# Searches for Higgs and New Physics at the Tevatron

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for the CDF and D0 collaborations

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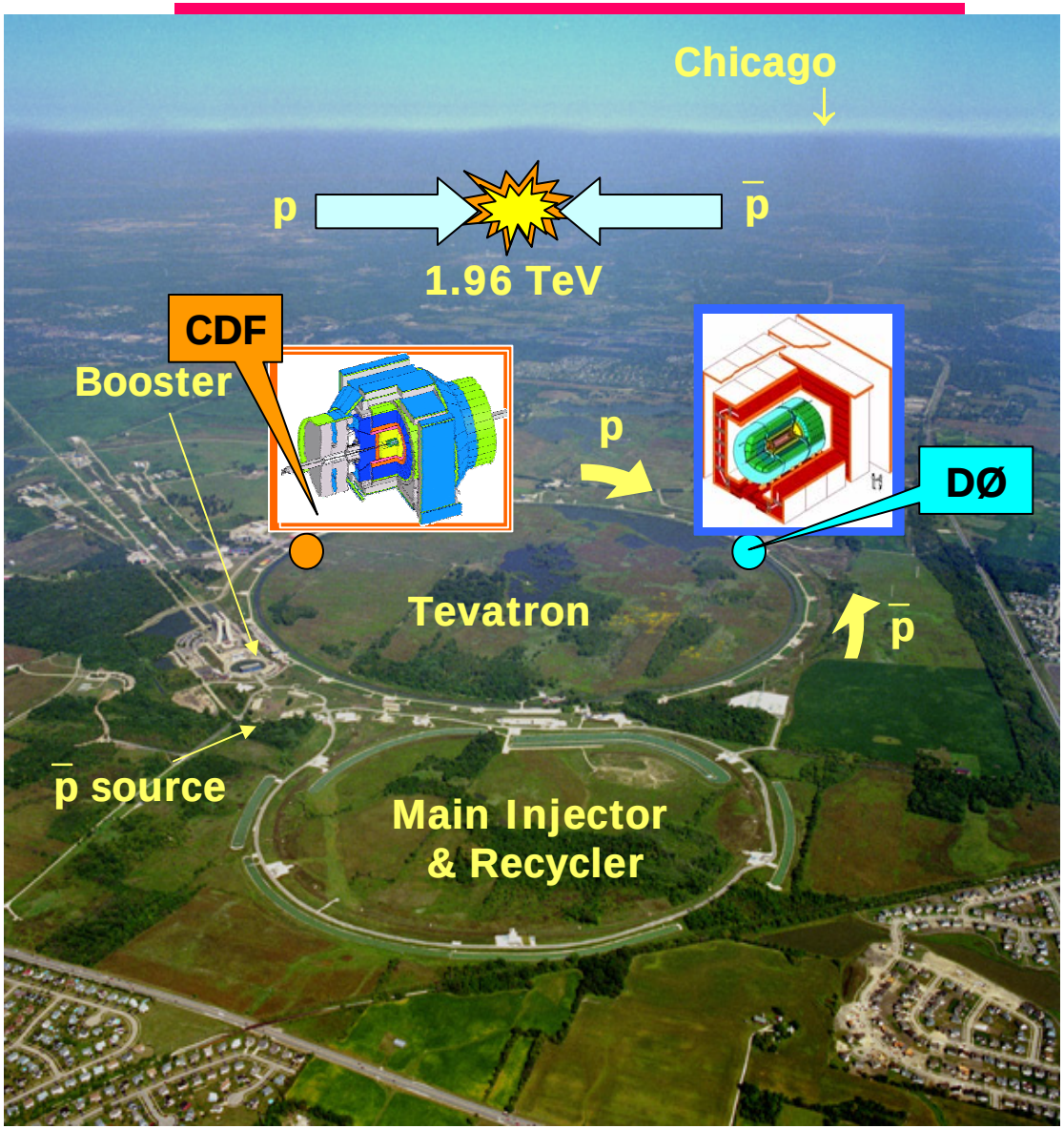
# Outline

- Tevatron Performance
- SM Higgs search
- MSSM Higgs Search
- New Physics
- Summary

# Tevatron Run II



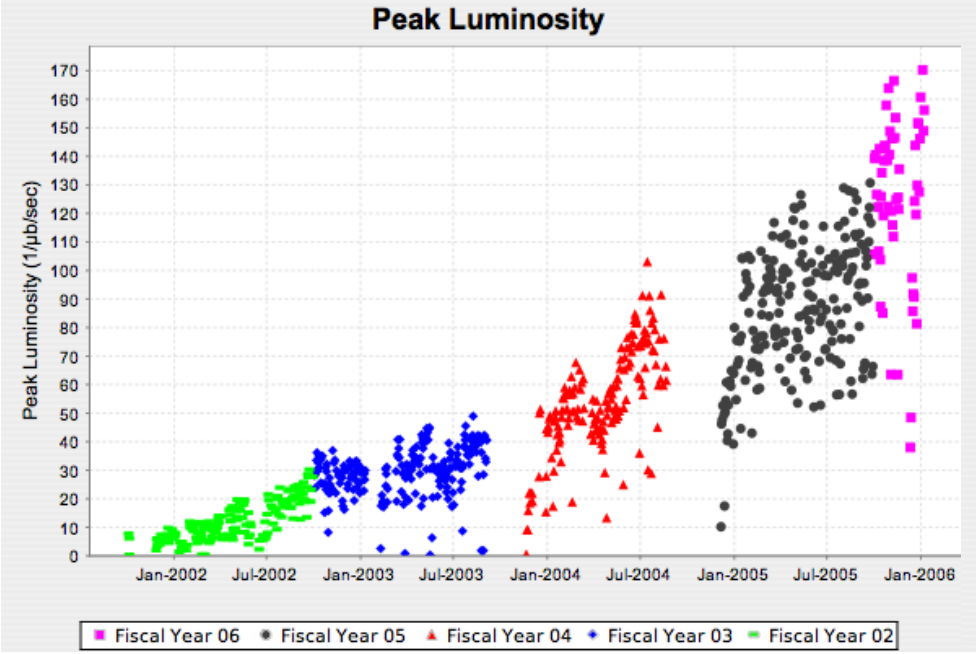

## The World's Highest Energy Accelerator

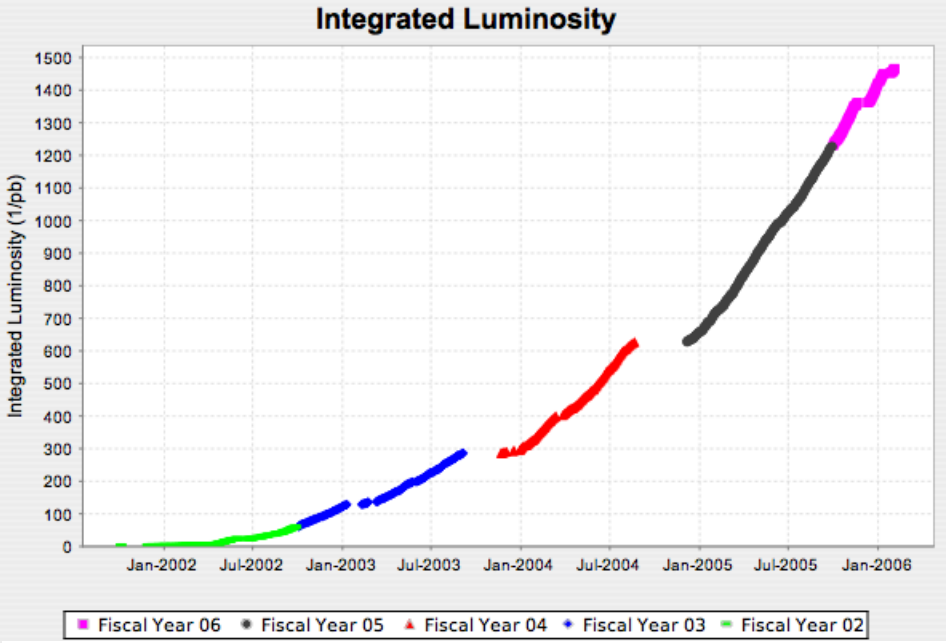
Run I
- 1992 - 1996
- $E_{CM}$ = 1.8 TeV
- ~120 $pb^{-1}$

**Run IIa**
- **2001 - 2006**
- **$E_{CM}$ = 1.96 TeV**
- **~ 1.4 $fb^{-1}$**

**Run IIb**
- **2006 - 2009**
- **$E_{CM}$ = 1.96 TeV**
- **~ 7 $fb^{-1}$**

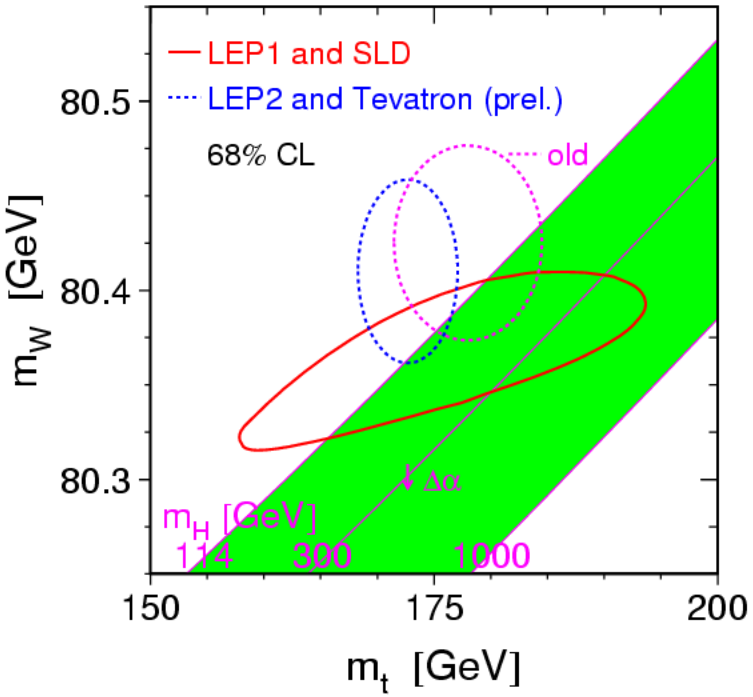
# Tevatron Performance

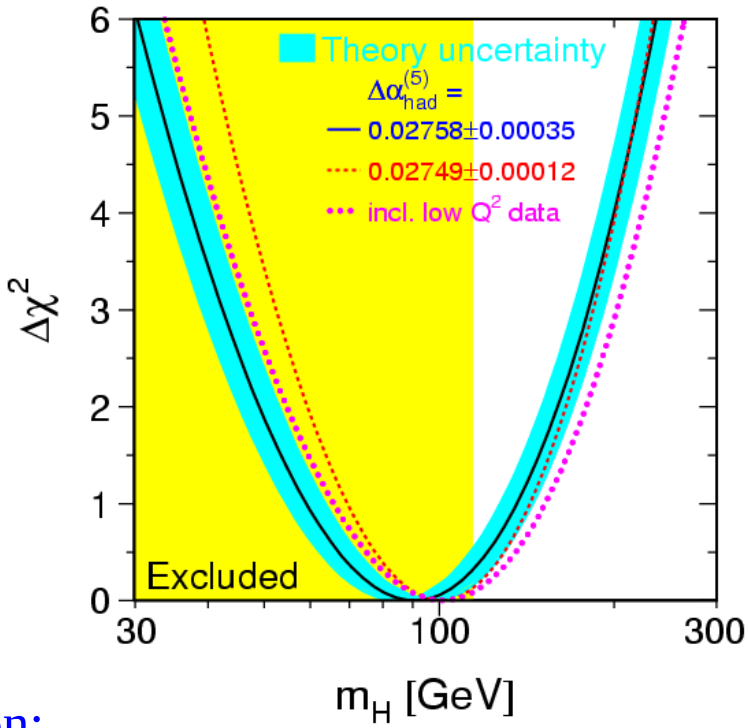



- Record high:
  - Peak luminosity: $172\times10^{30}$ cm$^{-2}$ s$^{-1}$
  - Weekly intergrated luminosity: 27 pb$^{-1}$/week
- Total delivered intergrated luminosity: 1.4 fb$^{-1}$

# Experimental Limits on Higgs Mass




Direct searches by LEP on SM Higgs Boson:

$m_H > 114.4$ GeV (95% CL)

Indirect limit from fits to precision EW measurements from LEP-SLC-Tevatron

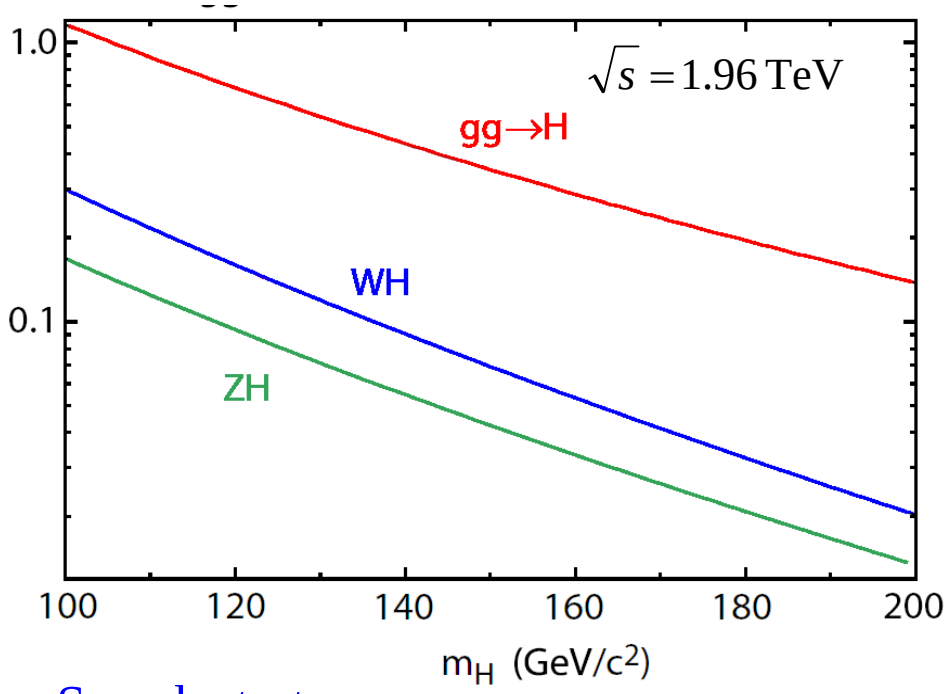
$m_H < 219$ GeV (95% CL)

using "latest" $m_t$=172.7 ± 2.9 GeV (CDF+D0, Run I+II)

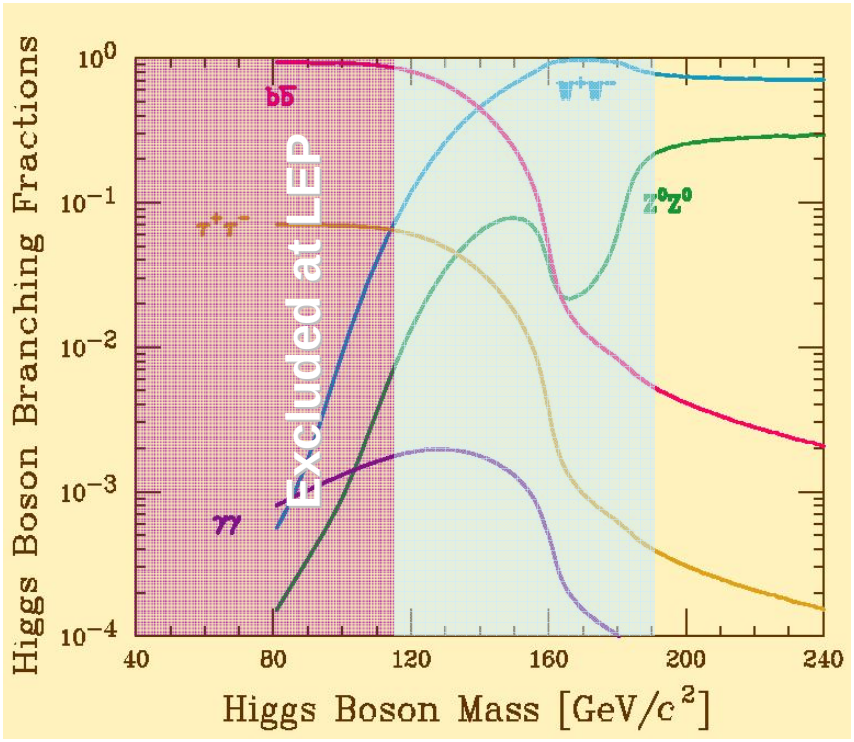
preferred value: $m_H = 91\ ^{+45}_{-32}$ GeV

# SM Higgs Production and Decay

## Production




## Decay




Search strategy:

$M_H$ <135 GeV associated production WH and ZH with H→bb decay

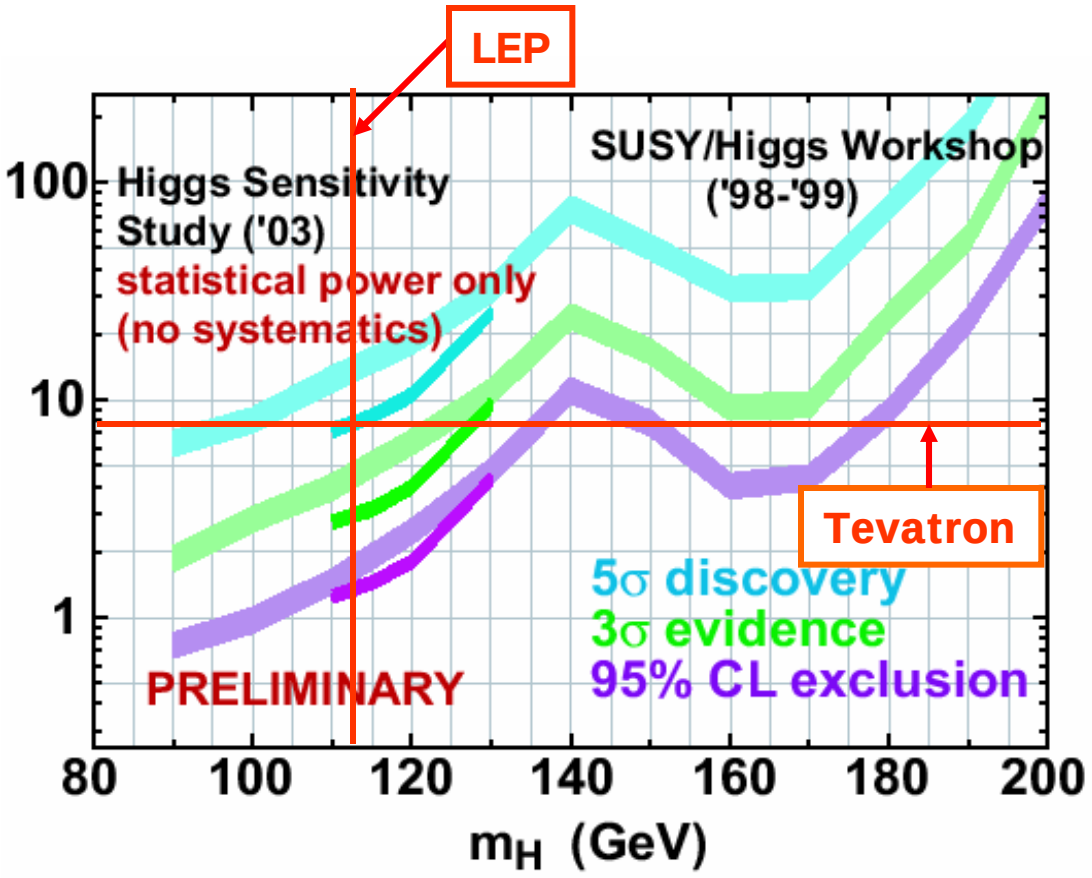
Backgrounds: Wbb, Zbb, top…

$M_H$ >135 GeV gg →H (or WH) production with H→$WW^*$ decay

Backgrounds: WW/WZ production…

# Higgs sensitivity

The integrated luminosity required per experiment, to either exclude a SM Higgs at 95% C.L. or discover it at the 3σ or 5σ level; no systematics

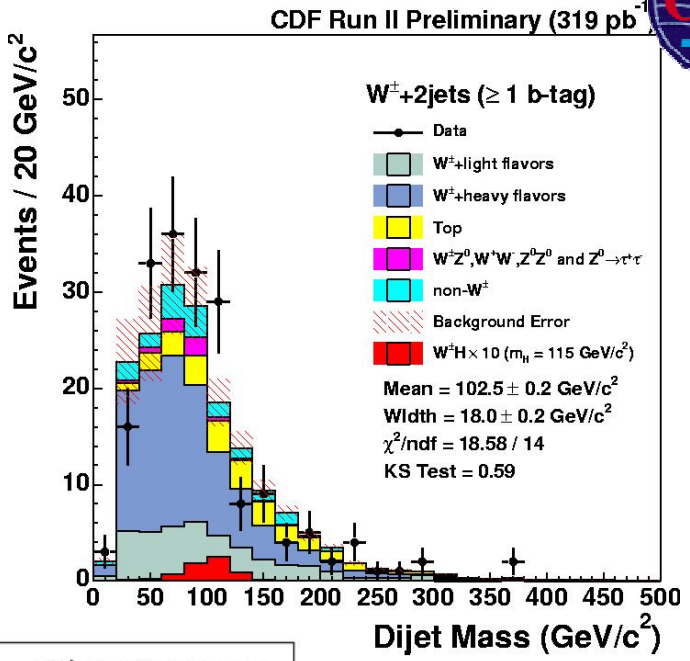


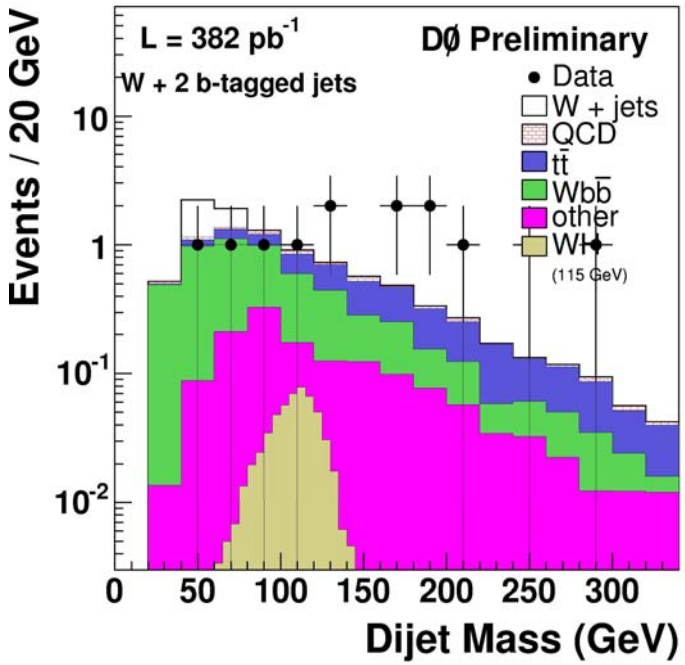

Tevatron enters sensitive region with 2 $fb^{-1}$ by the end of 2006.

- No single channel guarantees success.
- Combine two experiment's results.
- Improved understanding of detectors is necessary.
- Need advanced analysis techniques to maximize sensitivity.

# WH → ℓνbb

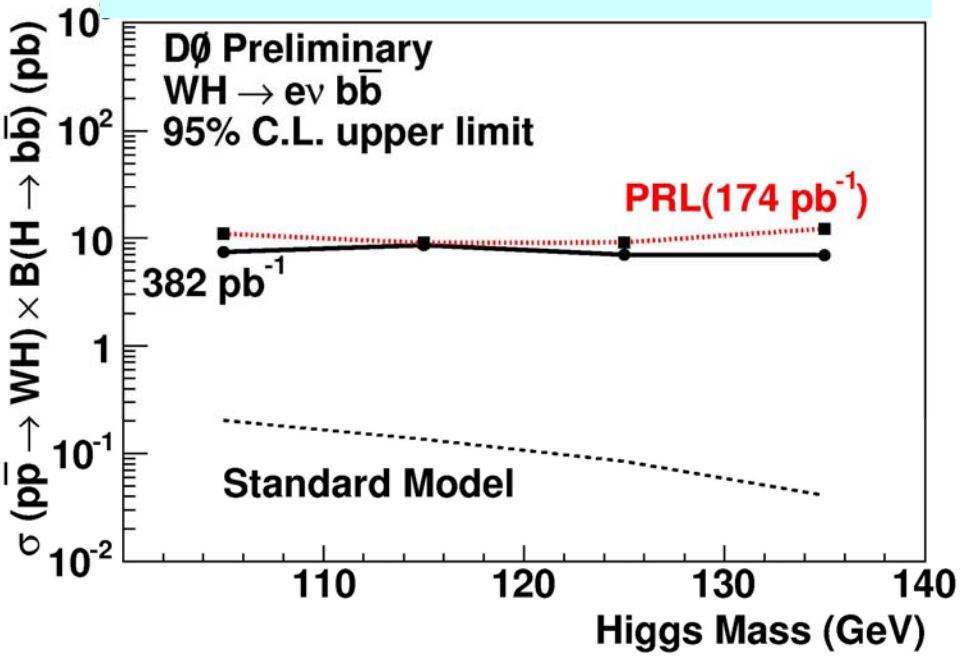
- Best channel for low mass higgs.
- Event signature:
  - A high $p_T$ lepton (e or μ)
  - Large missing $E_T$
  - Two b-jets (≥ 1 b-tag)
- Backgrounds:
  - Wbb, Wcc,
  - W+jets (mistags)
  - Diboson
  - Top
  - QCD



# WH → ℓνbb

D0: WH→ eνbb ( 382 pb$^{-1}$ )



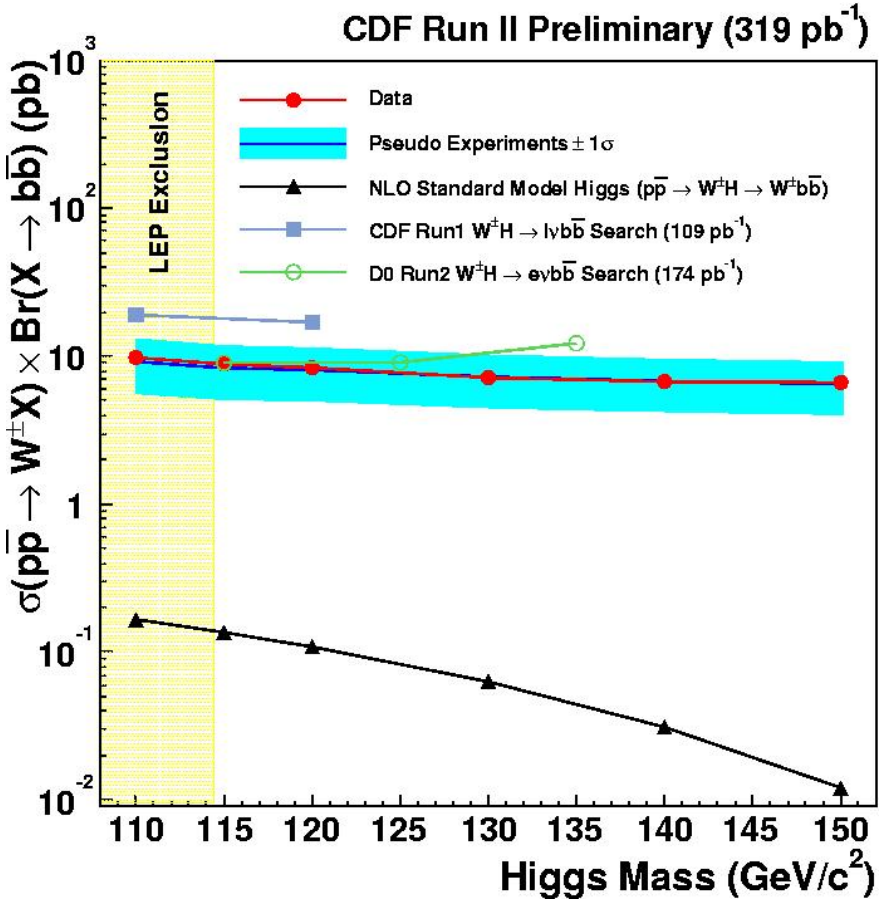

After 2 b-tags, observe 13 events,

expect: Wbb: 4.29±1.03

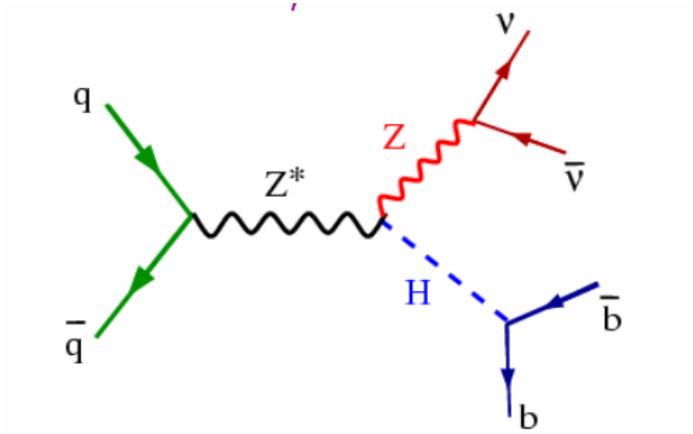
Other bkg: 5.73±1.45

WH: 0.14±0.03

CDF: WH→ ℓνbb (319 pb$^{-1}$)
(eνbb, μνbb combined)

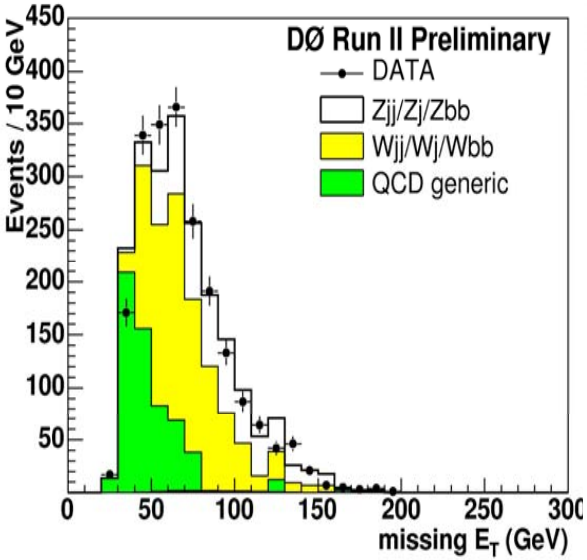


# ZH → ννbb

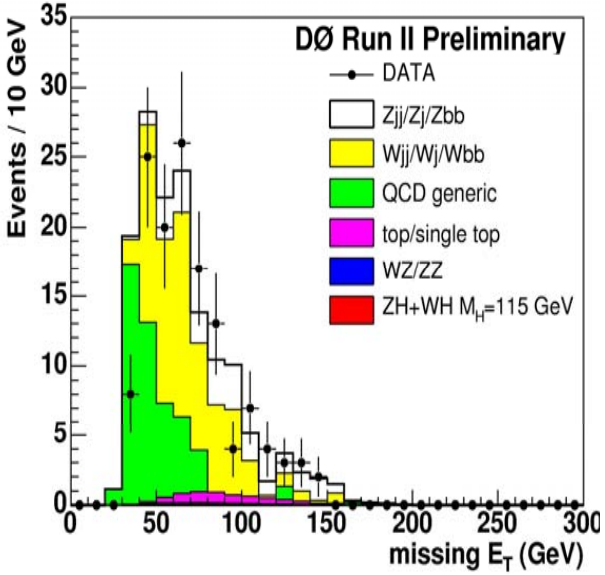



- Missing $E_T$ > 25 GeV,
- 2 acoplanar b-jets, $E_T$ > 20 GeV
- Background: W+jets, Z+jets, top, WZ, ZZ
  - No isolated track, $H_T$ < 200 GeV
- Instrumental bkg: multijets w/mistag
  - Jet acopalarnarity, various asymmetries

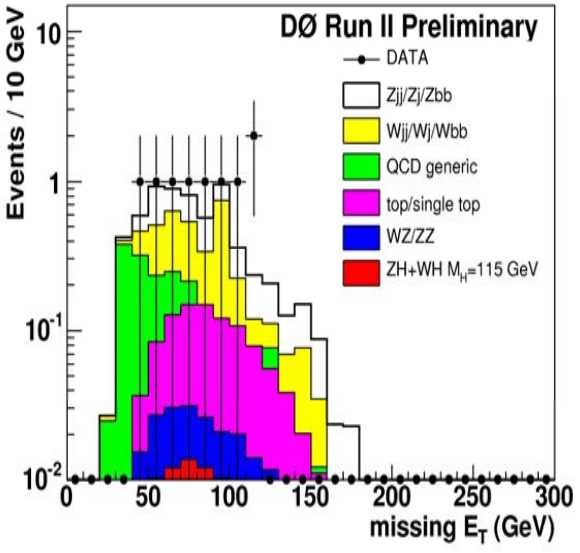
no b-tag




single b-tag

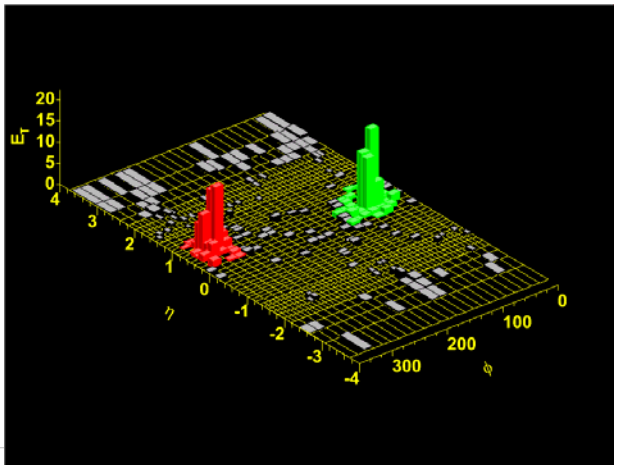



double b-tag



# ZH → ννbb

| Dijet mass cut | ZH 120 | mistag | QCD | Top | EWK | Total bkg | observed |
|---|---|---|---|---|---|---|---|
| Before | 0.16 | 7.04 | 2.58 | 2.09 | 7.0 | 19.7 | 19 |
| Mass cut for 120 GeV higgs | 0.13 | 2.2 | 0.9 | 0.8 | 0.5 | 4.36 | 6 |



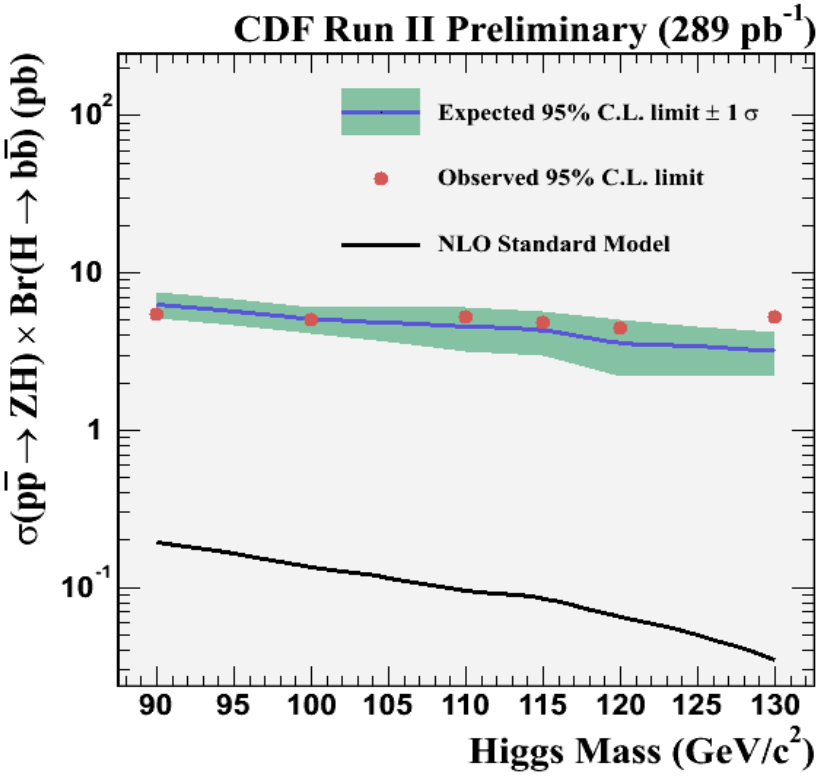

. 2 jets

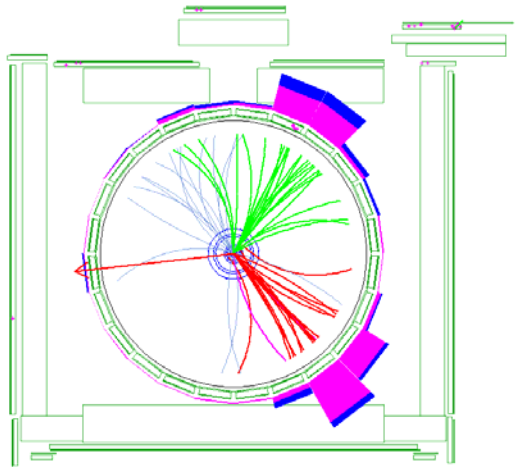
$E_T$ >25GeV

. veto 3nd jet

. $\not{E}_T$ >70GeV

. ≥ 1 b-tag



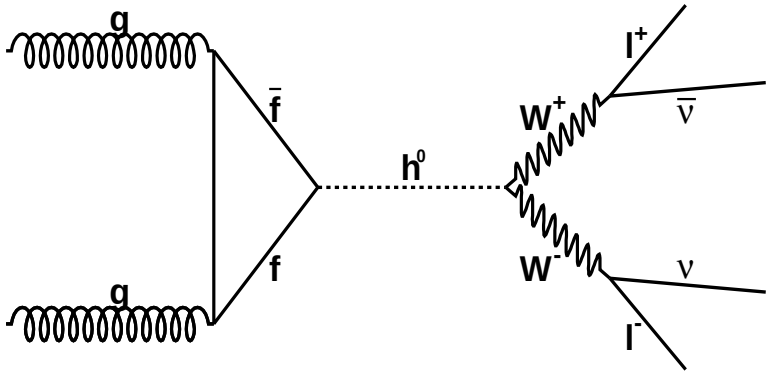



Jets: 84.7GeV, 71.9GeV (b-tagged)

missing $E_T$: 98 GeV,

dijet mass: 128.6 GeV

# $H \rightarrow W^+W^- \rightarrow \ell^+\ell^-\nu\nu$




- Leptonic decay channels are promising: $e\nu e\nu$, $\mu\nu\mu\nu$ or $e\nu\mu\nu$
- Backgrounds include WW, tt, W/Z+jets, $Z/\gamma^*$, QCD.

WW is dominant background.

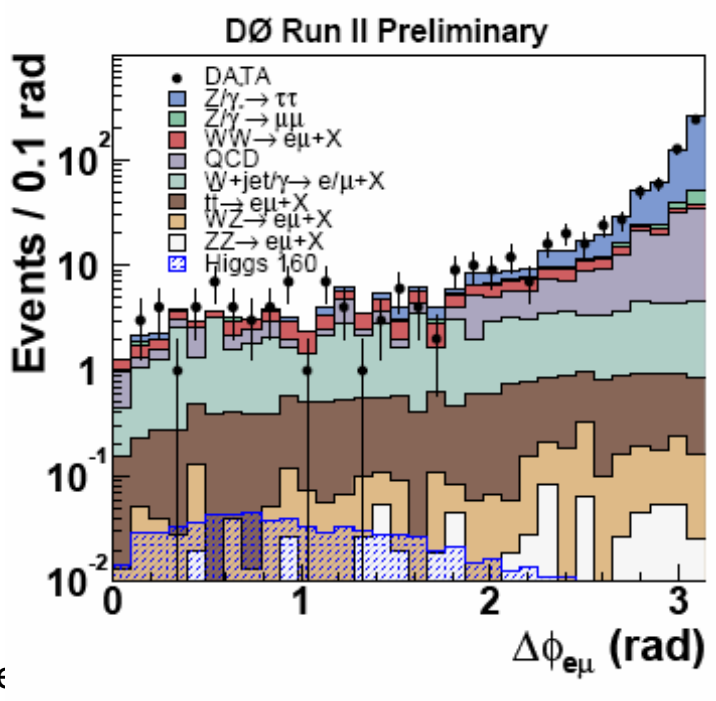
Heavy Higgs:

Br($H \rightarrow WW^*$)>0.9, when $m_H$>160 GeV

Search strategy:

- Two high $\mathbf{p_T}$ leptons with large missing $\mathbf{E_T}$
- Opening angle between leptons ($\Delta\Phi_{ll}$) is useful discriminant

Two leptons from Higgs tend to move in parallel (small $\Delta\Phi_{ll}$ ) , due to spin correlations in $H \rightarrow WW$ decay products.



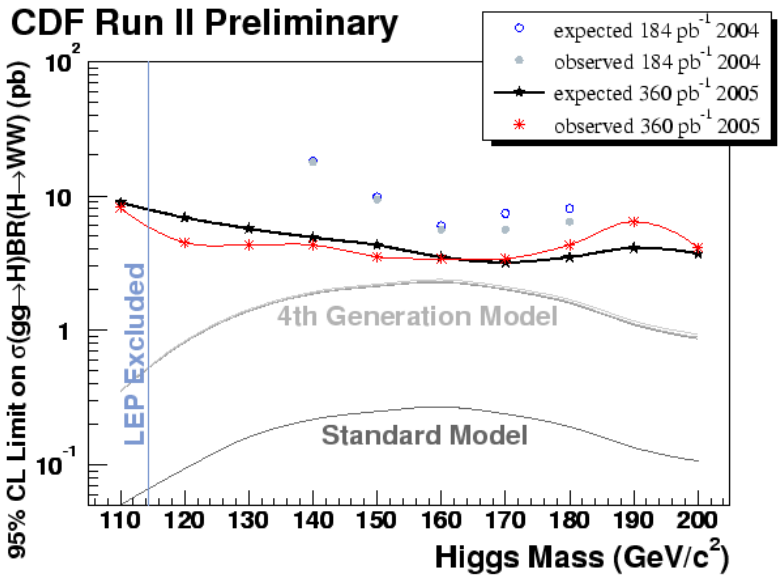
# $H \rightarrow W^+W^- \rightarrow \ell^+\ell^-\nu\nu$

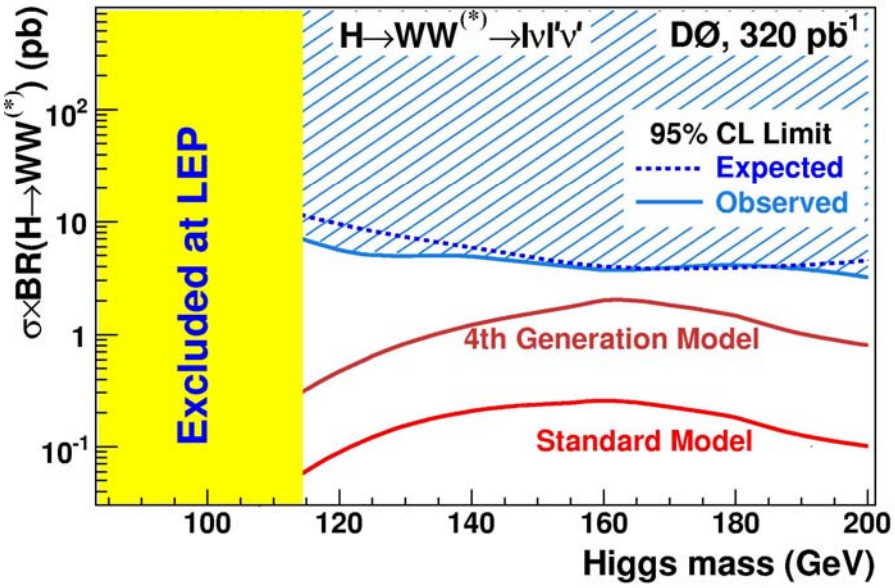
## CDF: ~ 360 pb$^{-1}$

| | $m_H$=160GeV |
|---|---|
| Expected signal | 0.58±0.04 |
| diboson | 10.2±1.0 |
| Other bkg | 3.6±0.7 |
| Total bkg | 13.8±1.2 |
| data | 16 |

## D0: ~ 320 pb$^{-1}$

| | $m_H$=160GeV |
|---|---|
| Expected signal | 0.68±0.01 |
| diboson | 12.3±0.3 |
| Other bkg | 7.5±1.1 |
| Total bkg | 19.8±1.2 |
| data | 19 |



# WH→WWW*→ $\ell^{\pm}\nu\ell^{\pm}\nu qq$

- Associated Higgs production, WH, where Higgs decays to WW
- Very clean signature: 2 like sign e or μ + 2 jets + Missing $E_T$

D0 (eeμ/μμ 384-363 $pb^{-1}$):

- 2 like-sign isolated e or μ, pT>15 GeV, veto 3rd lepton
- Track quality cuts (reduce charge flip)
- Missing $E_T$ > 20 GeV

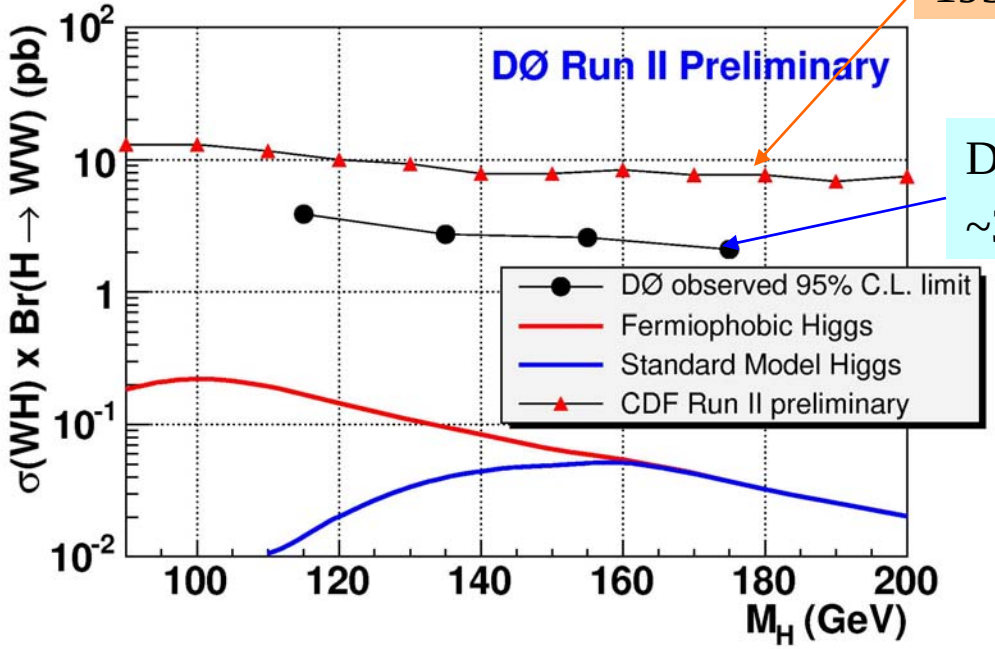
Background:

physics: WZ → $\ell\nu\ell\ell$

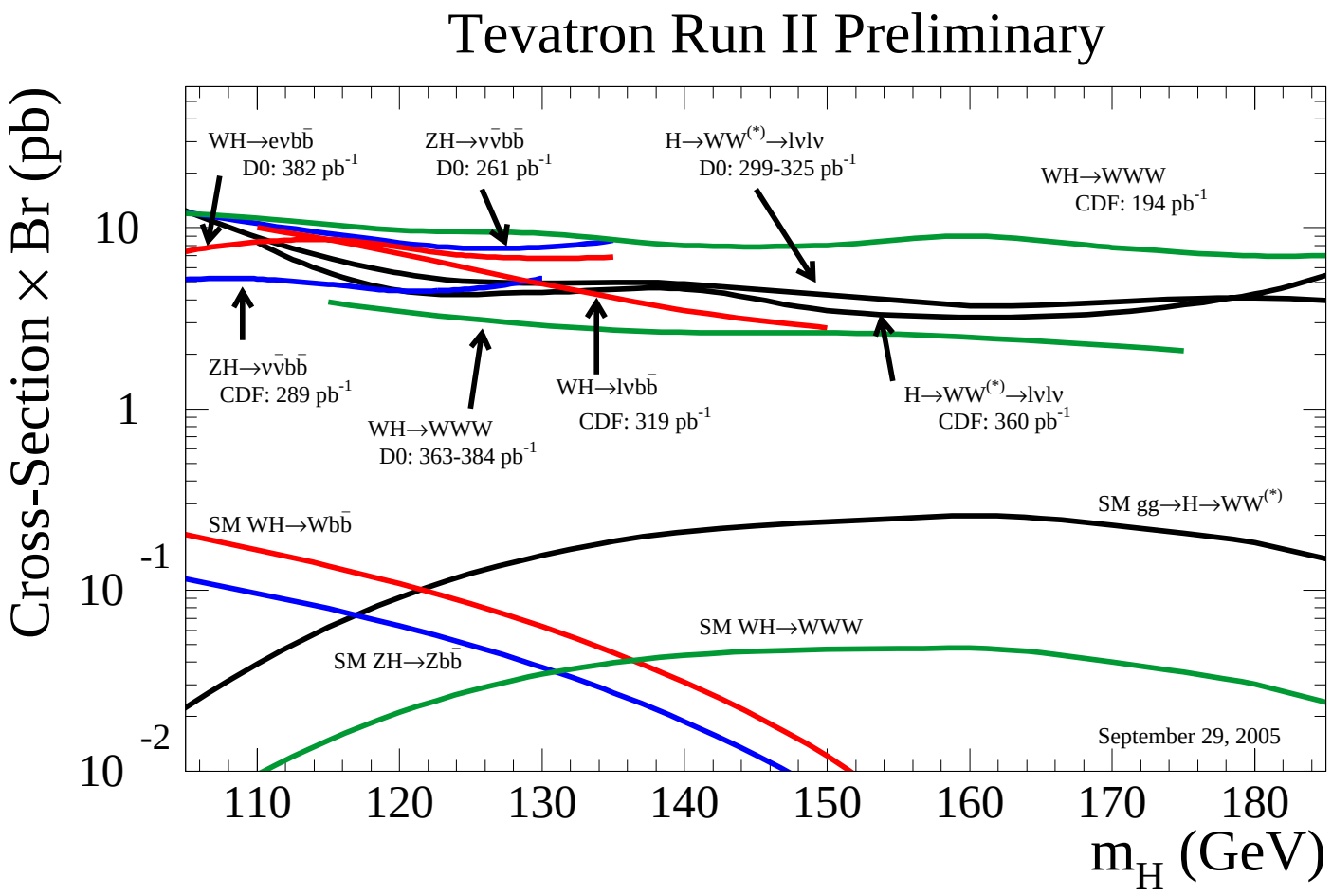
instrumental:

- charge flips ( Z/γ*→ $\ell\ell$ )
- QCD or W+jets

| D0 Analysis | ee | eμ | μμ |
|---|---|---|---|
| Observed | 1 | 3 | 2 |
| Total bkg | 0.70 | 4.32 | 3.72 |



# SM Higgs: where we stand today

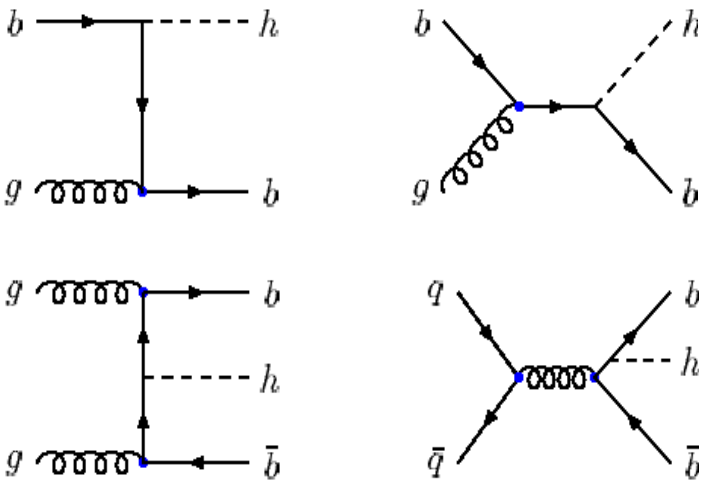


# Supersymmetry

- Main motivation – protect Higgs boson mass from large radiative corrections (Hierarchy problem).
- Phenomenology – every SM particle gets a SUSY partner with $\Delta S=1/2$.
  - SUSY partners have same quantum numbers, but opposite R-parity.
    - $R=(-1)^{3B+L+2S} = +1$ (SM) or $-1$ (SUSY).
  - If R-parity is conserved (RPC) –
    - SUSY particles are produced in pairs.
    - Lightest SUSY particle (LSP) is stable.
    - Missing $E_T$ from LSP is a typical SUSY signature.
  - Higgs sector required to have two Higgs doublets.
- Large number of SUSY searches in CDF and D0.

  too many to describe here, can only present some of them today.

# MSSM Search: (b)bh →bbb(b)




**Sample Selection:**

- Trigger >3 jets with $E_T$>15 GeV,
- Offline cut on $E_T$ of leading jets optimised for each Higgs mass.
- 3 b-tagged jets or more

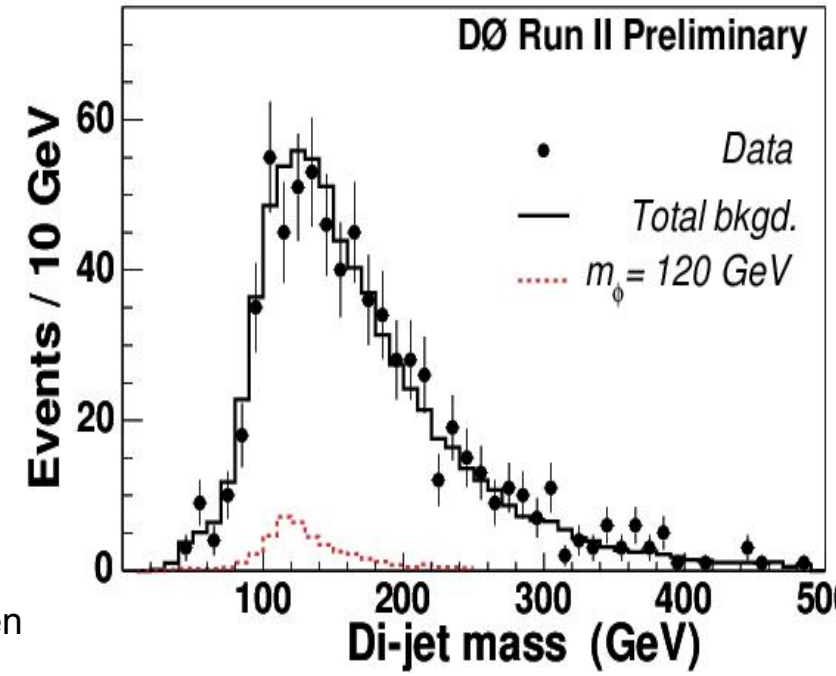
**Backgrounds:**

bbjj, ccjj, cccc, bbcc, bbbb

Z(bb,cc), tt

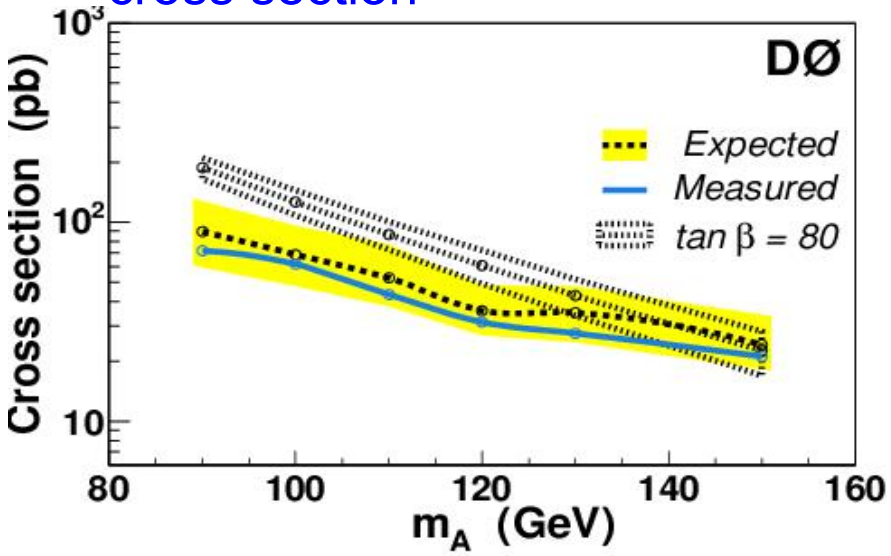
"QCD fakes" : jjjj

- Search for neutral Higgs in a two-Higgs-doublet MSSM SUSY model.
- Cross-section rises as $\tan^2\beta$
- 260 $pb^{-1}$ sample of triple b-tagged multi-jet events.
- No distinction between h or H and A

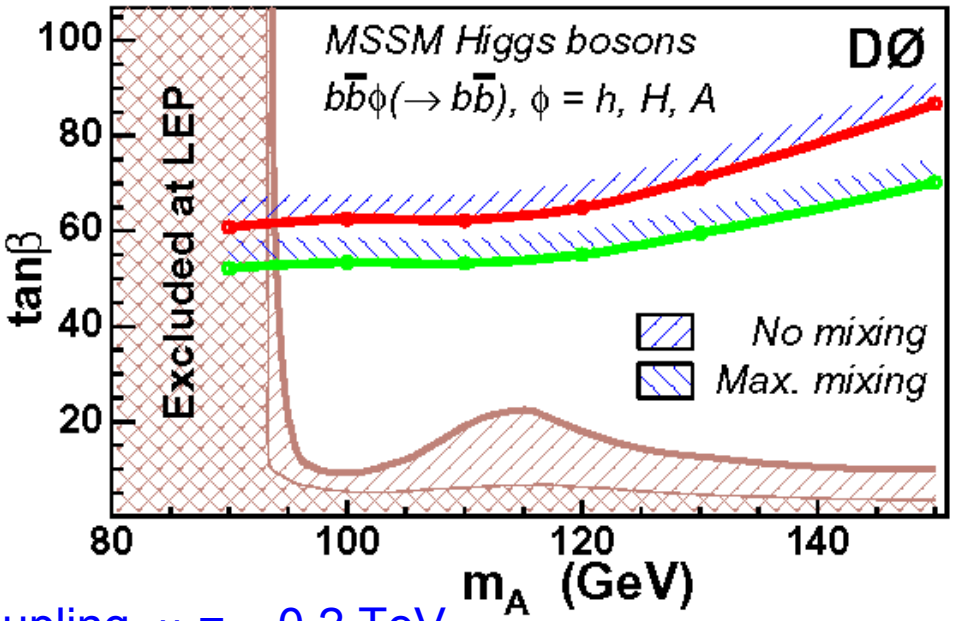


# b(b)h → bbb(b)

- Expected and measured 95% C.L. upper limits on the signal cross section




- The 95% C.L. upper limits on tanβ as a function of $m_A$ and for two scenarios of MSSM




- No mixing in stop sector: $X_t = 0$

  $X_t = A_t - \mu\cot\beta$, $A_t$ – tri-linear coupling, $\mu = -0.2$ TeV

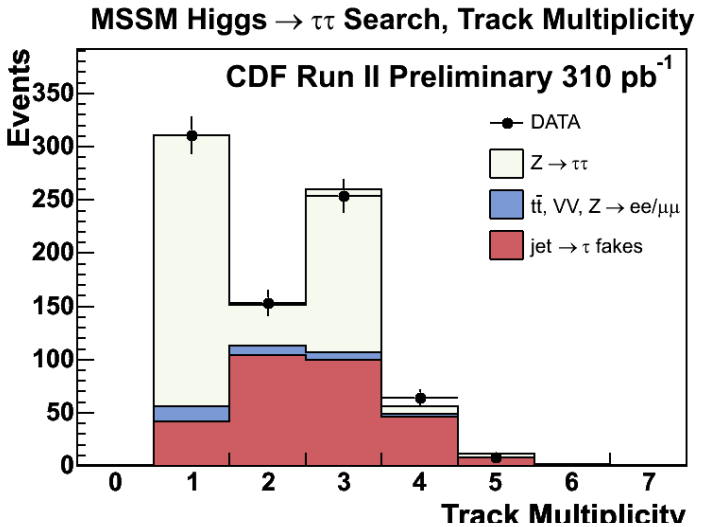
- Maximal mixing: $X_t = \sqrt{6}\times M_{SUSY}$, $M_{SUSY} = 1$ TeV

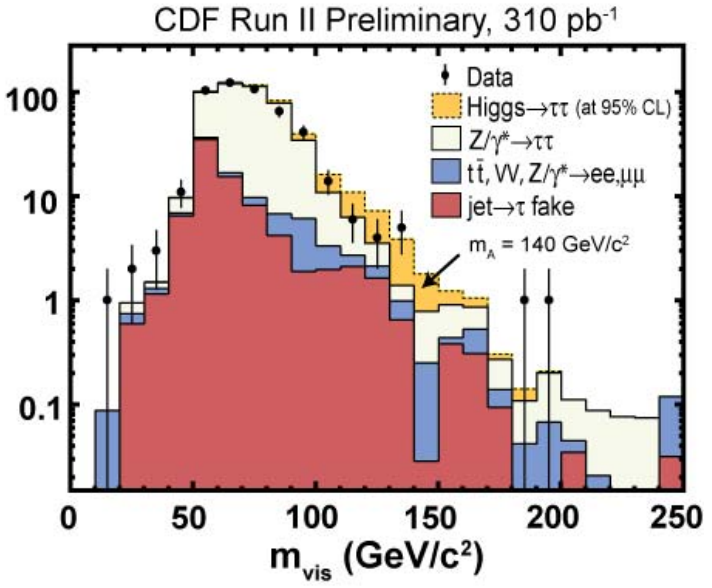
- With 5 $fb^{-1}$ of data, assuming the current performance, can probe tanβ values down to 20-30 depending on the mass, model

# $h \rightarrow \tau^+\tau^-$

- In MSSM at high tanβ, higgs production can be much larger than SM.
- Event signature:
  - a lepton, e or μ, (from τ decay)
  - a τ–jet (pencil-like)
  - missing $E_T$
- Backgrounds:
  - $Z \rightarrow \tau^+\tau^-$
  - W+jets, QCD (fakes)
  - Top, diboson, $Z \rightarrow ee/\mu\mu$
- tau efficiency: ~ 46%
- Fake rate: ~ 1.5% for 20 GeV jet;
  ~ 0.1% for 100 GeV jet

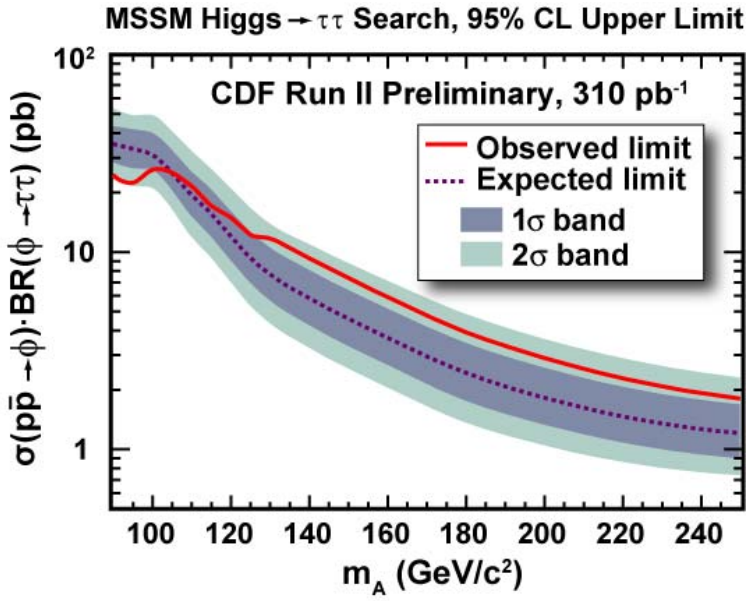
$m_{vis}$: invariant mass of $(\ell, \tau_{had}, \not{E}_T)$

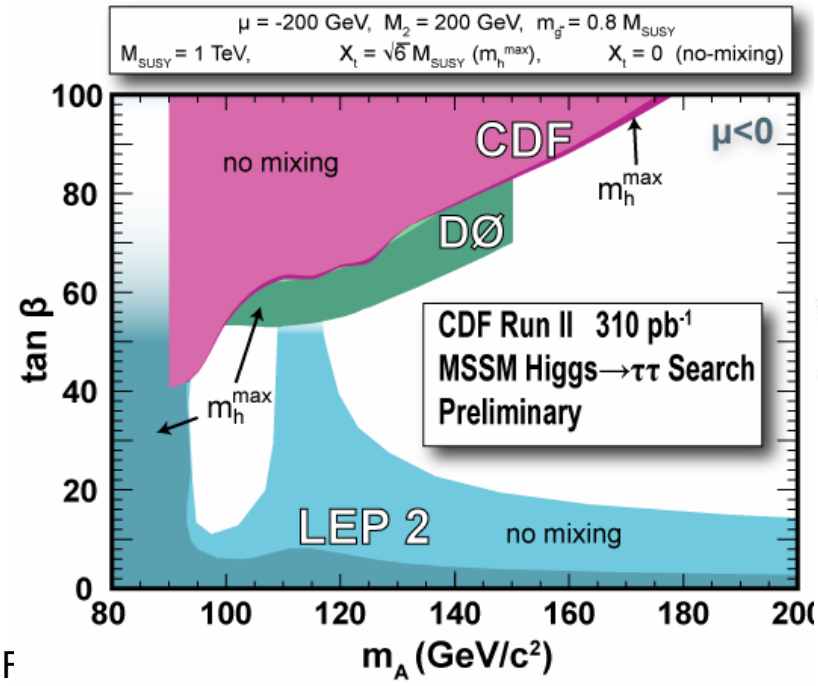


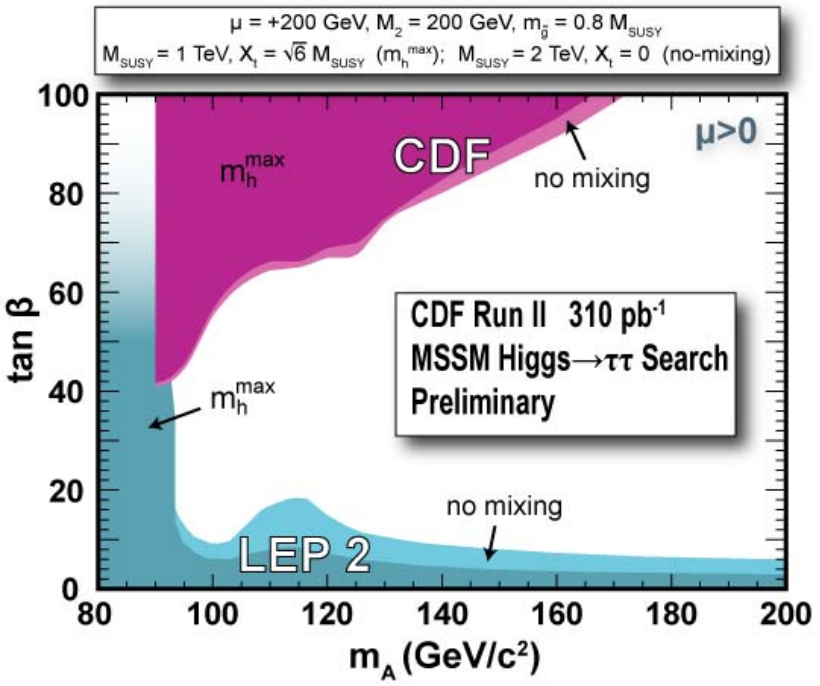



# $h \rightarrow \tau^+\tau^-$

- Data: 310 $pb^{-1}$
- Expected total background: 496±5±28±25
- Observe: 487 events
- Binned likelihood fit of $m_{vis}(\ell, \tau_{had}, \not{E}_T)$ for set limit.

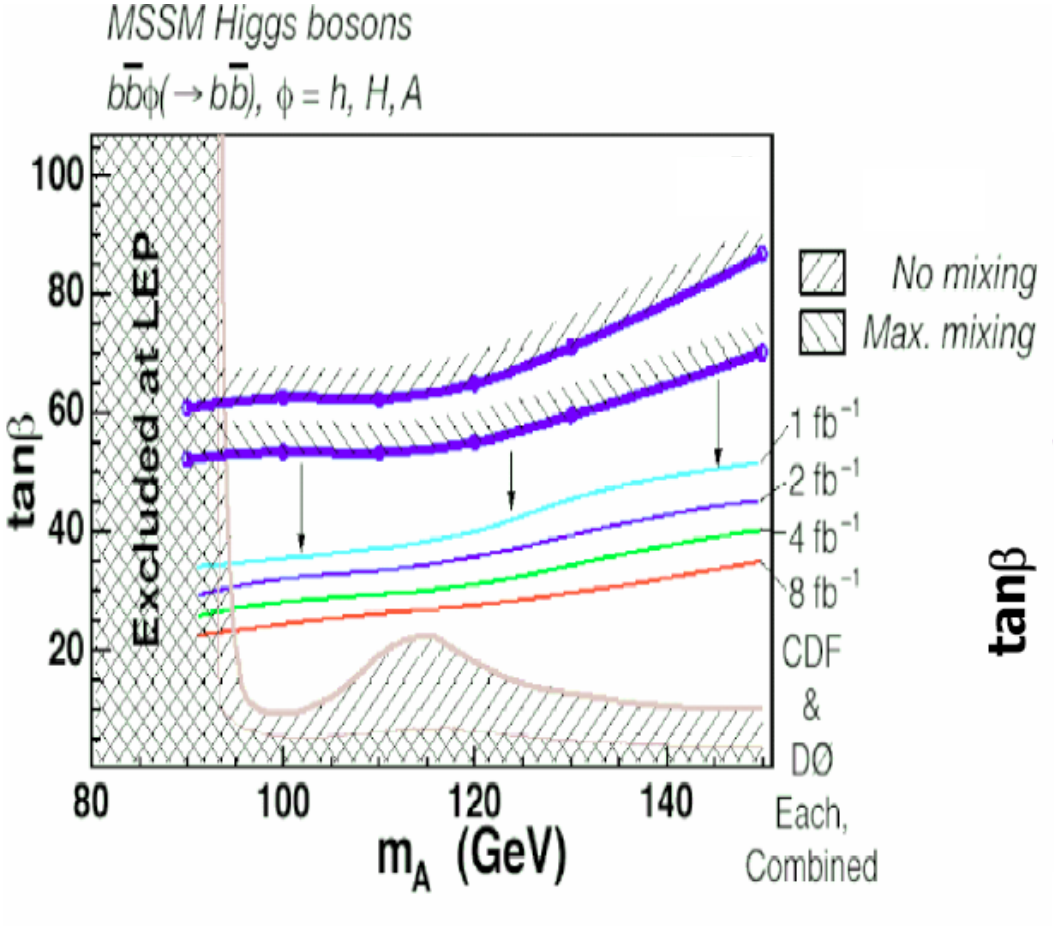


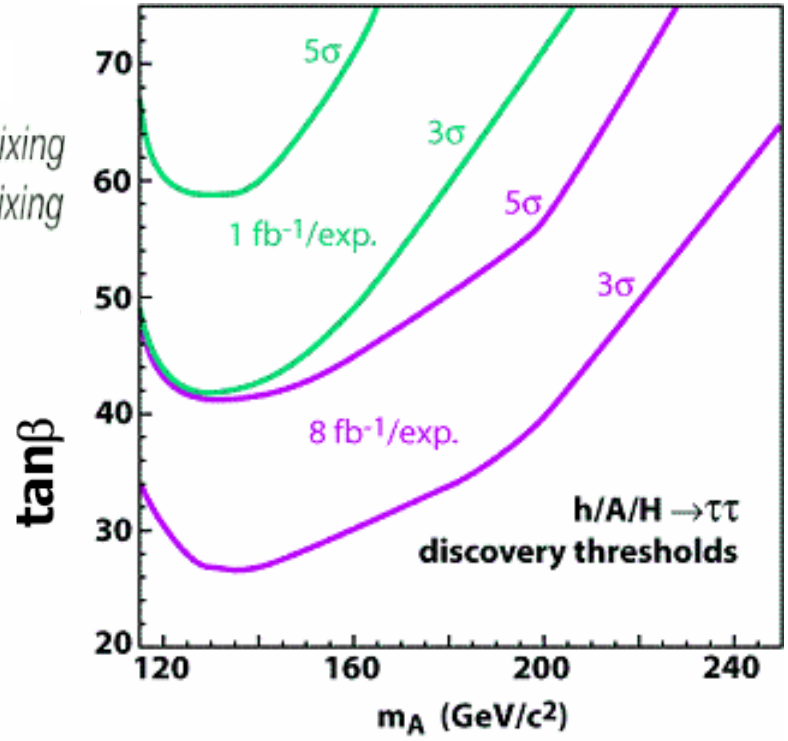



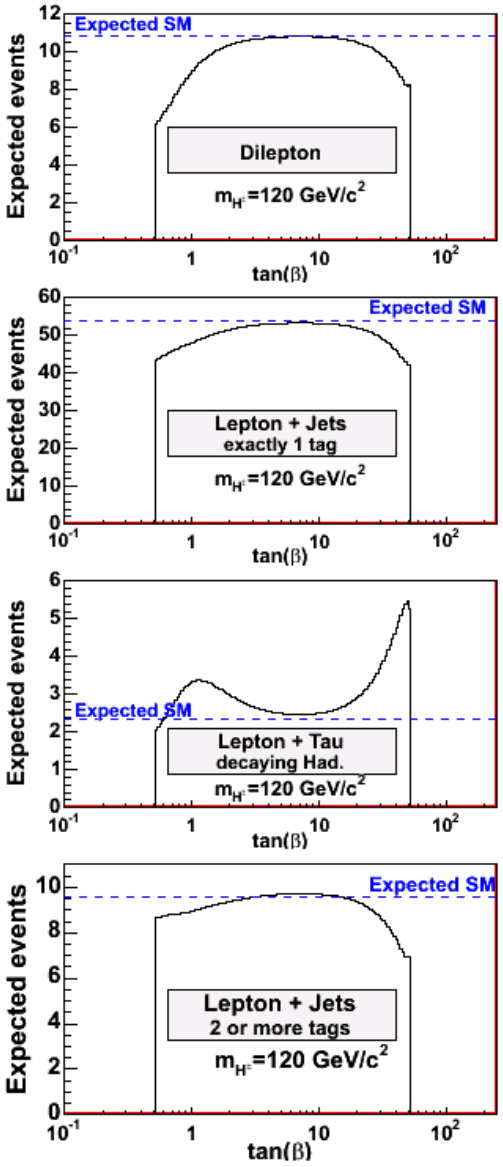
# MSSM Higgs Prospects

- Projections are made for the *combined* reach of CDF and D0.

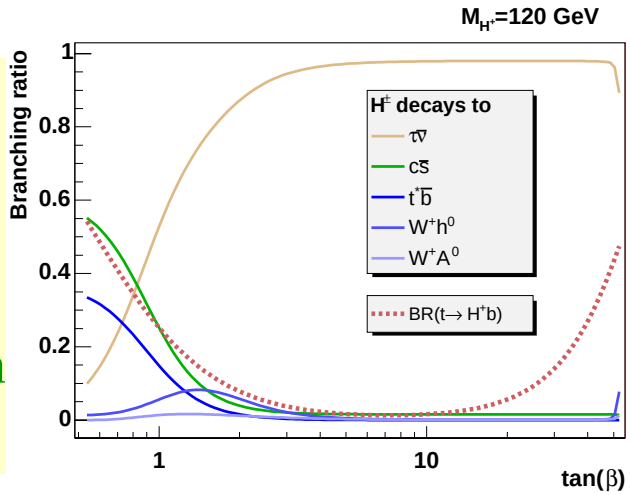


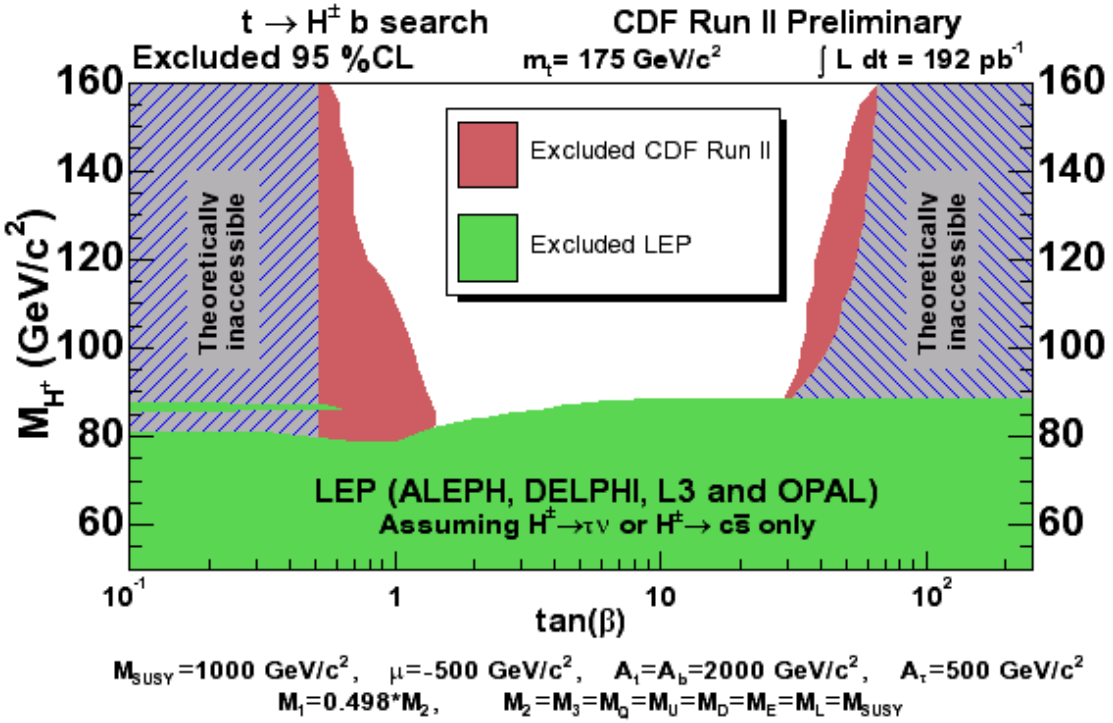



# MSSM Charged Higgs: $t \rightarrow H^+b$



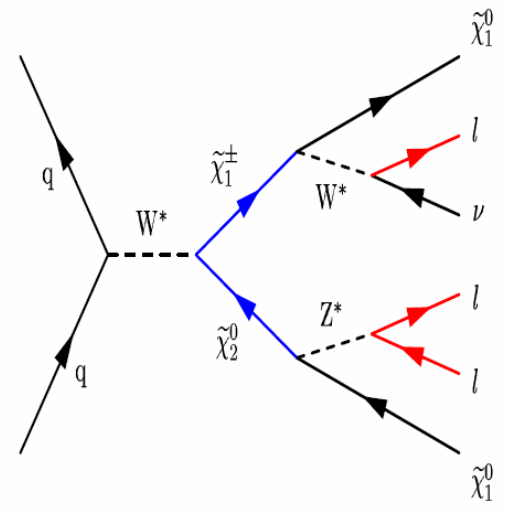

- BR(t→H$^+$b) can be large, competing with the t→W$^+$b.
- Search based on the tt cross section (top disappearance in lepton channels).




$M_{SUSY}$=1000 GeV/c$^2$, μ=-500 GeV/c$^2$, $A_t$=$A_b$=2000 GeV/c$^2$, $A_\tau$=500 GeV/c$^2$
$M_1$=0.498*$M_2$, $M_2$=$M_3$=$M_Q$=$M_U$=$M_D$=$M_E$=$M_L$=$M_{SUSY}$

# Chargino/Neutralinos

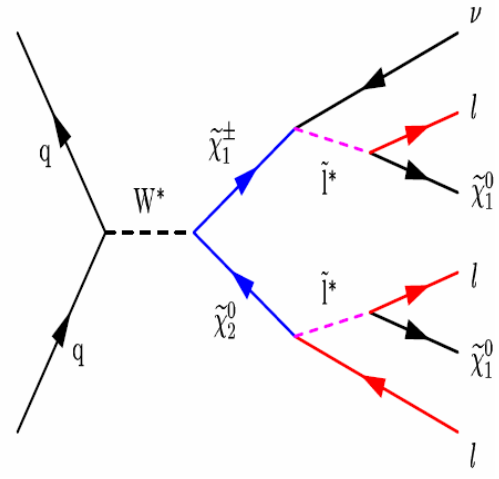


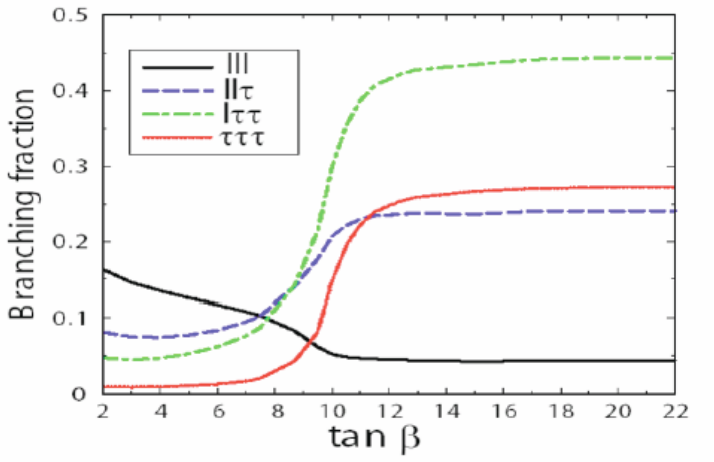

Higgsinos and gauginos mix→charginos/neutralinos

LEP: $m_{\tilde{\chi}^{\pm}} > 103.5\ GeV/c^2$

$\chi_2^0 \chi_1^{\pm} \rightarrow \ell^{\pm}\ell^{\mp}\ell^{\pm}\chi_1^0\chi_1^0 X$

$\ell$ = e, μ, τ



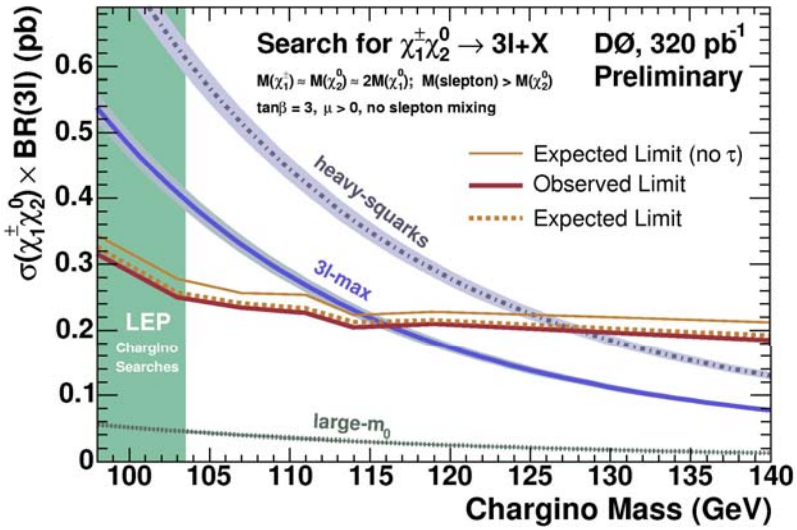




- Small x-section, but
- Trileptons with missing $E_T$ are very clean, low background.
- Major backgrounds:
  - Dibosons.
  - QCD (fakes).
  - Top

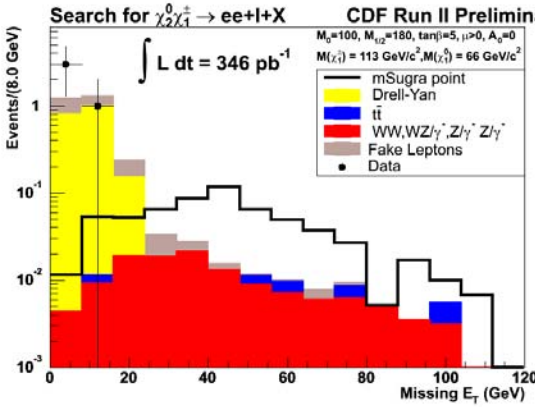
# Chargino/Neutralinos

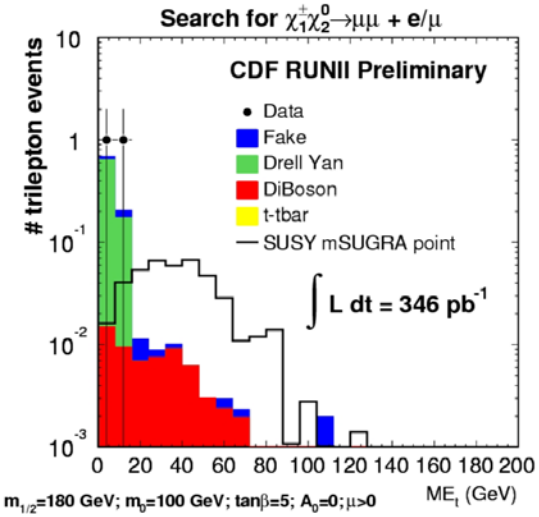
## D0: 6 analyses (325 pb$^{-1}$)

| Channel | SM bkg | Data |
|---|---|---|
| ee + track | 0.21±0.12 | 0 |
| eμ + track | 0.31±0.13 | 0 |
| μμ + track | 1.75±0.57 | 2 |
| eτ + track | 0.58±0.14 | 0 |
| μτ + track | 0.36±0.13 | 1 |
| μμ like sign | 0.66±0.37 | 1 |




## CDF: e,μ final states 346 pb$^{-1}$



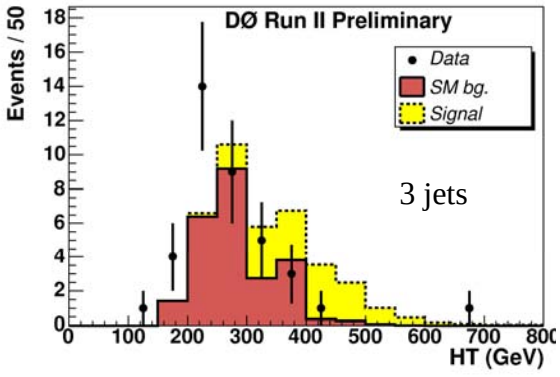



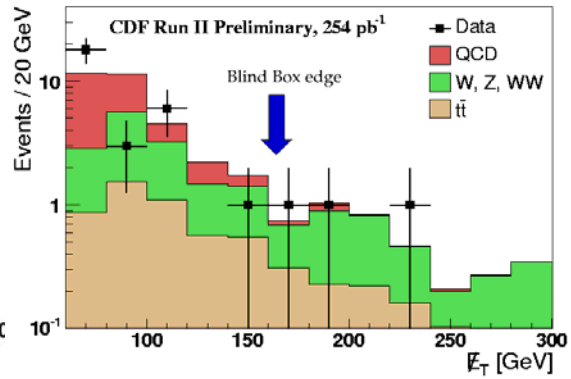

| Channel | SM bkg | Data |
|---|---|---|
| ee$\ell$ | 0.17±0.05 | 0 |
| μμ$\ell$ | 0.09±0.03 | 0 |

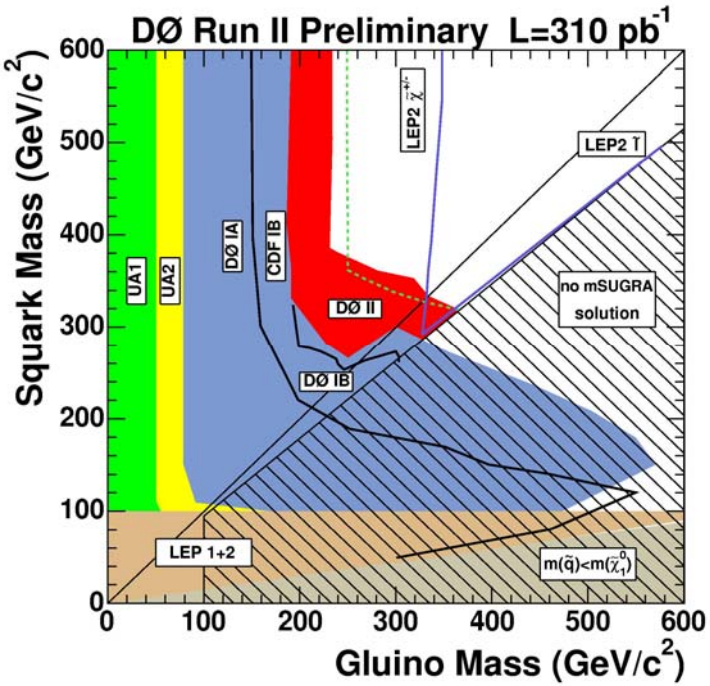
# Squark/Gluino

- Squarks and gluinos are pair-produced by strong interaction and decay into quarks and LSP.
  - Signature: jets + missing $E_T$ (2, 3, or 4 jets). $\tilde{q}\rightarrow q\tilde{\chi}^0$ $\tilde{g}\rightarrow qq\tilde{\chi}^0$
  - Backgrounds: W, Z, top, QCD.

| Channel | SM bkg | Data |
|---|---|---|
| D0 2 jets (310 pb$^{-1}$) | 12.8±5.4 | 12 |
| D0 3 jets (310 pb$^{-1}$) | 6.1±3.1 | 5 |
| D0 4 jets (310 pb$^{-1}$) | 7.1±0.9 | 10 |
| CDF 3 jets (254 pb$^{-1}$) | 4.1±1.5 | 3 |



# Scalar bottom

- Sbottom pair production: $q\bar{q} \rightarrow \tilde{b}\bar{\tilde{b}} \rightarrow b\bar{b}\chi_1^0\chi_1^0$.
  - Event signature: 2 acoplanar b jets + missing $E_T$.
  - Backgrounds: W, Z, diboson, top, QCD.

$\not\!\!E_T > 60$ GeV

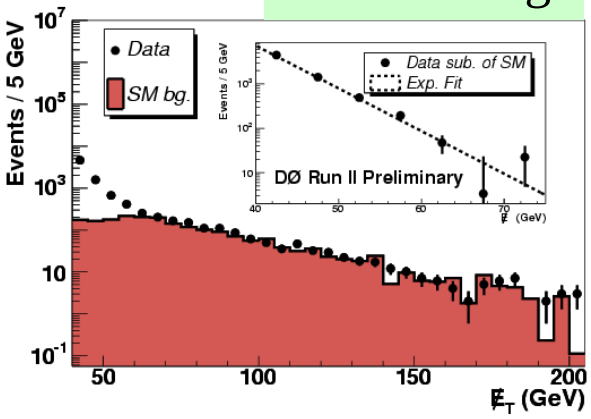
Jet $E_T > 40, 15$ GeV

$\Delta\phi < 165^0$

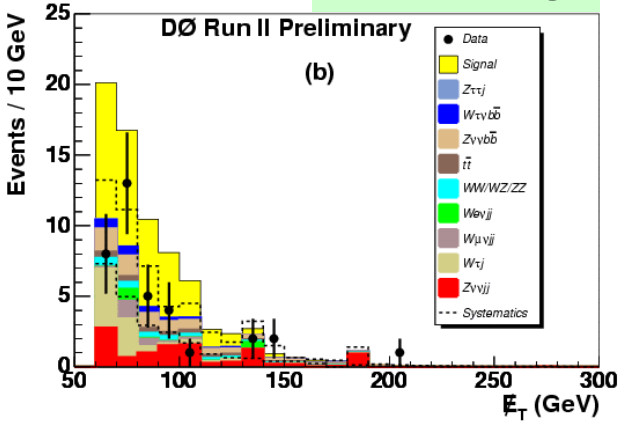
$\geq$ 1b-tag (impact par.)

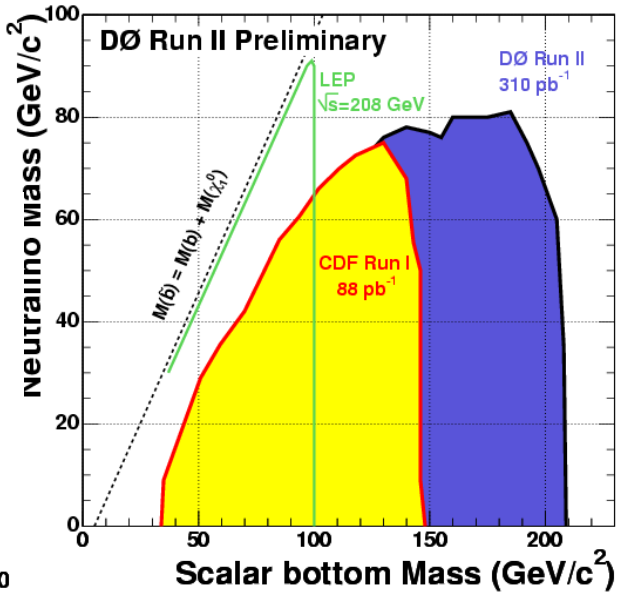
| 318 pb$^{-1}$ | SM background | Data |
|---|---|---|
| Before b-tag | 1335±48 | 1433 |
| After b-tag | 38.6±2.8 | 36 |

Before b-tag




After b-tag



# GMSB SUSY $\gamma\gamma+\not{E}_T$

In Gauge-Mediated SUSY the lightest neutralino decays to gravitino via $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$

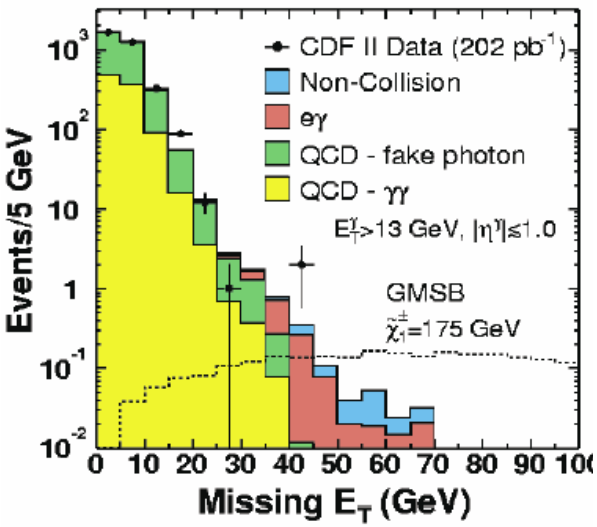
- Event signature: 2 photons + missing $E_T$.

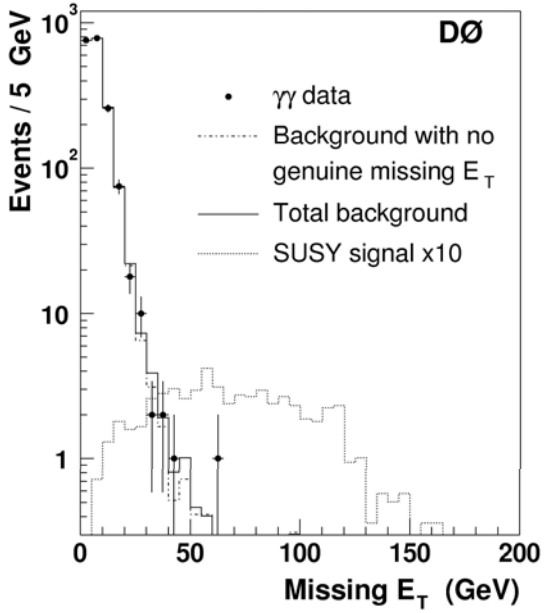
CDF & D0 Combined result (first of many to come)

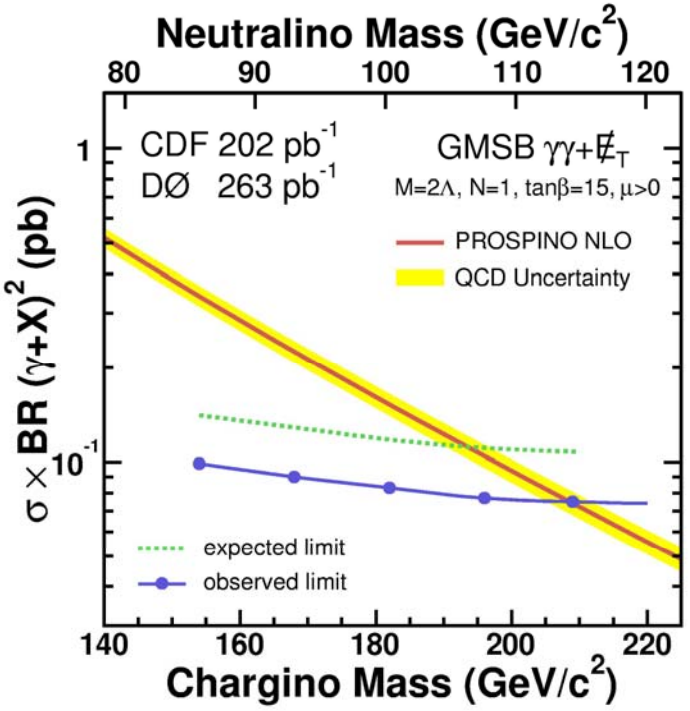
| | SM bkg | Data | $m_{\chi^+}$(GeV) |
|---|---|---|---|
| D0 (263 pb$^{-1}$) | 3.7±0.6 | 2 | 195 |
| CDF (202 pb$^{-1}$) | 0.3±0.1 | 0 | 167 |
| Comb. | | | 209 |

*PRL 94, 041801 (2005)*

*PRD 71, 031104(R) (2005);*

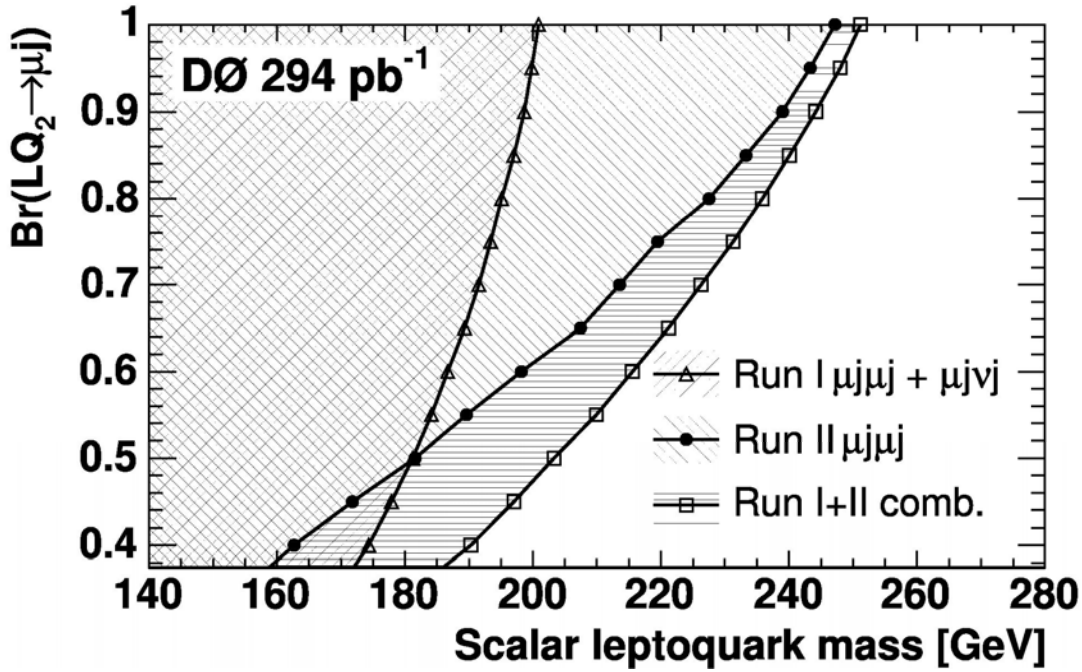


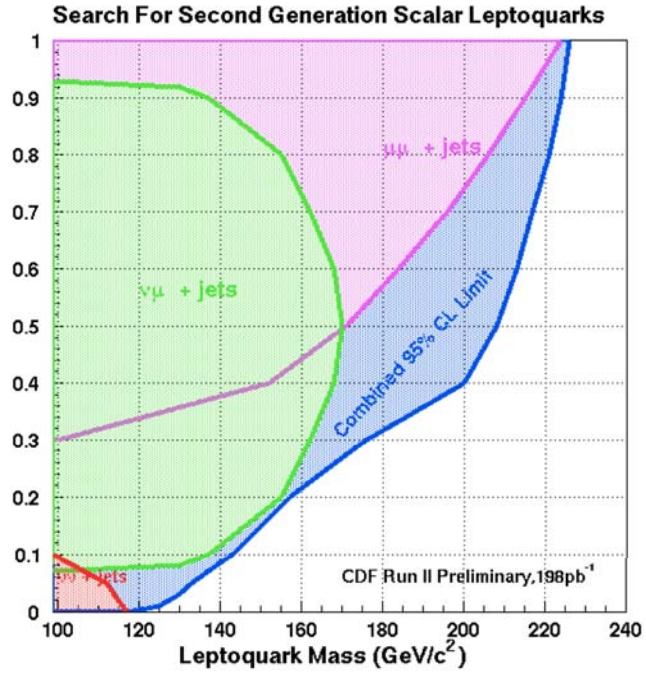



# 2nd Generation Leptoquarks

- Pair production: $qq \rightarrow LQLQ \rightarrow \mu\mu qq$ , $\beta = Br(LQ \rightarrow \mu q)$
- Search channels: $2\mu+2j$ (CDF and D0); $\mu+2j+\not{E}_T$ (CDF); $\not{E}_T+2j$ (CDF).
- Backgrounds: $Z/\gamma*$, QCD (fake)
- No evidence found.



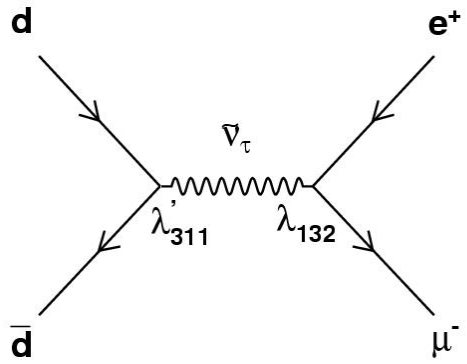




Submitted to *PRL*

# R-parity Violation

- R-parity violating (RPV) interactions violate B or L, but are not ruled out.
- LSP decays to SM particles ($\chi_1^0 \rightarrow \ell^+\ell^-\nu$).
- SUSY particles can be produced singly.

$d\bar{d} \rightarrow \tilde{\nu}_\tau \rightarrow e\mu$




Signal region:

$100 < M_{e\mu} < 180$Gev

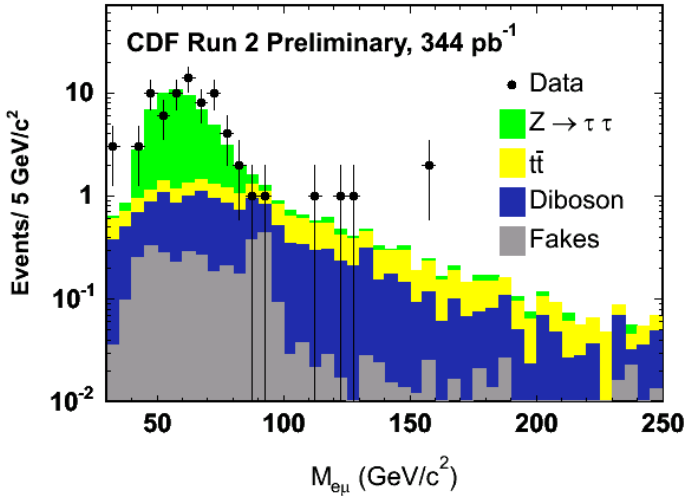
| SM bkg | Data |
|---|---|
| 7.66±0.63 | 5 |

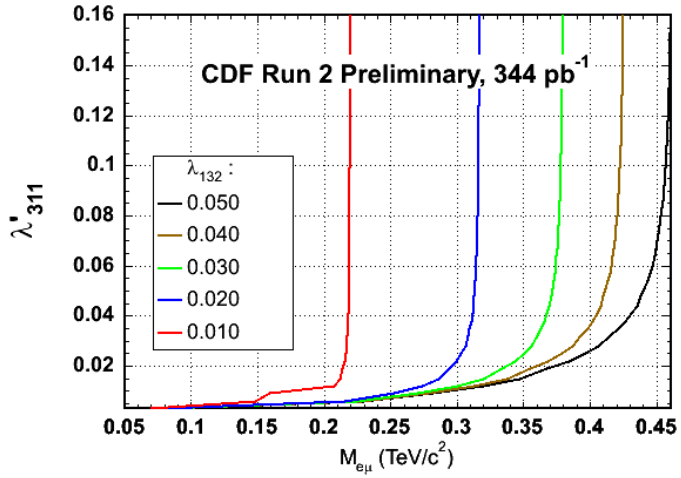
Backgrounds:

. Diboson

. Top

. Z→ττ

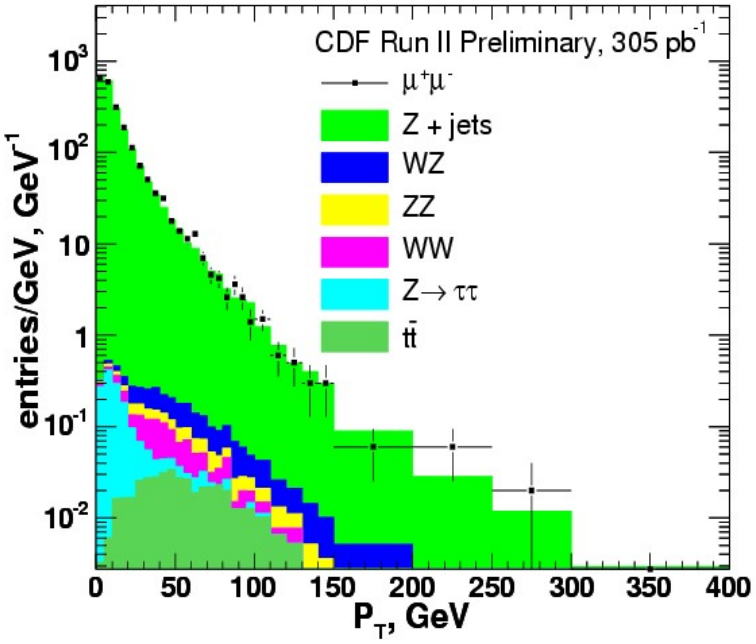


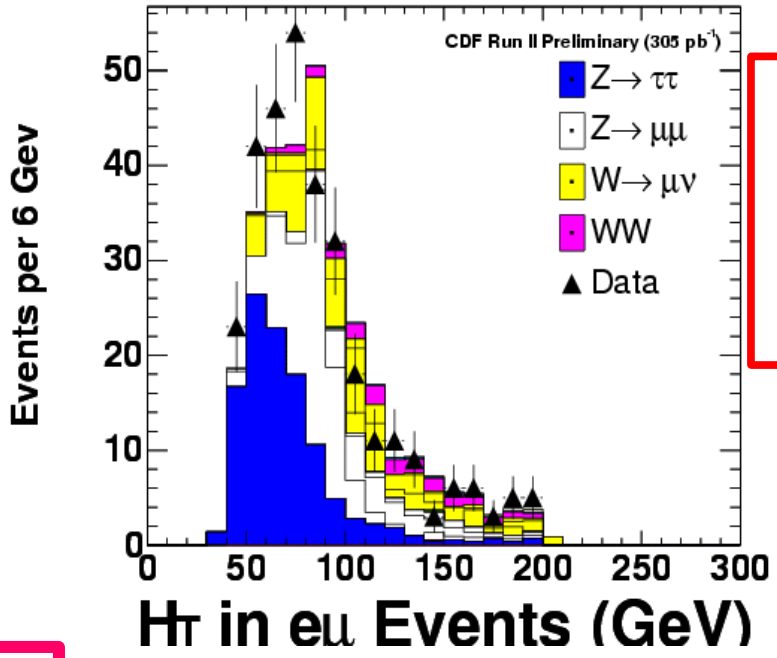
# Signature-based searches for dileptons + X

- Look for excess above SM prediction in dilepton + X (X = photon, lepton, b-jet, $H_T$, Missing $E_T$; dileptons can be same-sign or opposite-sign)
  - Set cuts on first 1/3rd of dataset (now, 305pb$^{-1}$), apply to next part of data (coming soon)
  - can be further applied to many models; e.g. heavy quarks as first example

High $p_T$ Z's (inclusive) in dimuons




Dilepton (ee, μμ, eμ) + high $H_T$




Good agreement in $H_T$<200 control region. No events in $H_T$>400 signal region.

No excess seen in these channels!

$H_T$ == scalar sum of electron and jet $E_T$, muon $p_T$, missing $E_T$

# Summary

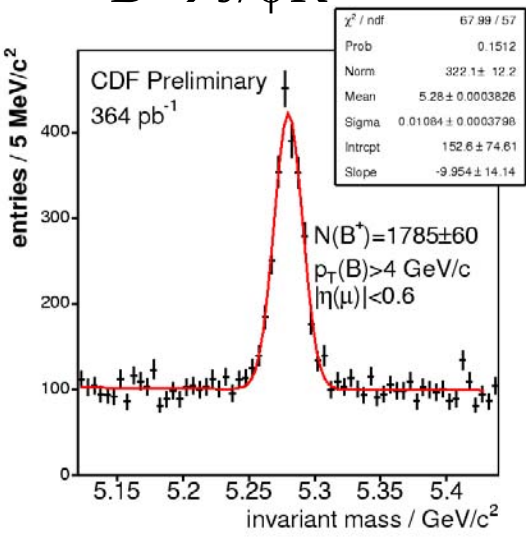
- CDF and D0 have searched for Higgs and new physics in many different channels.
  - No Higgs has been found yet.
  - No evidence for new physics.
- Tevatron is performing well. Delivered ~1.4 $fb^{-1}$ luminosity for each experiment so far.
  - New analyses with 1 $fb^{-1}$ coming soon.
  - Expect ~8 $fb^{-1}$ total in Run II.
  - Will be able to reach $3\sigma$ evidence or 95% CL exclusion for Higgs up to 180 GeV in mass. if nature is kind
- Many additional searches not covered in this talk
  - LED, new gauge bosons, stop, technicolor,…
- Experiments will be upgraded 2006.
- Prospects are excellent for exciting new physics results!

# Backup slides

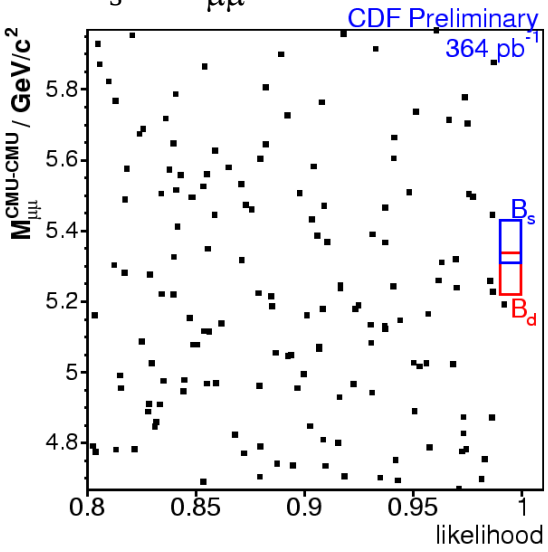
# $B_s \rightarrow \mu\mu$

- In SM, small BR ~ $3.5\times10^{-9}$
- But in SUSY, enhancement ~ $\tan^6\beta$ factor

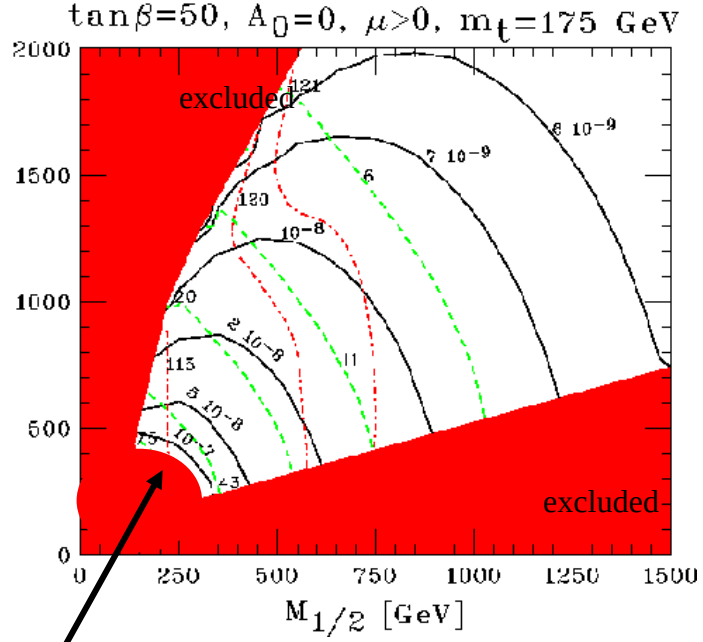
$B^+ \rightarrow J/\psi K^+$




$B_s$: $m_{\mu\mu}$ vs limelihood




mSUGRA $M_0$ vs $M_{1/2}$




| at 90% C.L. | Luminosity | BR($B_s \rightarrow \mu\mu$) |
|---|---|---|
| CDF | 364 $pb^{-1}$ | $<1.5\times10^{-7}$ |
| D0 | 300 $pb^{-1}$ | $<3.0\times10^{-7}$ |

Excluded by CDF