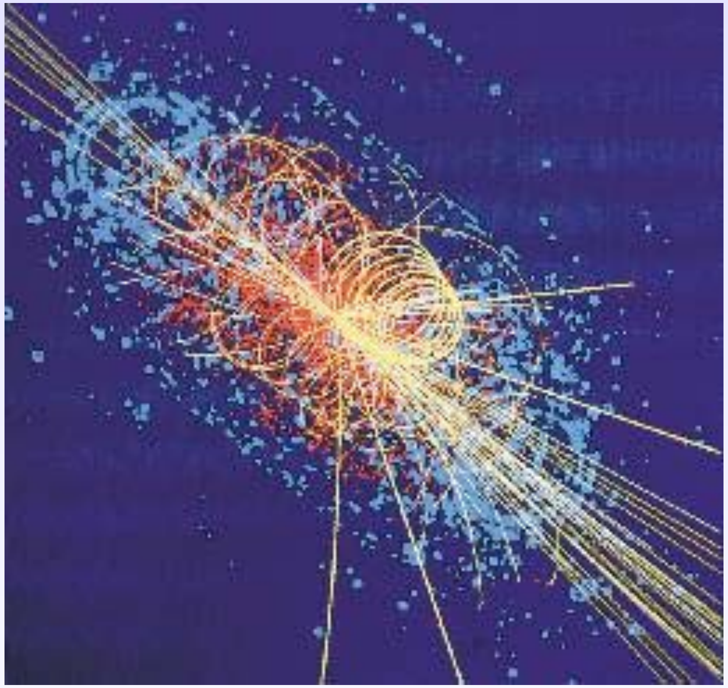
Physics at Hadron Colliders

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) → 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
…….

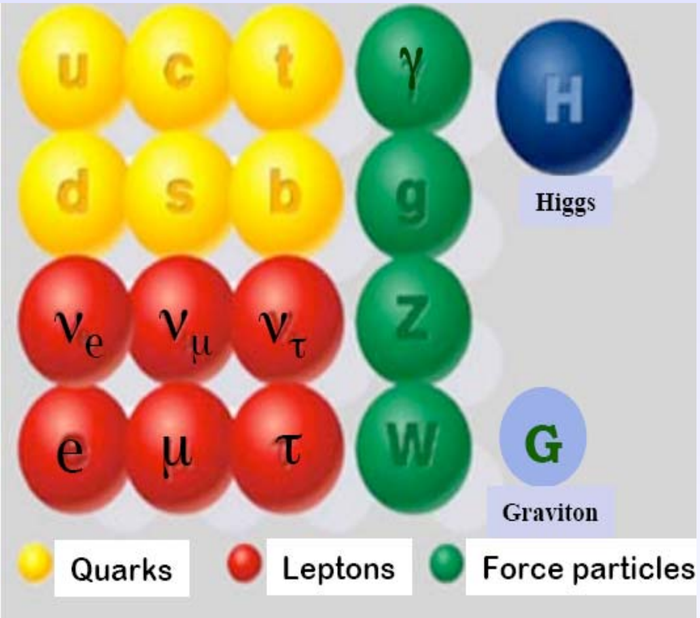
All predict new physics at the TeV scale !!

Strong motivation for LHC mass reach ~ 3 TeV

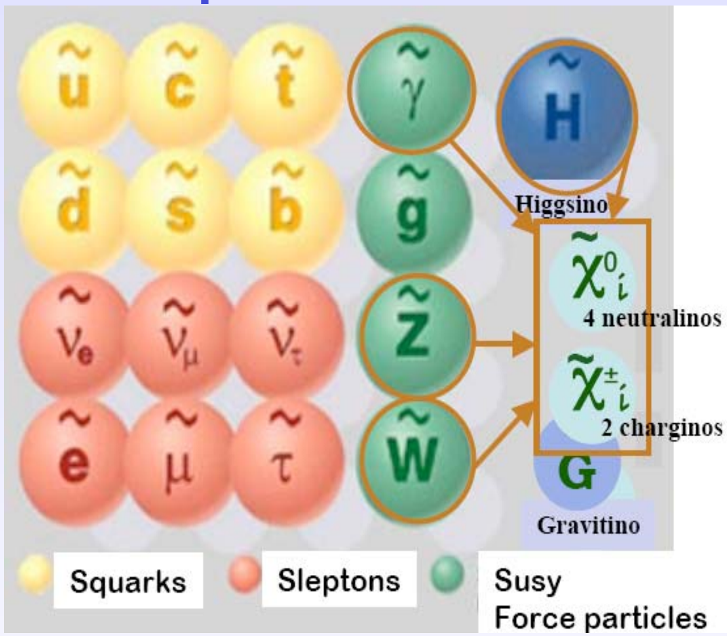
Supersymmetry

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.
  LSP is also weakly interacting:
  LSP ≡ χ^0_1 (lightest neutralino, in many models)

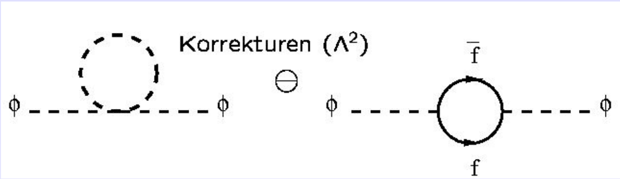
→ LSP is a good candidate for cold dark matter

→ 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



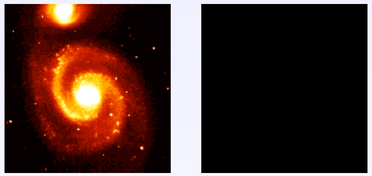
$$\Delta m_H = f(m_B^2 - m_f^2)$$

→ $m_{SUSY} \sim 1$ TeV

(Hierarchy or naturalness problem)

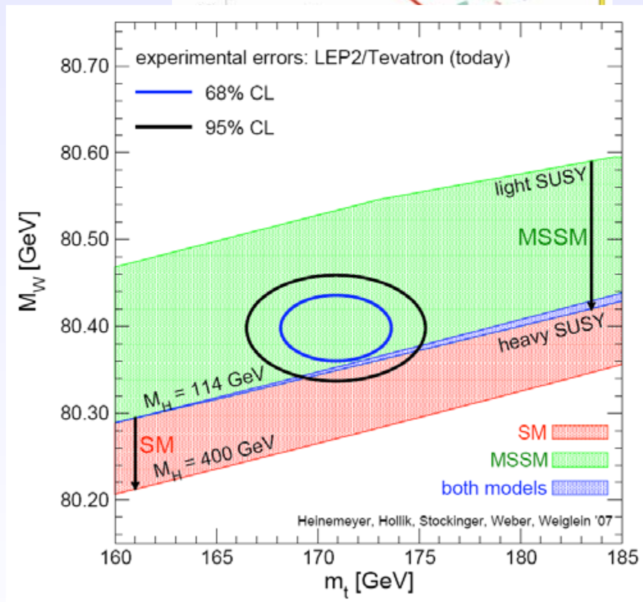
2. Unification of coupling constants of the three interactions seems possible

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

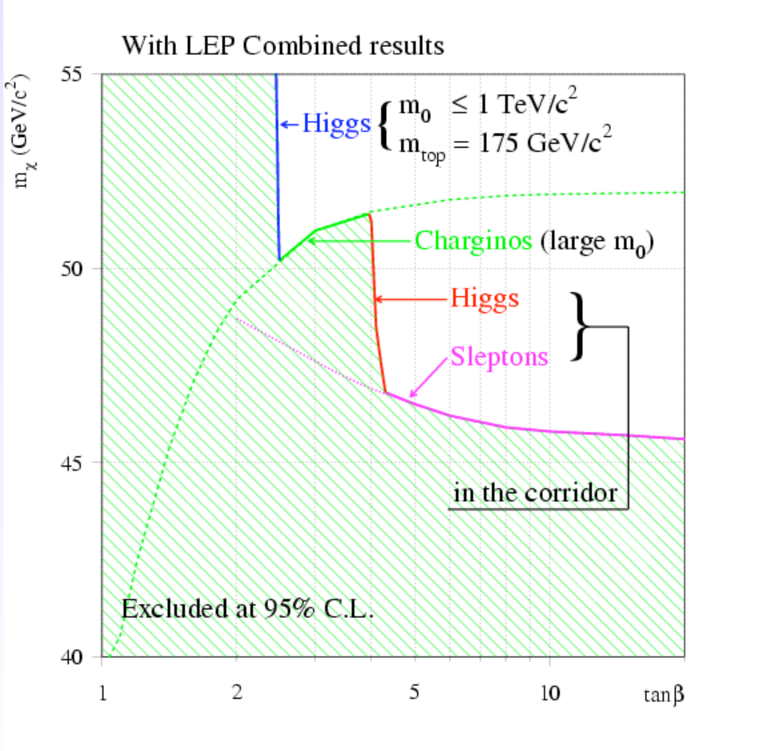
⬇

LHC should say “final word” about (low energy) 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

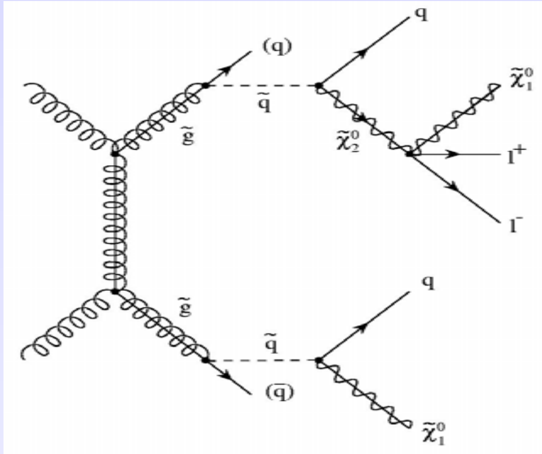
assumption:
lightest neutralino = LSP

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}

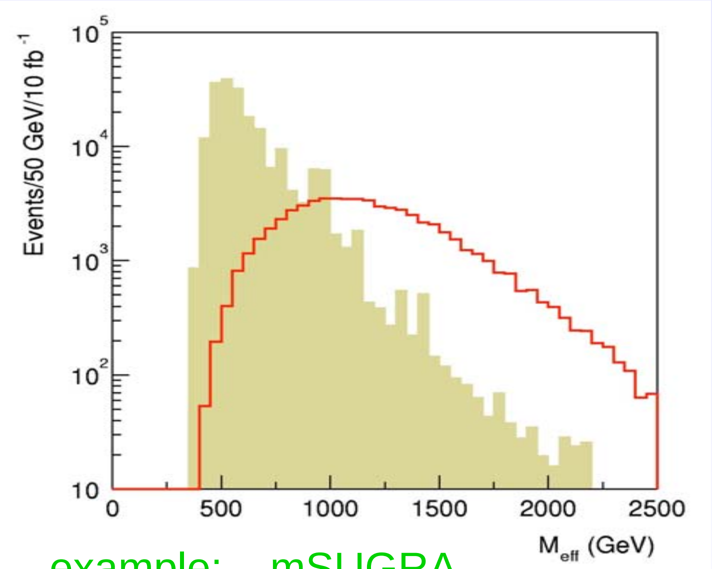
1. Step: Look for deviations from the Standard Model
   Example: Multijet + E_T^{miss} signature

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:

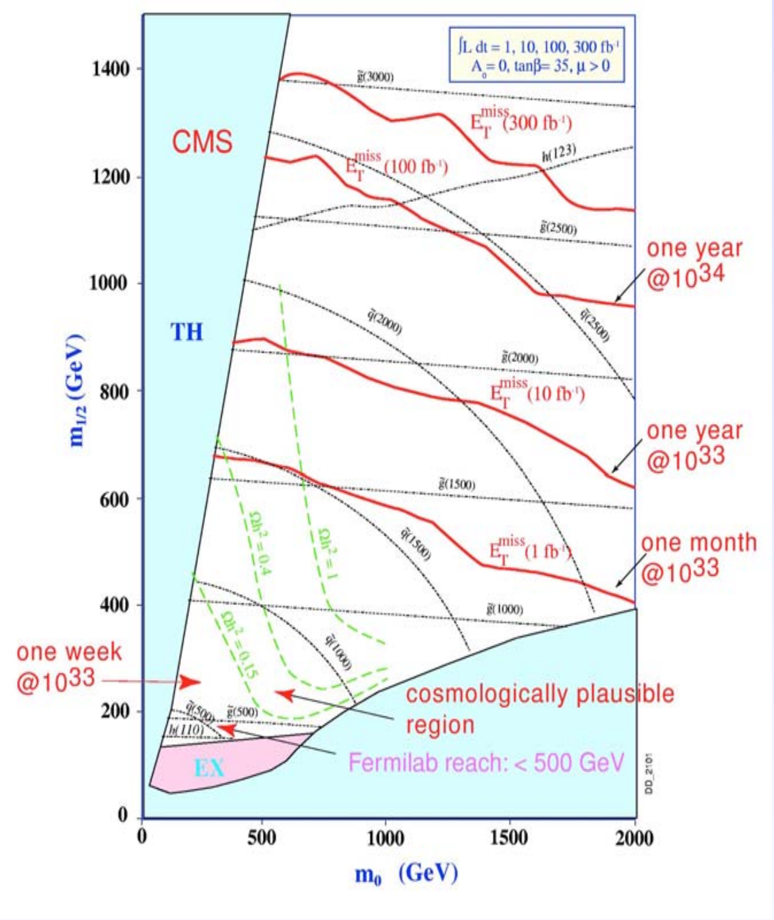
1 fb^{-1}	⇒	M ~ 1500 GeV
10 fb^{-1}	⇒	M ~ 1900 GeV
100 fb^{-1}	⇒	M ~ 2500 GeV

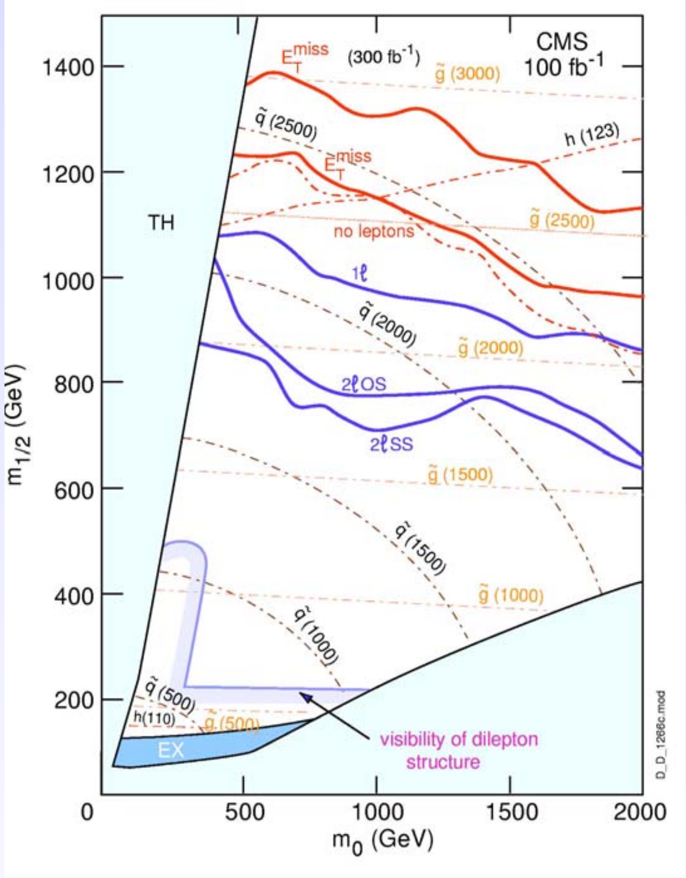
TeV-scale SUSY can be found quickly !

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**





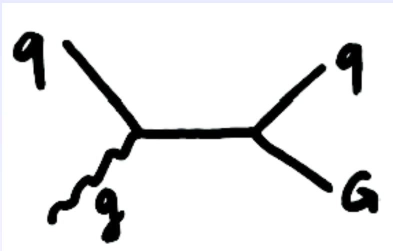
Expect multiple signatures for TeV-scale SUSY

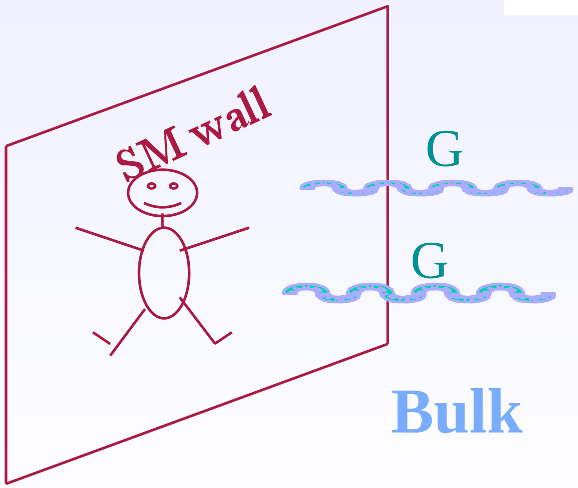
How can the underlying theoretical model be identified ?

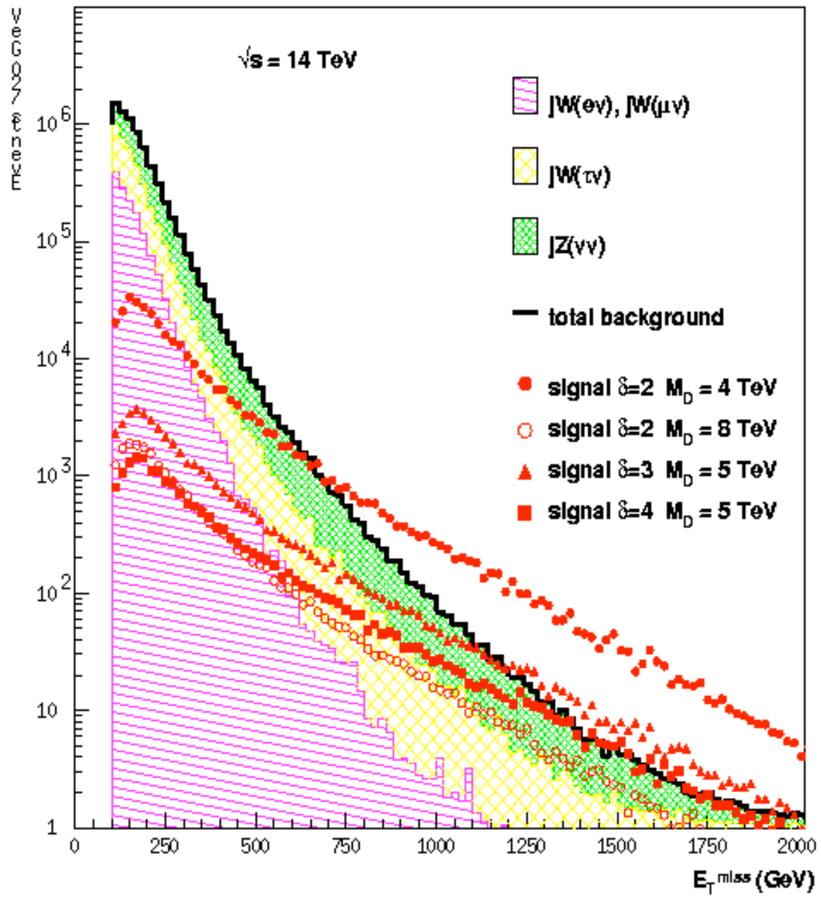
- Not easy !!
- Other possible scenarios for Physics Beyond the Standard Model could lead to similar final state signatures
  e.g. search for direct graviton production in extra dimension models

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

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

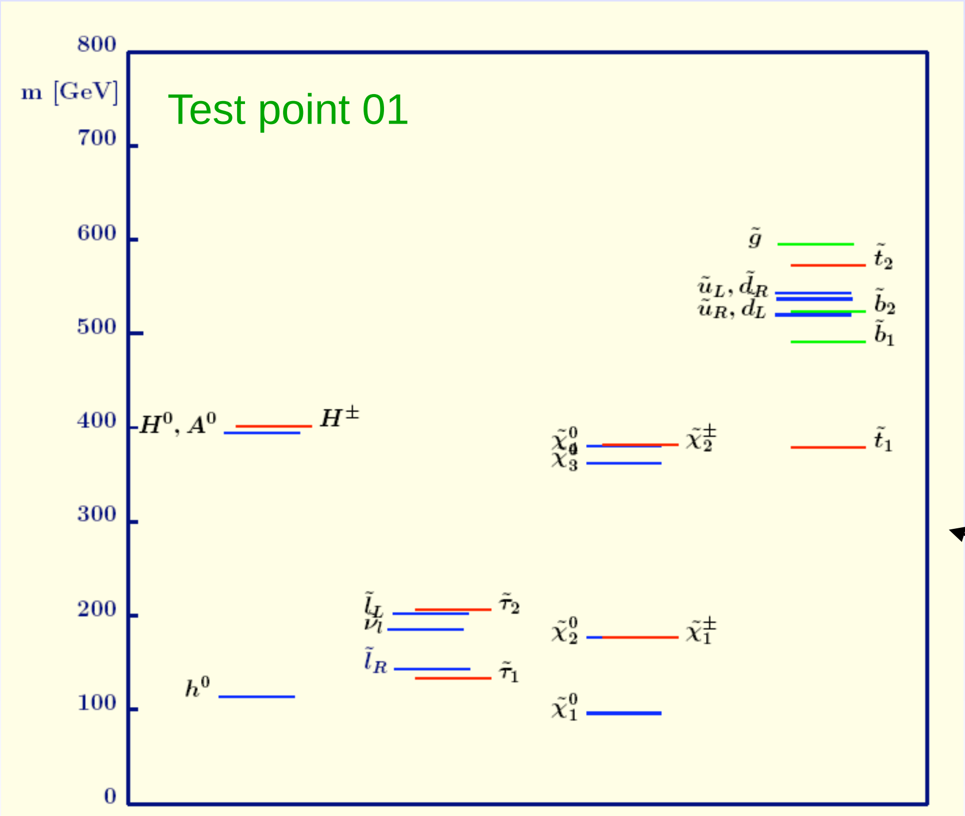


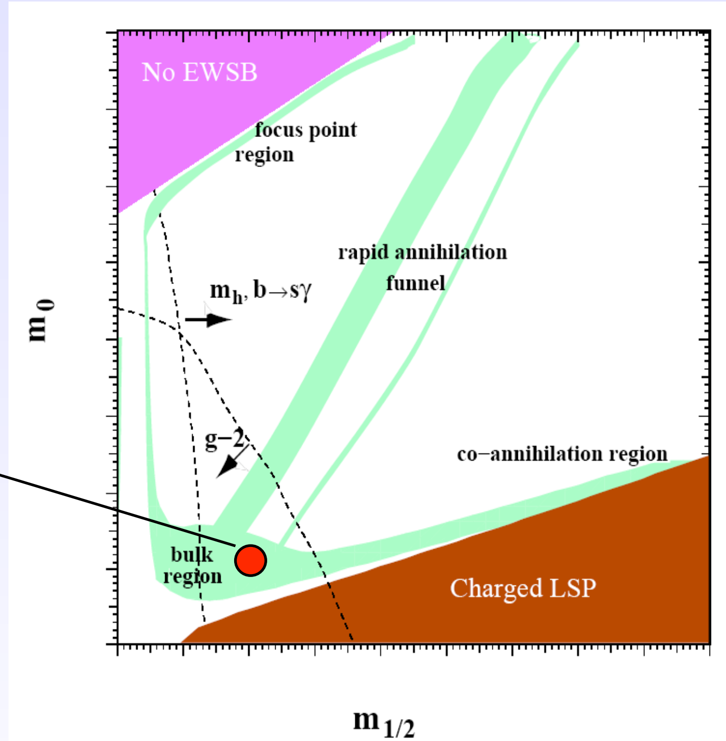




How can the underlying theoretical model be identified ?

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





LHC: strongly interacting squarks and gluinos

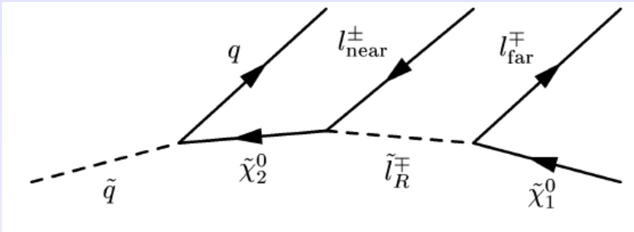
ILC : precise investigation of electroweak SUSY partners

LHC Strategy: End point spectra of cascade decays

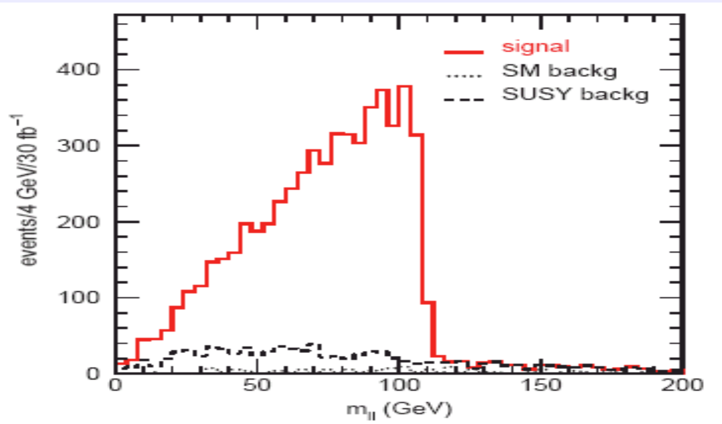
Example: $\tilde{q} \rightarrow q\tilde{\chi}_2^0 \rightarrow q\tilde{\ell}^{\pm}\ell^{\mp} \rightarrow q\ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$

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

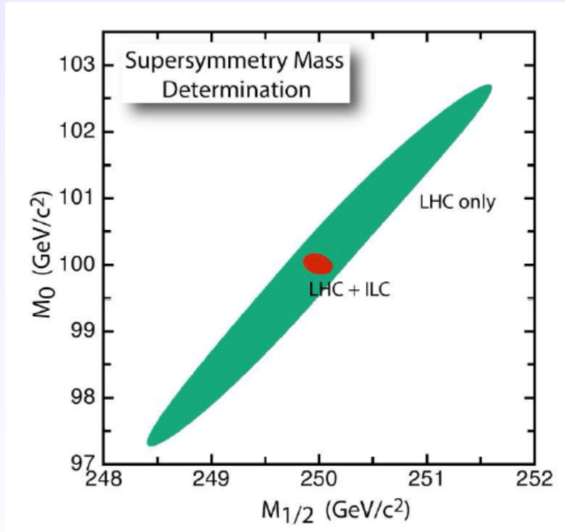
$$M_{\ell_1 q}^{max} = \frac{\sqrt{(m_{\chi_2^0}^2 - m_{\tilde{\ell}}^2)(m_{\tilde{q}}^2 - m_{\chi_2^0}^2)}}{m_{\chi_2^0}}$$



Results for point 01:



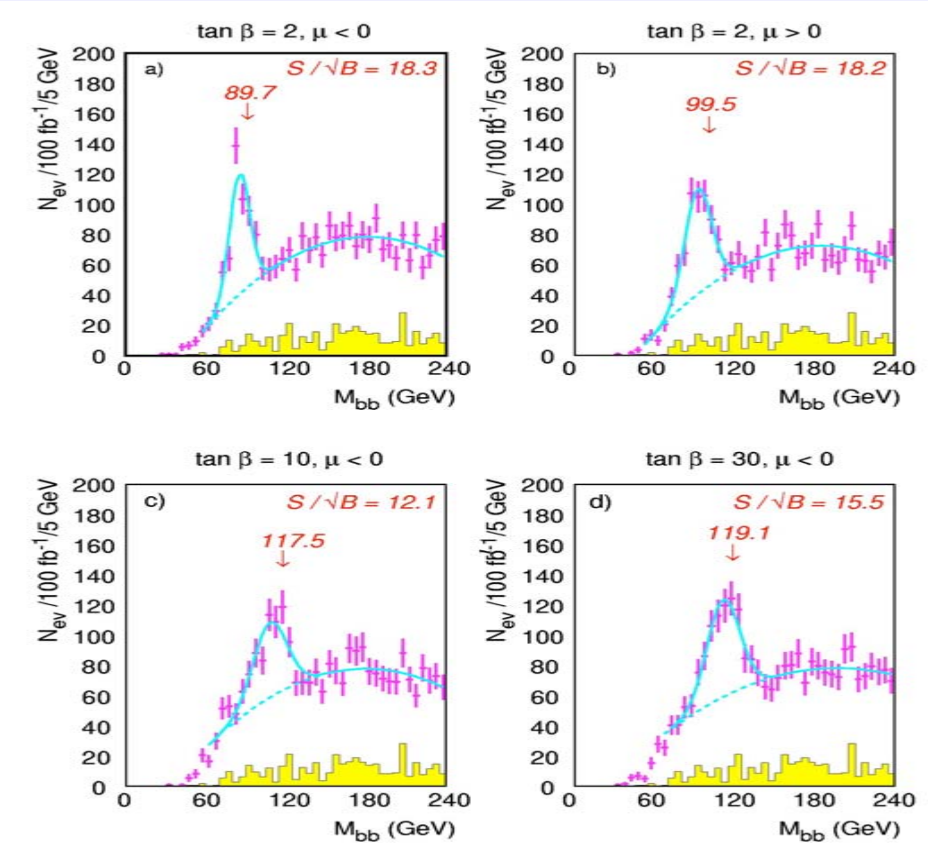
	LHC	LHC⊕ILC
$\Delta m_{\tilde{\chi}_1^0}$	4.8	0.05 (input)
$\Delta m_{\tilde{l}_R}$	4.8	0.05 (input)
$\Delta m_{\tilde{\chi}_2^0}$	4.7	0.08
$\Delta m_{\tilde{q}_L}$	8.7	4.9
$\Delta m_{\tilde{q}_R}$	11.8	10.9
$\Delta m_{\tilde{g}}$	8.0	6.4
$\Delta m_{\tilde{b}_1}$	7.5	5.7
$\Delta m_{\tilde{b}_2}$	7.9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

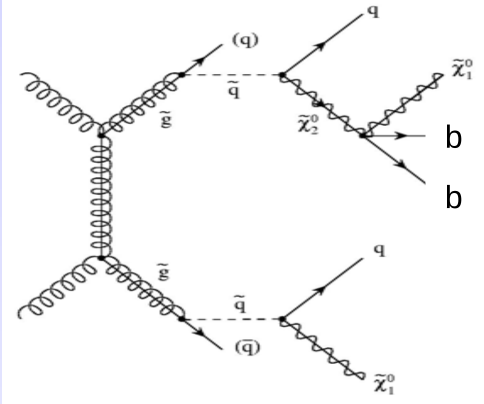


$L = 300\ fb^{-1}$

$h \rightarrow bb$:

CMS





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

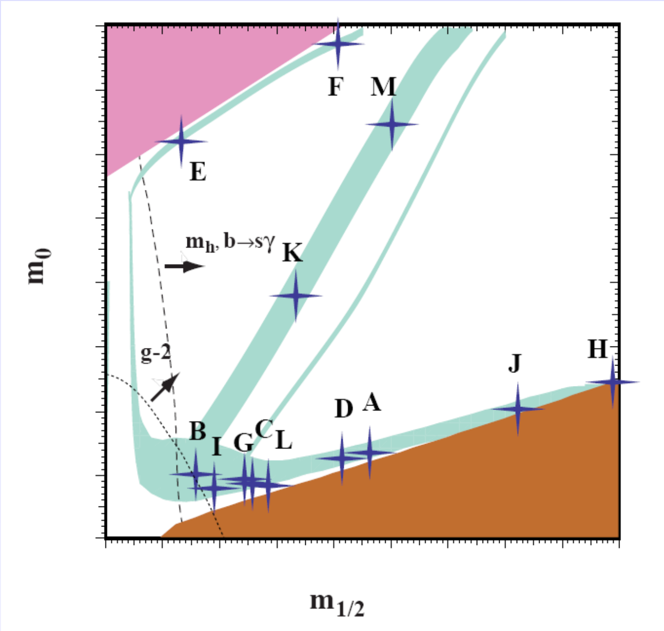
Could be a Higgs discovery mode !

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

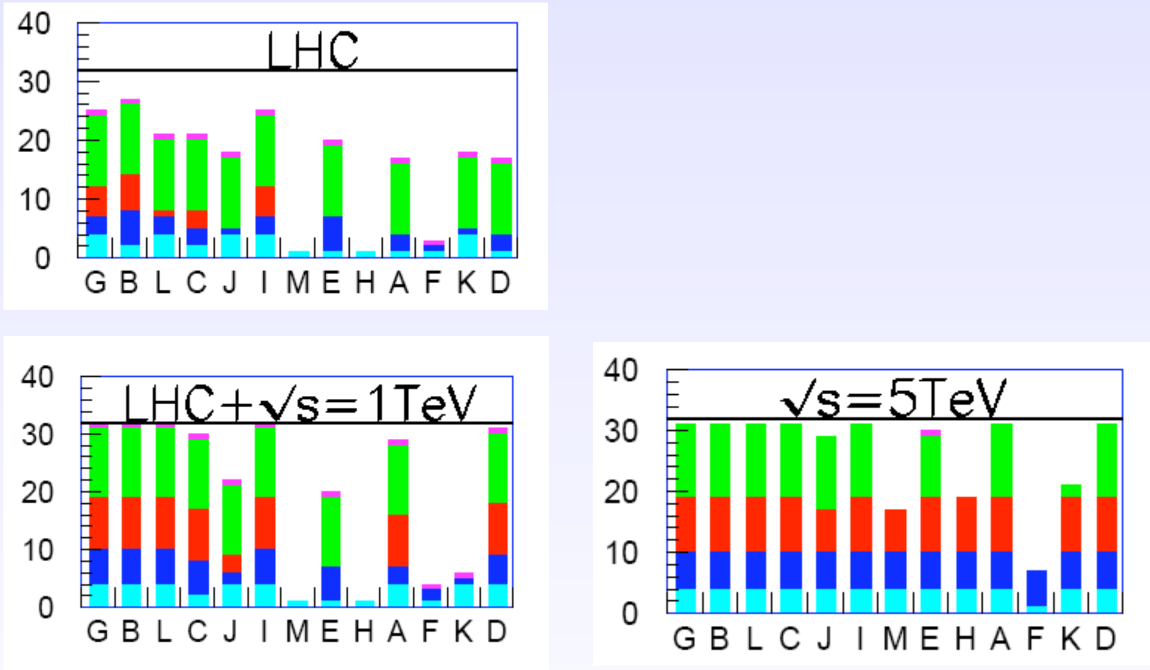
Strategy in SUSY Searches at the LHC:

- 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 $\rightarrow$ SUSY model parameters

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



Number of observable SUSY particles:

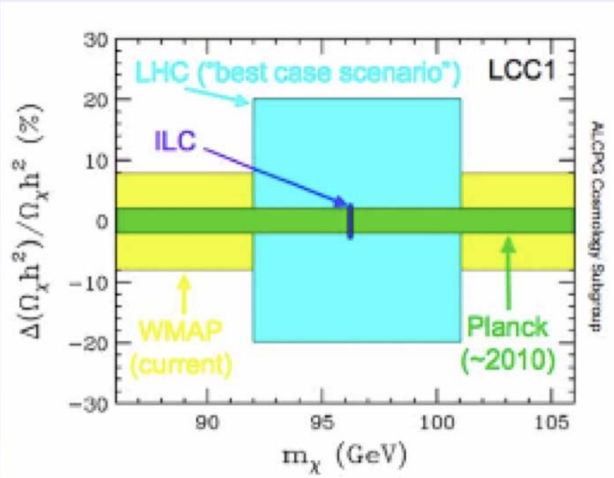


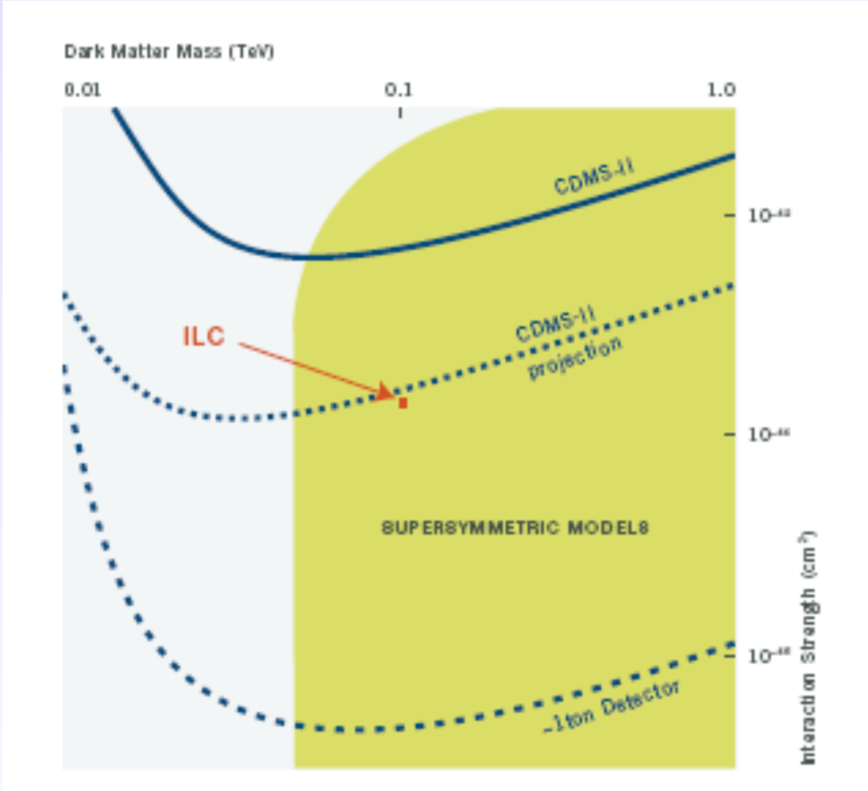
)* Study by J. Ellis et al., hep-ph/0202110

Dark Matter at Accelerators ?

Parameter of the SUSY-Model $\Longrightarrow$ Predictions for the relic density of Dark Matter

Importance for direct and indirect searches of Dark Matter



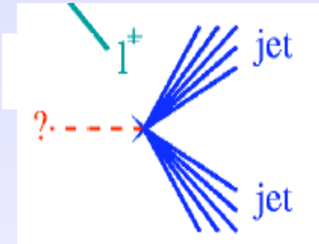


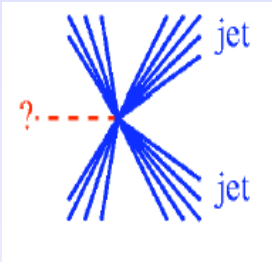
The Search for

SUSY at the Tevatron

The two classical signatures

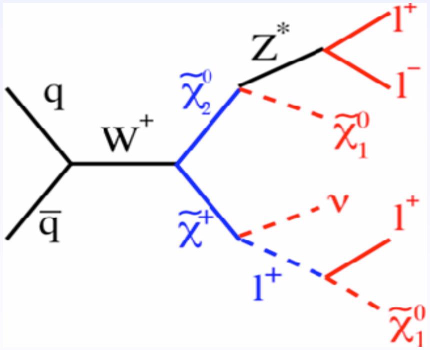
1. Search for Squarks and Gluinos: Jet + E_T^{miss} signature
   produced via QCD processes





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)

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

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

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

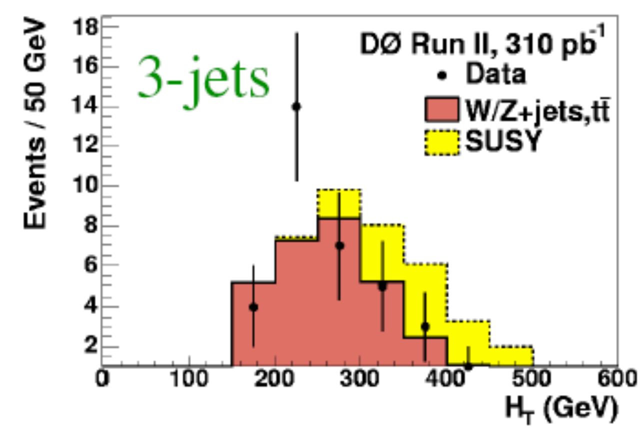
(iii) Gluino analysis
large m_0, m(squark) > m(gluino)

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

- Main backgrounds: $Z \to \nu\nu$ + 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:

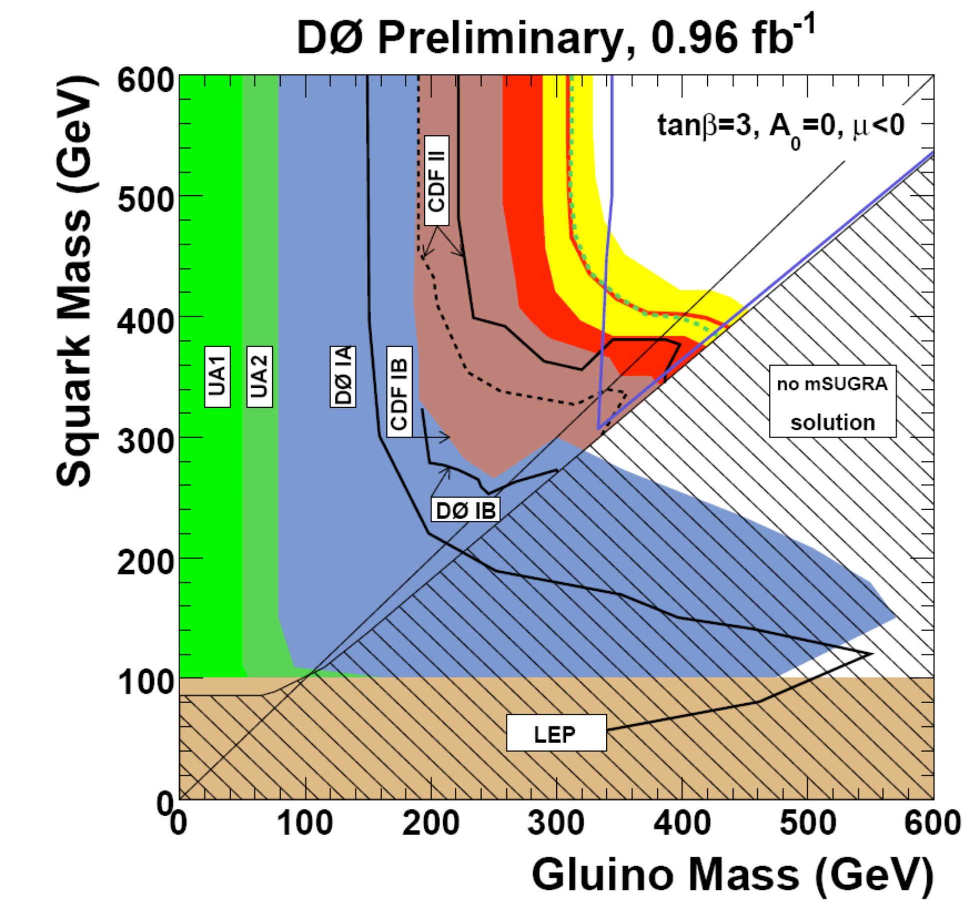
- $H_T = \Sigma \; E_T(\text{jets})$

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



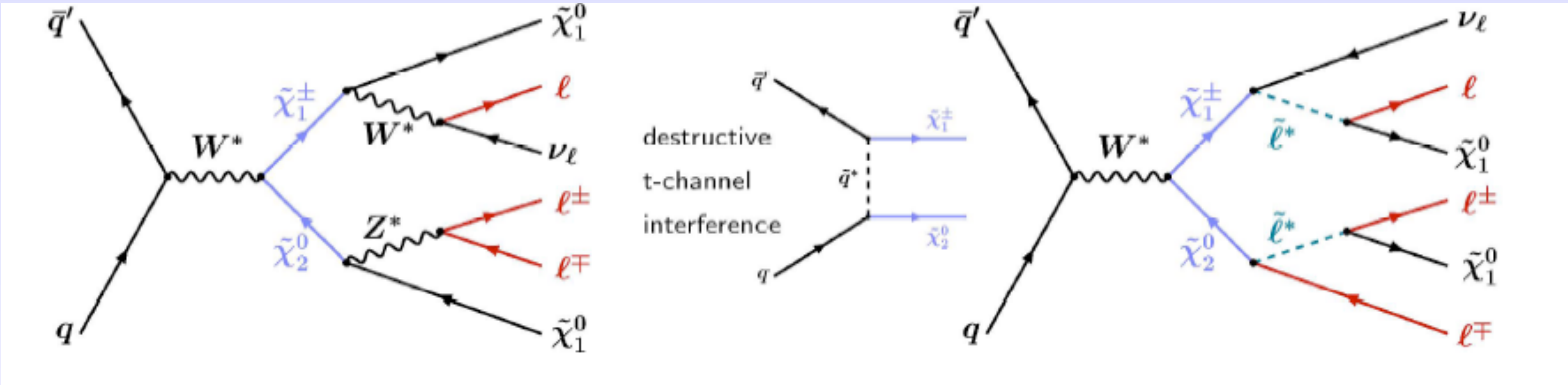
Exclusion limits
(incl. systematic uncertainties)*:

m(gluino) > 289 GeV/c^2
m(squark) > 375 GeV/c^2

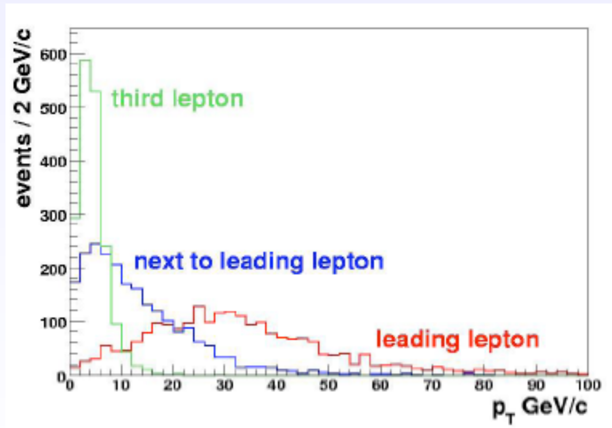
)* uncertainties from structure functions, change of renormalization and factorization scale μ by a factor of 2, NLO calculation, default choice: μ = m(gluino), m(squark) or ½(m(gluino)+m(squark)) for gg, qq, qg production

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

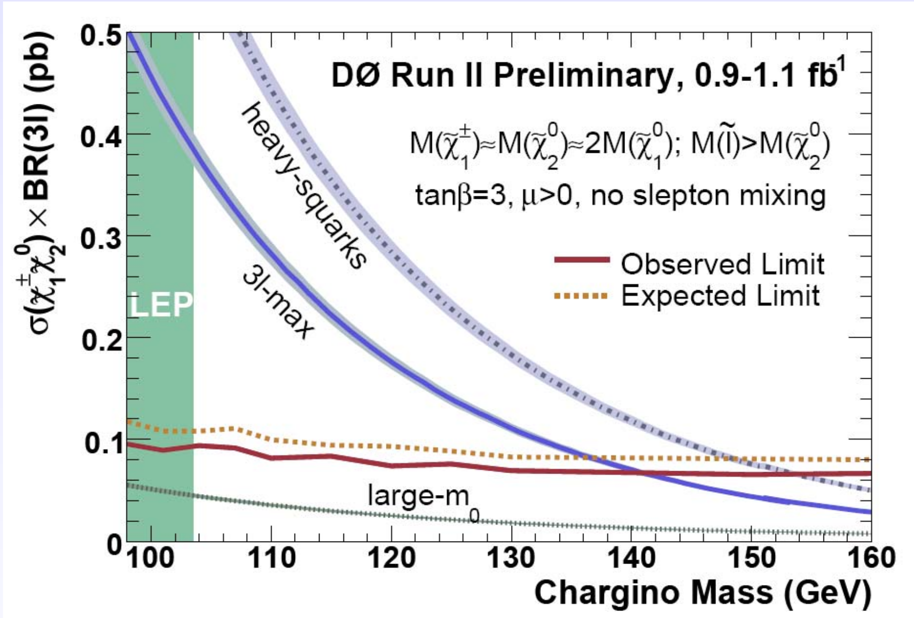


Analysis:

- Search for 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 identified 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

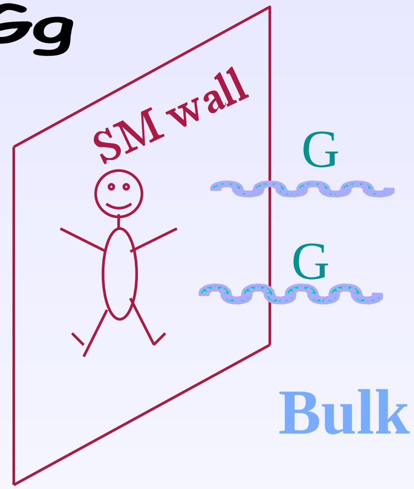
Can LHC probe extra dimensions ?

- 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**

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

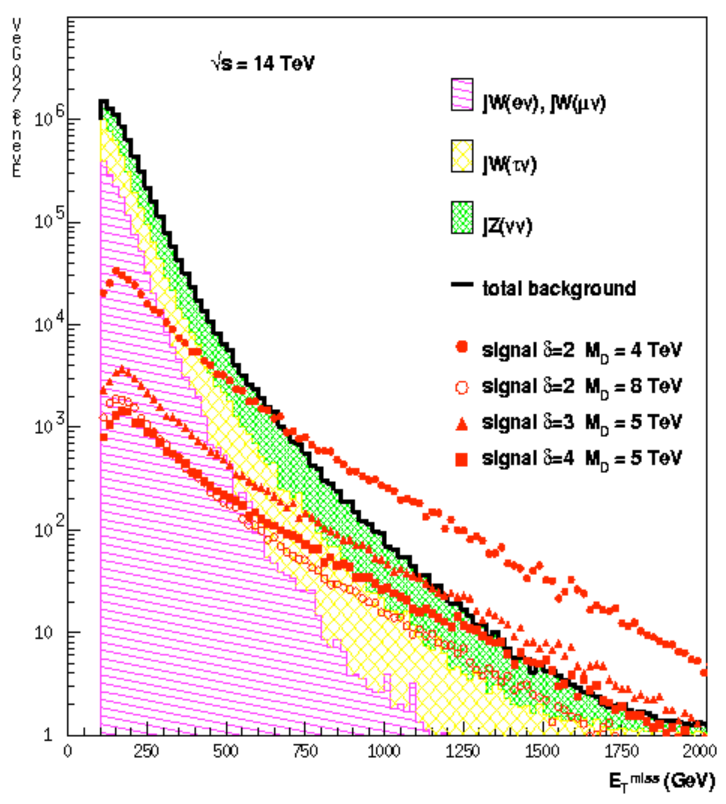
$$q\bar{q} \rightarrow G\gamma$$



$\Rightarrow$ **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

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

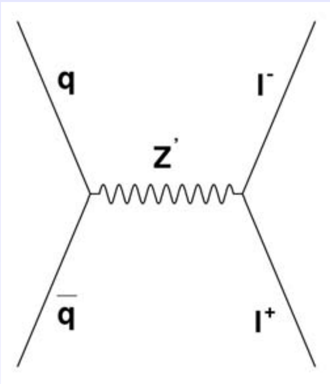
2. **What about Leptoquarks ?**

   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)

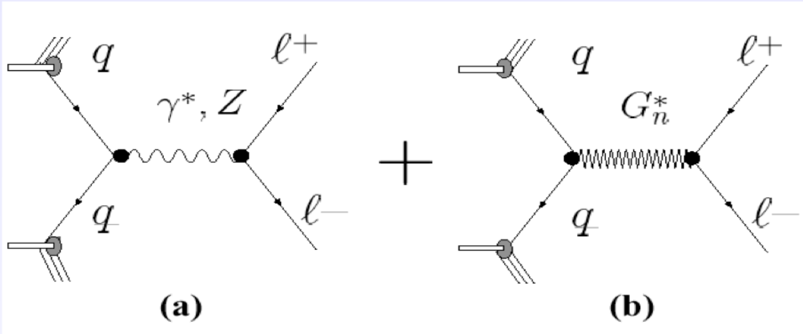
Fermilab Search for New Resonances in High Mass Di-leptons

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



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

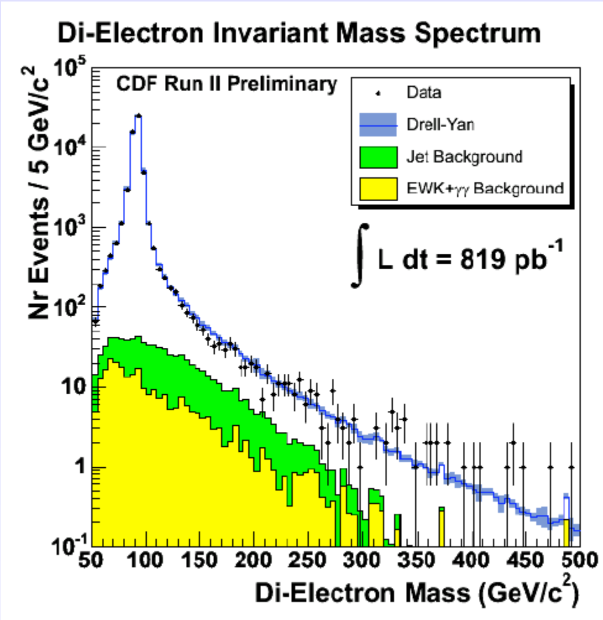
appear in Extra Dim. Scenarios



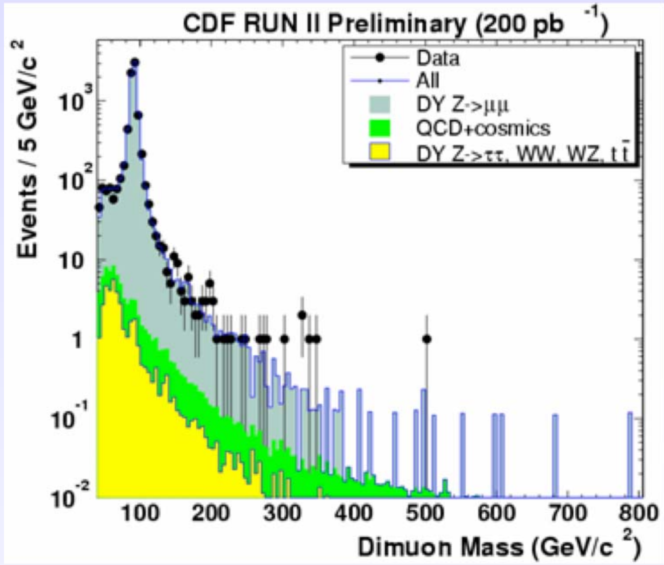
Main background from Drell-Yan pairs

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.

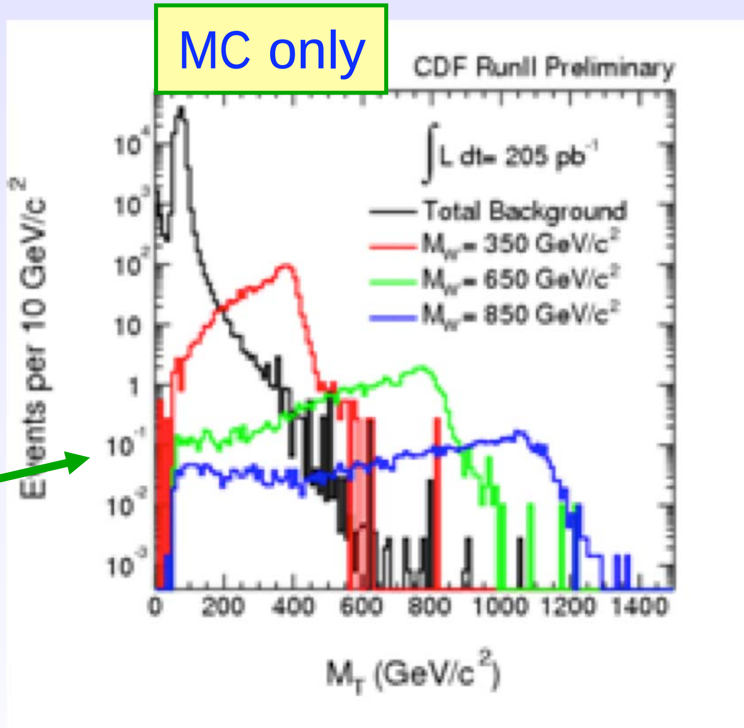
Z´ mass limits (SM couplings)		ee	μμ	ττ	
95% C.L.	CDF /D0:	850	835	394	GeV/c^2

Search for W’ → eν

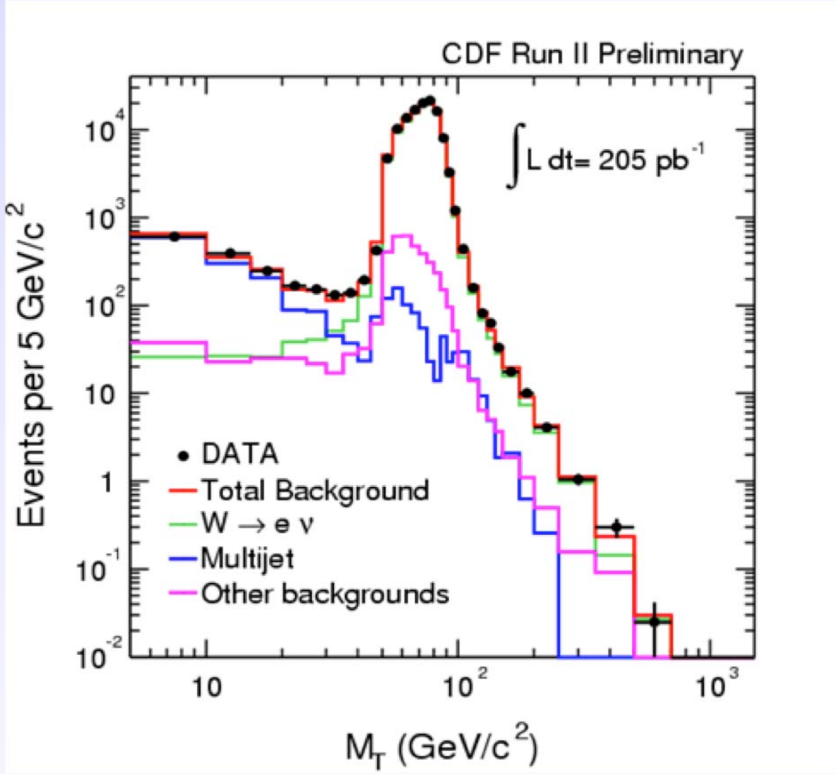
- W’: additional charged heavy vector boson
- appears in theories based on the extension of the gauge group
- e.g. Left-right symmetric models: $SU(2)_R$ W_R
- assume: the neutrino from W’ decay is light and stable.
- signature:

high p_T electron + high P_T^{miss}

→ peak in transverse mass distribution



Search for W' → eν



Data:

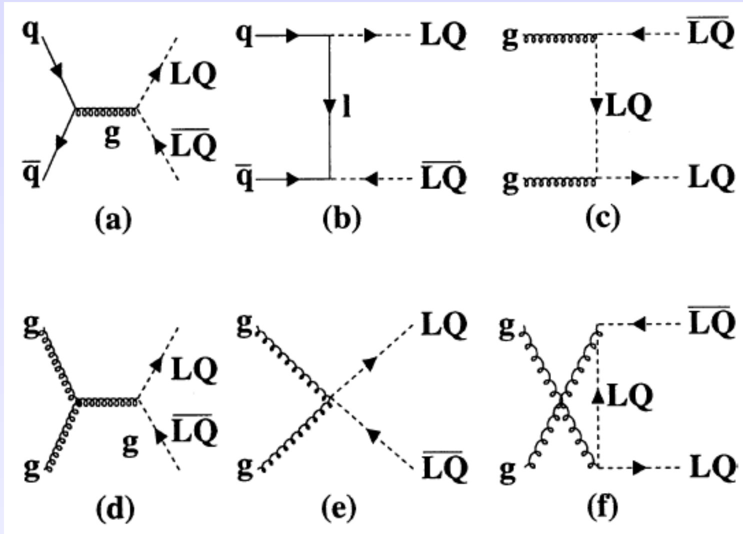
consistent with one well known W + background

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

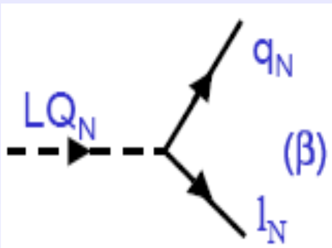
(assuming Standard Model couplings)

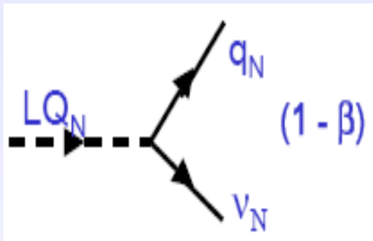
Search for Scalar Leptoquarks (LQ)

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



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





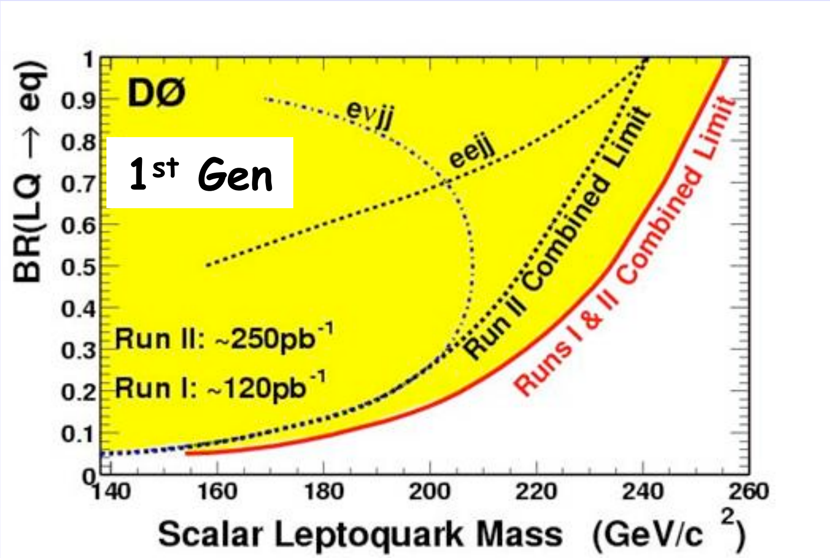
β= LQ branching fraction to charged lepton and quark
N = generation index
Leptoquarks of 1., 2., and 3. generation

Experimental Signatures:

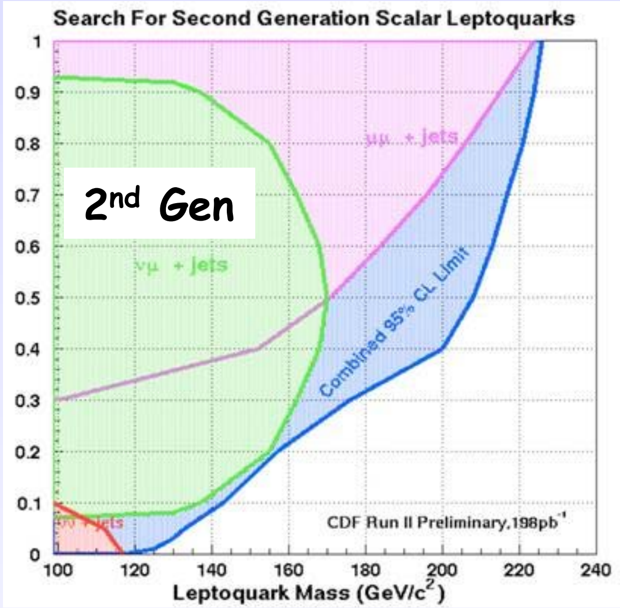
- two high p_T isolated leptons + jets .OR.
- one isolated lepton + P_T^{miss}+ jets .OR.
- P_T^{miss} + jets

1st, 2nd and 3rd generation Leptoquarks

channels: eejj, eν jj



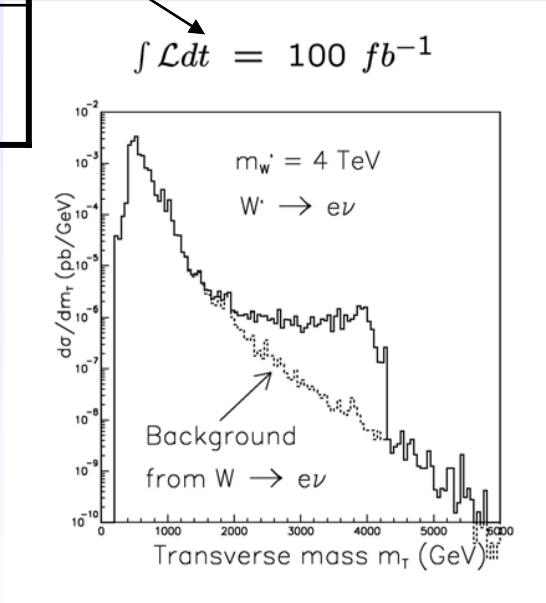
channels: μμjj, ενjj, ννjj



95% C.L. Mass Limits	1. Generation LQ	2. Generation LQ	3. Generation LQ
CDF (Run II) D0 (Run I + II)	235 GeV/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 $Q^* \to q\,\gamma$	M (q*) ~ 3.5 TeV	M (q*) ~ 6 TeV
Leptoquarks	M (LQ) ~ 1 TeV	M (LQ) ~ 1.5 TeV
$Z' \to \ell\ell$, jj $W' \to \ell\,\nu$	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



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