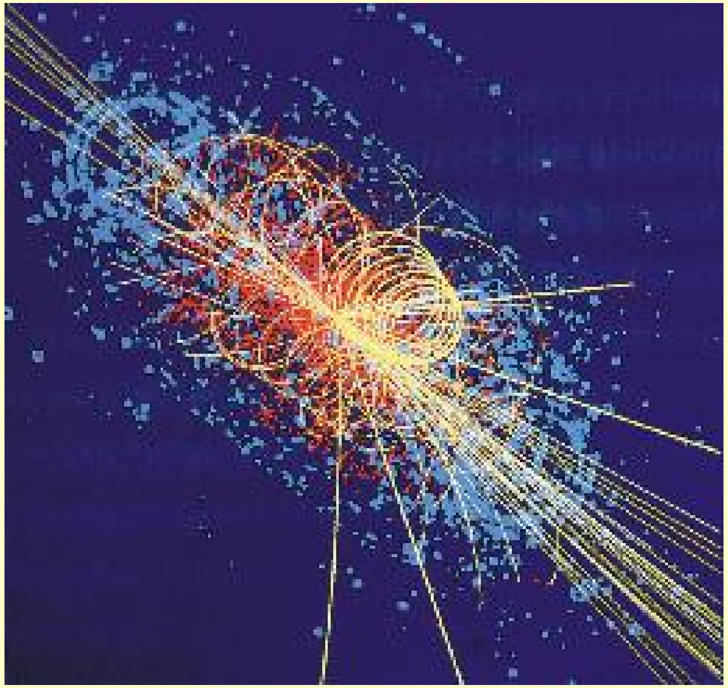
Physics at Hadron Colliders

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

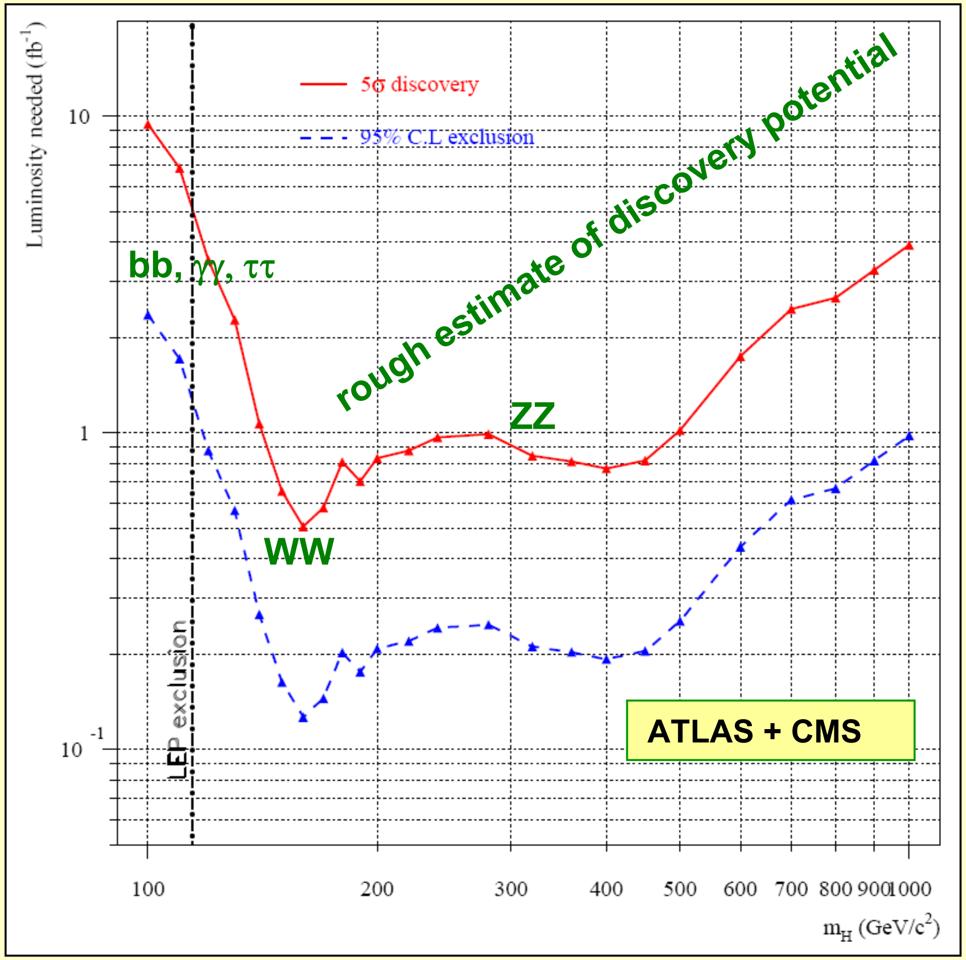
The Higgs boson at the LHC

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

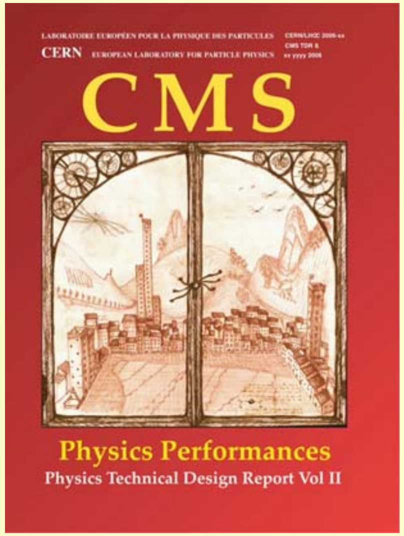
(low mass ~ 115 GeV/c^2 more difficult)

comments:

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

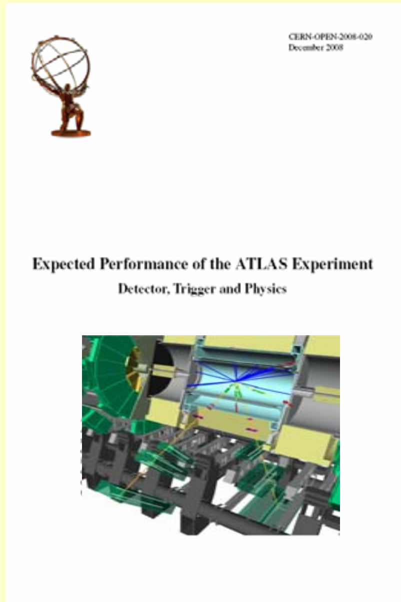
What is new on LHC Higgs studies ?

- 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)



- 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
  - …..

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



- 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.
  - …

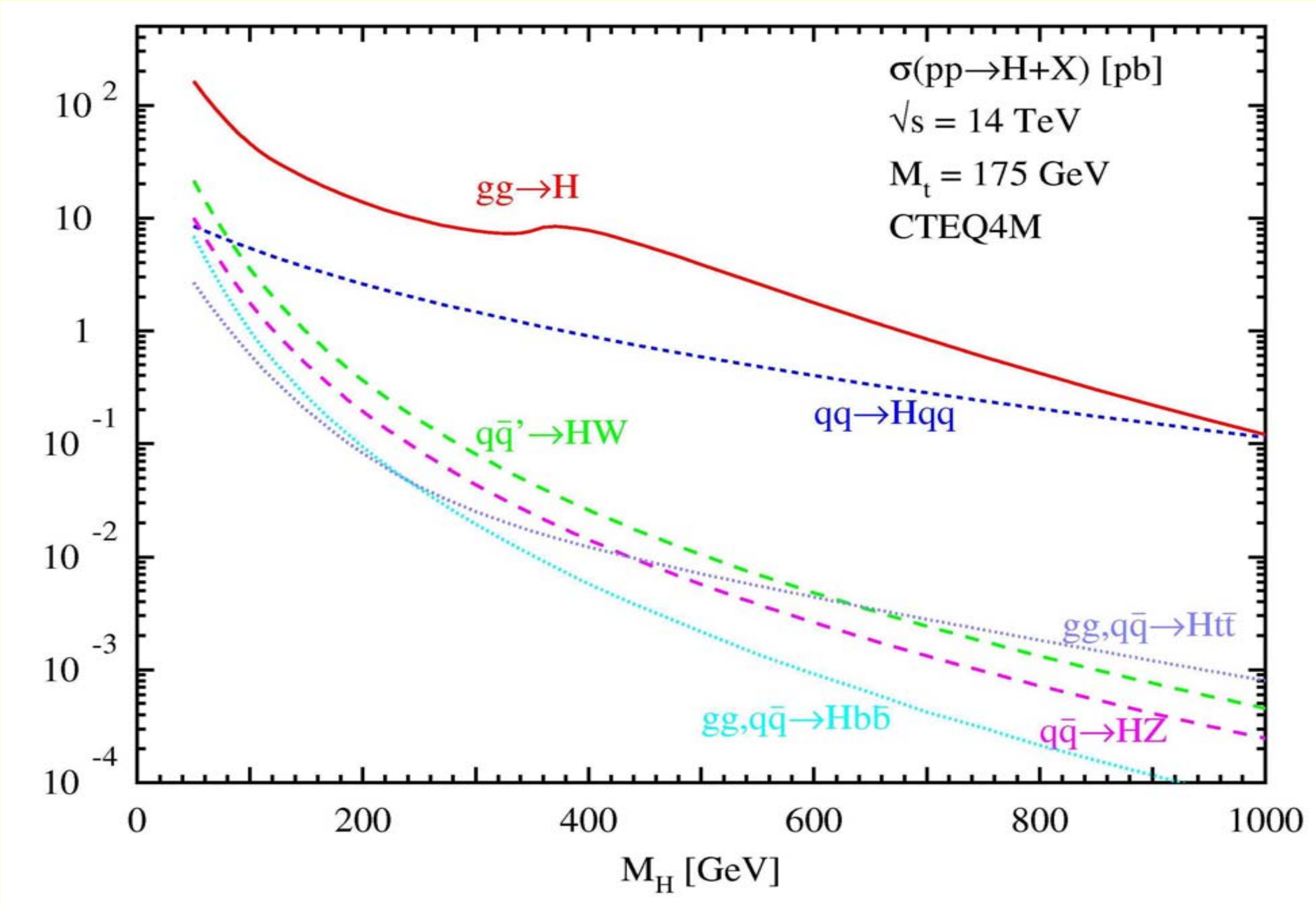
  Tevatron data are extremely valuable for validation (see yesterday's lecture)

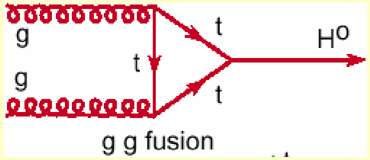
- More detailed, better understood reconstruction methods
  (partially based on test beam results,…)

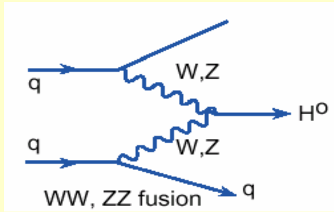
- Further studies of new Higgs boson scenarios
  (Various MSSM benchmark scenarios, CP-violating scenarios, Invisible Higgs boson decays,…..)

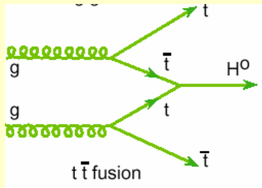
Standard Model
Higgs Boson Searches

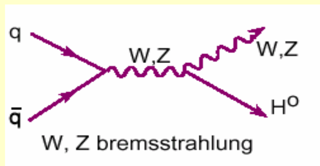
NLO cross sections, M.Spira et al.



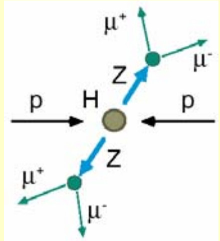








$H \rightarrow ZZ^{(*)} \rightarrow \ell\ell\ell\ell$



Signal: σ BR = 5.7 fb (m_H = 100 GeV)

Background: Top production

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

σ BR ≈ 1300 fb

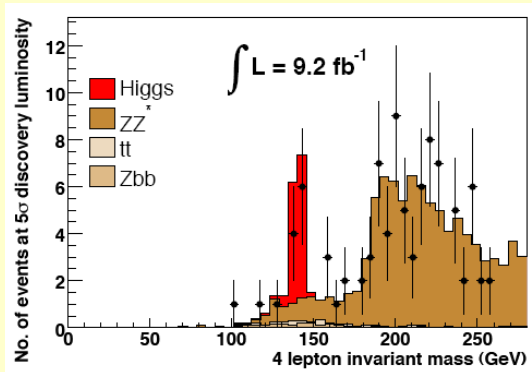
Associated production Z bb

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

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

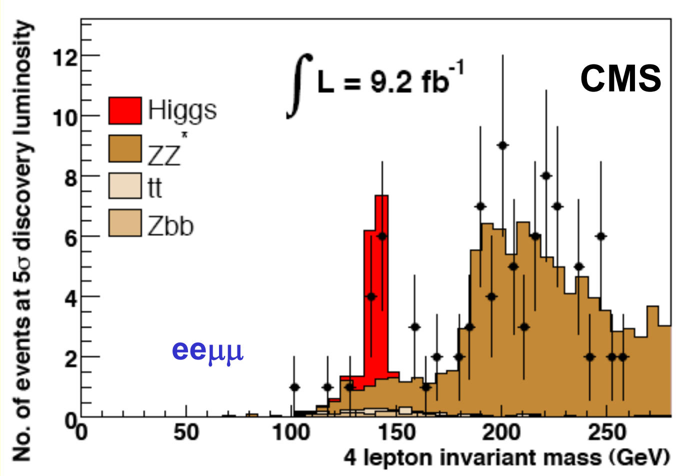
$M(\ell\ell) \sim M_Z$
$M(\ell'\ell') \sim < M_Z$

Background 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

$H \to ZZ^* \to \ell\ell\ \ell\ell$

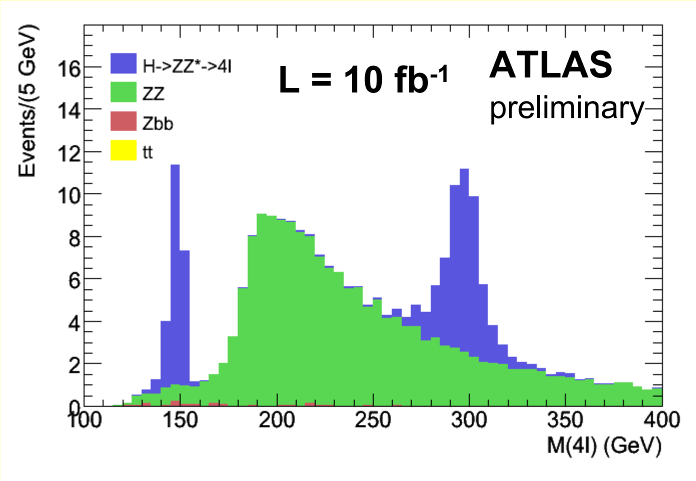


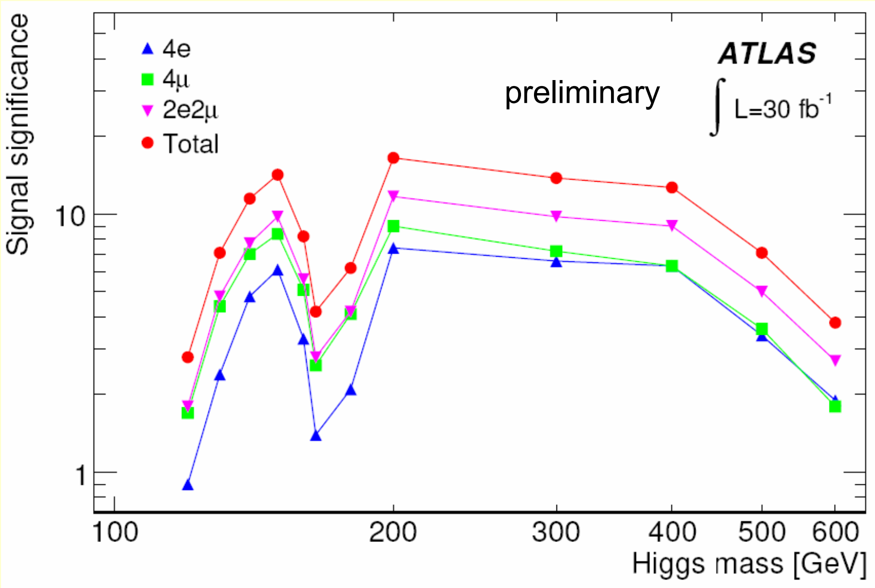
Main backgrounds: ZZ (irreducible),
tt, Zbb (reducible)

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)

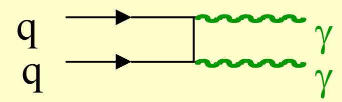




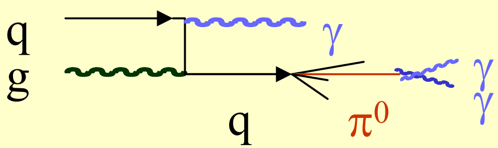
$H \rightarrow \gamma\gamma$

Main backgrounds:

$\gamma\gamma$ irreducible background



γ-jet and jet-jet (reducible)

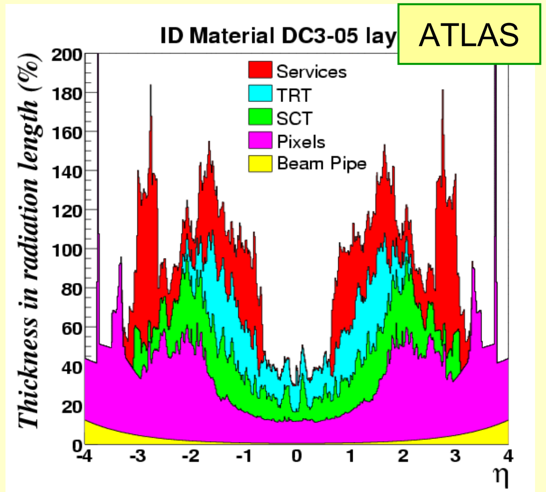


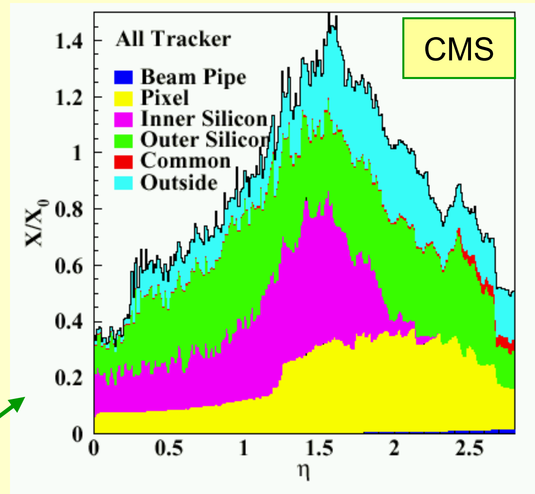
$\sigma_{\gamma j+jj} \sim 10^6 \, \sigma_{\gamma\gamma}$ with large uncertainties

$\rightarrow$ 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)



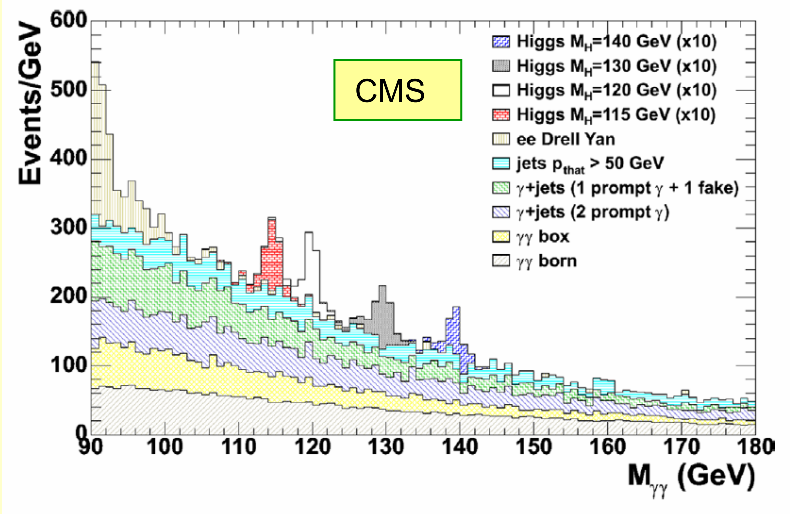


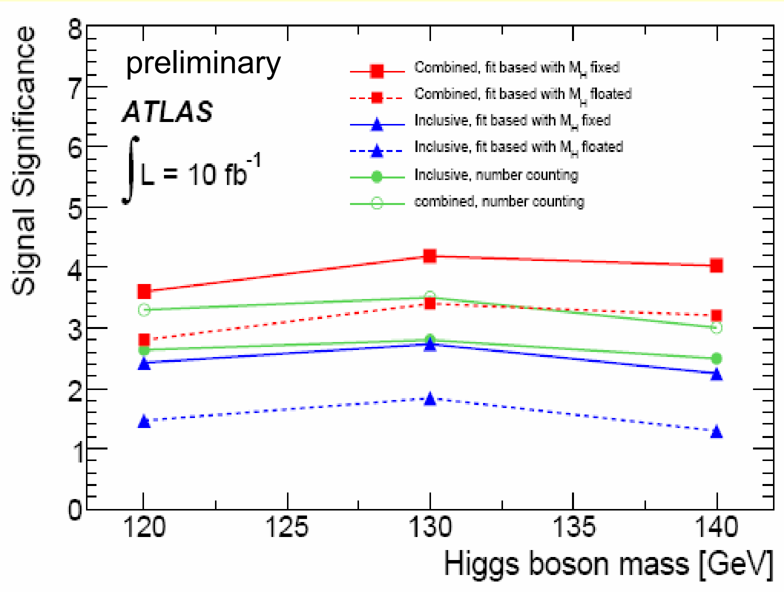
CMS: fraction of converted γs

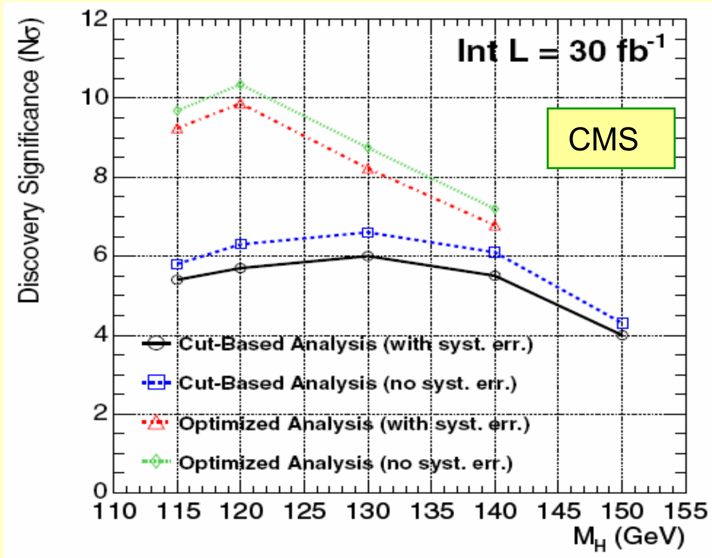
Barrel region:	42.0 %
Endcap region:	59.5 %

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





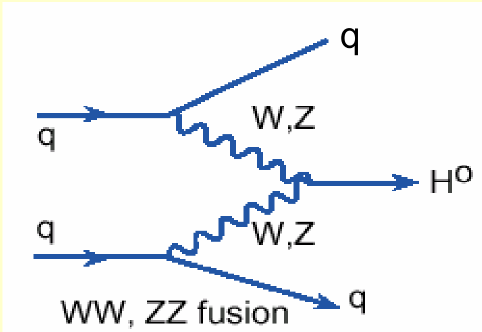


- Comparable results for ATLAS and CMS
- Improvements possible by using more exclusive $\gamma\gamma$ + jet topologies

Vector Boson Fusion qq H

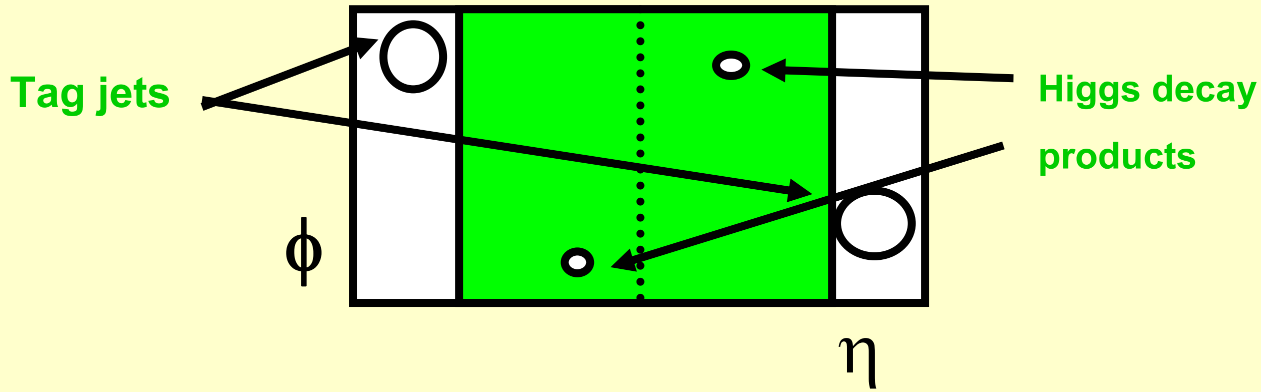
Motivation: Increase discovery potential at low mass
Improve and extend measurement of Higgs boson parameters
(couplings to bosons, fermions)

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:

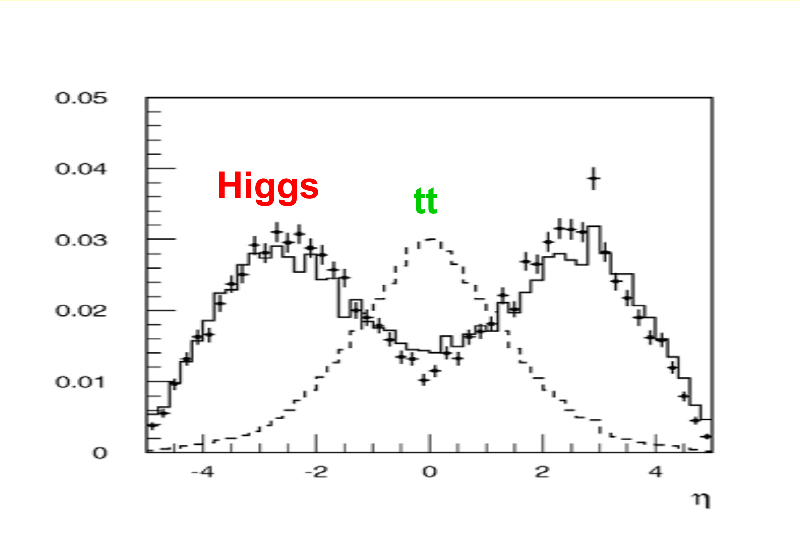
- two high p_T forward jets (tag jets)
- little jet activity in the central region (no colour flow)
  $\Rightarrow$ central jet Veto



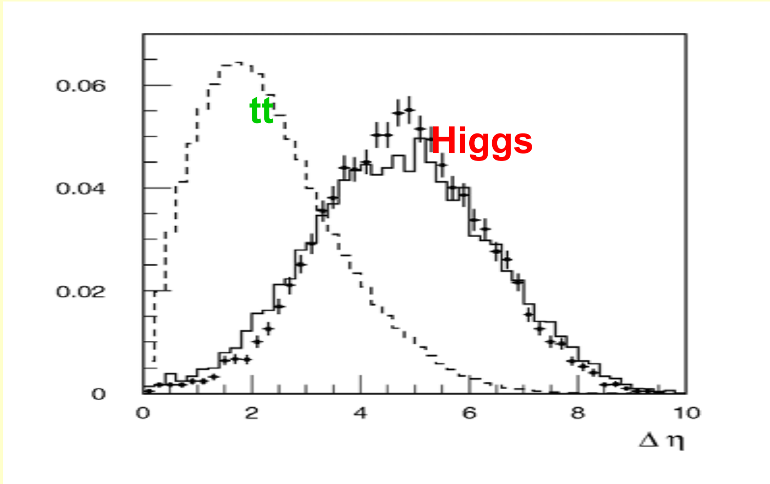
Forward jet tagging

Rapidity distribution of tag jets

VBF Higgs events vs. tt-background



Rapidity separation

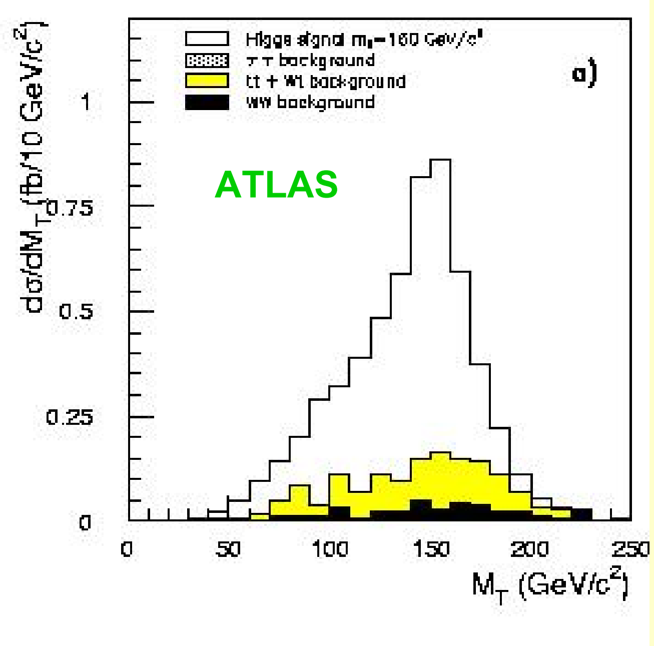


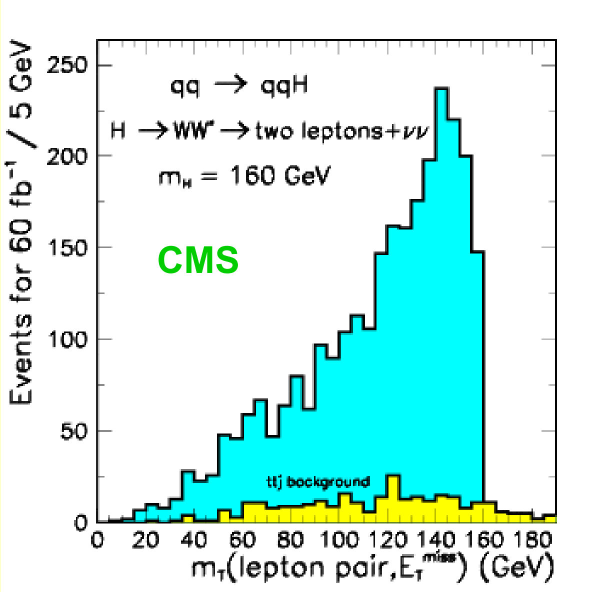
qq H → qq W W*
→ qq ℓν ℓν

Selection criteria:

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

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



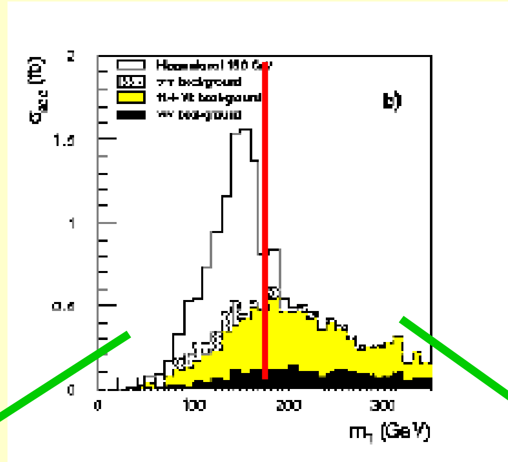


Transverse mass distributions: clear excess of events above the background from tt-production

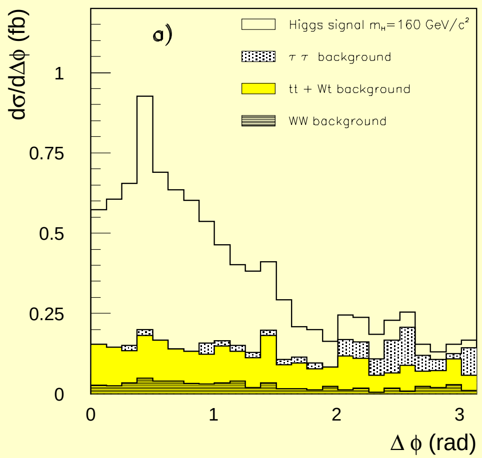
Presence of a signal can also be demonstrated in the $\Delta\phi$ distribution (i.e. azimuthal difference between the two leptons)

Evidence for spin-0 of the Higgs boson

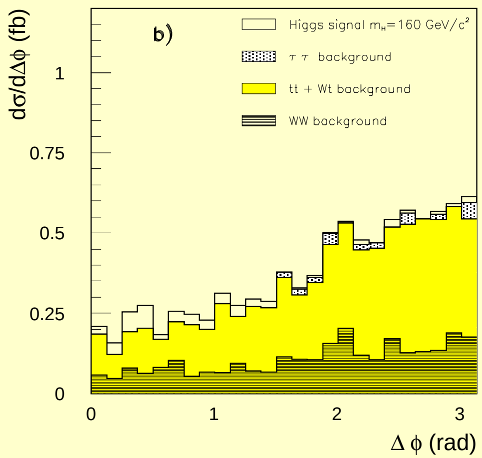
Spin-0 → WW → ℓνℓν expect leptons to be close by in space



relaxed cuts on the leptons (angular cuts not applied)



signal region



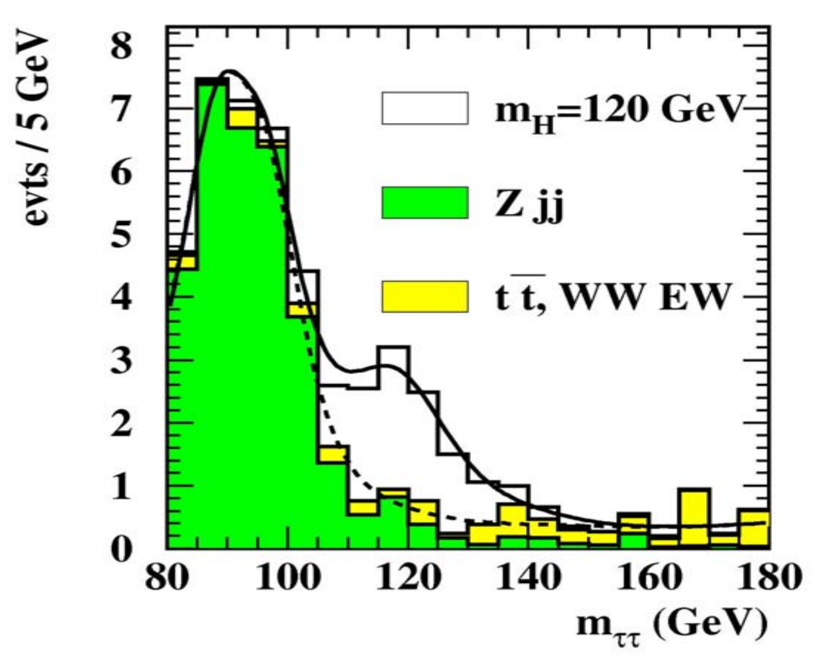
background region

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

$qq\,H \to qq\,\tau\,\tau$

$\to qq\ \ell\nu\nu\ \ell\nu\nu$

$\to qq\ \ell\nu\nu\ h\nu$



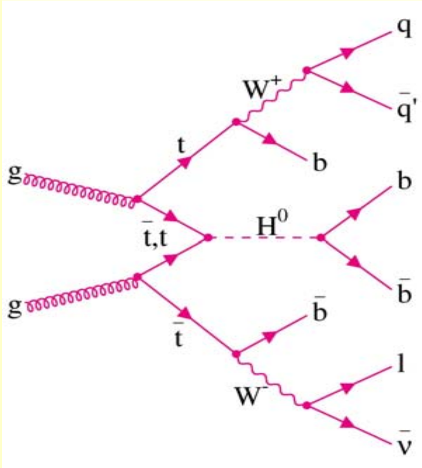
Experimental challenge:

- 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

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

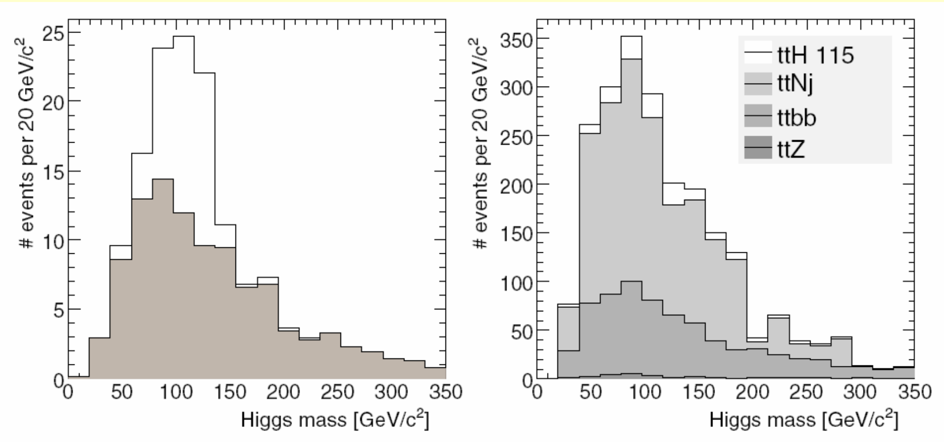


Complex final states: H→ bb, t → bjj, t → bℓν
t → bℓν, t → bℓν
t → bjj, t → bjj

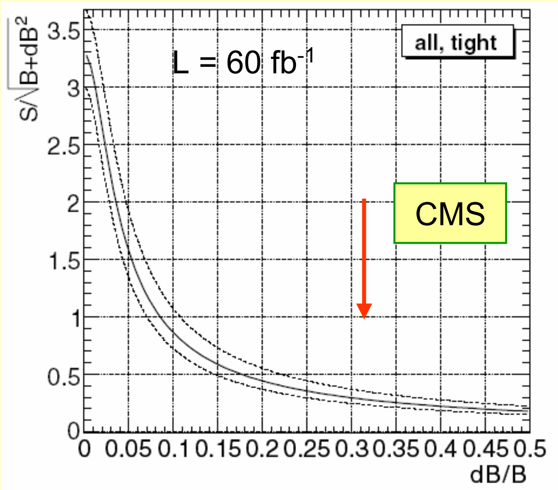
Main backgrounds:
- combinatorial background from signal (4b in final state)
- ttjj, ttbb, ttZ,…
- Wjjjjj, WWbbjj, etc. (excellent b-tag performance required)

• 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}



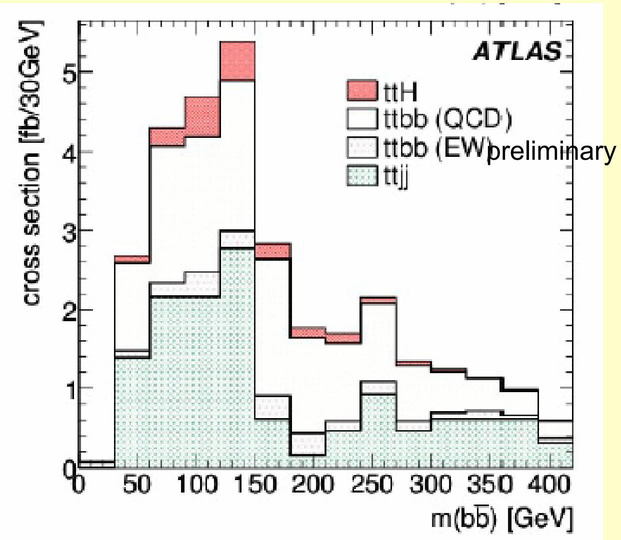
Signal events only …. backgrounds added

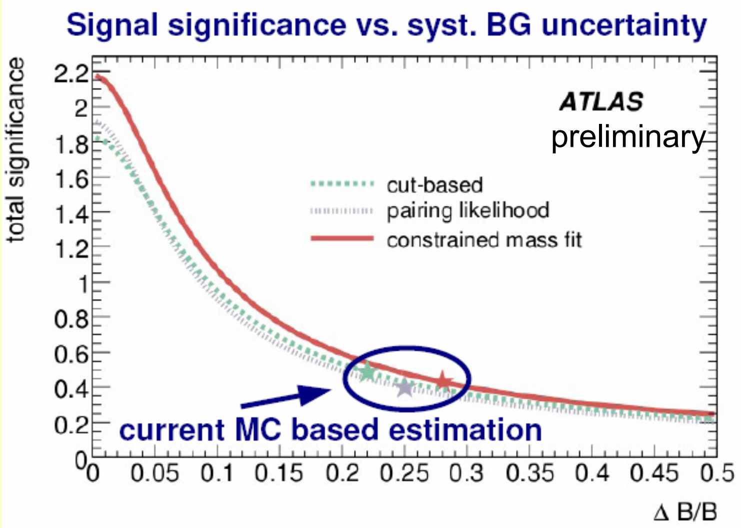


Signal significance as function of background uncertainty

…..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,…)

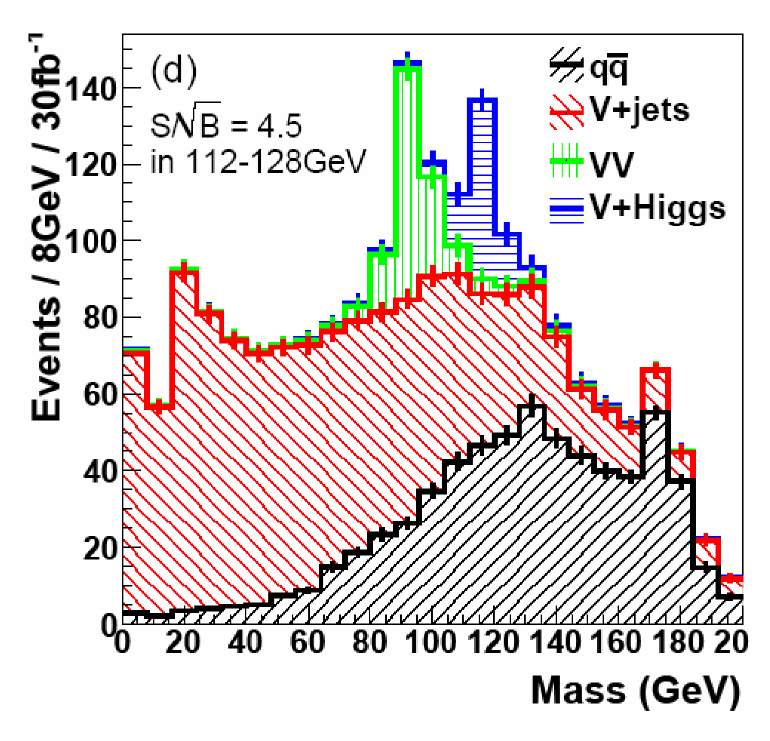
… new hope: exploit highly boosted WH and ZH, H → bb events

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

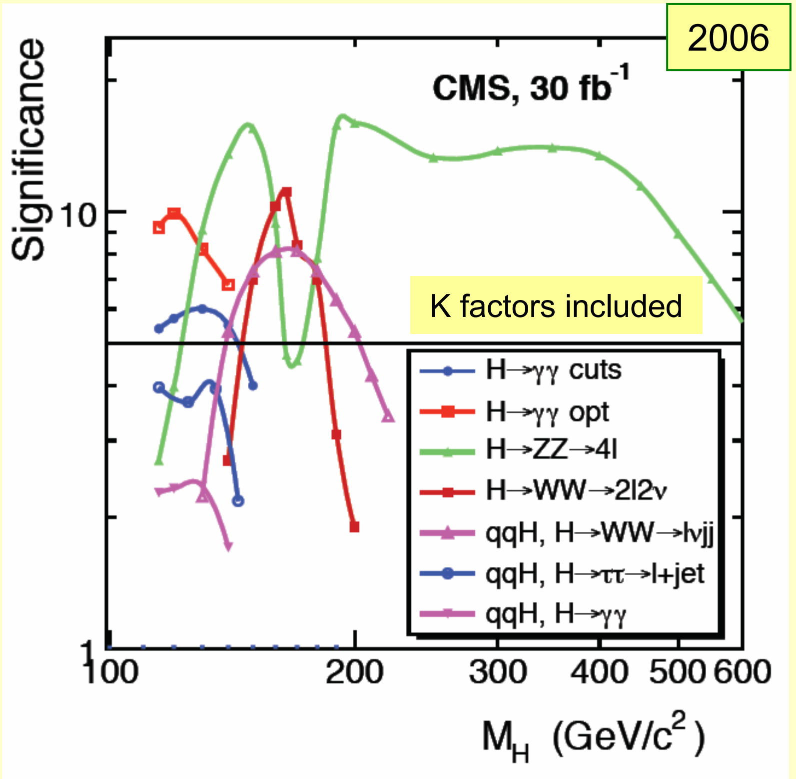
- Search for Higgs boson recoiling with large p_T against a W or Z boson (p_T > 200 GeV)
  (large reduction of signal but improved signal-to-background conditions)
- b-jets from Higgs decay are merged in one jet
- Apply sub-jet analysis, split the jet in two, including b-tagging

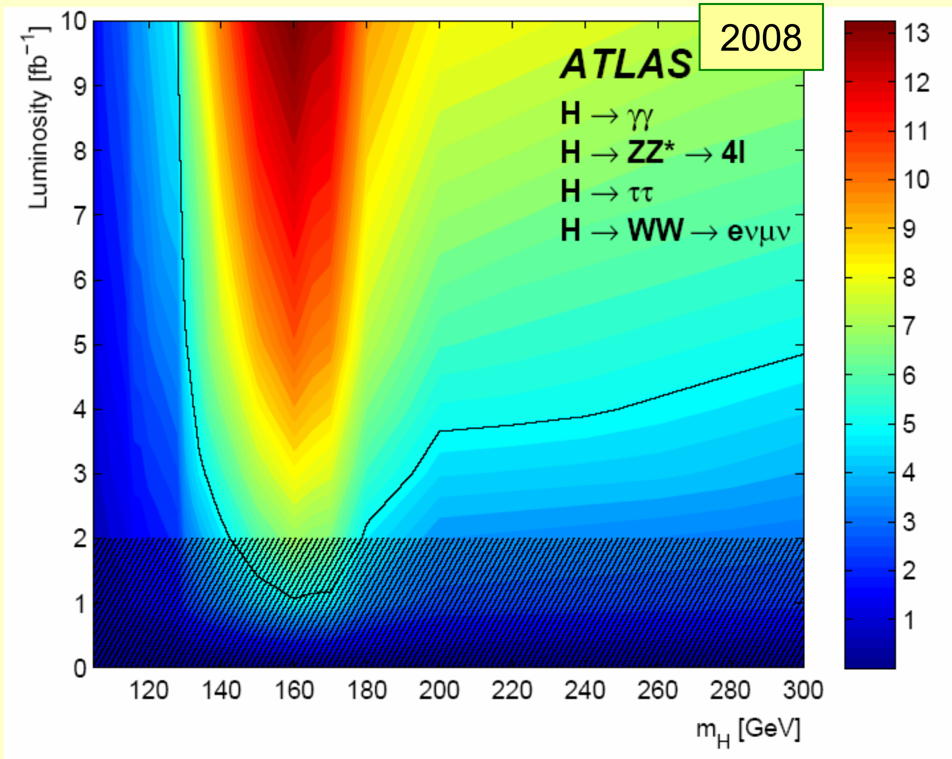
- Looks promising
- So far only particle level study
- Experimental studies with detailed detector simulations are currently being carried out

Result of a particle level study



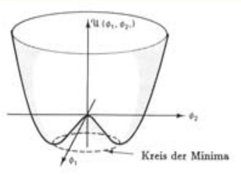
LHC Higgs boson discovery potential





- 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$\rightarrow$ 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

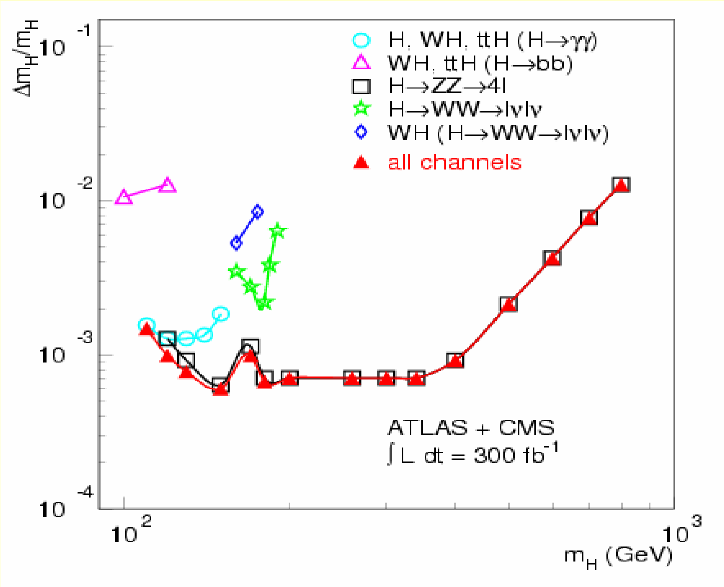
Angular distributions in the decay channel H → ZZ(*) → 4 ℓ are sensitive to spin and CP eigenvalue

4. Higgs self coupling

Possible channel: **gg → HH → WW WW → $\ell\nu$ 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

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)

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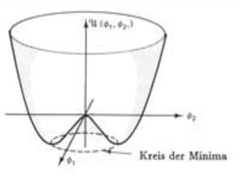

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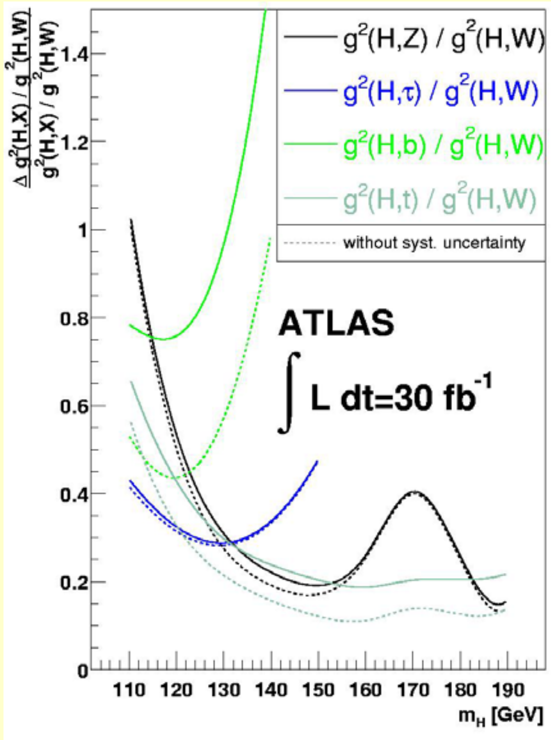
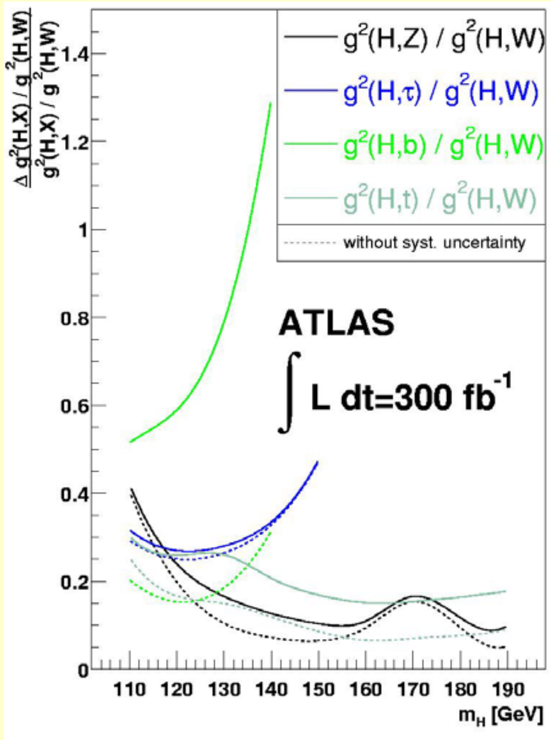
Measurement of Higgs Boson Couplings

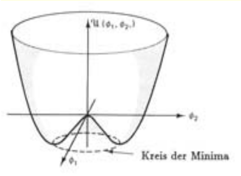
Global likelihood-fit (at each possible Higgs boson mass)
Input: measured rates, separated for the various production modes

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





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



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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$\rightarrow$ 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 $\rightarrow$ ZZ(*) $\rightarrow$ 4 ℓ are sensitive to spin and CP eigenvalue

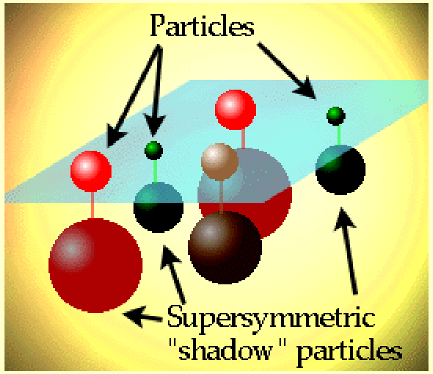
4. Higgs self coupling

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,...

$\Rightarrow$ 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)

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

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

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

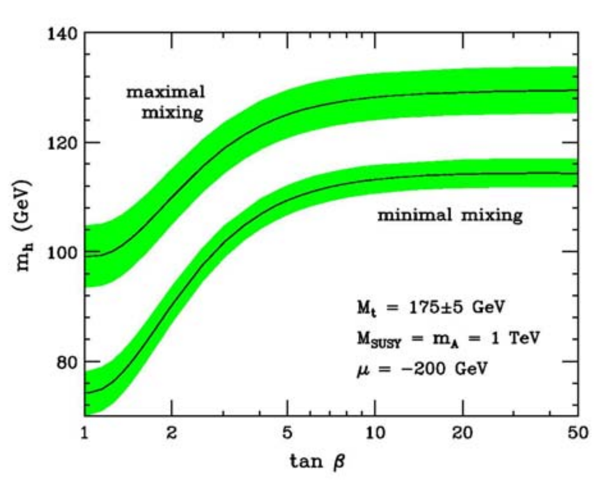
→ upper mass bound depends on top mass and mixing in the stop sector

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

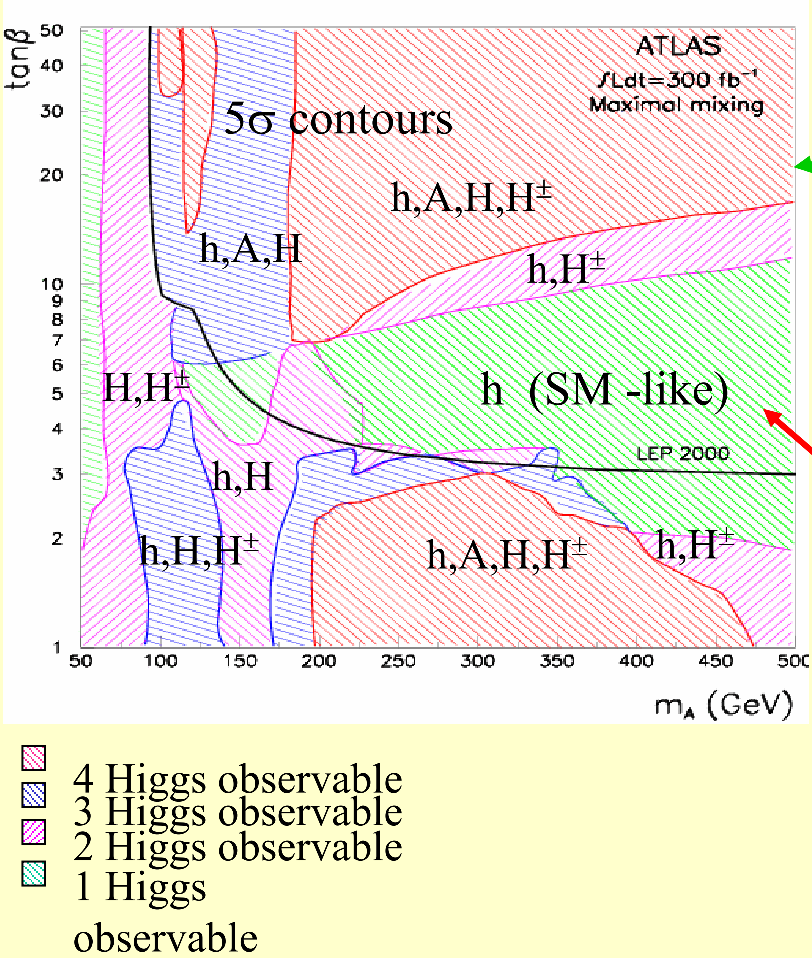
where: $M_S^2 = \frac{1}{2}\left(M_{\tilde{t}_1}^2 + M_{\tilde{t}_2}^2\right)$ and $x_t = (A_t - \mu\cot\beta)\;/\;M_S$

→ 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



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.

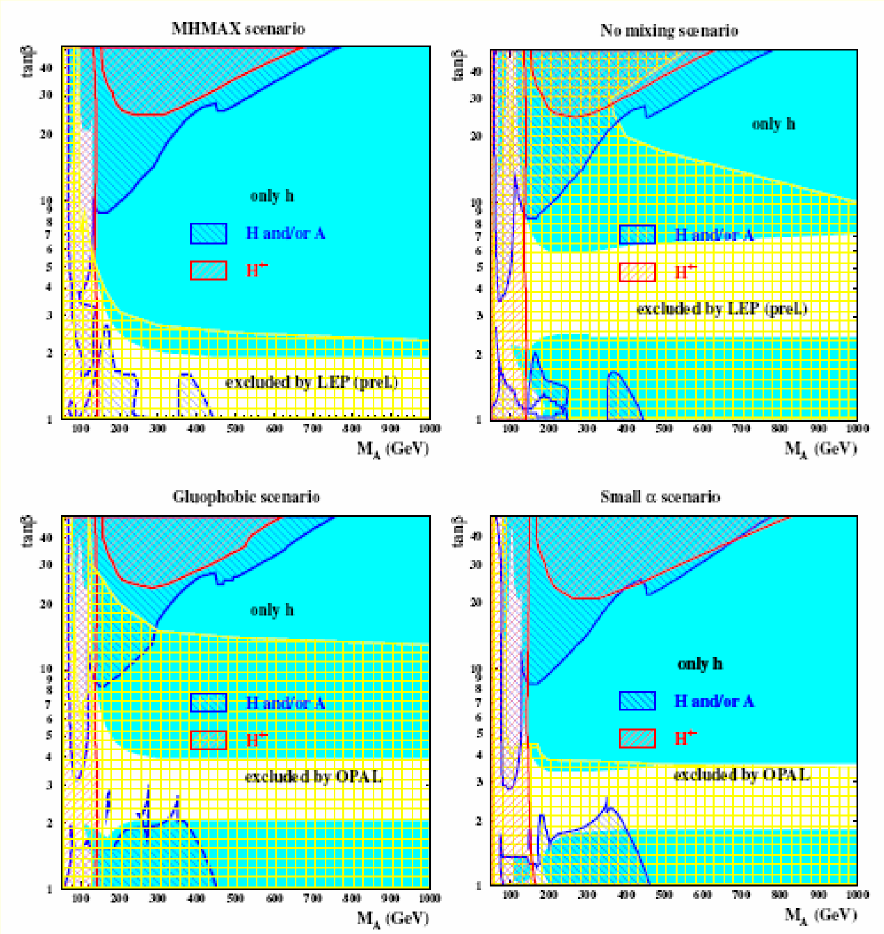
* Validated by recent ATLAS and CMS full simulation studies *

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

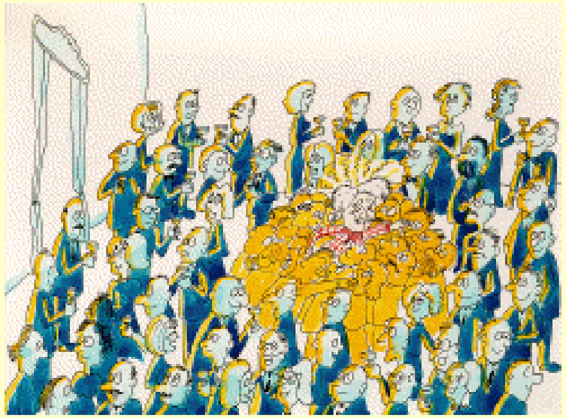
Small α scenario (M_{SUSY} = 800 GeV/c^2)
coupling to b (and **t**) suppressed
(cancellation of sbottom, gluino loops) for large tan β and M_A 100 to 500 GeV/c^2

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
…….

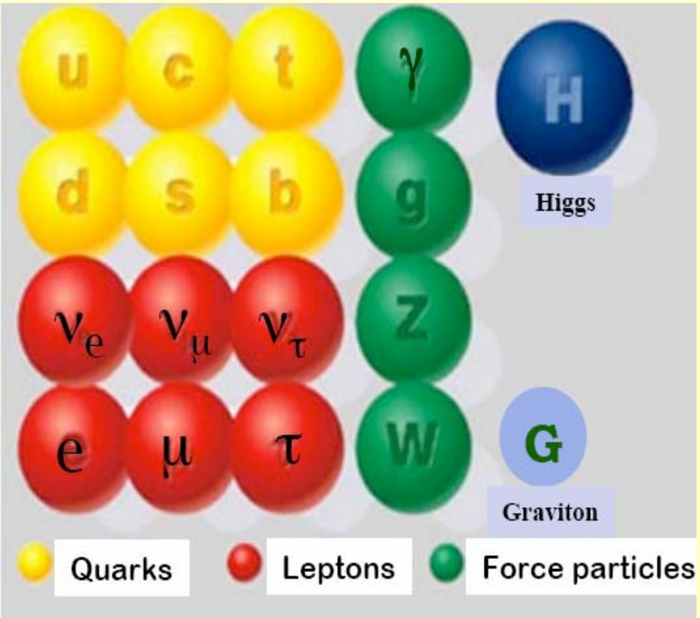
Many extensions predict new physics at the TeV scale !!

Strong motivation for LHC, mass reach ~ 3 TeV

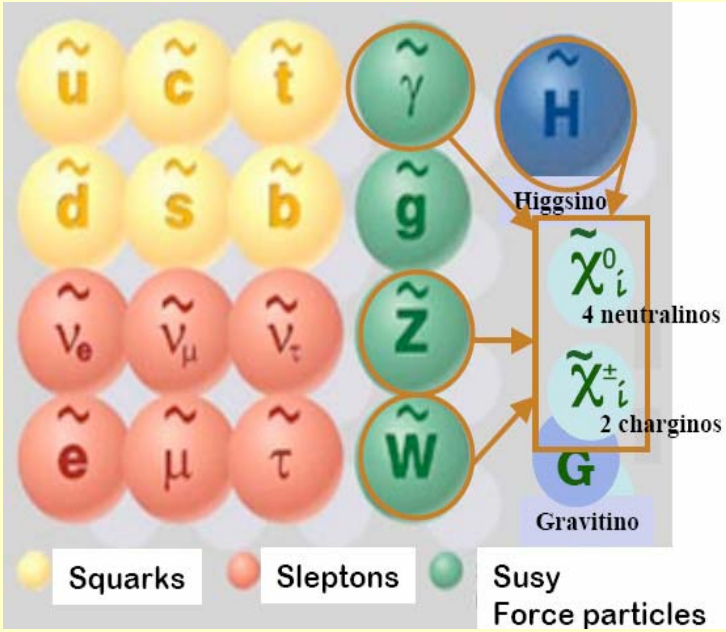
Supersymmetry

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.

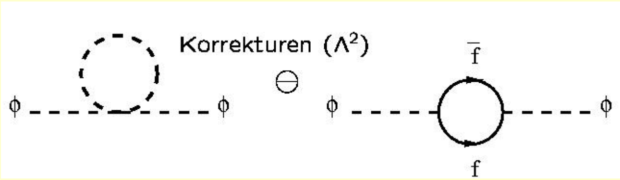
LSP is only weakly interacting:
LSP $\equiv \chi^0{}_1$ (lightest neutralino, in many models)

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

$\rightarrow$ 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

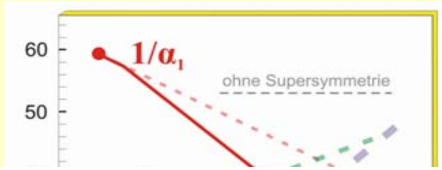


$$\Delta m_H = f(m_B^2 - m_f^2)$$

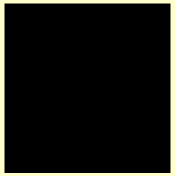
→ m_{SUSY} ~ 1 TeV

(Hierarchy or naturalness problem)

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

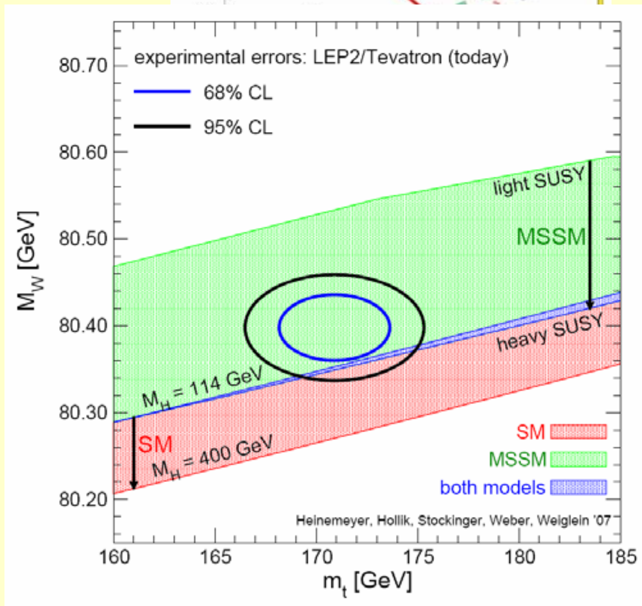


3. SUSY provides a candidate for dark matter,



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) $\rightarrow$ 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

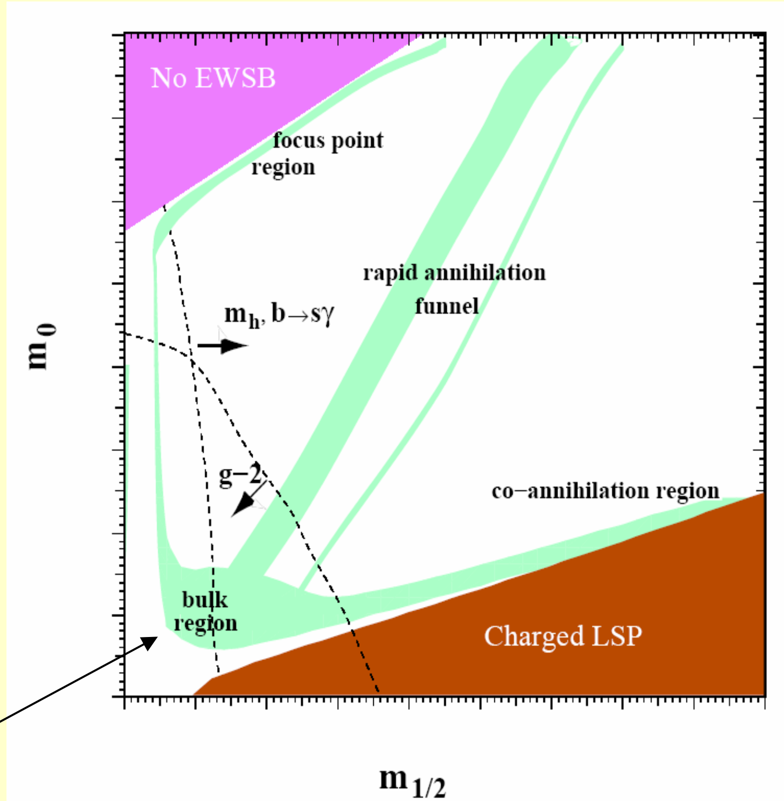
$$\rho_\chi = m_\chi n_\chi \, , \quad n_\chi \sim \frac{1}{\sigma_{ann}(\chi\chi \to \ldots)}$$

Interpretation in a simplified model

cMSSM
(constrained Minimal Supersymmetric
Standard Model)

Five parameters:

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

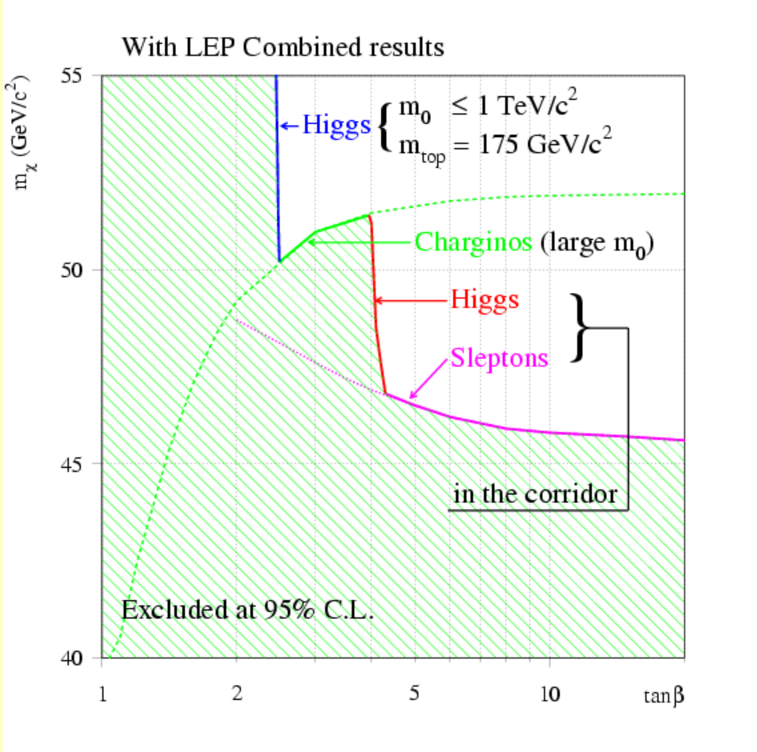


regions of parameter space which are consistent with the measured relic density of dark matter (WMAP,…..)

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

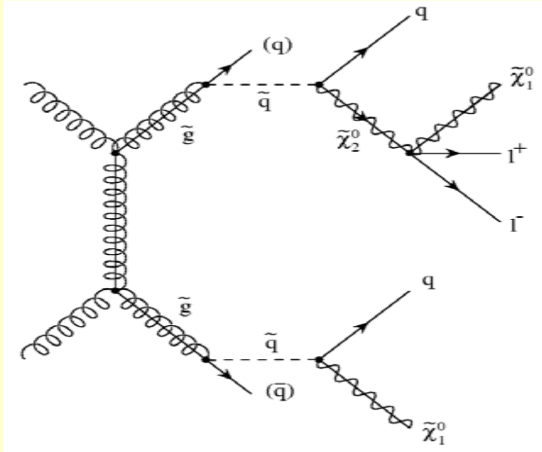
assumption:
lightest neutralino = LSP

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)



$\Rightarrow$ 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

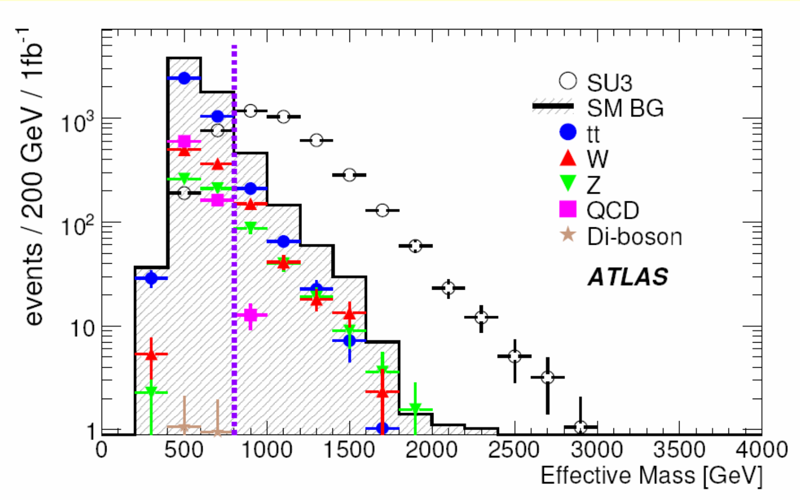
3. Step: Determine model parameters (difficult)
   Strategy: select particular decay chains and use kinematics to determine mass combinations

Squarks and Gluinos

- 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)



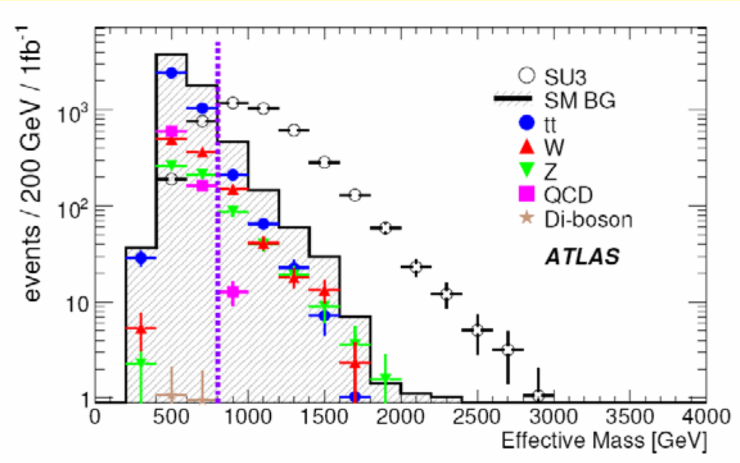
LHC reach for Squark- and Gluino masses:

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

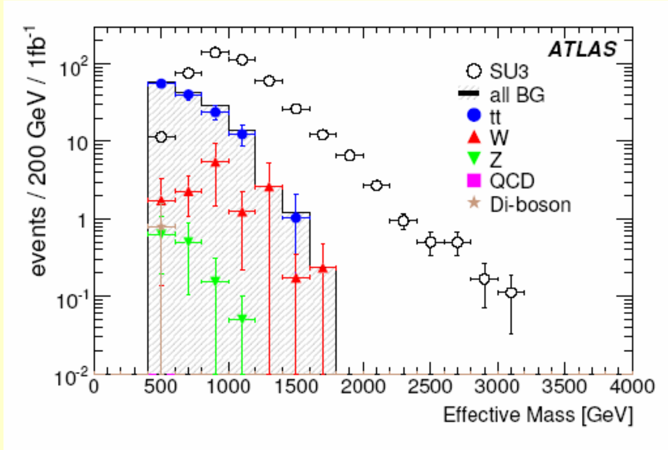
Deviations from the Standard Model due to SUSY at the TeV scale can be detected fast !

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

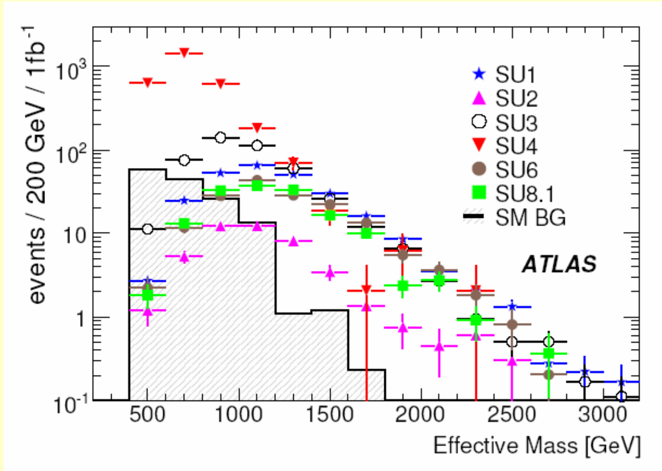


SU3, 4 jets + 0 lepton final states



SU3, 4 jets + 1 lepton final states

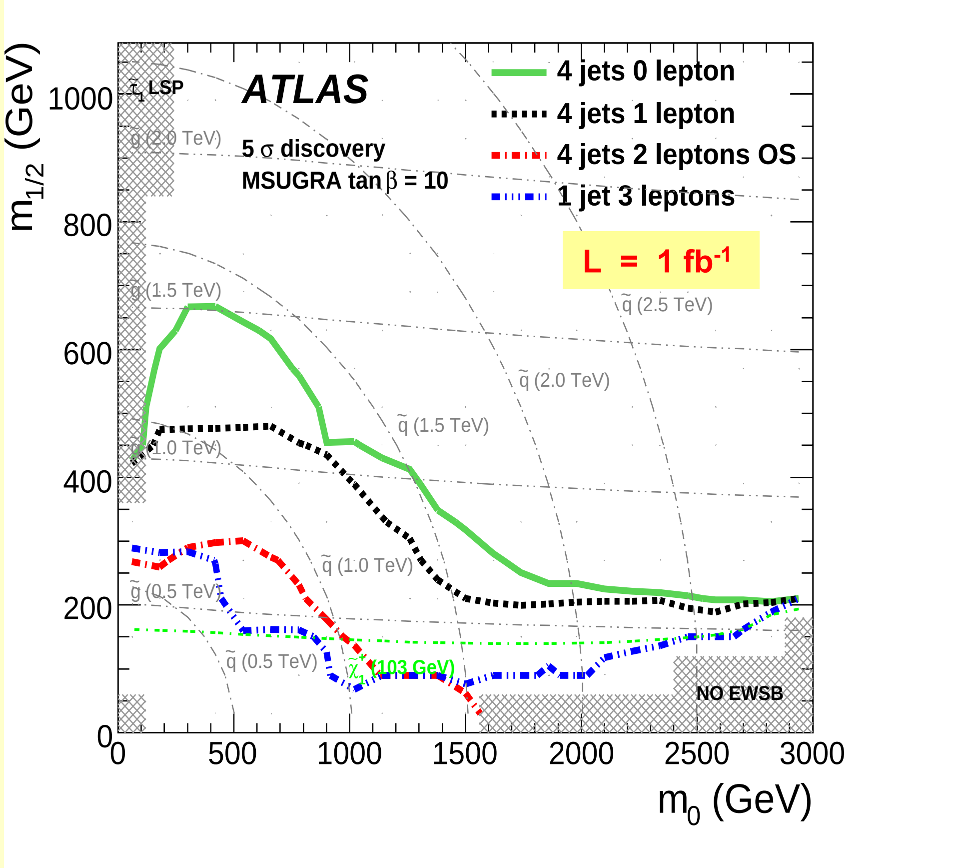
- Smaller signal rates, but better S:B conditions
- Discovery potential is more robust, in particular at the beginning, when systematic uncertainties on the backgrounds are large
- Similar analyses with τ lepton and b quark final states



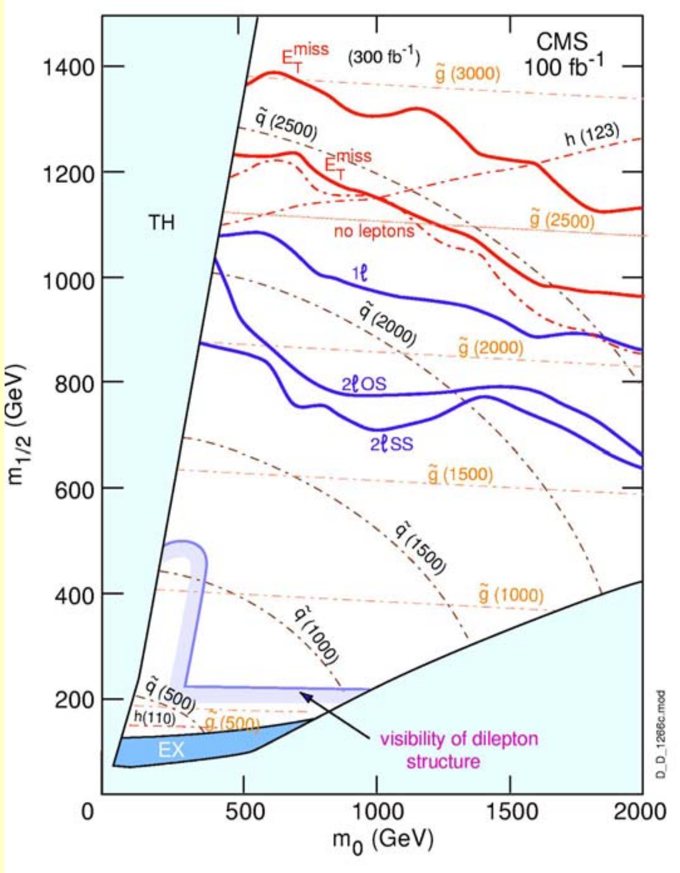
4 jets + 1 lepton final states for other benchmark points

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

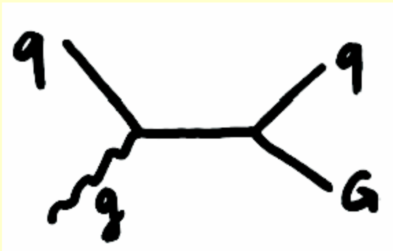
  Long term mass reach (300 fb^{-1}): 2.5 – 3 TeV

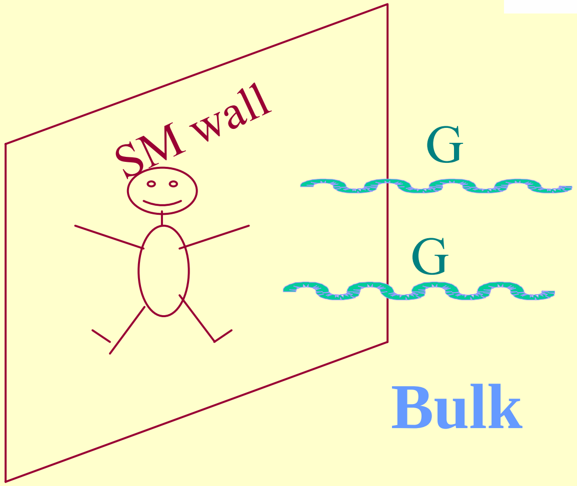
How can the underlying theoretical model be identified ?

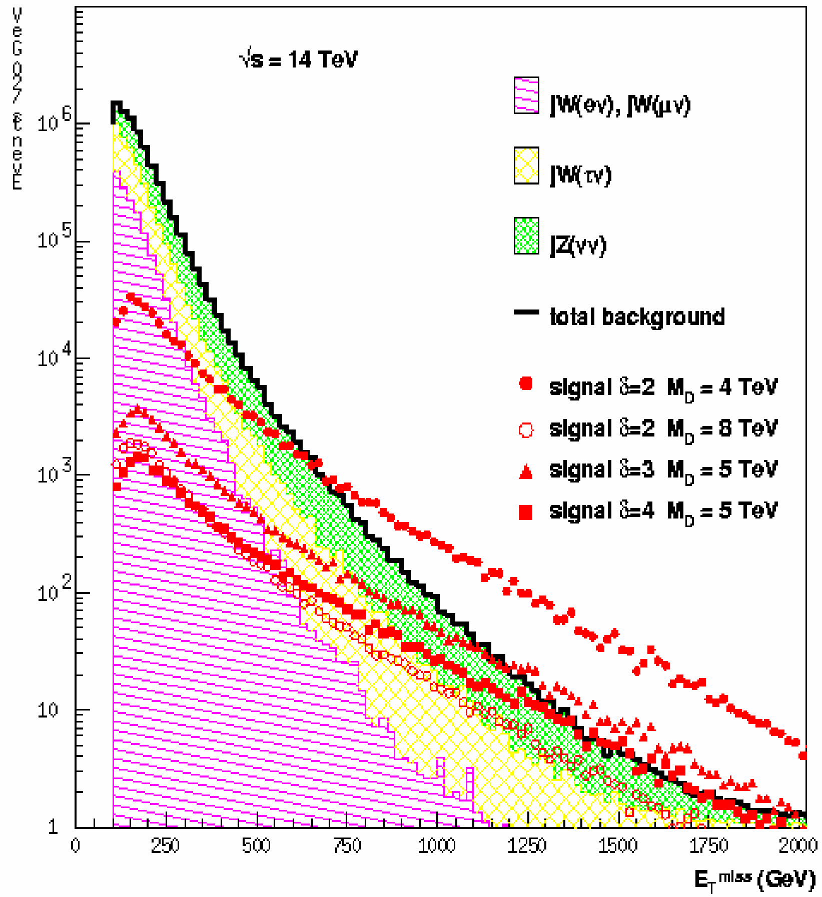
- Not easy !!
- Other possible scenarios for Physics Beyond the Standard Model could lead to similar final state signatures
  e.g. search for direct graviton production in extra dimension models

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

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

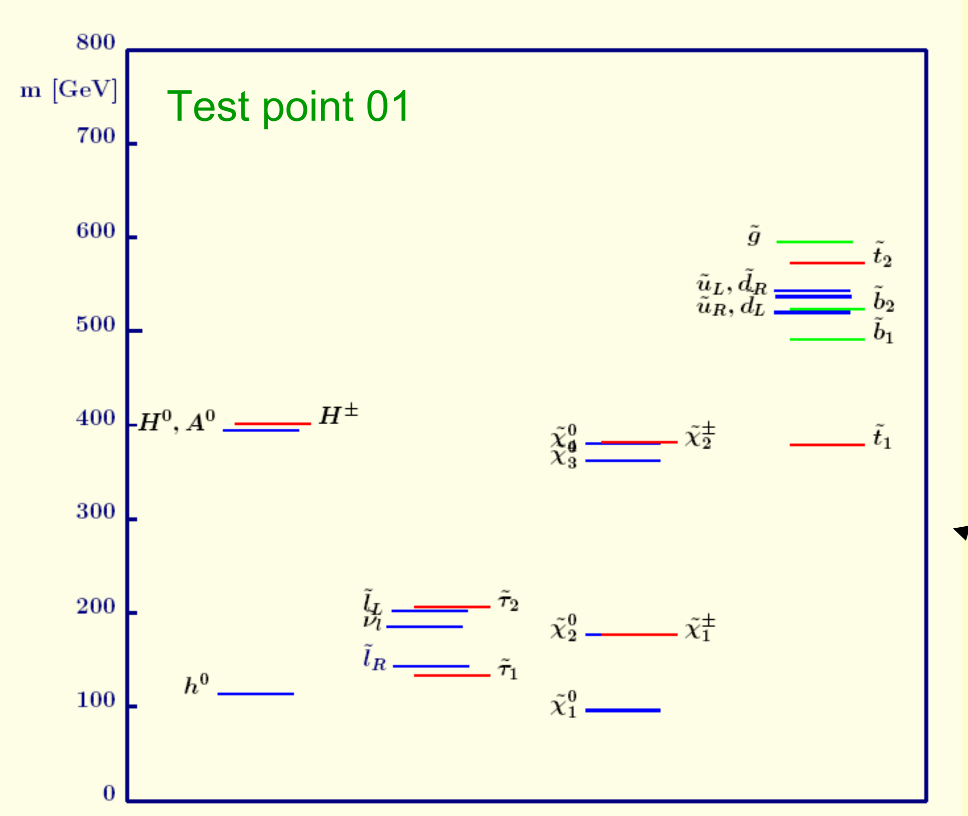


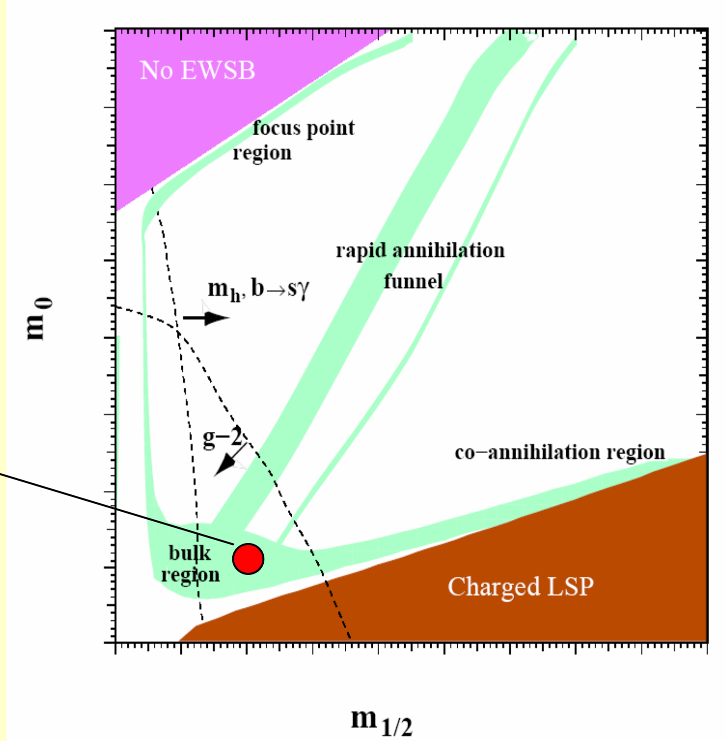




How can the underlying theoretical model be identified ?

Measurement of the SUSY spectrum → Parameter of the theory





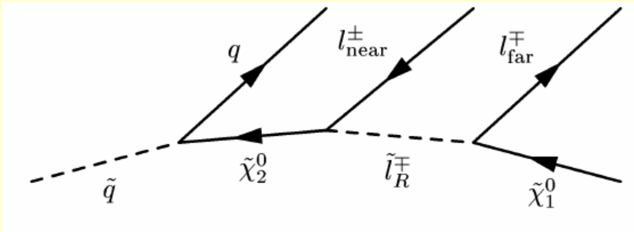
LHC: strongly interacting squarks and gluinos

ILC / CLIC: precise investigation of electroweak SUSY partners

LHC Strategy: End point spectra of cascade decays

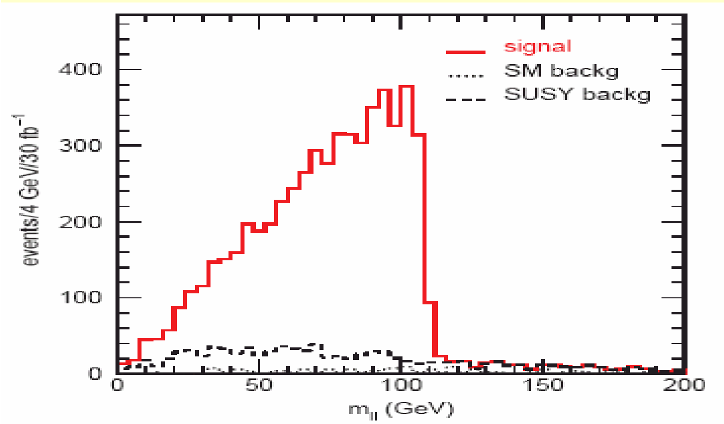
Example: $\tilde{q} \rightarrow q\tilde{\chi}_2^0 \rightarrow q\tilde{\ell}^{\pm}\ell^{\mp} \rightarrow q\ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$

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

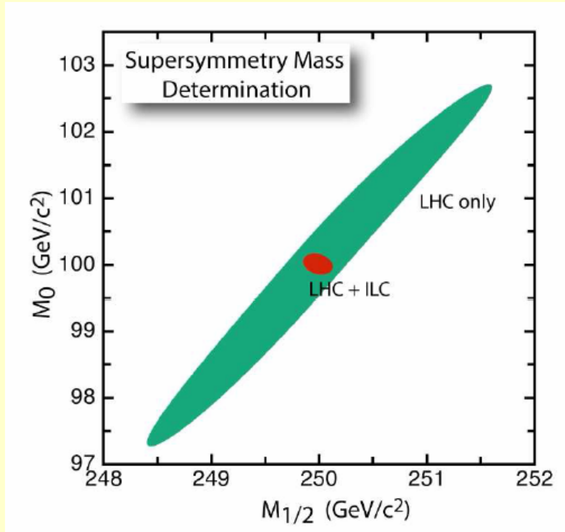


$$M_{\ell_1 q}^{max} = \frac{\sqrt{(m_{\chi_2^0}^2 - m_{\tilde{\ell}}^2)(m_{\tilde{q}}^2 - m_{\chi_2^0}^2)}}{m_{\chi_2^0}}$$

Results for point 01:



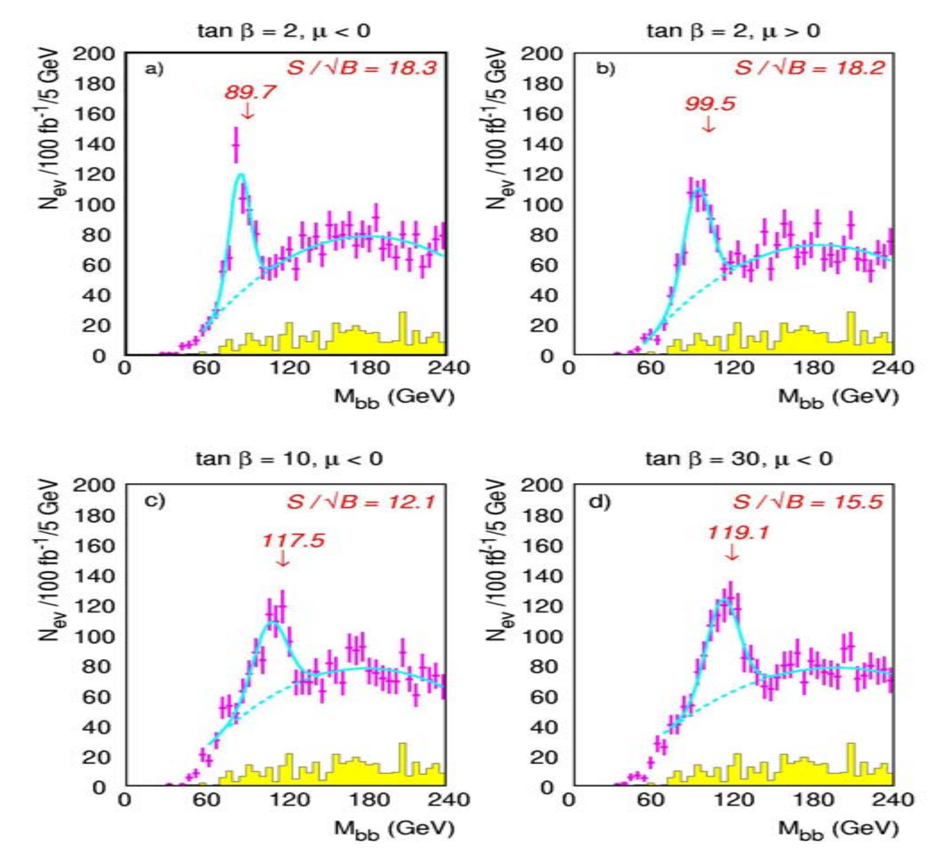
	LHC	LHC⊕ILC
$\Delta m_{\tilde{\chi}_1^0}$	4.8	0.05 (input)
$\Delta m_{\tilde{l}_R}$	4.8	0.05 (input)
$\Delta m_{\tilde{\chi}_2^0}$	4.7	0.08
$\Delta m_{\tilde{q}_L}$	8.7	4.9
$\Delta m_{\tilde{q}_R}$	11.8	10.9
$\Delta m_{\tilde{g}}$	8.0	6.4
$\Delta m_{\tilde{b}_1}$	7.5	5.7
$\Delta m_{\tilde{b}_2}$	7.9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

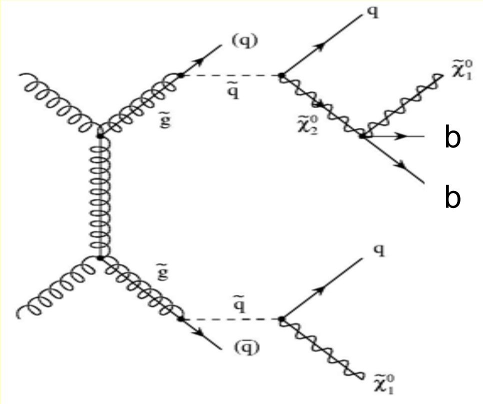


L = 300 fb^{-1}

$h \rightarrow bb$:

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 !

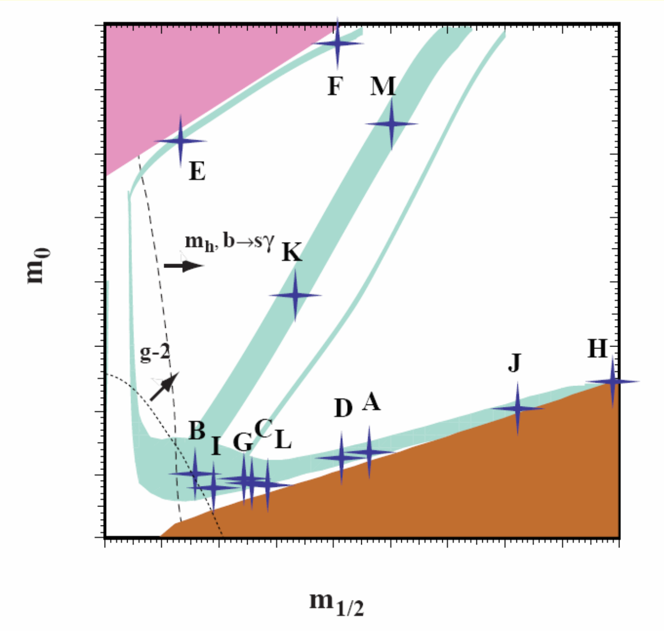
SM background can be reduced

by applying a cut on E_T^{miss}

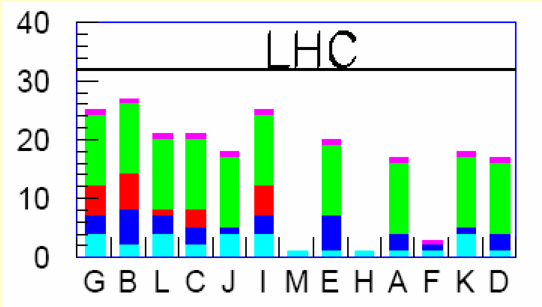
Strategy in SUSY Searches at the LHC:

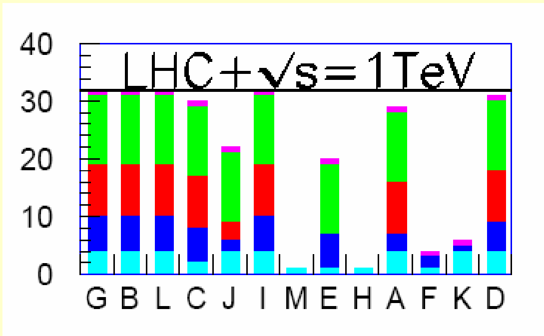
- Search for multijet + E_T^{miss} excess
- If found, select SUSY sample (simple cuts)
- Look for special features (γ's , long lived sleptons)
- Look for $\ell^{\pm}$, $\ell^{+} \ell^{-}$, $\ell^{\pm} \ell^{\pm}$, b-jets, τ's
- End point analyses, global fit $\rightarrow$ SUSY model parameters

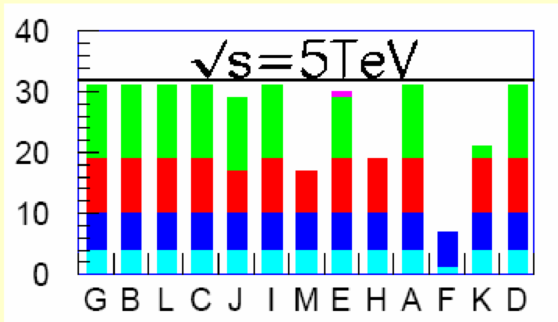
The LHC and the ILC (International Linear Collider, in study/planning phase) are complementary in SUSY searches



Number of observable SUSY particles:





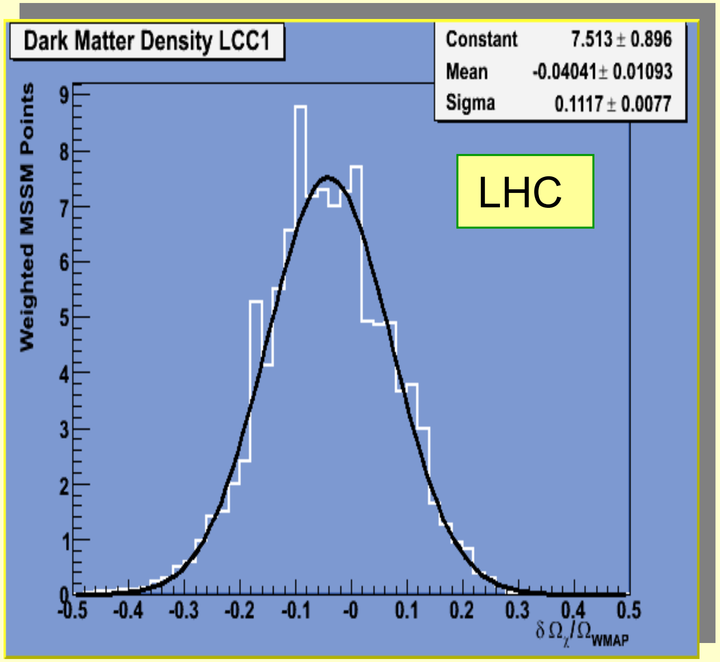


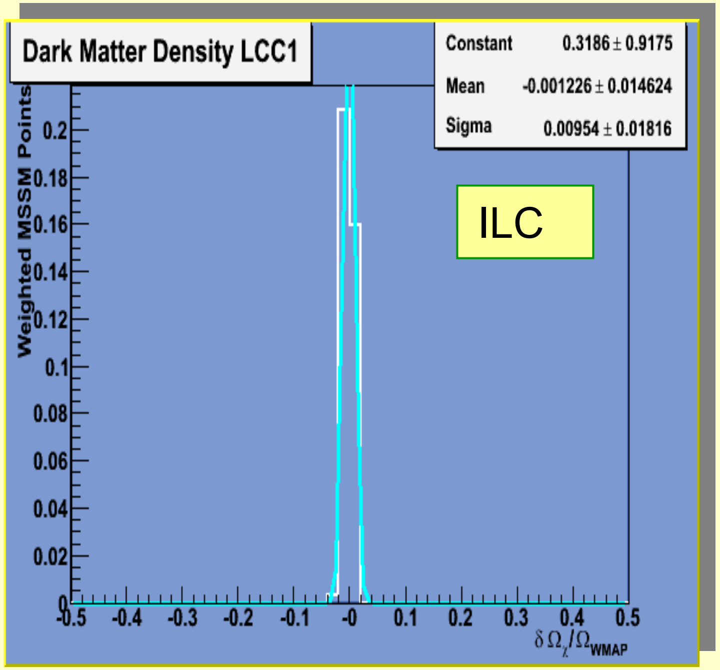
)* Study by J. Ellis et al., hep-ph/0202110

Dark Matter at Accelerators ?

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

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



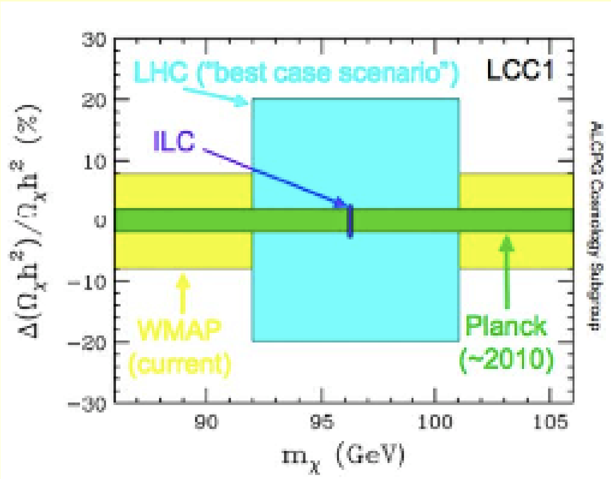


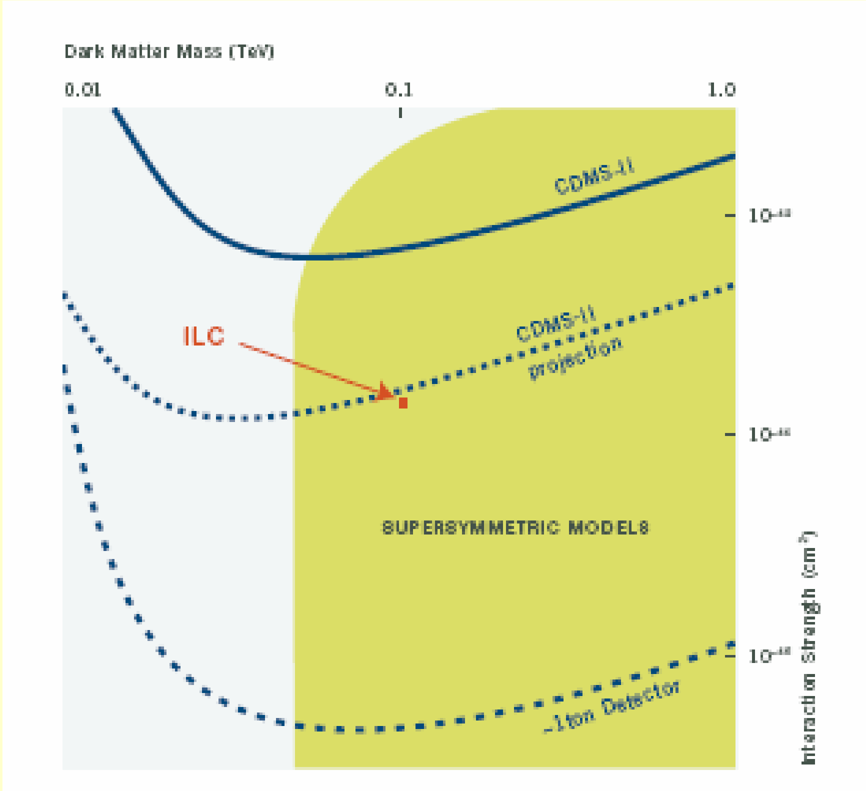
Battaglia et al.

L = 300 fb^{-1} $\delta\Omega / \Omega \sim 11\%$

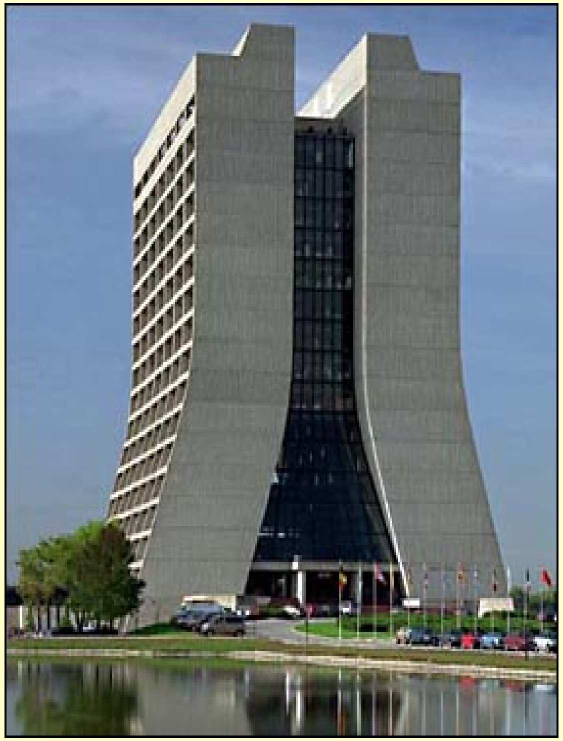
L = 1000 fb^{-1} $\delta\Omega / \Omega \sim 1\%$

Importance for direct and indirect searches of Dark Matter





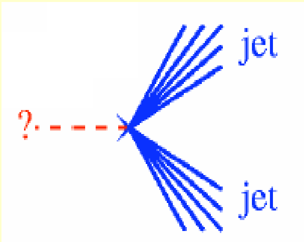
The Search for

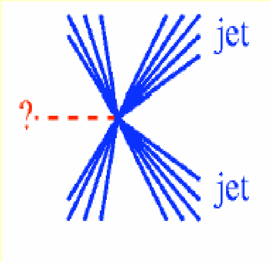


SUSY at the Tevatron

The two classical signatures

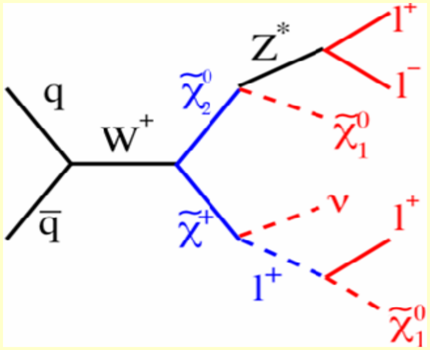
1. Search for Squarks and Gluinos: Jet + E_T^{miss} signature
   produced via QCD processes





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)

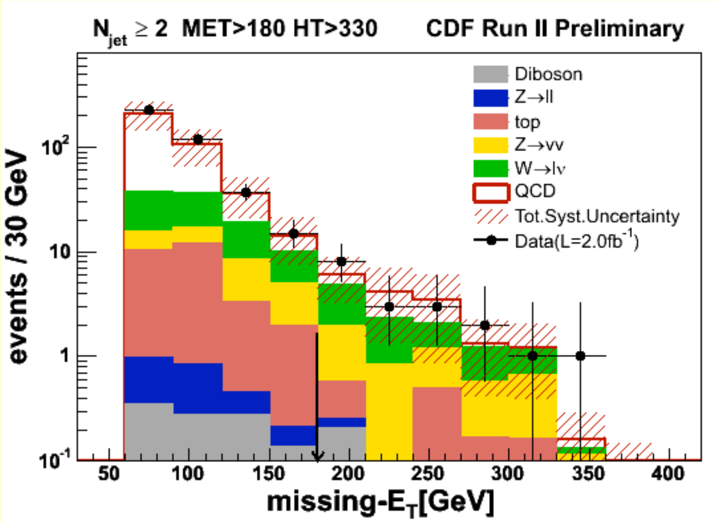
$$\tilde{q}\,\tilde{g} \rightarrow q\,\tilde{\chi}_1^0\,q\,\bar{q}\,\tilde{\chi}_1^0$$

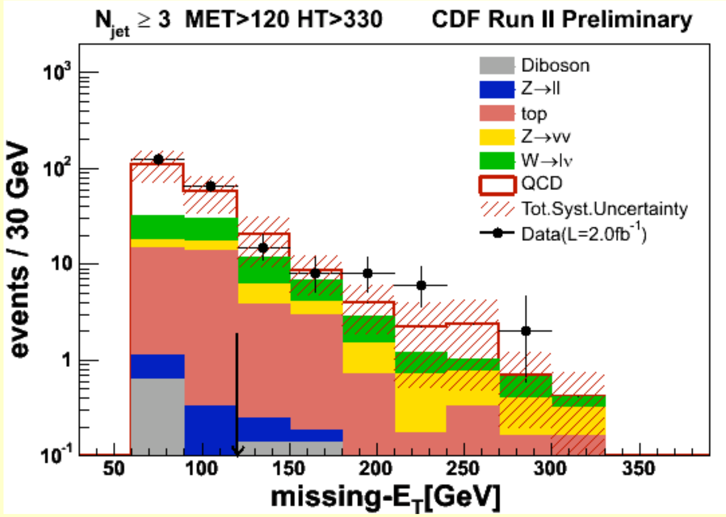
(iii) Gluino analysis
large m_0, m(squark) > m(gluino)

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

- Main backgrounds: $Z \rightarrow \nu\nu$ + jets, tt, W + jet production
- Event selection:
  - * require at least 2, 3 or 4 jets with P_T > 60 / 40 / 30 / 20 GeV
  - * veto on isolated electrons and muons
  - * isolation of 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

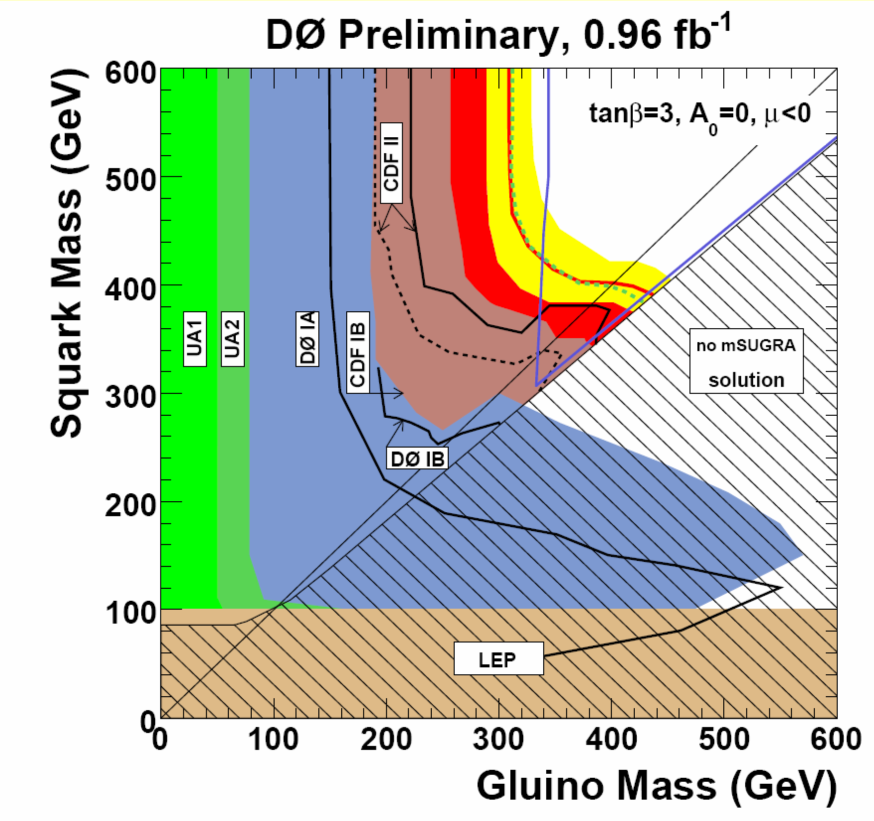
Observed events in data:

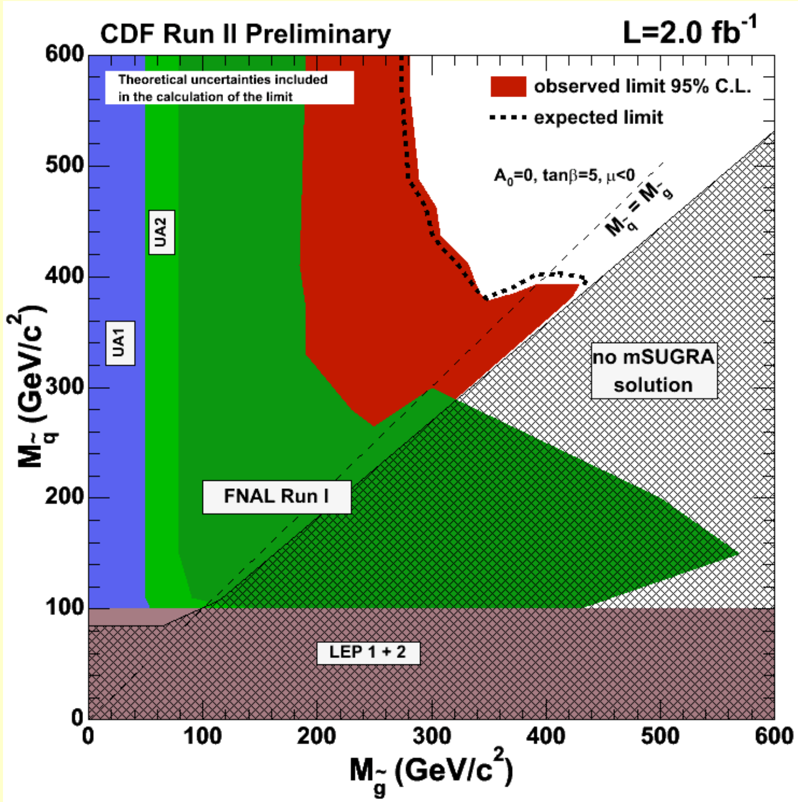
Region	Observed data
4-jets	45
3-jets	38
2-jets	18

No excess above background from Standard Model processes

→ NO evidence for SUSY (yet) → Set limits on masses of SUSY particles

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



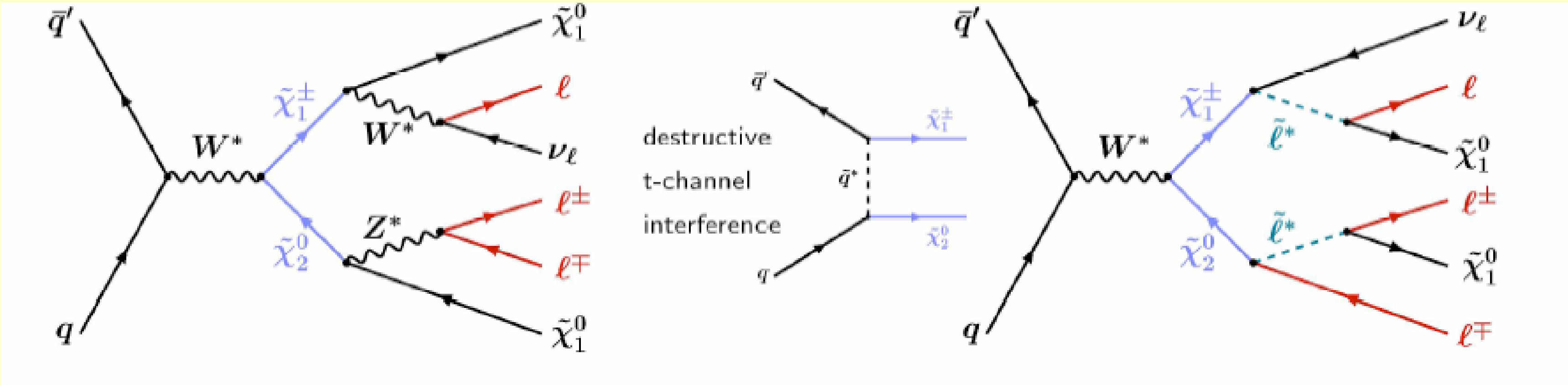


Exclusion limits
(incl. systematic uncertainties)*:
m(gluino) > 290 GeV/c^2
m(squark) > 375 GeV/c^2

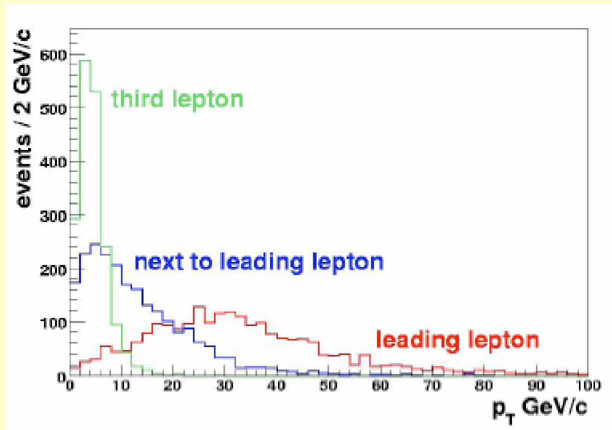
)* uncertainties from structure functions, change of renormalization and factorization scale μ by a factor of 2, NLO calculation, default choice: μ = m(gluino), m(squark) or ½(m(gluino)+m(squark)) for gg, qq, qg production

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)



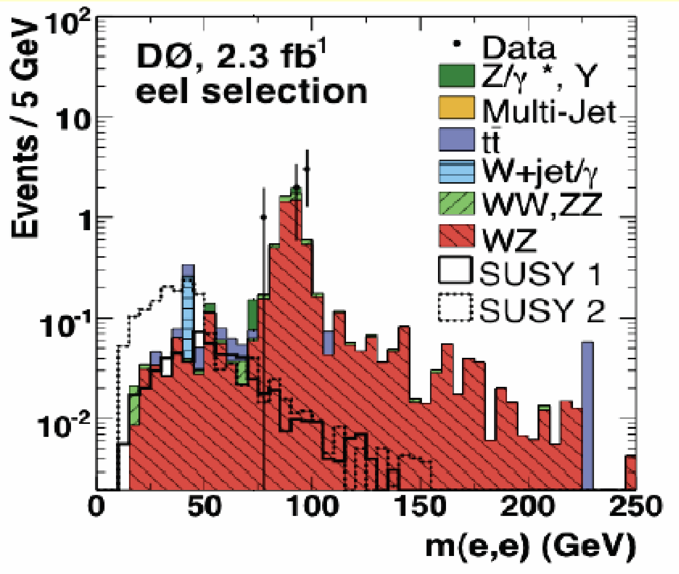
- For small gaugino masses (~100 GeV/c^2)
  one needs to be sensitive to low P_T leptons

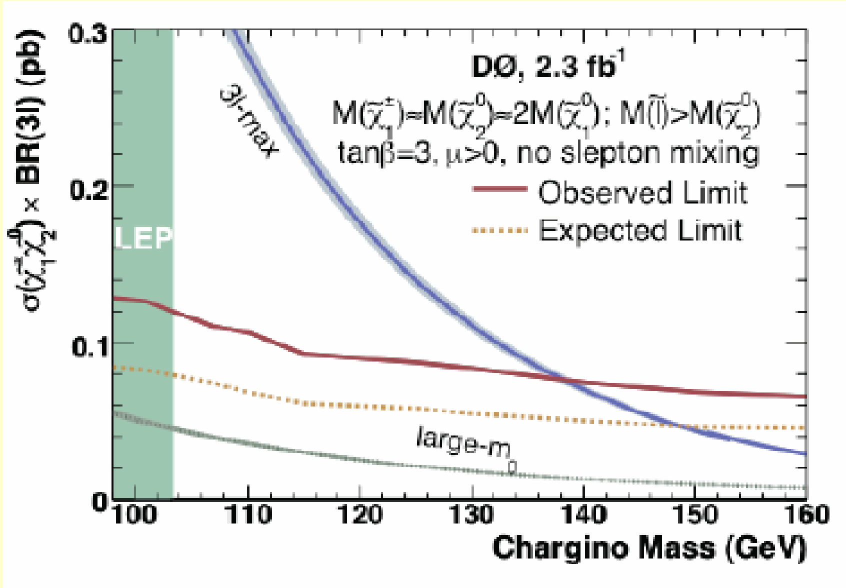


Analysis:

- 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)

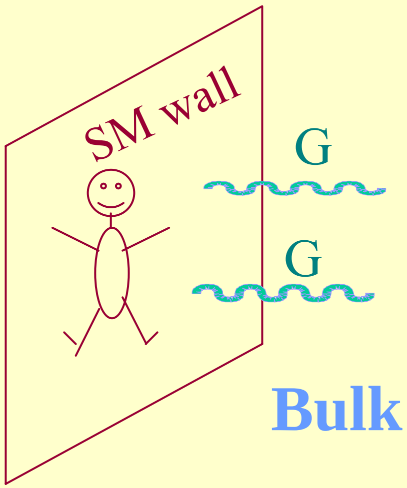
- New physics can appear at the TeV-mass scale,
  i.e. accessible at the LHC

Example: **Search for direct Graviton production**

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

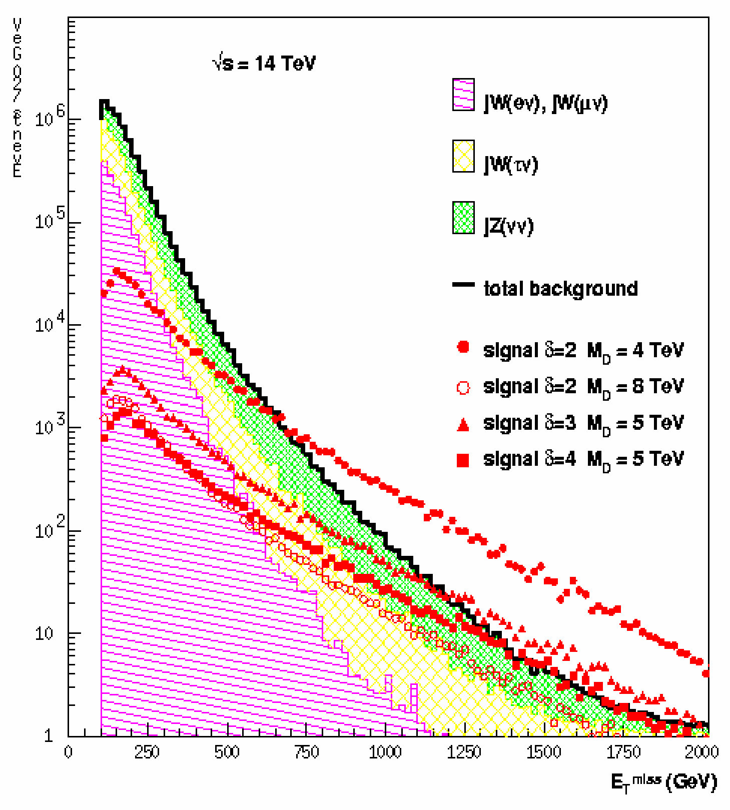
$q\bar{q} \rightarrow G\gamma$

$\Rightarrow$ **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 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: $W' \to \ell\, \nu$

$Z' \to \ell\, \ell$

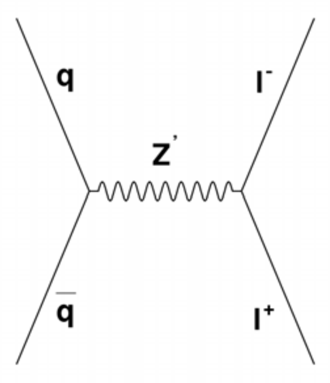
2. Leptoquarks ?

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)

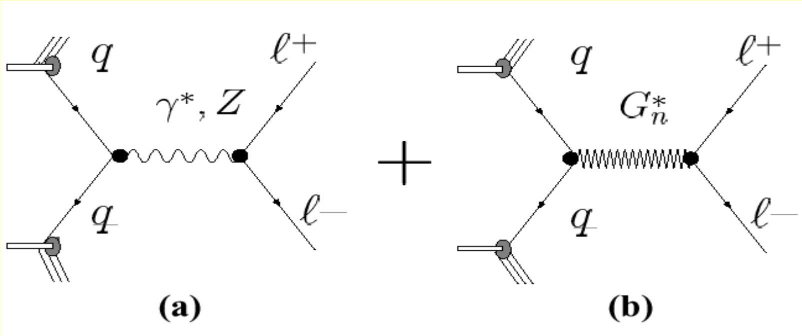
Fermilab Search for New Resonances in High Mass Di-leptons

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



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

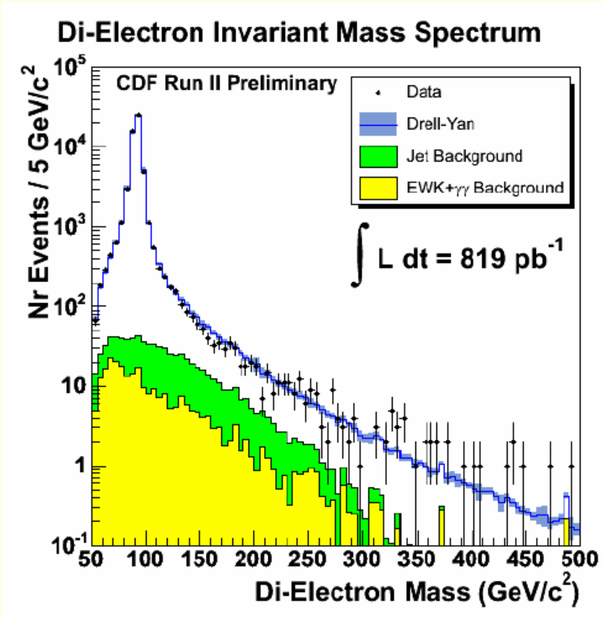
  appear in Extra Dim. Scenarios



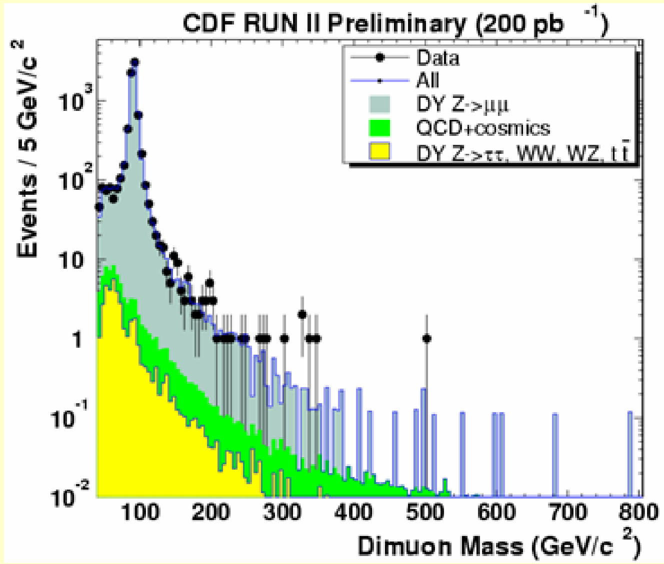
Main background from Drell-Yan pairs

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.

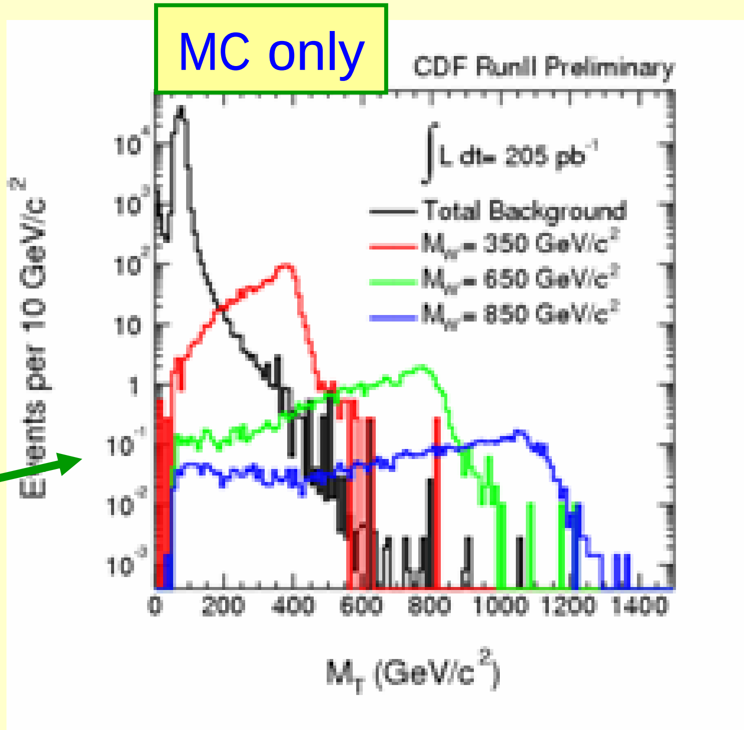
		ee	μμ	ττ	
Z´ mass limits (SM couplings)					
95% C.L.	**CDF /D0:**	**965**	**835**	**394**	**GeV/c²**

Search for W' → eν

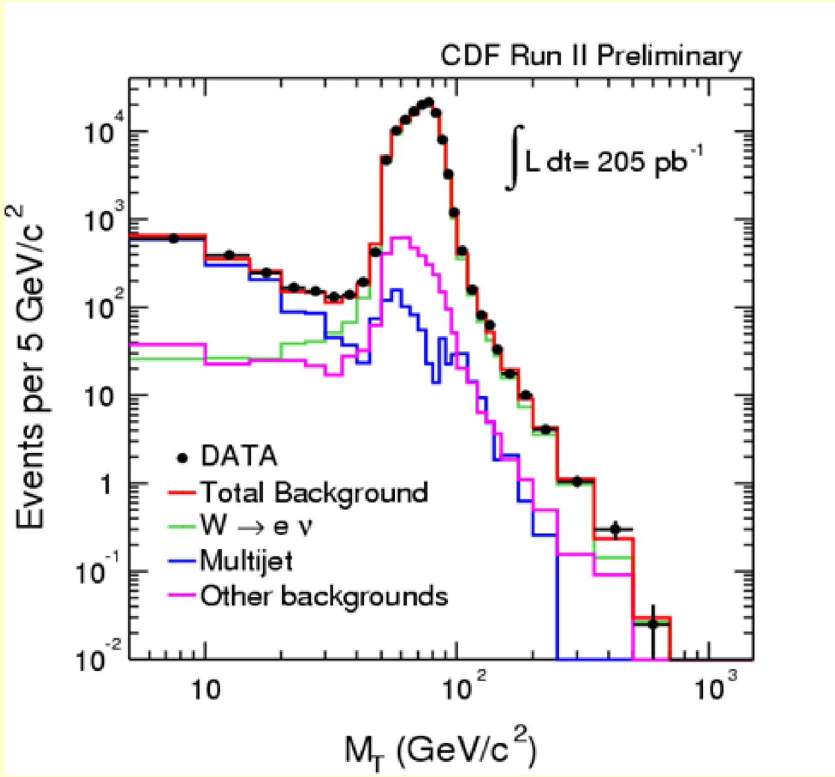
- W': additional charged heavy vector boson
- appears in theories based on the extension of the gauge group
- e.g. Left-right symmetric models: $SU(2)_R$ W_R
- assume: the neutrino from W' decay is light and stable.

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

→ peak in transverse mass distribution



Search for W' → eν



Data:

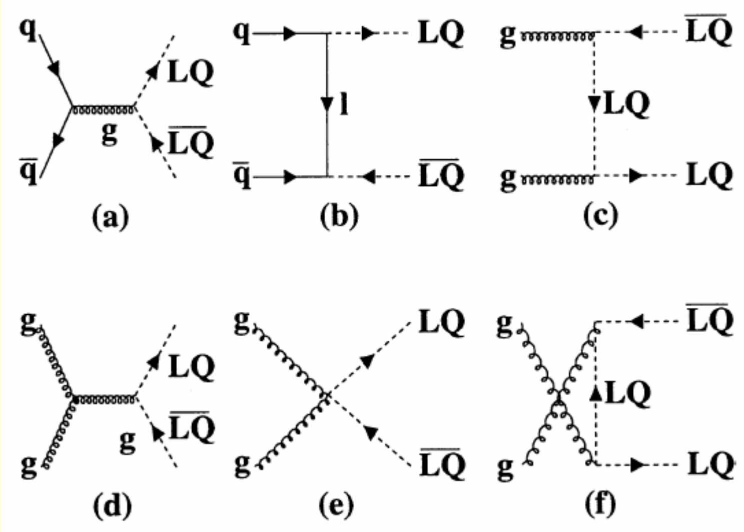
consistent with one well known W + background

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

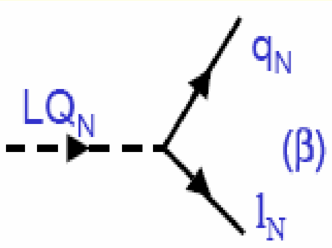
(assuming Standard Model couplings)

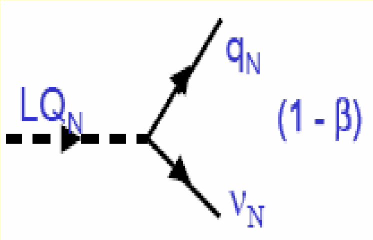
Search for Scalar Leptoquarks (LQ)

- 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

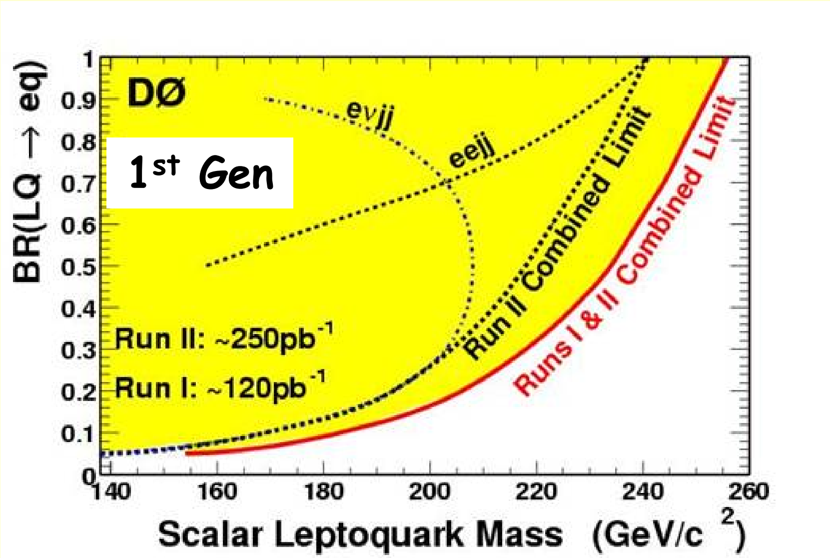
N = generation index
Leptoquarks of 1., 2., and 3. generation

Experimental Signatures:

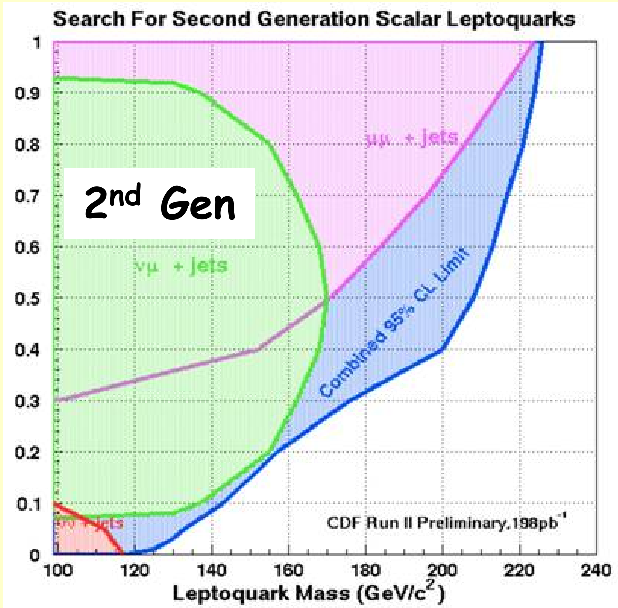
- two high p_T isolated leptons + jets .OR.
- one isolated lepton + P_T^{miss}+ jets .OR.
- P_T^{miss} + jets

1st, 2nd and 3rd generation Leptoquarks

channels: eejj, eν jj



channels: μμjj, ενjj, ννjj

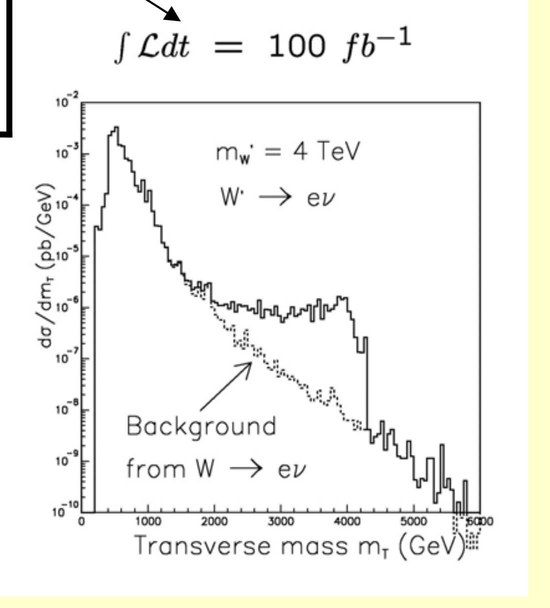


95% C.L. Mass Limits	1. Generation LQ	2. Generation LQ	3. Generation LQ
CDF (Run II) D0 (Run I + II)	235 GeV/c^2 256 GeV/c^2	224 GeV/c^2 200 GeV/c^2 (Run I)	129 GeV/c^2

LHC reach for other BSM Physics

(a few examples for 30 and 100 fb^{-1})

	30 fb $^{-1}$	100 fb $^{-1}$
Excited Quarks Q* → q γ	M (q*) ~ 3.5 TeV	M (q*) ~ 6 TeV
Leptoquarks	M (LQ) ~ 1 TeV	M (LQ) ~ 1.5 TeV
Z‘ → ℓℓ, jj W‘→ ℓ ν	M (Z‘) ~ 3 TeV M (W‘) ~ 4 TeV	M (Z‘) ~ 5 TeV M (W‘) ~ 6 TeV
Compositeness (from Di-jet)	Λ ~ 25 TeV	Λ ~ 40 TeV



Sensitivity to New Physics with jets in Early LHC data

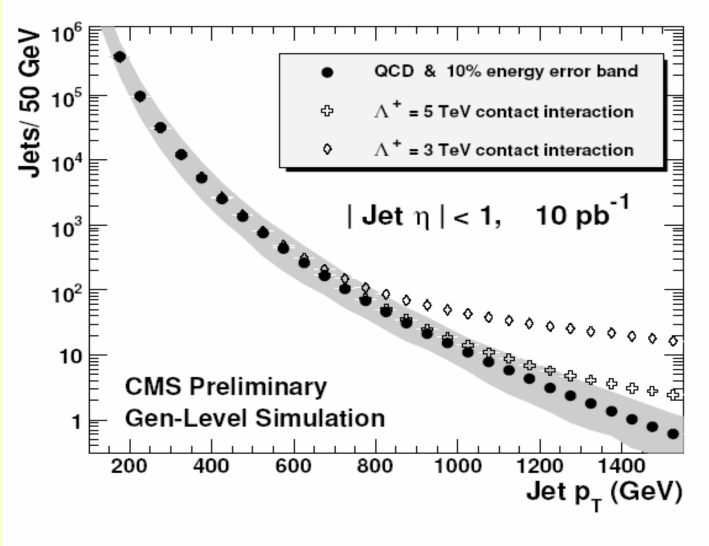
- Even with JES uncertainties expected with early data and an int. luminosity of only 10 pb^{-1} compositeness scales of ~ 3 TeV can be reached

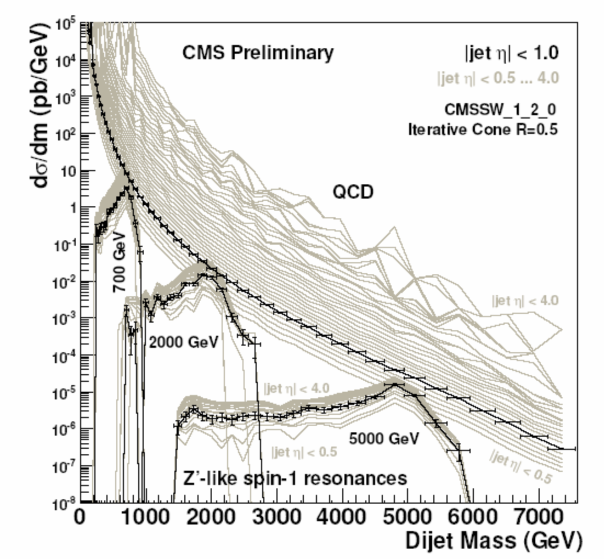
  (close to the present Tevatron reach of Λ > 2.7 TeV)

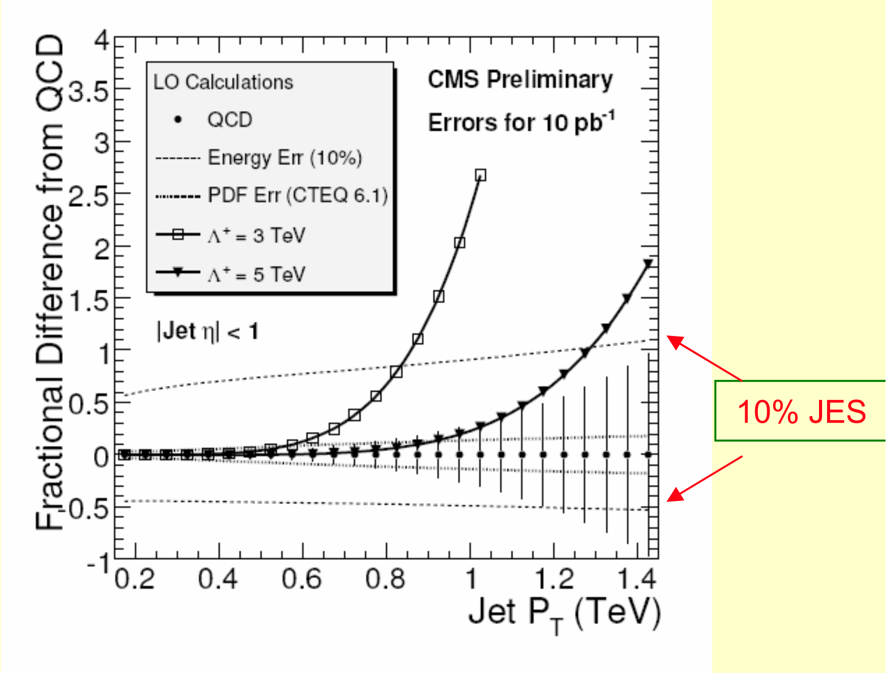
- Resonances decaying into two jets:

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

Present Tevatron limits: 320 < m < 740 GeV







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, ….)

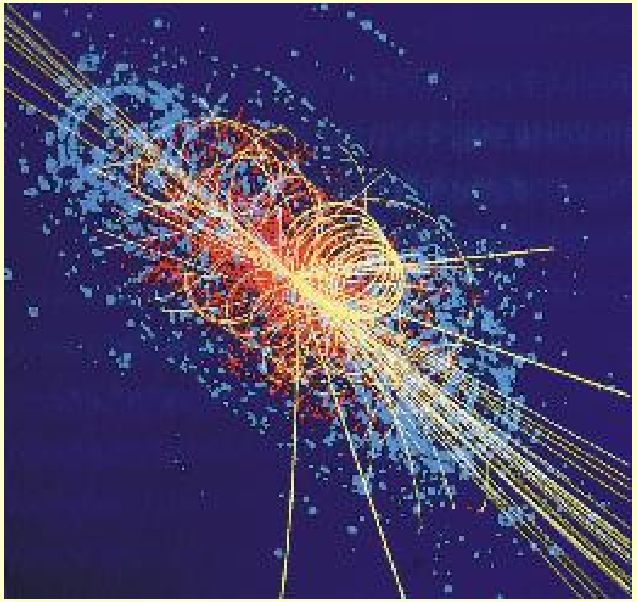
It has a crucial role in physics: can say the final word about

- 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.