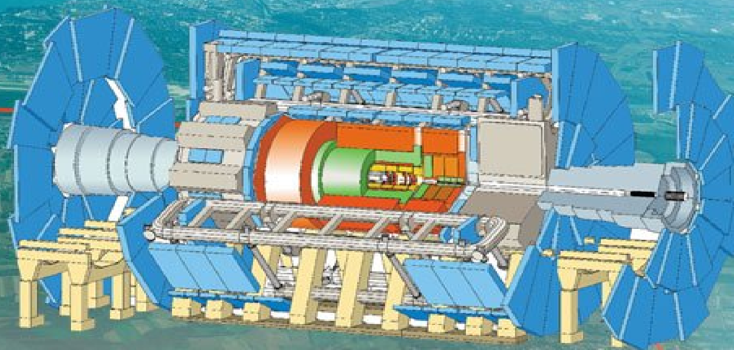
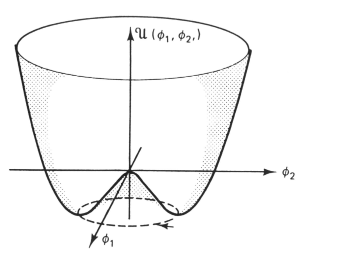
Physics at the LHC

- Prospects for physics with early data-

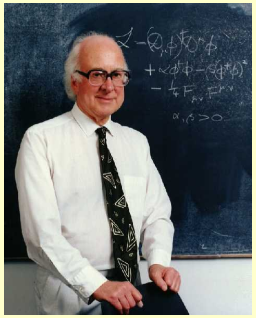


- Introduction

  Status of the accelerator and experiments
- Early measurements and calibrations
- Searches for New Physics
- Higgs boson searches



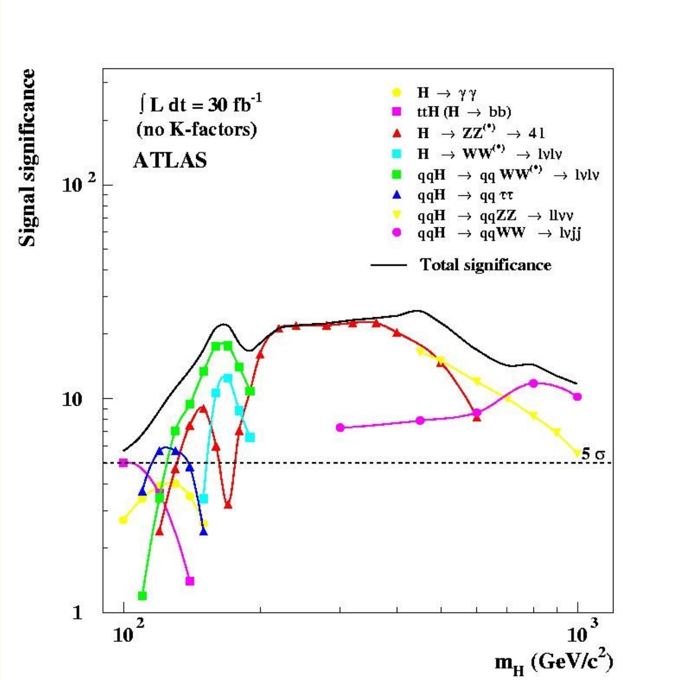
The Higgs Boson



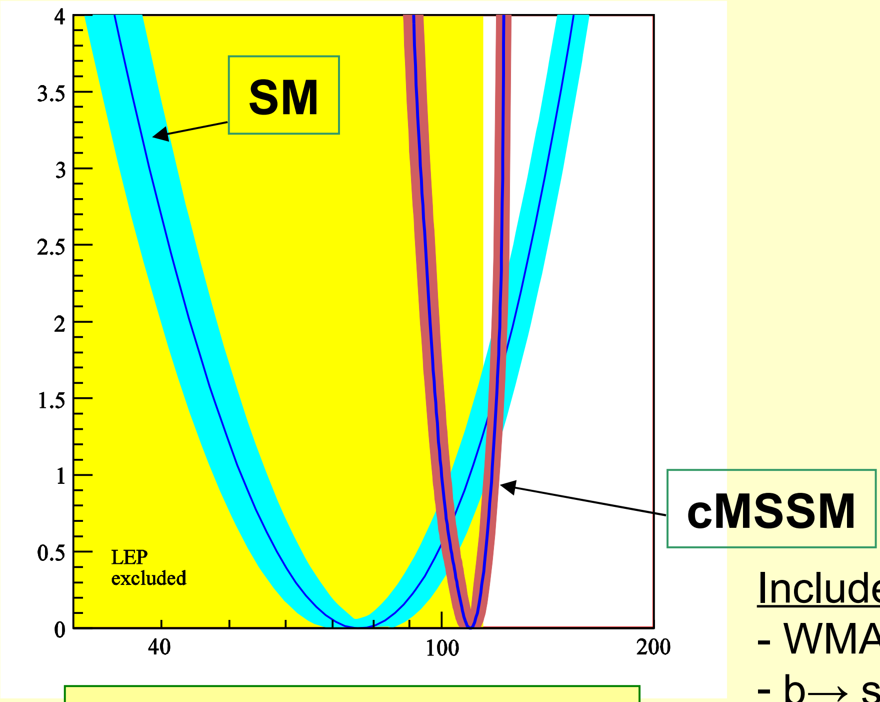
- "Revealing the physical mechanism that is responsible for the breaking of electroweak symmetry is one of the key problems in particle physics"

- "A new collider, such as the LHC must have the potential to detect this particle, should it exist."

O. Buchmüller et al., arXiv:0707.3447



…expected to be achieved (ATLAS & CMS studies)

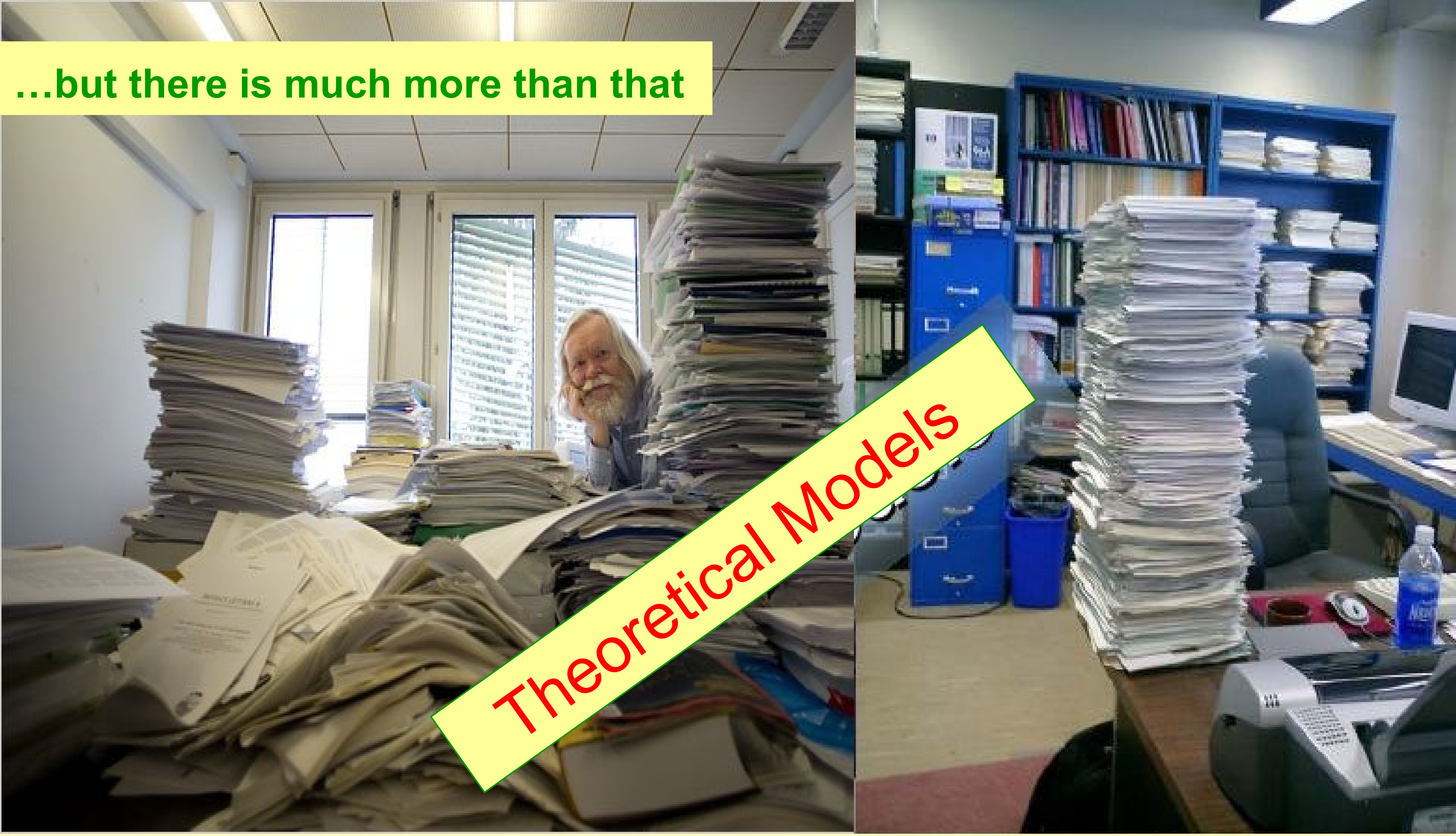


m_h = 110 (+8) (-10) ± 3 (theo) GeV/c²

….watch the low mass region !

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

…but there is much more than that



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

1. **Explore a new energy regime**

   - Search for “expected” signatures of New Physics

   - Must be open to unexpected new physics

2. **Make precise tests of the Standard Model**

   - There is much sensitivity to physics beyond the SM, in both high-energy and precision sectors

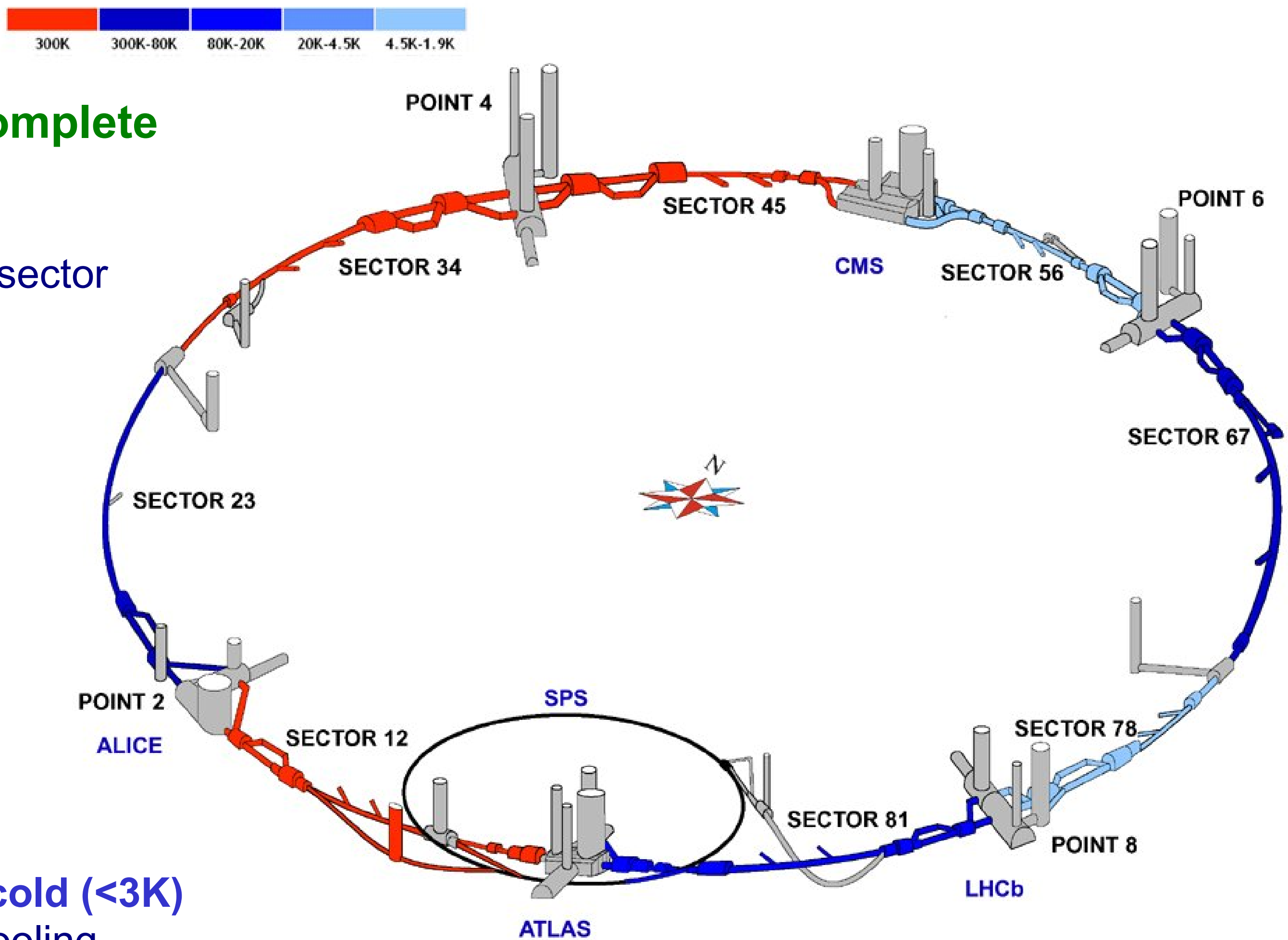
   - Many Standard Model measurements which can be used to test and tune the detector performance

The LHC machine…

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

… becomes a reality after ~15 years of hard work

LHC Machine Status



LHC installation ~complete

Cool-down to 1.9 K

- takes ~8 weeks per sector (in parallel)

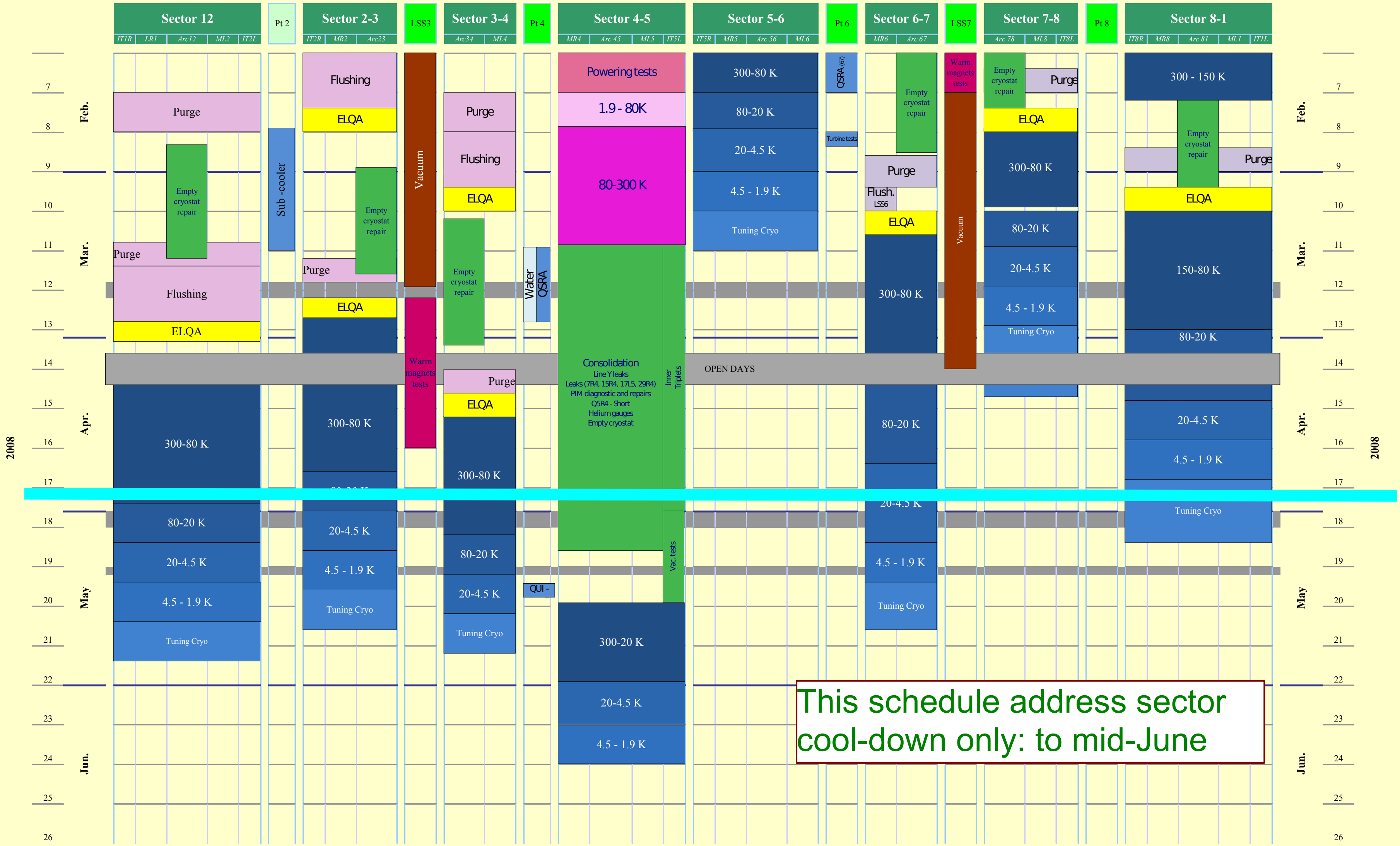
Now:

- **sectors 56 and 78 cold (<3K)**
- sectors 23, 67, 81 cooling
- sector 45 has been cold
- sectors 12, 34 start cooling soon

Snapshot: 12 April

Latest status: http://hcc.web.cern.ch/hcc

LHC machine status (cont.)



This schedule address sector cool-down only: to mid-June

Commissioning of beams to high energy: estimated time ~ 30 days, however, the LHC operating efficiency will be < 100% at the beginning

⇒ assume ~ 2 months from 1st turn to high energy collisions

Beam energy for 2008

Test cooling of sector 45:

- magnet training quenches seen with currents above 5 TeV equivalent
- estimate is that training all magnets to 7 TeV may take 2-3 months (cold)

This would put collisions in 2008 in doubt

Suggested to run at ~10 TeV in 2008

- train magnets in winter shutdown
- start up at 14 TeV in 2009

Final decision to be taken end of this month

Luminosities in Stage A

Bunches	β*	I_b	Luminosity	Event rate
1 x 1	18	10^{10}	10^{27}	Low
43 x 43	18	3 x 10^{10}	3.8 x 10^{29}	0.05
43 x 43	4	3 x 10^{10}	1.7 x 10^{30}	0.21
43 x 43	2	4 x 10^{10}	6.1 x 10^{30}	0.76
156 x 156	4	4 x 10^{10}	1.1 x 10^{31}	0.38
156 x 156	4	9 x 10^{10}	5.6 x10^{31}	1.9
156 x 156	2	9 x 10^{10}	1.1 x10^{32}	3.9

per crossing

pileup !!

M. Lamont, Oct 07

Stage A: first operations, low total currents until beam dump reliable

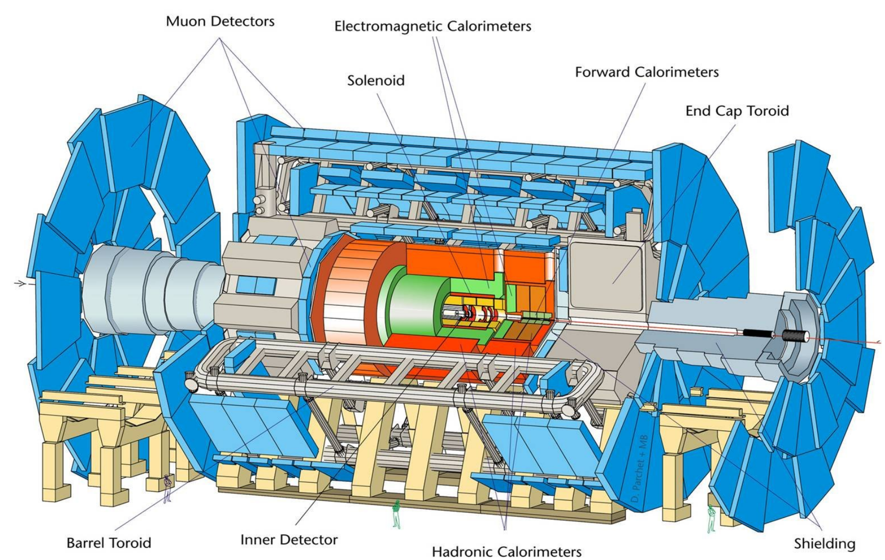
Expected integrated luminosity:

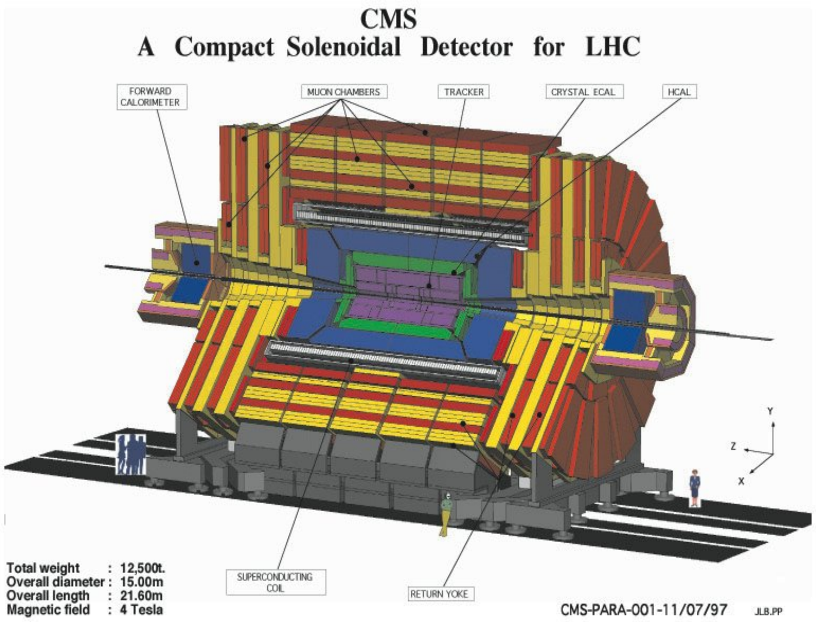
- "first fills" lumi ~ 2 nb^{-1} at ~10^{28} cm^{-2} s^{-1} in a few days
- canonical "10h fill" around 10^{32} ~ 2-3 pb^{-1}

⇒ **Up to ~ 100 pb^{-1} in 2008?**

Status of the experiments

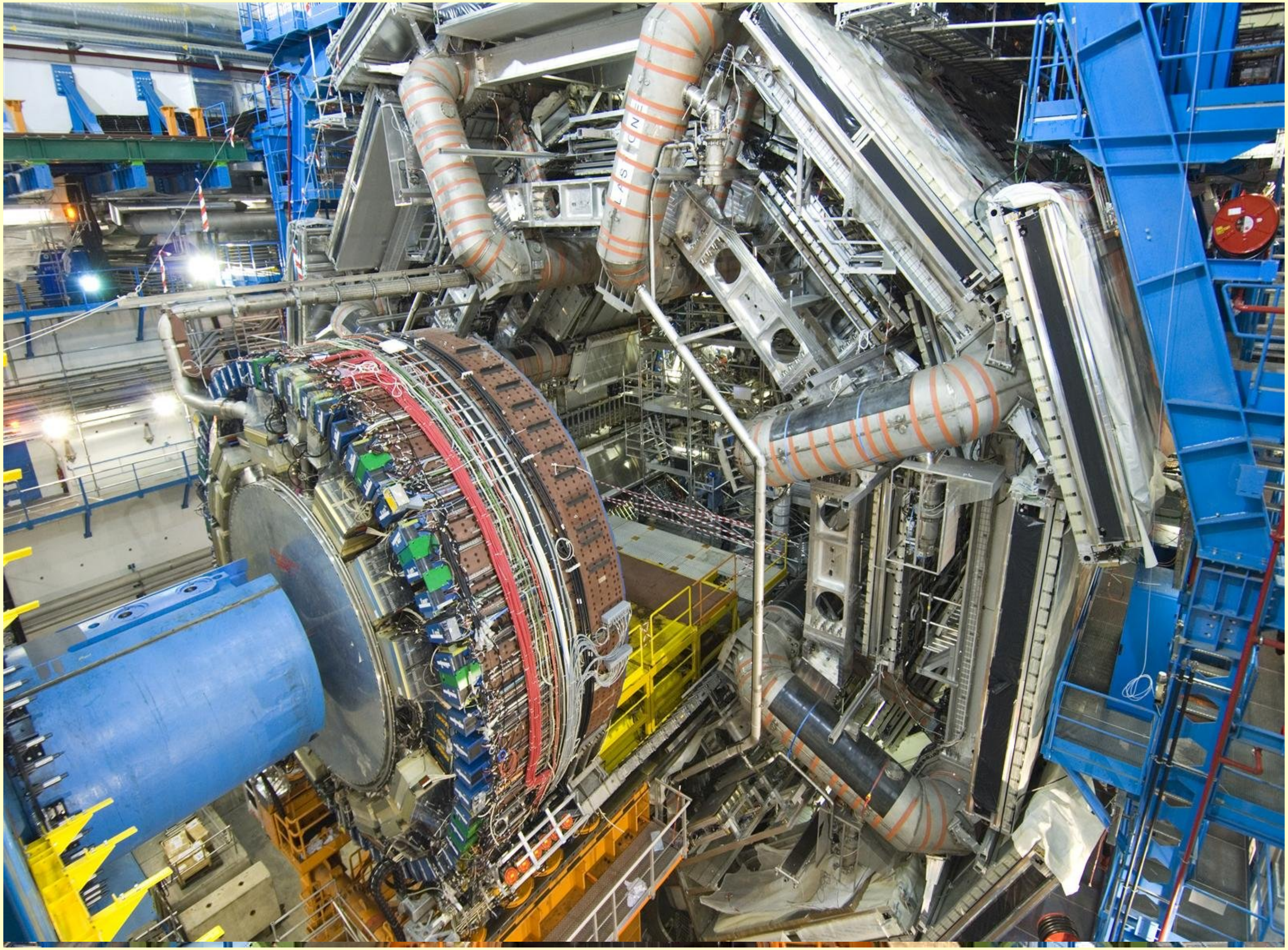
ATLAS





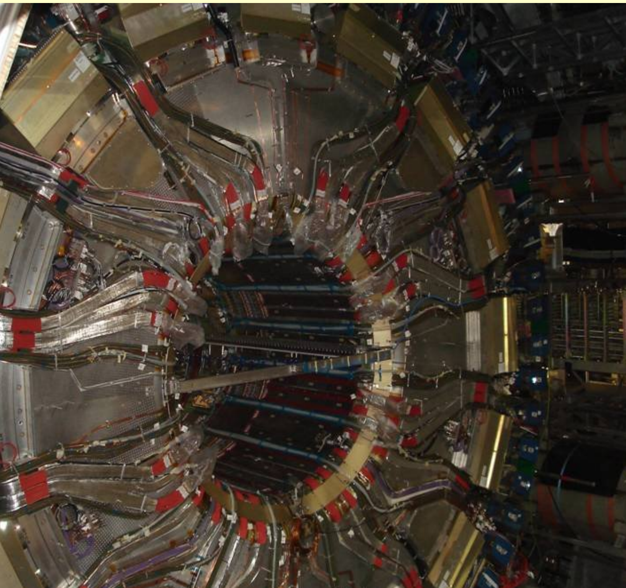
- Detectors are installed, testing and commissioning in full swing
- ATLAS and CMS will be ready for first pp collisions in Summer 2008

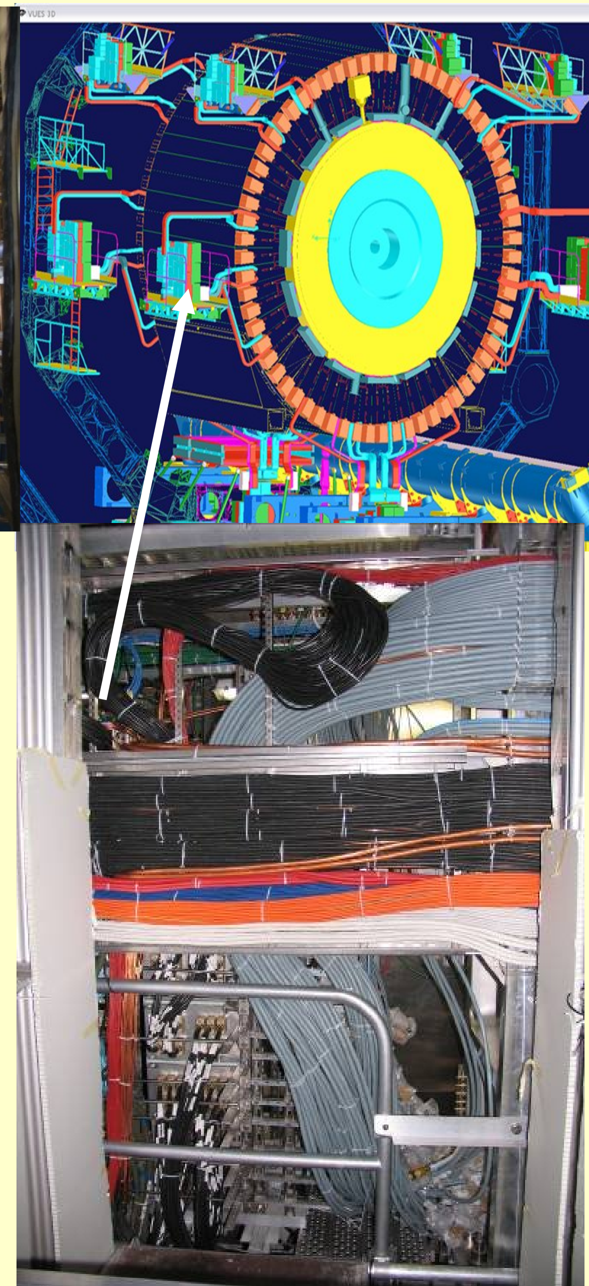
ATLAS Installation



October 2006

Installation of Inner Detector Services



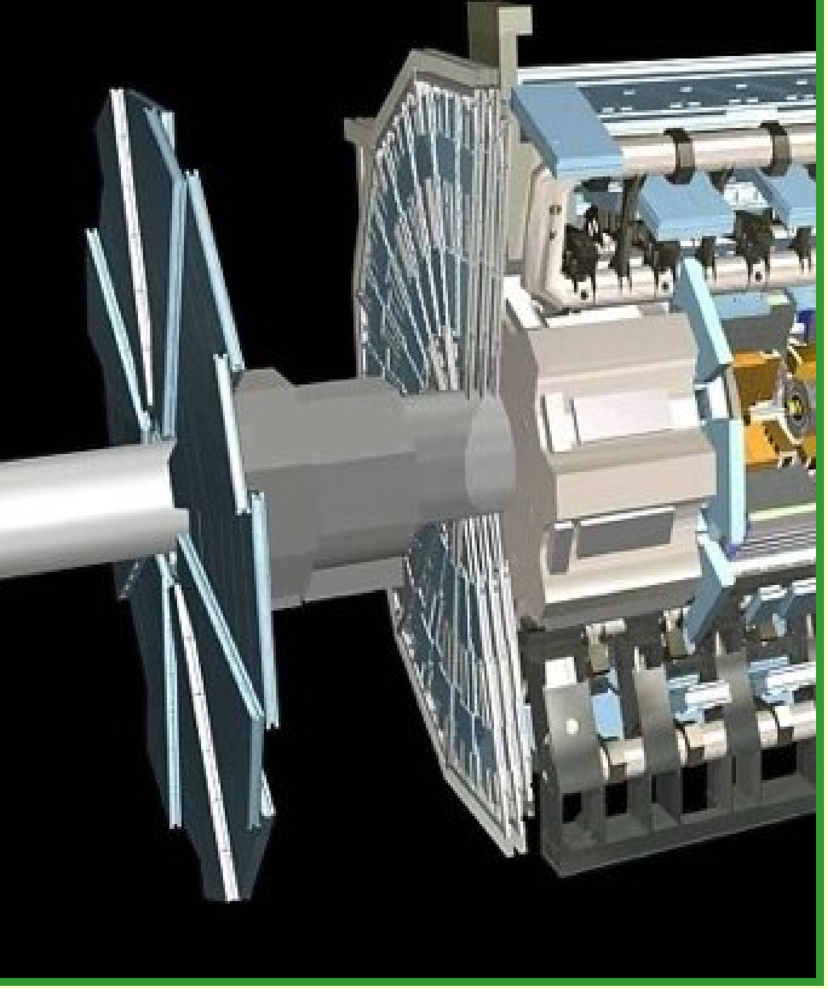


~ 800 man-months of installation work over

~18 months, ~ 45 people involved/day

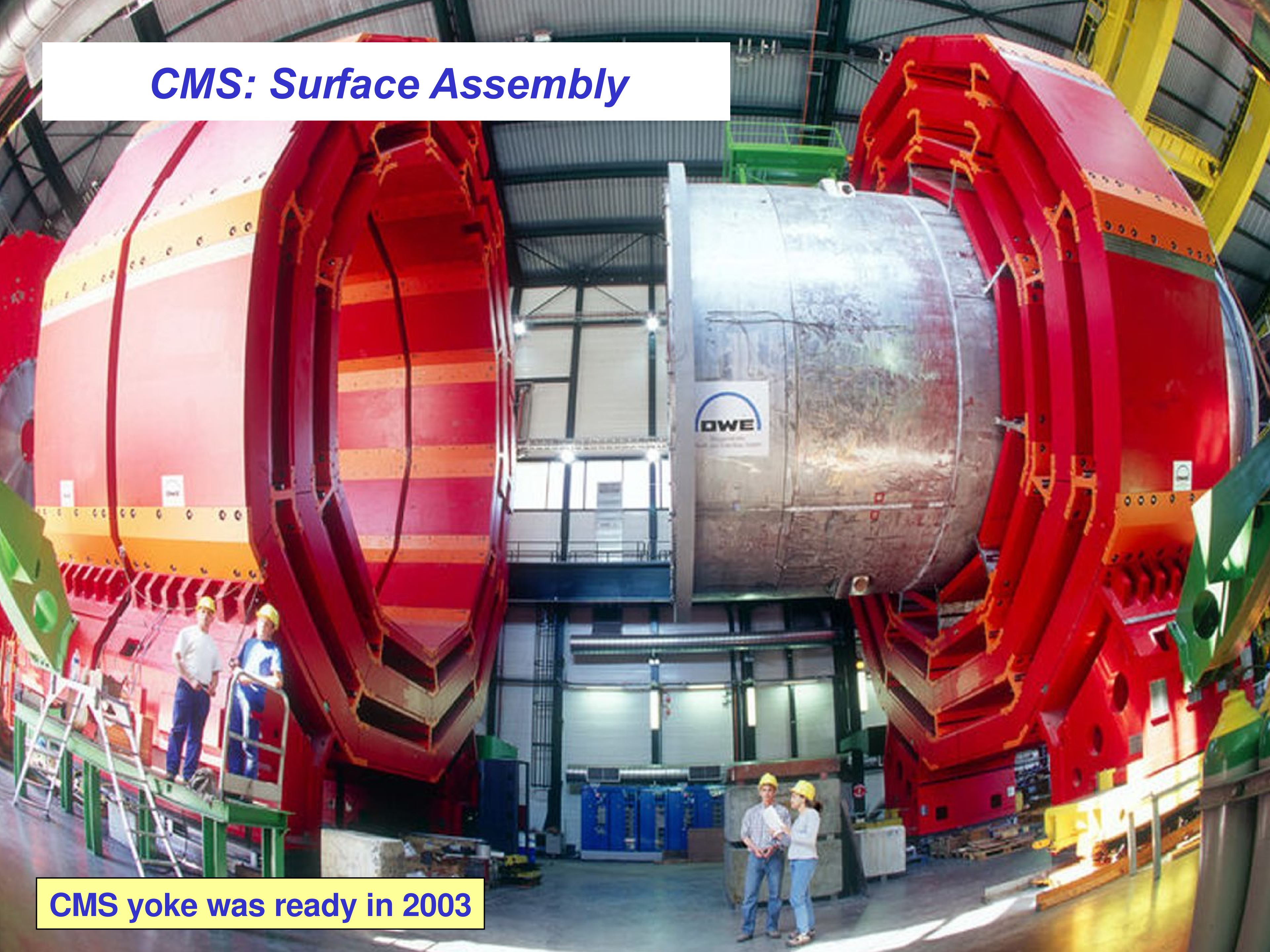
- ✓ ~ 9300 SCT cable-bundles
- ✓ ~ 3600 pixel cable-bundles
- ✓ ~ 30100 TRT cables
- ✓ ~ 2800 cooling & gas pipes

All tested and qualified



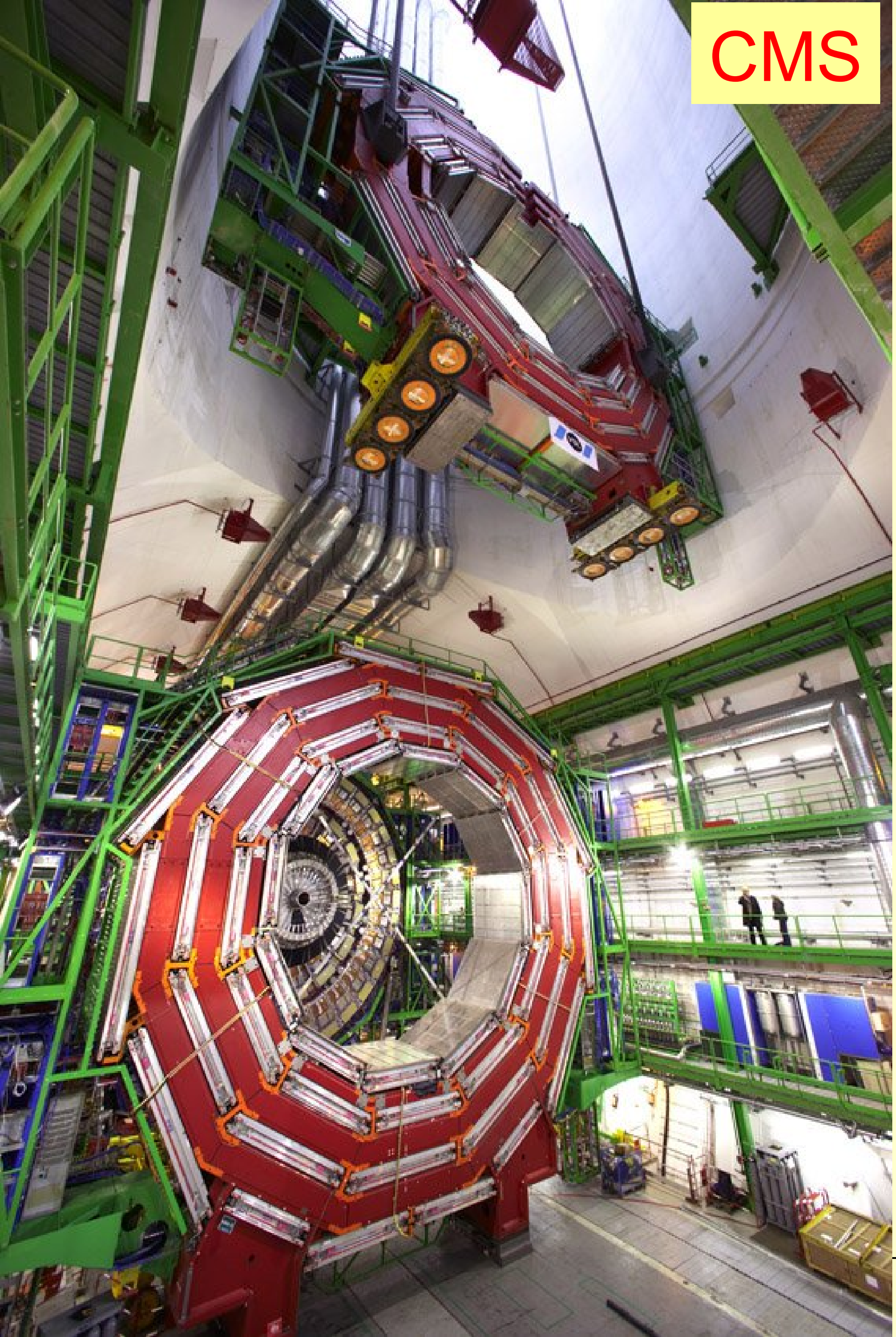
Forward muon spectrometer
- 'Big Wheels' are all installed
- The end-wall wheel installation has started

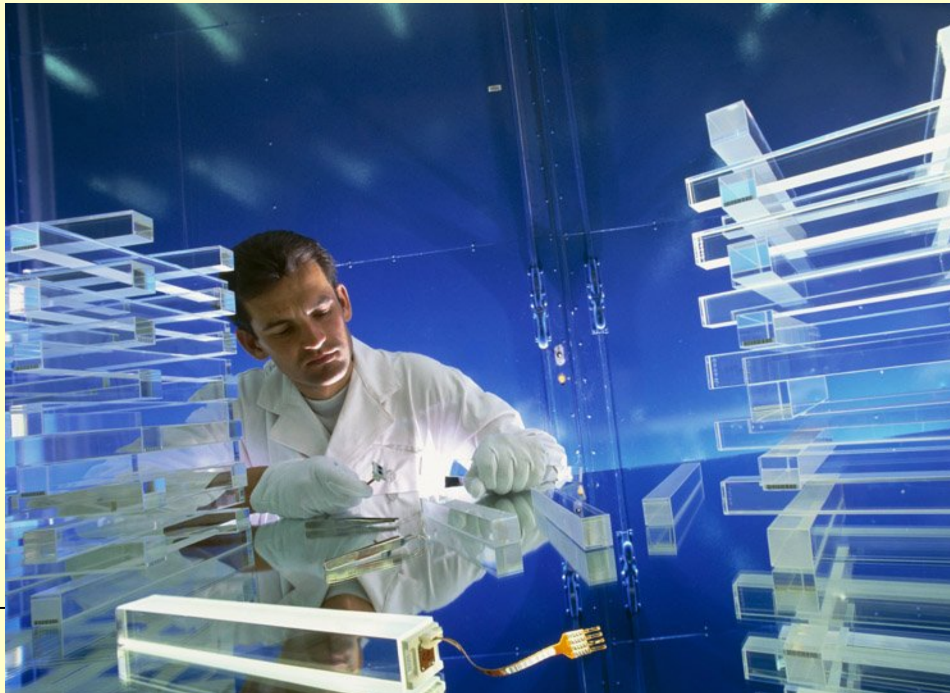
CMS: Surface Assembly



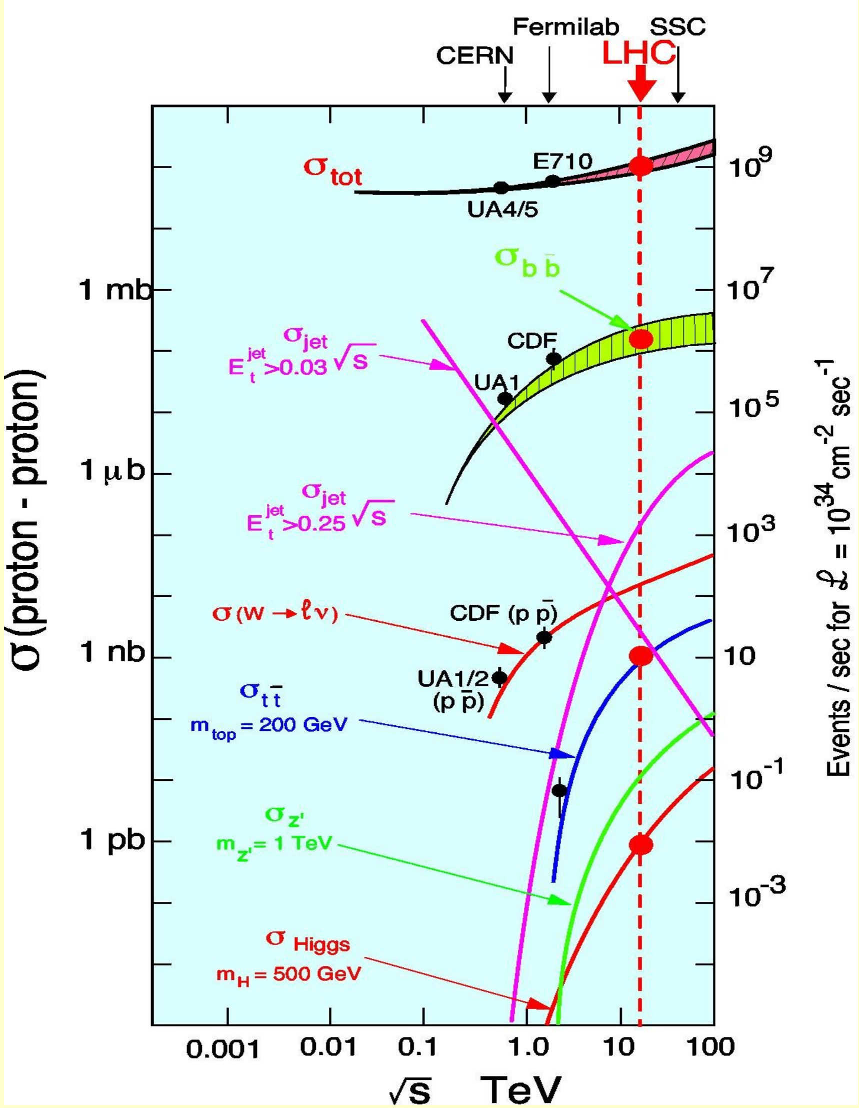
CMS yoke was ready in 2003

Closing CMS for the first time (July 2006)


CMS



Cross Sections and Production Rates



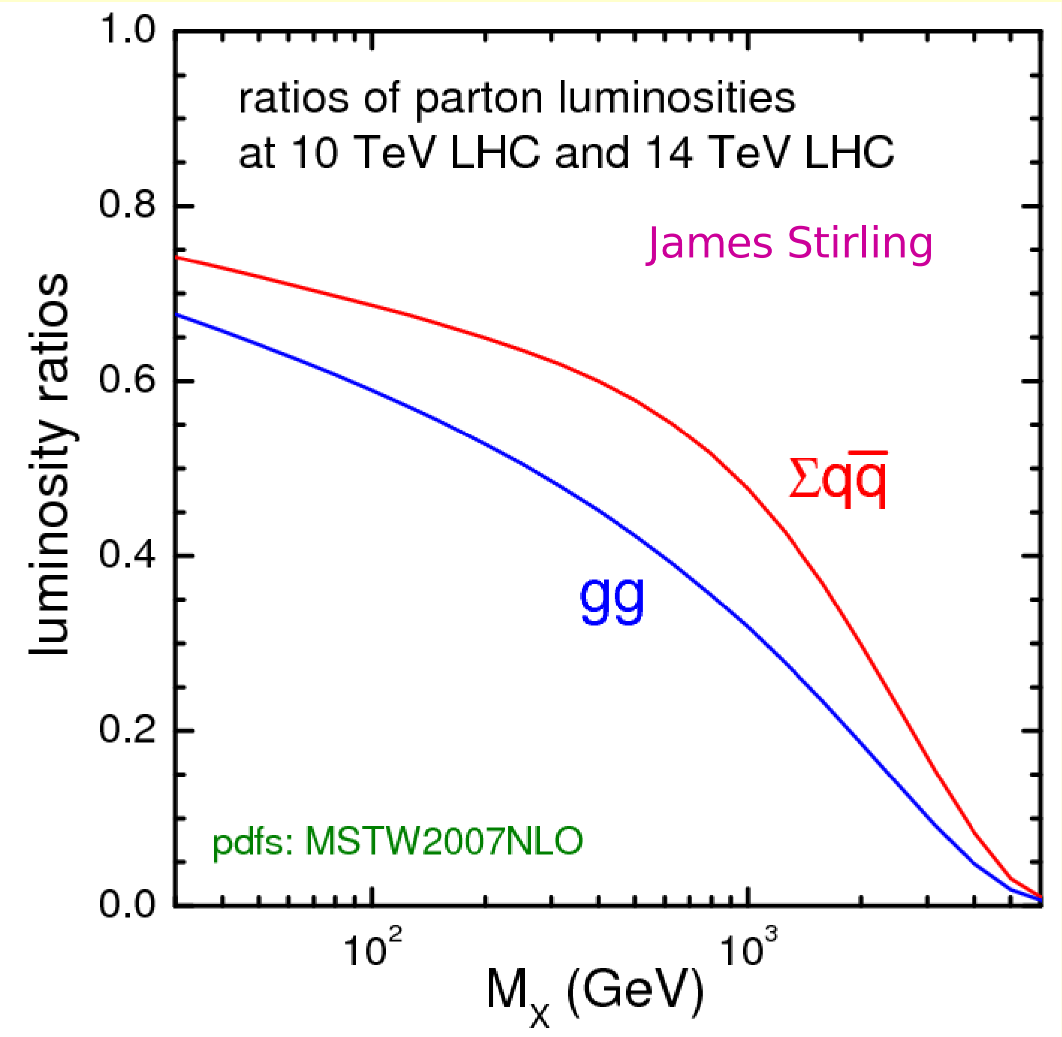
Rates for $L = 10^{34}$ cm^{-2} s^{-1}: (LHC)

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

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

Rates for Standard Model processes still high for $L = 10^{32}$ cm^{-2} s^{-1}

10 vs 14 TeV ?



At 10 TeV, more difficult to create high mass objects...

Below about 200 GeV, this suppression is <50% (process dependent)

e.g. tt ~ factor 2 lower cross-section

Above ~2-3 TeV the effect is more marked

The rest of the talk discusses $\sqrt{s}$=14 TeV capabilities

First goals …. (2008/09) (?)

- Understand and calibrate detector and trigger

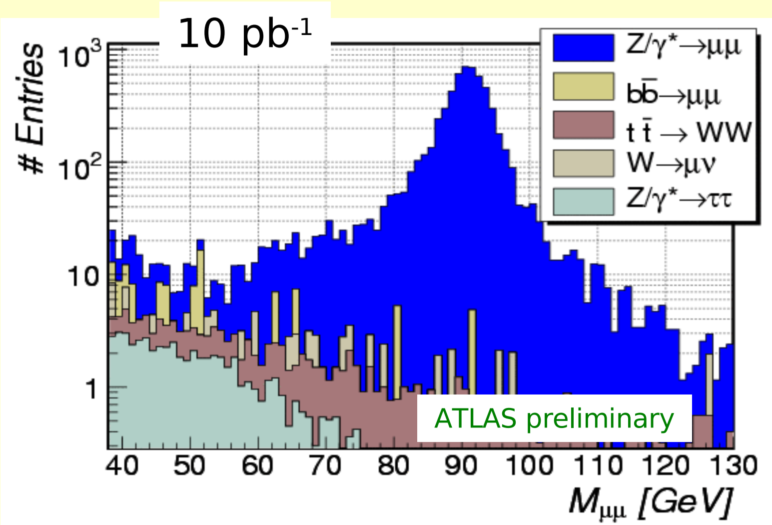
  in situ using well-known physics samples

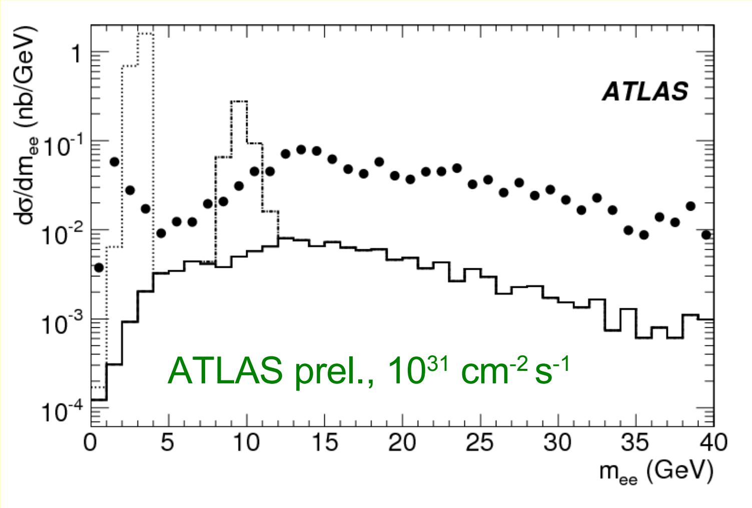
e.g. - $Z \rightarrow ee, \mu\mu$ tracker, calorimeter, muon chambers calibration and alignment

- $tt \rightarrow b\ell\nu\ bjj$ 10^3 events / day after cuts at 10^{32} cm^{-2} s^{-1}

→ jet scale from W→jj

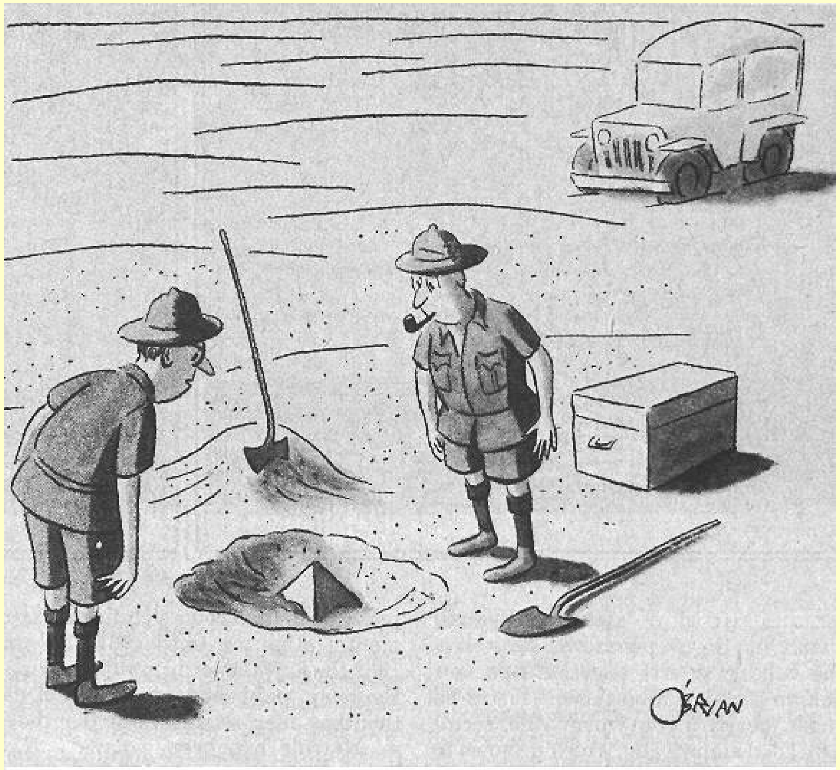
→ b-tag performance





......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)

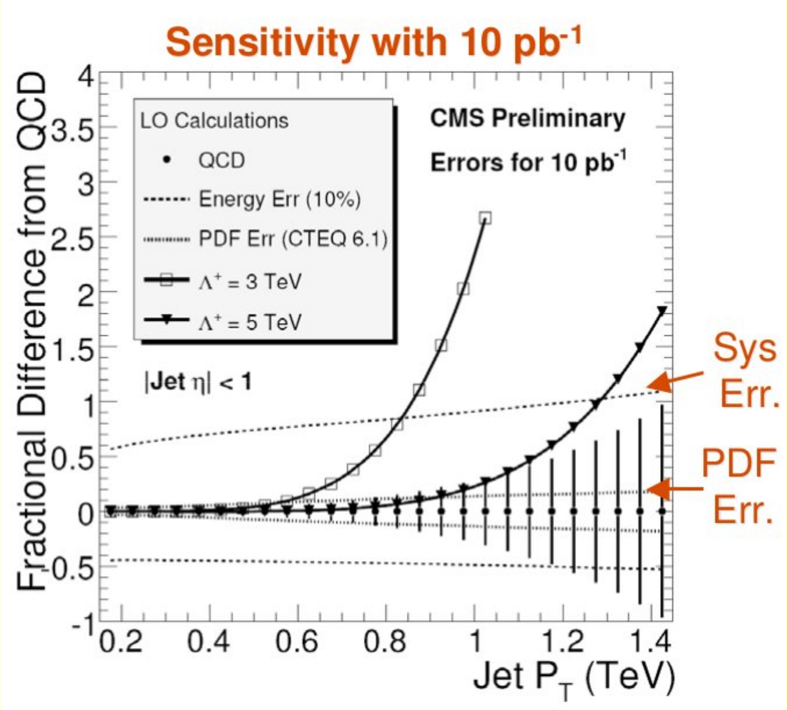
  e.g. measure cross-sections for W, Z, tt, QCD jets, and events features (P_T spectra etc.)

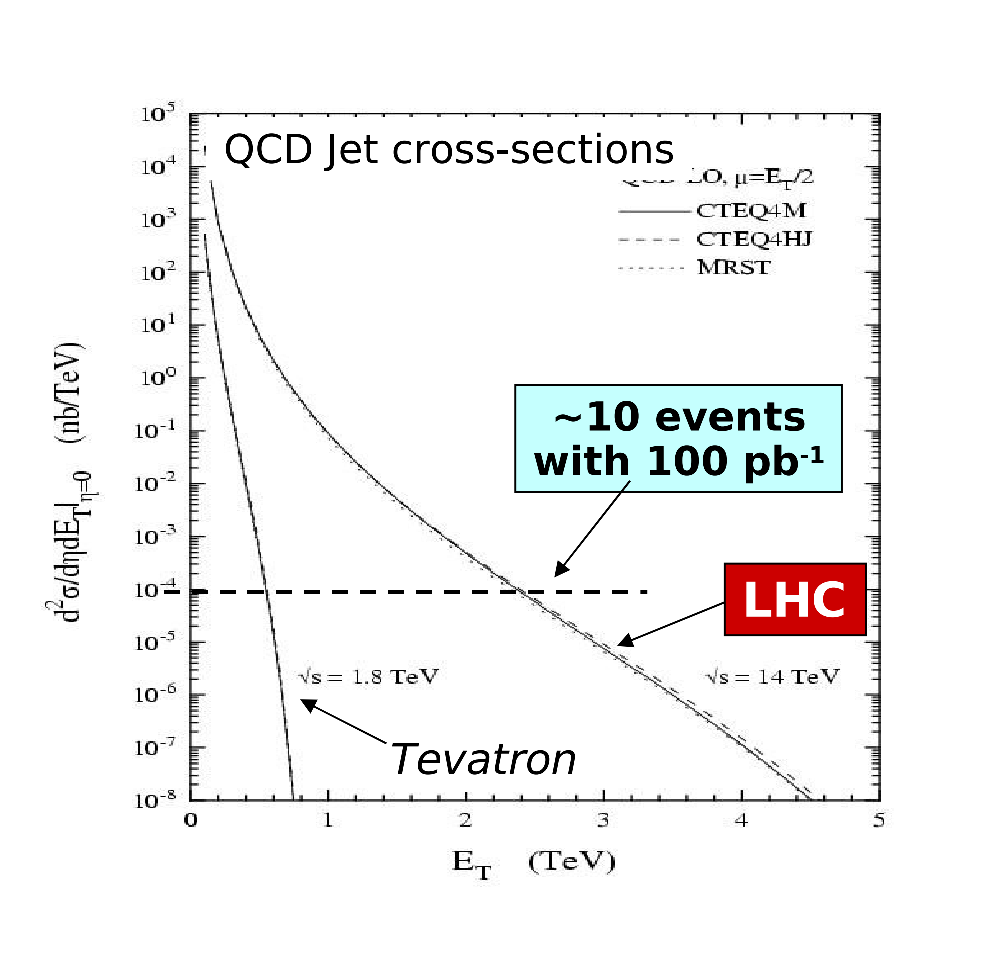
  (tt and W/Z+ jets are omnipresent in Searches for New Physics)

QCD Jets

Huge cross-sections – rapidly probe QCD at a scale above Tevatron

New physics sensitivity at high-E_t? Must understand resolution well…





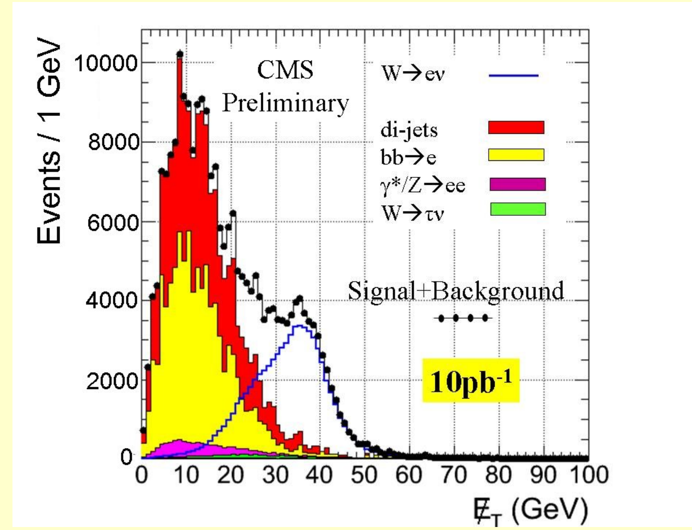
Study of sensitivity to contact interactions from dijet p_T spectrum

W and Z Cross-Sections

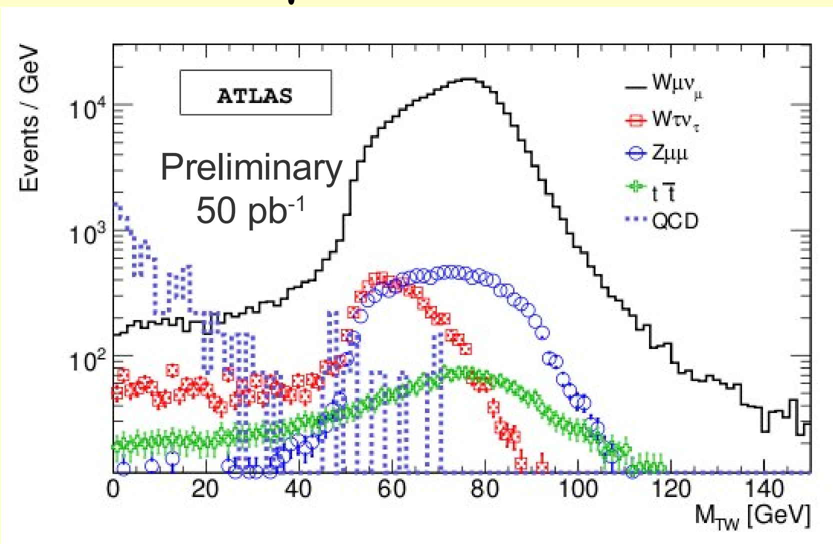
Even with early data (10-50 pb^{-1}),
high statistics of W and Z samples

→ data-driven cross-section measurements

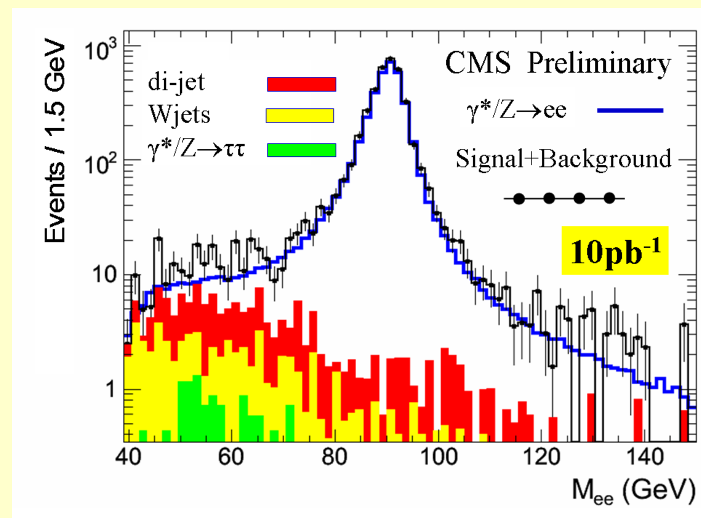
$W \rightarrow e\,\nu$



$W \rightarrow \mu\,\nu$



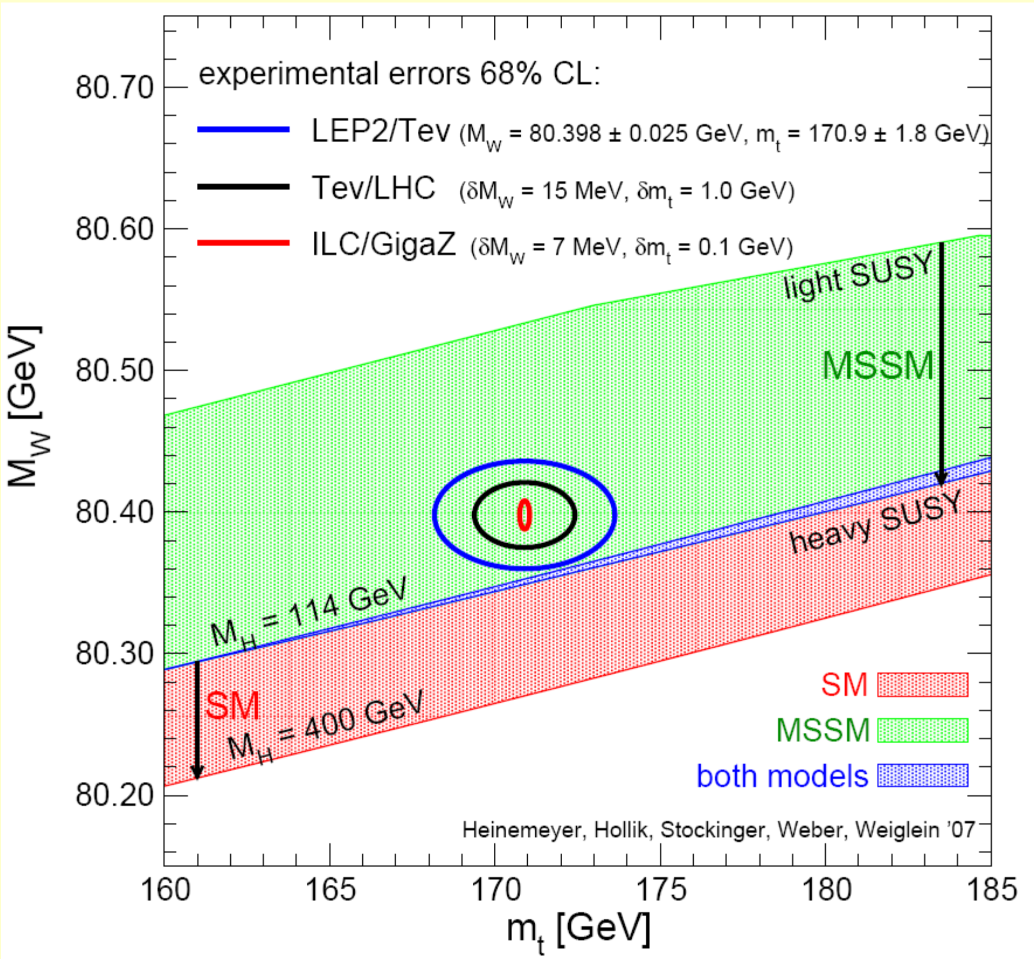
$Z \rightarrow ee$



Limited by luminosity error: ~ 5-10% in first year,
Longer term goal ~ 2%

(process might be used later for luminosity measurement)

Expectation for precision measurements at the LHC



<u>Expected precision</u>:

Tevatron (2 fb^{-1}):

δm_W = ± 25 MeV/c^2

δm_t = ±1.5 GeV/c^2

LHC (10 fb^{-1}):

δm_W ~ ±15 MeV/c^2

δm_t ~ ±1.0 GeV/c^2

experimental precision is limited Experimentally by the precise knowledge of the lepton energy scale

Where are the experimental limits ?
or: what is the benchmark for theory loop-precision ?

Study by M. Boonekamp et al. (still preliminary):

- Follow up and refinements of the main idea to **use the enormous Z $\rightarrow$ $\ell\ell$ sample** to fix the lepton energy scale (more detailed / differential analysis, P_T and η dependent)
- Control as well kinematical distributions (non trivial, tiny differences between W and Z)

Estimated exp. uncertainties (preliminary):

Source	Effect	$\partial m_W / \partial_{rel}\alpha$ (MeV/%)	$\delta_{rel}\alpha$ (%)	δm_W (MeV)
Prod. Model	W width	3.2	0.4	1.3
	y^W distribution	–	–	1
	p_T^W distribution	–	–	1
	QED radiation	–	–	<1 (*)
Lepton measurement	Scale & lin.	800	0.005	4
	Resolution	1	1.0	1
	Efficiency	–	–	4.5 (e) ; <1 (μ)
Recoil measurement	Scale	-200	–	–
	Resolution	-25	–	–
	Combined	–	–	5 (**)
Backgrounds	$W \to \tau\nu$	0.11	2.5	1.5
	$Z \to \ell(\ell)$	-0.01	2.8	0.2
	$Z \to \tau\tau$	0.01	4.5	0.1
	Jet events	0.04	10	0.4
Pile-up and U.E				<1 (e); $\sim 0(\mu)$
Beam crossing angle				<0.1
Total (m_T^W)				$\sim$8 (e); 7(μ)

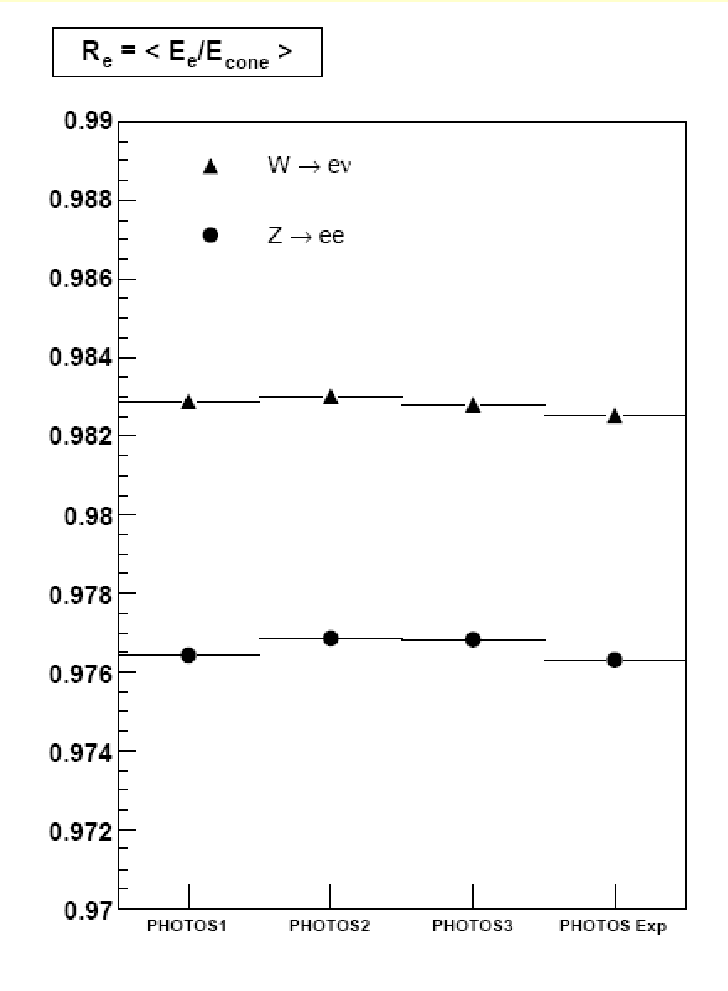
*) Note: uncertainties from radiative corrections are assumed to have LEP-precision

These numbers (~ 5 MeV) could be seen as a benchmark for theo. precision, to probably match the exp. precision….

**) Note: some estimates can only be done reliably once we have data, however, given numbers provide a reasonable goal

Sensitivity to QED final state radiation:

Average fraction of energy in the reconstructed electron cluster, norm. to original electron energy



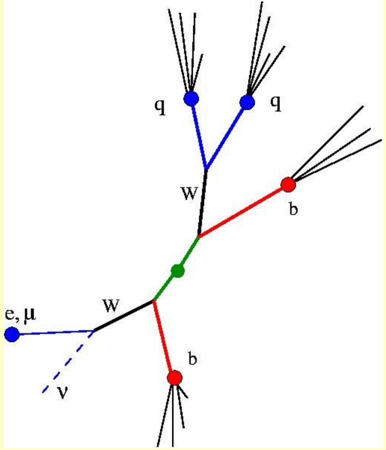
Photos:

(2) Photon emission up to $O(\alpha)$
(3) Photon emission up to $O(\alpha^2)$
(4) Photon emission up to $O(\alpha^4)$
(5) Photon emission, exponentiation

Note:
- since LEP Z mass is used, effects for both W and Z must be understood with high precision;
- Corrections need to be available in form of Monte Carlo simulation !!
  Exp. reconstruction (cluster for electron, muon track) must be performed
- Sensitivity:
  Scale uncertainty Δ=0.01% $\leftrightarrow$ 8 MeV

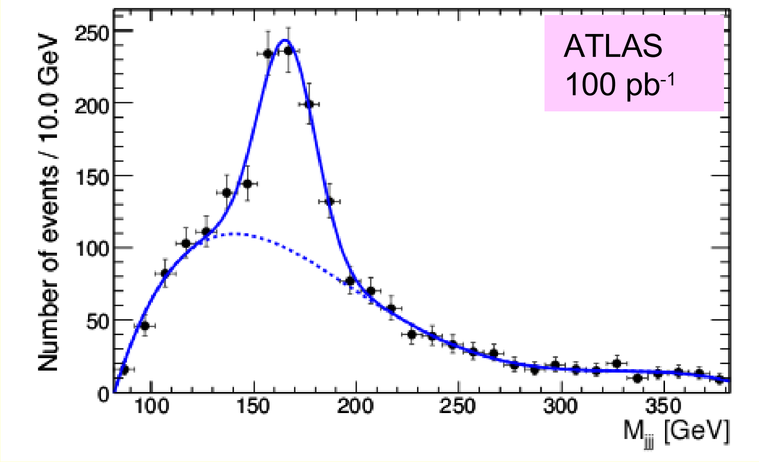
M. Boonekamp et al.

Early Physics: Top quark without b-tag



Extremely simple selection:

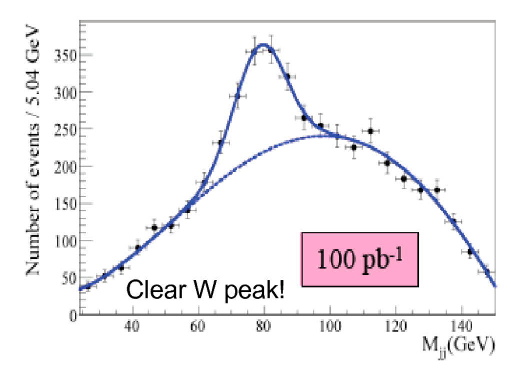
- Use tt Wb Wb $\ell\nu$b qqb decays
- 1 isolated lepton (p_T>20 GeV)
- Exactly 4 jets ($p_{T>}$40 GeV)
- no kinematic fit, no b-tagging (!)



Signal visible after few weeks at 10^{32}

- clear W mass peak visible
- use for jet energy calibration
- ideal to commission b-tagging !
- study one of the most important background to searches

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



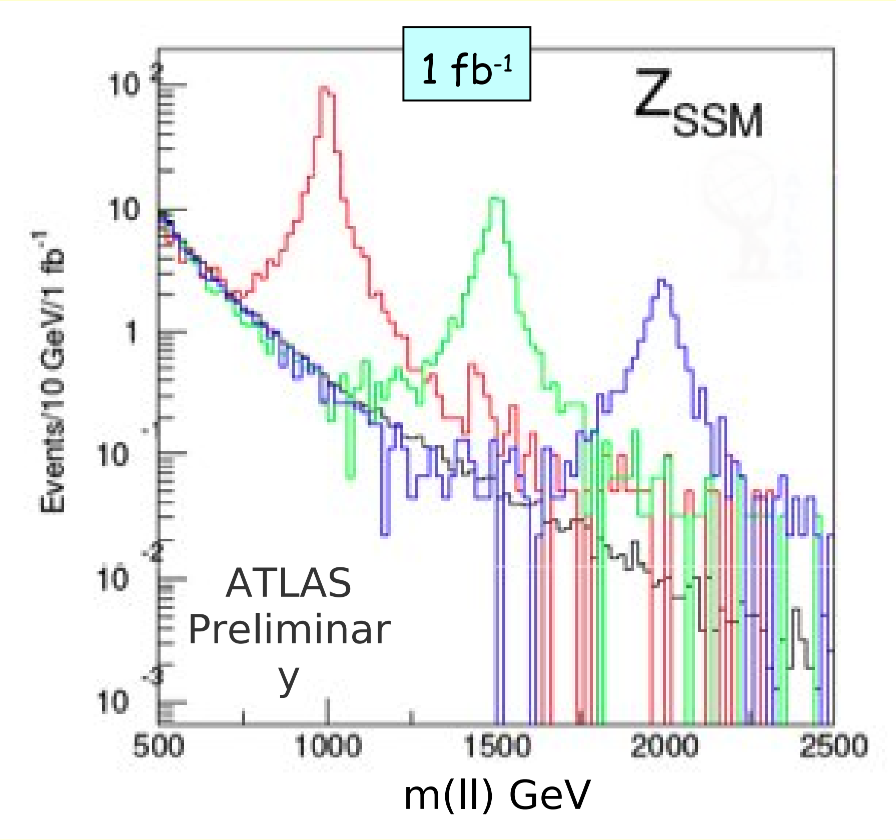
Early Surprises ??

- as already mentioned, the experiments must be open for surprises /
  unknowns /
  unexpected discoveries

- requires unbiased measurements of
  - inclusive lepton spectra
  - dileptons spectra……
  - ETmiss spectrum…….
  - ……

One example of many….

$Z' \rightarrow e^+e^-$ with SM-like couplings (Z_{SSM})



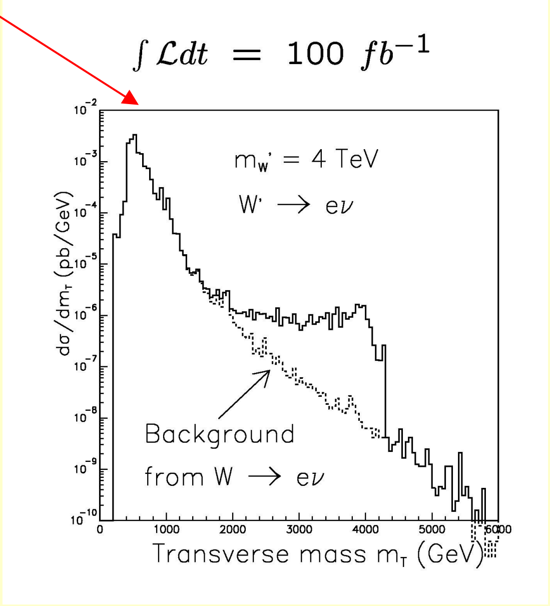
Mass (TeV)	Events / fb^{-1} (after cuts)	Luminosity needed for a 5σ discovery + (10 obs. events)
1	~160	~70 pb^{-1}
1.5	~30	~300 pb^{-1}
2	~7	~1.5 fb^{-1}

Discovery window above Tevatron limits
m ~ 1 TeV, perhaps even in 2008... (?)

LHC reach for BSM Physics with higher luminosity

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

	30 fb^{-1}	100 fb^{-1}
Excited Quarks $Q^* \to q\,\gamma$	M (q*) ~ 3.5 TeV	M (q*) ~ 6 TeV
Leptoquarks	M (LQ) ~ 1 TeV	M (LQ) ~ 1.5 TeV
$Z' \to \ell\ell$, jj $W' \to \ell\,\nu$	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

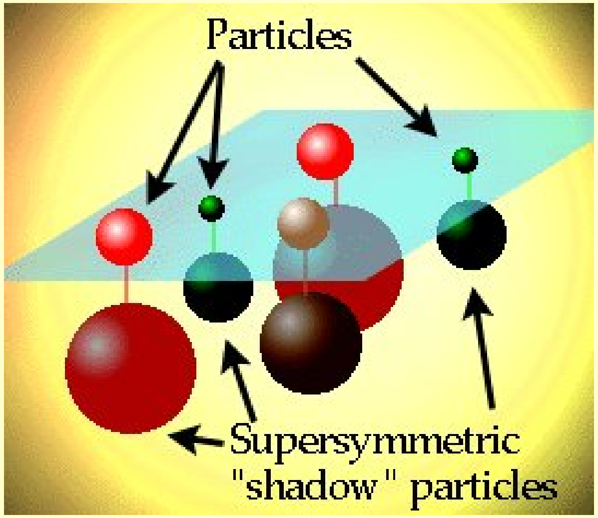


Search for

Supersymmetry

First hints of supersymmetry might show up as well already in early data……

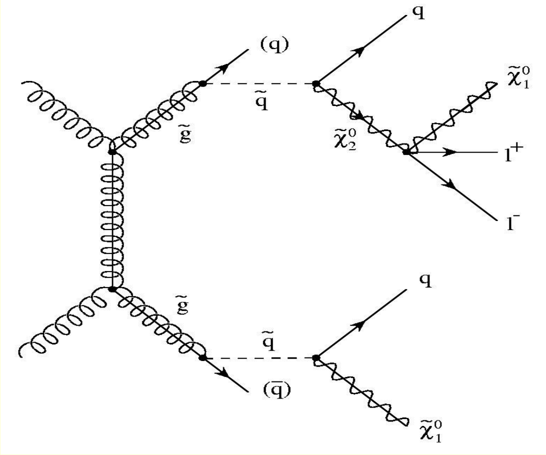
e.g. deviations from the Standard Model expectation in the E_T^{miss} spectrum



Search for Supersymmetry

- Squarks and Gluinos are strongly produced

  They decay through cascades to the lightest SUSY particle (LSP)



$\Longrightarrow$ combination of Jets, Leptons, E_T^{miss}

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

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

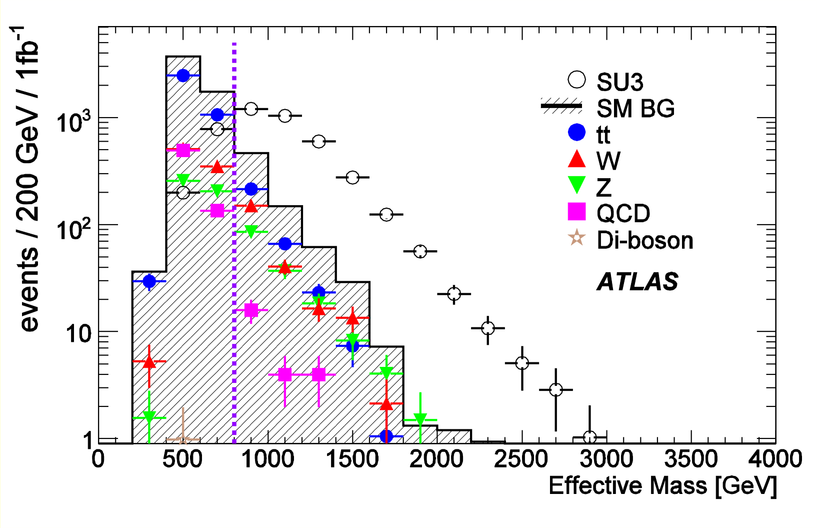
3. Step: Determine model parameters (difficult)
   Strategy: select particular decay chains and use kinematics to determine mass combinations

Squarks and Gluinos

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

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

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



LHC reach for Squark- and Gluino masses:

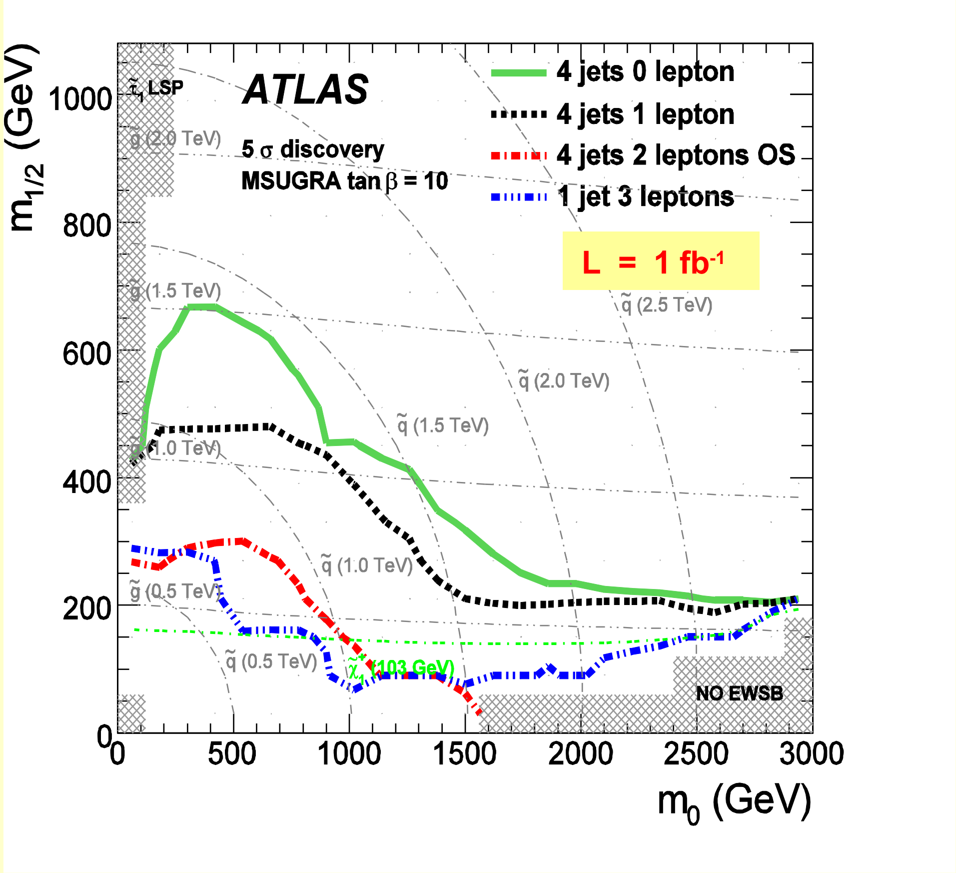
0.1 fb^{-1}	$\Rightarrow$	M ~ 750 GeV
1 fb^{-1}	$\Rightarrow$	M ~ 1350 GeV
10 fb^{-1}	$\Rightarrow$	M ~ 1800 GeV

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

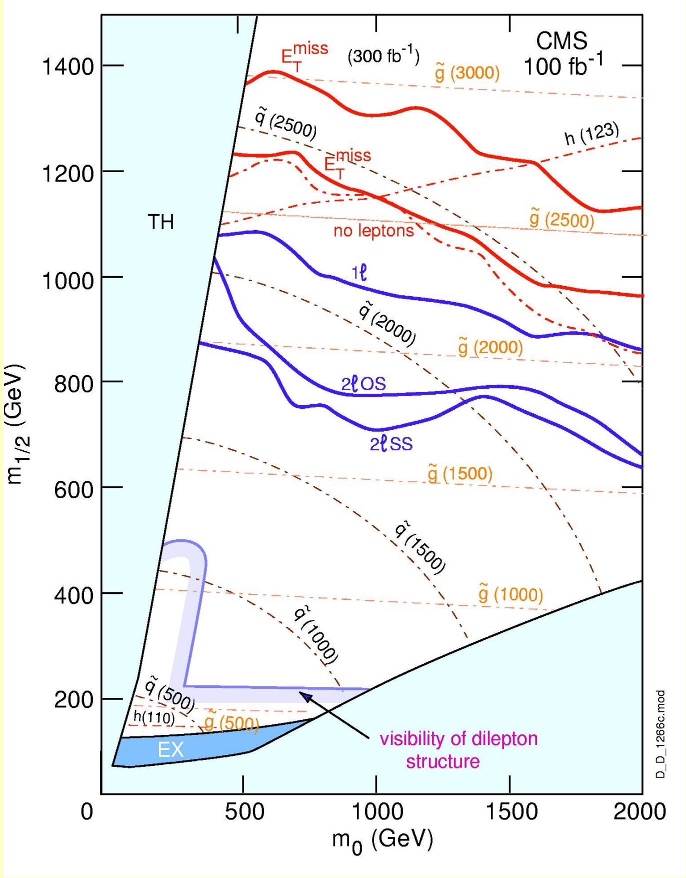
example: mSUGRA, point SU3
m_0 = 100 GeV, $m_{1/2}$ = 300 GeV
$\tan\beta$ = 6, A_0 = -300, $\mu > 0$

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

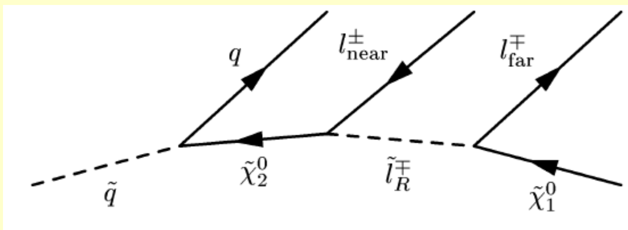
LHC Strategy for determination of model parameters:

End point spectra of cascade decays

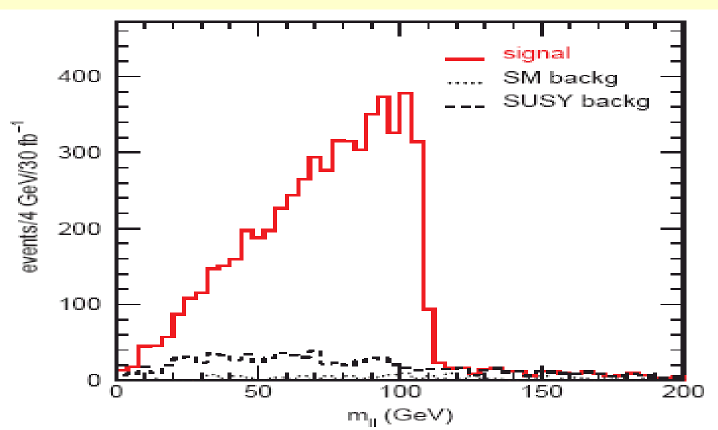
Example: $\tilde{q} \to q\tilde{\chi}_2^0 \to q\tilde{\ell}^{\pm}\ell^{\mp} \to q\ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$

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

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

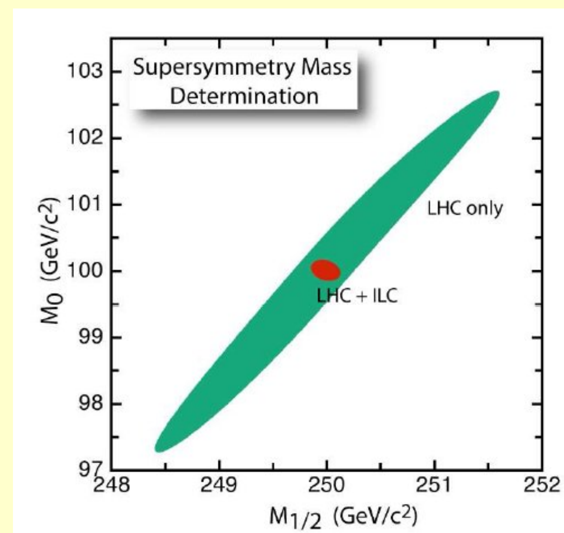


Results for point 01:



	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

$L = 300\ fb^{-1}$



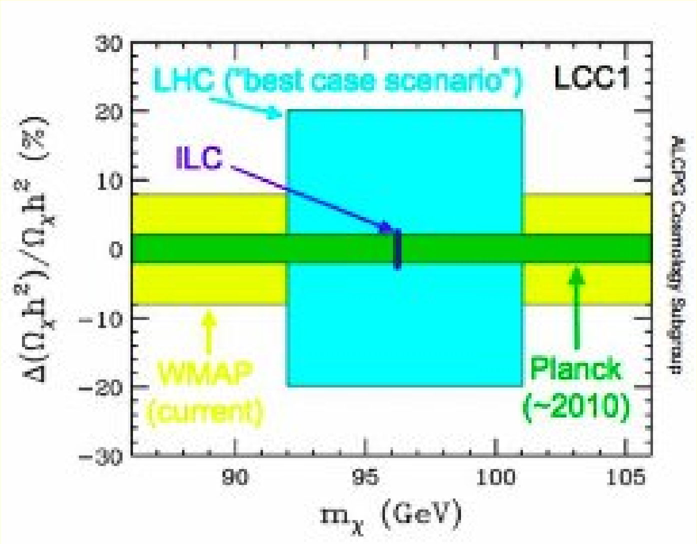
Strategy in SUSY Searches at the LHC:

- 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. $\tilde{\chi}_2^0 \to \tilde{\ell}^{\pm}\ell^{\mp} \to \tilde{\chi}_1^0 \ell^+\ell^- \to \tilde{G}\gamma\ell^+\ell^-$

$\Rightarrow$ 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 multijet background)

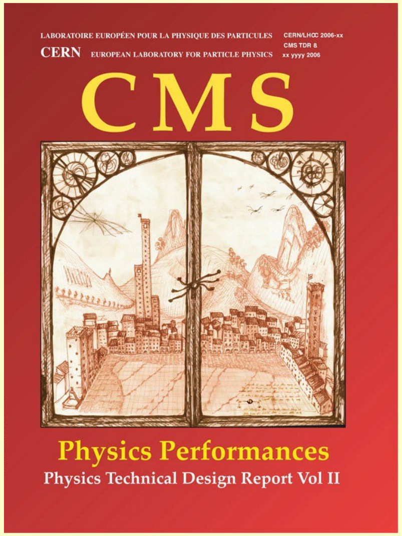
The Search for

The Higgs boson

The first Higgs at ATLAS

What is new on LHC Higgs studies ?

- Many studies have meanwhile been performed using detailed GEANT simulations of the detectors
  - Physics Performance Technical Design Report from the CMS collaboration
  - ATLAS CSC (Computing System Commissioning) notes to be released in ~ 1 month



CERN / LHCC 2006-021

- New (N)NLO Monte Carlos (also for backgrounds)
  - MCFM Monte Carlo, J. Campbell and K. Ellis, http://mcfm.fnal.gov
  - MC@NLO Monte Carlo, S.Frixione and B. Webber, wwwweb.phy.cam.ar.uk/theory/
  - T. Figy, C. Oleari and D. Zeppenfeld, Phys. Rev. D68, 073005 (2003)
  - E.L.Berger and J. Campbell, Phys. Rev. D70, 073011 (2004)
  - C. Anastasiou, K. Melnikov and F. Petriello, hep-ph/0409088 and hep-ph/0501130
  - …..

- New approaches to match parton showers and matrix elements
  - ALPGEN Monte Carlo + MLM matching, M. Mangano et al.
  - SHERPA Monte Carlo, F. Krauss et al.
  - …

  Tevatron data are extremely valuable for validation, work has started

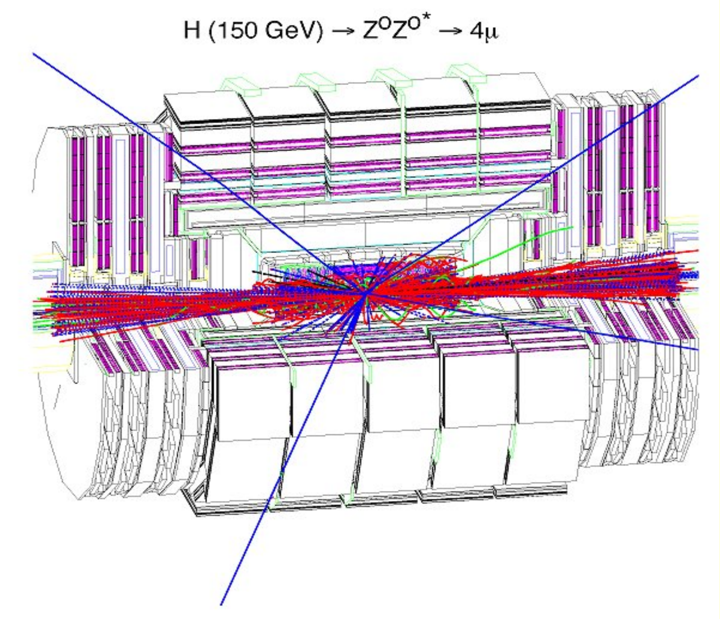
- More detailed, better understood reconstruction methods

  (partially based on test beam results,…)

- Further studies of new Higgs boson scenarios

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

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

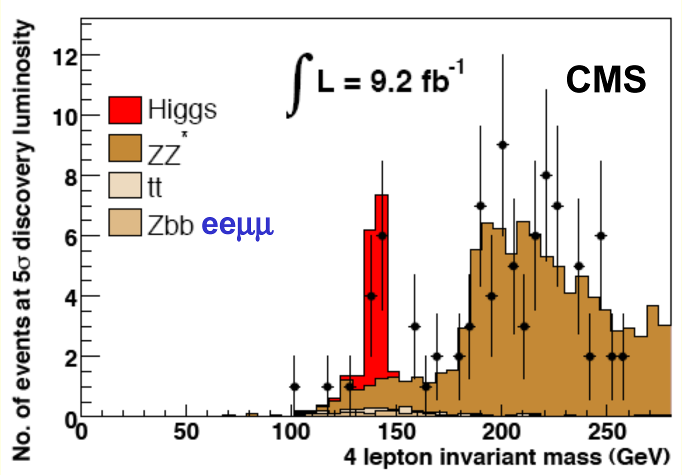


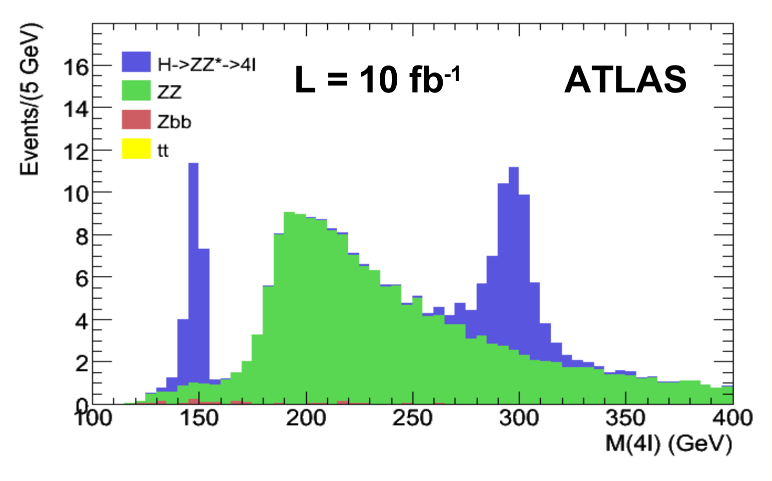
- Main backgrounds: ZZ (irreducible), tt, Zbb (reducible)
- Main experimental tools for background suppression:
  - lepton isolation in the tracker and in the calorimeter
  - impact parameter

Updated ATLAS and CMS studies:

- ZZ background: NLO K factor used
- background from side bands

(gg->ZZ is added as 20% of the LO qq->ZZ)

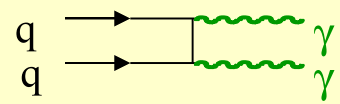




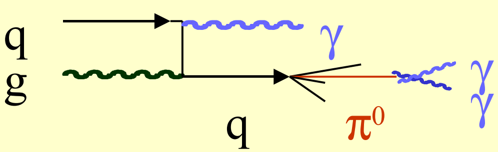
$H \to \gamma\gamma$

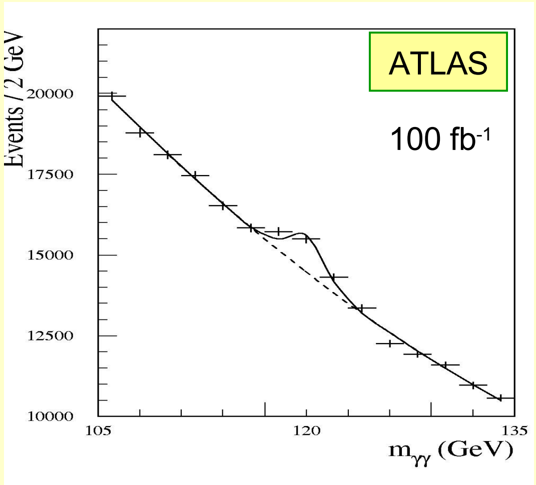
Main backgrounds:

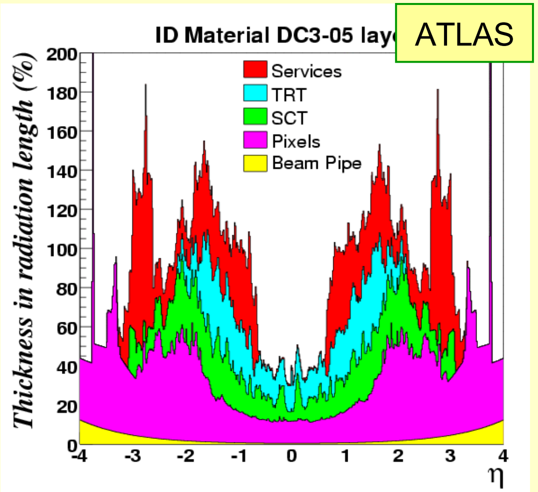
$\gamma\gamma$ irreducible background

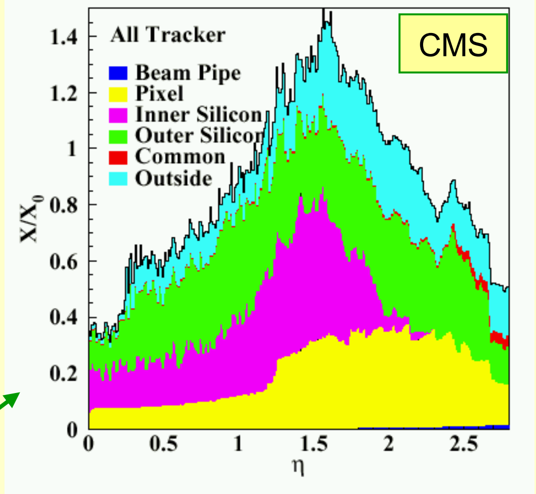


γ-jet and jet-jet (reducible)









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

$\to$ 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

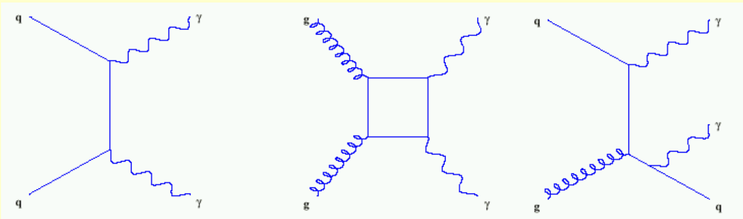
Barrel region: 42.0 %

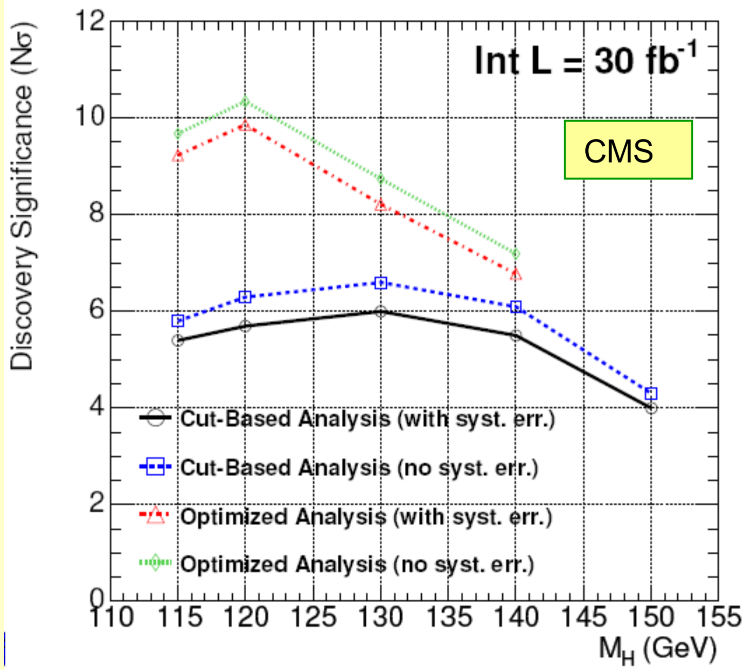
Endcap region: 59.5 %

CMS Study: TDR (updated)

New elements of the analysis:

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





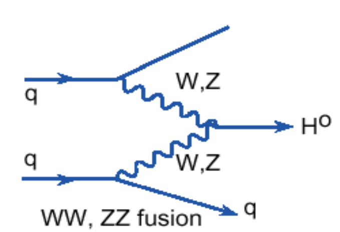
- NLO calculations available (Binoth et al., DIPHOX, RESBOS)
- Realistic detector material
- More realistic K factors (for signal and background)
- Improvements possible by using more exclusive $\gamma\gamma$ + jet topologies

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

Vector Boson Fusion qq H



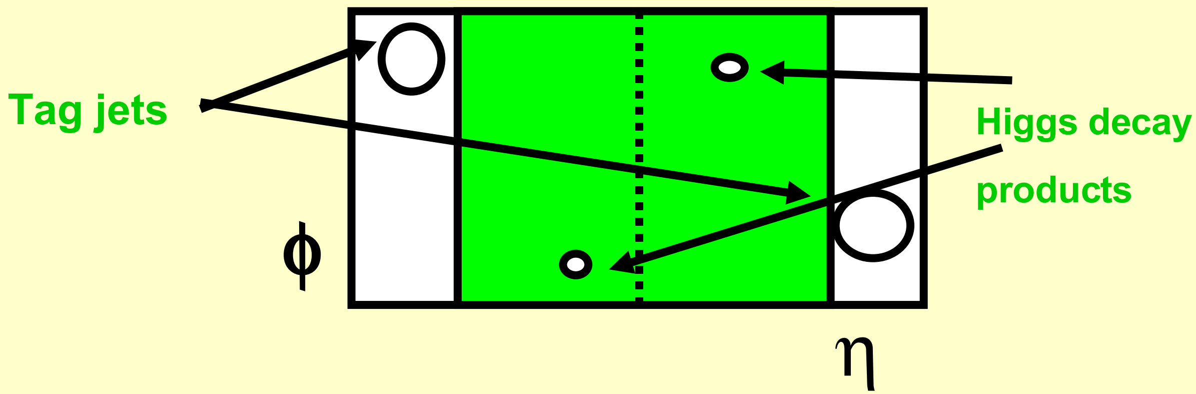
Motivation: Increase discovery potential at low mass
Improve and extend measurement of Higgs boson parameters
(couplings to bosons, fermions)

Established (low mass region) by D. Zeppenfeld et al. (1997/98)

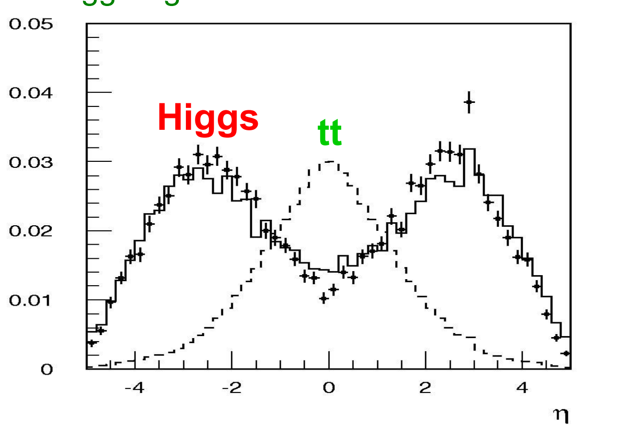
Earlier studies: R.Kleiss W.J.Stirling, Phys. Lett. 200 (1988) 193;
Dokshitzer, Khoze, Troyan, Sov.J. Nucl. Phys. 46 (1987) 712;
Dokshitzer, Khoze, Sjöstrand, Phys.Lett., B274 (1992) 116.

Distinctive Signature of:

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



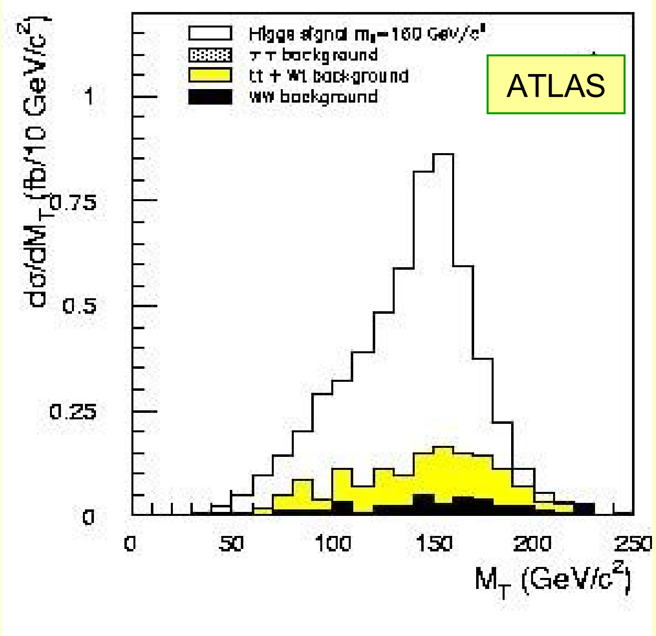
Rapidity distribution of jets in tt and Higgs signal events:



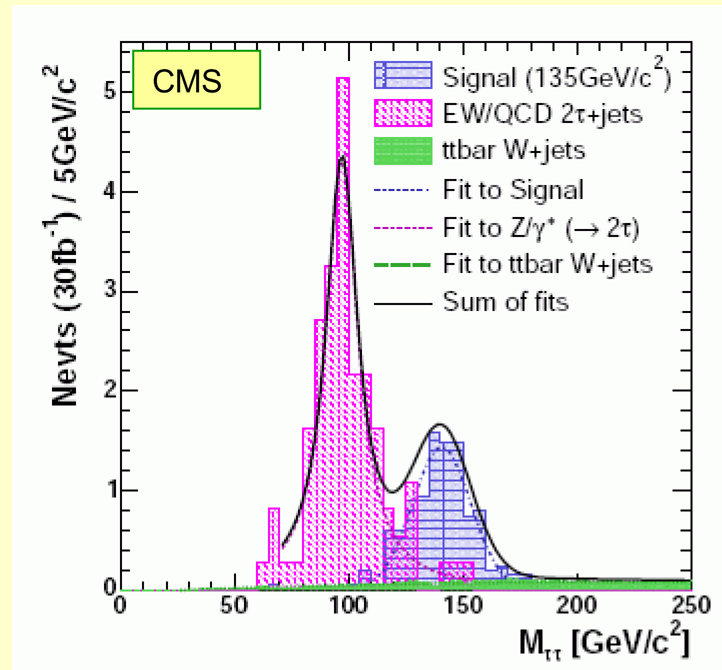
Two search channels at the LHC:

qq H → qq W W*
→ qq ℓν ℓν

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



qq H → qq τ τ
→ qq ℓνν ℓνν
→ qq ℓνν hν

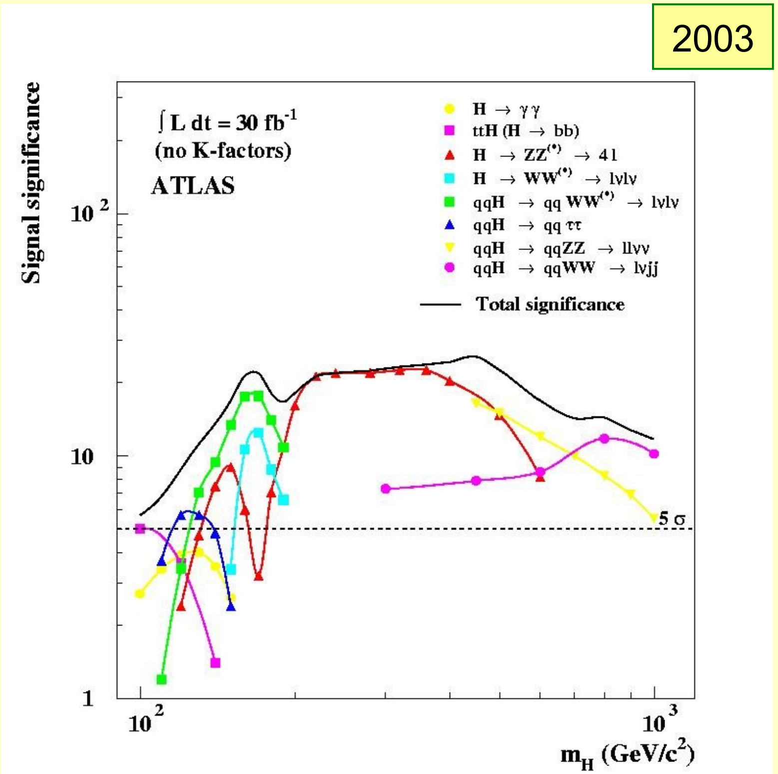


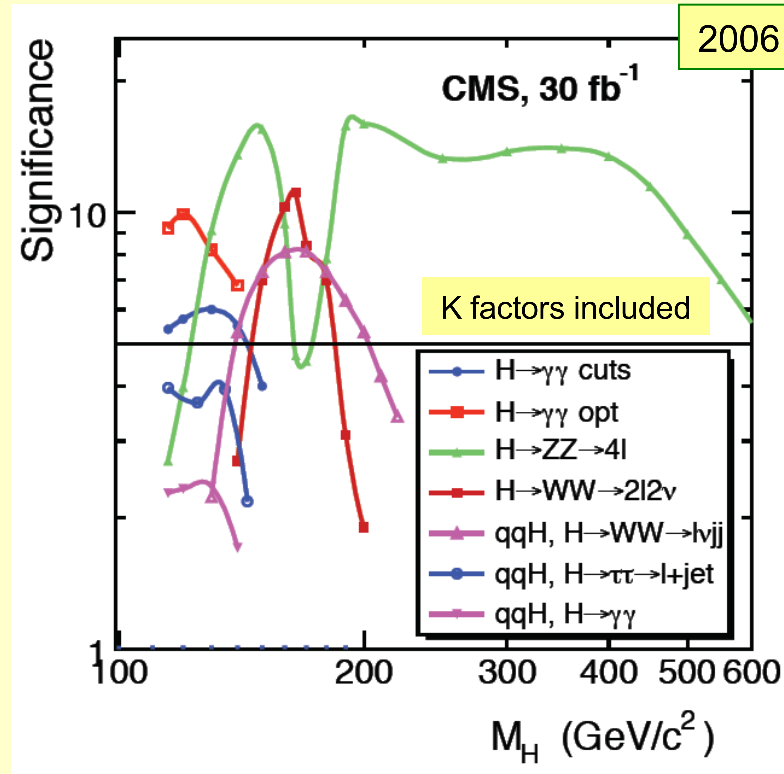
Selection criteria:

- 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

Sensitivity confirmed in full simulation

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

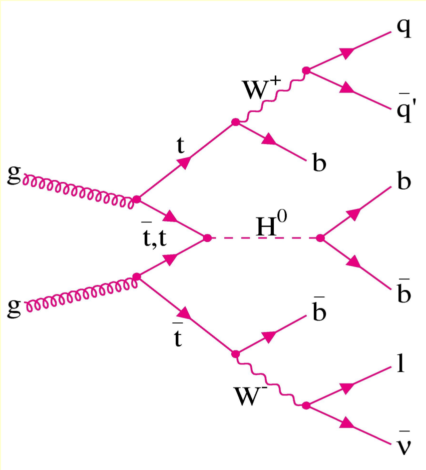
  Vector boson fusion channels play an important role at low mass !

Important changes w.r.t. previous studies:

- **$H \to \gamma\gamma$** sensitivity of ATLAS and CMS comparable
- **$ttH \to tt\ bb$** disappeared in CMS study (updated (ME) background estimates, under study in ATLAS)

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

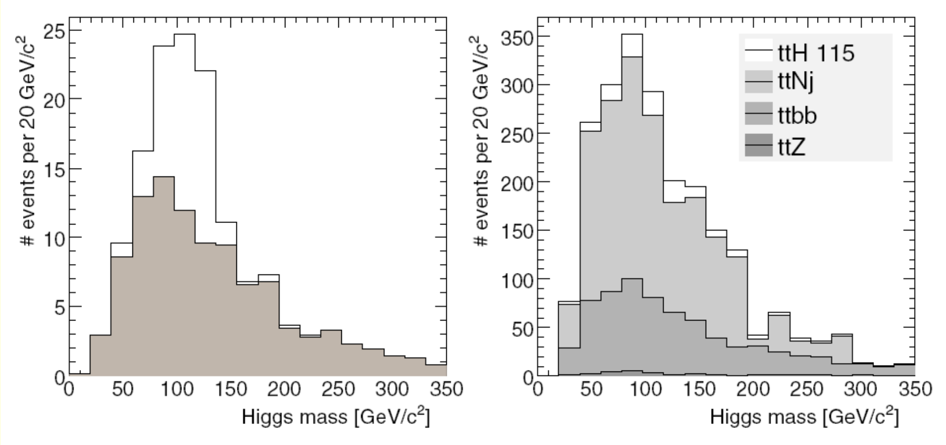
Complex final states: H→ bb, t → bjj, t → b孭ν
t → bℓν, t → b孭ν
t → bjj, t → bjj



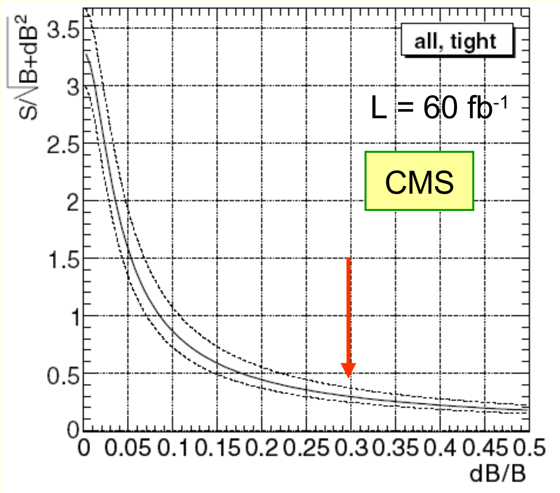
Main backgrounds:
- combinatorial background from signal (4b in final state)
- ttjj, ttbb, ttZ,…
- Wjjjjj, WWbbjj, etc. (excellent b-tag performance required)

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

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



Signal events only …. backgrounds added

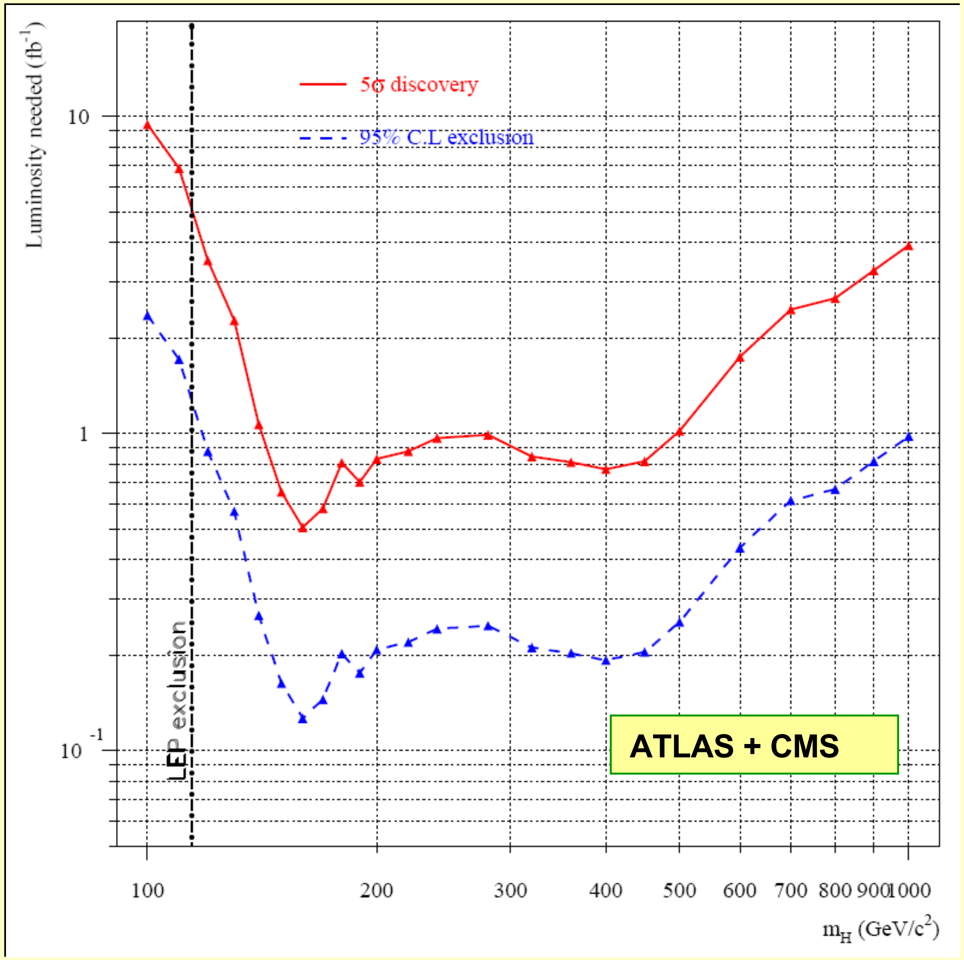


Signal significance as function of background uncertainty

Comparable results for ATLAS

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)

Summary / Conclusions

- After more than 15 years of hard work The *Large Hadron Collider* and the experiments will start operation this year (in a few months !!)
  ….. and Particle Physics is about to enter a new era

- Experiments are well prepared to record the first data

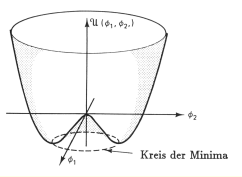
- Interesting physics might come out already this year or early next year

- On the longer term: 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

Backup slides



Is it a Higgs Boson ?

-can the LHC measure its parameters ?-

1. Mass

Higgs boson mass can be measured with a precision of 0.1%
over a large mass range (130 - ~450 GeV/c^2)
($\gamma\gamma$ and ZZ→ 4ℓ resonances, el.magn. calo. scale uncertainty assumed to be ± 0.1%)

2. Couplings to bosons and fermions

3. Spin and CP

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

C.P. Buszello et al. Eur. Phys. J. C32 (2003) 209;
S. Y. Choi et al., Phys. Lett. B553 (2003) 61.
→ ATLAS and CMS studies on H → ZZ → 4ℓ
\+ new studies using VBF (CP from tagging jets) in ATLAS (→ **Talks in parallel sessions)**

4. Higgs self coupling

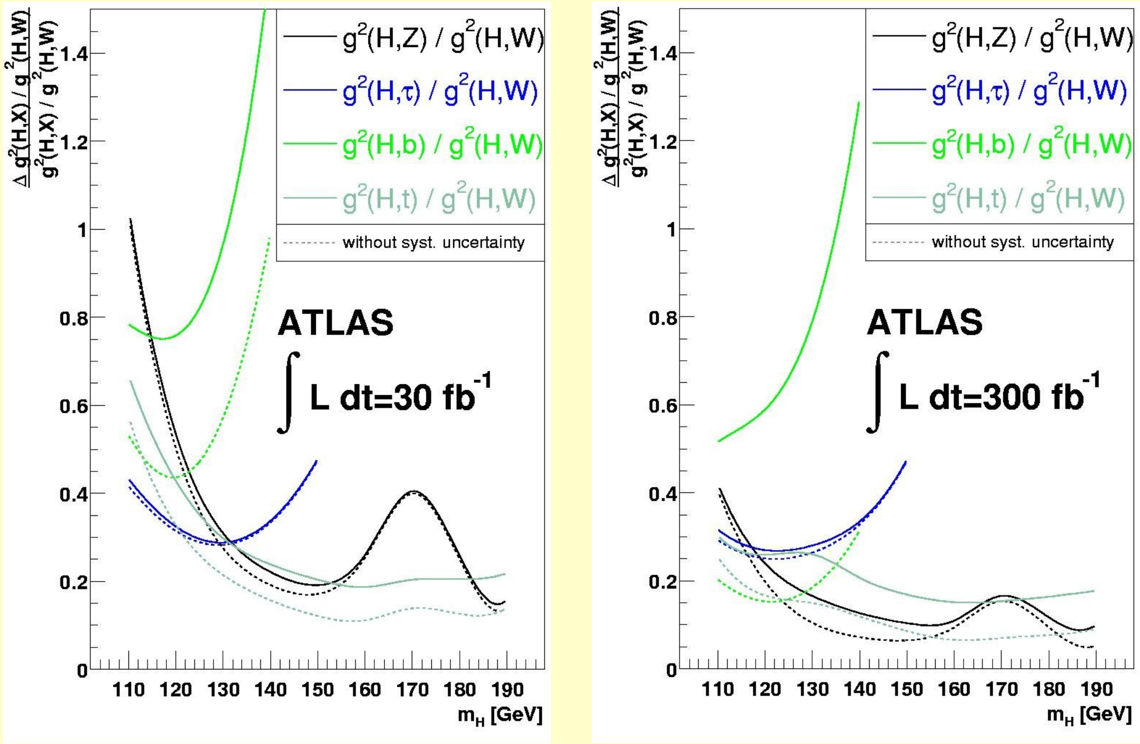
Possible channel: **gg → HH → WW WW → ℓν jj ℓν jj** (like sign leptons)
Small signal cross sections, large backgrounds from tt, WW, WZ, WWW, tttt, Wtt,...

⇒ no significant measurement possible at the LHC
very difficult at a possible SLHC (6000 fb^{-1})
limited to mass region around 160 GeV/c^2 (update will appear soon)

Measurement of Higgs Boson Couplings

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

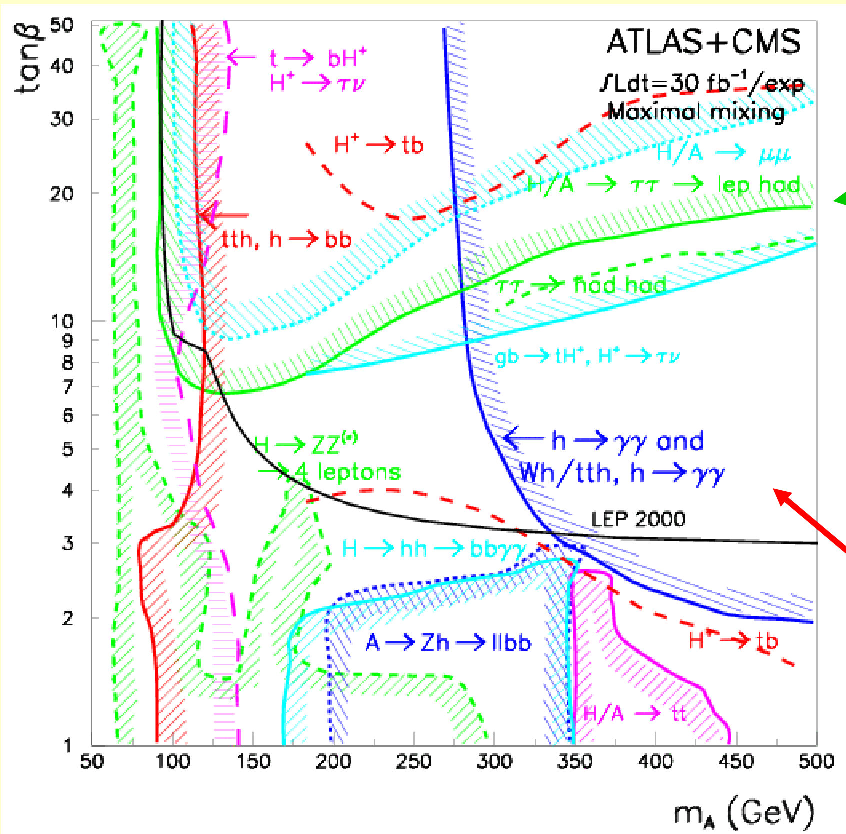
Output: Higgs boson couplings, normalized to the WW-coupling



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

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)

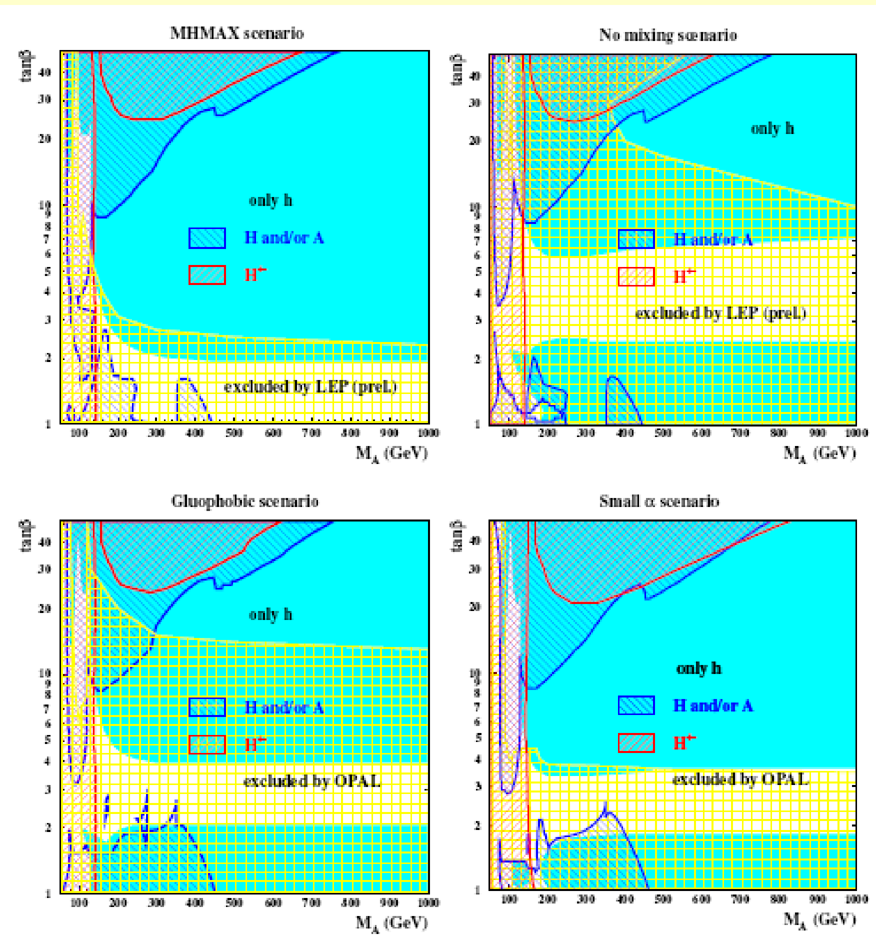
Here only SM-like h observable if SUSY particles neglected.

* 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

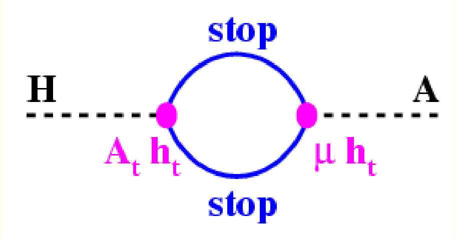
Gluophobic scenario (M_{SUSY} = 350 GeV/c^2)
coupling to gluons suppressed
(cancellation of top + stop loops)
small rate for g g → H, H→ γγ and Z→4 ℓ

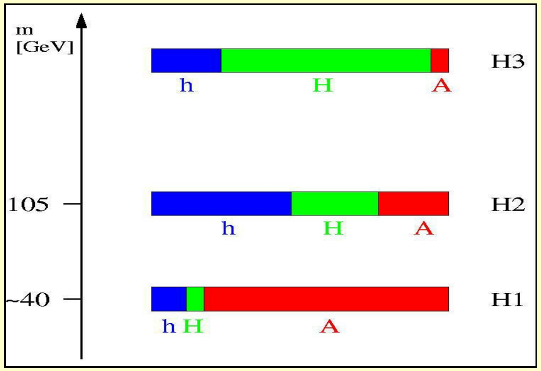
Small α scenario (M_{SUSY} = 800 GeV/c^2)

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))

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

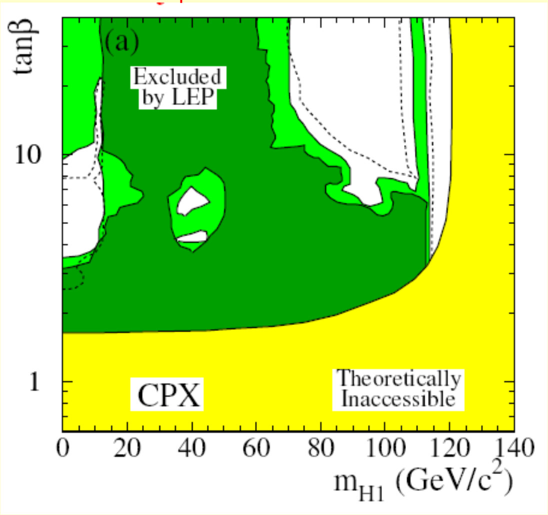
- No lower mass limit for H_1 from LEP !

(decoupling from the Z)

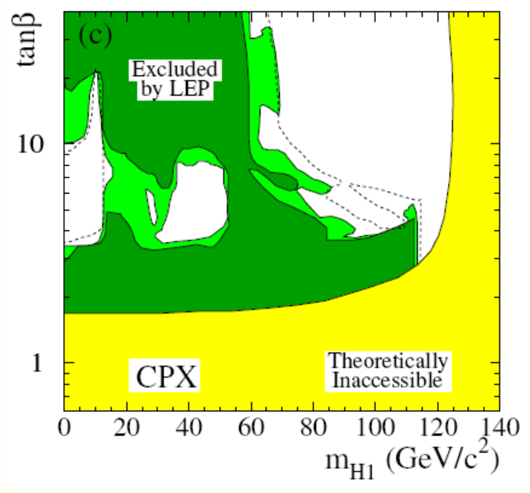
details depend on m_{top} and on theory model

(FeynHiggs vs. CPsuperH)

m_{top} = 169.3 GeV/c^2

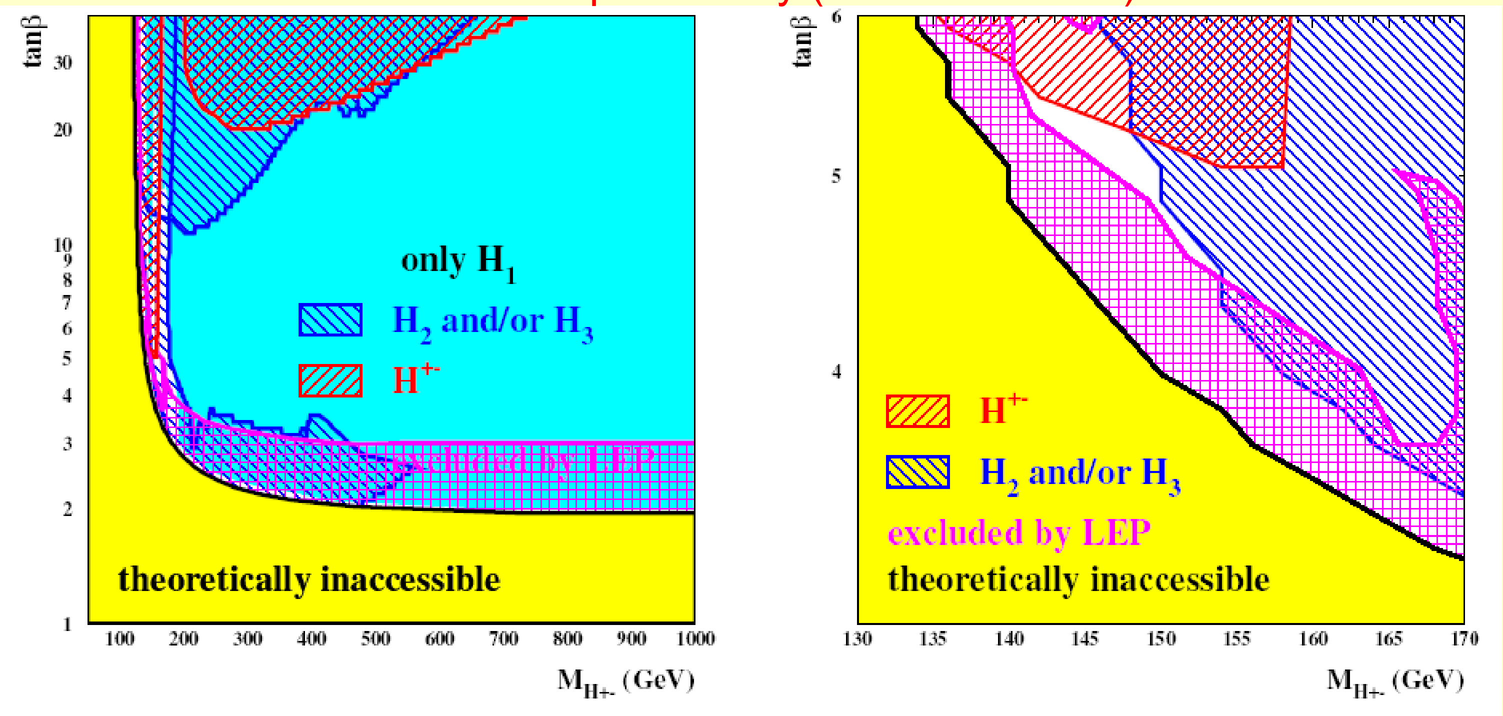


m_{top} = 174.3 GeV/c^2



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:

  $tt \rightarrow Wb\ H^+b \rightarrow \ell\nu b\ WH_1b,\ \ H_1 \rightarrow bb$

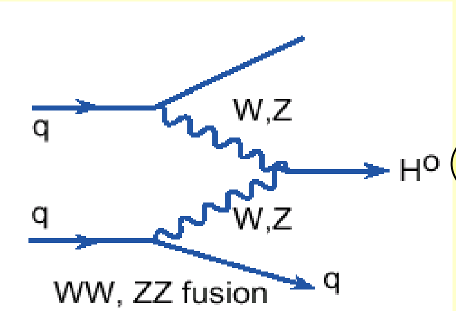
Invisible Higgs decays ?

Possible searches: $t\bar{t}H \rightarrow \ell\nu b\, qqb + P_T^{miss}$

$ZH \rightarrow \ell\ell + P_T^{miss}$

$qqH \rightarrow qq + P_T^{miss}$

- 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)

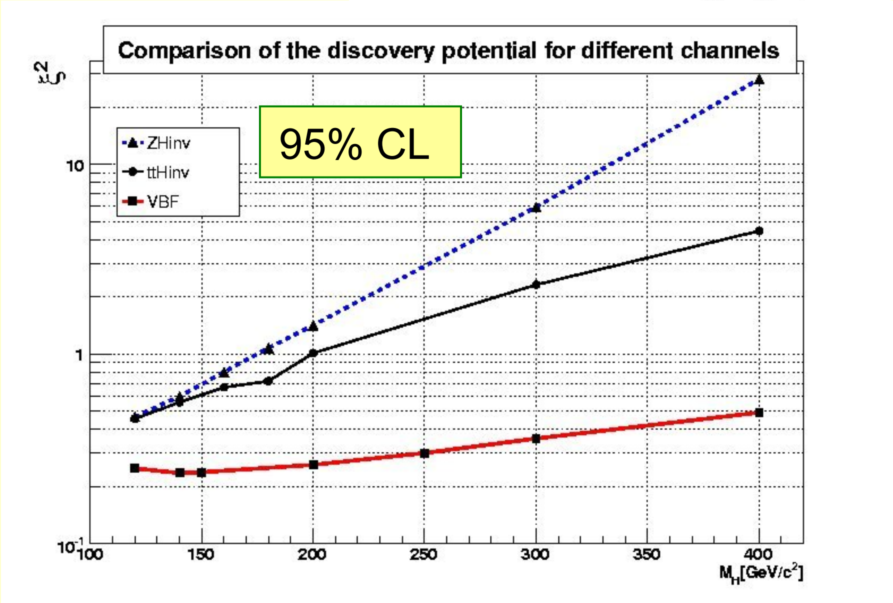


P_T^{miss}

All three channels have been studied:

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

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



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