Physics Program

of the experiments at

Large Hadron Collider

Lecture 13

- **Supersymmetry**
  - **Tevatron limits**
  - **LHC analyses so far**

Supersymmetry

The idea: particle physics is symmetric under transformation of Fermion ↔ Boson

→ one supersymmetric partner for each SM particle

→ stabilizes Higgs mass, unification of coupling constants, dark matter candidate

Superpartners are heavy → SUSY is broken → masses unknown

Prediction:

- Extended Higgs sector: 5 Higgs bosons h,H,A,$H^{\pm}$
- Many new particles: Charginos/Neutralinos/Gluinos, Squarks, Sleptons

Names		spin 0	spin 1/2
squarks, quarks (×3 families)	Q	$(\widetilde{u}_L \quad \widetilde{d}_L)$	$(u_L \quad d_L)$
	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$
sleptons, leptons (×3 families)	L	$(\widetilde{\nu} \quad \widetilde{e}_L)$	$(\nu \quad e_L)$
	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$
Higgs, higgsinos	H_u	$(H^+_u \quad H^0_u)$	$(\widetilde{H}^+_u \quad \widetilde{H}^0_u)$
	H_d	$(H^0_d \quad H^-_d)$	$(\widetilde{H}^0_d \quad \widetilde{H}^-_d)$

Names	spin 1/2	spin 1
gluino, gluon	$\widetilde{g}$	g
winos, W bosons	$\widetilde{W}^{\pm} \quad \widetilde{W}^0$	$W^{\pm} \quad W^0$
bino, B boson	$\widetilde{B}^0$	B^0

$SU(3)_C$ X $SU(2)_L$ X $U(1)_Y$

Quarks

Leptons

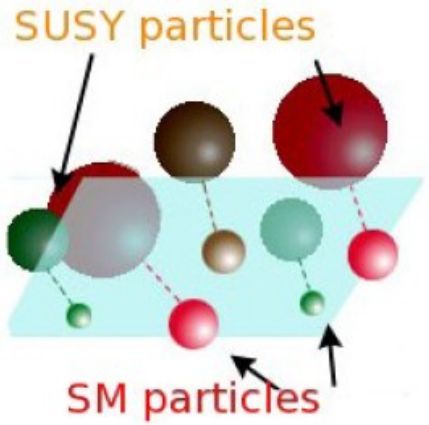
Bosons

sBosons	sFermions
$\tilde{q}_L, \tilde{q}_R$	$\tilde{g}$
$\tilde{\nu}$	$\tilde{\gamma}, \tilde{Z}, \tilde{W}^{\pm}$
$\tilde{l}_L, \tilde{l}_R$	$\tilde{H}_1^0, \tilde{H}_2^+, \tilde{H}_1^-, \tilde{H}_2^0$
$\tilde{q}_1, \tilde{q}_2$	$\tilde{\chi}_i^{\pm}$ $\tilde{\chi}_i^0$

- SUSY (fermion<->boson)

Different models

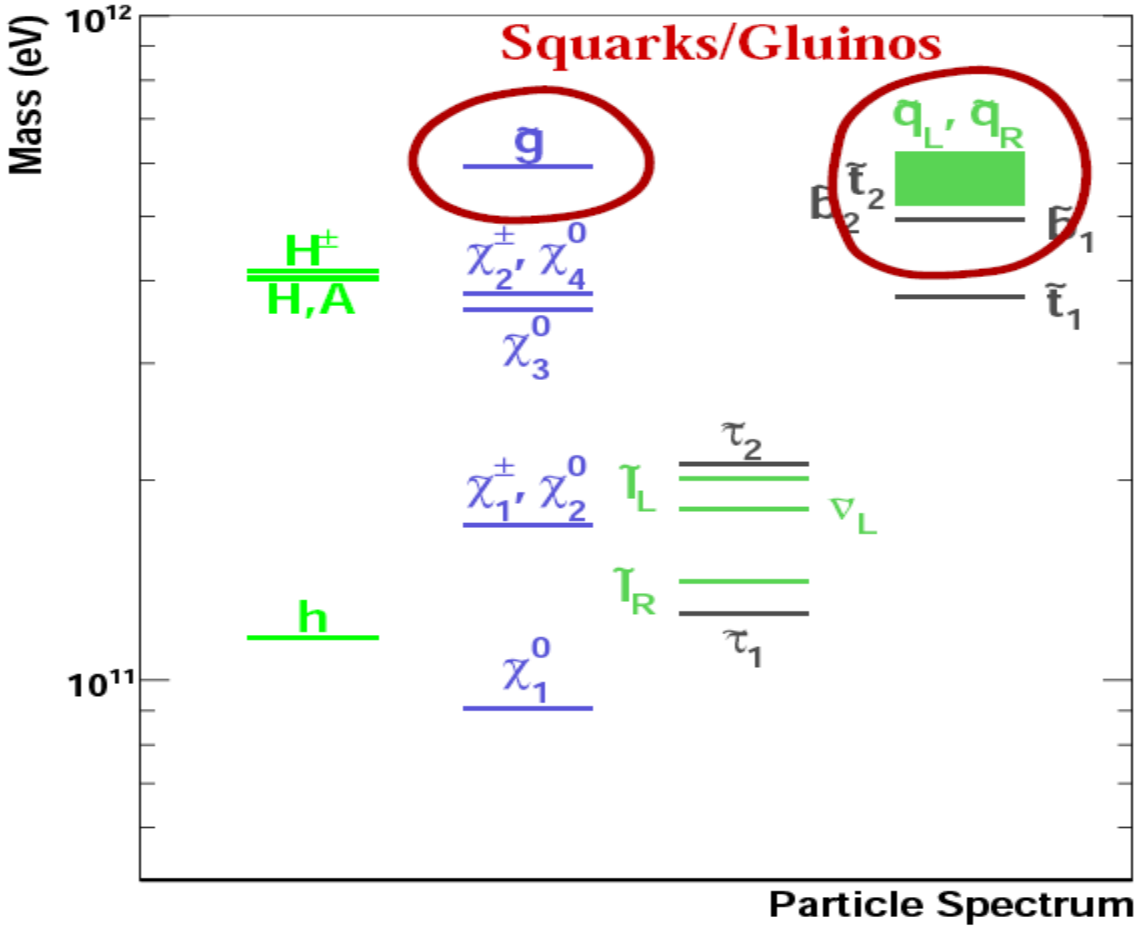
- MSSM, conserved R-parity = $(-1)^{3(B-L)+2s-1}$
  - pair production of SUSY particles
  - decay to SM particles and the stable LSP (the lightest SUSY particle)
- GMSB, gravitino is LSP
- R-parity violated models (decaying LSP)



Experimental signatures

(Detector) EM objects, tracks, jets, missing energy

A typical mass spectrum



Tevatron: inclusive search for generic squarks/gluinos

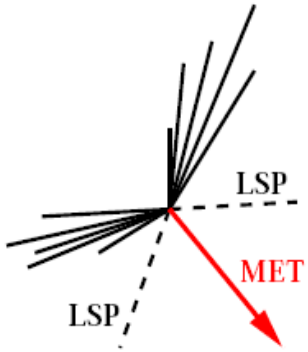
Squarks/Gluinos produced via strong interaction

→ large cross sections at hadron colliders

Decays: jets + LSP

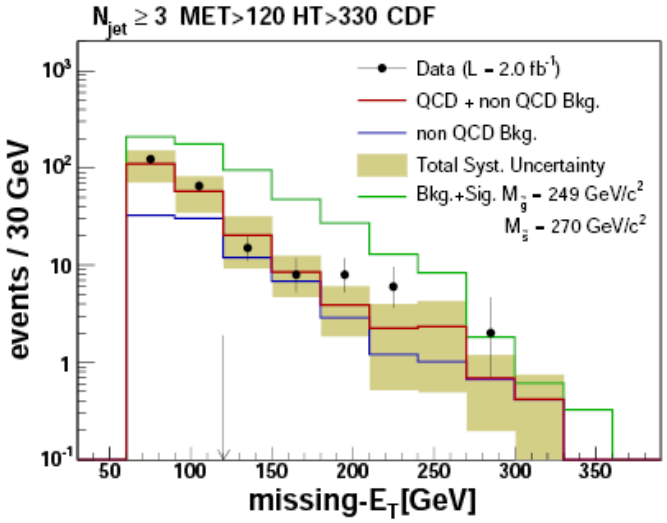
– LSP assumed to be stable (R_p conserved)

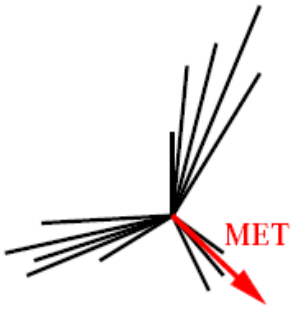
→ Signature: jets + $\not{E}_T$



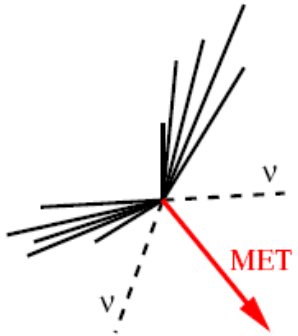
$\tilde{q}\tilde{q} \rightarrow qq + \not{E}_T$

CDF analysis





Multijet Background



Background:

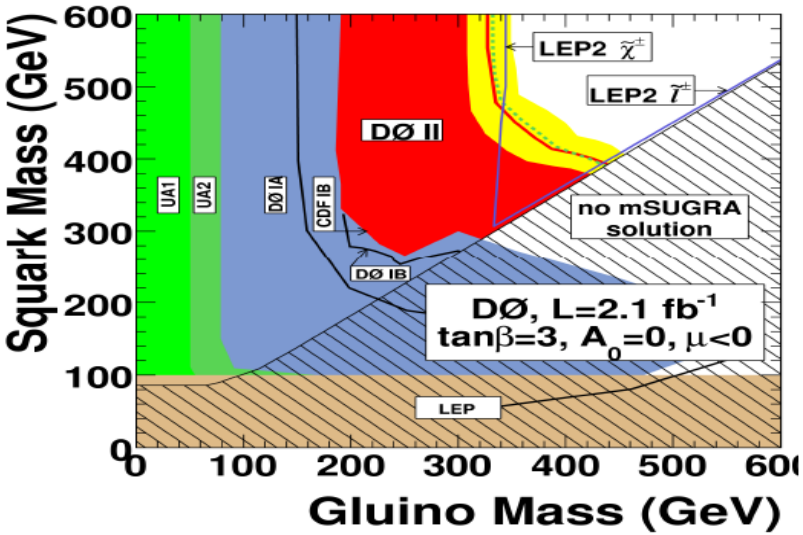
Z→ $\nu\nu$+jets

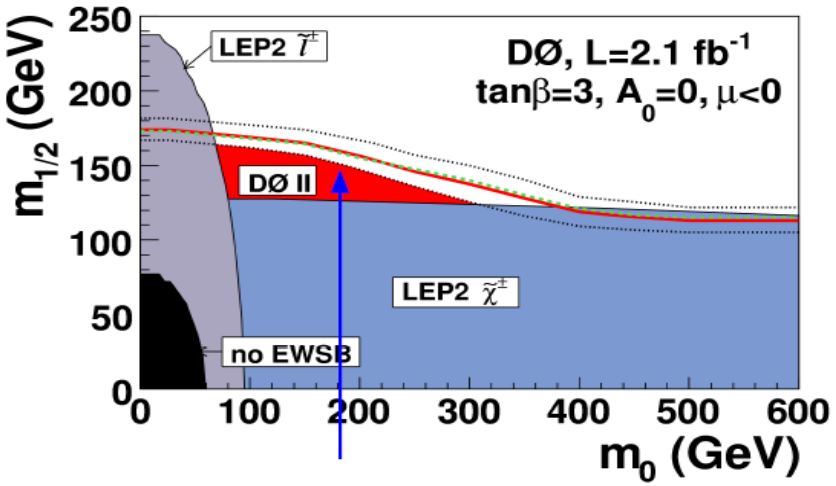
Tevatron:

Squarks and Gluinos (2.1 fb^{-1} jets+MET inclusive)

95% C.L. limits set on squark and gluino masses and mSUGRA parameters

D0 PLB, 660, 449 (2008), similar limits CDF PRL 102 (2009) 121801





Improvement vs LEP2 results

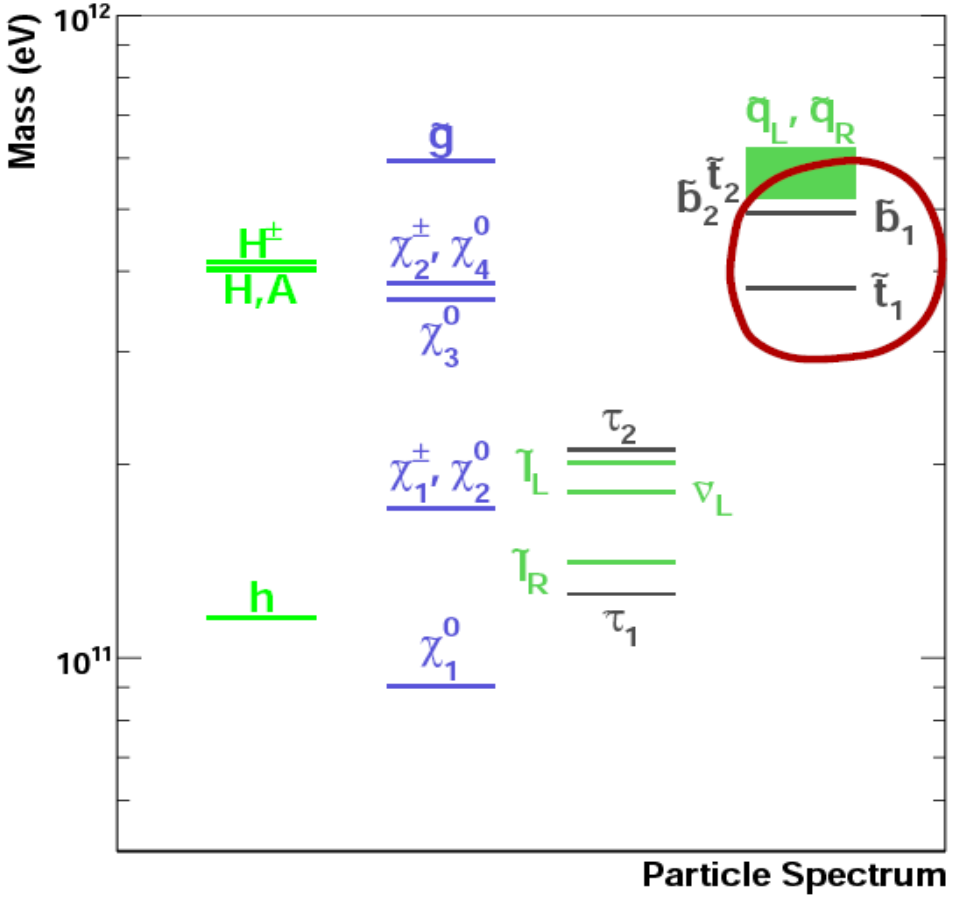
Excluded:

M(squark) < 379 GeV, M(gluino) < 308 GeV

(most conservative hypothesis accounting PDF and RF scale uncertainty on the signal NLO cross-section)

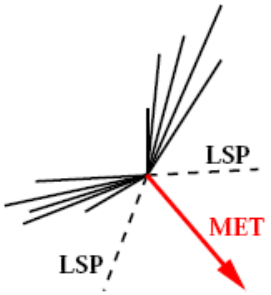
masses up to 390 GeV for M(squark)≈M(gluino)

A typical mass spectrum



stop/sbottom expected to be light

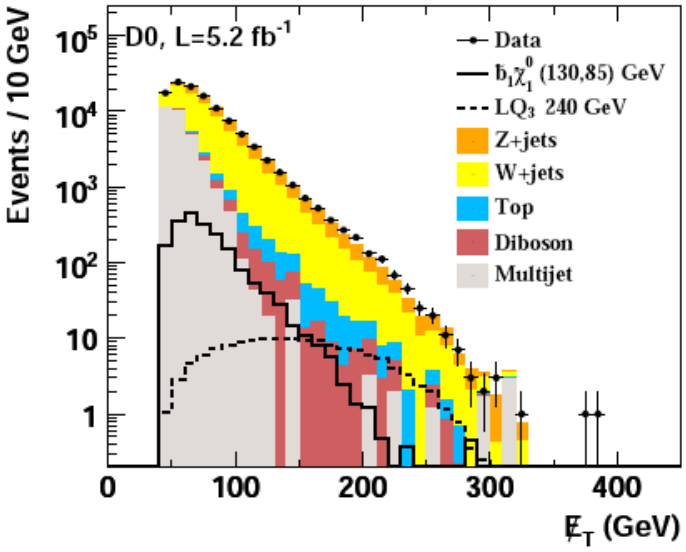
Tevatron: Search for sbottom quarks



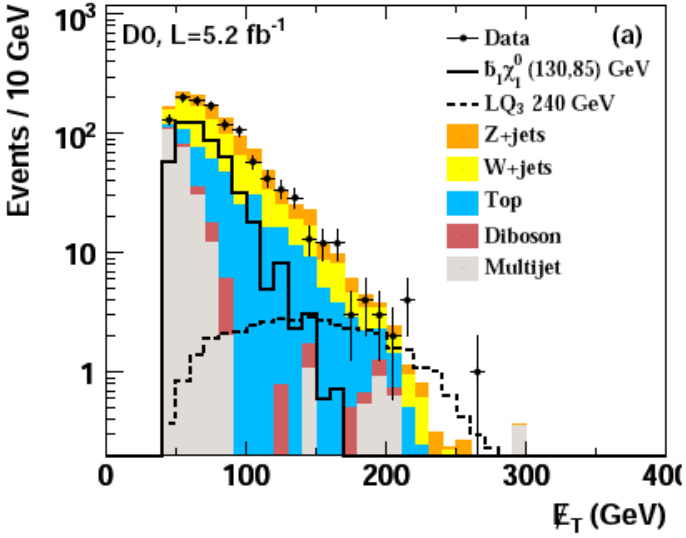
Decay: $\tilde{b} \rightarrow b + \tilde{\chi}_1^0$

$\rightarrow$ jets+$\not\!\!E_T$ analysis with b-tagging

New result: DØ, 5.2 fb^{-1}



before b-tagging



after b-tagging

Tevatron: search for supersymmetry: sbottom quarks

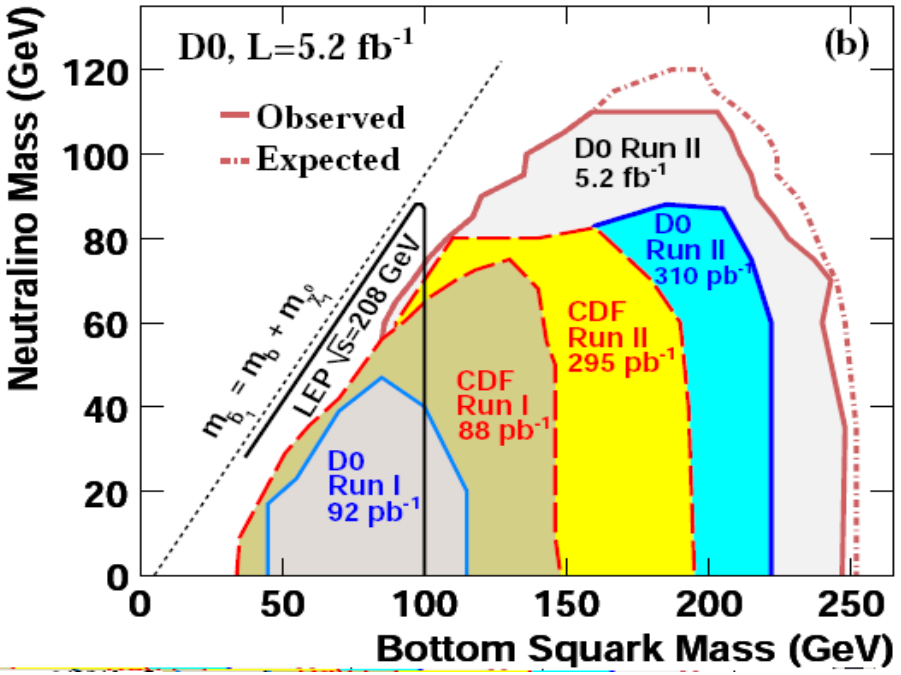
Visible energy in event depends on $\tilde{b}$-$\tilde{\chi}_1^0$ mass difference $\Delta m \rightarrow$ mass-dependent cuts

Example low Δm: 901 events observed, 971 ± 152 events expected

- No reach for $\tilde{b}$-$\tilde{\chi}_1^0$ mass differences below 30 GeV (trigger)

Example high Δm: 7 events observed, 6.9 ± 1.7 events expected

- Probing sbottom masses up to 250 GeV



Tevatron: search for charginos and neutralinos

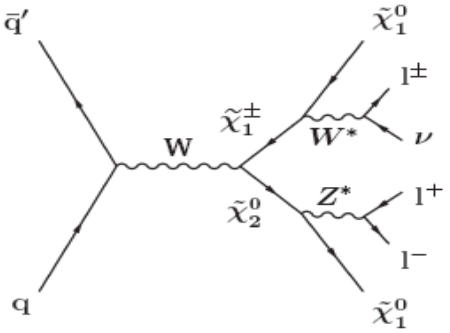
Most sensitive channel: $\tilde{\chi}^{\pm}\tilde{\chi}^{0}_{2} \rightarrow 3\ell + \not{E}_T$

Challenges:

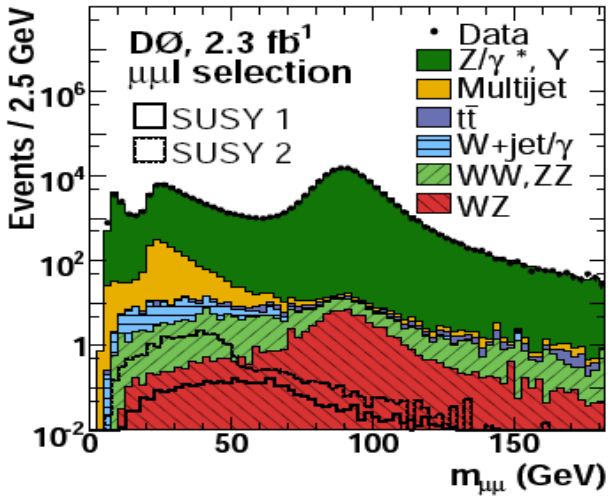
- production cross section (electroweak) relatively small
- low-p_T leptons

Large number of trilepton and dilepton plus track analyses from CDF and DØ

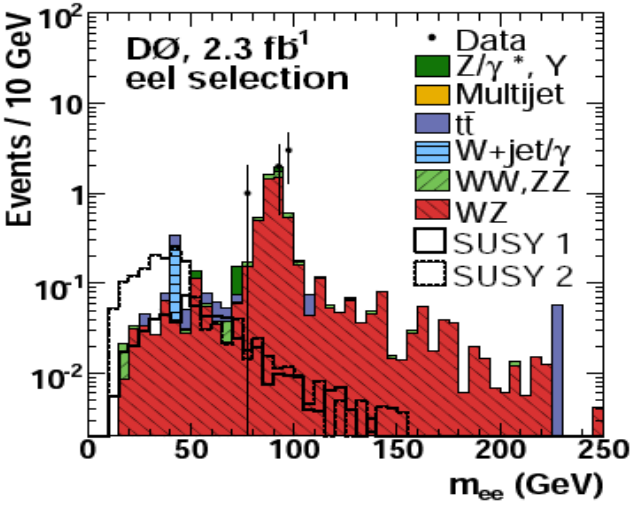
- pt cuts as low as 3 GeV



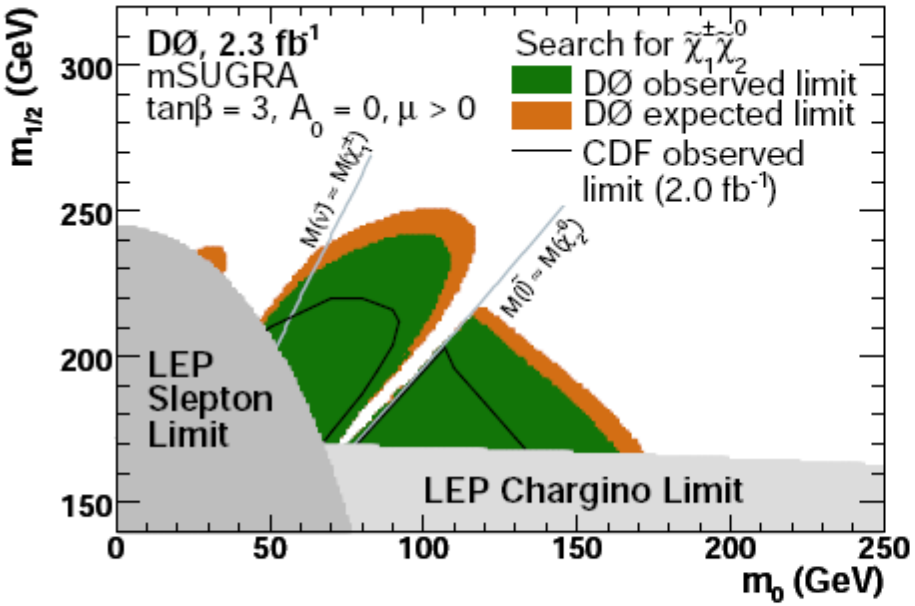
requiring 2 leptons

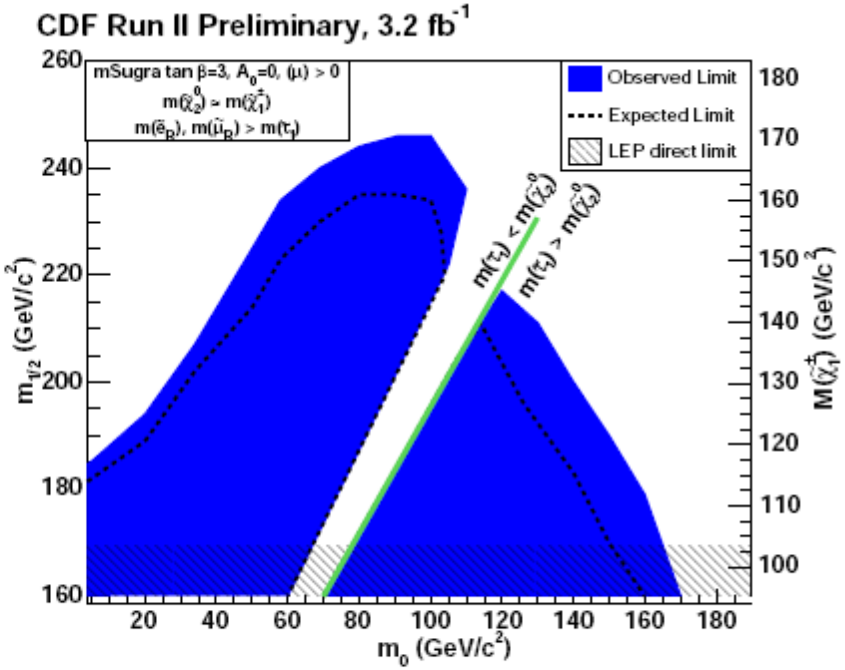


requiring 3 leptons



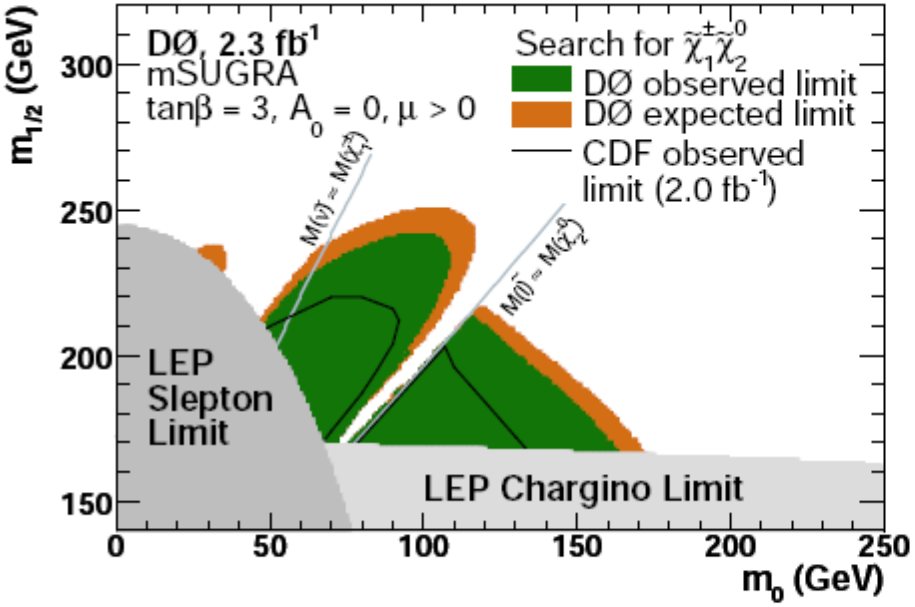
Tevatron search for charginos and neutralinos

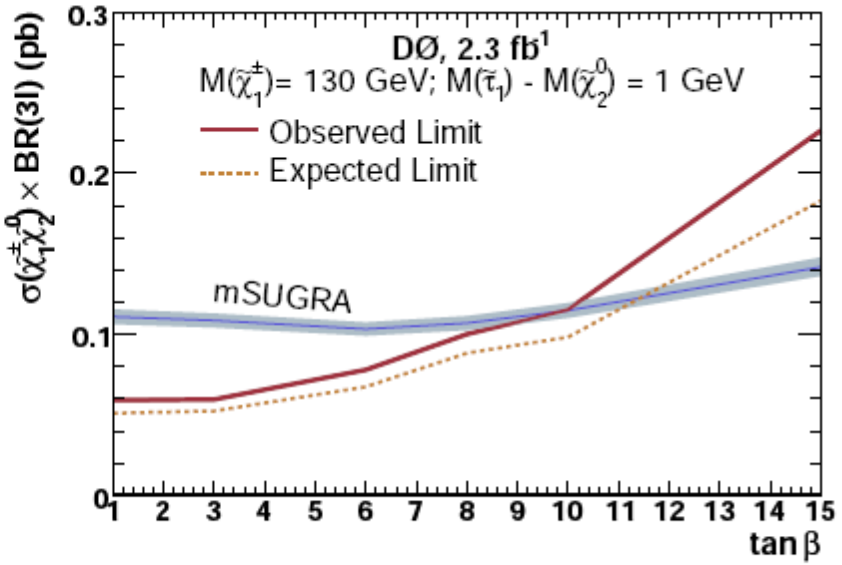




- Analyses probing chargino masses up to 176 GeV
- Reach degrades with increasing tanβ

Search for charginos and neutralinos

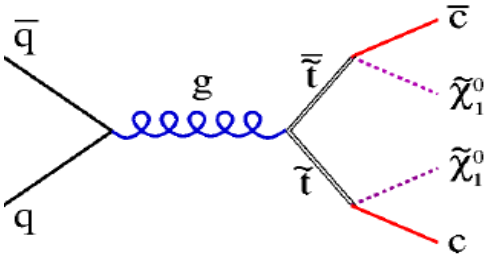




- Analyses probing chargino masses up to 176 GeV
- Reach degrades with increasing tanβ

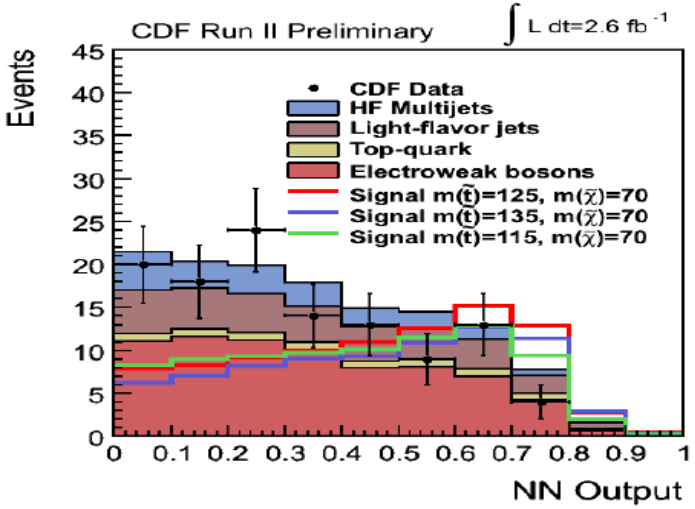
Tevatron:searches for stop quarks

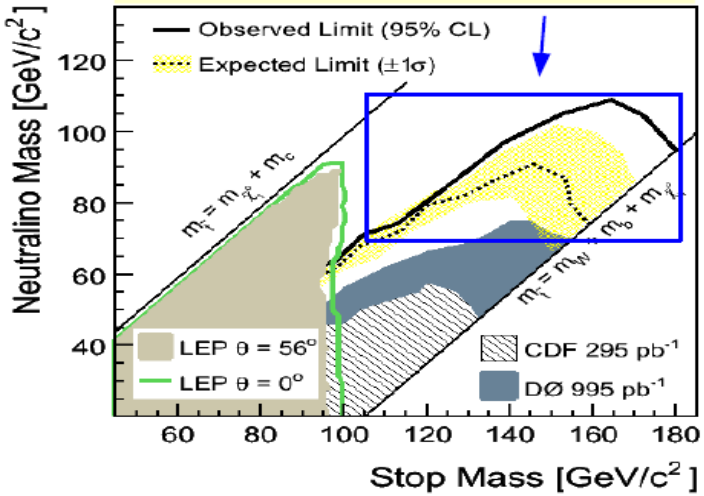
Stop quarks (2.6 fb^{-1} 2c-jets+MET)



Signal selections : at least 2 Jets ET>25 GeV
MET> 50 GeV, 1 heavy flavor tag (vertex algorithm)
NN selection (MET, jets kinematic)
Backgrounds : W/Z+jets, HF multijet, top

Data	Exp. Bkg.
115	132+/-24

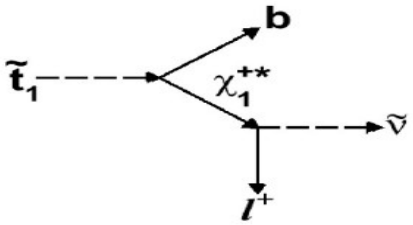




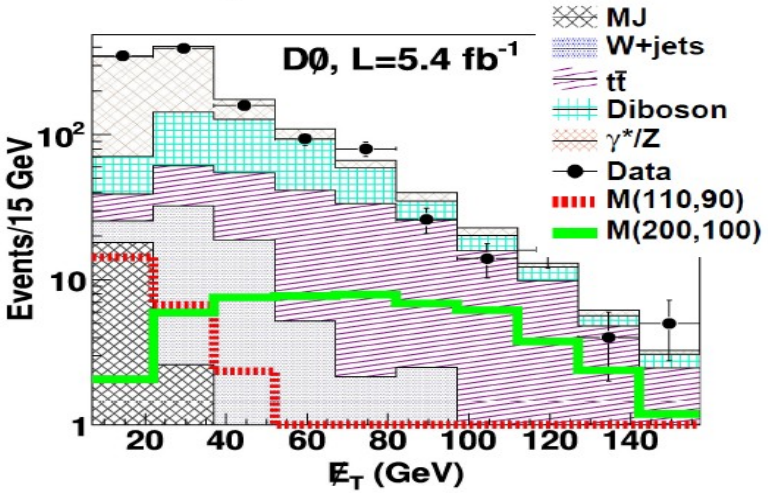
Excluded @ 95% C.L. , m(LSP)=80 GeV : m(Stop) < 180 GeV

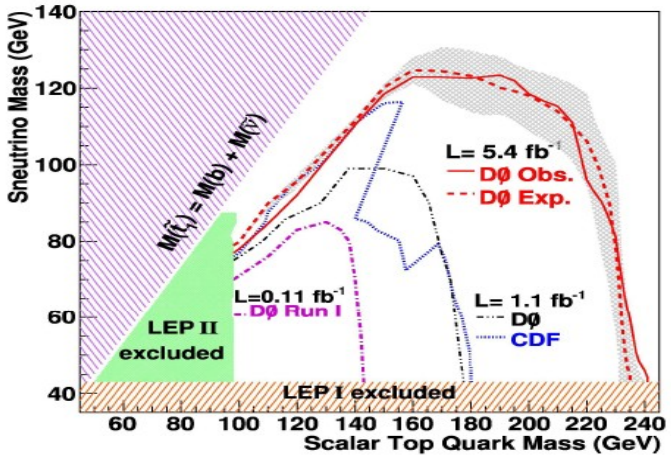
Tevatron:searches for stop quarks

Stop quarks (5.4 fb^{-1} 2jets+eμ+MET)



Signal selections : $\Delta M = M_{\tilde{t}_1} - M_{\tilde{\nu}}$ **determines the kinematic, pT(e)>15 GeV, pT(μ)> 10 GeV, veto on (MET<20 GeV for** $\Delta\phi$**(e,μ) < 2.8) and (MET,e,μ) composite kinematic discriminants against Z(ττ)–>e,μ+νν, WW, ttbar,** W+jets





Significantly improved constraints at 95% C.L. in the $(M_{\tilde{t}_1}, M_{\tilde{\nu}})$ **mass plane**

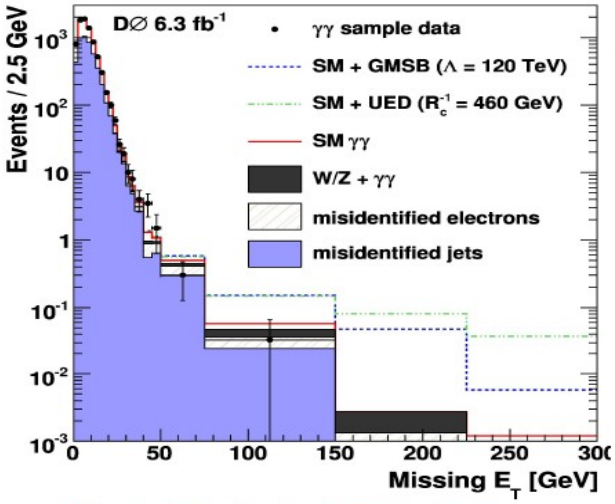
Tevatron: searches for GMSB

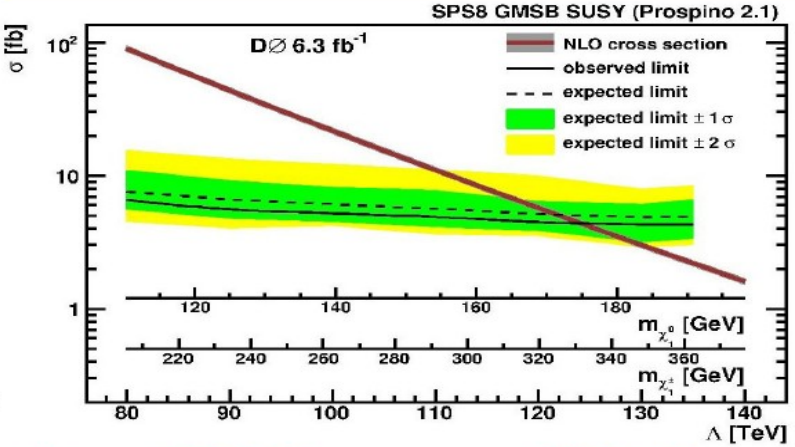
GMSB ($\gamma\gamma$+MET)

pp->$\gamma\gamma$+MET+X
Lightest neutralino decays to γ and gravitino (LSP)

Signal selections : ET(γ) >25 GeV, MET> 50 GeV
Backgrounds : real MET - Wγ, W+jet, W/Z+$\gamma\gamma$ +
Instrumental - SM $\gamma\gamma$, γ+jet, multijet (dominant)

Data	Exp. Bkg	m(L)=120TeV
4	6.9+/-1.01	5.2+/-0.4

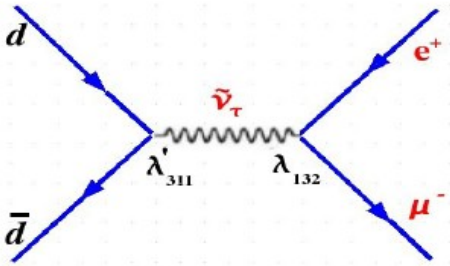




Excluded @ 95% C.L. : m(Λ) < 124 TeV, m($\tilde{\chi}_1^0$) < 175 GeV

Tevatron: searches for RPV

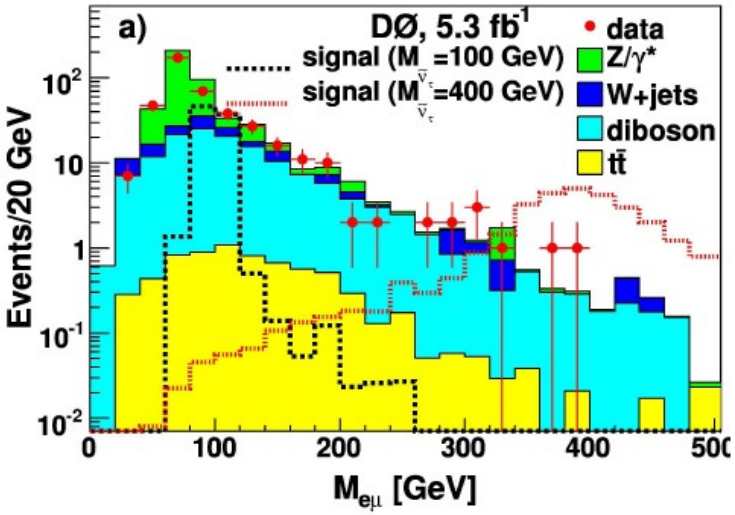
RPV SUSY (Sneutrino -> eμ, 5.3 fb^{-1})

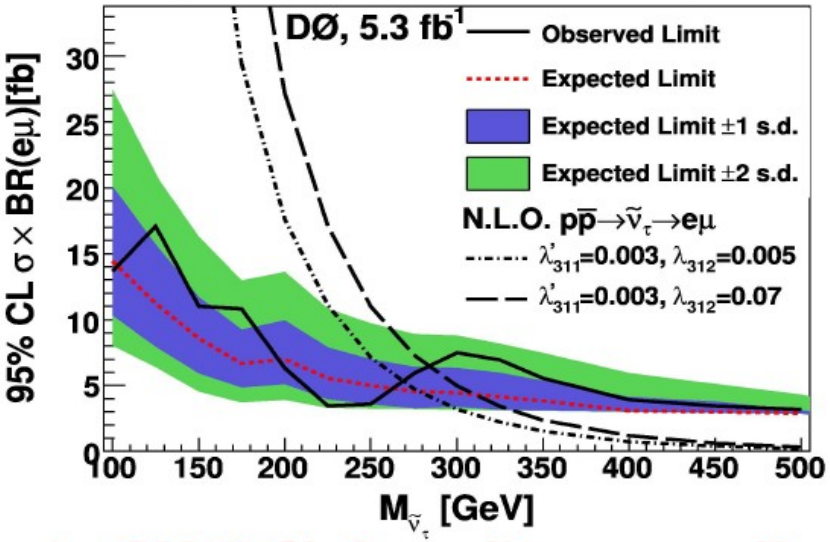


Signal selections : Isolated e,μ with PT >25 GeV,
Backgrounds : Drell-Yan $Z/\gamma^* - \tau\tau$ (dominant),
W+jets, Diboson, ttbar

Data	Exp. Bkg
414	410+/-38

Checking for M(eμ) peak

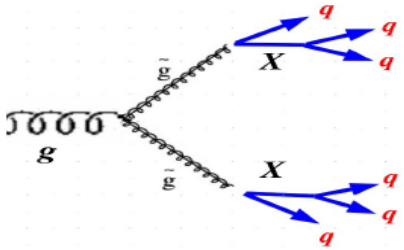




Excluded @ 95% C.L. : m(sneutrino) < 280 GeV, depending on coupling

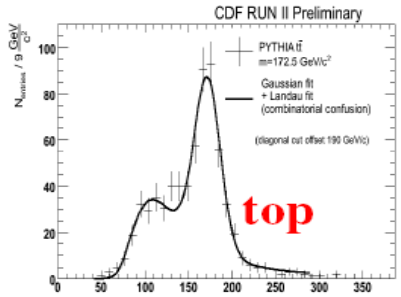
Tevatron: searches for RPV

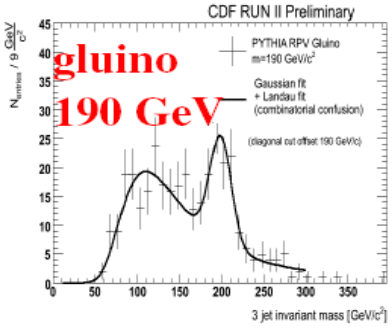
RPV 3jet resonances 3.2 fb^{-1}

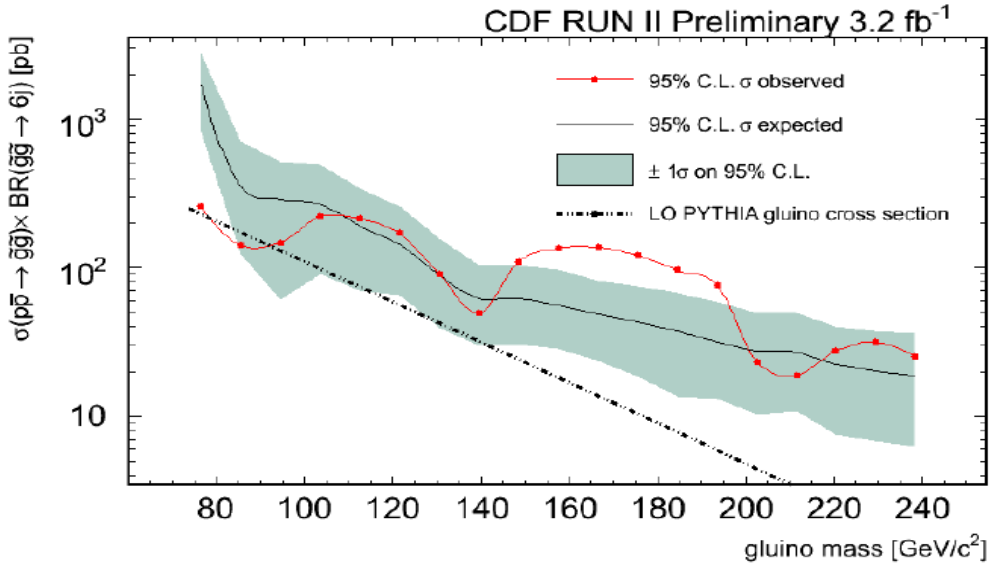


Signal selections : 6+ jets, small MET <50 GeV, ΣpT(6jets) > 250 GeV. [M3J,ΣpT(3jets)] correlation

Backgrounds : QCD, ttbar



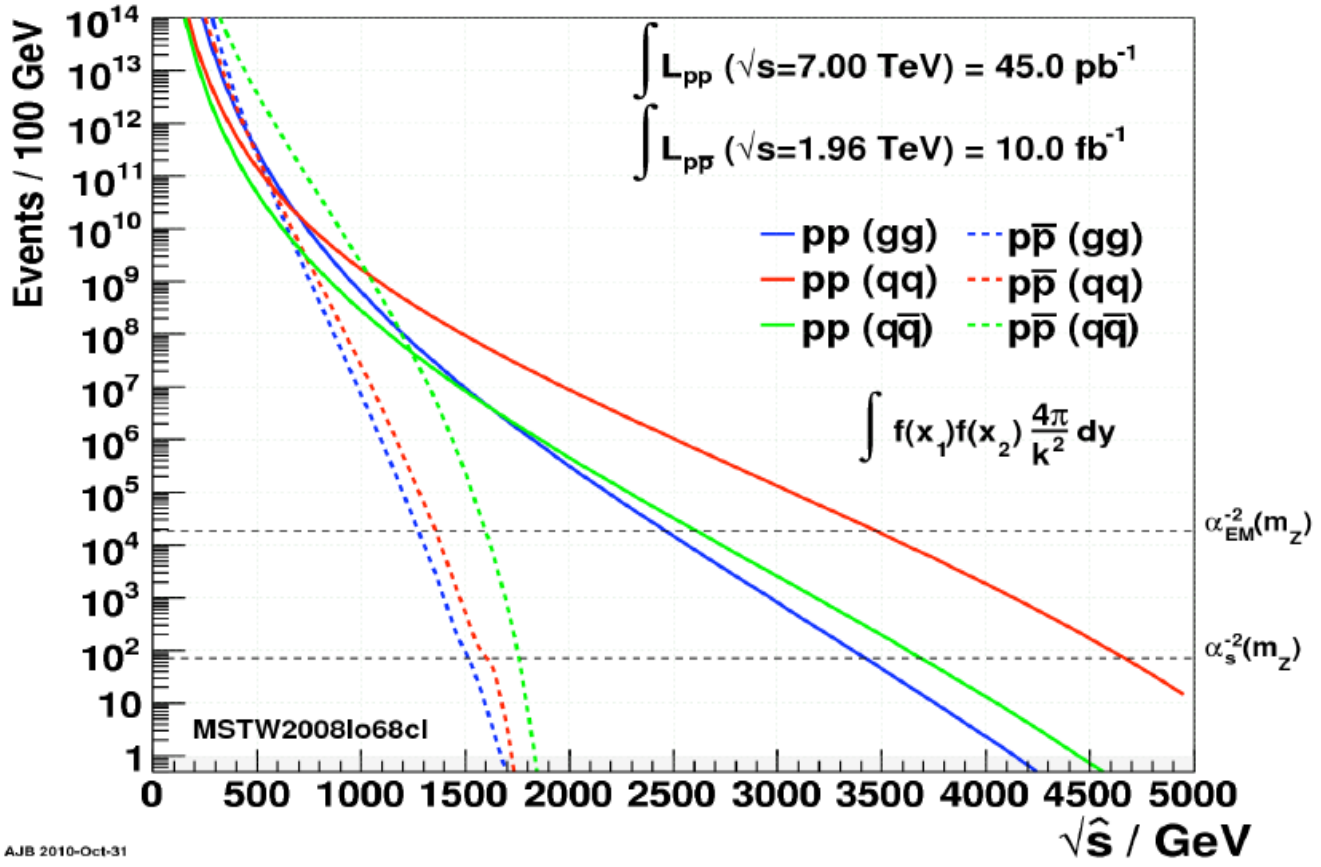




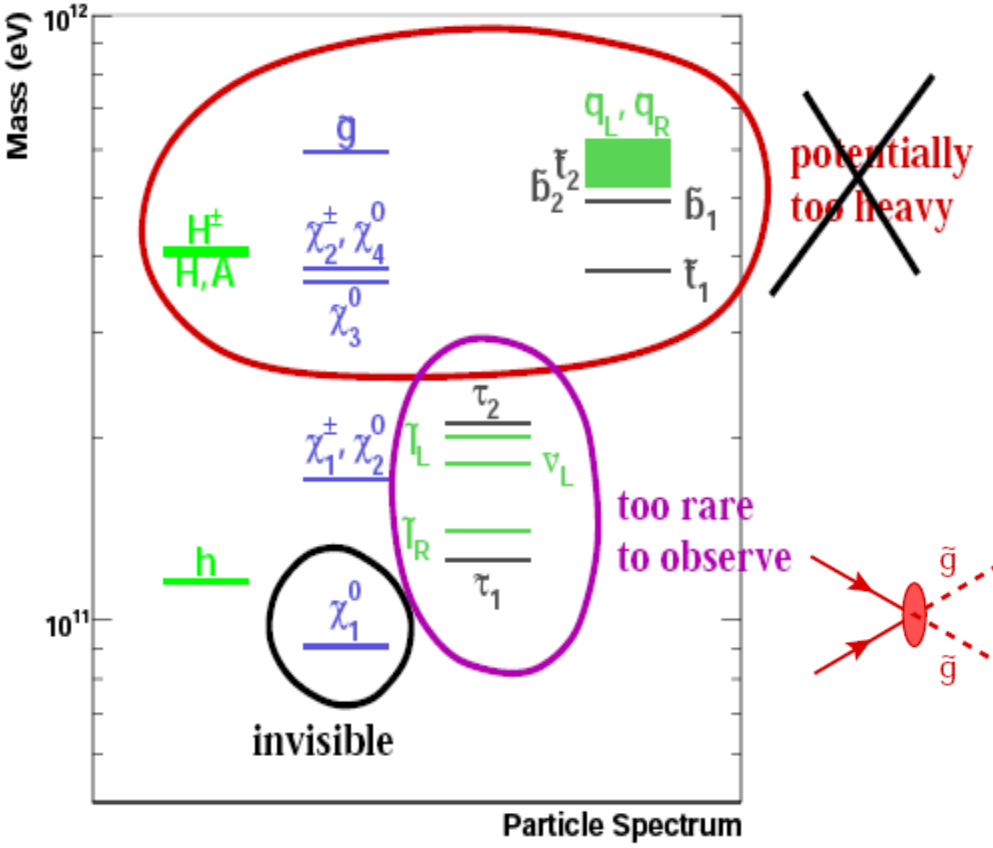
95% C.L. limits using invariant mass of 3jet ensembles

LHC versus Tevatron

- LHC: already higher parton-parton luminosity for High Mass States

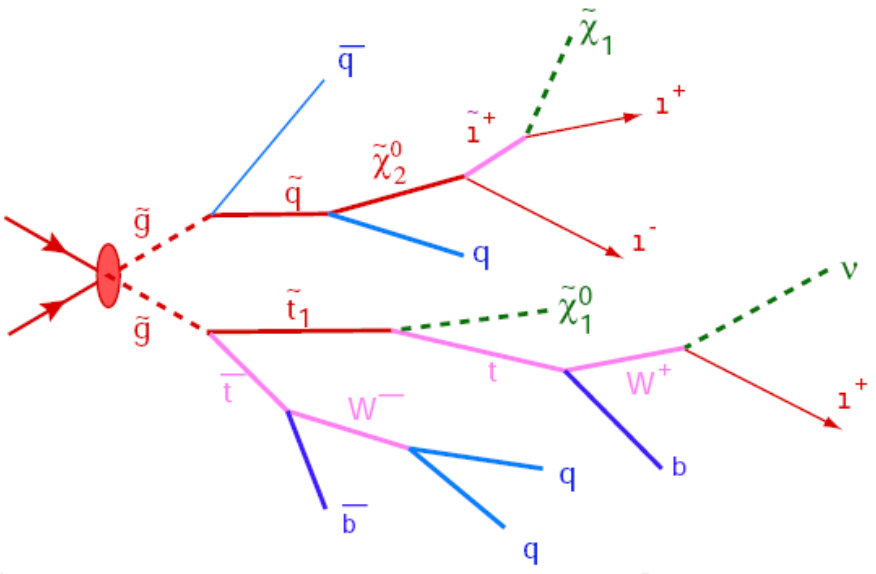


Search for supersymmetry at the LHC



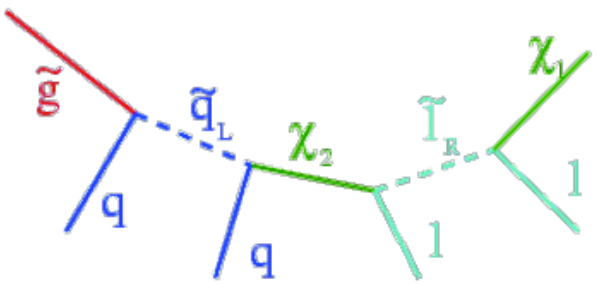
All particles accessible

- strong production dominates
- potentially long decay cascades



ATLAS SUSY search strategy

- Several complementary, generic SUSY search strategies on ATLAS
  - Search for **excess** of events with (b-)Jets, EtMiss, leptons



- Inclusive, "model independent" searches
- Compare with low mass mSUGRA benchmark (SU4)
- Sensitive to **any** model with strongly interacting particles decaying semi-invisibly

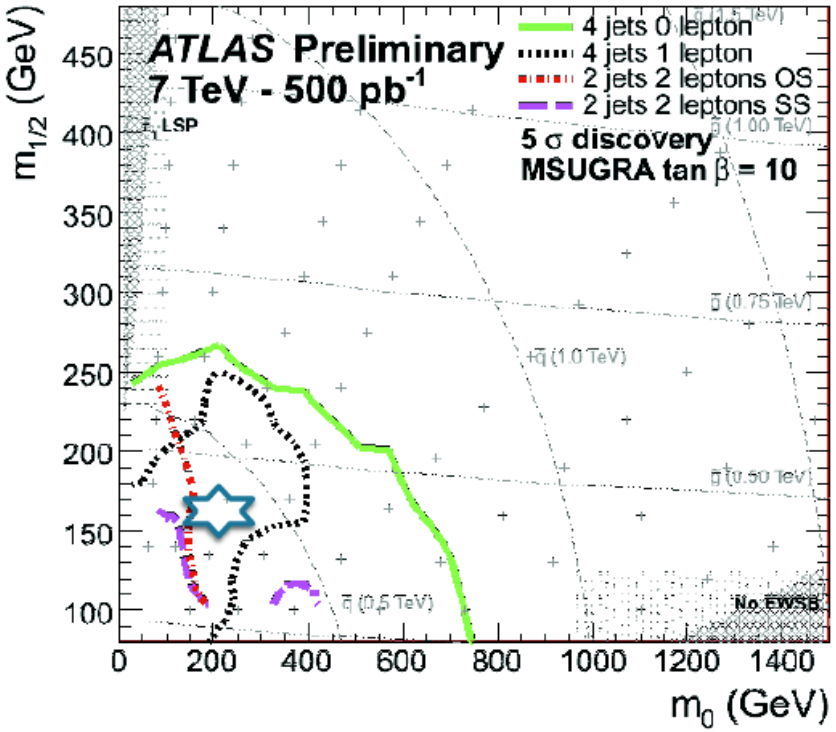
- Early studies; focus on understanding BGs, systematics, detector performance
- L ≅ few 10's – 100's nb^{-1}
- Check control regions
- First data-MC comparisons of **SUSY sensitive** observables

(Cuts loosened c.f. previous studies, for low luminosity)

Jets+EtMiss channels
- without/with Leptons
- with b-tagged Jets

SUSY benchmark point SU4

- mSUGRA low mass point, close to Tevatron bounds
- m_o = 200 GeV
- $m_{1/2}$ = 160 GeV
- A_o = -400 GeV
- tanβ = 10
- μ > 0

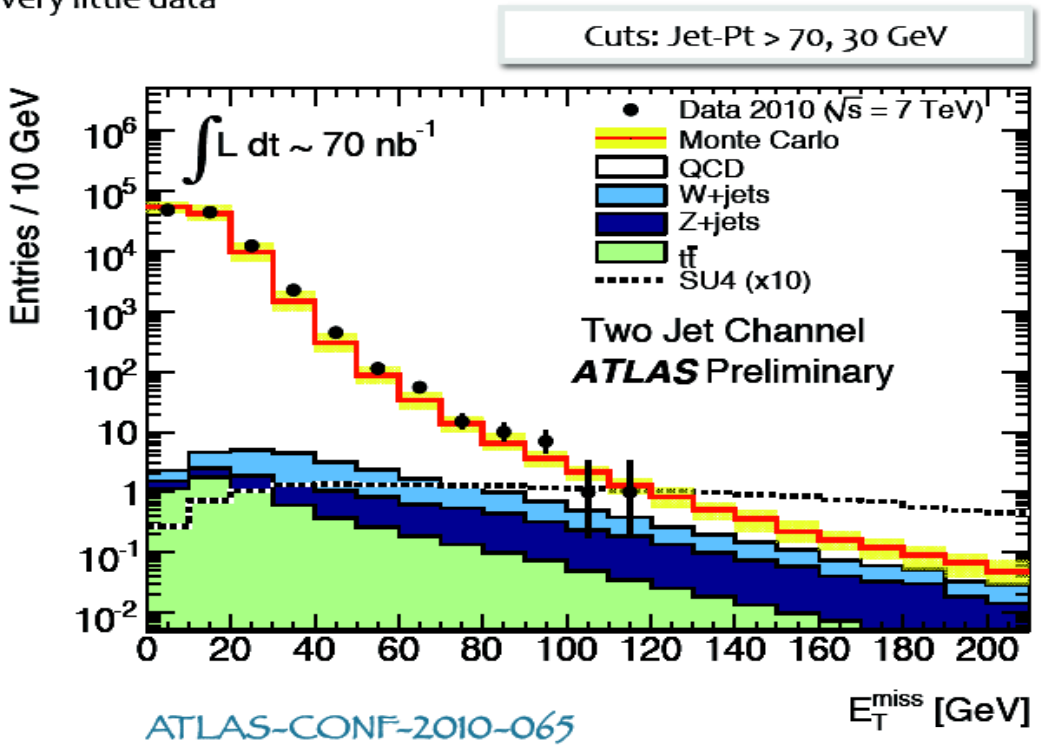


SUSY searches without leptons

- SUSY signal typically dominated by **squark** and **gluino** production (MultiJet+EtMiss)
- Generically most sensitive search mode
- Competitive limits achievable with very little data

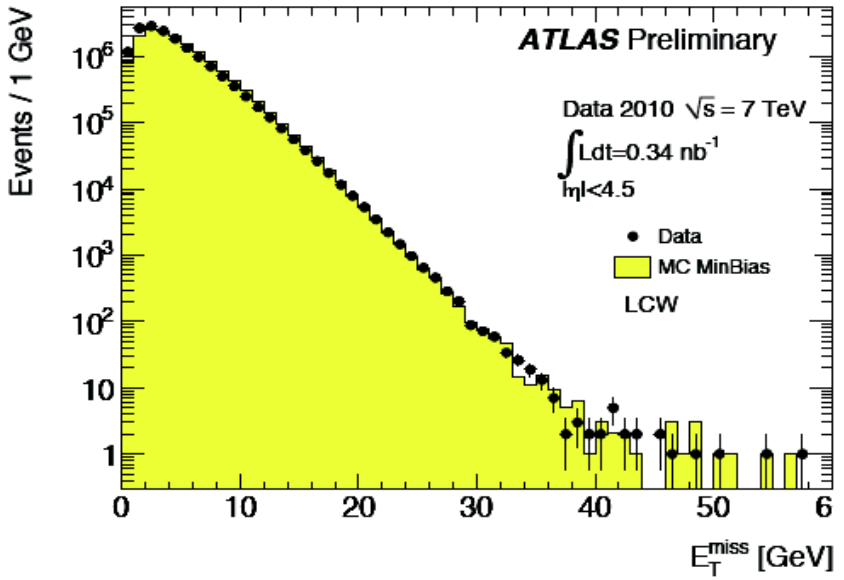
- Jets+EtMiss (0-lepton)
- = 1, ≥ 2, ≥ 3, ≥ 4-Jet channels
- QCD MC normalised to data (after dijet cuts)
- systematic uncertainties
  - Jet Energy Scale (25 – 40% on N_{evt})
  - Luminosity (11%)
  - Others smaller

- Good description by MC of key observables (EtMiss, Meff … and many more)

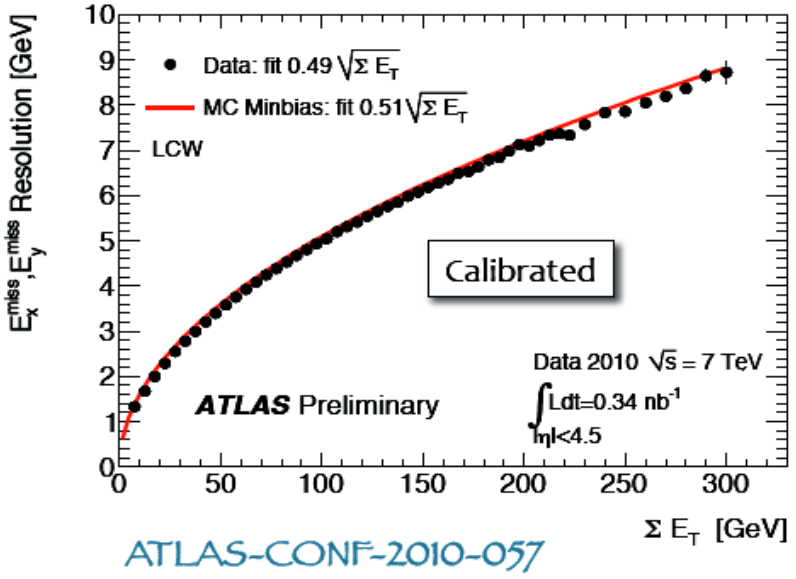


EtMiss performance

Calibrated EtMiss from minimum-bias events



Measured over ~ full calorimeter coverage (360° in φ, |η| < 4.5, ~ 200k cells)



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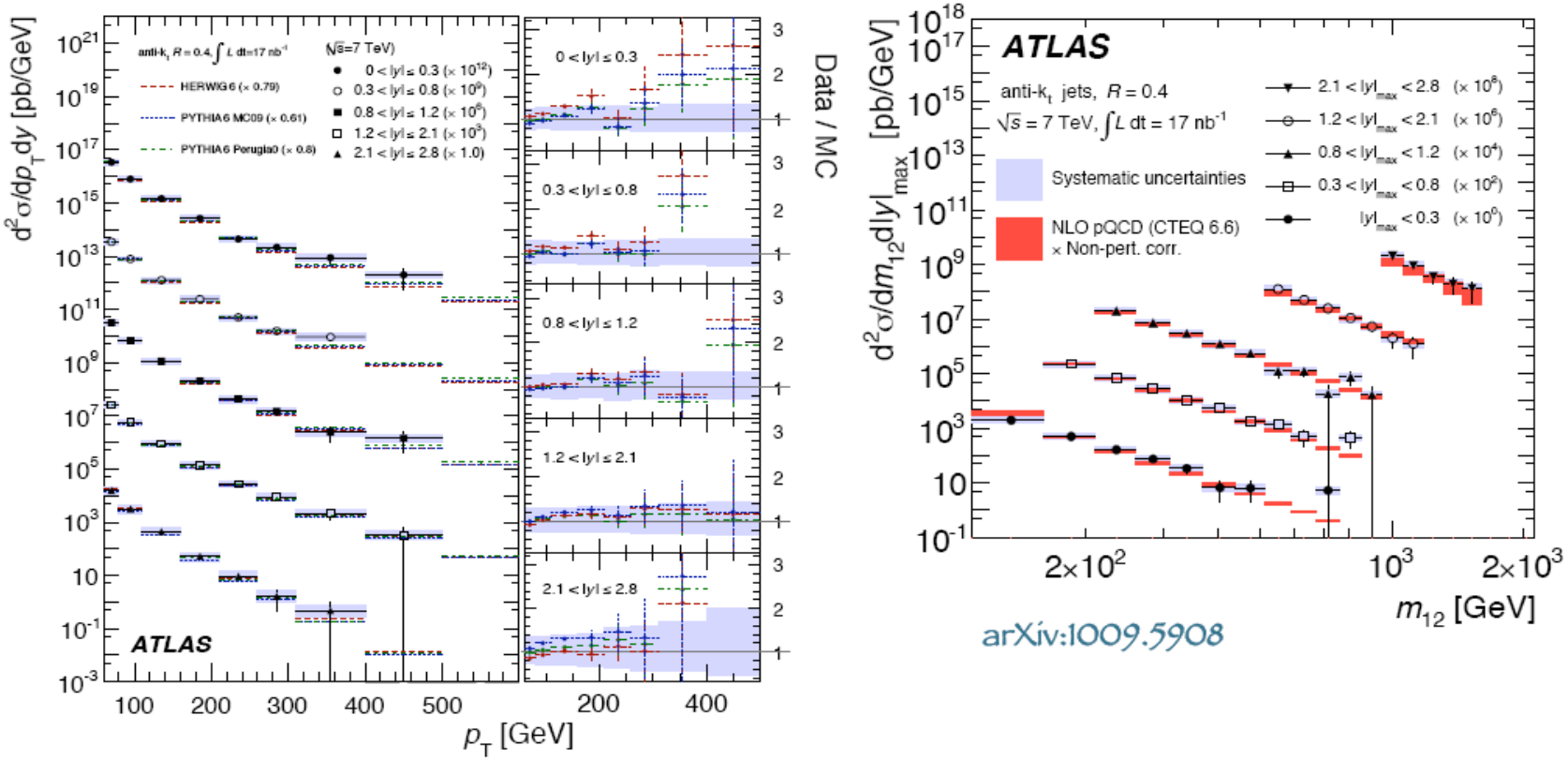
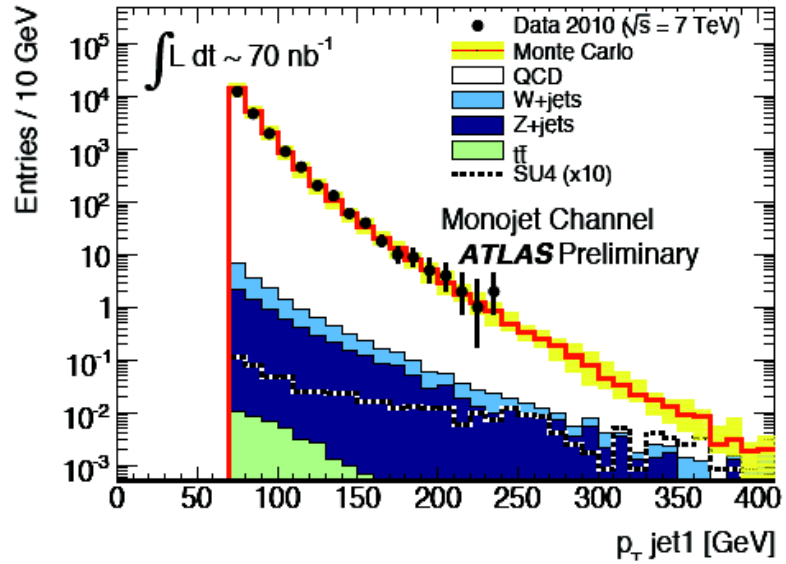
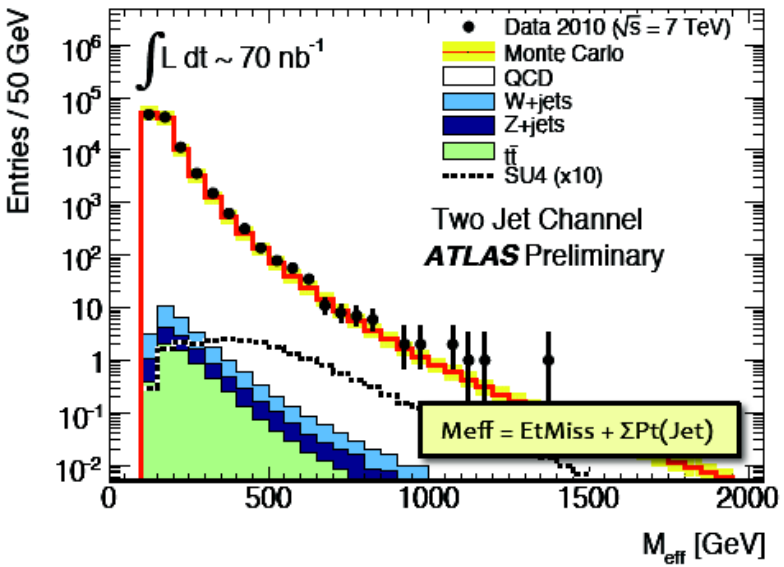
- Sensitive to calorimeter performance (noise, coherent noise, dead cells, mis-calibrations, cracks etc.), cosmics and beam-related BGs
- Good agreement between data and MC

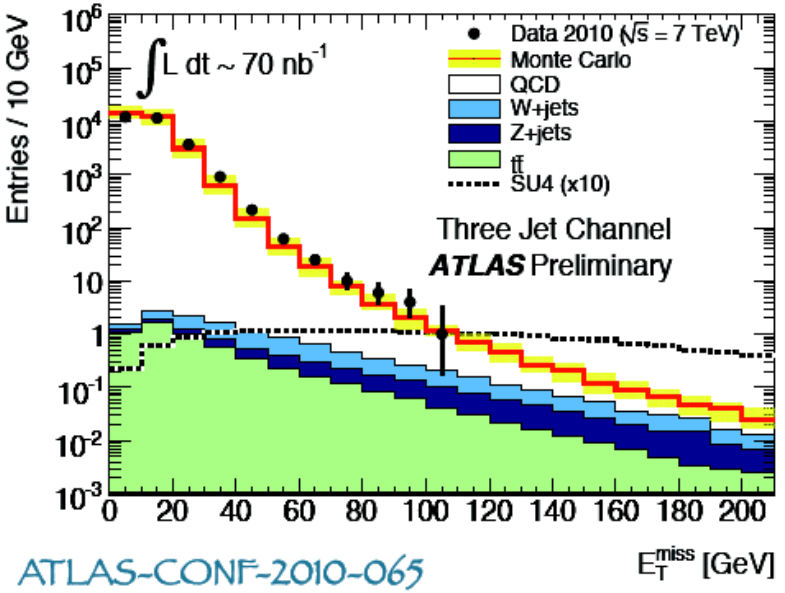
Jet performance

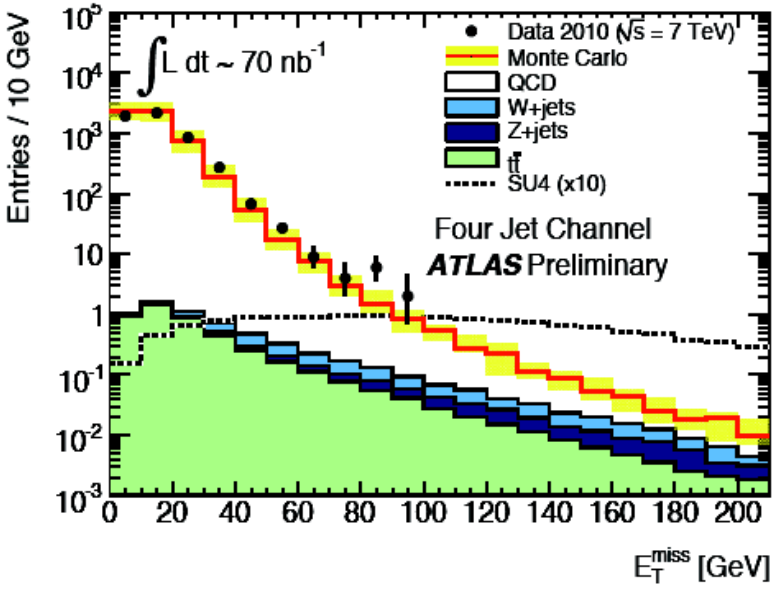


- Data and theoretical predictions consistent in all rapidity regions over wide Pt and Mjj range









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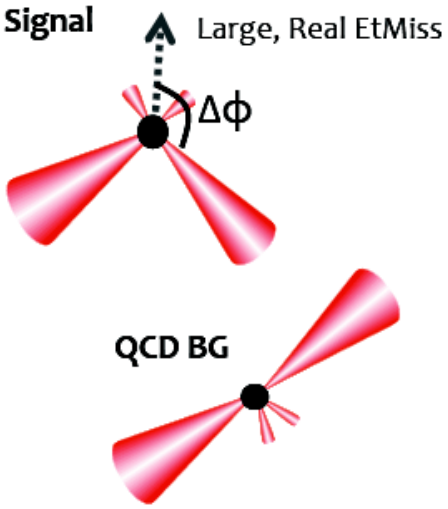
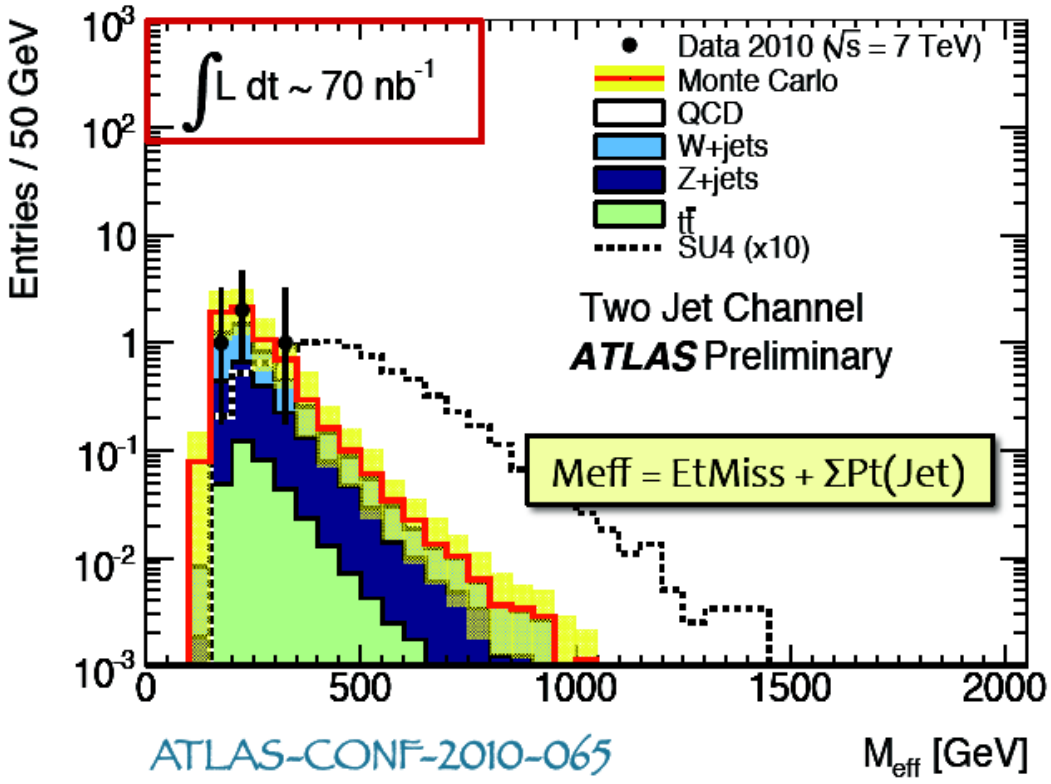
Searches without leptons

2-Jets+EtMiss (0-lepton)

- SUSY cuts:
  - Jet-Pt > 70, 30 GeV
  - EtMiss > 40 GeV
  - $\Delta\phi$(Jet, EtMiss) > 0.2
  - EtMiss > 0.3×Meff





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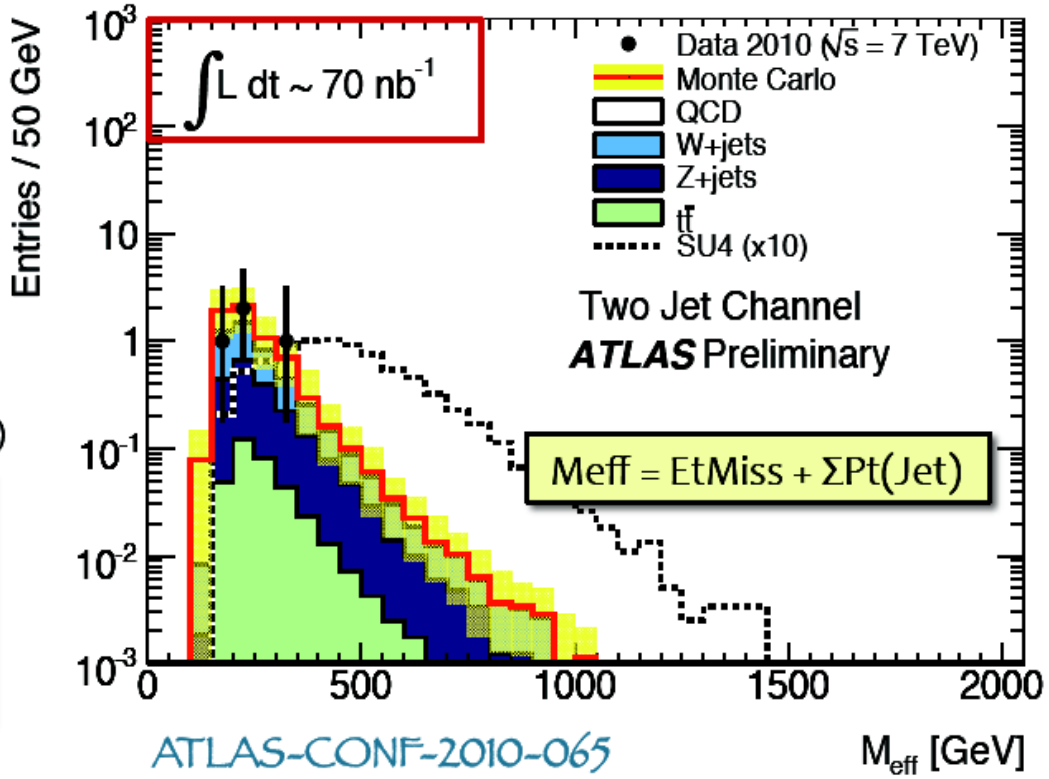
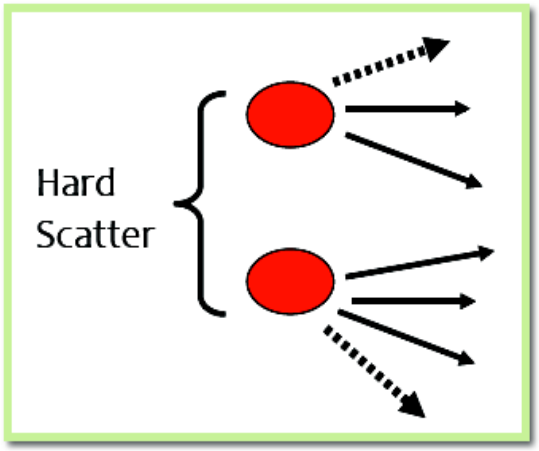
After SUSY cuts (inclusive channels)

	Data	SM expectation
2-Jet	4	6.6 ± 3.0
3-Jet	0	1.9 ± 0.9
4-Jet	1	1.0 ± 0.6

No significant deviations from expected SM BG



Stransverse mass: m_{T2}



M_{T_2} useful in events where 2 identical particles decay semi-invisibly

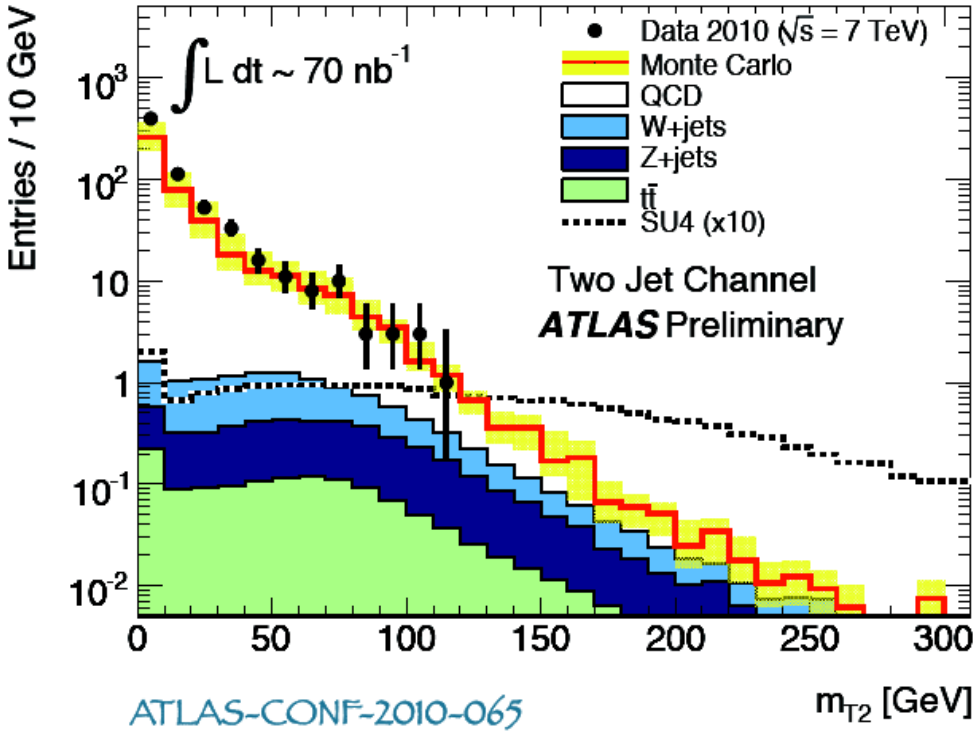
"Try all possible directions for the neutralinos and find the minimum heavy sparticle mass"

$$M_{T2} \equiv \min_{\mathbf{p}^{(1)}+\mathbf{p}^{(2)}=\mathbf{p}_T} \left[\max\left\{m_T\left(\mathbf{p}_T^{j(1)}, \mathbf{p}^{(1)}\right) m_T\left(\mathbf{p}_T^{j(2)}, \mathbf{p}^{(2)}\right)\right\}\right]$$

J.Phys.G29:2343-2363,2003 Phys.Lett.B463:99-103,1999

Mass variables for discovery

- **stransverse mass** (M_{T2}): generalisation of transverse mass to pair decays
- Gives event-by-event lower bound on mass of any pair-produced semi-invisibly decaying particle



General Properties:

- Small M_{T2} values if:
  - Jet-Pt small
  - EtMiss small
  - $\Delta\phi$(Jet,EtMiss) small
  - FS particles are from decay of "low mass" parents (e.g. W)

arXiv:0907.2713 [hep-ph]

SUSY searches with leptons

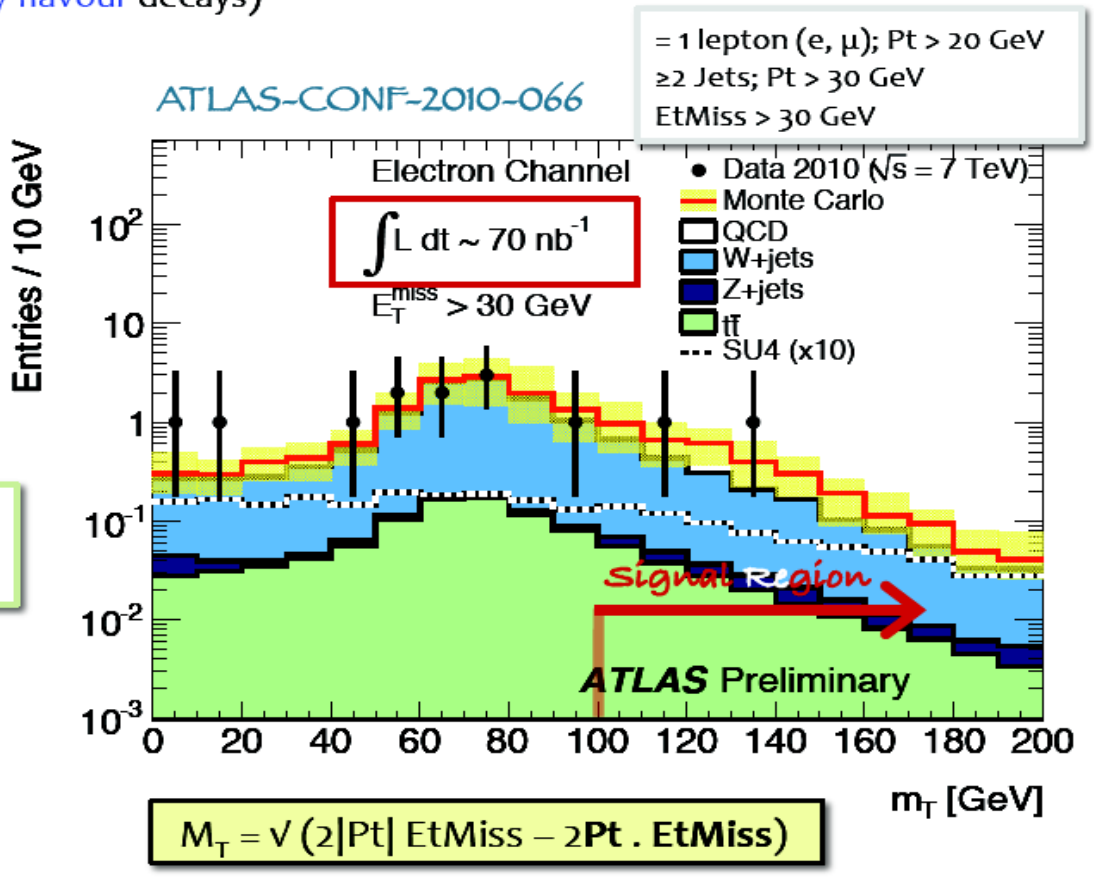
- In addition to Jets and EtMiss, SUSY events can copiously produce **leptons** (from gaugino, slepton, heavy flavour decays)

- Jets+EtMiss+1-Lepton
- 1 lepton requirement reduces QCD
- BG dominated by W+Jets (and QCD)
- normalised to data in control regions

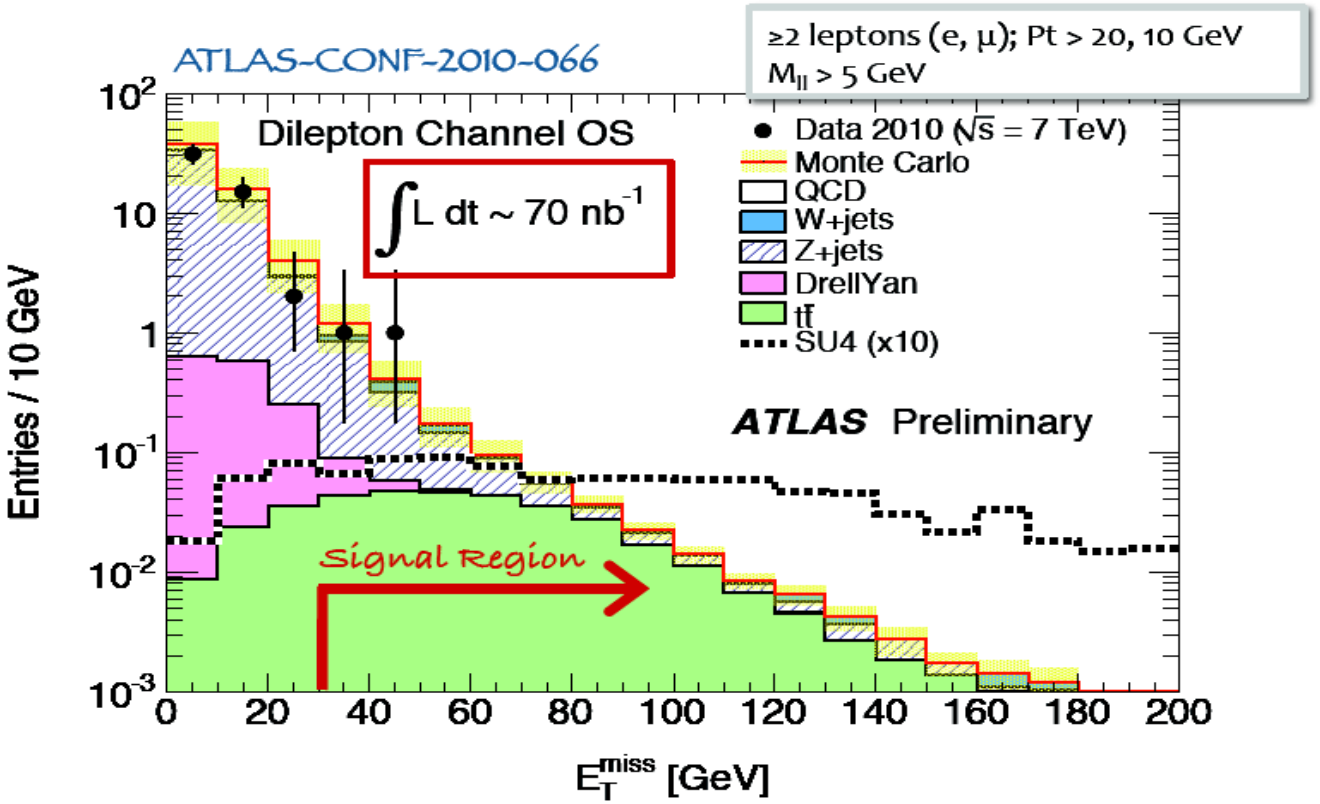
- Good agreement with MC (1-e and 1-μ channels)

After all SUSY cuts:

	Data	SM expectation
1-e	2	3.6 ± 1.6
1-μ	1	2.8 ± 1.2



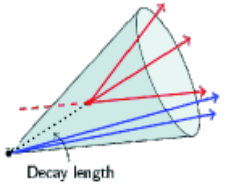
SUSY searches with leptons



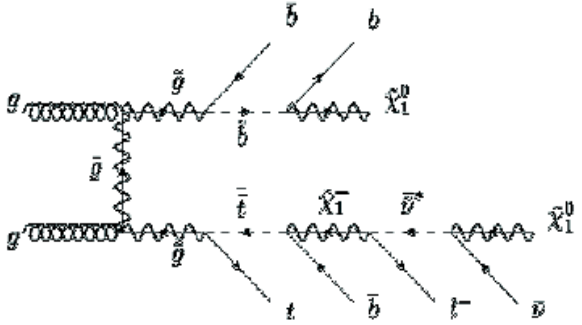
- 2-Lepton+EtMiss (OS and SS measured); Good agreement with MC

SUSY searches with b-jets

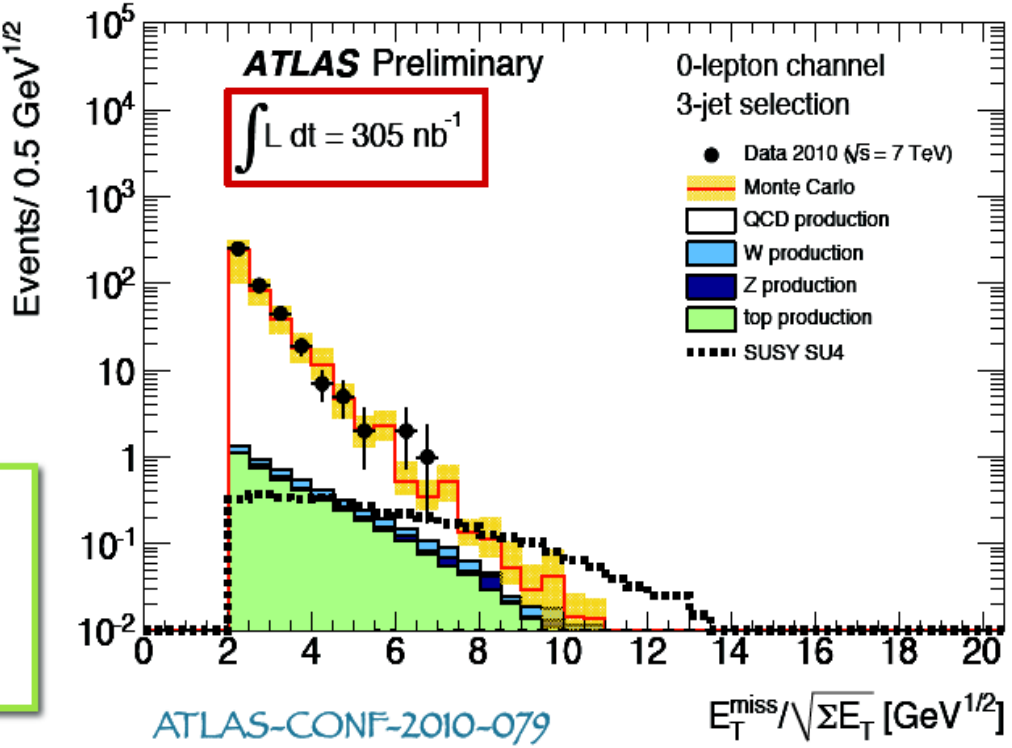
- SUSY signals typically rich in **b-Jets**
- B-tagging algorithm: reconstructed secondary vertices
- Decay length significance: $L/\sigma(L) > 6$
- $\varepsilon \equiv O(50\%)$
- 2, 3-Jet; 0, 1-lepton channels studied (at least 1 b-Jet)
- Cut on EtMiss **significance:**
  $EtMiss/\sqrt{\Sigma E_T} > 2\ \sqrt{GeV}$



EG.



- Good agreement between data and MC for range of observables (before and after b-tagging)



MultiJet+EtMiss

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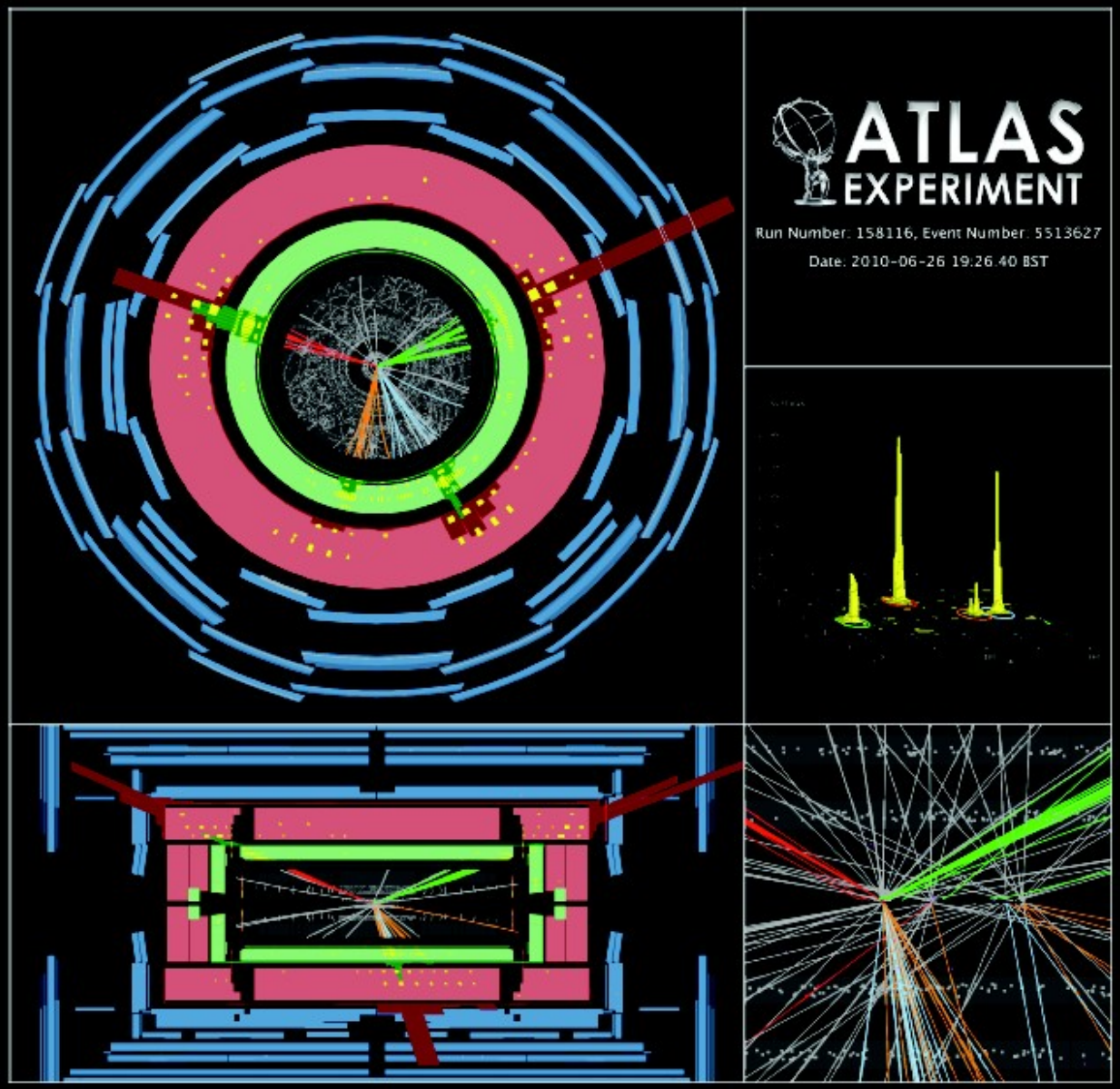


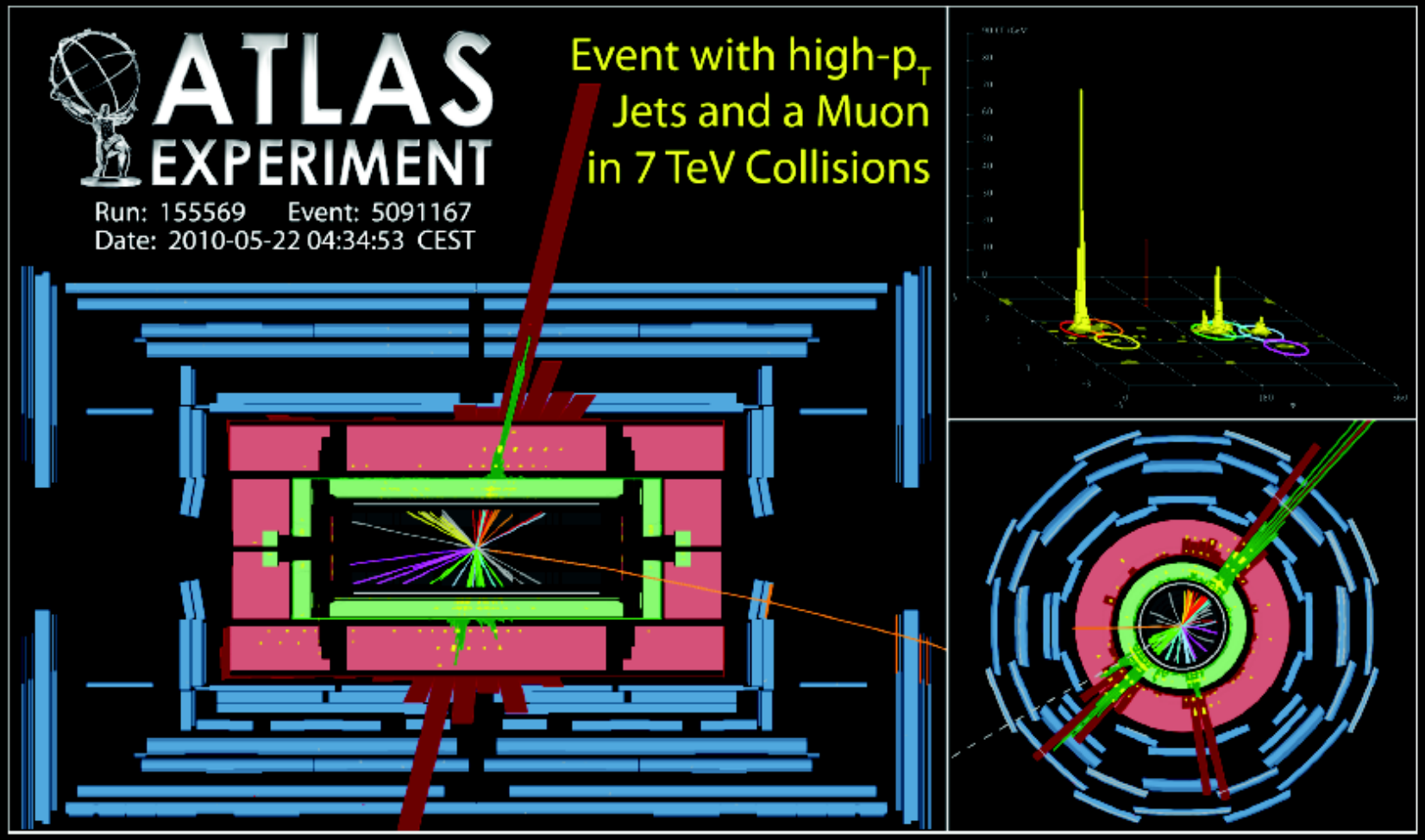
Meff = 1.5 TeV (3 jets)
= 1.65 TeV (4 jets)

All high energy jets associated with same vertex

EtMiss = 100 GeV

Fails final selection ($\Delta\phi$(Jet, EtMiss))

MultiJet+EtMiss+1-Lepton



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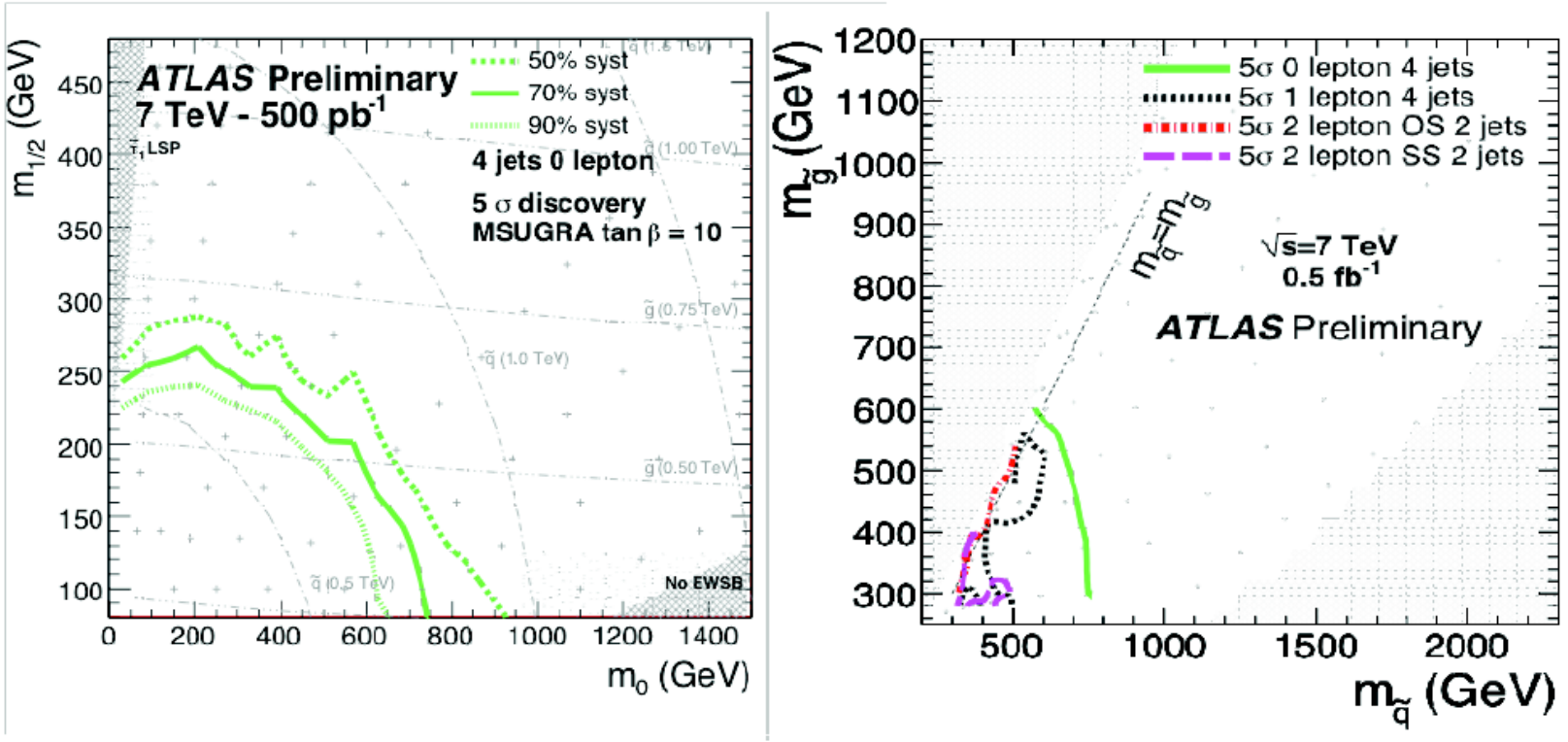
Meff = 915 GeV (2 jets)
= 1.12 TeV (all jets)

EtMiss = 118 GeV

No secondary vertex

1 well isolated, positive muon, Pt = 25 GeV, η = 2.33

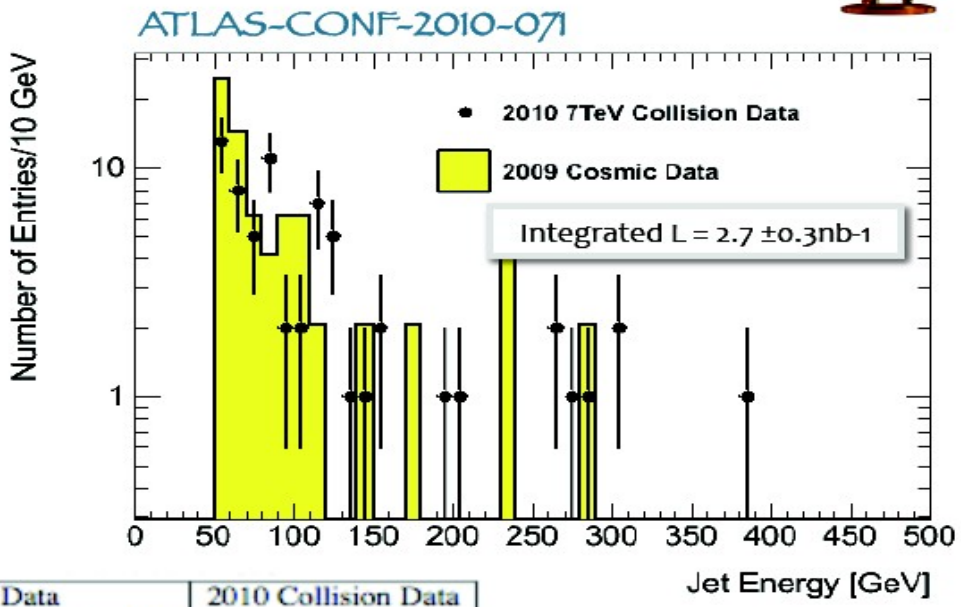
SUSY prospects at 7 TeV



- Significant increase in sensitivity with full 2010 integrated luminosity

Stopped gluinos

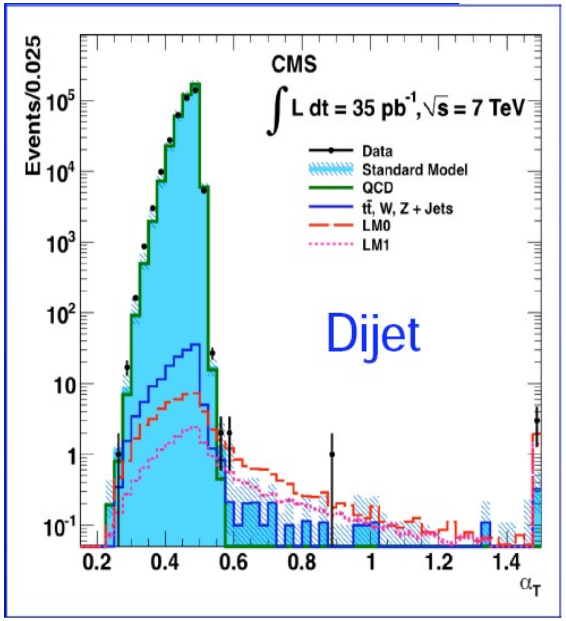
- Meta-Stable heavy particles predicted in many BSM models:
  - Split-SUSY, GMSB
- Could be created in collisions, then come to rest in ATLAS
- Search for signatures of hard jet events in empty bunch crossing

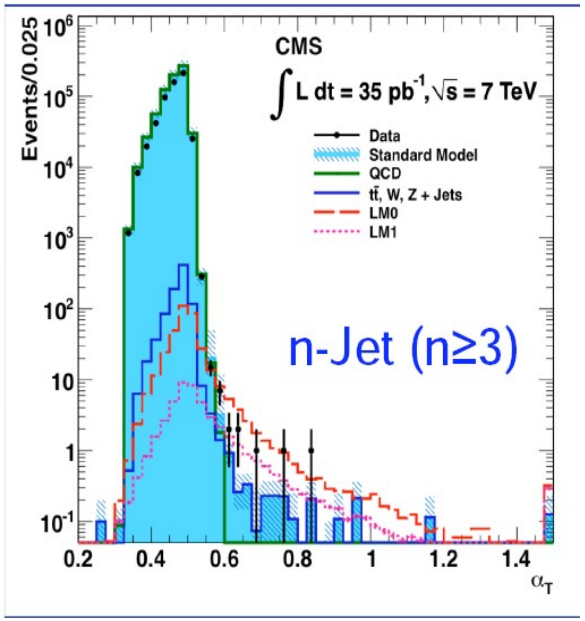


	2009 Cosmic Data		2010 Collision Data
Selection Criteria	Yield of cosmics	Cosmics (scaled)	Yield of data
Good runs and data quality cuts	9.43×10^5	–	1.58×10^6
Leading Jet $\|\eta\|<1.2$	6.26×10^5	1.29×10^6	1.29×10^6
Jet n90>3	3.83×10^5	7.89×10^5	7.90×10^5
number of Jets<4	3.82×10^5	7.87×10^5	7.83×10^5
Muon Segment Veto	530±23.0	1092±47.4	1170
Leading Jet Energy > 50 GeV	39±6.2	80±12.8	75
Leading Jet Width > 0.05	6±2.4	12±4.9	8
Jet n50<6	3±1.7	6±3.5	4
Leading Jet EMF<0.95	2±1.4	4±2.9	4

SUSY searches with CMS
Jets + MET final state

Analysis design to be robust against energy mismeasurements.
Backgrounds levels estimated using data.





For perfectly measured dijet α_T=0.5.
Jet mismeasurements diminish α_T,
whereas genuine MET enlarges it
(any deviation from back to back system do).

$$\alpha_T = E_T^{jet\ 2} / M_T$$

M_T → transverse mass

SUSY searches with CMS
Jets + MET final state

The search is model independent, but the results are interpreted using CMSSM.

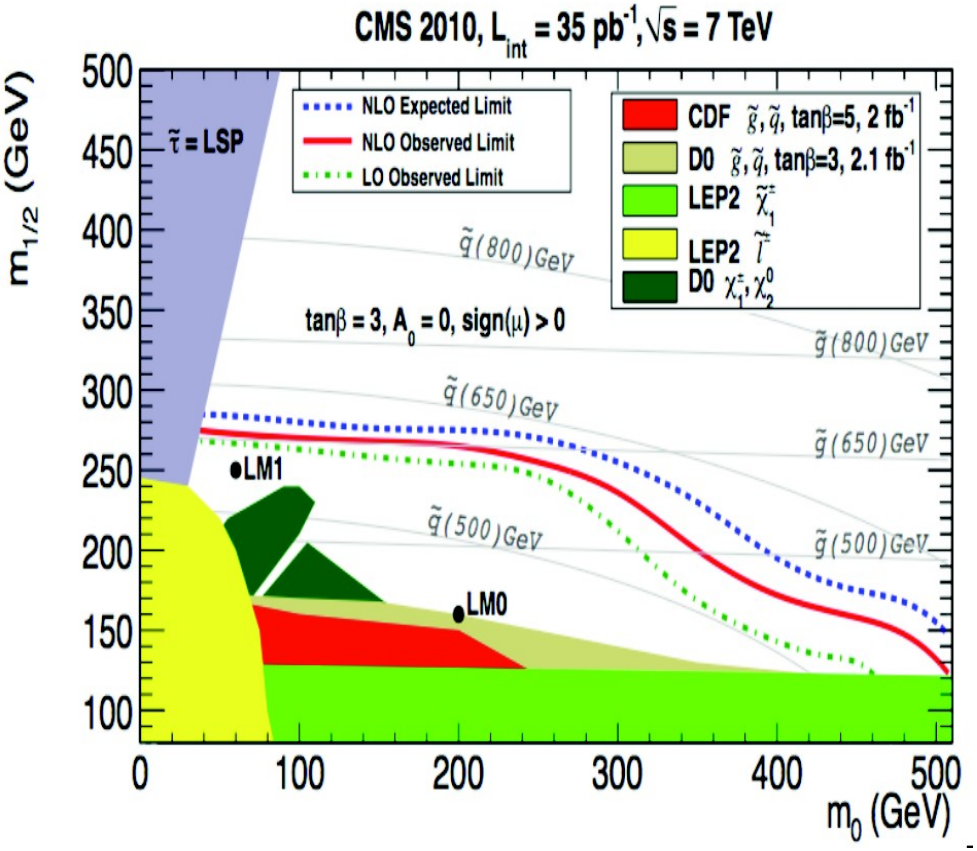
Sample	m_0 (GeV/c^2)	$m_{1/2}$ (GeV/c^2)	A_0	$\tan\beta$	sign(μ)	σ LO (pb)	lightest $\tilde{q}$ (GeV/c^2)	χ_1^0 (GeV/c^2)
LM0	200	160	-400	10	+	110	207	60
LM1	60	250	0	10	+	16.1	410	97

- Dominant production channels at the LHC are squark-squark, squark-gluino and gluino-gluino
- Final states (R-parity conserved: several hadronic jets and large MET due to escaping LSP

SUSY searches with CMS

Using very clean signatures for early SUSY signals (α_T, di-photon+MET, multi-leptons etc) we are already exceeding limits on SUSY set by the Tevatron experiments. **In a few months the eclusion range established in the last 20 years expanded ~factor two.** CMS SUS-10-003

Prospects for 2011-12: discover squarks and gluinos (if SUSY is a symmetry of nature) above 1TeV.



Next topics

- 19.01 - Wrapping up on data 2010:
  - SM physics: selected results
  - Searches: selected results

  I have not discussed B-physics program, but for comprehensive review follow
    - Cracow-Warsaw meeting, Warsaw, 21 January 2010