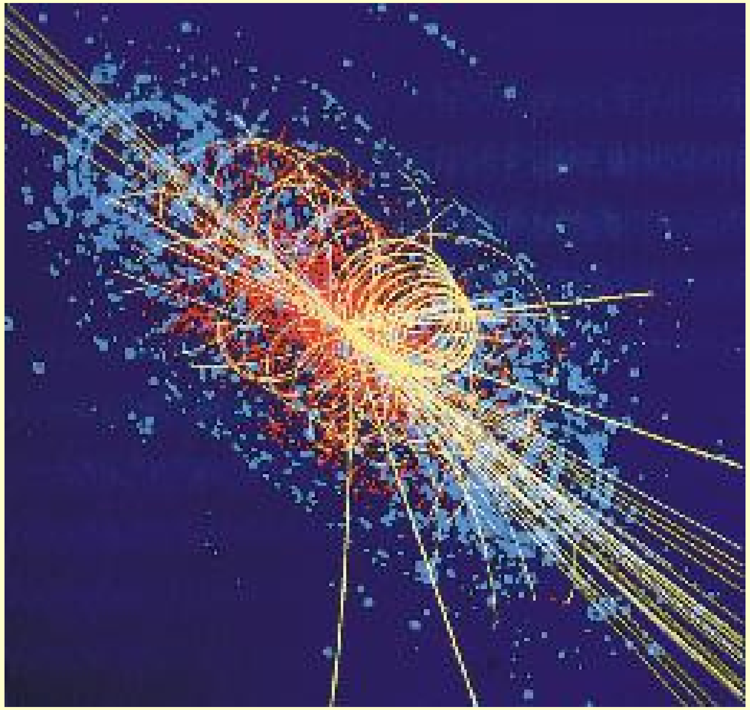
The Search for Higgs and SUSY

-From the Tevatron to the LHC-



- **Introduction**
- **Status of accelerators and detectors**
- **Search for Supersymmetry**
  - Status and prospects at the Tevatron
  - The LHC potential
- **Where is the Higgs boson ?**

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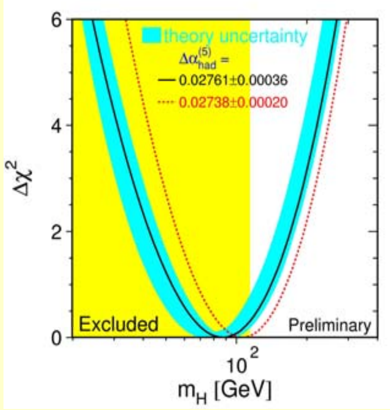
Key Questions of Particle Physics

1. **Mass:** **What is the origin of mass?**

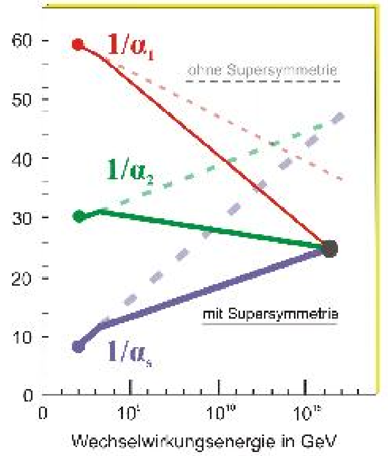
   - How is the electroweak symmetry broken ?
   - Does the Higgs boson exist ?



2. Unification: **What is the underlying fundamental theory ?**

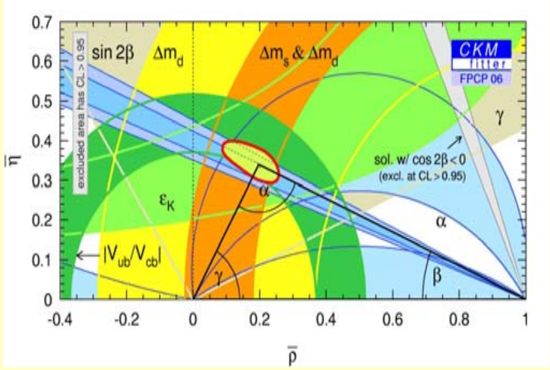
   Motivation: Gravity not yet included;
   Standard Model as a low energy approximation

   - Is our world supersymmetric ?
   - Are there extra space time dimensions ?
   - Other extensions ?



3. Flavour: **or the generation problem**

   - Why are there three families of matter?
   - Neutrino masses and mixing?
   - What is the origin of CP violation?



The role of Hadron Colliders

1. **Mass**

- Search for the Higgs boson

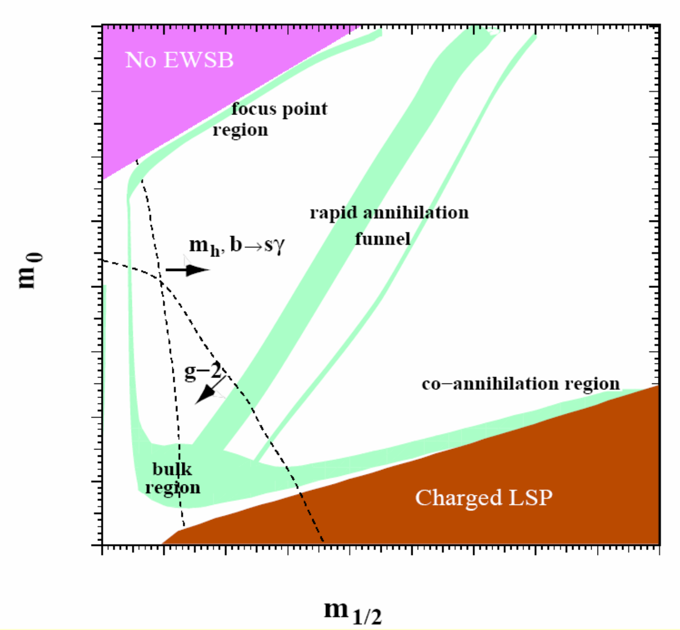
2. **Unification**

- Test of the Standard Model
- Search for Supersymmetry
- Search for other Physics Beyond the SM

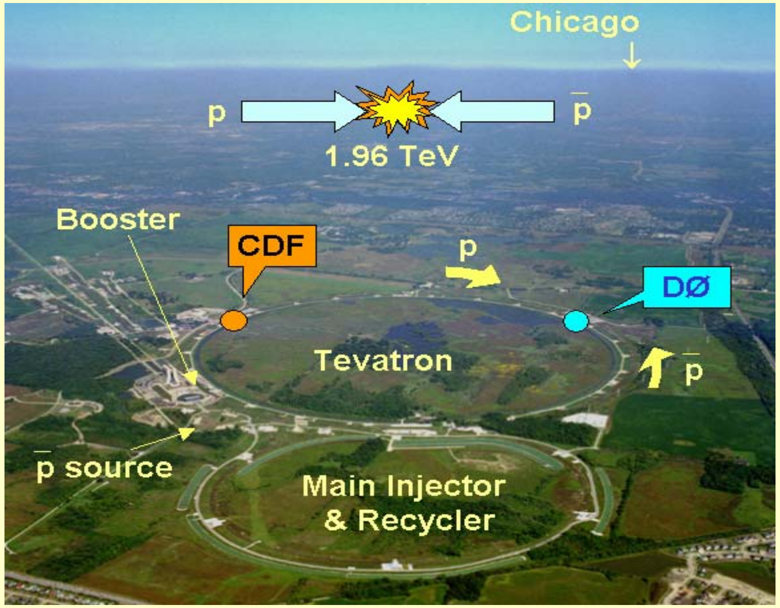
3. **Flavour**

- B hadron masses and lifetimes
- Mixing of neutral B mesons
- CP violation

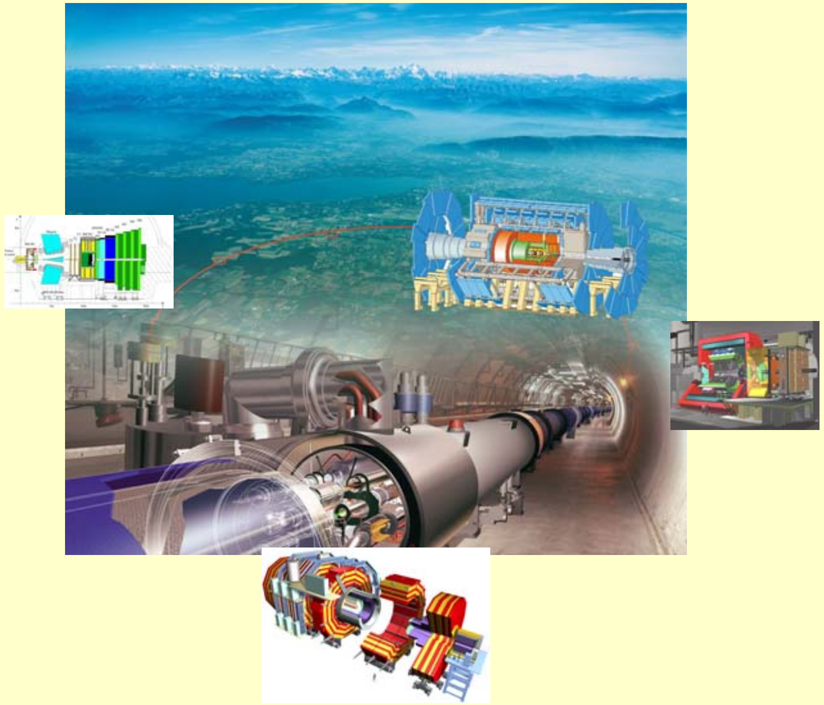
The link between SUSY and Dark Matter ?



M. Battaglia, I. Hinchliffe, D.Tovey, hep-ph/0406147



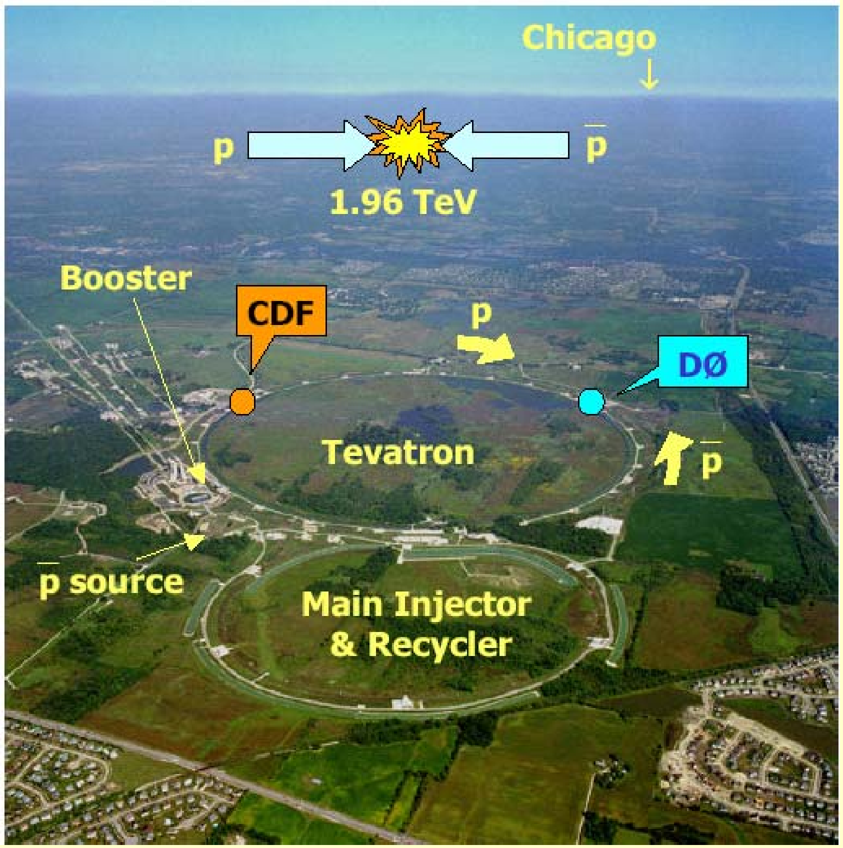
Accelerators and Detectors



The Tevatron Collider at Fermilab

Proton antiproton collider

2 Experiments: CDF and DØ



- **1992 - 1996: Run I, $\sqrt{s}$ = 1800 GeV**

  6 x 6 bunches, 3 µs spacing

  $\int L\,dt$ = 125 pb^{-1}

- **1996 - 2001: upgrade programme**

  Accelerator: new injector (x5)

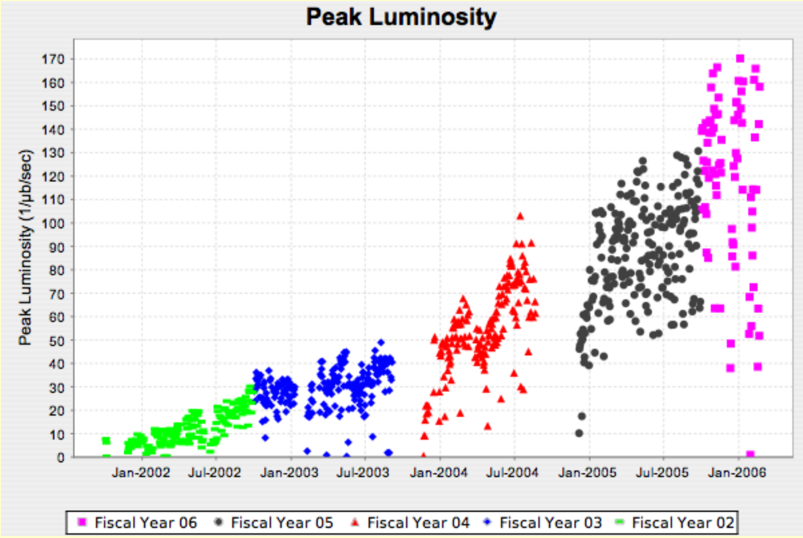
  antiproton recycler (x2)

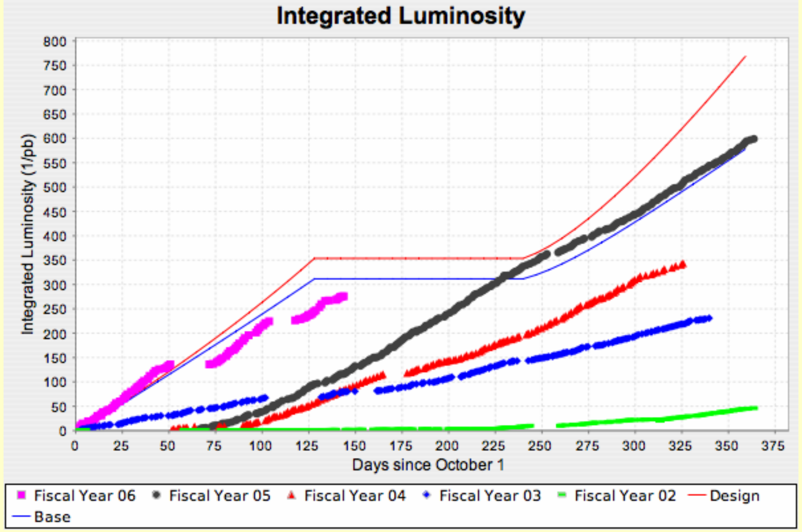
  36x36 bunches, 396 ns spacing

  + Detectors

- **Since March 2001: Run II a, $\sqrt{s}$ = 1960 GeV, 1.2 fb^{-1}**
- **2006 - 2009: Run II b, $\sqrt{s}$ = 1960 GeV, 5 - 8 fb^{-1}**

Status of data taking





- Steady increase in instantaneous luminosity with time (after a very slow start-up)

A few milestones:
July 04: Anti-p in the recycler
new record: L = 1.0 10^{32} cm^{-2} s^{-1}

Data taking period 2005:
design luminosity reached/surpassed

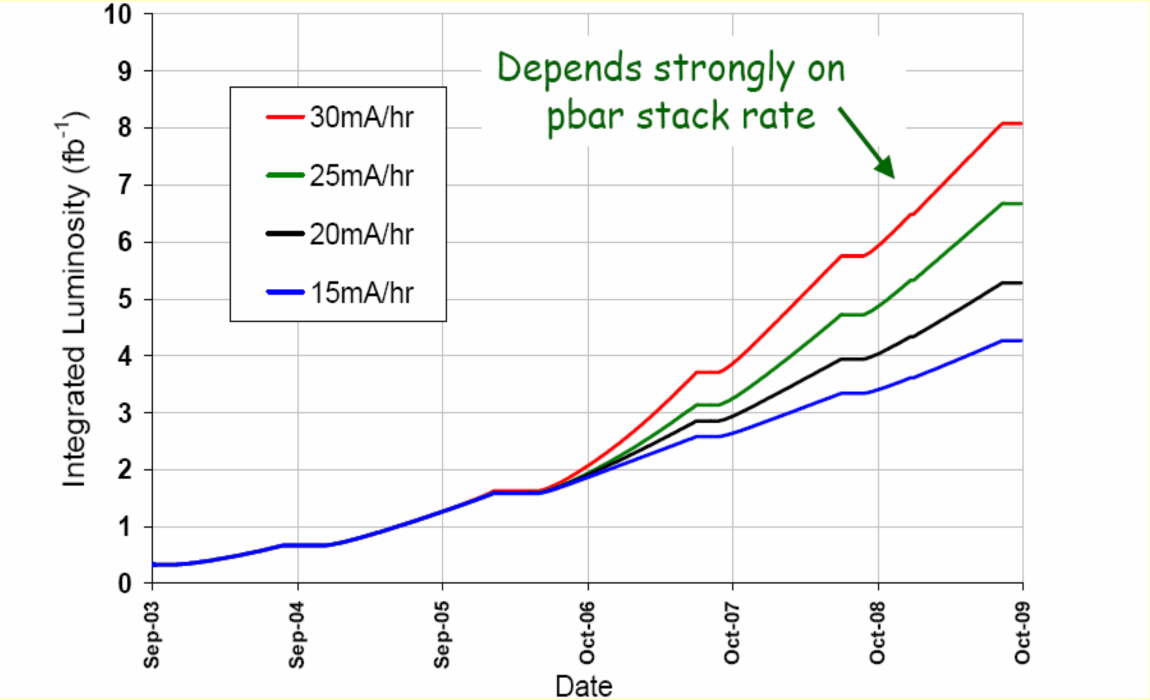
Jan 06: highest luminosity: L=1.7 10^{32} cm^{-2} s^{-1}

- Shutdown since March 2006
  Improvements to the machine
  (add. electron cooling in the recycler, factor 2 in luminosity)

  and detectors
  (mainly trigger upgrade, and silicon b-layer)

Tevatron Luminosity projections

Tevatron running scheduled (at present) until end of Oct. 2009

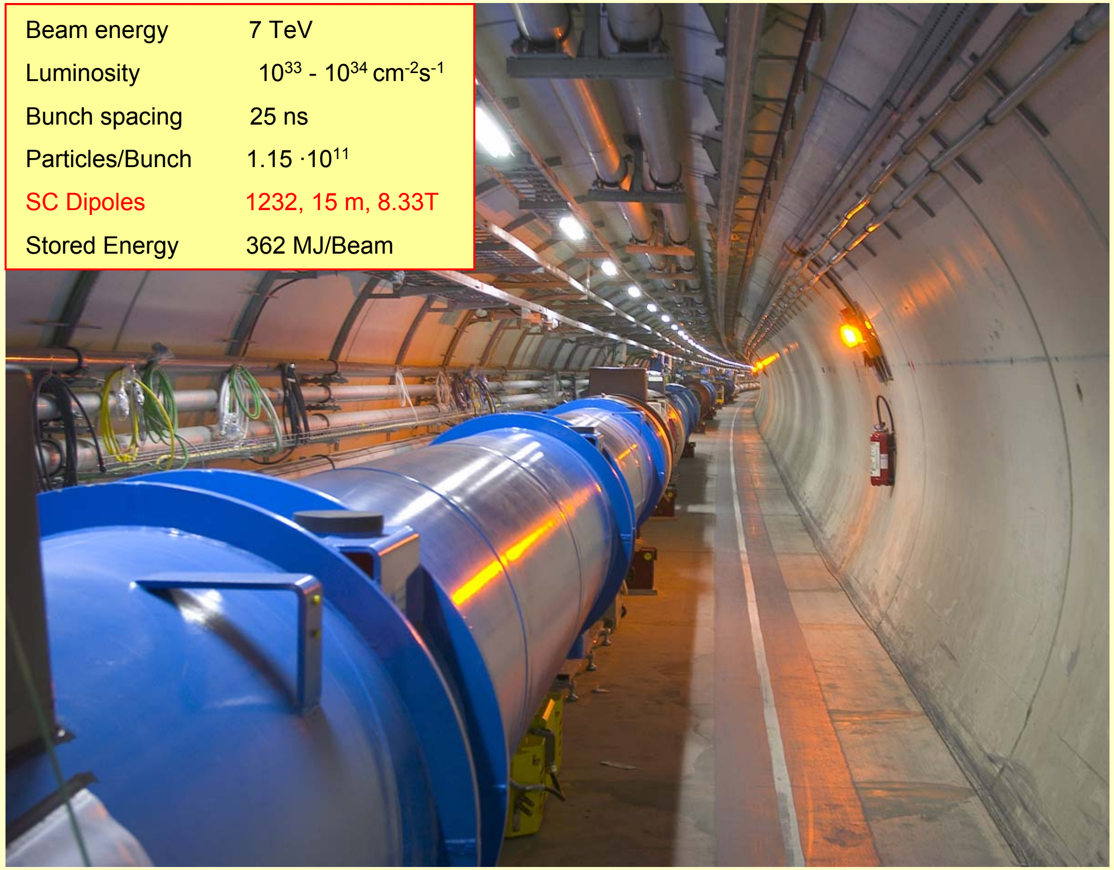


final performance depends strongly on pbar stacking rate in the accumulator
(at present 20 mA/h = 0.2 · 10^{12} pbar /h) → 5 fb^{-1}

goal: = 0.3 · 10^{12} pbar/h → 8 fb^{-1}

Status of the LHC machine

Beam energy	7 TeV
Luminosity	10^{33} - 10^{34} $cm^{-2}s^{-1}$
Bunch spacing	25 ns
Particles/Bunch	$1.15 \cdot 10^{11}$
SC Dipoles	1232, 15 m, 8.33T
Stored Energy	362 MJ/Beam



- Key components available
- Installation progressing in parallel and at high speed; aim to finish by end March 2007
- "Every effort is being made to have first collisions by end of 2007"

Plan under discussion

A "likely" startup scenario:

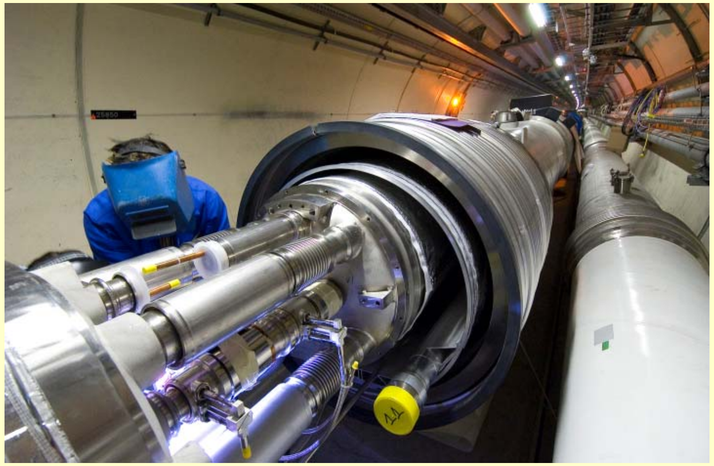
Late 2007: Proton run ~ 10 - 100 pb^{-1} (for 10 pb^{-1}: number of tt events comparable to Tevatron with 1 fb^{-1})

→ detector and trigger commissioning, calibration, early physics

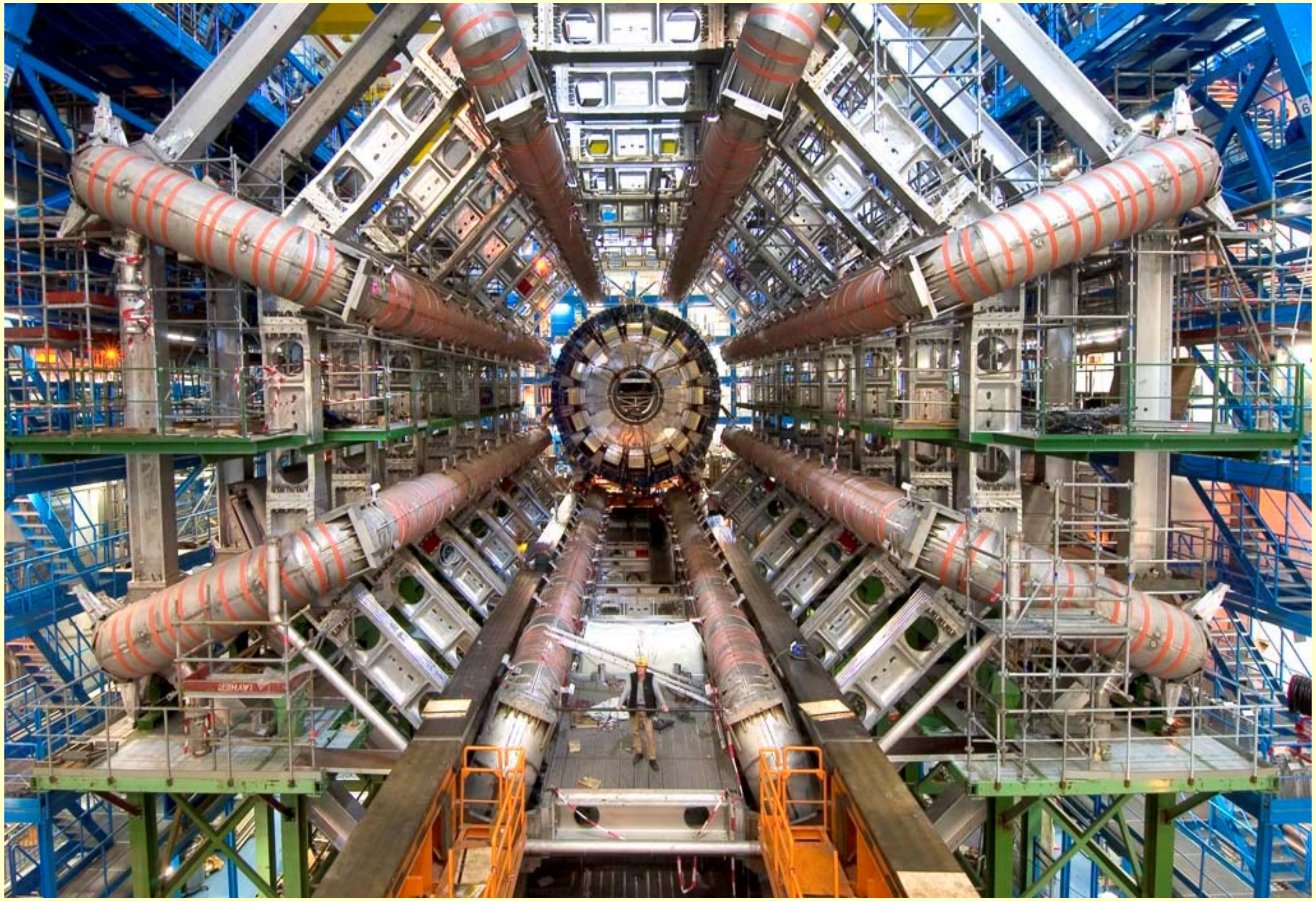
By end 2008: Physics runs: ~ 1 – 10 fb^{-1}

Preparation for installation, Hall SMI2

Installation work, underground



ATLAS Installation

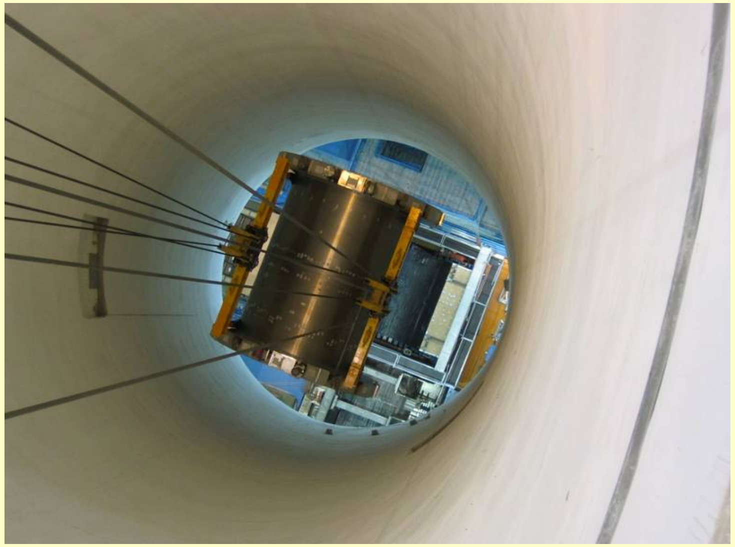


November 2005

- Impressive progress! Nearly all detector components at CERN;
- Installation in the pit proceeding well, although time delays, work in parallel to catch up;
- On critical path: Installation of Inner detector services and forward muon wheels (time);
- ATLAS expected to be ready in August 2007   … one more tough year ...

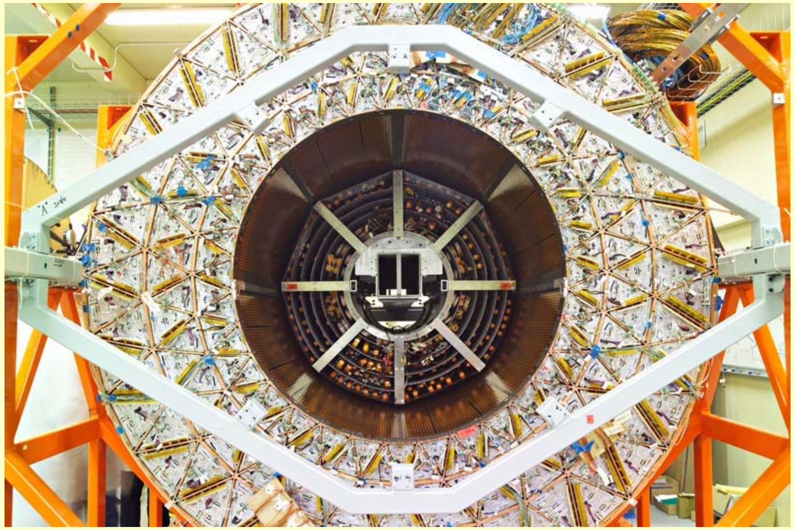
…. a few ATLAS pictures

Insertion of the solenoid in the calorimeter cryostat
(Japan-ATLAS contribution)



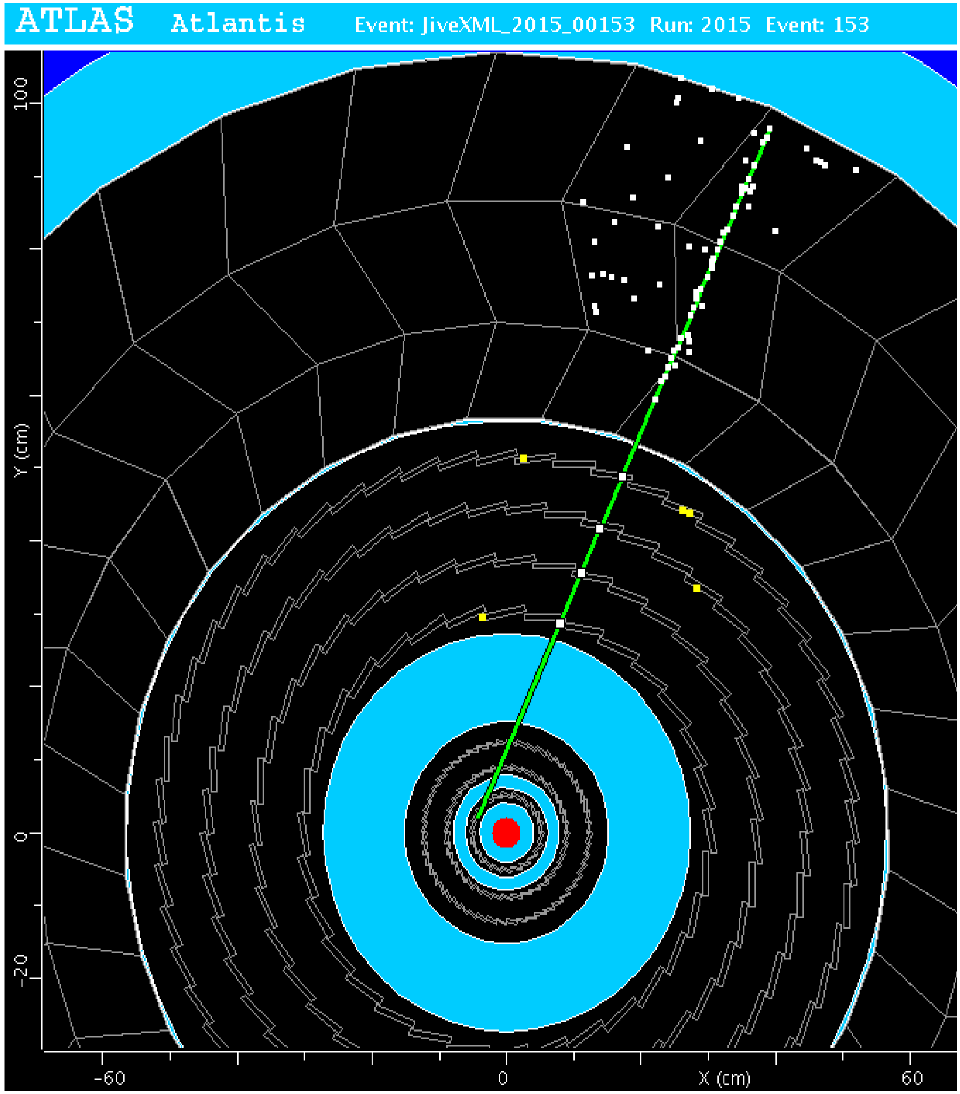
Lowering of ECAL into the ATLAS cavern

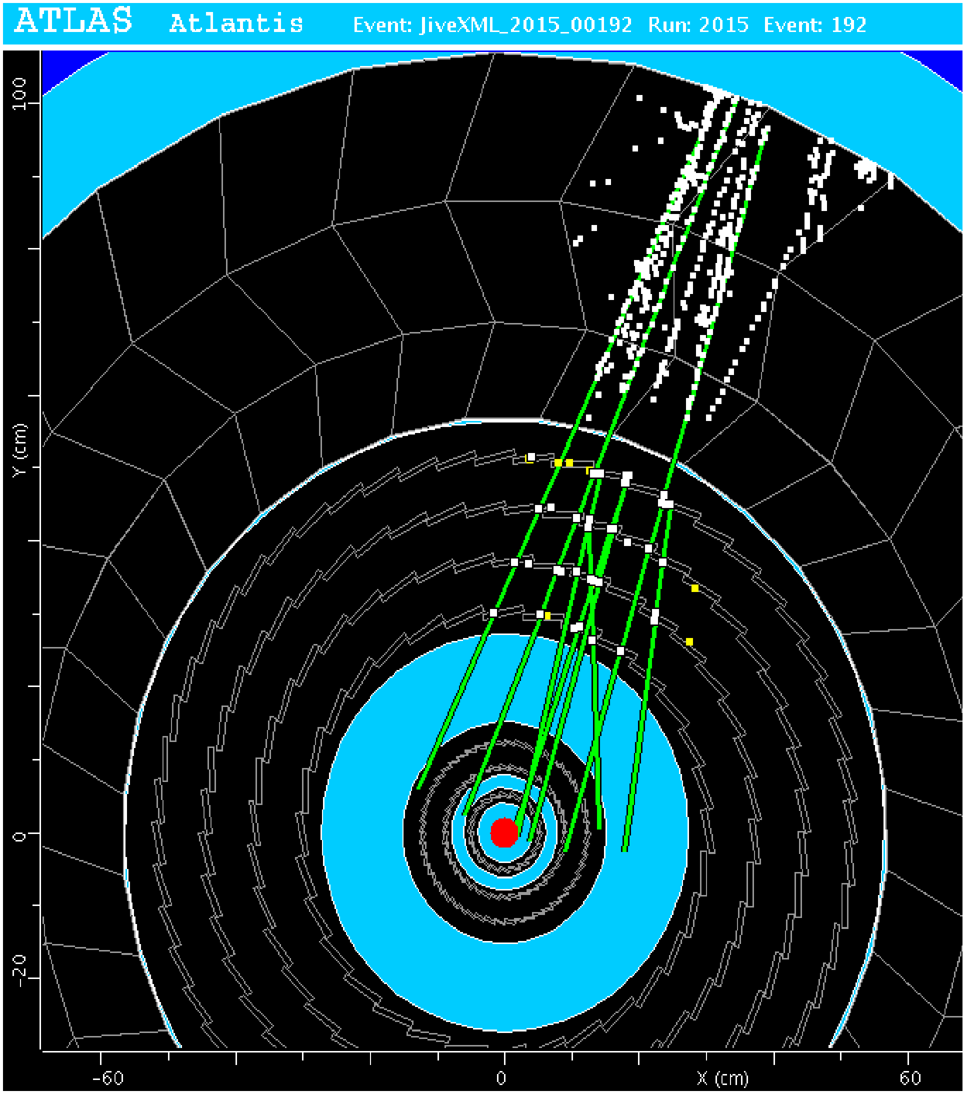
TGC assembly at CERN
(Japan-ATLAS contribution)



Insertion of the Silicon Tracker (barrel) in the TRT
(February 2006), (Japan-ATLAS contribution)

The first tracks in the ATLAS detector
-cosmic particles-



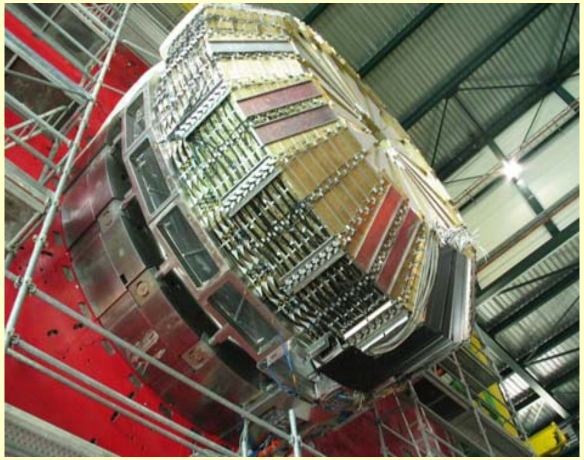


CMS Installation

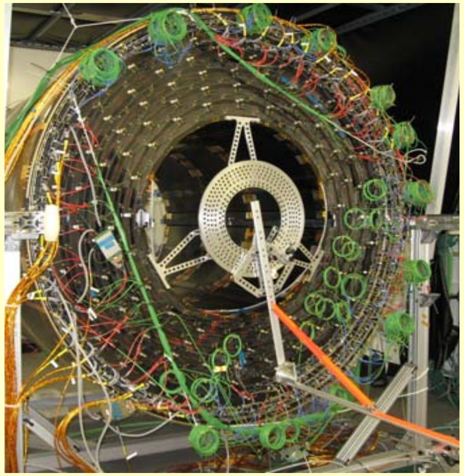
UXC will be ready for lowering 31 August 06

Coil inserted, 14. September

Cathode Strip chambers and yoke endcaps



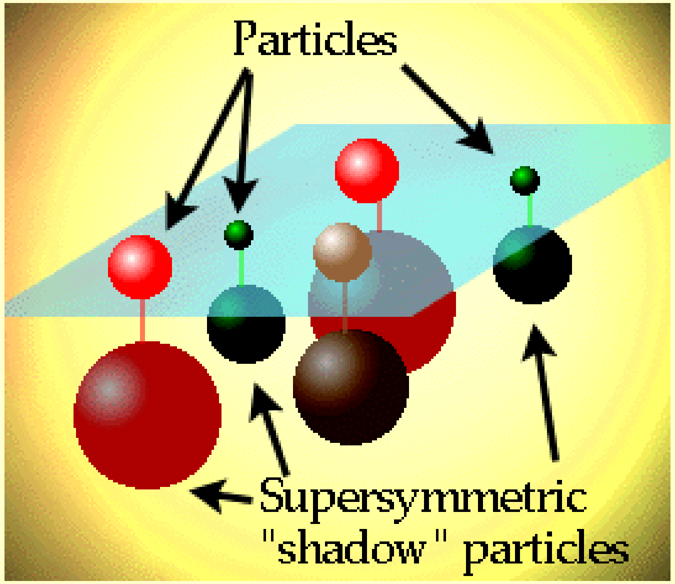
Hadronic calorimeter, endcap



Tracker, outer barrel

On critical path: ECAL crystal delivery (Barrel: Feb. 07, Endcaps: Jan. 08)
Pixel installation for 2008 physics run.

The Search for

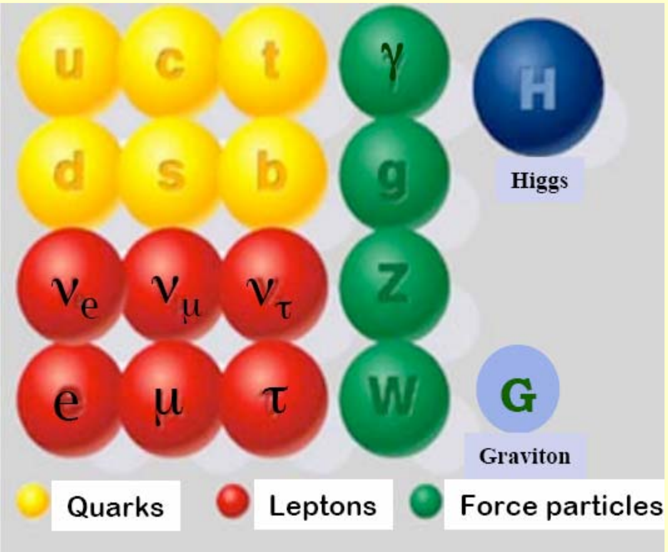


Supersymmetry

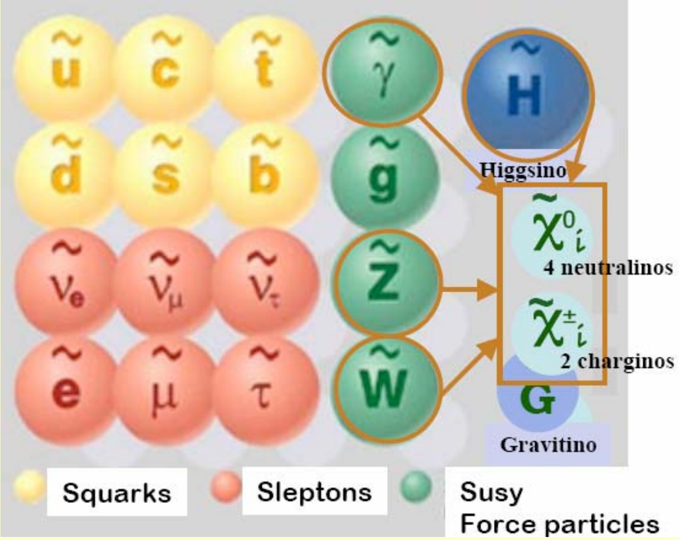
Supersymmetry

Extends the Standard Model by predicting a new symmetry
Spin ½ matter particles (fermions) ⇔ Spin 1 force carriers (bosons)

Standard Model particles



SUSY particles

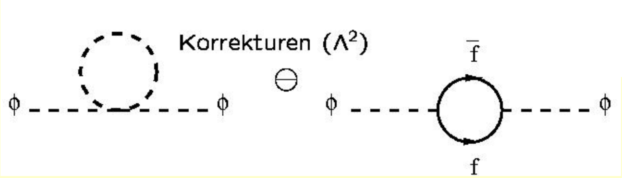


New Quantum number: R-parity: $R_p = (-1)^{B+L+2s}$ = +1 SM particles
- 1 SUSY particles

<u>R-parity conservation</u>:
- SUSY particles are produced in pairs
- The lightest SUSY particle (LSP) is stable

Why do we like SUSY so much?

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

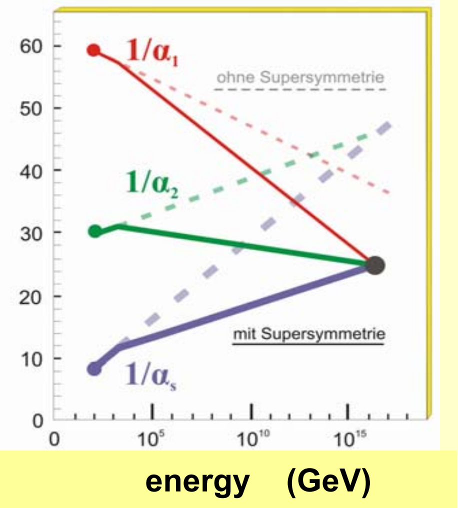


$$\Delta m_H = f(m_B^2 - m_f^2)$$

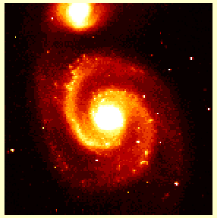
→ $m_{SUSY} \sim 1$ TeV

(Hierarchy or naturalness problem)

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



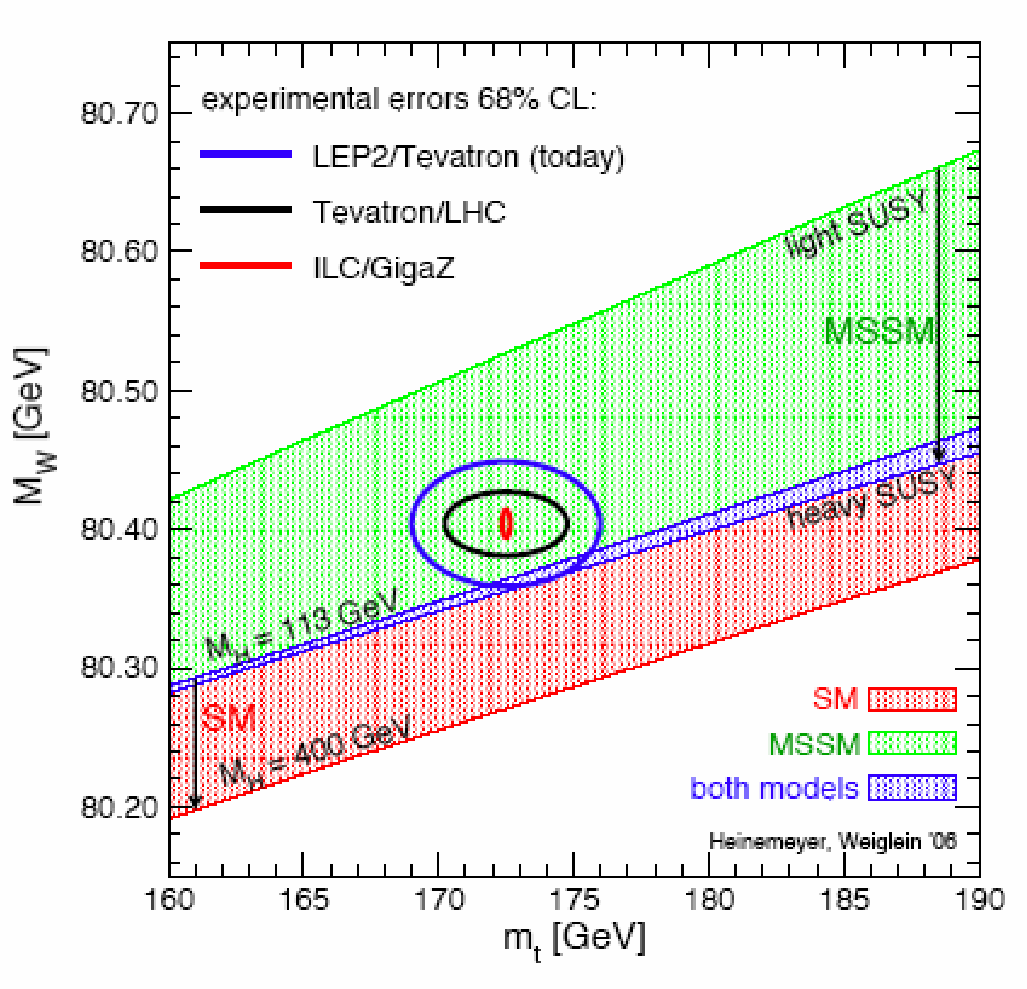
3. SUSY provides a candidate for dark matter,



The lightest SUSY particle (LSP)

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

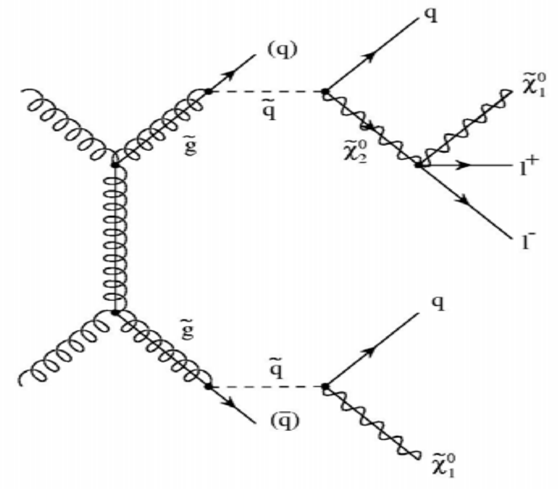
M_W and m_{top} vs. SM and SUSY predictions



SUSY Production at Hadron Colliders

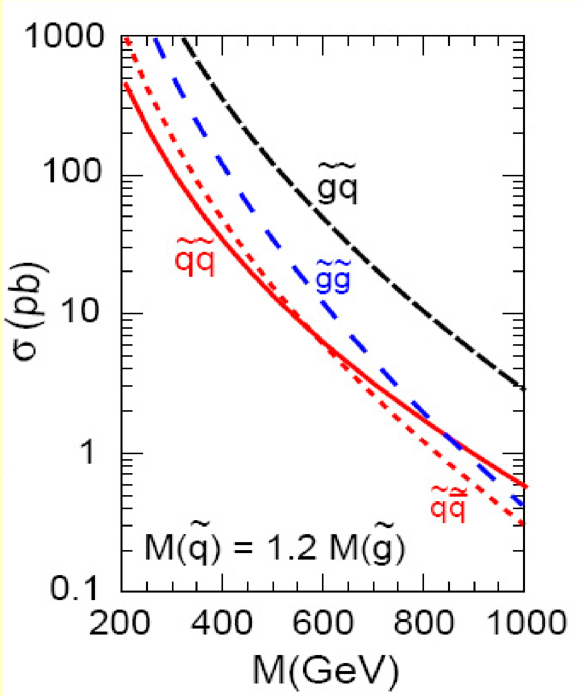
- The SUSY cross-sections at Hadron Colliders are dominated by the associated strong production of gluinos and squarks.

- Decays via cascades into the **LSP**



→ Combination of:
  Jets
  + Missing transverse energy (E_T^{miss})
  + Leptons

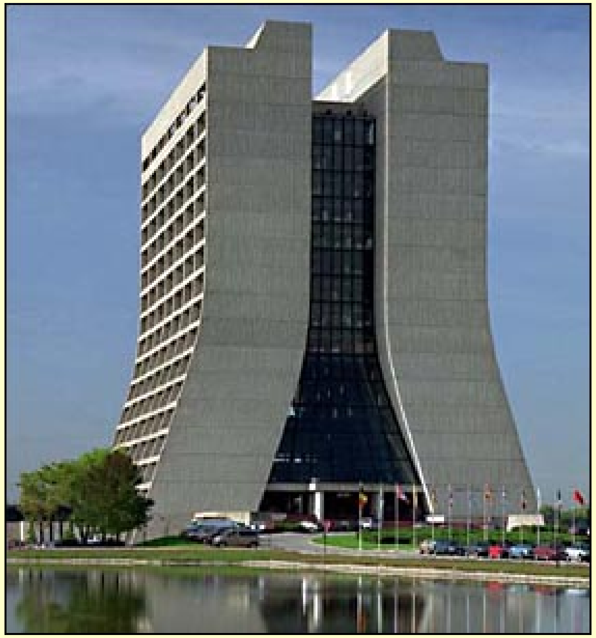
Production cross sections at the LHC



- Huge background from QCD jet production can be suppressed (E_T^{miss}, Leptons…)

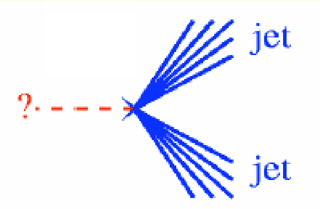
The Search for

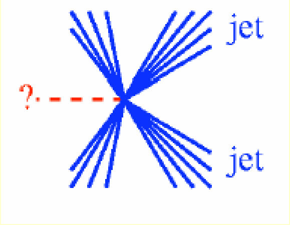
SUSY at the Tevatron



The two classical signatures

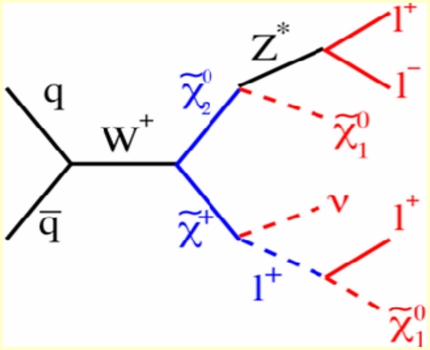
1. Search for Squarks and Gluinos: Jet + E_T^{miss} signature
   produced via QCD processes





2. Search for Charginos and Neutralinos: Multilepton + E_T^{miss} signature
   produced via electroweak processes (associated production)

$$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow l^\pm l^\mp l^\pm \tilde{\chi}_1^0 \tilde{\chi}_1^0 X$$



A few detector performance issues at the Tevatron

- Basic signatures needed for the SUSY and Higgs searches:

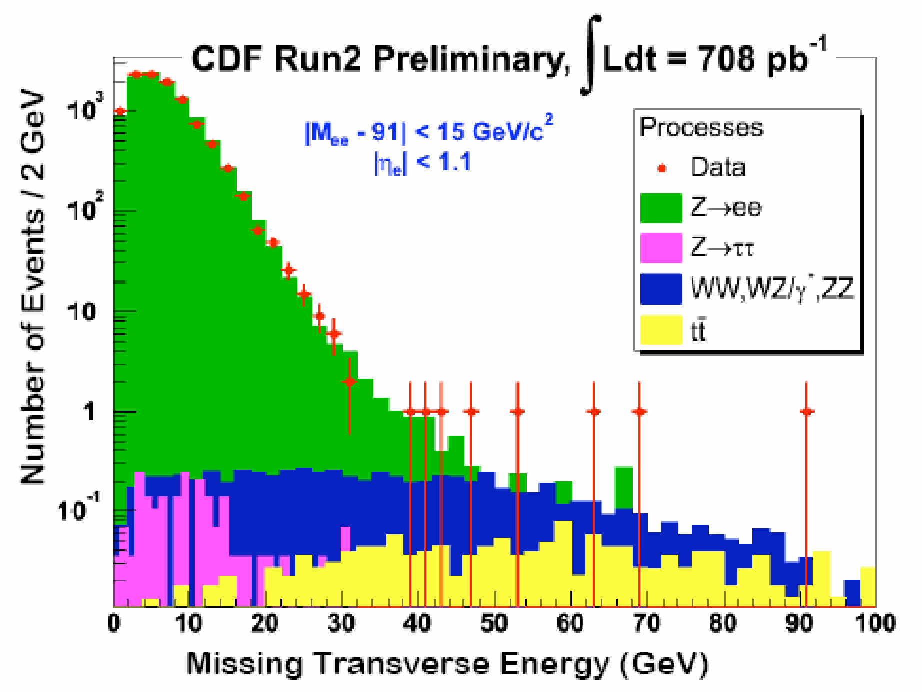
  - Lepton Identification (e, μ, and τ (hadronic decays))
    however, still restricted to the central detector region for most analyses

  - Measurement and calibration of missing transverse energy E_T^{miss}

  - The tagging of b-quarks

(i) Missing transverse energy

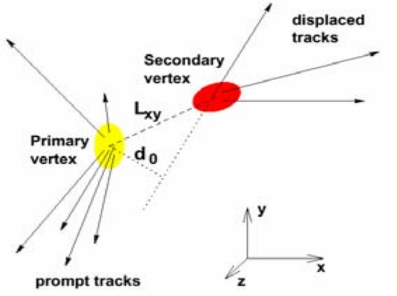
- Checks have been made on **QCD di-jet** and **$Z\rightarrow\ell\ell$** samples



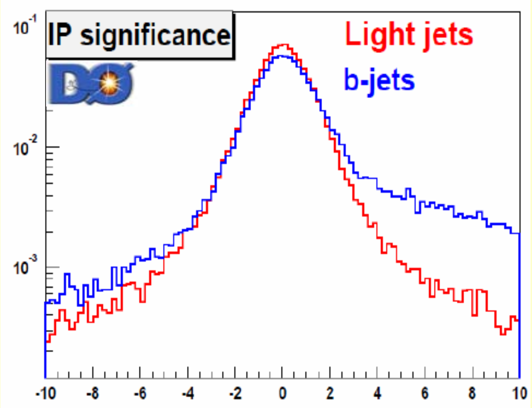
- Good description, including tails of the distribution
- Contributions from physics processes to large E_T^{miss}: WW,WZ and ZZ production
  tt production

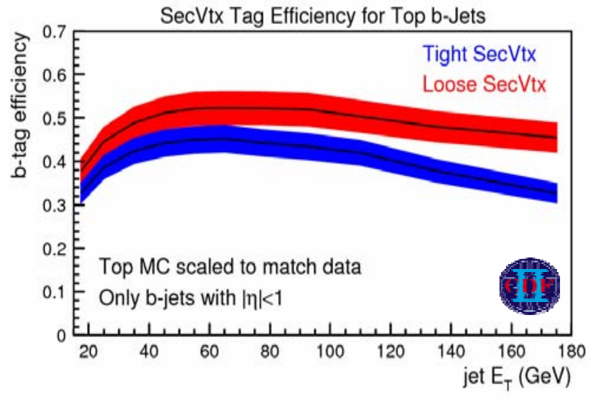
+ fake contributions from:
lepton or jet mismeasurements, instrumental effects, mismeasurement of the vertex
→ rejection by applying special cuts

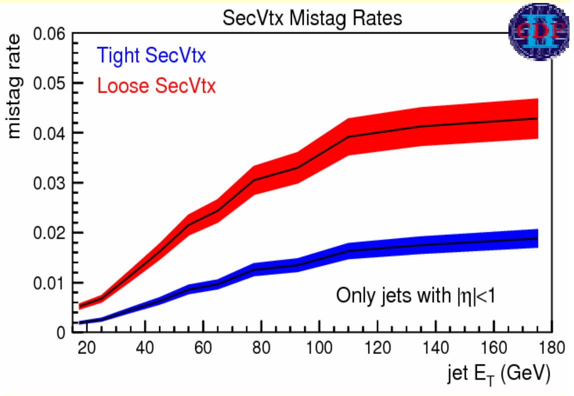
(ii) The tagging of b-quarks



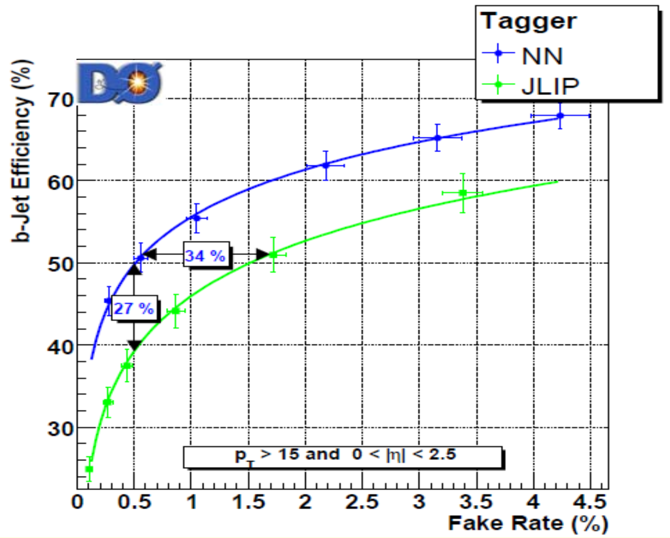
- Both collaborations (CDF and DØ) use similar methods:
  - Lifetime tags
  - Secondary vertex tags







\+ Combination of both, using multivariate techniques, e.g. neural networks



<u>Input variables:</u>

vertex mass, impact parameter significance, χ^2, jet track multiplicities (displaced + total), jet probability ;

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)

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

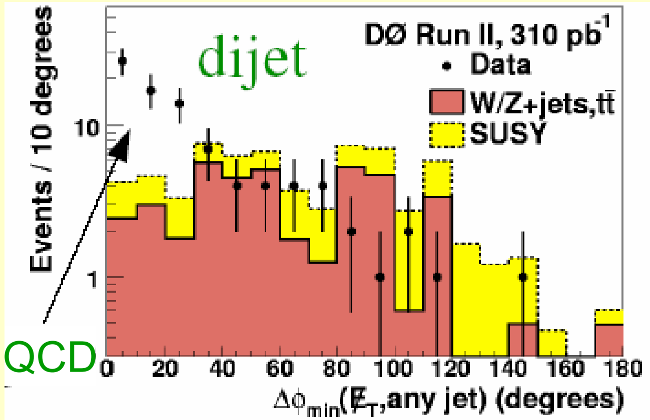
(iii) Gluino analysis
large m_0, m(squark) > m(gluino)

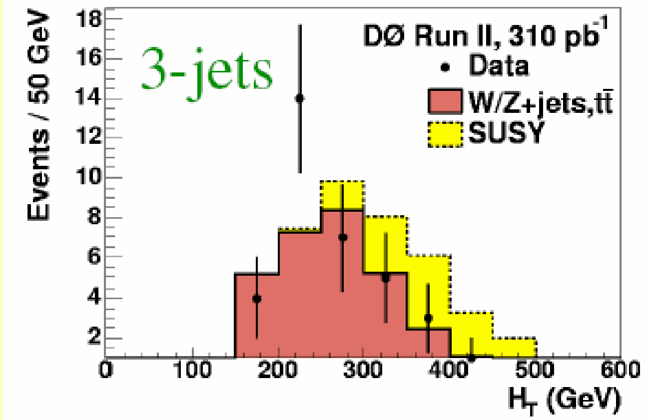
$$\tilde{g}\,\tilde{g} \rightarrow q\,\bar{q}\,\tilde{\chi}_1^0\,q\,\bar{q}\,\tilde{\chi}_1^0$$

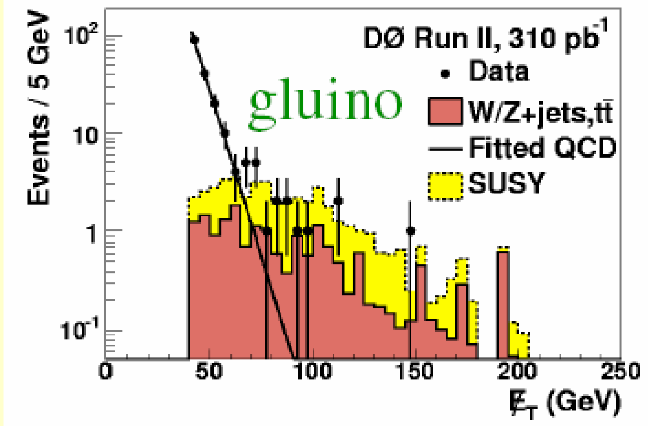
- Main backgrounds: $Z \rightarrow \nu\nu$ + jets, tt, W + jet production

- Event selection: 2 jets with $P_T^1 < 60$, $P_T^2 > 40$ GeV, $|\eta| < 0.8$ (common preselection)
  * require at least 2, 3 or 4 jets with $P_T > 60 / 40 / 30 / 20$ GeV
  * confirm the jets by their associated tracks
  * veto on isolated electrons and muons
  * isolation of P_T^{miss} and all jets
  * optimization of the final cuts → discriminating variables

Search for Squarks and Gluinos (cont.)







DØ analyses L = 310 pb^{-1}

Discriminating variables:

- $H_T = \Sigma\ E_T$(jets)
- E_T^{miss}

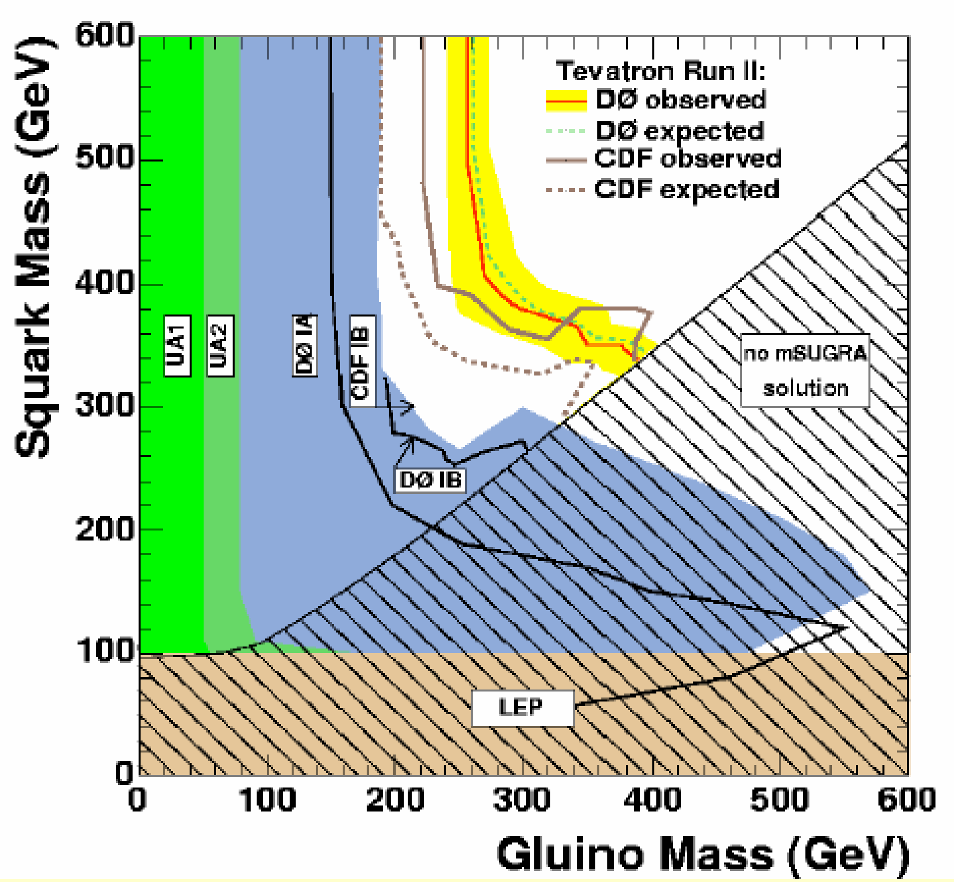
Final E_T^{miss} and H_T cuts:

- Dijet analysis: E_T^{miss} > 175 GeV, H_T > 250 GeV
- 3-jet analysis: > 100 GeV, > 325 GeV
- Gluino analysis: > 75 GeV, > 250 GeV

Comparison between data and expected background:

	Data	Total background
"Dijet"	6	4.8 +4.4 -2.0 (stat) +1.1 -0.8 (sys)
"3 jets"	4	3.9 +1.3 -1.0 (stat) +0.7 -0.8 (sys)
"Gluino"	10	10.3 +1.5 -1.4 (stat) +1.9 -2.5 (sys)

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



Excluded mass values:

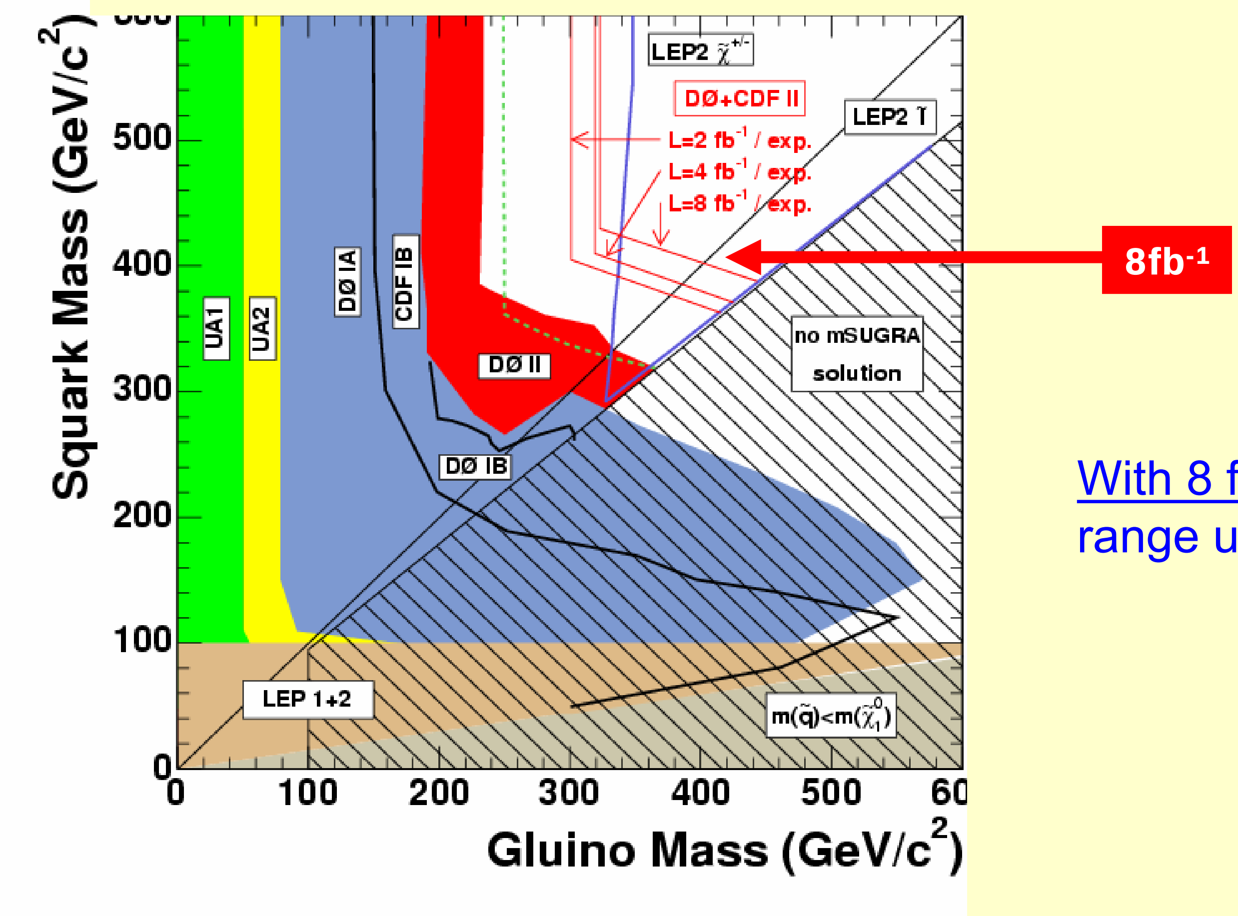
m(gluino), m(squark) > ~ 330 GeV
for equal masses

Comparable result from the CDF Experiment
(preliminary result, 378 pb^{-1})

<u>major systematic uncertainties</u>:

- renormalization scale - vary m(gluino)/2 < μ < 2 m(gluino) -
- parton density functions (gluon distribution at large x) qg-processes
- jet energy scale,….

Future Prospects for Squark and Gluino Searches



8fb^{-1}

With 8 fb^{-1}: explore mass range up to ~ 400 GeV/c^2

Search for Sbottom

- Lightest sbottom are pair produced and decay via $\tilde{b}_1 \rightarrow b\,\tilde{\chi}_1^0$

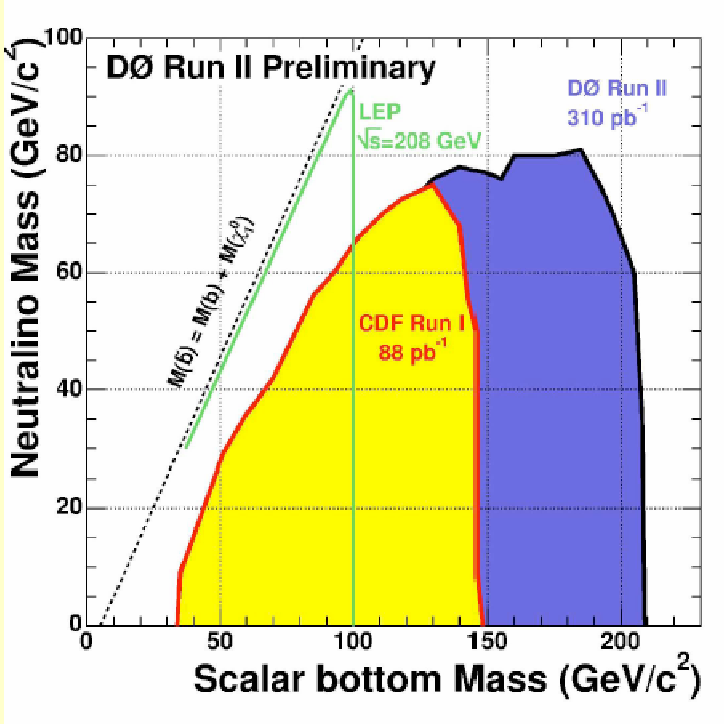
  → search for acoplanar quark pair, E_T^{miss}, apply b-tagging

  note: difficult for small mass difference ΔM (between sbottom and LSP)

- Comparison between data and expectations, cuts optimized for different mass combinations

	(140,80) GeV	(160,75) GeV	(205,60) GeV
Data	36	15	2
Back.	38.6 ± 2.8	19.6 ± 1.7	4.40 ± 0.44
Signal	35.0 ± 1.2	21.6 ± 0.7	6.10 ± 0.17

Excluded region:



Search for Stop

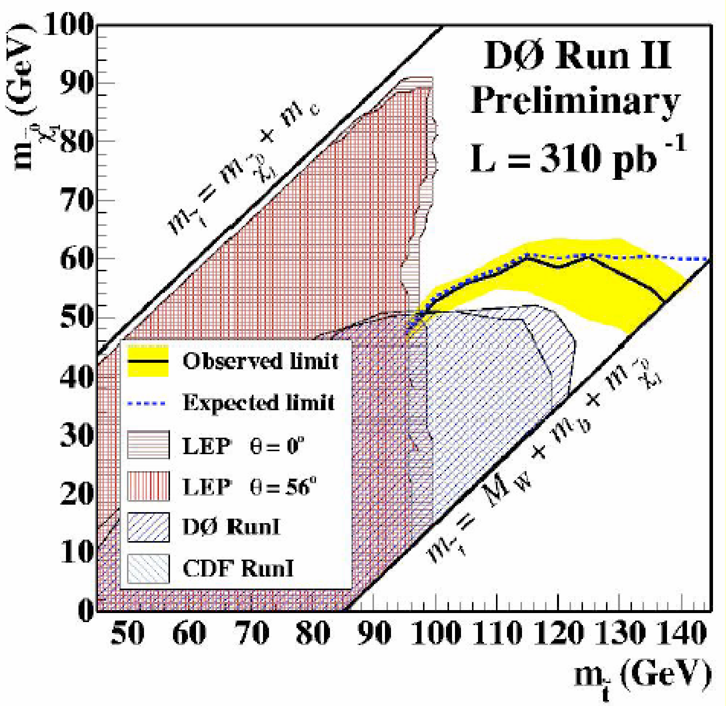
- Stop quarks are searched in various decay modes:

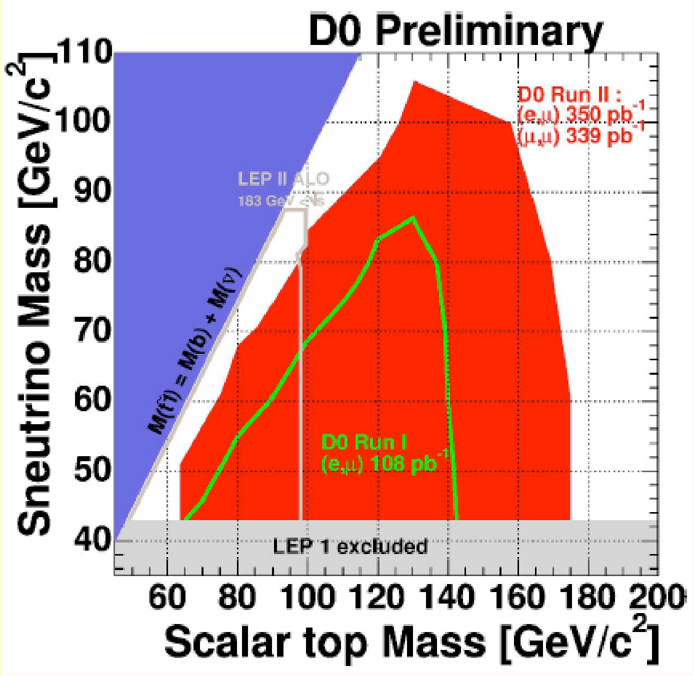
$\tilde{t}_1 \rightarrow c\,\tilde{\chi}^0_1$

(difficult, requires c-tagging)

$\tilde{t}_1 \rightarrow b\,l\,\tilde{\nu}$

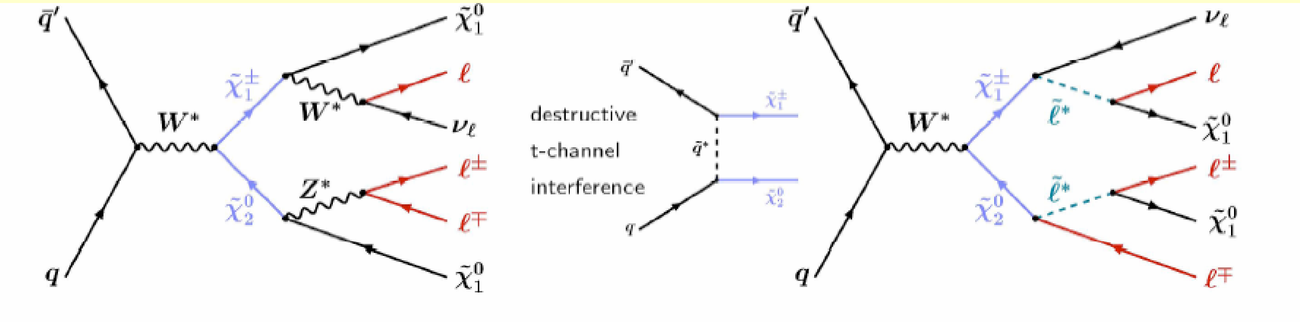
(di-lepton + Etmiss + btag signature)



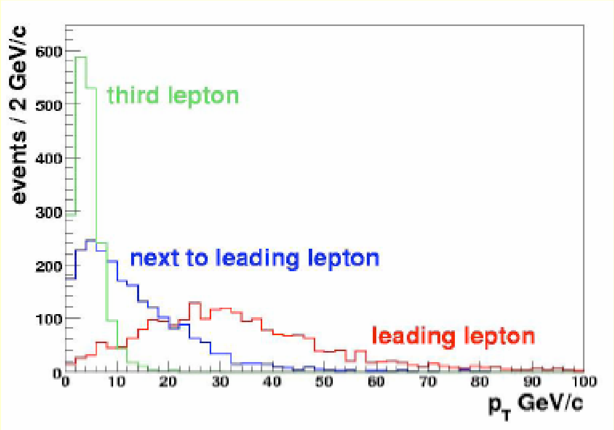


Search for Charginos and Neutralinos
- the tri-lepton channel-

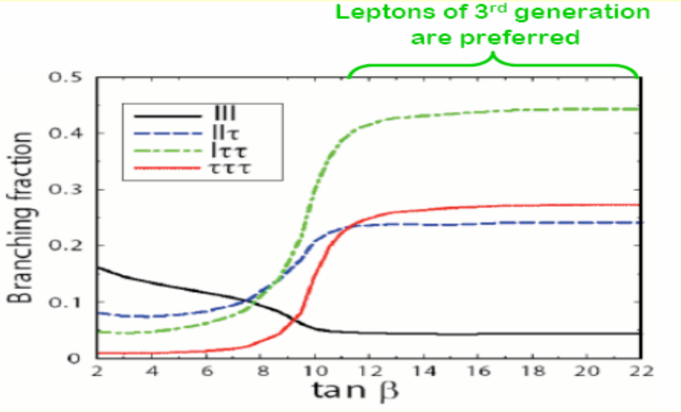
- Gaugino pair production via electroweak processes
  (small cross sections, ~0.1 – 0.5 pb, however, small expected background)



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



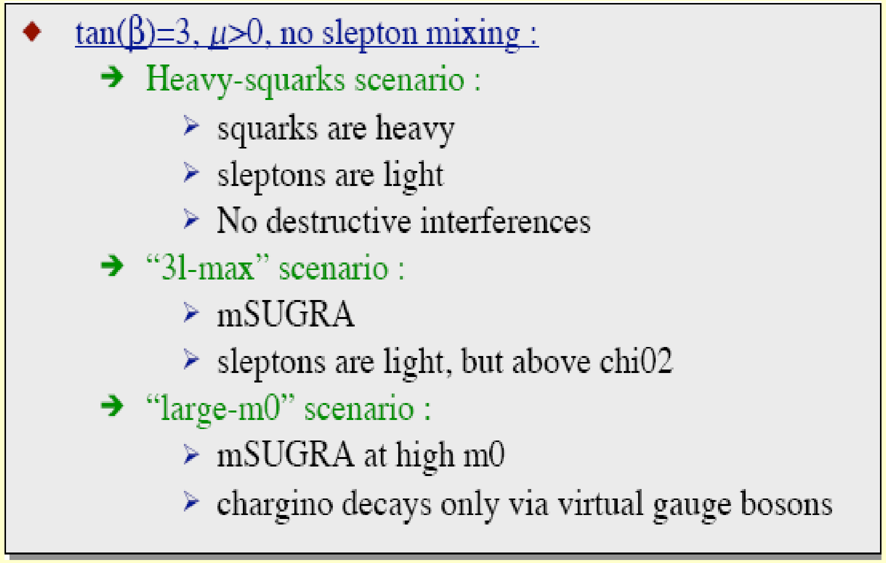
- For large tan β: tau decays are important !



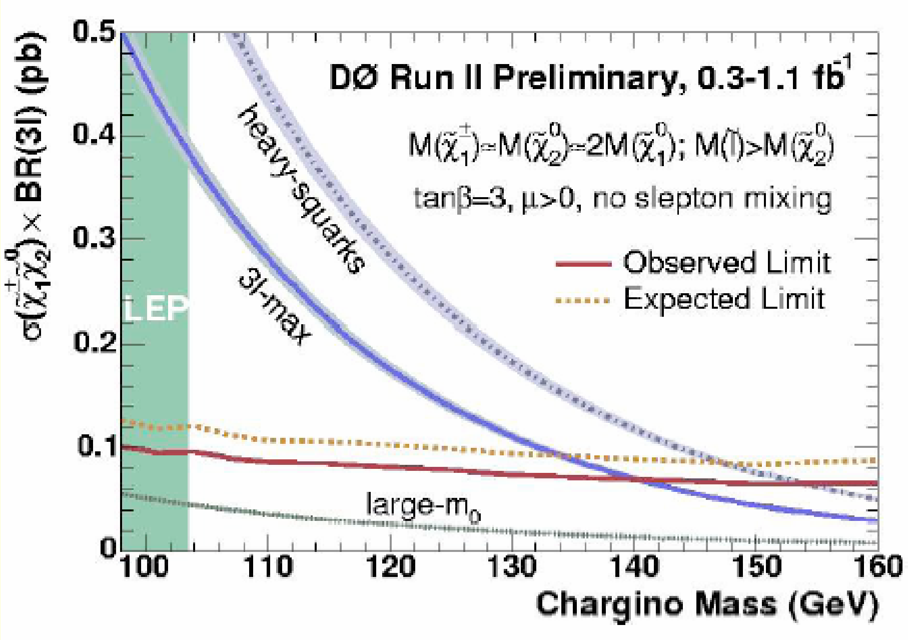
Analysis:

- Search for five different (ℓℓℓ) + like-sign μμ final states with missing transverse momentum
- In order to gain efficiency, no lepton identification is required for the 3rd lepton, select: two id. Leptons + a track with P_T > 4 GeV/c

mSUGRA interpretation

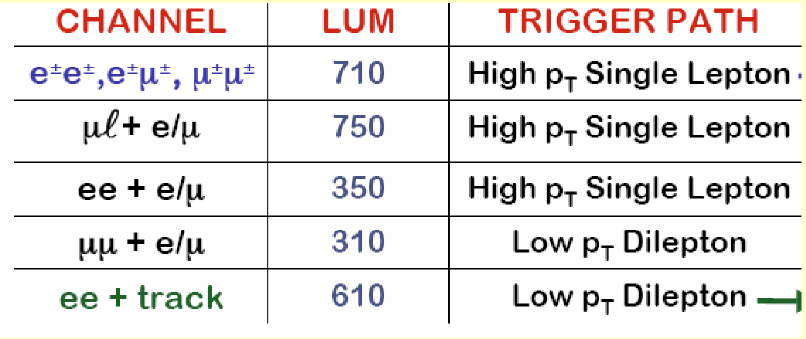


- ◆ tan(β)=3, μ>0, no slepton mixing :
  - ➔ Heavy-squarks scenario :
    - ➢ squarks are heavy
    - ➢ sleptons are light
    - ➢ No destructive interferences
  - ➔ “3l-max” scenario :
    - ➢ mSUGRA
    - ➢ sleptons are light, but above chi02
  - ➔ “large-m0” scenario :
    - ➢ mSUGRA at high m0
    - ➢ chargino decays only via virtual gauge bosons

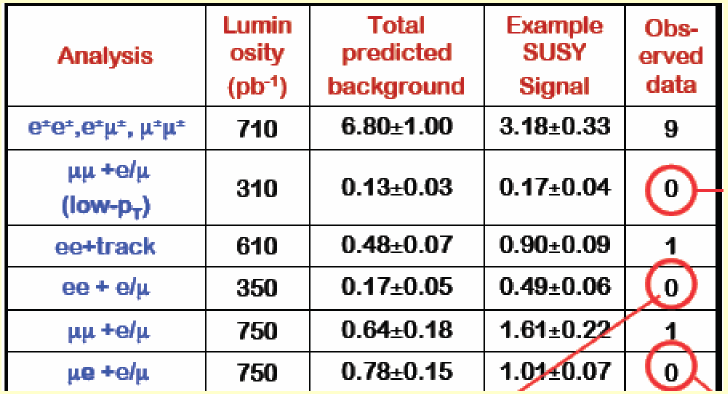


For specific scenarios: sensitivity / limits above LEP limits;
e.g., $M(\chi^{\pm})$ > 140 GeV/c^2 for the 3l-max scenario
Excluded σ x BR: 0.08 pb

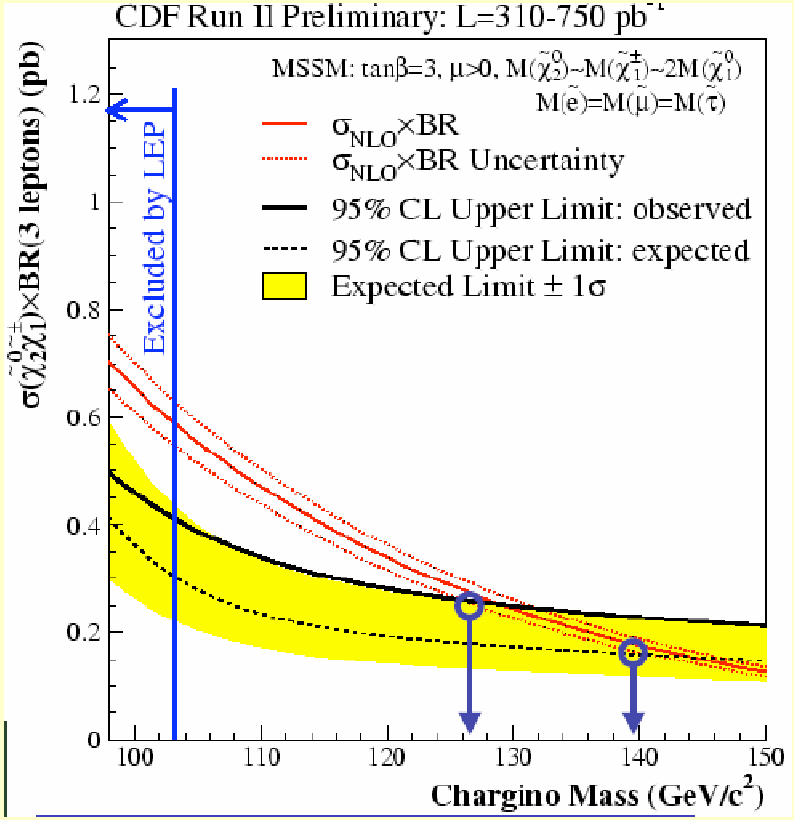
Trilepton results from CDF:



CHANNEL	LUM	TRIGGER PATH
$e^\pm e^\pm, e^\pm \mu^\pm, \mu^\pm \mu^\pm$	710	High p_T Single Lepton
$\mu \ell$ + e/μ	750	High p_T Single Lepton
ee + e/μ	350	High p_T Single Lepton
μμ + e/μ	310	Low p_T Dilepton
ee + track	610	Low p_T Dilepton



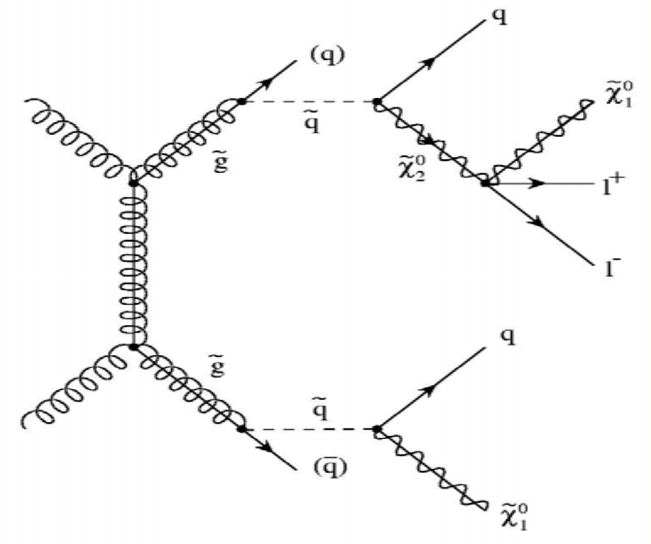
Analysis	Luminosity (pb^{-1})	Total predicted background	Example SUSY Signal	Observed data
$e^\pm e^\pm, e^\pm \mu^\pm, \mu^\pm \mu^\pm$	710	6.80±1.00	3.18±0.33	9
μμ +e/μ (low-p_T)	310	0.13±0.03	0.17±0.04	0
ee+track	610	0.48±0.07	0.90±0.09	1
ee + e/μ	350	0.17±0.05	0.49±0.06	0
μμ +e/μ	750	0.64±0.18	1.61±0.22	1
μe +e/μ	750	0.78±0.15	1.01±0.07	0



mSUGRA scenario,
tan β = 3, μ>0, no mixing,
m(sleptons) ~ m(χ_2)

Chargino Mass limit: m($\chi^\pm$) > 127 GeV/c^2
Excluded σ x BR (95%CL) 0.25 pb

Search for Supersymmetry at the LHC



⇒ Combination of
Jets, Leptons, E_T^{miss}

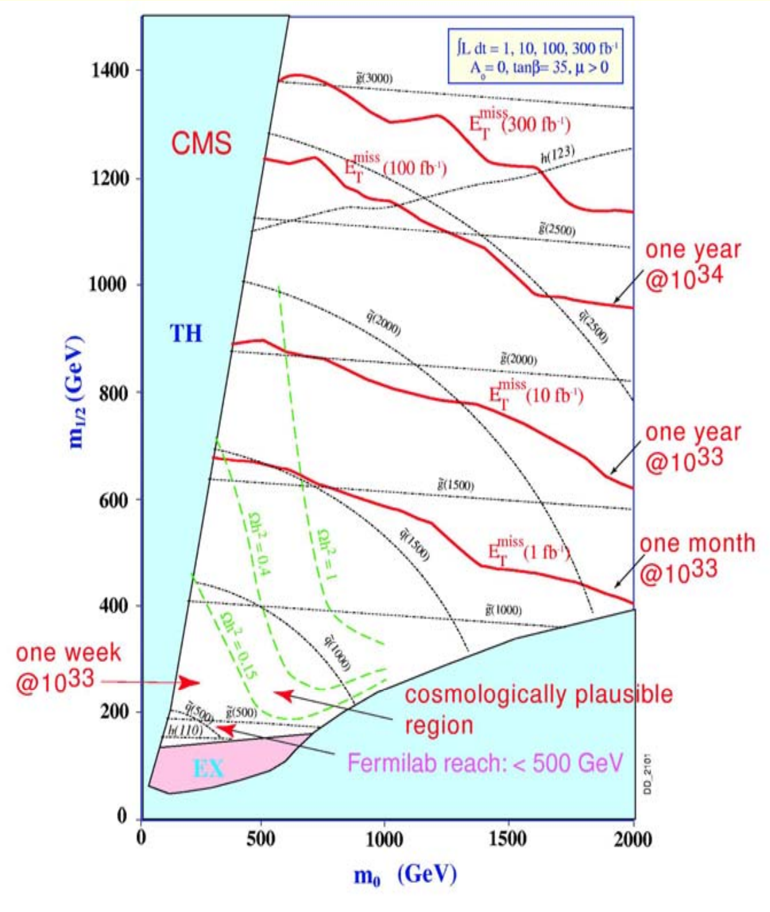
1. Step: Look for deviations from the Standard Model
   Example: Multijet + E_T^{miss} signature

2. Step: Establish the SUSY mass scale use inclusive variables, e.g. effective mass distribution

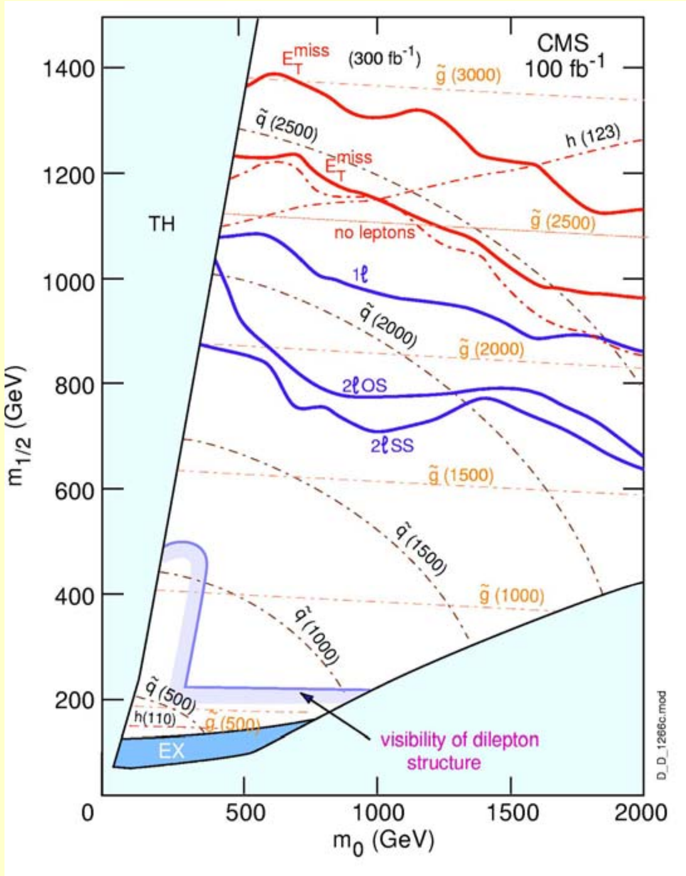
3. Step: Determine model parameters (difficult)
   Strategy: select particular decay chains and use kinematics to determine mass combinations

LHC reach in the m_0 - $m_{1/2}$ mSUGRA plane:

Multijet + E_T^{miss} signature



SUSY cascade decays give also rise to many other inclusive signatures: **leptons, b-jets, τ's**



Expect multiple signatures for TeV-scale SUSY

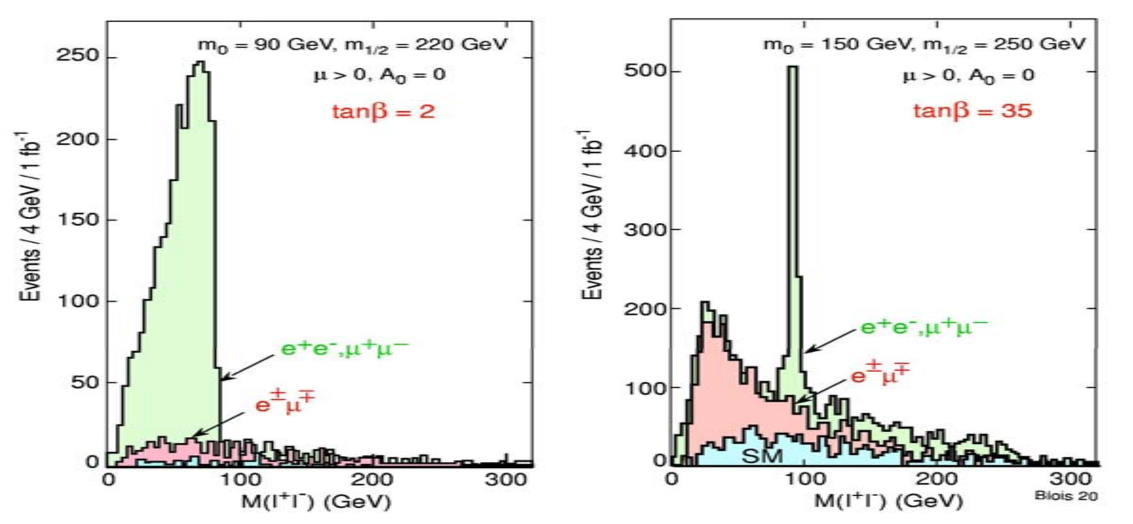
Determination of model parameters

- Invisible LSP ⇒ no mass peaks, but kinematic endpoints
  ⇒ mass combinations

- Simplest case: $\chi^0_2 \rightarrow \chi^0_1 \, \ell^+ \ell^-$ endpoint: $M_{\ell\ell} = M(\chi^0_2) - M(\chi^0_1)$

(significant mode if no $\chi^0_2 \rightarrow \chi^0_1 Z$, $\chi^0_1 h$, $\tilde{\ell}\,\ell$ decays)

- Require: 2 isolated leptons, multiple jets, and large E_T^{miss}

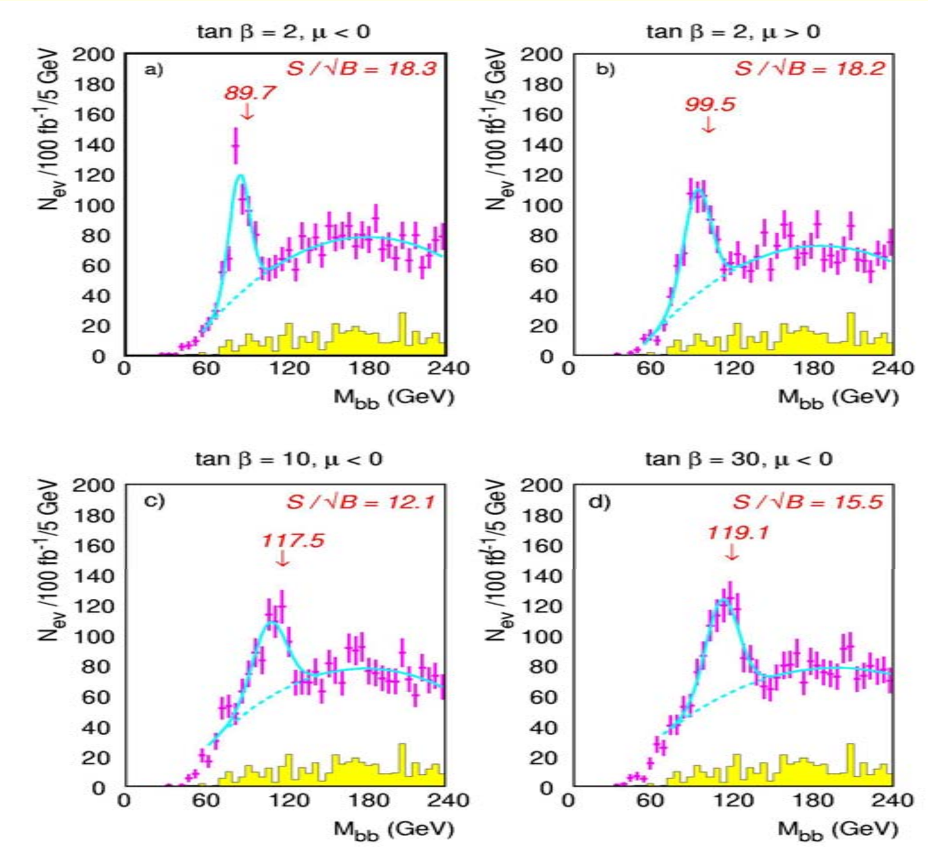


Modes can be distinguished

using shape of $\ell\ell$-spectrum

h $\to$ bb:

CMS



important if $\chi^0_2 \to \chi^0_1 h$ is open;

bb peak can be reconstructed in many cases

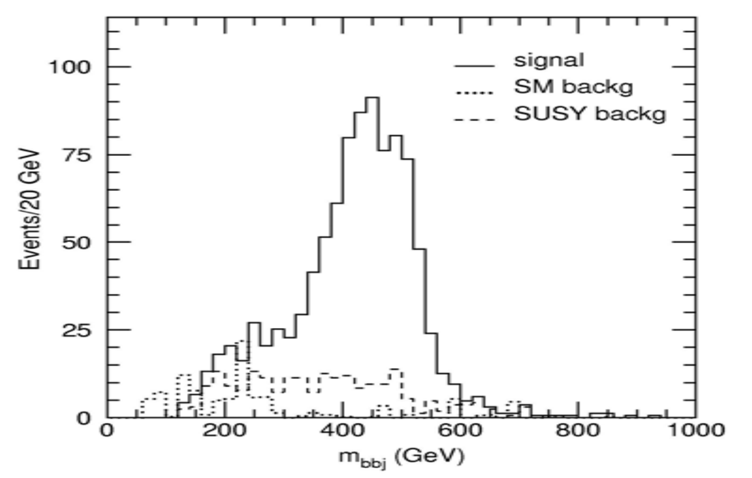
Could be a Higgs discovery mode !

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

work backwards the decay chain:
example: SUGRA study point 5

$$pp \to \tilde{q}_L \tilde{q}_R: \qquad \tilde{q}_R \to \tilde{\chi}_1^0 q$$
$$\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{\chi}_1^0 h q \qquad \to \tilde{\chi}_1^0 b\bar{b}q$$

combine h → bb with jets to determine other masses



$\tilde{q} \longrightarrow \tilde{\chi}_1^0 h q$ endpoint

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

Models other than SUGRA

GMSB:

- LSP is light gravitino
- Phenomenology depends on nature and lifetime of the NLSP
- Generally longer decay chains, e.g. $\tilde{\chi}_2^0 \to \tilde{\ell}^\pm \ell^\mp \to \tilde{\chi}_1^0 \ell^+ \ell^- \to \tilde{G} \gamma \ell^+ \ell^-$
- $\Rightarrow$ models with prompt NLSP decays give add handles and hence are easier than SUGRA
- NLSP lifetime can be measured:
  - For $\tilde{\chi}_1^0 \to \tilde{G}\gamma,$ use Dalitz decays (short lifetime) or search for non-pointing photons
  - Quasi stable sleptons: muon system provides excellent „Time of Flight" system

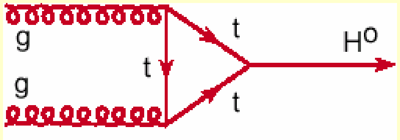
RPV :

- R-violation via $\chi^0{}_1 \to \ell\ell\nu$ or $qq\ell$, $qq\nu$ gives additional leptons and/or E_T^{miss}
- R-violation via $\chi^0{}_1 \to$ cds is probably the hardest case; (c-tagging, uncertainties on QCD N-jet background)

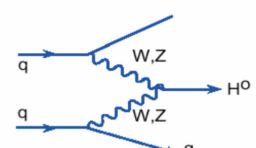
Where is the

Higgs Boson ?

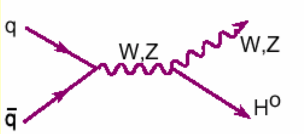
Higgs Boson Production cross sections at NLO



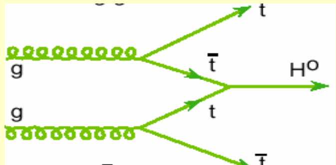
g g fusion



WW, ZZ fusion

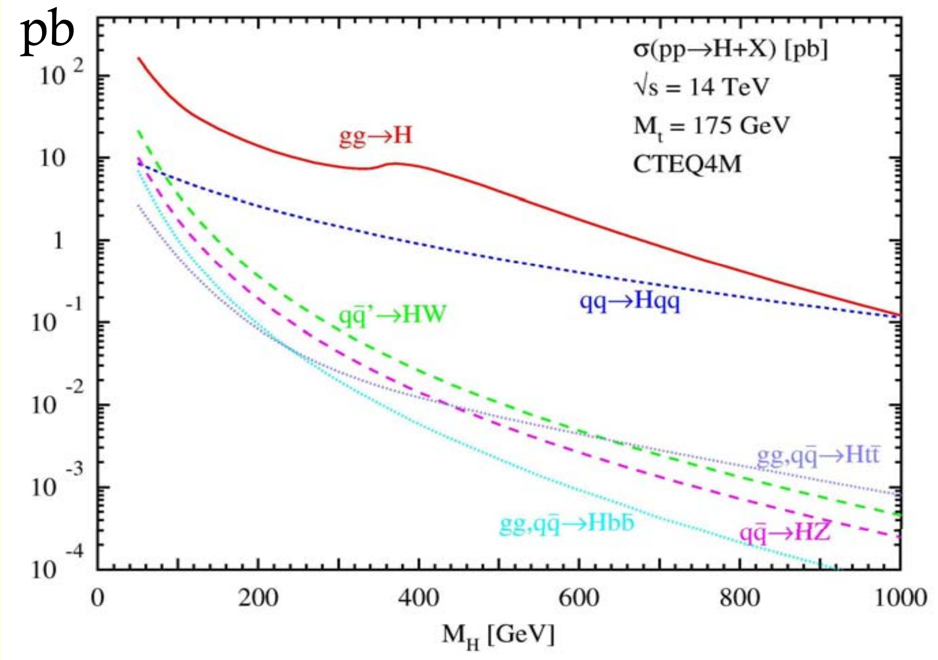


W, Z bremsstrahlung

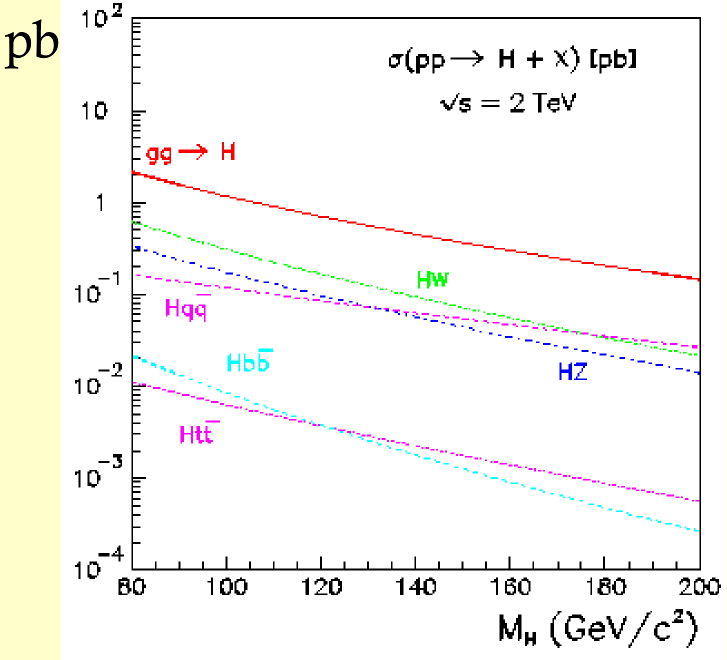


t t̄ fusion

LHC M. Spira et al.



Tevatron M.Spira et al.



qq → W/Z + H cross sections ~10 x larger at the LHC
gg → H ~70-80 x larger at the LHC

Gluon fusion dominates at both colliders,
W/Z H associated production is more important at the Tevatron

Some important comments:

- Computation of NLO cross sections: huge theoretical effort !!

- So far, LHC experimentalists (at least from one experiment) have refrained from systematically using these higher order corrections („no K factors“)

  main arguments: K-factors are not known for all background processes,
  → consistent treatment between signal and background,
  most likely a conservative approach

- New Tools → Experimentalists are about to use/familiarize + validate them:

(i) 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, wwweb.phy.cam.ar.uk/theory/webber/MCatNLO

new

- 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 (differential cross sections through NNLO)

(ii) New approaches to match parton showers and matrix elements:

(some based on algorithm developed by Catani, Krauss, Kuhn and Webber (CKKW)*)

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

new

- PYTHIA, adapted by S. Mrenna
- SHERPA Monte Carlo, F. Krauss et al., www.sherpa-mc.de

Tevatron data are extremely important for validation,
work has started, see e.g., TeV4LHC workshops

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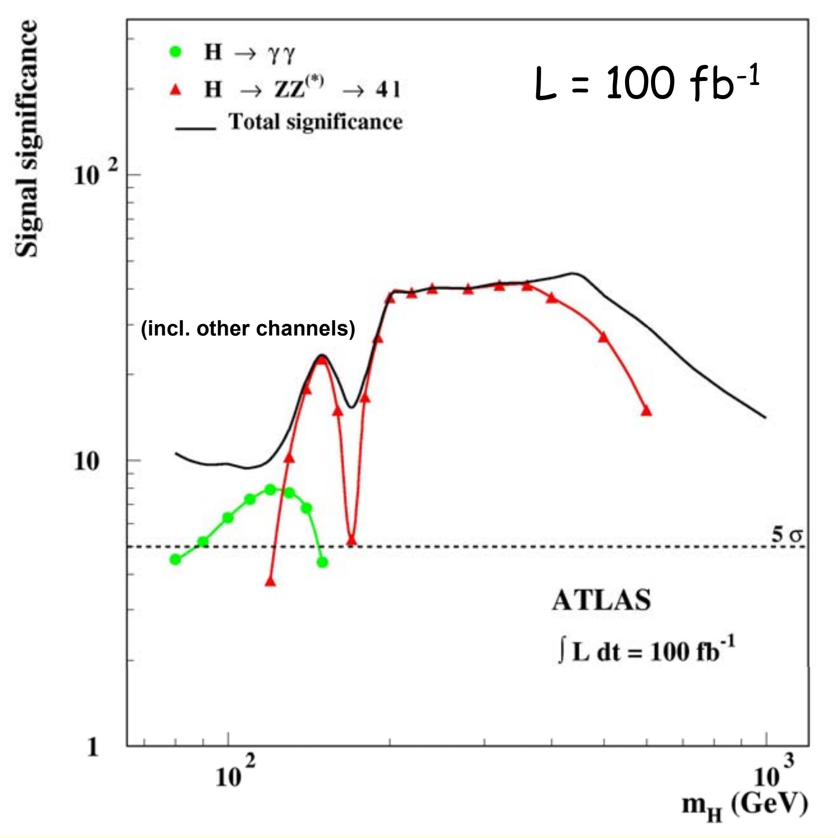
*) S. Catani, F. Krauss, R. Kuhn, B. R. Webber, JHEP 0111 (2001) 063.



The full allowed mass range

from the LEP limit (~114 GeV/c^2)

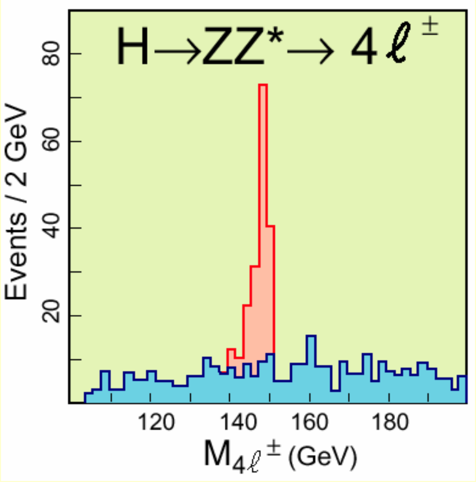
up to

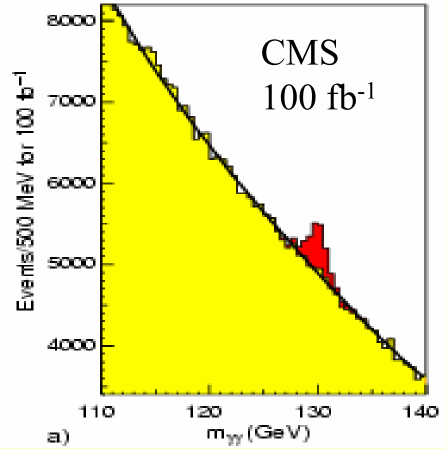
theoretical upper bound of ~1000 GeV/c^2

can be covered using the two “safe” channels

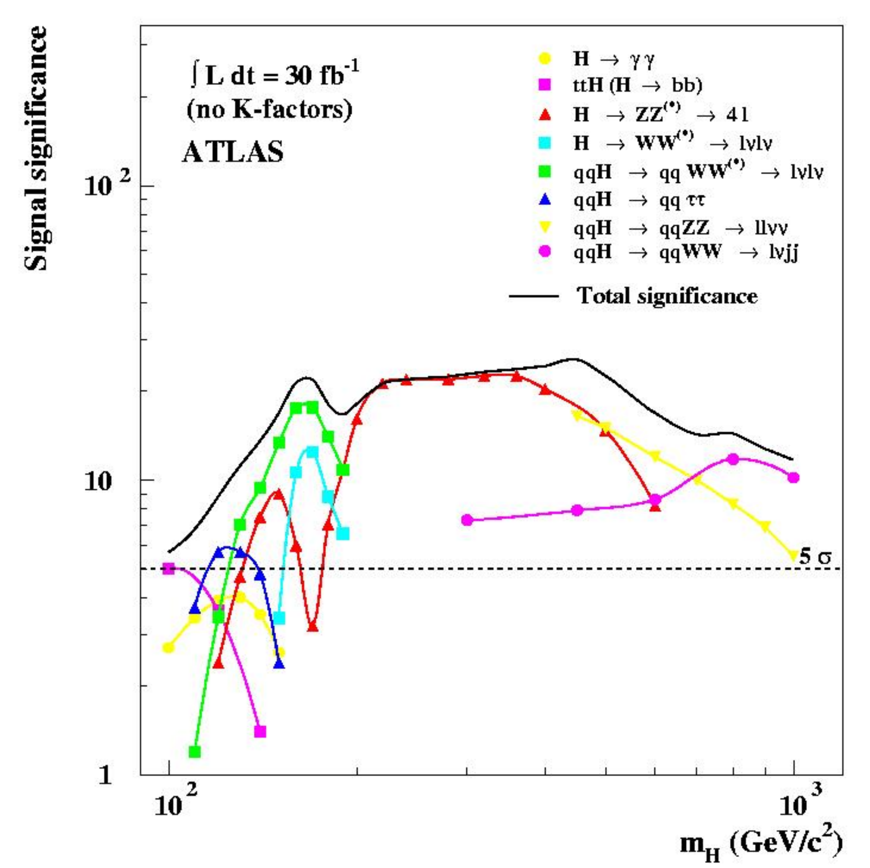
$H \rightarrow ZZ \rightarrow \ell\ell\ \ell\ell$ and

$H \rightarrow \gamma\gamma$





ATLAS Higgs discovery potential for 30 fb^{-1}



at high mass:

Lepton final states are essential
(via H → WW , ZZ)

at low mass:

Lepton and Photon final states
(via H → WW*, ZZ* or direct $\gamma\gamma$)

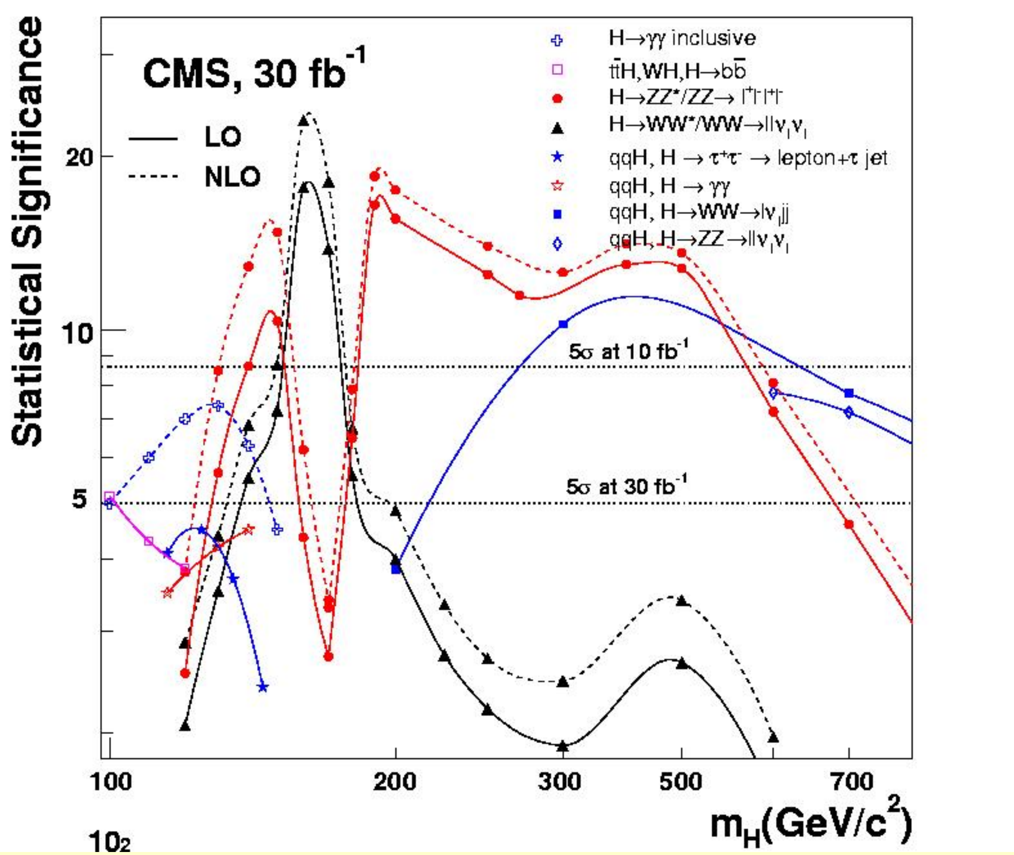
Tau final states

The dominant **bb decay mode** is only useable in the associated production mode (ttH)

- **Full mass range can already be covered after a few years at low luminosity**
- **Vector boson fusion channels play an important role**

- **Several channels available over a large range of masses**

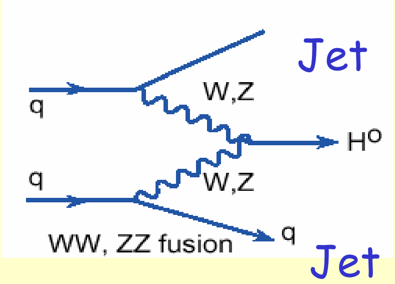
Comparable situation for the CMS experiment



Effects of NLO contributions are shown for several channels

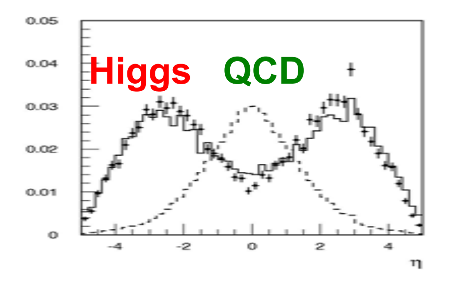
Update:
CMS is writing Physics Report (TDR), expected in June 2006

Higgs Search in Vector Boson Fusion



Motivation: Increase discovery potential at low mass
Improve measurement of Higgs boson parameters
(couplings to bosons, fermions)
(proposed by D. Zeppenfeld et al.)

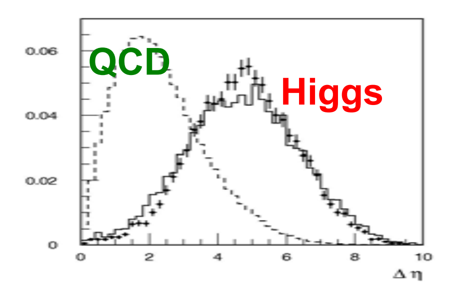
Pseudorapidity of jets

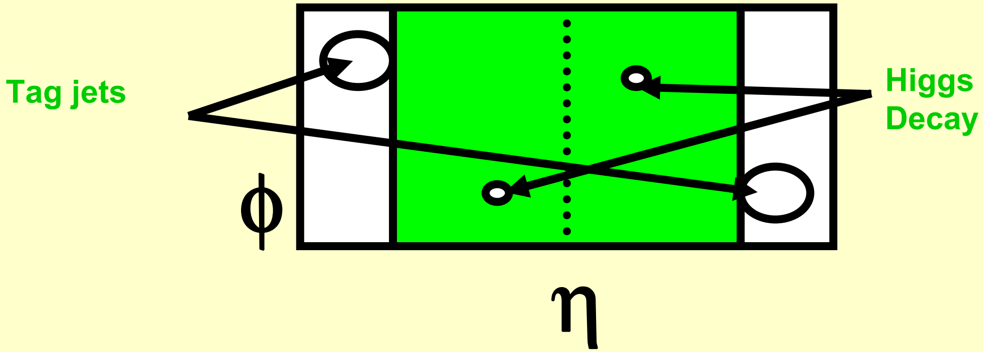


Distinctive Signature of:

- two high P_T leptons
- missing transverse momentum
- two high P_T forward tag jets
- little jet activity in the central region
  ⇒ central jet Veto

Difference in pseudorapidity



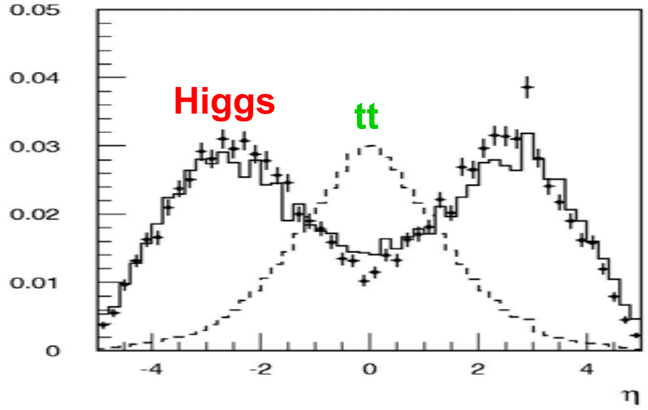


⇒ Experimental Issues:

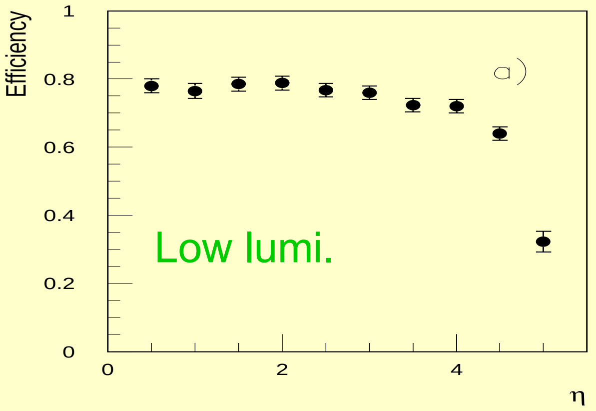
- Forward jet reconstruction
- Jets from pile-up in the central / forward region

Studied in full simulation by ATLAS and CMS

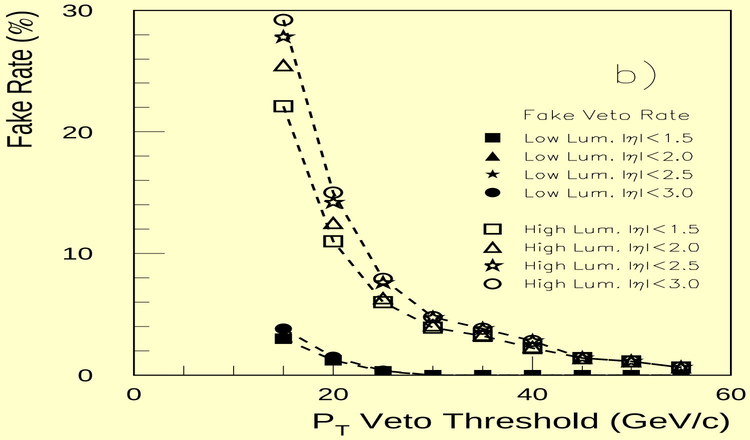
Rapidity distribution of jets in tt and Higgs signal events:



Efficiency of forward jet reconstruction



Fraction of events with jet in central region



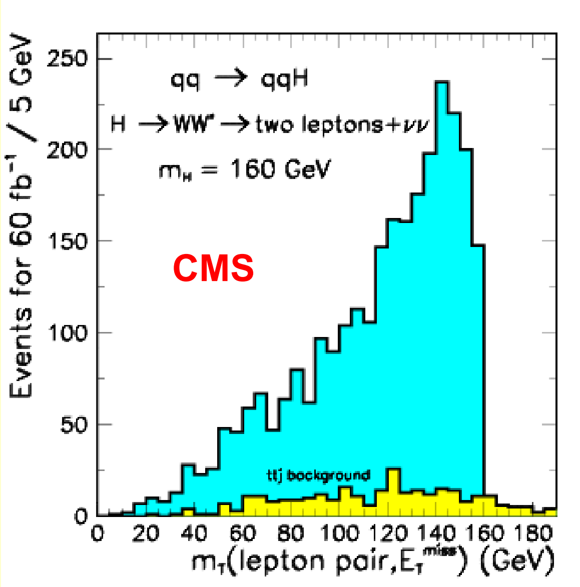
Looks feasible at low luminosity, higher tag jet P_T- thresholds needed at high luminosity;
However, first data needed to confirm activity in the forward regions (underlying event)

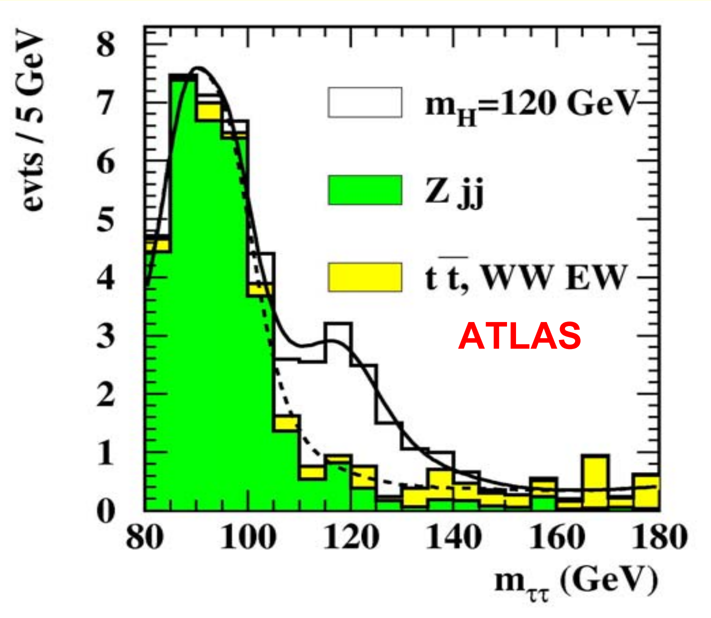
Two search channels at the LHC:

$$\begin{aligned} qq\,H &\rightarrow qq\;W\,W^* \\ &\rightarrow qq\;\ell\nu\;\ell\nu \end{aligned}$$

$$\begin{aligned} qq\,H &\rightarrow qq\;\tau\,\tau \\ &\rightarrow qq\;\ell\nu\nu\;\ell\nu\nu \\ &\rightarrow qq\;\ell\nu\nu\;h\nu \end{aligned}$$

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





(Japan-ATLAS contributions)

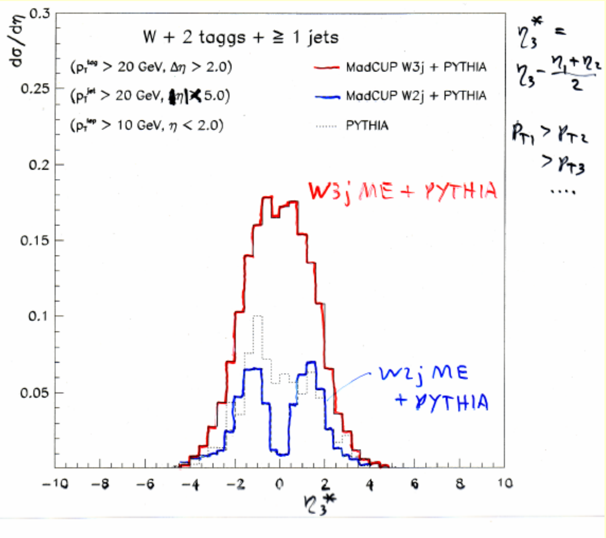
Selection criteria:

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

How reliable are these signals ?

Can the jet veto be calculated reliably ?

- Comparison between explicit matrix element calculations and shower Monte Carlos for W + jj production (D. Zeppenfeld, E. Richter-Was, TeV4LHC workshop)



$$\eta_3^* = \eta_3 - ½\,(\eta_1+\eta_2)$$

First study: Z + jet production

DØ data vs. PYTHIA and SHERPA (see later)

-
- arlos
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  C
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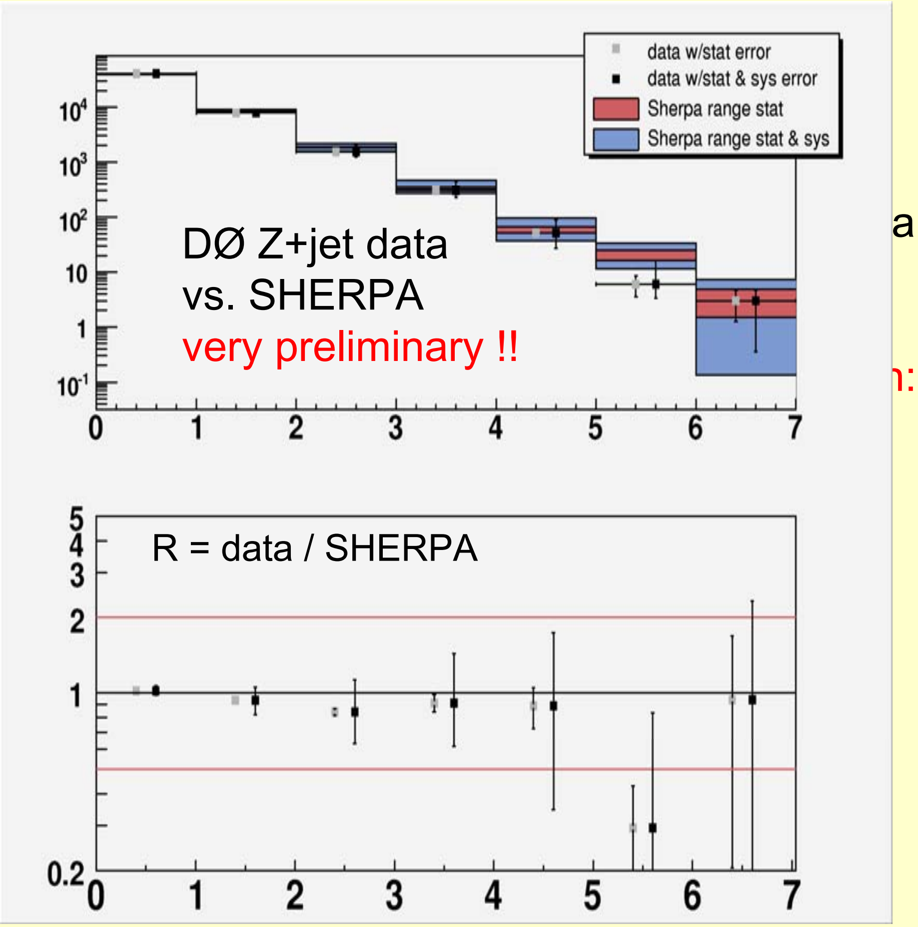
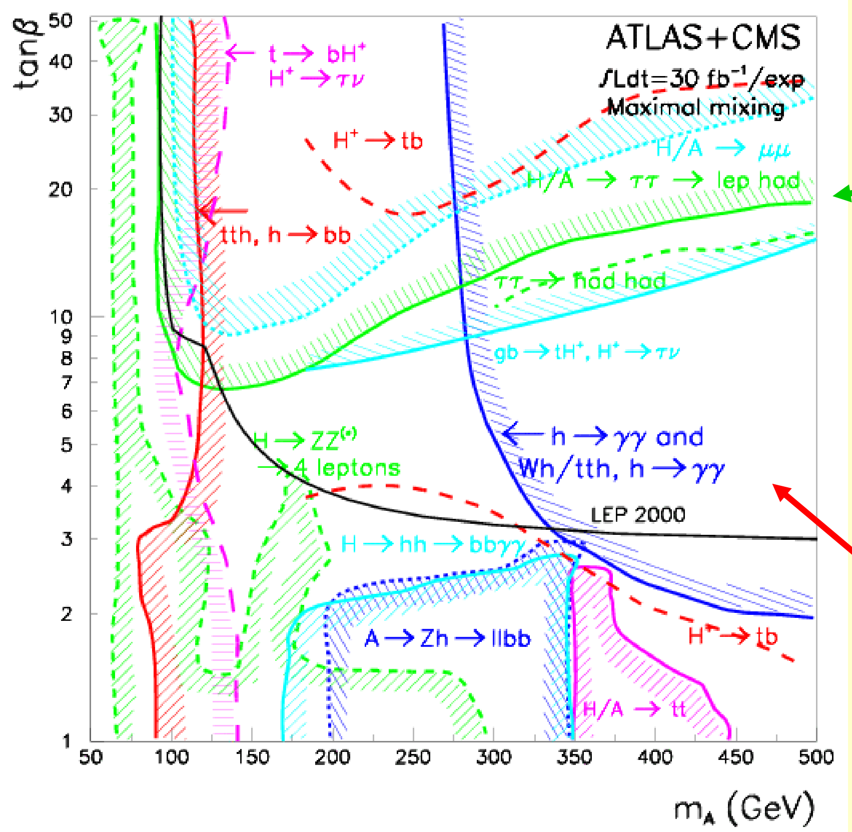


jet multiplicity

MSSM Higgs bosons h, H, A, $H^{\pm}$

$m_h < 135$ GeV/c^2
$m_A \approx m_H \approx m_{H\pm}$ at large m_A



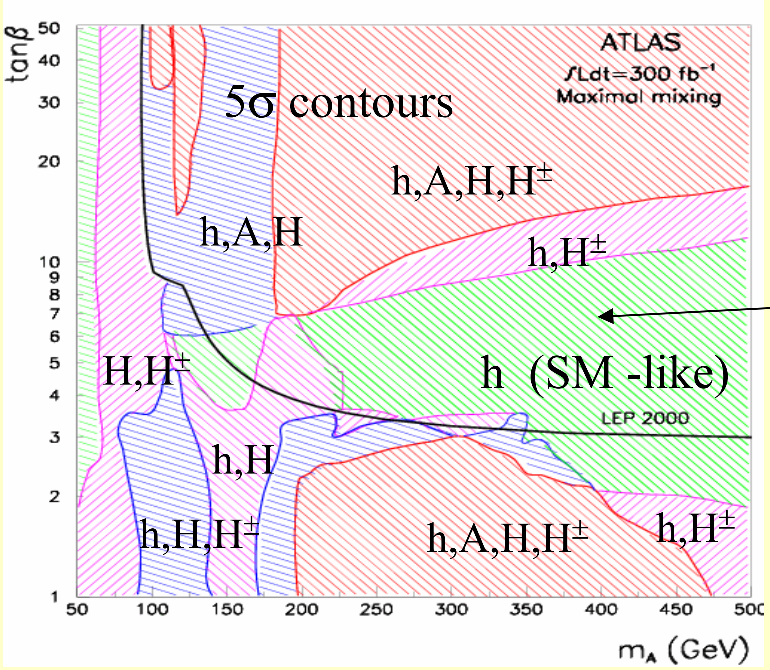
A, H, H± cross-sections ~ $\tan^2\beta$

- best sensitivity from A/H → $\tau\tau$, H± → $\tau\nu$
  (not easy the first year ..)

- A/H → $\mu\mu$ experimentally easier
  (esp. at the beginning)

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

LHC discovery potential for MSSM Higgs bosons



▨ 4 Higgs observable
▨ 3 Higgs observable
▨ 2 Higgs observable
▨ 1 Higgs observable

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

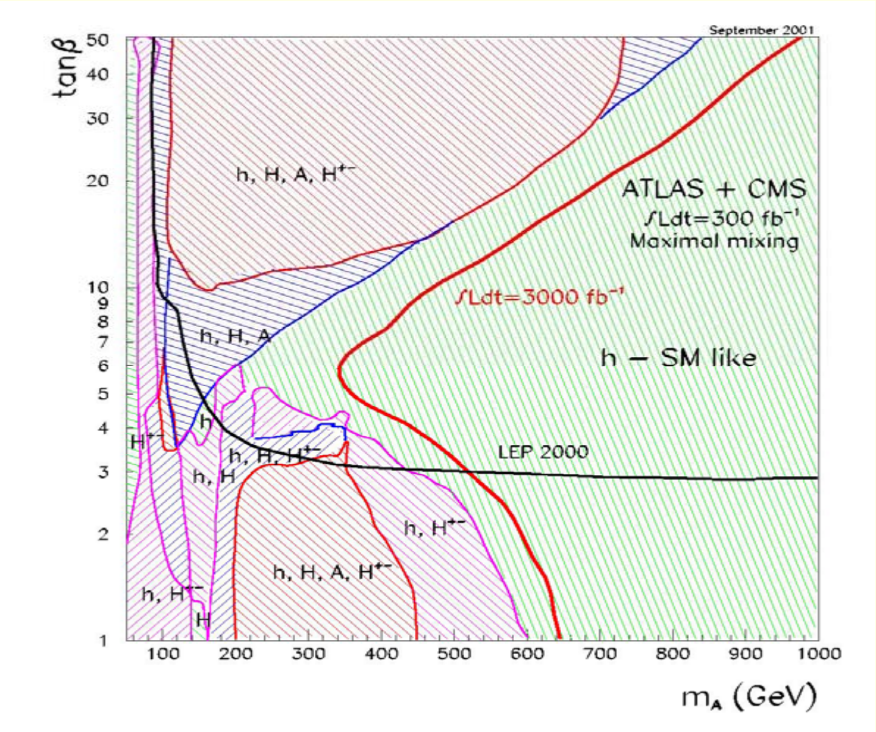
Assuming decays to SM particles only

- Region at large m_A and moderate tan β only covered by h; difficult to detect other Higgs bosons

Possible coverage:
* via SUSY decays (model dependent, see below)
* luminosity (only moderate improvement)

MSSM discovery potential for Super-LHC

ATLAS + CMS, 2 x 3000 fb^{-1}



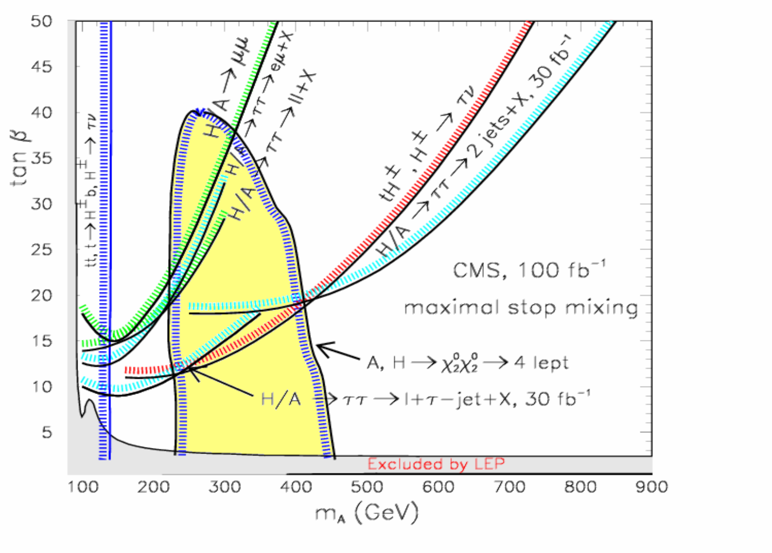
- Situation can be improved, in particular for $m_A < \sim 400$ GeV
- But: (S)LHC can not promise a complete observation of the heavy part of the MSSM Higgs spectrum ....

.... although the observation of sparticles will clearly indicate that additional Higgs bosons should exist.

Higgs decays via SUSY particles

If SUSY exists : search for

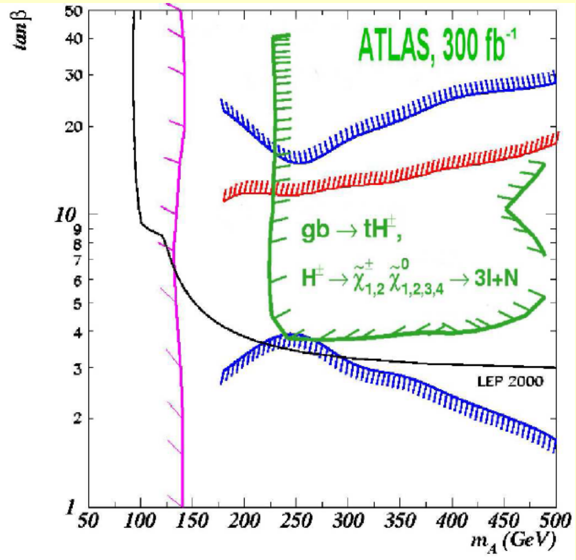
$H/A \rightarrow \chi^0_2\chi^0_2 \rightarrow \ell\ell\chi^0_1\ \ell\ell\chi^0_1$



CMS: special choice in MSSM (no scan)

M_1 = 60 GeV/c^2
M_2 = 110 GeV/c^2
μ = -500 GeV/c^2

$gb \rightarrow tH^+$, $H^\pm \rightarrow \chi_{2,3}{}^0\, \chi_{1,2}{}^\pm \rightarrow 3\ell + E_T{}^{miss}$

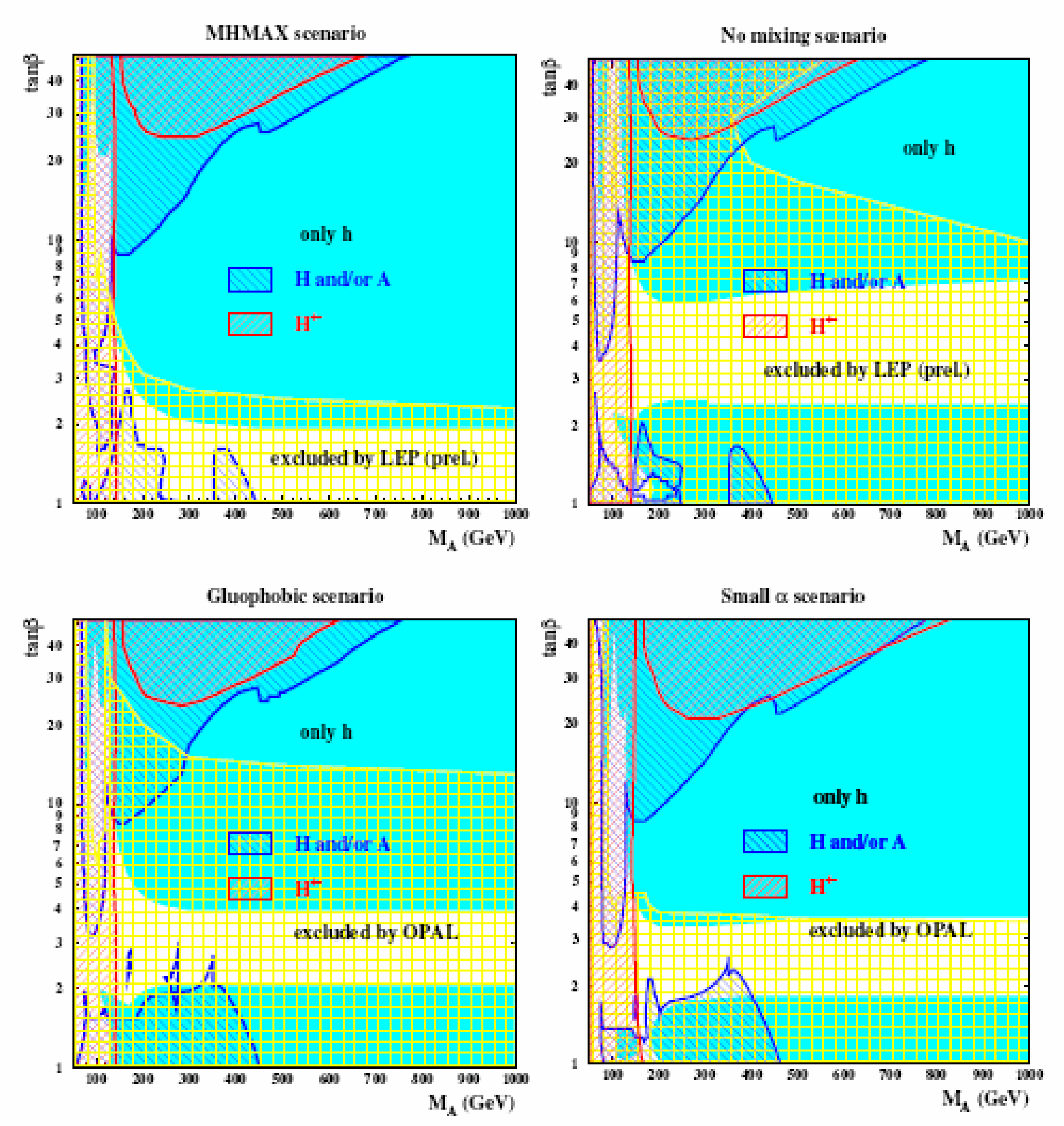


ATLAS: special choice in MSSM (no scan)

M_1 = 60 GeV/c^2
M_2 = 210 GeV/c^2
μ = 135 GeV/c^2
m(s-ℓ_R) = 110 GeV/c^2
m(s-τ_R) = 210 GeV/c^2

Exclusions depend on MSSM parameters (slepton masses, μ)

MSSM discovery potential for various benchmark scenarios



- Full parameter range can be covered with modest luminosity, 30 fb^{-1}, for all benchmark scenarios !

- Only one Higgs boson, h, in some regions
  (moderate tanβ – large m_A wedge)

  valid if CP is conserved !!

Different in CP violating scenarios

Different MSSM benchmark scenarios:

Benchmark scenarios as defined by M. Carena et al.

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

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

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

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

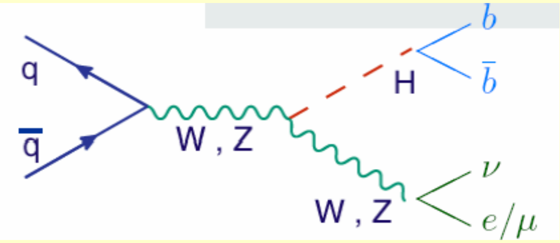
Results from the

present Tevatron

Run II data

data corresponding to
350 – 950 pb^{-1} analyzed

Low Mass: WH → e/μ ν bb



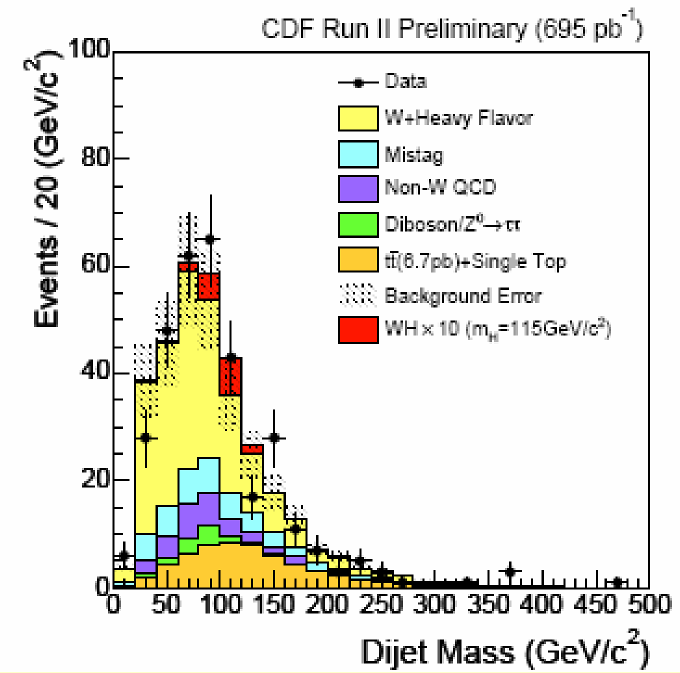
Data sample: 695 pb^{-1}

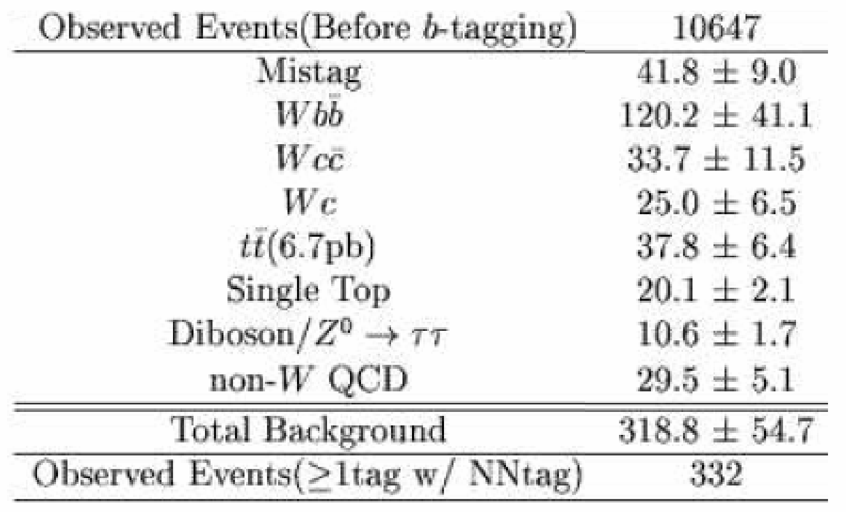
Event selection:

- 1 high P_T central e or μ
- P_T^{miss} > 20 GeV/c
- 2 jets, at least 1 b-tagged
- veto events with > 1 lepton

Backgrounds:

- Wbb, Wcc, Wjj (mistags)
- WW, WZ, ZZ, Z→ ττ
- tt, single top
- QCD multijet



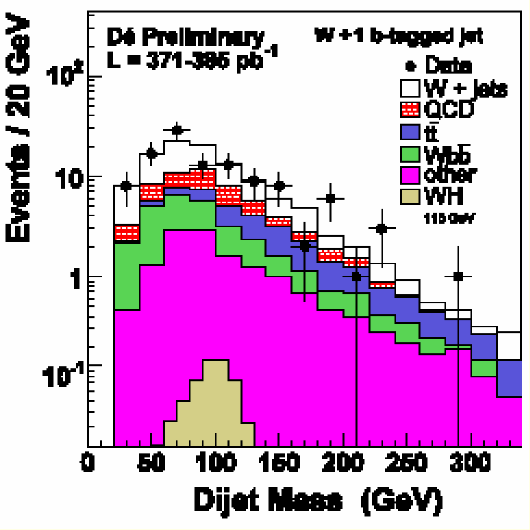


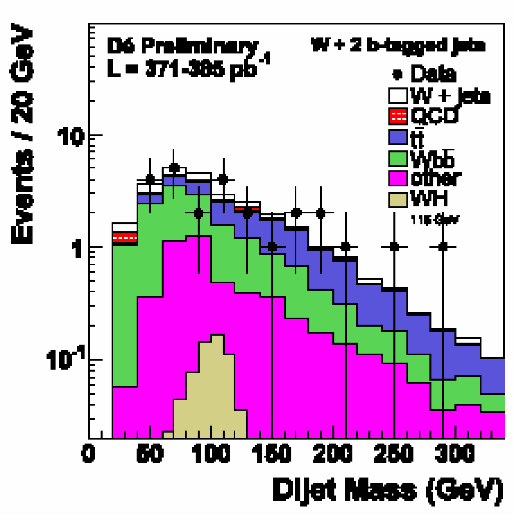
Observed Events(Before b-tagging)	10647
Mistag	41.8 ± 9.0
$Wb\bar{b}$	120.2 ± 41.1
$Wc\bar{c}$	33.7 ± 11.5
Wc	25.0 ± 6.5
$t\bar{t}$(6.7pb)	37.8 ± 6.4
Single Top	20.1 ± 2.1
Diboson/$Z^0 \to \tau\tau$	10.6 ± 1.7
non-W QCD	29.5 ± 5.1
Total Background	318.8 ± 54.7
Observed Events(≥1tag w/ NNtag)	332

Low Mass: WH → eν bb

Data sample: ~380 pb^{-1}

Event selection: 1 e/μ, (|η| < 1.1, E_T>20 GeV), E_T^{miss} > 25 GeV,
2 jets (E_T > 20 GeV, |η| < 2.5)
1 or 2 b-tags





Limit from combined channels:

– $m_H = 115$ GeV, $75 < m_{jj} < 125$ GeV

events	single tag	double tag
observed	32	6
predicted	45	9.3

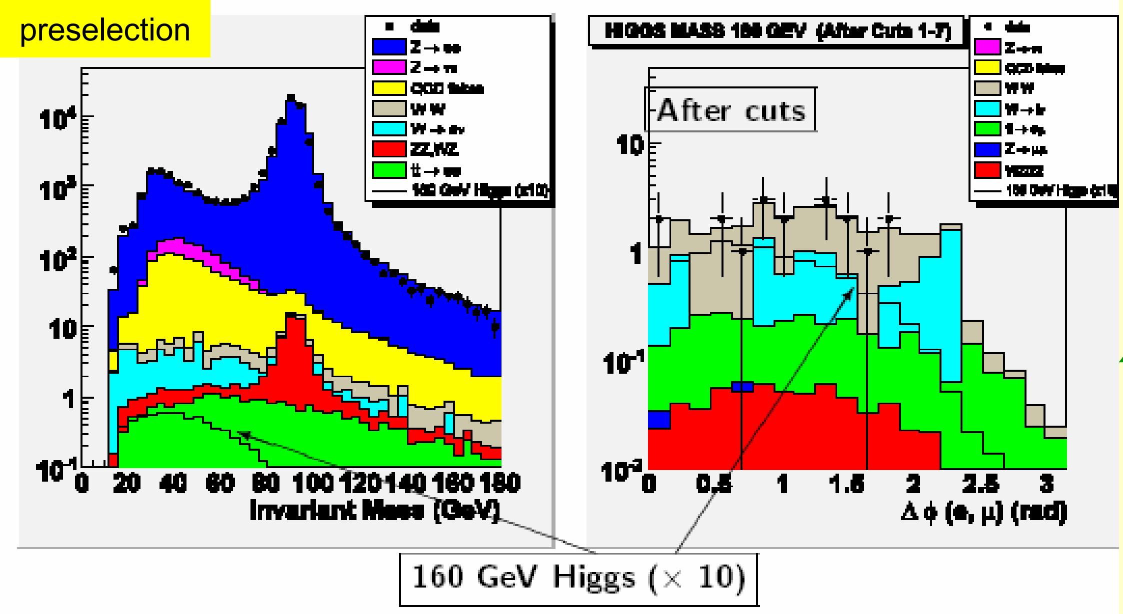
* $\sigma_{95} = 2.5$ pb

High mass: H → WW → ℓν ℓν

- Analyses have been performed by both CDF and DØ
- based on data corresponding to an int. luminosity of up to ~ 950 pb^{-1}

Search for ee and eμ + E_T^{miss} events

e, μ with $P_T > 20/15$ GeV/c

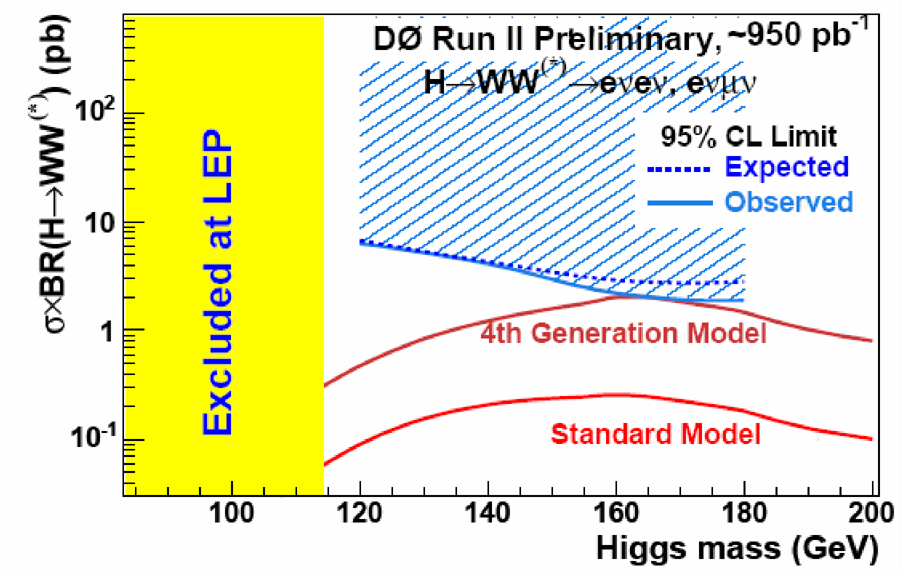


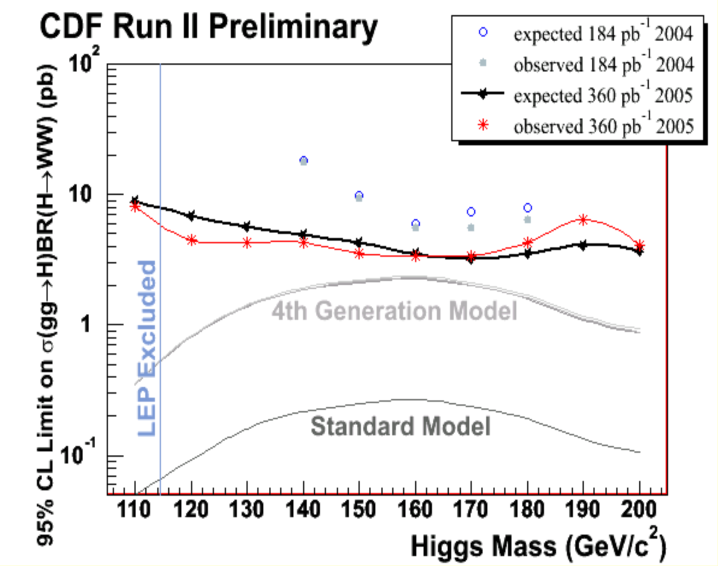
additional cuts:

$E_T^{miss} > 20$ GeV
$M(\ell\ell) < m_H/2$
$M_T(\ell\ell E_T^{miss}) < m_H - 10$ GeV

Data are consistent with expectations from SM backgrounds

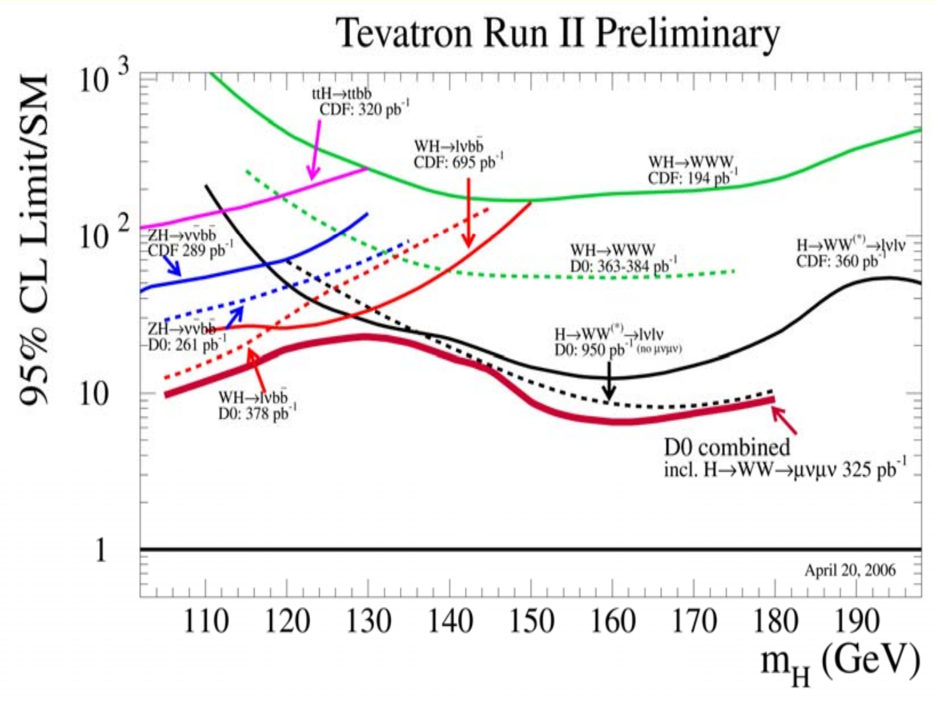
Limits on H → WW → ℓν ℓν cross sections





Higgs boson searches at the Tevatron

- Many analyses (in many different channels) have been performed
- No excess above SM background ⇒ Limits extracted



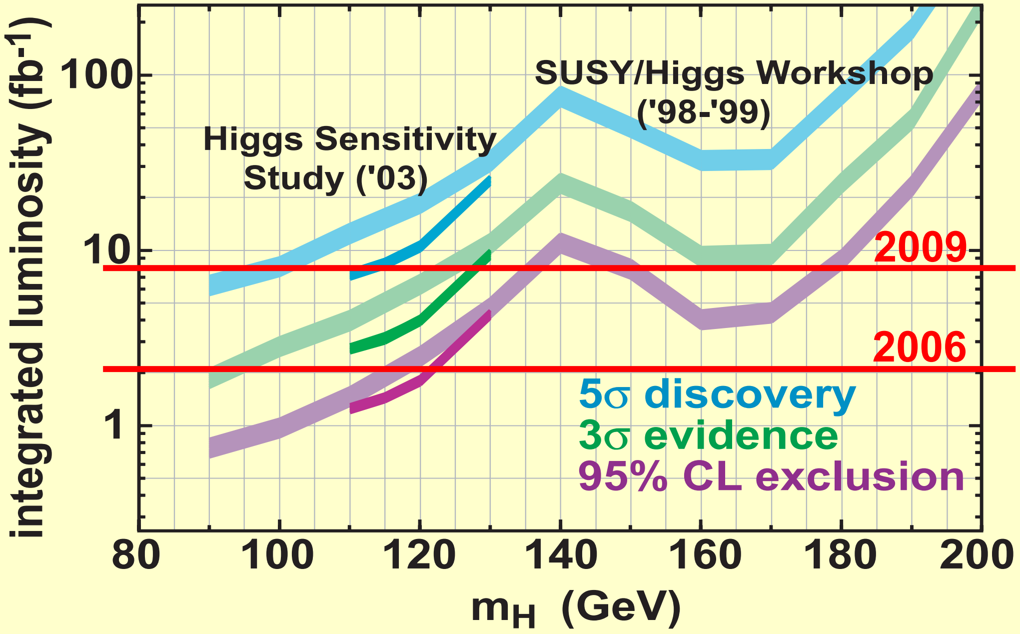
Combination of current analyses (DØ): for ~378 - 950 pb^{-1}

- upper limit about ~ 15 times larger than SM prediction at 115 GeV/c^2
- for L = 2 fb^{-1}: → gain = $\sqrt{L} / 0.378$ → still a factor ~6 missing

- Can the missing factors be gained ??

Anticipated improvements:

- increase acceptance (forward leptons, forward b-tagging)
- improvements in b-tagging (neural network)
- improvements in selection efficiencies (track-only leptons, neural networks)
- improved di-jet mass resolution
- ....



95% CL exclusion: ~ 2 fb^{-1}: 115 GeV/c^2
8 fb^{-1}: 135 GeV/c^2

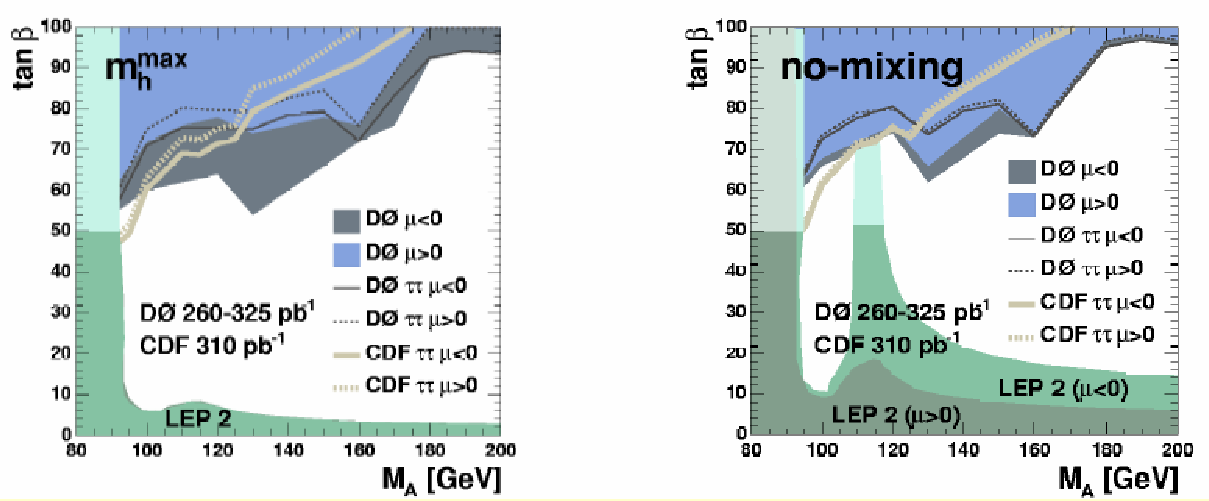
3 σ evidence: 5 fb^{-1}: 115 GeV/c^2

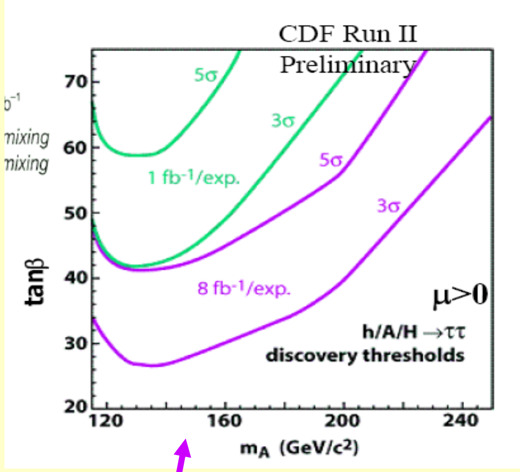
Updated Sensitivity Estimates
(assumes all factors can be reached)

improvements not demonstrated yet, no guarantee, but there is a chance....

MSSM Higgs boson searches at the Tevatron

Search for A/H → bb and A/H → ττ





Start to access interesting regions of parameter space and to constrain models at large tan β;
(however, beware of large radiative corrections !)

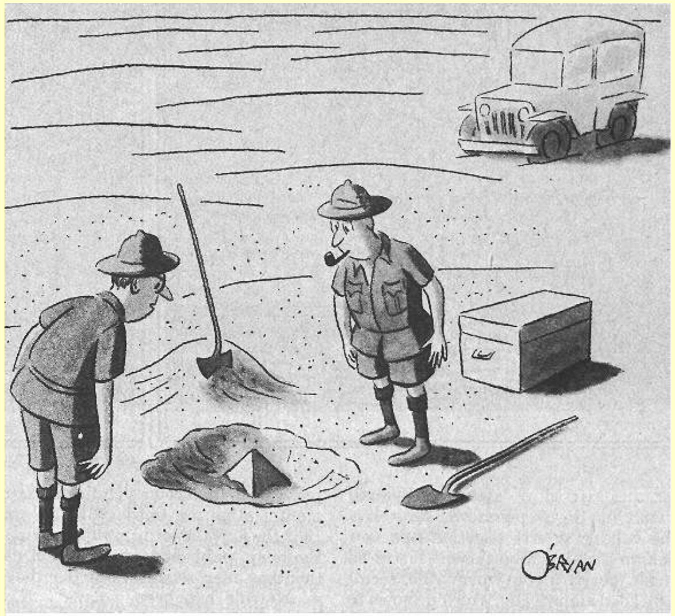
Good prospects for discovery of MSSM Higgs bosons in the (large tanβ–small m_A) region, if 8fb^{-1} can be achieved.

From the Tevatron to the LHC

In addition to measuring top quark properties, testing the Standard Model and making discoveries the Tevatron has a key role in:

Testing and validation of Monte Carlos
Transfer of knowledge on Object ID and Computing

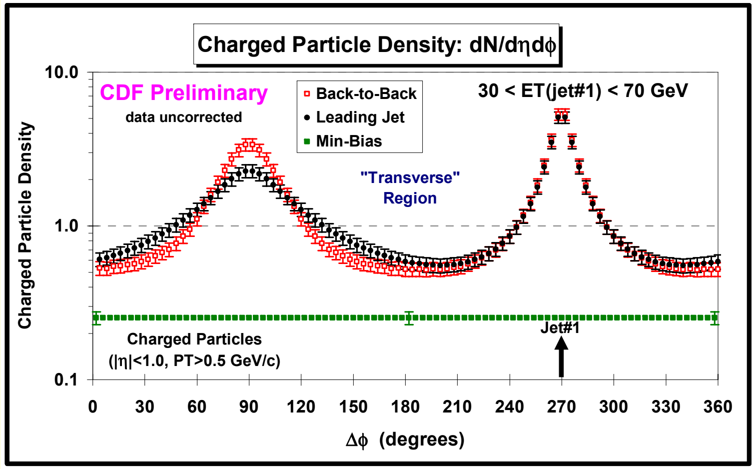
Certified Monte Carlos + reliable theoretical calculations at NLO, NNLO++….
will allow to minimize uncertainties on the backgrounds at the LHC



"This could be the discovery of the century. Depending, of course, on how far down it goes."

Two examples:

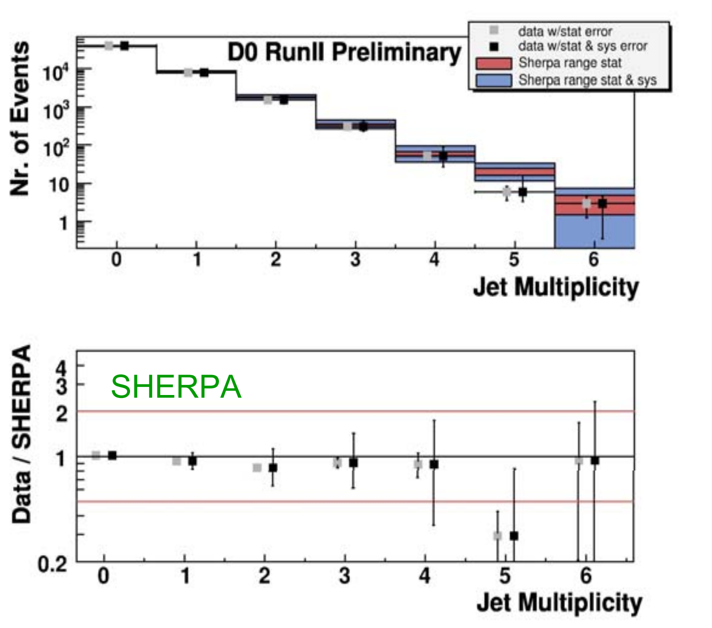
(i) Study of Minimum Bias Events
(important for LHC simulations, pile-up,…….)

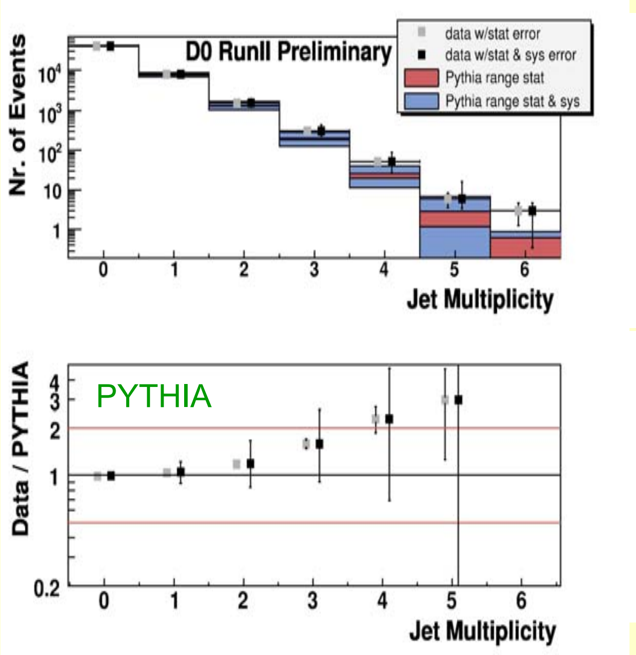


(ii) Study of CKKW matching procedures
(important application: description of jet vetos
in searches for New Physics)

Z+ jet data, comparison to the SHERPA and PYTHIA Monte Carlos

SHERPA also describes correlations among jets





Conclusions

Hadron Colliders will play a crucial role in physics over the forthcoming years:

Tevatron:
- data taking is running smoothly now (after a slow start-up)
- data are (so far) in good agreement with SM expectations
- discovery window for SUSY still exists
- interesting information on the Higgs boson (limits, 3σ effects) can be achieved

LHC:
- huge discovery potential, can say the final word about

  The Standard Model Higgs mechanism

  and

  Low-energy SUSY and other TeV-scale predictions

The results will most likely modify our understanding of Nature