Early Physics at the LHC

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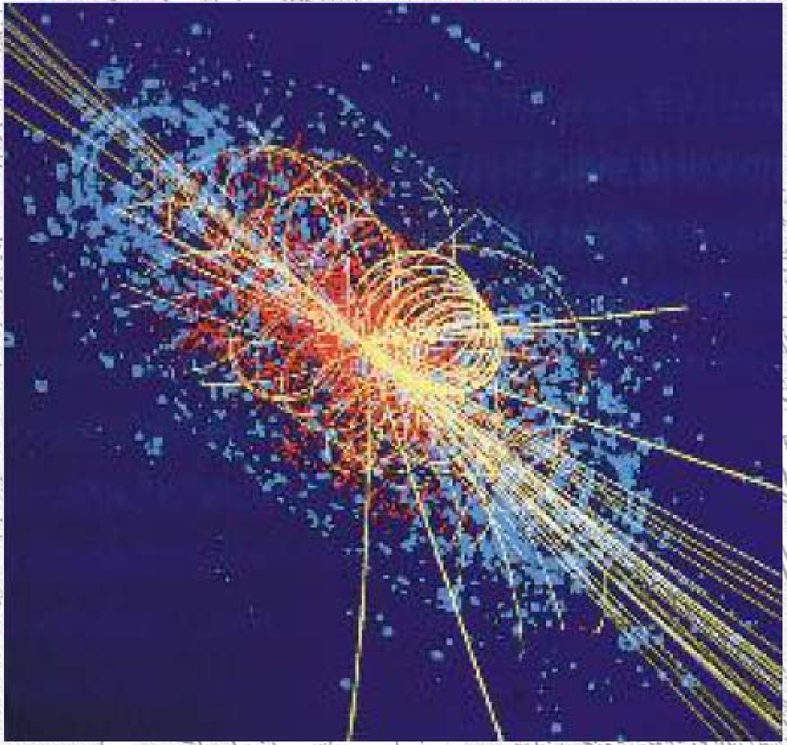
Outline

- Lecture 1:
  Physics at proton colliders
  Status of LHC

- Lecture 2:
  Standard Model physics

- Lecture 3:
  Searches for new particles & phenomena
  e.g. Higgs and SUSY



Search for New Physics at the LHC

Some general considerations on LHC early phase

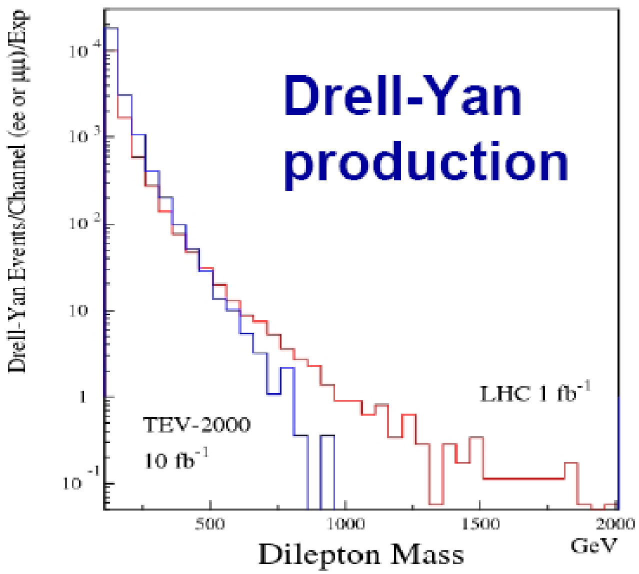
- time scale for discoveries not neceesrily determined by ramp-up of integrated luminosity
- but progress and level of detector understanding
  - malfunctions, calibration, alignment

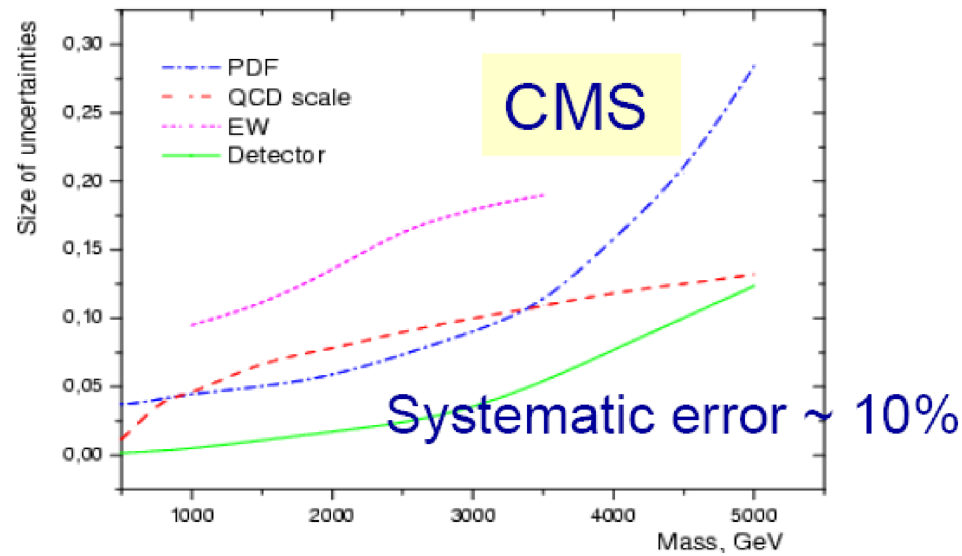
- difficult issues
  - jets
  - missing ET
  - forward detectors

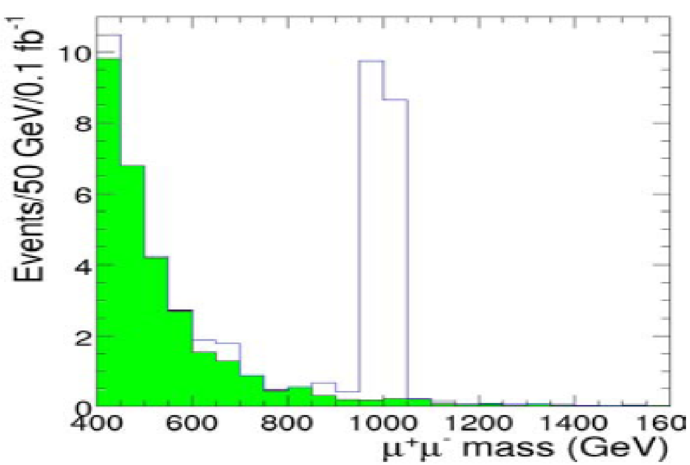
- less critical
  - lepton based measurements
    in particular muons

Understanding of the Detector

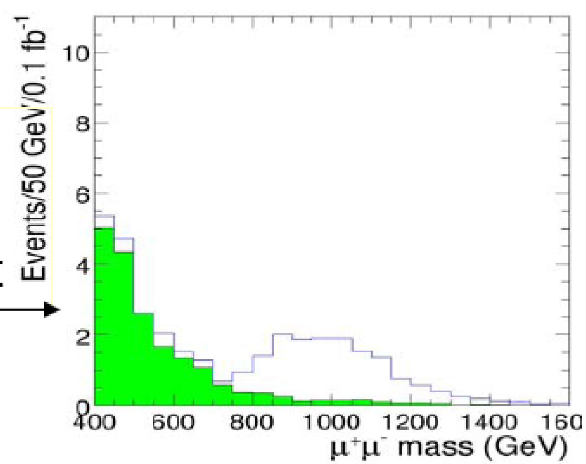
- **Example for an easy case: muon pairs**







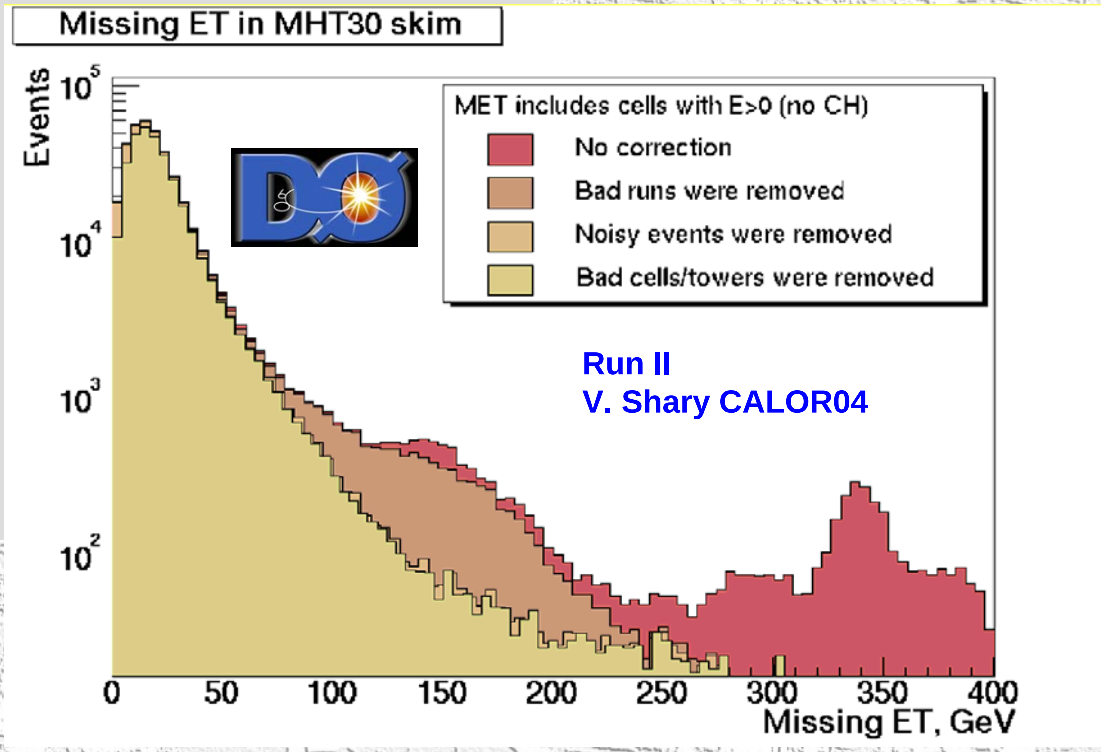
At **100 pb^{-1}**:
1 TeV Z' with
initial alignment



Understanding of the Detector

Difficult example: missing ET

- is a very powerful tool to look for new physics
- but very complicated variable and difficult to understand:
- collison effects
  - pile-up
  - underlying event
- beam related background
  - beam halo
  - cosmic muons
- detector effects
  - instrumental noise
  - dead/hot channels
  - inter-module calibration



Search for Higgs Bosons

Emphasis on SM Higgs

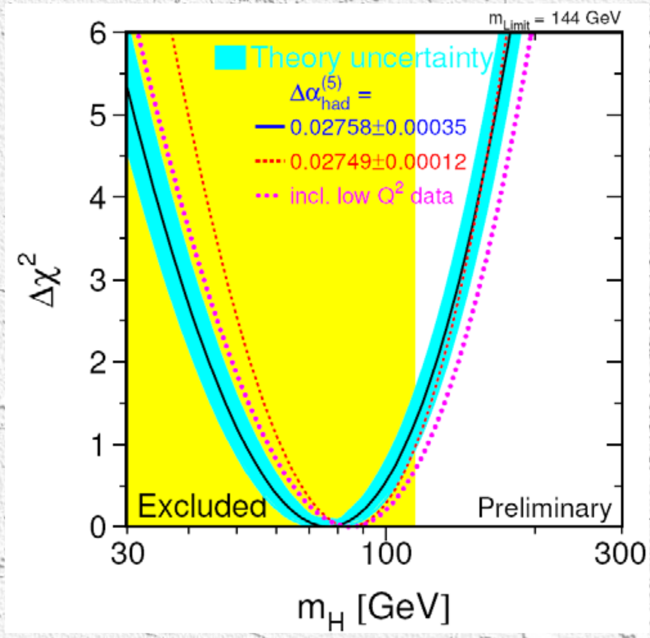
Standard Model Higgs Boson

What do we know today about the SM Higgs boson?

- **needed in the SM to accomodate masses (heavy gauge bosons and fermions)**
- **mass is not predicted, except that $m_H < 1000$ GeV**
- **direct searches at LEP**

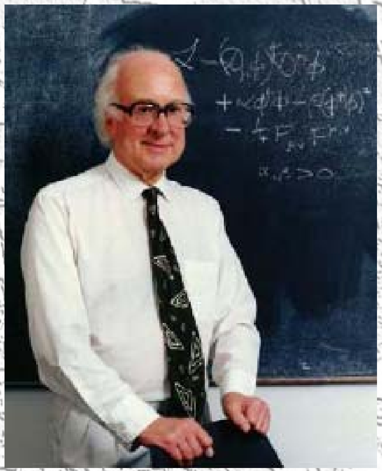
$m_H > 114.4$ GeV

- **electroweak precision measurements (incl. m_t measurement)**



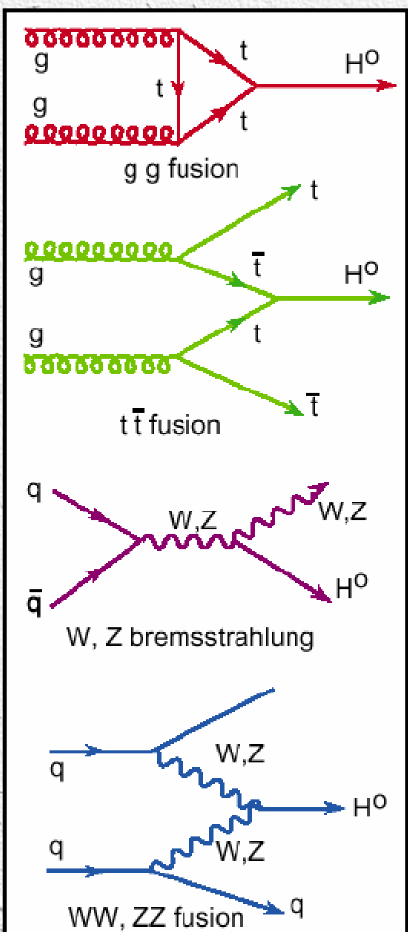
⇒ $m_H < 144$ GeV (95% CL)

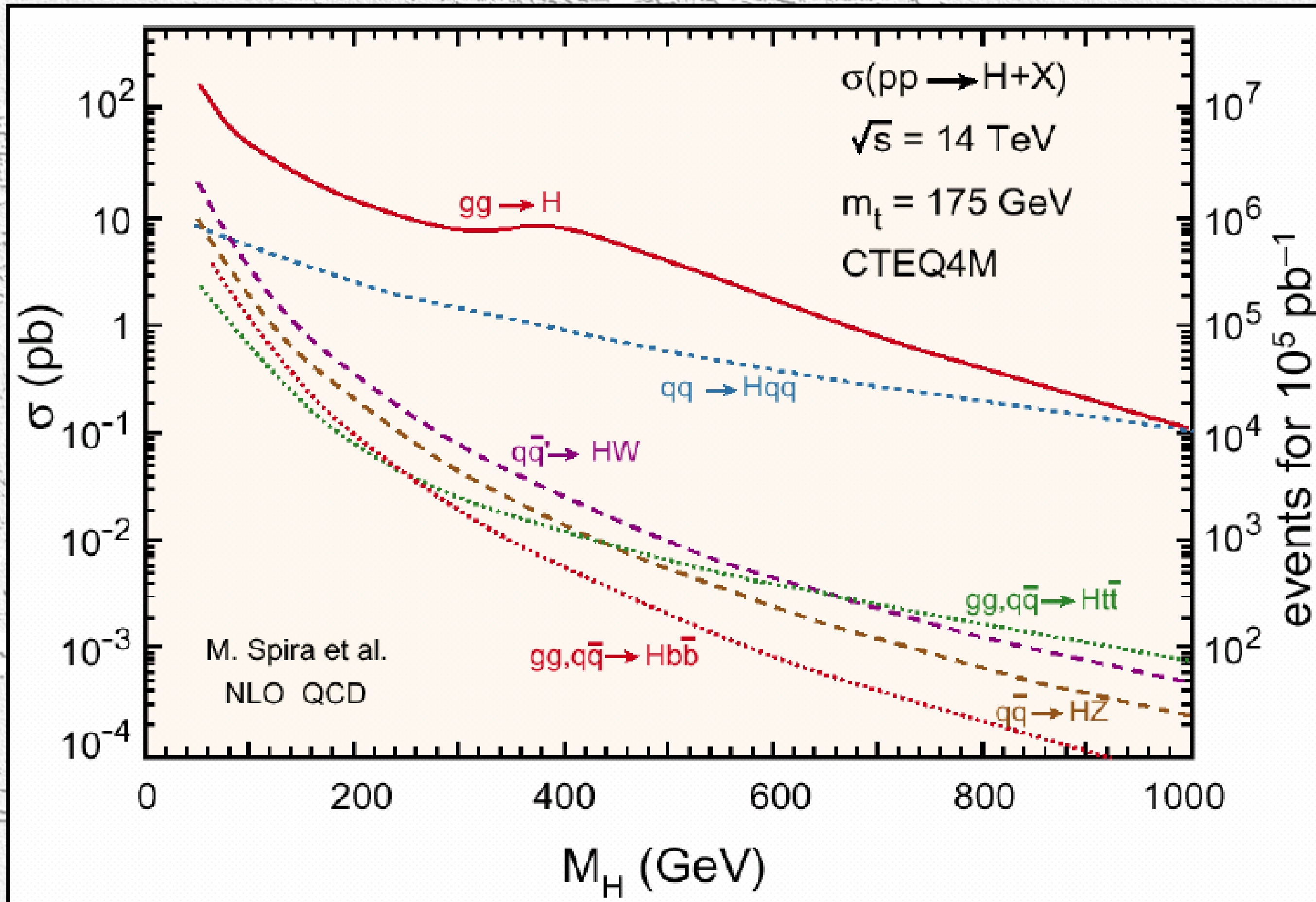
⇒ the Higgs should be around the corner!



Higgs Boson Production at the LHC

Once the mass is know all other Higgs properties are fixed!



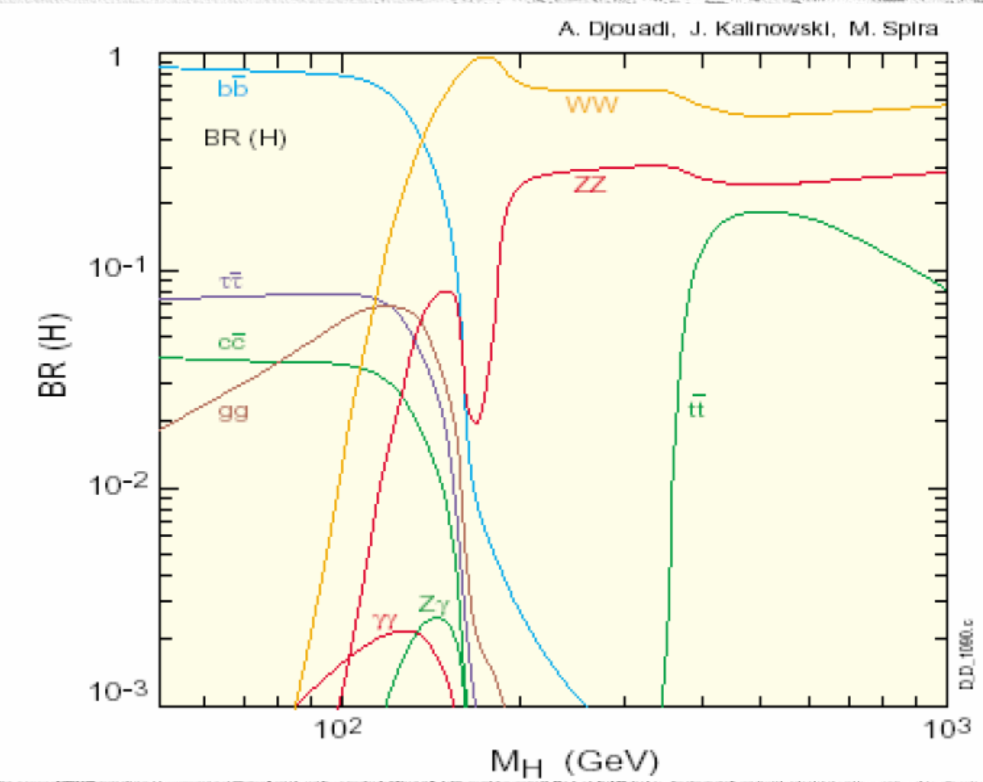


- Gluon-gluon fusion and W, Z fusion are dominant
- Cross section at the Tevatron almost factor 100 smaller!

Higgs Boson Decay

Higgs couples proportional to masses
⇒ preferentially decaying into heaviest particle kinematically allowed

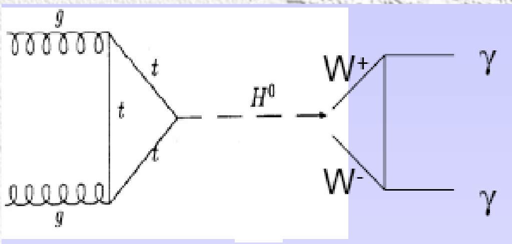
Branching ratio versus m_H:



- **Low mass (115 < m_H < 140 GeV**
  H → bb make up most of the decays problem at the LHC because of the huge QCD background !
- **Intermediate (140 < m_H < 180 GeV)**
  H → WW opens up
  use leptonic W decay modes
- **High mass (m_H > 180 GeV)**
  H → ZZ → 4 leptons
  golden channel!

Higgs Boson Decay

What to do in the preferred low mass region, i.e. $m_H < 140$ GeV?
- use $H \rightarrow \gamma\gamma$
- very low branching ratio $O(10^{-3})$
- but clean signature



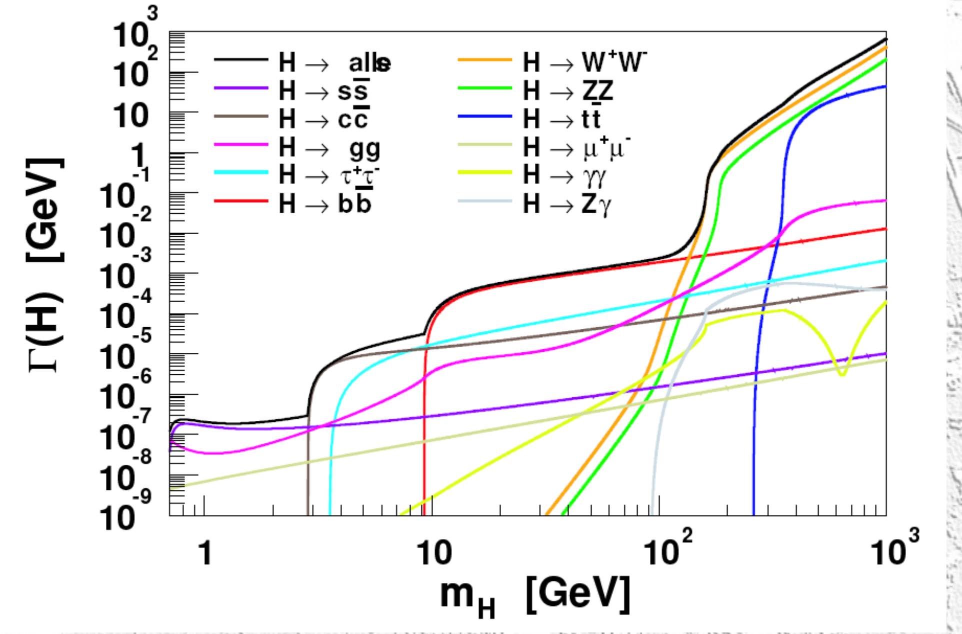
internal loop with heavy charged particle
W boson or top quark

Total width of the Higgs (= inverse lifetime)
- at low masses Higgs is a very sharp resonance

$$\Gamma_H << 1 \text{ MeV}$$

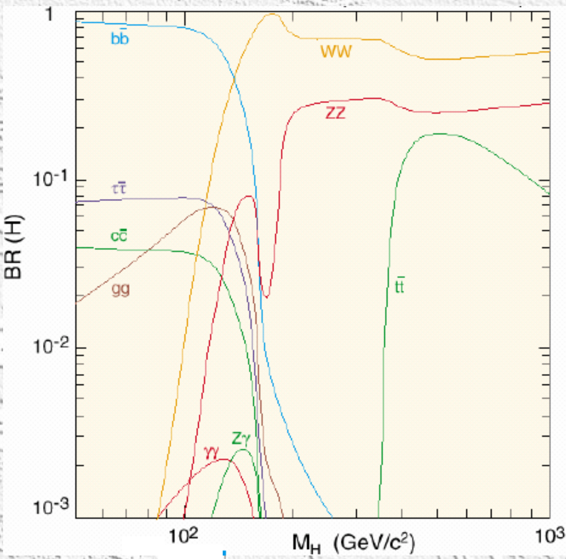
- Γ_H explodes once $H \rightarrow WW, ZZ$ open up for $m_H \rightarrow 1$ TeV

$$\Gamma_H \approx m_H$$

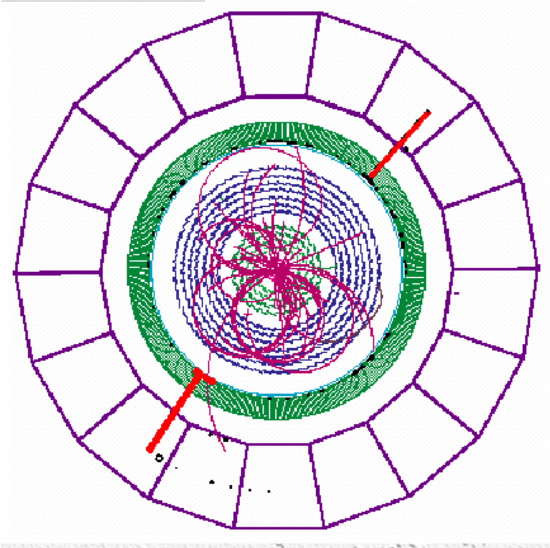


Search for the Higgs Boson

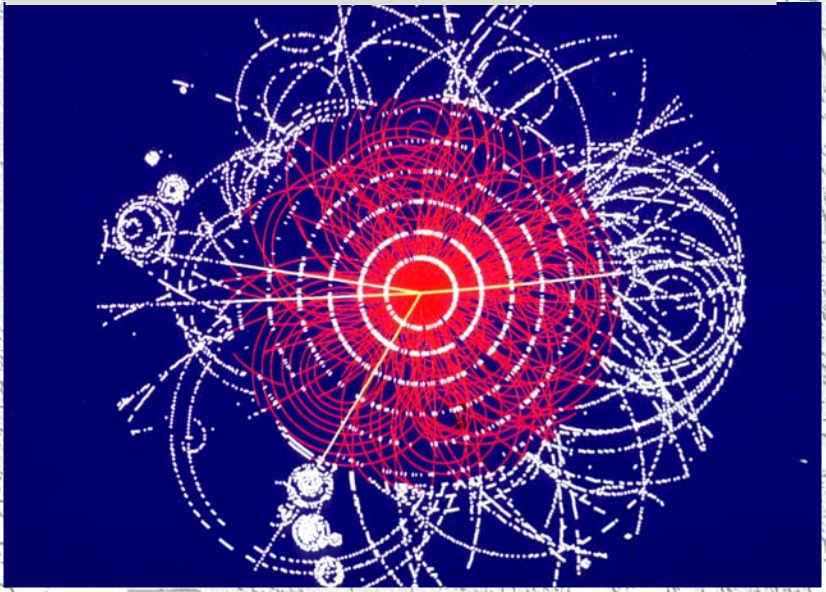
LEP:	LHC:	
H → bb	H → bb	enormous QCD bkgd
	H → γγ	low m_H (BR ≈ 10^{-3})
	H → W^+W^-	medium m_H
	H → ZZ	high m_H



H → γγ

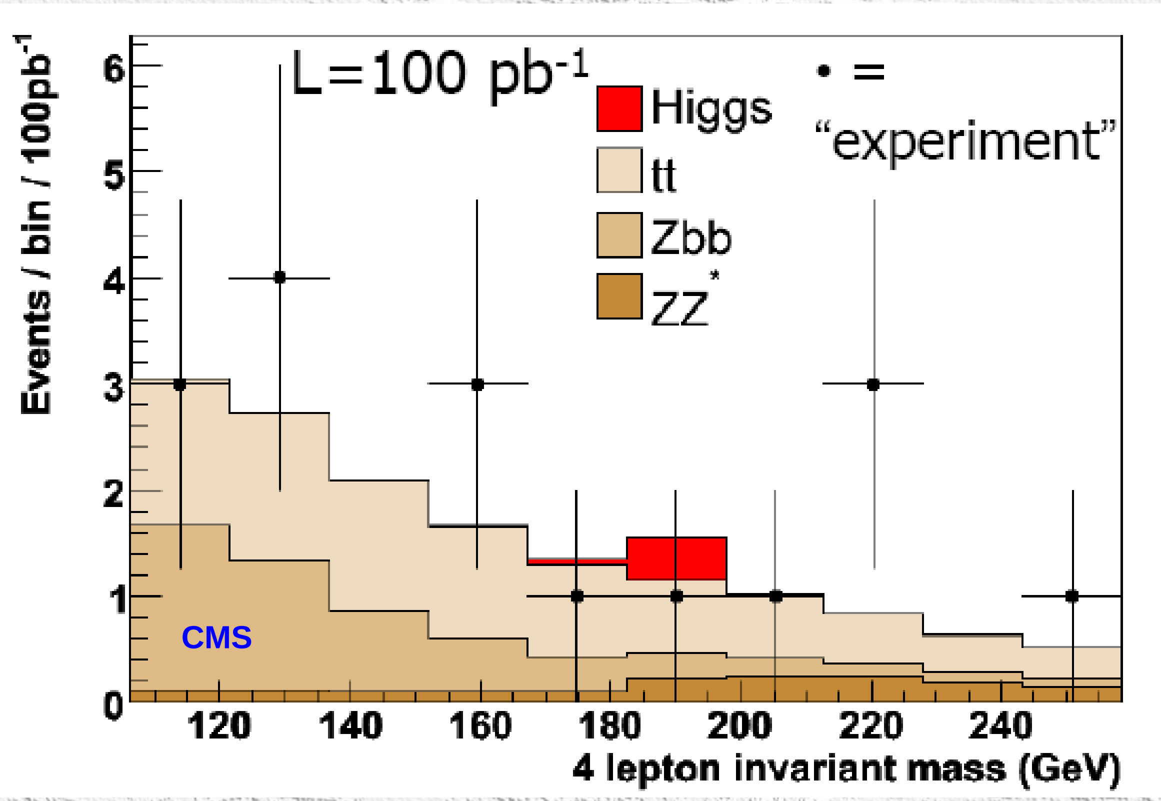


H → ZZ → 4μ (golden channel)



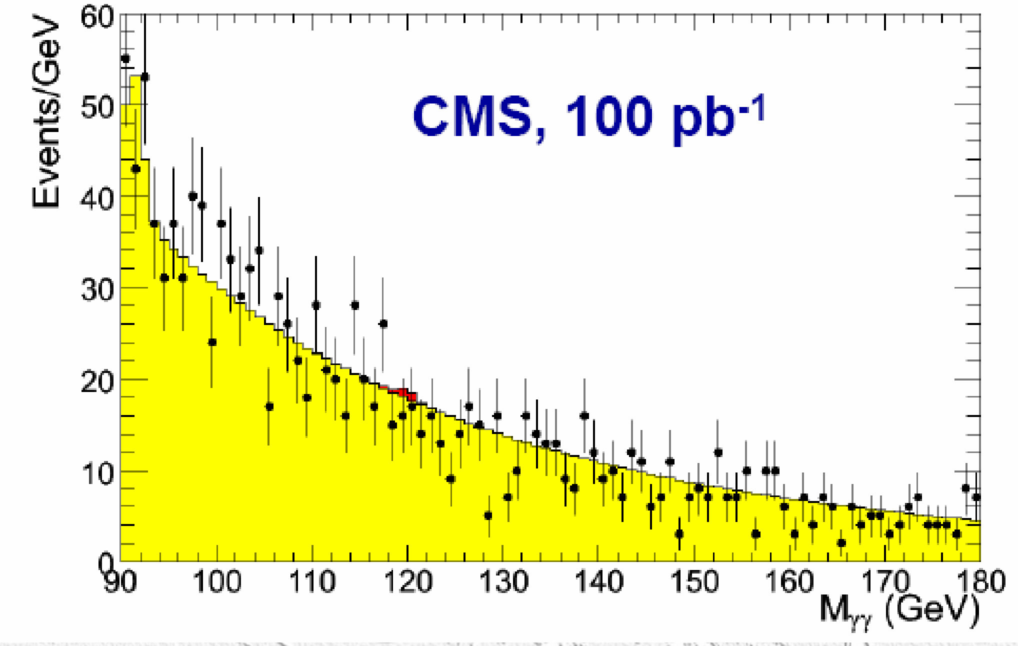
Early Higgs Searches

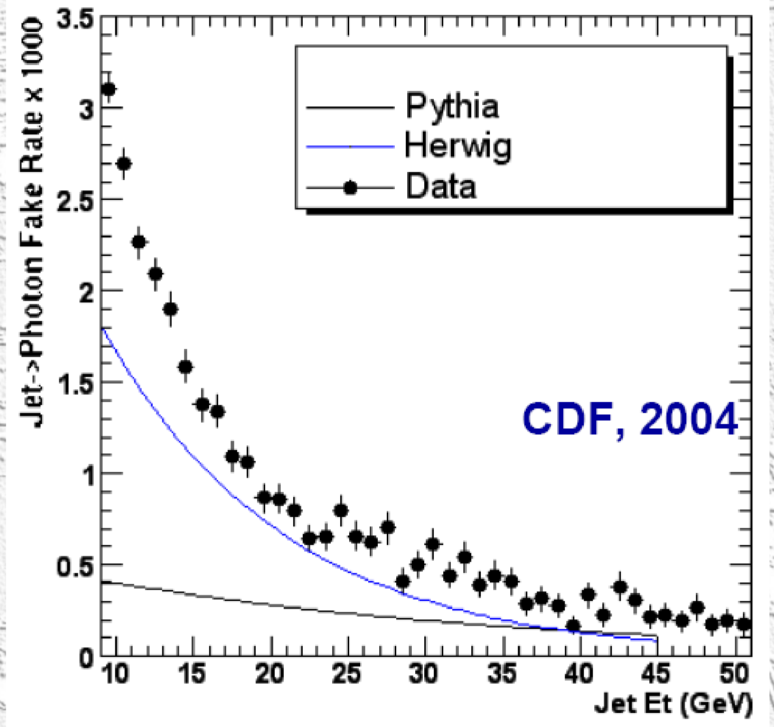
Early Higgs searches
- e.g. H → ZZ → eeμμ with 0.1 fb^{-1}



Early Higgs Searches

- $H \rightarrow \gamma\gamma$
- needs most integrated luminosity

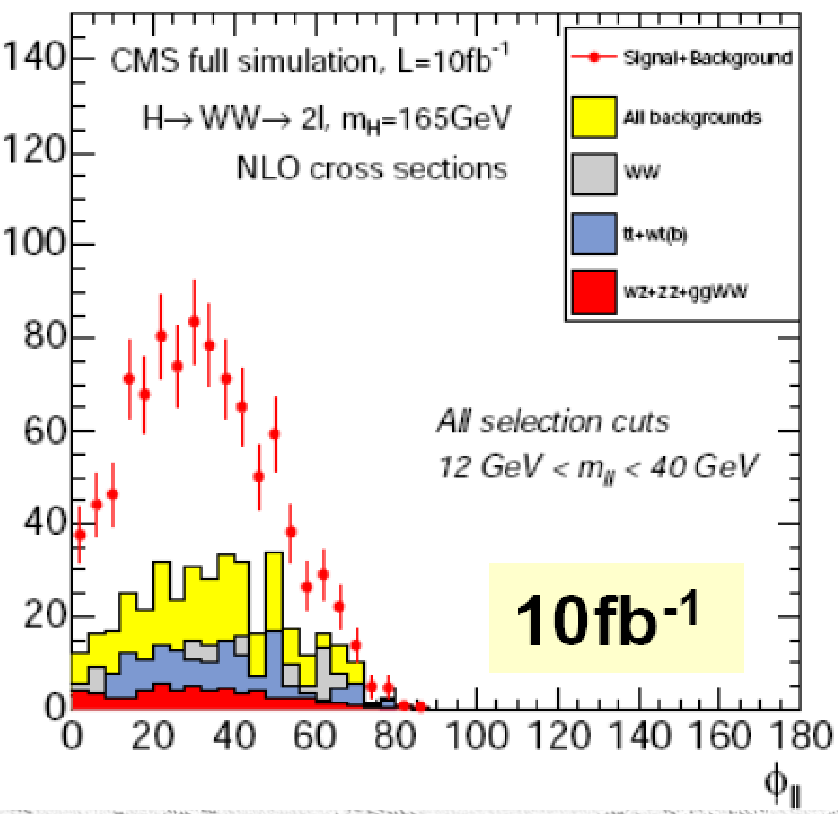


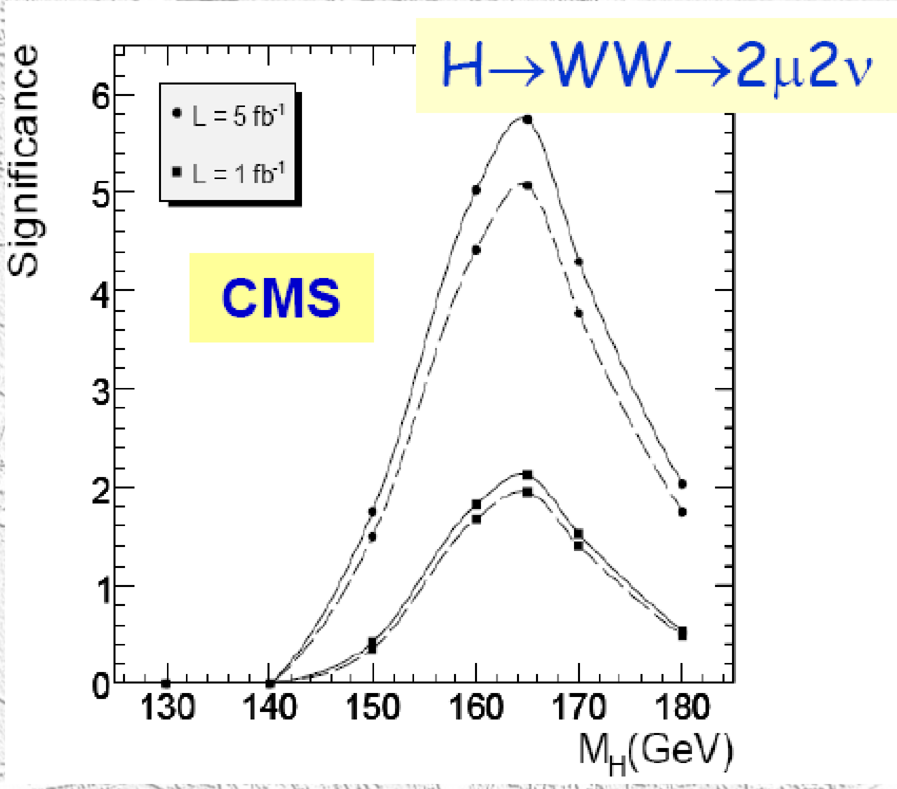


Important: determine background from data, e.g. jet photon fake rate CDF

Early Higgs Searches

- Best chances around $m_H \approx 2\, m_W$ in $H \rightarrow WW \rightarrow 2l + 2\nu$ channel



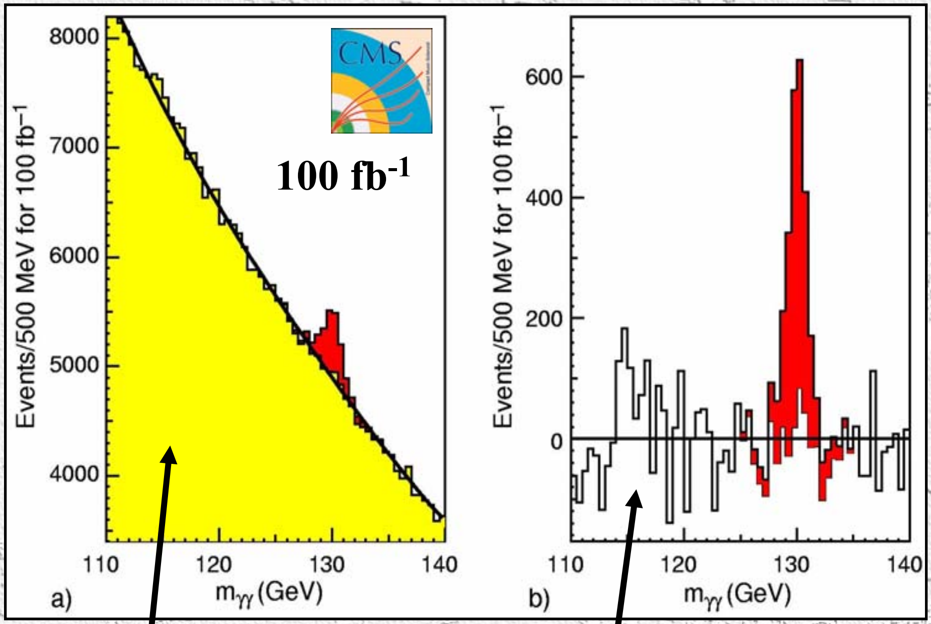


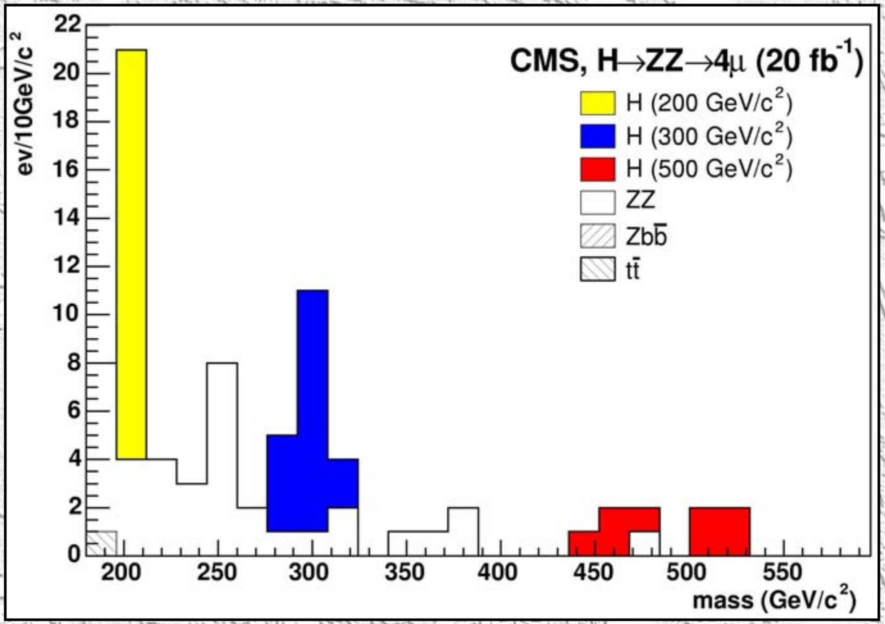
Search for the Higgs Boson at LHC

Possible future Higgs discovery plots:

$H \to \gamma\gamma$:
$m_H = 130$ GeV
$\sigma_{mH} \approx 1$ GeV

$H \to ZZ \to 4\mu$:
$m_H = 200$ (300, 500) GeV





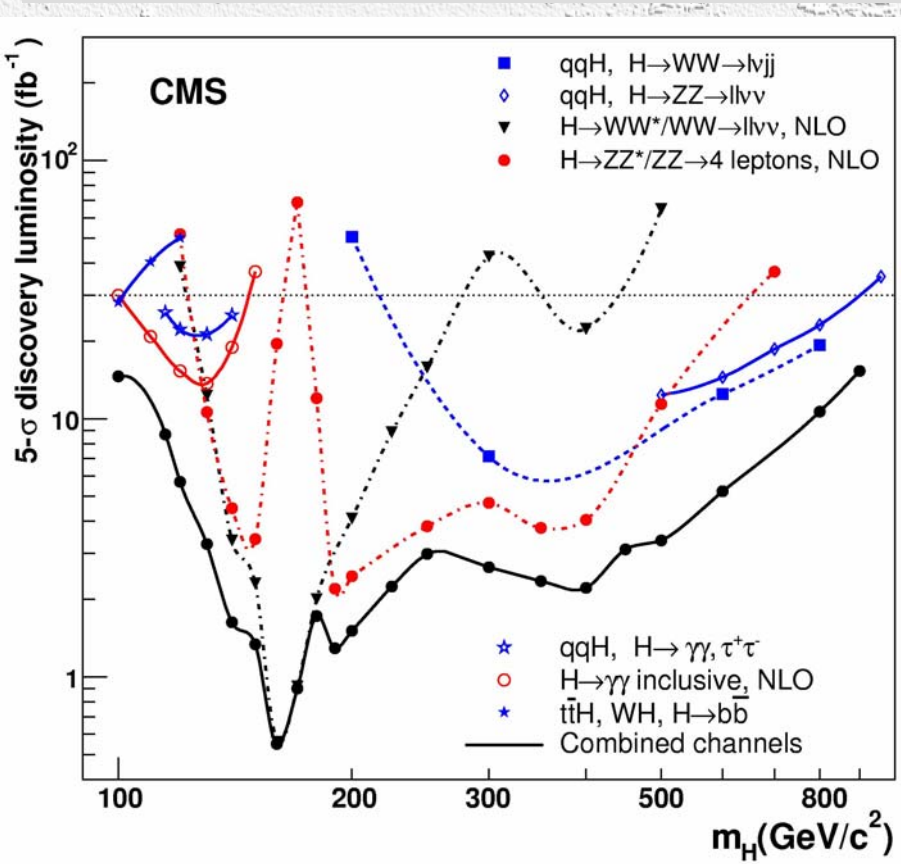
large combinatorial background

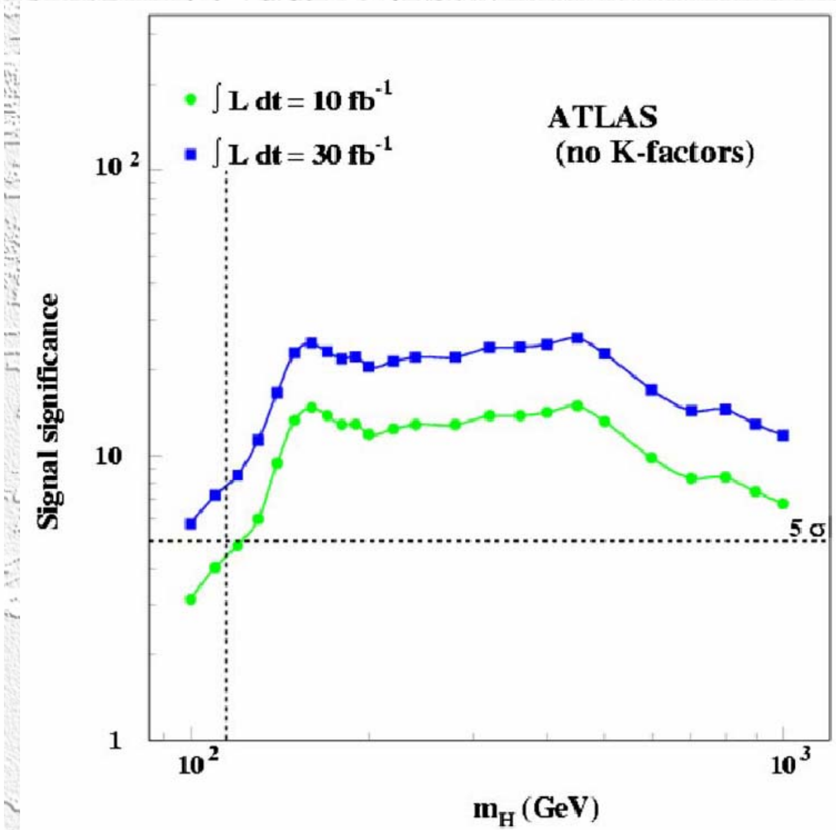
background subtracted

Note the increasing signal width

Search for the Higgs Boson at the LHC

Combine all search channels and determine expected significance as function of the luminosity and Higgs mass:





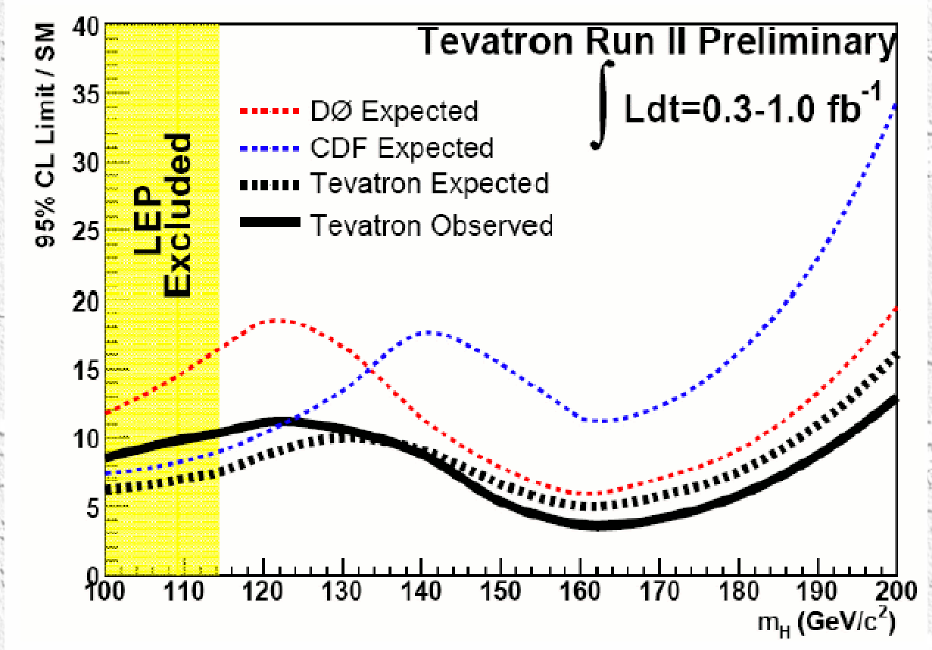
10 fb^{-1} sufficient for 5 σ discovery of the Higgs corresponds to 1 year at low luminosity 10^{33}/cm^2/s

Summary on Higgs search

- The LHC will explore the entire Higgs mass region and definitely answer the question if there is a Higgs boson or not

- The modest amount of 10 fb^{-1} of luminosity is required could be collected in 1-2 years

- How about the Tevatron experiments?



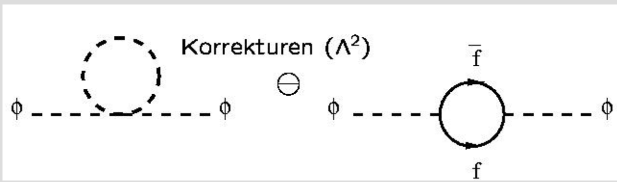
- Status summer 2007
- 95% CL Limit / SM cross section

Search for New Phenomena

Supersymmetry (MSSM)

Why SUSY?

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

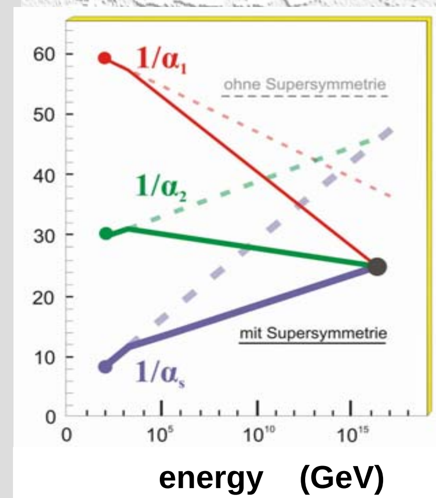


$$\Delta m_H = f(m_B^2 - m_f^2)$$

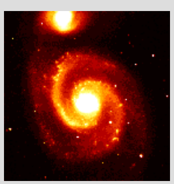
→ m_{SUSY} ~ 1 TeV

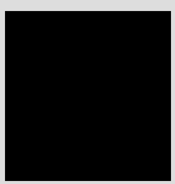
(Hierarchy or naturalness problem)

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



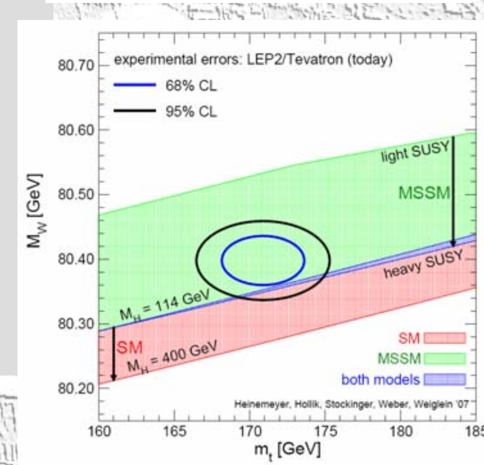
3. **SUSY provides a candidate for dark matter,**





The lightest SUSY particle (LSP)

4. **A SUSY extension is a small perturbation, consistent with the electroweak precision data**

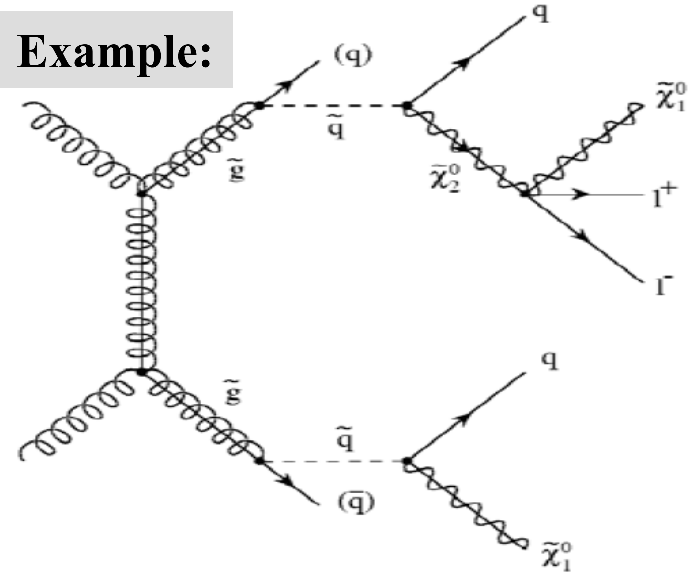


SUSY Search at LHC

Production of SUSY particles at the LHC

- squarks and gluinos are pair-produced through strong interaction, i.e. high cross sections
- but also sleptons and other SUSY particles can be pair-produced
- SUSY particles decay in a chain to SM particles plus the LSP

Example:



Signature:

- leptons, jets and missing E_T
- depend of SUSY particles produced, on their branching ratios etc.

Strategy to discover SUSY at the LHC:

- look for deviation from SM in distributions e.g. multi-jet + E_T^{miss}, multilepton+ E_T^{miss}
- establish SUSY mass scale
- try to determine model parameters (difficult!)

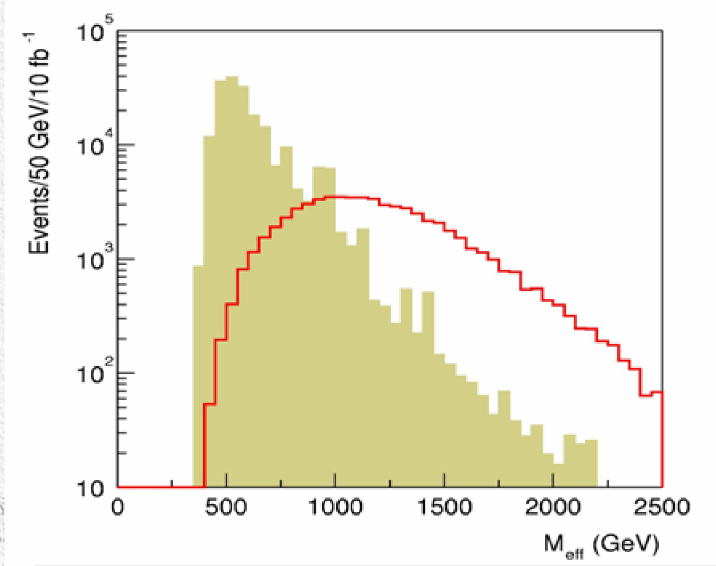
Squarks and Gluinos

- Strongly produced, cross sections comparable to QCD cross sections at the same mass scale

- If R-parity conserved, cascade decays produce distinctive events: multiple jets, leptons, and E_T^{miss}

- Typical selection: $N_{jet} > 4$, $E_T > 100, 50, 50, 50$ GeV, $E_T^{miss} > 100$ GeV

- Define: $M_{eff} = E_T^{miss} + P_T^1 + P_T^2 + P_T^3 + P_T^4$ (effective mass)



example: mSUGRA
m_0 = 100 GeV, $m_{1/2}$ = 300 GeV
tan b = 10, $A_0 = 0$, m > 0

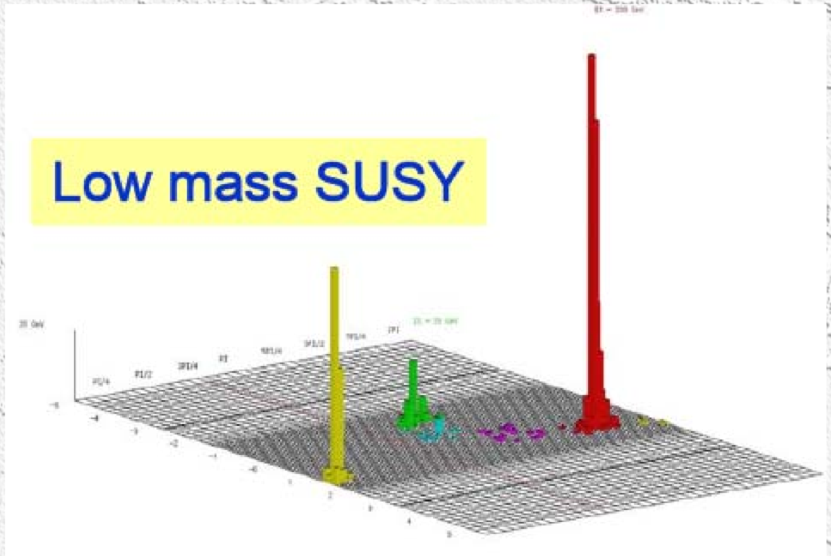
LHC reach for Squark- and Gluino masses:

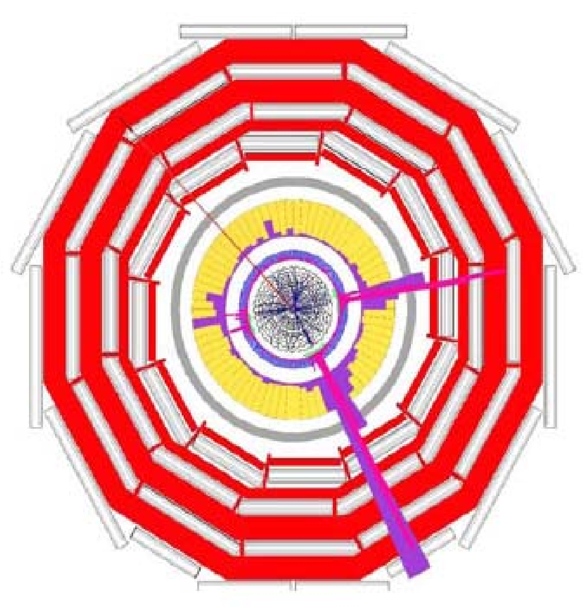
1 fb^{-1}	⇒	M ~ 1500 GeV
10 fb^{-1}	⇒	M ~ 1900 GeV
100 fb^{-1}	⇒	M ~ 2500 GeV

TeV-scale SUSY can be found quickly !

Early SUSY Searches

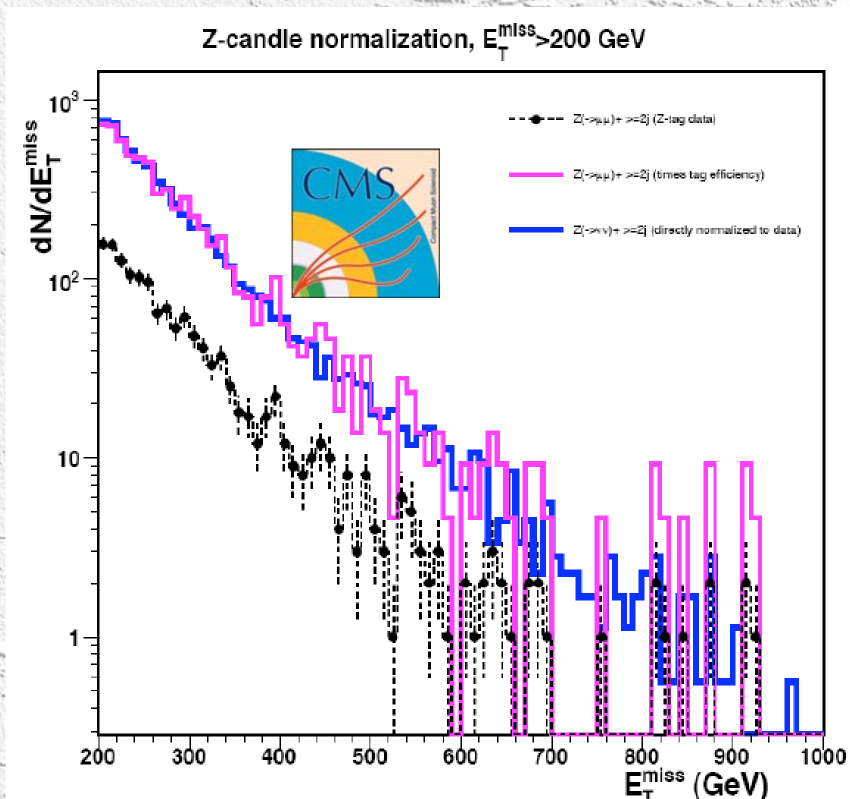
- Low mass SUSY ($M_{sp} \approx 500$ GeV) accessible with O(100 pb^{-1})
- However time to discovery will be determined by
  - time to understand detector performance, e.g. E_T^{miss}
  - time to collect control samples e.g. W+jets, Z+jets, top,…



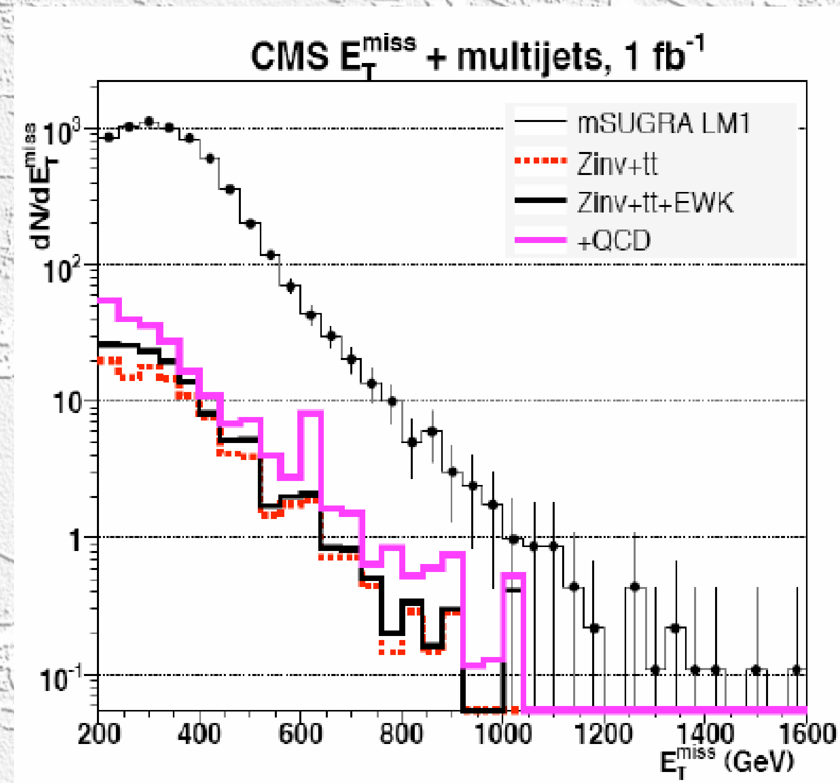


Early SUSY Searches

- Control over physics background
- Example Etmiss + jets:
  - background from Z→nunu (+jets)
  - normalise to Z→ μμ (+jets)

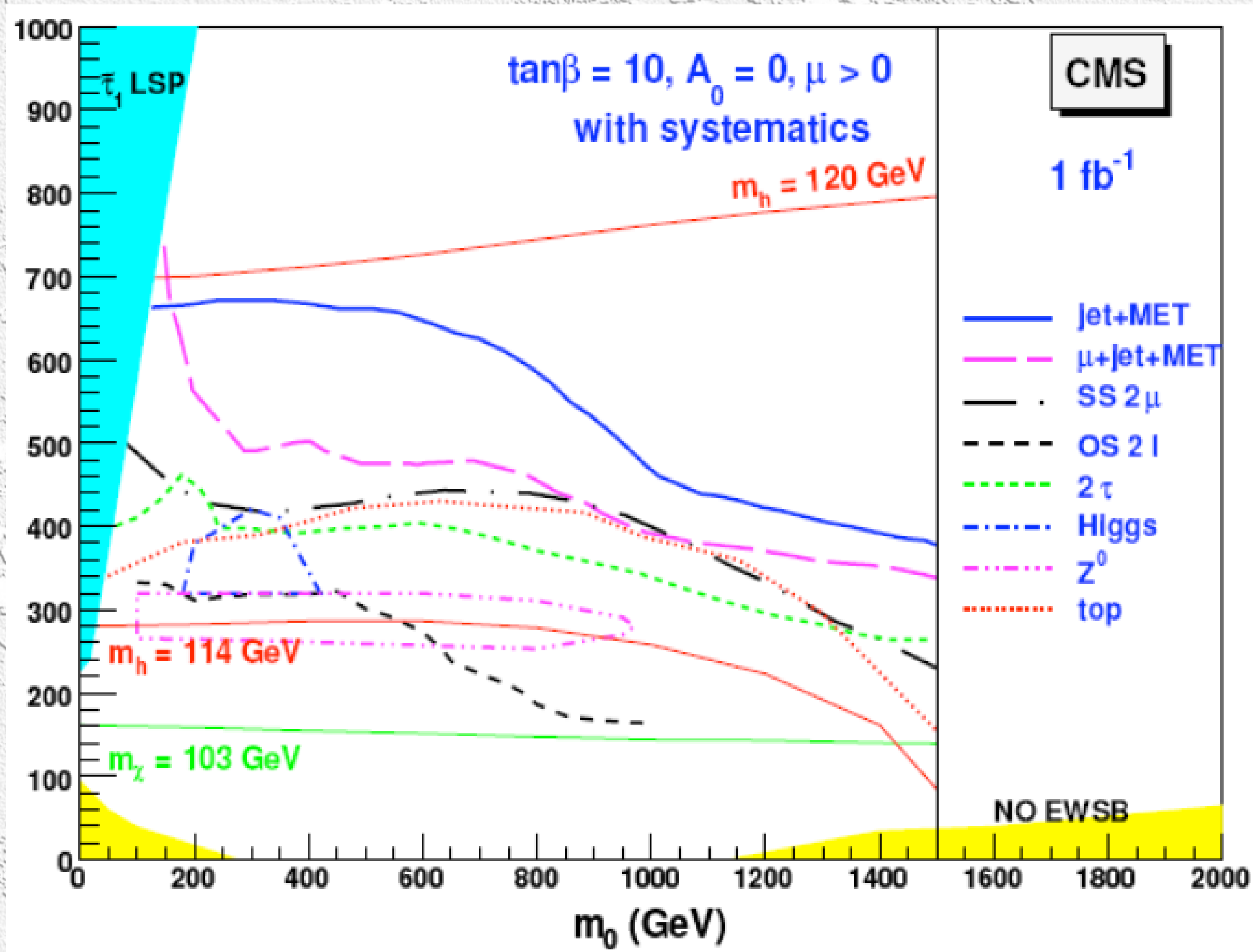


- Inclusive searches for 1 fb^{-1}



Early SUSY Searches

Inclusive searches for 1 fb-1



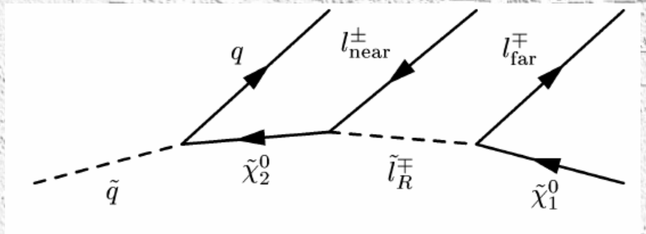
SUSY Searches

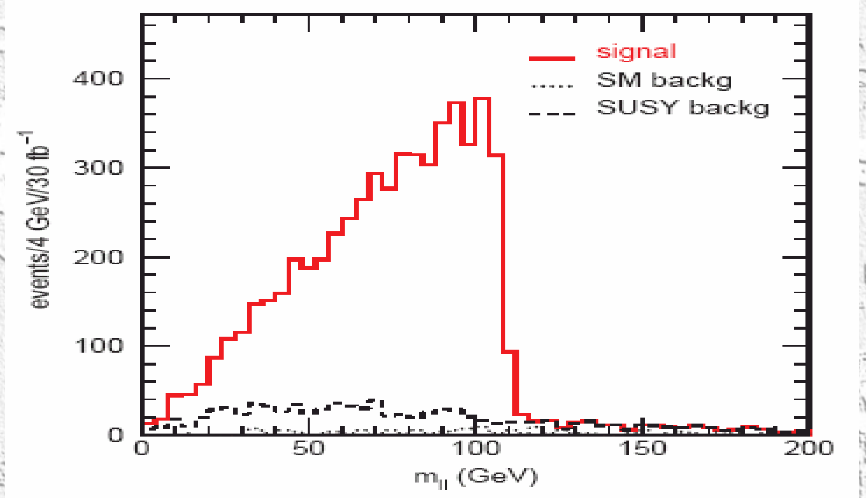
LHC Strategy: End point spectra of cascade decays

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

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

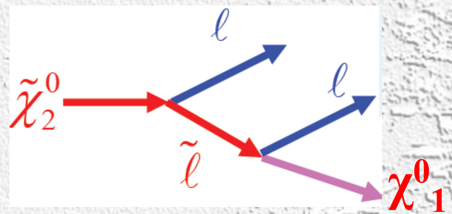
$$M_{\ell_1 q}^{max} = \frac{\sqrt{(m_{\chi_2^0}^2 - m_{\tilde{\ell}}^2)(m_{\tilde{q}}^2 - m_{\chi_2^0}^2)}}{m_{\chi_2^0}}$$

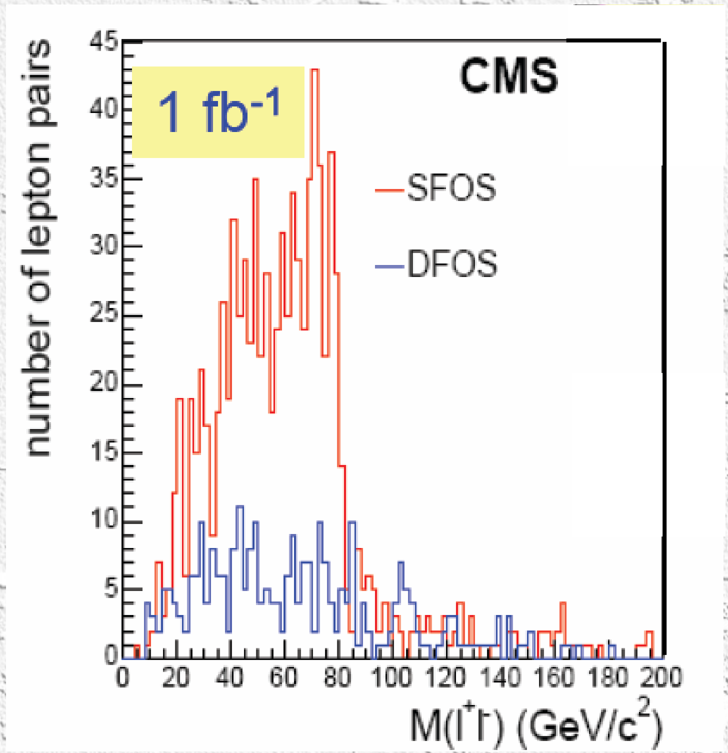




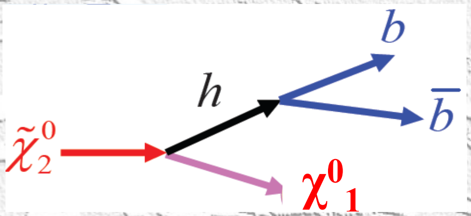
SUSY signals

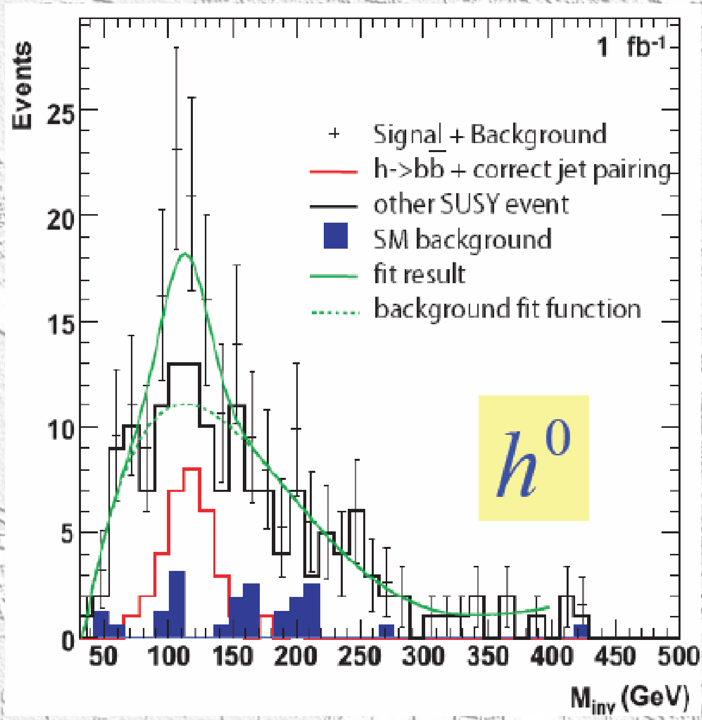
Second ligthest neutralino χ^0_2
- **cascade decay**
- **leptons + E_T^{miss}**





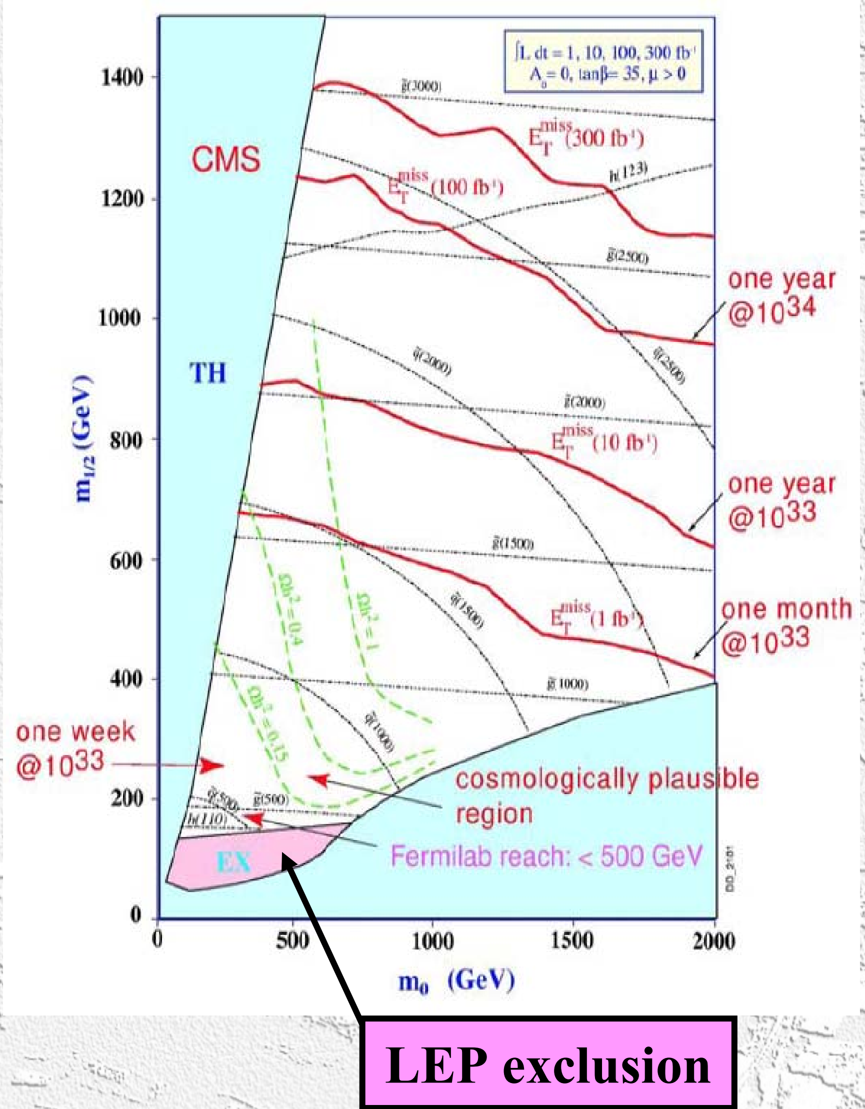
- **cascade decay with h**
- **b-jets + E_T^{miss}**





SUSY Search at LHC

Example: discovery reach as function of luminosity and model parameters which fix the mass scale of SUSY parameters



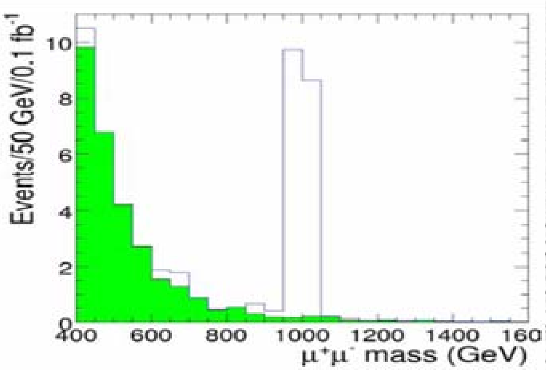
- **achievable limits exploiting E_T^{miss} signatures**
- **requires very good understanding of detectors**

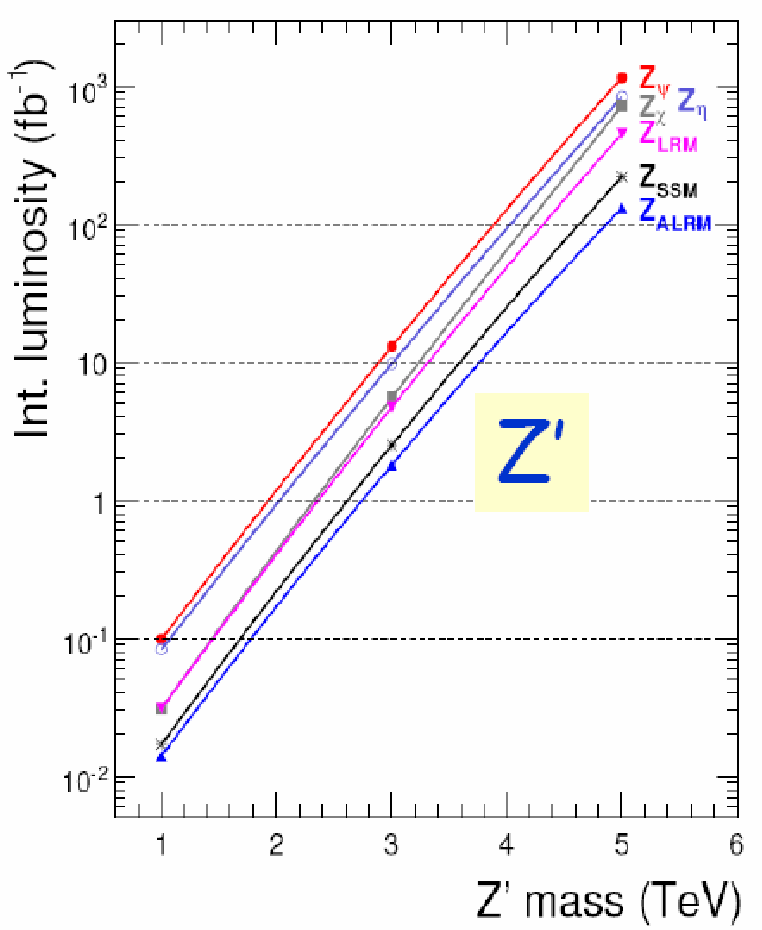
Conclusion:
- **LHC will eclipse today's limits on SUSY particles and parameters**
- **or discover SUSY if it exists at the TeV scale**

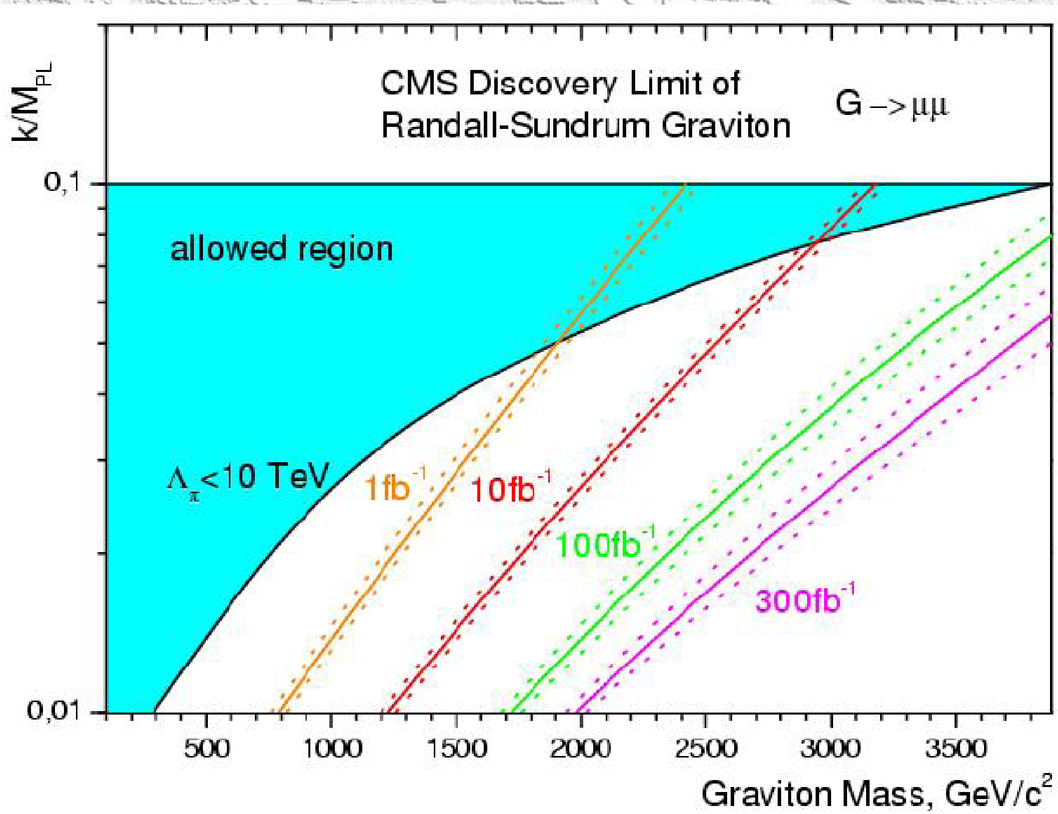
Example for other BSM Searches

Extra Dimensions: Z´/ Randall-Sundrum

With 1 fb^{-1}:
- **Z´ discovery up to 2 - 2.5 TeV**
- **most of RS parameter space covered**







Summary

- LHC start expected 2nd half 2008
  luminosity O(100 pb^{-1})
  - commissioning of detectors
  - calibrations, alignment
  - initial SM measurements: QCD, W/Z, top, …
  - light SUSY?
- 1 fb^{-1}, in range for 2009
  - start SM precision measurements
  - enter Higgs discovery era
  - explore SUSY over large area
  - new resonances, e.g. *Z´*
- 10 - 30 fb^{-1}, until 2011/12
  - most SM measurements, incl. precision m_t, m_W
  - cover entire Higgs mass range
  - start exploring multi-TeV region

End of Lecture 3