# Recent Results from the Tevatron

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Rencontres de Physique des Particules 2007

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- B Physics Highlights
- Single Top Production
- Properties of Top Quark
- Top Quark and W boson Masses
- Search for Higgs Bosons
- Search for Supersymmetry

Full set of results available at:

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

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

# The Tevatron Collider

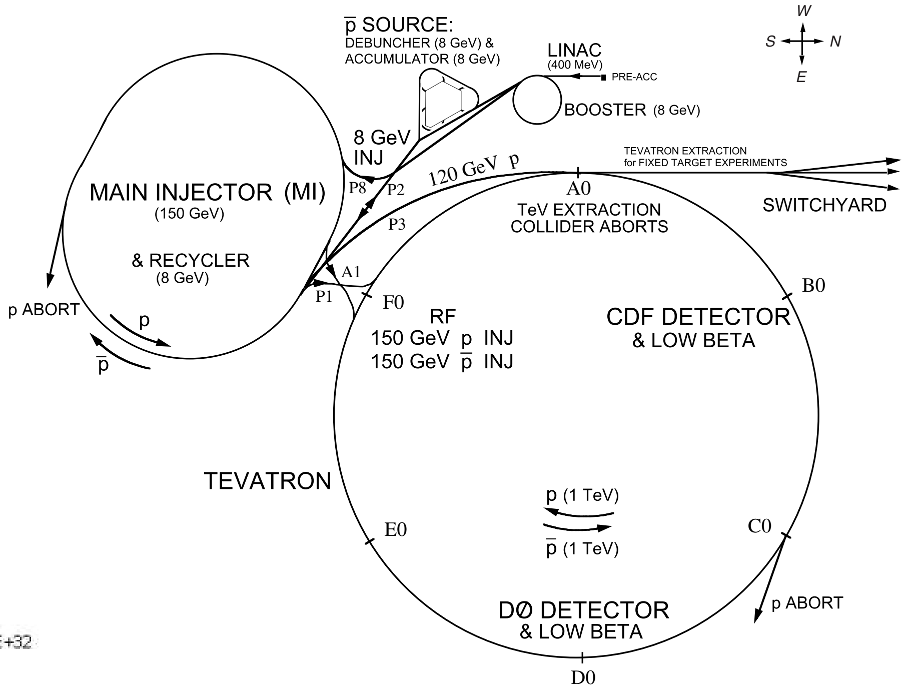
**Proton Antiproton Collider**

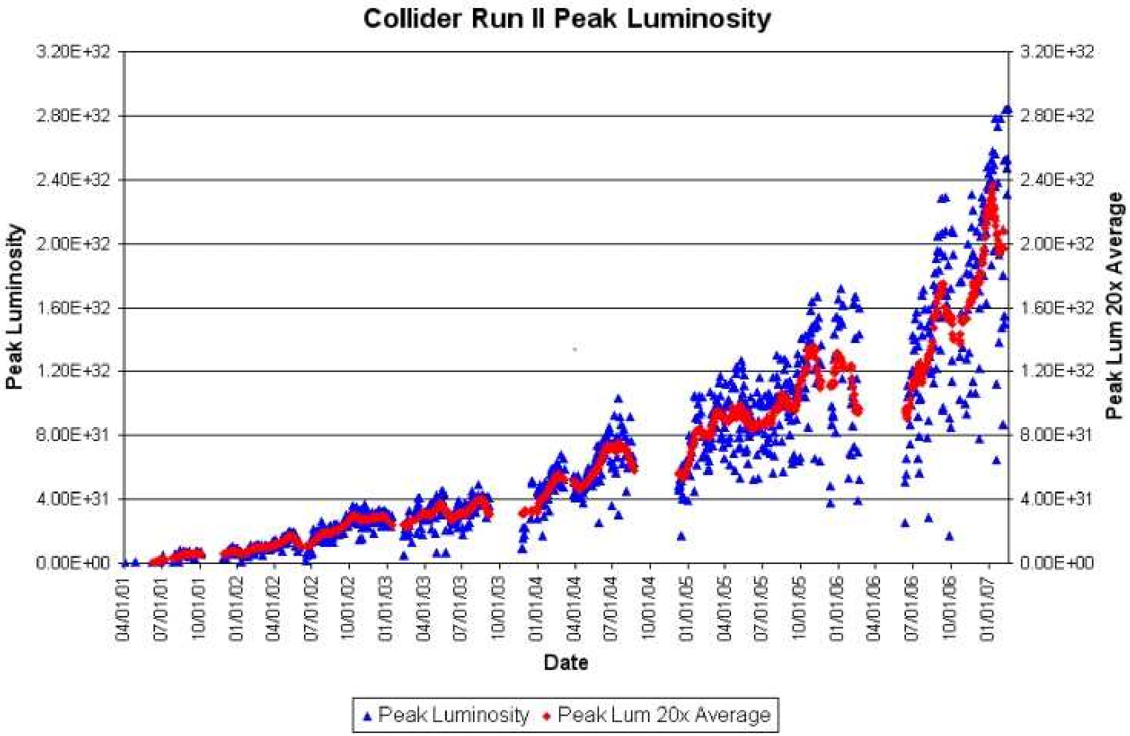
**Centre-of-mass energy: 1.96 TeV**

**Integrated Luminosity: 2.5 $\text{fb}^{-1}$ so far**

**Peak luminosity: $2.9 \times 10^{32}$ $\text{cm}^{-2}\text{s}^{-1}$**

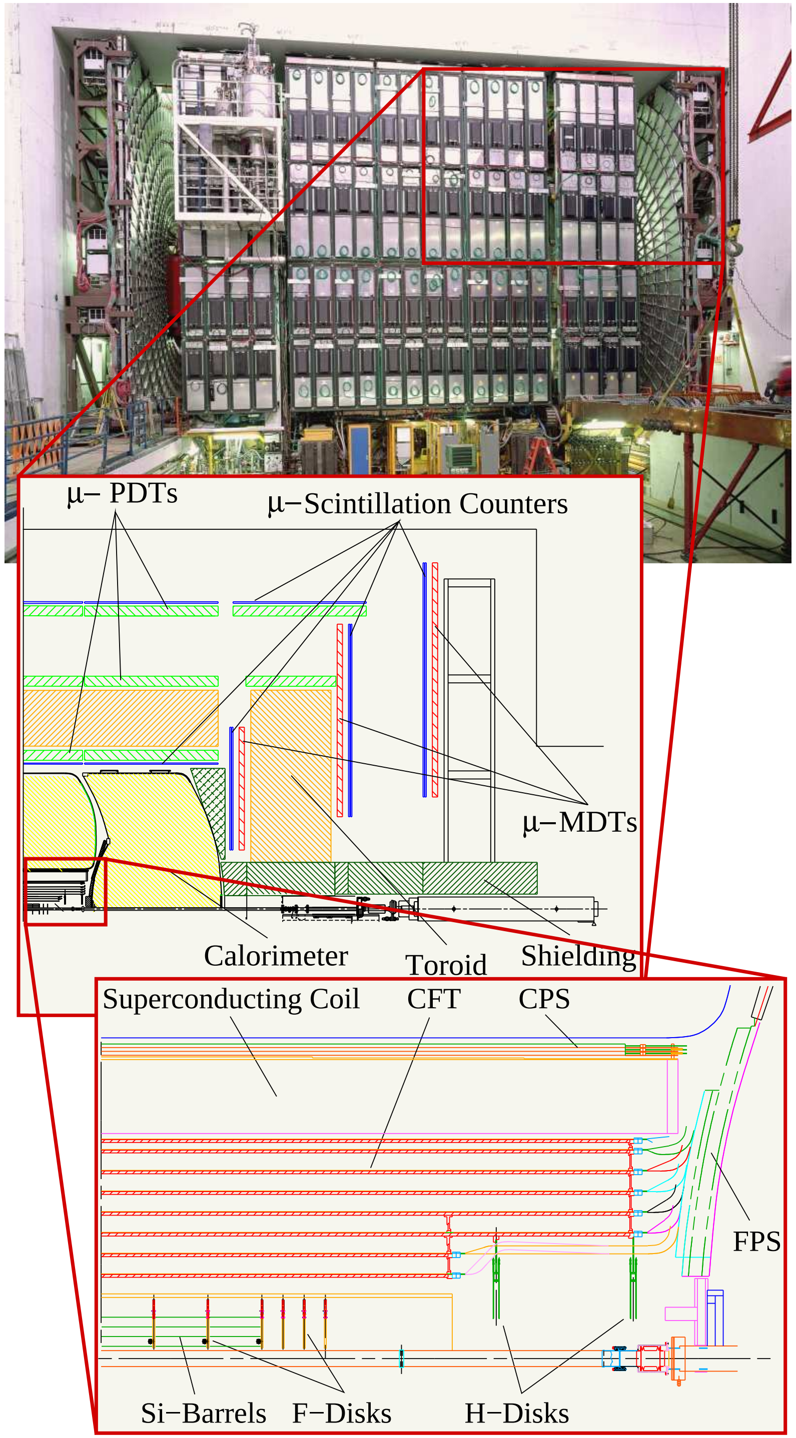
**Expecting to accumulate 6-8 $\text{fb}^{-1}$ by 2009**




Electron Cooling in operation

# The Tevatron Experiments



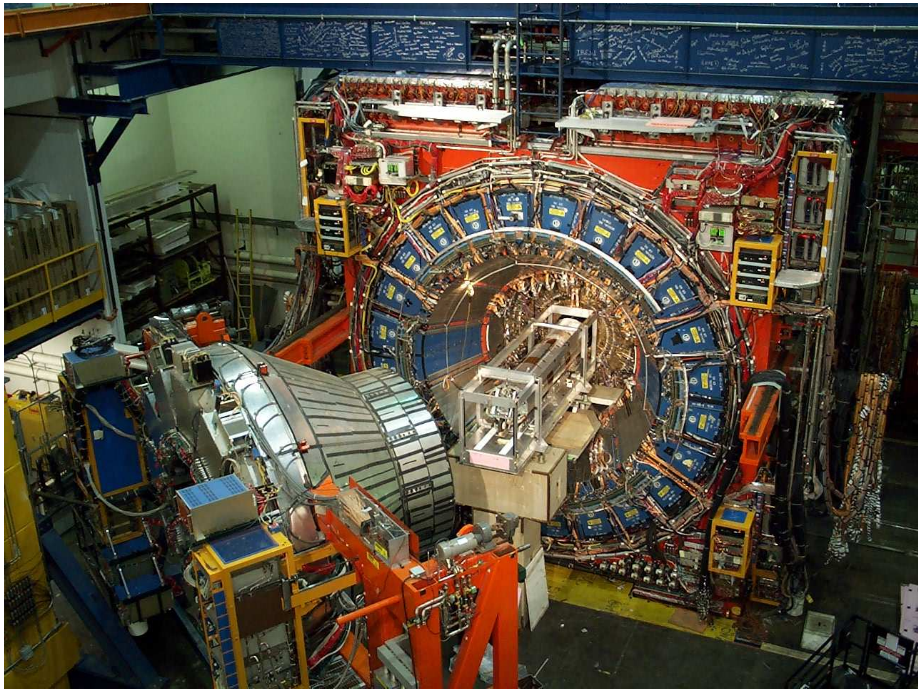

| Two General-Purpose Detectors: | CDF | DØ |
|---|---|---|
| Electron acceptance | $\|\eta\| < 2.0$ | $\|\eta\| < 3.0$ |
| Muon acceptance | $\|\eta\| < 1.5$ | $\|\eta\| < 2.0$ |
| Silicon Precision tracking | $\|\eta\| < 2.0$ | $\|\eta\| < 3.0$ |
| Hermetic Calorimeter | $\|\eta\| < 3.6$ | $\|\eta\|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

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

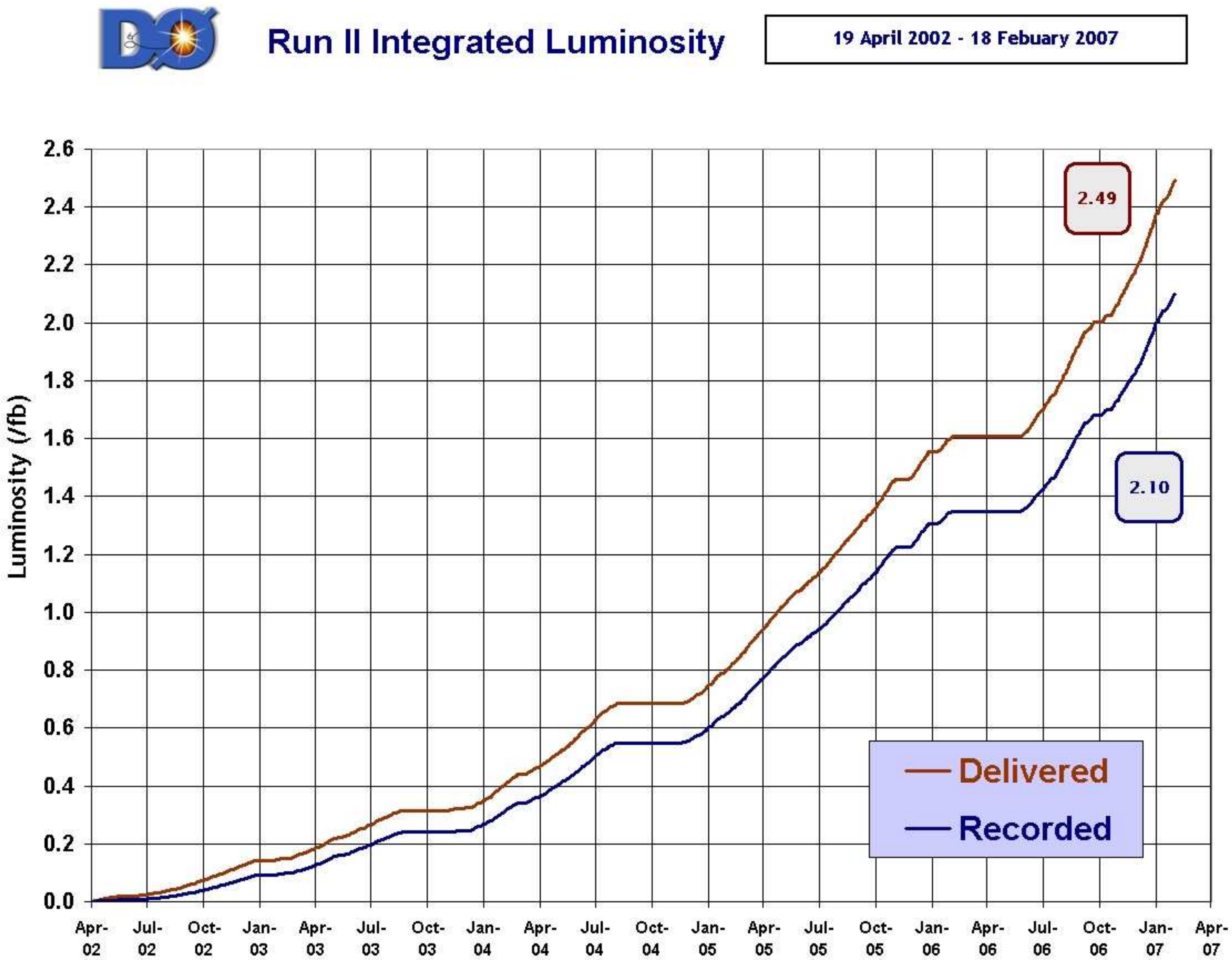
– Dilepton triggers starting at $p_T > 4$ GeV

– Jets+$\not{E}_T$ triggers with $\not{E}_T > 25$ GeV

**RunIIb upgrades successfully installed**



# The Tevatron Experiments – Dataset



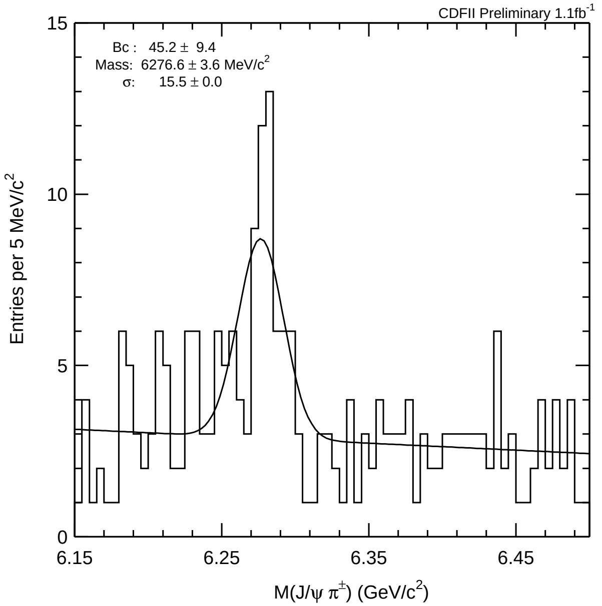

- Current data-taking efficiencies 85–90%
- Results presented here based on 1 $fb^{-1}$

# B Physics – Discoveries

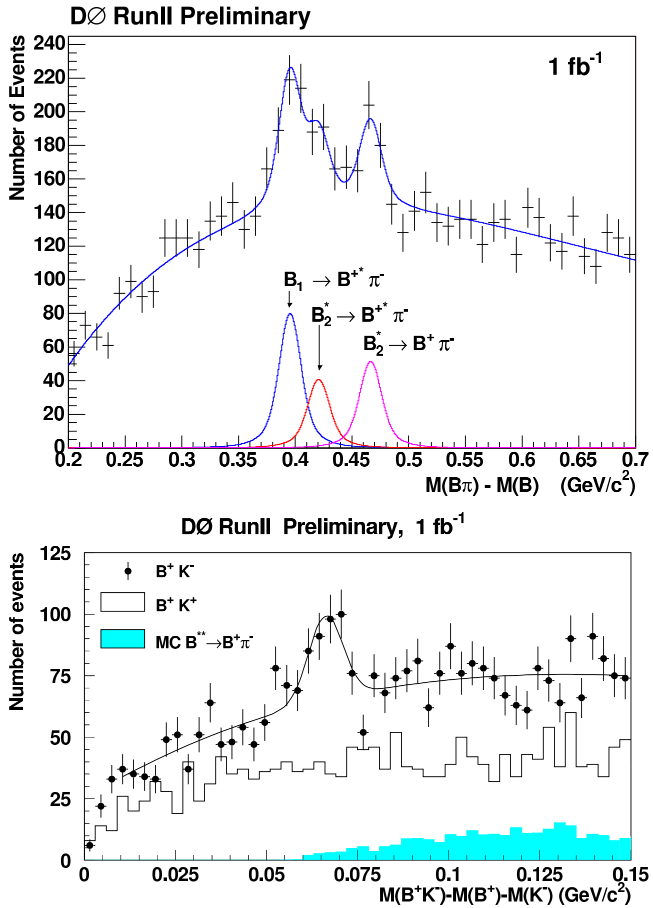
## The Tevatron is a B Factory

- huge cross sections for production of $b\bar{b}$ quark pairs
- b-quark fragmentation: access to heavy B mesons and baryons

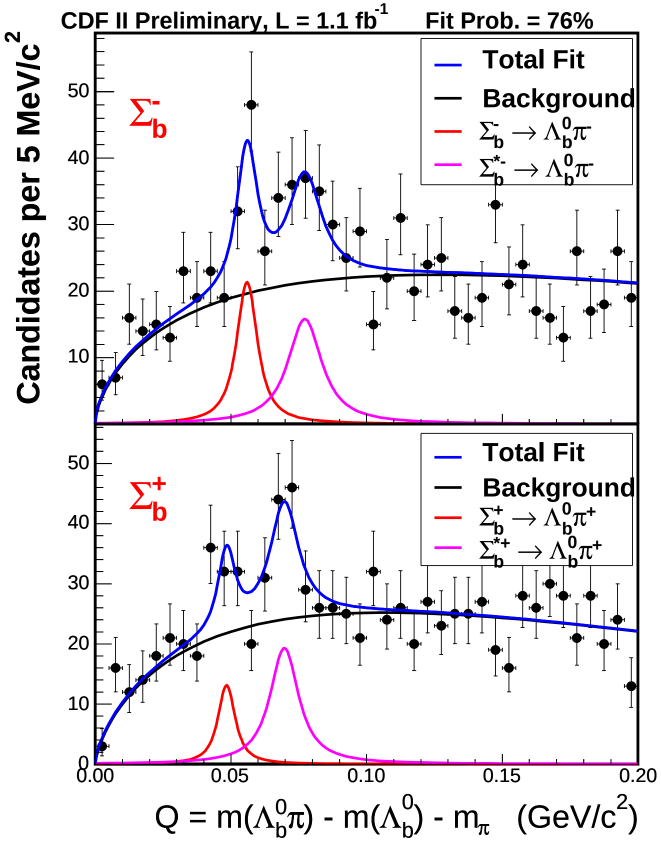
$B_c$: $>6\sigma$ observation




$B_1$, $B_2^*$, $B_{s2}^*$ observed



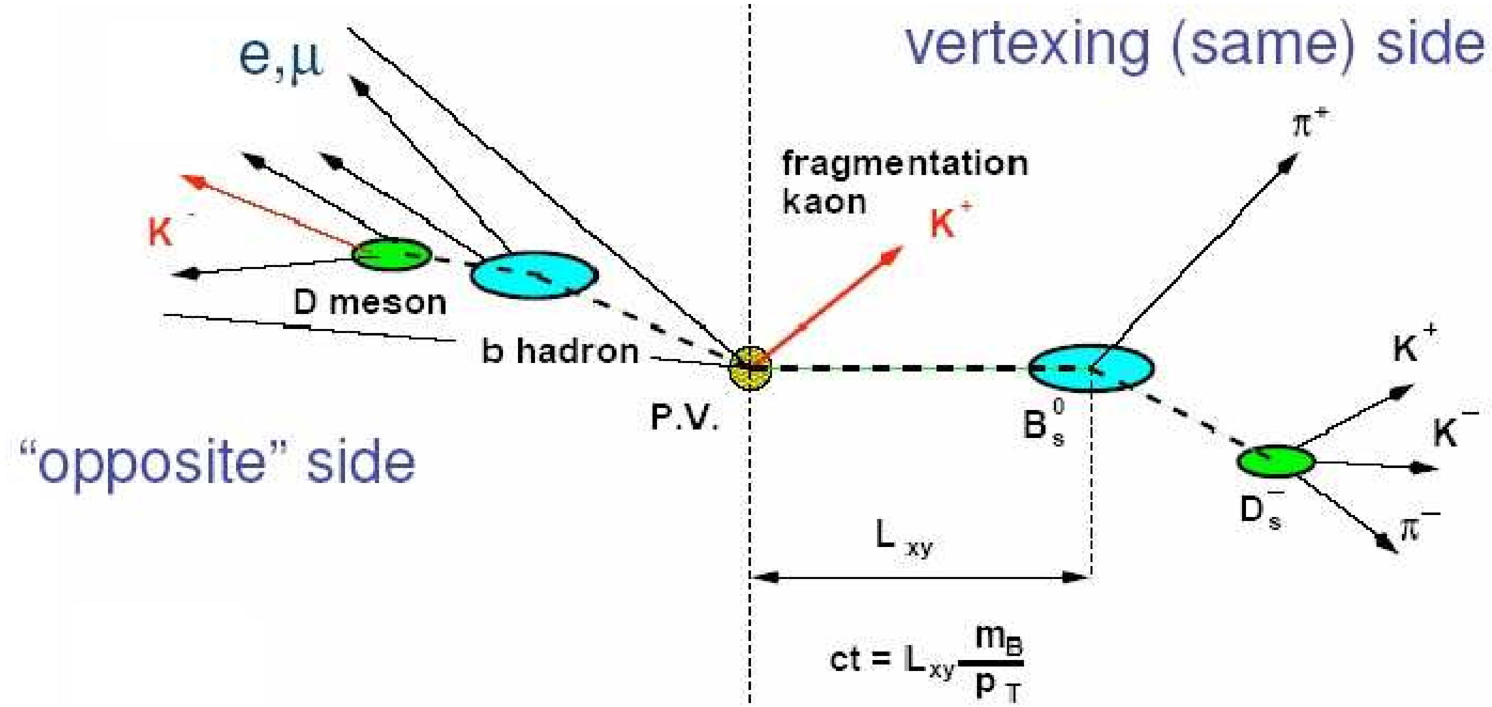

$\Sigma_b^{\pm}$ observed



# $B_s$ Mixing – The Method

**$B_s$ sample: can measure time evolution of $B^0_s$-$\bar{B}^0_S$ oscillation**

- tag $B^0_s$ flavour at production and decay
- measure $B^0_s$ decay length and momentum




- Leptonic decays (CDF+DØ): need to correct for missing momentum from neutrino
- Hadronic decays (CDF): full reconstruction of $B^0_s$ decay → excellent time resolution

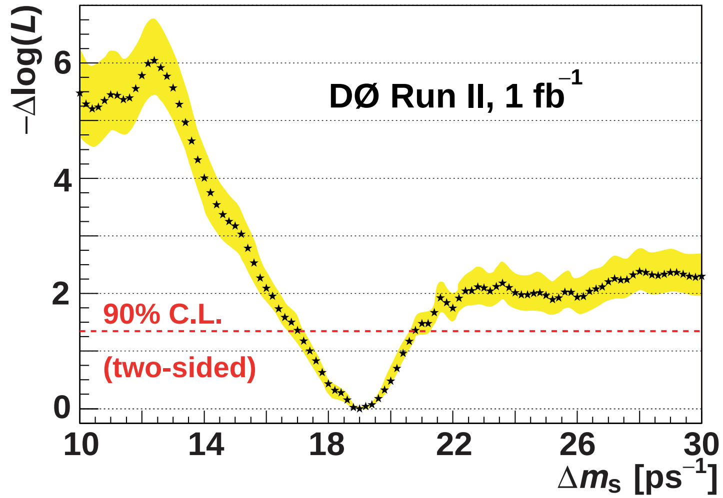
# $B_s$ Mixing – Results

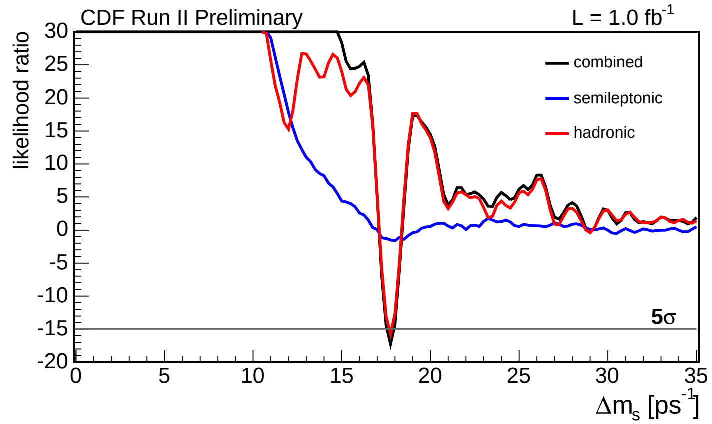
**March 2006: first direct limits by DØ**

$$17 < \Delta m_s < 21 \text{ ps}^{-1}$$

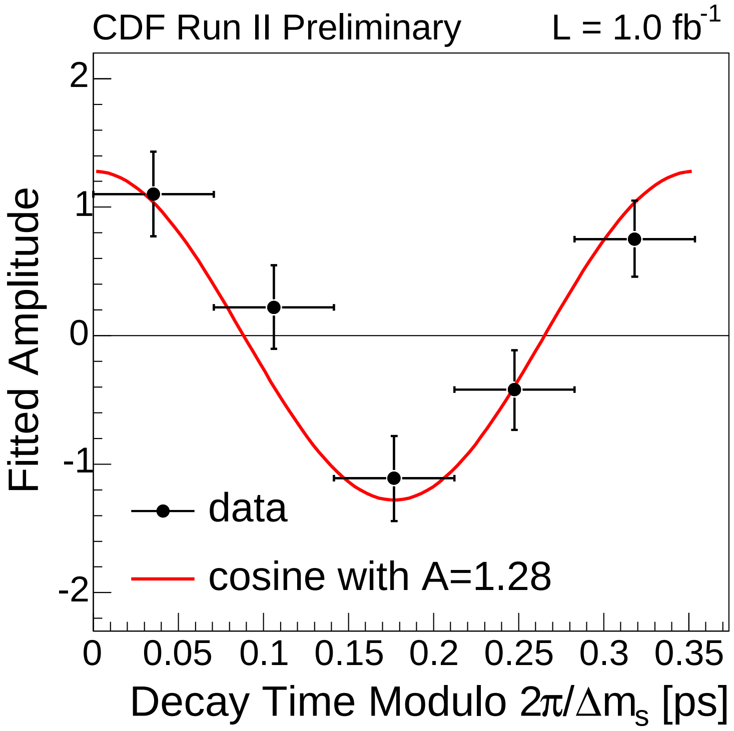
**Now: precision measurement by CDF**

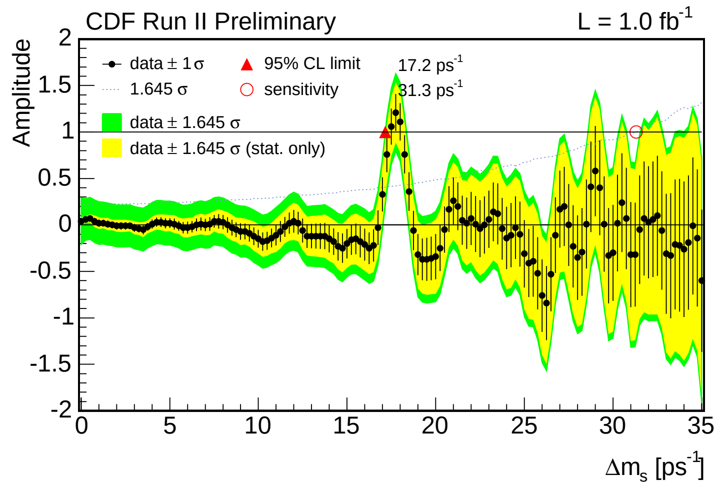
$$\Delta m_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst}) \text{ ps}^{-1}$$




**Oscillation is visible by eye!:**

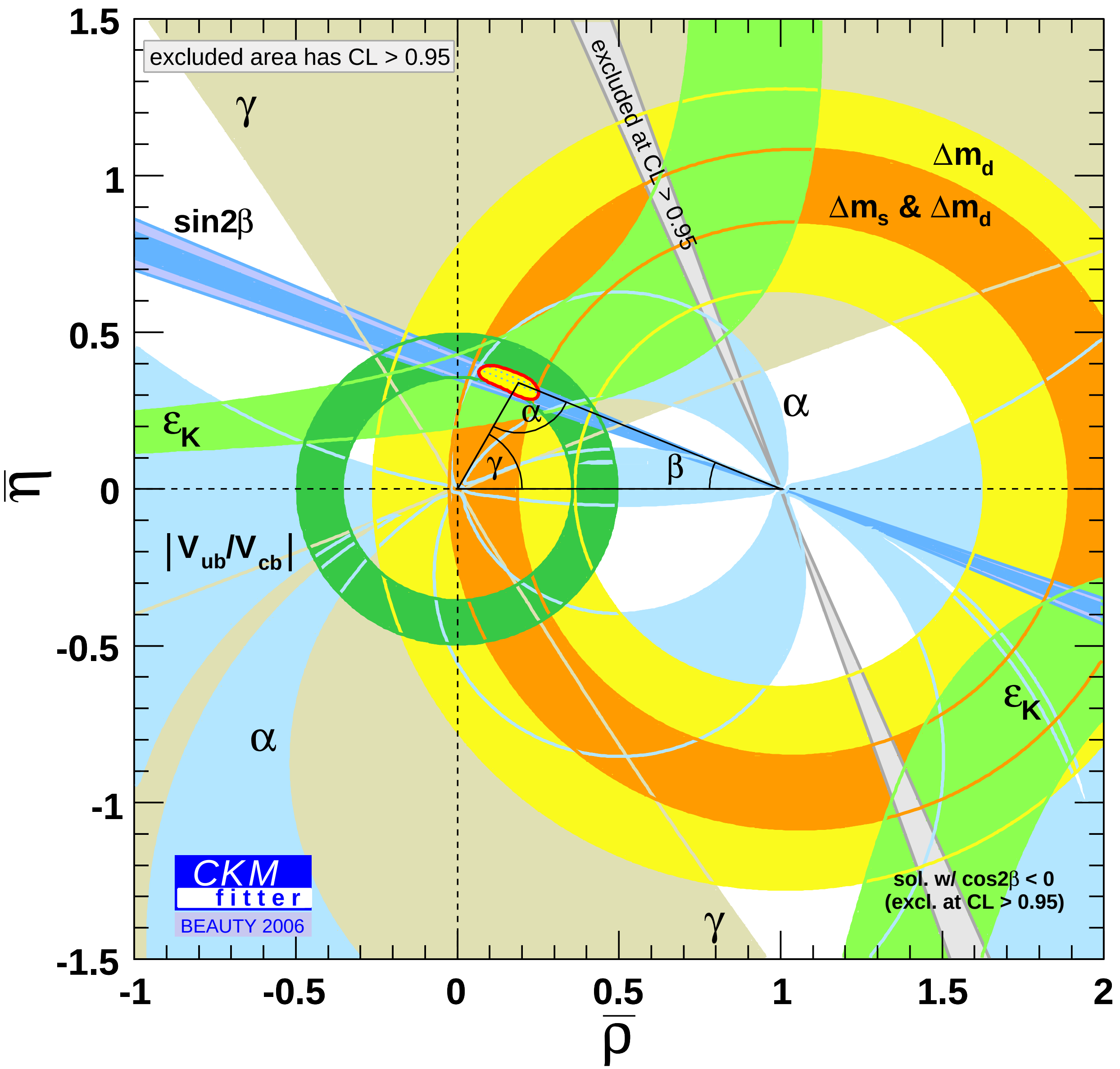


# $B_s$ Mixing – Results from CKMfitter

**Measurement of $\Delta m_s$ constrains CKM matrix elements:**

$$|V_{td}|/|V_{ts}| = 0.2060 \pm 0.0007\ (\text{exp})\ {}^{+0.0081}_{-0.0060}\ (\text{theor})$$



# More $B_s$ Physics: CP Violation

**CP violation in $B_s^0$ system:**

- SM prediction for CPV phase $\Phi_S = (4.2 \pm 1.4) \times 10^{-3}$
- potentially modified by new physics

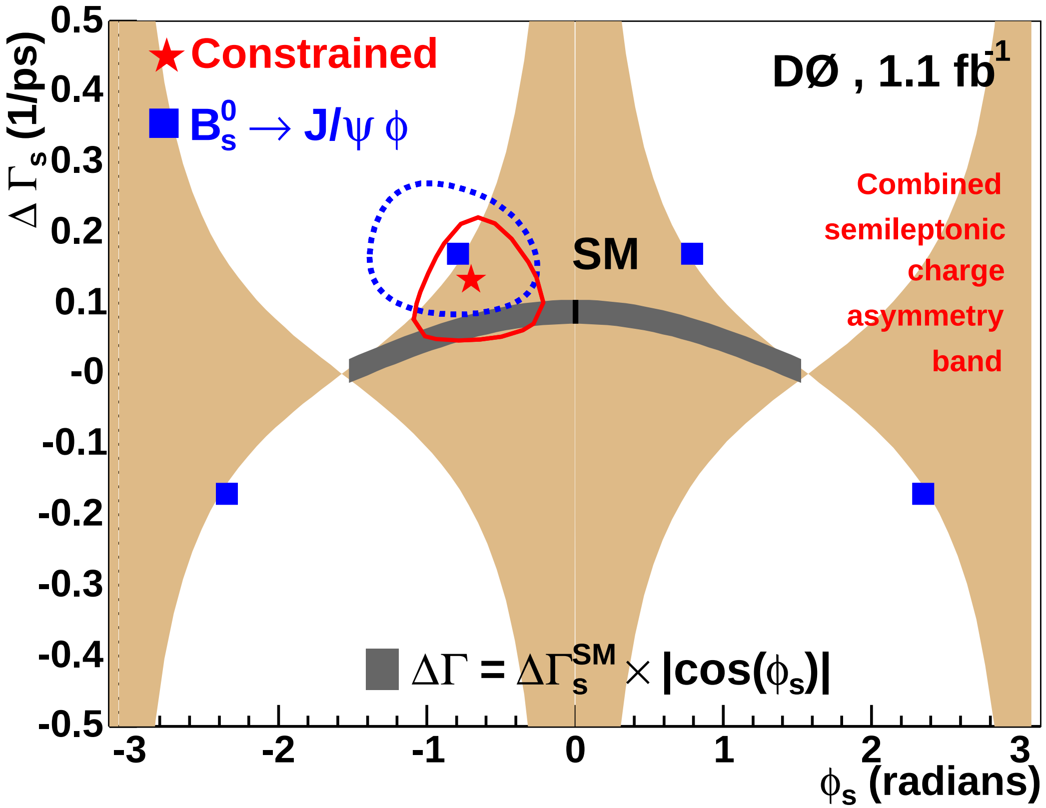
**DØ: new combined constraint extracted from 4 measurements**

- time-dependent angular distributions in $B_s^0 \to J/\Psi\Phi$
- effective mean lifetime from flavour-specific $B_s^0$ decays
- charge asymmetry in semileptonic $B_s^0$ decays

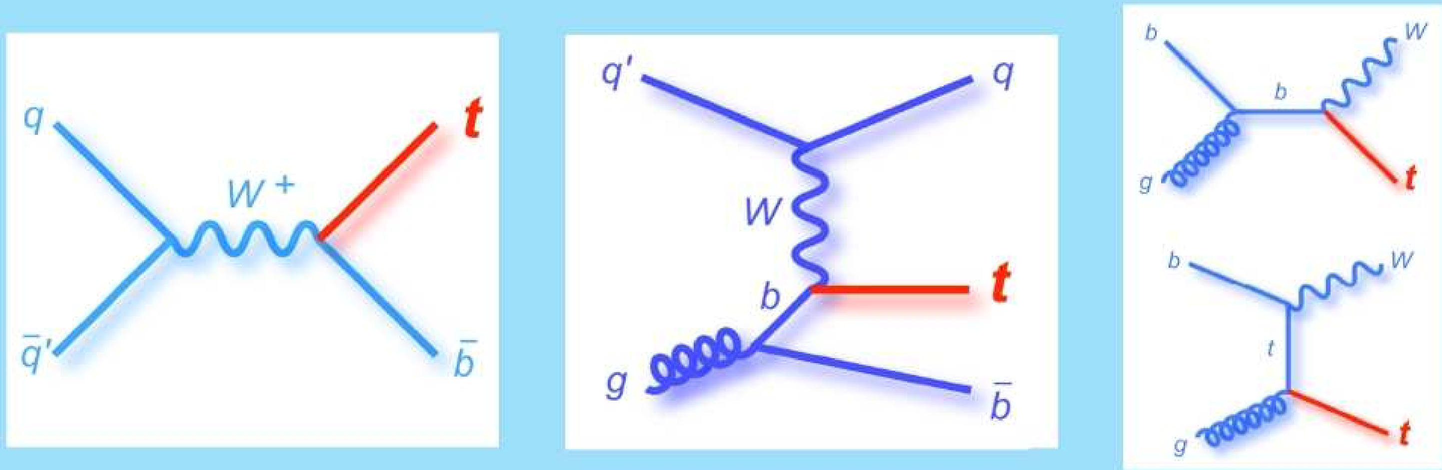
**(Still) 4 solutions, including:**

$$\Delta\Gamma_s = 0.13 \pm 0.09\ \mathrm{ps}^{-1}$$

$$\Phi_s = -0.70^{+0.47}_{-0.39}$$



# Single Top Production – Introduction




s-channel: "*tb*"
$\sigma_{NLO}$ = 0.88 ± 0.11 pb

t-channel: "*tqb*"
$\sigma_{NLO}$ = 1.98 ± 0.25 pb

"*tW* production"
$\sigma_{NLO}$ = 0.21 pb
(Too small to see at the Tevatron)

**Physics Goals:**

– Direct measurement of $V_{tb}$

– Test for new physics:
resonances: W'→tb, ...
anomalous couplings, FCNC...

**Channels:**

– W-decays to electron or muon

– 2-4 jets, with 1-2 b-tags

| Source | Event Yields in 0.9 fb$^{-1}$ Data<br>Electron+muon, 1tag+2tags combined<br>2 jets | 3 jets | 4 jets |
|---|---|---|---|
| *tb* | 16 ± 3 | 8 ± 2 | 2 ± 1 |
| *tqb* | 20 ± 4 | 12 ± 3 | 4 ± 1 |
| $t\bar{t} \rightarrow ll$ | 39 ± 9 | 32 ± 7 | 11 ± 3 |
| $t\bar{t} \rightarrow l$+jets | 20 ± 5 | 103 ± 25 | 143 ± 33 |
| $W+b\bar{b}$ | 261 ± 55 | 120 ± 24 | 35 ± 7 |
| $W+c\bar{c}$ | 151 ± 31 | 85 ± 17 | 23 ± 5 |
| $W+jj$ | 119 ± 25 | 43 ± 9 | 12 ± 2 |
| Multijets | 95 ± 19 | 77 ± 15 | 29 ± 6 |
| Total background | 686 ± 41 | 460 ± 39 | 253 ± 38 |
| Data | 697 | 455 | 246 |

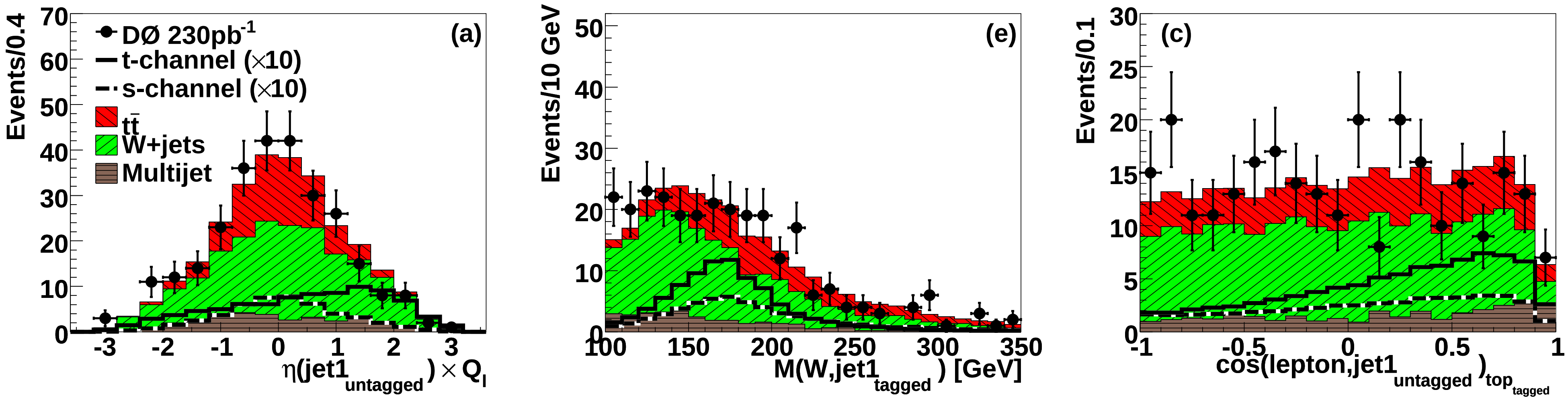
# Single Top Production – The Method

## Main challenge: signal buried in huge backgrounds

→ need state of the art generators to model W+jets production (MLM matching, alpgen)

→ employ multivariate discriminants optimally exploiting full information

## Examples of input variables:



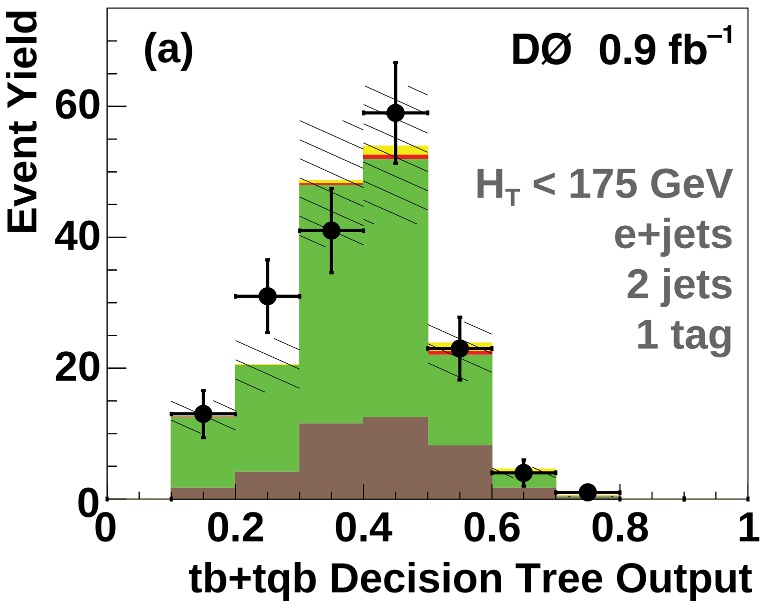

## DØ Analysis: Boosted Decision Trees, Matrix Element Method, Bayesian Neural Networks

– signal extracted from discriminant distributions using binned likelihood fits

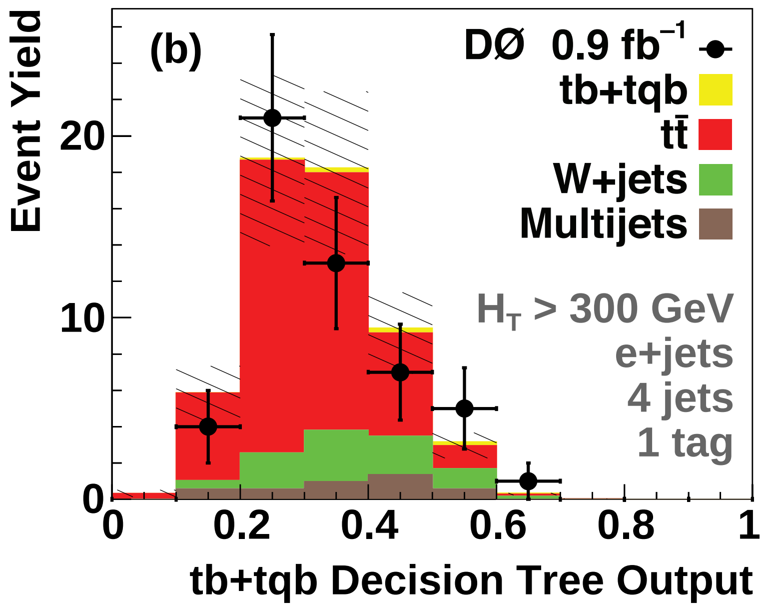
# Single Top Production – Cross Checks

Verify modeling of discriminants in control samples:

W+jets control sample



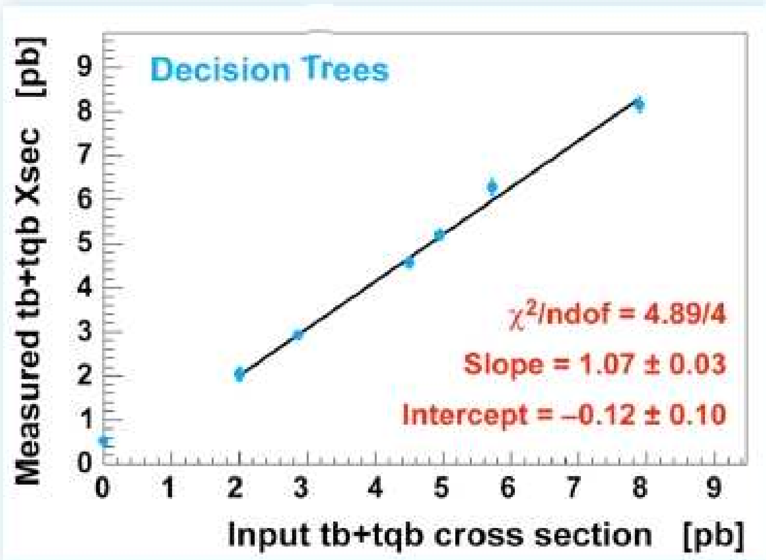

$t\bar{t}$ control sample




Ensemble testing used to:

- check for bias, calibrate method
- determine significance (p-value)

Best sensitivity: Decision Tree analysis



# Single Top Production – Results

**DØ: 3.4$\sigma$ evidence of single top production**

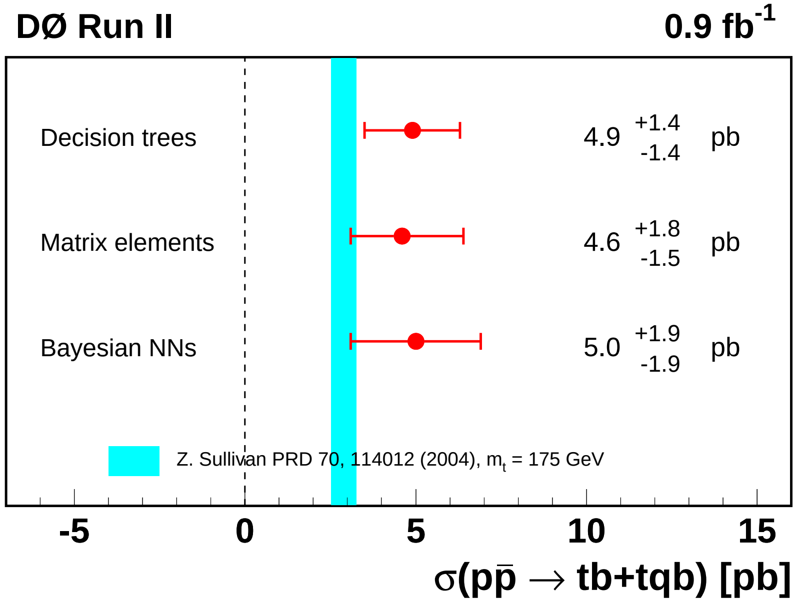
$$\sigma(p\bar{p} \to tb + X, tqb + X) = 4.9 \pm 1.4 \text{ pb}$$

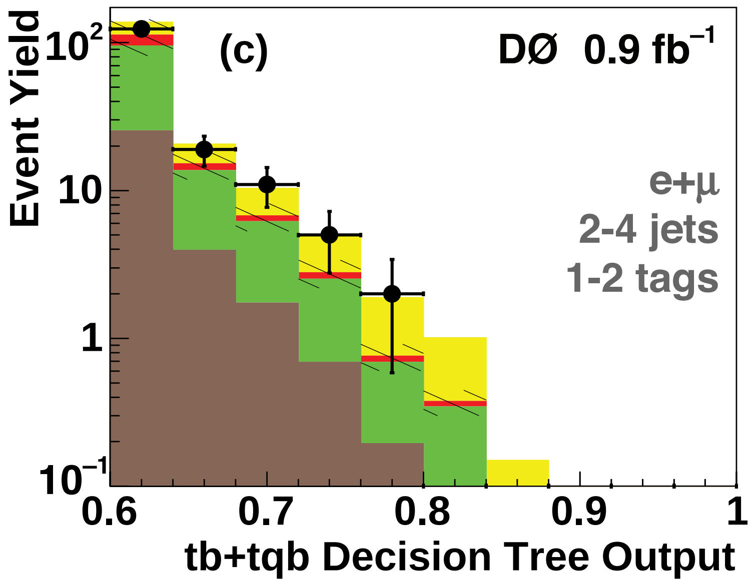
**First direct measurement of $|V_{tb}|$:**

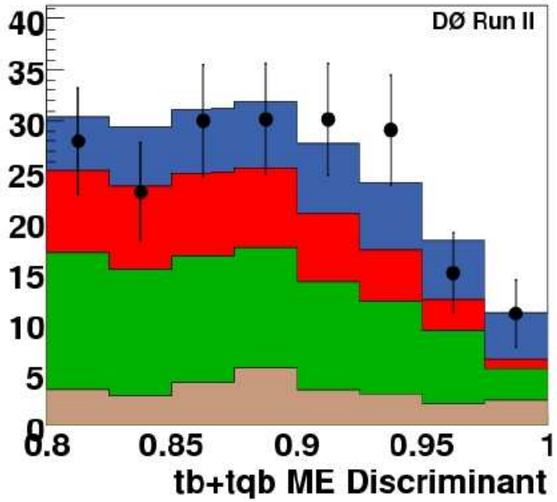
$$0.68 < |V_{tb}| \leq 1 \text{ at 95\% C.L.}$$

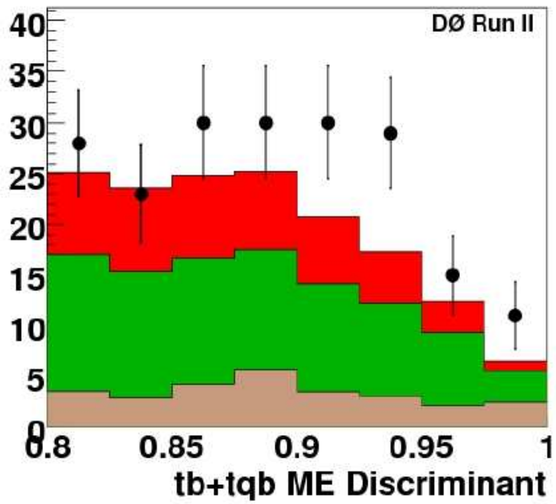
**CDF: two conflicting results**

- ME analysis: $\sigma = 2.7^{+1.5}_{-1.3}$ pb (2.3$\sigma$)
- NN analysis: $\sigma < 2.6$ pb at 95% C.L.
- to be resolved with more data...



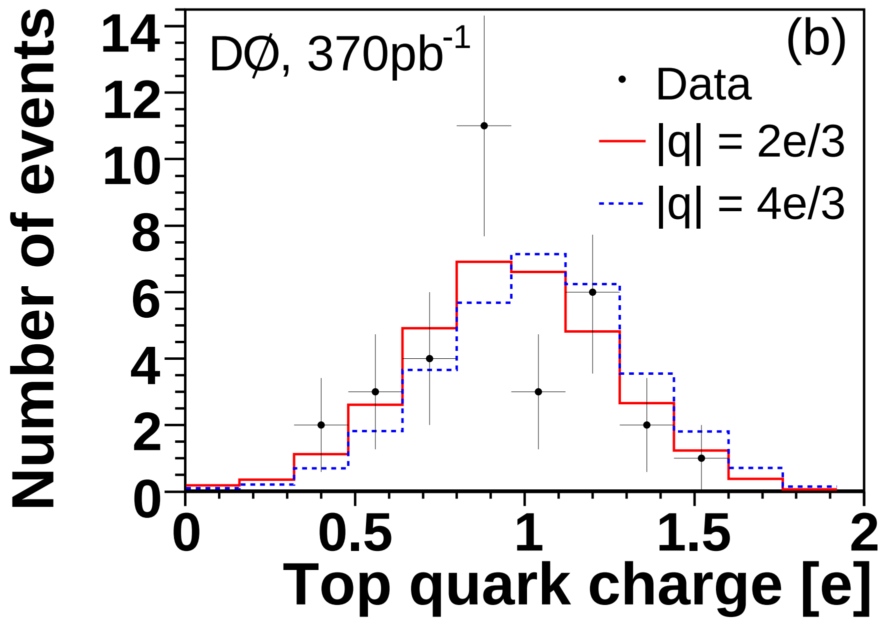



# Properties of the Top Quark

## Towards measurements of the complete set of quantum numbers

**Top Charge:**

– **Charge consistent with $2/3e$, $4/3e$ excluded at 94% CL**



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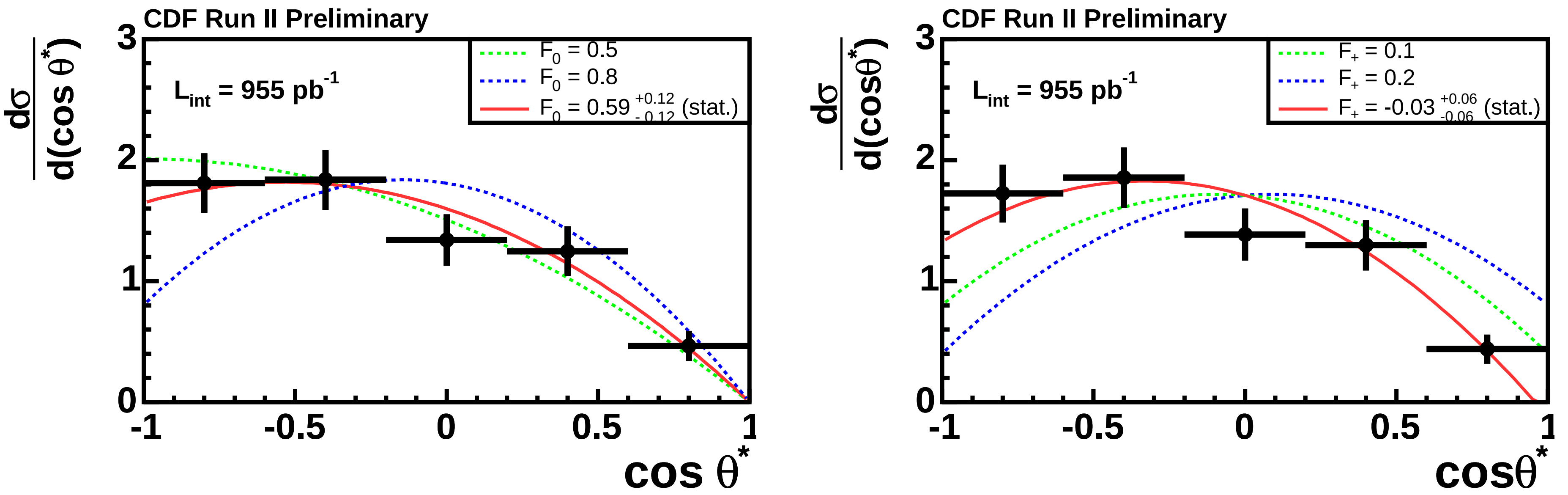
**Top electroweak coupling: any hint of V+A contribution? → W-Helicity**

$$F+ = -0.03 \pm 0.06 \text{ (stat) } ^{+0.04}_{-0.03} \text{ (syst)} \rightarrow F+ < 0.10 \text{ at 95\% C.L.}$$



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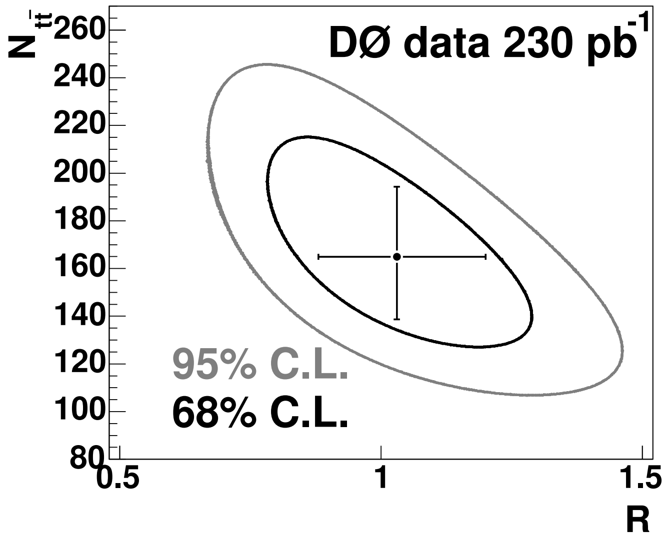
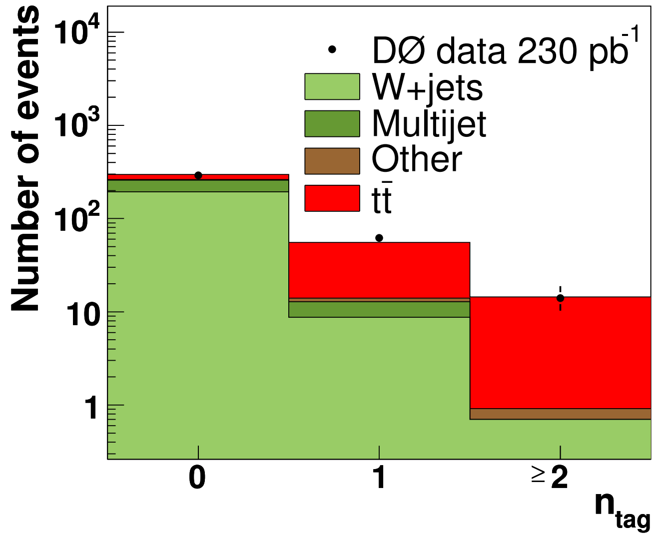
**Top electroweak coupling: $V_{tb}$ from R=BR($t \longrightarrow Wb$)/BR($t \longrightarrow Wq$)**

Simultaneous measurement of R and $t\bar{t}$ cross section

$$R = 1.03^{+0.19}_{-0.17} \longrightarrow |V_{tb}| > 0.78 \text{ at 95\% C.L.}$$



# Properties of the Top Quark

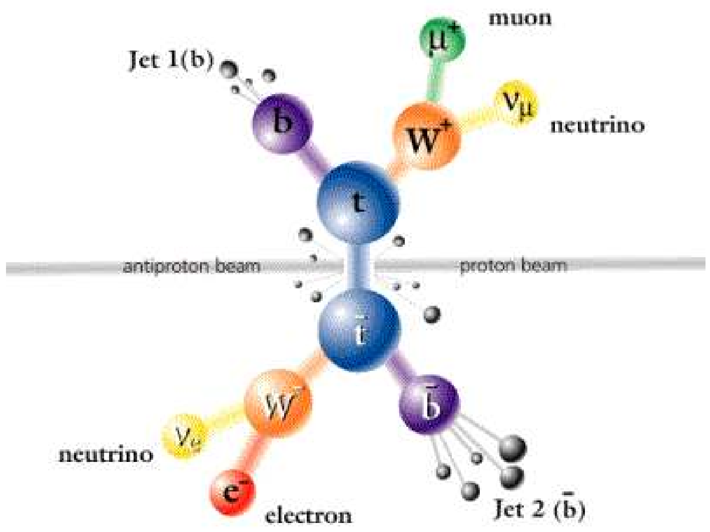
## Towards measurements of the complete set of quantum numbers

**Current Status:**

| | Measurement | SM prediction |
|---|---|---|
| $\sigma_{t\bar{t}}$ | 7.3±0.9 pb | 6.7±0.9 pb |
| $\sigma(gg \to t\bar{t})/\sigma(gg + qq \to t\bar{t})$ | 0.25±0.26 | 0.18 |
| $c\tau_{top}$ | $<53.5\mu$m (95% C.L.) | $10^{-10}\mu$m |
| BR$(t \to Wb)$/BR$(t \to Wq)$ | $1.03^{+0.19}_{-0.17}$ | 0.998 |
| $F_0$ | 0.59±0.14 | 0.75 |
| $F_+$ | <0.10 (95% C.L.) | 0 |
| Charge | Not 4/3 (94% C.L.) | 2/3 |
| Spin | | 1/2 |

$\longrightarrow$ still plenty of room for improvements with larger statistics!

# Top Mass Measurement – Introduction



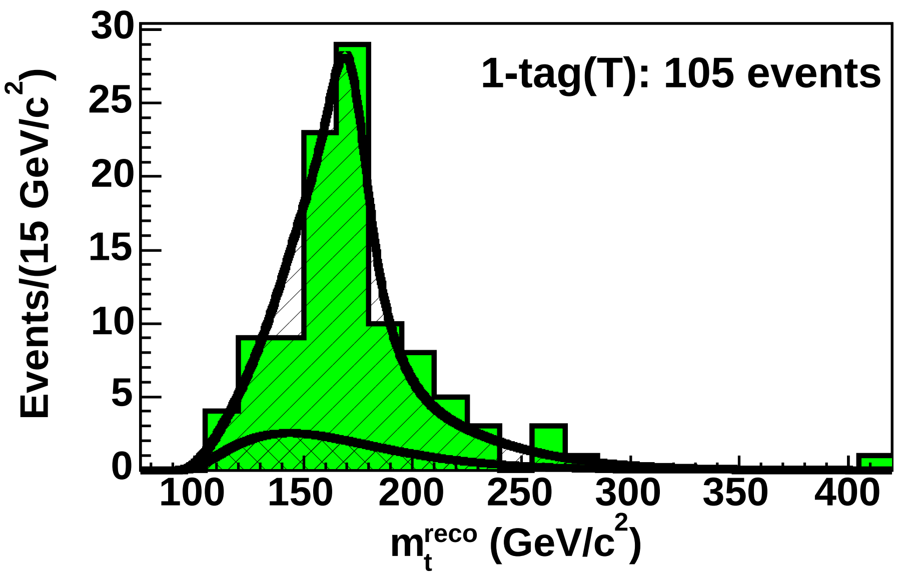

**Decay modes of W-bosons define 3 main channels:**

| Channel | Signature | Events/1 fb$^{-1}$ |
|---|---|---|
| "Dilepton" | $\ell\ell$+bb+$\not{E}_T$ | 50 |
| "Lepton + Jets" | $\ell$+qq+bb+$\not{E}_T$ | 200 |
| "All Jets" | 4q+bb | 300 |

**Golden Channel: Lepton + Jets**

- good statistics
- good signal/background ratio
- only 1 neutrino escaping

→ overconstrained system



# Top Mass Measurement – The Method

## Matrix Element Method (pioneered by DØ, Run I):

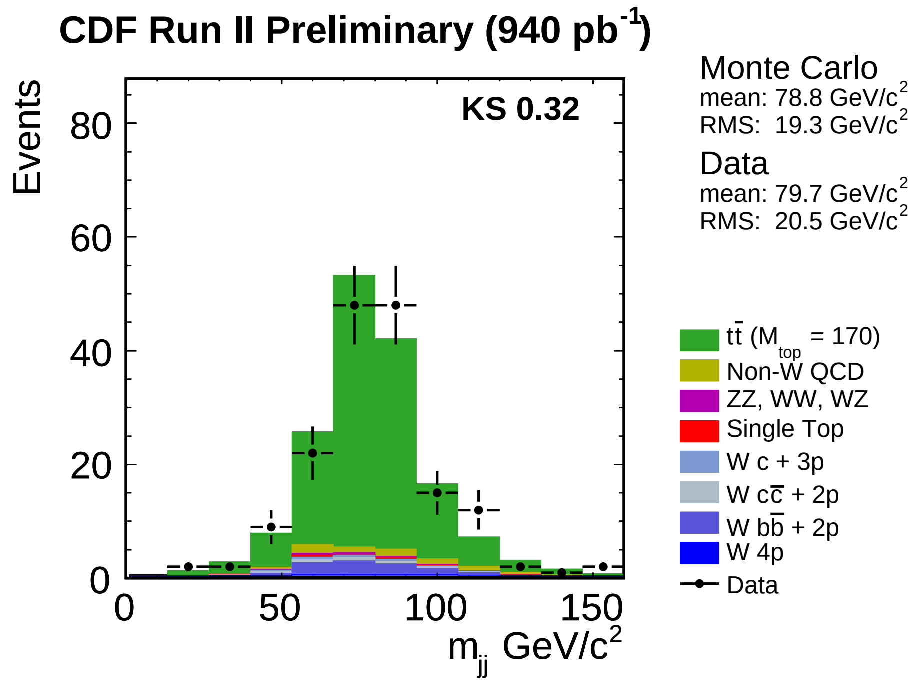
- check reconstructed events for consistency with top mass hypothesis $m_t$
- use full information: relate parton-level matrix element with reconstructed momenta x via transfer function W
- for each event, calculate likelihood $P_{signal}$ for given $m_t$ and jet energy scale JES

$$P_{signal}(x; JES, m_t) = \frac{1}{\sigma(m_t)} \int dq_1 dq_2\, f(q_1) f(q_2)\; d^n y\, \frac{\partial\sigma(y; m_t)}{\partial^n y} W(x, y; JES)$$

- maximize likelihoods to determine $m_t$ and JES

## Jet Energy Scale:

- calibrated in $\gamma$+jets vs. $\eta$, $E_t$...
- additional scale factor constrained in situ by W→qq mass



# Top Mass Measurement – Results

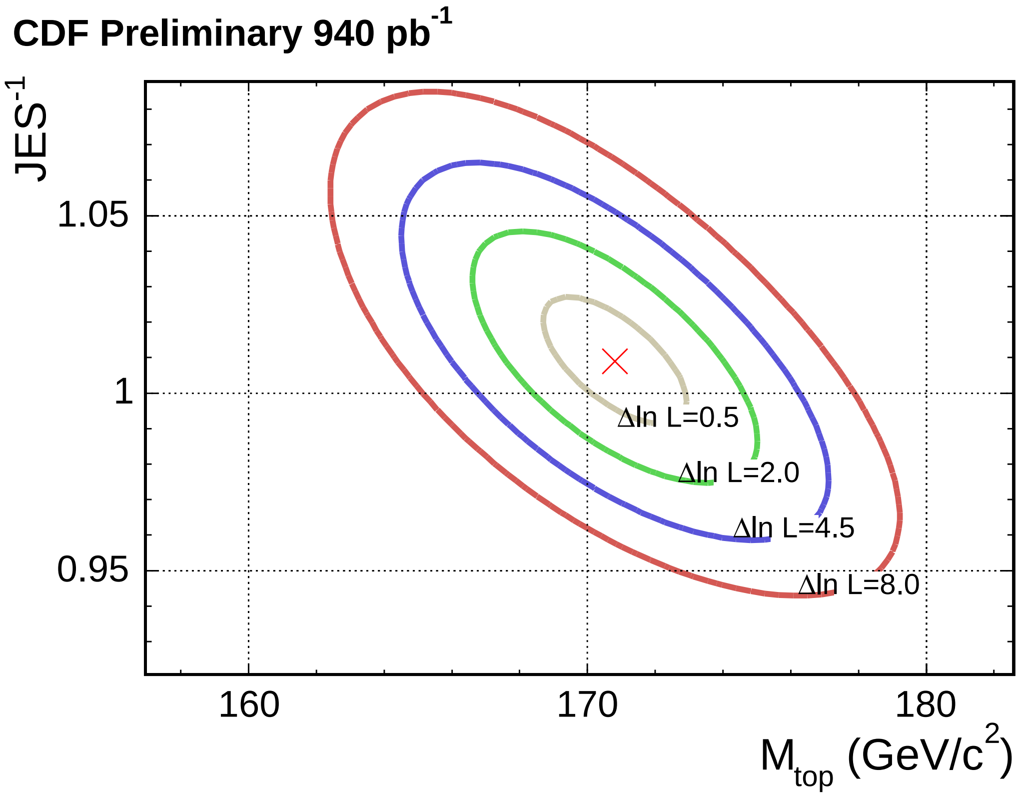
**Most precise single measurement: CDF lepton+jets**

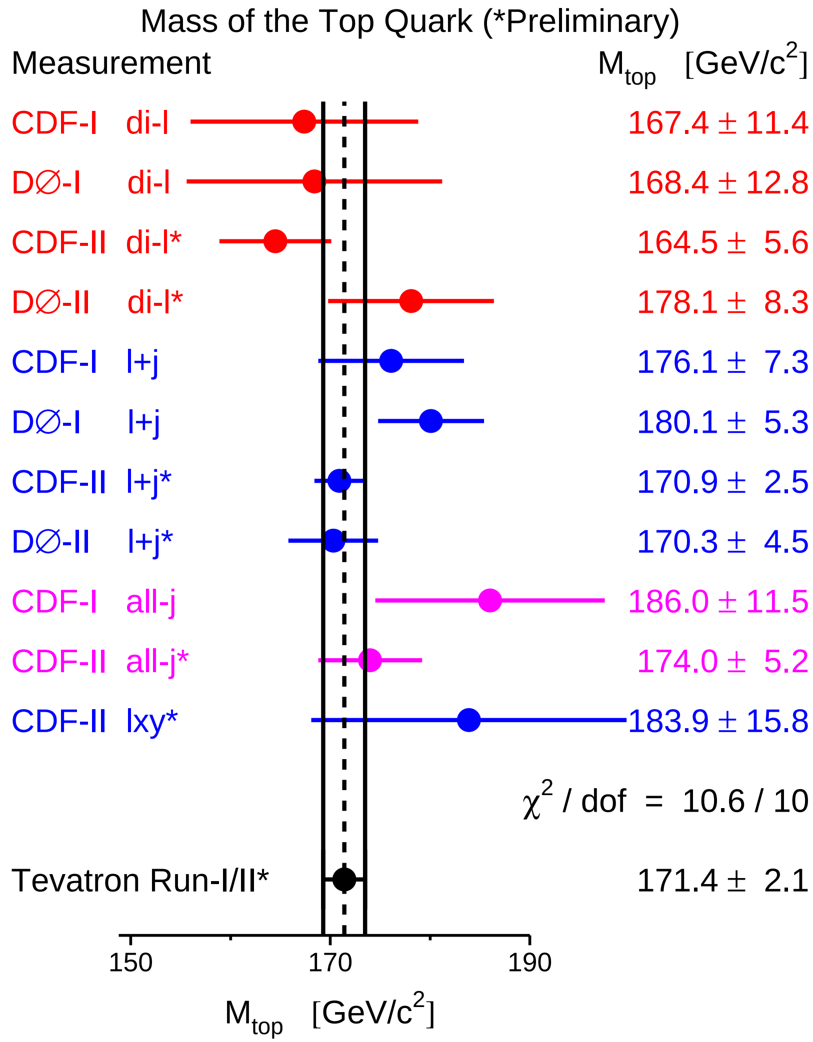
$$m_t = 170.9 \pm 2.2 \text{ (stat+JES)} \pm 1.4 \text{ (syst) GeV} \quad \text{(JES} = 0.99 \pm 0.02\text{)}$$

**World Average:**

$$m_t = 171.4 \pm 1.2 \text{ (stat)} \pm 1.8 \text{ (syst) GeV}$$

**DØ 1 fb$^{-1}$ results about to be released**



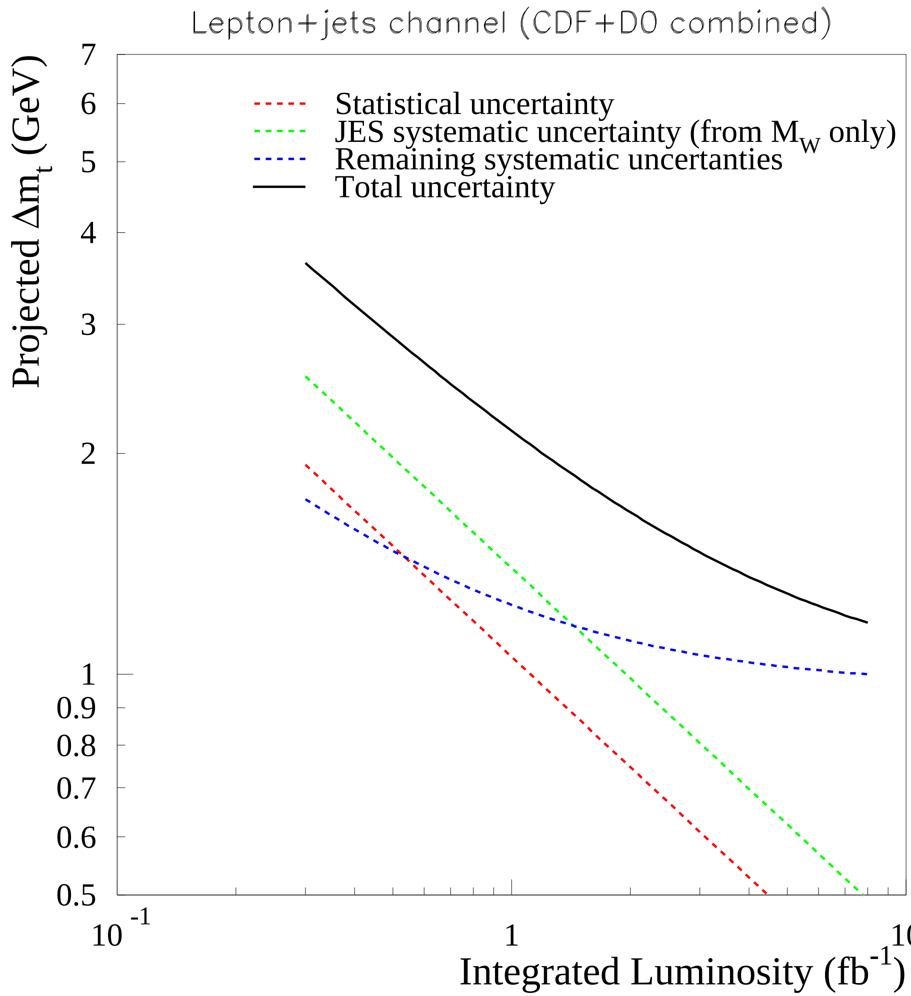



# Top Mass Measurement – Projection

## Breakdown of systematic uncertainties:

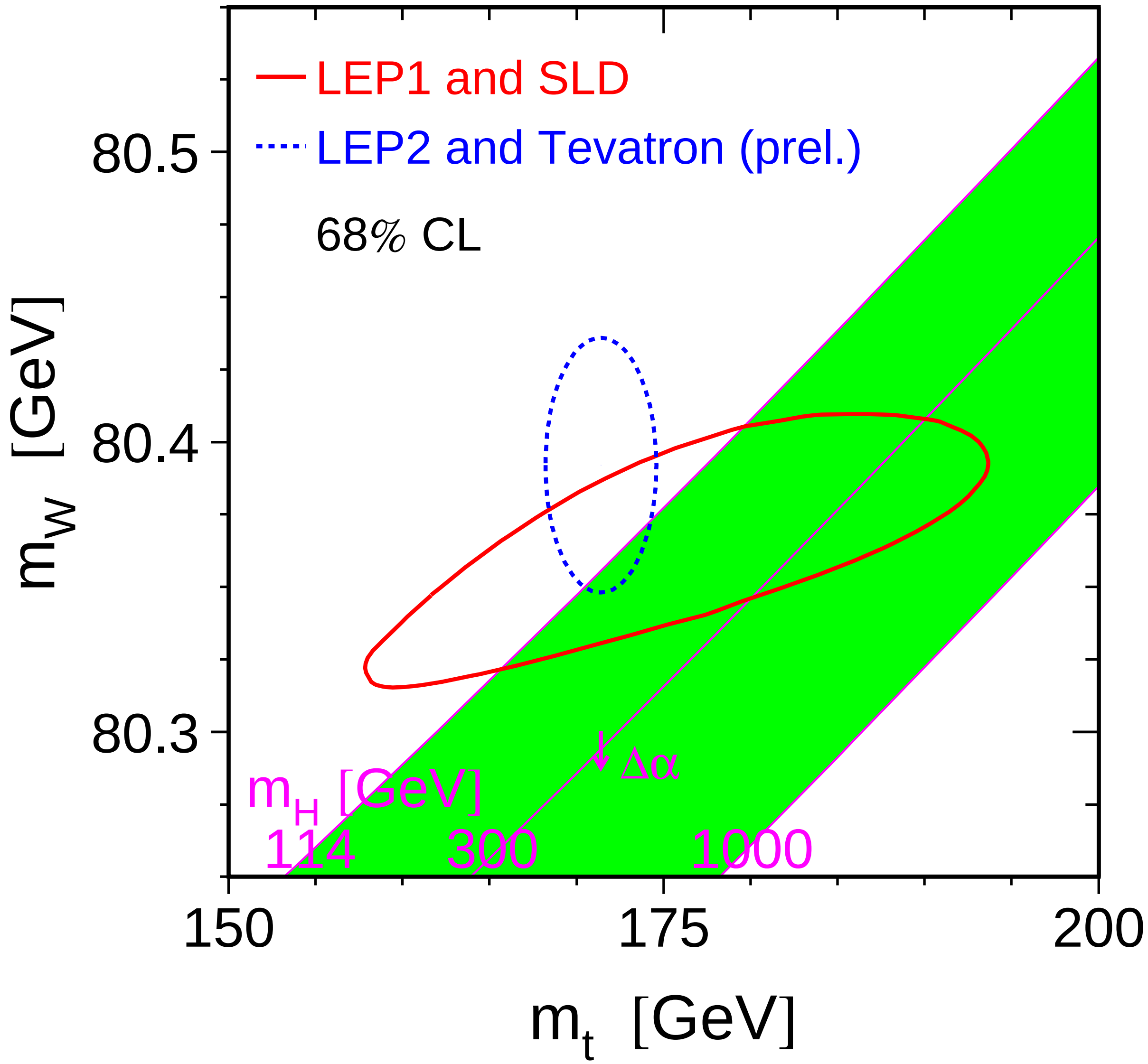
| Systematic uncertainties (GeV/$c^2$) | |
|---|---|
| JES residual | 0.42 |
| Initial state radiation | 0.72 |
| Final state radiation | 0.76 |
| Generator | 0.19 |
| Background composition and modeling | 0.21 |
| Parton distribution functions | 0.12 |
| b-JES | 0.60 |
| b-tagging | 0.31 |
| Monte Carlo statistics | 0.04 |
| Lepton $p_T$ | 0.22 |
| Multiple Interactions | 0.05 |
| Total | 1.36 |

## Projection:



# Top Mass Measurement – Interpretation

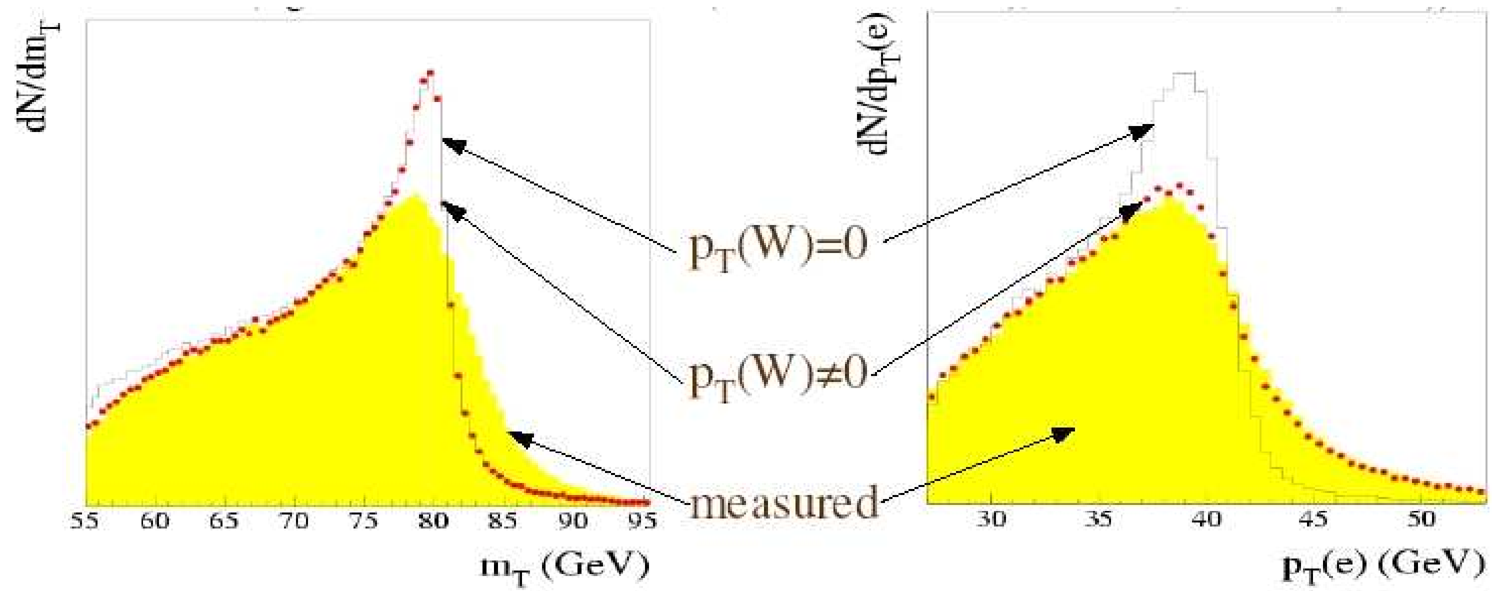
**Summer 2006:**




**Desperately needed: improved W mass measurement**

# W Mass Measurement – The Method

**Measure $m_W$ from Jacobian edge in transverse mass:**




→ minimal dependence on modeling of $p_T(W)$

→ crucial: calibration of energy measurements

**Target precision: 29 MeV / 80392 MeV = 0.03% !!**

→ extreme requirements on understanding of systematics

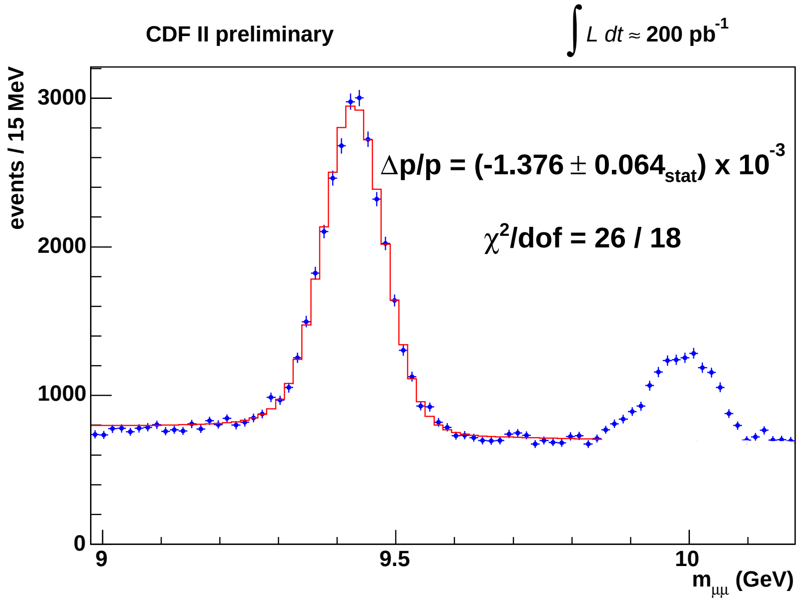
**CDF Analysis based on 200 pb$^{-1}$ (January 2007):**

– 7 years of very hard work...

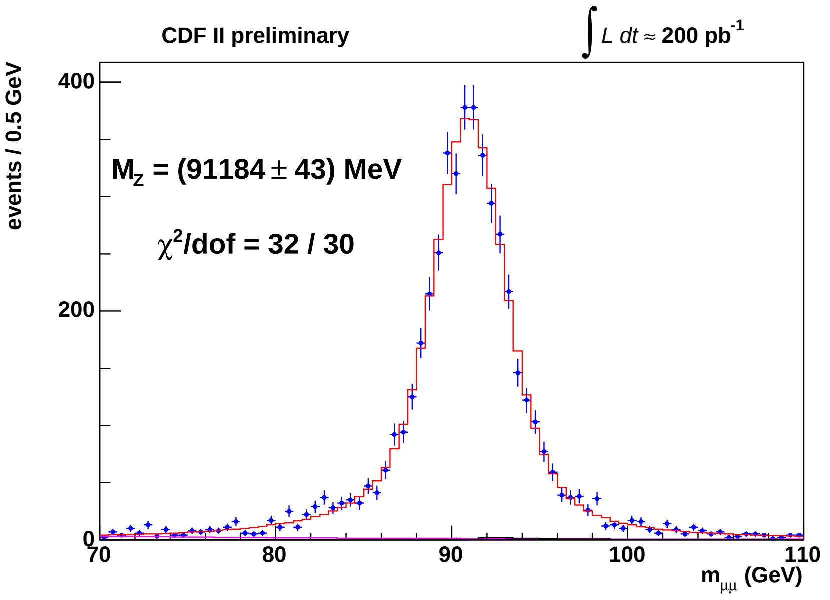
– samples sizes: 64k W→e$\nu$, 50k W→ $\mu\nu$, 3k Z→ee, 5k Z→ $\mu\mu$

# W Mass Measurement – Calibration

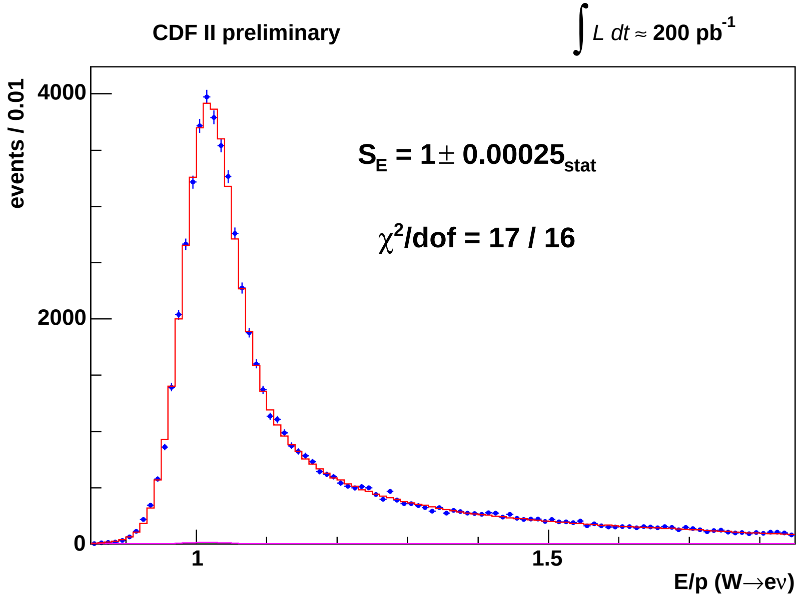
## Momentum calibration from J/Ψ, Υ:



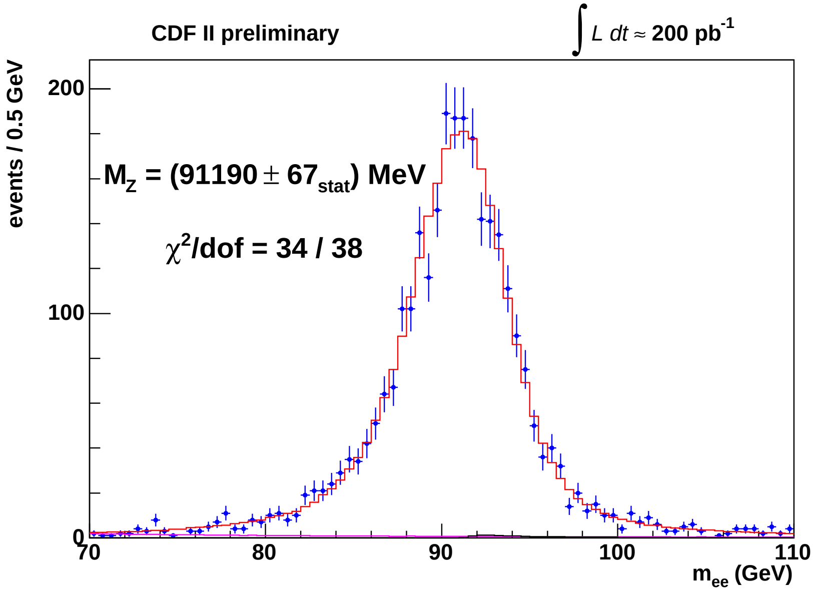

## Cross-checked on Z→ μμ:



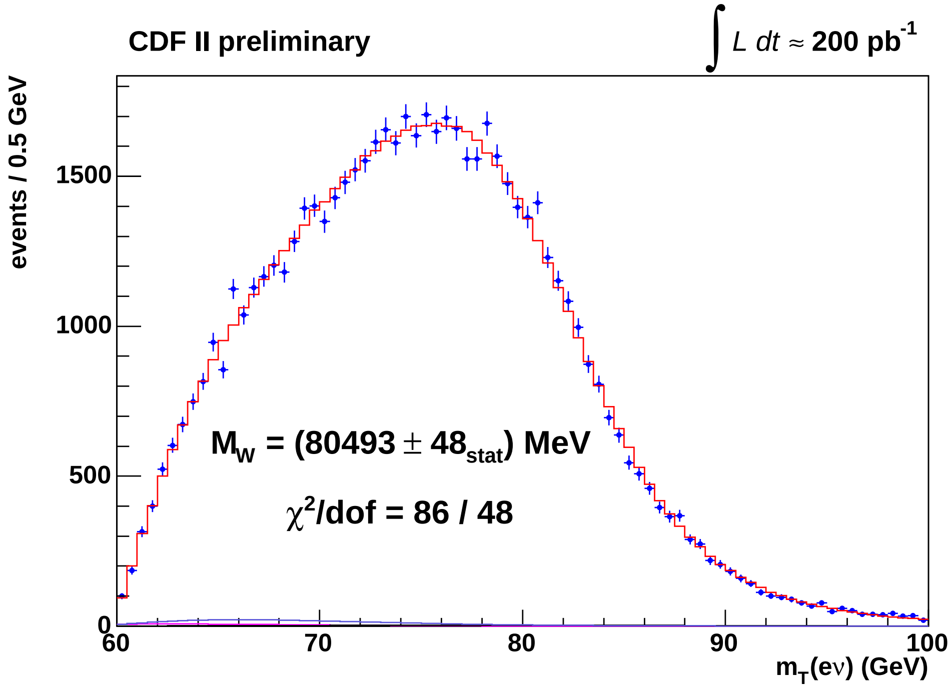

## EM calibration using E/p:

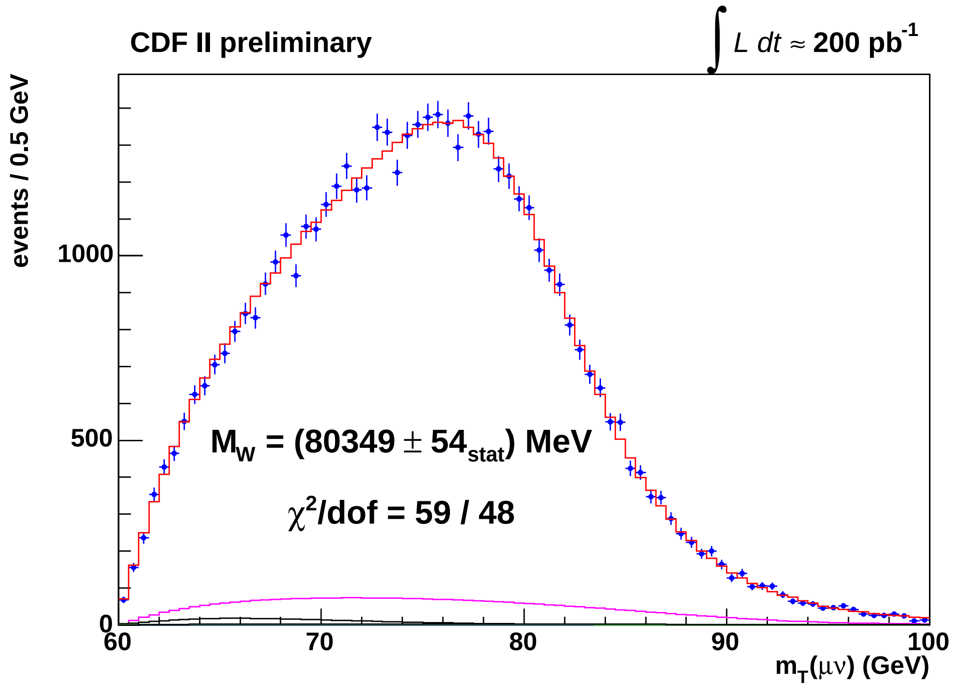



## Cross-checked on Z→ee:



# W Mass Measurement – Results




## CDF Result (200 $pb^{-1}$):

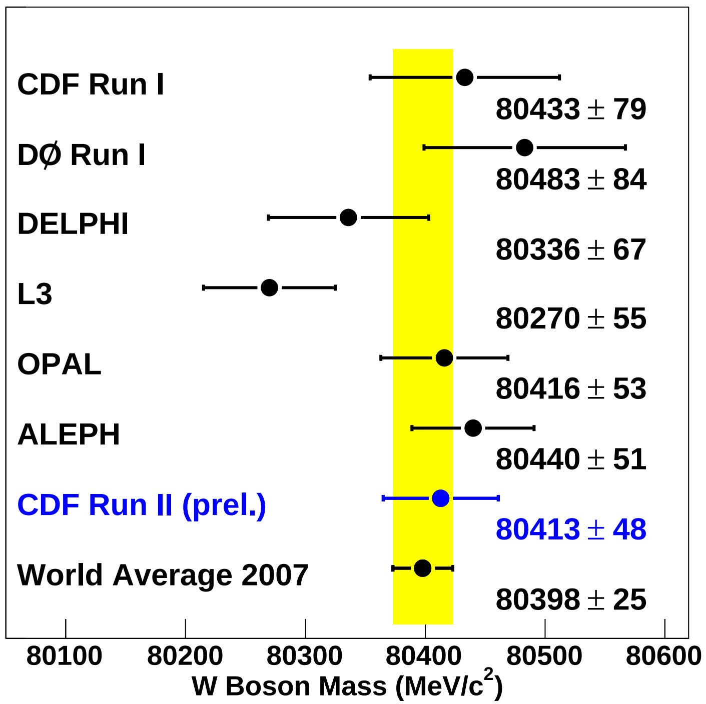
80413±48 MeV (± 34(stat), ±34(syst))

## World Average:

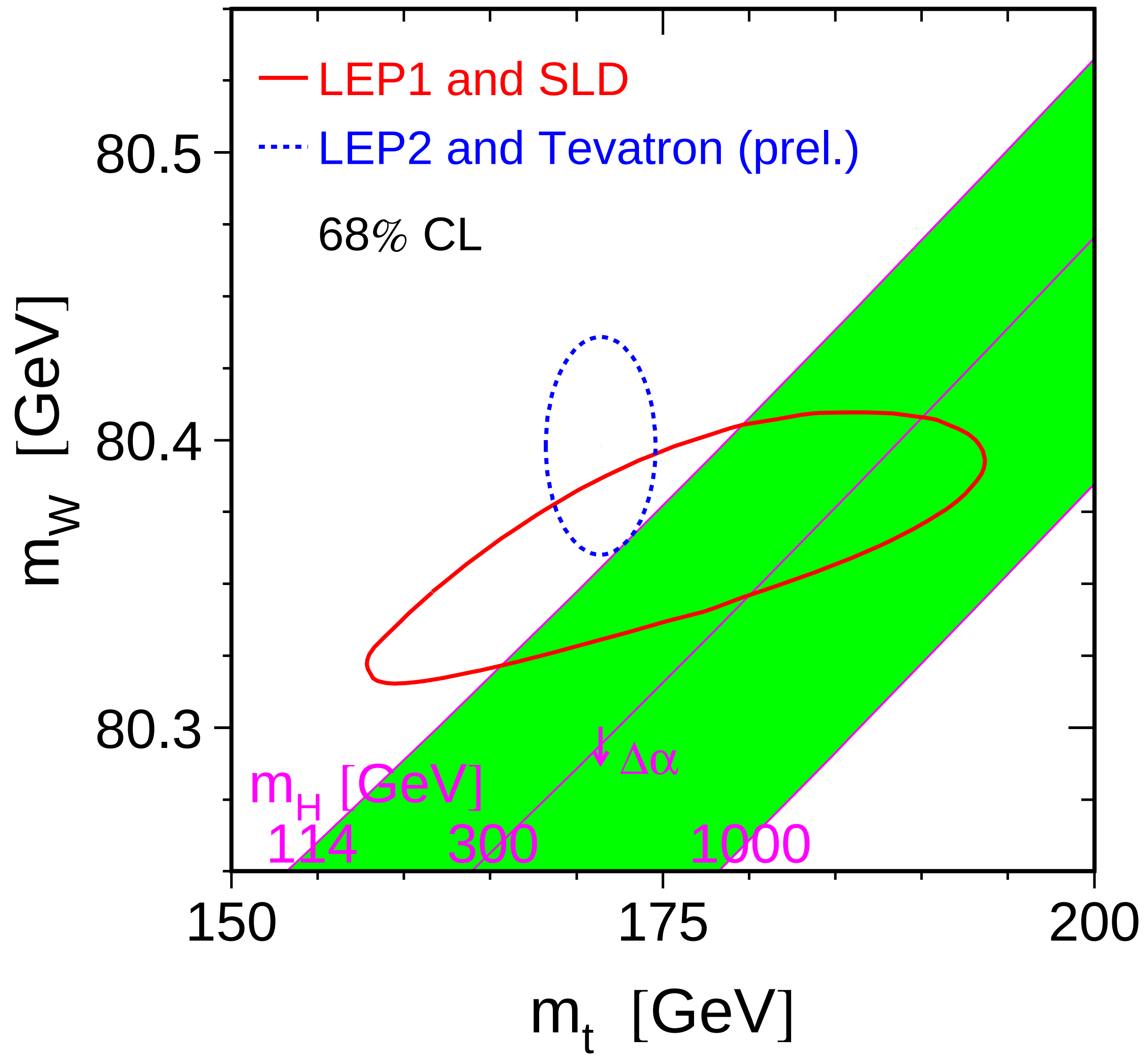
- previous: 80392±29 MeV
- new: 80398±25 MeV

## Projection (CDF only):

$\Delta m_W$ <25 MeV with 1.5 $fb^{-1}$



# W Mass Measurement – Interpretation

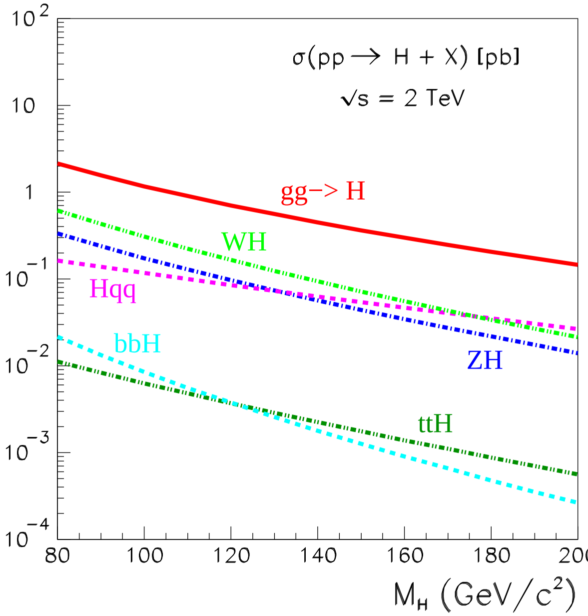



**Indirect constraints on the Higgs mass:**

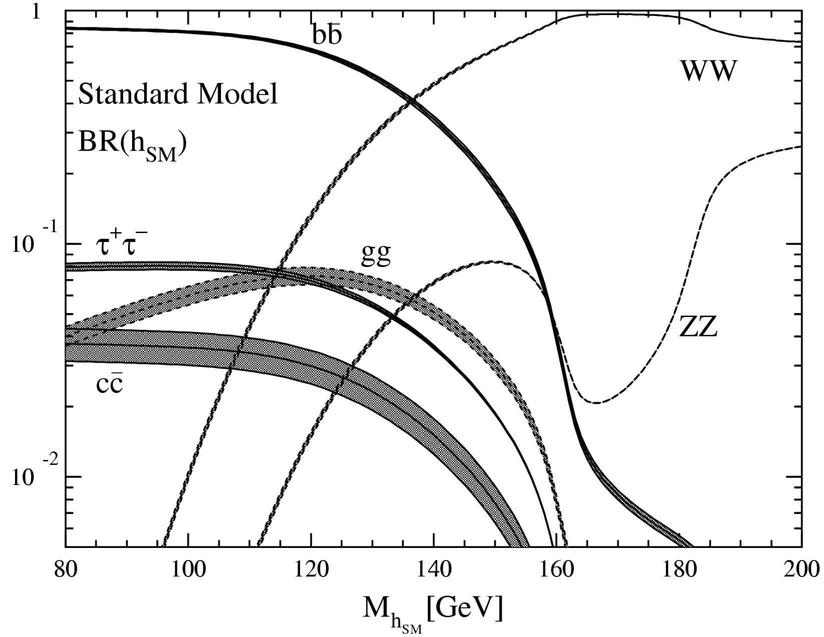
- $m_H$=80 $^{+36}_{-26}$ GeV (was 85 $^{+39}_{-28}$ GeV)
- $m_H < 153$ GeV at 95% C.L. (was <166 GeV)

# Search for Higgs Bosons – Production and Decay

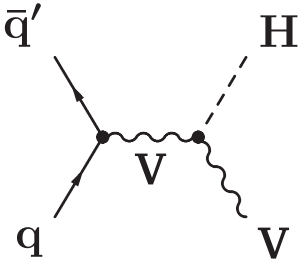
Production Cross-Sections




Branching Ratios




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



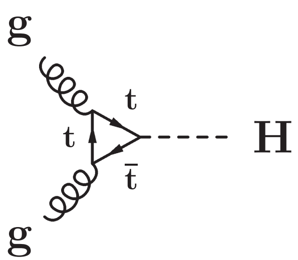

Dominant decay mode: $H \longrightarrow b\bar{b}$

Production: in association with W,Z

$\longrightarrow$ leptonic W,Z-decays provide best signature

$\longrightarrow$ b-tagging to suppress background from W/Z+jets

## Heavy Higgs bosons ($m_H$ >130 GeV):




Dominant decay mode: $H \longrightarrow WW$

Production: Gluon-Gluon Fusion

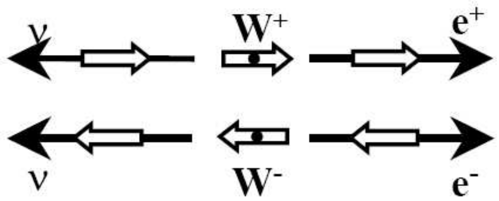
$\longrightarrow$ relatively high cross-section

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

# Search for Higgs Bosons: H⟶WW

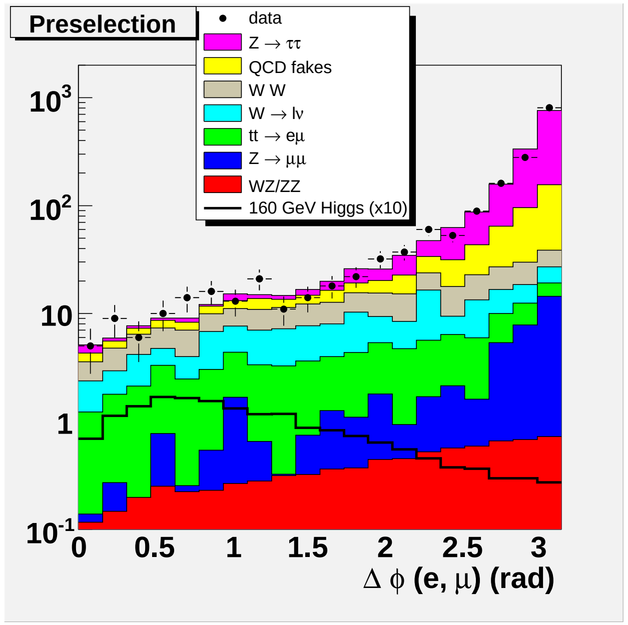
**Main irreducible background: WW⟶ $\ell\nu\ell\nu$**

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

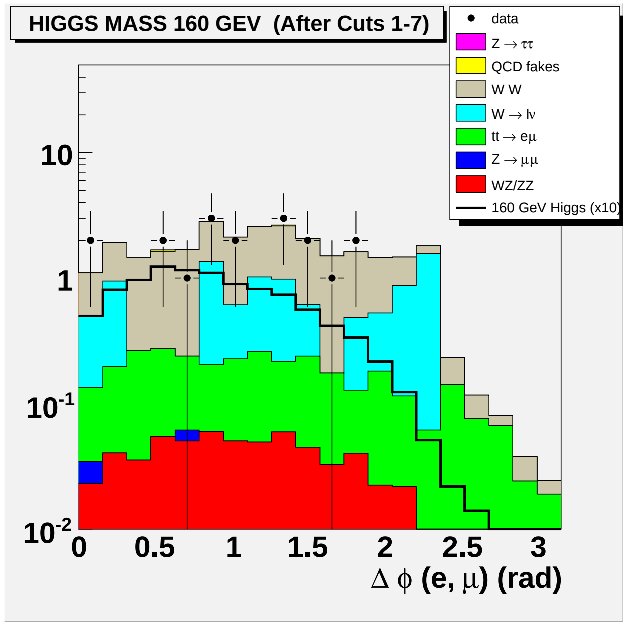



⟶ Charged leptons from Higgs decay tend to have small opening angle ΔΦ

Preselection




After all cuts




**Note:**

– 4 SM Higgs events expected after all cuts for CDF+DØ

– but: total expected background is 81 events (mostly WW)

⟶ not yet sensitive (but getting close)

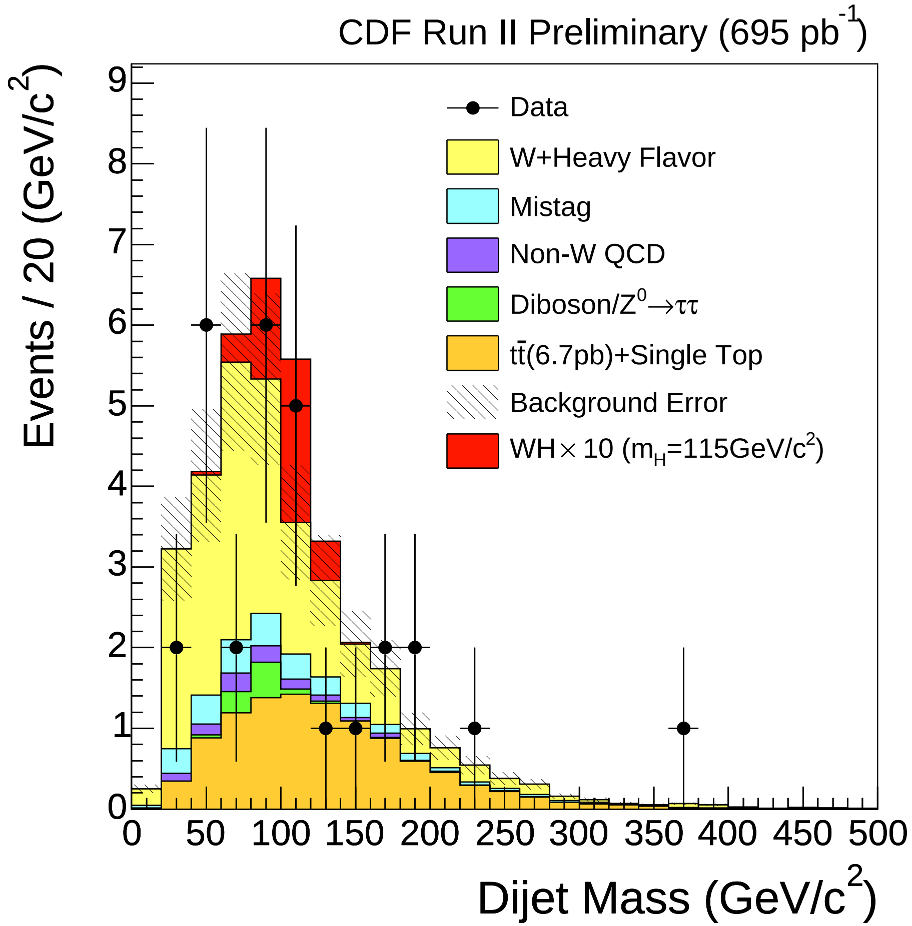
# Search for low-mass Higgs Boson

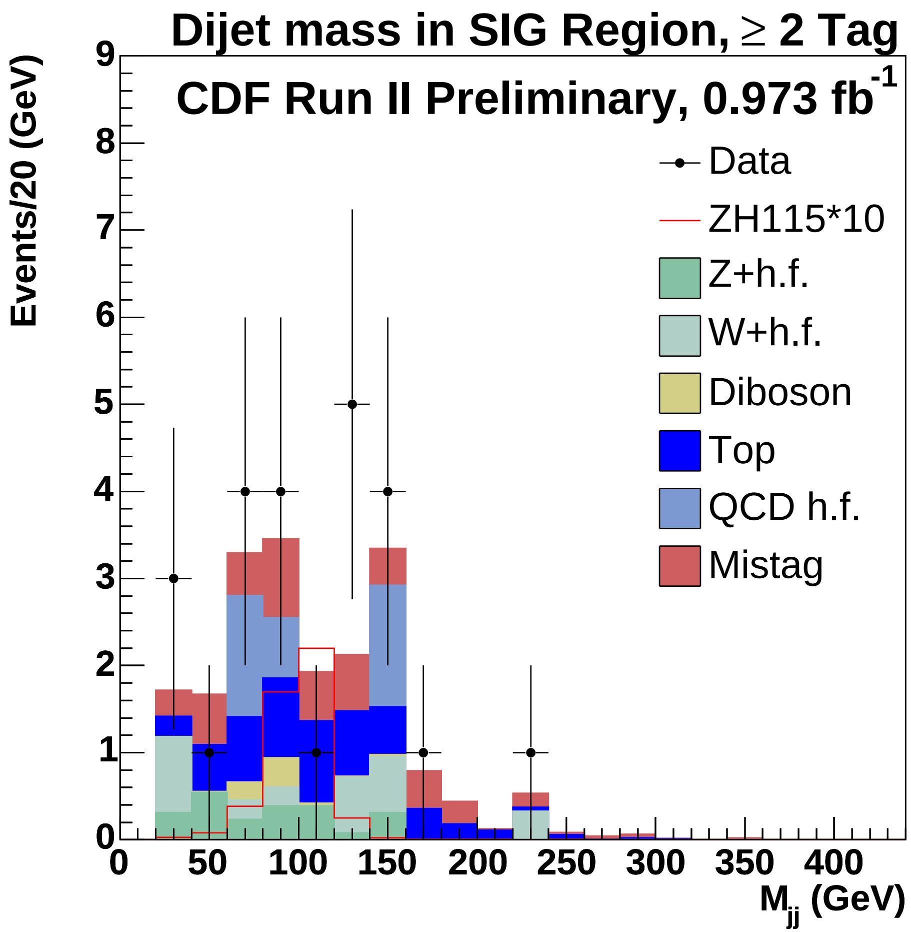
**For best sensitivity, need to combine many channels:**

$$WH \to \ell\nu b\bar{b},\ ZH \to \nu\nu b\bar{b},\ ZH \to \ell\ell b\bar{b},\ WH \to WWW$$

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

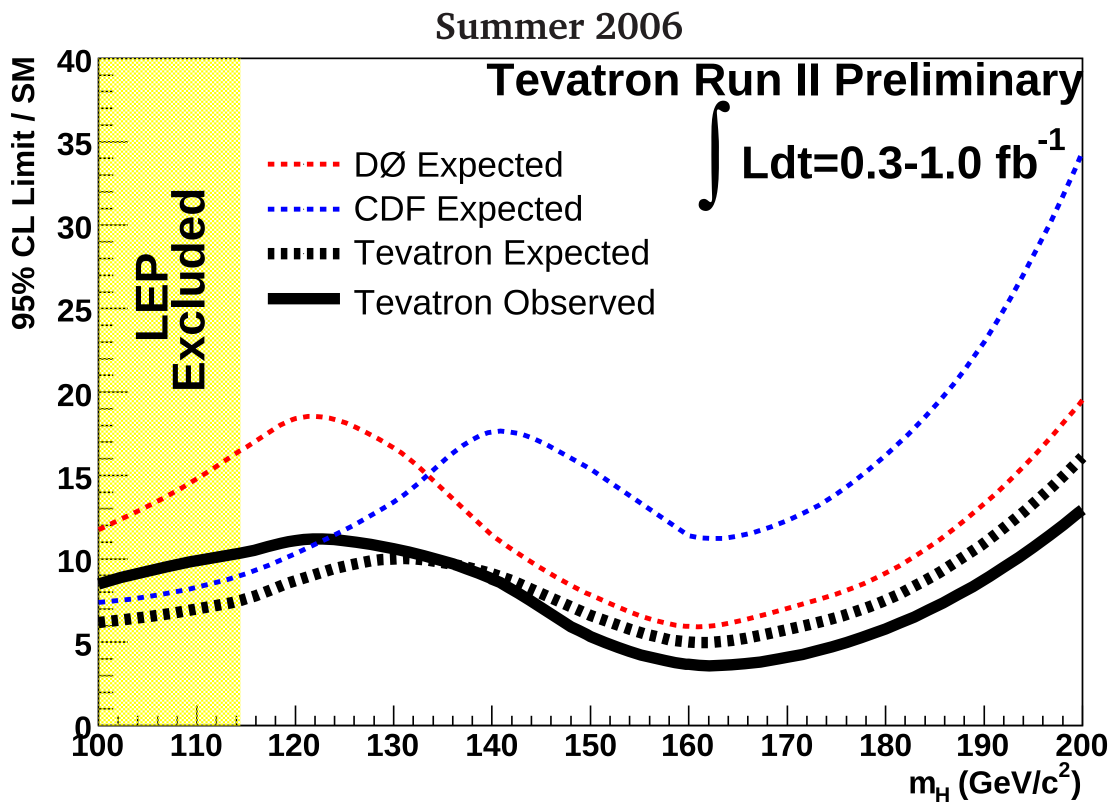
– reconstruct Higgs mass to discriminate from irreducible $Vb\bar{b}$ background




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

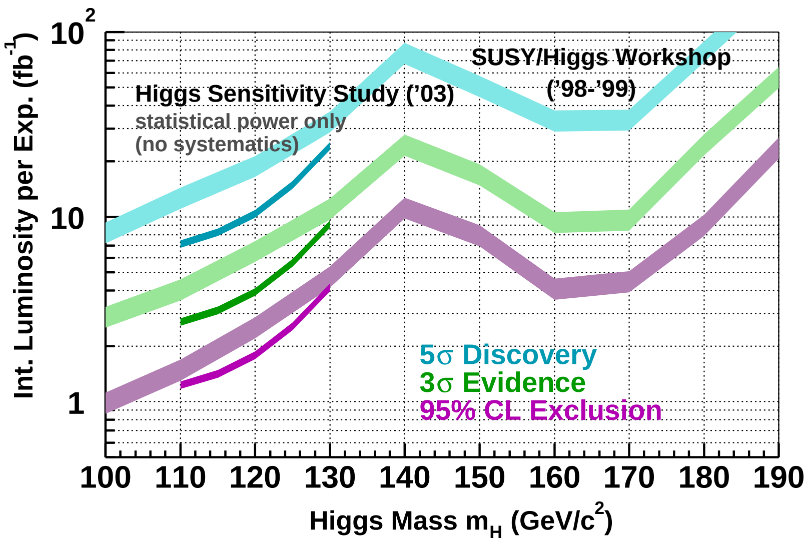
# Search for Standard Model Higgs Boson




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

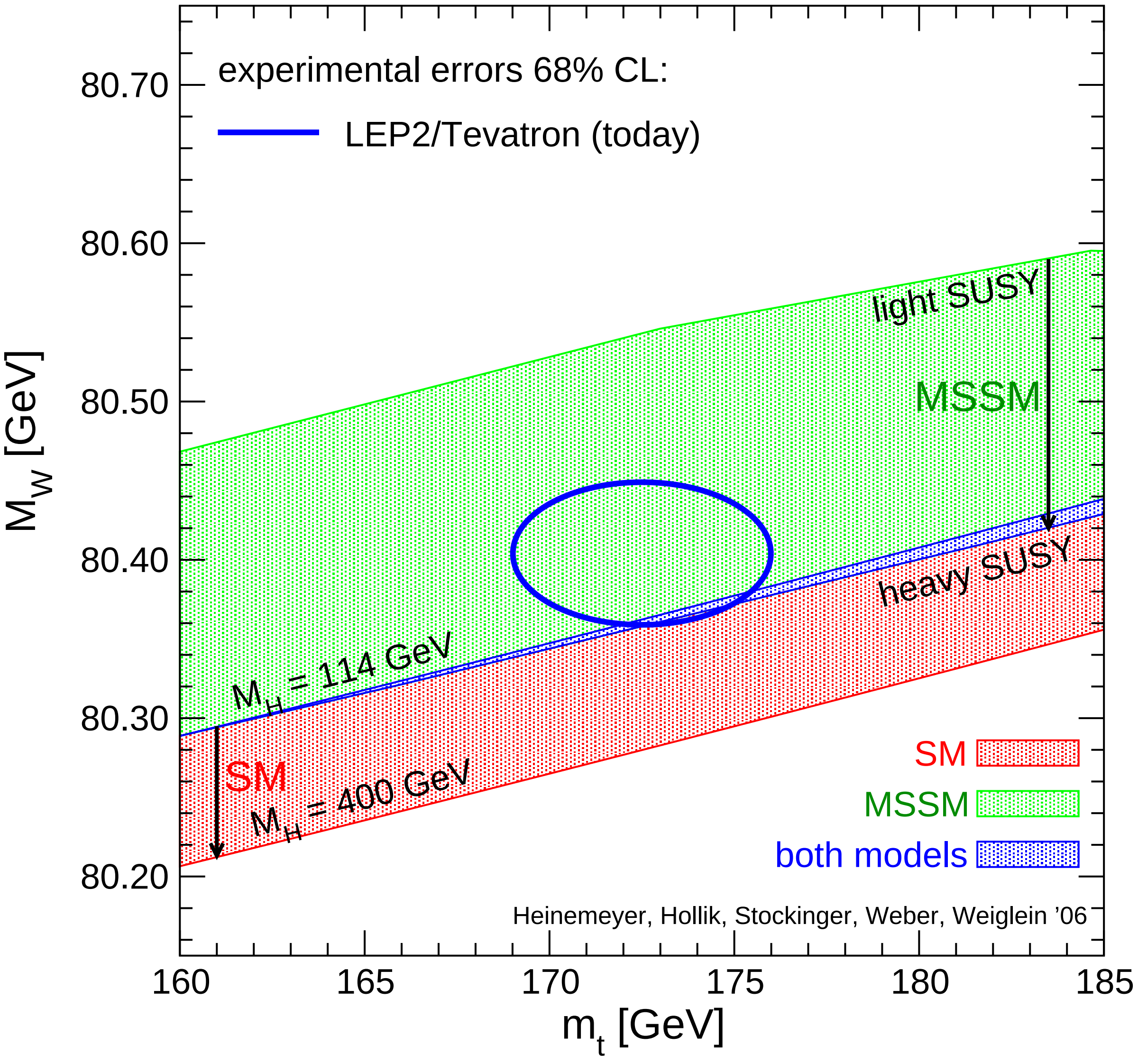
**In the pipeline:**

- more channels: $WH \to \tau\nu b\bar{b}$
- analysis improvements: NN, b-tagging, Eflow...
- analyze full datasets, updated combination



# W Mass Measurement – Interpretation II

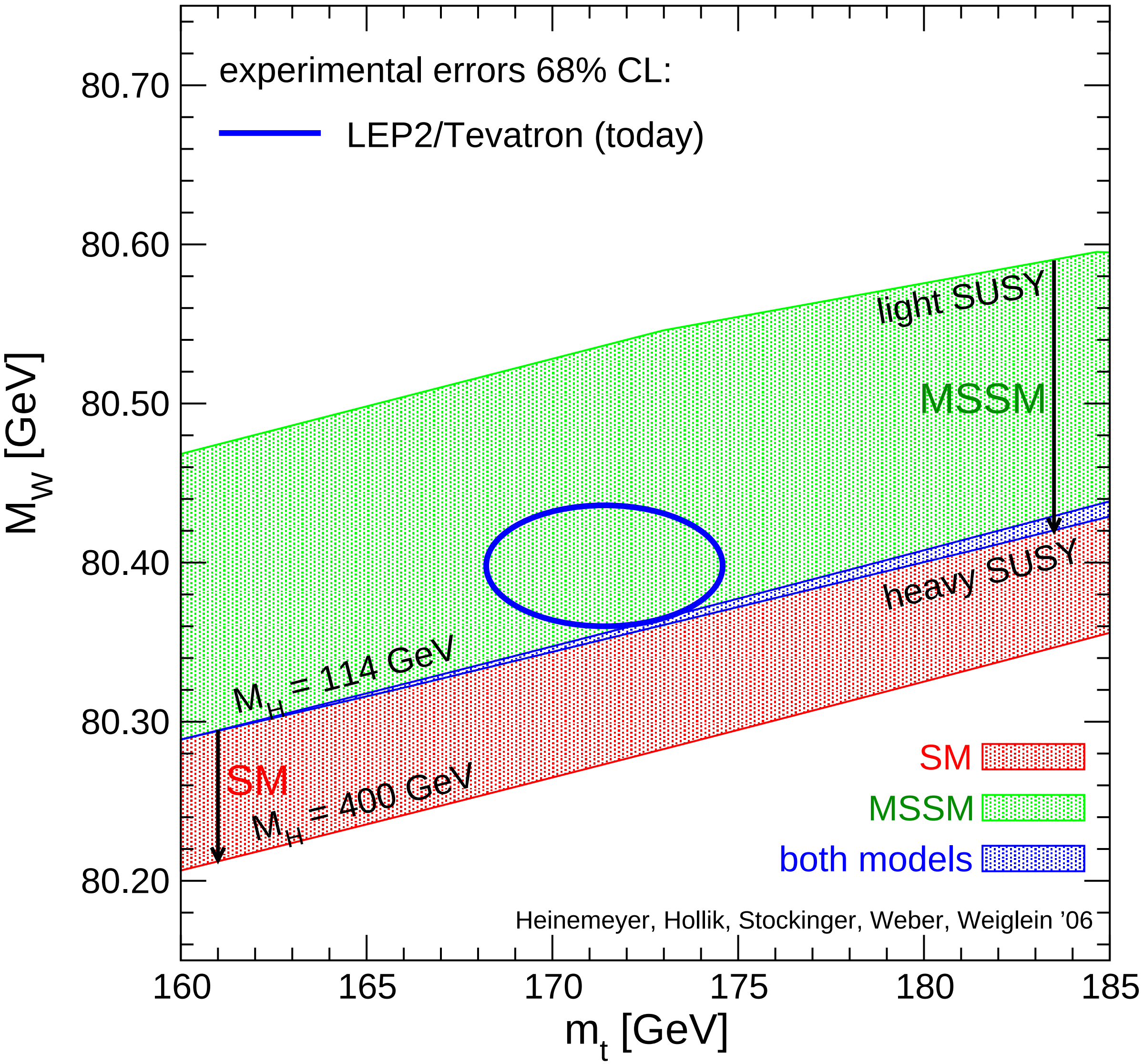
**Before:**




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

# W Mass Measurement – Interpretation II

**After:**

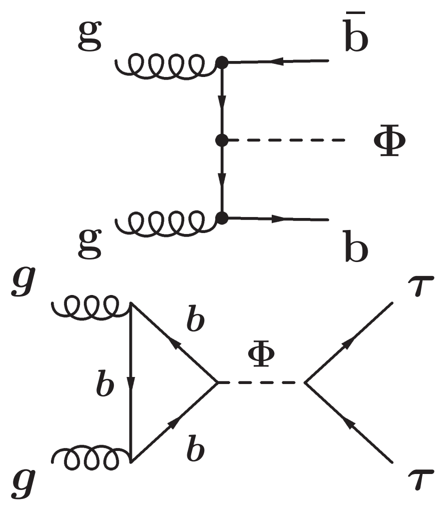



**Supersymmetric theories predict additional particles that modify loop corrections**

# Search for SUSY Higgs

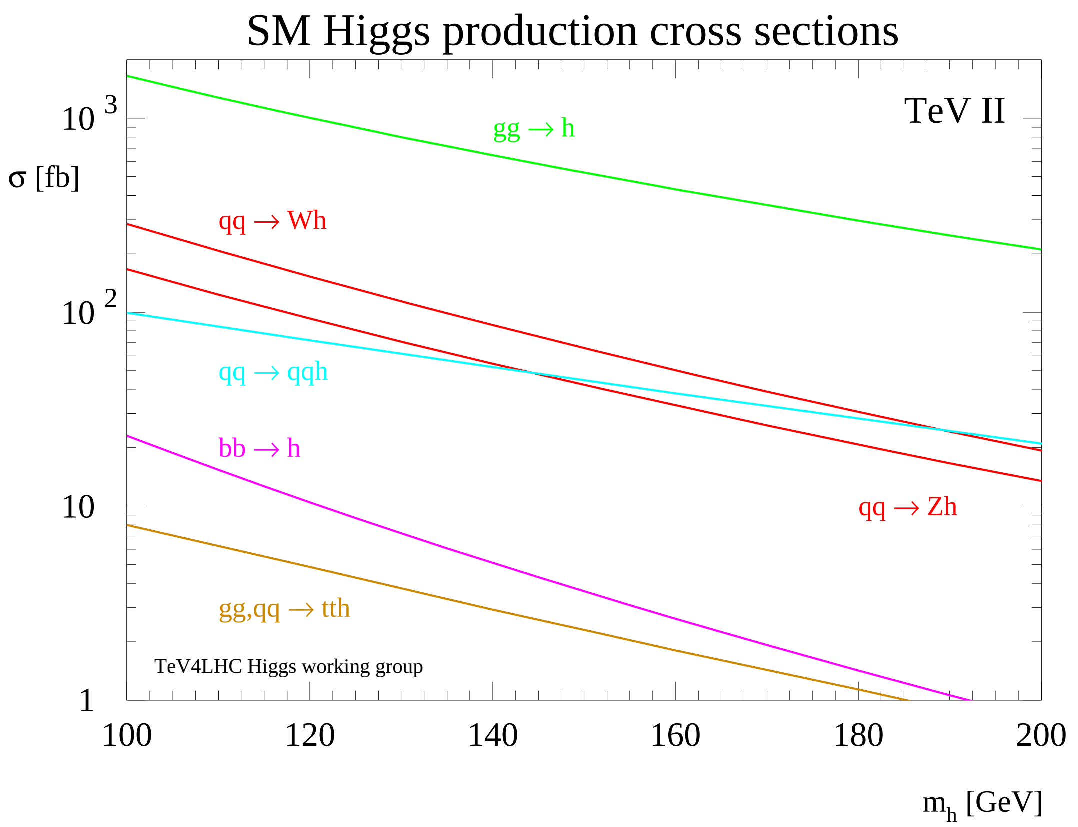
**SUSY Higgs sector specified (at LO) by 2 parameters:**

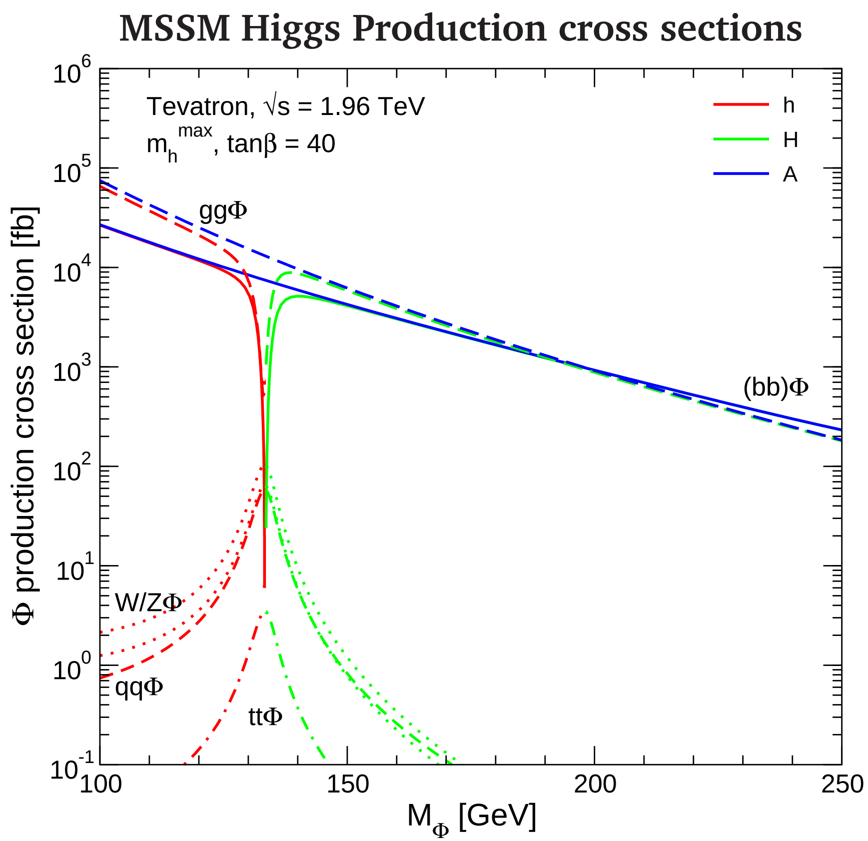
- $m_A$: mass of pseudo-scalar Higgs boson
- $\tan\beta$: ratio of vacuum expectation values




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

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



# Search for SUSY Higgs

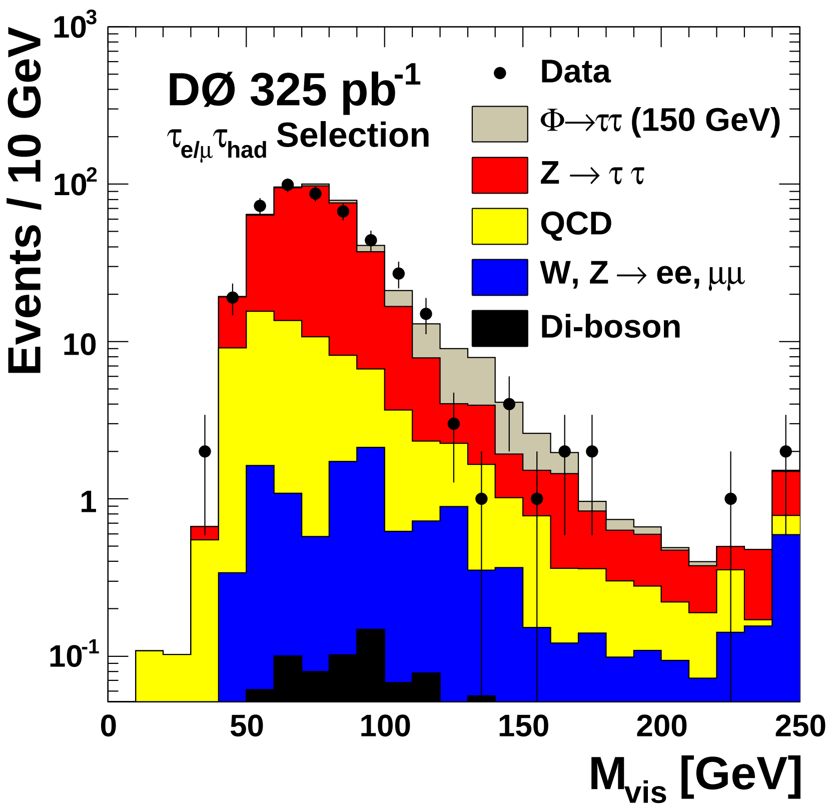
| Mode | Fraction (%) | Comments |
|---|---|---|
| $\tau_e\tau_e$ | 3 | Large DY BGND |
| $\tau_\mu\tau_\mu$ | 3 | Large DY BGND |
| $\tau_e\tau_\mu$ | 6 | Small QCD BGND |
| $\tau_e\tau_h$ | 23 | Golden |
| $\tau_\mu\tau_h$ | 23 | Golden |
| $\tau_h\tau_h$ | 41 | Large QCD BGND |

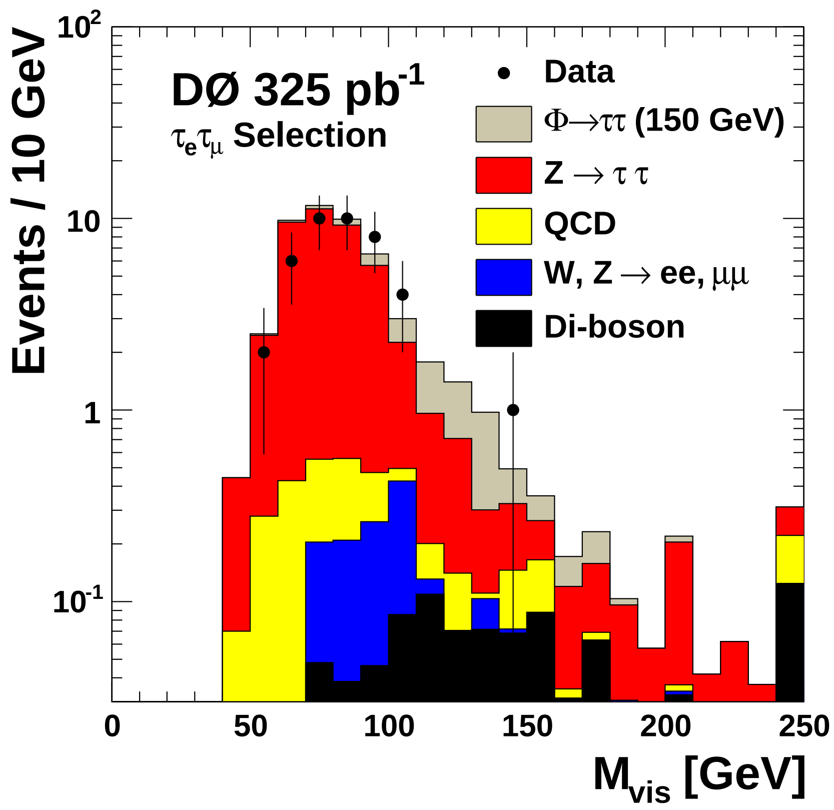
**Selections:**

A) two isolated taus with one leptonic tau decay

B) isolated electron and muon

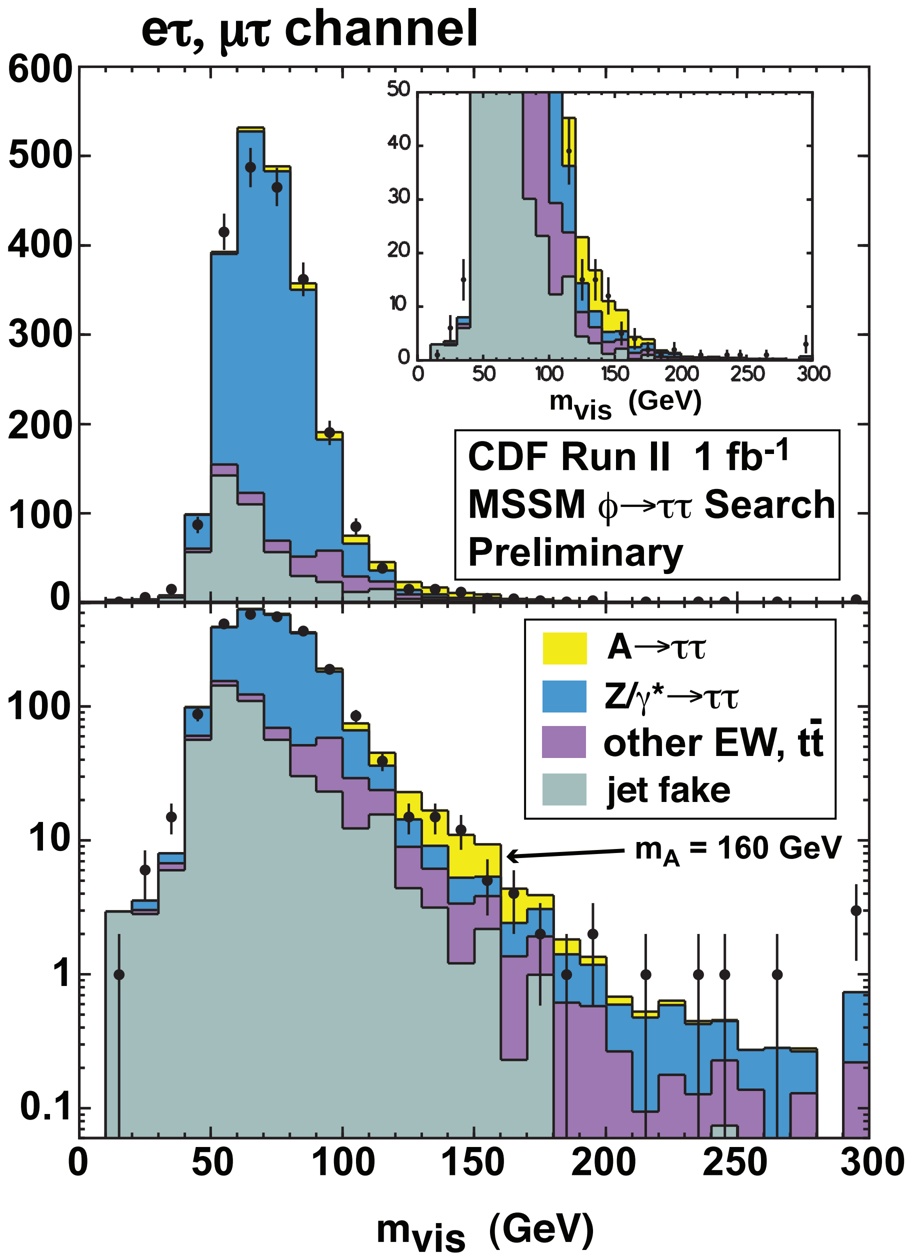
- Irreducible background from $Z \to \tau^+\tau^-$
- Reconstruction of effective mass from visible tau decay products and $\not{E}_T$

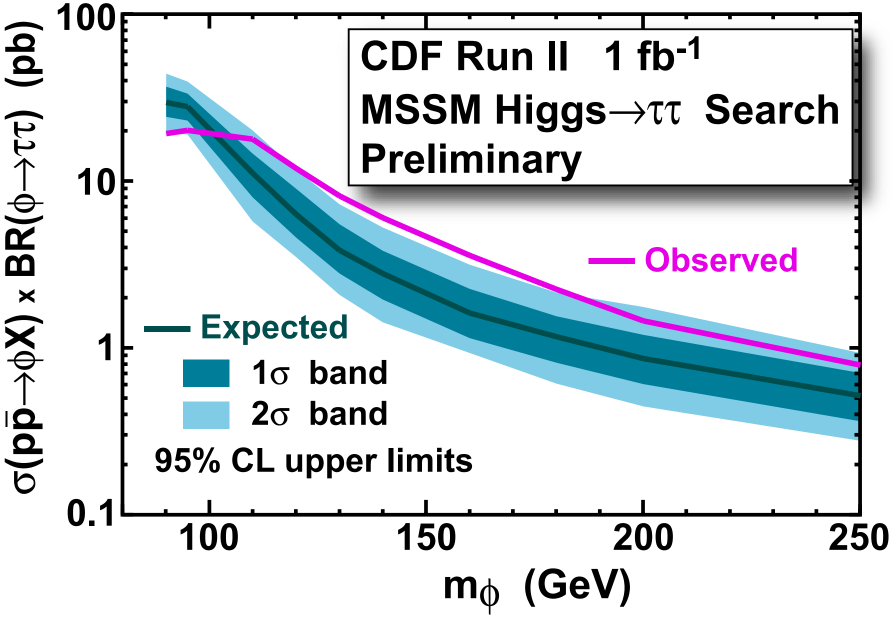


# Search for SUSY Higgs

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

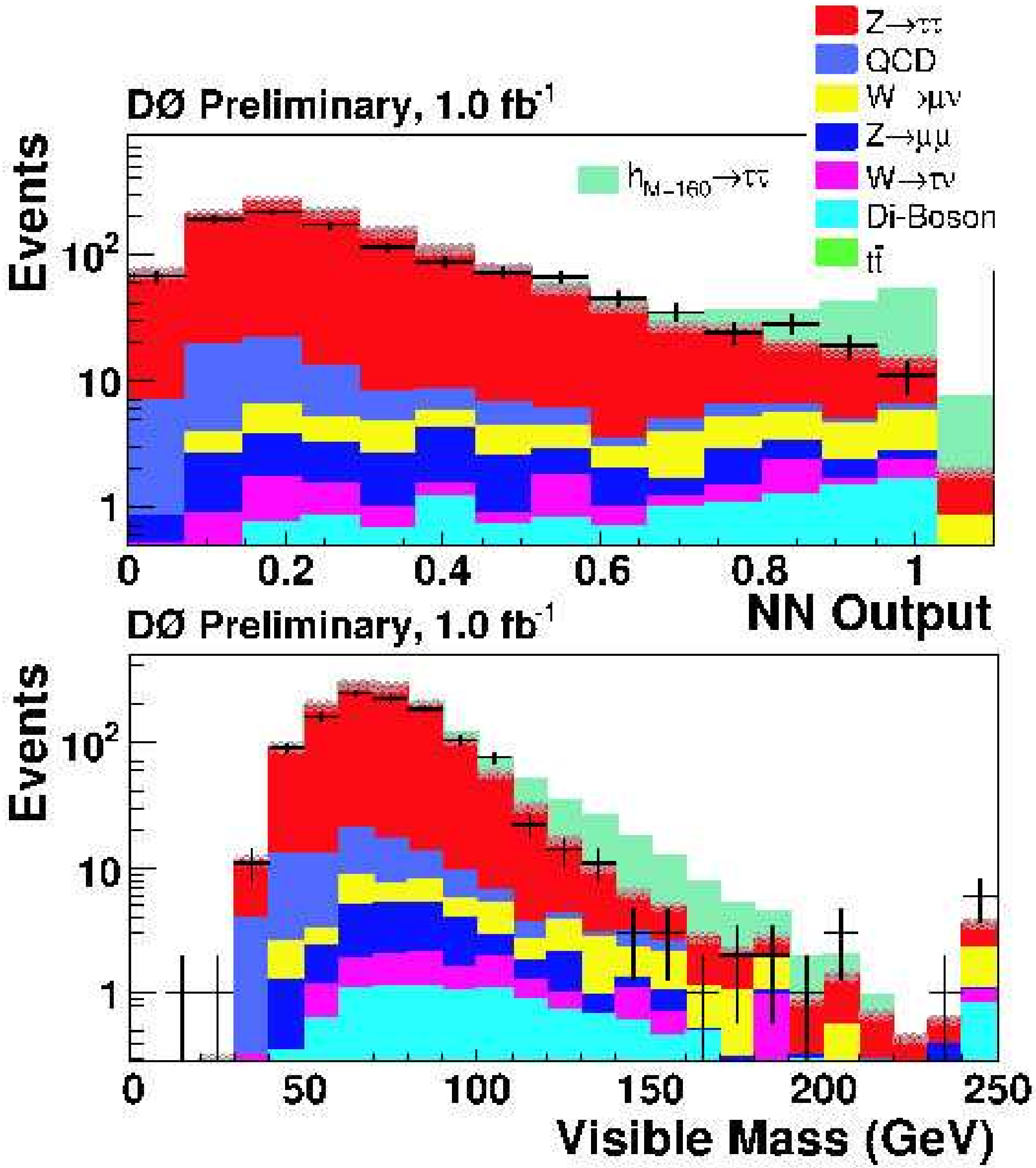



- $2\sigma$ excess at $m_A \approx$150 GeV
- would correspond to tan$\beta\approx$50
- confirmed by DØ?

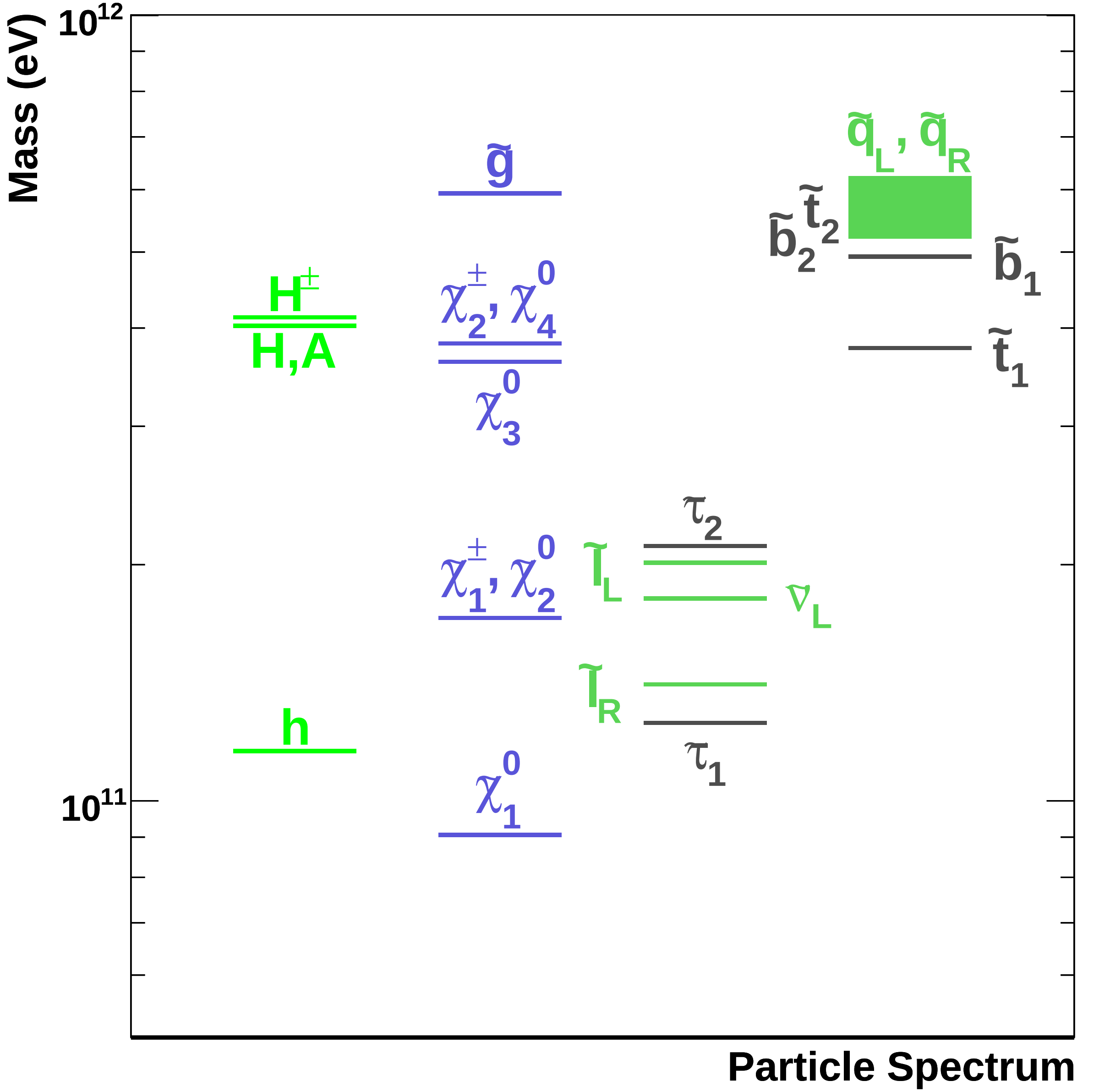
# Search for SUSY Higgs

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

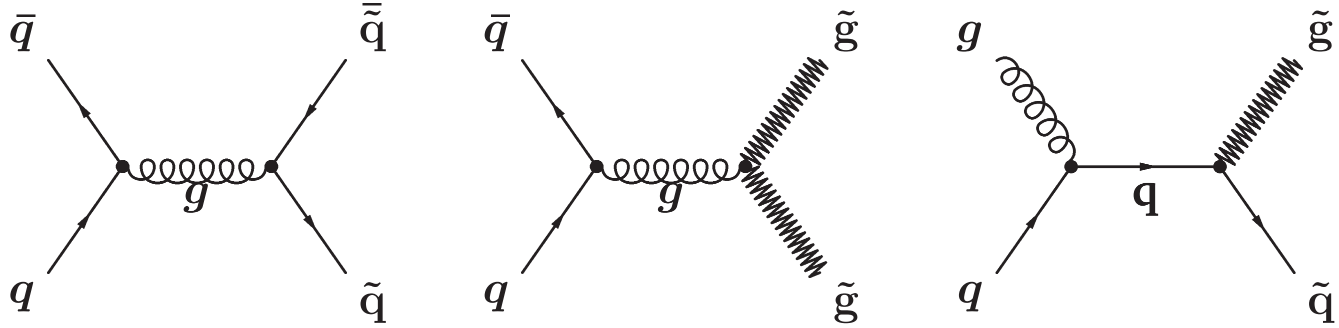



**But: more than twice the data on tape, ready to be analyzed**

# What other particles does SUSY predict?



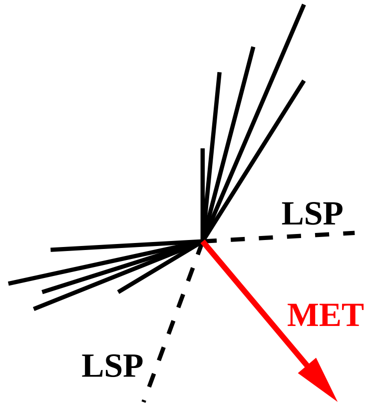
# Search for Supersymmetry – Squarks/Gluinos

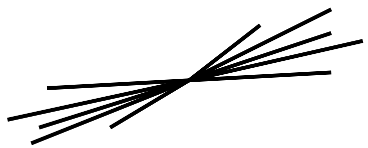



- Squarks/Gluinos produced via strong interaction
  → large cross sections at hadron colliders
- Decays: jets + LSP
  - LSP assumed to be stable ($R_p$ conserved)
  → Signature: jets + $\not{E}_T$
- DØ: 1 fb$^{-1}$ collected with dedicated trigger:
  acoplanar jets + $\not{E}_T$

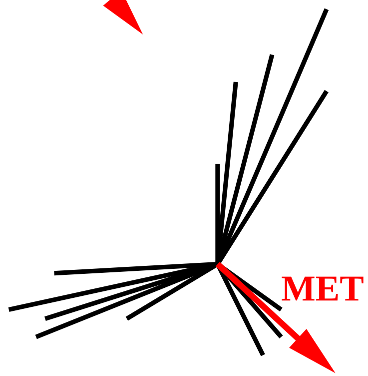
| Mass region | Main Channel | Signature |
|---|---|---|
| $m_{\tilde{q}} < m_{\tilde{g}}$ | $\tilde{q}\tilde{q}$ | 2j + $\not{E}_T$ |
| $m_{\tilde{q}} > m_{\tilde{g}}$ | $\tilde{g}\tilde{g}$ | 4j + $\not{E}_T$ |
| $m_{\tilde{q}} \approx m_{\tilde{g}}$ | $\tilde{q}\tilde{q}$,$\tilde{q}\tilde{g}$ | 2j/3j + $\not{E}_T$ |

$\tilde{q}\tilde{q} \to qq + \not{E}_T$



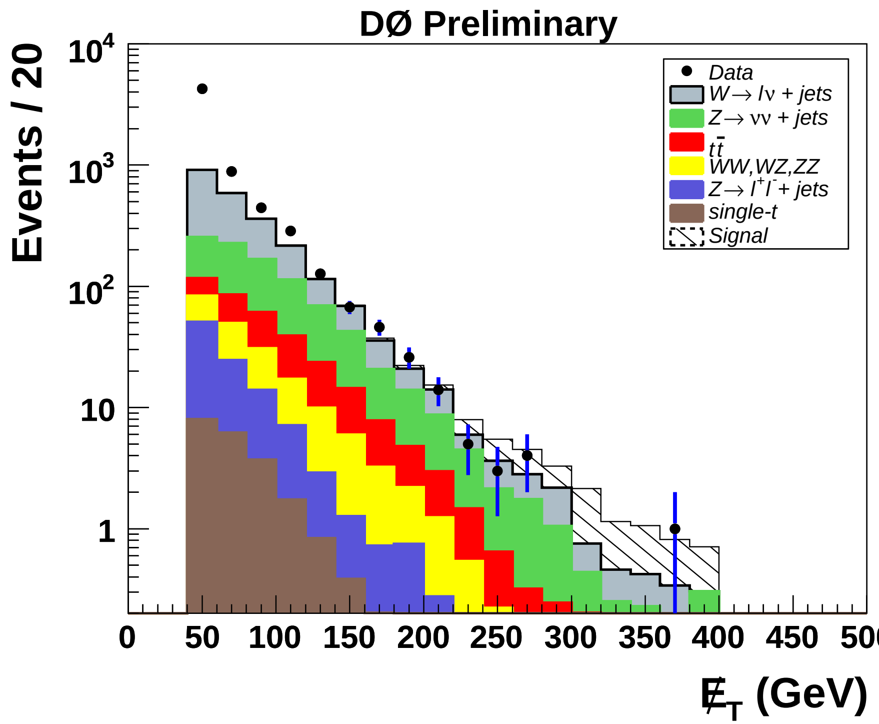
Dijet Background



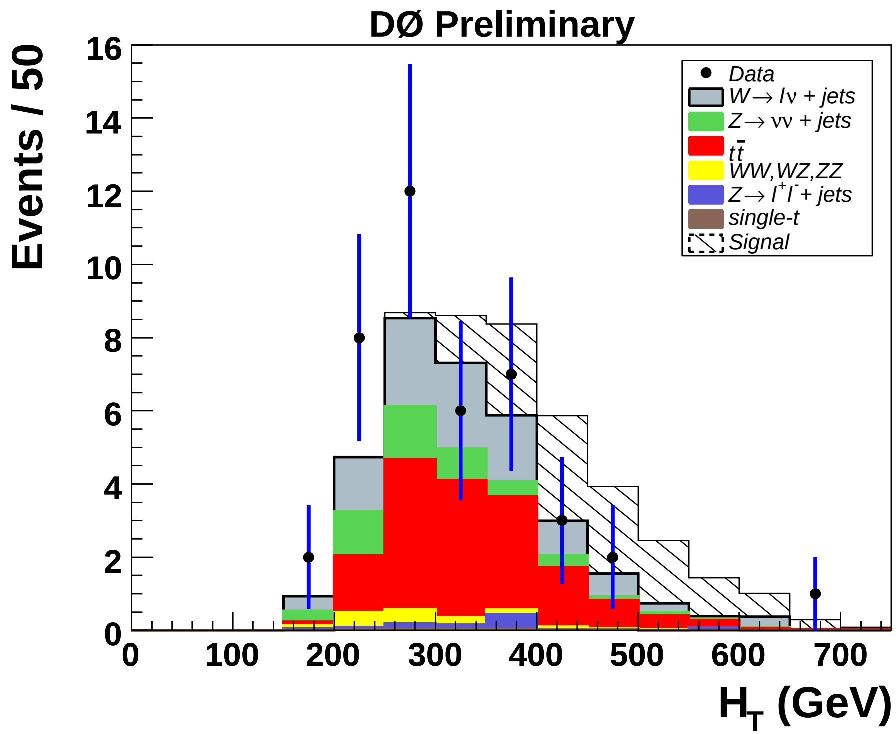

3-jet Background

# Search for Supersymmetry – Squarks/Gluinos

2j+$\not{E}_T$ analysis

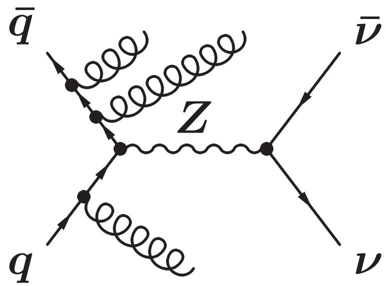



3j+$\not{E}_T$ analysis




**Main backgrounds:**

- Multijets with fake $\not{E}_T$
- W+jets with W→ $e\nu, \mu\nu, \tau\nu$
- Z+jets with Z→ $\nu\bar{\nu}$

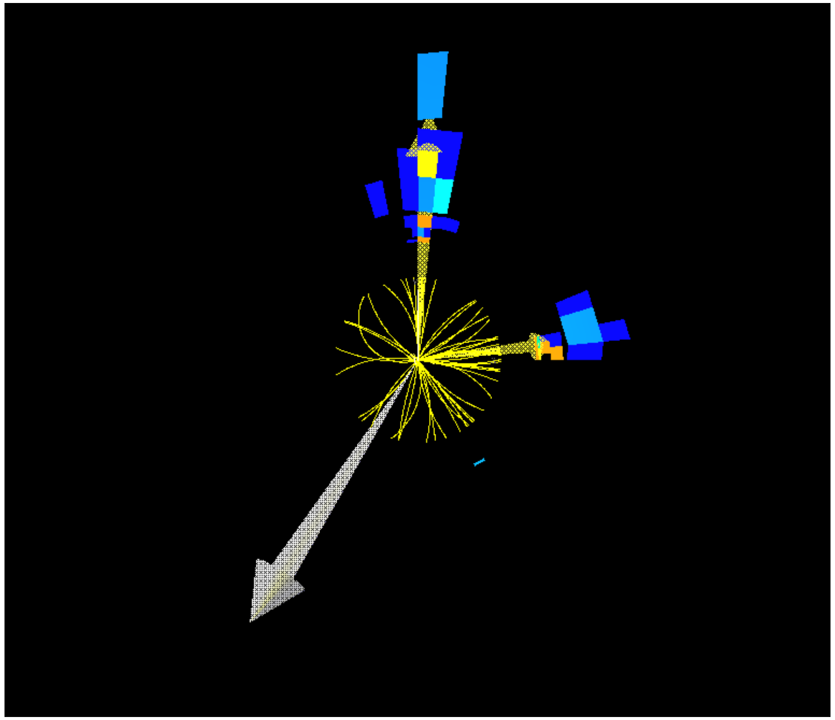



**Main selection cuts:**

- 2/3/4 jets and large $\not{E}_T$
- angular separation $\not{E}_T$, jets
- isolated lepton veto

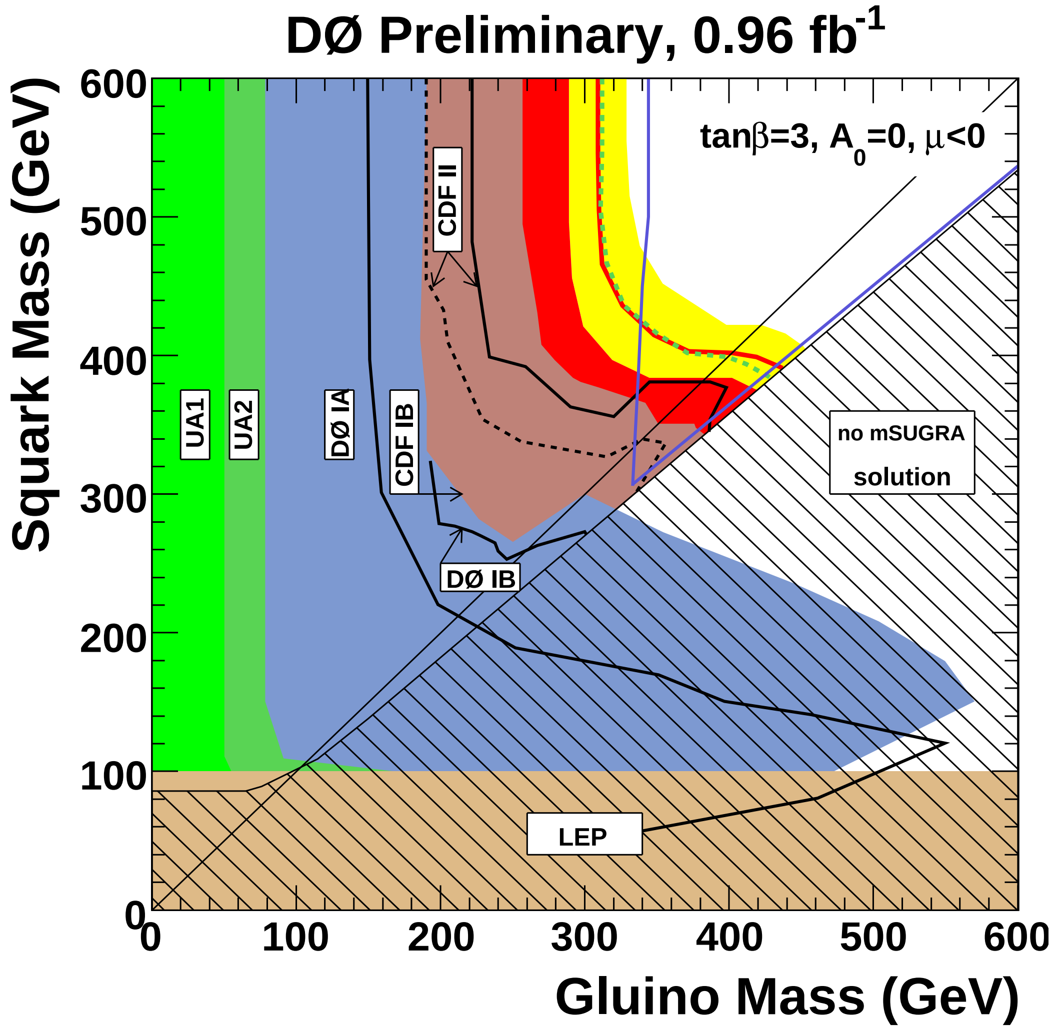
| Mass region | Main Channel | Signature | $\not{E}_T$ | $H_T = \sum p_T^{jet}$ | Exp. Bckgd. | Data |
|---|---|---|---|---|---|---|
| $m_{\tilde{q}} < m_{\tilde{g}}$ | $\tilde{q}\tilde{q}$ | 2j + $\not{E}_T$ | >225 GeV | >300 GeV | 7.5±1.7 | 5 |
| $m_{\tilde{q}} > m_{\tilde{g}}$ | $\tilde{g}\tilde{g}$ | 4j + $\not{E}_T$ | >100 GeV | >300 GeV | 33±6 | 34 |
| $m_{\tilde{q}} \approx m_{\tilde{g}}$ | $\tilde{q}\tilde{q}$,$\tilde{q}\tilde{g}$ | 2j/3j + $\not{E}_T$ | >150 GeV | >400 GeV | 6.1±1.3 | 6 |

# Search for Supersymmetry – Squarks/Gluinos



$\tilde{q}\tilde{q}$ candidate event

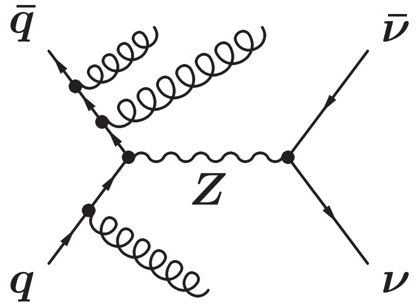
($\not{E}_T$=368 GeV, $p_T^{j1}$=282 GeV, $p_T^{j2}$=174 GeV)



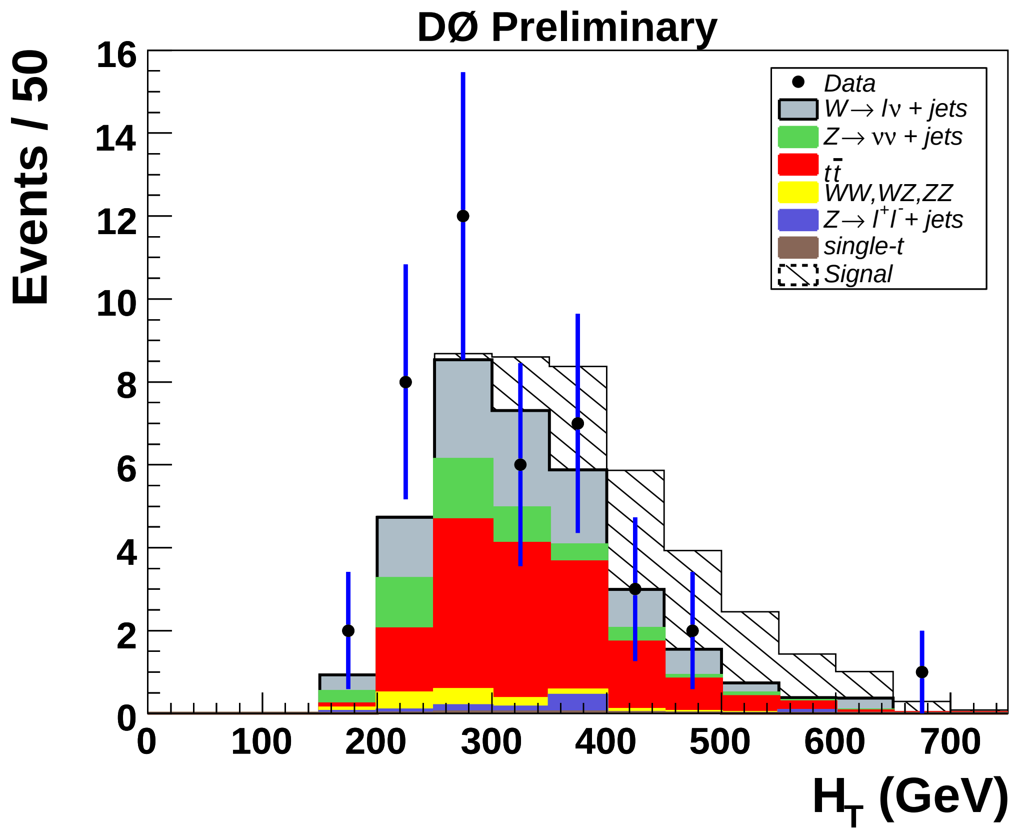

- No evidence for squark/gluino production at the Tevatron
- New limits in squark/gluino mass plane (mSUGRA: $tan\beta = 3$, $A_0 = 0$, $\mu < 0$)
- Sensitivity beyond indirect limits from LEP

# 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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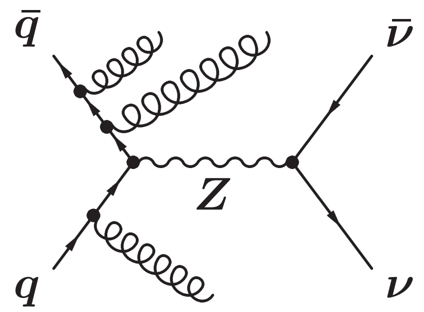
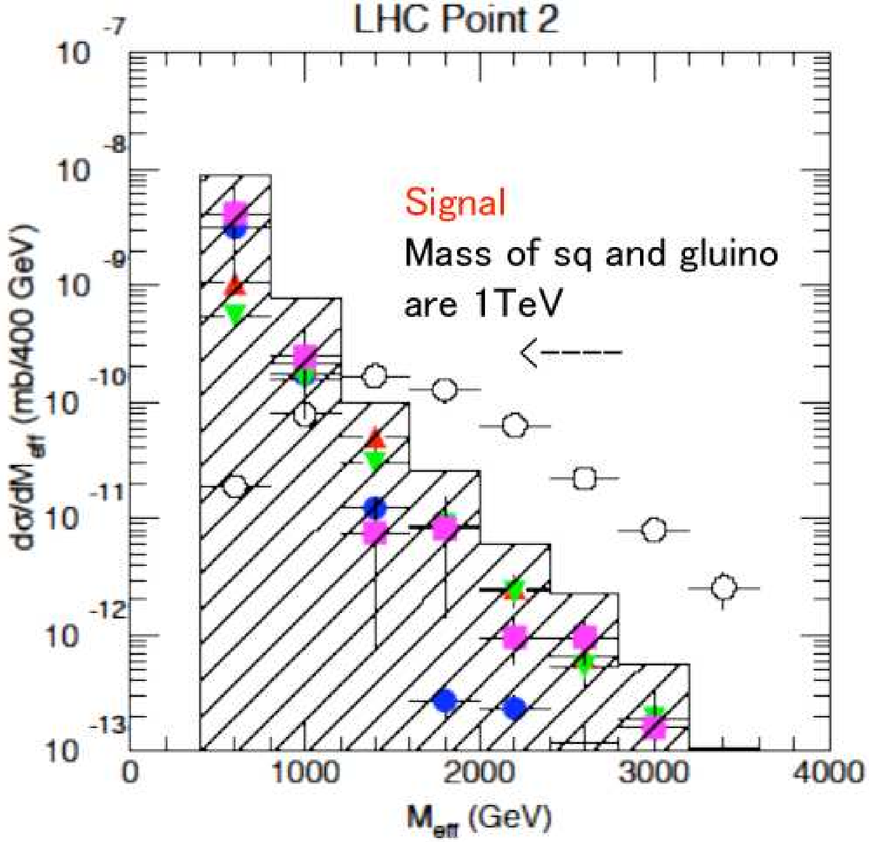
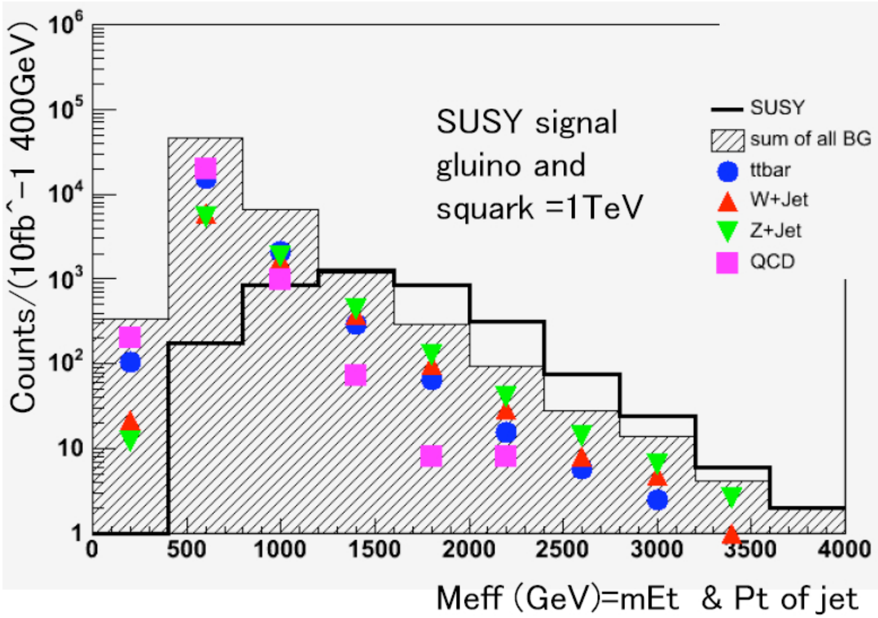



ATLAS TDR Study (Parton Shower MC)




New Study (Matrix Element MC)

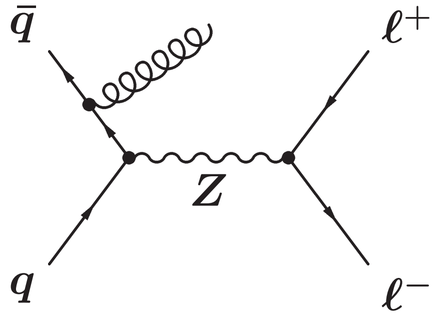



(S. Asai et al.)

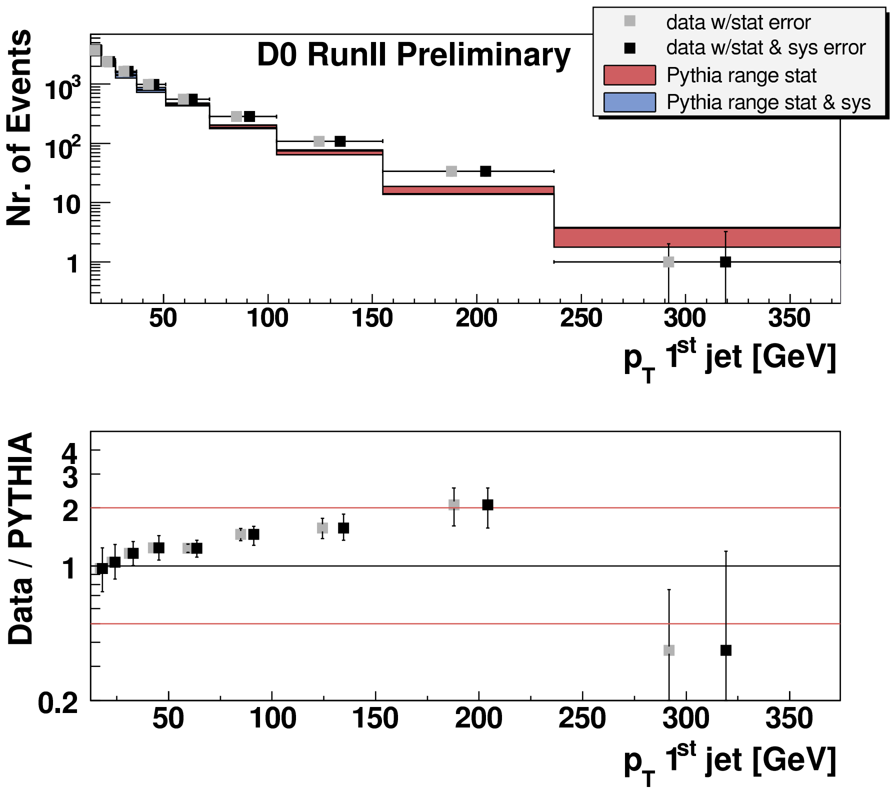
# Vector Boson plus Jet Production at the Tevatron

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

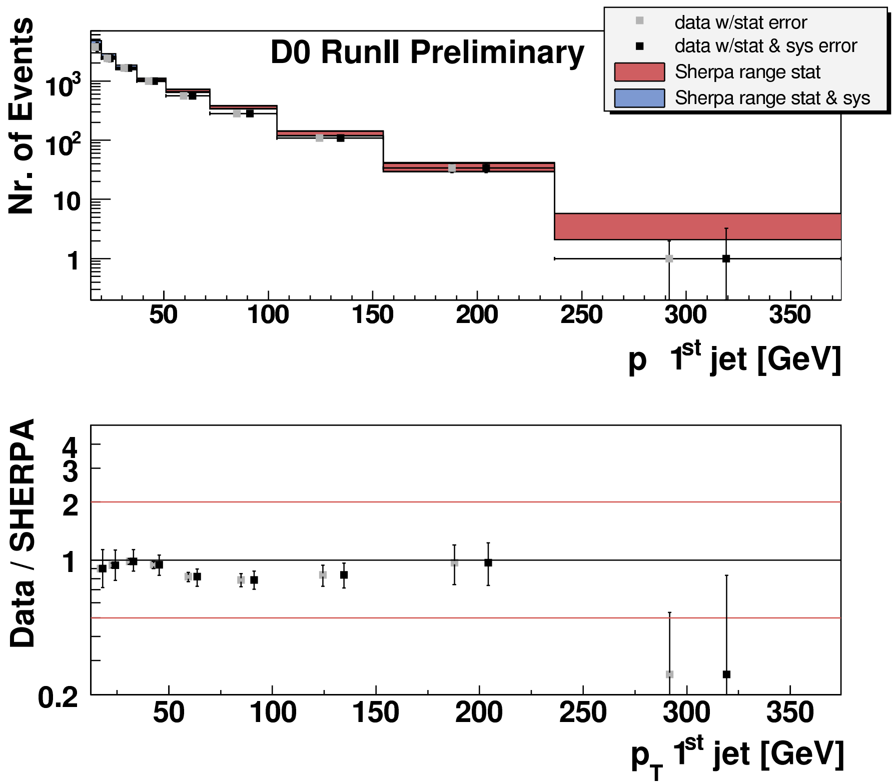
### $P_T$ Distribution of leading Jet




### DØ Data vs. PYTHIA



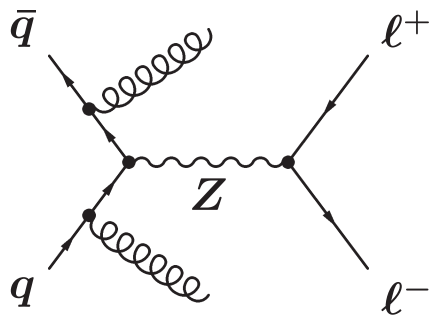

### DØ Data vs. SHERPA



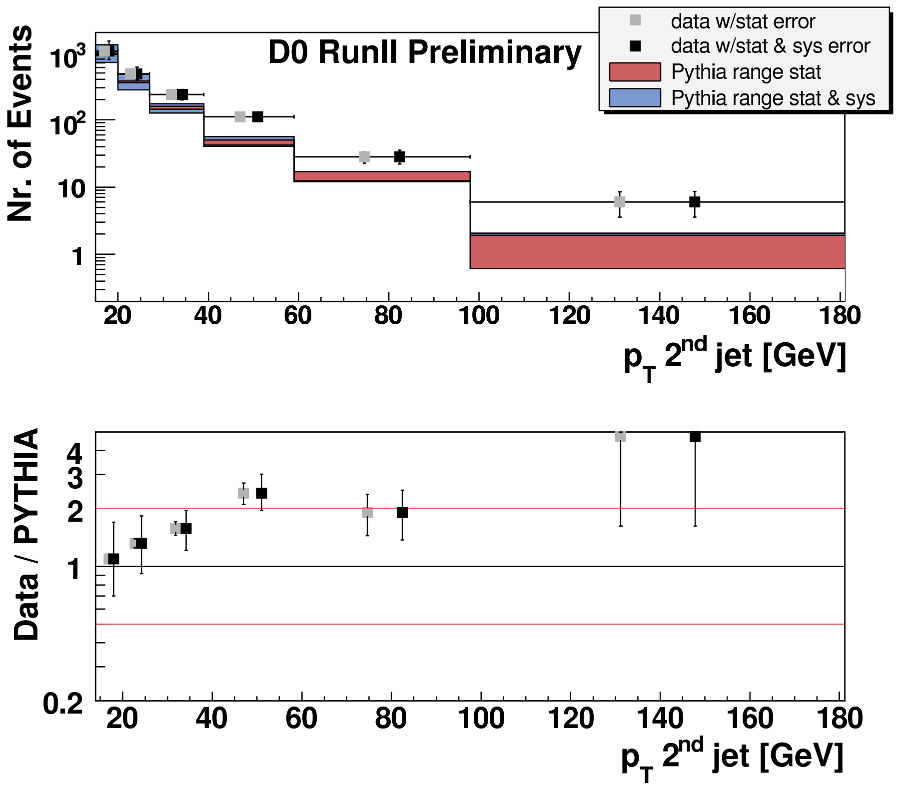
# Vector Boson plus Jet Production at the Tevatron

## 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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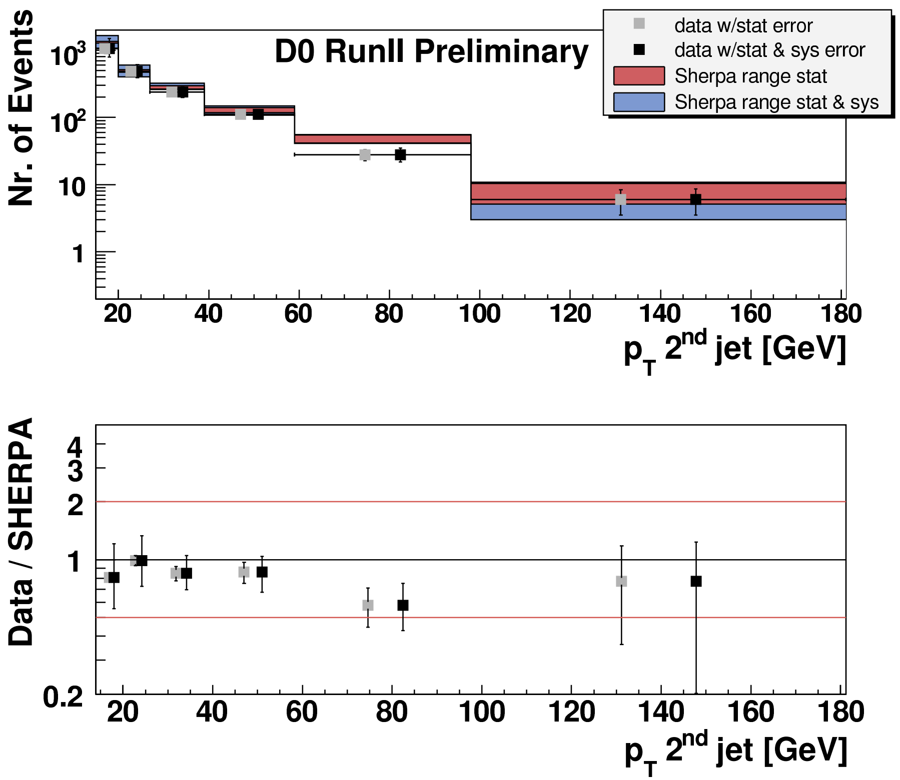

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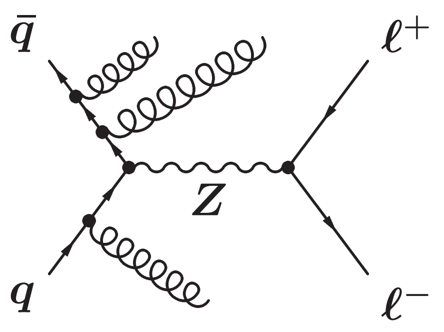
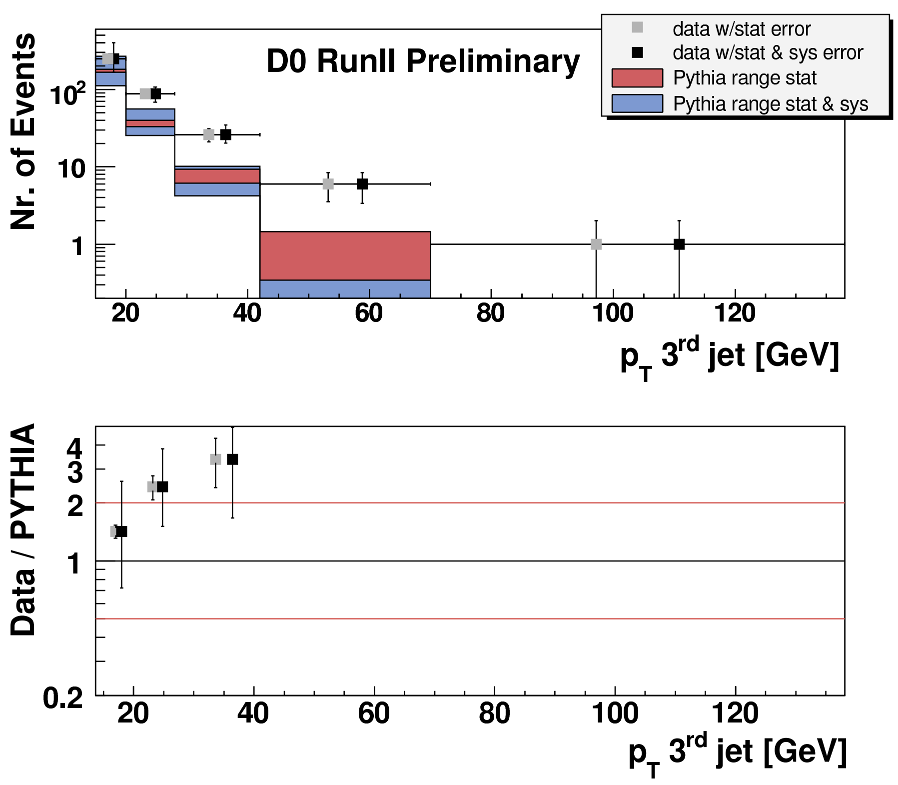
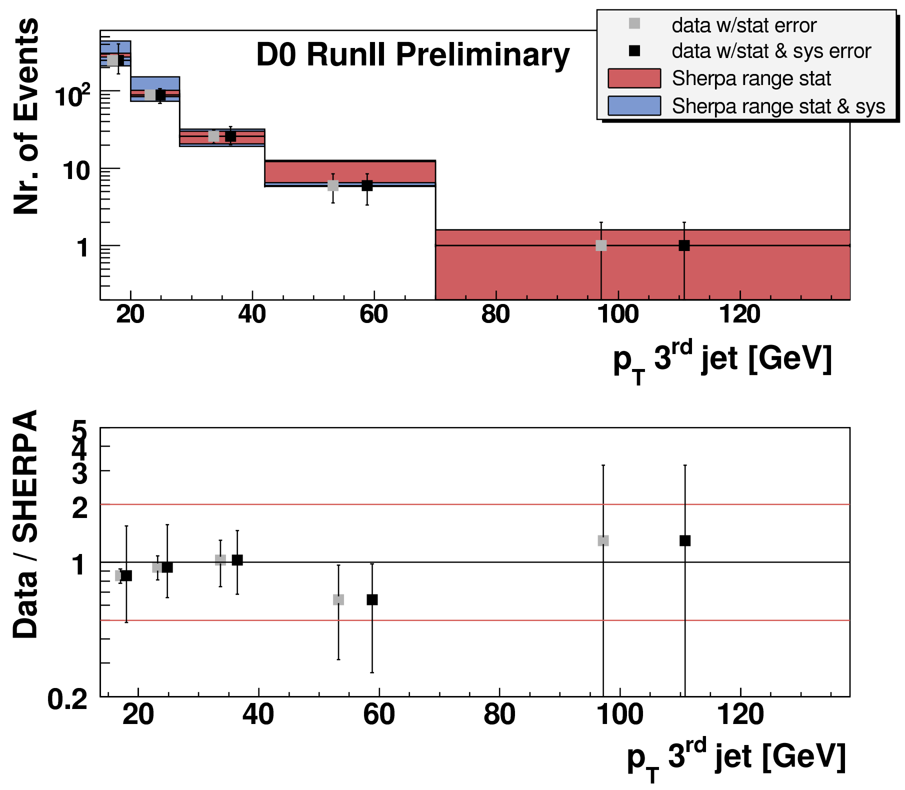



**DØ Data vs. PYTHIA**




**DØ Data vs. SHERPA**



# Conclusions

- Tevatron Collider has reached design luminosity, 2.5 fb$^{-1}$ delivered so far
- CDF and DØ are in the headlines (5 press releases in 1 year)
- B$_s$ mixing observation and precision measurement
- Evidence for single top production
- Improved measurements of top and W mass
- Higgs searches on the way to reaching sensitivity
- Massive set of results from searches for SUSY and other NP
- Preparing for LHC physics with dedicated measurements at the Tevatron

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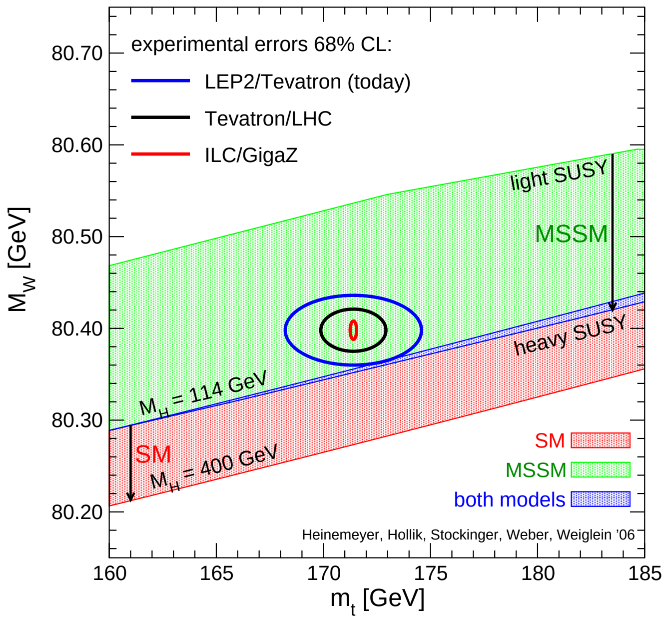
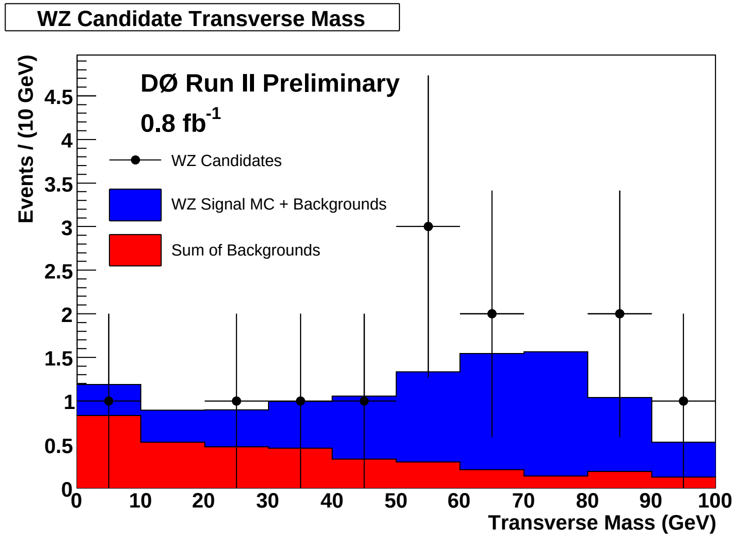
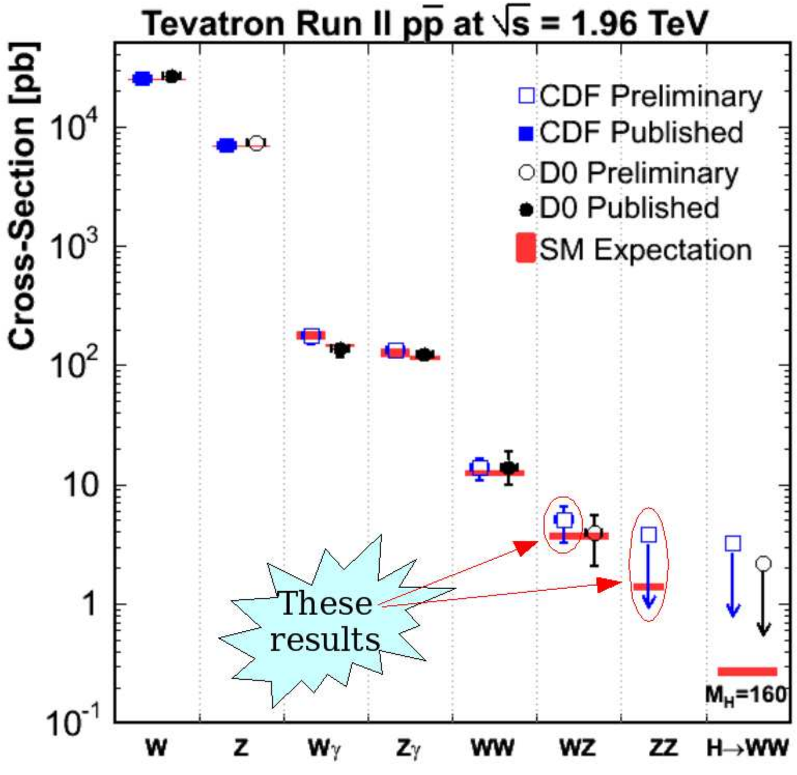


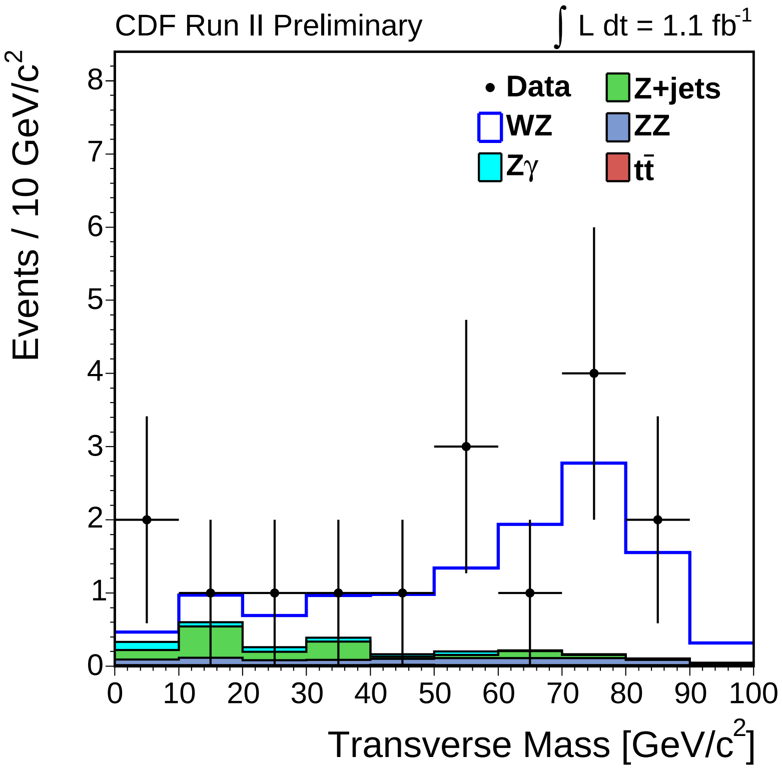

Let’s hope we stay away from the dark side!

# BACKUP

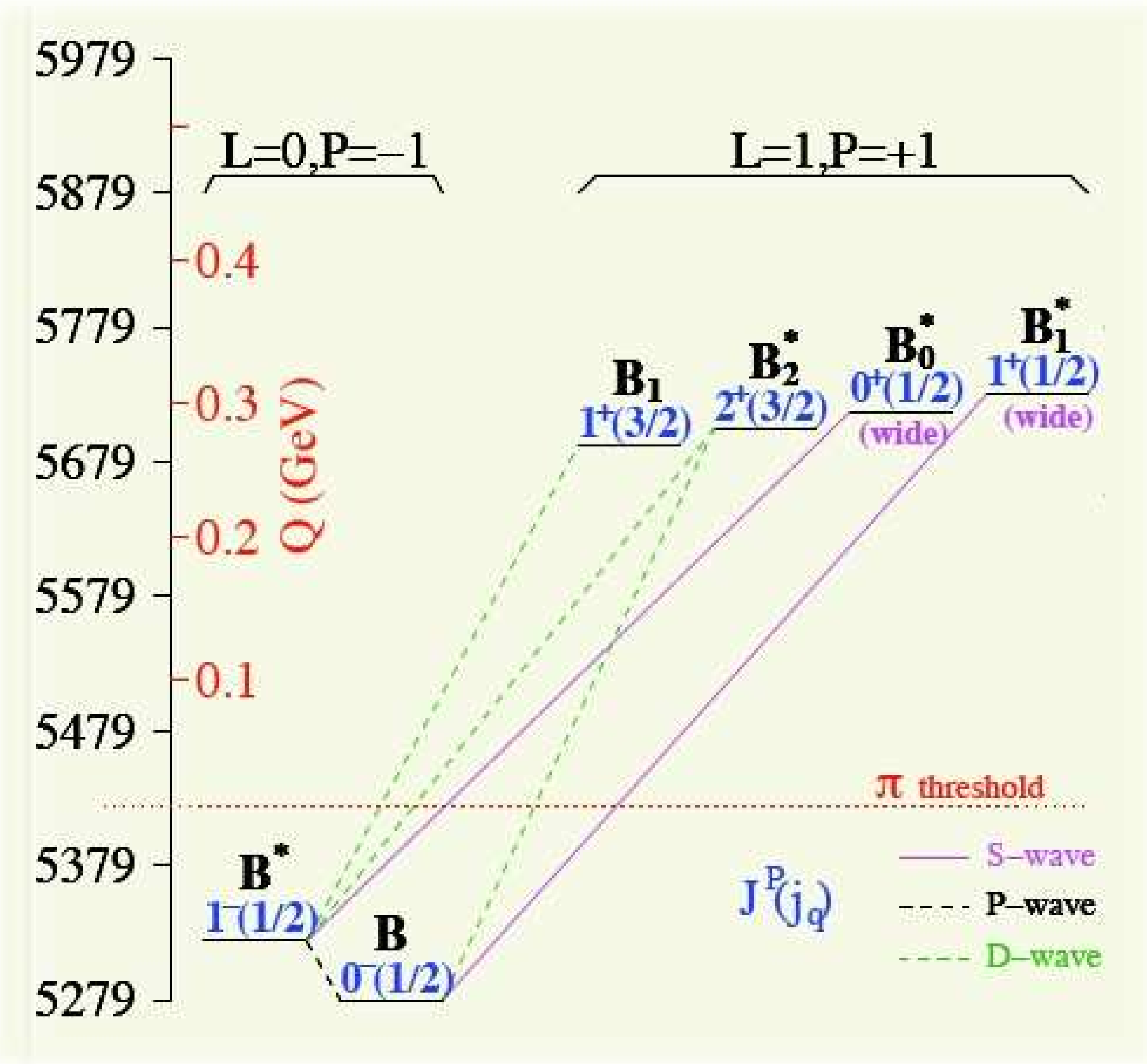
# Diboson Production



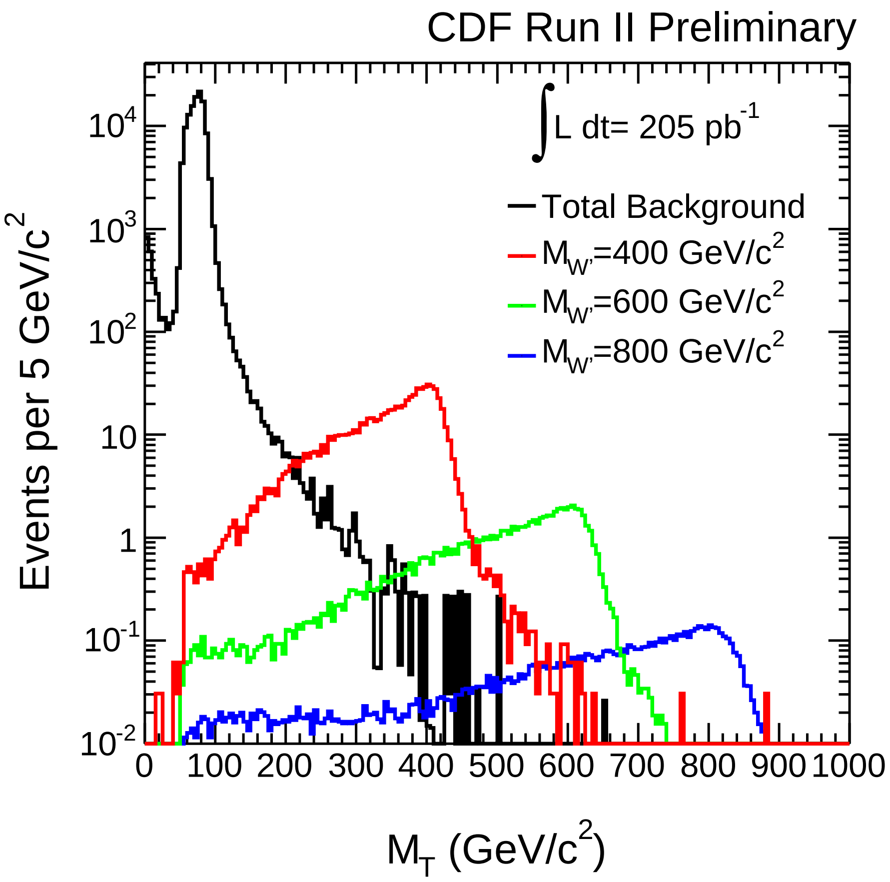
# Heavy B meson states



# Search for Heavy Gauge Bosons

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

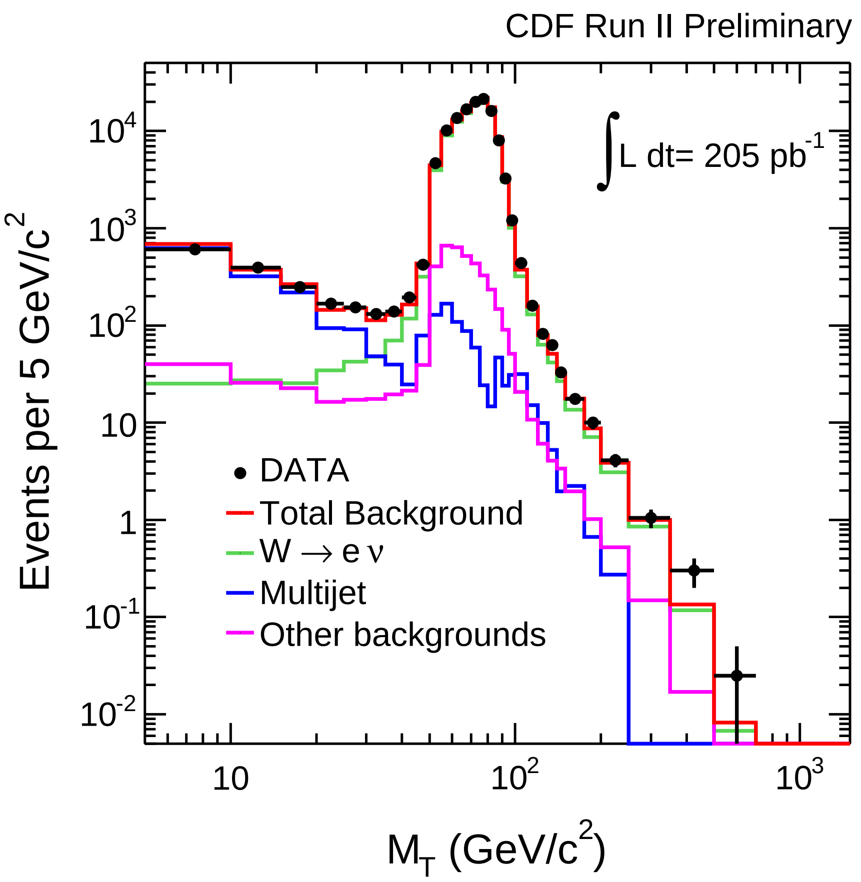
$\longrightarrow$ **search for leptonic decays of high-mass resonances: W'$\rightarrow \ell\nu$, Z'$\rightarrow \ell\ell$**

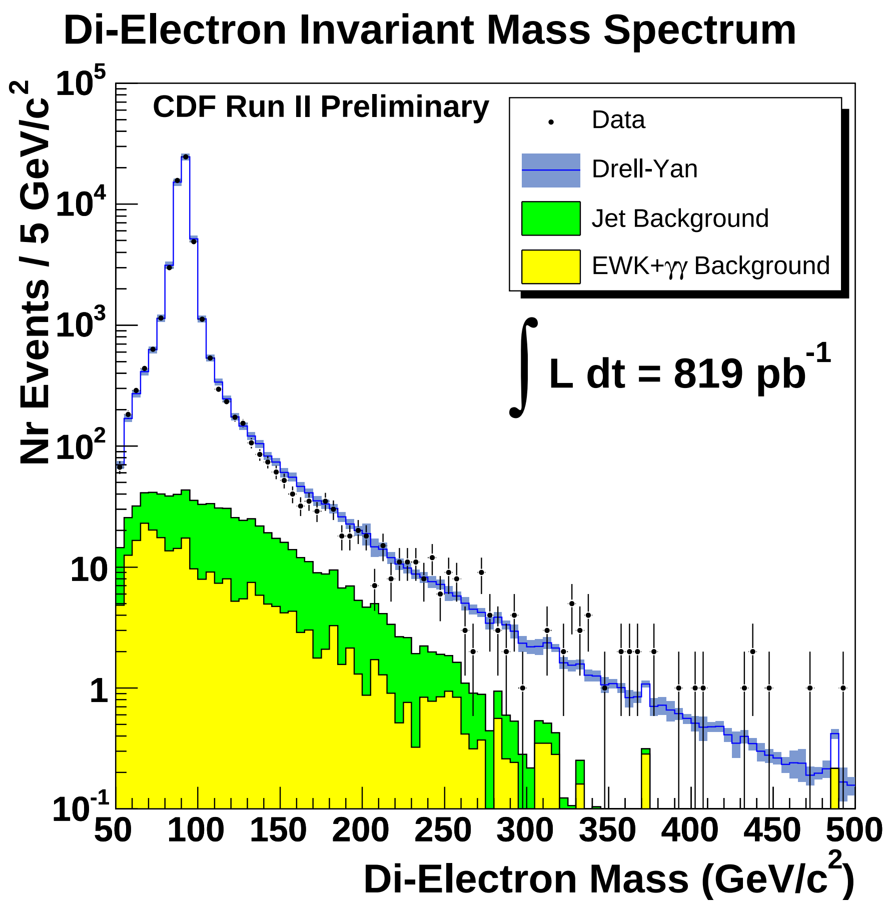


# Search for Heavy Gauge Bosons

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

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



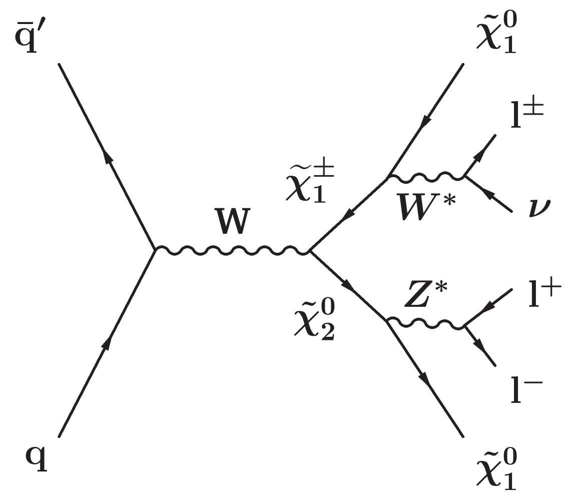



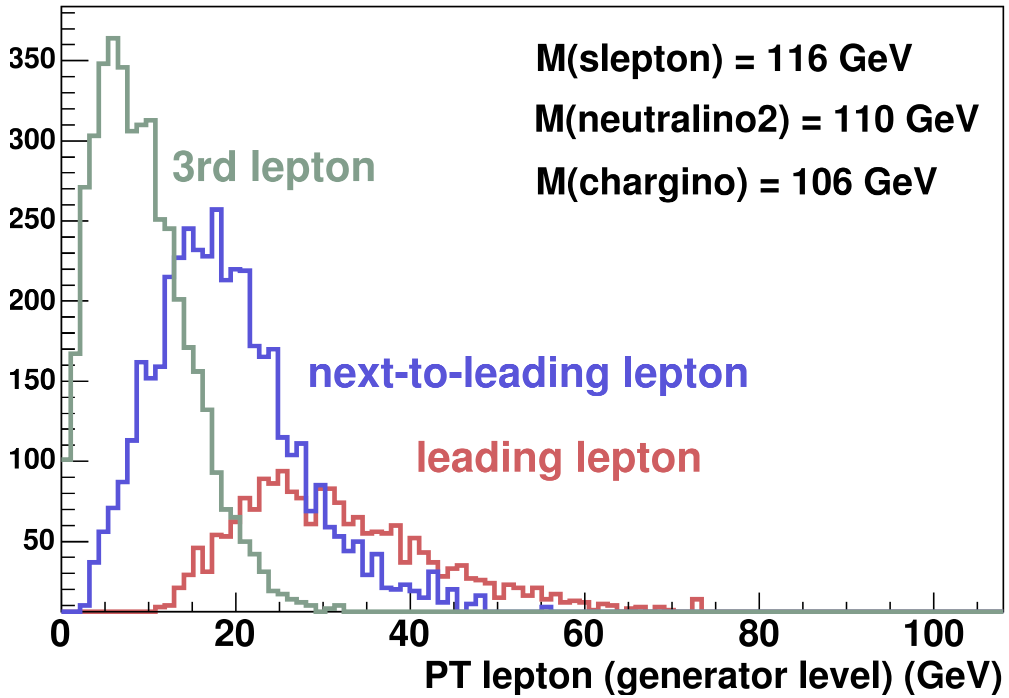

**Limit (CDF): $M_{W'}$>788 GeV**

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

# Search for Charginos and Neutralinos

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



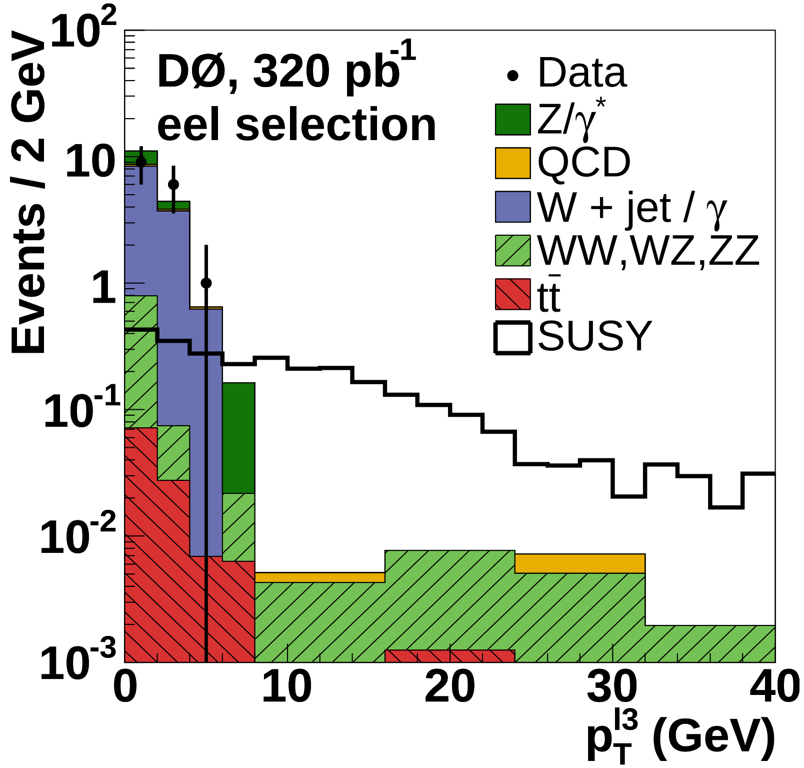



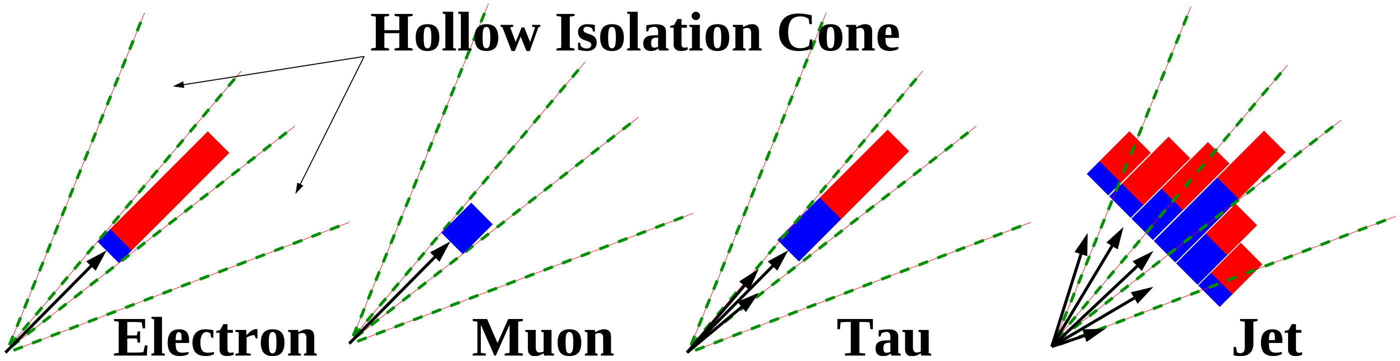
# Search for Charginos and Neutralinos

**Analysis Strategy:**

- two identified leptons plus isolated track
- isolation criteria designed to be efficient for electrons, muons and hadronic $\tau$-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$^{-1}$):**

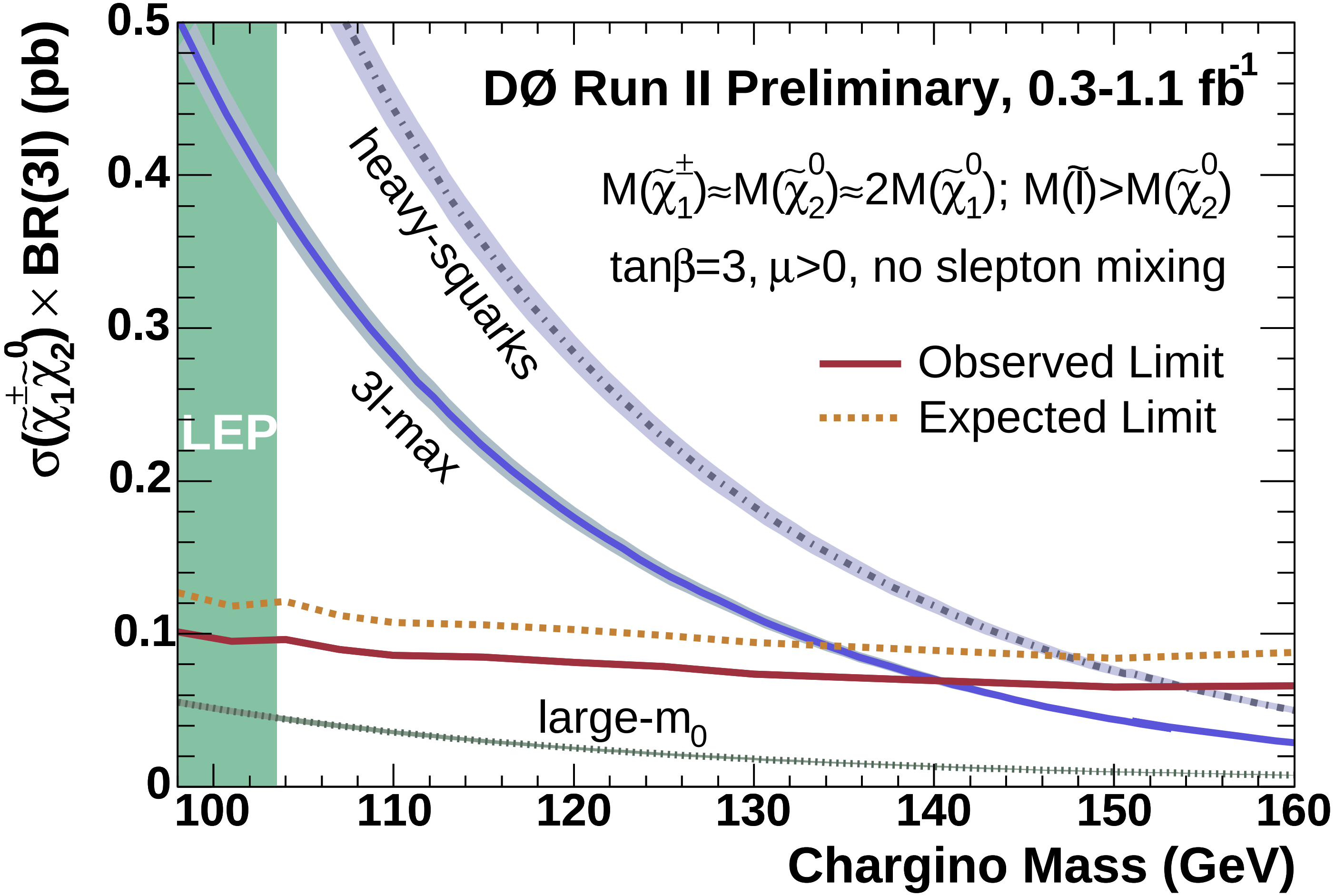
| Selection | Expected Background | Observed | Signal ($m_{\tilde{\chi}^{\pm}}$=110 GeV) |
|---|---|---|---|
| $ee\ell$ | 0.76±0.67 | 0 | 4.6±0.3 |
| $e\mu\ell$ | 0.31±0.13 | 0 | 1.6±0.1 |
| $\mu\mu\ell$ | 1.75±0.57 | 2 | 1.3±0.2 |
| ls-$\mu\mu$ | 1.10±0.40 | 1 | 4.2±0.7 |
| Combined | 3.92±0.98 | 3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

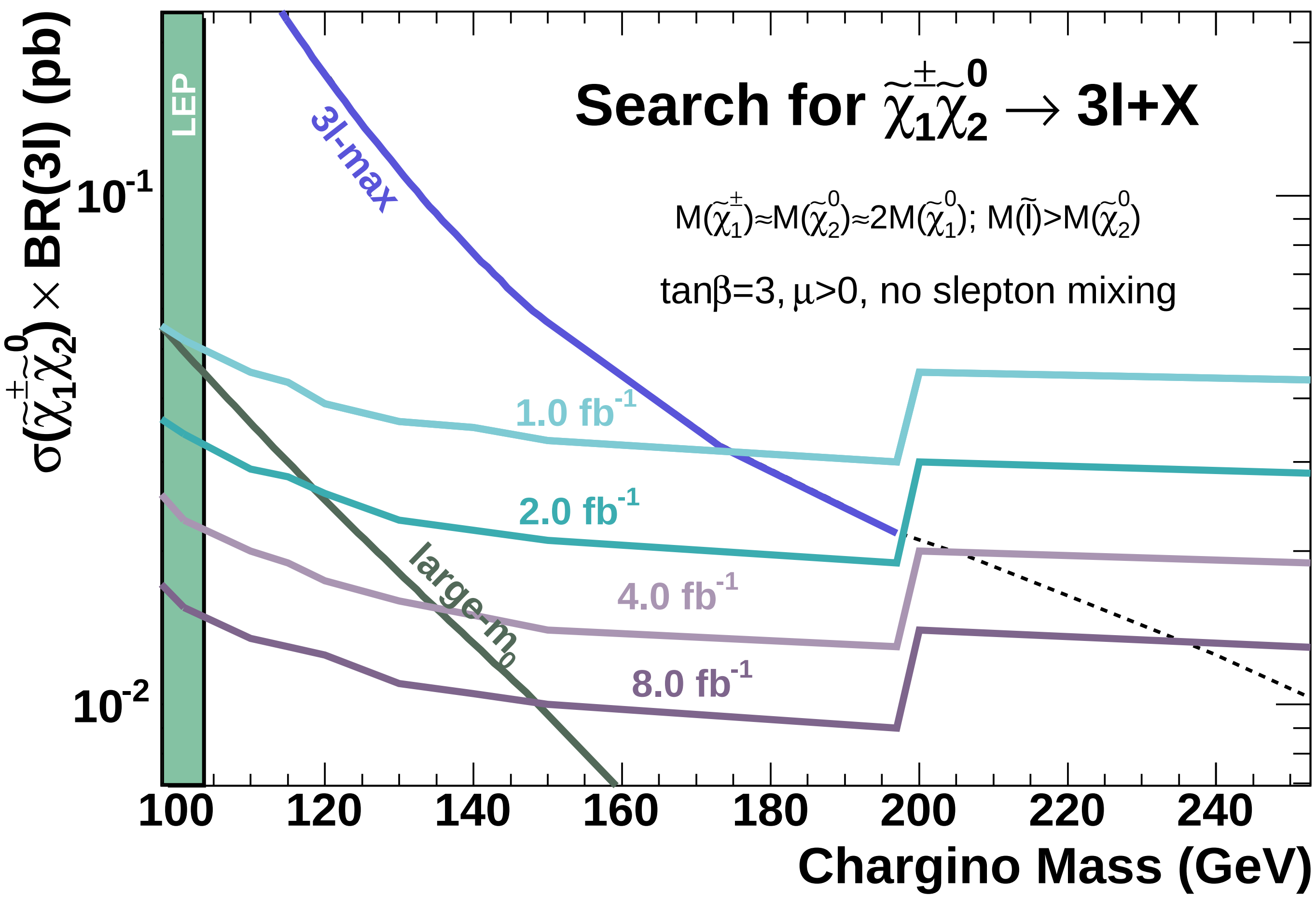



**Limits constrain SUSY beyond LEP chargino limits:**

- **3ℓ-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



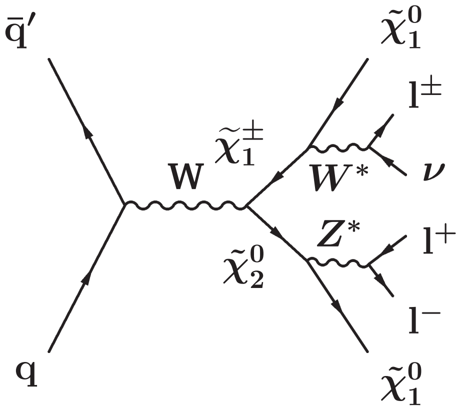

**Run IIb projections (assuming some analysis improvements):**

- 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

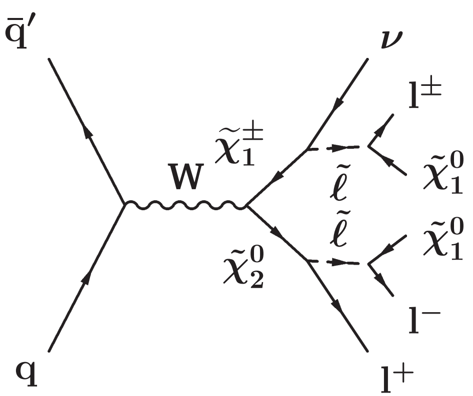
**Full update with 1 $fb^{-1}$ dataset currently in progress**

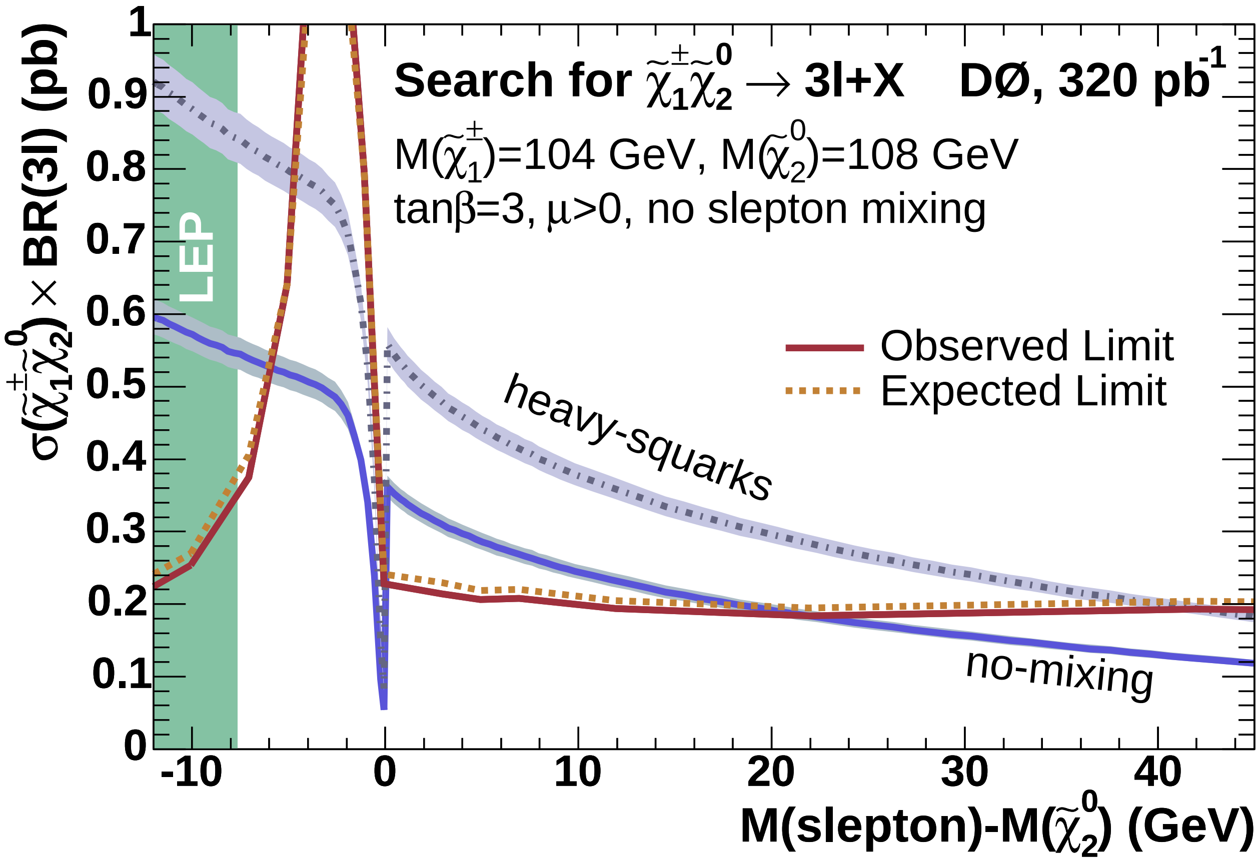
# Search for Charginos and Neutralinos

**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**

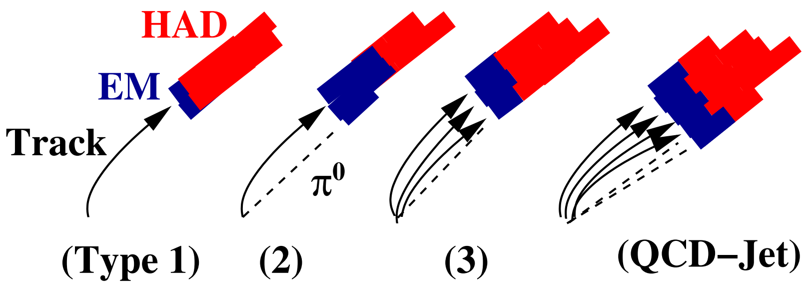
$\longrightarrow$ chargino/neutralino decay cascades proceed via stau

$\longrightarrow$ multiple $\tau$ leptons in final state

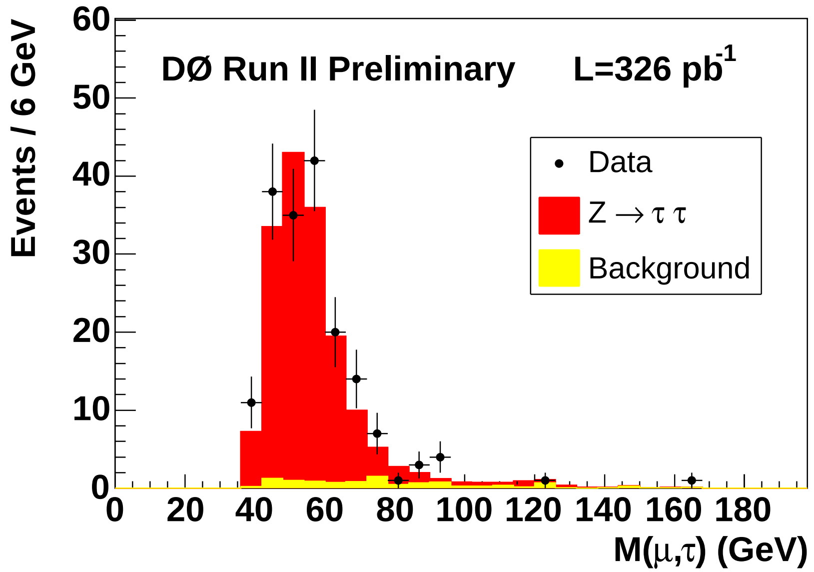
**65% of $\tau$ leptons decay hadronically**

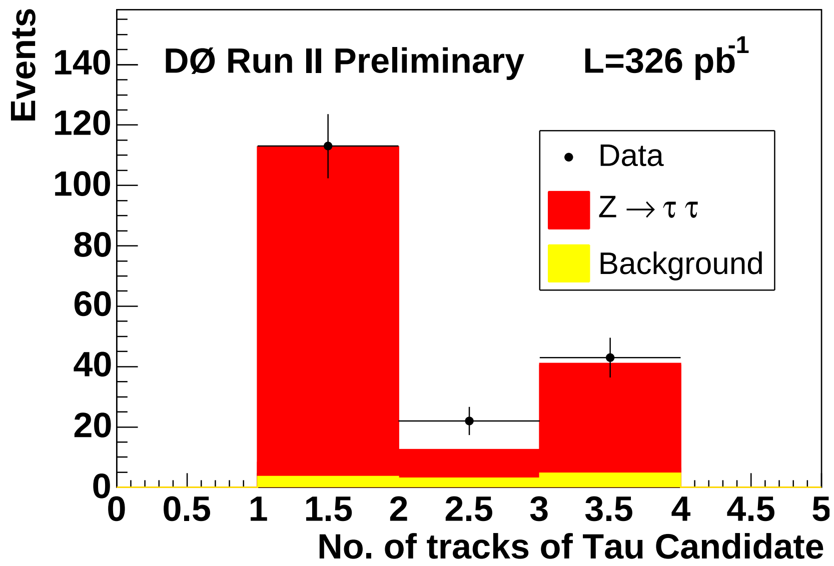
– reconstructed as 1 or 3 tracks pointing to narrow energy deposition in calorimeter

– using neural networks to separate $\tau$-decays from jets




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

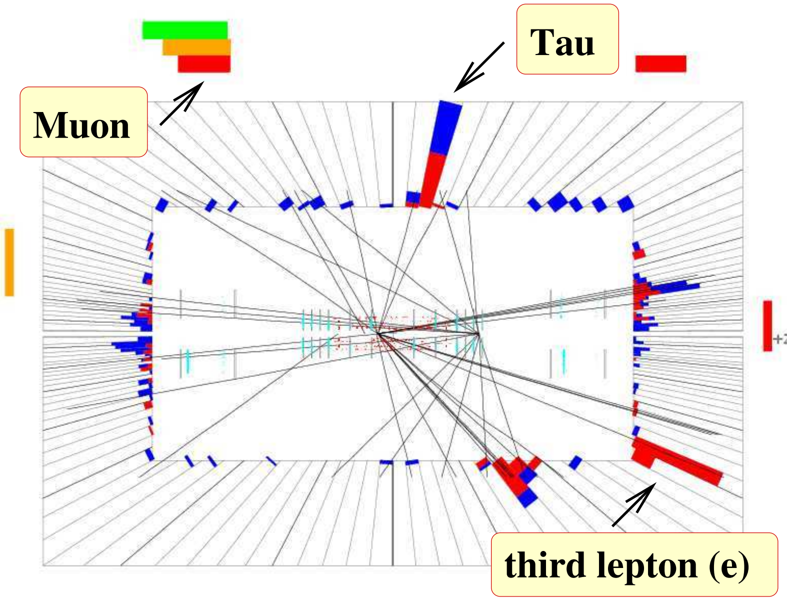


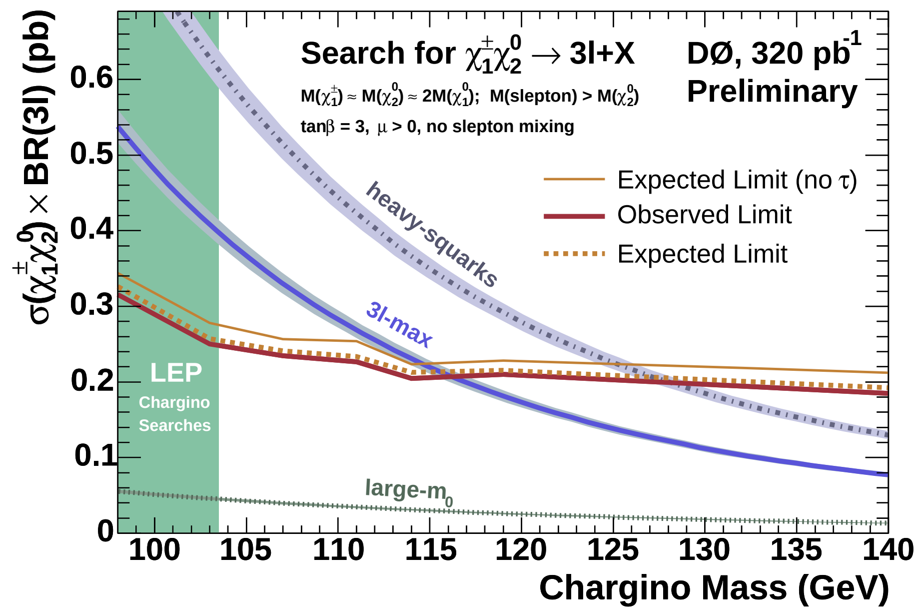



# Search for Charginos and Neutralinos

## 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 |



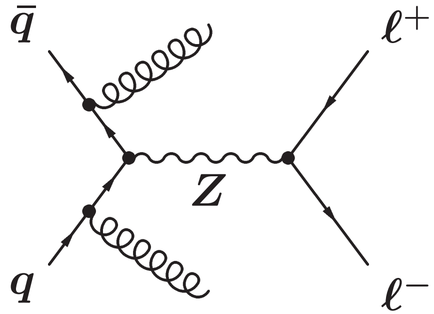




**Interpretation of results in models with light stau (high tan$\beta$) still in progress**

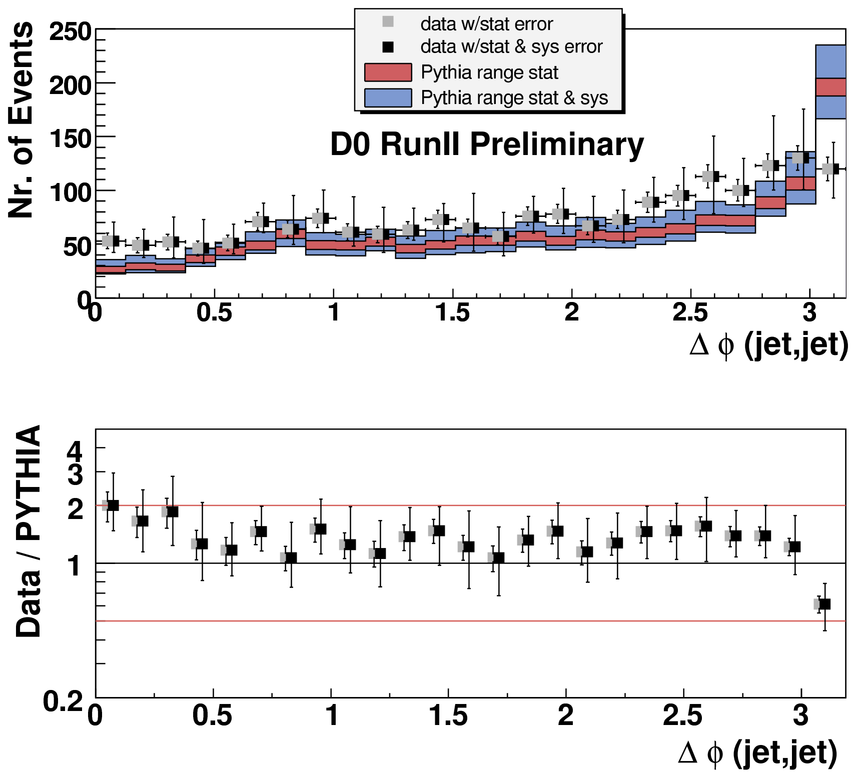
# Vector Boson plus Jet Production at the Tevatron

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

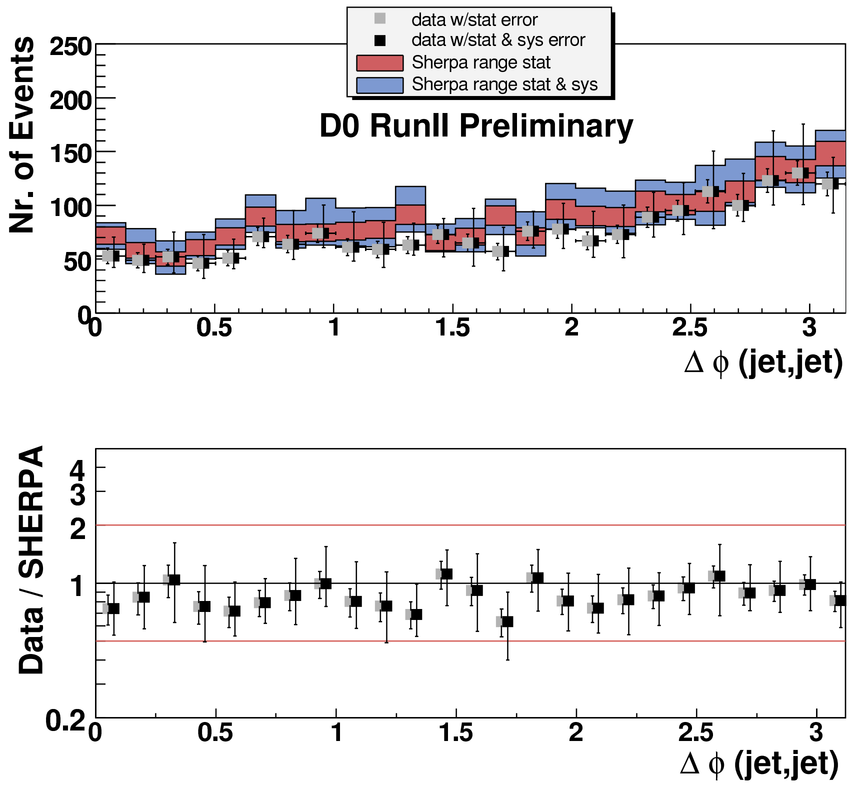
**Azimuthal angle between leading and next-to-leading Jet**




### DØ Data vs. PYTHIA

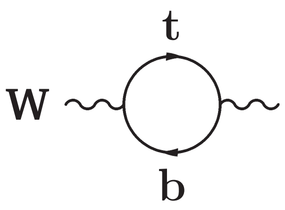



### DØ Data vs. SHERPA

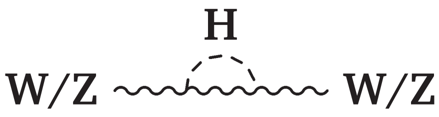


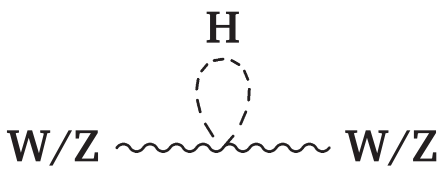
# Pinning down EWSB at the Tevatron

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

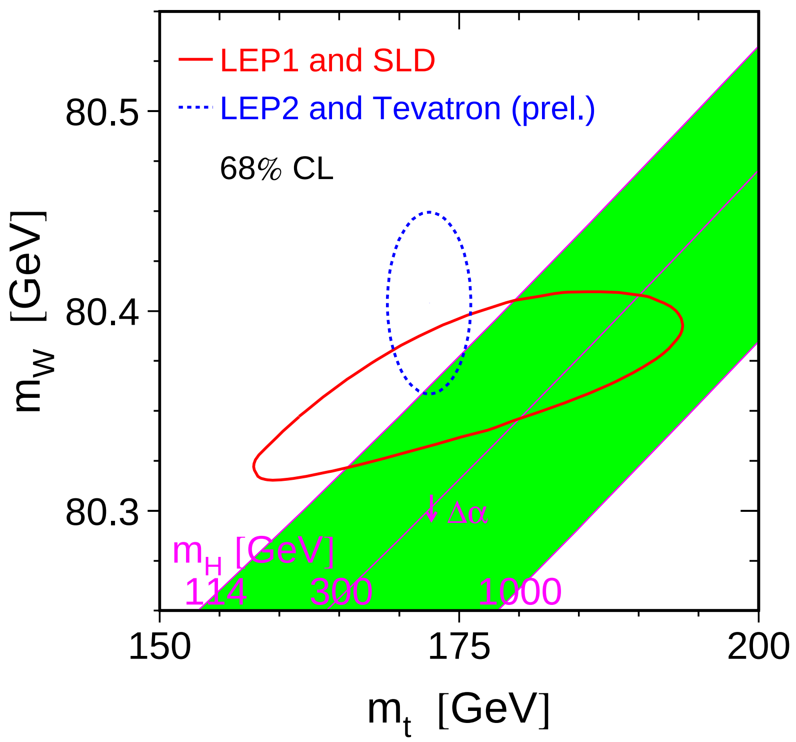


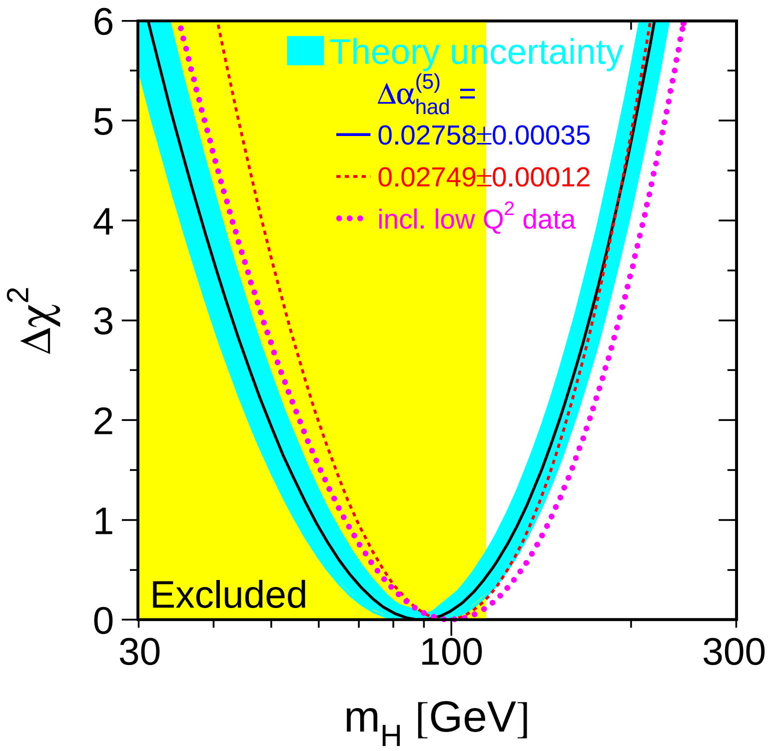

$\sim m_{\rm top}^2$




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



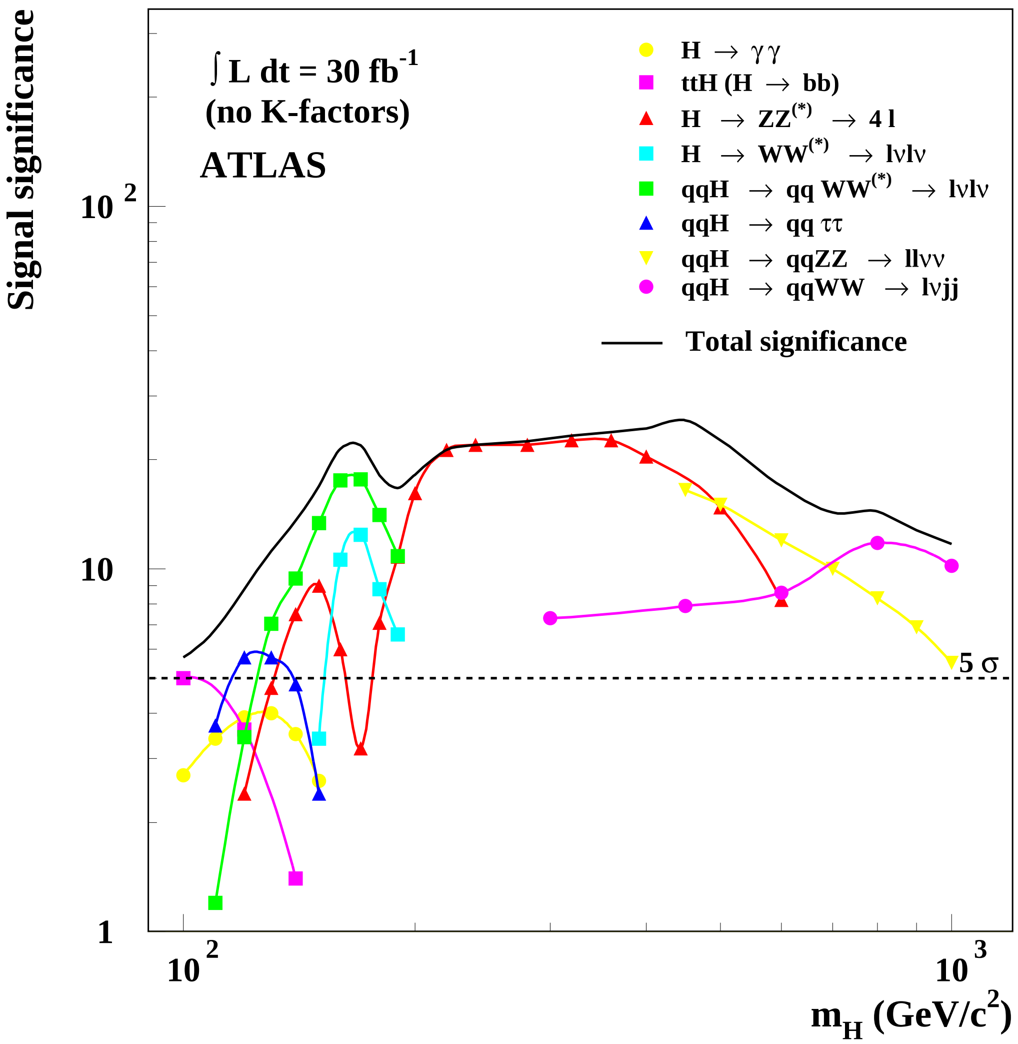

$\longrightarrow$ **Indirect constraints on Higgs boson mass:**

$m_H$**=89 + 42 - 30 GeV**

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

# 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

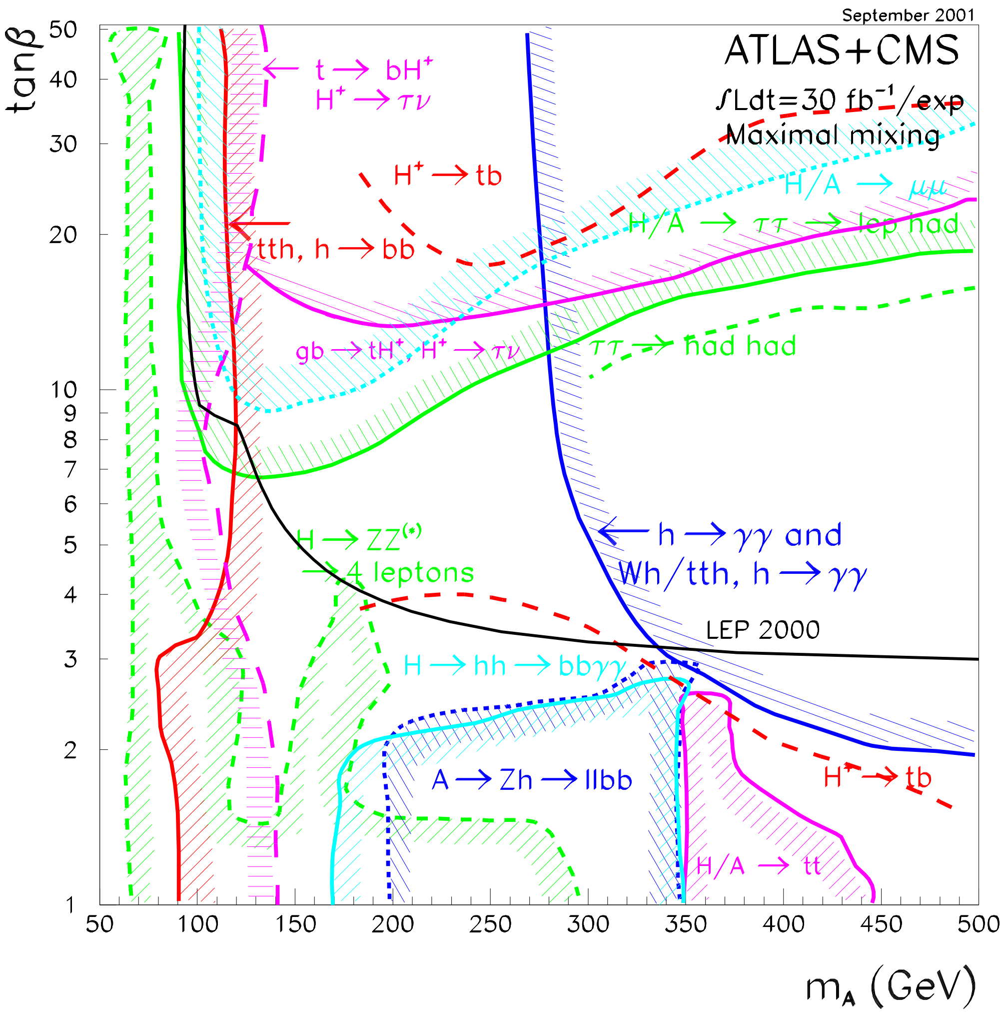


# Outlook: MSSM Higgs Searches at the LHC

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

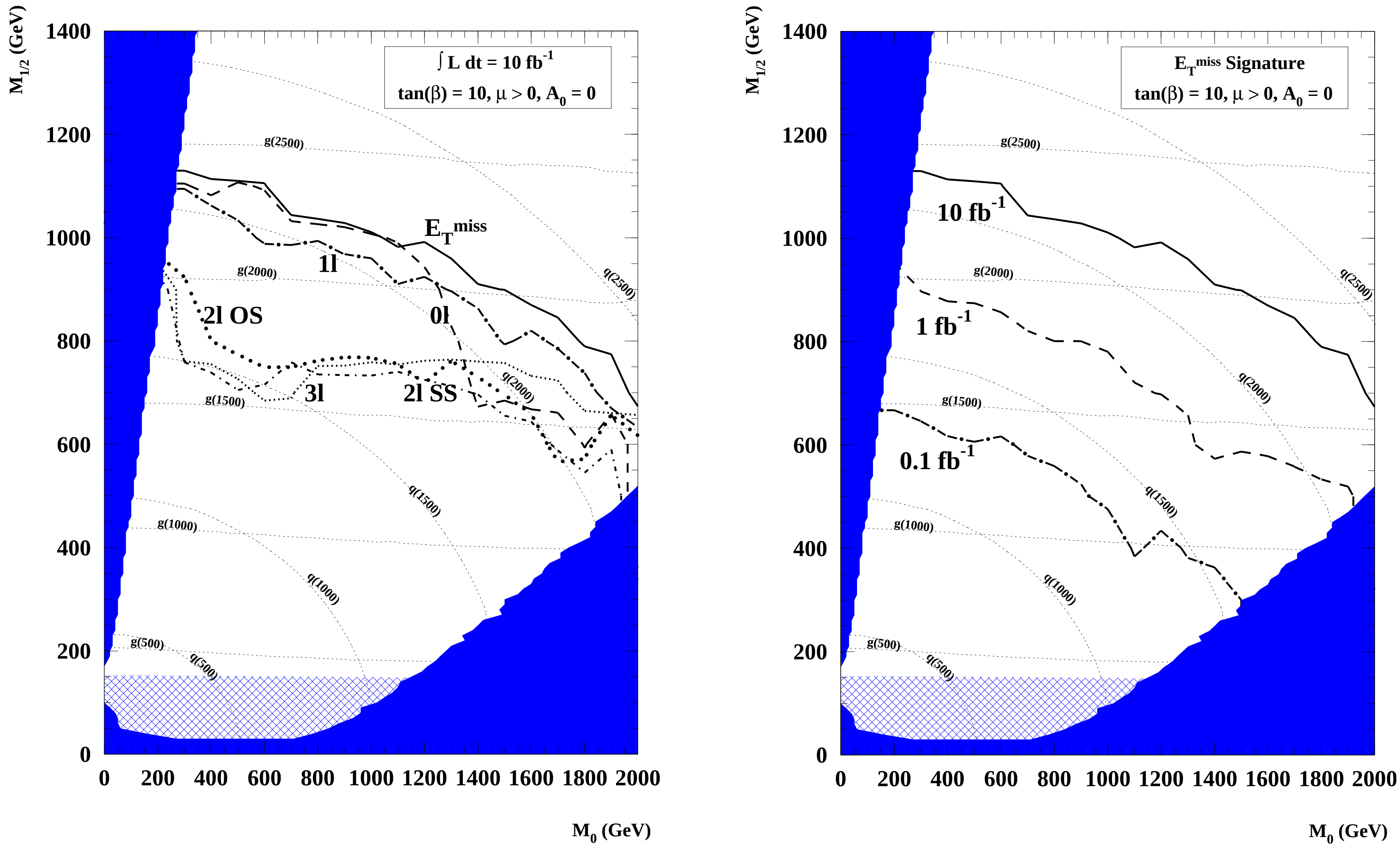
– **LHC can detect MSSM Higgs bosons at 5$\sigma$ across entire parameter space**

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



# Outlook: SUSY at the LHC

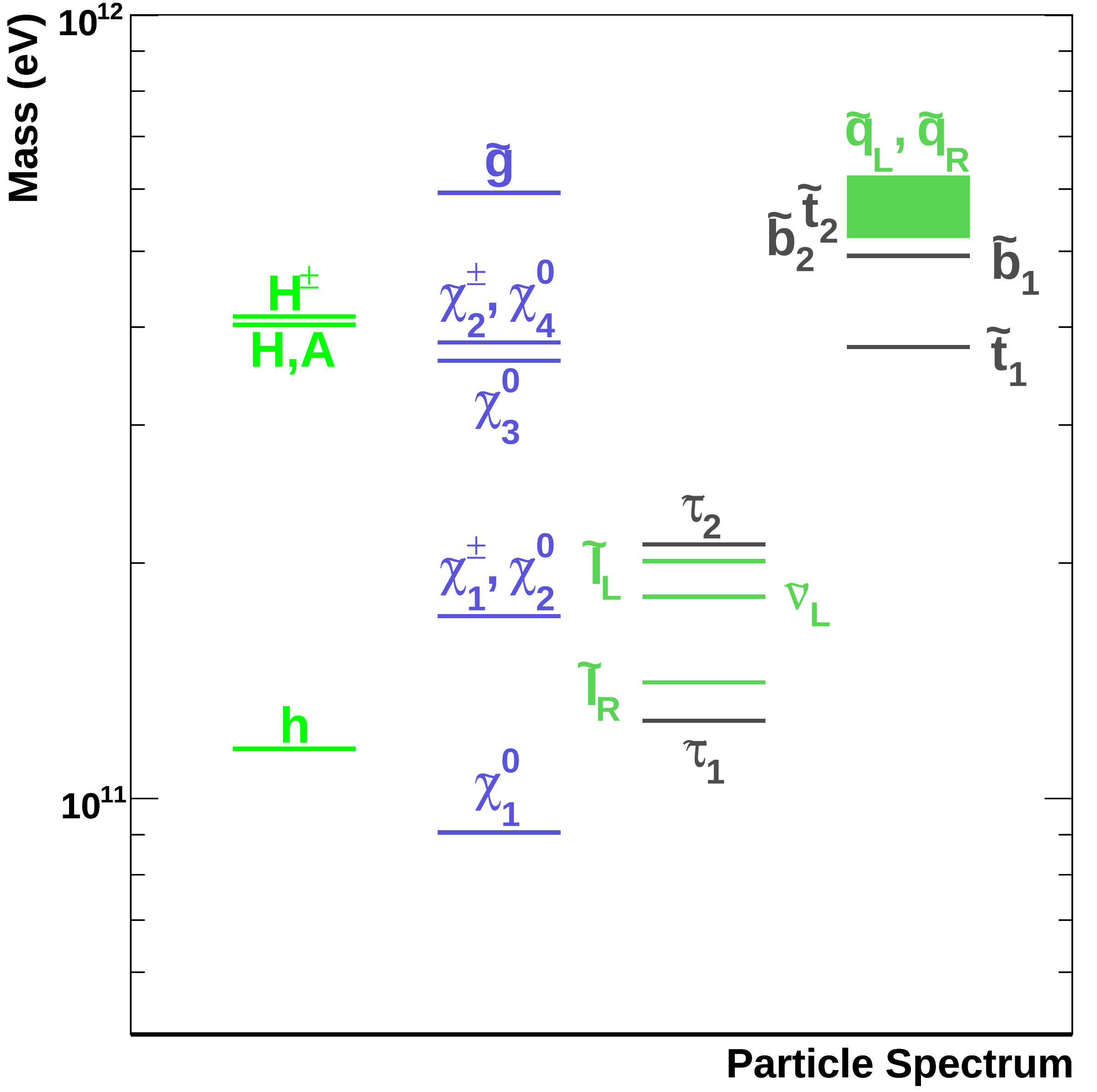
## ATLAS Discovery reach for Supersymmetry:




## Most likely limitation for a fast SUSY discovery:

– calibration, data quality, trigger commissioning...

# Typical mass spectrum of SUSY particles

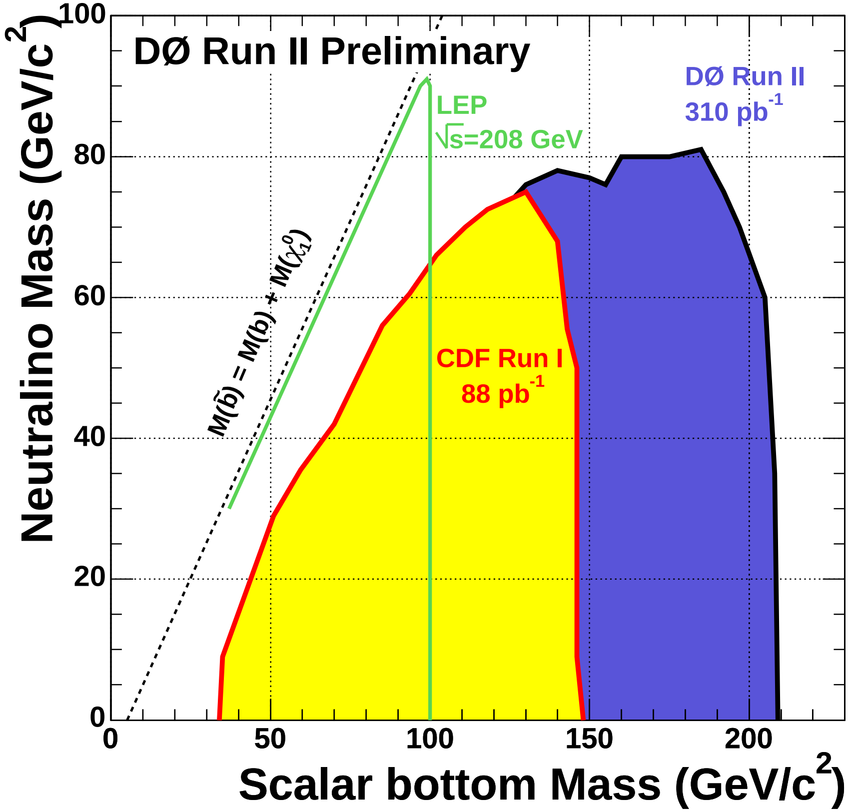


# Search for Supersymmetry – Sbottoms/Stops

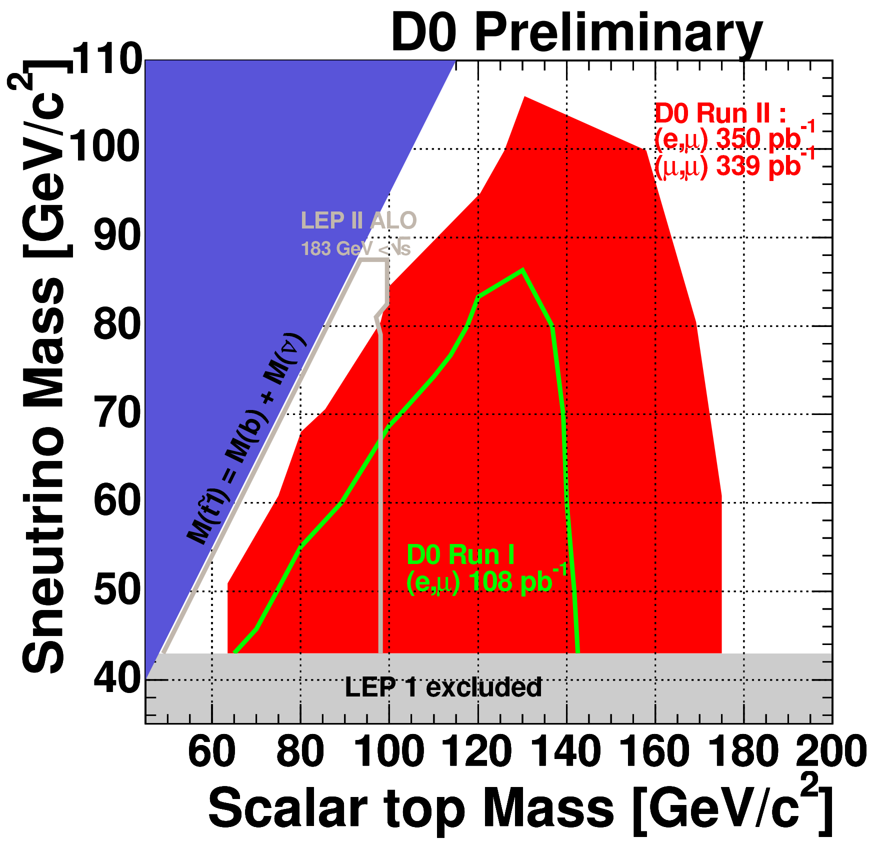
**Dedicated DØ searches for light sbottom or stop quarks**

- 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 Supersymmetry: R-Parity Violation

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

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

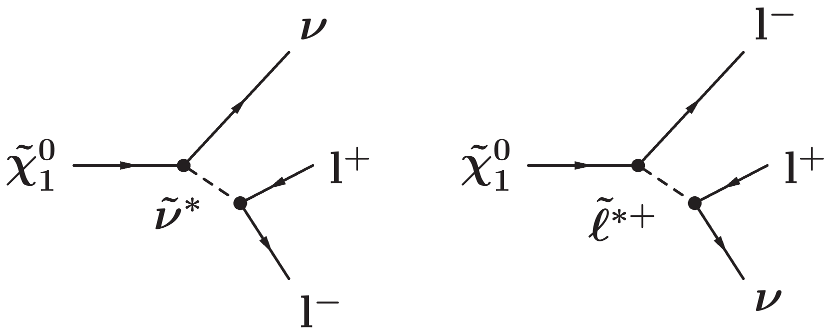
– couplings are constrained by searches for L- and B-violation, but could be non-zero

– all terms violate conservation of multiplicative quantum number R-parity

$\longrightarrow$ need to study SUSY with and without conservation of R-Parity

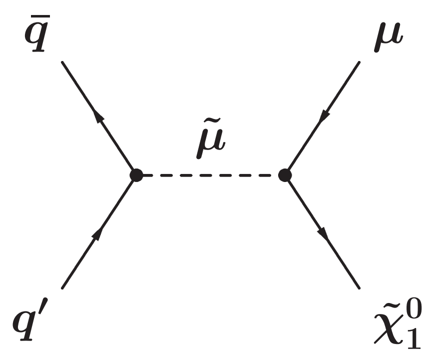
Important consequences of R-parity violation for SUSY collider signatures:

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)

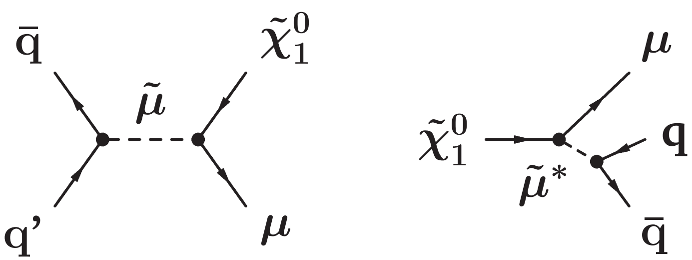
DØ search channels:

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

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

# 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:

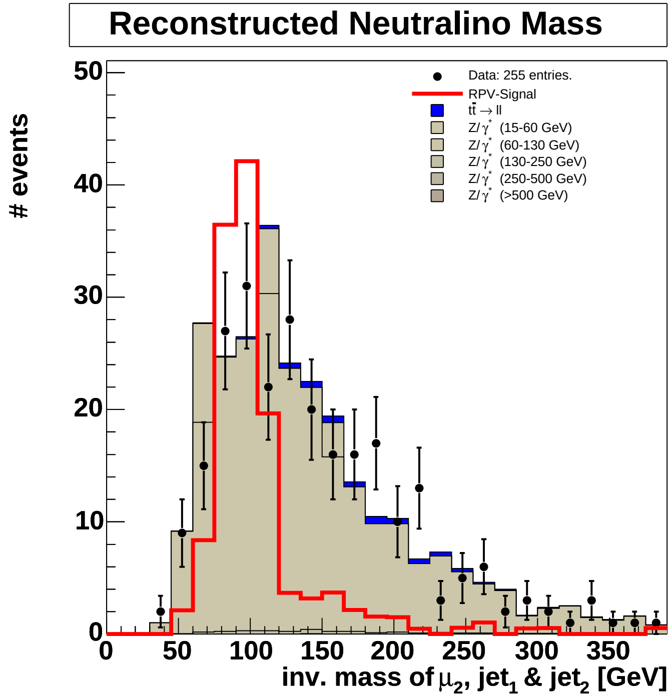
- between 0.1 and 1.6 events (depending on mass hypothesis)

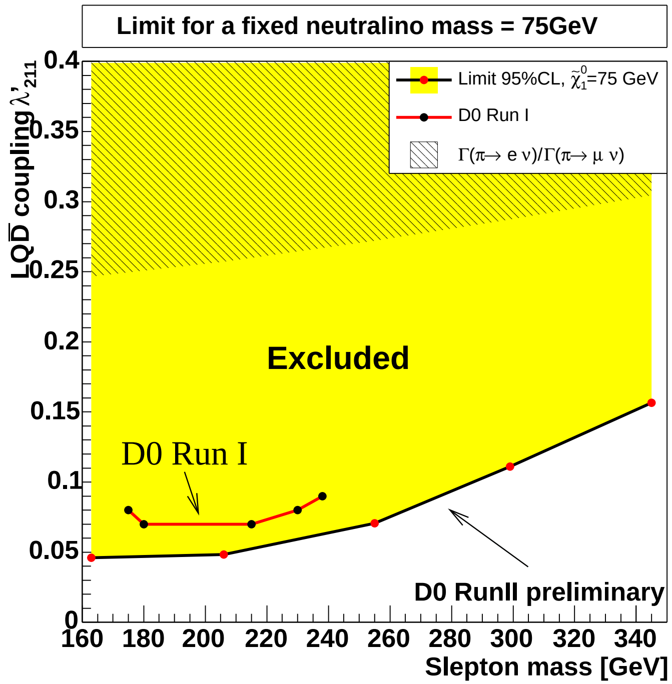
## No excess observed in data:

- two or less events for all masses

## Interpretation:

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



# Search for Charginos and Neutralinos – R-Parity Violation

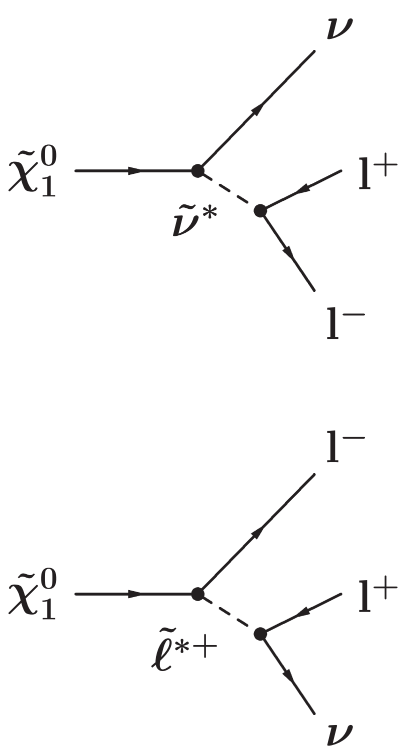
**Most general Superpotential contains 45 R-parity violating Yukawa terms:**

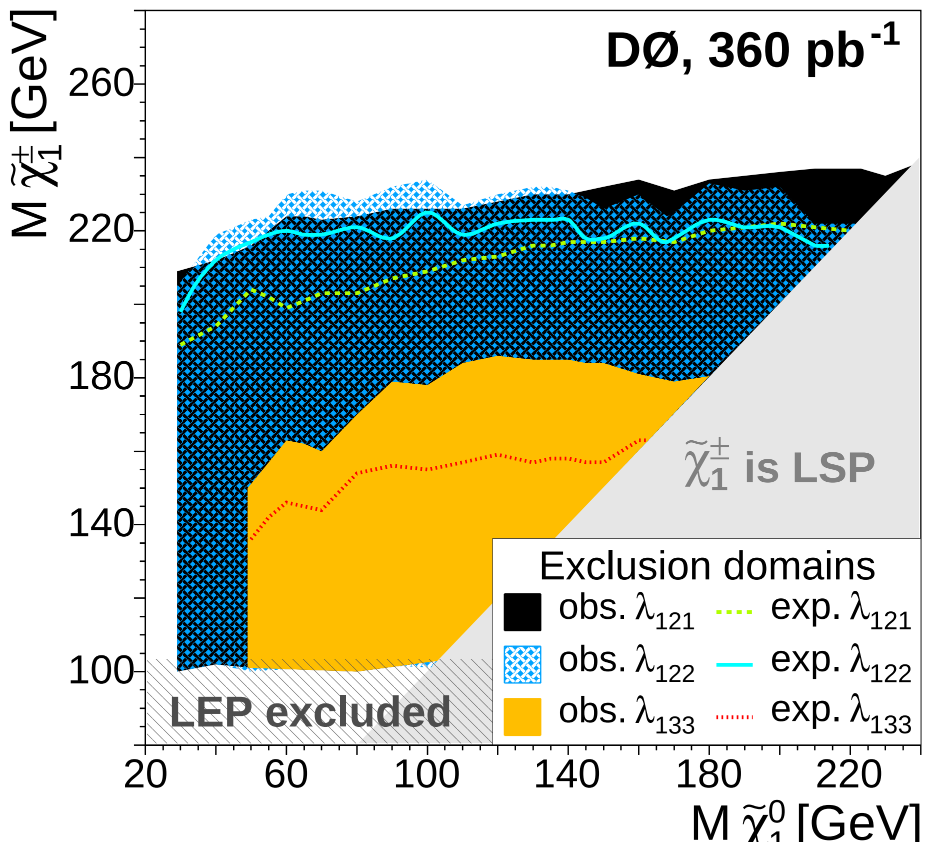
$$W_{RPV} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

- $\longrightarrow$ **LSP can decay into SM fermions**
- $\longrightarrow$ **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 Stable Charginos

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

$\longrightarrow$ slow-moving massive stable charged particle

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

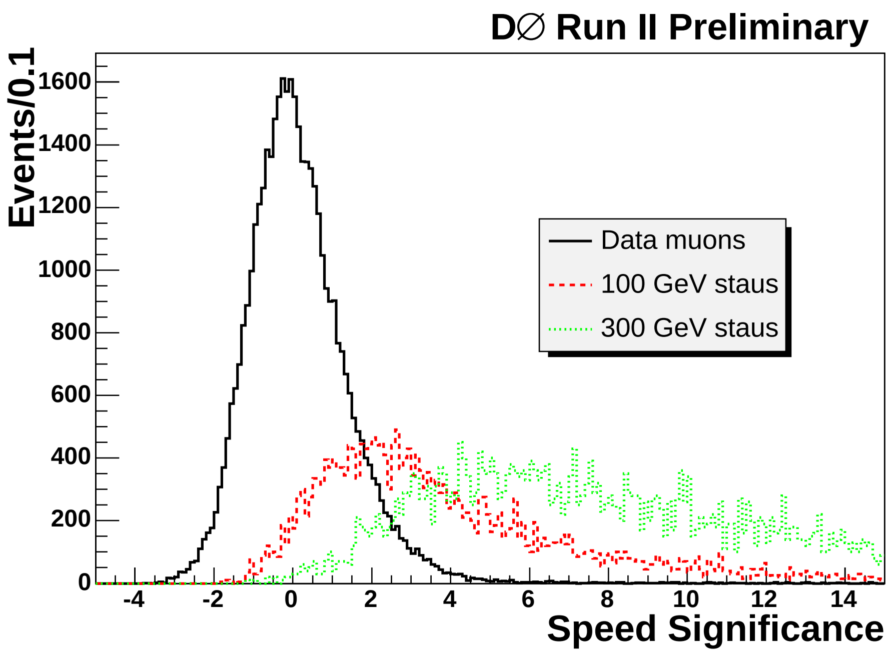
Additional Handle: large dE/dx in tracker and calorimeter (not used by current analysis)

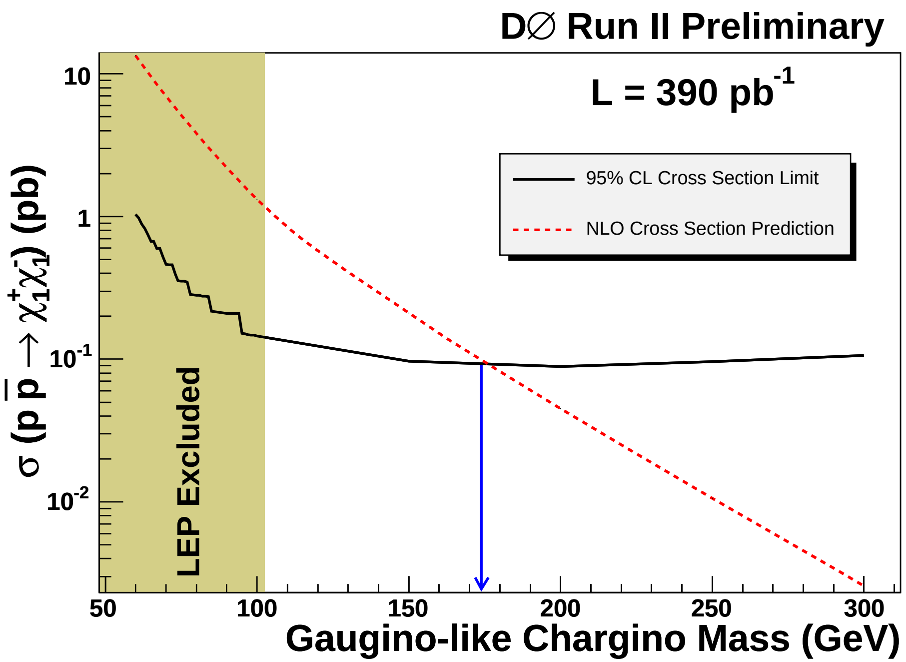
Analysis of 390 $\text{pb}^{-1}$ of data collected with dimuon trigger:

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

Results (m$>$100 GeV): no events observed, 0.66$\pm$0.06 events expected

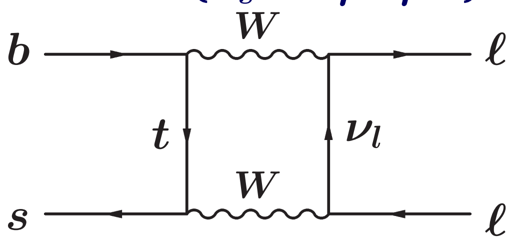
$\longrightarrow$ new chargino mass limits: 140 GeV (higgsino-like), 174 GeV (gaugino-like)



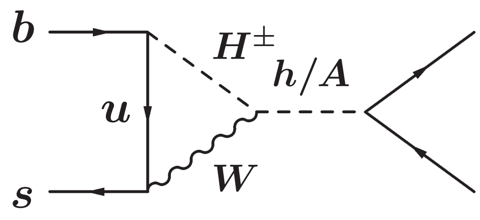



# Search for Supersymmetry: $B_s \to \mu^+\mu^-$

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



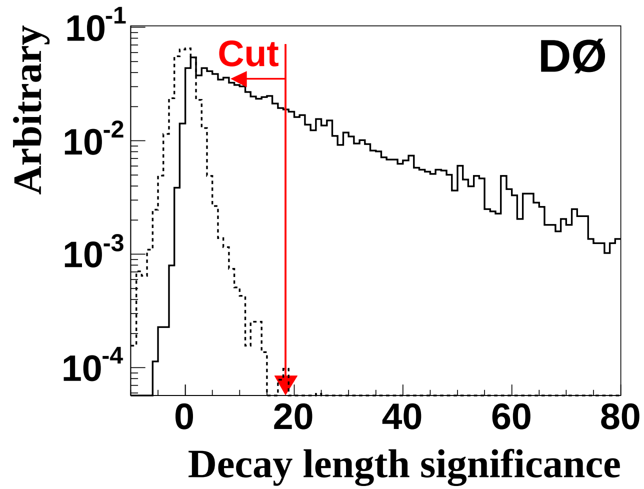

SUGRA: enhancement $\sim (tan\beta)^6$

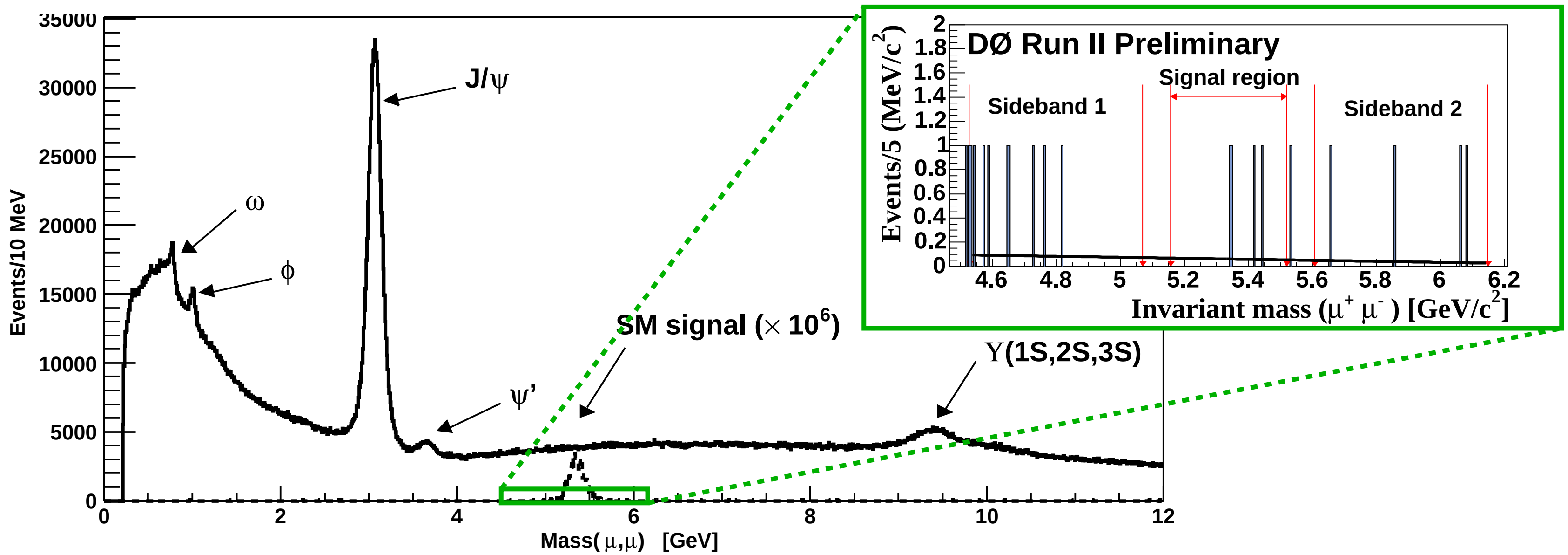



→ significant at high tan$\beta$: $BR = O(10^{-7})$

→ complementary to trilepton search

- Tevatron: large production rate for $B_s$
- Selection: two isolated muons, displaced vertex



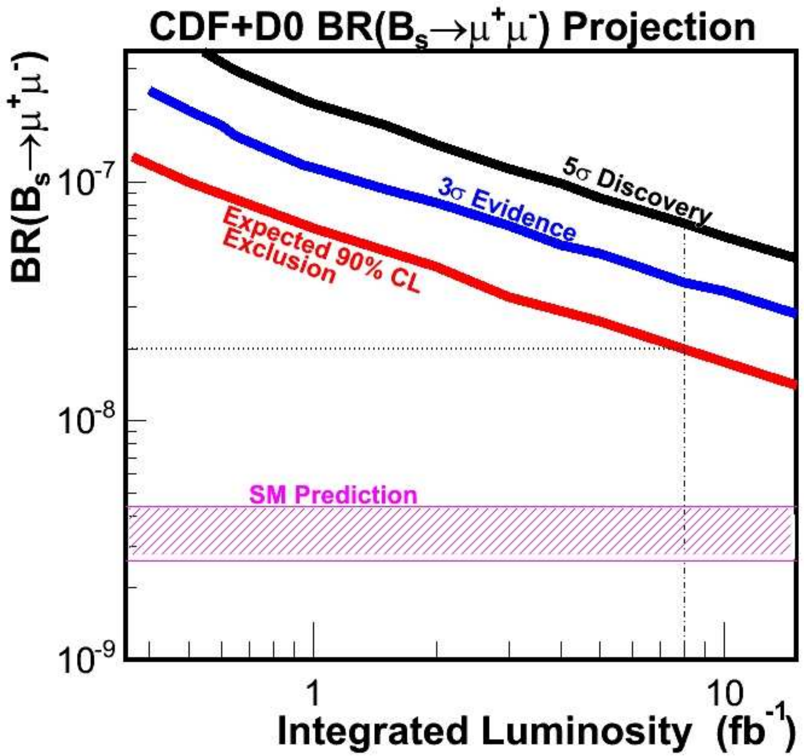
# Search for Supersymmetry: $B_s \rightarrow \mu^+\mu^-$

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

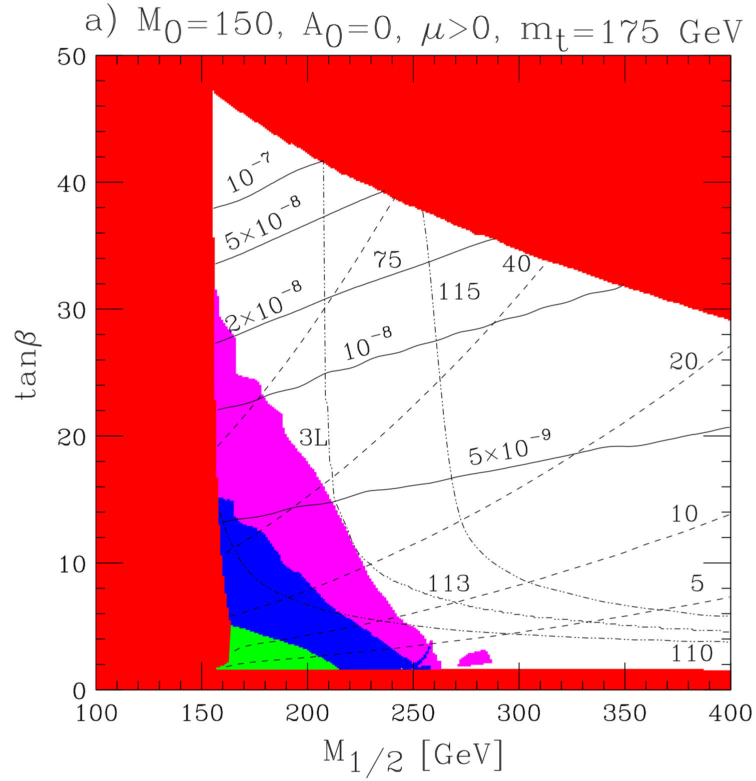
| | | | |
|---|---|---|---|
| DØ | (300 pb$^{-1}$): | 4.3±1.2 expected, 4 observed → | $BR(B_s \rightarrow \mu^+\mu^-) < 3.7\times10^{-7}$ |
| CDF | (364 pb$^{-1}$): | 1.5±0.2 expected, 0 observed → | $BR(B_s \rightarrow \mu^+\mu^-) < 2.0\times10^{-7}$ |
| | | TEVNPWG Combination: | $BR(B_s \rightarrow \mu^+\mu^-) < 1.5\times10^{-7}$ |

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

→ will test large part of SUGRA parameter space




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

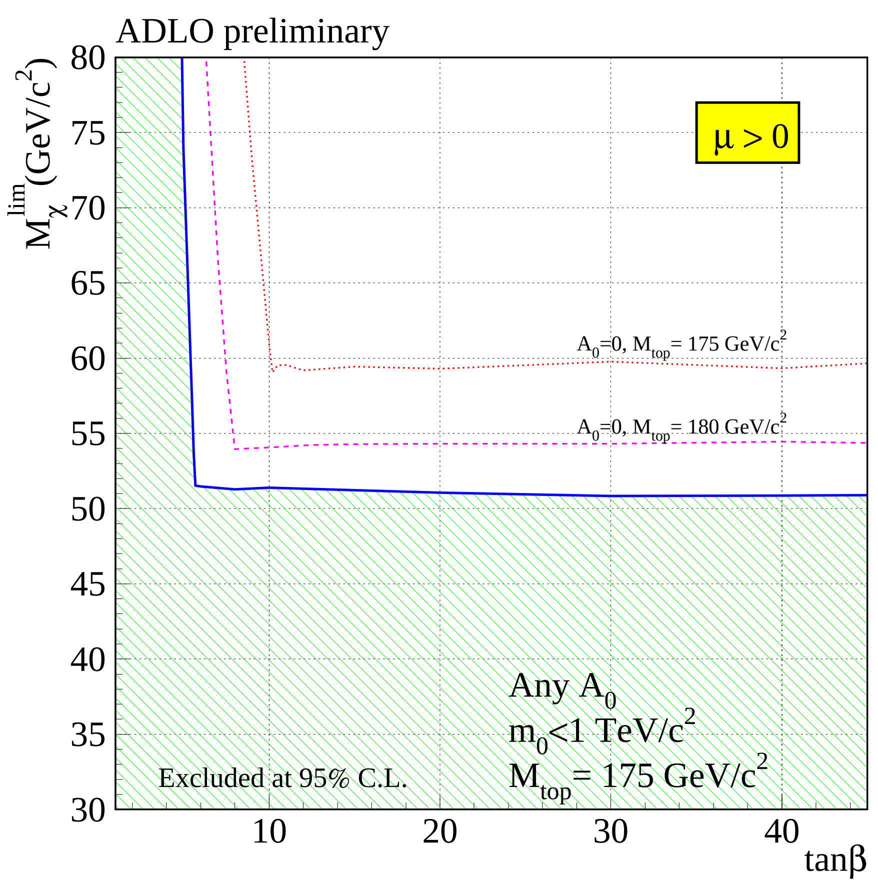


# Search for Supersymmetry at LEP

- 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**