# Search for Higgs Bosons and New Particles at the Tevatron

## Prospecting for Gold at the Tevatron

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**Universität Freiburg**


**XXXIV SLAC Summer Institute, July 18, 2006**

# Outline

# The Tevatron Collider

**Proton Antiproton Collider**

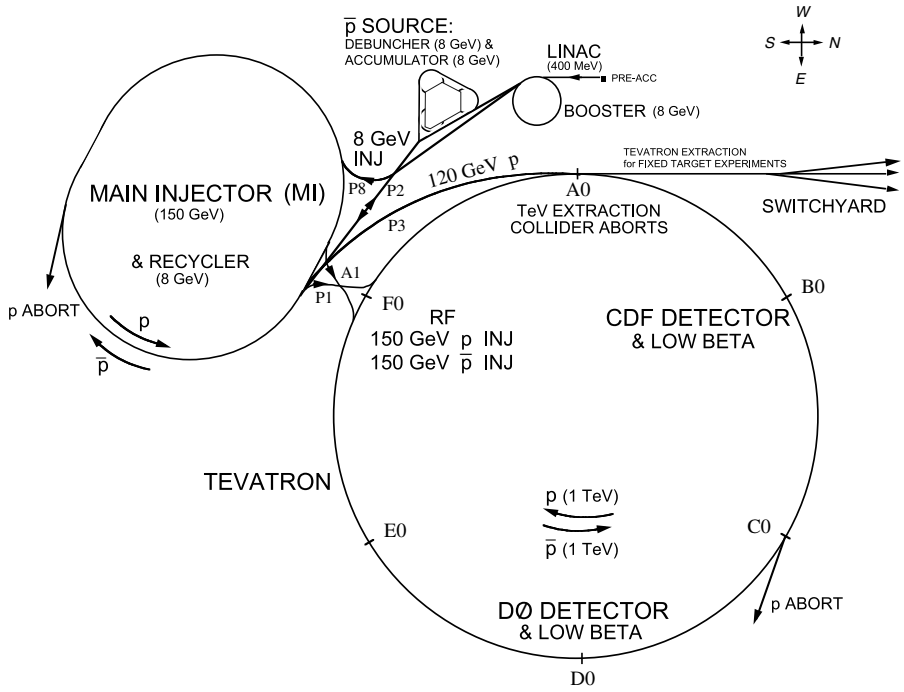
**Centre-of-mass energy: 1.96 TeV**

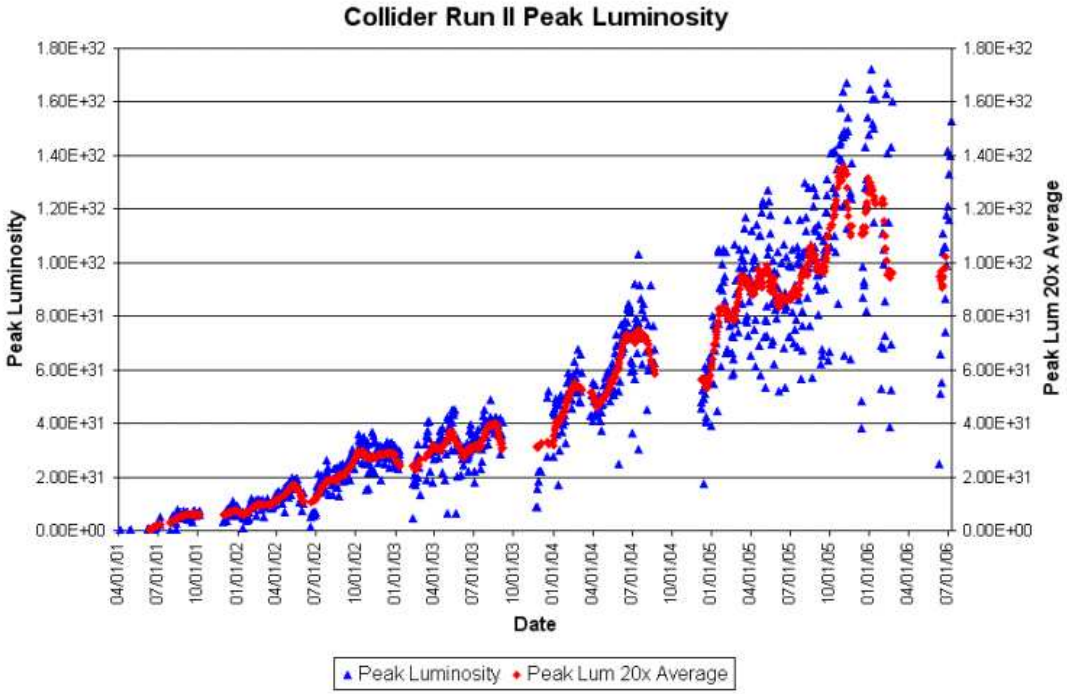
**Integrated Luminosity: 1.4 fb$^{-1}$ so far**

**Peak luminosity:**

- **currently at $1.7\times10^{32}$ cm$^{-2}$s$^{-1}$**
- **ultimate: $3\times10^{32}$ cm$^{-2}$s$^{-1}$**

**Expecting to accumulate 8 fb$^{-1}$ by 2009**




**Electron Cooling in operation**

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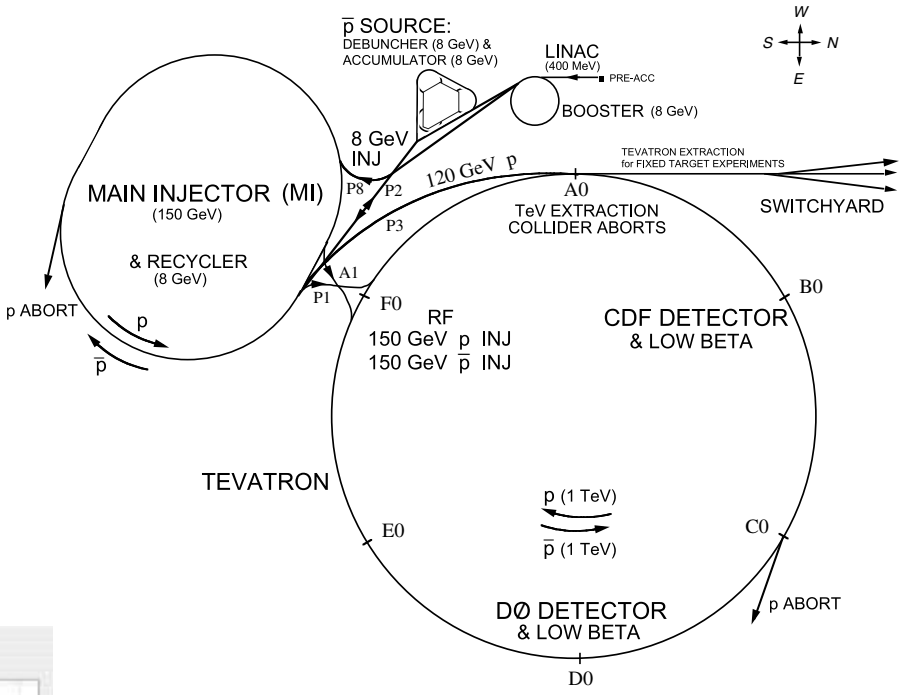


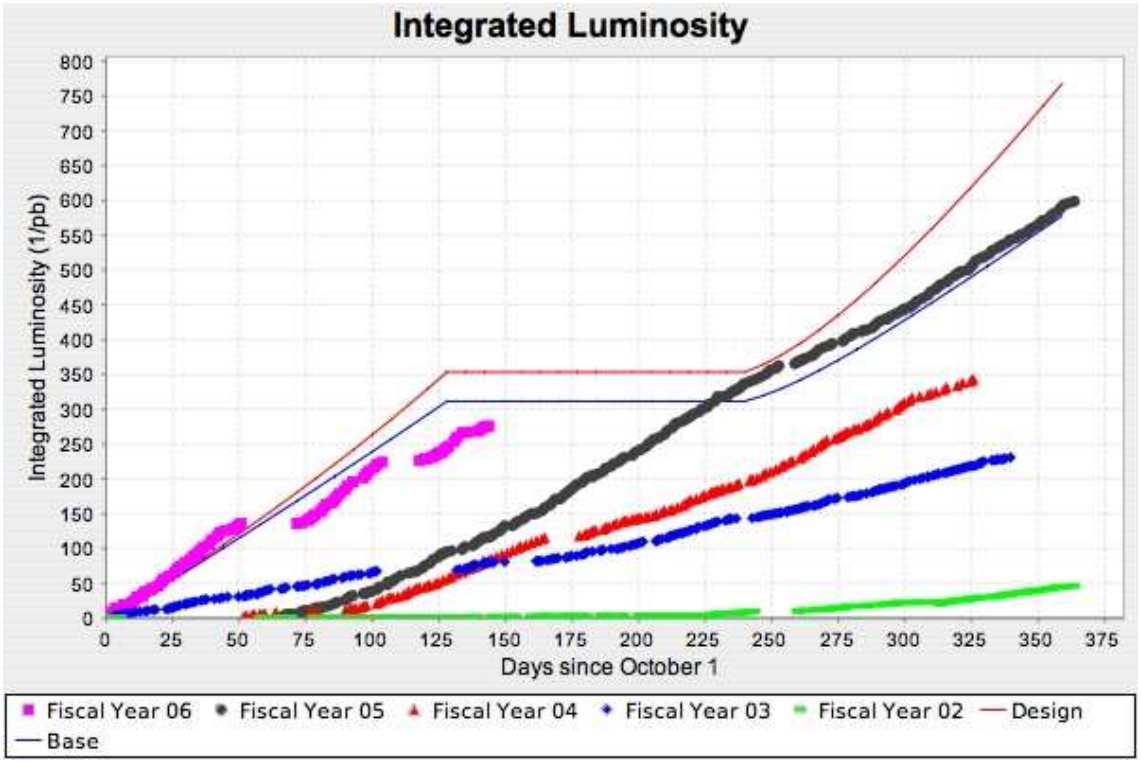


Electron Cooling in operation

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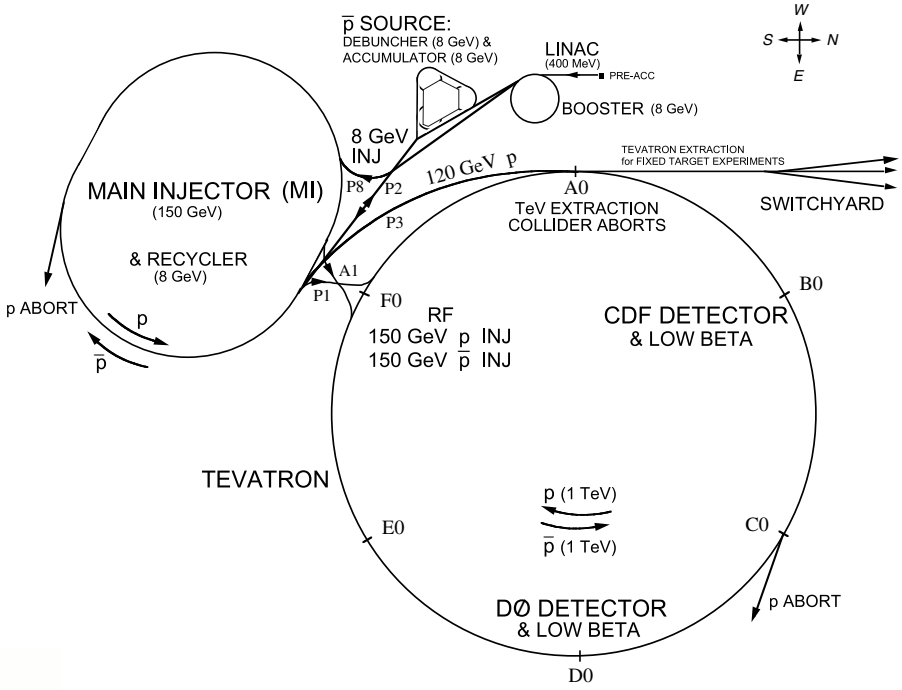
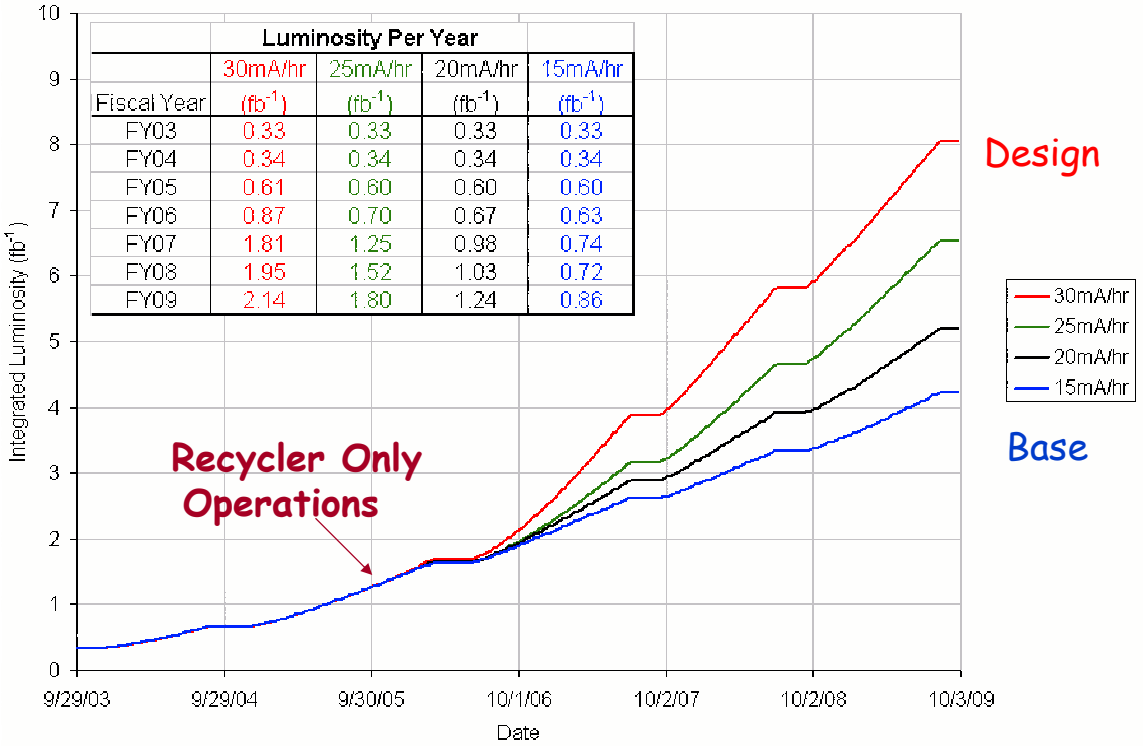



| Luminosity Per Year | | | | |
|---|---|---|---|---|
| | 30mA/hr | 25mA/hr | 20mA/hr | 15mA/hr |
| Fiscal Year | ($fb^{-1}$) | ($fb^{-1}$) | ($fb^{-1}$) | ($fb^{-1}$) |
| FY03 | 0.33 | 0.33 | 0.33 | 0.33 |
| FY04 | 0.34 | 0.34 | 0.34 | 0.34 |
| FY05 | 0.61 | 0.60 | 0.60 | 0.60 |
| FY06 | 0.87 | 0.70 | 0.67 | 0.63 |
| FY07 | 1.81 | 1.25 | 0.98 | 0.74 |
| FY08 | 1.95 | 1.52 | 1.03 | 0.72 |
| FY09 | 2.14 | 1.80 | 1.24 | 0.86 |




Main Injector und Recycler

# Physics at the Tevatron

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

- **Advantage: High centre-of-mass energy**

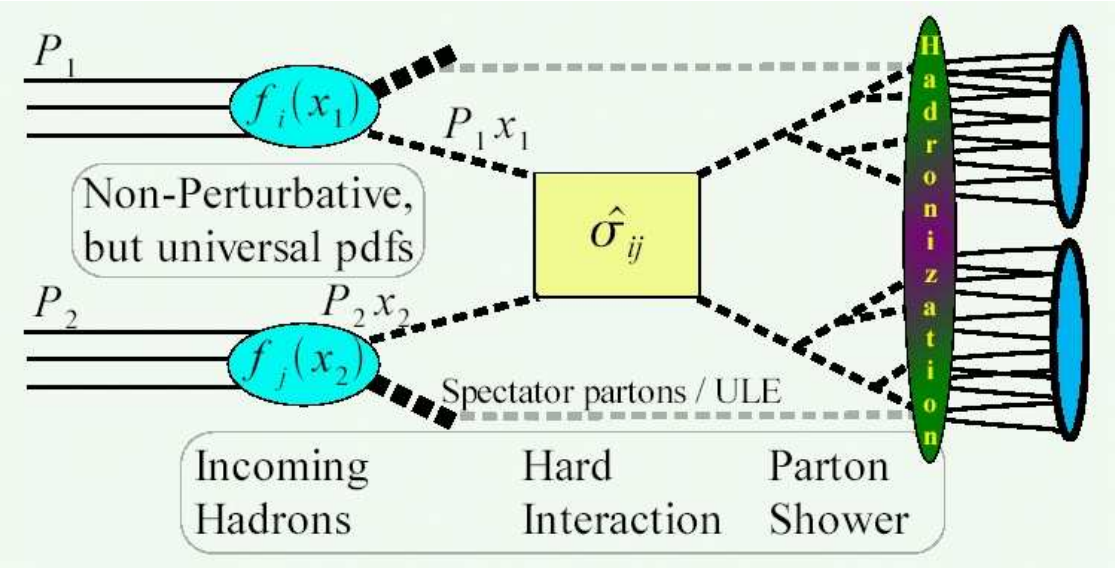
  → production of massive particles (LEP: m $\lesssim$ 100 GeV)

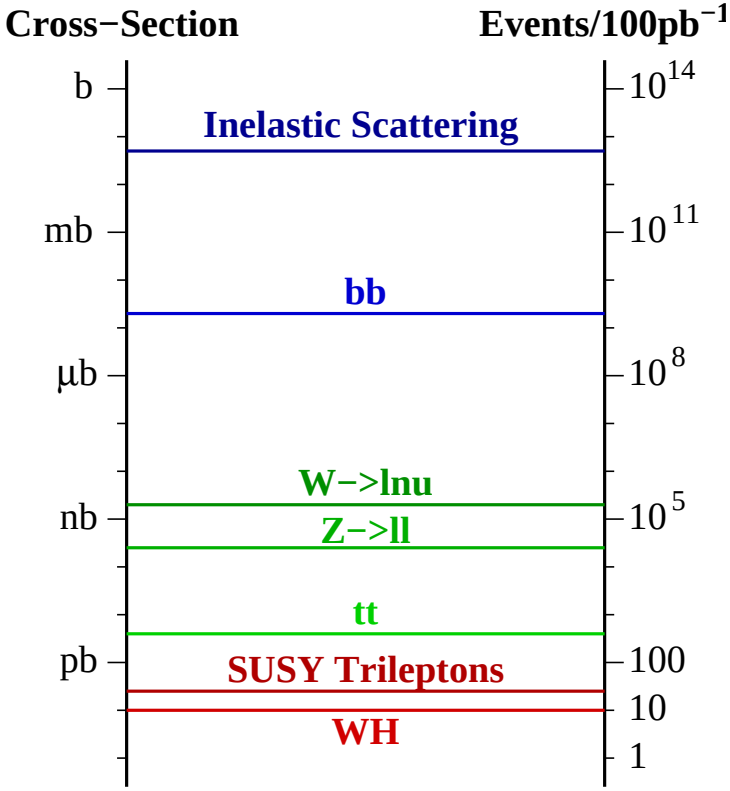
- **Disadvantage: Strong Interaction**

  → complicated final states:
  - particles from fragmentation of $p/\bar{p}$ remnants
  - gluon radiation → jets

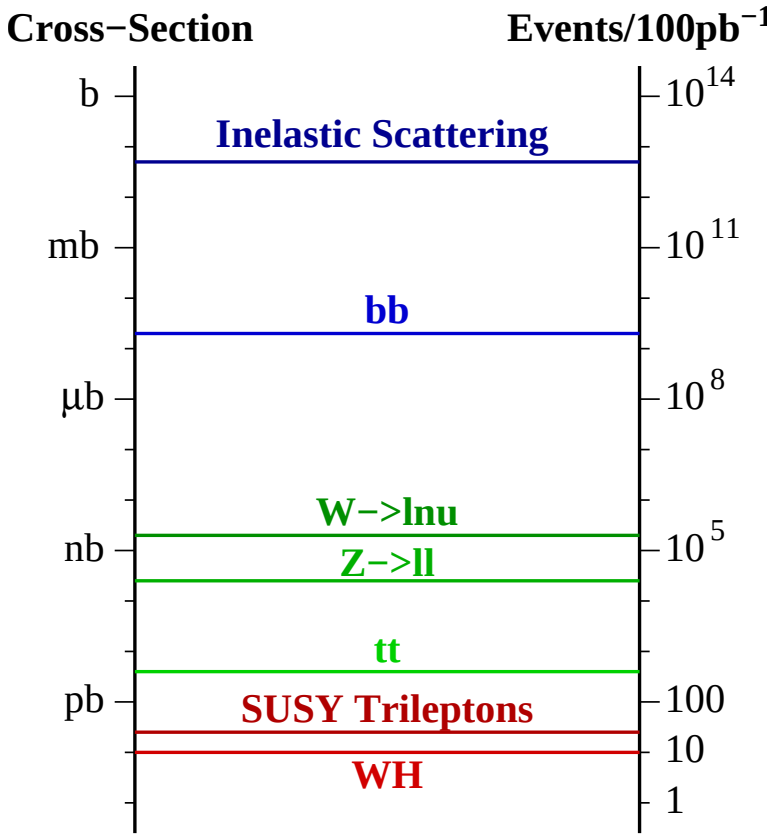
  → huge event rates for jet production

  → multiple interactions per crossing



# Prospecting for Gold at the Tevatron

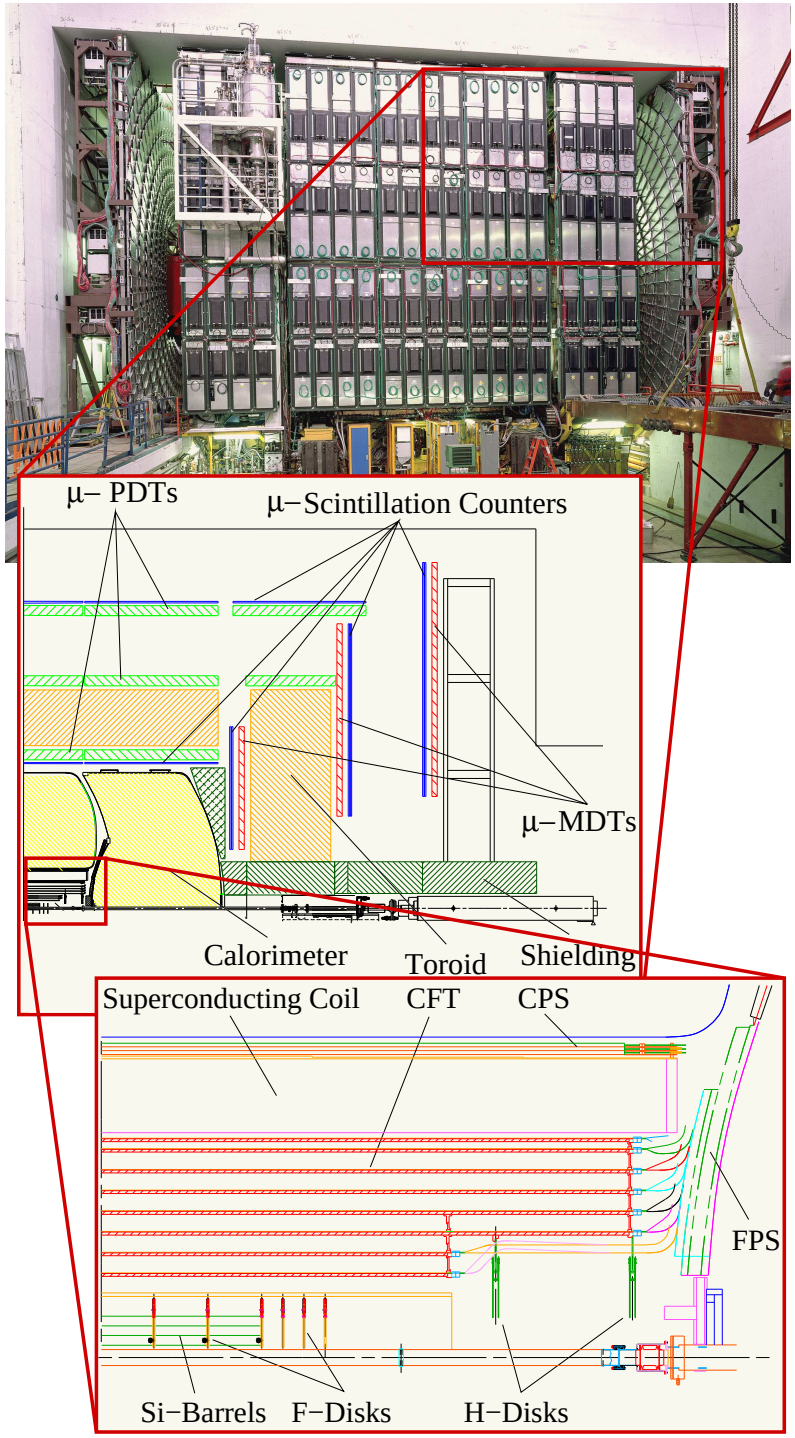

- CDF/DØ are searching for about 1 WH event in $10^{12}$ inelastic scatters
- 1 Higgs boson seems to be about 5x5x5 cm of Gold

→ prospector needs to sift through $10^{8}$ m$^{3}$ of water to find 1 Higgs boson

→ about 40 years of sifting, 12 hours every day...

**Sounds painful - is there a better way?**

# The Tevatron Experiments




**Two General-Purpose Detectors:**

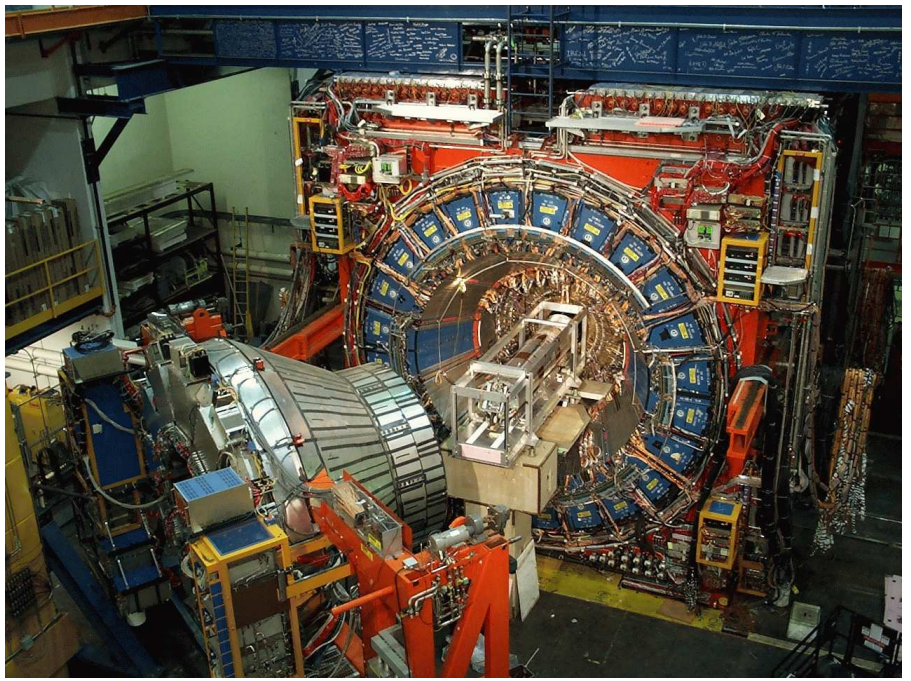
| | CDF | DØ |
|---|---|---|
| Electron acceptance | $\|\eta\| < 2.0$ | $\|\eta\| < 3.0$ |
| Muon acceptance | $\|\eta\| < 1.5$ | $\|\eta\| < 2.0$ |
| Silicon Precision tracking | $\|\eta\| < 2.0$ | $\|\eta\| < 3.0$ |
| Hermetic Calorimeter | $\|\eta\| < 3.6$ | $\|\eta\| < 4.2$ |

**Powerful trigger systems (2.5 MHz→100 Hz)**

- Dilepton triggers starting at $p_T > 4$ GeV
- Jets+$\not\!\!E_T$ triggers with $E_T > 25$ GeV

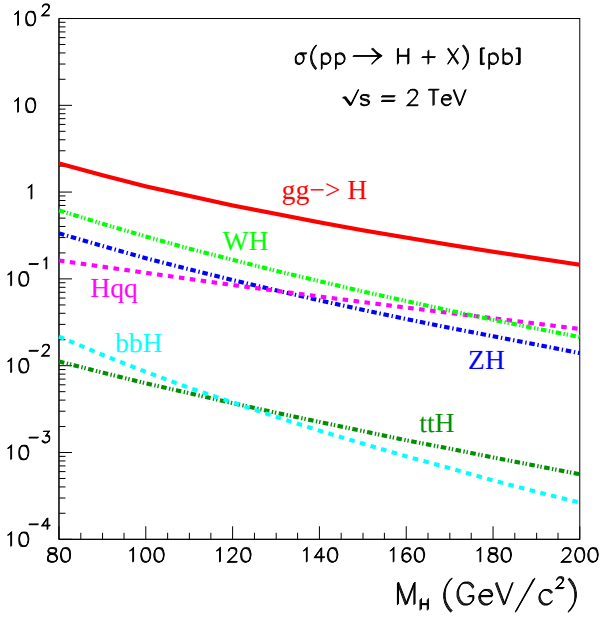
**RunIIa: 1.2 fb$^{-1}$ on tape**

- Current Average Efficiency ≈ 90%

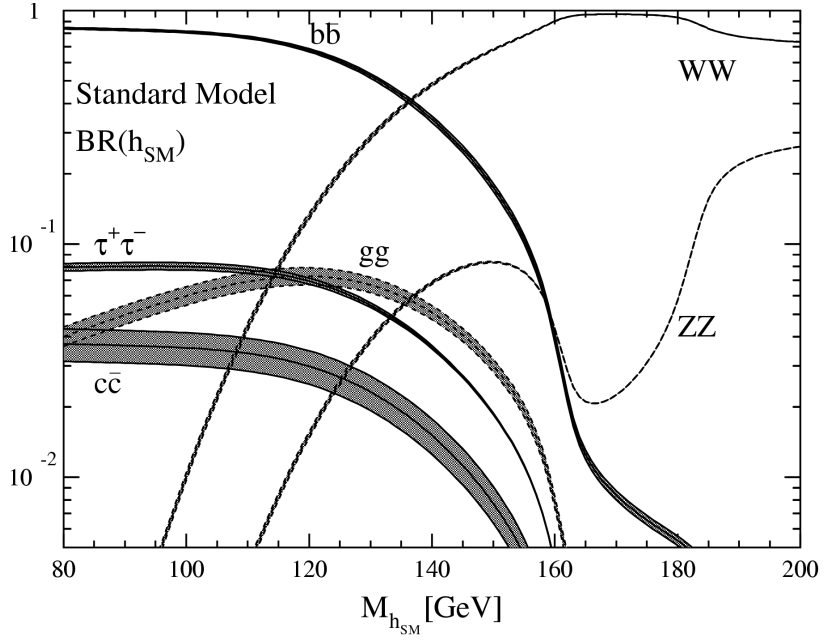


# Search for Higgs Bosons – Production and Decay

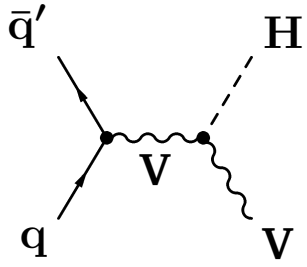
**Production Cross-Sections**




**Branching Ratios**




## Light Higgs bosons ($m_H$ <130 GeV):



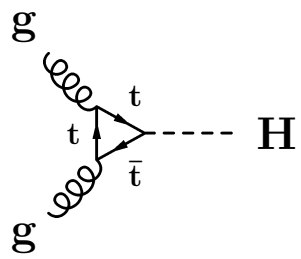

**Dominant decay mode: H→b$\bar{\text{b}}$**

**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 ($m_H$ >130 GeV):




**Dominant decay mode: H→WW**

**Production: Gluon-Gluon Fusion**

**→ relatively high cross-section**

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

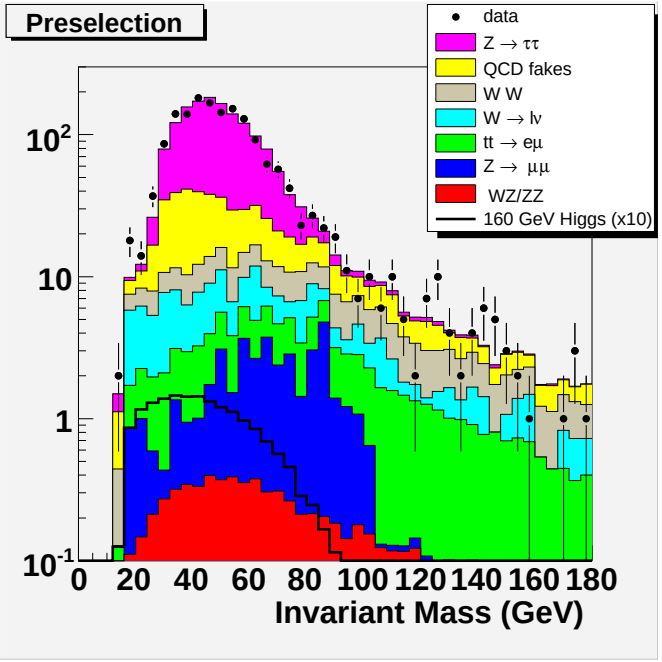
# Search for Higgs Bosons: H→WW

**New DØ search for H→WW→ $\ell\nu\ell\nu$ based on 950 pb$^{-1}$**

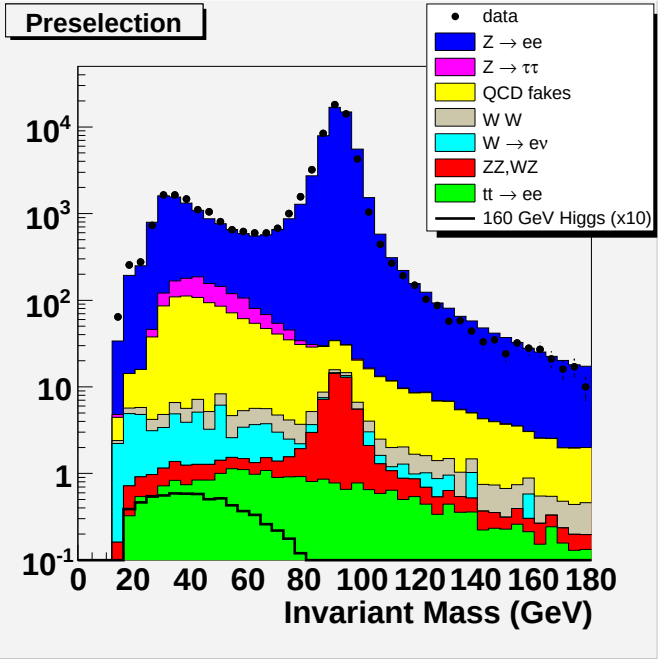
**Clean final state: 2 isolated charged leptons plus missing transverse energy**

→ **massive reduction of multijet background already at trigger level**

**Preselection $e\mu$ Channel**




**Preselection $ee$ Channel**

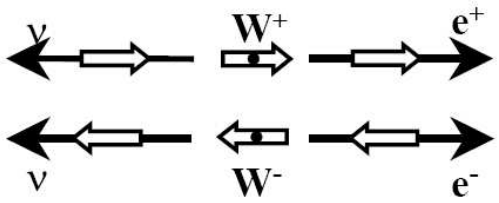



**Main Backgrounds:**

- **Multijets: small $\not\!\!E_T$, 2 fake leptons (but: huge cross section)**
- **W+$\gamma$, W+jet with W→ $\ell\nu$: 1 fake lepton**
- **Z/$\gamma^*$ → $\ell\ell$: small $\not\!\!E_T$**
- **$WW \to \ell\nu\ell\nu$: irreducible**

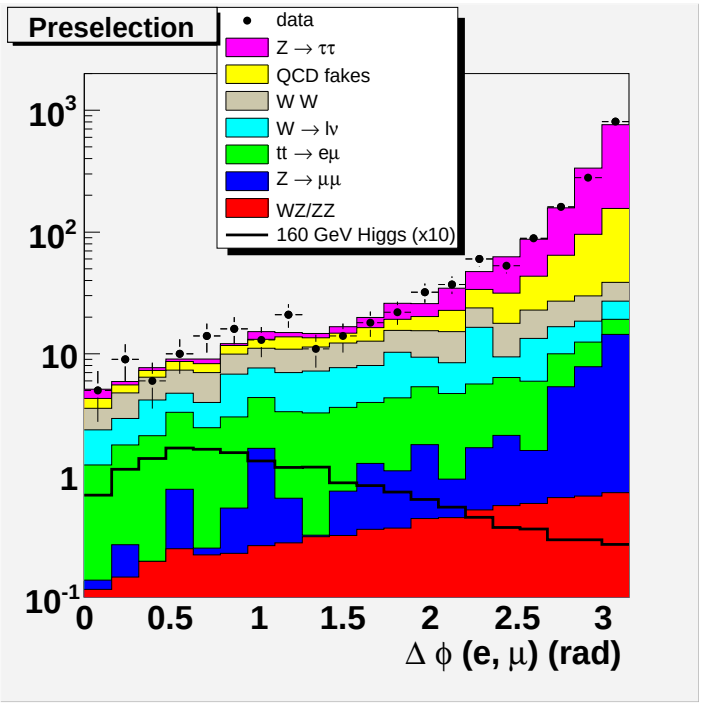
# Search for Higgs Bosons: H→WW

## Additional information: angular correlations exploiting spin of Higgs boson

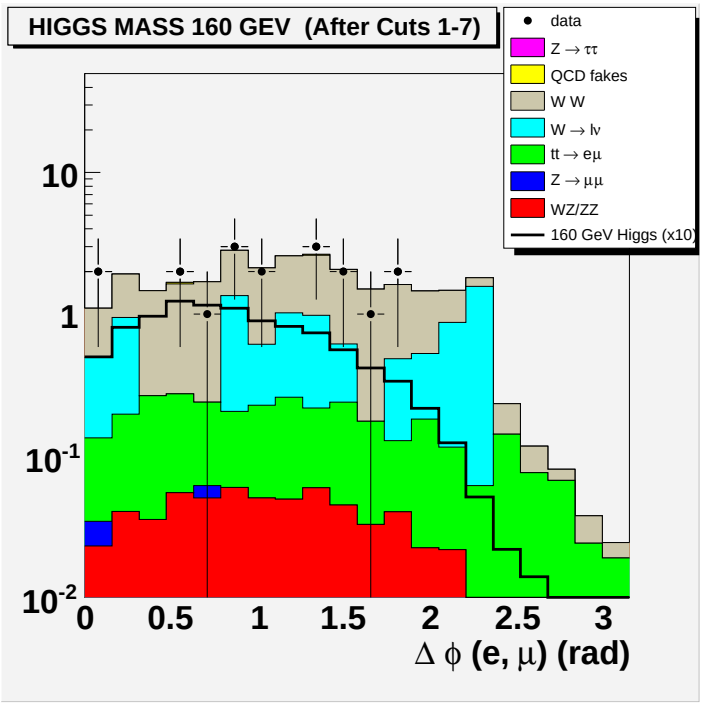



→ Charged leptons from Higgs decay tend to have small opening angle $\Delta\Phi$

Preselection




After all cuts

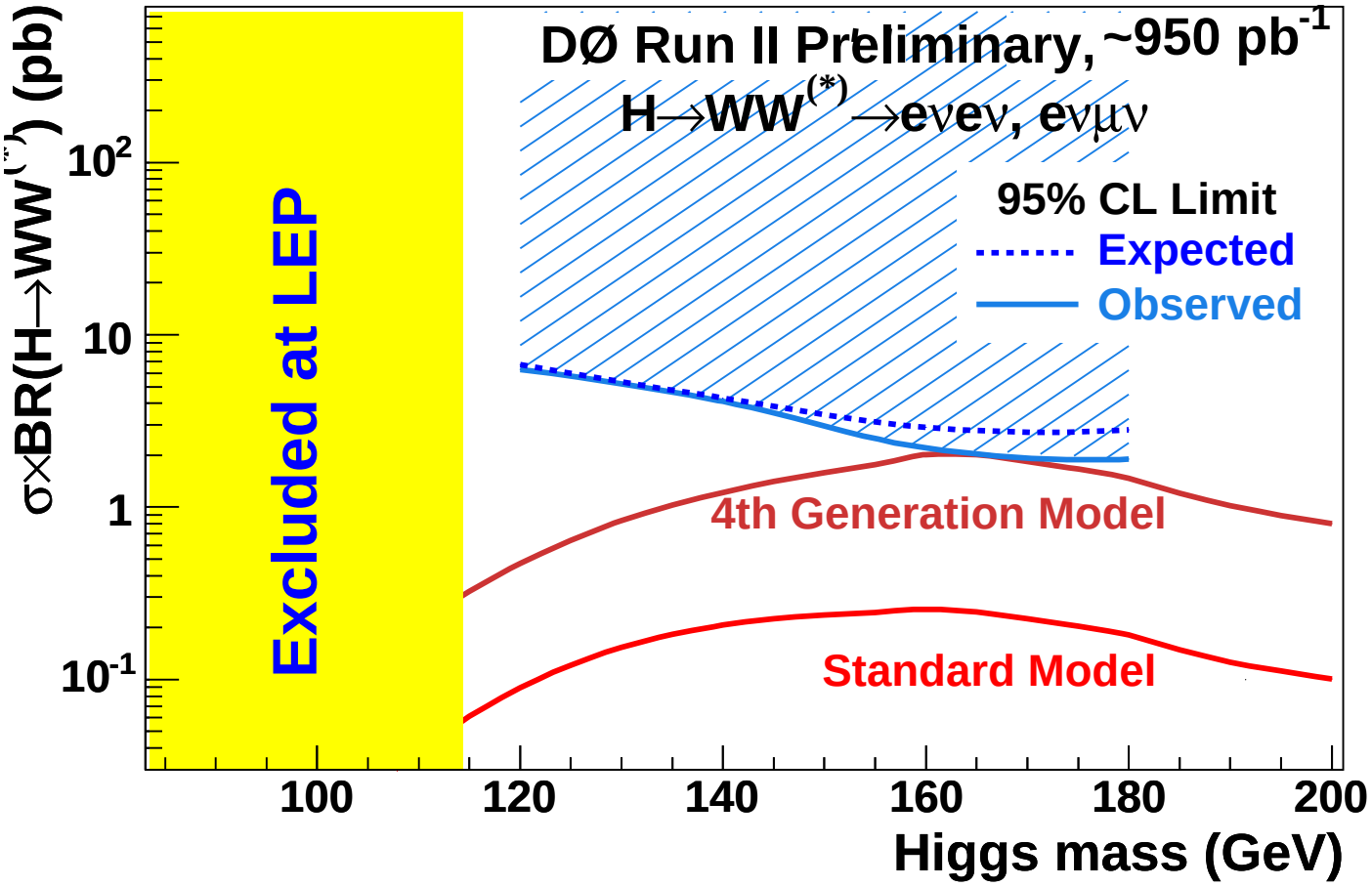



**Note:**

- 18 events observed in $e\mu$ channel (mostly $WW$)
- 1 event expected for SM Higgs boson with $m_H = 160$ GeV

# Search for Higgs Bosons: H→WW

No excess of events observed → limits on $\sigma$ x BR(H→WW)



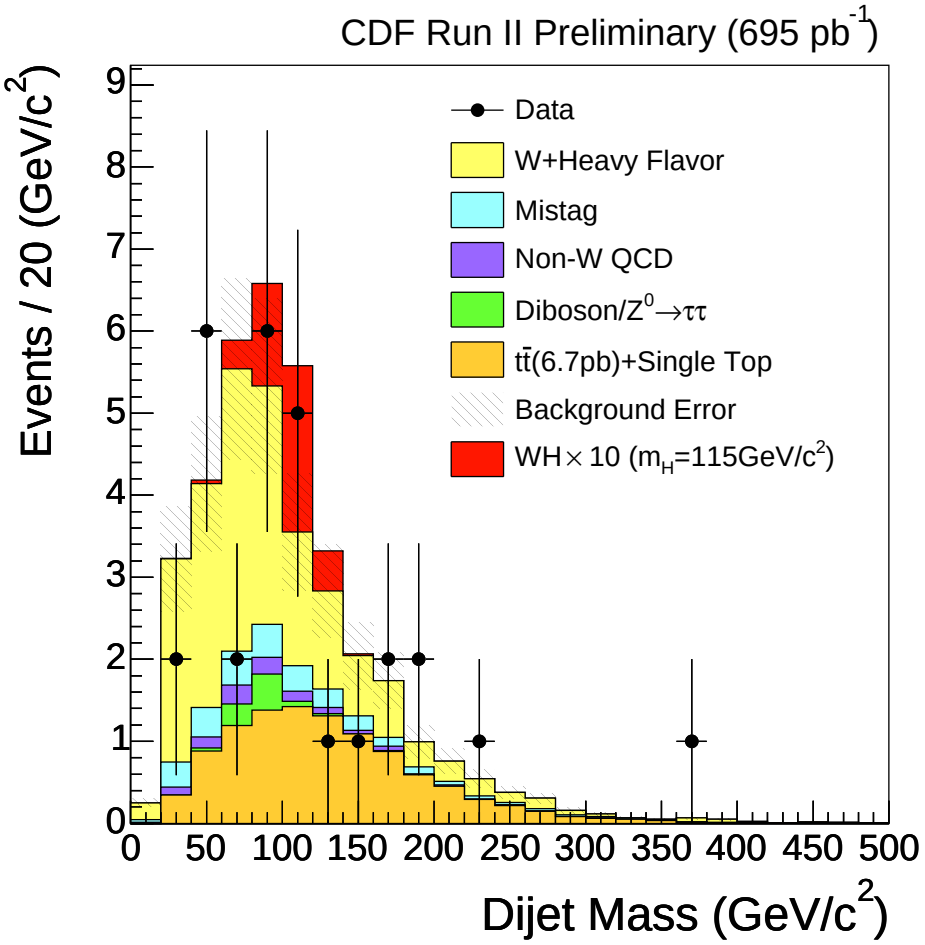

Standard Model with 4th generation:

- heavy quark loops enhance cross-section
- now excluded for $m_H$=160–170 GeV

# Search for Standard Model Higgs Boson

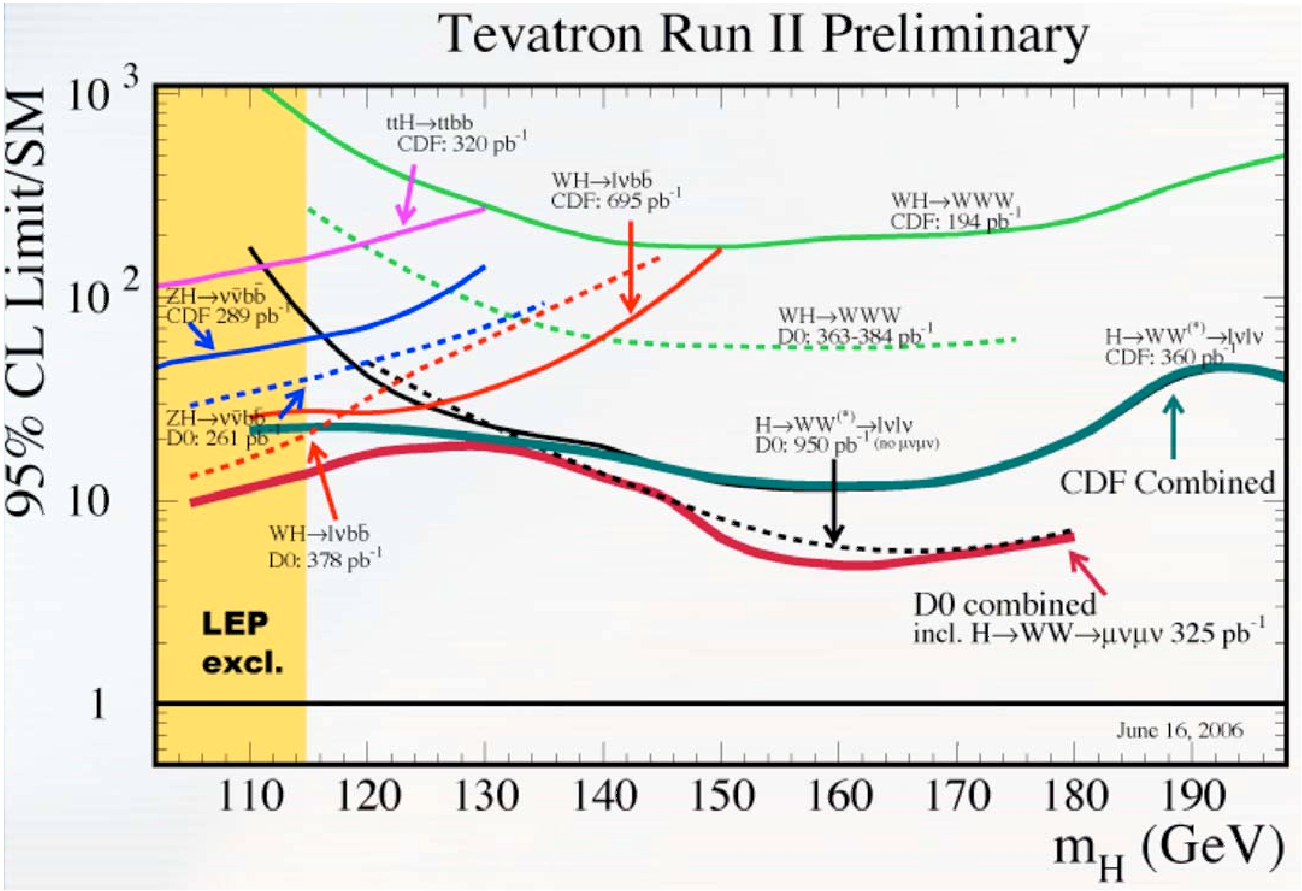
**For best sensitivity over entire mass range:**

**combine with searches for $WH \to WWW$ and $WH \to \ell\nu b\bar{b}$, $ZH \to \nu\nu b\bar{b}$**




**Results from 14 channels are statistically tested for presence of a SM Higgs boson as a function of $m_H$ (CLs method):**

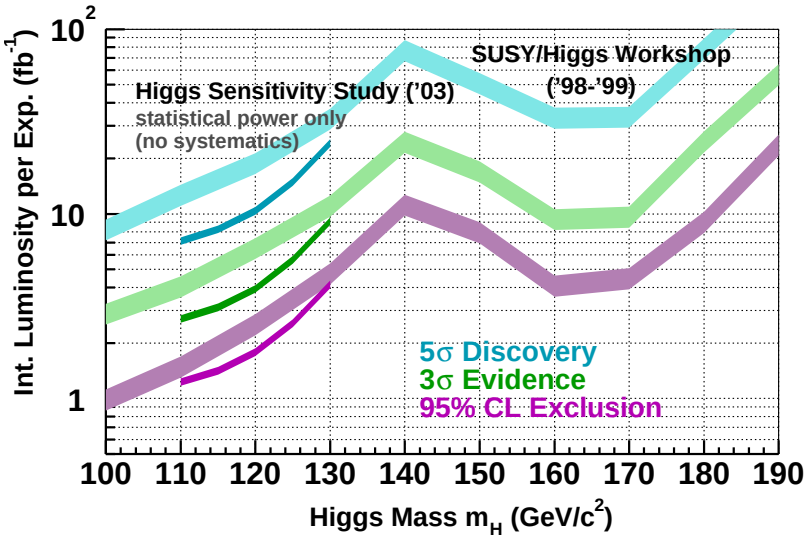
# Search for Standard Model Higgs Boson




**Projected to reach sensitivity at 95% C.L. with 2 fb$^{-1}$**

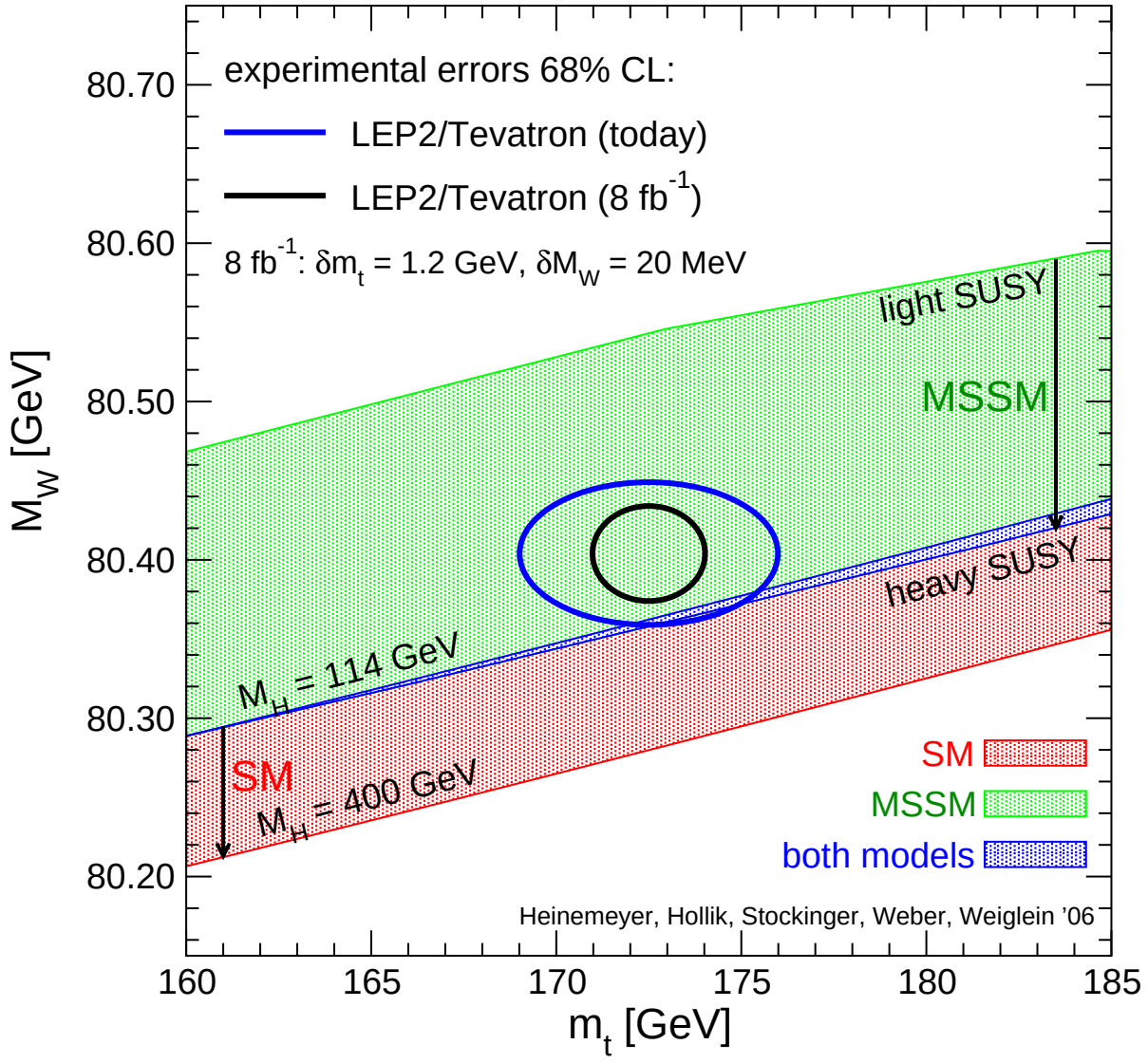
**In the pipeline for summer:**

- more channels: $ZH \rightarrow \ell\ell b\bar{b}$, $WH \rightarrow \tau\nu b\bar{b}$
- analysis improvements: NN, b-tagging, Eflow...
- combine results from CDF+DØ: TEVNPHWG
- analyze full Run IIa dataset



# Beyond the Standard Model: Supersymmetry

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




**On which side would you like to place your money?**

# Supersymmetry

**The idea: particle physics is symmetric under transformation fermion ↔ boson**

→ implies one supersymmetric partner for each SM particle

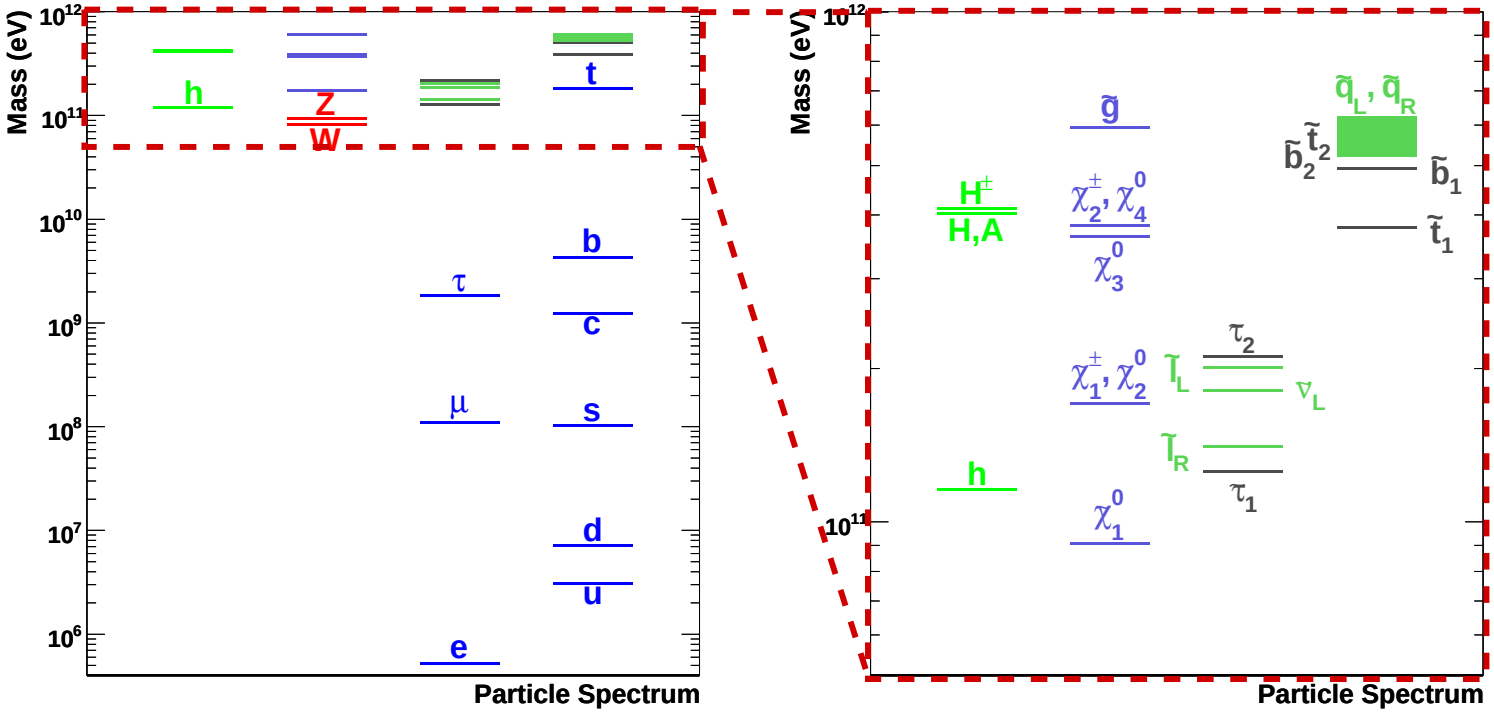
**Superpartners are heavy → SUSY must be broken**

- Details of SUSY breaking mechanism unknown

→ 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,$H^{\pm}$



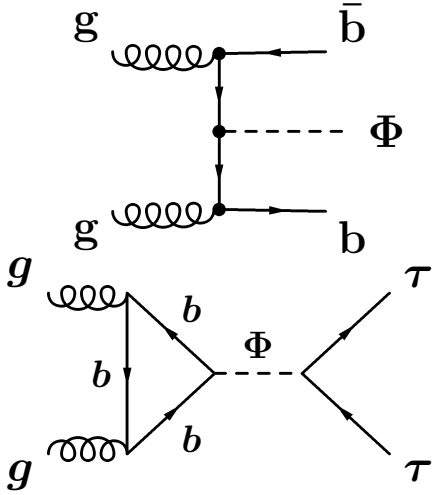
# Search for SUSY Higgs

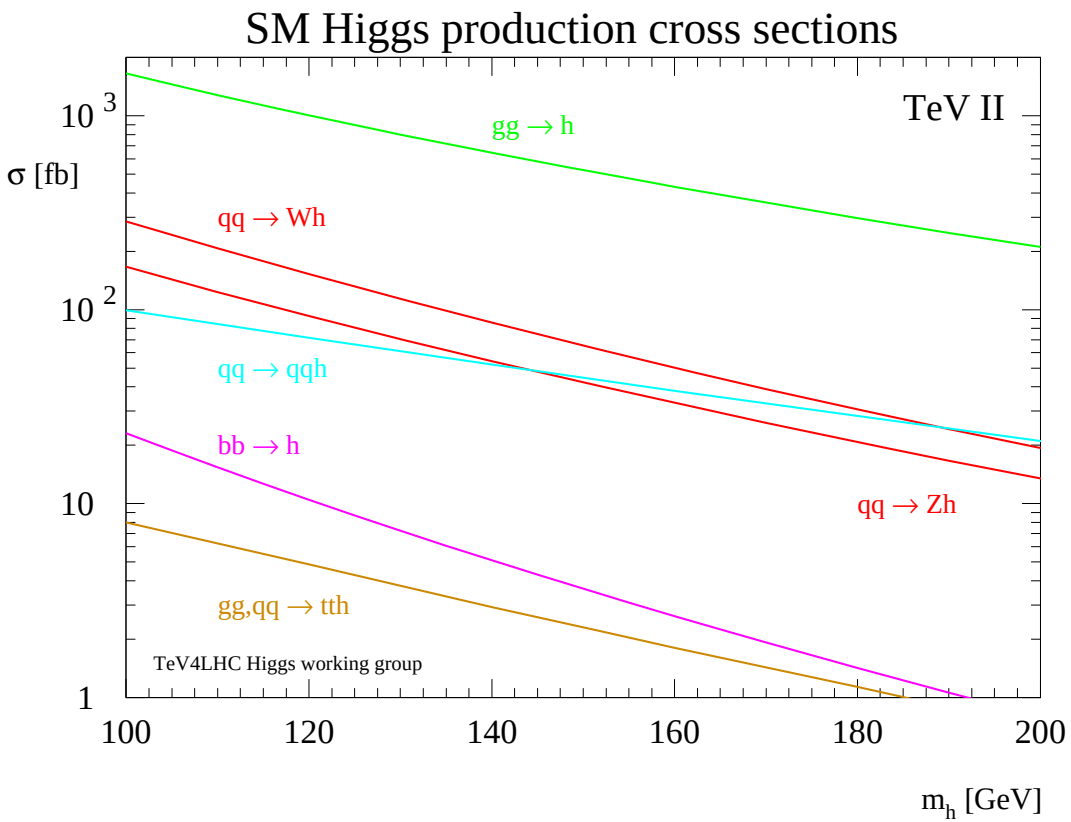
**SUSY Higgs sector specified (at LO) by 2 parameters:**

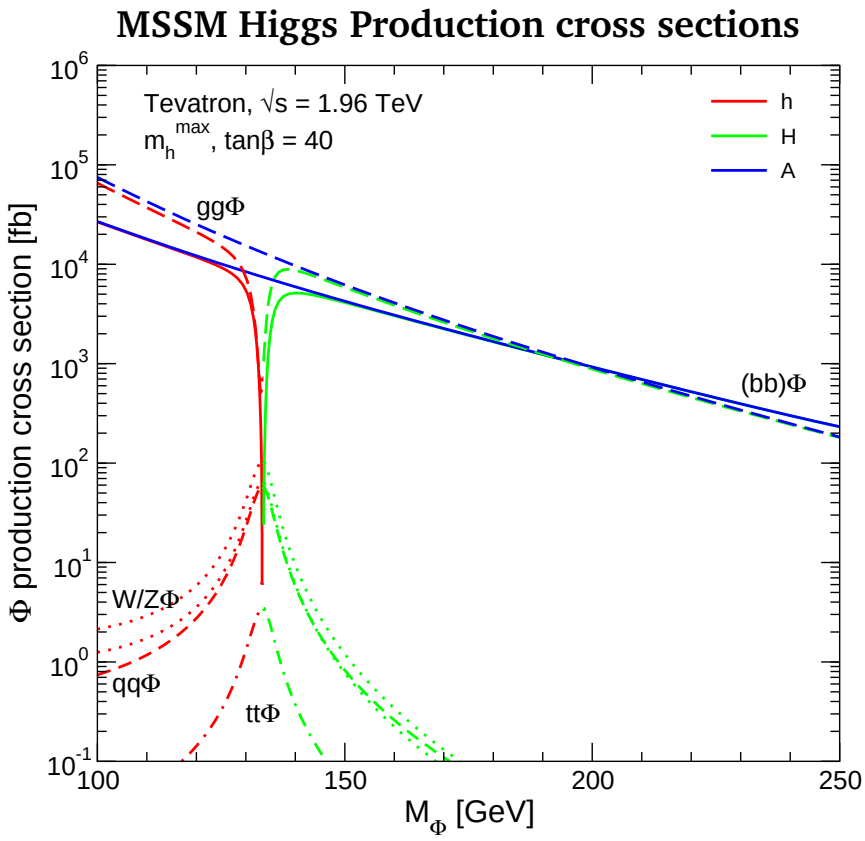
- $m_A$: mass of pseudo-scalar Higgs boson
- $\tan\beta$: ratio of vacuum expectation values

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

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



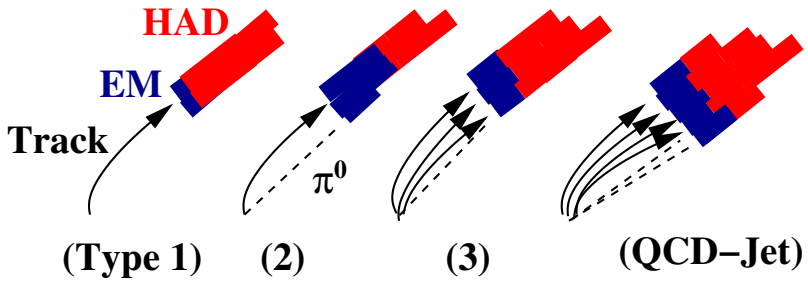



# Search for SUSY Higgs

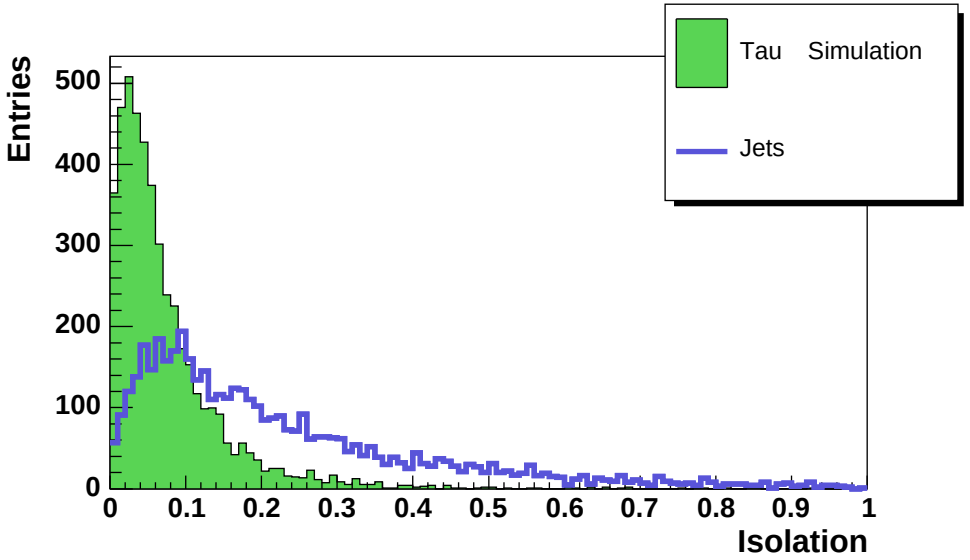
**New DØ analysis: Search for $h \longrightarrow \tau\tau$ in 325 pb$^{-1}$**

**Main challenge: 65% of $\tau$ leptons decay hadronically**

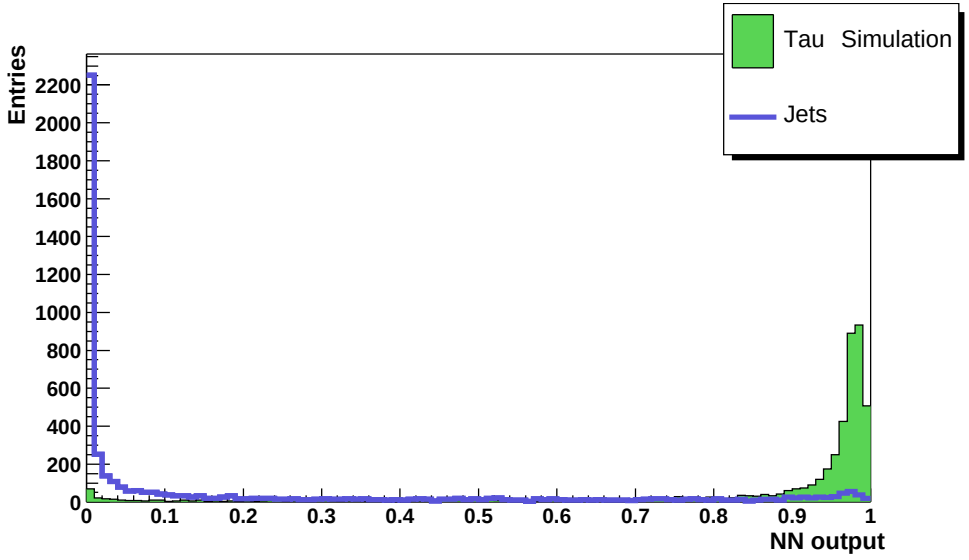
- reconstructed as 1 or 3 tracks pointing to narrow energy deposition in calorimeter
- using neural networks to separate $\tau$-decays from jets




Input Variable: Isolation in Calorimeter




Output of Neutral Network



# Search for SUSY Higgs

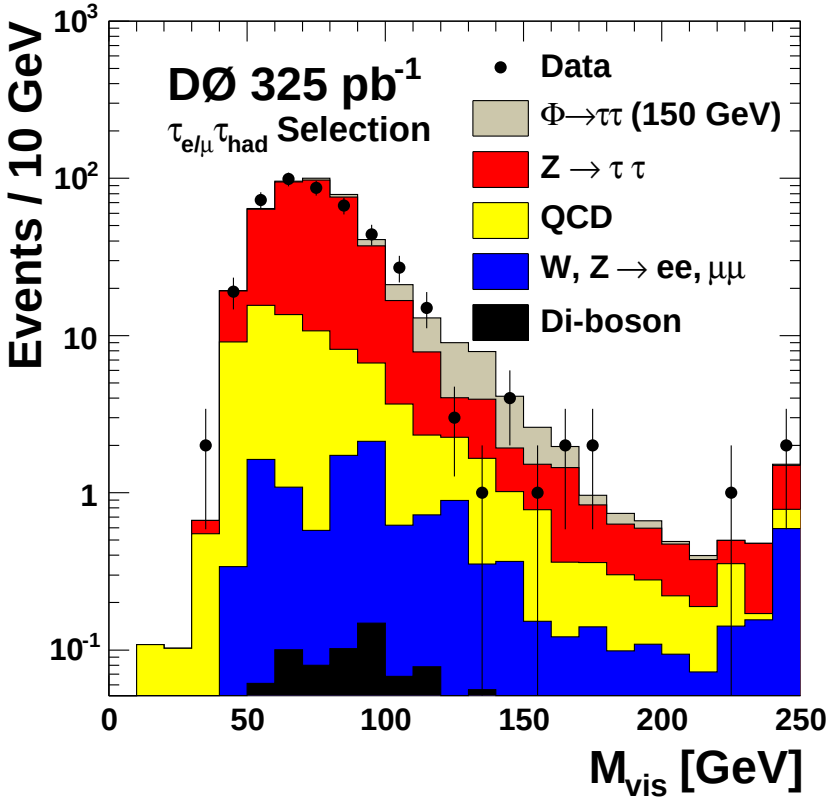
| Mode | Fraction (%) | Comments |
|---|---|---|
| $\tau_e\tau_e$ | 3 | Large DY BGND |
| $\tau_\mu\tau_\mu$ | 3 | Large DY BGND |
| $\tau_e\tau_\mu$ | 6 | Small QCD BGND |
| $\tau_e\tau_h$ | 23 | Golden |
| $\tau_\mu\tau_h$ | 23 | Golden |
| $\tau_h\tau_h$ | 41 | Large QCD BGND |

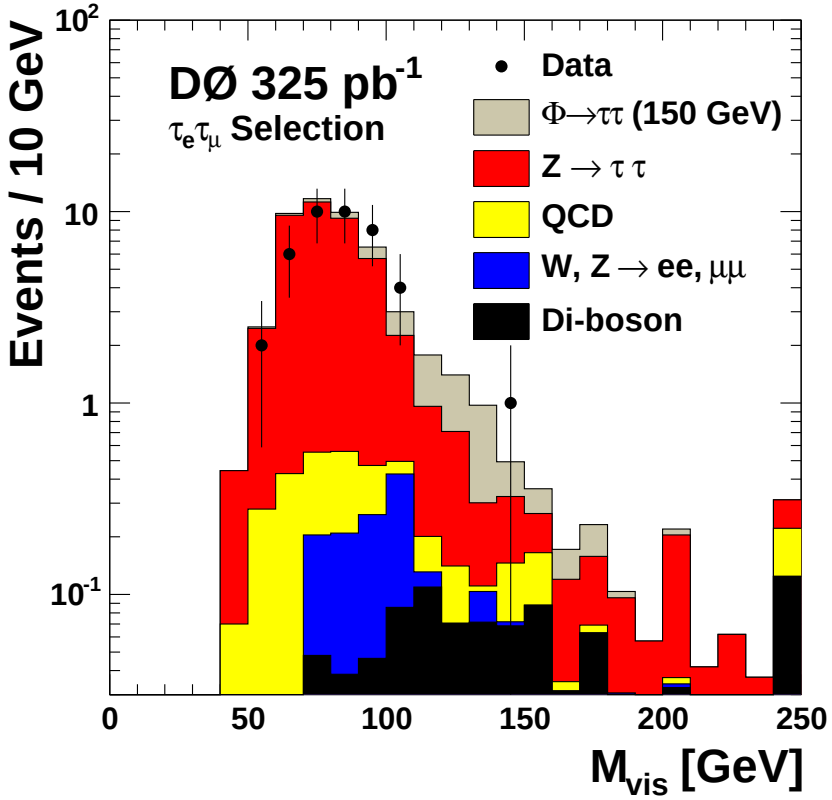
**Selections:**

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 $\not\!\!E_T$



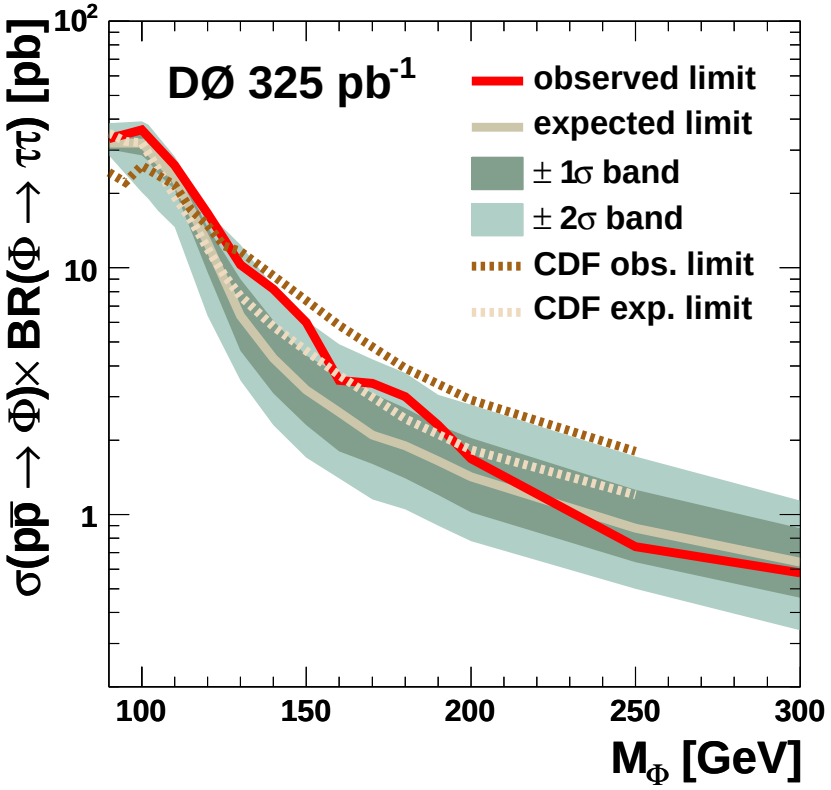
# Search for SUSY Higgs

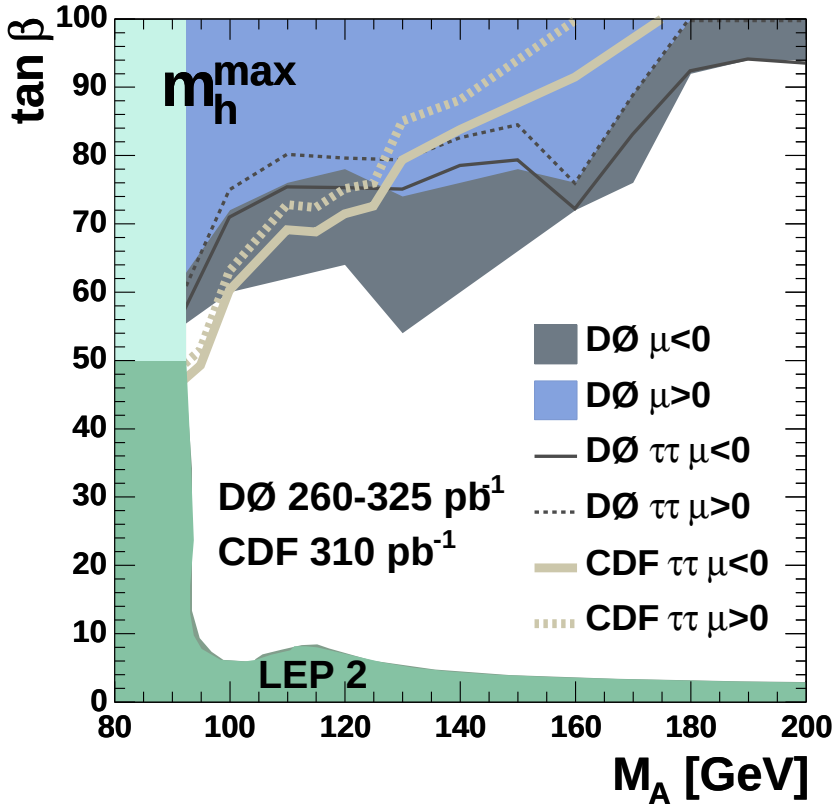
**So far no hint for a signal**

$\rightarrow$ limits on $\sigma \times \mathrm{BR}(h \rightarrow \tau^+\tau^-)$

**Combination of results from search for $h \rightarrow \tau\tau$ and hb(b)$\rightarrow$bbb(b)**

- powerful constraints on tan$\beta$ even at large $m_A$
- Tevatron combination currently in progress (TEVNPHWG)



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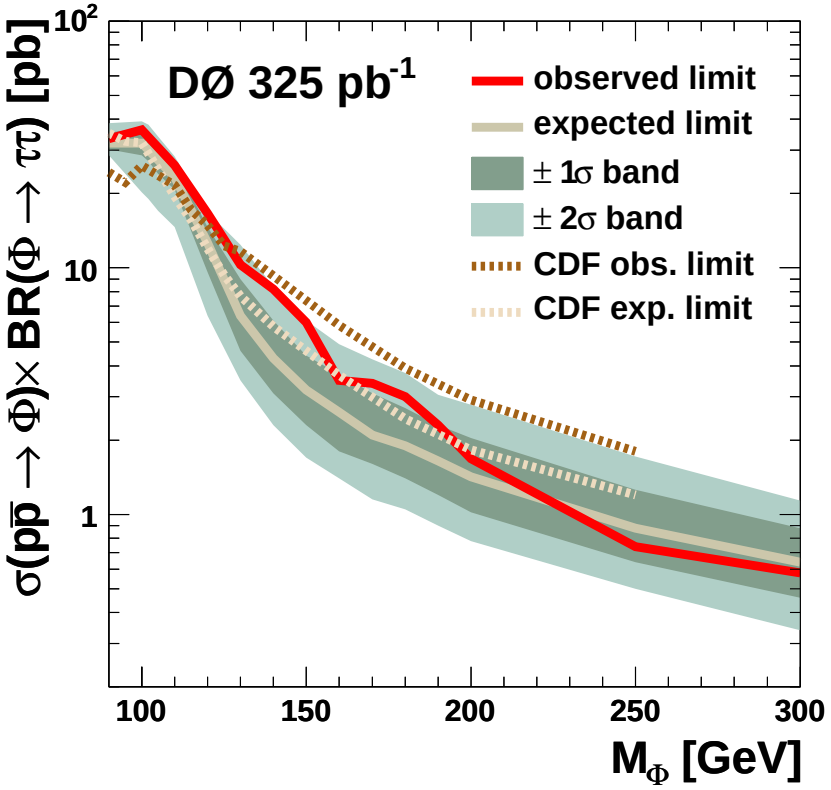
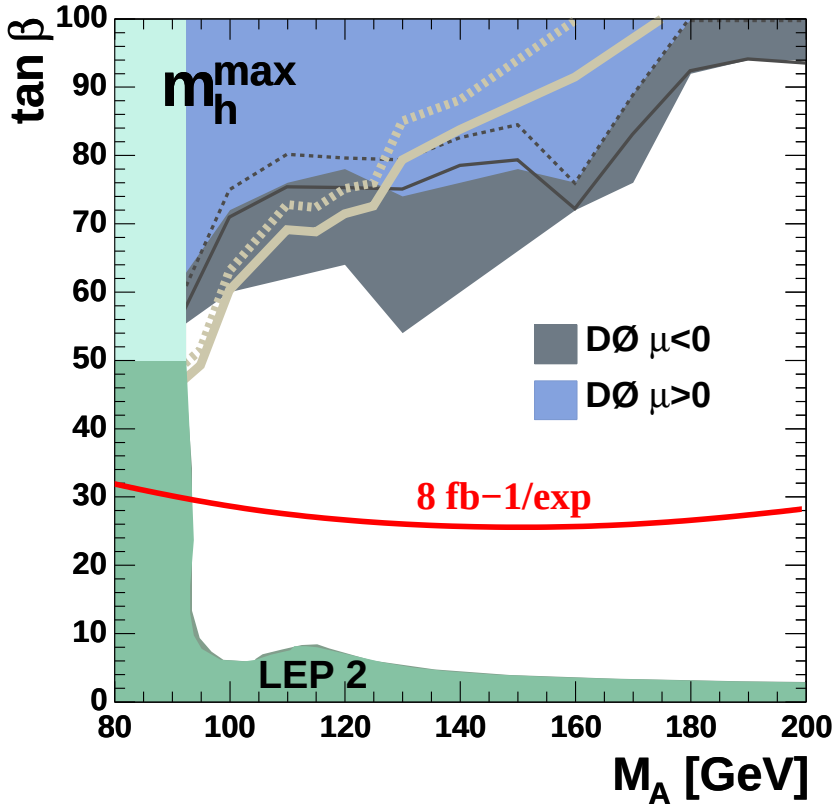
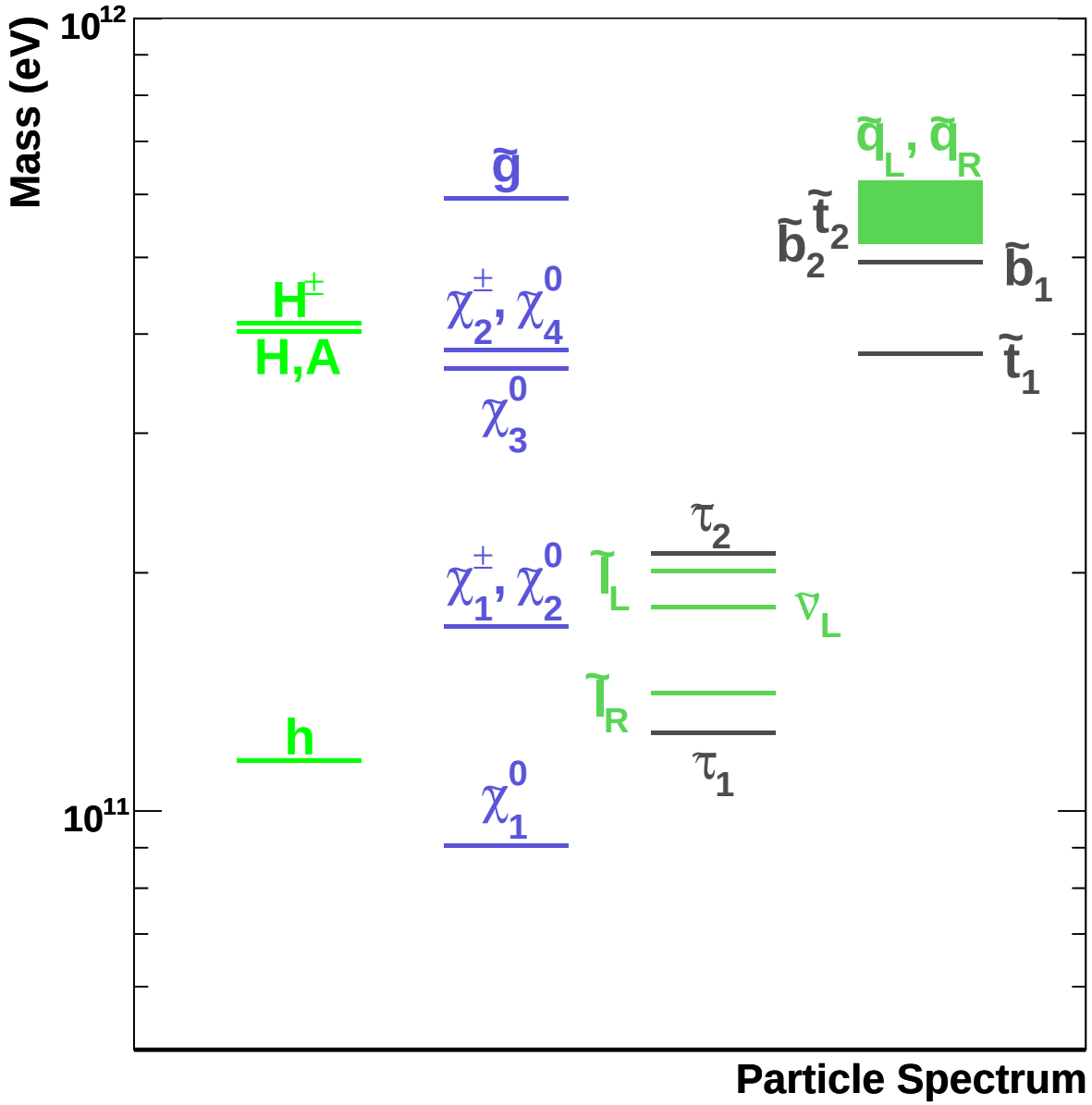
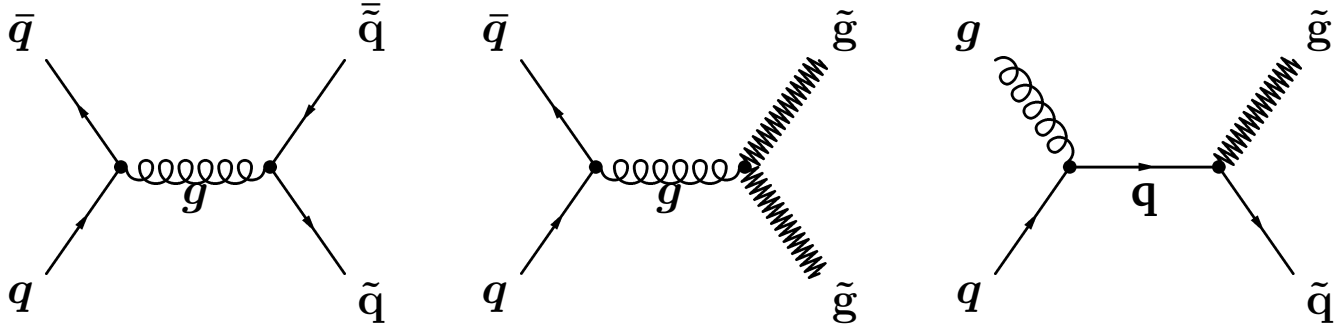


# What other particles does SUSY predict?



# Search for Supersymmetry – Squarks/Gluinos




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

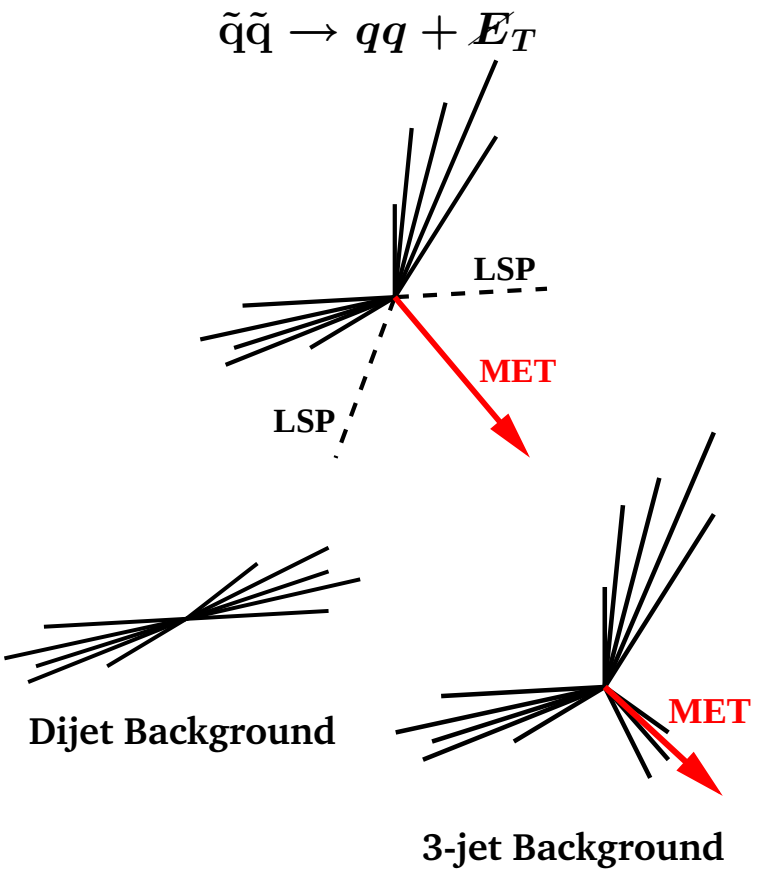
  → large cross sections at hadron colliders

- **Decays: jets + LSP**
  - LSP assumed to be stable ($R_p$ conserved)

  → Signature: jets + $\not\!\!E_T$

- **DØ: 310 pb$^{-1}$ collected with dedicated trigger:**
  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 + $\not\!\!E_T$ |
| $m_{\tilde{q}} \approx m_{\tilde{g}}$ | $\tilde{q}\tilde{q}$,$\tilde{q}\tilde{g}$ | 2j/3j + $\not\!\!E_T$ |

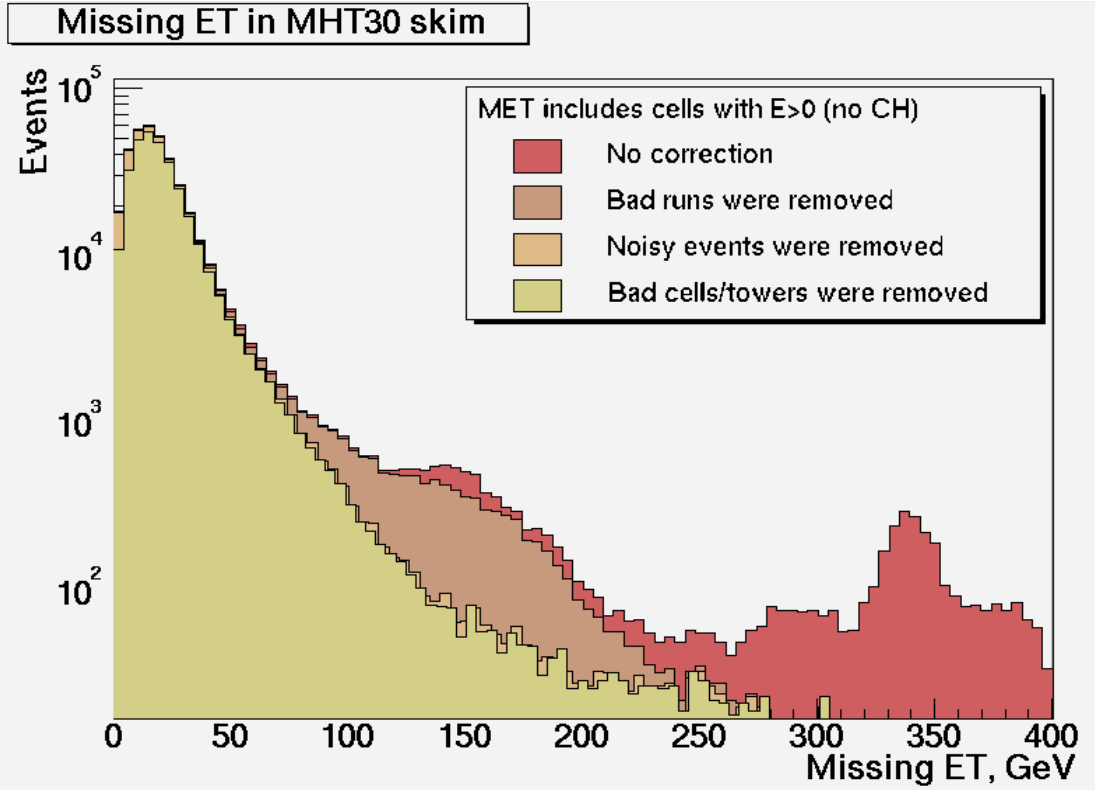


# Search for Supersymmetry – Squarks/Gluinos

**Searching for one SUSY event with high $\not\!\!E_T$ out of $10^{14}$ $p\bar{p}$ collisions**

→ very sensitive to rare calorimeter problems

Missing $E_T$ distribution (before quality cuts)




**Deployed extensive data quality monitoring effort**

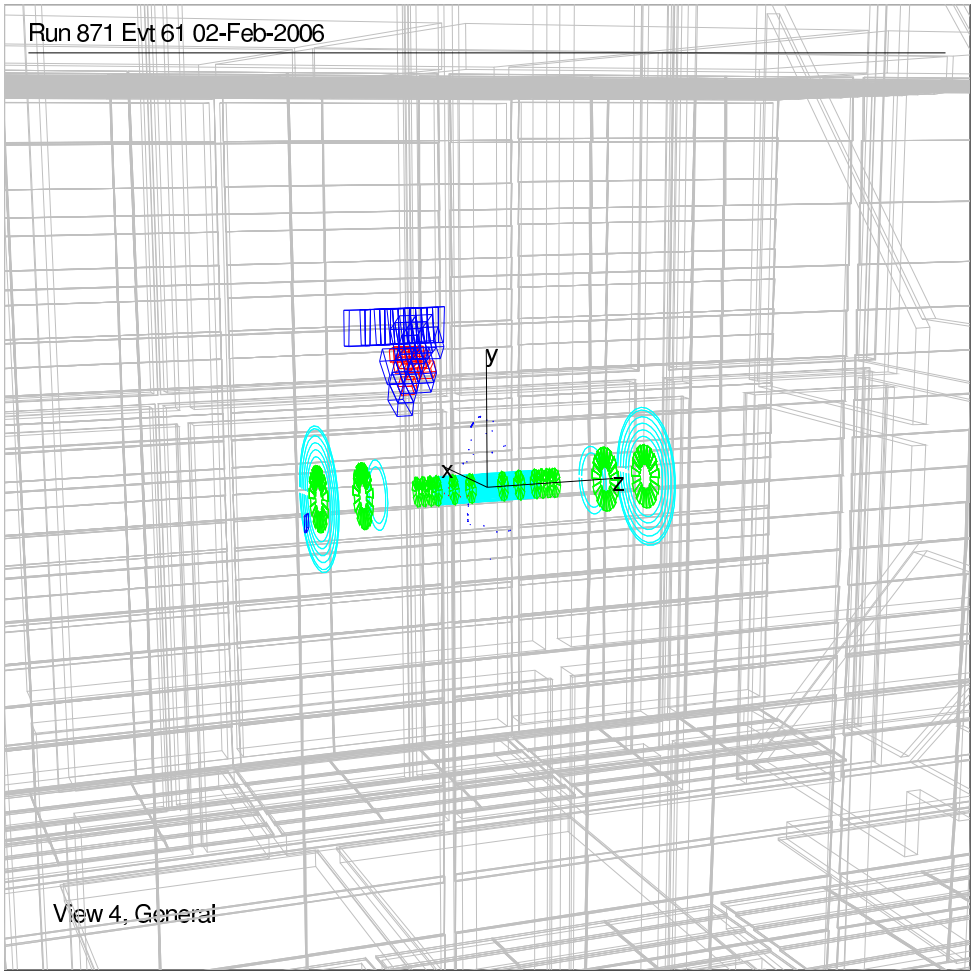
→ offline tools to veto bad blocks of data

→ early online detection and fixing of detector problems

# Search for Supersymmetry – Squarks/Gluinos

**Note: Distinction of noise and new physics non-trivial**

- **Should this event be discarded as noise?:**



# Search for Supersymmetry – Squarks/Gluinos

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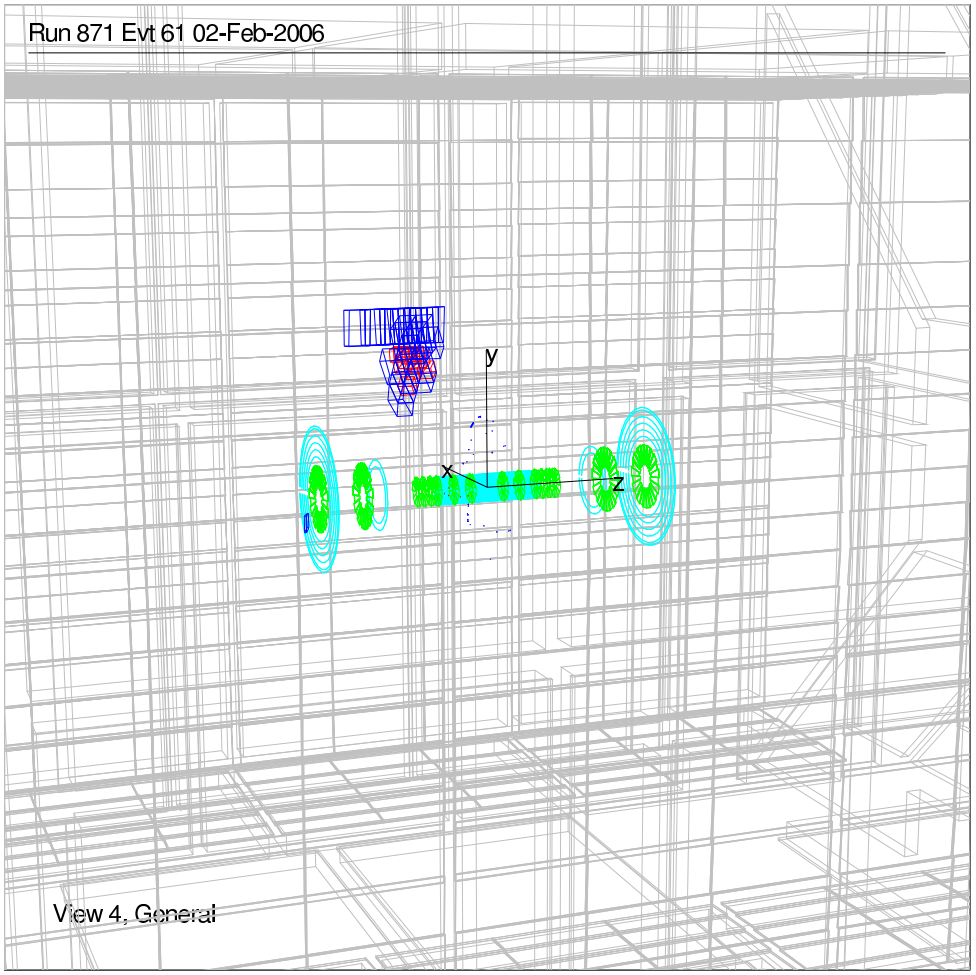
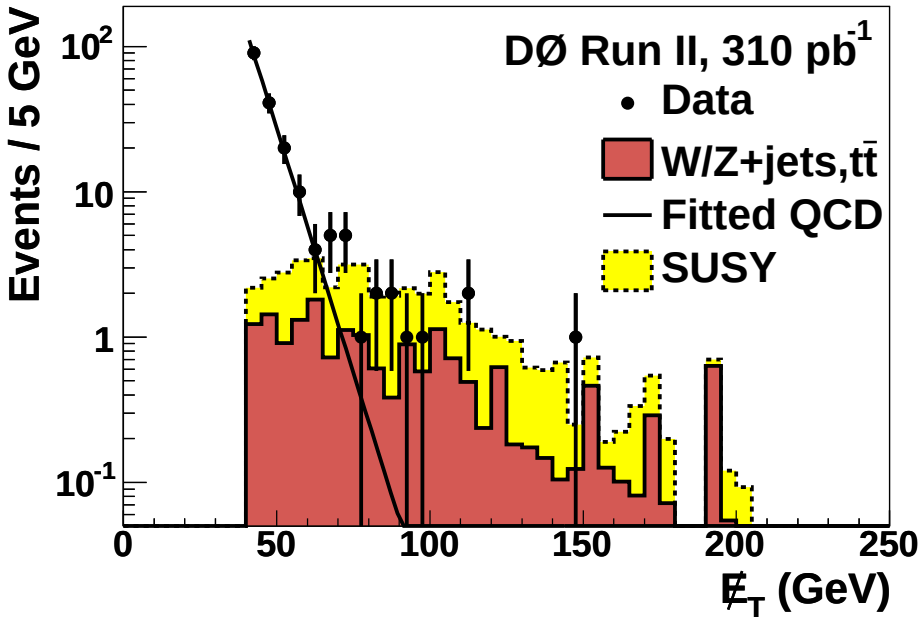


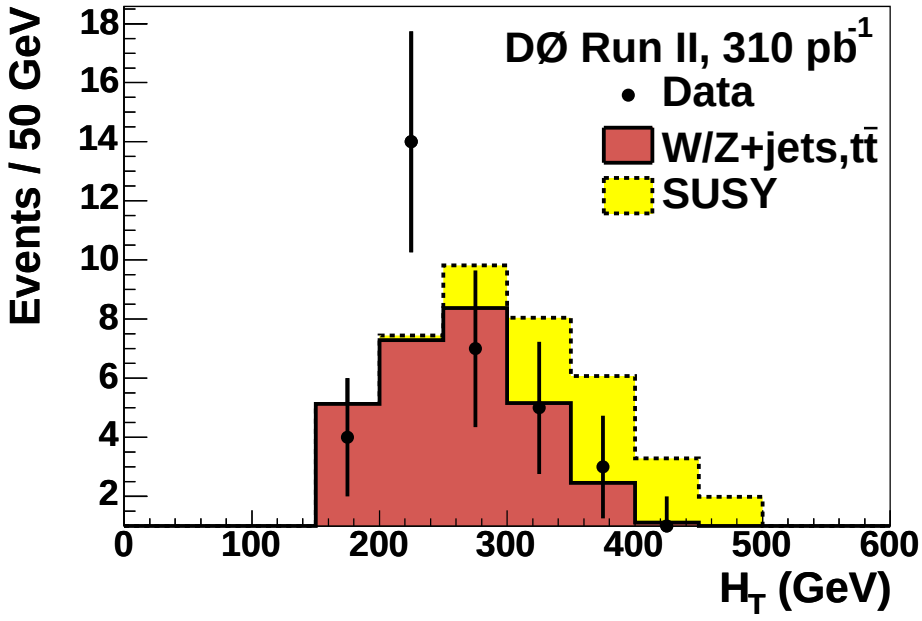

- **Event from simulation of long-lived gluinos (new DØ search based on 350 $pb^{-1}$)**
- **Gluinos can get stuck in calorimeter and decay at random times**

# Search for Supersymmetry – Squarks/Gluinos

4j+$\not\!\!E_T$ analysis

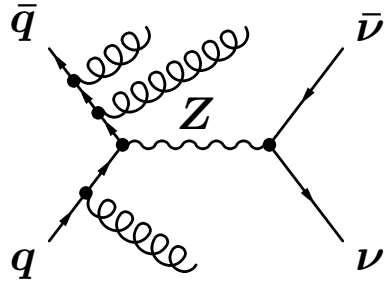



3j+$\not\!\!E_T$ analysis




**Main backgrounds:**

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

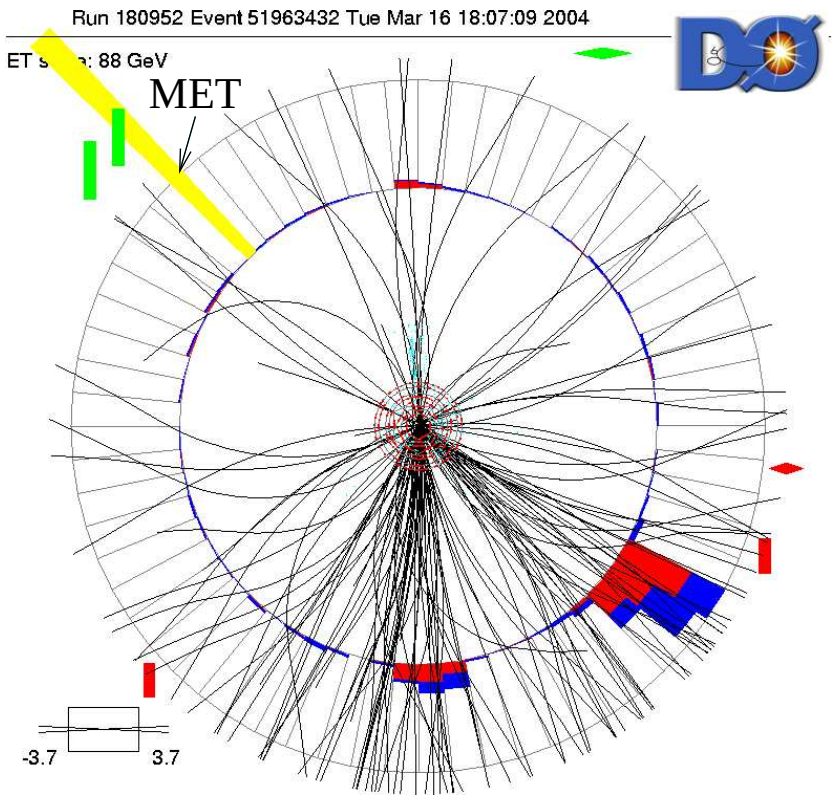



**Main selection cuts:**

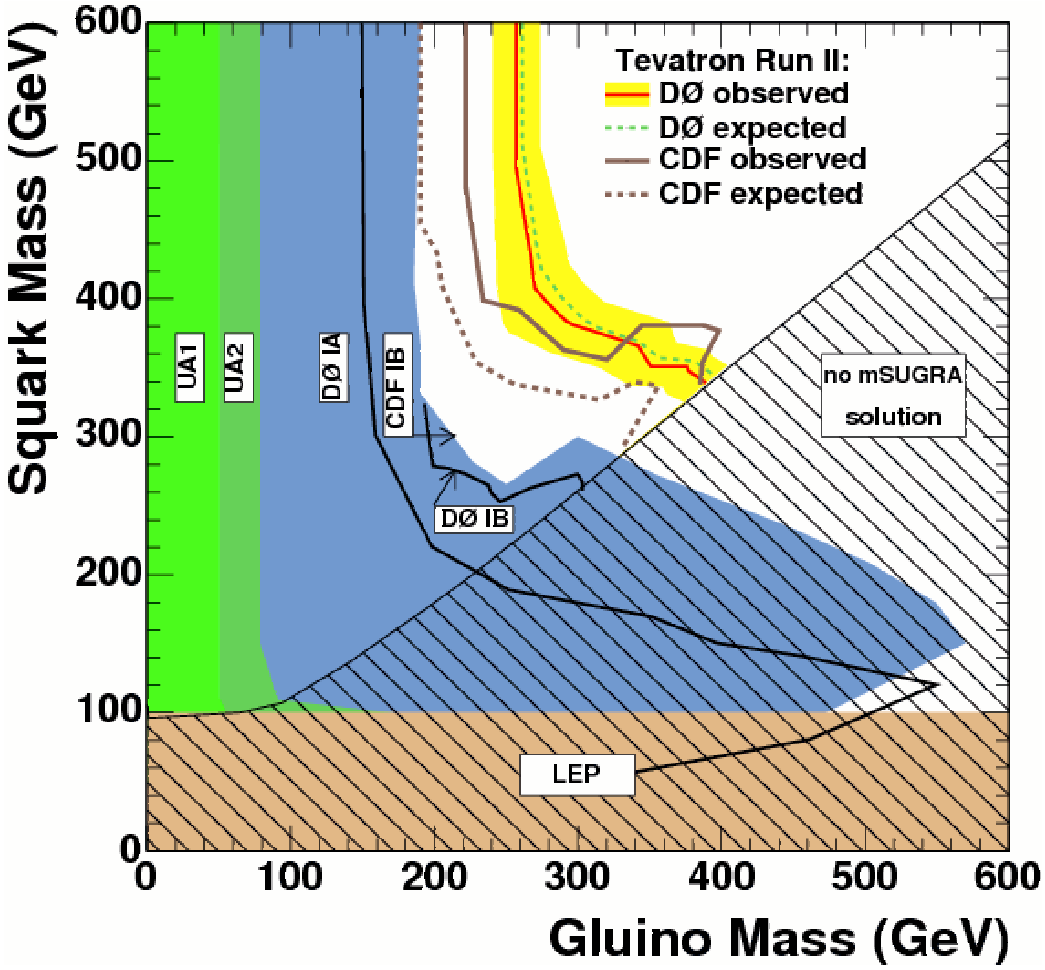
- 2/3/4 jets and large $\not\!\!E_T$
- angular separation $\not\!\!E_T$, jets
- isolated lepton veto

| 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 + $\not\!\!E_T$ | >175 GeV | >275 GeV | $4.8^{+4.5}_{-2.2}$ | 6 |
| $m_{\tilde{q}} > m_{\tilde{g}}$ | $\tilde{g}\tilde{g}$ | 4j + $\not\!\!E_T$ | >75 GeV | >225 GeV | 10.3±2.6 | 10 |
| $m_{\tilde{q}} \approx m_{\tilde{g}}$ | $\tilde{q}\tilde{q},\tilde{q}\tilde{g}$ | 2j/3j + $\not\!\!E_T$ | >100 GeV | >350 GeV | 3.9±1.3 | 4 |

# Search for Supersymmetry – Squarks/Gluinos



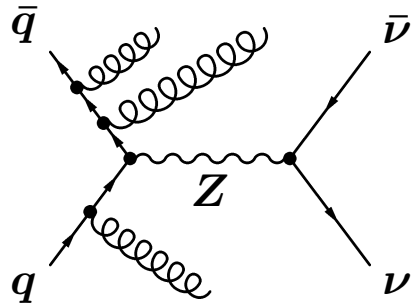

$\tilde{q}\tilde{q}$ candidate event
($\not\!\!E_T$=354 GeV, $p_T^{j1}$=264 GeV,
$p_T^{j2}$=106 GeV)



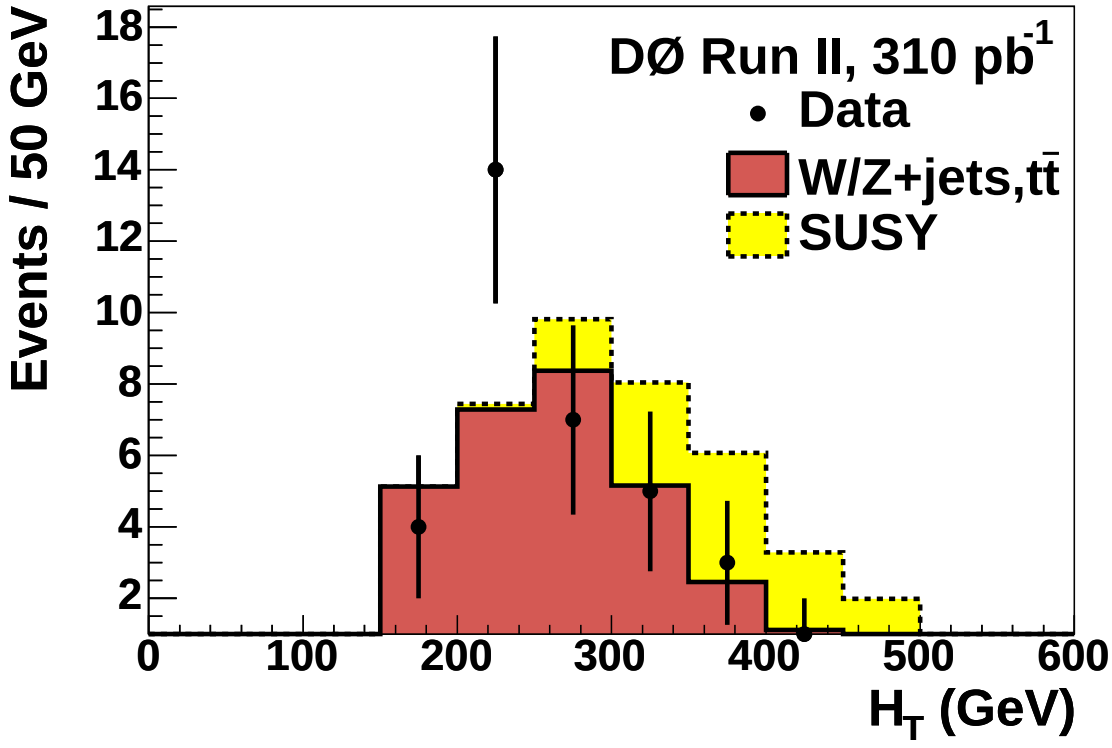

- No evidence for squark/gluino production at the Tevatron
- New limits in squark/gluino mass plane (mSUGRA: $tan\beta = 3$, $A_0 = 0$, $\mu < 0$)
- Ultimate reach with 8 fb$^{-1}$: gluinos $\sim$320 GeV, squarks $\sim$400 GeV

# Search for Supersymmetry at LHC – V+jets Background

- Search for SUSY in Jets+$\not\!\!E_T$ is flagship analysis at the LHC
- Modelling of V+jets backgrounds is crucial
- Default pythia modelling is not adequate




DØ Squark/Gluino Search



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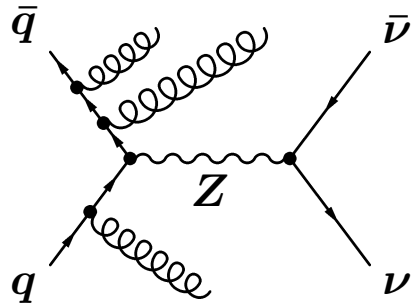
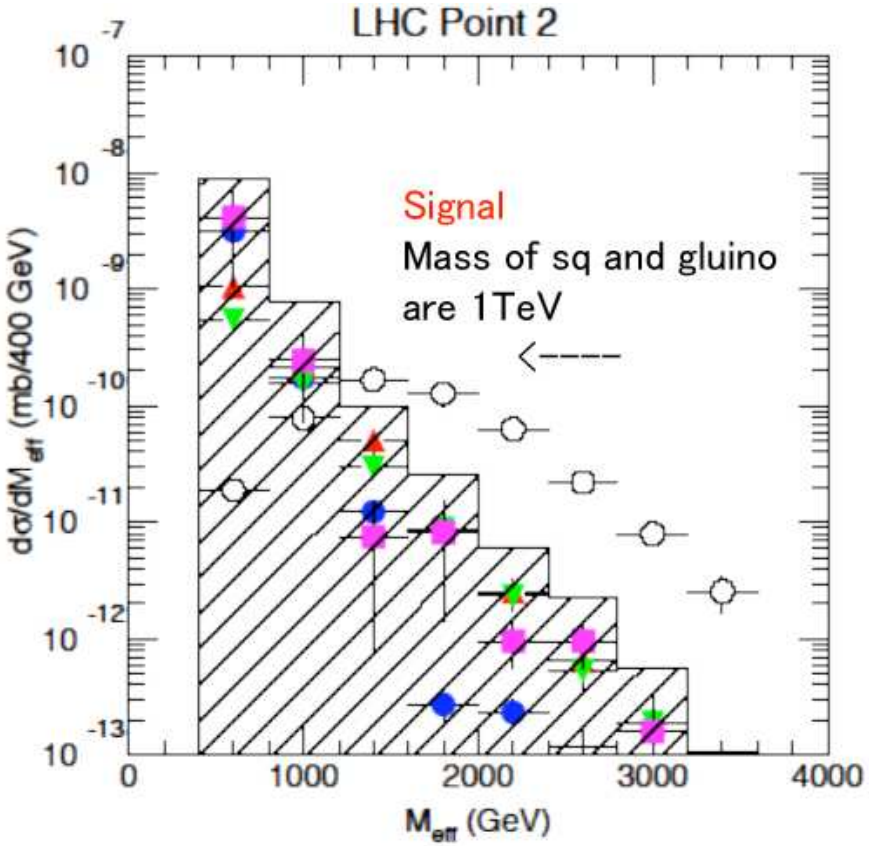
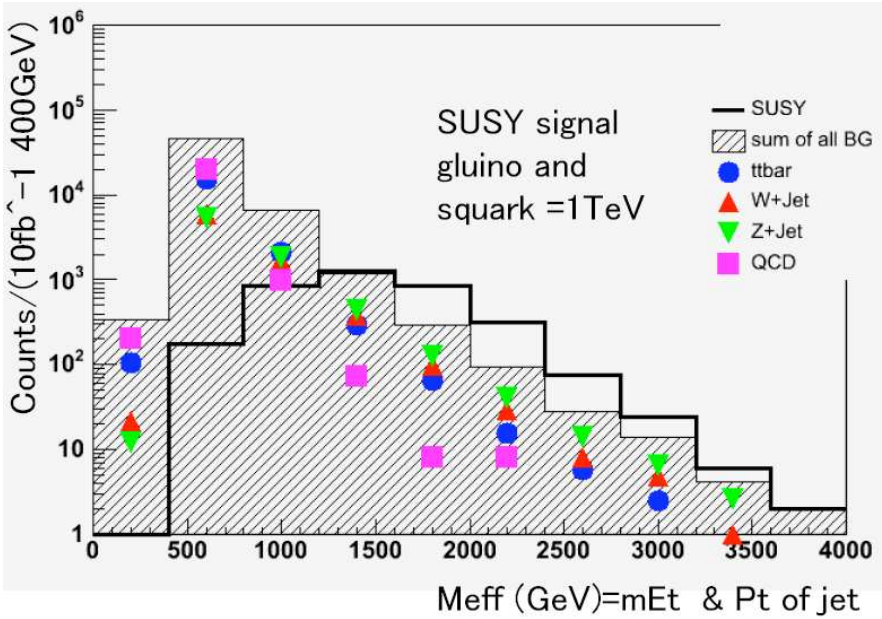



**ATLAS TDR Study (Parton Shower MC)**




**New Study (Matrix Element MC)**

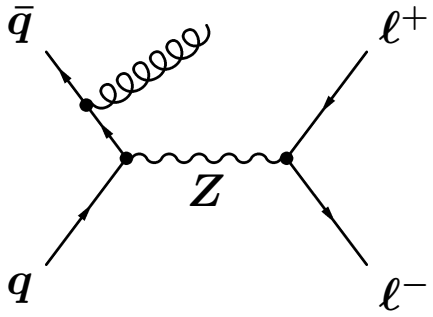



**(S. Asai et al.)**

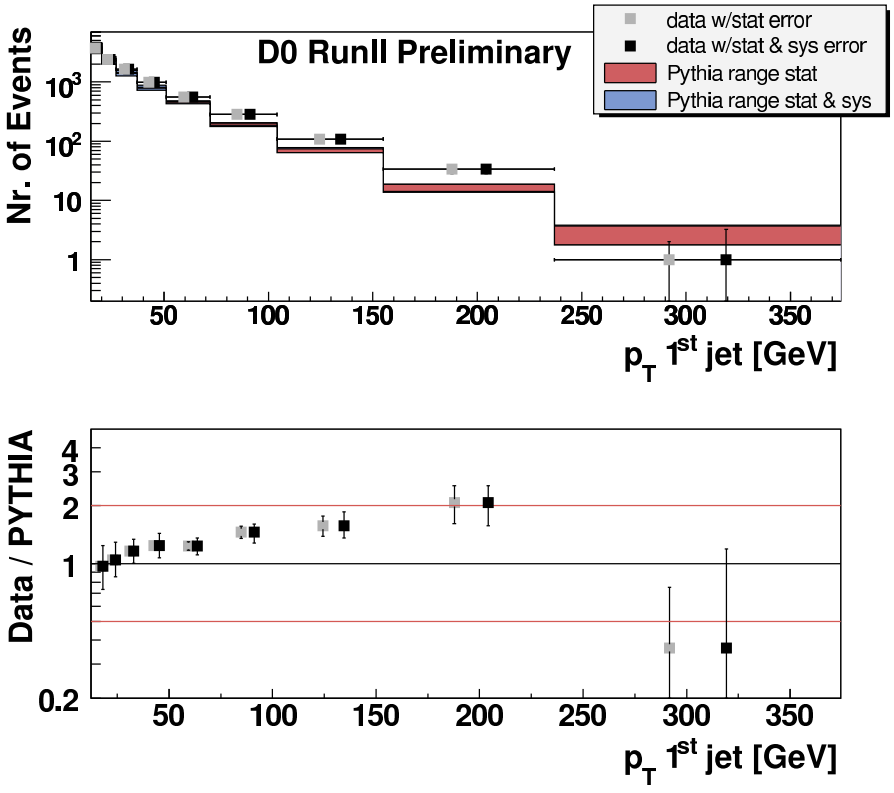
# Vector Boson plus Jet Production at the Tevatron

## Dedicated DØ Analyses to test new MC Generators in Z+jets data (950 pb$^{-1}$)

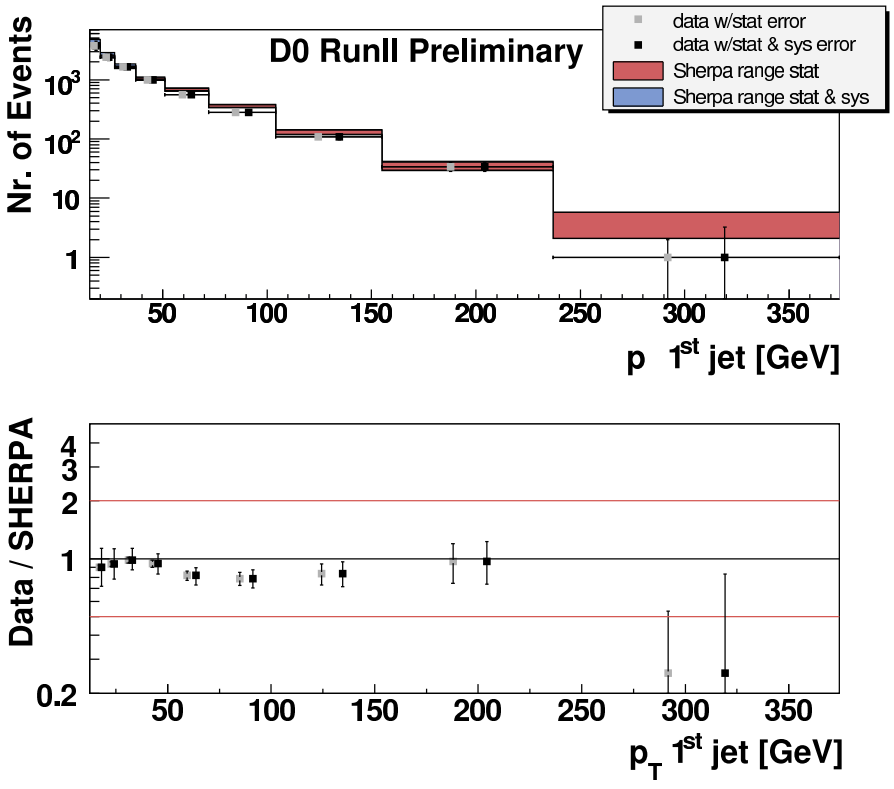
### $P_T$ Distribution of leading Jet




### DØ Data vs. PYTHIA



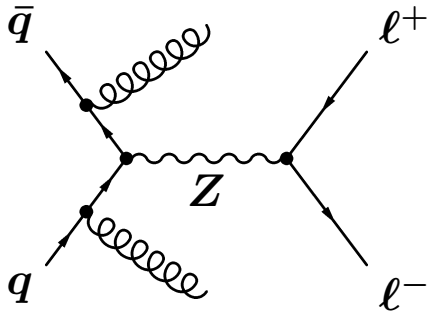

### DØ Data vs. SHERPA



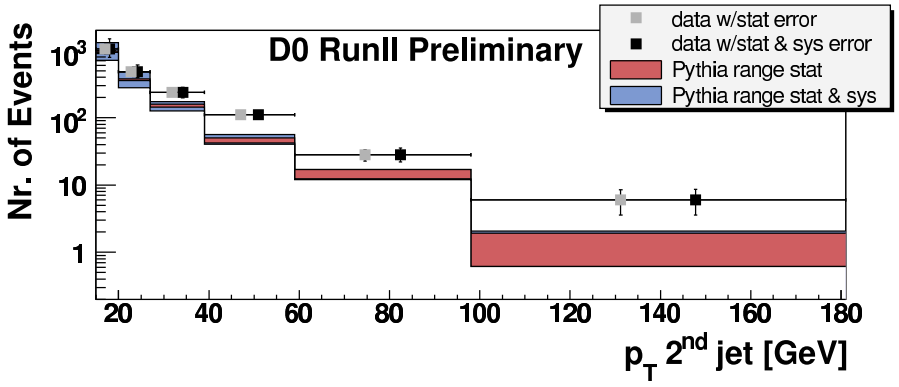
# Vector Boson plus Jet Production at the Tevatron

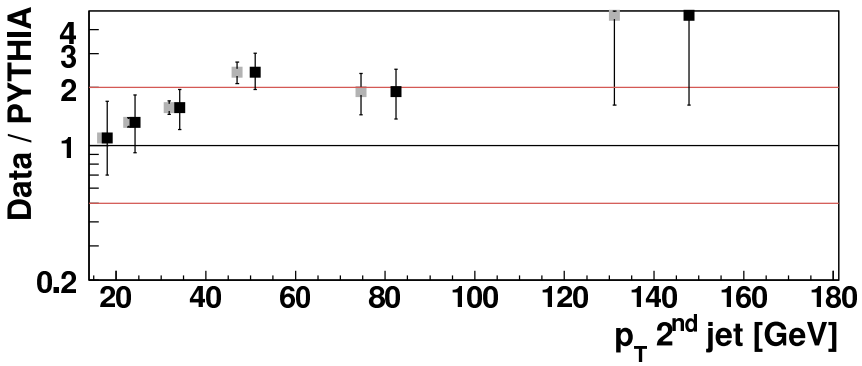
## Dedicated DØ Analyses to test new MC Generators in Z+jets data (950 $pb^{-1}$)

### $P_T$ Distribution of next-to-leading Jet




### DØ Data vs. PYTHIA

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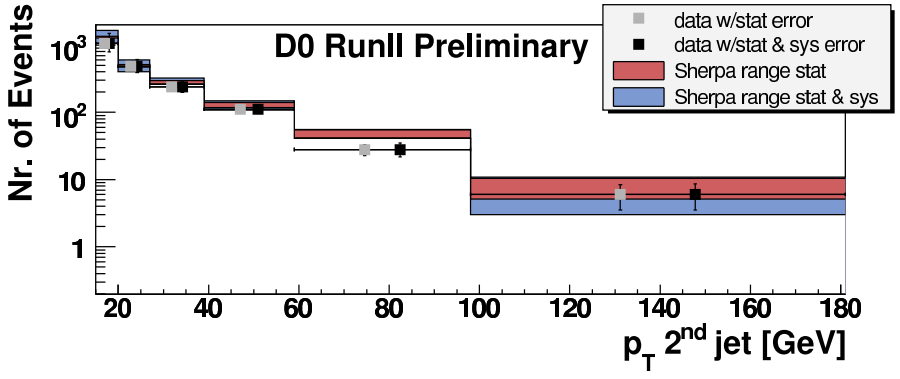


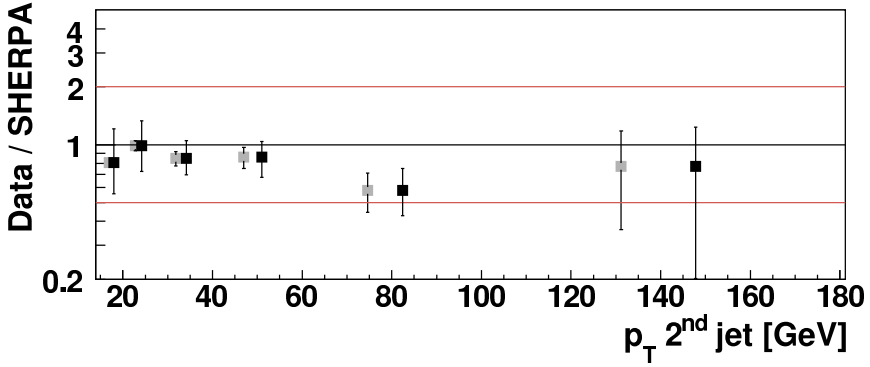

# Vector Boson plus Jet Production at the Tevatron

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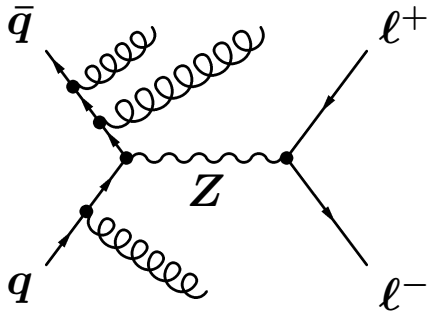
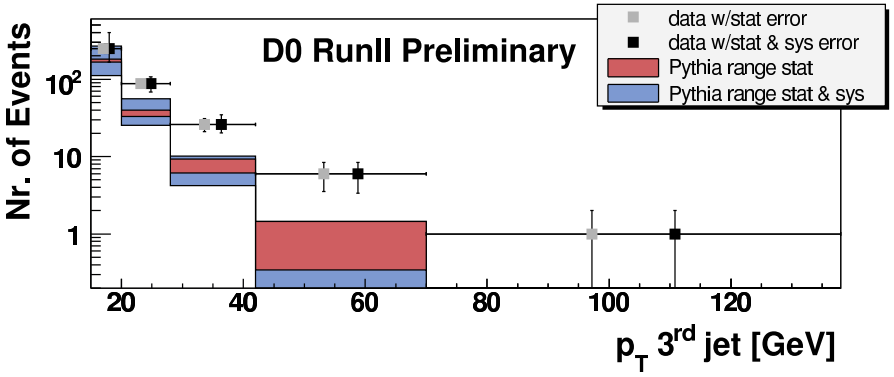
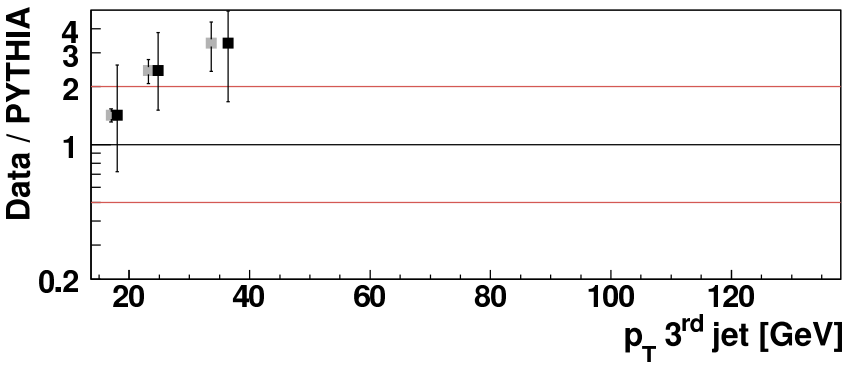
### $P_T$ Distribution of next-to-next-to-leading Jet

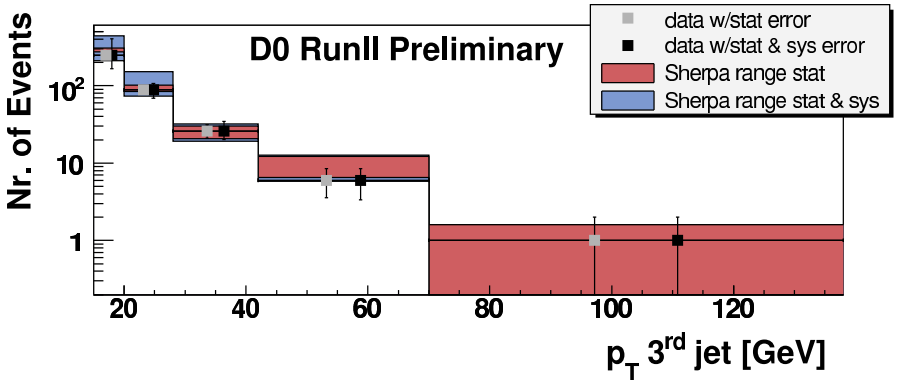


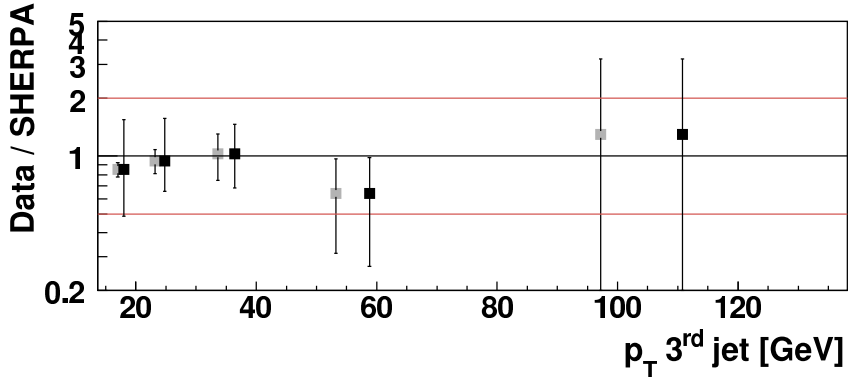

### DØ Data vs. PYTHIA




### DØ Data vs. SHERPA



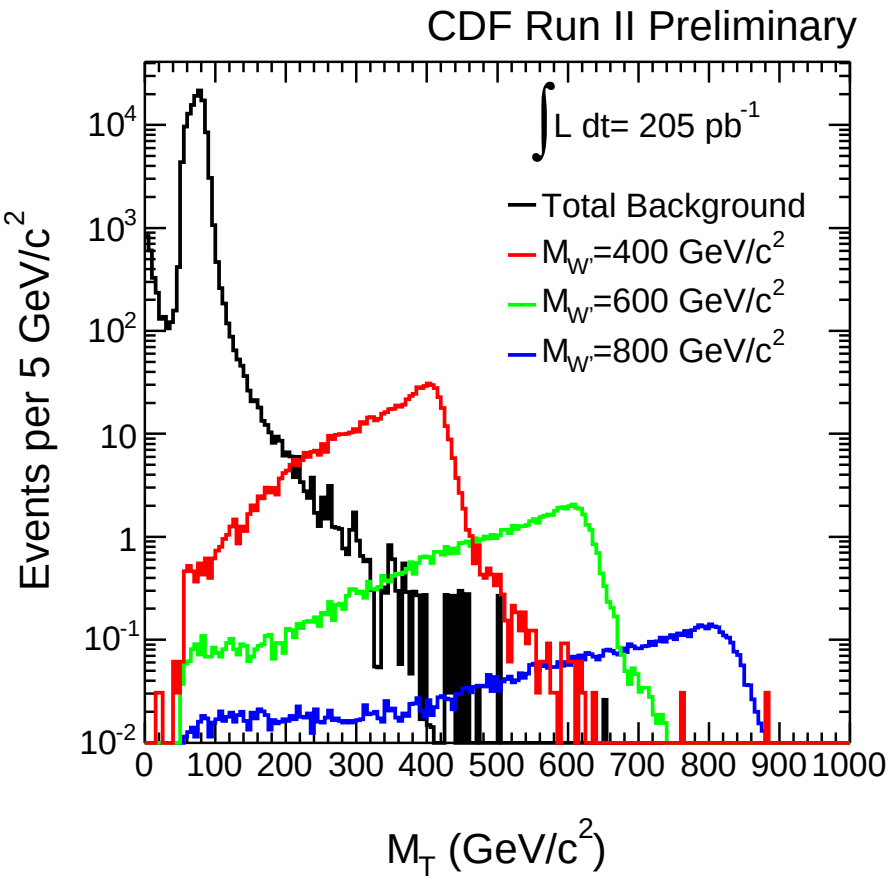
# Beyond Supersymmetry


**Still need to discuss: Gravitons, extra gauge bosons**

# Search for Heavy Gauge Bosons

**Many models predict extra charged or neutral gauge bosons (W', Z')**

**→ search for leptonic decays of high-mass resonances: W'→ $\ell\nu$, Z'→ $\ell\ell$**



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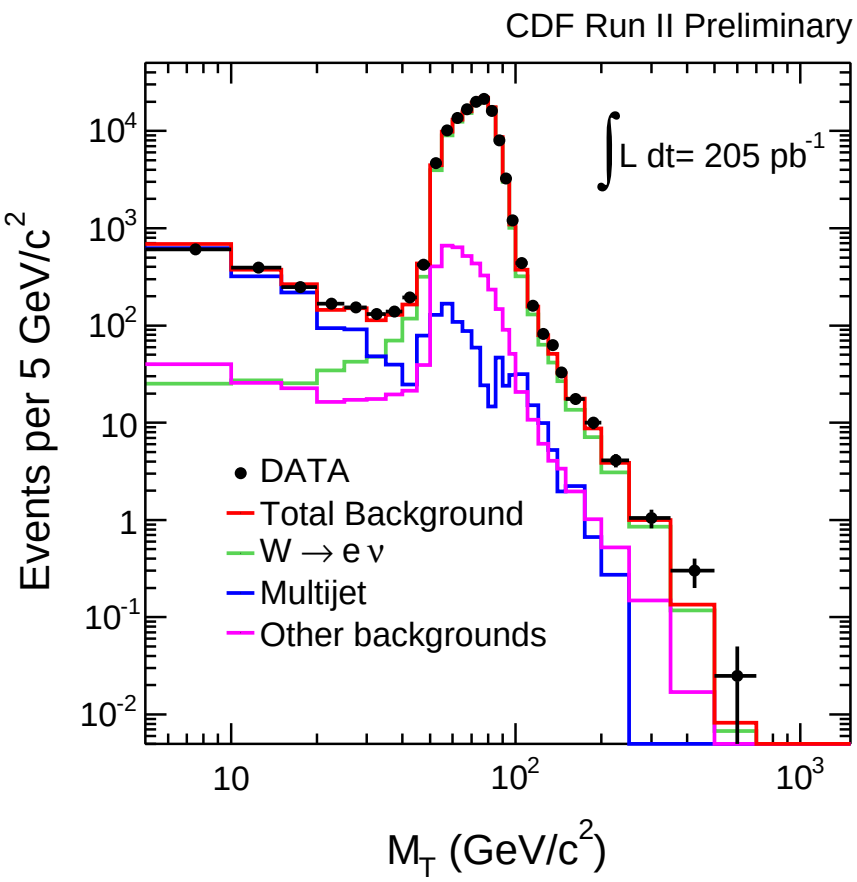
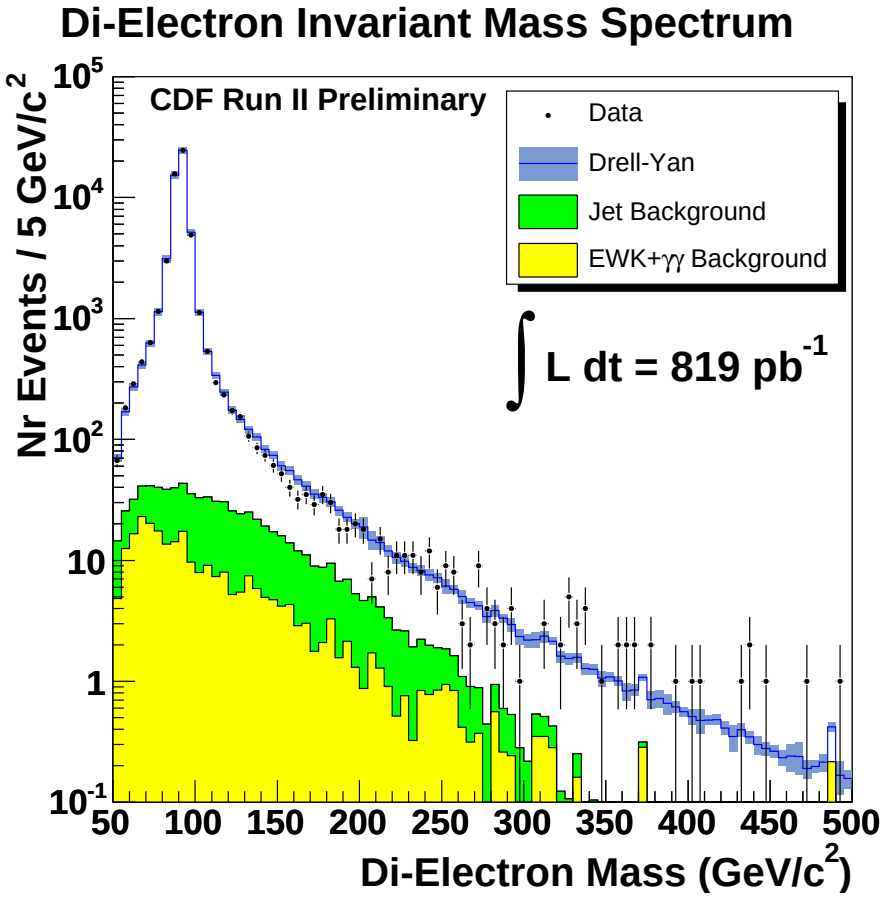



**Limit (CDF): $M_{W'}$>788 GeV**



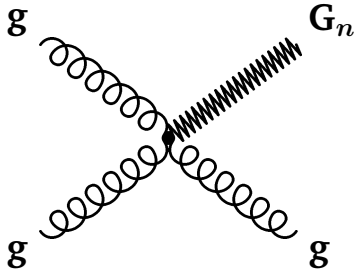

**Limit (CDF): $M_{Z'}$>850 GeV**

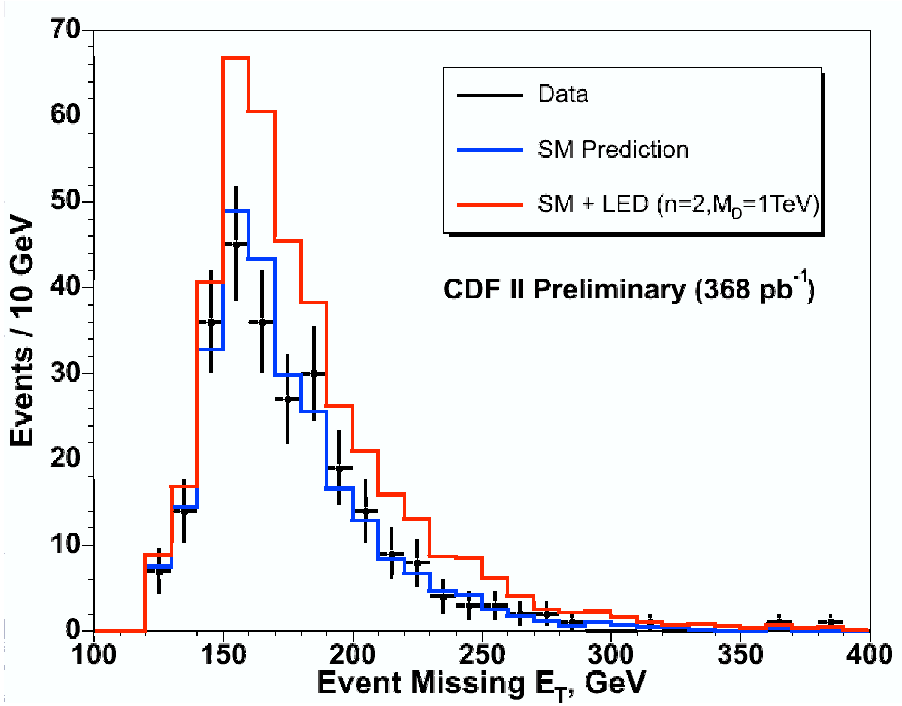
# Search for Extra Dimensions – Graviton Production

## Large Extra Dimension (ADD)

**Gravitons escape detection**

→ monojet signature



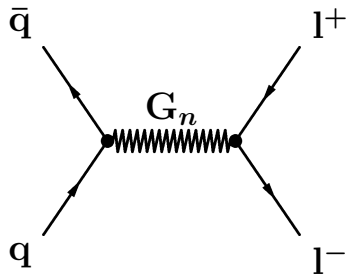



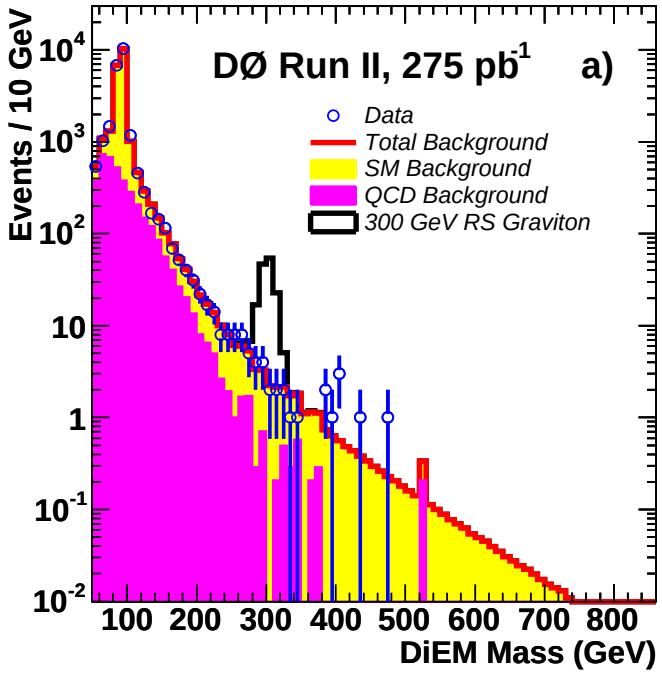

Limits (CDF): $M_D$ >1.33 TeV (n=2)

## Randall-Sundrum Gravitons

**Graviton states are heavy**

→ dilepton/diphoton resonances




Limits (DØ): $M_G$>785 GeV ($\kappa$=0.1)

# Conclusions

- Tevatron sets new limits on SM/MSSM Higgs bosons, SUSY, Extra Dimensions and W'/Z'
- Higgs searches about 1 year away from reaching sensitivity at 95% C.L.
- Vast amount of additional results available (see CDF/DØ web pages)
- Preparing for LHC physics with dedicated measurements at the Tevatron

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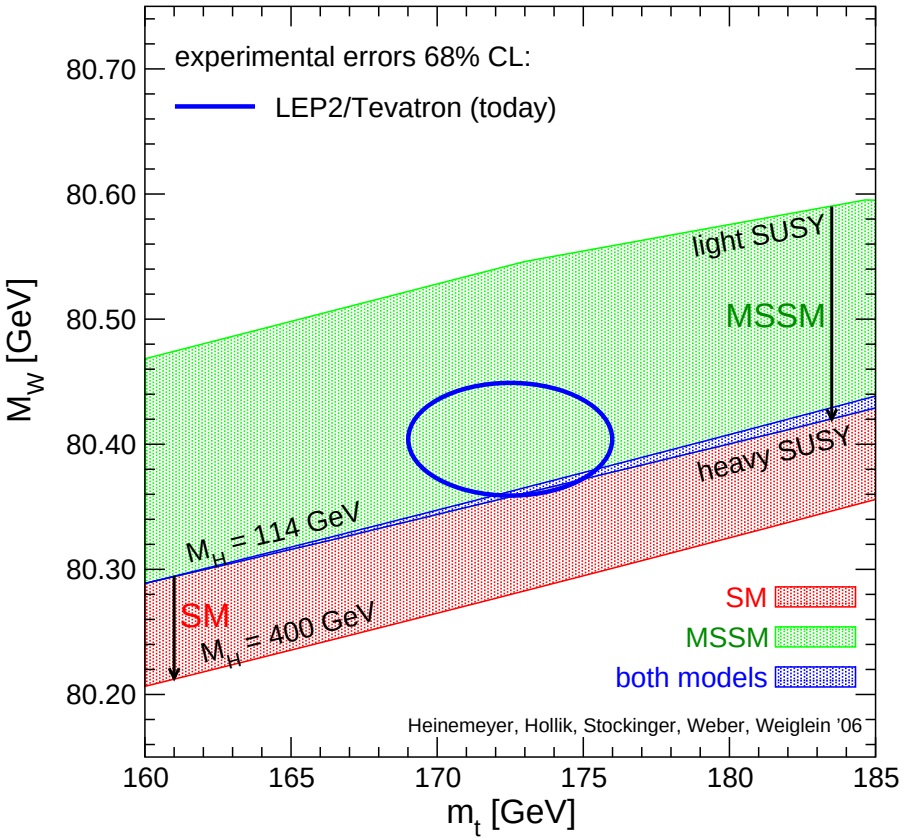
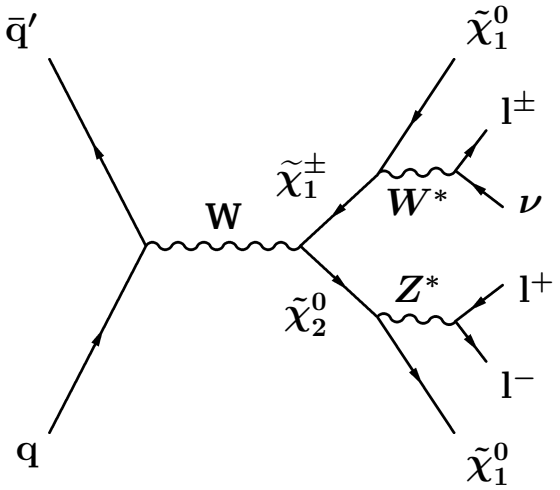


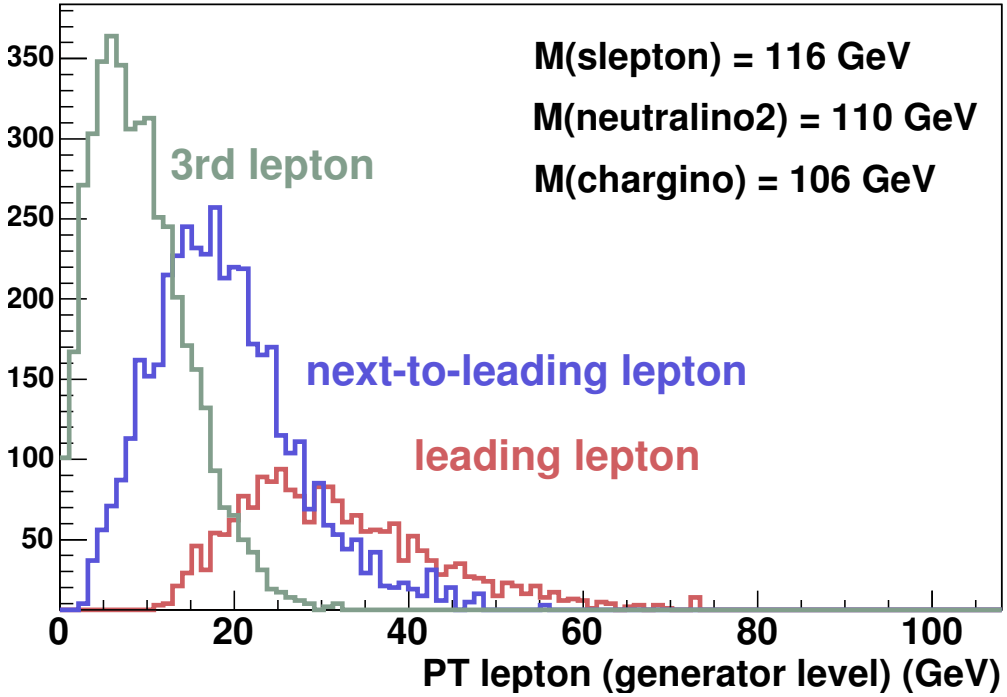

Let's hope we'll hit the gold mine!

# BACKUP

# Search for Charginos and Neutralinos

- **Production cross section (electroweak) relatively small**
  → **need clean leptonic signature to suppress backgrounds**
- **Golden channel:** $\tilde{\chi}^{\pm}\tilde{\chi}^{0}_{2} \rightarrow 3\ell + \not{E}_T$
- **Experimental Challenge: low-$p_T$ leptons**
  → **need multilepton triggers with low thresholds**
  → **need efficient lepton identification at low $p_T$**



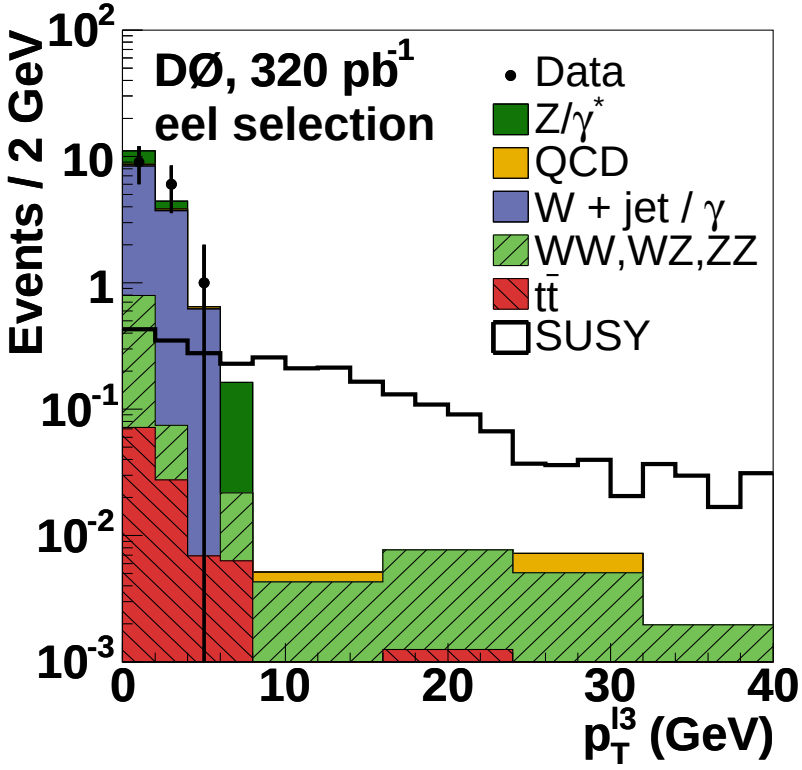



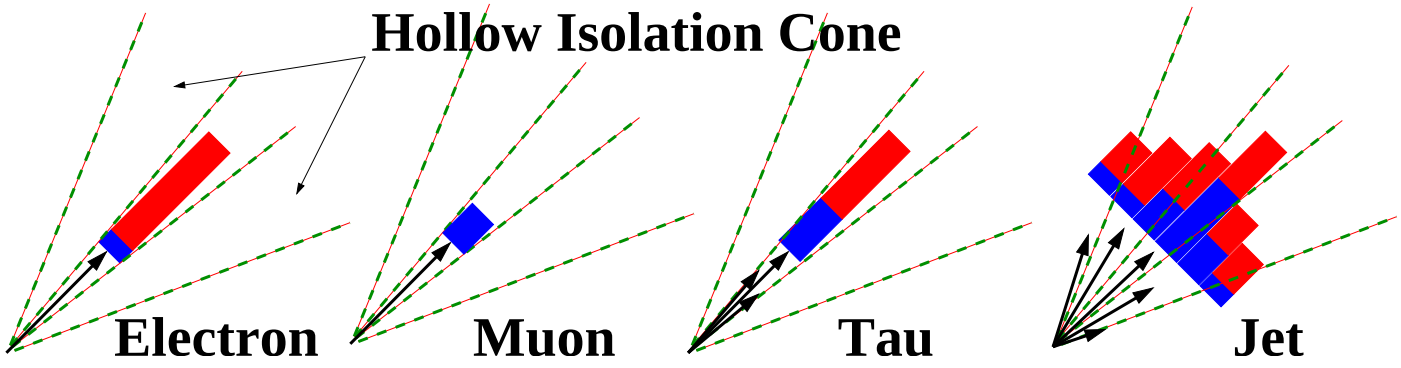
# Search for Charginos and Neutralinos

**Analysis Strategy:**

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

| 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 | >7 GeV |
| $\mu\mu\ell$ | >11 GeV | >5 GeV | >3 GeV |
| ls-$\mu\mu$ | >11 GeV | >5 GeV | – |



# Search for Charginos and Neutralinos

**Results (0.3–1.1 fb$^{-1}$):**

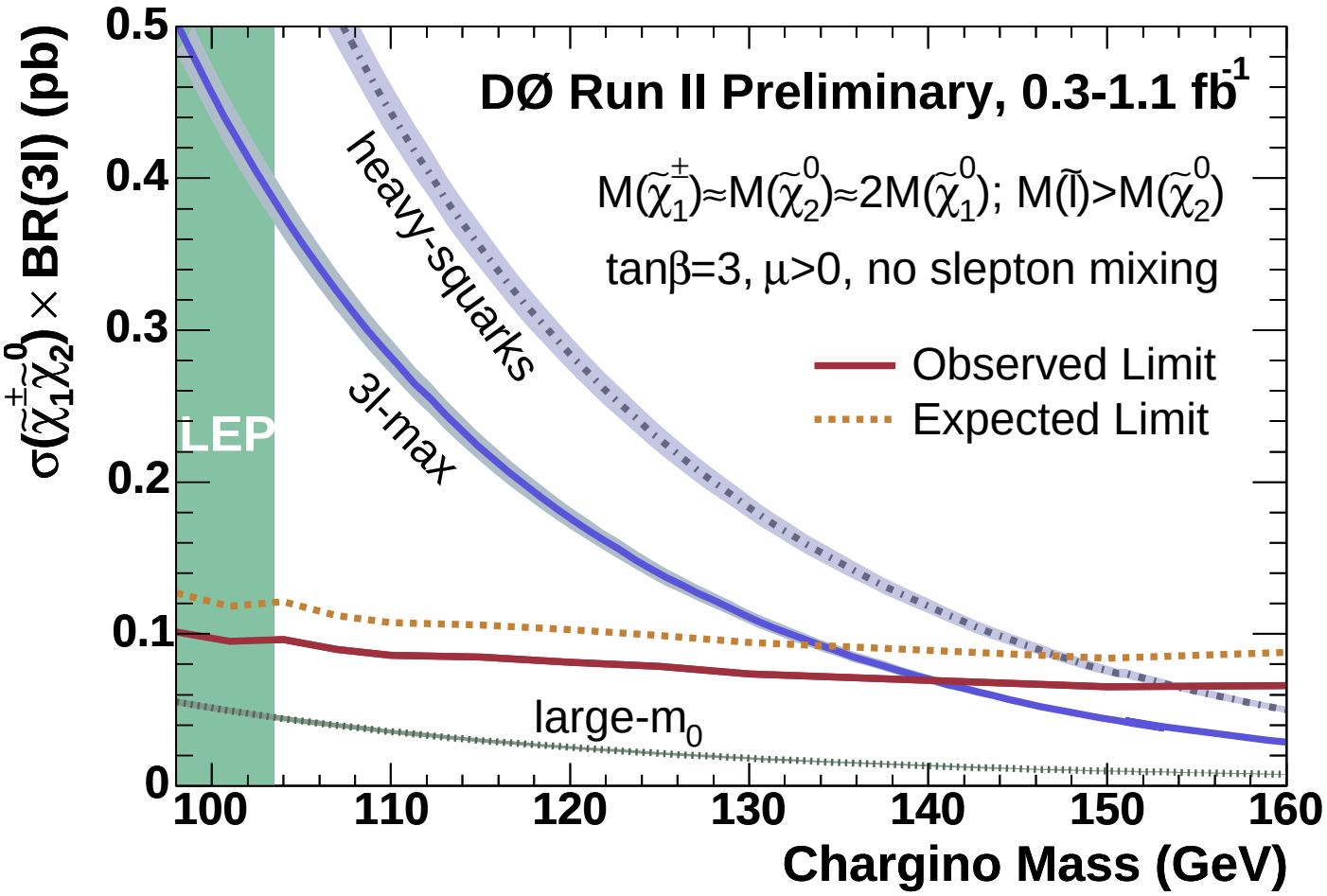
| Selection | Expected Background | Observed | Signal ($m_{\tilde{\chi}^{\pm}}$=110 GeV) |
|---|---|---|---|
| $ee\ell$ | 0.76±0.67 | 0 | 4.6±0.3 |
| $e\mu\ell$ | 0.31±0.13 | 0 | 1.6±0.1 |
| $\mu\mu\ell$ | 1.75±0.57 | 2 | 1.3±0.2 |
| ls-$\mu\mu$ | 1.10±0.40 | 1 | 4.2±0.7 |
| Combined | 3.92±0.98 | 3 | 11.7±0.8 |

– Backgrounds dominated by WZ, WW, W$\gamma$ (plus $b\bar{b}$ for dimuon channels)

→ No evidence for chargino/neutralino production

→ Limits on product of cross section and leptonic branching fraction

# Search for Charginos and Neutralinos

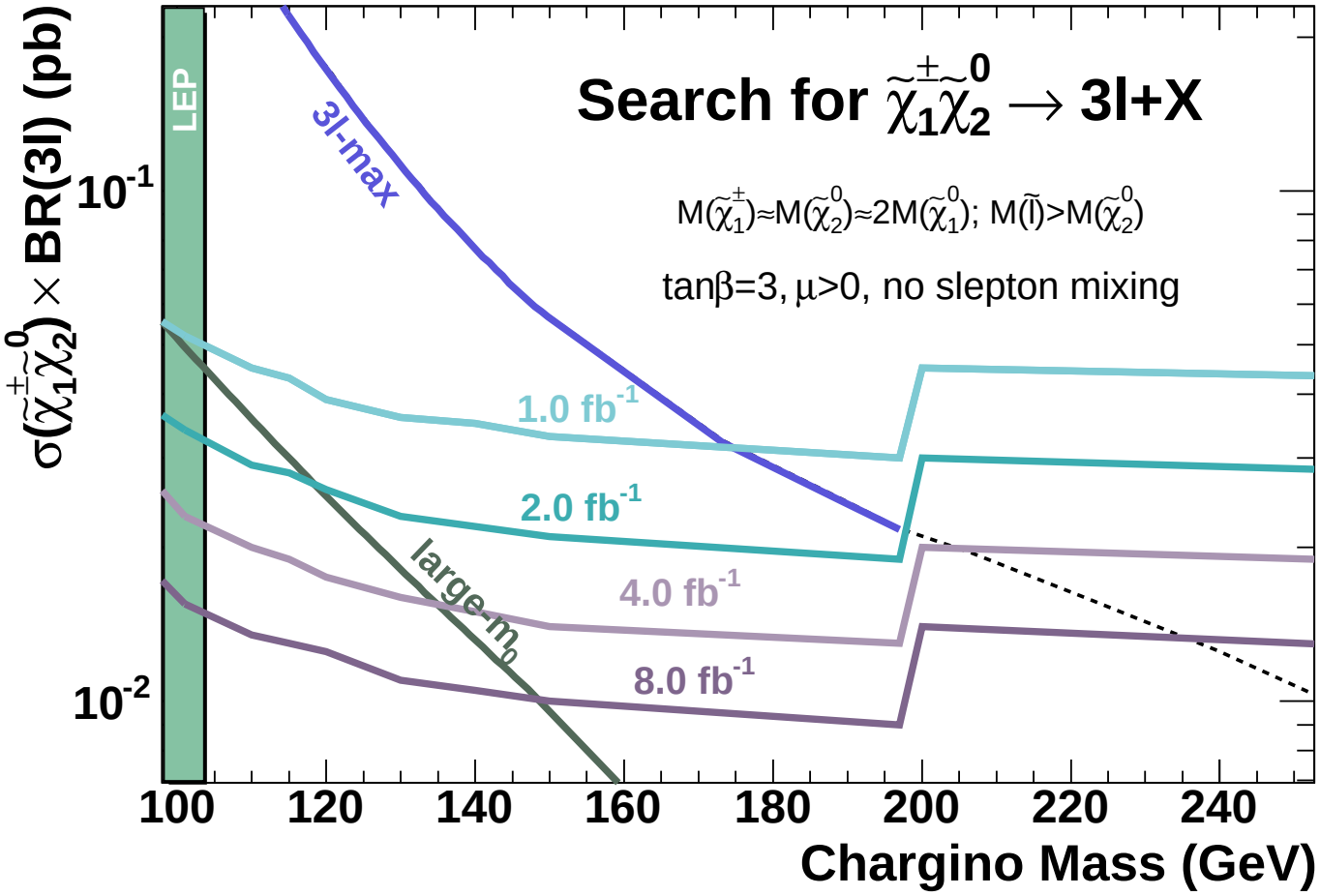



**Limits constrain SUSY beyond LEP chargino limits:**

- **$3\ell$-max scenario: $m_{\tilde{\chi}^\pm} > 140$ GeV**
- **heavy-squarks scenario: $m_{\tilde{\chi}^\pm} > 154$ GeV**

**Full update with 1 fb$^{-1}$ dataset currently in progress**

# Search for Charginos and Neutralinos

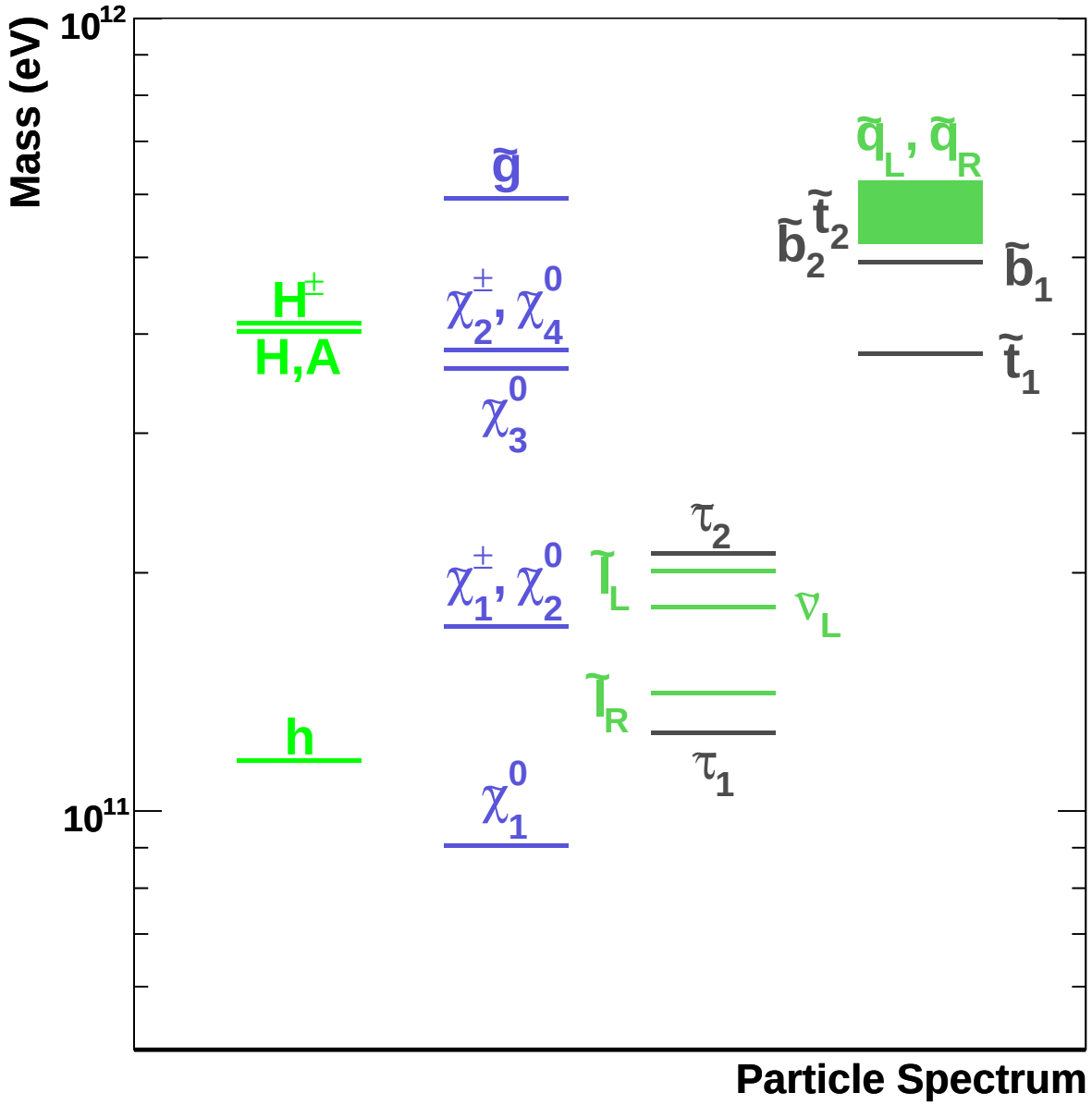



**Run IIb projections (assuming some analysis improvements):**

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

**Full update with 1 fb$^{-1}$ dataset currently in progress**

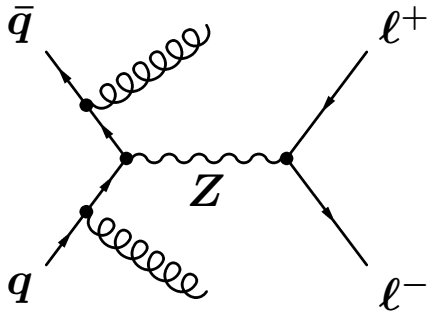
# Typical mass spectrum of SUSY particles



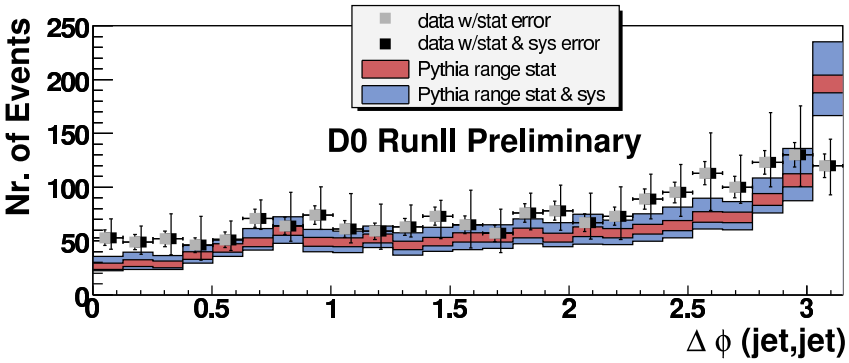
# Vector Boson plus Jet Production at the Tevatron

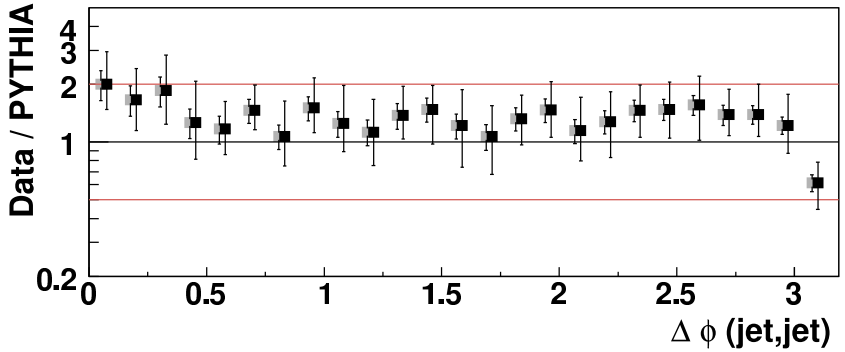
## Dedicated DØ Analyses to test new MC Generators in Z+jets data (950 $pb^{-1}$)

### Azimuthal angle between leading and next-to-leading Jet

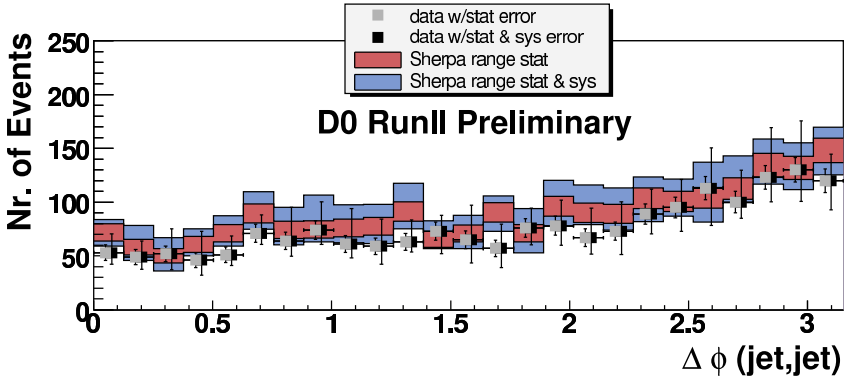


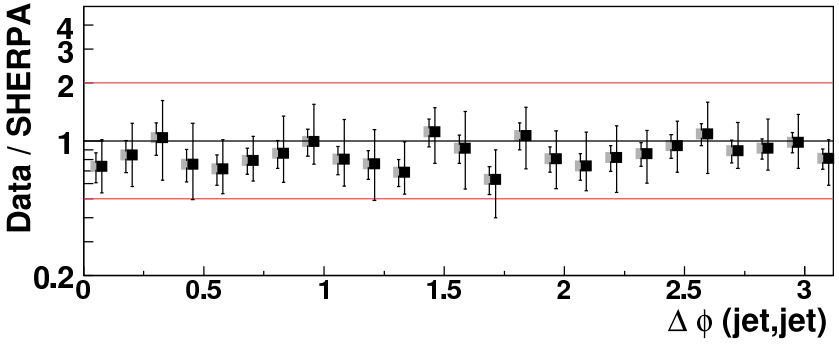

### DØ Data vs. PYTHIA



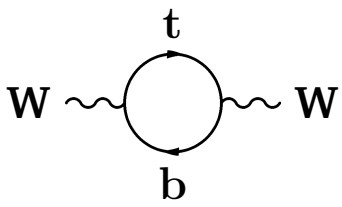

### DØ Data vs. SHERPA



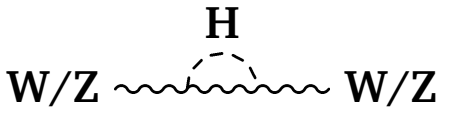



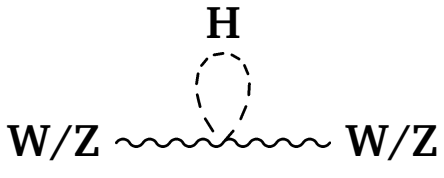
# Pinning down EWSB at the Tevatron

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

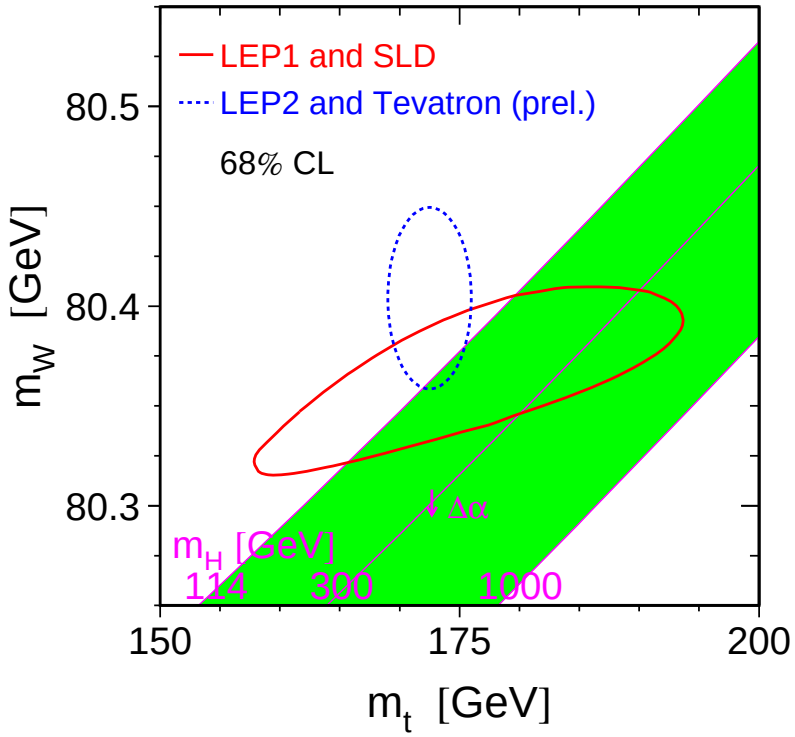


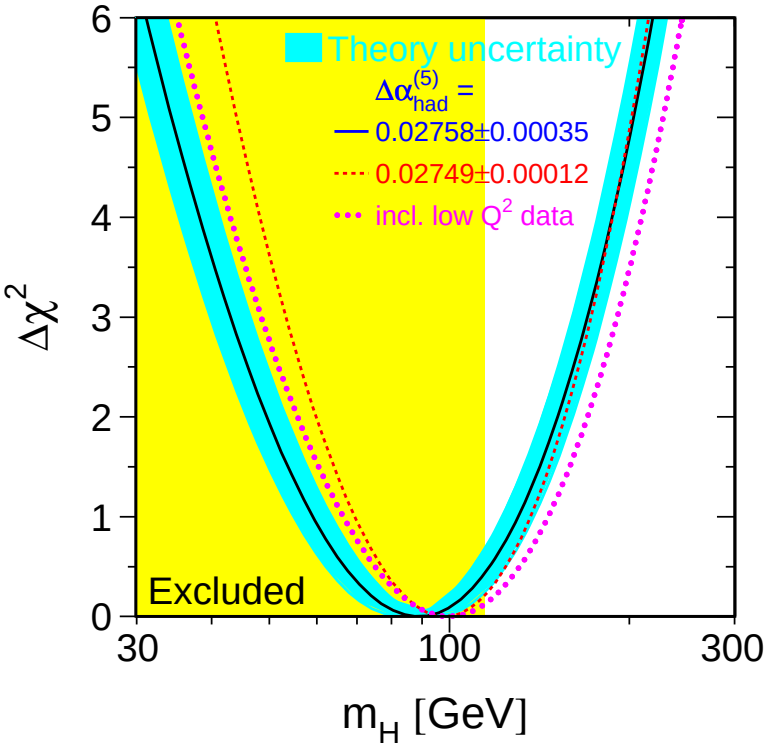

$\sim m^2_{\rm top}$




$\sim \ln \frac{m_H}{m_W}$




→ **Indirect constraints on Higgs boson mass:**

$m_H$=89 + 42 - 30 GeV

$m_H < 175$ GeV at 95% C.L.

# Pinning down EWSB at the Tevatron

**Current combined results from CDF and DØ:**

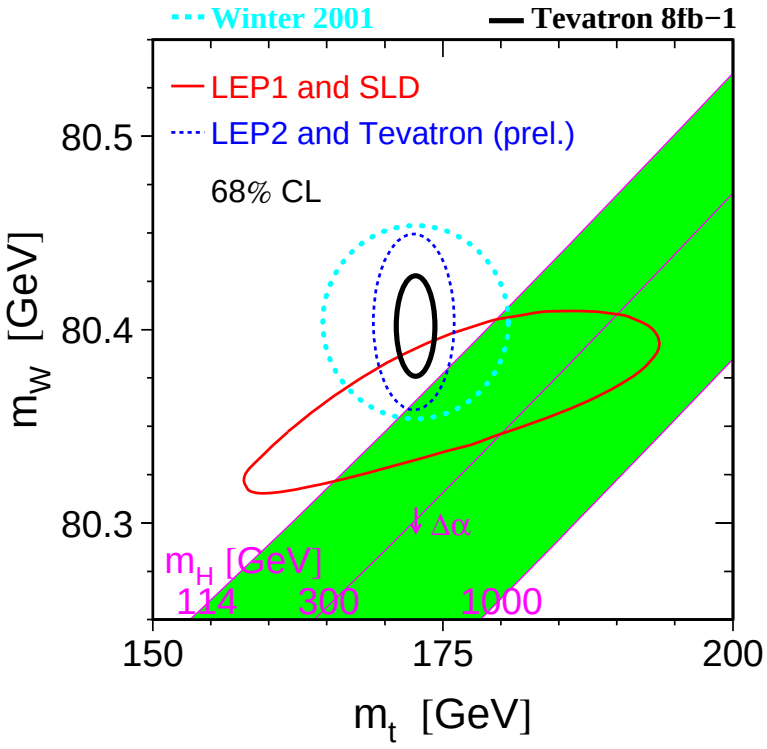
$m_t$ = 172.5±1.3(stat)±1.9(syst) GeV

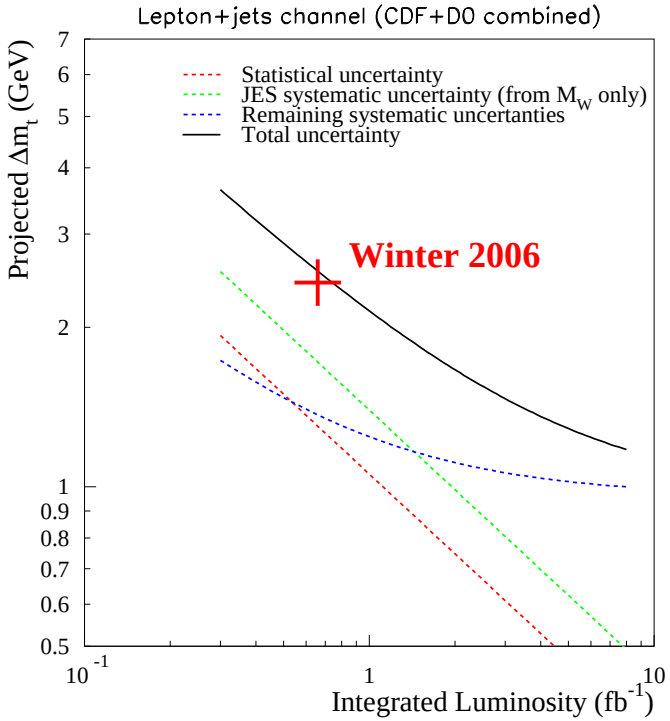
$m_W$ = 80.454±0.059 GeV (Run I)

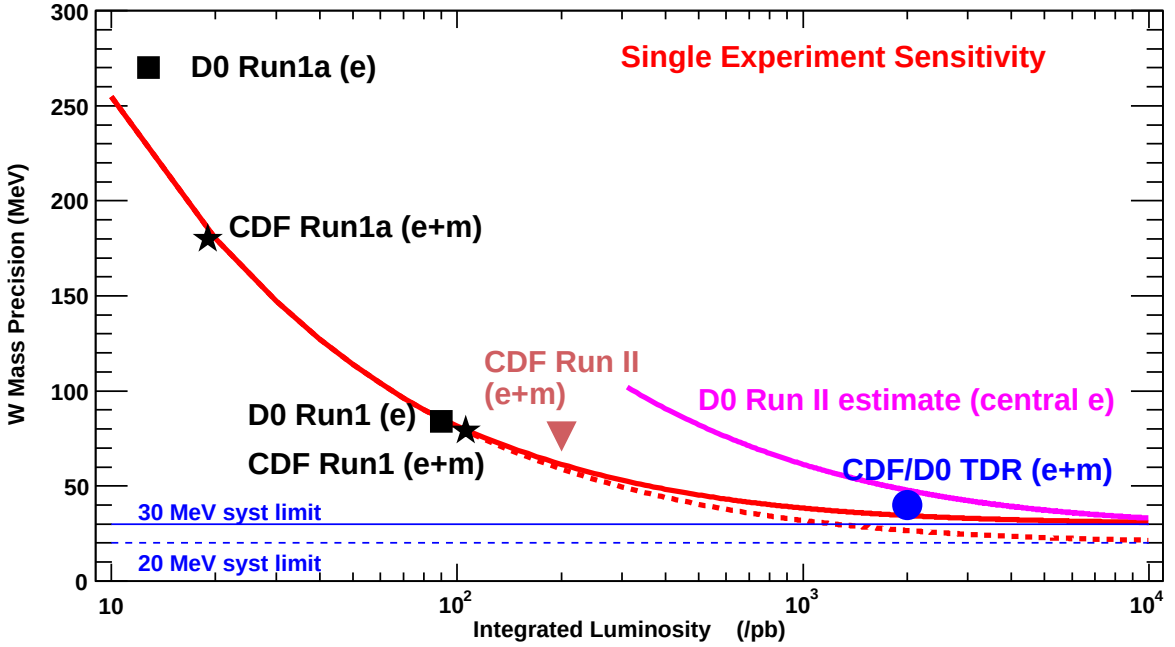
**Projected uncertainties for 8 fb$^{-1}$:**

$m_t$: ±1.2 GeV

$m_W$: ±20-30 MeV

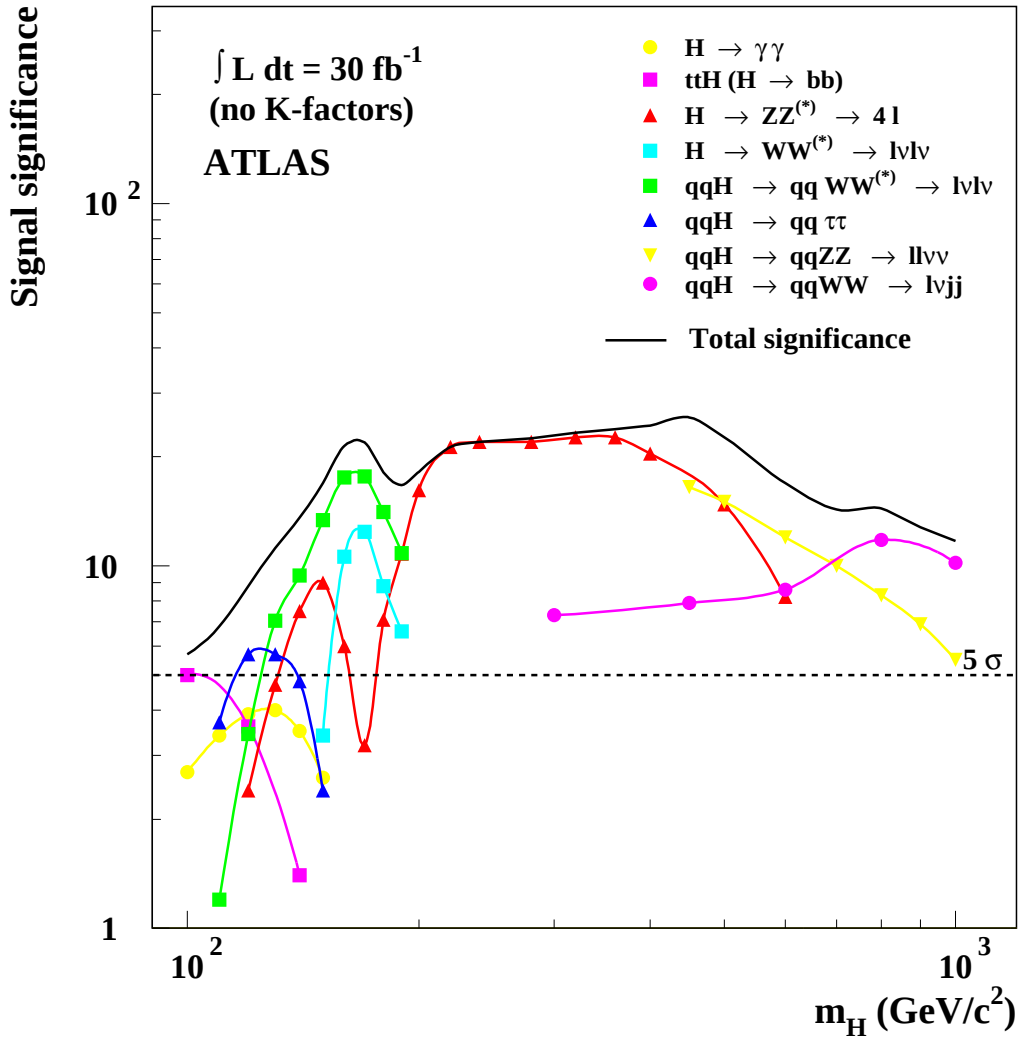


# Outlook: Search for SM Higgs boson at the LHC

- For discovery at $5\sigma$ level need LHC
- LHC sensitive across entire mass range with moderate luminosity
- Note: discovery in low-mass region non-trivial

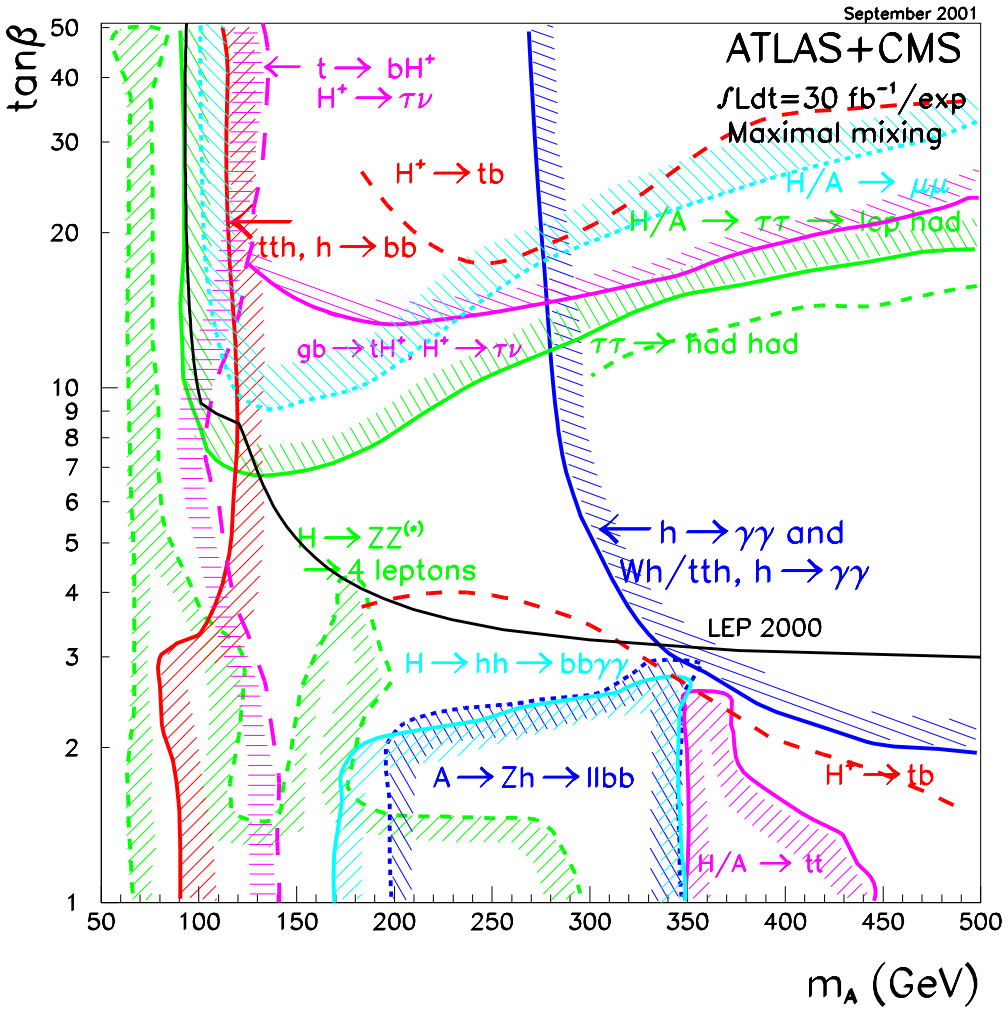


# Outlook: MSSM Higgs Searches at the LHC

– Discovery at $5\sigma$ level extremely unlikely at Tevatron

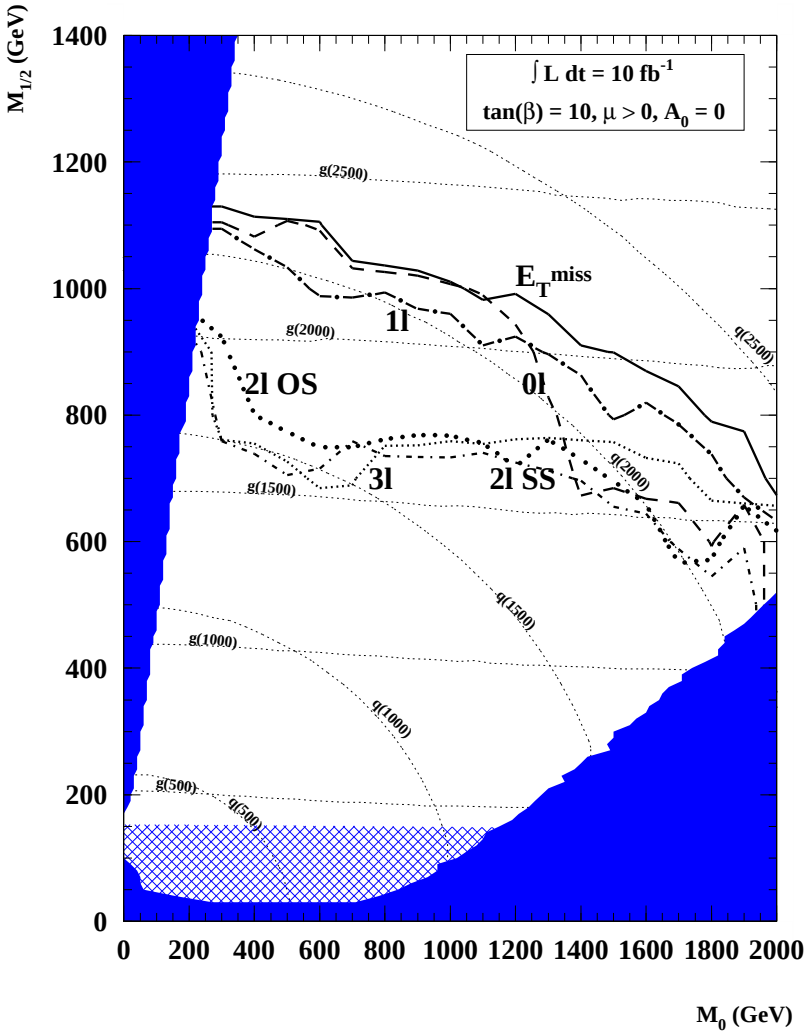
– LHC can detect MSSM Higgs bosons at $5\sigma$ across entire parameter space

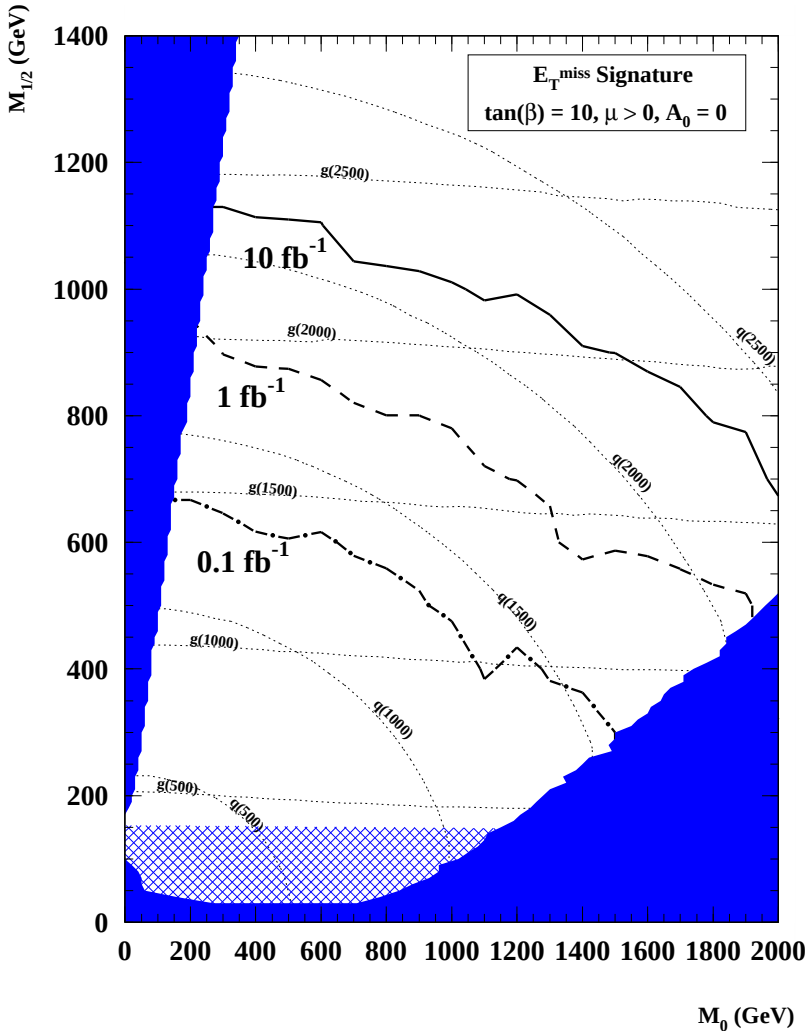
– Several production/decay channels accessible for a given point in $\tan\beta, m_A$ plane



# Outlook: SUSY at the LHC

## ATLAS Discovery reach for Supersymmetry:




## Most likely limitation for a fast SUSY discovery:

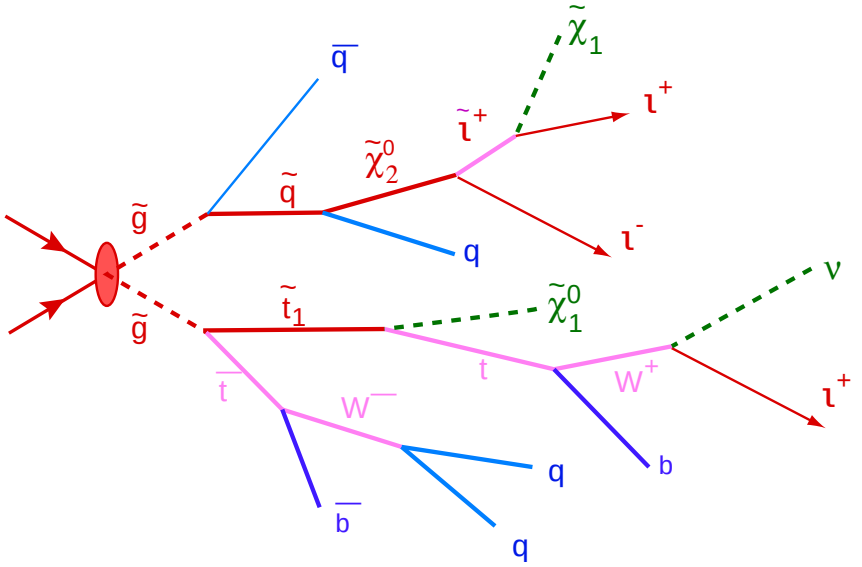
- calibration, data quality, trigger commissioning...

# Outlook: SUSY physics at the LHC and ILC

**First step after discovery:**

- extract masses, couplings, spins...
- verify SUSY hypothesis

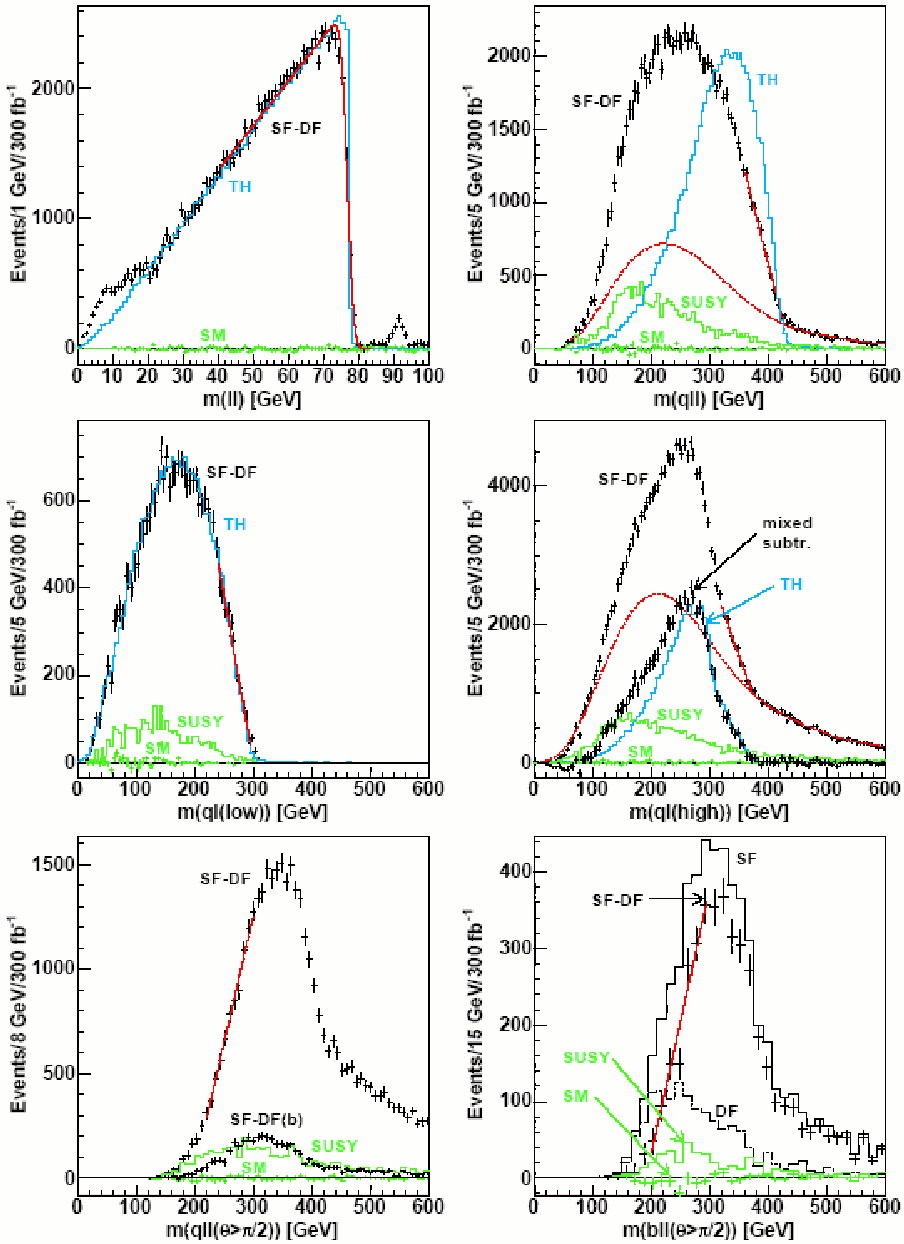
**Signals at LHC will likely involve complicated cascade decays:**




→ need to study endpoint spectra to extract masses

**Next step (ILC):**

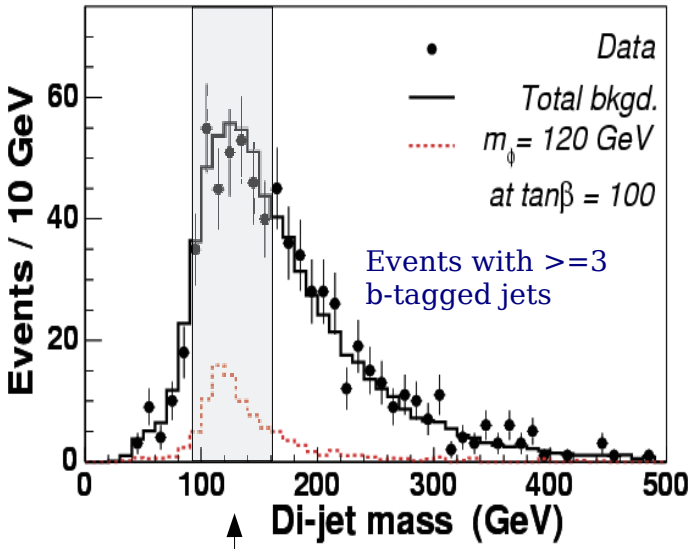
- precision measurements to test underlying fundamental theory

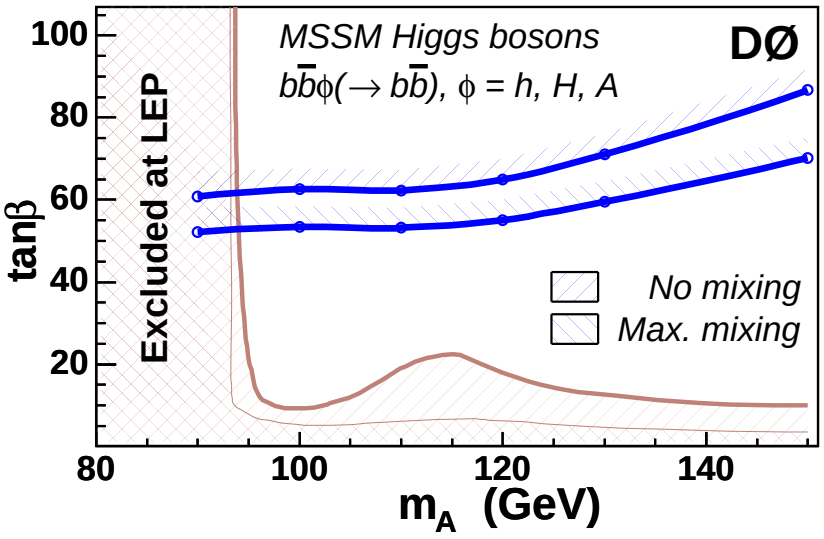


# Search for SUSY Higgs: hb(b)→bbb(b)

**SUSY: $hbb$-coupling enhanced at large tan$\beta$ → large cross-sections for $hb(b)$ production**

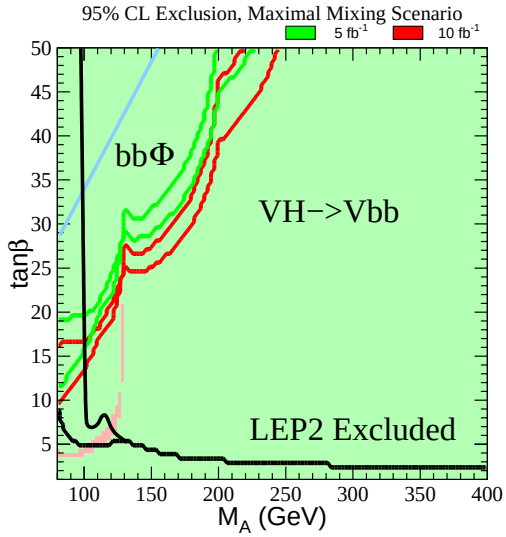
- **Selection: at least 3 b-jets**
- **Backgrounds: multijet production (modelled using data, cross-checked with MC)**
- **Reconstruction of Higgs boson mass in $b\bar{b}$ spectrum**




- **still no hint for a signal**

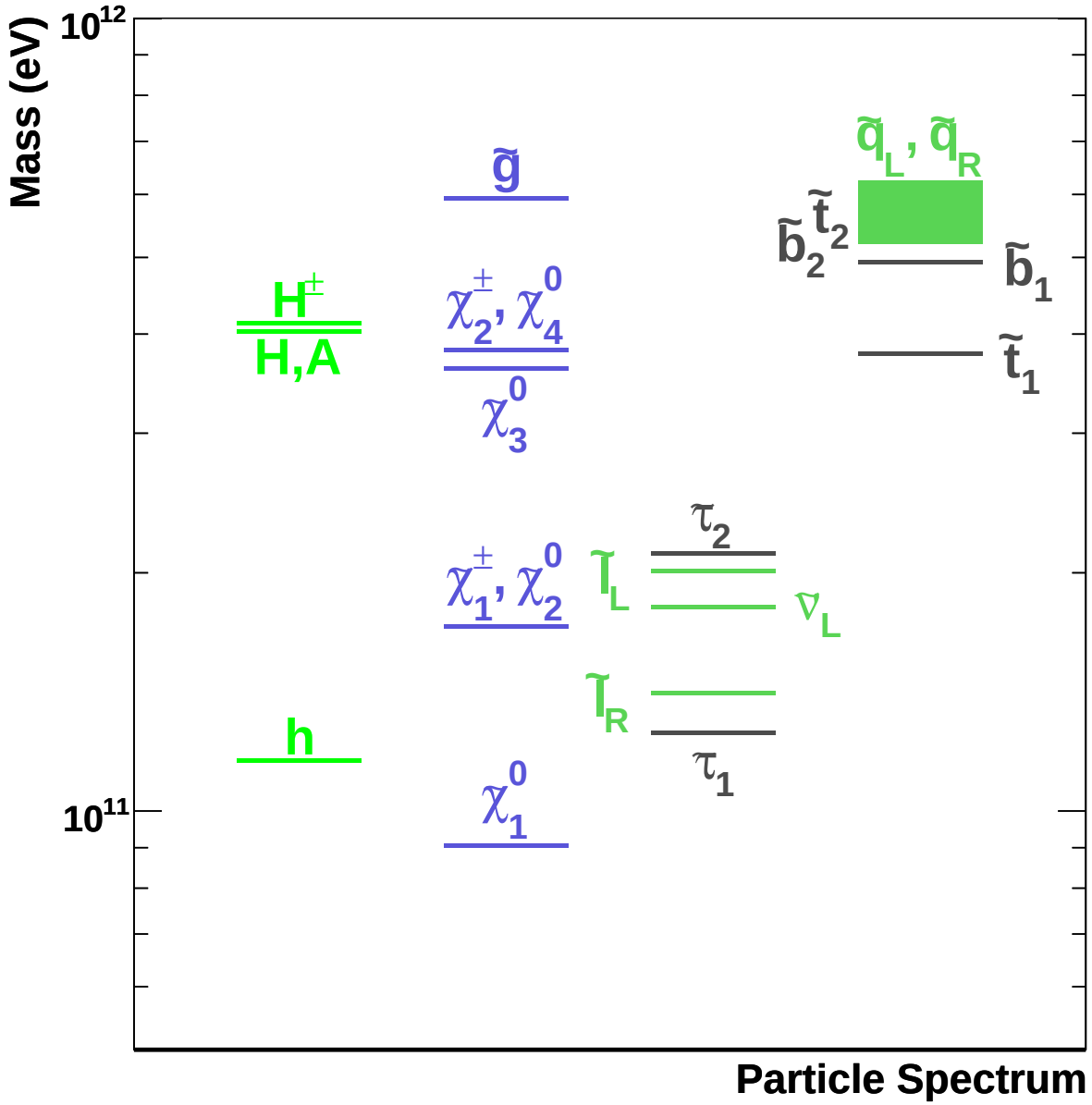
→ **significantly improved limits on tan$\beta$ as a function of $m_A$**




**Reminder:**

- **SUSY predicts at least one Higgs boson with m$\leq$135 GeV**
- **combination of $b\bar{b}h$ and VH analyses should allow a test at 95% C.L. with 5fb$^{-1}$ (mhmax scenario)**

# Typical mass spectrum of SUSY particles

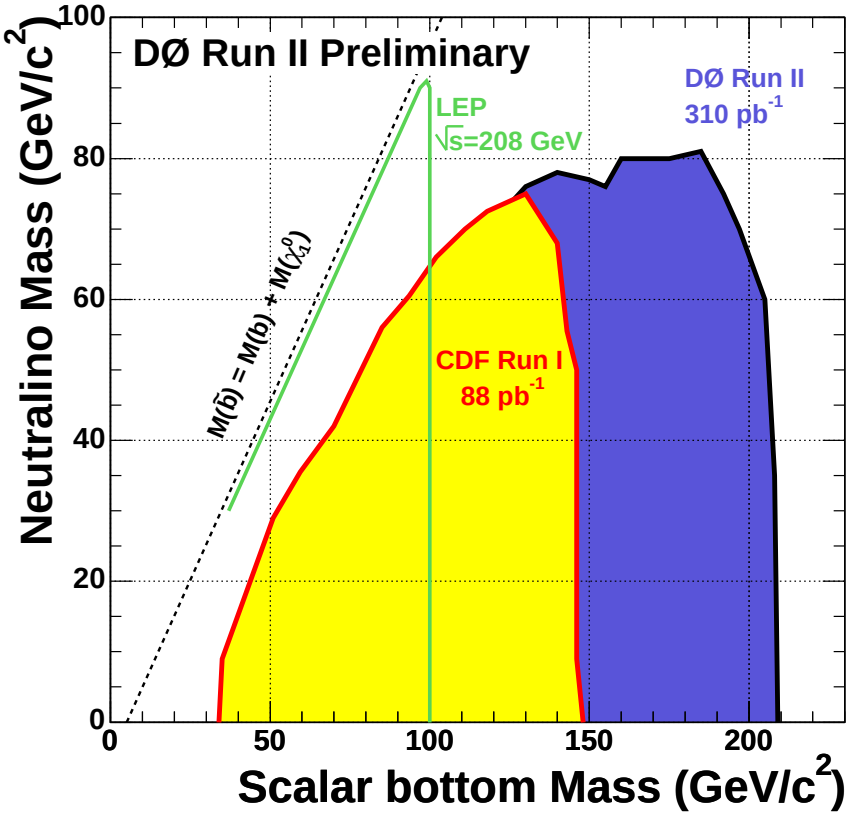


# Search for Supersymmetry – Sbottoms/Stops

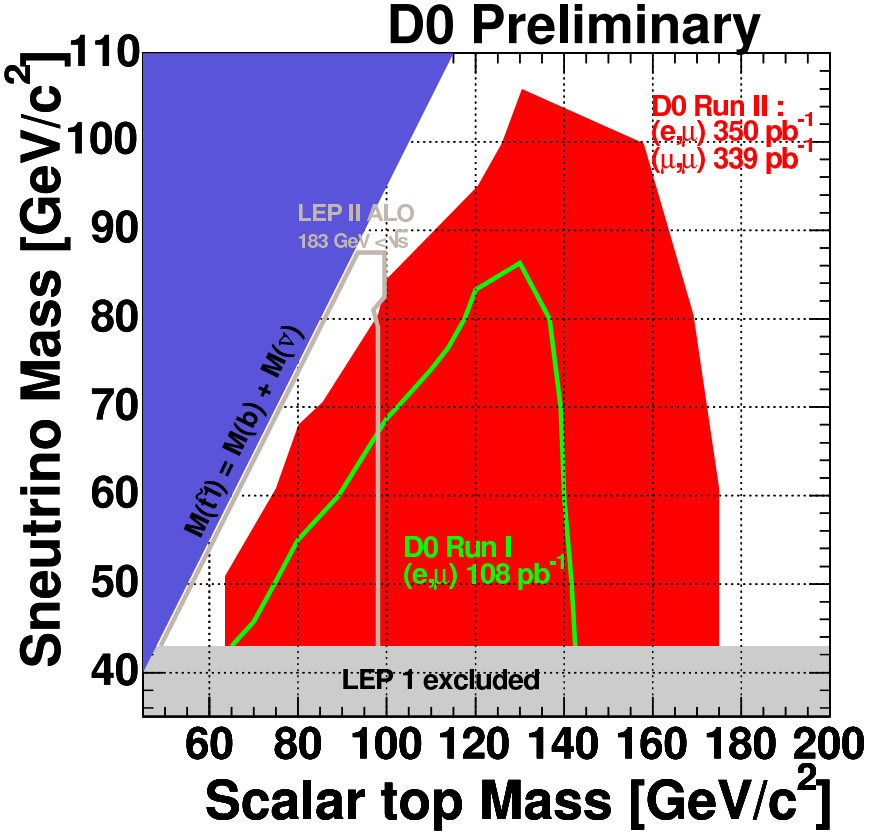
**Dedicated DØ searches for light sbottom or stop quarks**

- can use b- and charm-tagging to substantially reduce backgrounds
- still significant potential with more integrated luminosity

$\tilde{b}\tilde{b} \rightarrow bb + \not{E}_T$




$\tilde{t}\tilde{t} \rightarrow \ell\ell + bb + \not{E}_T$



# Search for Charginos and Neutralinos – R-Parity Violation

**Most general Superpotential contains 45 R-parity violating Yukawa terms:**

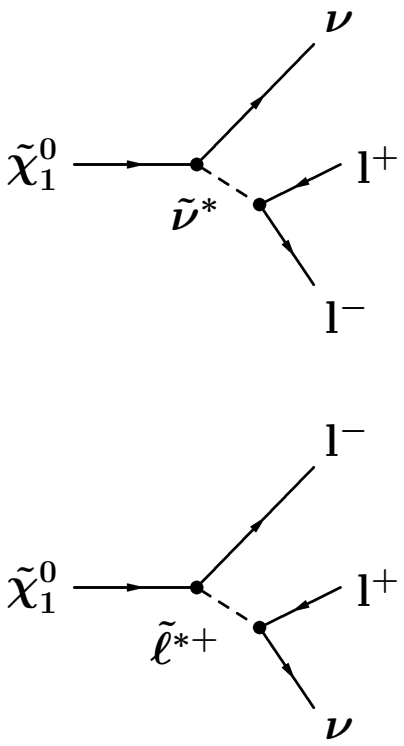
$$W_{RPV} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

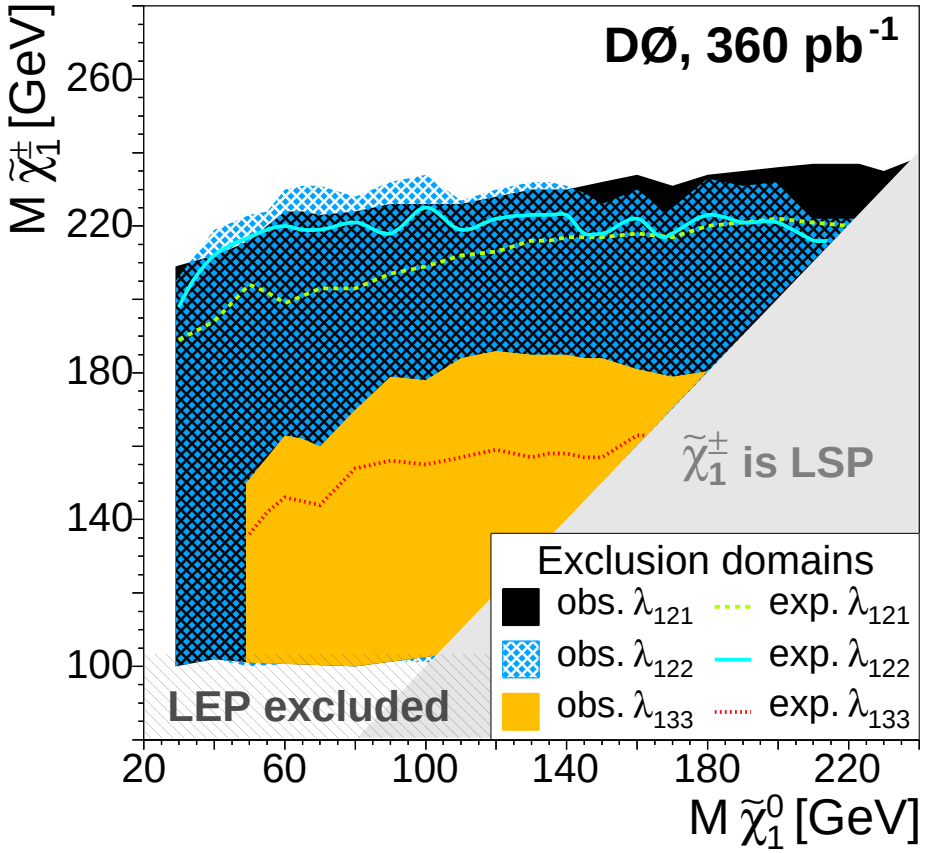
→ **LSP can decay into SM fermions**

→ **For LLE-coupling: Chargino/Neutralino production yields 4l+$\not{E}_T$+X**

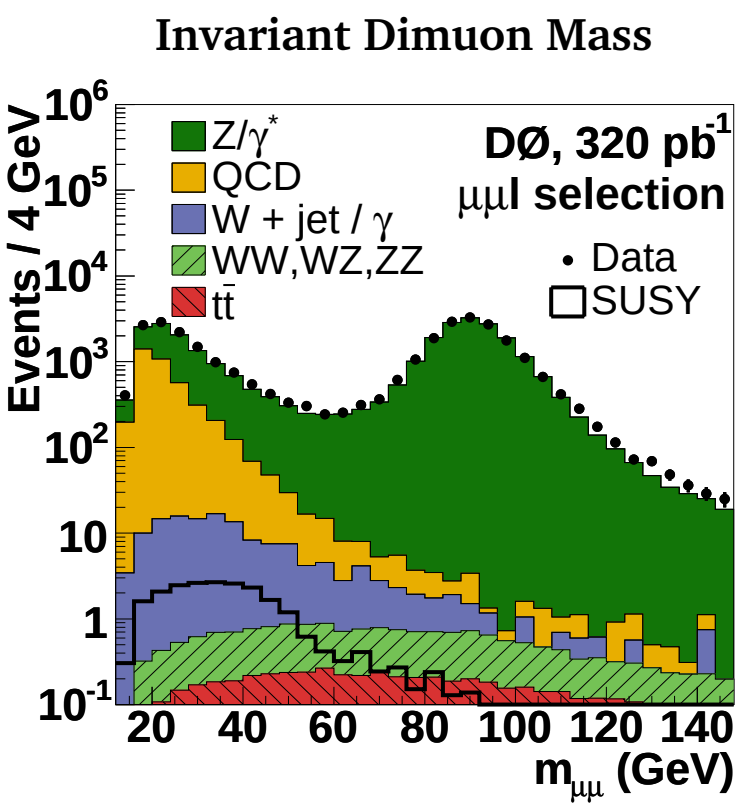
**DØ: Analyzed 360 pb$^{-1}$ with 5 dedicated trilepton selections:**

– eee+$\not{E}_T$+X, ee$\mu$+$\not{E}_T$+X, ee$\tau$+$\not{E}_T$+X, e$\mu\mu$+$\not{E}_T$+X, $\mu\mu\mu$+$\not{E}_T$+X

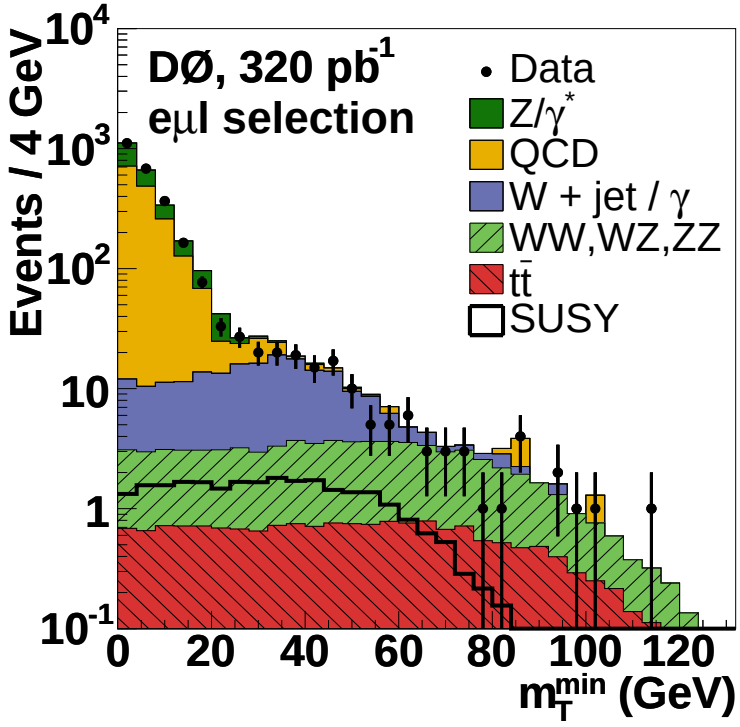


# Search for Charginos and Neutralinos




$$m_T = \sqrt{2p_T^{\ell} \not{E}_T (1 - \cos \Phi_{\ell, \not{E}_T})}$$




**Backgrounds:**

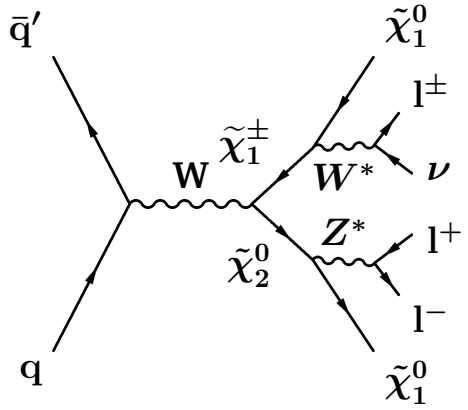
- Multijets with fake leptons
- Drell-Yan, $Z$-production with $Z \rightarrow ll$
- WW,WZ,ZZ production

**Main selection cuts:**

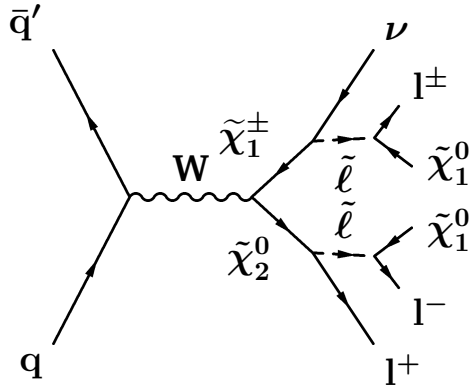
- Three leptons ($\ell\ell$+track)
- Missing transverse Energy
- veto events containing $Z \rightarrow \ell\ell$ decays

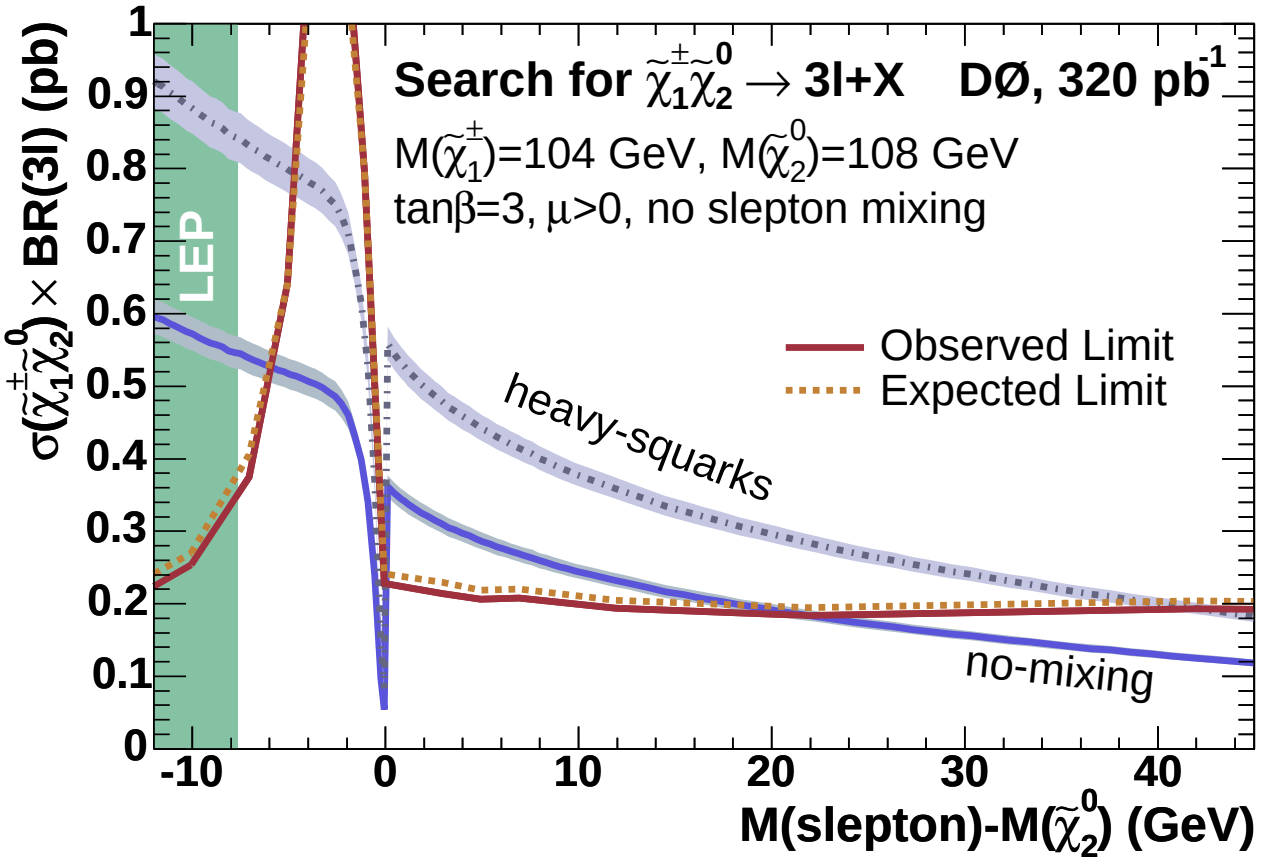
# Search for Charginos and Neutralinos

**Heavy sleptons:**




**Light sleptons:**




**ΔM<0: two-body decays into real sleptons**

**ΔM<-6 GeV: good efficiency, high branching fractions**

**-6 GeV<ΔM<0: very soft third lepton → limit set by ls-$\mu\mu$-analysis**

**ΔM>0: three-body decays via slepton- and W/Z-exchange**

**ΔM$\gtrsim$0: slepton-exchange maximal → large BR(3$\ell$): "*3l-max scenario*"**

**ΔM$\gg$0: W/Z-exchange dominates → small BR(3$\ell$): "*large-$m_0$ scenario*"**

# Search for Charginos and Neutralinos

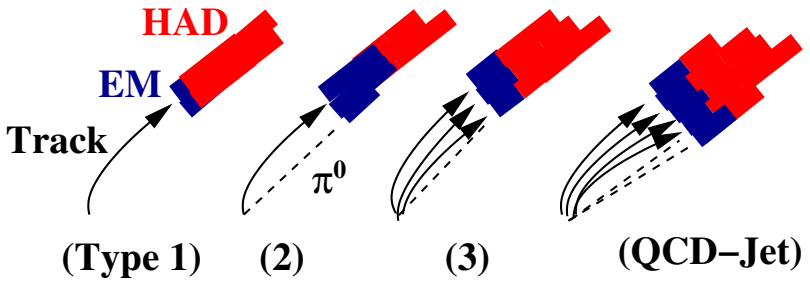
**SUSY mass spectrum likely contains light stau leptons**

→ chargino/neutralino decay cascades proceed via stau

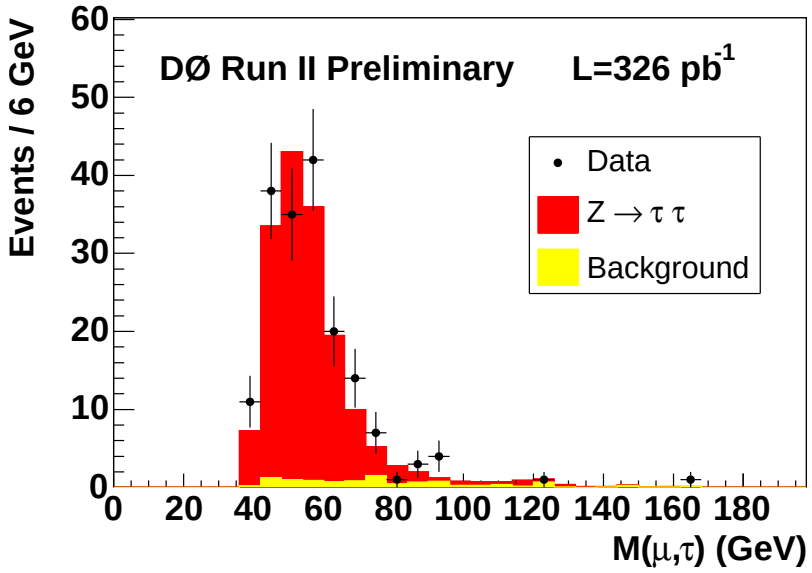
→ multiple $\tau$ leptons in final state

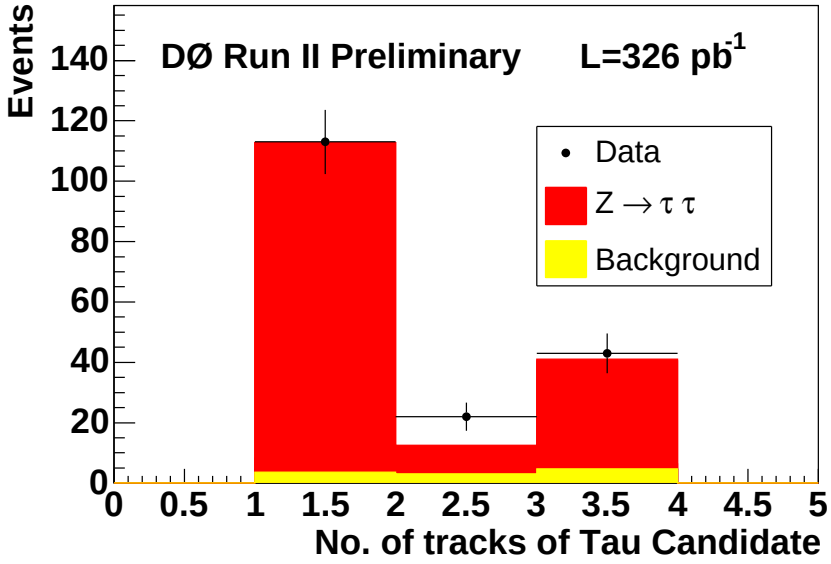
**65% of $\tau$ leptons decay hadronically**

- reconstructed as 1 or 3 tracks pointing to narrow energy deposition in calorimeter
- using neural networks to separate $\tau$-decays from jets




**Reference signal: $Z \rightarrow \tau\tau \rightarrow e/\mu$+hadrons**

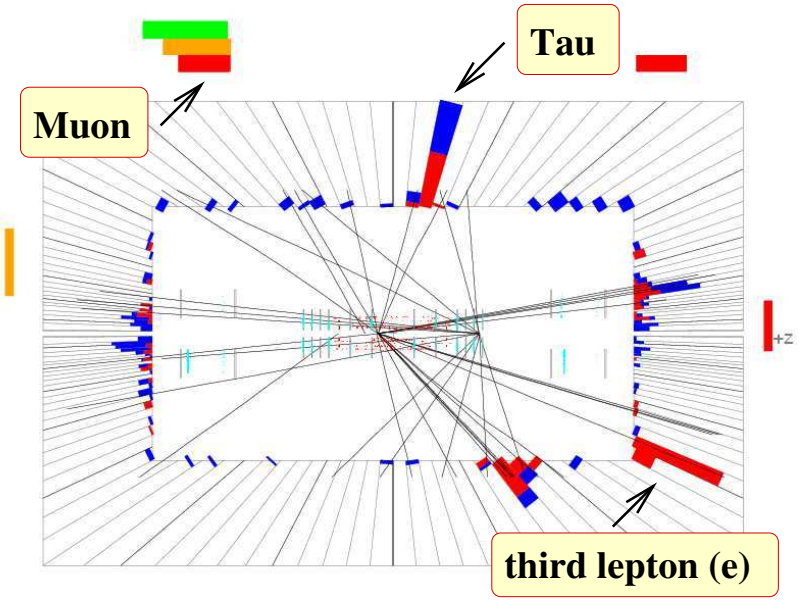


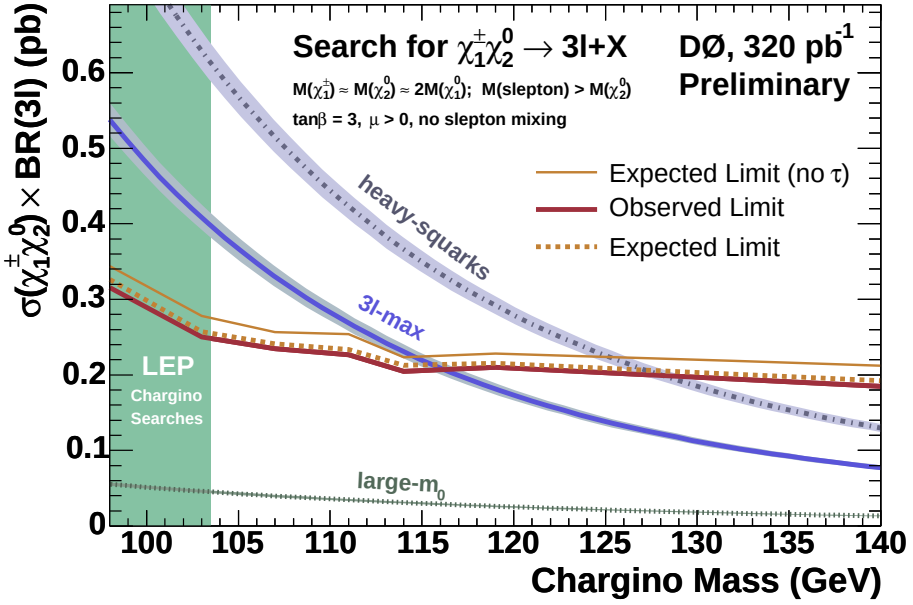



# Search for Charginos and Neutralinos

## Two new DØ trilepton analyses: $e/\mu + \tau +$ isolated track

| Selection | Expected Background | Observed | Signal ($m_{\tilde{\chi}^{\pm}}$=110 GeV) |
|---|---|---|---|
| $ee\ell$ | 0.21±0.12 | 0 | 1.9±0.2 |
| $e\mu\ell$ | 0.31±0.13 | 0 | 1.6±0.1 |
| $\mu\mu\ell$ | 1.75±0.57 | 2 | 1.3±0.2 |
| ls-$\mu\mu$ | 0.66±0.37 | 1 | 0.7±0.1 |
| $e\tau\ell$ | 0.58±0.14 | 0 | 0.4±0.1 |
| $\mu\tau\ell$ | 0.36±0.13 | 1 | 0.7±0.1 |
| Combined | 3.87±0.81 | 4 | 6.6±0.3 |




## Interpretation of results in models with light stau (high tan$\beta$) still in progress

# Search for Stable Charginos

Charginos with small mass difference to LSP can be quasi-stable (Anomaly-mediated SB)

→ slow-moving massive stable charged particle

Experimental signature: two high-pt muons with out-of-time scintillator hits

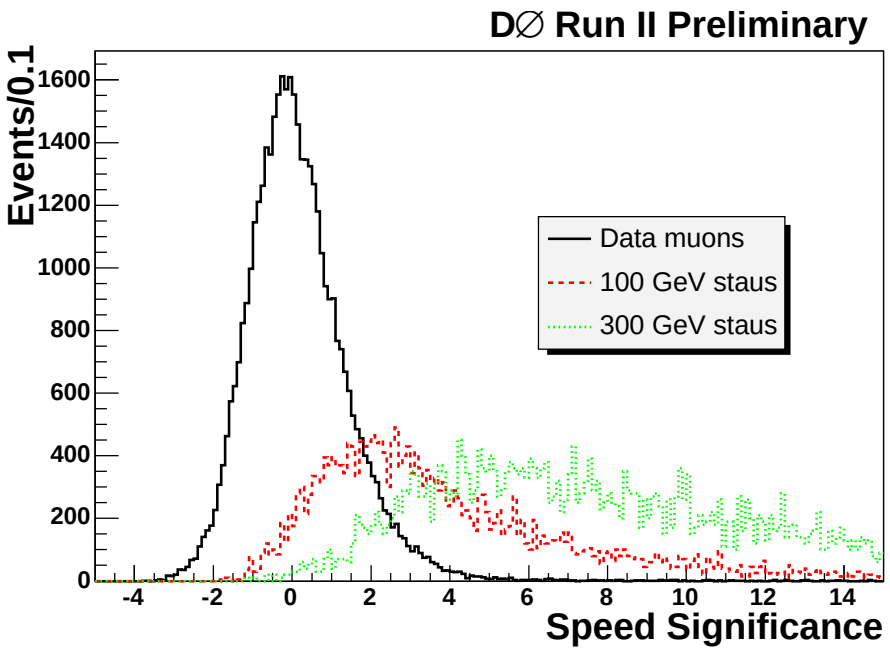
Additional Handle: large dE/dx in tracker and calorimeter (not used by current analysis)

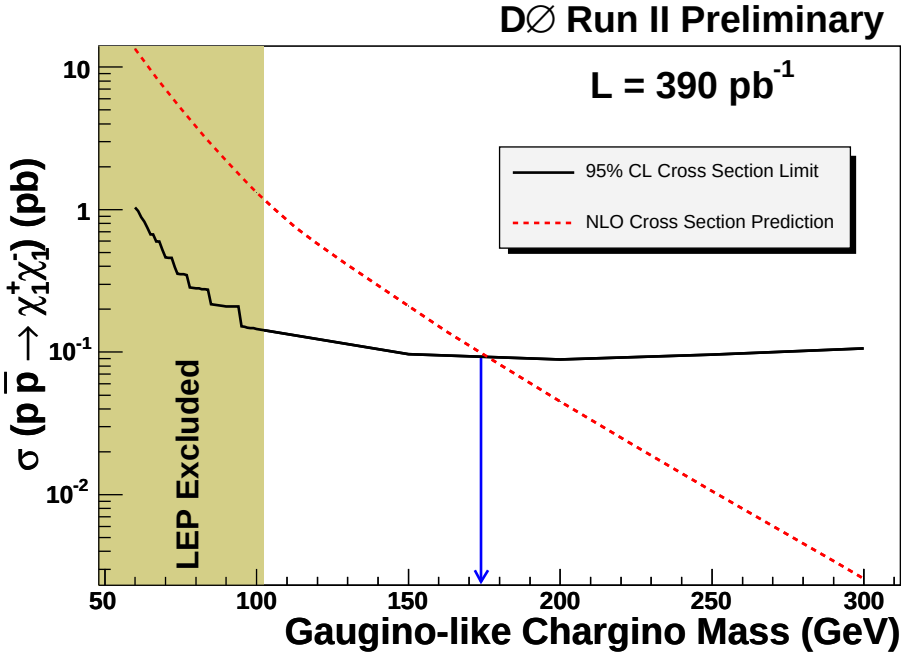
Analysis of 390 $pb^{-1}$ of data collected with dimuon trigger:

- require speed of muons to be significantly below $c$
- kinematic cuts against $Z \to \mu\mu$ with poorly measured timing

Results (m>100 GeV): no events observed, 0.66±0.06 events expected

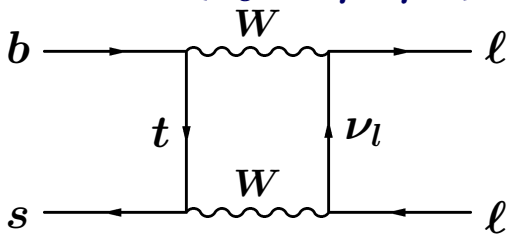
→ new chargino mass limits: 140 GeV (higgsino-like), 174 GeV (gaugino-like)



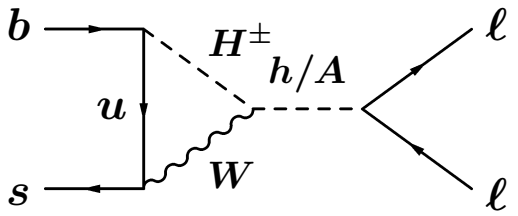



# Search for Supersymmetry: $B_s \to \mu^+\mu^-$

**SM prediction: BR($B_s \to \mu^+\mu^-$)=3.8×$10^{-9}$**




**SUGRA: enhancement ~ $(tan\beta)^6$**

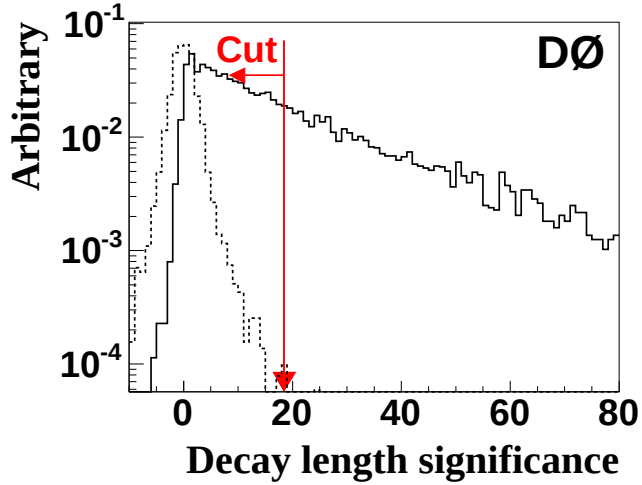


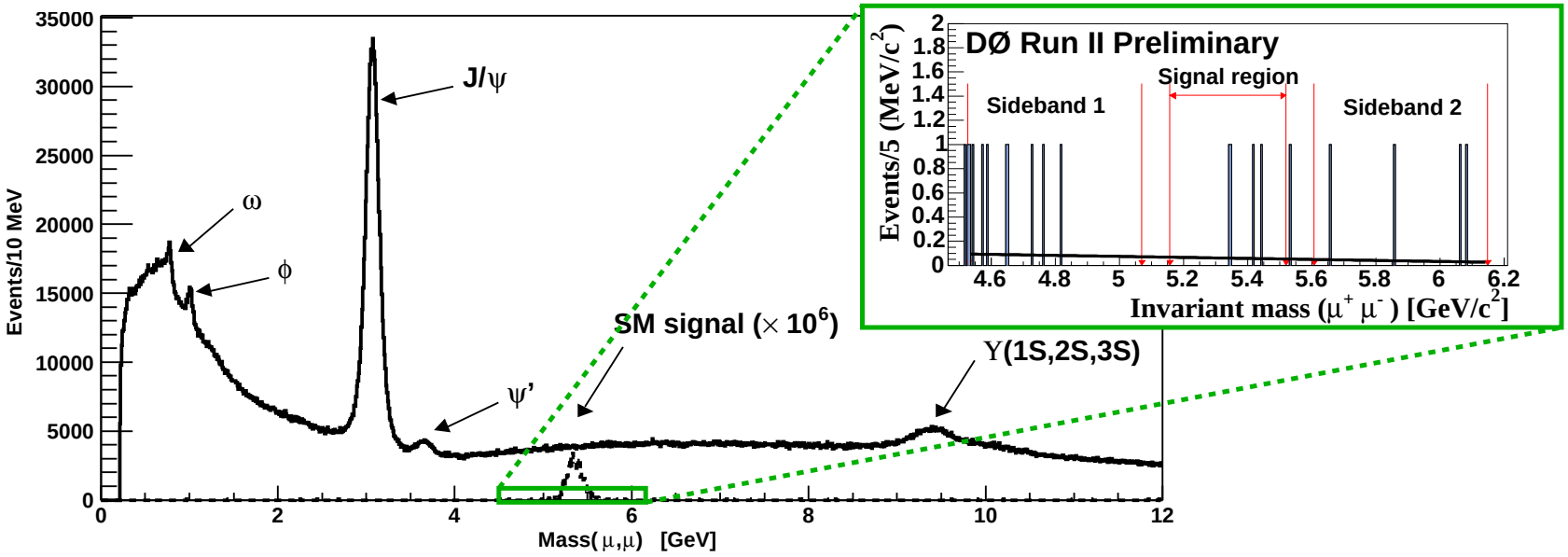

→ significant at high tan$\beta$: BR=$O(10^{-7})$

→ complementary to trilepton search

– Tevatron: large production rate for $B_s$

– Selection: two isolated muons, displaced vertex



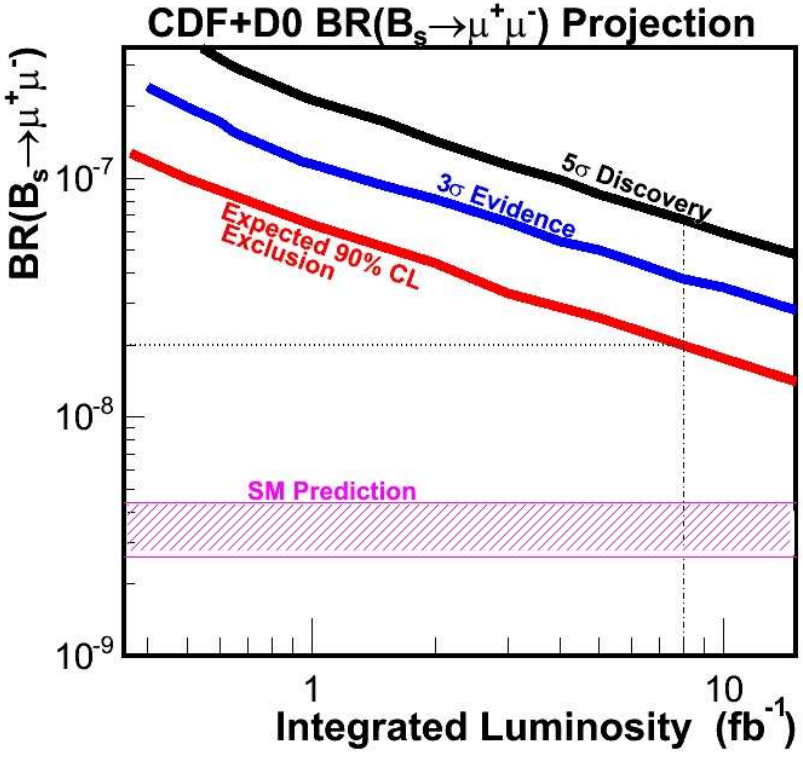
# Search for Supersymmetry: $B_s \to \mu^+\mu^-$

**Results (limits at 95% C.L.):**

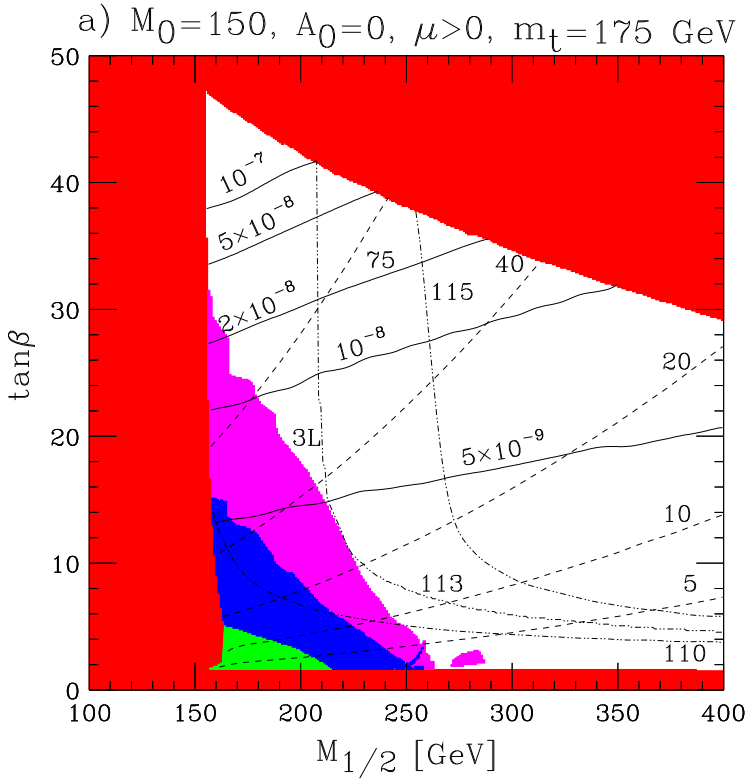
| | | | |
|---|---|---|---|
| DØ | (300 pb$^{-1}$): | 4.3±1.2 expected, 4 observed → | BR($B_s \to \mu^+\mu^-$)<3.7×10$^{-7}$ |
| CDF | (364 pb$^{-1}$): | 1.5±0.2 expected, 0 observed → | BR($B_s \to \mu^+\mu^-$)<2.0×10$^{-7}$ |
| | | TEVNPWG Combination: | BR($B_s \to \mu^+\mu^-$)<1.5×10$^{-7}$ |

**Projection for Run IIb: sensitivity will approach $10^{-8}$**

→ **will test large part of SUGRA parameter space**




Dedes, Dreiner, Nierste, Richardson
(hep-ph/0207026)



# Search for Supersymmetry: R-Parity Violation

**Most general Superpotential contains 45 Yukawa terms leading to violation of Lepton/Baryon-Number:**

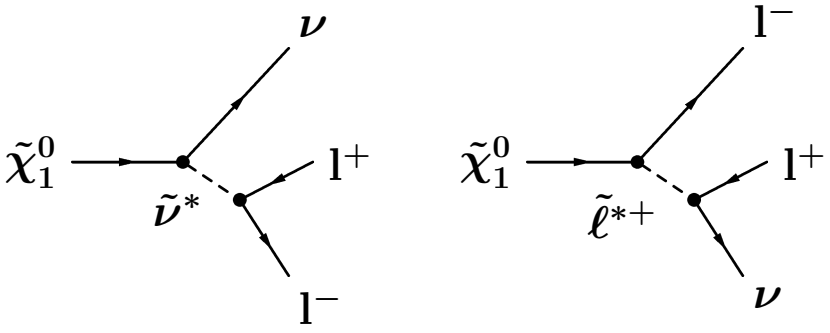
$$\begin{aligned} W &= W_{RPC} + W_{RPV} \\ W_{RPV} &= \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k \end{aligned}$$

- couplings are constrained by searches for L- and B-violation, but could be non-zero
- all terms violate conservation of multiplicative quantum number R-parity

→ need to study SUSY with and without conservation of R-Parity

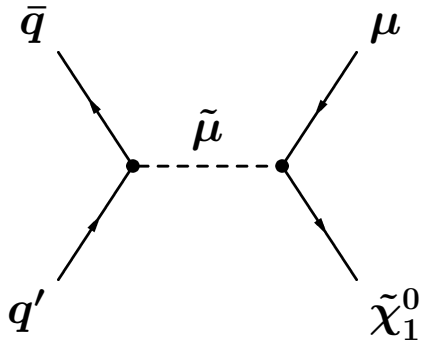
**Important consequences of R-parity violation for SUSY collider signatures:**

**LSP can decay into SM fermions:**




(For non-zero $L_i L_j \bar{E}_k$-coupling)

**Resonant production of SUSY particles:**




(For non-zero $L_i Q_j \bar{D}_k$-coupling)

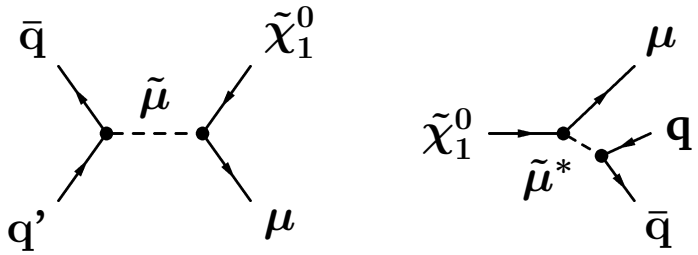
**DØ search channels:**

$$\tilde{\chi}^{\pm}\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0 + X \to 4\ell + \not{E}_T + X$$

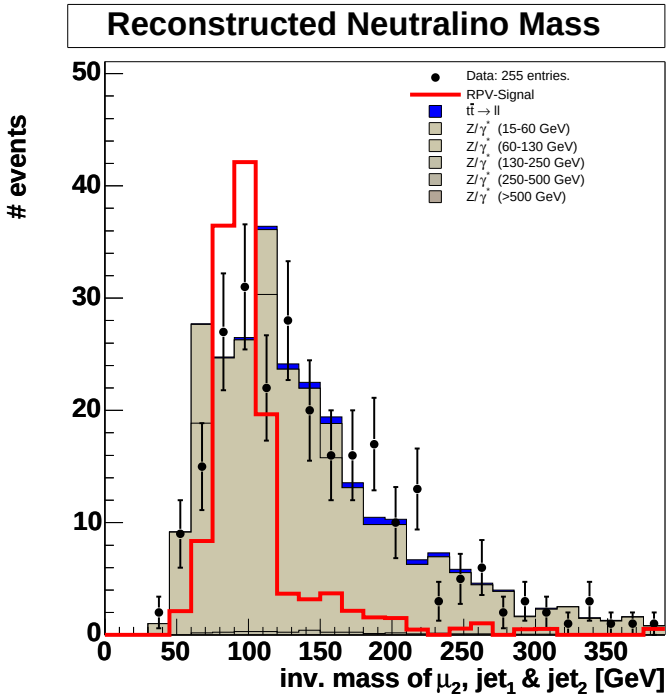
$$\tilde{\mu} \to \mu + \tilde{\chi}_1^0 \to 2\mu + 2j$$

# Search for Supersymmetry: RPV

## Search for resonant smuon production (154 pb$^{-1}$):




- Two muons with $p_T$>8 and $p_T$>20 GeV
- Two jets with $p_T$>15 GeV
- Topological cuts to reduce Z+jets background
- Reconstruction of Neutralino and Smuon invariant masses




## Background Expectation:

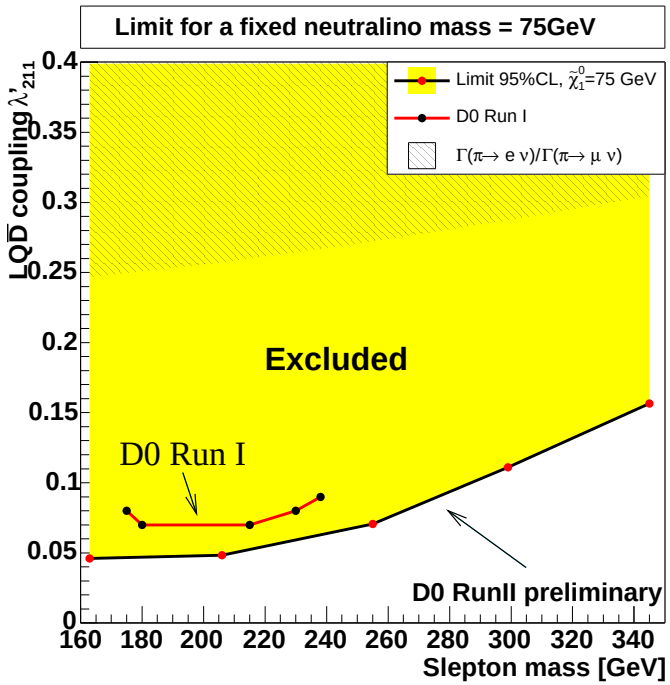
- between 0.1 and 1.6 events (depending on mass hypothesis)

## No excess observed in data:

- two or less events for all masses

## Interpretation:

- limits on $\lambda'_{211}$ as a function of Smuon and Neutralino mass

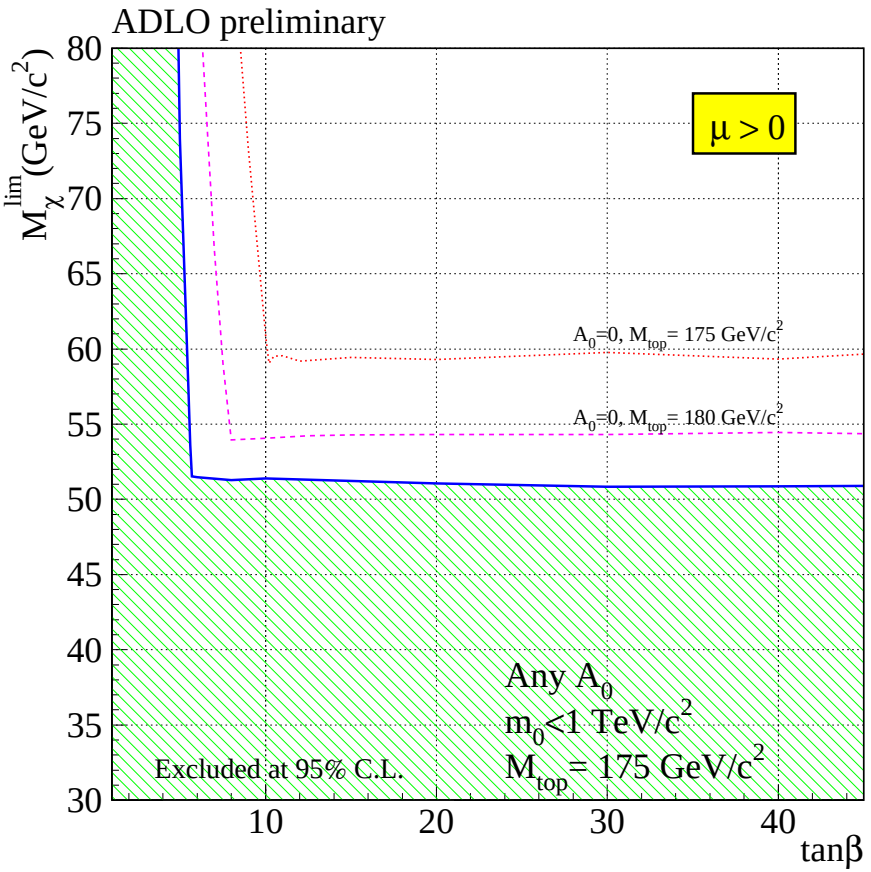


# Search for Supersymmetry at LEP

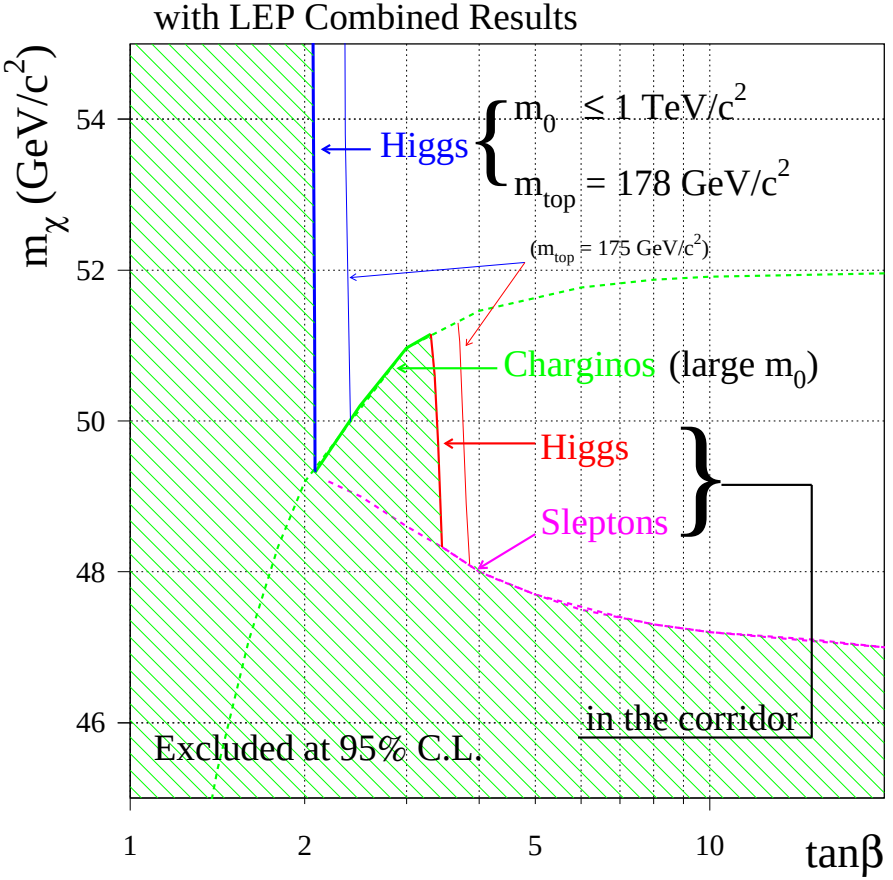
- Very clean environment, highly efficient searches for large variety of signatures
- Main limitation: maximum beam energy of ≈104 GeV
- Strong limits on SUSY from searches for charginos, sleptons and Higgs bosons:

  $m_{\tilde{\chi}^{\pm}} > 103.5$ GeV, $m_{\tilde{\ell}} \gtrsim 95$ GeV, $m_h > 114.4$ GeV
- Within a given model, can derive mass limits on LSP (dark matter candidate)

**LSP Mass Limit in mSUGRA**




**LSP Mass Limit in MSSM**



# Suche nach Leptoquarks

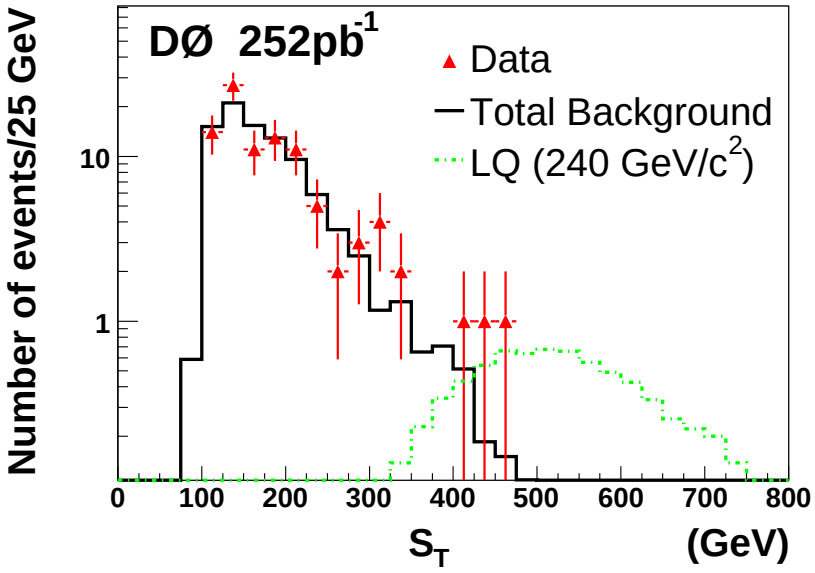
**Leptoquarks koppeln an Leptonen und Quarks (Motivation: Grand Unification)**

**Beide Experimente: Suche nach LQLQ→llqq̄, lνqq̄, ννqq̄ im Run II-Datensatz (250 pb$^{-1}$)**

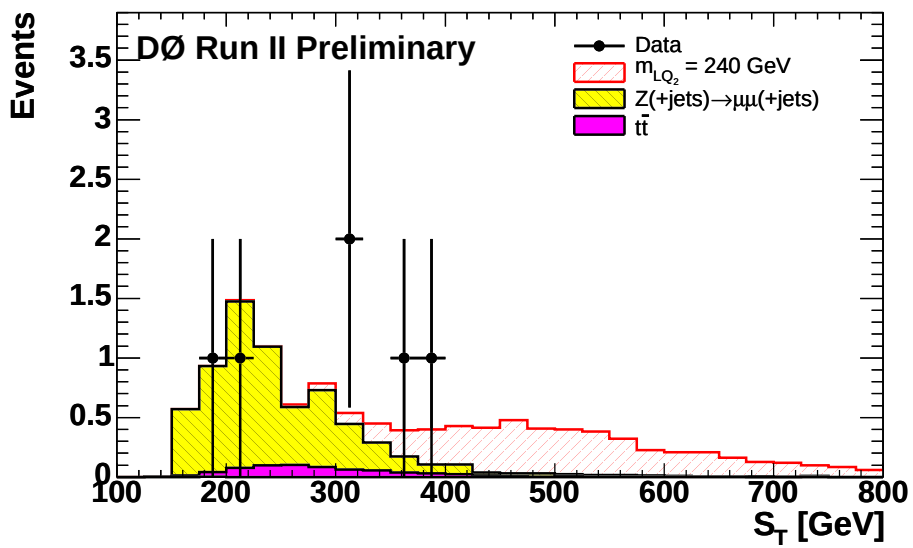
- **Selektionen: 2l+2j, l+2j+$\not\!\!E_T$, 2j+$\not\!\!E_T$ (mit l=e,$\mu$)**
- **Hohe LQ-Masse → hohe Transversalimpulse für Zerfallsprodukte**

  **→ Suche nach Überschuß bei hohem $S_T = p_T^1 + p_T^2 + p_T^3 + p_T^4$**

**1. Generation**




**2. Generation**




**Verbesserte Massengrenzen:**

- **1. Generation: m>256 GeV für BR(eq)=1**
- **2. Generation: m>251 GeV für BR($\mu$q)=1**
- **Alle Generationen: m>117 GeV für BR($\nu$q)=1**