Searches for New Phenomena at DØ

High Mass Dileptons/Diphotons

Supersymmetry
- Squarks / Gluinos and Charginos / Neutralinos
- SUSY with R-parity Violation
- Gauge Mediated SUSY Breaking

Long Lived Massive Particles

2nd generation Leptoquarks

SUSY Higgs

Standard Model Higgs – “light” and “heavy”

Arnd Meyer – RWTH Aachen

The Tevatron Connection

Fermilab, June 24 2005

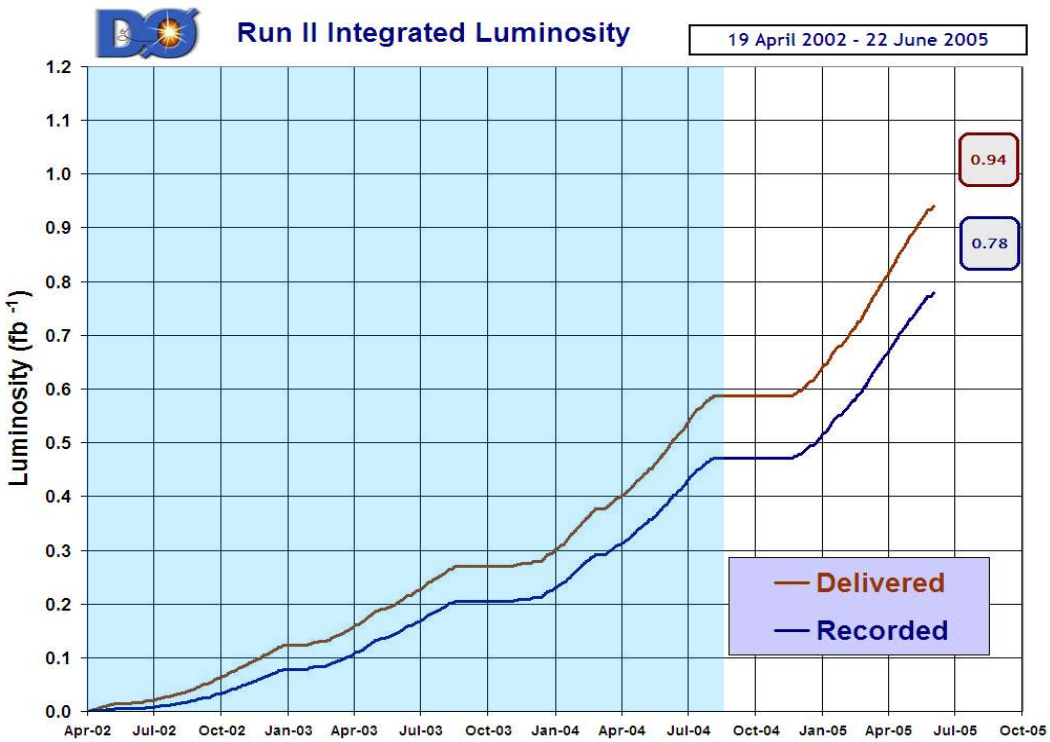
RWTH AACHEN
RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN

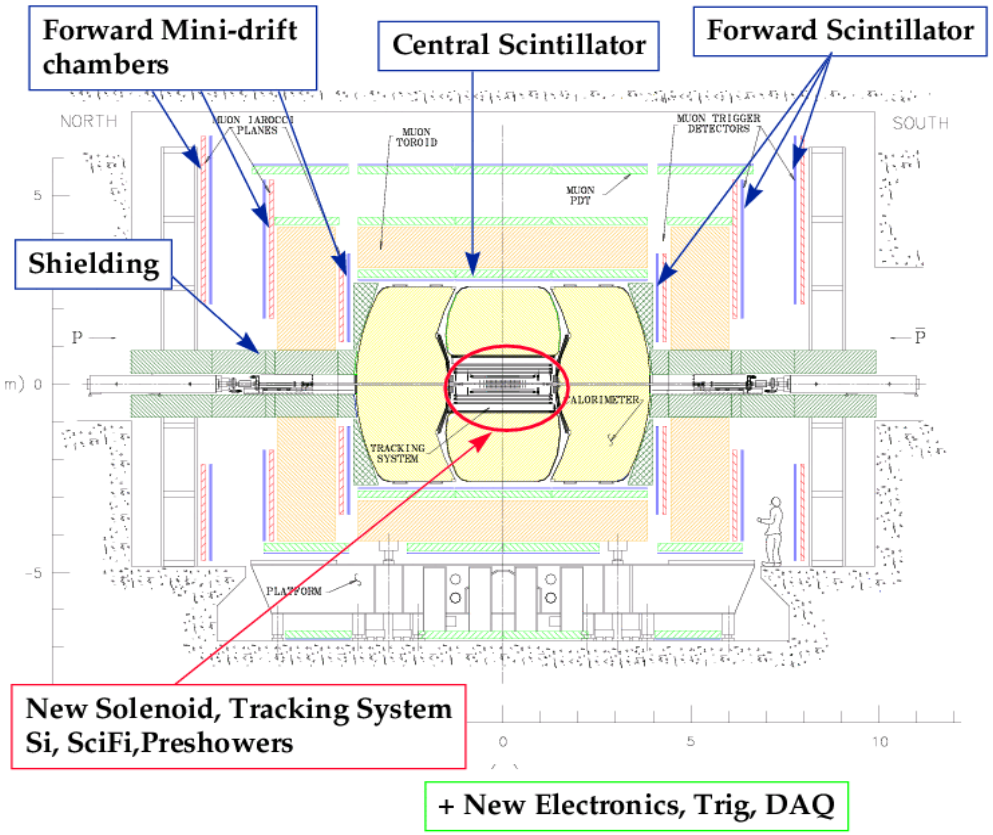
bmb+f
Großgeräte der physikalischen Grundlagenforschung

The DØ Experiment

DØ Strengths:
Excellent and wide muon coverage, hermetic calorimetry

Collected close to 800 pb^{-1} so far in Run II
Analyses shown here use up to 400 pb^{-1}



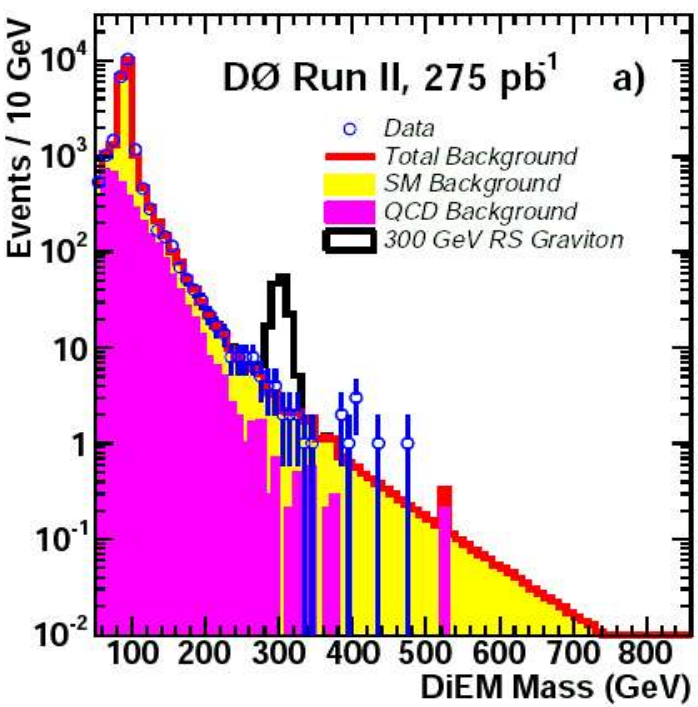


Electron Acceptance	$\lvert\eta\rvert < 3.0$
Muon Acceptance	$\lvert\eta\rvert < 2.0$
Precision Tracking (Silicon)	$\lvert\eta\rvert < 3.0$

Detector is running stable with ~90% data taking efficiency

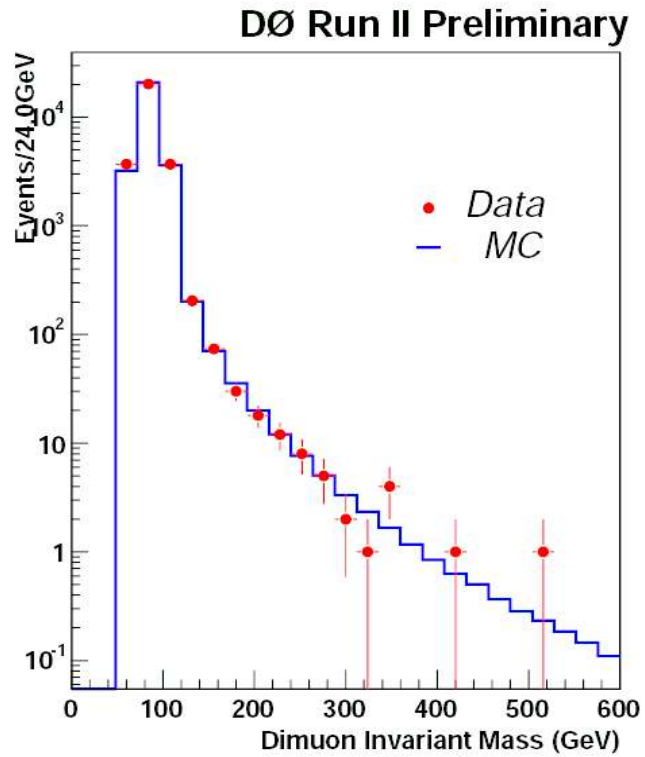
High Mass $\mu\mu$, ee, $\gamma\gamma$

- Dimuon and dielectron samples are not only among the most important samples for the understanding of the detector
- Their invariant mass spectra (and the diphoton mass spectrum) can also be used to **probe a large variety of models**
  - "Peak searches": Z', Randall-Sundrum Gravitons, ...
  - Indirect searches: Large Extra Dimensions, quark-lepton compositeness, ...



Dielectron + diphoton

Dimuon



High Mass $\mu\mu$, ee, $\gamma\gamma$

Preliminary results:

Large Extra Dimensions in $\mu\mu$, ee, $\gamma\gamma$ (200-250 pb^{-1})

Fundamental Planck scale M_S > 1.43 TeV (GRW model); TeV^{-1} extra dimensions: M_C > 1.12 TeV

Quark-Lepton compositeness in $\mu\mu$ (400 pb^{-1}) and ee (270 pb^{-1})

Limits on compositeness scale ranging from 4.2 to 9.8 TeV

Search for a heavy Z' in $\mu\mu$ (250 pb^{-1})

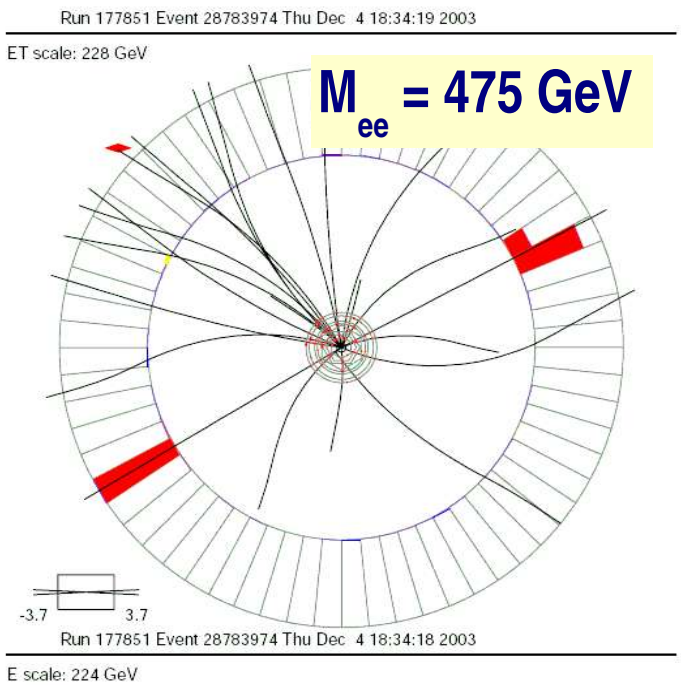
m(Z') > 680 GeV for SM-like couplings

Randall-Sundrum Gravitons in $\mu\mu$, ee, $\gamma\gamma$ (260 pb^{-1}, publ.)

Exclude graviton masses below 250 – 785 GeV, dep. on coupling

Technicolor: ρ_T and ω_T in ee (200 pb^{-1})

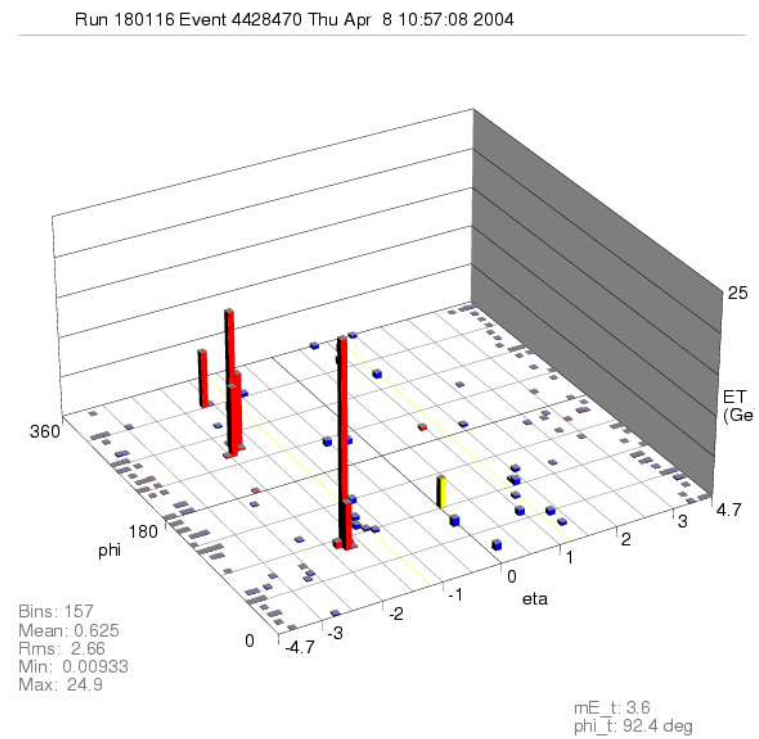
Exclude m(ρ_T, ω_T) below 367 GeV, depending on model parameters

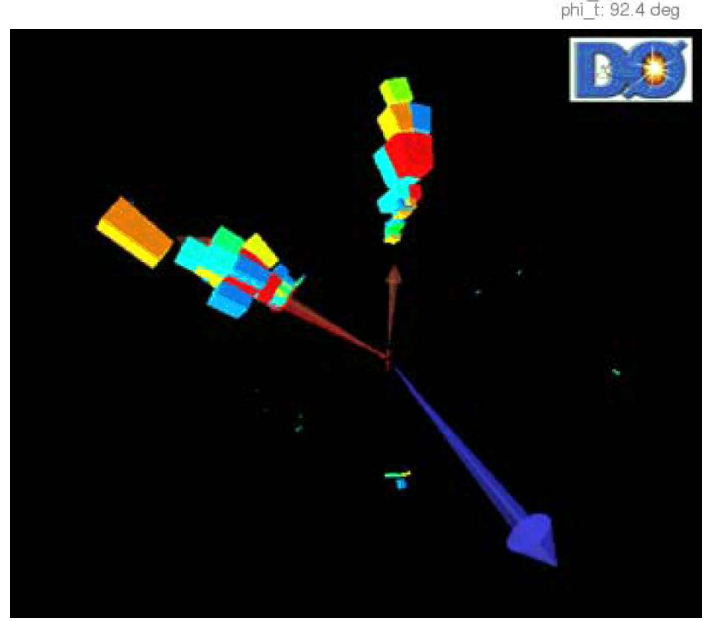


No significant excess anywhere... but potential for future excitement

Supersymmetry

- **Direct searches for SUSY partners at the Tevatron**
  - Squarks / Gluinos
    - Strong production – large cross sections
    - Masses possibly relatively high
  - Charginos / Neutralinos
    - Small cross sections
    - Cascade decays can provide clean signatures
- LEP searches for Charginos, Sleptons, Higgs: $m(\tilde{\chi}^{\pm})>103.5$ GeV, $m(\tilde{l})>95$ GeV, $m(h)>114.4$ GeV
- **Signatures vary with model assumptions**
  - MSSM with R-parity conserved: $\not{E}_T$ (jets + $\not{E}_T$, trileptons + $\not{E}_T$)
  - MSSM with R-parity violation: Multileptons, leptons + jets
  - GMSB (with Neutralino NLSP): Diphotons
  - Long-lived particles





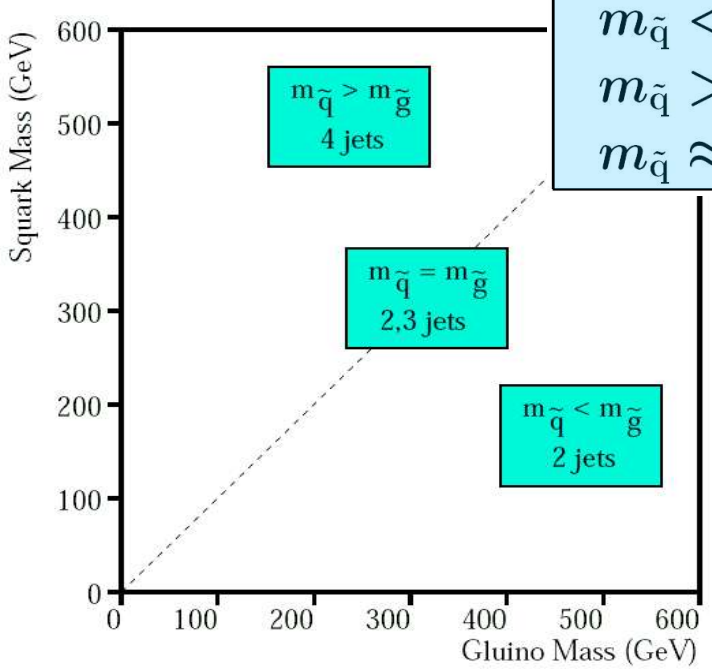
$\not{E}_T$ = 354 GeV

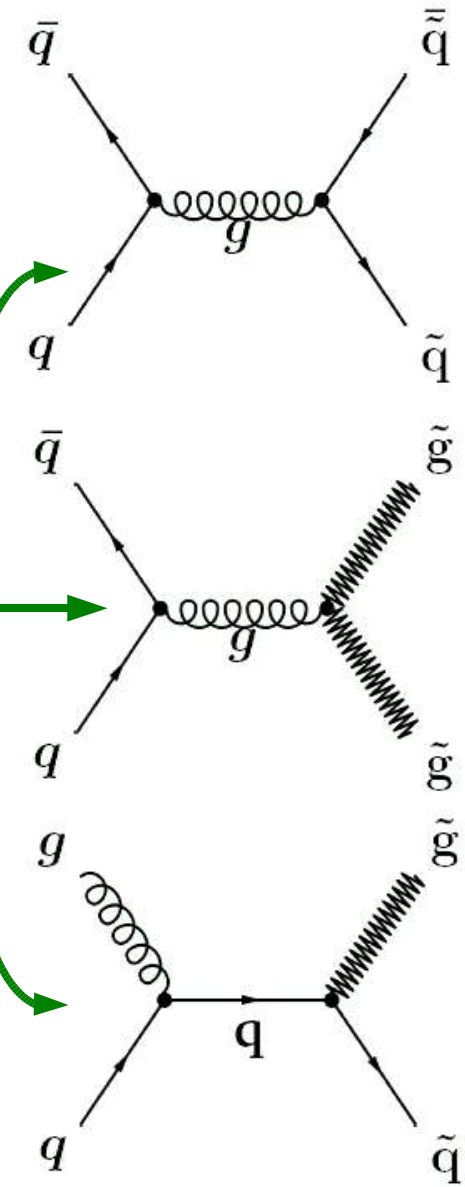
Squarks and Gluinos

- $p\bar{p}$ collider: strong production of Squarks / Gluinos → **large cross section**
- LSP assumed to be stable (R_p conserved) → signature: **jets + $\not{E}_T$**
- Using $\int L\,dt = 310\ pb^{-1}$ collected with dedicated trigger: acoplanar jets + $\not{E}_T$

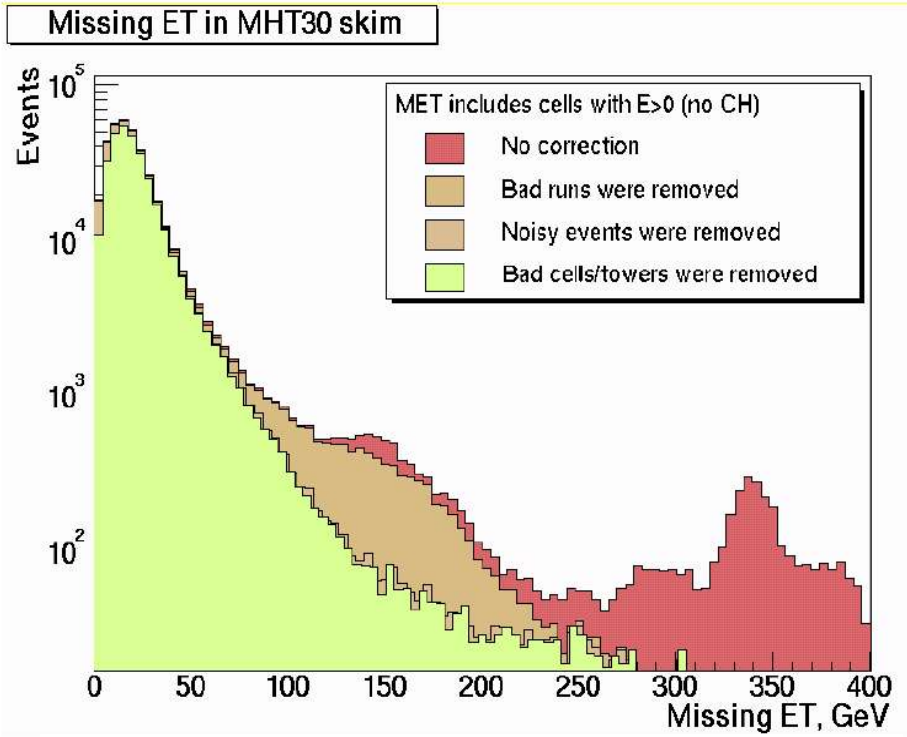
3 search channels

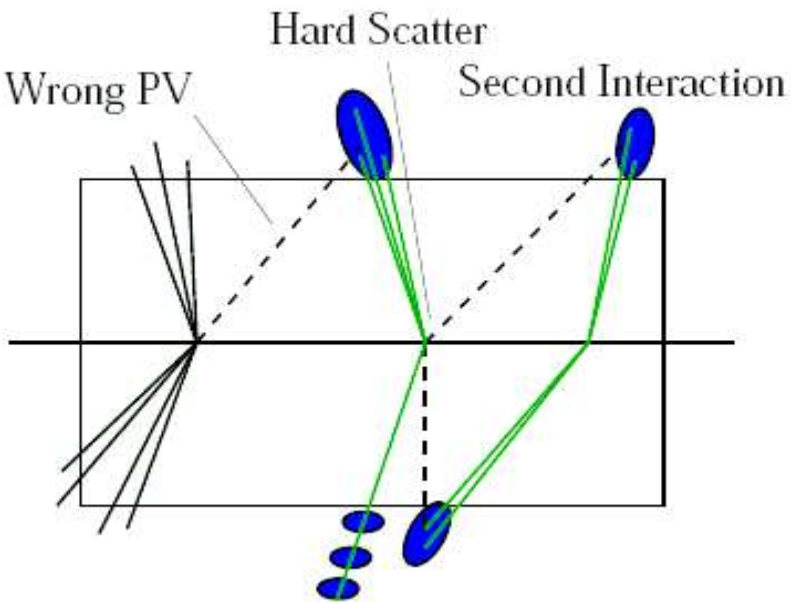
Mass region	Main Channel	Signature
$m_{\tilde{q}} < m_{\tilde{g}}$	$\tilde{q}\tilde{q}$	$2j + \not{E}_T$
$m_{\tilde{q}} > m_{\tilde{g}}$	$\tilde{g}\tilde{g}$	$4j + \not{E}_T$
$m_{\tilde{q}} \approx m_{\tilde{g}}$	$\tilde{q}\tilde{q},\tilde{q}\tilde{g}$	$2j/3j + \not{E}_T$





Squarks and Gluinos



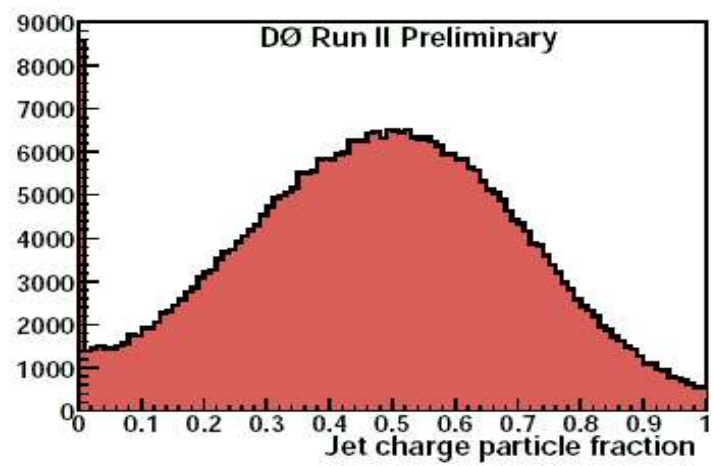


Extensive **data quality effort** to eliminate rare calorimeter problems

"Fake" missing E_T can be caused by

- wrong primary vertex
- Energy from additional interactions
- Cosmic ray muons
- Calorimeter noise and beam background

Substantially reduced by requiring a minimum charged particle fraction associated with each jet



Squarks and Gluinos

Main backgrounds: Multijets with fake $\not{E}_T$

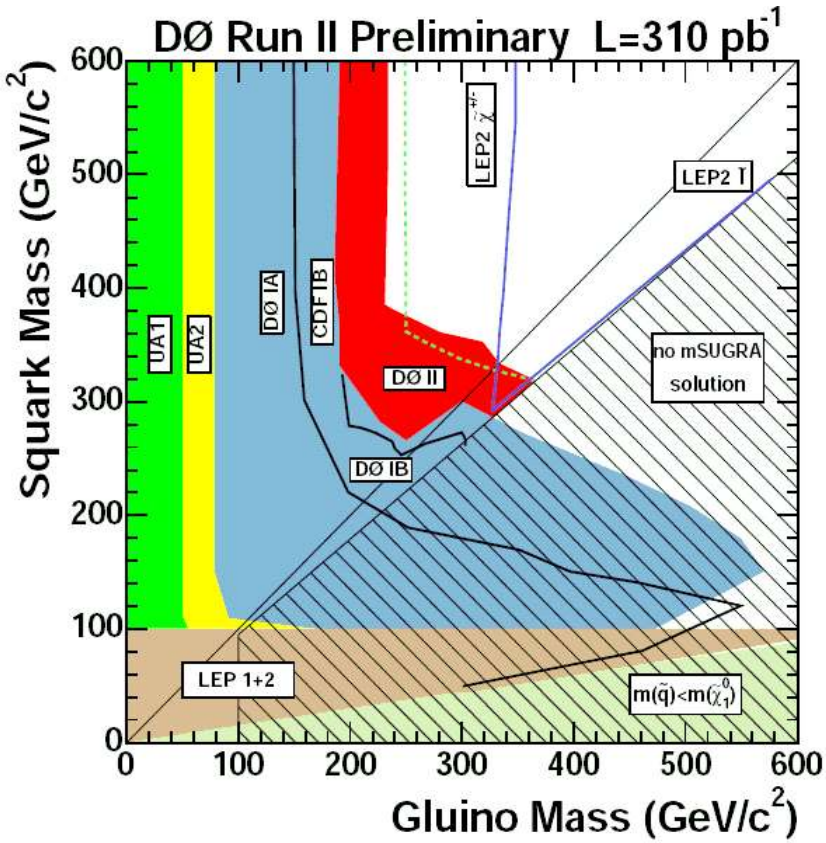
W+jets with W $\rightarrow$ e/μ/τ ν

Z+jets with Z $\rightarrow$ $\nu\nu$

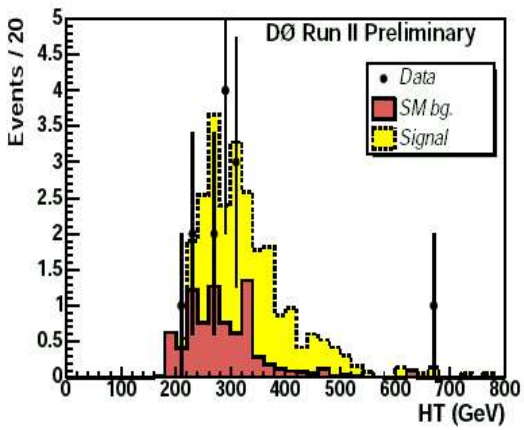
Selection: 2/3/4 jets + large $\not{E}_T$

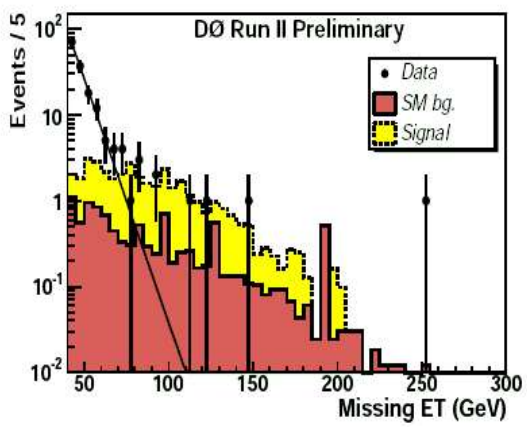
Sep. between $\not{E}_T$ and jets

Veto on isolated leptons



"Gluino"-analysis before final cuts



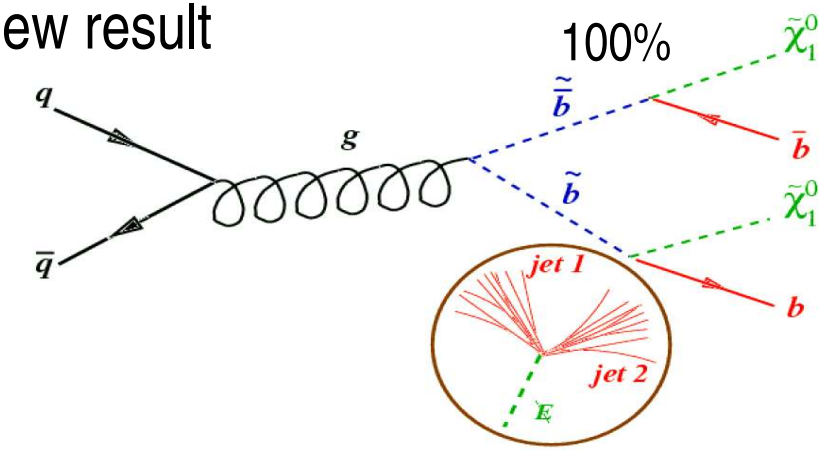


mSUGRA: tanβ=3, A0=0, μ<0

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	>250 GeV	12.8±5.4	12
$m_{\tilde{q}} > m_{\tilde{g}}$	$\tilde{g}\tilde{g}$	4j + $\not{E}_T$	>75 GeV	>250 GeV	7.1±0.9	10
$m_{\tilde{q}} \approx m_{\tilde{g}}$	$\tilde{q}\tilde{q}$,$\tilde{q}\tilde{g}$	2j/3j + $\not{E}_T$	>100 GeV	>325 GeV	6.1±3.1	5

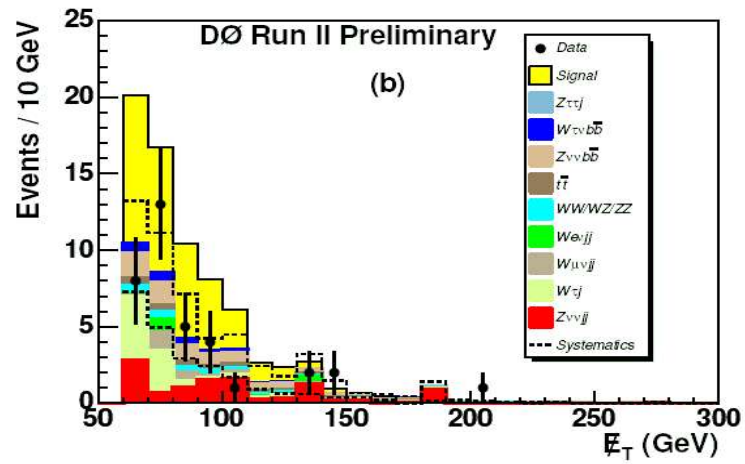
Sbottom Pair Production

New result



$\int L\,dt = 310\ pb^{-1}$ of data collected with acoplanar jets + $\not{E}_T$ trigger

Signal: generic MSSM, vary $m(\tilde{b})$ and $m(\tilde{\chi}_1^0)$



<u>Selection:</u> 2 or 3 jets (leading jets E_T > 40-70/15-40 GeV)

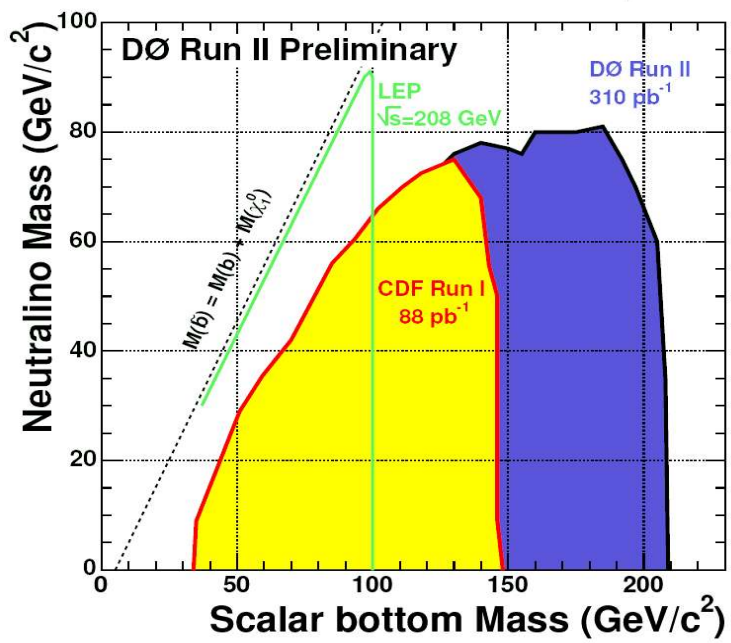
Single tight b-tag

$\not{E}_T$ > 60-100 GeV

Depending on $m(\tilde{b})$

Veto events with isolated μ, e, track (p_T > 5 GeV)

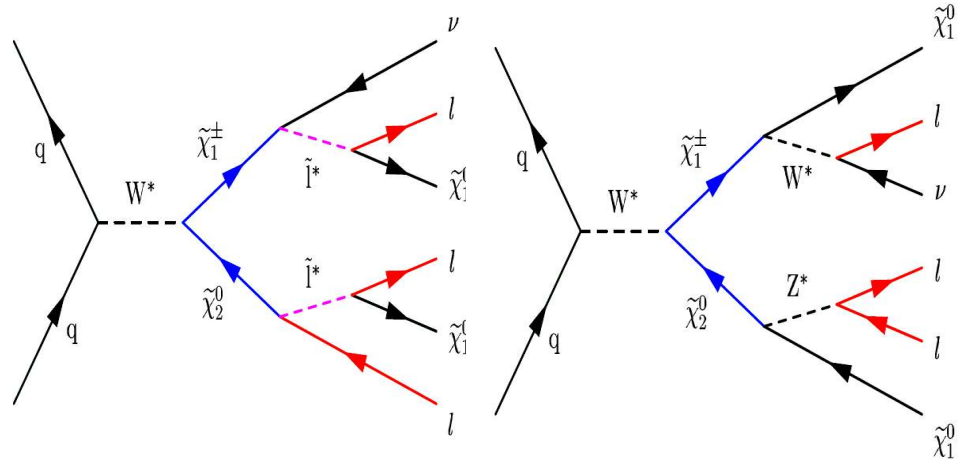
Cuts against mismeasured $\not{E}_T$ and other instrumental background

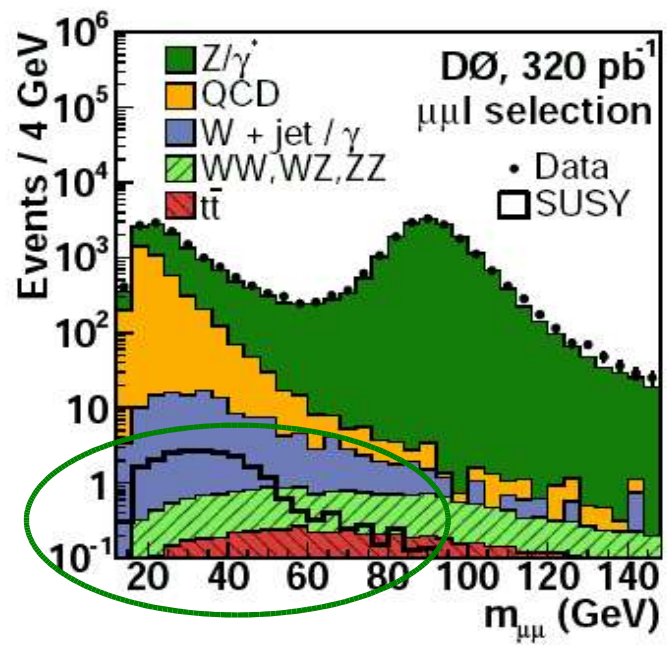


	low $m(\tilde{b})$	medium $m(\tilde{b})$	high $m(\tilde{b})$
SM expect.	38.6 ± 2.8	19.6 ± 1.7	4.4 ± 0.4
Data	36	15	2

Charginos/Neutralinos

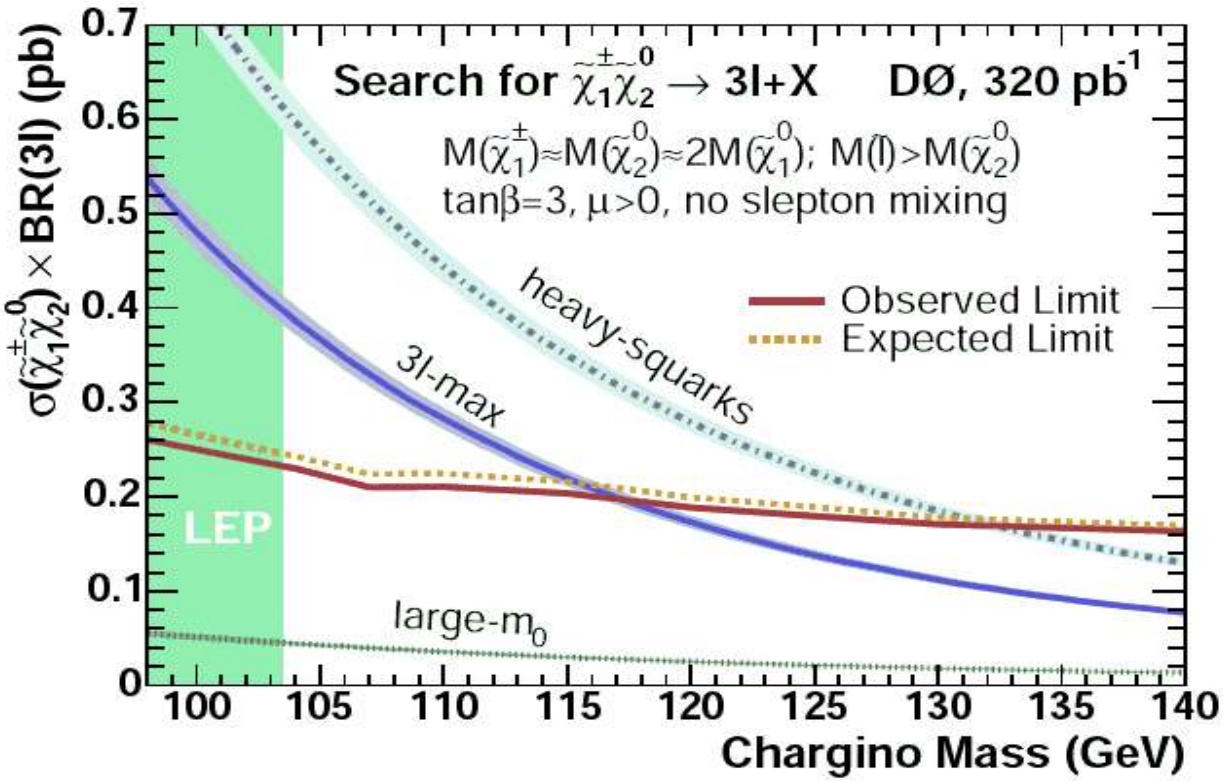
- **Golden channel**: leptonic cascade decays → **three leptons + missing E_T**
- **But:** small event rates (σ x BR < 0.5pb), and leptons with low transverse momenta
- Six dedicated selections, $\int L\,dt \simeq 320\ pb^{-1}$
  - ee + track, eμ + track, $\mu\mu$ + track, $\mu^{\pm}\mu^{\pm}$
  - eτ + track, $\mu\tau$ + track
- Backgrounds
  - Multijets with "fake" leptons
  - Drell-Yan, Z-production with Z → ll
  - WW, WZ, Wγ
- Main selection cuts
  - Three leptons (ll + track), p_T > 11 / 5-8 / 3-7 GeV (depending on channel)
  - Missing transverse energy
  - Veto events with Z → ll decays





Charginos/Neutralinos: Combined

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
Combined	2.93±0.79	3	5.5±0.3



"3l-max": maximize leptonic BR (m(slepton) ≃ m(χ_2^0) → sfermion decays dominate)

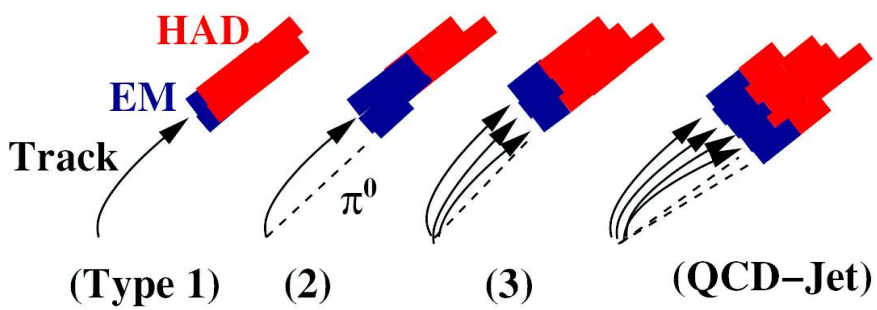
"Large m_0": Decays via W*/Z* dominate → leptonic BR small

"Heavy squarks" (relaxing mass unification): enhanced cross section

Sensitivity for mSUGRA beyond LEP limits, significant improvement on Run I limits

Exclude Chargino masses below 117 (132) GeV in "3l-max" (heavy squarks) scenario

Charginos/Neutralinos: τ



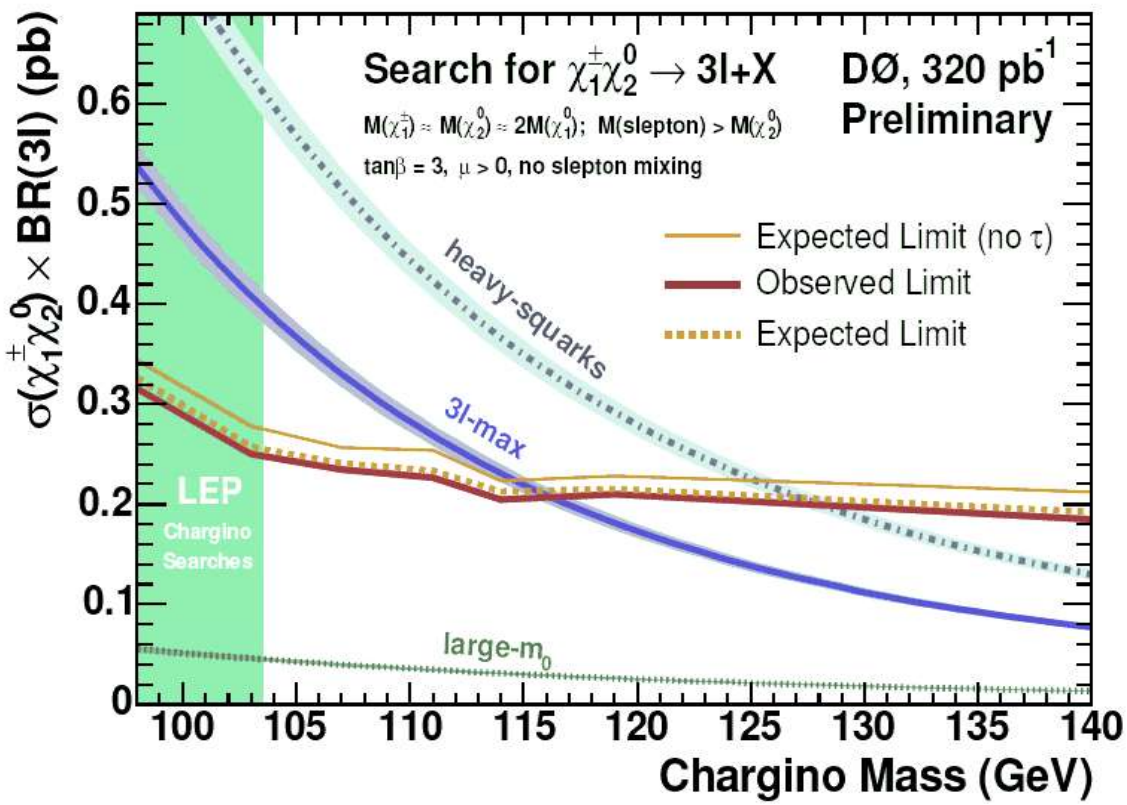
Selection	Expected Background	Observed	Signal ($m_{\tilde{\chi}^\pm}$=110 GeV)
$ee\ell$	0.21±0.12	0	1.9±0.2
$e\mu\ell$	0.31±0.13	0	1.6±0.1
$\mu\mu\ell$	1.75±0.57	2	1.3±0.2
ls-$\mu\mu$	0.66±0.37	1	0.7±0.1
$e\tau\ell$	0.58±0.14	0	0.4±0.1
$\mu\tau\ell$	0.36±0.13	1	0.7±0.1
Combined	3.87±0.81	4	6.6±0.3

SUSY with light stau (large tan β) → **multiple tau leptons in final state**

Reconstruct tau as 1 or 3 tracks pointing to a narrow energy deposition in the calorimeter

Use a set of neural networks to separate tau decays from jets

Interpretation of results in models with light stau in progress



R-parity Violating SUSY

$$\text{R-parity: } R_P = (-1)^{3B+L+2S}$$

S is the particle spin,
B is the baryon number,
L is the lepton number

Most general Superpotential:

$$W = W_{MSSM} + W_{R_P}$$

$$W_{R_P} = \frac{1}{2}\lambda_{ijk}\varepsilon_{ab} L_i^a L_j^b E_k^c + \lambda'_{ijk}\varepsilon_{ab} L_i^a Q_j^b D_k^c + \lambda''_{ijk}\varepsilon_{xyz} U_i^{cx} D_j^{cy} D_k^{cz} + \kappa_i \varepsilon_{ab} L_i^a H_2^b$$

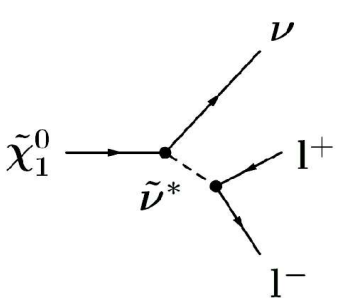
i,j,k = 1,2,3 generation indices

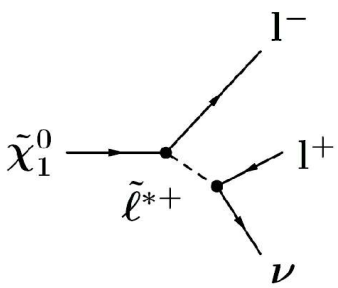
L: lepton doublet superfield
E: lepton singlet superfield
Q: quark doublet superfield
D: down-like quark singlet superfield

Couplings are constrained by searches for L- and B- violation

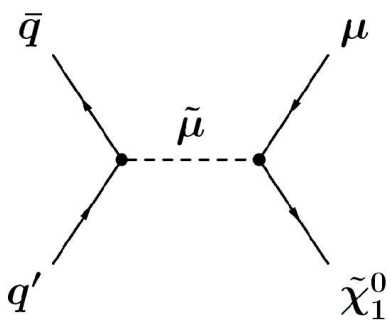
R_P violated in decay
multilepton final state

Resonant production
two muon and two jets final state





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

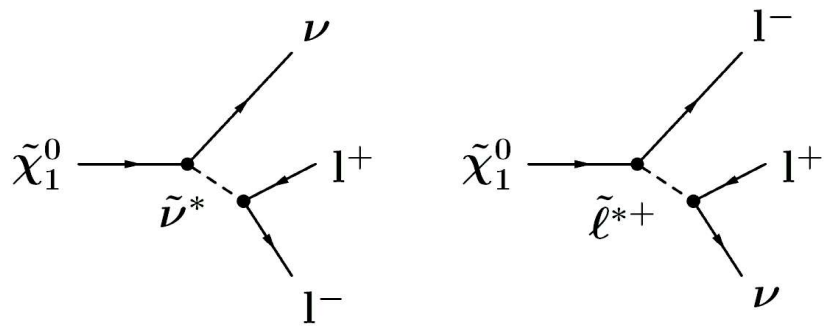


(For non-zero $L_i Q_j \bar{D}_k$-coupling)

Charginos/Neutralinos: RPV

- Associated production of Charginos/Neutralinos, decay via LLE couplings λ_{ijk} into 2 charged leptons and 1 neutrino
  - More than one possible final state for each coupling
  - Small missing E_T (neutrinos)

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



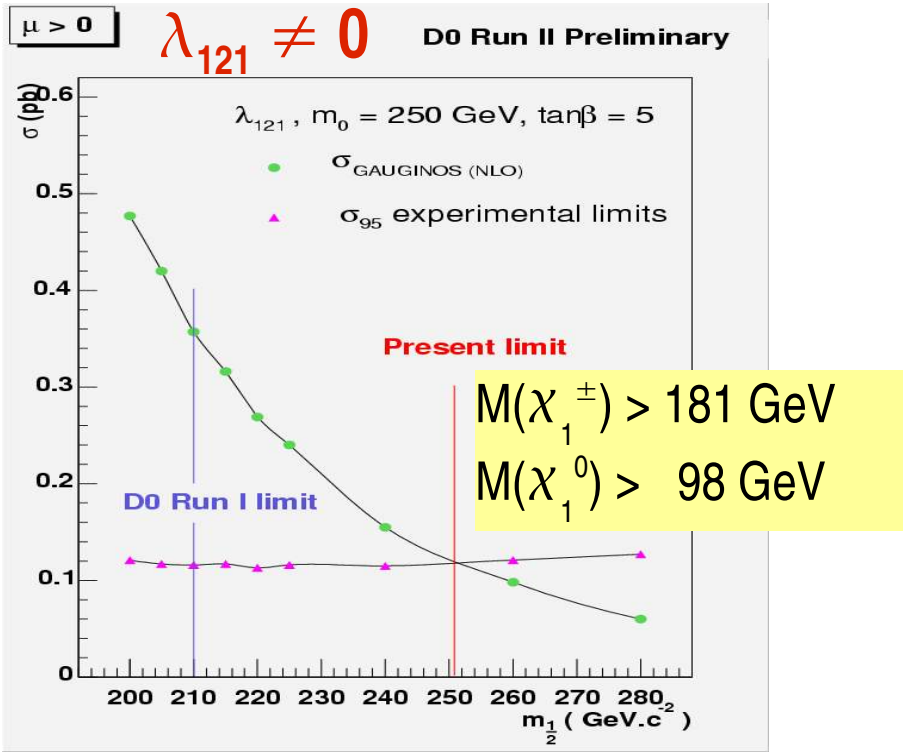
(For non-zero $L_iL_j\bar{E}_k$-coupling)

- Analyzed up to 240 pb^{-1} with 5 dedicated selections
  - 3 (of 4) isolated leptons
  - Very low p_T requirement on 3rd lepton (down to 3 GeV)
  - Loose $\not{E}_T$ cuts
  - SM Backgrounds dominated by Drell-Yan with "fake" 3rd lepton, and diboson production
- No excess over SM expectation, limits set in several reference scenarios for non-zero couplings λ_{121}, λ_{122}, and λ_{133}

Selection	Background	Observed
$\mu\mu\mu$, $e\mu\mu$	0.6 ± 1.4	2
$ee\mu$, eee	0.5 ± 0.4	0
$ee\tau$	1.0 ± 1.4	0

Charginos/Neutralinos: RPV

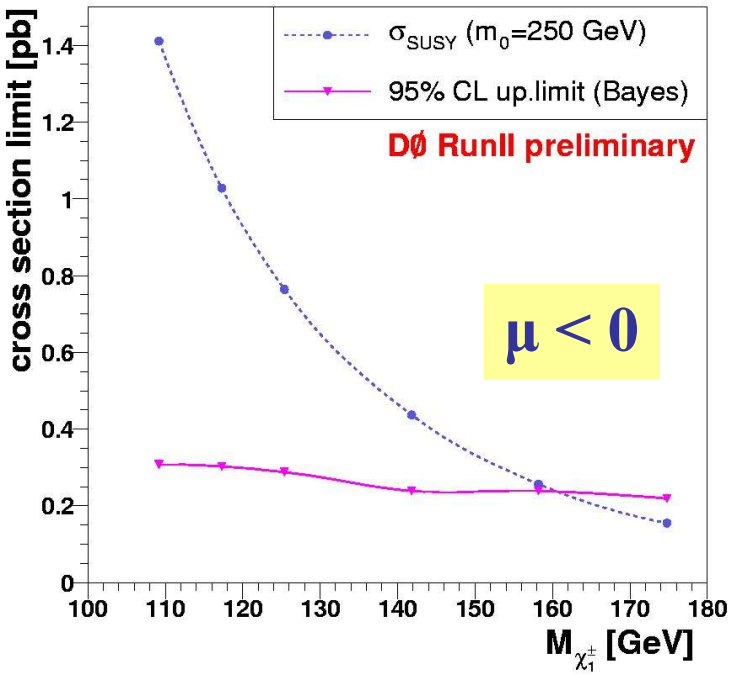
$\lambda_{121} \neq 0$

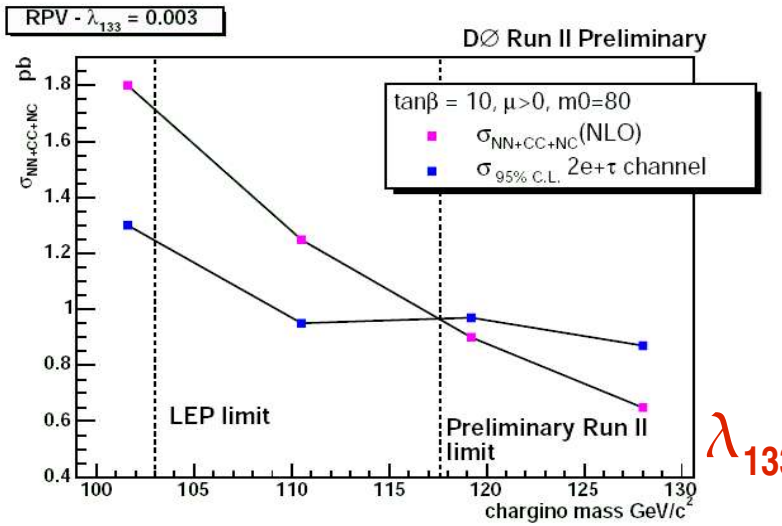


$M(\chi_1^{\pm}) > 181$ GeV

$M(\chi_1^{0}) > 98$ GeV

$\lambda_{122} \neq 0$



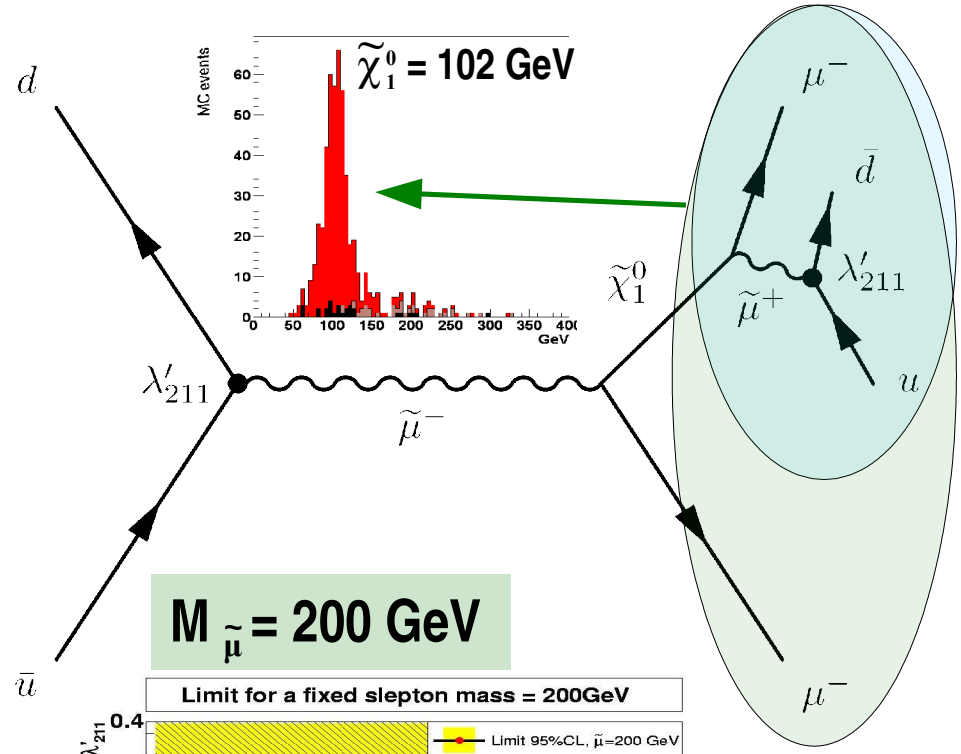


$\lambda_{133} \neq 0$

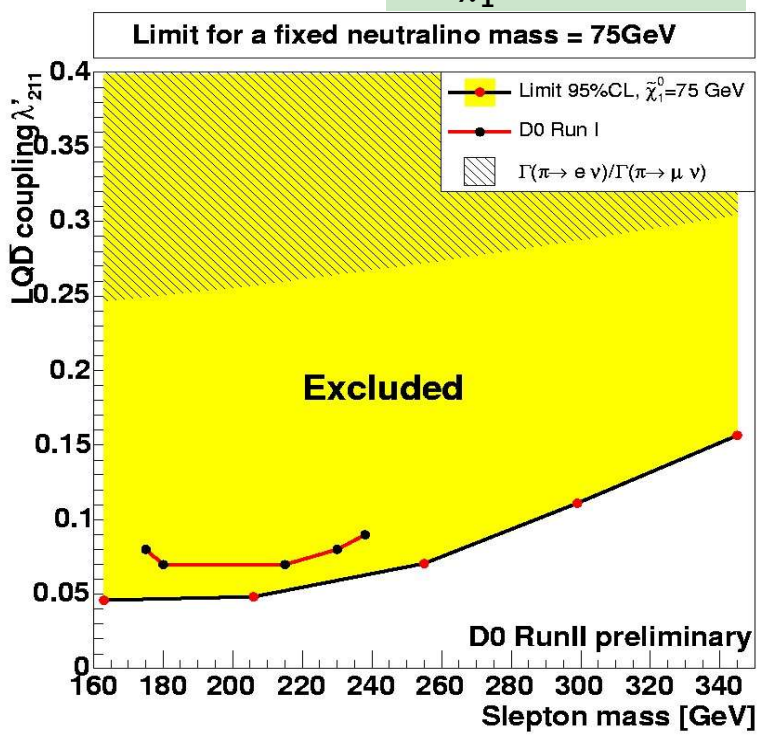
Expect update with more data and combination of channels

RPV: LQD Coupling λ'_{211}

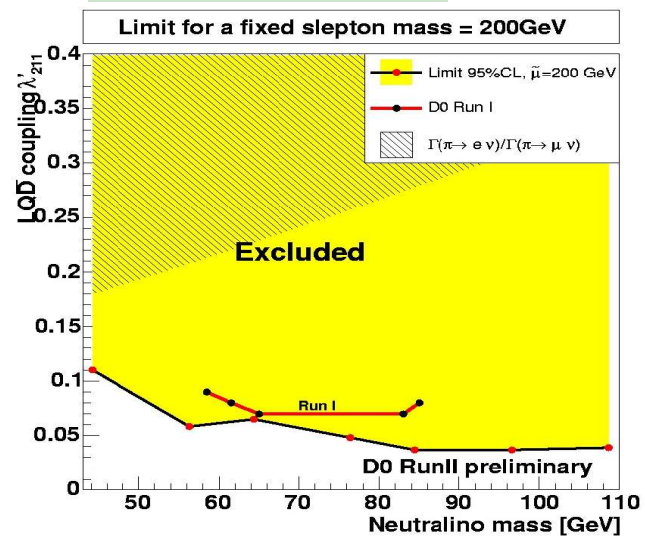
- Result shown here based on $\int L\,dt = 154\ pb^{-1}$
- 2 jets above ~20 GeV, 2 isolated muons above ~20 GeV (depending on point under study)
- Reconstruct **Neutralino** and **smuon** candidate invariant mass



$M_{\tilde{\chi}^0_1}$ = 75 GeV



$M_{\tilde{\mu}}$ = 200 GeV



Working on update with more data and extended selection, SUSY parameter scan

Gauge Mediated SUSY Breaking

Gauge Mediated SUSY breaking: Gravitino $\tilde{G}$ is LSP

Assuming Neutralino NLSP: $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$

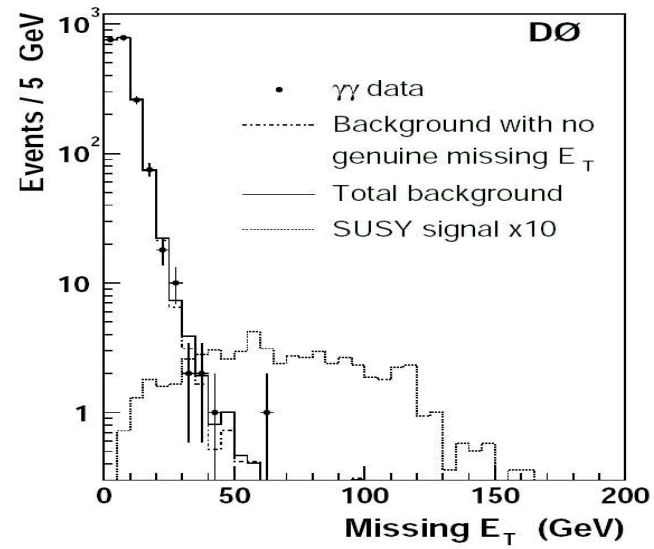
→ Chargino/Neutralino production leads to final states containing $\gamma\gamma + \not{E}_T$

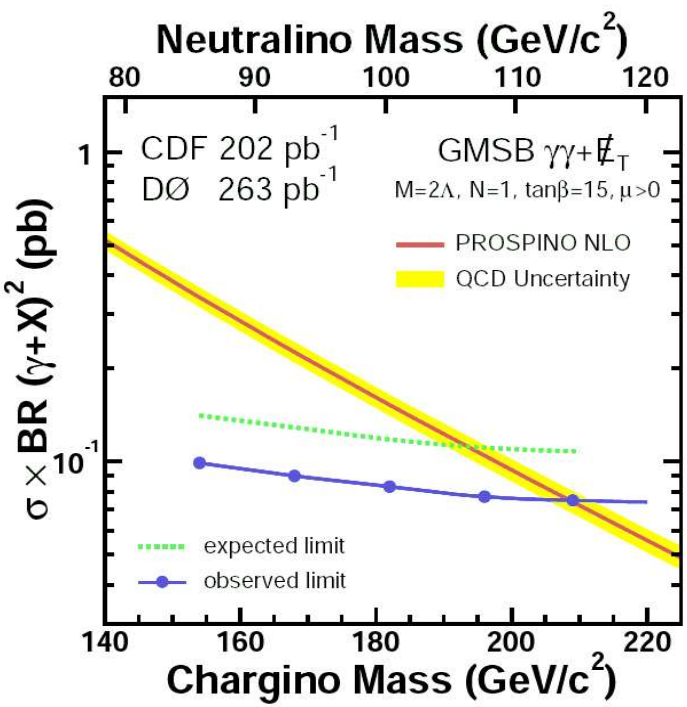
→ Inclusive search for 2 photons plus $\not{E}_T$ ($\int L\, dt = 263\ pb^{-1}$)

Selection: Two central photons with $E_T > 20$ GeV

Optimized cut $\not{E}_T > 40$ GeV

Observe 2 events, expect 3.7 ± 0.6 events from "fakes"





Mass limits on Chargino and Neutralino (N_5=1, M_m=2, tanβ=15, μ>0):

$m(\tilde{\chi}_1^0) > 108$ GeV $\quad m(\tilde{\chi}^{\pm}) > 195$ GeV

Combine with CDF result (202 pb^{-1}):

$m(\tilde{\chi}_1^0) > 93$ GeV $\quad m(\tilde{\chi}^{\pm}) > 168$ GeV

First combined Run II result (TEVNPWG):

$m(\tilde{\chi}_1^0) > 114$ GeV $\quad m(\tilde{\chi}^{\pm}) > 209$ GeV

Charged Massive Stable Particles

Benchmark model: **pair production of stable staus** (gauge-mediated SUSY, stau as NLSP, model line "D" from Snowmass 2001)

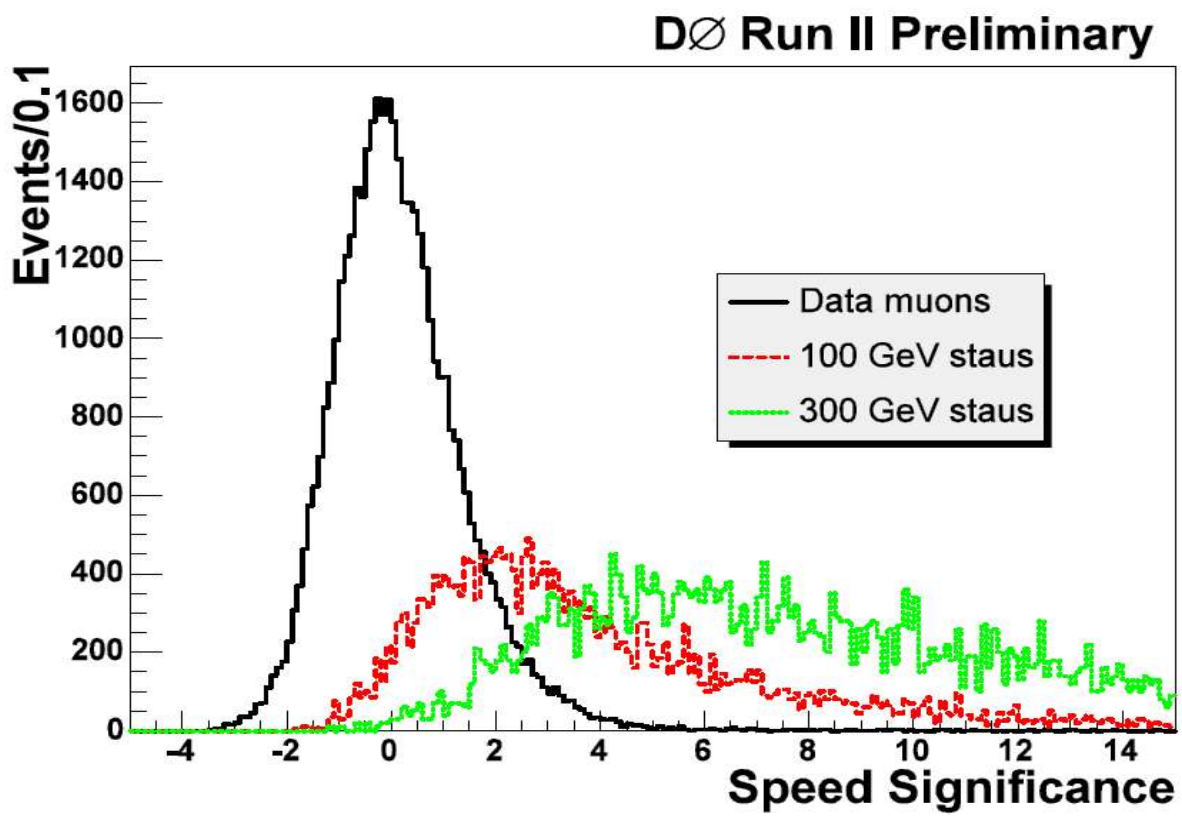
Massive stable particles can occur in many models

Stable = lifetime long enough to escape the detector

Would look like a **muon, but with inconsistent speed and mass**

Selection:
- Dimuon data set
- Timing in muon system to discriminate slow moving particles
- Kinematic cuts against $Z \rightarrow \mu\mu$ with poorly measured timing

Energy loss not (yet) used



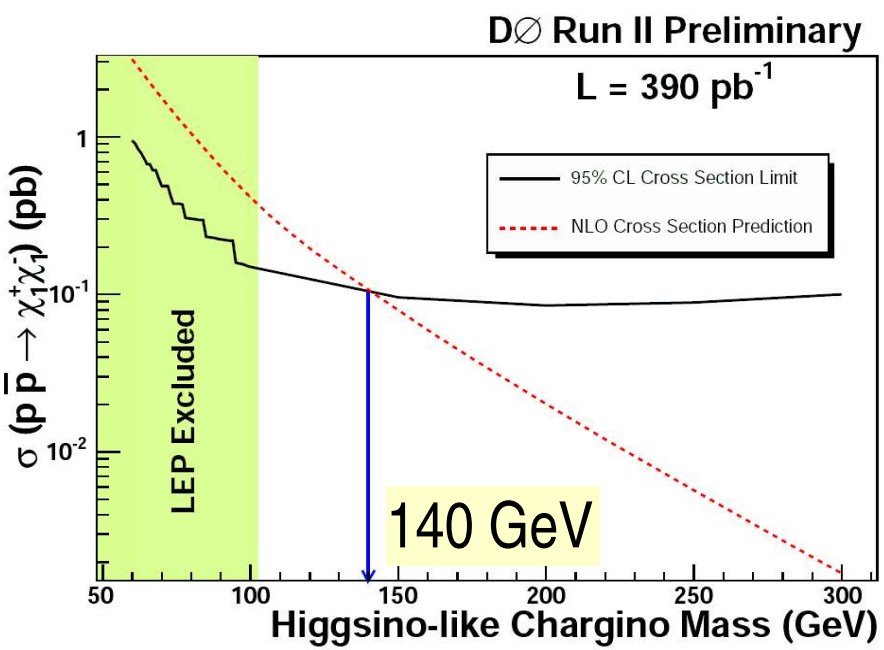
$$\text{speed significance} = \frac{1 - \text{speed}}{\sigma_{\text{speed}}}$$

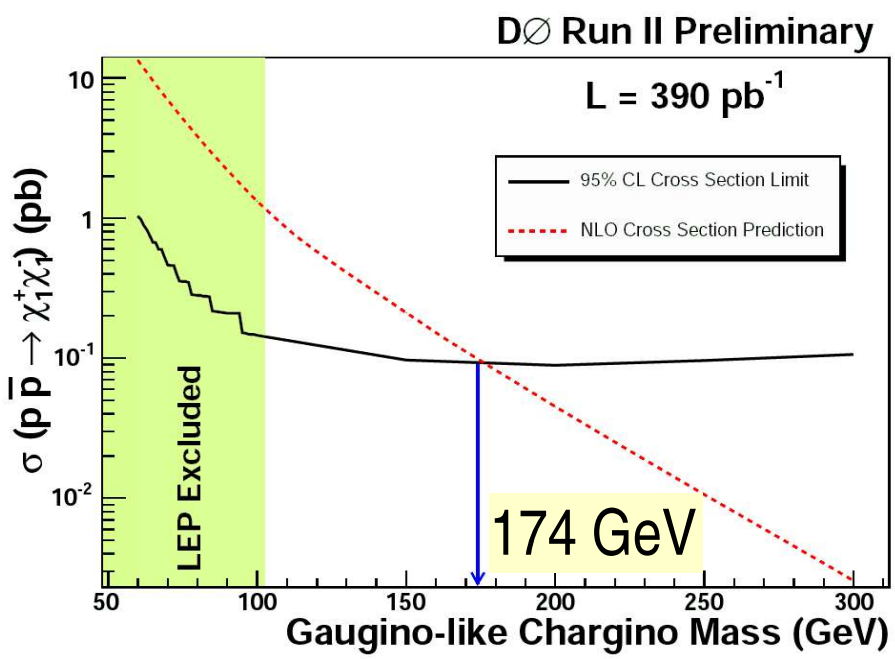
AMSB Interpretation

After all cuts, find **no events in $\int L\,dt = 390\ pb^{-1}$ with 0.66 ± 0.06 expected background**

Limit on stable stau production does not yet constrain models

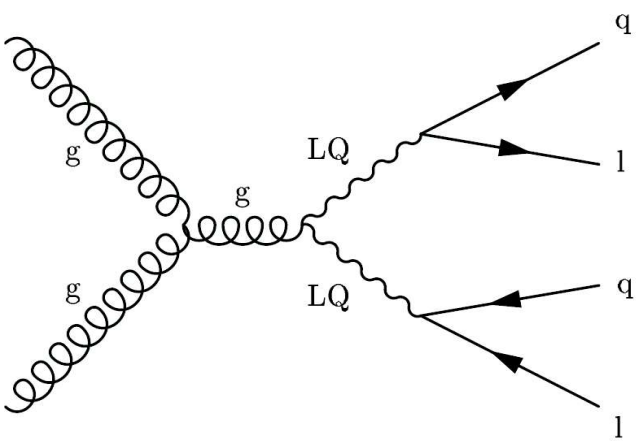
<u>Another interpretation:</u>
The lightest Chargino can live long enough to escape the detector if the mass difference to the lightest neutralino is below ~ 150 MeV, e.g. in Anomaly-Mediated Supersymmetry Breaking





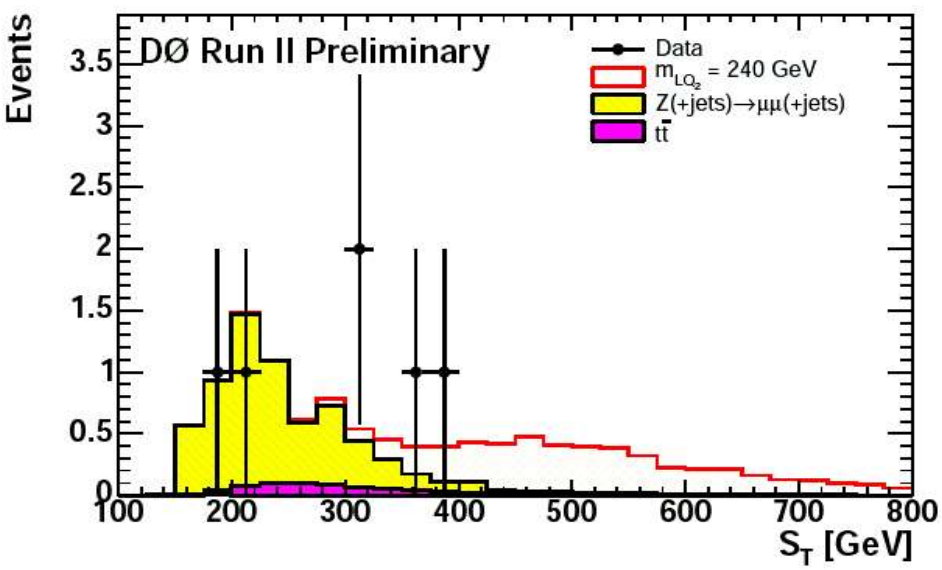
2nd Generation Leptoquarks

Leptoquark:
- Boson with third-integer charge, carrying lepton and quark quantum numbers
- 3 generations, each coupling to one fermion generation only (lepton number violation, FCNC)



This analysis: **2nd generation** (1st generation published)

- Pair production → μj + μj channel
- $\int L\,dt = 294\ pb^{-1}$, single- and dimuon triggers
- 2 muons with $p_T > 15$ GeV, 2 jets with $p_T > 25$ GeV
- Z Veto $m(\mu\mu) > 105$ GeV
- Refit exploiting expectation of no $\not{E}_T$

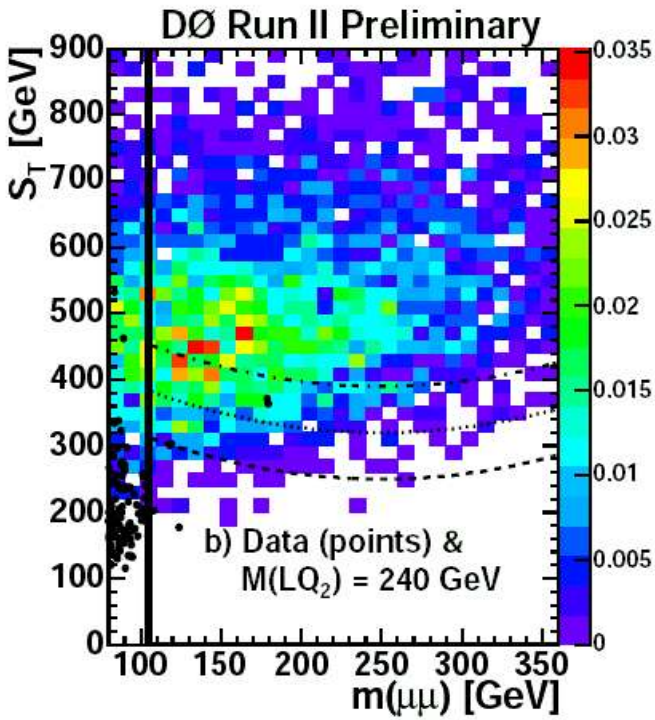


Observe 6 events, expect 6.8 ± 2.0 (dominated by DY/Z + jets)

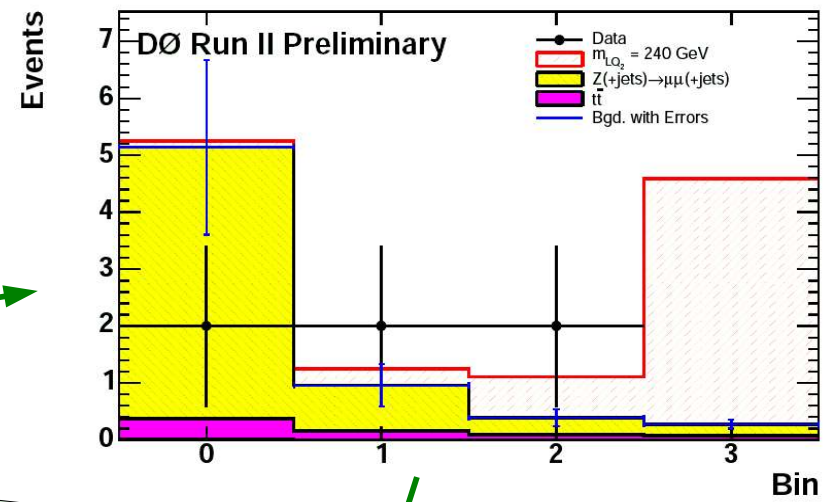
$S_T = \sum E_T$ of μj + μj system

New result

2nd Generation Leptoquarks

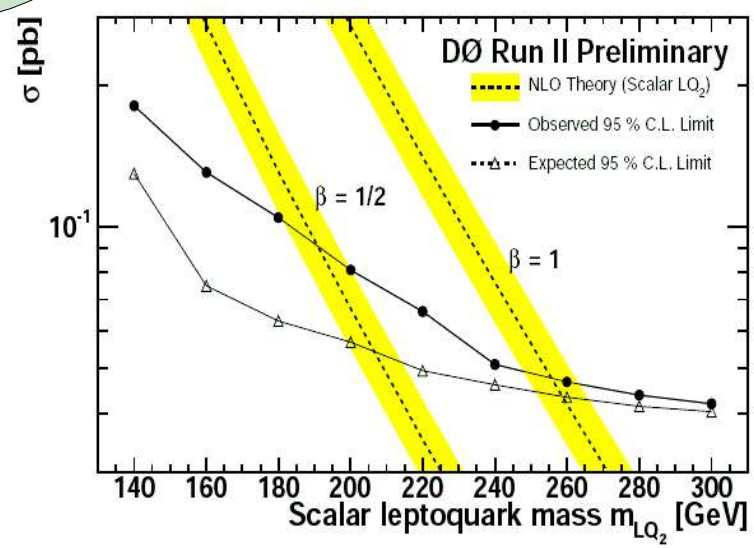


4 bins with different S/B ratio



Combine 4 bins

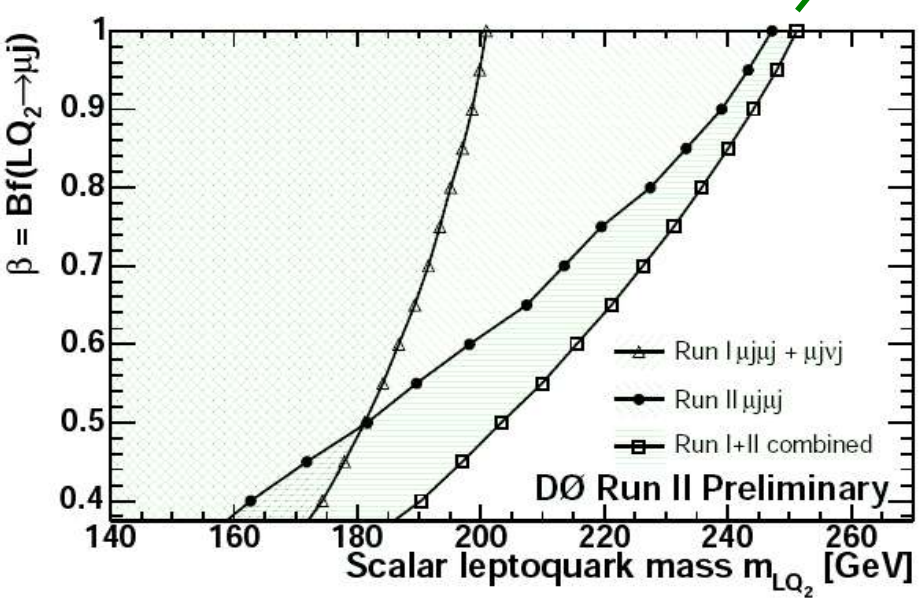
m(LQ$_2$) > 251 GeV (β=1)



m(LQ$_2$) > 247 GeV (β=1)

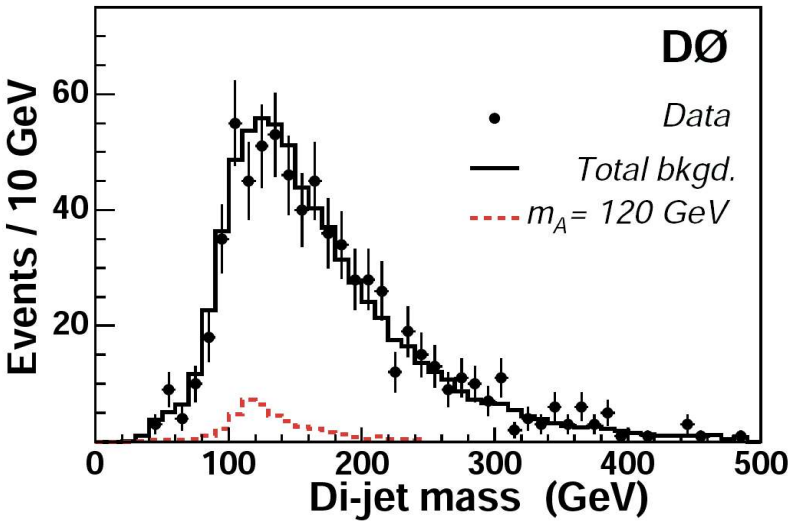
Limits for scalar LQ depend on mass and BR only

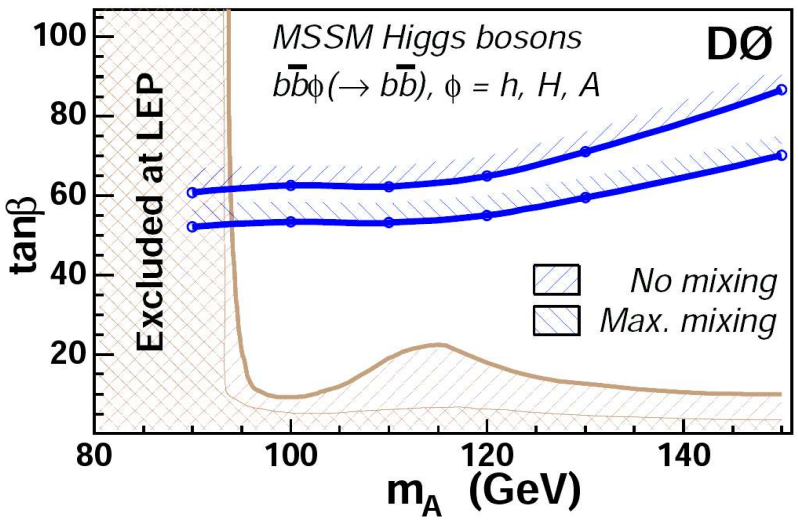
Combine with Run I (includes μj + νj)



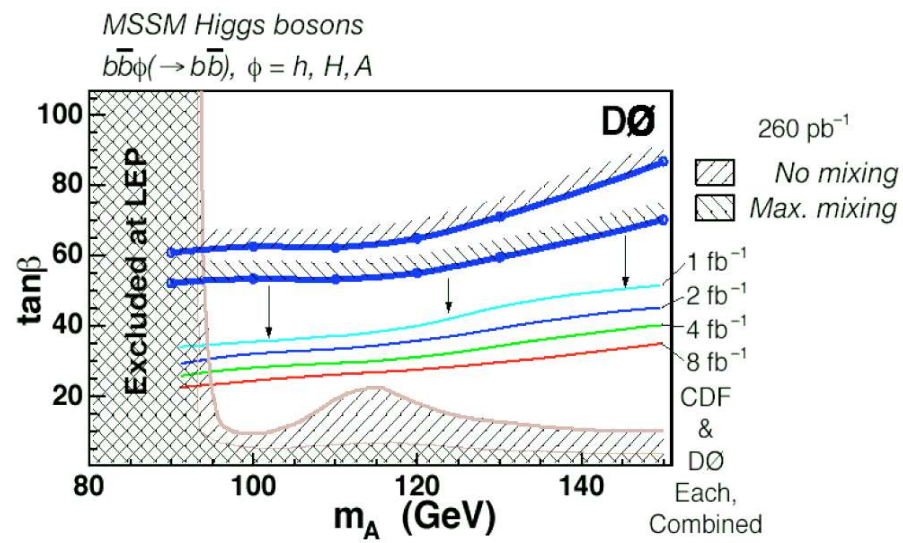
SUSY Higgs: $hb(\bar{b}) \rightarrow b\bar{b}b(\bar{b})$

- In MSSM, 5 Higgs bosons: neutral A, h, H, charged $H^{\pm}$
- $hb\bar{b}$ coupling enhanced at large tan β → large cross section for hbb production (at tree level, ~ tan $^2\beta$)
- Selection requires at least 3 b-tagged jets
- Backgrounds: multijet production, modelled using data
- Reconstruct Higgs boson mass in bbbar spectrum





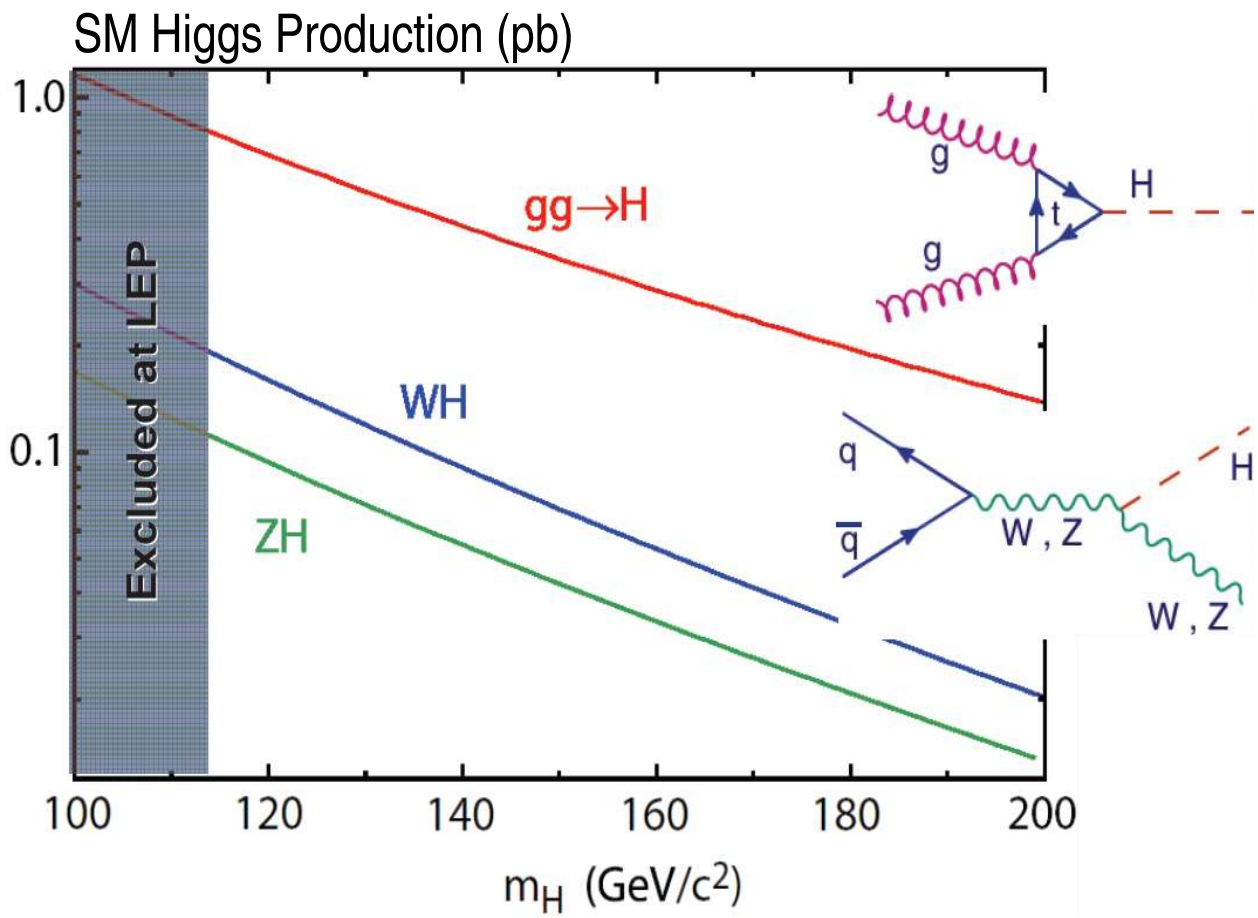
- No hint for a signal in 260 pb^{-1}
- Significantly improved limits on tan β as a function of m_A



Reminder:

- SUSY predicts at least one Higgs boson with m < 135 GeV
- Combination of different analyses should allow a test at 95% CL with 5 fb^{-1} (mhmax scenario)

(SM) Higgs Overview



Experimental challenges: the full program!

(Lepton ID, missing E_T, b-tagging, bbbar mass resolution, angular correlations for WW, ...)

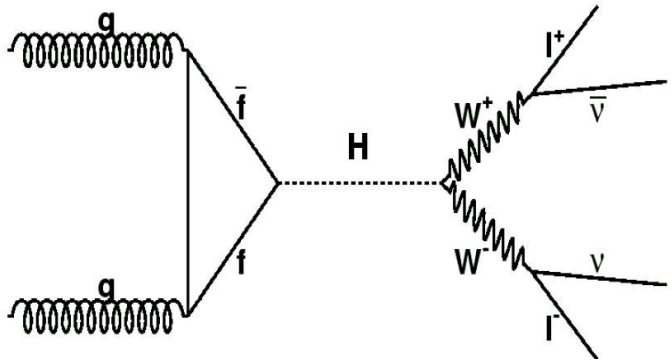
Sensitivity for SM Higgs above LEP limit (m_H > 114.4 GeV) requires > 2 fb^{-1} (per experiment)

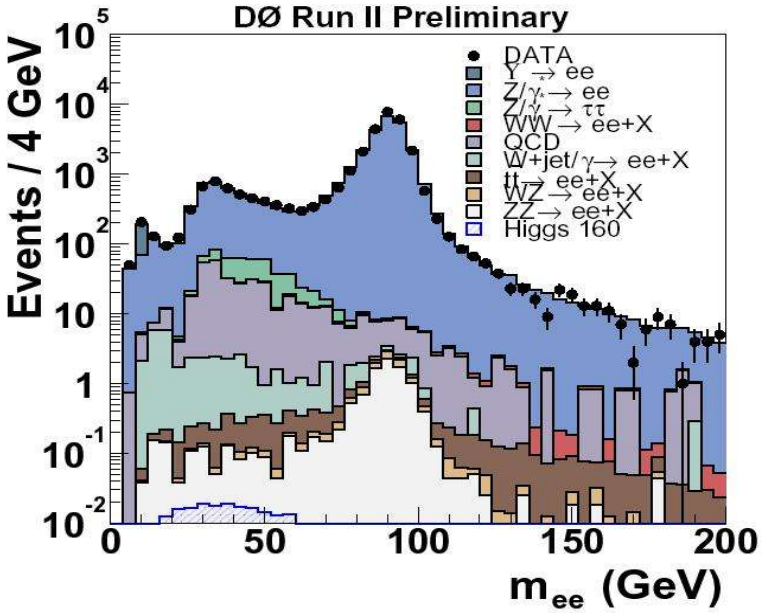
SM Higgs Decay:

< 135 GeV H → bb dominant
> 135 GeV H → WW

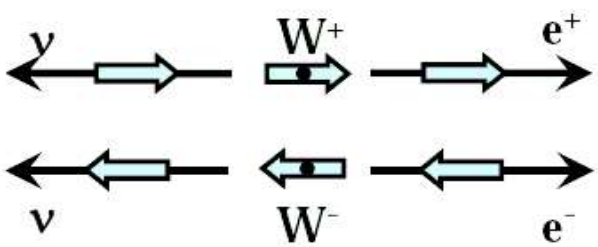
- **H → WW(*)**
- **WH → lν bb**
- **ZH → νν bb**
- **bbh → bbbb**
- H → γγ
- ZH → llbb
- Higgs searches with taus
- W/Z + jets
- Z → bb
- H^{++}, H^{--}

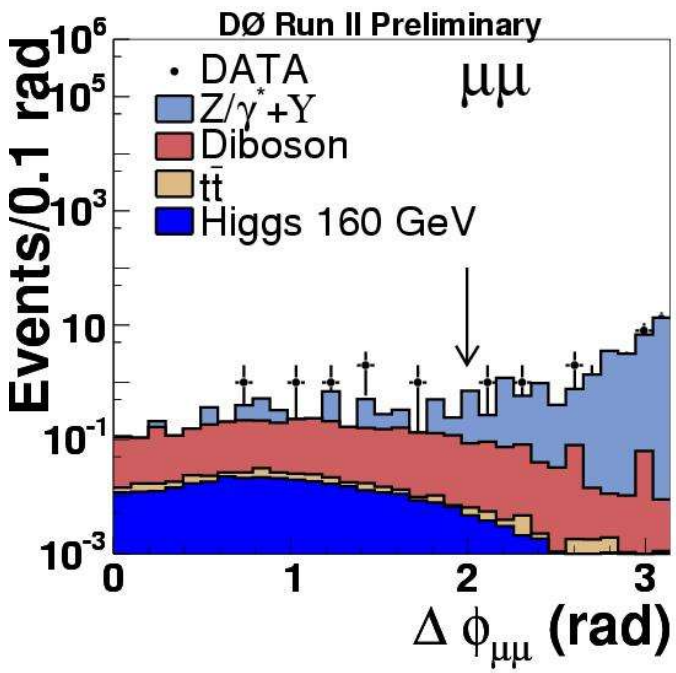
gg → H, H → WW(*)





- Use $\int L\,dt$ = 299 – 325 pb^{-1} of dilepton data:
  2 high p_T isolated leptons with opp. charge: ee, $\mu\mu$, eμ,
  $\not{E}_T$ > 20 GeV
- Additional kinematic cuts to suppress physics backgrounds, depending on Higgs mass
- Exploit spin correlation in decay



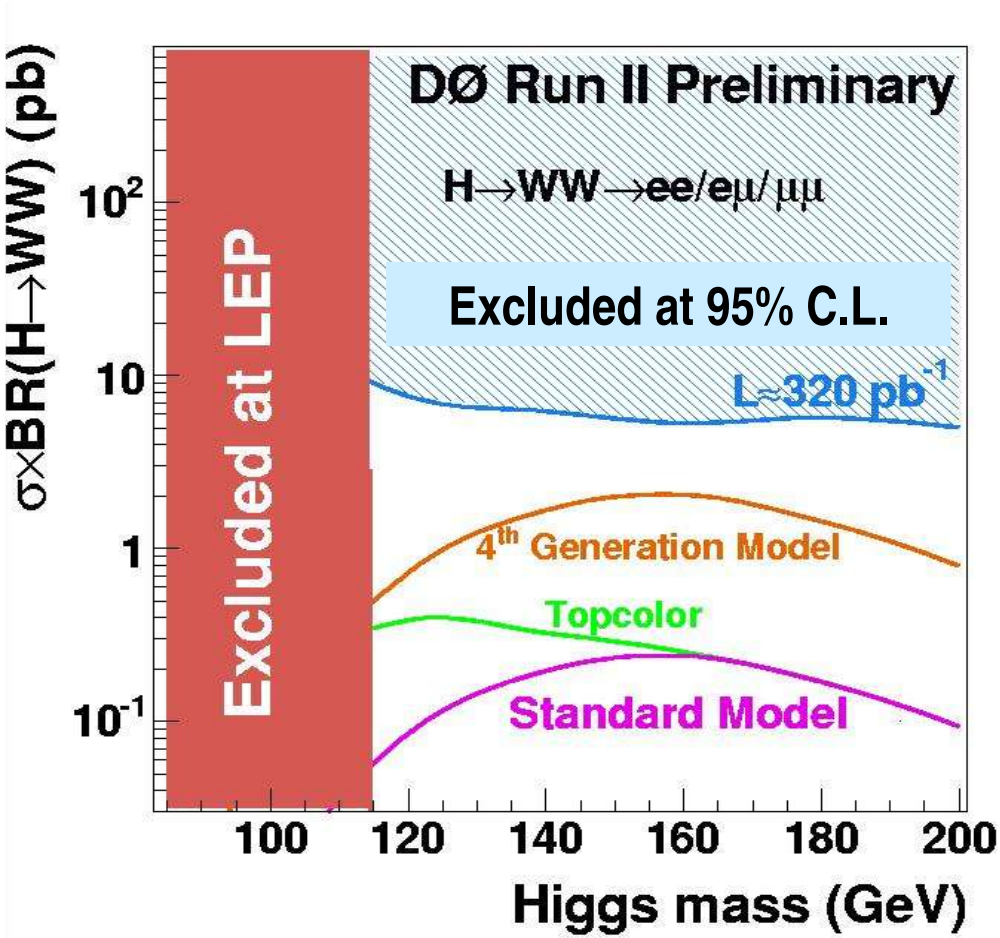


- Remaining backgrounds dominated by Z/DY, Diboson production, and W+jet/photon

gg → H, H → WW(*)

Example: expected and observed number of events for m_H = 160 GeV

Diboson	W+jet/γ	Z/γ*	tt+multijet	Total	Data
11.7±0.2	2.1±0.7	3.3±0.7	0.64±0.1	**17.6±1.0**	**20**

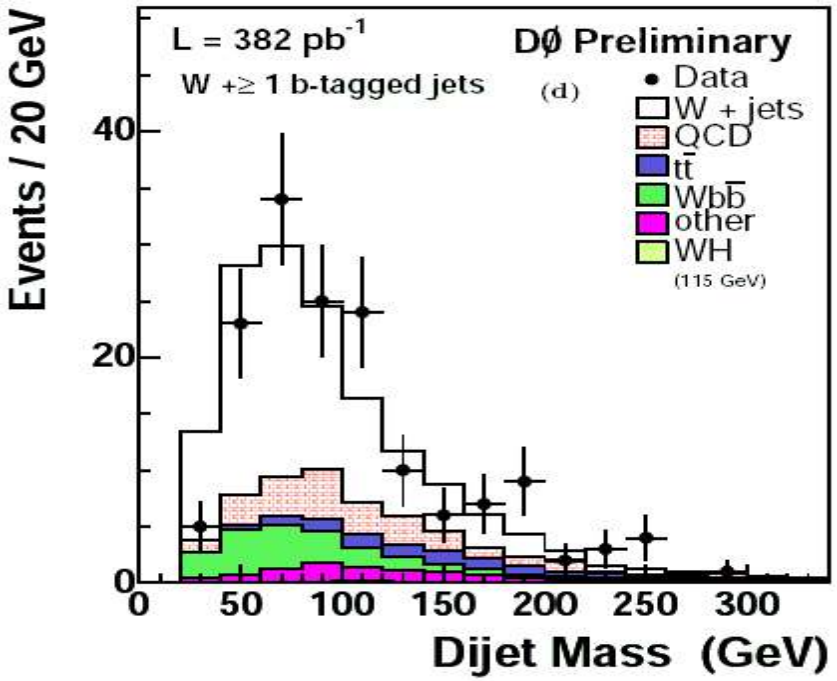


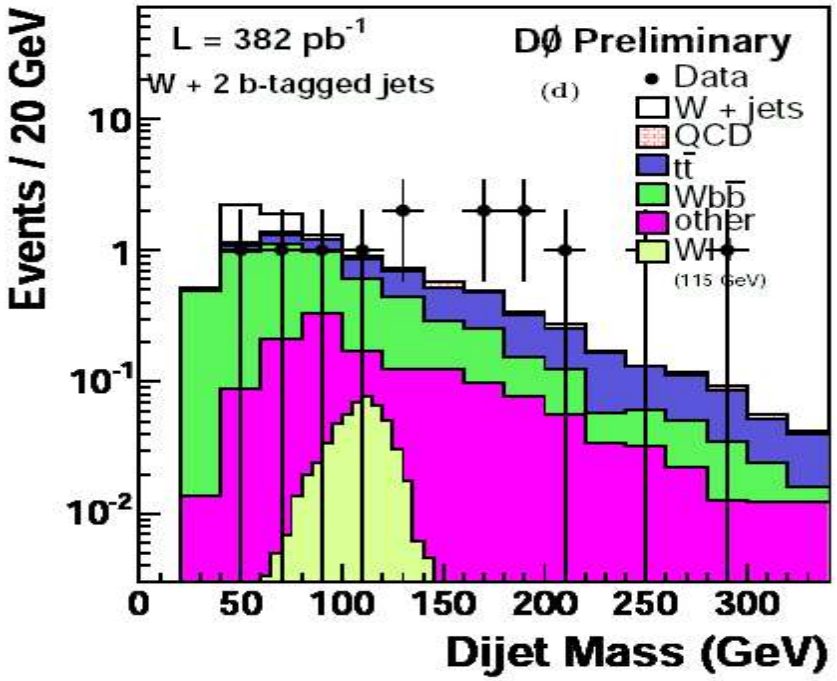
Associated Production: WH
$W \to e\,\nu$, $H \to bb$

The benchmark channel

Update with more data

Selection: Isolated central e p_T > 20 GeV, $\not{E}_T$ > 25 GeV, 2 jets > 20 GeV – then add b-tags



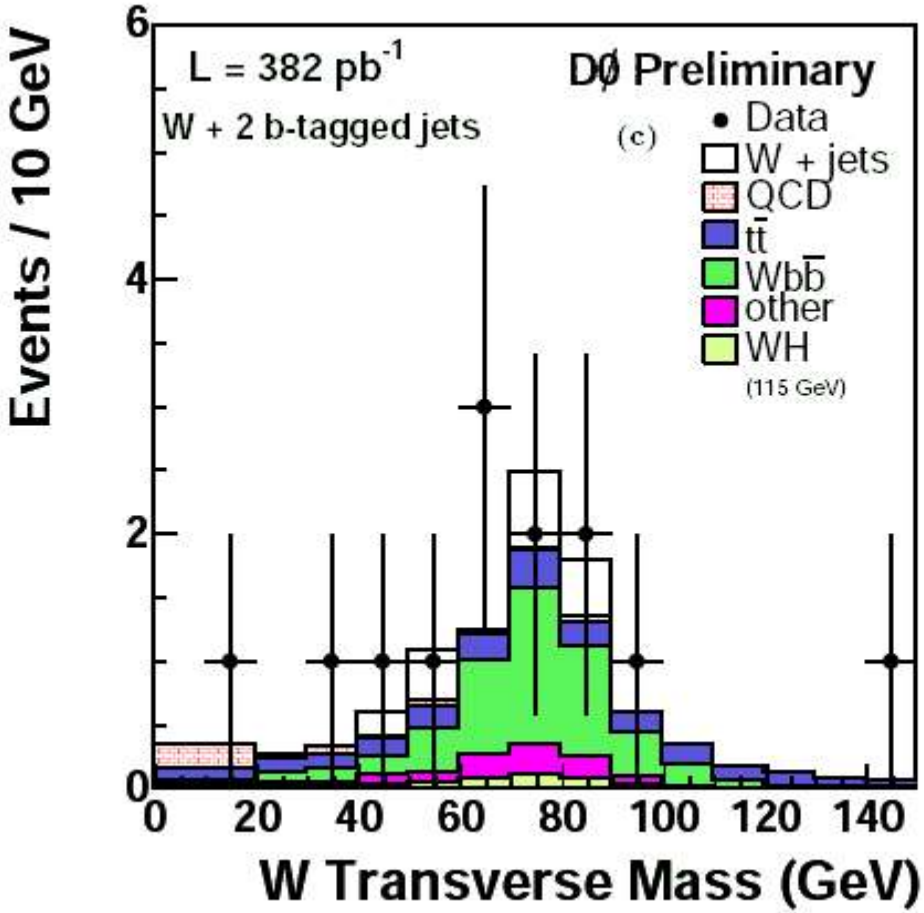


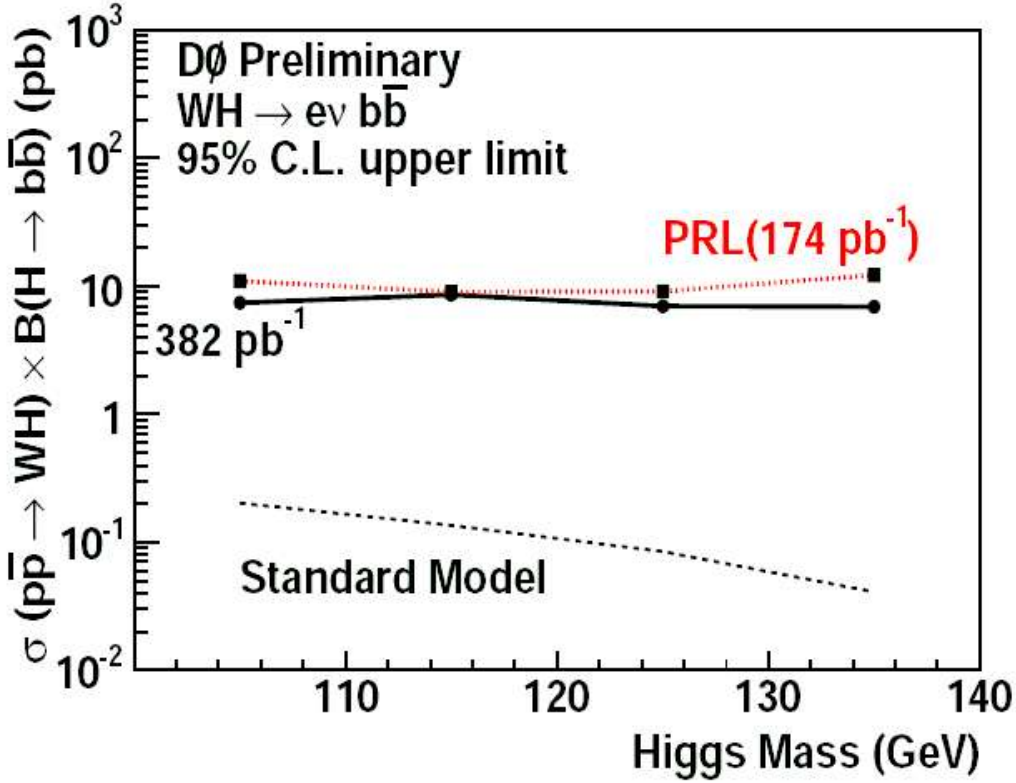
Expect	18.1	± 4.3	Wbb	Expect	4.29	± 1.03	Wbb
	0.4	± 0.1	WH		0.14	± 0.03	WH
	154	± 37	Background		5.73	± 1.45	Background
Observe	172 events			Observe	13 events		

Mostly Z/W + jets

Mostly ttbar, Z/W + jets, single top

Associated Production: WH
$W \to e\,\nu$, $H \to bb$





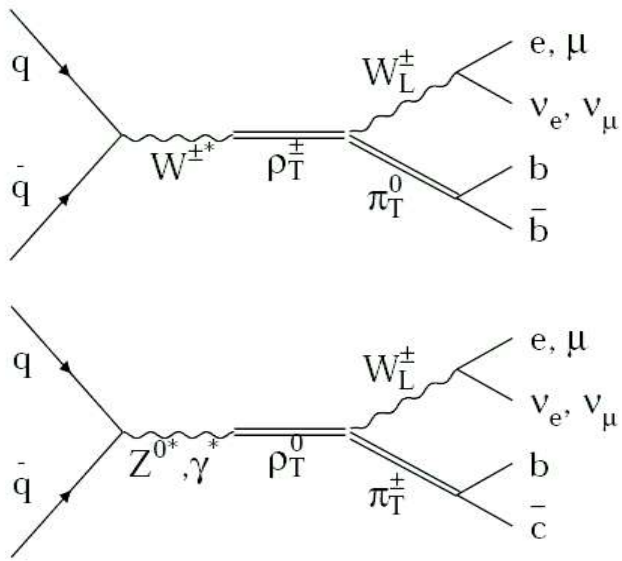
Prospects:

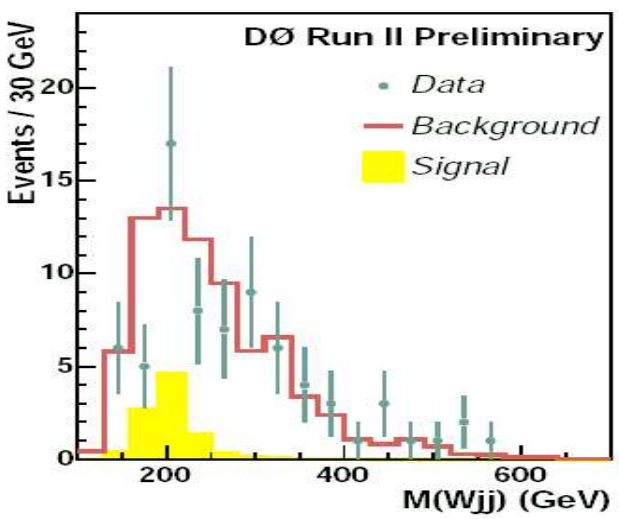
expect gain in sensitivity with **looser and improved b-tagging**
Also gains from jet energy scale, tau channel, multivariate analysis techniques
Muon channel being finalized

Limits clearly above SM expectation
Nevertheless, becoming interesting for other models with similar signatures

$\rho_T \to W(\to e\nu) + \pi_T$

$\rho_T \to W(\to e\nu) + \pi_T(\to bQ)$





Selection:

central electron $p_T > 15$ GeV

missing $E_T > 20$ GeV

$m_T(e, E_T) > 30$ GeV

2 jets, $p_T > 20$ GeV, ≥ 1 b-tagged

Additional selection: $\Delta\phi$(jj), m(jj), m(Wjj)

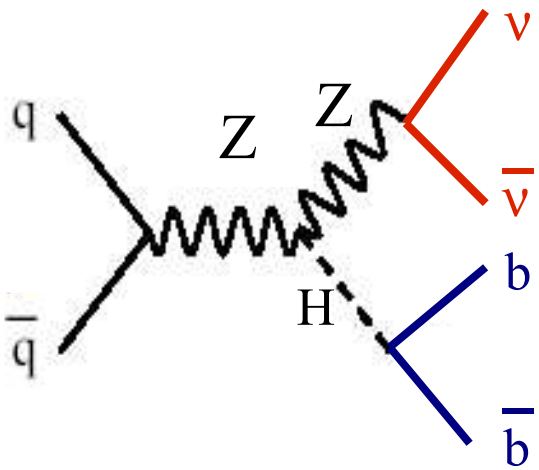
Expect 6.6 ± 1.7

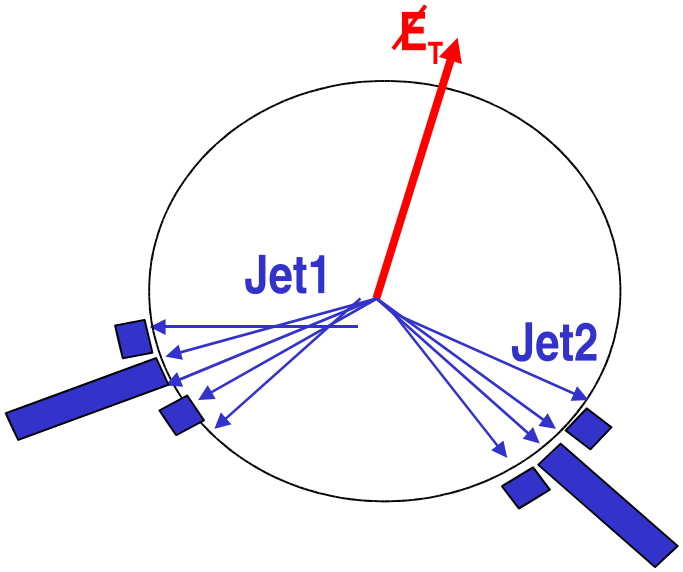
Observe 4 events in $\int L\,dt = 238\ pb^{-1}$

$m(\rho_T) = 200$ GeV, $m(\pi_T) = 105$ GeV

$\to \sigma < 6.4$ pb (95% CL)

Associated Production: ZH
$Z \to \nu\nu$, $H \to bb$





$\int L\,dt = 261\ pb^{-1}$

Large missing $E_T > 25$ GeV

2 acoplanar (b-)jets with $E_T > 20$ GeV

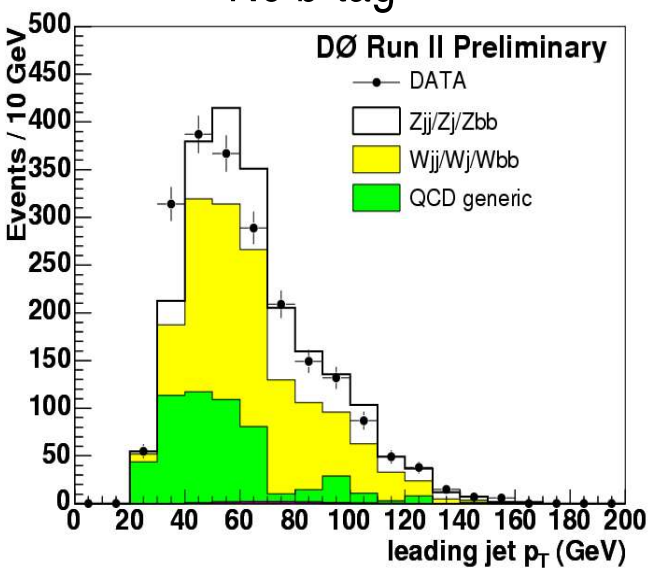
Form various asymmetries to reduce backgrounds

Expected background

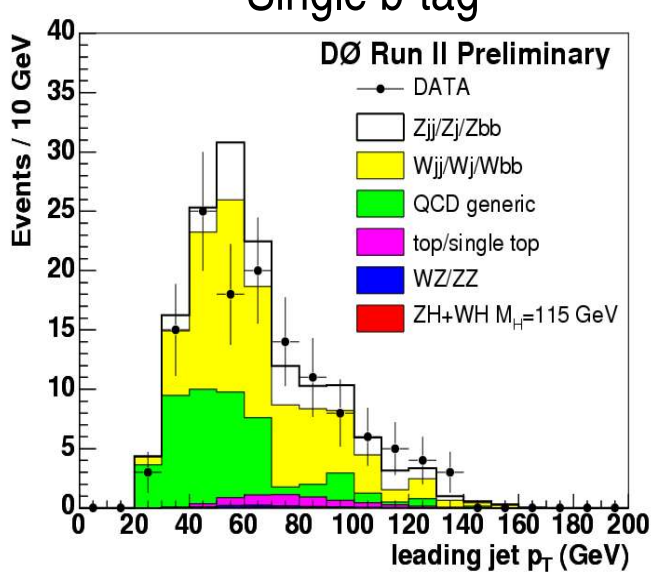
6.4 ± 2.1 events

Observe 9 events

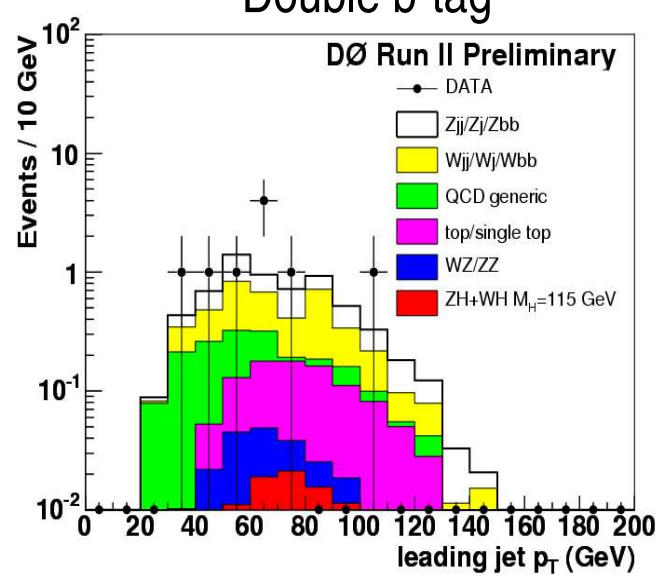
No b-tag



Single b-tag



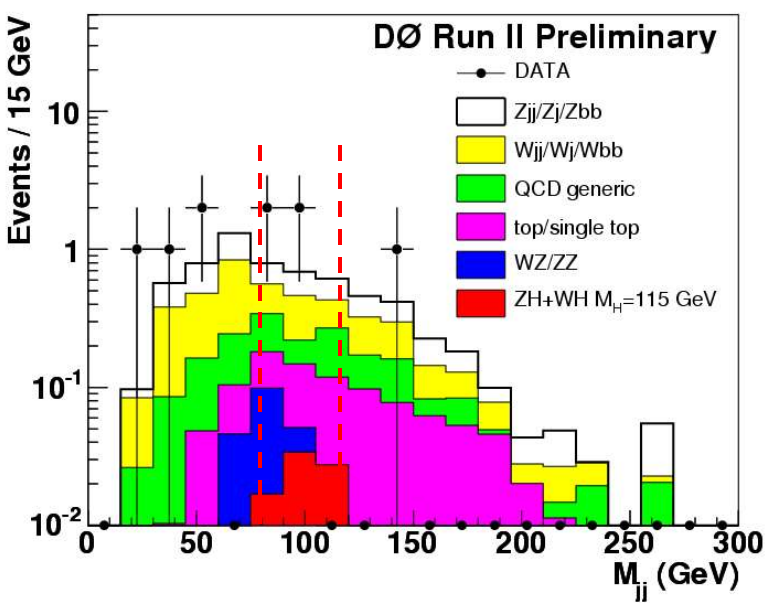
Double b-tag

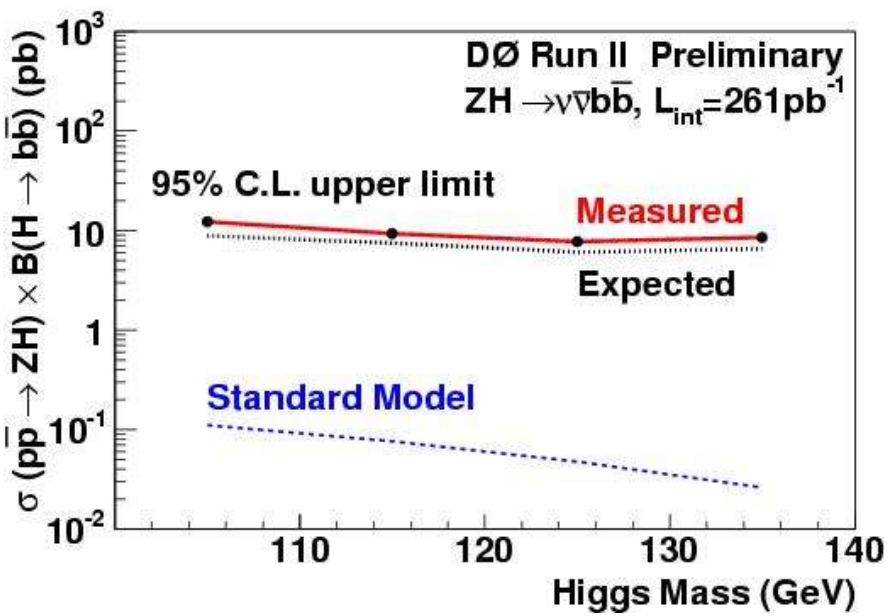


Associated Production: ZH
$Z \to \nu\nu$, $H \to bb$

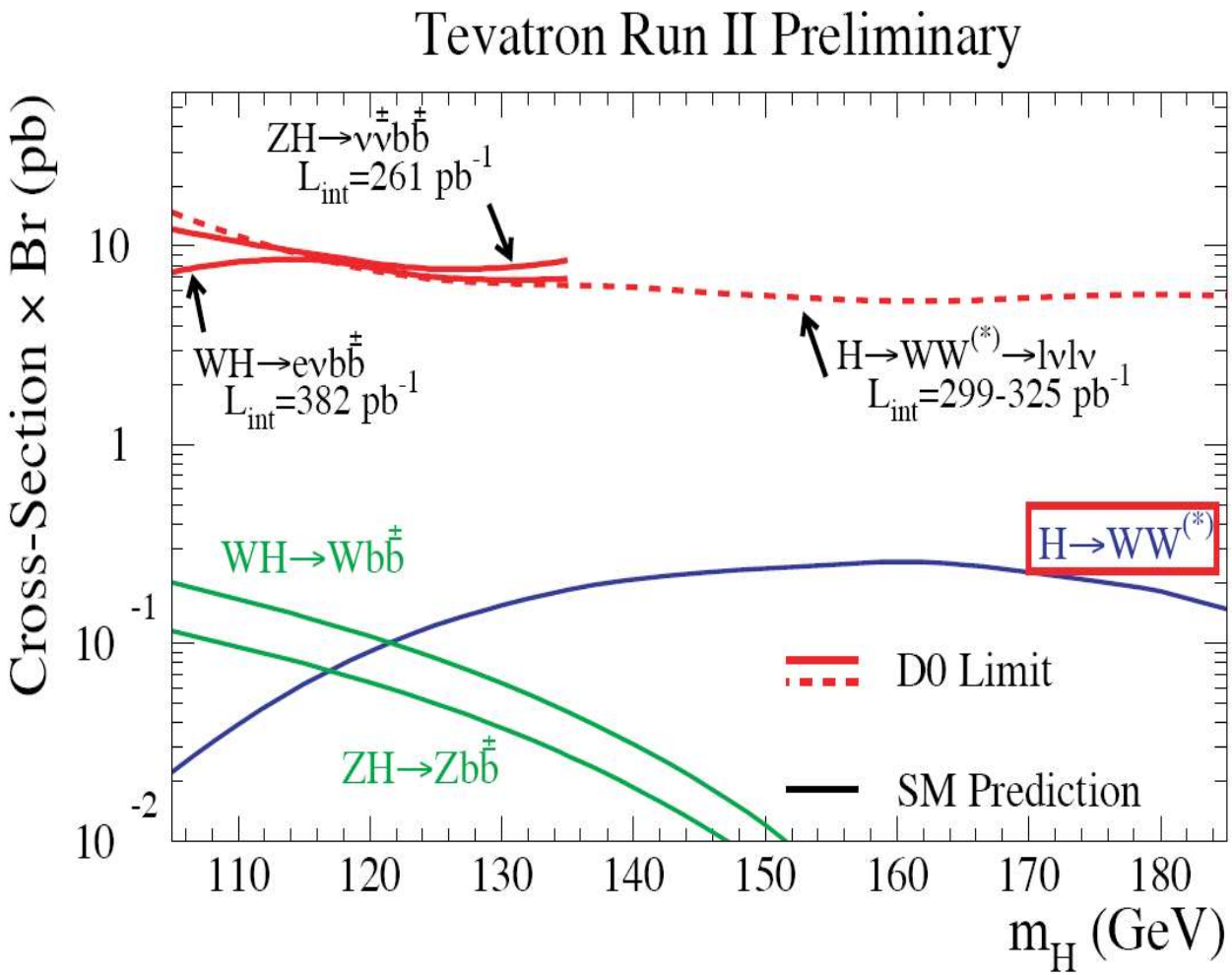
Search for an excess in the di-b-jet mass distribution

Mass (GeV)	105	115	125	135
Window	[70,120]	[80,130]	[90,140]	[100,150]
Data	4	3	2	2
Acceptance (%)	0.29 ±0.07	0.33 ±0.08	0.35 ±0.09	0.34 ±0.09
Total bkgd.	2.75 ±0.88	2.19 ±0.72	1.93 ±0.66	1.71 ±0.57
Expected limit (pb)	8.8	7.5	6.0	6.5
Limit @95% C.L. (pb)	**12.2**	**9.3**	**7.7**	**8.5**





SM Higgs Summary



Expect improvements from:

- Advanced analysis techniques
- Improved b-tagging (e.g. NN)
- Improved calorimeter calibration, esp. hadronic
- Reduced Jet Energy Scale uncertainty
- More efficient and precise object ID
- Reduced backgrounds with better dijet mass resolution (cal-track-jets)
- Longterm: Hardware upgrades (Trigger, Silicon Layer 0)
- ... and obviously more data

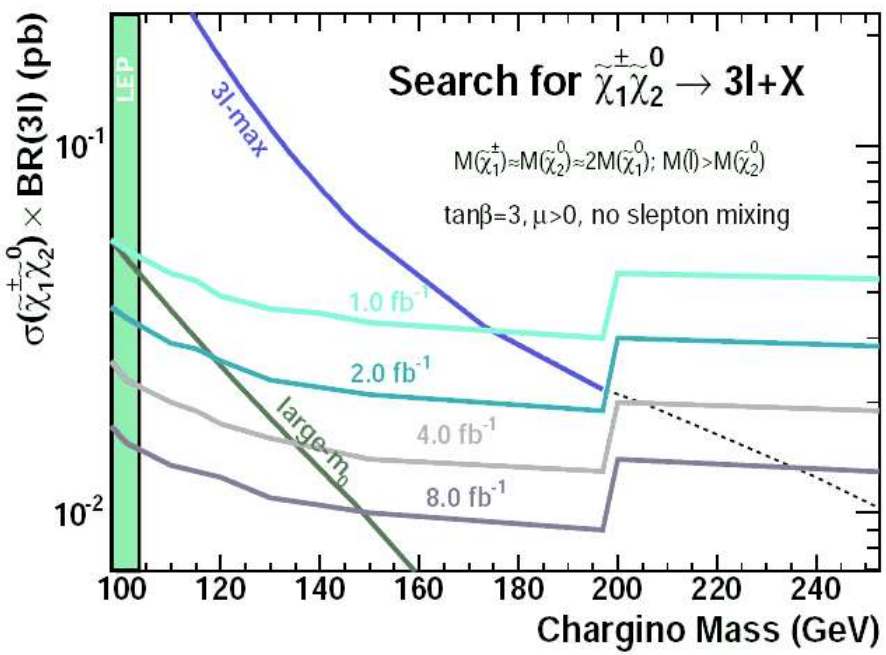
How does this compare to the Higgs Sensitivity Study Working Group (2003)?

– Factor ~ 2 – 3 worse in sensitivity; can be recovered

– See Beate's talk for details

Conclusions

- DØ experiment is running well, and the place to discover or constrain new physics
- Recorded about 0.8 fb^{-1}, analyses shown based on up to $\simeq$ 400 pb^{-1}
- High mass dilepton and diphoton searches in all variations: no surprises, but interesting candidate events
- Searches for non-SM particles have entered uncharted territory (Desert? Jungle?)
  - Probing MSSM with R-parity conservation / non-conservation, GMSB, AMSB, Technicolor, ...
  - With a large variety of experimental tools: Missing E_T (+ jets, + trileptons), multileptons incl. taus, leptons + jets, diphotons, b-tags, ...
- New results on sbottom, Higgs searches, long-lived massive particles, 2nd generation leptoquarks, ...
- Preparing for analysis of 1 fb^{-1} data set



Vancouver, Last Week

Workshop last week in Vancouver – major topics included the preparation of 1fb^{-1} analyses, and being prepared for multi–fb^{-1}