Search for the Standard Model Higgs in the ZH $\rightarrow l^+l^- b\bar{b}$ Channel

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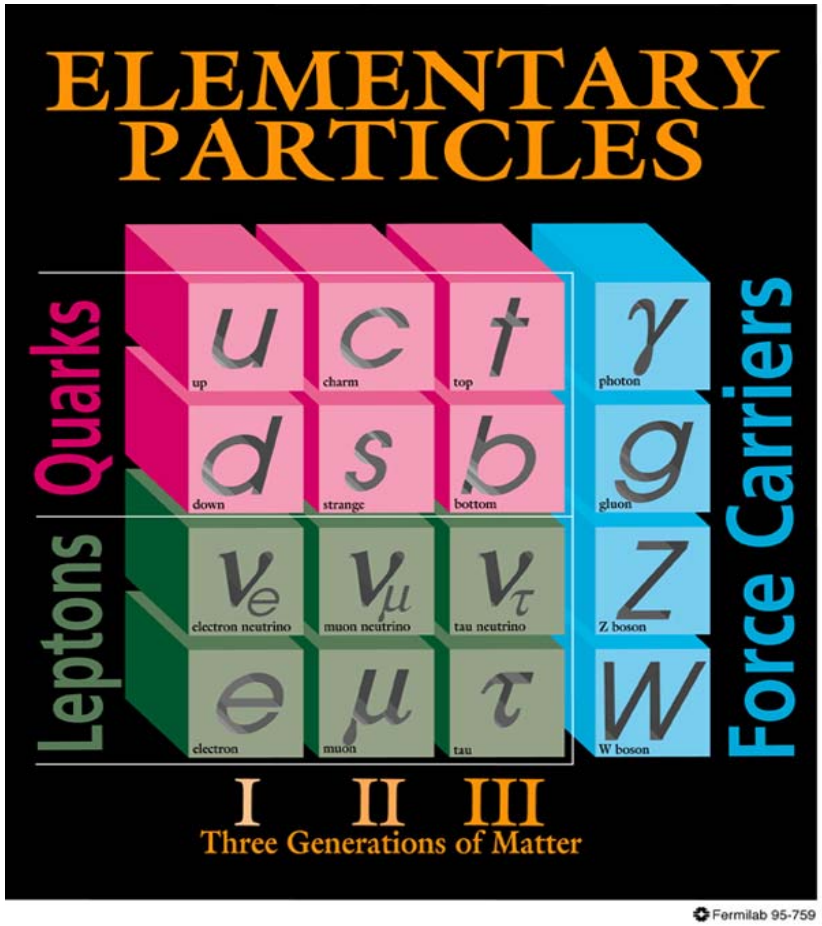
Outline

- Why the Higgs?
- Tevatron and CDF II
- Event selection
- Improving signal-background separation
  - Neural network jet corrections
  - Neural network classification
- Results
- Prospects for future

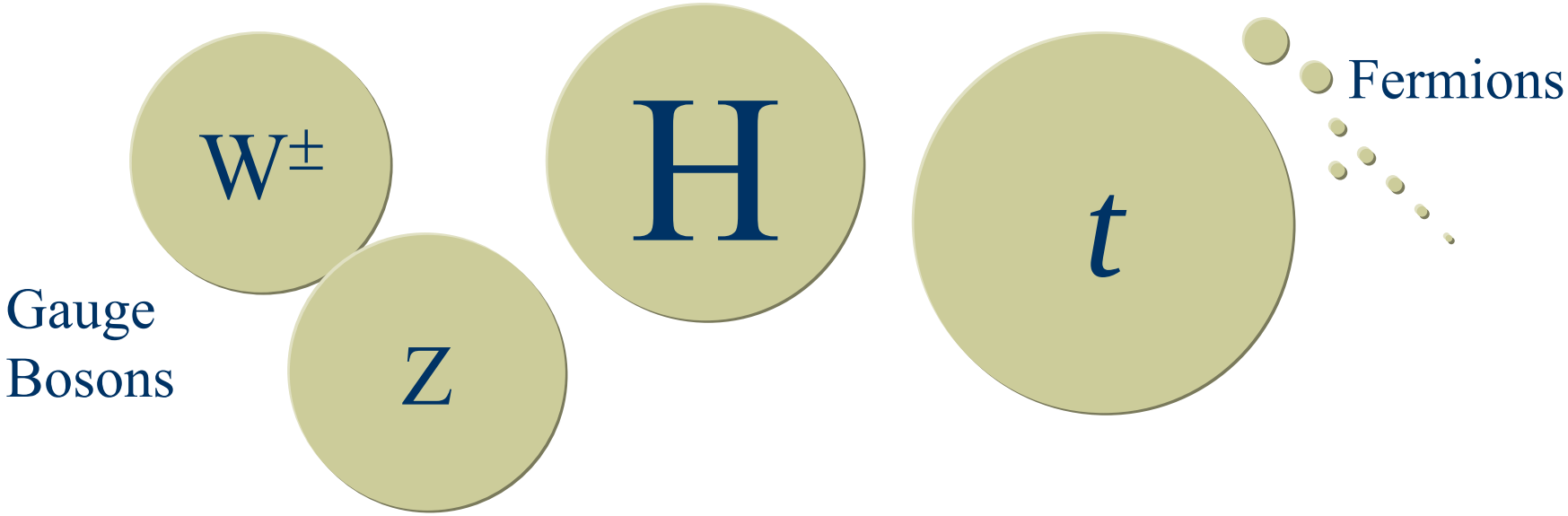
Standard Model



- Excellent description of particle physics
  - All observable parameters within 3 σ of expectations
- Combines weak, EM, and strong forces.
- Electrodynamics and weak forces combined into SU(2) x U(1) symmetry
- But . . . W and Z bosons required to be massless

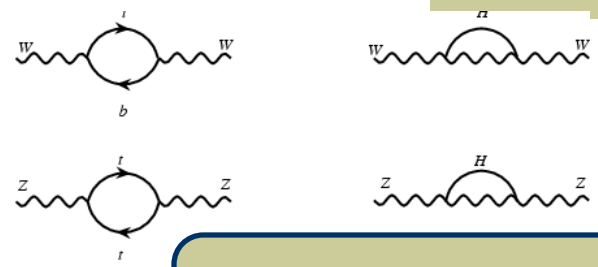
Enter the Higgs Mechanism

- The Higgs field breaks electroweak symmetry and consequently adds masses to the gauge bosons
  - Mass is directly proportional to interaction with Higgs field
- Fermions similarly can attain mass with interaction with Higgs
- As a consequence of Higgs field, a new spin 0 boson is predicted



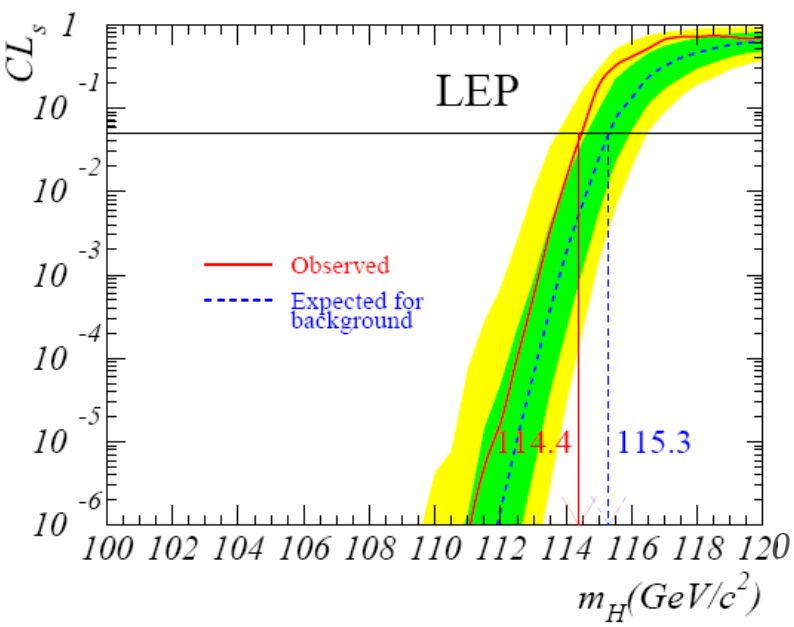
Constraints on the Higgs Boson

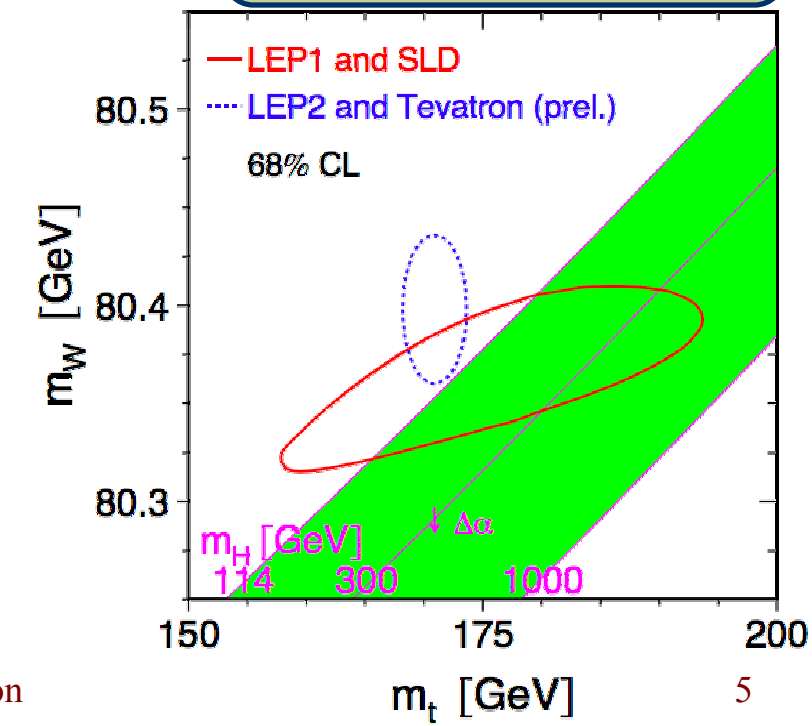
- Higgs searches ongoing for last 30 years
- **Direct search at LEP:**
  $M_{Higgs} > 114.4$ GeV/c^2 @ 95%
- **Indirect searches:** including new Tevatron precision measurements
  - **M_{top}= 170.9 ± 1.8 GeV/c^2**
  - **M_W=80.398 ± 0.025 GeV/c^2**



m_H = 76 +33 -24 GeV/c^2

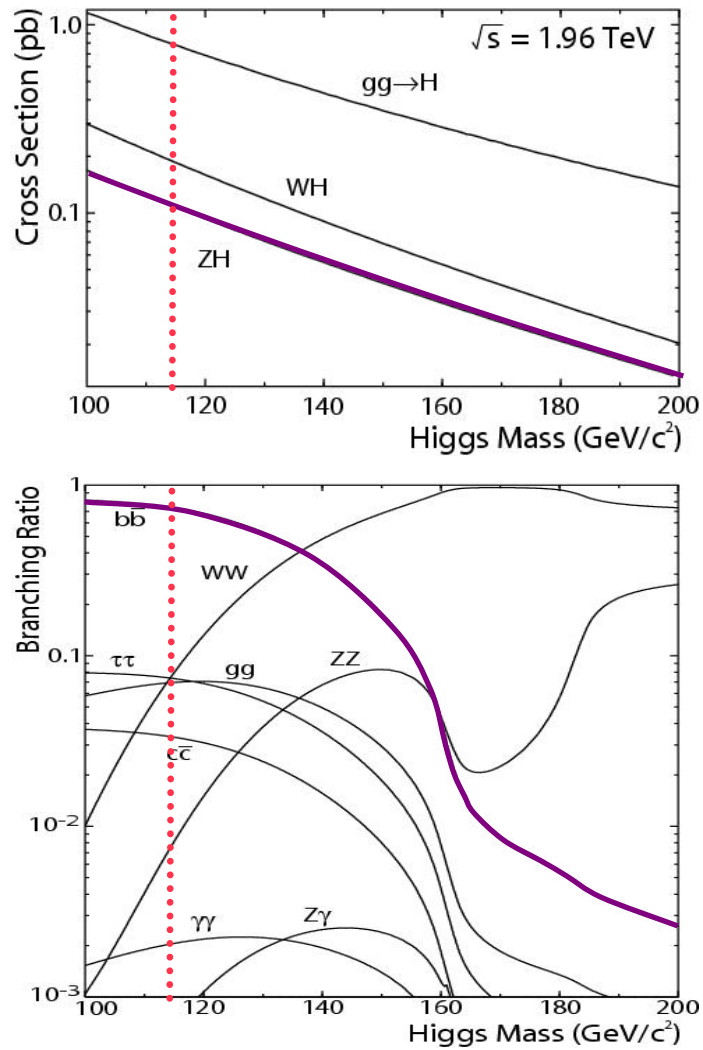
m_H < 144 GeV/c^2 @ 95 % CL





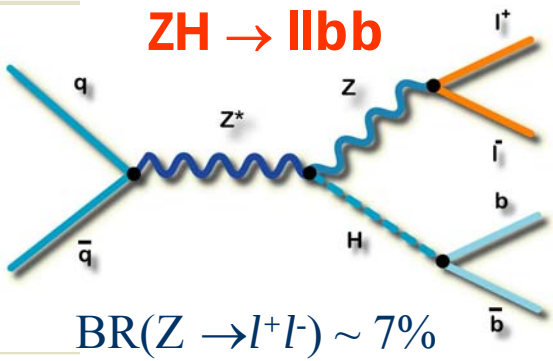
Higgs Boson at the Tevatron

- Higgs Boson interact with other particles proportionally to their mass
- At Higgs masses less than 135 GeV/c^2, $b\bar{b}$ is the primary Higgs decay
- Associated production (WH/ZH) of Higgs has much lower backgrounds than direct production



Higgs at the Tevatron

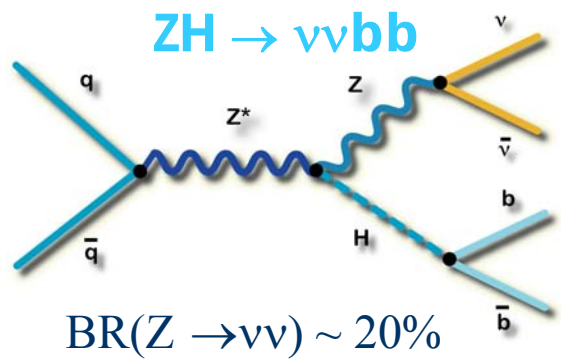
ZH → llbb



BR(Z →l^+l^-) ~ 7%

σ(ZH) ~ .1 pb

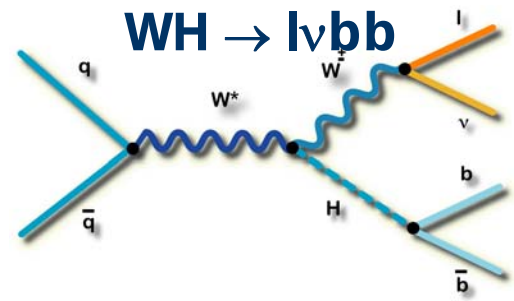
ZH → ννbb



BR(Z →νν) ~ 20%

σ(ZH) ~ .1 pb

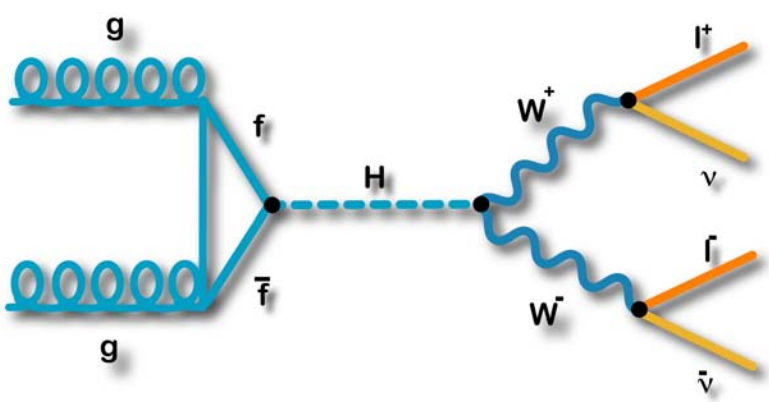
WH → lνbb

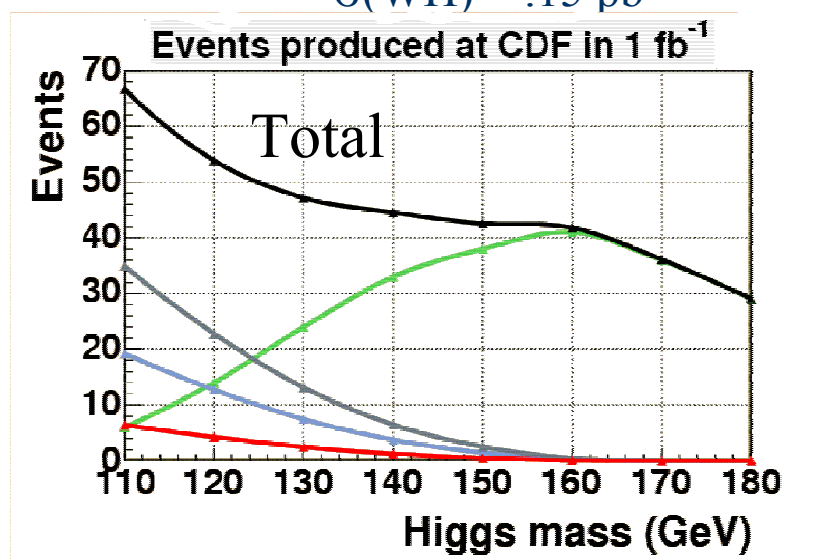


BR(W →lν) ~ 22%

σ(WH) ~ .15 pb

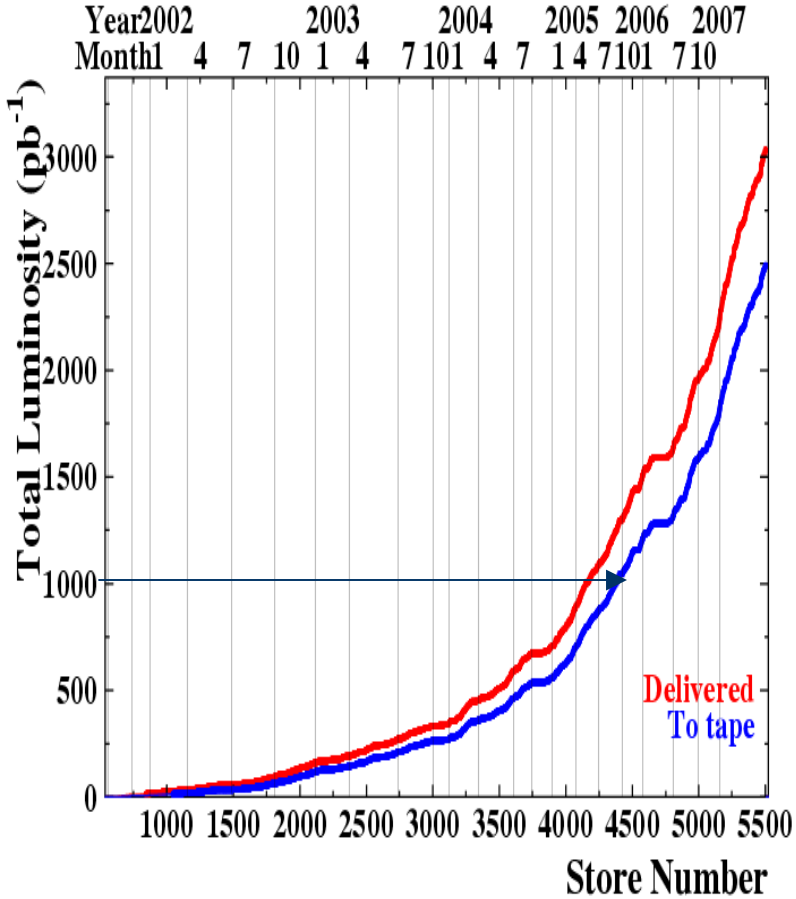
gg → H → WW → lνlν





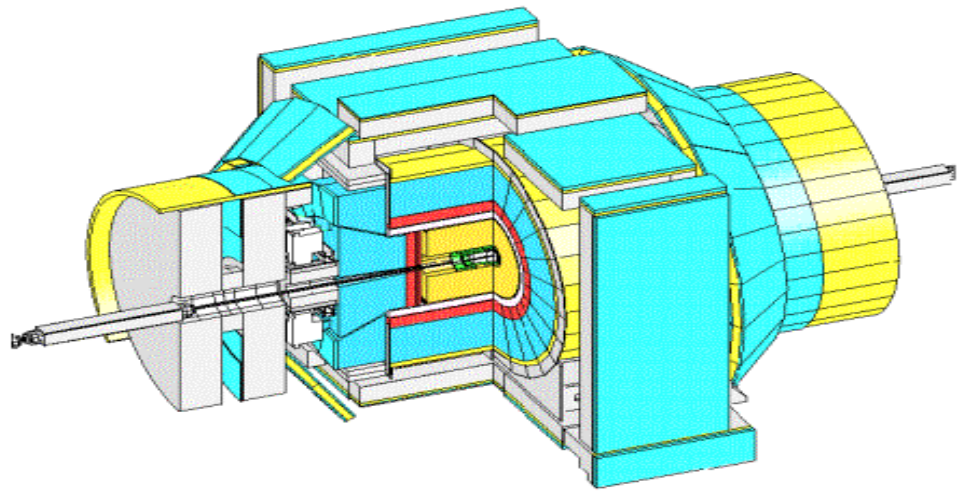
Tevatron Run II 2000-2009 (est.)

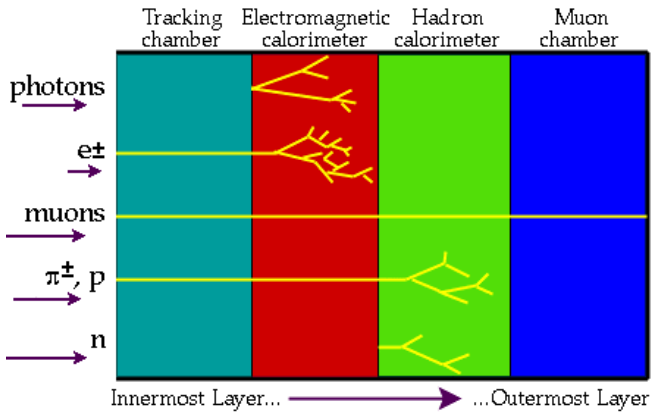
- Proton-Antiproton collider
- Center of mass energy 1.96 TeV
- Current Peak Instantaneous Luminosity:
  $286*10^{30}$ cm^{-2}/s
- Integrated Luminosity:
  - 3.0 fb^{-1} Delivered
  - 2.5 fb^{-1} on tape at CDF
- Projected total luminosity for Run II: 6-8 fb^{-1}
- This analysis 1 fb^{-1}



CDF II Detector

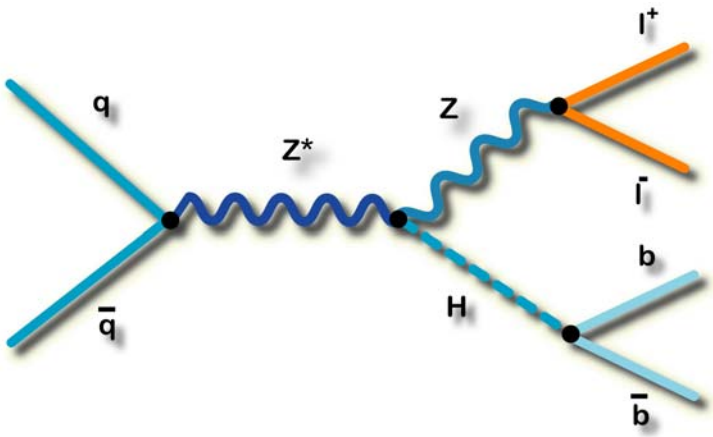
- Forward-background and radially symmetrical
- Multipurpose: Run II achievements
  - First observation of B_s mixing - 17.77 ± 0.10 (stat.) ± 0.07 (syst.) ps^{-1}
  - World's most precise single measurement of the *W* boson mass (80413 ± 34 ± 34 MeV/c^2)
  - World's most precise single measurements of top quark mass (170.9 ± 1.6 ± 2.0 GeV/c^2)
  - Many other work in electroweak, QCD, b hadrons, top quark, and exotic physics

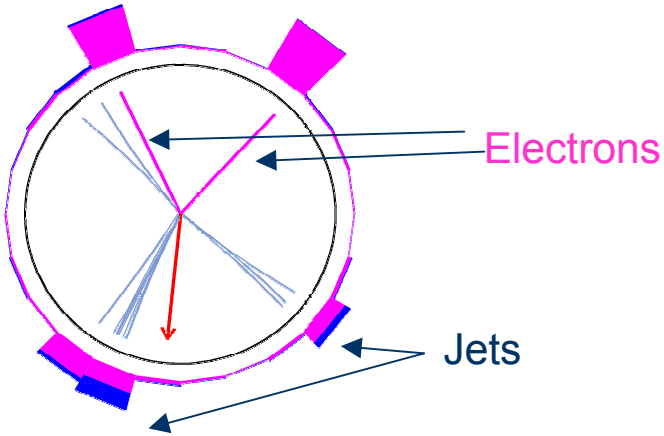




Features of ZH→l^+l^-bb

- The signal is small
  For $M_H = 120$ GeV/c^2
  - $\sigma(ZH) \sim .1$ pb
    - ~100 events/1 fb^{-1}
  - BR($Z \rightarrow l^+l^-$) = 6.8%
    - ~7 events/fb^{-1} remaining
  - BR($H \rightarrow bb$) ~ 70%
    - ~5 events/1fb^{-1} remaining
- But so are the backgrounds
- And all final products are measurable
  - Find two leptons that form a Z boson
  - Find two or more jets from b-hadrons





ZH MC simulation

Guiding Goals of this Analysis

- Try to push the limits of basic event selection
  - Increase lepton acceptance
- Use innovative techniques to separate signal from backgrounds

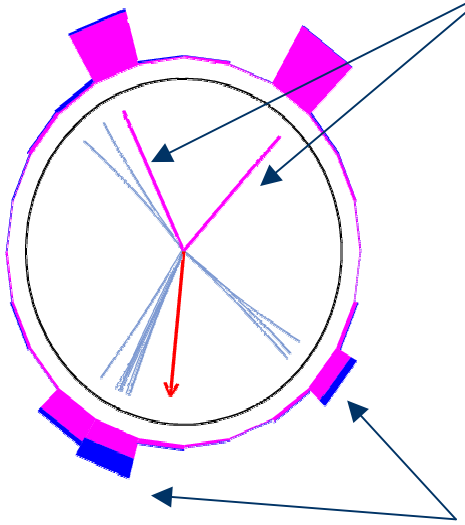
Steps of the Analysis

- Find events with a Z and b-tagged jets
- Separate events into two loose and exclusive single tight b-tags
- Correct jet energy using a neural network

  (NN jet corrections)
- Use event kinematics in an optimized 8 input 2 output artificial neural network

  (NN classification)
- Fit neural network output shape to find expected and measured upper limit

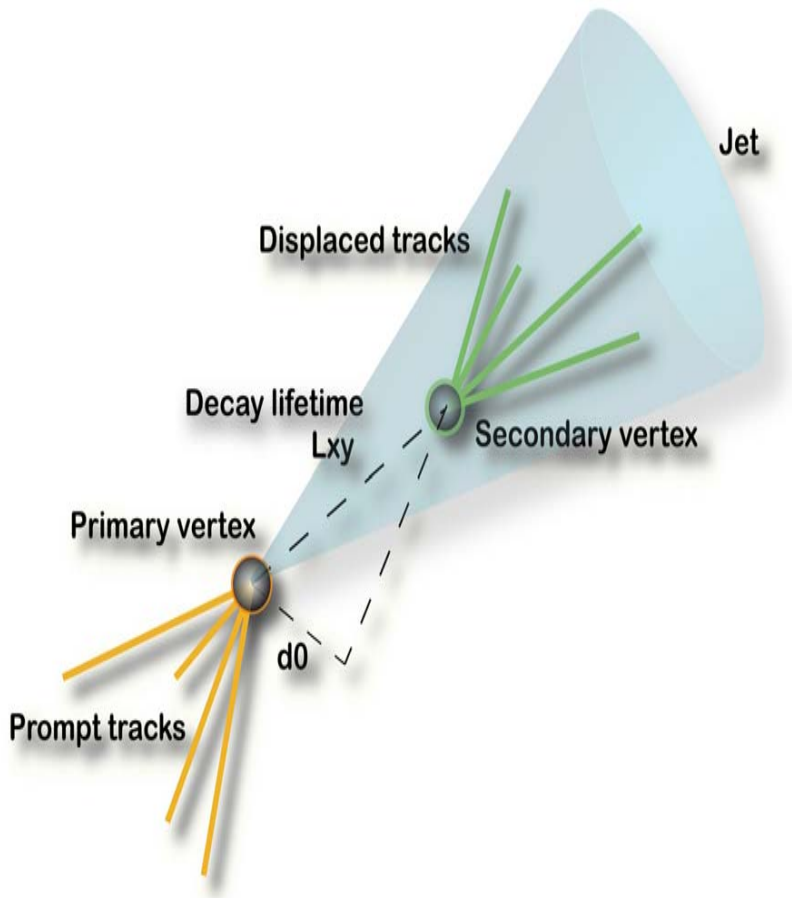
Event Criteria



- 2 or more jets
  - 1st Jet E_T >25 GeV
  - Other jets E_T>15 GeV
  - $|\eta|< 2$
  - B-tagging requirement

- "Tight" lepton is required for event to be triggered
  - $|\eta| < 1$
  - E_T (P_T) > 18 GeV(/c) for electrons (muons)
  - Other fiducial requirements
    - Isolation
    - Had/Em of electrons
    - Calorimeter energy deposition of muons
- "Loose" lepton Selection
  - Lower E_T (P_T) requirement
  - Looser requirements
- Reconstruction as Z
  - Same flavor opposite sign leptons
  - $76 < M_{ll} < 106$ GeV/c^2
- Looser lepton criteria yields ~70% signal events

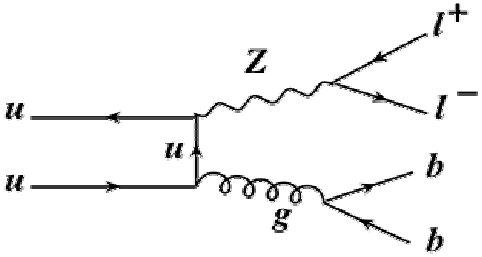
B-tagging

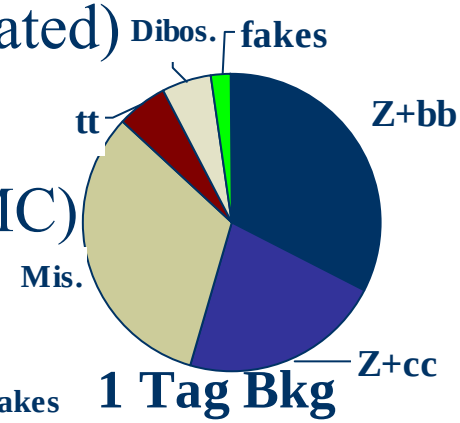


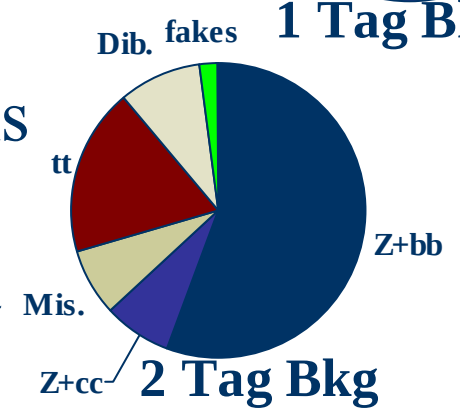
- Secondary Vertex Algorithm at CDF
  - 40 - 50 % efficient (tight, loose)
  - 0.5 - 1.5 % fake rate from light jets
- Can take advantage of the Higgs decaying to bb
  - from ~1:1000
  - to ~1:100
- A separate channel for events with 2 b-tags
  - Most fake b-jets removed

Background Contributions

- $Z \rightarrow l^+l^- +$ jets
  - $Z \rightarrow l^+l^- + bb$ (MC)
  - $Z \rightarrow l^+l^- + cc$ (MC)
  - $Z \rightarrow l^+l^-$ + other jets ("mistags"-data simulated)
- $t\bar{t} \rightarrow WbWb \rightarrow l\nu b\, l\nu b$
  - Dilepton events within Z mass window (MC)
- Diboson - (2 leptons + 2 jets - MC)
  - ZZ, ZW, WW+2p
- QCD background - "fake" leptons
  - Muons modeled by same-sign data
  - Electrons – estimated using jet data

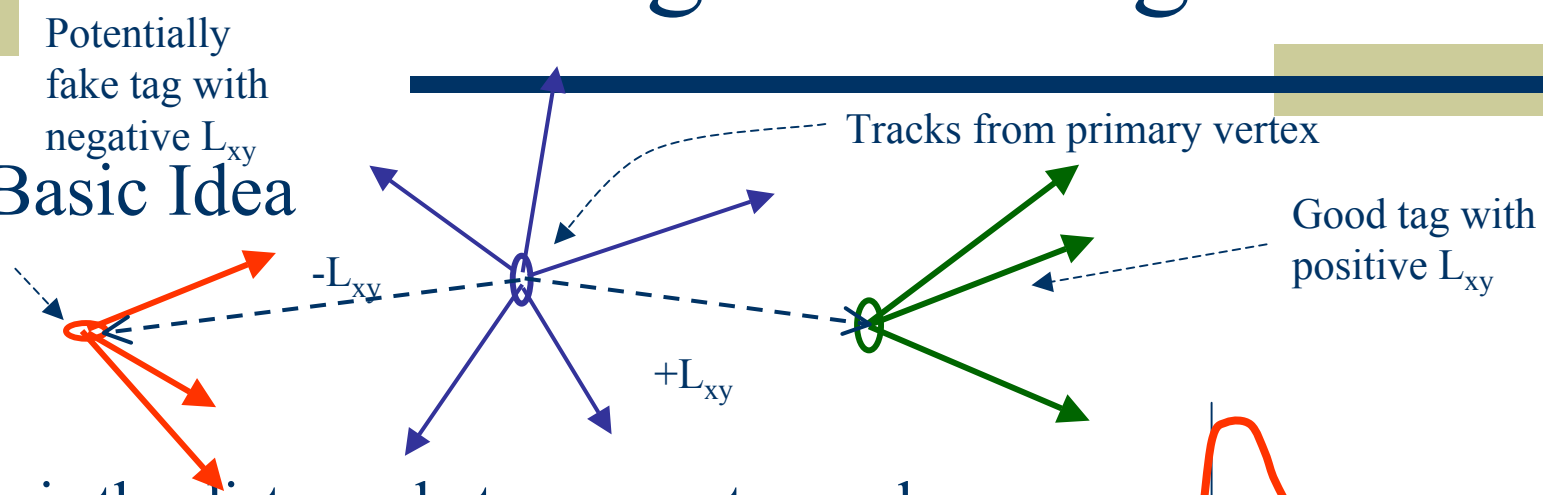




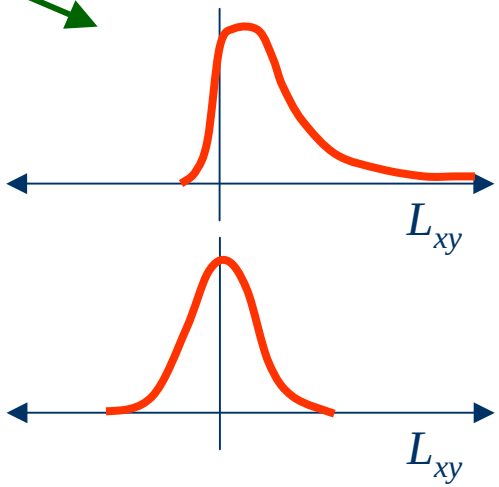


Mistag Modeling

- Basic Idea



- L_{xy} is the distance between vertex and primary in *x-y* plane
- Positive Tags: $L_{xy} > 0$
- Light flavor jets: slightly more likely to have positive than negative L_{xy}



- CDF has made a function based on jet properties to estimate likelihood of jets being "mistagged"
  - Higher energy Jets are **more** likely to be mistagged

Fake Electron Estimations

- Jet → Electron fake rate function for loose electrons
  - Use jet only data
  - Calculated as a function of Jet E_T
  - Separate functions for Central and Plug electrons
- Steps to eliminate possible real electron contributions
  - Real electron in jet data would greatly inflate our electron fake rate
  - Do not use trigger jet to calculate error function
    - Eliminates biggest source of electrons from $W \rightarrow e\nu$
    - Missing E_T cut < 15 GeV

Events Expected in 1 fb^{-1}

Backgrounds

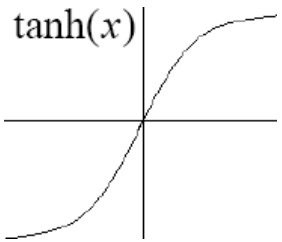
Background	2 Tags	1 Tags
tt	2.8	5.2
Diboson	1.5	5.2
fakes	0.2	2
Z + bb	6.3	35
Z + cc	1.0	22
Mistags	1.0	32
Total bkg.	12.8	101
Data	11	100

Signal

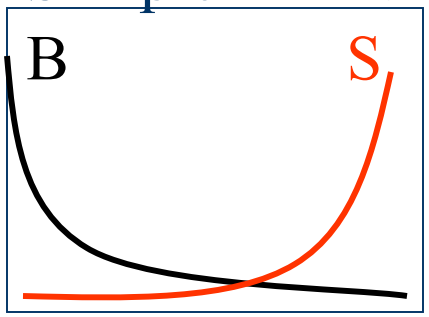
Higgs Mass (GeV/c^2)	σ(ZH)*BR (H $\rightarrow$ *bb*) SM	2 Tags	exclusive 1 Tag
100	0.14 pb	0.41	0.87
110	0.092 pb	0.32	0.65
115	0.080 pb	0.28	0.56
120	0.061 pb	0.23	0.45
130	0.037 pb	0.15	0.27
140	0.017 pb	0.09	0.15
150	0.007 pb	0.03	0.06

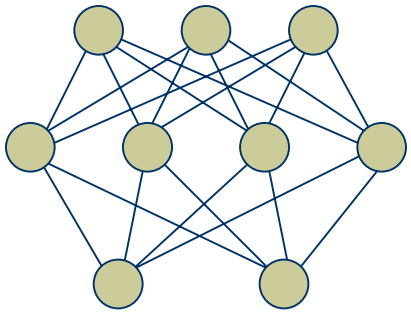
Introduction to Artificial Neural Networks

- Designed to mimic a brain
  - Interconnected nodes
  - Connections "learned" based on experience
  - Each nodes "fires" based on incoming information
- Has been shown to be able to reproduce any non-linear function



Sample 1-D NN

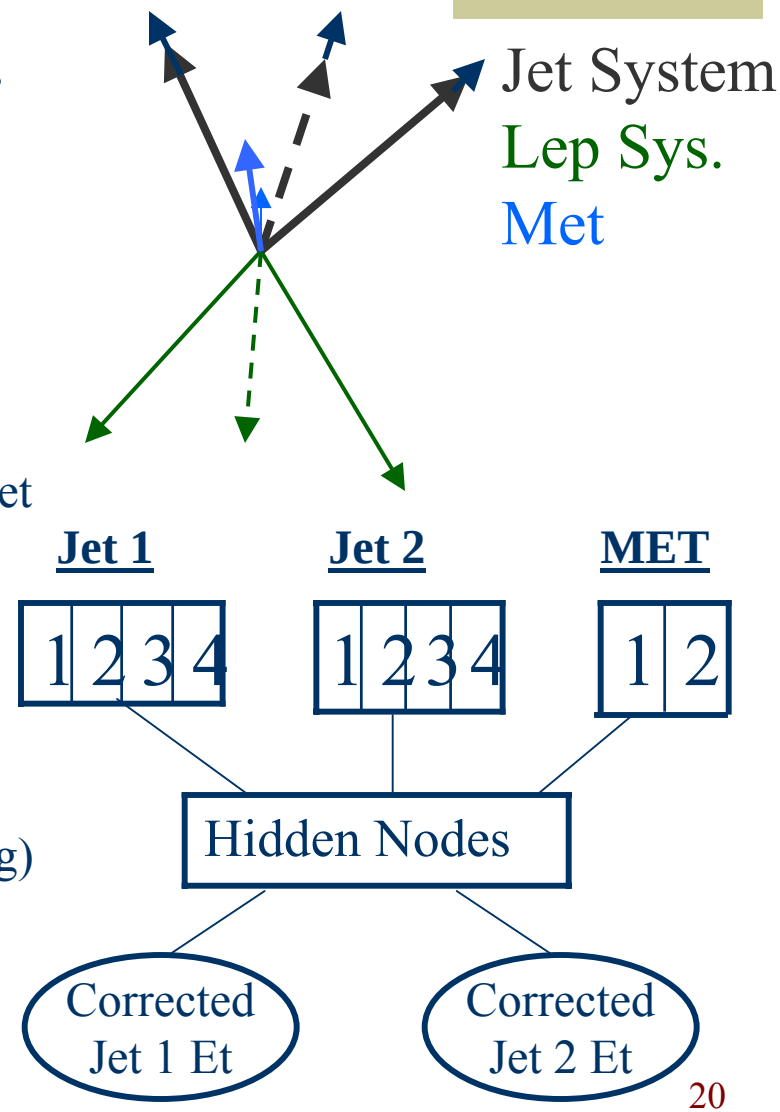




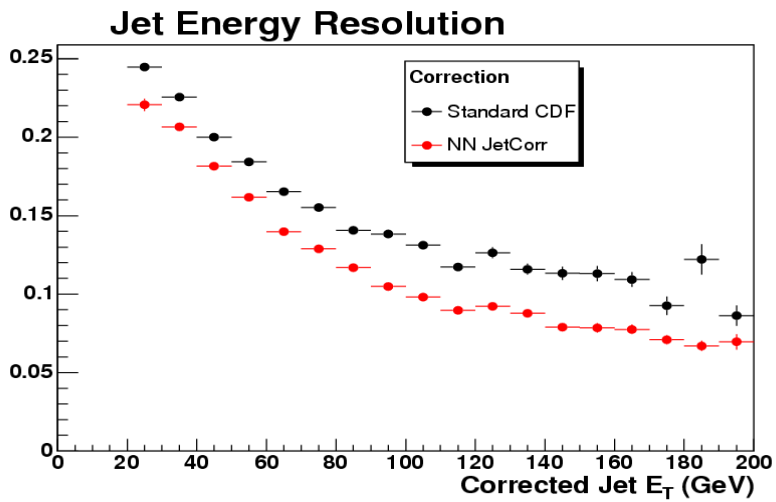
- Train neural networks toward target outputs.
  - Look to reduce error
  - $E = 1/N_P \sum (\vec{T} - \vec{O})^2$
  - Repeat based on previous performance
- Adjustable parameters
  - Weight of each nodes inputs
  - Threshold for "firing" of each node

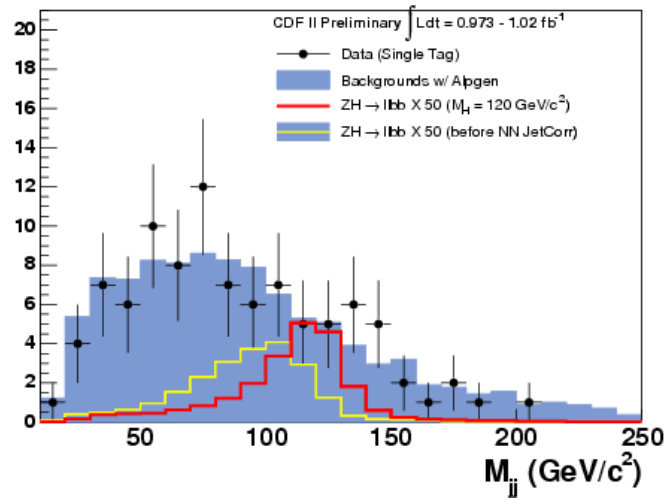
NN Jet Corrections

- Training to match corrected jet energies to generator level parton energies
- Input Variables from 2 b-quark jets
  - **1** Corrected Jet E_t
  - **2** Detector η
  - **3** Jet φ
  - **4** MET projected on axis of individual jet
- Total event MET and MET φ
- Two output nodes - corrected jet energies
- Create single NN for all masses
  - (H_{mass} from 60-180 GeV used in training)
  - ttbar used in training as well



NN Jet Energy Correction Comparison





M_{jj} Ave Std.	2-tag	1-tag
NN JetCorr	11%	14%
Standard	18%	22%

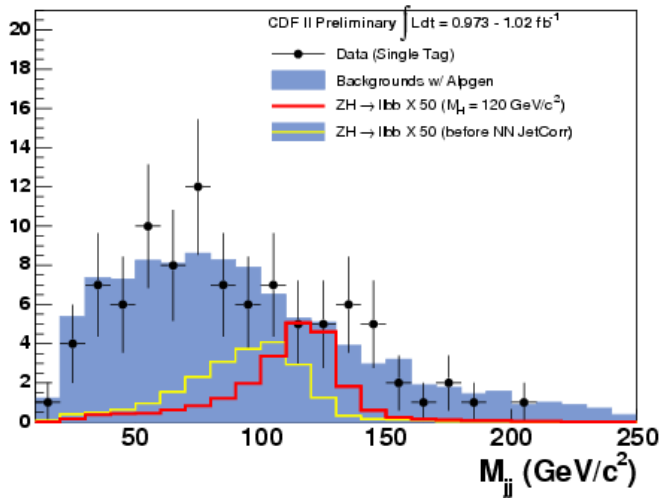
- Jet energy resolution is better using the NN
- More accurate and precise measurement of Higgs Boson mass
- Rule of thumb for fitting M_{JJ}

  1% improvement mass resolution

  ~ 10% luminosity

Neural Network Event Classification

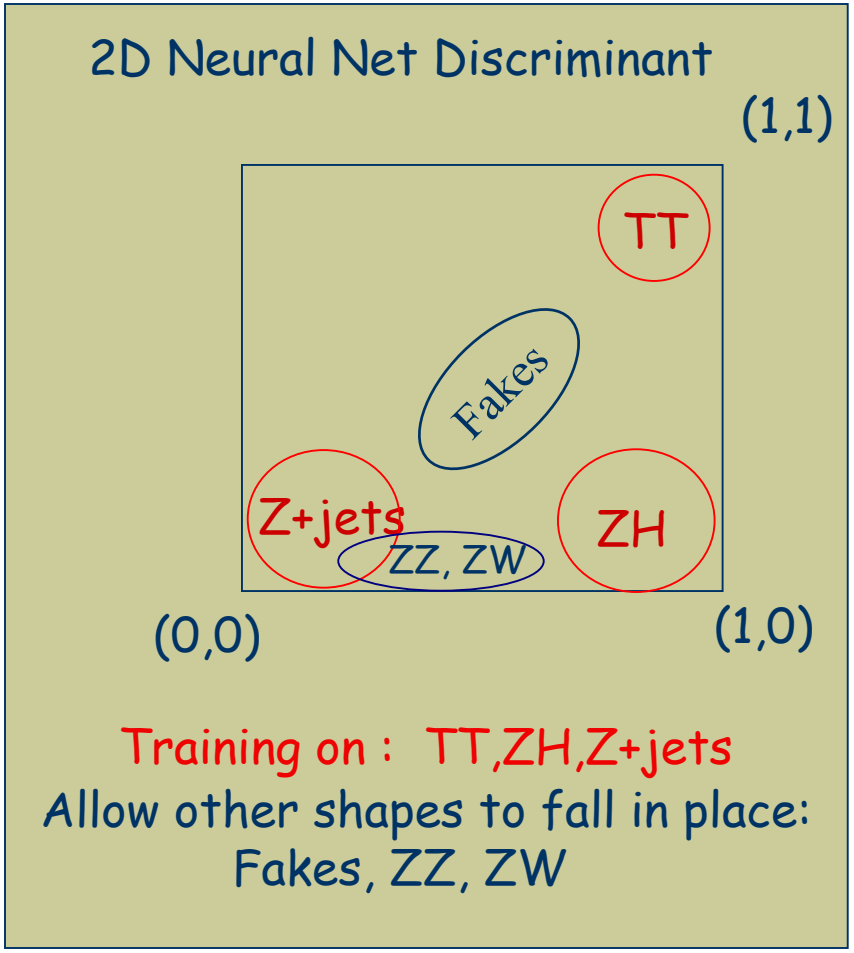
- A separate neural network from NN jet corrections
- Dijet mass still has large backgrounds
- A NN takes advantage of correlations between different variables



- With a 1-D NN that separated Z+jets from ZH, *tt* remains prominent in most Higgs like region
  - Therefore a 2-D network is used
- NN estimated to improve search by a factor of 2.5x more luminosity versus dijet mass alone

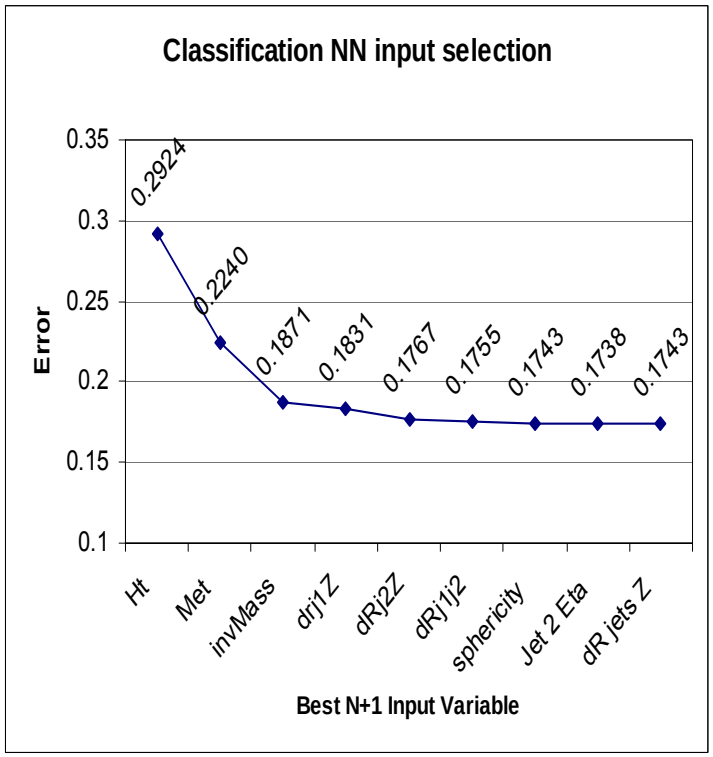
Classification Artificial Neural Network with 2-D output

- Develop NN classification after NN jet corrections
- Training
  - Neural net output determined by exposure to training data Iteratively adjust parameters to minimize error
  - Training accomplished through JETNET program (Peterson et al. CERN-TH/7135-94)
- Will fit resulting shape from data against signal background shapes to measure upper limit of ZH cross-section



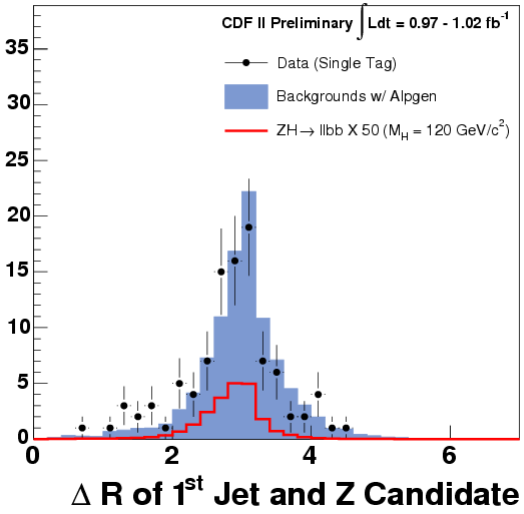
Kinematic Input Variables in Neural Network Classification

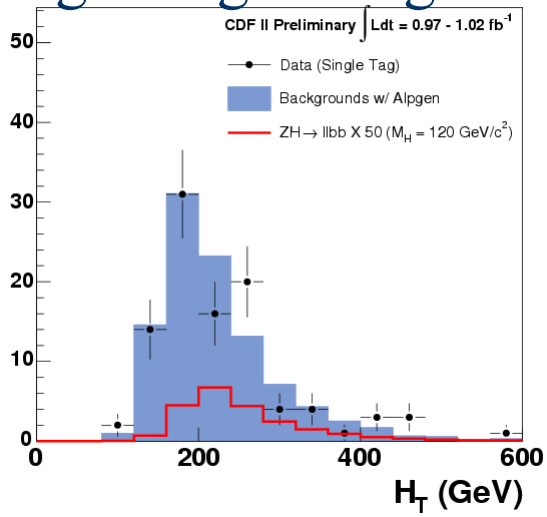
- H_t (Sum of 2 leptons, Missing E_t, and top two jets)
- Missing E_t
- Mass of top two jets
- ΔR of Jet 1 and Z candidate
  - $(\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2})$
- ΔR of Jet 2 and Z candidate
- ΔR of Jet 1 and Jet 2
- Sphericity
- Jet 2 η

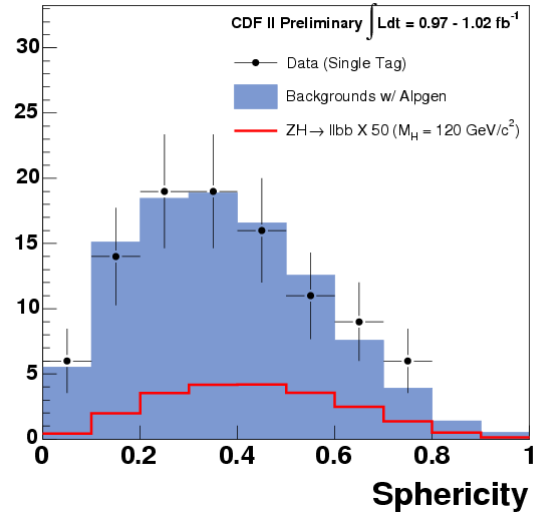


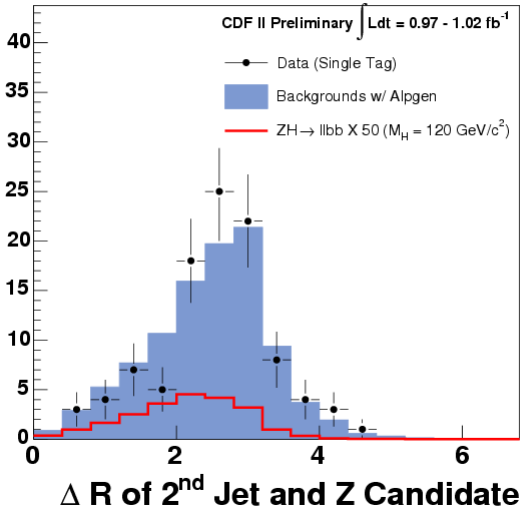
Input Kinematic Variables

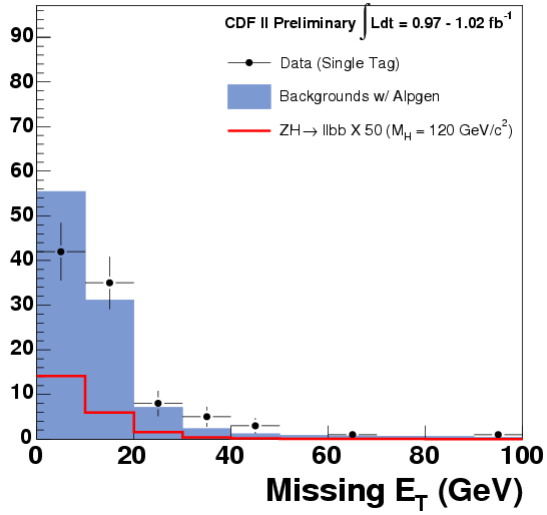
Single Tag Histograms

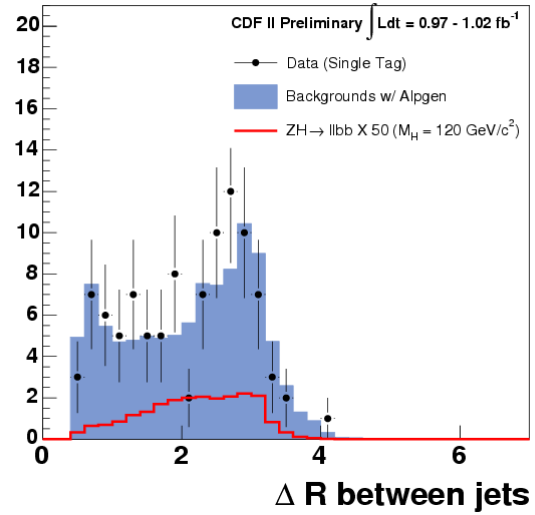




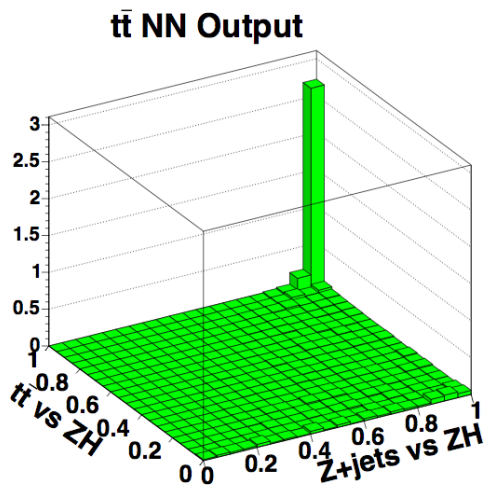


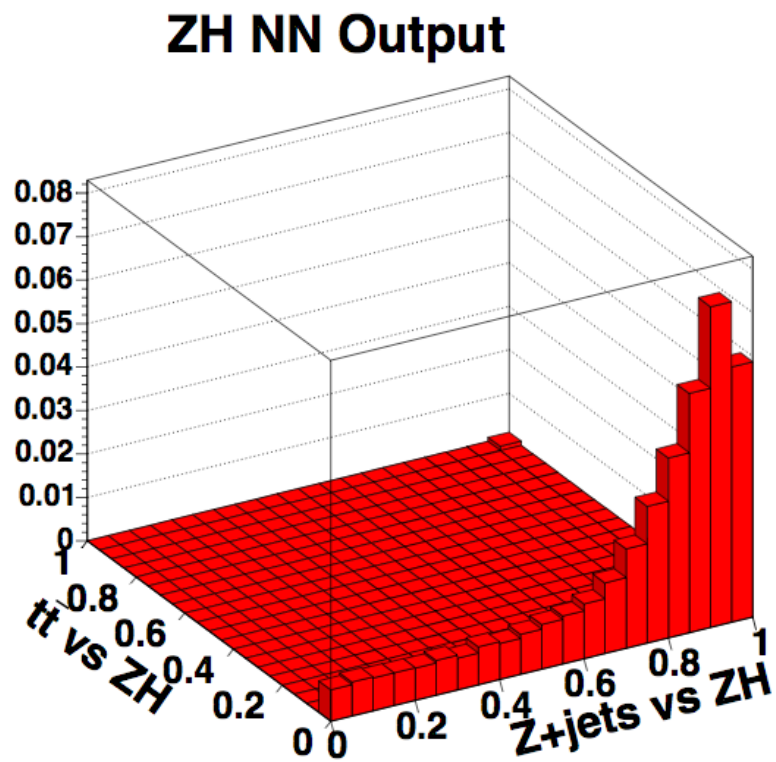


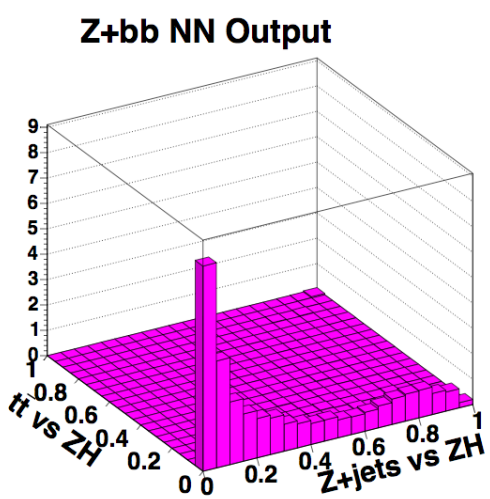




Neural Network Shapes



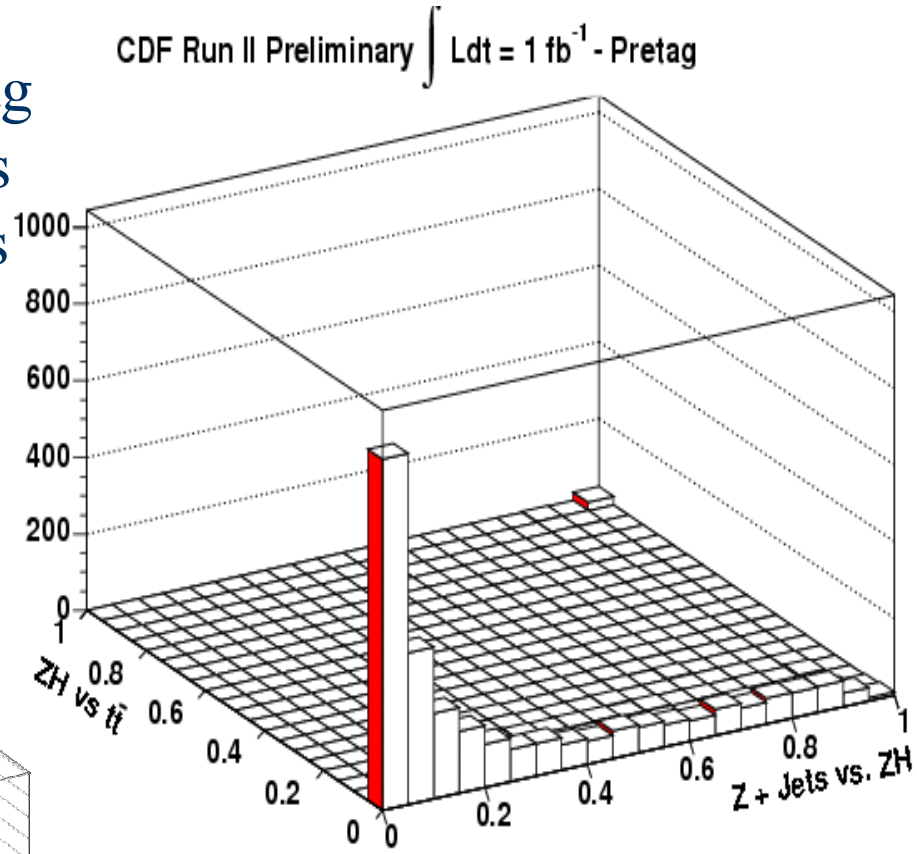


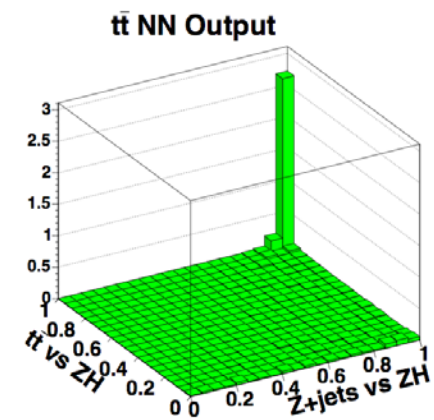


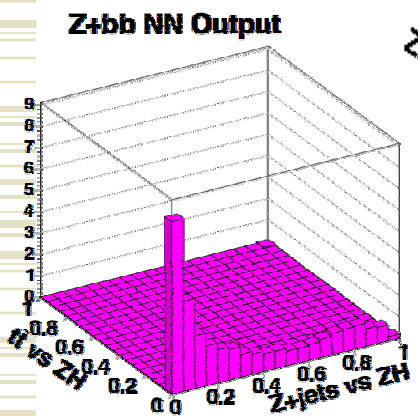
Normalized to single tag expectations

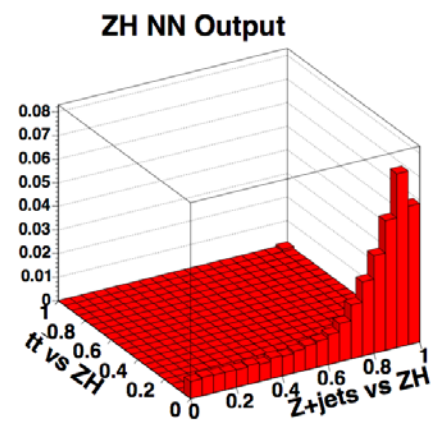
“Pretag” Data Output

With no b-tag requirements
~95% Z+jets
Use as NN validation



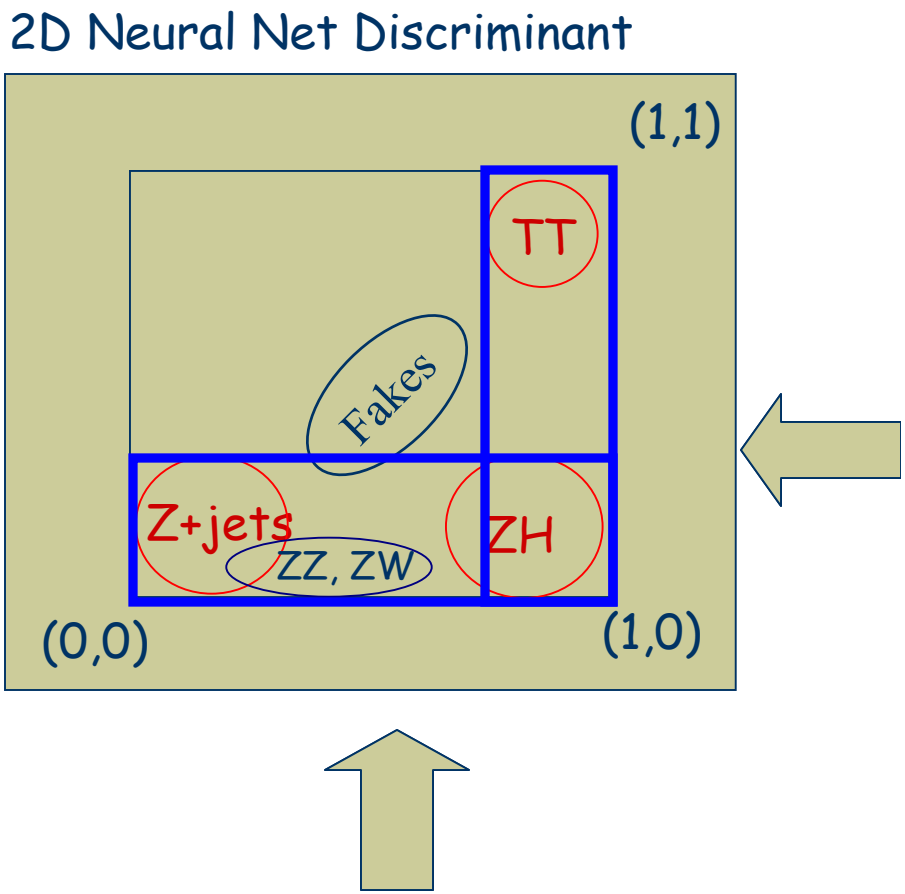




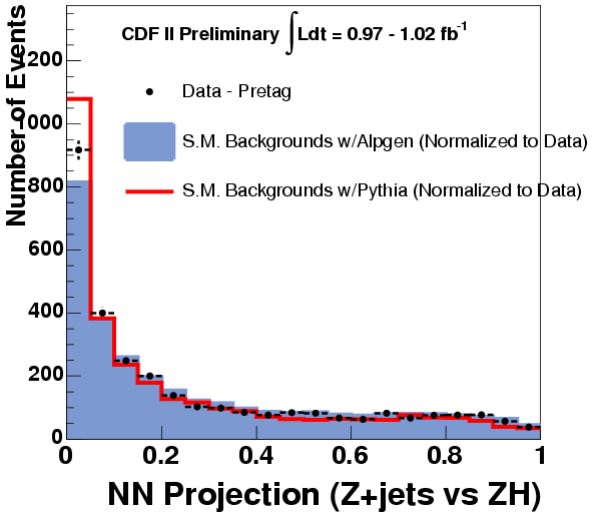


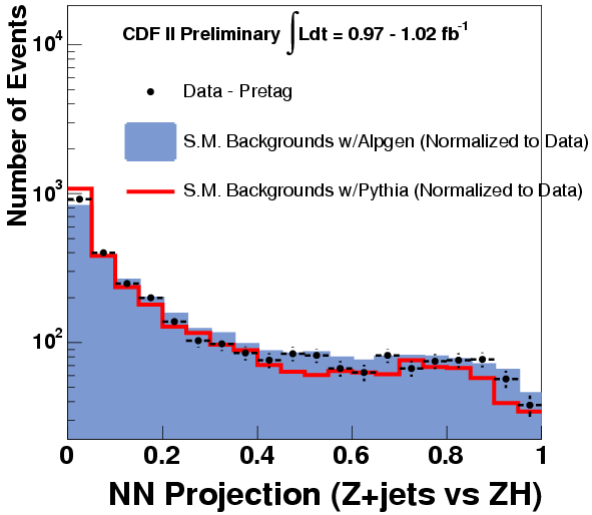
Projections and Slices

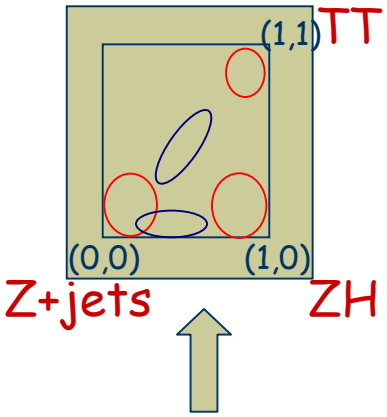
- Looking at projections
  - Z+jets vs ZH axis
    - 0 → 1 increasing energy
    - Most energetic corner (1) has *tt* and ZH
    - Slice
      - Separates Z+jets v ZH
      - Excludes *tt*
  - ZH vs *tt*
    - 0 → 1 increasing Met
    - 0 contains Z+jets and ZH, most events
    - Slice
      - Separates: ZH v *tt*
      - Most Z+jets excluded

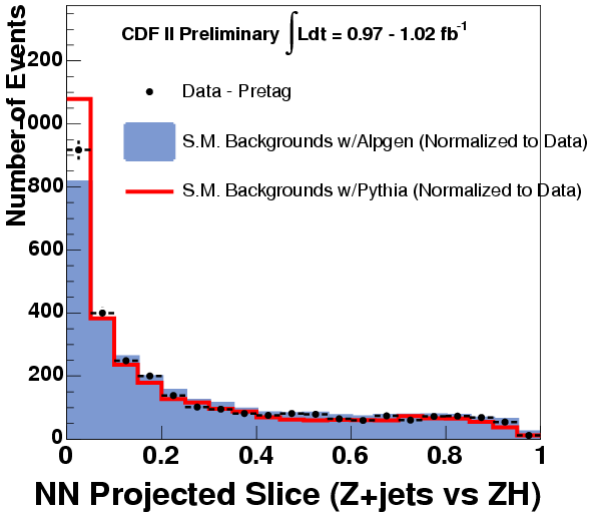


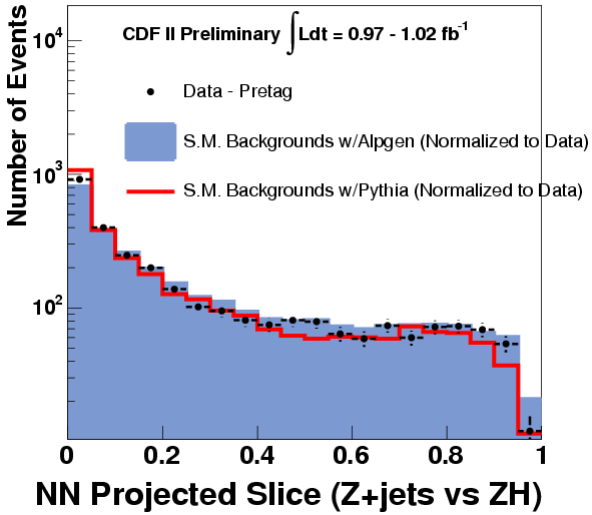
Pretag Output Projections

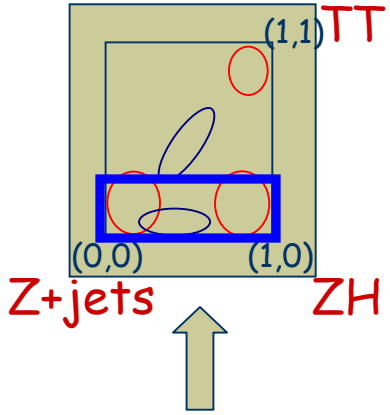




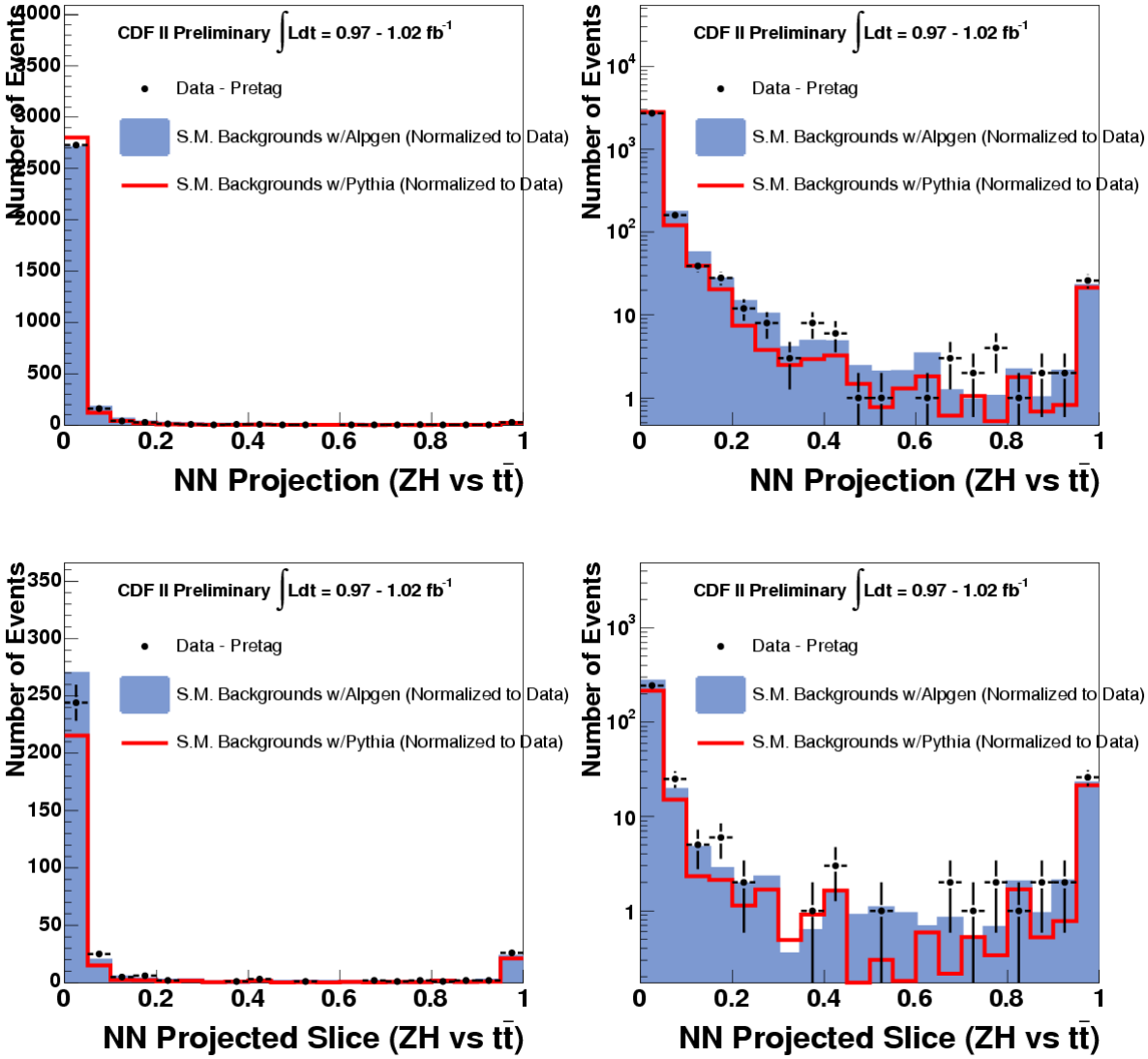


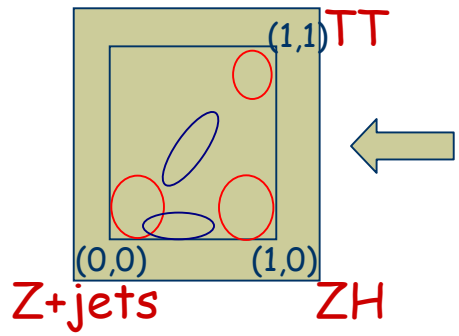


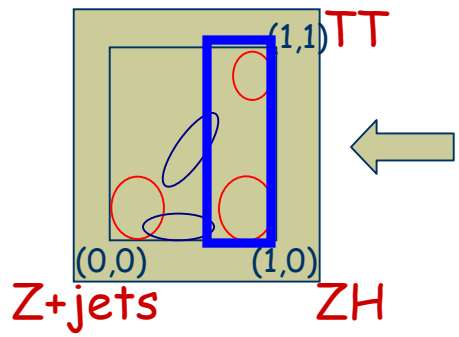




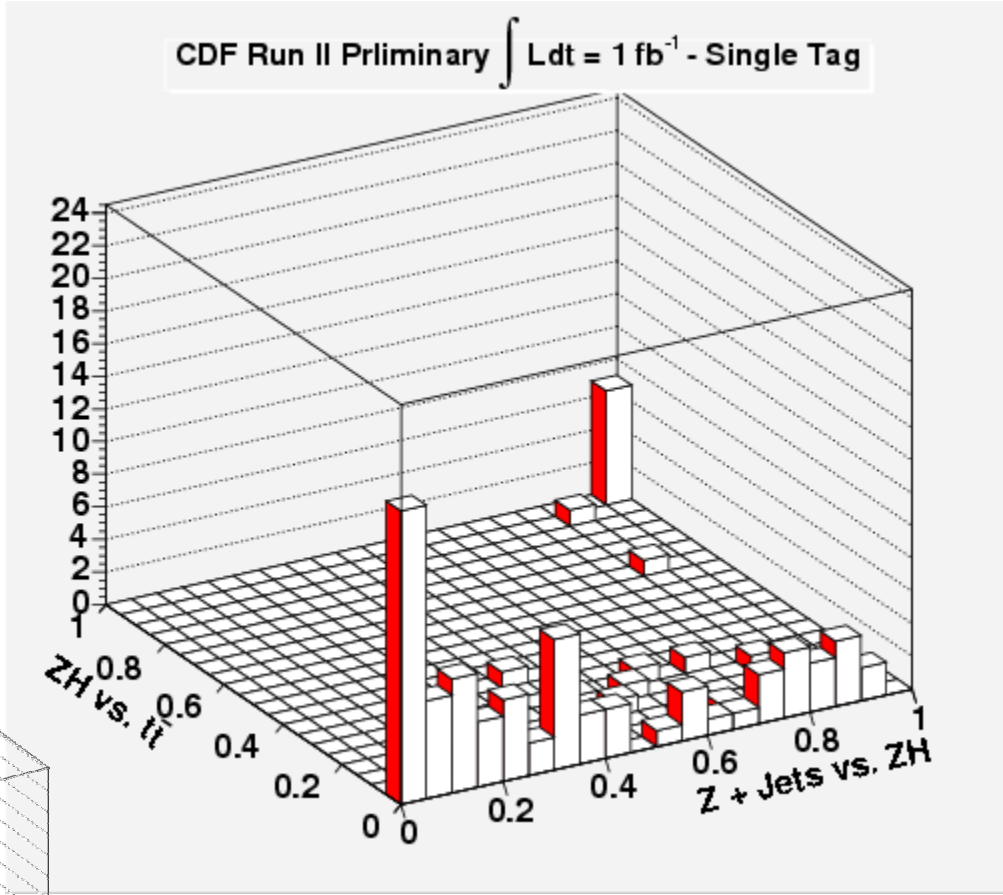
Pretag Output Projections

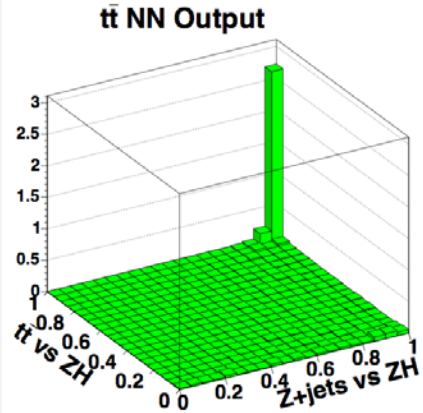


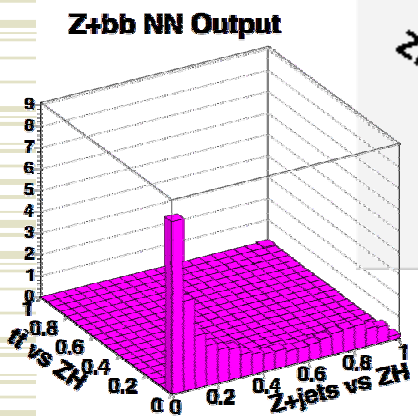


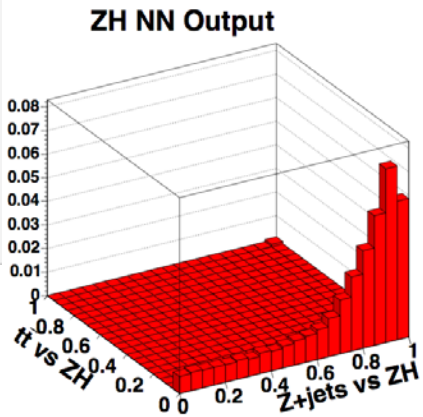


Single Tag Output

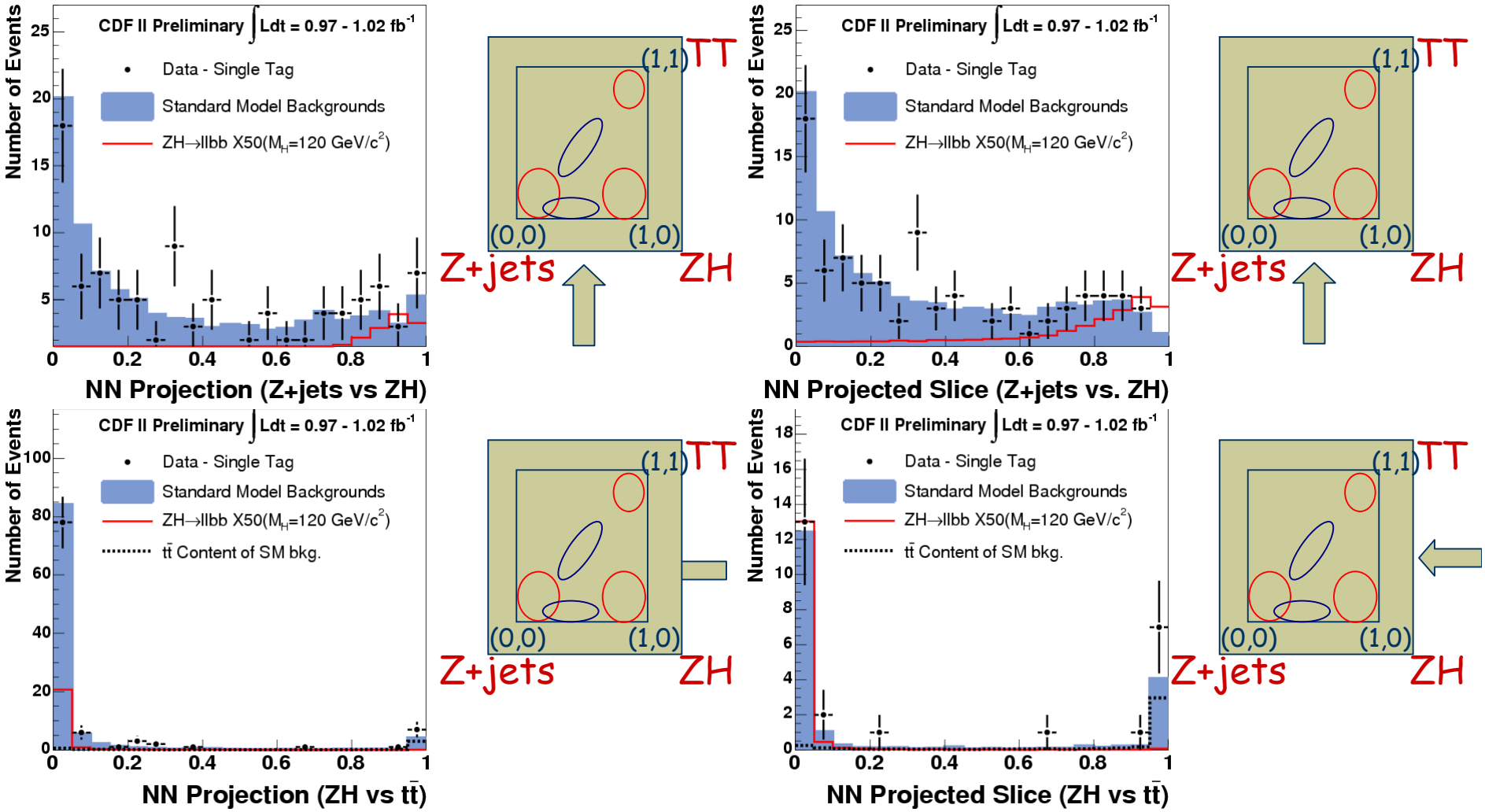




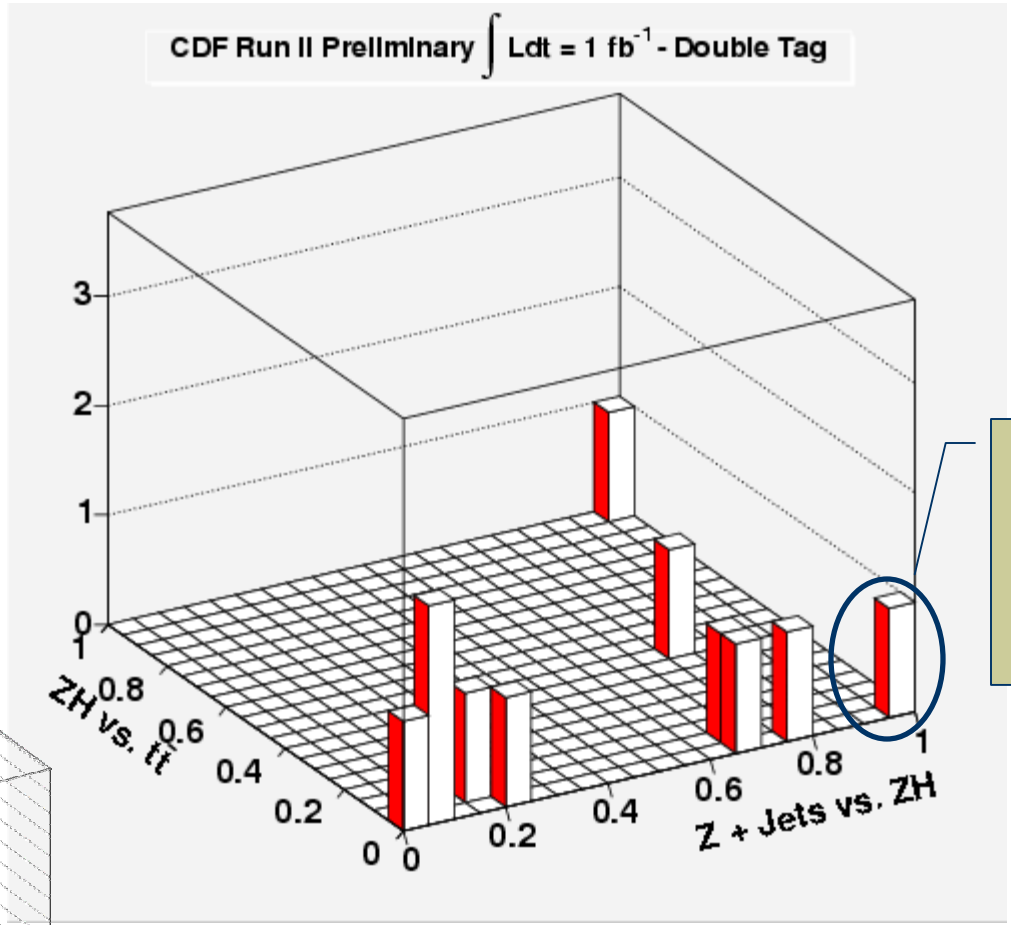


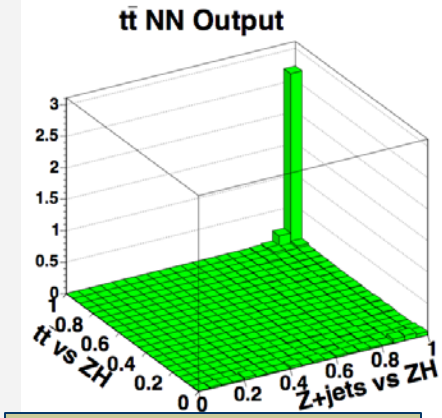


Single Tag Output Projections

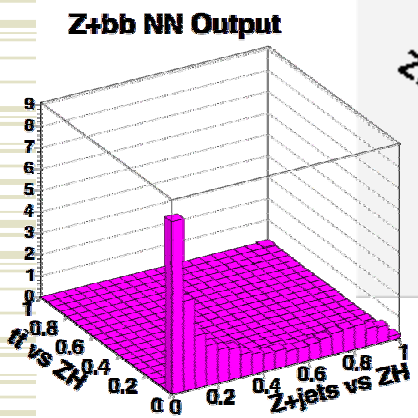


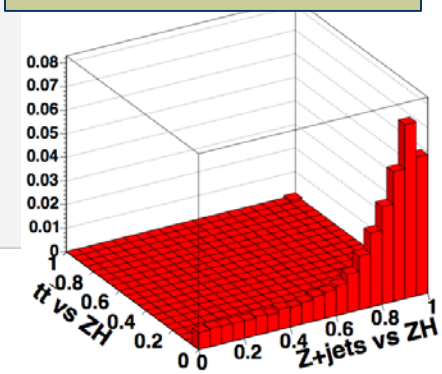
Double Tag Output



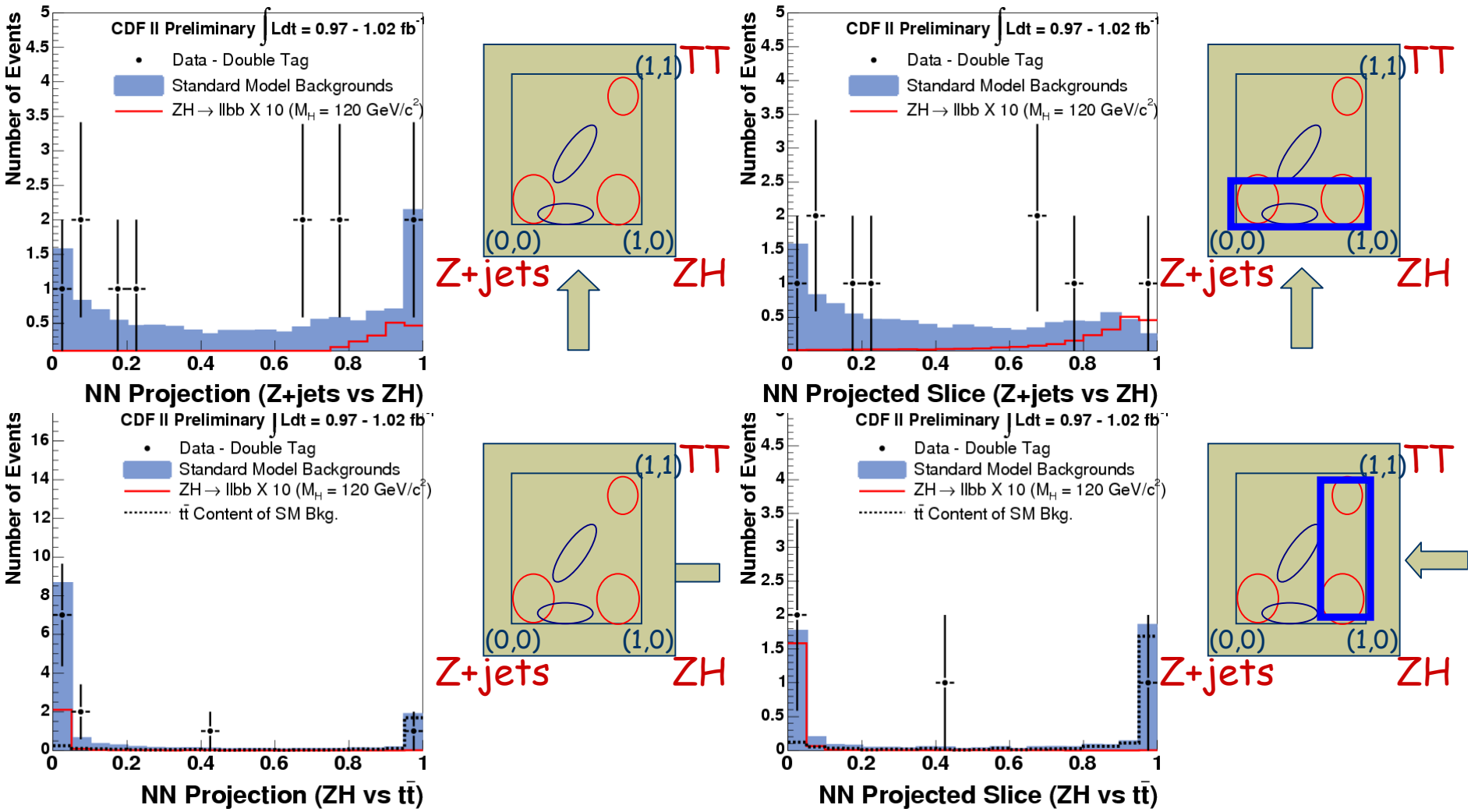


Higgs Like Double Tagged Event





Double Tag Output Projections



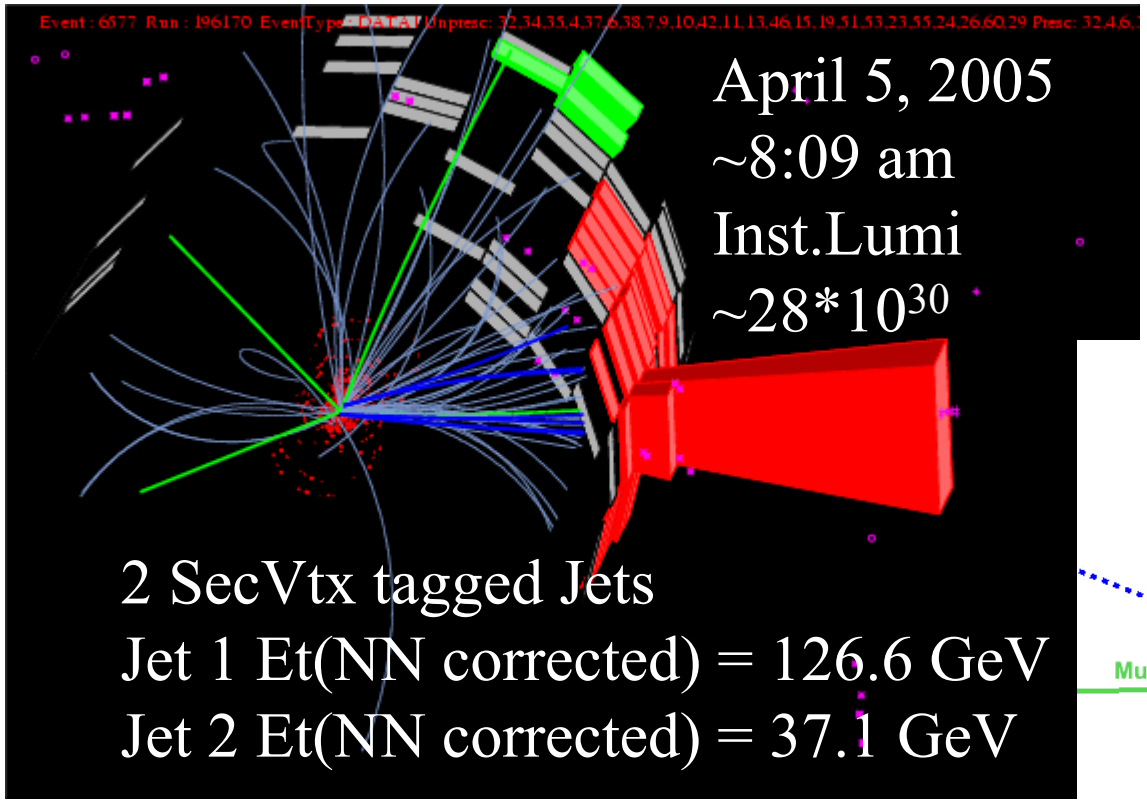
Run 196170 Event 6577

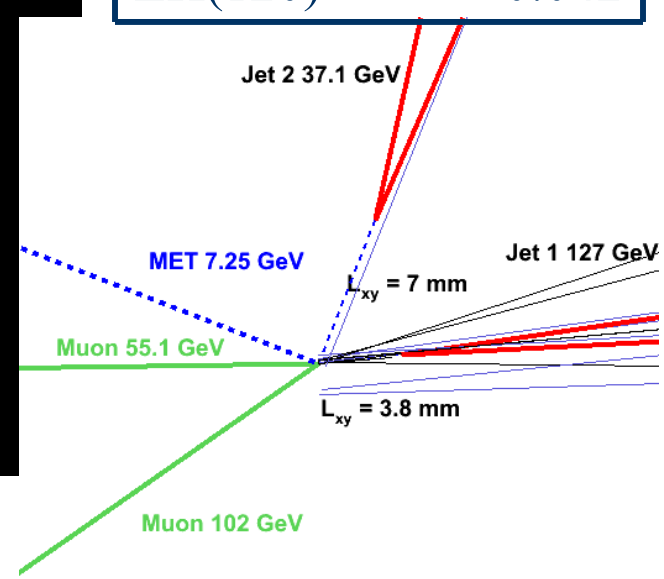
NN output = 0.958, 0.009

M_{JJ} = 120 GeV/c^2

S/B = 1/4.2

Zbb	0.11
tt	0.019
Zcc	0.017
ZZ	0.016
Mistag	0.010
Total bkg	0.18
ZH(120)	0.042





Setting a Limit

- Fit data using background (b) only template and signal + background (s+b) template
  - Vary signal cross-section
  - Systematics are included in a possible model of the fit
  - Takes advantage of sidebands to determine background rates
- Run many pseudo-experiments based on nominal expectations
  - Randomly "create" data from templates
  - Fit "pseudo-data" just like real data
- Find likelihood ratio (Q) of the s+b model versus b only
- Exclude values of σ_{ZH} where Q is less than 5% likely from s+b hypothesis

Systematics

All Systematics errors increase the expected limit by 14%

Main culprits (>5% affect on expected limit)

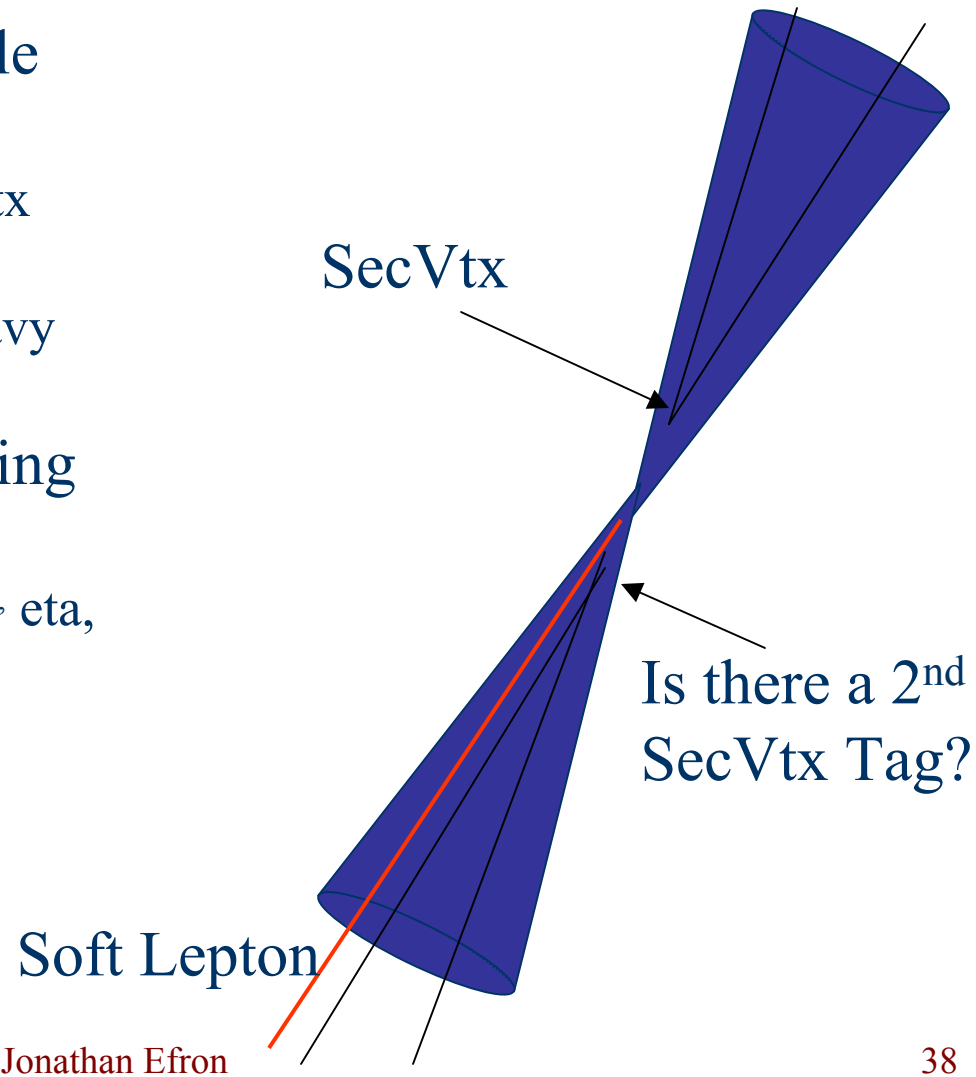
- 8% B hadron b-tagging efficiency (per tag): – worsens limit 12 %
- 6% Luminosity uncertainty: - worsens limit 7%
- 40% error on Z+heavy flavor production : - worsens limit 6%

Other systematics

- Jet Energy : +/- 1 sigma fluctuations (shape and counting)
- Z+l.f. mistag error (and shapes): 17%
- Alpgen vs Pythia for Z+jets NN Output Shapes
- C hadron b-tagging efficiency: 16% per tag
- Lepton scale factors : 1% each
- PDF : 2%
- Diboson cross-section normalization: 20%
- *tt* cross-section: 20%
- QCD fake rate error: 50%
- Initial State Radiation/Final State Radiation : for signal ZH signal

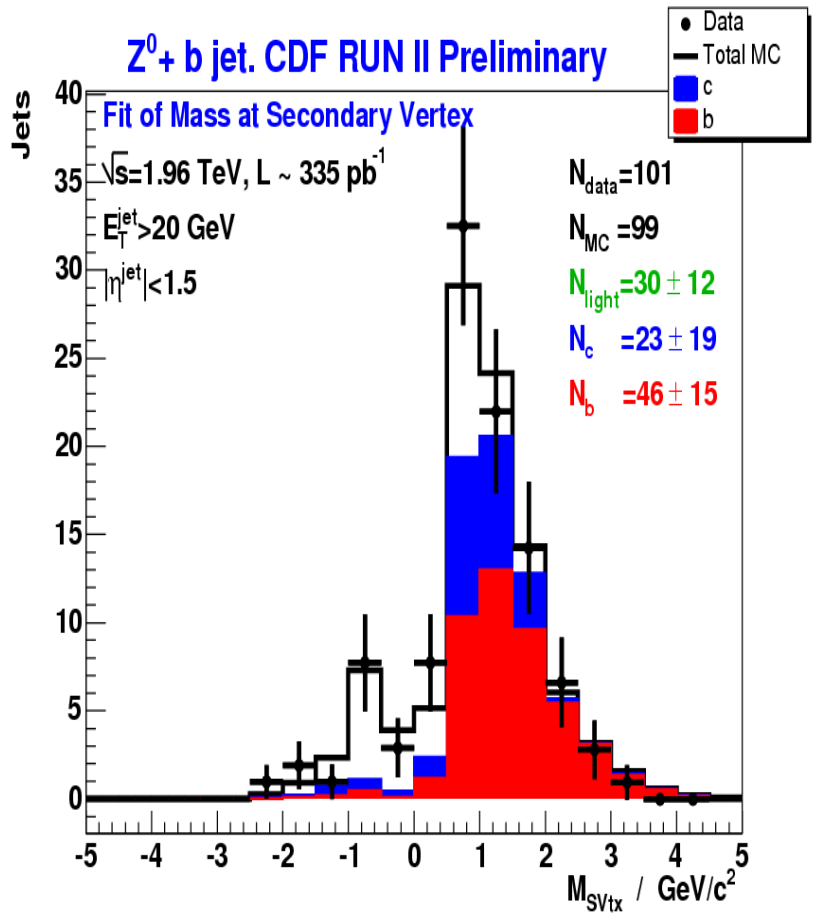
B-tagging Efficiency

- Measured in dijet sample
  - One jet with soft lepton
  - Second jet with a SecVtx tag
  - Very pure sample of heavy flavor jets
- Efficiency measured using soft lepton-tagged jet
  - Parameterized for Jet E_T, eta, etc. . .
- Source of uncertainty
  - Statistical
  - Heavy flavor fraction
  - Mistag uncertainty

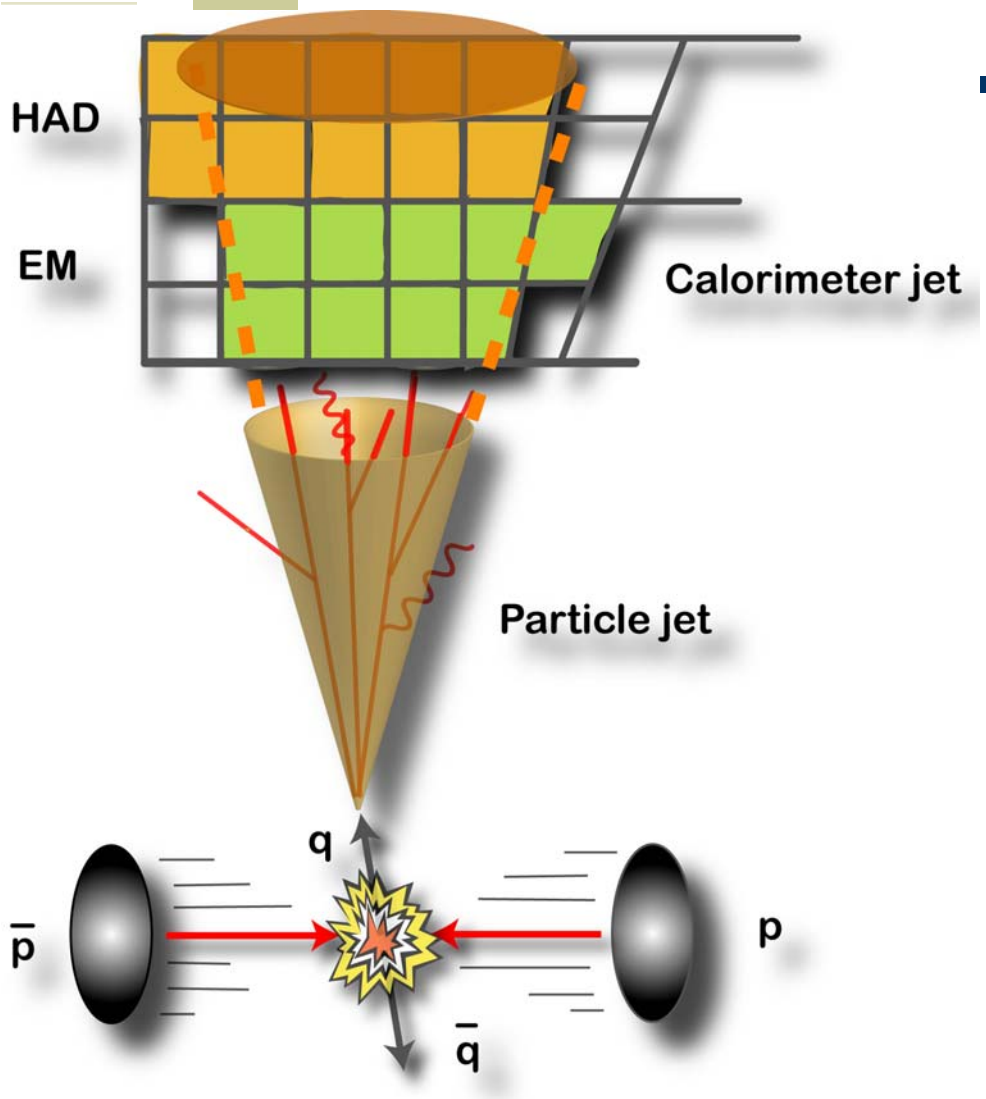


Z + Heavy Flavor Cross-section

- 40% systematic motivated by error on error from Z + b-jet measurement
- Measurement fit mass of SecVtx tags to templates of Z+b, Z+c and Z+lf
- $\sigma_{Z+b\text{-}jet} = 0.93 \pm 0.32$ (stat.) $\pm$ 0.14 (syst.) pb
- Phys. Rev. D 74, 032008 (2006)

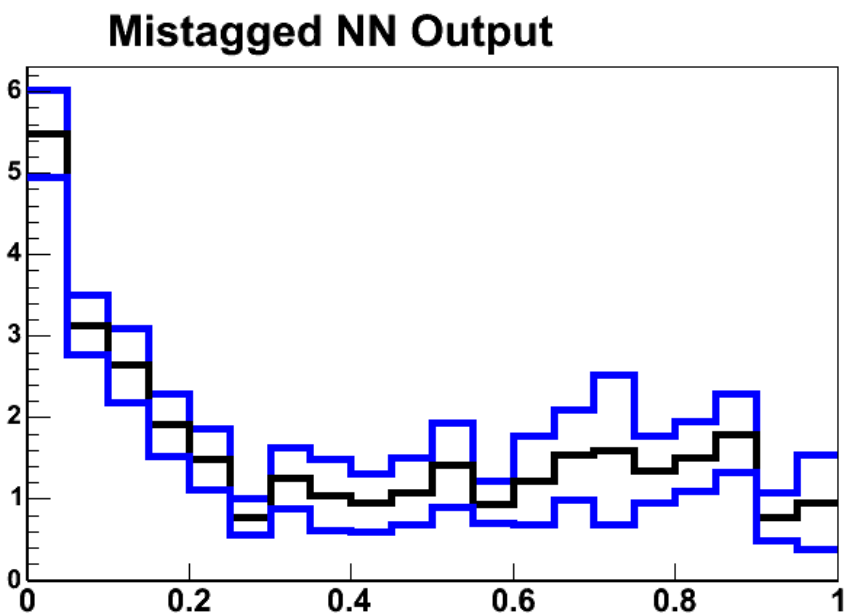


Jet Energy Scale

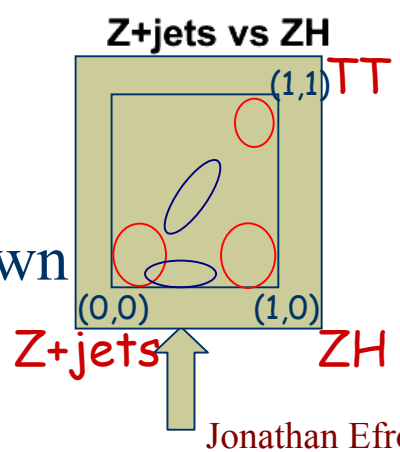


- Determine parton energy from measurements in calorimeter
- Correct for
  - Detector effects
  - Fragmentation/Hadronization
  - Underlying event
- Energy scale determined from data and MC
- Uncertainties in jet energy scale directly affect kinematic uncertainties
  - Allow uncertainties to change acceptance
  - Allow uncertainties to change kinematic shape of NN output
  - Correlated errors between MC modeling

Mistag Shape Errors



Single Tag Mistag shape
BLACK nominal shape
BLUE shifted up and down mistagged shape

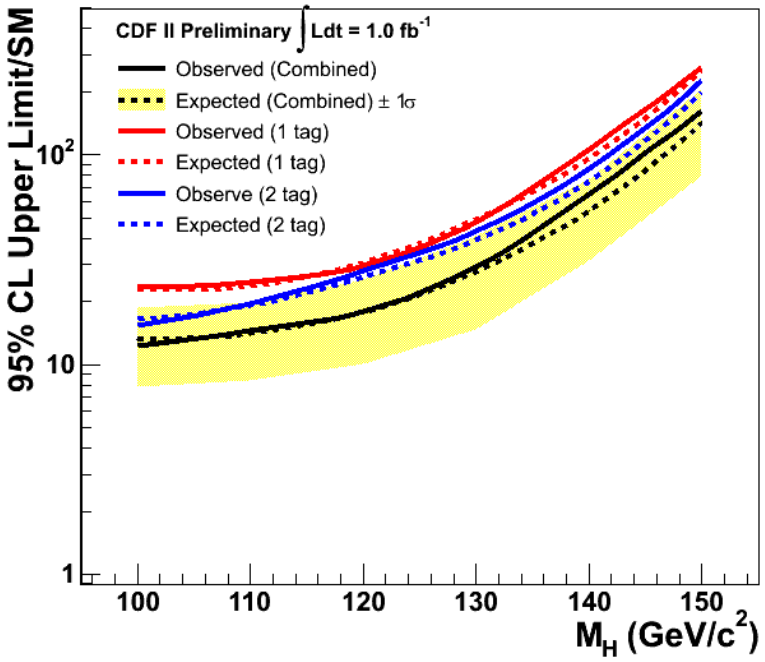


- Adjust all bins by their bin error to get alternative shapes
  - Contributions to shape errors
    - Pretag statistical errors
    - Ratio of negative tags to mistags
    - Errors of mistag matrix

$ZH \rightarrow l^+l^- bb$ with 1 fb^{-1} Upper Limit at 95% CL

Mass (GeV/c^2)	1-tag σ_{ZH}/SM	2-tags σ_{ZH}/SM	Combined σ_{ZH}/SM
100	23 (23)	15 (16)	12 (13)
110	25 (24)	20 (19)	14 (14)
115	28 (27)	23 (22)	16 (16)
120	30 (31)	28 (26)	18 (18)
130	48 (49)	43 (39)	29 (28)
140	110 (96)	86 (75)	65 (54)
150	260 (250)	220 (200)	160 (140)

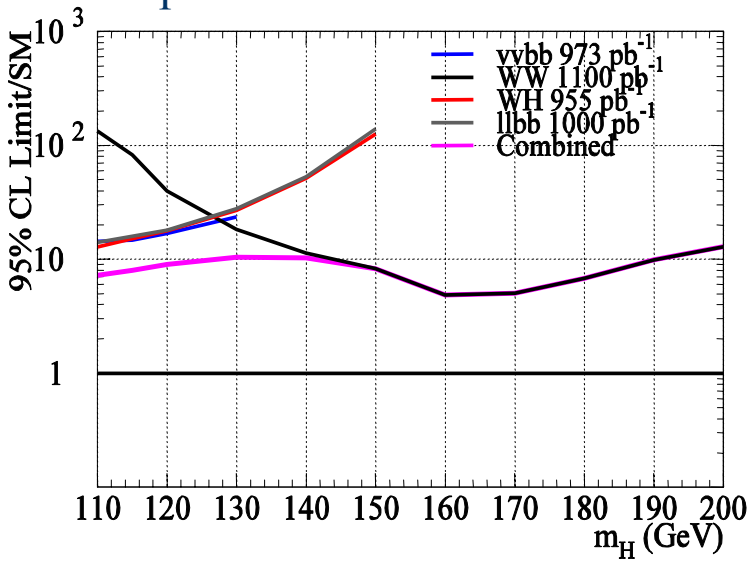
Observed Limit (Expected Limit)



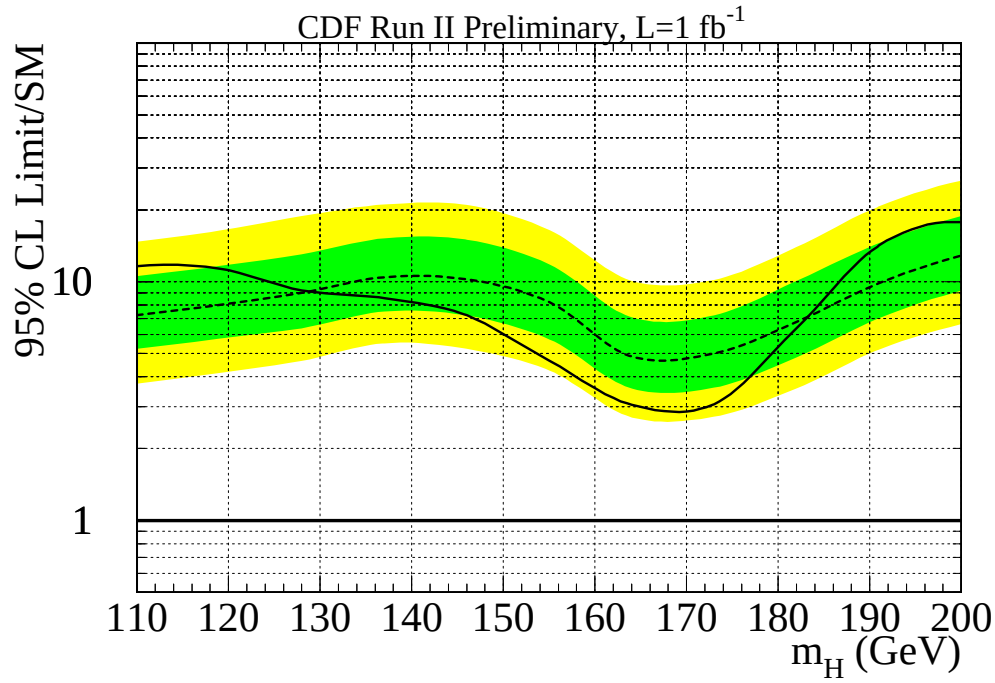
115 GeV/c^2 limit corresponds to 1.3 pb for $\sigma_{ZH} * BR(H \rightarrow bb)$

Higgs at CDF II with 1fb^{-1}

Expected Limits CDF II Preliminary



- Expected limits similar to other SM low-mass Higgs searches
  - Despite lowest cross-section
  - Despite lowest branching ratio

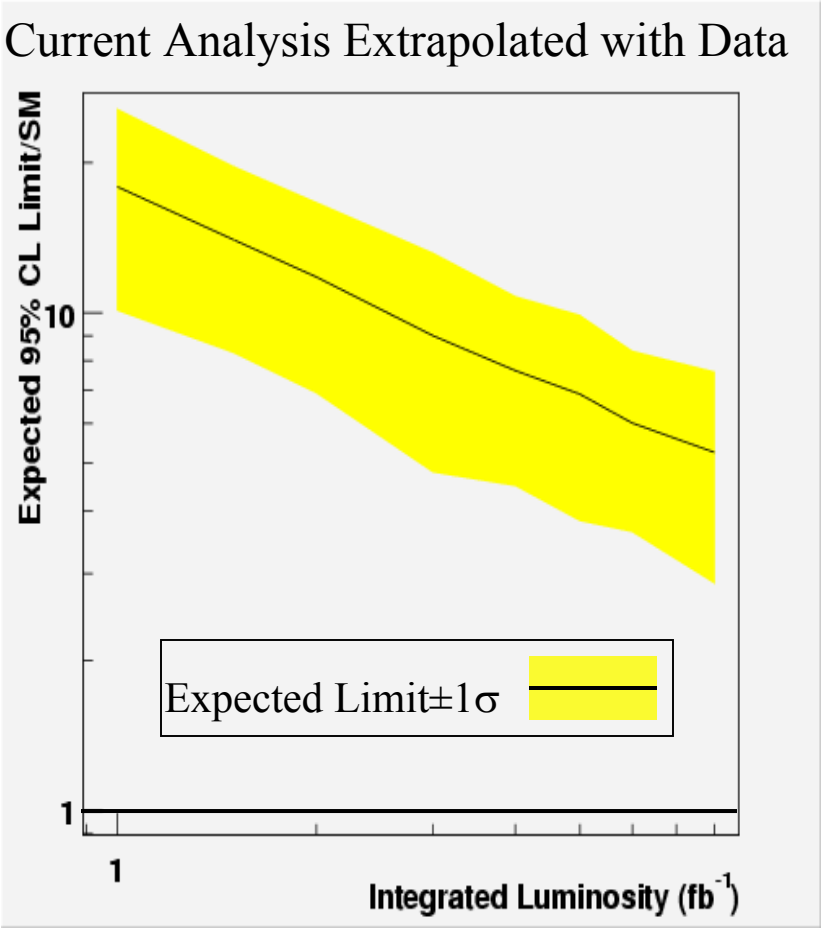


- CDF collectively, expected limit is 8.0 times SM at M_H = 115 GeV/c^2
- Observed = 11 x SM

Step One to Discovery

- Scaling current analysis with 8 fb^{-1} of data, expected upper limit is 5.2 times SM at

  $M_H = 120\ GeV/c^2$
- Improvements in the works
  - Greater event acceptance
  - Improve b-taggers
    - Higher efficiency
    - Wider eta range
  - Lower systematics
  - Mix in other advanced selection techniques



Conclusions

- Standard Model adds a Higgs sector to explain electroweak symmetry breaking, resulting in Higgs Boson
- Designed an analysis using the CDF detector to search for ZH$\longrightarrow l^+l^- b\bar{b}$
  - Use different artificial neural networks to signal to background
- Set an upper limit on production of ZH to 16 times the SM expectation and a Higgs mass of 115 GeV/c^2
- Opportunity for discovery at the Tevatron exists
  - Combination within CDF and with D0 necessary