# Searches for the Higgs Boson and Supersymmetry at the Tevatron

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On Behalf of the DØ and CDF Collaborations

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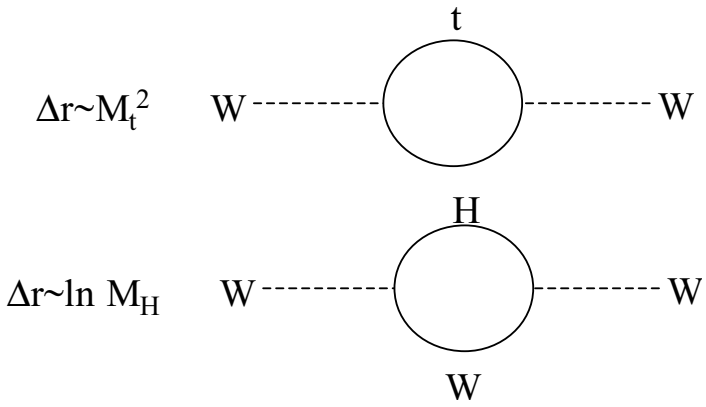
La Thuile, 09.03.2007

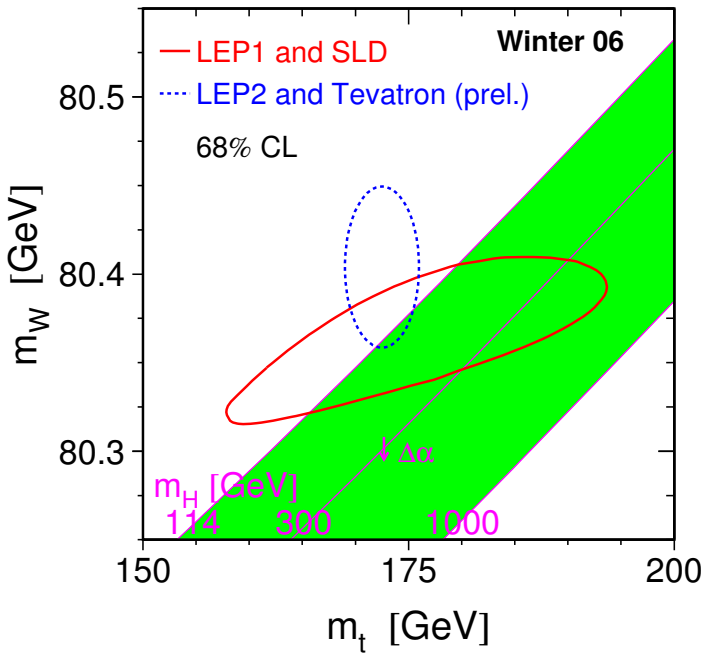
# SM Higgs Constraints from EW Theory

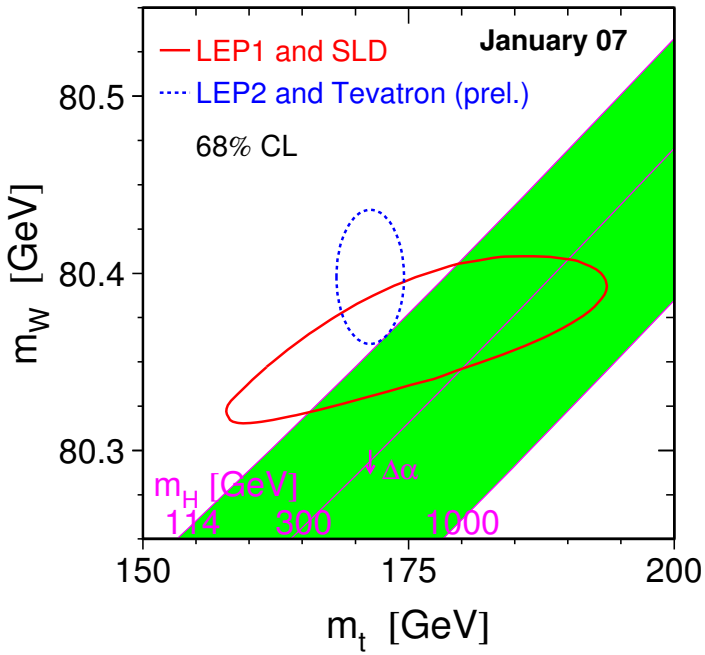
- SM: $M_H$ constrained by radiative corrections to $M_W$




- new precision measurements of $M_W$ and $M_t$ from Tevatron
  $\longrightarrow$ see talks by C. Hays, P.M. Fernandez

$\Rightarrow$ A light SM Higgs boson is favored!

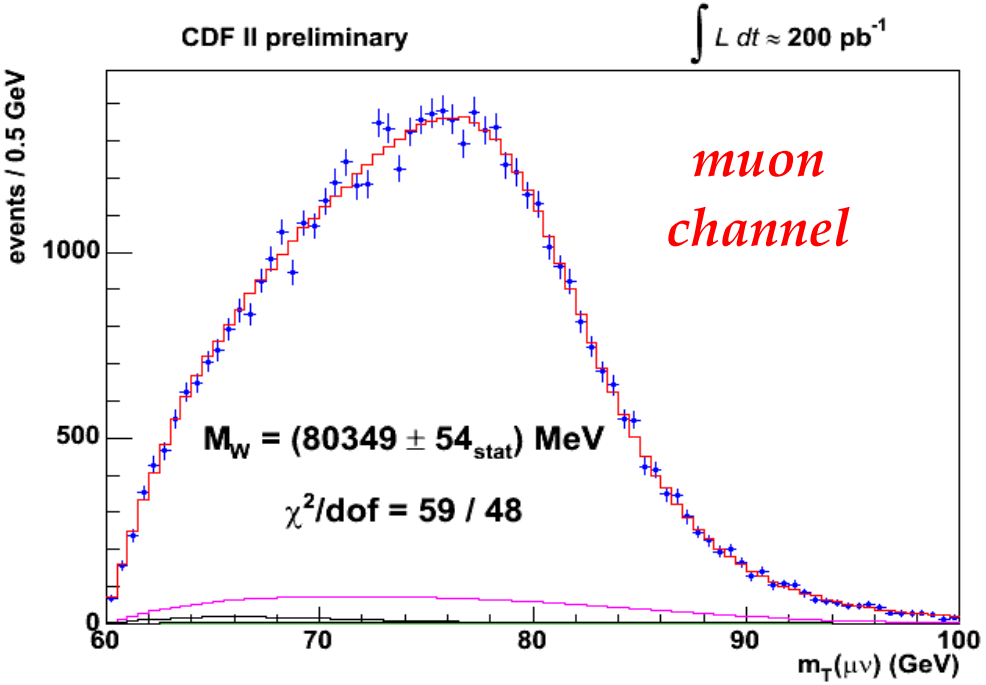


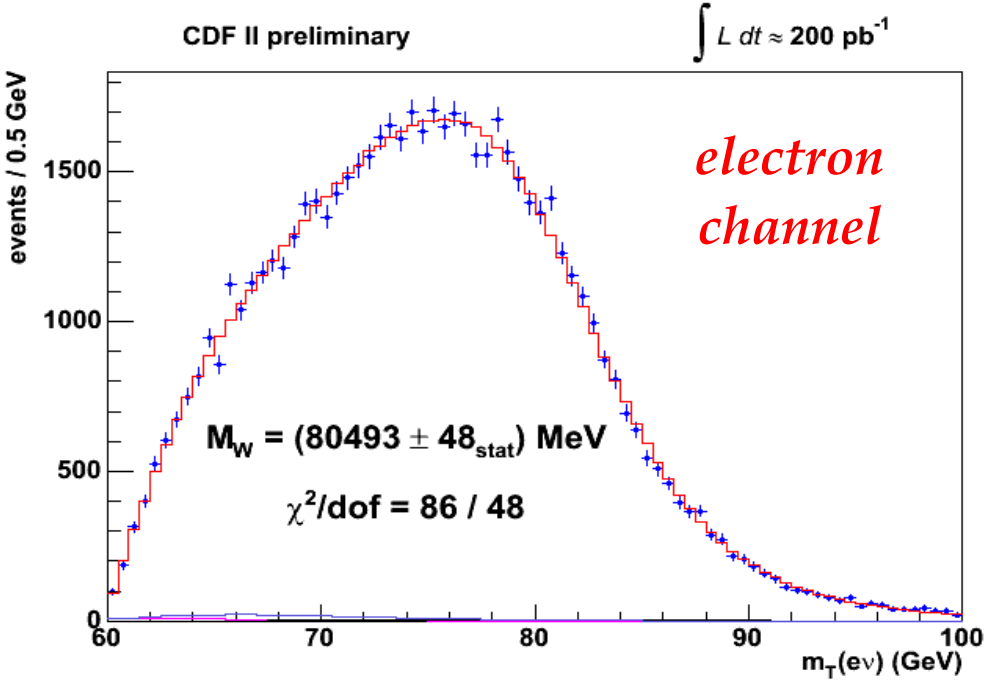



# *W* Mass Fits

Mass fit results blinded with [-100,100] MeV offset throughout analysis
Upon completion, offset removed to determine final result

*Transverse mass fits:*



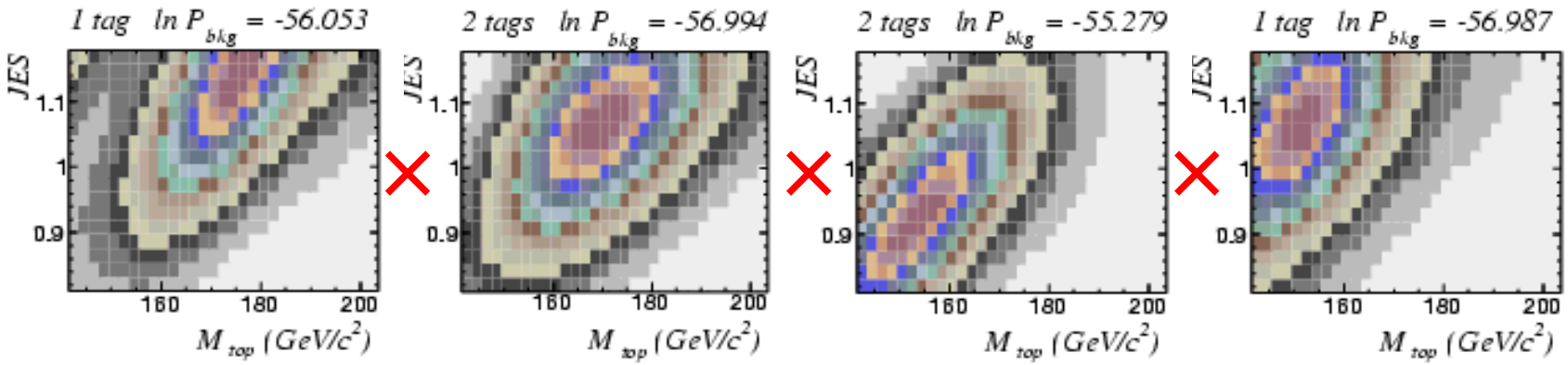

**$m_W$ = 80417 ± 48 MeV (stat + sys)**

**for $e$ + μ combination ($P(\chi^2)$ = 7%)**

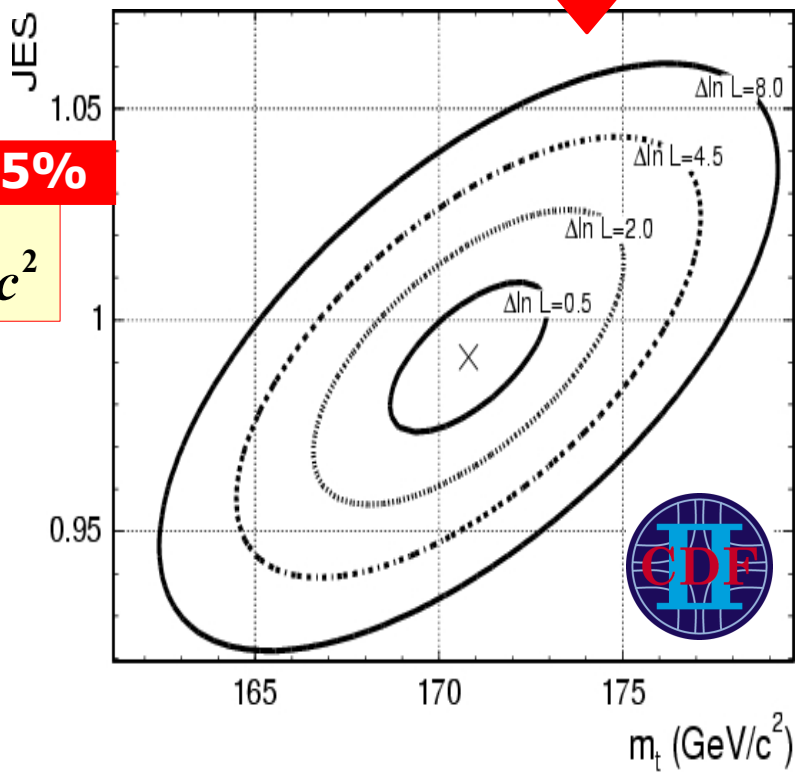
# CDF: Matrix Element, Lepton+Jets 955pb$^{-1}$

sample likelihood: signal probability background probability

$$L(M_{\text{top}}, \text{JES}, C_s) \propto \prod_{i=1}^{\text{events}} \left[ C_s P_{t\bar{t}}^{(i)}(M_{\text{top}}, \text{JES}) + (1 - C_s) P_{\text{bck}}^{(i)}(\text{JES}) \right]$$




- $M_{top}$, JES extracted in a 2-D maximum likelihood fit



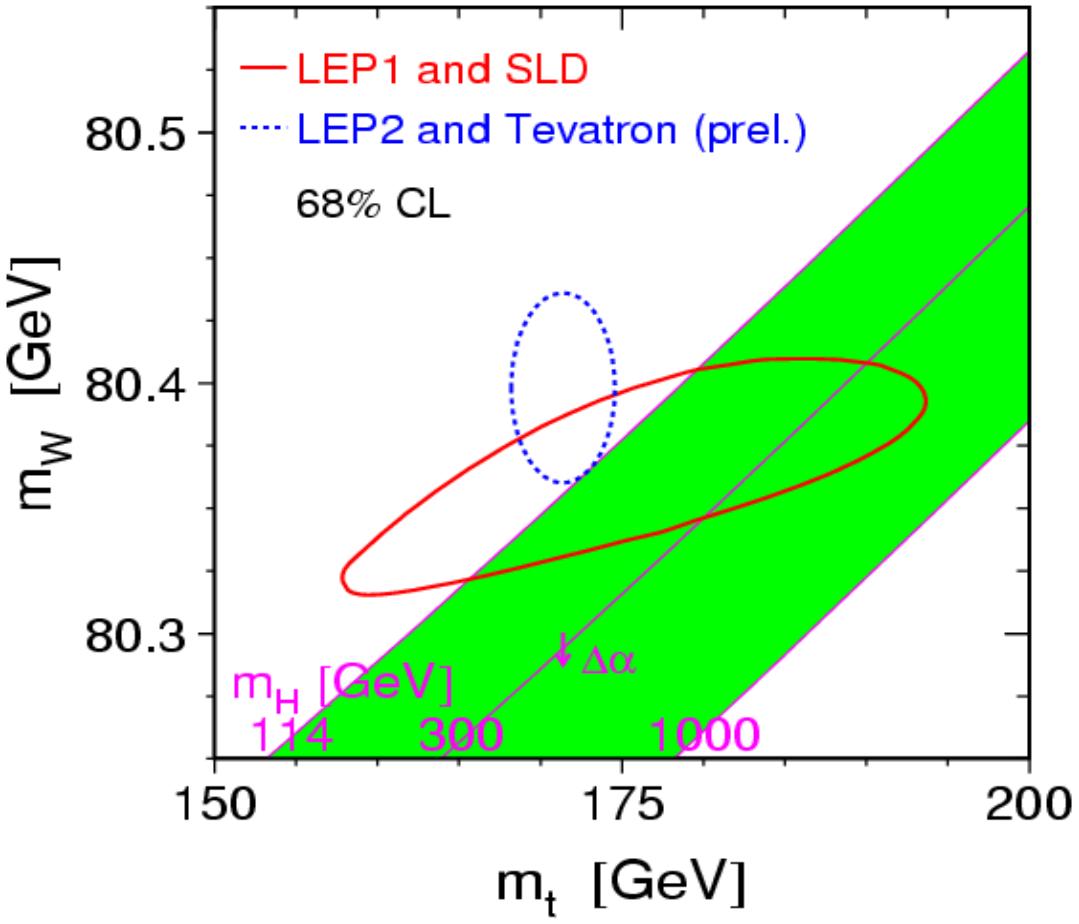

Result using 167 candidate events (≥1 b-tag):

$$M_{\text{top}} = 170.8 \pm 1.6(\text{stat.}) \pm 1.5(\text{JES}) \pm 1.4(\text{syst.}) \text{ GeV}/c^2$$

**...most precise single top quark mass measurement so far!**

- In-situ technique greatly reduces JES uncertainty. Will further scale down with integrated luminosity.

# New Higgs Mass Prediction



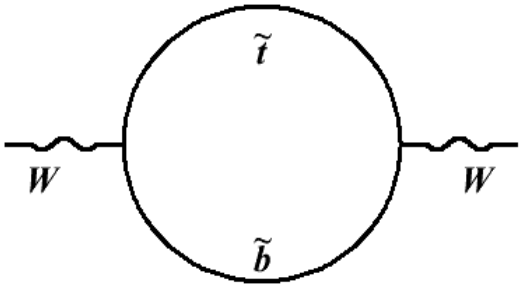

***Predicted Higgs mass from global electroweak data:***

$m_H = 80^{+36}_{-26}$ GeV (< 153 GeV at 95% CL)

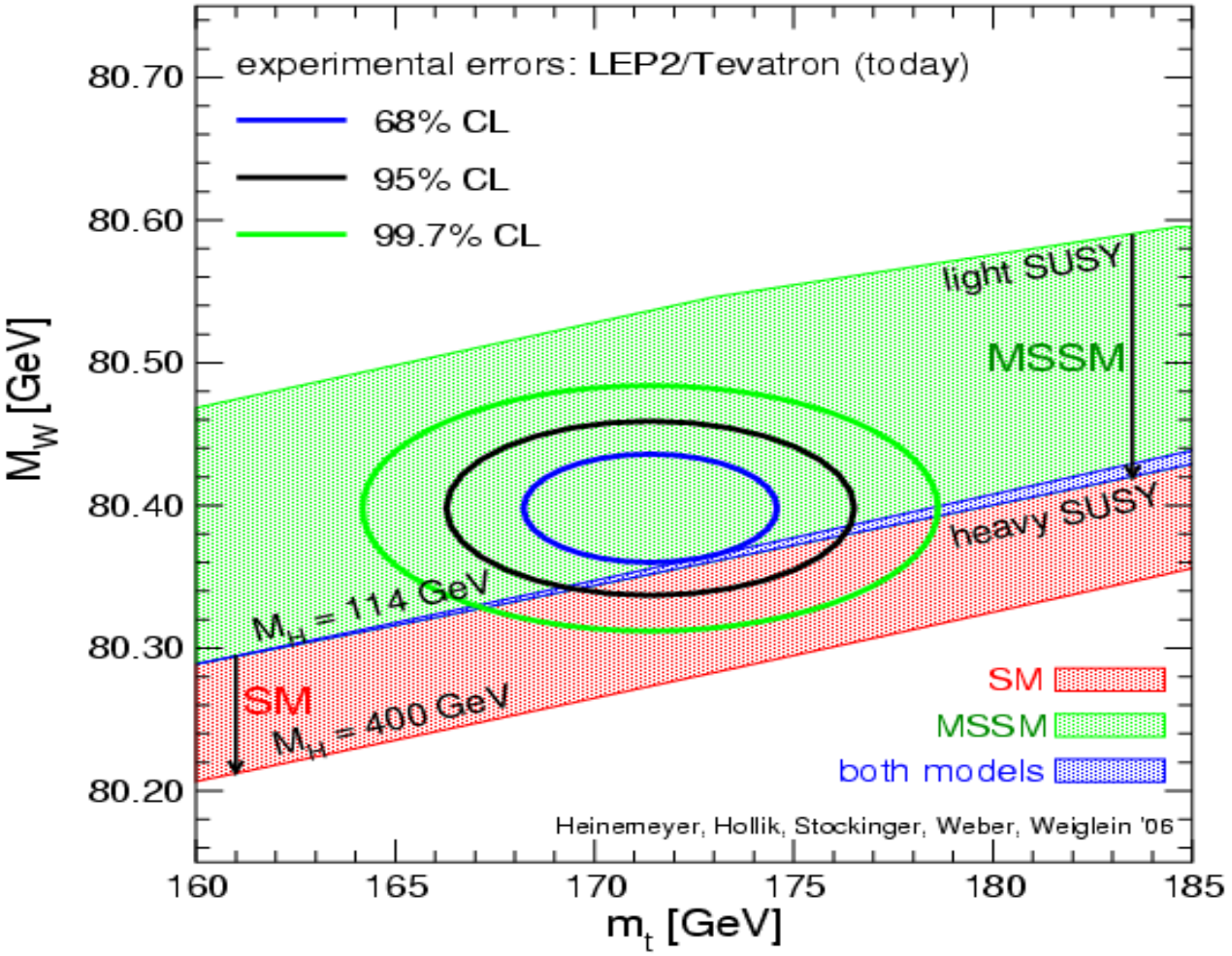
Direct search from LEP II: $m_H > 114.4$ GeV at 95% CL

# Effect on New Physics Models

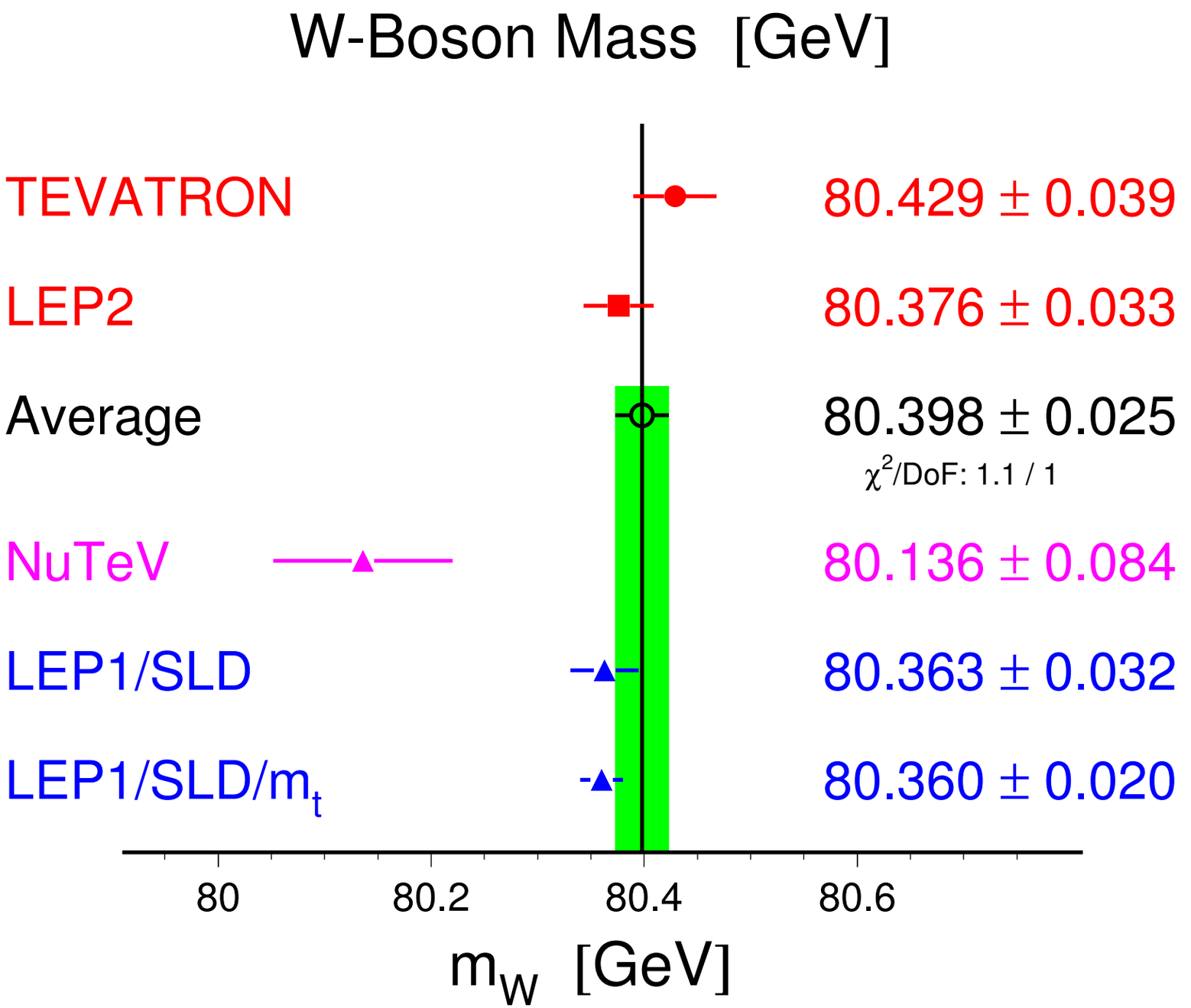
Supersymmetry now preferred at 1σ level...

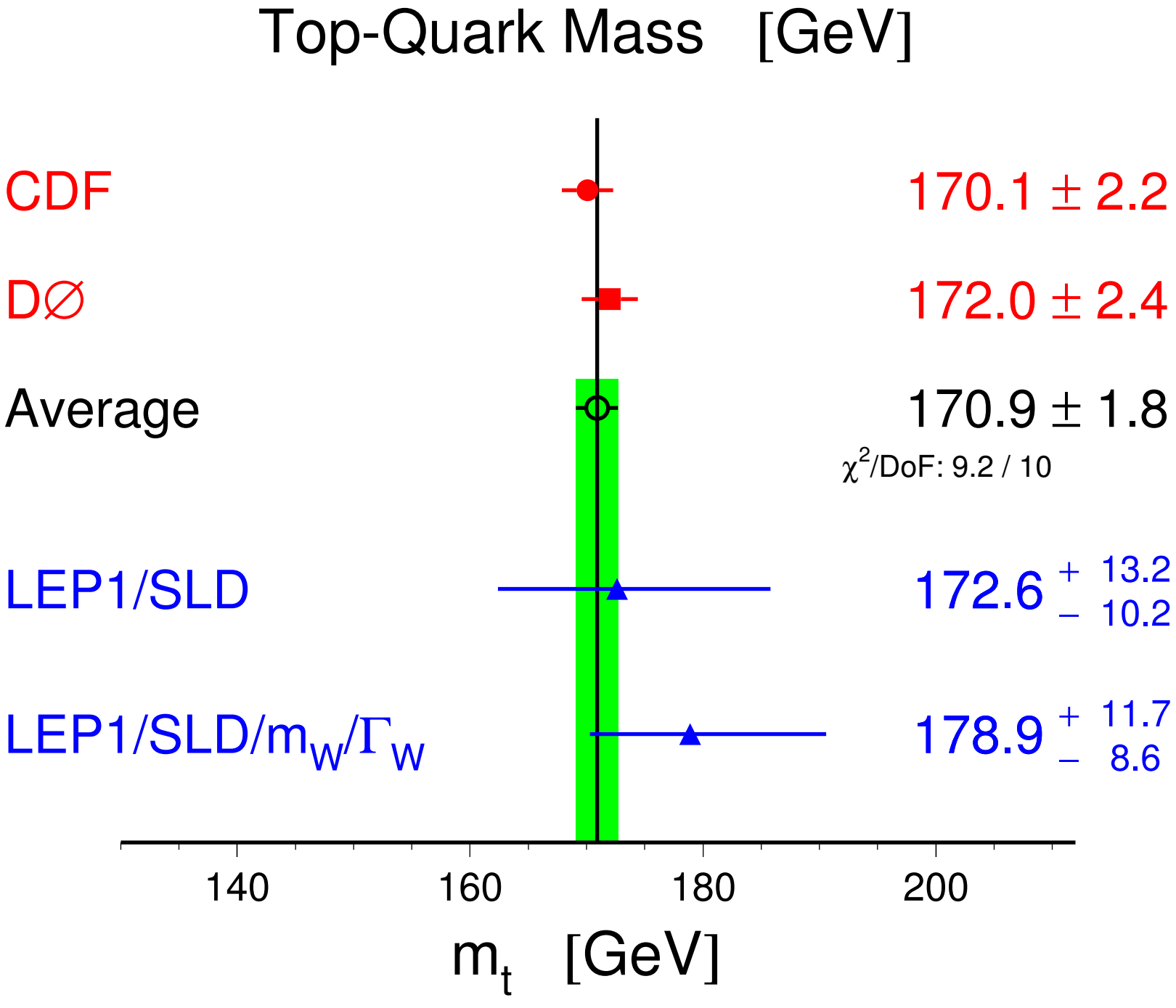


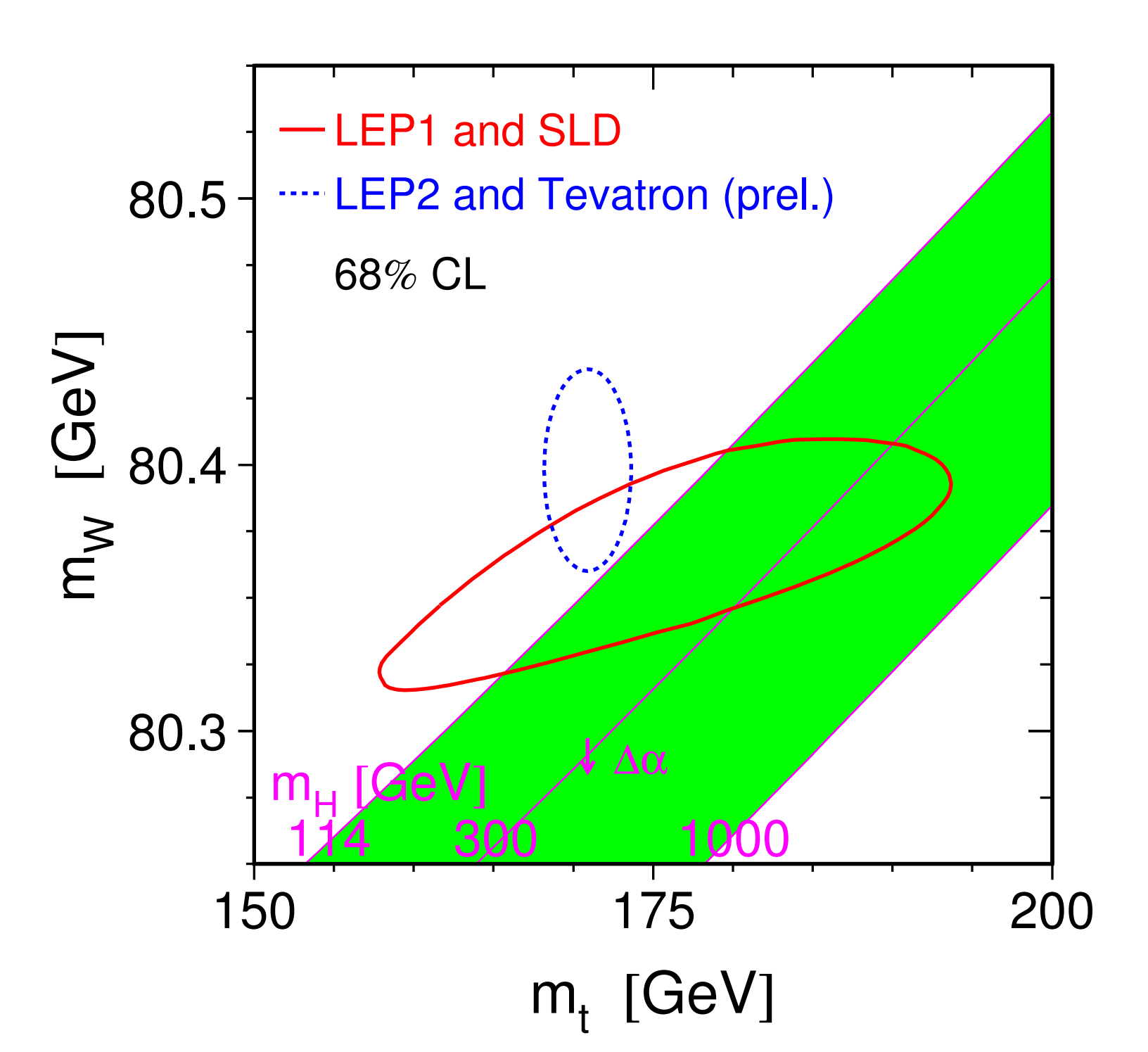

*New world average:*

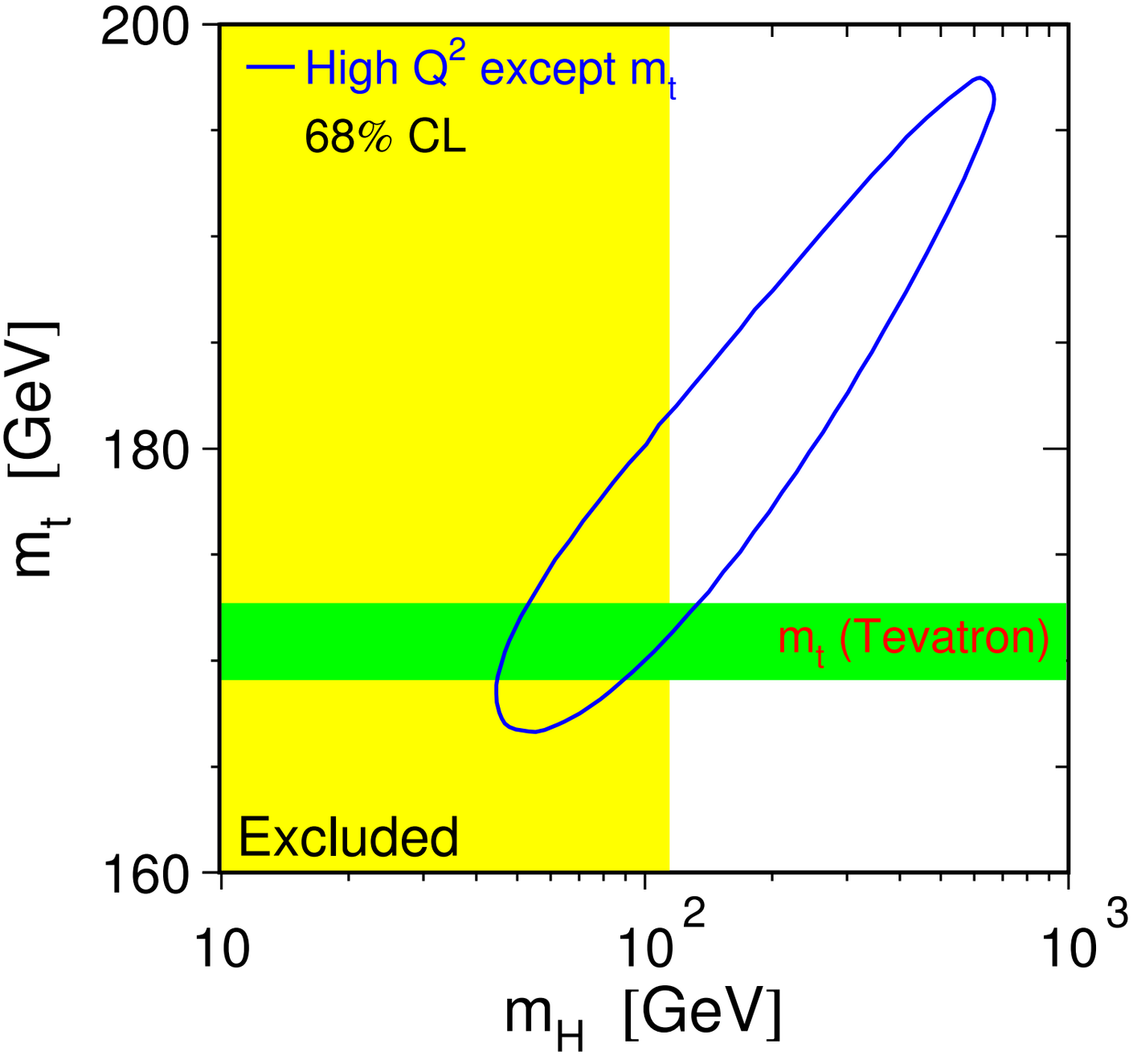


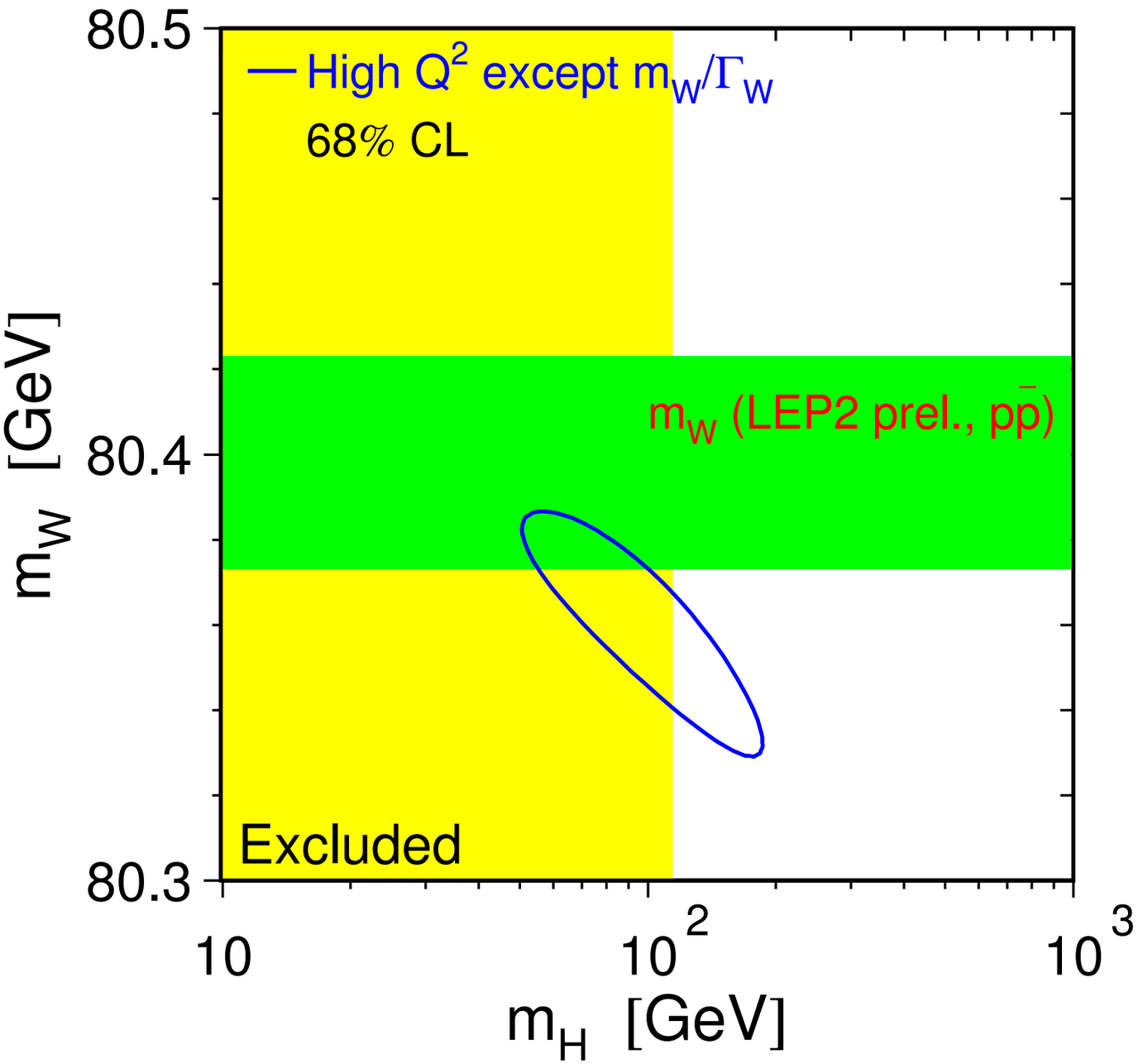
# NEW: status March 2007

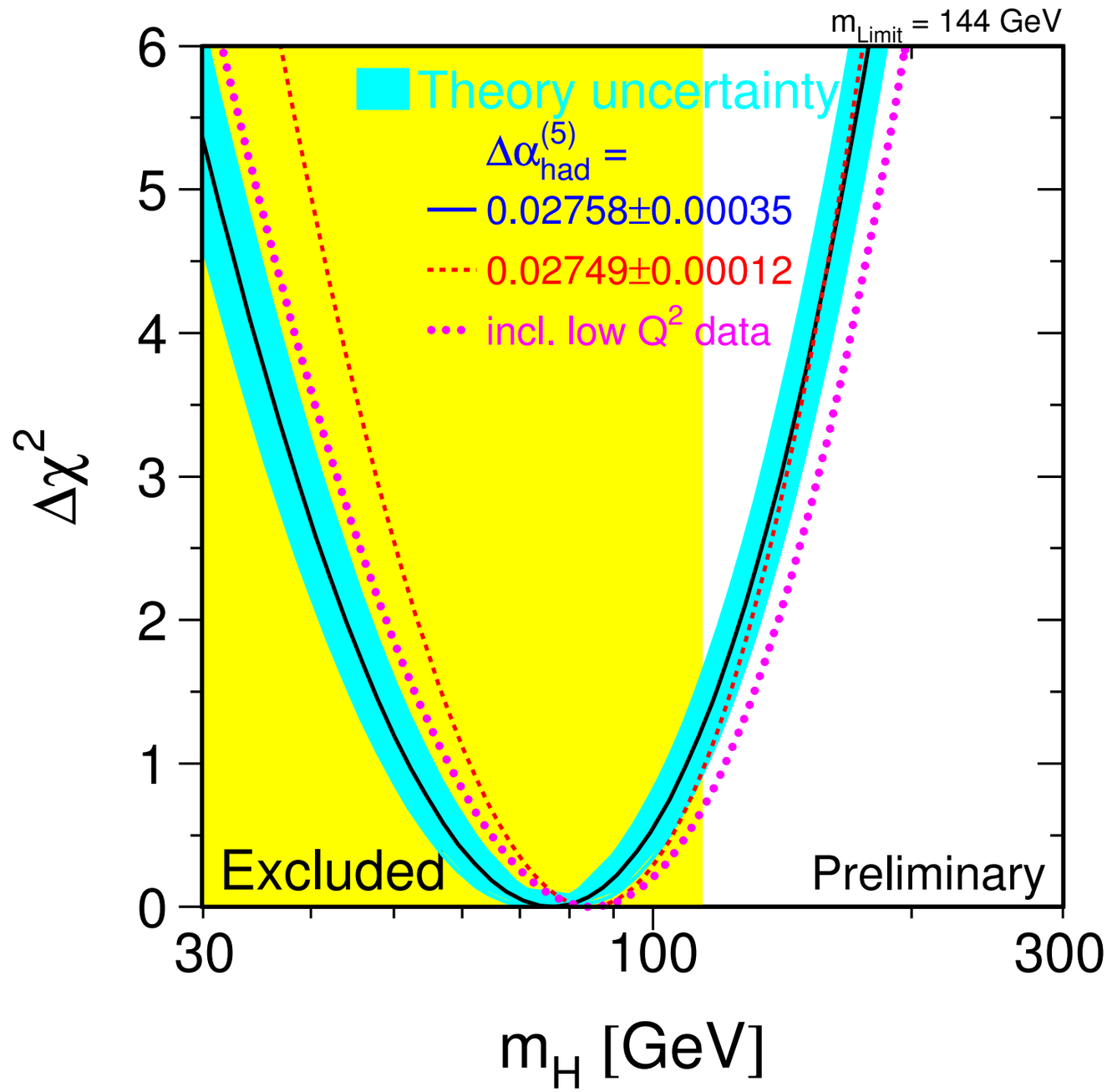



Top-Quark Mass [GeV]
CDF
DØ
Average
LEP1/SLD
LEP1/SLD/m_W/Γ_W
170.1 ± 2.2
172.0 ± 2.4
170.9 ± 1.8
χ²/DoF: 9.2 / 10
172.6 + 13.2 − 10.2
178.9 + 11.7 − 8.6
140
160
180
200
m_t [GeV]

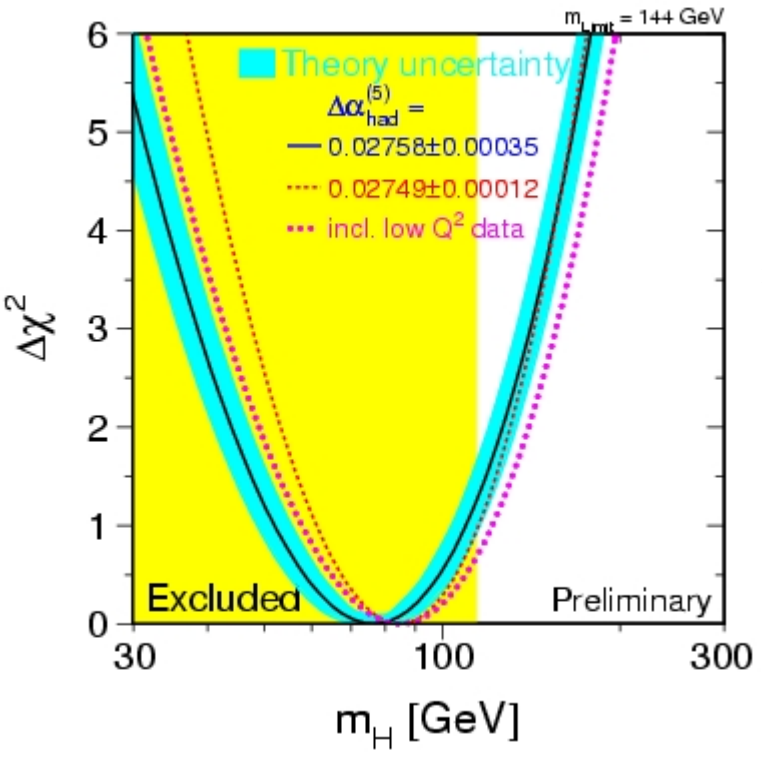

LEP1 and SLD
LEP2 and Tevatron (prel.)
68% CL
80.5
80.4
80.3
$m_W$ [GeV]
$m_H$ [GeV]
114
300
1000
$\Delta\alpha$
150
175
200
$m_t$ [GeV]


200
180
160
$m_t$ [GeV]
High $Q^2$ except $m_t$
68% CL
$m_t$ (Tevatron)
Excluded
10
$10^2$
$10^3$
$m_H$ [GeV]


80.5
80.4
80.3
$m_W$ [GeV]
High $Q^2$ except $m_W/\Gamma_W$
68% CL
$m_W$ (LEP2 prel., $p\bar{p}$)
Excluded
10
$10^2$
$10^3$
$m_H$ [GeV]


$m_{Limit}$ = 144 GeV
Theory uncertainty
$\Delta\alpha^{(5)}_{had}$ =
0.02758±0.00035
0.02749±0.00012
incl. low $Q^2$ data
Excluded
Preliminary
$\Delta\chi^2$
$m_H$ [GeV]
0
1
2
3
4
5
6
30
100
300

# NEW: status March 2007



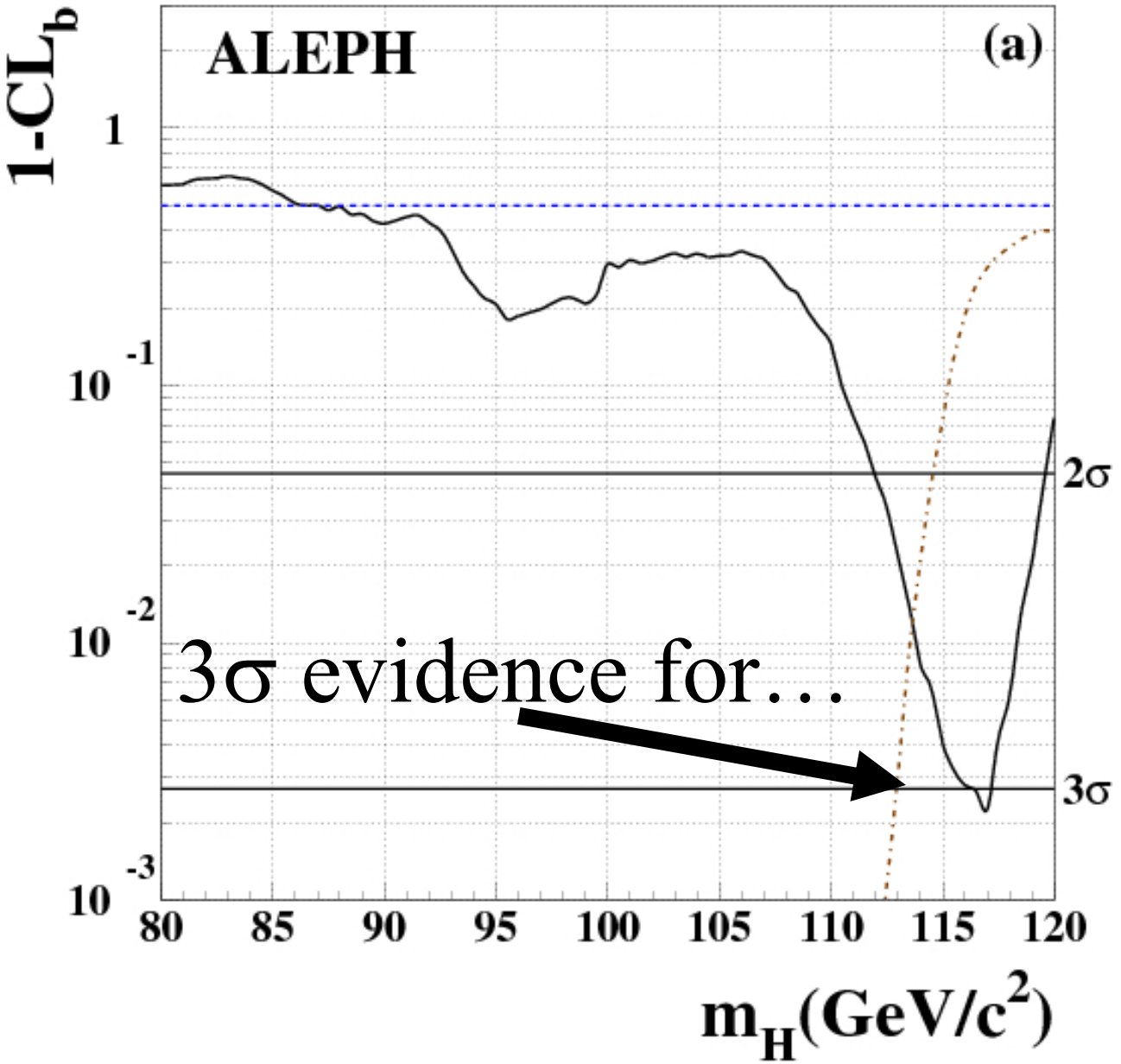

**Of particular interest is the constraint on the mass of the Higgs boson, because this fundamental ingredient of the Standard Model has not been observed yet. The figure on the left shows the Delta-chi2 curve derived from high-Q2 precision electroweak measurements, performed at LEP and by SLD, CDF, and D0, as a function of the Higgs-boson mass, assuming the Standard Model to be the correct theory of nature. The preferred value for its mass, corresponding to the minimum of the curve, is at 76 GeV, with an experimental uncertainty of +33 and -24 GeV (at 68 percent confidence level derived from Delta chi2 = 1 for the black line, thus not taking the theoretical uncertainty shown as the blue band into account). This result is only little affected by the low-Q2 results such as the NuTeV measurement discussed above.**

**While this is not a proof that the Standard-Model Higgs boson actually exists, it does serve as a guideline in what mass range to look for it. The precision electroweak measurements tell us that the mass of the Standard-Model Higgs boson is lower than about 144 GeV (one-sided 95 percent confidence level upper limit derived from Delta chi2 = 2.7 for the blue band, thus including both the experimental and the theoretical uncertainty). This limit increases to 182 GeV when including the LEP-2 direct search limit of 114 GeV shown in yellow (see below).**

# By the Way!!!

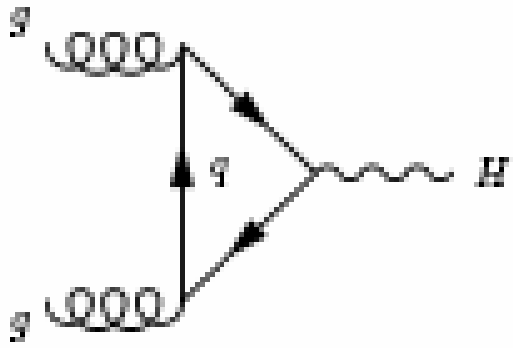
Signal/ background for Each LEP Higgs candidate

The Value over which we sum for the likelihood



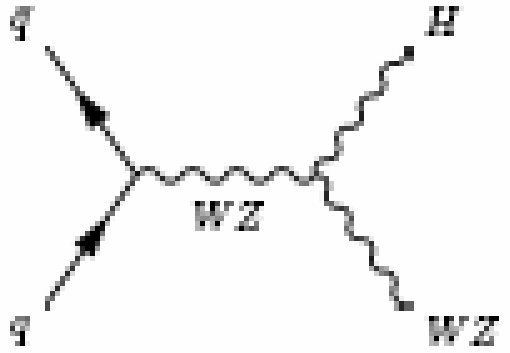
# SM Higgs Production

- 4 main mechanisms
- Gluon Fusion Dominates at Tevatron: HWW
- Associated Production: WH, ZH, WWH, TTH

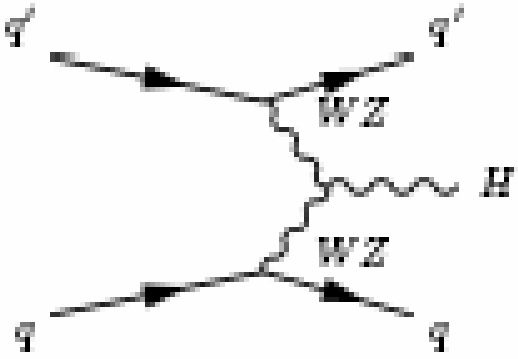



HWW

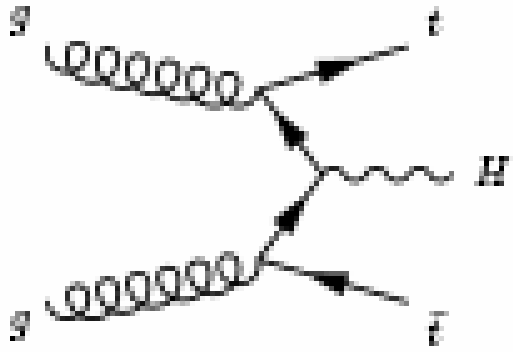
Hγγ,HZZ




WH,ZH, WWH

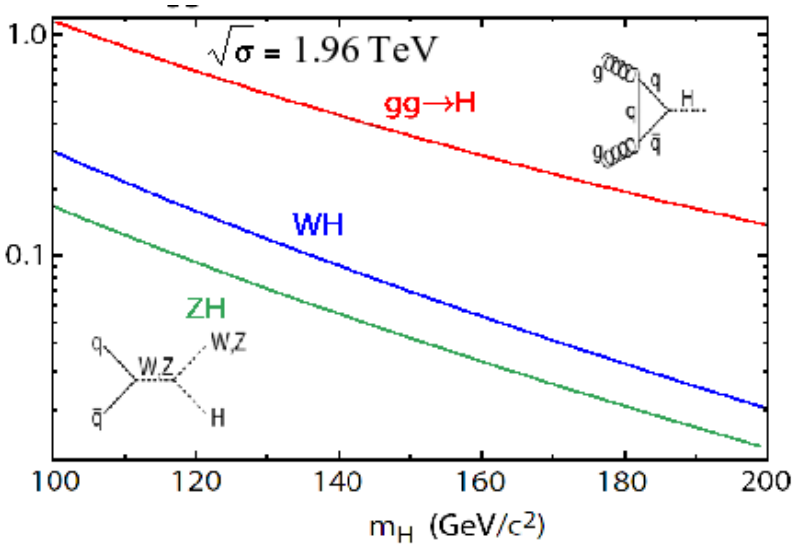


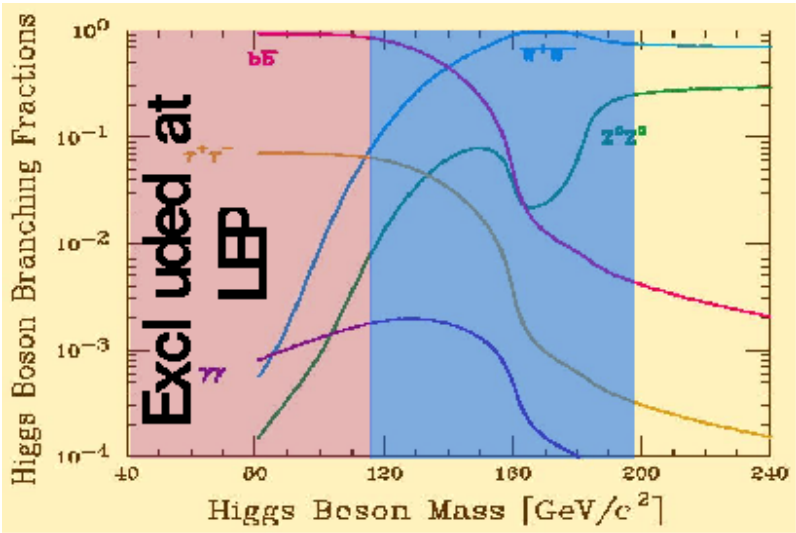

VBF




TTH

# SM Higgs Production and Decay

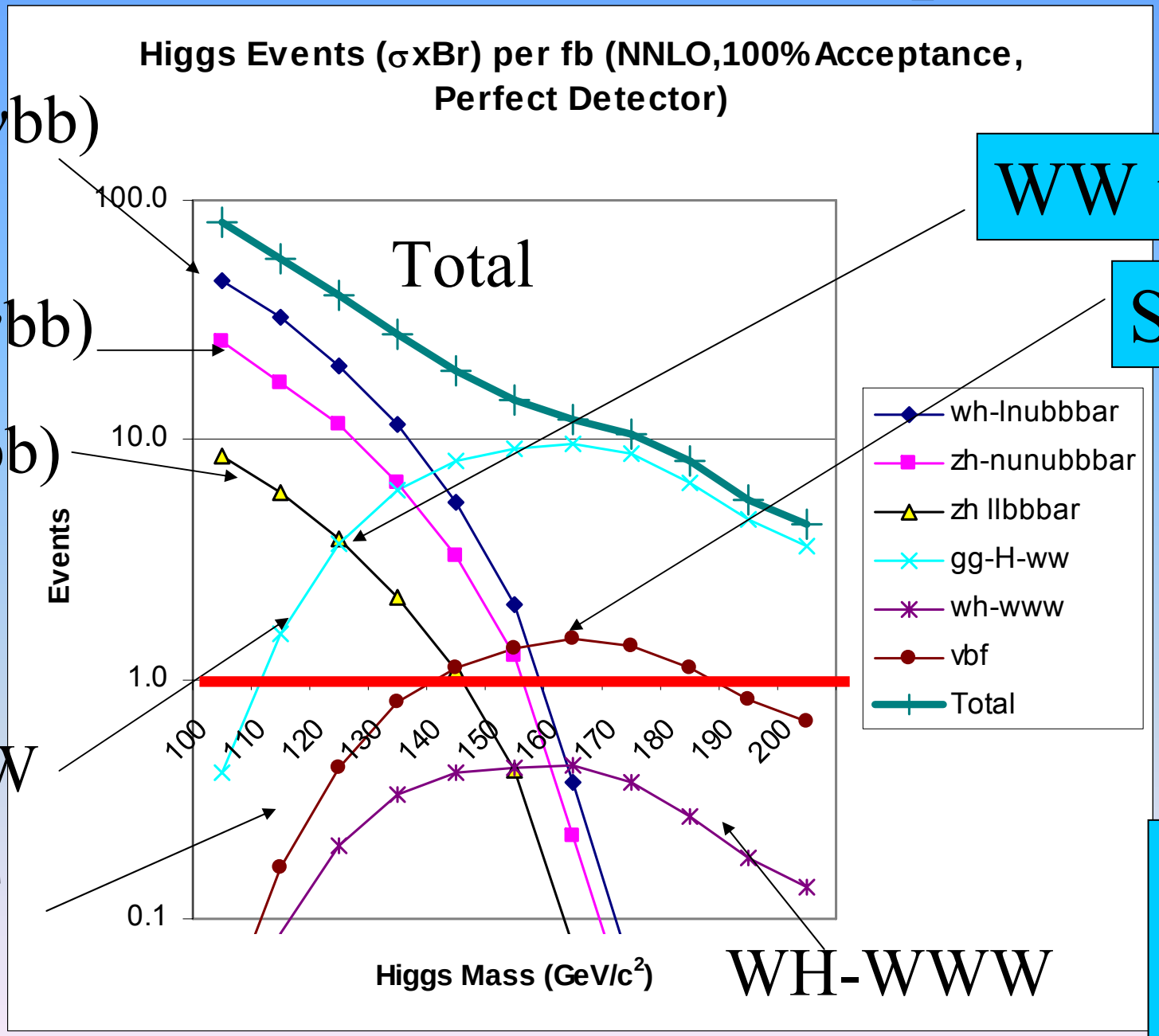



## Search strategy:

- $M_H \lesssim 135\,\mathrm{GeV}$: associated production $WH$, $ZH$ with $H \to b\bar{b}$
  - backgrounds: $Wb\bar{b}$, $Zb\bar{b}$, $W/Zjj$, top, $WZ$, QCD
  - additional sensitivity from $WH(\to WW^*)$, $H \to WW^*$
- $M_H \gtrsim 135\,\mathrm{GeV}$: $gg \to H \to WW^{(*)}$
  - backgrounds: $WW$, $WZ$, $W + \mathrm{jet}/\gamma$, $t\bar{t}$, $Z/\mathrm{DY}$, QCD
  - additional sensitivity from $WH$, $ZH$

# CDF Channels NOW Ntupled 1 fb$^{-1}$




WH(lνbb)

ZH(ννbb)

ZH(llbb)

gg-WW

VBF

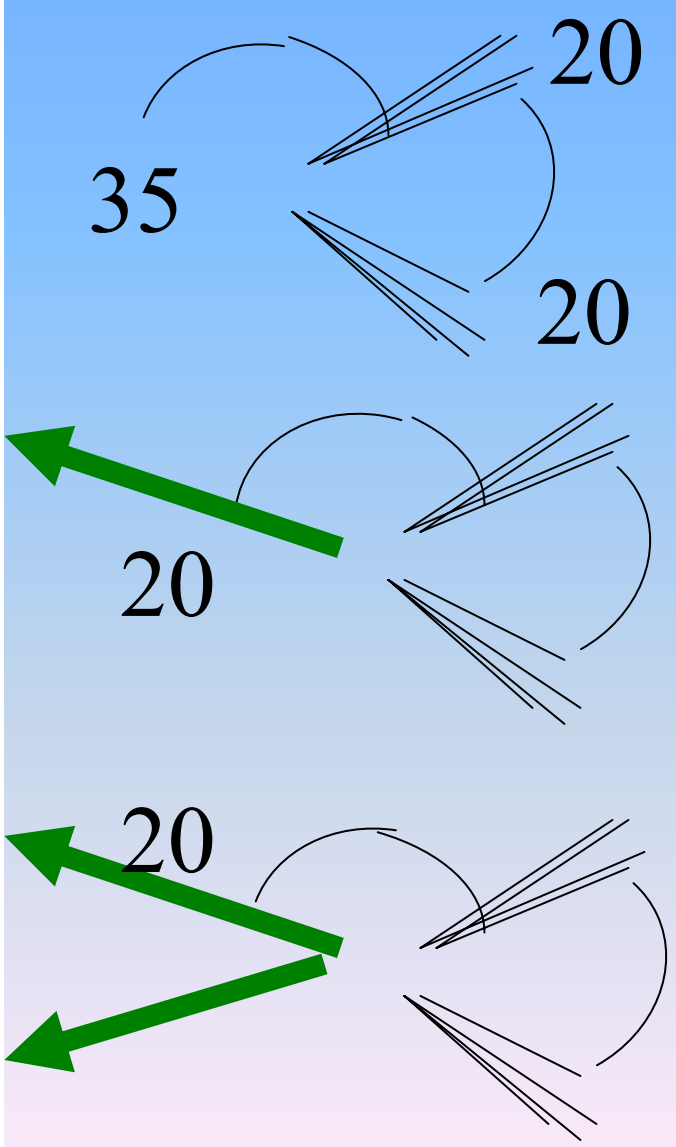
WW to 120ish

Small VBF

WH-WWW

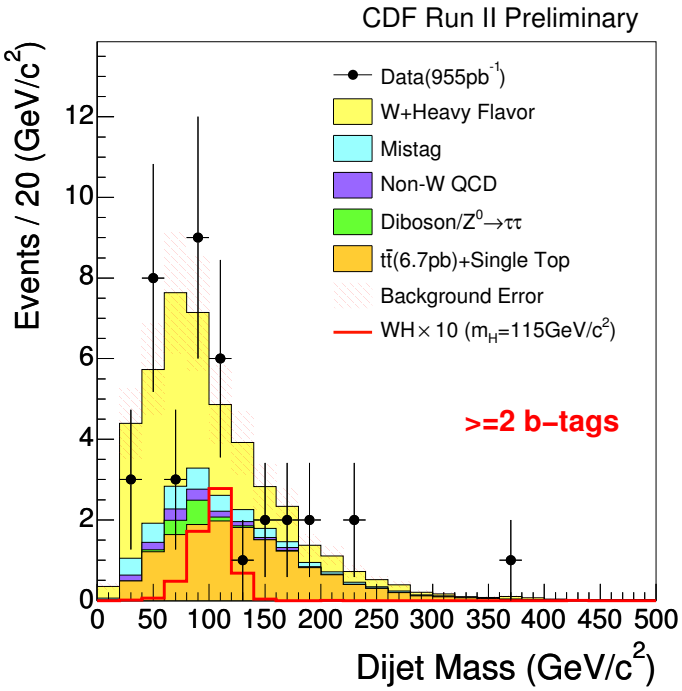
Before Selection! (ε~2-7%)

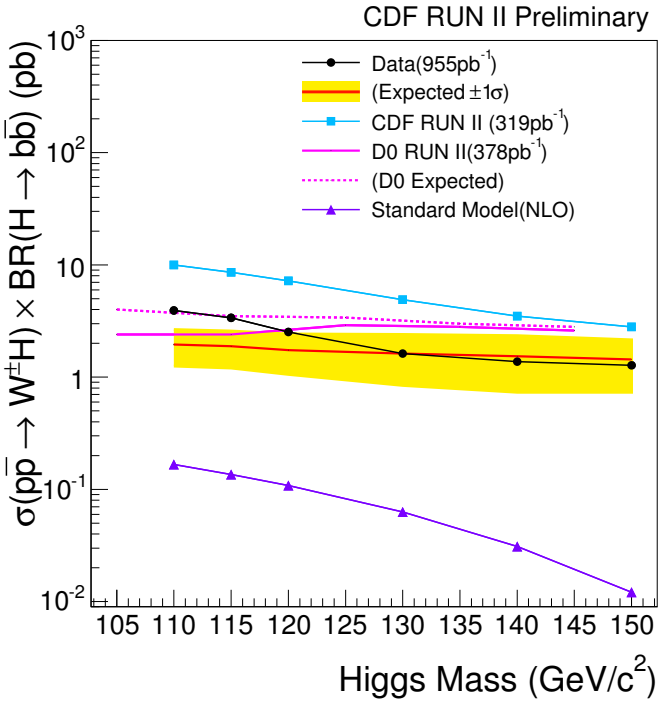
# Associated Production: Z/W bb

| Topology & Trigger | Background Control | Worst Systematic |
| --- | --- | --- |
|   | NN Input | Z+jets<br>W+jets<br>Z+jets |

# $WH \to l^{\pm}\nu b\bar{b}$

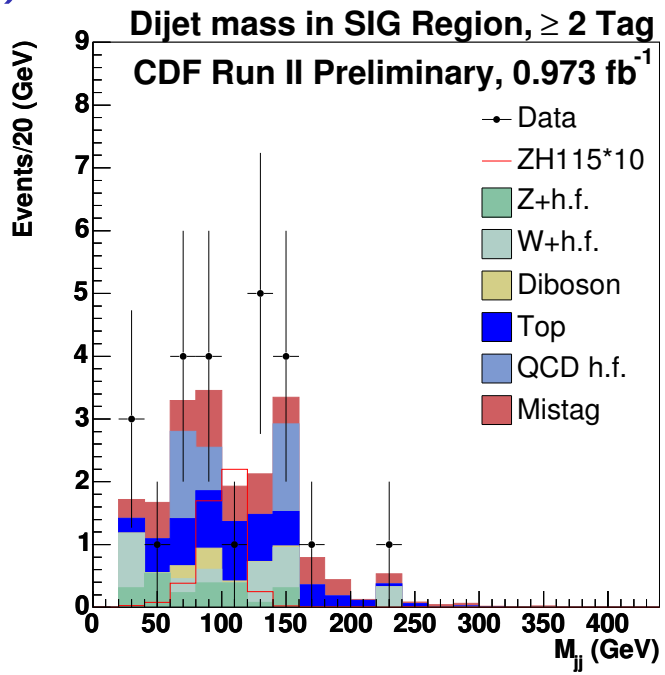
- recent CDF measurement based on $L = 1\,\mathrm{fb}^{-1}$
- selection:
  - $e$ or $\mu$ with high transverse momentum $p_T > 20\,\mathrm{GeV}$
  - large missing $E_T$, $\not\!\!E_t > 20\,\mathrm{GeV}$
  - two jets, $E_T > 15\,\mathrm{GeV}$ (with $b$-tags)
- $b$-tagging:
  - secondary vertex (SVT)
  - neural network (NN)
  - best sensitivity: 1 SVT w/ NN && $\geq$2 SVT
- search for resonant peak in $m_{jj}$
- for $M_H \sim 115\,\mathrm{GeV}$: $\sigma_{\mathrm{excl}}/\sigma_{\mathrm{SM}} \sim 20$ (single measurement)

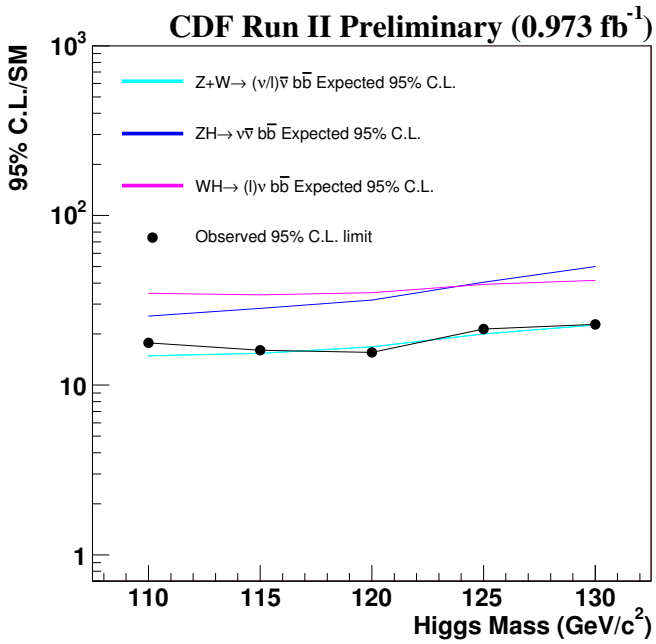


# $ZH \to \nu\bar{\nu}b\bar{b}$, $WH \to (l^{\pm})\nu b\bar{b}$

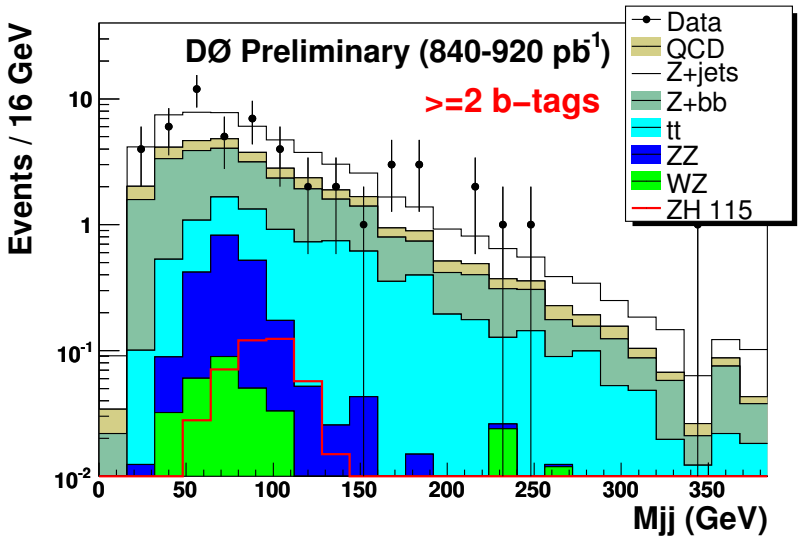
- analysis includes $WH \to (l^{\pm})\nu b\bar{b}$, where $l^{\pm}$ is undetected
- selection:
  - large $\not\!\!E_t > 75\,\mathrm{GeV}$
  - 2 jets with $\geq 1$ $b$-tag
  - topological cuts
- large bgd. from QCD multi-jet and $Zjj$ with mistag
- sensitivity at $M_H \sim 115\,\mathrm{GeV}$:
  - $ZH$, $WH$: each $\sigma_{\mathrm{excl}}/\sigma_{\mathrm{SM}} \sim 30$
  - combined: $\sigma_{\mathrm{excl}}/\sigma_{\mathrm{SM}} \sim 16$

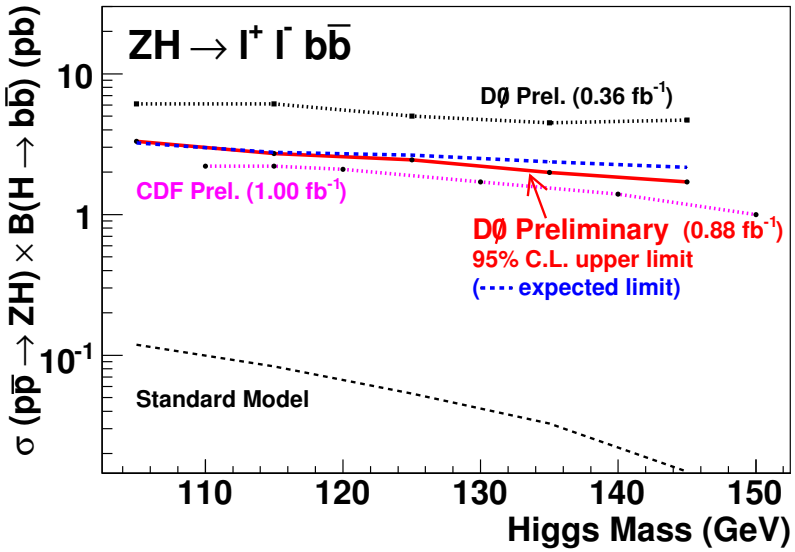


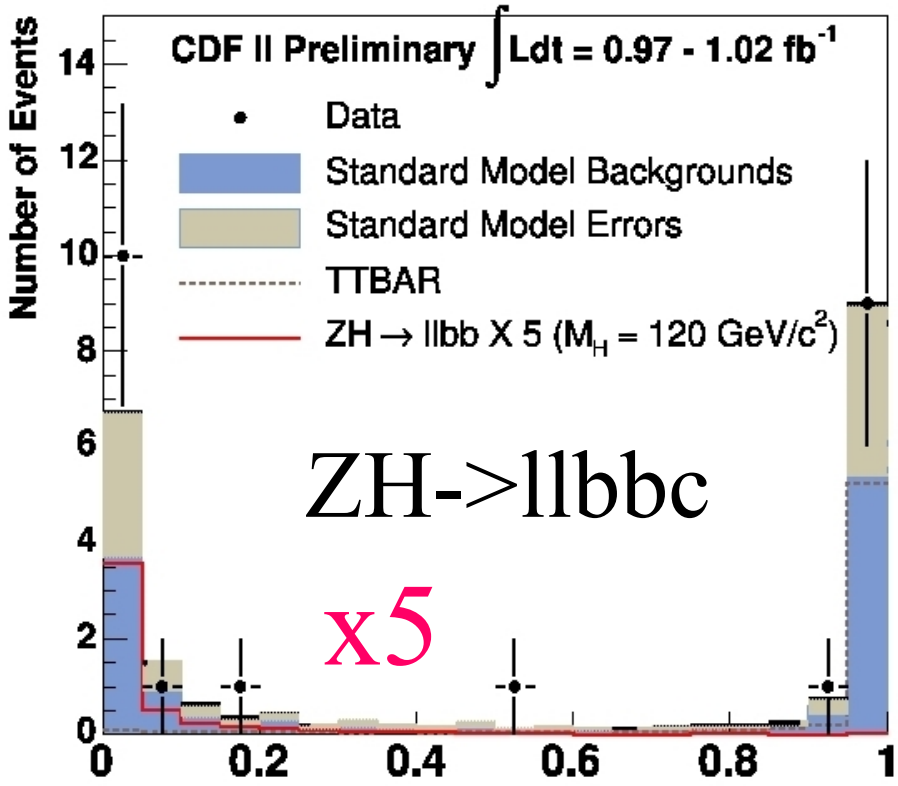
# $ZH \to l^+l^- b\bar{b}$

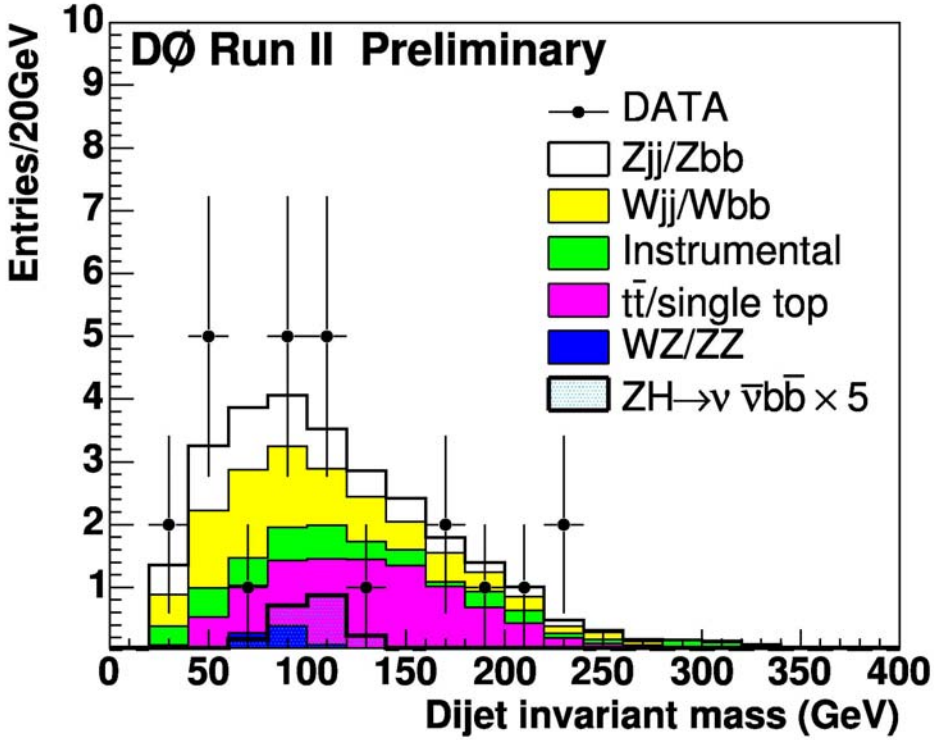
- new (Nov. 06) DØ result
- selection:
  - $ee$ or $\mu\mu$ with $m_{ll} \sim M_Z$
  - $\geq 2$ jets, both $b$-tagged
- NN $b$-tagger: 72% $b$-tagging efficiency at 4% light-jet fake rate ($|\eta| < 1.5$)
- background: mostly $Zb\bar{b}$, $Zjj$
- CDF: improved sensitivity with NN selection
- sensitivity at $M_H \sim 115\,\mathrm{GeV}$: $\sigma_{\mathrm{excl}}/\sigma_{\mathrm{SM}} \sim 25 - 30$
  $\Rightarrow$ similar sensitivity as $Z(\to \nu\bar{\nu})H$ despite low $Z \to l^+l^-$ $Br$

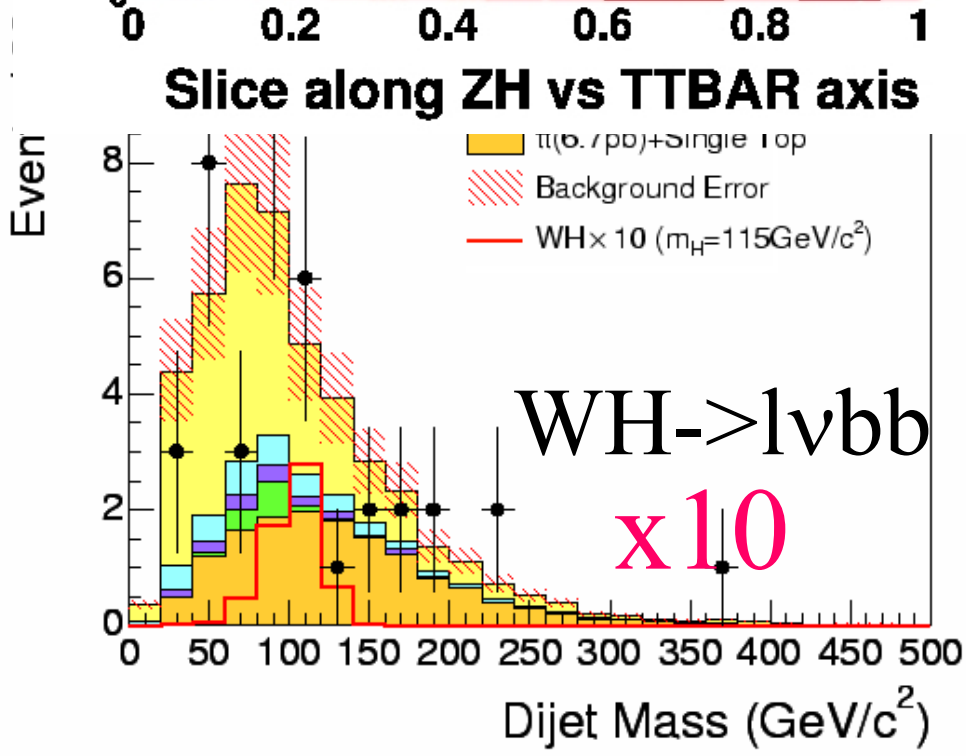


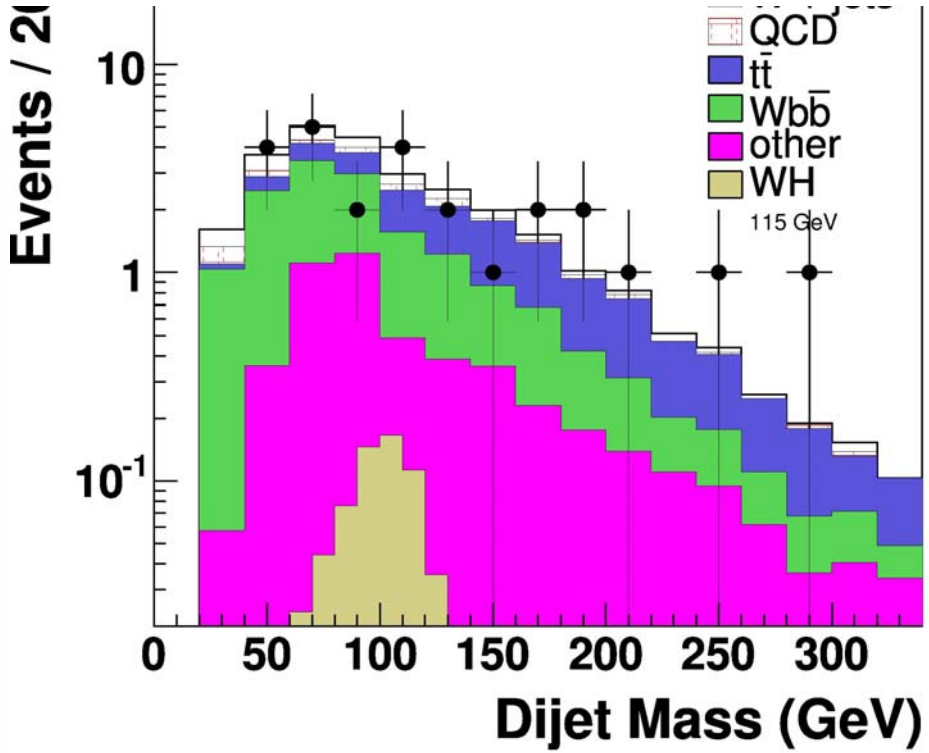



## Search for ZH→ l⁺l⁻ bb̄

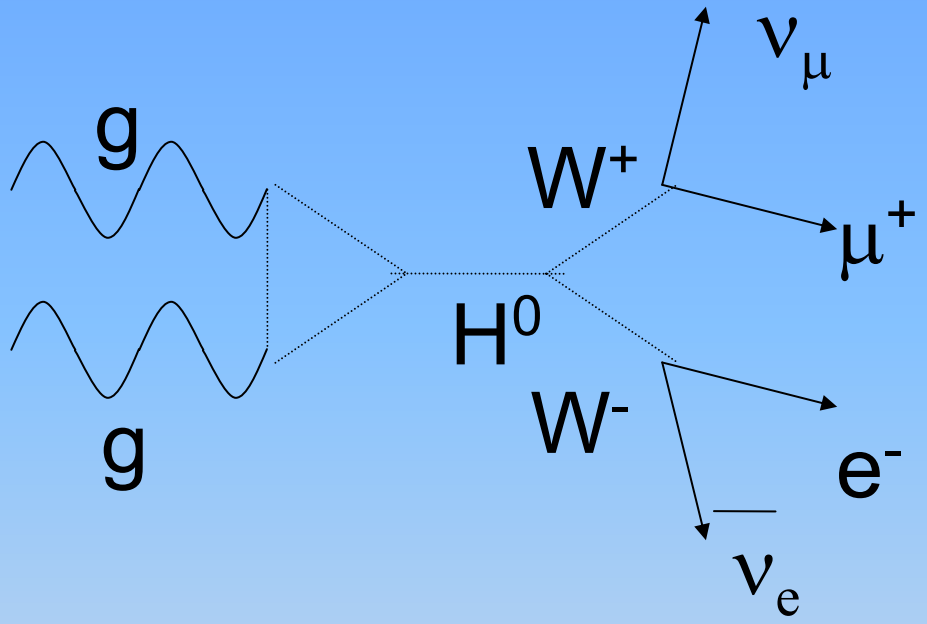


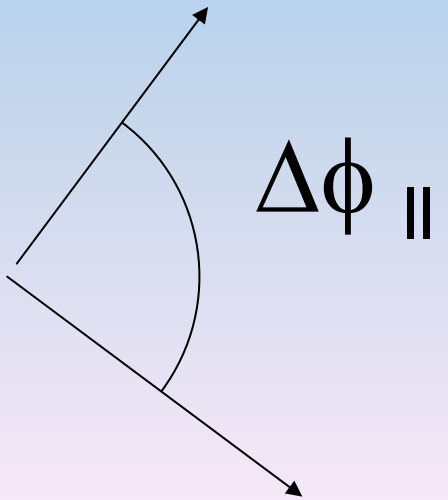



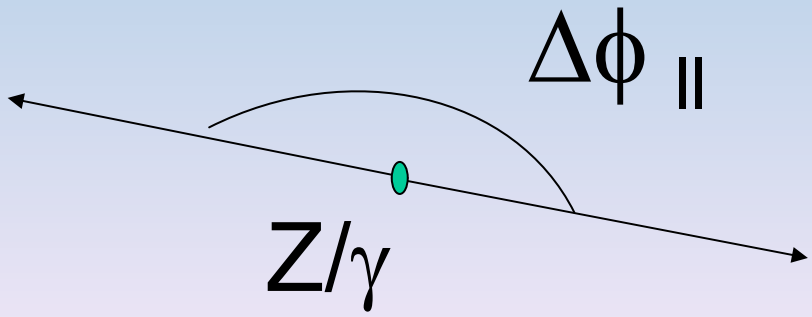
# HWW/VBF Production Features




- High Pt Leptons not back to back
- Spin 0 Higgs correlates spins of leptons: e,μ parallel and neutrinos also: Examine $\Delta\phi_{ll}$

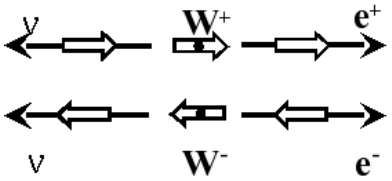
WW



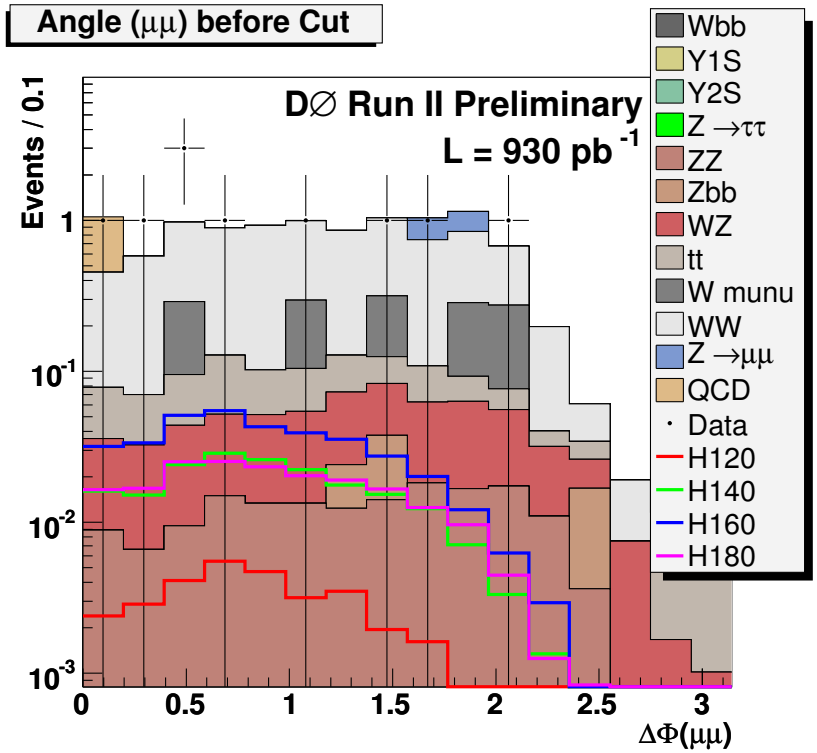
# $H \to WW^{(*)} \to l\nu l'\nu$

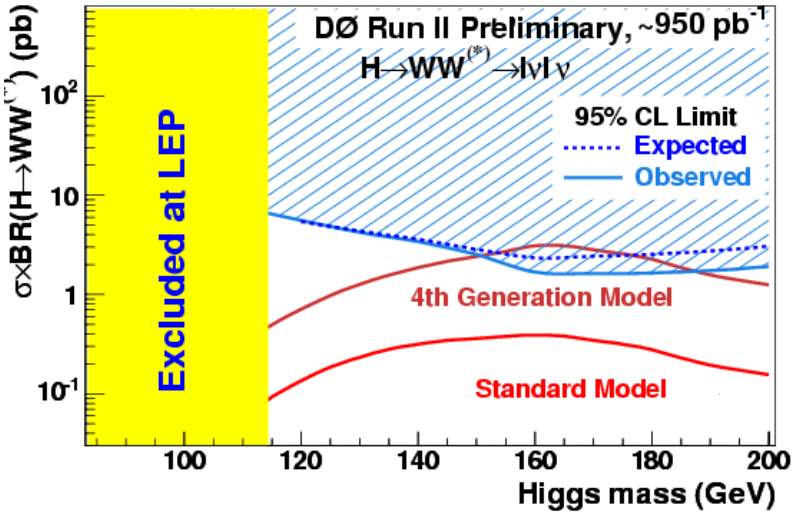
- selection:
  - $ee$, $e\mu$ or $\mu\mu$
  - $\not\!\!E_t$ and $\not\!\!E_t$ significance (cf. jet $E_T$ resolution)
  - kinematic cuts
- spin correlation



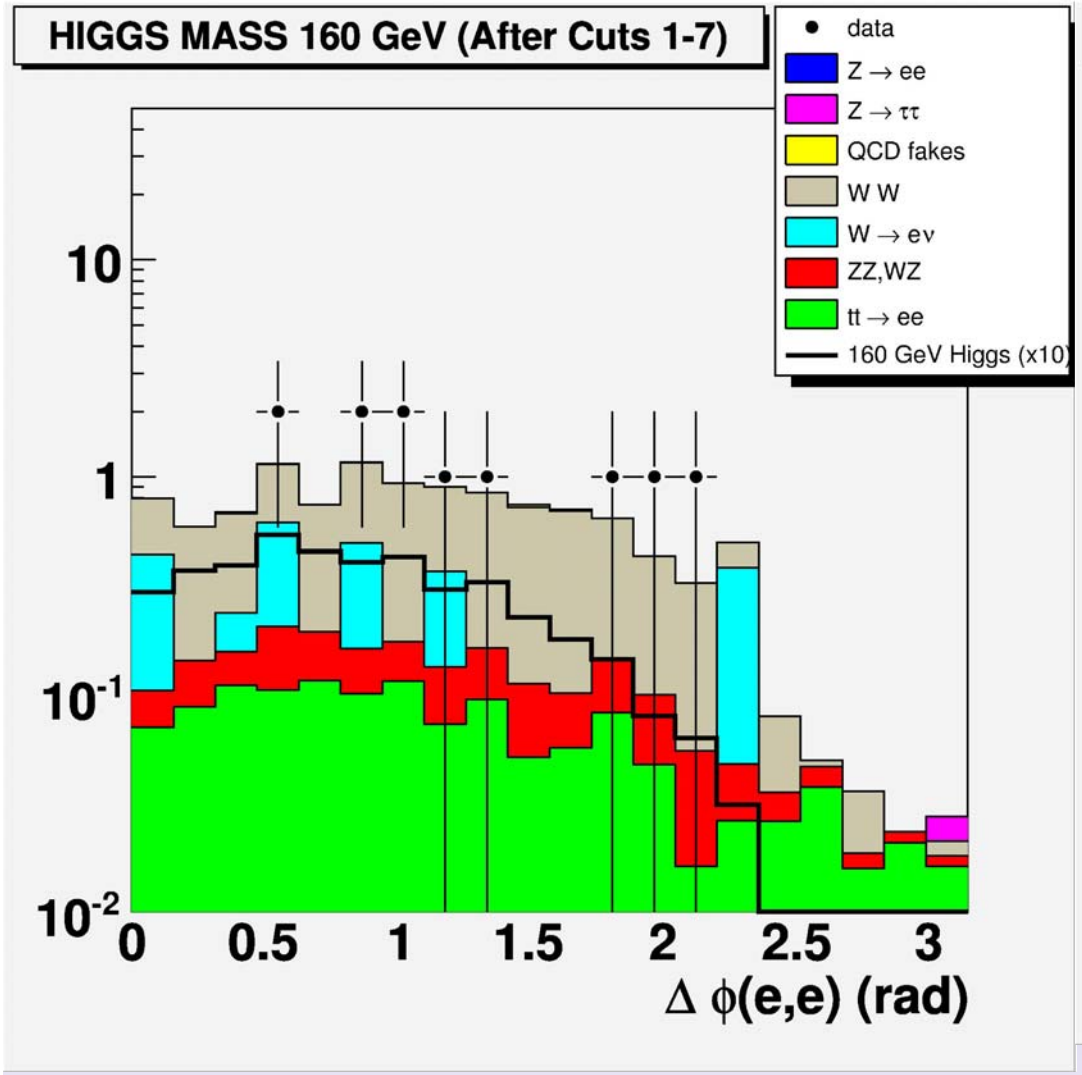

$\to$ di-lepton opening angle $\Delta\phi_{ll'}$ to discriminate against dominating $WW$ background

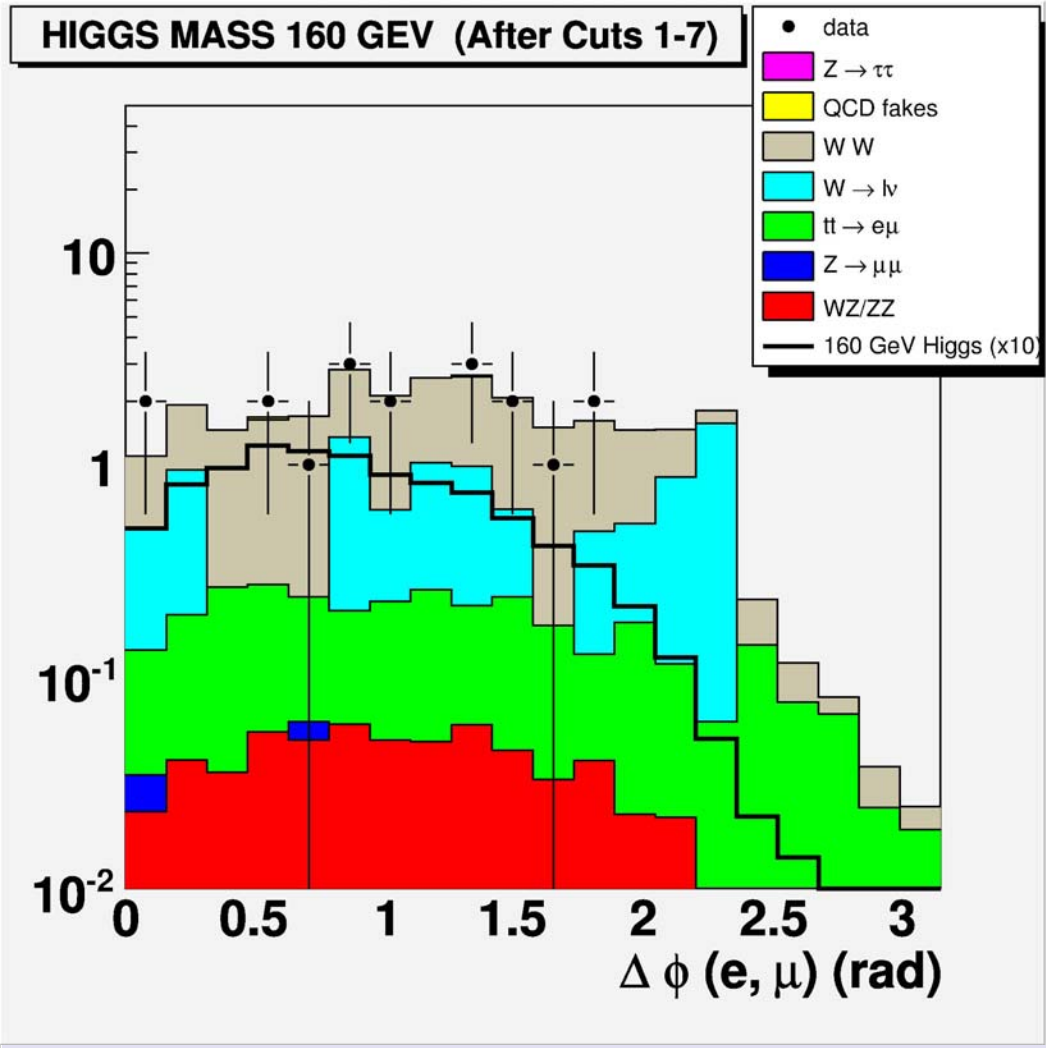
- sensitivity at $M_H \sim 160\,\mathrm{GeV}$: $\sigma_{\mathrm{excl}}/\sigma_{\mathrm{SM}} \sim 4$ $\Rightarrow 4^{th}$ gene. model already excl. for $M_H = 150 - 185\,\mathrm{GeV}$!
- CDF: new results (not shown)



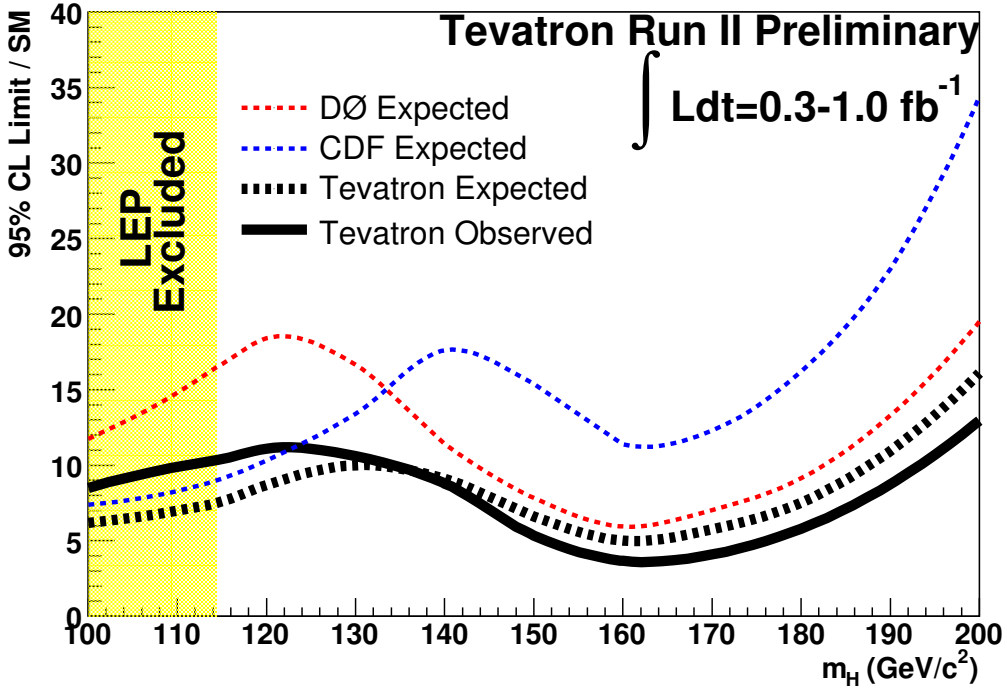



# D0


HIGGS MASS 160 GeV (After Cuts 1-7)
data
Z → ee
Z → ττ
QCD fakes
W W
W → eν
ZZ,WZ
tt → ee
160 GeV Higgs (x10)
10
1
10^-1
10^-2
0
0.5
1
1.5
2
2.5
3
Δ φ(e,e) (rad)

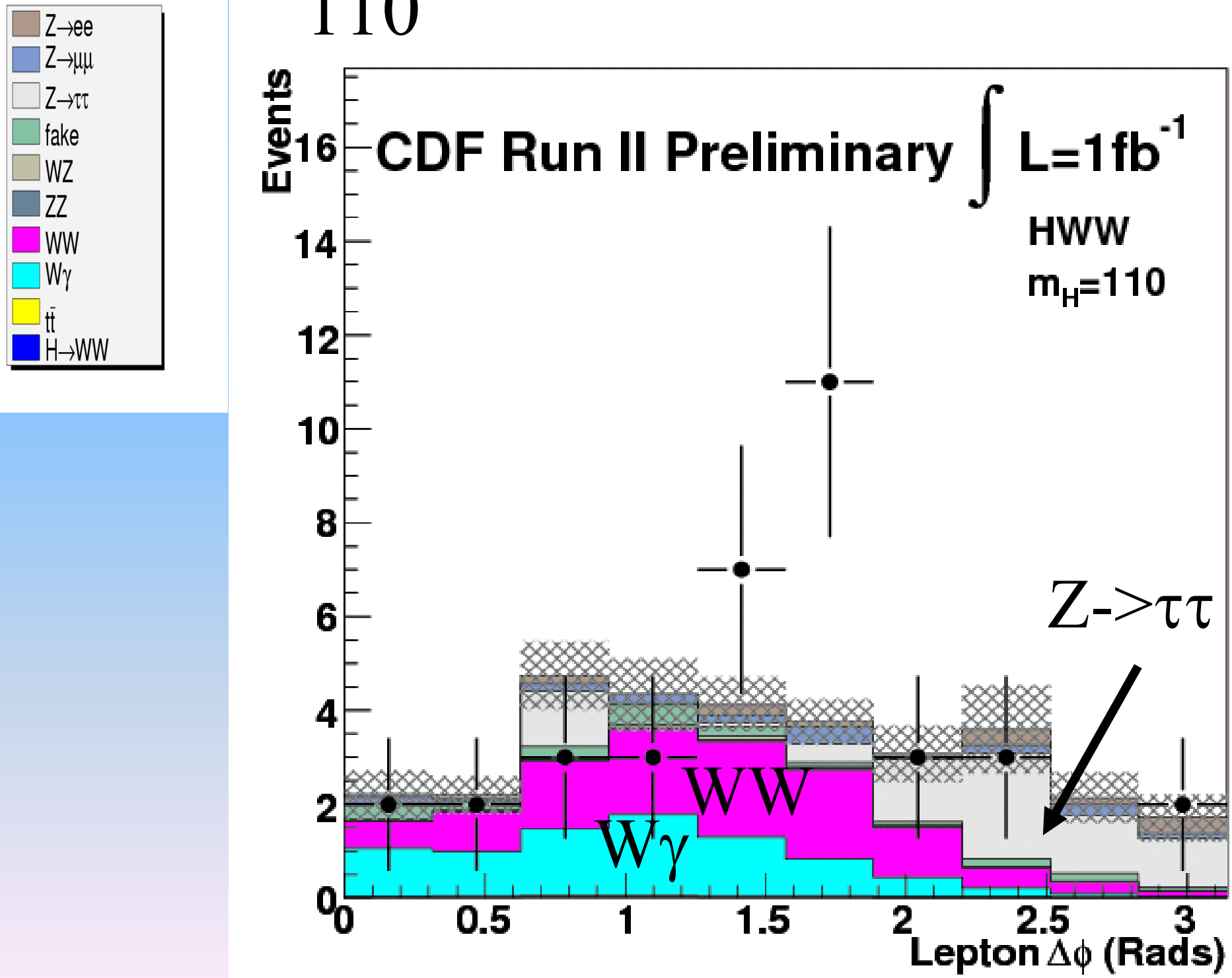

HIGGS MASS 160 GEV (After Cuts 1-7)
data
Z → ττ
QCD fakes
W W
W → lν
tt → eμ
Z → μμ
WZ/ZZ
160 GeV Higgs (x10)
10
1
10^-1
10^-2
0
0.5
1
1.5
2
2.5
3
Δ φ (e, μ) (rad)

# Combined Tevatron SM Higgs Limits

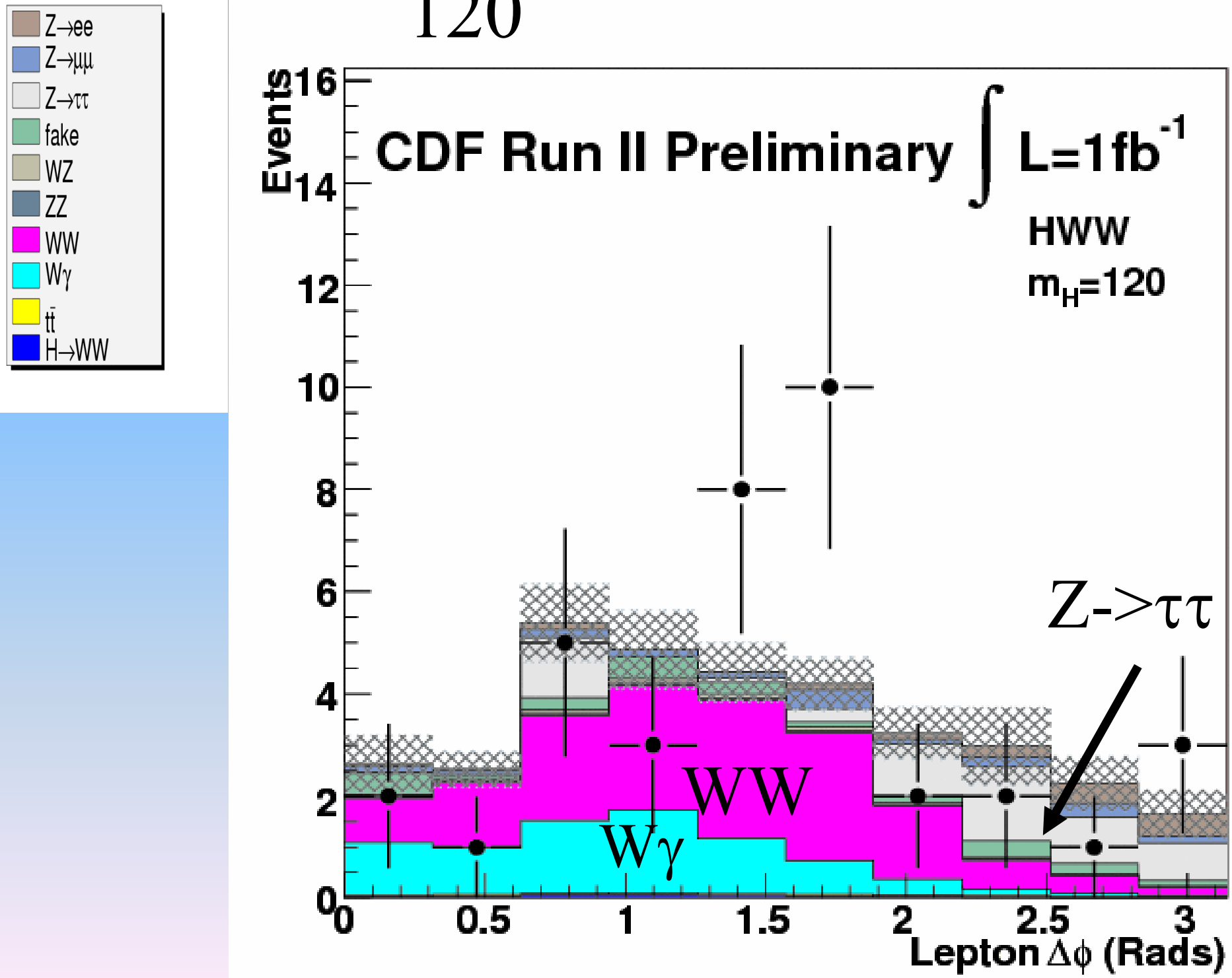


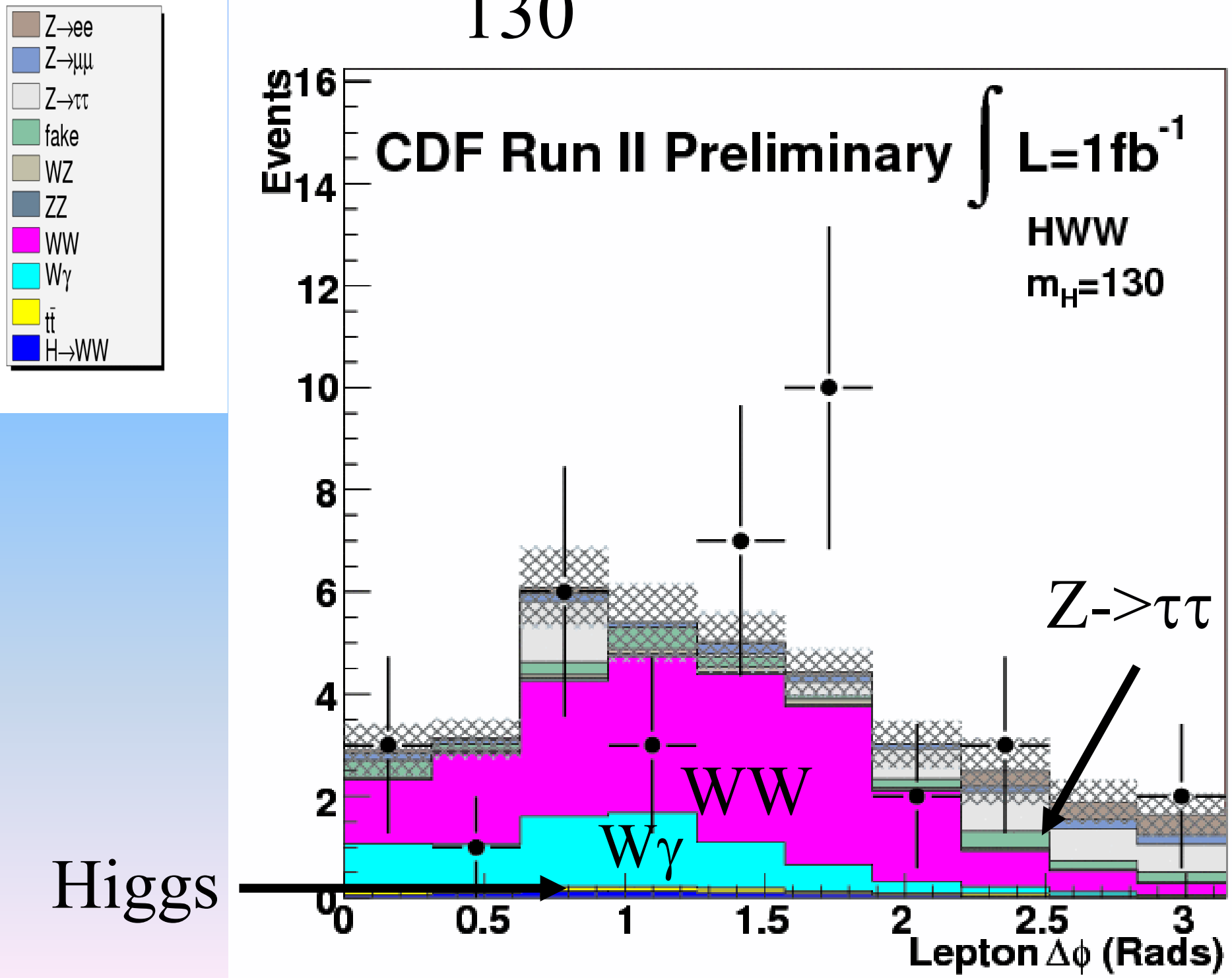

- first CDF and DØ combined limits (status: Summer 06)
  - $ZH$, $WH$ (low mass): only CDF's $1\,\mathrm{fb}^{-1}$ results included
  - $H \to WW^{(*)}$ (high mass): only DØ's $1\,\mathrm{fb}^{-1}$ results included
- new measurements with $1\,\mathrm{fb}^{-1}$ not yet in combination:
  - CDF: $H \to WW^{(*)}$, DØ: $ZH \to l^+l^-b\bar{b}$
- new updates to be released within the next weeks
- prospects: $L = 4 - 8\,\mathrm{fb}^{-1}$ (by 2009), improved $b$-tagging (NN) and selections

# 110

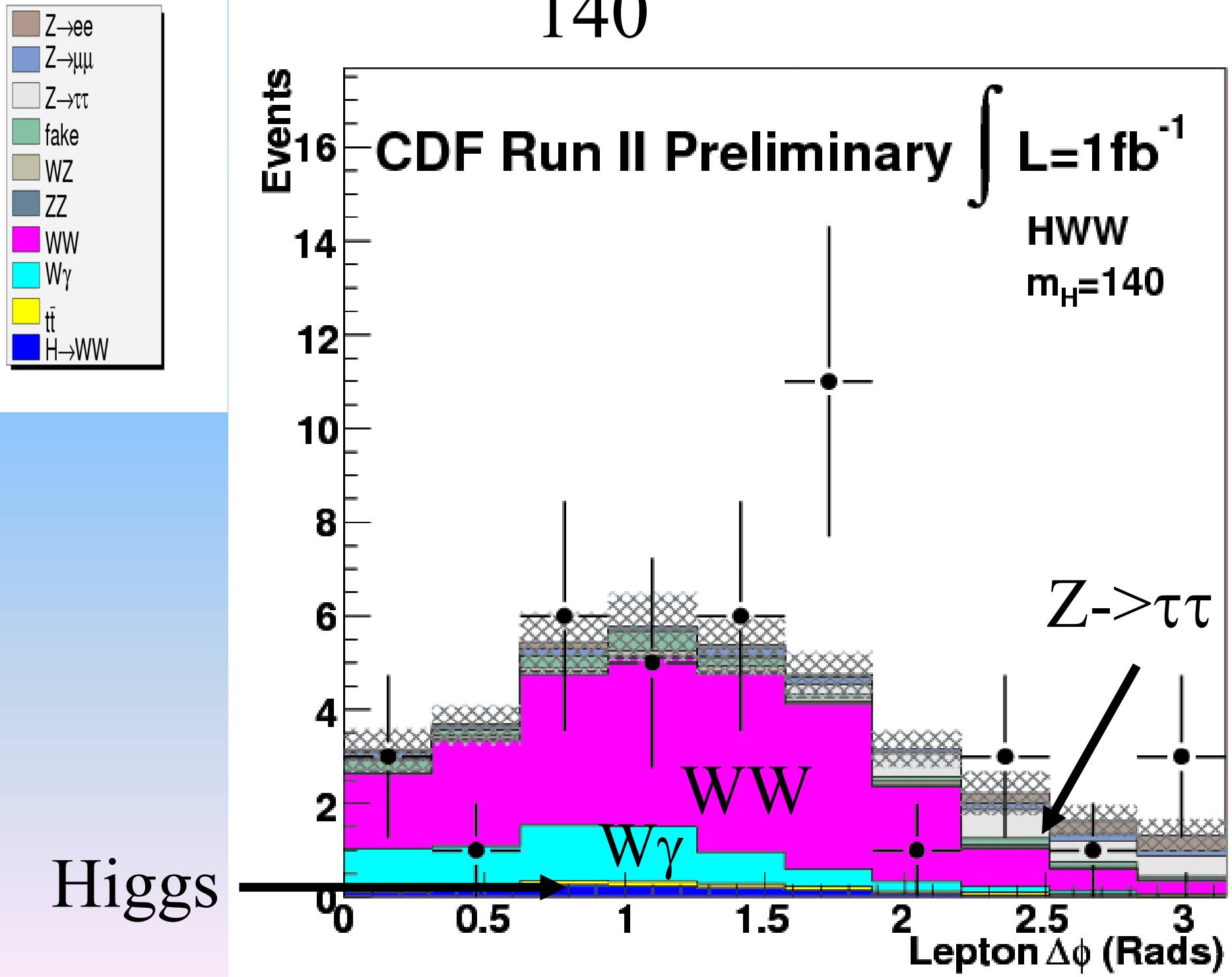

Z→ee
Z→μμ
Z→ττ
fake
WZ
ZZ
WW
Wγ
tt̄
H→WW
Events
CDF Run II Preliminary ∫ L=1fb-1
HWW
mH=110
Z->ττ
WW
Wγ
Lepton Δφ (Rads)
0
2
4
6
8
10
12
14
16
0.5
1
1.5
2
2.5
3

# 120

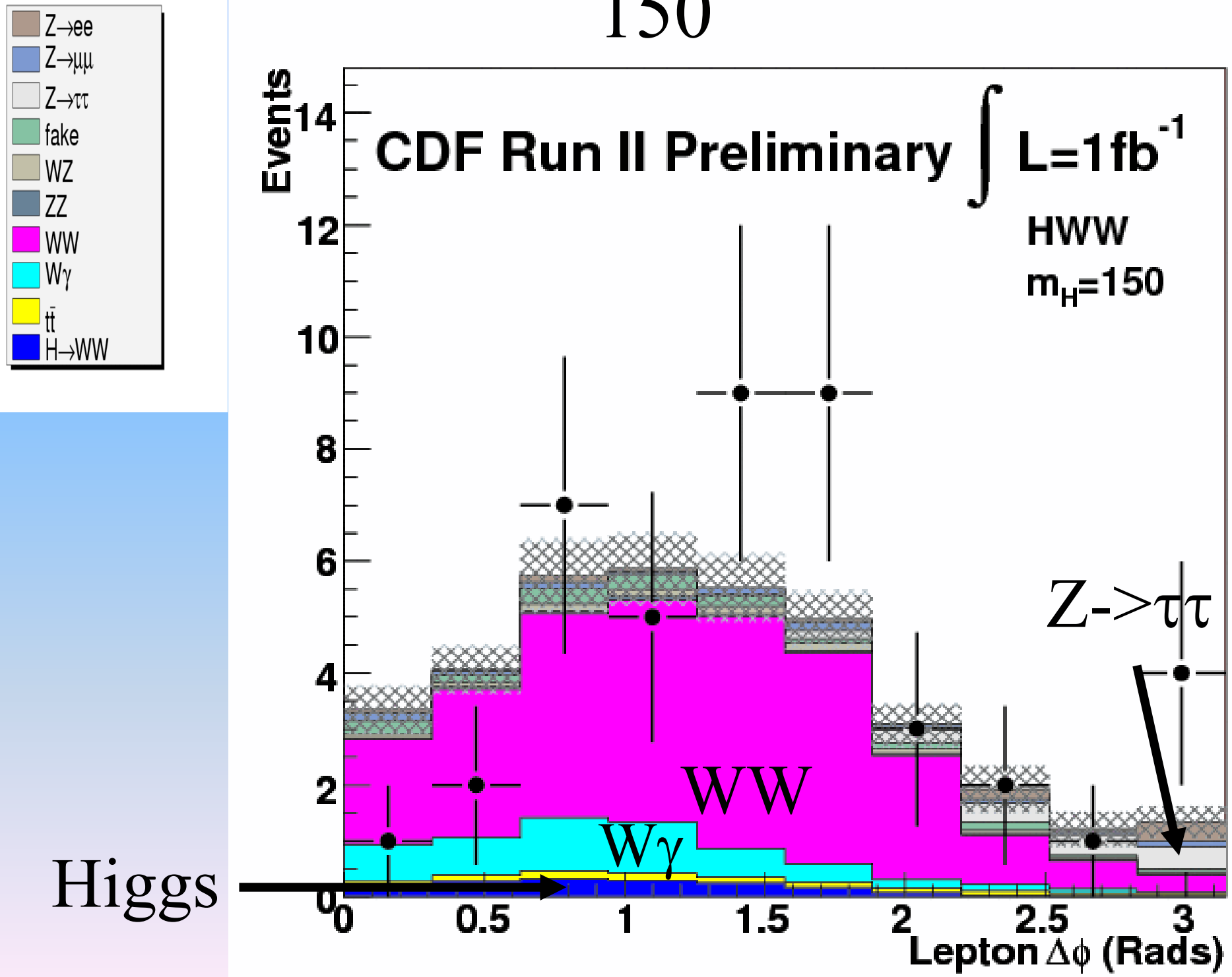

Z→ee
Z→μμ
Z→ττ
fake
WZ
ZZ
WW
Wγ
tt̄
H→WW
CDF Run II Preliminary ∫ L=1fb-1
HWW
mH=120
Events
Z->ττ
WW
Wγ
Lepton Δφ (Rads)


Z→ee
Z→μμ
Z→ττ
fake
WZ
ZZ
WW
Wγ
tt̄
H→WW
CDF Run II Preliminary ∫ L=1fb-1
HWW
mH=130
Events
Lepton Δφ (Rads)
Z->ττ
WW
Wγ

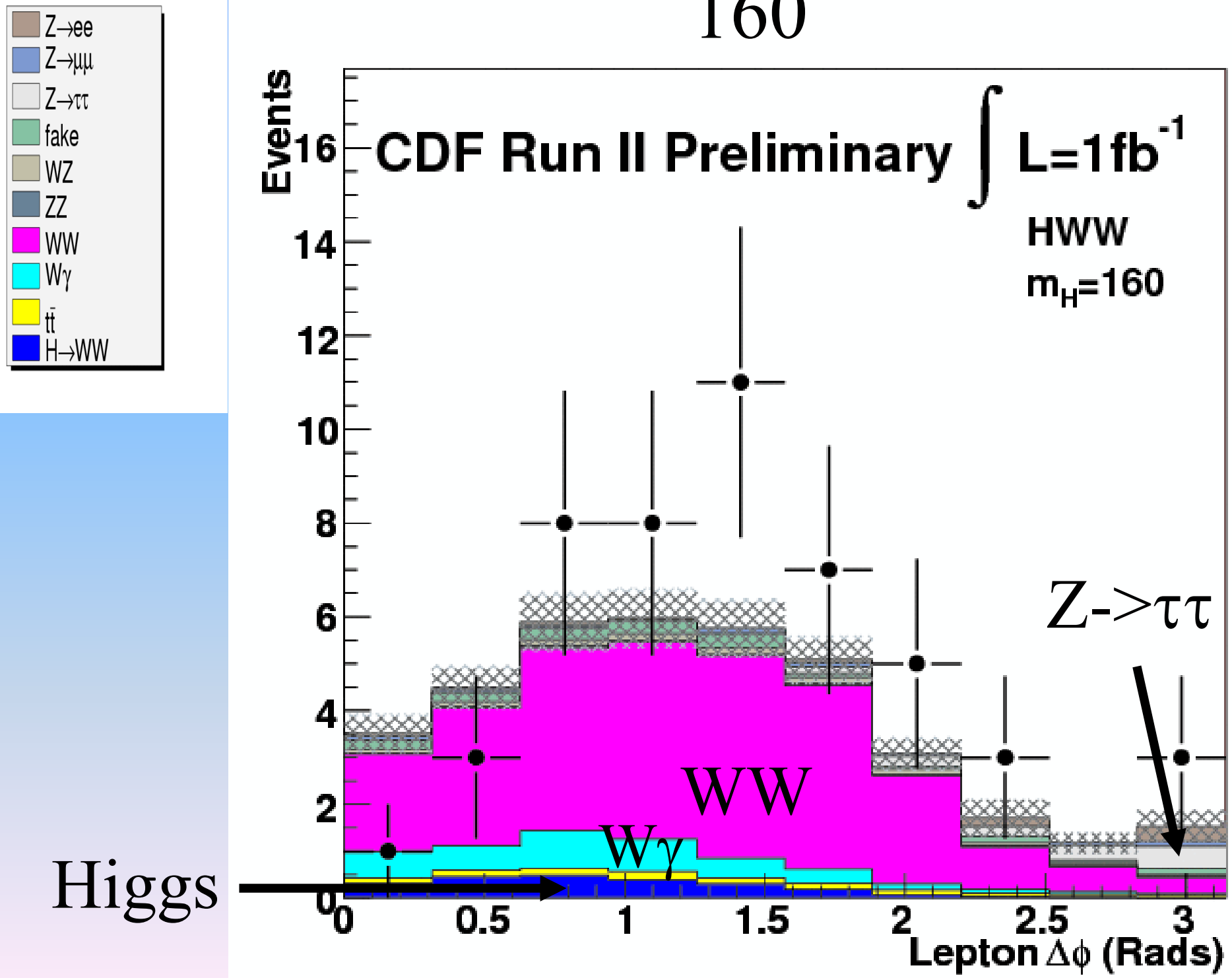
Higgs


Z→ee
Z→μμ
Z→ττ
fake
WZ
ZZ
WW
Wγ
tt̄
H→WW
Events
CDF Run II Preliminary ∫ L=1fb-1
HWW
mH=140
Z->ττ
WW
Wγ
Lepton Δφ (Rads)
0
0.5
1
1.5
2
2.5
3
2
4
6
8
10
12
14
16

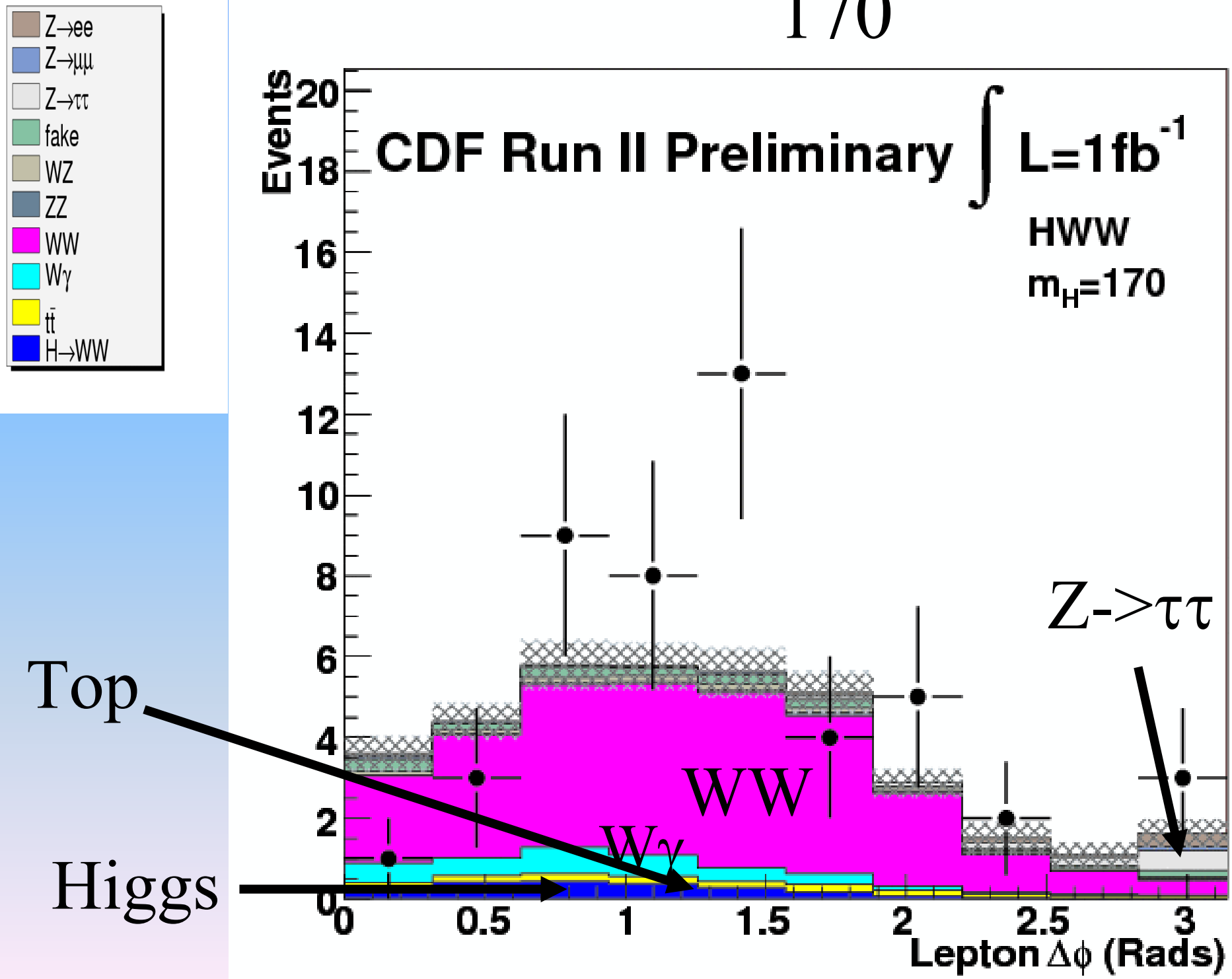
Higgs

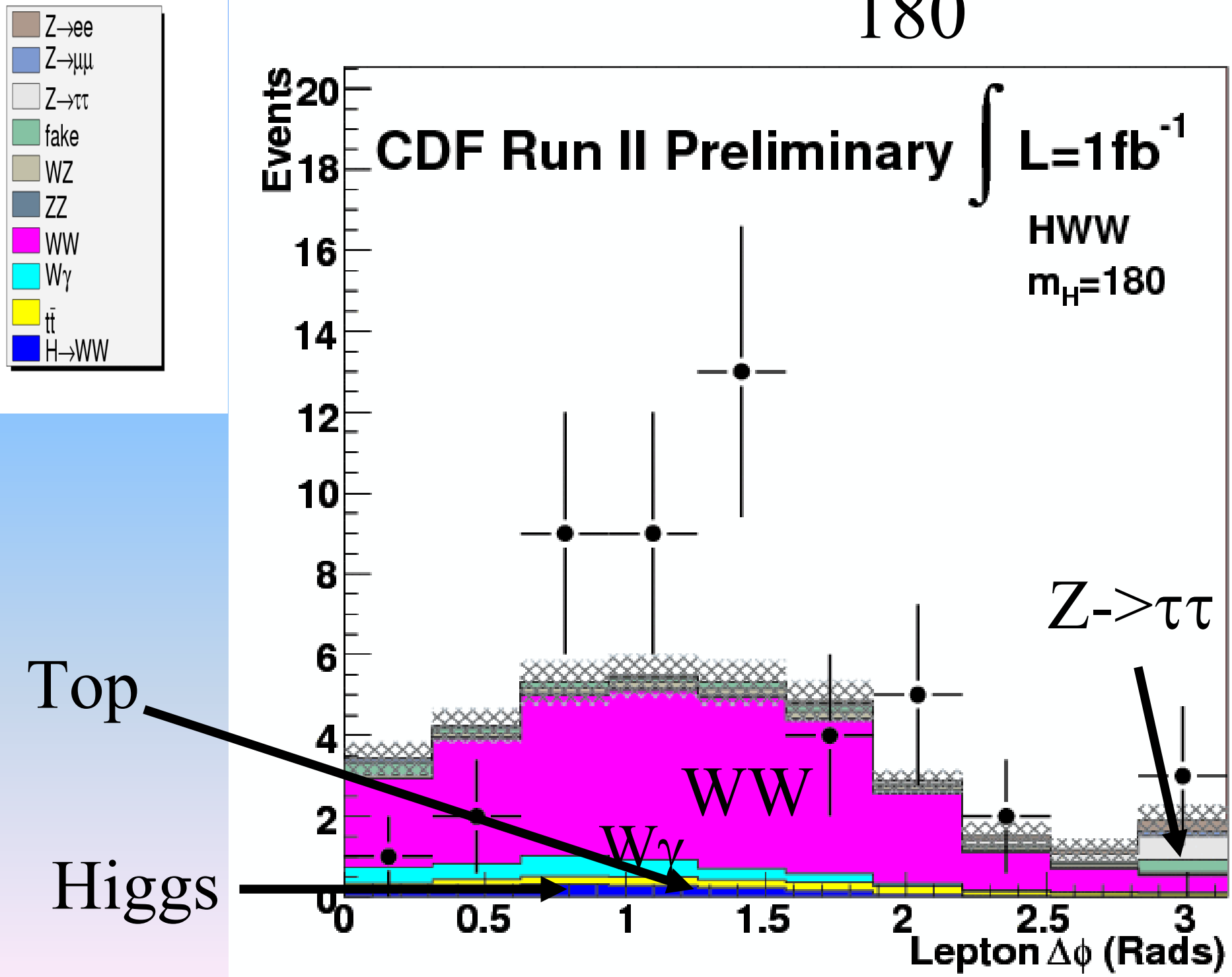

Z→ee
Z→μμ
Z→ττ
fake
WZ
ZZ
WW
Wγ
tt̄
H→WW
CDF Run II Preliminary ∫ L=1fb-1
HWW
mH=150
Events
Lepton Δφ (Rads)
Z->ττ
WW
Wγ

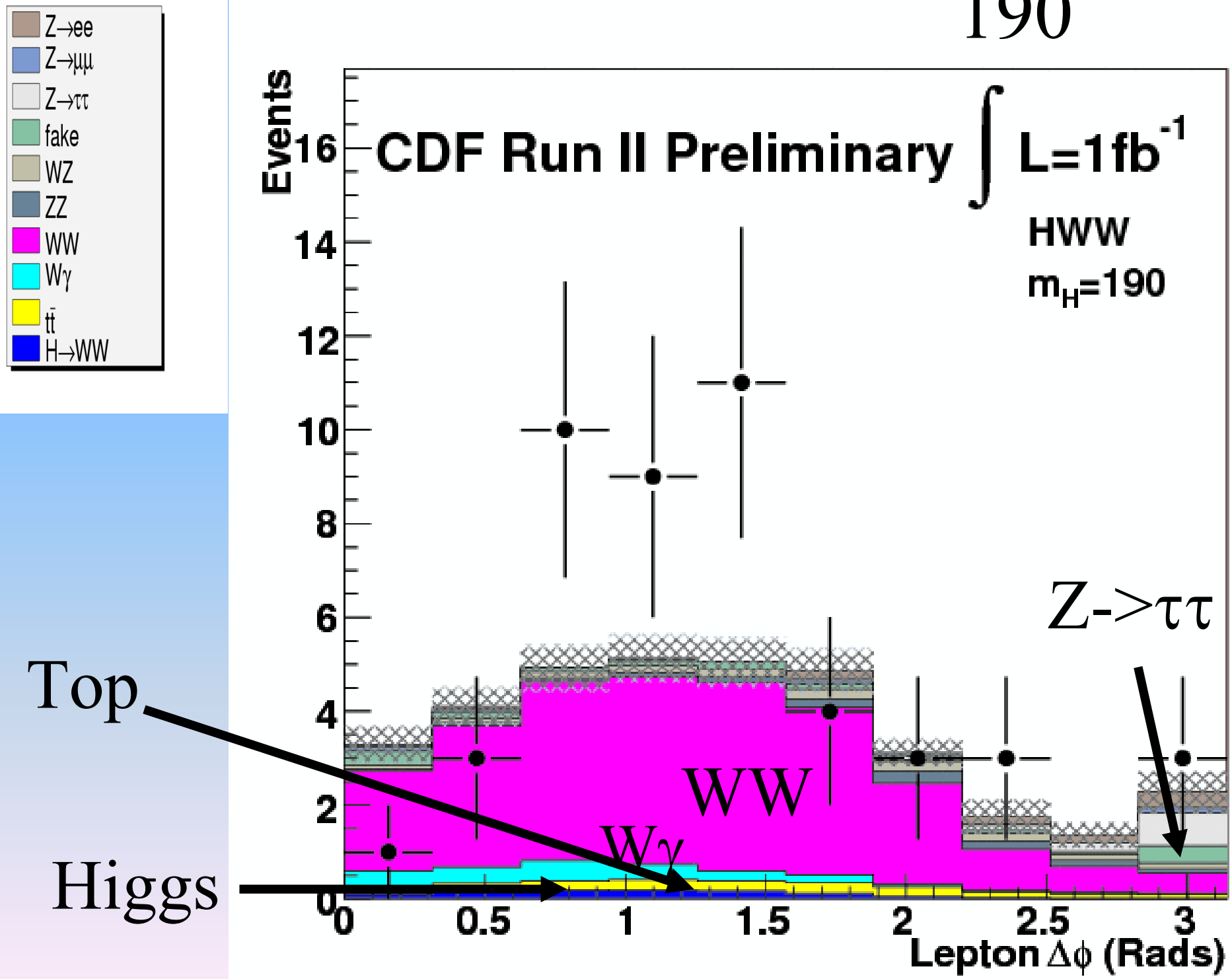
Higgs

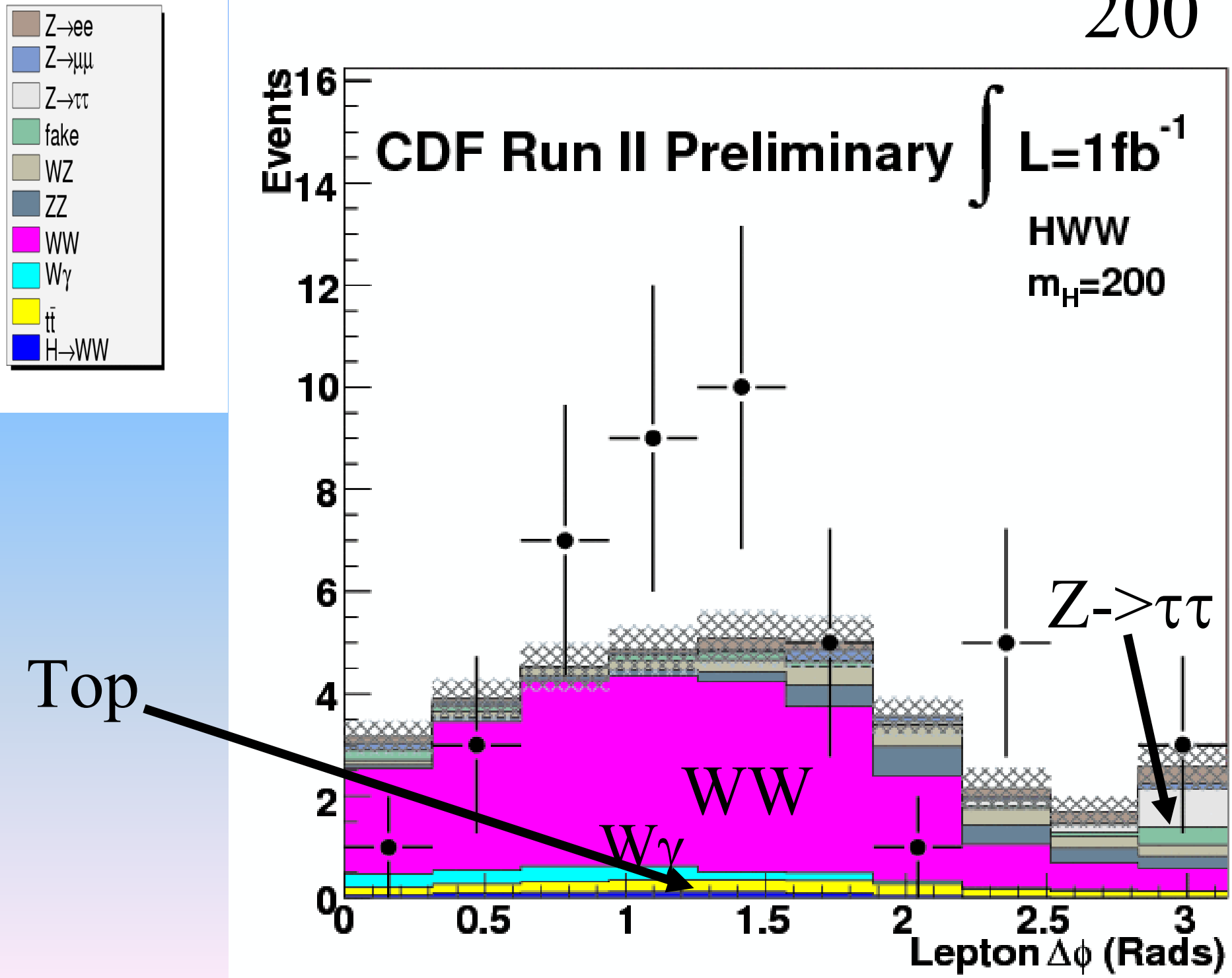

Z→ee
Z→μμ
Z→ττ
fake
WZ
ZZ
WW
Wγ
tt̄
H→WW
Events
CDF Run II Preliminary ∫ L=1fb-1
HWW
mH=160
Z->ττ
WW
Wγ
Lepton Δφ (Rads)
0
2
4
6
8
10
12
14
16
0.5
1
1.5
2
2.5
3

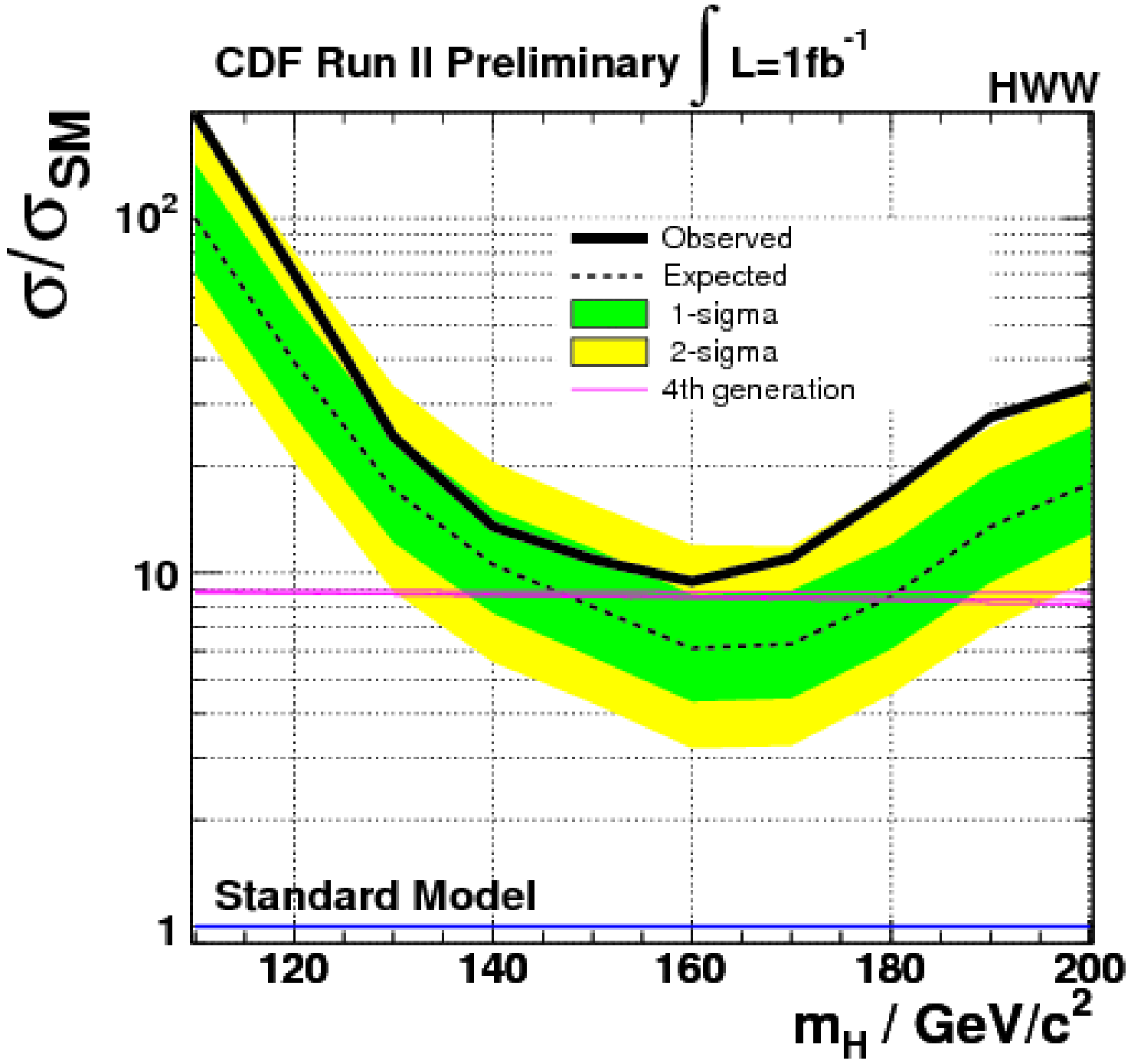
Higgs


Z→ee
Z→μμ
Z→ττ
fake
WZ
ZZ
WW
Wγ
tt̄
H→WW
Events
CDF Run II Preliminary ∫ L=1fb-1
HWW
mH=170
Z->ττ
WW
Wγ
Top
Higgs
Lepton Δφ (Rads)

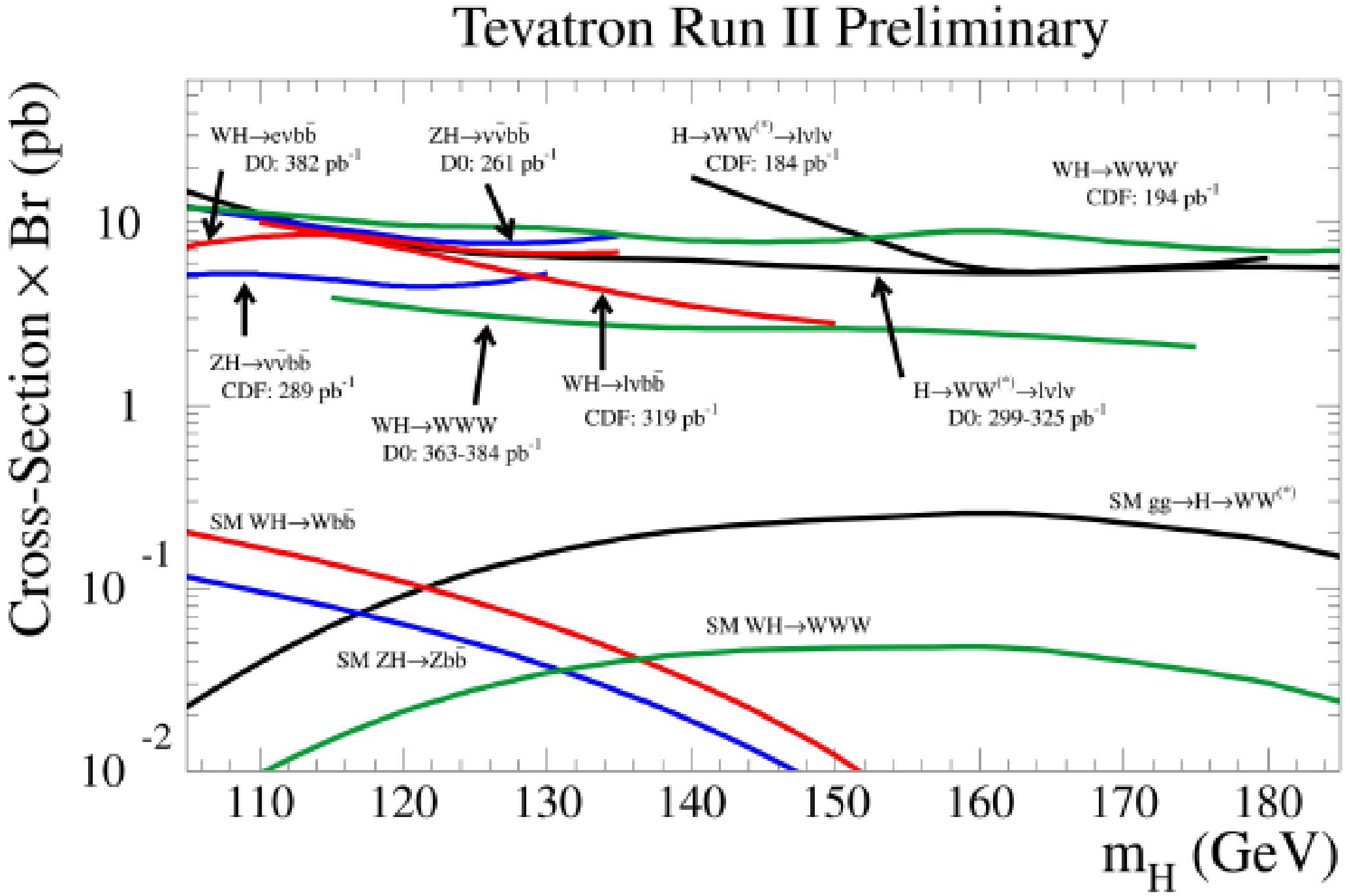

Z→ee
Z→μμ
Z→ττ
fake
WZ
ZZ
WW
Wγ
tt̄
H→WW
Events
CDF Run II Preliminary ∫ L=1fb-1
HWW
mH=180
Z->ττ
WW
Wγ
Top
Higgs
Lepton Δφ (Rads)


Z→ee
Z→μμ
Z→ττ
fake
WZ
ZZ
WW
Wγ
tt̄
H→WW
CDF Run II Preliminary ∫ L=1fb-1
HWW
mH=190
Events
Lepton Δφ (Rads)
Z->ττ
WW
Wγ
Top
Higgs

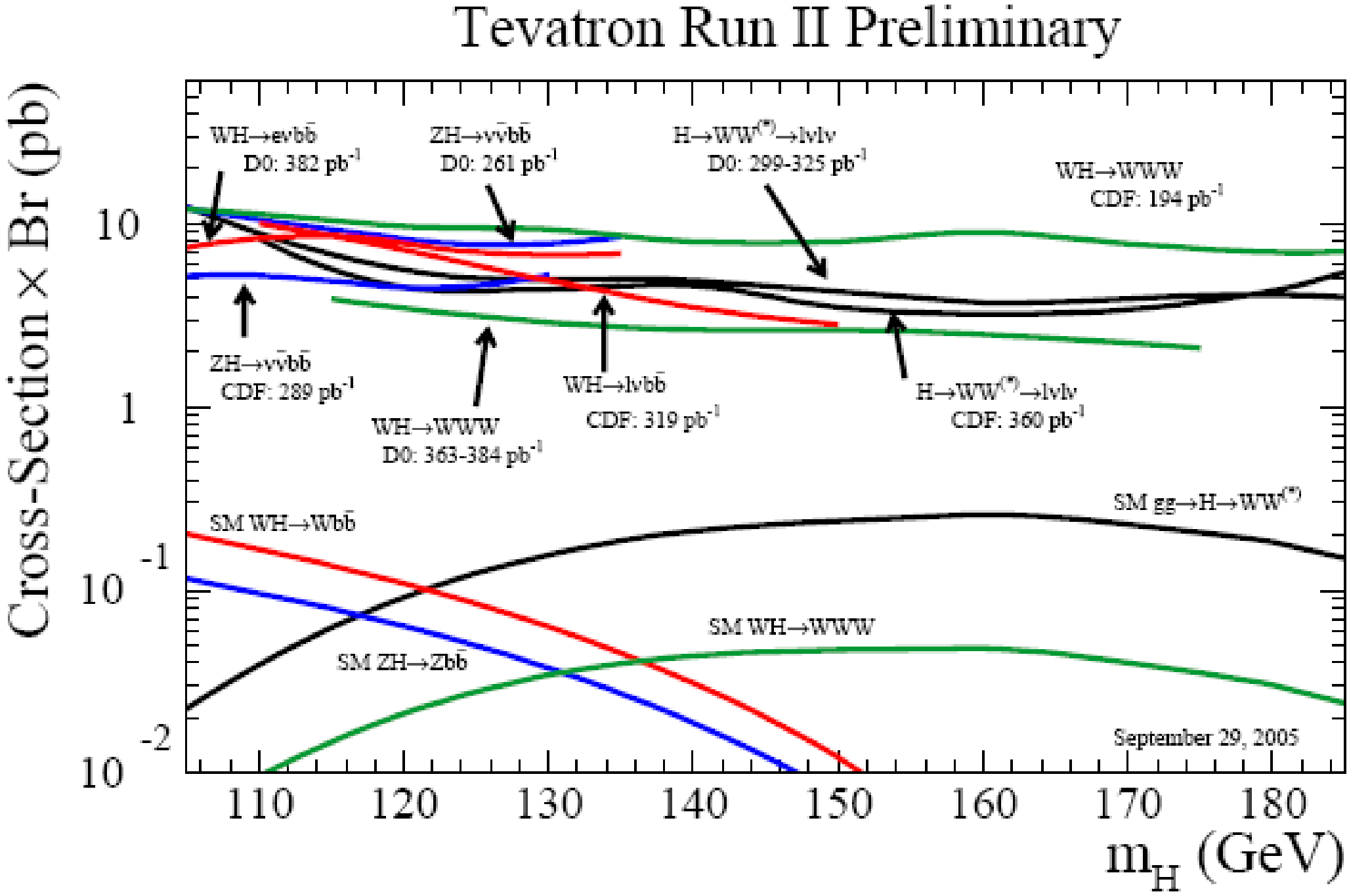

Z→ee
Z→μμ
Z→ττ
fake
WZ
ZZ
WW
Wγ
tt̄
H→WW
CDF Run II Preliminary ∫ L=1fb-1
HWW
mH=200
Events
Lepton Δφ (Rads)
Top
WW
Wγ
Z->ττ


CDF Run II Preliminary ∫ L=1fb-1
HWW
σ/σSM
10²
10
1
Observed
Expected
1-sigma
2-sigma
4th generation
Standard Model
120
140
160
180
200
mH / GeV/c²

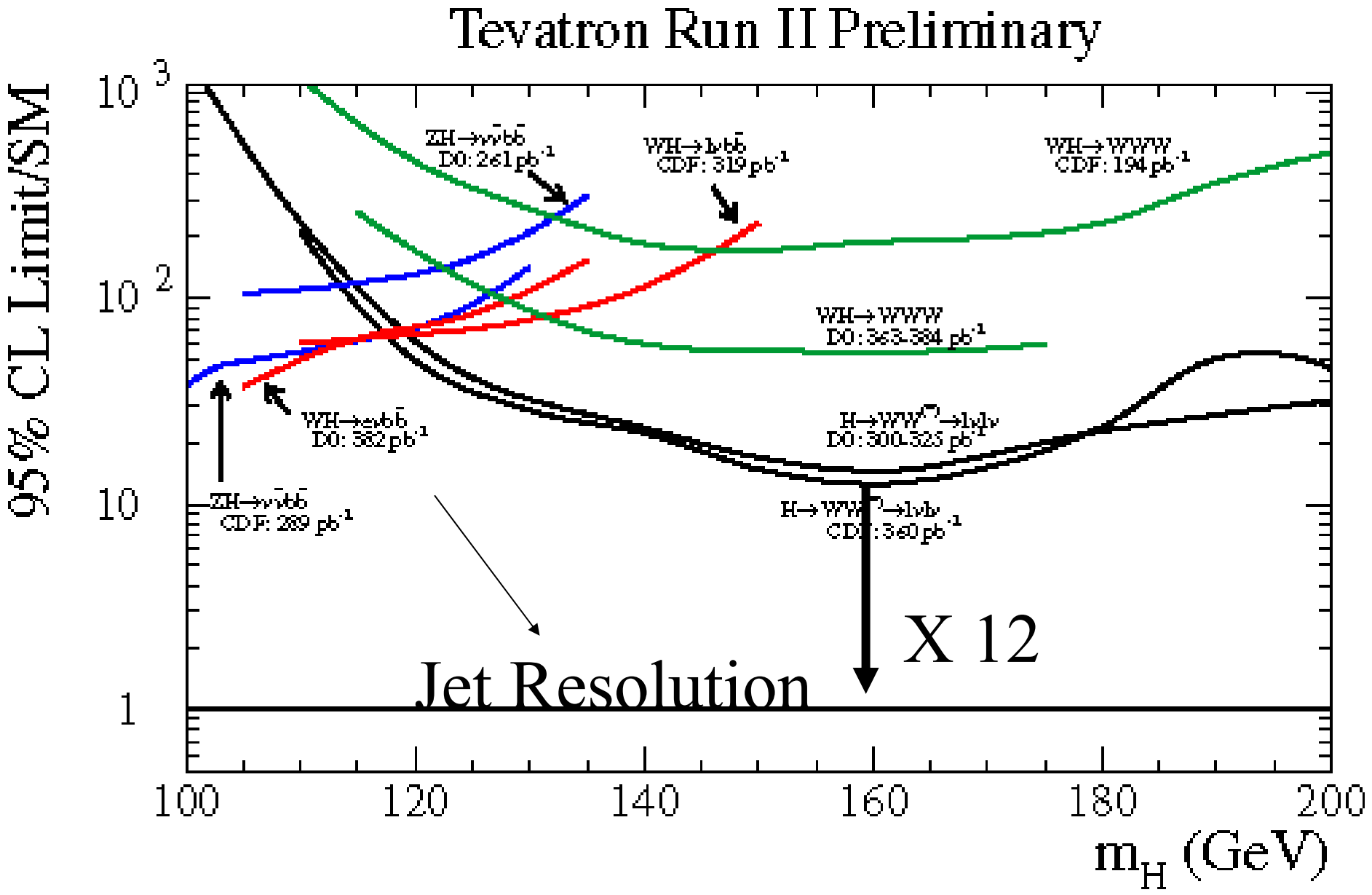
Collected CDF/D0 Plot for Summer 2005 Conferences



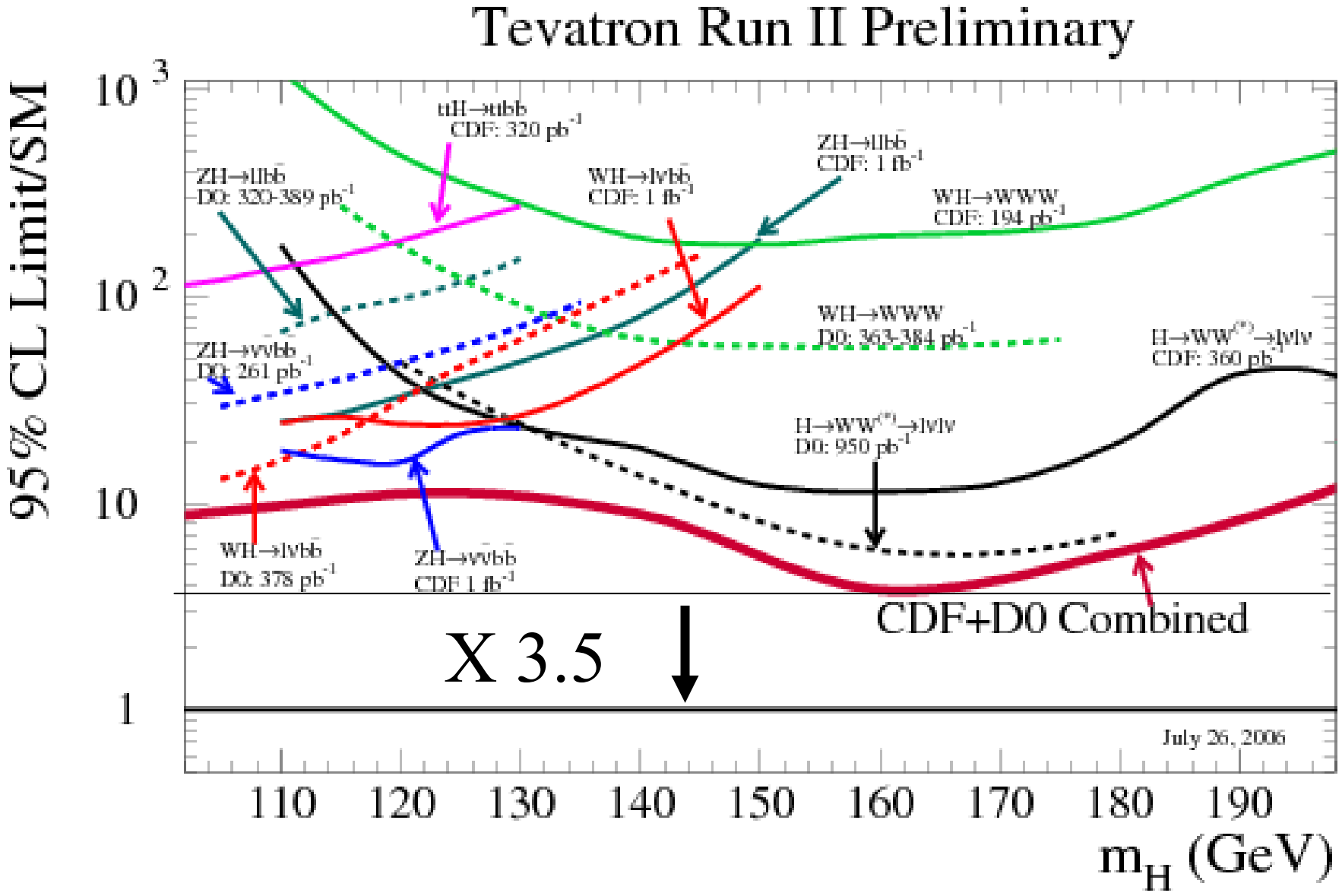
# And in Late September 2005



# CDF Limits: Feb 2006

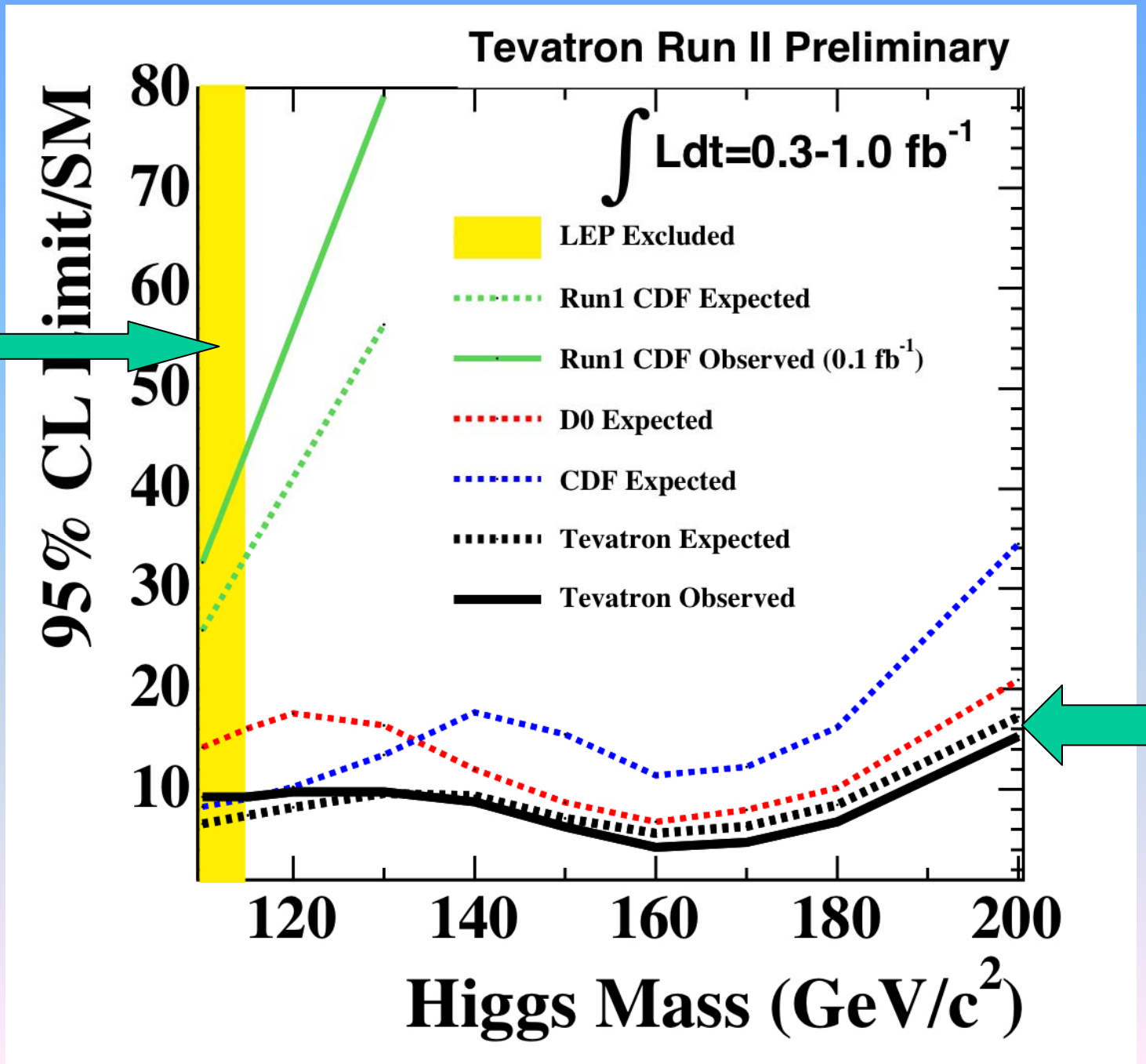


# CDF Limits: Feb 2007



# Already < x15 for all masses

Run I




x15

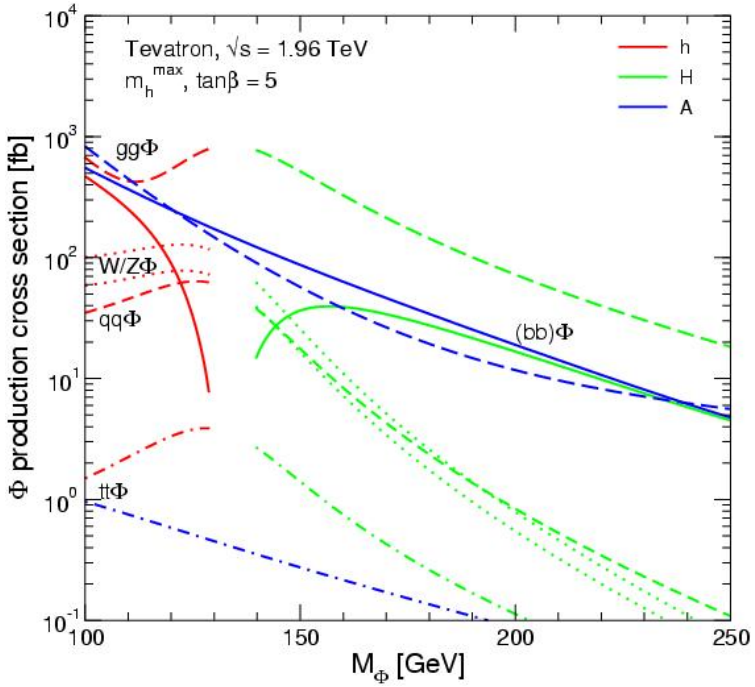
# Summary

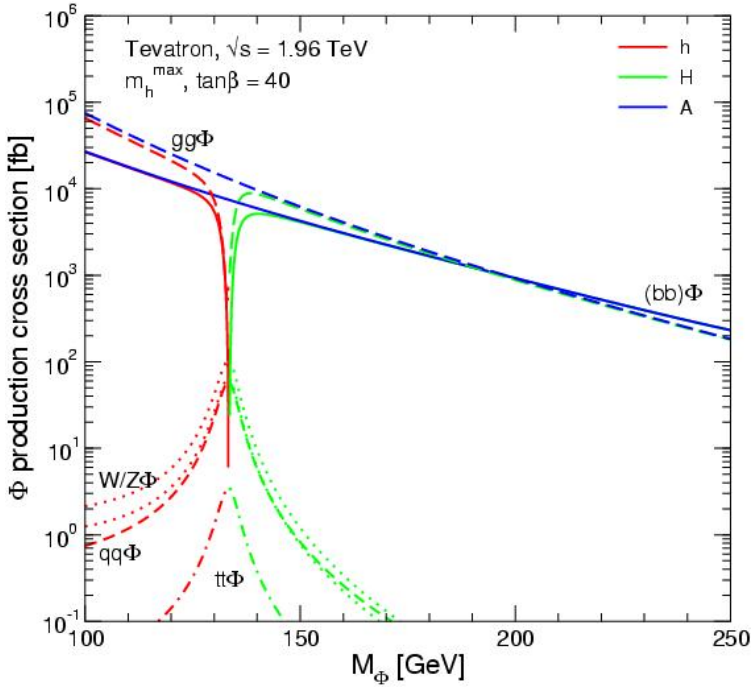
- SM Higgs
  - many updates with $1\,\mathrm{fb}^{-1}$ within the last year
  - first Tevatron combination in Summer 06
    prospects: promising but challenging

- for further details see:
  CDF: `http://http://www-cdf.fnal.gov/physics/physics.html`
  DØ: `http://www-d0.fnal.gov/Run2Physics/WWW/results.htm`

# SUSY Higgs

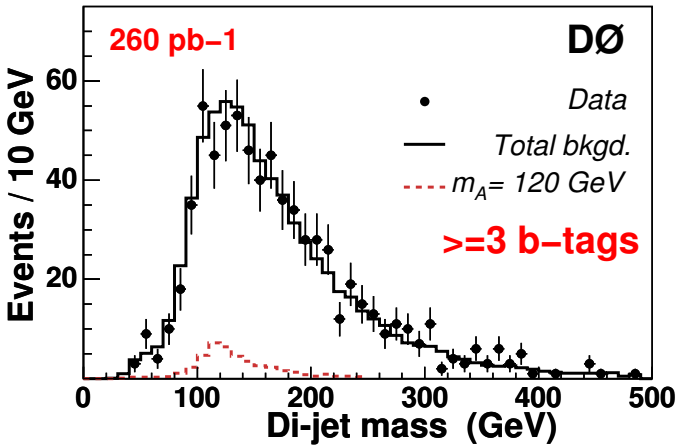
- MSSM: 2-Higgs-doublet model:
  - 5 $H$-bosons: $h^0$, $H^0$, $A^0$, $H^\pm$
  - all $^0 = \phi^0$
  - prediction: $m_h \lesssim 135\,\mathrm{GeV}$
- Higgs v.e.v.'s $v_u$, $v_d$: ratio $\tan\beta = v_u/v_d$
  $\rightarrow$ $\sigma(gg \rightarrow H)$ and $\sigma(b\bar{b}H)$ enhanced at large $\tan\beta$
- at large $\tan\beta$: $A$ nearly mass-degenerate with $h$ or $H$, $\sigma(A) \sim \sigma(h/H)$
- decays at large $\tan\beta$:
  - $Br(\phi \rightarrow b\bar{b}) \sim 90\%$
    $\Rightarrow b\bar{b}\phi \rightarrow b\bar{b}b\bar{b}$
  - $Br(\phi \rightarrow \tau^+\tau^-) \sim 10\%$
    $\rightarrow \phi \rightarrow \tau^+\tau^-$

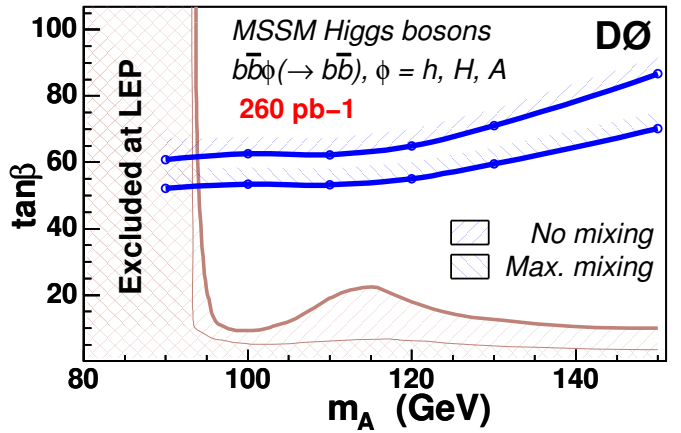


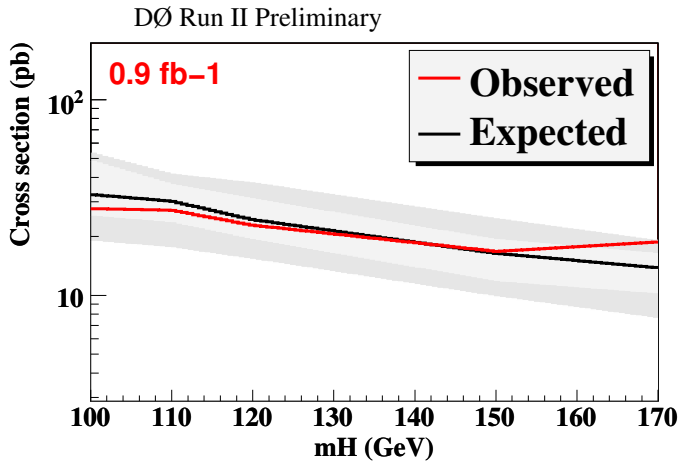



# MSSM $b\bar{b}\phi \to b\bar{b}b\bar{b}$

- selection:
  - 3 $b$-tagged jets
  - search for peak in $m(j_1, j_2)$
- backgrounds:
  - $b\bar{b}j(j)$, $b\bar{b}b\bar{b}$, $Z(\to b\bar{b})j$, $t\bar{t}$
  - shape: $2b$-tagged $\times$ (mis-)tag
  - normalized to $3b$-tagged outside signal region
- sensitivity at $M_A \sim 120\,\mathrm{GeV}$:
  $\tan\beta >\sim 50 - 60$
  (depending on $\tilde{t}$ mixing param. $X_t$)
- update based on $0.9\,\mathrm{fb}^{-1}$
  - NN $b$-tagger: $\epsilon(b\text{−tag}) = 49\%$ at $\epsilon(\mathrm{mis-tag}) = 0.33\%$
  - $\sigma$(excl.) improved by $\sim 1/3$

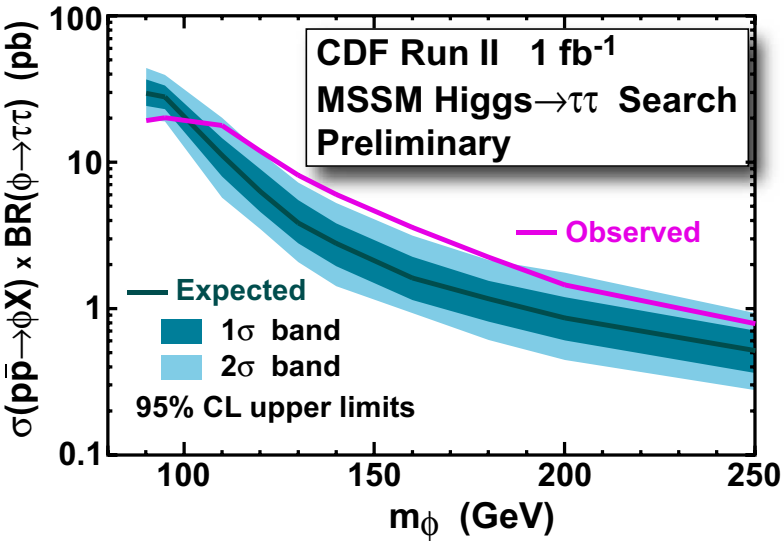


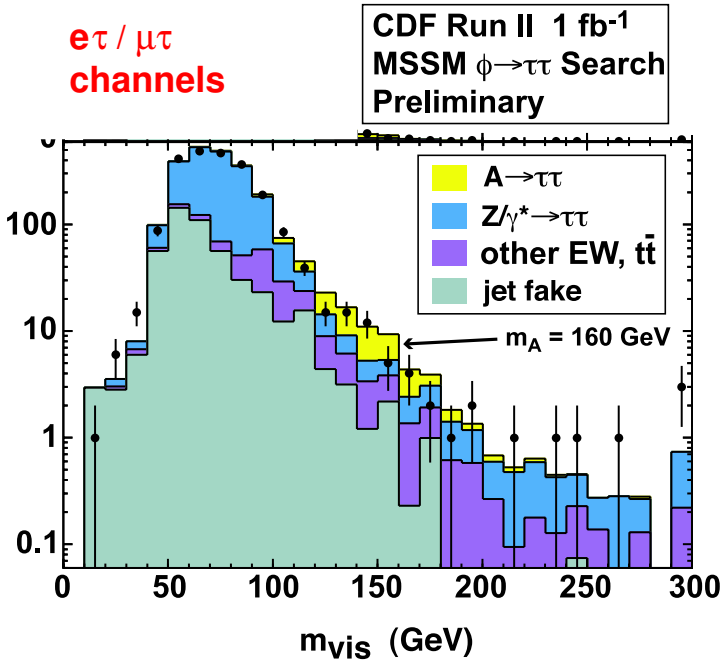



# MSSM $\phi \to \tau\tau$

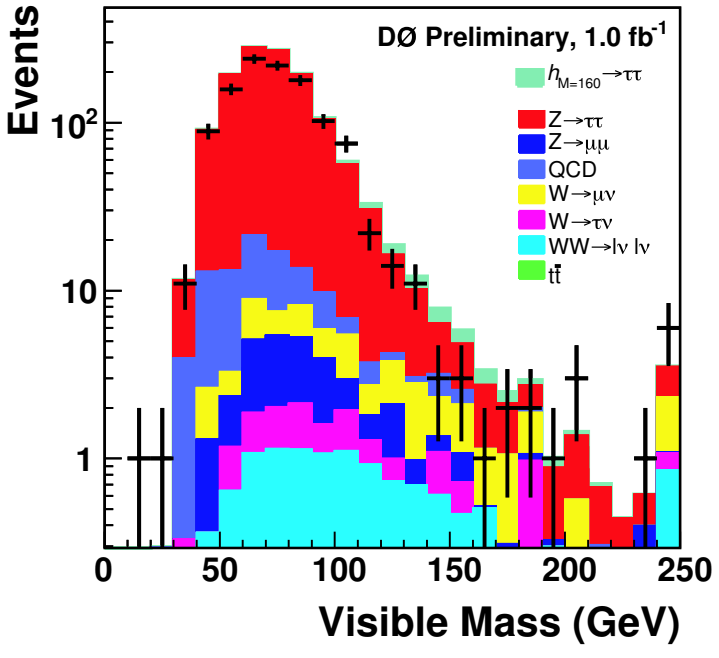
- 2 new results based on $1\,\mathrm{fb}^{-1}$
  - CDF: $e\mu$, $e\tau$, $\mu\tau$
  - DØ: $\mu\tau$ selection
- partial reconstruction of $M_\phi$:
  $m_{\mathrm{vis}} = |P^{\mathrm{vis}}_{\tau_1} + P^{\mathrm{vis}}_{\tau_2} + \not{P}_t\,|$
  - CDF: some excess seen (only $e\tau$, $\mu\tau$), but significance $< 2\sigma$
  - DØ: no excess, (limits from NN analysis)




eτ / μτ channels




$\mu\tau$ channel



# SUSY and $A^0 \rightarrow \tau^+\tau^-$

- $H^0, h^0, A^0$; $H^\pm$

Light,SM-Like  Heavier,tan β enhanced

$h^0$ $M_h < 130$  $H^0\ A^0$ Tan β ~ 50

$H^0$  $h^0\ A^0$

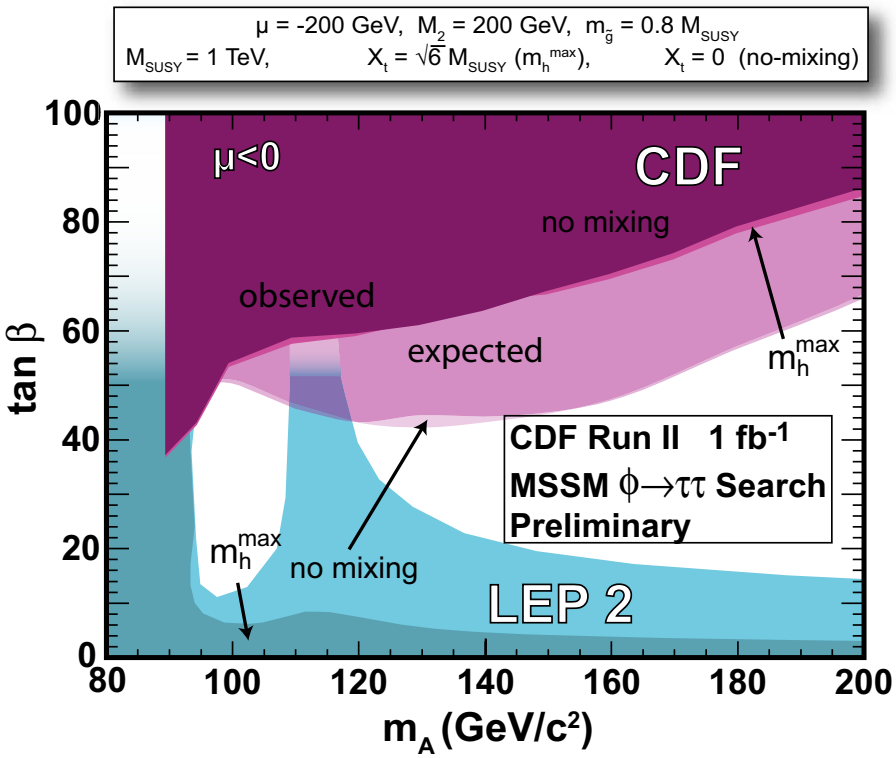
$A \rightarrow \tau^+\tau^-$ + charge conjugate; h = hadronic

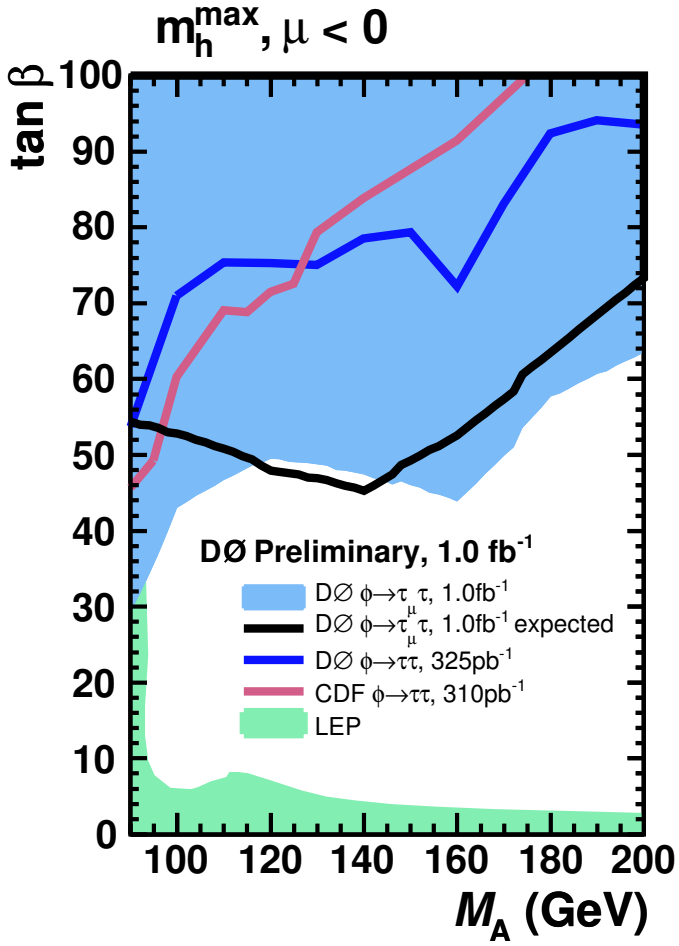
$\mu^- \bar{\nu}_\mu \nu_\tau$  $e^- \bar{\nu}_e \nu_\tau$  $\mu^- \bar{\nu}_\mu \nu_\tau$

$e^+ \nu_e \nu_\tau$  $h^+ \nu_\tau$  $h^+ \nu_\tau$

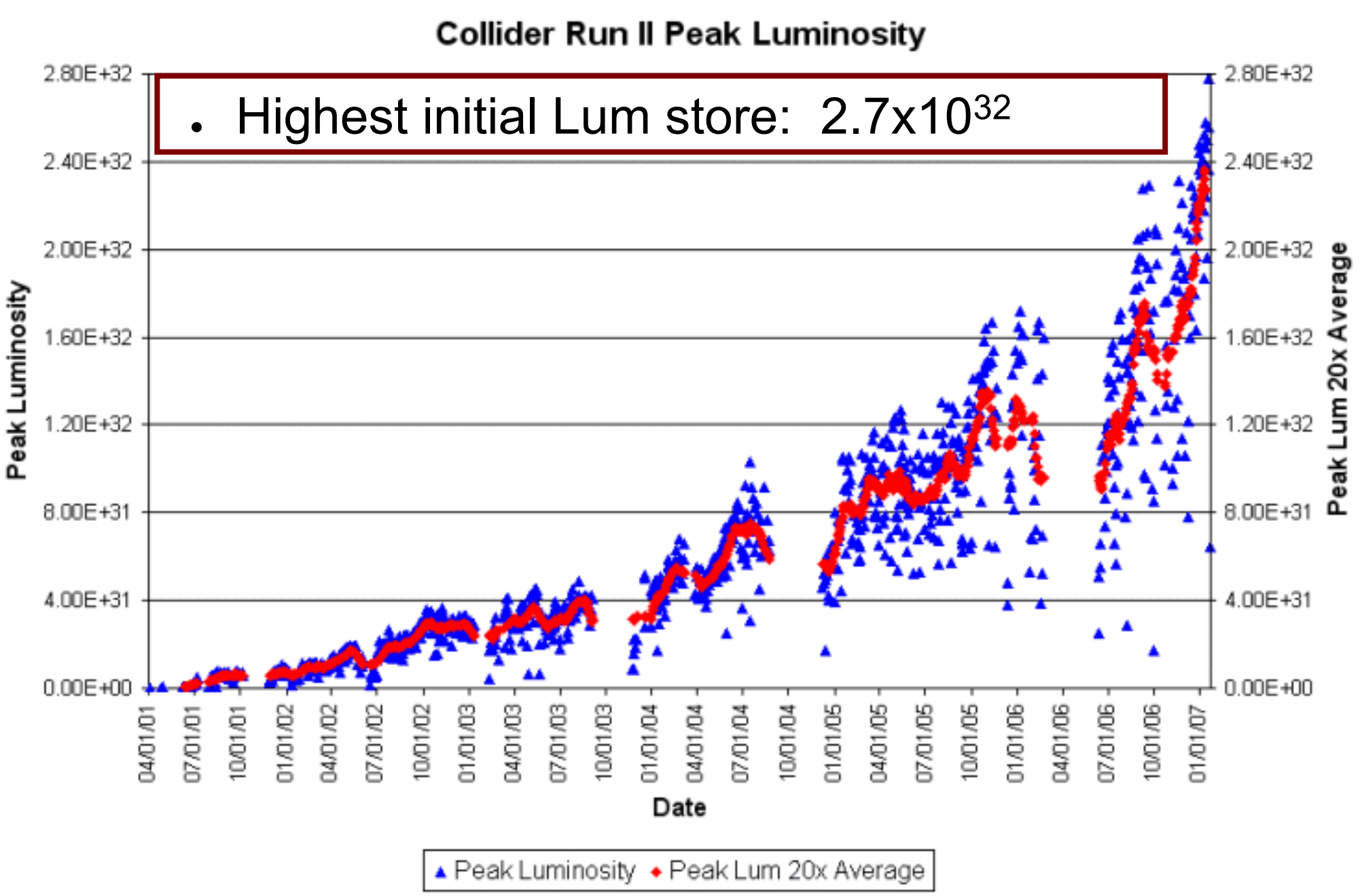
Measure Visible:  $M_{e\mu}$  $M_{eh}$  $M_{\mu h}$

# MSSM $\phi \to \tau\tau$: Exclusion Regions



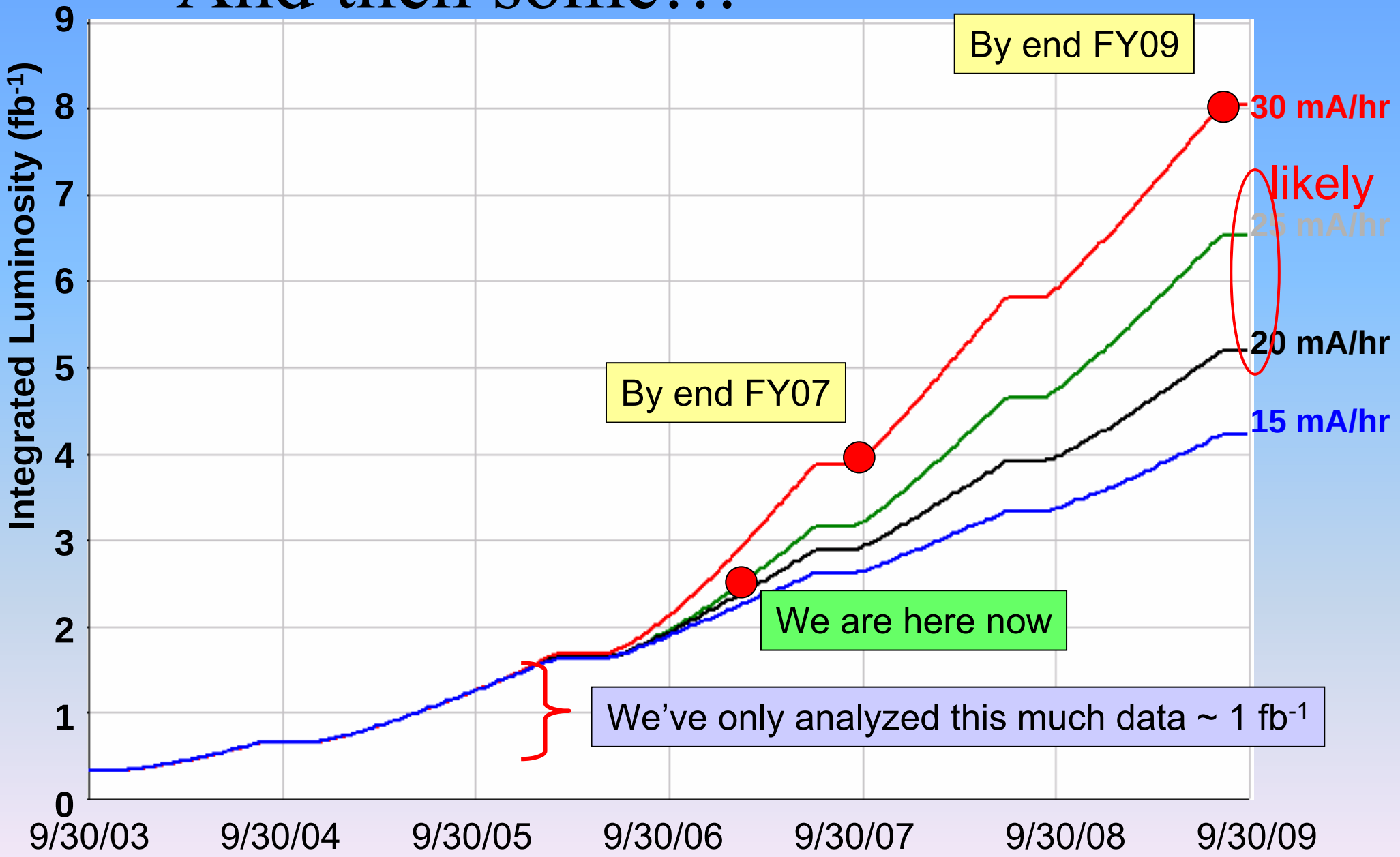




- only minimal change in excluded region for different model assumptions
  - $\tilde{t}$-mixing: no-mixing and $m_h^{\max}$ (parameters that maximize $M_h$)
  - $\mu > 0$ or $\mu < 0$ (Higgs mass term)

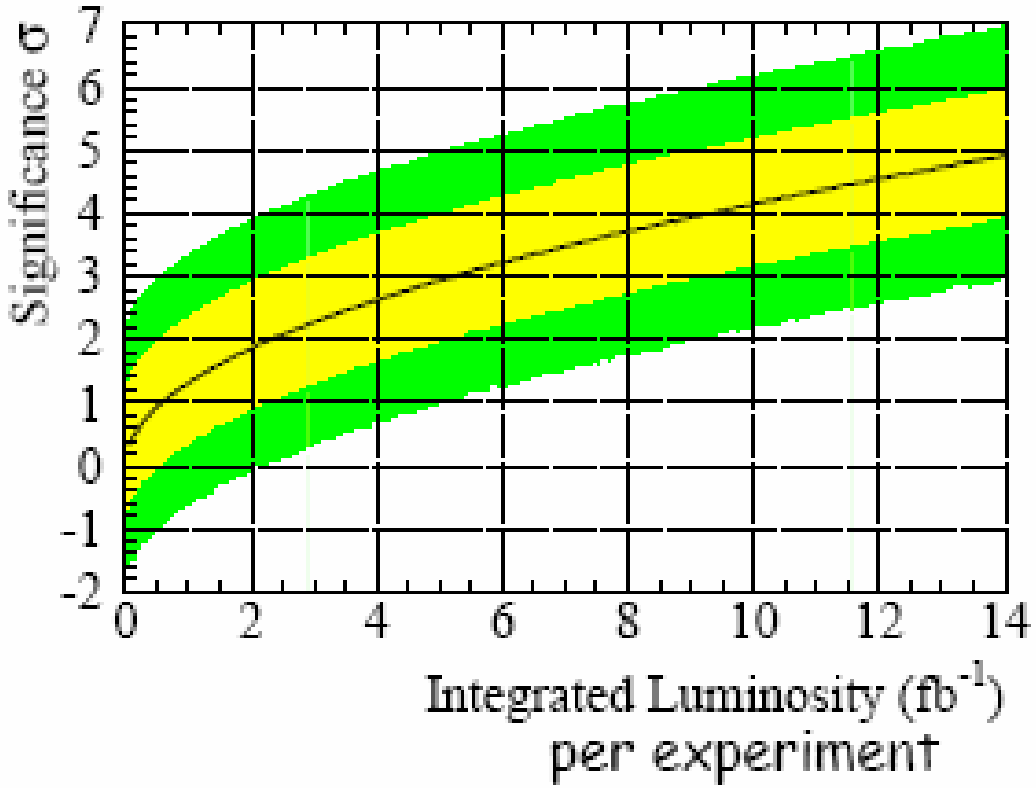



- Best week: 45 $pb^{-1}$ month 165 $pb^{-1}$
- Could get to 7 $fb^{-1}$ by Oct 09

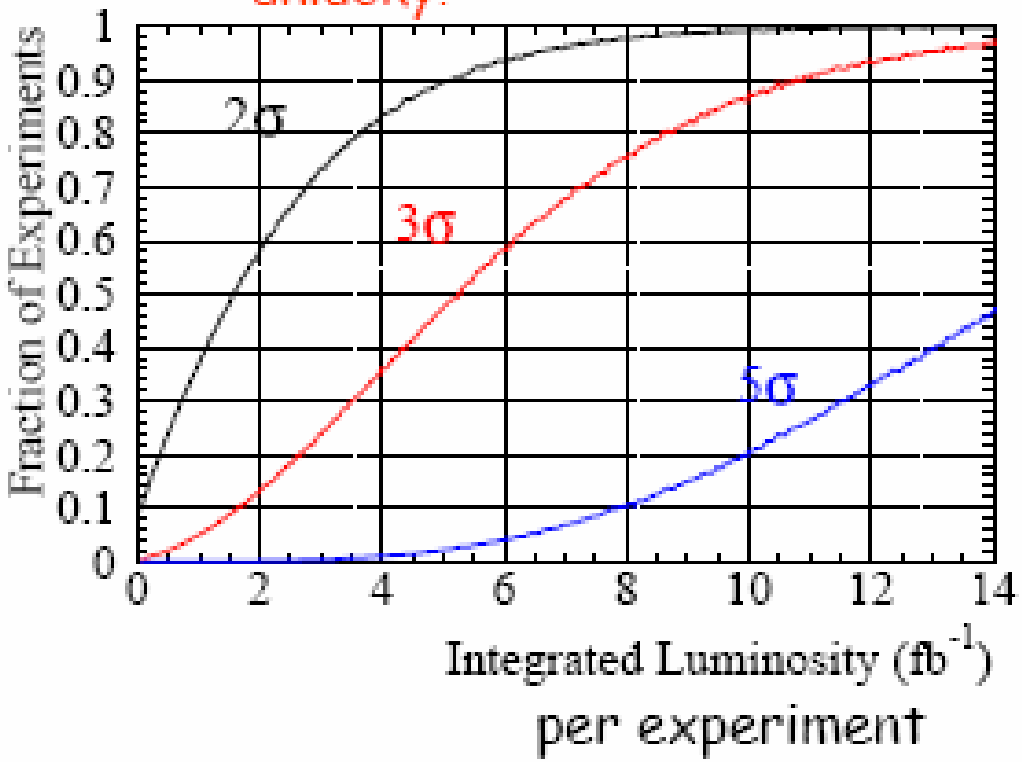
# And then some…



# Expected Signal Significance CDF+DØ vs Luminosity




It's possible to be lucky or unlucky!




$m_H$=115 GeV assumed

# Deeper Physics Reach