Search for Squarks, Gluinos and 3rd generation Squarks at D0 (Run II)

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for

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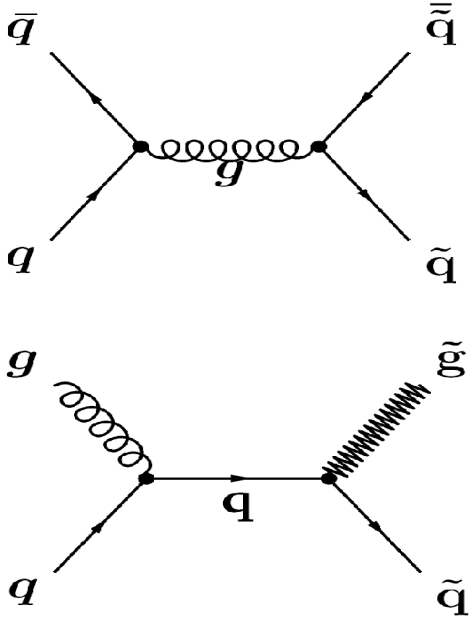
Outline

- Introduction
- Search for squarks and gluino
- Search for 3rd generation squarks
  - Sbottom
  - Stop :
    - c neutralino
    - b lepton sneutrino

Introduction : Squark production at the Tevatron

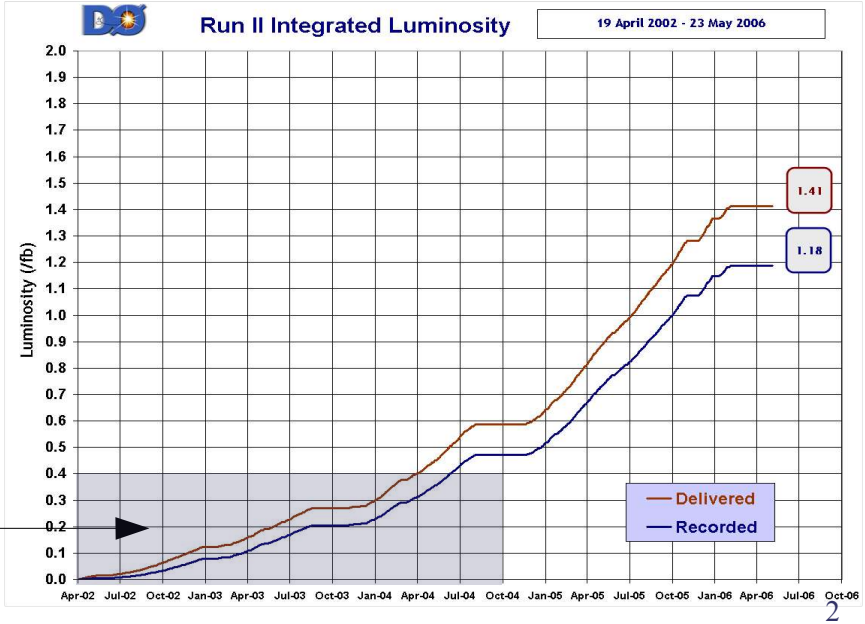
Large cross-section for squark pair production at the Tevatron :

- $\sqrt{s} = 1.96$ TeV : $\sigma \sim 1$ pb



- Delivered integrated luminosity : 1.4 fb^{-1}
- 1.2 fb^{-1} on tape

- **Data for today's results : ~ 0.4 fb^{-1}**



Search for Squarks ($\tilde{u}$ -> $\tilde{b}$) & Gluino

Framework : mSUGRA

χ^0_1 = Lightest Supersymmetric Particle

$\tan\beta = 3$, $\mu < 0$, $A_0 = 0$: No (tri-linear) mixing $(m_0, m_{1/2})$ fixes $(M_{\tilde{q}}, M_{\tilde{g}})$

Low m_0 : M(Squarks) < M(Gluino)

$qq, gg \to \tilde{q}\tilde{q} \to qq\, \tilde{\chi}^0_1 \tilde{\chi}^0_1$

Signature : 2 acoplanar jets

Backgrounds : jj W → jj l ν, jj Z → jj $\nu\bar{\nu}$

Intermediate m_0 : M(Gluino) ~ M(Squarks)

$qg \to \tilde{q}\tilde{g} \to 3q\, \tilde{\chi}^0_1 \tilde{\chi}^0_1$

$qq, gg \to \tilde{g}\tilde{g} \to 4q\, \tilde{\chi}^0_1 \tilde{\chi}^0_1$

Signature : N(jets) ≥ 3

Backgrounds : jj W → jj l ν, $t\bar{t} \to b\bar{b}$ jj l ν

High m_0 : M(Gluino) < M(Squarks)

$qq, gg \to \tilde{g}\tilde{g} \to 4q\, \tilde{\chi}^0_1 \tilde{\chi}^0_1$

Signature : N(jets) ≥ 4

Backgrounds : QCD, jj Z → 4j, $t\bar{t} \to b\bar{b}$ jj l ν

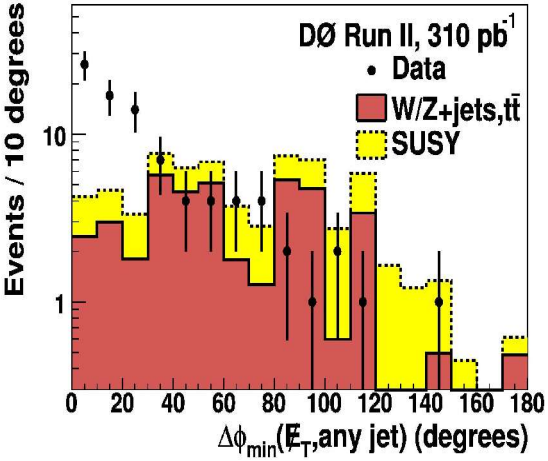
Search for Squarks ($\tilde{u}$ -> $\tilde{b}$) & Gluino : Selections

Common selection :

- $E_T(Jet_1) \geq 60$ GeV
- Veto on isolated e & μ : diminishes W/Z + jets
- $\Delta\phi(Jet_{1,2}, MET) > 90^0, 50^0$: diminishes poorly reconstructed jets

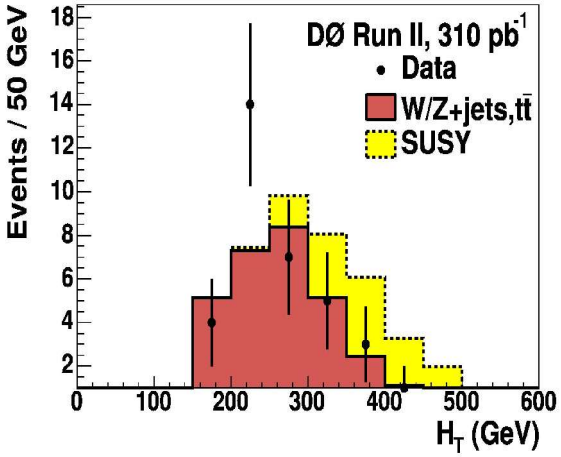
"Dijet" selection :

- $E_T(Jet_2) \geq 50$ GeV
- MET $\geq$ 175 GeV
- $H_T \geq 275$ GeV



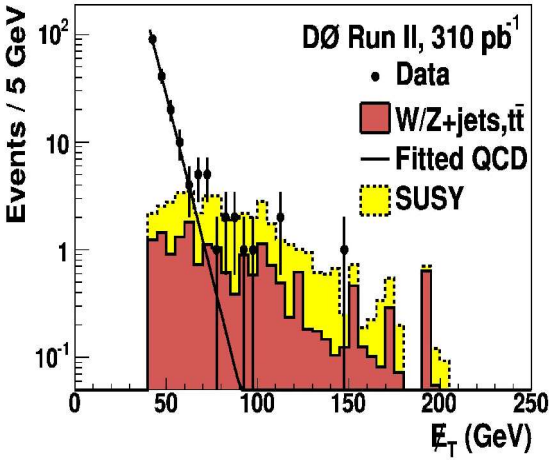
"3-jet" selection :

- $E_T(Jet_{2,3}) \geq 40, 30$ GeV
- MET $\geq$ 100 GeV
- $H_T \geq 350$ GeV



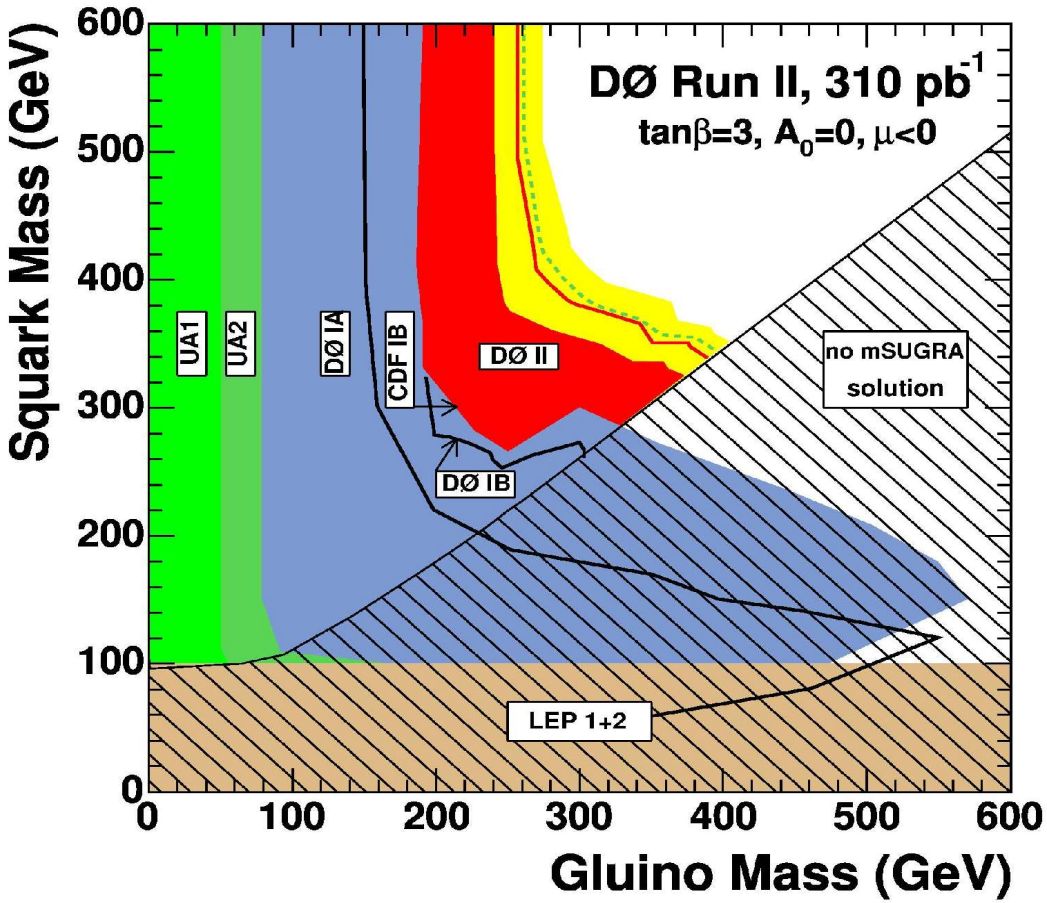
"Gluino" selection :

- $E_T(Jet_{2,3,4}) \geq 40, 30, 20$ GeV
- MET $\geq$ 75 GeV
- $H_T \geq 225$ GeV

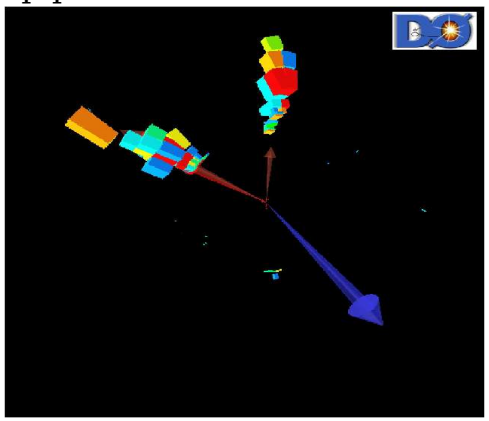


Search for Squarks ($\tilde{u}$ -> $\tilde{b}$) & Gluino : Results

Analysis	$(m_0, m_{1/2})$ (GeV)	$(m_{\tilde{q}}, m_{\tilde{g}})$ (GeV)	σ_{nom} (pb)	$\varepsilon_{sig.}$ (%)	$N_{obs.}$	$N_{backgrd.}$	σ_{95} (pb)
"dijet"	(25,145)	(318,366)	0.63	$6.2 \pm 0.4^{+1.1}_{-0.9}$	6	$4.8^{+4.4}_{-2.0}{}^{+1.1}_{-0.8}$	0.44
"3-jets"	(191,126)	(330,330)	0.64	$4.7 \pm 0.3^{+0.8}_{-0.7}$	4	$3.9^{+1.3}_{-1.0}{}^{+0.7}_{-0.8}$	0.45
"gluino"	(500,80)	(507,240)	2.41	$2.3 \pm 0.2^{+0.4}_{-0.3}$	10	$10.3^{+1.5}_{-1.4}{}^{+1.9}_{-2.5}$	1.72



$\tilde{q}\,\tilde{q}$ event ?



MET = 350 GeV
E_T ($Jet_{1,2}$) = 264, 106 GeV

Fermilab-Pub-06/06-077-E
Analysis will be interpreted within MSSM

Motivation for 3rd generation squarks

MSSM lagrangian with soft breaking terms :

Quark left- & -right superpartners (scalars) can strongly mix to form mass eigenstates :

$$M^2_{\tilde{q}} = \begin{pmatrix} \tilde{M}^2_Q + M^2_Q + M^2_Z\left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right)\cos 2\beta & M_Q\left(A_T + \frac{\mu}{\tan\beta}\right) \\ M_Q\left(A_T + \frac{\mu}{\tan\beta}\right) & \tilde{M}^2_U + M^2_Q + \frac{2}{3}M^2_Z\sin^2\theta_W\cos 2\beta \end{pmatrix}$$

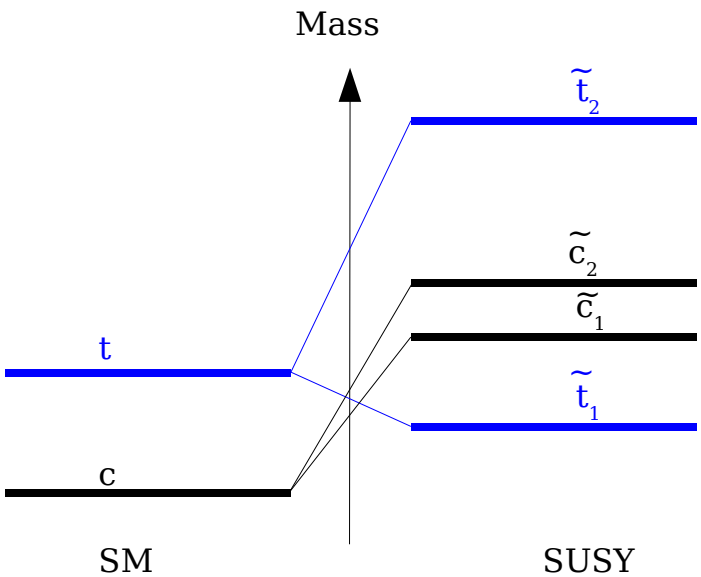
"Up" squarks

μ : Higgs parameter ($\mu H_1 H_2$)
A_T : Tri-linear (stop) mixing term
$\tan\beta = \langle H^0_2\rangle / \langle H^0_1\rangle$
$\mathbf{M_Q = M_t}$

Mass difference of quark superpartners :
Proportionnal to $M_Q = M_t$:

Strong mixing in the stops $\tilde{t}_{1,2}$ sector

→ $\tilde{t}_1$ might be the lightest squark



Motivation for the $\tilde{t}_1$: cosmology argument

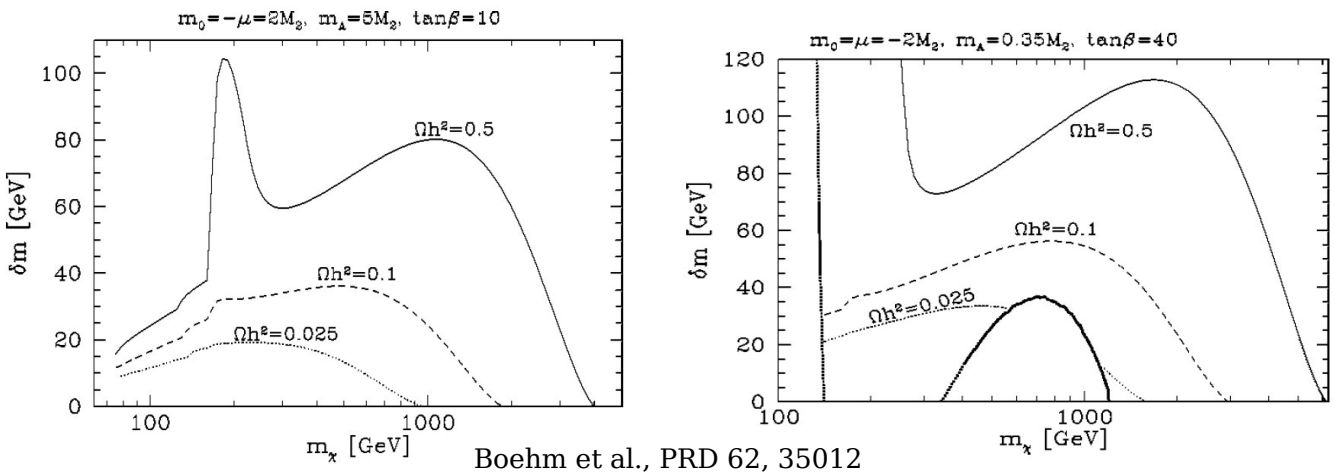
Neutralino : LSP Natural candidate for Cold Dark Matter

$0.1 < \Omega_{CDM}h^2 < 1$: "reproduced" in most of SUSY parameter space...

...IF $\chi^0_1\chi^0_1$ annihilation : only process changing the number of superparticles

IF : $\delta m = M(\tilde{P}) - M(\chi^0_1)$ small : co-annihilations dominates : $\Omega_{CDM}h^2 \approx 0.1$

- $\chi^0_1\,\tilde{t}_1$ ---> tg, tH^0_i, bH^+
- $\tilde{t}_1\,\tilde{t}^{(*)}_1$ ---> $t\bar{t}$, gg, $H^0_iH^0_j$, H^-H^+, $b\bar{b}$



Boehm et al., PRD 62, 35012

- $\Delta m = M(\tilde{t}_1) - M(\chi^0_1) \leq 60$ GeV/c^2 : compatible with

  $\Omega_{CDM}h^2 = 0.11 \pm 0.02$ @ 95% CL (WMAP & SDSS)

- Challenge at a hadronic collider : Low Δm !

Sbottom search : $\tilde{b}_1 \to b\,\chi^0_1$

Framework : MSSM

Enhanced at large tanβ Vary $(M_{b1}, M_{\chi 0})$ χ^0_1 = LSP

2 acoplanar (b) Jets

Common selection :

- N(Jet) = 2, 3
- Acoplanarity < 165^0 : diminishes QCD
- $\Delta\phi_{min}$(Jets,MET) > 35^0 : diminishes QCD
- Veto on isolated track (p_T>5GeV/c) : diminishes W/Z + jets

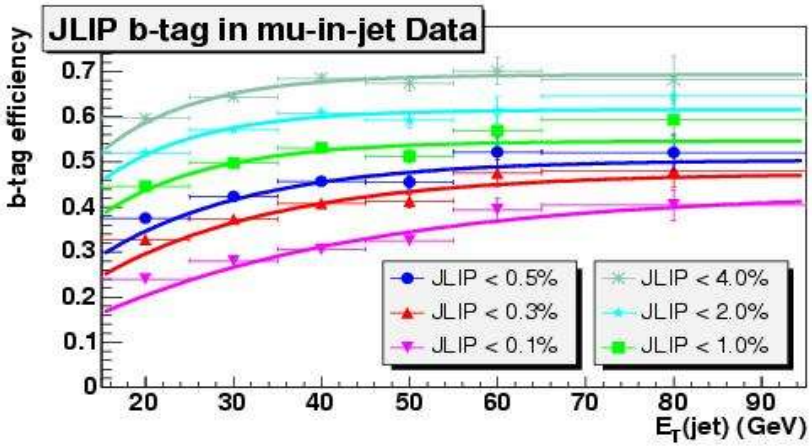
Selection vs

$M_{\tilde{b}1}$-$M_{\chi 0}$ = 60,85,145 GeV/c^2 :

- MET ≥ 60, 80, 100 GeV
- $E_T(Jet_1)$ ≥ 40, 70 GeV $E_T(Jet_2)$ ≥ 15, 40 GeV

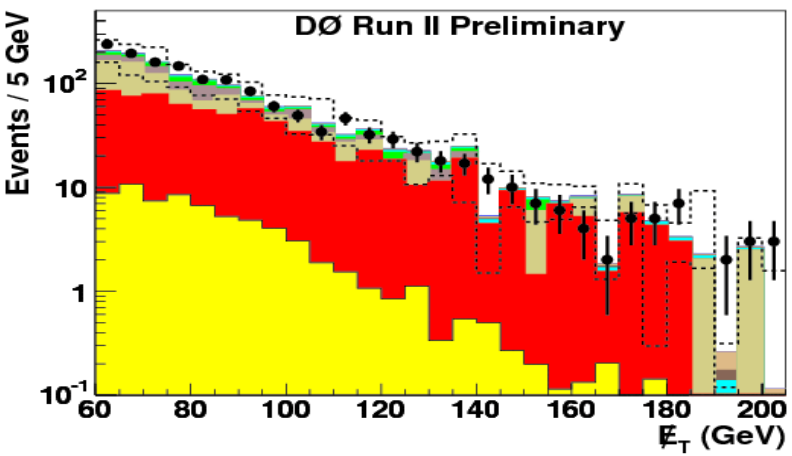
b tagging :

Jet LIfetime Probability :
Probability for Tracks, associated to a Jet, to originate from the Primary Vertex

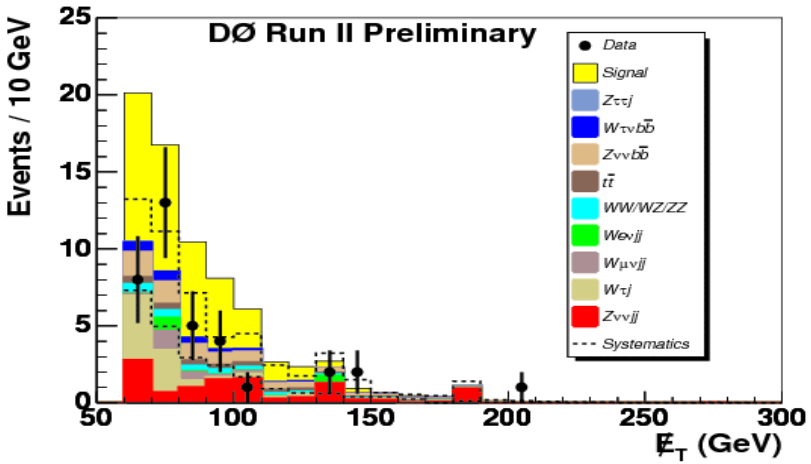


Sbottom search : $\tilde{b}_1 \to b\,\chi^0_1$

After selection



After selection + tight single b-tag



Signal :

Efficiencies = 0.4 - 12 %

Systematics < 30 % (Jet-Energy Scale, -ID, -Reconstruction, -tagging)

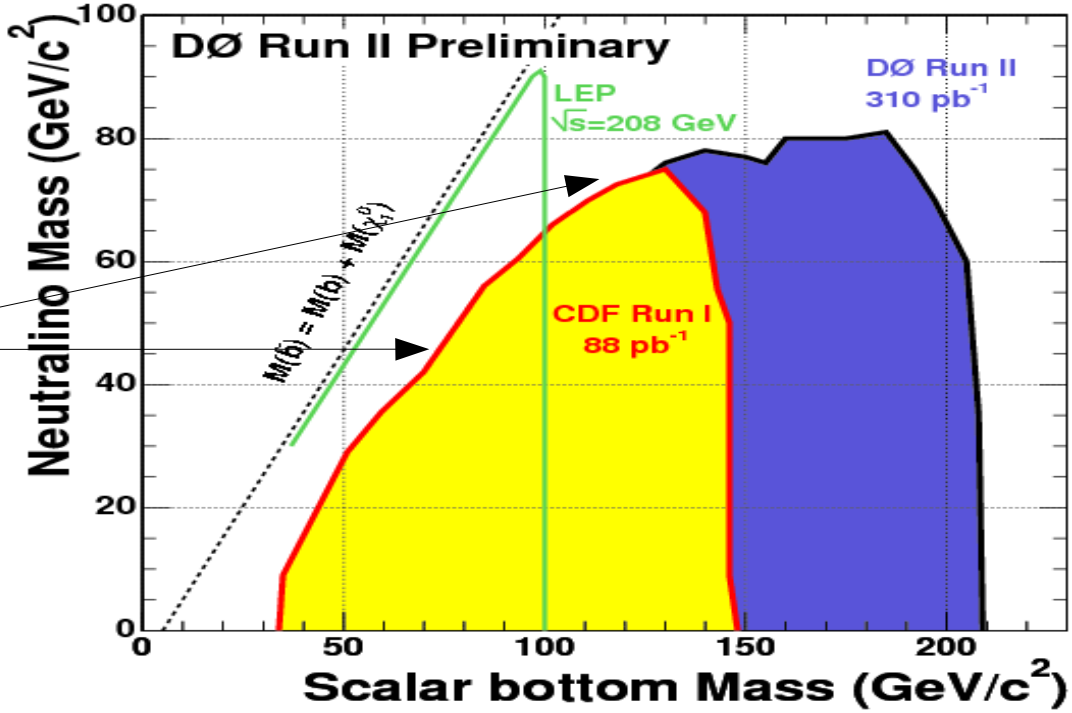
Limitation at low Δ m:

Trigger

$E_T(Jet_{1,2}) \geq 40, 15$ GeV

Perspective :

Further improvement with NN b-tag

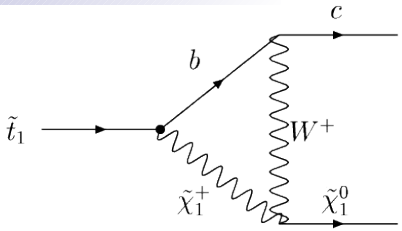


Stop searches : $\tilde{t}_1 \to c\,\chi^0_1$

Framework : MSSM

Vary $(M_{\tilde{t}1}, M_{\chi 0})$ χ^0_1 = LSP

2 acoplanar (c) Jets



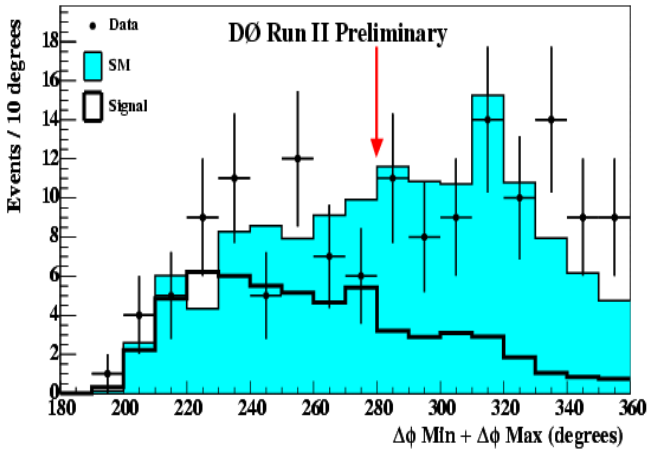
Veto on isolated leptons
2 jets, one loosely tagged

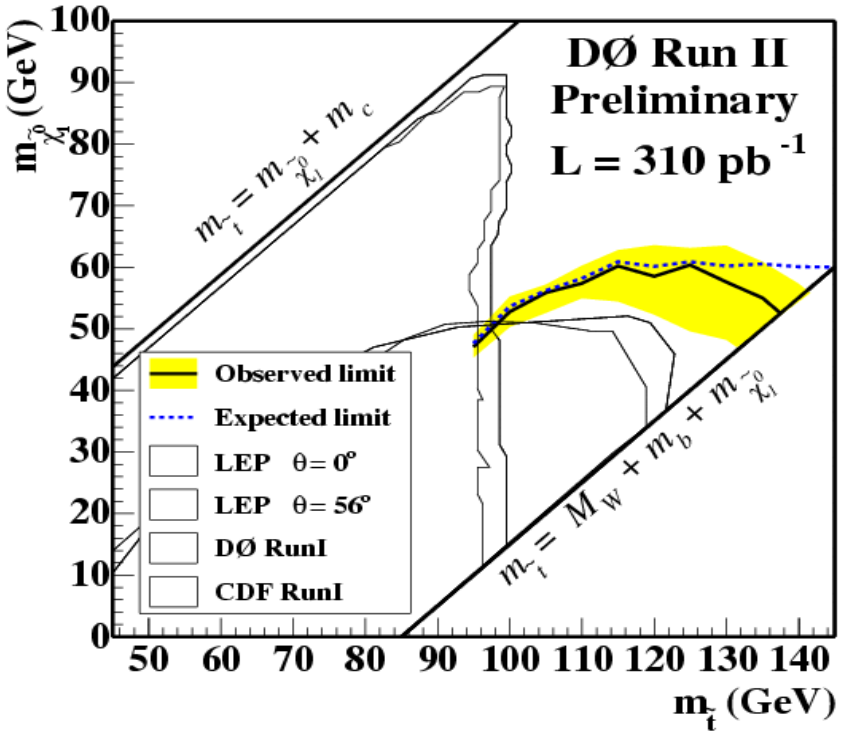
Main backgrounds :

- QCD
- Z/W (-> ν ν / l ν) + 2 jets

Selection : Minimization of σ_{UL}(exp.) :

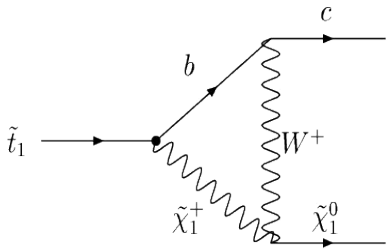
- MET ≥ 60 -> 90 GeV
- $E_T(Jet_1) \geq 40 \to 70$ GeV
- $E_T(Jet_2) \geq 20 \to 50$ GeV
- $\Delta\phi_{min}(Jets,MET) + \Delta\phi_{max}(Jets,MET) < 250^0 \to 300^0$





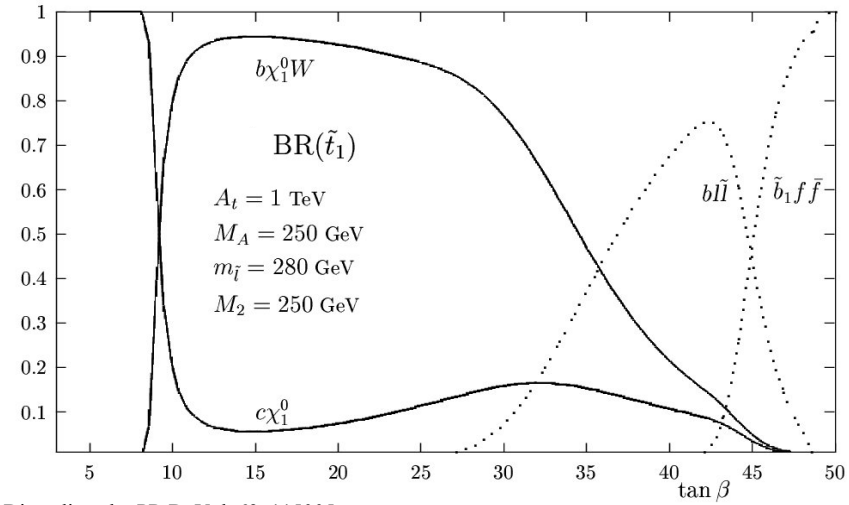
Stop searches : decays

Is c χ^0_1 the only / best window to search for stops ?

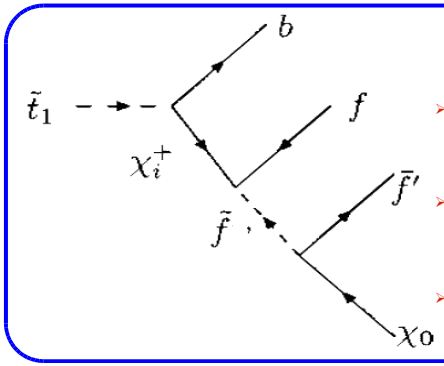


- Big contribution **if** $\log(\Lambda_{GUT}^2/M_W^2) \sim 65$: by choice !
  MSSM : squark mass unification at low energy...
- $|V_{bc}| \sim 0.05$
- Prefered at low tanβ : excluded by LEP Higgs searches

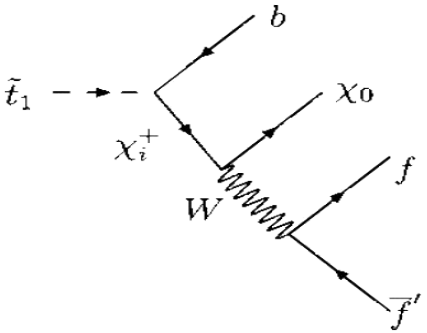
3-body decays



Djouadi et al. : PR D, Vol. 63, 115005



- $\tilde{f}'$ = sneutrino
  f = lepton $\bar{f}'$ = neutrino
- Contributes more if $M(\tilde{\nu}) \sim 80$ GeV/c^2
- Br ($\chi^\pm$ -> $\tilde{\nu}$ lept) = 1/3



- No hypothesis on $M(\tilde{\nu})$
- 2leptons+2jets+MET : feasible
  Lower branching ratio

Road to go :

- Explore the easiest case : $\tilde{\nu}$ exchange scenario
- Calibrate for W exchange scenario (2-3 fb^{-1})

Stop searches : $\tilde{t}_1 \to b\, l\, \tilde{\nu}$

Framework : MSSM

χ^0_1 = LSP

$\tan\beta = 20$, $\mu = +225$ GeV

$M_{\tilde{g}} = 500$ GeV/c^2

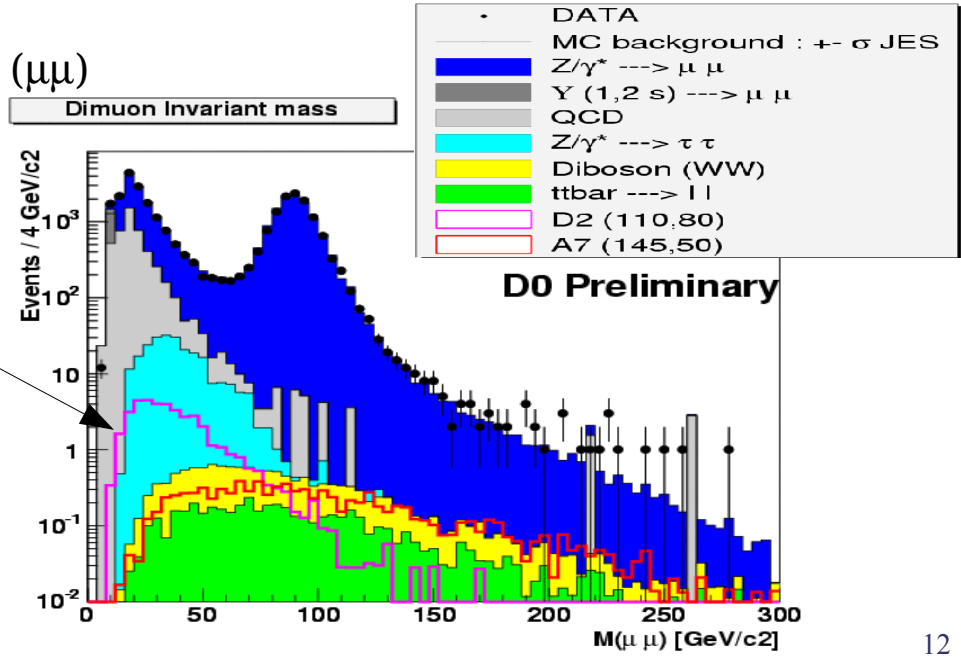
$M_A = 800$ GeV/c^2

- A_T, trilinear stop mixing : controls $M_{\tilde{t}1}$
- $M_{L1,2}$, slepton masses : controls $M_{\tilde{\nu}}$
- M_1, bino mass : controls $M_{\chi 0}$
- M_2, wino mass : controls $M_{\chi +}$: Chargino virtual

$$\tilde{t}_1\bar{\tilde{t}}_1 \longrightarrow b\bar{b} \qquad \begin{array}{ll} \tilde{\chi}^{\pm} & \tilde{\chi}^{\pm} \\ \hookrightarrow \mu\tilde{\nu} \longrightarrow \mu\nu\tilde{\chi}^0_1 & \hookrightarrow \mu\tilde{\nu} \longrightarrow \mu\nu\tilde{\chi}^0_1 \\ \hookrightarrow e\tilde{\nu} \longrightarrow e\nu\tilde{\chi}^0_1 & \hookrightarrow \mu\tilde{\nu} \longrightarrow \mu\nu\tilde{\chi}^0_1 \end{array}$$

Sensitivity to Δm signal :

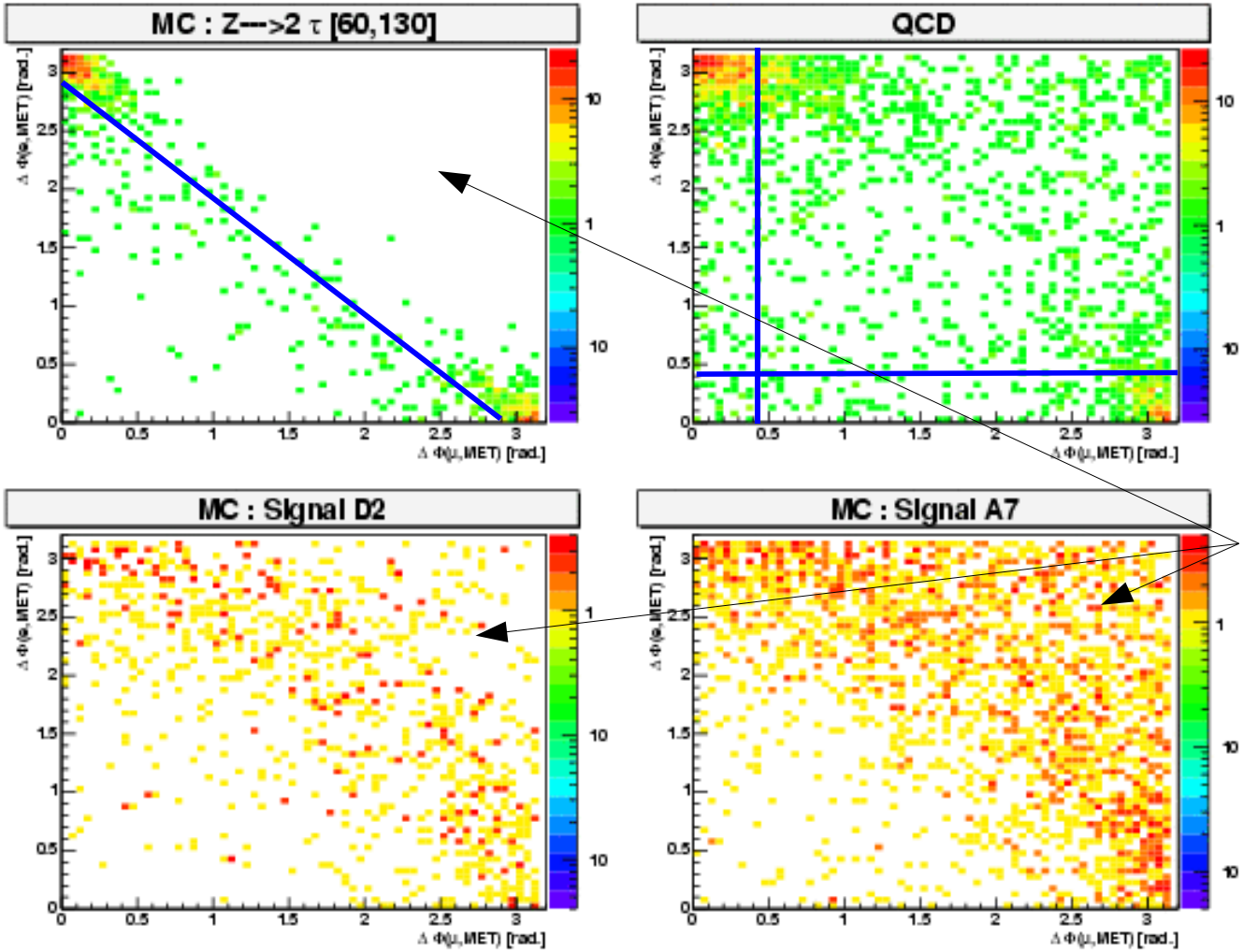
- $(\mu\mu)$: $p_T(\mu 1,2) > 8$, 6 GeV/c
- $(e\mu)$: $p_T(e,\mu) > 12$, 8 GeV/c



Topology : Δϕ (e,MET) versus Δϕ (μ,MET) :

e μ
MET

Use difference of correlation Δϕ (leptons,MET) for Z-> τ τ , QCD <-> signal



Step I :

Δϕ (e,MET) > 0.4 rad.

Δϕ (μ,MET) > 0.4 rad.

MET > 15 GeV

Maximizing S / √B

Step II :

Sliding cut versus Δm

Δϕ (e,MET)+Δϕ (μ,MET) > 2.8 , 2.9 rad.

Minimizing $\sigma_{expected}$

e μ
MET

$\tilde{t}_1$ -> b l $\tilde{\nu}$ searches : eμ channel

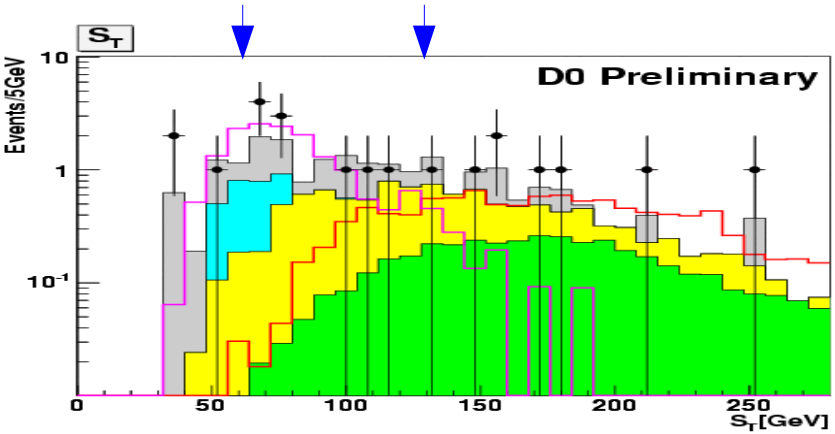
$\mathcal{L}$ = 350 pb^{-1}

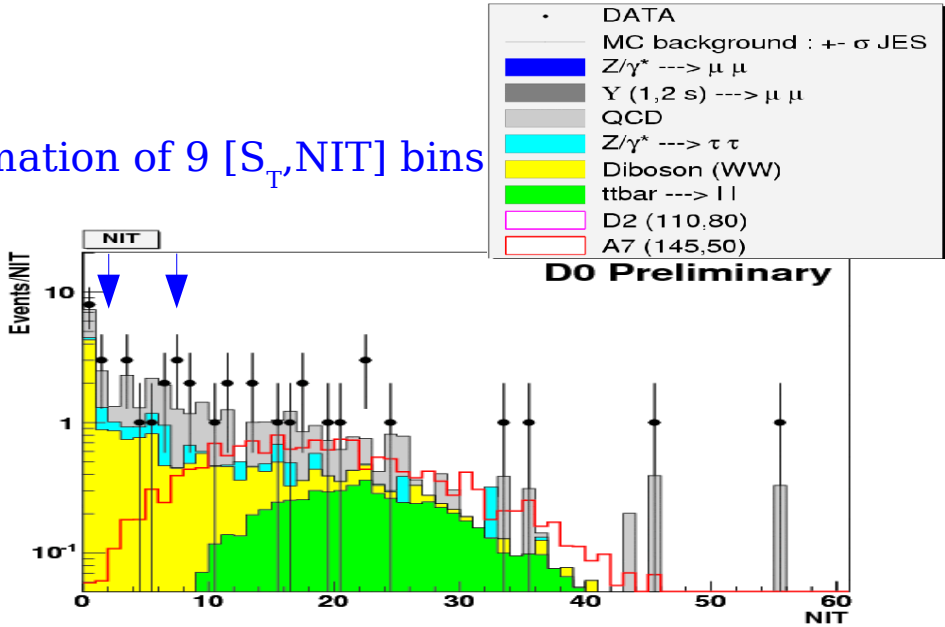
Kinematic regions	QCD	$Z \to 2\tau$	Diboson $\sim WW$	$t\bar{t}$	Background	Data	Signal hard	Signal soft
$\Delta m \leq 40$ GeV	9	2.1	7.6	4.3	23.0 ± 3.1	21	11.5	16.4
50 GeV $\leq \Delta m \leq$ 60 GeV	14.8	3.0	11.1	5.7	34.6 ± 4.0	34	15.2	18.5
70 GeV $\leq \Delta m$	18.2	3.3	12.8	6.5	40.7 ± 4.4	42	16.7	20.4

Remaining backgrounds : QCD, WW

Efficiency = 12.2 % 2.7 %
Systematics < 5 %

- $S_T = p_T(e) + p_T(\mu) + MET$:
  - Separation : High Δm signal <-> QCD
  - Separation : Low Δm signal <-> WW
- Number of Non-Isolated Tracks (NIT) :
  - Separation : High Δm signal <-> WW
- **Step III :** Combine the statististical information of 9 [S_T,NIT] bins

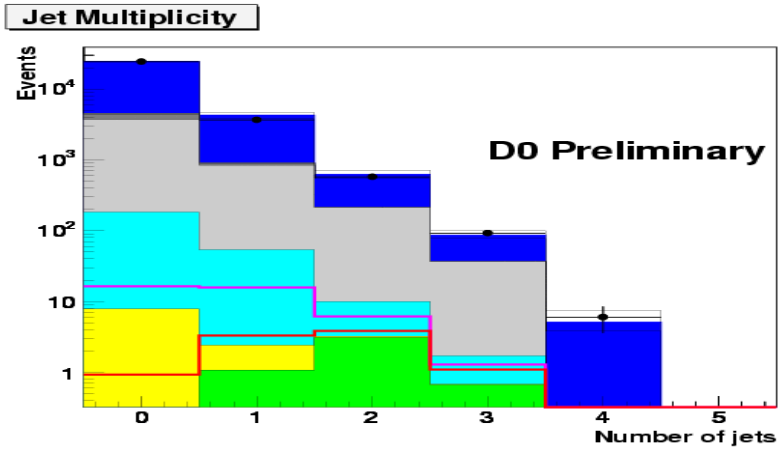




$\tilde{t}_1$ -> b ℓ $\tilde{\nu}$ searches : μμ channel

Selection : Veto / select Z / Signals

- Topology :
  - M(μμ)
  - MET
  - Δϕ(μ1,MET) versus MET
- At least one jet, loosely tagged



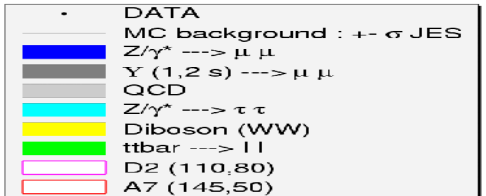
$\mathcal{L}$ = 339 pb^{-1}

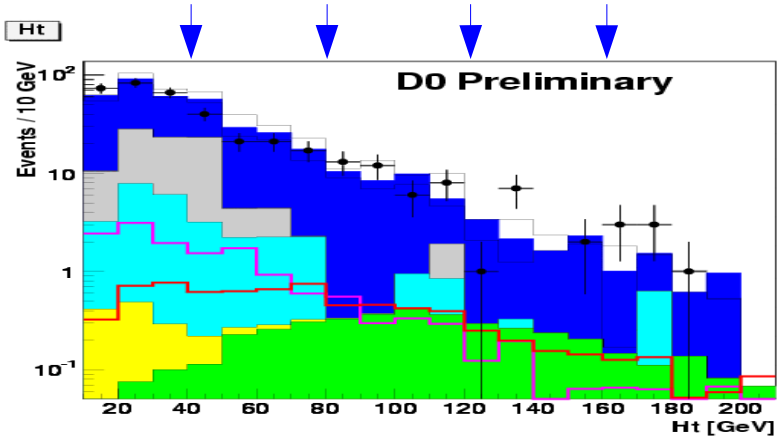
Cut	$\Upsilon_{1,2s}$	QCD	$Z \to 2\mu(2\tau)$	WW	$t\bar{t}$	Background	Data	Signal hard	Signal soft
Quality Cuts	973	4525	23782	9.6	5.1	29295 ± 348	28733	9.8	41.1
After selection	0	0	0.6	0.03	2.3	2.88 ± 0.43	1	3.06	3.30

Efficiency = 4.5 % 0.1 %
Systematics : 12 – 22 %

Separate different signals from top :

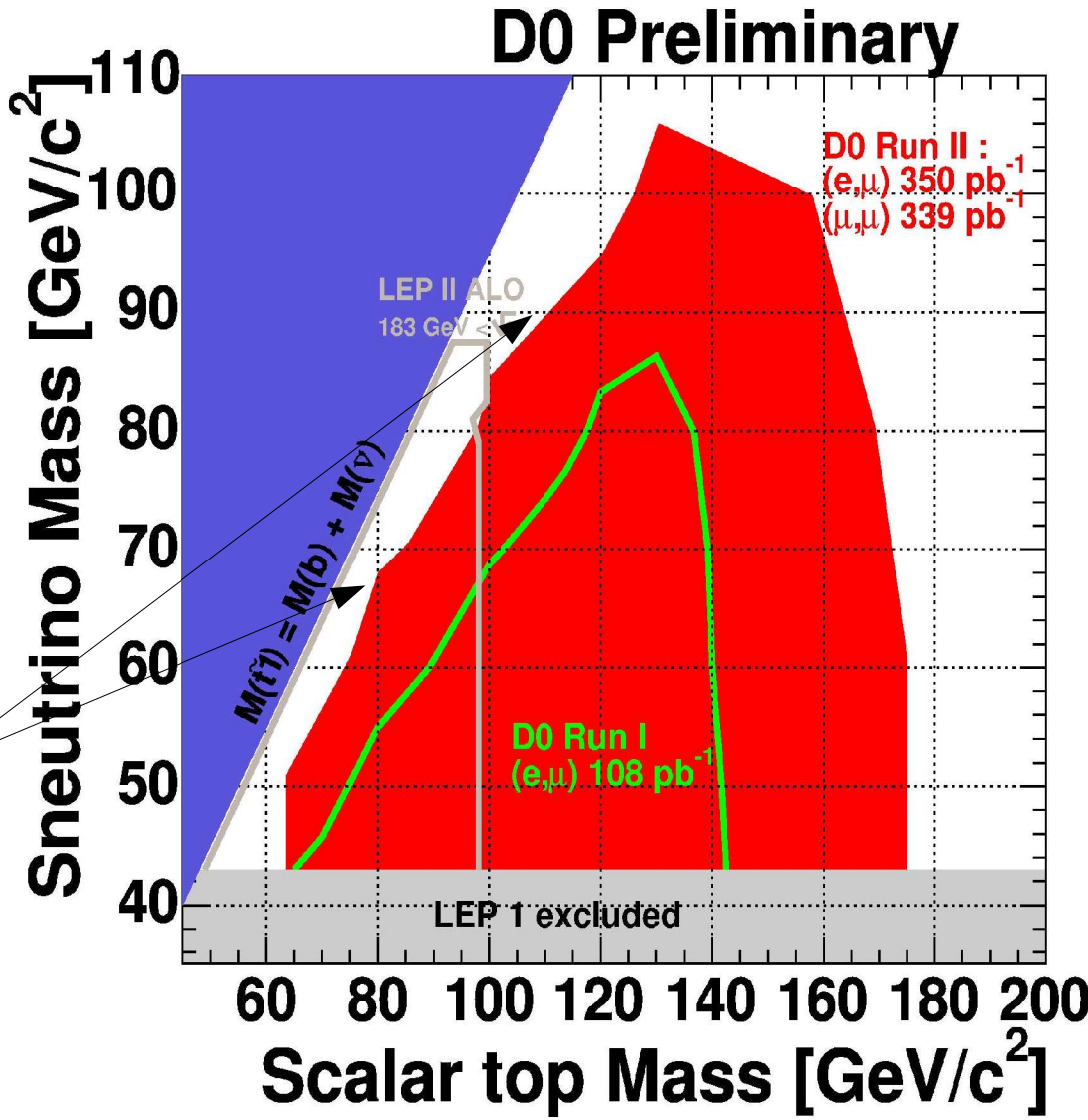
Combine the statististical information of 5 $H_T = \Sigma_{j=Jets} E_T(j)$ bins





$\tilde{t}_1 \to b\,\ell\,\tilde{\nu}$ searches : combining eμ & μμ channels

- **(eμ) :**
  - Sensitivity well beyond RunI
  - Low Δm :
    Sensitivity limited :
    Dominated by QCD
- **(μμ) :**
  - Low background
  - Trigger(μ) :
    ε~100% for p_T > 5 GeV/c
  - Low Δm :
    Sensitivity limited :
    E_T(Jet) / MET > 15 / 20 GeV
- **Sensitivity for low Δm signal**



Conclusions / Perspectives

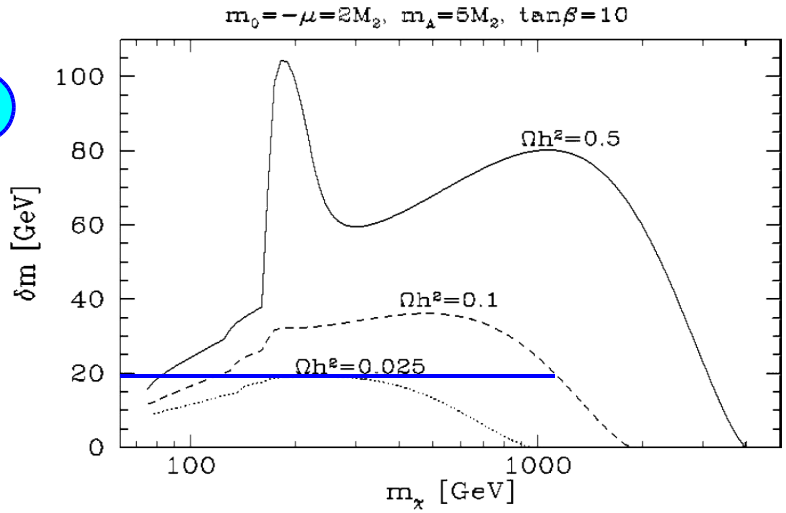
D0 (RunII) has searched for gluino & squarks : 1st -> 3rd generation :

- Dijet / Multi-jet searches :
  - **Squark/Gluino :** $M(\tilde{q}) > 325$ GeV/c^2 $M(\tilde{g}) > 241$ GeV/c^2
    Generic Jet/MET search : Ready for MSSM interpretation
  - **Sbottom :** Significant exclusion in terms of $\tilde{b}_1/\chi^0_1$ masses
  - **Stop -> c χ^0_1 :** $M(\tilde{t}_1,\chi^0_1) > (131,46)$ GeV/c^2 for c-MET final state
- Di-lepton searches :
  - Able to go down to low lepton p_T : 6, 8 GeV/c
  - **Stop -> b l $\tilde{\nu}$:** Sensitivity to low $\Delta m \approx 15$ GeV/c^2
- Extended sensitivities with 1 fb^{-1} Data...

Possible SUSY perspective at the LHC :

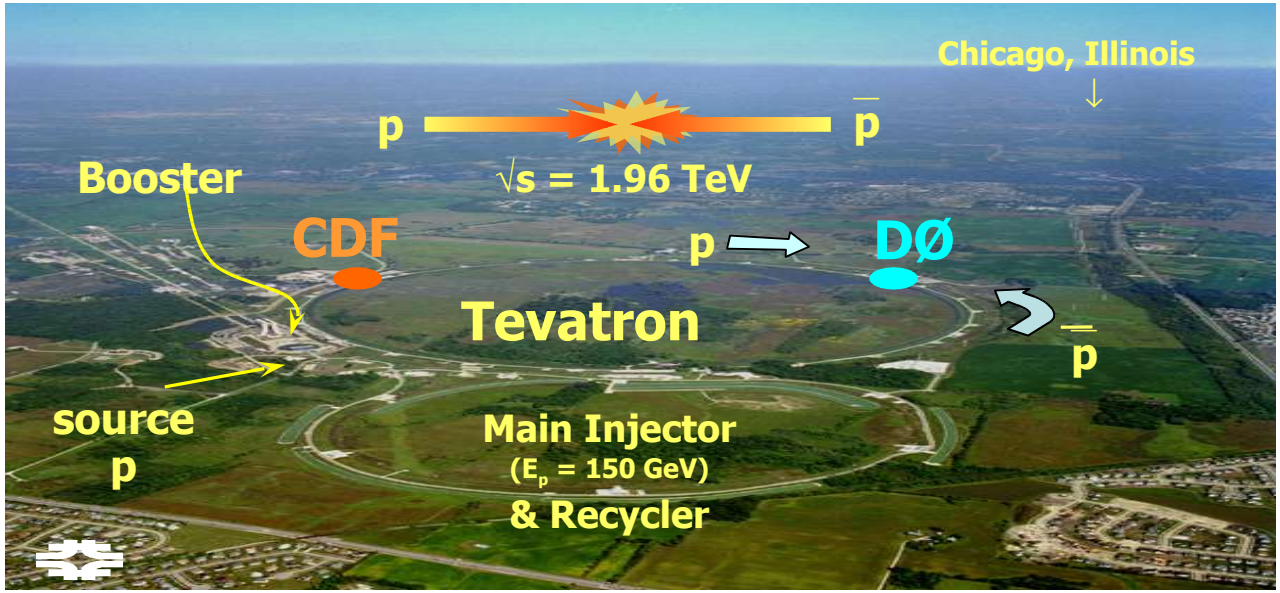
Sensitivity $M(\chi^0_1 / \tilde{t}_1) \geq 1$ TeV/c^2

LHC "should" see superparticles

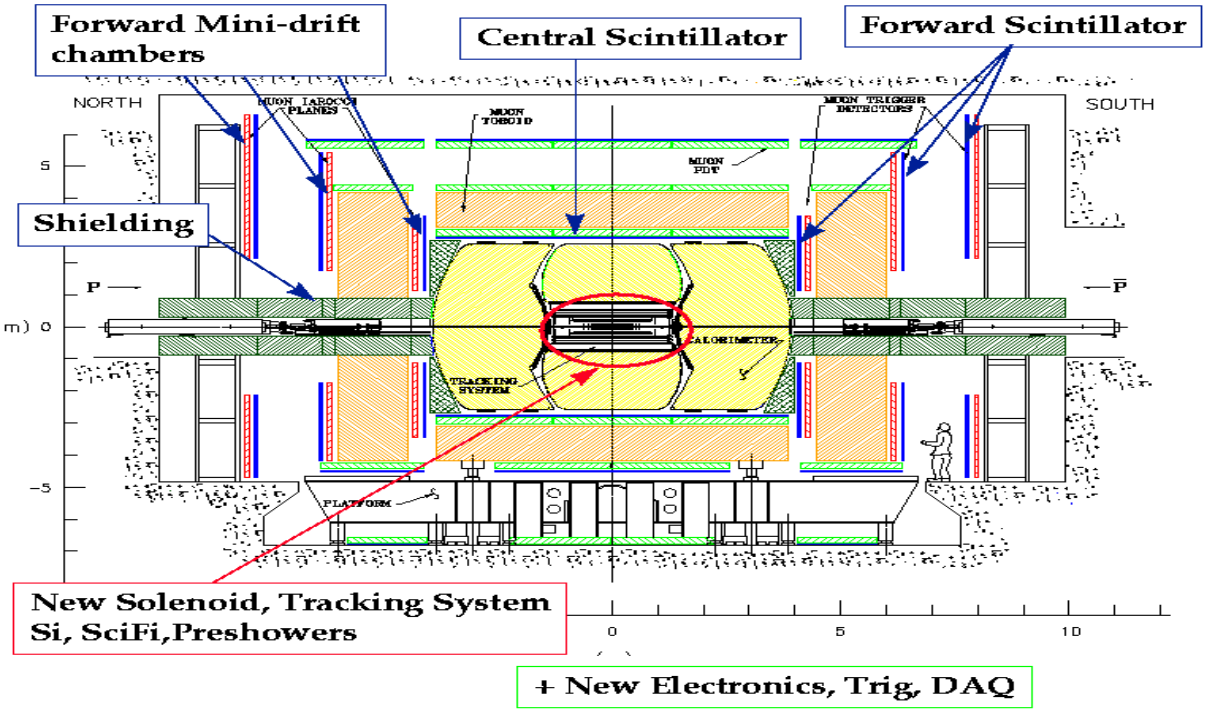


Backup slides

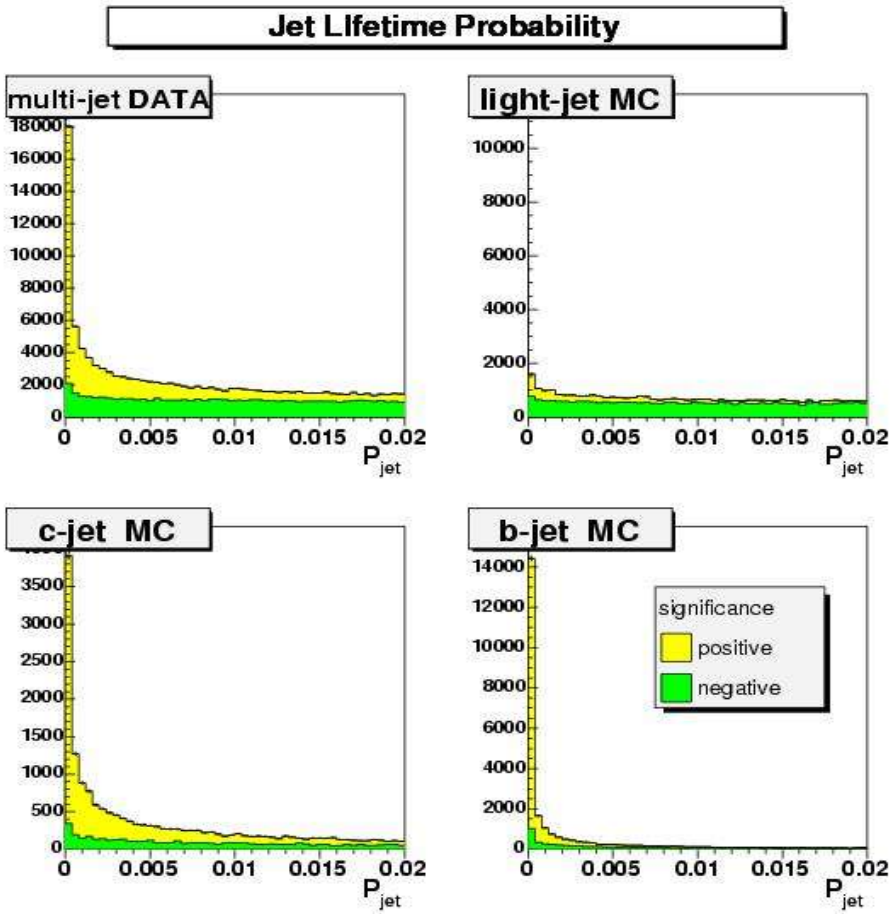
Tevatron

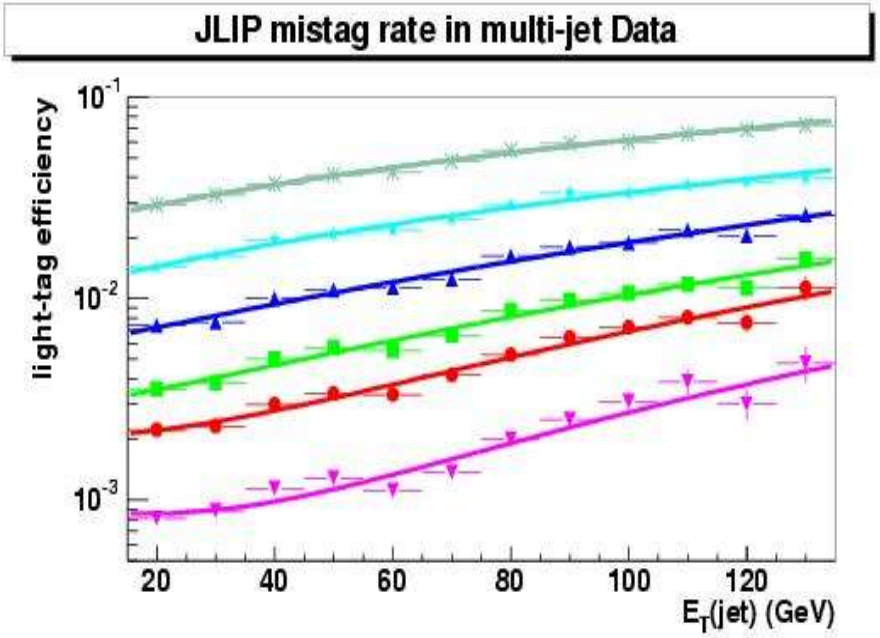


- Tracking detectors :
  - Silicon Modules
  - Scintilllating Fibres
- Solenoïd : 2 T
- Calorimeter : LAr / U $|\eta| < 4$
- Muon detectors $|\eta| < 2$:
  - Scintillators
  - Mini Drift Tubes



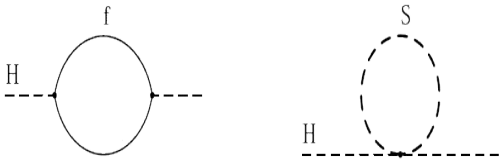
B tagging


Jet LIfetime Probability
multi-jet DATA
light-jet MC
c-jet MC
b-jet MC
significance
positive
negative
P_{jet}


JLIP mistag rate in multi-jet Data
light-tag efficiency
E_T(jet) (GeV)

Motivations for the t_1 : special relations with the Higgs

Yukawa (s)top/Higgs Coupling



→ $M(h) = f\,[\,M(\tilde{q},\tilde{t}_1)\,]$

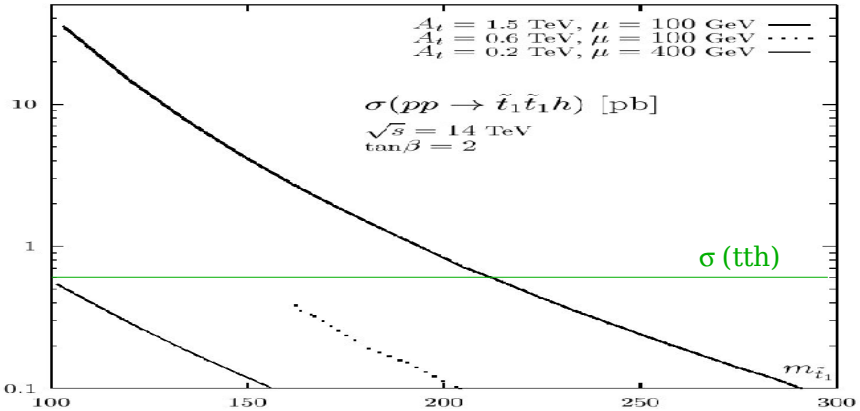
Very strong stop mixing $M_Q\,(A_T + \mu/\tan\beta)$ → $M(\tilde{t}) < M(t)$

pp -> $h\,\tilde{t}\,\tilde{t}$ favoured / -> htt

Decoupled regime : light h "SM like", $\{H, H^{\pm}, A\}$ much heavier (degenerate)

h -> $\gamma\gamma$

Coupling : $g_{h\tilde{t}\tilde{t}} = \ldots + [\,-m_t^2 + m_t \sin 2\theta_{\tilde{t}}(A_T + \mu/\tan\beta)/2]\,/\,M_Z^2$



Djouadi et al., PRL 80, 1830

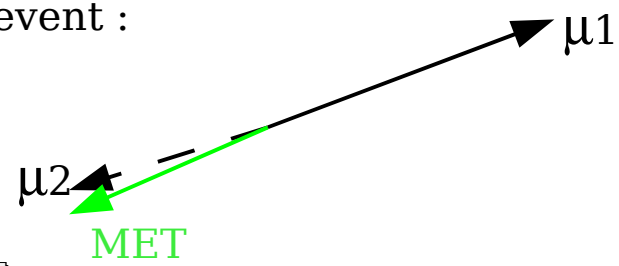
- $A_T \sim 0$: $\sigma(\tilde{t}\,\tilde{t}\,h) = 2\,\sigma(\tilde{t}_1\tilde{t}_1 h) \geq \sigma(tth)$
- A_T intermediate : destructive interference
- A_T (very) large : $\sigma(\tilde{t}_1\tilde{t}_1 h) > \sigma(tth)$ for $M(\tilde{t}_1) < 220$ GeV/c^2

- For big part of SUSY parameter space : $\sigma(\tilde{t}_1\tilde{t}_1 h) > \sigma(tth)$
- Even if $\sigma(\tilde{t}_1\tilde{t}_1 h) \sim \sigma(tth)$: $\Gamma(ll\,jj\,\gamma\gamma) - \Gamma(tth)$ -> **$\tilde{t}_1\tilde{t}_1 h$ coupling** :
  - Largest electroweak MSSM coupling
  - Test of scalar potential (soft breaking of SUSY)

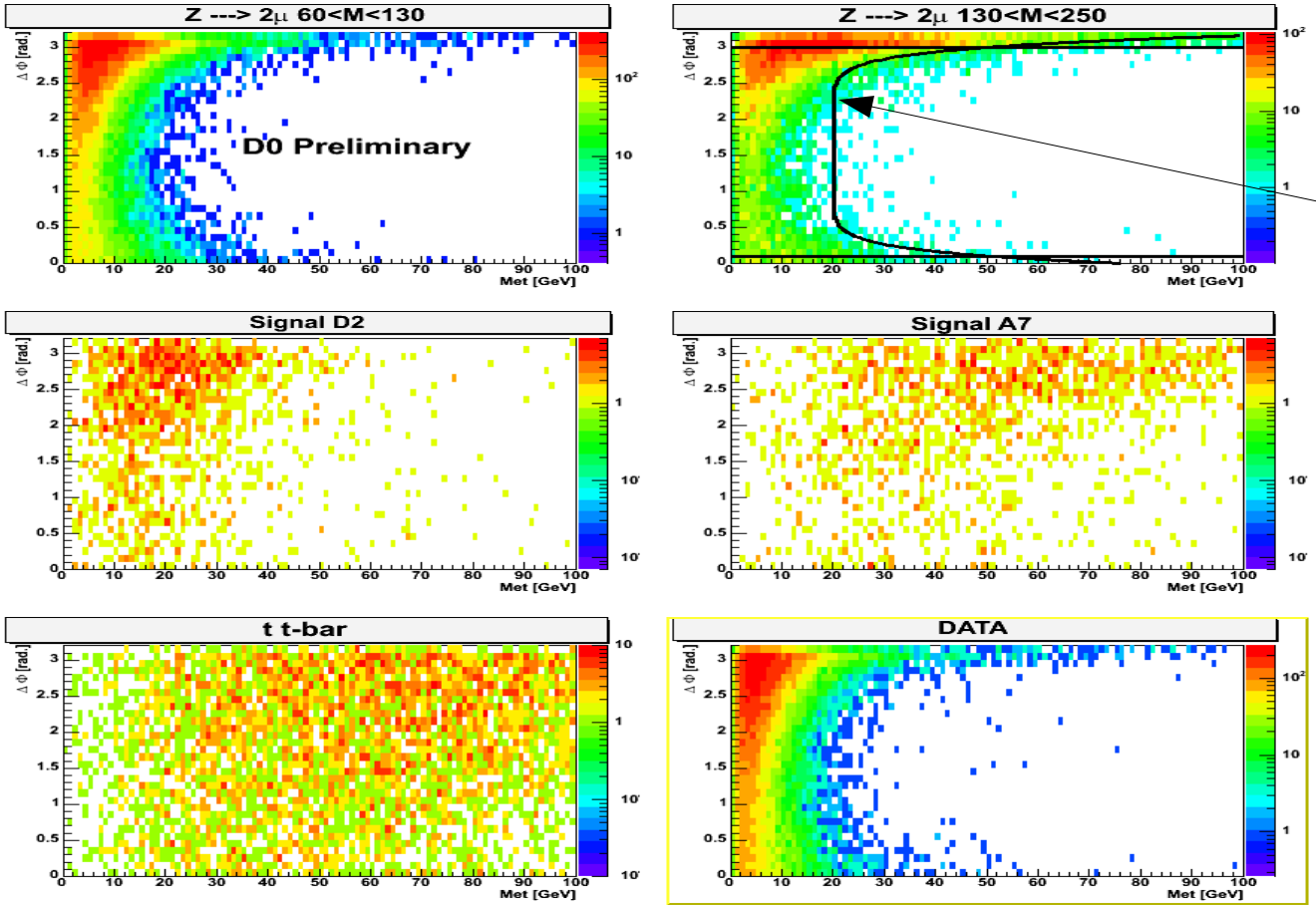
Selection : Use topology...

Δφ (μ1,MET) vs MET :

Z->μμ event :

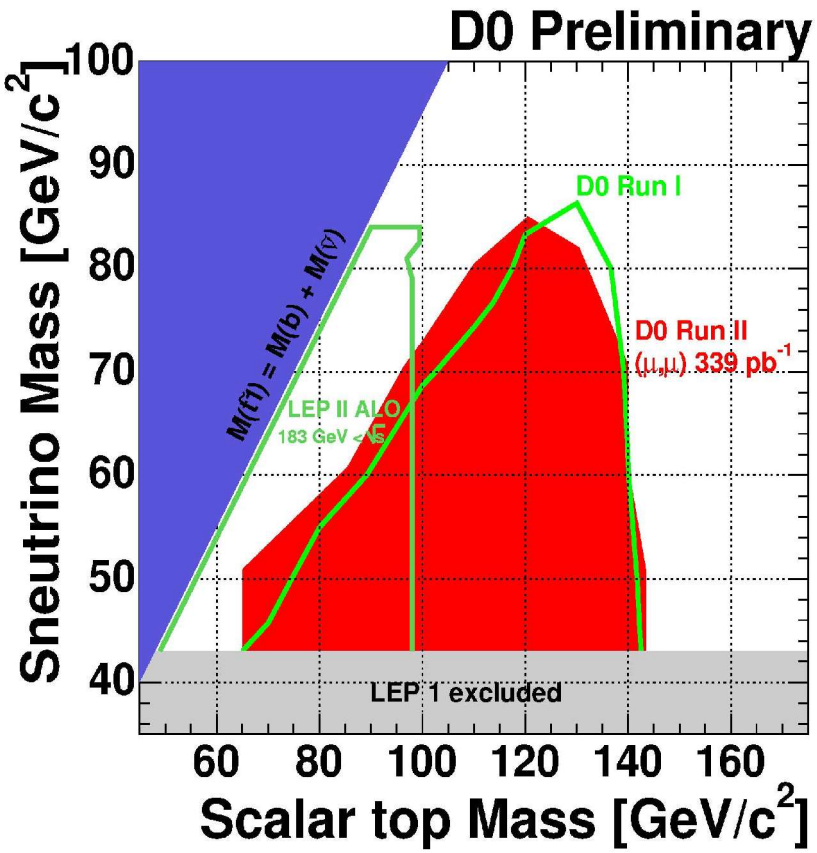
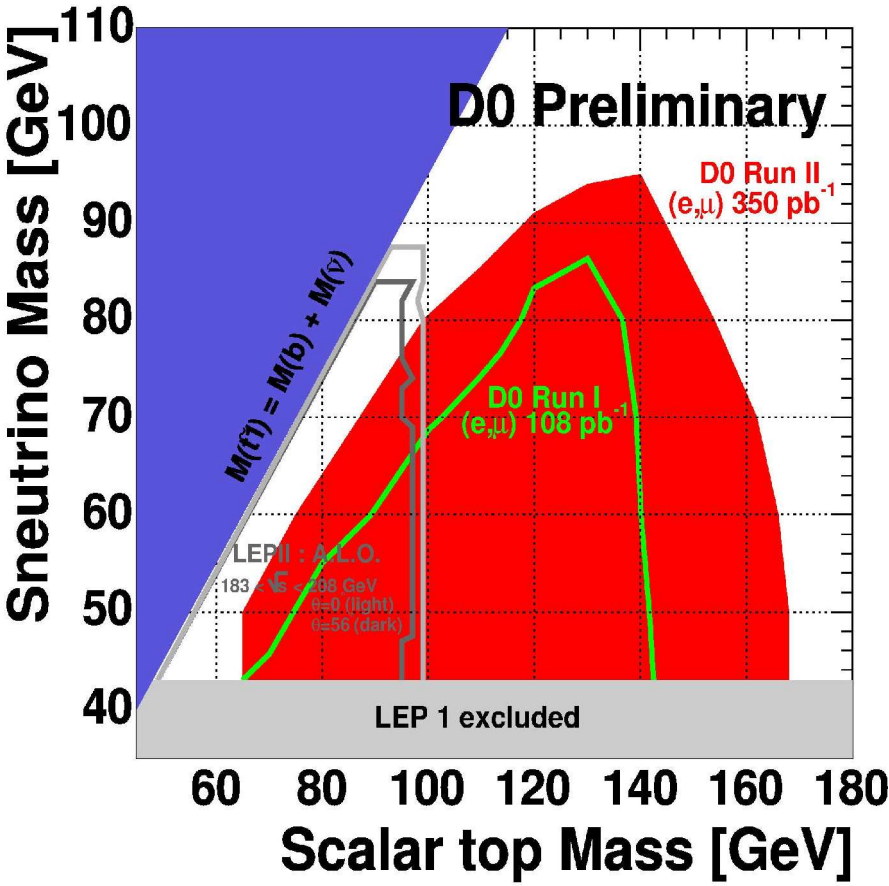


Poorly reconstructed muons correlate with MET



Topologic cut

Even topologically :

Z -> μμ < Signal < ttbar !

$\tilde{t}_1 \to b\,\ell\,\tilde{\nu}$ searches : eμ & μμ results individually