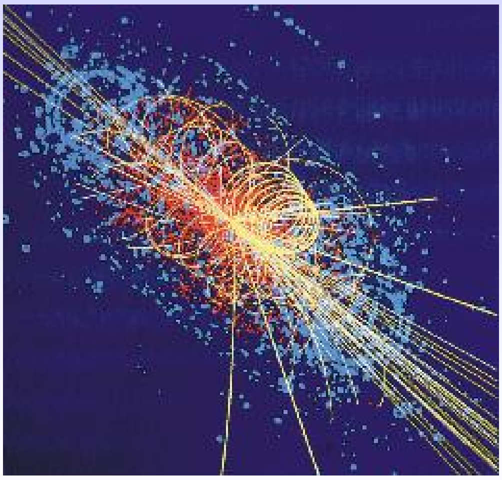
Physics at Hadron Colliders

Lecture 4



Search for Physics Beyond the Standard Model

- **Supersymmetry**
- **Heavy particles decaying into di-leptons**
- **What if there are extra dimensions?**

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
   - …..

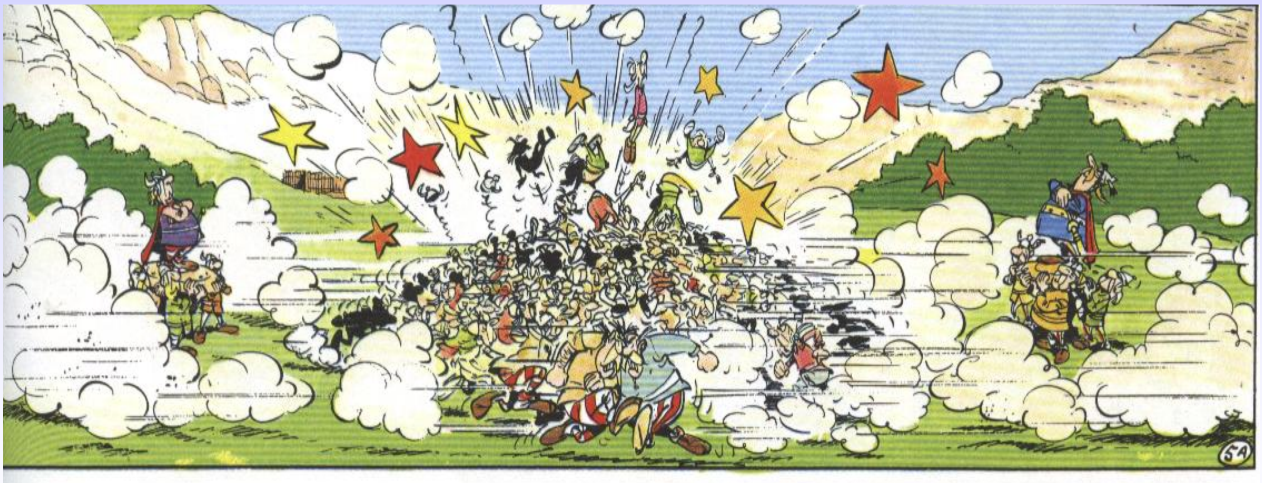
All this calls for a ***more fundamental theory*** of which the Standard Model is a low energy approximation → **New Physics**

Candidate theories: Supersymmetry
Extra Dimensions
Technicolor
…….

All predict new physics at the TeV scale !!

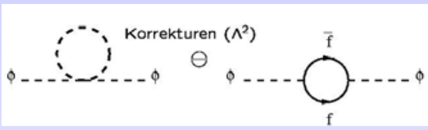
Strong motivation for LHC mass reach ~ 3 TeV

The Search for Supersymmetry



Why do we like her so much?

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

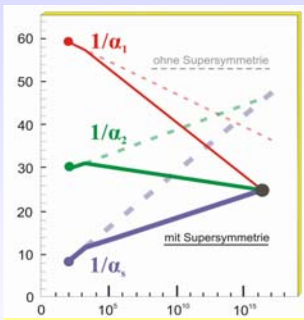


$$\Delta m_H = f(m_B^2 - m_f^2)$$

→ m_{SUSY} ~ 1 TeV

(Hierarchy or naturalness problem)

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



energy (GeV)

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)

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Either SUSY does not exist

OR

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

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LHC should say "final word" about (low energy) SUSY since theory predicts $m_{SUSY} \lesssim$ a few TeV

The Minimal Supersymmetric Standard Model (MSSM)

Symmetry between fermions (matter) and bosons (forces)

For each particle *p* with spin s, there exists a SUSY partner $\tilde{p}$ with spin Δs =1/2.

Ex. :	q (s=1/2)	→	$\boxed{\tilde{q}}$	(s=0)	squarks
	g (s=1)	→	$\boxed{\tilde{g}}$	(s=1/2)	gluino

Many new particles predicted !

Here : Minimal Supersymmetric extension of the Standard Model (MSSM)
which has minimal particle content

⬇

MSSM particle spectrum :

5 Higgs bosons : h, H, A, $H^{\pm}$

quarks	$\rightarrow$	squarks	$\tilde{q}$
leptons	$\rightarrow$	sleptons	$\tilde{e}, \tilde{\mu}, \tilde{\nu}$, etc.
$W^{\pm}$	$\rightarrow$	winos	$\rightarrow \chi^{\pm}_1, \chi^{\pm}_2$ **2 charginos**
$H^{\pm}$	$\rightarrow$	charged higgsino	
γ	$\rightarrow$	photino	$\rightarrow \chi^0_{1,2,3,4}$ **4 neutralinos**
Z	$\rightarrow$	zino	
h, H	$\rightarrow$	neutral higgsino	
g	$\rightarrow$	gluino	$\tilde{g}$

SUSY phenomenology

There is a multiplicative quantum number:

R-parity $R_p = \begin{cases} +1 & \text{Standard Model particles} \\ -1 & \text{SUSY particles} \end{cases}$

which is conserved in most popular models (considered here).

Consequences:

- SUSY particles are produced in pairs
- Lightest Supersymmetric Particle (LSP) is stable.
  In most models LSP is also weakly interacting:

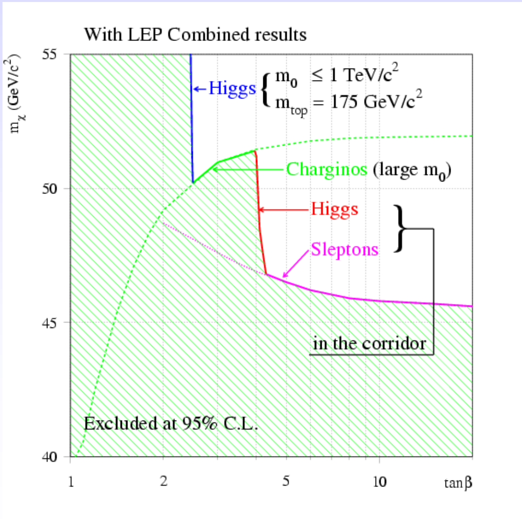
$\boxed{\text{LSP} \equiv \chi^0_1}$

$\rightarrow$ 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)

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



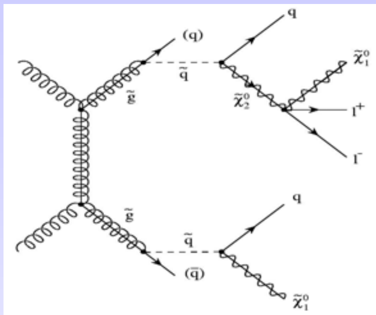
LEP-II limit on the mass of the Lightest SUSY particle

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)



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

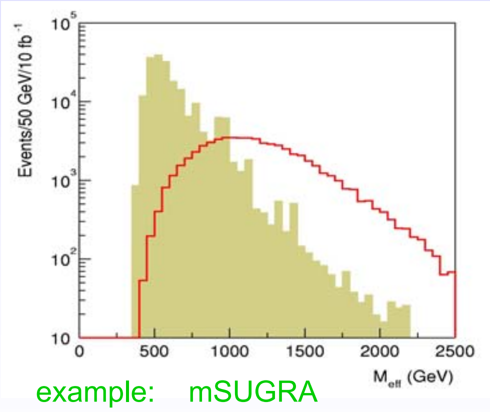
1. Step: Look for deviations from the Standard Model
   Example: Multijet + E_T^{miss} signature

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
$\tan\beta$ = 10, $A_0 = 0$, $\mu > 0$

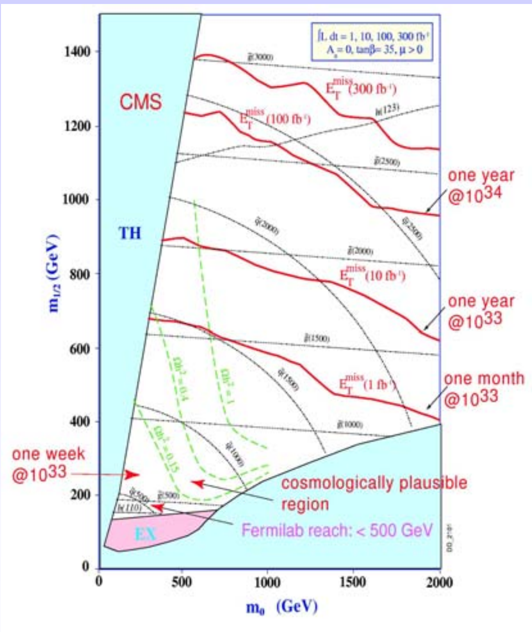
LHC reach for Squark- and Gluino masses:

1 fb^{-1}	$\Rightarrow$	M ~ 1500 GeV
10 fb^{-1}	$\Rightarrow$	M ~ 1900 GeV
100 fb^{-1}	$\Rightarrow$	M ~ 2500 GeV

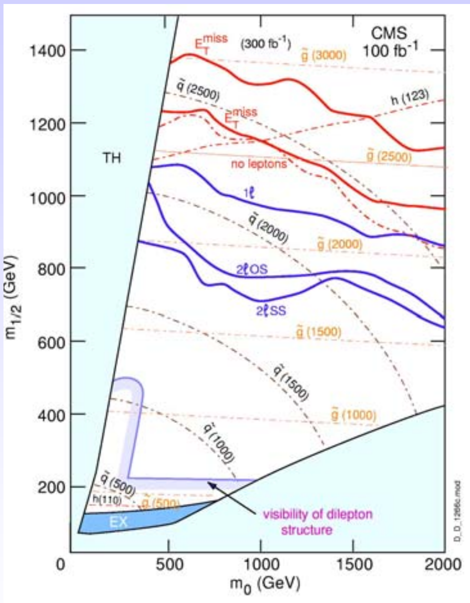
TeV-scale SUSY can be found quickly !

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

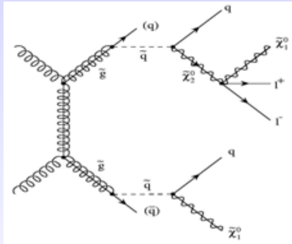
Determination of model parameters

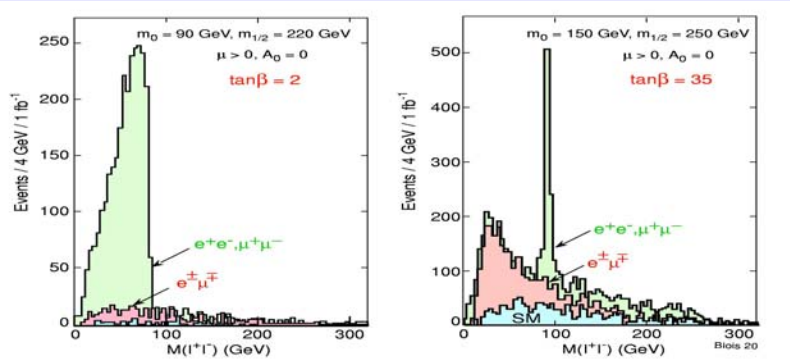
- Invisible LSP $\Rightarrow$ no mass peaks, but kinematic endpoints
  $\Rightarrow$ mass combinations

- 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}

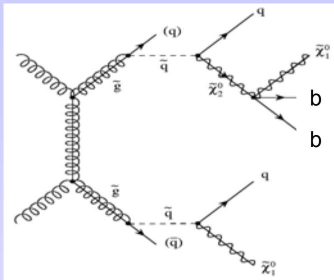




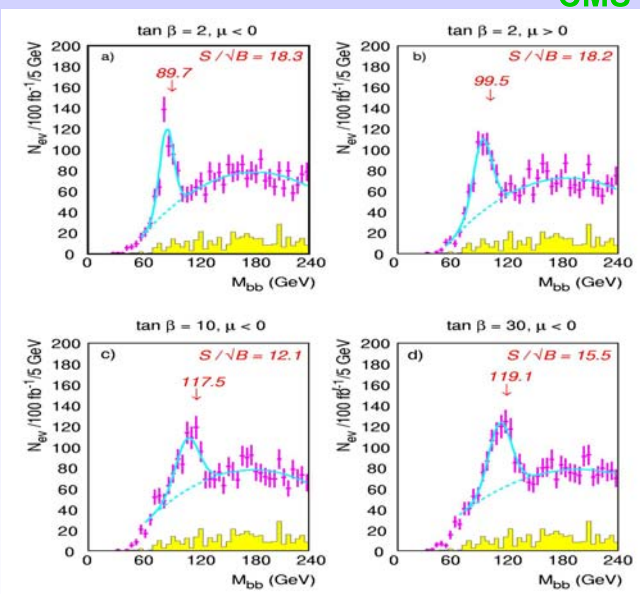
Modes can be distinguished

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}

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

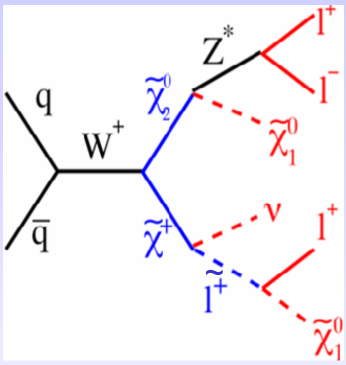
Status of SUSY Searches at the Tevatron - a few examples-

(1) Search for Charginos and Neutralinos

- These particles can decay via W* / Z* or sleptons into **Leptons + P_T^{miss}**

Example: associated $\chi_0^2\chi_1^\pm$ production

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

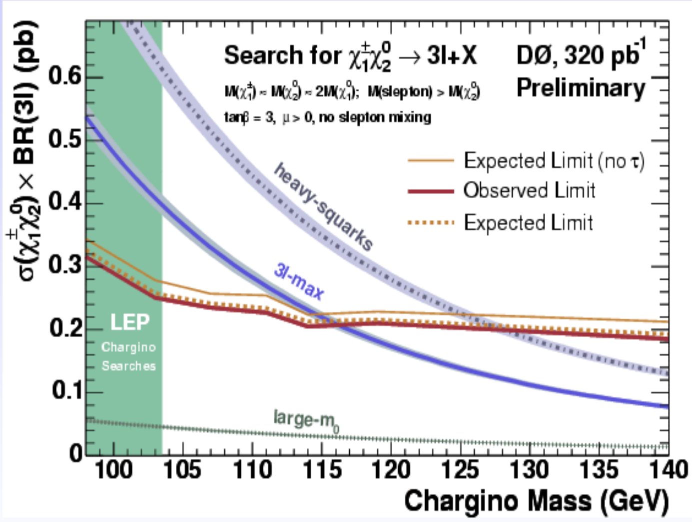


- Small background from Standard Model processes (striking signature), but also a small signal cross section
- Leptonic branching ratios are enhanced if slepton masses are close to gaugino masses

Analysis: Search for 5 (ℓℓℓ) + like-sign di-muon final states with missing transverse momentum

mSUGRA interpretation

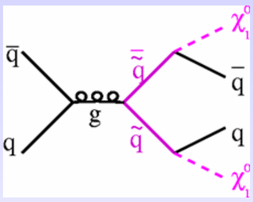
Selection	background expected	# obs. events
ee+l	0.21±0.12	0
eμ+l	0.31±0.13	0
μμ+l	1.75±0.57	2
$\mu^{\pm}\mu^{\pm}$	0.64±0.38	1
eτ+l	0.58±0.14	0
μτ+l	0.36±0.13	1
SUM	3.85±0.75	4



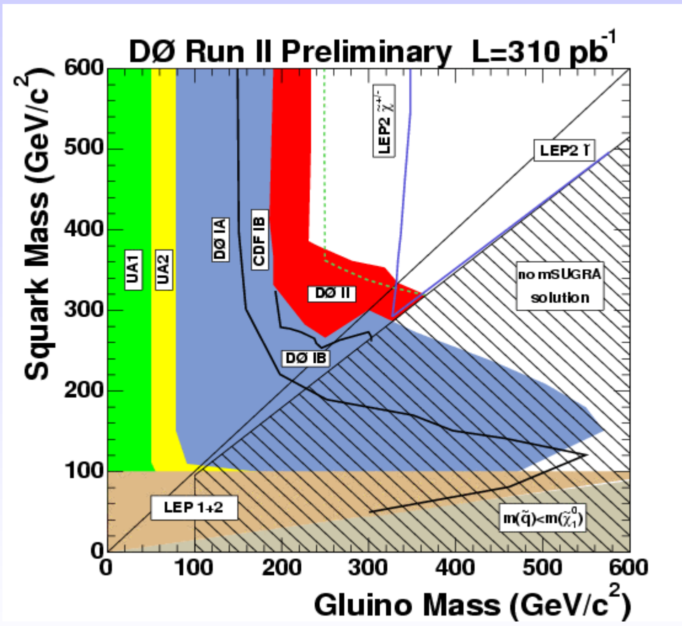
For specific scenarios: sensitivity / limits above LEP limits

(2) Search for Squarks and Gluinos

- Copiously produced (QCD production)



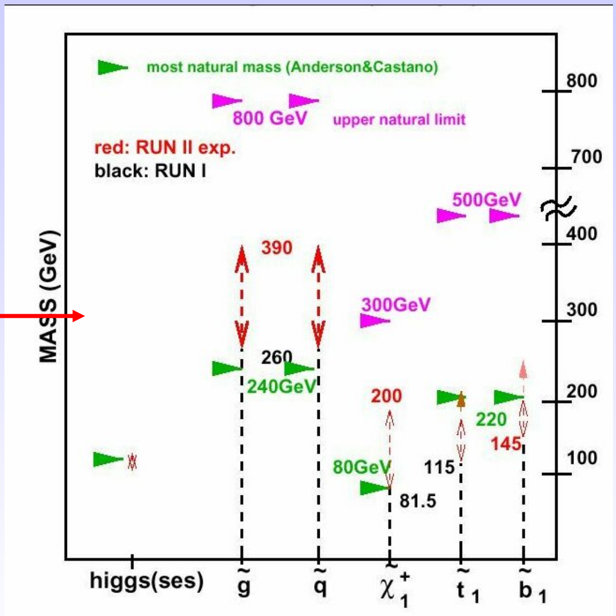
- Cascade decays into multi-jet + P_T^{miss} final states
  (2,3 or 4 jets, depending on squark / gluino mass relations)



Limits beyond LEP mSUGRA reach for m(squark) ~ m(gluino)

The Reach for SUSY at the Tevatron

SUSY:
Extend reach for SUSY particle masses
(for 10 fb^{-1})



Can LHC probe extra dimensions ?

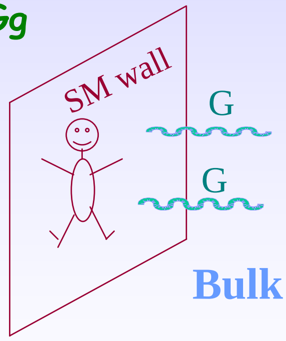
- Much recent theoretical interest in models with extra dimensions
  (Explain the weakness of gravity (or hierarchy problem) by extra dimensions)
- New physics can appear at the TeV-mass scale,
  i.e. accessible at the LHC

Example: **Search for direct Graviton production**

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

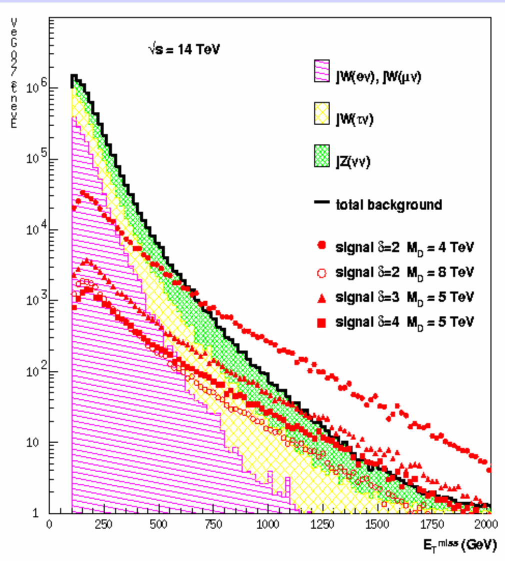
$q\bar{q} \rightarrow G\gamma$

$\Rightarrow$ **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($\rightarrow\nu\nu$), jet+W$\rightarrow$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

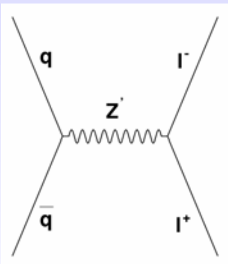
2. What about Leptoquarks ?

   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)

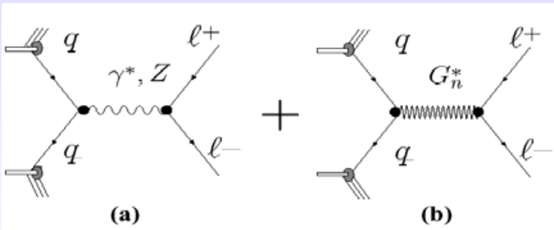
Fermilab Search for New Resonances in High Mass Di-leptons

- Neutral Gauge Boson Z'
  - SM Coupling assumed



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

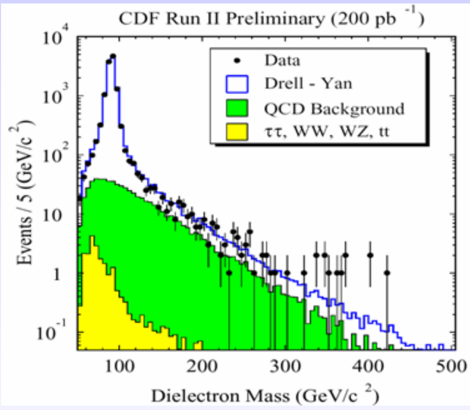
  appear in Extra Dim. Scenarios

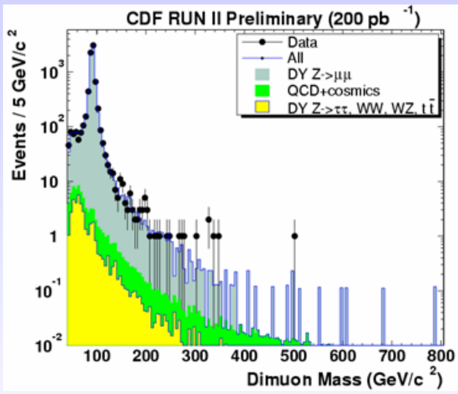


Main background from Drell-Yan pairs

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.

Z´ mass limits (SM couplings)		ee	μμ	ee+μμ	ττ	
95% C.L.	CDF :	750	735	815	394	GeV/c^2
	DØ:	780	680			

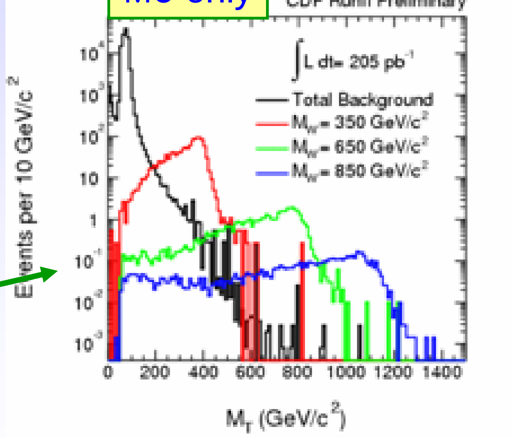
Search for W’ → eν

- 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:

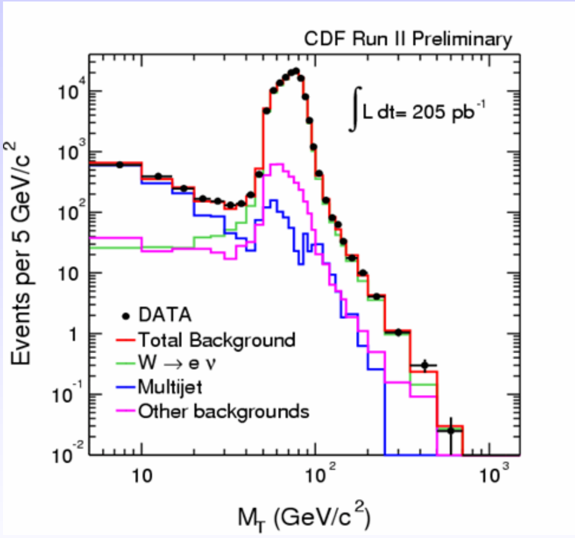
high p_T electron + high P_T^{miss}

→ peak in transverse mass distribution

MC only



Search for W' → eν



Data:

consistent with one well known W + background

↓

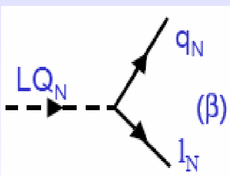
Limit: M(W') > 842 GeV/c^2

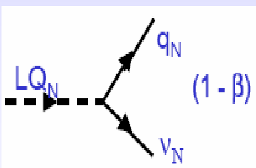
(assuming Standard Model couplings)

Search for Scalar Leptoquarks (LQ)

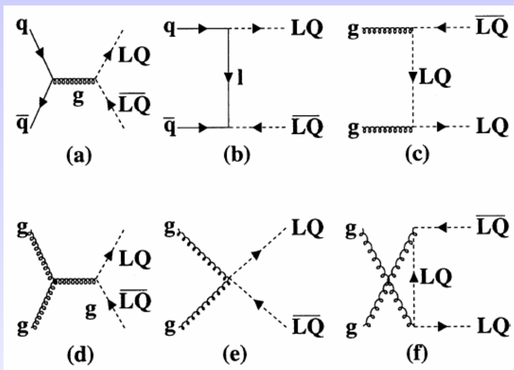
- Production:
  pair production via QCD processes (qq and gg fusion)

- **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

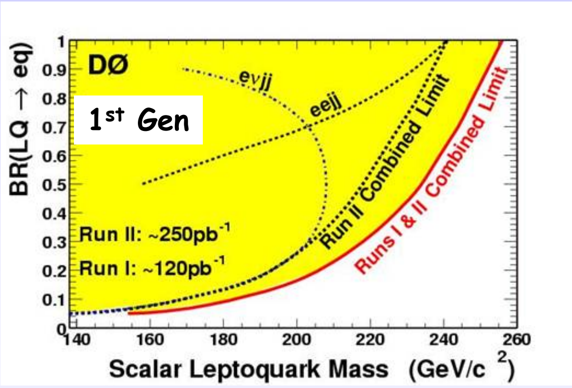


Experimental Signatures:

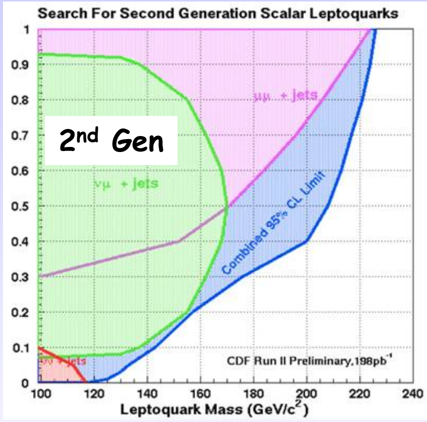
- two high p_T isolated leptons + jets .OR.
- one isolated lepton + P_T^{miss}+ jets .OR.
- P_T^{miss} + jets

1st, 2nd and 3rd generation Leptoquarks

channels: eejj, eν jj



channels: μμjj, ενjj, ννjj

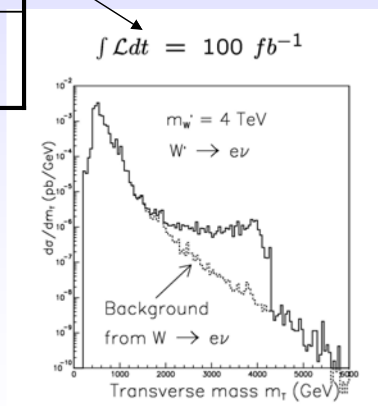


95% C.L. Mass Limits	1. Generation LQ	2. Generation LQ	3. Generation LQ
CDF (Run II) D0 (Run I + II)	235 GeV/c² 256 GeV/c²	224 GeV/c² 200 GeV/c² (Run I)	129 GeV/c²

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