Dark Matter at the Tevatron

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Multi3

A cubic approach to Dark Matter
Padova, Department of Physics G.Galilei,
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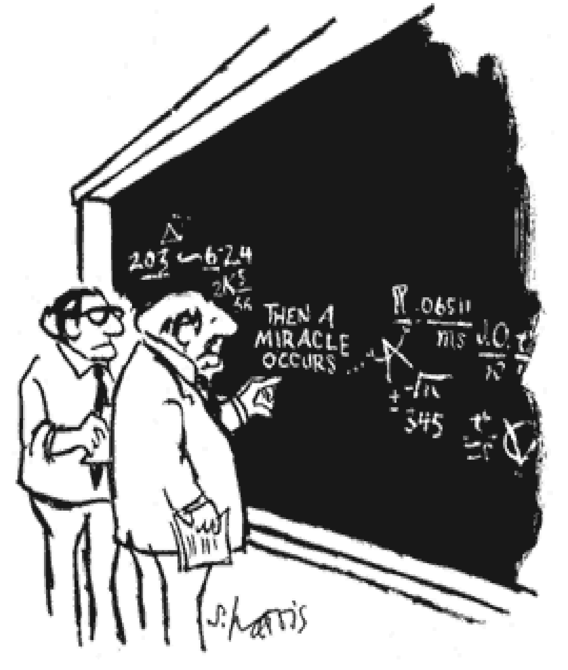
TRIUMF

Visitor at
Penn
University of Pennsylvania

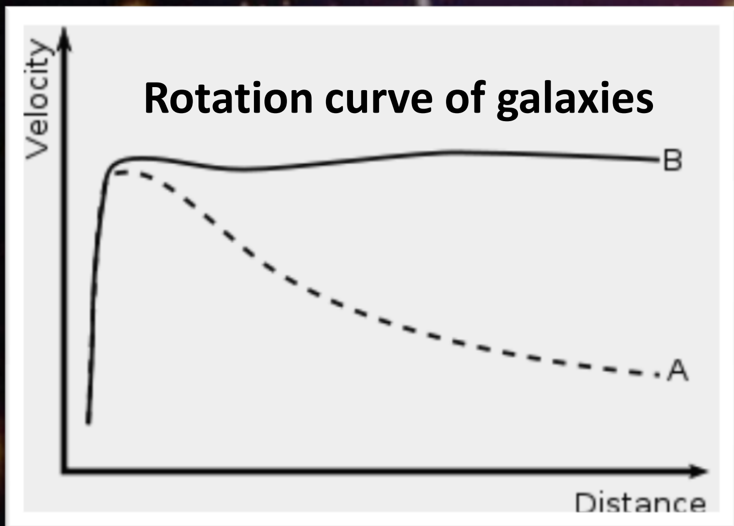
Outline

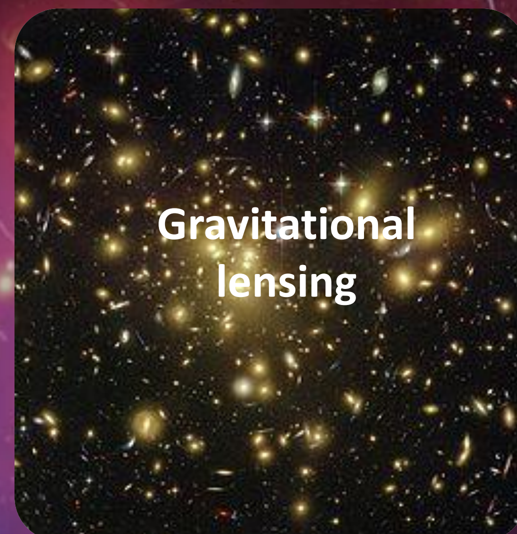
- SUSY and How it could help
- Searching for New Particles in Collider Experiments
  - Recreating the conditions at the Early Universe at Tevatron
  - Searches for cold dark matter
  - Searches for warm dark matter
- Summary and outlook

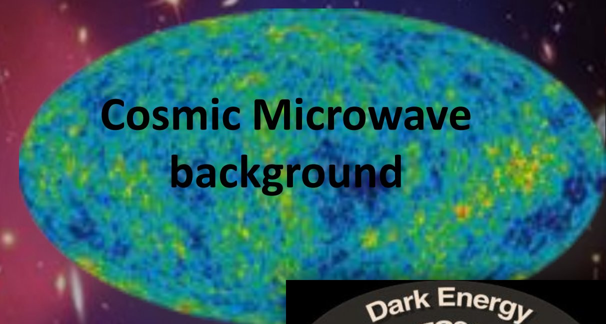


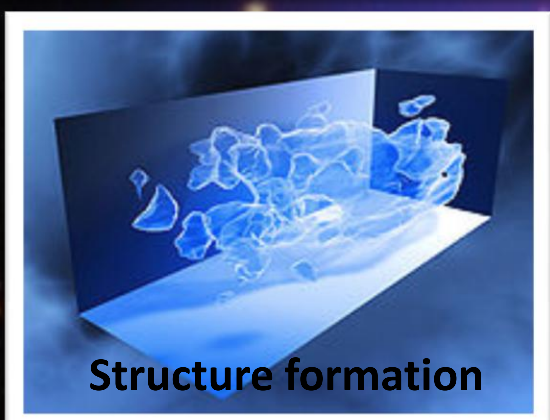
"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

Dark matter
in cosmology and astronomy









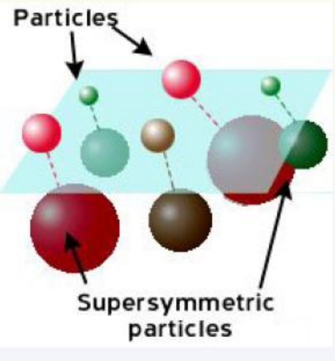
No known particles have the properties of Dark Matter

There are new fundamental particles to be discovered!

How does SUSY help?

(Among the) best motivated theories for BSM

- Cancellation of quadratic divergences to the Higgs mass
- Unification of gauge interactions
- Prediction of light Higgs boson
- Predictions of SUSY gauge theory in agreement with SM



SUSY is a broken symmetry

R-parity = $(-1)^{3B+L-2S}$ (Rp=+1 for SM, Rp=-1 for SUSY)

- To protect the proton lifetime, R-parity must be conserved

⇒ Sparticles are pair-produced

⇒ Lightest SUSY particle (LSP) is stable

SUSY provides an excellent Candidate for Dark Matter

- LSP mass theoretically constrained to < 1 TeV
- Most precise constraint on SUSY provided by WMAP:

$$\Omega_{CDM} = 1.099 \pm 0.0062$$

Stabilization of the mass scale of EWKSB

(if) Thermal equilibrium in the Early Universe

Possible SUSY DM Candidates (I)

- LSP is neutral and weakly interacting
  - If electrically or colored charged, it would bind to conventional matter ⇒ anomalous heavy nuclei (unseen)

Impose a natural relation:

$\sigma_A = k\alpha^2/m^2$, so $\Omega_{DM} \sim m^2$

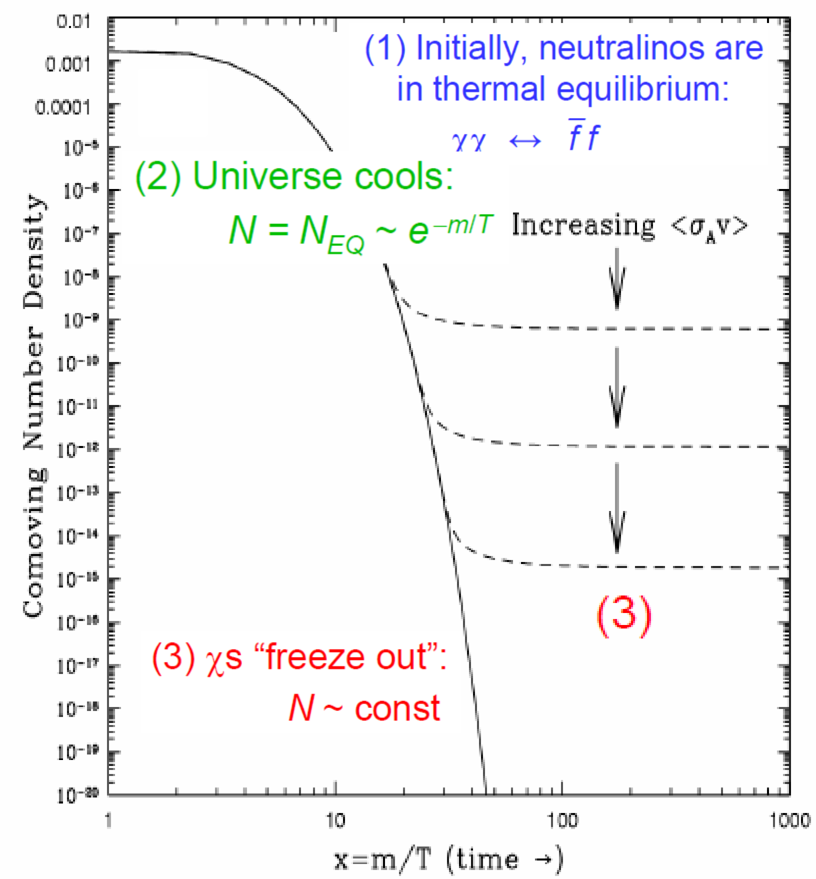
- Order of 100 GeV
- χ degenerate to LSP

Cold Dark Matter

Lightest Neutralino

$$\tilde{\chi}(\equiv \tilde{\chi}_1^0) = N_{\tilde{B}}\tilde{B} + N_{\tilde{W}}\tilde{W} + N_{\tilde{H}_1}\tilde{H}_1 + N_{\tilde{H}_1}\tilde{H}_1.$$

$$\mathcal{M}_N = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$



Possible SUSY DM Candidates (II)

- LSP does not need to interact weakly (the relic density prefers that!)
- Only gravitational interactions are required

- Gravity included in SUSY
  - Gravitino (s=3/2) mass in [ev-TeV] range
  - Gravitino can be LSP
- NLSP in thermal freeze out, decaying later into gravitino
  - Gravitino not in thermal equilibrium in Early Universe

Warm Dark Matter

NSLP, either neutral or charged
- Lightest neutralino
- Light stau
- Light stop
- Sneutrino

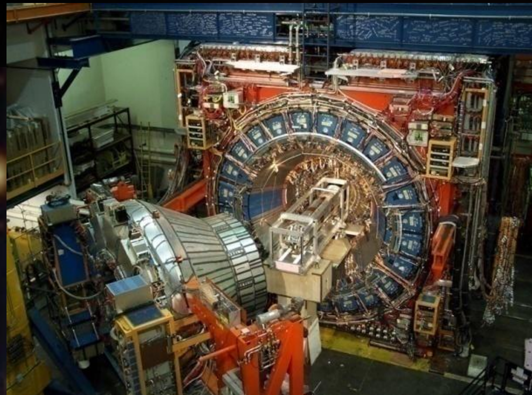
SUSY Models

Several are the scenarios of how the Universe might have evolved

	Model	DM Candidate	Signature
Minimal Solution	mSUGRA	Cold DM	Lightest neutralino
Non-minimal solution	mSUGRA	Cold DM	Long lived sparticles (decaying to neutralino)
Non-minimal solution	GMSB	Warm DM	Gravitino; long lived neutralino decaying to gravitino

Mass hierarchy and lifetimes dictate the search strategy

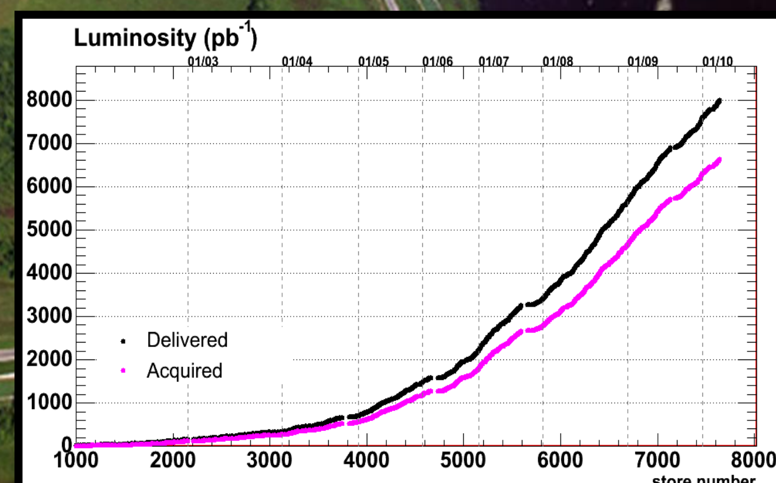
CDF and D0 at Tevatron



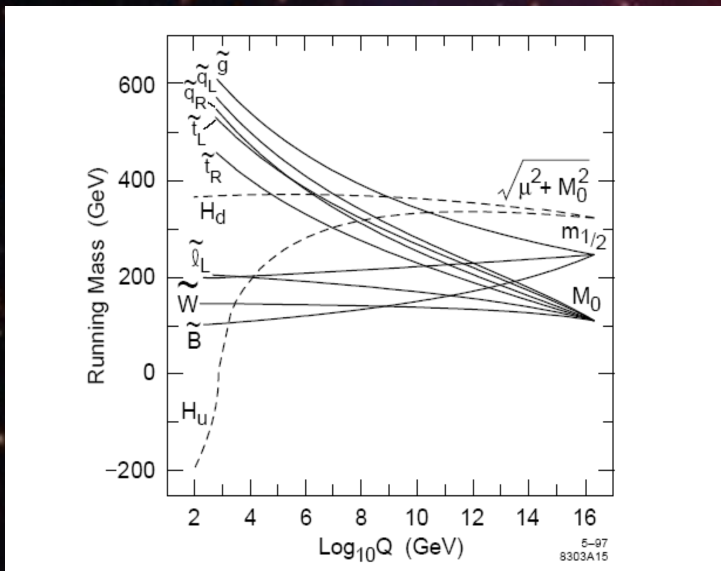
Tevatron collides proton-antiproton beams at 1.96 TeV

Allows us to look back at the conditions of the Early Universe about 1-10 ps after the Big Bang!

- Two multi-purpouse detectors, CDF and D0
  - Central tracker for pT measurement of charged particles
  - Calorimeters for E measurement of charged and neutral particles
  - Muon chambers



Cold Dark Matter scenarios

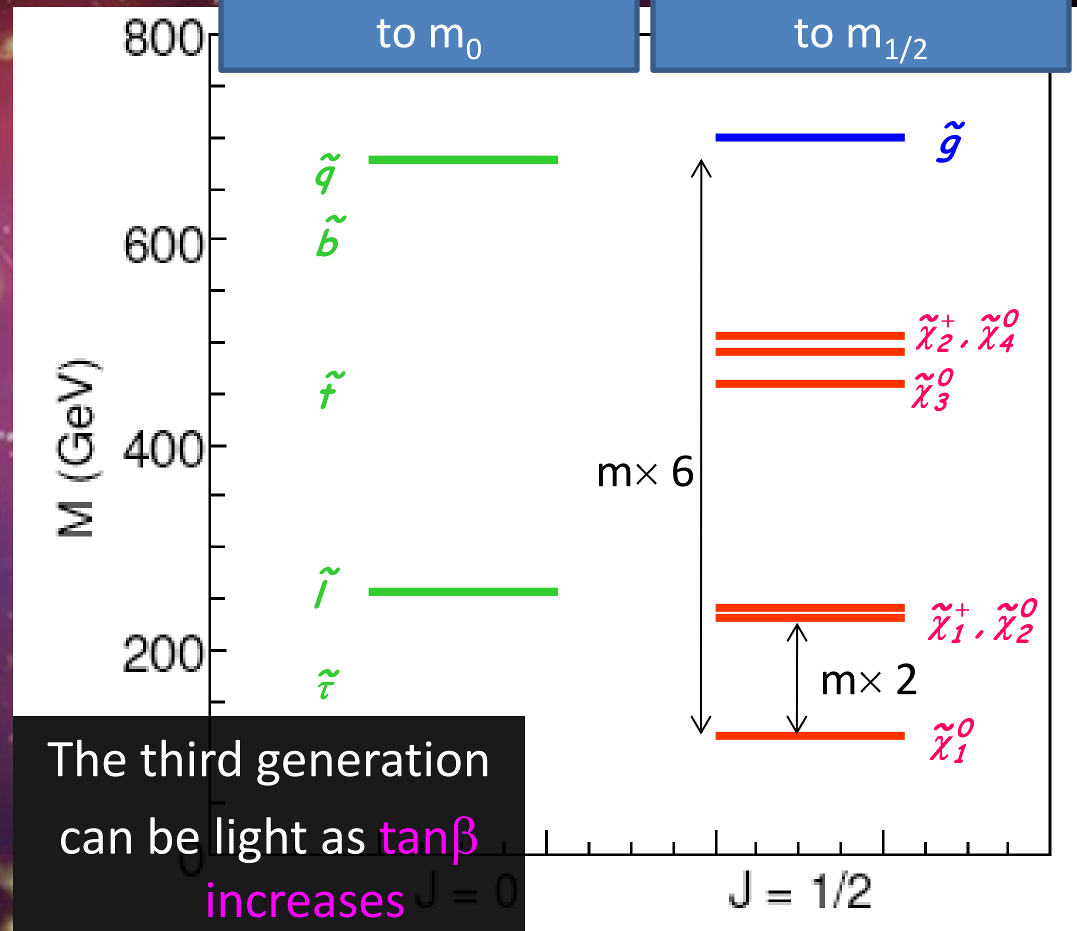


mSUGRA, 5 parameters at GUT scale

1. Unified gaugino mass $m_{1/2}$
2. Unified scalar mass m_0
3. Ratio of H_1, H_2 vevs $\tan\beta$
4. Trilinear coupling A_0
5. Higgs mass term $\mathrm{sgn}(\mu)$

mass proportional to m_0

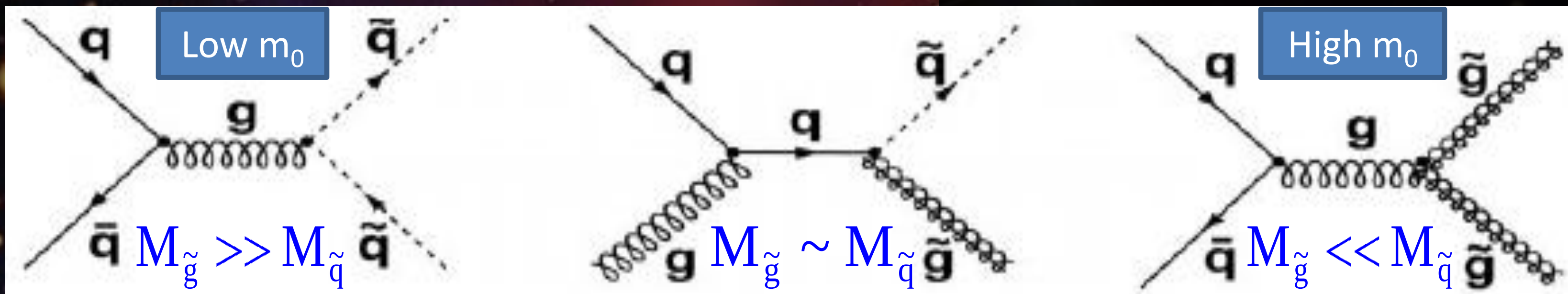
mass proportional to $m_{1/2}$



The third generation can be light as $\tan\beta$ increases

Squark and Gluino (I)

Strong production ⇒ could be abundantly produced! (~ 1 pb)



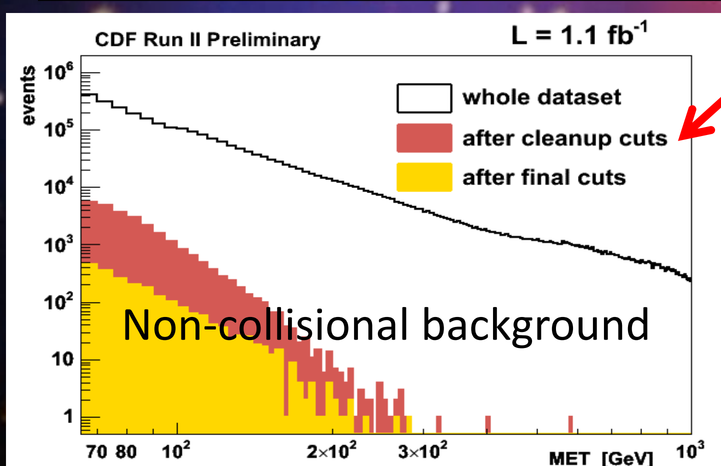
$\tilde{q}_R \to q\, \tilde{\chi}_1^0$

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

2 jets + MET, 3 jets + MET 4 jets + MET

Multiple final states + Unified Analysis best coverage

Main experimental challenge is the expected large background



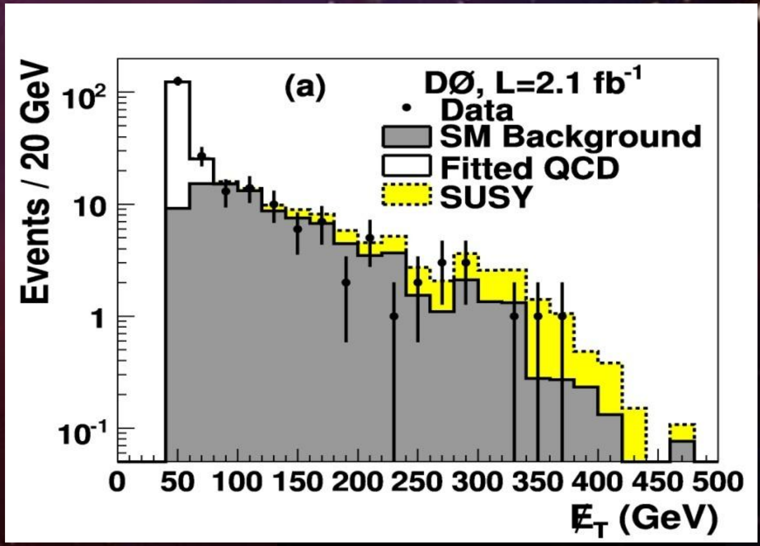
QCD cross sections are up to 10 orders of magnitude larger than SUSY cross sections

Contamination due to mis-measured MET

Squark and Gluino (II)

Background	Estimation	Selection
QCD	(DØ) Fit to low MET in data	Δφ jet-MET
	(CDF) MC tuned to Tevatron data. Normalization to data in low MET	
W/Z+jets	Exclusive n-parton samples normalized to measured xs	Electron/muon veto; isolated track, fraction of jet EM energy
tt, diboson	MC normalized to NLO or NNLO xs	Electron/muon veto

Preselection Cut		All Analyses	
$\not\!\!E_T$		> 40	
|Vertex z pos.|		< 60 cm	
Acoplanarity		$< 165^\circ$	
Selection Cut	"dijet"	"3-jets"	"gluino"
Trigger	dijet	multijet	multijet
jet$_1$ p_T [a]	≥ 35	≥ 35	≥ 35
jet$_2$ p_T [a]	≥ 35	≥ 35	≥ 35
jet$_3$ p_T [b]	–	≥ 35	≥ 35
jet$_4$ p_T [b]	–	–	≥ 20
Electron veto	yes	yes	yes
Muon veto	yes	yes	yes
$\Delta\phi(\not\!\!E_T, \text{jet}_1)$	$\geq 90^\circ$	$\geq 90^\circ$	$\geq 90^\circ$
$\Delta\phi(\not\!\!E_T, \text{jet}_2)$	$\geq 50^\circ$	$\geq 50^\circ$	$\geq 50^\circ$
$\Delta\phi_{\min}(\not\!\!E_T, \text{any jet})$	$\geq 40^\circ$	–	–
H_T	≥ 325	≥ 375	≥ 400
$\not\!\!E_T$	≥ 225	≥ 175	≥ 100

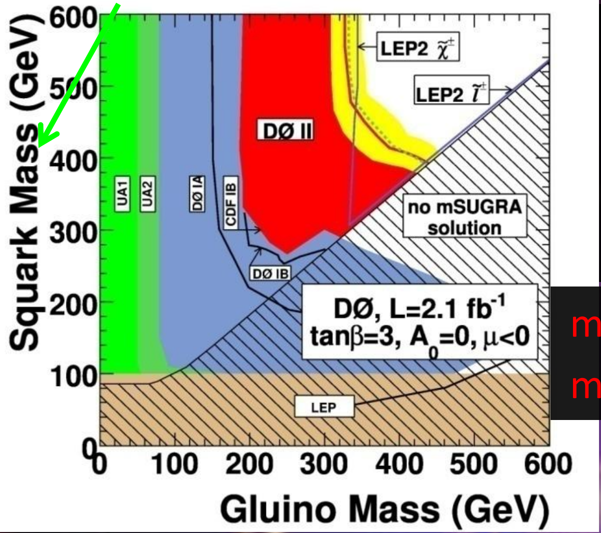


Squark and gluino (III)

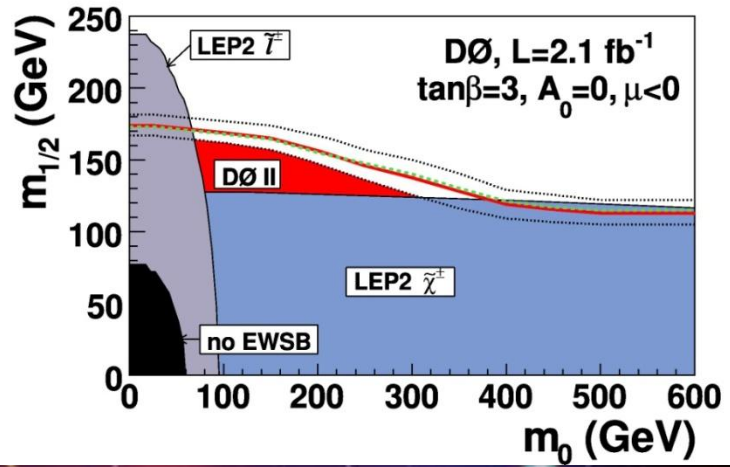
[Phys.Rev.Lett.102 121801 (2009)]

[Phys.Lett.B 660, 449 (2008)]

Average on all squarks (no stop)



Last step consists of invoking the SUSY breaking mechanism



m(squark)<379 GeV

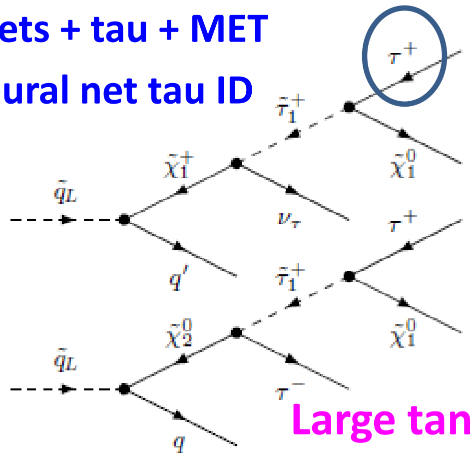
m(gluino)<308GeV

"Tau" corridor

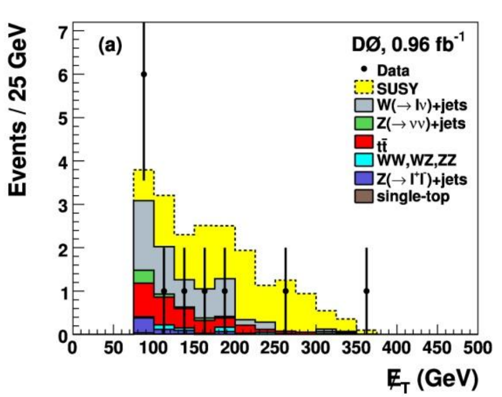
- Stau is lightest slepton $M(\tilde{\tau}_1) < M(\tilde{\chi}_1^{\pm}), M(\tilde{\chi}_2^0)$
- M(squark)<M(gluino) $p\bar{p} \to \tilde{q}_R \tilde{q}_L,\ \tilde{q}_R \to q\tilde{\chi}_1^0$

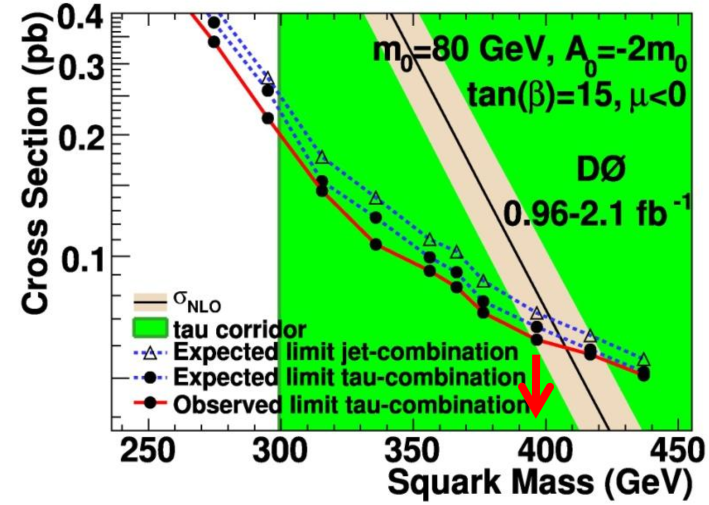
2 Jets + tau + MET

Neural net tau ID



Large tanβ





[Phys.Lett.B 680, 24 (2009)]

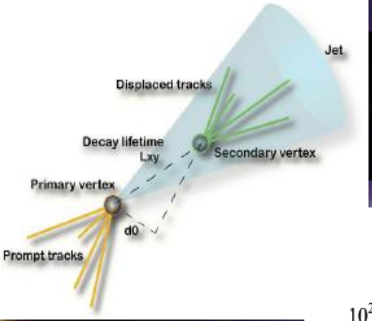
Direct Sbottom production

(~ 0.1pb)

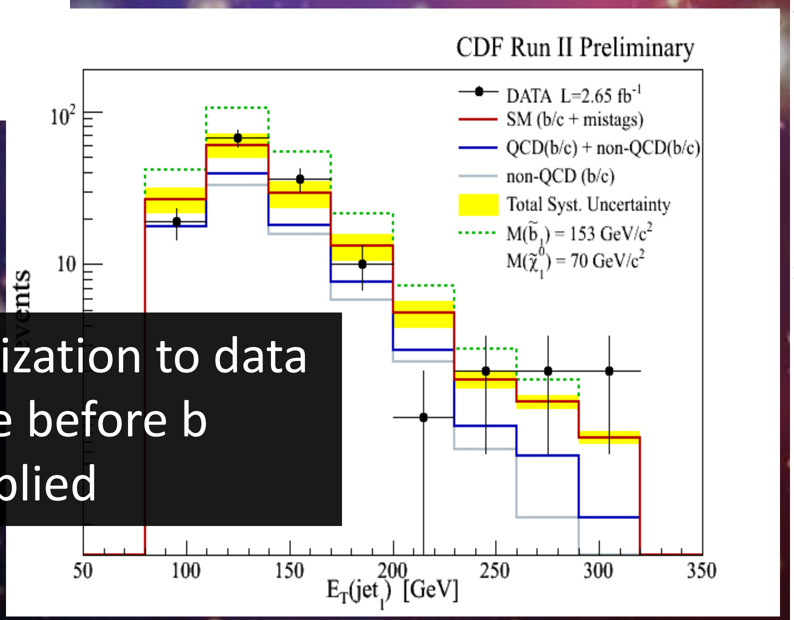
- Direct production $p\bar{p} \longrightarrow \tilde{b}_1\bar{\tilde{b}}_1 \xrightarrow{\text{BR}=100\%} (b\chi^0)\,(b\chi^0)$
- 2 Jets + MET signature
- Search optimized depending on the Δm=m(sbottom)-m(χ)

Gluino mass independent

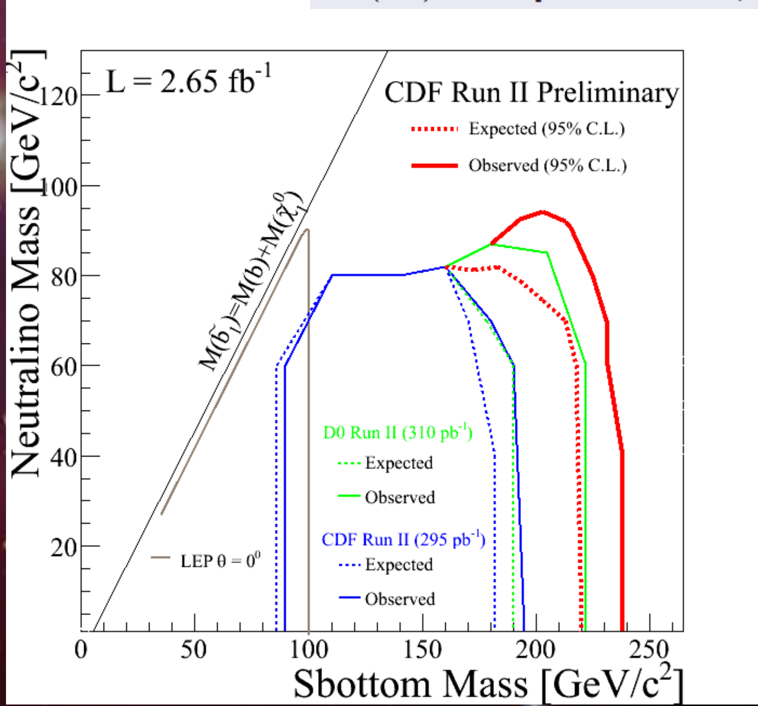
$$M_{\tilde{\chi}_1^0} \in [0 \rightarrow 100 \text{ GeV}]$$
$$M_{\tilde{b}_1} \in [80 \rightarrow 280 \text{ GeV}]$$
$$\sigma(\tilde{b}\tilde{b}) \in [10^{-2} \rightarrow 10^{2} \text{ pb}]$$



b-quarks ID-ed using life time information



QCD: normalization to data in the sample before b tagging is applied



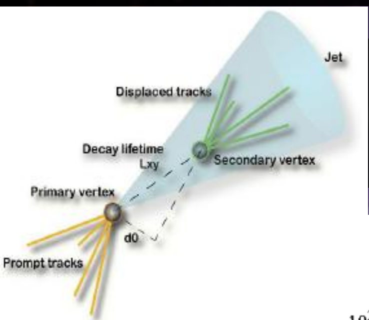
Direct Sbottom production

CDF 9969

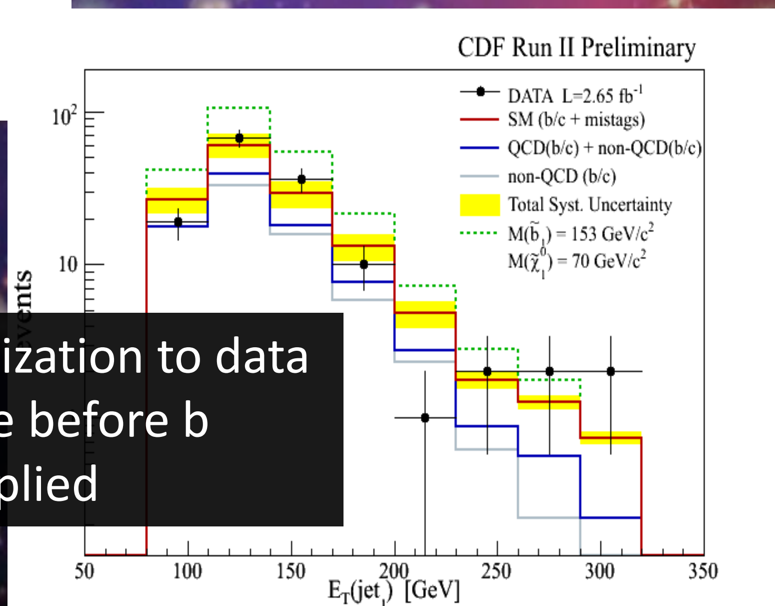
5931-CONF (2009)

- Direct production (~ 0.1pb) $p\bar{p} \longrightarrow \tilde{b}_1\bar{\tilde{b}}_1 \xrightarrow{\text{BR=100\%}} (b\chi^0)\,(b\chi^0)$
- 2 b-Jets + MET signature
- Search optimized depending on the Δm=m(sbottom)-m(χ)

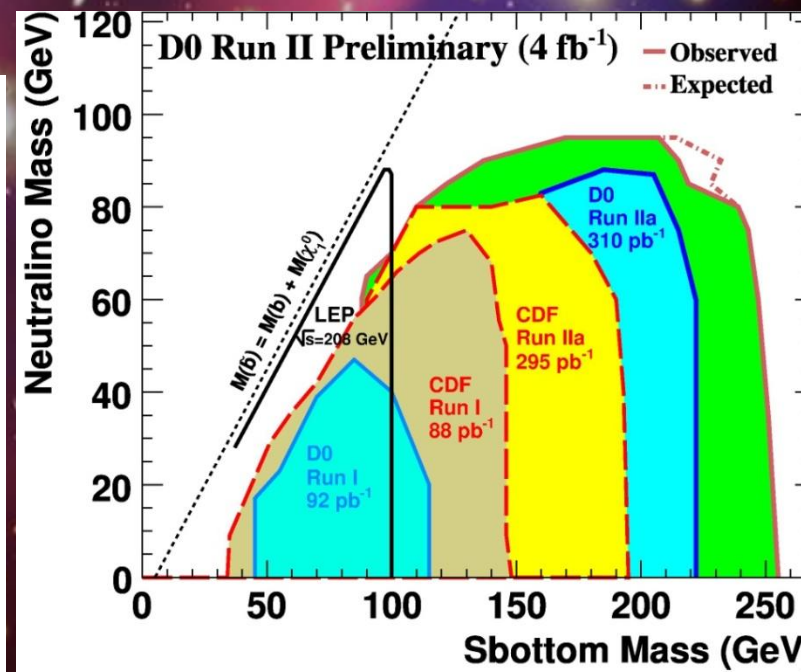
Gluino mass independent



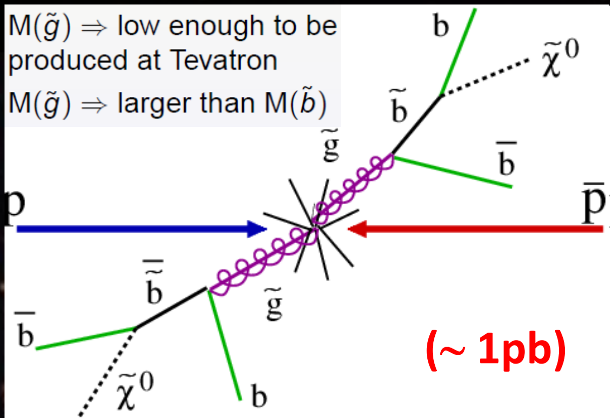
b-quarks ID-ed using life time information



QCD: normalization to data in the sample before b tagging is applied



Gluino mediated Sbottom production

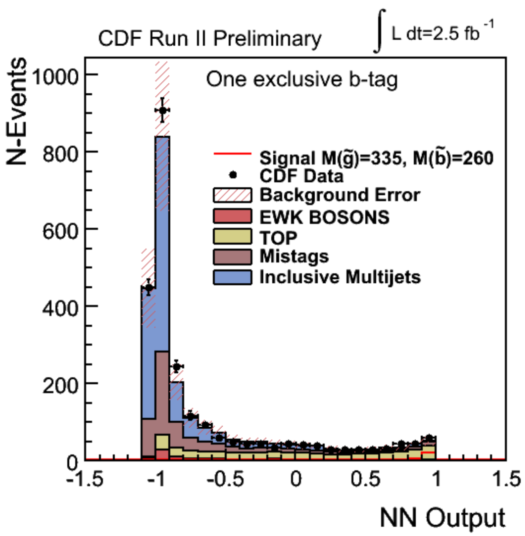


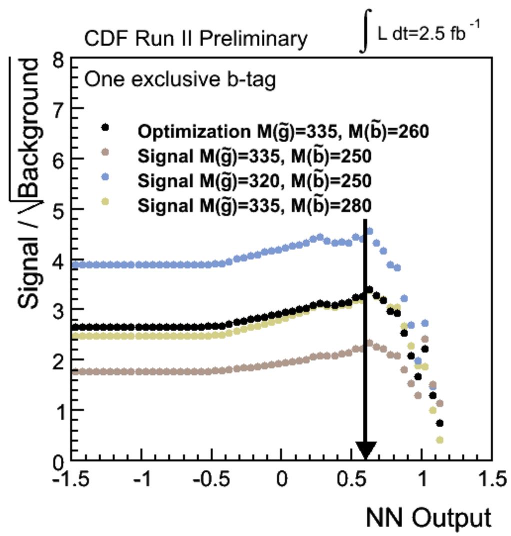
Search optimized depending on Δm=m(sbottom)-m(gluino)

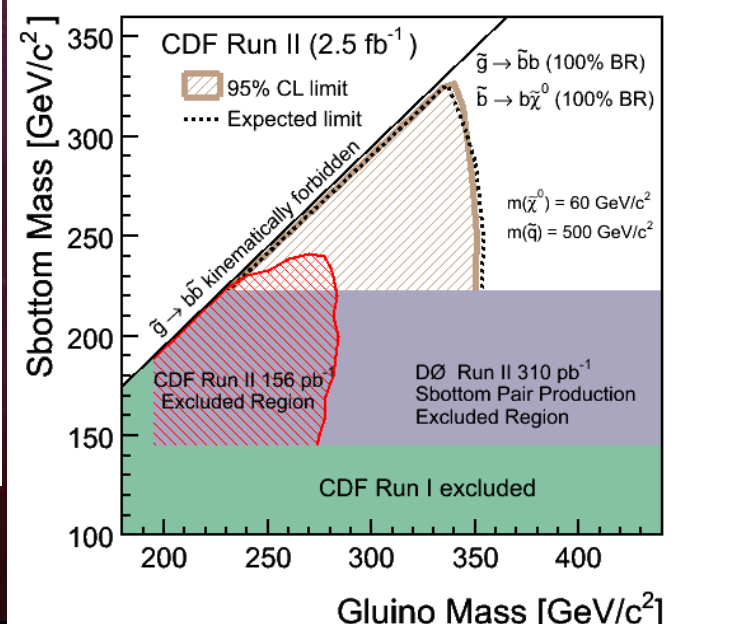
2 b-Jets + MET signature

- Process strongly dependent on the $\tilde{g}$ cross section production
- Test in the SUSY region $m_t, m_{\tilde{\chi}^+} > m_{\tilde{b}} > m_{\tilde{\chi}^0}$
- $\tilde{g} \rightarrow b\tilde{b}$, $\tilde{b} \rightarrow b\tilde{\chi}^0$ with 100% B.R.

$M(\tilde{g})$ = 335, $M(\tilde{b})$ = 260, $M(\tilde{\chi})$ = 60 $\Rightarrow$ Large Δm
$M(\tilde{g})$ = 335, $M(\tilde{b})$ = 315, $M(\tilde{\chi})$ = 60 $\Rightarrow$ Small Δm





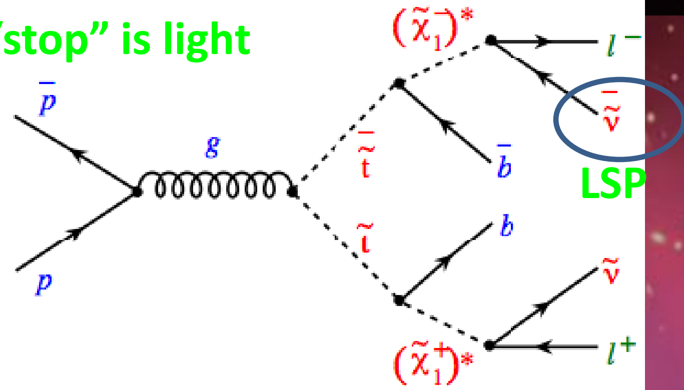


- 1st- Neural Network to remove the QCD background
- 2nd- Neural Network to remove the $t\bar{t}$ background

Stop production (I)

Very rich programme at both CDF and Do!

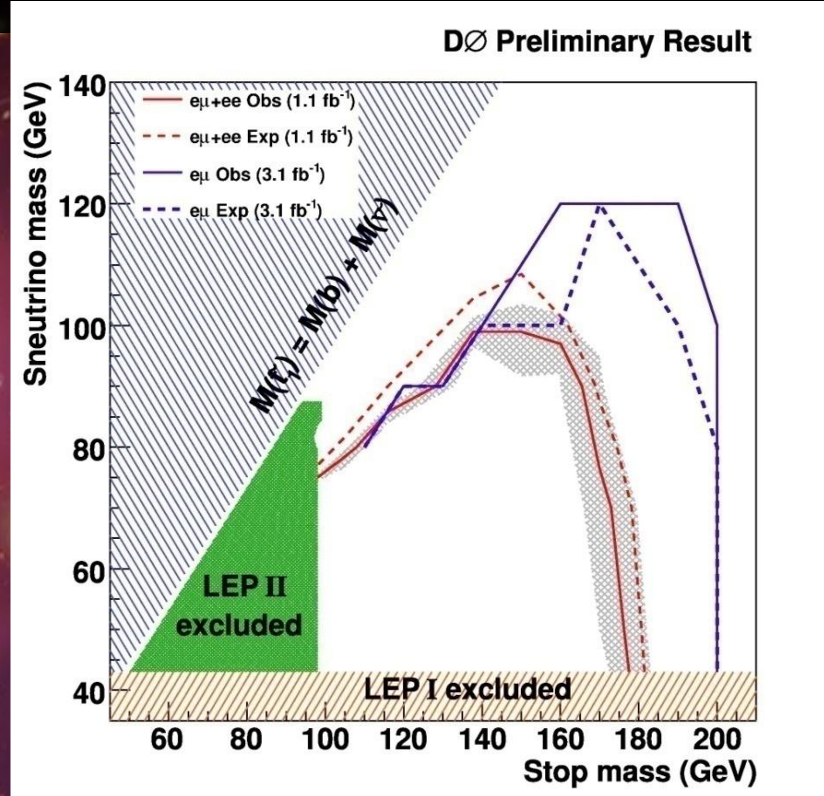
"stop" is light

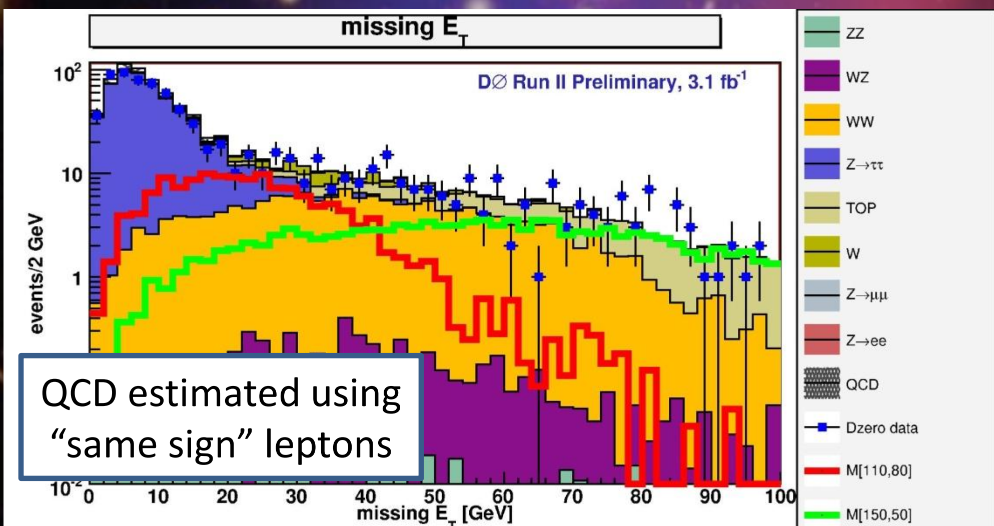


Topology: Δm=m(stop)-m(sneutrino)

Final state:

- CDF (1 fb^{-1}): l^+l^-+N_{jet}>1+MET (ll=ee, μμ, eμ)
- D0 (3.1 fb^{-1}): $e^+\mu^-$+(jets)+MET





QCD estimated using "same sign" leptons

Results at large Δm=m(stop)-m(sneutrino)

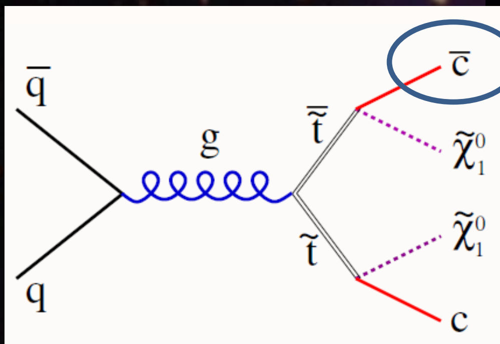
- D0 (3.1 fb^{-1}): m(stop)>200 GeV
- CDF (1 fb^{-1}): m(stop)>180 GeV

5937-CONF (2009)

CDF 9775

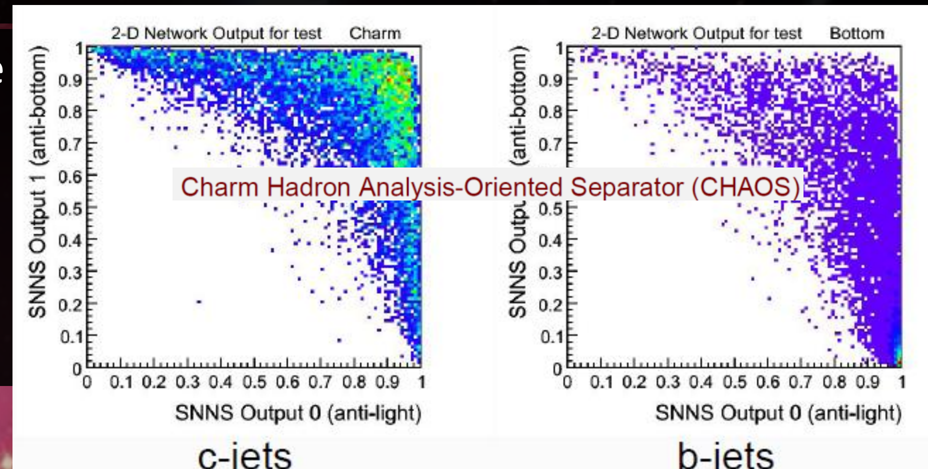
[Phys.Lett.B 665, 1 (2008)](#)
[CDF 9834](#)

Stop production (II)

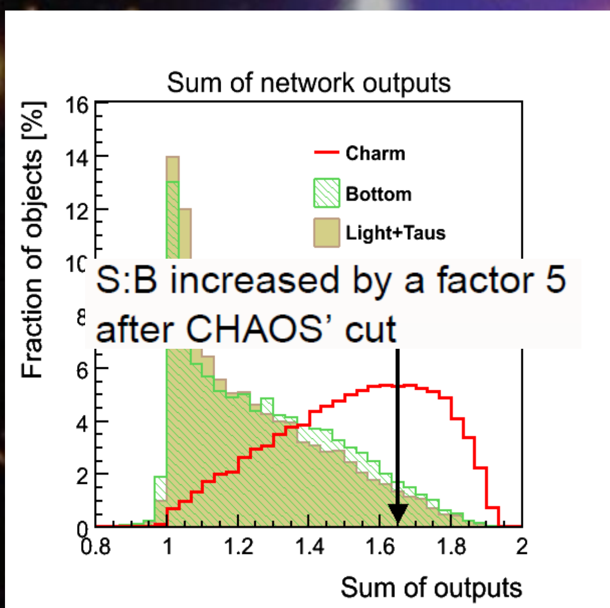


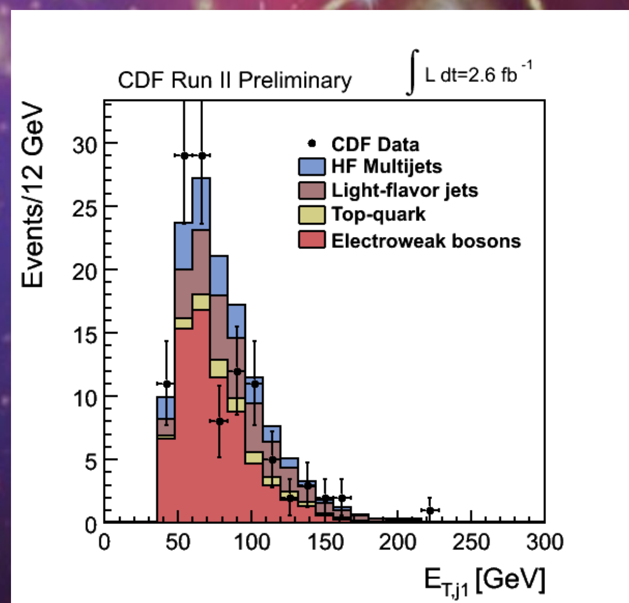
New tagging technique to **ID c-jets**

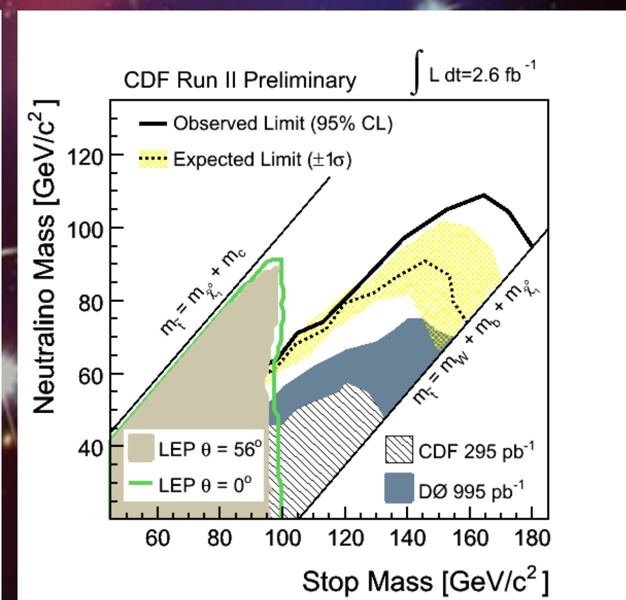
NN with 2D output to distinguish the flavor of the tagged jet



2 c-Jets + MET signature







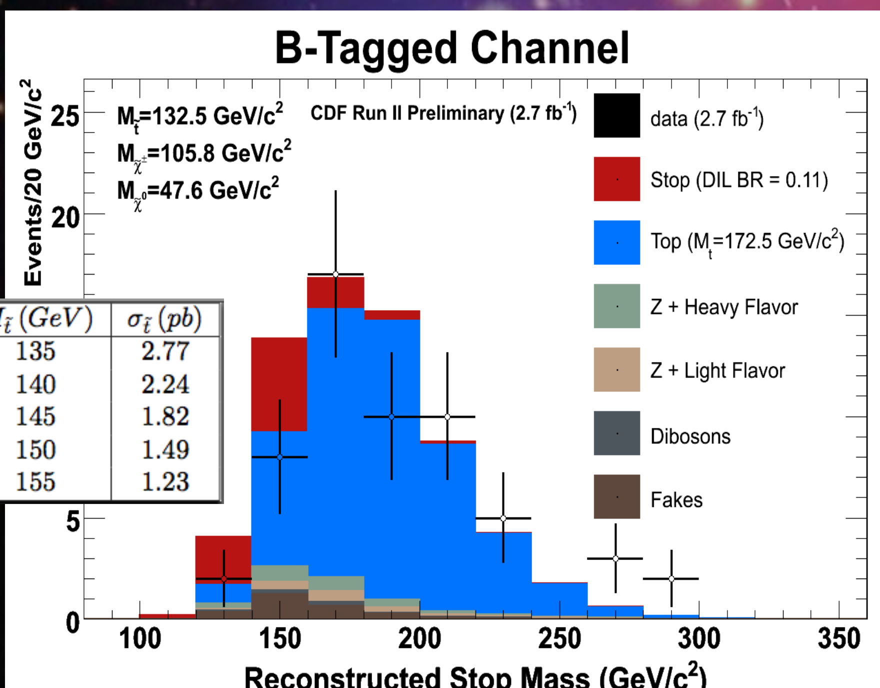
Stop mimicking the SM top

$\tilde{t}_1 \xrightarrow{BR=100\%} b\tilde{\chi}_1^{\pm} \rightarrow$ Variety of χ decay channels $\rightarrow b\tilde{\chi}_1^0 l\nu$

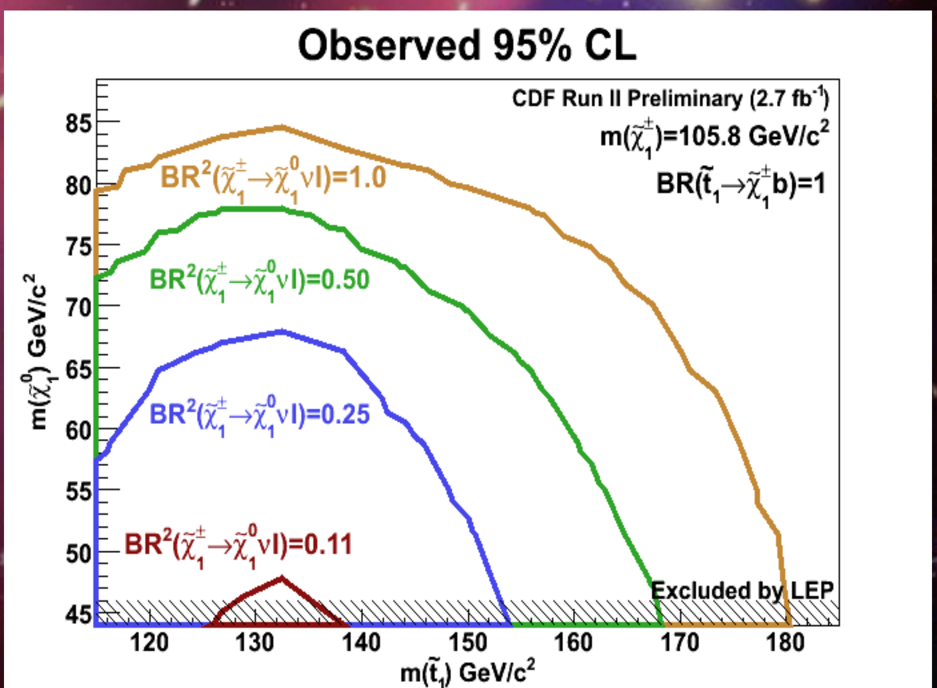
Signatures similar to those of SM top
Potentially be hiding in Tevatron data
Affecting the kinematics of the top events

Reconstruct the stop mass
Kinematical fit

2 leptons, 2 b-Jets + MET signature



$M_{\tilde{t}}$ (GeV)	$\sigma_{\tilde{t}}$ (pb)
135	2.77
140	2.24
145	1.82
150	1.49
155	1.23



Golden Channel!

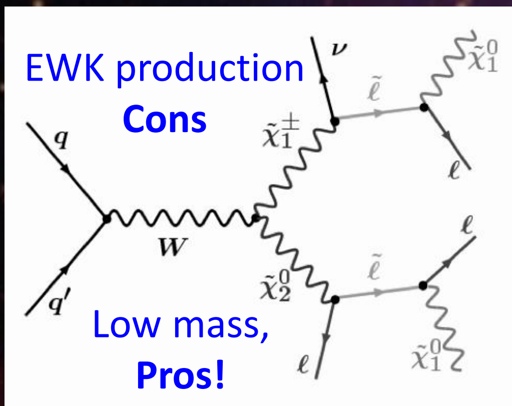
Chargino and Neutralino (I)

Very clean final state with three leptons and MET

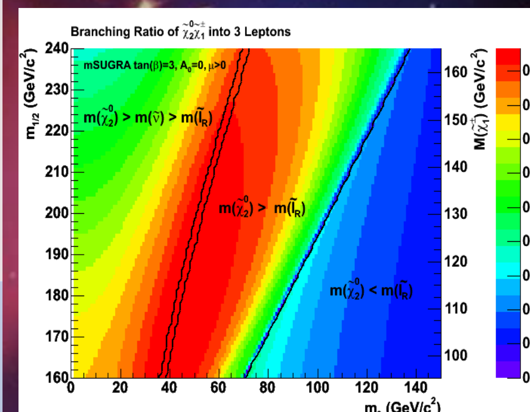
(~ 0.5pb)

EWK production
Cons

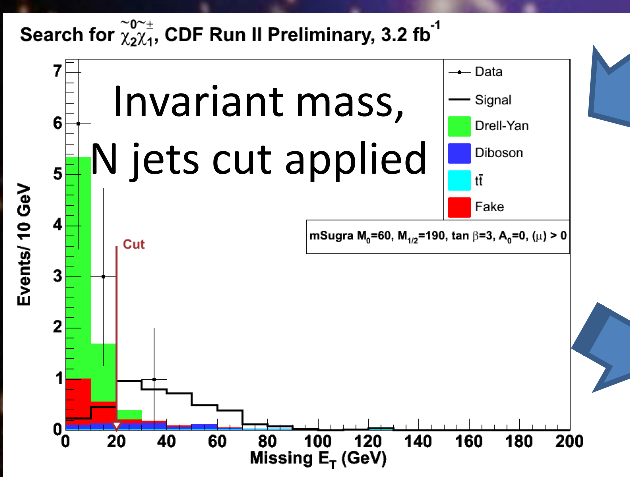
Low mass,
Pros!



Channel	Kinematics
"Tight" and "loose" leptons (electron and muons)	1st lepton: E_T=15-20 GeV; 2nd,3rd lepton: E_T=5-10 GeV
"Tight" leptons (electrons and muons) and ID-ed taus	1st lepton: E_T=12-20 GeV; 2nd,3rd lepton: E_T=4-16 GeV



Invariant mass,
N jets cut applied



Minimal selection applied to suppress the SM background but retaining most of the SUSY signal

CDF II Preliminary, 3.2 fb^{-1}

	$Z\to ee$	$Z\to\mu\mu$	$Z\to\tau\tau$	WW	WZ	ZZ	$t\bar{t}$	Fakes	Total Background	Signal Point	Observed
ttt	0.19	0.00	0.00	0.02	0.38	0.08	0.02	0.16	0.83 ± 0.18	3.64 ± 0.53	1
ttC	0.00	0.06	0.00	0.00	0.21	0.07	0.00	0.04	0.39 ± 0.08	2.62 ± 0.39	0
tll	0.00	0.00	0.08	0.00	0.10	0.03	0.01	0.03	0.25 ± 0.08	1.12 ± 0.19	0
Trilepton	0.19	0.06	0.08	0.02	0.69	0.18	0.03	0.23	1.47 ± 0.21	7.38 ± 0.68	1
ttT	1.33	0.27	1.10	0.53	0.24	0.11	0.29	1.98	5.85 ± 1.25	7.15 ± 0.96	4
tlT	0.83	0.60	0.52	0.40	0.07	0.07	0.14	0.91	3.53 ± 0.72	4.06 ± 0.57	2
Dilepton + Track	2.16	0.87	1.62	0.93	0.31	0.18	0.43	2.89	9.38 ± 1.44	11.21 ± 1.12	6

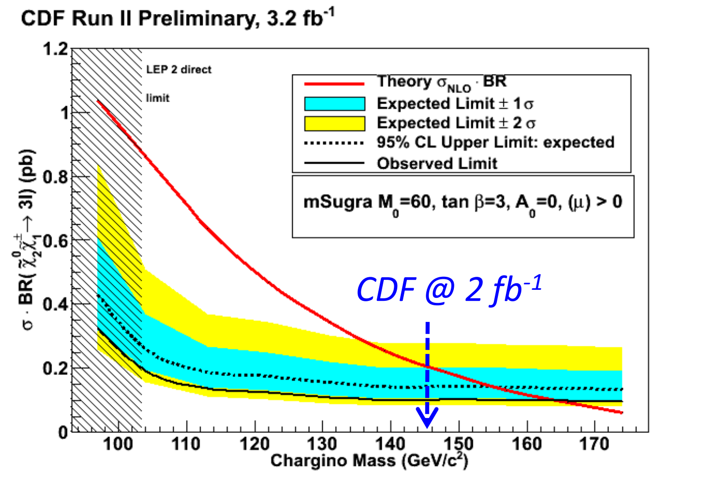
mSugra Signal point: $M_0 = 60, M_{1/2} = 190, \tan\beta = 3, A_0 = 0$

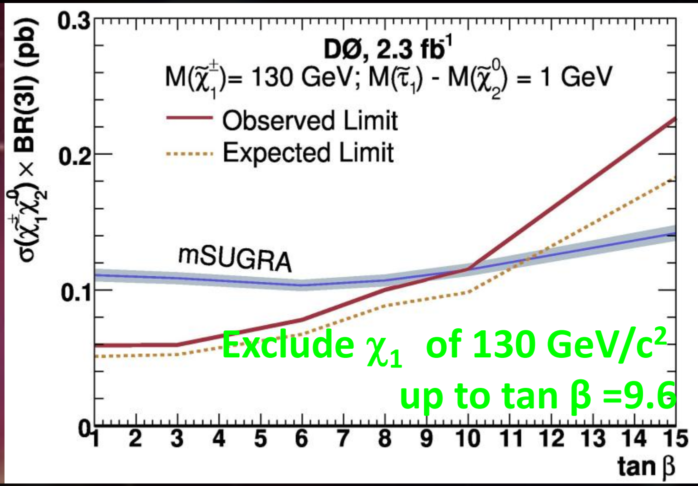
Chargino and Neutralino (II)

Phys.Rev.B 680 34 (2009)

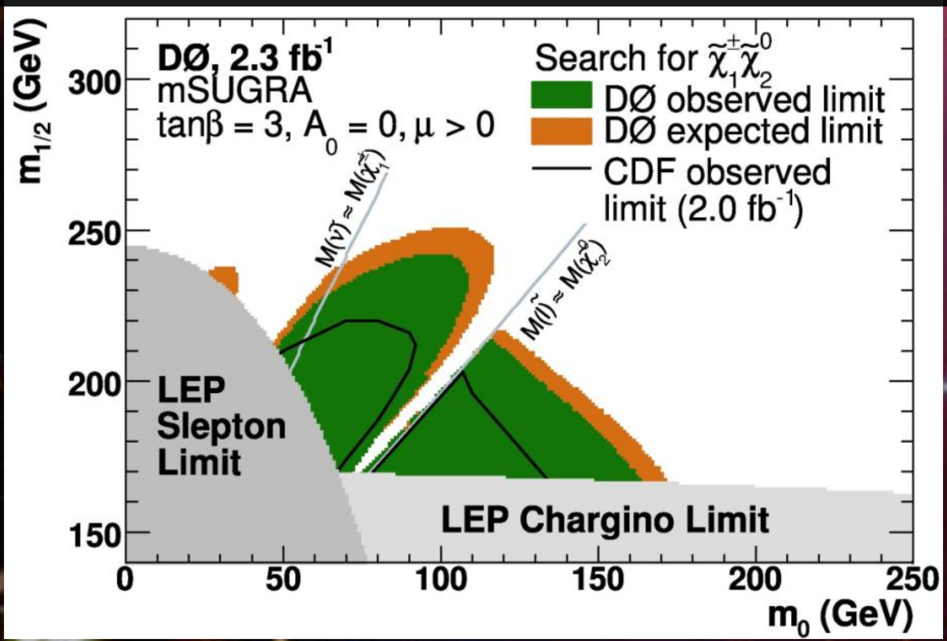
PRL 101, 251801(2008)

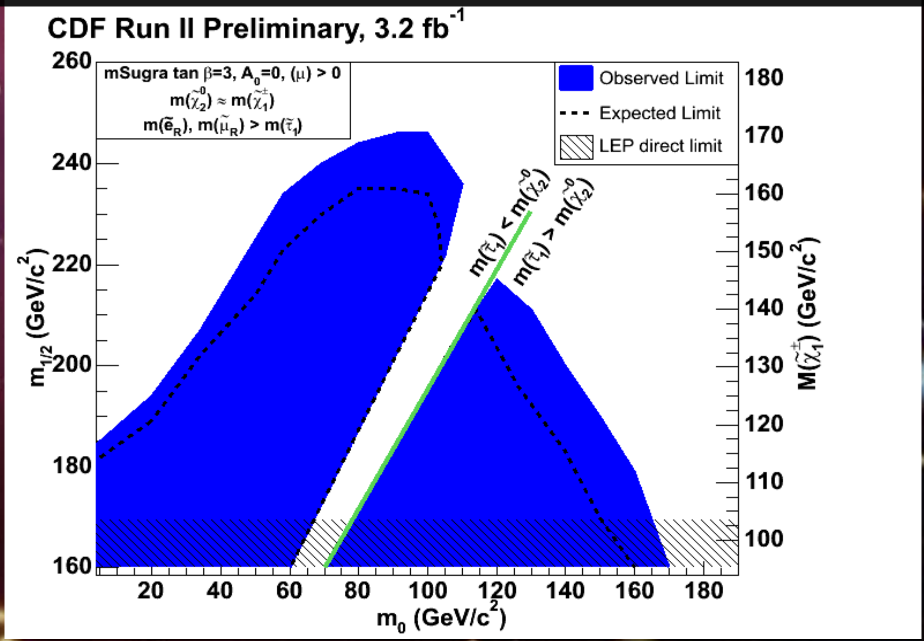
3.2/fb CDF 9817



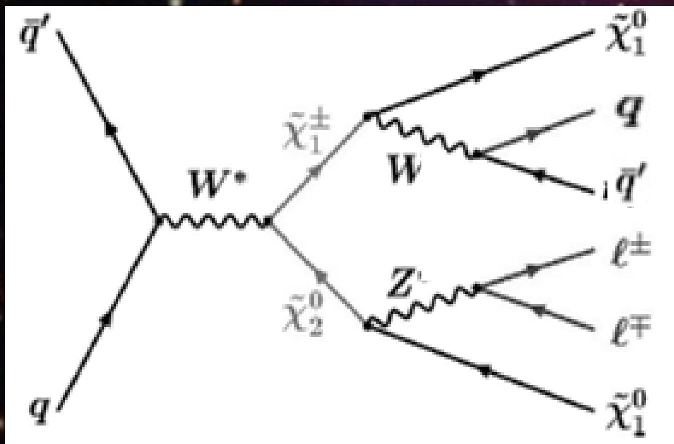


CDF: $m\chi^{\pm}_1 < 164$ (155 Exp.) GeV/c^2 *in the same scenario* (with 2.3 fb^{-1}) , DØ : $m\chi^{\pm}_1 < 155$ (160 Exp.) GeV/c^2





Heavy charginos & neutralinos

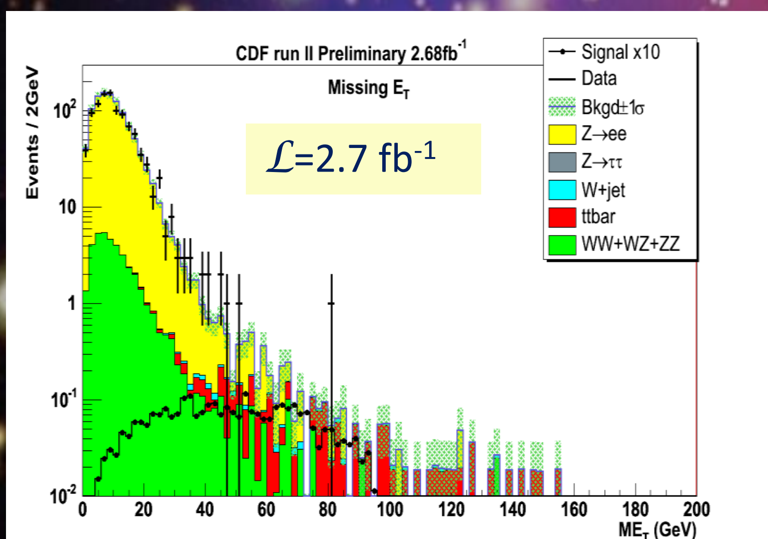


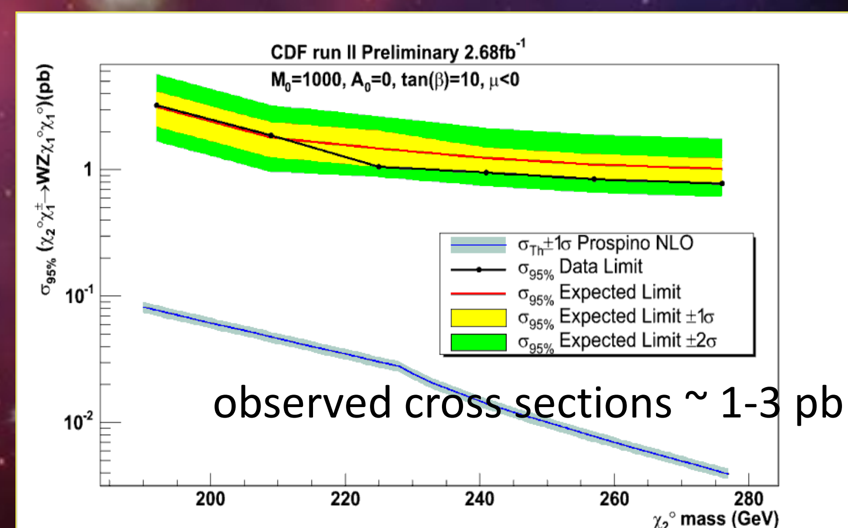
Signature of 2 leptons + MET

(2 leptons in the Z invariant mass window)

If MET > 40 GeV: data 7 events,

Exp. Background 6.41 $\pm$ 0.95

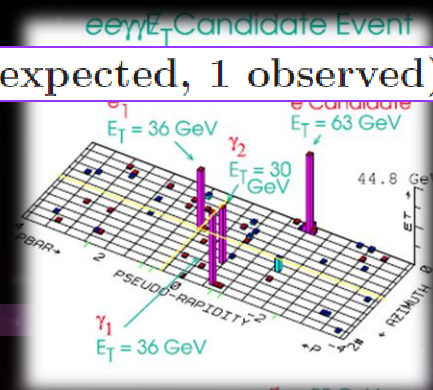




observed cross sections ~ 1-3 pb

WARM Dark Matter scenarios

Run I $ee\gamma\gamma \not{E}_T$ (10^{-6} expected, 1 observed)



GMSB

1. Λ SUSY breaking scale
2. Messanger mass scale (Λ /2)
3. N number of messanger (1)
4. C_G gravitino mass factor (free)
5. Ratio of H_1, H_2 vevs tanβ (15)
6. Higgs mass term sgn(μ) (>0)

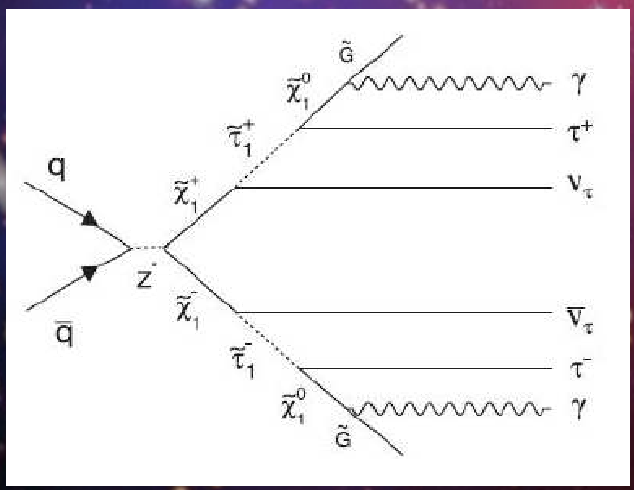
Scenario considered:

- LSP is the "gravitino
- NLSP is neutralino (lifetime → order ns)

Mass and lifetime of χ drive the search strategy

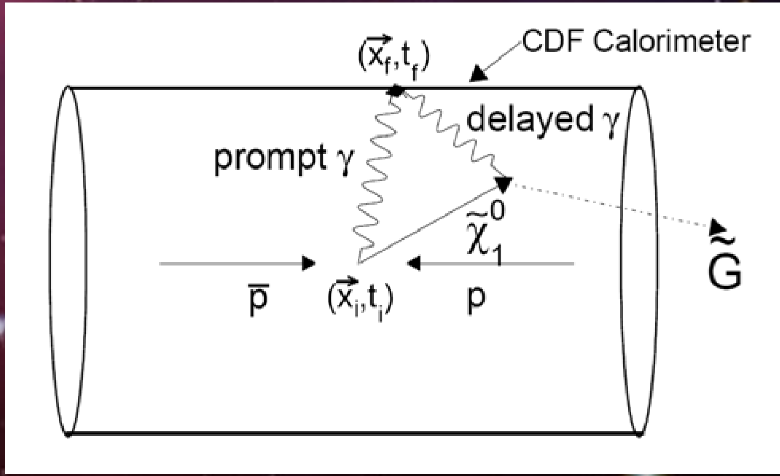
$\sigma(\chi\chi) \approx 25-45\%$ of σ_{GMSB}

if m(squark, gluino) $= 600-800$ GeV



Long life time → delayed photons

Short life time → Prompt Photons

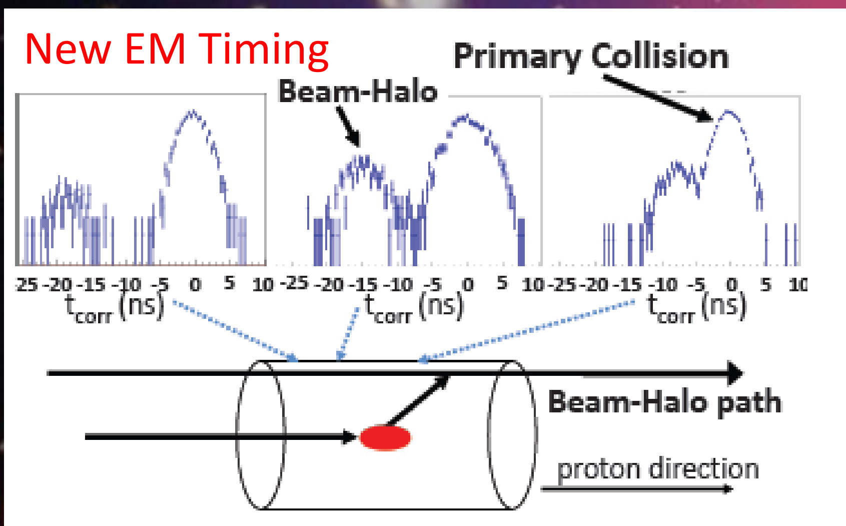


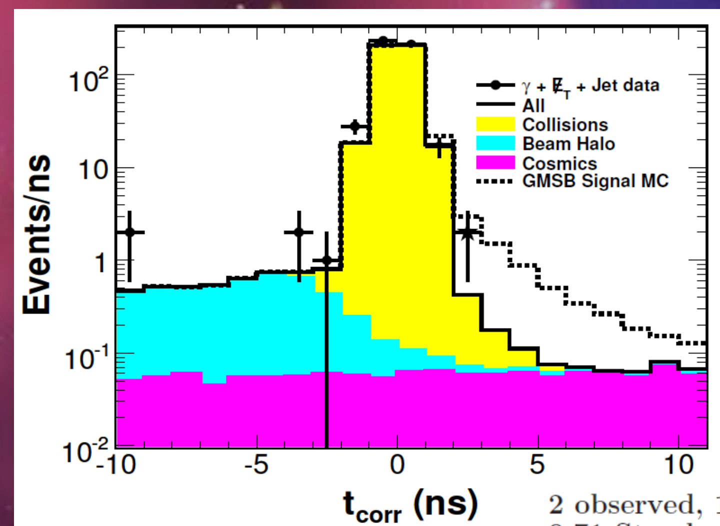
Long lived neutralino (I)

Cosmological constraints favor a gravitino with keV mass and lifetime ~ nanoseconds

Long lived ⇒ γ + Jet + MET Signature
- Discriminating variable: arrival time at EMTiming system

Photon E_T:	30 GeV
$\not{E}_T$:	40 GeV
Jet E_T:	35 GeV
$\Delta\phi$:	1.0 rad
t_{min}:	2.0 ns



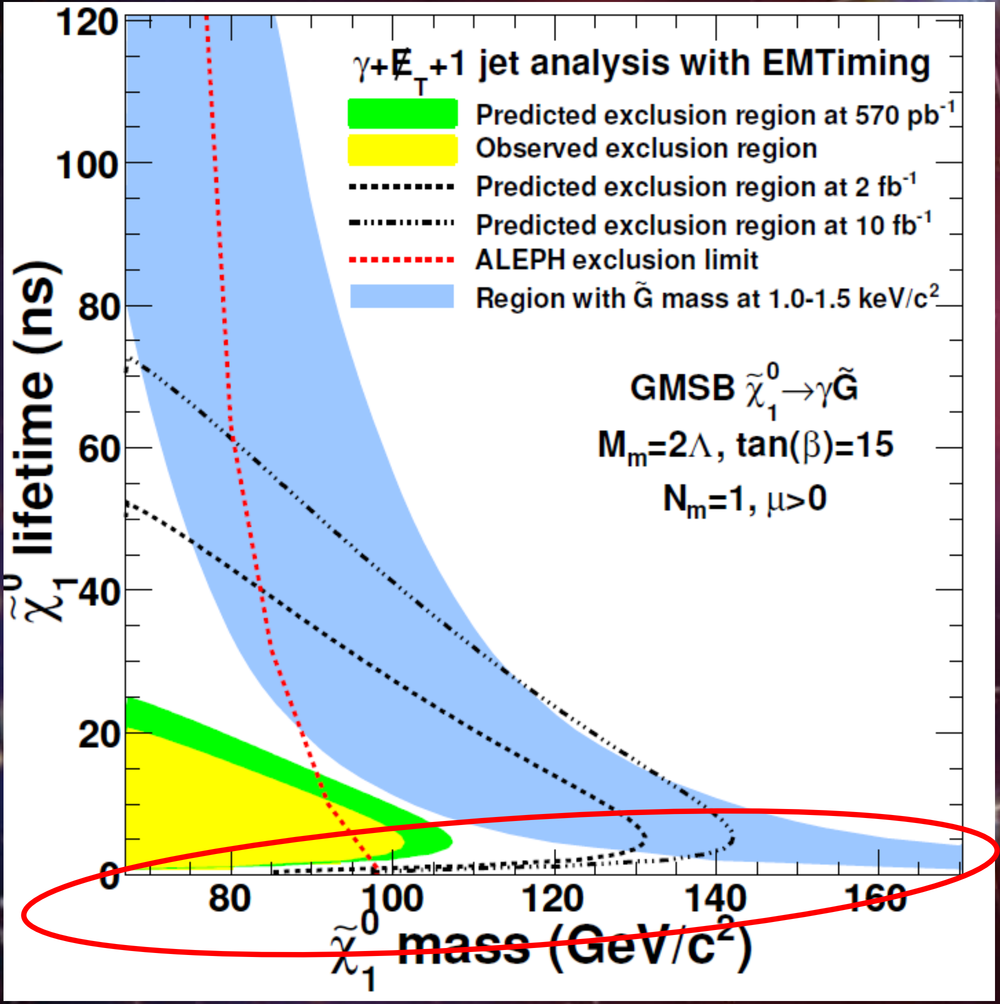


2 observed, 1.3 ± 0.7 expected
0.71 Standard Model,
0.46 Cosmics, 0.07 Beam Halo

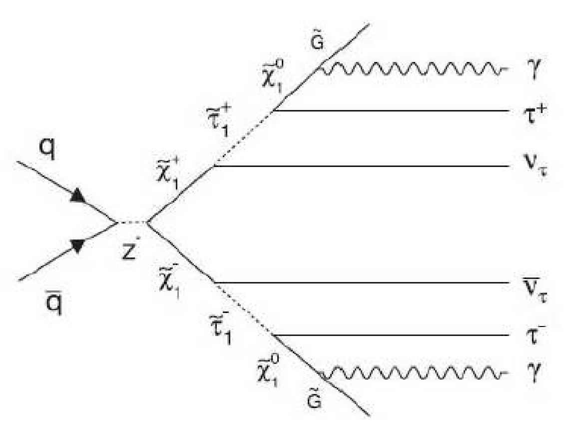
- Collision background: SM processes (estimated from timing of W→eν events)
- Non Collision background: Beam halo, cosmics (distinguished using the E deposit in "non collision" events and the arrival time)

Long lived neutralino (II)

PRD 78, 0321015 (2008)
PRL 99, 121801 (2007)

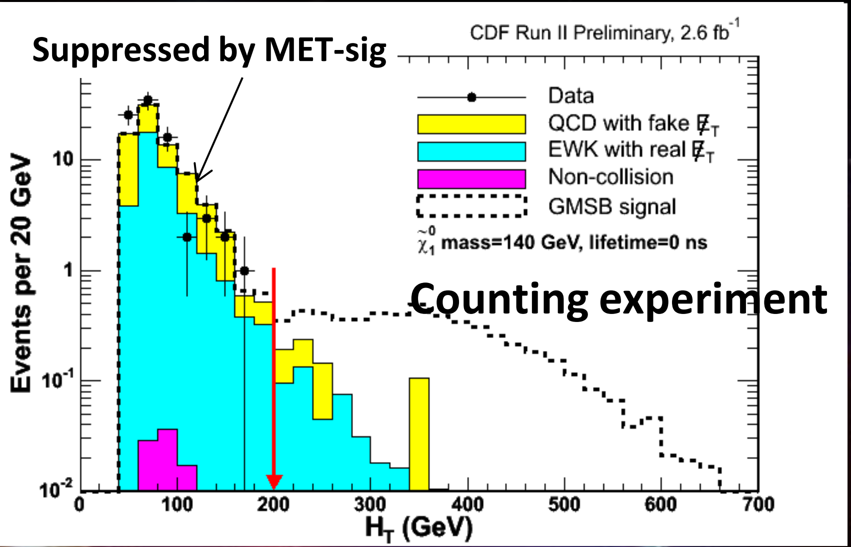


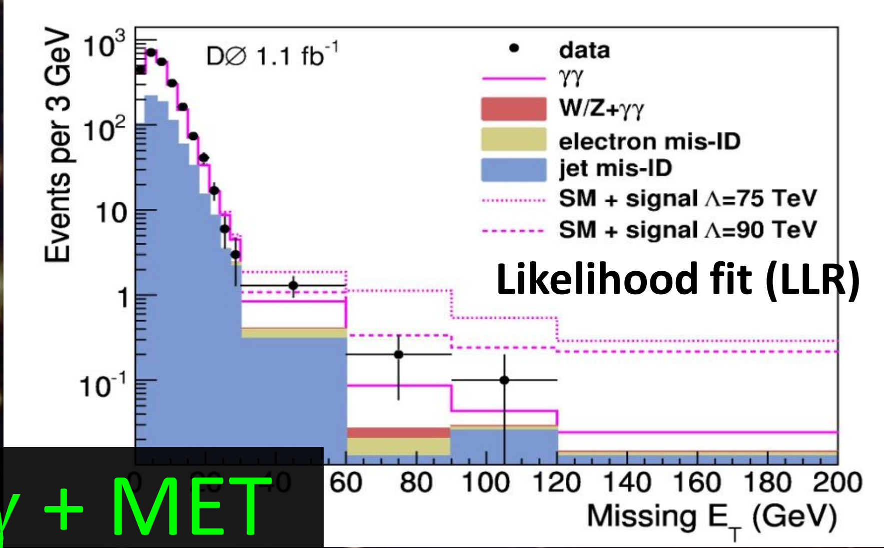
γ + jet + MET



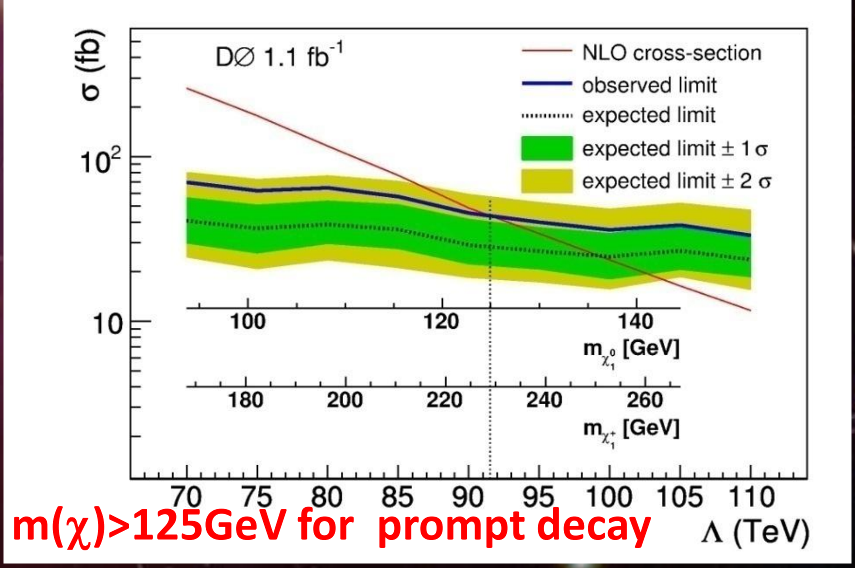
Short lived neutralino (I)

- Background suppression
  - Large MET (D0), MET-Sig (CDF) for fake MET
  - Angular distribution to suppress wrong vertex and SM processes
- Technique
  - EM Pointing (D0)
  - EM Timing (CDF), MET Model (CDF)





γ γ + MET



m(χ)>125GeV for prompt decay

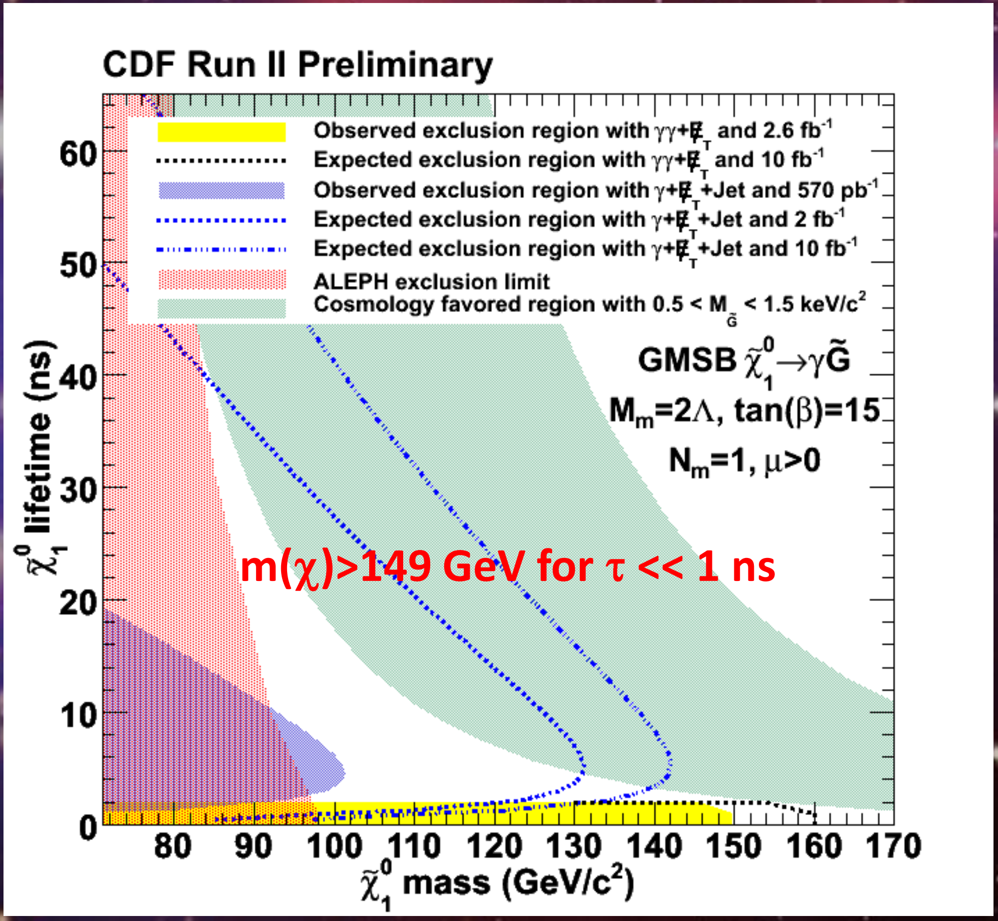
Short lived neutralino (II)

PRL 104, 011801 (2010)

Phys.Lett.B, 856 (2008)

- CDF: projections are calculated assuming linear scaling of background with luminosity (uncertainty fractions remain constant)

γ γ + MET

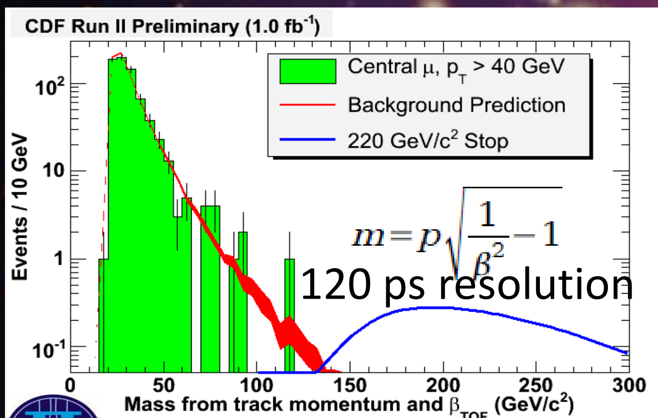


Long lived

- Long lived particles predicted in a variety of DM models

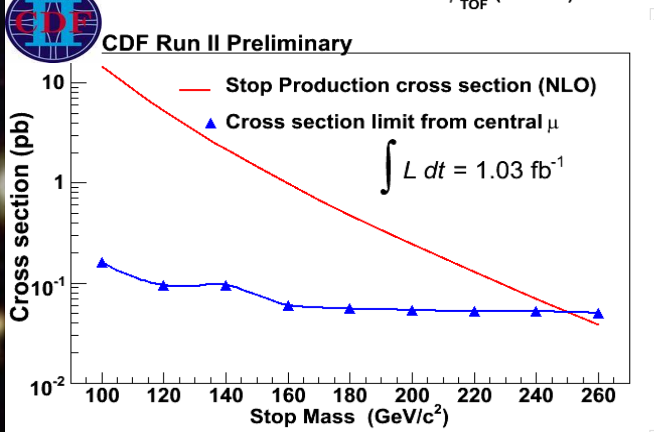
Anomaly mediated SUSY, GMSB
Split SUSY, ED

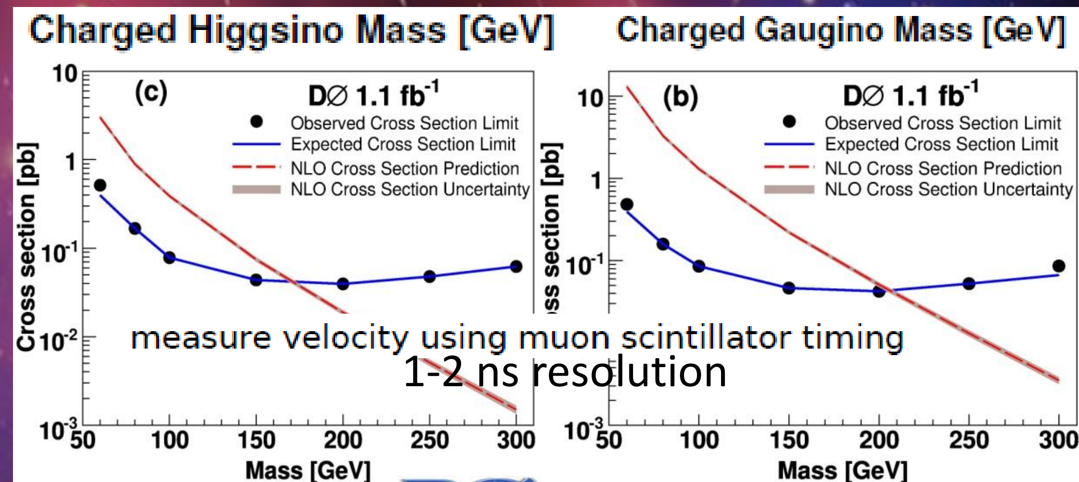
  - Long life time ⇐ Weak couplings, Kinematical constraints, New symmetries
- Dedicated searches have sensitivity up to ~ 10 ns



$$m = p\sqrt{\frac{1}{\beta^2} - 1}$$

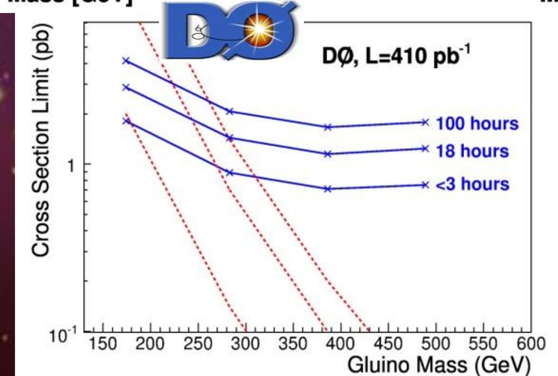
120 ps resolution





measure velocity using muon scintillator timing

1-2 ns resolution

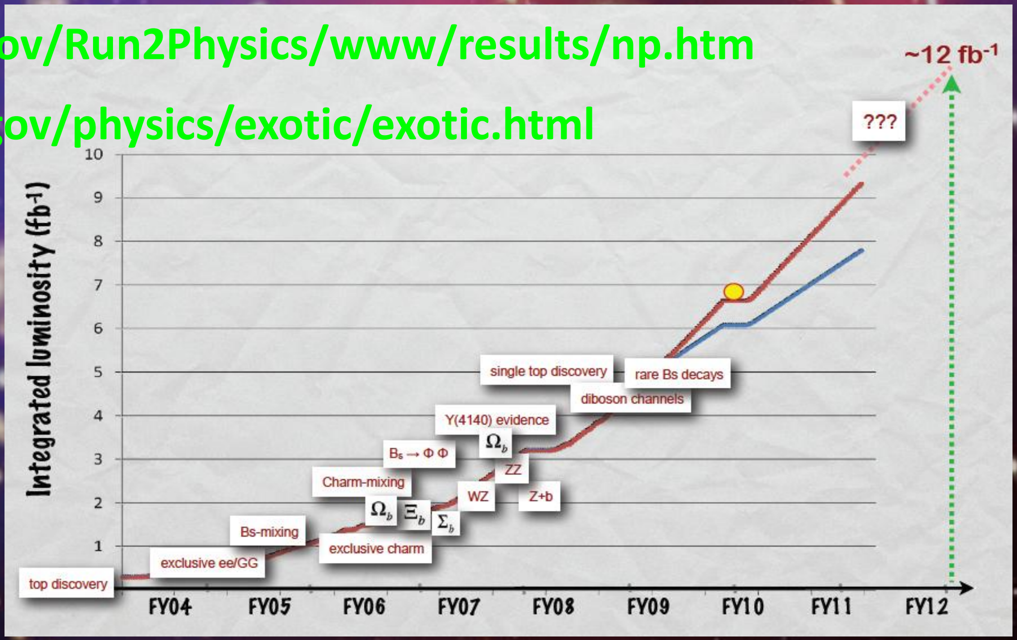


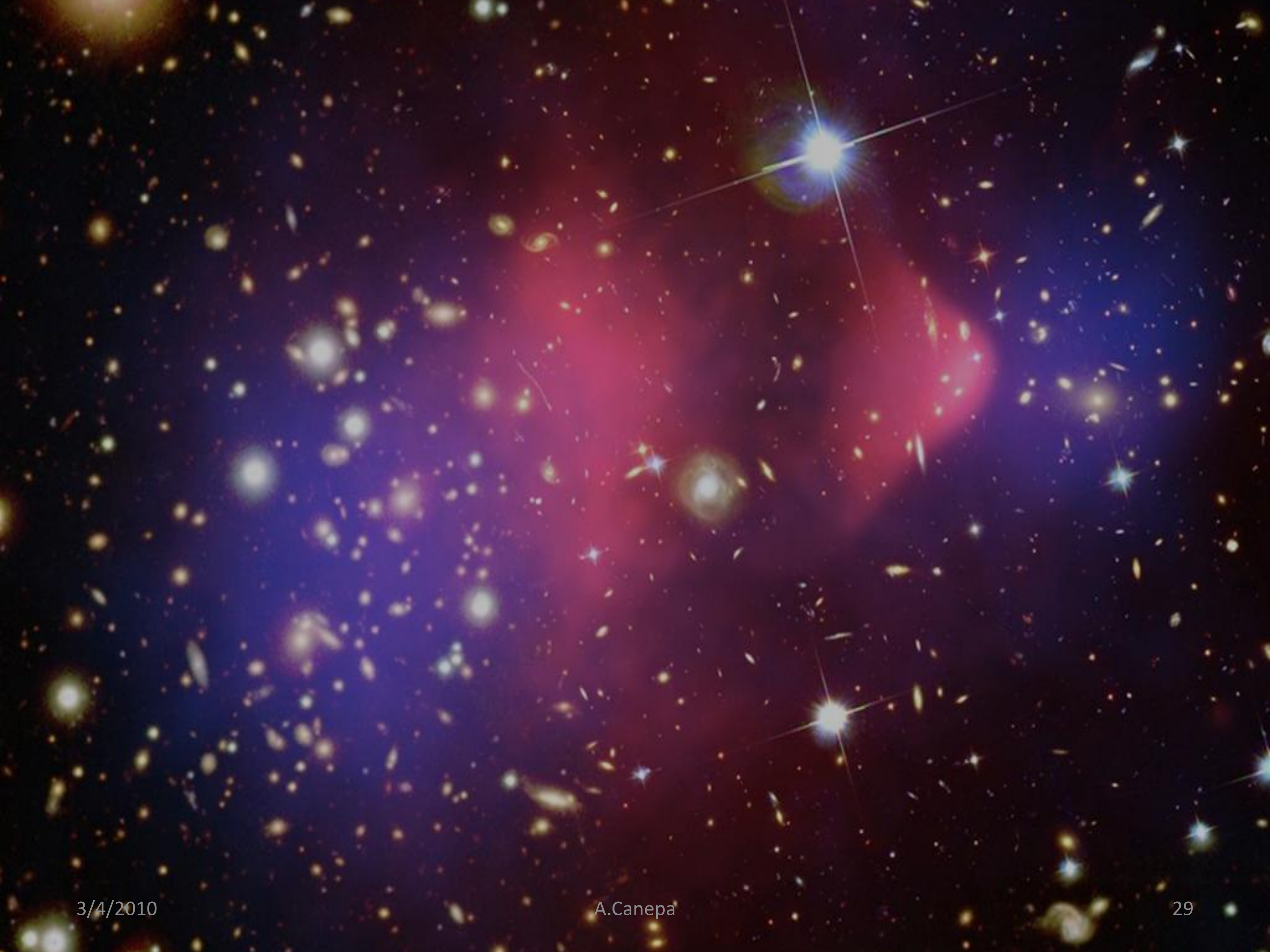
Summary

- Very rich programme for Dark Matter at the Tevatron (up to 5/fb)
  - Searches for neutralino, sneutrino, gravitino
  - Unfortunately no signs of SUSY DM yet
  - World's best mass limits on gauginos and sfermions
- More data will be cumulated in the next years!

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

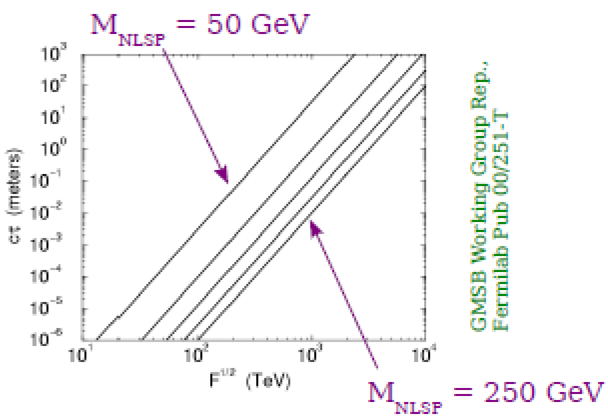
http://www-cdf.fnal.gov/physics/exotic/exotic.html





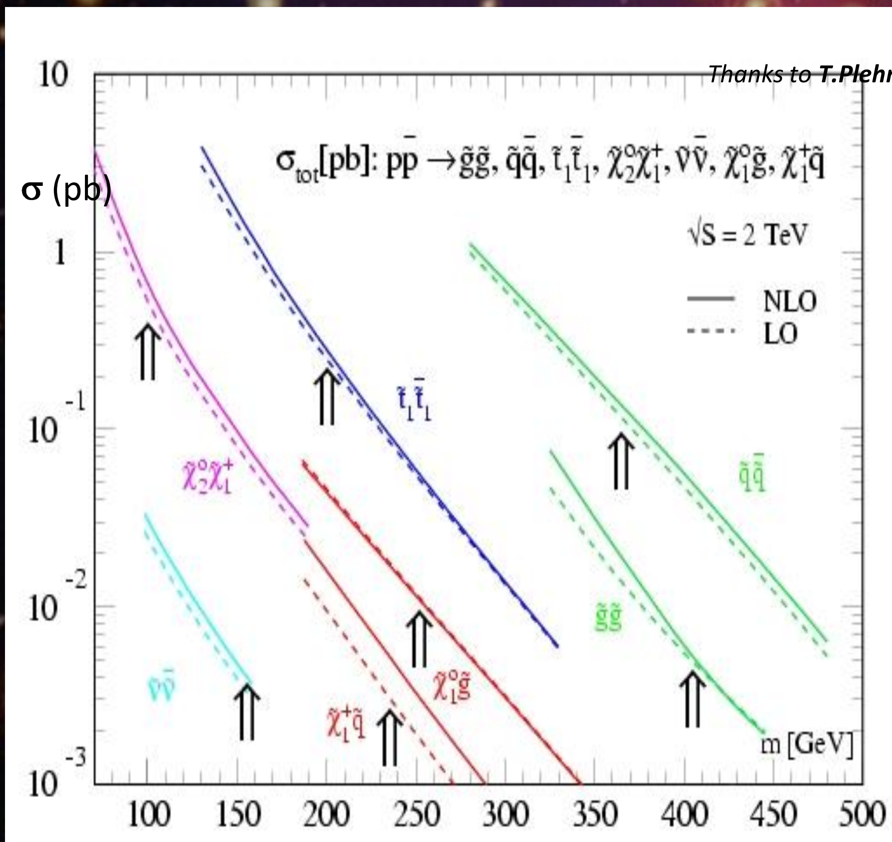
CHAMPS Models

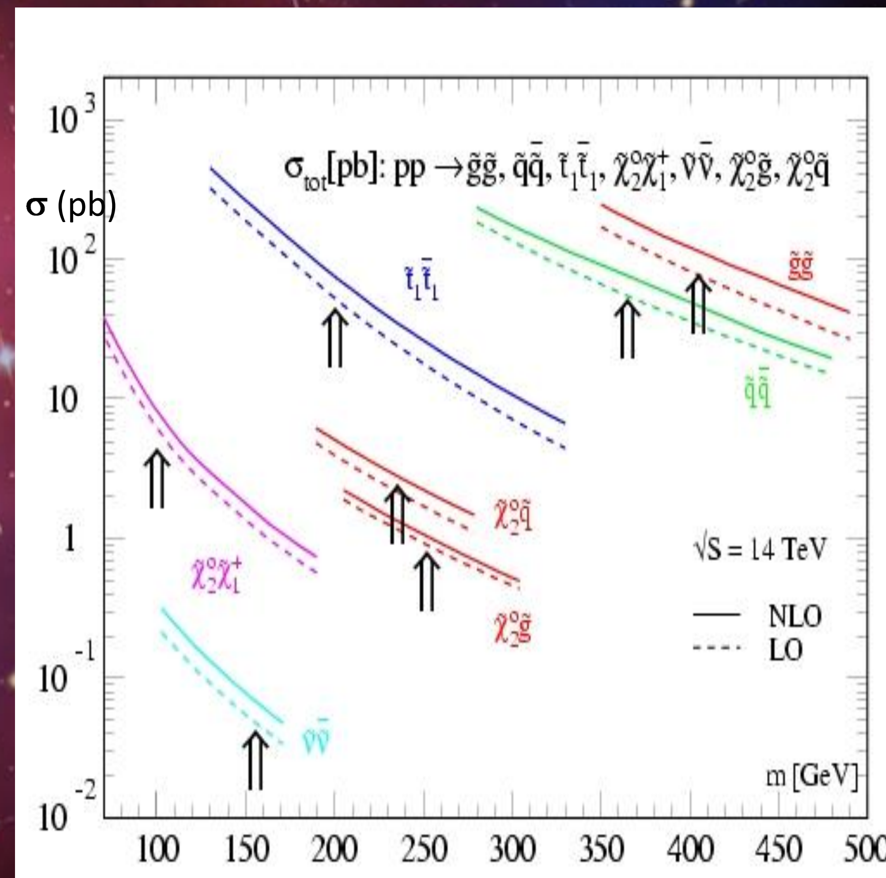
- Anomaly-mediated SUSY breaking
  (Randall, Sundrum Nucl. Phys B 557, 79 (1999); Giudice, et al., JHEP 9812, 027 (1998), ...)
  - Lightest chargino and neutralino nearly degenerate
    - $\tilde{\chi}_1^+ \rightarrow \pi^+ \tilde{\chi}_1^0$ (the LSP) kinematically forbidden
- Gauge-mediated SUSY breaking
  (see Giudice and Rattazzi, Phys. Rept. 322, 419 (1999))
  - Coupling of NLSP (typically the stau) to gravitino LSP can be very small
    - Lifetime $\propto$ (SUSY breaking scale)^4
    - SUSY breaking scale is unconstrained



- Split-SUSY
  (N. Arkani-Hamed, S. Dimopoulos, JHEP 0506, 073 (2005)
  - Gluino decay mediated by very high mass squarks
- Extra dimensions
  (Many authors, e.g., Barbieri, Hall, Nomura, Phys. Rev D63, 105007 (2001))

Cross Section at Tevatron/LHC





Mass (GeV/c²)