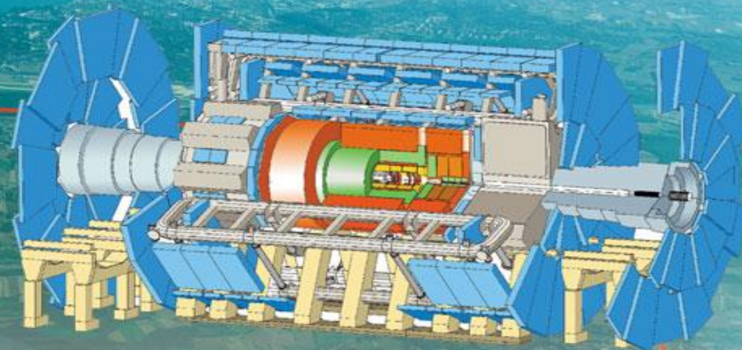
New Horizons in Particle Physics

- From the Higgs boson to Dark Matter at the LHC-

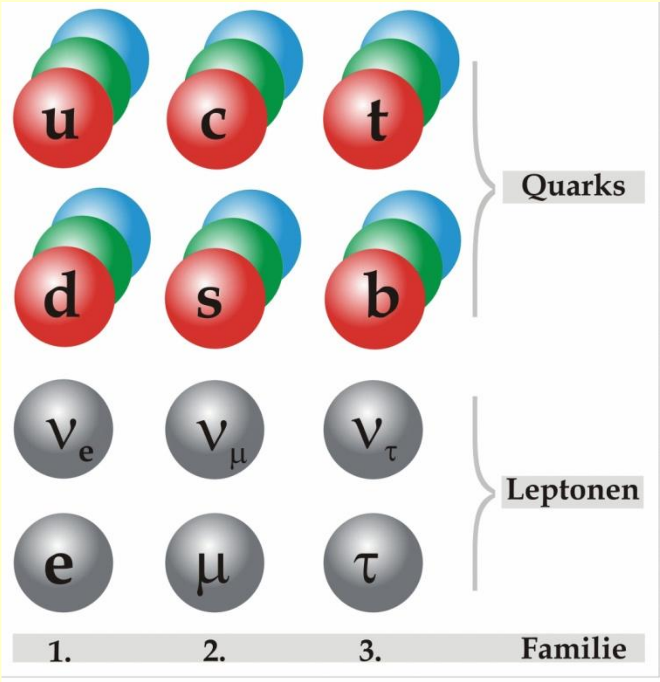


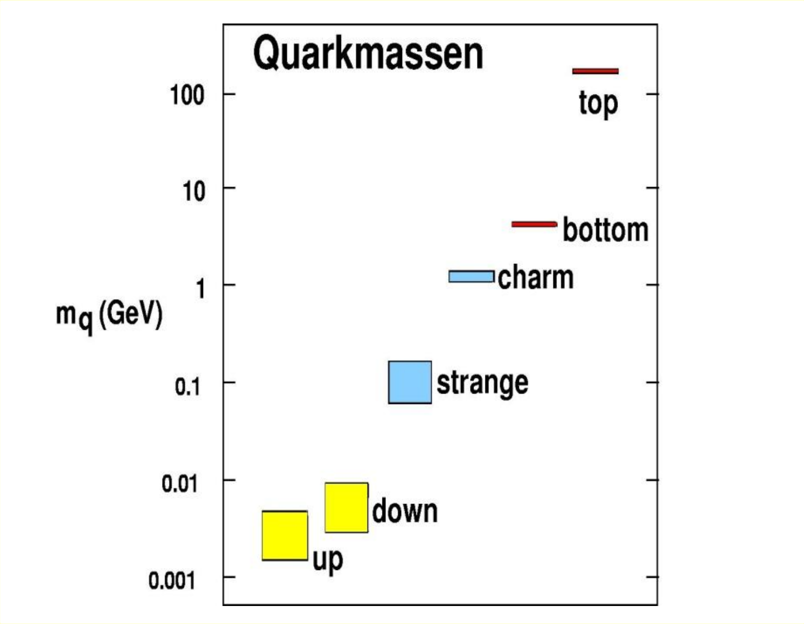
- **Introduction**

  Where do we stand today?
- **The open questions**
- **What answers can we expect from the *Large Hadron Collider (LHC)* ?**
- **Dark Matter at the LHC ?**

The Standard Model of Particle Physics

(i) Building blocks of matter: Quarks and Leptons





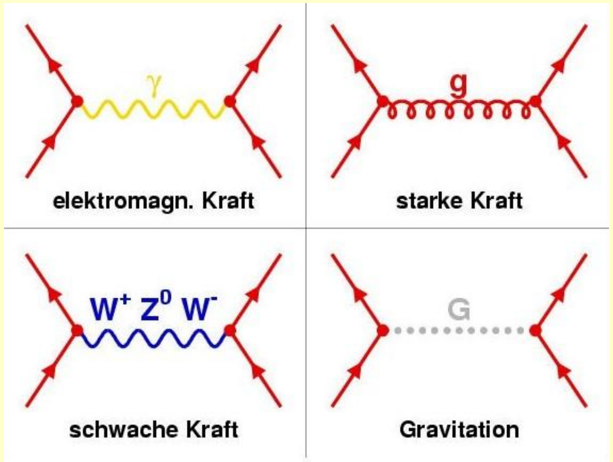
m (e) = 0,000511 GeV/c^2
m (τ) = 1,8 GeV/c^2

m (u) = 0,005 GeV/c^2
m (t) = 178 GeV/c^2

In comparison: m (p) = 0,938 GeV/c^2

(ii) Forces / Interactions:

mediated via the exchange of field quanta /bosons



$m_\gamma = 0$, $m_g = 0$

$M_W = 80.398 \pm 0.025$ GeV / c^2
$M_Z = 91.1875 \pm 0.0021$ GeV / c^2

(iii) Higgs field

Needed to break (hide) the electroweak symmetry

⇒ **Higgs particle** (s. talk by Gian Giudice)
Theoretical arguments: $m_H < \sim 1000$ GeV/c^2

Theoretical description:

Gauge theories of electroweak and Strong interactions

(i) Electroweak theory

S. Glashow
A. Salam
S. Weinberg

(ii) Quantum Chromodynamics

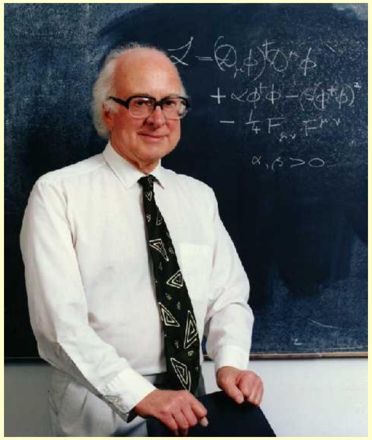
D.J. Gross
H.D. Politzer
F.E. Wilcek

Problem: symmetry requires massless gauge bosons

Where do we stand today?

e^+e^- colliders LEP at CERN and SLC at SLAC + the Tevatron pp collider + HERA at DESY + KEK in Japan + many other experiments (fixed target…….) have explored the energy range up to **~100 GeV** with incredible precision

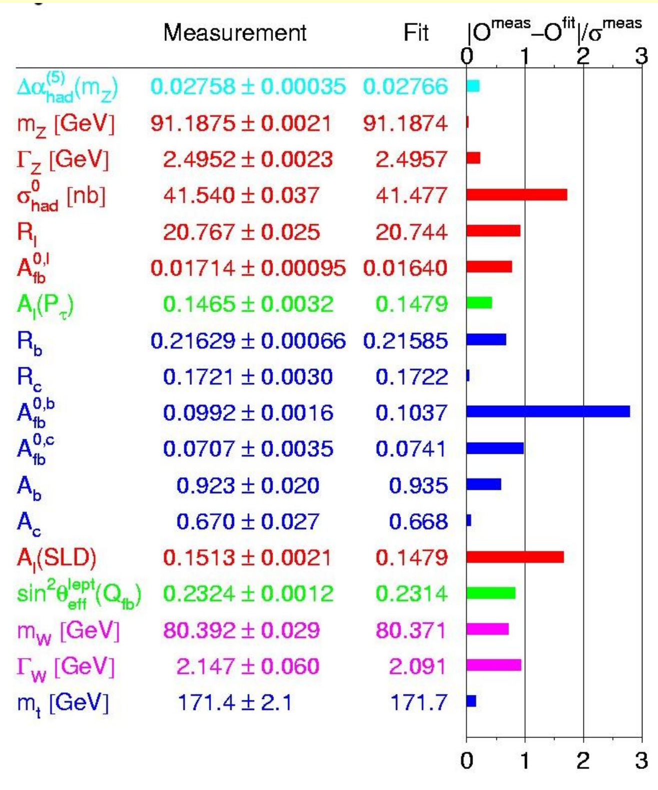
- The Standard Model is consistent with all experimental data !
- No Physics Beyond the SM observed
- No Higgs seen (yet)



Only unambiguous example of observed Higgs

(P. Higgs, Univ. Edinburgh)

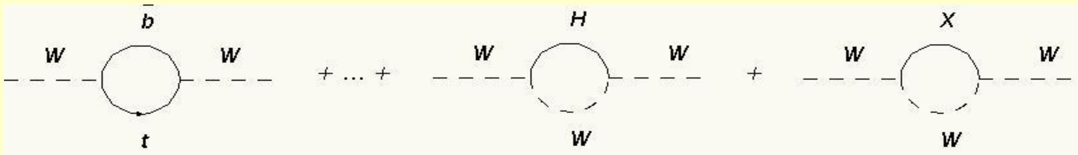
Summer 2007

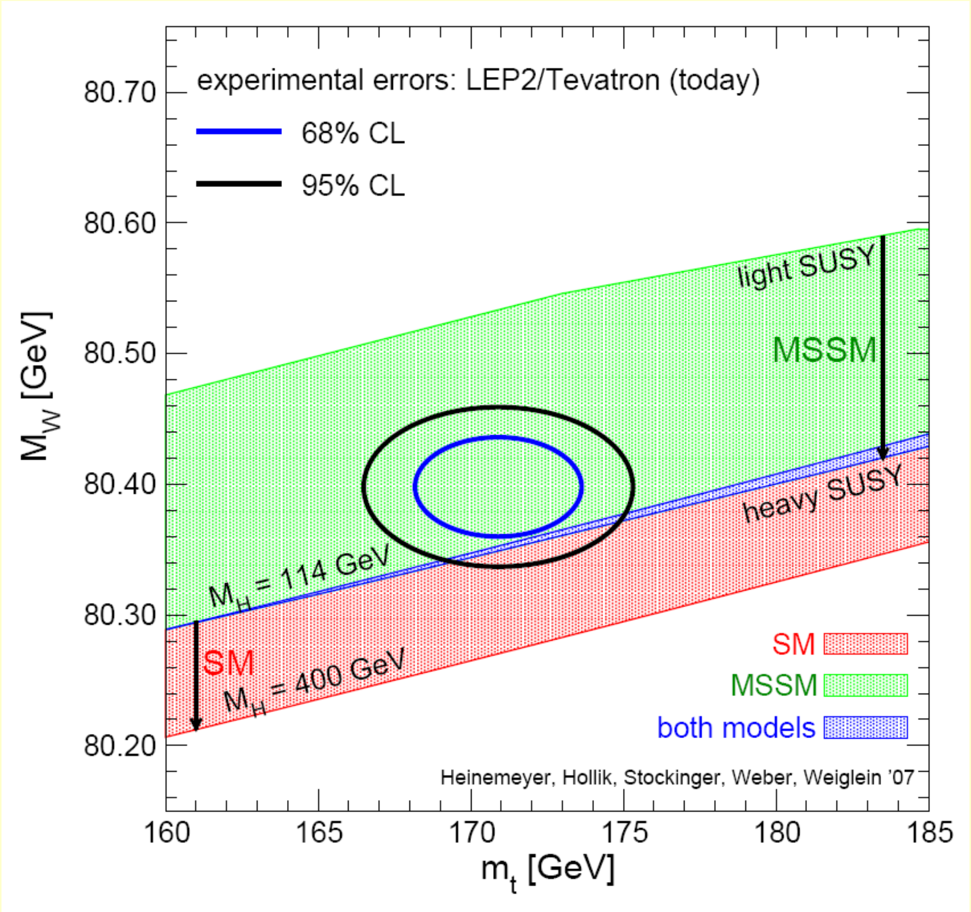


Direct searches at LEP: $m_H > 114.4$ GeV/c^2 (95% CL)

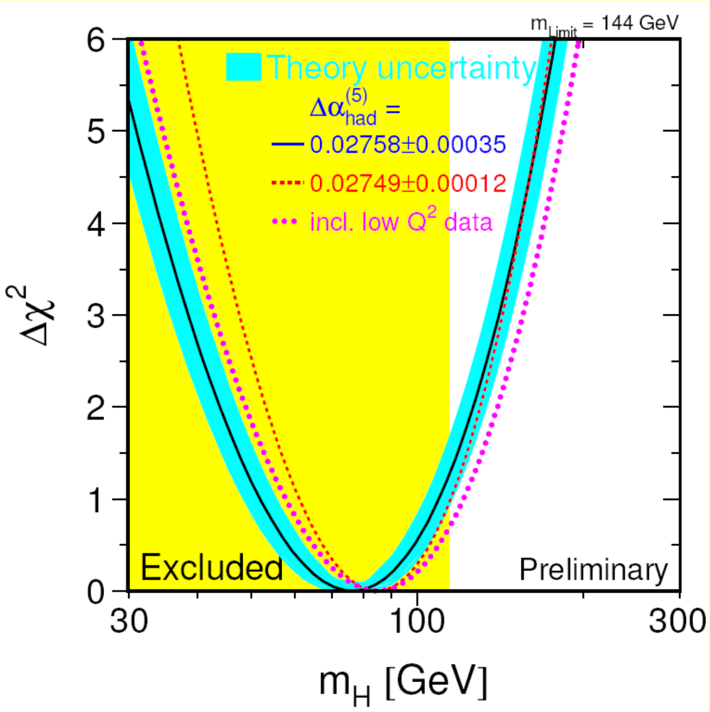
Consistency with the Standard Model

Sensitivity to the Higgs boson and other new particles via quantum corrections:





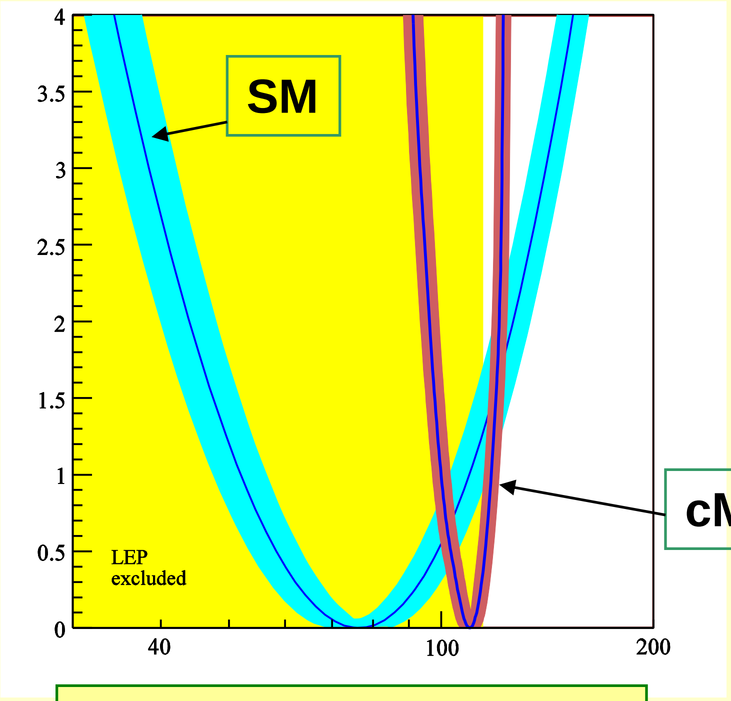
Interpretation within the Standard Model



m_H = 80 (+36) (-26) GeV/c^2
m_H < 144 GeV/c^2 (95 % CL)

Constraints on the Higgs mass in a supersymmetric theory

O. Buchmüller et al., arXiv:0707.3447

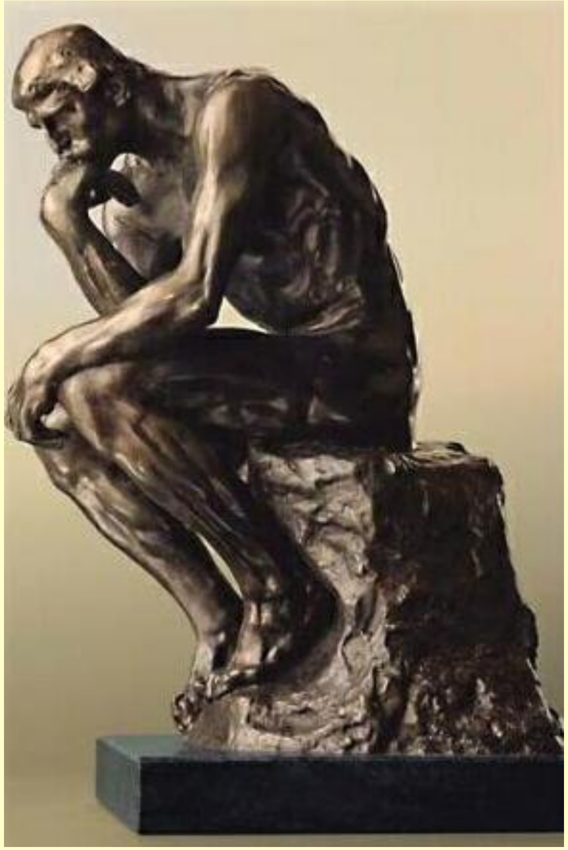


m_h = 110 (+8) (-10) ± 3 (theo) GeV/c^2

….watch the low mass region !

Includes:
- WMAP
- $b \rightarrow s\gamma$
- a_μ

The Open Questions



Key Questions of Particle Physics

1. Mass: What is the origin of mass?

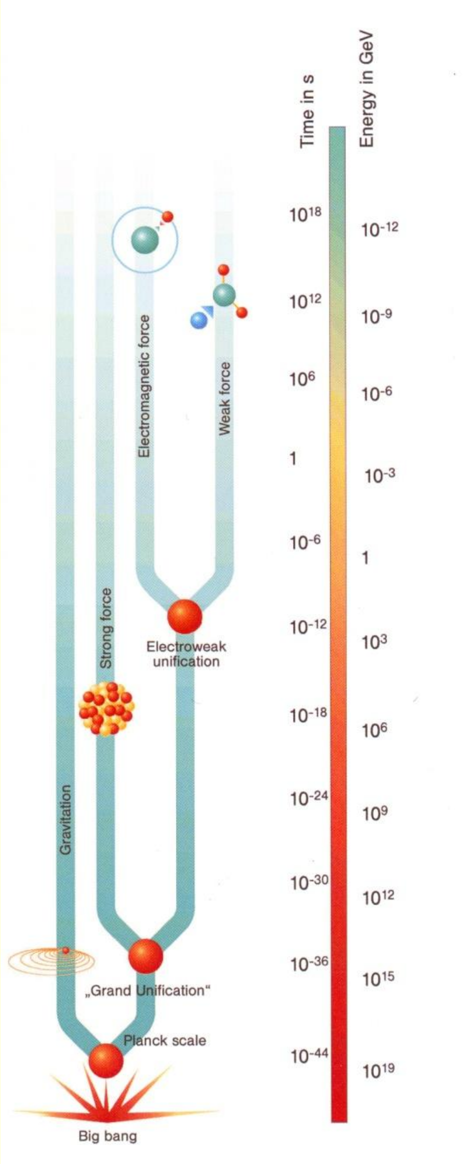
- How is the electroweak symmetry broken ?
- Does the Higgs boson exist ?

2. Unification: What is the underlying fundamental theory ?

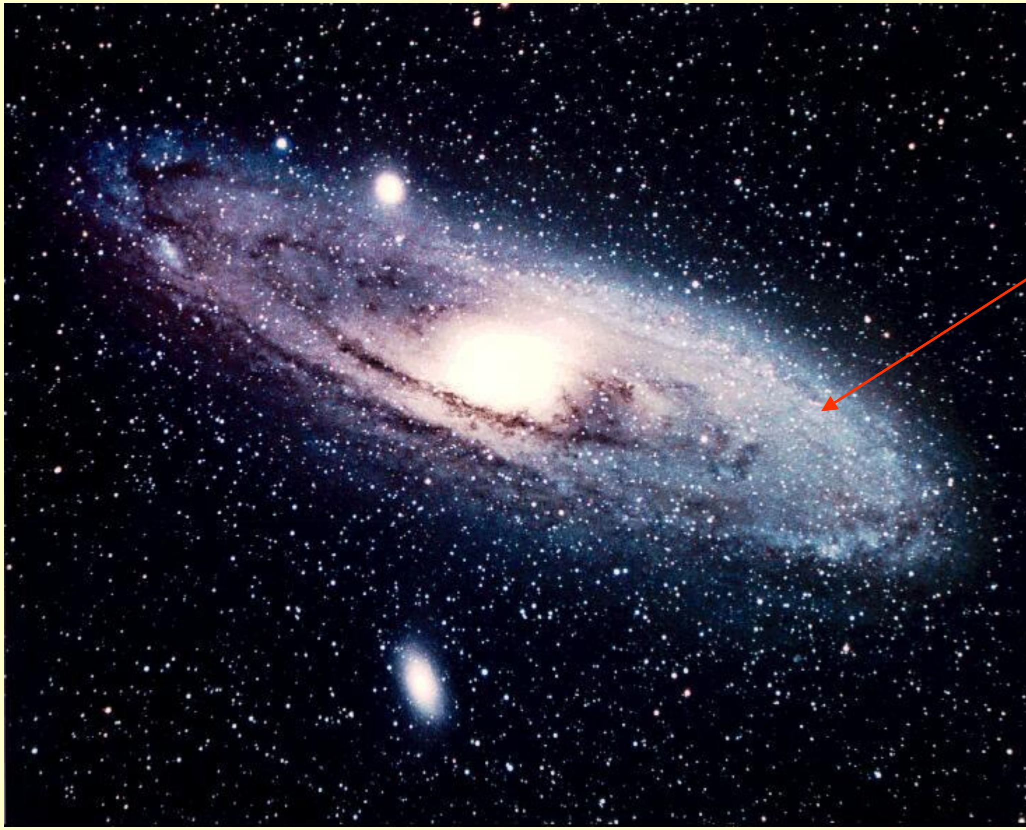
- Can the interactions be unified at larger energy?
- How can gravity be incorporated ?
- Is our world supersymmetric ?
- ….

3. Flavour: or the generation problem

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



Problems at a larger scale



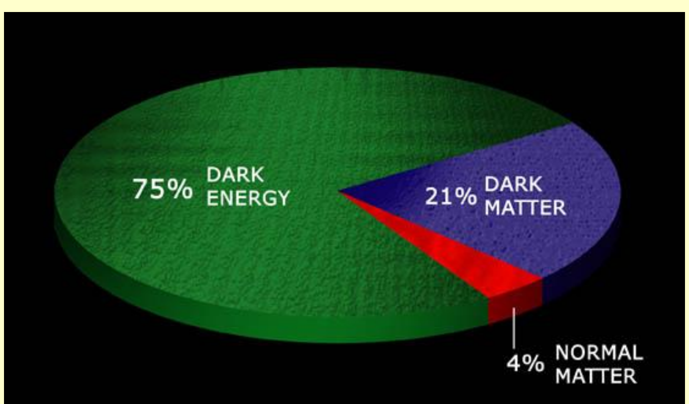
We are here

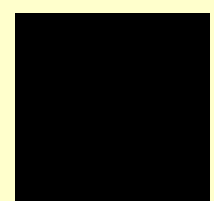
Surrounded by

- Mass
  (planets, stars, ….,hydrogen gas)

- **Dark Matter**

- **Dark Energy**





- Supersymmetry
- Extra dimensions
- ….
- Composite quarks and leptons
- ....
- New gauge bosons
- Leptoquarks
- Little Higgs Models
- ….
- Invisibly decaying Higgs bosons

Answers to some of these questions are expected on the TeV energy scale

1. Mass

- Search for the Higgs boson

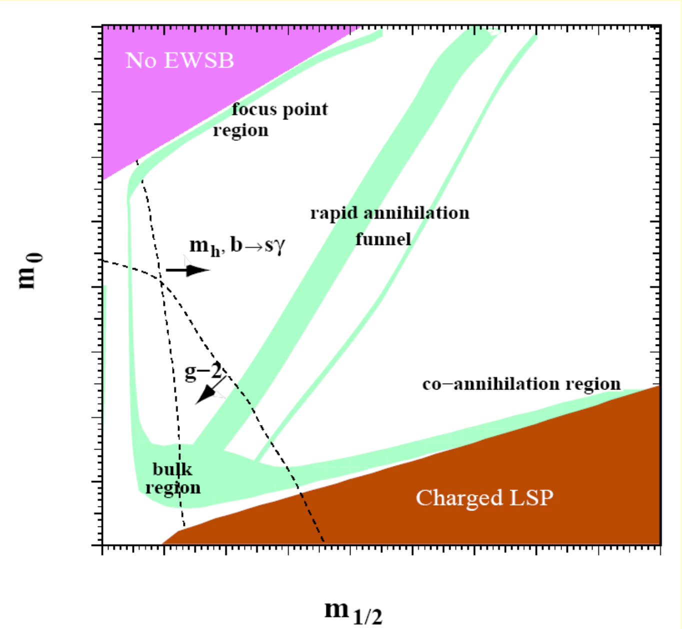
2. Unification

- 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

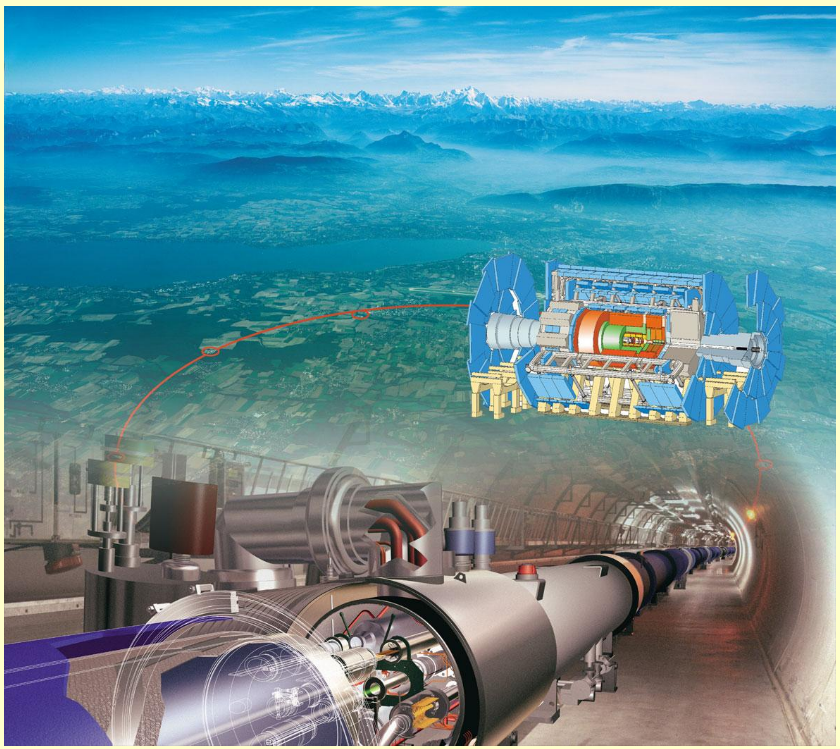
The link between SUSY and Dark Matter ?



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

New Accelerators

The Large Hadron Collider (LHC)
-The discovery machine-

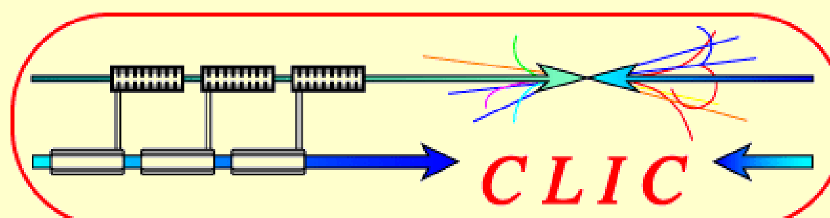


The International Linear Collider (ILC)
-The precision machine-

e^+e^- linear accelerator

In planning phase, > 2015/2020

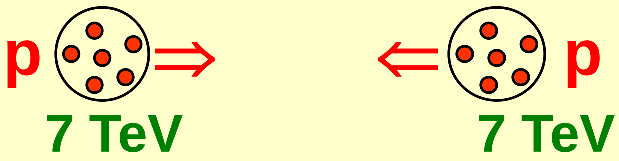
$\sqrt{s}$ = 0.5 – 1 TeV



$\sqrt{s}$ = 3 – 5 TeV

The Large Hadron Collider (LHC)

- Proton-proton accelerator in the LEP-tunnel at CERN



- Highest energies per collision so far in a laboratory

- Four planned experiments:

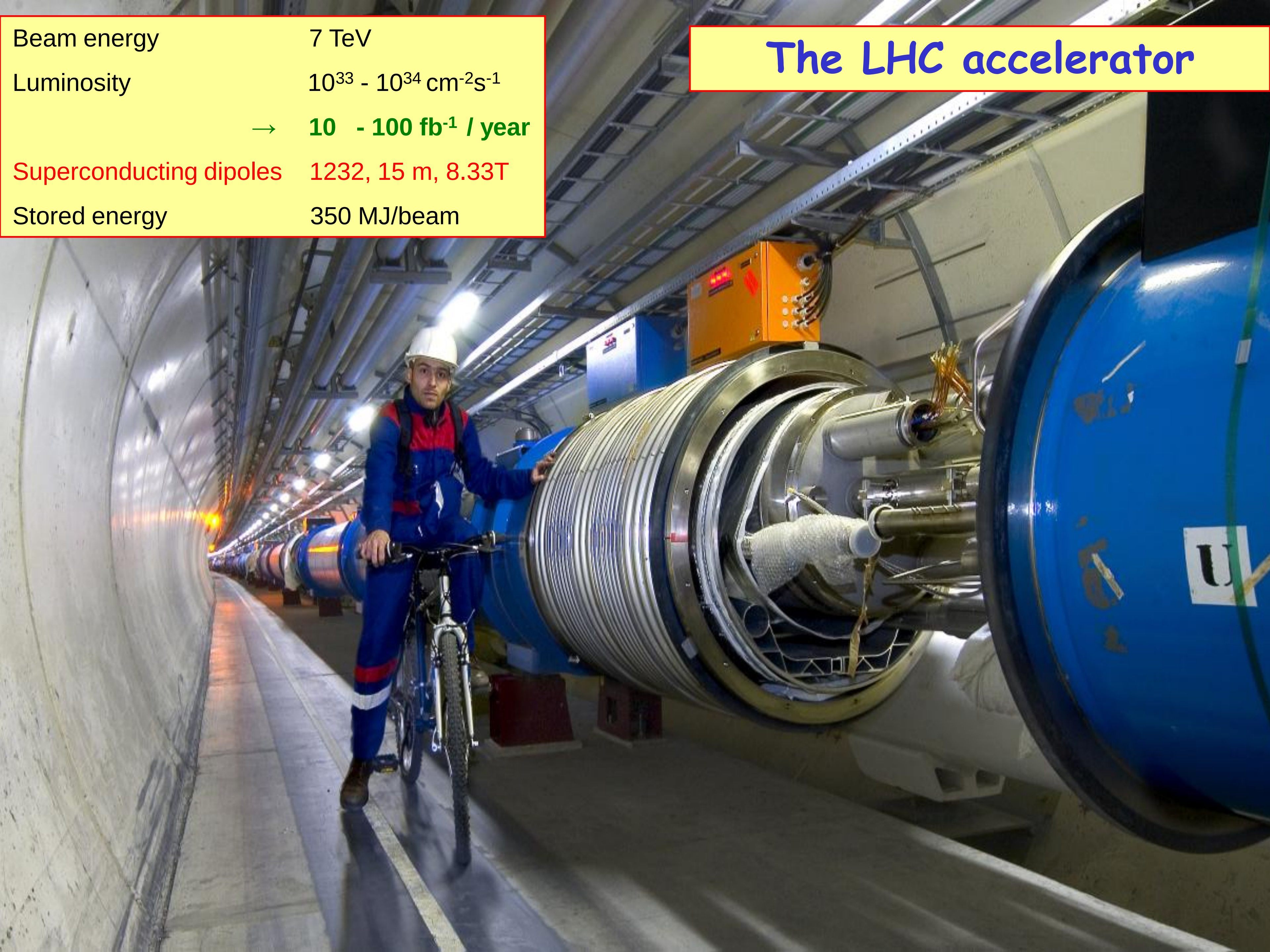
ATLAS, CMS	(pp physics)
LHC-B	(physics of b-quarks)
ALICE	(Pb-Pb collisions)

- Constructed in an international collaboration

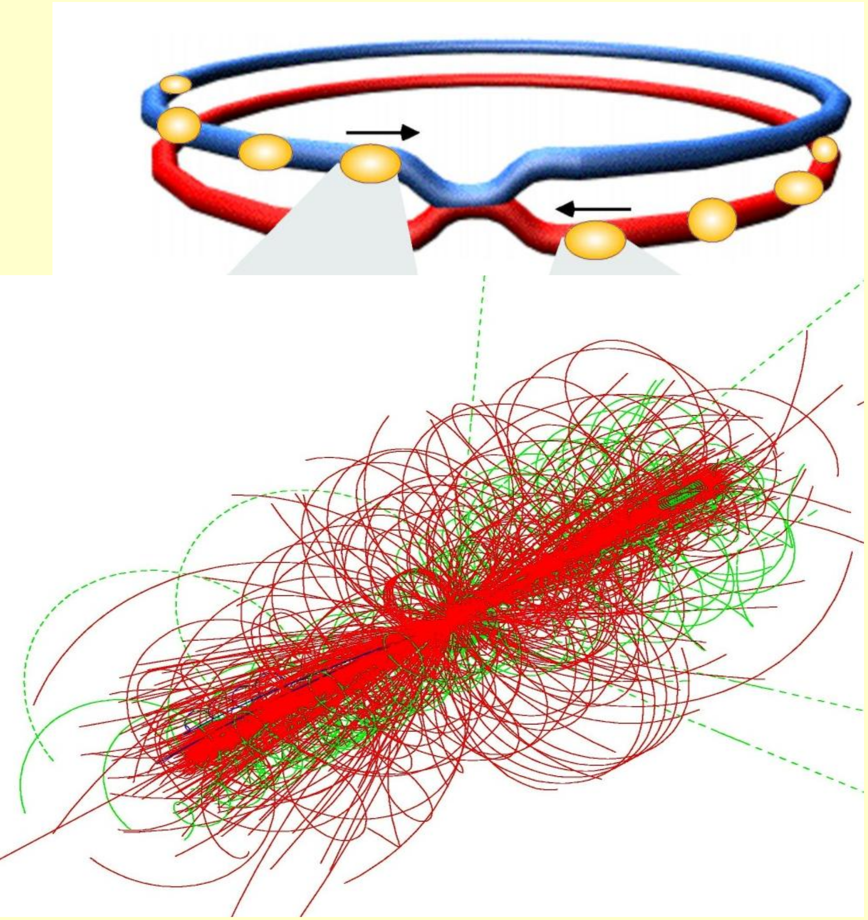
- Startup planned for Summer 2008

The LHC accelerator

Beam energy	7 TeV
Luminosity	10^{33} - 10^{34} $cm^{-2}s^{-1}$
→	**10 - 100 fb^{-1} / year**
Superconducting dipoles	1232, 15 m, 8.33T
Stored energy	350 MJ/beam



Proton proton collisions at the LHC



Proton – proton:

2835 x 2835 bunches
Separation: 7.5 m (25 ns)

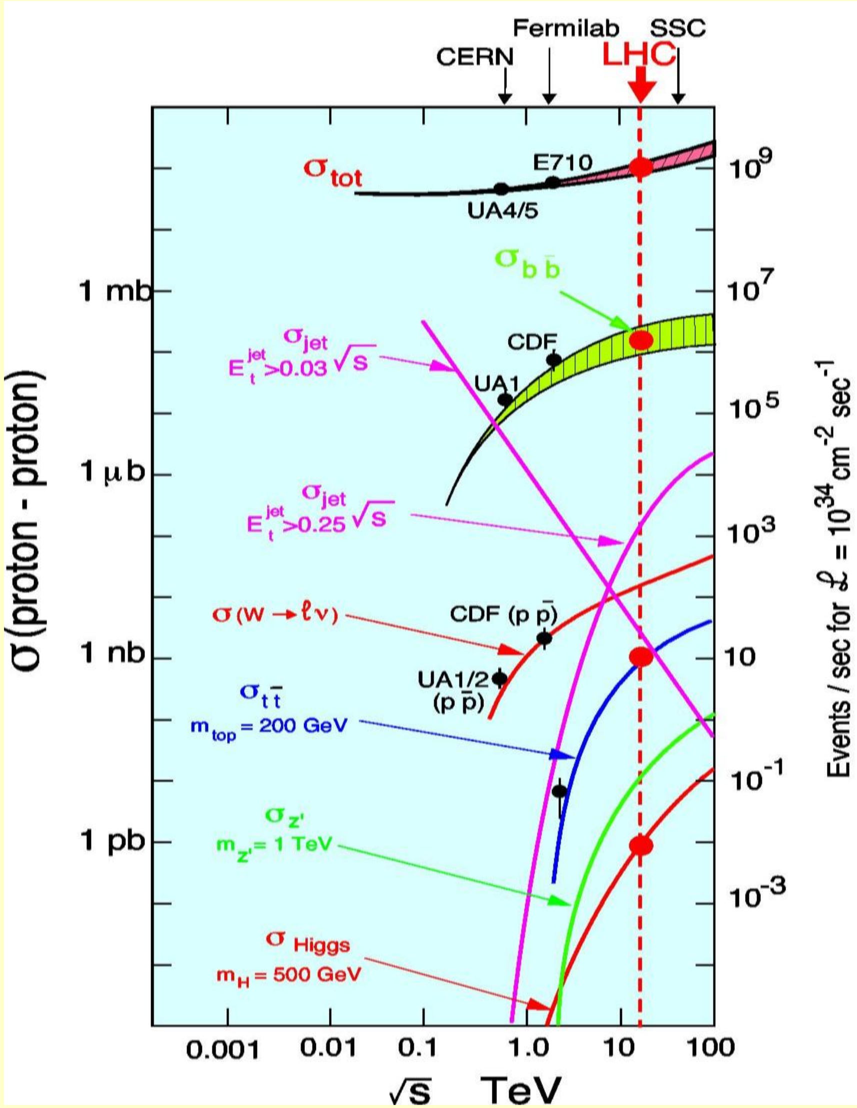
10^{11} protons / bunch
Crossing rate of p-bunches: 40 Mio. / s
Luminosity: L = 10^{34} cm^{-2} s^{-1}

~10^9 pp collisions / s
(superposition of 23 pp-interactions per bunch crossing: **pile-up**)

~1600 charges particles in the detector

⇒ high particle densities
high requirements for the detectors

Cross Sections and Production Rates

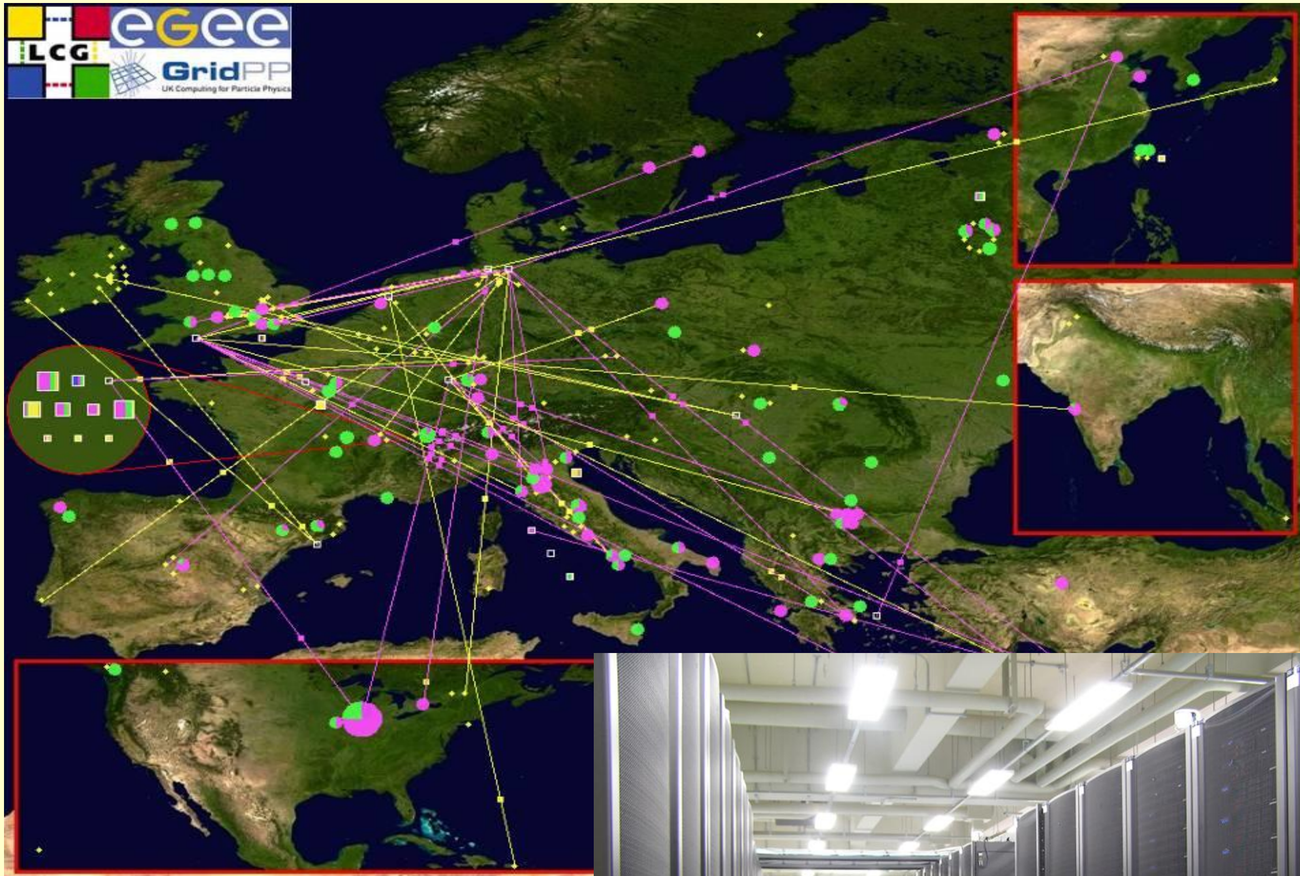


Rates for L = 10^{34} cm^{-2} s^{-1}: (LHC)

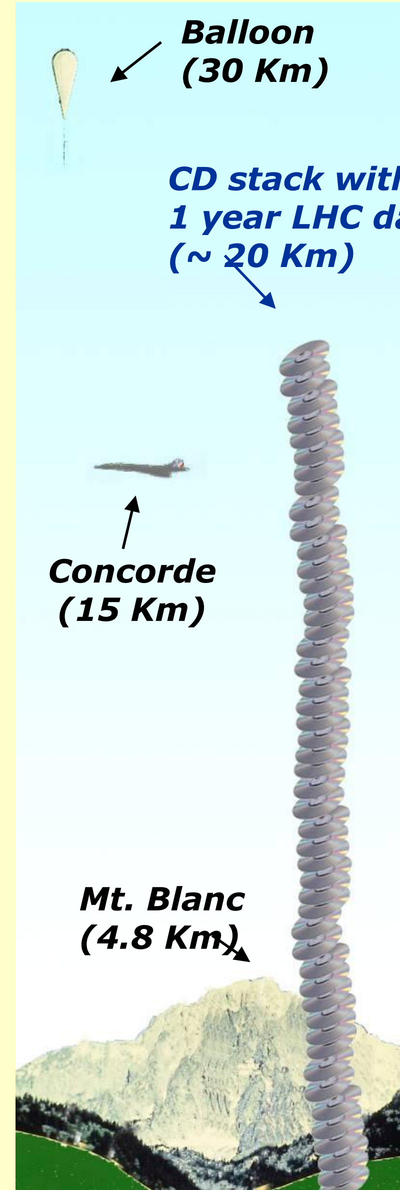
• Inelastic proton-proton reactions:	10^9 / s
• bb pairs • tt pairs	5 10^6 / s 8 / s
• W $\rightarrow$ e ν • Z $\rightarrow$ e e	150 / s 15 / s
• **Higgs (150 GeV)** • **Gluino, Squarks (1 TeV)**	**0.2 / s** **0.03 / s**

LHC is a factory for:
top-quarks, b-quarks, W, Z, ……. Higgs, ……

LHC data handling, GRID computing



Japanese Tier-2 center at Tokyo University

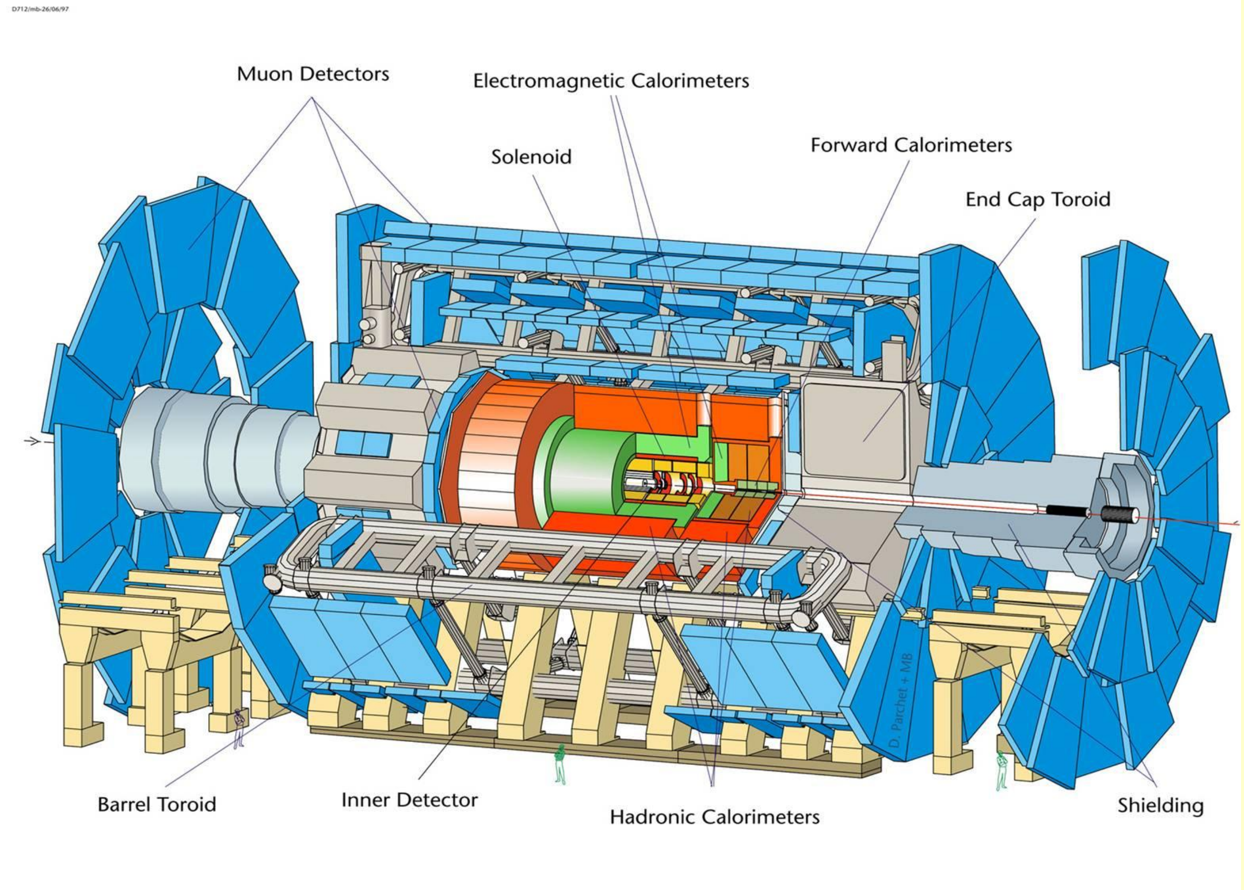


Trigger system selects ~200 “collisions” per sec.

LHC data volume per year: 10-15 Petabytes

= 10-15 $\cdot 10^{15}$ Byte

The ATLAS experiment



Diameter	25 m
Barrel toroid length	26 m
End-cap end-wall chamber span	46 m
Overall weight	7000 Tons

- Solenoidal magnetic field (2T) in the central region (momentum measurement)

  High resolution silicon detectors:
  - 6 Mio. channels (80 µm x 12 cm)
  - 100 Mio. channels (50 µm x 400 µm)

  space resolution: ~ 15 µm

- Energy measurement down to 1º to the beam line

- Independent muon spectrometer (supercond. toroid system)

ATLAS Collaboration

(October 2007)

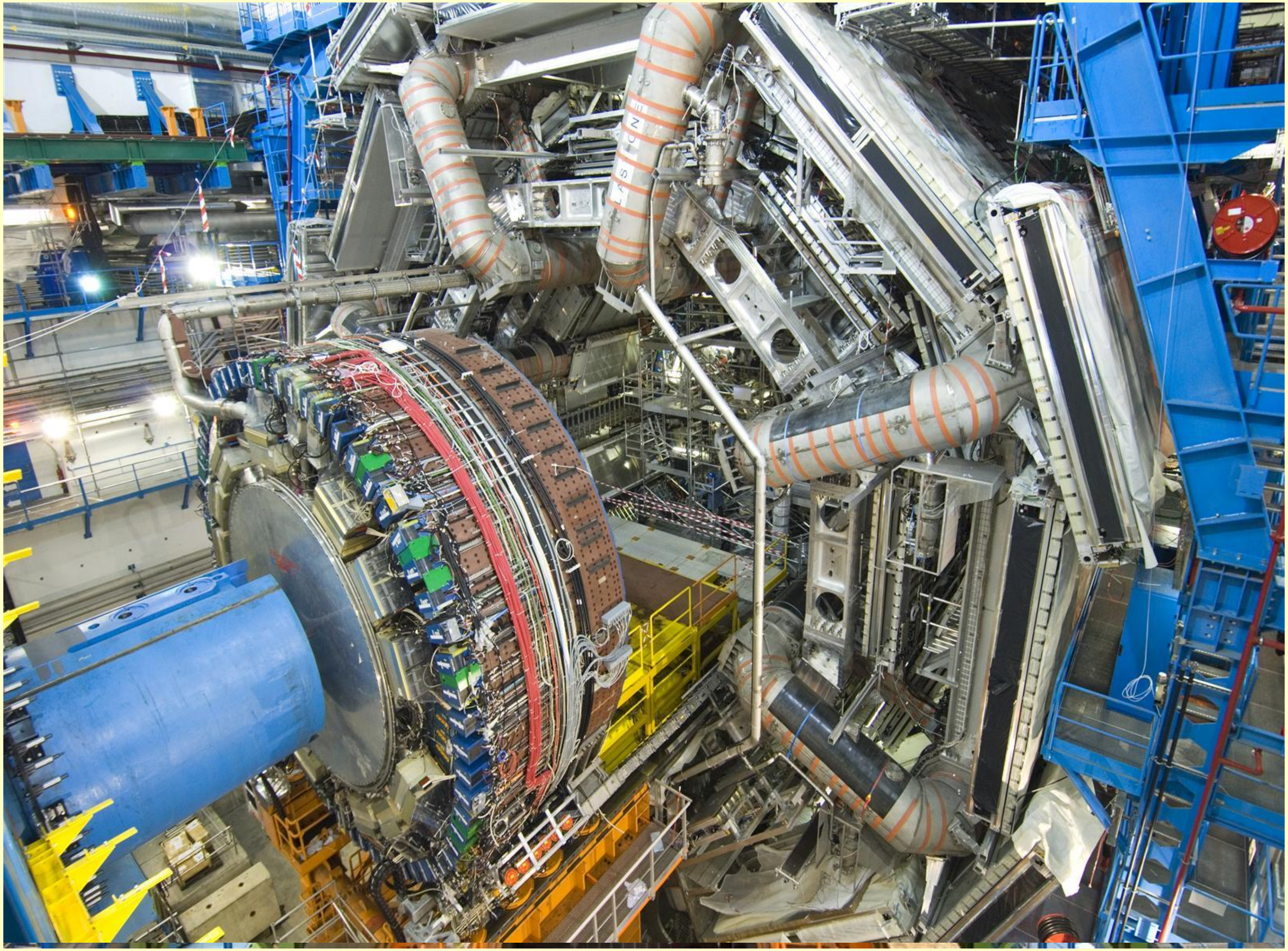
37 Countries

167 Institutes

2100 Physicists

Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berlin, Bern, Birmingham, Bogota, Bologna, Bonn, Boston, Brandeis, Bratislava/SAS Kosice, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, Carleton, Casablanca/Rabat, CERN, Chinese Cluster, Chicago, Chile, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, DESY, Dortmund, TU Dresden, JINR Dubna, Duke, Frascati, Freiburg, Geneva, Genoa, Gießen, Glasgow, Göttingen, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima, Hiroshima IT, Indiana, Innsbruck, Iowa SU, Irvine UC, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, Mannheim, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, LMU München, MPI München, Nagasaki IAS, Nagoya, Naples, New Mexico, New York, Nijmegen, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII,Pavia, Pennsylvania, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Regina, Ritsumeikan, UFRJ Rio de Janeiro, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC, Southern Methodist Dallas, NPI Petersburg, Stockholm, KTH Stockholm, Stony Brook, Sydney, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Toronto, TRIUMF, Tsukuba, Tufts, Udine/ICTP, Uppsala, Urbana UI, Valencia, UBC Vancouver, Victoria, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Yale, Yerevan

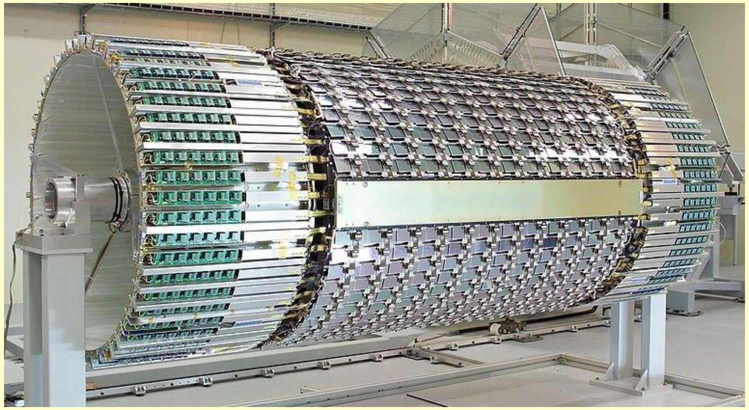
ATLAS Installation



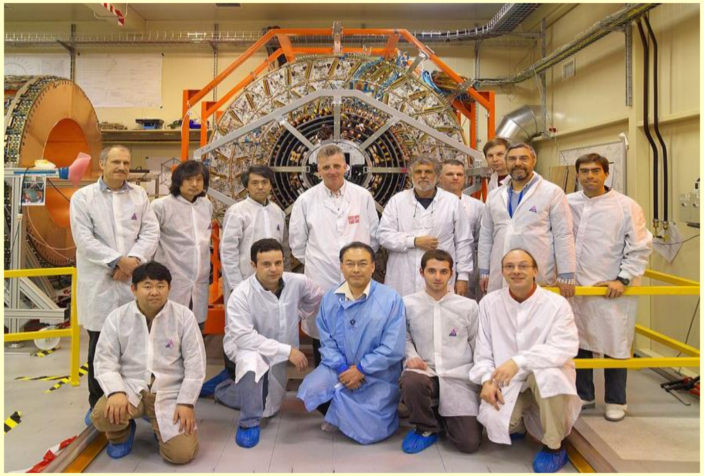
October 2006

Significant Contributions of the Japanese groups to the ATLAS detector

Superconducting Solenoid, KEK



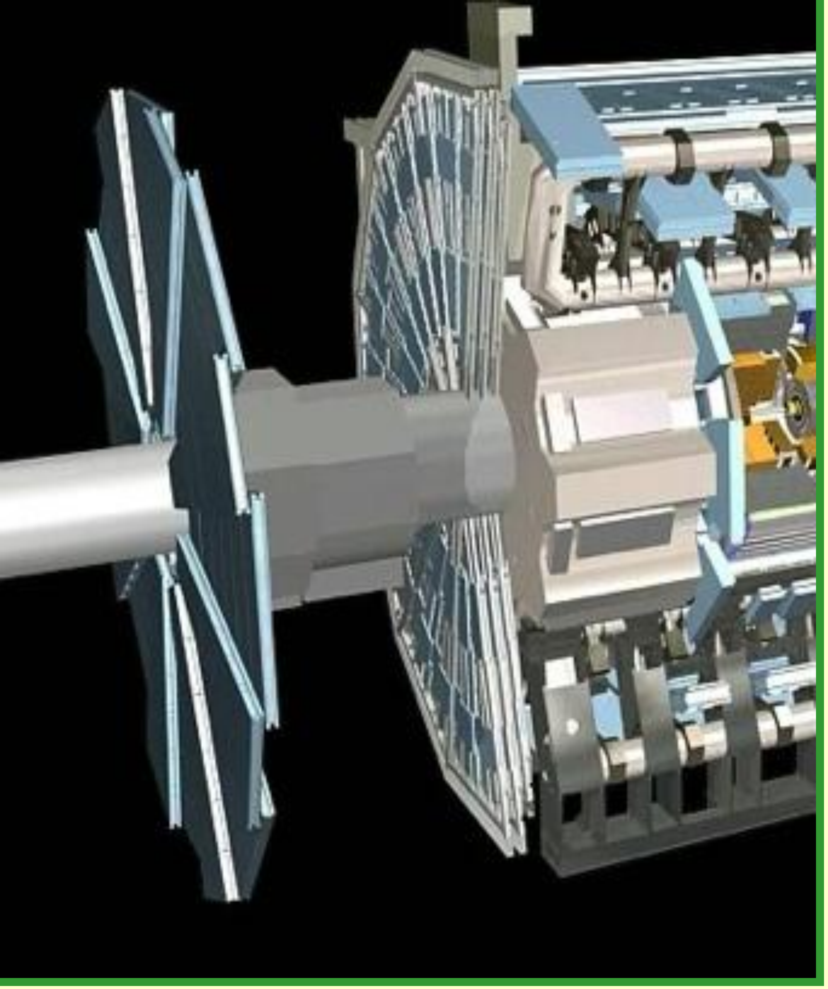
6000 sensors and 980 modules of the barrel Semiconductor tracking system
KEK, Tsukuba, Okayama, Hiroshima, Kyoto Edu.



Integration of the system at CERN

Significant contribution from Japanese industry:

Hamamatsu Phonics, Kawasaki Heavy Industries, Toshiba, Kuraray, Arisawa, Fujikura, …

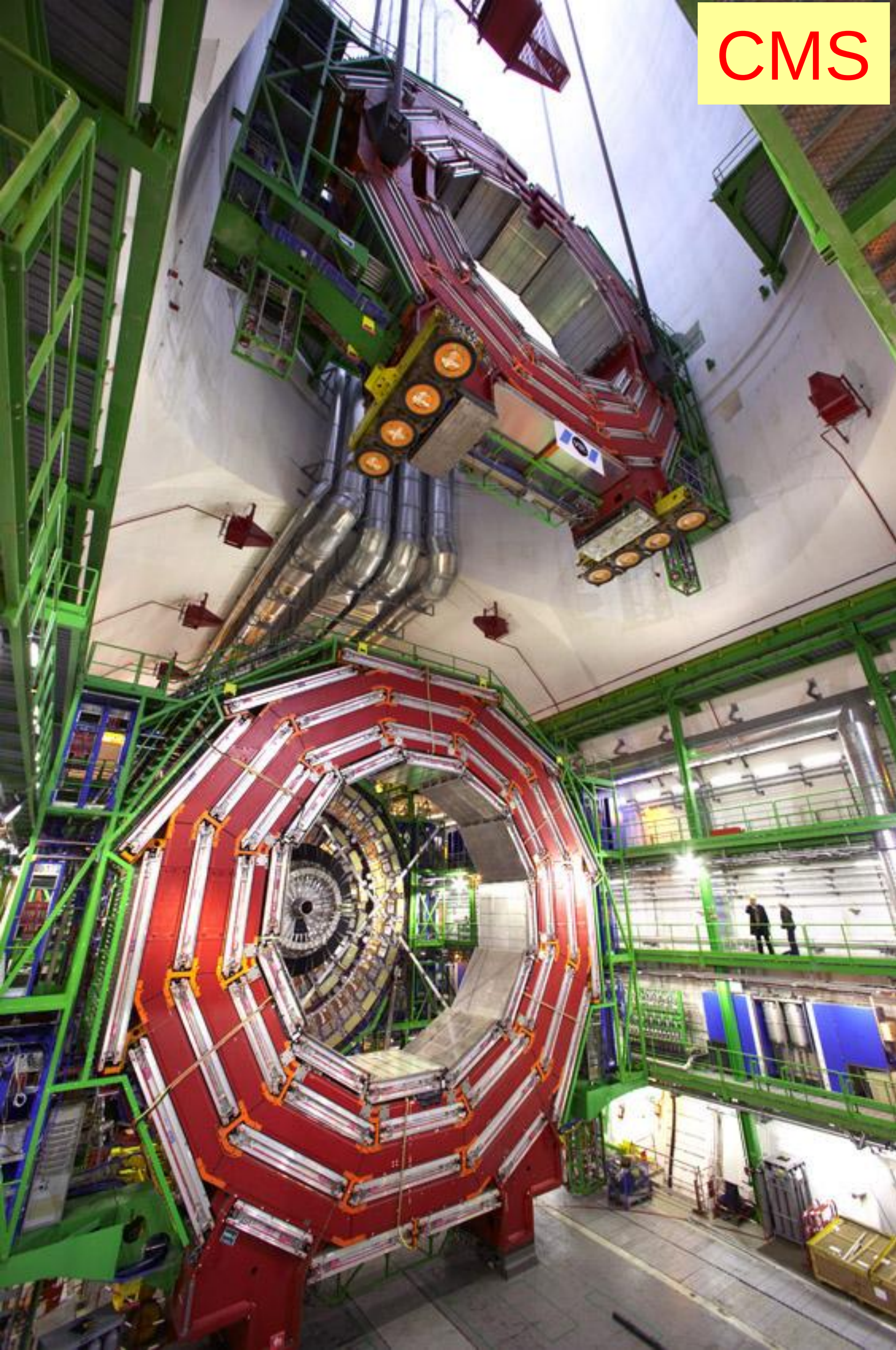


Muon detector system
In the forward region

KEK, Tokyo ICEPP, Kobe, Nagoya,
Shinshu, Tokyo MU, Osaka

~ 30% of TGC chamber construction
> 90% of electronics
+ installation and commissioning

CMS



First goals …. (2008/09) (?)

- Understand and calibrate detector and trigger

  in situ using well-known physics samples

e.g. - $Z \rightarrow ee, \mu\mu$ tracker, calorimeter, muon chambers calibration and alignment

- $tt \rightarrow b\ell\nu$ bjj 10^4 events / day after cuts
  → jet scale from $W \rightarrow jj$
  → b-tag performance

$\Rightarrow$ **defines t_0 !!**

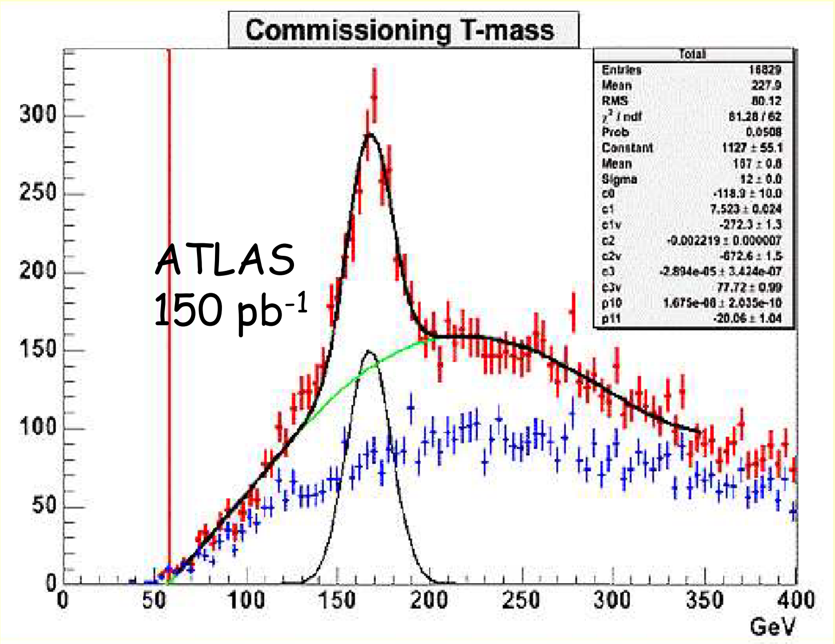
Early Physics: Top quark without b-tag

Extremely simple selection:

- Use $t\bar{t} \rightarrow Wb\, Wb \rightarrow \ell\nu b\, qqb$ decays
- 1 isolated lepton (p_T>20 GeV)
- Exactly 4 jets ($p_{T>}$40 GeV)
- no kinematic fit, no b-tagging (!)
- invariant mass of 3 highest p_T jets

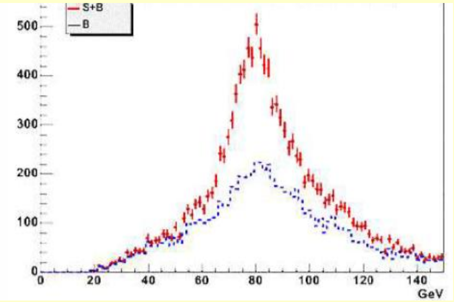
Signal visible after few days at 10^{33}

- stat. error on m_{top} ~ 400 MeV after one week
- Δm_{top} = 7 GeV (assuming 10% b-jet-scale error)
- use for jet energy calibration
- ideal to commission b-tagging!
- study most important BG to searches



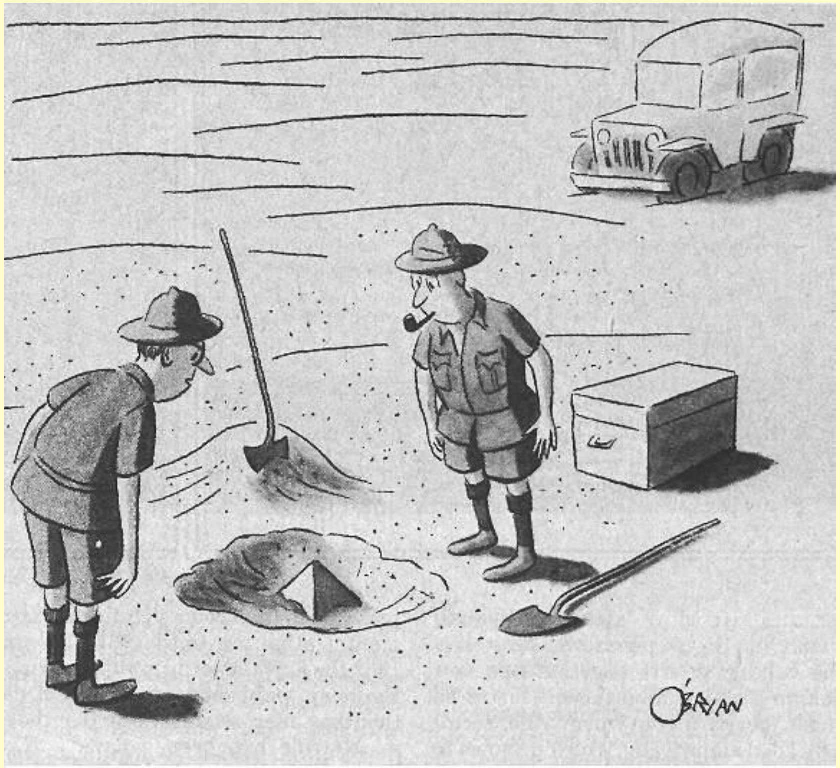
$M(j_1 j_2 j_3)$

also: hadronic W-mass peak (→jet E-scale)



......and in parallel.....

....prepare the road for discovery



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

- Understand basic SM physics at $\sqrt{s}$ = 14 TeV

  → first checks of Monte Carlos
  (hopefully well understood at Tevatron)

  e.g. measure cross-sections for W, Z, tt, QCD jets, and events features (P_T spectra etc.)

  (tt and W/Z+ jets are omnipresent in Searches for New Physics)

What can be done with the first 10-30 fb^{-1} ?

The Search for

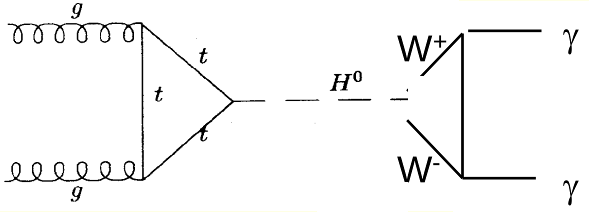
The Higgs boson

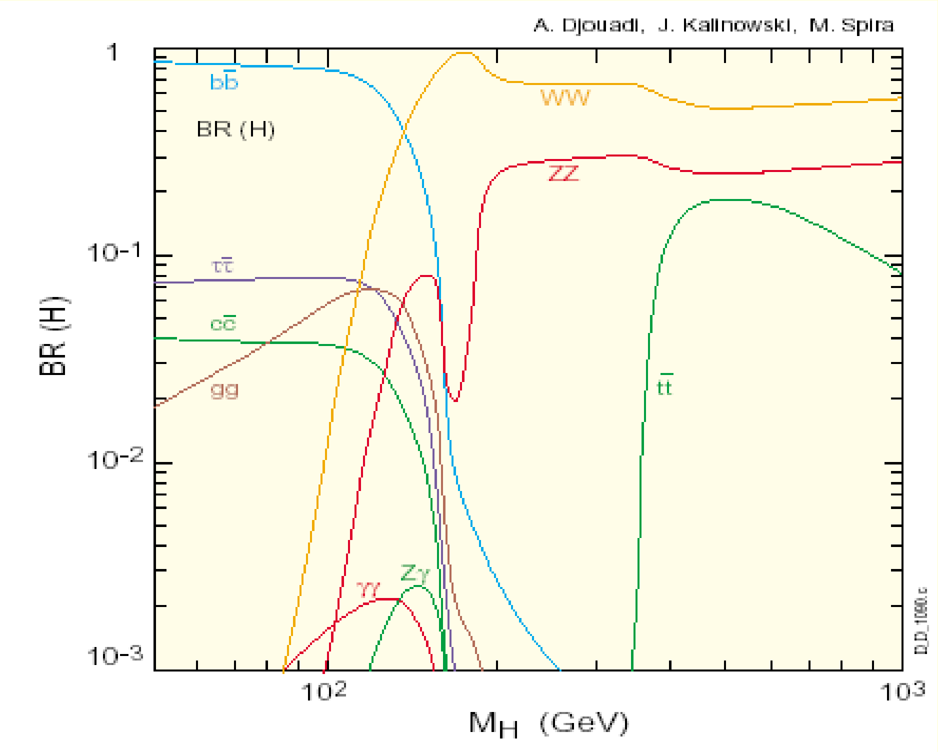
Decays of the Higgs Boson

- Decay characteristics are known, as soon as the mass is known:

H → W^+, Z, t, b, c, τ^+,..........., g, γ

H → W^-, Z, t, b, c, τ^- ,.........., g, γ





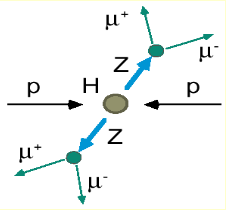
Important Decays at Hadron colliders:

Final states with leptons or photons
(via H → WW, ZZ or H → γγ)

The dominant **bb decays** in the low mass Region are very difficult to detect (due to the large background from jet Production via QCD processes)

Only possible in associated production of a Higgs boson with other particles, e.g. ttH

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



Signal: σ BR = 5.7 fb (m_H = 100 GeV)

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

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

Background: Top production

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

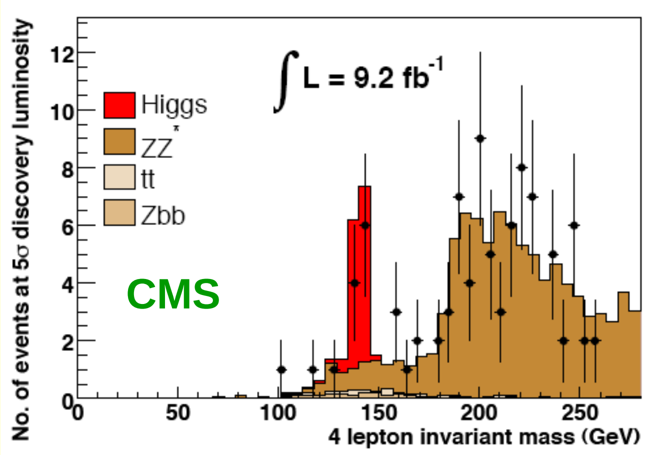
σ BR ≈ 1300 fb

Associated production Z bb

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

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

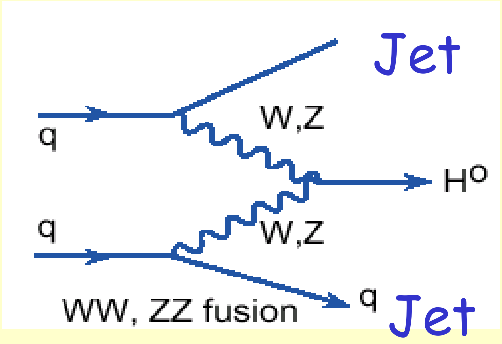
Dominant background after isolation: ZZ continuum



Discovery potential over a large mass range: ~130 < m_H < 600 GeV/c^2

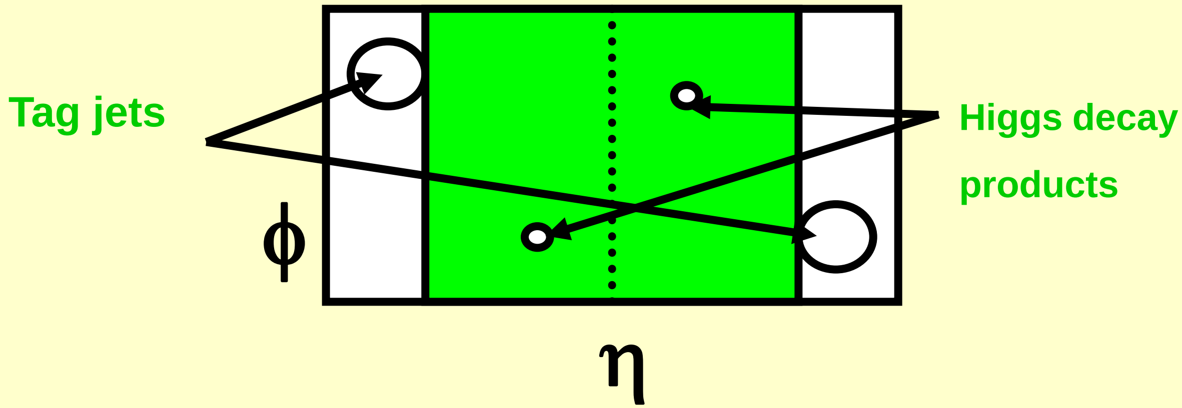
More difficult channels can also be used: Vector Boson Fusion qq H

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



Distinctive Signature of:

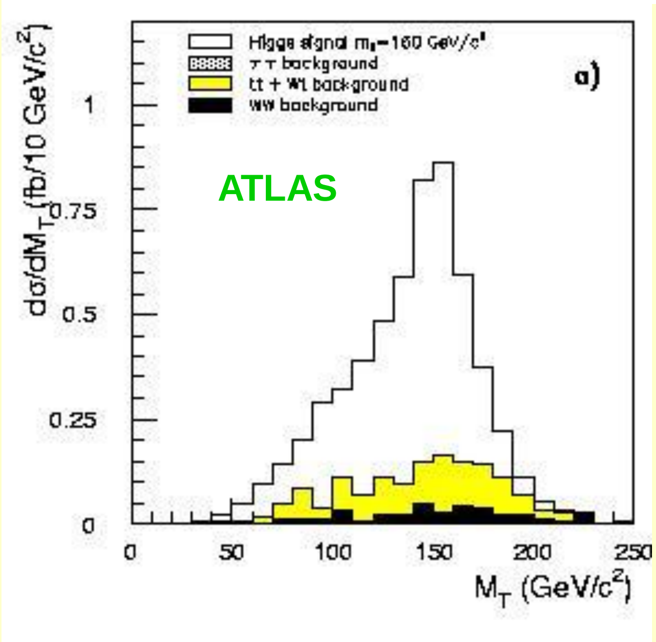
- **two high P_T forward tag jets**
- **little jet activity in the central region**
  $\Rightarrow$ **central jet Veto**



Two search channels at the LHC:

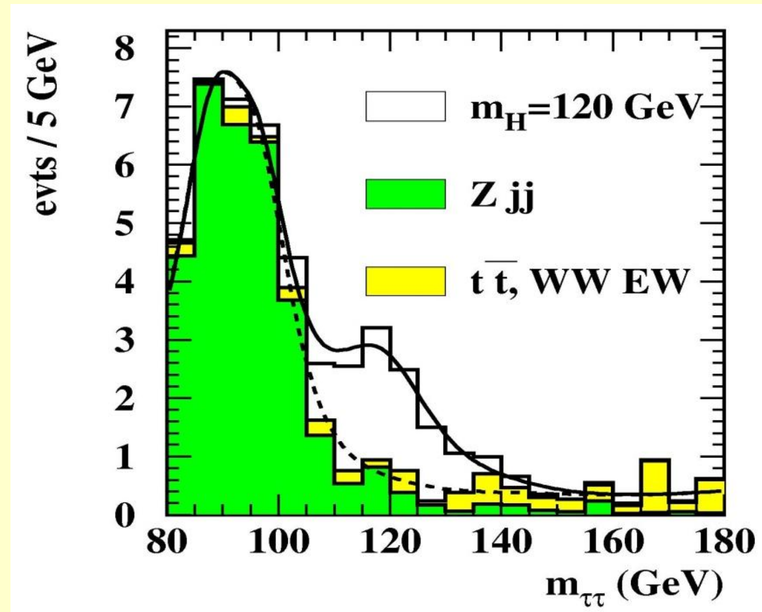
qq H → qq W W*
→ qq ℓν ℓν

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

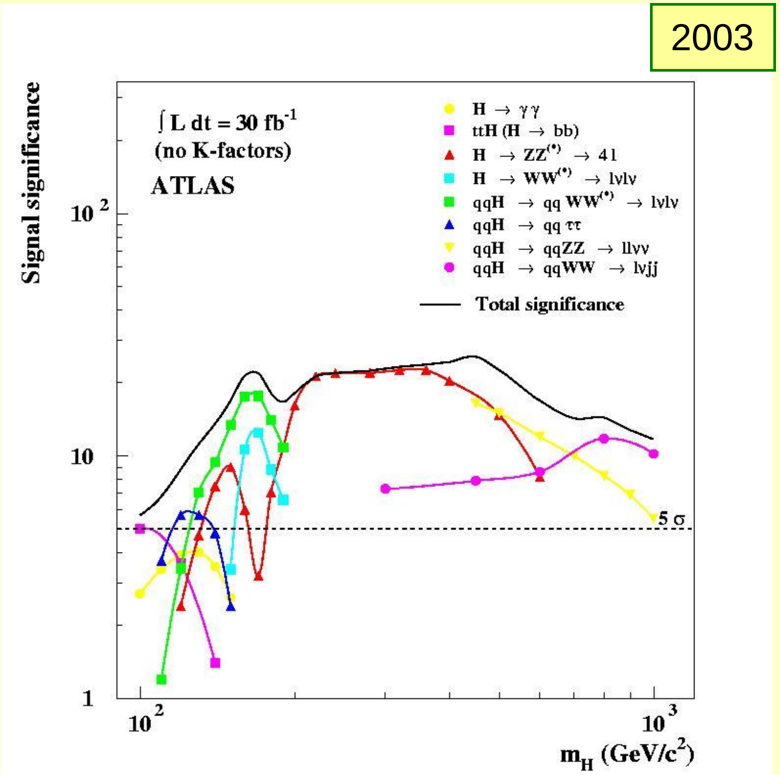


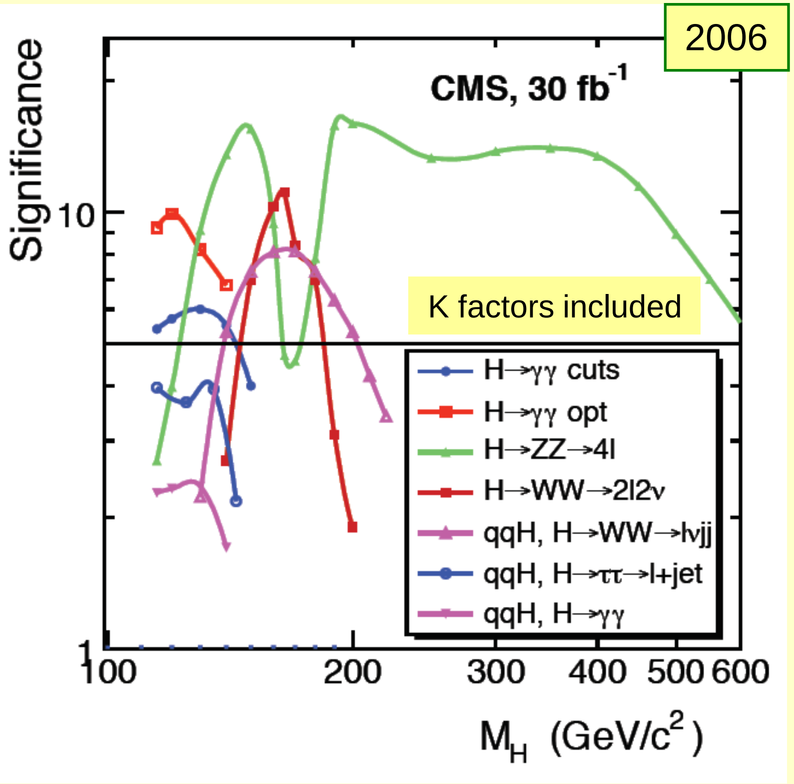
Transverse mass distribution:
clear excess above Standard Model background

qq H → qq τ τ
→ qq l ν ν l ν ν
→ qq l ν ν h ν



LHC discovery potential for 30 fb^{-1}





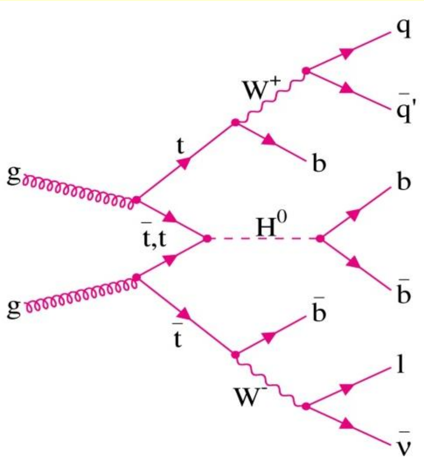
- Full mass range can already be covered after a few years at low luminosity
- Several channels available over a large range of masses

  Vector boson fusion channels play an important role at low mass !

Important changes w.r.t. previous studies:

- **H → γγ** sensitivity of ATLAS and CMS comparable
- **ttH → tt bb** disappeared in CMS study (updated (ME) background estimates, under study in ATLAS)

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

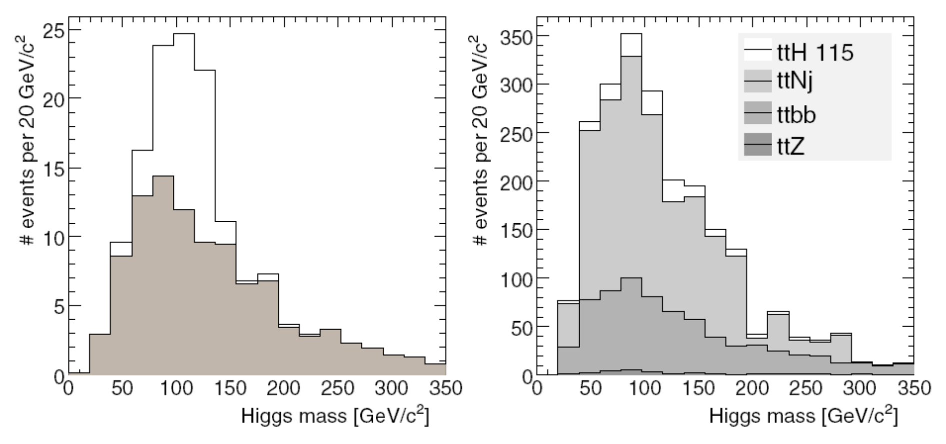


Complex final states: H→ bb, t → bjj, t → bℓν
t → bℓν, t → bℓν
t → bjj, t → bjj

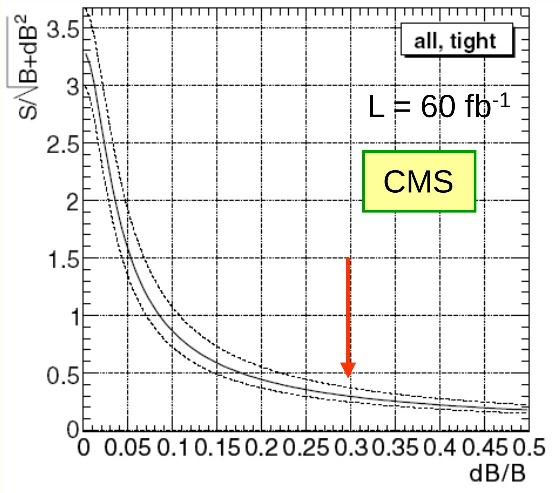
Main backgrounds:
- combinatorial background from signal (4b in final state)
- ttjj, ttbb, ttZ,…
- Wjjjjjj, WWbbjj, etc. (excellent b-tag performance required)

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

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



Signal events only …. backgrounds added

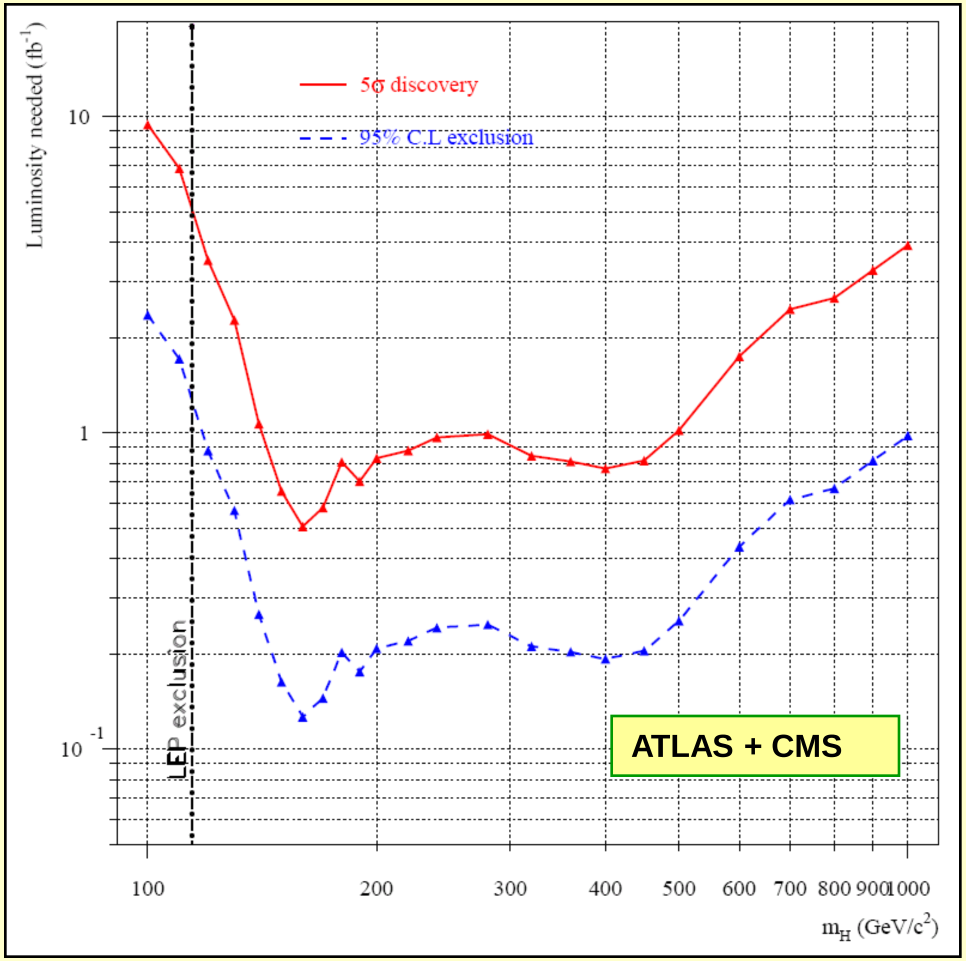


Signal significance as function of background uncertainty

ATLAS study ongoing, results expected in ~ 2 months

Combined ATLAS + CMS discovery potential

- Luminosity required for a 5σ discovery or a 95% CL exclusion -



J.J. Blaising et al, Eur. Strategy workshop

~ 5 fb^{-1} needed to achieve a 5σ discovery

(well understood and calibrated detector)

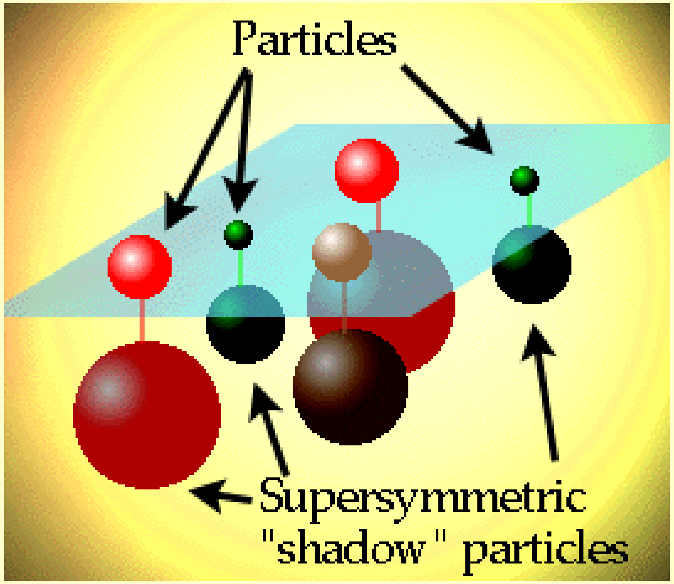
~ < 1 fb^{-1} needed to set a 95% CL limit

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

comments:

- present curves assume the old ttH, H→ bb performance
- systematic uncertainties assumed to be luminosity dependent
  (no simple scaling, σ ~ √L, possible)

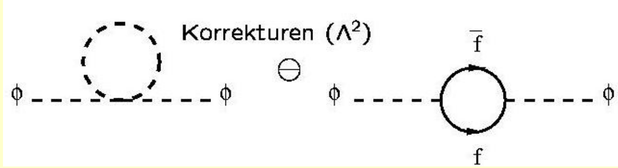
The Search for



Supersymmetry

Why do we like SUSY so much?

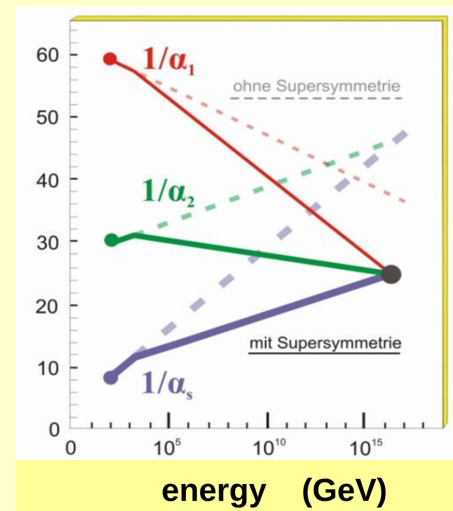
1. Quadratically divergent quantum corrections to the Higgs boson mass are avoided



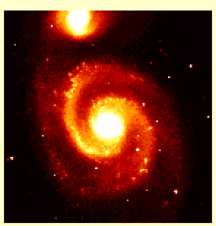
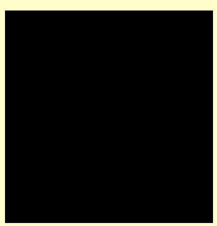
$$\Delta m_H = f(m_B^2 - m_f^2)$$ → m_{SUSY} ~ 1 TeV

(Hierarchy or naturalness problem)

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



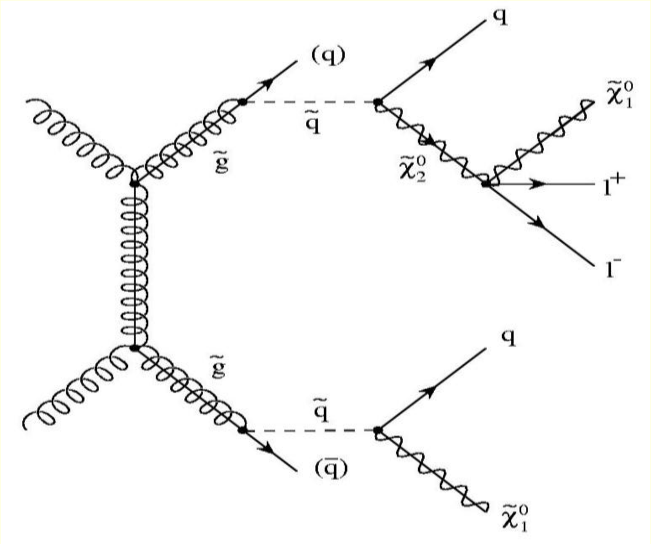
3. SUSY provides a candidate for dark matter,

The lightest SUSY particle (LSP)

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

Search for Supersymmetry at the LHC



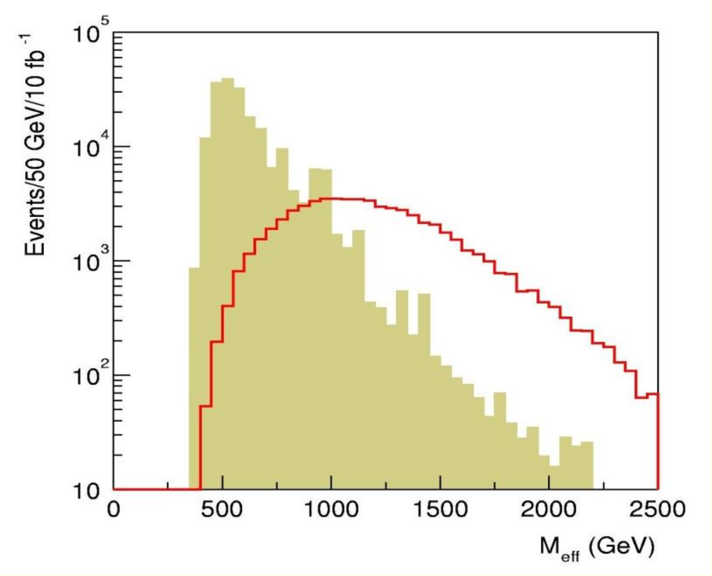
$\Rightarrow$ combination of
jets, leptons, E_T^{miss}

1. Step: search for deviations from the Standard Model

2. Step: can the parameter of the model be determined ?

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
$\tan\beta$ = 10, $A_0 = 0$, $\mu > 0$

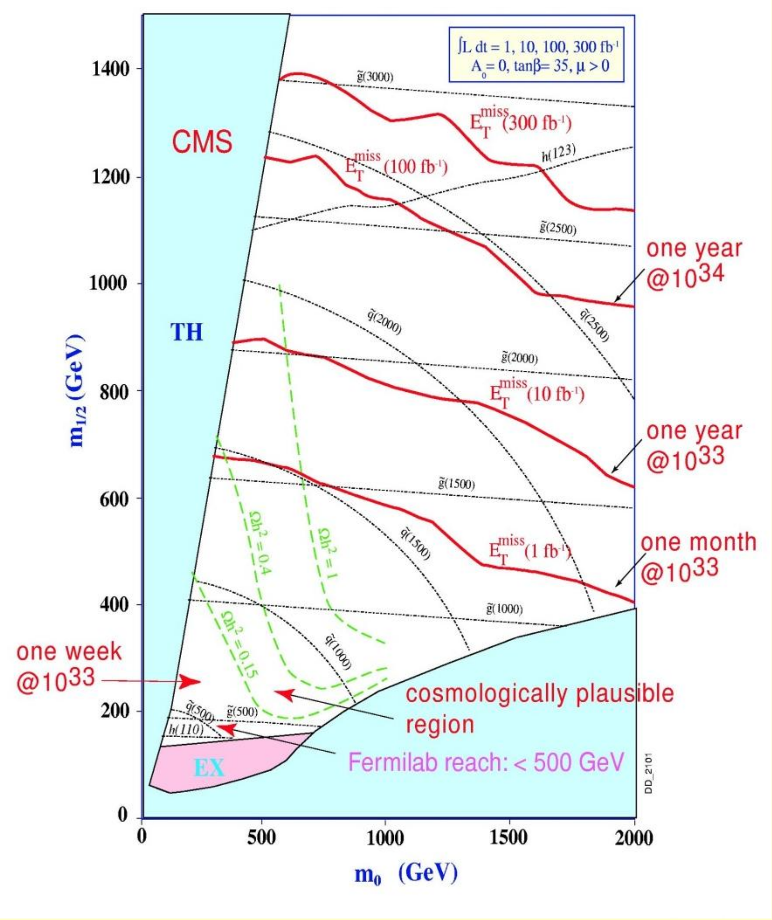
LHC reach for Squark- and Gluino masses:

1 fb^{-1}	$\Rightarrow$	M ~ 1500 GeV
10 fb^{-1}	$\Rightarrow$	M ~ 1900 GeV
100 fb^{-1}	$\Rightarrow$	M ~ 2500 GeV

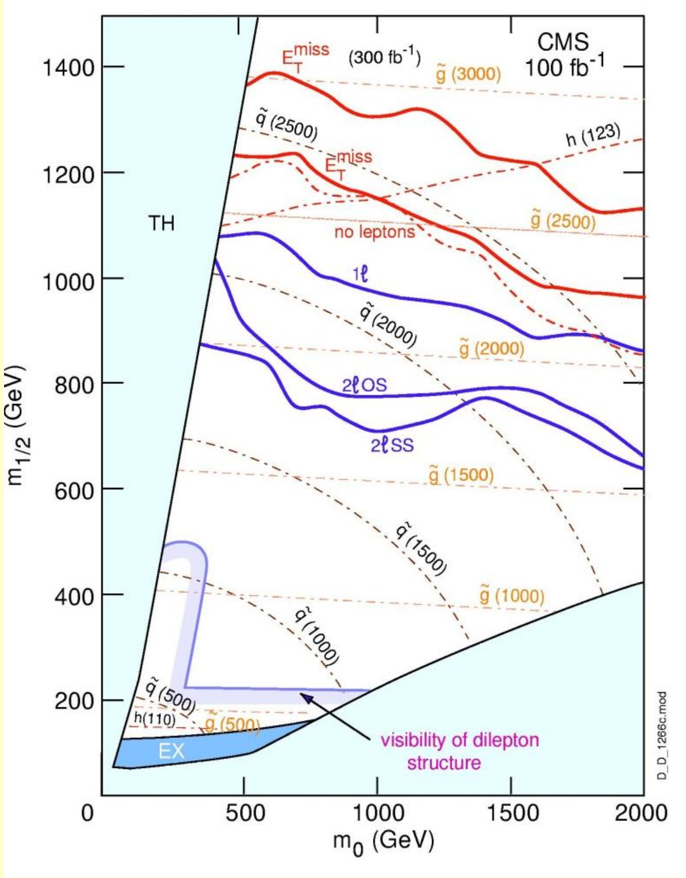
Deviations from the Standard Model due to SUSY at the TeV scale can be detected fast !

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**



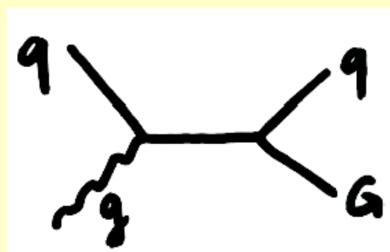
Expect multiple signatures for TeV-scale SUSY

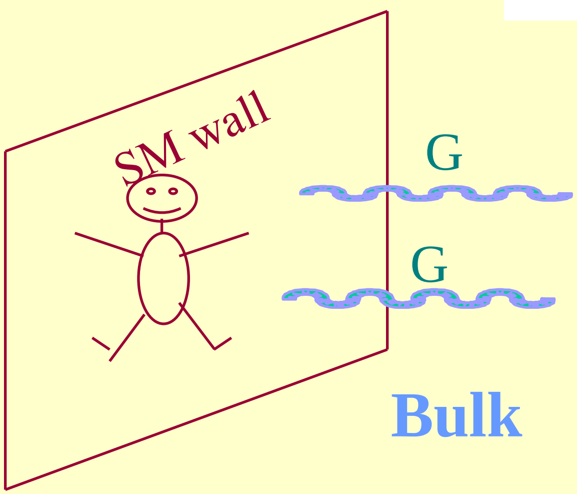
How can the underlying theoretical model be identified ?

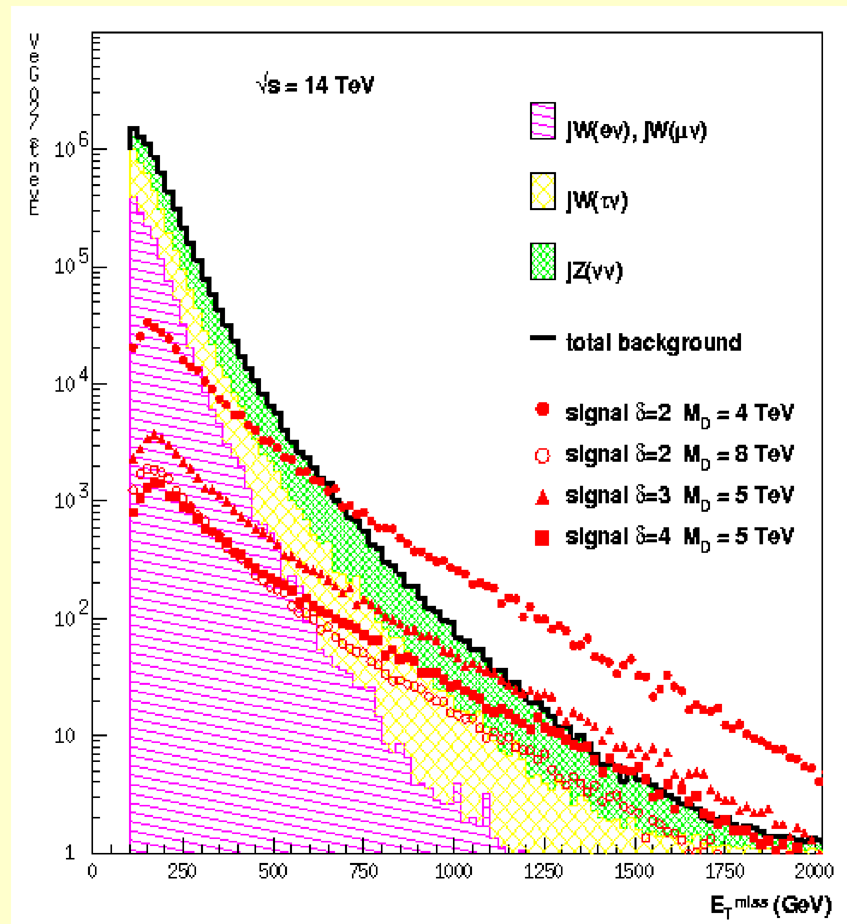
- Not easy !!
- Other possible scenarios for Physics Beyond the Standard Model could lead to similar final state signatures
  e.g. search for direct graviton production in extra dimension models

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

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

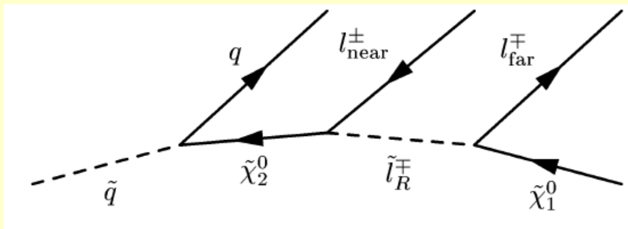






LHC Strategy: End point spectra of cascade decays

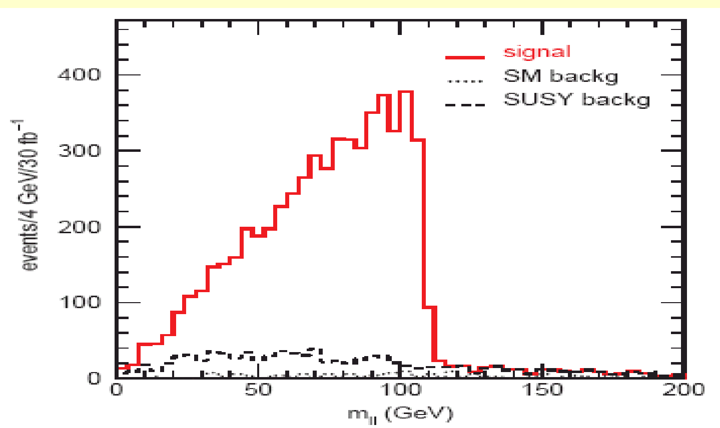
Example: $\tilde{q} \to q\tilde{\chi}_2^0 \to q\tilde{\ell}^{\pm}\ell^{\mp} \to q\ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$



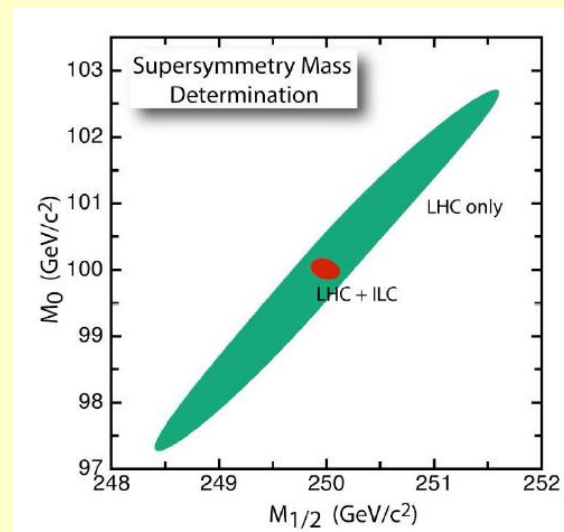
$$M_{\ell^+\ell^-}^{max} = \frac{\sqrt{(m_{\chi_2^0}^2 - m_{\tilde{\ell}}^2)(m_{\tilde{\ell}}^2 - m_{\chi_1^0}^2)}}{m_{\tilde{\ell}}}$$

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

Results for point 01:



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



L = 300 fb^{-1}

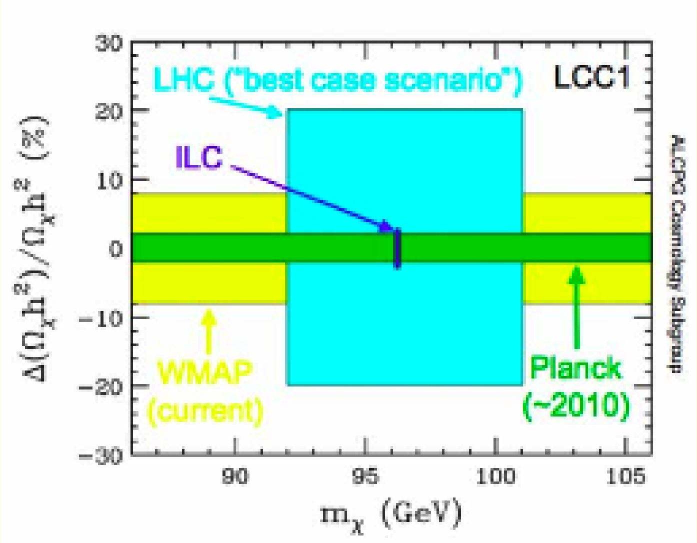
Strategy in SUSY Searches at the LHC:

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

$\Rightarrow$ Parameters of the SUSY model

Complex: requires close cooperation between experimentalists and theorists !

$\Rightarrow$ Predict dark matter relic density, check consistency with other measurements



Models other than SUGRA

GMSB:

- LSP is light gravitino
- Phenomenology depends on nature and lifetime of the NLSP
- Generally longer decay chains, e.g. $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^{\pm}\ell^{\mp} \rightarrow \tilde{\chi}_1^0\ell^+\ell^- \rightarrow \tilde{G}\gamma\ell^+\ell^-$

- $\Rightarrow$ models with prompt NLSP decays give add handles and hence are easier than SUGRA

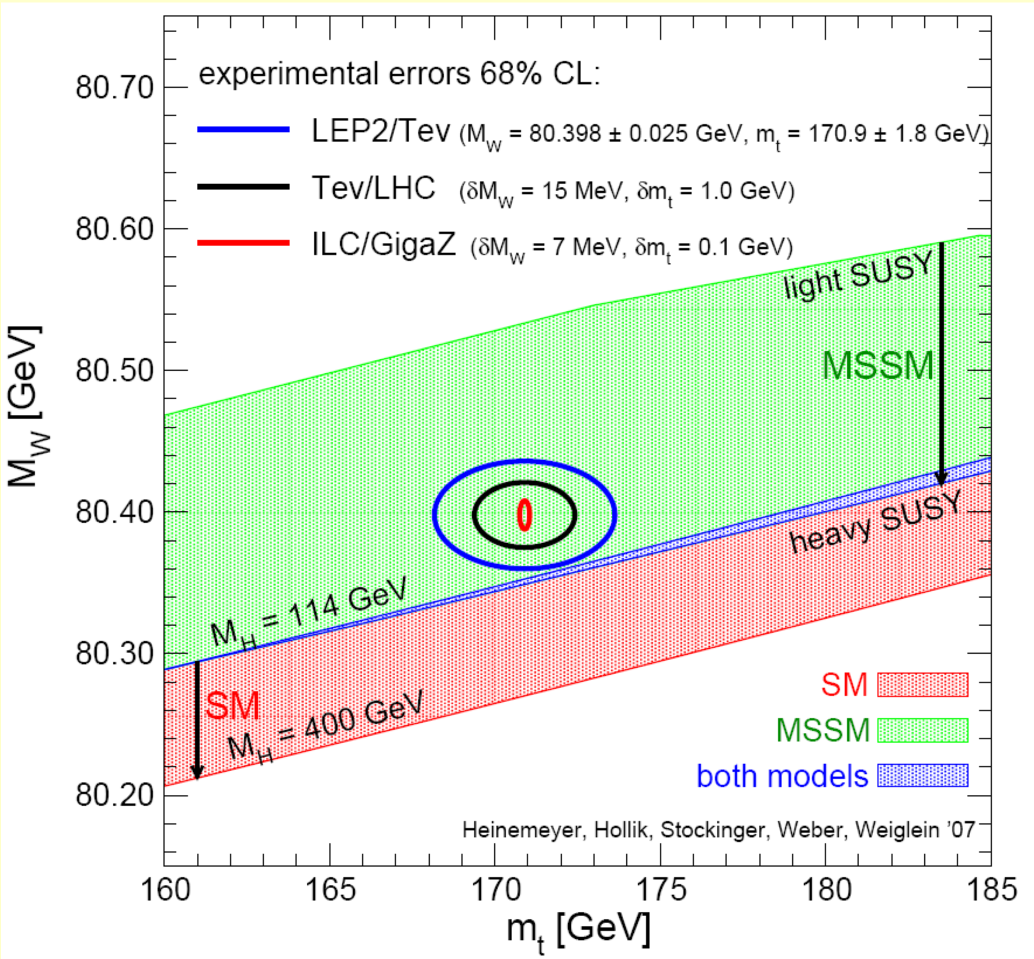
- NLSP lifetime can be measured:
  - For $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma,$ use Dalitz decays (short lifetime) or search for non-pointing photons
  - Quasi stable sleptons: muon system provides excellent „Time of Flight" system

RPV :

- R-violation via $\chi^0_1 \rightarrow \ell\ell\nu$ or $qq\ell$, $qq\nu$ gives additional leptons and/or E_T^{miss}

- R-violation via $\chi^0_1 \rightarrow$ cds is probably the hardest case; (c-tagging, uncertainties on QCD N-jet background)

Final test: Precision measurements at the LHC / ILC



<u>Expected precision</u>:

LHC (10 fb^{-1}):
$\delta\, m_W$ = < $\pm$ 15 MeV/c^2
$\delta\, m_t$ = < $\pm$1.0 GeV/c^2

Summary / Conclusions

- The *Large Hadron Collider* is the largest and most ambitious project realized in particle physics so far (technology, complexity, resources, collaboration, ……….)

- With its startup in 2008, Particle Physics is about to enter a new era

- Questions of
  - Existence of Higgs particles,
  - Low energy supersymmetry or
  - many other phenomena beyond the Standard Model at the TeV scale

  can be answered.

The answers will most likely modify our understanding of Nature
…..
and give guidance to theory and future experiments

Der Higgs Mechanismus, eine Analogie:

Prof. D. Miller
UC London

Higgs-Hintergrundfeld
erfüllt den Raum

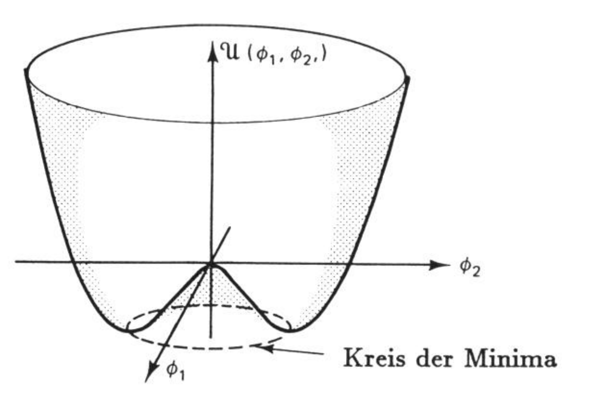
Ein Teilchen
im Higgs-Feld...

... Widerstand gegen
Bewegung ...
Trägheit $\leftrightarrow$ Masse

In the Standard Model of particle physics, the electroweak symmetry is broken (hidden) via the **Higgs mechanism**:

- Complex scalar field with potential

$$\mathcal{U}(\phi) = \mu^2(\phi^*\phi) + \lambda(\phi^*\phi)^2$$



$v = -\mu^2 / \lambda = (\sqrt{2}\, G_F)^{-½} = 246$ GeV/c^2
Vacuum expectation value

- Mass terms for vector fields
(interaction with the Higgs field)

$$M_{W^\pm} = \tfrac{1}{2} vg \quad M_Z = \tfrac{1}{2} vg / \cos\theta_W = M_W / \cos\theta_W$$

- Mass terms for fermions:

$$m_f = g_f\, v / \sqrt{2} \quad \Rightarrow \quad g_f \sim m_f$$

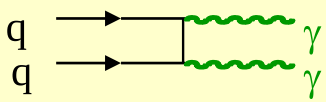
- **Higgs particle**

Mass is not predicted !
Theoretical arguments: $M_H < \sim 1000$ GeV/c^2

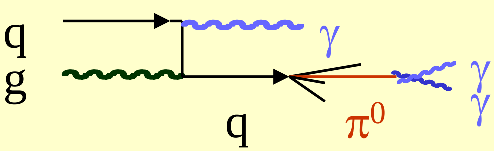
$H \rightarrow \gamma\gamma$

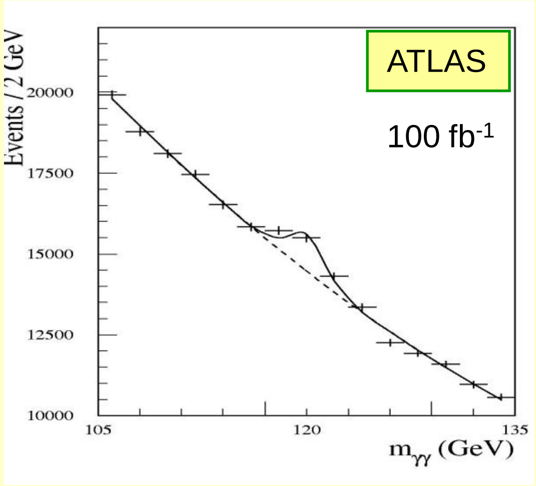
Main backgrounds:

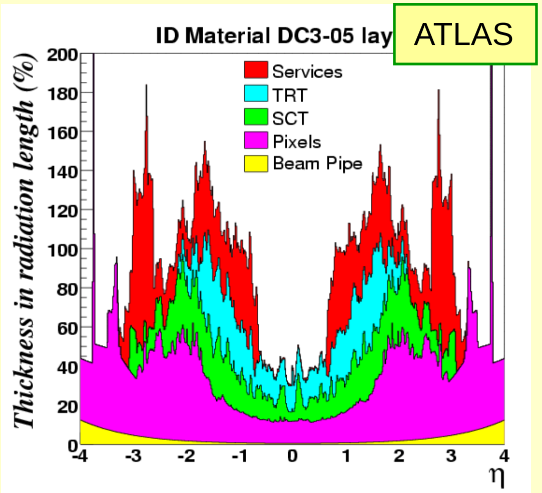
$\gamma\gamma$ irreducible background



γ-jet and jet-jet (reducible)



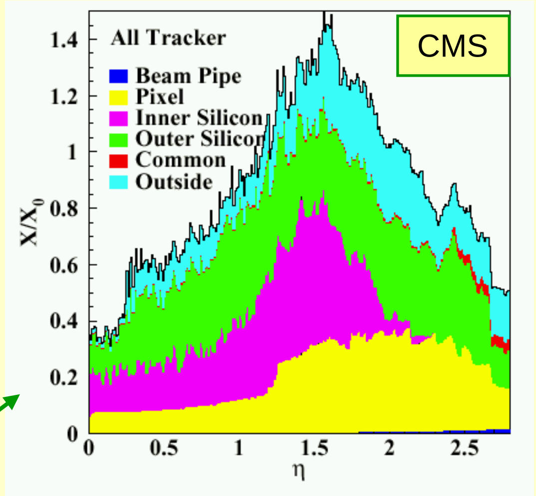




$\sigma_{\gamma j+jj} \sim 10^6\ \sigma_{\gamma\gamma}$ with large uncertainties

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

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



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

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

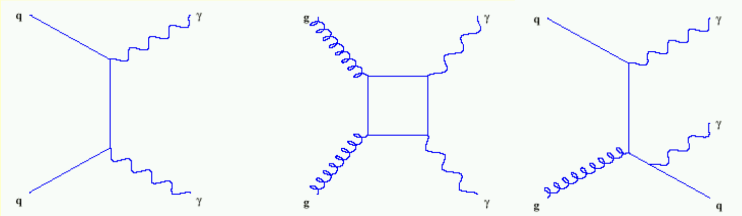
CMS: fraction of converted γs

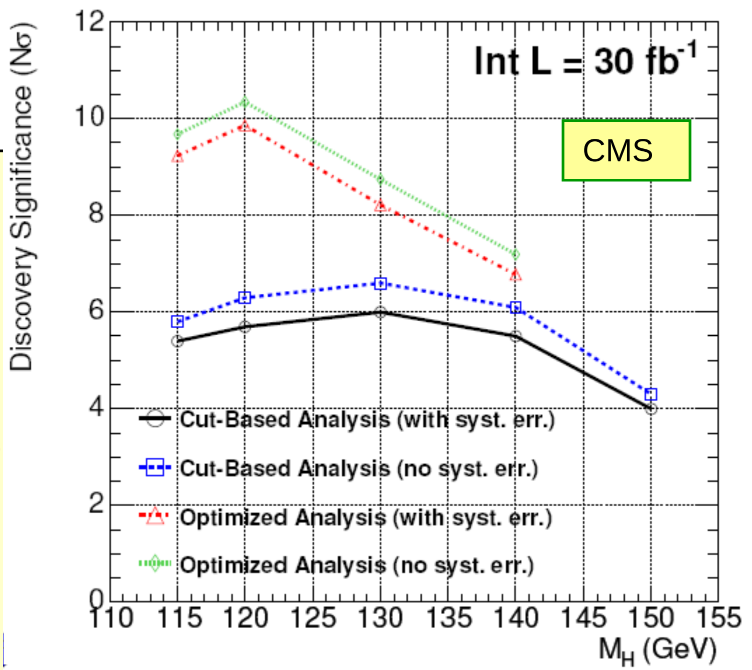
Barrel region:	42.0 %
Endcap region:	59.5 %

CMS Study: TDR (updated)

New elements of the analysis:

- more contributions to the $\gamma\gamma$ background





- NLO calculations available (Binoth et al., DIPHOX, RESBOS)
- Realistic detector material
- More realistic K factors (for signal and background)
- Split signal sample acc. to resolution functions
- Improvements possible by using more exclusive $\gamma\gamma$ + jet topologies

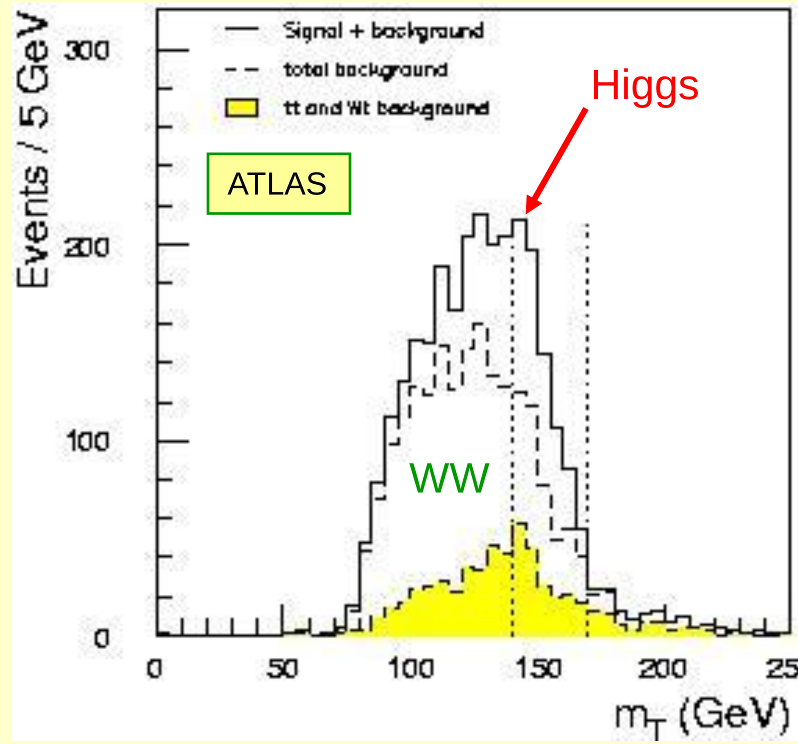
Signal significance for m_H = 130 GeV/c^2 and 30 fb^{-1}

ATLAS	LO (TDR, 1999)	3.9 σ
	NLO (update, cut based)	6.3 σ
	NLO (likelihood methods)	8.7 σ
CMS	NLO (cut based, TDR-2006)	6.0 σ
	NLO (neural net optimization, TDR-2006)	8.2 σ

Comparable results for ATLAS and CMS

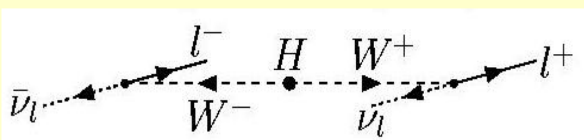
H → WW → ℓν ℓν

- Large H → WW BR for m_H ~ 160 GeV/c^2
- Neutrinos → no mass peak,
  → use transverse mass
- Large backgrounds: WW, Wt, tt



- Two main discriminants:

(i) Lepton angular correlation



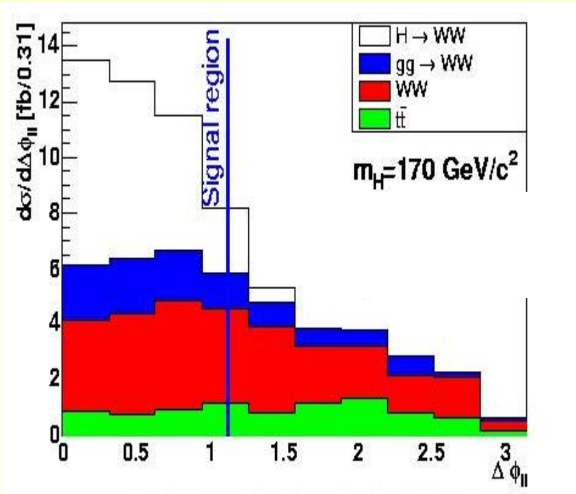
(ii) Jet veto: no jet activity in central detector region

Difficulties:
(i) need precise knowledge of the backgrounds
Strategy: use control region(s) in data, extrapolation in signal region
(ii) jet veto efficiencies need to be understood for signal and background events
→ reliable Monte Carlo generators

Discovery reach in H → WW → ℓν ℓν

New developments:

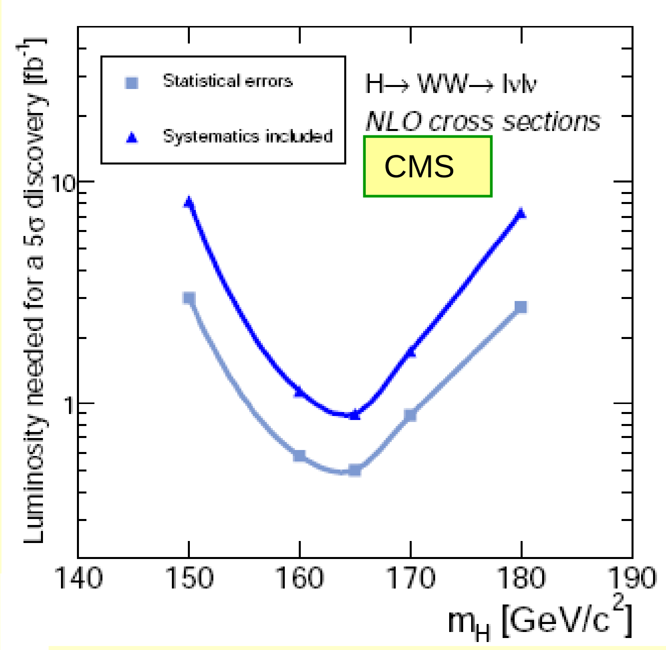
- gg → WW box contribution found to be important
  Small cross section (5% of WW backgr.) before cuts, but Δϕ shape similar to signal (30% contribution after cuts)



M. Dührssen et al., hep-ph/0504006

- Include both tt and single t background at NLO (Les Houches 2005)

CMS Phys. TDR 2006

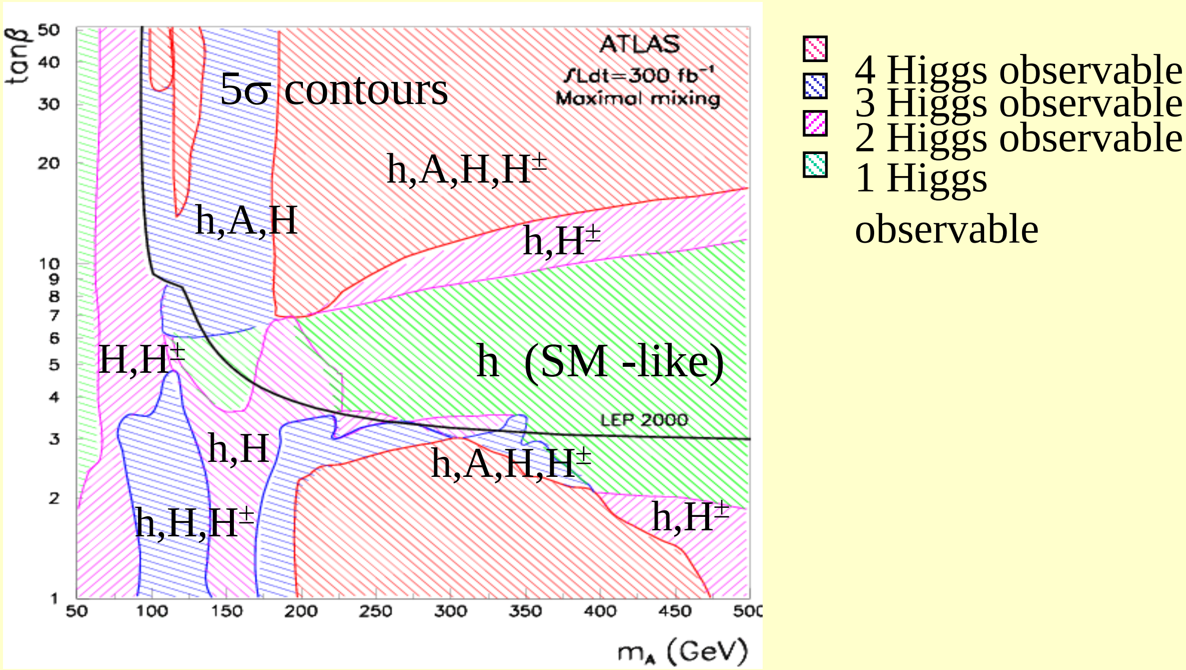


LHC:
luminosity needed for a 5σ discovery

Estimated background uncertainties:

- tt from data:	±16% at 5 fb^{-1}
- WW from data:	±17% at 5 fb^{-1}
- Wt from theory:	± 22%
- gg → WW from theory:	± 30%

LHC discovery potential for Higgs bosons in SUSY (MSSM)



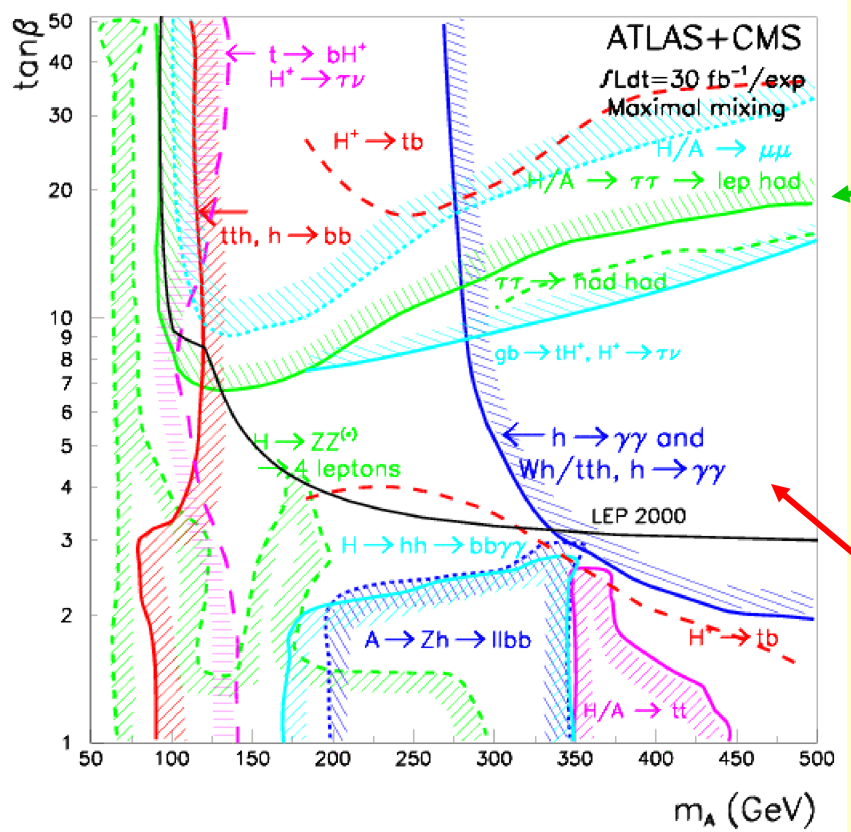
Two Higgs doubletts: 5 Higgs particles **H, h, A**
H^+, H^-

Higgs sector is determined by two parameters: m_A, $\tan\beta$

Parameter space is fully covered:
→ „Also in a minimal supersymmetric world, at least one Higgs boson will be discovered at the LHC“

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 → ττ, H± → τν
  (not easy the first year ....)
- A/H → μμ experimentally easier
  (esp. at the beginning)

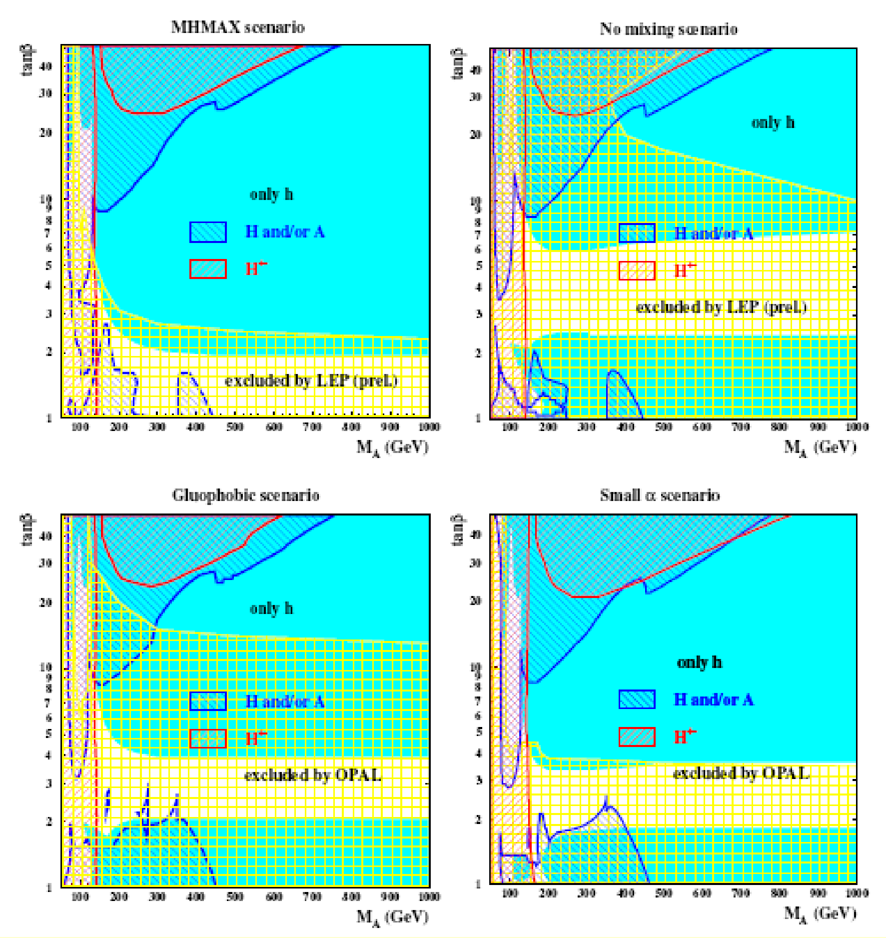
Here only SM-like h observable if SUSY particles neglected.

* Validated by CMS TDR full simulation studies *

Updated MSSM scan for different benchmark scenarios

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

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



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

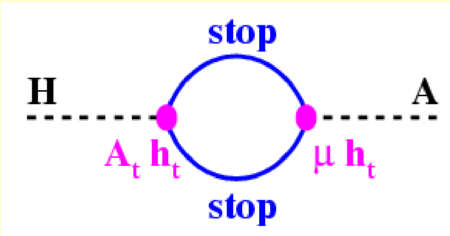
Nomixing scenario (M_{SUSY} = 2 TeV/c^2)
(1TeV almost excl. by LEP)
small m_h → difficult for LHC

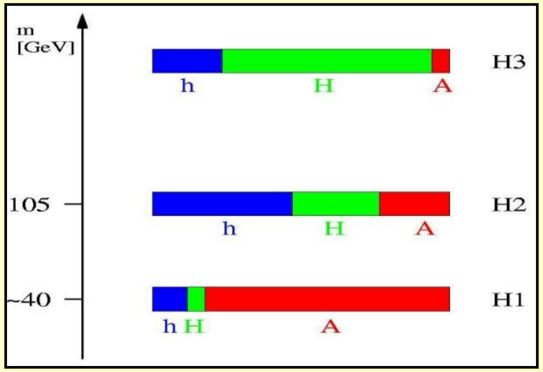
Gluophobic scenario (M_{SUSY} = 350 GeV/c^2)
coupling to gluons suppressed
(cancellation of top + stop loops)
small rate for g g → H, H→ γγ and Z→4 ℓ

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

Higgs search at the LHC in CP-violating scenarios

- CP conservation at Born level, but CP violation via complex **A_t, A_b, M....**





- CP eigenstates h, A, H mix to mass eigenstates H_1, H_2, H_3

- Effect maximized in a defined benchmark scenario (CPX)

(M. Carena et al., Phys.Lett. B 495 155 (2000))

$\arg(A_t) = \arg(A_b) = \arg(M_{gluino}) = 90^o$

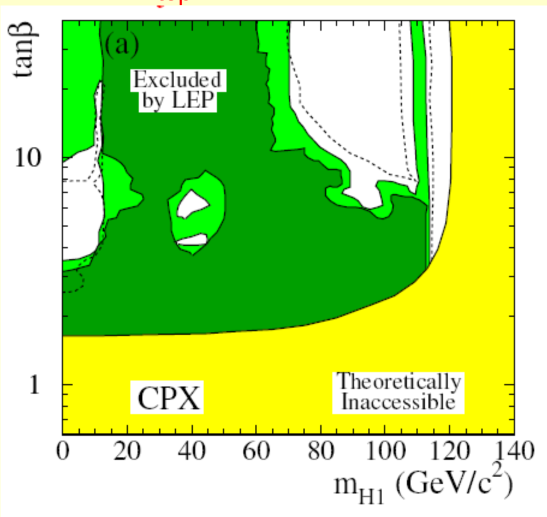
- No lower mass limit for H_1 from LEP !

(decoupling from the Z)

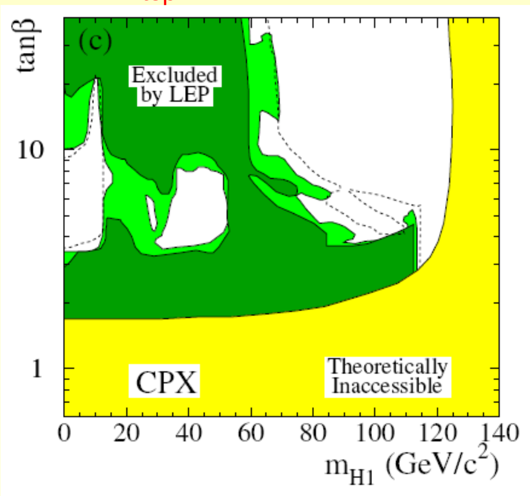
details depend on m_{top} and on theory model

(FeynHiggs vs. CPsuperH)

m_{top} = 169.3 GeV/c^2

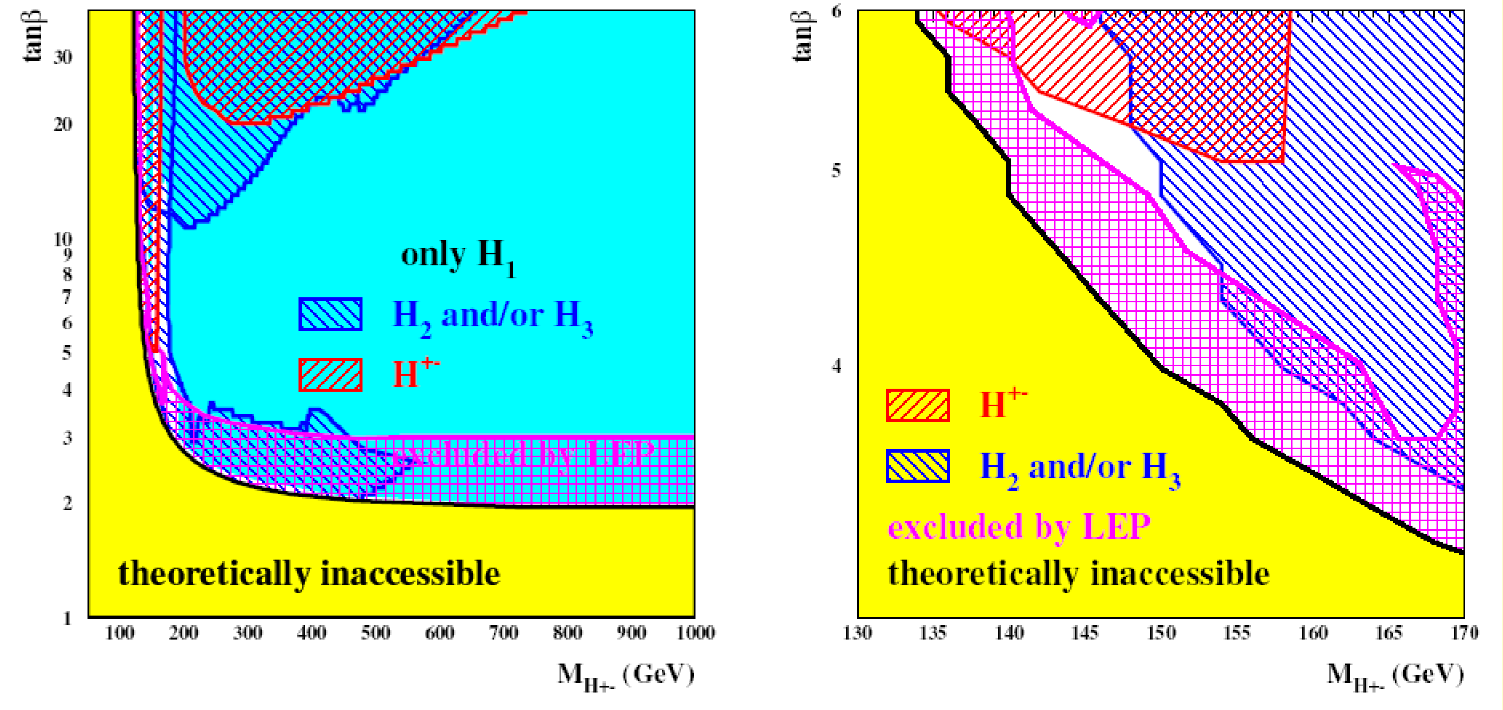


m_{top} = 174.3 GeV/c^2



MSSM discovery potential for the CPX scenario

ATLAS preliminary (M. Schumacher)

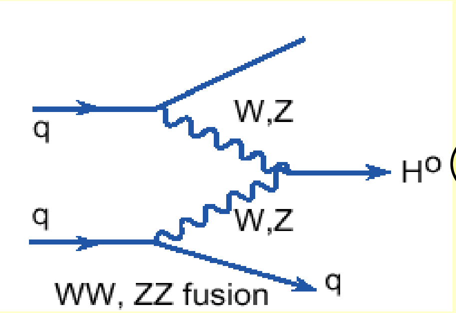


- Large fraction of the parameter range can be covered,
  however, small hole at (intermediate tanβ , low m_{H+}) corresponding to low m_{H_1}

- More studies needed, e.g. investigate lower H_1 masses,
  additional decay channels:
  $tt \rightarrow Wb\ H^+b \rightarrow \ell\nu b\ WH_1b,\ \ H_1 \rightarrow bb$

Invisible Higgs decays ?

Possible searches: tt H $\rightarrow$ ℓνb qqb + P_T^{miss}
Z H $\rightarrow$ ℓℓ + P_T^{miss}
qq H $\rightarrow$ qq + P_T^{miss}



P_T^{miss}

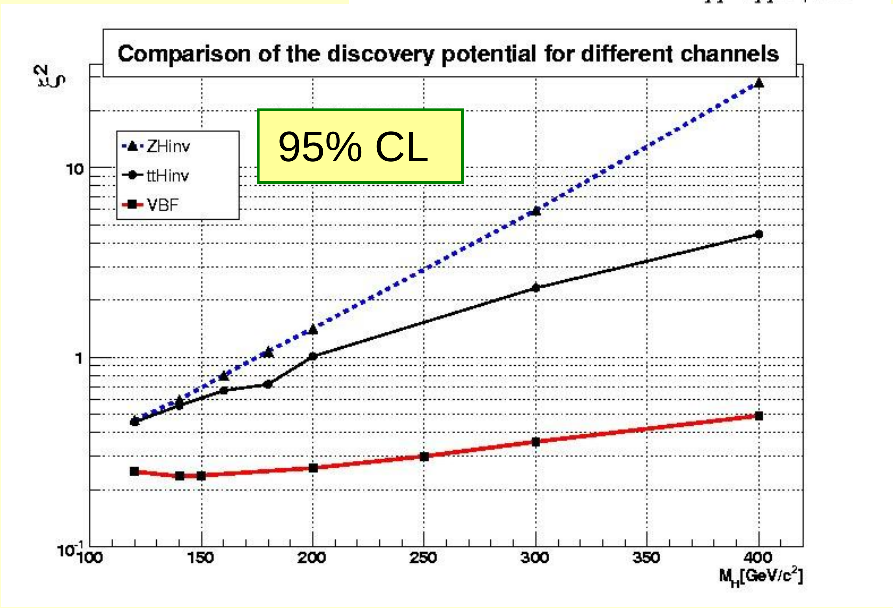
- J.F. Gunion, Phys. Rev. Lett. 72 (1994)
- D. Choudhury and D.P. Roy, Phys. Lett. B322 (1994)
- O. Eboli and D. Zeppenfeld, Phys. Lett. B495 (2000)

All three channels have been studied:

key signature: excess of events above SM backgrounds with large P_T^{miss} (> 100 GeV/c)

Sensitivity:

$$\xi^2 = Br(H \to Inv.) \frac{\sigma_{qq \to qqH}}{\sigma_{qq \to qqH}|_{SM}}$$



ATLAS preliminary

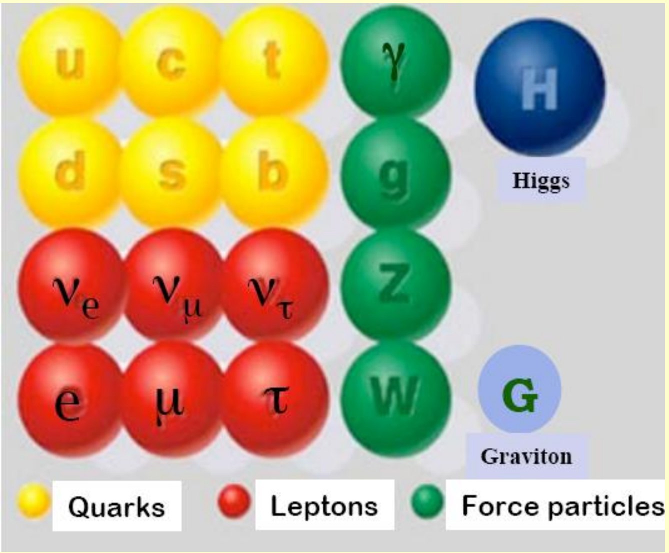
Problems / ongoing work:

- ttH and ZH channels have low rates
- More difficult trigger situation for qqH
- backgrounds need to be precisely known (partially normalization using ref. channels possible)
- non SM scenarios are being studied at present first example: SUSY scenario

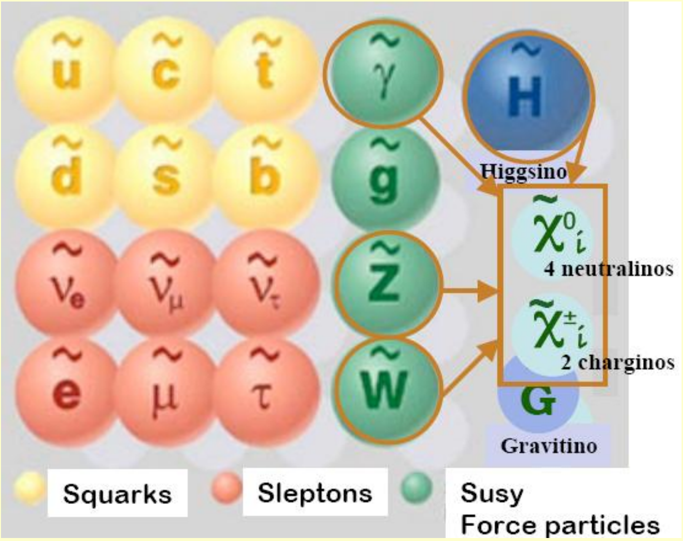
Supersymmetry

Extends the Standard Model by predicting a new symmetry between
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

Link to the Dark Matter in the Universe ?

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

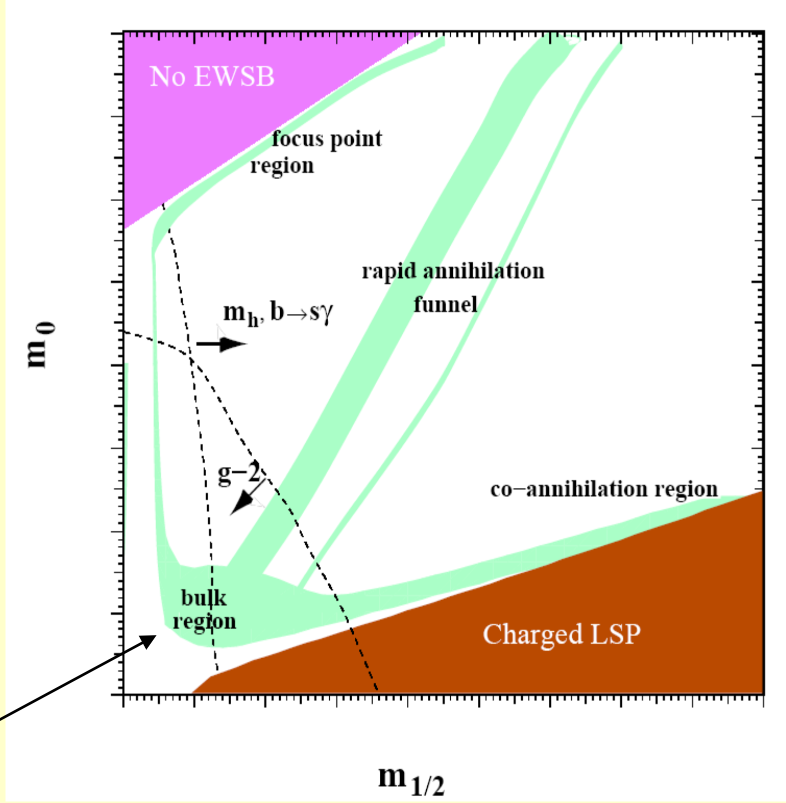
$$\rho_\chi = m_\chi n_\chi \,, \quad n_\chi \sim \frac{1}{\sigma_{ann}(\chi\chi \to \ldots)}$$

Interpretation in a simplified model

cMSSM
(constrained Minimal Supersymmetric
Standard Model)

Five parameters:

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

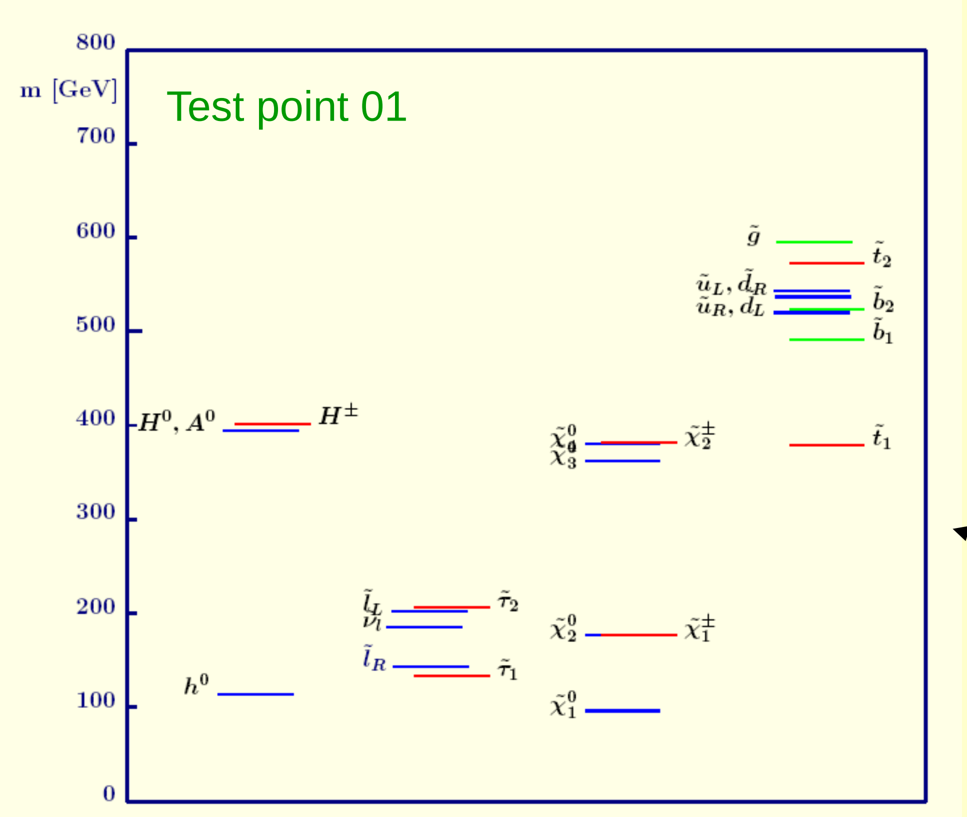


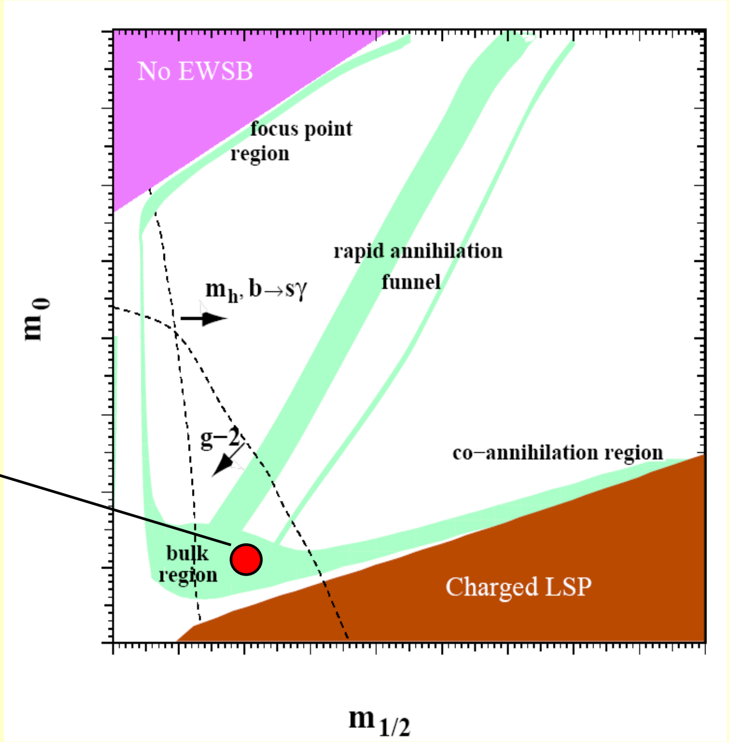
regions of parameter space which are consistent with the measured relic density of dark matter (WMAP,…..)

s. talk by J. Ellis

How can the underlying theoretical model be identified ?

Measurement of the SUSY spectrum $\rightarrow$ Parameter of the theory

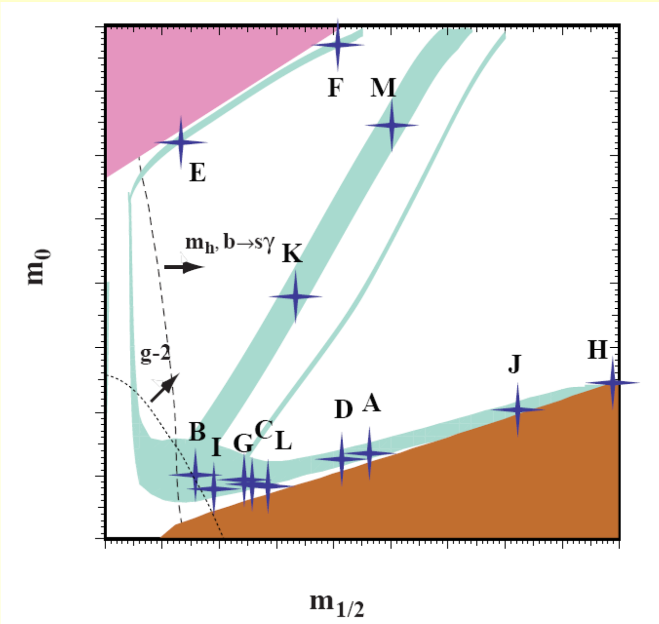




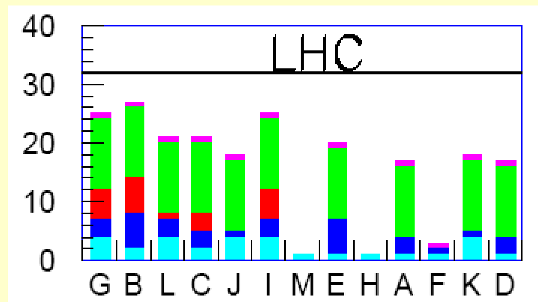
LHC: strongly interacting squarks and gluinos

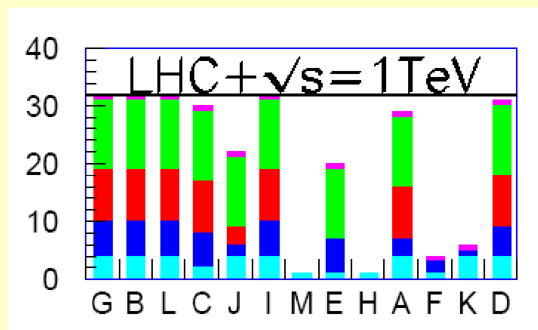
ILC : precise investigation of electroweak SUSY partners

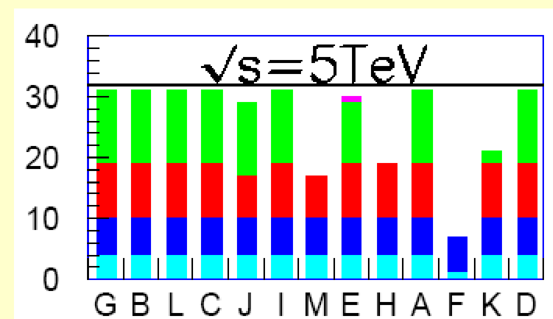
The LHC and the ILC (International Linear Collider, in study/planning phase) are complementary in SUSY searches



Number of observable SUSY particles:





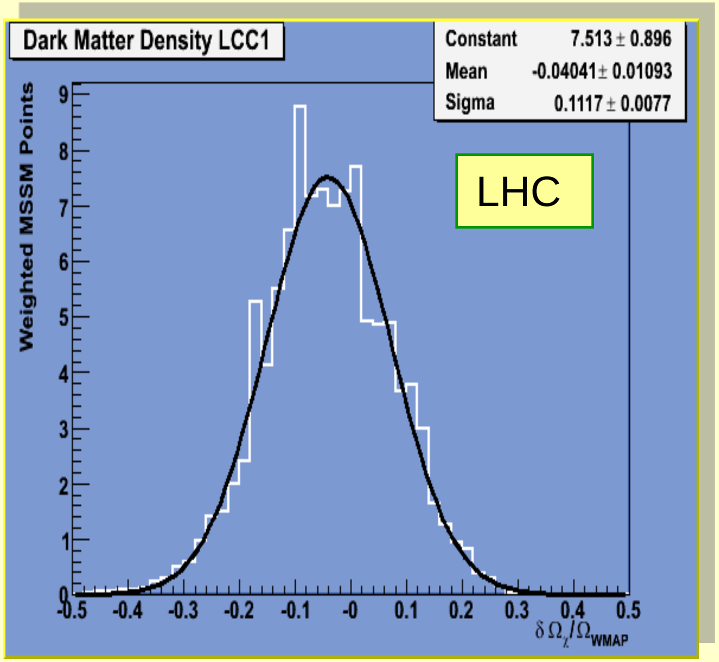


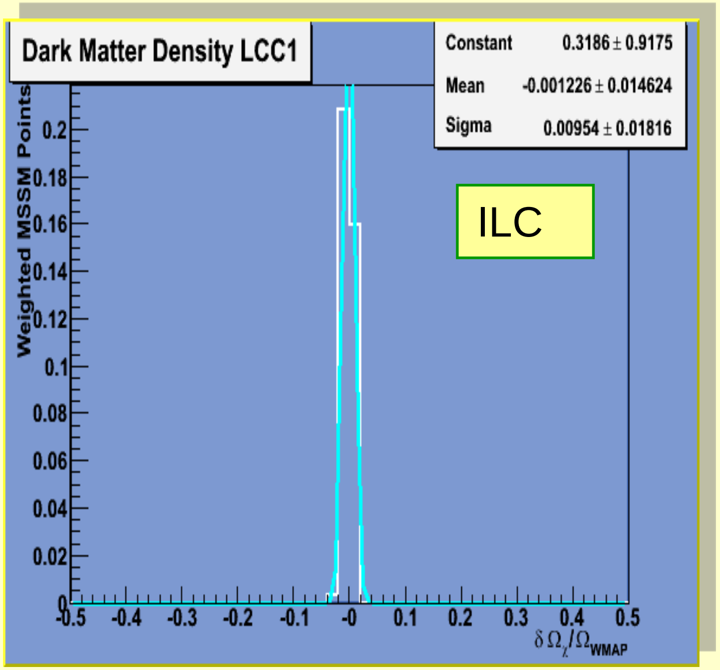
)* Study by J. Ellis et al., hep-ph/0202110

Dark Matter at Accelerators ?

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

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



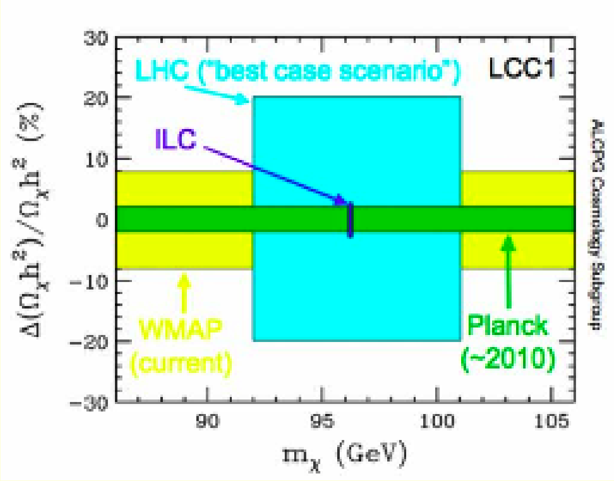


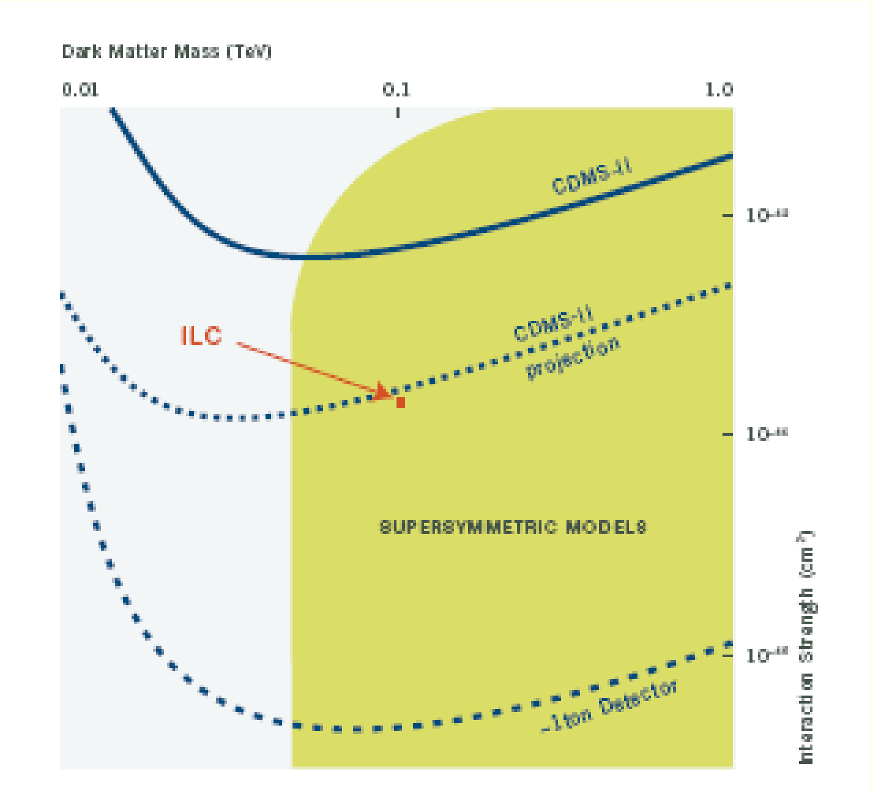
Battaglia et al.

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

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

Importance for direct and indirect searches of Dark Matter





LHC reach for other BSM Physics
(a few examples for 30 and 100 fb^{-1})

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