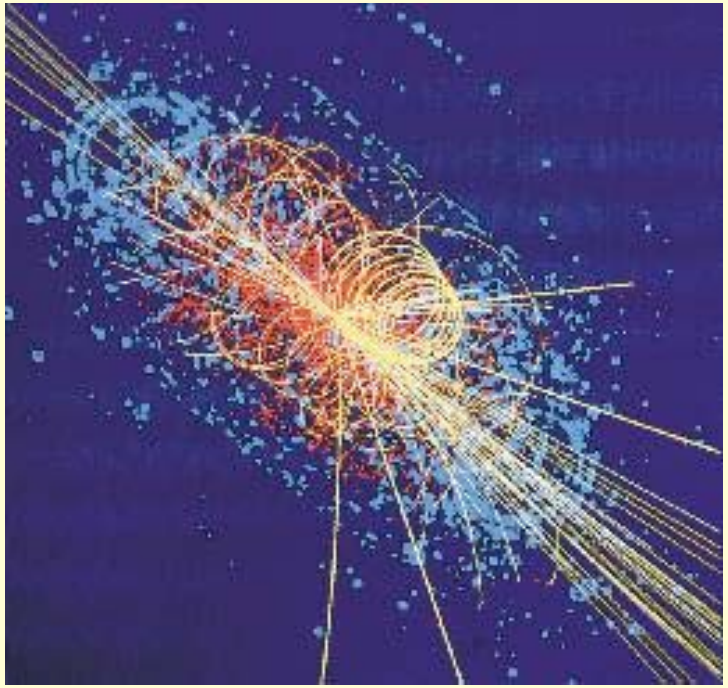
Physics at Hadron Colliders

Part 3



Higgs and Physics Beyond the Standard Model

- **Higgs Bosons at the LHC**
- **Supersymmetry**
  (Tevatron and LHC)
- **Other Extensions of the Standard Model**
  - Extra dimensions
  - Extra gauge bosons
  - Leptoquarks ….

The Search for

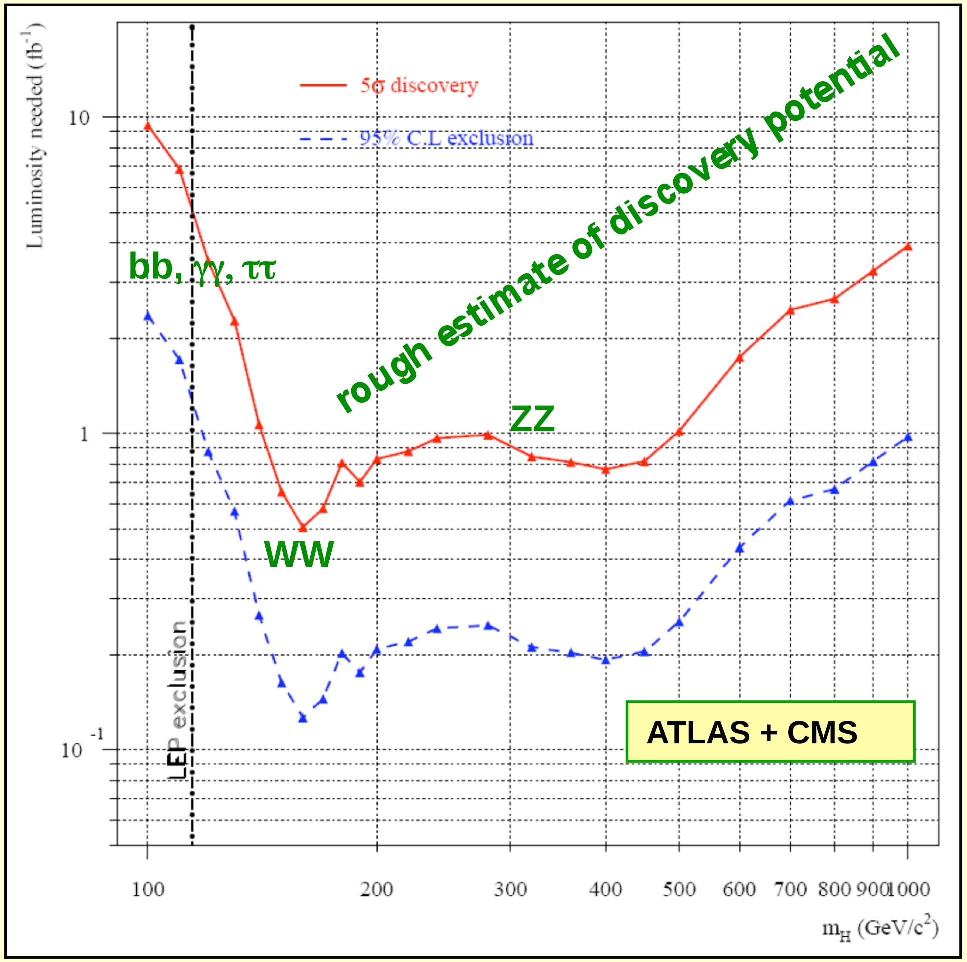
The Higgs boson at the LHC

In contrast to the TeVatron:

the first Higgs has already been seen at ATLAS

…. also the prospects for the discovery of the Higgs particle are good

- Luminosity required for a 5σ discovery or for a 95% CL limit – (< 2006 estimates)



J.J. Blaising, A. De Roeck, J. Ellis, F. Gianotti, P. Janot, G. Rolandi and D. Schlatter,
Eur. Strategy workshop (2006)

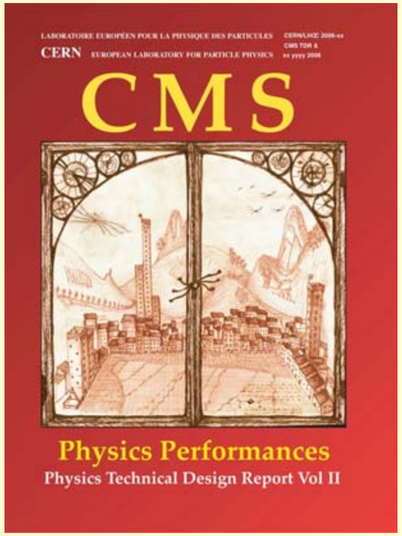
~ < 1 fb^{-1} needed to set a 95% CL limit in most of the mass range
(low mass ~ 115 GeV/c^2 more difficult)

comments:
- these curves are optimistic on the ttH, H→ bb performance
- systematic uncertainties assumed to be luminosity dependent (no simple scaling, σ ~ √L, possible)

What is new on LHC Higgs studies ?

• Many studies have meanwhile been performed using detailed GEANT simulations of the detectors

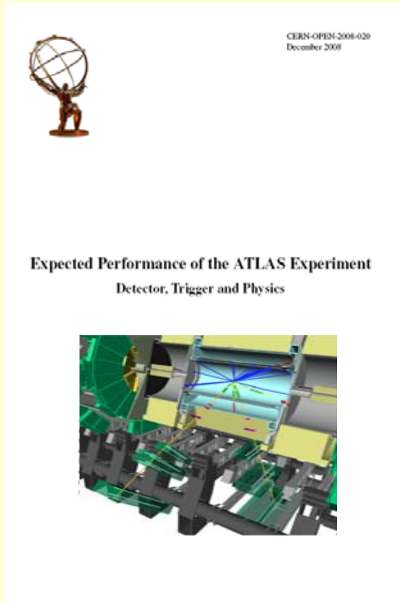
- Physics Performance Technical Design Report from the CMS collaboration
- ATLAS CSC book (Computing System Commissioning)



CMS: CERN / LHCC 2006-021
ATLAS: CERN-OPEN 2008-020

• New (N)NLO Monte Carlos (also for backgrounds)

- MCFM Monte Carlo, J. Campbell and K. Ellis, http://mcfm.fnal.gov
- MC@NLO Monte Carlo, S.Frixione and B. Webber, wwwweb.phy.cam.ar.uk/theory/
- T. Figy, C. Oleari and D. Zeppenfeld, Phys. Rev. D68, 073005 (2003)
- E.L.Berger and J. Campbell, Phys. Rev. D70, 073011 (2004)
- C. Anastasiou, K. Melnikov and F. Petriello, hep-ph/0409088 and hep-ph/0501130
- .....



• New approaches to match parton showers and matrix elements

- ALPGEN Monte Carlo + MLM matching, M. Mangano et al.
- SHERPA Monte Carlo, F. Krauss et al.
- ...

Tevatron data are extremely valuable for validation (see yesterday's lecture)

• More detailed, better understood reconstruction methods

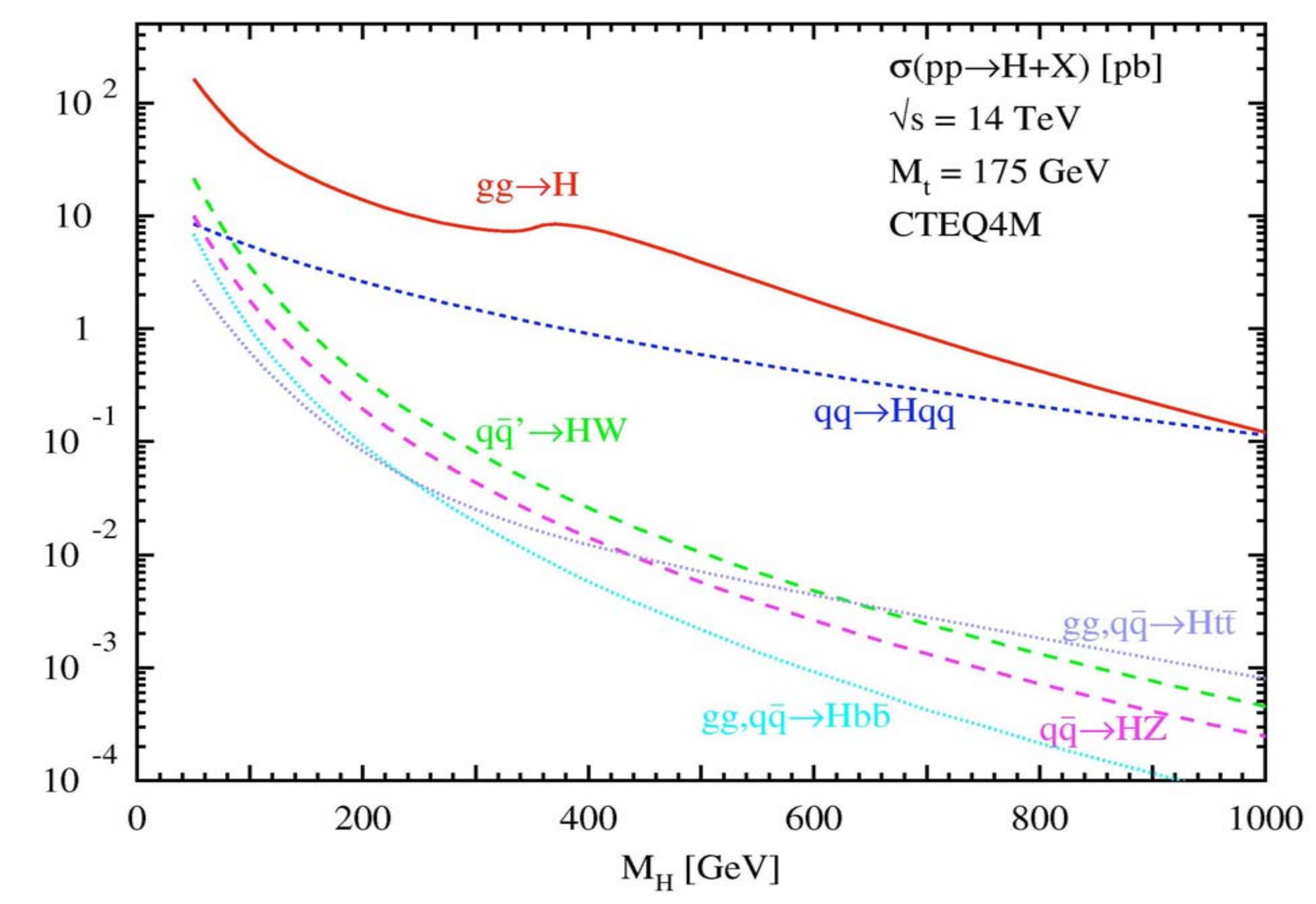
(partially based on test beam results,….)

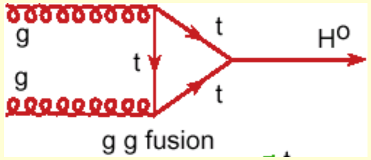
• Further studies of new Higgs boson scenarios

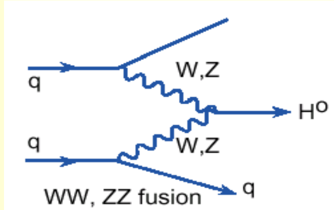
(Various MSSM benchmark scenarios, CP-violating scenarios, Invisible Higgs boson decays,…..)

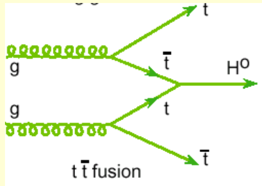
Standard Model
Higgs Boson Searches

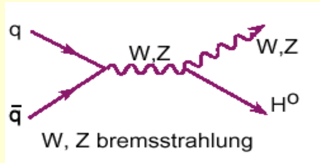
NLO cross sections, M.Spira et al.





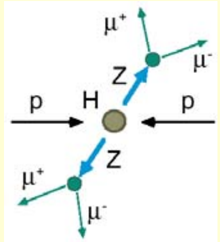






$H \rightarrow ZZ^{(*)} \rightarrow \ell\ell\ell\ell$

Signal: σ BR = 5.7 fb (m_H = 100 GeV)



$P_T(1,2) > 20$ GeV
$P_T(3,4) > 7$ GeV
$|\eta| < 2.5$
Isolated leptons

$M(\ell\ell) \sim M_Z$
$M(\ell'\ell') \sim < M_Z$

Background: Top production

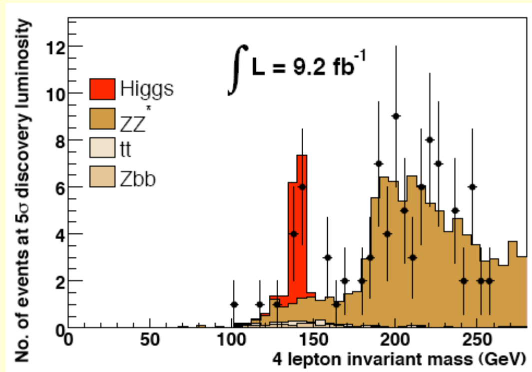
$tt \rightarrow Wb\,Wb \rightarrow \ell\nu\; c\ell\nu\; \ell\nu\; c\ell\nu$

σ BR ≈ 1300 fb

Associated production Z bb

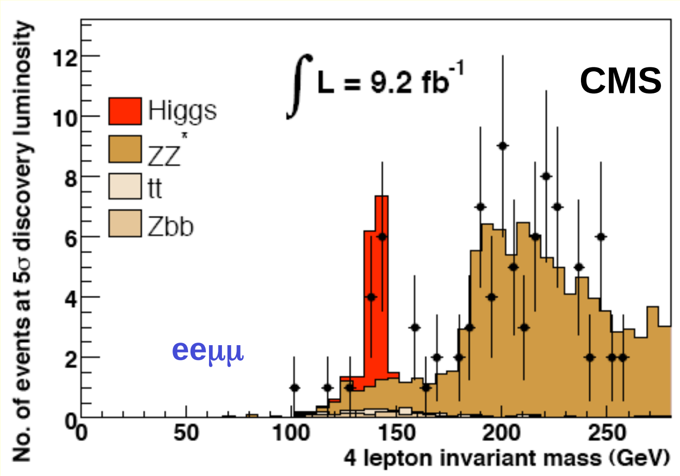
$Z\,bb \rightarrow \ell\ell\; c\ell\nu\; c\ell\nu$

Background rejection: Leptons from b-quark decays
→ non isolated
→ do not originate from primary vertex
(B-meson lifetime: ~ 1.5 ps)



Dominant background after isolation cuts: ZZ continuum

$H \rightarrow ZZ^* \rightarrow \ell\ell\ \ell\ell$

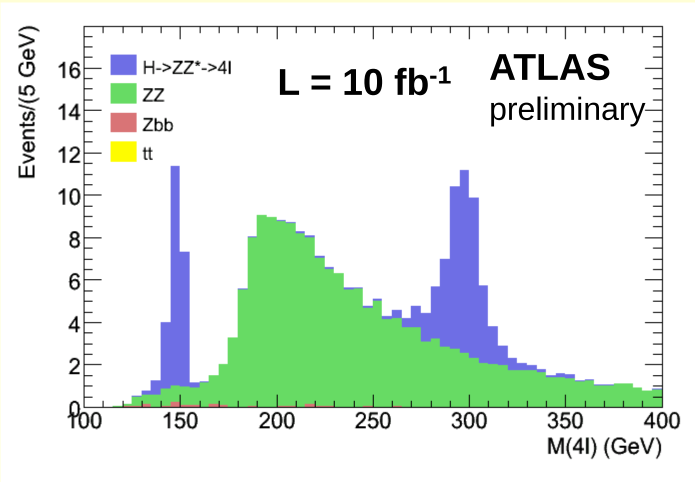


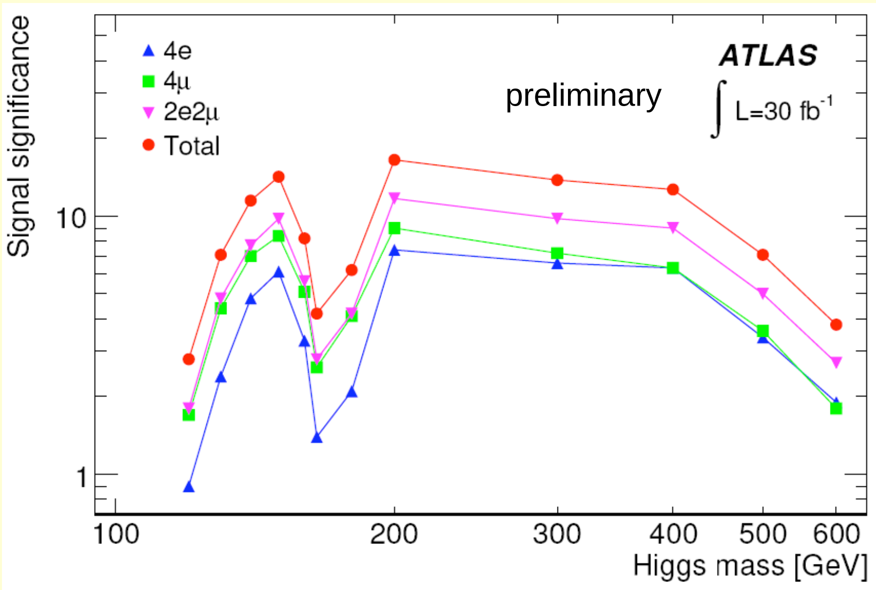
Main backgrounds: ZZ (irreducible),
tt, Zbb (reducible)

Updated ATLAS and CMS studies:

- ZZ background: NLO K factor used
- background from side bands

(gg->ZZ is added as 20% of the LO qq->ZZ)

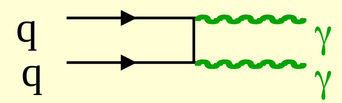




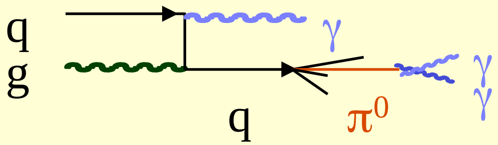
$H \rightarrow \gamma\gamma$

Main backgrounds:

$\gamma\gamma$ irreducible background



γ-jet and jet-jet (reducible)



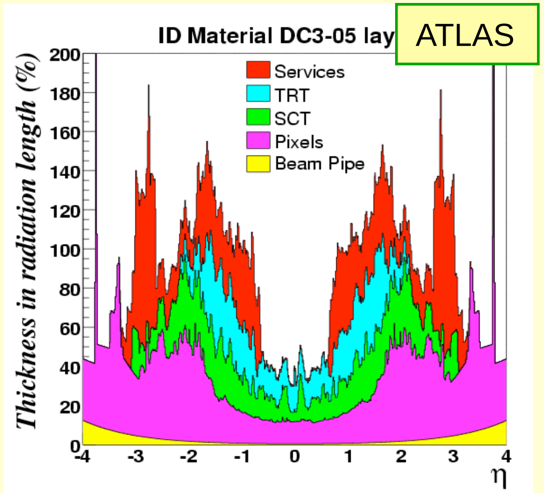
$\sigma_{\gamma j+jj} \sim 10^6\ \sigma_{\gamma\gamma}$ with large uncertainties

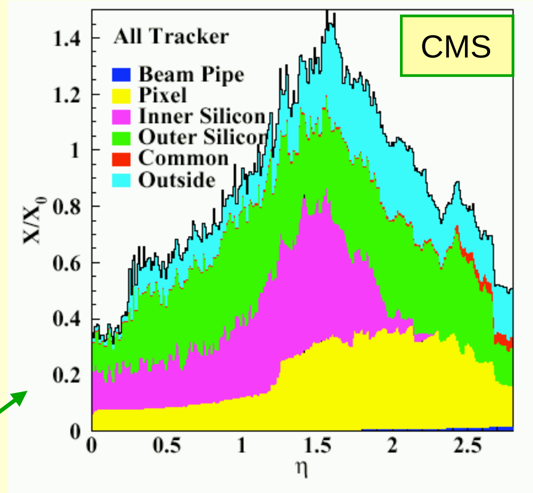
$\rightarrow$ need $R_j > 10^3$ for $\varepsilon_\gamma \approx 80\%$ to get

$\sigma_{\gamma j+jj} \ll \sigma_{\gamma\gamma}$

- Main exp. tools for background suppression:
  - photon identification
  - γ / jet separation (calorimeter + tracker)

  - note: also converted photons need to be reconstructed
    (large material in LHC silicon trackers)





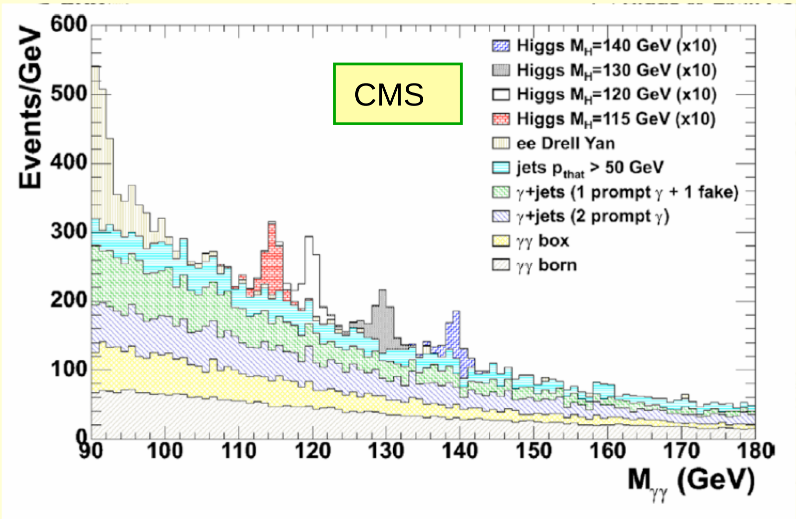
CMS: fraction of converted γs

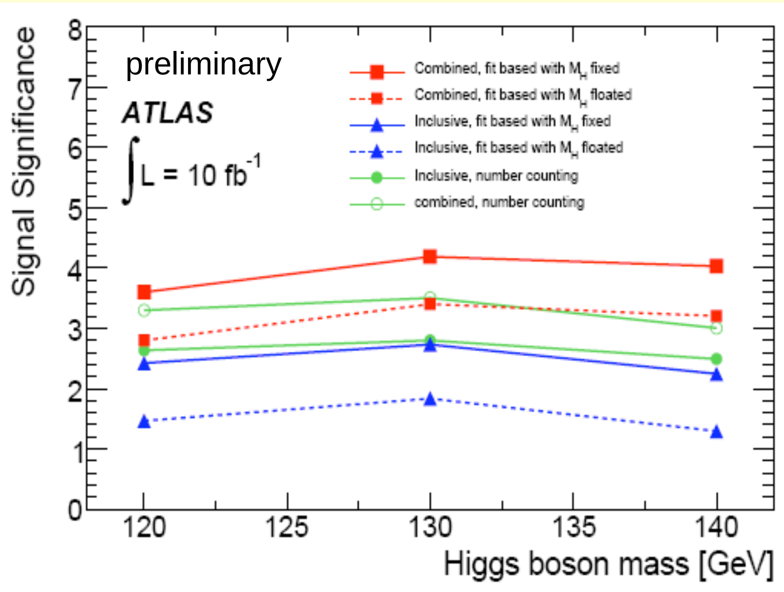
Barrel region: 42.0 %

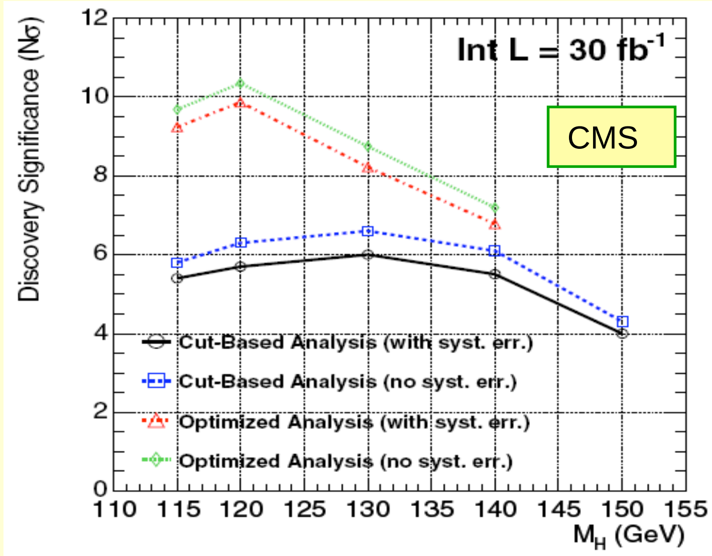
Endcap region: 59.5 %

New elements of the analyses:

- NLO calculations available
  (Binoth et al., DIPHOX, RESBOS)
- Realistic detector material
- More realistic K factors (for signal and background)
- Split signal sample acc. to resolution functions







- Comparable results for ATLAS and CMS
- Improvements possible by using more exclusive $\gamma\gamma$ + jet topologies

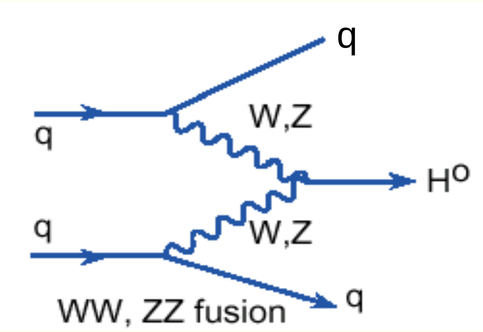
Vector Boson Fusion qq H

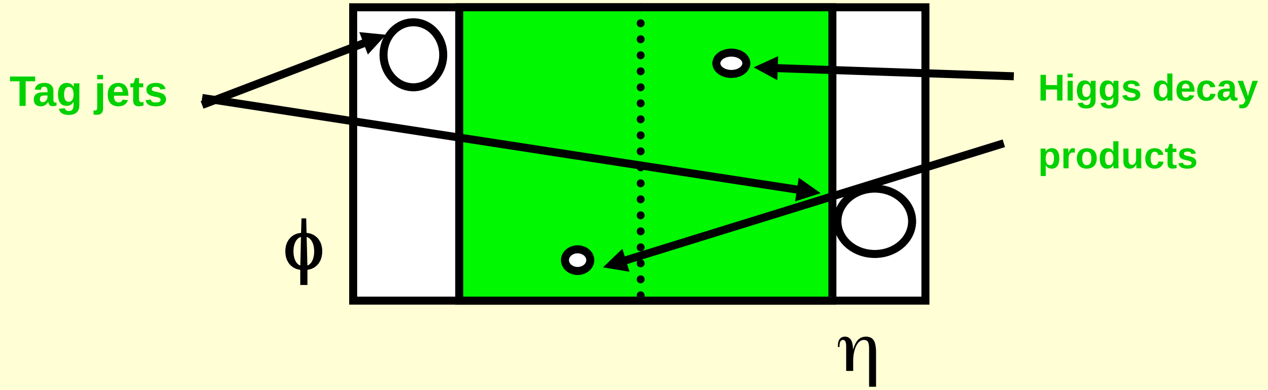
Motivation: Increase discovery potential at low mass
Improve and extend measurement of Higgs boson parameters
(couplings to bosons, fermions)

Established (low mass region) by D. Zeppenfeld et al. (1997/98)
Earlier studies: R.Kleiss W.J.Stirling, Phys. Lett. 200 (1988) 193;
Dokshitzer, Khoze, Troyan, Sov.J. Nucl. Phys. 46 (1987) 712;
Dokshitzer, Khoze, Sjöstrand, Phys.Lett., B274 (1992) 116.

Distinctive Signature of:

- two high p_T forward jets (tag jets)
- little jet activity in the central region (no colour flow)
  $\Rightarrow$ central jet Veto

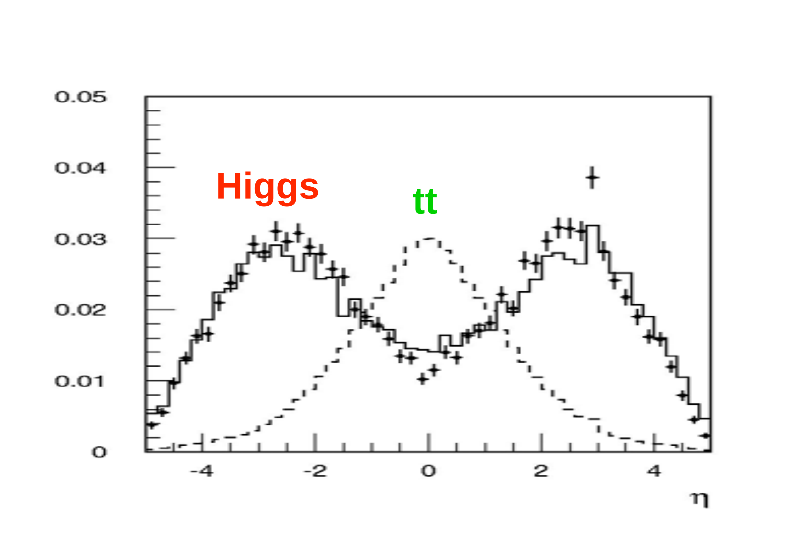




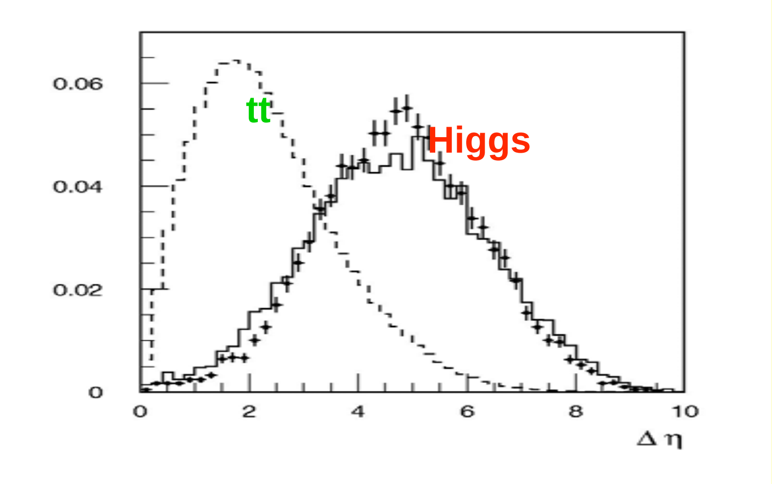
Forward jet tagging

Rapidity distribution of tag jets

VBF Higgs events vs. tt-background



Rapidity separation

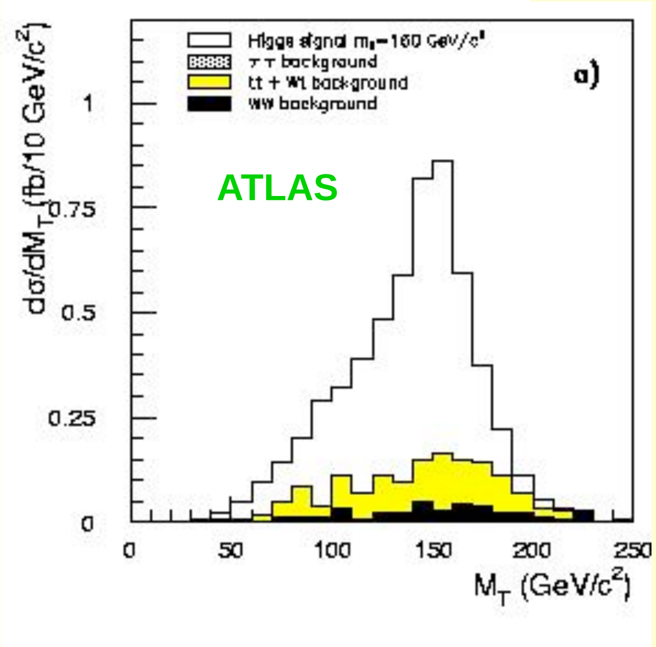


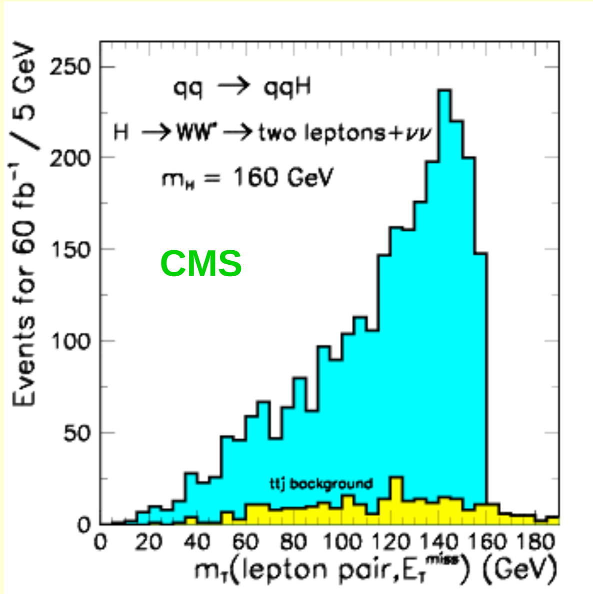
qq H → qq W W*
→ qq ℓν ℓν

Selection criteria:

- Lepton P_T cuts and
- Tag jet requirements ($\Delta\eta$, P_T, large mass)
- Jet veto (important)
- Lepton angular and mass cuts

$$M_T = \sqrt{(E_T^{ll} + E_T^{\nu\nu})^2 - (\vec{p}_T^{\,e\mu} + \vec{p}_T^{\,miss})^2}$$



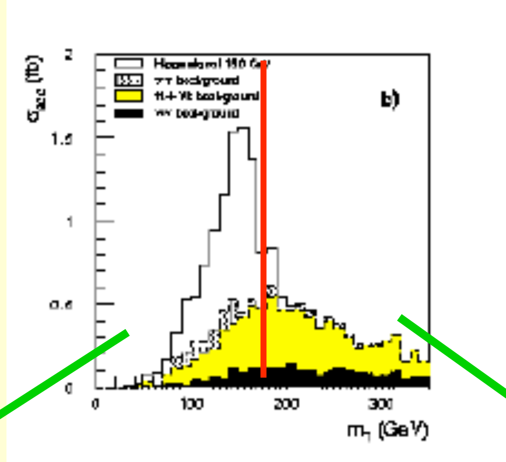


Transverse mass distributions: clear excess of events above the background from tt-production

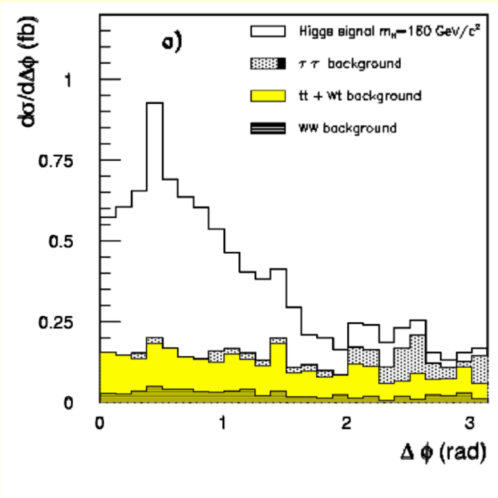
Presence of a signal can also be demonstrated in the Δ ϕ distribution
(i.e. azimuthal difference between the two leptons)

Evidence for spin-0 of the Higgs boson

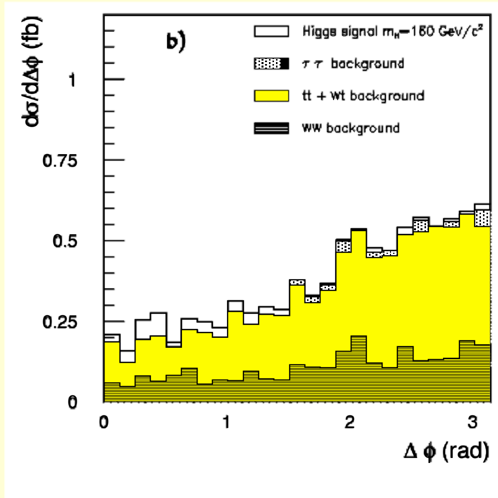
Spin-0 → WW → ℓνℓν expect leptons to be close by in space



relaxed cuts on the leptons
(angular cuts not applied)



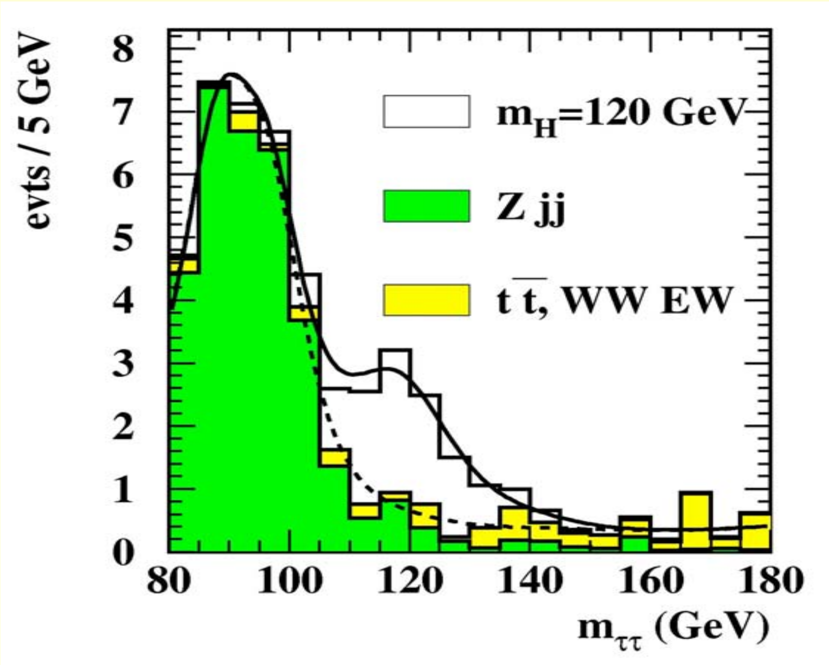
signal region



background region

$H \to \tau\tau$ decay modes visible for a SM Higgs boson in vector boson fusion

$qq\,H \to qq\,\tau\tau$
$\to qq\ \ell\nu\nu\ \ell\nu\nu$
$\to qq\ \ell\nu\nu\ h\nu$



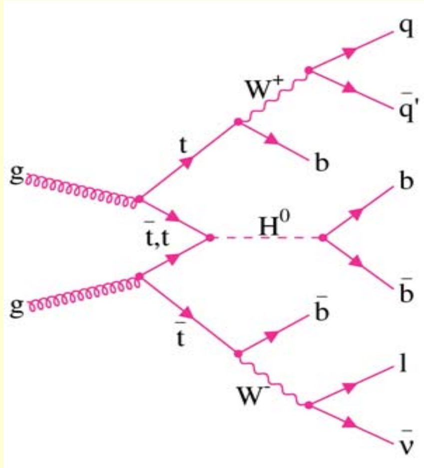
<u>Experimental challenge</u>:

- Identification of hadronic taus
- Good E_T^{miss} resolution
  ($\tau\tau$ mass reconstruction in collinear approximation,
  i.e. assume that the neutrinos go in the direction of the visible decay products,
  good approximation for highly boosted taus)

  → Higgs mass can be reconstructed
- Dominant background: $Z \to \tau\tau$

  the shape of this background must be controlled the high mass region
  → use data ($Z \to \mu\mu$) to constrain it

$t\bar{t}H \rightarrow t\bar{t}b\bar{b}$

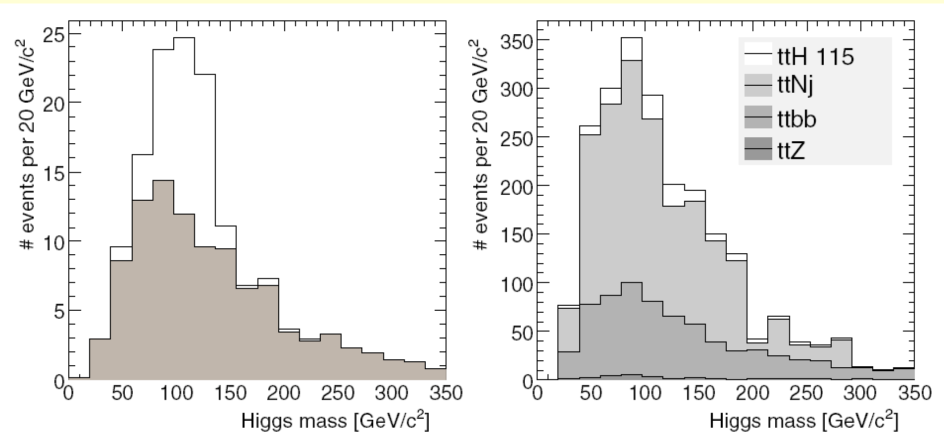


Complex final states: H→ bb, t → bjj, t → bℓν
t → bℓν, t → bℓν
t → bjj, t → bjj

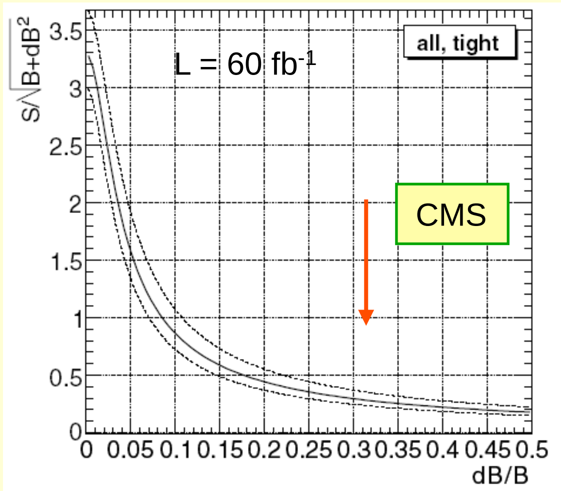
Main backgrounds:
- combinatorial background from signal (4b in final state)
- ttjj, ttbb, ttZ,…
- Wjjjjj, WWbbjj, etc. (excellent b-tag performance required)

• Updated CMS study (2006): ALPGEN matrix element calculations for backgrounds
→ larger backgrounds (ttjj dominant), experimental + theoretical uncertainties, e.g. ttbb, exp. norm. difficult…..

M (bb) after final cuts, 60 fb^{-1}



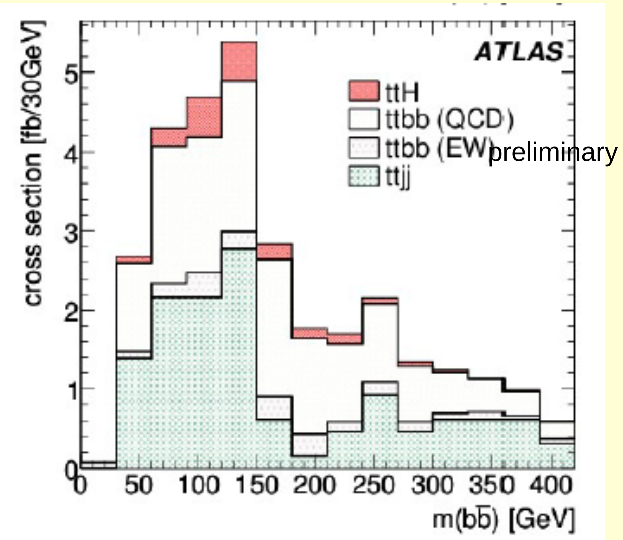
Signal events only …. backgrounds added

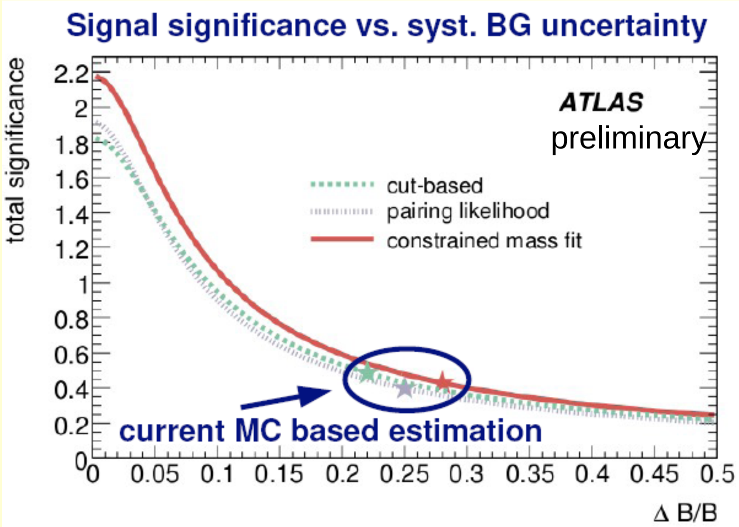


Signal significance as function of background uncertainty

…..comparable situation in ATLAS   (ttH cont.)

Preselection cut	$t\bar{t}H$ (fb)	$t\bar{t}b\bar{b}$(EW) (fb)	$t\bar{t}b\bar{b}$(QCD) (fb)	$t\bar{t}X$ (fb)
lepton cuts (ID + p_T)	$57. \pm 0.2$	141 ± 1.0	1356 ± 6	63710 ± 99
+ $\geq$ 6 jets	36 ± 0.2	77 ± 0.9	665 ± 4	26214 ± 64
+ $\geq$ 4 loose b-tags	16.2 ± 0.2	23 ± 0.7	198 ± 3	2589 ± 25
+ $\geq$ 4 tight b-tags	3.8 ± 0.06	4.2 ± 0.2	30 ± 0.8	51 ± 2
	LO	LO	LO	NLO





estimated uncertainty on the background: ± 25% (theory, + exp (b-tagging))

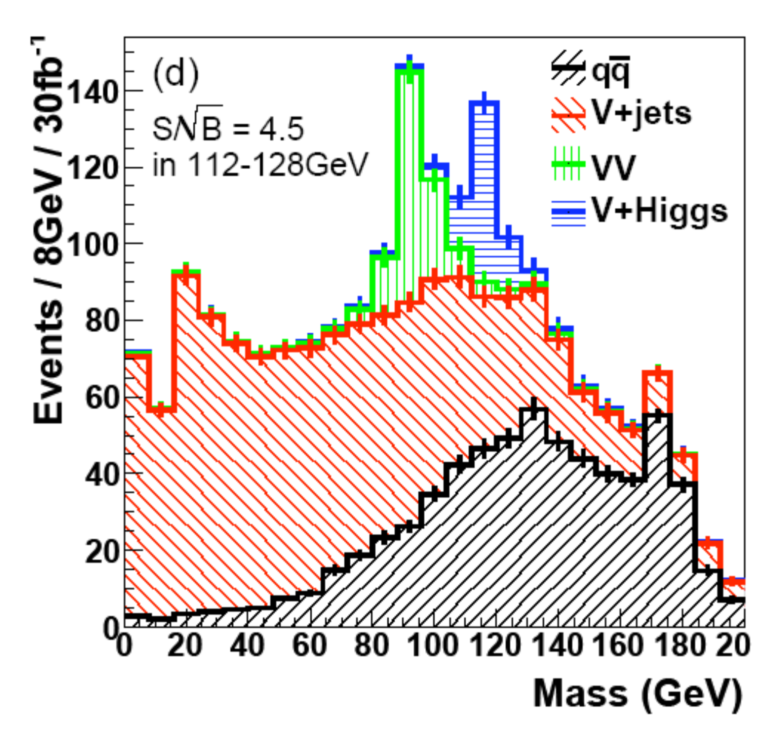
⇒ Normalization from data needed to reduce this (non trivial,…)

… new hope: exploit highly boosted WH and ZH, $H \rightarrow bb$ events

New idea: J. Butterworth et al., PRL 100 (2008) 242001

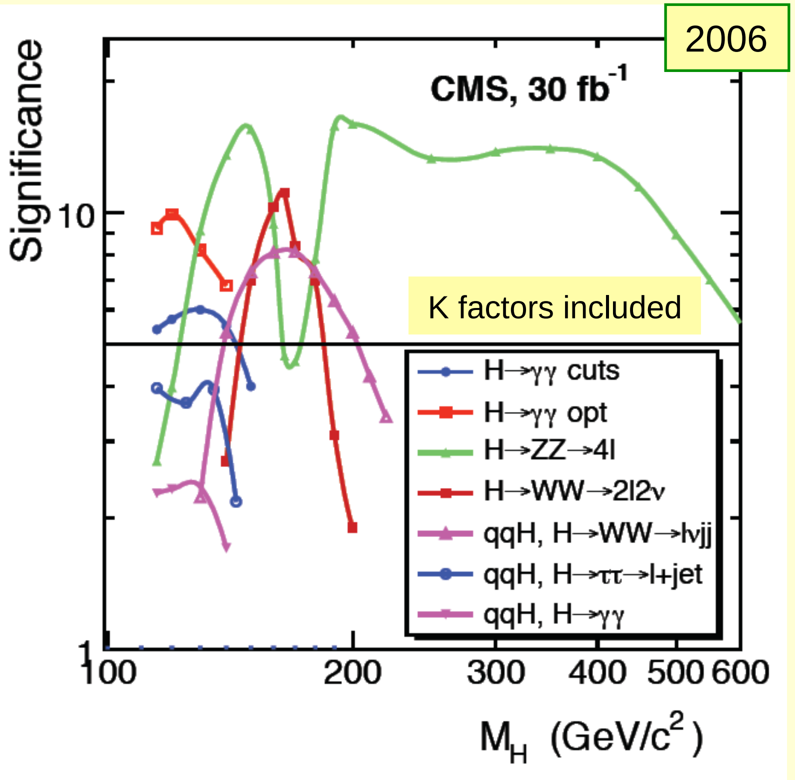
Result of a particle level study

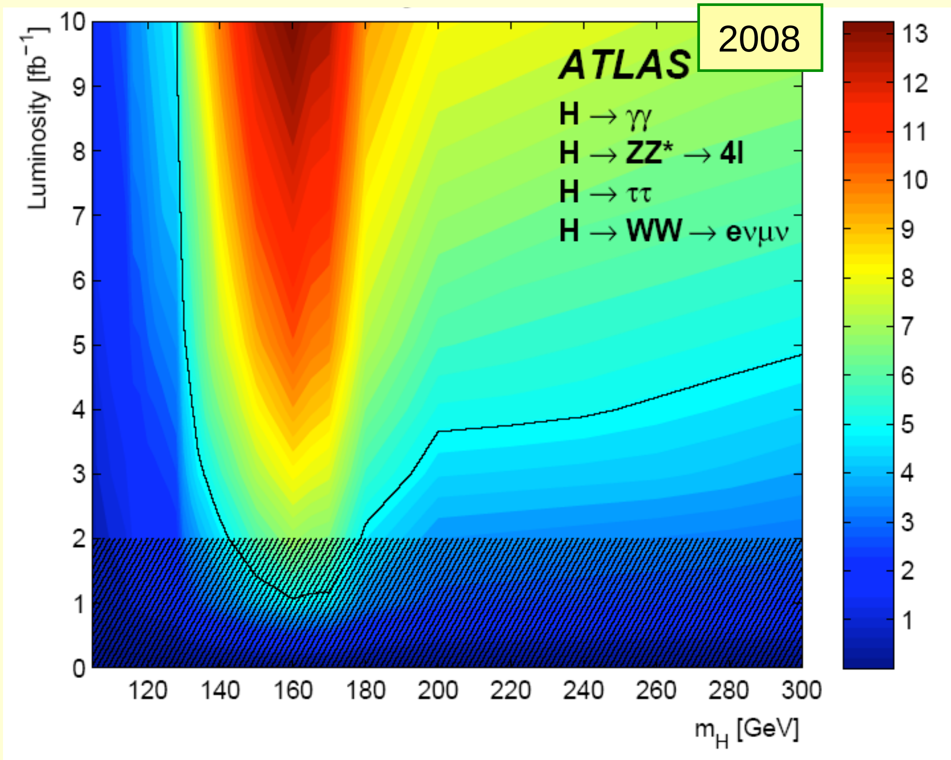
- Search for Higgs boson recoiling with large p_T against a W or Z boson (p_T > 200 GeV)
  (large reduction of signal but improved signal-to-background conditions)
- b-jets from Higgs decay are merged in one jet
- Apply sub-jet analysis, split the jet in two, including b-tagging



- Looks promising
- So far only particle level study
- Experimental studies with detailed detector simulations are currently being carried out

LHC Higgs boson discovery potential

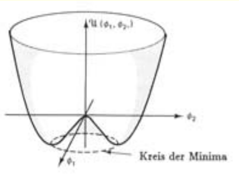




- Comparable performance in the two experiments
  [at high mass: more channels (in WW and ZZ decay modes) available than shown here]
- Several channels and production processes available over most of the mass range
  → calls for a separation of the information + global fit (see below)

Important changes w.r.t. previous studies:

- **ttH → tt bb** disappeared in both ATLAS and CMS studies from the discovery plot



Is it a Higgs Boson ?

-can the LHC measure its parameters ?-

1. Mass

Higgs boson mass can be measured with a precision of 0.1%
over a large mass range (130 - ~450 GeV/c^2)
($\gamma\gamma$ and ZZ→ 4ℓ resonances, el.magn. calo. scale uncertainty assumed to be ± 0.1%)

2. Couplings to bosons and fermions

(→ see next slide)

3. Spin and CP

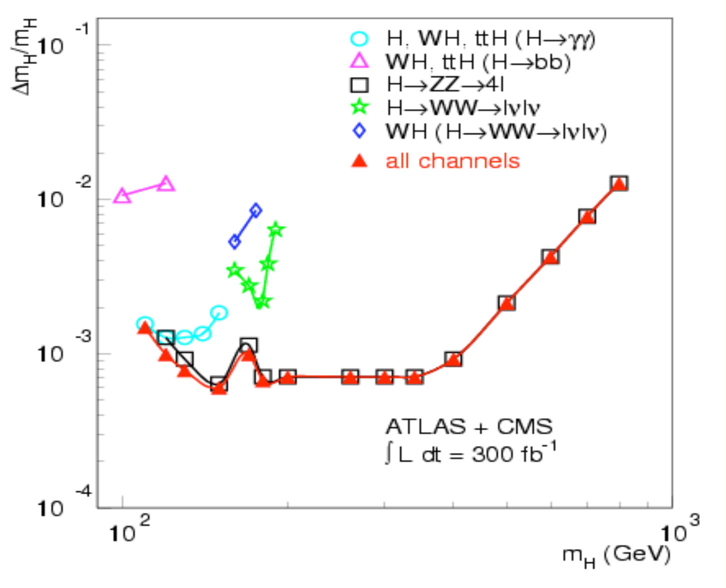
Angular distributions in the decay channel H → ZZ(*) → 4 ℓ are sensitive to spin and CP eigenvalue

4. Higgs self coupling

Possible channel: **gg → HH → WW WW → ℓν jj ℓν jj** (like sign leptons)
Small signal cross sections, large backgrounds from tt, WW, WZ, WWW, tttt, Wtt,...

⇒ no significant measurement possible at the LHC
very difficult at a possible SLHC (6000 fb^{-1})
limited to mass region around 160 GeV/c^2

Measurement of the Higgs boson mass

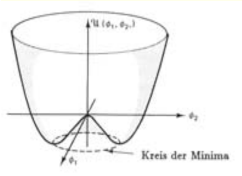


Dominated by ZZ→ 4ℓ and γγ resonances !

well identified, measured with a good resolution

Dominant systematic uncertainty: γ /ℓ E scale.
Assumed 0.1 %
Goal 0.02 %
Scale from Z → ℓℓ (close to light Higgs)

Higgs boson mass can be measured with a precision of 0.1%
over a large mass range (130 - ~450 GeV / c^2)



Is it a Higgs Boson ?

-can the LHC measure its parameters ?-

1. Mass

Higgs boson mass can be measured with a precision of 0.1%
over a large mass range (130 - ~450 GeV/c^2)
($\gamma\gamma$ and ZZ→ 4ℓ resonances, el.magn. calo. scale uncertainty assumed to be ± 0.1%)

2. Couplings to bosons and fermions

(→ see next slide)

3. Spin and CP

Angular distributions in the decay channel H → ZZ(*) → 4 ℓ are sensitive to spin and CP eigenvalue

4. Higgs self coupling

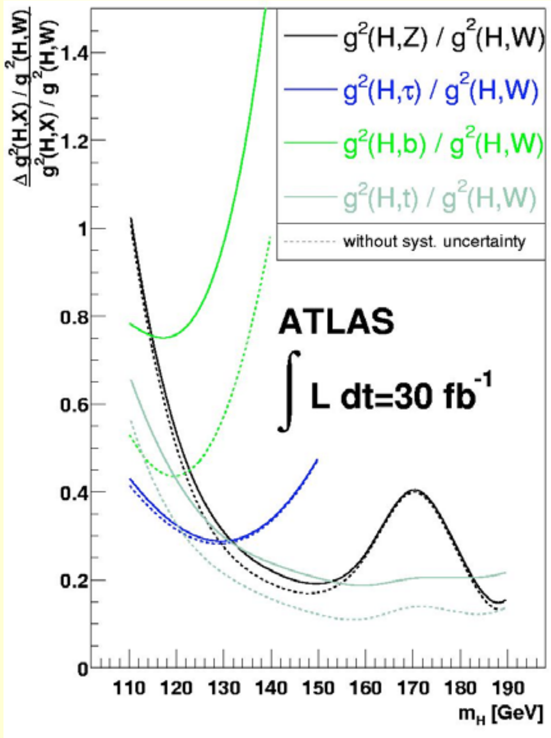
Possible channel: **gg → HH → WW WW → ℓν jj ℓν jj** (like sign leptons)
Small signal cross sections, large backgrounds from tt, WW, WZ, WWW, tttt, Wtt,...

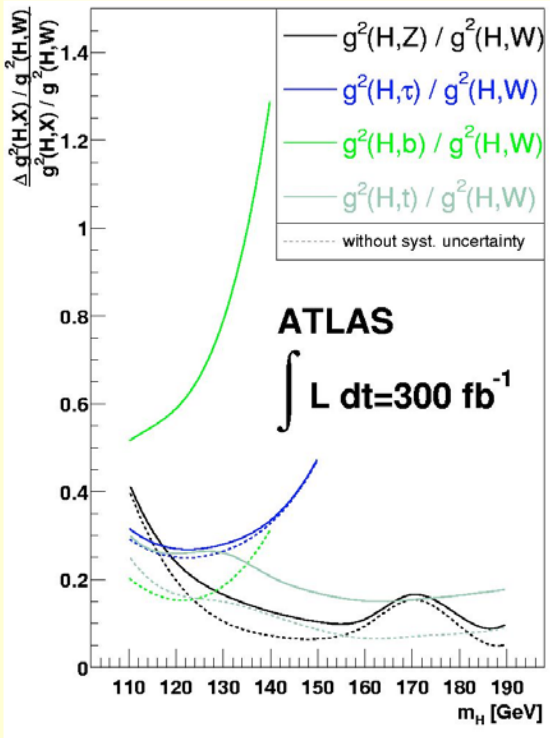
⇒ no significant measurement possible at the LHC
very difficult at a possible SLHC (6000 fb^{-1})
limited to mass region around 160 GeV/c^2

Measurement of Higgs Boson Couplings

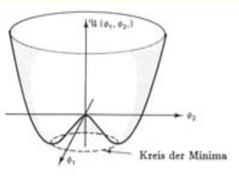
Global likelihood-fit (at each possible Higgs boson mass)
Input: measured rates, separated for the various production modes

Output: Higgs boson couplings, normalized to the WW-coupling





Relative couplings can be measured with a precision of ~20% (for 300 fb^{-1})



Is it a Higgs Boson ?

-can the LHC measure its parameters ?-

1. Mass

Higgs boson mass can be measured with a precision of 0.1%
over a large mass range (130 - ~450 GeV/c^2)
($\gamma\gamma$ and $ZZ \rightarrow 4\ell$ resonances, el.magn. calo. scale uncertainty assumed to be ± 0.1%)

2. Couplings to bosons and fermions

(→ see next slide)

3. Spin and CP

Angular distributions in the decay channel $H \rightarrow ZZ^{(*)} \rightarrow 4\,\ell$ are sensitive to spin and CP eigenvalue

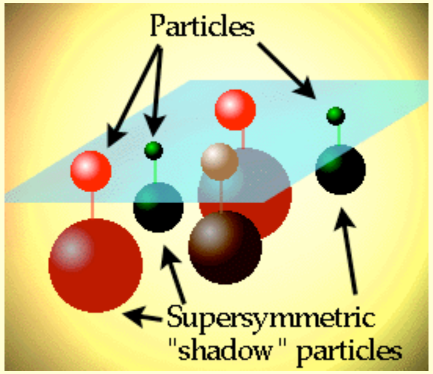
4. Higgs self coupling

Possible channel: **$gg \rightarrow HH \rightarrow WW\,WW \rightarrow \ell\nu\, jj\;\; \ell\nu\, jj$** (like sign leptons)
Small signal cross sections, large backgrounds from tt, WW, WZ, WWW, tttt, Wtt,...

⇒ no significant measurement possible at the LHC
very difficult at a possible SLHC (6000 fb^{-1})
limited to mass region around 160 GeV/c^2

The Higgs Sector

in the MSSM



The Higgs Sector in the MSSM

Two Higgs doublets: 5 Higgs particles **H, h, A**
H^+, H^-

Determined by two parameters: m_A, $\tan\beta$

Fixed mass relations at tree level:
(Higgs self coupling in MSSM fixed by gauge couplings)

$$m^2_{H,h} = \frac{1}{2}\left(m_A^2 + m_Z^2 \pm \sqrt{(m_A^2+m_Z^2)^2 - 4m_Z^2 m_A^2 \cos^2 2\beta}\right)$$

$$m_h^2 \leq m_Z^2 \cos^2 2\beta \leq m_Z^2$$

Important radiative corrections !! (tree level relations are significantly modified)

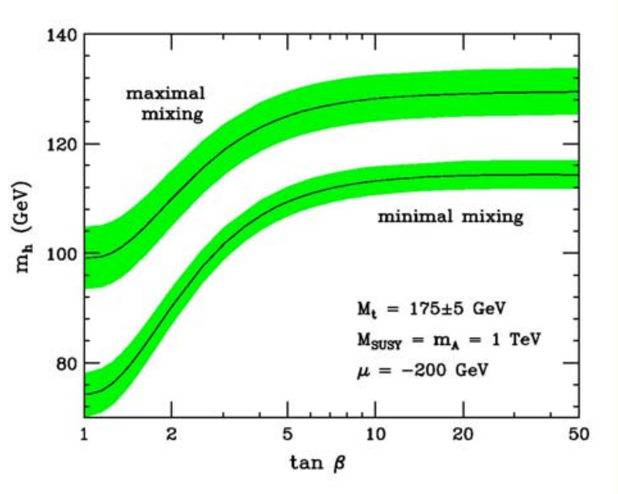
→ upper mass bound depends on top mass and mixing in the stop sector

$$m_h^2 \leq m_Z^2 + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + x_t^2\left(1 - \frac{x_t^2}{12}\right)\right]$$

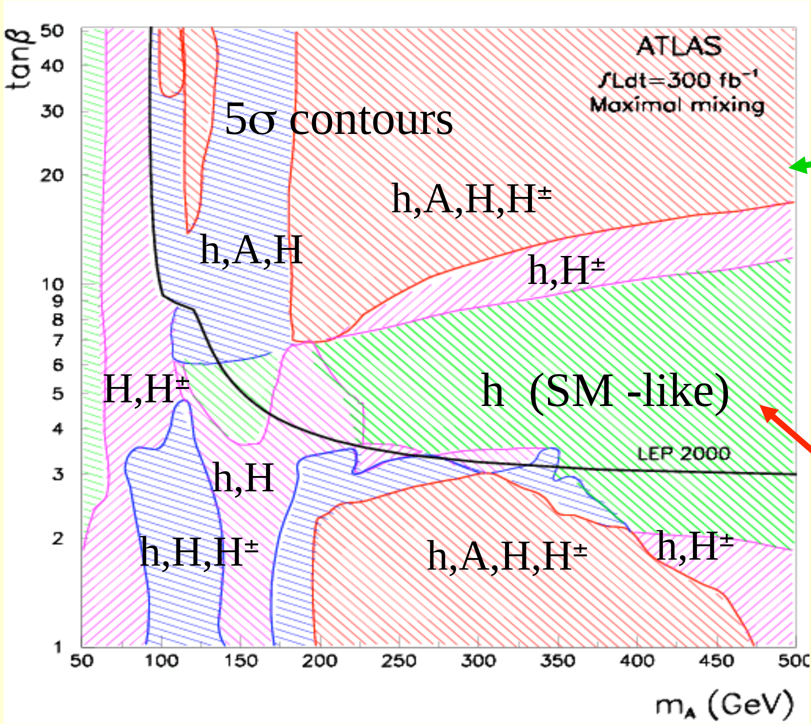
where: $M_S^2 = \frac{1}{2}\left(M_{\tilde{t}_1}^2 + M_{\tilde{t}_2}^2\right)$ and $x_t = (A_t - \mu \cot\beta) \,/\, M_S$

→ m_h < 115 GeV for no mixing
→ m_h < 135 GeV for maximal mixing

i.e., no mixing scenario: in LEP reach
max. mixing: easier to address at the LHC



LHC discovery potential for SUSY Higgs bosons



- 4 Higgs observable
- 3 Higgs observable
- 2 Higgs observable
- 1 Higgs observable

A, H, H± cross-sections ~ $\tan^2\beta$

- best sensitivity from A/H → ττ, H± → τν
  (not easy the first year ....)

- A/H → μμ experimentally easier
  (esp. at the beginning)

Here only SM-like h observable if SUSY particles neglected.

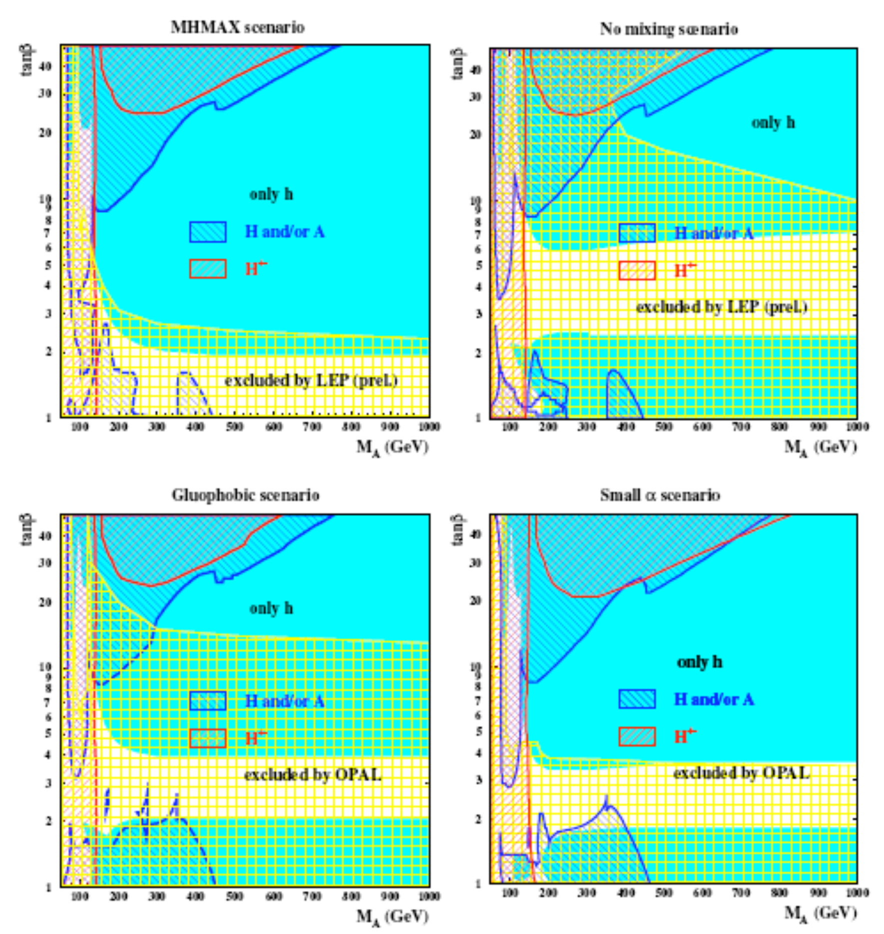
* Validated by recent ATLAS and CMS full simulation studies *

Coverage in the large m_A wedge region can be improved (slightly) by:
- Higher luminosity: sLHC
- Additional SUSY decay modes (however, model dependent)

Updated MSSM scan for different benchmark scenarios

Benchmark scenarios as defined by M.Carena et al. (h mainly affected)

ATLAS preliminary,   30 fb^{-1},   5σ discovery



MHMAX scenario (M_{SUSY} = 1 TeV/c^2)
maximal theoretically allowed region for m_h

Nomixing scenario (M_{SUSY} = 2 TeV/c^2)
(1TeV almost excl. by LEP)
small m_h → difficult for LHC

Gluophobic scenario (M_{SUSY} = 350 GeV/c^2)
coupling to gluons suppressed
(cancellation of top + stop loops)
small rate for g g → H, H→ $\gamma\gamma$ and Z→4 ℓ

Small α scenario (M_{SUSY} = 800 GeV/c^2)
coupling to b (and **t**) suppressed
(cancellation of sbottom, gluino loops) for large tan β and M_A 100 to 500 GeV/c^2

Der Higgs Mechanismus, eine Analogie:

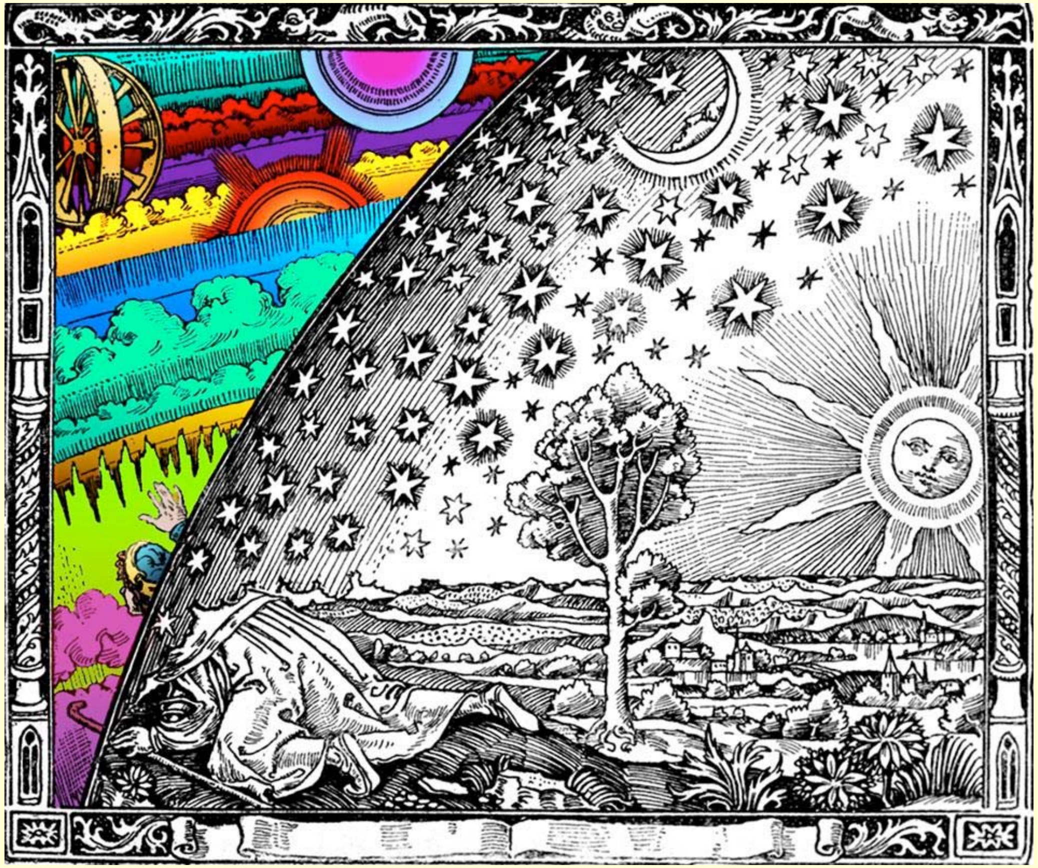
Prof. D. Miller
UC London

Higgs-Hintergrundfeld
erfüllt den Raum

Ein Teilchen
im Higgs-Feld...

... Widerstand gegen
Bewegung ...
Trägheit ↔ Masse

Physics Beyond the Standard Model ?



Why ?

1. Gravity is not yet incorporated in the Standard Model

2. Dark Matter not accomodated

3. 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
…….

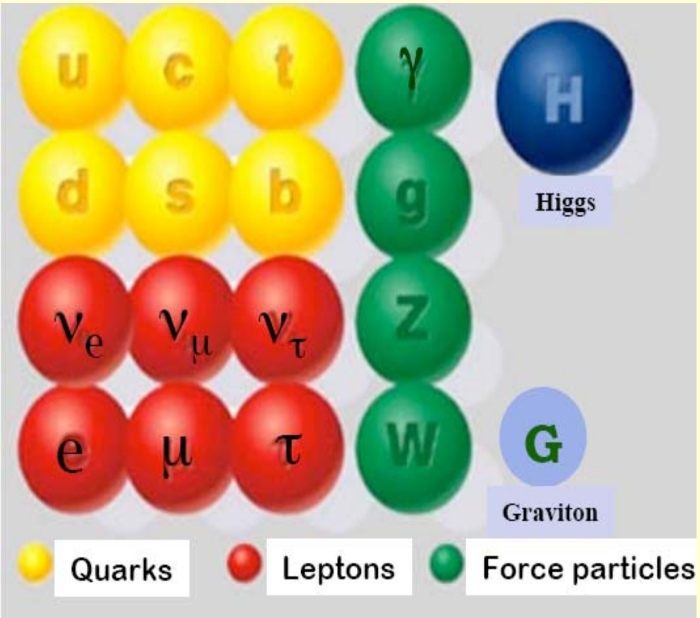
Many extensions predict new physics at the TeV scale !!

Strong motivation for LHC, mass reach ~ 3 TeV

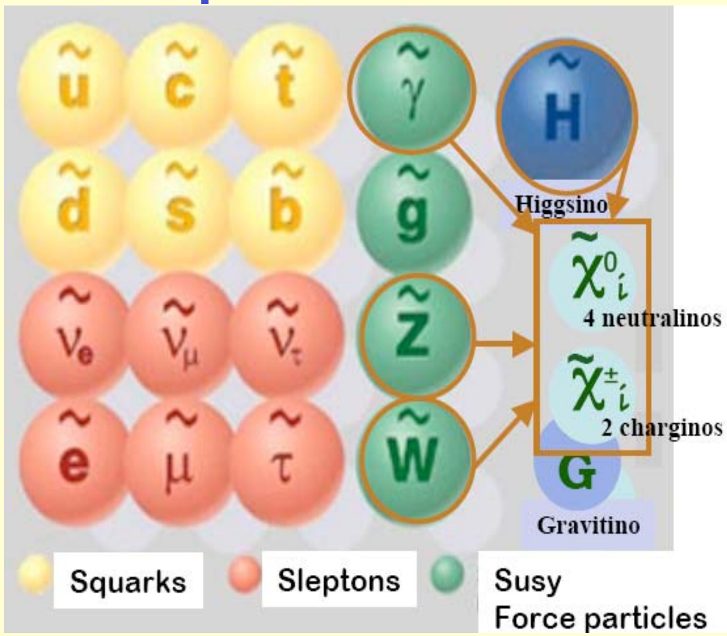
Supersymmetry

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.

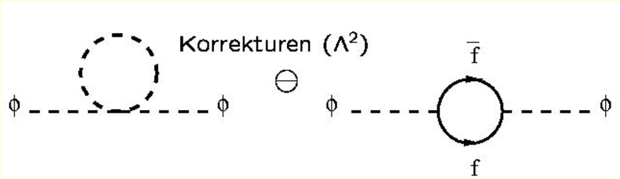
LSP is only weakly interacting:
LSP ≡ χ^0_1 (lightest neutralino, in many models)

→ 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

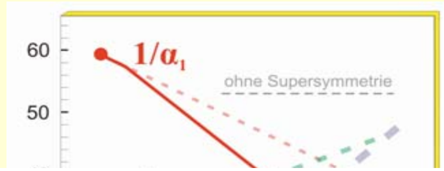


$$\Delta m_H = f(m_B^2 - m_f^2)$$

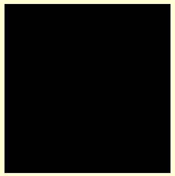
→ $m_{SUSY} \sim 1$ TeV

(Hierarchy or naturalness problem)

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

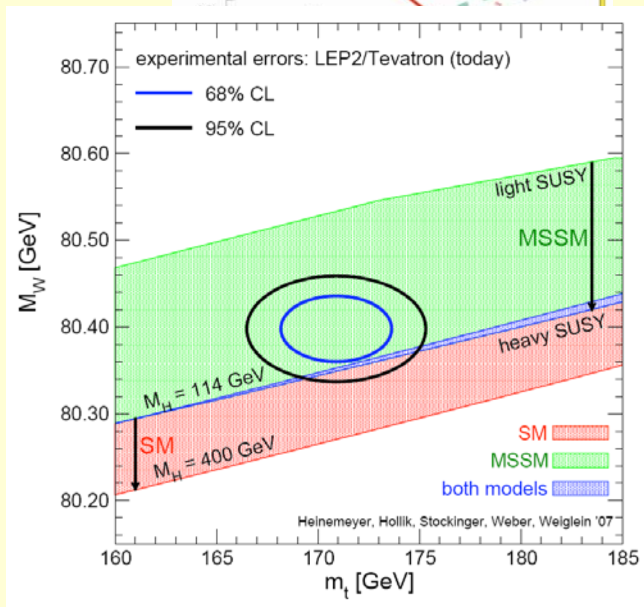


3. SUSY provides a candidate for dark matter,



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

Link to the Dark Matter in the Universe ?

Parameter of the SUSY model $\Rightarrow$ predictions for the relic density of dark matter

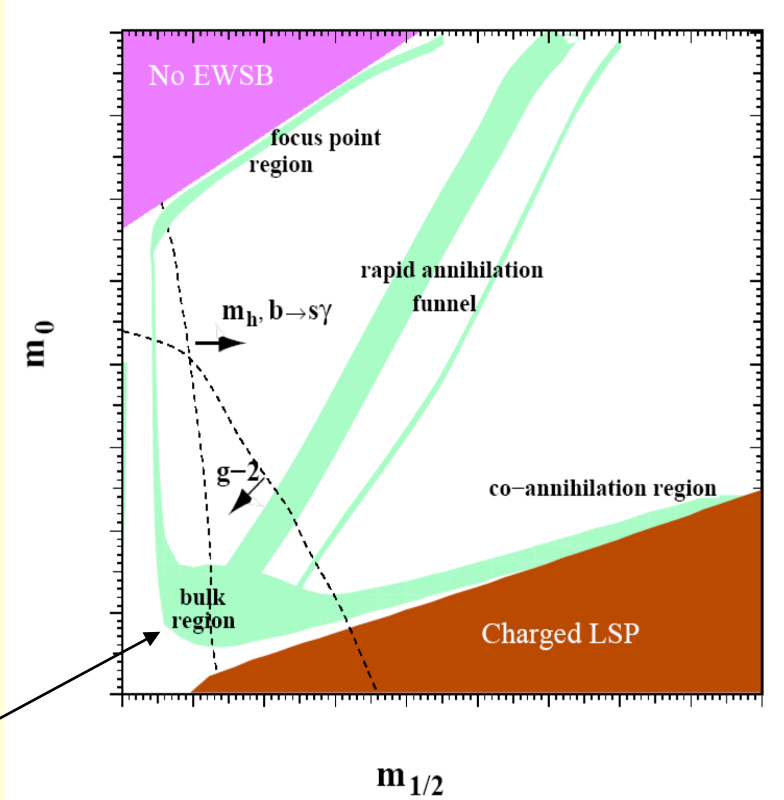
Interpretation in a simplified model

$$\rho_\chi = m_\chi n_\chi \, , \quad n_\chi \sim \frac{1}{\sigma_{ann}(\chi\chi \rightarrow \ldots)}$$

cMSSM
(constrained Minimal Supersymmetric
Standard Model)

Five parameters:

m_0, $m_{1/2}$ particle masses at the GUT scale
A_0 common coupling term
tan β ratio of vacuum expectation value of the two Higgs doublets
μ (sign μ) Higgs mass term

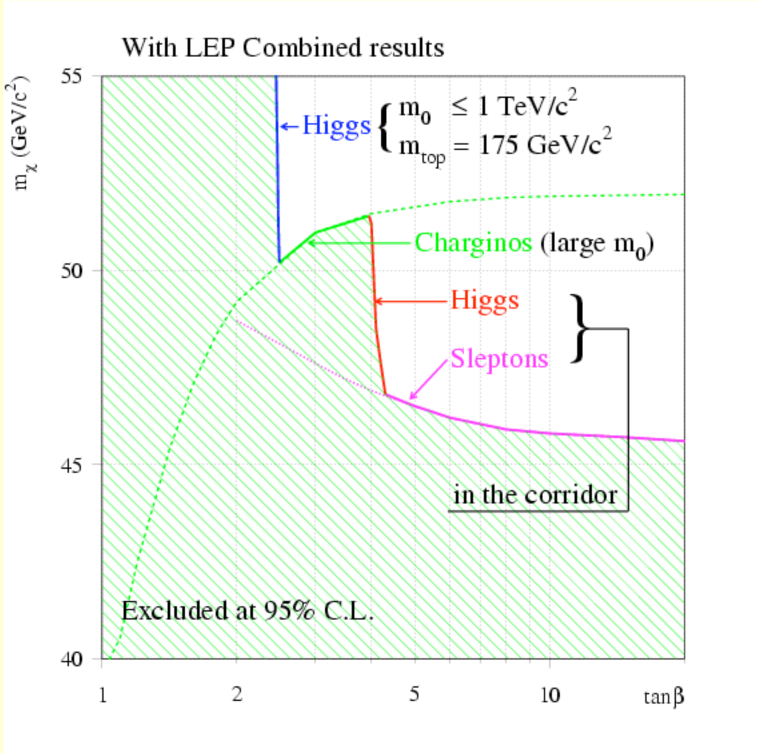


regions of parameter space which are consistent with the measured relic density of dark matter (WMAP,…..)

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)	>	~ 350 GeV	Tevatron
	m (LSP, lightest neutralino)	>	~ 45 GeV	LEP II



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

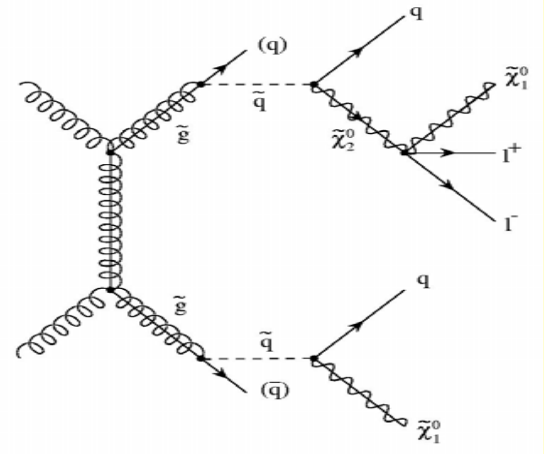
assumption:
lightest neutralino = LSP

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}

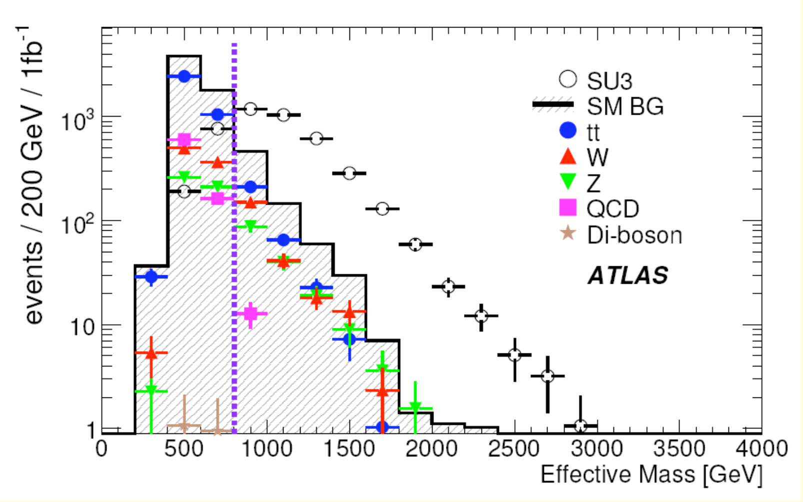
1. Step: Look for deviations from the Standard Model
   Example: Multijet + E_T^{miss} signature

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

- 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)



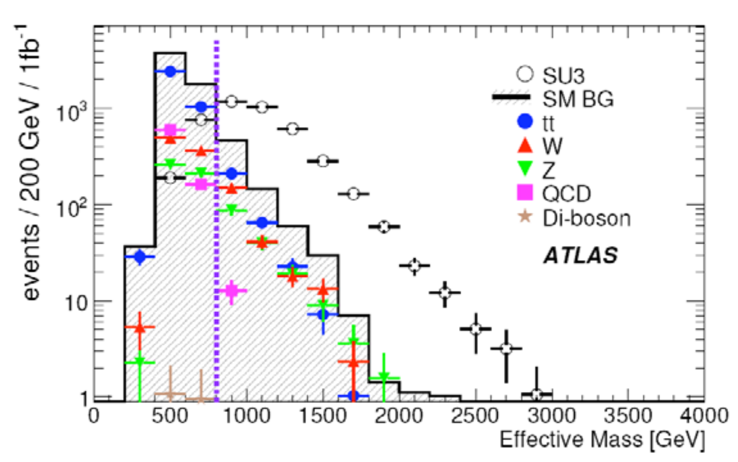
LHC reach for Squark- and Gluino masses:

0.1 fb^{-1}	⇒	M ~ 750 GeV
1 fb^{-1}	⇒	M ~ 1350 GeV
10 fb^{-1}	⇒	M ~ 1800 GeV

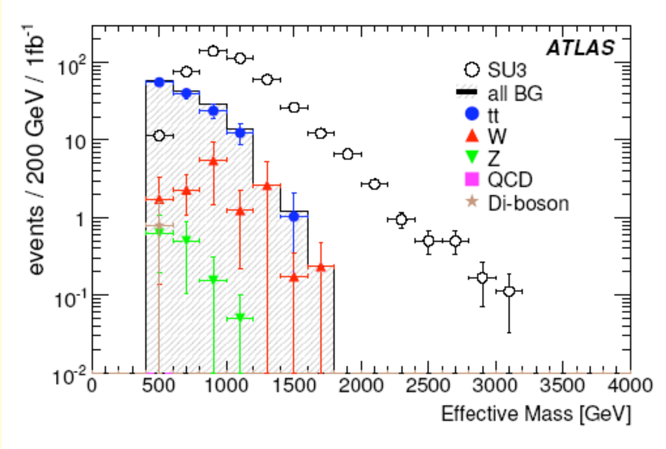
Deviations from the Standard Model due to SUSY at the TeV scale can be detected fast !

example: mSUGRA, point SU3 (bulk region)
m_0 = 100 GeV, $m_{1/2}$ = 300 GeV
tan β = 6, A_0 = -300 GeV, $\mu > 0$

...additional potential: inclusive searches with leptons



SU3, 4 jets + 0 lepton final states

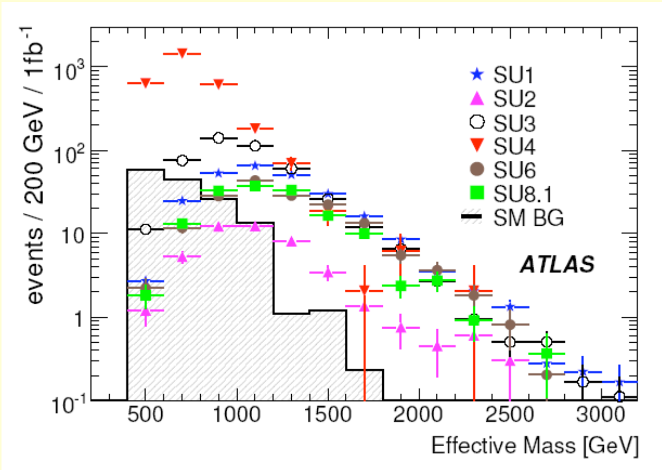


SU3, 4 jets + 1 lepton final states

- Smaller signal rates, but better S:B conditions

- Discovery potential is more robust, in particular at the beginning, when systematic uncertainties on the backgrounds are large

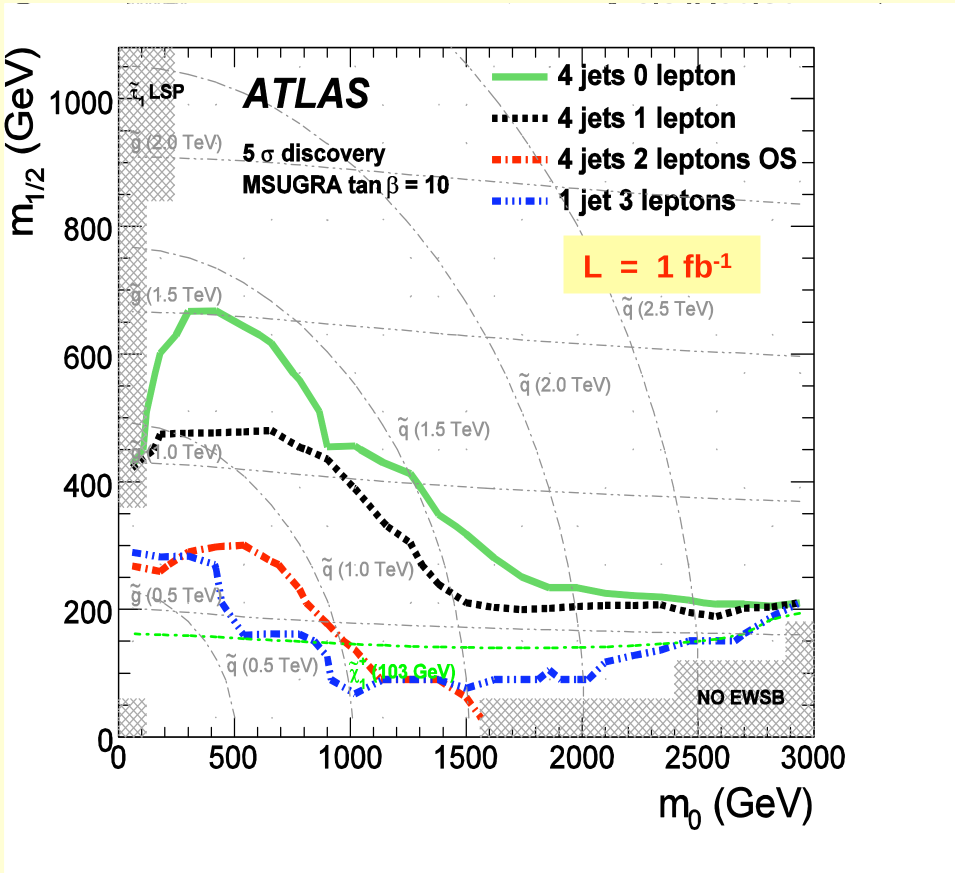
- Similar analyses with τ lepton and b quark final states



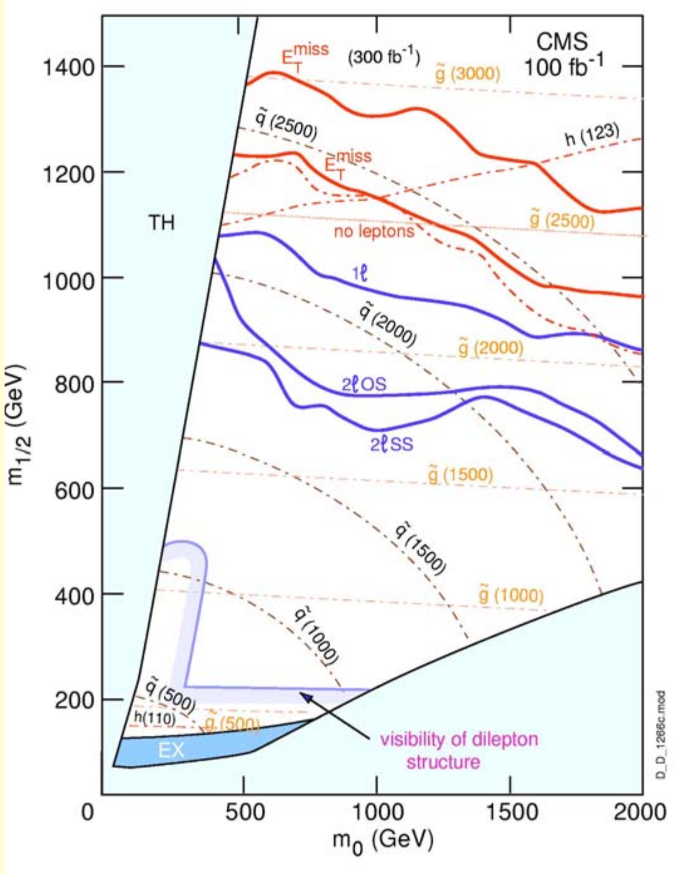
4 jets + 1 lepton final states for other benchmark points

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**



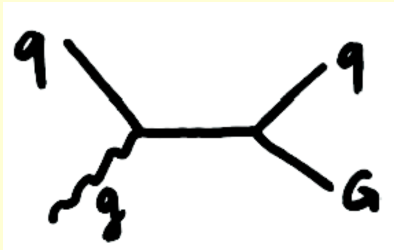
- Tevatron reach can be extended with early data
- Expect multiple signatures for TeV-scale SUSY
  Long term mass reach (300 fb^{-1}): 2.5 – 3 TeV

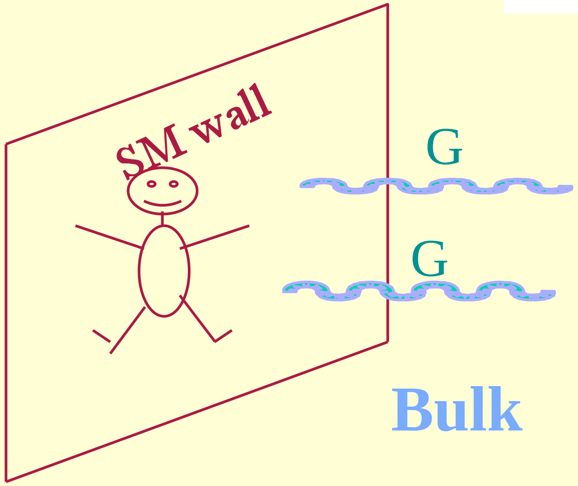
How can the underlying theoretical model be identified ?

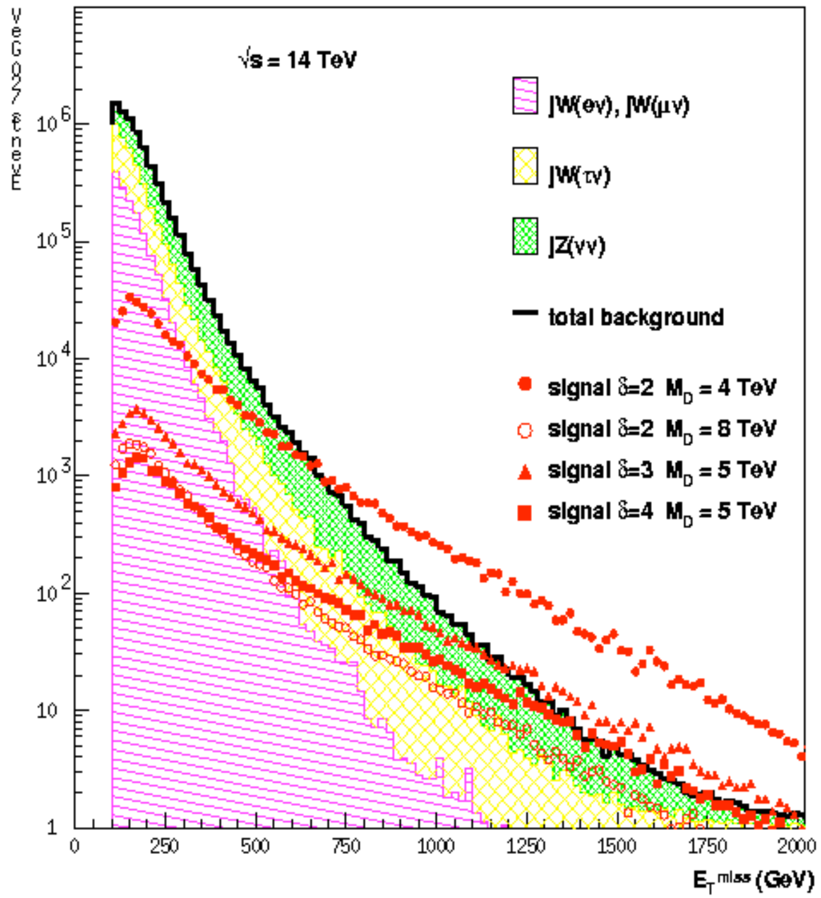
- Not easy !!
- Other possible scenarios for Physics Beyond the Standard Model could lead to similar final state signatures
  e.g. search for direct graviton production in extra dimension models

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

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

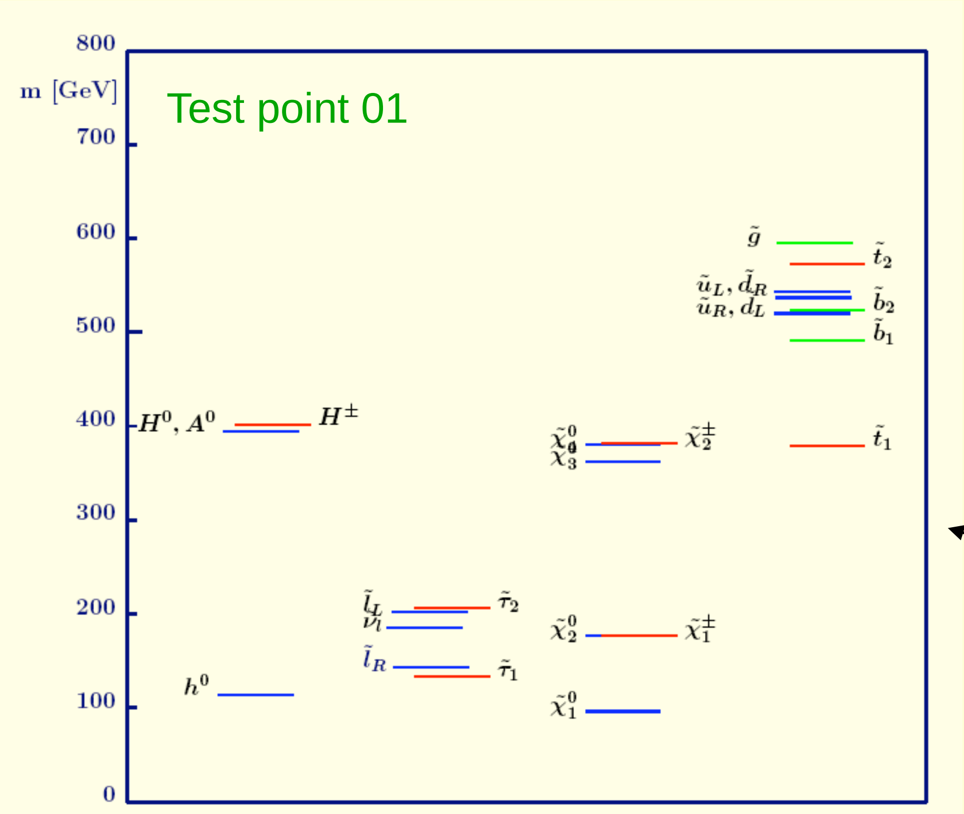


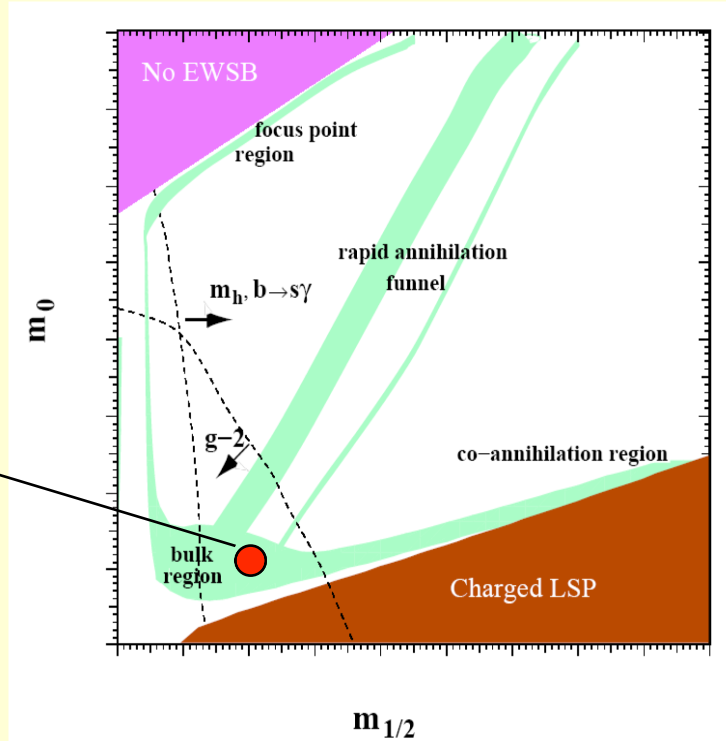




How can the underlying theoretical model be identified ?

Measurement of the SUSY spectrum → Parameter of the theory





LHC: strongly interacting squarks and gluinos

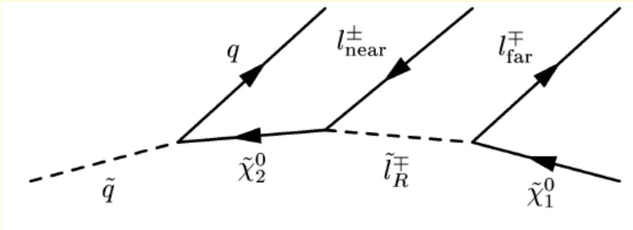
ILC / CLIC: precise investigation of electroweak SUSY partners

LHC Strategy: End point spectra of cascade decays

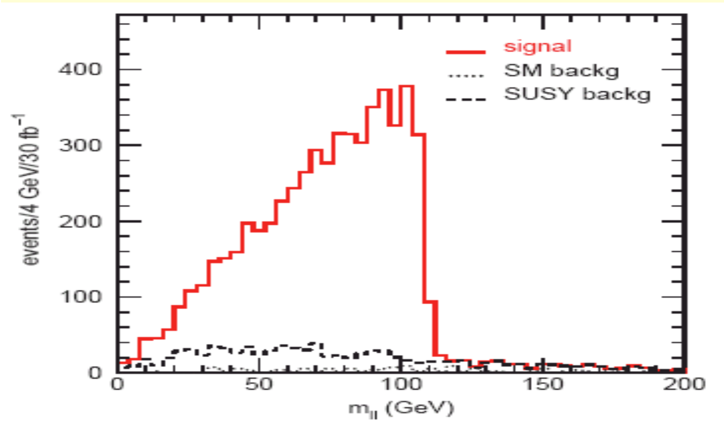
Example: $\tilde{q} \rightarrow q\tilde{\chi}_2^0 \rightarrow q\tilde{\ell}^{\pm}\ell^{\mp} \rightarrow q\ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$

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

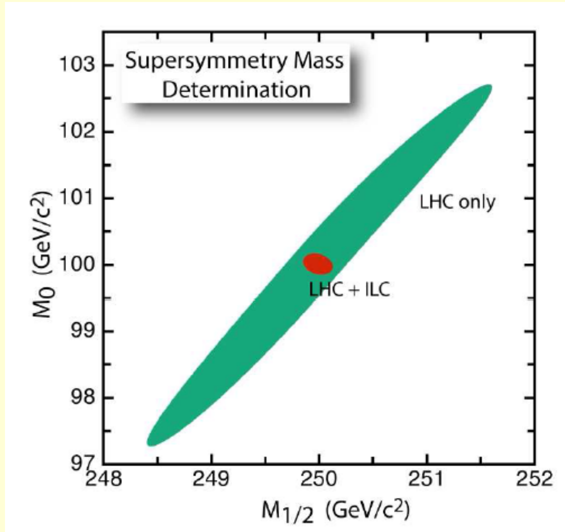
$$M_{\ell_1 q}^{max} = \frac{\sqrt{(m_{\chi_2^0}^2 - m_{\tilde{\ell}}^2)(m_{\tilde{q}}^2 - m_{\chi_2^0}^2)}}{m_{\chi_2^0}}$$



Results for point 01:



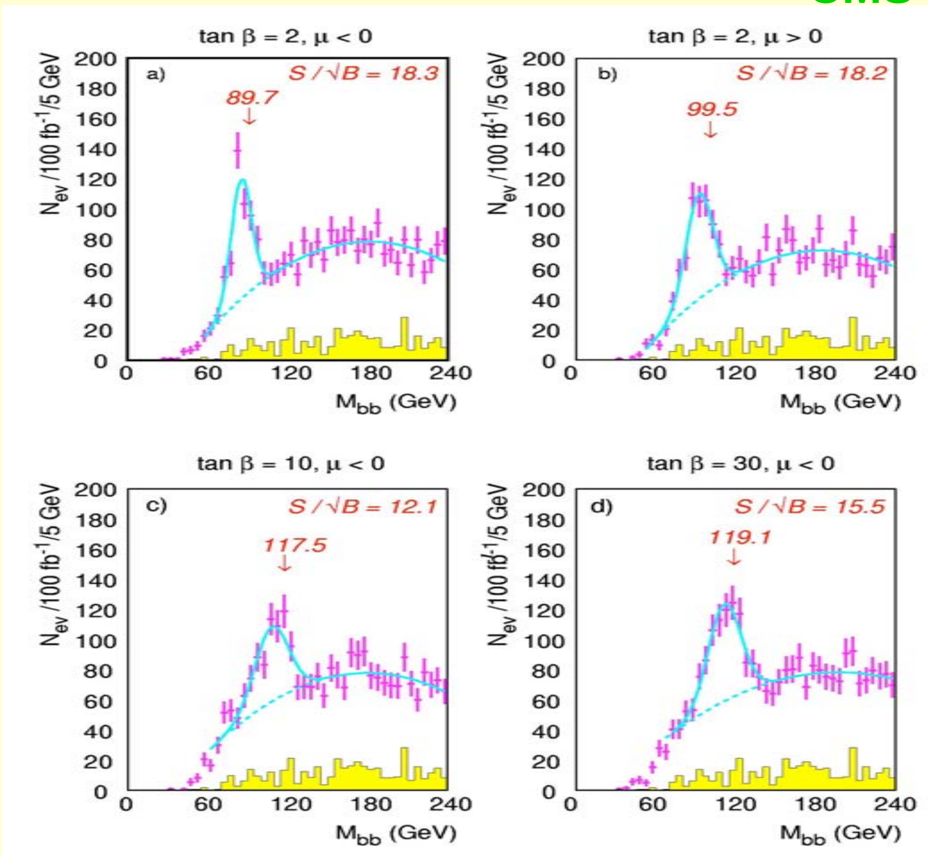
	LHC	LHC⊕ILC
$\Delta m_{\tilde{\chi}_1^0}$	4.8	0.05 (input)
$\Delta m_{\tilde{l}_R}$	4.8	0.05 (input)
$\Delta m_{\tilde{\chi}_2^0}$	4.7	0.08
$\Delta m_{\tilde{q}_L}$	8.7	4.9
$\Delta m_{\tilde{q}_R}$	11.8	10.9
$\Delta m_{\tilde{g}}$	8.0	6.4
$\Delta m_{\tilde{b}_1}$	7.5	5.7
$\Delta m_{\tilde{b}_2}$	7.9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

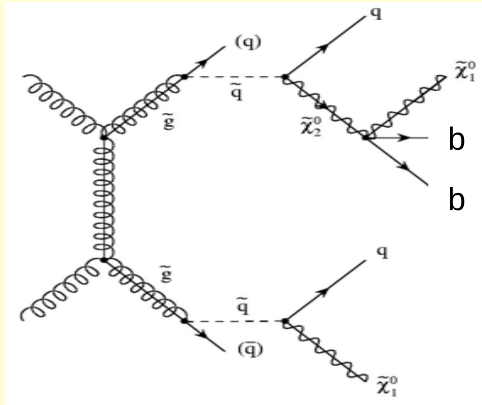


L = 300 fb^{-1}

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 !

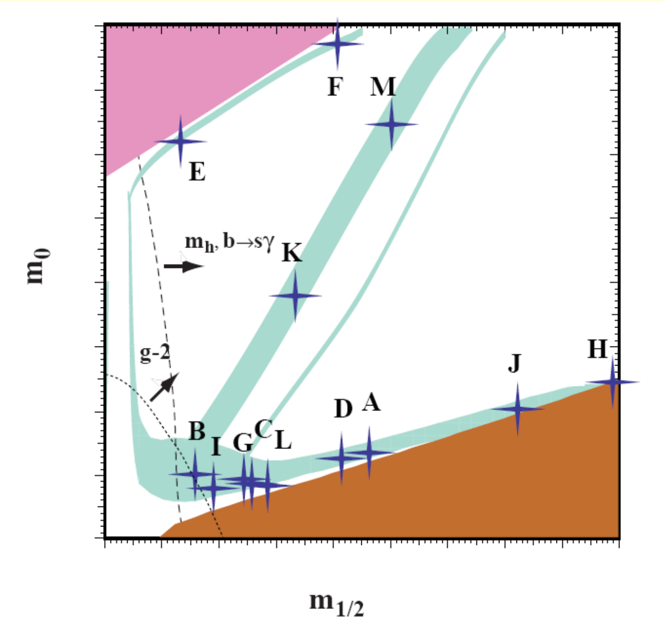
SM background can be reduced

by applying a cut on E_T^{miss}

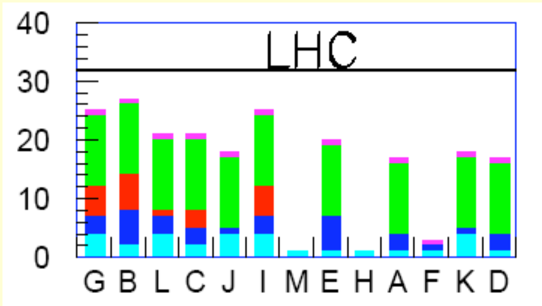
Strategy in SUSY Searches at the LHC:

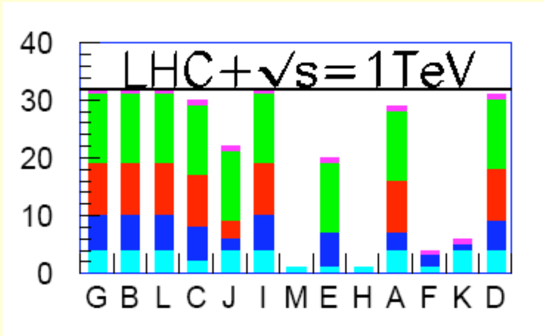
- Search for multijet + E_T^{miss} excess
- If found, select SUSY sample (simple cuts)
- Look for special features (γ's , long lived sleptons)
- Look for $\ell^\pm$, $\ell^+ \ell^-$, $\ell^\pm \ell^\pm$, b-jets, τ's
- End point analyses, global fit $\rightarrow$ SUSY model parameters

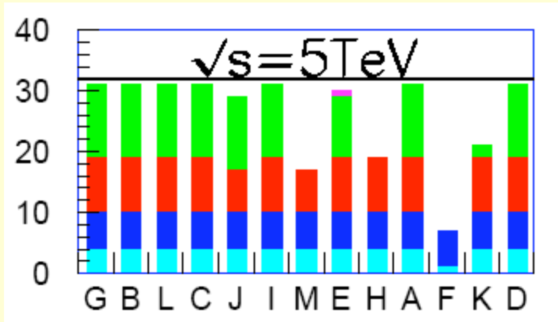
The LHC and the ILC (International Linear Collider, in study/planning phase) are complementary in SUSY searches



Number of observable SUSY particles:





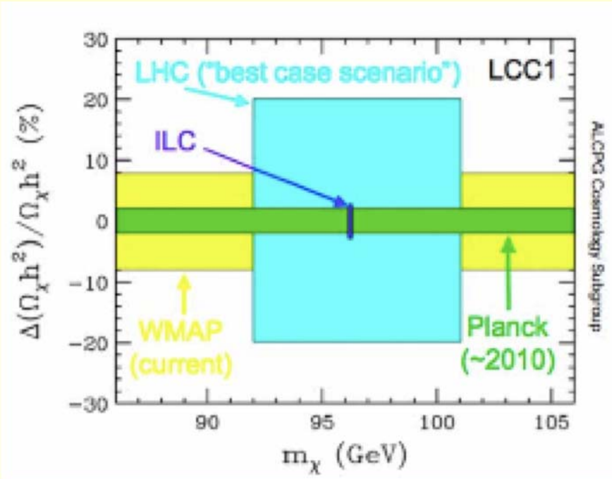


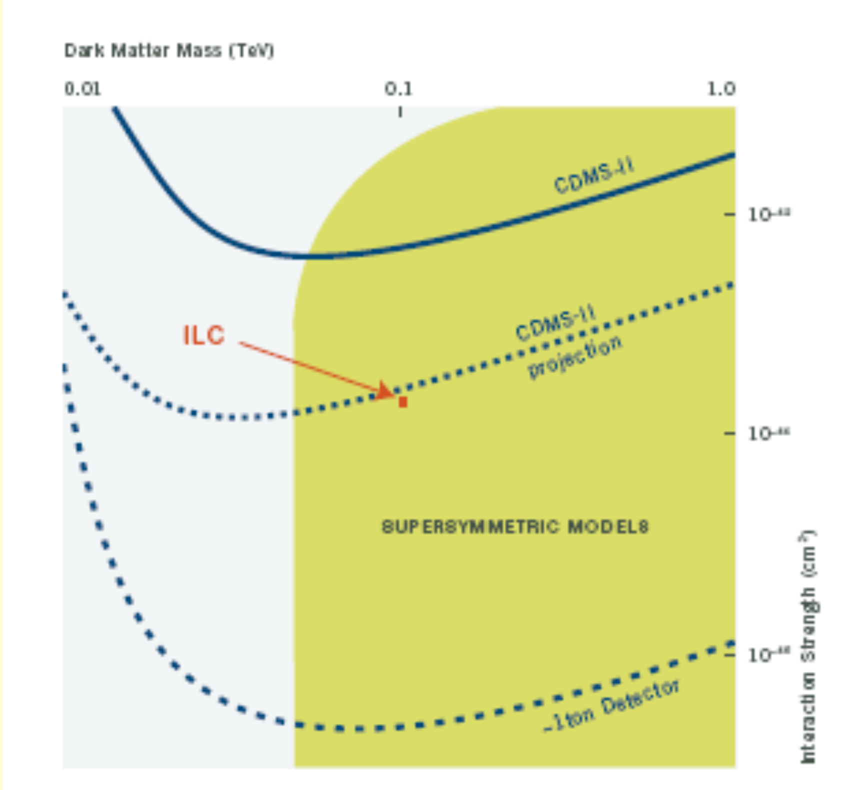
)* Study by J. Ellis et al., hep-ph/0202110

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



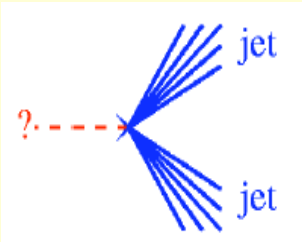


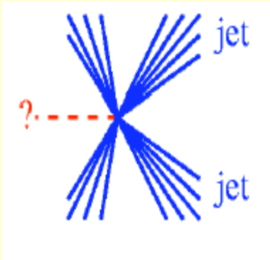
The Search for

SUSY at the Tevatron

The two classical signatures

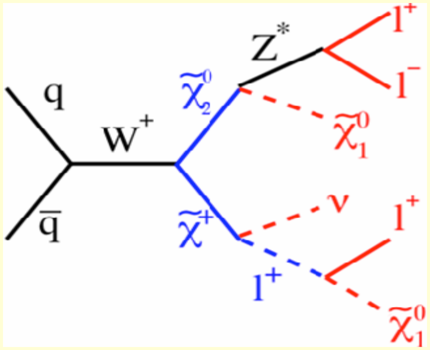
1. Search for Squarks and Gluinos: Jet + E_T^{miss} signature
   produced via QCD processes





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)

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

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

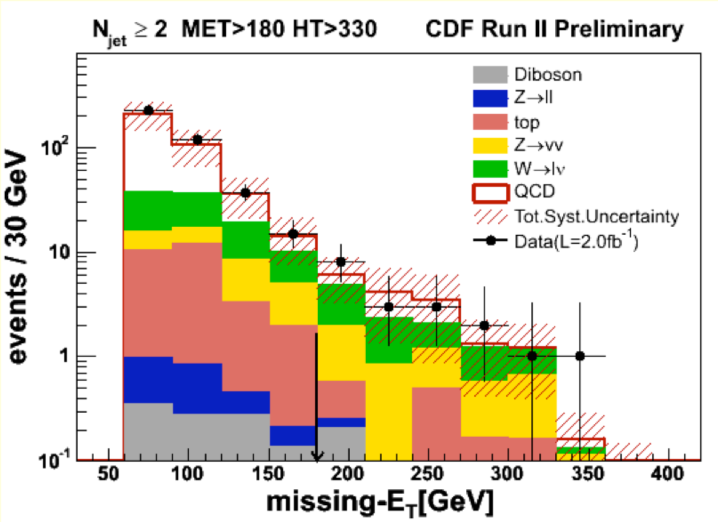
$$\tilde{q}\,\tilde{g} \rightarrow q\,\tilde{\chi}_1^0\,q\,\bar{q}\,\tilde{\chi}_1^0$$

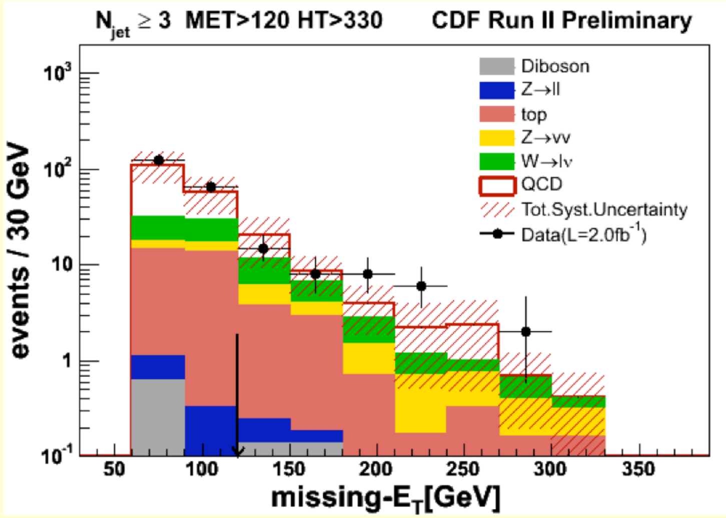
(iii) Gluino analysis
large m_0, m(squark) > m(gluino)

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

- Main backgrounds: Z → νν + 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 E_T^{miss} and all jets
  * optimization of the final cuts → discriminating variables

Search for Squarks and Gluinos (cont.)





Expected background:

samples	2-jets	3-jets	4-jets
QCD	4.37 ± 2.01	13.34 ± 4.67	15.26 ± 7.60
top	1.35 ± 1.22	7.56 ± 3.85	22.14 ± 7.29
$Z\rightarrow \nu\nu$+jets	3.95 ± 1.09	5.39 ± 1.74	2.74 ± 0.95
$Z\rightarrow ll$+jets	0.09 ± 0.04	0.16 ± 0.11	0.14 ± 0.08
$W\rightarrow l\nu$+jets	6.08 ± 2.15	10.69 ± 3.84	7.68 ± 2.85
WW/WZ/ZZ	0.21 ± 0.19	0.35 ± 0.17	0.49 ± 0.34
tot SM	16 ± 5	37 ± 12	48 ± 17

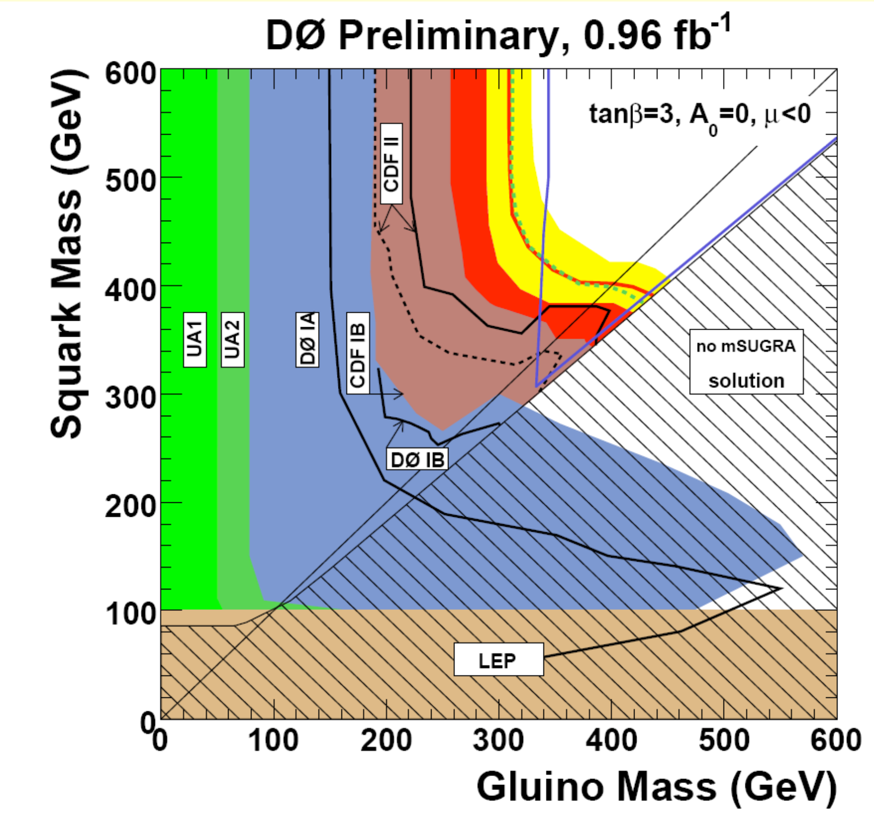
Observed events in data:

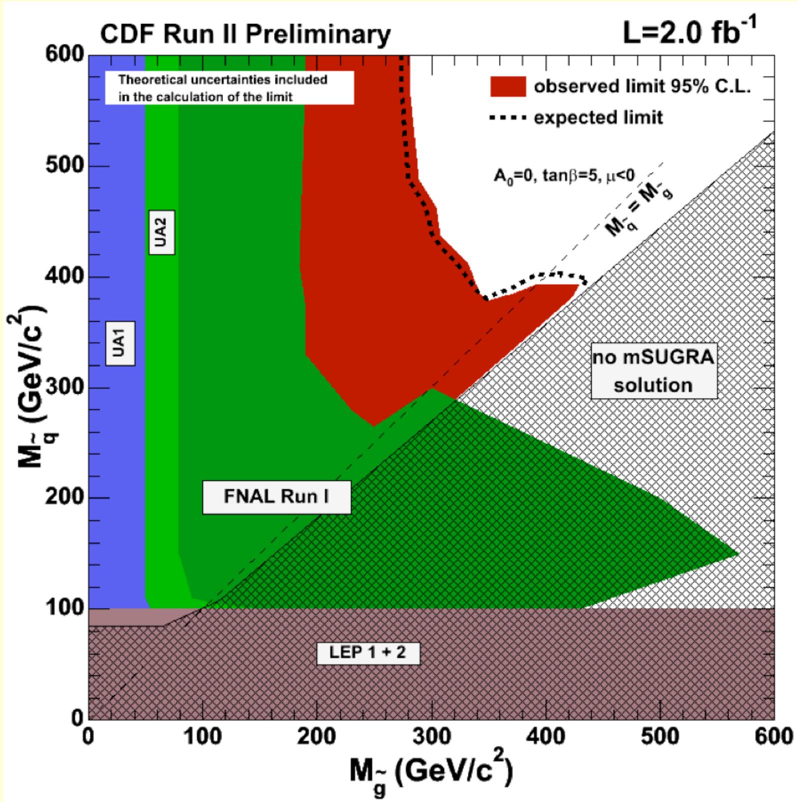
Region	Observed data
4-jets	45
3-jets	38
2-jets	18

No excess above background from Standard Model processes

$\rightarrow$ NO evidence for SUSY (yet) $\rightarrow$ Set limits on masses of SUSY particles

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



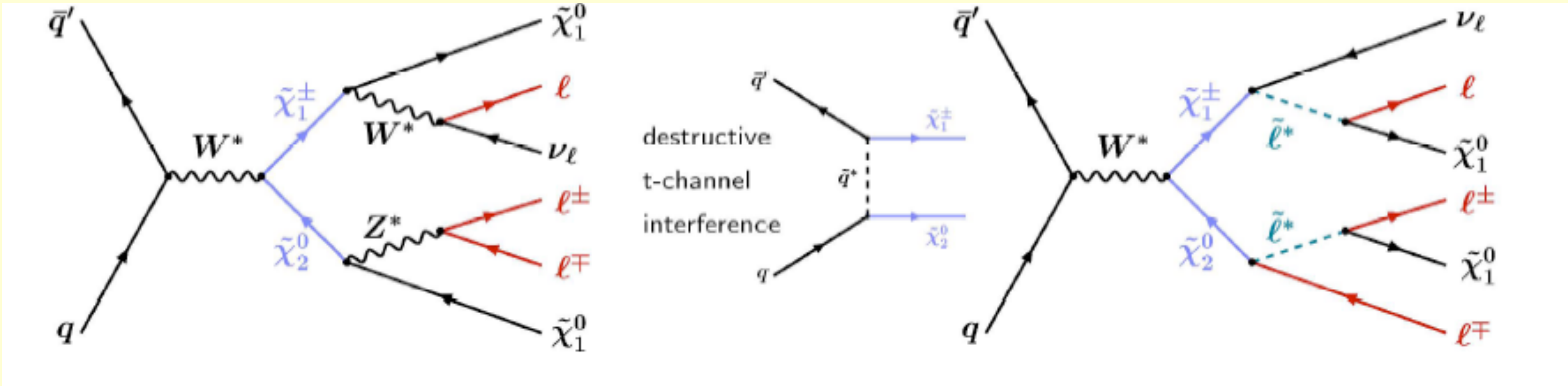


Exclusion limits
(incl. systematic uncertainties)*:
m(gluino) > 290 GeV/c^2
m(squark) > 375 GeV/c^2

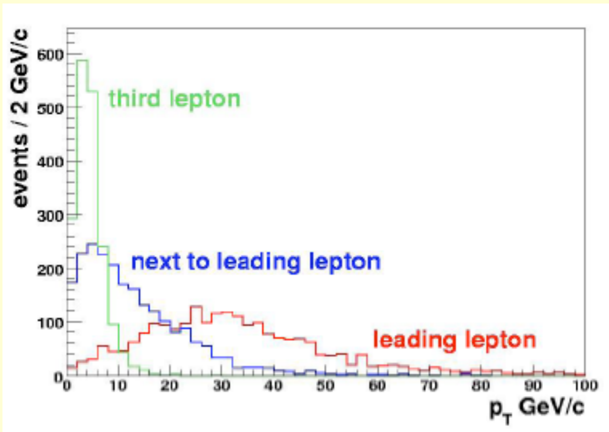
)* uncertainties from structure functions, change of renormalization and factorization scale μ by a factor of 2, NLO calculation, default choice: μ = m(gluino), m(squark) or ½(m(gluino)+m(squark)) for gg, qq, qg production

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)



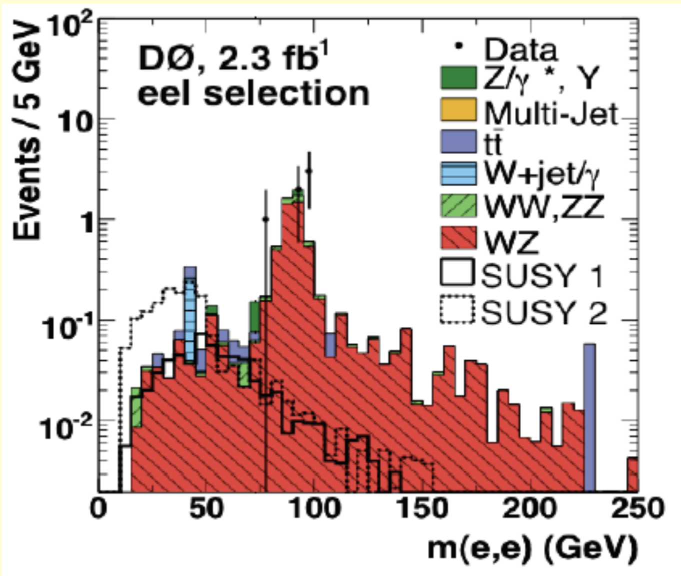
- For small gaugino masses (~100 GeV/c^2)
  one needs to be sensitive to low P_T leptons

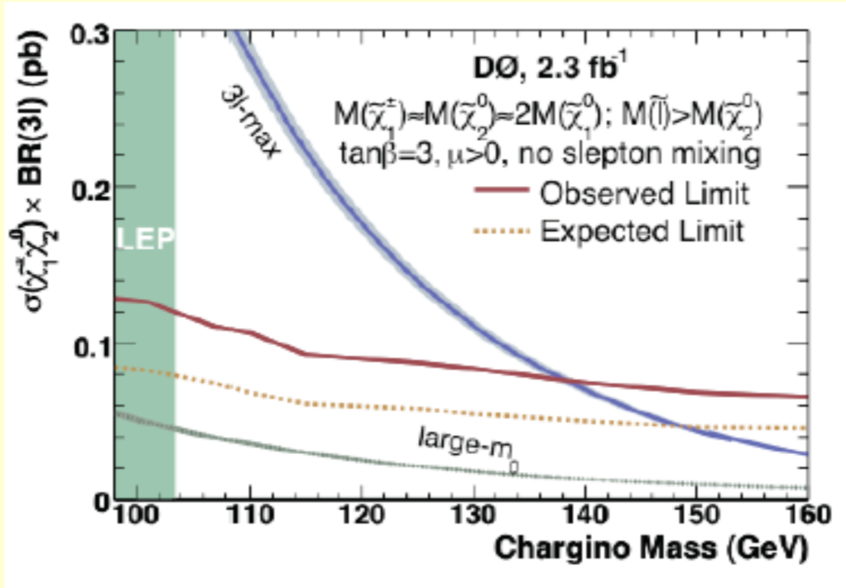


Analysis:

- Search for different $(\ell\ell\ell)$ + like-sign $\mu\mu$ 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





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


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)

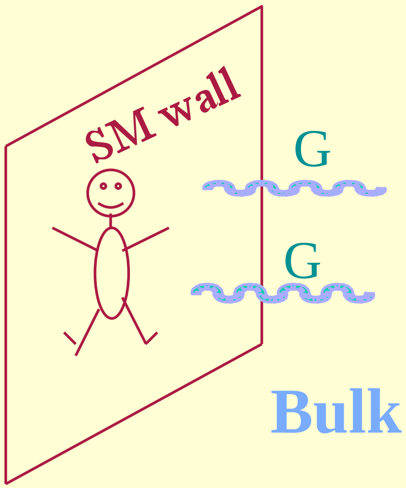
- New physics can appear at the TeV-mass scale,
  i.e. accessible at the LHC

Example: **Search for direct Graviton production**

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

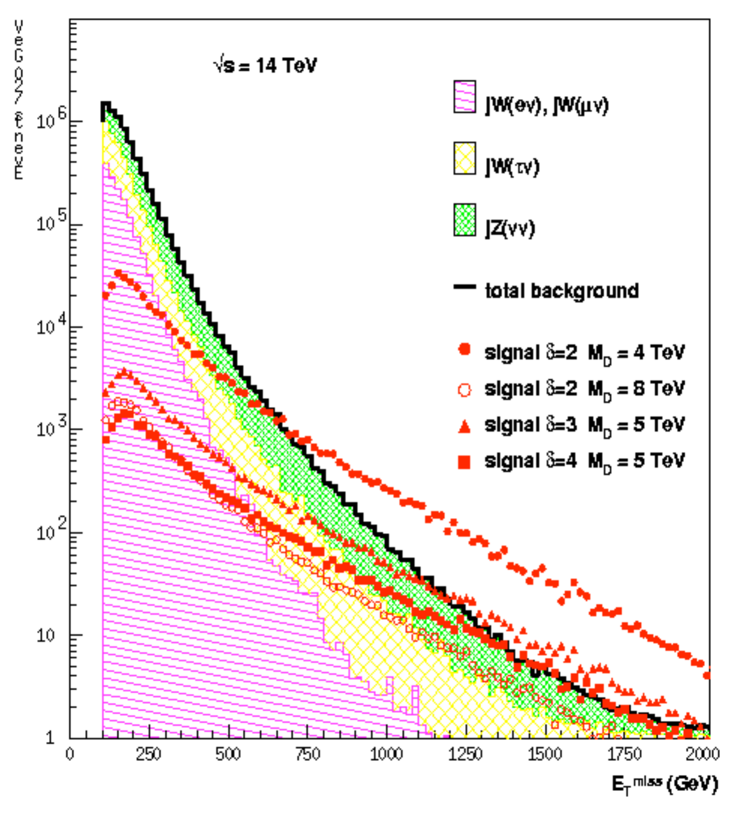
$$q\bar{q} \to G\gamma$$

⇒ **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 sensitive, but conclusions on the underlying theory are difficult and require a detailed measurement program

More ideas?

1. New resonances decaying into lepton pairs

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

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

$Z\times \rightarrow \ell \, \ell$

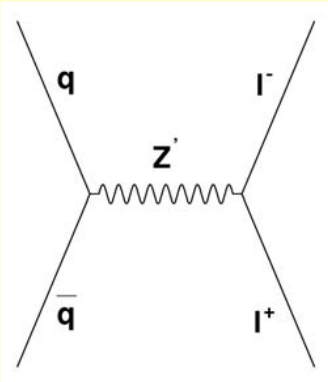
2. Leptoquarks ?

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)

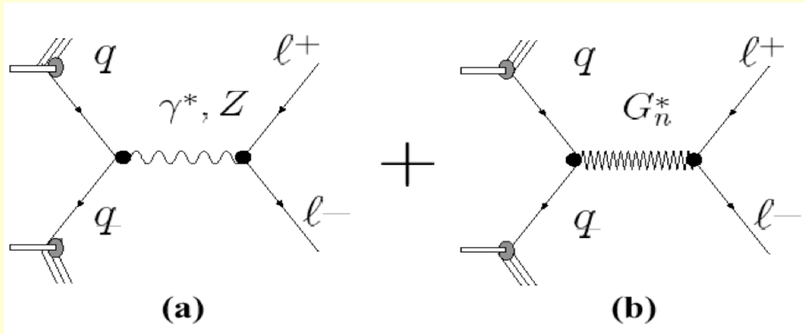
Fermilab Search for New Resonances in High Mass Di-leptons

- **Neutral Gauge Boson Z´**
  assume SM-like couplings



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

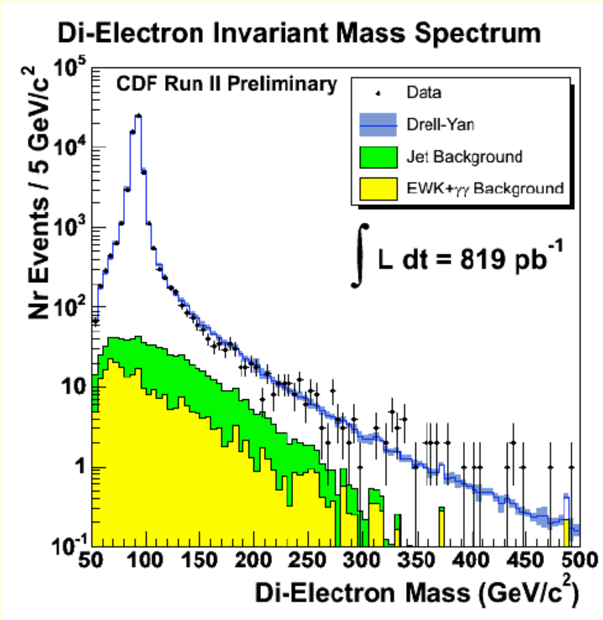
appear in Extra Dim. Scenarios



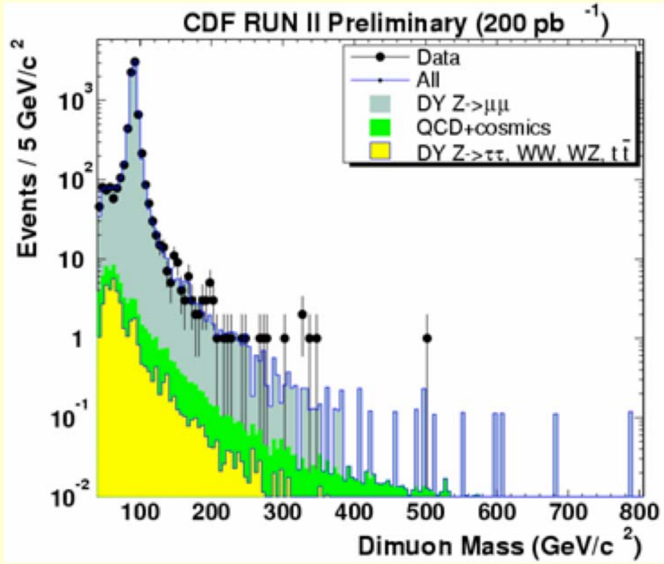
Main background from Drell-Yan pairs

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.

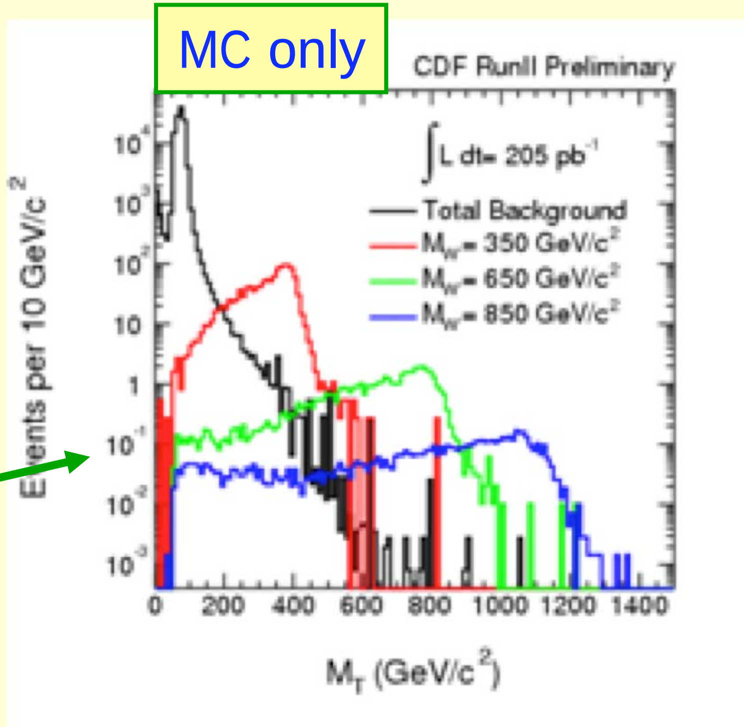
		ee	μμ	ττ	
Z´ mass limits (SM couplings) 95% C.L.	CDF /D0:	965	835	394	GeV/c^2

Search for W' → eν

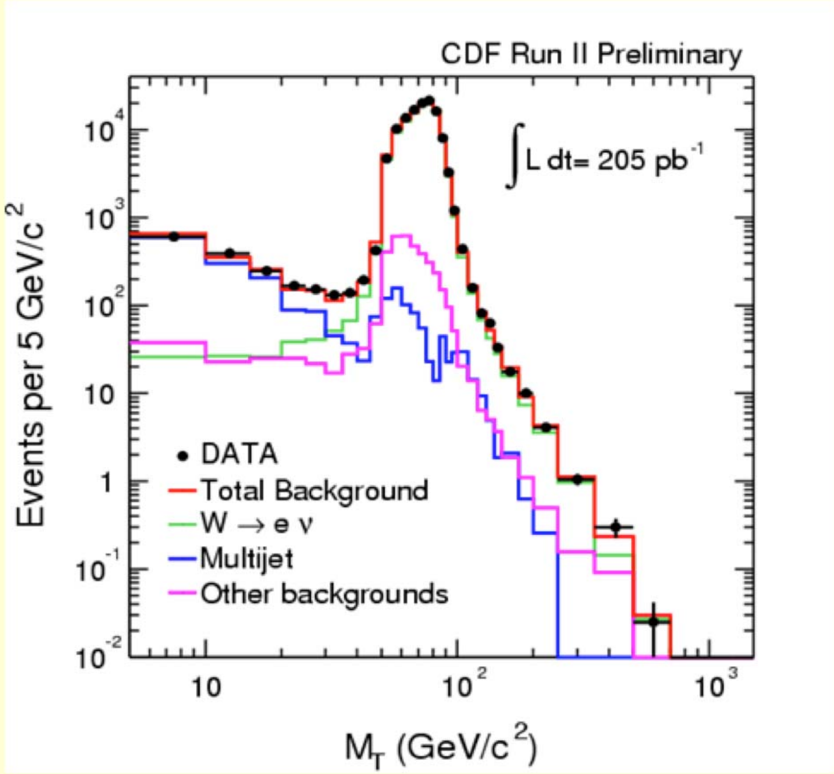
- W': additional charged heavy vector boson
- appears in theories based on the extension of the gauge group
- e.g. Left-right symmetric models: $SU(2)_R$ W_R
- assume: the neutrino from W' decay is light and stable.

Signature: high p_T electron + high E_T^{miss}

→ peak in transverse mass distribution



Search for W' → eν



Data:

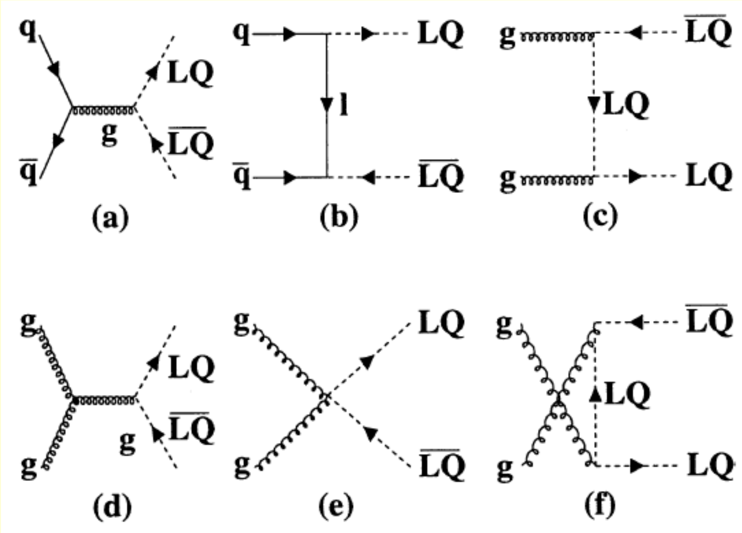
consistent with one well known W + background

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

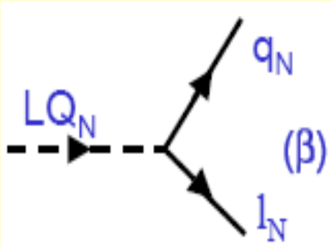
(assuming Standard Model couplings)

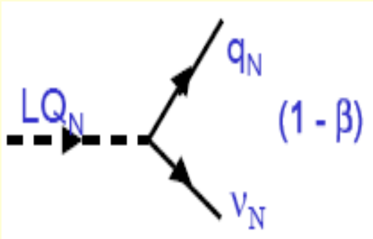
Search for Scalar Leptoquarks (LQ)

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



- Decay: into a lepton and a quark





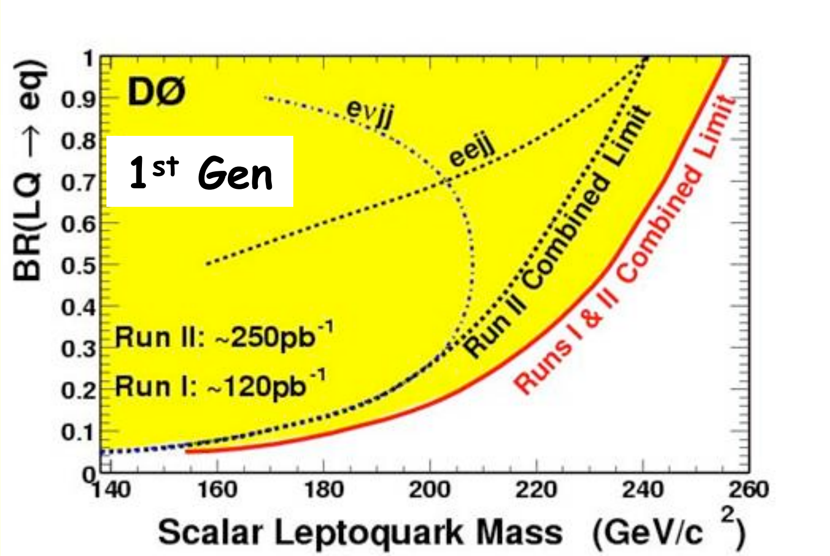
β= LQ branching fraction to charged lepton and quark
N = generation index
Leptoquarks of 1., 2., and 3. generation

Experimental Signatures:

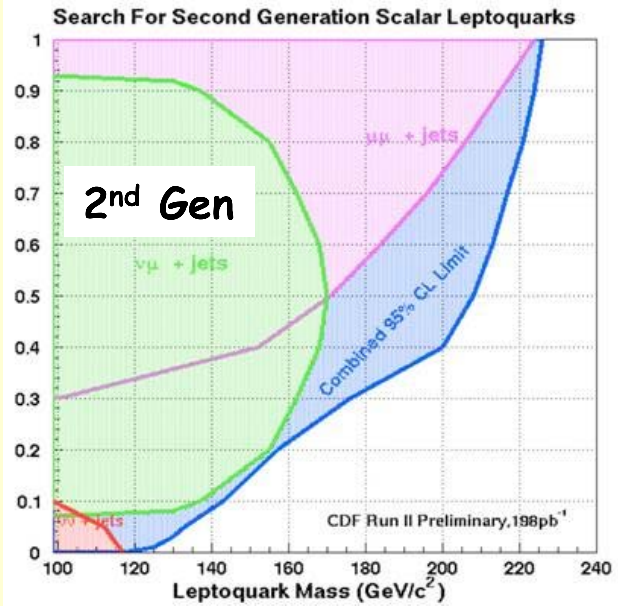
- two high p_T isolated leptons + jets .OR.
- one isolated lepton + P_T^{miss}+ jets .OR.
- P_T^{miss} + jets

1st, 2nd and 3rd generation Leptoquarks

channels: eejj, eν jj



channels: μμjj, ενjj, ννjj

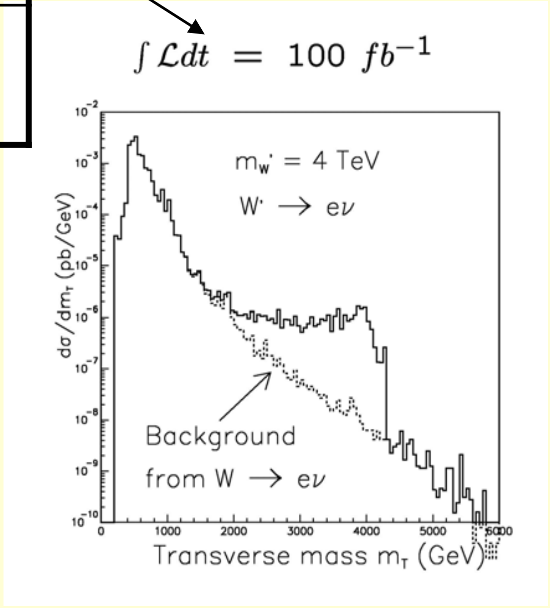


95% C.L. Mass Limits	1. Generation LQ	2. Generation LQ	3. Generation LQ
CDF (Run II)	235 GeV/c^2	224 GeV/c^2	129 GeV/c^2
D0 (Run I + II)	256 GeV/c^2	200 GeV/c^2 (Run I)	

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



Sensitivity to New Physics with jets in Early LHC data

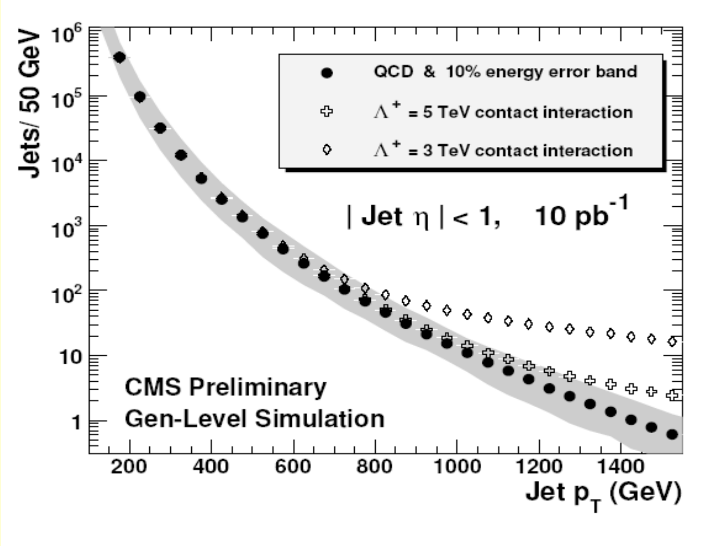
- Even with JES uncertainties expected with early data and an int. luminosity of only 10 pb^{-1} compositeness scales of ~ 3 TeV can be reached

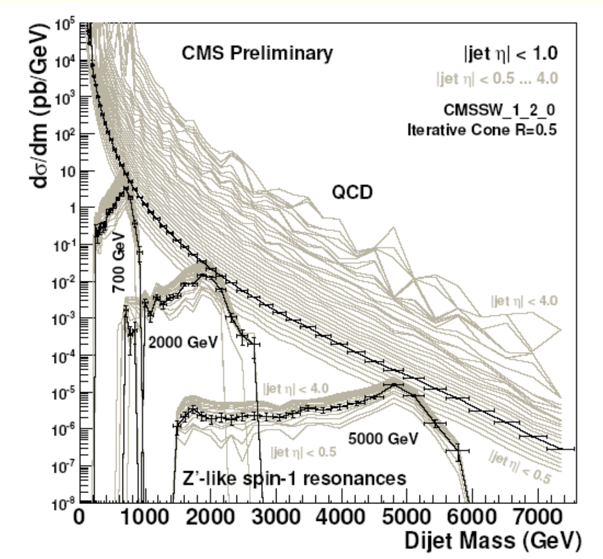
  (close to the present Tevatron reach of $\Lambda > 2.7$ TeV)

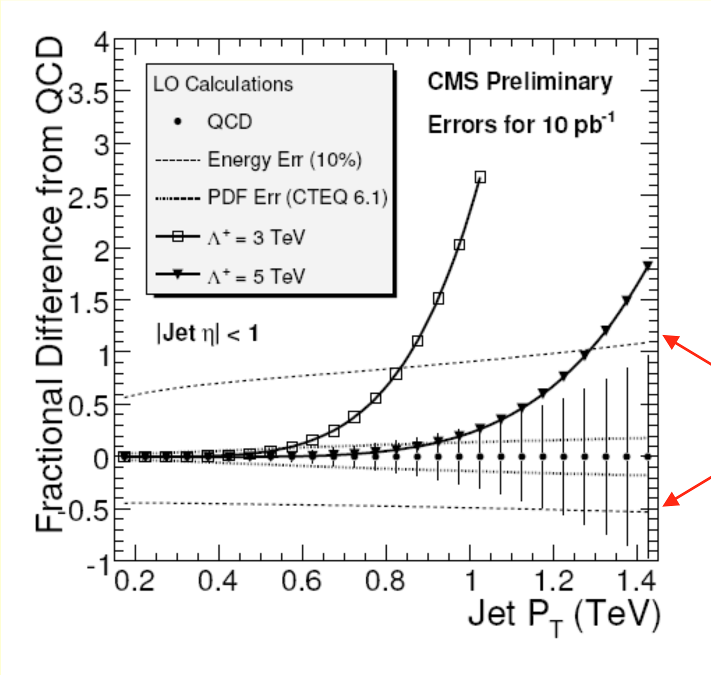
- Resonances decaying into two jets:

Discovery sensitivity around 2 TeV
(Spin-1 Z´ like resonance) for ~200 pb^{-1}

Present Tevatron limits: 320 < m < 740 GeV







10% JES

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 ~10 - 15 MeV
   - m_t 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, ….)

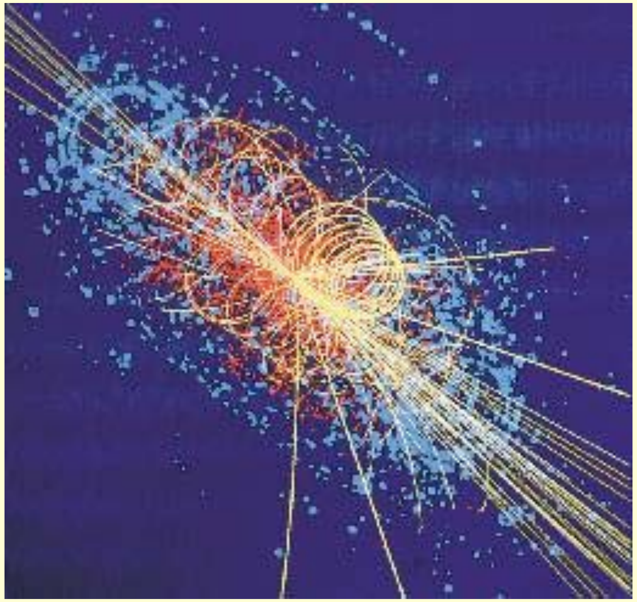
It has a crucial role in physics: can say the final word about

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

⬇

It will most likely modify our understanding of Nature

End of lectures



- 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
  (school pages)

Acknowledgements: Thanks to C. Buttar, G. Hasketh, C. Hays, E. Nurse, K. Peters for their excellent talks at the UK-HEP forum on Tevatron results and to the Tevatron speakers at Moriond 09, from which these lectures profited a lot.