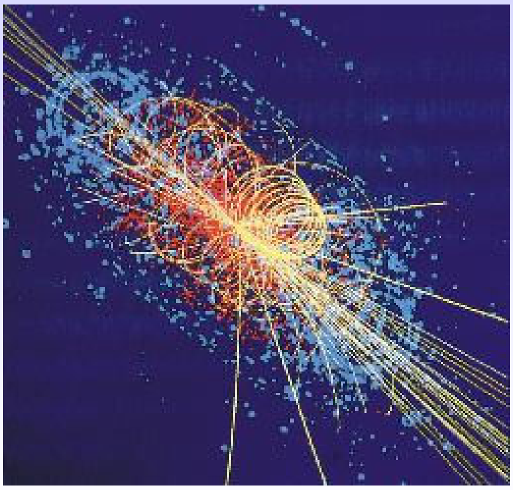
Physics at Hadron Colliders

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 R. Rattazzi

1. Gravity is not incorporated yet in the Standard Model
2. Many open questions in the Standard Model
   - Hierarchy problem: m_W (100 GeV) → m_{Planck} (10^{19} GeV)
   - Unification of couplings
   - Flavour / family problem
   - …..

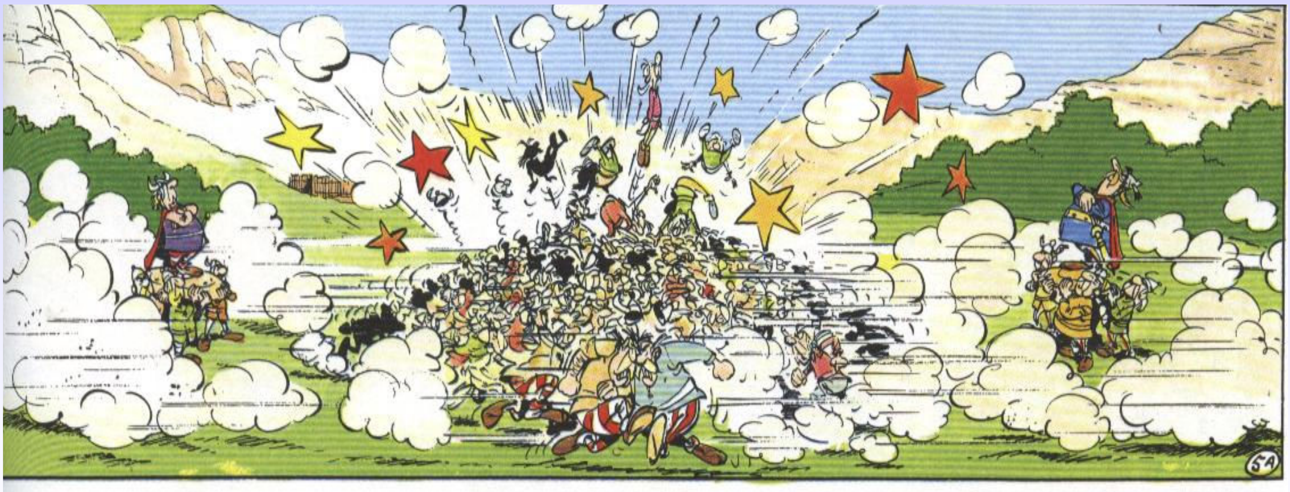
All this calls for a ***more fundamental theory*** of which the Standard Model is a low energy approximation → **New Physics**

Candidate theories: Supersymmetry
Extra Dimensions
Technicolor
…….

All predict new physics at the TeV scale !!

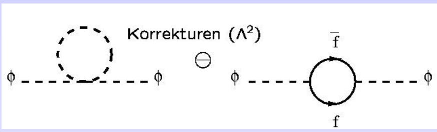
Strong motivation for LHC mass reach ~ 3 TeV

The Search for Supersymmetry



Why do we like her so much?

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

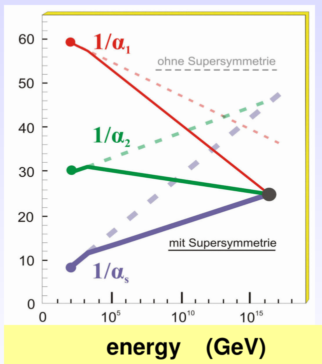


$$\Delta m_H = f(m_B^2 - m_f^2)$$

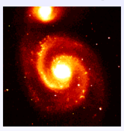
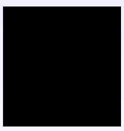
→ m_{SUSY} ~ 1 TeV

(Hierarchy or naturalness problem)

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



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

5. About half of the particles are already discovered !

the only problem:……

No experimental evidence for SUSY so far !

↓

Either SUSY does not exist

OR

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

↓

LHC should say "final word" about (low energy) SUSY since theory predicts $m_{SUSY} \leq$ 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 s-1/2.

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

Many new particles predicted !

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

↓

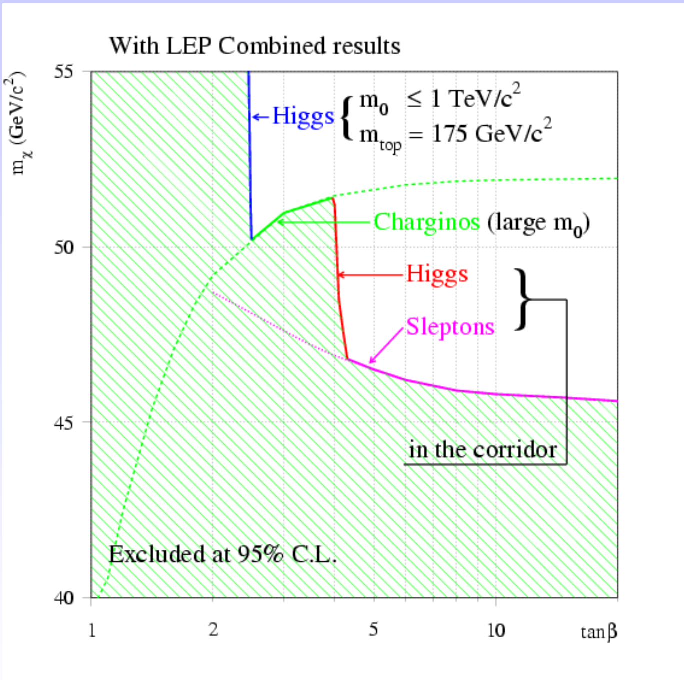
MSSM particle spectrum :

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

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

Masses not known. However charginos/neutralinos are usually lighter than squarks/sleptons/gluinos.

Present limits : m (sleptons, charginos) > 90-100 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

SUSY phenomenology

There is a multiplicative quantum number:

R-parity $R_p =$
- +1 Standard Model particles
- −1 SUSY particles

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:

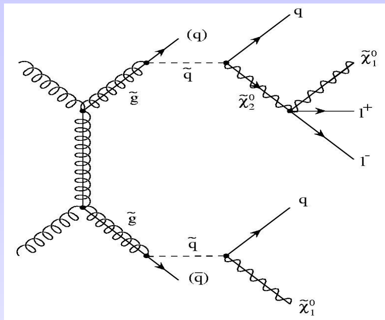
  LSP $\equiv \chi^0_1$

  → LSP is good candidate for cold dark matter
  → LSP behaves like a ν → escapes detection
  → E_T^{miss} (typical SUSY signature)

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}

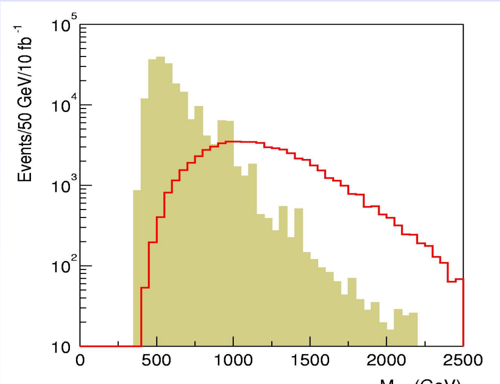
1. Step: Look for deviations from the Standard Model
   Example: Multijet + E_T^{miss} signature

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 same Q^2
- 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
$\tan\beta = 10$, $A_0 = 0$, $\mu > 0$

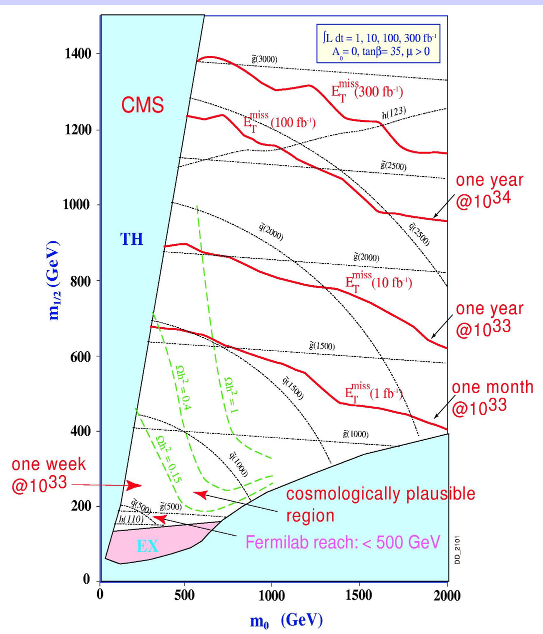
LHC reach for Squark- and Gluino masses:

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

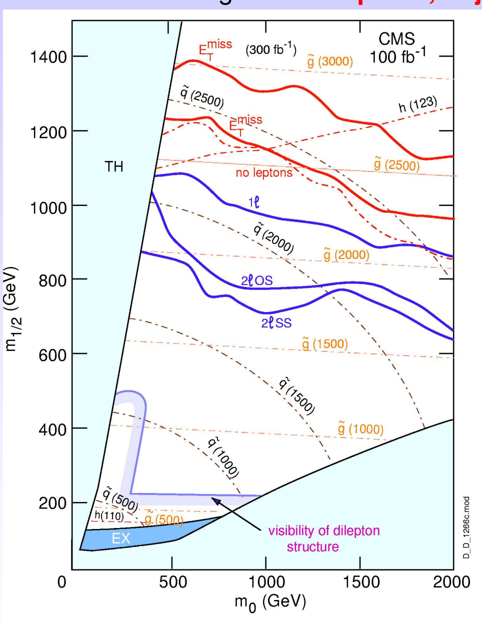
TeV-scale SUSY can be found quickly !

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

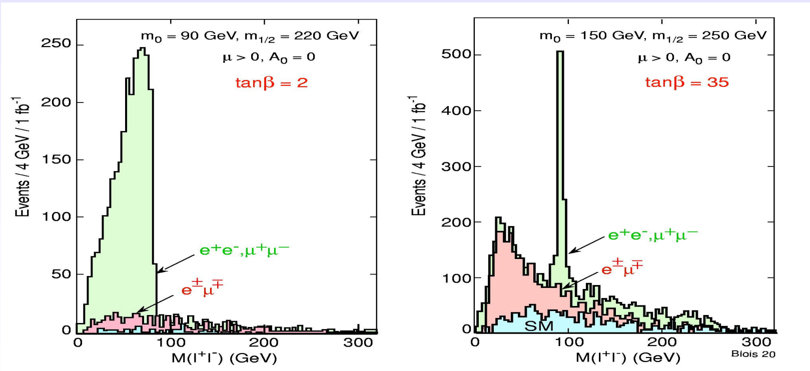
Determination of model parameters

- 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}

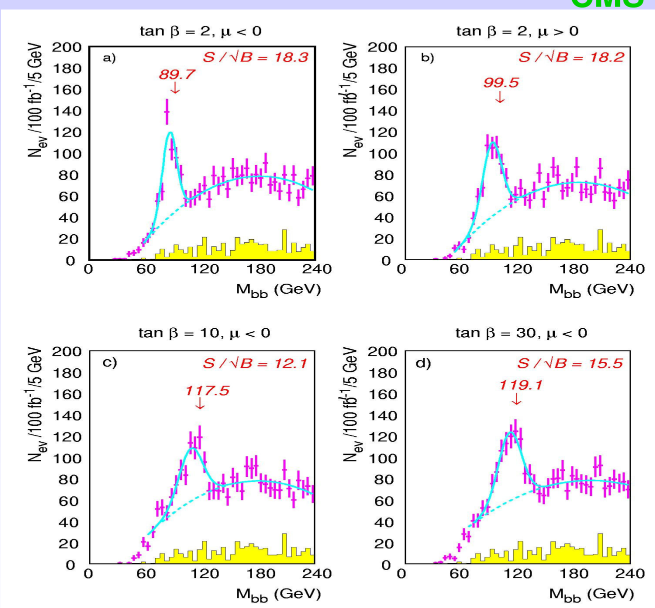


Modes can be distinguished

using shape of $\ell\ell$-spectrum

h $\rightarrow$ bb:

CMS



important if $\chi^0_2 \rightarrow \chi^0_1 h$ is open;

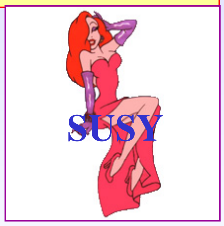
bb peak can be reconstructed in many cases

Could be a Higgs discovery mode !

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

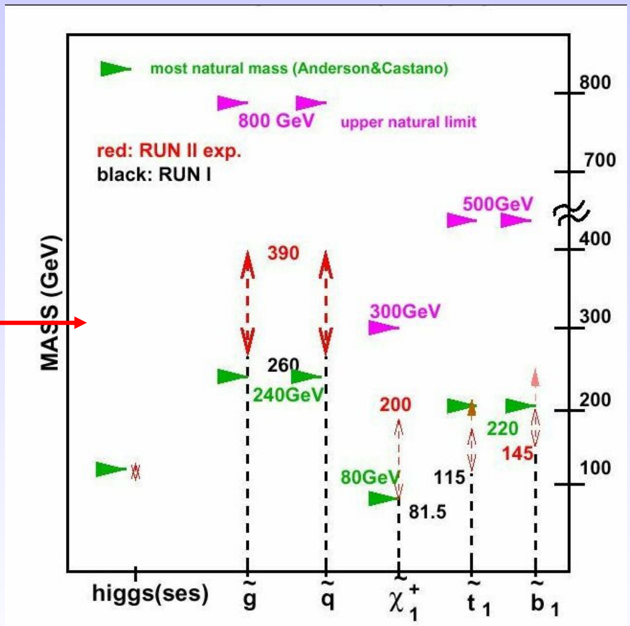
Strategy in SUSY Searches at the LHC:

- 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



The Reach for SUSY at the Tevatron

SUSY:
Extend reach for SUSY particle masses



Can LHC probe extra dimensions ?

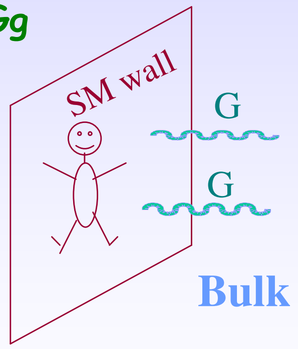
- Much recent theoretical interest in models with extra dimensions
  (Explain the weakness of gravity (or hierarchy problem) by extra dimensions)
- New physics can appear at the TeV-mass scale,
  i.e. accessible at the LHC
- **Gravitons** propagating in the extra dimensions will appear as massive states

Example: **Search for direct Graviton production**

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

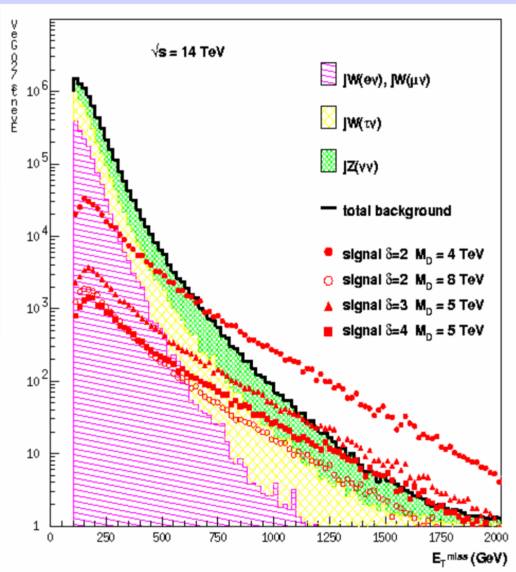
$$q\bar{q} \rightarrow G\gamma$$

$\Rightarrow$ **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}	**= for**	**9.1,**	**7.0,**	**6.0 TeV**
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 crazy ideas?

1. What about heavy new resonances decaying into lepton pairs

   examples: W ´ and Z´

   use again leptonic decay mode to search for them: W´ → ℓ ν
   Z´ → ℓ ℓ

   Increased sensitivity in the Tevatron Run II

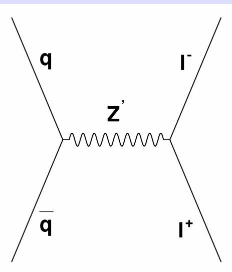
2. What about Leptoquarks ?

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

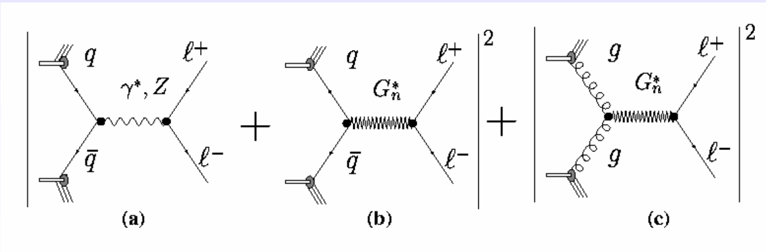
   here: search for low mass Leptoquarks (TeV scale)

Fermilab Search for New Resonances in High Mass Di-leptons

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



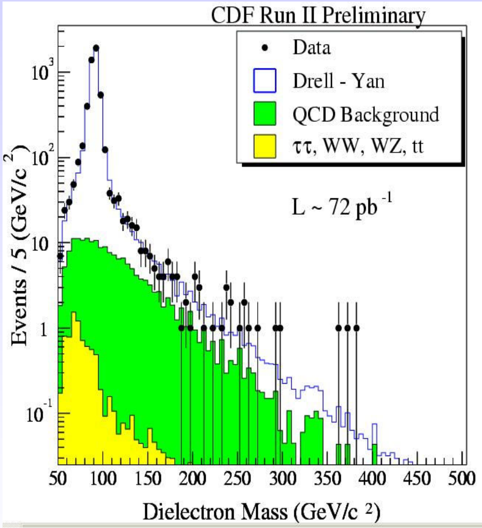
- **Randall-Sundrum narrow Graviton resonances decaying to di-leptons**
  - Gravitons in extra dimensions
  - Free parameters:
    - Mass M_G
    - Coupling **k**/M_{PL}



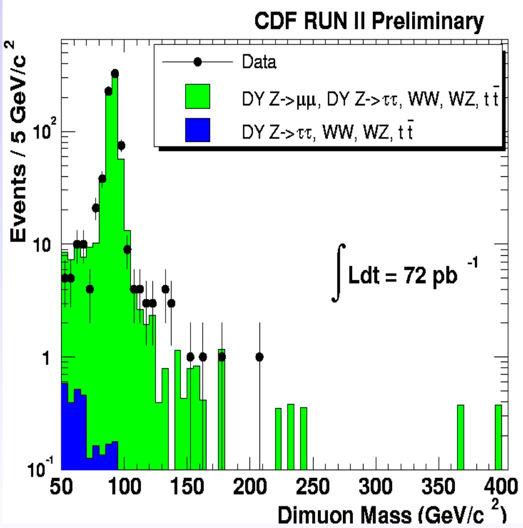
Main background from Drell-Yan pairs

Search for New Resonances in High Mass Di-leptons

Di-electron Invariant Mass



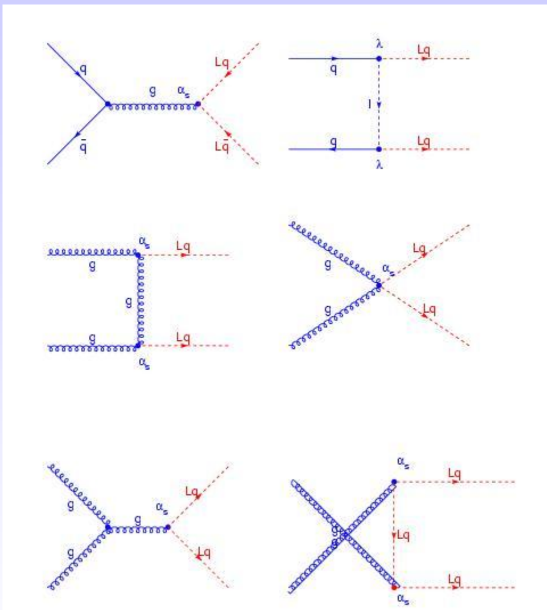
Di-muon Invariant Mass



Data are consistent with SM background. No excess observed.

Search for 1. Generation scalar Leptoquarks

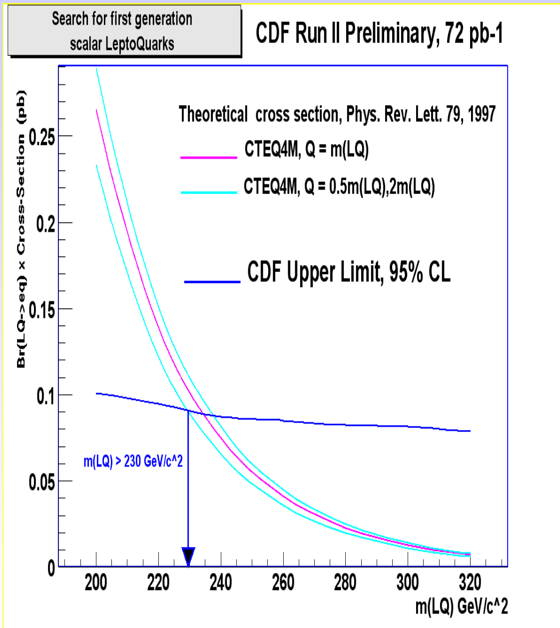
- **Production**
  - qg → LQ + LQ
  - gg → LQ + LQ
  - qq → LQ + LQ
- **Decay**
  - LQLQ → l^+l^-qq,
  - LQLQ → $l^\pm\nu$qq,
  - LQLQ → ννqq
- **Experimental signature**
  - 2 high pt isolated leptons + jets
  - one isolated lepton + MET + jets
  - MET + jets



Search for First Generation scalar LQ

- **Event Selection:**
  - 2 central electrons with E_T > 25 GeV
  - 2 jets with $E_T(j_1)$ > 30 and $E_T(j_2)$ > 15 GeV
  - Z veto
  - Cuts on *sum* of jet and electron E_T's to reject SM backgrounds

- **Expected Bkg:** 3.4 ± 3.2 events
  (DY+2 jet events, tt)



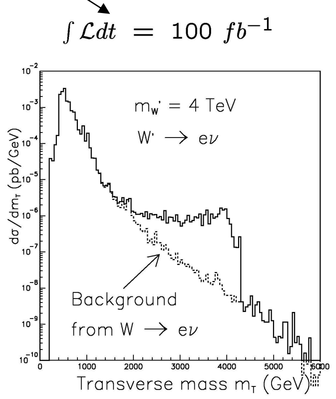
0 events observed in 72 pb-1.
M(LQ) > 230 GeV/c² @ 95% CL
(Run I: 220 GeV/c²)

LHC mass reach: 1.5 – 2 TeV

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