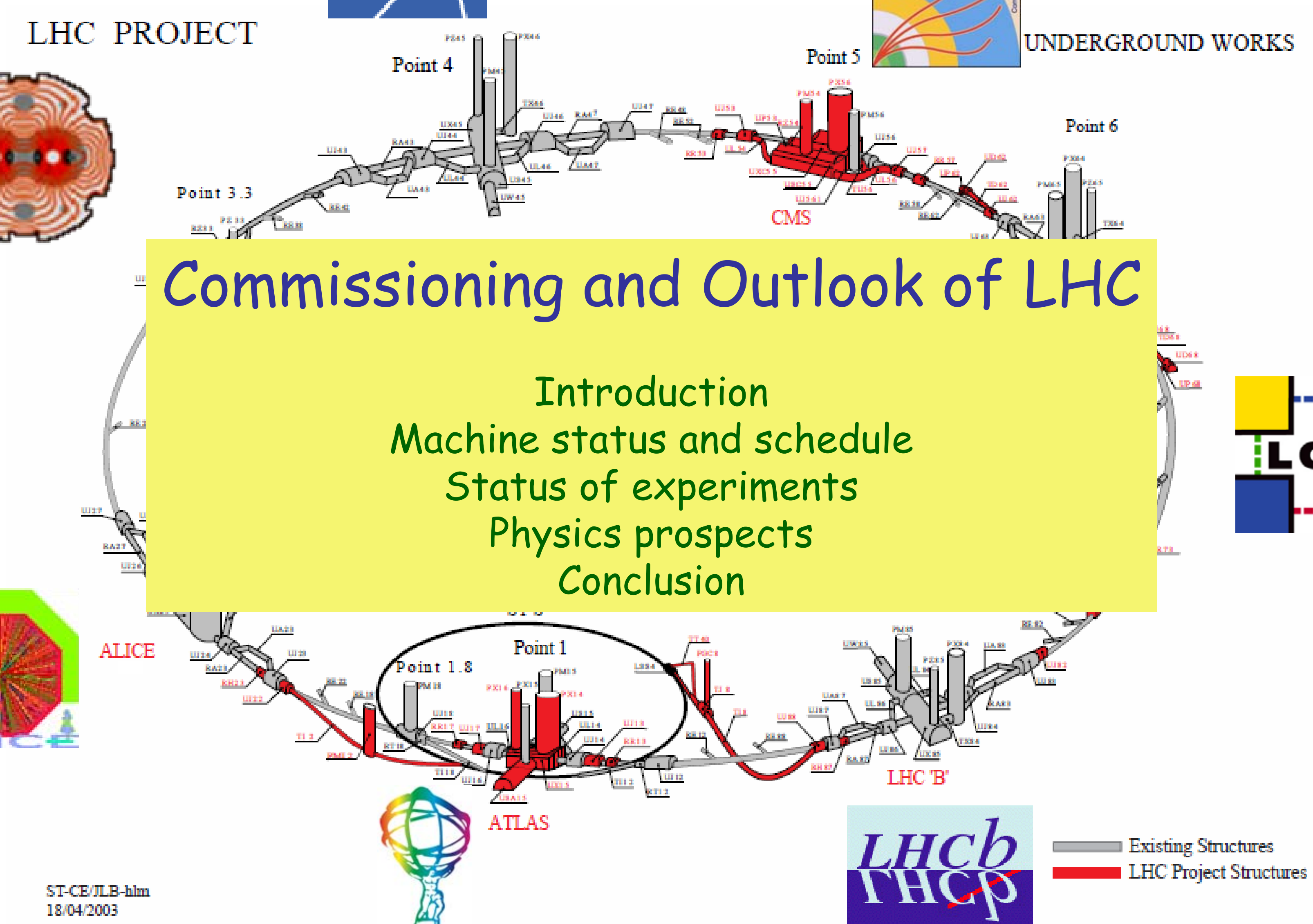
2. Nov. 2006
DPF+JPS+… in Hawaii
T. Kobayashi
(Univ. of Tokyo / ICEPP)

Commissioning and Outlook of LHC

Introduction
Machine status and schedule
Status of experiments
Physics prospects
Conclusion



My first talk at JPS on LHC project (14 years ago)

物理学会(新潟大)

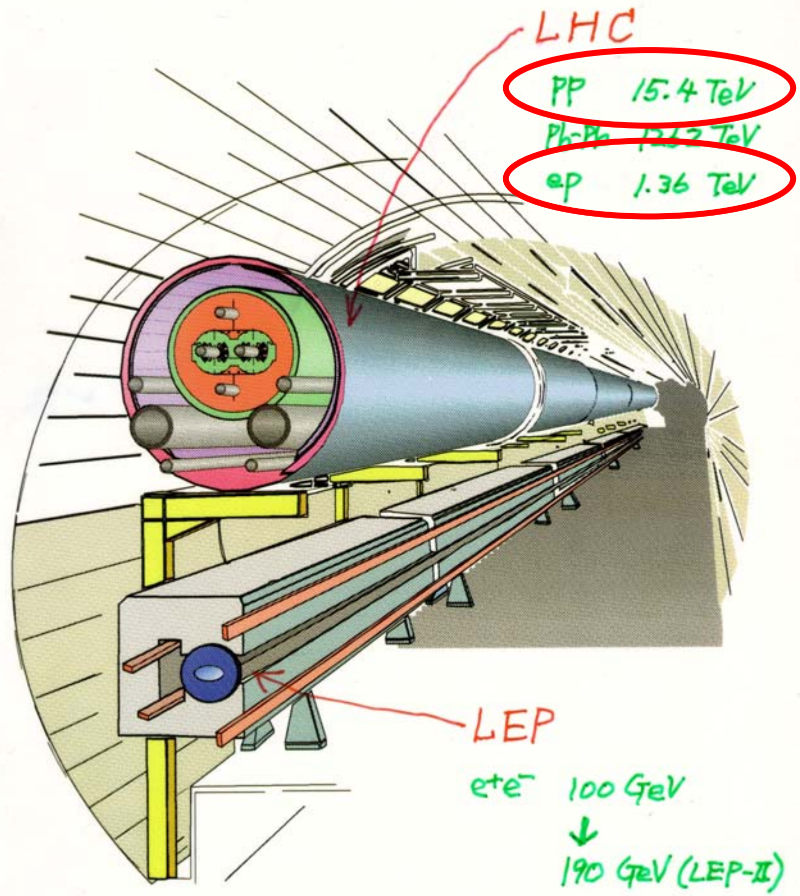
at Niigata University

CERN - LHC計画

4. Oct. 1992
東京大学素粒子物理国際センター
小林富雄

1. LHC計画の概略
   - 加速器
   - 目指す物理
   - これまでの経緯と今後
2. 検出器 (pp実験)
   ATLAS, CMS, L3P
3. Physics Performance
4. まとめ

Large Hadron Collider in LEP Tunnel



LHC --- A Versatile Machine

HE 100

Mar.1992
Evian

SUMMARY OF EXPRESSIONS OF INTEREST

• **PP** :	a) Main Detectors	- ASCOT → ATLAS	P. Norton
		- CMS	M. Della Negra J.C. Lottin
		- EAGLE → ATLAS	P. Jenni
		- L3+1 → L3P → ?	S.C.C. Ting
	b) B Physics	- CP Violation in B (forward spectrometer in collider mode)	P. Schlein
		- CP Violation in B (extracted beam FT)	G. Carboni
		- CP violation in B (GAS JET FT)	T. Nakada LHCb
• **Heavy Ions** :		- Dedicated general purpose detector	J. Schukraft ALICE
		- DELPHI	G. Jarlskog
		- CMS	L. Ramello
• **Neutrinos** :			K. Winter
		à la NOMAD ←	L. Vannucci

+ TOTEM, LHCf, MOEDAL, FP420, --

Oct. 1992

LHC Schedule

1991年12月 Council

Approval in Principle

(現時点での建設費見積り --- 約2000MSF)

Constr. cost ~ 2000 MCHF

検出器

1992 - 1993年

技術的 feasibility

建設費の詳細見積り

1993年12月 Council

Final approval

1992年3月 Evian --- EOI

1992年10月1日 --- LOI → LHCC

1992年末 --- Technical Proposal へ向けての実験採択

1993年末 --- Final approval

1994年 建設開始

Start constr. --- 1994

1999年 実験開始

Exp. start --- 1999 → Now 2007 / 2008

LHC Physics Prospects Then and Now

Oct. 1992

LHCでの物理

pp collider

- Higgs粒子探索 (80GeV<M_H<1TeV)

  strong Higgs sector (technicolor?)

MSM~OK (main stream) ⇒ EW対称性破れの機構解明

Mechanism of EWSB

- SUSY Higgs (h, A, H, $H^{\pm}$)
- SUSY粒子 ($\tilde{g}$, $\tilde{q}$, ---)
- top quark
- 標準理論の研究 (WWγ coupling, ---)
- Extended Gauge models (Z'粒子)
- quark の構造 (~10^{-18}cm)
- CP-violation ($B_d^0 \to J/\psi\ K_s^0$)
- unexpected new physics

Nov. 2006

Light Higgs
Vector Boson Fusion

Little Higgs, Higgsless, --

SUGRA, GMSB, AMSB,
split SUSY, --

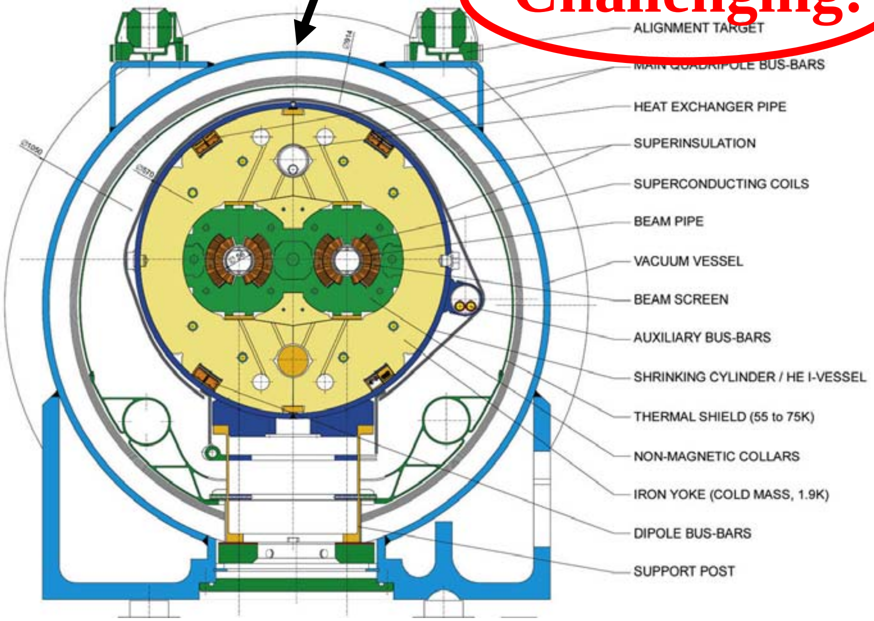
Extra dimensions
(large, warped, universal, --)
Black holes

LHC Machine Parameters

Proton-Proton Collider

Circumference:	26.7 km	(using LEP tunnel)
Beam Energy:	**7 TeV**	(Injection E: 450 GeV, PS→SPS→LHC)
1232 MR dipoles	**B=8.33 Tesla**, L=14.3m, 1.9K (**2-in-1 magnets**)	
368 MR quads	B'=223 T/m, L=3.1m	
No. of Bunches:	2808	
Bunch spacing:	24.95 ns	
Bunch size at IP:	16 μ m	
Bunch length at IP:	77 mm	
Half crossing angle:	160 μ rad	
Luminosity:	**10^{34} cm^{-2}s^{-1}**	

Challenging!



Heavy Ion Collider

Pb-Pb E_{cm} :	1148 TeV
Pb-Pb Luminosity:	10^{27} cm^{-2}s^{-1}

~23 pp collisions/crossing

Apr. 2005
First magnets were installed
in the LHC tunnel.

Oct. 2005

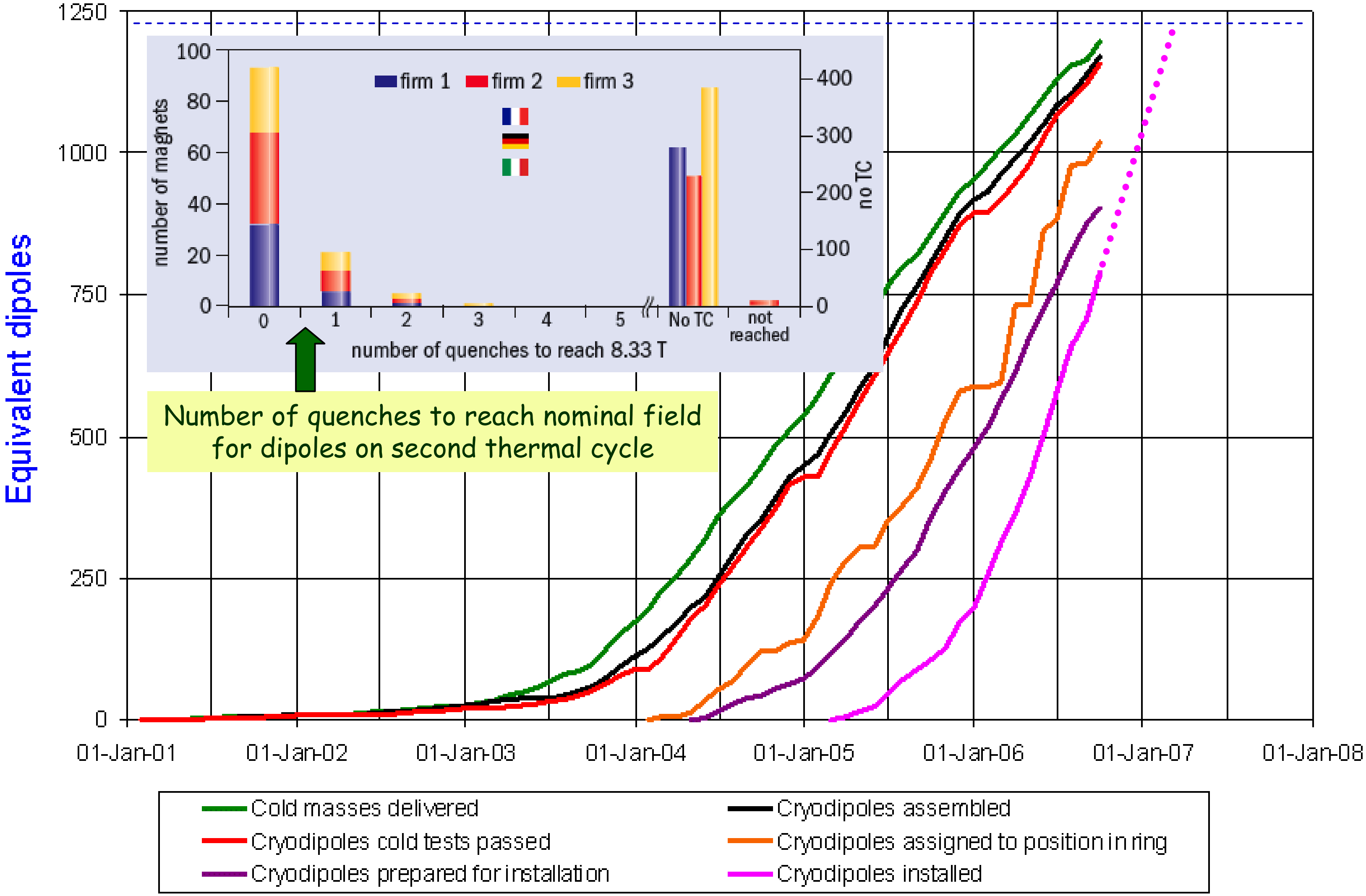
July 2006
Half-way point(616th) for
the 1232 dipole magnets

"The longest journey:
the LHC dipoles arrive on time"
(CERN Courier, Oct. 2006)

LHC Progress Dashboard

Accelerator Technology Department

Cryodipole overview



Successful international collaboration (Japan – US – CERN)

The CERN Control Centre (CCC) that combines all the control rooms for the accelerators, the cryogenic system and the technical infrastructure came into operation on 1st February, 2006.

(Revised) LHC schedule
as presented to CERN Council on 23 June 2006

- Last magnet installed : March 2007
  Machine and experiments closed : 31 August 2007

- First collisions ($\sqrt{s}$ = 900 GeV, L~10^{29} cm^{-2} s^{-1}) : November 2007
  Commissioning run at injection energy until end 2007, then shutdown (3 months ?)

- First collisions at $\sqrt{s}$=14 TeV (followed by first physics run): Spring 2008

Goal : deliver integrated luminosity of few fb^{-1} by end 2008

L. Evans, CERN Council, 23/6/2006

from end June 2008 (S. Myers)

- Sectors 7-8 and 8-1 will be fully commissioned up to 7 TeV in 2006-2007.
  If we continue to commission the other sectors up to 7 TeV,
  we will not get circulating beam in 2007.

- The other sectors will be commissioned up to the field needed for de-Gaussing.

- Initial operation will be at 900 GeV (CM) with a static machine (no ramp, no squeeze) to debug machine and detectors.

- Full commissioning up to 7 TeV will be done in the winter 2008 shutdown

Staged commissioning plan for protons

Stage I | II | III | IV

Hardware commissioning	Machine checkout	Beam commissioning	43 bunch operation	75ns ops	25ns ops I	Install Phase II and MKB	25ns ops II

No beam | Beam

I. **Pilot physics run**
- First collisions
- 43 bunches, no crossing angle, no squeeze, moderate intensities
- Push performance (156 bunches, partial squeeze in 1 and 5, push intensity)
- Performance limit 10^{32} cm^{-2} s^{-1} (event pileup)

II. **75ns operation**
- Establish multi-bunch operation, moderate intensities
- Relaxed machine parameters (squeeze and crossing angle)
- Push squeeze and crossing angle
- Performance limit 10^{33} cm^{-2} s^{-1} (event pileup)

2008

III. **25ns operation I**
- Nominal crossing angle
- Push squeeze
- Increase intensity to 50% nominal
- Performance limit 2 10^{33} cm^{-2} s^{-1}

2008-2009

up to 1-2 fb^{-1} end 2008, up to 10fb^{-1} end 2009 ?

IV. **25ns operation II**
- Push towards nominal performance

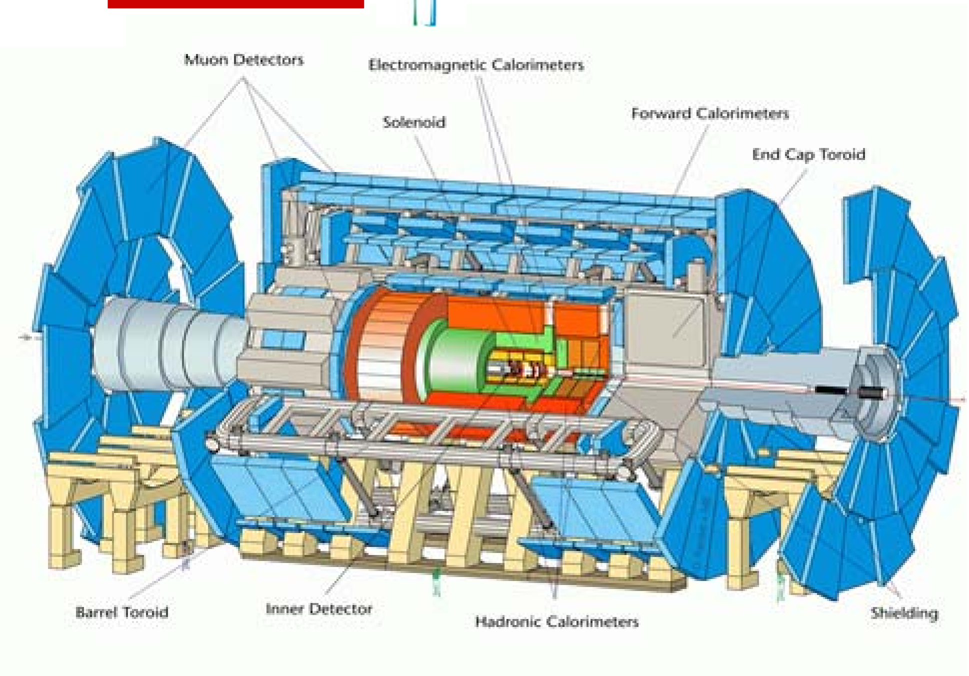
$\geq$ 2010

$O(100)$ fb^{-1}

Note: dates and integrated luminosities are MY interpretation (F. Gianotti)

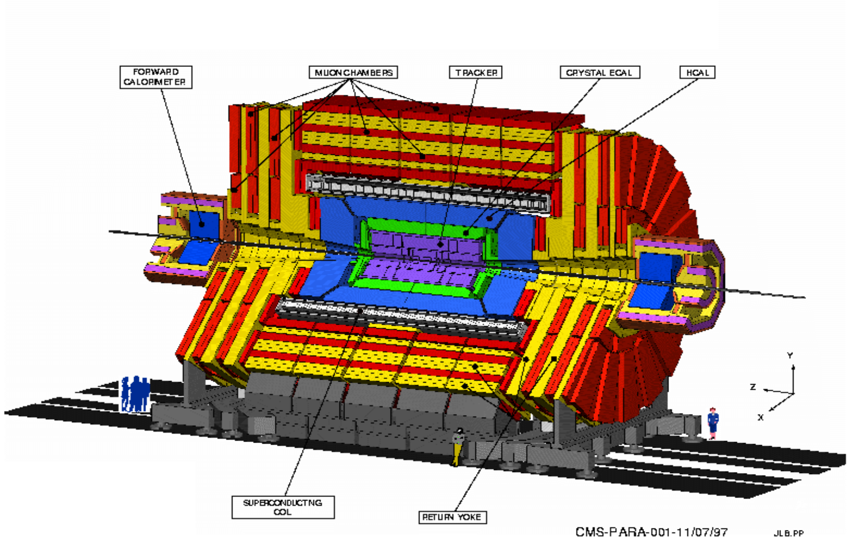
General purpose detectors for pp collisions

ATLAS



Length : ~45 m
Diameter : ~24 m
Weight : ~ 7,000 tons
Electronic channels : ~ 10^8
Solenoid : 2 T
Air-core toroids

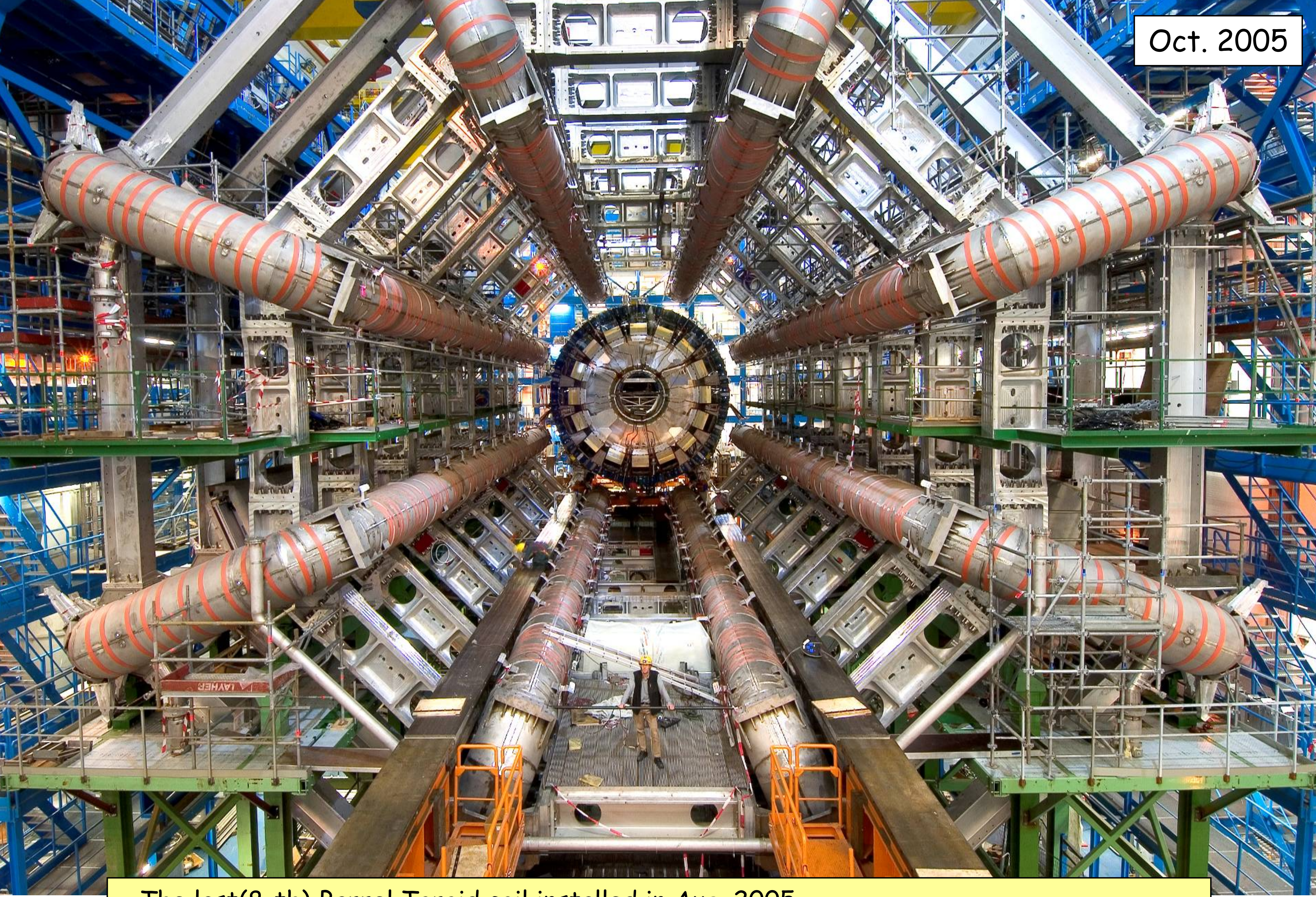
CMS



Length : ~22 m
Diameter : ~14 m
Weight : ~ 12,500 tons
Solenoid : 4 T
Fe yoke
Compact and modular

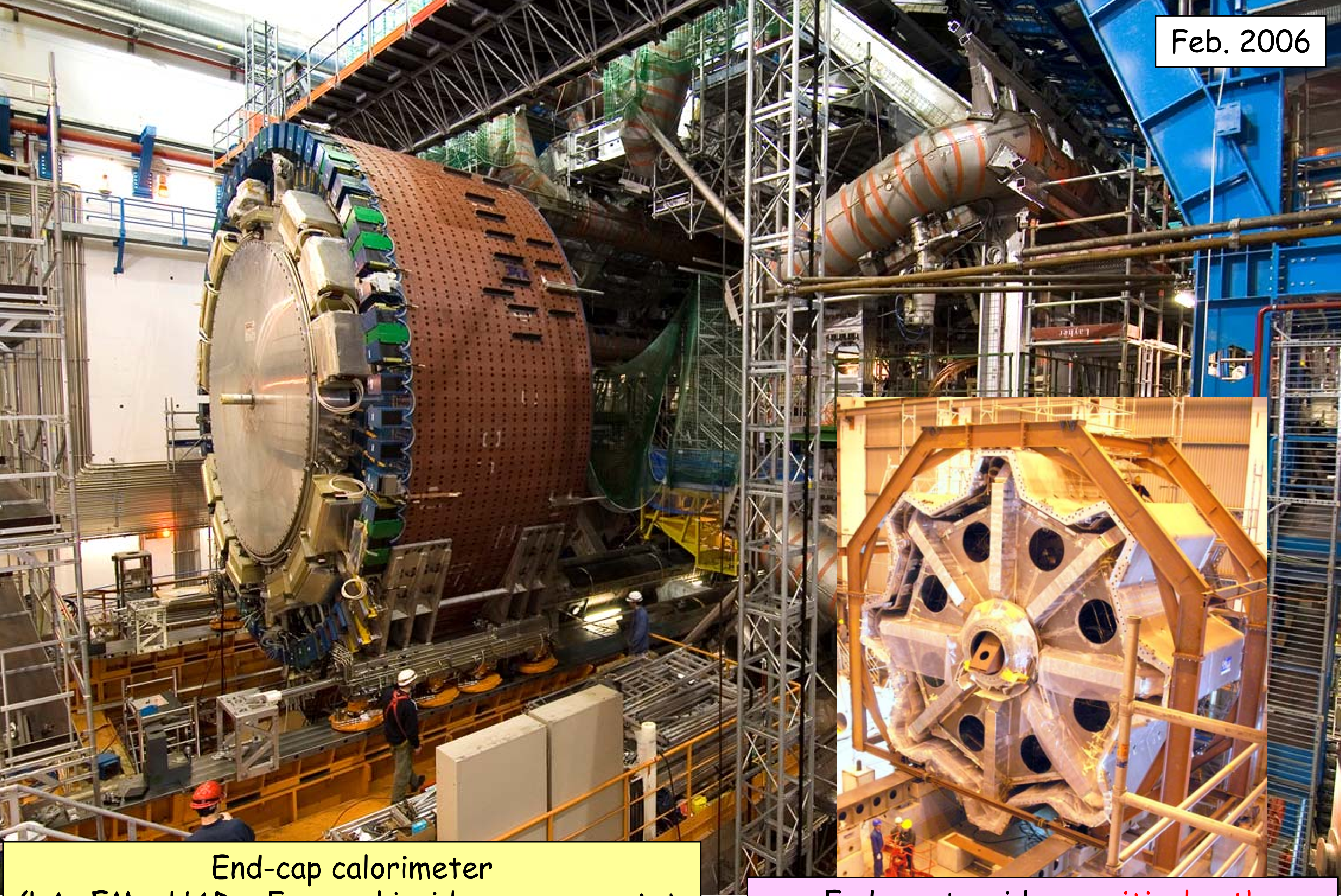
Detector elements

	ATLAS	CMS
TRACKER	Si pixels + strips TRT → particle identification $\sigma/p_T \sim 5\times10^{-4}\, p_T \oplus 0.01$	Si pixels + strips No particle identification $\sigma/p_T \sim 1.5\times10^{-4}\, p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segmentation
HAD CALO	Fe-scint. + Cu-liquid argon ($\geq 10\ \lambda$) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. ($\geq 5.8\ \lambda$ + catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	MDT, CSC, RPC, TGC $\sigma/p_T \sim 7\ \%$ at 1 TeV standalone	DT, CSC, RPC $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker



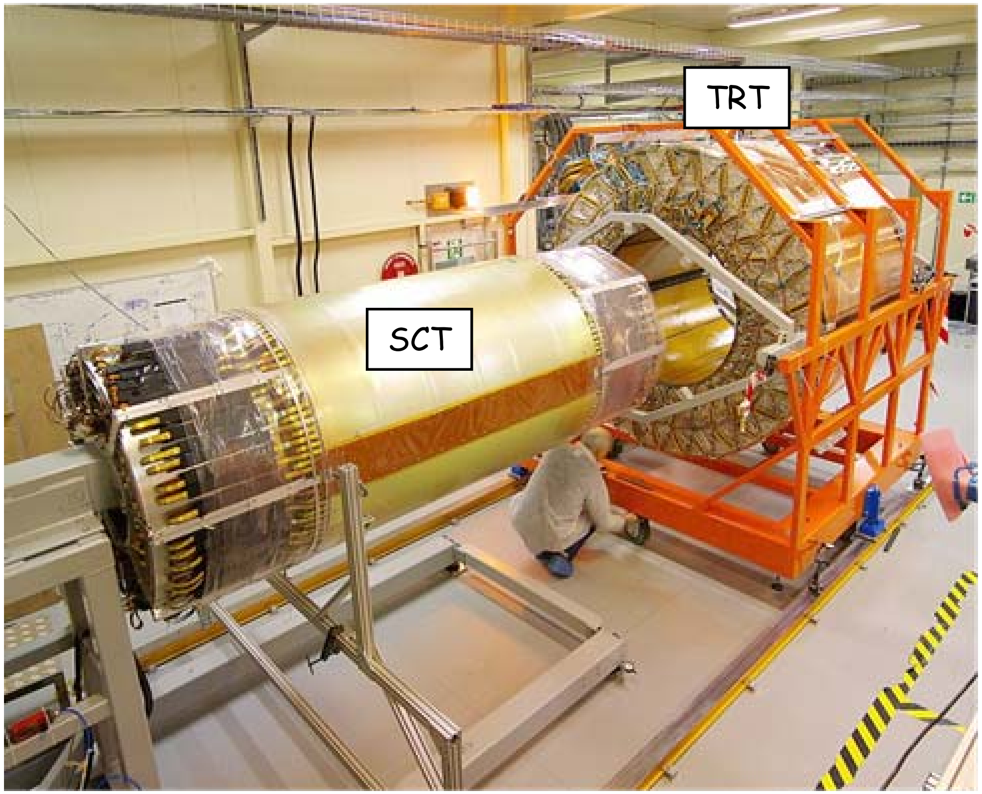
- The last(8-th) Barrel Toroid coil installed in Aug. 2005
- Barrel calorimeter (LAr EM + HAD Fe/Scint. Tilecal) in final position at Z=0 (Nov. 2005)
- Barrel toroid: cool down completed, first tests towards full field started in Sep. 2006

Feb. 2006

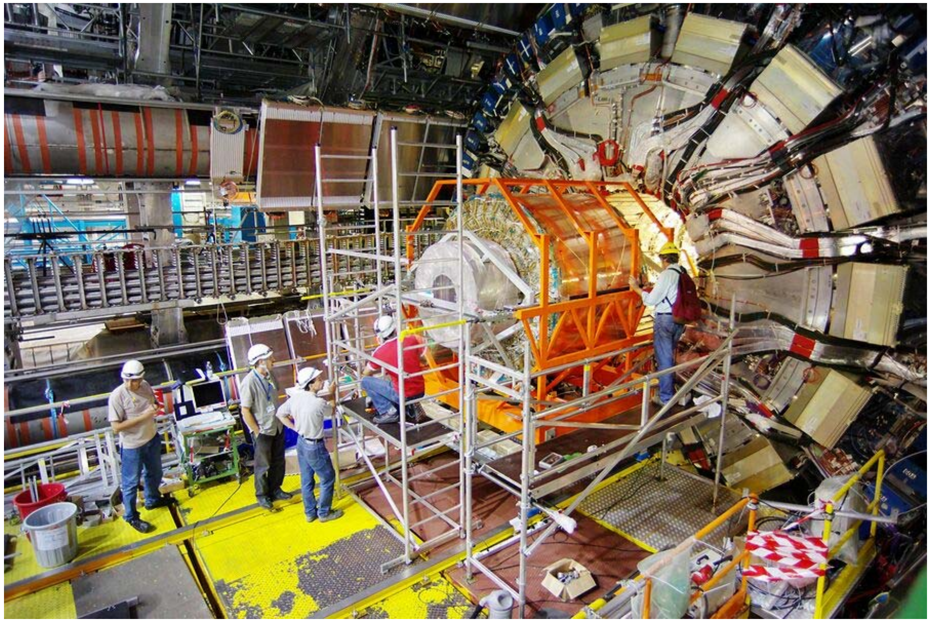


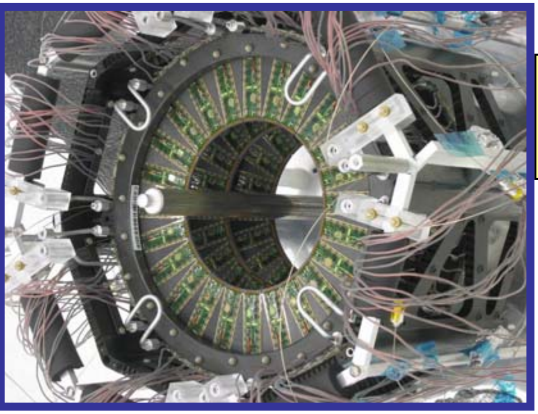
End-cap calorimeter
(LAr EM + HAD + Forward inside same cryostat,
surrounded by HAD Fe/Scint. Tilecal)
being moved inside the barrel toroid

End-cap toroids → critical path
some delay due to technical problem
(cold mass support alignment mechanics)



In February, barrel Si detector (SCT) was inserted into barrel TRT.
→ Installation in the pit in Aug. 2006

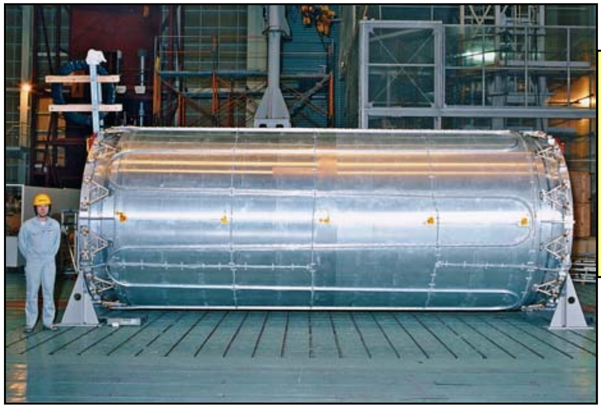




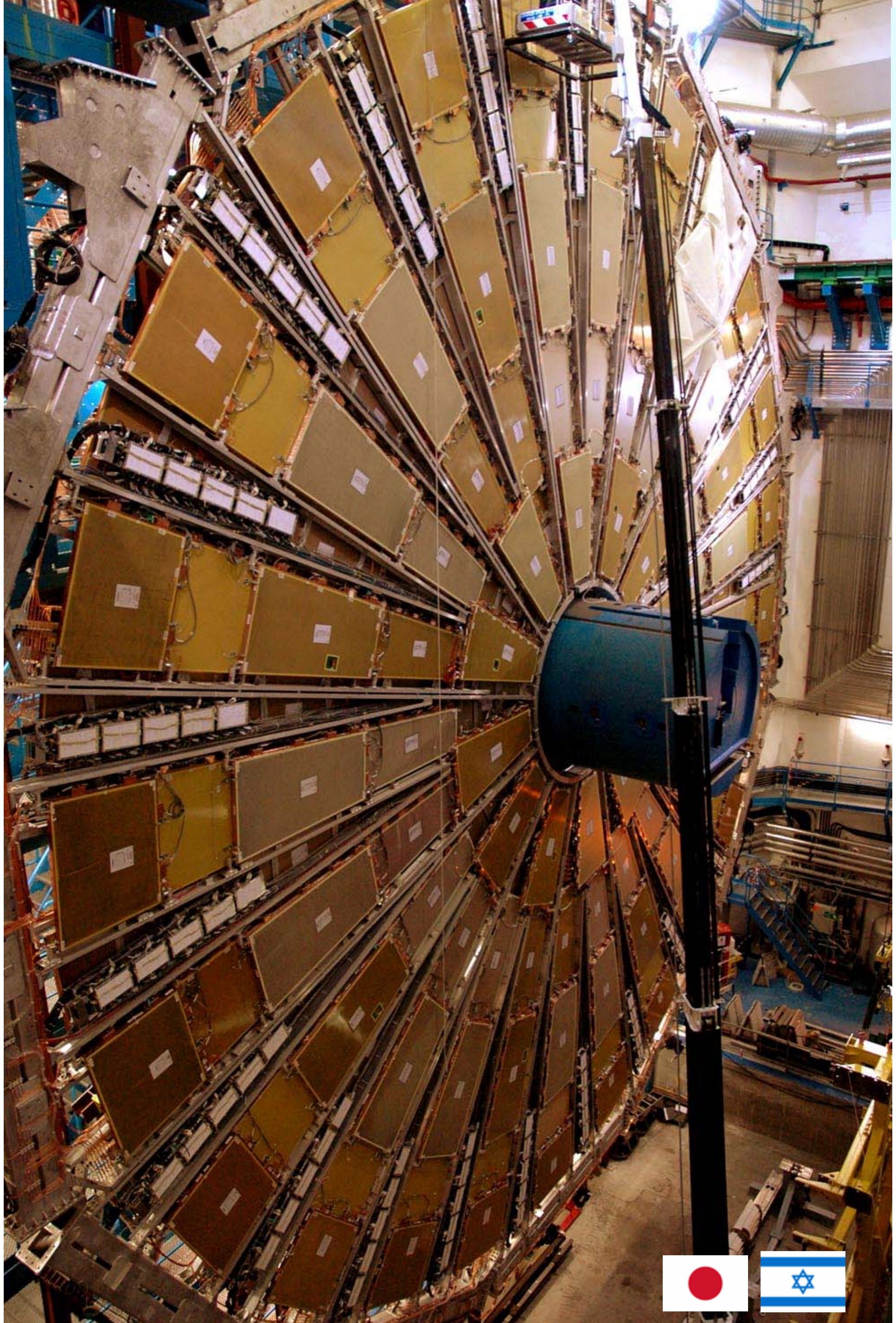
Three completed Pixel disks (one end-cap)

Installation of the two end-caps will be in Jan./Feb. 2007.

Both end-caps as well as barrel pixel detectors will be ready for installation in the pit in April 2007.



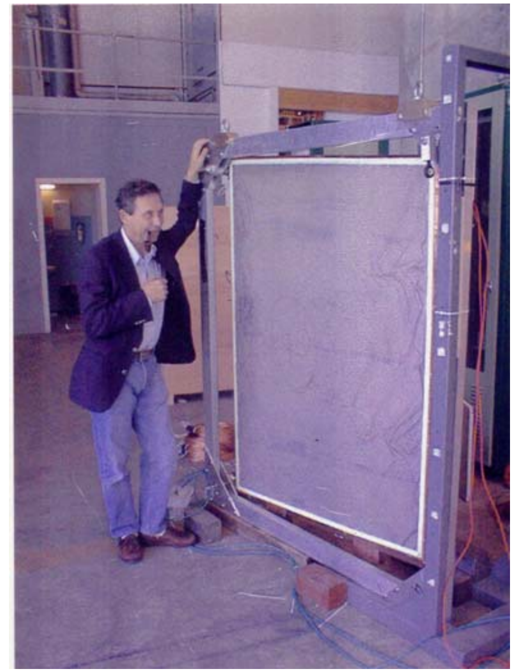
Central Solenoid: fully commissioned (2T) in-situ in Aug. 2006, and field mapping meas. done



Sep. 2006

TGC (Thin Gap Chamber) for Forward Muon Trigger:

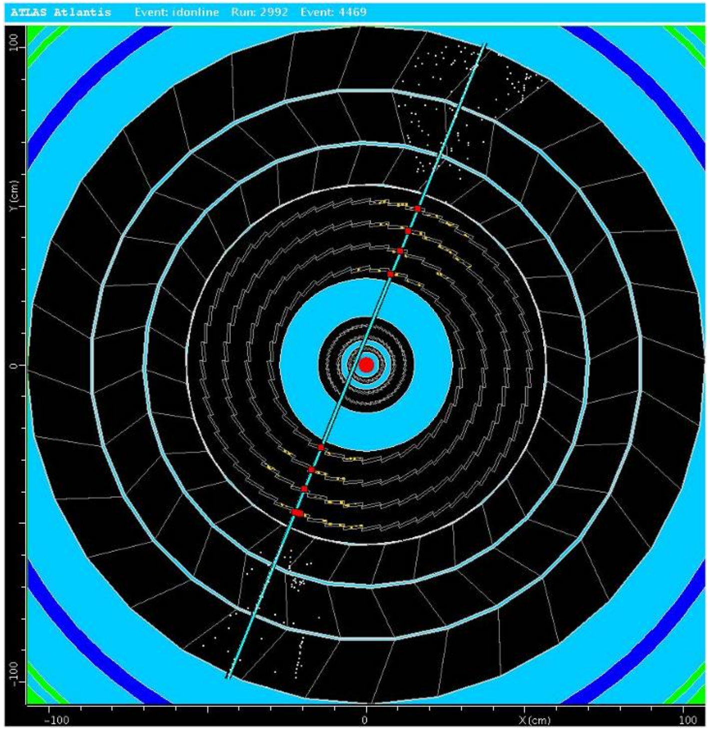
First Big Wheel in the pit



"12 years ago, we only dreamed about it...." (G. Mikenberg)

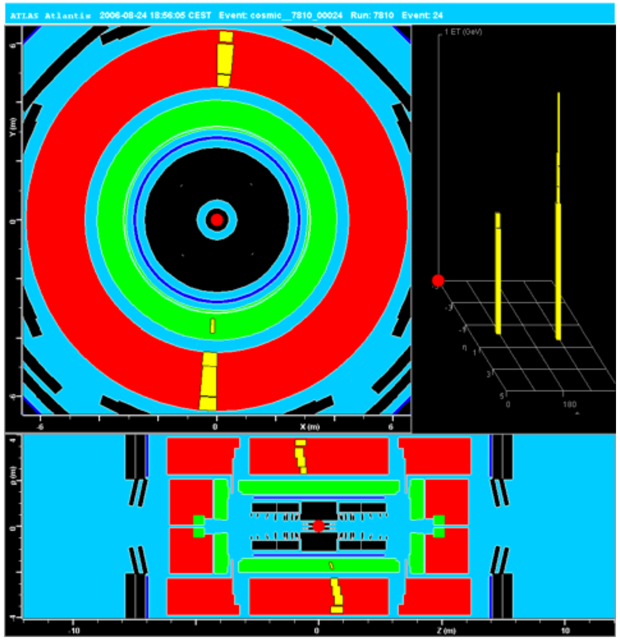
→ 5 more TGC BWs and 2 MDT BWs to come!

Installation of Barrel Muon chambers (MDT, RPC) will be completed until the end of 2006.

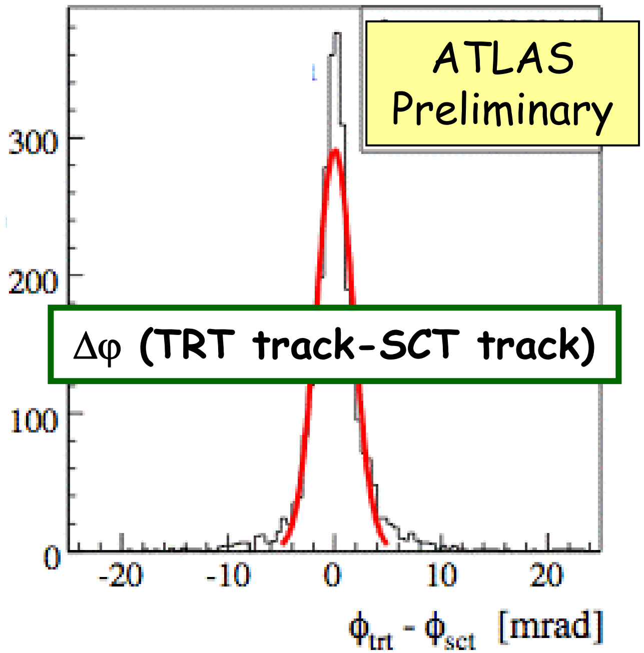


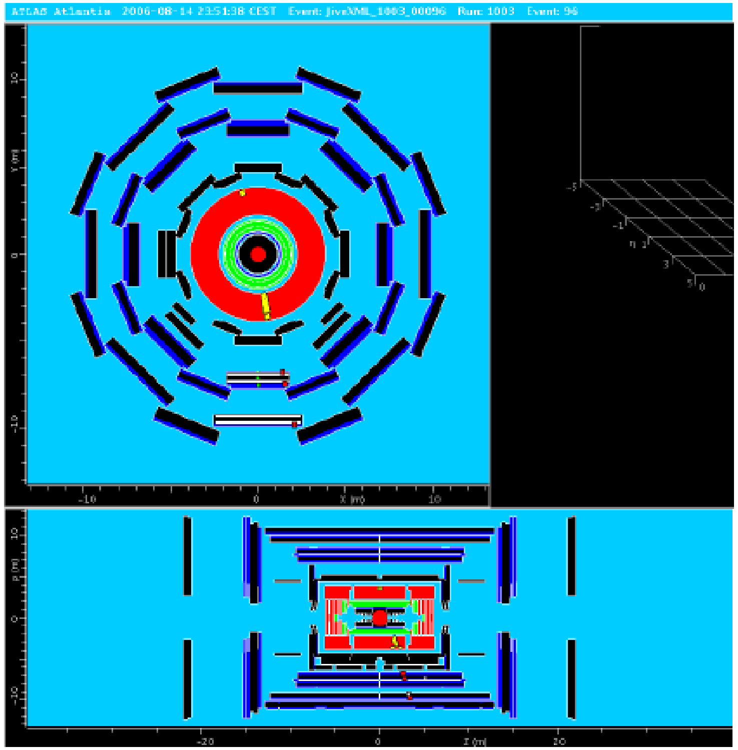
Cosmics data taken
in barrel SCT+TRT

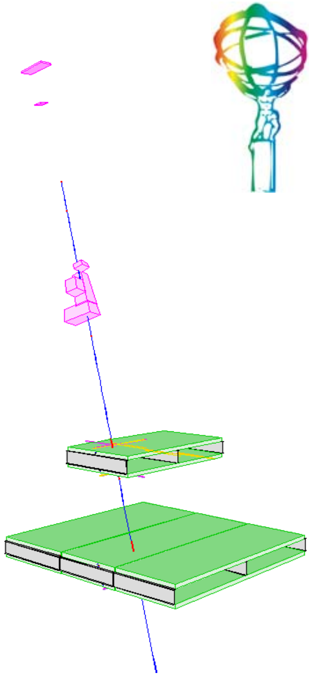
and
in barrel LAr+Tile



and also
in MDT+RPC(LVL-1)+Tile

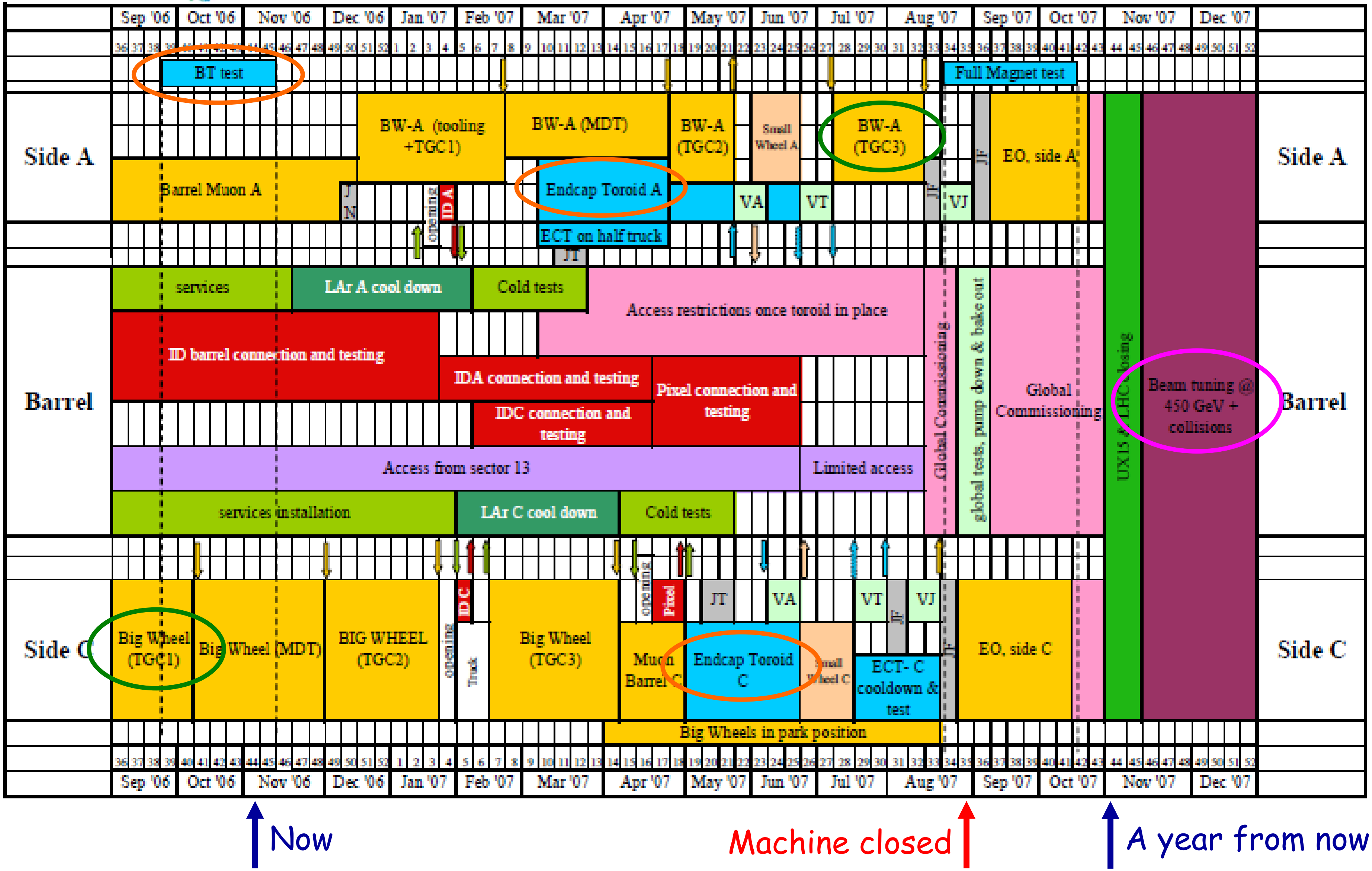






ATLAS Installation Activities in the Cavern

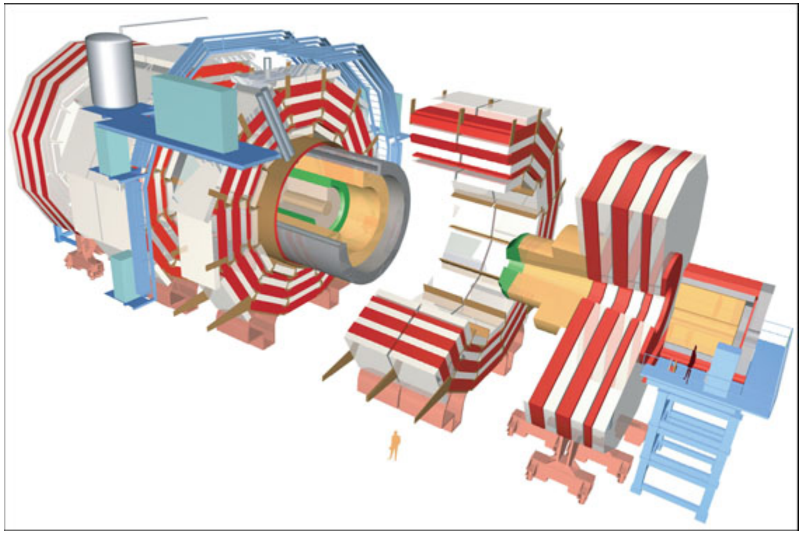
15-09-2006



Underground UXC Cavern

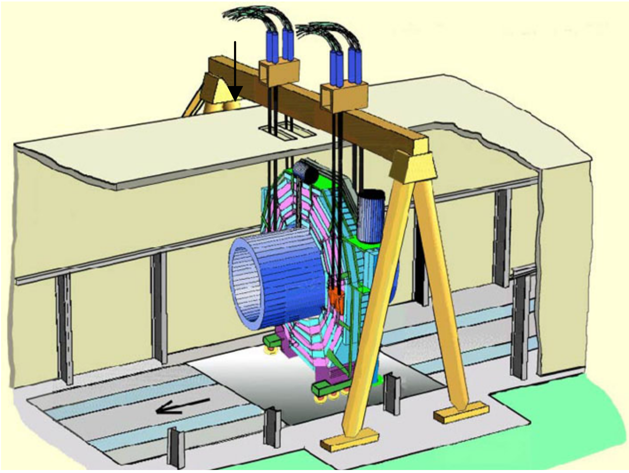
M. Della Negra
LHCC (10 May 2006)

Test of the fire extinguishing system
(12 May 2006)



- Compact and modular
- Assembled at the surface and lowered in the cavern piece by piece by "gantry" crane

→ "15-piece jigsaw puzzle" (A. Ball)

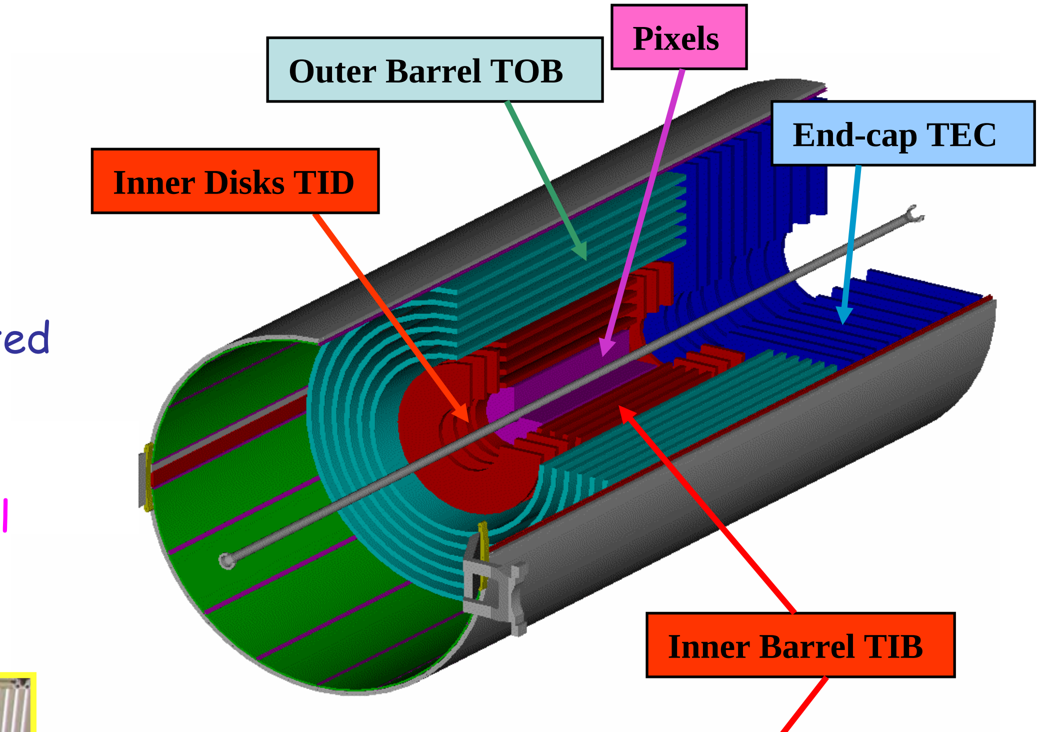


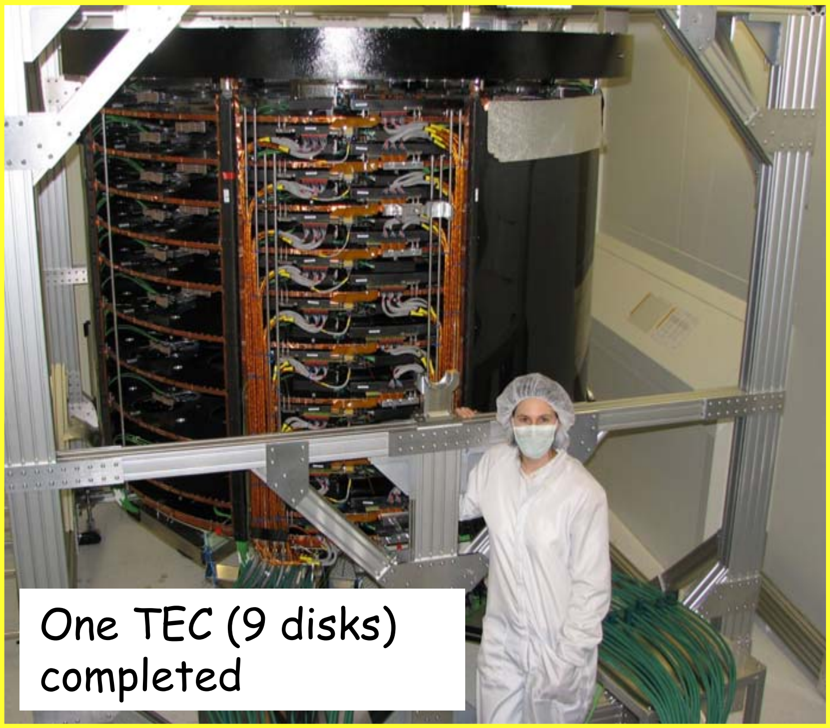
YB0 lowering (2000t): Dec. 2006

Inner tracker:
~ 220 m^2 of Si sensors
10.6 million Si strips
65.9 million Pixels

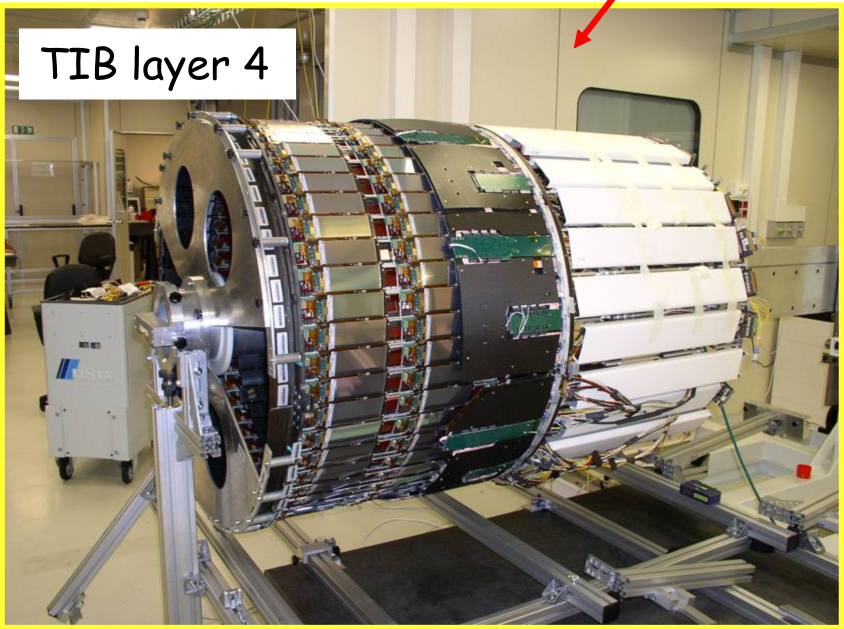
- Assembly of all 16000 modules completed
- Integration progressing well
- Installation at Point 5 in June 2007

(Pixel detector will not be in the initial detector, but it will be installed to be ready for the physics run in 2008.)





One TEC (9 disks) completed



TIB layer 4

Electromagnetic calorimeter

Barrel : 36 SuperModules (SM), 1700 crystals each
Total of ~ 61000 barrel crystals (>90% delivered)
30 bare SM assembled, 22 equipped with electronics

2 barrel SM installed inside HCAL for MTCC

Critical item

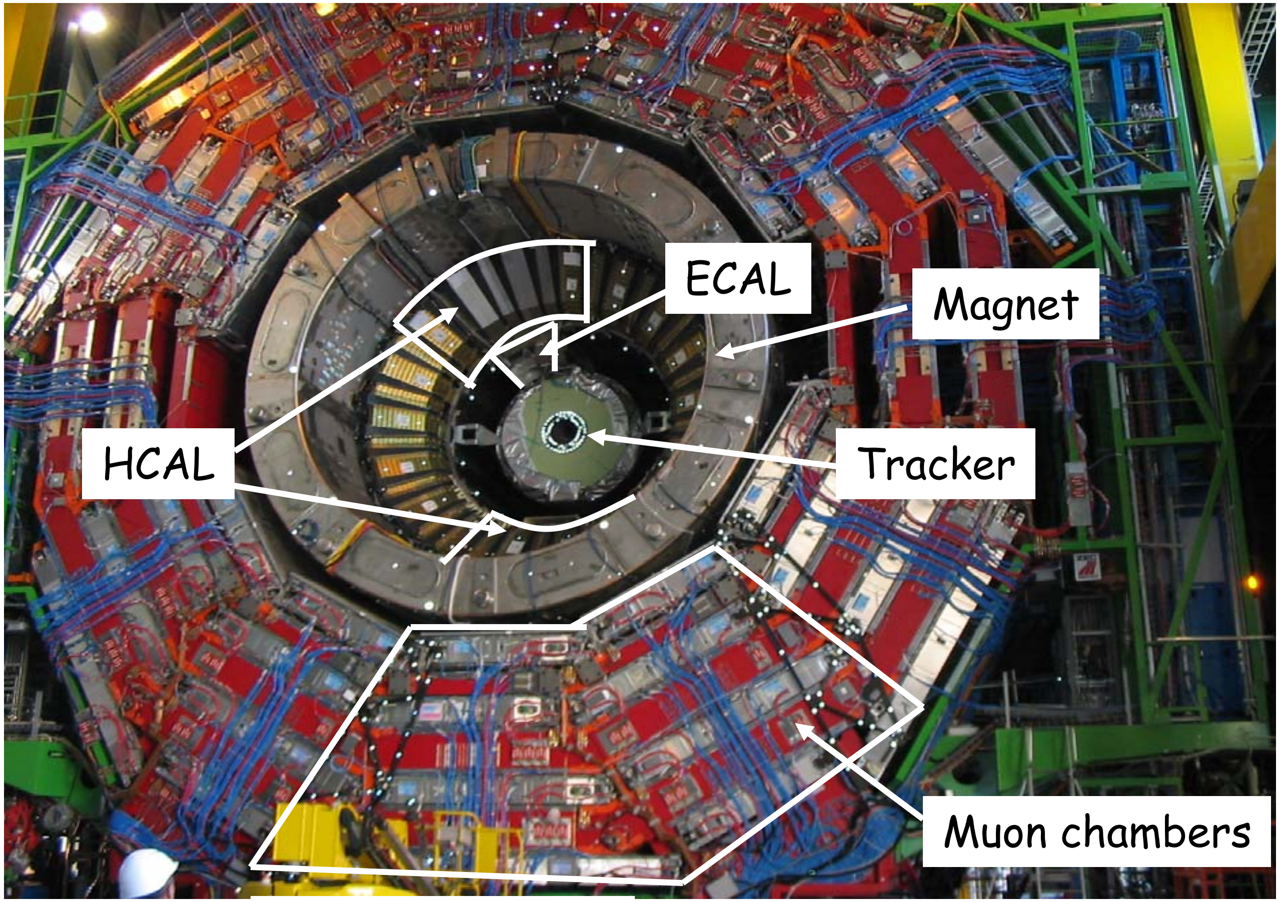
Crystal delivery determines ECAL schedule: last barrel (end-cap) crystal delivered in Feb. 2007 (Feb. 2008). Plan is to have barrel completed for commissioning run in 2007 and end-caps installed for 2008 physics run.

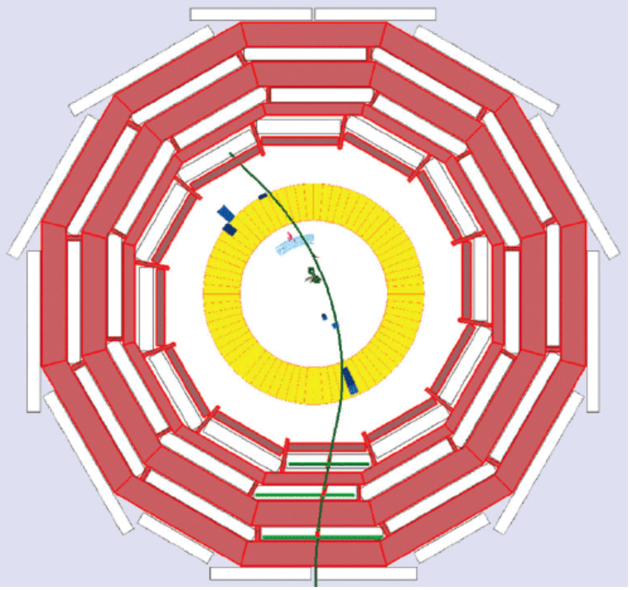
Magnet Test and Cosmic Challenge (MTCC)

Cosmics run of a ~full detector slice (few percent of CMS coverage) inside 4T field.

Test: detector installation and closing; magnet commissioning and field map; combined operation of full chain detector-electronics-DAQ-trigger-DCS-software identical to final experiment; timing, calibration, alignment procedures

→ very successful
→ start the "jigsaw puzzle"

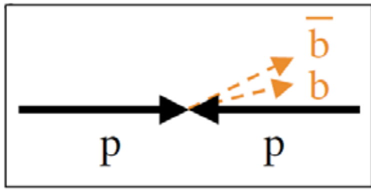


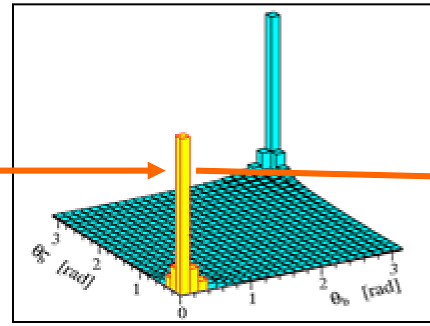


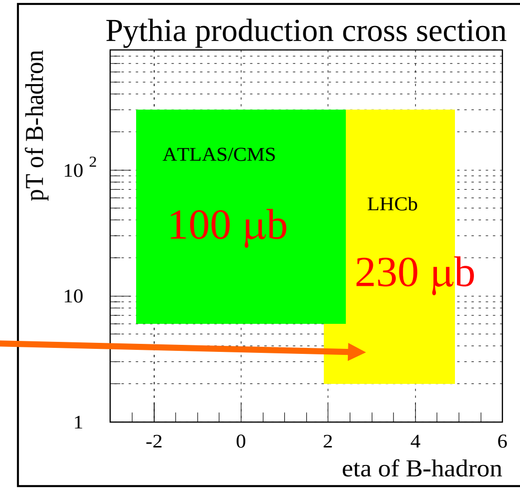
A cosmic track recorded at full field(4T) in a "slice" of CMS detector (Aug. 2006)

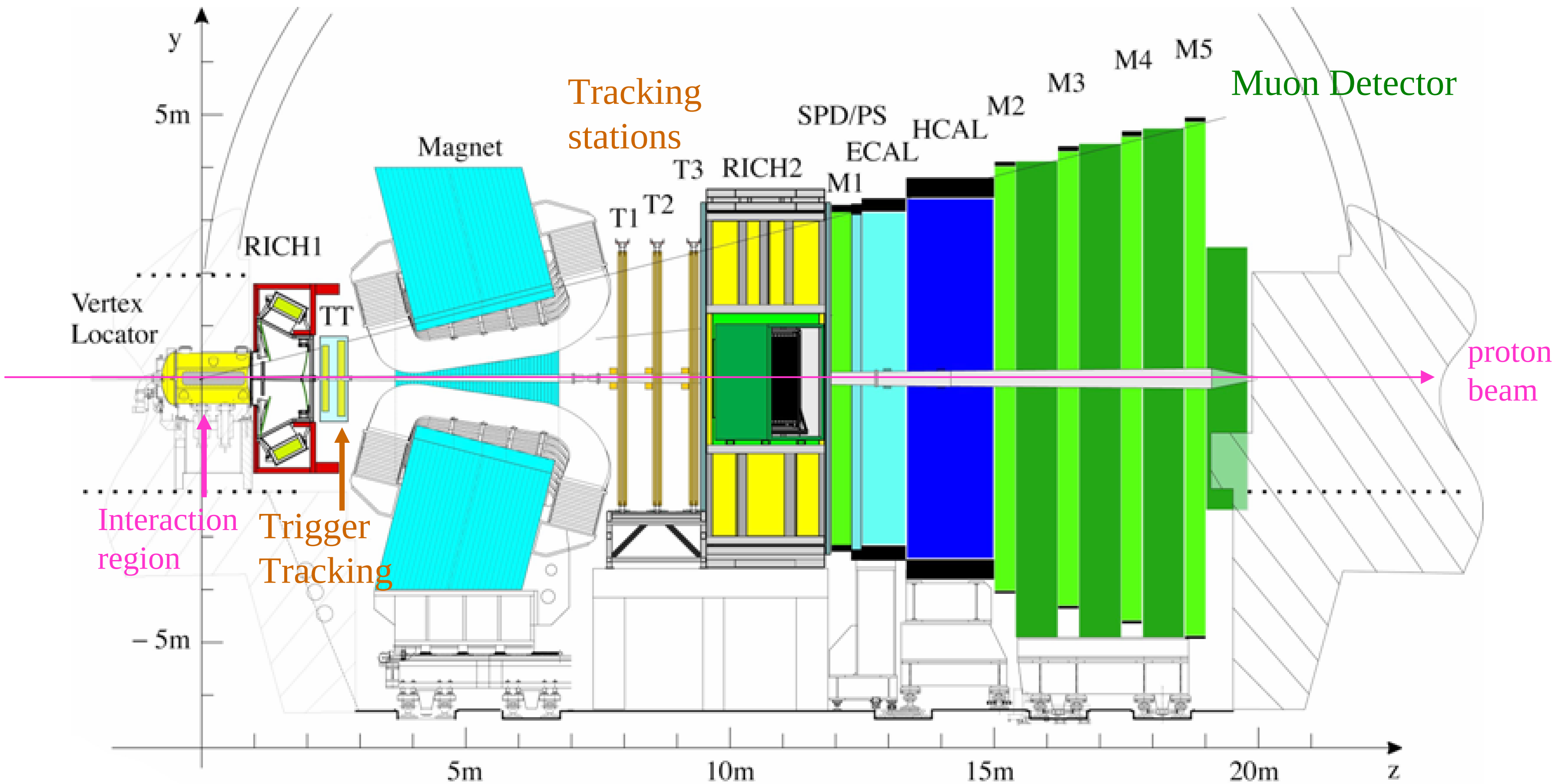
LHCb

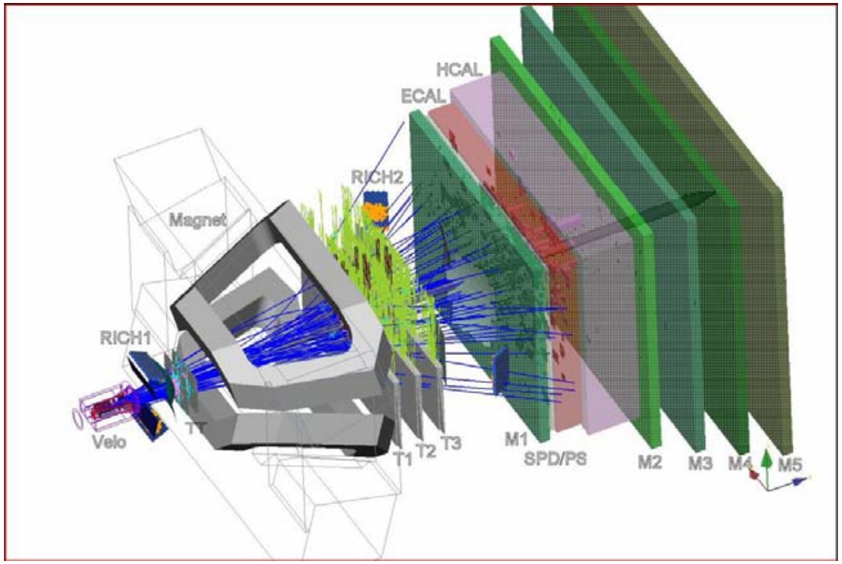
Dedicated B physics precision experiment
to study CP violation and rare decays









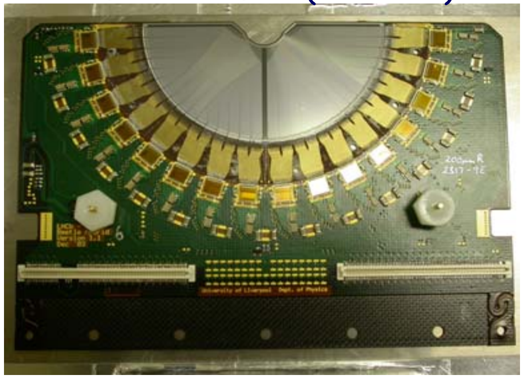


- Good mass and eigentime resolution: VELO + tracking system
- Hadron identification: RICH system
- L0 Lepton and Hadron p_T trigger: Calorimeter and muon system

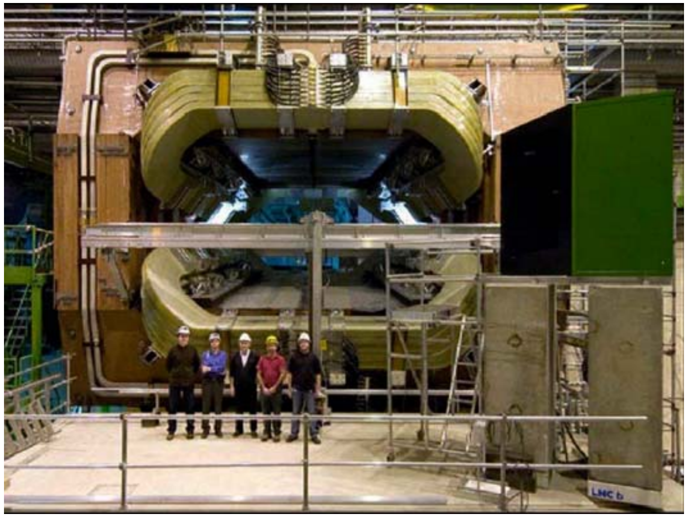
- LHCb will give unprecedented statistics for B decays, including access to the B_s, B_c and b-baryons.
- Many measurements of rare decays, CP asymmetries, B_s-B_s(bar) oscillations, … will be performed.

- Low luminosity (~10^{32}) required for the LHCb experiment will allow to exploit full physics potential from the beginning of LHC operation.
- LHCb will be ready for the LHC pilot run in 2007.
- Detector and reconstruction are expected to be calibrated and tuned for the Physics Run in 2008.

VELO and Ecal (Shashlik)



Dipole magnet (4 Tm)

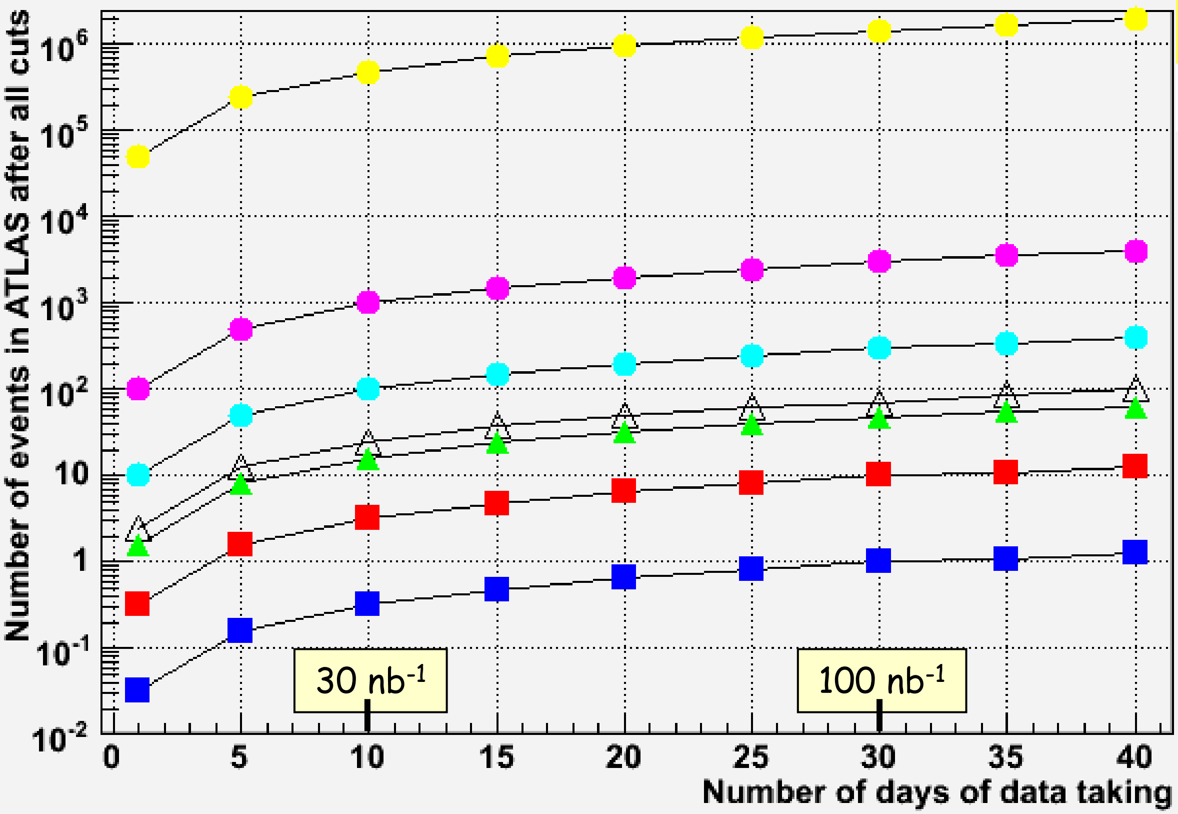


What data samples in 2007 ?

30% data taking efficiency included (machine plus detector)
Trigger and analysis efficiencies included

ATLAS preliminary

$\sqrt{s}$ =900 GeV, L = 10^{29} cm^{-2} s^{-1}



Jets p_T > 15 GeV

(b-jets: ~1.5%)

Jets p_T > 50 GeV

Jets p_T > 70 GeV

$\Upsilon \to \mu\mu$

$J/\psi \to \mu\mu$

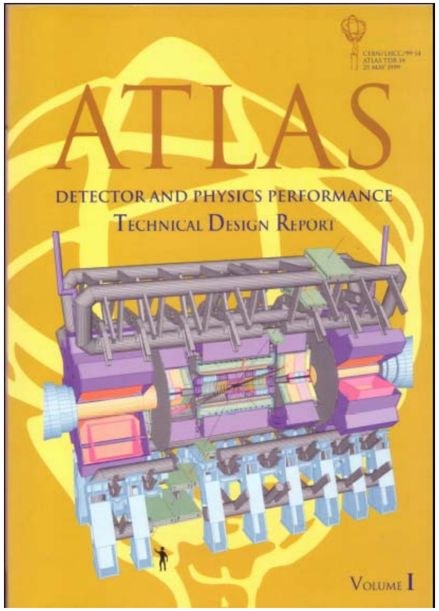
$W \to e\nu, \mu\nu$

$Z \to ee, \mu\mu$

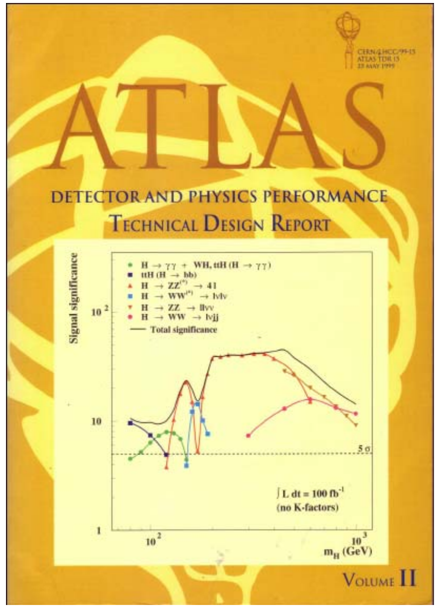
+ 1 million minimum-bias/day

- Start to commission triggers and detectors with collision data (minimum bias, jets, ..) in real LHC environment
- Maybe first physics measurements (minimum-bias, underlying event, QCD jets, …) ?
- Observe a few $W \to l\nu$, $\Upsilon \to \mu\mu$, $J/\psi \to \mu\mu$?

Physics TDRs

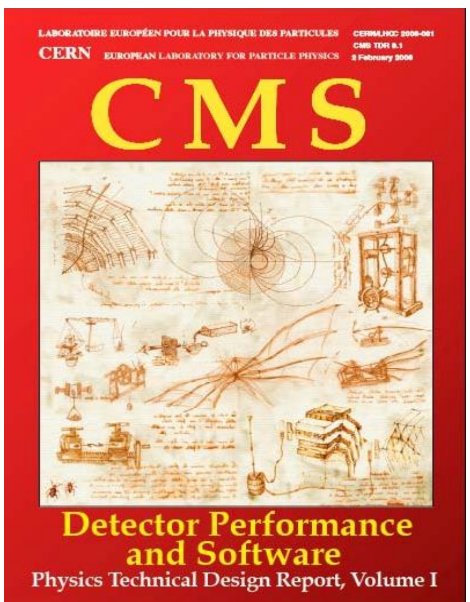


May 1999

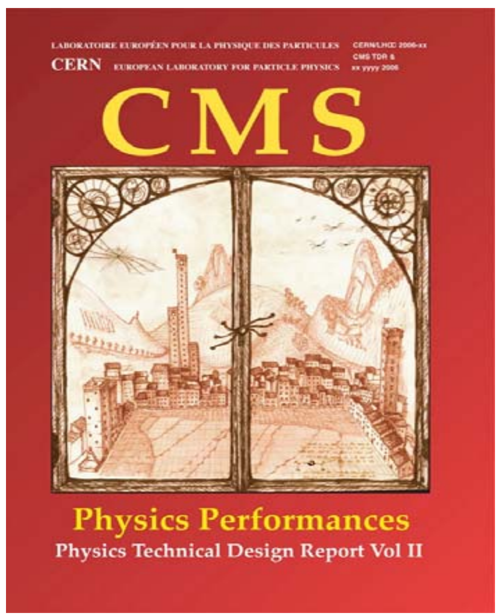


May 1999

CSC (Computing System Commissioning) notes are to be produced in spring 2007, covering software and physics analysis validation for the early physics run with 0.1 fb^{-1} and 1 fb^{-1}.



Feb. 2006



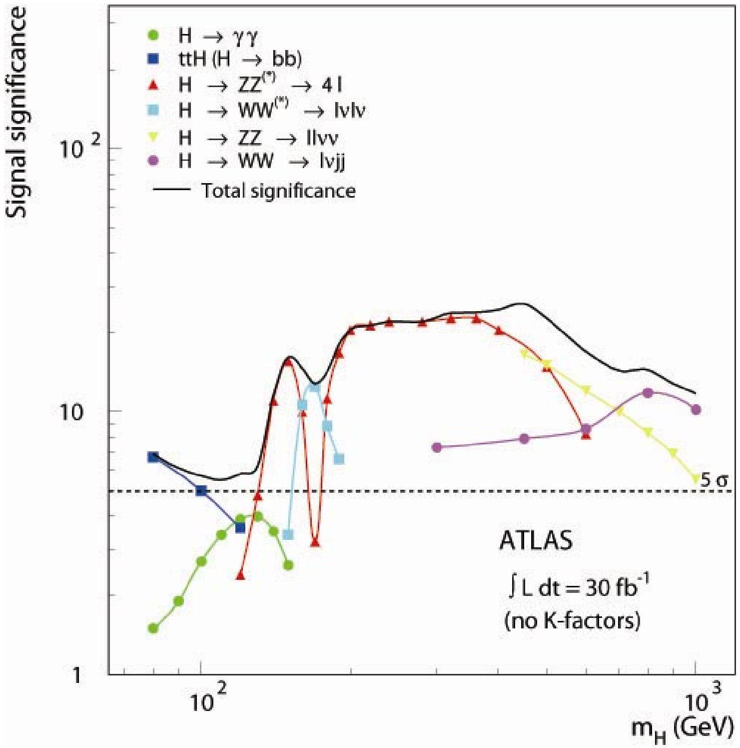
Jun. 2006

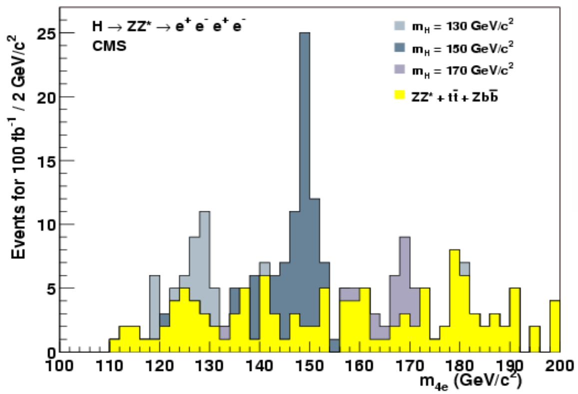
Instead of 3-rd vol. of TDR, short notes on startup will be submitted to LHCC in summer 2007, along with the very early physics reach with 0.1 fb^{-1} and 1 fb^{-1}.

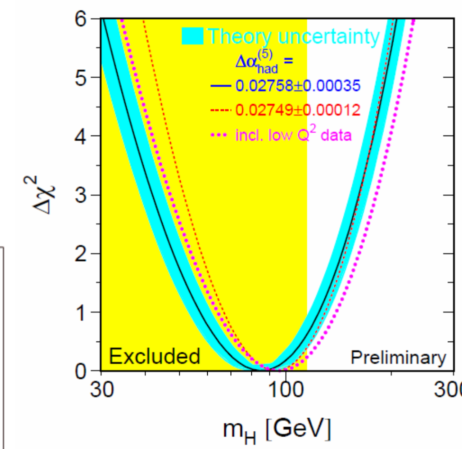
http://cmsdoc.cern.ch/cms/cpt/tdr/

SM Higgs Boson Search

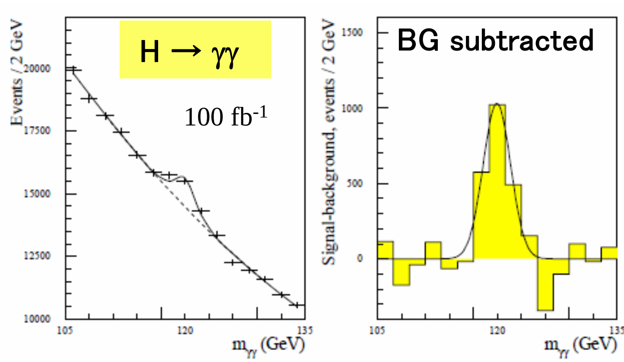
Now, Higgs boson mass is lower:
m_H between 114 GeV and 200 GeV



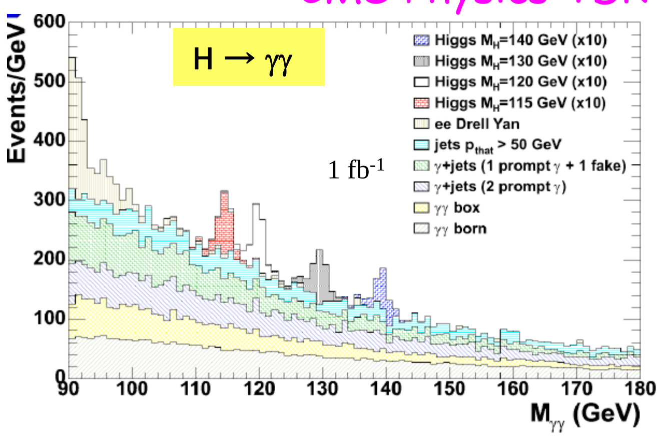


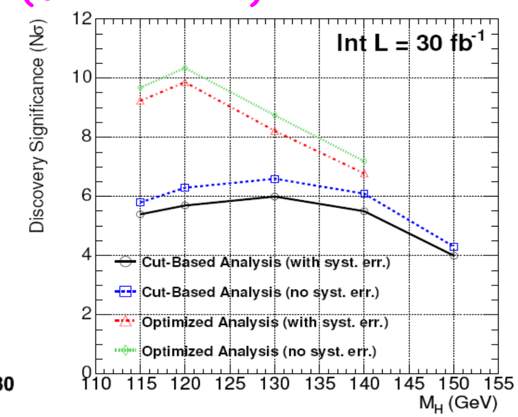


ATLAS Physics TDR (May 1999)



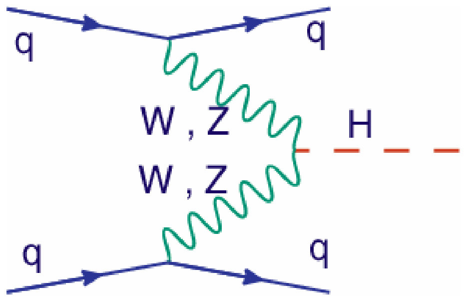
CMS Physics TDR (June 2006)





Vector Boson Fusion Process

D.L.Rainwater, D.Zeppenfeld, K.Hagiwara (1999)



Feature of VBF Process:

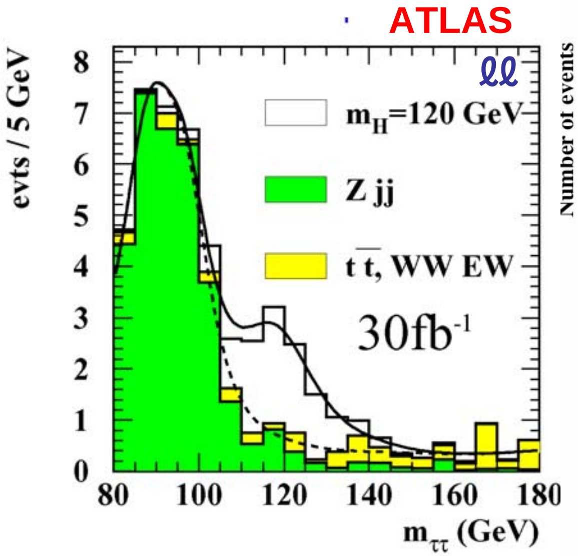
- Cross-section is lower than the gluon fusion process
- High P_T jet in the forward region
- Higgs decay products observed in the central rapidity gap (no color flow)

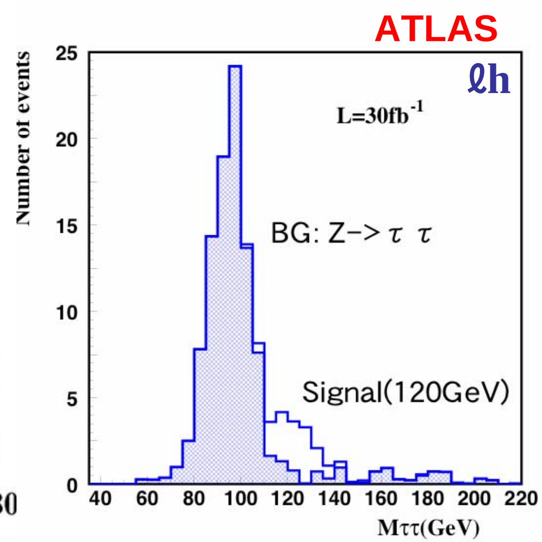
➔ Large reduction of background

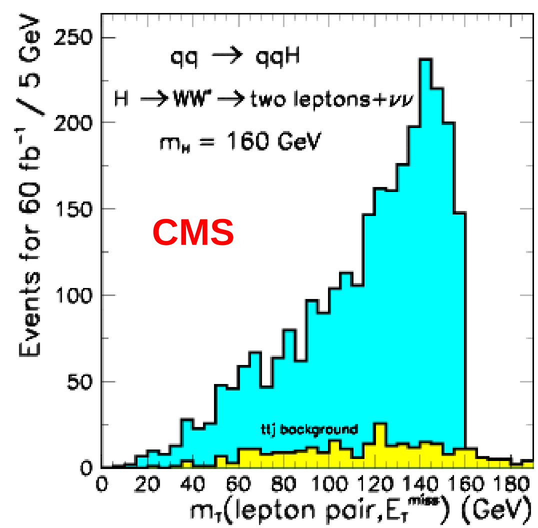
$qq\,H \rightarrow qq\,\tau\,\tau$
$\rightarrow qq\ \ell\nu\nu\ \ \ell\nu\nu$
$\rightarrow qq\ \ell\nu\nu\ \ h\nu$

$qq\,H \rightarrow qq\ \ W\,W^*$
$\rightarrow qq\ \ \ell\nu\ \ \ell\nu$

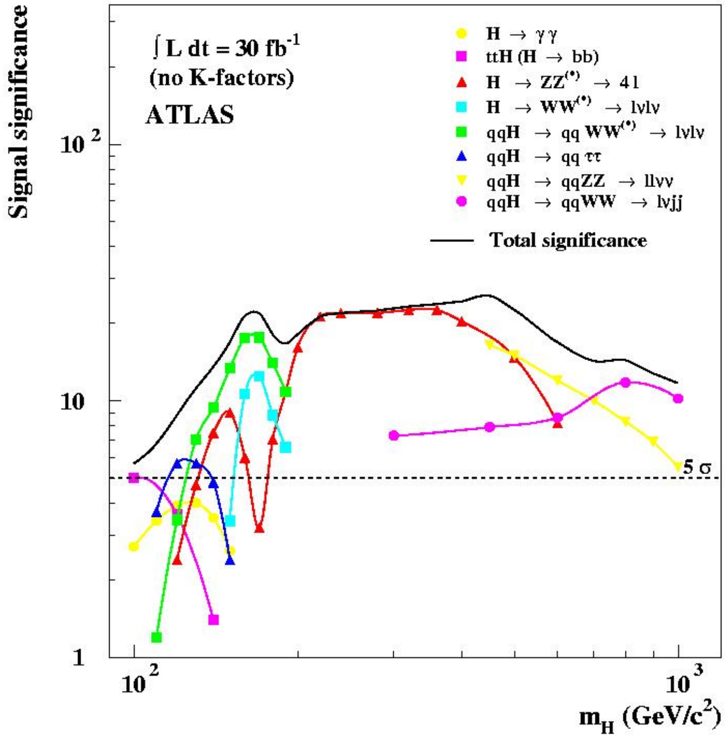
$$M_T = \sqrt{(E_T^{ll} + E_T^{\nu\nu})^2 - (\vec{p}_T^{\,e\mu} + \vec{p}_T^{\,miss})^2}$$

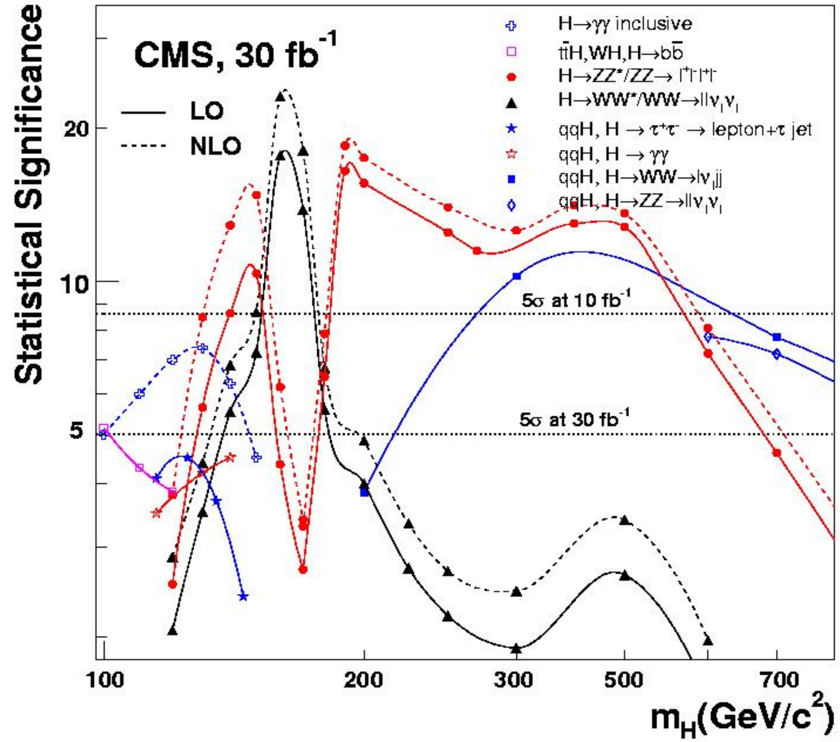




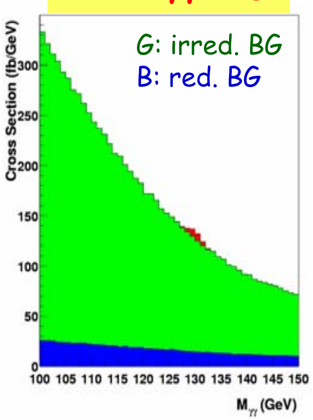


SM Higgs boson discovery would be made in early years of LHC run (2009/2010?)

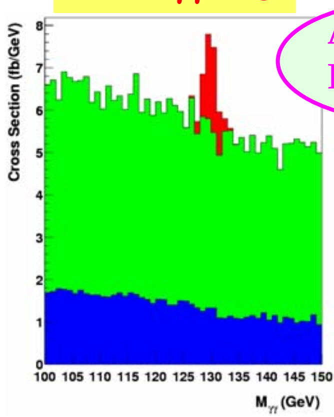




H → γγ +0j

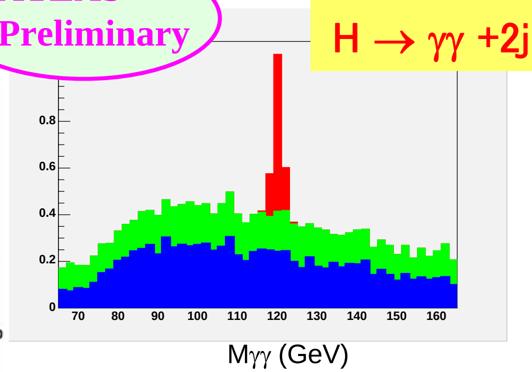


H → γγ +1j

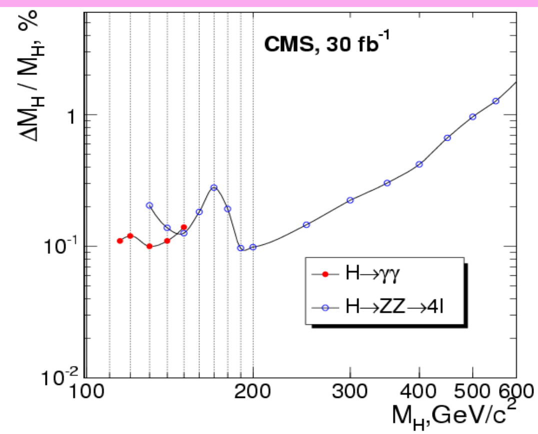


ATLAS Preliminary

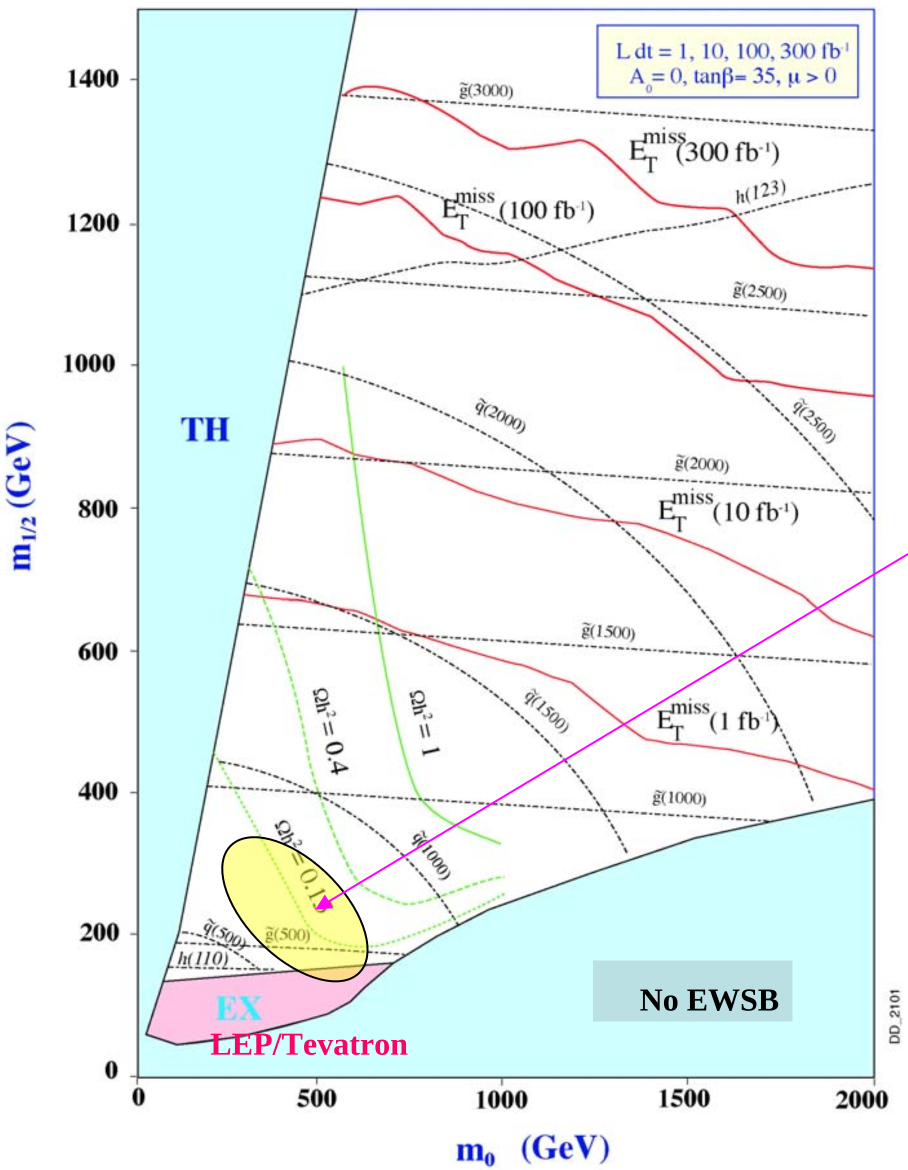
H → γγ +2j



and measurements of mass, …



Discovery Potential of SUSY (mSUGRA)

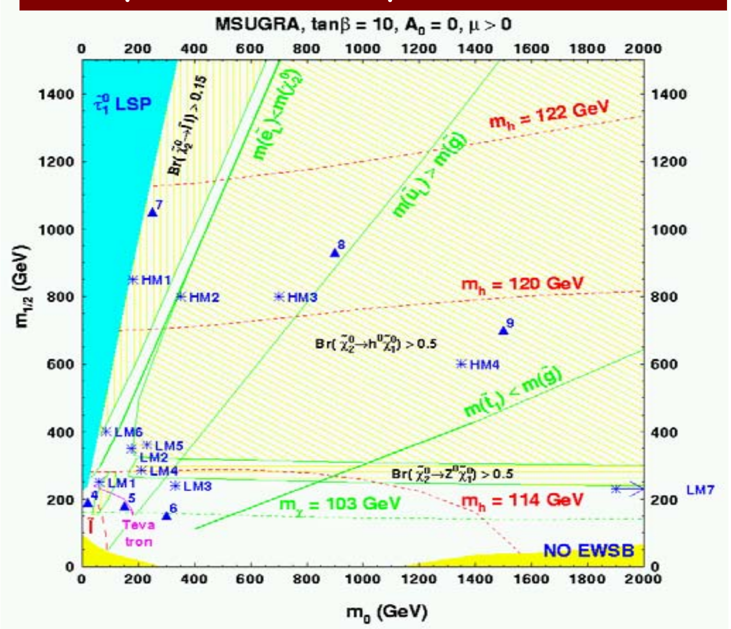


$m_{1/2}$: universal gaugino mass at GUT scale
m_0: universal scalar mass at GUT scale
$\tan\beta$: vev ratio for 2 Higgs doublets
sign(μ): sign of Higgs mixing parameter
A_0: trilinear coupling

- If low energy Supersymmetry exists, LHC will almost certainly observe it
- Squarks and Gluinos detectable up to 2.5-3 TeV mass with 300 fb^{-1}

Need only a short time to cover the interesting region for Cold DM

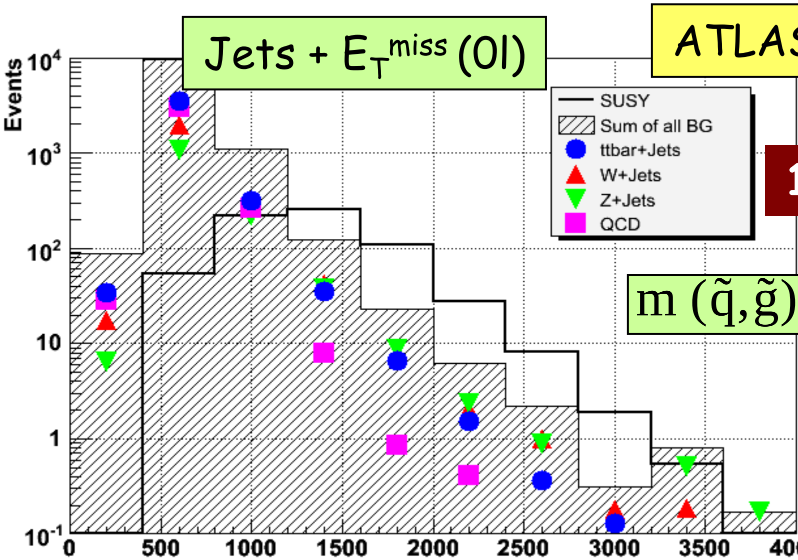
Many benchmark points studied …



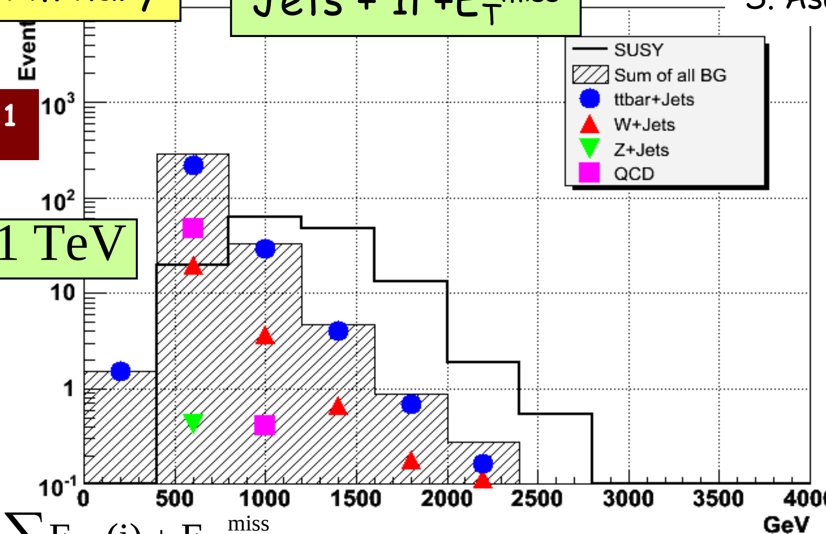
Search for SUSY : Understanding of BG is important

ATLAS preliminary

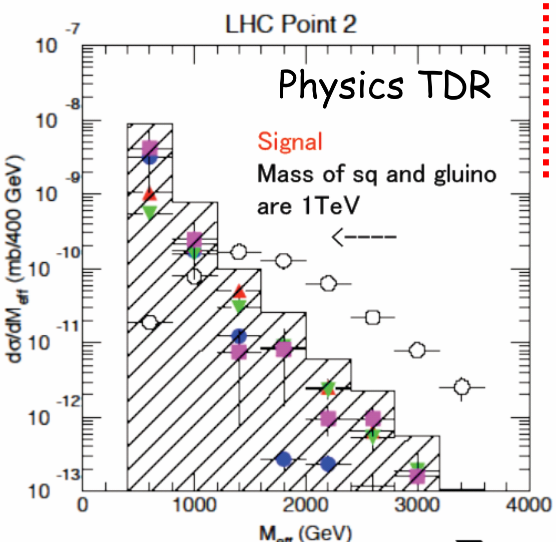
S. Asai



$m(\tilde{q},\tilde{g}) \sim 1$ TeV



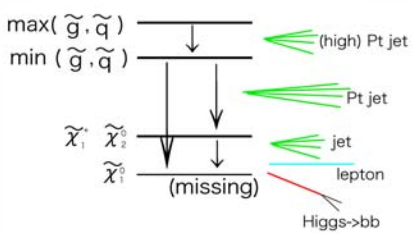
$$M_{eff}\ (\mathrm{GeV}) = \sum_{i=1,4} E_T(i) + E_T^{miss}$$



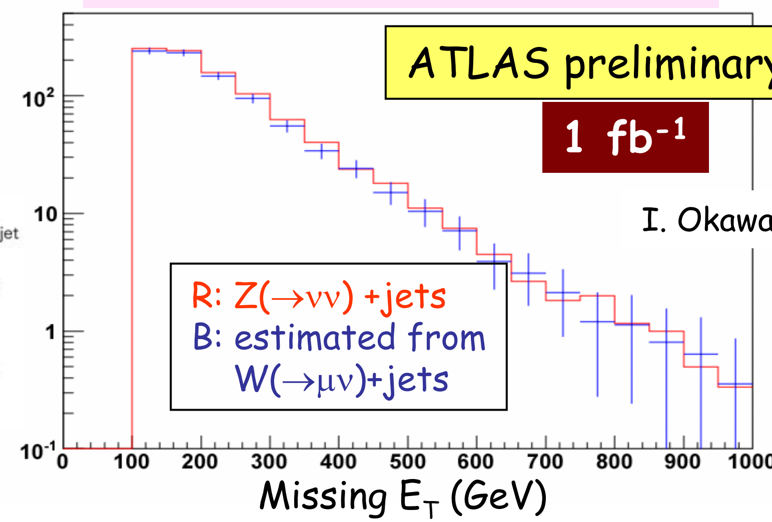
$$= \not{E}_T + \sum P_T$$

PS+ME

Improving MC simulations



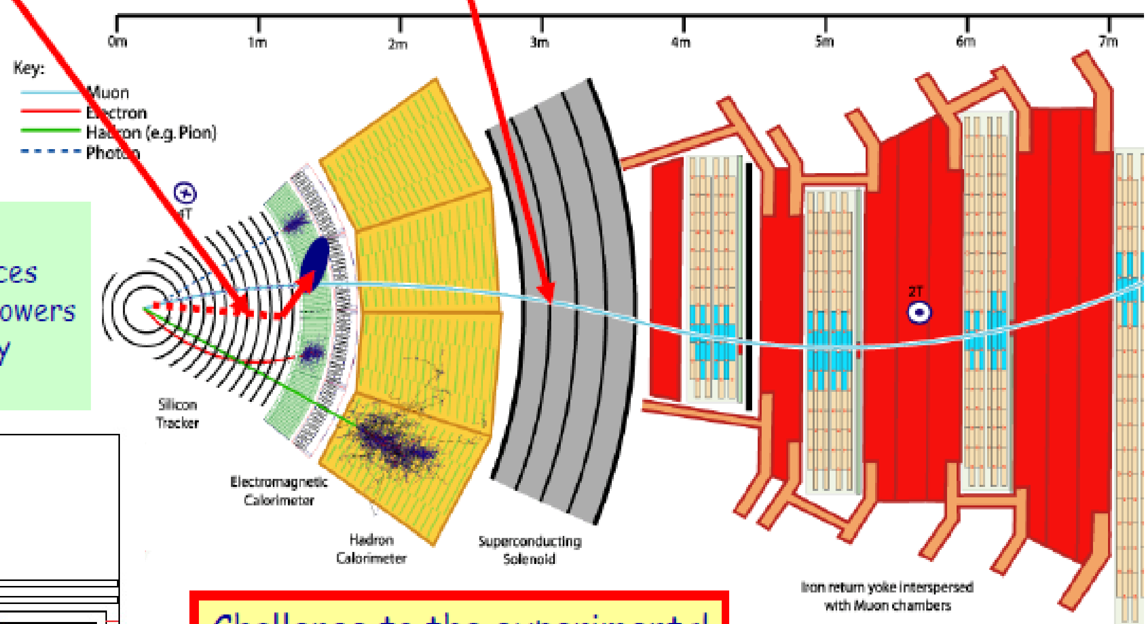
Estimate physics backgrounds using data (control samples)



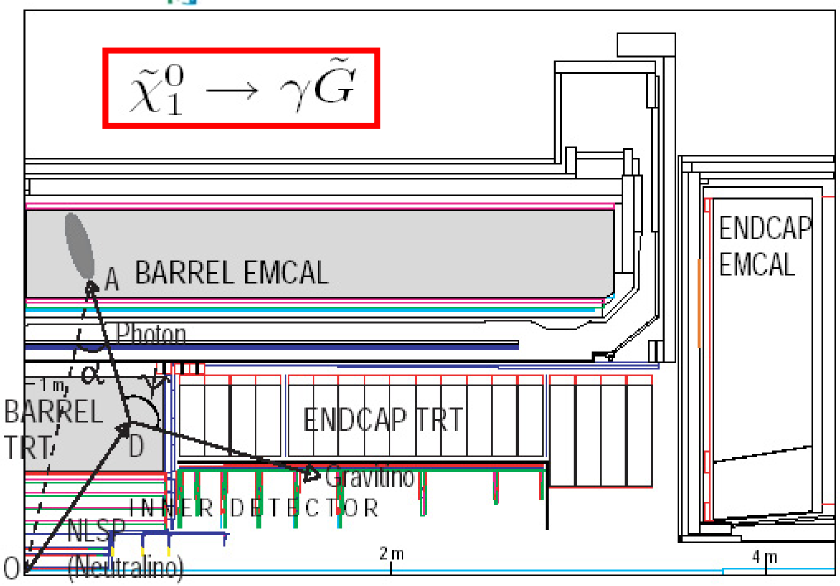
I. Okawa et al.

Possible Signals in Gauge Mediated SUSY Breaking Models

In some models/phase space the gravitino is the LSP
Then the NLSP (neutralino, Stau lepton) can live 'long'
Eg. $\chi \rightarrow \gamma +$ gravitino or heavy (slow) stau slepton



Signatures
- Displaced vertices
- Non-pointing showers
- Long lived 'heavy muons'



Challenge to the experiments!

Phys.Rev.D69(2004)035003 (K.Kawagoe et al.)

GMSB G2b point

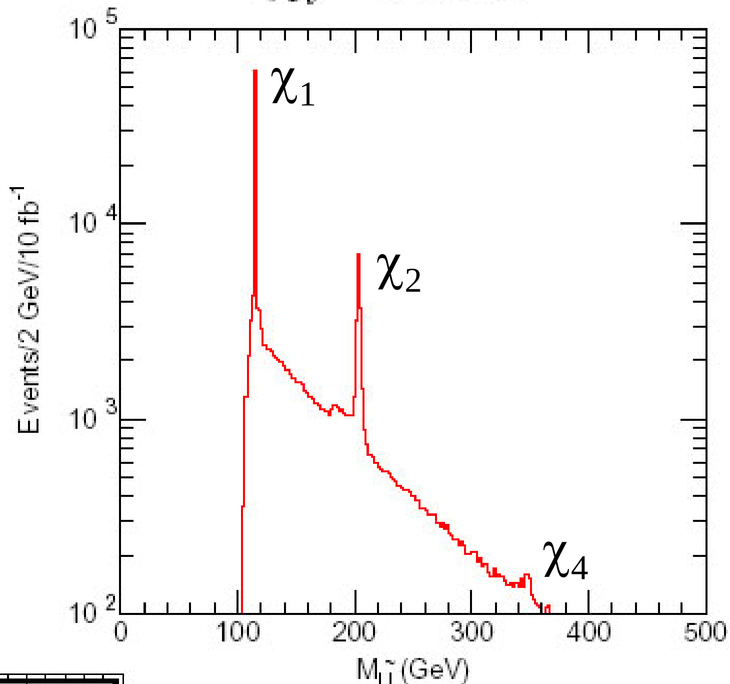
ATLAS Physics TDR (May 1999)

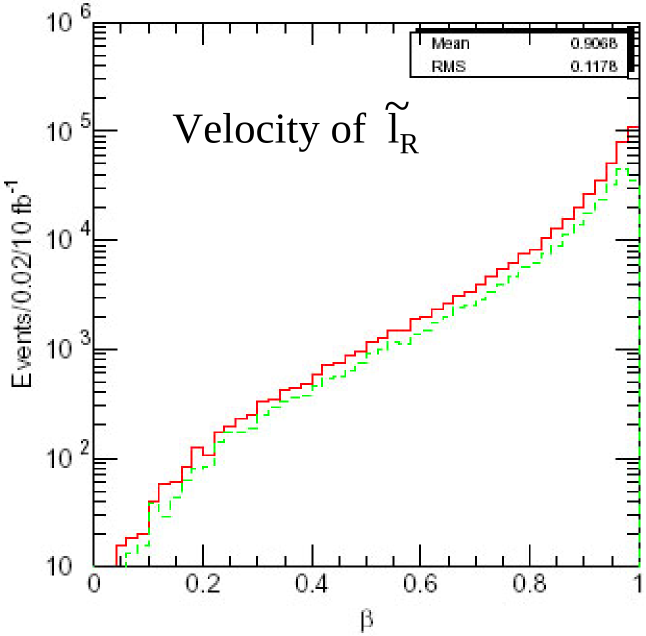
NLSP = $\tilde{\tau}_1$ and $c\tau \approx 1\,\mathrm{km}$

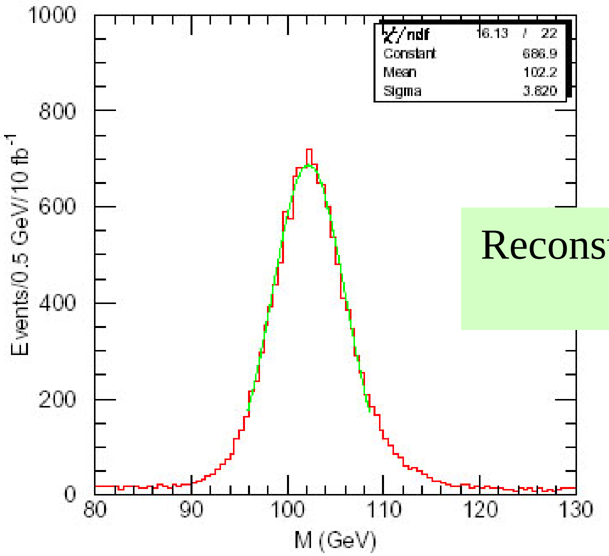
$\tilde{e}_R$ and $\tilde{\mu}_R$ are also long-lived

➔ stable heavy charged leptons

$\tilde{\chi}_i^0 \rightarrow \tilde{\ell}_R \ell$



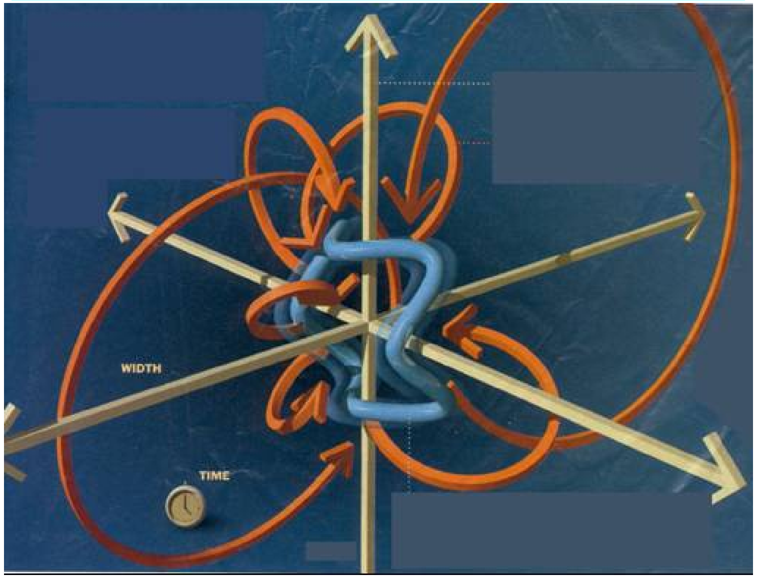




Reconstructed slepton mass
$\sigma_M / M \sim 4\%$

ATLAS MDT ➔ $\sigma_t \sim$ 1ns

Extra Dimensions



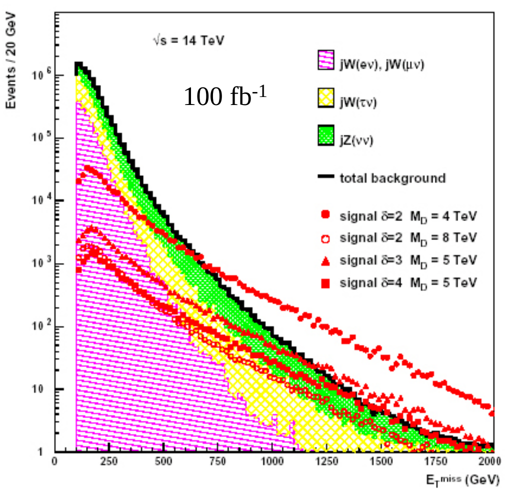
Large Extra Dimensions (ADD)
- Gravity in bulk / flat space
- Missing energy / interference / black holes

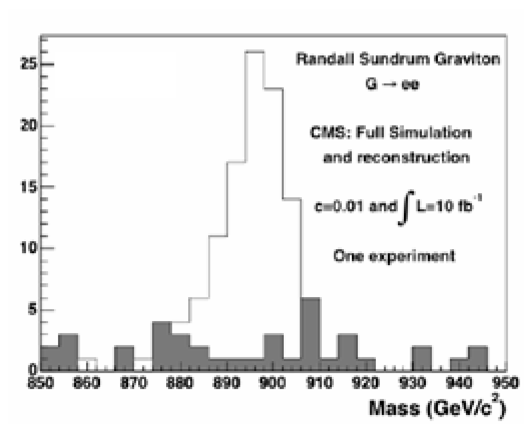
Warped Extra Dimensions (RS)
- Gravity in bulk / curved space
- Spin 2 resonances in >TeV range / black holes

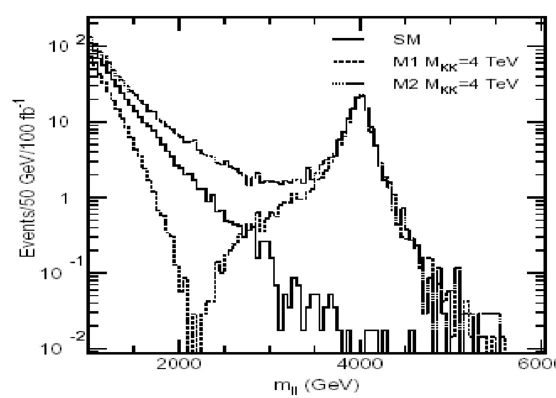
TeV Scale Extra Dimensions
- Gauge bosons / Higgs in bulk
- Spin 1 resonances in >TeV range
- Interference with Drell-Yan

Universal Extra Dimensions
- Everybody in the bulk!
- Fake SUSY spectrum of KK states

E_T(jet) > 1 TeV





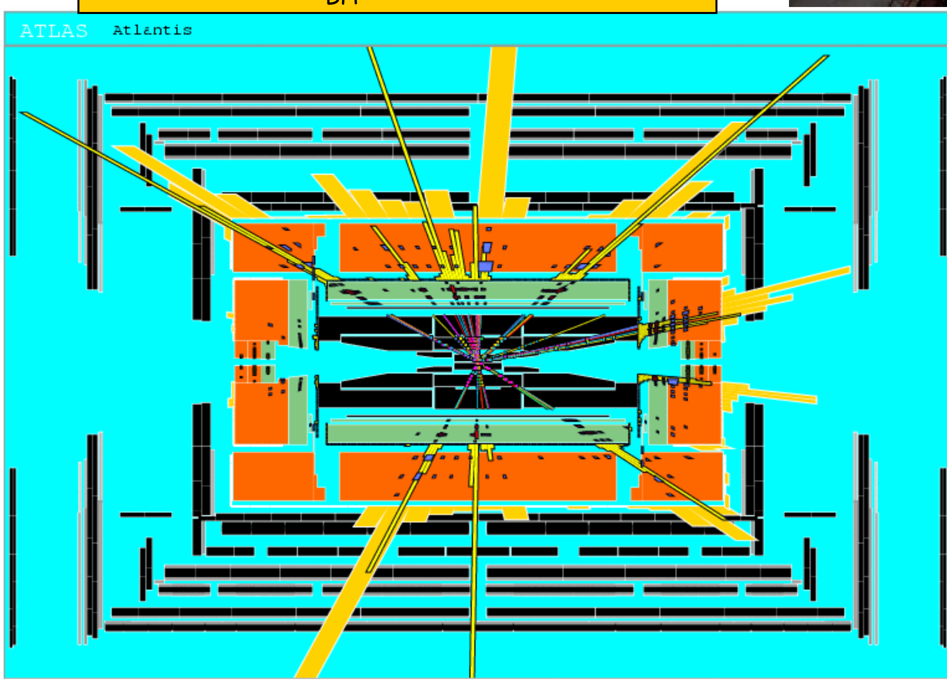


Extra Dimensions:
What if Planck Scale in TeV Range?

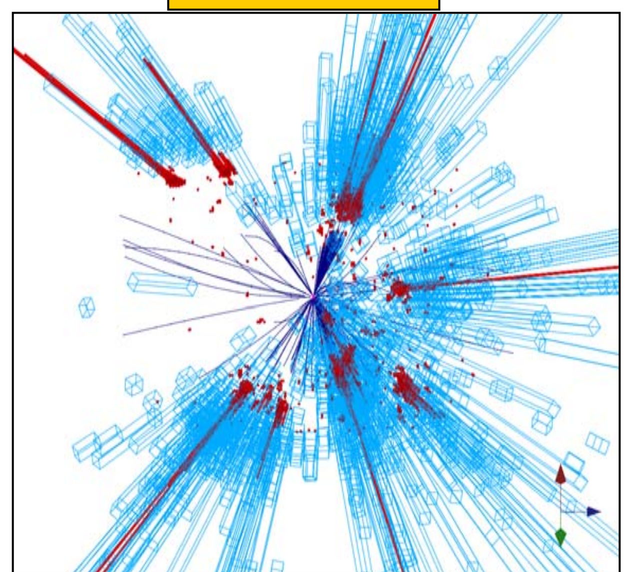
CERN Press Release (2.Oct.2006)

Stephen Hawking Tours the Future of Particle Physics at CERN

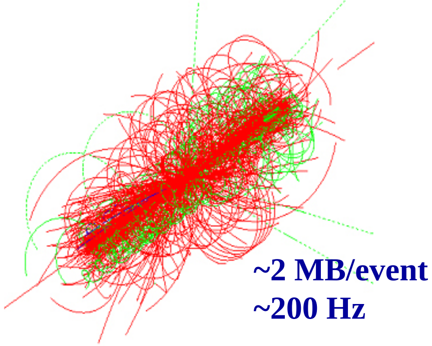
Simulation of a mini black hole event with $M_{BH} \sim 8$ TeV in ATLAS



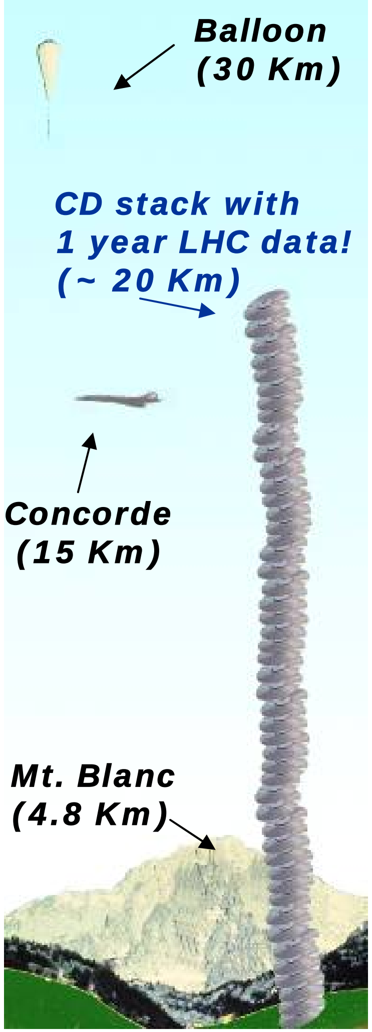
... and in CMS

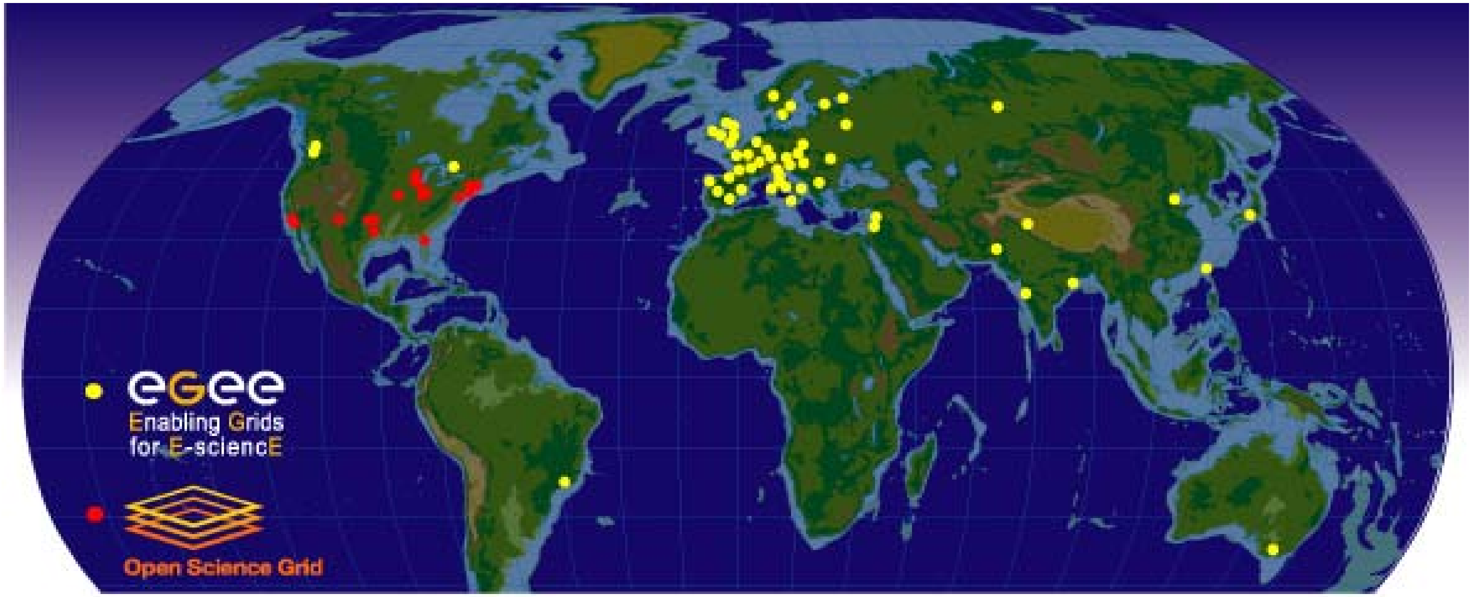


WLCG Collaboration



- 4 LHC experiments (→ large amount of data)
- ~120 computing/analysis centers in ~40 countries
- Computing grid infrastructures:
  EGEE, OSG, Nordic Grid
  (→ Interoperability is crucial.)

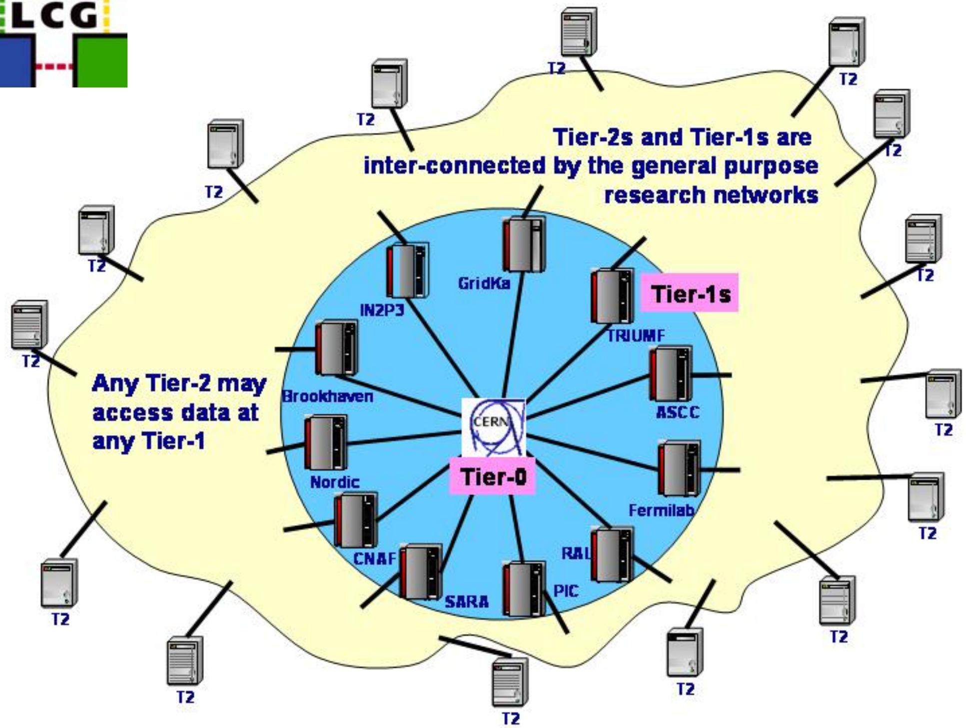




NORDUGRID

A map of the worldwide LCG infrastructure operated by EGEE and OSG.

WLCG: Distribution of Computing Services



Tier-0 (CERN)
- Data acquisition & initial processing
- Data storage
- Distribution of data → Tier-1 centers

Tier-1 (11 centers)
- Data-heavy analysis
- Data storage

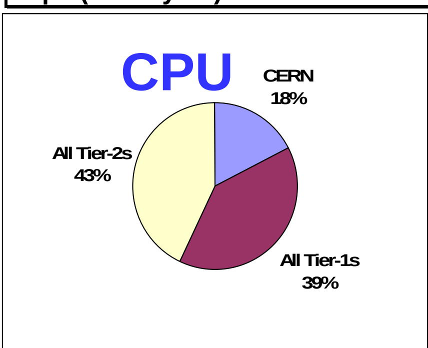
Tier-2 (~100 centers in ~40 countries)
- Simulation
- End-user analysis

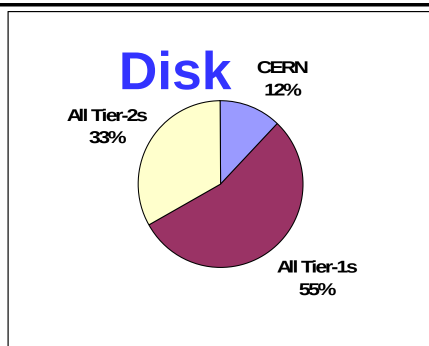
Summary of Computing Resource Requirements

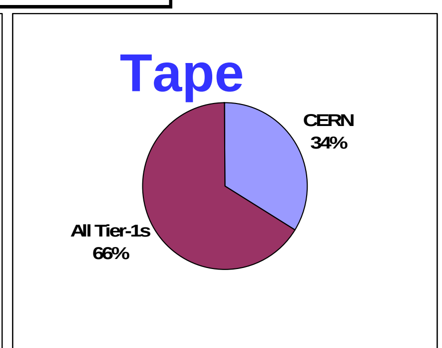
All experiments - 2008

From LCG TDR - June 2005

	CERN	*All Tier-1s*	*All Tier-2s*	*Total*
CPU (MSPECint2000s)	25	56	61	142
Disk (PetaBytes)	7	31	19	57
Tape (PetaBytes)	18	35		53







Big Challenge!

http://www.cern.ch/lcg/

Summary of LHC New Physics Reach

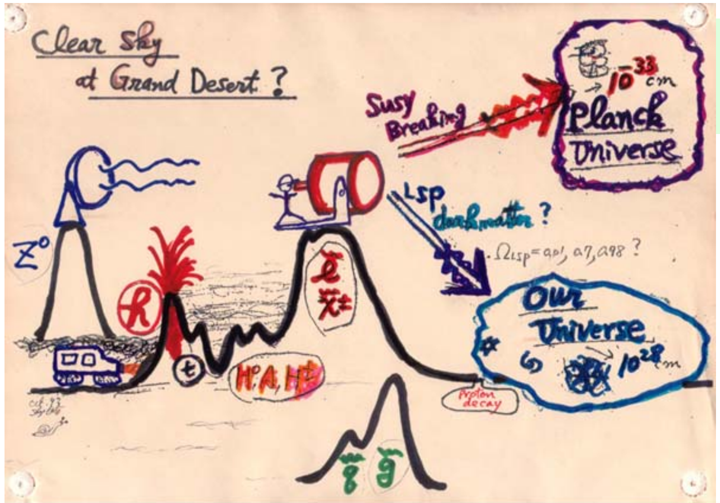
SM Higgs	100 GeV ~ 1 TeV
MSSM Higgs	covers full (m_A, $\tan\beta$)
SUSY (squark, gluino)	2.5 - 3 TeV (300 fb^{-1})
New gauge bosons (Z')	< 4.5 TeV (100 fb^{-1})
Quark substructure (Λ_C)	< 25/40 TeV (30/300 fb^{-1})
q*, l*	< 6.5/3.4 TeV (100 fb^{-1})
Large ED (M_D for n=2,4)	< 9/5.8 TeV (100 fb^{-1})
Small ED (M_C)	< 5.8 TeV (100 fb^{-1})
Black holes	< 6 ~ 10 TeV
M(top quark)	σ_M ~ 1 GeV (~ 0.5 %)
M_W	σ_M ~ 15 MeV
CP-violation in B-decay	$\sigma(\sin 2\beta)$ ~ 0.016 (30 fb^{-1})
Rare B-decay ($B_S \rightarrow \mu\mu$)	~ 5σ (130 fb^{-1})

Discovery for sure
+ some measurements

can say "final word"
about (low E) SUSY

Both experiments can cope with the new physics possibilities which were not foreseen at the beginning of the project.

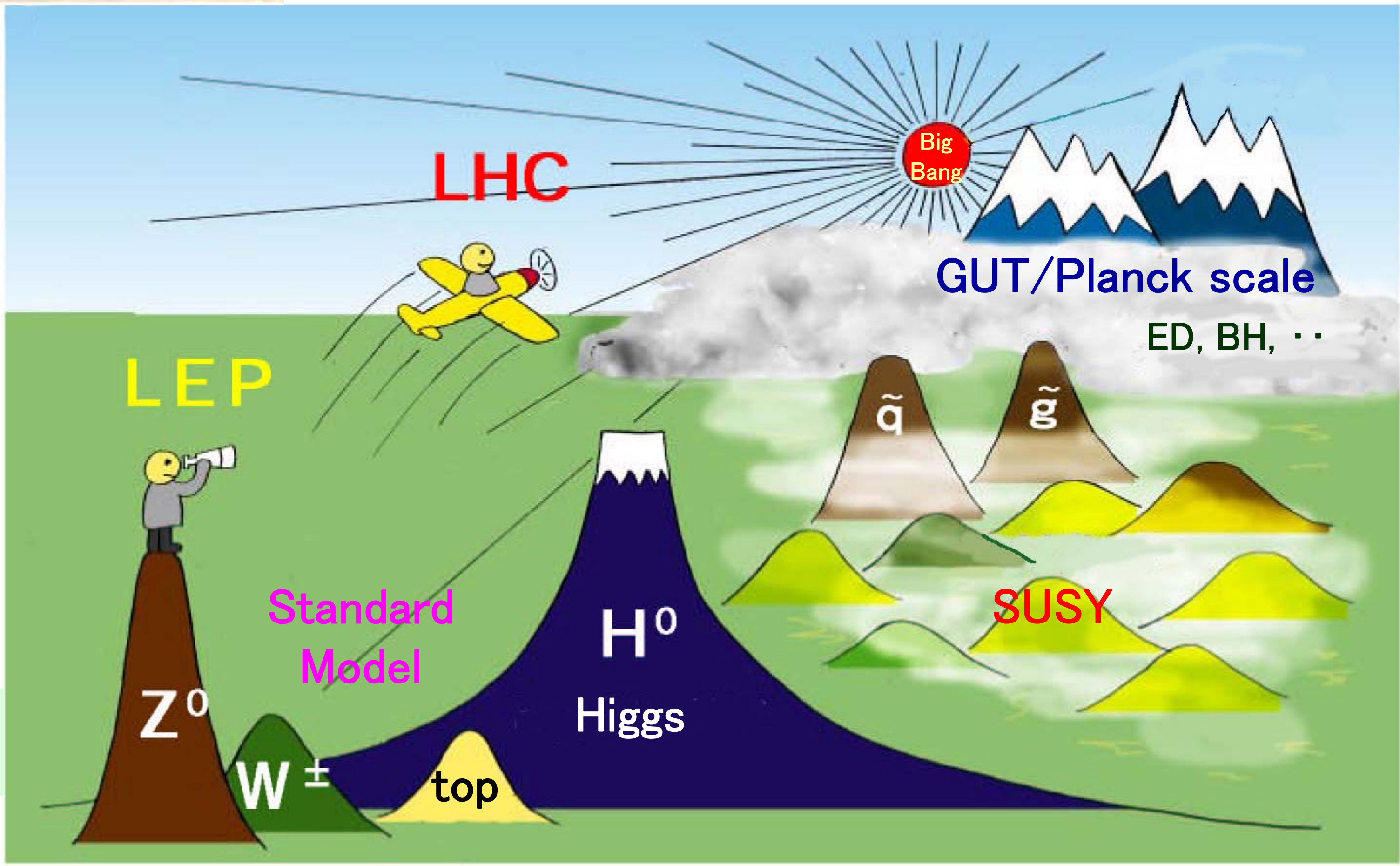
Any one of those would change the understanding of our universe !



S. Orito (1992)
ICEPP Symposium
"From LEP to the Planck Scale"

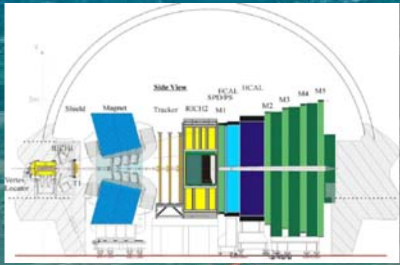
LHC
Looking Down at New Phenomena in the TeV Region

It's about to take off!

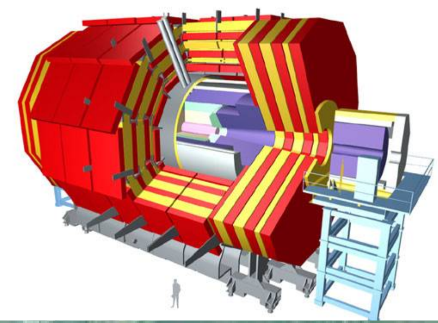


T. Mori (2001)
LEP Symposium @ICEPP
"Beyond the EW Scale"

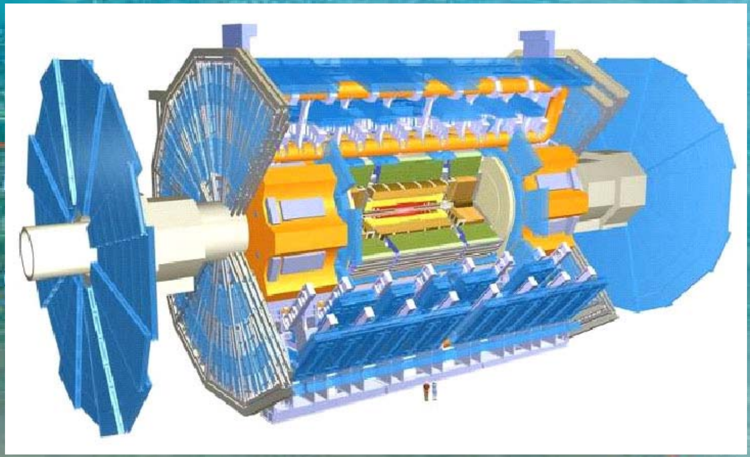
Many thanks to:



T. Nakada



A. Ball, K. Bell,
A. De Roeck



S. Asai, F. Gianotti,
G. Mikenberg

L. Evans, S. Myers,
L. Robertson

· · and many others