Searches for Higgs bosons and New Physics at the Tevatron

Volker Büscher

Universität Bonn

DESY Seminar, March 18/19, 2008

- Indirect constraints from precision measurements
- The SM Higgs boson
- MSSM Higgs bosons
- Supersymmetry: Squarks, Gluinos, Charginos
- Heavy Resonances

Full set of Tevatron results available at:

http://www-d0.fnal.gov/Run2Physics/WWW/results.htm

http://www-cdf.fnal.gov/physics/physics.html

The Tevatron Collider

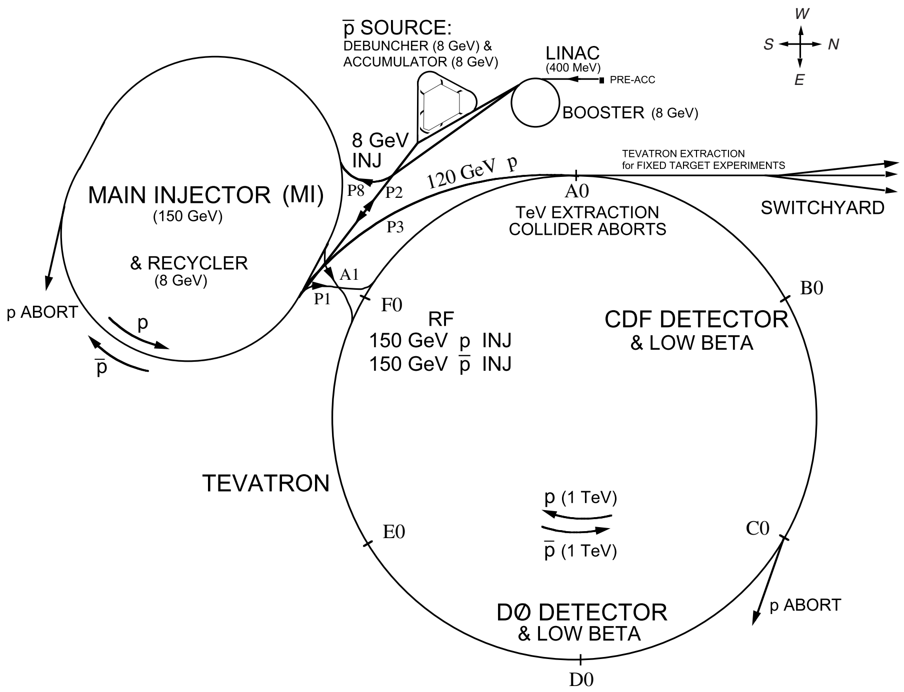
Proton Antiproton Collider

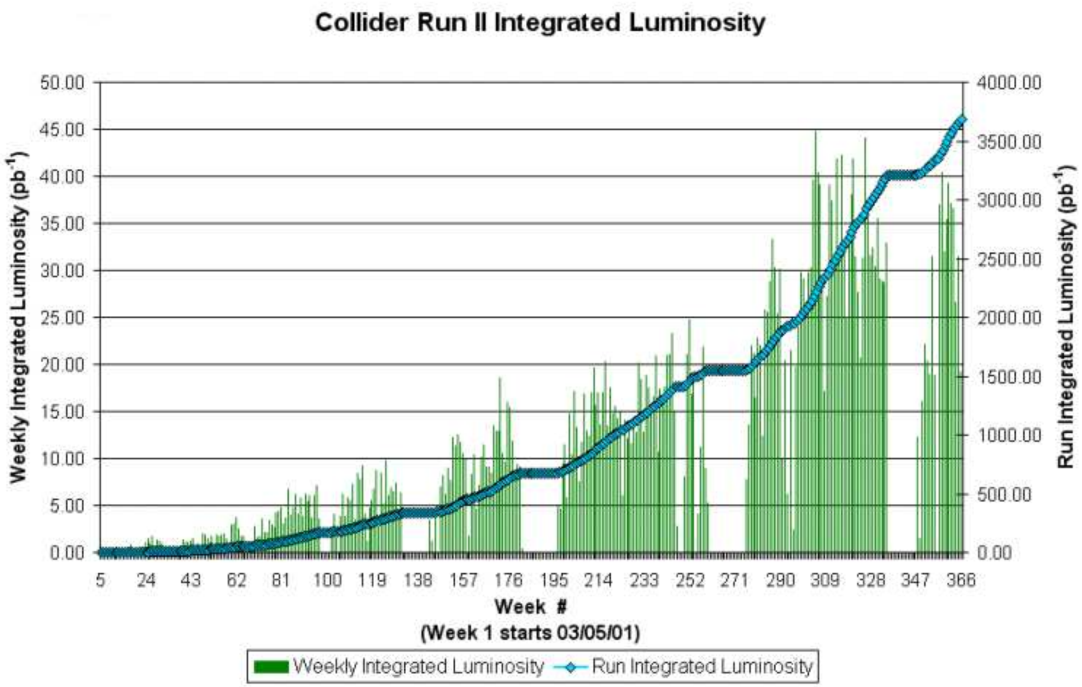
Centre-of-mass energy: 1.96 TeV

Integrated Luminosity: 3.8 fb^{-1} so far

Peak luminosity: 2.8×10^{32} $cm^{-2}s^{-1}$

Expecting to accumulate 6-9 fb^{-1} by 2009/10





Electron Cooling in operation

The Tevatron Collider

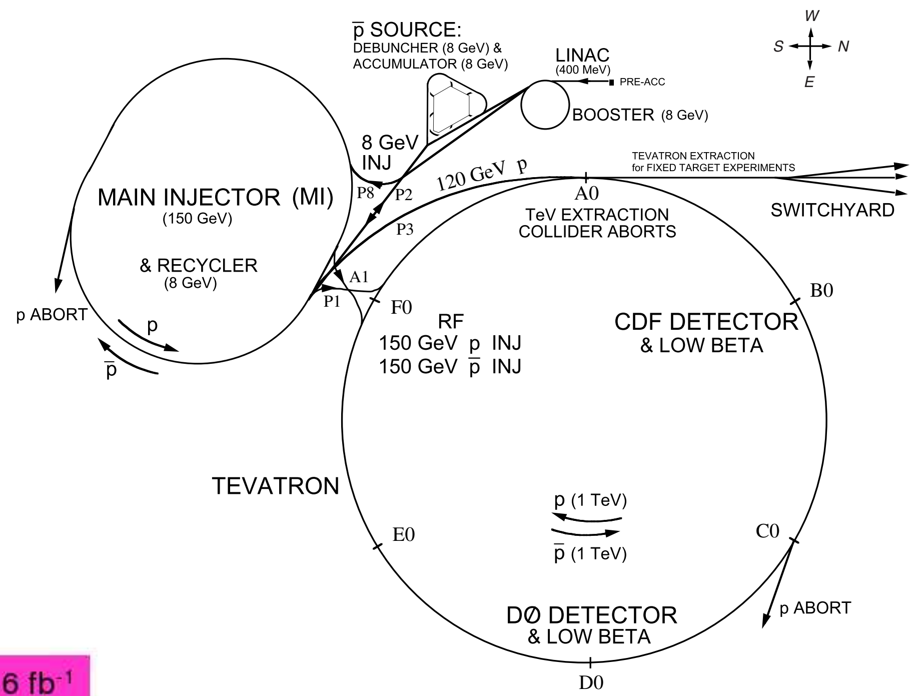
Proton Antiproton Collider

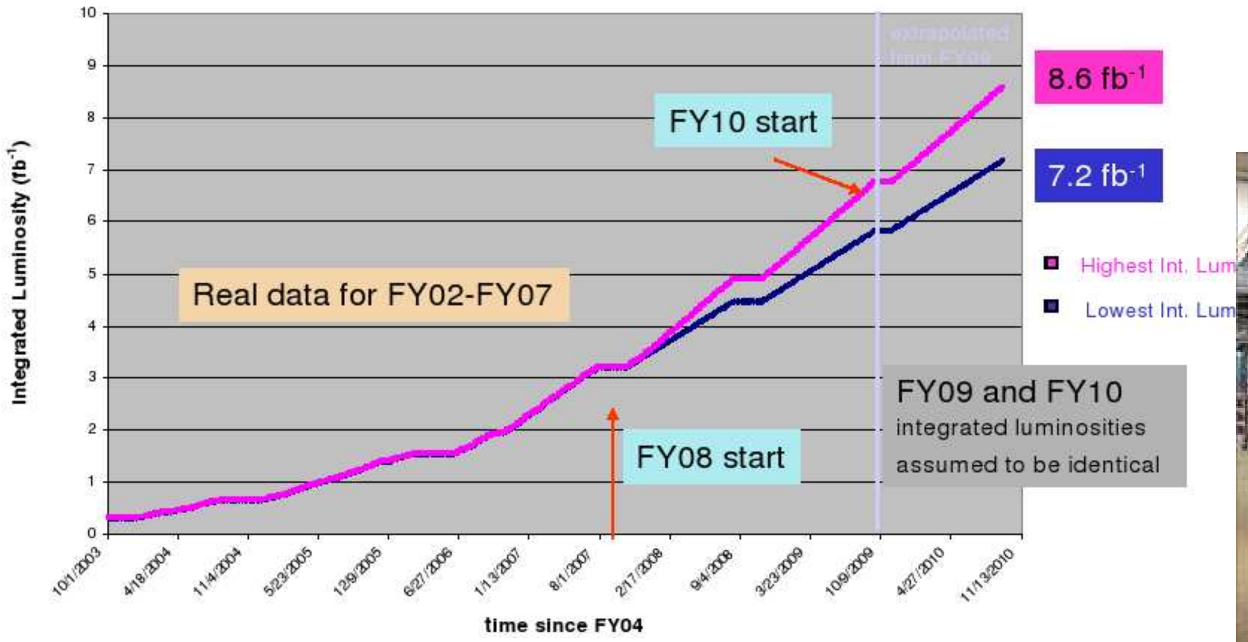
Centre-of-mass energy: 1.96 TeV

Integrated Luminosity: 3.8 fb^{-1} so far

Peak luminosity: 2.8×10^{32} $cm^{-2}s^{-1}$

Expecting to accumulate 6-9 fb^{-1} by 2009/10





Electron Cooling in operation

Physics at Hadron Colliders

Tevatron: Proton-Antiproton Collider at $\sqrt{s} = 1.96$ TeV, collisions every 396 ns

- Advantage: High centre-of-mass energy

  $\longrightarrow$ production of massive particles (LEP: m $\lesssim$ 100 GeV)

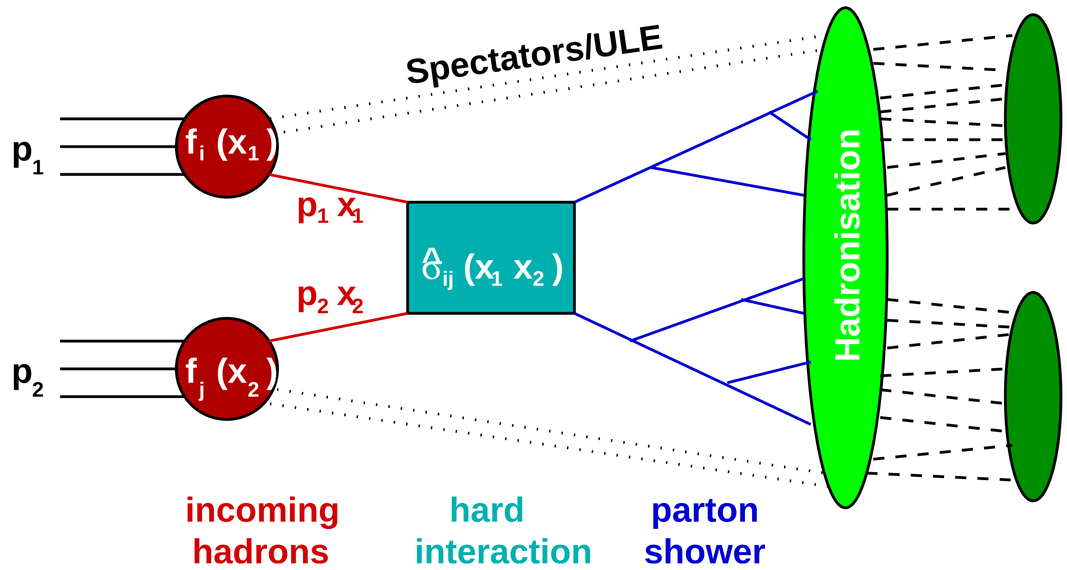
- Disadvantage: Strong Interaction

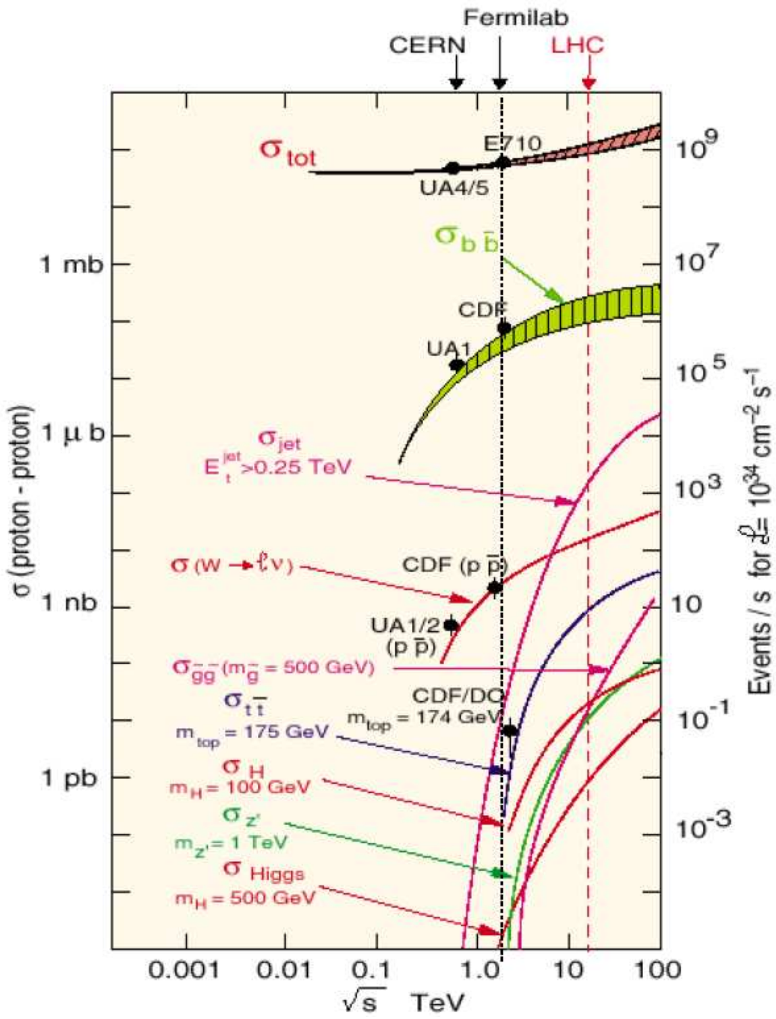
  $\longrightarrow$ huge event rates for jet production

  $\longrightarrow$ multiple interactions per crossing

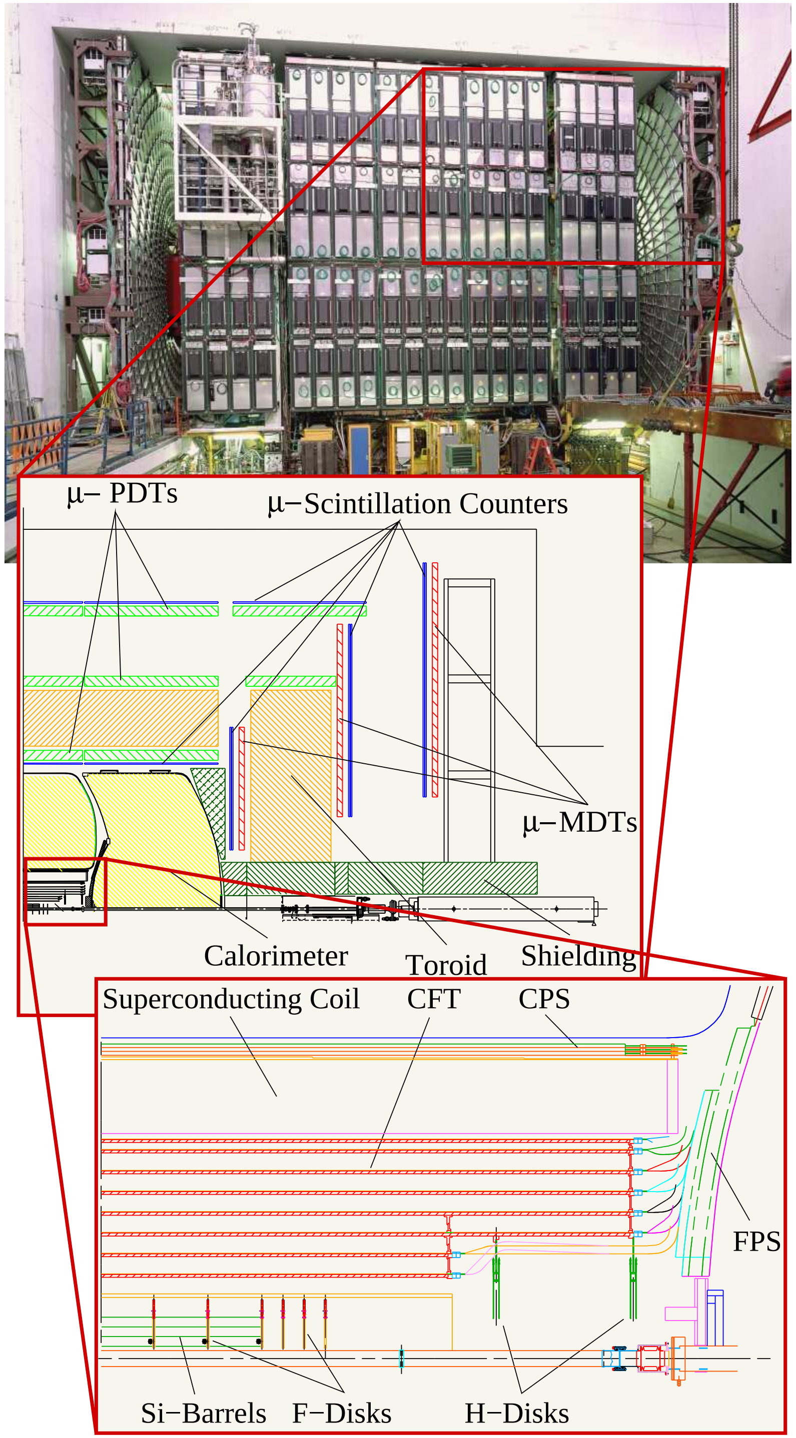
  $\longrightarrow$ complicated final states:

  - particles from fragmentation of $p/\bar{p}$ remnants
  - gluon radiation $\longrightarrow$ jets





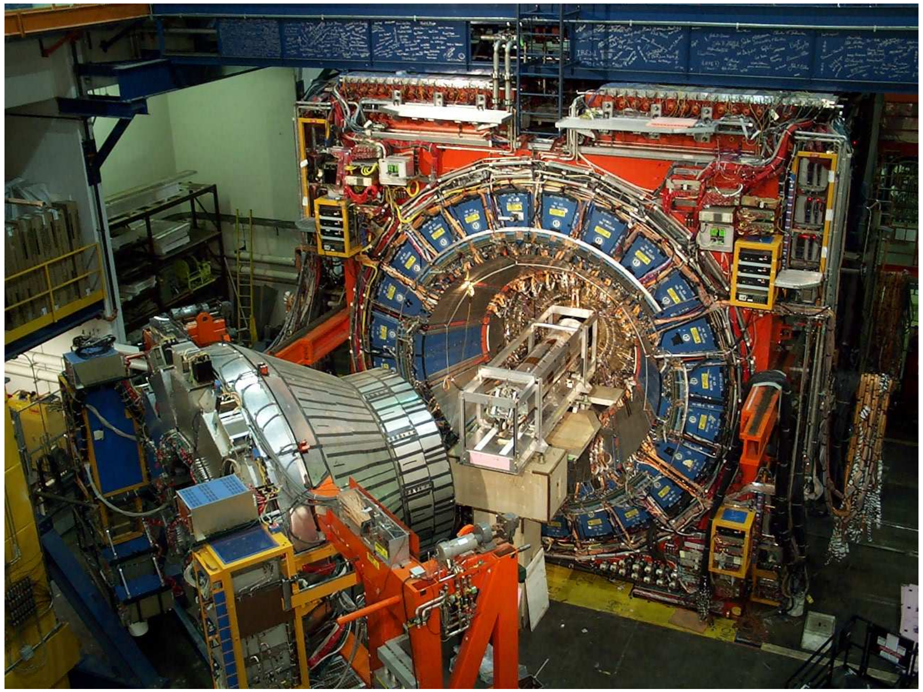
The Tevatron Experiments



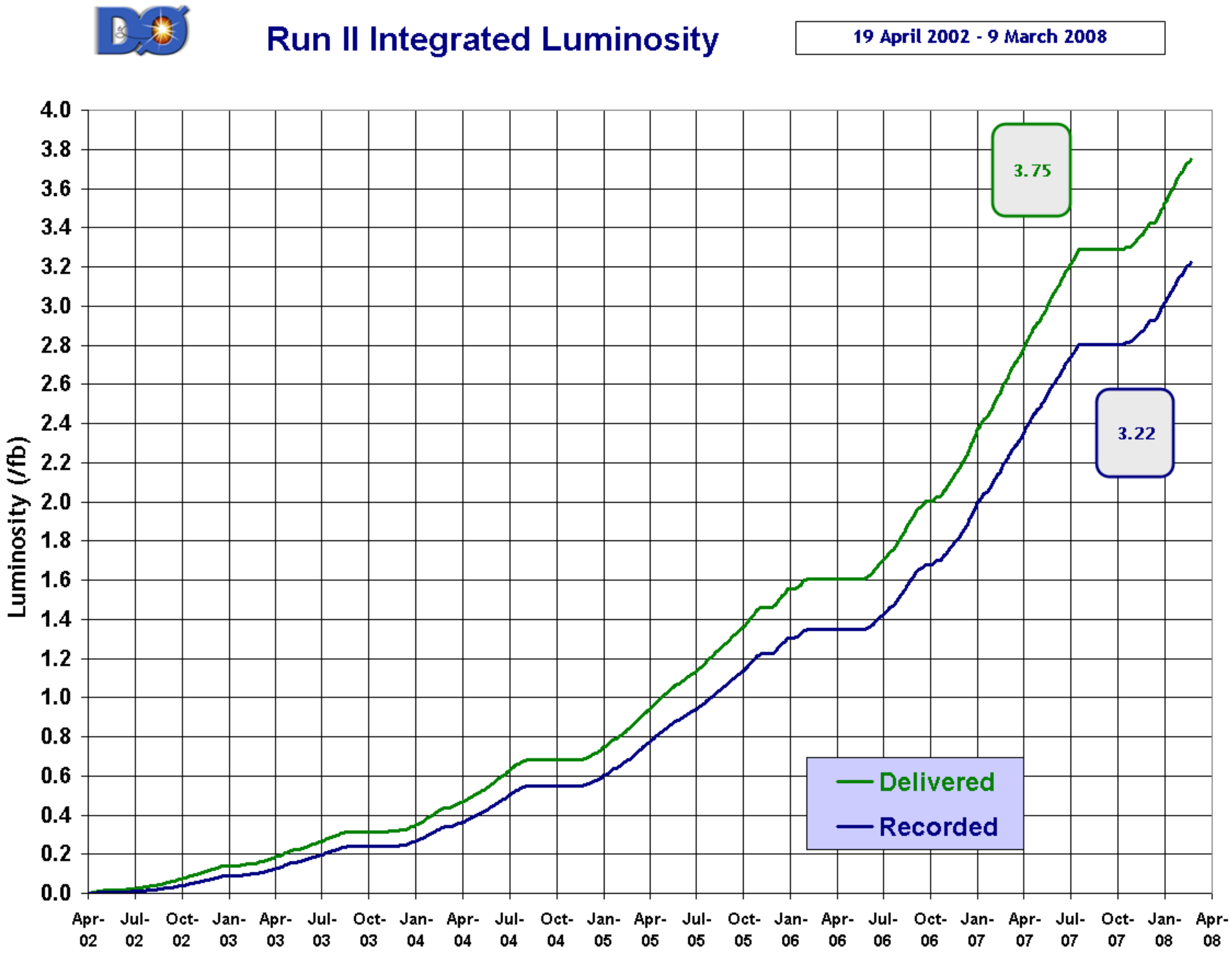
Two General-Purpose Detectors:	CDF	DØ
Electron acceptance	$\lvert\eta\rvert < 2.0$	$\lvert\eta\rvert < 3.0$
Muon acceptance	$\lvert\eta\rvert < 1.5$	$\lvert\eta\rvert < 2.0$
Silicon Precision tracking	$\lvert\eta\rvert < 2.0$	$\lvert\eta\rvert < 3.0$
Hermetic Calorimeter	$\lvert\eta\rvert < 3.6$	$\lvert\eta\rvert < 4.2$

Powerful trigger systems (2.5 MHz⟶100 Hz)

- Dilepton triggers starting at $p_T > 4$ GeV
- Jets+$\not{E}_T$ triggers with $\not{E}_T > 25$ GeV



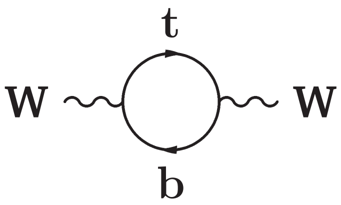
The Tevatron Experiments – Dataset



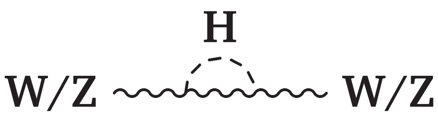
- 3.2 + 3.0 fb^{-1} recorded by DØ + CDF
- Most results presented here based on 2 fb^{-1}

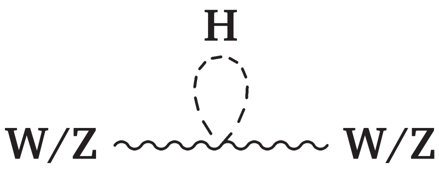
Pinning down EWSB at the Tevatron

Standard Model relates m_H, m_t, m_W via radiative corrections:

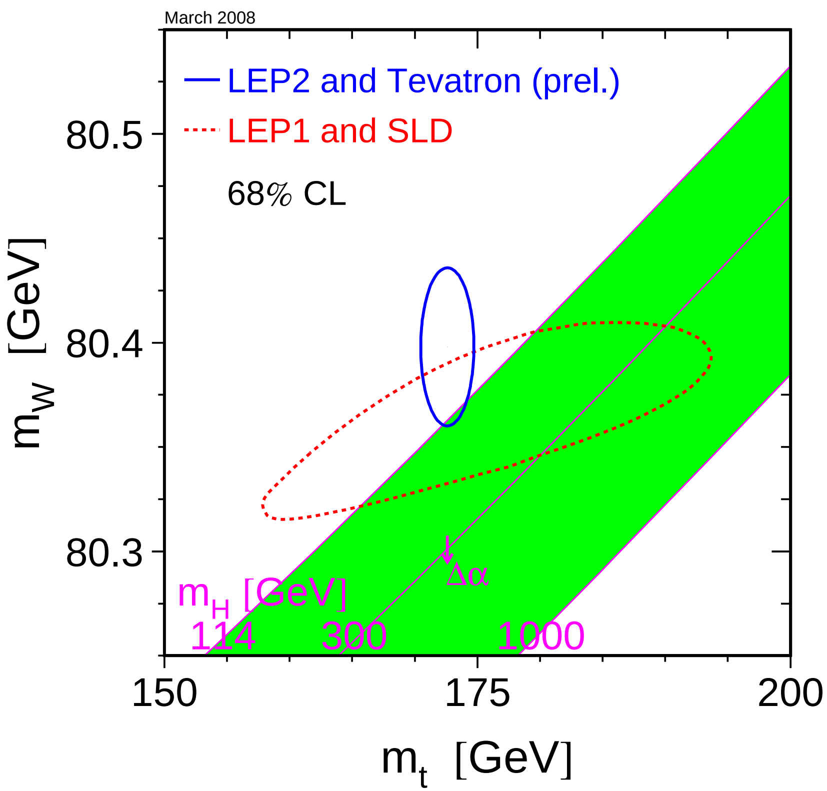


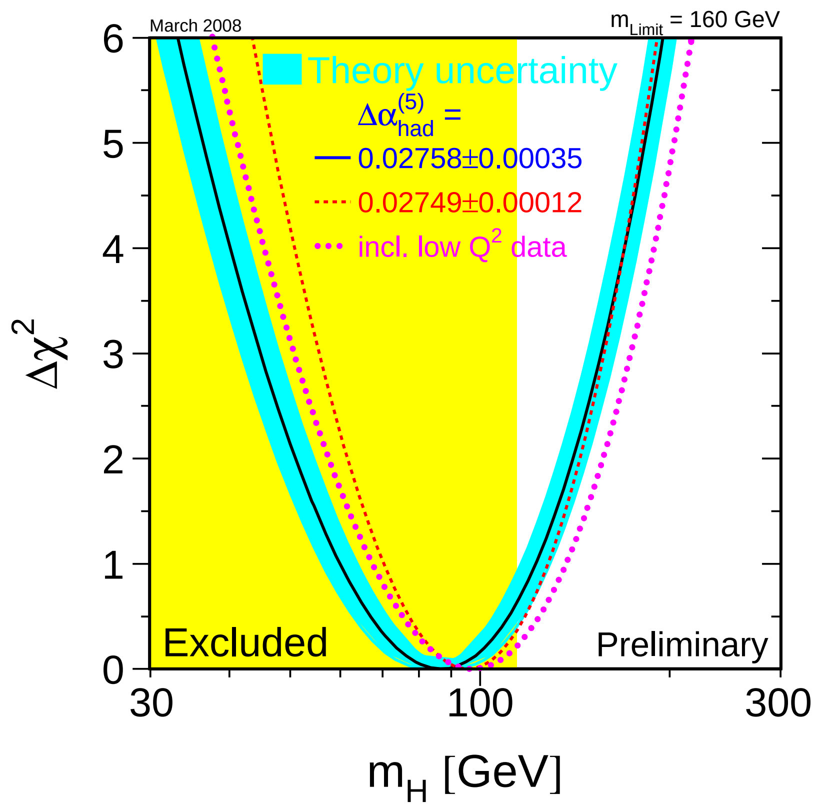
$\sim m_{\rm top}^2$





$\sim \ln \frac{m_{\rm H}}{m_{\rm W}}$





→ Indirect constraints on Higgs boson mass:

$m_H = 87^{+36}_{-27}$ **GeV and** $m_H < 160$ **GeV at 95% C.L.**

Pinning down EWSB at the Tevatron

Combined top mass measurement from CDF+DØ:

m_t = 172.6±0.8(stat)±1.1(syst) GeV

New CDF W mass measurement (200 pb^{-1}):

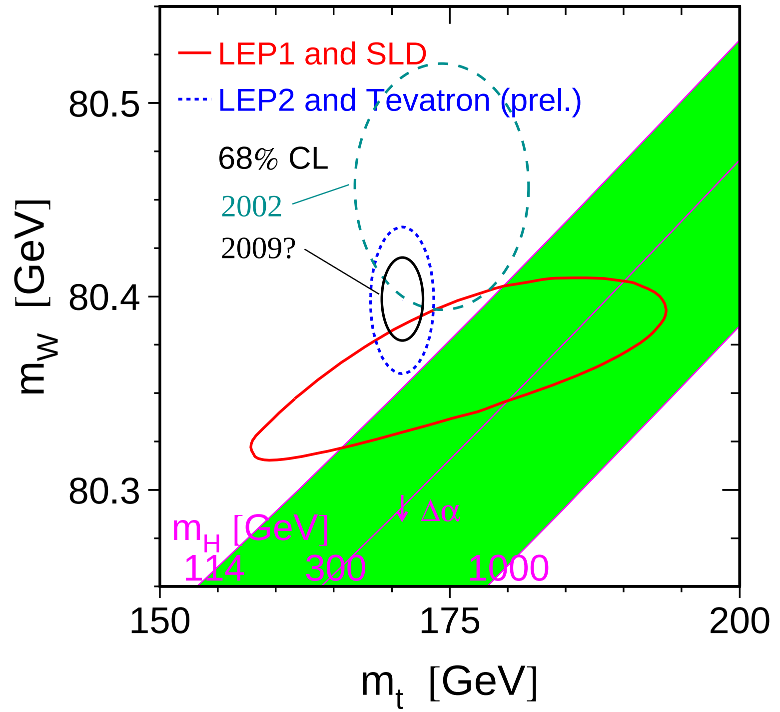
m_W = 80.413±0.048 GeV

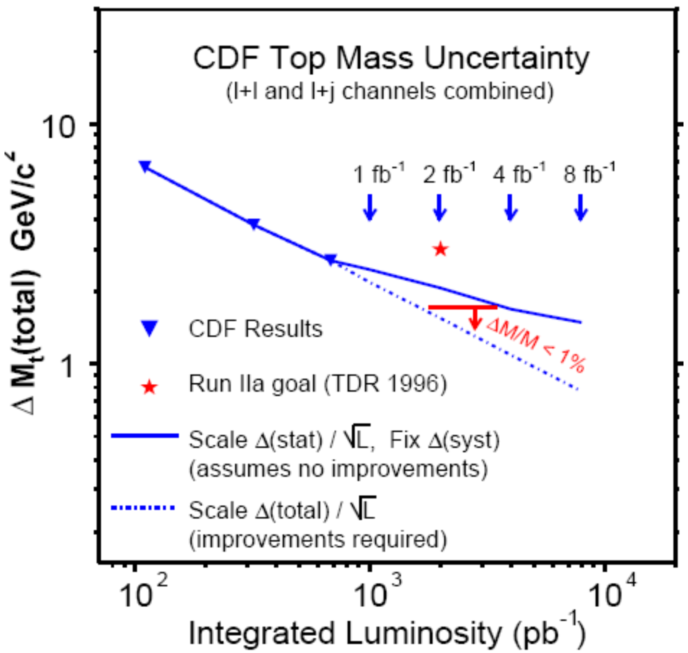
new world average: m_W = 80.398±0.025 GeV

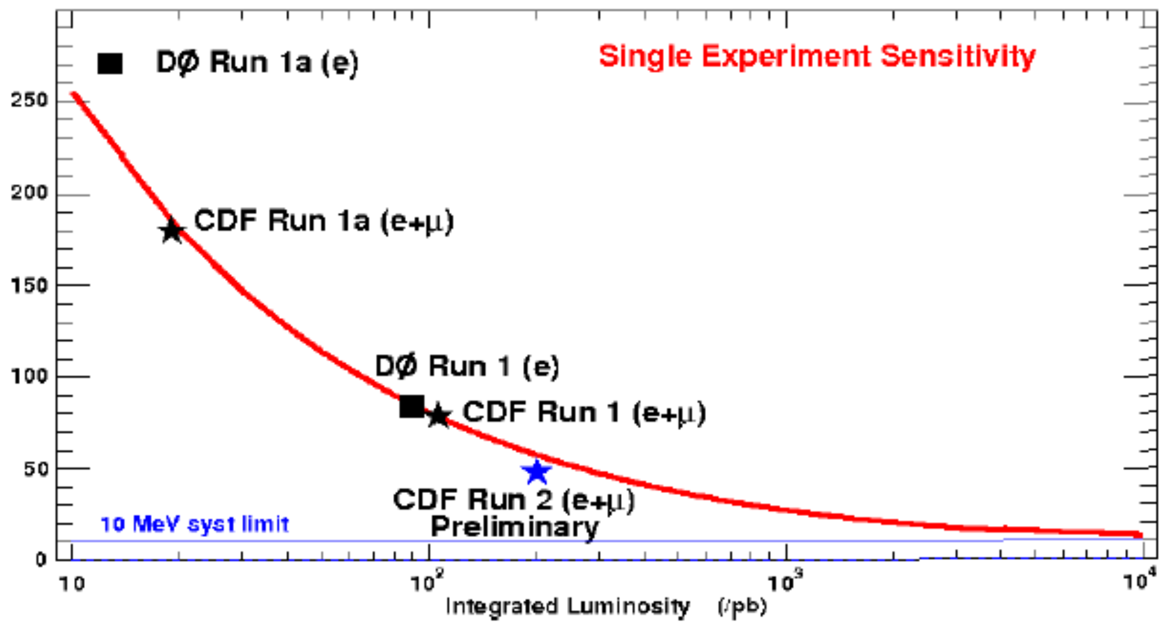
Projected uncertainties for 8 fb^{-1}:

m_t: ±1.2 GeV

m_W: ±15-20 MeV

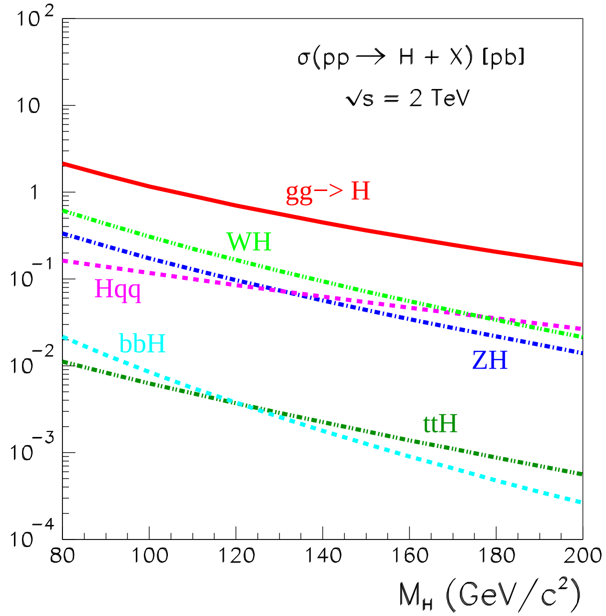




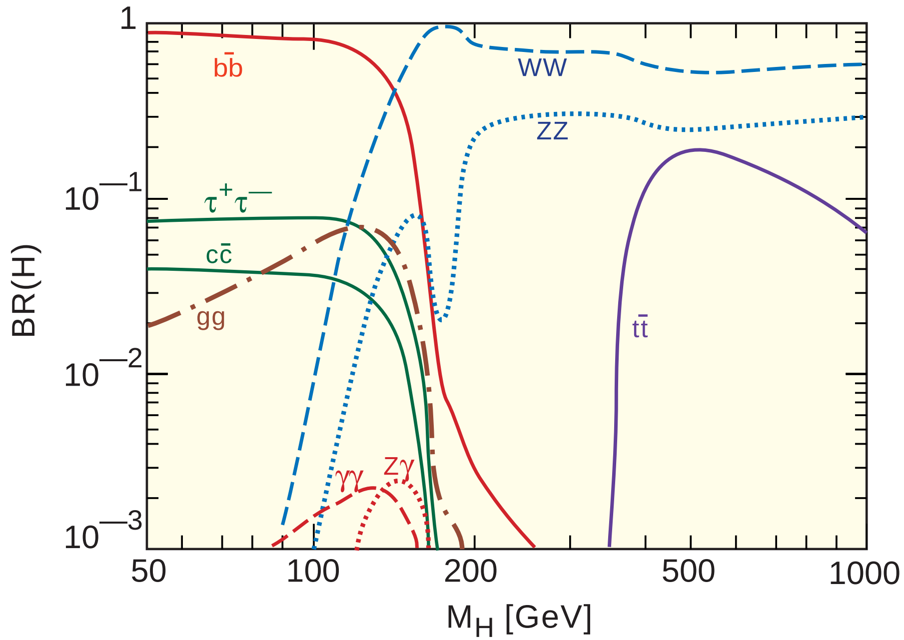


Search for Higgs Bosons – Production and Decay

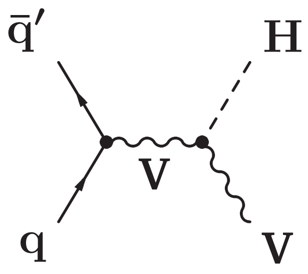
Production Cross-Sections



Branching Ratios



Light Higgs bosons ($m_H \lesssim$ 135 GeV):



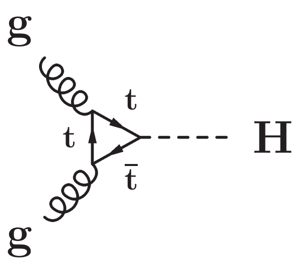
Dominant decay mode: $H \to b\bar{b}$

Production: in association with W,Z

→ leptonic W,Z-decays provide best signature

→ b-tagging to suppress background from W/Z+jets

Heavy Higgs bosons ($m_H \gtrsim$ 135 GeV):



Dominant decay mode: $H \to WW$

Production: Gluon-Gluon Fusion

→ relatively high cross-section

→ clean 2-lepton+$\not{E}_T$ signature via $H \to WW \to l\nu l\nu$

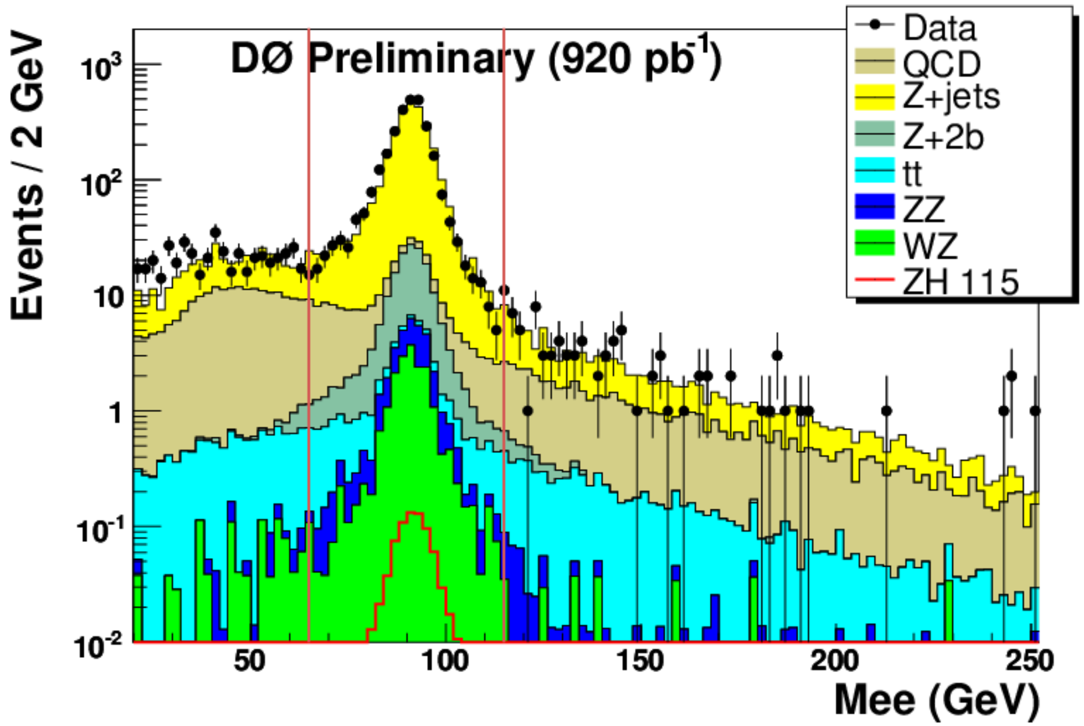
Search for low-mass Higgs Boson

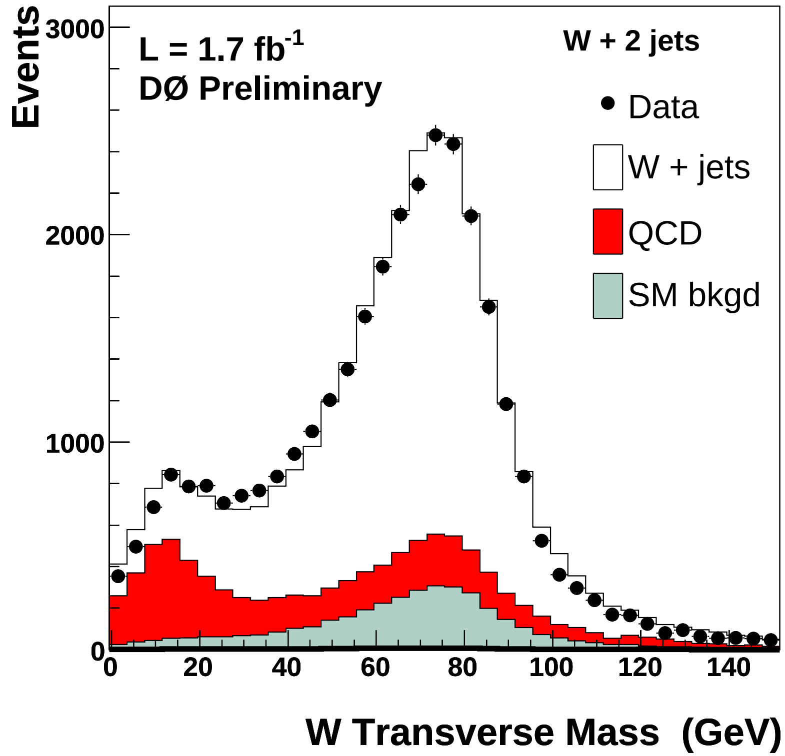
For best sensitivity, need to combine many channels:

$$WH \to \ell\nu b\bar{b},\ ZH \to \nu\bar{\nu}b\bar{b},\ ZH \to \ell^+\ell^- b\bar{b}\ (\text{with } \ell = e, \mu)$$

Challenge: very low signal rates, massive backgrounds from V+jets

First step: select events consistent with W/Z+2 jets



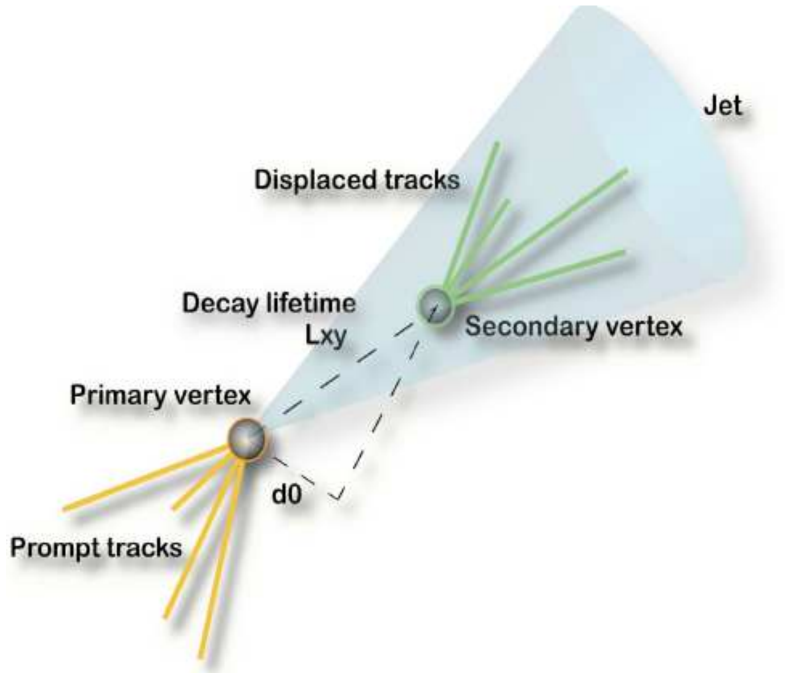


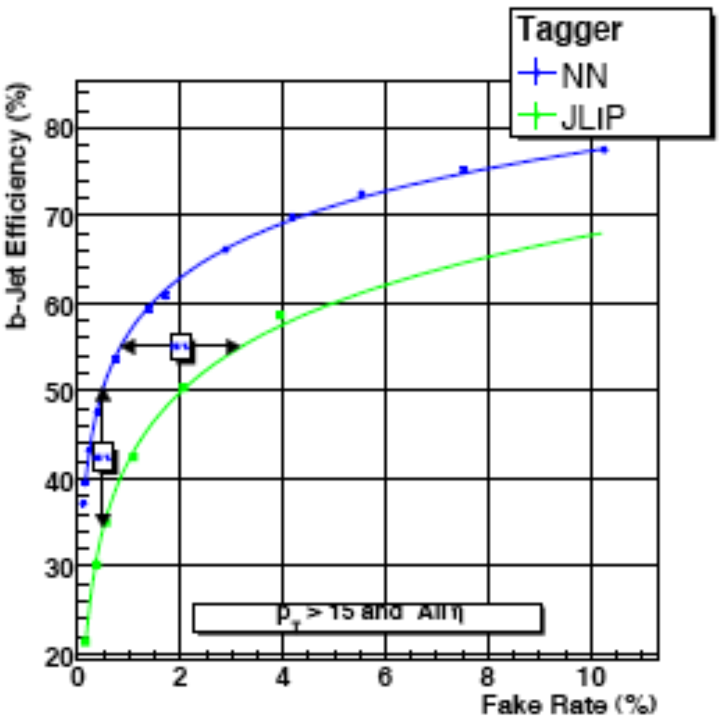
Search for low-mass Higgs Boson

Second step: b-tagging

Exploiting B-meson lifetime, mass and decay modes to separate b- from light-quark jets:

- impact parameter
- secondary vertices
- vertex mass
- vertex track multiplicity
- soft leptons



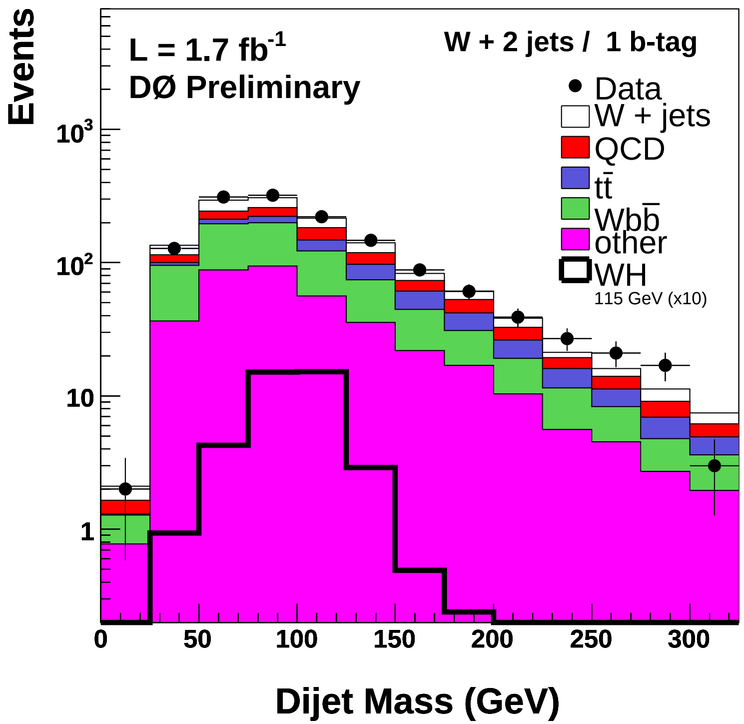


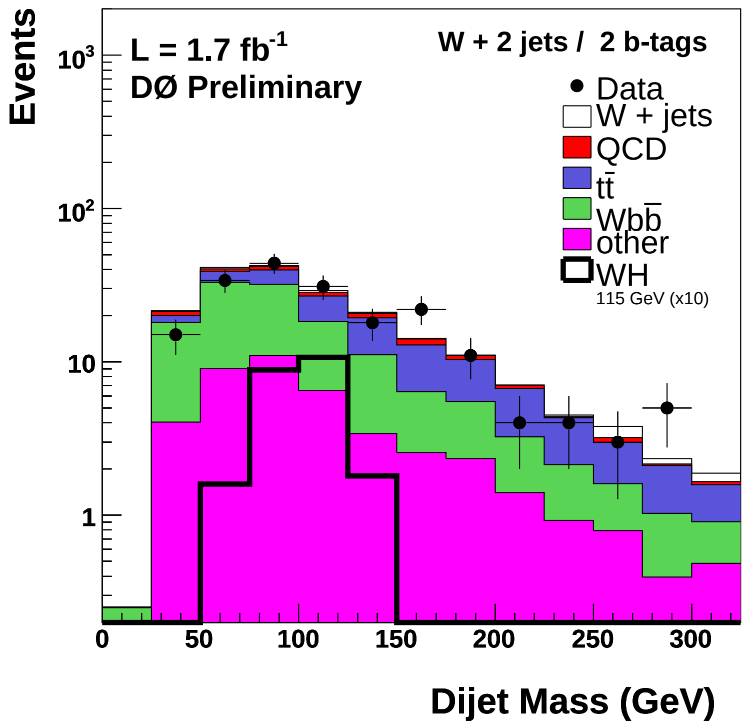
Similar strategies in both experiments:

- use neural networks for optimal combination of tagging information
- use several NN operating points to define channels with high/low s/b:
  - 1 tight b-tag (low s/b, “single tag”),
  - 2 loose b-tags (high s/b, “double tag”)

Search for low-mass Higgs Boson

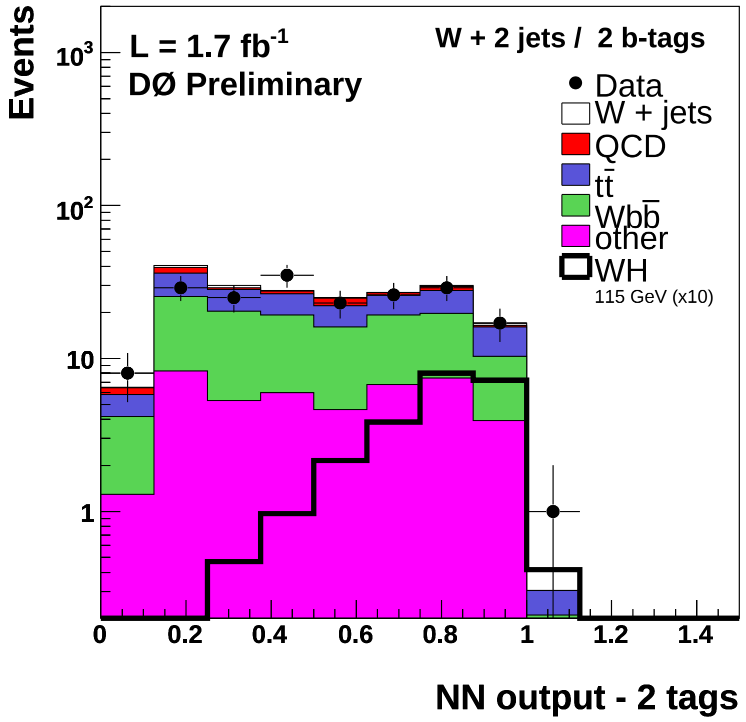
- Backgrounds dominated by W/Z+bb, $t\bar{t}$
- Main handle: invariant mass of two b-jets

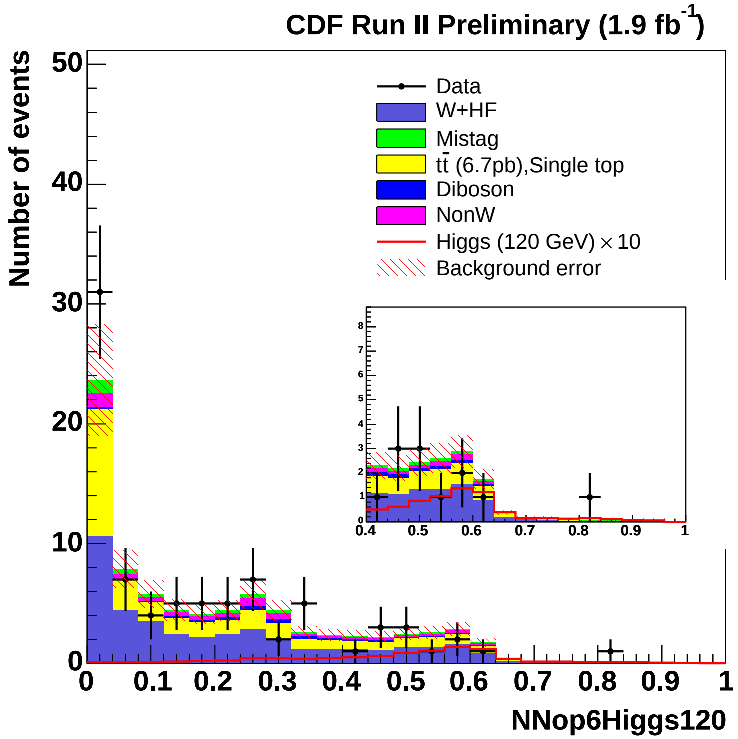




Search for low-mass Higgs Boson

– For optimal separation power, use neural networks:





Note: signal-to-background ratios are at most 10-20%

$\longrightarrow$ need full combination of all channels to reach sensitivity

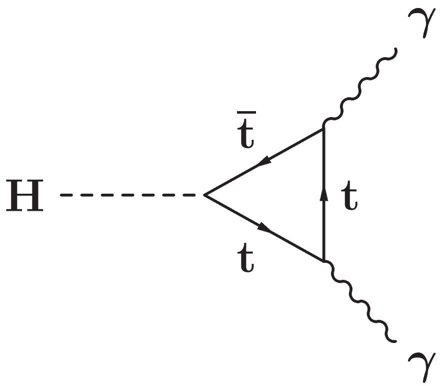
$\longrightarrow$ need to control systematics at a level $\ll$10%!

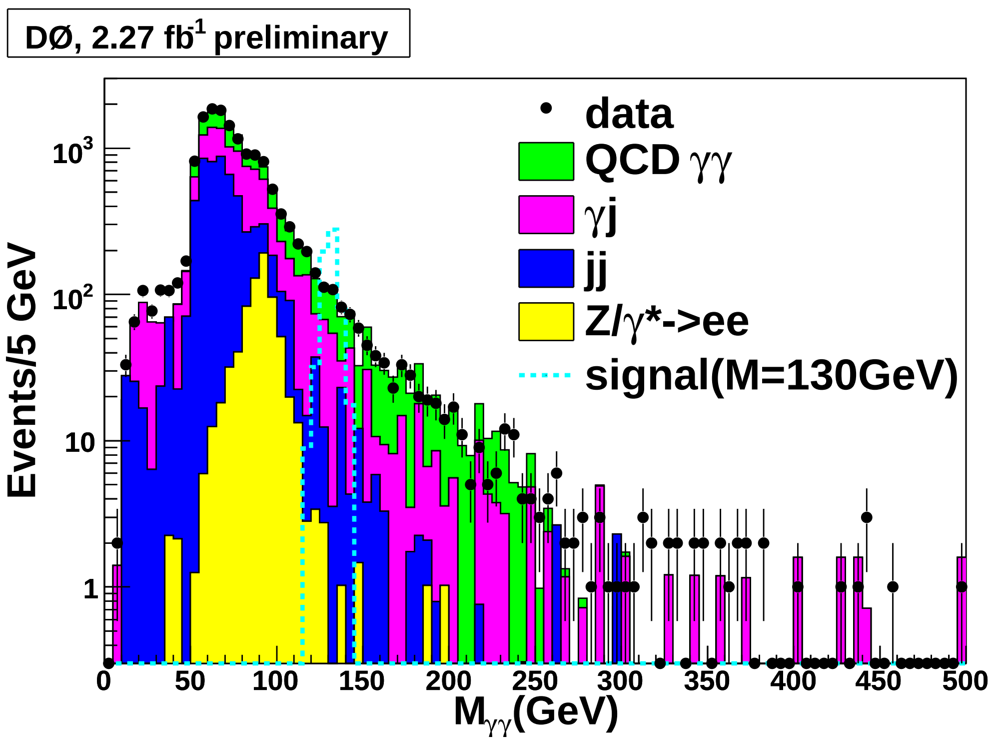
Main concern: modeling of V+jets backgrounds

- shapes: from MC (alpgen, MCFM, CKKW)
- normalisation: combination of (N)NLO cross-sections and sideband-fitting

New channels added for Winter 2008

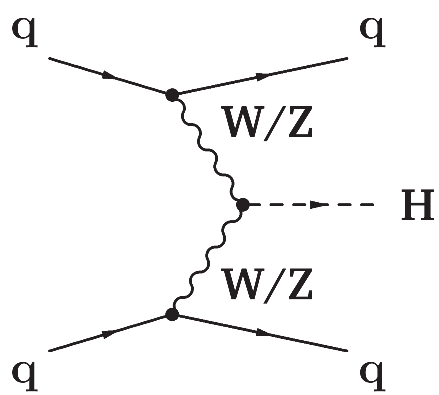
DØ: H→ γγ

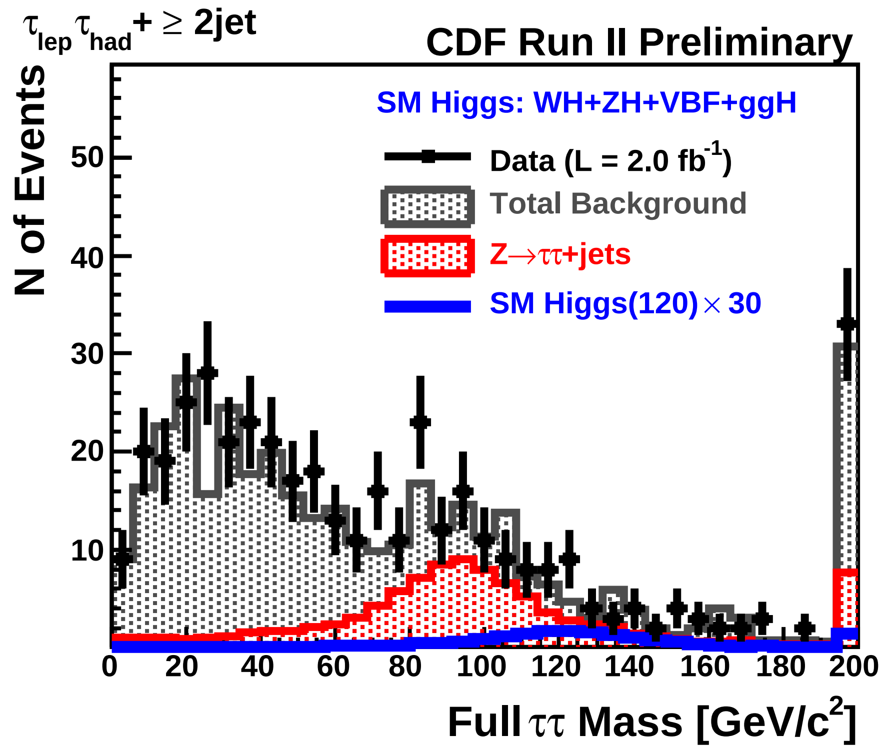




Expected Limit: 40 x σ_{SM} (m_H=120 GeV)

CDF: H+jj with H→ ττ



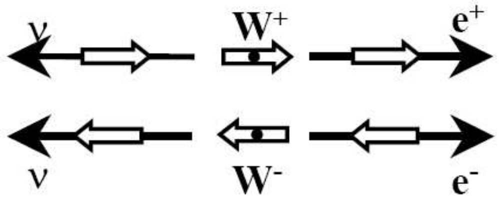


Expected Limit: 25 x σ_{SM} (m_H=120 GeV)

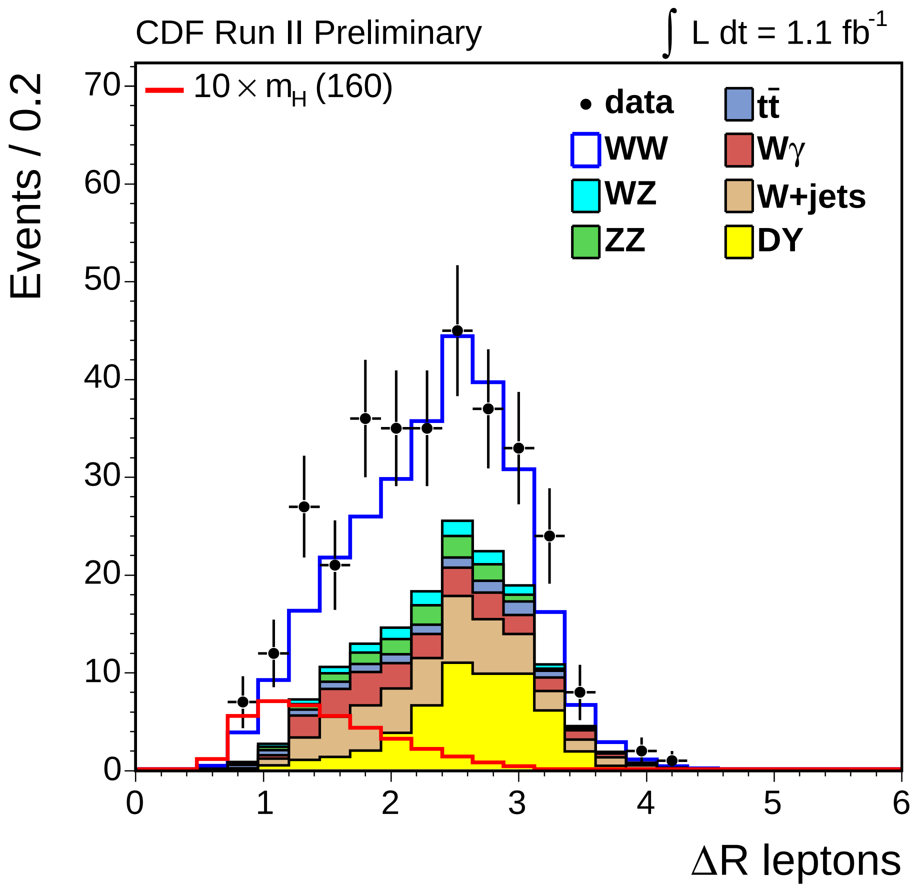
Search for high-mass Higgs Boson: H→WW

Main irreducible background: WW$\longrightarrow \ell\nu\ell\nu$

Additional information: angular correlations exploiting spin of Higgs boson



→ Charged leptons from Higgs decay tend to have small opening angle ΔΦ



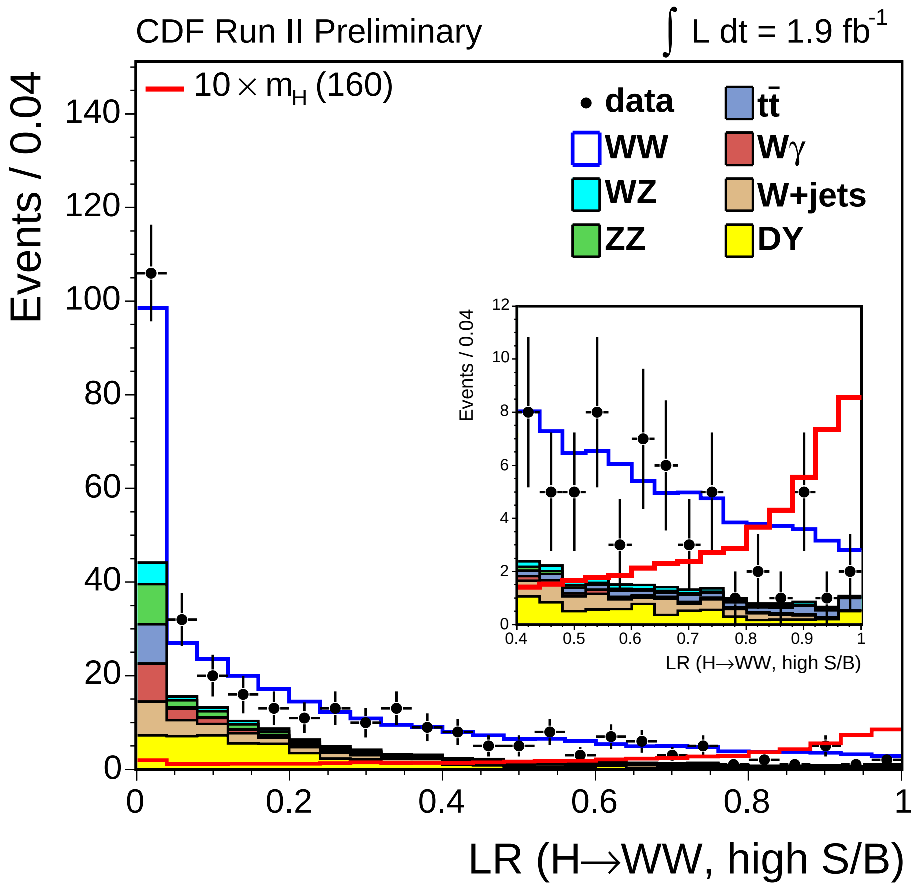
For best sensitivity, use multivariate techniques

Search for high-mass Higgs Boson: H→WW

- For each event, use full kinematic information x_{obs} to calculate probabilities that event comes from signal (P_H) and background (P_B):

$$P_{H/B}(x_{obs}) = \frac{1}{\sigma_{H/B}} \int dy^n_{true}\, \sigma^{theory}_{H/B}(y_{true})\, \epsilon(y_{true})\, G(x_{obs}, y_{true})$$

- Then calculate likelihood ratio $\frac{P_H}{P_H+P_B}$ for optimal separation of signal and background:



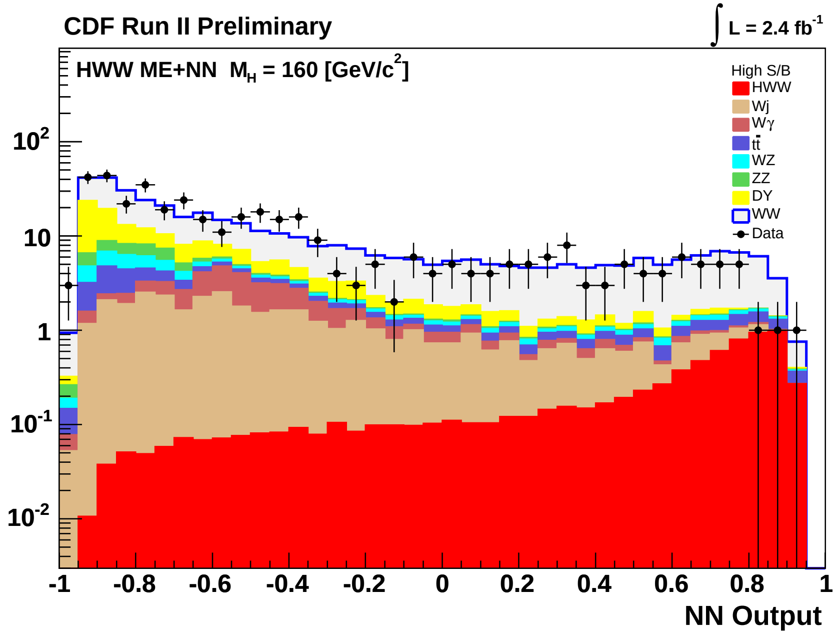
Search for high-mass Higgs Boson: H⟶WW

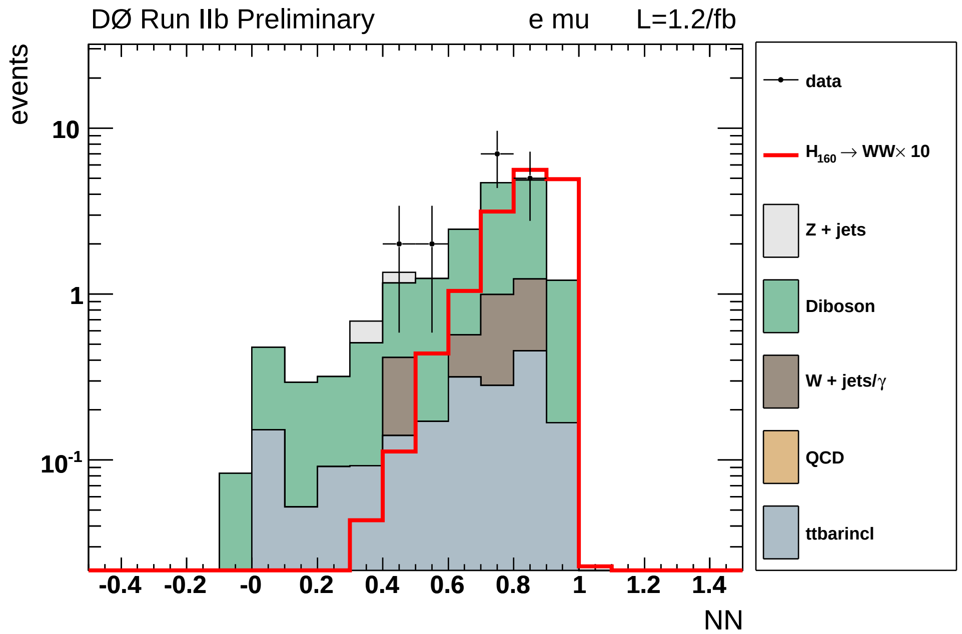
- For each event, use full kinematic information x_{obs} to calculate probabilities that event comes from signal (P_H) and background (P_B):

$$P_{H/B}(x_{obs}) = \frac{1}{\sigma_{H/B}} \int dy^n_{true}\, \sigma^{theory}_{H/B}(y_{true})\, \epsilon(y_{true})\, G(x_{obs}, y_{true})$$

- Then calculate likelihood ratio $\frac{P_H}{P_H+P_B}$ for optimal separation of signal and background

- Finally, combine with other kinematic variables in a neural network:





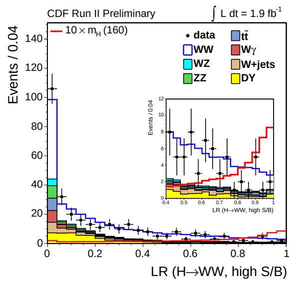
Tevatron Full Combination

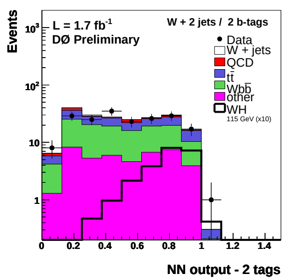
Massive exercise in advanced statistics

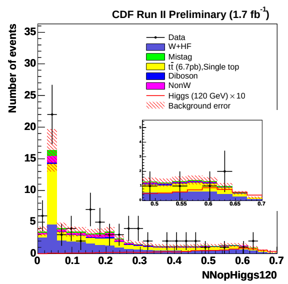
– currently combining 28 different channels

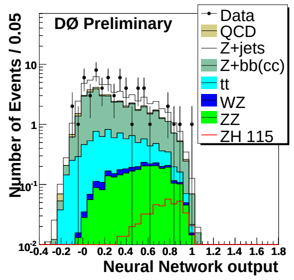
– full distributions of final variables are analyzed

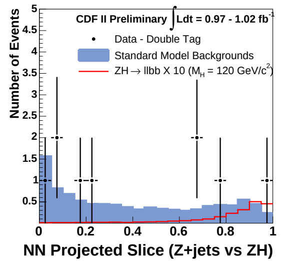
$\longrightarrow$ 28 NN/LR/Mass distributions











$>$ 50 different sources of systematic uncertainties are considered

– taking into account correlations bin-to-bin and channel-to-channel

$\longrightarrow$ $>$50 300x300 covariance matrices...

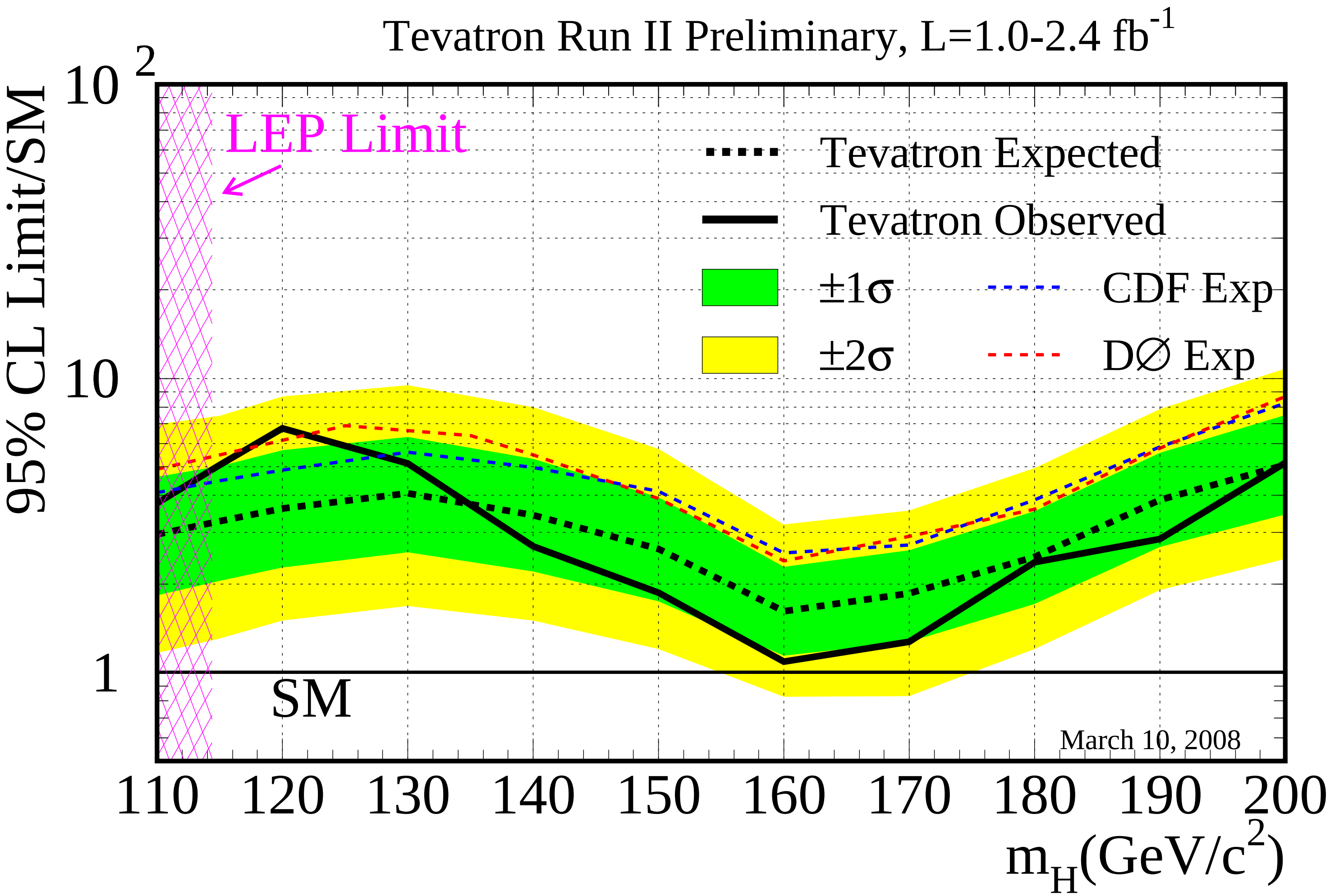
Systematic uncertainties need to be constrained in sidebands

$\longrightarrow$ very complicated procedure...

– used several techniques (Bayesian, mod. frequentist) and 4 independent programs to cross-check calculations

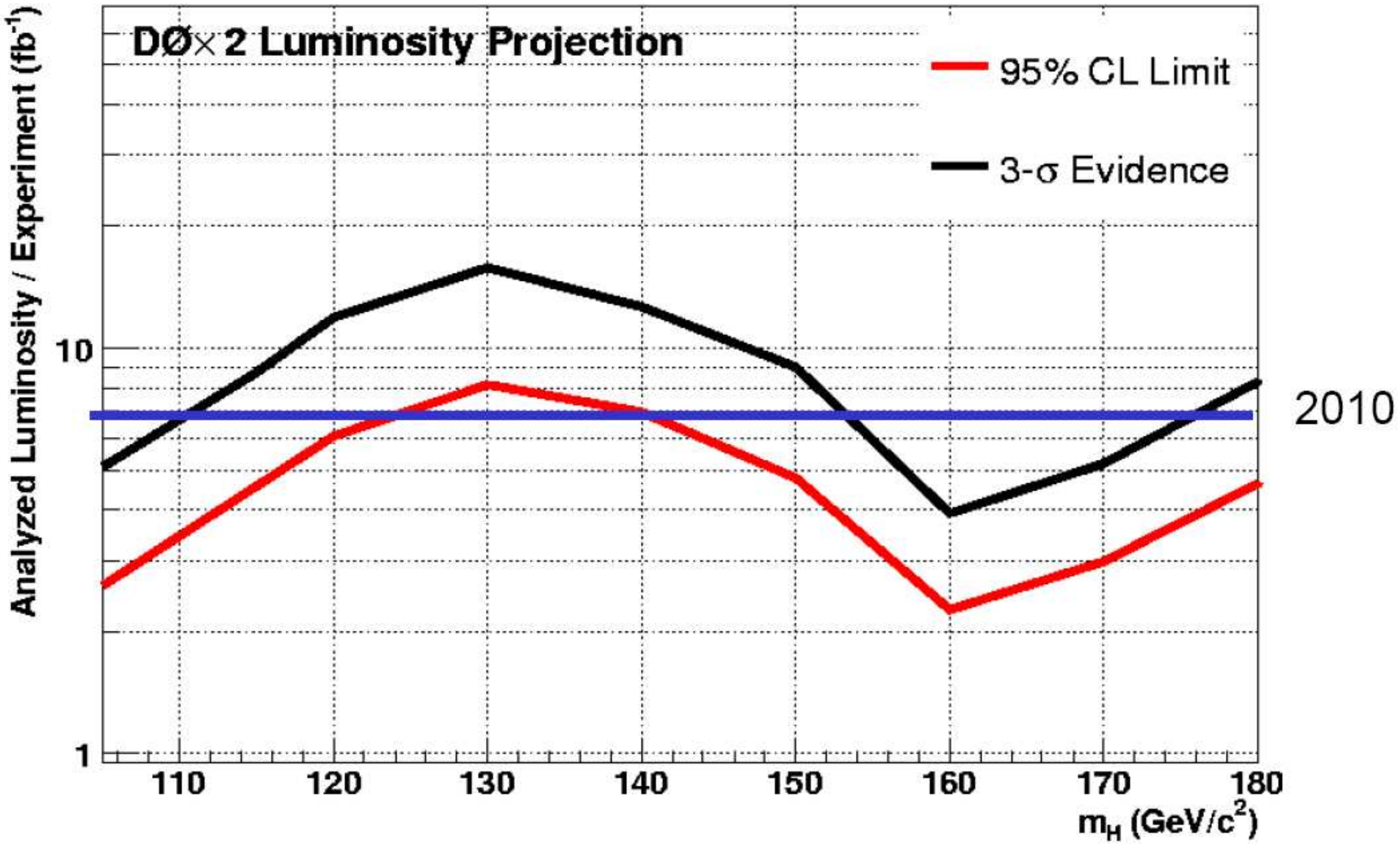
$\longrightarrow$ results agree within 10%

Tevatron Full Combination



- Sensitivity improvement still scaling faster than luminosity
- Exciting times are ahead!

Tevatron Full Combination



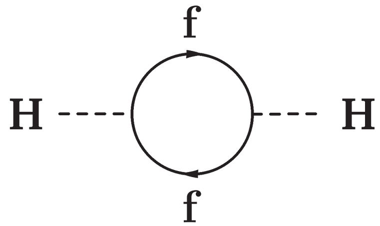
- Sensitivity improvement still scaling faster than luminosity
- Exciting times are ahead!

Beyond the Standard Model

Strong hint for new physics: The hierarchy problem

– fermion loop corrections to Higgs mass are divergent

$\longrightarrow$ Higgs mass should be of the order of the cutoff scale Λ (e.g. M_{Planck})



$$\Delta M_H^2 = N_f \frac{\lambda_f^2}{8\pi^2}\left[- \Lambda^2 + 6 m_f^2 \log\frac{\Lambda}{m_f} - 2 m_f^2 \right] + \mathcal{O}(1/\Lambda^2)$$

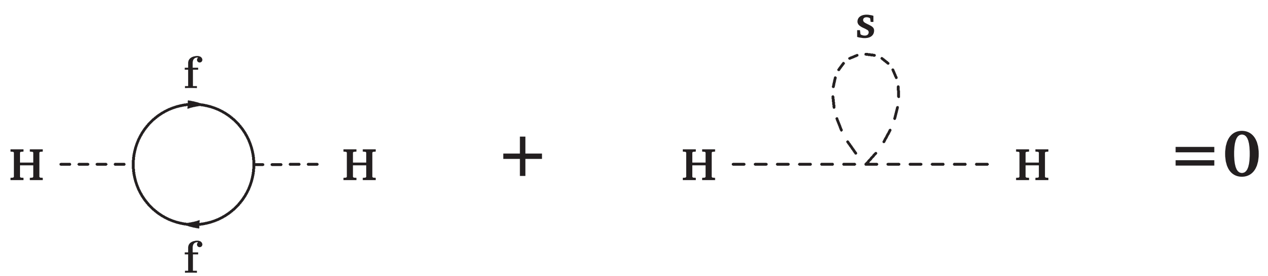
– in contradiction to indirect evidence for a light SM Higgs boson

$\longrightarrow$ there must be something beyond the SM that modifies these corrections

Two main options:

1. New physics at O(1 TeV) $\longrightarrow$ loop corrections stay “reasonably” small
2. New symmetry that suppresses loop corrections

   Most straightforward way: cancel fermion loops with boson loops



Cancellation exact for equal couplings and mass

Supersymmetry

The idea: particle physics is symmetric under transformation fermion $\leftrightarrow$ boson

$\rightarrow$ implies one supersymmetric partner for each SM particle

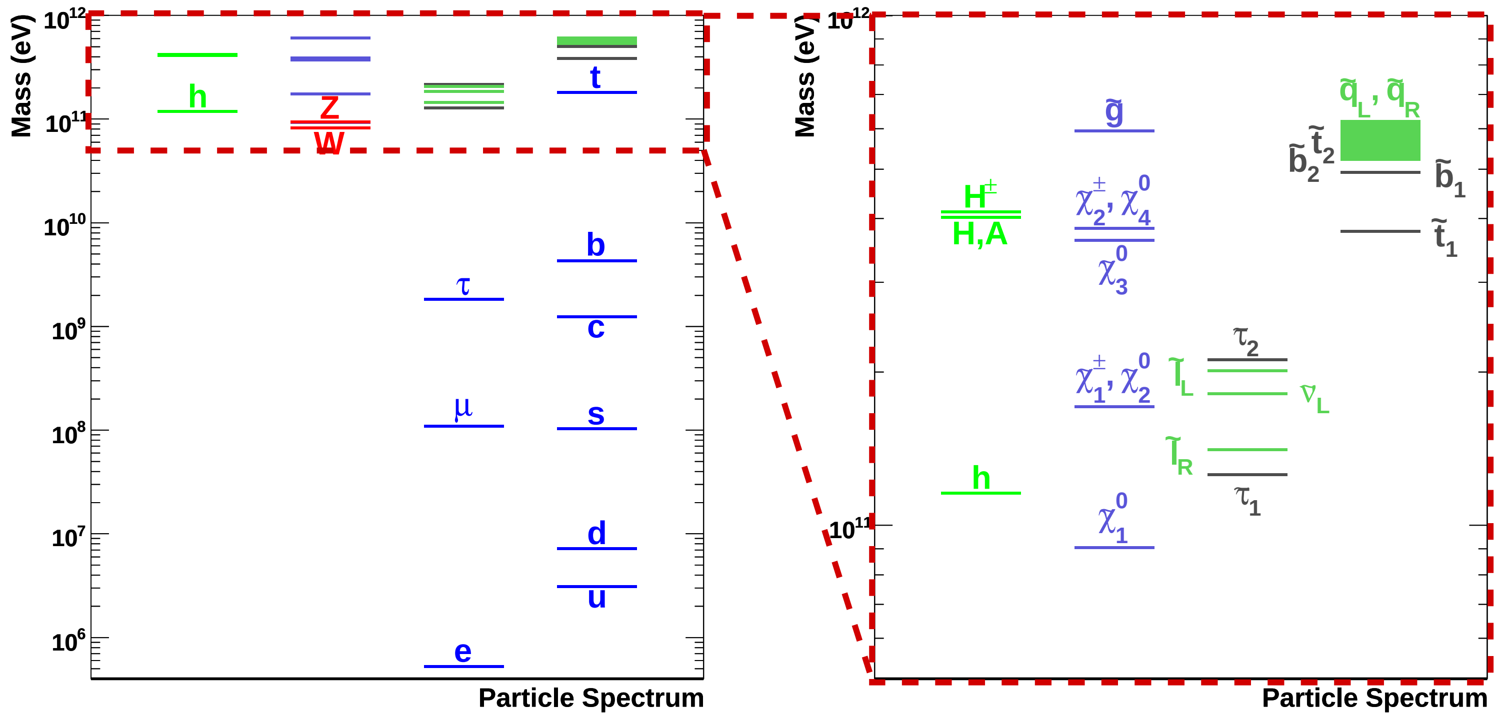
Superpartners are heavy $\rightarrow$ SUSY must be broken

- Details of SUSY breaking mechanism unknown

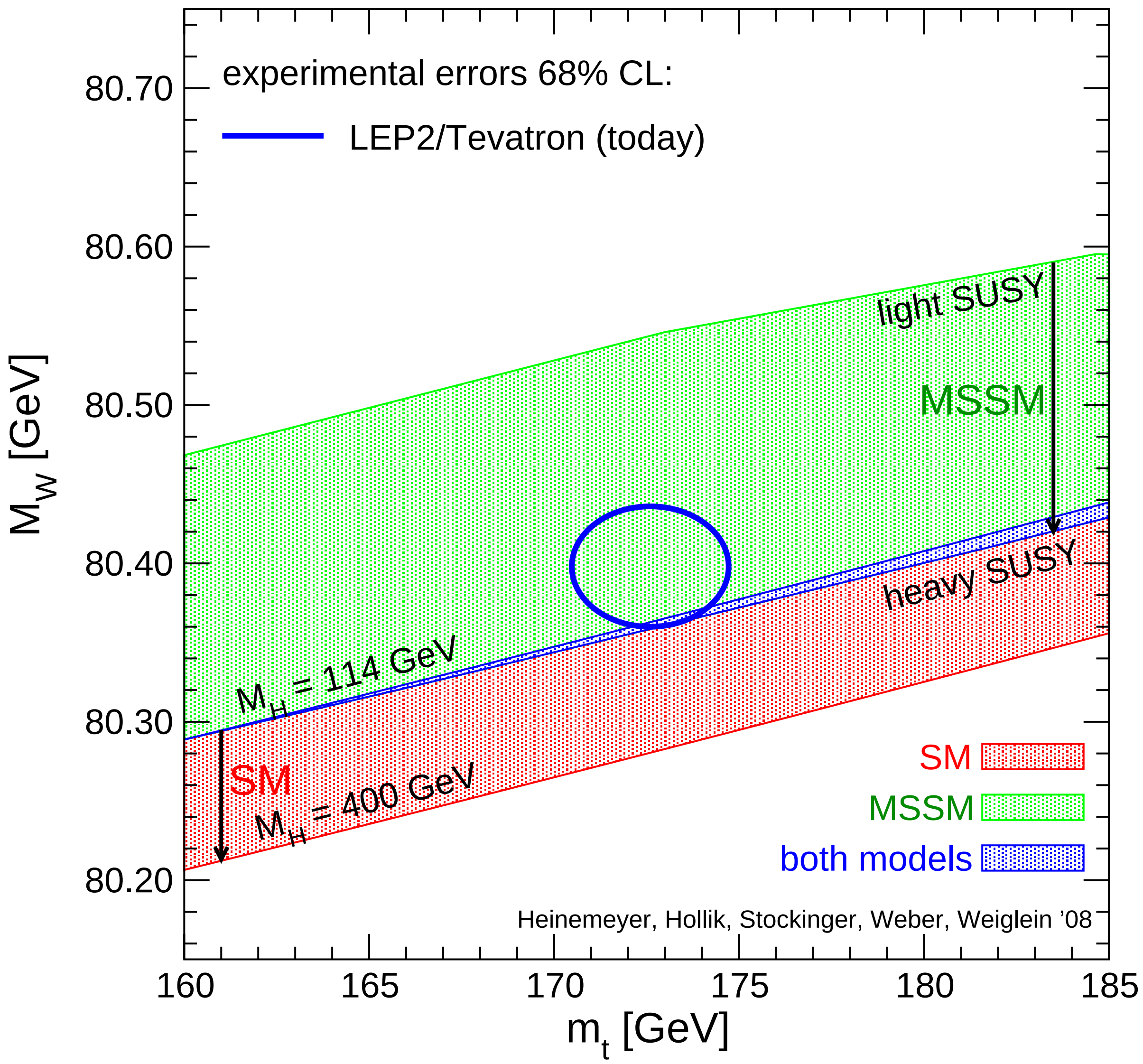
$\rightarrow$ need to consider several models: gravity-, gauge-, anomaly-mediated breaking

Predictions:

- Many new SUSY particles: Charginos/Neutralinos/Gluinos, Squarks, Sleptons
- Extended Higgs sector: 5 physical Higgs bosons h,H,A,$H^{\pm}$



M_W vs. m_t for SM vs. MSSM

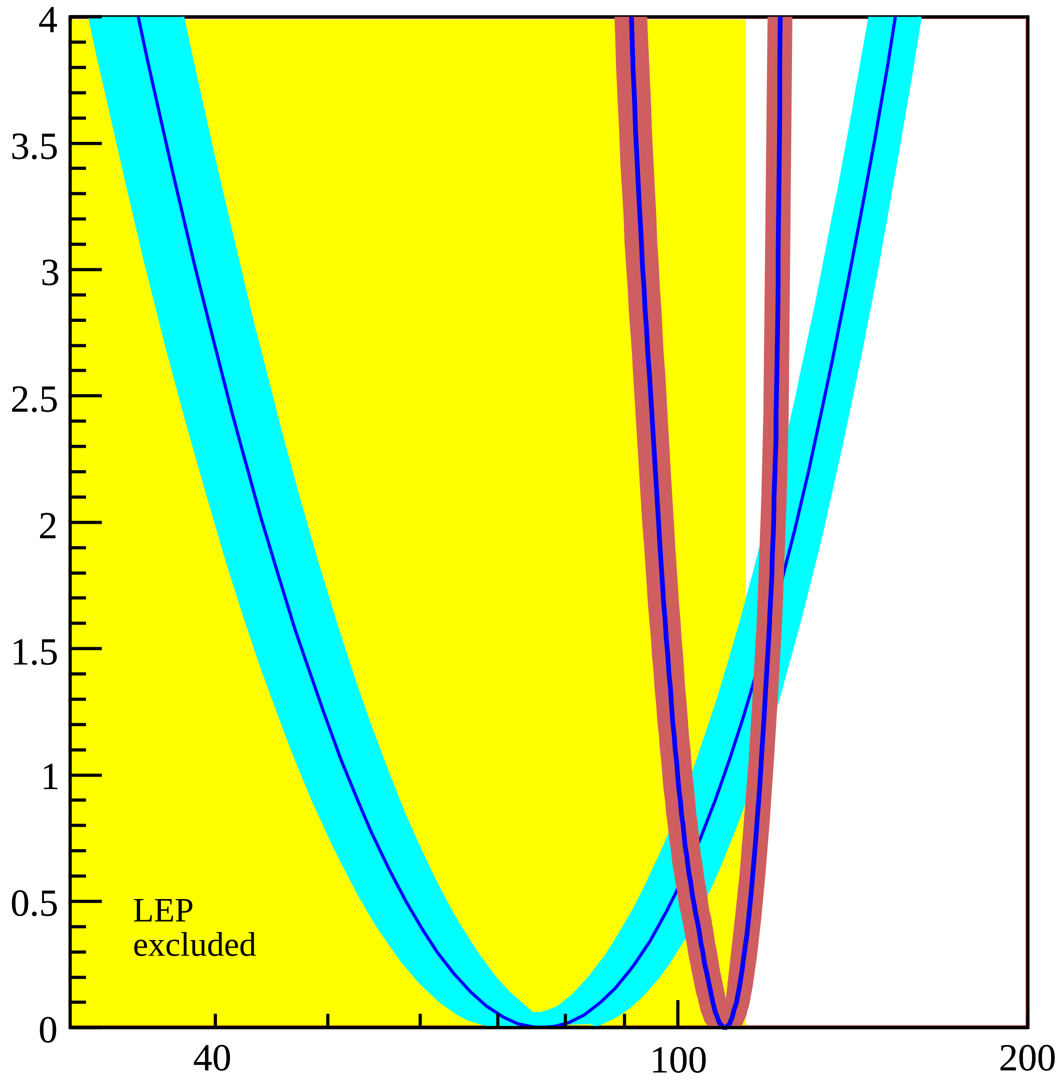


– **Supersymmetric theories predict additional particles that modify loop corrections**

– **Lightest MSSM Higgs boson: $m_h \lesssim 135$ GeV**

Blue Band Plot for SM vs. MSSM

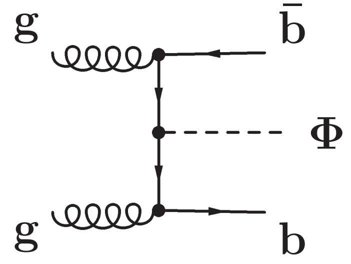
O. Buchmueller et al., arXiv:0707.3447



Adding constraints from CDM, b$\longrightarrow$sγ etc. allows prediction of m$_h$ in MSSM:

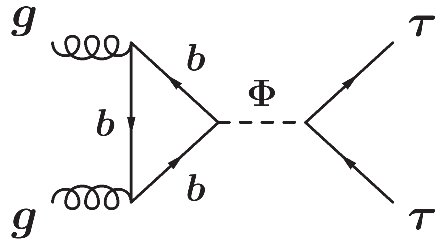
$$m_h = 110\ ^{+8}_{-10}\ (\text{exp})\ \pm 3\ (\text{theo})\ \text{GeV}$$

Search for SUSY Higgs



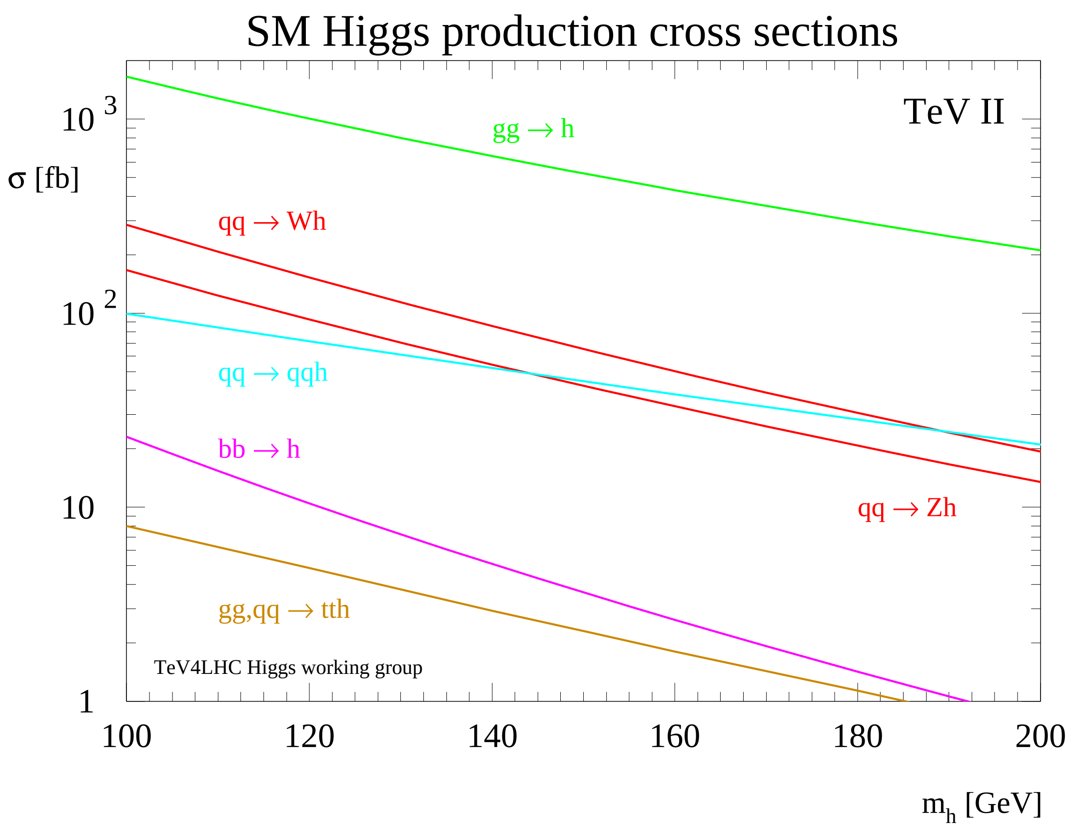
Important: Higgs-$b\bar{b}$-coupling depends on $\tan\beta$

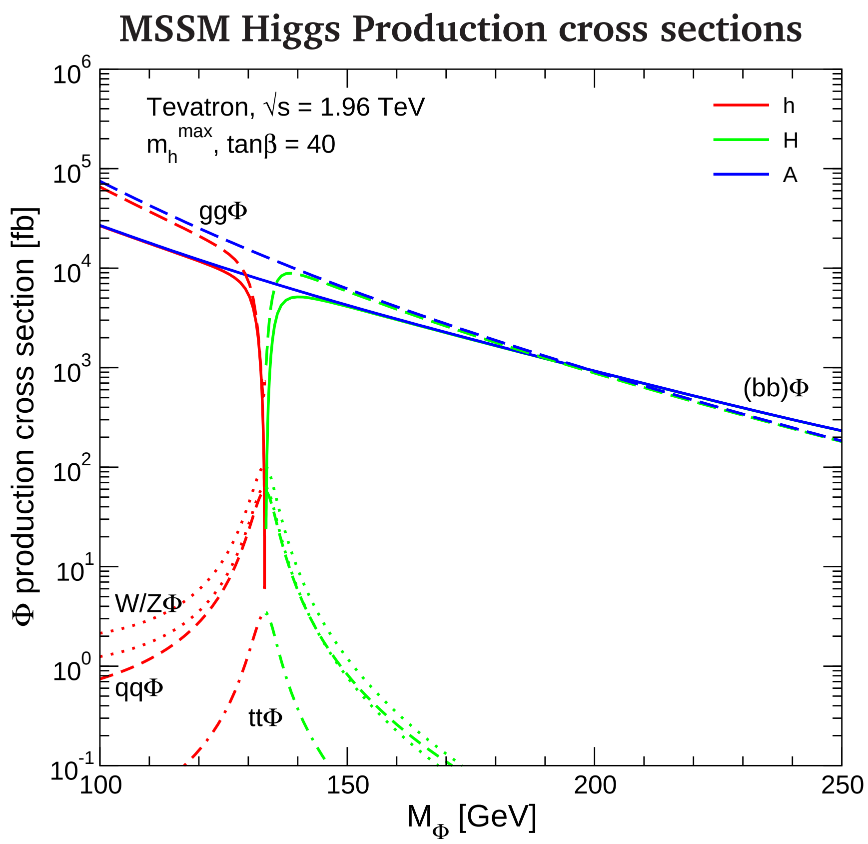
$\longrightarrow$ **large cross-sections for Higgs production at high $\tan\beta$**



Additional search channels at high $\tan\beta$:

- **associated production with bb: bbΦ with Φ $\longrightarrow$bb,$\tau\tau$**
- **enhanced gluon fusion cross-section: gg$\longrightarrow$ Φ $\longrightarrow$ $\tau\tau$**





Search for SUSY Higgs: $\Phi \rightarrow \tau\tau$

Mode	Fraction (%)	Comments
$\tau_e\tau_e$	3	Large DY BGND
$\tau_\mu\tau_\mu$	3	Large DY BGND
$\tau_e\tau_\mu$	6	Small QCD BGND
$\tau_e\tau_h$	23	Golden
$\tau_\mu\tau_h$	23	Golden
$\tau_h\tau_h$	41	Large QCD BGND

Selections:

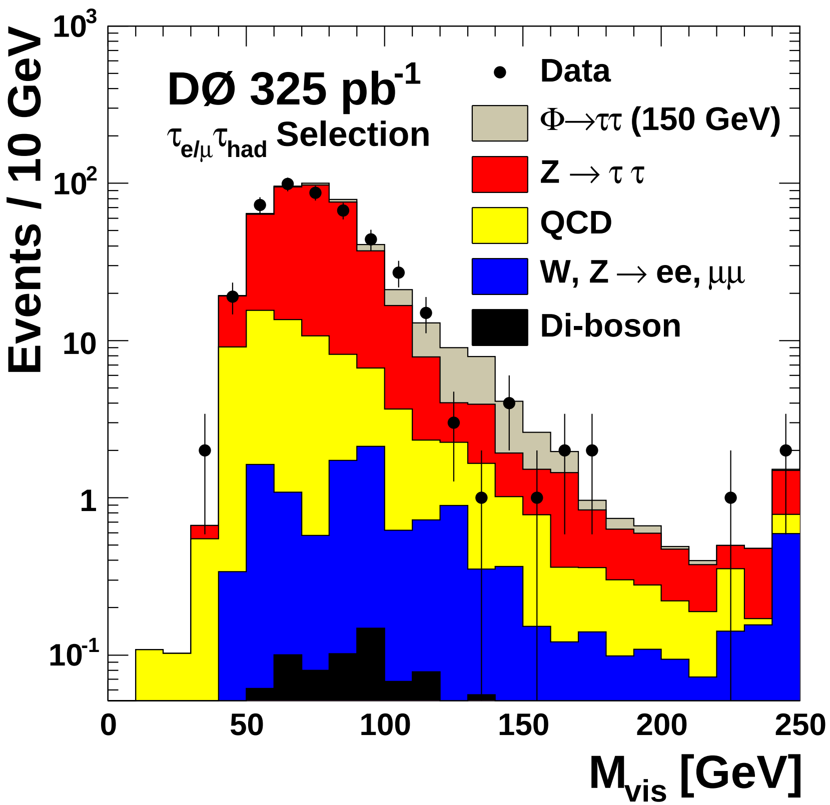
A) two isolated taus with one leptonic tau decay

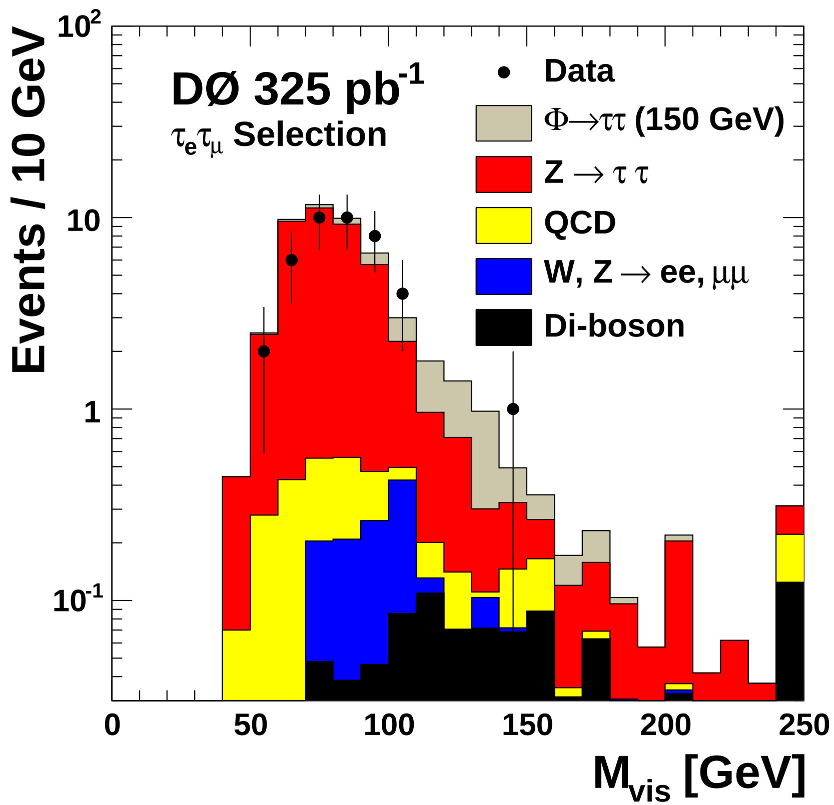
B) isolated electron and muon

– Irreducible background from $Z \rightarrow \tau^+\tau^-$

– Reconstruction of effective mass from visible tau decay products and $\not{E}_T$

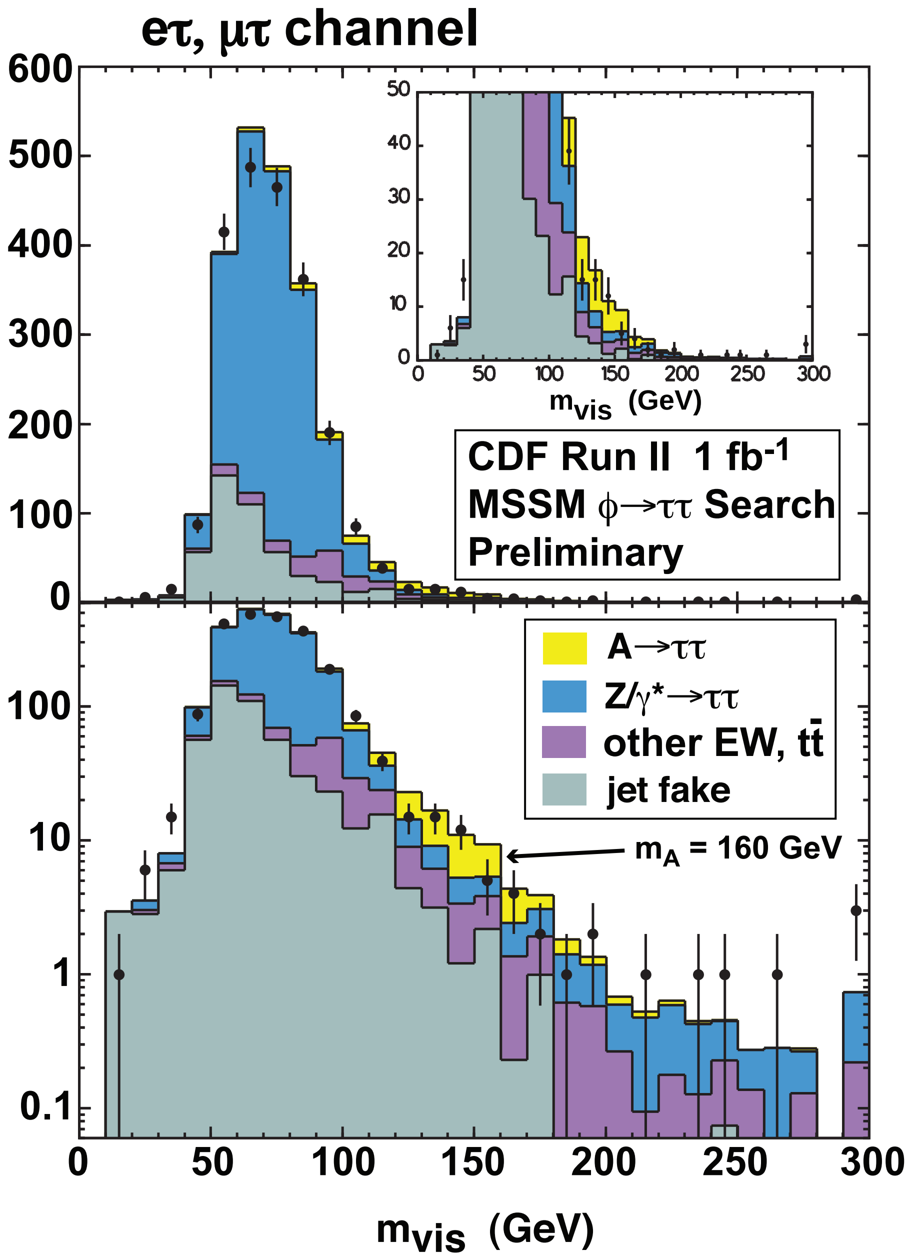
Summer 2006

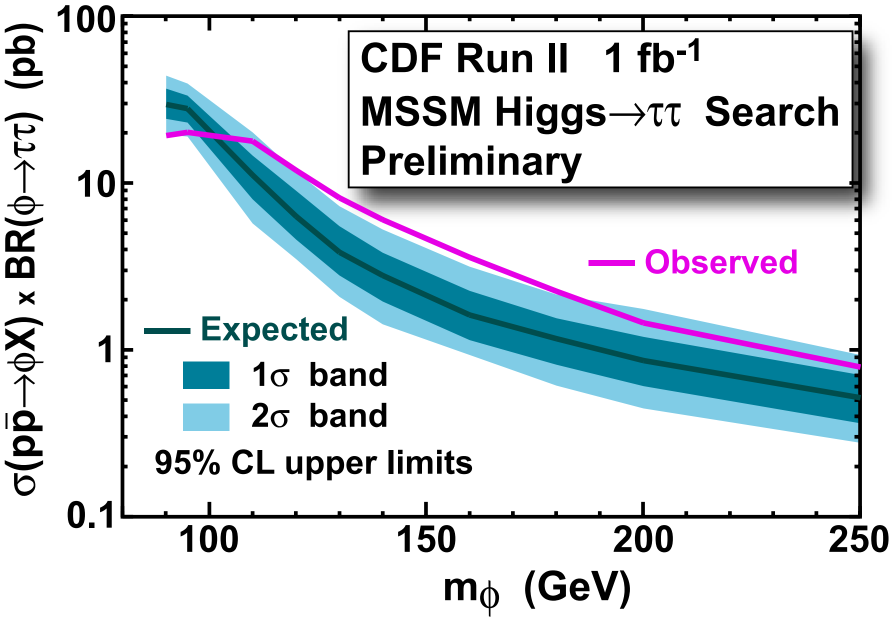




Search for SUSY Higgs: $\Phi \to \tau\tau$

January 2007: new CDF results with 1 fb^{-1}

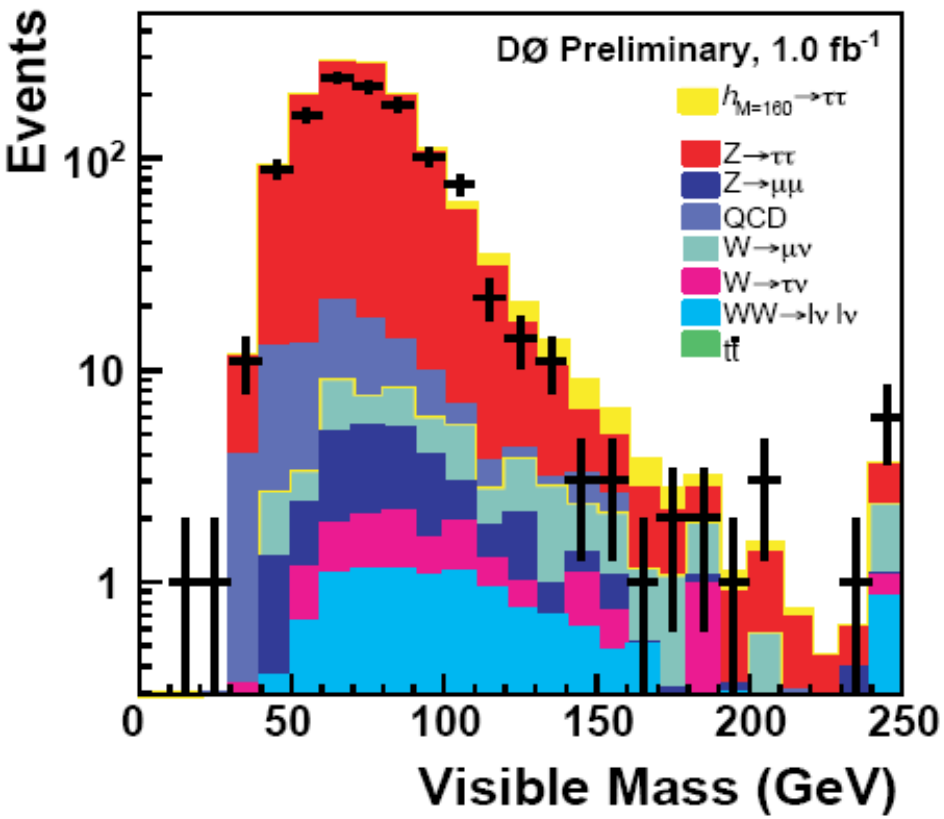


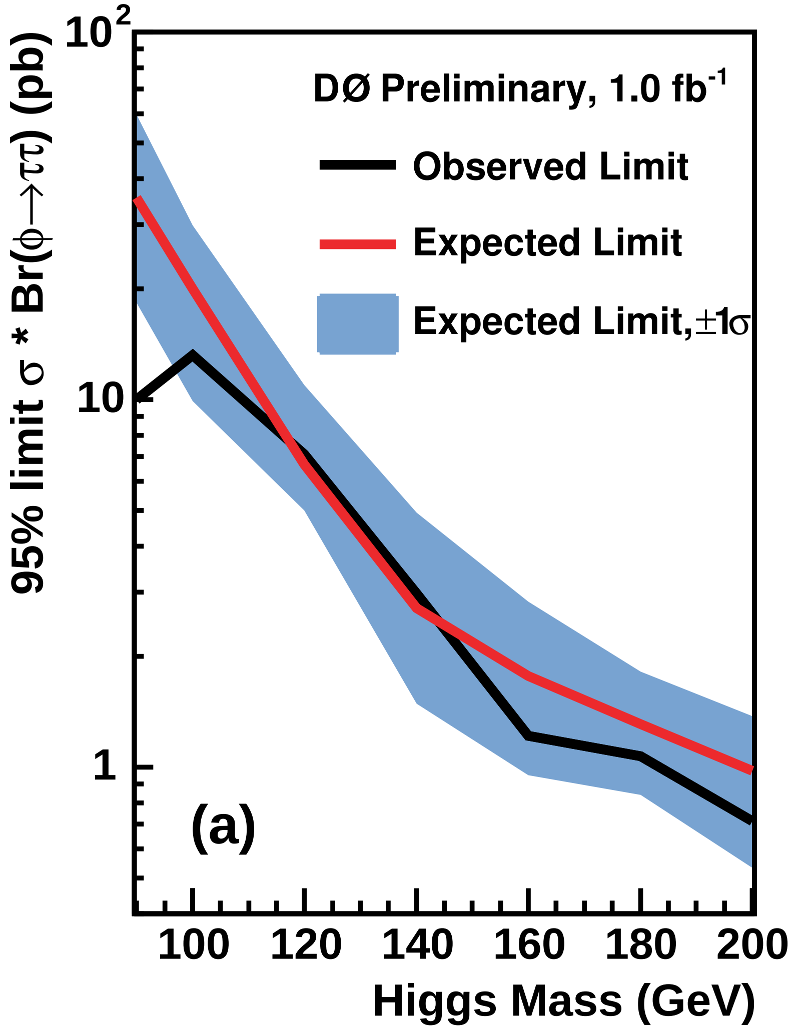


- 2σ excess at $m_A \approx$150 GeV
- would correspond to tan$\beta\approx$50
- confirmed by DØ?

Search for SUSY Higgs: $\Phi \rightarrow \tau\tau$

February 2007: new DØ results with 1 fb^{-1}

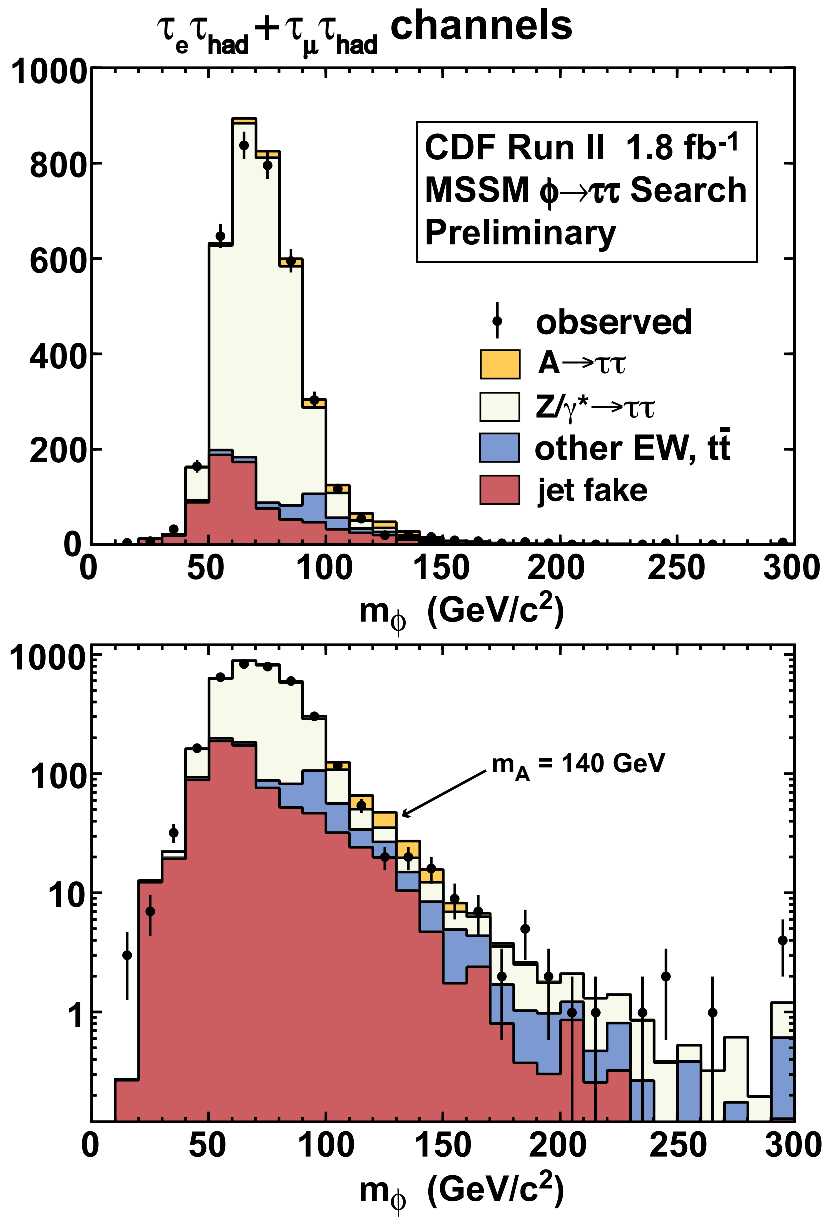


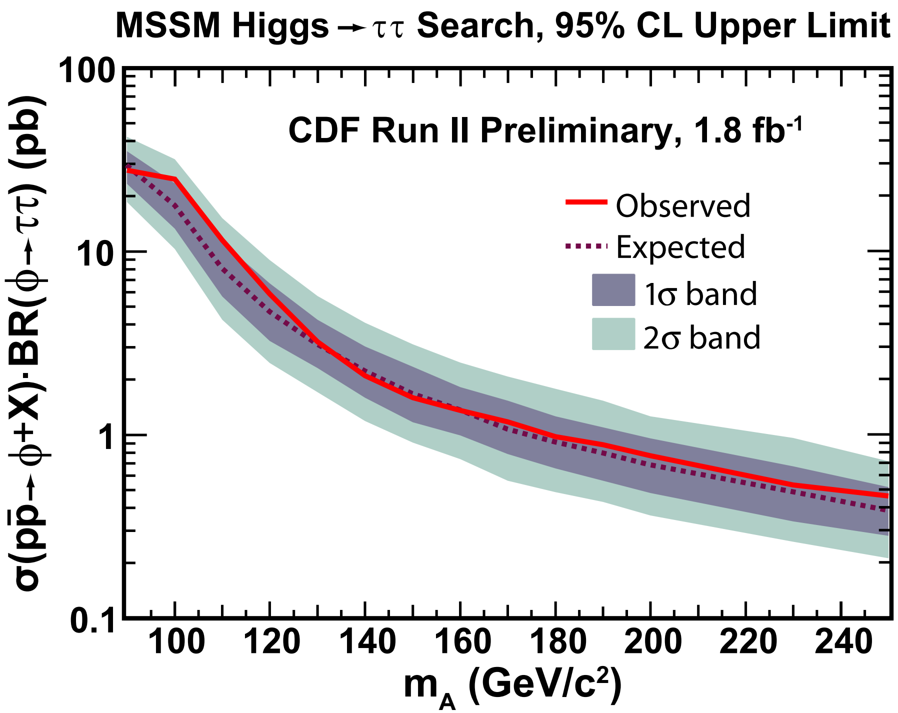


→ unfortunately no confirmation of signal

Search for SUSY Higgs: $\Phi \to \tau\tau$

October 2007: new CDF results with 1.8 fb^{-1}



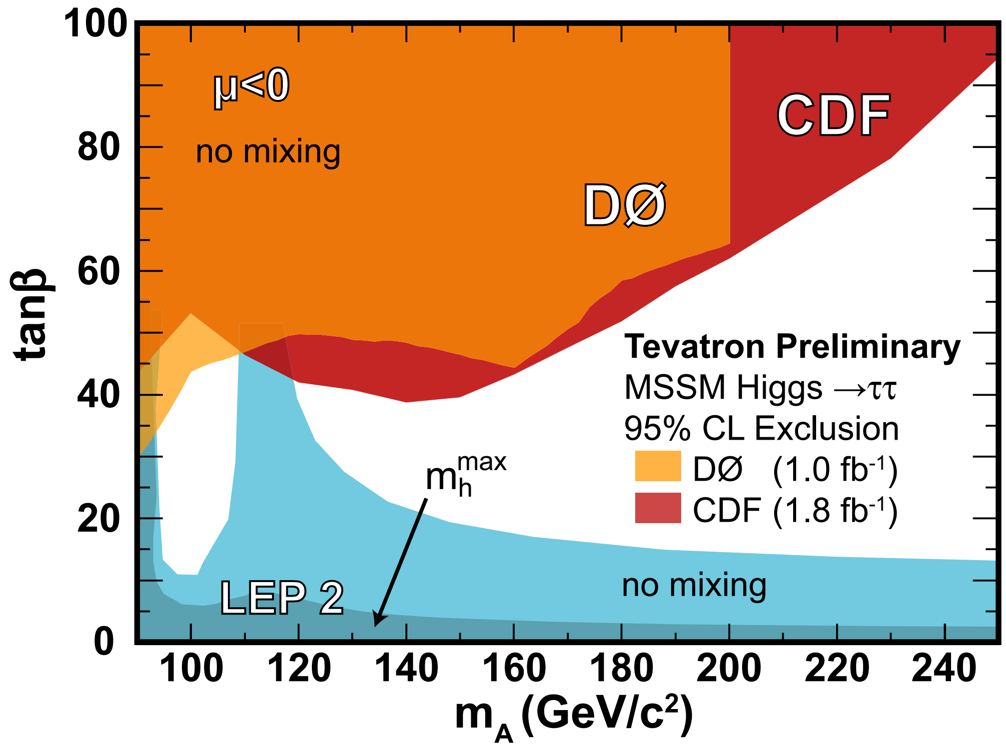


– Excess is gone

Search for SUSY Higgs: $\Phi \rightarrow \tau\tau$

Interpretation within MSSM: limits on tanβ as a function of m_A

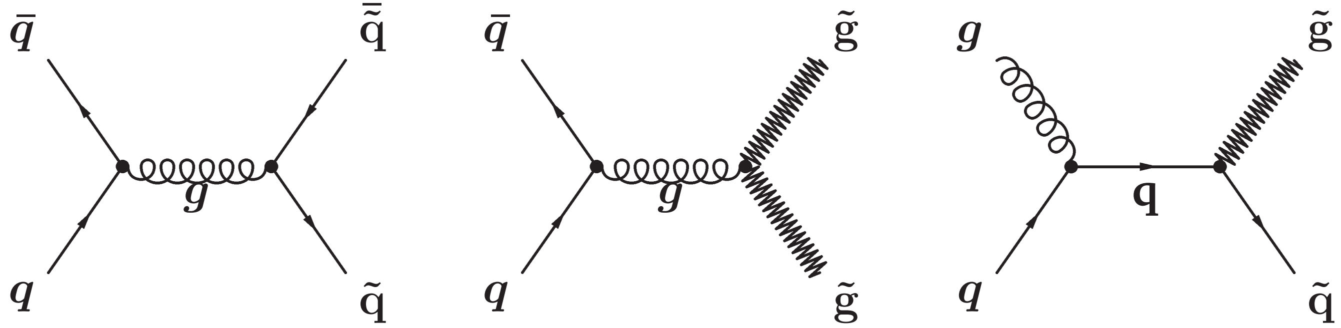
- based on DØ 1 fb^{-1} $\mu\tau_h$, CDF 1.8 fb^{-1} $\mu\tau_h$, $e\tau_h$, $e\mu$
- limits from bbh channels currently not competitive
- no Tevatron combination yet
- benchmark scenarios: no-mixing and mhmax



Expect to reach sensitivity to tan$\beta\approx$20 with full Run II dataset

In addition: expect to probe large m_A with WH/ZH channels

Search for Supersymmetry – Squarks/Gluinos



- **Squarks/Gluinos produced via strong interaction**

  $\longrightarrow$ **large cross sections at hadron colliders**

- **Decays: jets + LSP**
  - **LSP assumed to be stable ($\not\!R_p$ conserved)**

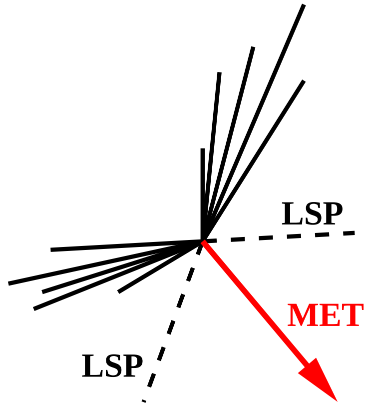
  $\longrightarrow$ **Signature: jets + $\not\!\!E_T$**

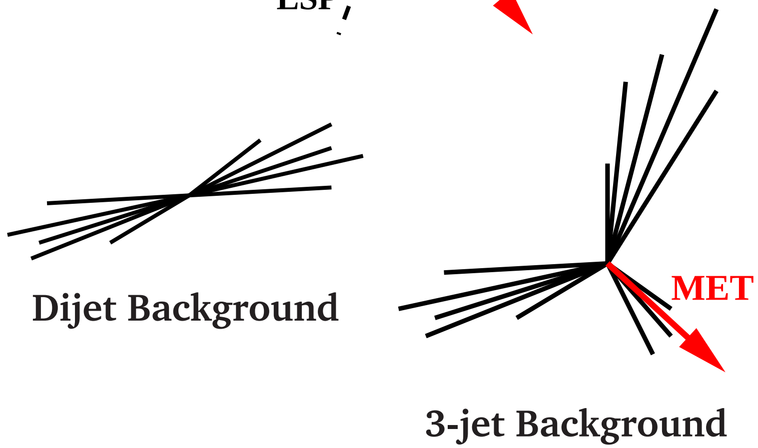
- **Data collected with dedicated triggers:**

  acoplanar jets + $\not\!\!E_T$

Mass region	Main Channel	Signature
$m_{\tilde{q}} < m_{\tilde{g}}$	$\tilde{q}\tilde{q}$	2j + $\not\!\!E_T$
$m_{\tilde{q}} > m_{\tilde{g}}$	$\tilde{g}\tilde{g}$	4j + $\not\!\!E_T$
$m_{\tilde{q}} \approx m_{\tilde{g}}$	$\tilde{q}\tilde{q}$,$\tilde{q}\tilde{g}$	3j + $\not\!\!E_T$

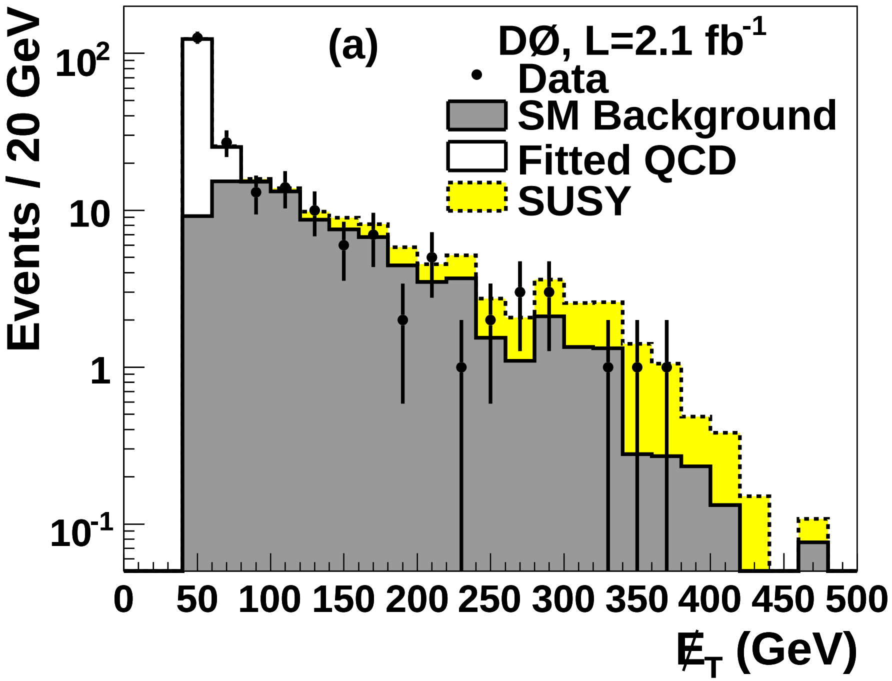
$\tilde{q}\tilde{q} \longrightarrow qq + \not\!\!E_T$



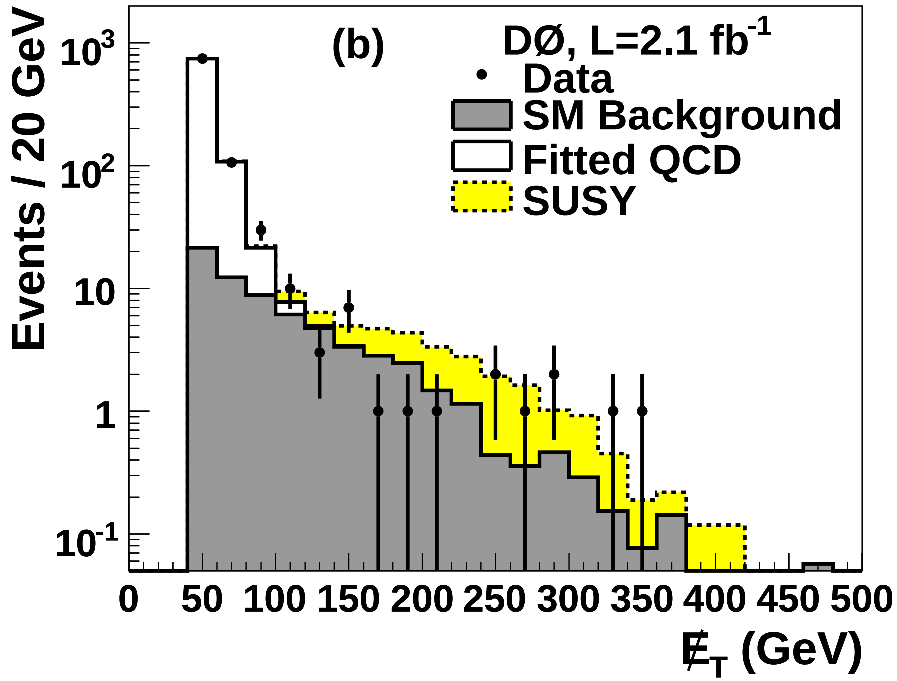


Search for Supersymmetry – Squarks/Gluinos

2j+$\not\!\!E_T$ analysis

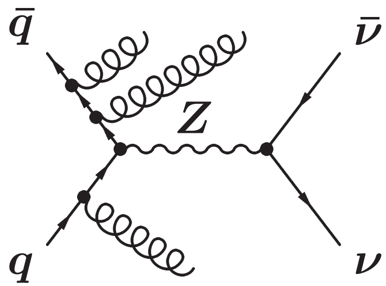


3j+$\not\!\!E_T$ analysis



Main backgrounds:

- Multijets with fake $\not\!\!E_T$
- W+jets with W$\rightarrow e\nu, \mu\nu, \tau\nu$
- Z+jets with Z$\rightarrow \nu\bar{\nu}$

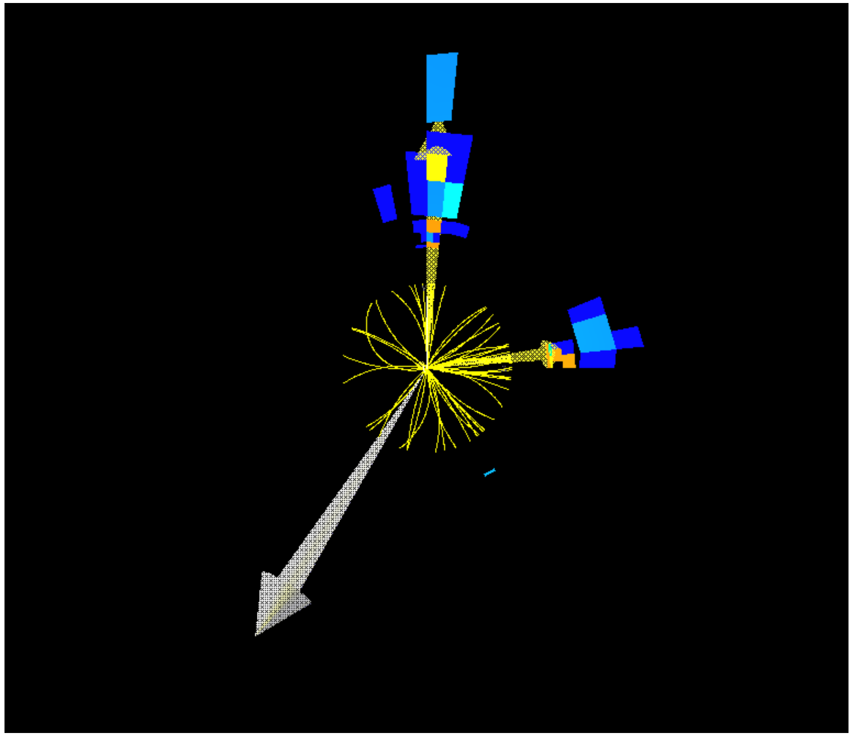


Main selection cuts:

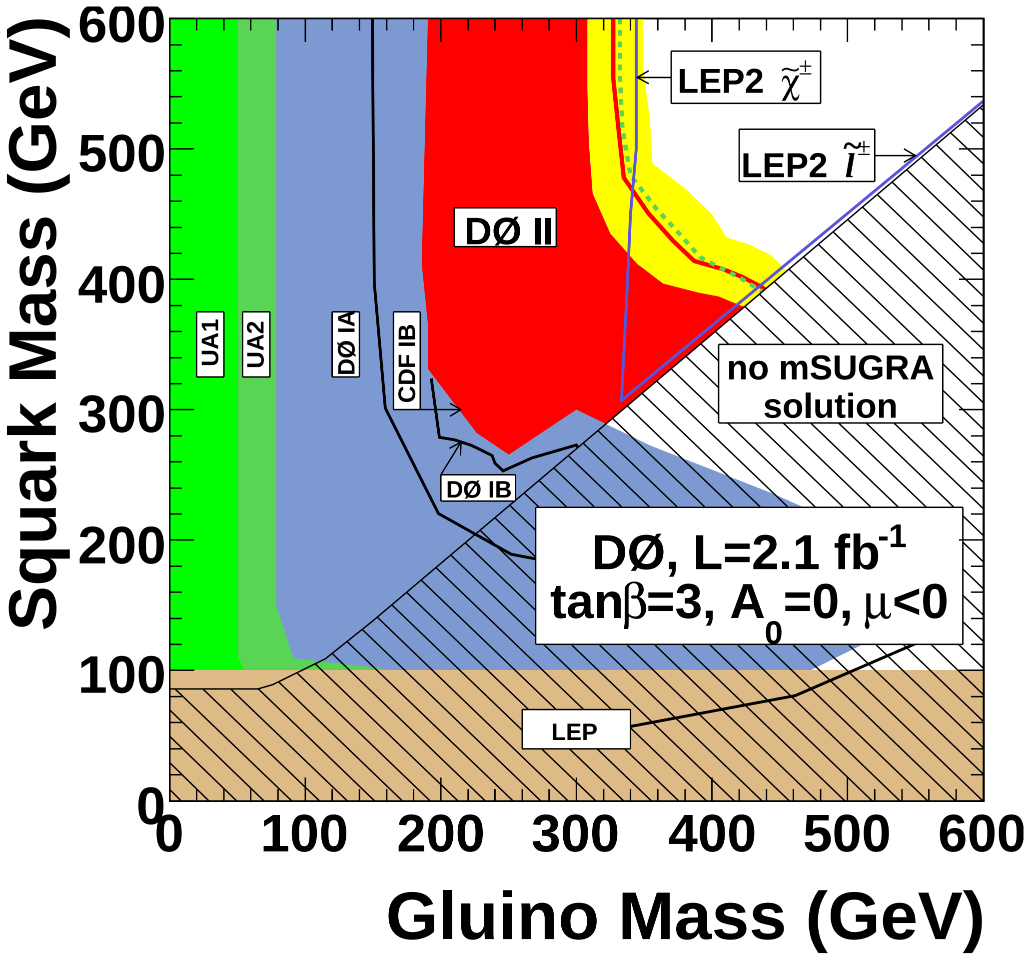
- 2/3/4 jets and large $\not\!\!E_T$
- angular separation $\not\!\!E_T$, jets
- isolated lepton veto

Mass region	Main Channel	Signature	$\not\!\!E_T$	$H_T = \sum p_T^{jet}$	Exp. Bckgd.	Data
$m_{\tilde{q}} < m_{\tilde{g}}$	$\tilde{q}\tilde{q}$	2j + $\not\!\!E_T$	>225 GeV	>325 GeV	11±3	11
$m_{\tilde{q}} > m_{\tilde{g}}$	$\tilde{g}\tilde{g}$	4j + $\not\!\!E_T$	>100 GeV	>400 GeV	18±5	20
$m_{\tilde{q}} \approx m_{\tilde{g}}$	$\tilde{q}\tilde{q}$,$\tilde{q}\tilde{g}$	3j + $\not\!\!E_T$	>175 GeV	>375 GeV	11±3	9

Search for Supersymmetry – Squarks/Gluinos



$\tilde{q}\tilde{q}$ candidate event
($\not{E}_T$=368 GeV, p_T^{j1}=282 GeV, p_T^{j2}=174 GeV)

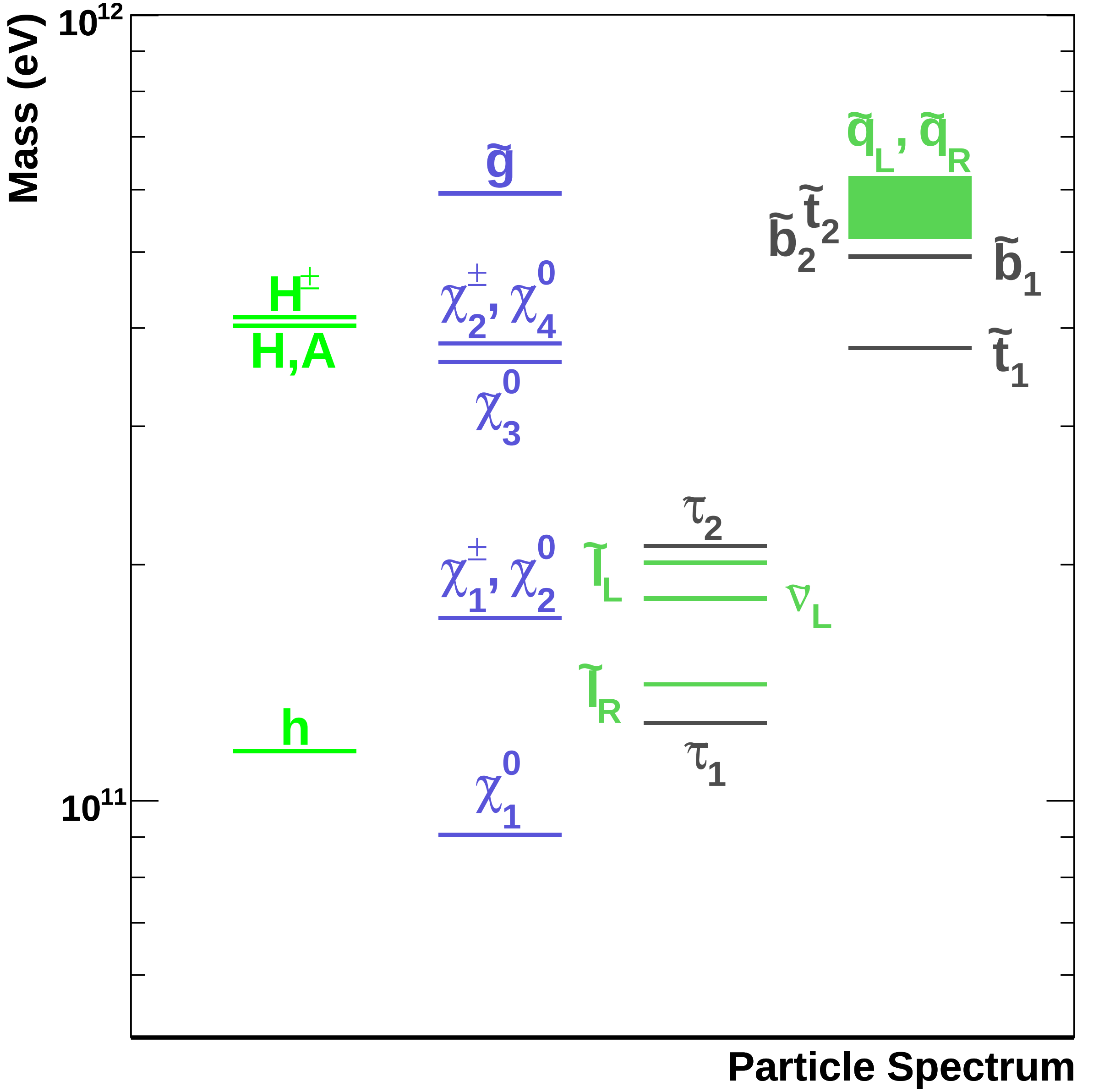


– No evidence for squark/gluino production at the Tevatron

– New limits in squark/gluino mass plane (mSUGRA: tanβ=3, $A_0 = 0$, $\mu < 0$)

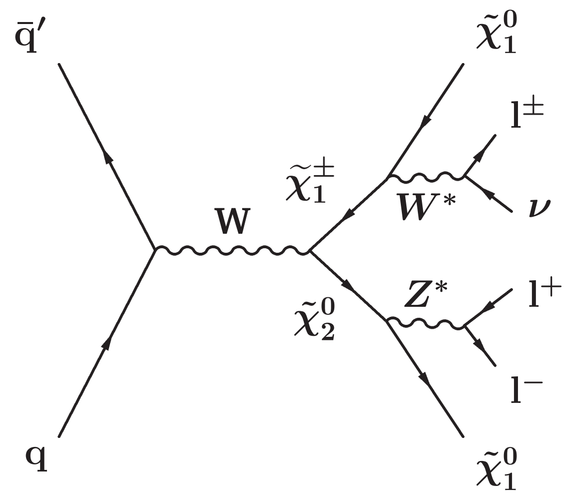
– Sensitivity beyond indirect limits from LEP

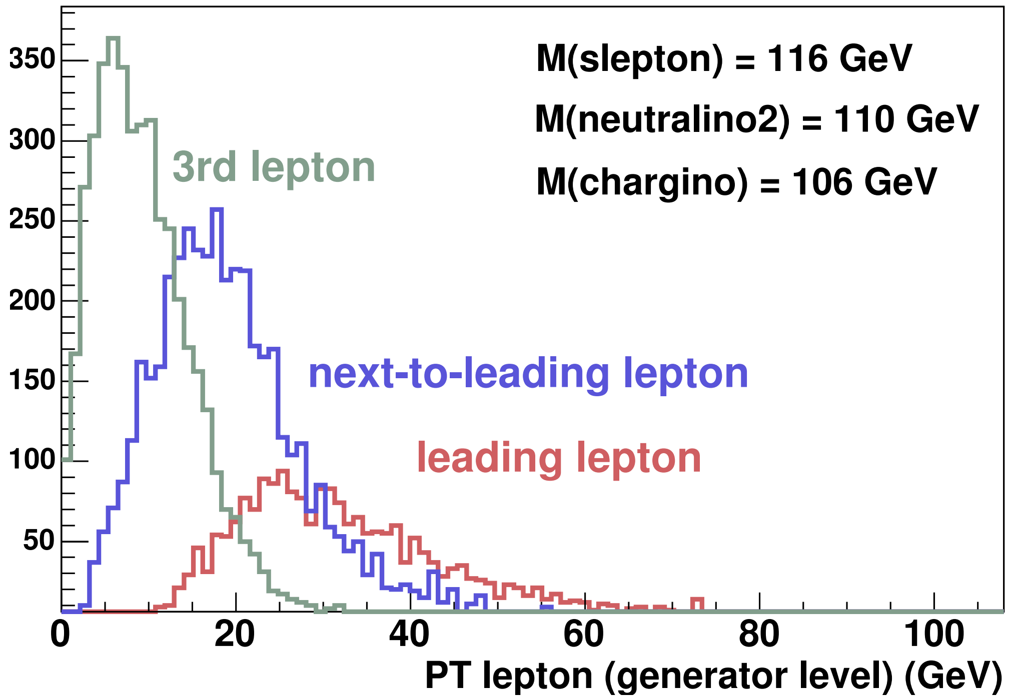
What other particles does SUSY predict?



Search for Charginos and Neutralinos

- Production cross section (electroweak) relatively small
  $\longrightarrow$ need clean leptonic signature to suppress backgrounds
- Golden channel: $\widetilde{\chi}^{\pm}\tilde{\chi}^0_2 \longrightarrow 3\ell + \not{E}_T$
- Experimental Challenge: low-p_T leptons
  $\longrightarrow$ need multilepton triggers with low thresholds
  $\longrightarrow$ need efficient lepton identification at low p_T

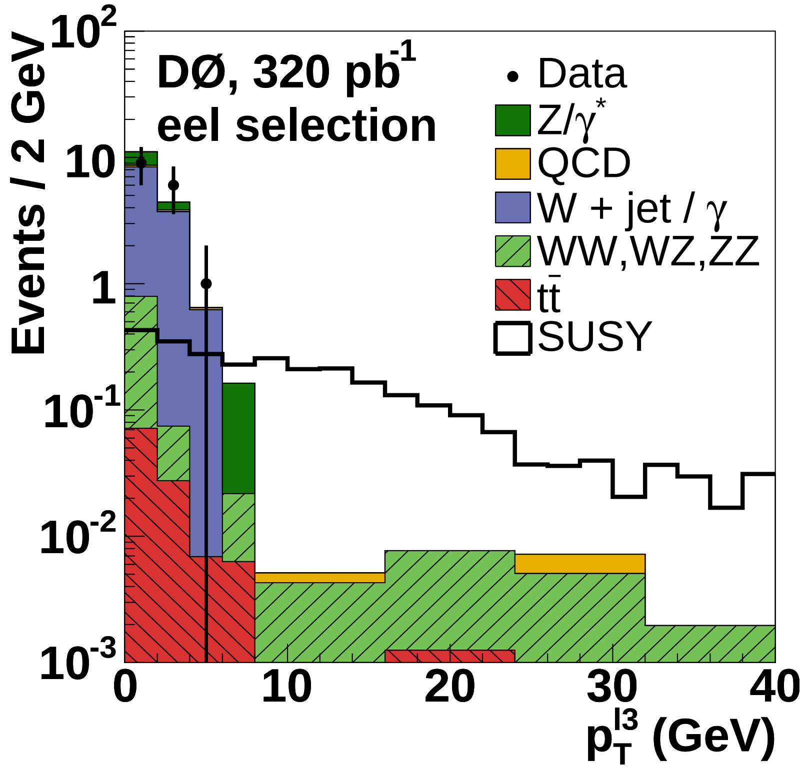




Search for Charginos and Neutralinos

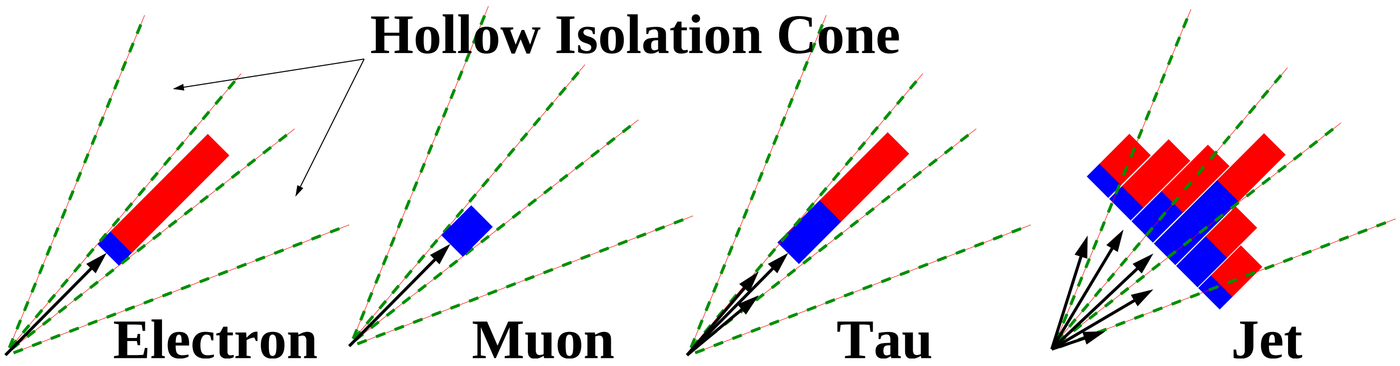
Analysis Strategy:

- two identified leptons plus isolated track
- isolation criteria designed to be efficient for electrons, muons and hadronic τ-decays



Transverse momentum thresholds (DØ):

Selection	$p_T^{\ell 1}$	$p_T^{\ell 2}$	$p_T^{\ell 3}$
$ee\ell$	$>$12 GeV	$>$8 GeV	$>$4 GeV
$e\mu\ell$	$>$12 GeV	$>$8 GeV	$>$5 GeV
$\mu\mu\ell$	$>$12 GeV	$>$8 GeV	$>$4 GeV
ls-$\mu\mu$	$>$11 GeV	$>$5 GeV	–



Search for Charginos and Neutralinos

DØ Results (0.9–1.7 fb^{-1}):

Selection	Expected Background	Observed	Signal ($m_{\tilde{\chi}^\pm}$=110 GeV)
$ee\ell$	1.8±0.7	0	6.8±0.4
$e\mu\ell$	0.9±0.4	0	4.0±0.2
$\mu\mu\ell$	0.3±0.8	2	2.5±0.2
ls-$\mu\mu$	1.1±0.4	1	4.2±0.7
Combined	4.1±1.2	3	17.5±0.8

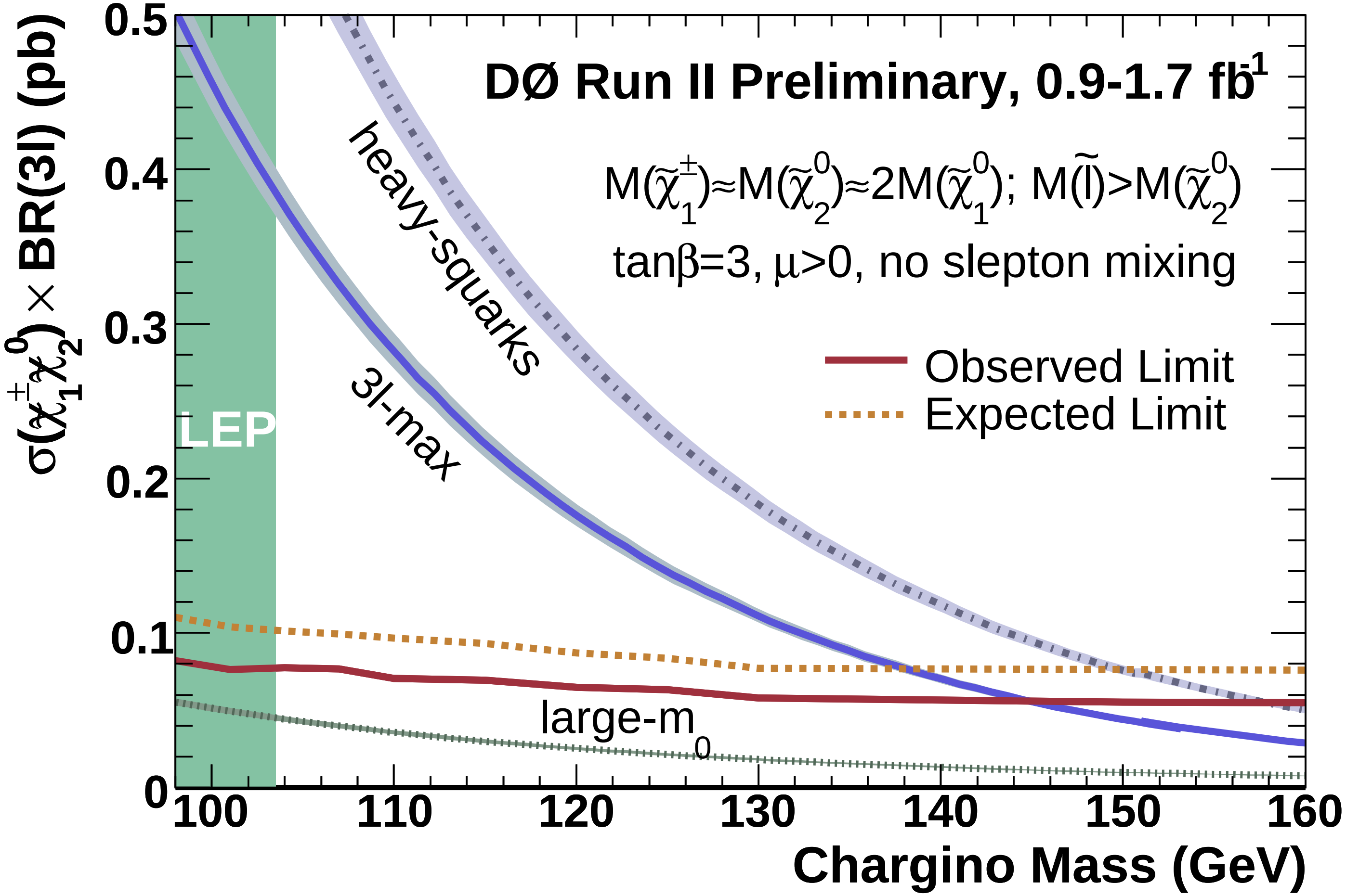
CDF Results (2 fb^{-1}):

(t=tight,l=loose)	3t	2t,1l	1t,2l	2t+trk	1t,1l+trk
Expected Background	0.5±0.1	0.25±0.04	0.14±0.03	3.2±0.7	2.3±0.6
Observed	1	0	0	4	2
Signal ($m_{\tilde{\chi}^\pm}$=120 GeV)	2.3±0.3	1.6±0.2	0.7±0.1	4.4±0.7	2.4±0.4

→ No evidence for chargino/neutralino production

→ Limits on product of cross section and leptonic branching fraction

Search for Charginos and Neutralinos

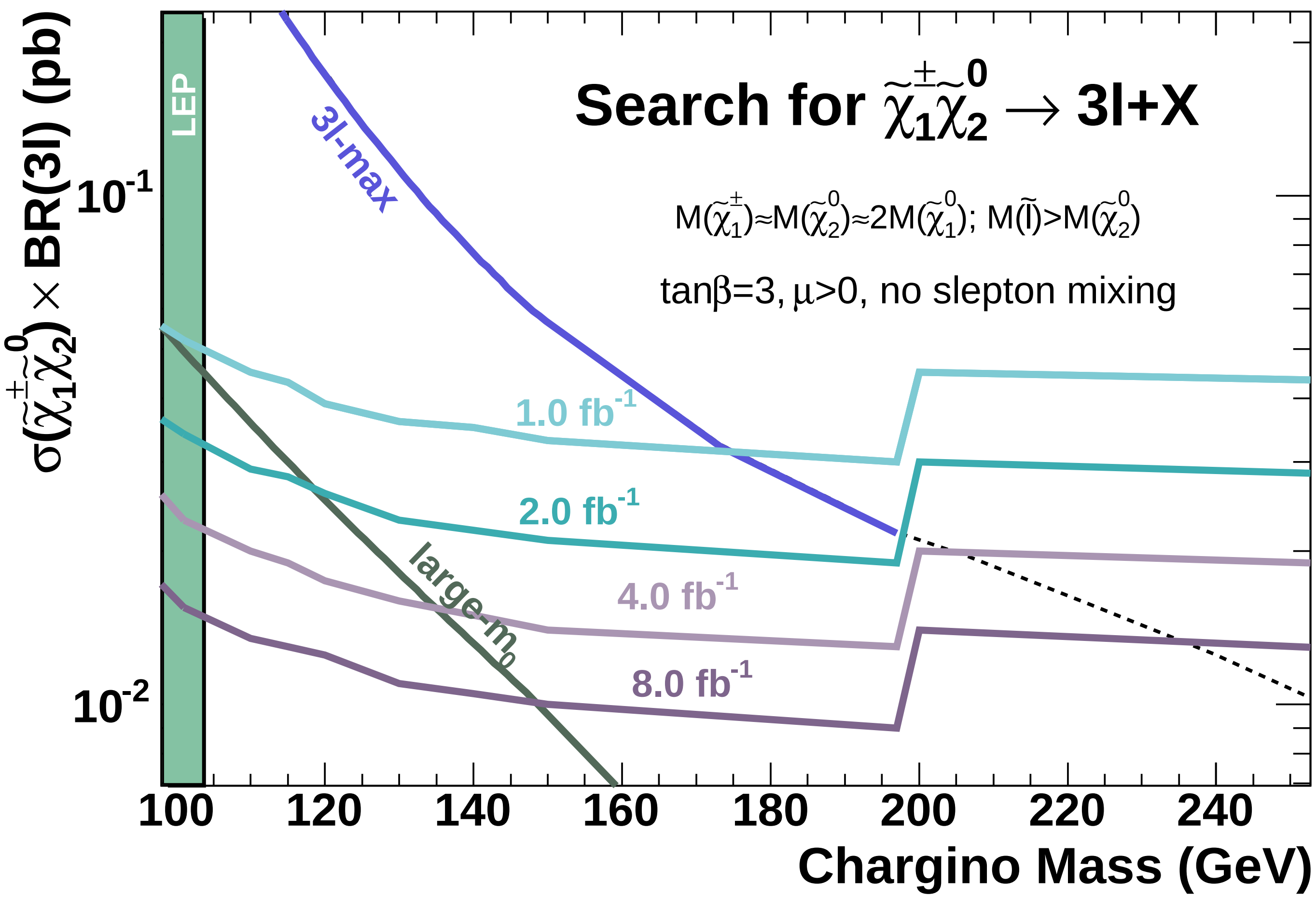


Limits constrain SUSY beyond LEP chargino limits:

– 3ℓ-max scenario: $m_{\tilde{\chi}^\pm} > 145$ GeV

Updates with 3 fb^{-1} datasets currently in progress

Search for Charginos and Neutralinos



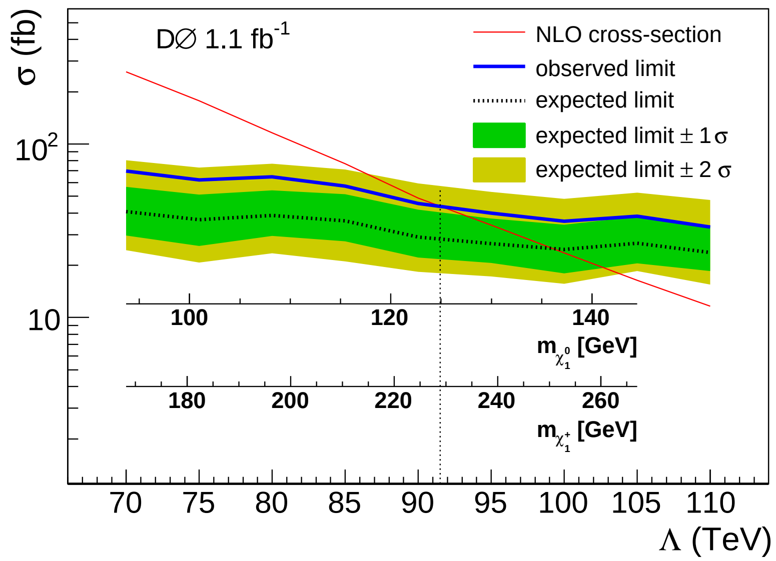
Run II projections (combining CDF and DØ):

- **3ℓ-max scenario: will probe $m_{\tilde{\chi}^{\pm}} > 200$ GeV**
- **large-m_0 scenario: sensitive up to $m_{\tilde{\chi}^{\pm}} \approx 150$ GeV**

Updates with 3 fb^{-1} datasets currently in progress

Beyond mSUGRA

Many other SUSY models on the market → large variety of SUSY searches at the Tevatron

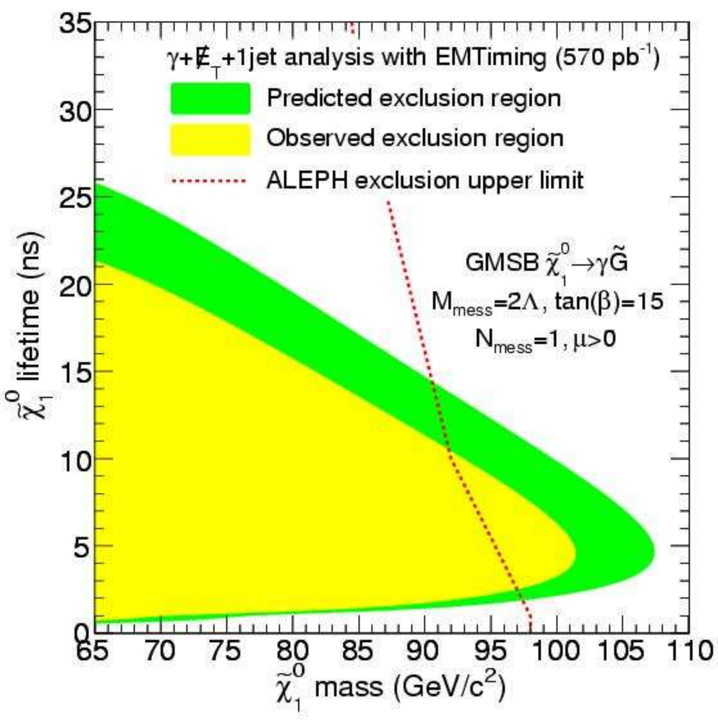


Gauge-Mediated SUSY Breaking

- Inclusive $\gamma\gamma + \not{E}_T$: charginos excluded up to 229 GeV (DØ)
- Long-lived neutralinos: limits up to 101 GeV (CDF)

Anomaly-Mediated SUSY Breaking

- Stable charginos: excluded up to 174 GeV (DØ)



Split Supersymmetry

- Long-lived Gluinos $\tilde{g} \to g\tilde{\chi}_1^0$:

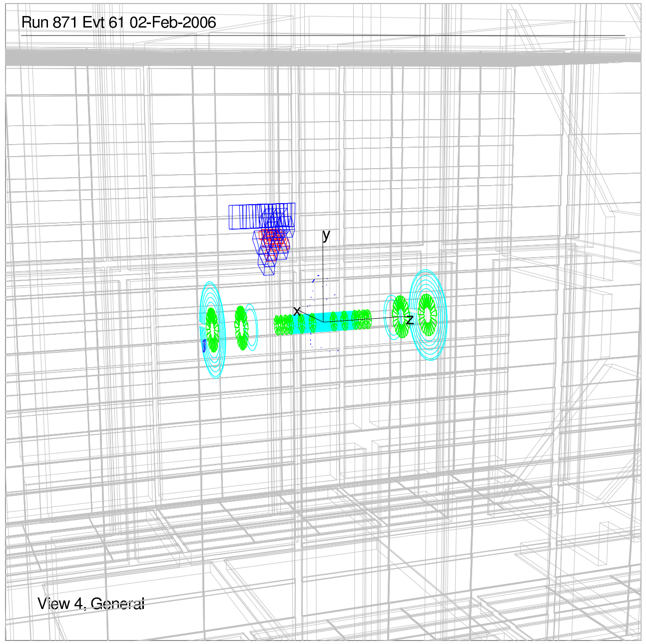
  limits up to 320 GeV for lifetimes up to 100 hours (DØ)

R-Parity Violation

- LLE couplings: limits on charginos up to 234 GeV (DØ)

Beyond mSUGRA

Many other SUSY models on the market $\longrightarrow$ large variety of SUSY searches at the Tevatron



Gauge-Mediated SUSY Breaking

- **Inclusive $\gamma\gamma + \not\!\!E_T$: charginos excluded up to 229 GeV (DØ)**
- **Long-lived neutralinos: limits up to 101 GeV (CDF)**

Anomaly-Mediated SUSY Breaking

- **Stable charginos: excluded up to 174 GeV (DØ)**

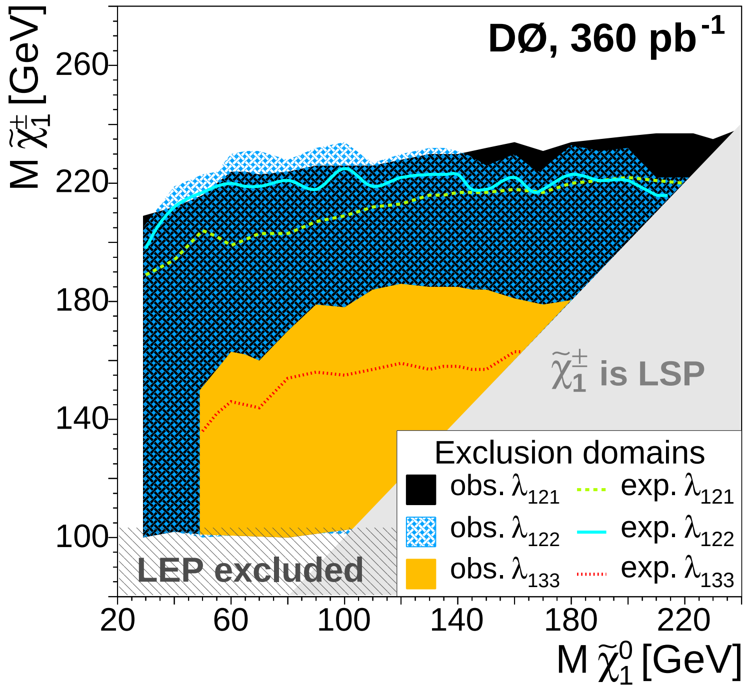
Split Supersymmetry

- **Long-lived Gluinos $\tilde{g} \longrightarrow g\tilde{\chi}_1^0$:**

  limits up to 320 GeV for lifetimes up to 100 hours (DØ)

R-Parity Violation

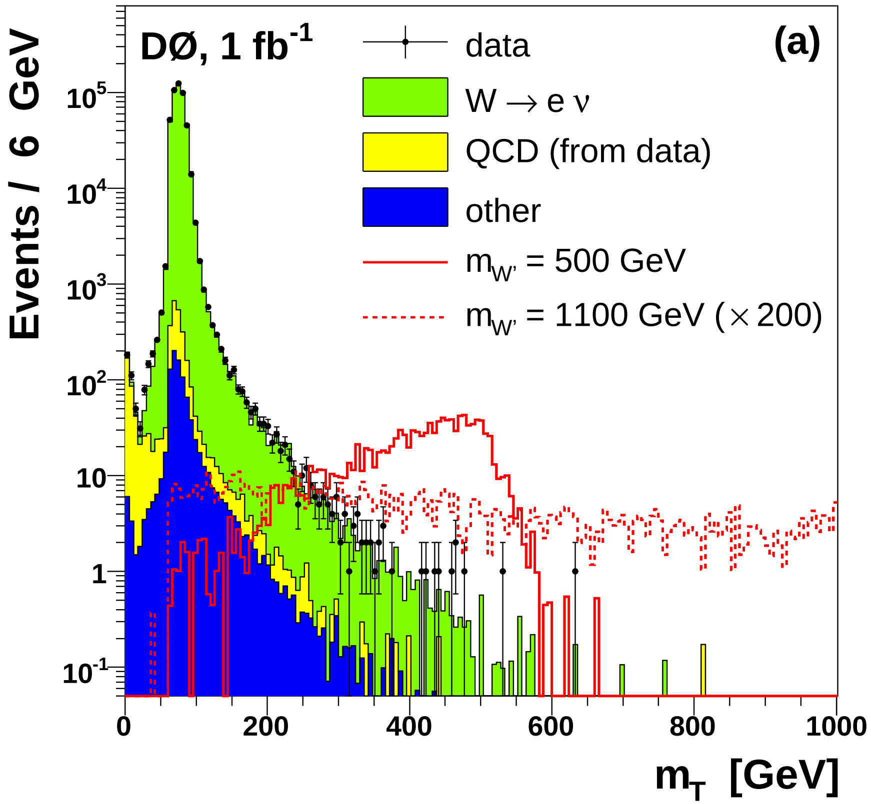
- **LLE couplings: limits on charginos up to 234 GeV (DØ)**



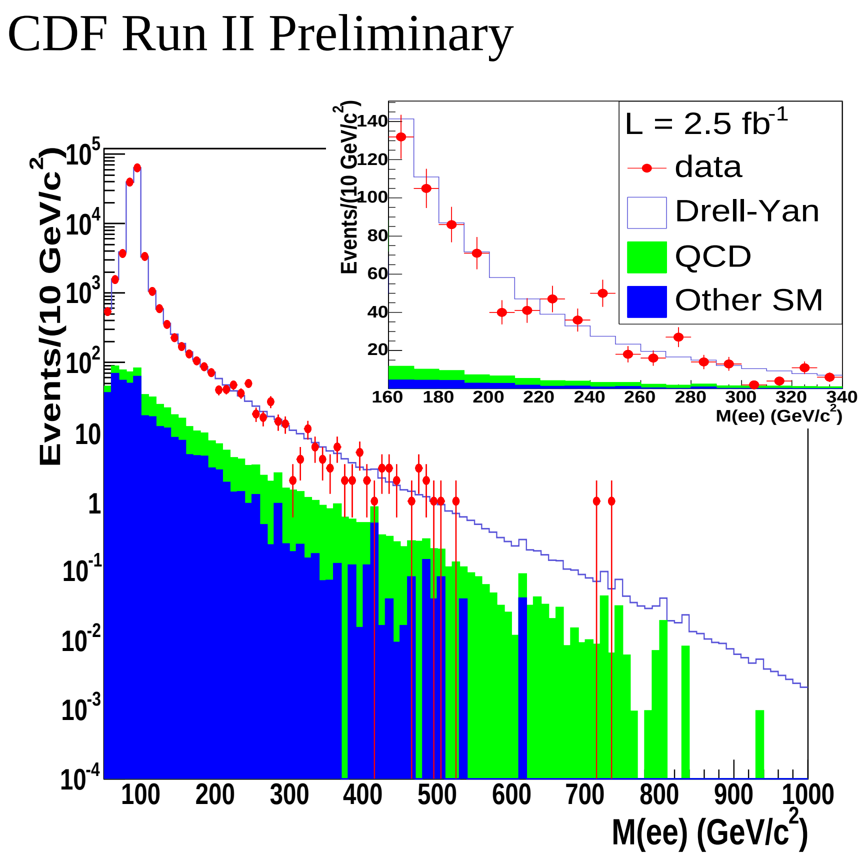
Beyond Supersymmetry – Heavy Resonances

Searches for heavy charged or neutral difermion resonance X:

- Channels considered for $X^0 \longrightarrow f\bar{f}$: ee, $\mu\mu$, $\tau\tau$, $q\bar{q}$, $t\bar{t}$ (plus eμ, $\gamma\gamma$)
- Channels considered for $X^{\pm} \longrightarrow ff'$: e$\nu$, $q\bar{q}$, tb



DØ: $M_{W'} > 1.0$ TeV



CDF: $M_{Z'} > 966$ GeV

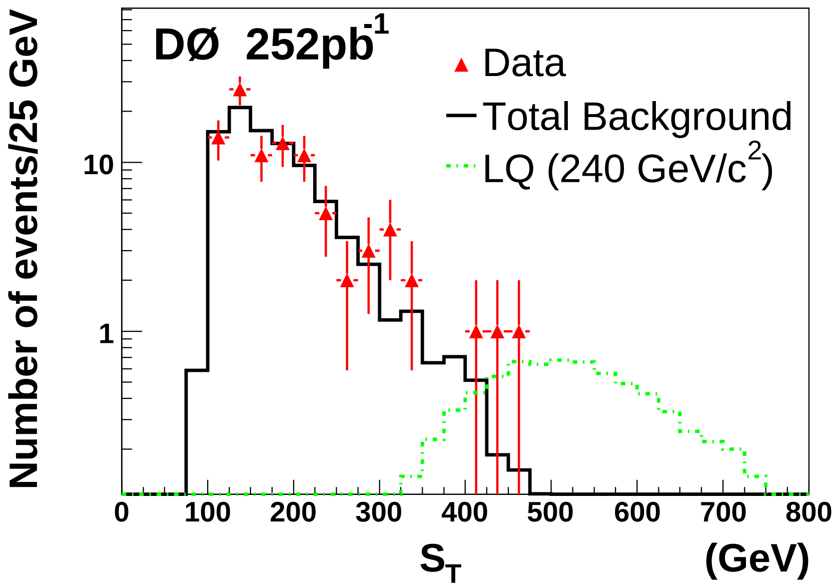
Beyond Supersymmetry – Heavy Resonances

Searches for Leptoquarks LQ⟶lq:

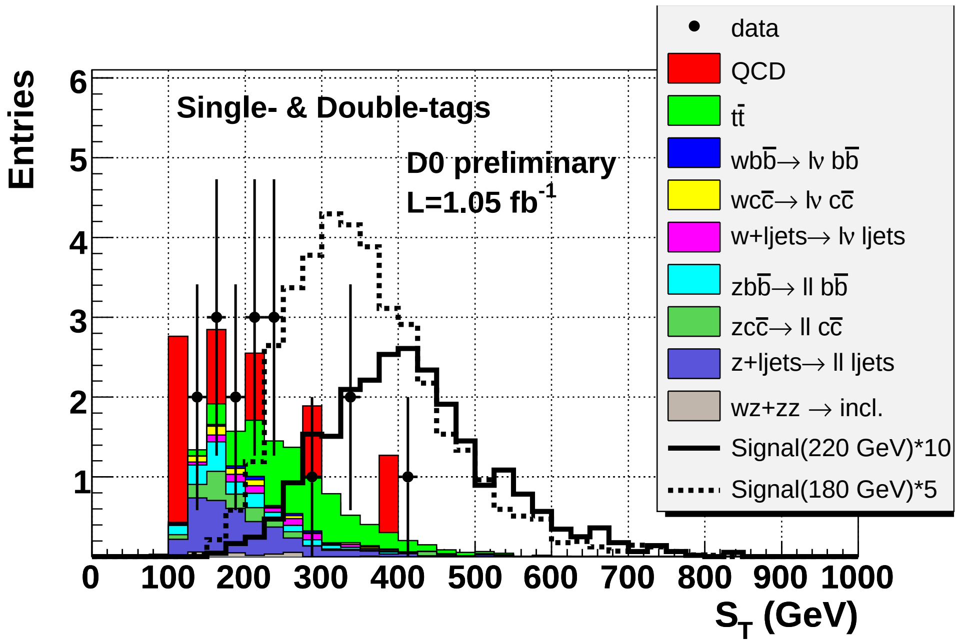
- Final states considered: eeqq, eνqq, $\mu\mu$qq, $\mu\nu$qq, $\nu\nu$qq, $\tau\tau$bb, $\nu\nu$bb
- High LQ mass ⟶ decay products with high transverse momenta

  ⟶ check for excess at high $S_T = p_T^1 + p_T^2 + p_T^3 + p_T^4$

1st Generation (eeqq)



3rd Generation ($\tau\tau$bb)



Mass limits for BR(LQ⟶lq)=1:

- 1st Generation: M>256 GeV
- 2nd Generation: M>251 GeV
- 3rd Generation: M>180 GeV

Conclusions

Tevatron is running very well: 3 fb^{-1} on tape, good prospects for 8 fb^{-1} by 2010

Precision measurements of Top and W mass pinpoint SM Higgs boson mass

SM Higgs search finally reaching sensitivity

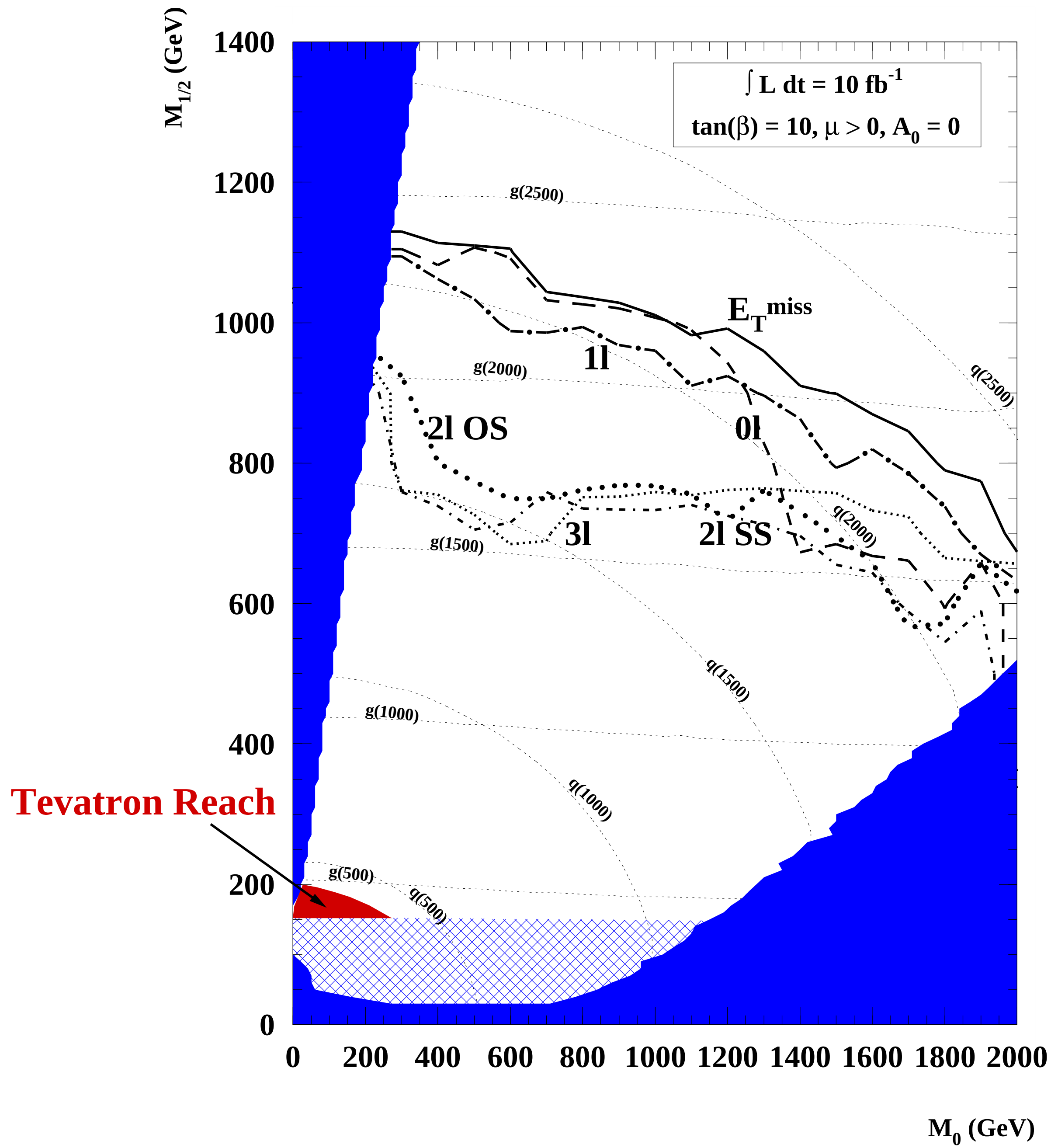
SUSY Higgs: limits on tanβ at low m_A (consistent with $B_s \rightarrow \mu\mu$)

Direct searches for Supersymmetry:

- Squarks, Gluinos: excluded below about 380 GeV, 310 GeV
- Charginos: excluded below 145 GeV (in favourable scenarios)
- numerous signatures and models beyond mSUGRA have been investigated

Searches for heavy resonances probing masses up to 1 TeV

Conclusions



Still plenty of room for SUSY discovery at LHC!

BACKUP