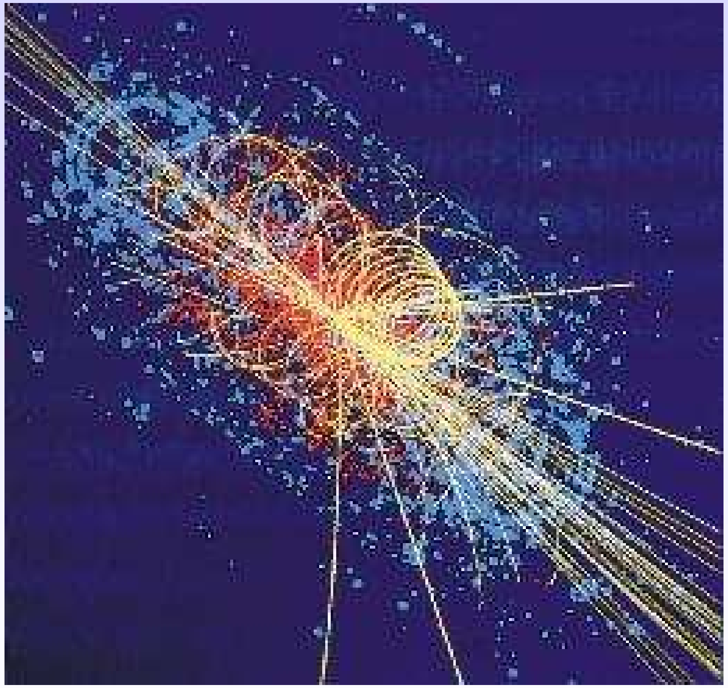
Physics at Hadron Colliders

4. Search for Physics Beyond the Standard Model



- **Supersymmetry**
- **Other Extensions of the Standard Model**
  - **- Extra dimensions**
  - **- Extra gauge bosons**

Why do we look for extensions of the Standard Model ?

1. Gravity is not incorporated in the Standard Model

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

All this calls for a ***more fundamental theory*** ,the Standard Model
Being only a low energy approximation $\rightarrow$ **New Physics**

Candidate theories: Supersymmetry
Extra Dimensions
Technicolor
…….

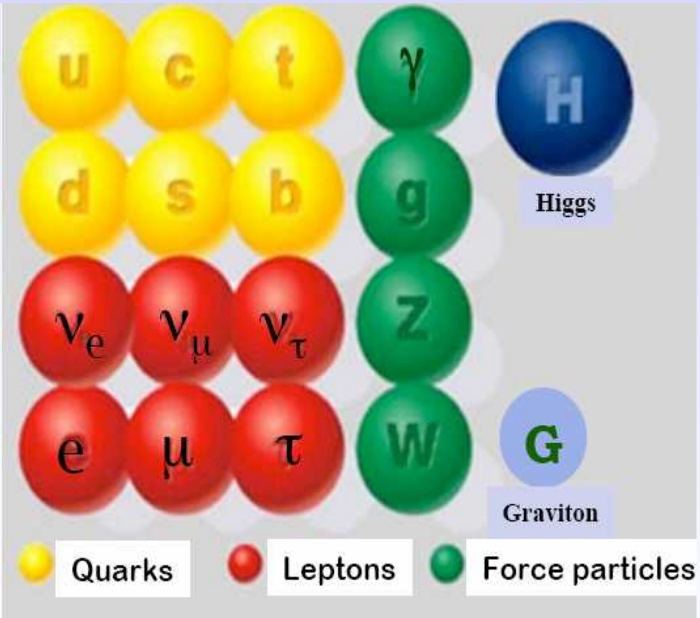
All predict new physics at the TeV scale !

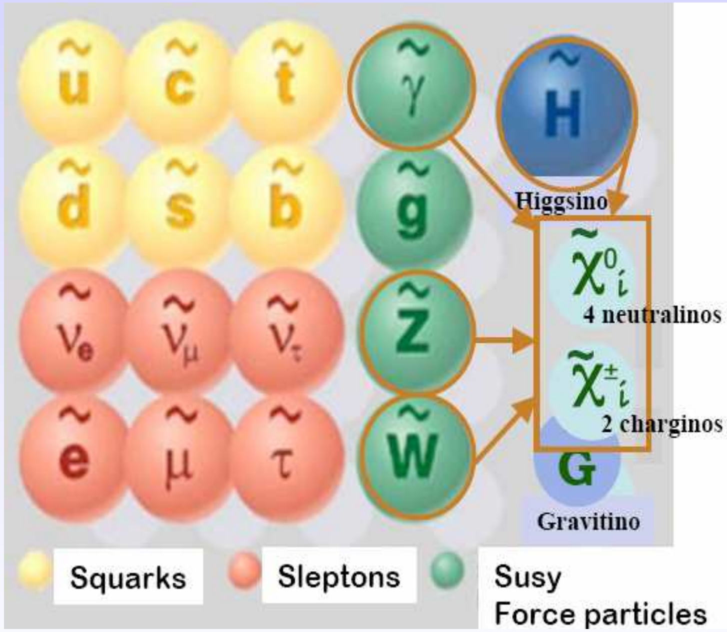
Strong motivation for LHC mass reach ~ 3-5 TeV

Supersymmetry

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

Standard Model particles **SUSY particles**





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.
  In most models LSP is also weakly interacting:
  LSP $\equiv \chi^0_1$ (lightest neutralino)

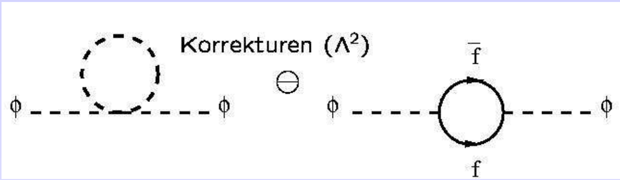
  $\rightarrow$ LSP is a good candidate for cold dark matter

  $\rightarrow$ LSP behaves like a ν $\rightarrow$ it escapes detection

  $\rightarrow$ 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

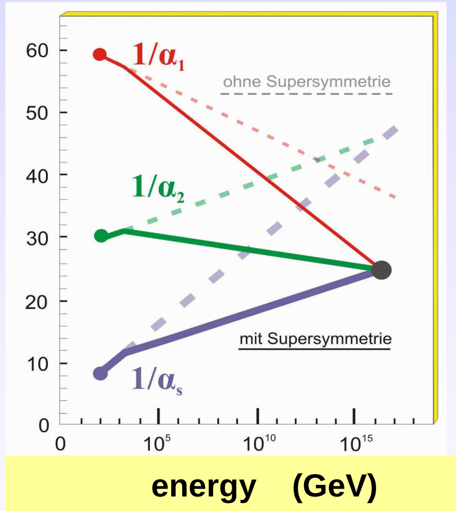


$$\Delta m_H = f(m_B^2 - m_f^2)$$

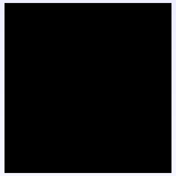
→ m_{SUSY} ~ 1 TeV

(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

the only problem:……

No experimental evidence for SUSY so far !

↓

Either SUSY does not exist

OR

m_{SUSY} large (>> 1 TeV) $\rightarrow$ not accessible at present machines

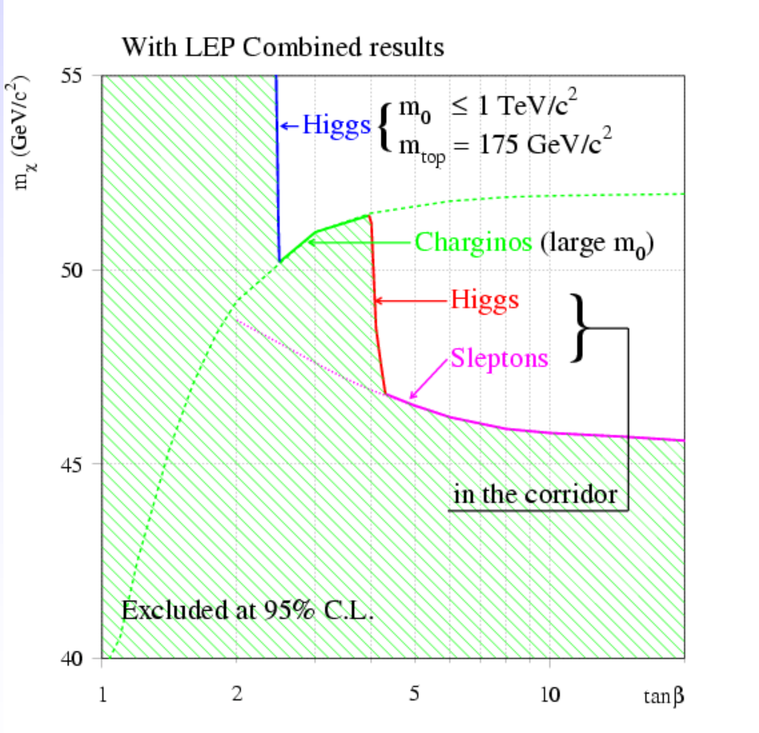
↓

LHC should say "final word" about low energy SUSY

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)	>	~ 250 GeV	Tevatron Run 1
	m (LSP, lightest neutralino)	>	~ 45 GeV	LEP II



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

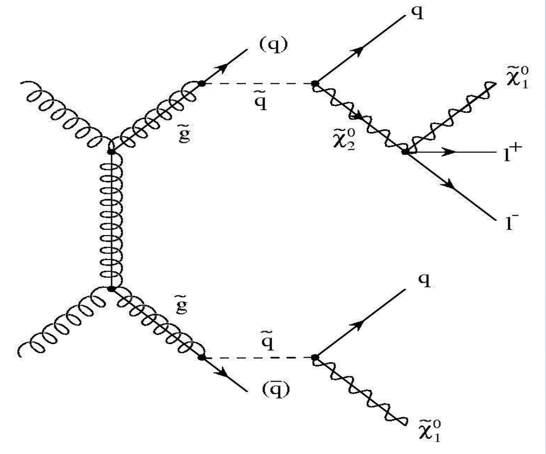
assumption:
lightest neutralino = LSP

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)



⇒ combination of
Jets, Leptons, E_T^{miss}

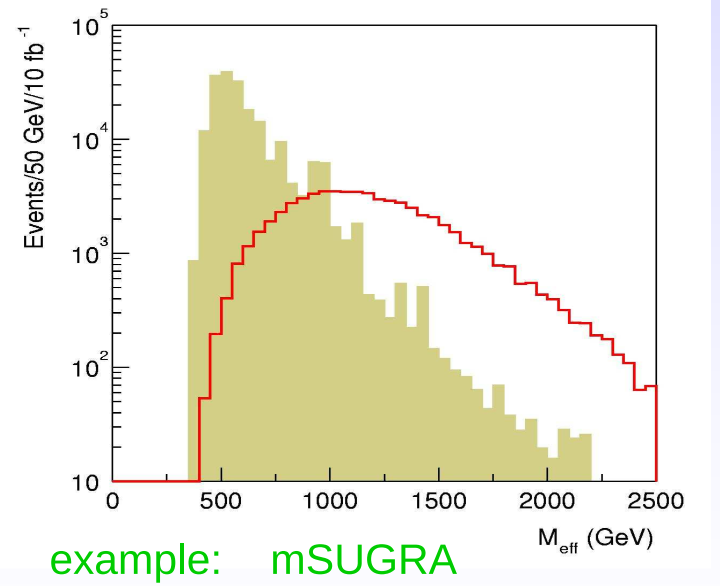
1. Step: Look for deviations from the Standard Model
   Example: Multijet + E_T^{miss} signature + leptons

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

- Strongly produced, cross sections comparable to QCD cross sections at the same mass scale
- 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)



example: mSUGRA
m_0 = 100 GeV, $m_{1/2}$ = 300 GeV
$\tan\beta$ = 10, $A_0 = 0$, $\mu > 0$

LHC reach for Squark- and Gluino masses:

1 fb^{-1}	⇒	M ~ 1500 GeV
10 fb^{-1}	⇒	M ~ 1900 GeV
100 fb^{-1}	⇒	M ~ 2500 GeV

TeV-scale SUSY can be found quickly !

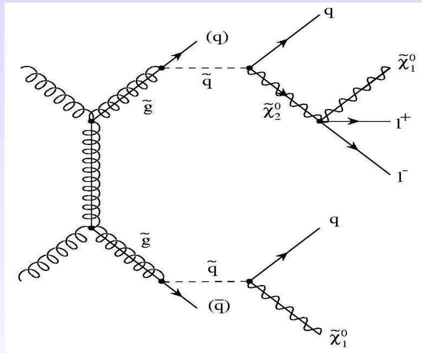
Determination of model parameters

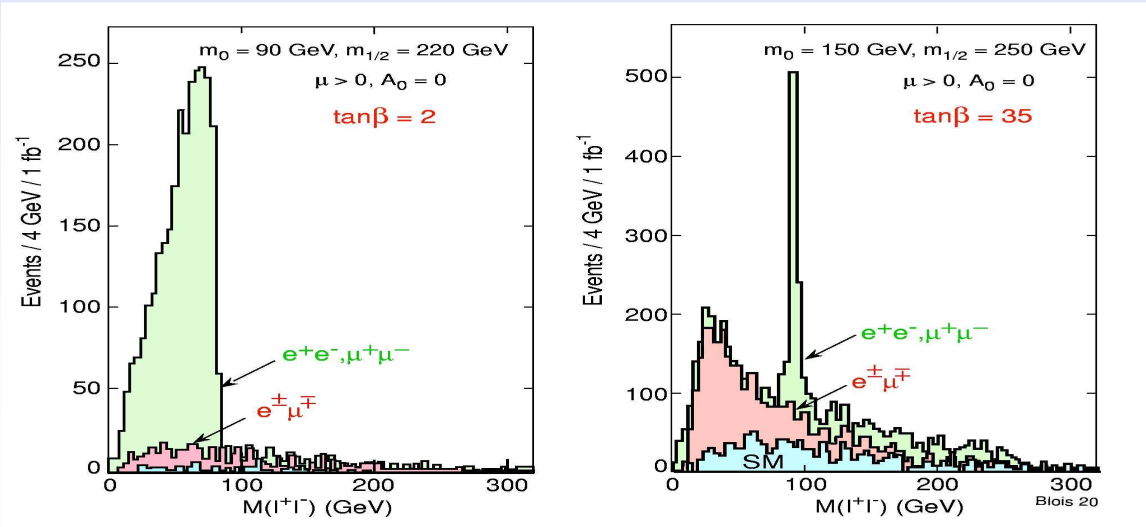
- Invisible LSP $\Rightarrow$ no mass peaks, but kinematic endpoints
  $\Rightarrow$ mass combinations

- Simplest case: $\chi^0_2 \rightarrow \chi^0_1\ \ell^+\ \ell^-$ endpoint: $M_{\ell\ell} = M(\chi^0_2) - M(\chi^0_1)$

  (significant mode if no $\chi^0_2 \rightarrow \chi^0_1 Z$, $\chi^0_1 h$, $\tilde{\ell}\ \ell$ decays)

- Require: 2 isolated leptons, multiple jets, and large E_T^{miss}



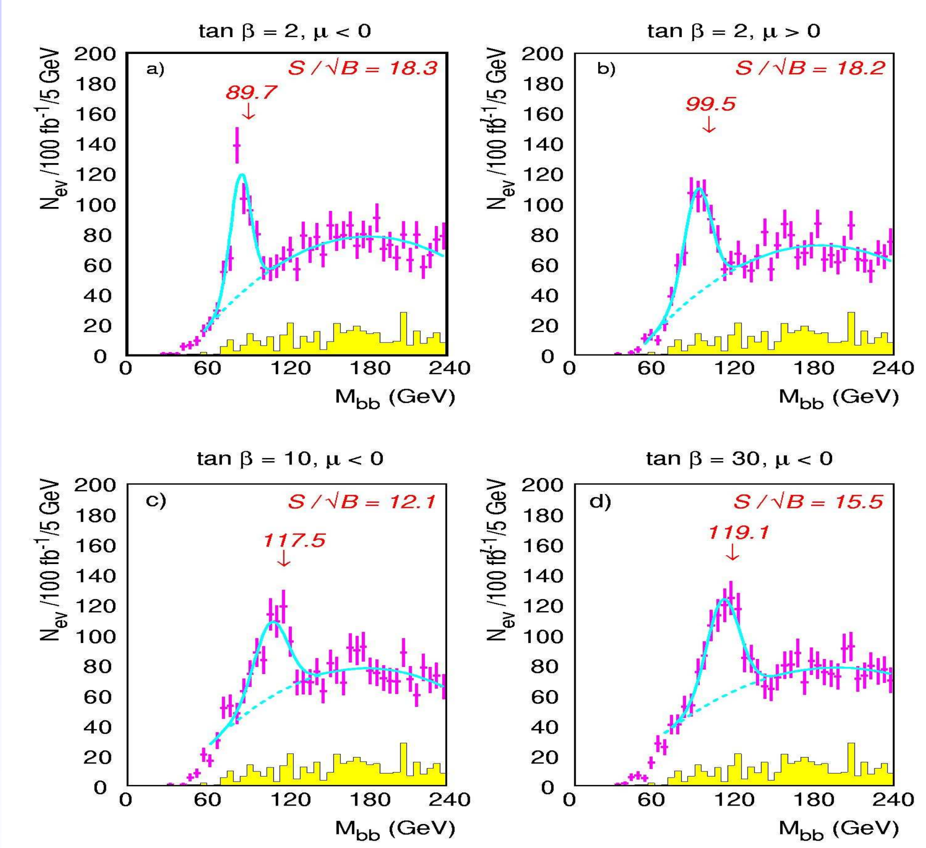


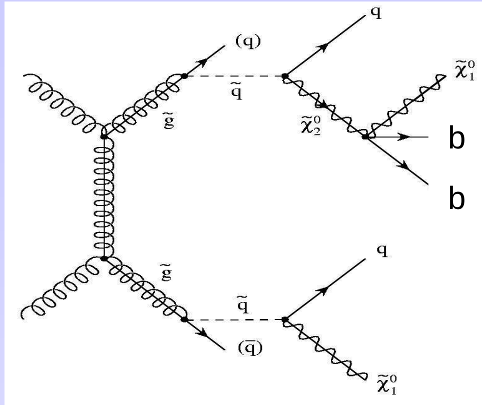
Modes can be distinguished

using shape of $\ell\ell$-spectrum

$h \rightarrow bb$:

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

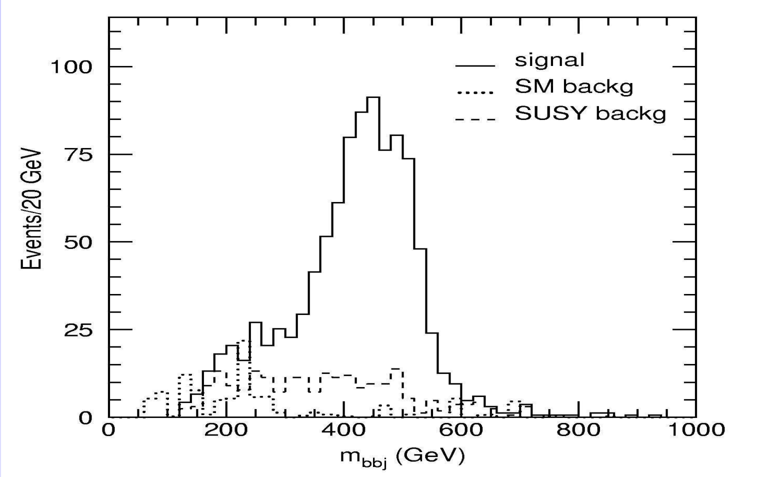
by applying a cut on E_T^{miss}

work backwards the decay chain:
example:

$pp \to \tilde{q}_L \tilde{q}_R$: $\quad \tilde{q}_R \to \tilde{\chi}_1^0 q$

$\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{\chi}_1^0 h q \quad \to \tilde{\chi}_1^0 b\bar{b} q$

combine h $\to$ bb with jets to determine other masses



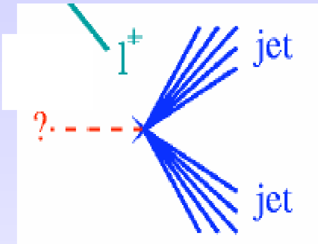
$\tilde{q} \longrightarrow \tilde{\chi}_1^0 h q$ endpoint

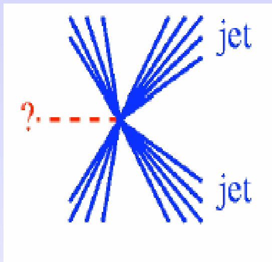
Strategy in SUSY Searches at the LHC:

- 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 $\to$ SUSY model parameters

Search for SUSY at the Tevatron

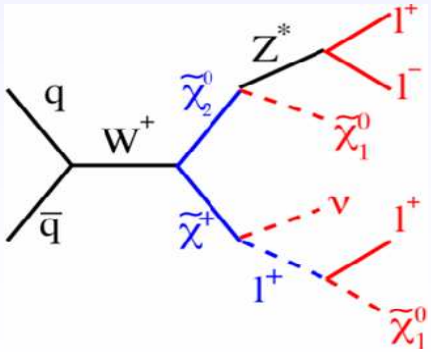
1. Search for Squarks and Gluinos: Jet + E_T^{miss} signature
   produced via QCD processes





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)

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

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

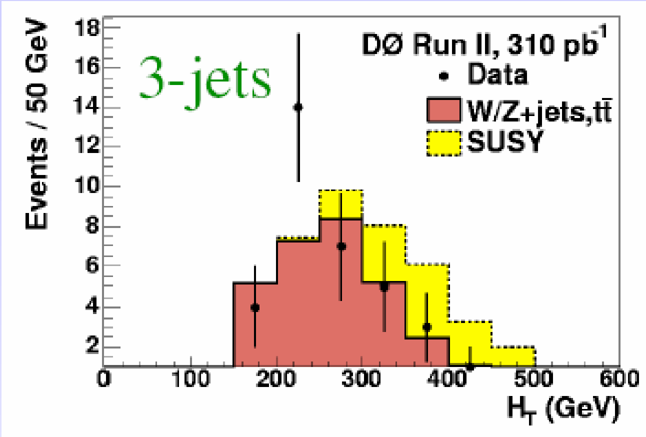
  $$\tilde{q}\,\tilde{g} \rightarrow q\,\tilde{\chi}^0_1\,q\,\bar{q}\,\tilde{\chi}^0_1$$

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

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

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

Search for Squarks and Gluinos (cont.)



DØ analysis L = 310 pb^{-1}

Example: 3 jet + E_T^{miss} search

Discriminating variable:

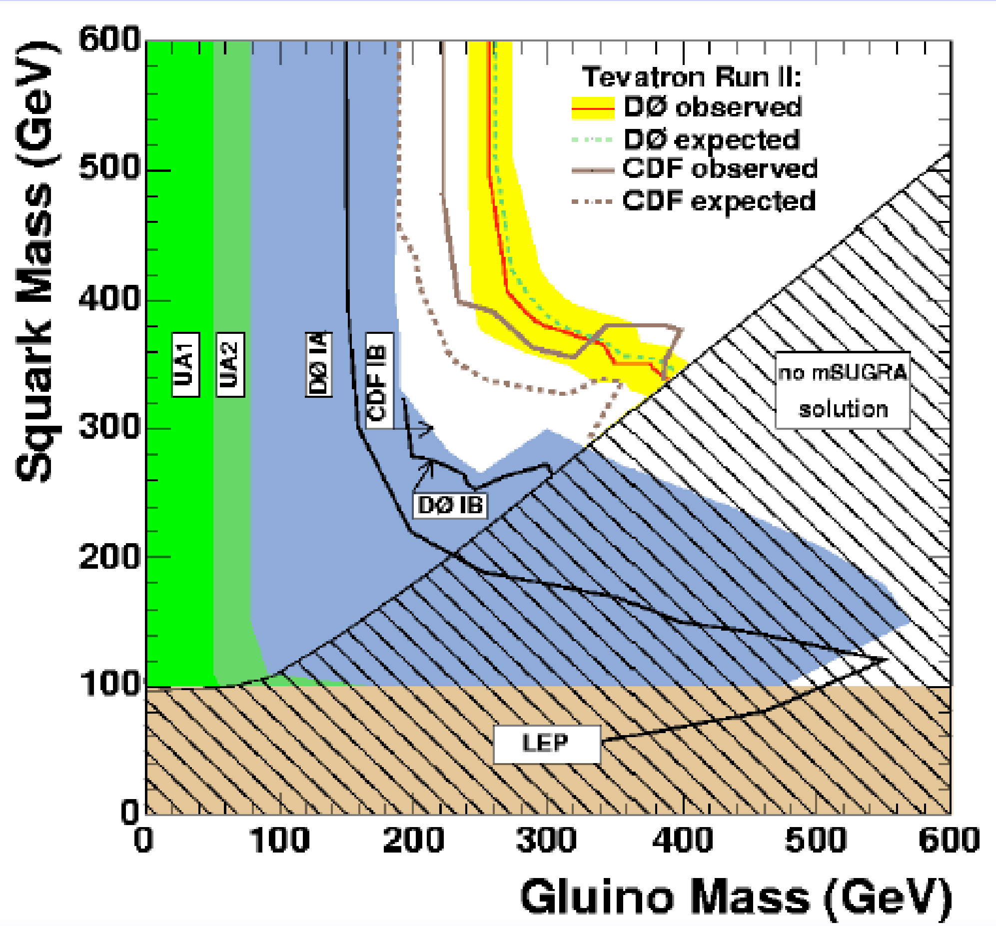
- $H_T = \Sigma\ E_T(jets)$

Comparison between data and expected background:

	Data	Total background
"Dijet"	6	4.8 +4.4 -2.0 (stat) +1.1 -0.8 (sys)
"3 jets"	4	3.9 +1.3 -1.0 (stat) +0.7 -0.8 (sys)
"Gluino"	10	10.3 +1.5 -1.4 (stat) +1.9 -2.5 (sys)

No excess above background → NO evidence for SUSY

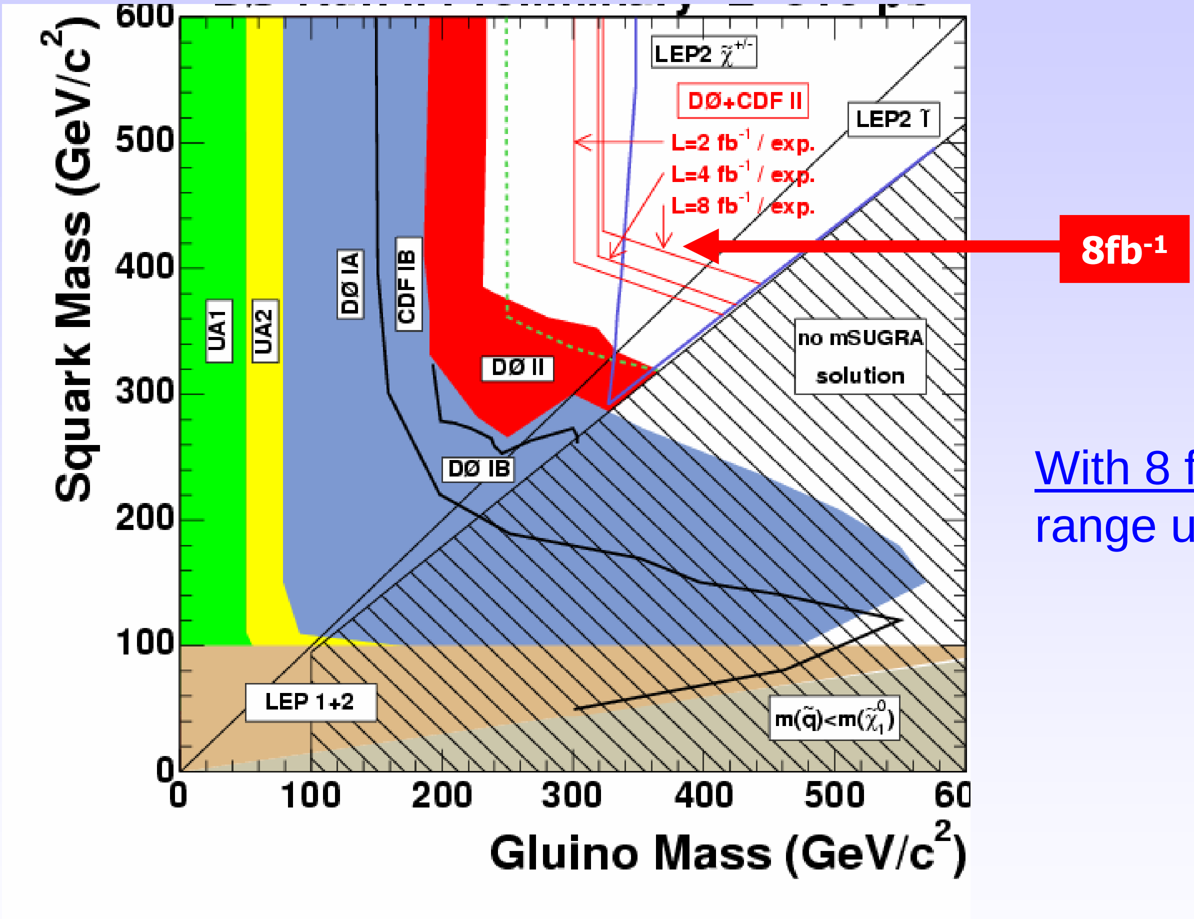
Excluded regions in the m(squark) vs. m(gluino) plane



Excluded mass values:

m(gluino), m(squark) > ~ 330 GeV

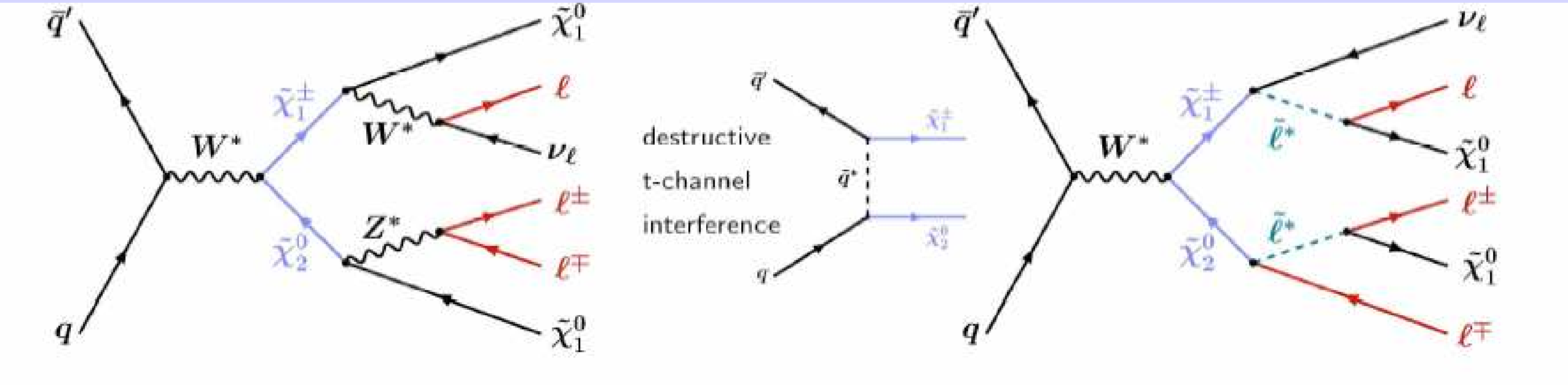
Future Prospects for Squark and Gluino Searches



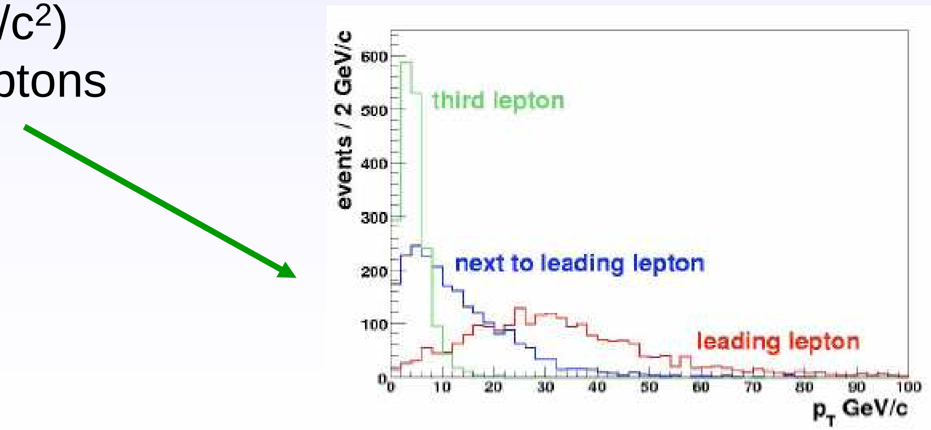
With 8 fb^{-1}: explore mass range up to ~ 400 GeV/c^2

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/c²)
  one needs to be sensitive to low P_T leptons

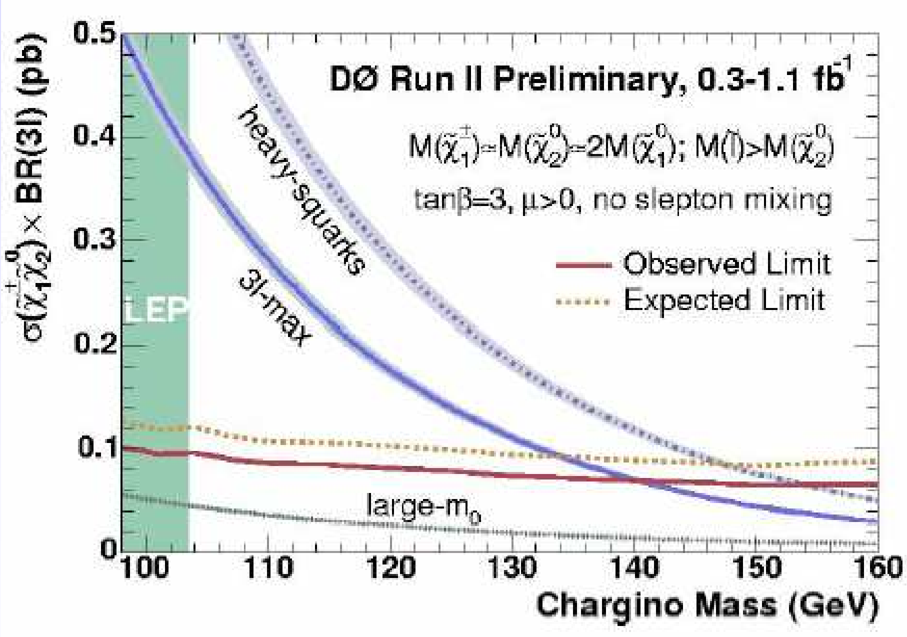


Analysis:

- Search for five different (ℓℓℓ) + like-sign μμ final states with missing transverse momentum
- In order to gain efficiency, no lepton identification is required for the 3rd lepton, select: two id. Leptons + track with P_T > 4 GeV/c

mSUGRA interpretation

	Lum. (fb^{-1})	Data	Total background
ee+l	1.2	0	0.76 ±0.67 (stat)
μμ+l	0.3	2	1.75 ±0.57 (stat)
eμ+l	0.3	0	0.31 ±0.13 (stat)
SS μμ	0.9	1	1.10 ±0.40 (stat)
eτ+l	0.3	0	1.58 ±0.14 (stat)
μτ+l	0.3	1	0.36 ±0.13 (stat)



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


Alternative models

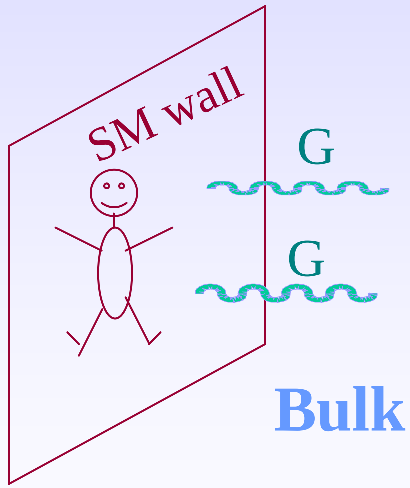
Extra dimensions at the LHC

- 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**

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

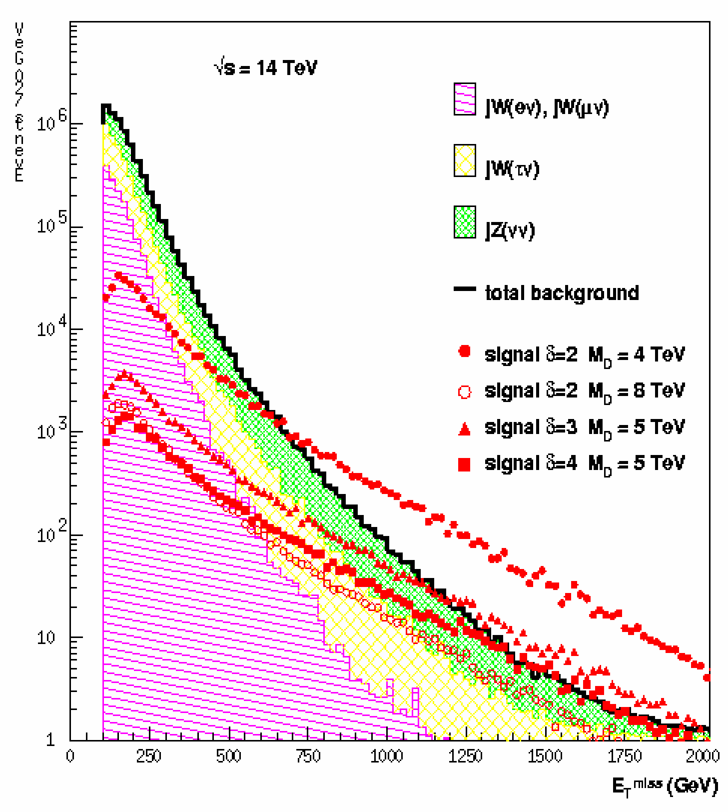
$$q\bar{q} \rightarrow G\gamma$$



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

Search for escaping gravitons at LHC

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)

M_D^{max}	=	9.1,	7.0,	6.0 TeV
	for			
δ	=	2,	3,	4
Extension:		10^{-5},	10^{-10},	10^{-12} m

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

„LHC experiments are also sensitive to this field of physics" → robust detectors

Search for heavy resonances

examples: heavy gauge bosons W ´ and Z´

many possible theoretical models

use leptonic decay modes: $W' \rightarrow \ell \nu$ $Z' \rightarrow \ell \ell$

Sensitivity for Tevatron Run II data

Simulations with LHC experiments

Theoretical models

- SM extension (purely academical)
  Symmetry: $SU(2)_L \times U(1)_Y$
  New heavy bosons: W´ and Z´ with SM couplings

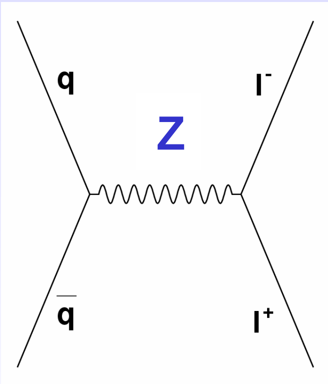
- Superstrings inspired E(6)
  Symmetry: $E(6) \rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi$
  New heavy bosons: neutral states χ and ψ

- L-R symmetric models
  Symmetry: $SU(2)_R \times SU(2)_L \times U(1)_Y$
  New heavy bosons: W_R and Z_R with V+A couplings

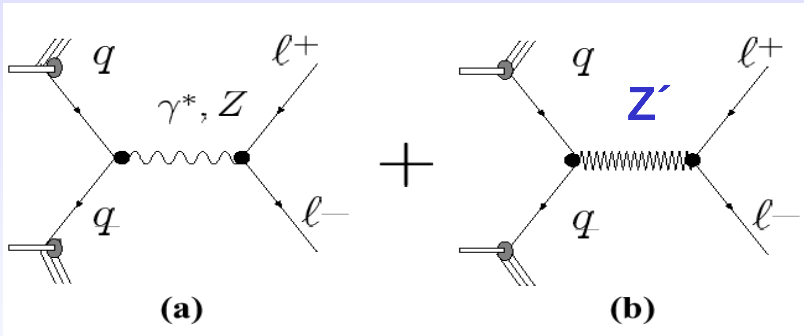
- Little Higgs models
  Symmetry: $SU(5) \rightarrow [SU(2) \times U(1)]^2$
  New heavy bosons: W_H and Z_H with V-A couplings

Search for New Resonances in High Mass Di-leptons

Neutral Gauge Boson Z



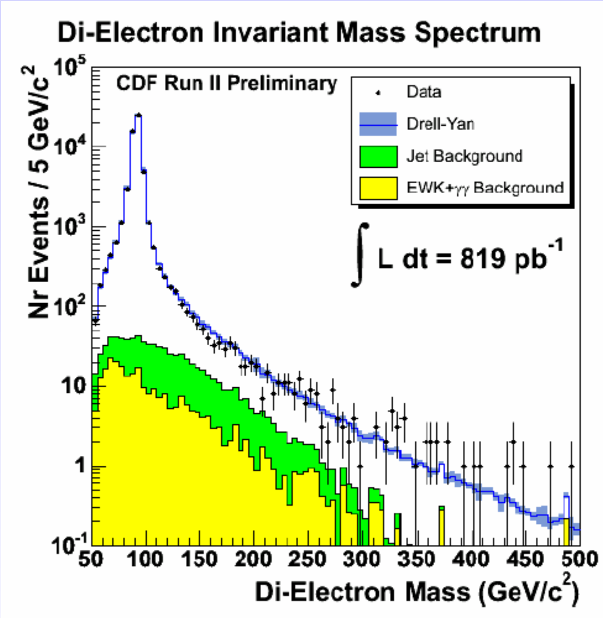
Neutral Gauge Boson Z'



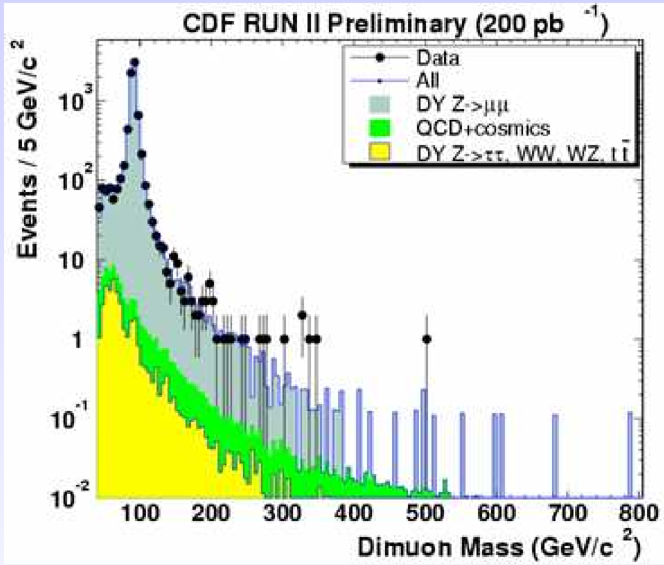
Main background from Drell-Yan pairs

Tevatron data and mass limits

Di-electron Invariant Mass



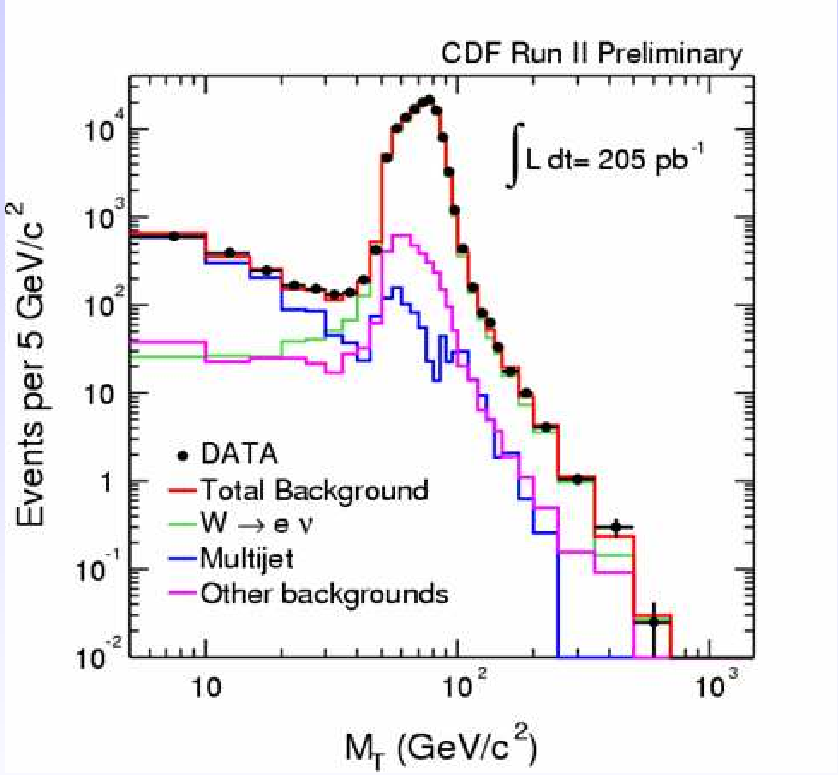
Di-muon Invariant Mass



Data are consistent with SM background → No excess observed.

Z´ mass limits (SM couplings)		ee	μμ	ττ	
95% C.L.	CDF /D0:	850	835	394	GeV/c^2

Search for W' → eν



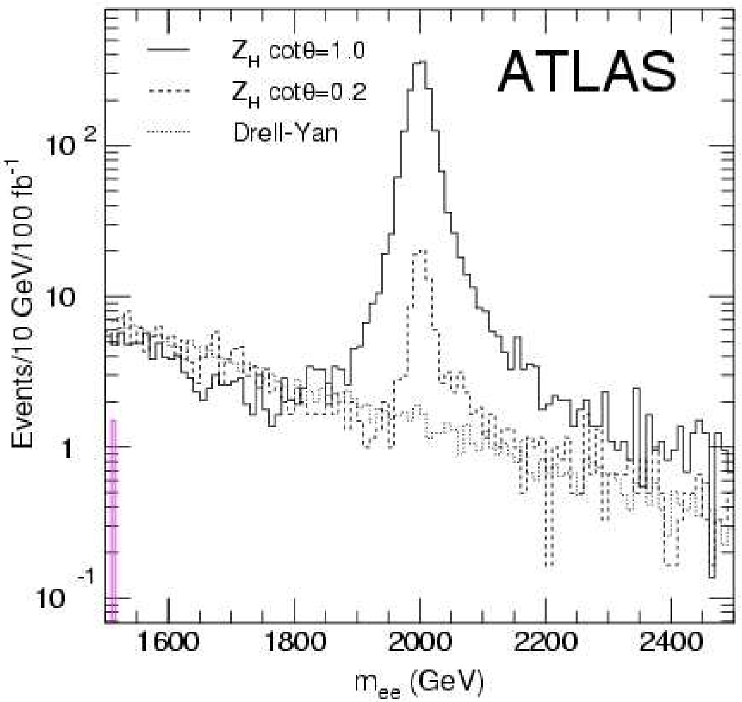
Data consistent with well known W background

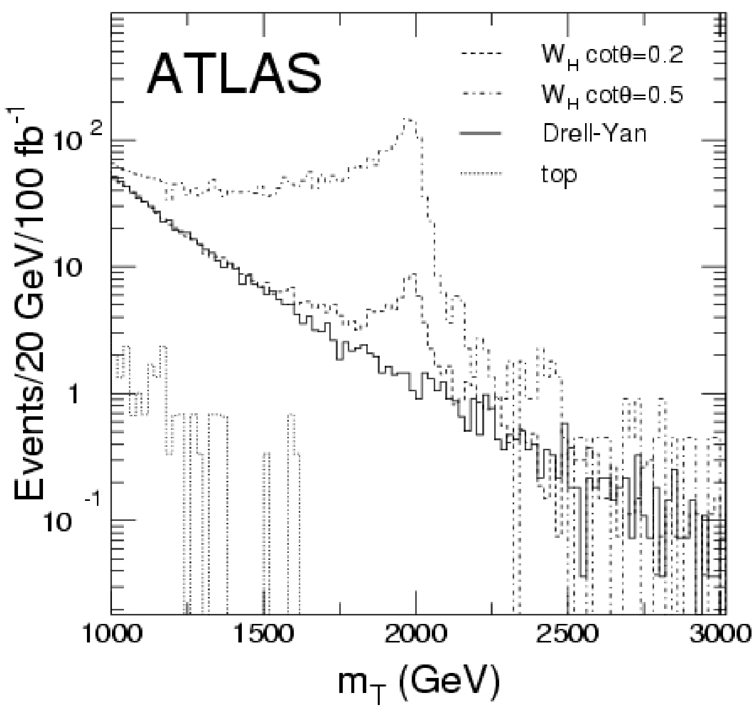
Limit: M(W') > 842 GeV/c^2

(assuming Standard Model couplings)

Search for Z´ → e^+e^- and W' → eν at the LHC

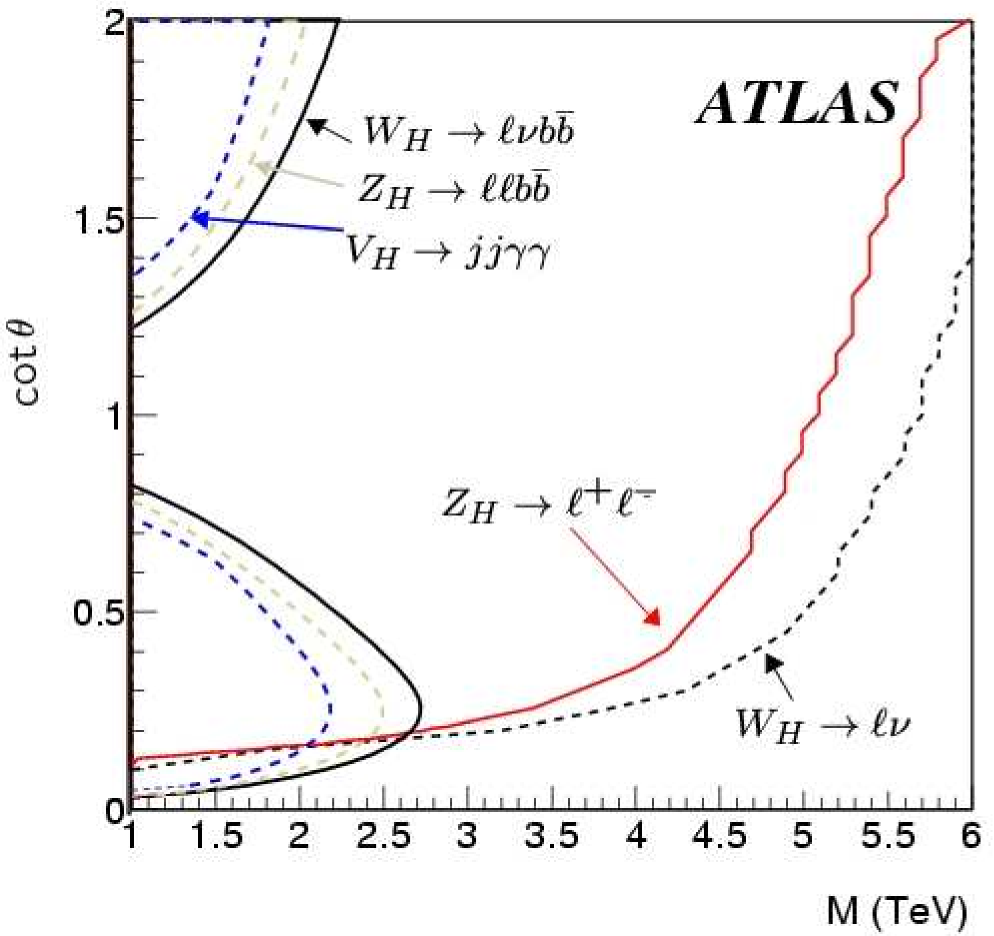
- Z´ and W´ are the heavy gauge bosons Z_H and W_H predicted by the Little Higgs model
- Assume $M(Z_H)=M(W_H)=2$ TeV
- ATLAS simulations for $L=300\ pb^{-1}$





Potential mass limits at the LHC

ATLAS discovery potential for Z_H and W_H assuming L=300 pb^{-1}



Summary of the lecture

- Experiments at Hadron Colliders have a huge discovery potential

  - 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

- No new signals observed at Tevatron (for the moment)