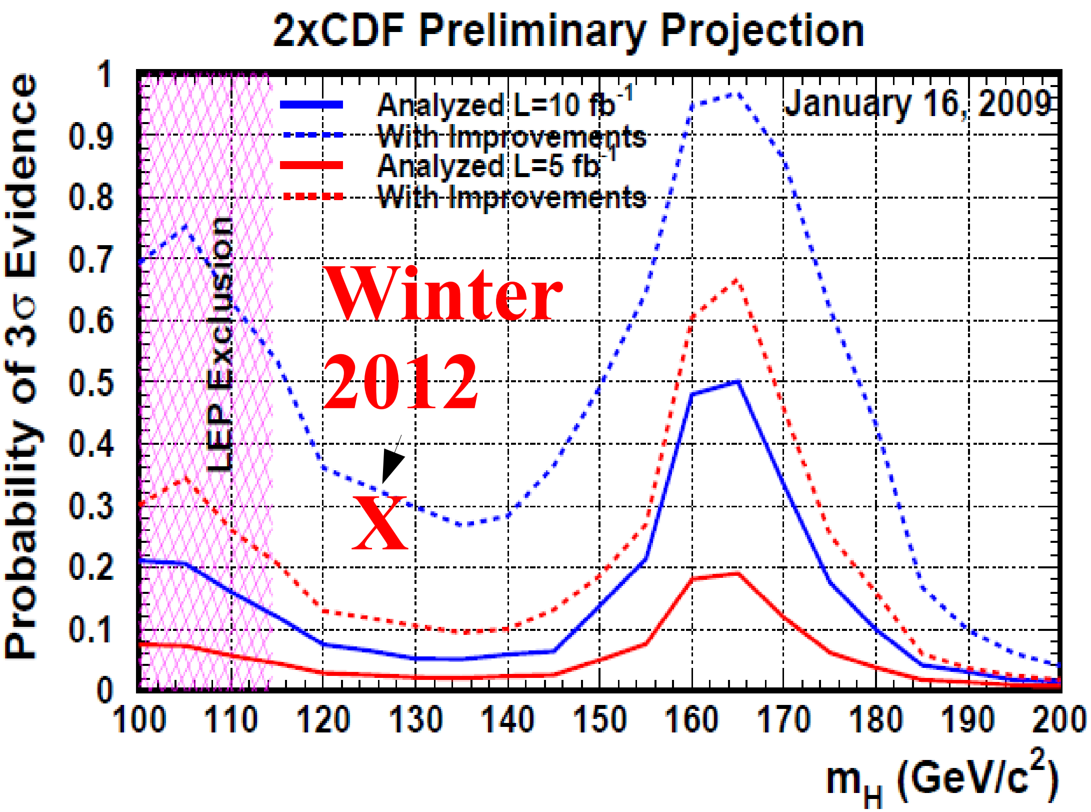
2011→2012 Full Limit Comparisons

- Major gains in expected sensitivity from data and tagging
  - ~30% from 115-125
  - ~15% at high mass
  - CDF expects to be sensitive to at most √2*SM @ MH=130
  - Expects to exclude [152-175] GeV



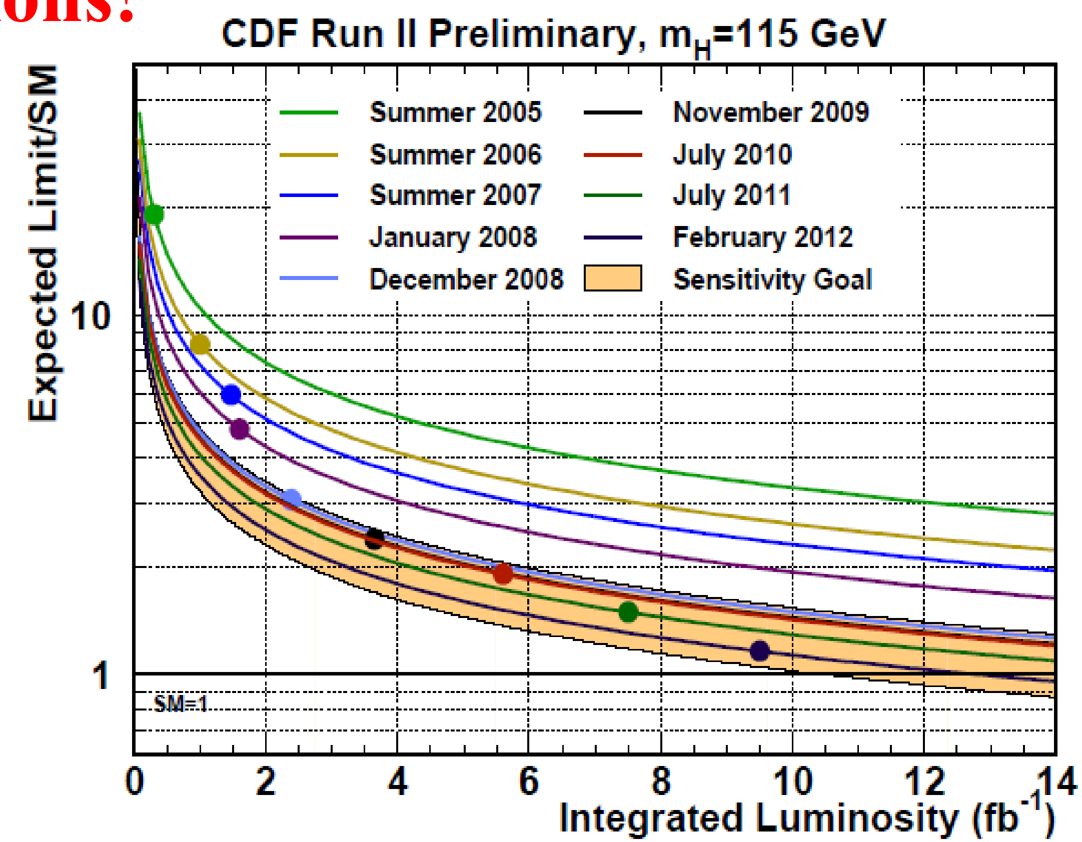
Coming Soon

- **Next Week:**
  - Release observed limits next Weds at Moriond!
  - Tevatron Combination talk at Moriond EWK by Wade Fisher!
  - Potential for ~1xSM exclusion sensitivity
- **Near Future**
  - Consolidate improvements across all channels
    - >5% improvement in 125 GeV sensitivity still possible
  - Publish PRL/PRD/NIM for analyses/methods



Conclusions

- The CDF Collaboration has produced Higgs searches with expected sensitivities
  a factor of 2 better than 2007
  beyond luminosity additions!
- CDF is sensitive to <√2xSM Everywhere
  - 2XCDF would have >25% chance of 3-sigma!
- Tevatron Leads in H→bb
- The Tevatron full dataset combined Higgs search will be exciting!



Conclusions

- For additional details see
  - Tevatron: http://tevnphwg.fnal.gov/results/SM_Higgs_Winter_12/
  - CDF: http://www-cdf.fnal.gov/physics/new/hdg/Results.html
  - D0: http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.html

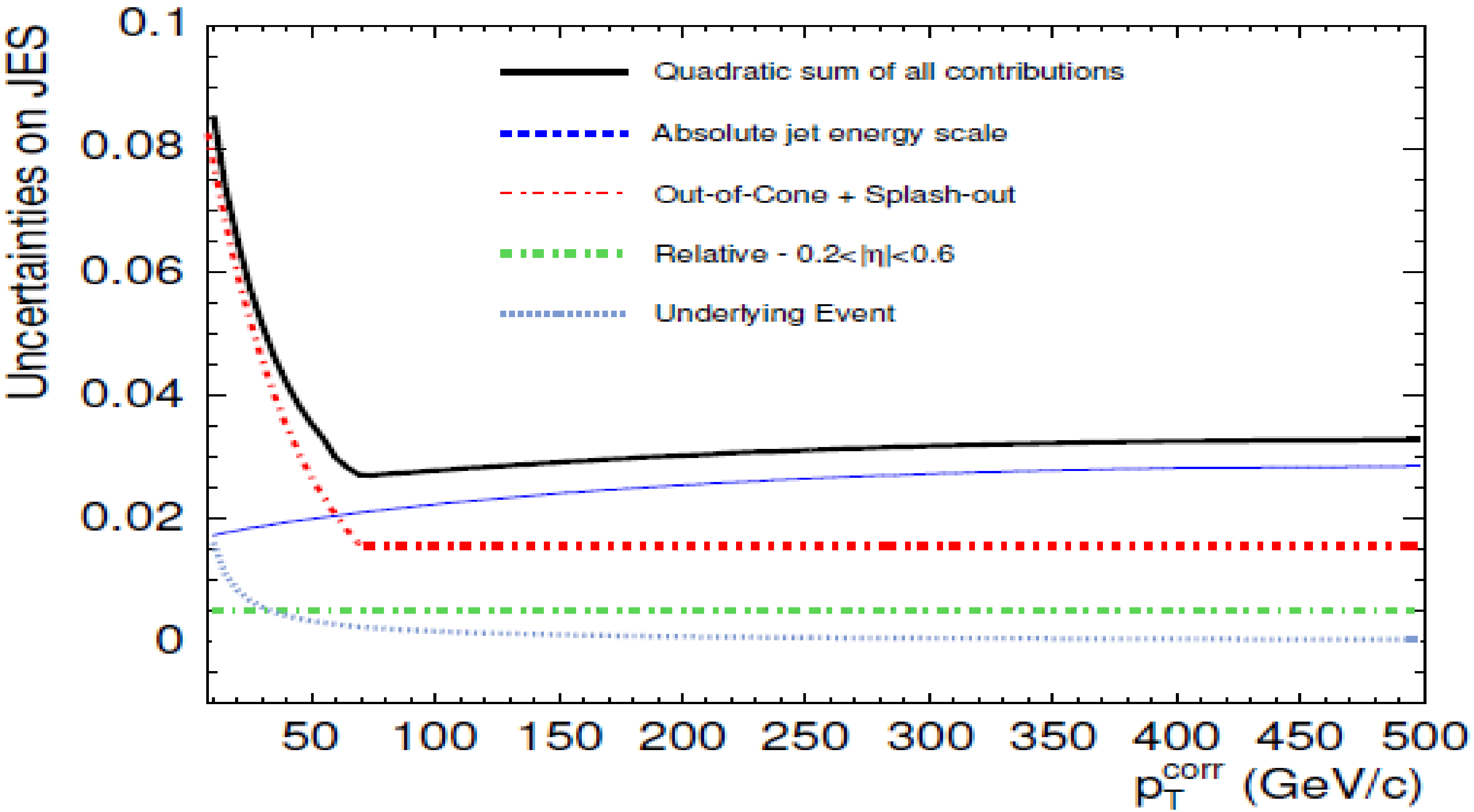
- Thanks to everyone at CDF who contributed to this update!
- Bigger thanks to everyone who designed, built, or operated CDF!
- FNAL Computing Division: Thanks for all the computing power and software!
- FNAL Beams Division: Thanks for all the collisions!
- Photographs of Fermilab and its wildlife were taken by Reidar Hahn, FNAL VMS

Thank you for your attention

Questions?

CDF JES

- JES



Uncertainties on JES
0.1
0.08
0.06
0.04
0.02
0
Quadratic sum of all contributions
Absolute jet energy scale
Out-of-Cone + Splash-out
Relative - 0.2<|η|<0.6
Underlying Event
50
100
150
200
250
300
350
400
450
500
p_T^{corr} (GeV/c)

PDFs

- PDFs

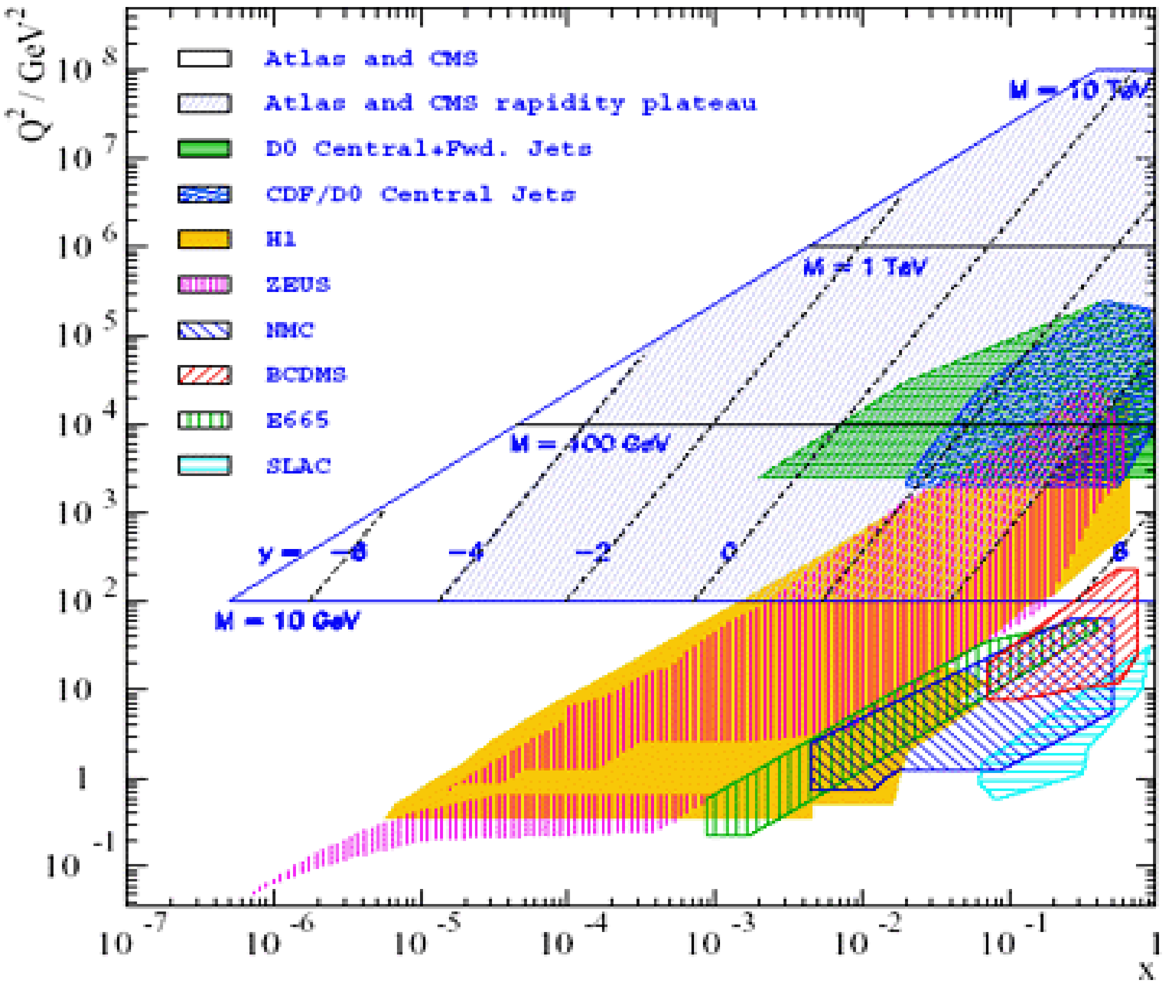
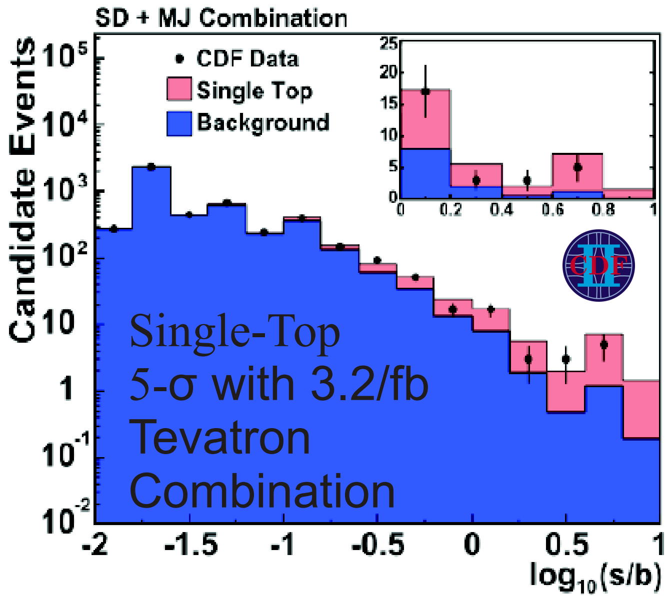
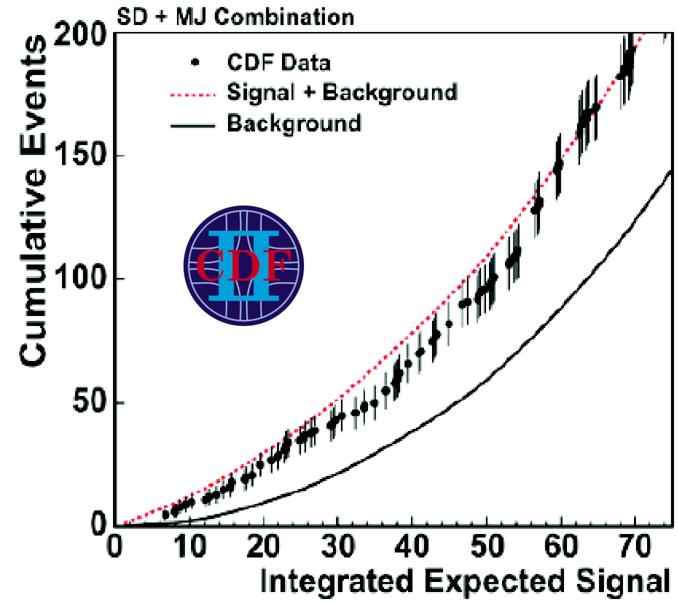


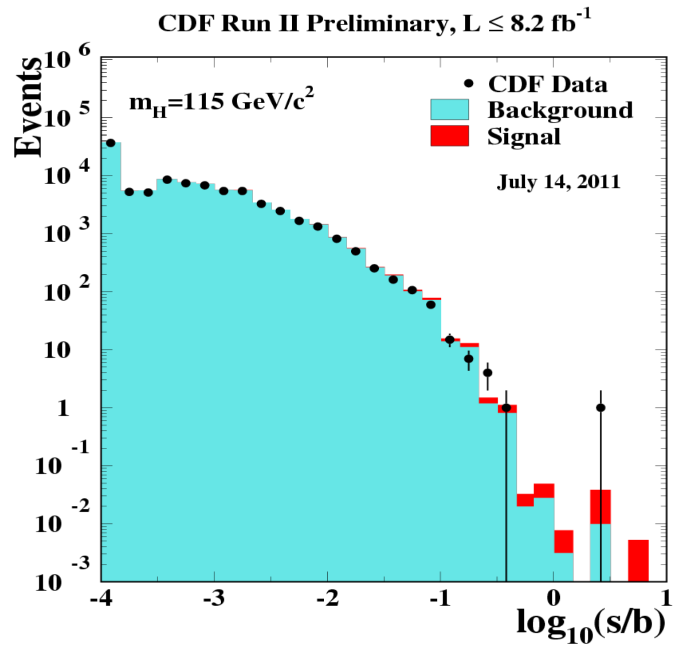
FIG. 1: Kinematic coverage of the DIS and collider pp-$p\bar{p}$ experiments. For pp and $p-\bar{p}$ colliders, the Bjorken x_1 and x_2 of the interacting quarks are related to the mass M of the Drell-Yan pair and its rapidity y as $x_{1,2} = M/\sqrt{S}\exp(\pm y)$ where S is the center of mass energy squared for the experiment.

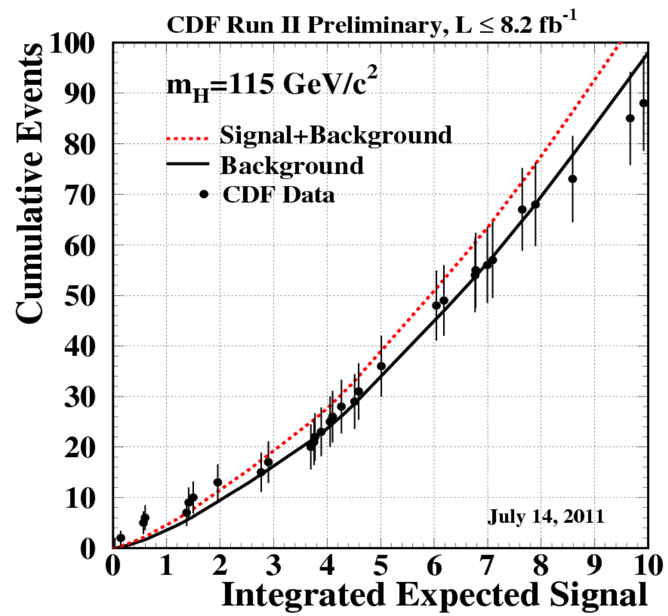
Comparing The Higgs Search To Single-Top Discovery

- Same machinery was run for the Single Top obs/discovery 2008-9
- Currently going through same steps with WZ/ZZ→ leptons+HF to validate low-Mass Higgs Search









Comparison To EWK Diboson