Detectors at the Large Hadron Collider

Challenges, Status

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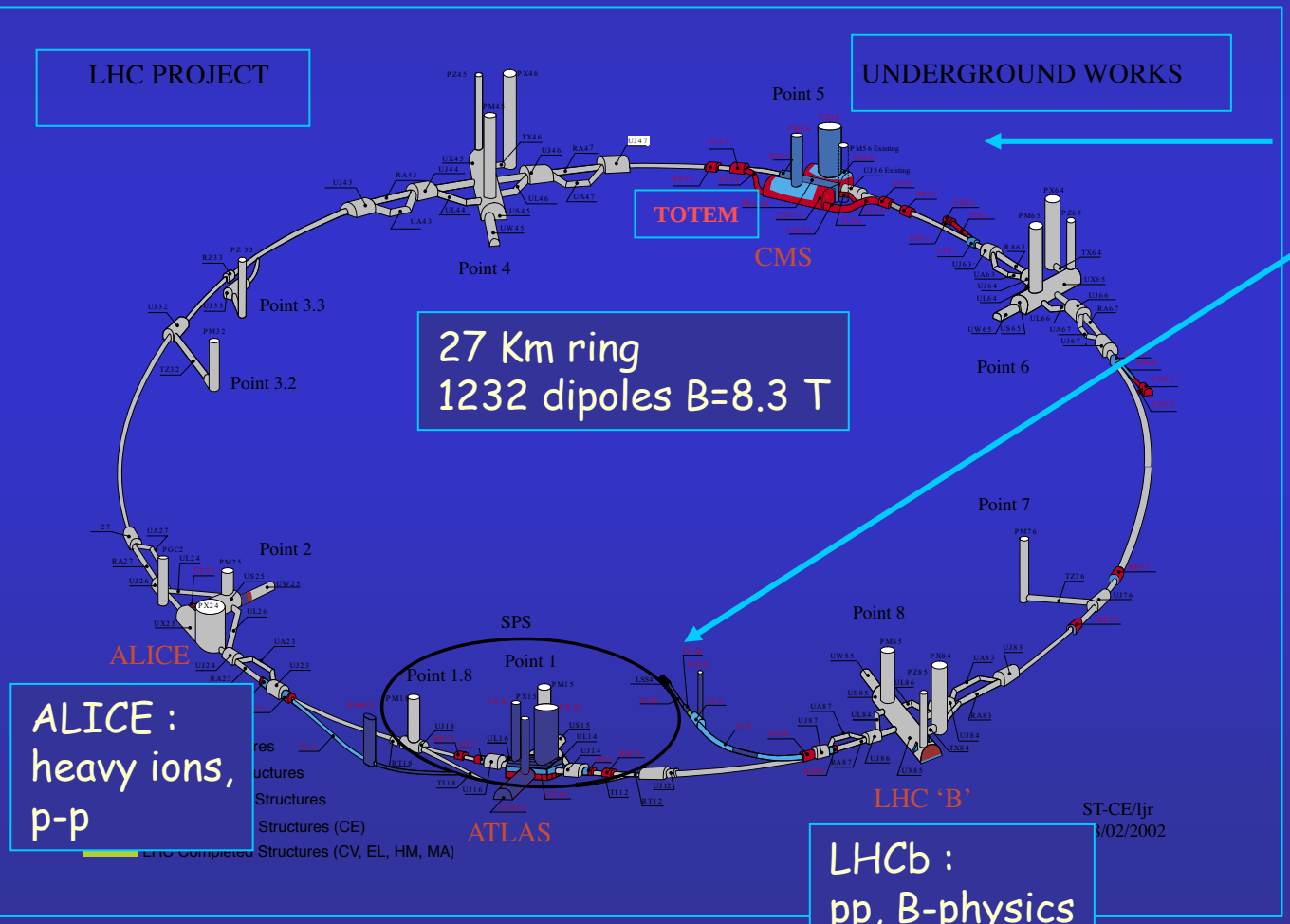
February 15, 2005

- pp $\sqrt{s}$ = 14 TeV (Pb Pb 5.5 TeV/N)
- Start-up : Summer 2007
- Initial/low luminosity L ~ 10^{33} cm^{-2} s^{-1}
  ≤ 2 minimum bias/x-ing → "Tevatron-like" environment
- Design/high luminosity L = 10^{34} cm^{-2} s^{-1}
  ~ 20 minimum bias/x-ing → fast rad hard detectors

Note : 10 fb^{-1} collected in 10^7 s ≡ 3 months at 10^{33} , i.e. in one year assuming 30% running efficiency



ATLAS and CMS
pp, general purpose

ALICE :
heavy ions,
p-p

LHCb :
pp, B-physics

ATLAS, CMS

Event rate ~20 per bunch crossing (every 25 ns)
--> 10^9 events / s --> >10^{11} tracks /s

Very remarkable: experiments will, in this environment:

- reconstruct secondary vertices from B mesons, only mm's away from the primary vertex.
- reconstruct individual photons with sufficient energy and spatial resolution for (light) Higgs detection

in addition to many more capabilities: they are 'general purpose' ('4π') detectors, featuring tracking, magnetic momentum analysis, calorimetry, muon spectrometry, in an, almost, **hermetic** setup.

Not unlike earlier detectors: they should allow discovery of the unexpected!

Atlas and **CMS** took up the challenge to elucidate electro-weak symmetry breaking, find 'the' Higgs boson and more...

LHCb took up the challenge to exploit the prolific production of b-quarks in the forward direction to study CP violation and rare decays

ALICE took up the challenge to explore the evolution of the quark-gluon plasma over a large, new region of the phase diagram

TOTEM took up the challenge to accurately measure the total cross section (and more)

Pixel Detectors

Radiation hardness of sensors has been achieved empirically, there are many parameters that can be varied – crystal cut orientation (<100>, <111>); geometry of implants; pixel dimensions, pitches; temperature; etc., etc. Increasing depletion voltage can (up to limit) compensate for signal loss

Radiation hardness of electronics can be achieved by using special rules and processes (e.g. DMILL), but there was a very pleasant 'coincidence': the 0.25 μ technology appears to be intrinsically radiation hard (will be widely used by LHC experiments, not only for pixel detectors)

Electromagnetic Calorimetry

New concepts for electromagnetic calorimetry have been developed:

- LAr 'accordion' (Atlas) – no 'dead space'; very good spatial resolution
- $PbWO_4$ crystals (CMS) – very good energy resolution R&D: from cm^3 to m^3

Energy resolution, spatial resolution, no 'dead' regions

in order to have adequate sensitivity to
'light Higgs' H --> $\gamma\gamma$

Two more (out of many more) remarkable features of the LHC detectors:

CMS will have a SC central solenoid, 6m in diameter, with a 4 T field

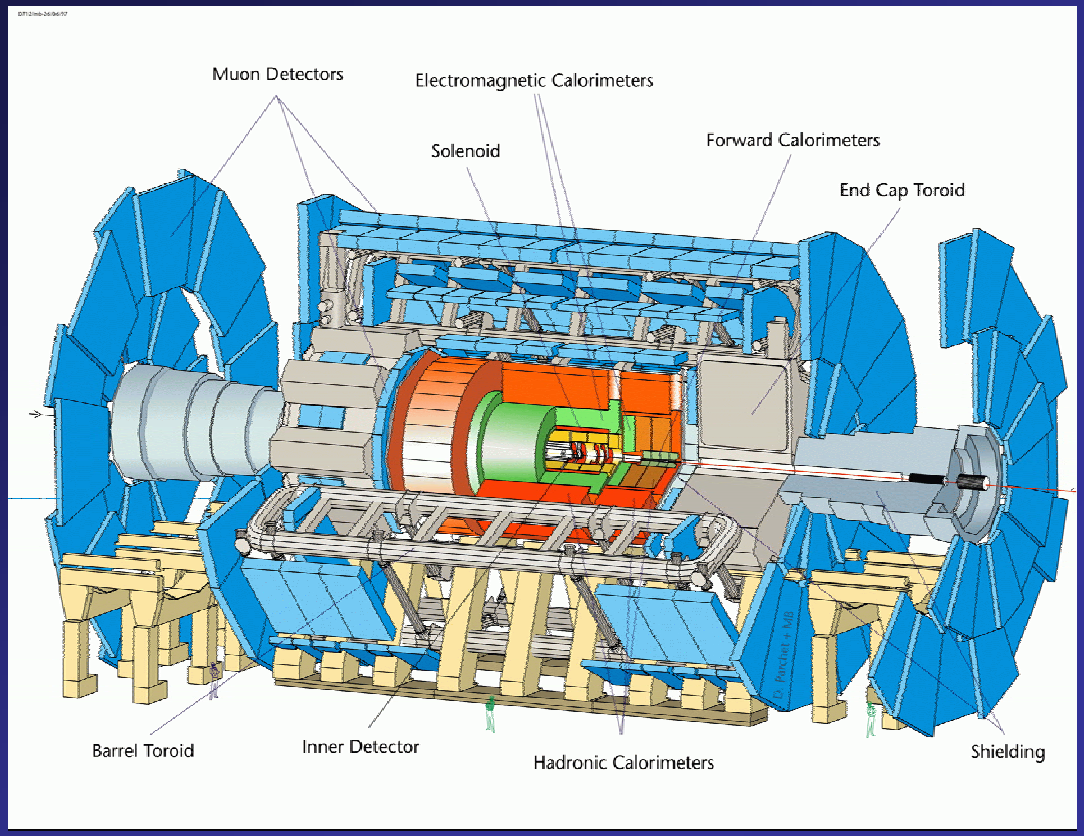
The Atlas muon spectrometer will have 8 large SC toroids and large muon chambers with remarkable mechanical precision

Other issues (and challenges):
Civil Engineering, Assembly, Installation

Civil Engineering of transfer tunnels, large underground caverns, access shafts, surface buildings etc. very well advanced; there were 'surprises'

Assembly, Installation is THE challenge right now

	ATLAS	CMS
MAGNET(S)	Air-core toroids + solenoid in inner cavity Calorimeters outside field 4 magnets	Solenoid Calorimeters inside field 1 magnet
TRACKER	Si pixels+ strips TRT $\rightarrow$ particle identification B=2T $\sigma/p_T \sim 5\times10^{-4}\, p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\times10^{-4}\, p_T \oplus 0.005$
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 (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air $\rightarrow$ σ/p_T < 10 % at 1 TeV standalone; larger acceptance	Fe $\rightarrow$ $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker



ATLAS
A Toroidal Lhc ApparatuS

Length : ~45 m
Radius : ~12 m
Weight : ~ 7000 tons

- Tracking ($|\eta|<2.5$, B=2T) :
  - -- Si pixels and strips
  - -- Transition Radiation Tracker (e/π separation)
- Calorimetry ($|\eta|<5$) :
  - -- EM : Pb-LAr
  - -- HAD: Fe-scintillator (central), Cu/W-LAr (fwd)
- Muon Spectrometer ($|\eta|<2.7$) :
  air-core toroids with muon chambers (standalone capabilities)

Status ATLAS

The ATLAS detector construction is proceeding within the framework of the accepted Completion Plan

Further important milestones have been passed in the construction, pre-assembly, integration and installation of the detector components, and several outstanding technical problems have been overcome recently

Large-scale system tests continue, and in particular the combined test beam runs have been a very major activity in 2004

The installation in the cavern was impacted by the most critical component construction delay for ATLAS given by the Barrel Toroid, but good progress can be noted there as well, on which a new schedule can be based

Very major software and computing activities are underway, with the running of DC2, which turned out to be a harder task than initially foreseen

Planning for the commissioning and the early physics phases is progressing well

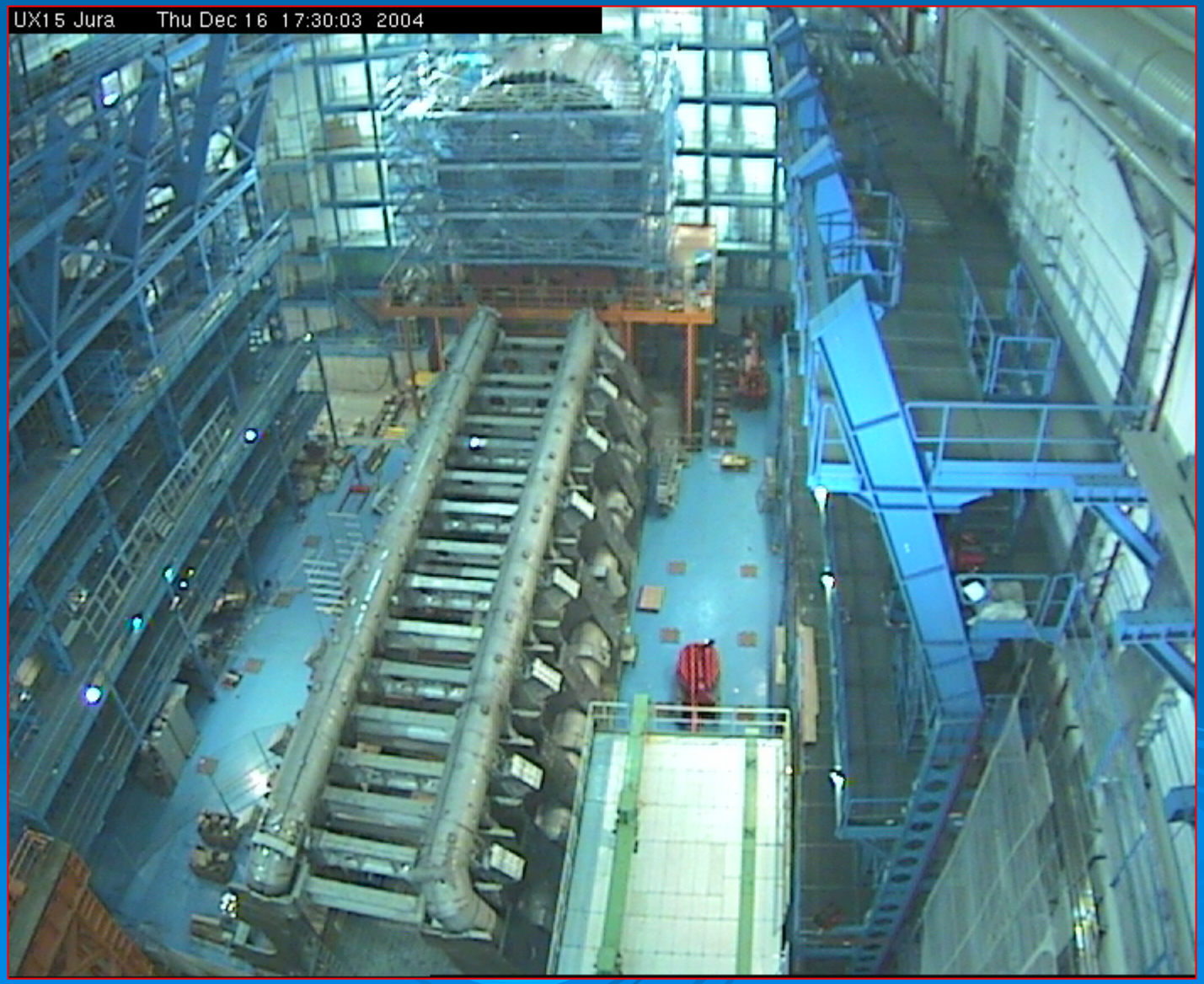
ATLAS remains on track for LHC physics in 2007

BT-1 installation in the cavern

Installation of the Barrel Cryostat on 28th October 2004 in the pit onto the lower part of the Barrel Tile Calorimeter

The positioning was adjusted to be well within the design specifications

The ATLAS detector: construction in the underground cavern

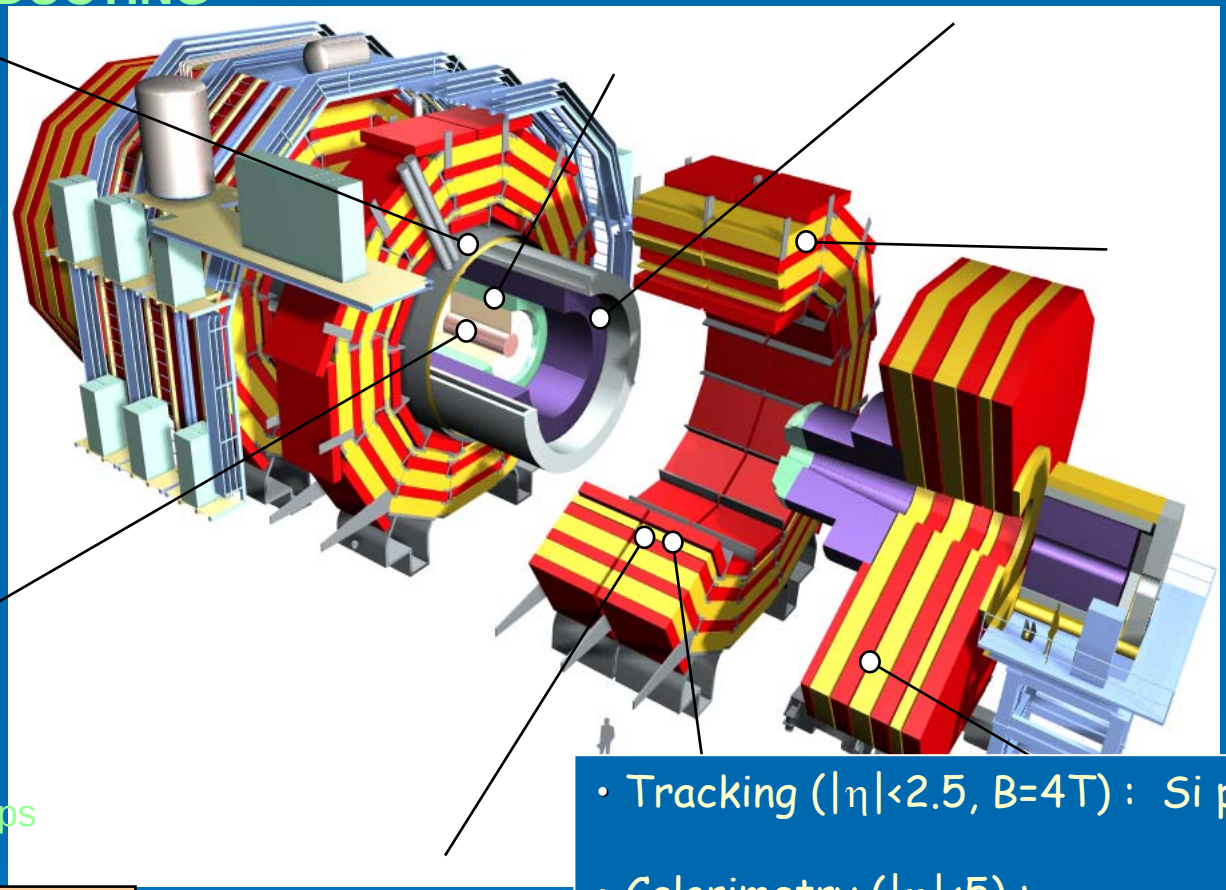


CALORIMETERS

Scintillating PbWO4 crystals **ECAL**

HCAL Plastic scintillator/brass sandwich

SUPERCONDUCTING COIL



IRON YOKE

TRACKER

Silicon Microstrips
Pixels

Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

MUON E

Drift Tube
Chambers

- Tracking ($|\eta|<2.5$, B=4T) : Si pixels and strips
- Calorimetry ($|\eta|<5$) :
  -- EM : $PbWO_4$ crystals
  -- HAD: brass-scintillator (central+ end-cap), Fe-Quartz (fwd)
- Muon Spectrometer ($|\eta|<2.5$) : return yoke of solenoid instrumented with muon chambers

Status

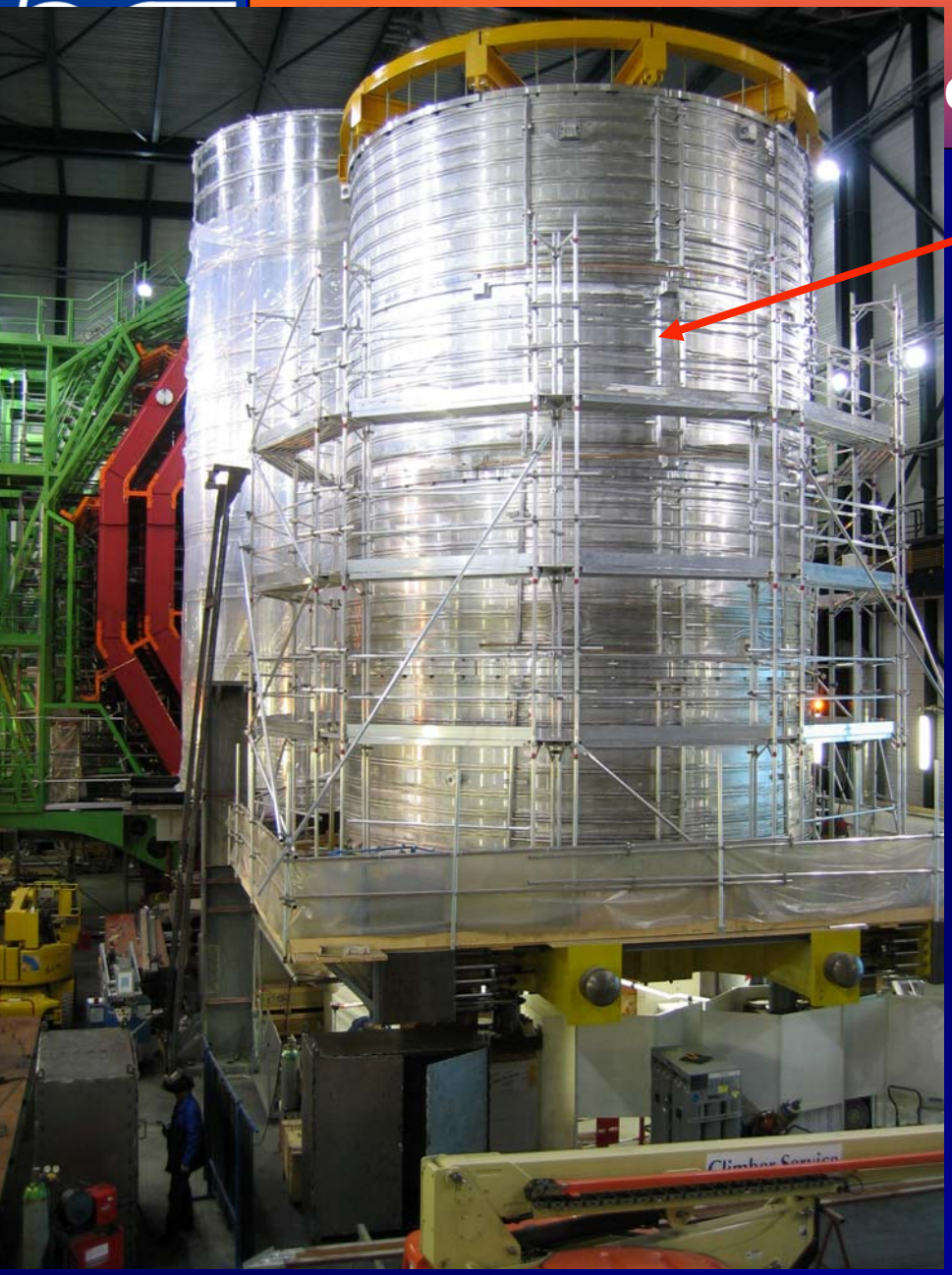
Civil Engineering: USC delivered 4 Aug 04 and UXC delivered 1 Feb 05 (~3 month delay).
Magnet: Project nearly complete. All 5 coil modules at CERN. Magnet test starts Oct 2005.
HCAL, Muons : construction on schedule and well advanced.

TO WATCH
ECAL: Crystals production, contracts need to be placed with multiple vendors, cost of crystals. No float in 'ready for installation' (rfi) milestone.
TRACKER: Re-start of mass assembly of Si modules. Integration and schedule. No float left in rfi.

CMS now tracking wrt to v34.1 Schedule
Ready to close 1 July 07 (ready to operate in Aug 07).

We will present an updated cost and funding of CMS at the next RRB in April 2005 when the exact size of the increases (in ECAL and Tracker) and additional contributions will be better known.

An initial CMS detector (minus the ECAL endcaps and pixels) will be ready for the pilot run in 2007.



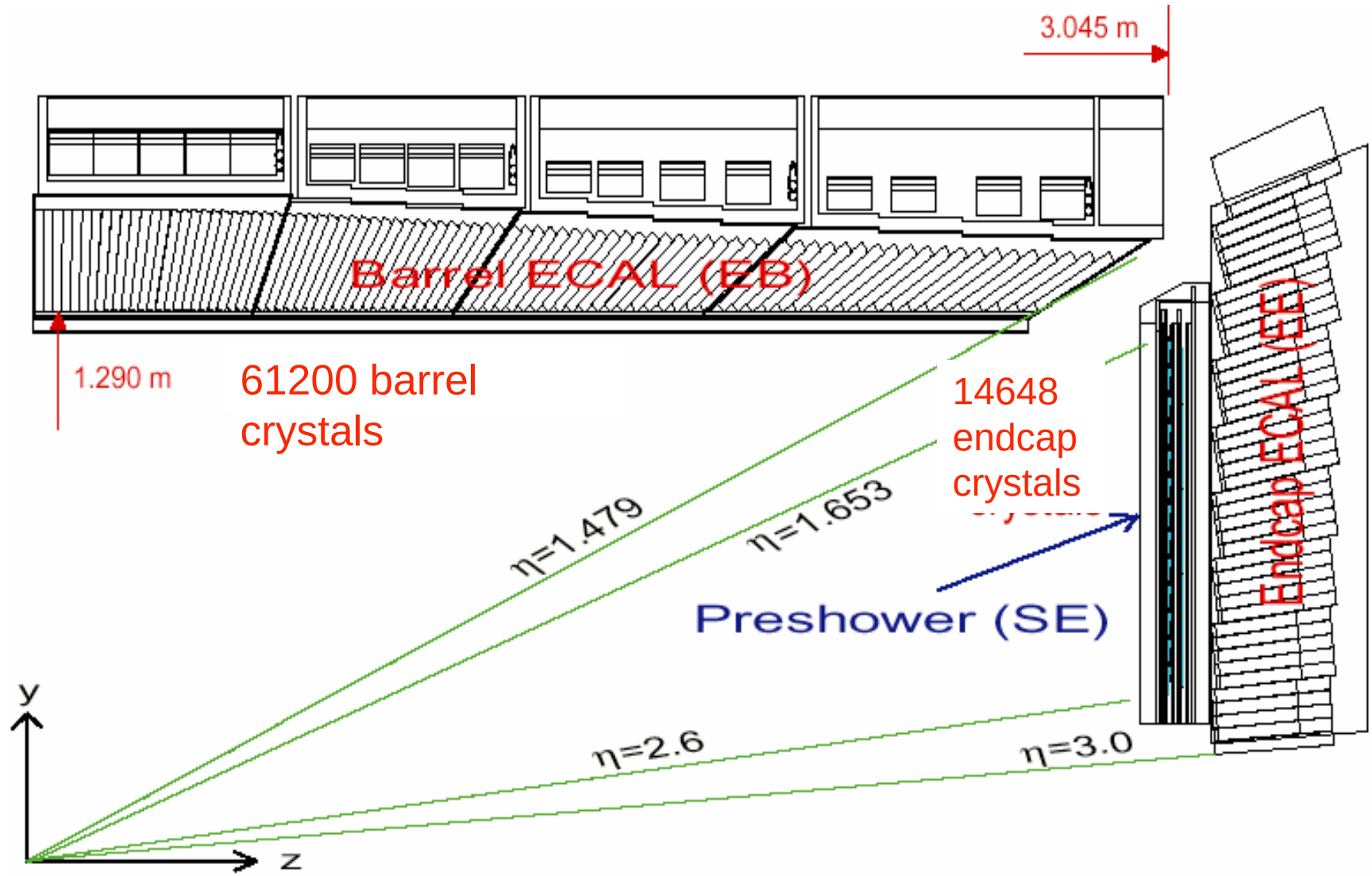
CMS: 4th Coil Module at Pt 5 since Dec 04

- Pt 5: 4 coil modules connected. Inner vac-tank can be seen behind coils.
- 5th module is being connected
- Cold mass swiveling and insertion by Jun05
- Start cool-down in Sept05.
- Q405 - Magnet Test and ‘Cosmics Challenge’

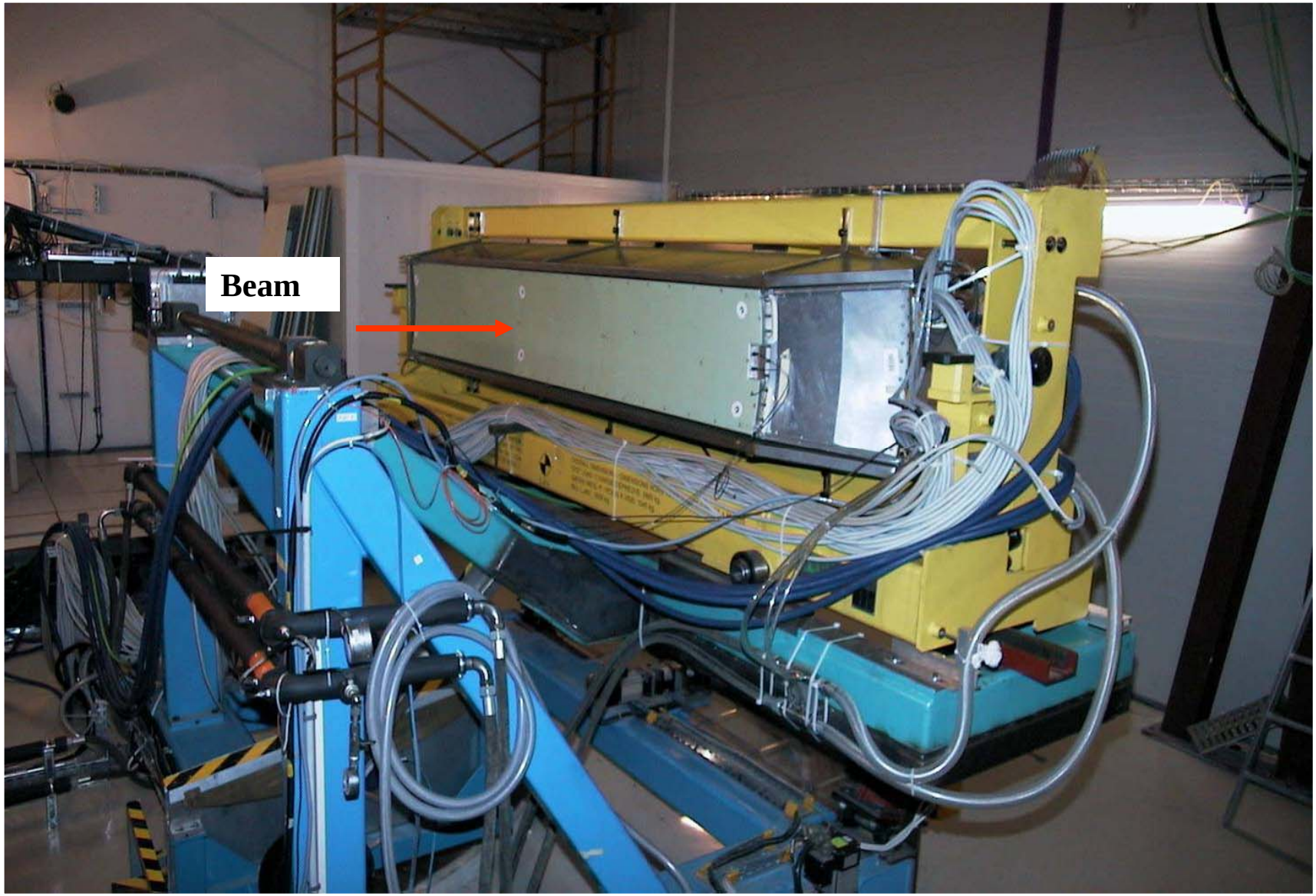
Tracker: Main Issues

- **Sensors**
- Thin Sensors : 95% in hand
- 6,000 Thick sensors in hand (4000 HPK and 2000 ST) out of 20,000 (need+10% Spares)
- Still miss 1400 sensors from ST (pending…. end of the negotiation)
- All remaining sensors have been ordered to HPK with last scheduled delivery in September 05.
- **Hybrids**
- Hybrid production re-launched after modifications, technical and managerial (improved quality control at factory)
- Module production will be launched in February. Expect to end module production in Q1-2006.
- A somewhat revised sequence of operations being worked out to catch up. Some of previous serial sequences put in parallel now. Investigating how to introduce 3 mo. contingency for ‘ready for installation’ milestone (1 Nov 2006).

ECAL

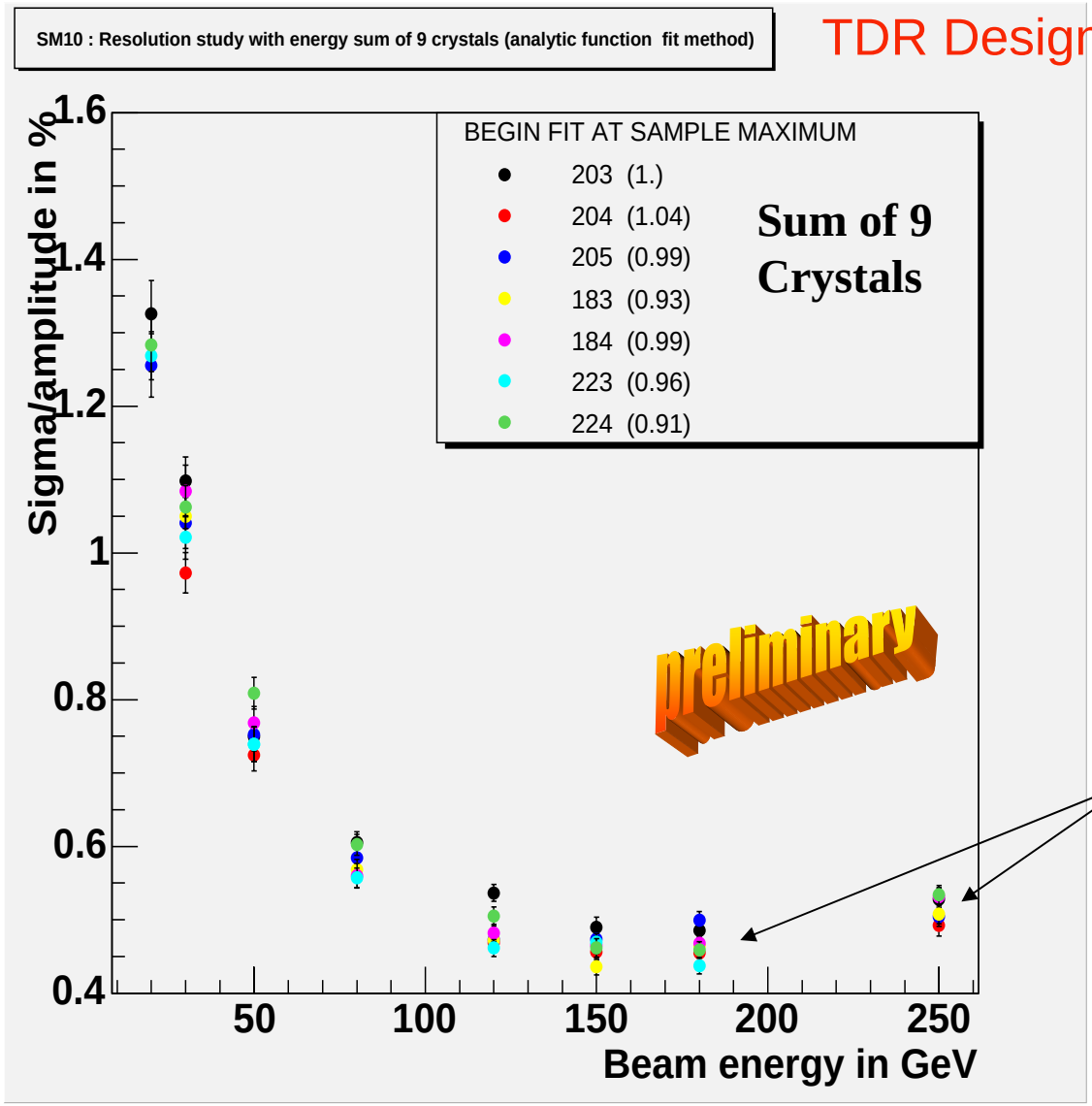

3.045 m
Barrel ECAL (EB)
1.290 m
61200 barrel crystals
14648 endcap crystals
Endcap ECAL (EE)
η=1.479
η=1.653
Preshower (SE)
η=2.6
η=3.0
y
z

ECAL: SM in Beam



ECAL: SM Preliminary Results

TDR Design Performance Achieved



Gain switch region
Requires detailed understanding

ECAL: Main Issue

- First six months program after factory (BTCP) restart has been executed with expected rate
- 31400 EB crystals have been delivered. Milestone of 50% of EB crystals passed. Need 62000 barrel and 15000 endcap crystals. First half-barrel lowered Q1-2005.
- Finish remainder on current contracts (10100 crystals) by Aug 2005 at a rate of 1200 crystals/mo.
- Preparing future contracts, in close collaboration and with help from CERN Management.
- SIC: Contract, based on tender response, in circulation at CERN. 2 SMs worth of EB crystals by June 06, 3250 EE crystals by June 07
- BTCP: place order by end Q1-05 for remainder of the barrel and endcap crystals in cooperation with Russian Ministry of Science and Technology.

Schedule and Initial detector

Pilot Run	Collisions in Summer 2007
Shutdown	Winter of 2007/2008
Physics Run	Spring 2008

CMS Initial Detector for Pilot Run in 2007

Without staged items AND without endcap ECAL, pixel detector (though latter will be ready). Only 2 DAQ slices will be deployed.

Install ECAL endcap + Preshower (EE/ES) and Pixels during the 2007/2008 winter shutdown

CMS Low Luminosity Detector for Physics Run in 2008

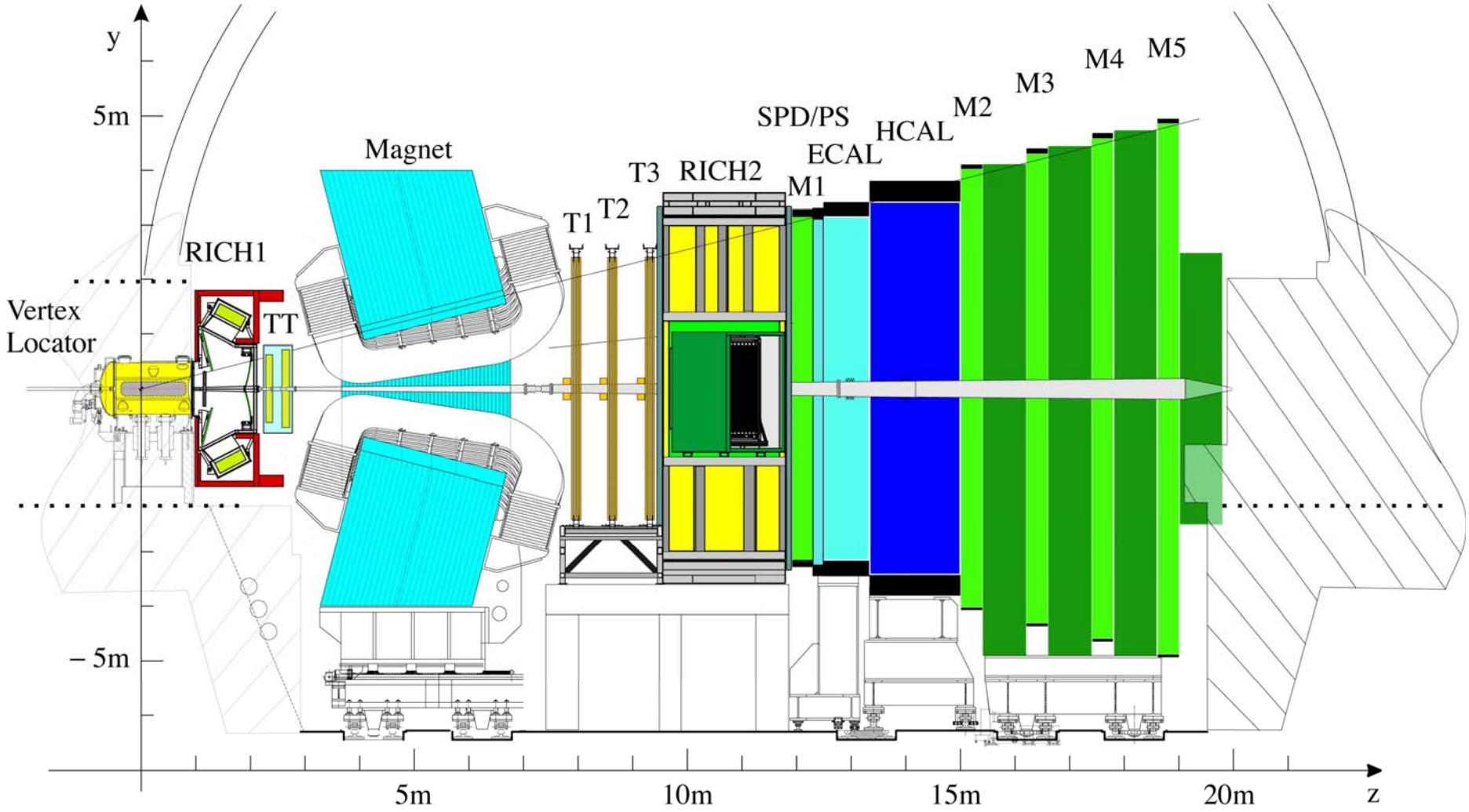
Items still staged are:

Muons: ME4/2, RE4, REs at small radius (RE1/1, RE2/1, RE3/1)

Tracker: 3rd forward pixel disks

DAQ (4 DAQ slices 6 DAQ slices?)

LHCb


y
5m
– 5m
Vertex
Locator
RICH1
TT
Magnet
T1
T2
T3
RICH2
M1
SPD/PS
ECAL
HCAL
M2
M3
M4
M5
5m
10m
15m
20m
z

LHCb is a dedicated experiment at LHC to study CP violation and other rare phenomena in B-meson decays.

Impressive progress by

LEP experiments

$|V_{cb}|$ (b→c+W), $|V_{ub}|$ (b→u+W),

$|V_{td}|$ (Δm_d), $|V_{ts}|$ (b→s penguin)

Experiments at Y(4S)

$|V_{cb}|$, $|V_{ub}|$,

$|V_{td}|$ (Δm_d), $|V_{ts}|$ (b→s penguin),

arg V_{td} (CP in b→c+W),

arg V_{ts} (CP in b→s penguin)

arg V_{ub} (CP in b→c+W⊗b→u+W via D-$\overline{D}$ mixing)

arg V_{ub} (CP in b→c+W⊗b→u+W

Tevatron experiments

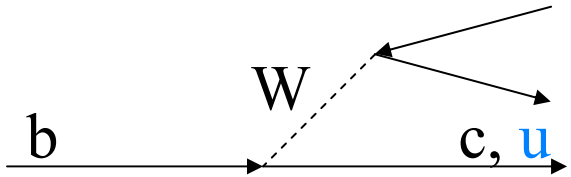
$|V_{td}|$, $|V_{ts}|$, arg V_{td}

Standard Model

Tree

$\Gamma(b \to c)$

$\Gamma(b \to u)$



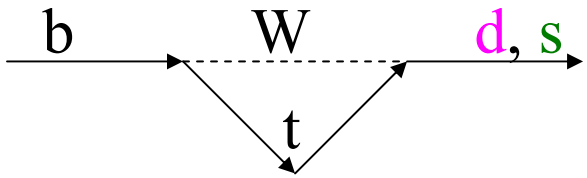
$|V_{cb}|$

$|V_{ub}|$

Penguin

$\Gamma(b \to s)$

$\Gamma(b \to d)$



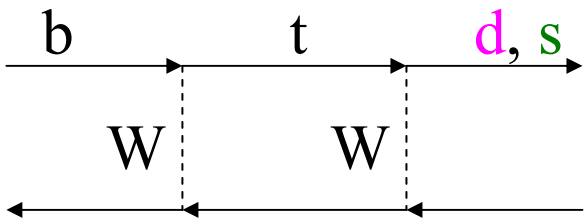
$|V_{td}|$

$|V_{ts}|$

Box

$\omega(B_d\text{-}\overline{B}_d)$

$\omega(B_s\text{-}\overline{B}_s)$



$|V_{td}|$

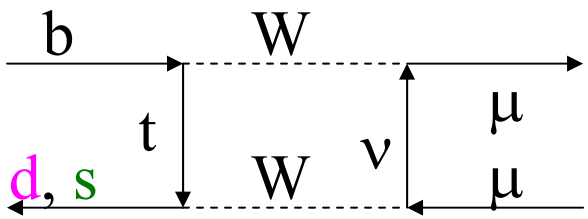
$|V_{ts}|$

$\not{CP}$(Tree⊗Box) $2 \arg V_{td}\,(V_{ts}) + \arg V_{cb}\,(V_{ub})$

$\not{CP}$(Peng⊗Box) $2 \arg V_{td}\,(V_{ts}) + \arg V_{td}$

$2 \arg V_{td}\,(V_{ts}) + \arg V_{ts}$

$\Gamma(B \to \mu\mu)$



$|V_{td}|$

$|V_{ts}|$

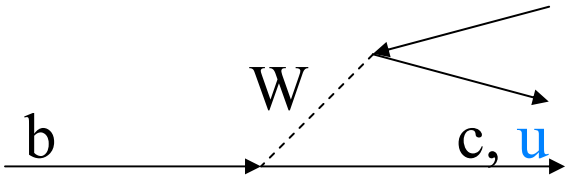
Standard Model

New Physics

Tree

$\Gamma(b\to c)$

$\Gamma(b\to u)$



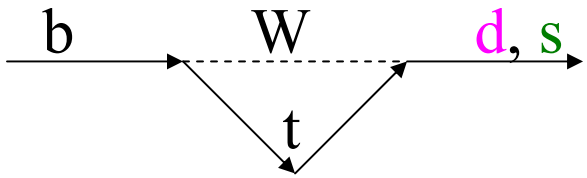
$|V_{cb}|$ unaffected

$|V_{ub}|$

Penguin

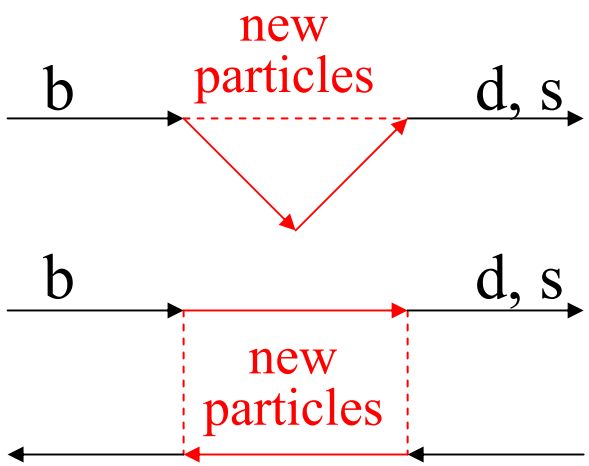
$\Gamma(b\to s)$

$\Gamma(b\to d)$



$|V_{td}| + \Delta_{peng(d)}$

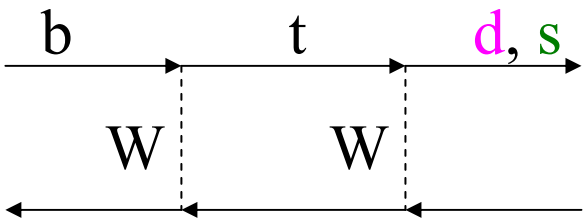
$|V_{ts}| + \Delta_{peng(s)}$



Box

$\omega(B_d\text{-}\overline{B}_d)$

$\omega(B_s\text{-}\overline{B}_s)$



$|V_{td}| + \Delta_{box(d)}$

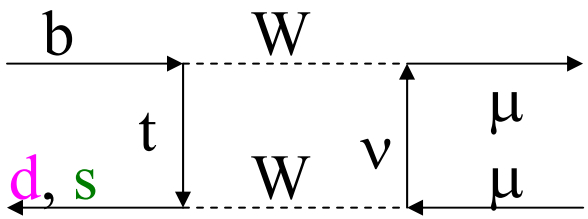
$|V_{ts}| + \Delta_{box(s)}$

$\not{CP}$(Tree⊗Box) $2\arg V_{td}\,(V_{ts}) + \arg V_{cb}\,(V_{ub}) + \Phi_{box(d)}\,(\Phi_{box(s)})$

$\not{CP}$(Peng⊗Box) $2\arg V_{td}\,(V_{ts}) + \arg V_{td} + \Phi_{box(d)}\,(\Phi_{box(s)}) + \Phi_{peng(d)}$

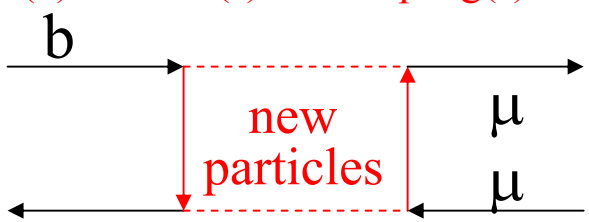
$2\arg V_{td}\,(V_{ts}) + \arg V_{ts} + \Phi_{box(d)}\,(\Phi_{box(s)}) + \Phi_{peng(s)}$

$\Gamma(B\to\mu\mu)$



$|V_{td}| + \Delta_{\mu\mu(d)}$

$|V_{ts}| + \Delta_{\mu\mu(s)}$



The LHCb Experiment will

-determine the CKM parameters in a model independent manner and look for new physics-

e.g.

- extracting B_d and B_s oscillation frequencies and phases: *B. Carron*
  (in the Standard Model V_{td} and V_{ts})
  -$B_d \to J/\psi K_S$, $B_s \to J/\psi\phi$, $B_s \to J/\psi\eta$,

- extracting arg V_{ub} from CP asymmetries in
  -$B_s \to D_s K$(+ B_s oscillation phase): *E. Rodrigues*
  no hadronic uncertainties
  no effect from new physics
  large asymmetries

  -$B_d \to \pi^+\pi^- \oplus B_s \to K^+K^-$(+ B_d and B_s oscillation phase) *L. Fabbri*
  hadronic uncertainties (U-spin)
  affected by new physics in penguin

  -$B_d \to DK^*$ *S.Amato* affected by new physics in D-$\overline{D}$

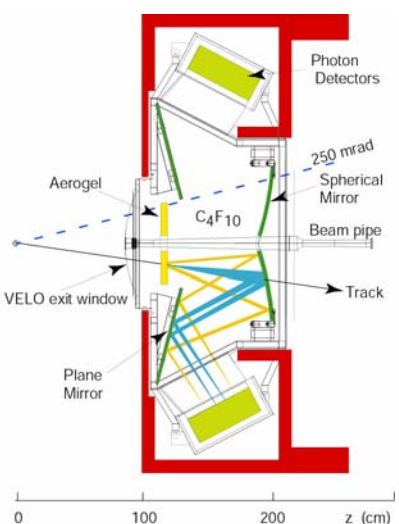
-and look for surprises-

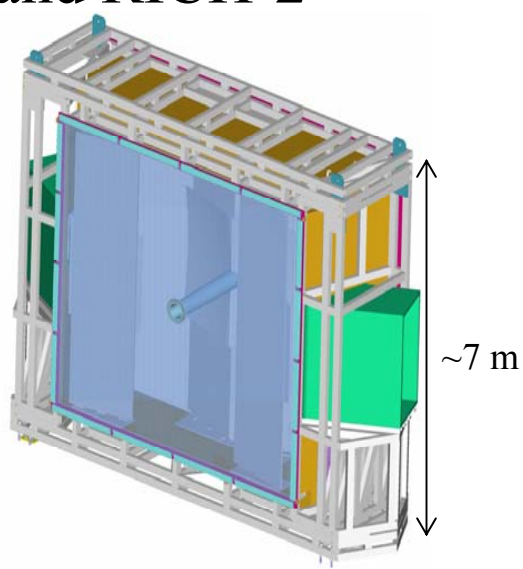
e.g. rare decays *I. Belyaev*

Most important features of the LHCb experiment

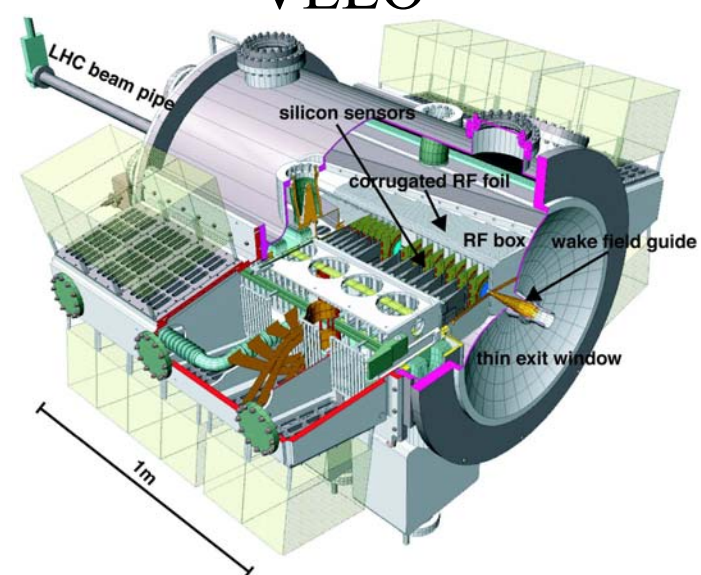
- Hadron (K/π) identification from few GeV/*c* up to ~100 GeV/*c*
  Two Ring Imaging Cherenkov counters with three radiators (RICH)
- Excellent B proper time resolution of ~40 fs
  Si micro-strip detector (VELO) very close to the beam
- Trigger also sensitive to the B meson final states with only hadrons
  Level-0 "high" p_T lepton/hadron trigger @ 40MHz → hardware
  Level-1 "high" p_T + impact parameter trigger @ 1 MHz
  High Level Trigger with all the data @ 40 kHz
  } → software

RICH-1 and RICH-2





VELO



Status LHCb

Good progress for the many subsystems:

-Beam pipe, Magnet, RICH2 mechanics, Calorimeter system, and Online system are progressing well.

-Outer Tracker, RICH1 mechanics, HPD and VELO are also making good progress, however with tight planning.

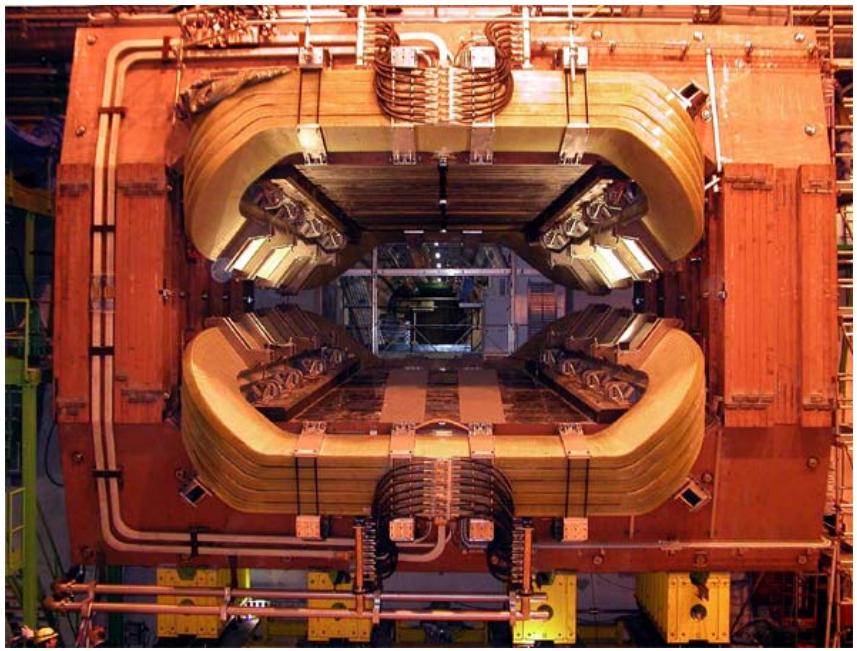
-We are looking forward to seeing the production of the Trigger Tracker and Inner Tracker start as planned. A major concern is how to solve the conflict with CMS on the delivery schedule for the TT sensors.

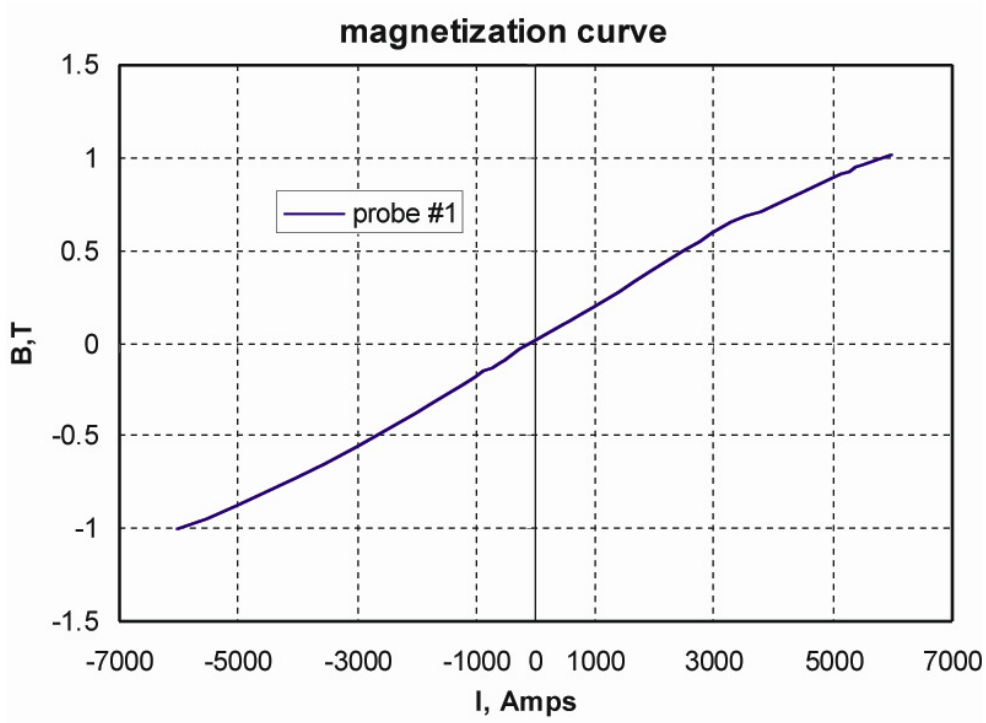
-Production of the Muon chambers is facing a substantial delay. Necessary action will be decided in March 2005 when we expect to have all the information needed.

-Need of computing resources is evolving and its effect on computing model is being investigated.

Magnet

Completed and successfully switched on



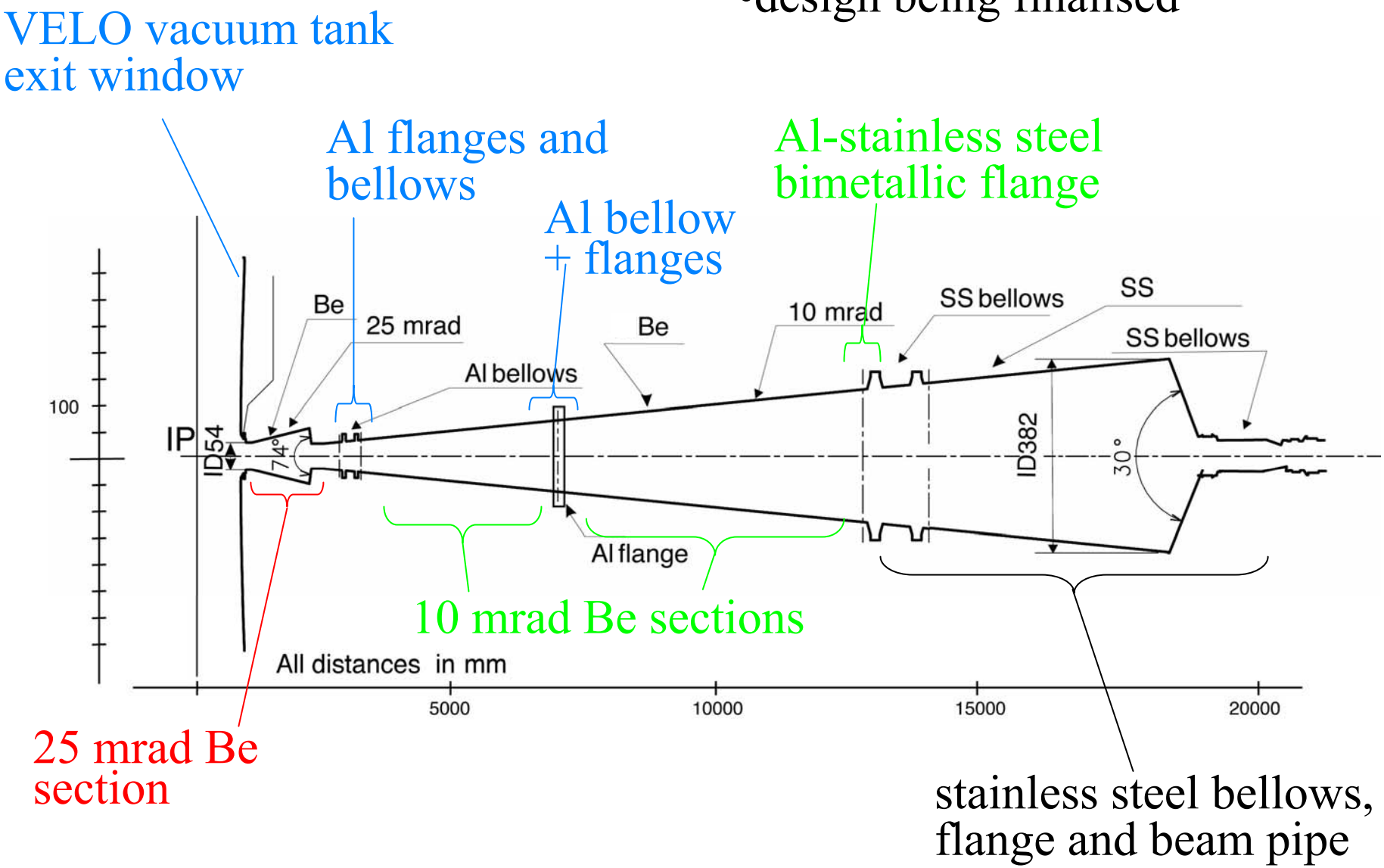


Fe Yoke 1.45 kt
Al normal conductive coil 2□25 t

Power 4.2MW at 1 T field

Beam pipe

- completed by industry
- ready for fabrication at CERN
- being fabricated by industry
- design being finalised

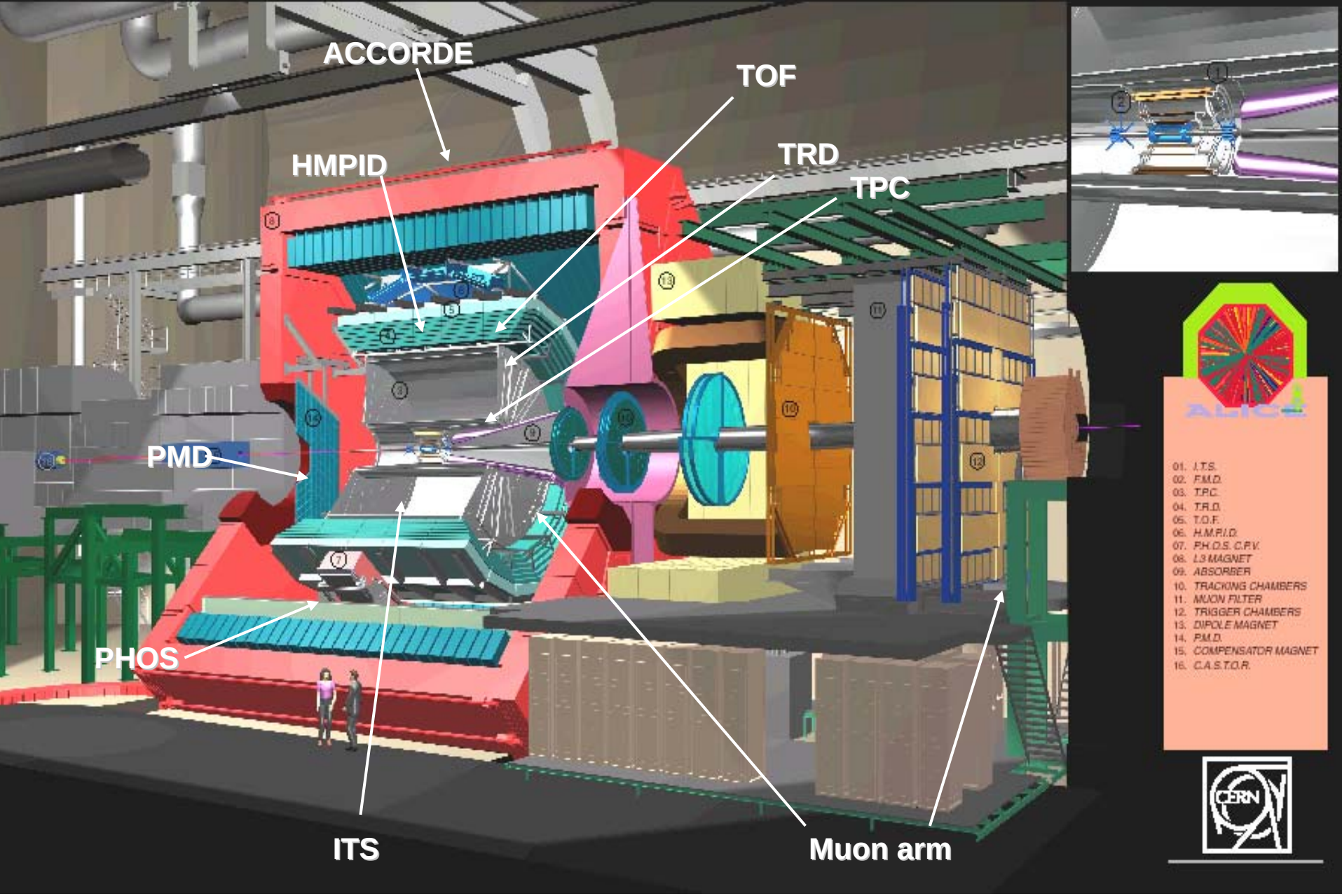


VELO window

Al bellows and flanges

25 mrad Be pipe

Al bellow and flange



ALICE Detector

ALICE R&D

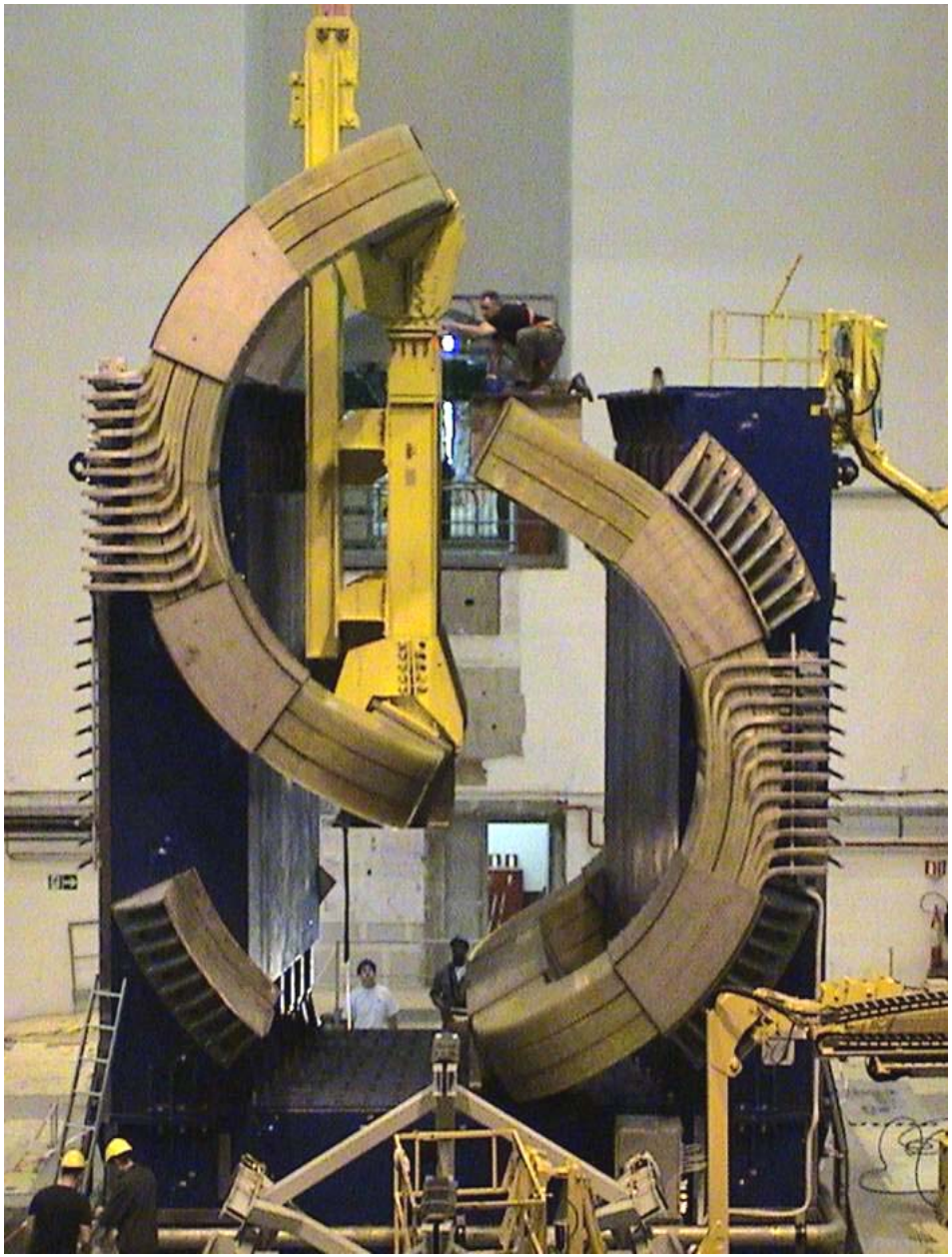
From 1990:strong R&D activity

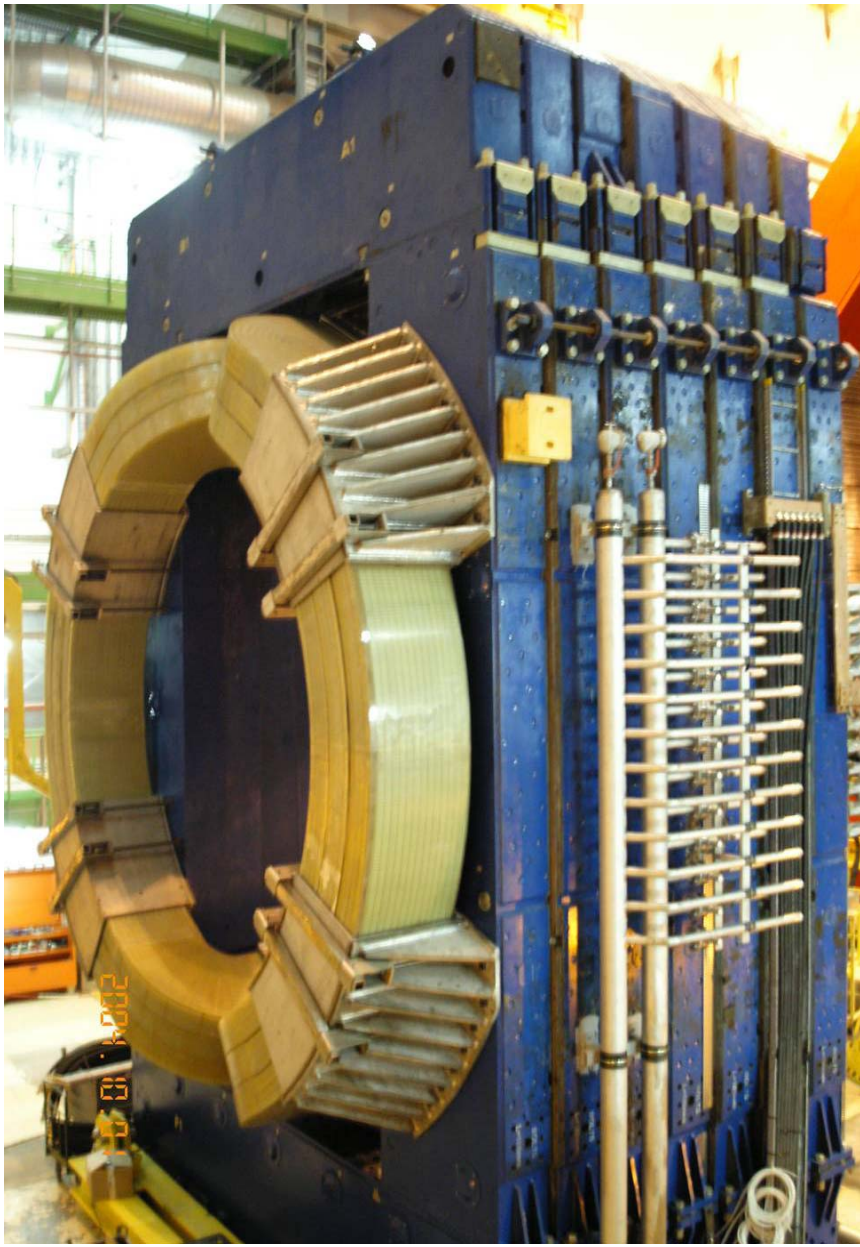
- **Inner Tracking System (ITS)**
  - Silicon Pixels (RD19)
  - Silicon Drift (INFN/SDI)
  - Silicon Strips (double sided)
  - low mass, high density interconnects
  - low mass support/cooling
- **TPC**
  - gas mixtures (RD32)
  - new r/o plane structures
  - advanced digital electronics
  - low mass field cage
- **em calorimeter**
  - new scint. crystals (RD18)
- **PID**
  - Pestov Spark counters
  - Parallel Plate Chambers
  - Multigap RPC's (LAA)
  - low cost PM's
  - solid photocathode RICH (RD26)
- **DAQ & Computing**
  - scalable architectures with COTS
  - high perf. storage media
  - GRID computing
- **misc**
  - micro-channel plates
  - rad hard quartz fiber calo.
  - VLSI electronics

Installation, Large Structures

- Main installation crane was out of service for 3 months
  - ⇨ major **disruption** to installation activities
  - ⇨ **impact minimized** using mobile cranes and re-scheduling of activities
- Space frame load tests and installation tests proceeding
  - ⇨ dummy T**RD and TOF modules inserted** successfully
  - ⇨ first l**oad tests & deformation measurements** done
- Muon arm foundation finished
- Muon Magnet: Coils were inserted
  - ⇨ proved to be much more **difficult and time consuming** than foreseen
  - ⇨ installation in **final position:** delayed to early 2005 (still not on critical path)
  - ⇨ **power test:** done end October
- Muon absorber assembly under way
  - ⇨ one section finished, remaining two in progress

Muon Magnet





Project Summary

- Infrastructure (structures, services, magnets,..) & Integration
  - ⇨ more complex & time consuming than foreseen => delays
    - ✪ reasons: both **technical** & **organizational** (safety, planning, work sharing with TS)
  - ⇨ **will be ready in time**, but <u>needs increased resources</u> (shift work, quality assurance)

- Read-out & Controls (DAQ, Trigger, DCS, ECS..)
  - ⇨ good progress, on schedule, **no concerns**

- Forward Detectors
  - ⇨ **ZDC**: **on schedule** **T0/V0/FMD**: late start, now starting construction, **will be ready**

- TPC
  - ⇨ **production finished** (FC, ROC, FEE) or soon finished (RCU)
  - ⇨ even with a very **conservative schedule** for ROC & FEE installation **ready well in time**
    - ✪ including thorough **pre-commissioning** on surface

Project Summary

- HMPID : well advanced, no concerns
- Muon arm
  - ⇨ **chamber** production: **ok** major activity of **electronics testing & assembly still ahead**
- TOF
  - ⇨ despite delays in the assembly tender, most **(>>20%)** if not all TOF modules **will be ready**
- TRD
  - ⇨ **radiator** production finished, **chamber** production getting on speed
  - ⇨ some **revisions** to **FEE** (TRAP chip, R/O board) and **mechanics** necessary
  - ⇨ some super-modules **will be ready**
- PHOS
  - ⇨ **1 module ready end 2005**, 2nd module by end 2006 may even be feasible
- ITS

Initial working detector well on track for collisions in summer 2007

We aim for more

(~completion of 'funded' detector for 2007)

TOTEM Physics: Total p-p Cross-Section

- Current models predict for 14 TeV: 90 – 130 mb
- Aim of TOTEM: ~ **1%** accuracy

- **Luminosity independent method**:

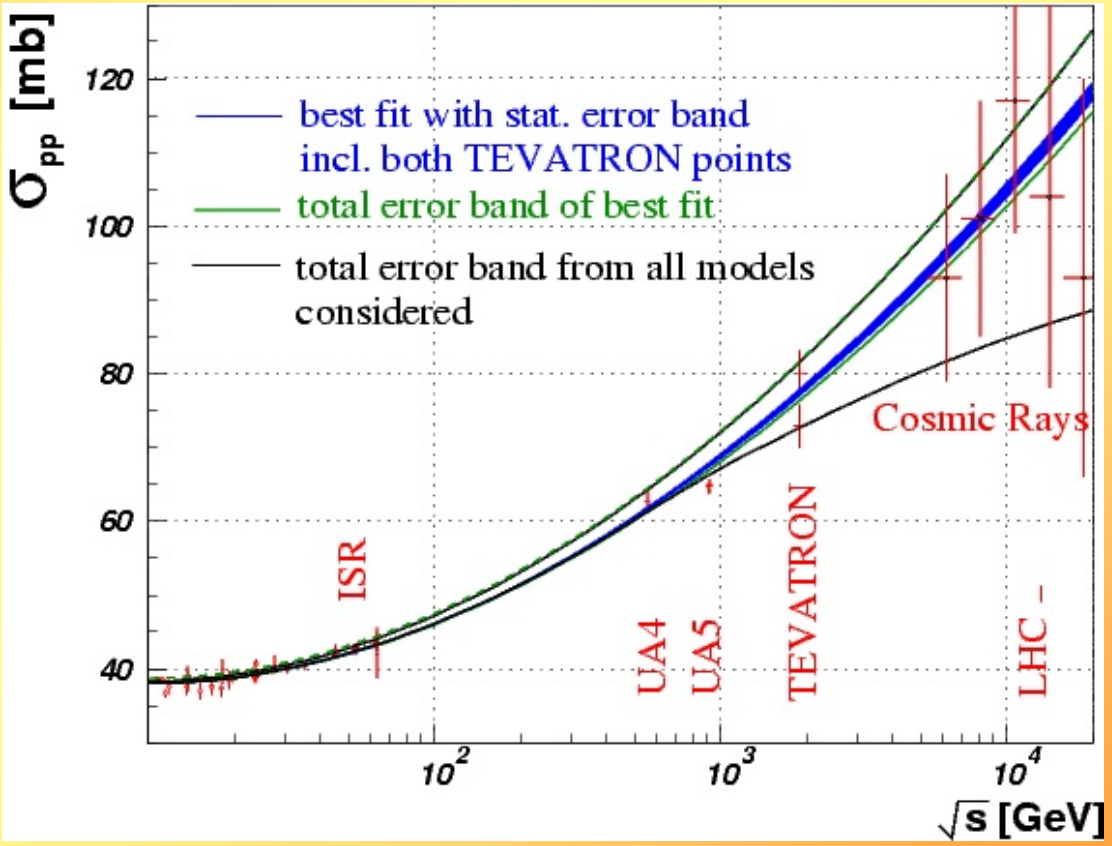
Optical Theorem

$$L\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2} \times \left.\frac{dN}{dt}\right|_{t=0}$$

$$L\sigma_{tot} = N_{elastic} + N_{inelastic}$$

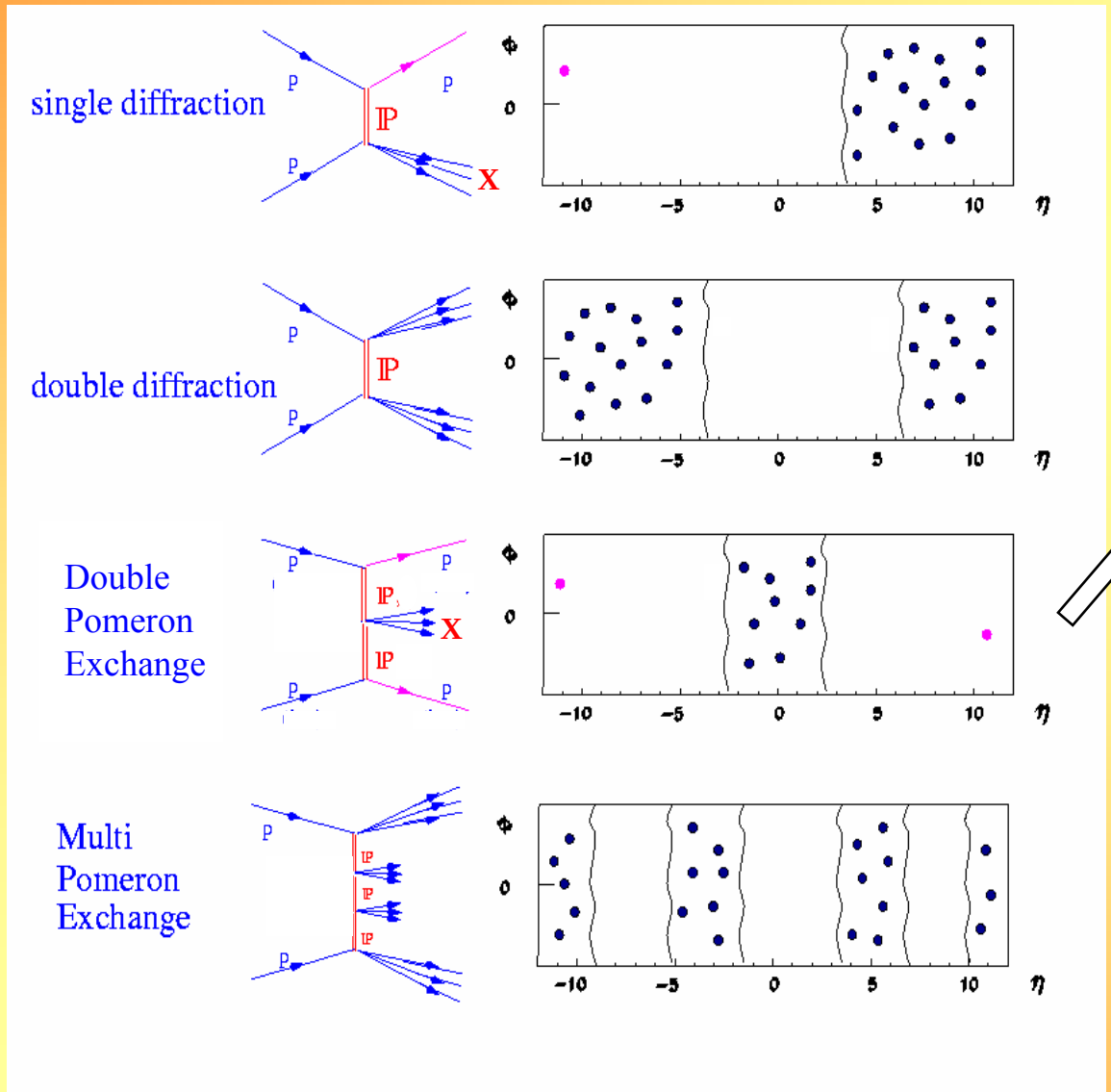
$$\sigma_{tot} = \frac{16\pi}{1+\rho^2} \times \frac{(dN/dt)|_{t=0}}{N_{el} + N_{inel}}$$

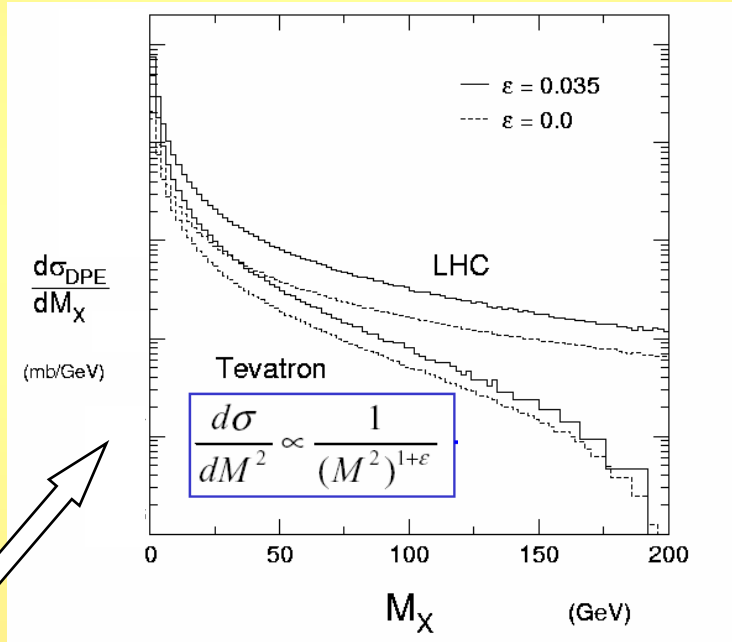
COMPETE Collaboration:



TOTEM+CMS Physics: Diffractive Events

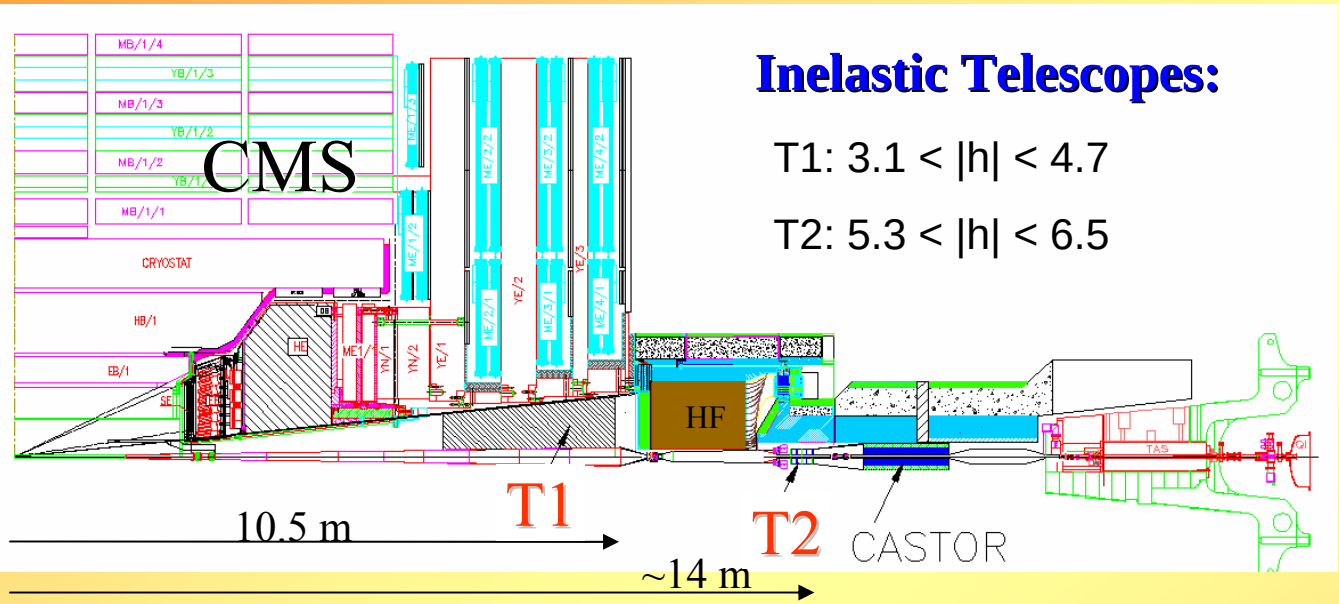
Measure > 90% of leading protons with RPs and diffractive system X with T1, T2 and CMS.





Central production of 0^{++} states X:
X = c_c, c_b, Higgs, dijets,
SUSY particles, ...

TOTEM Detectors

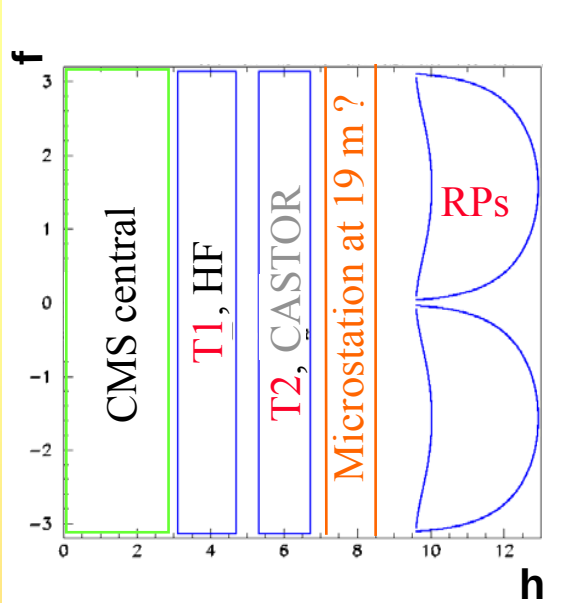


Inelastic Telescopes:

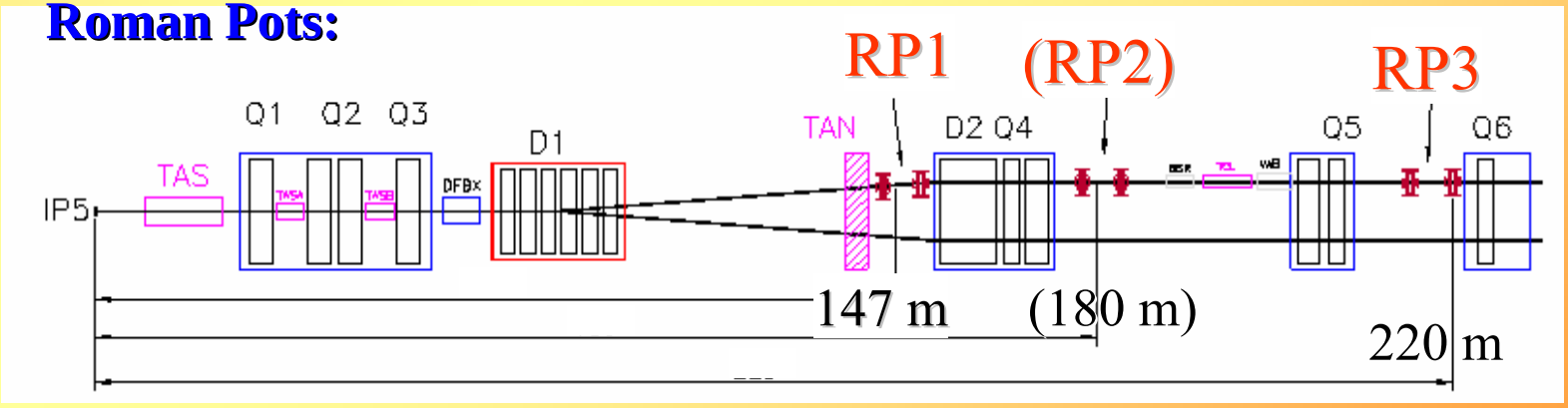
T1: 3.1 < |h| < 4.7

T2: 5.3 < |h| < 6.5

Acceptance:



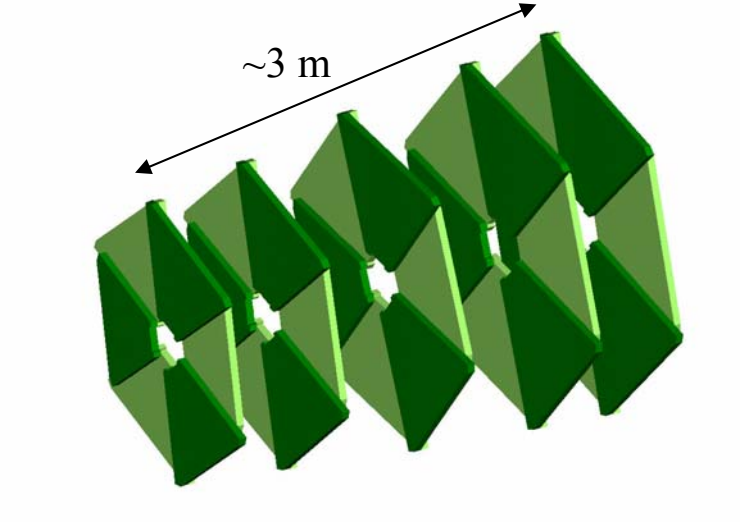
Roman Pots:

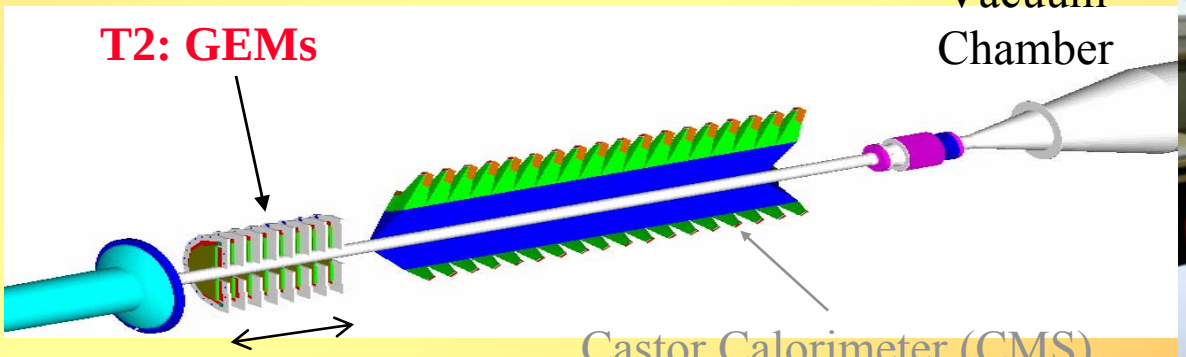


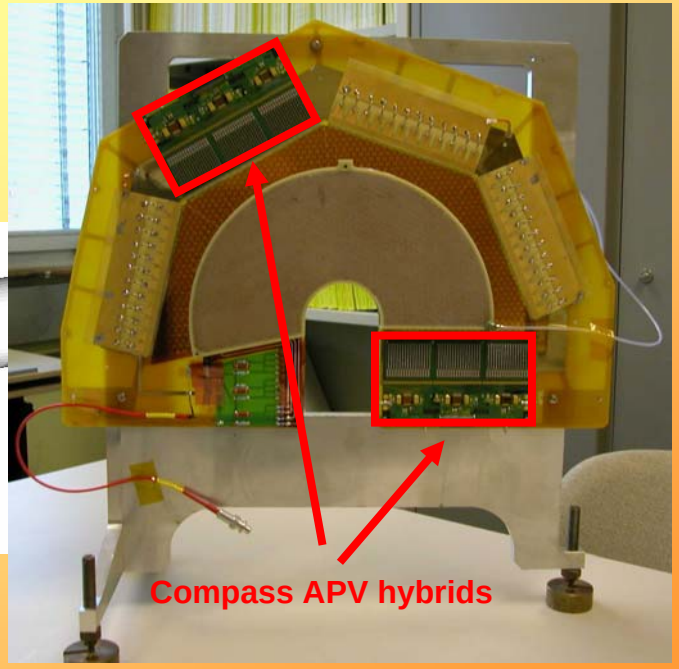
T1 and T2 Telescopes

2004 Test Beam in X5

T1: Cathode Strip Chambers

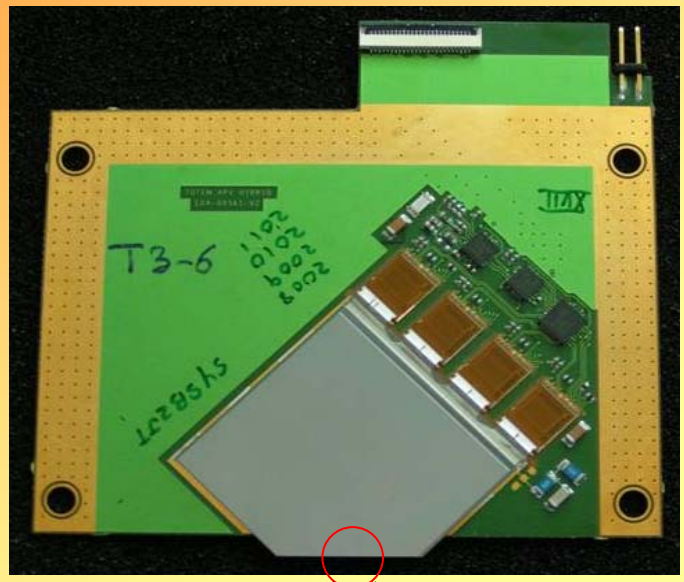




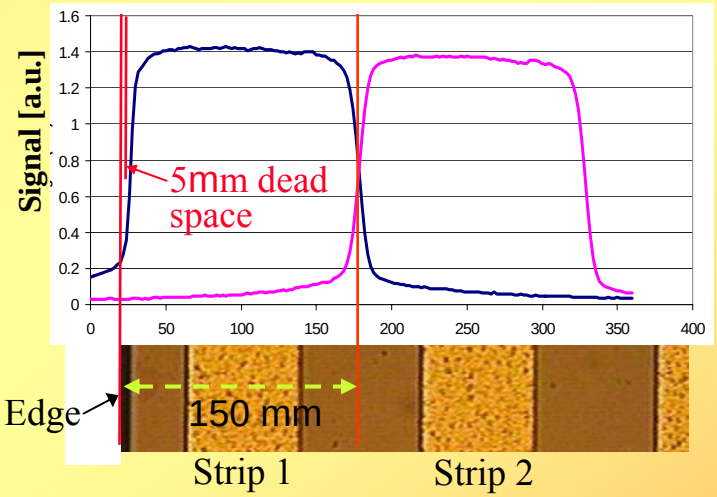


Edgeless Silicon Detectors for the RPs

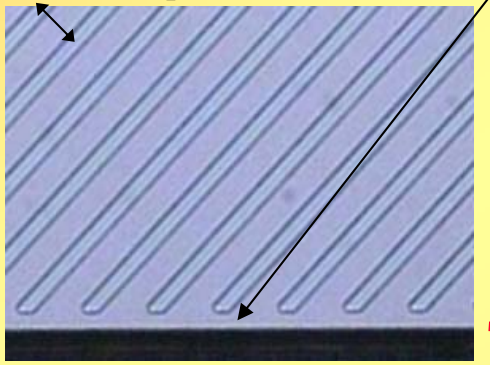
Measurement of very small proton scattering angles (few mrad):
active area of detectors must approach beam to ~1.5 mm.



Active edges: X-ray measurement

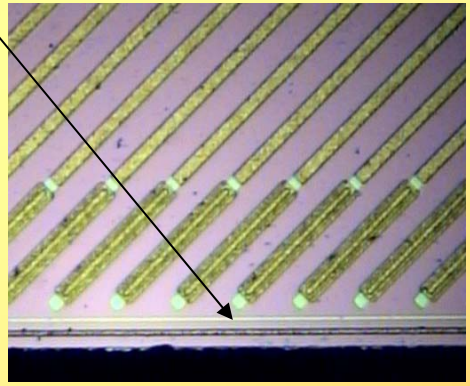


66 mm pitch



5–10 mm dead space

20–50 mm dead space

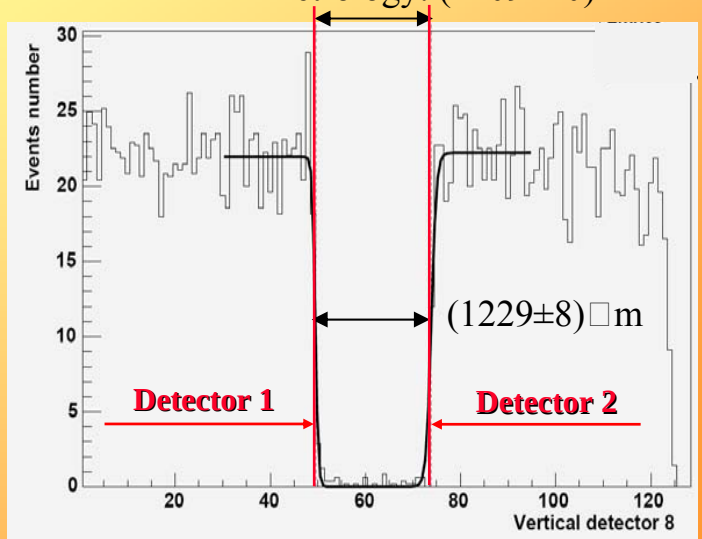


Active edges ("planar/3D")

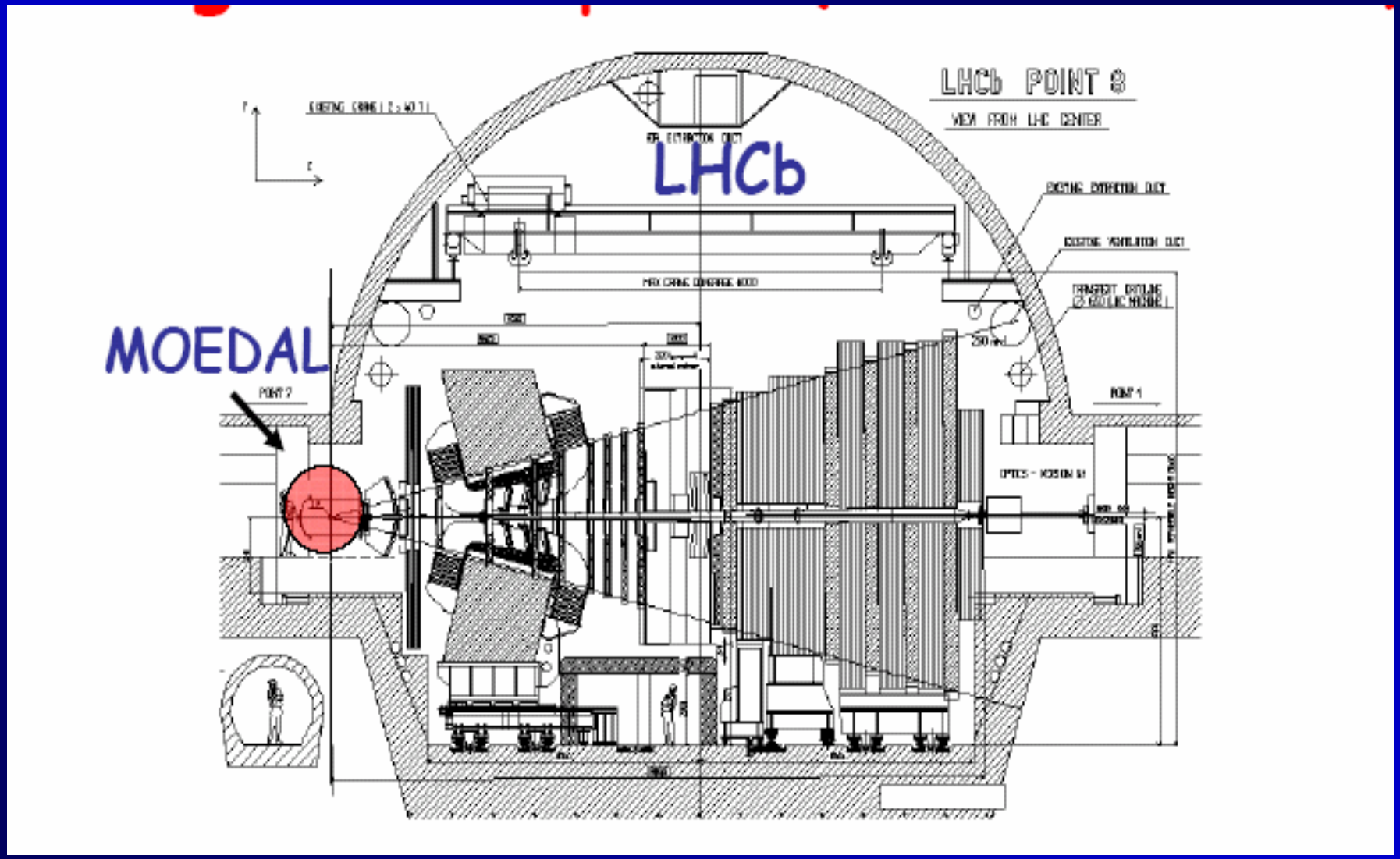
Planar technology with minimal guard rings

Planar technology: Testbeam

Metrology: (1209±10)□m



MOEDAL: Magnetic Monopole Search



4 May 2004
Letter of Intent to CERN LHCC [LHCC 2003-057/I-012 rev. 2]

Measurement of Photons and Neutral Pions in the Very Forward Region of LHC

O. Adriani(1), A. Faus(2), M. Haguenauer(3), K. Kasahara(4), K. Masuda(5), Y. Matsubara(5), Y. Muraki(5), T. Sako(5), T. Tamura(6), S. Torii(6), W.C. Turner(7), J. Velasco(2)

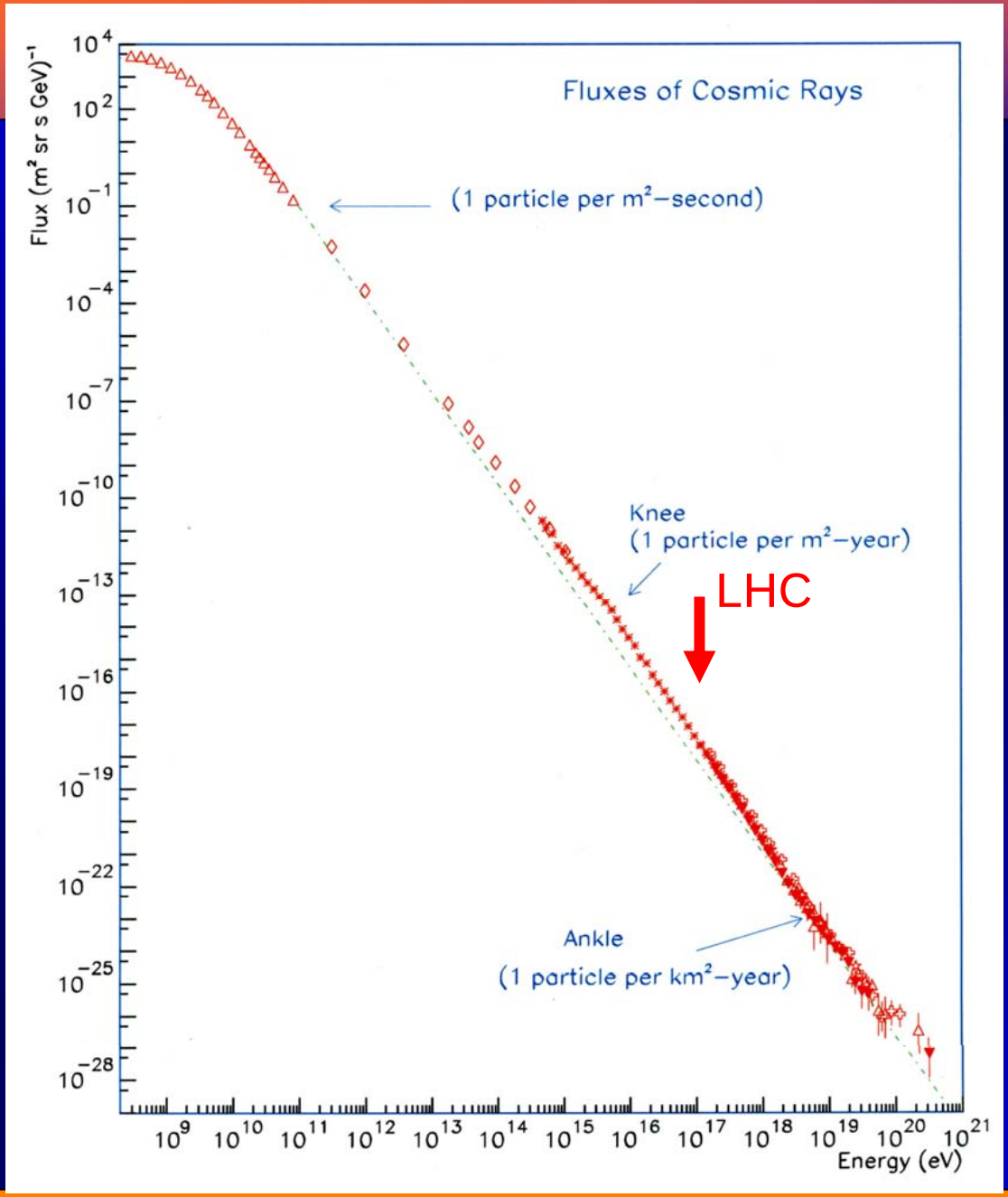
The **LHCf collaboration** (tentative)

(1) INFN, Univ. di Firenze, Firenze, Italy
(2) IFIC,Centro Mixto CSIC-UVEG, Valencia, Spain
(3) Ecole-Polytechnique, Paris, France
(4) Shibaura Institute of Technology, Saitama, Japan
(5) STE laboratory, Nagoya University, Nagoya, Japan
(6) Kanagawa University, Yokohama, Japan
(7) LBNL, Berkeley, California, USA

Abstract

An energy calibration experiment is proposed for ultra high energy cosmic ray experiments in the energy range between 10^{17}eV and 10^{20}eV. Small calorimeters will be located between the two beam pipes in the “Y vacuum chamber” 140m away from the interaction point of the Large Hadron Collider. Within an exposure time of a few hours at luminosity $\approx 10^{29}$ $cm^{-2}s^{-1}$, very important results will be obtained that will resolve long standing quests by the highest energy cosmic ray physics experiments.

The Cosmic Ray Spectrum



Which physics the first year(s) ?

Expected event rates at production in ATLAS or CMS at $L = 10^{33}\ cm^{-2}\ s^{-1}$

Process	Events/s	Events for 10 fb^{-1}	Total statistics collected at previous machines by 2007
$W \rightarrow e\nu$	15	10^8	10^4 LEP / 10^7 Tevatron
$Z \rightarrow ee$	1.5	10^7	10^7 LEP
$t\bar{t}$	1	10^7	10^4 Tevatron
$b\bar{b}$	10^6	10^{12} - 10^{13}	10^9 Belle/BaBar ?
H m=130 GeV	0.02	10^5	?
$\tilde{g}\tilde{g}$ m= 1 TeV	0.001	10^4	---
Black holes m > 3 TeV (M_D=3 TeV, n=4)	0.0001	10^3	---

➡ Already in first year, large statistics expected from:
-- known SM processes → understand detector and physics at $\sqrt{s}$ = 14 TeV
-- several New Physics scenarios

Computing – LCG Project

Computing Models defined

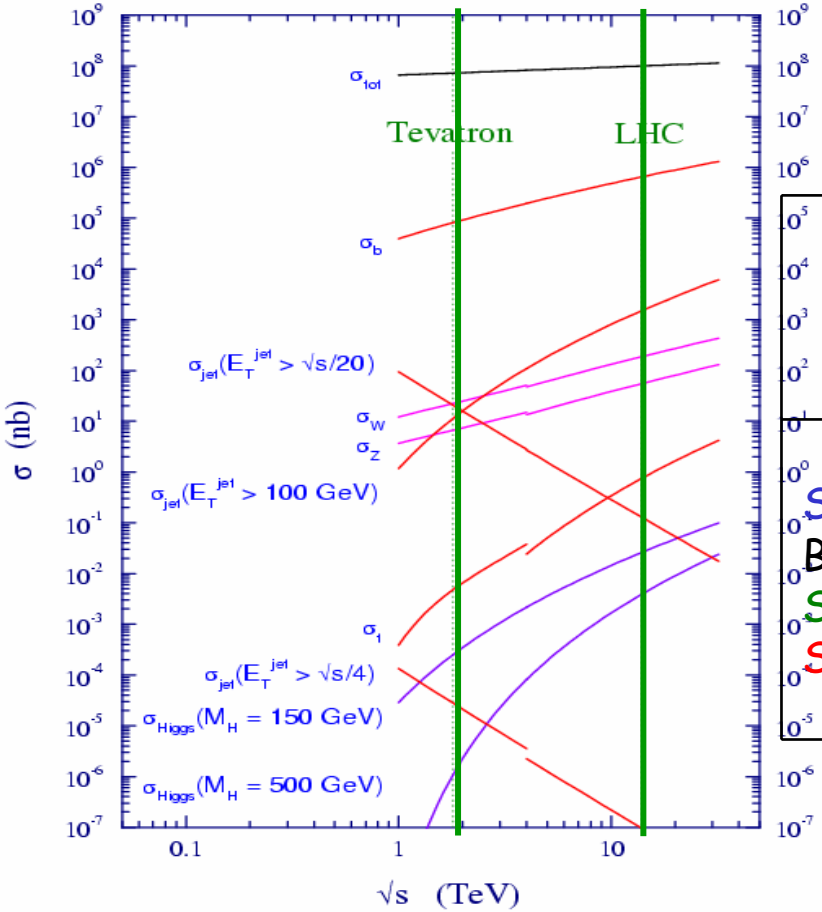
GRID essential (10^5 PC's; 10 PB/y)

Middleware evolving (EGEE)

Computing MoU's – Tier1's

Conclusions

The LHC collaborations still have a big job in front of them, but it is their top priority and realistic goal to have initial detectors ready to record 14 TeV pp collisions in the summer of 2007 and to have the necessary analysis infrastructure in place



Implications for light Higgs

(assuming the same luminosity/detector/analysis)

	$qq \to WH \to \ell\nu\, bb$ $qq \to ZH \to \ell\ell\, bb$ m_H=120 GeV	$gg \to H \to WW$ $\to \ell\nu\, \ell\nu$ m_H=160 GeV
S(14)/S(2)	≈ 5*	≈ 30
B(14)/B(2)	≈ 25	≈ 6
S/B(14)/S/B(2)	≈ 0.2	≈ 3
S/√B(14)/ S/√B(2)	≈ 1	≈ 7

*Acceptance ~ 2 times larger at Tevatron
(physics is more central, less initial-state g radiati

EW cross-sections (e.g. $qq \to W, Z, WH$) :
LHC/Tevatron ~ 10
QCD cross-sections (e.g. tt, $gg \to H$) :
LHC/Tevatron ≥ 100 (because of gluon PDF)

➡ e/jet ~ 10^{-3} $\sqrt{s}$ = 2 TeV
e/jet ~ 10^{-5} $\sqrt{s}$ = 14 TeV } p_T > 20 GeV

First goals ….

- Understand and calibrate detector and trigger in situ using well-known physics samples

e.g. - $Z \rightarrow ee, \mu\mu$ tracker, ECAL, Muon chambers calibration and alignment, etc.
- $tt \rightarrow b\ell\nu$ bjj 10^4 evts/day after cuts → jet scale from W→jj, b-tag performance, etc.

- 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 e.g. minimum bias, W, Z, tt, QCD jets (to ~ 10-20 %), events features, particle multiplicities, p_T and mass spectra, angular distributions, etc.
- measure top mass (to 5-7 GeV) → give feedback on detector performance (jet scale …)

Note : statistical error negligible after few days run

…. and then …

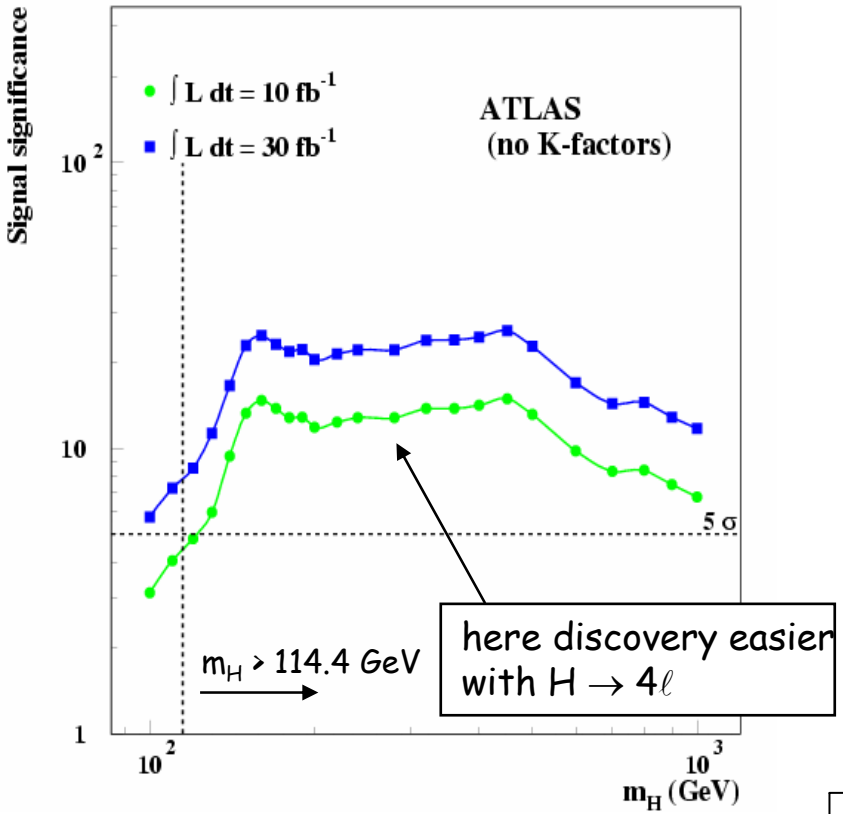
- Prepare the road to discovery:

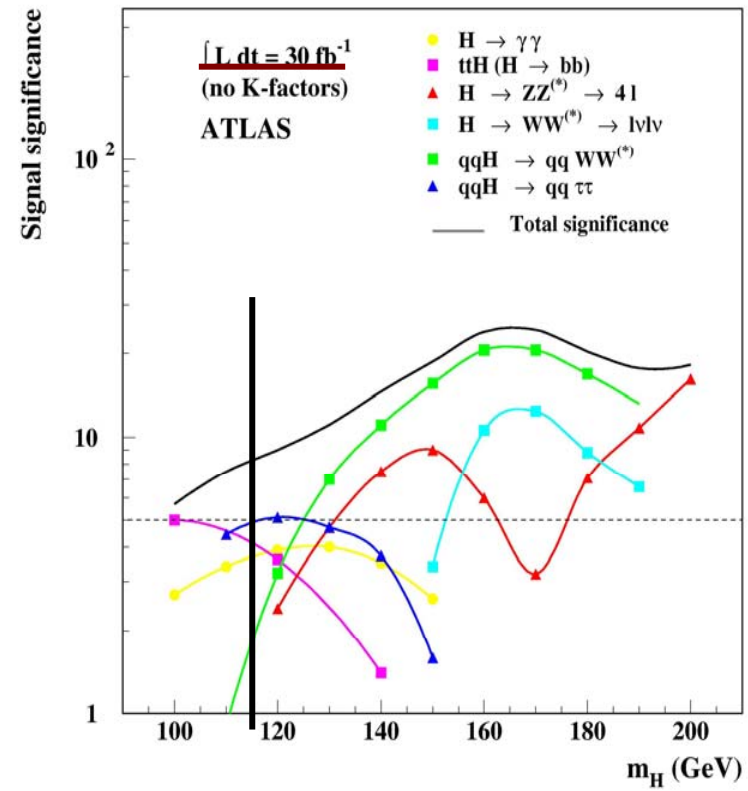
-- measure backgrounds to New Physics : e.g. tt and W/Z+ jets (omnipresent …)
-- look at specific "control samples" for the individual channels:
e.g. ttjj with $j \neq b$ "calibrates" ttbb irreducible background to ttH → ttbb

- Look for New Physics potentially accessible in first year (e.g. SUSY, …)

Note: if m_H < 120 GeV : fast Higgs discovery may be crucial in case of competition with Tevatron
This may be the most difficult physics goal for first year …

Standard Model Higgs





$m_H \sim 115$ GeV 10 fb^{-1}

ATLAS	$H \to \gamma\gamma$	$ttH \to ttbb$	$qqH \to qq\tau\tau$ ($\ell\ell$ + ℓ-had)
S	130	15	~ 10
B	4300	45	~ 10
S/ √B	2.0	2.2	~ 2.7

$$\text{total} \quad S/\sqrt{B} \approx 4^{+2.2}_{-1.3}$$

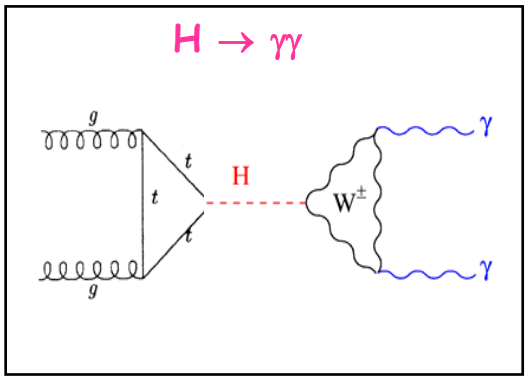
$$K-\text{factor} \equiv \frac{\sigma_{NLO}}{\sigma_{LO}} \approx 2 \quad \text{not included}$$

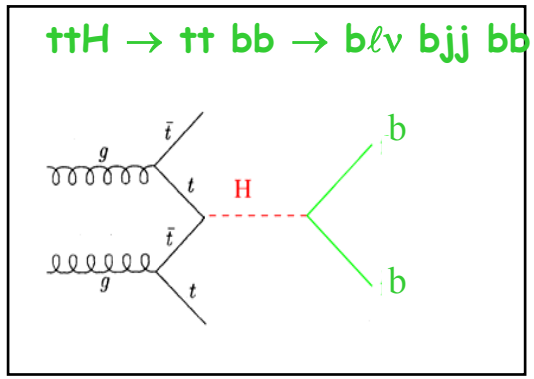
Full GEANT simulation, simple cut-based analyses

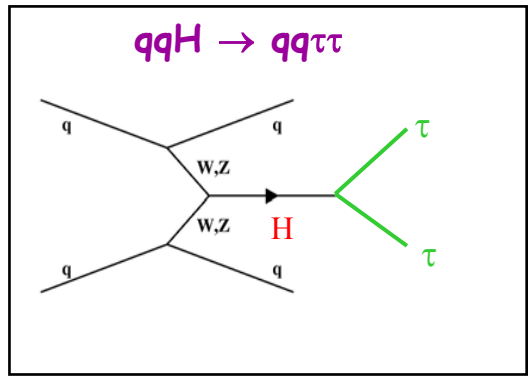
Remarks:

Each channel contributes ~ 2σ to total significance → observation of all channels important to extract convincing signal in first year(s)

The 3 channels are complementary → robustness:







- different production and decay modes
- different backgrounds
- different detector/performance requirements:
  - -- ECAL crucial for $H \to \gamma\gamma$ (in particular response uniformity) : $\sigma/m \sim 1\%$ needed
  - -- b-tagging crucial for ttH : 4 b-tagged jets needed to reduce combinatorics
  - -- efficient jet reconstruction over $|\eta| < 5$ crucial for $qqH \to qq\tau\tau$:
    forward jet tag and central jet veto needed against background

Note : -- all require "low" trigger thresholds

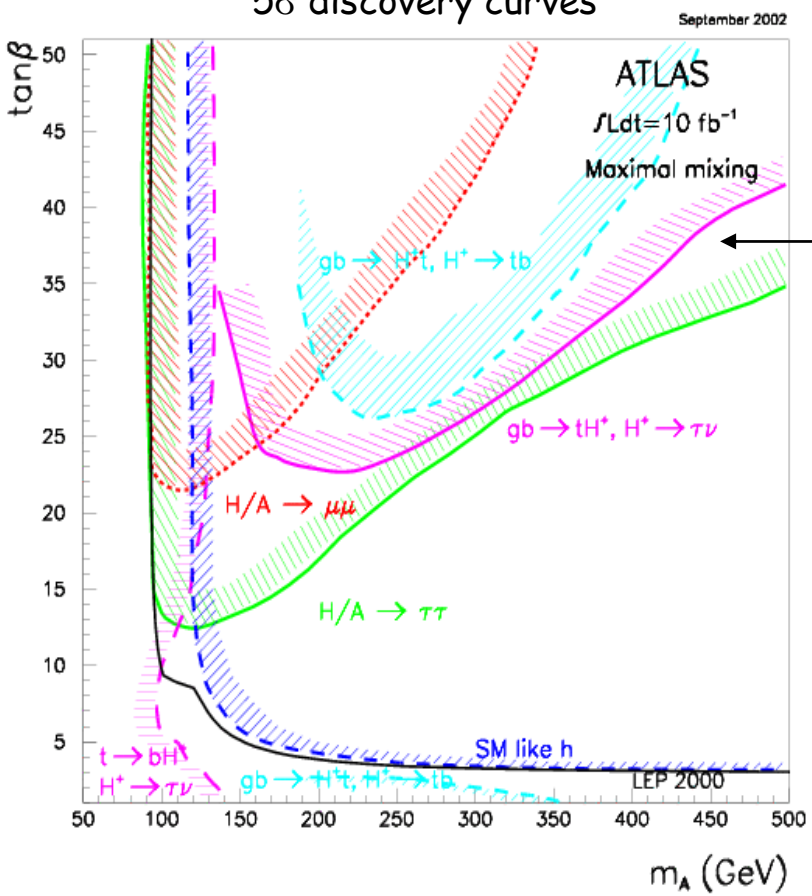
E.g. ttH analysis cuts : $p_T(\ell) > 20$ GeV, p_T (jets) > 15-30 GeV

-- all require very good understanding (1-10%) of backgrounds

MSSM Higgs bosons h, H, A,

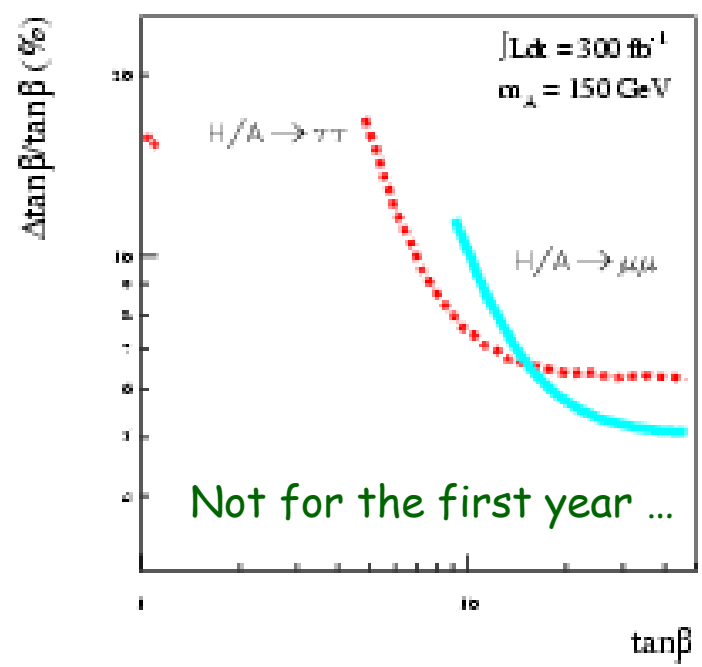
$m_h < 135$ GeV
$m_A \approx m_H \approx m_{H\pm}$ at large m_A

5σ discovery curves



-- A, H, $H^\pm$ cross-section ~ $tg^2\beta$
-- best sensitivity from $A/H \to \tau\tau$, $H^\pm \to \tau\nu$
(not easy the first year …)
-- $A/H \to \mu\mu$ experimentally easier
(esp. at the beginning)

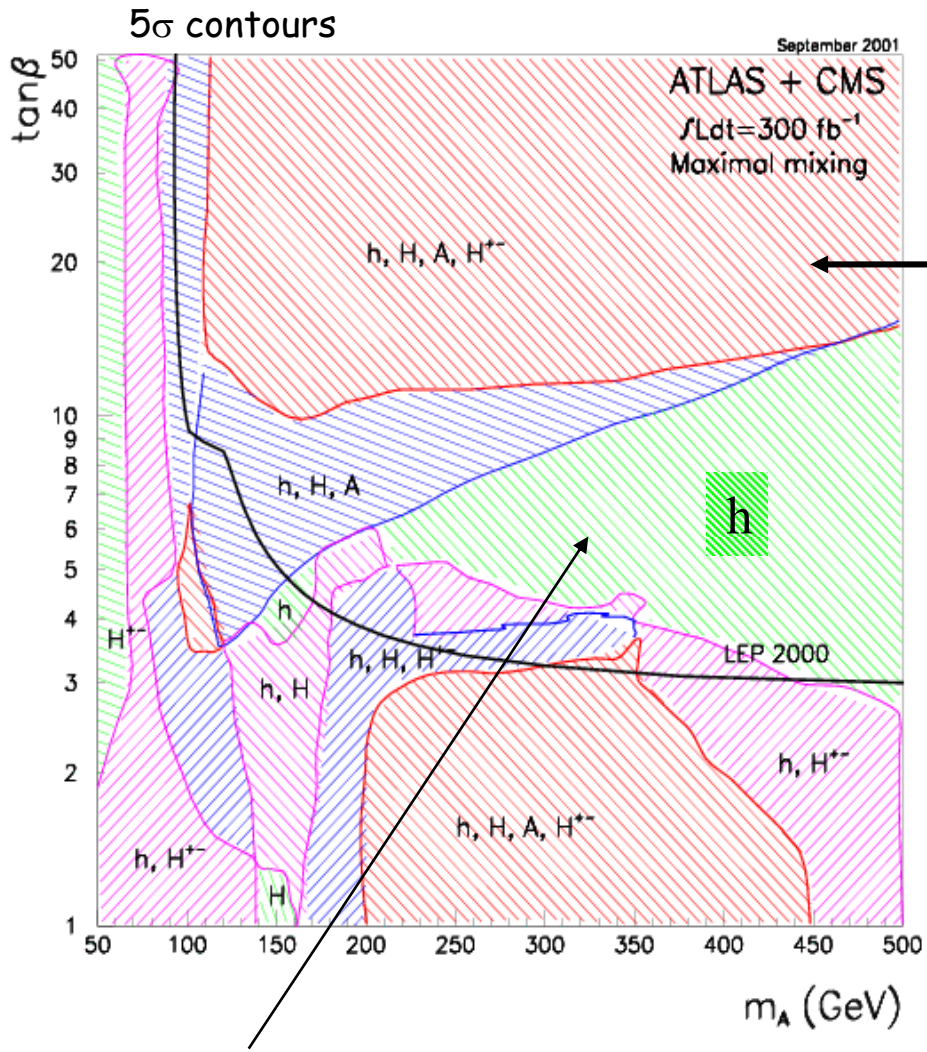
Measurement of tg β



Not for the first year …

- Large variety of channels and signatures accessible
- bbA/H → 4b is more difficult than at the Tevatron
(because of huge QCD background)

After several years ....



$H, A \to \mu\mu, \tau\tau$
$H^{\pm} \to \tau\nu$, tb

- 4 Higgs observable
- 3 Higgs observable
- 2 Higgs observable
- 1 Higgs observable

Assuming decays to SM particles only

Here only h (SM - like) observable at LHC, unless A, H, $H^{\pm} \to$ SUSY

$\to$ LHC may miss part of the MSSM Higgs spectrum

Observation of full spectrum may require high-E ($\sqrt{s} \approx 2$ TeV) Lepton Collider

SUPERSYMMETRY (SUSY) ≡ symmetry between fermions (matter) and bosons (forces)

- All SM particles p have SUSY partner $\tilde{p}$ with same couplings and quantum numbers except $\mathrm{spin}(\tilde{p}) = \mathrm{spin}(p) - 1/2$

SM particle	SUSY partner	spin
ℓ	sleptons $\tilde{\ell}$	0
q	squarks $\tilde{q}$	0
g	gluino $\tilde{g}$	1/2
$W^{\pm}$ (+Higgs)	charginos $\chi^{\pm}_{1,2}$	1/2
γ, Z (+Higgs)	neutralinos $\chi^{0}_{1,2,3,4}$	1/2

Particle spectrum in minimal models (MSSM)

+ 5 Higgs : h, H, A, $H^{\pm}$

$m_h < 135$ GeV

- R-Parity (multiplicative quantum number) = + 1 (-1) SM (SUSY) particles

If conserved : -- SUSY particles produced in pairs

-- Lightest Supersymmetric Particle (LSP) is stable

LSP ≡ χ^0_1 weakly interacting → dark matter candidate

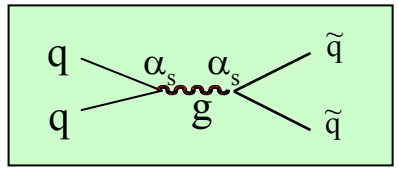
-- all SUSY particles decay to LSP

- Motivations : unification matter-forces/fermions-bosons is beautiful; allows incorporation of gravity; can stabilize Higgs mass; allows unification of forces at GUT scale; provides candidate for cold dark matter; not ruled out by present data; predicts light Higgs as favoured by data, etc.

SUSY searches at LHC

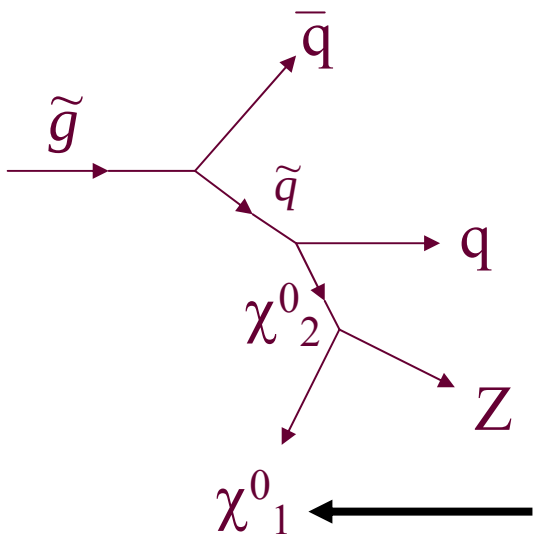
- Dominant processes : $\tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ production
  strong production → huge cross-section

e.g.



e.g. for $m(\tilde{q}, \tilde{g}) \sim 1$ TeV ~ 10^4 events produced in one year at low L

- $\tilde{q}, \tilde{g}$ heavy → cascade decays



→ spectacular signatures with many jets, leptons + missing E

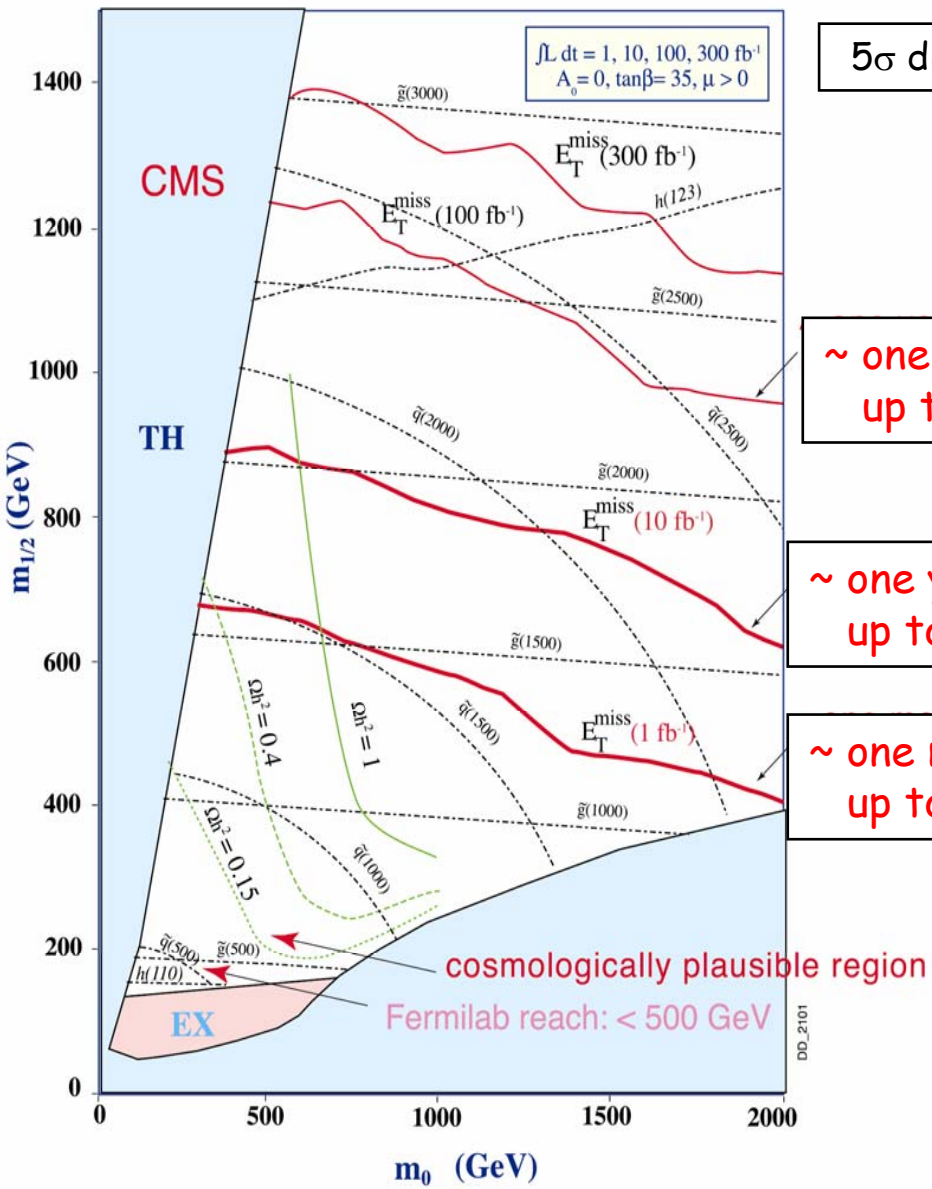
→ easy to extract SUSY signal from SM backgrounds at LHC

weakly interacting → not detected
→ missing energy in final state

SUPERSYMMETRY

Large $\tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ cross-section → ≈ 100 events/day at 10^{33} for $m(\tilde{q}, \tilde{g}) \sim 1$ TeV

→ SUSY could be found quickly



5σ discovery curves

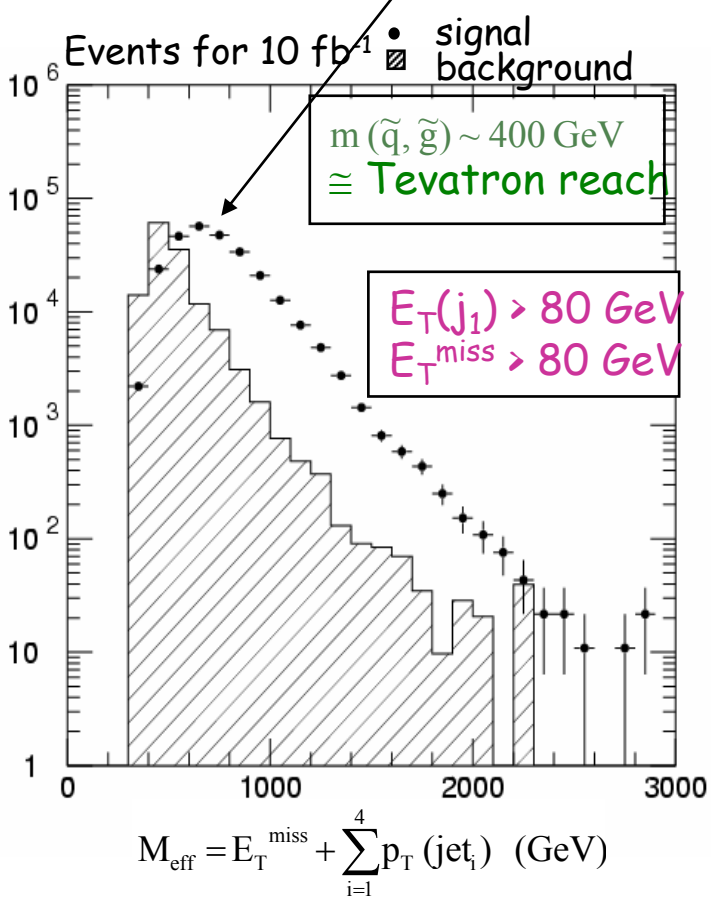
~ one year at 10^{34}: up to 2.8 TeV

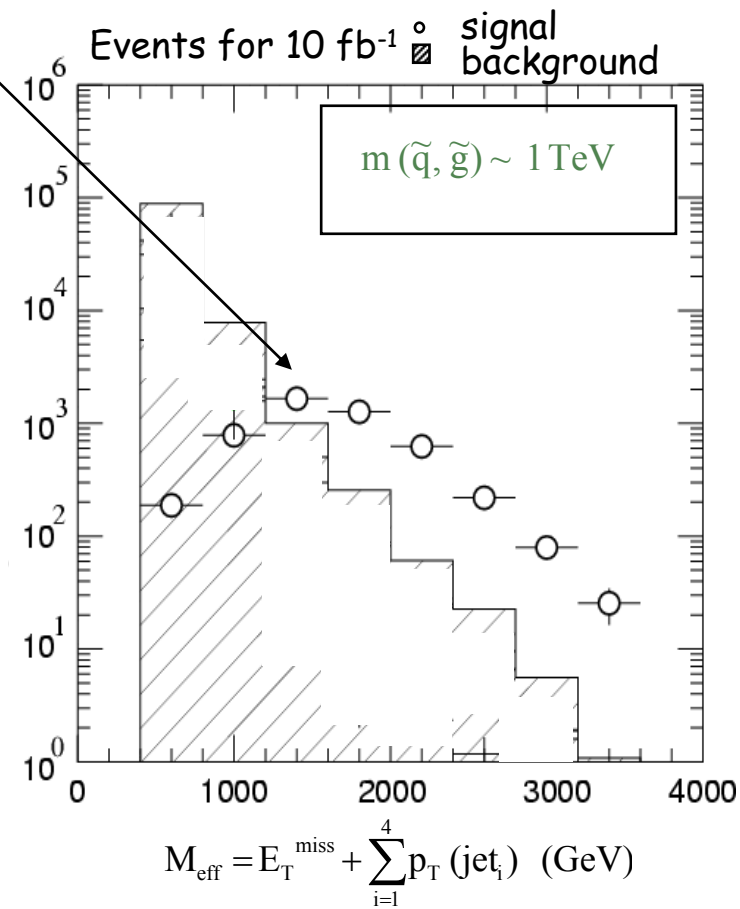
~ one year at 10^{33} : up to 2.3 TeV

~ one month at 10^{33} : up to 2 TeV

Multijet + E_T^{miss} (most powerful and model-independent signature if R-parity conserved)

Peak position correlated to $M_{SUSY} \equiv \min(m(\tilde{q}), m(\tilde{g}))$





ATLAS

From M_{eff} peak, first/fast measurement of SUSY mass scale to ≈ 20% (10 fb^{-1}, mSUGRA)

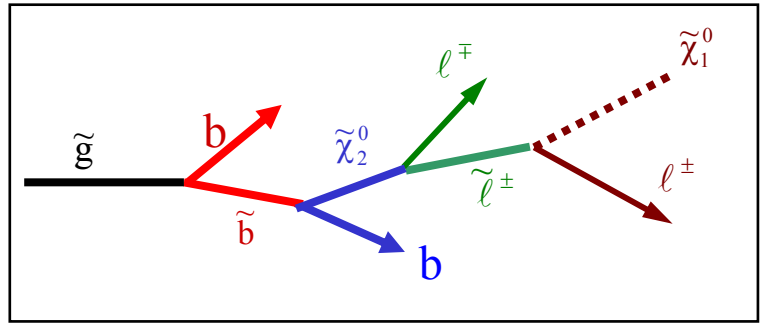
Detector/performance requirements:

-- calorimeter coverage and hermeticity for $|\eta|<5$

-- calorimeter energy scale calibration to ~5%

-- "low" Jet+E_T^{miss} trigger thresholds for low masses at overlap with Tevatron region (~400 Ge

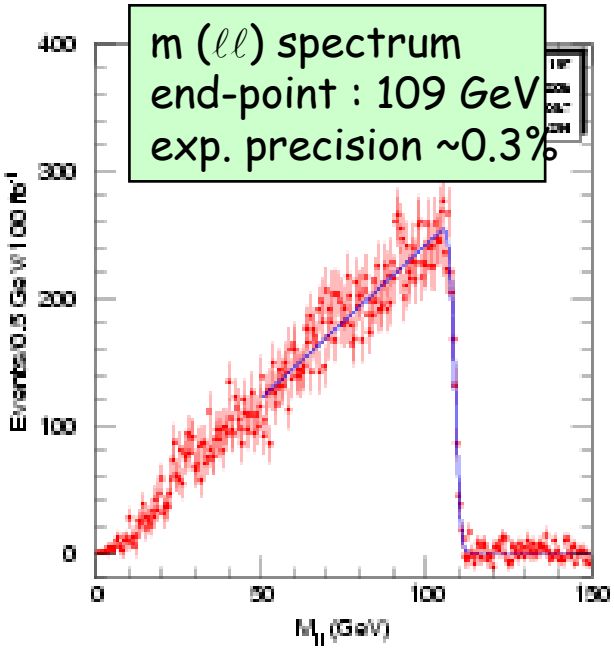
With more time and data:
precise SUSY measurements
(not for the first year ....)



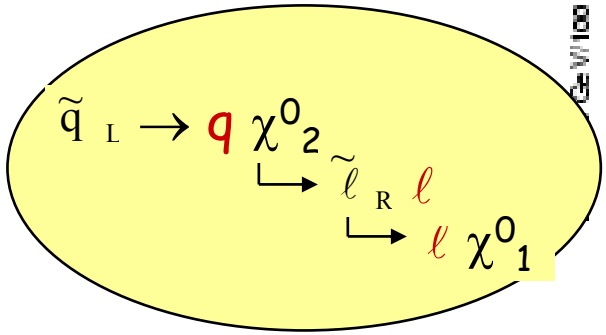
- ATLAS and CMS should be able to perform precise measurements of SUSY final state → determine sparticle masses and fundamental parameters of theory with precision ≈ 10% or better in many cases (at least in minimal models)
- Method: measure end-points of reconstructed mass spectra at each step of (long) squark/gluino decay chains. End-points depend only on involved masses only (pure kinematics ....) → "model-independent" measurements
- LSP is not directly observable but its mass can be constrained indirectly from other measurements in final state → constraints on cold dark matter

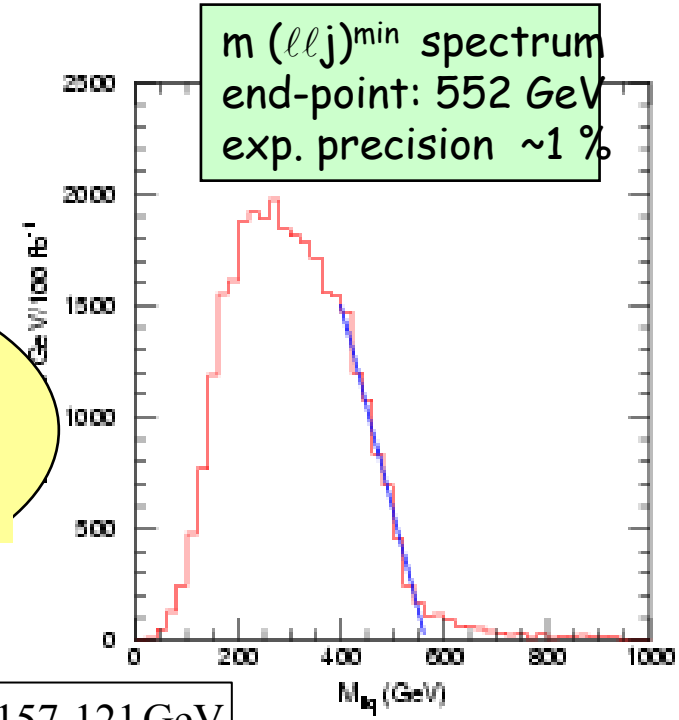
Ex. : LHC "Point 5" :

$$m(\tilde{q}) \sim 700\ \mathrm{GeV}$$
$$m(\tilde{g}) \sim 800\ \mathrm{GeV}$$
$$m(\chi^0{}_1) \sim 120\ \mathrm{GeV}$$

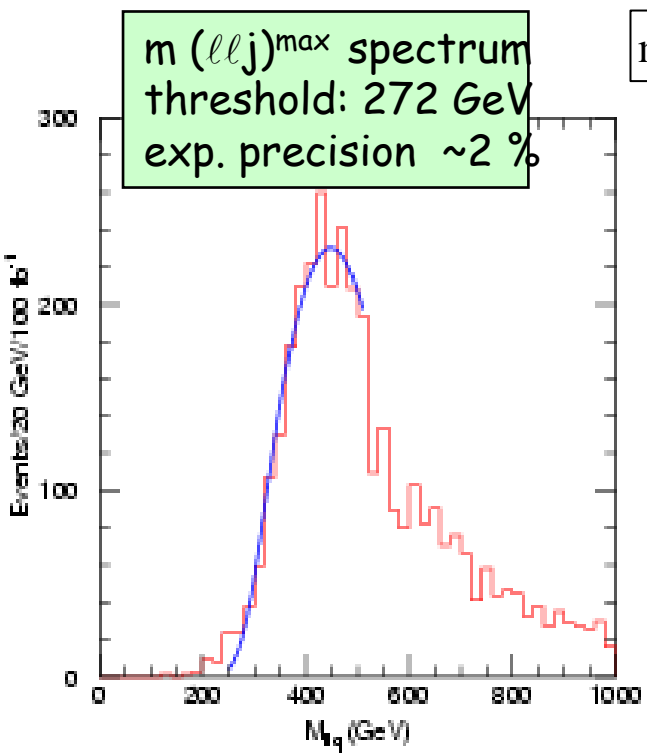


Example of
a typical chain:

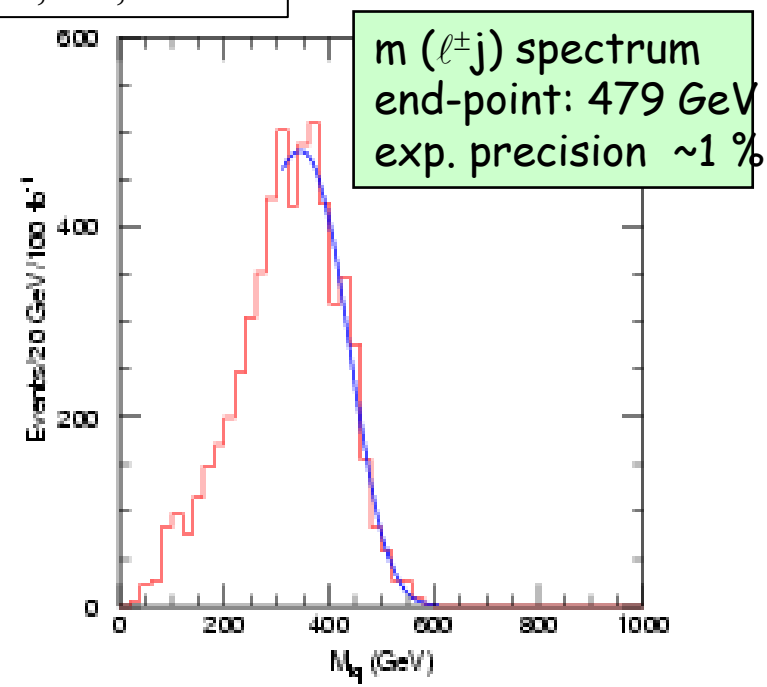




$$m(\tilde{q}_L, \chi^0_2, \tilde{\ell}_R, \chi^0_1) = 690, 232, 157, 121\ \text{GeV}$$



ATLAS
100 fb^{-1}
LHC Point 5



Putting all constraints together:

$\tilde{q}_L \rightarrow q\, \chi^0_2$

$\chi^0_2 \rightarrow h\, \chi^0_1$

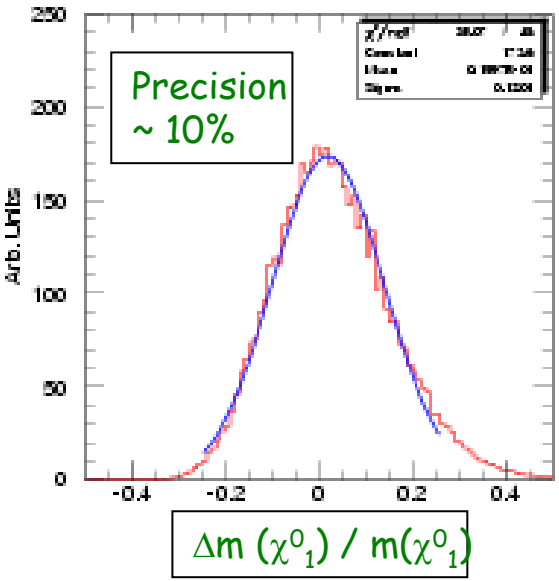
$h \rightarrow bb$

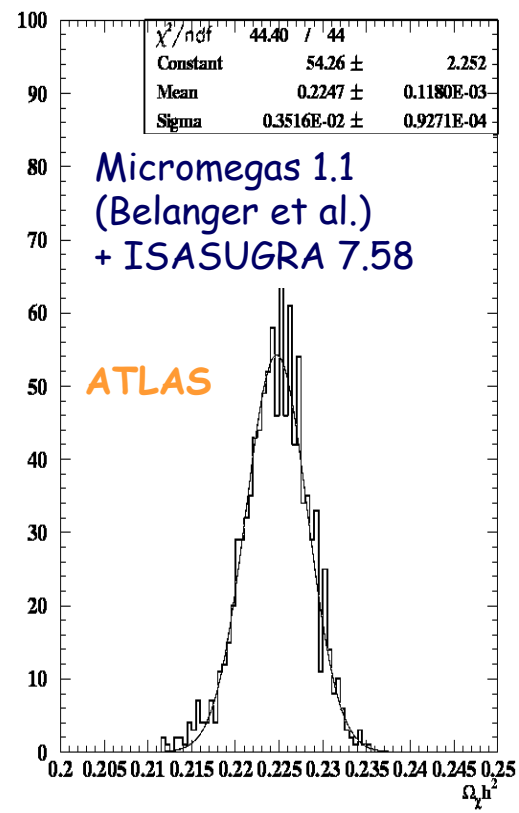
$\chi^0_2 \rightarrow \tilde{\ell}_R\, \ell$

$\tilde{\ell}_R \rightarrow \ell\, \chi^0_1$

m (bbj), m($\ell\ell$), m($\ell\ell$j)^{max}, m($\ell\ell$j)^{min}, m(ℓj)

Sparticle mass	Expected precision 100 fb^{-1}
squark left	± 3%
χ^0_2	± 6%
slepton mass	± 9%
χ^0_1	± 12%





From fit of mSUGRA to all experimental measurements at Point 5 can deduce cold darm matter relic density:

$\Omega_\chi h^2 = 0.2247 \pm 0.0035$

Conclusions

- LHC offers an impressive physics programme right from the beginning.
  Event statistics : 1 day at LHC at 10^{33} $\equiv$ 10 years at previous machines in some cases
  Machine luminosity/detector performance will be the crucial issue for 'fast' discoveries

- Detector construction is progressing well, although few items are on critical path

- Lot of emphasis on test beams (individual sub-detectors, several sub-detectors together) and on construction quality checks → results indicate that the detectors "as built" should give a good starting-point performance.

- However, data (and time …) will be needed at the beginning to:
  -- commission the detector and trigger in situ
  -- reach the performance needed to optimize the physics potential
  -- understand standard physics at $\sqrt{s}$ = 14 TeV and compare to MC predictions
  -- measure backgrounds to possible New Physics

- SUSY may be discovered "quickly", light Higgs more difficult … and what about surprises ?

- Contributions from Tevatron studies and data will be very important, especially in the initial phase to reach quickly the "discovery mode" and extract a convincing "early" signal