DESY Summer Student Program
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Physics in pp collisions

LHC, machine, detectors, physics

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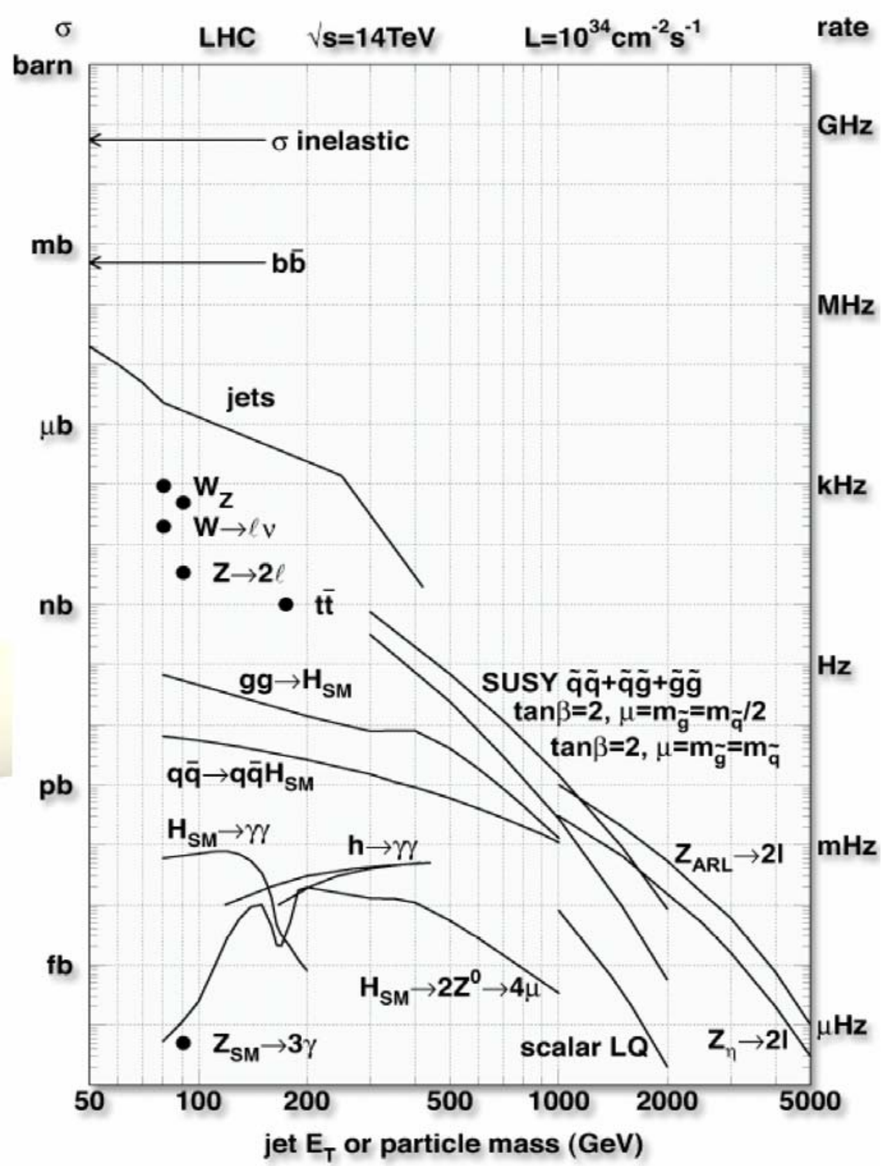
Yesterday:
- Motivation/Introduction: open questions in particle physics
- Hadron Collider Basics
- Detectors: ATLAS and CMS

Today:
- Physics: Existing results and prospects for the LHC
  - SM physics:
    - W and Z production at hadron colliders
    - Top quark production at hadron colliders
    - Search for the Standard Model Higgs boson
  - Search for physics beyond the Standard Model:
    - SUSY
    - (GUT → Leptoquarks)

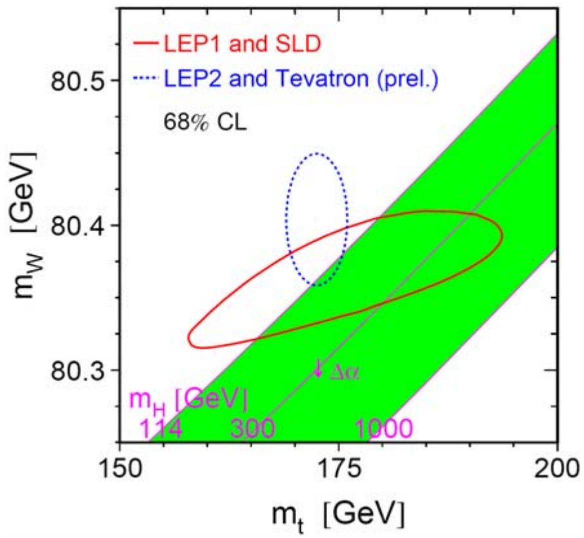
Overview of physics process in pp collisions



- At the LHC and in pp collisions in general a wide range of physics processes is accessible
  - High centre-of-mass energy and high luminosity allows to explore completely new regime
  - Discoveries expected
- Due to huge QCD background (jets), leptons (electron, muons) must be used to select electroweak processes and events of New Physics
- Note: at the LHC very high rates are expected for
  - Jets (of course)
  - W/Z
  - Top-pair production → “top factory”

Relevance of W and top mass measurements

- Indirect determination of W and top quark mass possible from comparison of precise experimental results with higher order calculations
- Comparison with direct measurements are a crucial consistency test of the Standard Model



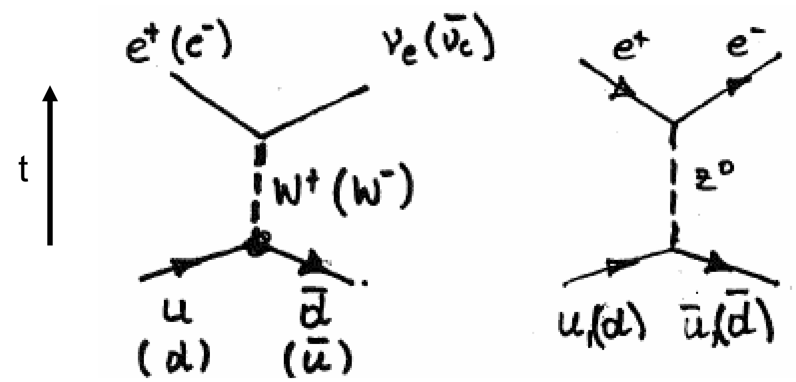
- Try to measure the mass of W and top as precisely as possible
- Most of the information comes from hadron colliders
  - Number of $W \rightarrow l\nu$ produced at TeVatron (6 fb^{-1}): 9 Mio events
  - Number of $W \rightarrow l\nu$ expected for LHC (10 fb^{-1}) : 60 Mio events

Discovery of W and Z bosons

History: Discoveries in the electroweak sector of the SM:

- Discovery of Neutral Current (Gargamelle, bubble chamber in neutrino beam, **1973**)
  → $m_W \sim 80$ GeV, $m_Z \sim 90$ GeV
- Rubbia+van der Meer: transformation of the CERN 450 GeV Super-p-synchrotron into a Proton-Anti-Proton collider (SppS): ~50 Events/mb·sec
  - two detectors: UA1 und UA2
  - **1983** discovery of $W^{\pm}$ und Z^0
- **1989-2000:** Measurements at LEP
- **now**: 1.96 TeV Tevatron (FNAL-Chicago)
- **Starting now**: *p p* @14 TeV at LHC (CERN-Geneva)

Production mechanisms:



- if $x_1 \neq x_2$ → p_Z of W is unkown (long.) → interesting variable in hadron collisions is p_T

Decay of the W:

- W couples to all left-handed fermions
- Expect the decay ratios:

$$W \to e^+\nu_e,\ \mu^+\nu_\mu,\ \tau^+\nu_\tau,\ u\bar{d}',\ c\bar{s}'$$

1 : 1 : 1 : 3 : 3

- exp.: BR(eν)=BR(μν)=BR(τν)=10.7%
- Corrections from hadronisation

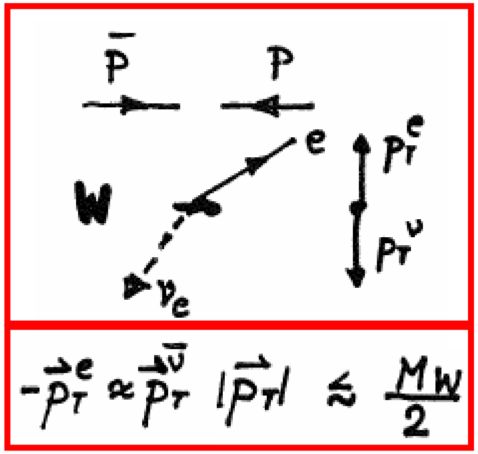
„Typical" W event:

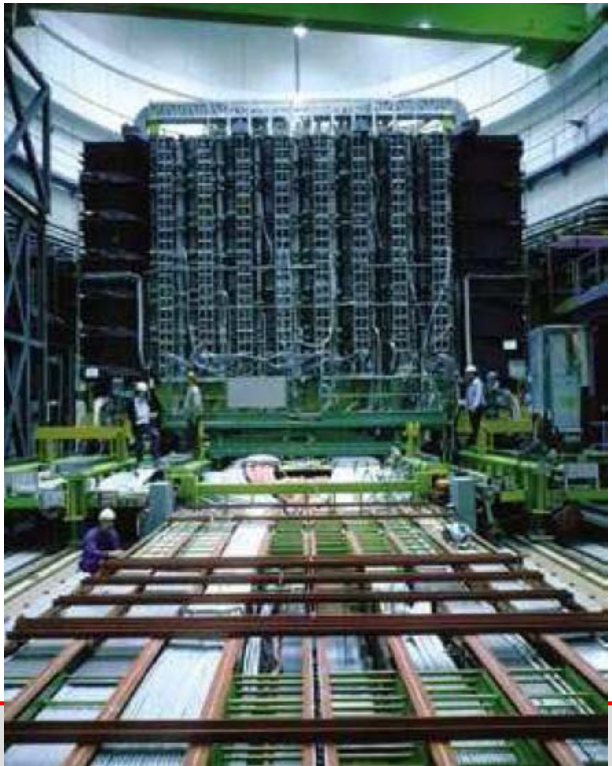
- W identification:

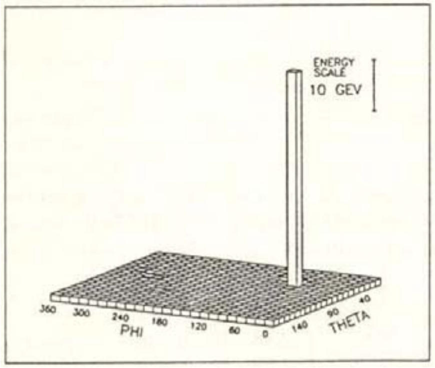
$$W^{\pm} \rightarrow e^{\pm} + \nu_e \qquad W^{\pm} \rightarrow \mu^{+} + \nu_e$$

  – Lepton with high p_T and $p_{T,miss}$ from $\nu_,$ "back to back"

Schematic event display:





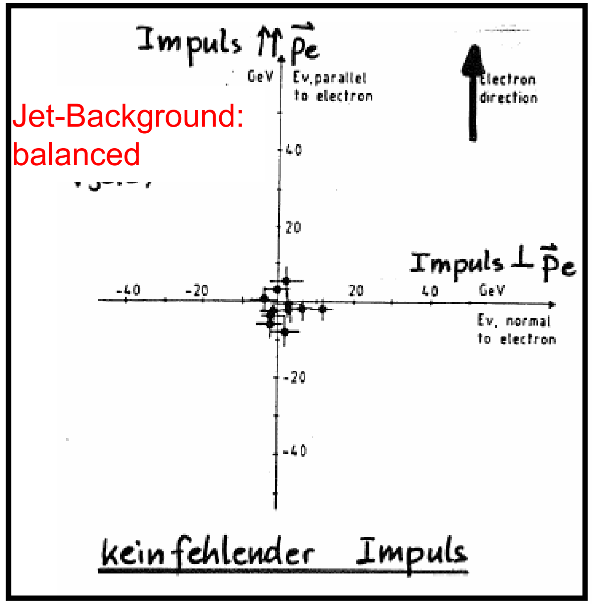


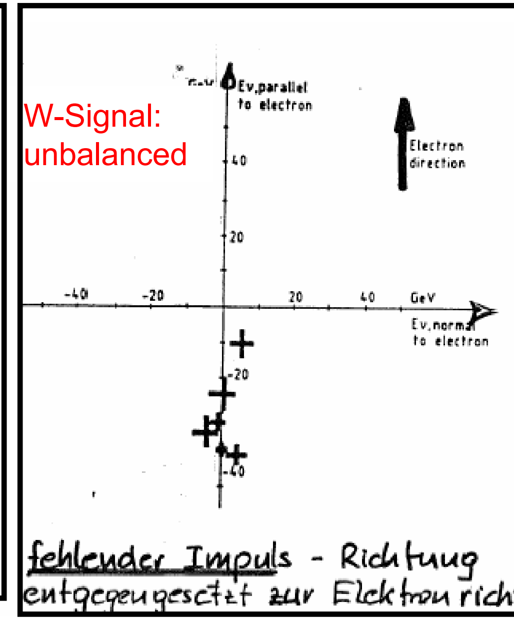
UA1-Detektor:

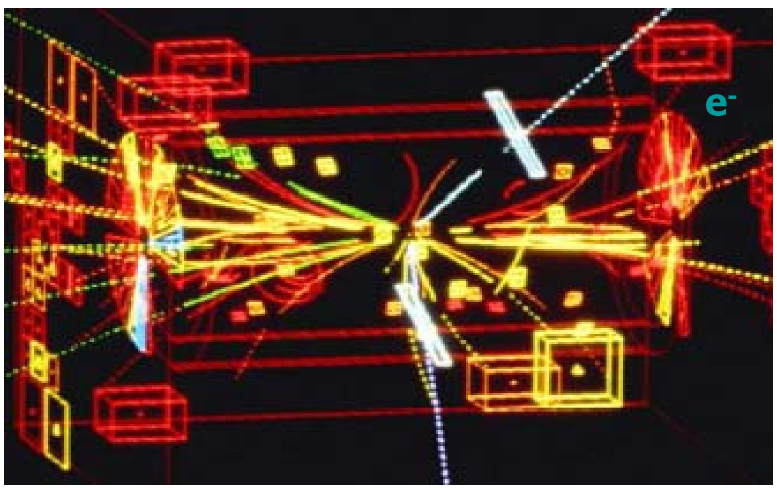
- Drift chamber 2x2x6 m^3
- B-filed: 0.7 Tesla
- em. Calorimeter
- Muon-system

Discovery of W and Z bosons

- **UA1/UA2-results:**
- Jan.1983: 7 Events W→ eν → M_W=81±5 GeV
- July 1983: 22 Events (UA1 +UA2) Z^0→ $e^+e^-/\mu^+\mu^-$ → M_Z=90 GeV (σ x Γ ~10x smaller than W! But clean signatures, since no missing ν.)
- **Typical Z^0-Event in UA1:**

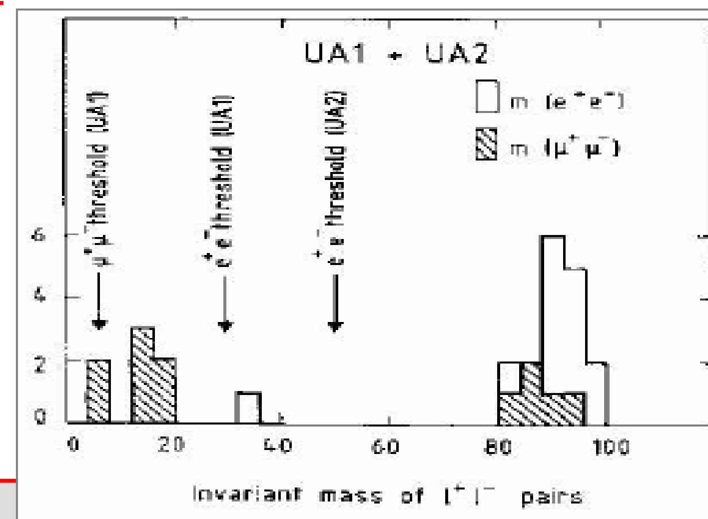






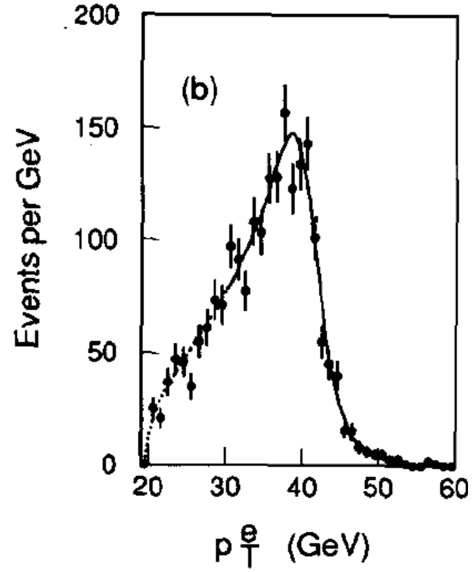
- **1984: Nobel Prize for S. van der Meer and C. Rubbia**

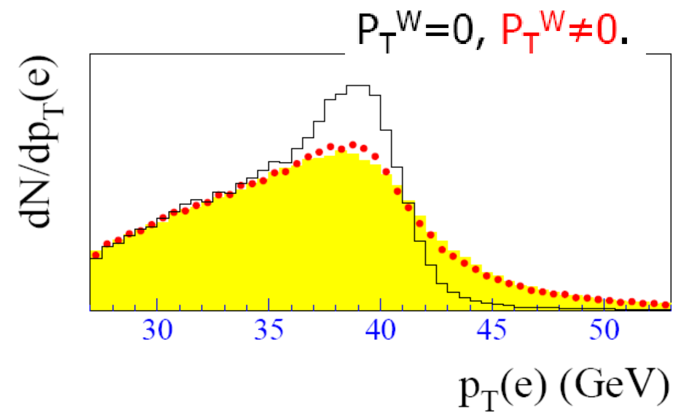
Invariant Di-Lepton-Mass:



Measurement of the W mass in pp collisions

- Mass of the W boson can be determined from p_{Te} distribution of the electrons:
  - "Jacobean-Peak"
  - $p_{Te}<M_W/2$
  - but sensitive to possible p_T of W (HO QCD effects)

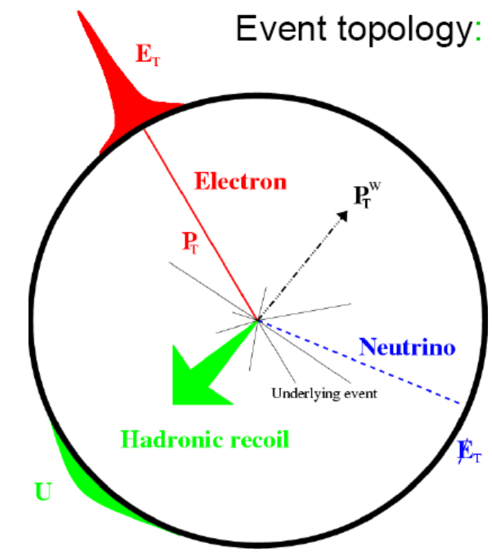


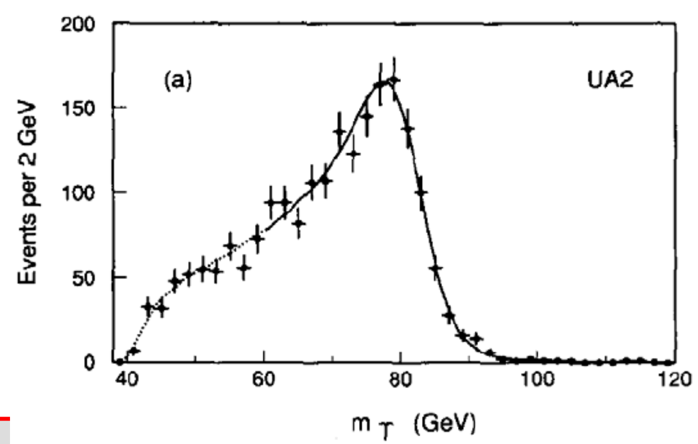


- Less sensitive to this effect: „transverse mass":

$$m_T=\sqrt{\left|p_T{}^l\right|^2+\left|p_T{}^\nu\right|^2-\left(\vec{p}_T{}^l+\vec{p}_T{}^\nu\right)^2}$$

  - Corresponds to invariant mass visible in transverse plane
  - $M_T<M_W$

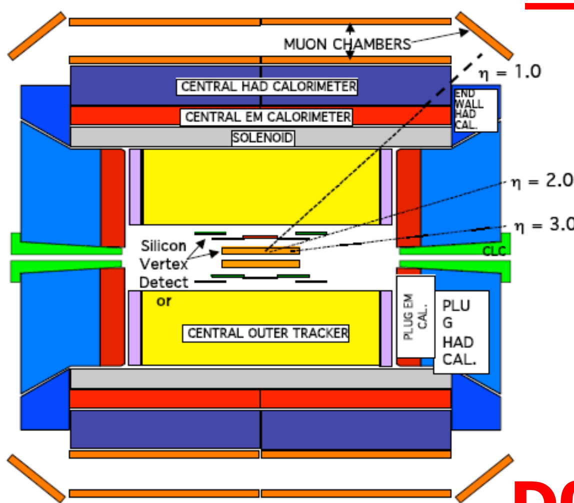


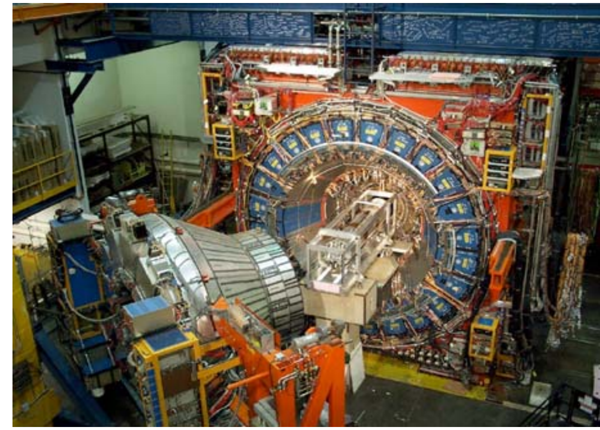


TeVatron

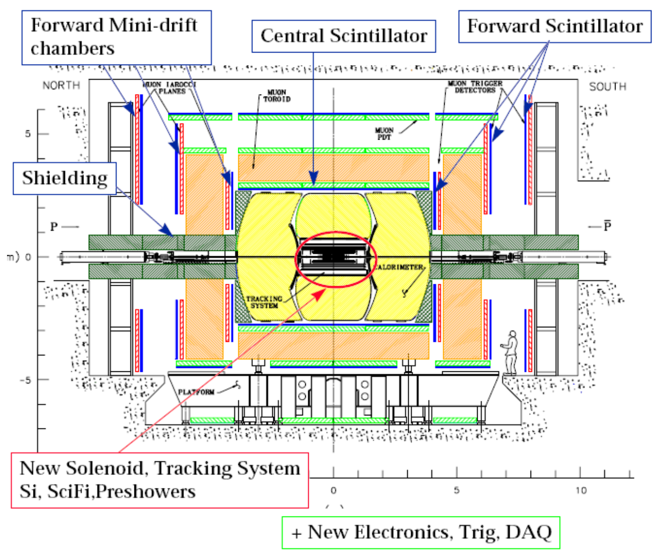
- Proton Antiproton Collider
- Two experiments: CDF, D0
- 1992-1996: Run I $\sqrt{s}$=1.8 TeV
  - $\int L\,dt$=125pb^{-1}
- 1996-2001: Upgrade of the machine:
  - New Injector, Anti-Proton-Recycler
  - Higher luminosity, higher rates
- Since March 2001: Run II $\sqrt{s}$=1.96 TeV
  - Up to now $\int L\,dt$=6fb^{-1}
  - Plan: operation until 2011(?)

CDF





D0

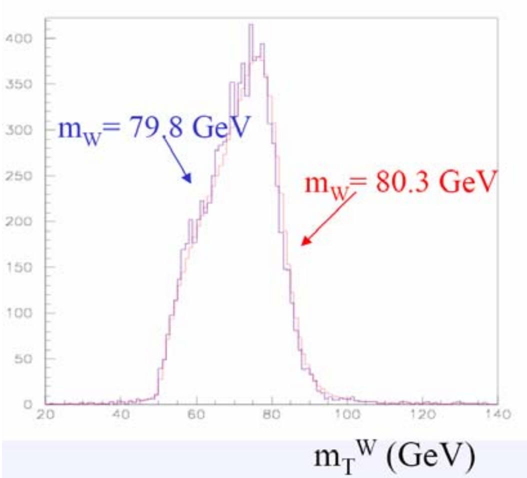


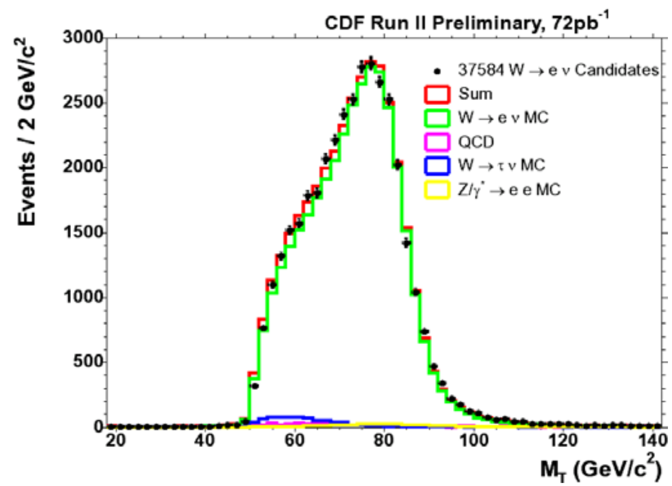
LAr-calorimeter (high granularity)

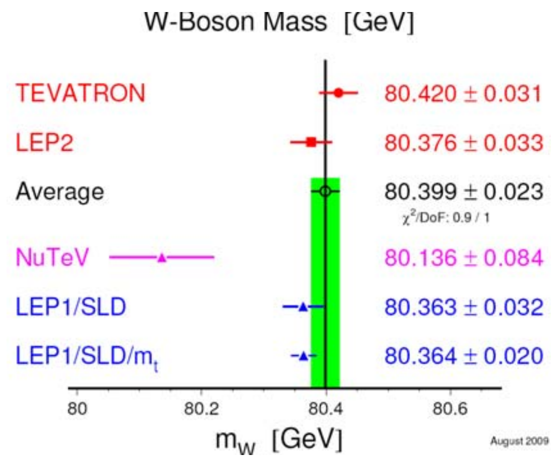
In run I: no magnetic field

Current M_W measurements

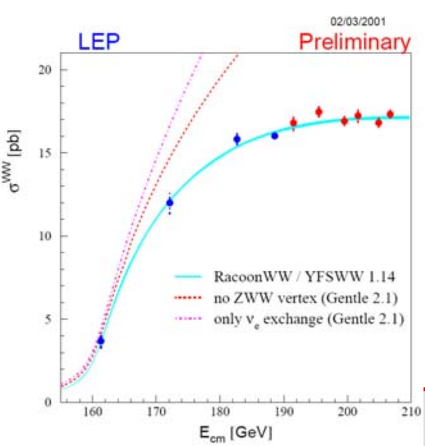
- Studies ongoing at the TeVatron.
  - Determination of M_W from comparison of M_T simulation for various M_W with data
  - Crucial: accuracy of the simulation!

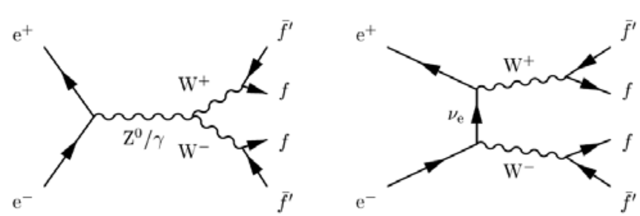






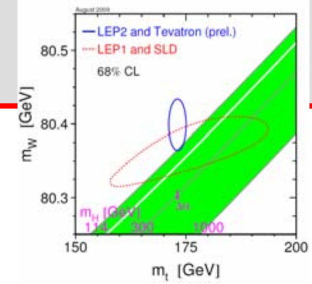
- Combination with results from LEP2



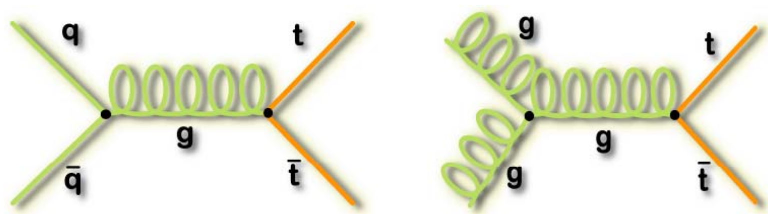


LHC: same techniques as Tevatron, aim: Δm_W=15 MeV

Top physics



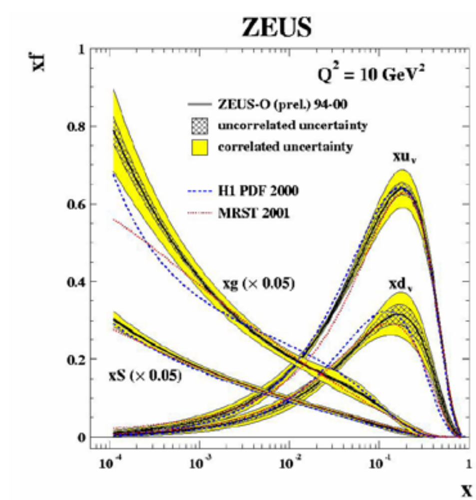
- M_{top} is a very important parameter of the SM
- From the current colliders the top quark can only be produced at TeVatron
- Production via strong interaction:



- Increase of gluon induced processes with √s due to $\sqrt{\hat{s}} = \sqrt{x_1 x_2 s}$ and proton structure
- Lower x values → more gluons

	Run 1 1.8 TeV	Run II 1.96 TeV	LHC 14 TeV
qq	90%	85%	5%
gg	10%	15%	95%
σ (pb)	5 pb	7 pb	600 pb

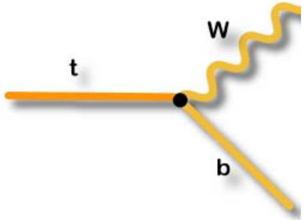
	LHC	Tevatron
100 GeV:	x ~ 0.007	0.05
5 TeV:	x ~ 0.36	--



- Much higher cross sections at the LHC: “top factory”

Decay of the top quark

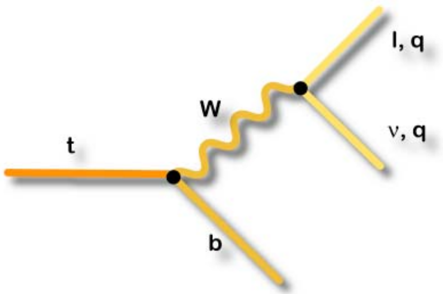
- Production at Hadron colliders: strong interaction
- Decay: weak interaction
- Remember: in matrix element of weak quark decays the corresponding CKM matrix element appears



$$\frac{-ig}{\sqrt{2}}\bar{t}\gamma^{\mu}\frac{1}{2}(1-\gamma^{5})V_{tb}bW_{\mu}$$

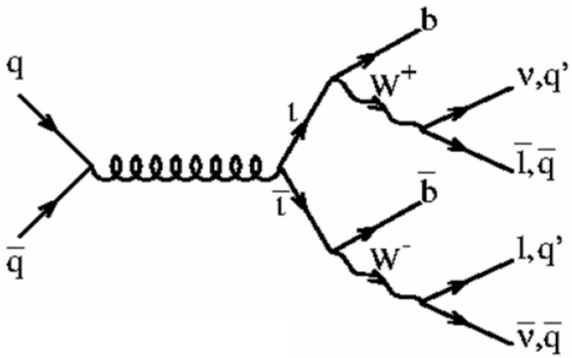
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} \sim 0.974 & \sim 0.23 & \sim 0.003 \\ \sim 0.022 & \sim 0.974 & \sim 0.04 \\ 0.004-0.01 & 0.04 & \sim 1 \end{pmatrix}$$

- Decays t→W+s ($\bar{t}$→W$\bar{s}$) and t→W+d ($\bar{t}$→ W$\bar{d}$) (allowed in principle) are strongly suppressed
- BR (t→Wb) = 100%



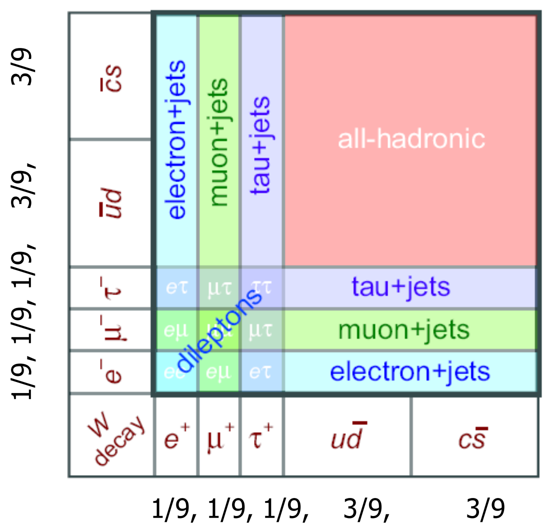
- Top is so heavy that it decays before hadronisation τ_{top}=4·10^{-25}s (due to the large phase space available)
  - There are no bound states with top flavour ("toponium").
  - In top physics a free quark is studied.

Final state topologies of $t\bar{t}$ events



- Topologies of $t\bar{t}$ events are determined by W- decay

Top Pair Decay Channels



3 event categories:

1) „Dileptons"

- + easy to identify (e and μ)
- – small cross section (fraction for e and μ is only 5 %)
- – missing energy from two neutrinos

2) „Lepton+Jets"

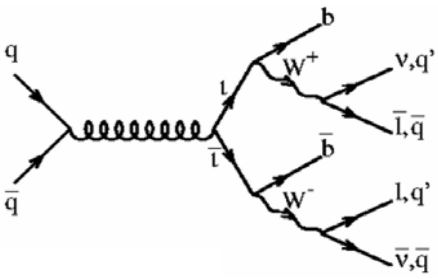
- + Cross section larger: ~ 30%
- + Only one neutrino to be considered in the reconstruction

3) purely hadronic

- – Hard to reconstruct (QCD background), not covered here.

Note: all events contain 2 b-jets

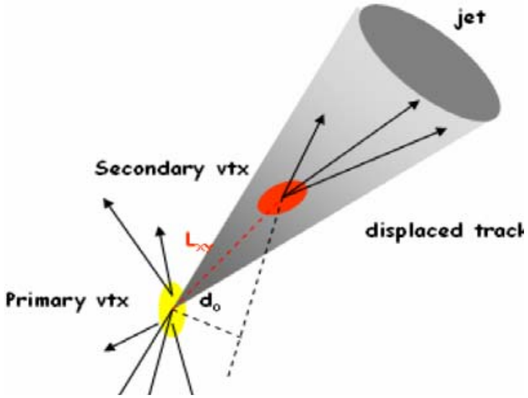
- All of the aforementioned topologies contain two jets from b quarks



Side remark: „B-Tagging":

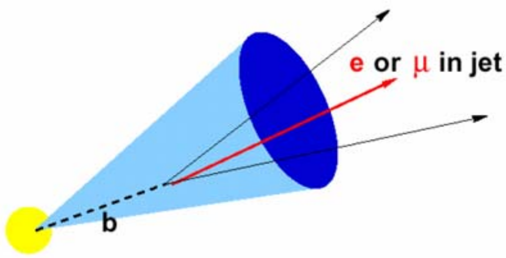
1) Search for secondary vertex $B^0:\ \mathrm{m} = 5.3\,\mathrm{GeV},\quad \tau = 1.6\,ps$

   – B mesons decay after $l = \beta\gamma c\tau = \frac{E}{m} c\tau \sim 1mm$



Good resolution of Si- detectors needed

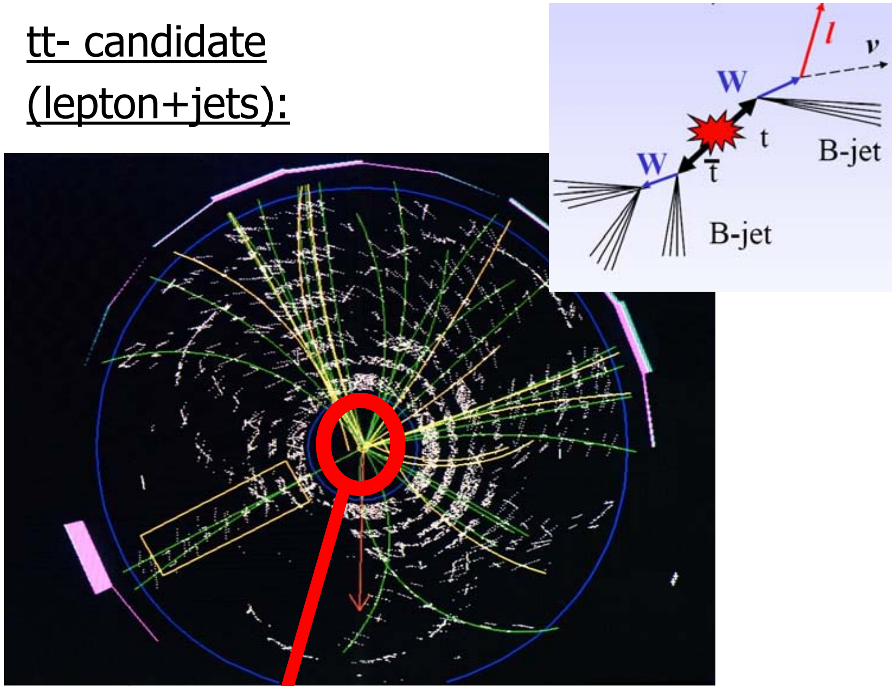
2) Search for leptons in jets from semileptonic b-decay:

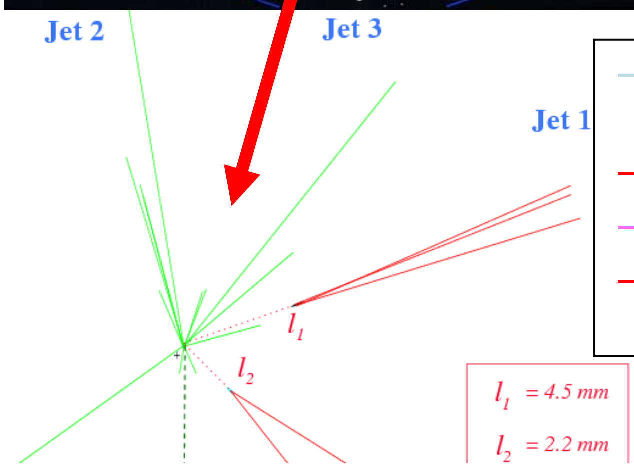


- $b \to \ell\nu c$ (BR ~ 20%)
- $b \to c \to \ell\nu s$ (BR ~ 20%)

Example top candidates from TeVatron

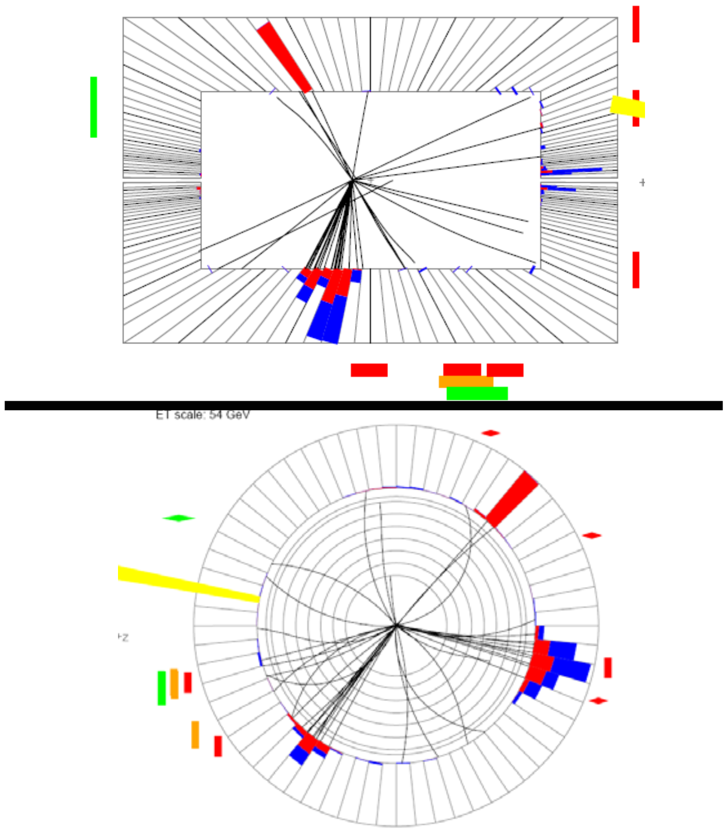
tt- candidate (lepton+jets):





- 2 normal jets
- 2 b-jets
- lepton,
- Missing energy

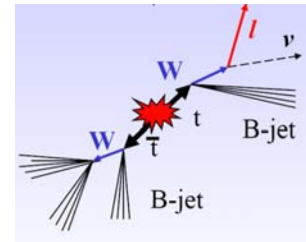
tt- candidate (Di-Lepton)



Object	p_T (GeV)	η	ϕ
electron	65.097	-0.539	0.853
muon	48.148	0.565	3.400
jet 1	192.272	-0.183	6.027
jet 2	80.943	-0.425	4.080
$\not{E}_T$	156.022		2.630

Top mass measurements

- Best channel: Lepton-Jets
  - Dileptons: direct measurements impossible due to two missing ν
  - Purely hadronic: bad ratio of signal to background
- Event selection:
  - 1 hard charged lepton (e oder μ)
  - E_{Tmiss}>20 GeV
  - ≥4 hard jets (two with b-tag)



- Unclear mapping of observed jets to quarks in final state: → 24 possibilities
- For all possible mappings a kinematic fit is performed
  - For each event the invariant mass of the blν-system is calculated; then the measured momentums of the final state object are varied within their experimental uncertainties.
  - Other varied parameter of the fit is m^{reco}_{top}.
  - $\Delta\chi^2$ is minimized, ie. the free parameters of the fit (momenta and m^{reco}_{top}) are determined such that they best fit the measurement and the hypothesis.
  - Chosen is the mapping which leads to the minimal $\Delta\chi^2$ after minimization
  - m^{reco}_{top} is regarded as the observed top mass for this event

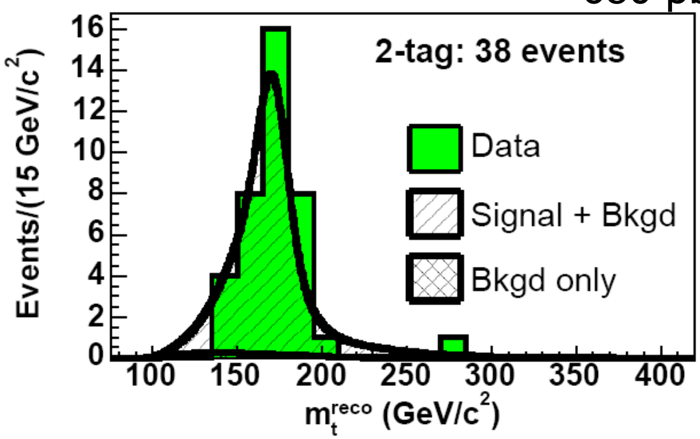
$$\chi^2 = \sum_{i=\ell,4jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,fit} - p_j^{UE,meas})^2}{\sigma_j^2} + \frac{(M_{\ell\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{b\ell\nu} - m_t^{reco})^2}{\Gamma_t^2} + \frac{(M_{bjj} - m_t^{reco})^2}{\Gamma_t^2},$$

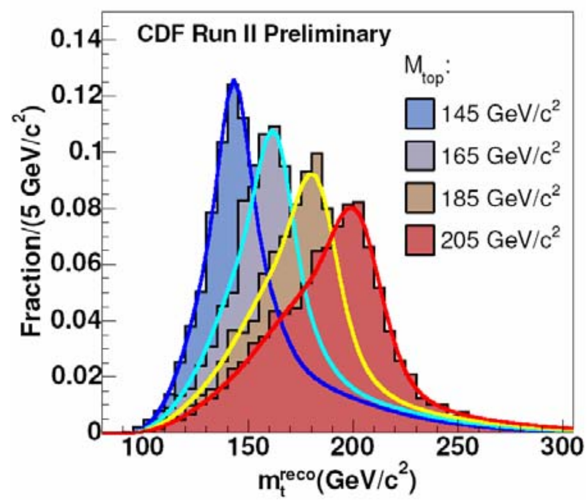
Top mass measurements

- Determination of the top mass from comparison with simulation for various m_{top} values → "templates"

CDF:

680 pb^{-1}

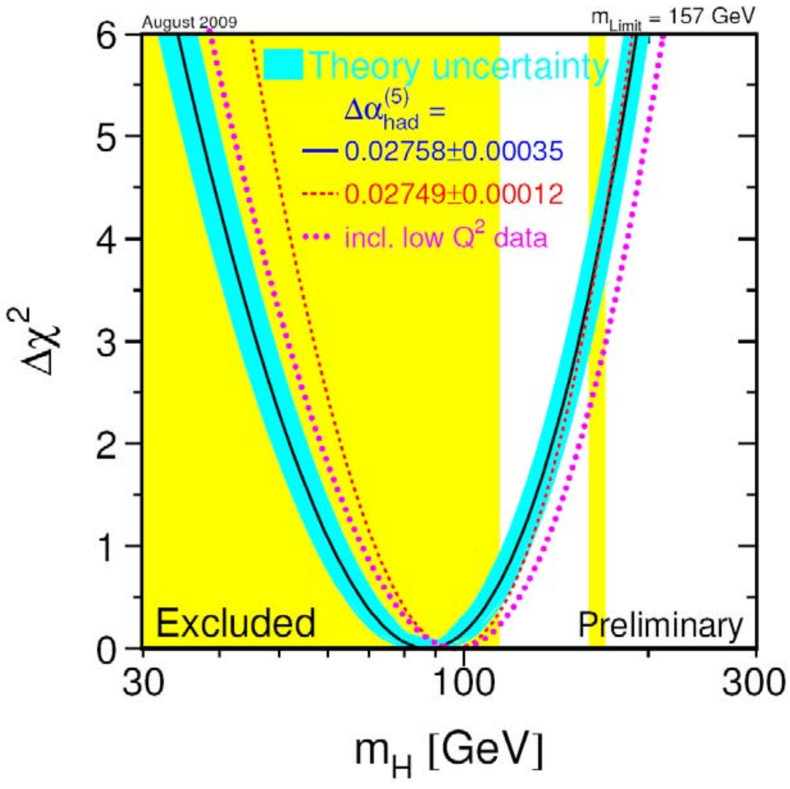




- There are other methods which are used at the TeVatron to determine m_{top}
- World average today: 173.1±1.3 GeV

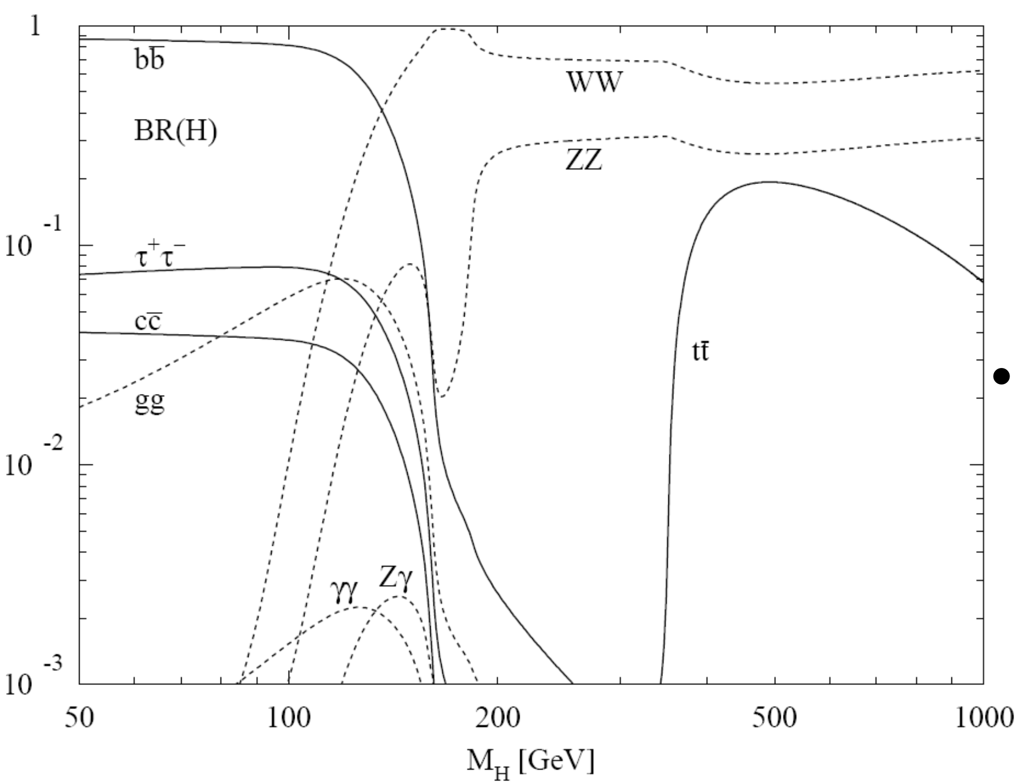
- Expectation for the LHC for 10 fb^{-1}: < ~1GeV

- Remember: indirect prediction of a light SM Higgs boson

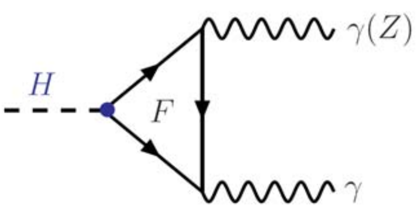


Couplings and decay of the Higgs boson

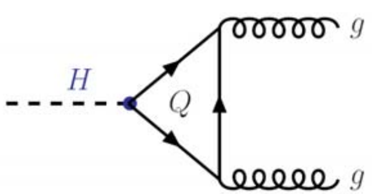
- <u>SM predicts</u>: the Higgs couples to SM particles proportional to their masses
- consequence: Higgs decays into the heaviest particle which is kinematically accessible
- **<u>Branching ratios of the Higgs:</u>**



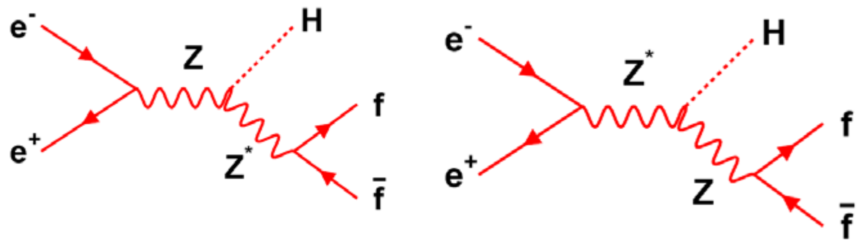
- Interesting and relevant for the searches at the LHC:
  - 100<M_H<140 GeV: $\gamma\gamma$-decay possible
  - Not possible on tree level since photon is mass-less
  - But: possible via fermion loops
  - small BR, but almost no background in pp



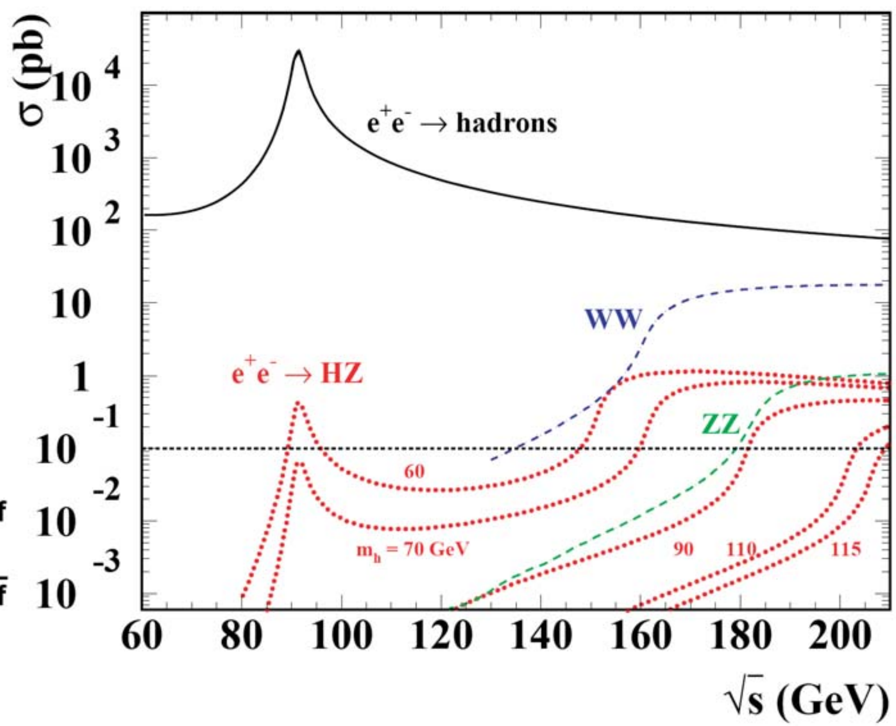
- similar:
  - H→ gg, gg→ H
  - Top quark loop



- in e^+e^- Higgs bosons produced by „Higgs-radiation" ($Z \rightarrow ZH$):

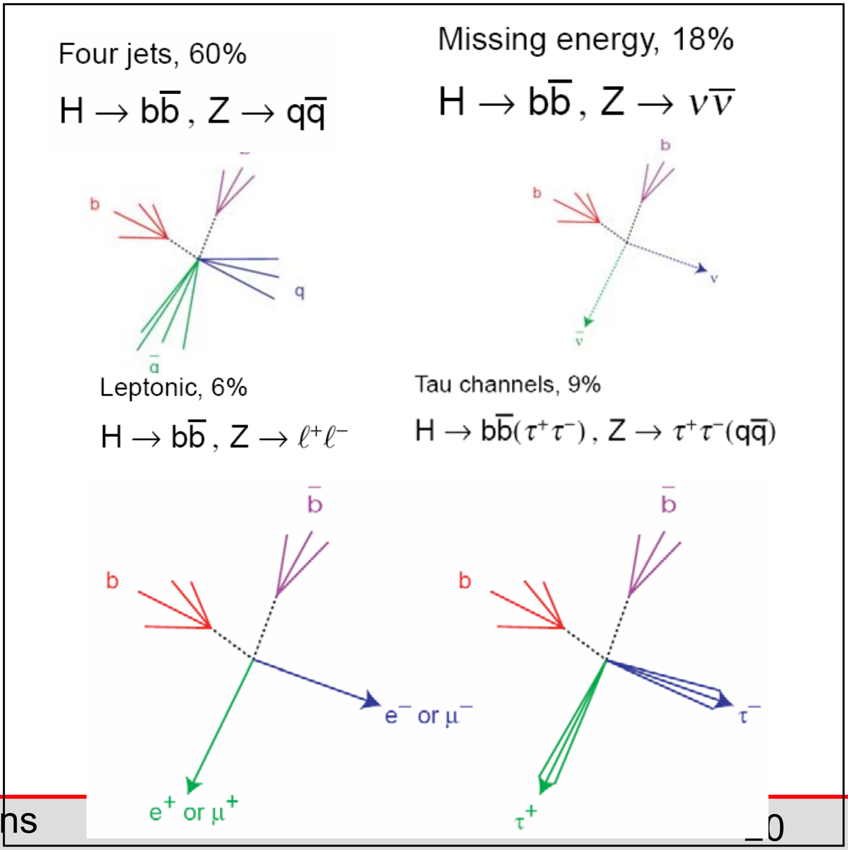


➢ $\sigma(\sqrt{s})$: „large" at Z-resonance and if $\sqrt{s} > m_Z + m_H$ (kin. threshold)



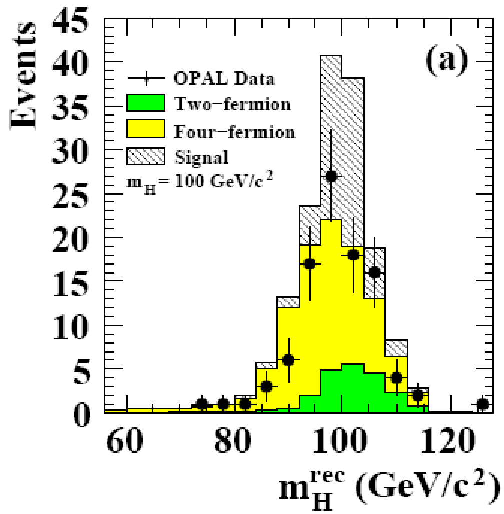
Example: Search for a Higgs signal in LEP2 data:

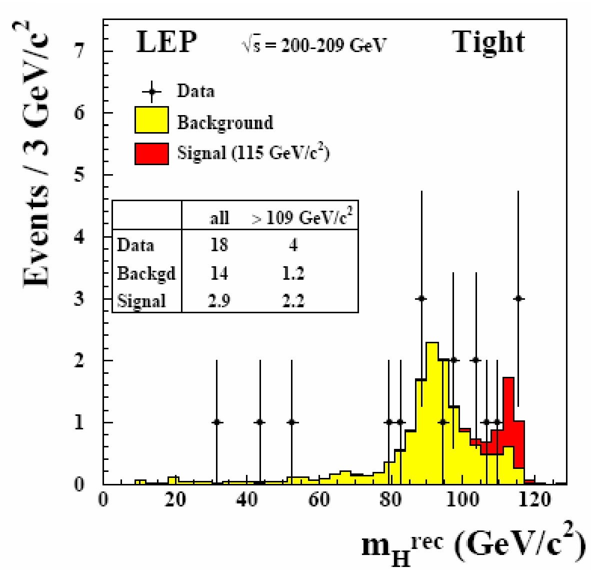
- E_{max}~209 GeV
  → sensitivity ~m_H<118 GeV
- **4 Event classes:**



Search for the Higgs in e^+e^- collisions

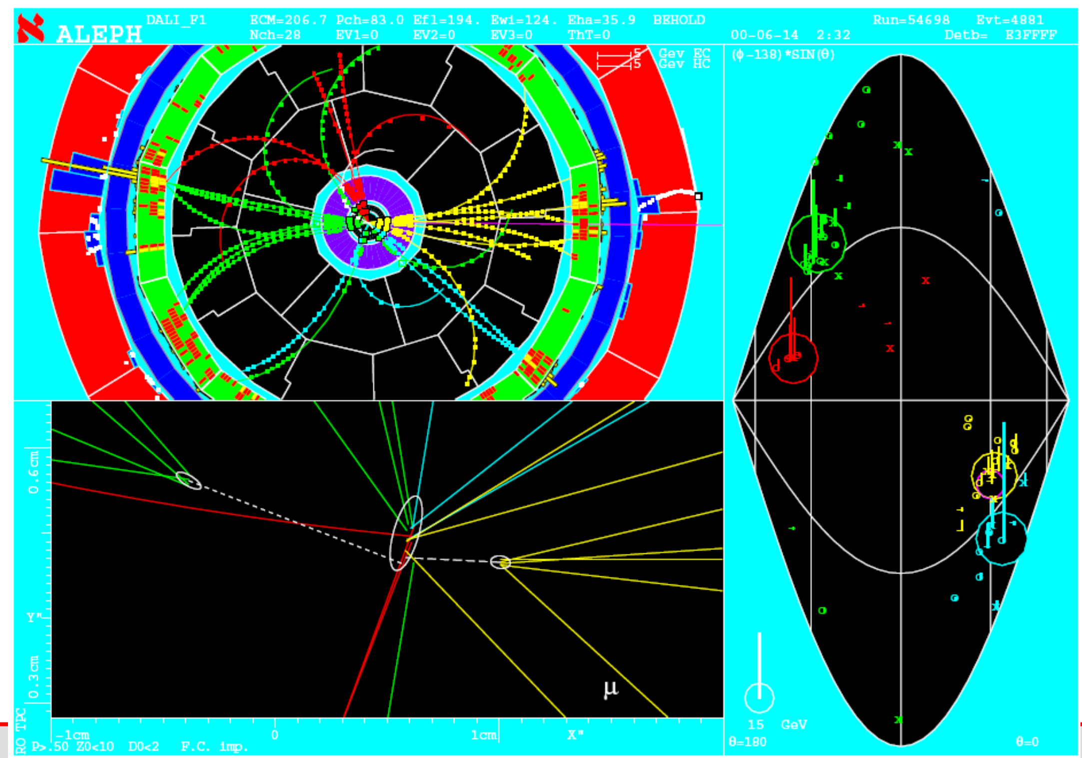
- No Higgs signal in data





- 2000: just before LEP shut-down: signal mainly driven by ALEPH events
- After complete reconstruction: 1.7 σ deviation at M_H=115 GeV.
- Final LEP result: m_H > 114.4 GeV with 95% CL.

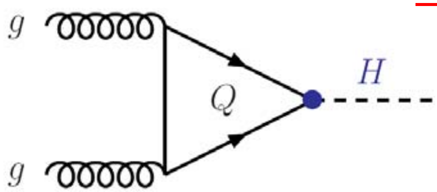
ALEPH event in $q\bar{q}b\bar{b}$ channel:



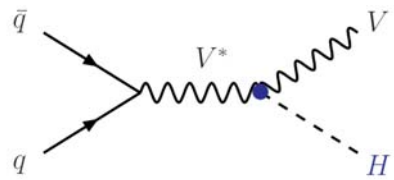
Higgs production in pp collisions

Possible production processes:

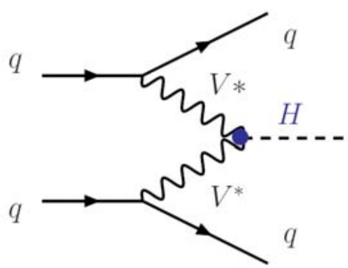
gg fusion



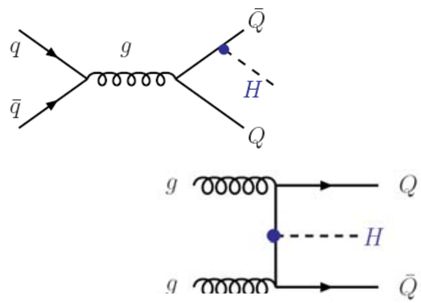
H-radiation, associated production



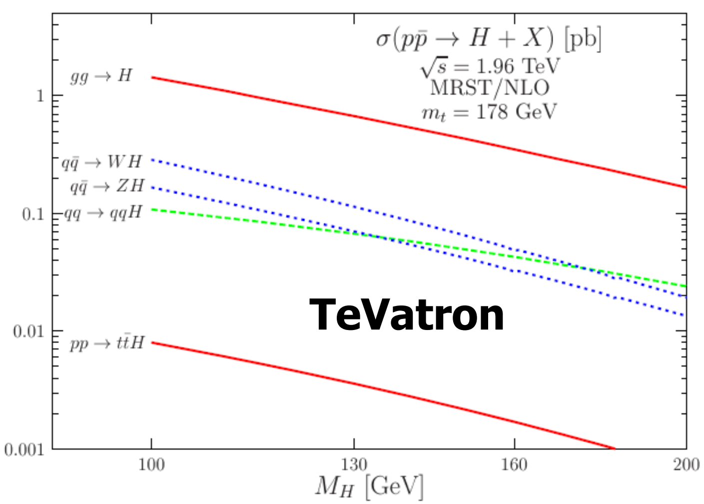
vector boson fusion

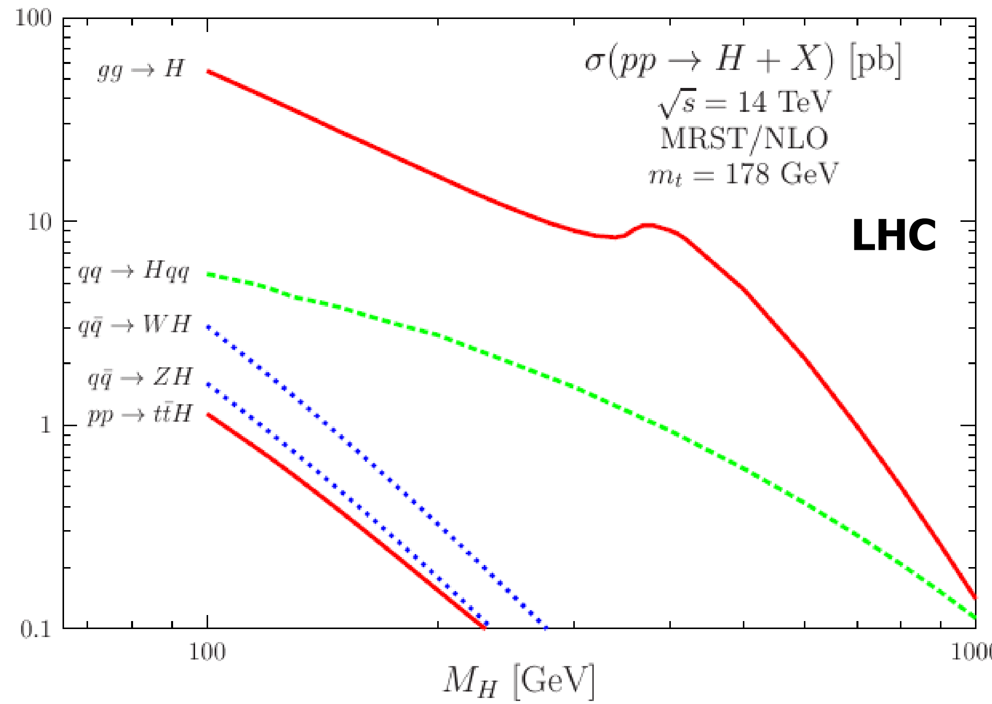


„assoc. prod." with heavy Q



- Most important at TeVatron: gg fusion and H radiation
- Note: cross sections much larger at the LHC
    - E.g gg→ H: ~70-80 times (reason again: gluon density in proton)





Higgs searches at the TeVatron

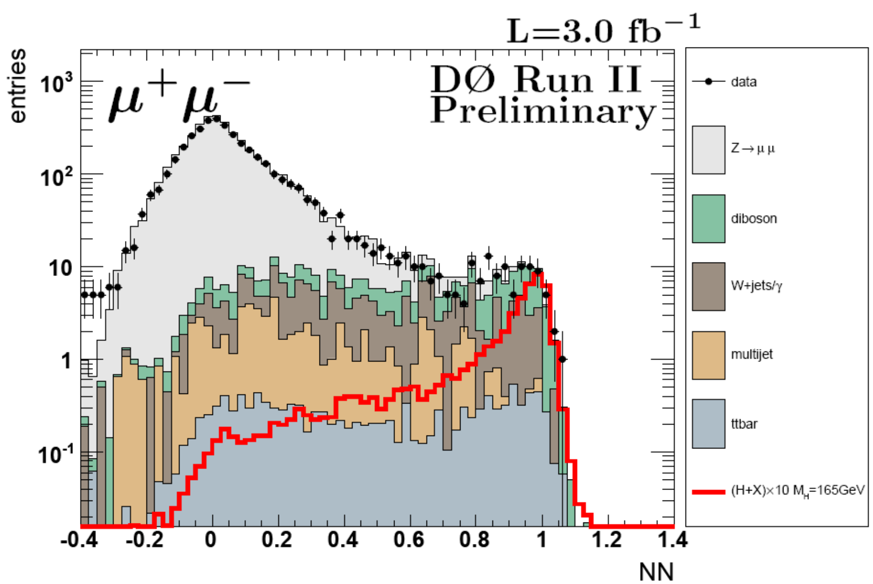
- production@TeVatron: **gg→H or WH, ZH**
- Most promising searches in main decay channels: **H→ $b\bar{b}$** (m_H<~135 GeV) and **H→WW** (m_H>~135 GeV)
- H→ $b\bar{b}$ not usable in gg→H due to QCD background, only usable in associate production.

Higgs- Signaturen am TeVatron:

- m_H<~135 GeV:
  - WH → lν bb
  - ZH → ll bb
  - ZH → νν bb
- m_H>~135 GeV:
  - H → W^+W^- → $l^+\nu$ $l^-\nu$ (inclusive) **(*)**
  - WH → WWW → $l^\pm l^\pm$ + X (leptons with same charge)
  - …

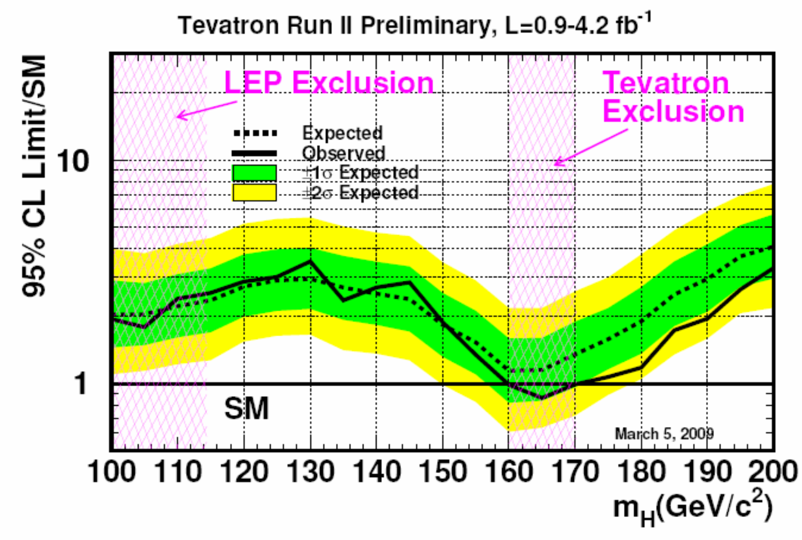
Example H→ WW→llνν

- Search strategy :
- Accumulation of Higgs candidates by dedicated selection cuts (preselection)
  - Require: two leptons with high p_T and $E_{T,miss}$
- Final selection by neural network



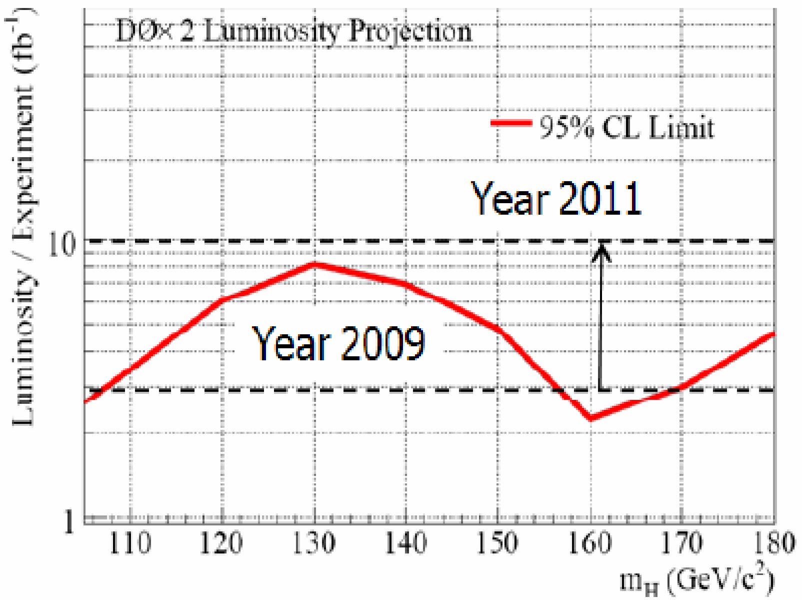
- Amount of data not yet sufficient

- Combination of CDF and D0 results (all search channels)
- Result from 13.March 2009

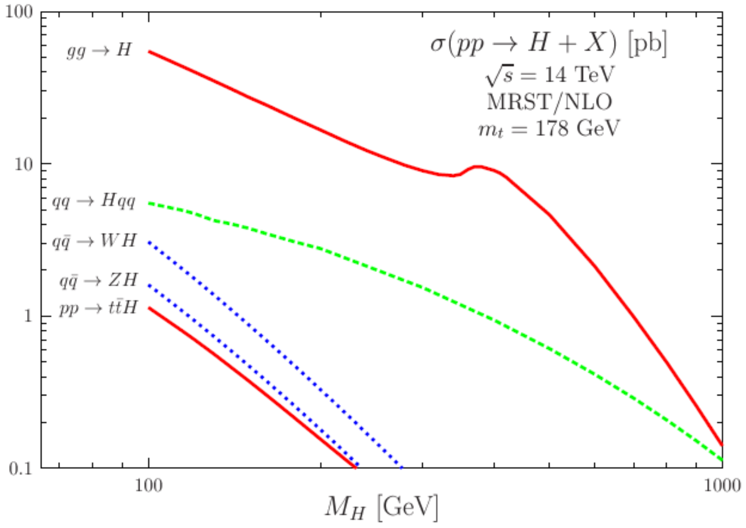


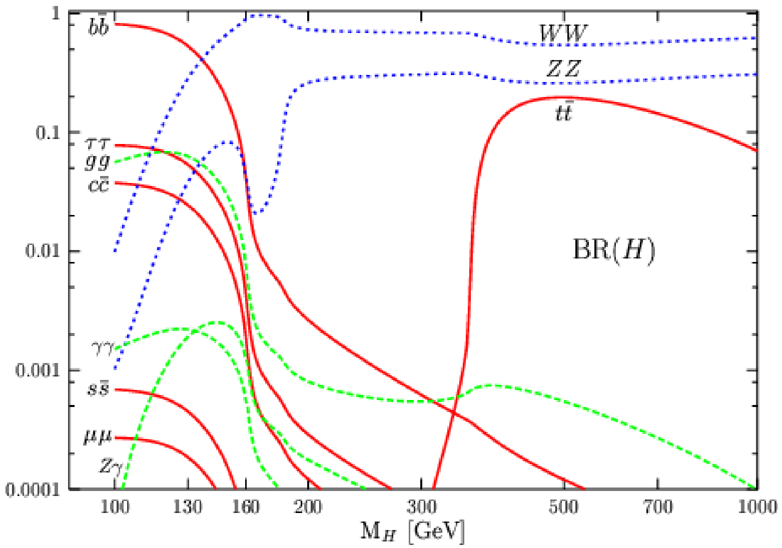
- Combination of all channel allows exclusion at m_H=160-170 GeV

What can we expect from TeVatron?



- >2011: 95% CL exclusion of the interesting region 115-185 GeV
- Maybe first evidence?



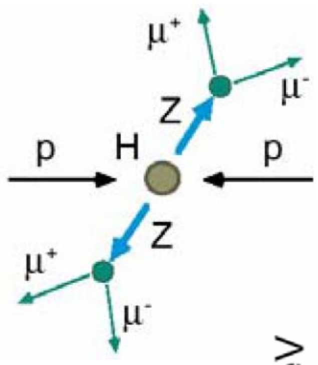


Important signatures at the LHC:

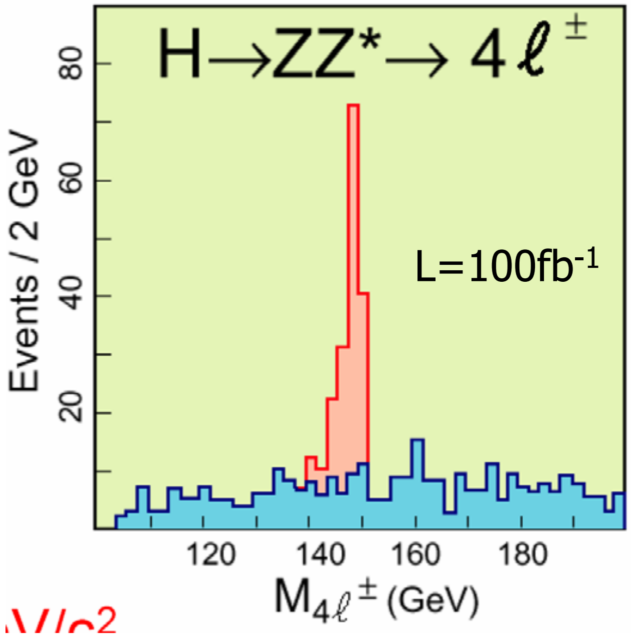
- Small masses:
  - $gg \to H \to \gamma\gamma$
  - $gg \to H \to ZZ \to 4l$
  - tt H with H→bb
  - qq H→ qq $\tau\tau$
- Large masses:
  - $gg \to H \to ZZ \to 4l$
  - $gg \to H \to WW \to l\nu l\nu$
  - qqH→qq WW
- Note: background!

"golden channels": H→ $\gamma\gamma$ H→4l

- signal:
  - $\sigma * BR$=5.7 fb (m_H=100 GeV)
- background:
  - tt→WbWb→lν clν lν clν
  - $\sigma * BR$=1300 fb
- selection:
  - $P_T(1,2)$ > 20 GeV
  - $P_T(3,4)$ >7 GeV
  - M(ll) ~ M_Z
  - Veto: leptons from B- decays

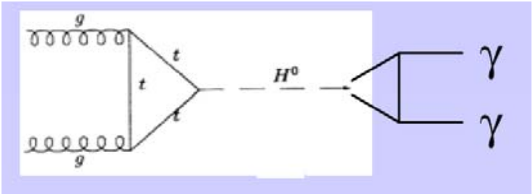


mass spectrum:



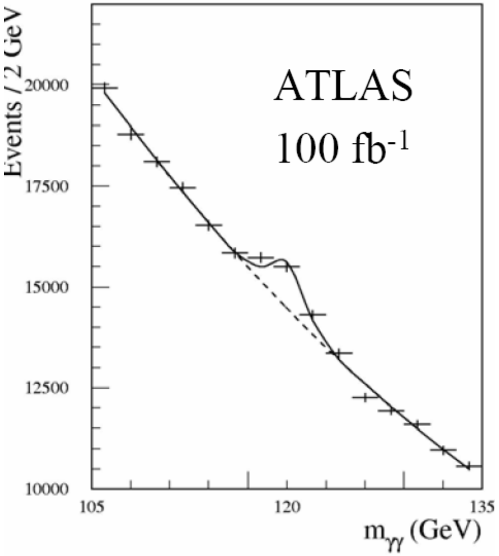
- Very narrow peak because of excellent measurement of muons.
- Discovery potential in the region m_H :130 GeV to 600 GeV

signal:



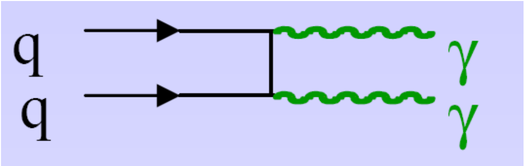
σ*BR ~ 50 fb   BR~10^{-3}

expected signals:

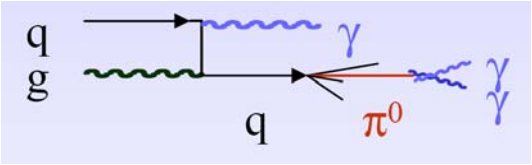


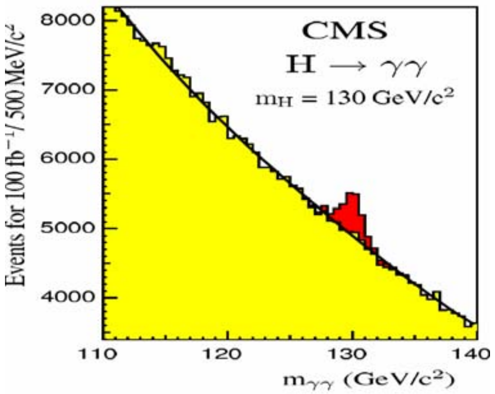
background:

- **γγ (irreducible)**: z.B.:
  - $\sigma_{\gamma\gamma}$ ~ 2 pb / GeV
  - Γ_H ~ MeV
  - needed: σ(m)/m~1%



- **γj+jj (reducible)**
  - high jet-rejection

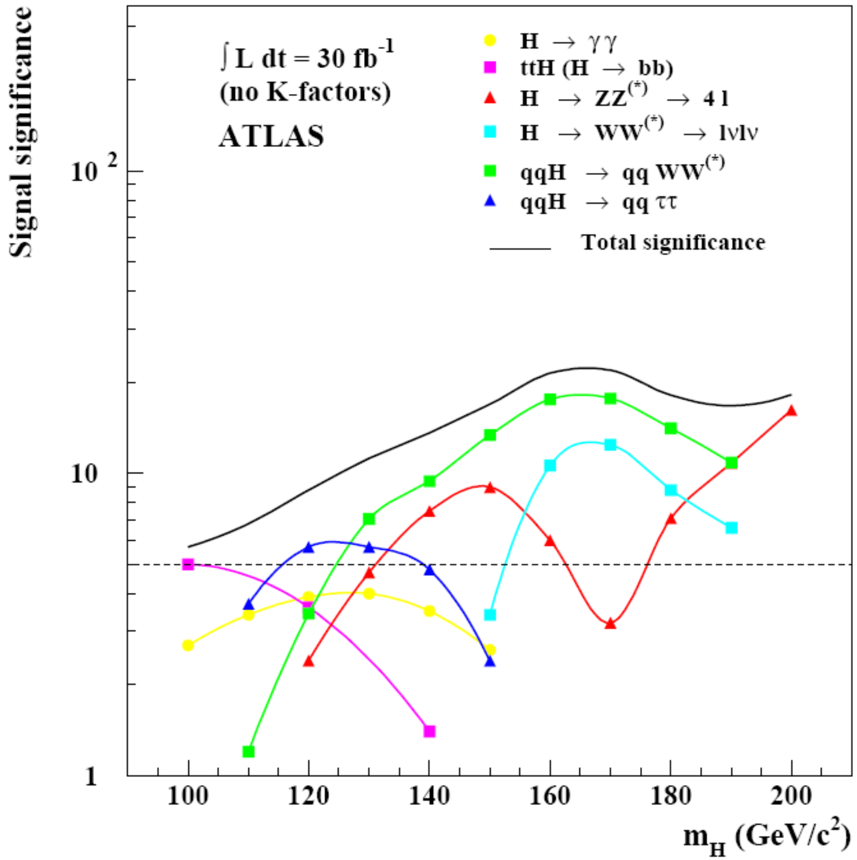




→ Challenge for electromagnetic calorimeters

- Discovery potential: 100-140 GeV

Individual and combined significances for 30 fb^{-1}



$$\text{Sign.} = \frac{N_S}{\sqrt{N_B}}$$

- There are several other search channels
- At the LHC the Higgs boson can be discovered in the full mass region in 30fb^{-1}.
- 30fb^{-1} corresponds to ~3 year of data taking!

Remember: Supersymmetrie (SUSY)

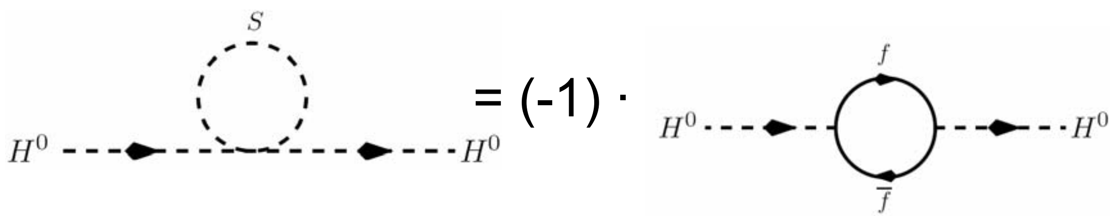
- Introduction of a new „SuperSymmetry“ Fermion ←→ Boson
- Introduction of SUSY Partners for all SM particles

SM Teilchen (R=1)	SUSY Partner (R=-1)
Quarks q	Squarks $\tilde{q}$
Leptons l	Sleptons $\tilde{l}$
W±, Z⁰, γ, Higgs: h, A⁰, H⁰, H±	Neutralinos, $\chi^0_{1,2,3,4}$ Charginos $\chi^{\pm}_{1,2}$
Gluons g	Gluino $\tilde{g}$

→ **New contributions to Higgs Mass**

- contributions cancel if ΔM< 1 TeV

→ Solution to hierarchy problem



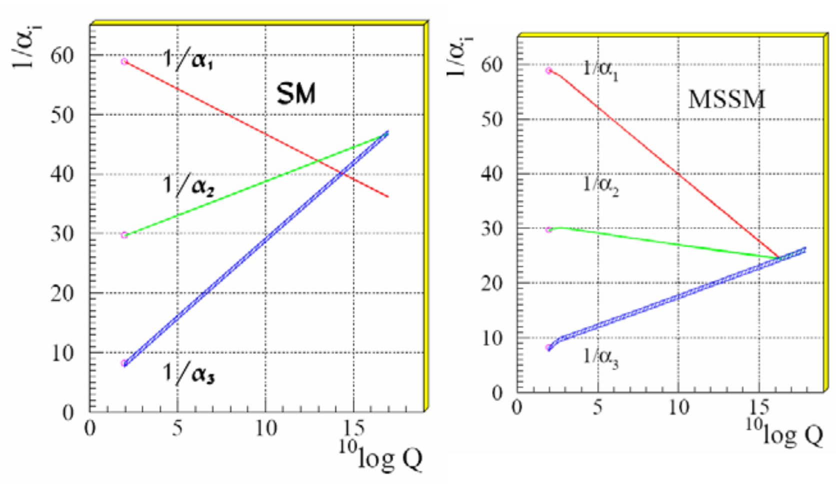
<u>SUSY can provide explanation for Dark Matter:</u>

If stable, the Lightest Susy Particle leads to the correct relic density in the universe

→ SUSY is first candidate theory for New Physics

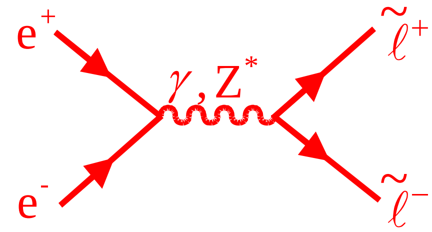
… and note: $M_{SUSY} < 1$ TeV

- Other properties of SUSY:
  - LSP (lightest supersymmetric particle, χ^0_1) can explain the density of cold dark matter in the universe.
  - Unification of couplings possible



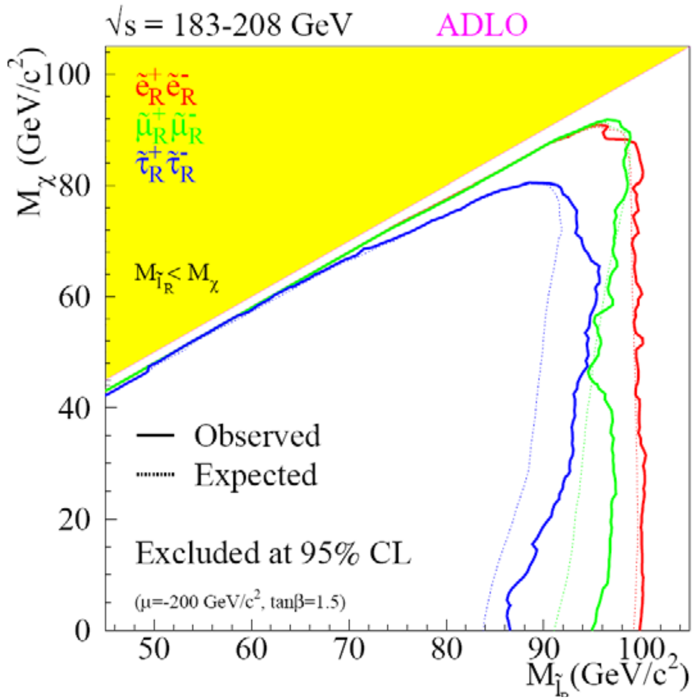
But:
- Many free parameters
- Not yet discovered

Example: search for sleptons at LEP



$\tilde{\ell} \rightarrow \ell\, \chi^0_1$

Signatur: 2 acoplanar leptons and missing energy

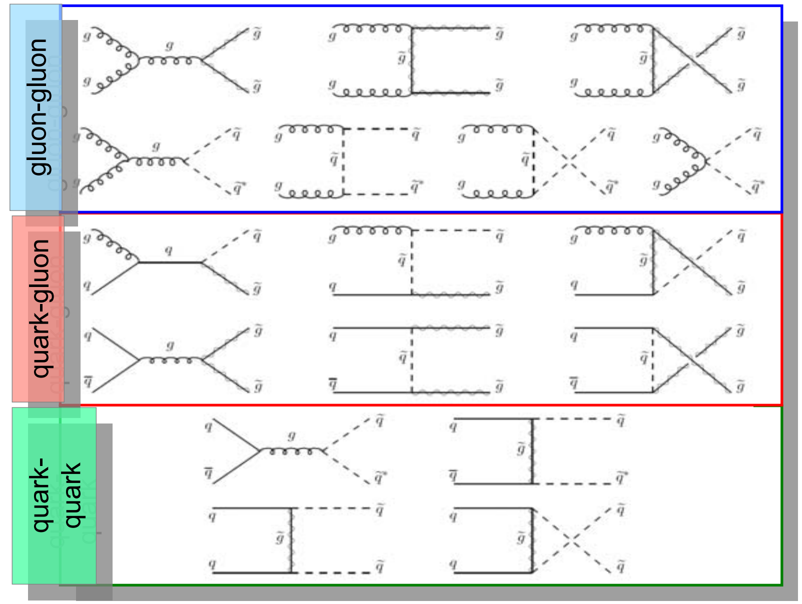


Sfermions with masses below $\sqrt{s_{LEP}}/2$ ~100 GeV are excluded

- Searches at all colliders: no signal
- Assumptions: SUSY particles are heavier than the experimentally covered area.

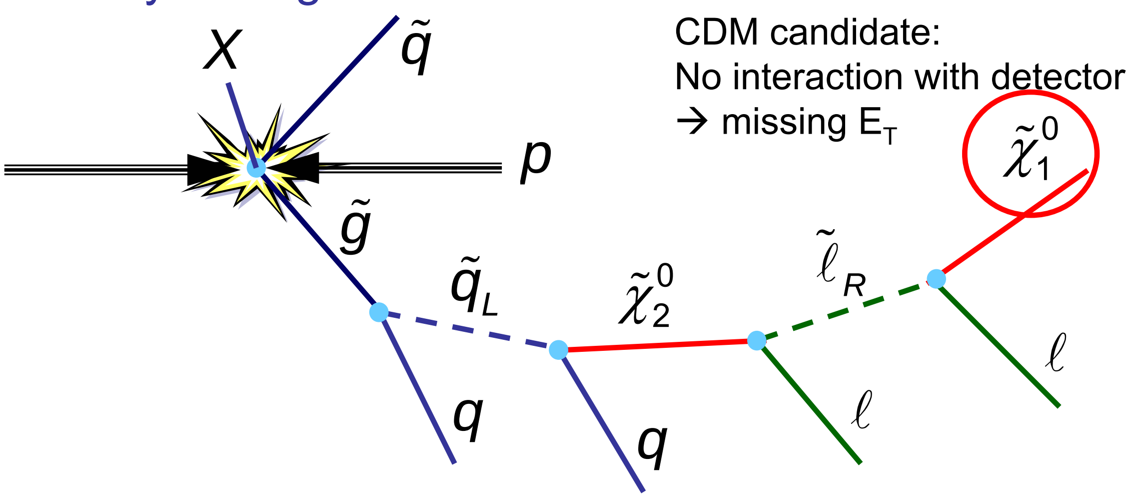
Supersymmetry at the LHC

- With its large centre-of-mass energy the LHC is able cover the full interesting region (up to m_{squark}=3 TeV)
- At the LHC squarks and gluinos are produced via the strong interaction
  - Cross sections are high



$$gg, q\bar{q}, qq, qg \rightarrow \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{g}$$

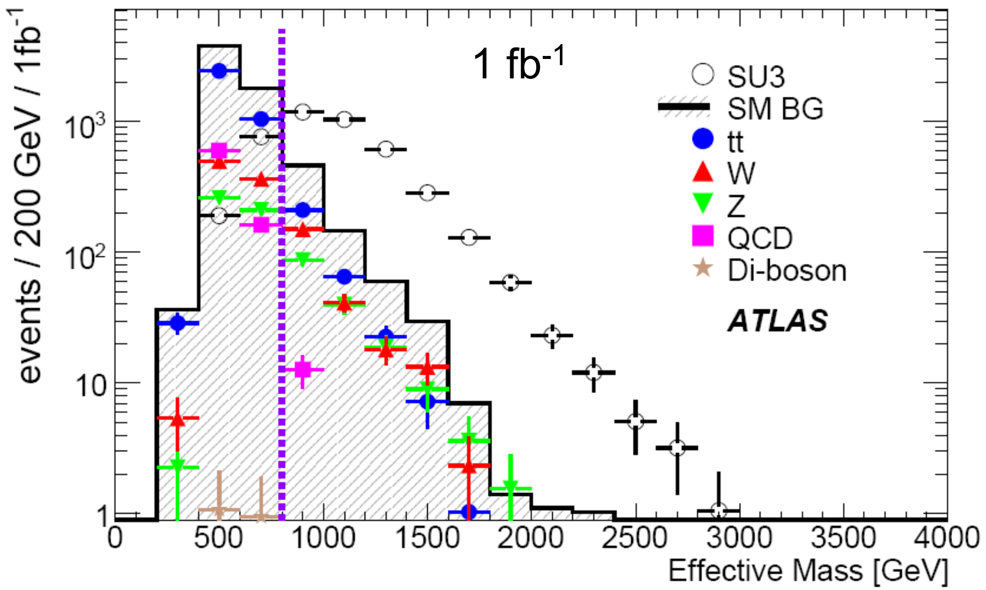
- Squark and Gluinos are usually the heaviest SUSY states
- Decay in long cascades to LSP:



- Inclusive selection in order to be independent from exact SUSY model
- In general we expect:
  - Missing E_T
  - Hard jets
  - (Hard leptons)

- <u>Typical inclusive selection for searches at the LHC:</u>
  - $E_{T,miss}$ > 200 GeV
  - ≥ 4 Jets with p_T > 100, 50, 50, 50 GeV

ATLAS simulation:



- Good variable to separate signal from background: effective mass

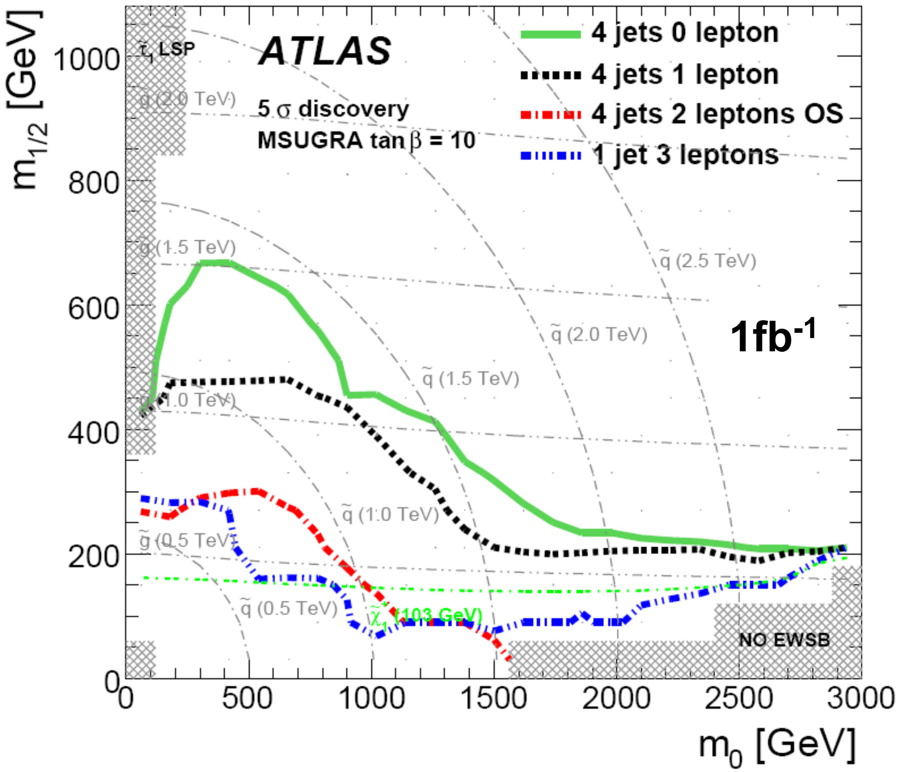
$$M_{\text{eff}} \equiv \sum_i |p_{T(i)}| + E_T^{\text{miss}}$$

  - Sum runs over all jets

- Results are shown for 1 fb^{-1} only!
- But note: understanding the detector will take some time; especially for missing E_T
- Only shown: a particular SUSY model
- In general: very good prospect to discover SUSY if it exists

SUSY discovery reach at LHC

5σ discovery reach in mSUGRA plane:



- With 1 fb^{-1}: Squarks with masses up to 1.5 TeV reached.
- Final reach: 3-3.5 TeV
- more difficult at LHC alone: reconstruction of SUSY masses (exclusive decay chains)
- but: needed to provide evidence for a specific SUSY model

ILC can help in many areas: “LEP for SUSY”

- **inclusive discovery of SUSY “easy” at the LHC**
- **identification of SUSY model more involved (need ILC)**

Summary

- Wide range of physics processes covered in pp collisions at the LHC
  - Complete new era in particle physics, unexplored regions.
- Expect from LHC: Full coverage of the allowed mass range for the Higgs
  - Many different channels → solid discovery
  - Golden channels $H \to \gamma\gamma$, $H \to 4l$
  - 5σ discovery possible with 30 fb^{-1} (3 years of data taking)
- Expect from LHC: Final word on Supersymmetry
  - SUSY signal expected below ~1 TeV to solve hierarchy problem
  - LHC can cover the region up to m_{squark}~3TeV
  - First data already enough for discovery in certain scenarios, but: need to understand the detector and the backgrounds first.
- Final word in many other theories of physics beyond the SM (e.g Leptoquarks)
  - Sensitivity for new particles up to ~2-3 TeV depending on the model

- After ~20 years of preparations the first data from the LHC are expected soon
  - Restart operation: fall this year
  - !! Very exciting time for experimentalists and theorists !!