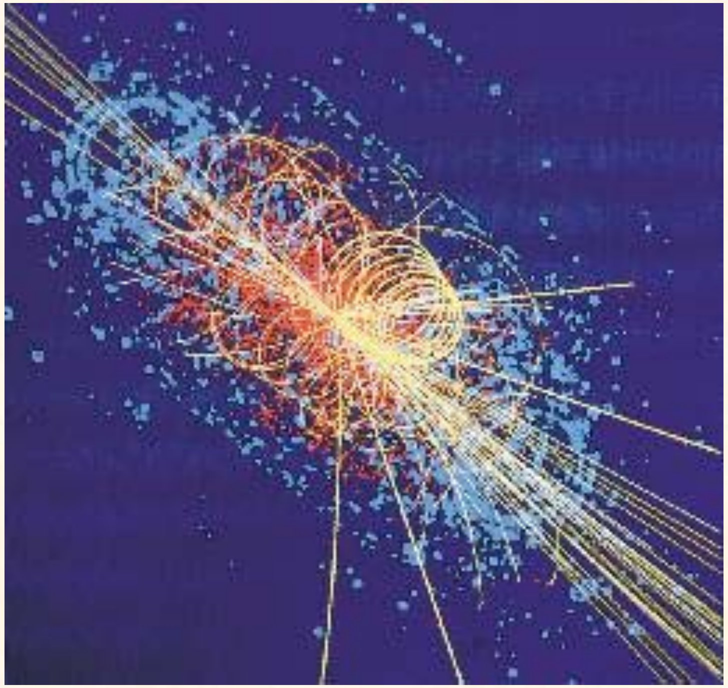
Physics at Hadron Colliders

Part 4



Physics Beyond the Standard Model

- **Supersymmetry**
  (Tevatron and LHC)

- **Other Extensions of the Standard Model**
  - Extra dimensions
  - Extra gauge bosons
  - Leptoquarks ….

Why ?

1. Gravity is not yet incorporated in the Standard Model

2. Dark Matter not accomodated

3. Many open questions in the Standard Model
   - Hierarchy problem: m_W (100 GeV) → m_{Planck} (10^{19} GeV)
   - Unification of couplings
   - Flavour / family problem
   - …..

All this calls for a ***more fundamental theory*** of which the Standard Model is a low energy approximation → **New Physics**

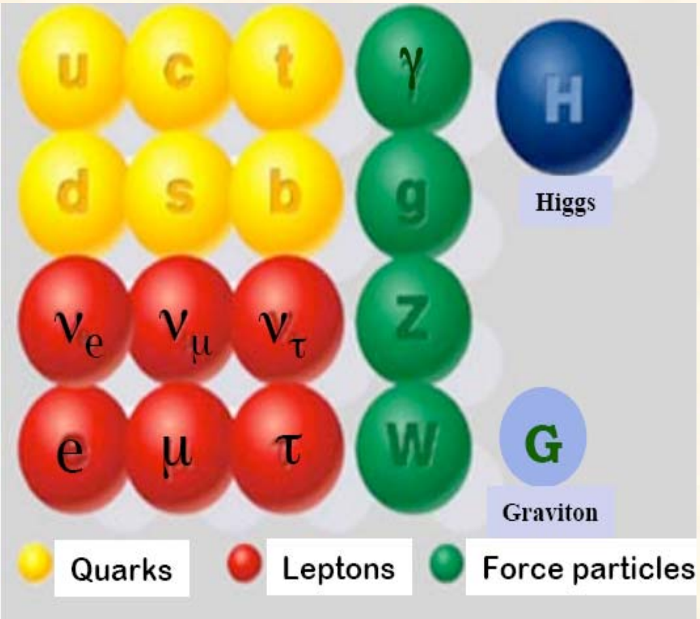
Candidate theories: Supersymmetry
Extra Dimensions
Technicolor
…….

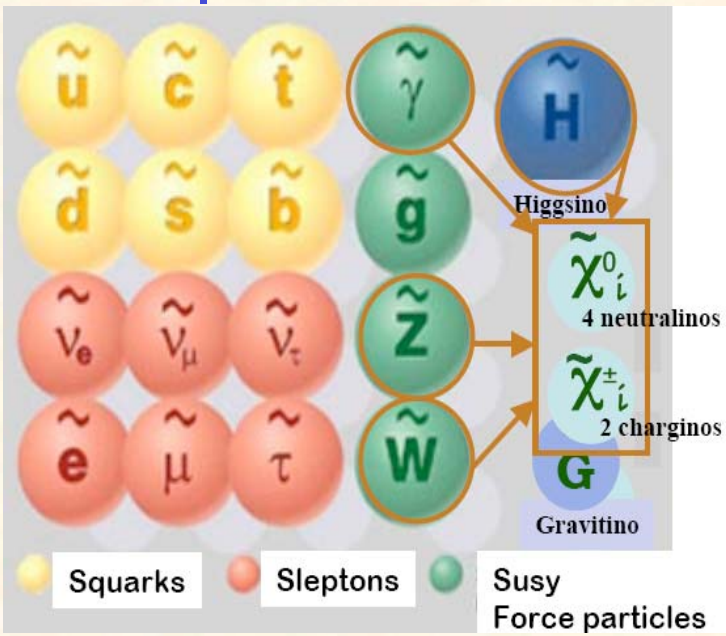
Many extensions predict new physics at the TeV scale !!

Strong motivation for LHC, mass reach ~ 3 TeV

Supersymmetry

Extends the Standard Model by predicting a new symmetry
Spin ½ matter particles (fermions) $\Leftrightarrow$ Spin 1 force carriers (bosons)





New Quantum number: R-parity: $R_p = (-1)^{B+L+2s}$ = +1 SM particles
- 1 SUSY particles

Experimental consequences of R-parity conservation:

- SUSY particles are produced in pairs
- Lightest Supersymmetric Particle (LSP) is stable.

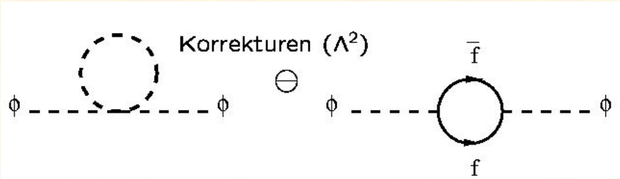
LSP is only weakly interacting:
LSP ≡ $\chi^0{}_1$ (lightest neutralino, in many models)

→ LSP behaves like a ν → it escapes detection

→ E_T^{miss} (typical SUSY signature)

Why do we like SUSY so much?

1. Quadratically divergent quantum corrections to the Higgs boson mass are avoided

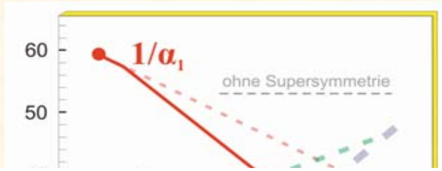


$$\Delta m_H = f(m_{\tilde{B}}^2 - m_f^2)$$

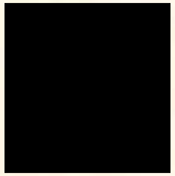
$\rightarrow$ m_{SUSY} ~ 1 TeV

(Hierarchy or naturalness problem)

2. Unification of coupling constants of the three interactions seems possible

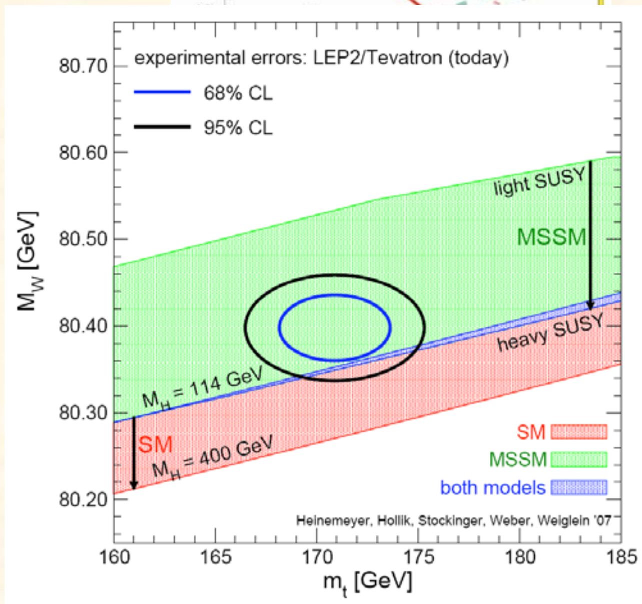


3. SUSY provides a candidate for dark matter



The lightest SUSY particle (LSP)

4. A SUSY extension is a small perturbation, consistent with the electroweak precision data



Link to the Dark Matter in the Universe ?

Parameters of the SUSY model $\Rightarrow$ predictions for the relic density of dark matter

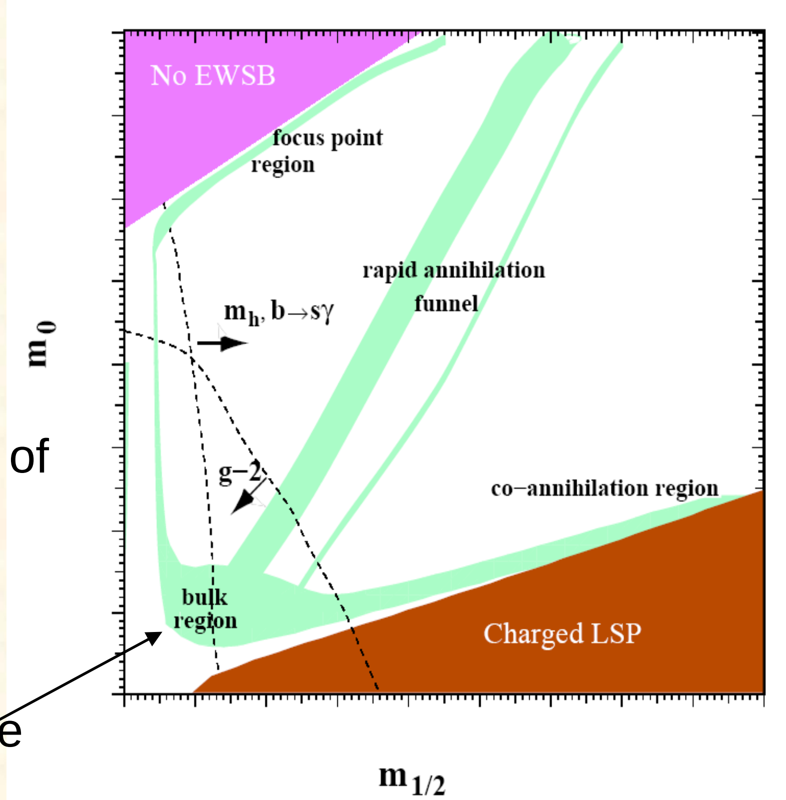
$$\rho_\chi \sim m_\chi n_\chi \,, \quad n_\chi \sim \frac{1}{\sigma_{ann}(\chi\chi \to \ldots)}$$

Interpretation in a simplified model

cMSSM
(constrained Minimal Supersymmetric
 Standard Model)

Five parameters:

m_0, $m_{1/2}$ particle masses at the GUT scale
A_0 common coupling term
tan β ratio of vacuum expectation value of the two Higgs doublets
μ (sign μ) Higgs mass term

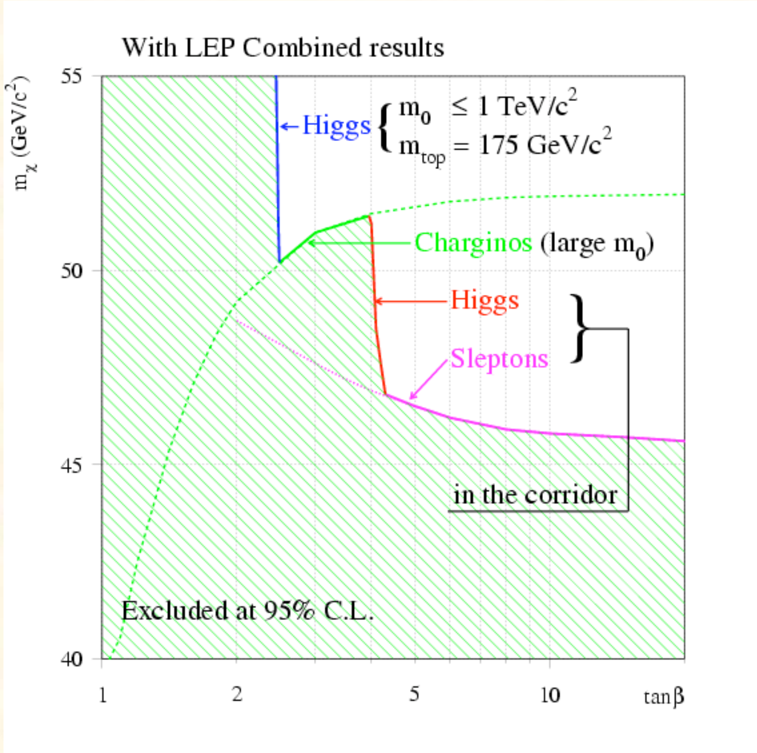


regions of parameter space which are consistent with the measured relic density of dark matter (WMAP,…..)

The **masses of the SUSY particles** are not predicted;
Theory has many additional new parameters (on which the masses depend)

However, charginos/neutralinos are usually lighter than squarks/sleptons/gluinos.

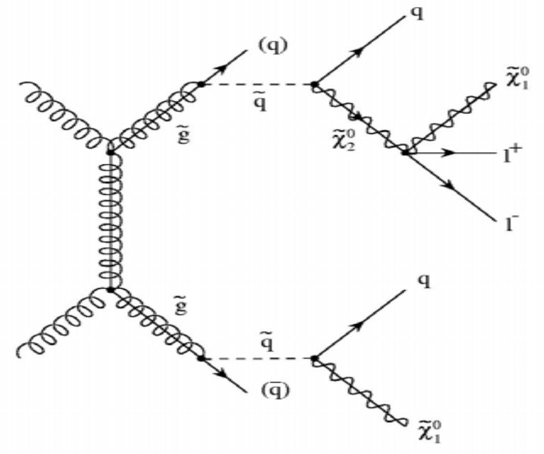
Present mass limits :	m (sleptons, charginos)	>	90-103 GeV	LEP II
	m (squarks, gluinos)	>	~ 350 GeV	Tevatron
	m (LSP, lightest neutralino)	>	~ 45 GeV	LEP II



LEP-II limit on the mass of the Lightest SUSY particle

assumption:
lightest neutralino = LSP

Search for Supersymmetry at the LHC



- If SUSY exists at the electroweak scale, a discovery at the LHC should be easy

- Squarks and Gluinos are strongly produced

  They decay through cascades to the lightest SUSY particle (LSP)

$\Longrightarrow$ combination of
Jets, Leptons, E_T^{miss}

1. Step: Look for deviations from the Standard Model
   Example: Multijet + E_T^{miss} signature

2. Step: Establish the SUSY mass scale use inclusive variables, e.g. effective mass distribution

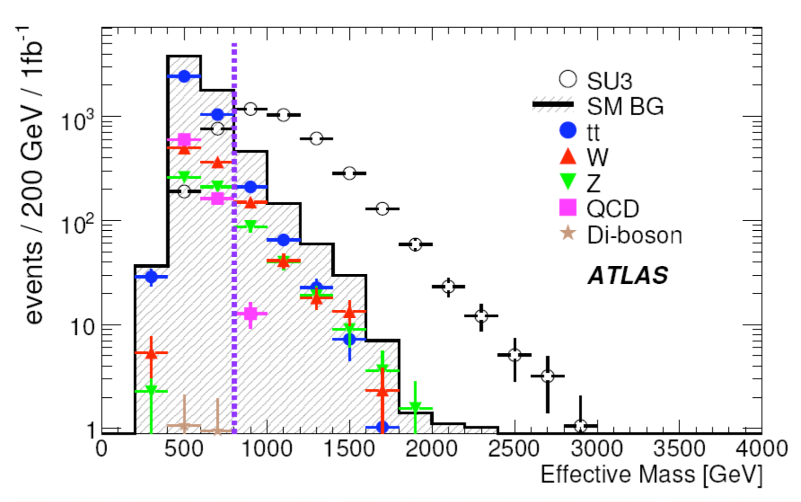
3. Step: Determine model parameters (difficult)
   Strategy: select particular decay chains and use kinematics to determine mass combinations

Squarks and Gluinos

- If R-parity conserved, cascade decays produce distinctive events:
  multiple jets, leptons, and E_T^{miss}

- Typical selection: $N_{jet} > 4$, $E_T > 100, 50, 50, 50$ GeV, $E_T^{miss} > 100$ GeV

- Define: $M_{eff} = E_T^{miss} + P_T^1 + P_T^2 + P_T^3 + P_T^4$ (effective mass)



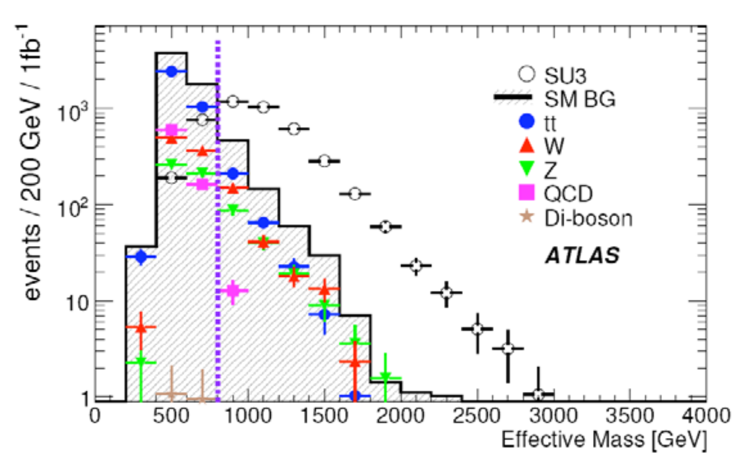
LHC reach for Squark- and Gluino masses:

0.1 fb^{-1}	⇒	M ~ 750 GeV
1 fb^{-1}	⇒	M ~ 1350 GeV
10 fb^{-1}	⇒	M ~ 1800 GeV

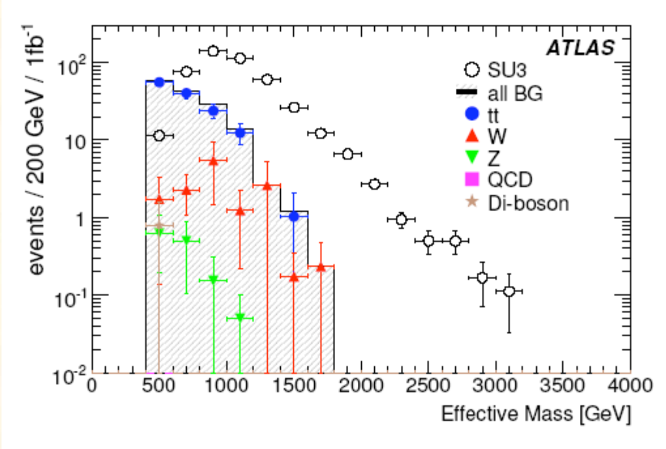
Deviations from the Standard Model due to SUSY at the TeV scale can be detected fast !

example: mSUGRA, point SU3 (bulk region)
m_0 = 100 GeV, $m_{1/2}$ = 300 GeV
tan β = 6, A_0 = -300 GeV, $\mu > 0$

...additional potential: inclusive searches with leptons

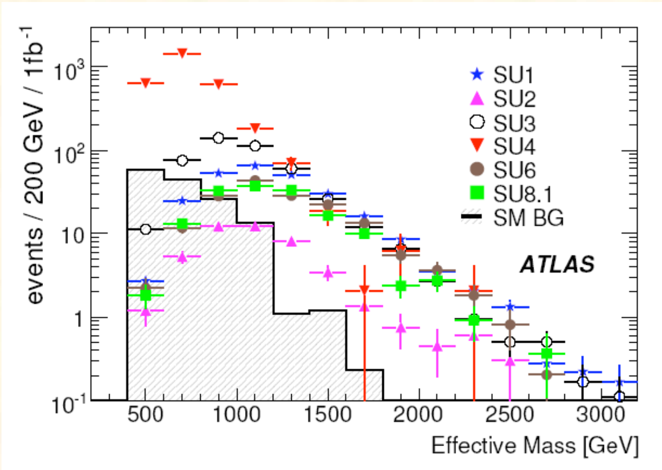


SU3, 4 jets + 0 lepton final states



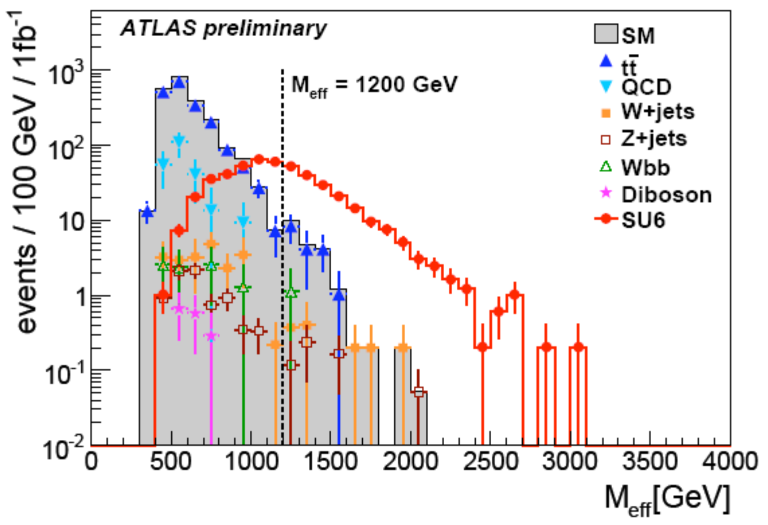
SU3, 4 jets + 1 lepton final states

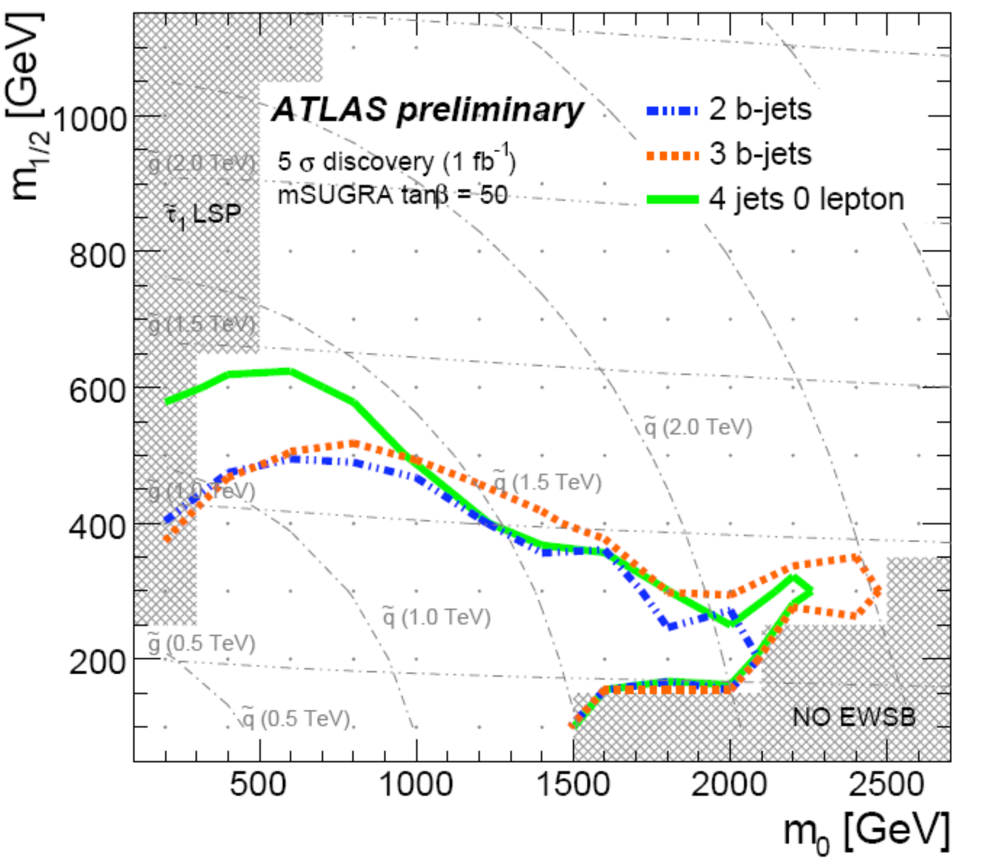
- Smaller signal rates, but better S:B conditions
- Discovery potential is more robust, in particular at the beginning, when systematic uncertainties on the backgrounds are large
- Similar analyses with τ lepton and b quark final states



4 jets + 1 lepton final states for other benchmark points

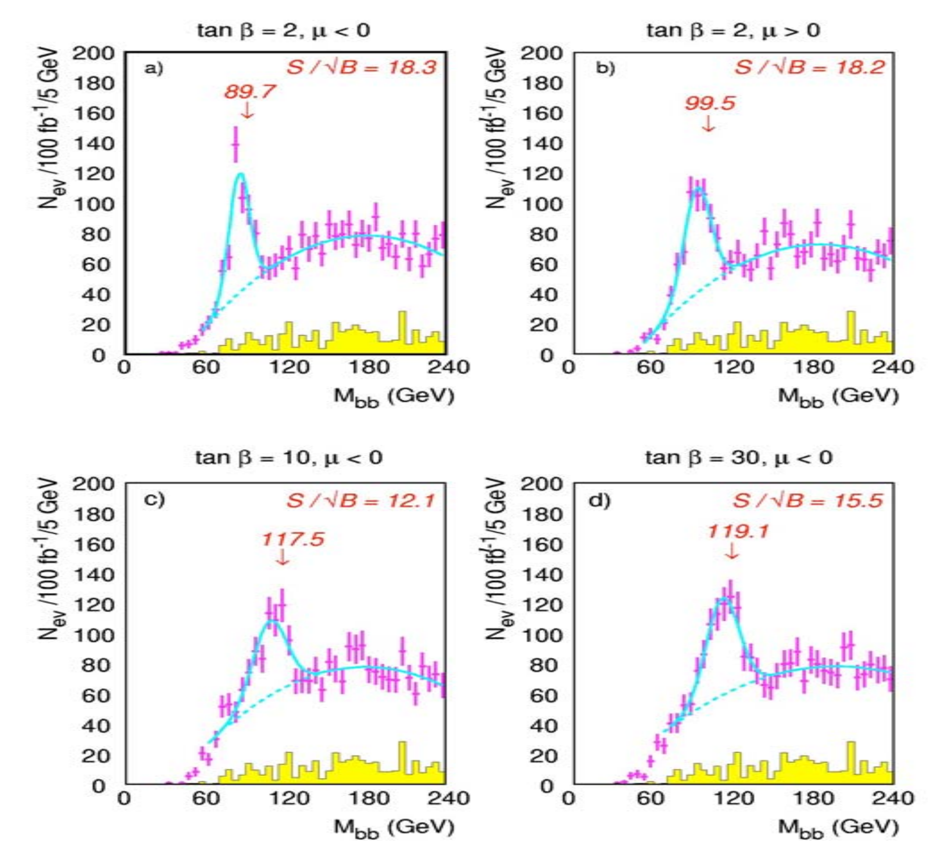
Example: search for final states with E_T^{miss} and two b-jets

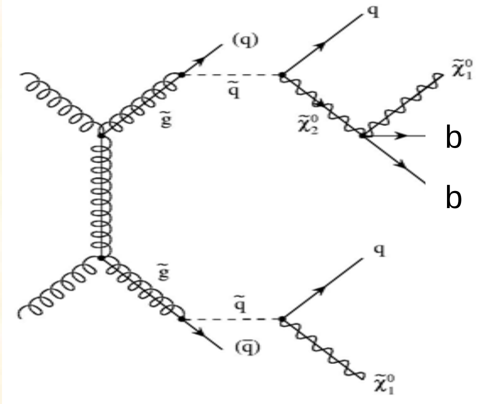




$h \rightarrow bb$:

CMS





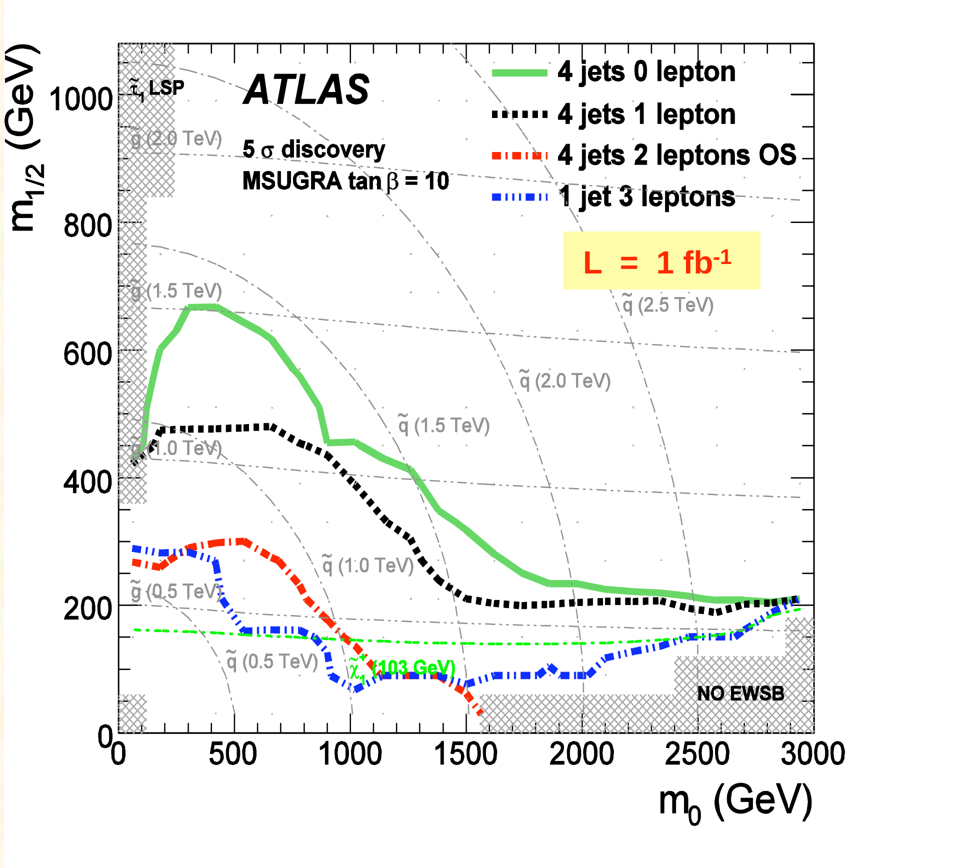
important if $\chi^0_2 \rightarrow \chi^0_1 h$ is open;
bb peak can be reconstructed in many cases

Could be a Higgs discovery mode !

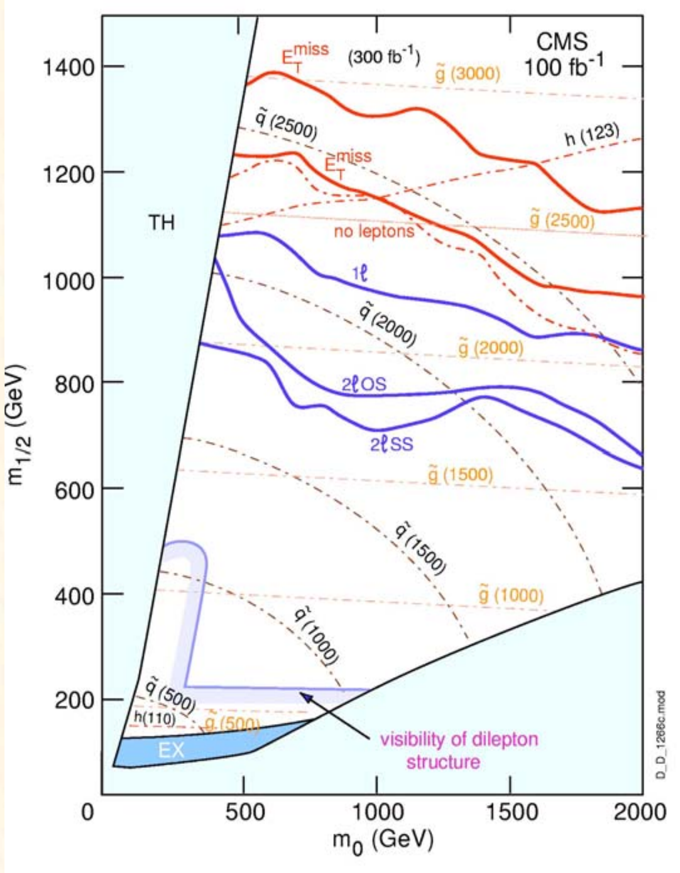
SM background can be reduced by applying a cut on E_T^{miss}

LHC reach in the m_0 - $m_{1/2}$ mSUGRA plane:

Multijet + E_T^{miss} signature



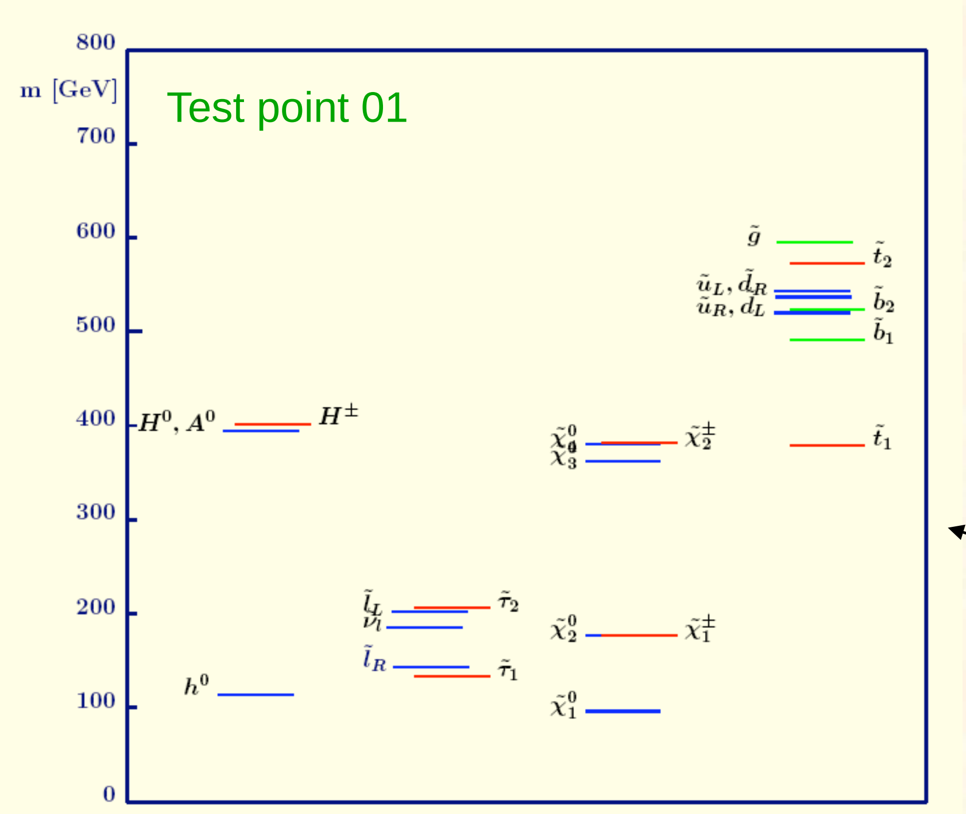
SUSY cascade decays give also rise to many other inclusive signatures: **leptons, b-jets, τ's**

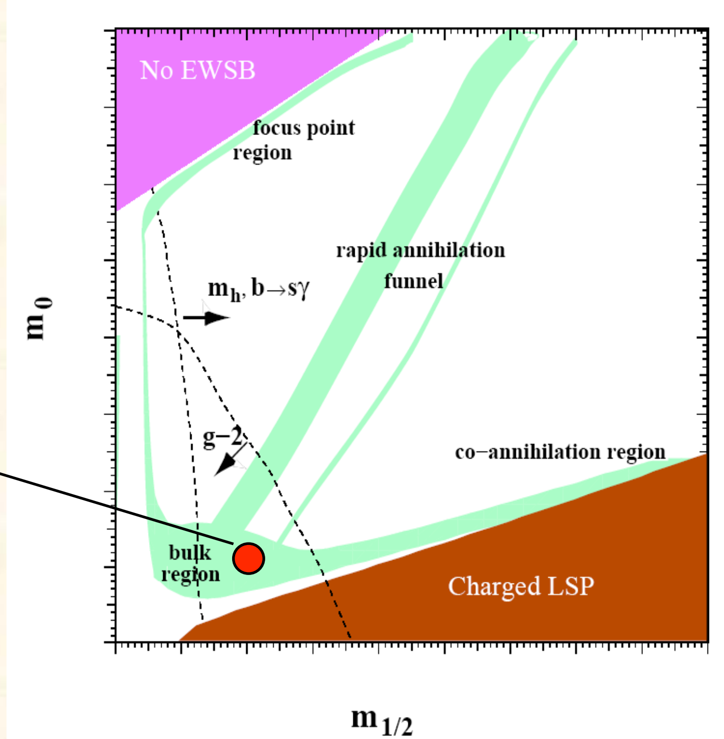


- Tevatron reach can be extended with early data
- Expect multiple signatures for TeV-scale SUSY
  Long term mass reach (300 fb^{-1}): 2.5 – 3 TeV

How can the underlying theoretical model be identified ?

Measurement of the SUSY spectrum $\rightarrow$ Parameter of the theory



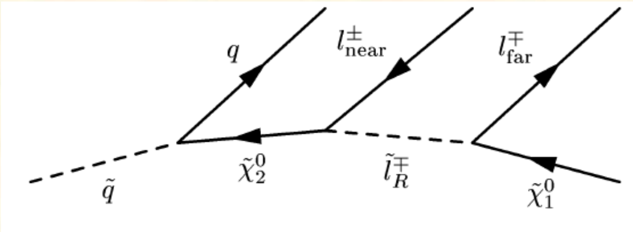


LHC: strongly interacting squarks and gluinos

ILC / CLIC: precise investigation of electroweak SUSY partners

LHC Strategy: End point spectra of cascade decays

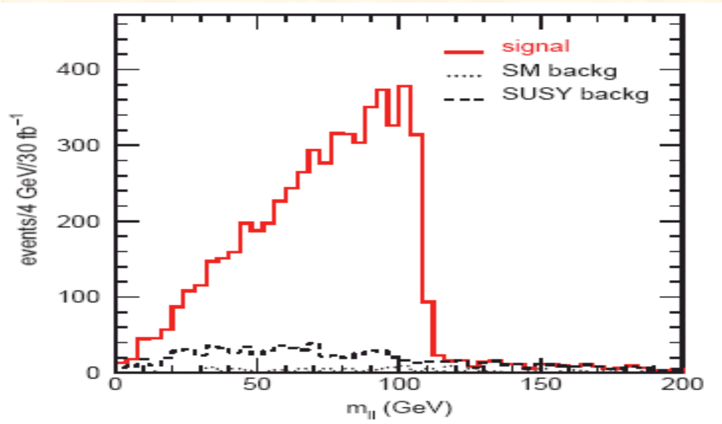
Example: $\tilde{q} \rightarrow q\tilde{\chi}_2^0 \rightarrow q\tilde{\ell}^{\pm}\ell^{\mp} \rightarrow q\ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$



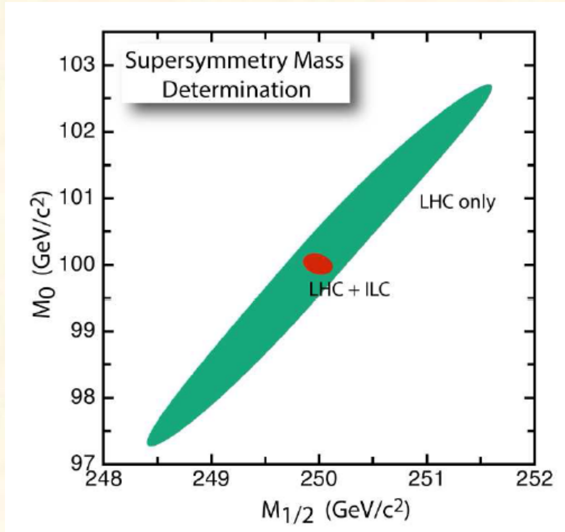
$$M^{max}_{\ell^+\ell^-} = \frac{\sqrt{(m^2_{\chi_2^0} - m^2_{\tilde{\ell}})(m^2_{\tilde{\ell}} - m^2_{\chi_1^0})}}{m_{\tilde{\ell}}}$$

$$M^{max}_{\ell_1 q} = \frac{\sqrt{(m^2_{\chi_2^0} - m^2_{\tilde{\ell}})(m^2_{\tilde{q}} - m^2_{\chi_2^0})}}{m_{\chi_2^0}}$$

Results for point 01:

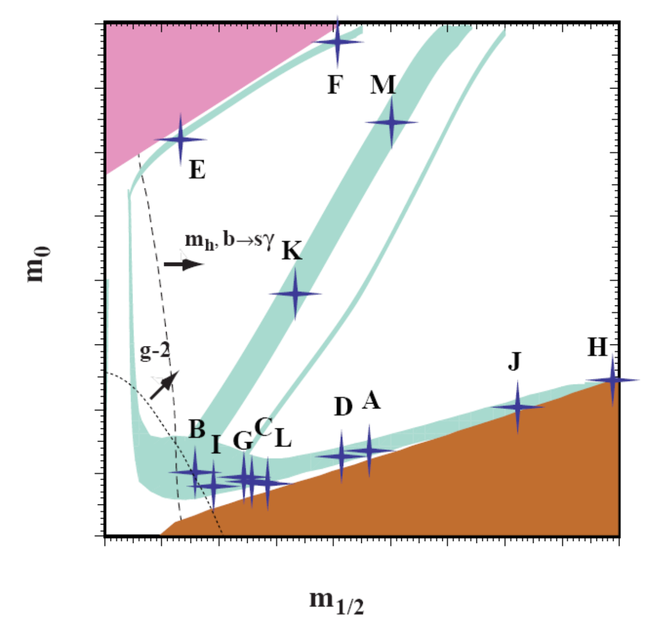


	LHC	LHC⊕ILC
$\Delta m_{\tilde{\chi}_1^0}$	4.8	0.05 (input)
$\Delta m_{\tilde{l}_R}$	4.8	0.05 (input)
$\Delta m_{\tilde{\chi}_2^0}$	4.7	0.08
$\Delta m_{\tilde{q}_L}$	8.7	4.9
$\Delta m_{\tilde{q}_R}$	11.8	10.9
$\Delta m_{\tilde{g}}$	8.0	6.4
$\Delta m_{\tilde{b}_1}$	7.5	5.7
$\Delta m_{\tilde{b}_2}$	7.9	6.2
$\Delta m_{\tilde{l}_L}$	5.0	0.2 (input)
$\Delta m_{\tilde{\chi}_4^0}$	5.1	2.23

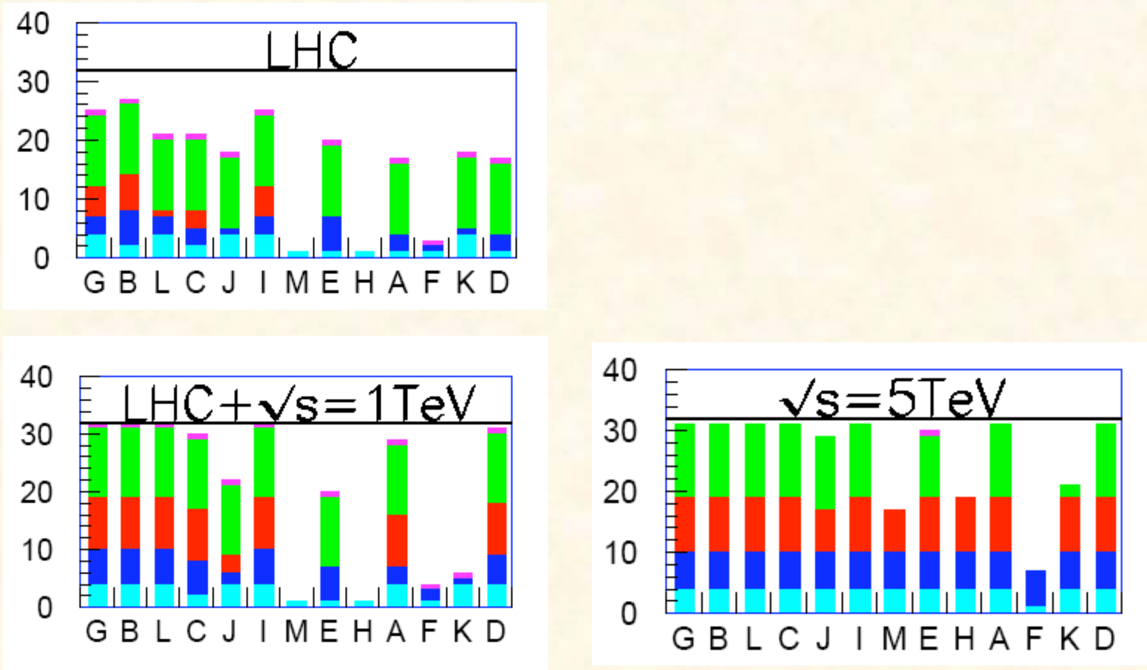


L = 300 fb^{-1}

The LHC and the ILC (International Linear Collider, in study/planning phase) are complementary in SUSY searches



Number of observable SUSY particles:



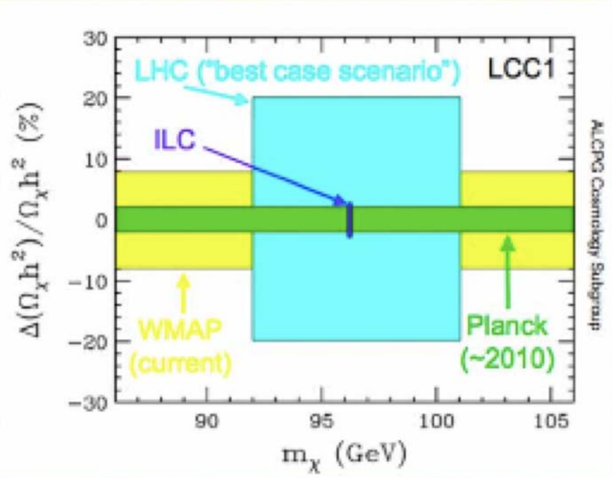
)* Study by J. Ellis et al., hep-ph/0202110

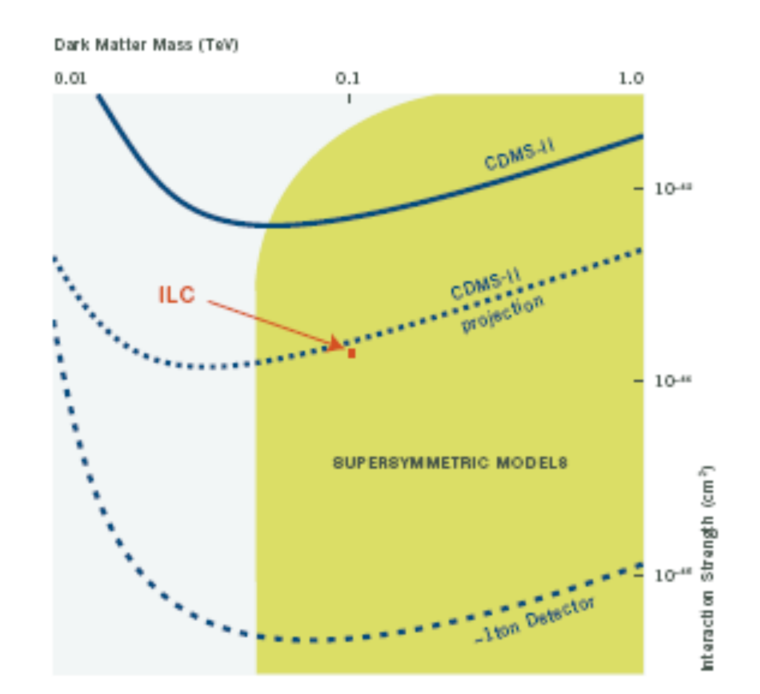
Strategy in SUSY Searches at the LHC:

- Search for multijet + E_T^{miss} excess
- If found, select SUSY sample (simple cuts)
- Look for special features (γ's , long lived sleptons)
- Look for $\ell^{\pm}$, $\ell^{+} \ell^{-}$, $\ell^{\pm} \ell^{\pm}$, b-jets, τ's
- End point analyses, global fit $\rightarrow$ SUSY model parameters

Importance for the interplay between direct and indirect Dark Matter searches

- Following a discovery of New Physics at the LHC (deviation from the Standard Model) the LHC will aim to test the Dark Matter hypothesis
- Estimation of relic density in a simple model-dependent scenario will be the first goal
- Less model-dependent scenarios will follow, detailed studies probably require the ILC
- Conclusive result is only possible in conjunction with astroparticle physics experiments
- Ultimate goal: observation of LSP at the LHC, confirmed by a signal in a direct dark matter experiment with predicted mass and cross-section



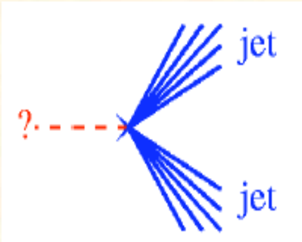


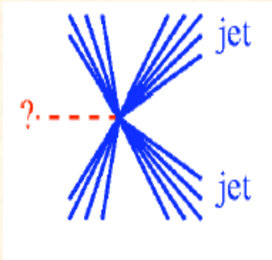
The Search for

SUSY at the Tevatron

The two classical signatures

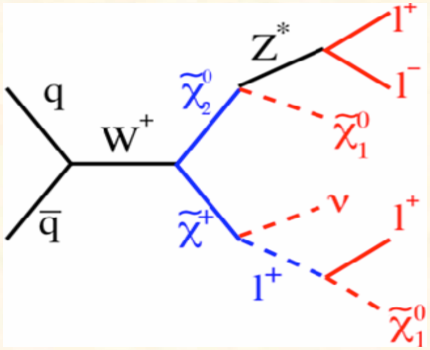
1. Search for Squarks and Gluinos: Jet + E_T^{miss} signature
   produced via QCD processes





2. Search for Charginos and Neutralinos: Multilepton + E_T^{miss} signature
   produced via electroweak processes (associated production)

$$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow l^\pm l^\mp l^\pm \tilde{\chi}_1^0 \tilde{\chi}_1^0 X$$



Search for Squarks and Gluinos

- Three different analyses, depending on squark / gluinos mass relations:

(i) dijet analysis
small m_0, m(squark) < m(gluino)

$$\tilde{q}\,\bar{\tilde{q}} \rightarrow q\,\tilde{\chi}_1^0\,\bar{q}\,\tilde{\chi}_1^0$$

(ii) 3-jet analysis
intermediate m_0 m(squark) ≈ m(gluino)

$$\tilde{q}\,\tilde{g} \rightarrow q\,\tilde{\chi}_1^0\,q\,\bar{q}\,\tilde{\chi}_1^0$$

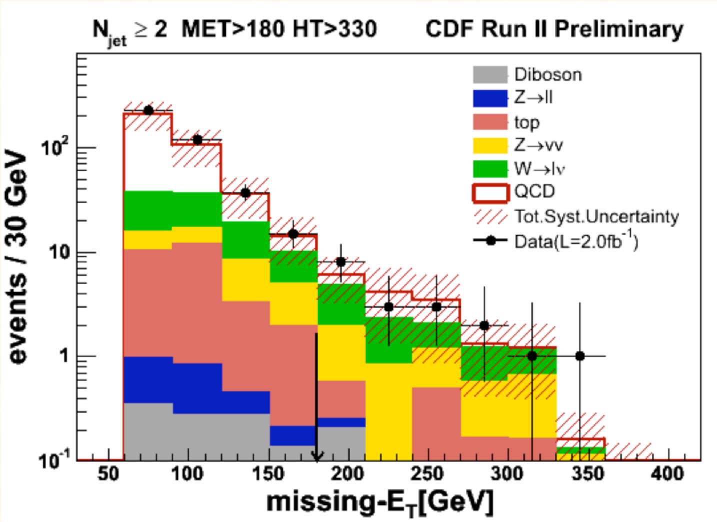
(iii) Gluino analysis
large m_0, m(squark) > m(gluino)

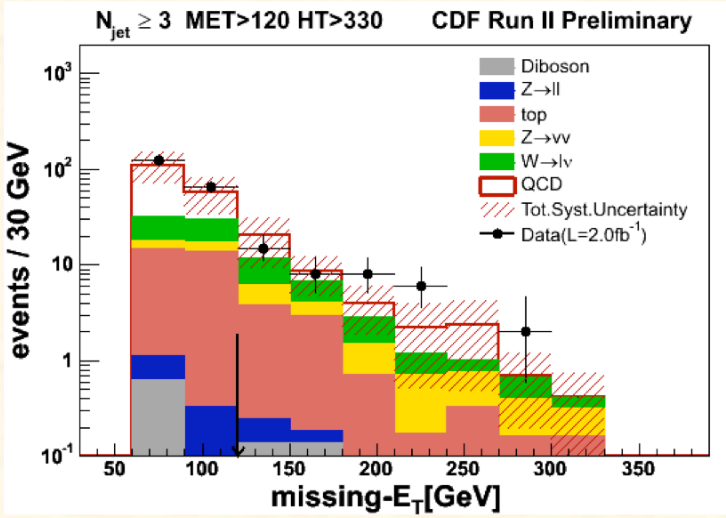
$$\tilde{g}\,\tilde{g} \rightarrow q\,\bar{q}\,\tilde{\chi}_1^0\,q\,\bar{q}\,\tilde{\chi}_1^0$$

- Main backgrounds: $Z \rightarrow \nu\nu$ + jets, tt, W + jet production

- Event selection:
  * require at least 2, 3 or 4 jets with P_T > 60 / 40 / 30 / 20 GeV
  * veto on isolated electrons and muons
  * isolation of E_T^{miss} and all jets
  * optimization of the final cuts → discriminating variables

Search for Squarks and Gluinos (cont.)





Expected background:

samples	2-jets	3-jets	4-jets
QCD	4.37 ± 2.01	13.34 ± 4.67	15.26 ± 7.60
top	1.35 ± 1.22	7.56 ± 3.85	22.14 ± 7.29
Z→ $\nu\nu$+jets	3.95 ± 1.09	5.39 ± 1.74	2.74 ± 0.95
Z→ ll+jets	0.09 ± 0.04	0.16 ± 0.11	0.14 ± 0.08
W→ $l\nu$+jets	6.08 ± 2.15	10.69 ± 3.84	7.68 ± 2.85
WW/WZ/ZZ	0.21 ± 0.19	0.35 ± 0.17	0.49 ± 0.34
tot SM	16 ± 5	37 ± 12	48 ± 17

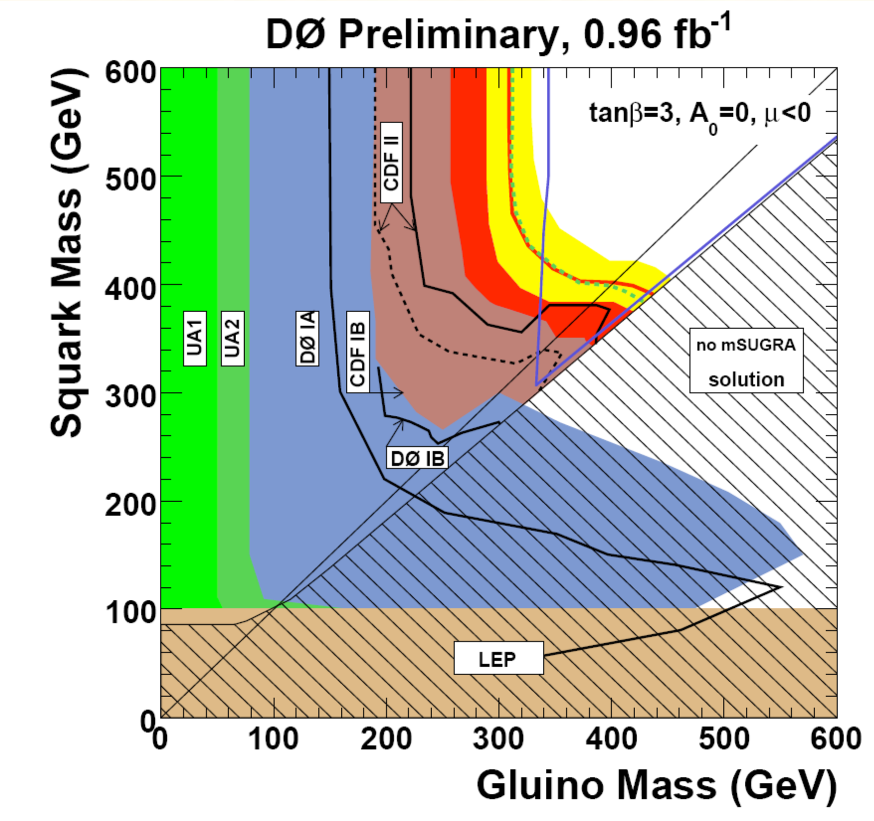
Observed events in data:

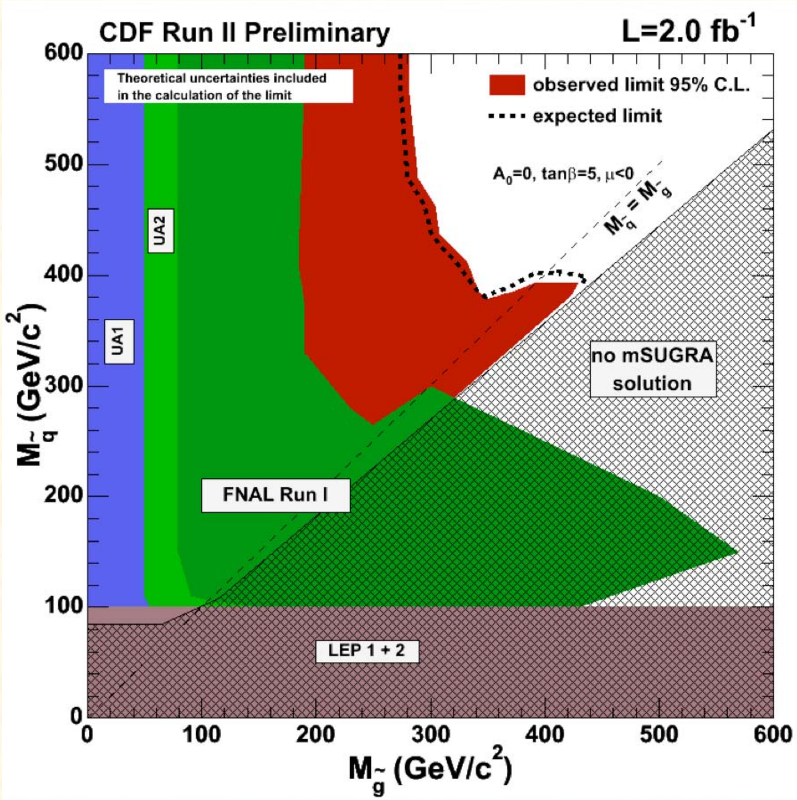
Region	Observed data
4-jets	45
3-jets	38
2-jets	18

No excess above background from Standard Model processes

→ No evidence for SUSY (yet) → Set limits on masses of SUSY particles

Excluded regions in the m(squark) vs. m(gluino) plane



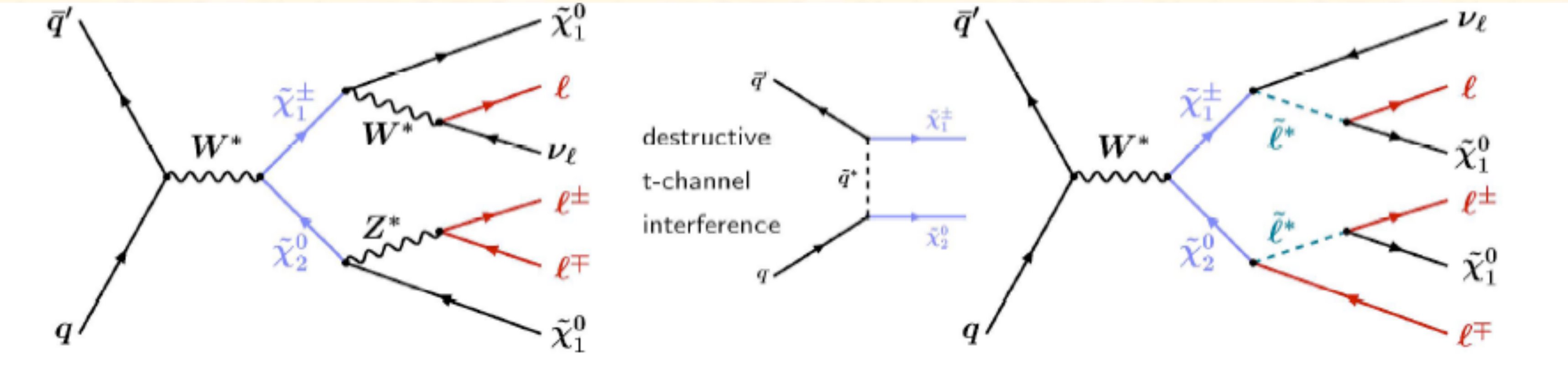


Exclusion limits
(incl. systematic uncertainties)*:
m(gluino) > 290 GeV/c^2
m(squark) > 375 GeV/c^2

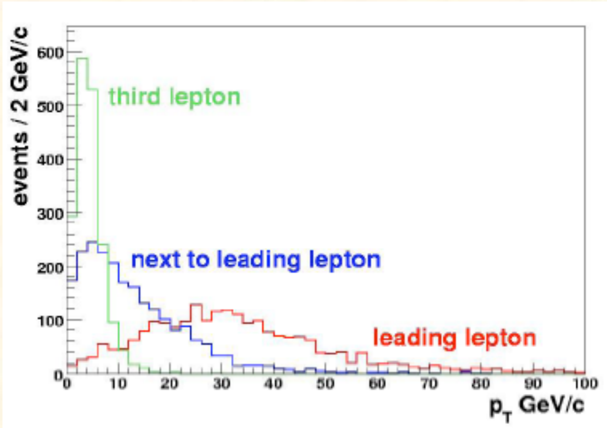
)* uncertainties from structure functions, change of renormalization and factorization scale μ by a factor of 2, NLO calculation, default choice: μ = m(gluino), m(squark) or ½(m(gluino)+m(squark)) for gg, qq, qg production

Search for Charginos and Neutralinos
- the tri-lepton channel-

- Gaugino pair production via electroweak processes
  (small cross sections, ~0.1 – 0.5 pb, however, small expected background)



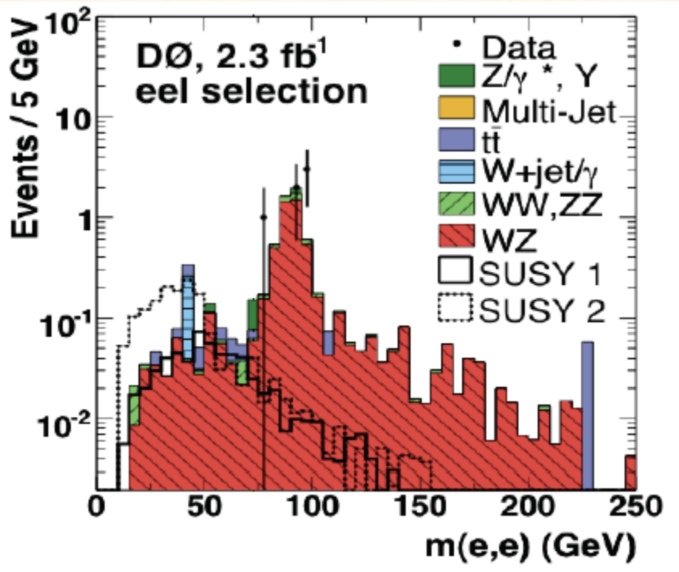
- For small gaugino masses (~100 GeV/c^2)
  one needs to be sensitive to low P_T leptons

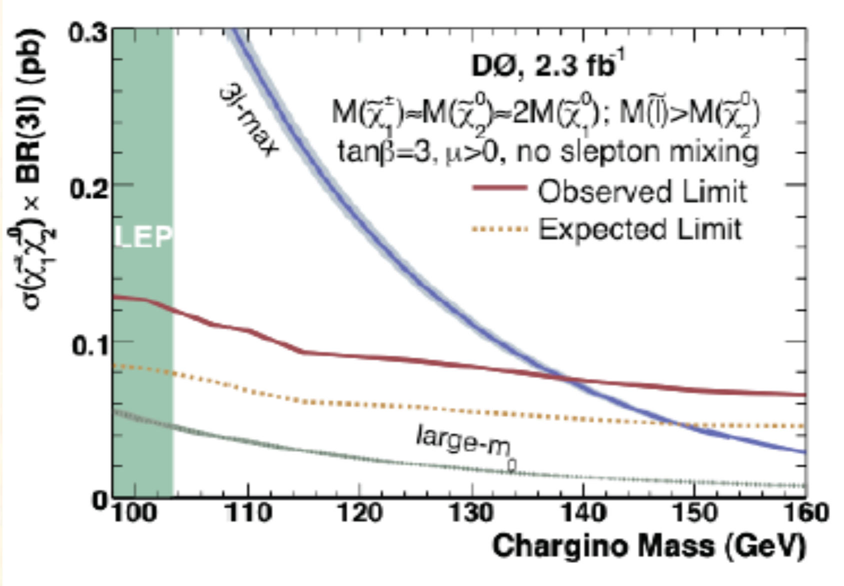


Analysis:

- Search for different $(\ell\ell\ell)$ + like-sign $\mu\mu$ final states with missing transverse momentum
- In order to gain efficiency, no lepton identification is required for the 3rd lepton, select: two identified leptons + a track with p_T > 4 GeV/c

mSUGRA interpretation





For specific scenarios: sensitivity / limits above LEP limits;
e.g., $M(\chi^{\pm}) > 140$ GeV/c^2 for the 3l-max scenario

Can LHC probe extra dimensions ?

- Much recent theoretical interest in models with extra dimensions
  (Explain the weakness of gravity (or hierarchy problem) by extra dimensions)

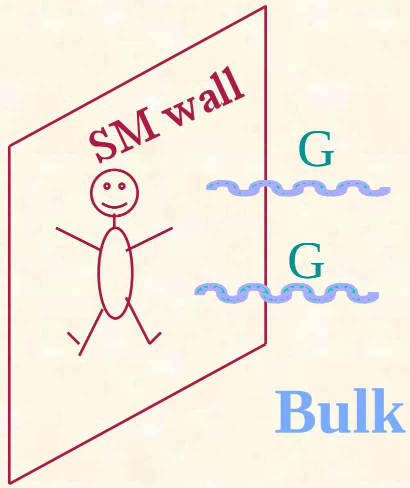
- New physics can appear at the TeV-mass scale,
  i.e. accessible at the LHC

Example: **Search for direct Graviton production**

$$gg \rightarrow gG,\ qg \rightarrow qG,\ q\bar{q} \rightarrow Gg$$

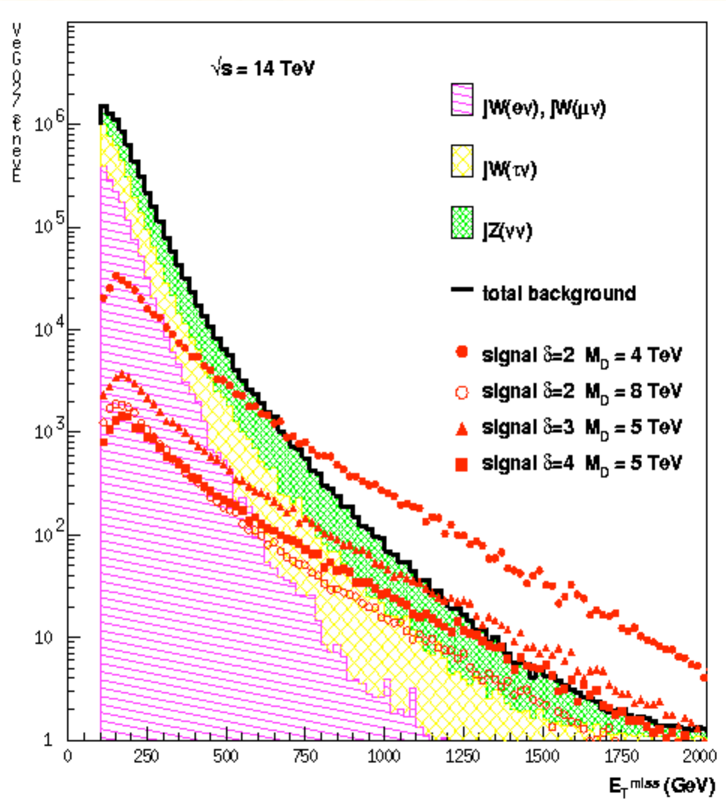
$$q\bar{q} \rightarrow G\gamma$$

$\Rightarrow$ **Jets or Photons with E_T^{miss}**



Search for escaping gravitons:

Jet + E_T^{miss} search:



$$G_N^{-1} = 8\pi R^{\delta} M_D^{2+\delta}$$

δ : # extra dimensions
M_D = scale of gravitation
R = radius (extension)

$\mathbf{M_D^{max}}$	**=**	**9.1,**	**7.0,**	**6.0 TeV**
	for			
δ	**=**	**2,**	**3,**	**4**

Main backgrounds:
jet+Z(→νν), jet+W→jet+(e,μ,τ)ν

LHC experiments are sensitive, but conclusions on the underlying theory are difficult and require a detailed measurement program

More ideas?

1. New resonances decaying into lepton pairs

examples: W ´ and Z´ or Graviton resonances (extra dimensions)

use again leptonic decay mode to search for them: $W' \rightarrow \ell\, \nu$

$Z' \rightarrow \ell\, \ell$

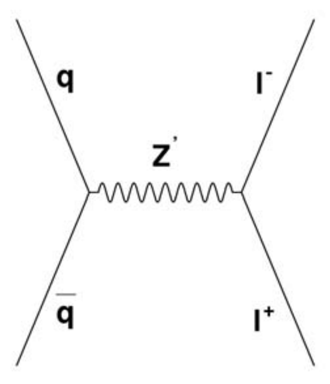
2. Leptoquarks ?

Particles that decay into leptons and quarks
(violate lepton and baryon number; appear in Grand Unified theories)

here: search for low mass Leptoquarks (TeV scale)

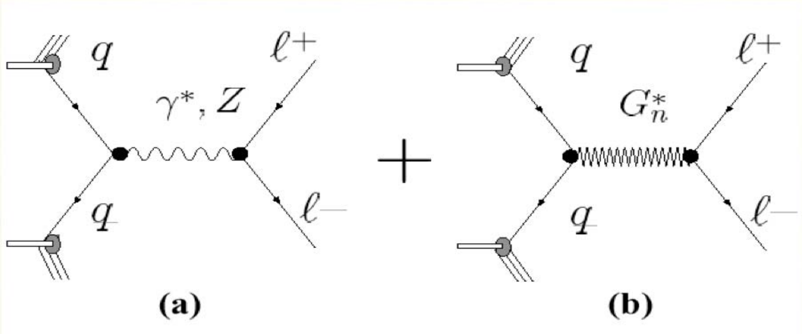
Fermilab Search for New Resonances in High Mass Di-leptons

- **Neutral Gauge Boson Z´**
  assume SM-like couplings



- **Randall-Sundrum narrow Graviton resonances decaying to di-lepton**

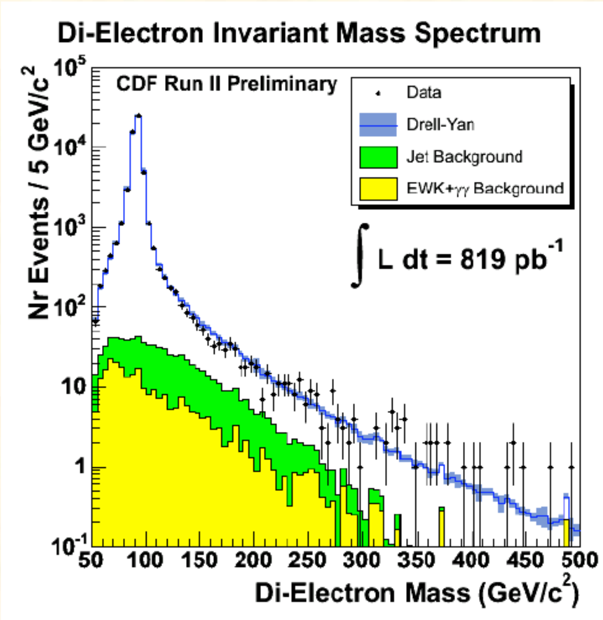
appear in Extra Dim. Scenarios



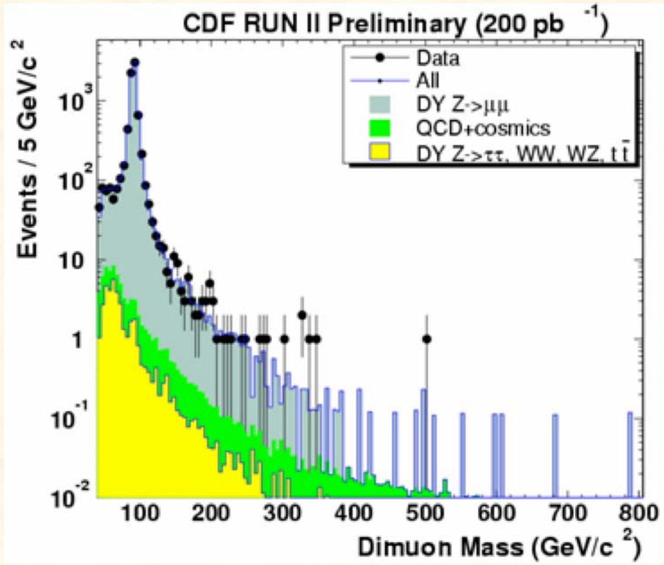
Main background from Drell-Yan pairs

Search for New Resonances in High Mass Di-leptons

Di-electron Invariant Mass



Di-muon Invariant Mass



Data are consistent with background from SM processes. No excess observed.

Z´ mass limits (SM couplings)		**ee**	**μμ**	**ττ**	
95% C.L.	**CDF /D0:**	**965**	**835**	**394**	**GeV/c^2**

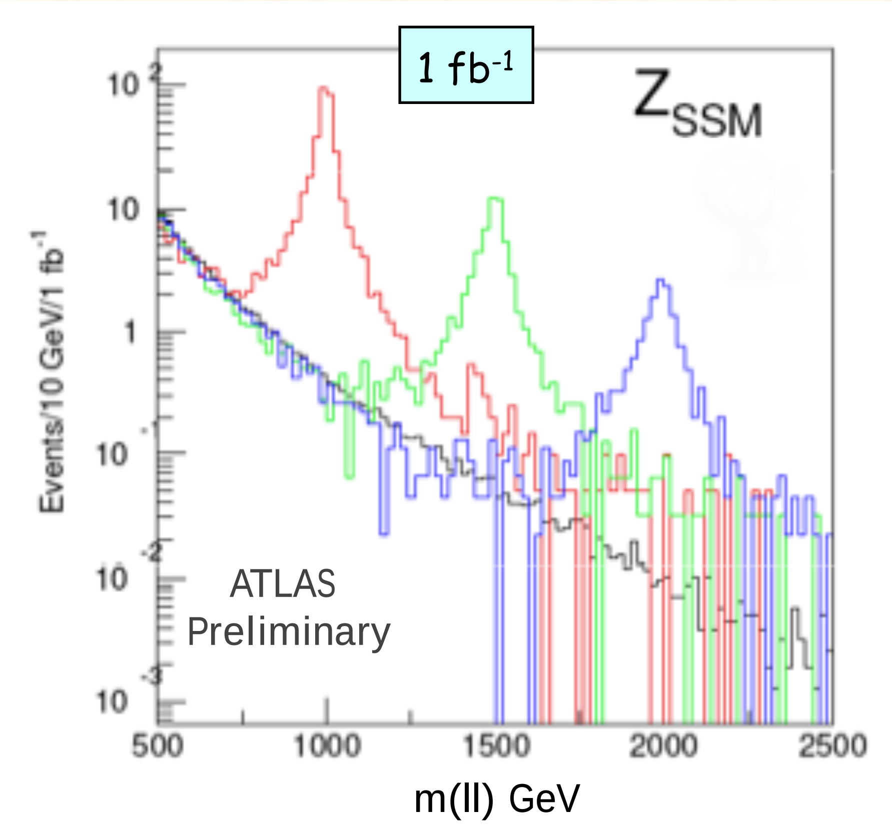
Early Surprises at the LHC??

- as already mentioned, the experiments must
  be open for surprises /
  unknowns /
  unexpected discoveries

- requires unbiased measurements of
  - inclusive lepton spectra
  - dileptons spectra……
  - E_T^{miss} spectrum…….
  - ……

One example of many….

$Z' \rightarrow e^+e^-$ with SM-like couplings (Z_{SSM})



$\sqrt{s}$ = 14 TeV

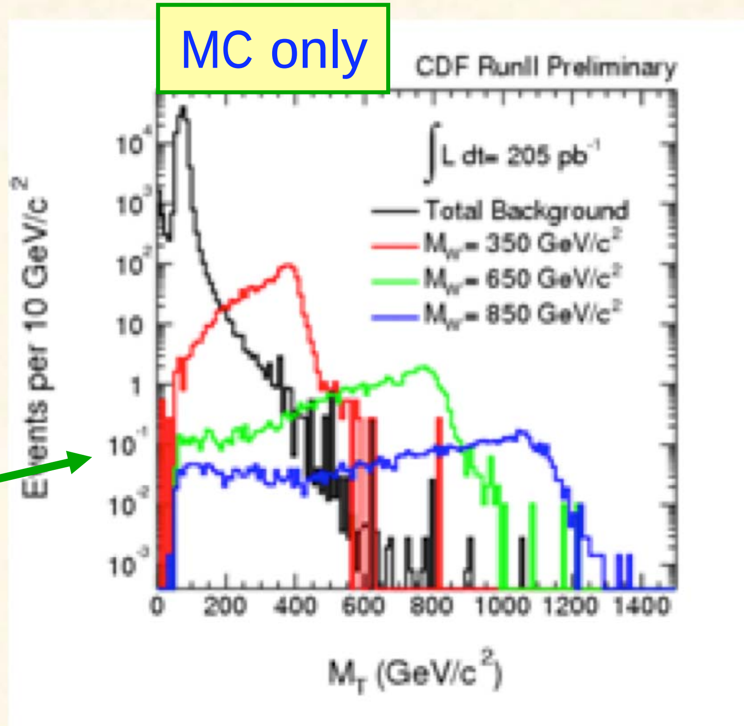
Mass (TeV)	Events / fb^{-1} (after cuts)	Luminosity needed for a 5σ discovery + (10 obs. events)
1	~160	~70 pb^{-1}
1.5	~30	~300 pb^{-1}
2	~7	~1.5 fb^{-1}

Discovery window above Tevatron limits
m ~ 1 TeV, perhaps even in 2011... (?)

Search for W' → eν

- W': additional charged heavy vector boson
- appears in theories based on the extension of the gauge group
- e.g. Left-right symmetric models: $SU(2)_R$ W_R
- assume: the neutrino from W' decay is light and stable.

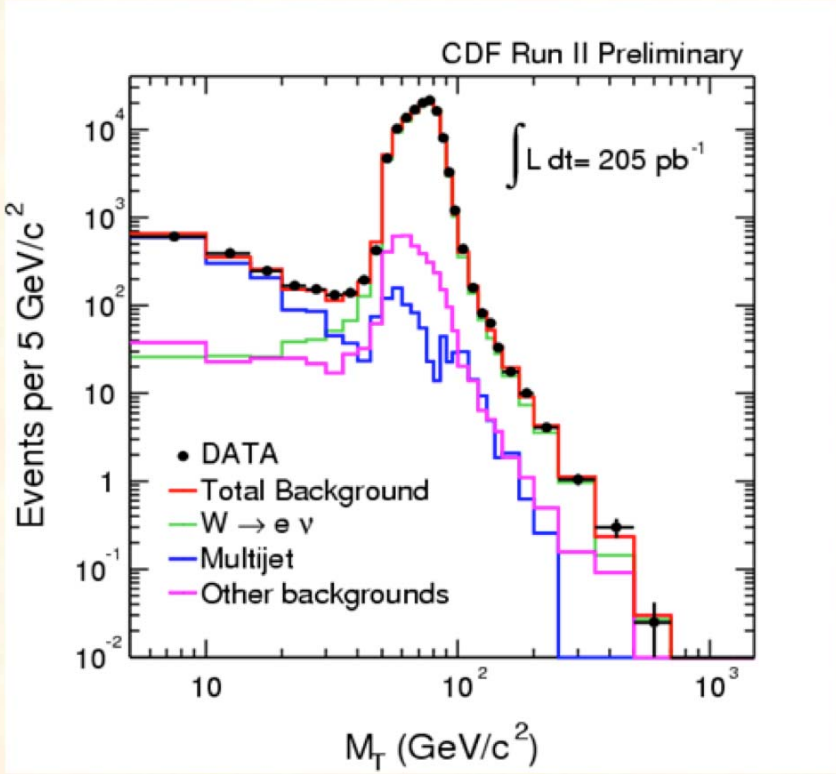
MC only



Signature: high p_T electron + high E_T^{miss}

→ peak in transverse mass distribution

Search for W' $\rightarrow$ eν



Data:

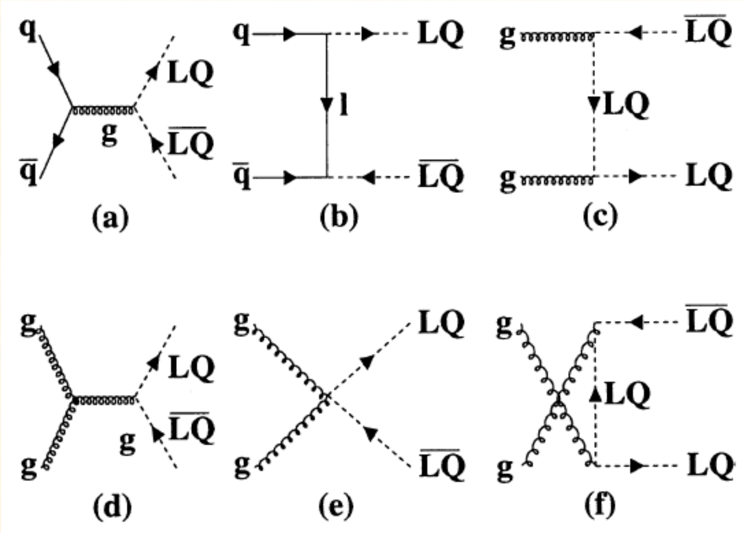
consistent with one well known W + background

Limit: M(W') > 842 GeV/c^2

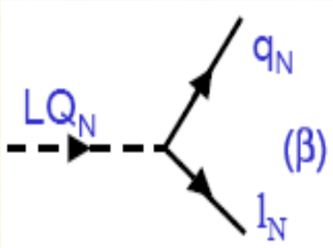
(assuming Standard Model couplings)

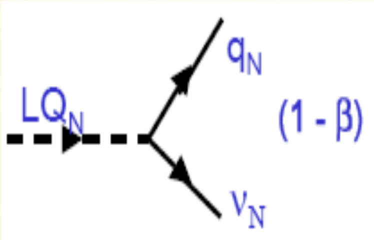
Search for Scalar Leptoquarks (LQ)

- Production:
  pair production via QCD processes
  (qq and gg fusion)



- Decay: into a lepton and a quark





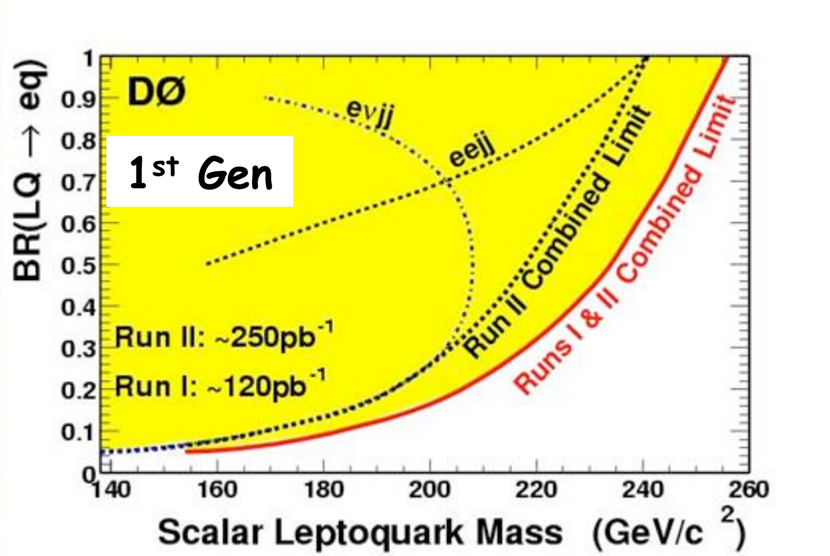
β= LQ branching fraction to charged lepton and quark
N = generation index
Leptoquarks of 1., 2., and 3. generation

Experimental Signatures:

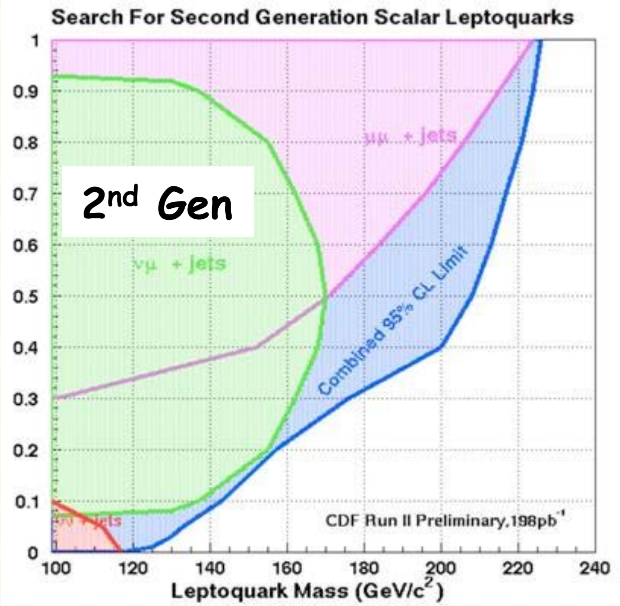
- two high p_T isolated leptons + jets .OR.
- one isolated lepton + P_T^{miss}+ jets .OR.
- P_T^{miss} + jets

1st, 2nd and 3rd generation Leptoquarks

channels: ee jj, eν jj



channels: μμjj, ενjj, ννjj

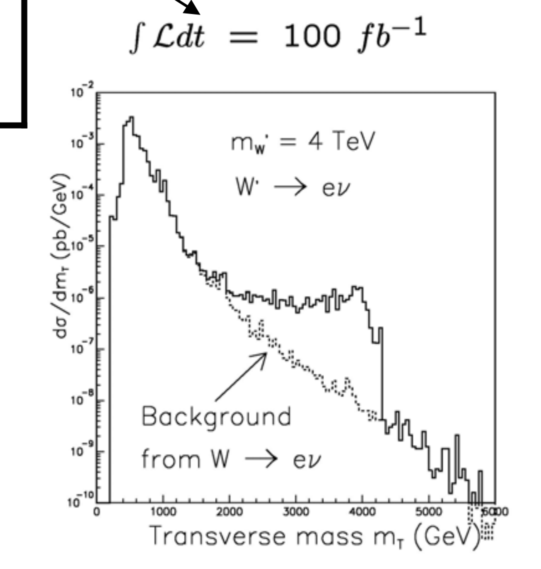


95% C.L. Mass Limits	1. Generation LQ	2. Generation LQ	3. Generation LQ
CDF (Run II) D0 (Run I + II)	235 GeV/c^2 256 GeV/c^2	224 GeV/c^2 200 GeV/c^2 (Run I)	129 GeV/c^2

LHC reach for other BSM Physics

(a few examples for 30 and 100 fb^{-1})

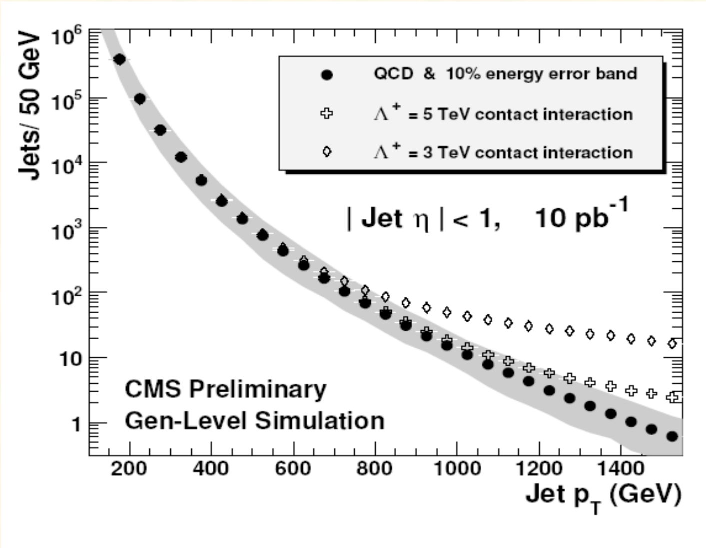
	30 fb^{-1}	**100 fb^{-1}**
Excited Quarks $Q^* \rightarrow q\,\gamma$	M (q*) ~ 3.5 TeV	M (q*) ~ 6 TeV
Leptoquarks	M (LQ) ~ 1 TeV	M (LQ) ~ 1.5 TeV
$Z' \rightarrow \ell\ell$, jj $W' \rightarrow \ell\,\nu$	M (Z') ~ 3 TeV M (W') ~ 4 TeV	M (Z') ~ 5 TeV M (W') ~ 6 TeV
Compositeness (from Di-jet)	Λ ~ 25 TeV	Λ ~ 40 TeV



Sensitivity to New Physics with jets in Early LHC data

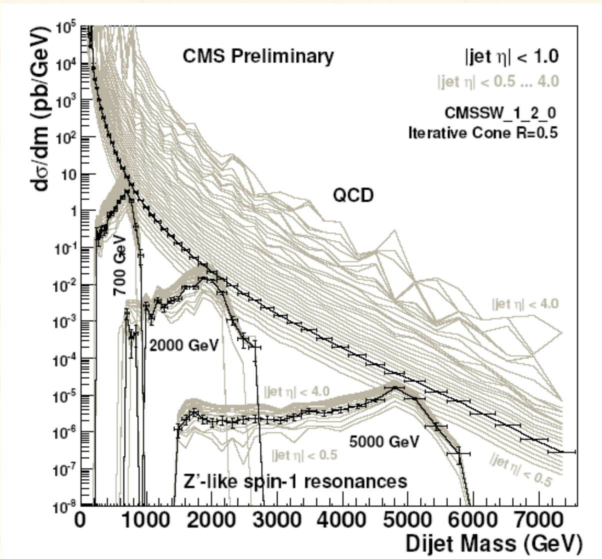
- Even with JES uncertainties expected with early data and an int. luminosity of only 10 pb^{-1} compositeness scales of ~ 3 TeV can be reached

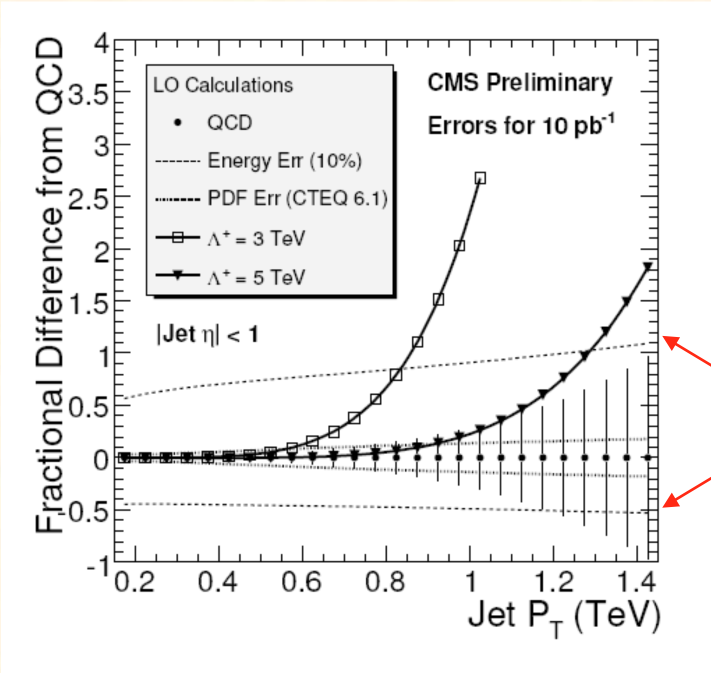
  (close to the present Tevatron reach of Λ > 2.7 TeV)



- Resonances decaying into two jets:

> Discovery sensitivity around 2 TeV
> (Spin-1 Z´ like resonance) for ~200 pb^{-1}
>
> Present Tevatron limits: 320 < m < 740 GeV





10% JES

Conclusions

1. Experiments at Hadron Colliders have a huge discovery potential

   - SM Higgs: full mass range, already at low luminosity;
     Vector boson fusion channels improve the sensitivity significantly

   - MSSM Higgs: parameter space covered

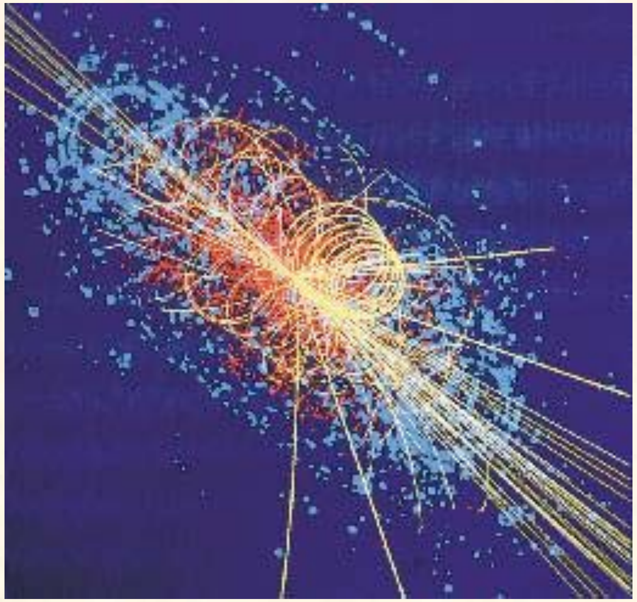
   - SUSY: discovery of TeV-scale SUSY should be easy,
     determination of model parameters is more difficult

   - Exotics: experiments seem robust enough to cope with new scenarios

2. Experiments have also a great potential for precision measurements
   - m_W to ~10 - 15 MeV
   - m_t to ~1 GeV
   - $\Delta m_H / m_H$ to 0.1% (100 - 600 GeV)

   + gauge couplings and measurements in the top sector ....

End of lectures



• In case you have any questions:
please do not hesitate to contact me: karl.jakobs@uni-freiburg.de

• Transparencies will be made available as .pdf files on the web (school pages)