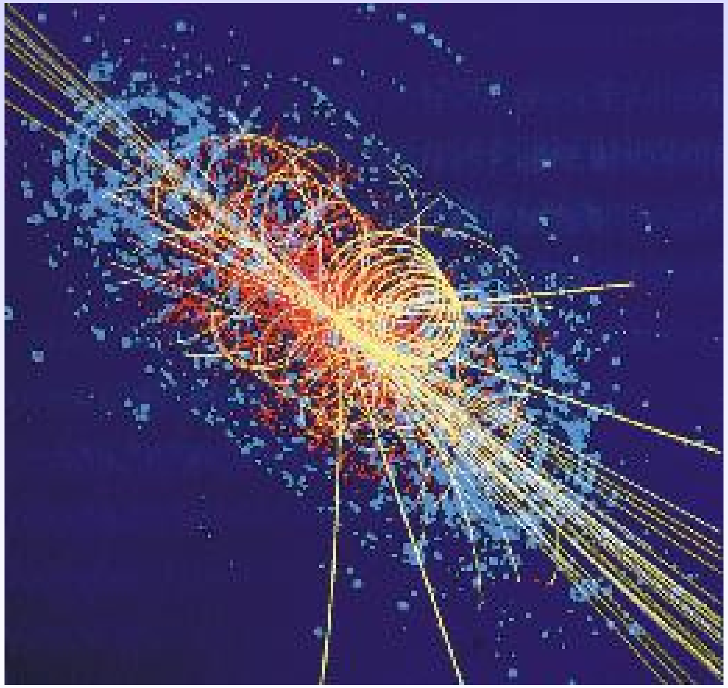
Physics at Hadron Colliders

Lecture 4



Search for Physics Beyond the Standard Model

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

Why do we think about extensions of the Standard Model ?

see lecture by E. Kiritsis

1. Gravity is not incorporated yet 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
   - …..

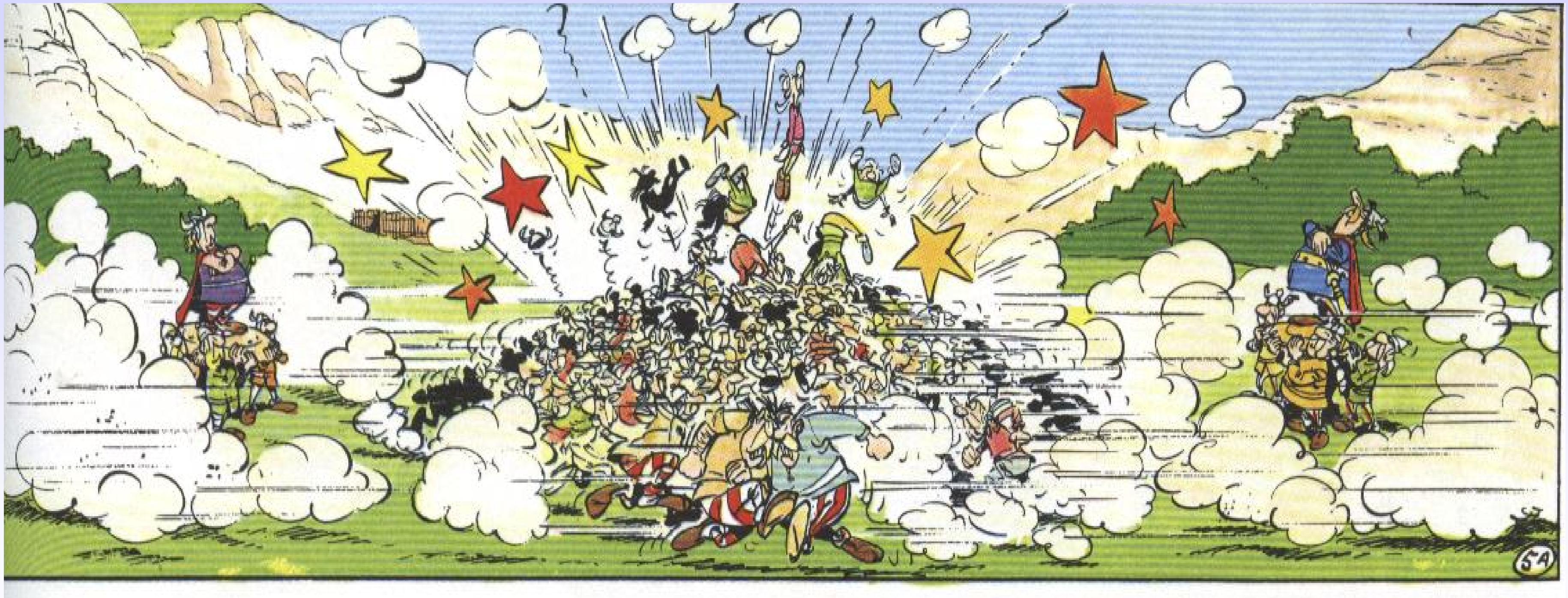
All this calls for a ***more fundamental theory*** of which the Standard Model is a low energy approximation → **New Physics**

Candidate theories: Supersymmetry
Extra Dimensions
Technicolor
…….

All predict new physics at the TeV scale !!

Strong motivation for LHC mass reach ~ 3 TeV

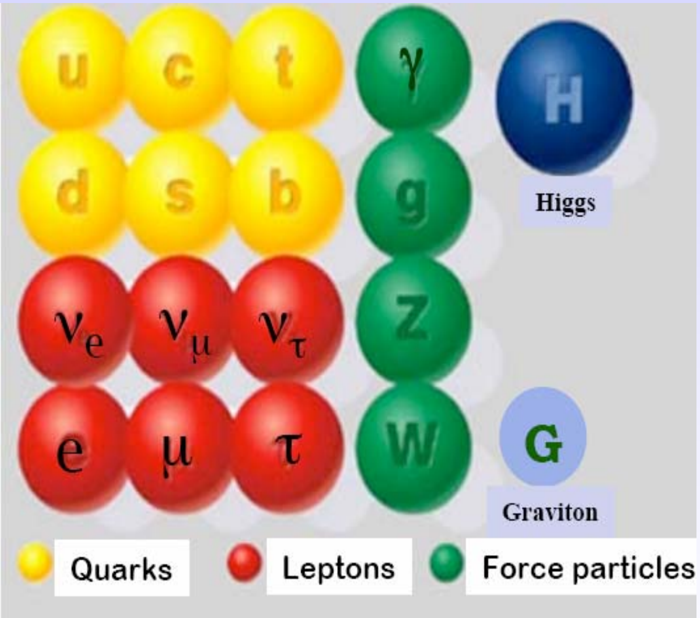
The Search for Supersymmetry



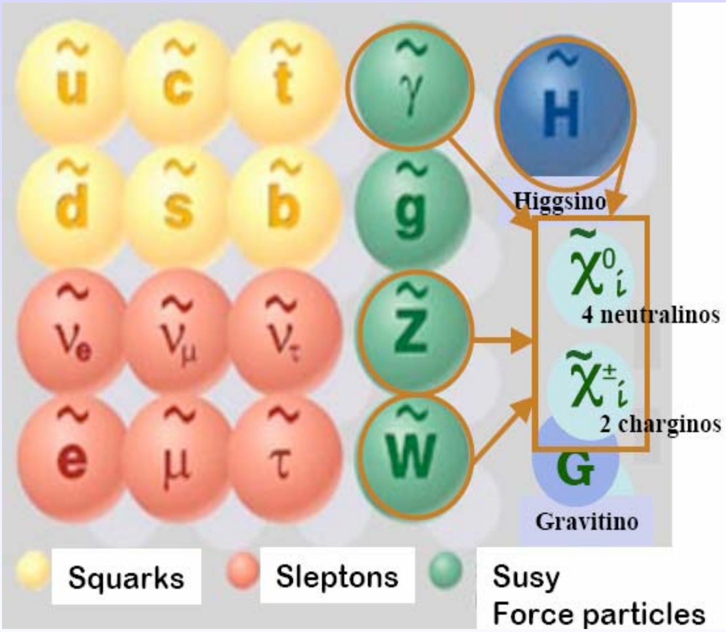
Supersymmetry

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)

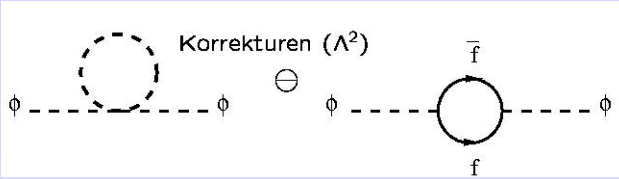
  $\rightarrow$ LSP is a good candidate for cold dark matter

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

  $\rightarrow$ E_T^{miss} (typical SUSY signature)

Why do we like her so much?

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

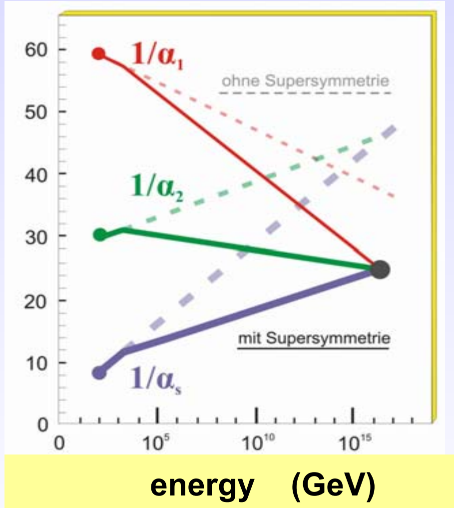


$$\Delta m_H = f(m_B^2 - m_f^2)$$

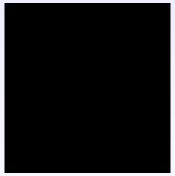
→ $m_{SUSY} \sim 1$ TeV

(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 !   (except that about half of the particles are already discovered)

↓

Either SUSY does not exist

OR

m_{SUSY} large (>> 100 GeV) → not accessible at present machines

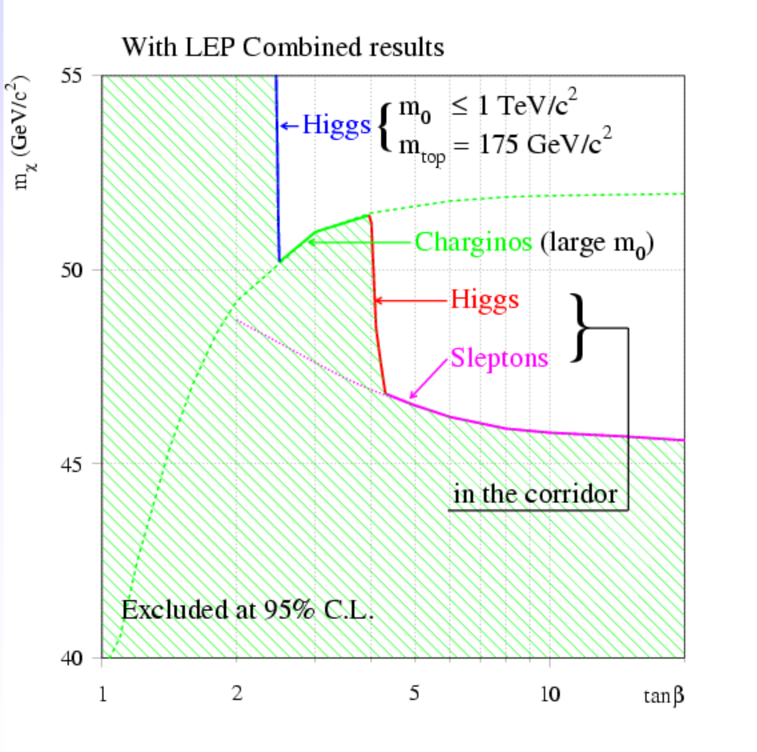
↓

LHC should say "final word" about (low energy)

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

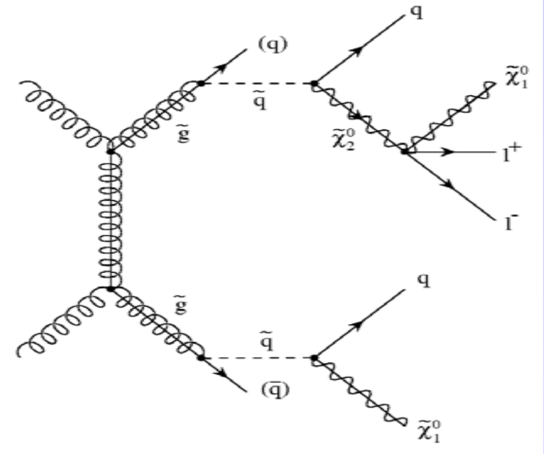
assumption:
lightest neutralino = LSP

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}

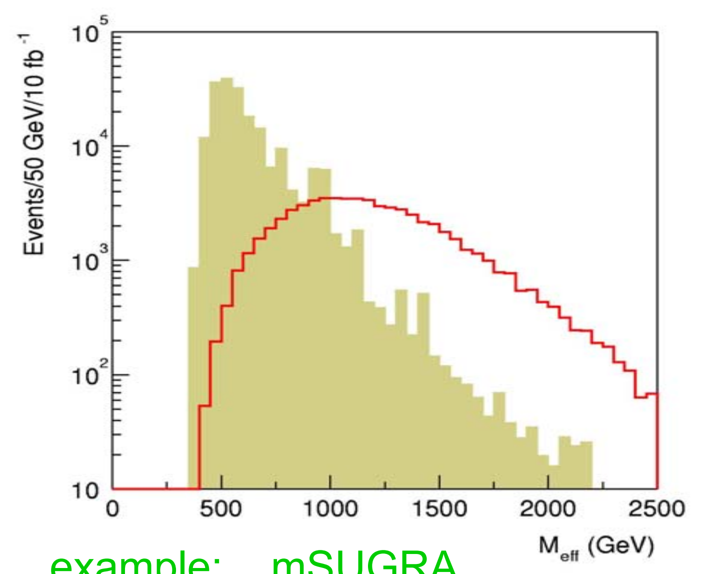
1. Step: Look for deviations from the Standard Model
   Example: Multijet + E_T^{miss} signature

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 β = 10, A_0 = 0, $\mu > 0$

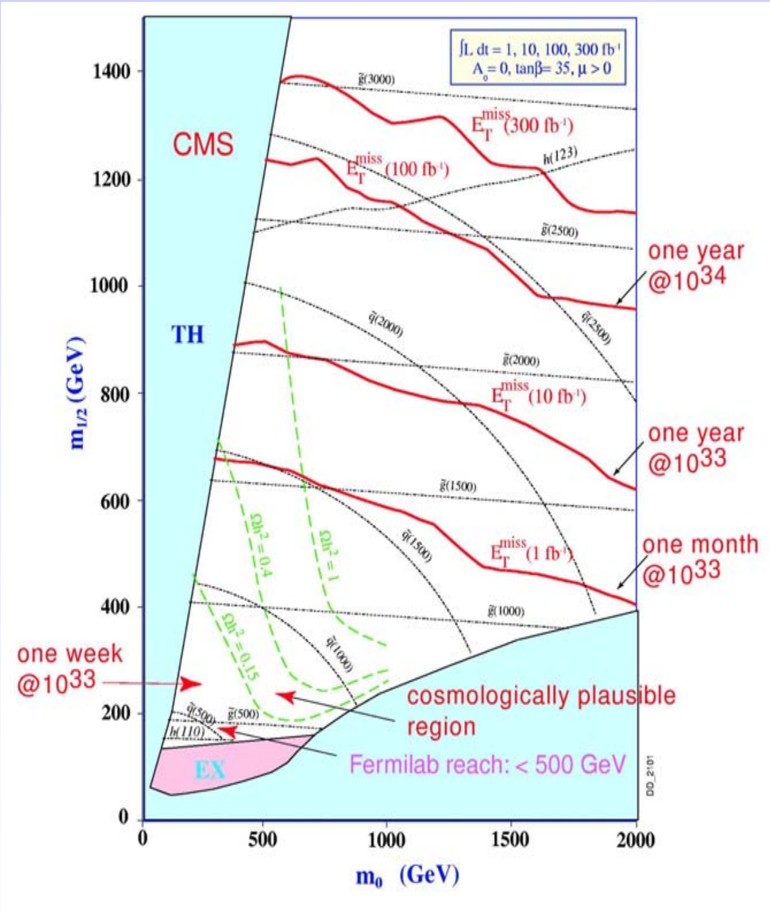
LHC reach for Squark- and Gluino masses:

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

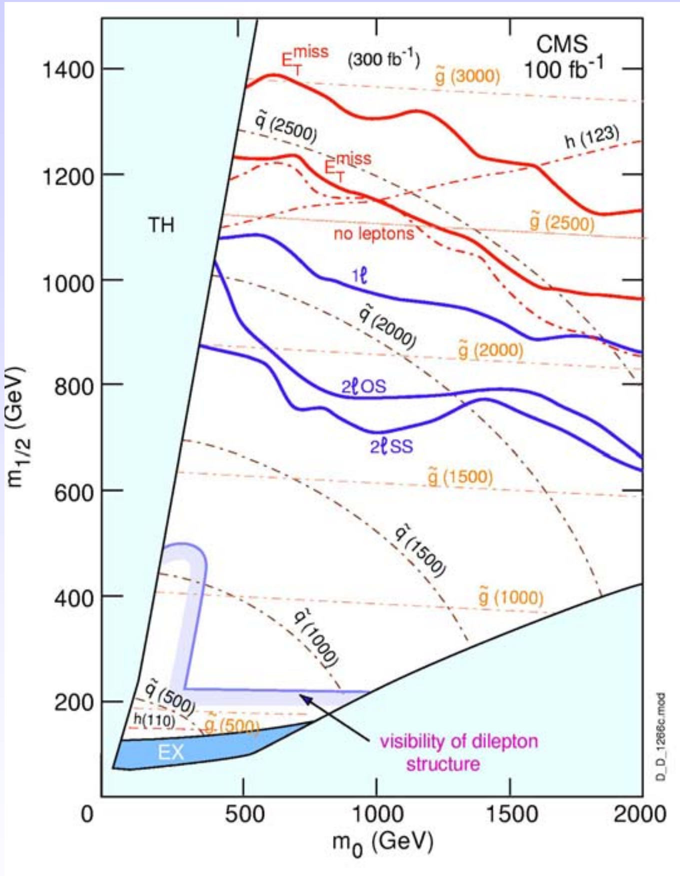
TeV-scale SUSY can be found quickly !

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**



Expect multiple signatures for TeV-scale SUSY

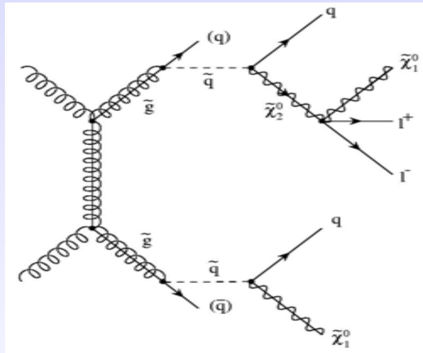
Determination of model parameters

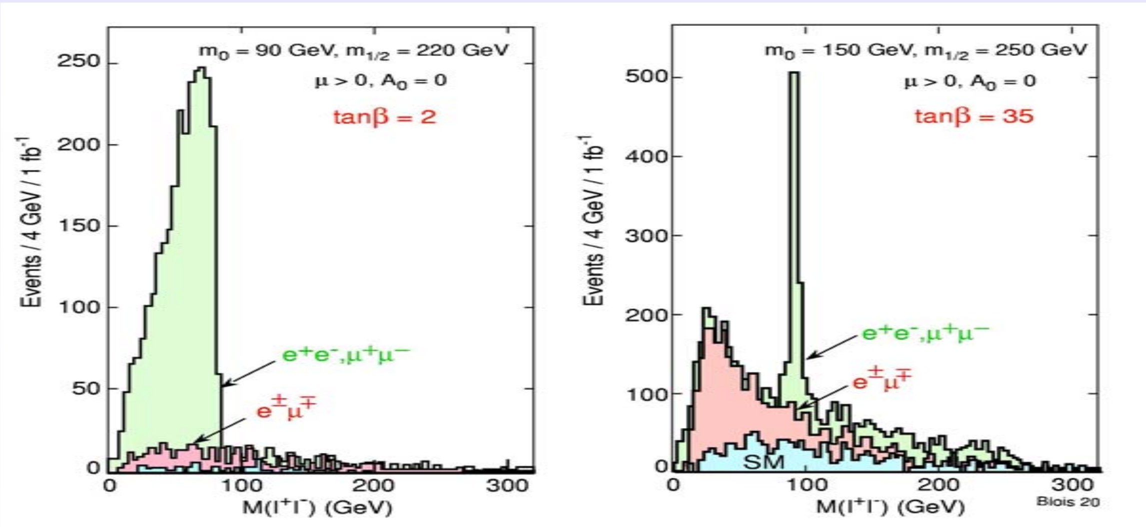
- Invisible LSP $\Rightarrow$ no mass peaks, but kinematic endpoints
  $\Rightarrow$ mass combinations

- 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}



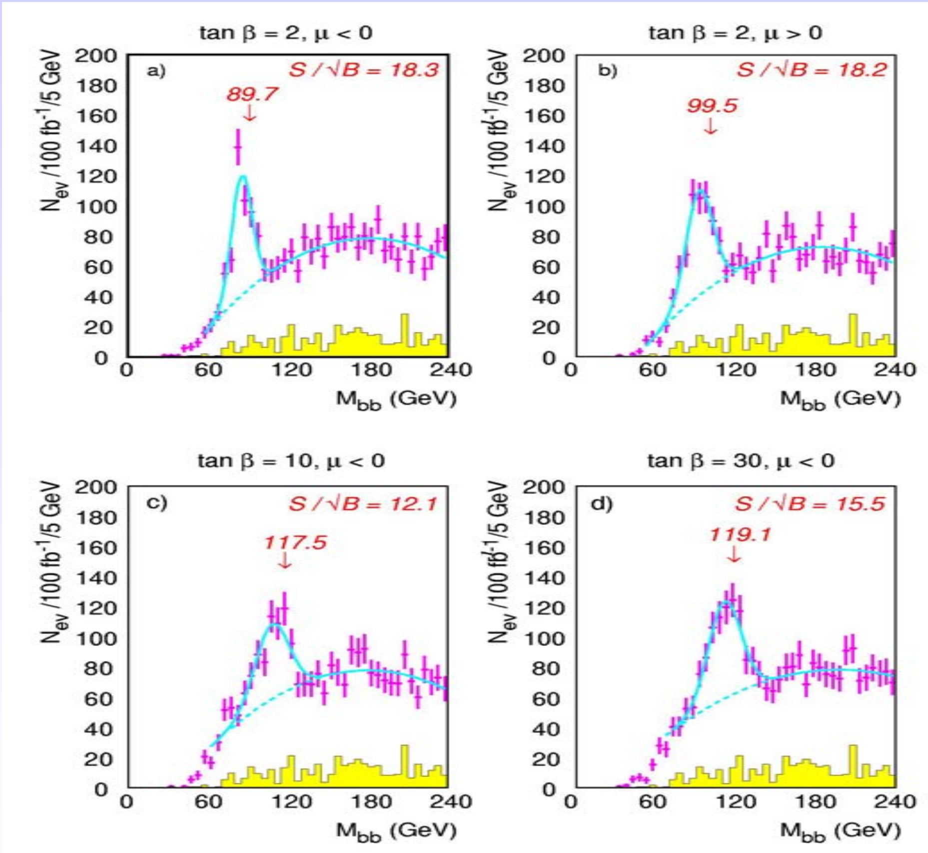


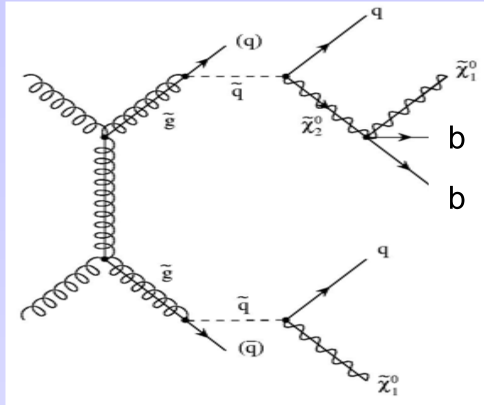
Modes can be distinguished

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 !

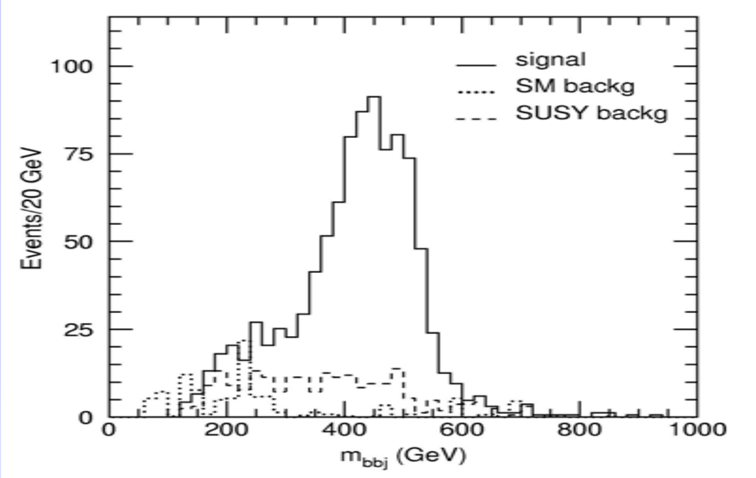
SM background can be reduced by applying a cut on E_T^{miss}

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:

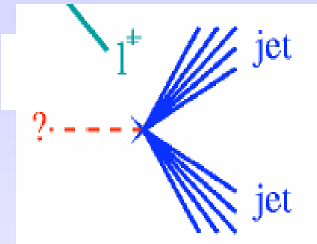
- Search for multijet + E_T^{miss} excess
- If found, select SUSY sample (simple cuts)
- Look for special features (γ's , long lived sleptons)
- Look for $\ell^\pm$, $\ell^+ \ell^-$, $\ell^\pm \ell^\pm$, b-jets, τ's
- End point analyses, global fit $\to$ SUSY model parameters

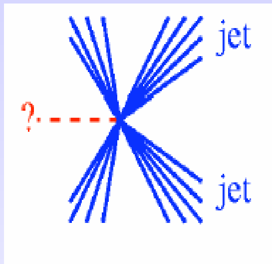
The Search for

SUSY at the Tevatron

The two classical signatures

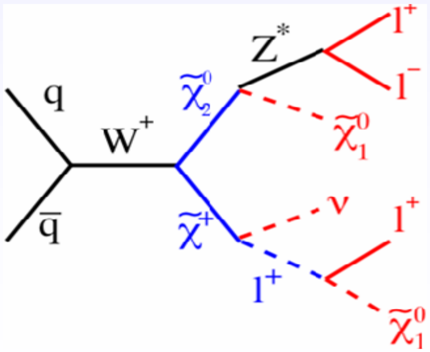
1. Search for Squarks and Gluinos: Jet + E_T^{miss} signature
   produced via QCD processes





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)

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

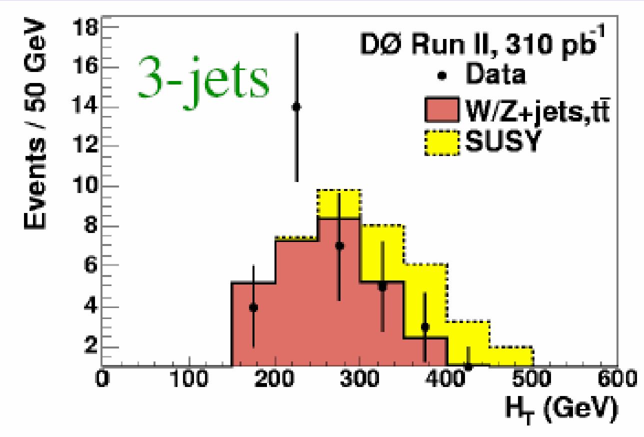
(iii) Gluino analysis
large m_0, m(squark) > m(gluino)

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

- 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 P_T^{miss} and all jets
  * optimization of the final cuts → discriminating variables

Search for Squarks and Gluinos (cont.)



DØ analysis L = 310 pb^{-1}

Example: 3 jet + E_T^{miss} search

Discriminating variable:

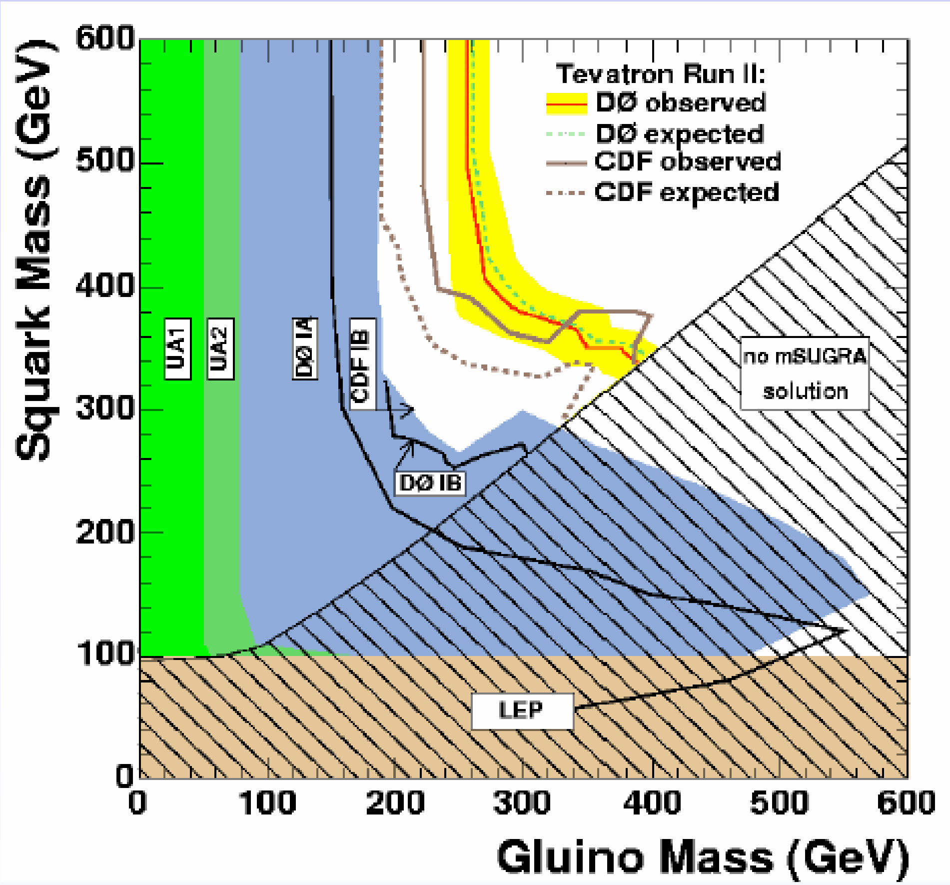
- $H_T = \Sigma\ E_T$(jets)

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 from Standard Model processes found
→ NO evidence for SUSY (yet) → Set limits on masses of SUSY particles

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



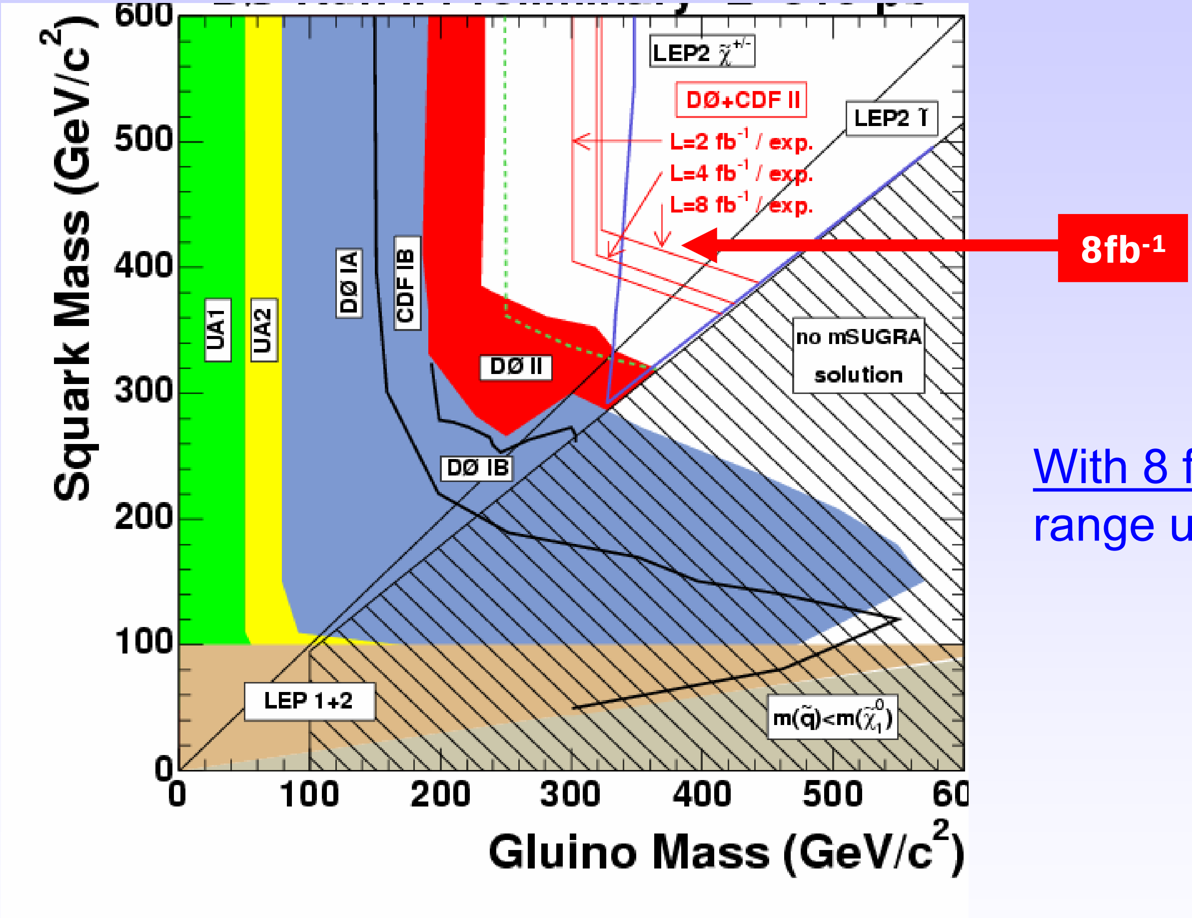
Excluded mass values:

m(gluino), m(squark) > ~ 330 GeV
for equal masses

<u>major systematic uncertainties</u>:

- renormalization scale - vary m(gluino)/2 < μ < 2 m(gluino) -
- parton density functions (gluon distribution at large x) qg-processes
- jet energy scale,….

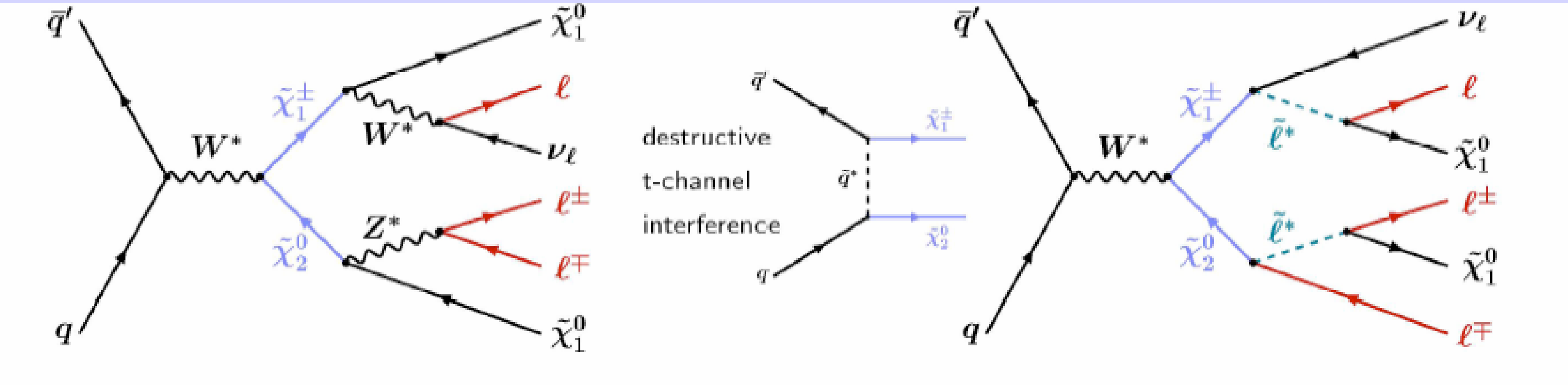
Future Prospects for Squark and Gluino Searches



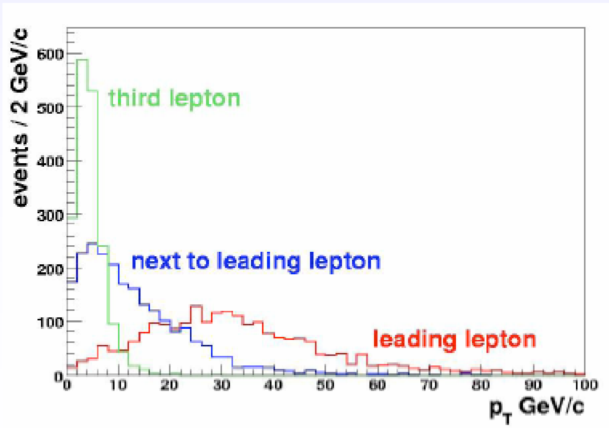
With 8 fb^{-1}: explore mass range up to ~ 400 GeV/c^2

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

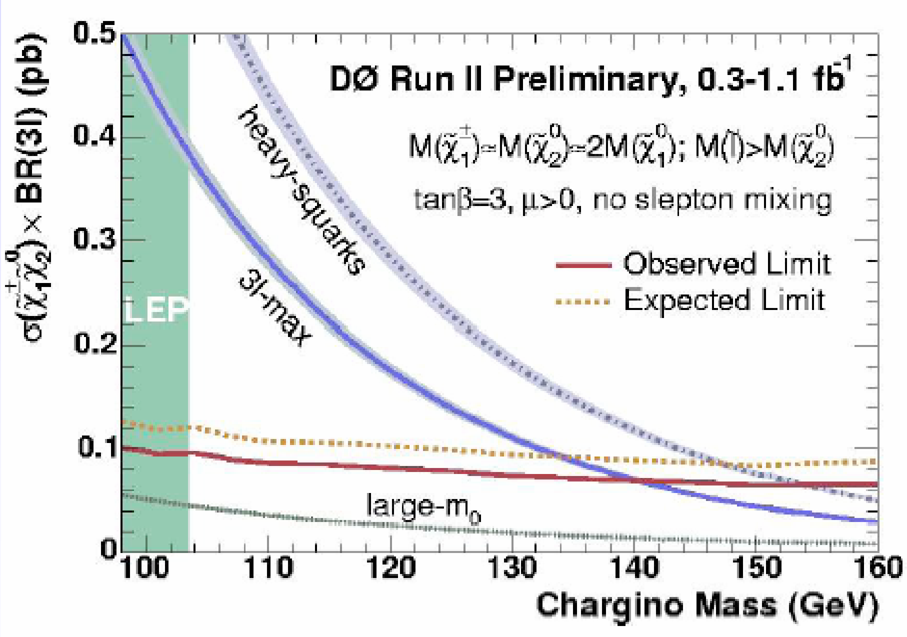


Analysis:

- 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 + a 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
Excluded σ x BR: 0.08 pb


Alternative models

Can LHC probe extra dimensions ?

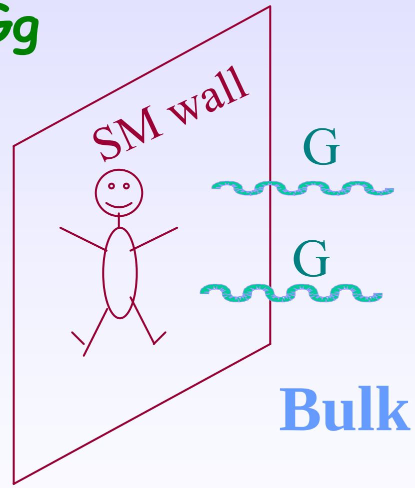
- Much recent theoretical interest in models with extra dimensions
  (Explain the weakness of gravity (or hierarchy problem) by extra dimensions)
- New physics can appear at the TeV-mass scale,
  i.e. accessible at the LHC

Example: **Search for direct Graviton production**

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

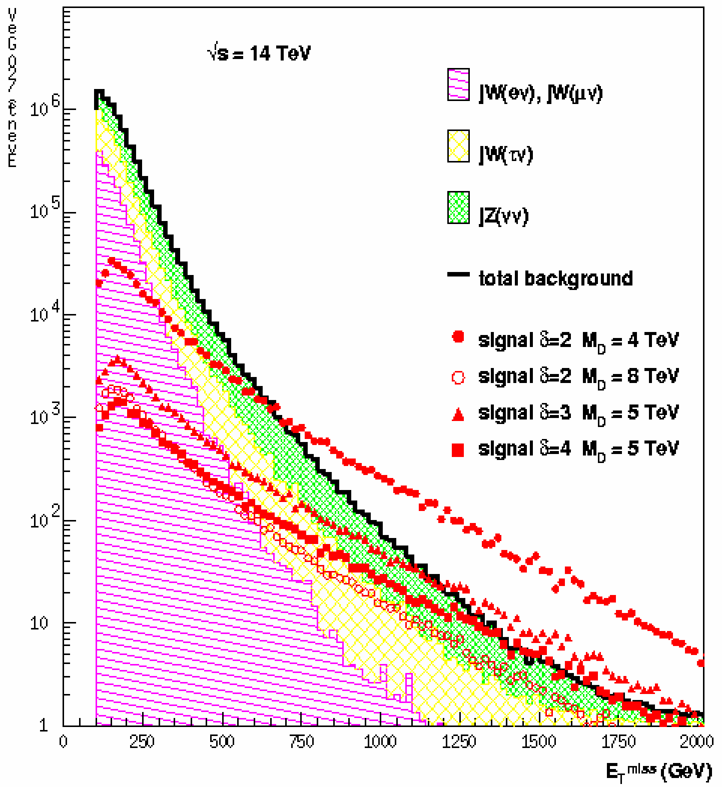
$q\bar{q} \rightarrow G\gamma$

$\Rightarrow$ **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)

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

More ideas?

1. What about heavy new resonances decaying into lepton pairs

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

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

   Increased sensitivity in the Tevatron Run II

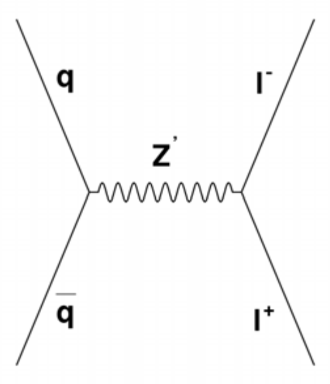
2. What about Leptoquarks ?

   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)

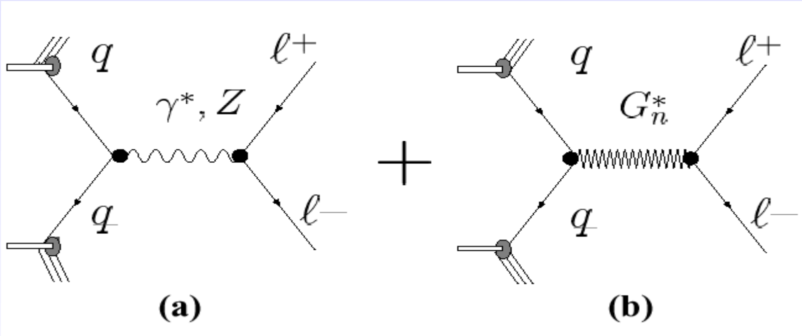
Fermilab Search for New Resonances in High Mass Di-leptons

- **Neutral Gauge Boson Z'**
  - SM Coupling assumed



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

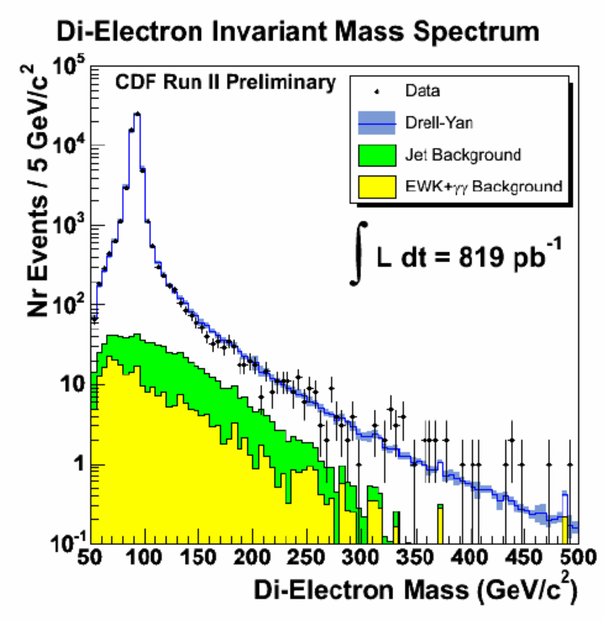
appear in Extra Dim. Scenarios



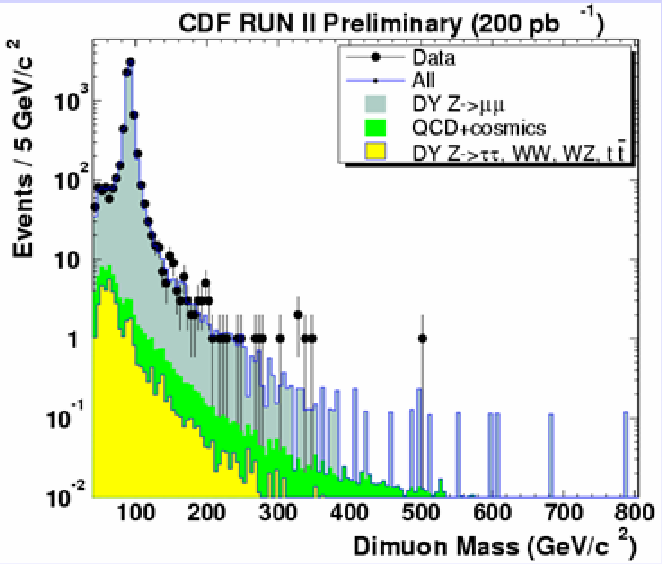
Main background from Drell-Yan pairs

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.

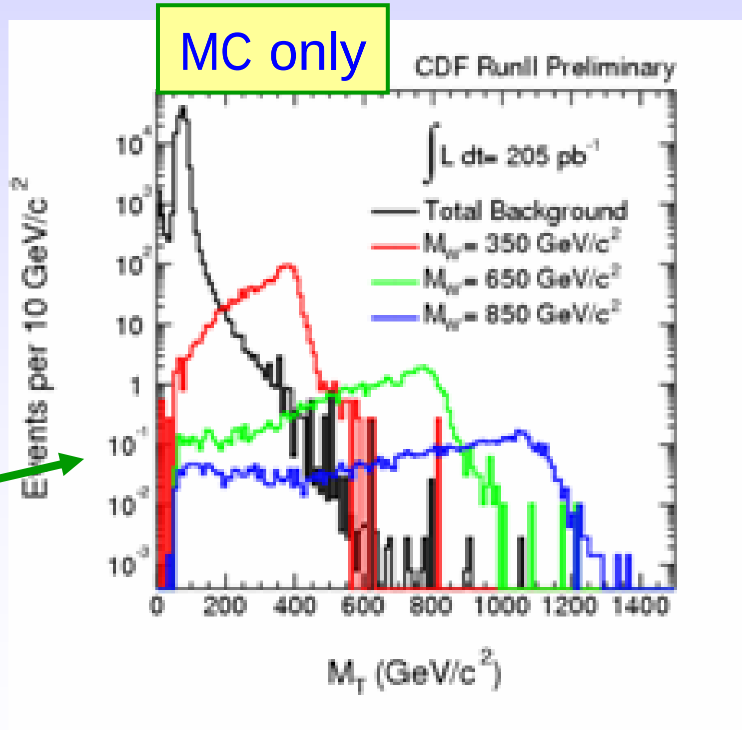
		ee	μμ	ττ	
Z´ mass limits (SM couplings)					
95% C.L.	**CDF /D0:**	**850**	**835**	**394**	**GeV/c²**

Search for W' → eν

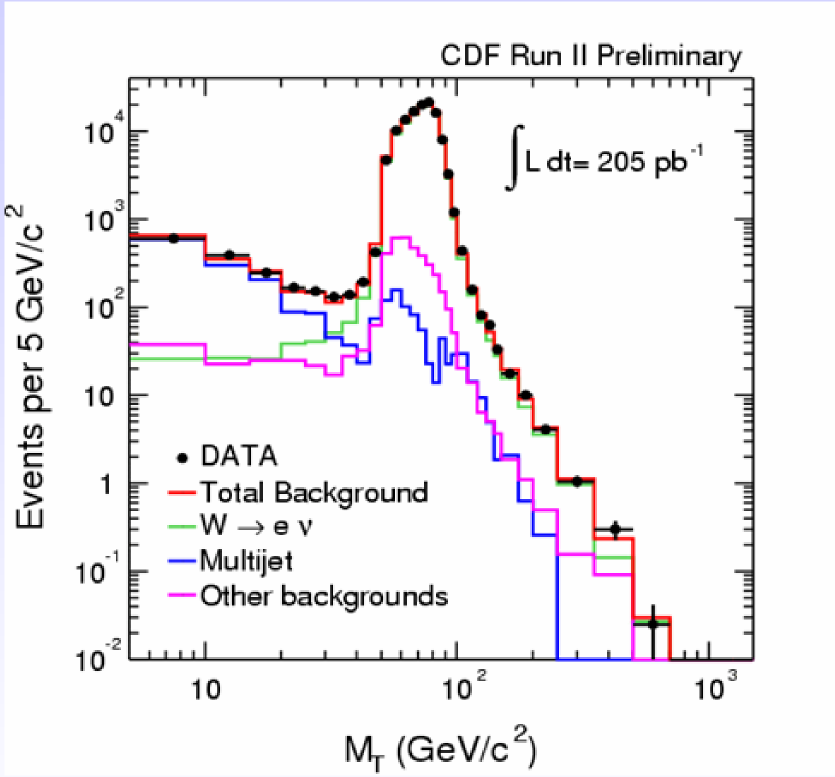
- W': additional charged heavy vector boson
- appears in theories based on the extension of the gauge group
- e.g. Left-right symmetric models: $SU(2)_R$ W_R
- assume: the neutrino from W' decay is light and stable.
- signature:

high p_T electron + high P_T^{miss}

→ peak in transverse mass distribution



Search for W' → eν



Data:

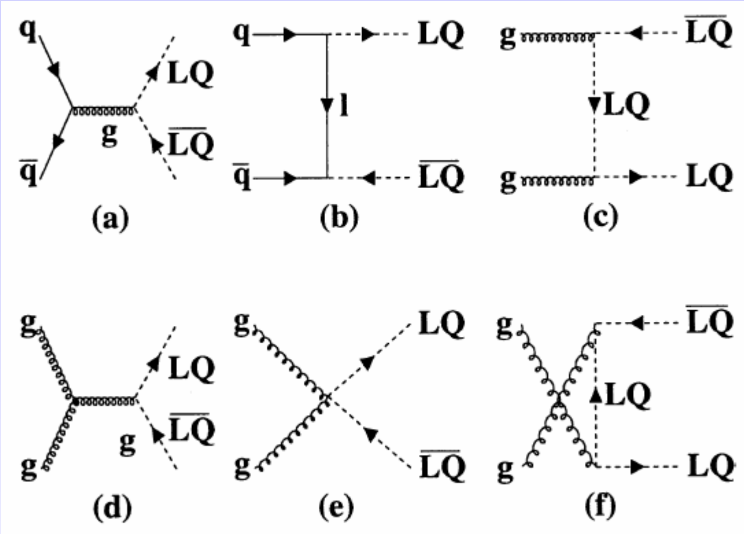
consistent with one well known W + background

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

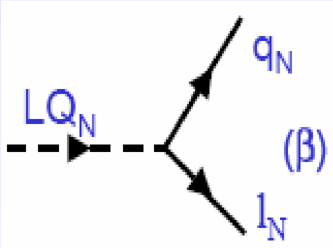
(assuming Standard Model couplings)

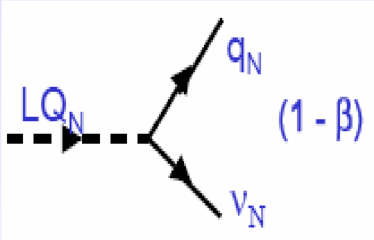
Search for Scalar Leptoquarks (LQ)

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



- **Decays:** **into a lepton and a quark**





β= LQ branching fraction to charged lepton and quark

N = generation index

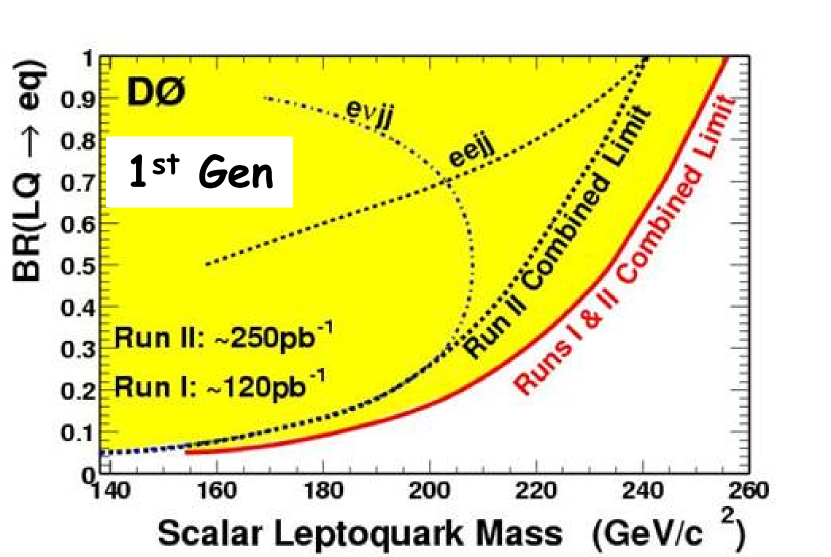
Leptoquarks of 1., 2., and 3. generation

Experimental Signatures:

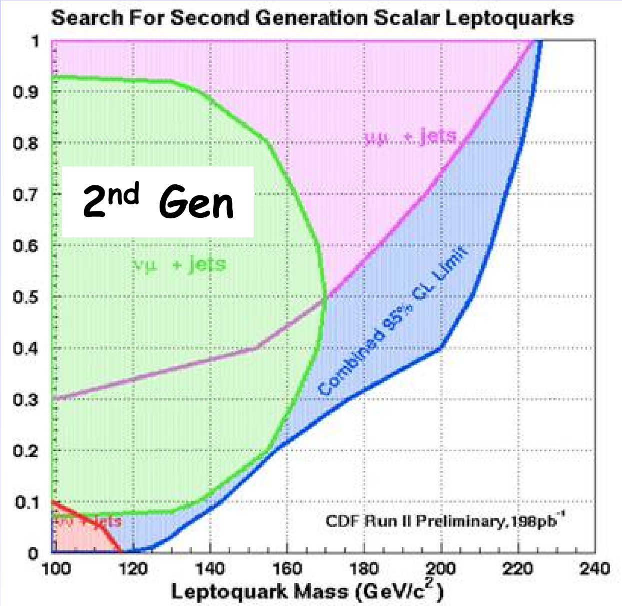
- two high p_T isolated leptons + jets .OR.
- one isolated lepton + P_T^{miss}+ jets .OR.
- P_T^{miss} + jets

1^{st}, 2^{nd} and 3^{rd} generation Leptoquarks

channels: eejj, eν jj



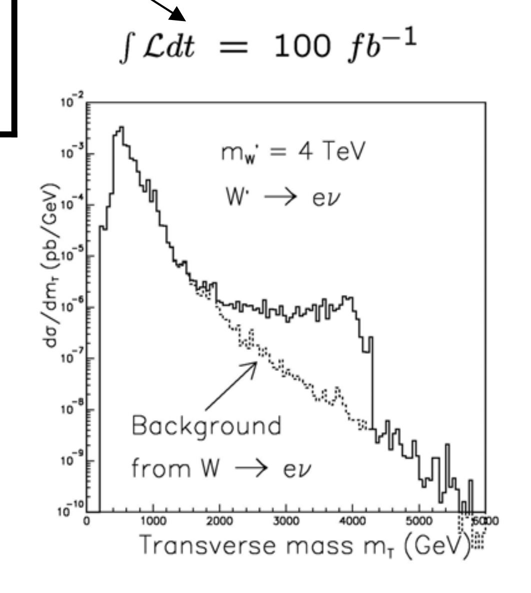
channels: μμjj, ενjj, ννjj



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* → q γ	M (q*) ~ 3.5 TeV	M (q*) ~ 6 TeV
Leptoquarks	M (LQ) ~ 1 TeV	M (LQ) ~ 1.5 TeV
Z' → ℓℓ, jj W'→ ℓ ν	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



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 ~15 MeV
   - m_{top} to ~ 1 GeV
   - $\Delta m_H / m_H$ to 0.1% (100 - 600 GeV)

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

LHC : most difficult and ambitious high-energy physics project ever realized
(human and financial resources, technical challenges, complexity, ….)

It has a crucial role in physics: can say the final word about

-- SM Higgs mechanism
-- low-energy SUSY and other TeV-scale predictions

⬇

It will most likely modify our understanding of Nature

There are very exciting times ahead of us !!

We hope that many of you will join us in the discovery enterprise

- 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
  (official summer school pages)

End of lectures