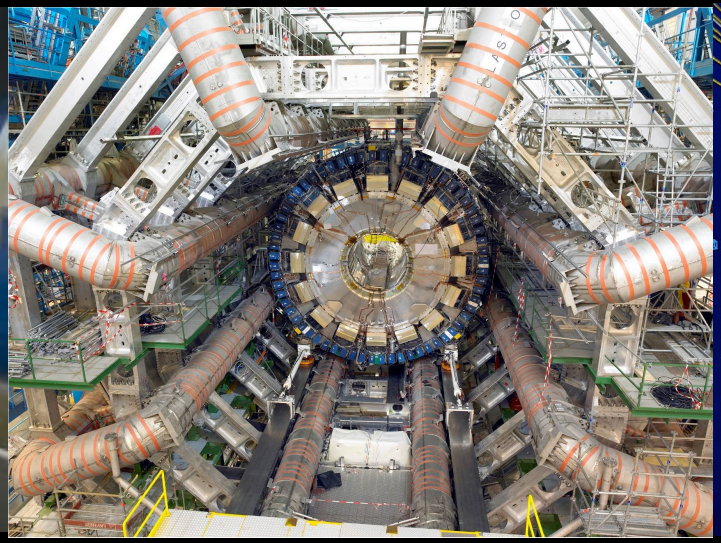
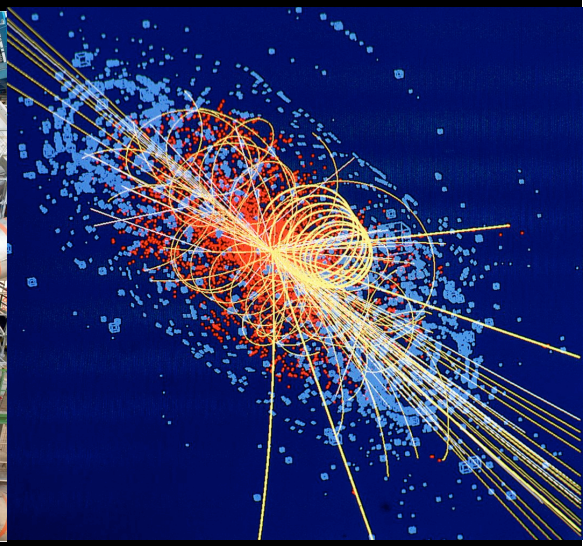
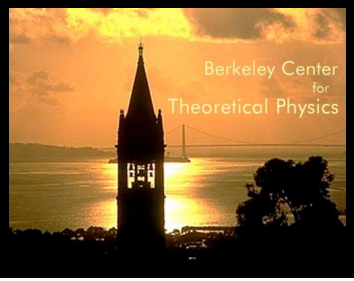
Exploring the TeV Scale at the LHC: Status and Perspectives

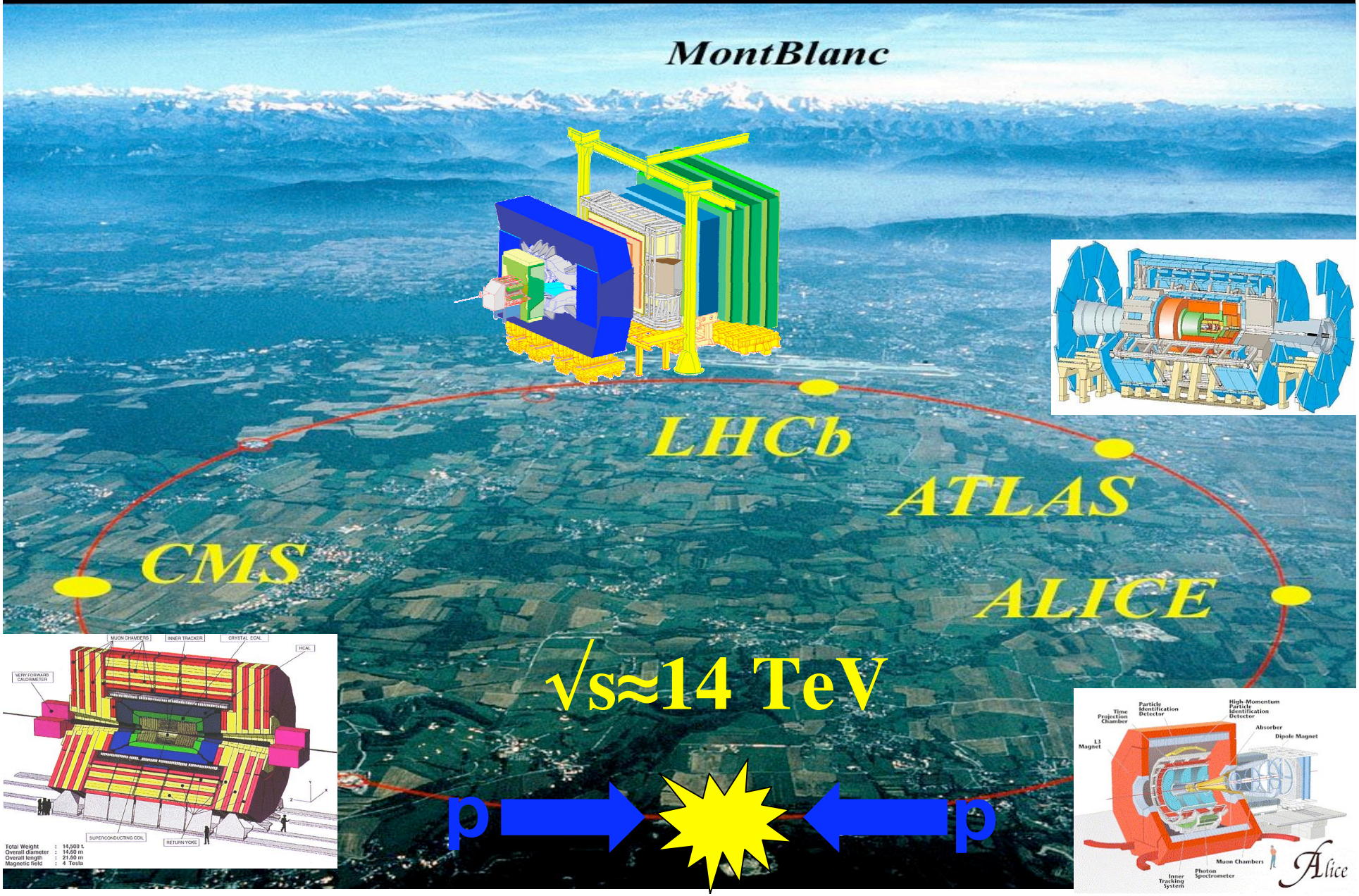
Beate Heinemann

UC Berkeley & Lawrence Berkeley National Laboratory



Opening of Berkeley Center for Theoretical Physics
October 2007

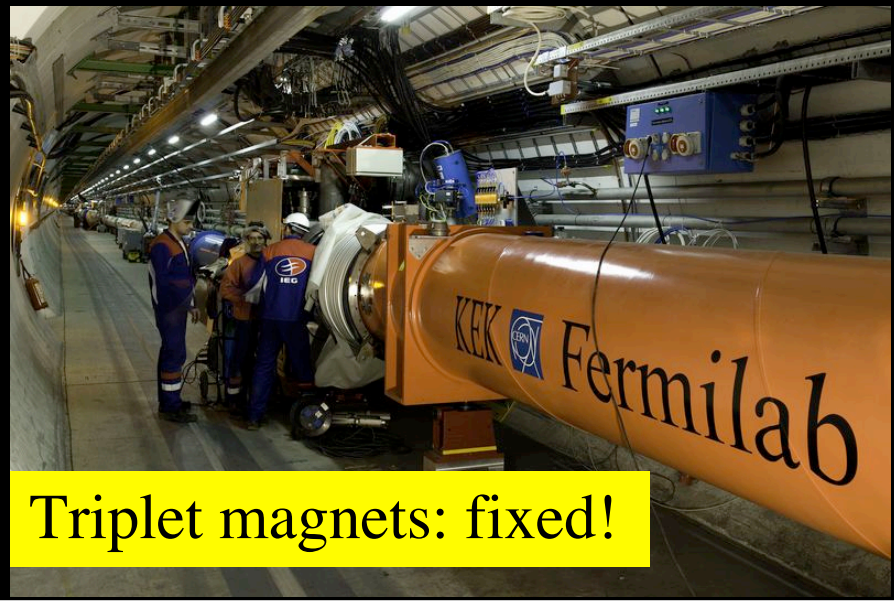
The Large Hadron Collider (LHC)



LHC Construction

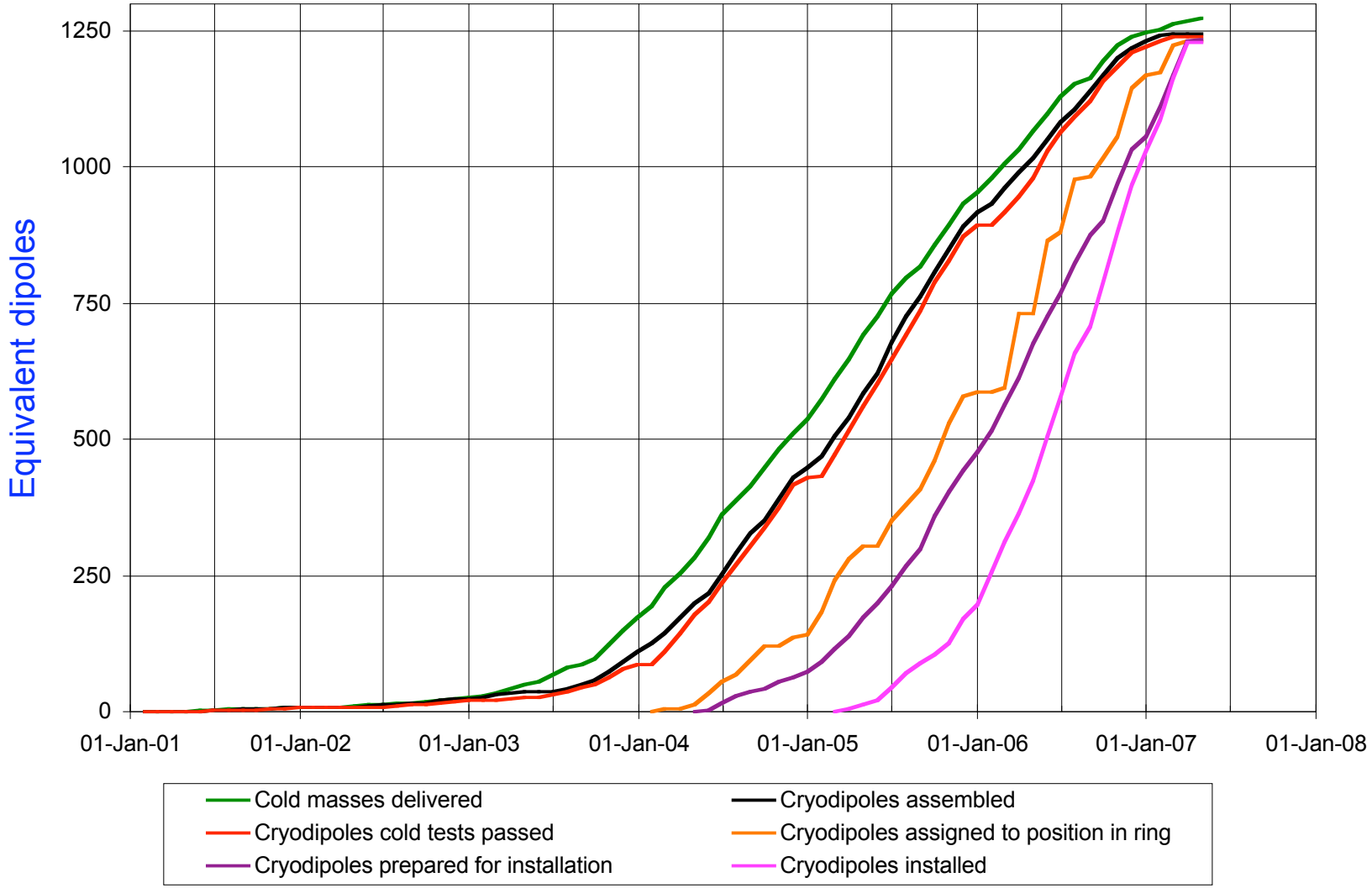
April 26th 2007
Descent of last magnet

Cryostating	425 FTE.years
Cold tests	640 FTE.years

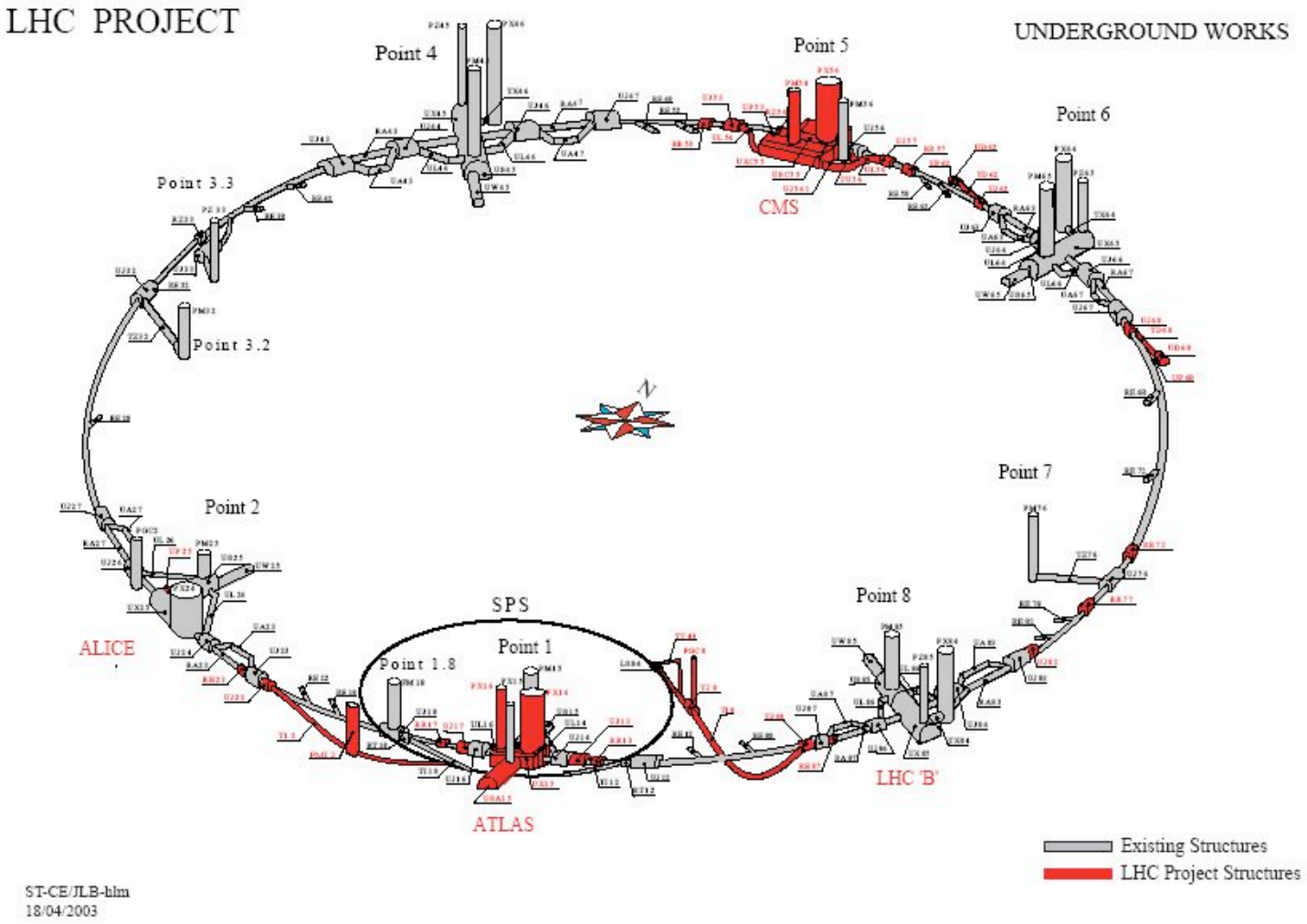


Triplet magnets: fixed!

Dipole magnets



LHC Machine Layout

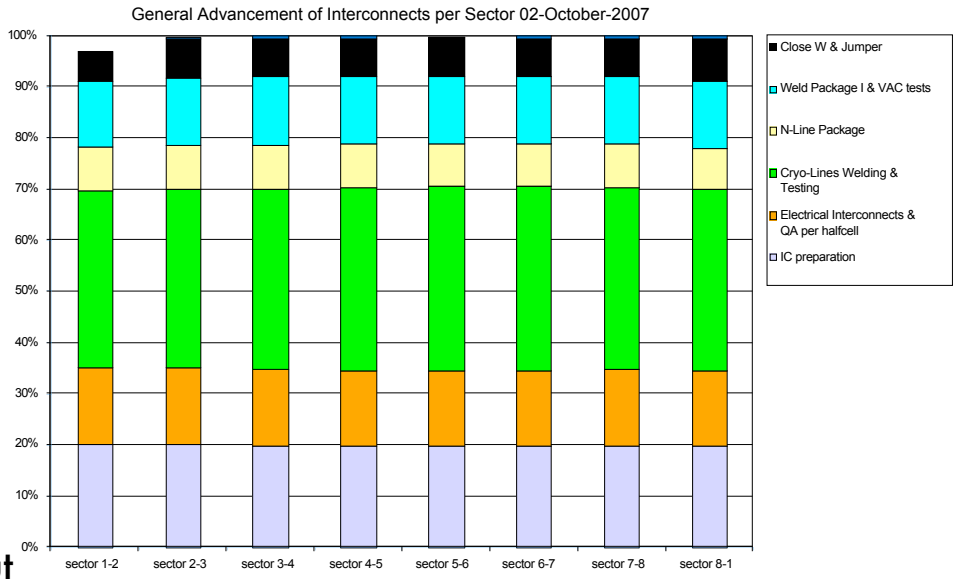


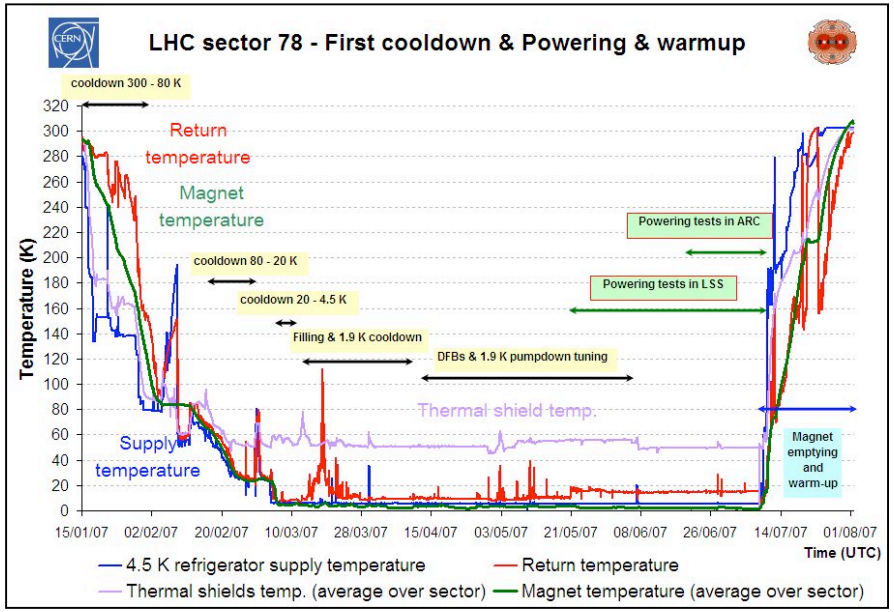
Machine consists of 8 cryogenically separate “sectors”

- e.g. “sector 81” means sector between ATLAS and LHCb

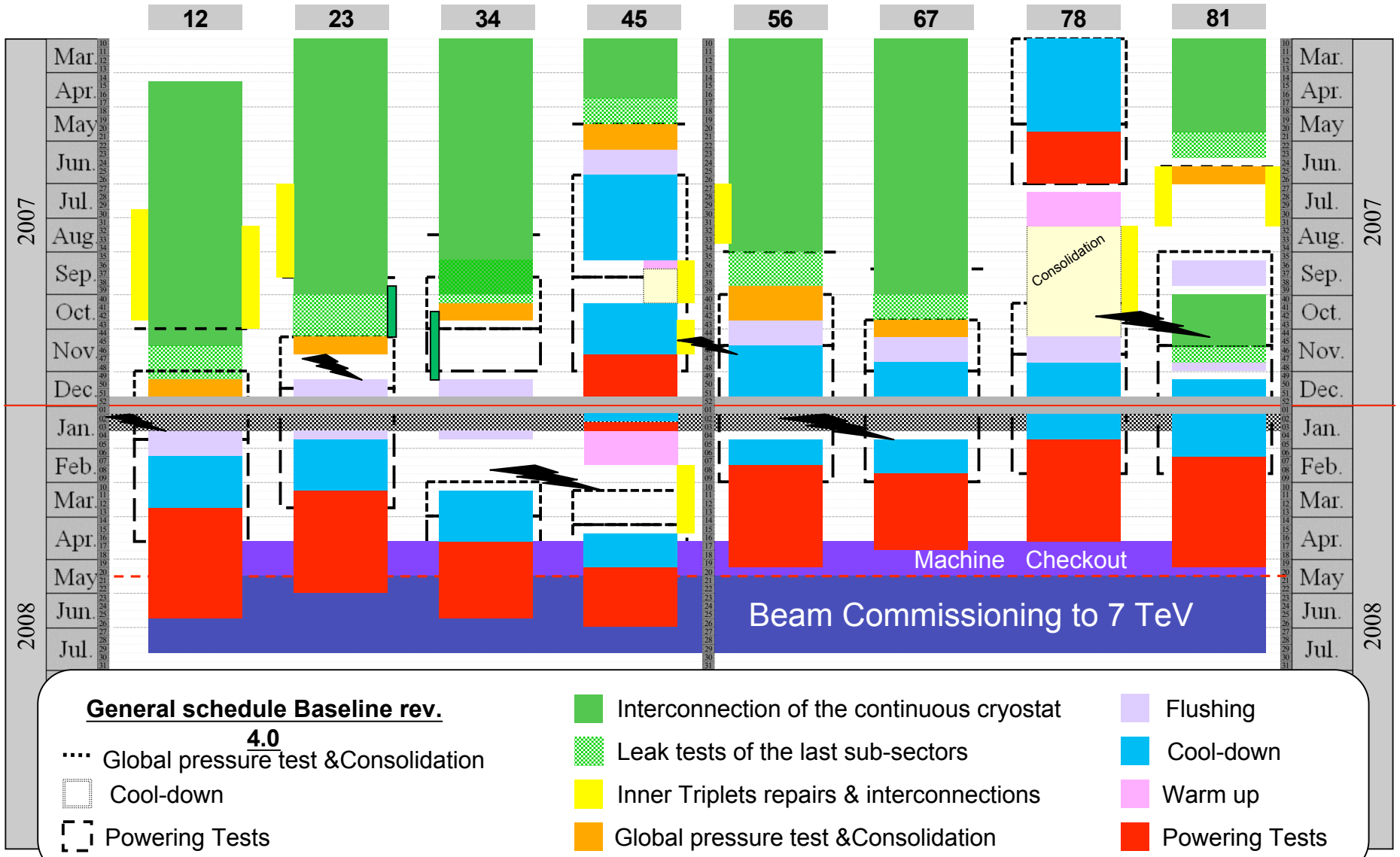
LHC Schedule

- For each sector:
  - Magnet interconnections:
    - Done for 7 out of 8
  - Cooldown to 1.9K:
    - Started for 2 sectors:
      1. Leak detected
      2. Ground fault detected
      3. "finger" problem after warmup but no more warmups scheduled
  - Powering tests
- Beam commissioning
- "Success oriented" schedule:
  - First beam: May 21 2008
  - Collisions ≈2 months later





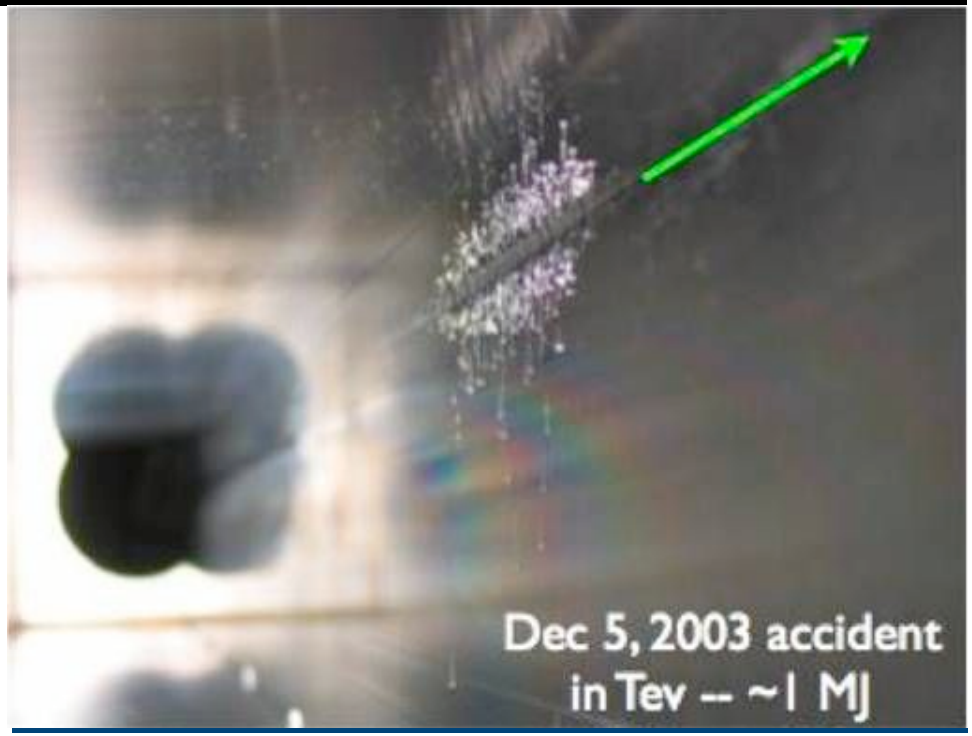
Updated General Schedule 10/07



Watch http://lhc.web.cern.ch/lhc/

When there is beam it's dangerous

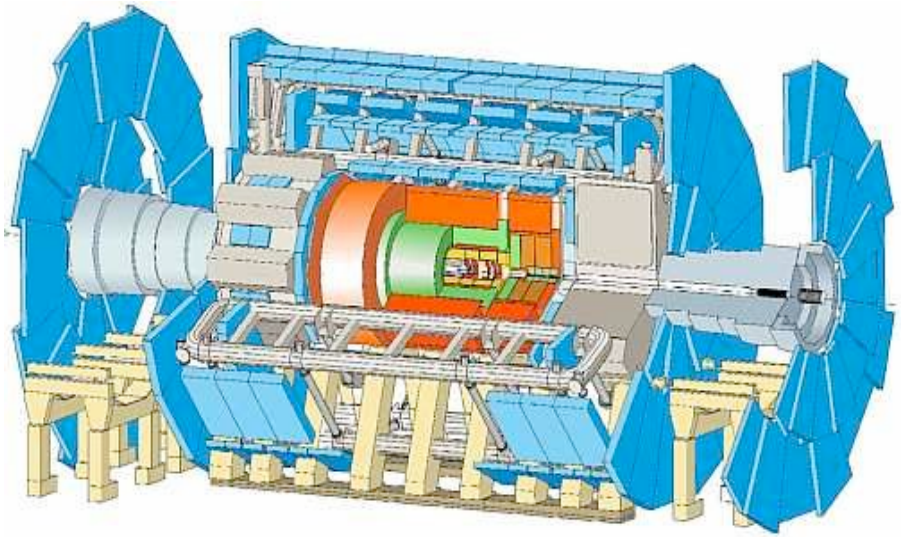
- **Tevatron beam accidents**
  - 1 MJ/beam = kinetic energy equivalent to a race car at 125 mph
  - E.g. CDF lost 2.5% silicon channels between 07/03 and 07/04 due to beam incidents
- **LHC**
  - 350 MJ/beam = "80 kg of TNT or 70 kg of Swiss Chocolate" *(S.Peggs)*
  - Uncontrolled LHC beam can cause major damage both to machine and experiments

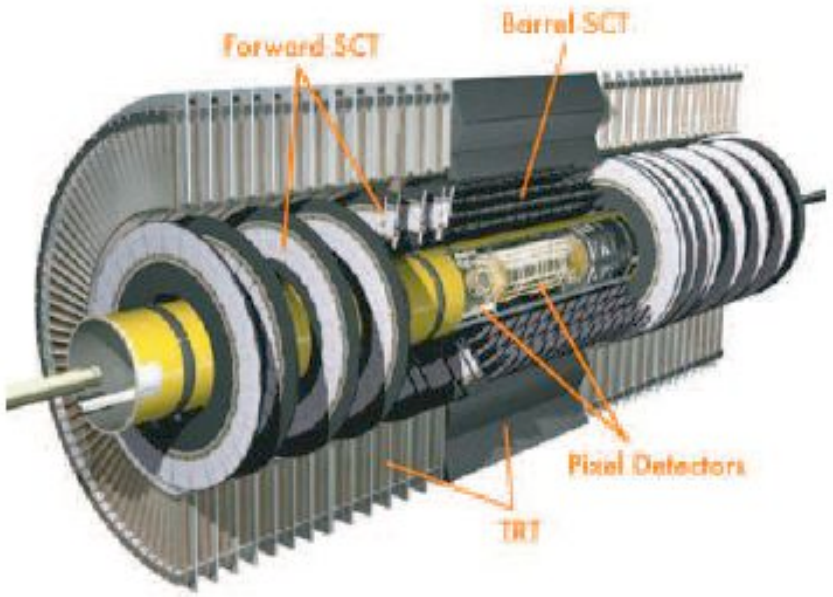


Lyn Evans: *"The time it will take us to go to design luminosity depends on how quickly we gain confidence in the safety of machine operation"*

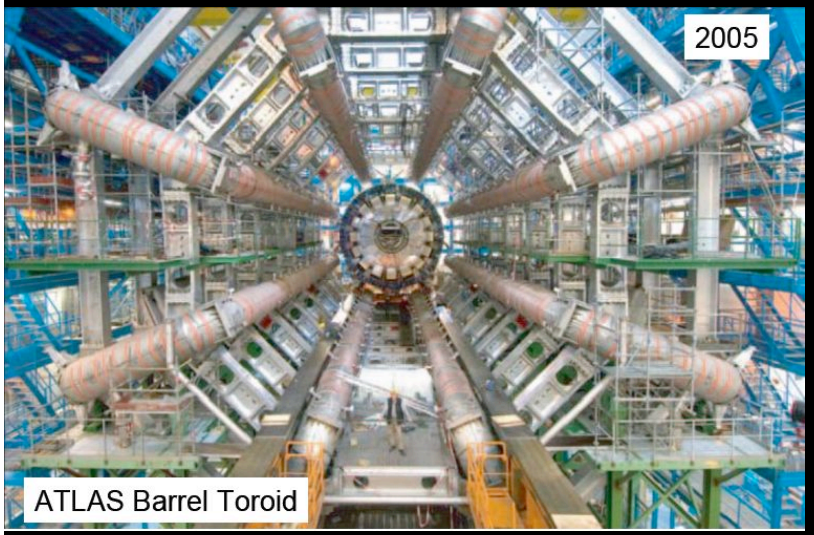
ATLAS

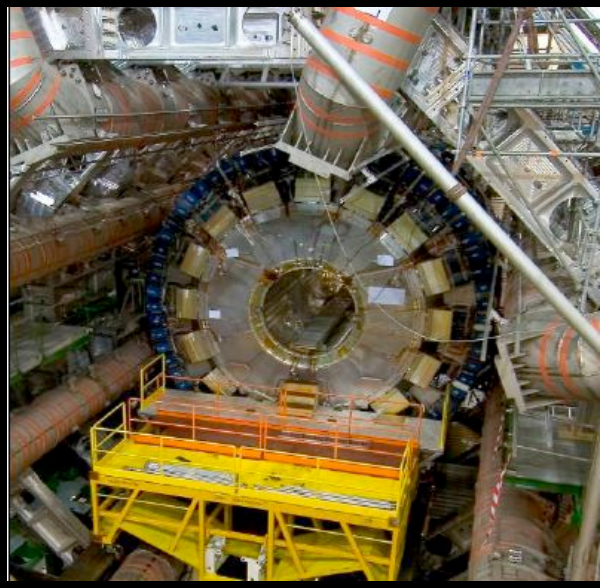
- General:
  - Weight ≈7000 tons
  - Length=42m, height=22m
- Muon spectrometers
  - Huge!
- Electromagnetic calorimeter
  - Liquid-Argon, accordeon shape
- Hadron calorimeter
  - Tile (scintillator)
- TRT
  - Transition radiation
- Silicon strips (SCT)
- Silicon pixels (80M pixels)
  - First time at hadron collider

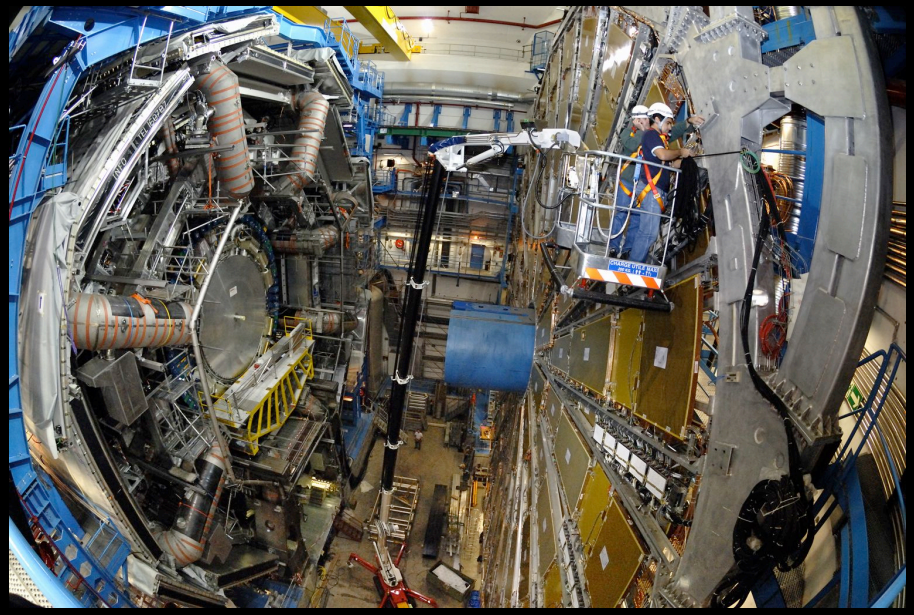


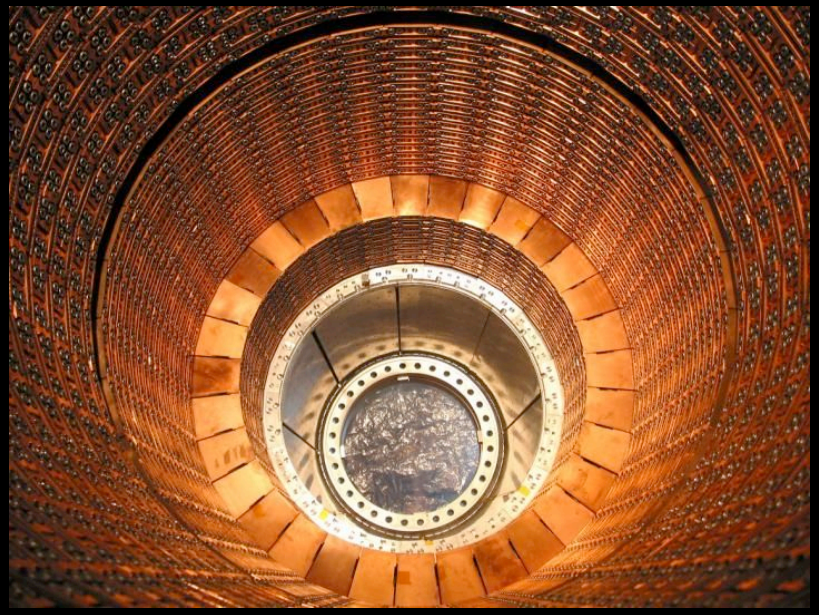


ATLAS Muon System and Calorimeters

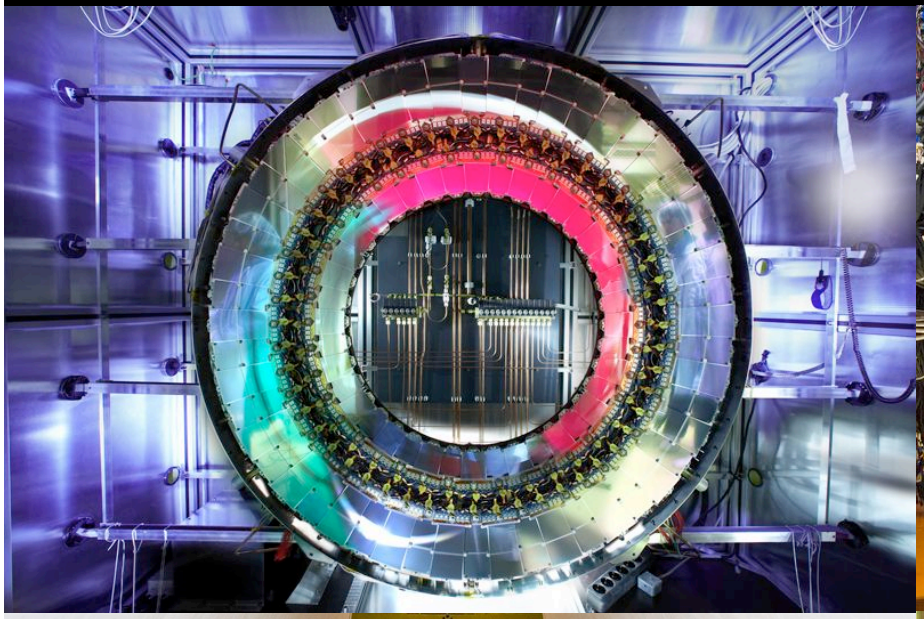


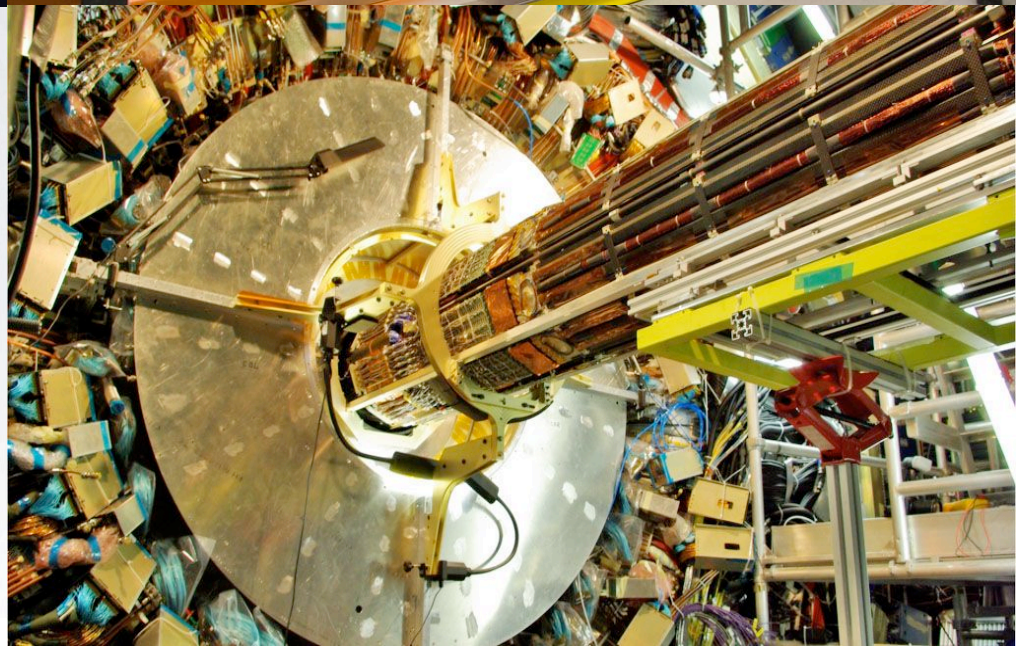




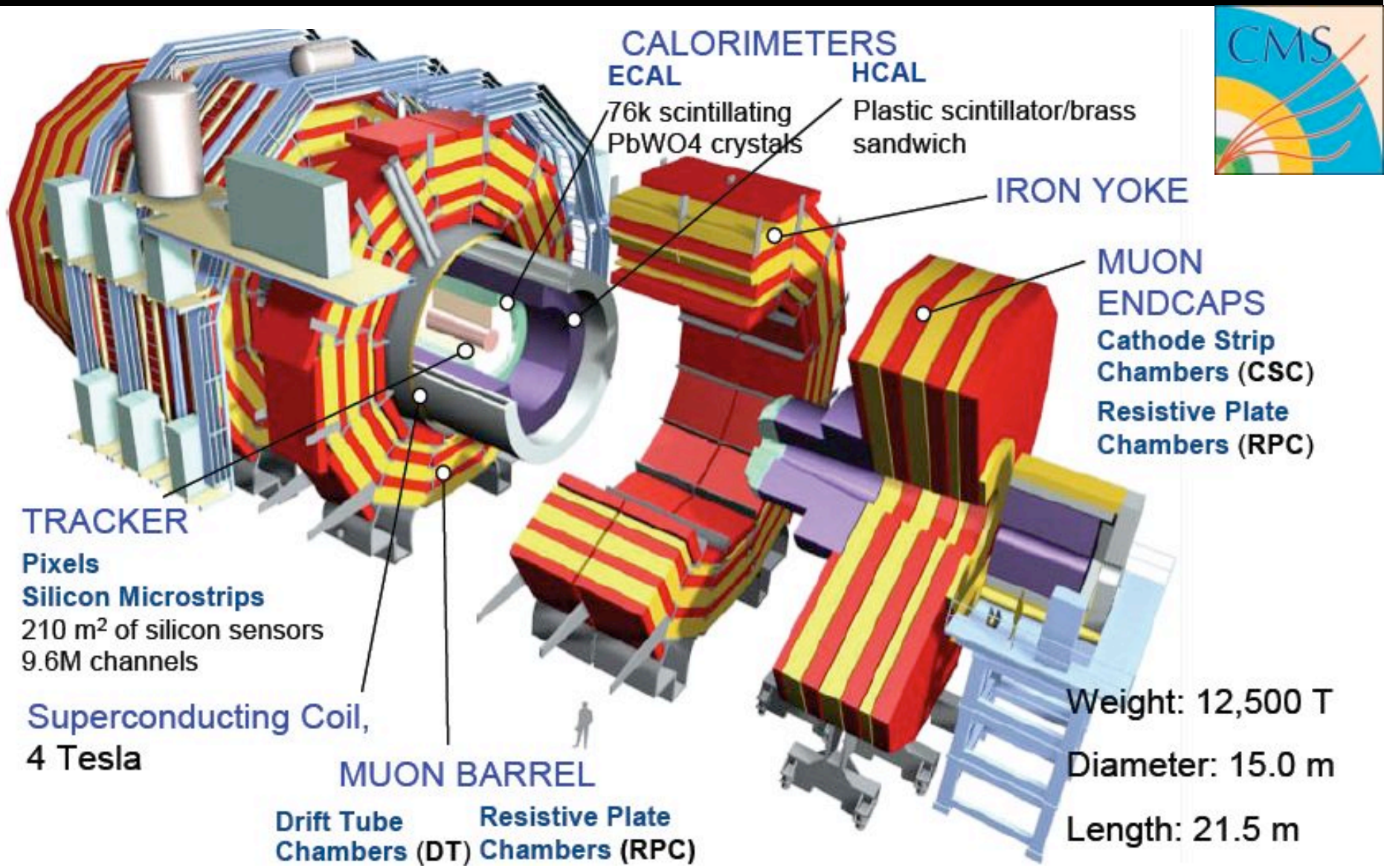


ATLAS Tracking Detectors

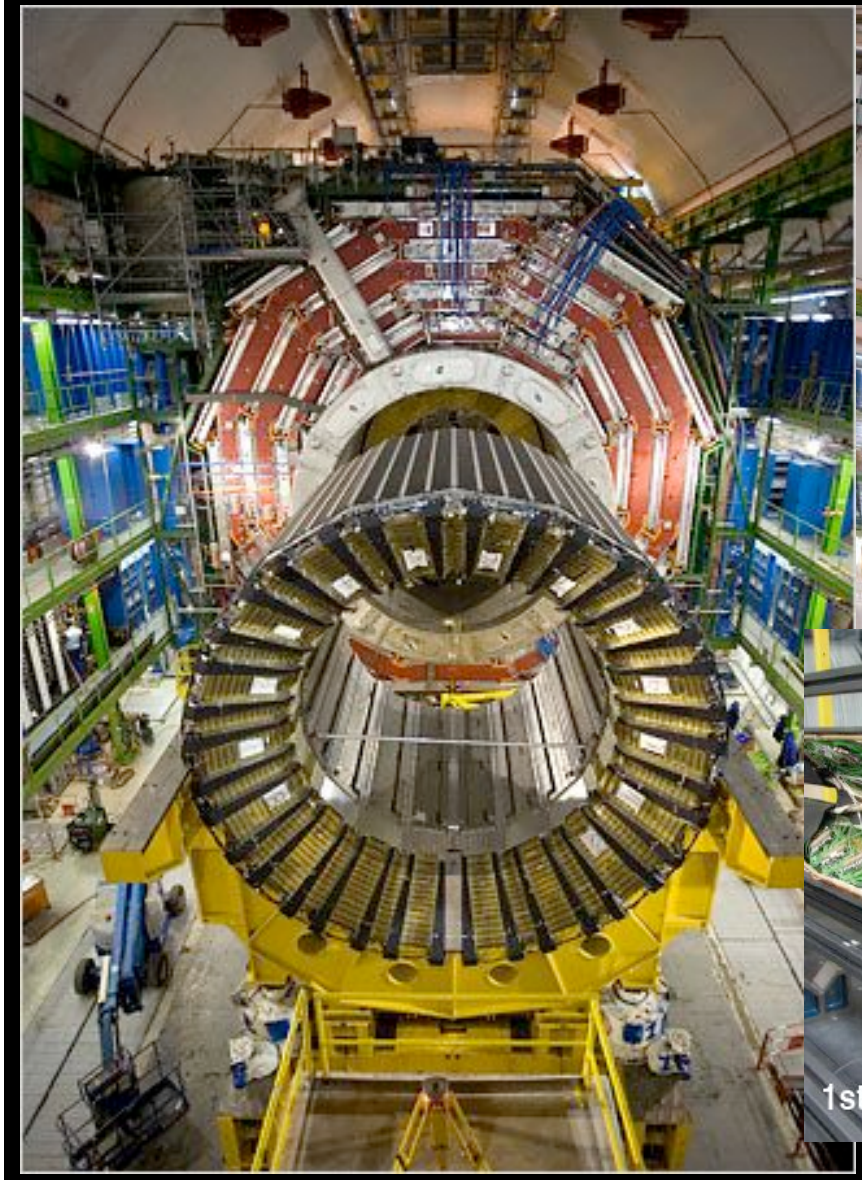


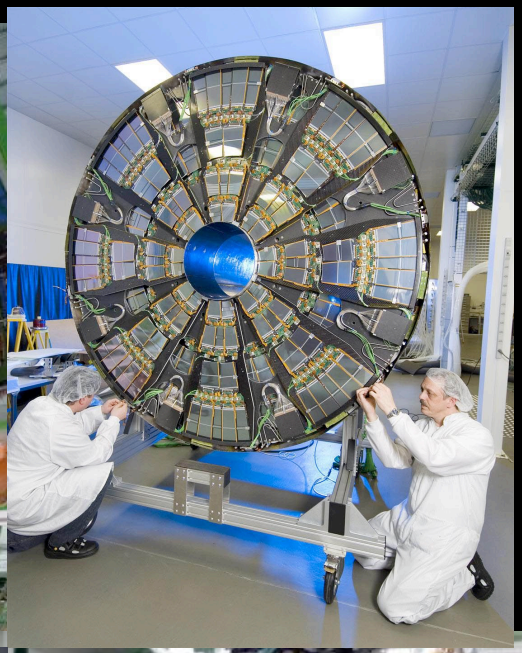


CMS

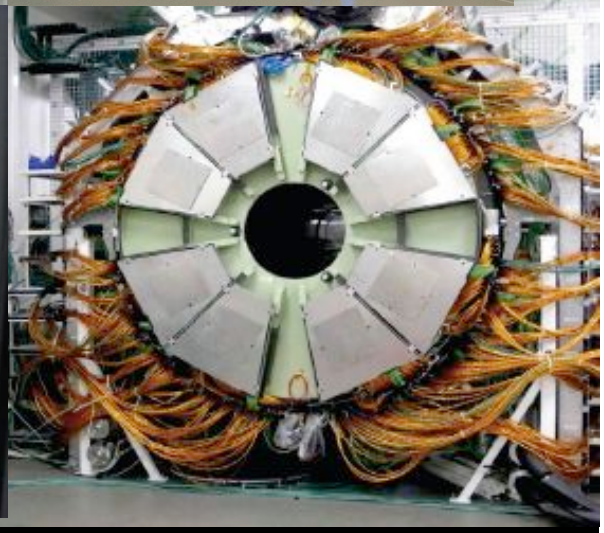

CALORIMETERS
ECAL
76k scintillating PbWO4 crystals
HCAL
Plastic scintillator/brass sandwich
IRON YOKE
MUON ENDCAPS
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)
TRACKER
Pixels
Silicon Microstrips
210 m² of silicon sensors
9.6M channels
Superconducting Coil,
4 Tesla
MUON BARREL
Drift Tube Chambers (DT)
Resistive Plate Chambers (RPC)
Weight: 12,500 T
Diameter: 15.0 m
Length: 21.5 m

CMS



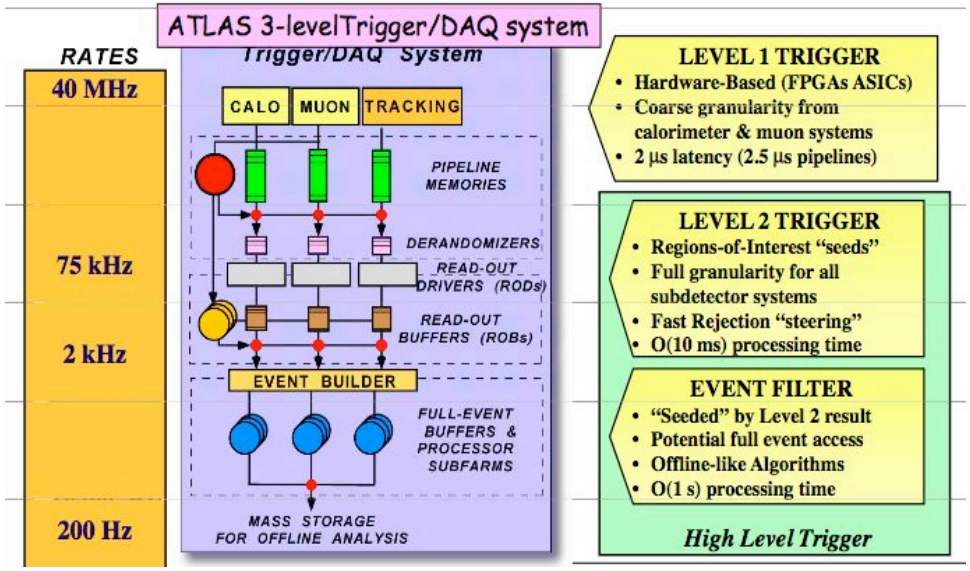


1st endcap quarter at CERN



Triggering is a Big Challenge

- **3-level trigger system filters events from 40MHz crossing rate to 200 Hz on tape**
  - L1 hardware trigger
  - L2 and L3 are software triggers
- **Typical unprescaled triggers at L=10^{33} $cm^{-2}s^{-1}$:**
  - (Isolated) e, μ: p_T>25 GeV
  - (Isolated) γ: p_T>50 GeV
  - (Isolated) τ: p_T>50-100 GeV
  - Jet: p_T>500 GeV
    - Lower threshold for b-jets
  - Jet(s)+Missing E_T>150 GeV
  - + Multi-object triggers which have then lower thresholds

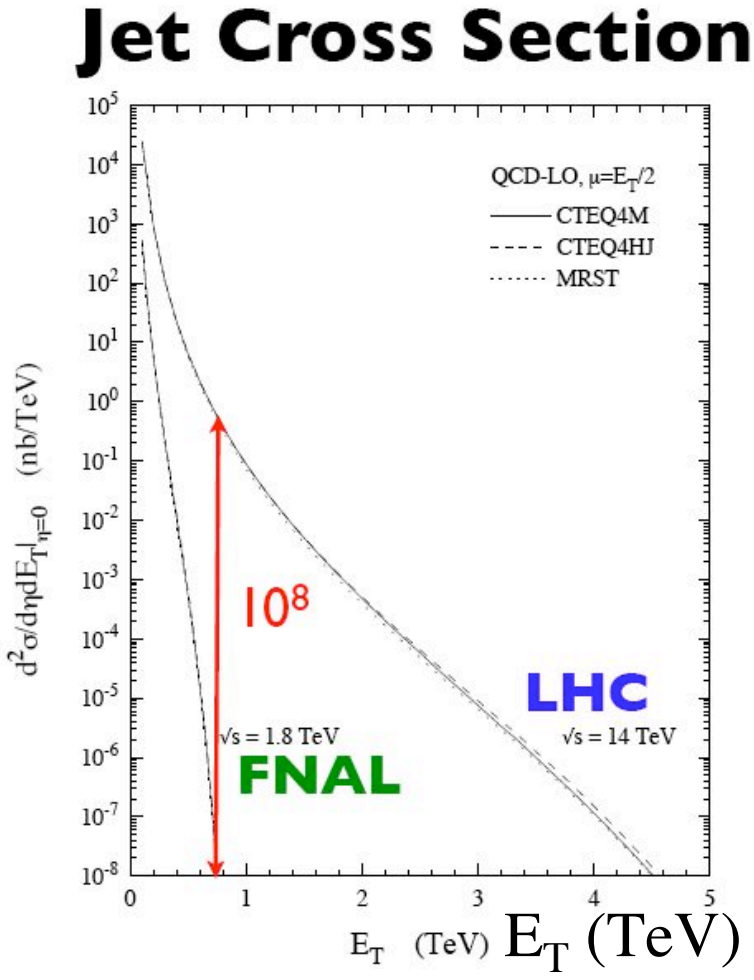


Triggers are kept rather generic => Sensitive to broad range of signatures
(but please let us know if your model is not being triggered!)

Towards Physics Measurements

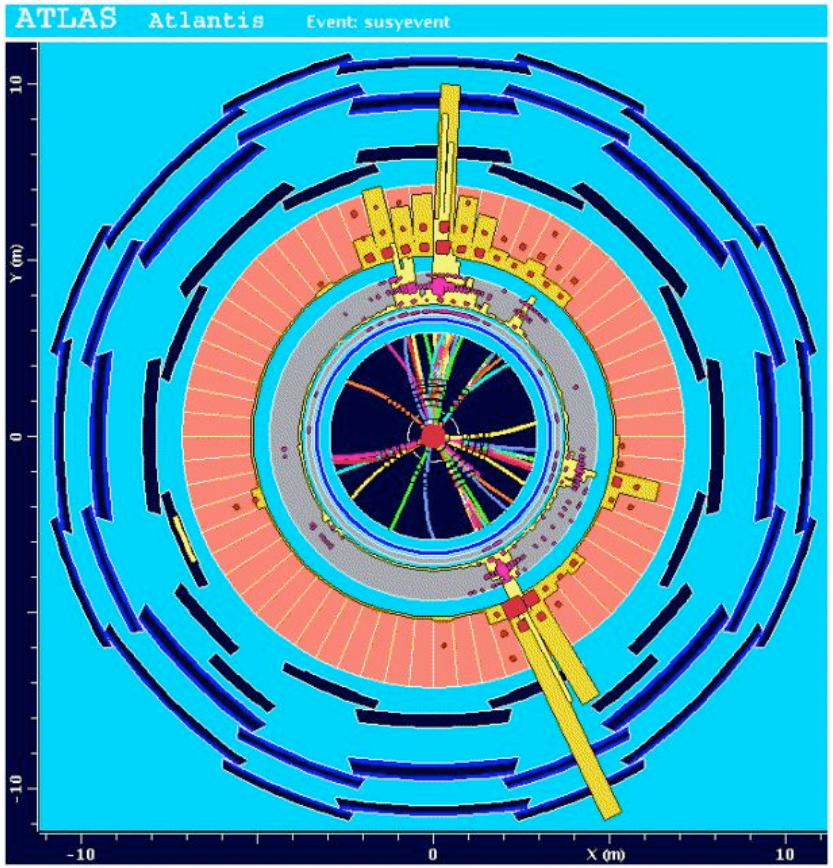
We are entering new Territory!

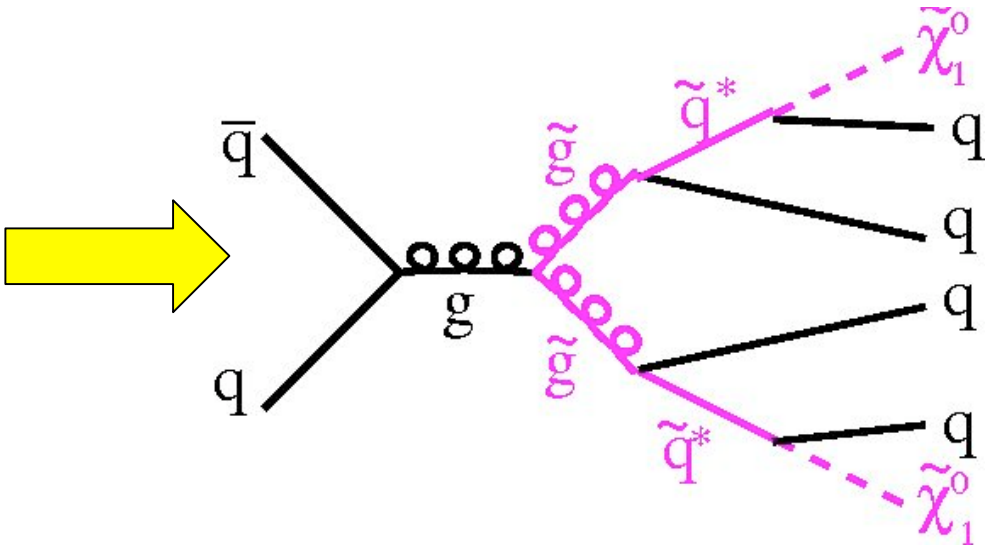
Cross Sections of Physics Processes (pb)			
	Tevatron	LHC	Ratio
$W^{\pm} \rightarrow l\nu$ (80 GeV)	2600	20000	10
$t\bar{t}$ (2x172 GeV)	7	800	100
$gg \rightarrow H$ (120 GeV)	1	40	40
$\tilde{\chi}^{+}_{1}\tilde{\chi}^{2}_{0}$ (2x150 GeV)	0.1	1	10
$\tilde{q}\tilde{q}$ (2x400 GeV)	0.05	60	1000
$\tilde{g}\tilde{g}$ (2x400 GeV)	0.005	100	20000
Z′ (1 TeV)	0.1	30	300



- Amazing cross section increase for strongly interacting heavy particles
  - ⇒**Excellent opportunity for discovery with early data!**
  - ⇒Thus even more critical to **understand detectors and software now!**

The Challenge





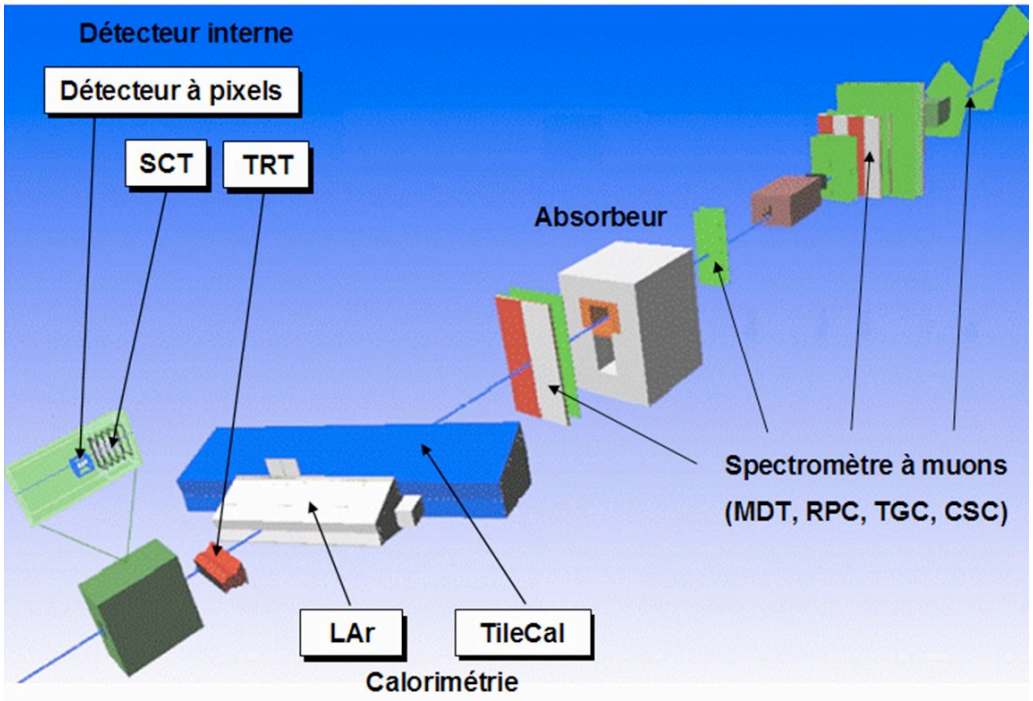
- Measured hits in detector => understand the underlying physics

Physics Strategy

- **Test Beam:**
  - Understand detector response in known environment before final assembly ($e,\mu,\gamma,\pi,..$)
    - Tune Monte Carlo simulation to describe response
- **Cosmic muons:**
  - Understand detector response to muons after assembly
    - Also commissions data acquisition/operations model/offline software/data distribution model …
- **Standard Model physics at 14 TeV**
  - Calibrate the detector with known particles and understand Standard Model at 14 TeV
    - Further tune simulation
- **Search for the unknown!**

Test Beam

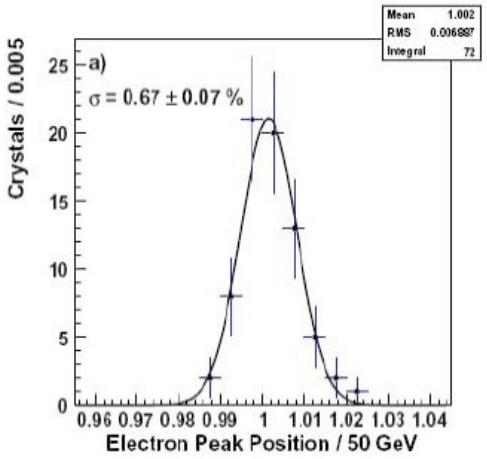
- E.g. combined ATLAS test beam in 2004
  - Operate 1% of full detector with real data acquisition system
    - Operational experience
  - Collected 90M events
    - Electrons, muons, pions, photons over large energy range
    - With and without magnetic field
  - Understand detector response to known particles



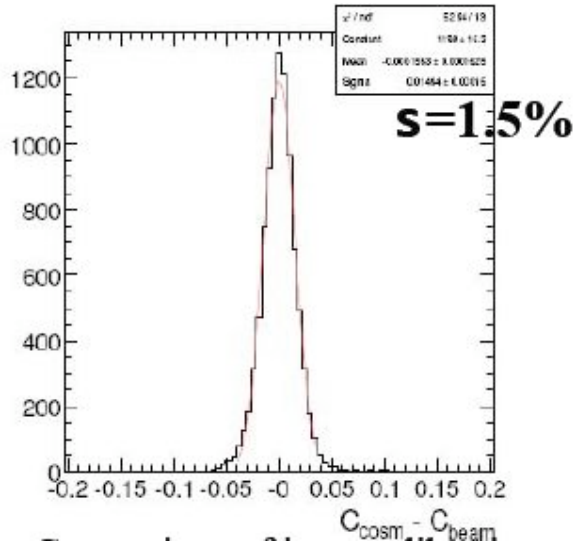
Detector Requirements

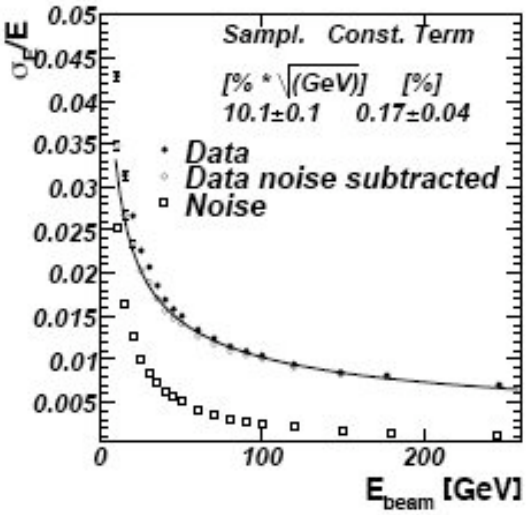
	expected performance on "day one"	data samples (examples) to improve the performance
ECAL uniformity	~1% (~2%) in ATLAS (CMS)	minimum-bias, $Z \to ee$
electron energy scale	~2%	$Z \to ee$
HCAL uniformity	3%	single pions, QCD jets
jet energy scale	$\leq$10%	$Z(\to \ell\ell)$+jet, $W \to jj$ in $t\bar{t}$ events
tracker alignment	20-200 μm in $R\phi$	generic tracks, isolated μ, $Z \to \mu\mu$

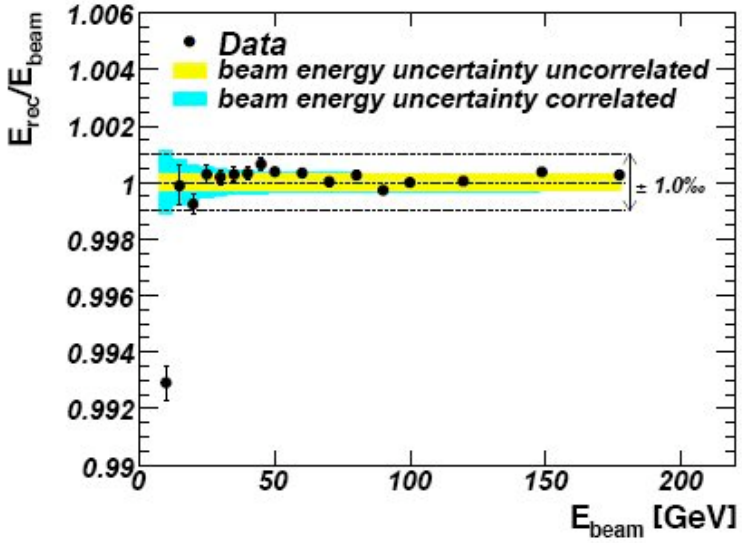
Test Beam + No Beam Results

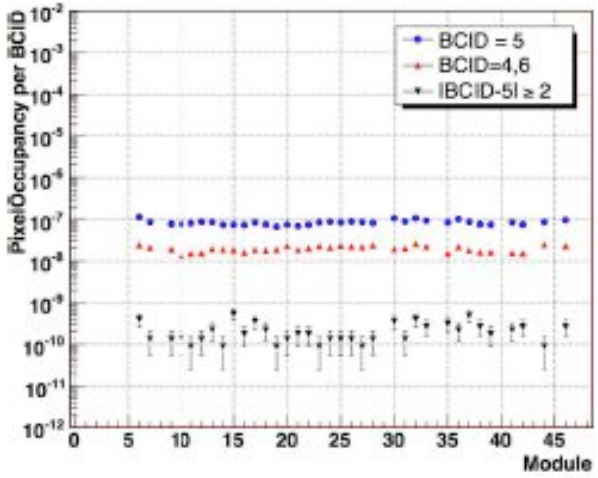


50 GeV electrons







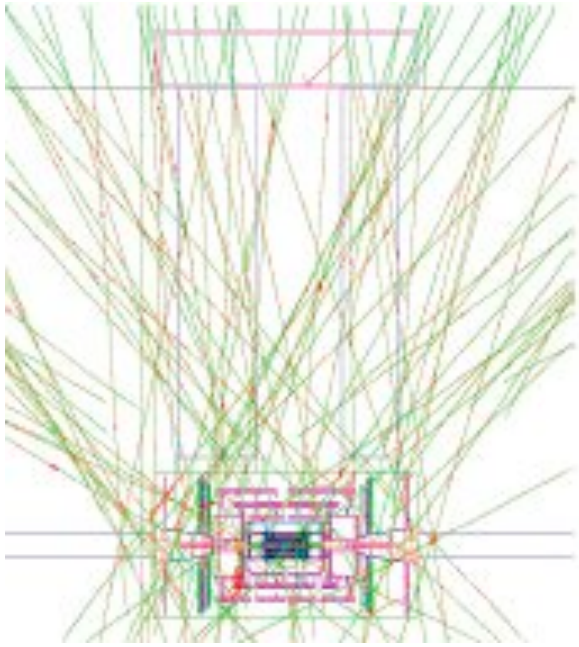


Wonderful detectors have been built!

Cosmic Rays

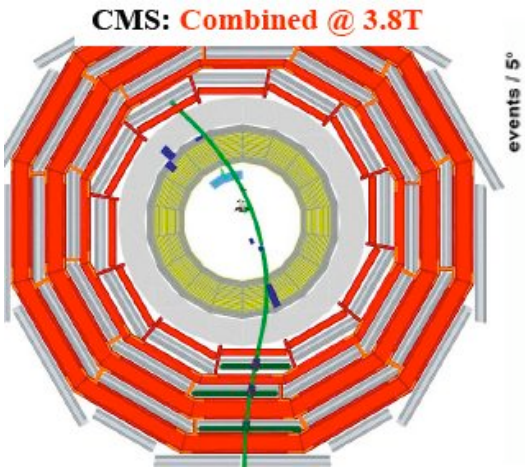
Cosmic Rays

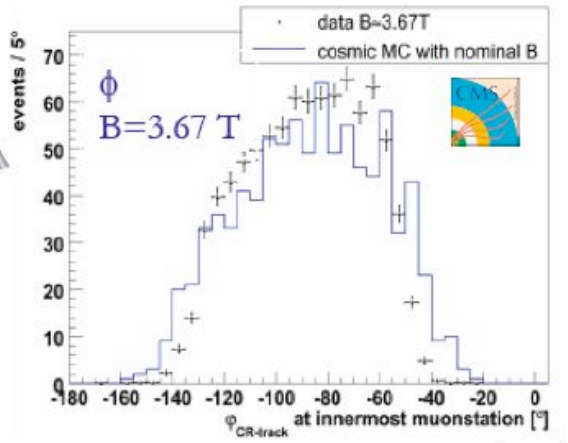
- Use cosmic ray muons to
  - integrate individual subdetectors to arrive finally at final detector setup
  - Gain expertise with operating the full detector
  - Debug software on real data
  - Understand detector response, calibrations, alignment

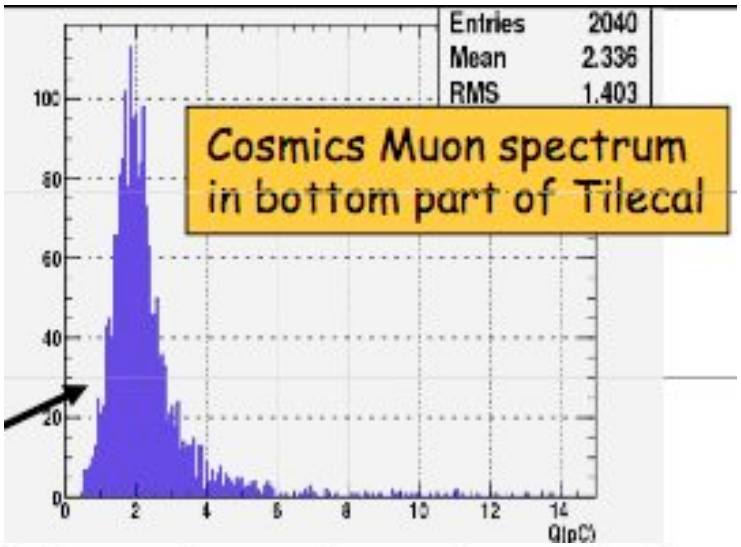


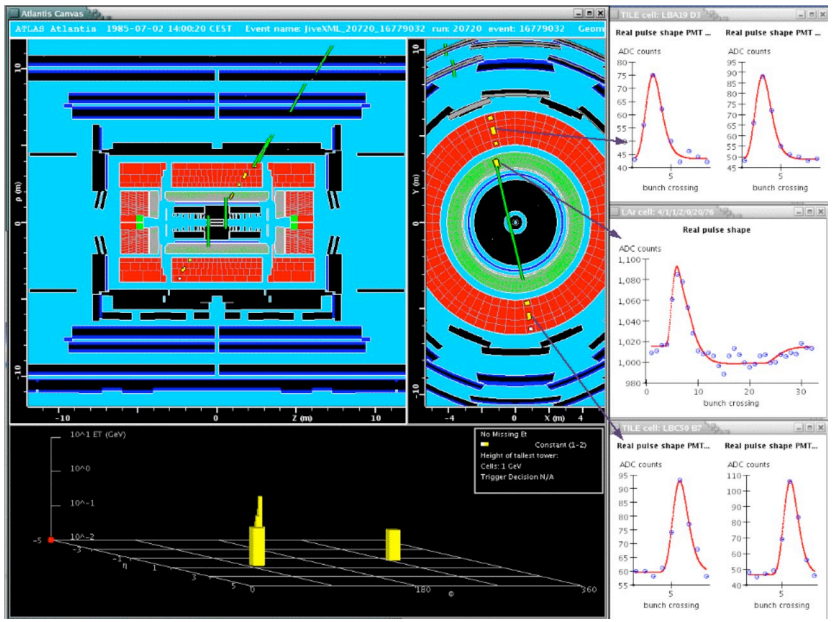
Cosmic Ray Flux in ATLAS cavern: ≈1kHz

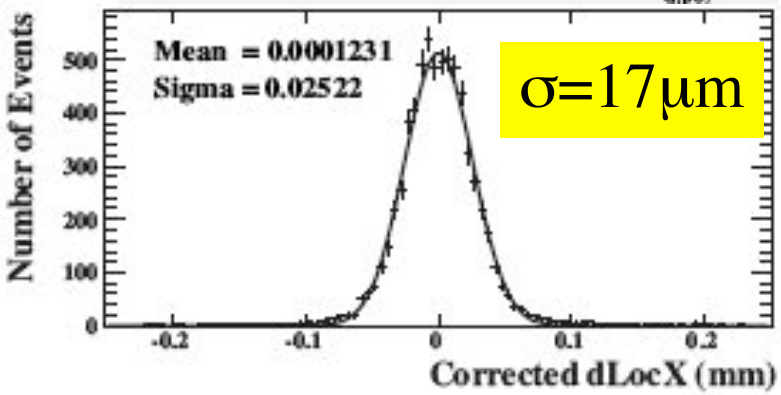
Cosmic Muon Data











Gain also quantitative understanding:
- e.g. alignment of tracking detectors
- e.g. MIP signal in calorimeters

Standard Model at 14 TeV

Standard Model at 14 TeV

At Luminosity $10^{31}cm^{-2}s^{-1}$

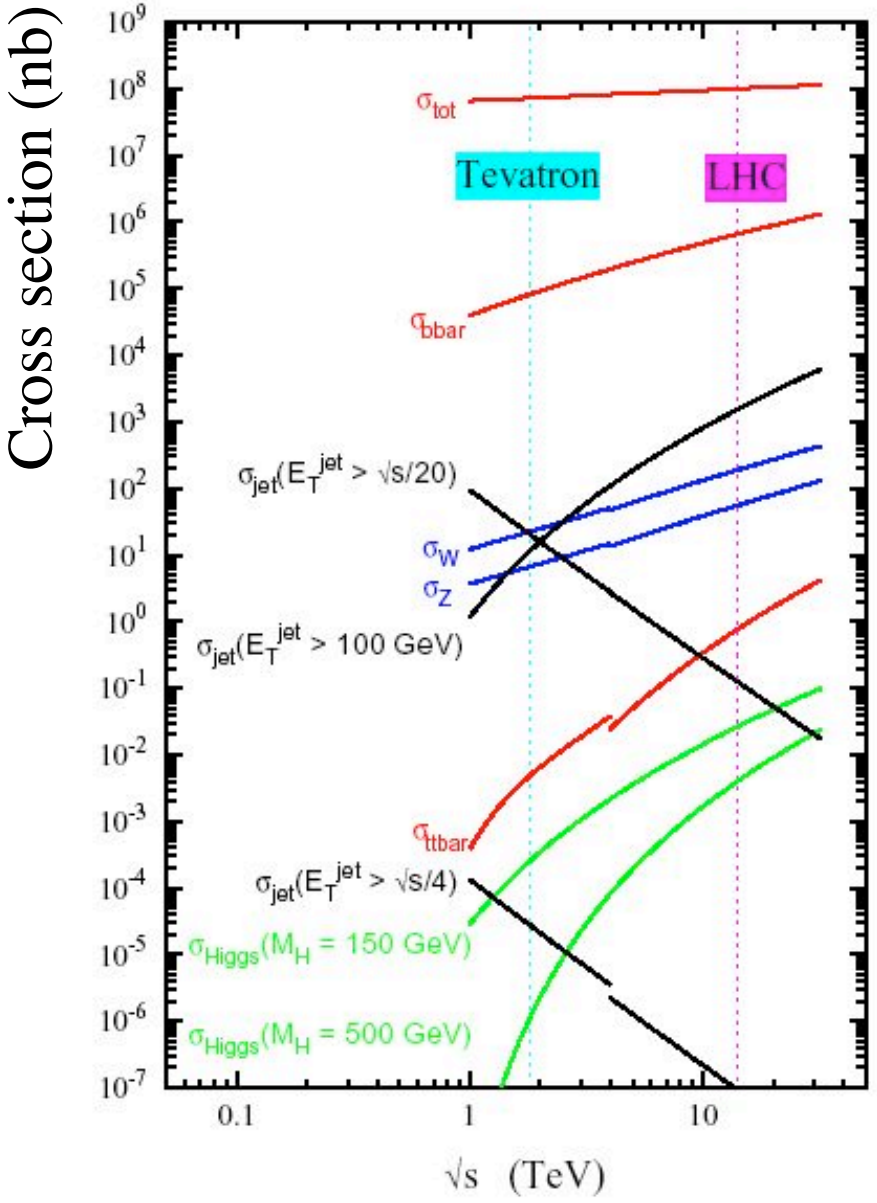
bb production:	→ 10^3 Hz
W→ ℓ ν:	→0.1 Hz
Z→ ℓ ℓ:	→0.01 Hz
t t production:	→0.01 Hz
SM Higgs	→0.0001 Hz

With $\int Ldt = 100\ pb^{-1}$:

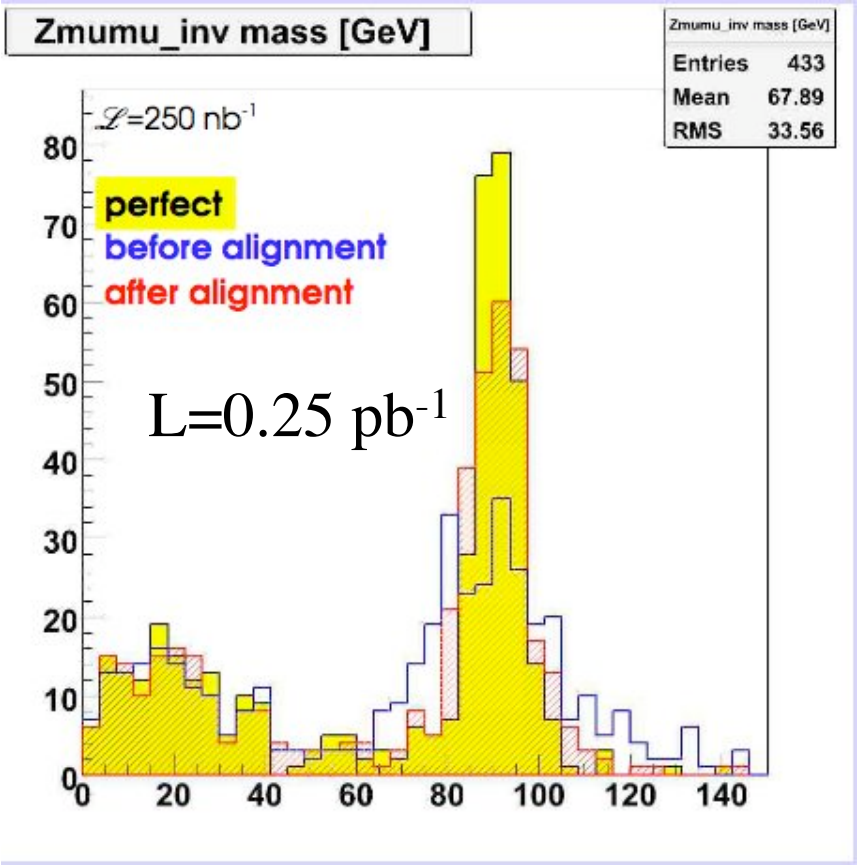
- 1,000,000 W→lν
- 100,000 Z→ll
- 80,000 tt→lν+X

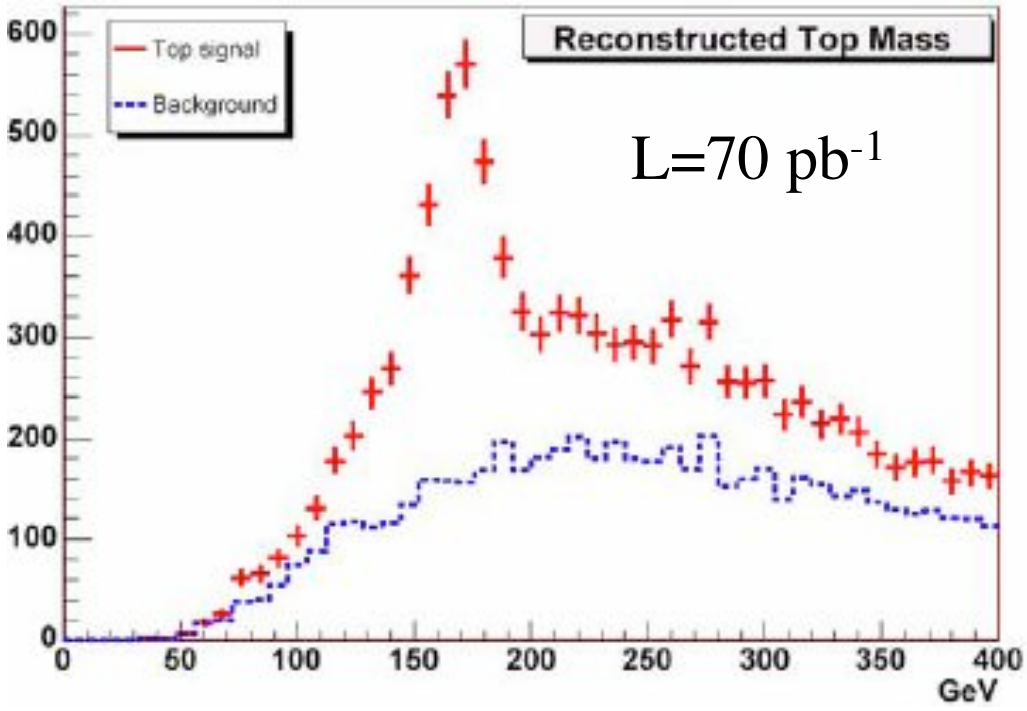
=>Samples sizes similar to Tevatron today

=>more than enough for detector understanding!



Examples for SM signals



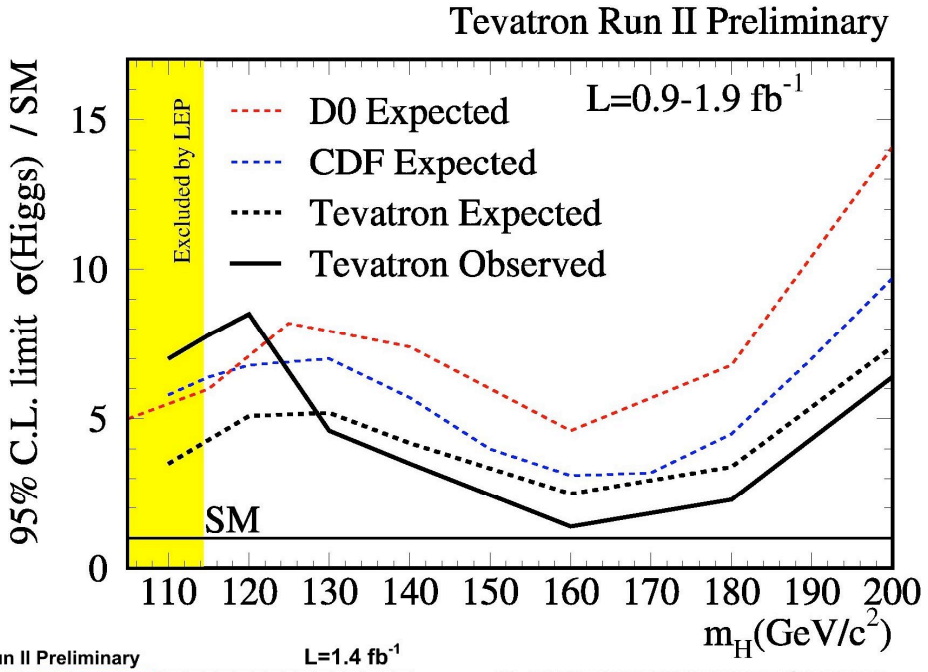


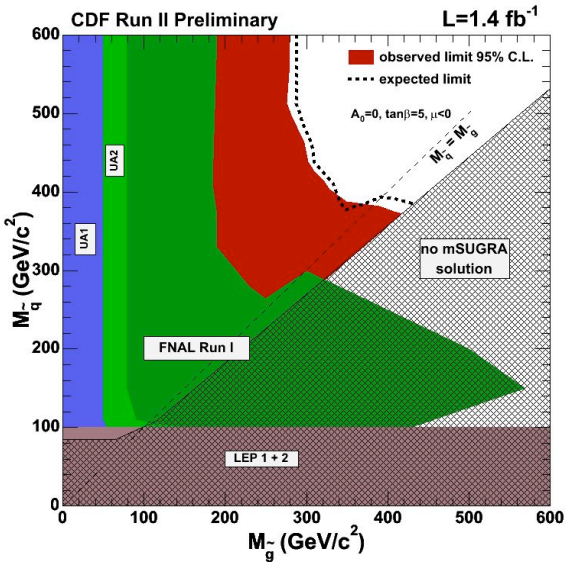
- Most likely we will collect the data quicker than we can understand them!

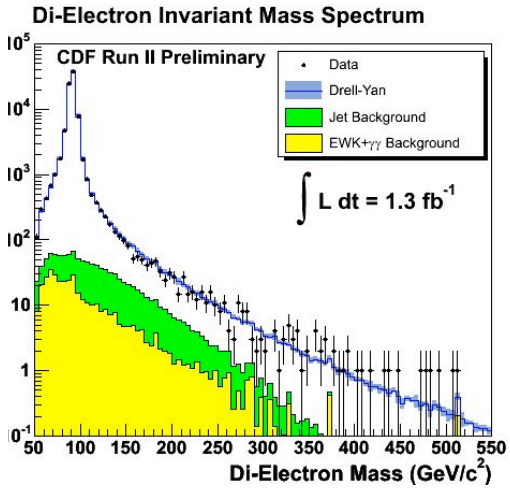
Searches for the Unknown

Status of the TeV Scale today

- Higgs boson:
  - LEP: m_H>114 GeV
  - Tevatron closing in
- SUSY particles:
  - $m(l,\tilde{\chi}^{\pm}_1)$>100 GeV
  - M(LSP)>50 GeV
  - $M(\tilde{g})$>300 GeV
  - $M(\tilde{q})$>400 GeV
- Z′:
  - M>900 GeV (SSM Z′)
- Extra dimensions (RS):
  - M_G>200-900 GeV

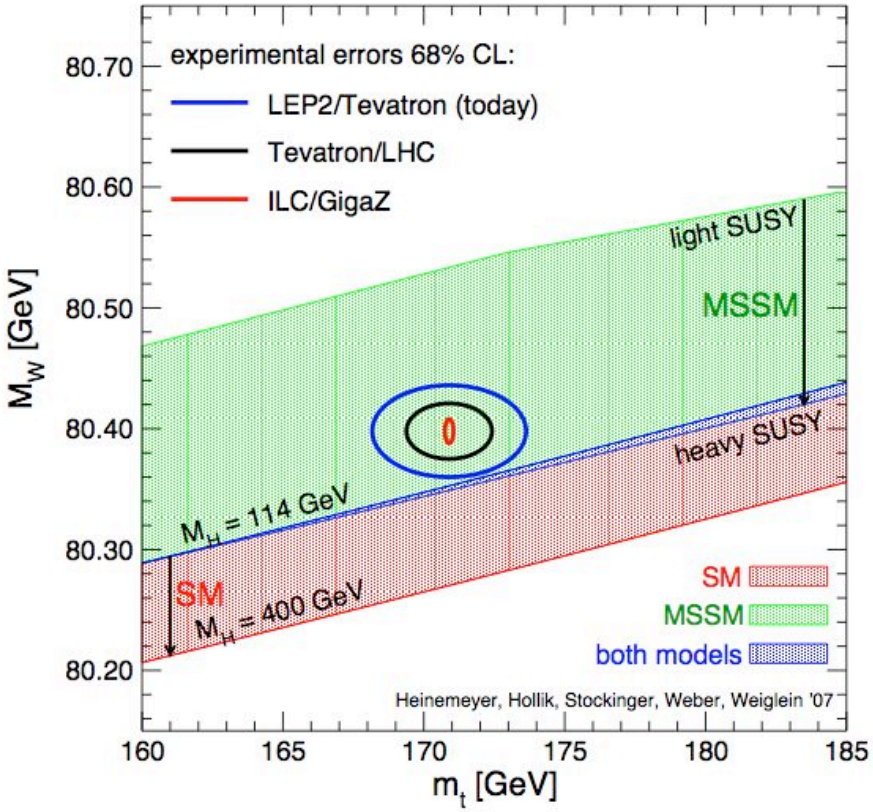


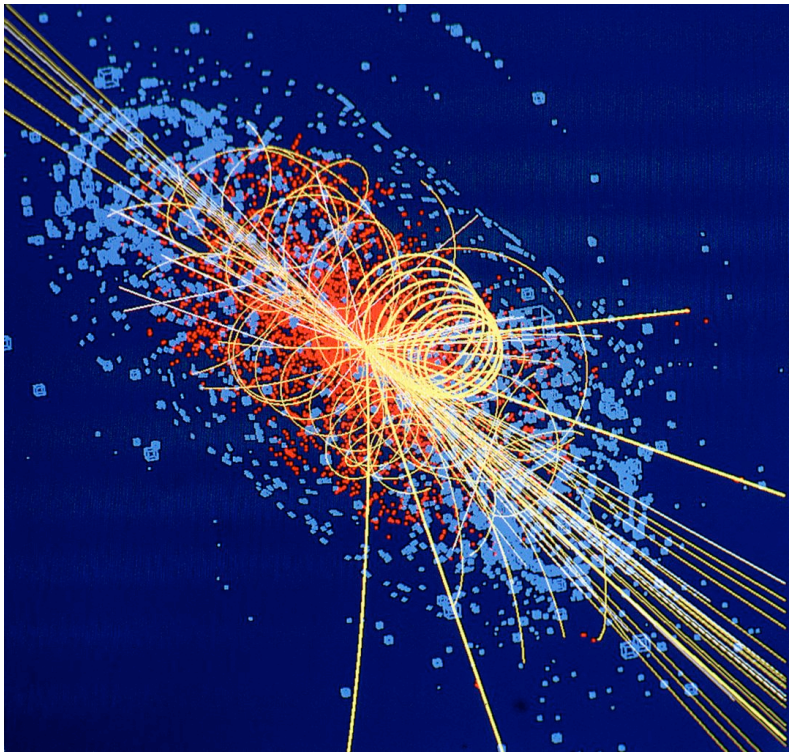




The Higgs Boson

Standard Model Higgs Boson

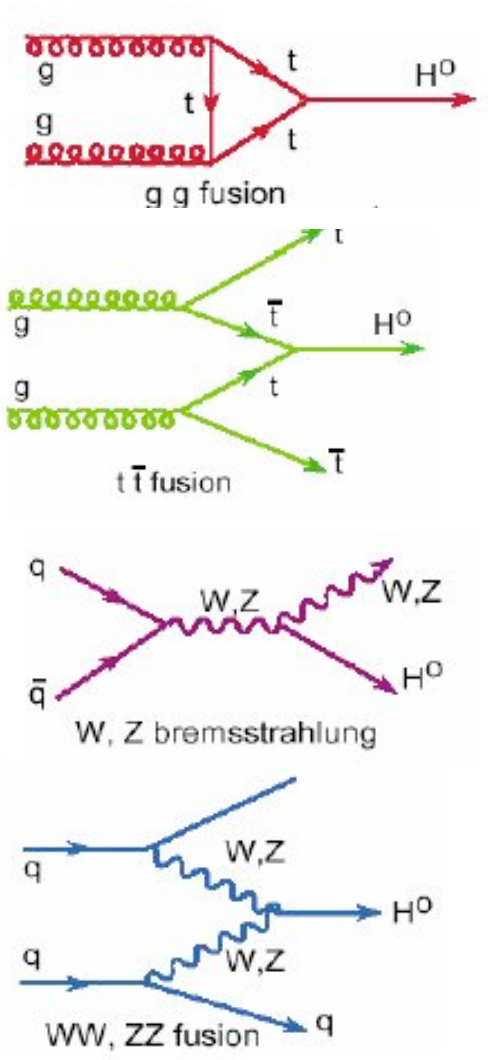


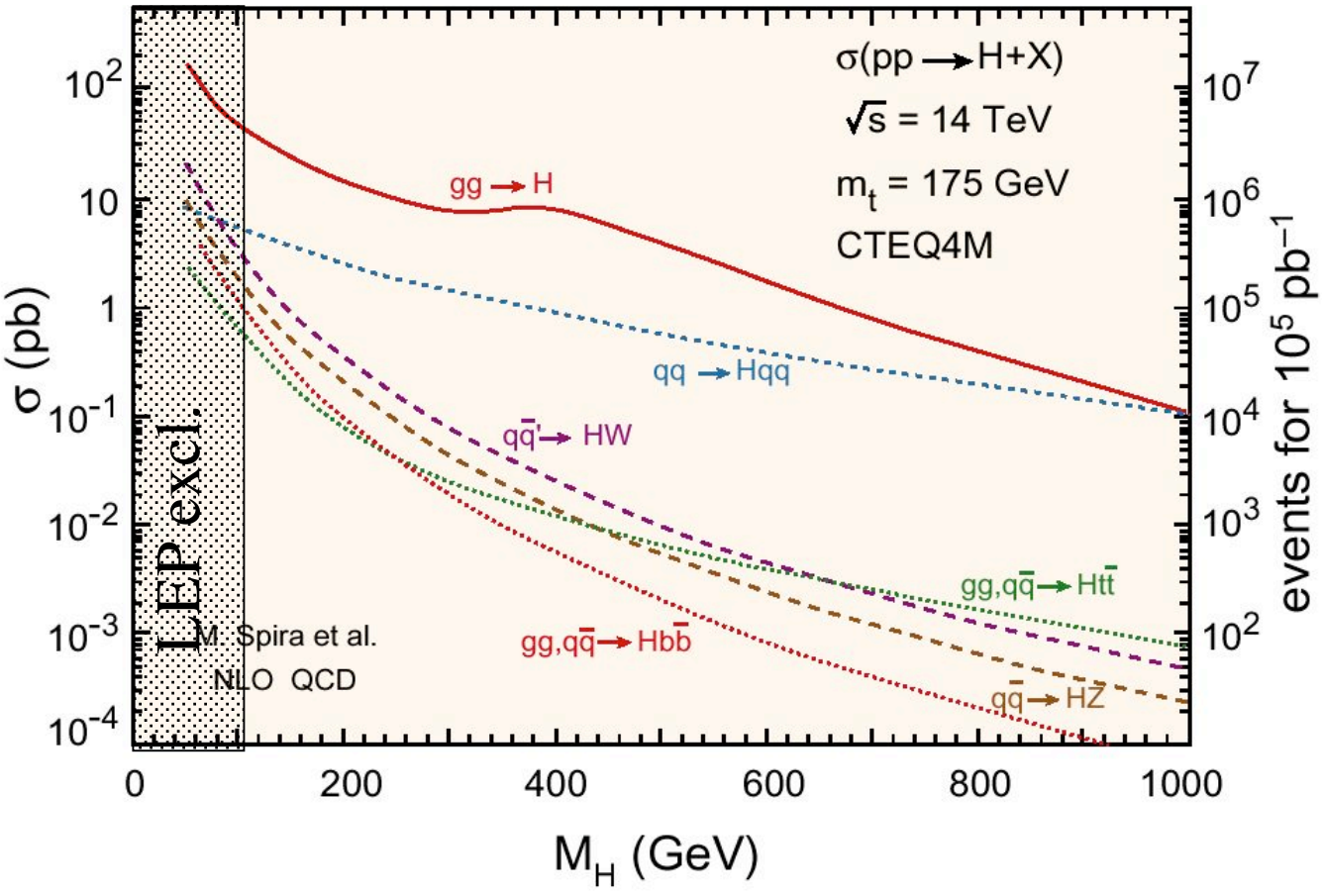


- Electroweak precision data favor low mass Higgs boson:
  - Data consistent with both Standard Model and MSSM
    - MSSM slightly preferred
  - Standard Model fit result: m_H<144 GeV/c^2 at 95%CL

Higgs Production at the LHC

M. Spira *et al.*

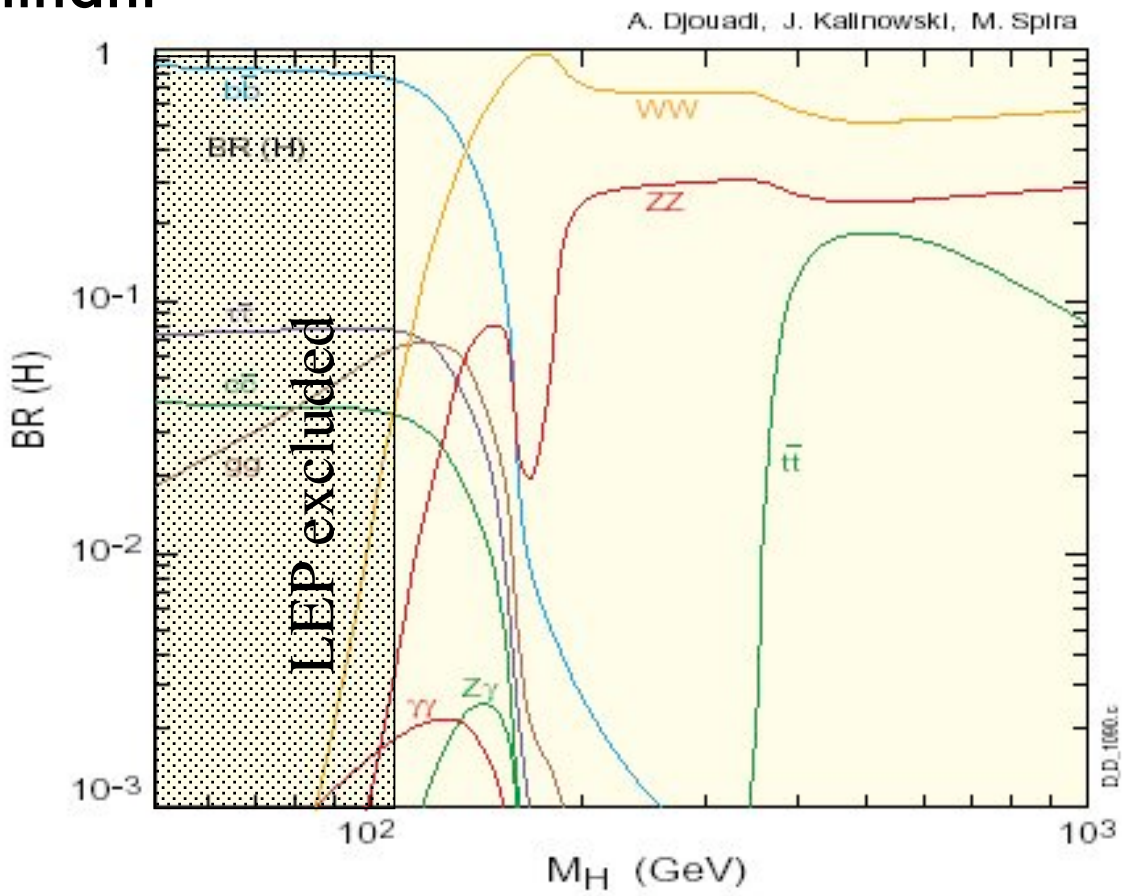




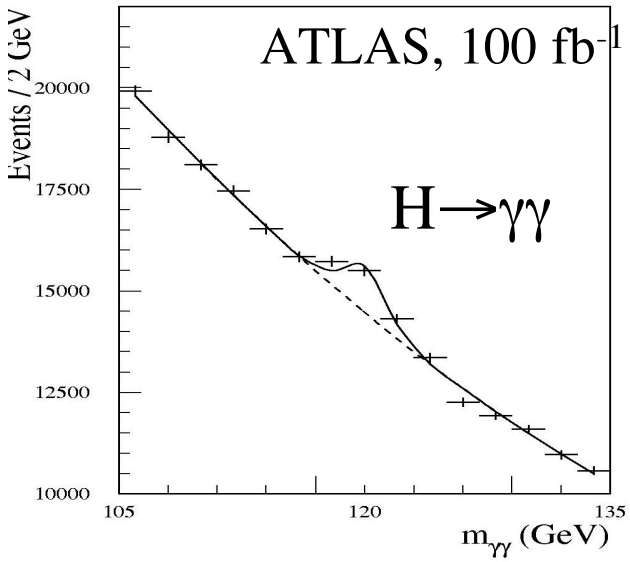
dominant: gg→ H, subdominant: Hqq (VBF)

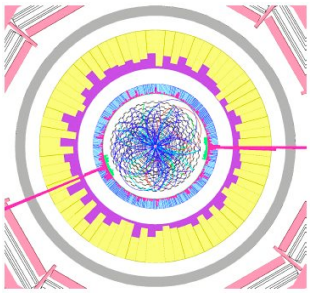
Higgs boson Decay

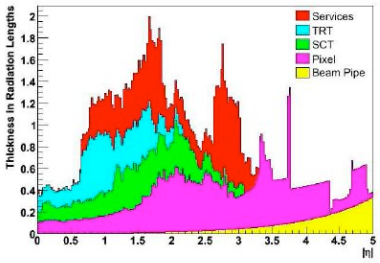
- M_H<130 GeV/c^2:
  - $b\bar{b}$ dominant
  - $\tau^+\tau^-$, W^+W^- subdominant
  - $\gamma\gamma$ small but useful
- M_H>130 GeV/c^2:
  - W^+W^- dominant
  - ZZ cleanest



Low Mass Higgs Signals

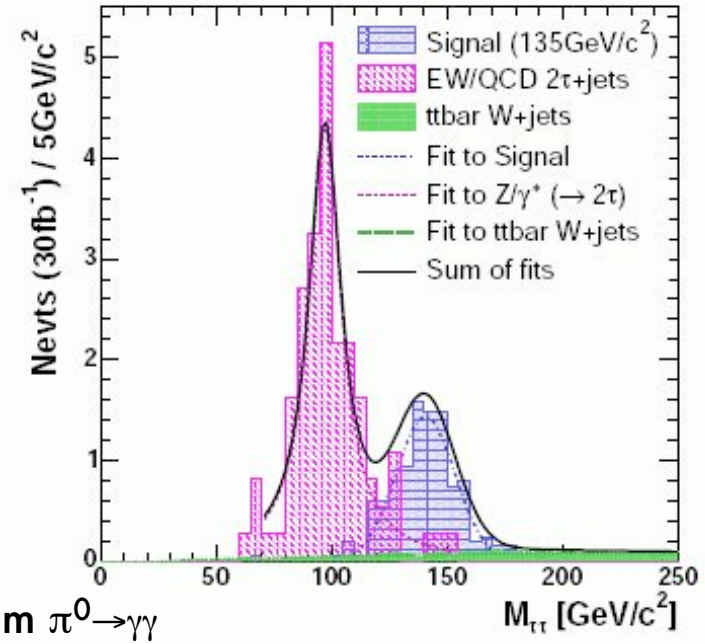




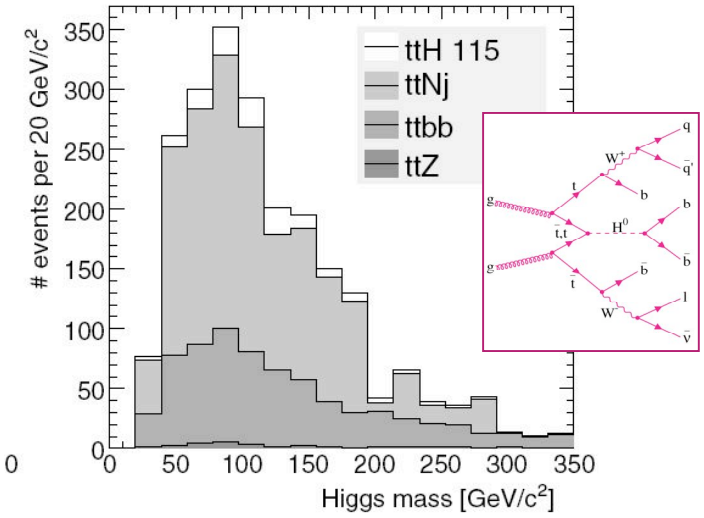


VBF H→ττ

CMS, 30 fb-1



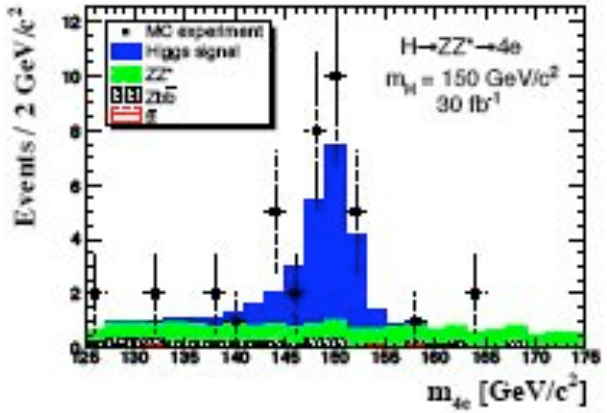
CMS, 60 fb-1

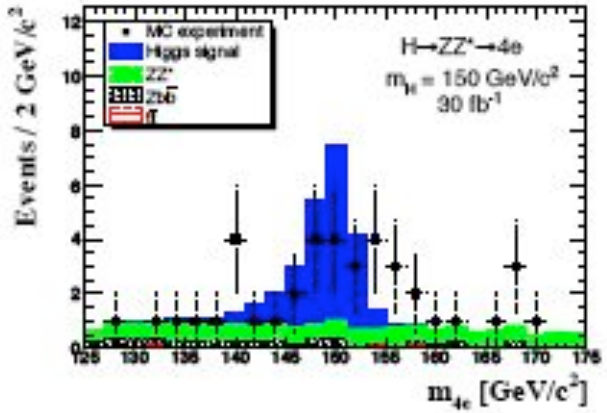


- **H→γγ challenges:**
  - Background from $\pi^0 \to \gamma\gamma$
  - Mass resolution requires brilliant calibration
  - At least 1 photon converts in 50% of events
- **VBF: Hqq→ττqq challenges:**
  - Central jet veto sensitive to underlying event
  - Need to understand forward jets
  - Background from jets looking like tau's
- **ttH→ttbb:**
  - Background very difficult / b-tagging performance

High Mass Higgs Signals

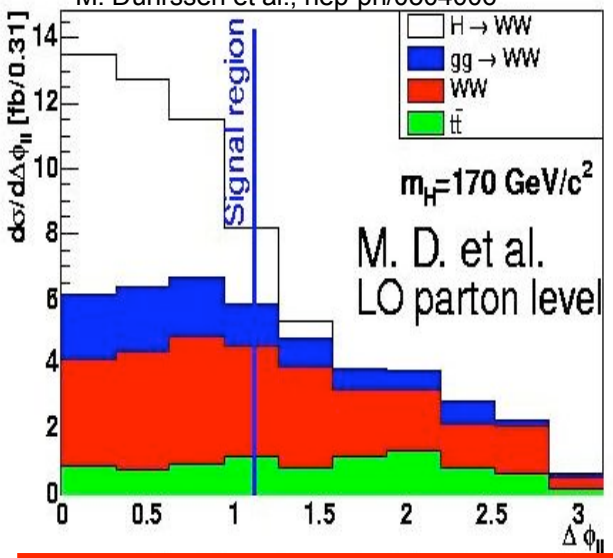
CMS H→ZZ →eeee example signals for m_H=150 GeV/c^2

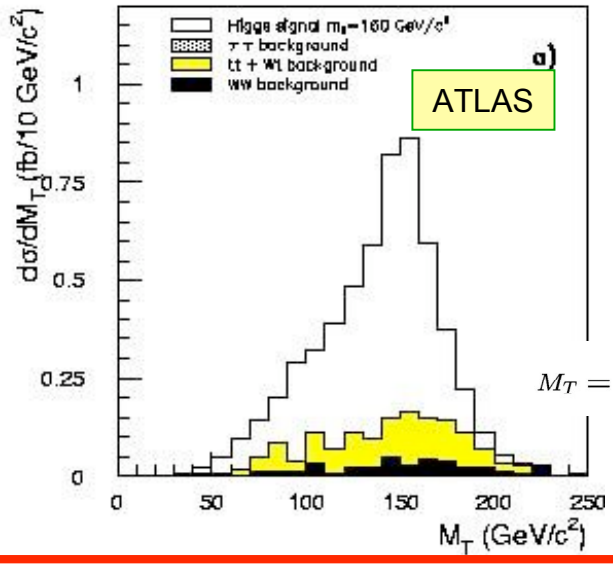




H→ZZ*

M. Dührssen et al., hep-ph/0504006





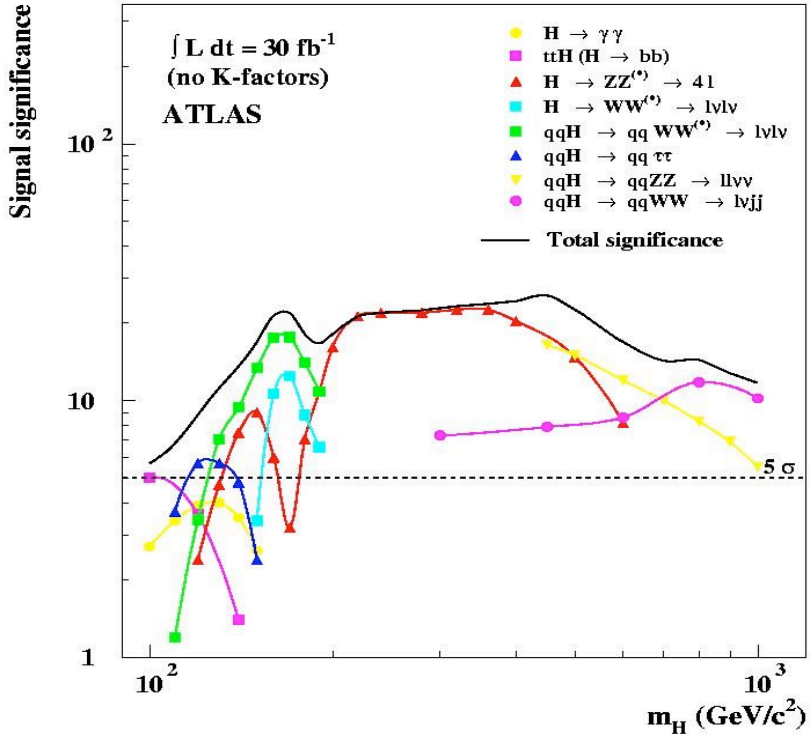
H→WW*

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

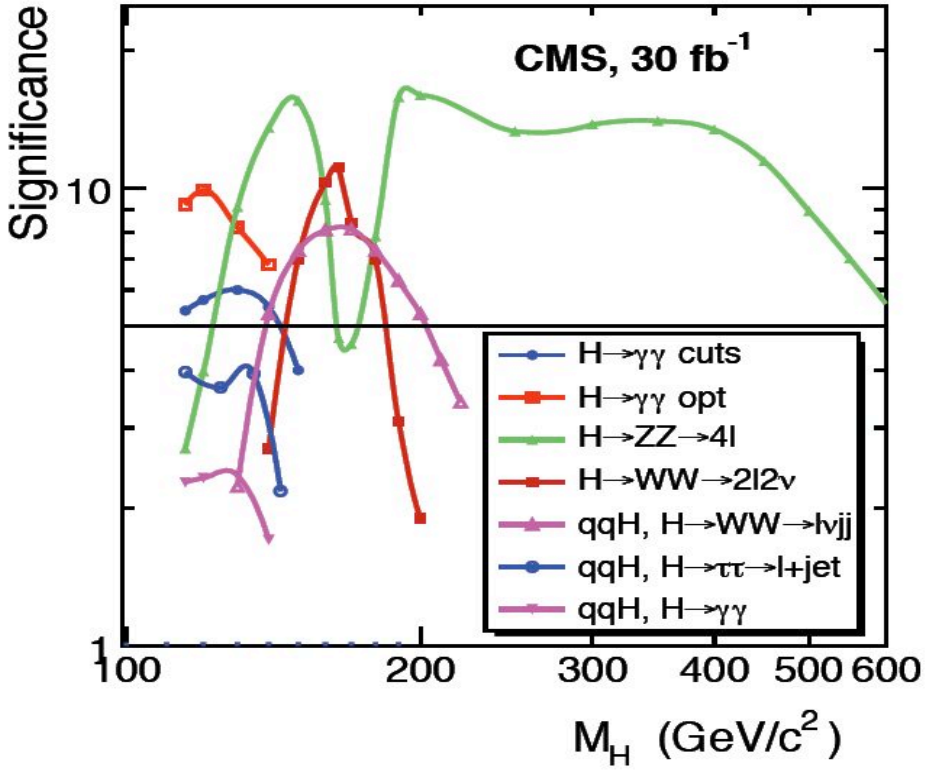
Clean signals on rather well understood backgrounds

Higgs Discovery Prospects

ATLAS, 2003

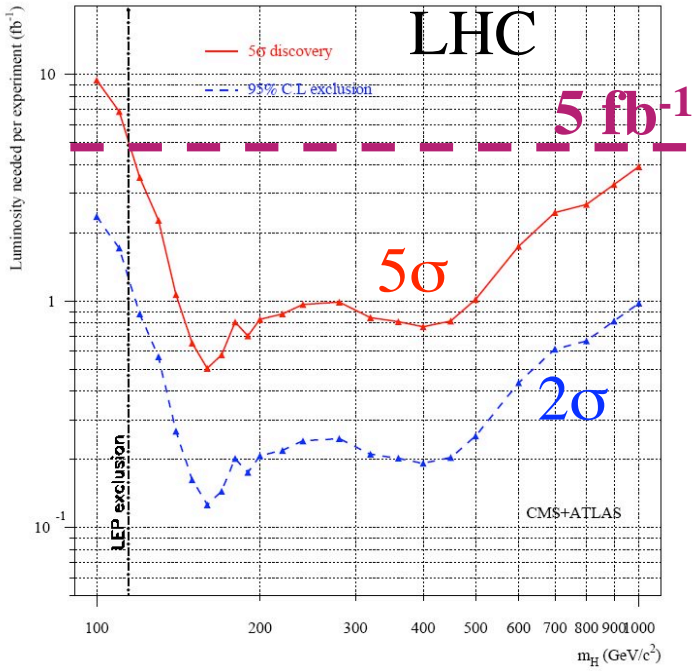


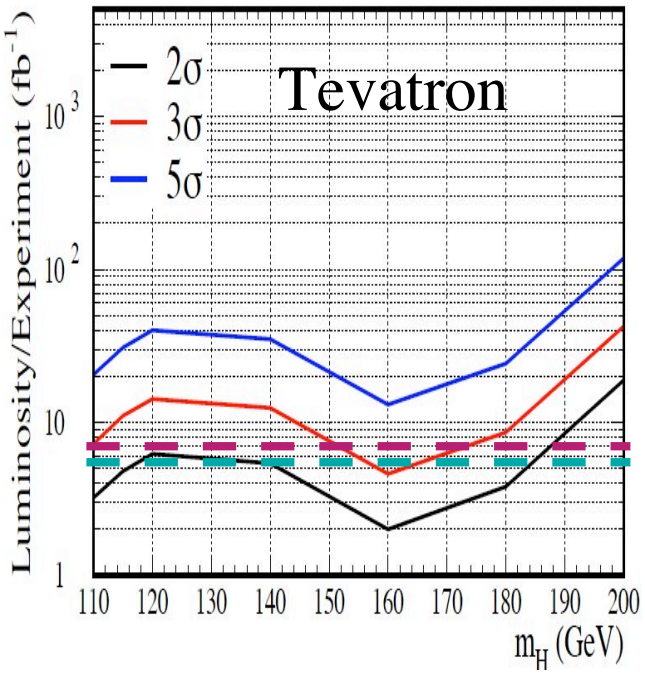
CMS, 2006



- High mass (m_H>120 GeV):
  - WW and ZZ provide excellent sensitivity
- Low mass:
  - ATLAS: Many channels contribute ttH, VBF H→ττ, H→γγ
  - CMS: H→γγ best, ttH found to be not feasible

Higgs Boson Discovery Prospects



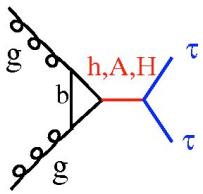


- Tevatron:
  - Combining 4 analyses (WH, ZH and WW)
  - might see a 3σ evidence with full luminosity (2009/2010?)
- LHC:
  - cover full mass range with 5σ significance with 5 fb^{-1} (2009/2010?)
    - Could be earlier if $m_H \geq 2 * m_W$
  - At low mass requires combination of three production and decay modes:
    - $gg \rightarrow H \rightarrow \gamma\gamma$, $WW \rightarrow H \rightarrow \tau\tau$, $ttH \rightarrow ttbb$

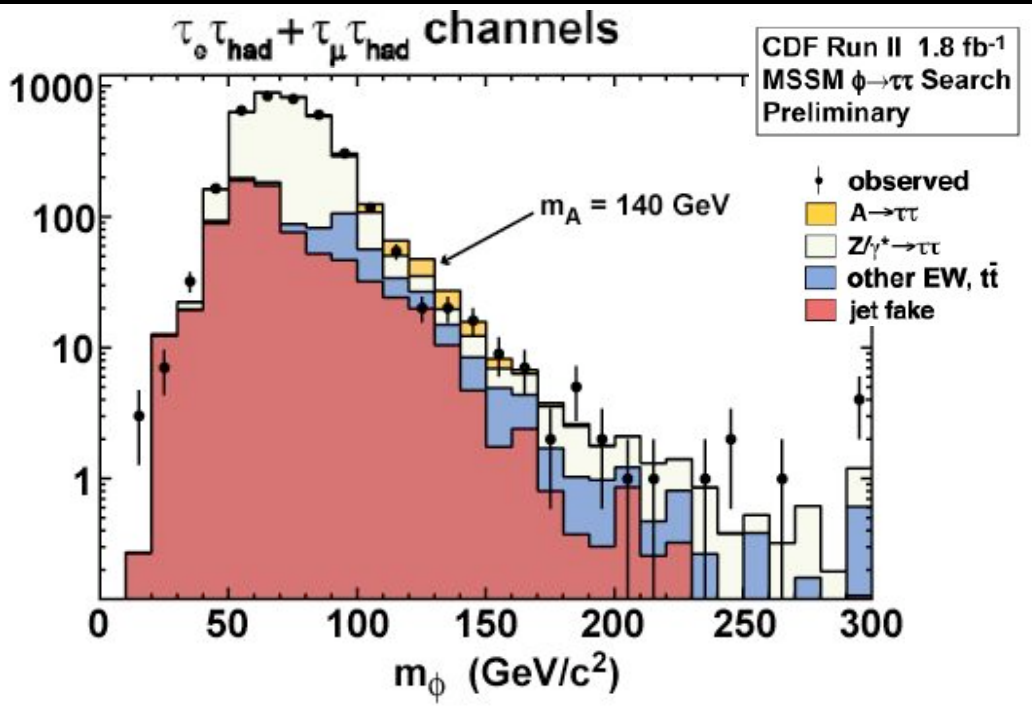
Supersymmetry

MSSM Higgs

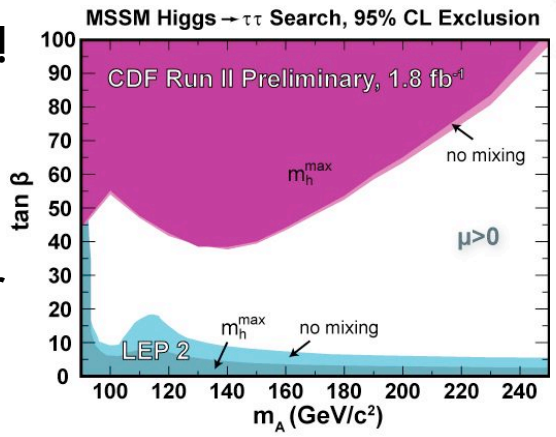
- 5 Higgs boson in MSSM
  - h,A,H,H±
  - At high tanβ:
    - A is degenerate in mass with h or H or both
    - Cross section enhanced as $\tan^2\beta$
    - Decay: 90% $b\bar{b}$, 10% $\tau^{\pm}\tau^{\pm}$

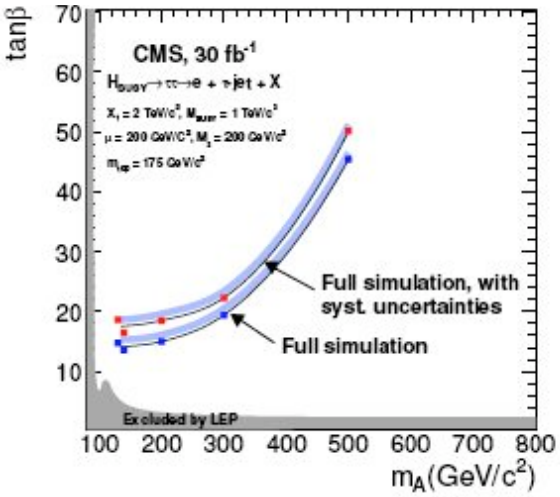


$$\sigma \times BR_{SUSY} = 2 \times \sigma_{SM} \times \frac{\tan\beta^2}{(1+\Delta_b)^2} \times \frac{9}{[9+(1+\Delta_b)^2]}$$

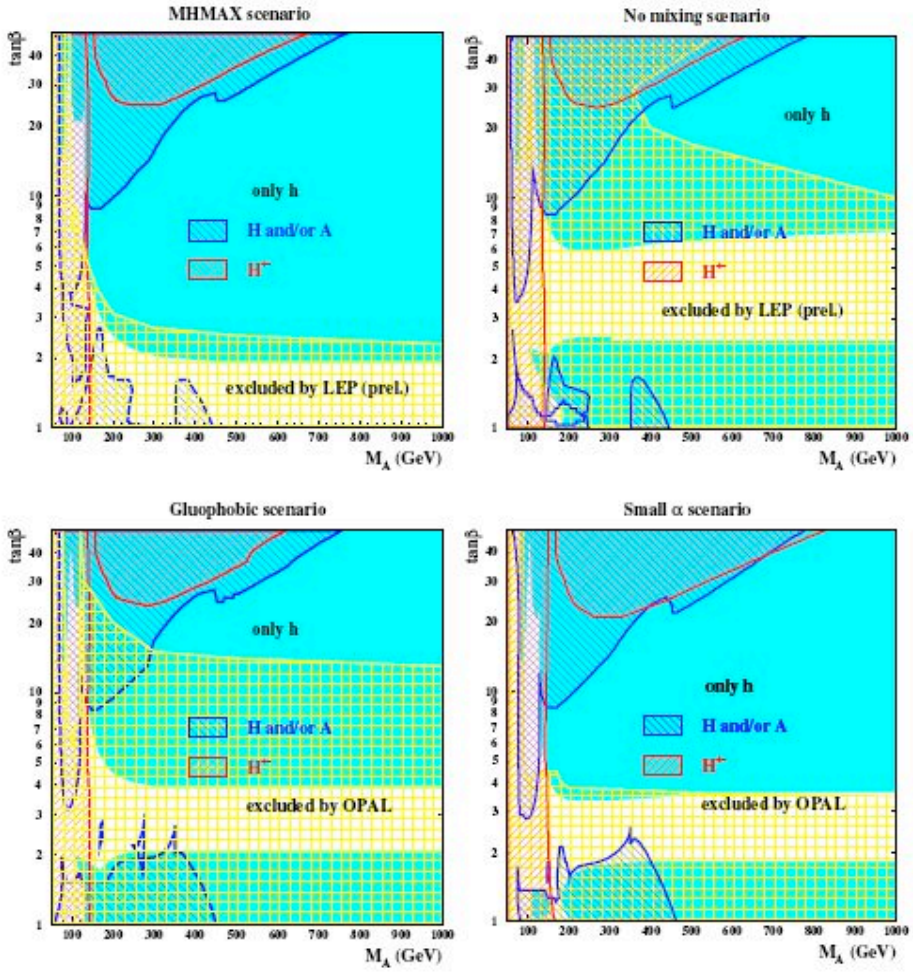


- Searches focus on ττ channel
  - Tau-leptons are challenging!
  - But used successfully at the Tevatron also
    - CDF result caused some excitement earlier this year
    - But has disappeared with more data





MSSM Higgs Scenarios



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

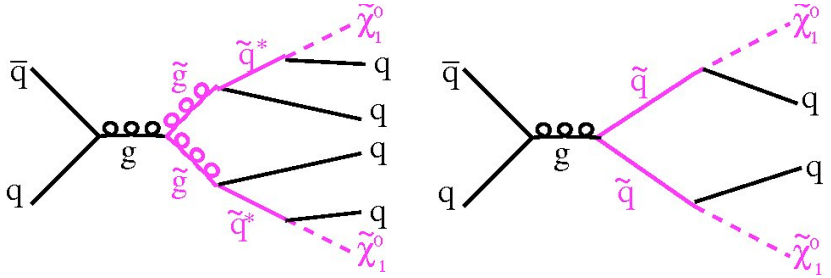
Gluophobic scenario (M_{SUSY} = 350 GeV/c^2)
coupling to gluons suppressed
(cancellation of top + stop loops)
small rate for gg → H, H→ γγ and Z→4 _

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

- Lots of parameter space where only the lightet higgs is observable unfortunately (=> strong motivation for ILC)

Sparticle Production

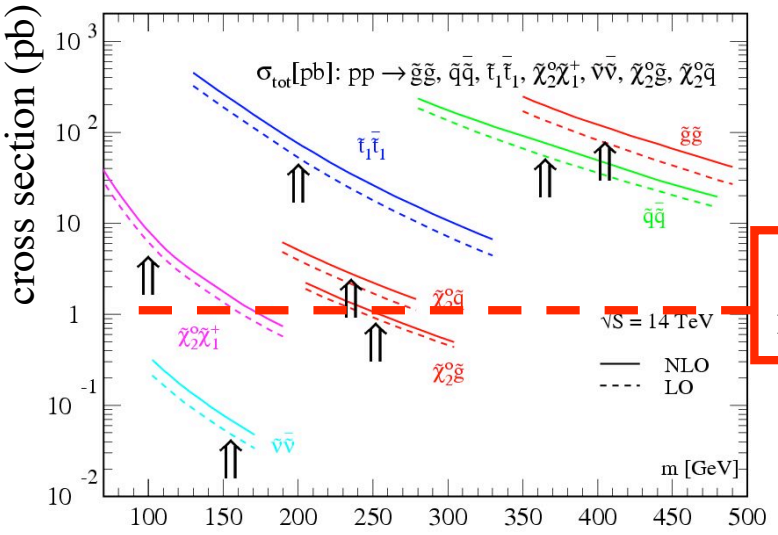
- Production of the *strongly interacting* sparticles dominates: pp→ $\tilde{g}\tilde{g}$,$\tilde{q}\bar{q}$,$\tilde{q}\tilde{q}$,$\tilde{g}\tilde{q}$



- Production cross section depends only on masses of gluino and squark
  - Rather model-independent search

- Large cross sections possible:
  - m($\tilde{g}$) ≈0.5-1.5 TeV
    → $\sigma_{pp\to SUSY}$ ≈ 0.1-100 pb

→ Potentially copious sparticle production at the LHC!

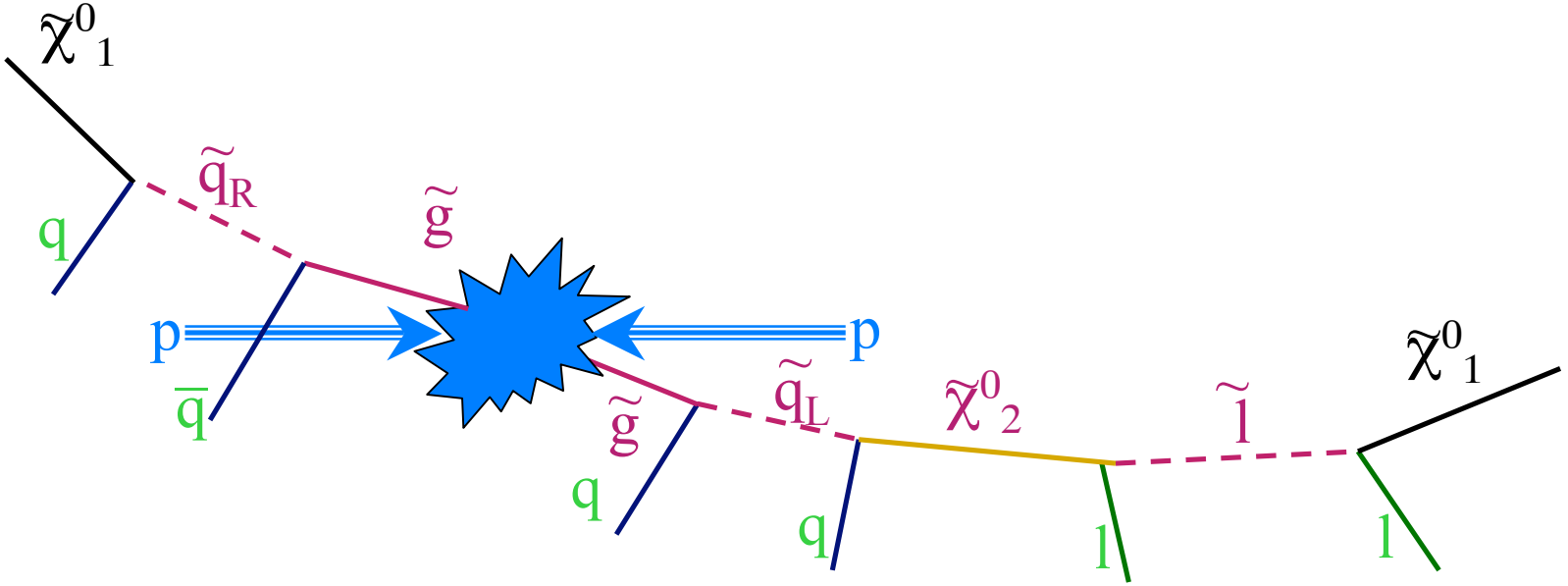


1000 events in 1 fb^{-1}

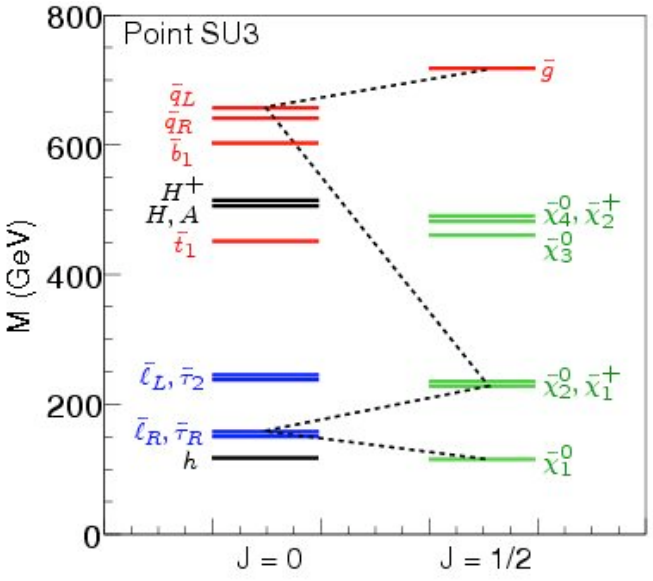
References: Beenakker, Höpker, Spira, Zerwas, 1995, 1997; Beenakker, MK, Plehn, Spira, Zerwas, 1998; Baer, Hall, Reno, 1998; Beenakker, Klasen, MK, Plehn, Spira, Zerwas, 1999; Beenakker, MK, Plehn, Spira, Zerwas, 2000; Berger, Klasen, Tait, 1999-2002; Beenakker, MK, Plehn, Spira, Zerwas, 2006

Sparticle Decays

- Event selection guided by typical decay chain of SUSY particles



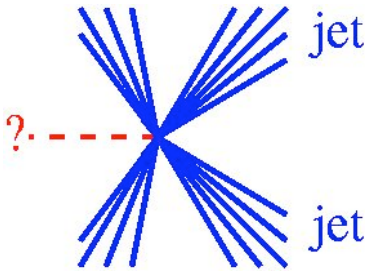
- Two strongly interacting sparticles produced
- Focus is on *"R-Parity"* conservation
  - Each sparticle decays into lighter sparticle + SM particle (→ jets + leptons)
  - cascade decays down to stable, undetected LSP (usually neutralino in mSUGRA) → large E_T^{miss}

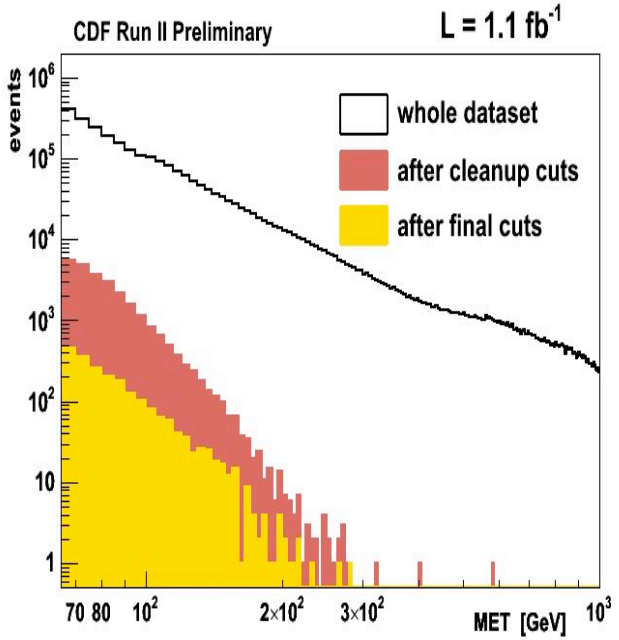


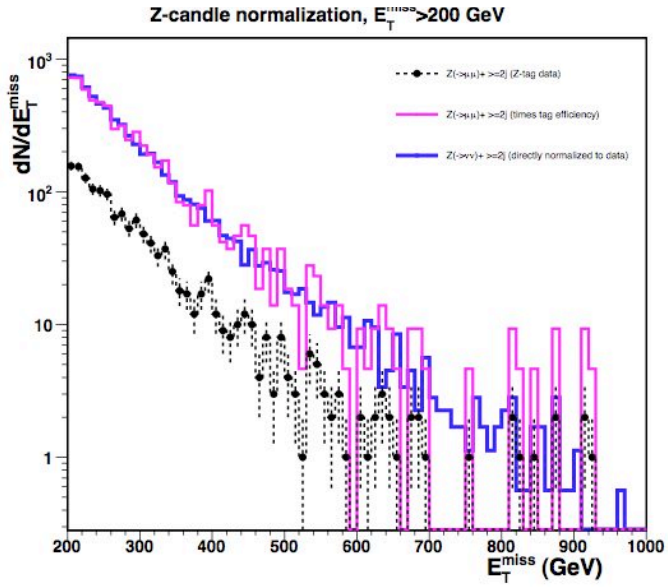
→ Canonical SUSY signature:
E_T^{miss}, high-p_T jets, often leptons

Missing E_T + jets

- Example Event selection
  - 4 high E_T jets
  - E_T^{MISS} > 100 GeV
  - Event sphericity>0.2
  - (No isolated leptons)
- SM backgrounds difficult
  - Multijet production
    - $Z(\nu\ \nu)$ + jets
    - $W(\mu\ \nu)$+ jets
    - Top + jet(s)
  - Instrumental
    - QCD multi-jet production
    - Electronic noise, etc.
  - All backgrounds need to be measured with data

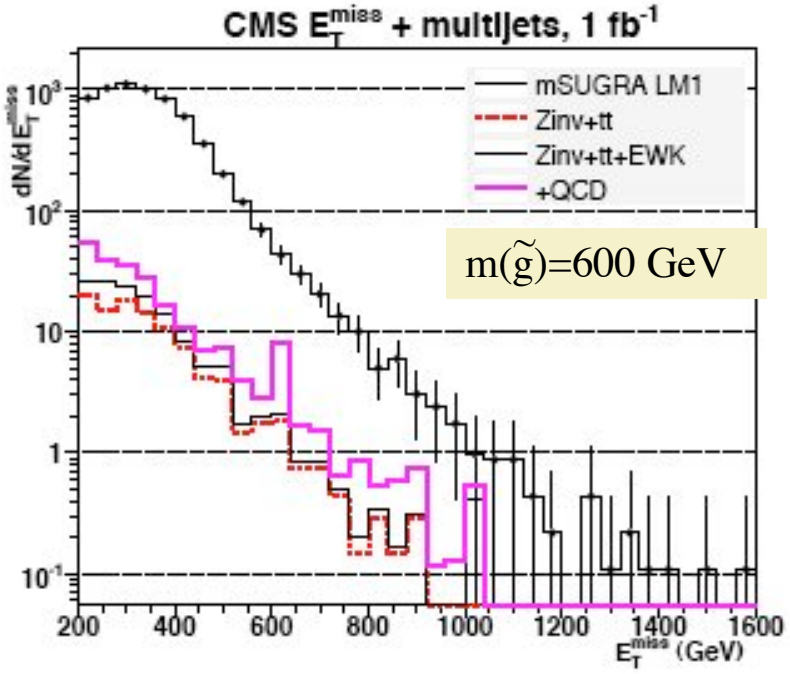




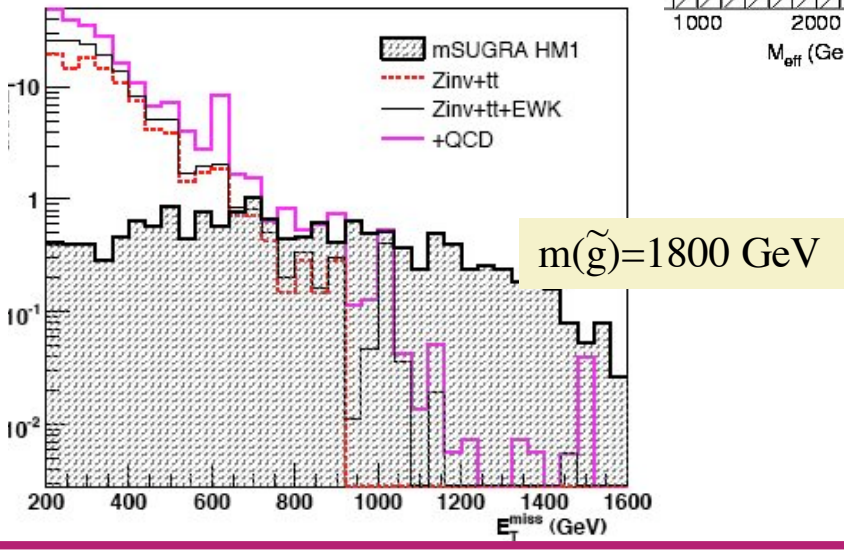


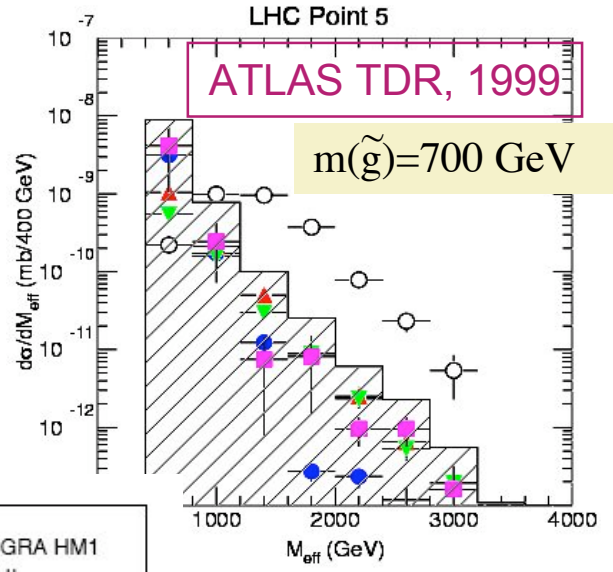
Missing E_T + jets

- Discriminating variables:
  - E_T^{MISS}
  - $M_{eff} = \sum_i |p_T^i| + E_T^{MISS}$



CMS, 2006





Also with latest state-of-the-art Monte Carlo programs of W/Z+jets there is an excellent discovery potential

Papers are already being written

6 December 2008

Evidence for squark and gluino production in pp collisions at $\sqrt{s}$ = 14 TeV

CMS collaboration

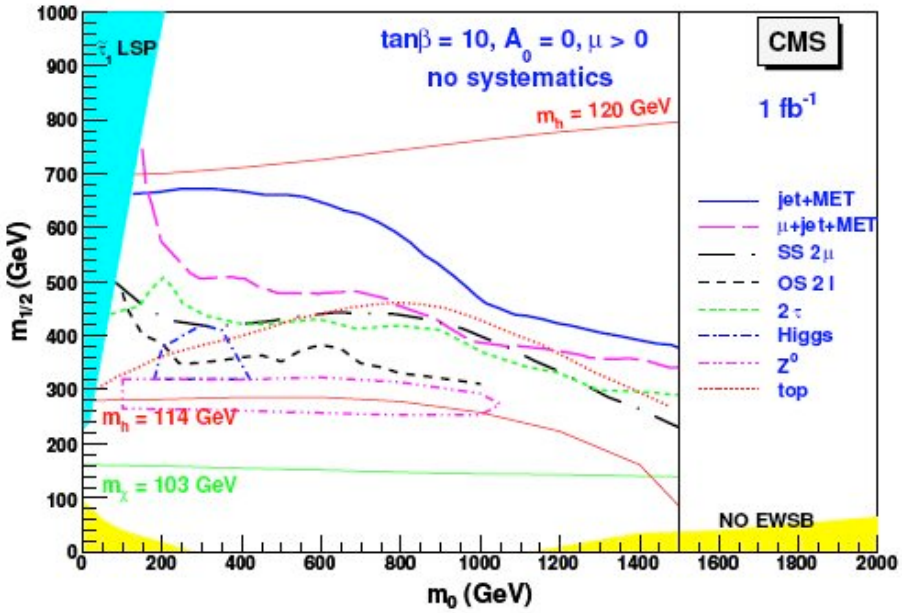
Abstract

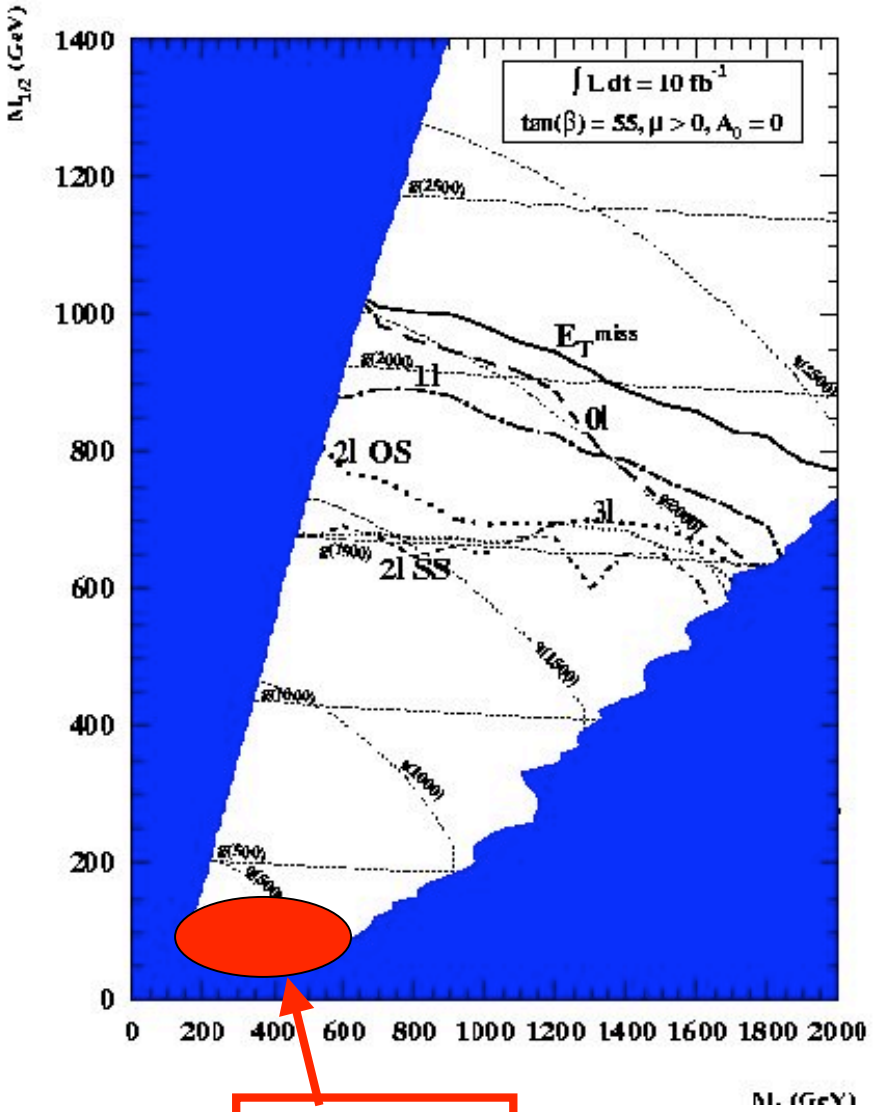
Experimental evidence for squark and gluino production in pp collisions $\sqrt{s}$ = 14 TeV with an integrated luminosity of 97 pb^{-1} at the Large Hadron Collider at CERN is reported. The CMS experiment has collected 320 events of events with several high E_T jets and large missing E_T, and the measured effective mass, i.e. the scalar sum of the four highest P_T jets and the event $\not{E}_T$, is consistent with squark and gluino masses of order of 650 GeV/c^2. The probability that the measured yield is consistent with the background is 0.26%.

Submitted to *European Journal of Physics*

- CMS is already writing papers just in case!

SUSY Discovery Reach

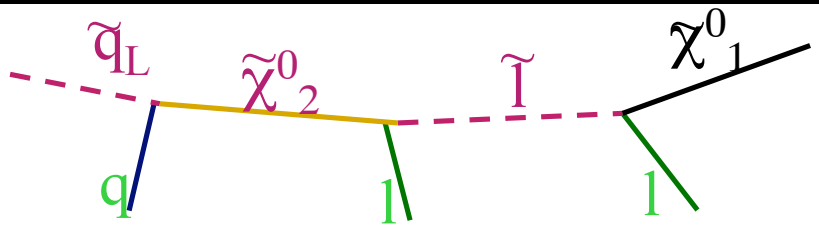


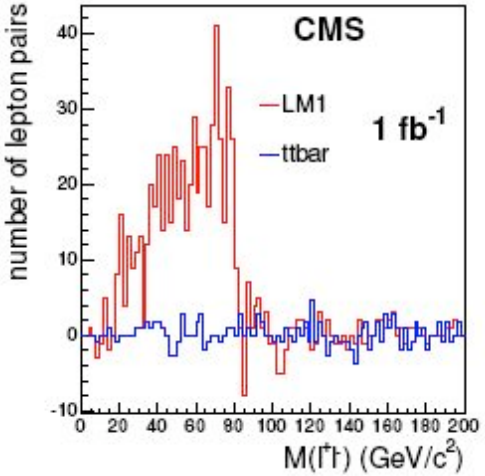


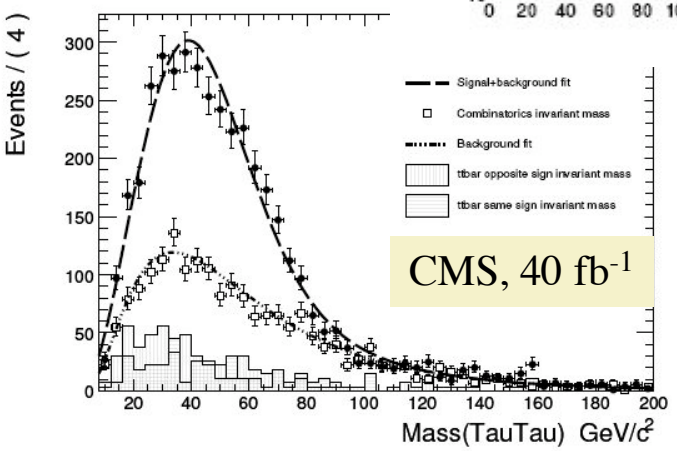
- With 1 fb^{-1}:
  - Sensitive to m($\tilde{g}$)<1000 GeV/
- With 10 fb^{-1}:
  - Sensitive to m($\tilde{g}$)<1800 GeV/
- Amazing potential!
  - If data can be understood
  - If current MC predictions are ≈ok

What kind of SUSY is it?

- We will need to do SUSY spectroscopy!
  - Rate of 0 vs 1 vs 2 vs n leptons
    - Sensitive to neutralino masses
  - Rate of tau-leptons:
    - Sensitive to tanβ
  - Kinematic edges
    - obtain mass values
  - Trileptons
    - Examine chargino/ neutralino couplings
  - Detailed examination of inclusive spectra







That would be my dream scenario! It's where the real fun starts!!

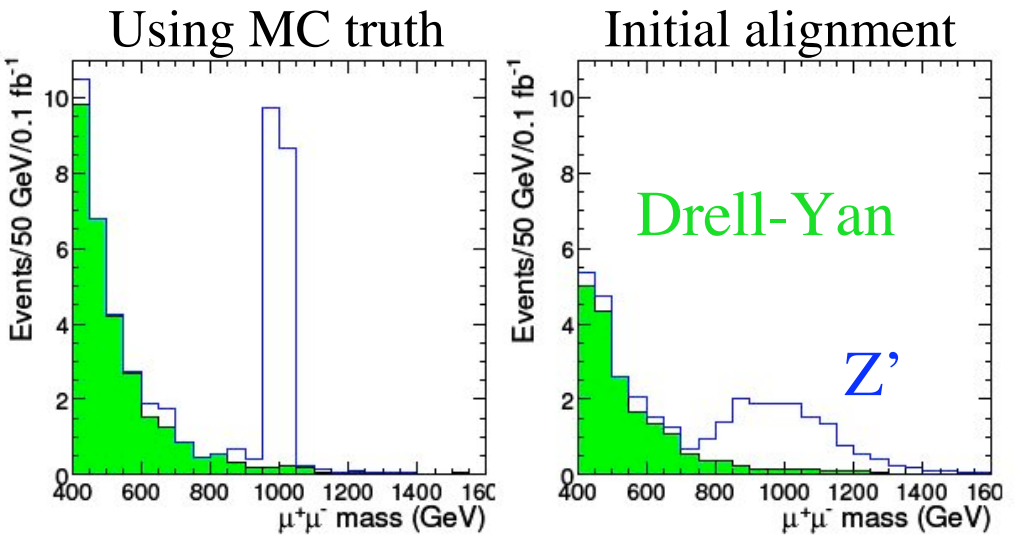
Z´ and Extra Dimensions

Z´ type particles should be easy!

- Signal creates clear peak
  - Easier for electrons than muons though
- Main background is well understood theoretically
- Applies to any narrow resonances decaying to electrons, muons, photons
- Muons suffer from worsening resolution at high momentum

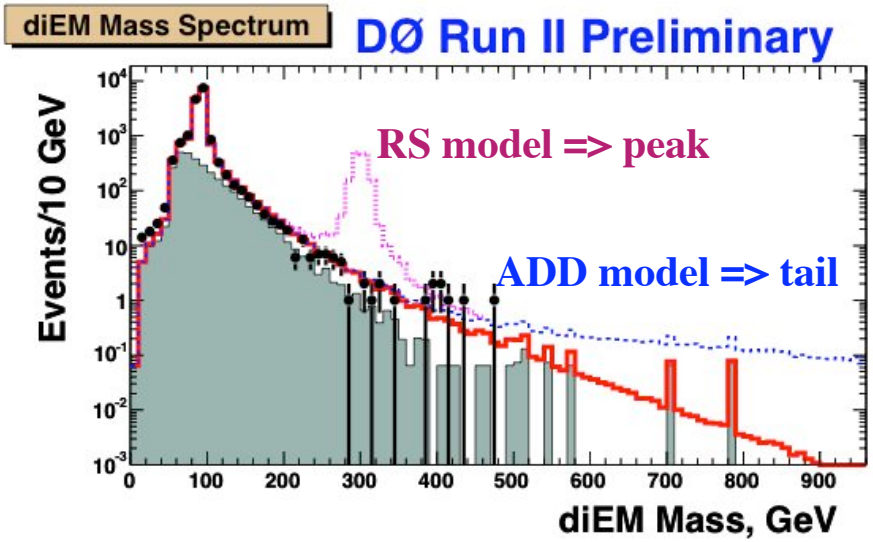
$Z' \rightarrow ee$, SSM

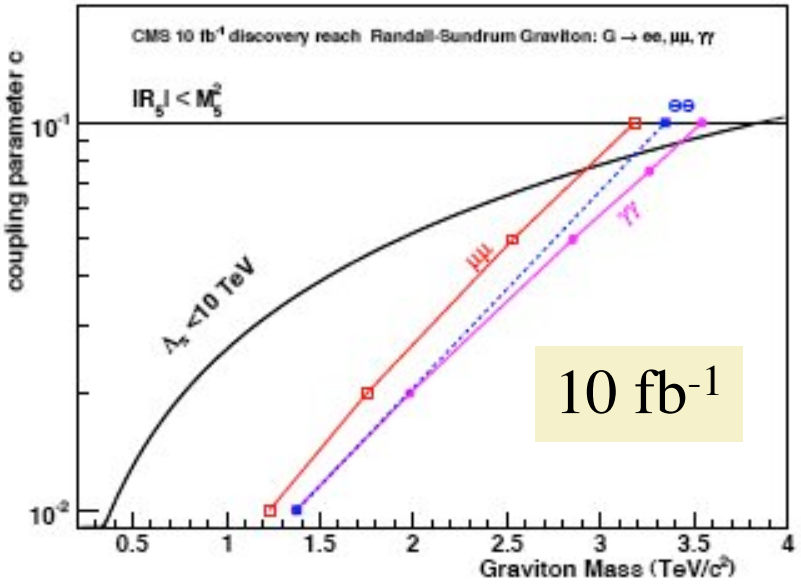
Mass	Expected events for 10 fb^{-1} (after all cuts)	$\int L\,dt$ needed for discovery (corresponds to 10 observed evts)
1 TeV	~ 1600	~ 70 pb^{-1}
1.5 TeV	~ 300	~ 300 pb^{-1}
2 TeV	~ 70	~ 1.5 fb^{-1}



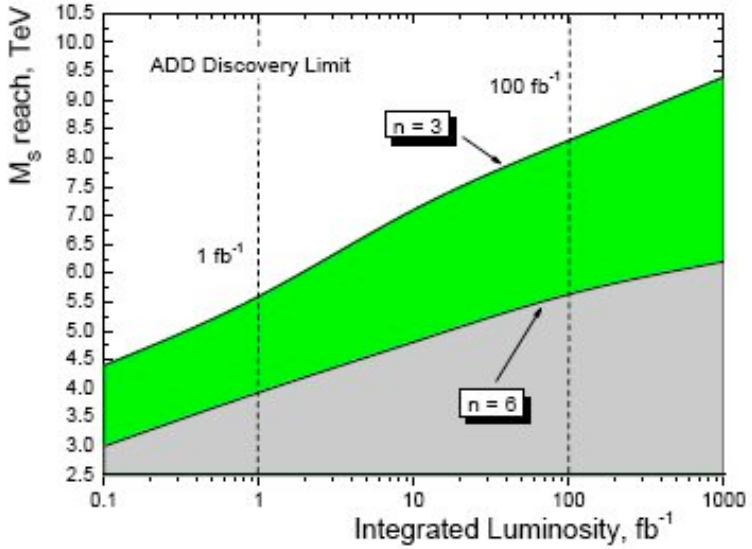
Probe ~1 TeV range already with 100 pb^{-1}

Extra Dimensions: Large or Warped?





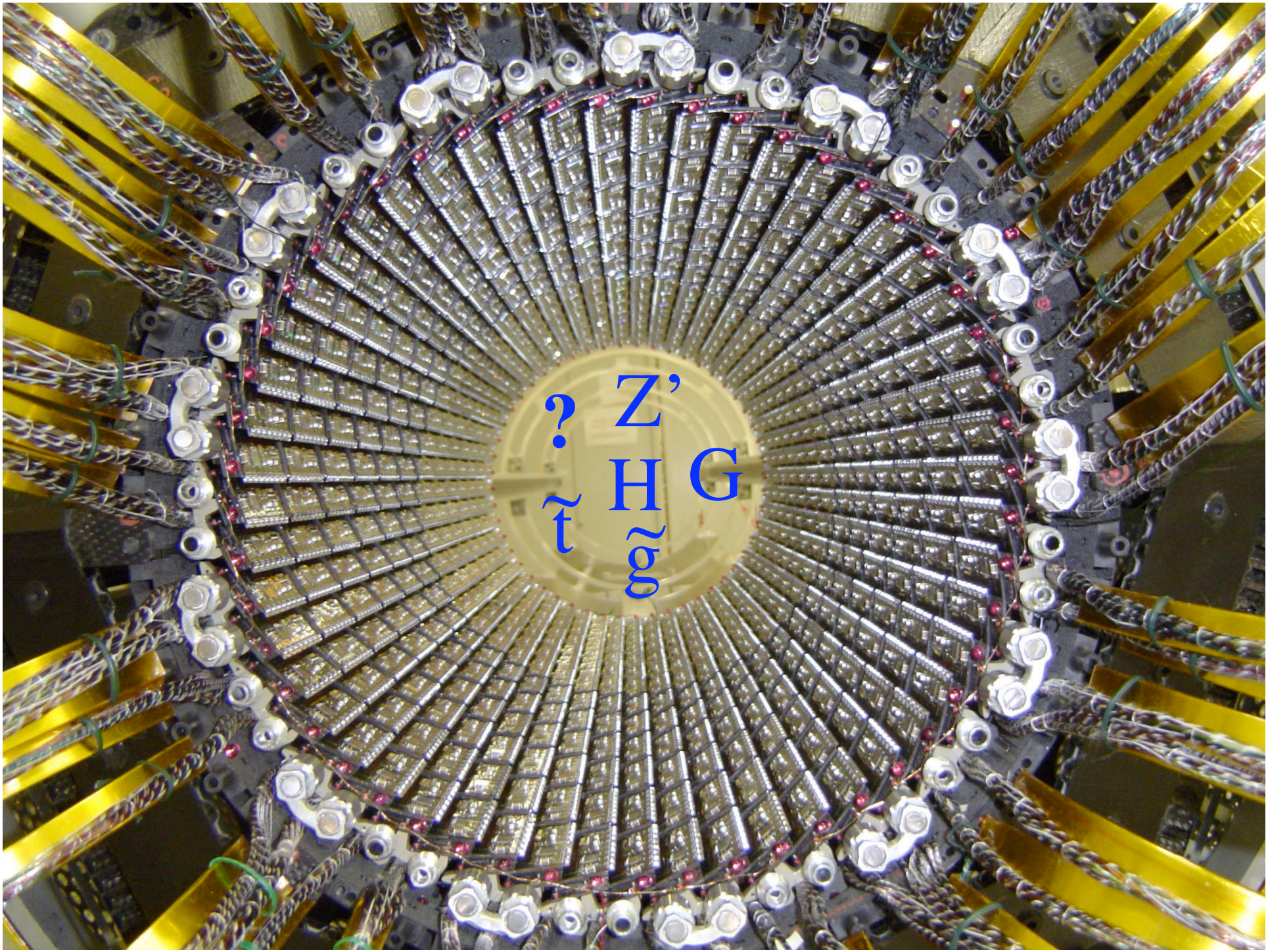
- Dilepton and diphoton mass spectra:
  - Probe RS model up to M_G=3 TeV with 10 fb^{-1}
  - Probe ADD model up to M_S=5 TeV with 1 fb^{-1}
- This is also quite easy



Conclusions and Outlook

- **Both the LHC accelerator and all the experiments are making excellent progress**
  - Incredibly complex machine, detectors, software, data handling
  - First collisions expected for summer'08 but further delays possible
  - Luminosity ramp-up time will primarily depend on how quickly confidence in the machine and diagnostics is gained
- **Amazing discovery potential already with very early data**
  - Major focus on final installation & commissioning with cosmic rays
  - Then establish the SM @ 14 TeV with early collision data
  - Establish the existence of a Higgs boson (or rule it out)
  - Find new physics at scales of up to about 5 TeV

After 20 years of construction time next year ~5000 physicists will analyze LHC data and hopefully find something spectacular!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