Electroweak Physics: W and Z Production and SM Higgs from the Tevatron

presented by

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on behalf of the DØ and CDF Collaborations

XLIst Rencontres de Moriond: EW Interactions and Unified Theories

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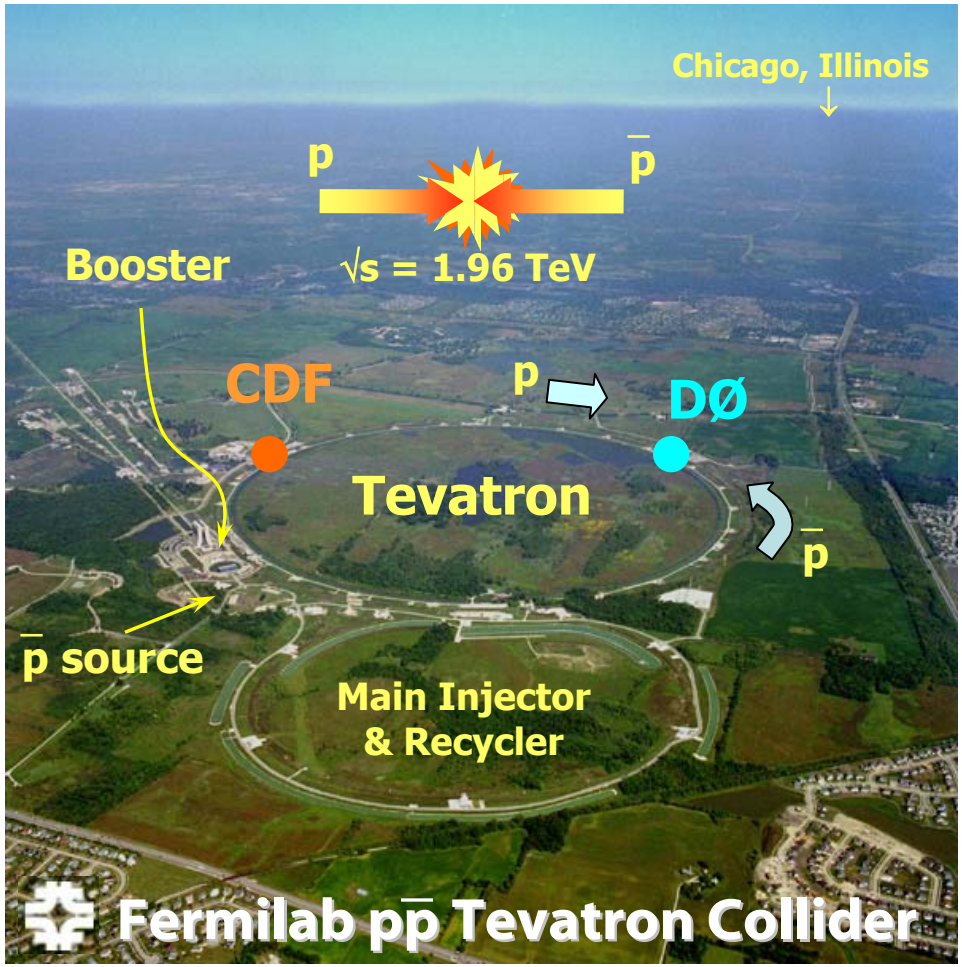
Outline

- **W and Z production**
  - **Motivation**
  - **W, Z $\sigma \times$ BR($\rightarrow$ leptons)**
  - **W charge asymmetry**
- **SM Higgs**
  - **Motivation**
  - **Search results and limits**
- **Summary**

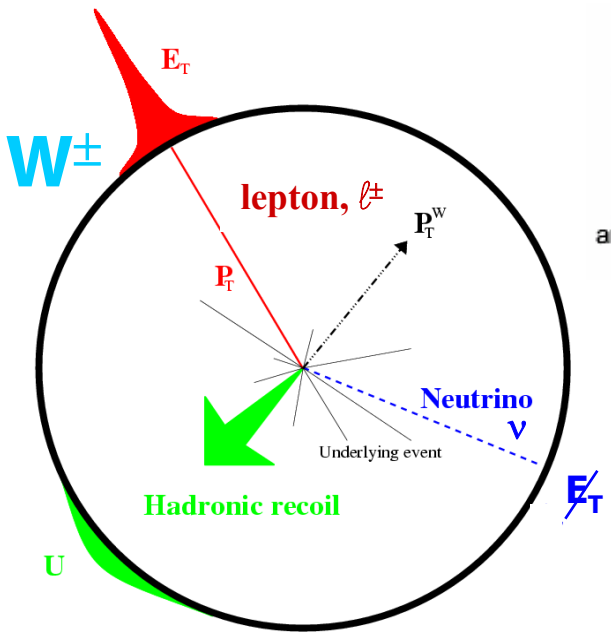


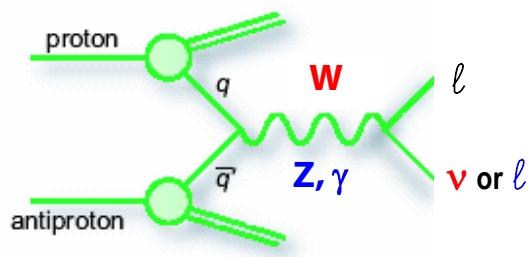
- **CDF, DØ results reported here use $\int \mathcal{L}\, dt \sim 0.1 - 0.4\ fb^{-1}$ dataset**

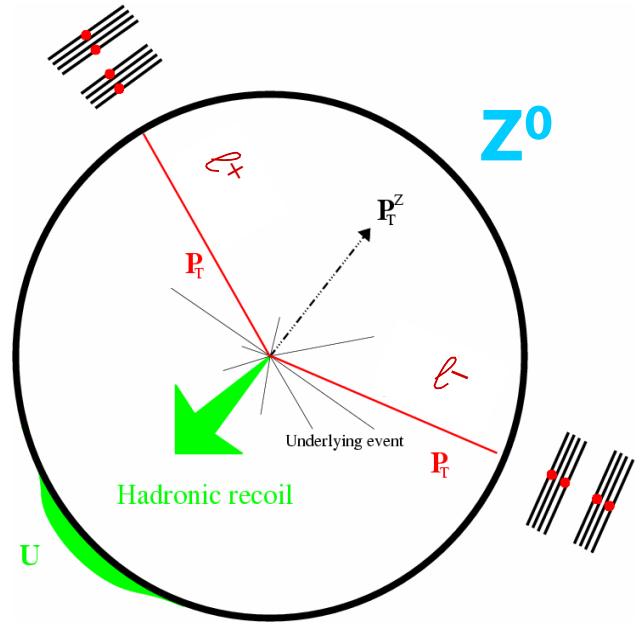
- *For Ref.,* **see talks, this conference:**
  - **dibosons: covered by J. Sjolin in Diboson Physics at the Tevatron**
  - **MSSM Higgs: covered by C. Ciobanu and R. Hauser in Tevatron SUSY results**

W/Z production: Motivation & Signature

- at hadron colliders, hadronic decays of W and Z boson overwhelmed by QCD backgrounds
  - identify signature through leptonic decays ⇒ clean, abundant source for high p_T leptons
- cross section and asymmetry measurements
  - understand detector performance
  - test SM predictions
- important backgrounds for top, Higgs and SUSY







- isolated, energetic lepton
- large Missing E_T ("$\not{E}_T$")

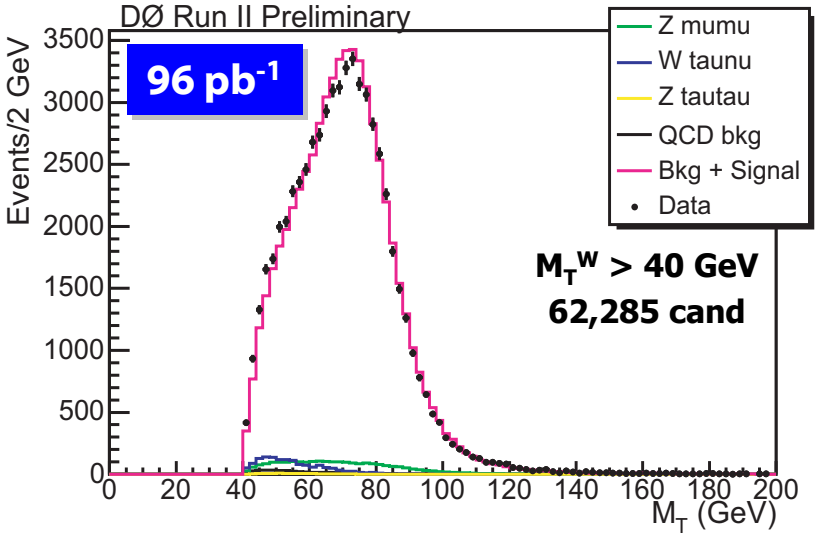
- 2 isolated, energetic leptons
- leptons with opposite charge

W/Z cross-sections: Event Selections (μ)

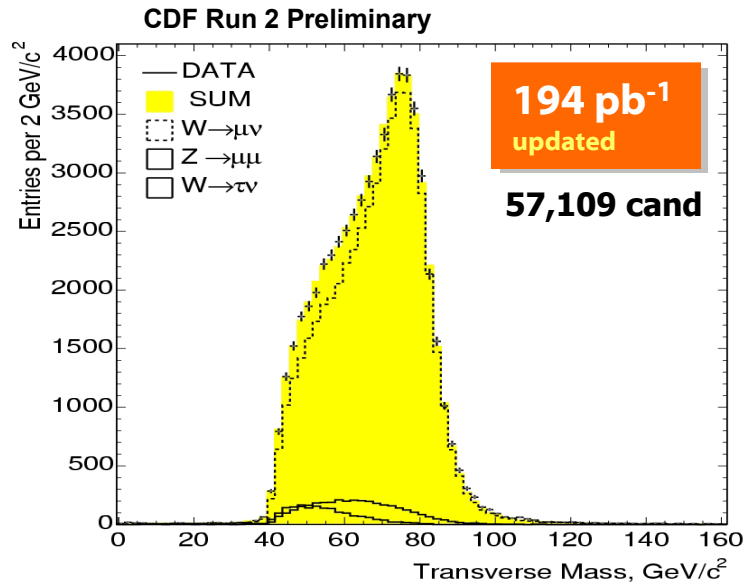
	$W \to \mu\nu_\mu$		$Z \to \mu\mu$	
	DØ	CDF	DØ	CDF
$\int \mathcal{L}\, dt$ (pb^{-1})	96	194	148	337
p_{T1}^{μ} (GeV)	> 20 (track)	> 20 (track)	> 15 (track)	> 20 (track)
p_{T2}^{μ} (GeV)	—	—	> 15 (track)	> 10 (track)
$\not{E}_T$ (GeV)	> 20	> 20	—	—
$\lvert\eta^{\mu}\rvert$	< 2.0	< 1.0	< 2.0	< 1.0

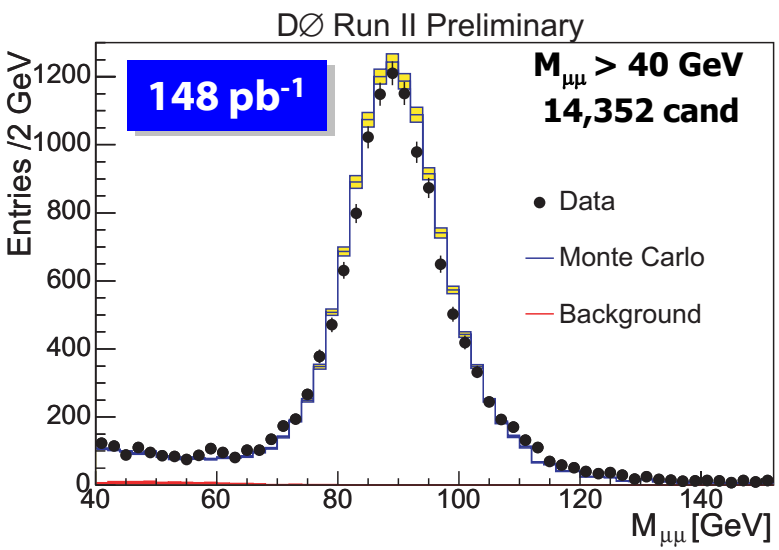
- **main backgrounds**
  - W: $Z \to \mu\mu$ (~ 3%), $W \to \tau\nu$ (~ 2.5%), and QCD jets (~ 0.5-1%)
  - Z: QCD jets primarily semi-leptonic decays of $b\bar{b}$ (~ 0.5%), $Z \to \tau\tau$ (~ 0.5%)

$W/Z \rightarrow \mu\nu_\mu, \mu\mu$

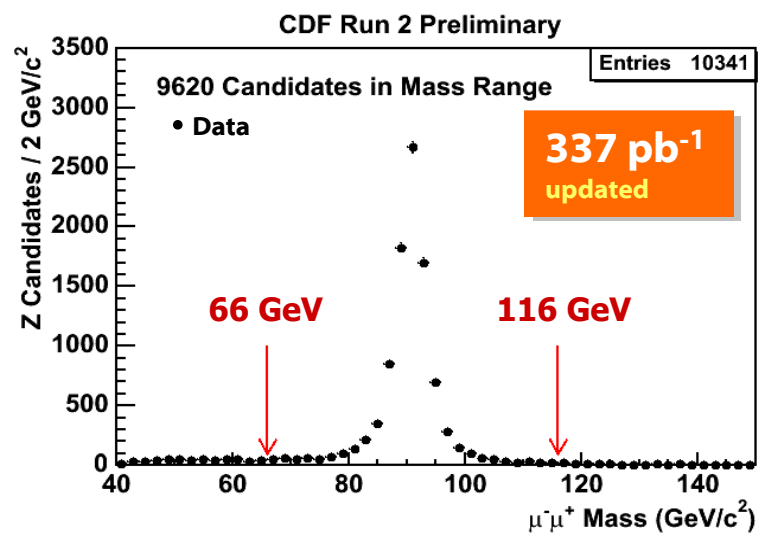


W→μν





Z→μμ



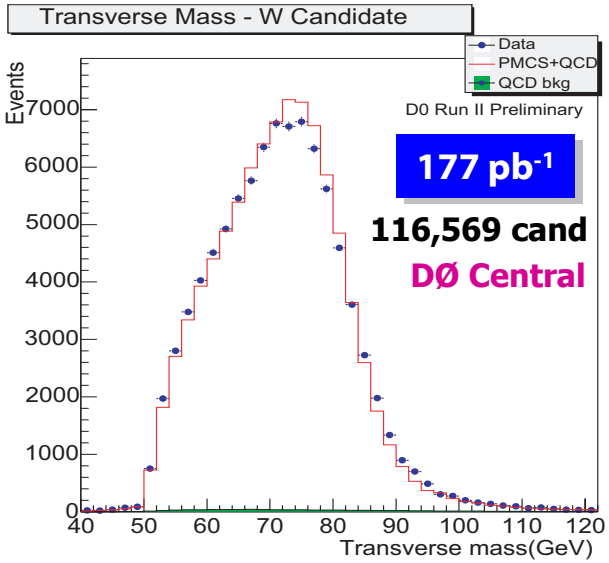
- **large # of events ⇒ higher acceptance of DØ muon system**
- **narrow peak ⇒ high resolution of CDF tracking system**

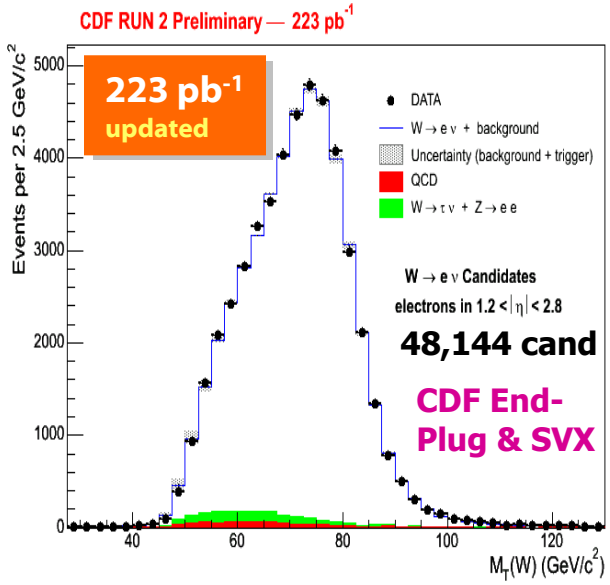
W/Z cross-sections: Event Selections (e)

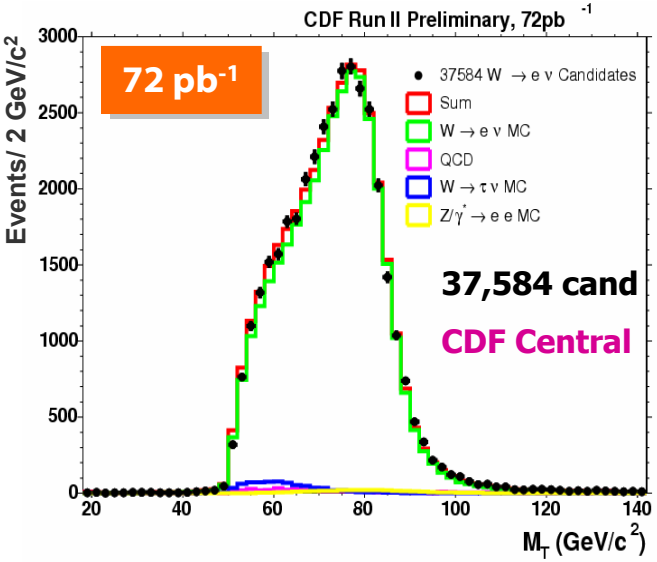
	$W \to e\nu_e$			$Z \to ee$	
	DØ	CDF II	CDF II	DØ	CDF II
$\int \mathcal{L}\, dt$ (pb^{-1})	177	72	223	177	72
E_{T1}^{e} (GeV)	> 25	> 25	> 20	> 25	> 25
E_{T2}^{e} (GeV)	—	—	—	> 25	> 25
$\not{E}_T$ (GeV)	> 25	> 25	> 25	—	—
$\lvert\eta_1^e\rvert$	< 1.05	< 1.0	[1.2, 2.8]	< 1.05	< 1.0
$\lvert\eta_2^e\rvert$	—	—	—	< 1.05	< 2.8

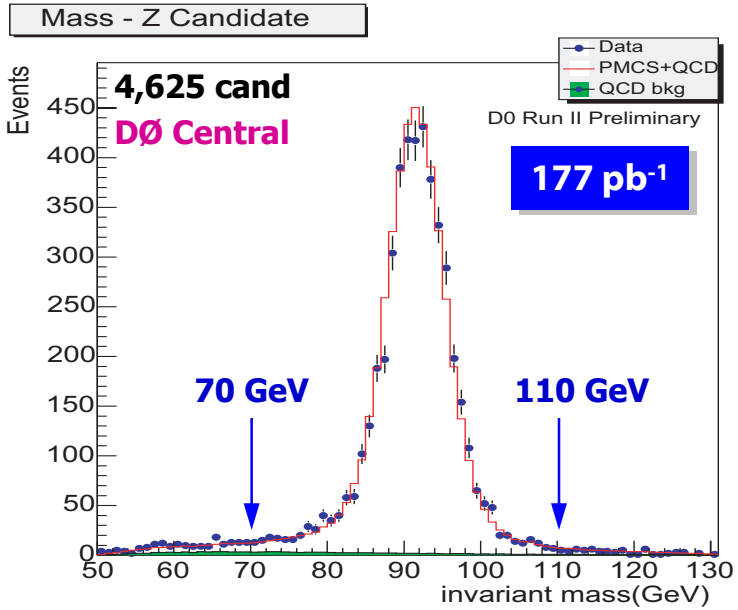
- **main backgrounds**
  - W: QCD jets with large EM content (~ 1-2%), $W \to \tau\nu$ (~ 2%), $Z \to ee$ (~ 0.5%)
  - Z: QCD jets with large EM content (~ 0.5%)

$W/Z \rightarrow e\nu_e$, ee

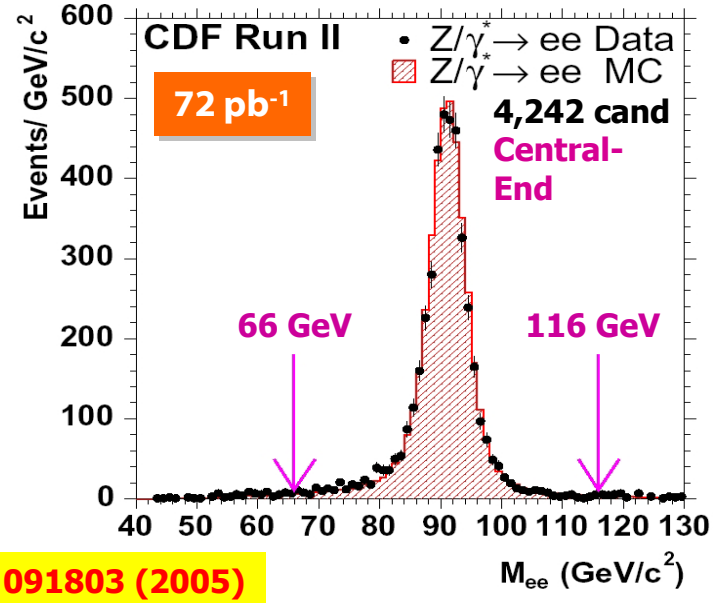








Z→ee

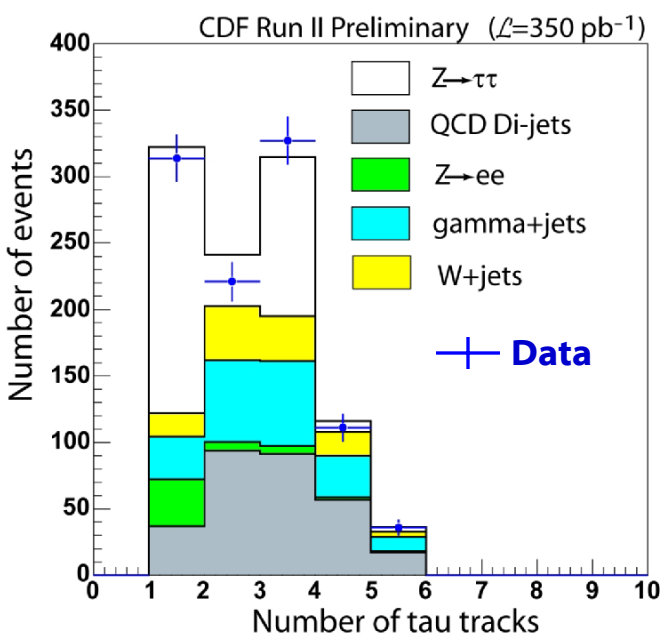


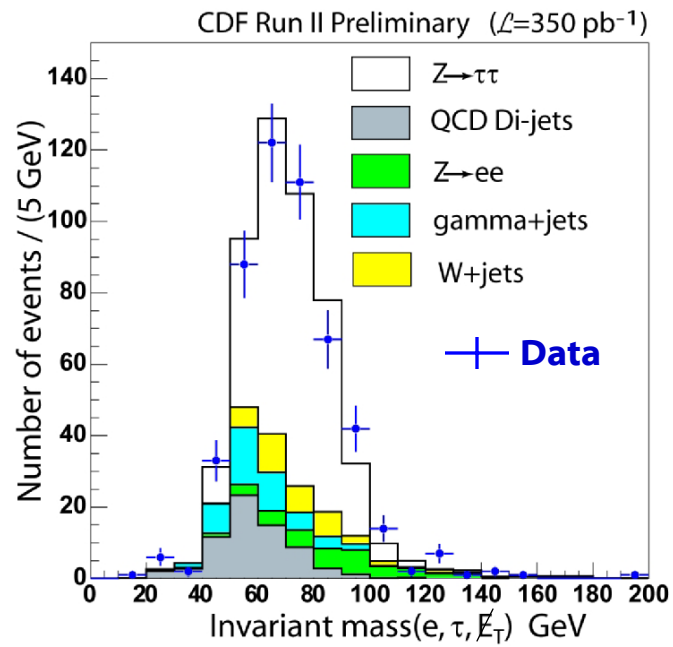
72 pb-1 CDF: PRL 94, 091803 (2005)

$Z \to \tau_e \tau_h$ Cross Section

- use channel $\tau_1 \to e + \tau_2 \to$ had
  - detect hadronic τ's as narrow, isolated calorimeter clusters matched to tracks
    - π^o info added such that M(π^o + track-cal cluster) consistent with τ mass
  - require isolated electrons ($E_T^e > 10$ GeV), hadronic τ ($E_T^\tau > 15$ GeV), $|\eta^\tau| < 1.0$
  - impose event topology cuts to suppress QCD and W + jet backgrounds

504 events, 37% QCD background
$\int \mathcal{L}\, dt = 350$ pb^{-1}; updated





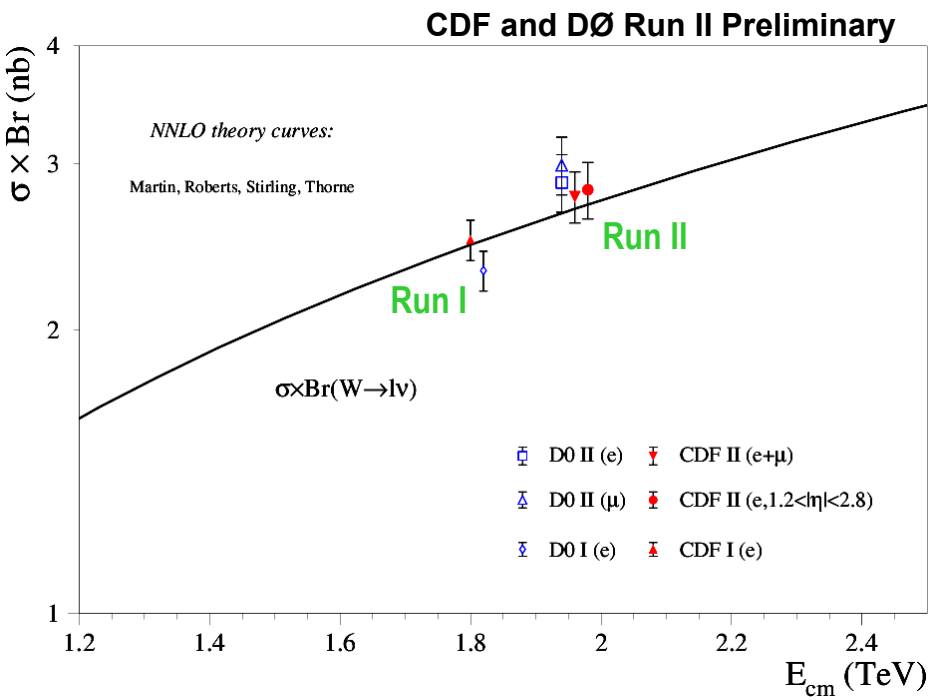
$$\sigma(p\bar{p} \to Z) \times BR(Z \to \tau\tau) =$$
$$265 \pm 20\ (\text{stat}) \pm 21\ (\text{sys}) \pm 15\ (\text{lum})\ \text{pb}$$

W/Z cross-sections: Tevatron Summary

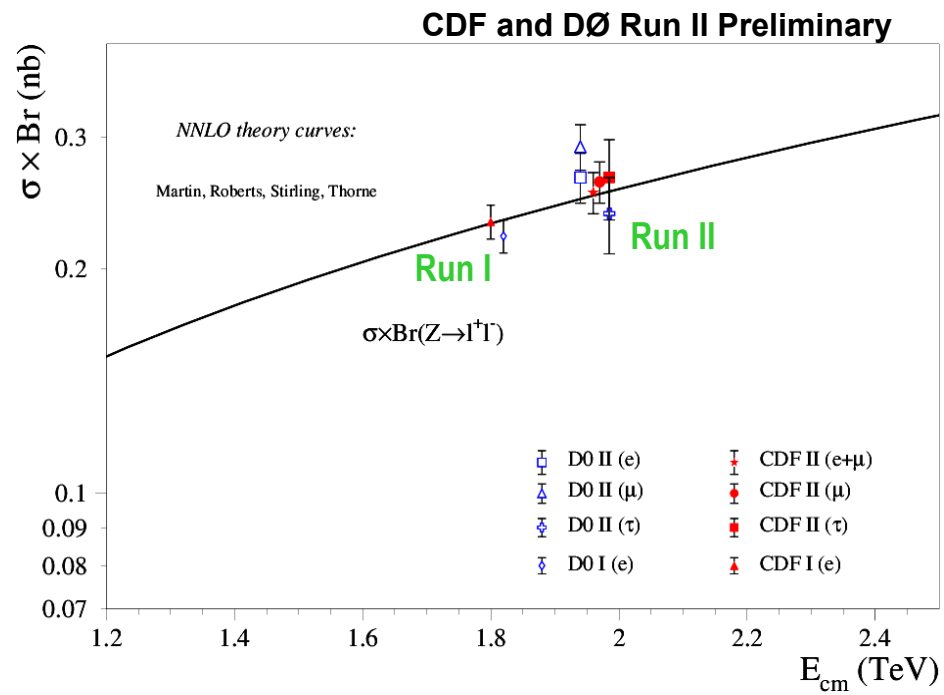
$\sigma\times$BR (pb)	DØ	CDF
$W\to\mu\nu_\mu$	$2989 \pm 15_{stat} \pm 81_{sys} \pm 194_{lum}$ (96 pb^{-1})	$2786 \pm 12_{stat}$ $+65\ -55_{sys} \pm 166_{lum}$ (194 pb^{-1} updated)
$Z\to\mu\mu$	$291 \pm 3.0_{stat} \pm 6.9_{sys} \pm 18.9_{lum}$ (148 pb^{-1})	$261.2 \pm 2.7_{stat}$ $+5.8\ -6.1_{sys} \pm 15.1_{lum}$ (337 pb^{-1} updated)
$W\to e\nu_e$	$2865 \pm 8.3_{stat} \pm 76_{sys} \pm 186_{lum}$ (177 pb^{-1})	$2780 \pm 14_{stat} \pm 60_{sys} \pm 167_{lum}$ (72 pb^{-1}) $2815 \pm 13_{stat}$ $+94\ -89_{sys} \pm 169_{lum}$ (223 pb^{-1})
$Z\to ee$	$264.9 \pm 3.9_{stat} \pm 9.9_{sys} \pm 17.2_{lum}$ (177 pb^{-1})	$255.8 \pm 3.9_{stat} \pm 5.5_{sys} \pm 15.4_{lum}$ (72 pb^{-1})
R(W/Z) $\Rightarrow \Gamma_W^{tot}$	$10.82 \pm 0.16_{stat} \pm 0.28_{sys}$ $\Rightarrow$ 2098 $\pm$ 74 MeV	$10.92 \pm 0.15_{stat} \pm 0.14_{sys}$ $\Rightarrow$ 2079 $\pm$ 41 MeV (72 pb^{-1} PRL)
SM Theory	2092.1 $\pm$ 2.5 MeV	
$W\to\tau\nu_\tau$	—	$2620 \pm 7.0_{stat} \pm 210_{sys} \pm 160_{lum}$ (72 pb^{-1})
$Z\to\tau\tau$	$237 \pm 15_{stat} \pm 18_{sys} \pm 15_{lum}$ (226 pb^{-1} PRD 71, 072004 (2005))	$265 \pm 20_{stat} \pm 21_{sys} \pm 15_{lum}$ (350 pb^{-1} updated)

Inclusive W/Z Cross-Sections

Tevatron W → ℓν cross sections



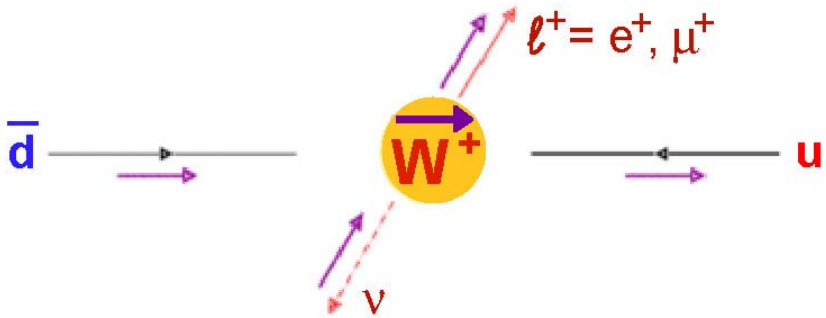
Tevatron Z → ℓℓ cross sections

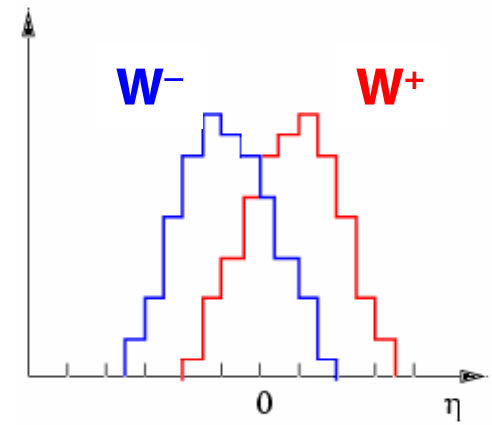


- consistent and in good agreement with NNLO theoretical calculations
- accuracy limited by systematic effects; main systematics:
  - lepton-id ~ 2-3% (for τ's: ~ 3-4%), PDF (CTEQ6) ~ 1-2%, backgrounds < 1% (for Z→ττ: ~ 4-5%)
- in general, σ × BR uncertainties dominated by luminosity measurements ~ 6%

W Production Charge Asymmetry

- many measurements at hadron colliders limited by PDF uncertainties
  - forward-backward W charge asymmetry yields important input on u and d PDF



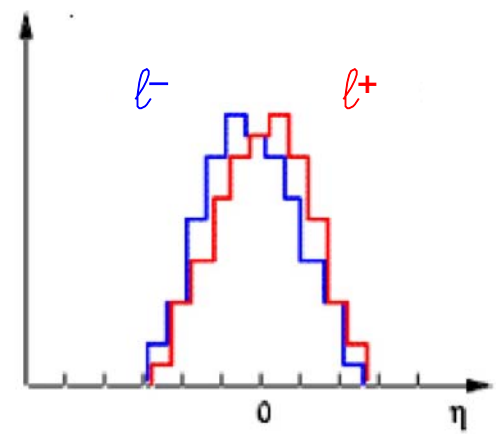


- u quarks carry higher momentum fraction than $\bar{d}$
  - ⇒ W^+ boosted in p direction, W^- in $\bar{p}$ direction

$$A(y_W) = \frac{d\sigma(W^+)/dy - d\sigma(W^-)/dy}{d\sigma(W^+)/dy + d\sigma(W^-)/dy}$$

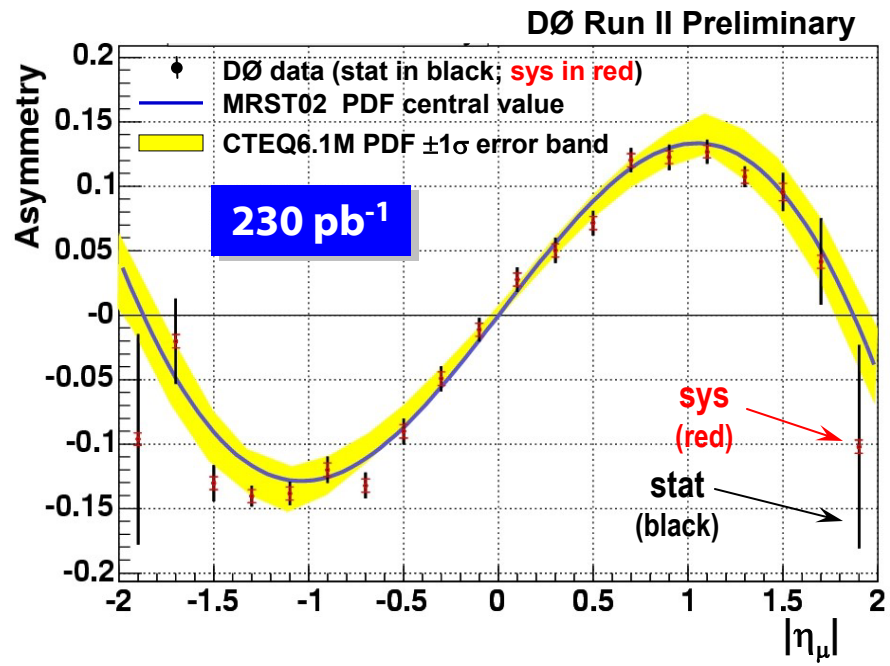
- measurable quantity is lepton charge asymmetry
  - convolution of W production asymmetry and V-A decay of W
- Charge Asymmetry factors into u and d PDF

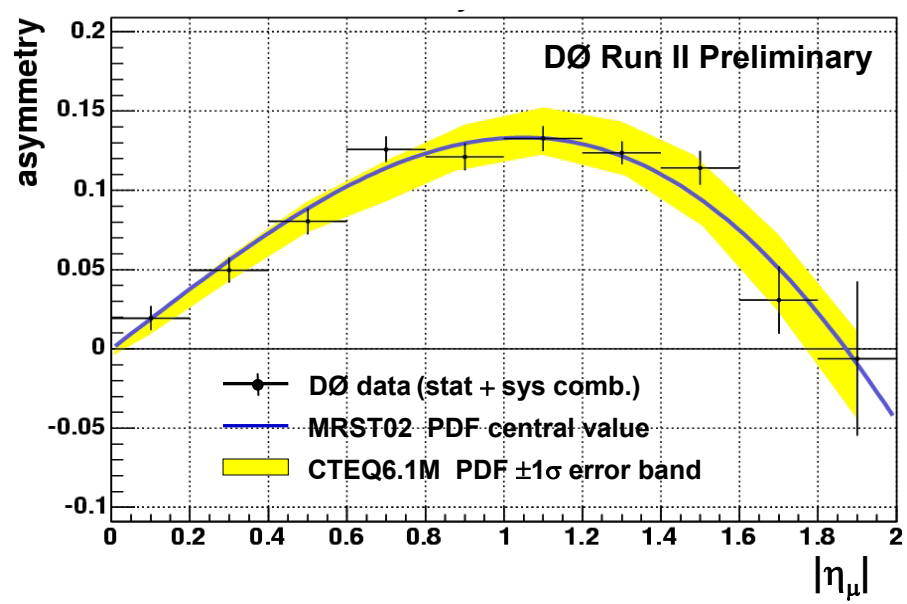
$$A(\eta_\ell) = \frac{d\sigma(\ell^+)/d\eta - d\sigma(\ell^-)/d\eta}{d\sigma(\ell^+)/d\eta + d\sigma(\ell^-)/d\eta} \approx \frac{\mathrm{d}(x)}{\mathrm{u}(x)}$$



W(→μν) Charge Asymmetry

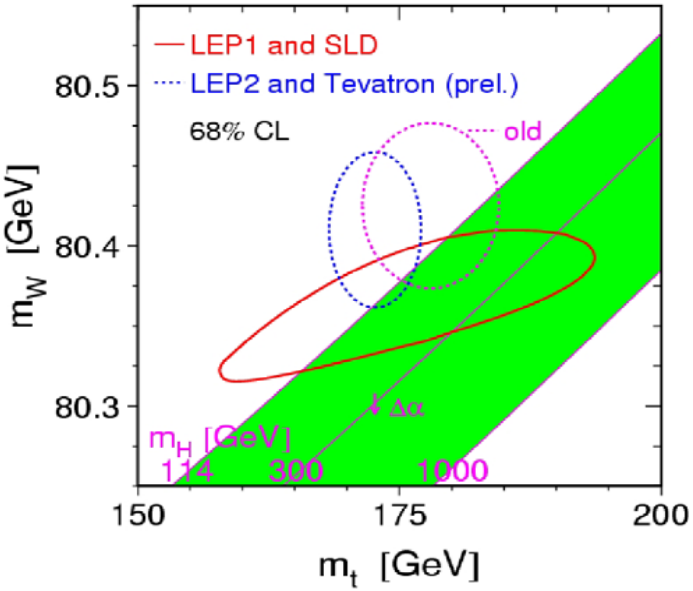
- W charge asymmetry provides new PDF constraints
  - new DØ result in W→μν channel
- widest |η| coverage desirable
  - increase acceptance at DØ by using forward μ triggers, η → 2
- require single, isolated muons similar to W→μν cross section studies
- measurement statistically limited
  - charge-id critical… mis-id probability at 0.01% for |η| ~ 2
  - CP folding to provide better statistical uncertainties





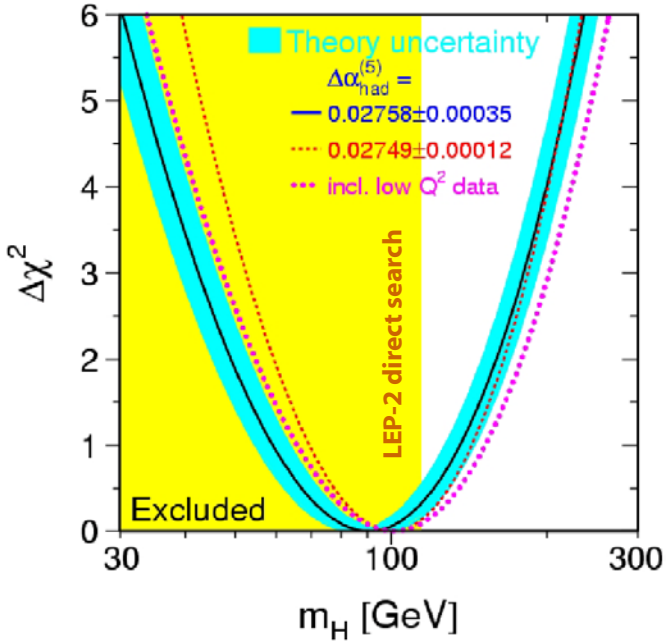
SM Higgs

- **Higgs boson is introduced in SM to explain Electroweak symmetry breaking (EWSB)**
  - **allows for differences in W, Z and γ mass**
  - **generates masses for fermions**

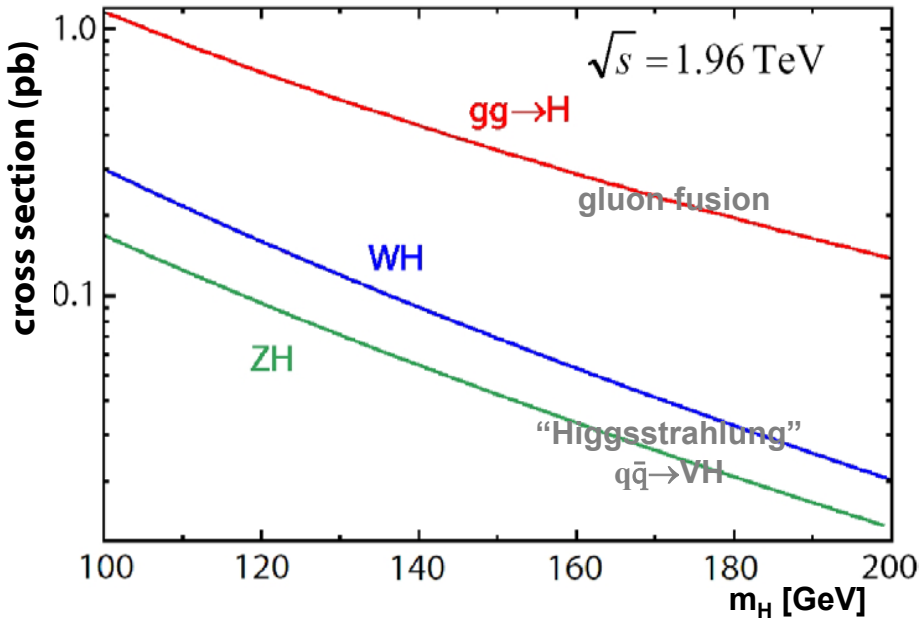


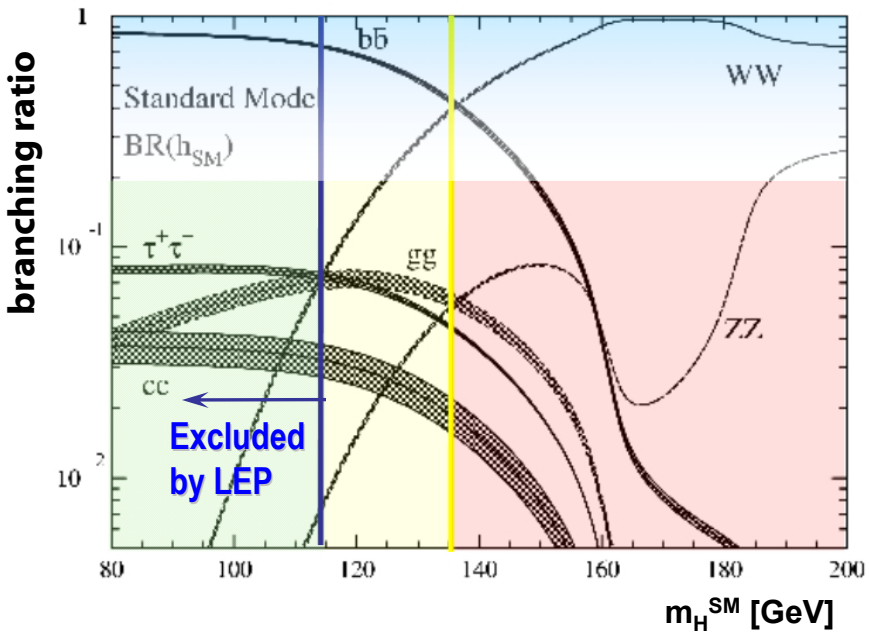
Experimental Constraints

- **Higgs couples to mass :**
  - **W and top mass measurements constrain M_H via effect of radiative corrections**
- **Direct Searches**
  - **CERN e^+e^- collider (LEP) set lower limit at $M_H > 114.4$ GeV (95% CL)**
- **Direct and indirect measurements via Global Electroweak fits**
  - **give an upper bound of $M_H < 219$ GeV (95% CL)**



Higgs Production and Decay

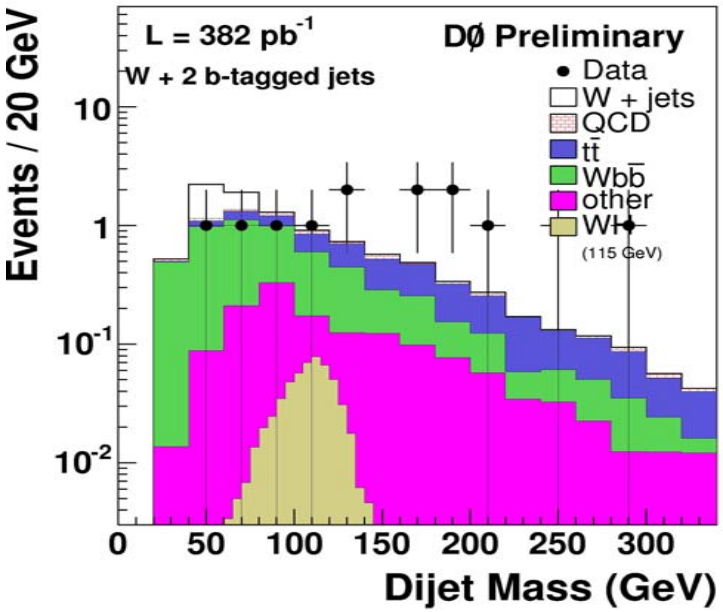




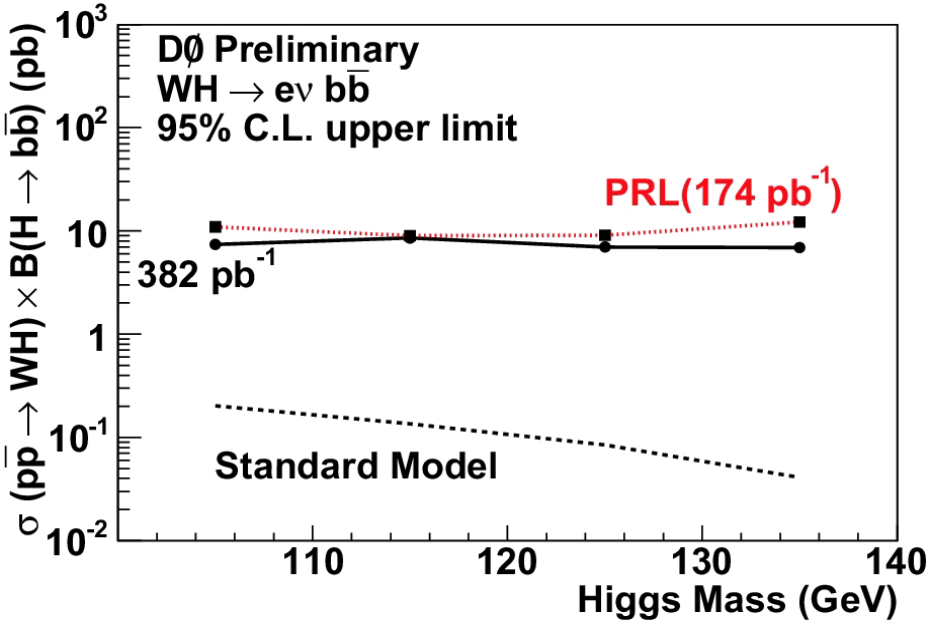
- **Two search strategies**
  - **$M_H < 135$ GeV, look for associated production with 2 b-jets from Higgs**
    - **exploit lepton-id & b-tagging**
  - **$M_H > 135$ GeV, exploit gluon fusion and reconstruct the 2 gauge bosons**
    - **focuses around lepton-id**

Higgs Search: $WH \rightarrow e^{\pm}\nu b\bar{b}$

- after gluon fusion, next largest production mode in association with W
  - DØ searches for $W \rightarrow e\nu$ plus two b-jets from Higgs
    - central, isolated electron with $E_T > 20$ GeV
    - $\not{E}_T > 25$ GeV
    - 2 tagged b-jets

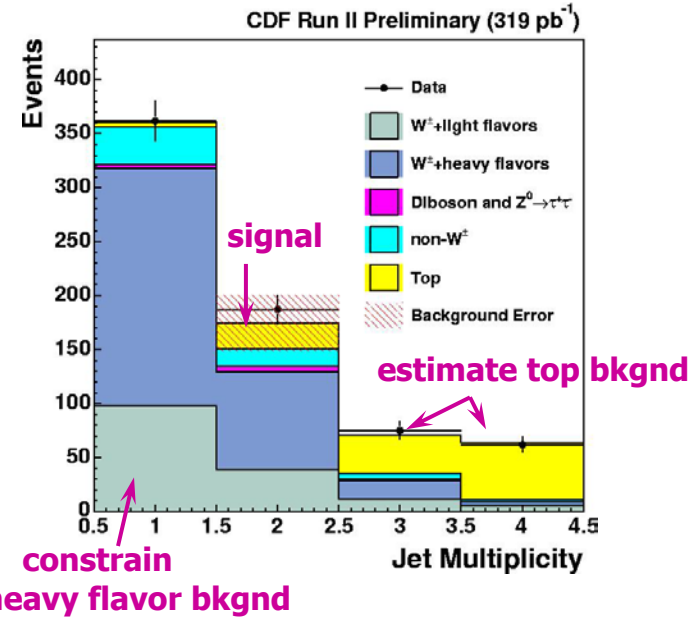


- observe 4 events in dijet mass window: $85 < M_{b\bar{b}} < 135$ GeV
  - 2.37 ± 0.59 expected from background
  - 95% CL upper limit on cross-section at 8.6 pb (M_H=115 GeV)

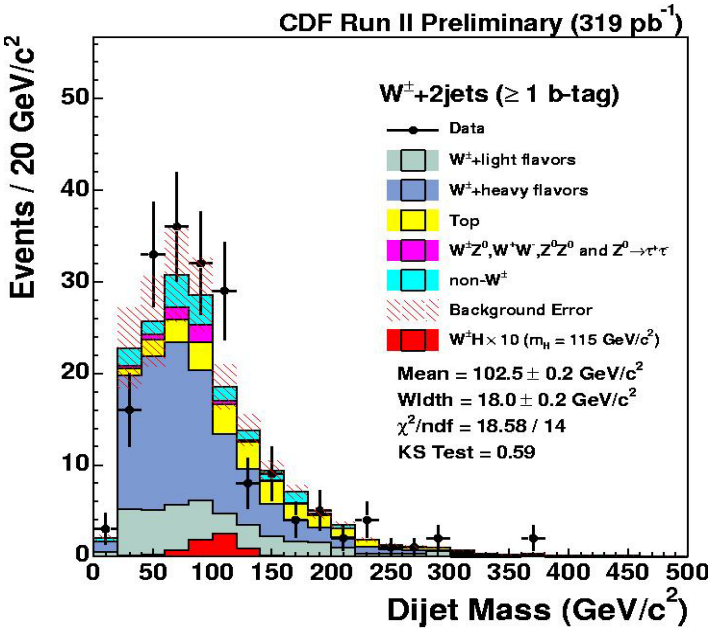


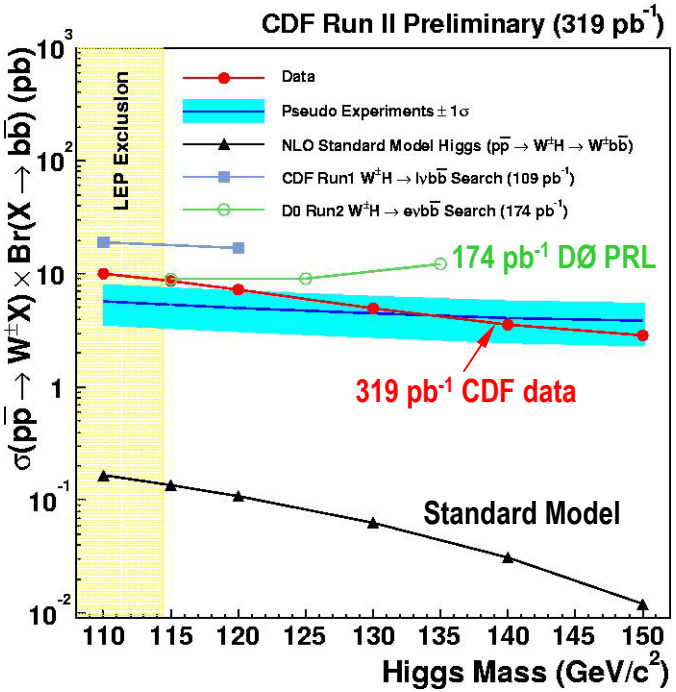
$WH \rightarrow \ell^{\pm}\nu b\bar{b}$

- CDF searches for $W \rightarrow e, \mu$ associated production
  - isolated lepton: $E_T^e > 20$ GeV, $p_T^{\mu} > 20$ GeV
  - $\not{E}_T > 20$ GeV
  - two taggable jets (require 1 or 2 b-tags)
- remaining events classified by jet multiplicities



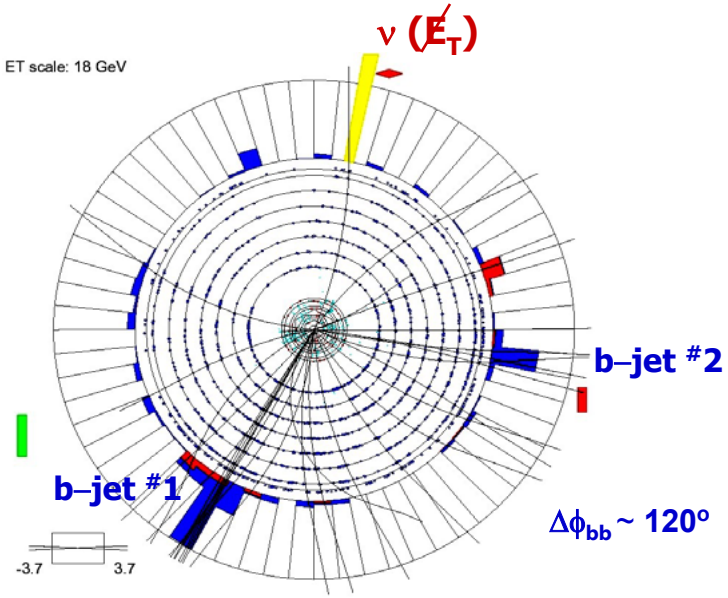
- 95% CL cross section upper limits
  - pseudo experiments $\Rightarrow$ determine expected performance in absence of signal $\Rightarrow$ include only background contributions



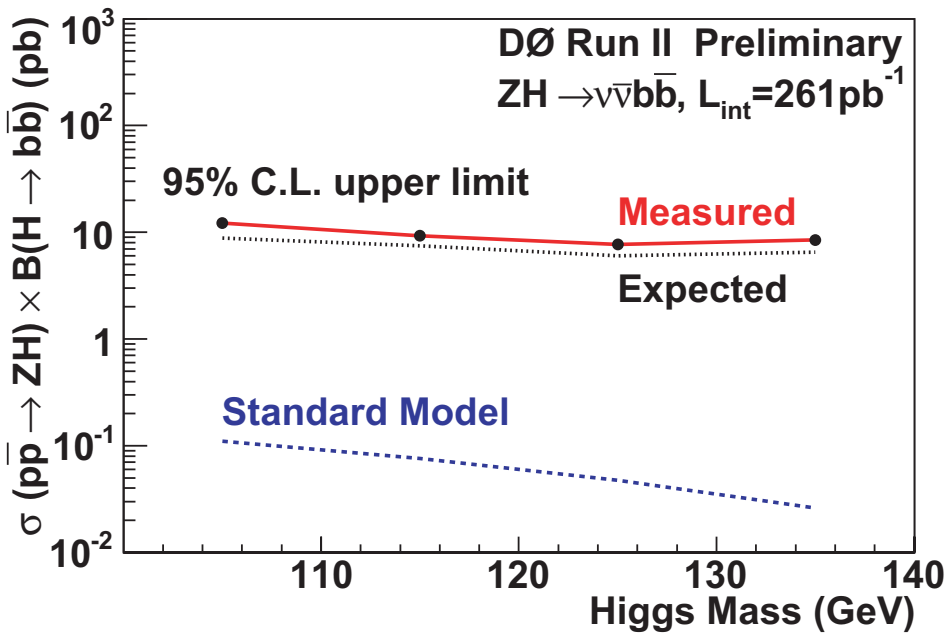


Missing E_T Channel: $ZH \rightarrow \nu\bar{\nu}b\bar{b}$

- very sensitive channel for Higgs search due to large branching ratio of $Z \rightarrow \nu\nu$
  - distinct signature
    - 2 b-jets boosted along Higgs momentum direction $\Rightarrow$ acoplanar *vs.* typical back-to-back QCD jets
  - backgrounds
    - W/Z + jets, WZ, ZZ, $t\bar{t}$
    - instrumental: multijet events with jets misidentified $\Rightarrow$ reduced by track and asymmetry cuts



- observe 3 events in dijet mass window: $80 < M_{b\bar{b}} < 130$ GeV
  - 2.2 ± 0.7 expected from background
  - 95% CL upper limit on cross-section at 9.3 pb ($M_H = 115$ GeV)



Missing E_T Channel: $ZH \rightarrow \nu\bar{\nu}b\bar{b}$

- CDF selects events based on
  - 2 jets, each with $E_T > 25$ GeV
  - minimum 1 b-tag
  - $\not{E}_T > 70$ GeV
    - reduce effects of jet or lepton mismeasurement

	ZH_{SM} 120 GeV	Total bkg	Data
Before mass window cut	0.16	19.7	19
Mass cut (for M_H=120 GeV)	0.13	4.36	6

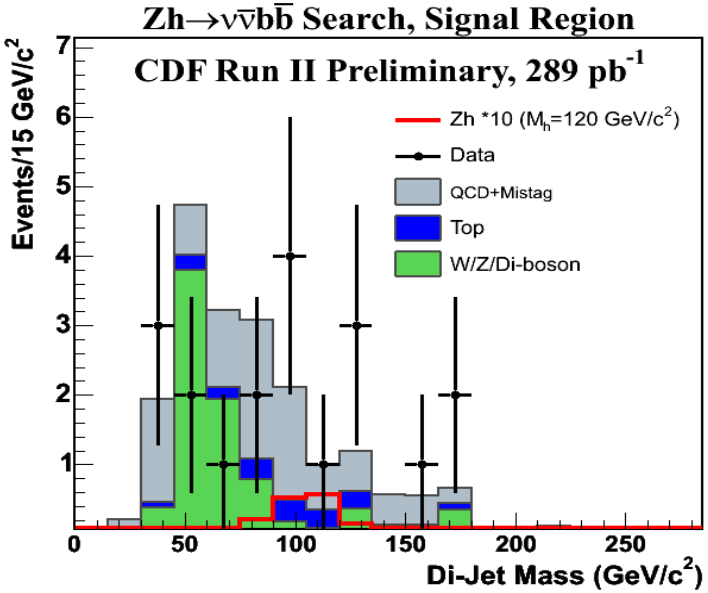
- apply mass window cuts to dijet invariant mass
  - for 120 GeV Higgs: 80 – 120 GeV window
    - observe 6 events
    - SM background prediction: 4.36 ± 1.02 events

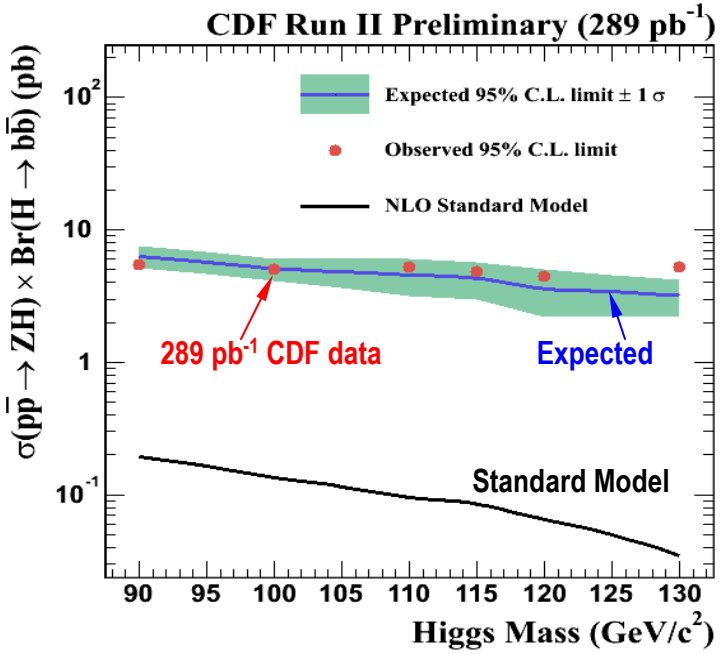
- establish 95% CL cross section upper limits
  - expected limit (M_H = 120 GeV)

$$\sigma(ZH)\cdot BR(H\rightarrow b\bar{b}) < 3.6 \pm 1.4\, pb$$

  - observed limit (M_H = 120 GeV)

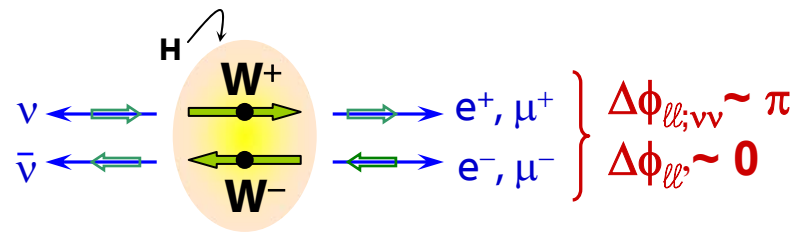
$$\sigma(ZH)\cdot BR(H\rightarrow b\bar{b}) < 4.5\, pb$$

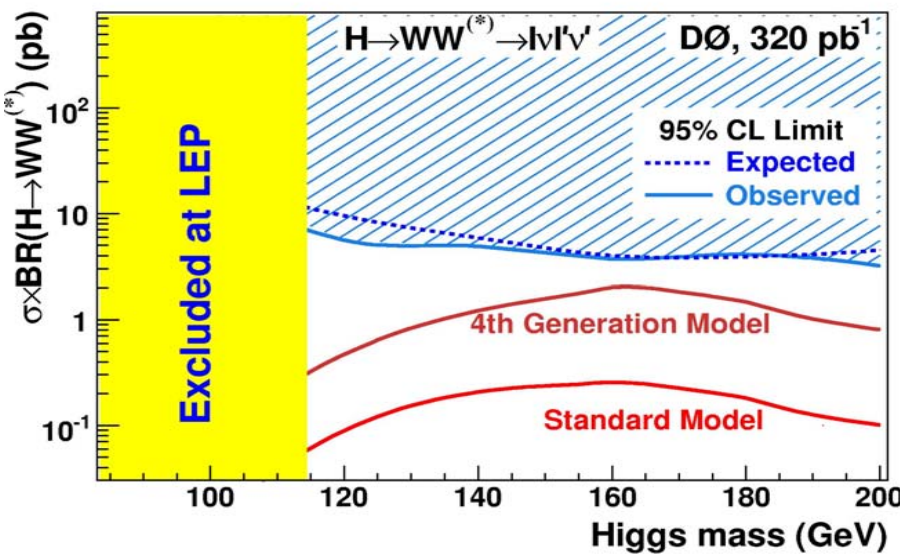




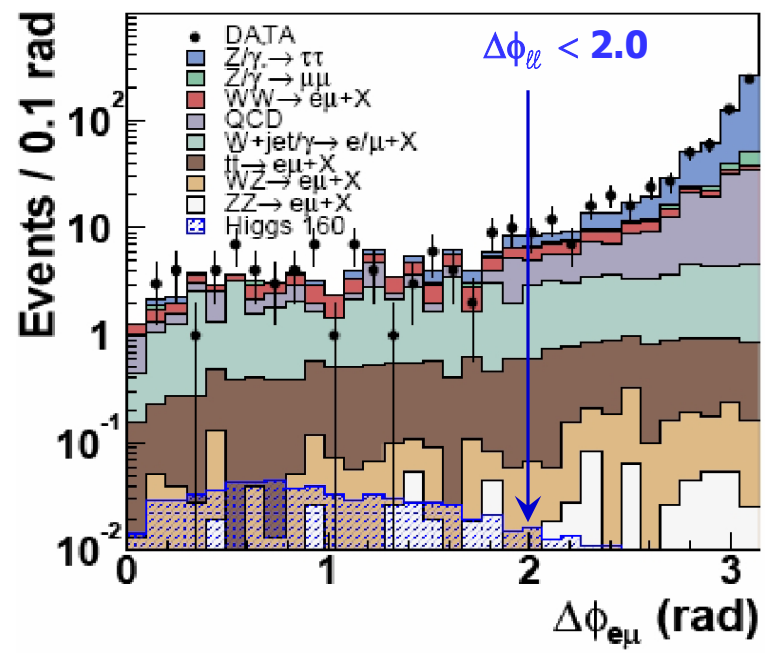
$H \rightarrow WW^* \rightarrow \ell^{\pm}\nu\ell'^{\mp}\nu$

- **dominant production mode for high mass Higgs**
  - **3 decay channels: isolated, opposite-sign dileptons: e^+e^-, $e^{\pm}\mu^{\mp}$, $\mu^+\mu^-$**
  - **several backgrounds: WW, WZ, ZZ, Z/γ^*, W + jets, W + γ, $t\bar{t}$, multijets**
    - **scalar Higgs spin correlation $\Rightarrow$ two leptons from $H \rightarrow WW^*$ emitted in-parallel and with opening angle $\Delta\phi_{\ell\ell} < 2.0$ *vs.* back-to-back multijet background**
    - **$\Delta\phi$(leptons, ν's) ~ 180° $\Rightarrow$ invariant mass for dileptons constrained to $M_H/2$**





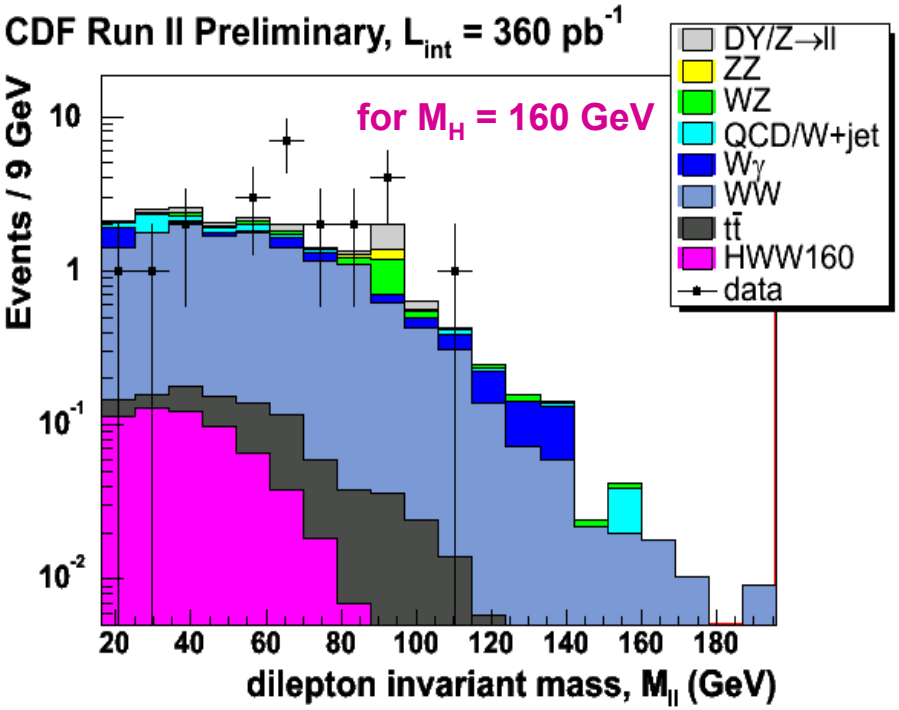
M_H (GeV)	100	120	140	160	180	200
Expected limits (pb)	20.3	9.5	5.9	4.0	3.9	4.5
Observed limits (pb)	18.5	5.6	4.9	3.7	4.1	3.2

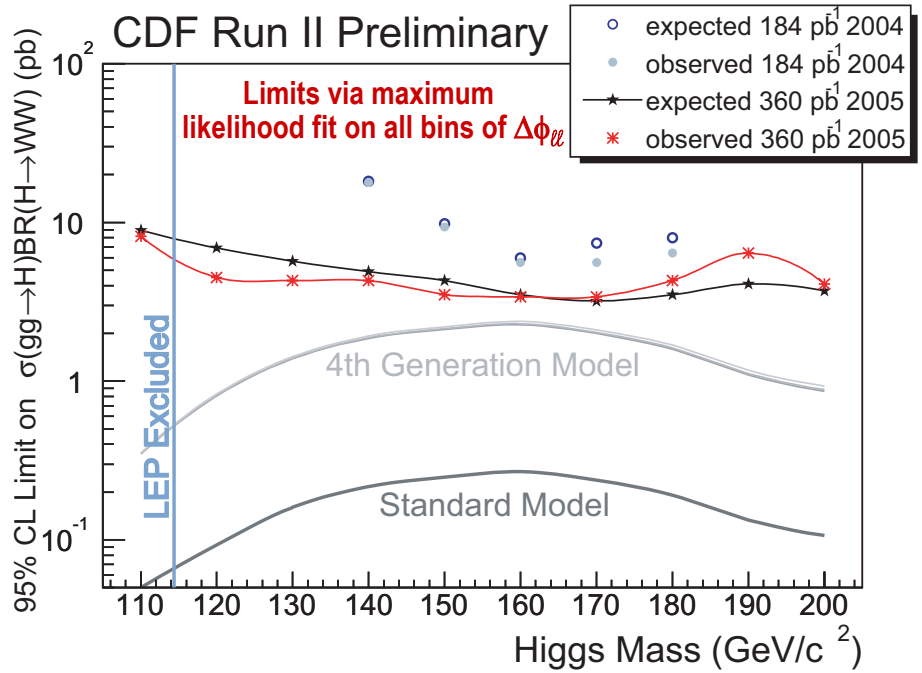


PRL 96, 011801 (2006)

$H \rightarrow WW^* \rightarrow \ell^{\pm}\nu\ell'^{\mp}\nu$

- **CDF updated result, based on 360 pb^{-1} data**
  - **use similar discriminating variables as DØ**
    - **small dilepton opening angle**
    - **low dilepton invariant mass $\Rightarrow$ constrained to $M_H/2$**





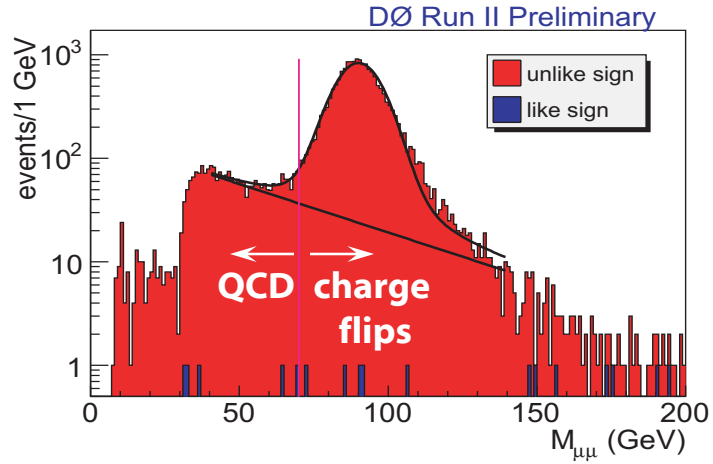
Number of Events for M_H = 160 GeV

Diboson bkgnd (WW, WZ, Wγ)	10.2 ± 1.0
Other backgrounds	3.6 ± 0.7
Total backgrounds	13.8 ± 1.2
Expected Signal (H→WW*)	0.58 ± 0.04
Observed (data)	16

M_H (GeV)	120	130	140	160	180	200
Expected limits (pb)	6.9	5.7	4.8	3.5	3.4	3.6
Observed limits (pb)	4.5	4.4	4.6	3.2	4.3	4.6

WH → WWW* → $\ell^{\pm}\nu\ell^{\pm}\nu q\bar{q}$

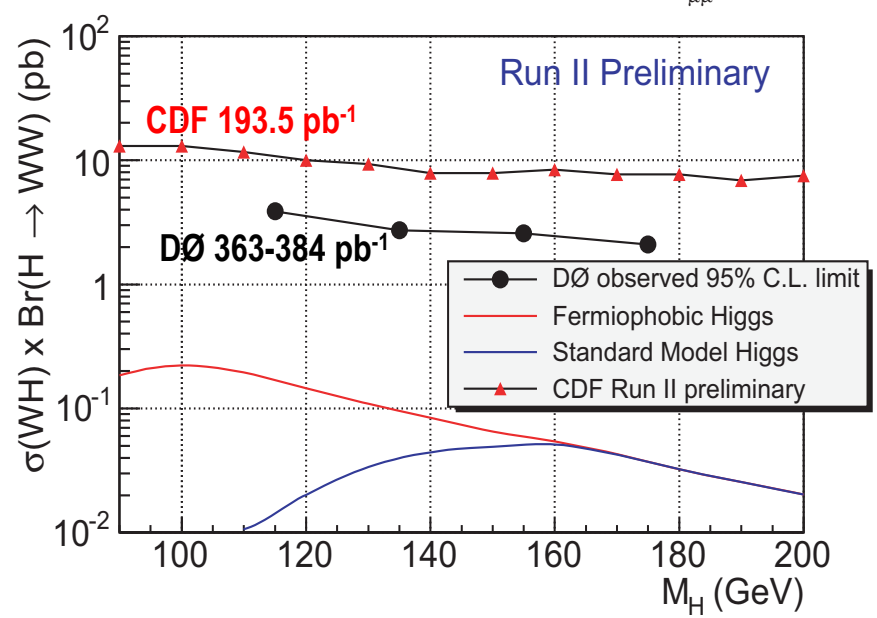
- signature of associated Higgs production requires like-sign dileptons (e, μ)
  - sign of one of W's from Higgs decay = sign of lepton from the associated W
  - avoids large SM backgrounds as in direct H→WW* searches
- here, main backgrounds
  - physics (WZ → $\ell\nu\ell\ell$ with one lepton lost from Z)
  - charge flips (mainly from Z/$\gamma^*\to\ell\ell$)
  - QCD (b-jets, punch-through hadrons, $\gamma\to e$)



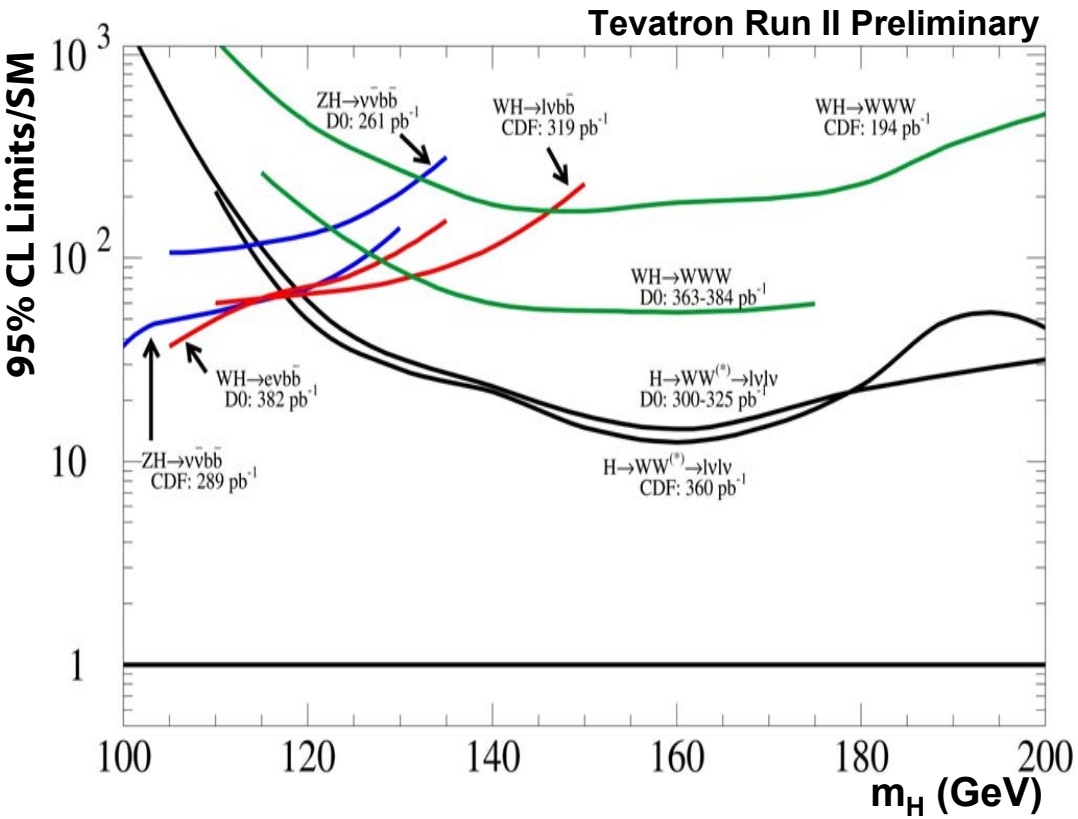
DØ Events:	ee	eμ	μμ
Observed in data	1	3	2
WZ physics bkg	0.43±0.03 ★	0.33±0.03	0.16±0.03
charge flips	0.20±0.06	0.05±0.03	3.40±0.73 ★
QCD bkg	0.07±0.04	3.94±0.23 ★	0.16±0.18
total background	0.70±0.08	4.32±0.23	3.72±0.75

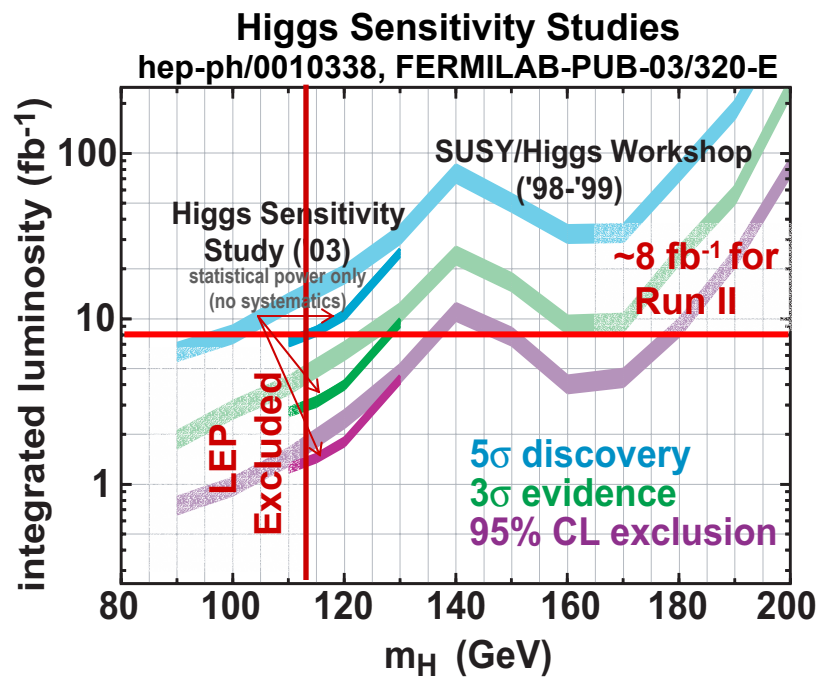
(★ largest contribution)

- DØ: uses data to estimate both QCD and background probability due to "charge flips"
- CDF: divides data into control and signal regions based on 1st, 2nd leading lepton p_T
  - observe 0 events, 0.95 ± 0.80 expected
  - 95% CL: 12 → 8 pb (M_H = 110 → 160 GeV)



Where are we today and where are we going?





- expected sensitivity as predicted by 2003 sensitivity study has not been reached
- can bridge gap between current limits and SM predictions by
  - optimizing analyses techniques
  - adding/combining channels
  - combining results from experiments
  - using more data
- differences appear to be recoverable

Summary

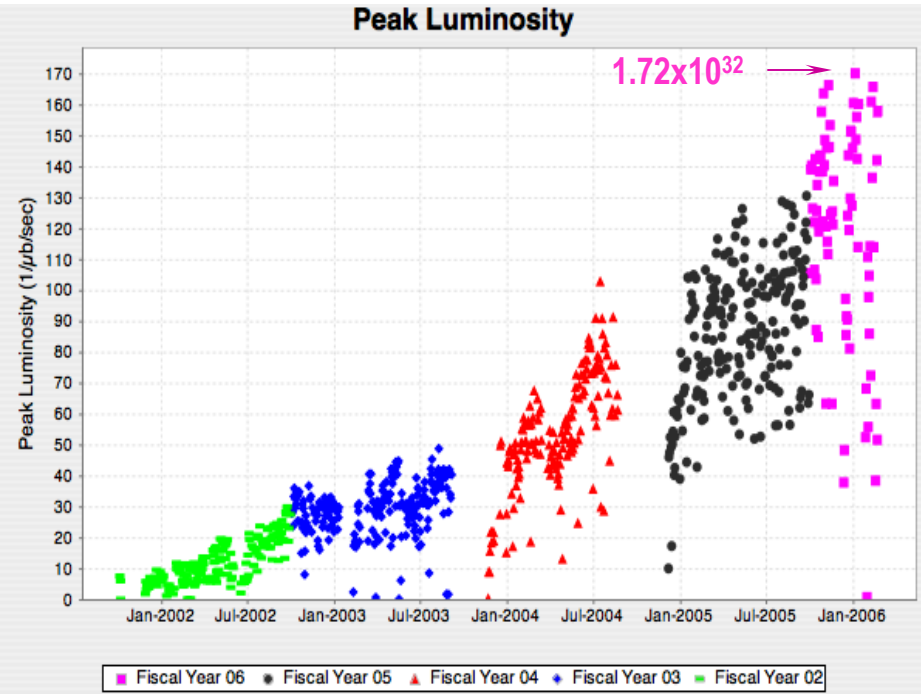
- Tevatron EW measurements reaching a few % precision
  - all results in good agreement with SM
  - due to time, many results could not be presented here: CDF's, DØ's Z/γ^* forward-backward asymmetry, DØ's Z/γ^* $d\sigma/dM$ and $d\sigma/dY$
  - lay the foundation for understanding other important processes

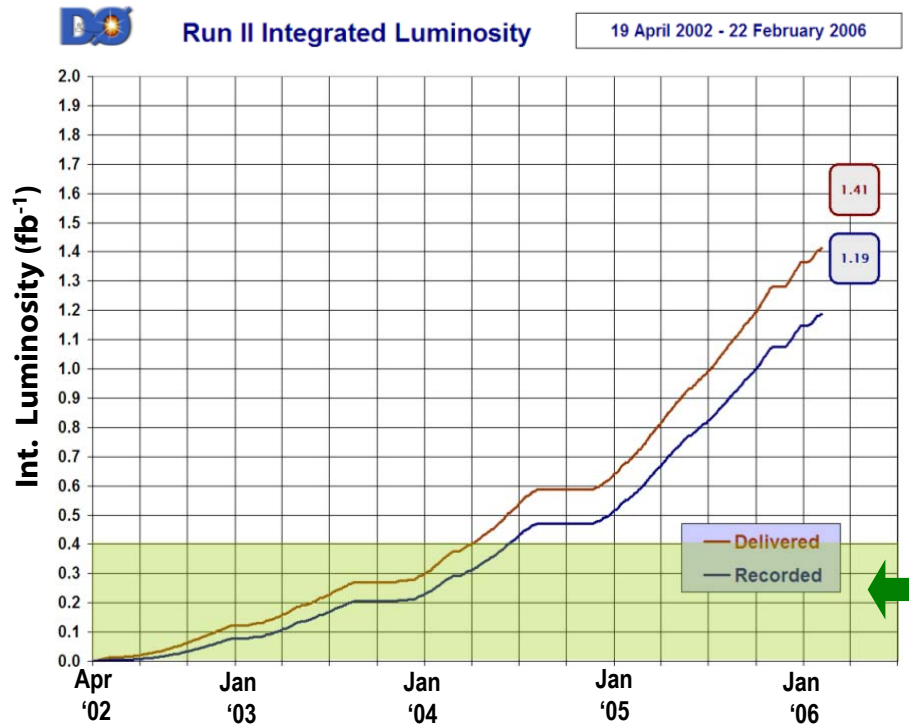
- SM Higgs
  - 95% CL limits established for a comprehensive set of search channels
  - analyses are trying to reach sensitivity outlined by sensitivity studies
    - combining channels as well as using advanced analysis methods underway

More than 1 fb^{-1} data is being studied by experiments and results expected by this summer!

Reference Slides

Tevatron Performance



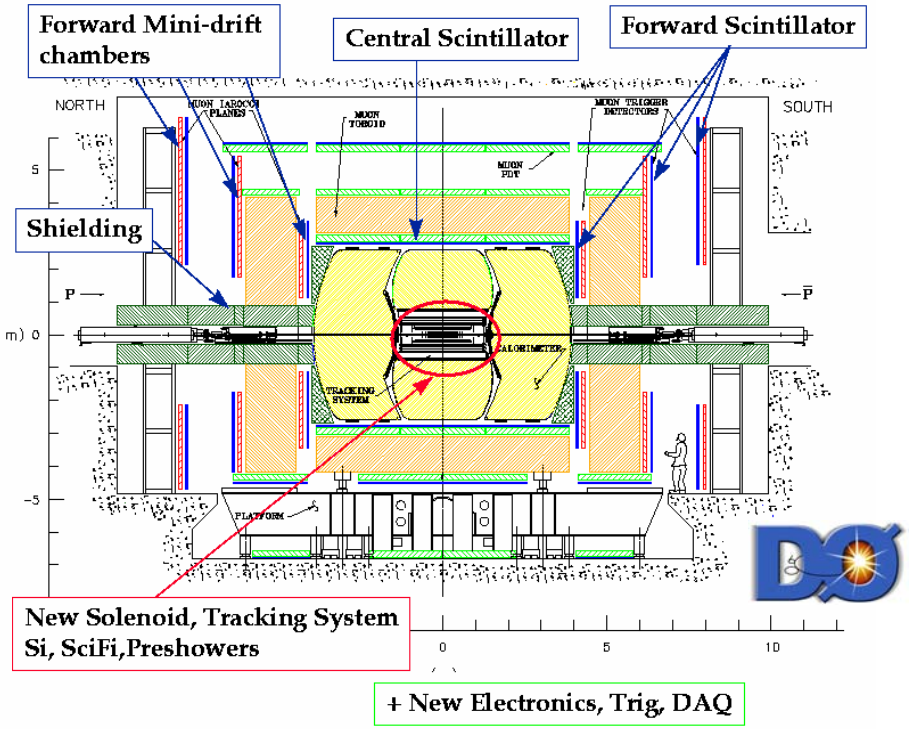


- **Tevatron Collider with both DØ and CDF operating successfully**
- **Tevatron delivered $\int \mathcal{L}\, dt \rightarrow 1.4\ fb^{-1}$**
  - **recorded ~ 1.2 fb^{-1} per experiment**
  - **peak luminosities > $1 \times 10^{32}\ cm^{-2}\ s^{-1}$**
  - **weekly integrated luminosity ~ 25 pb^{-1}/week**

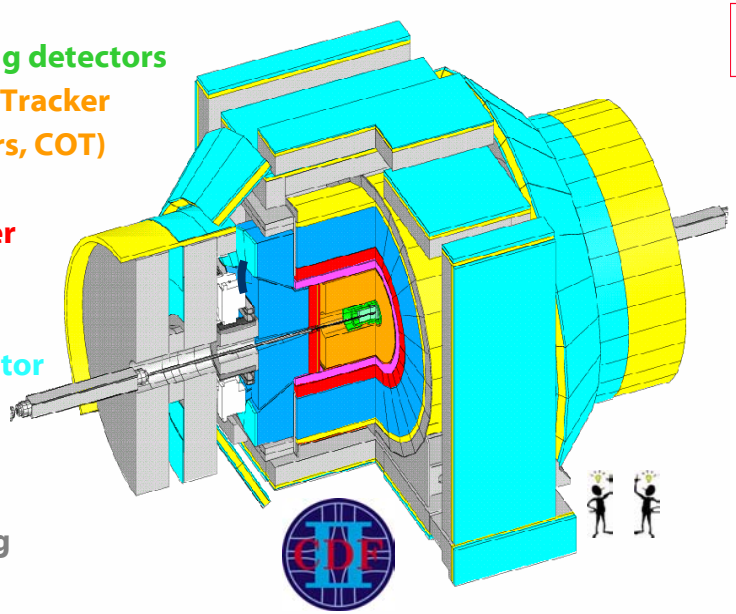
  - **datasets used for results reported here range from ~ 0.1 to 0.4 fb^{-1}**

Detectors

- silicon detector and scintillating fiber tracker in 2.0 T solenoidal field
- liquid argon/uranium calorimeters: central (CC) and two forward, end (EC) calorimeters
- muons: scintillators and mini-drift tubes, coverage up to $\eta = 2.0$



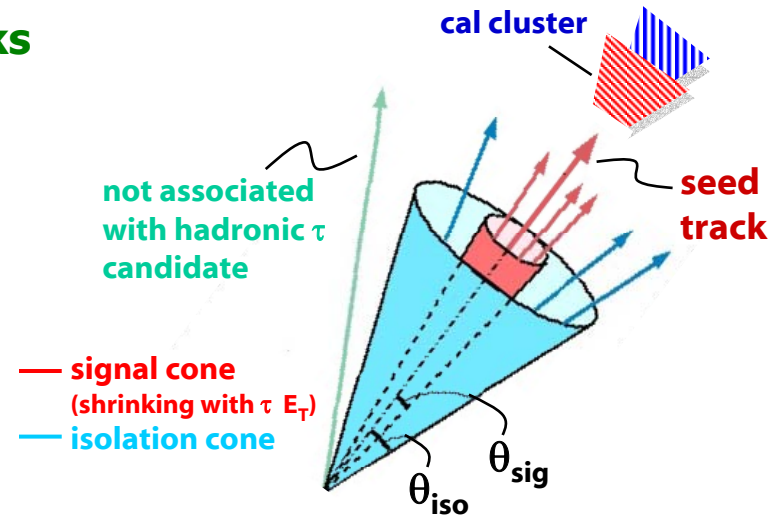
- Silicon tracking detectors
- Central Outer Tracker (drift chambers, COT)
- Solenoid Coil
- EM calorimeter
- Hadronic calorimeter
- Muon scintillator counters
- Muon drift chambers
- Steel shielding



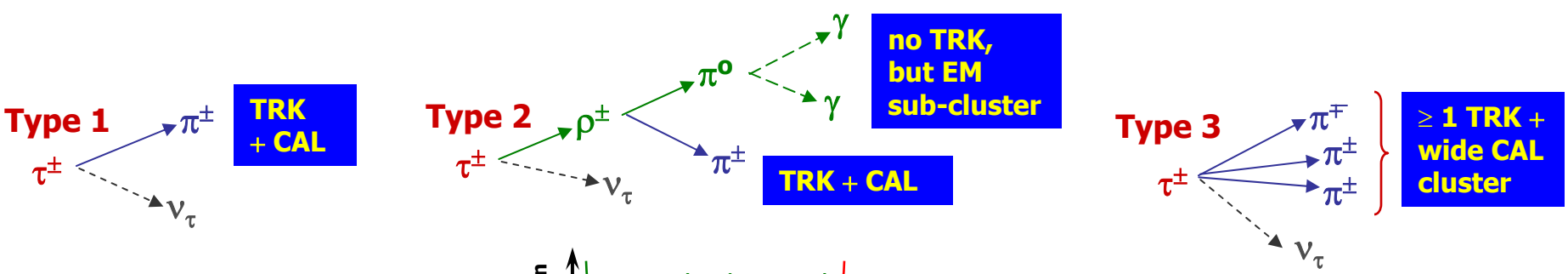
- silicon and central outer tracker system in 1.4 T magnetic field
- lead (iron) scintillating calorimeter for EM (hadronic) showering
- forward end-plug cal, $\eta \rightarrow 3.0$
- muon coverage to $\eta = 1.0$

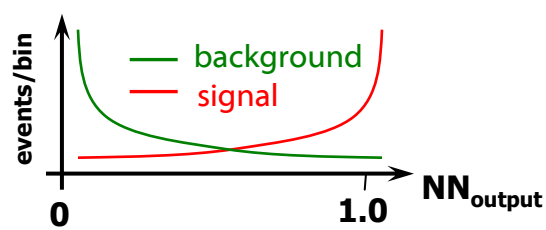
Towards $\sigma \times BR(Z \to \tau\tau)$: τ-identification

- narrow calorimeter clusters matched to tracks
  - define signal and isolation cones around seed track (= highest p_T track)
  - # of tracks inside signal cone = τ decay mode
  - add π^o info to track – cal cluster $\Rightarrow$ consistent with τ mass
  - EM-fraction < 0.8 $\Rightarrow$ remove electrons
  - τ-id based on "cuts" to key variables



- narrow calorimeter energy clusters matched to tracks
- separate τ's into 3 categories, defined by their decay mode
  - π-like (type 1), ρ-like (type 2), and 3-prongs (type 3)
  - implement neural nets (NN) for each τ-type to discriminate τ signal from QCD jets

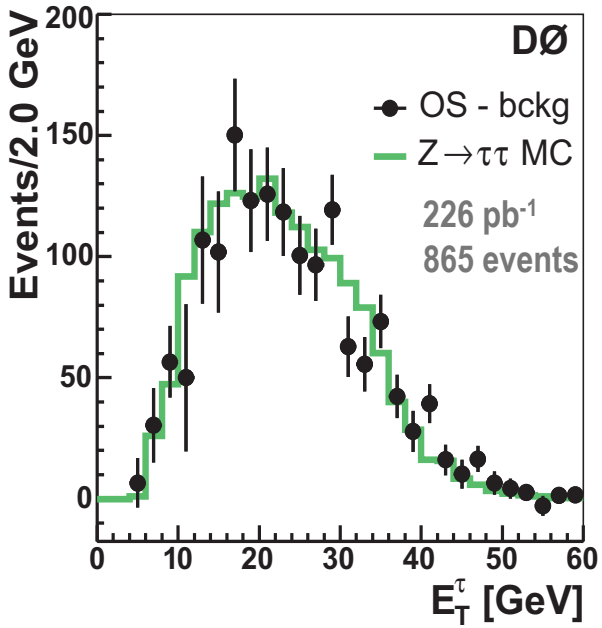


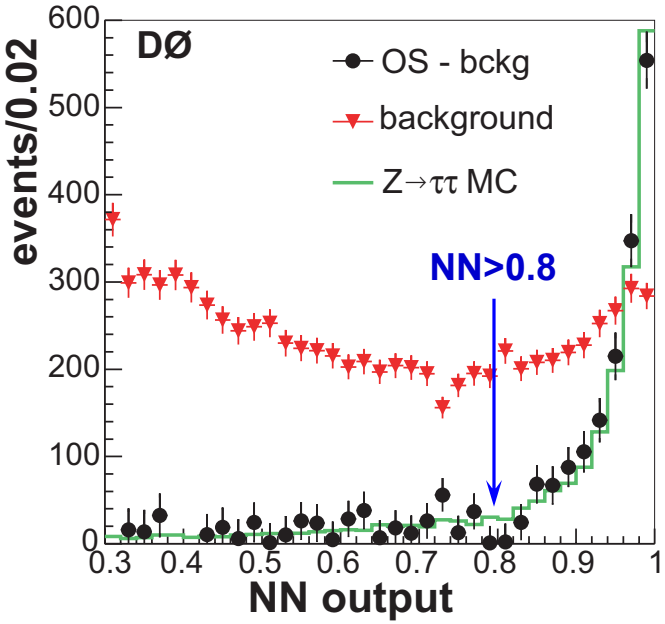


$Z \to \tau_\mu \tau_h$ Cross Section

- consider channel $\tau_1 \to \mu$ + $\tau_2 \to$ had or e
  - $p_T^\mu > 12$ GeV, $E_T^\tau > 10$ GeV (τ-types 1, 3), $E_T^\tau > 5$ GeV (τ-type 2), $|\eta^\tau| < 3.0$
  - select back-to-back $\mu\tau$ pairs ($|\phi_\mu - \phi_\tau| > 2.5$)
  - split $\mu\tau$ data sample into opposite sign (OS) and same sign (SS)
    - OS $\Rightarrow$ signal and SS $\Rightarrow$ estimate QCD background

2008 OS events with NN > 0.8; QCD ~ 46%, $W \to \mu\nu + Z \to \mu\mu$ ~ 6%
$\int \mathcal{L}\, dt = 226$ pb^{-1}

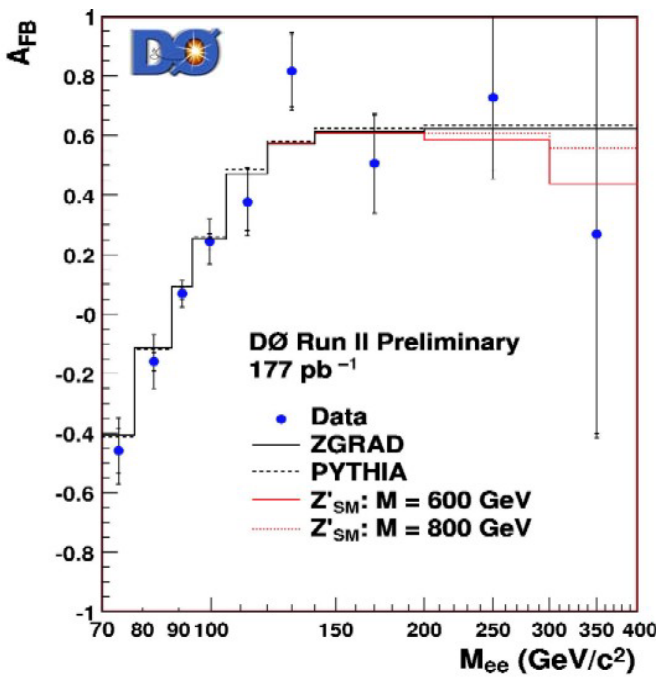


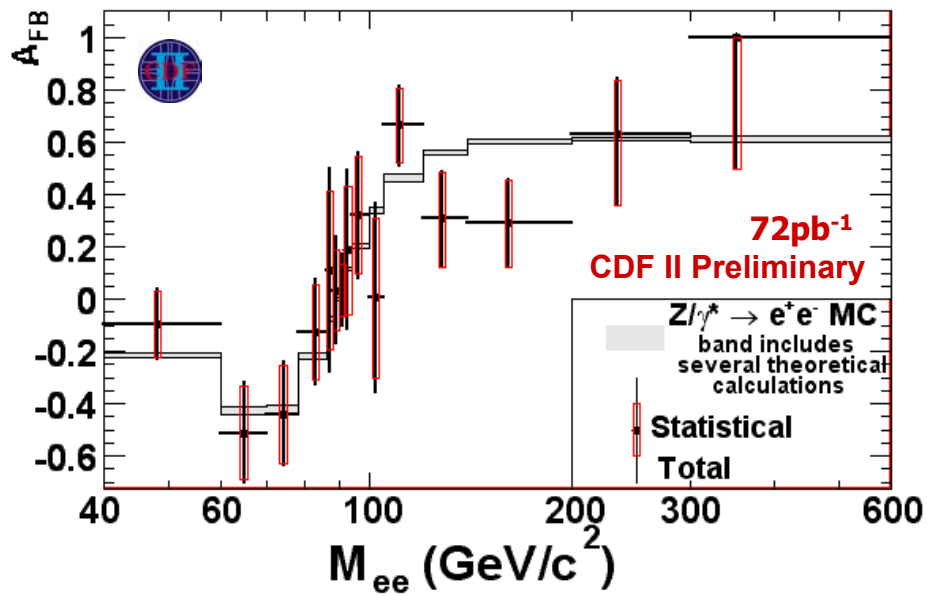


$\sigma(p\bar{p} \to Z) \times BR(Z \to \tau\tau) = 237 \pm 15$ (stat) ± 18 (sys) ± 15 (lum) pb
PRD 71, 072004 (2005)

$Z/\gamma^* \rightarrow ee$ Forward-Backward Asymmetry (A_{FB})

- **Interference between Z and γ^* exchanges**
  - $d\sigma/d\cos\theta = A(1+\cos^2\theta) + B\cos\theta$ with $B \neq 0$
    - introduces asymmetry in polar emission angle of leptons in $\ell^+\ell^-$ rest frame
  - $A_{FB} = 3B/8A = \sigma(\theta > 0) - \sigma(\theta < 0) / \sigma(\theta > 0) + \sigma(\theta < 0)$
    - interference of vector and axial couplings change with mass
    - A_{FB} changes with invariant mass $\Rightarrow$ SM value of 0.6 at high invariant mass
    - new resonances (*e.g.*, neutral gauge bosons) can alter A_{FB}

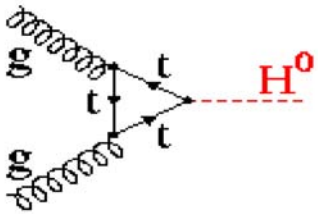




- **Distributions consistent with SM expectations**

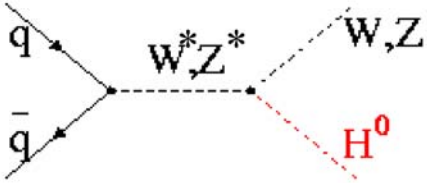
SM Higgs Production Processes

- **Gluon fusion: $gg \rightarrow H$**



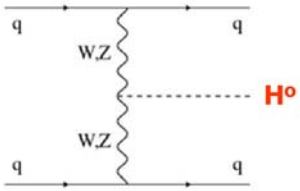
$\sigma = 0.70$ pb
for M(H) = 120 Gev/c^2
with QCD NLO correction

- **Higgsstrahlung: $q\bar{q} \rightarrow VH$**



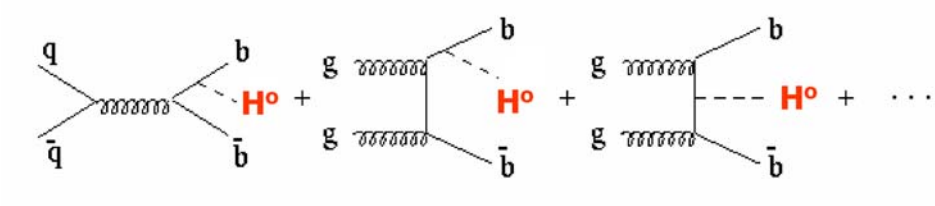
WH: σ = 0.16 pb
ZH: σ = 0.10 pb

- **Vector Boson fusion: $q\bar{q} \rightarrow q\bar{q}H$**



$\sigma = 0.10$ pb

- **Radiation off heavy quark: $q\bar{q} \rightarrow t\bar{t}H$, $b\bar{b}H$**

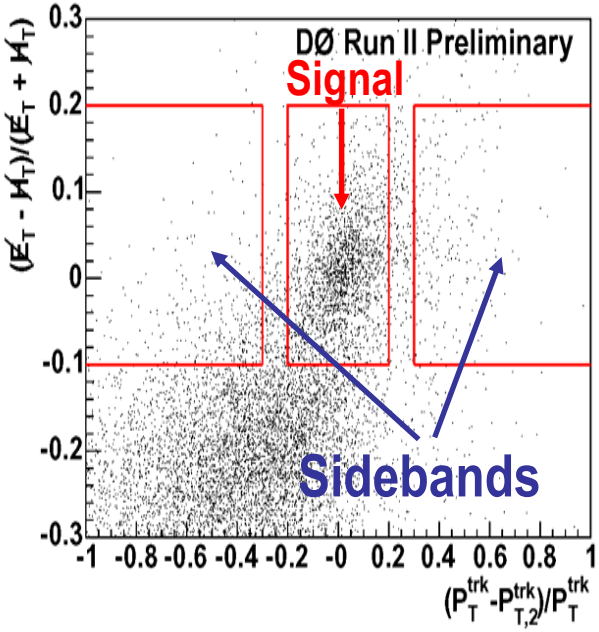


$\sigma = 0.004$ pb

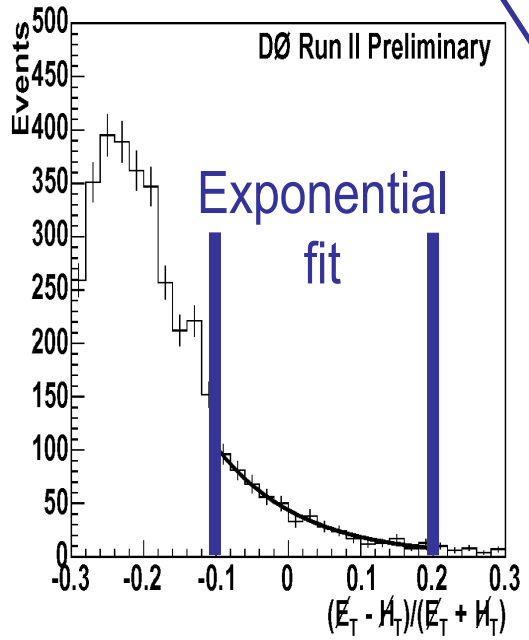
Higgs Search: Missing Energy Channel (DØ)

- Require large $\not{E}_T$ & acoplanar (non back-to-back) jets
- Instrumental backgrounds reduced by track and asymmetry cuts
  - Asymmetries computed: Asym($\not{E}_T$,$\not{H}_T$) and Asym(p_T^{trk},p_{T2}^{trk})

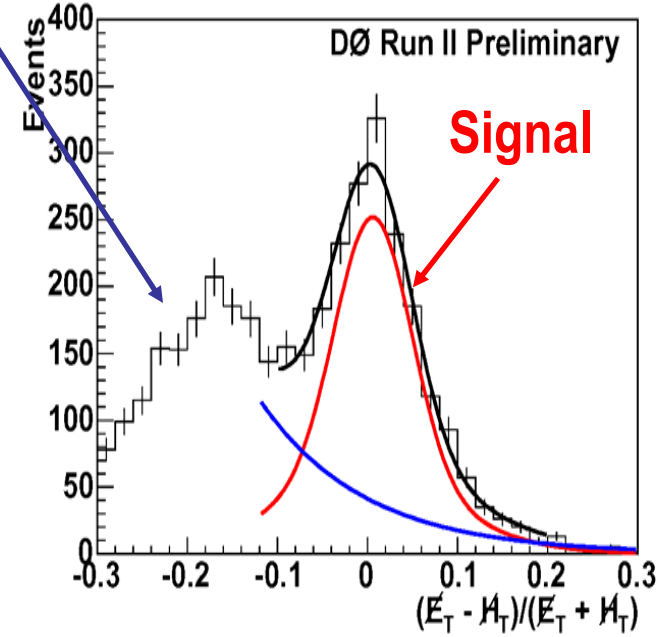
Data



Instr. Background from Sidebands (Data)

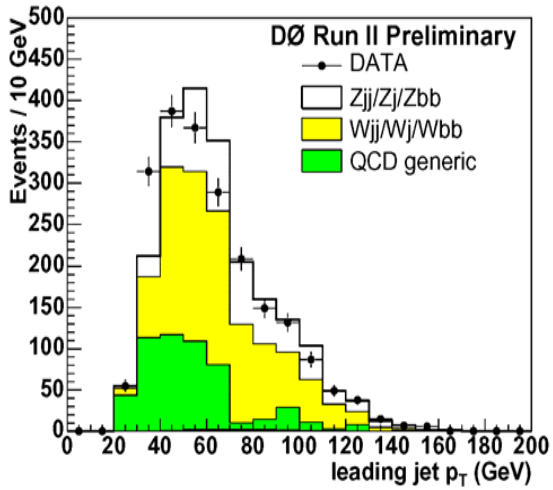


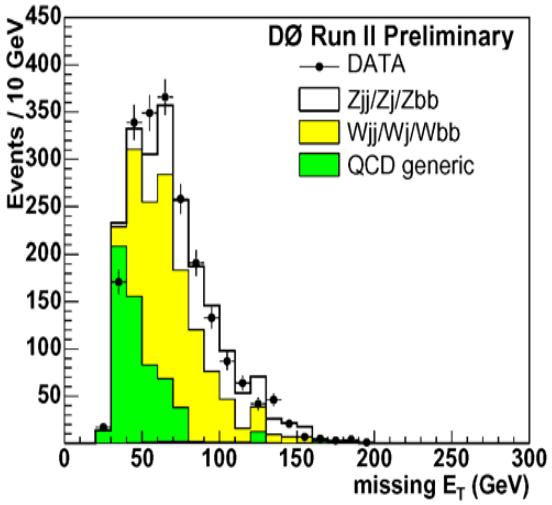
Data in signal region



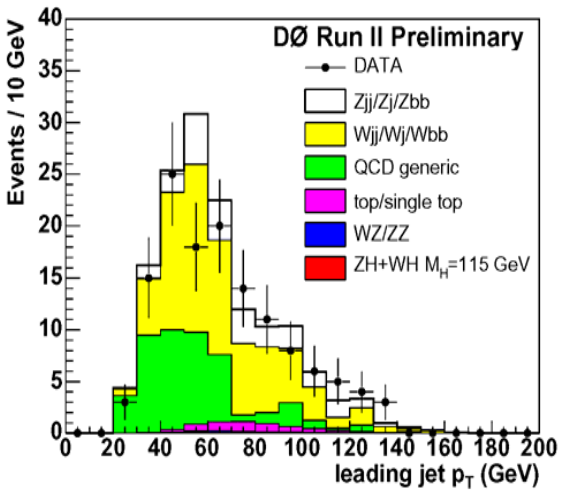
Higgs Search: Missing Energy Channel (DØ)

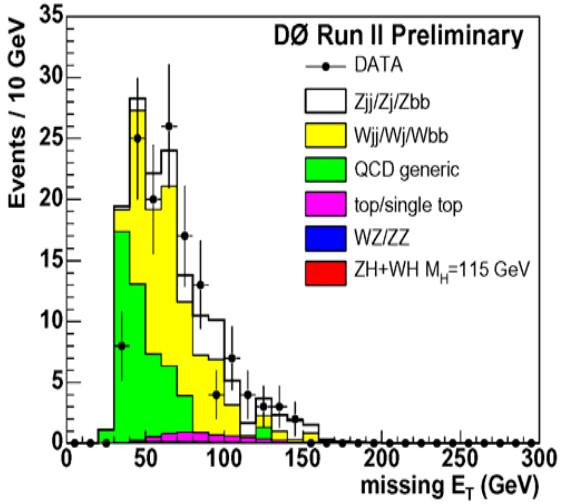
No b-tag



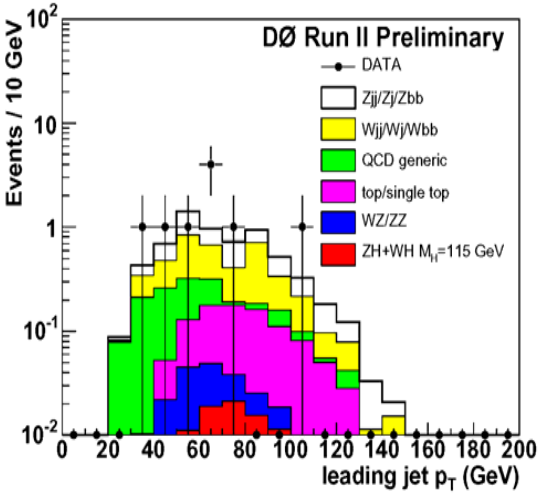


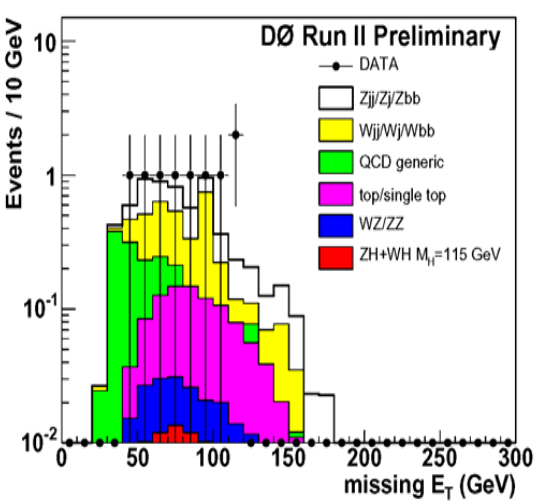
Single b-tag





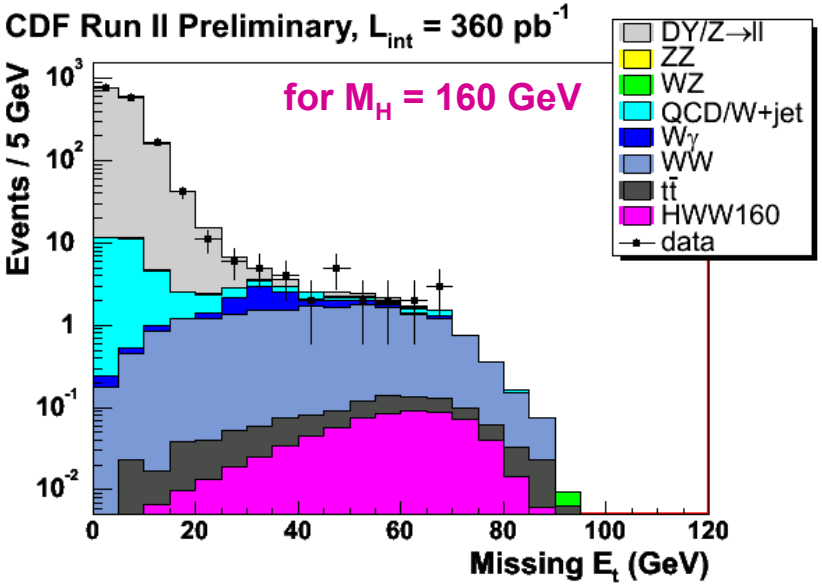
Double b-tag

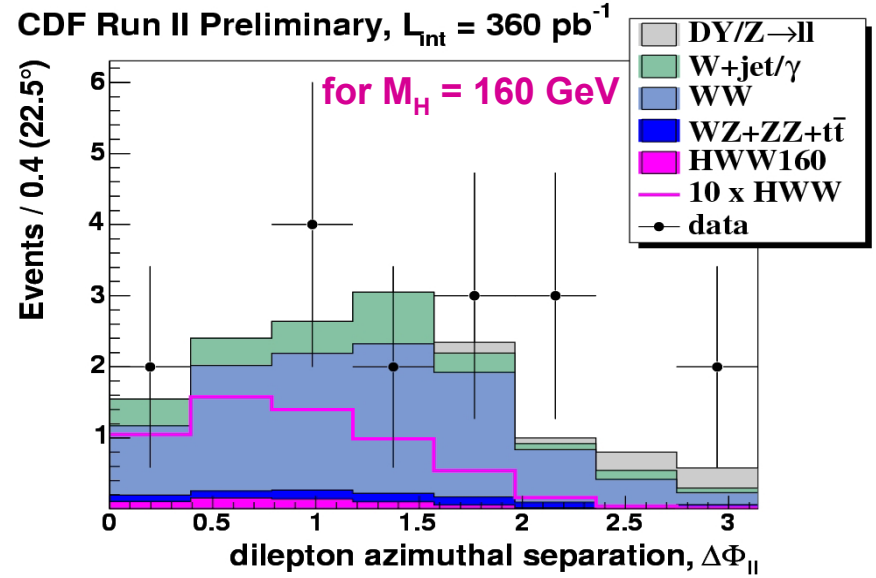


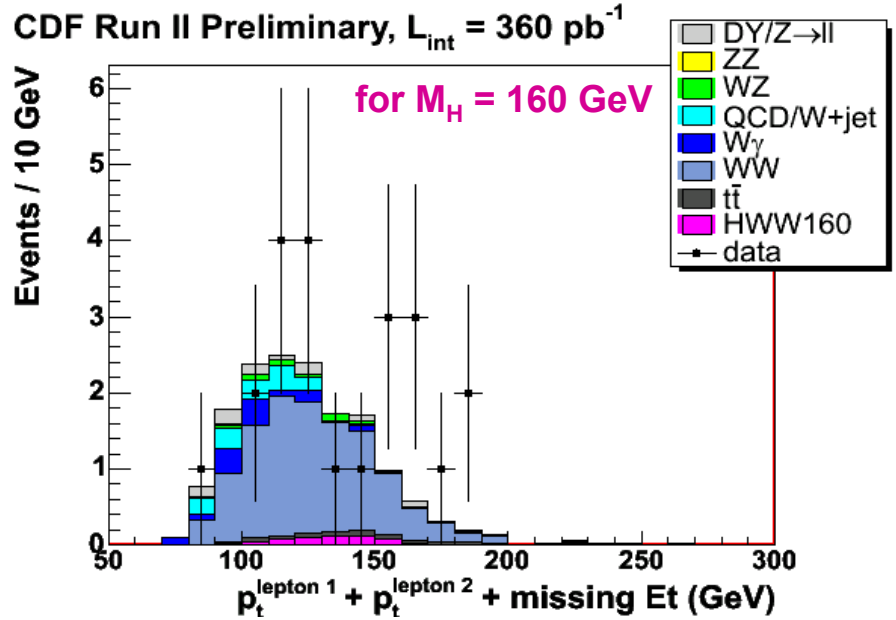


$H \rightarrow WW^* \rightarrow \ell^{\pm}\nu\ell'^{\mp}\nu$

- **Distinct signature:**
  - large $\not{E}_T$ ($> M_H/4$)
  - small dilepton opening angle
  - small dilepton invariant mass
    - suppress WW, WZ, ZZ via cuts on $\Sigma\, p_T^{\ell} + \not{E}_T$ and $M_{\ell\ell}$





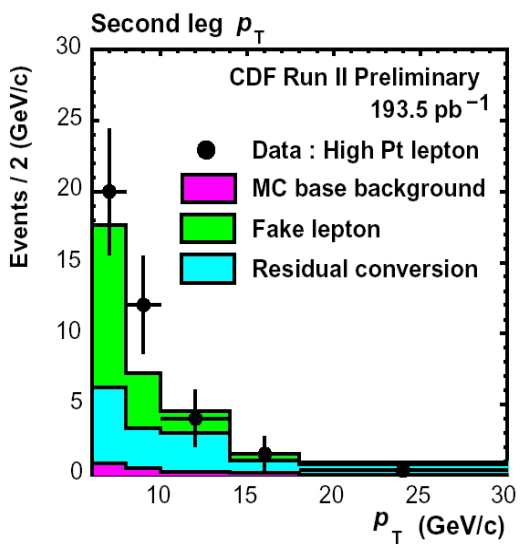


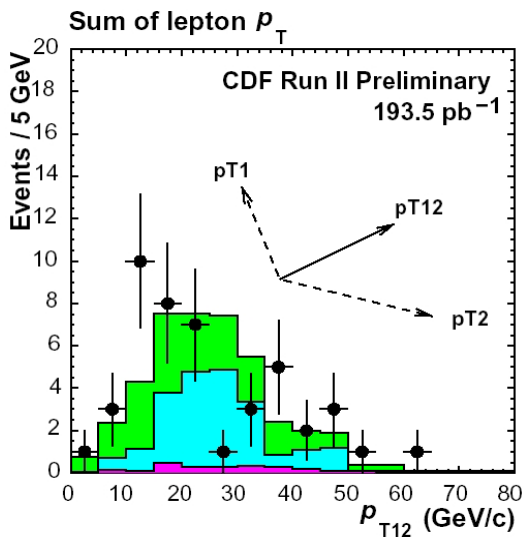
WH → WWW* → $\ell^{\pm}\nu\ell^{\pm}\nu q\bar{q}$

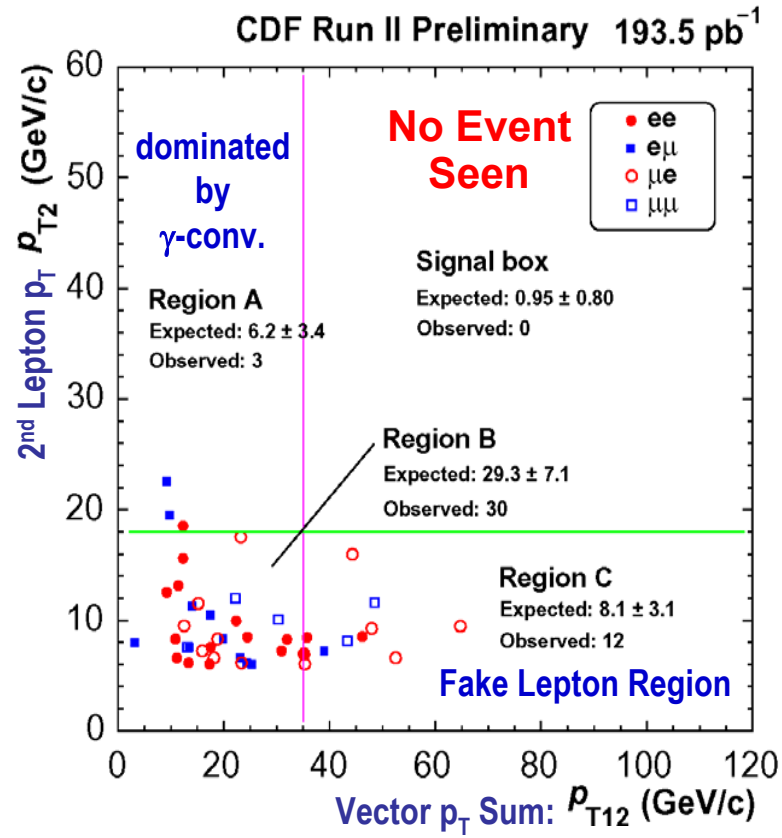
- signature of associated Higgs production contains like-sign dileptons (e, μ)
- CDF study: high-p_T isolated like-sign topology
  - divide into 3 control regions (A,B,C) with:

$$p_{T,2} > 18\text{GeV}, p_{T,12} = \left|\vec{p}_{T,1} + \vec{p}_{T,2}\right| > 35 \text{ GeV}$$

"1" = leading lepton; "2" = 2nd leading







- Signal Region: 0 events observed, 0.95 ± 0.80 expected
  - set cross section 95% CL upper limits: 12 pb (M_H = 110 GeV) and 8 pb (M_H =160 GeV)