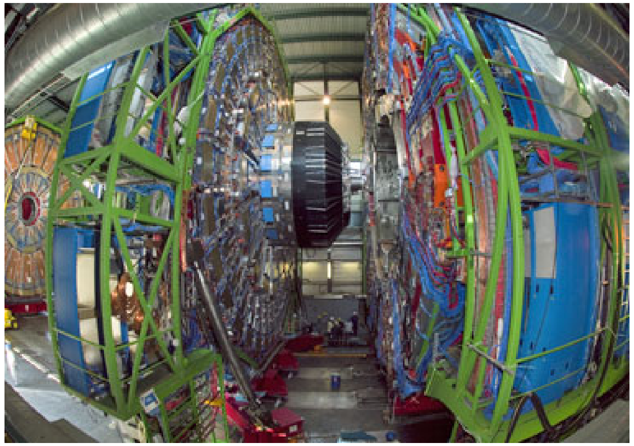
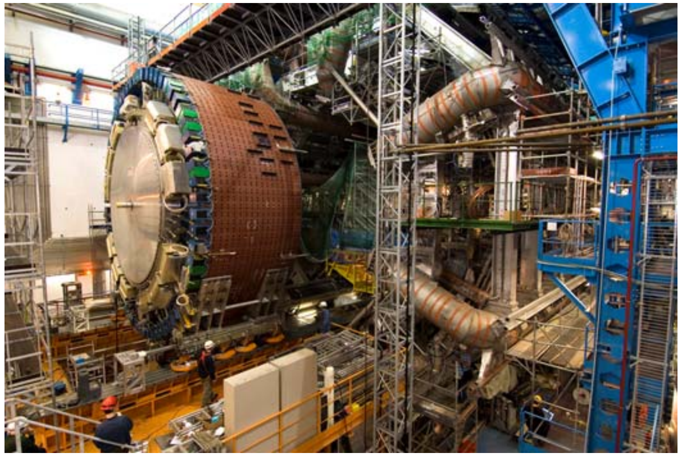
The LHC: Machine, Detectors and the Quest for New Physics

RTN Winter School 15-19 January 2007

Albert De Roeck
CERN



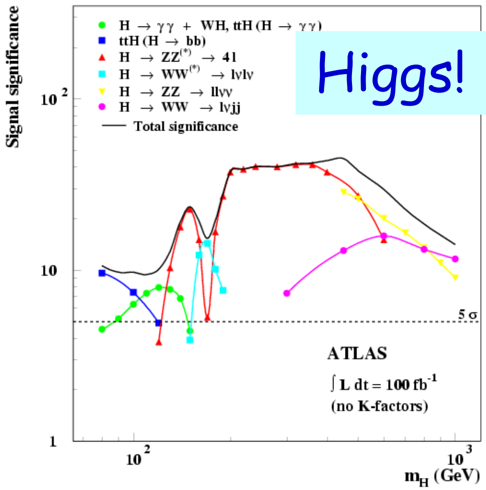


Contents

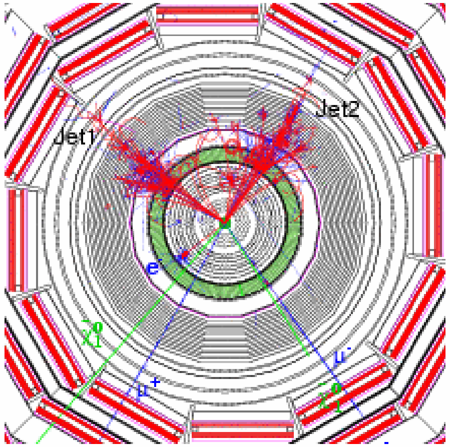
- Introduction
- The Large Hadron Collider (LHC)
- Experiments at the LHC
- The Quest for New Particles and New Physics
  - The Higgs Boson
  - Supersymmetry
  - Other scenarios of New Physics
- Summary

Preparing for a visit to the machine, CMS and LHCb

Physics at the LHC: pp @ 14 TeV

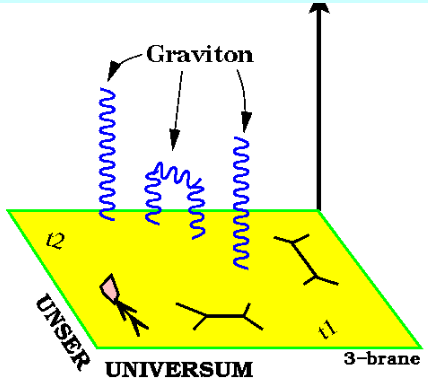


Higgs!

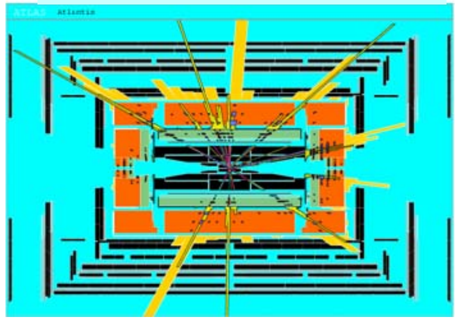


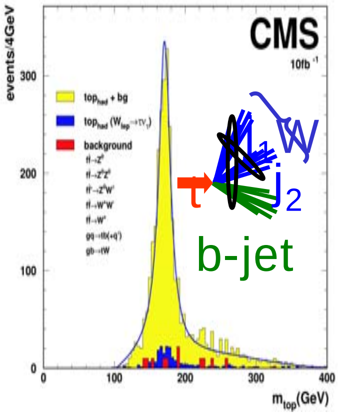
Supersymmetry?

Extra Dimensions?

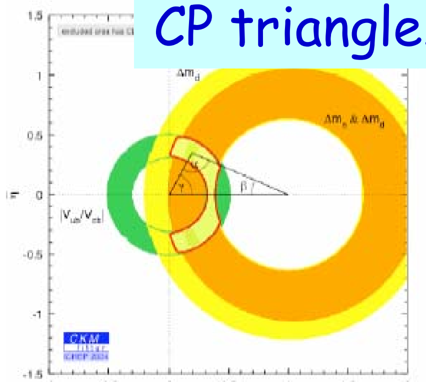


Black Holes???



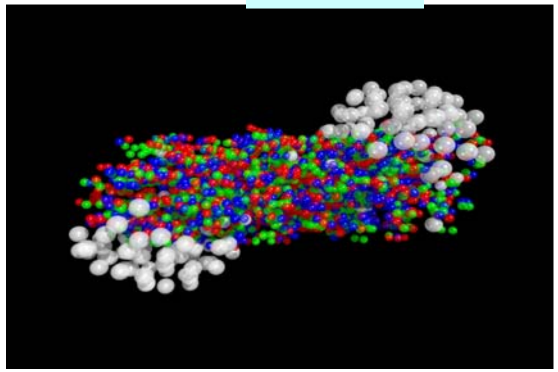


Precision measurements e.g top!



CP triangle!

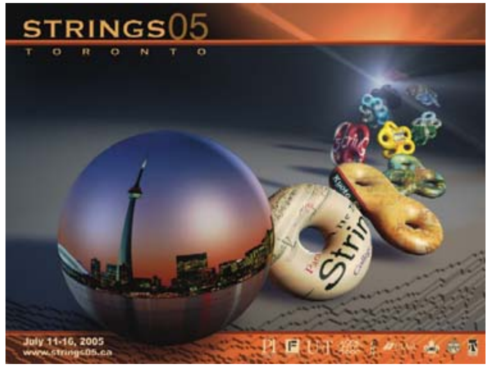
QGP?



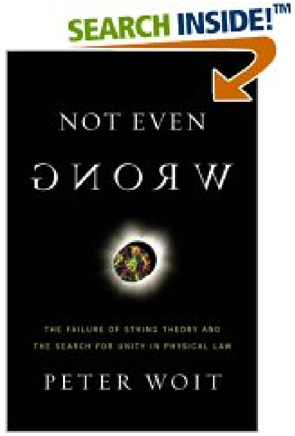
- LHC will explore directly the highly-motivated TeV-scale and say the final word about the SM Higgs mechanism and many TeV-scale New Physics predictions
- Will LHC show first hints for strings? Supersymmetry, Extra Dimensions…?

Preamble: String Theory & Particle Physics

Found on a Blog, discussing the program of STRINGS05
"The only talks related to particle physics & strings are Arkani-Hamed's and De Roeck's. De Roeck isn't even a string theorist and presumably will have nothing to say about string theory. Unless Arkani Hamed has figured out some way of using string theory to say what will happen at the LHC, his also won't be about string theory."

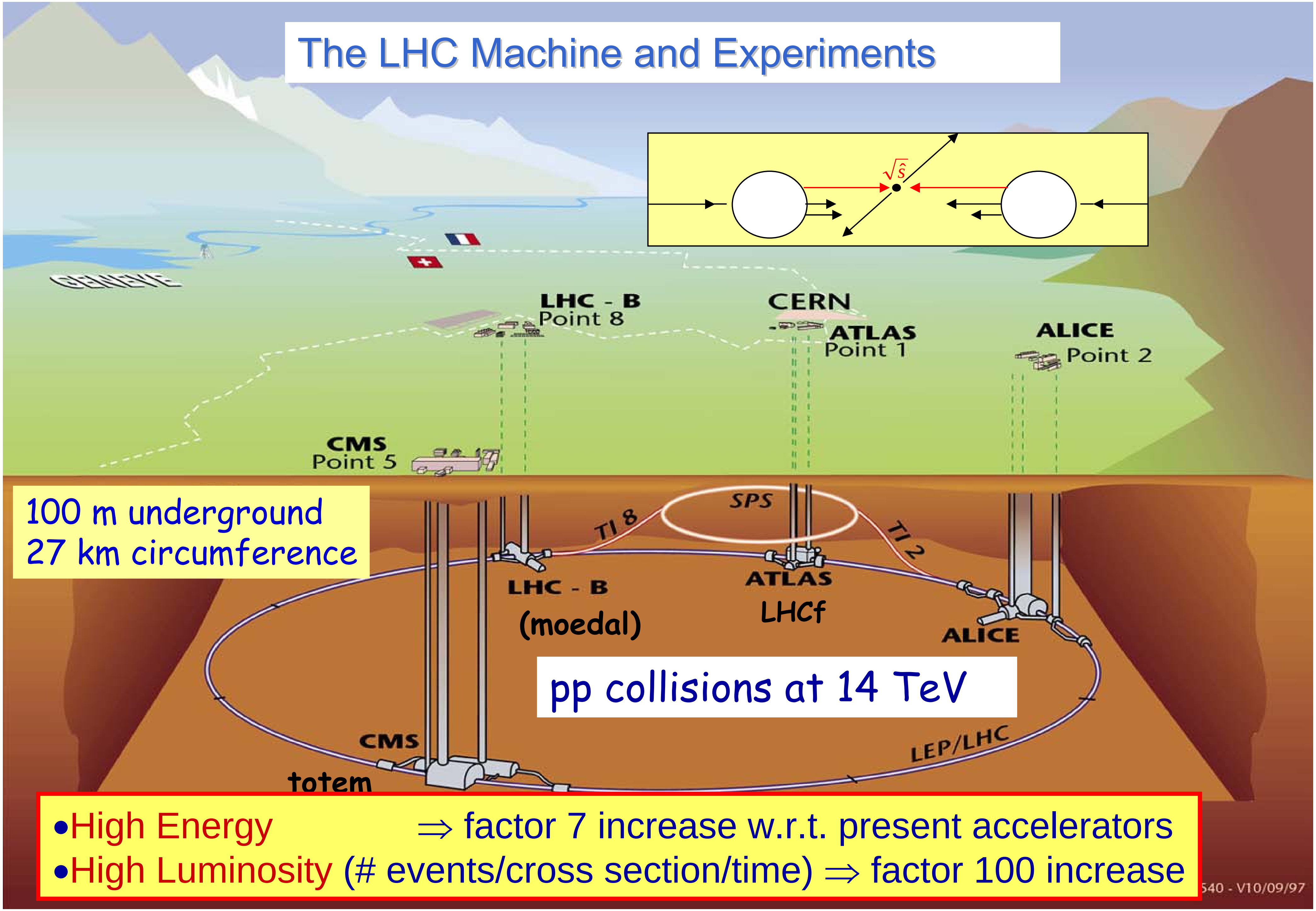


Peter Woit, author of



Lawrence Krauss (a Theorist & Star Trek Expert) writes (in 2006):
"I am optimistic that after almost 30 years of sensory deprivation in the field of particle physics, during which much hallucination has occurred by theorists, within 3 years, following the commissioning next year of the Large Hadron Collider in Geneva, we will finally obtain empirical data that will drive forward our understanding of the fundamental structure of nature, its forces, and of space and time."

The LHC Machine and Experiments



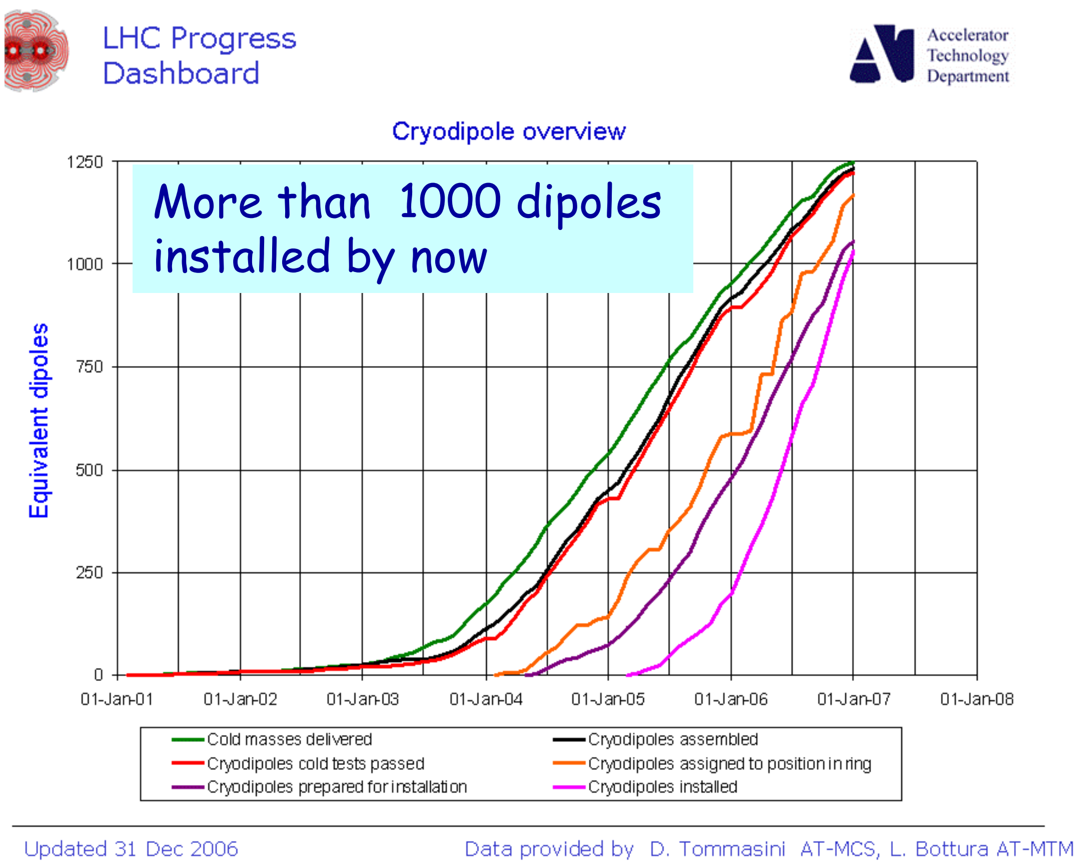
100 m underground
27 km circumference

pp collisions at 14 TeV

- High Energy $\Rightarrow$ factor 7 increase w.r.t. present accelerators
- High Luminosity (# events/cross section/time) $\Rightarrow$ factor 100 increase

The LHC Progress & Schedule

Crucial part: 1232 superconducting dipoles
Can follow progress on the LHC dashboard
http://lhc-new-homepage.web.cern.ch/lhc-new-homepage/



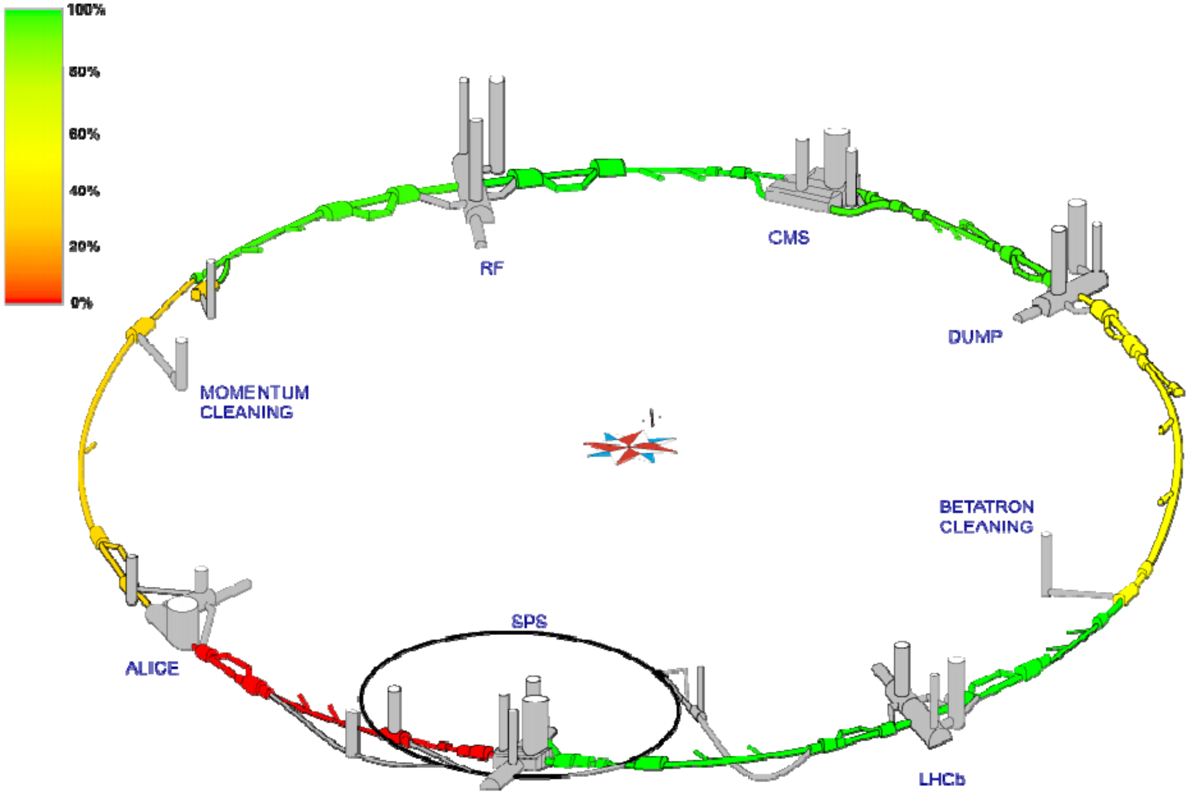
More than 1000 dipoles installed by now

The LHC Schedule(*)

- LHC will be closed and set up for beam on 1 September 2007
  - LHC commissioning will take time!
- First collisions expected in November/December 2007
  - A short pilot run
  - Collisions will be at injection energy ie cms of 0.9 TeV
- First physics run in 2008
  - ~ 0.1-1 fb^{-1}? 14TeV!
- Physics run in 2009 +…
  - $2 \bullet 10^{33}$ $cm^{-2}s^{-1} \Rightarrow 10^{34}$ $cm^{-2}s^{-1}$
  - 10-20 fb^{-1}/year $\Rightarrow$ 100 fb^{-1}/year

(*) eg. M. Lamont et al, September 2006.
Achtung! Lumi estimates are mine, not from the machine

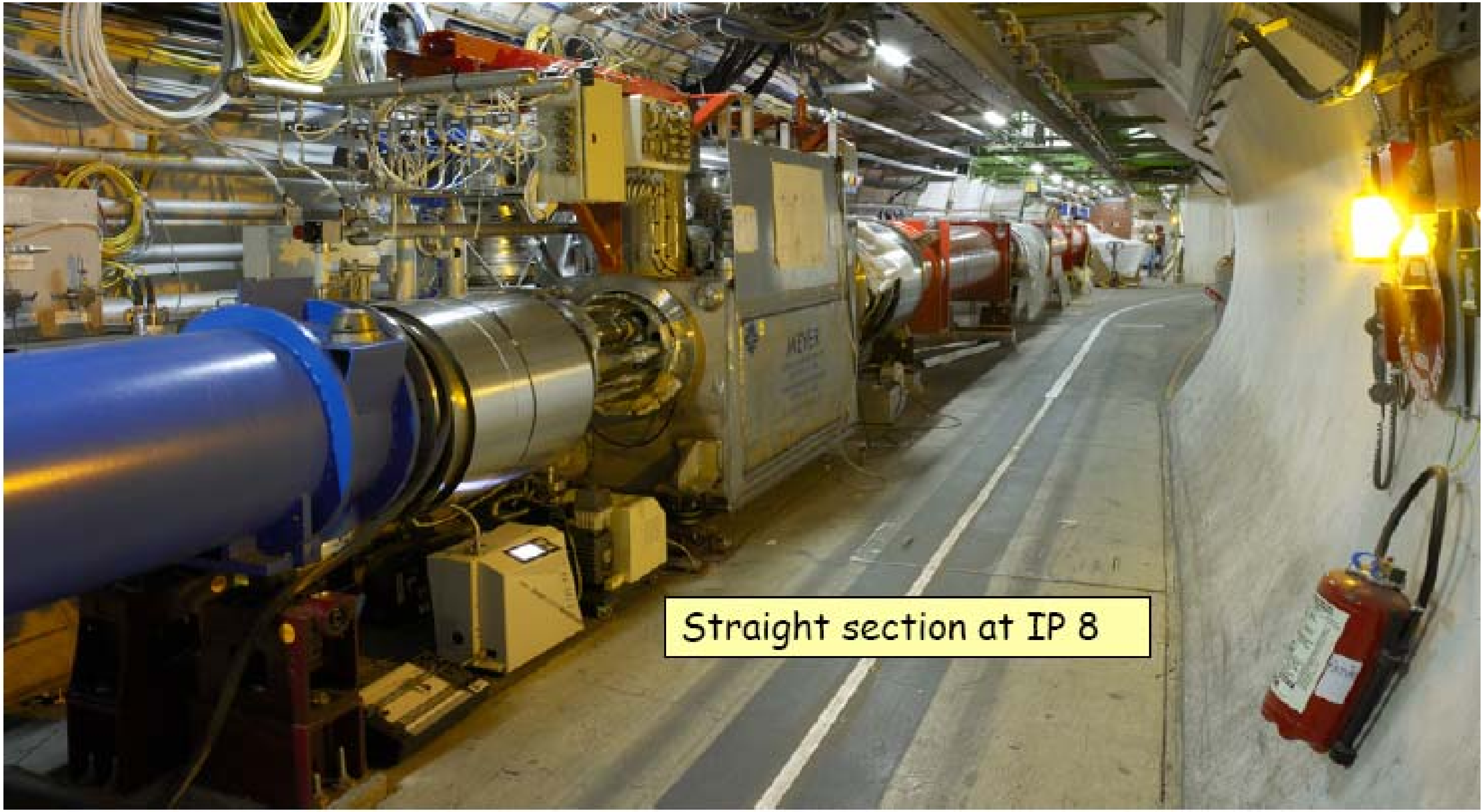
Magnet Installation Progress



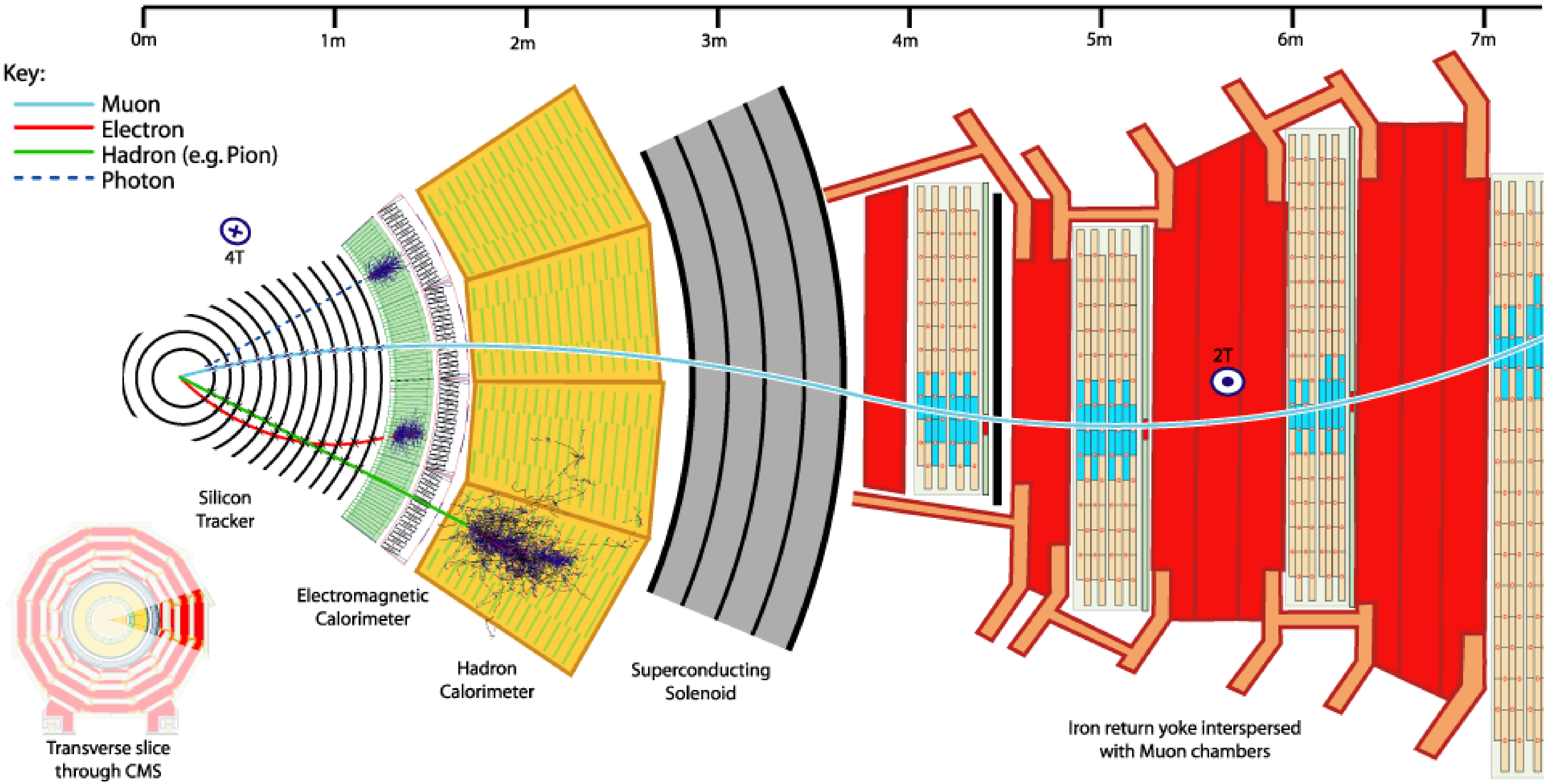
L. Evans: Presentation made to the Open Session of the LHC Machine Advisory Committee, 7 December 2006

Last magnet delivered	November 2006
Last magnet tested	January 2007
Last magnet installed	March 2007
Machine closed	August 2007
First collisions 450 GeV	November 2007
First Collisions 7 TeV	June 2008

LHC is more than just dipoles…

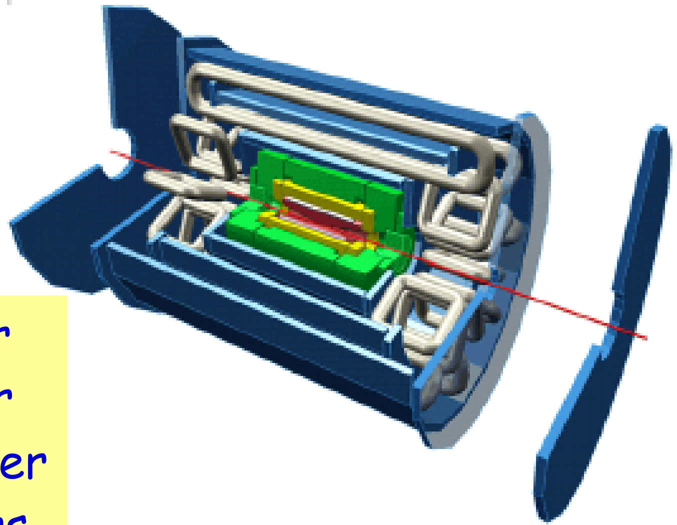


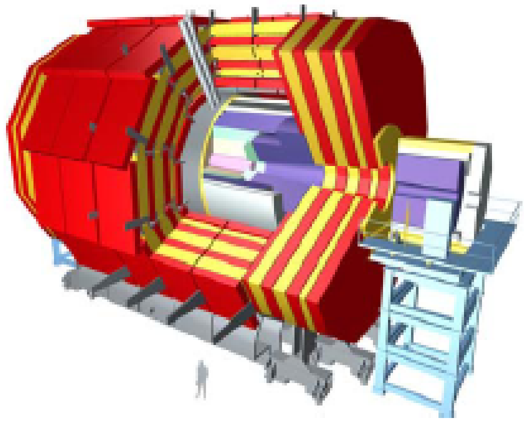
Particles in the detector



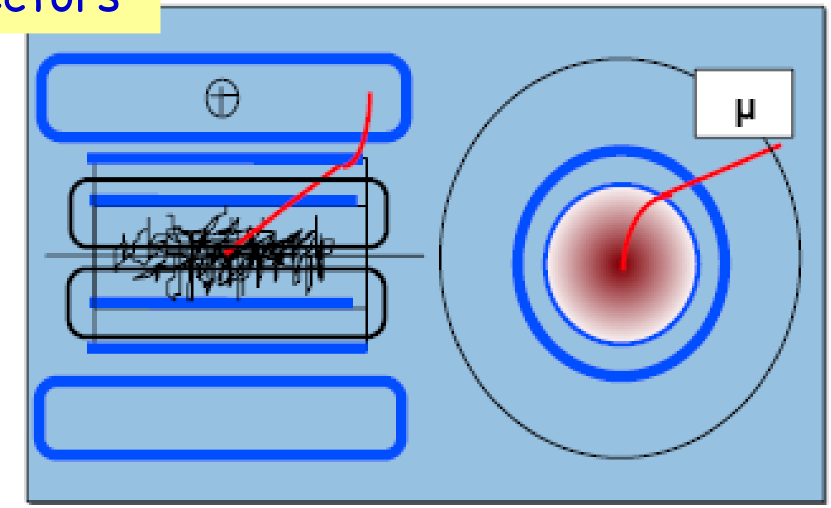
General Purpose Detectors at the LHC

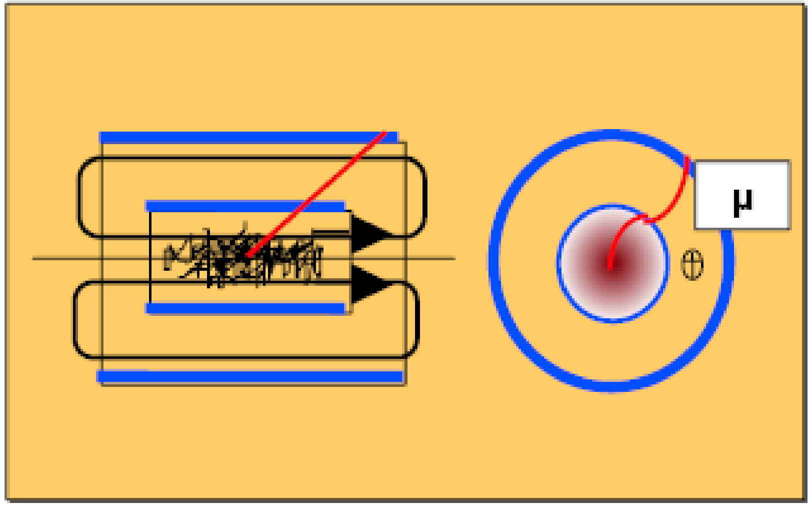
ATLAS A Toroidal LHC ApparatuS **CMS** Compact Muon Solenoid





- Central tracker
- EM calorimeter
- HAD calorimeter
- Muon Detectors





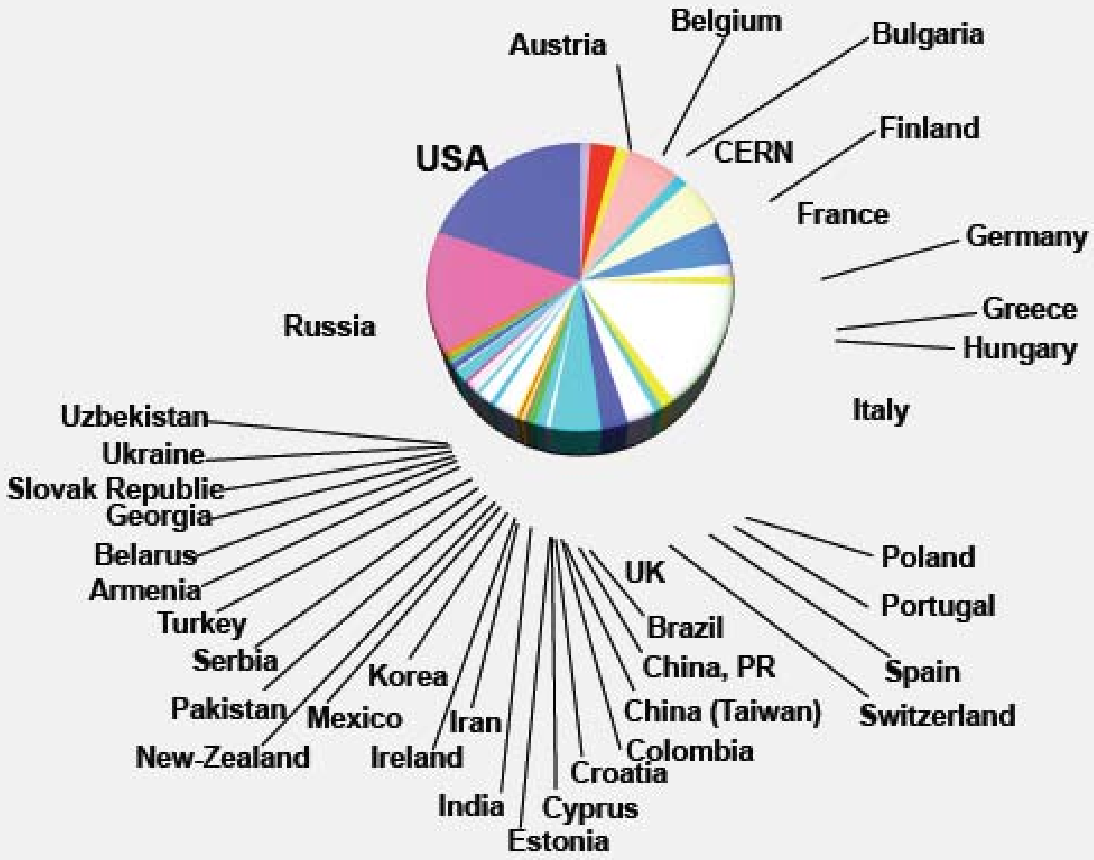
Trigger: Reduce 40 MHz collision rate to 100 Hz event rate to store for analysis

CMS Collaboration

	Institutions
Member States	61
Non-Mem. States	64
USA	49
Total	174

	Scientists
Member States	1055
Non-Mem. States	428
USA	547
Total	2030

Associated Institutes	
Number of Scientists	46
Number of Laboratories	8



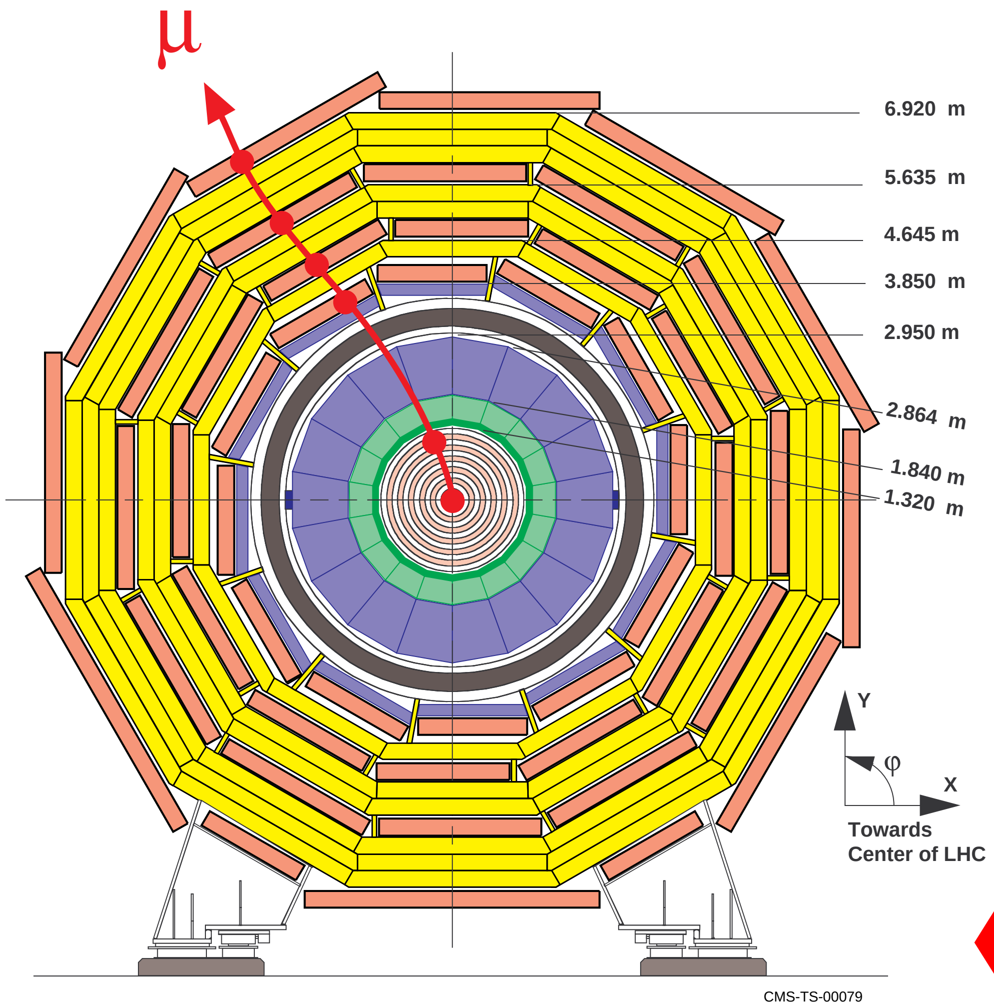
2030 Scientific Authors, 38 Countries, 174 Institutions

May, 04 2006/gm
http://cmsdoc.cern.ch/pictures/cmsorg/overview.html

Snapshot… numbers vary with time

Compact Muon Solenoid (CMS)

Letter of Intent (LOI): LHCC, TDR in 1994



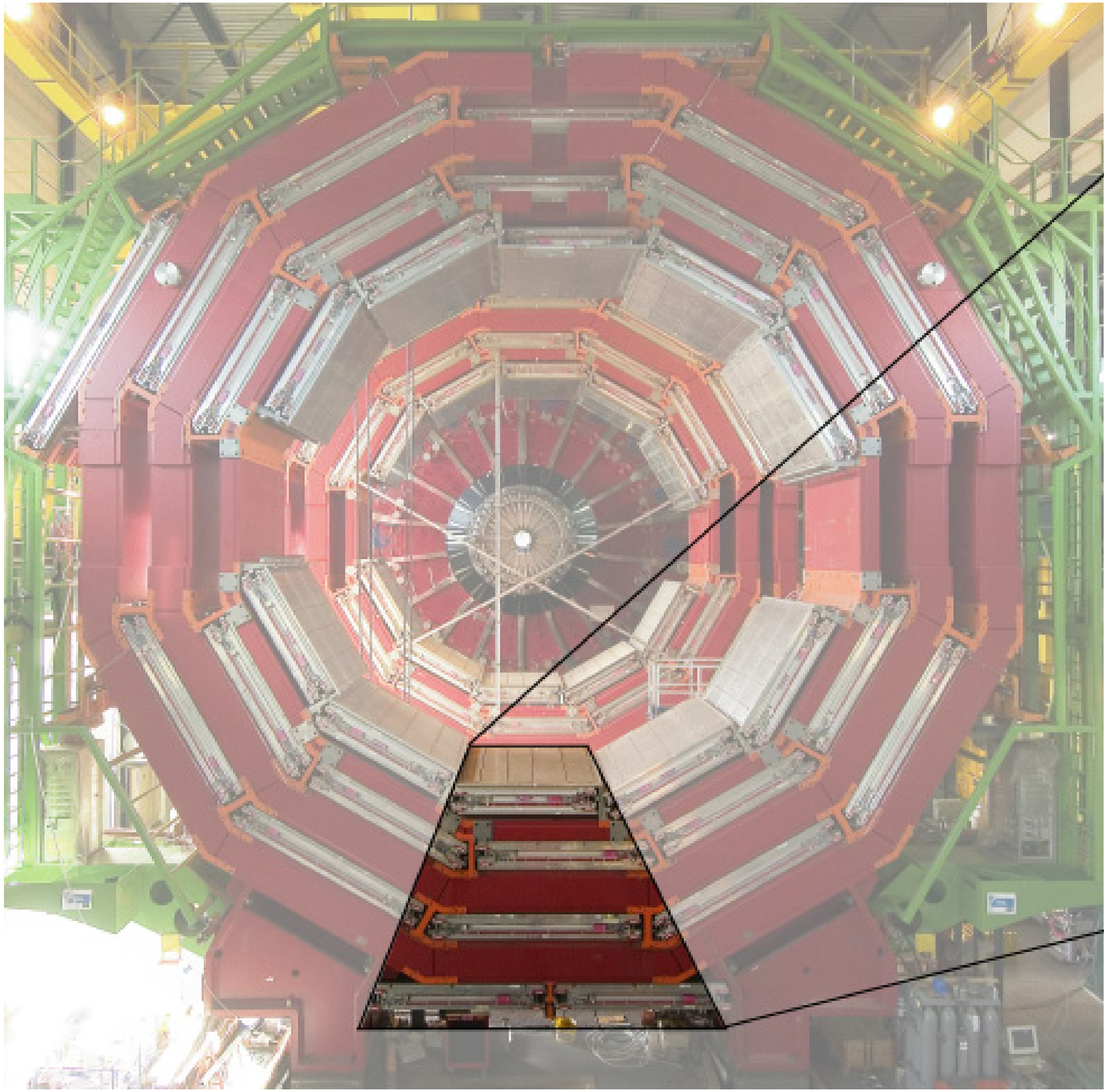
Transverse View

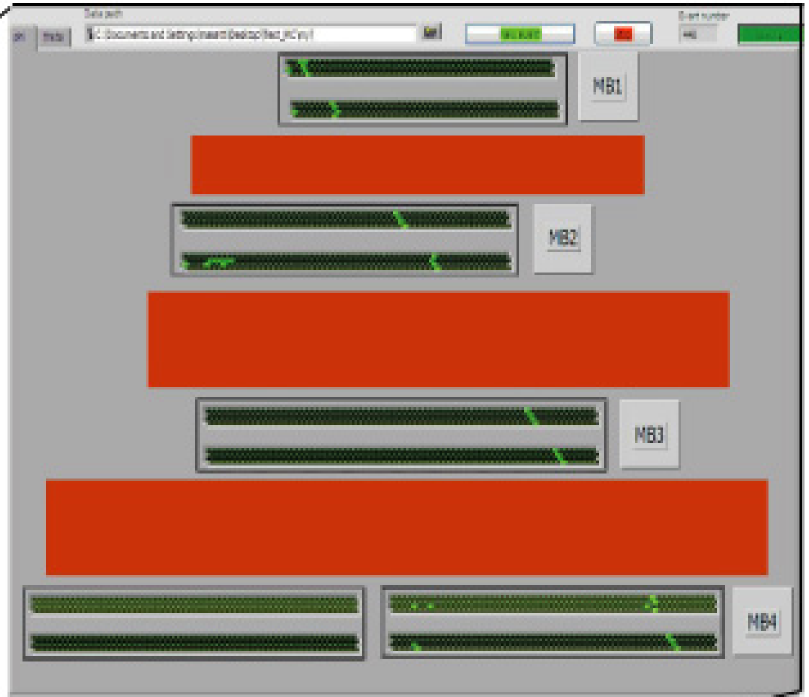
Design Priorities:

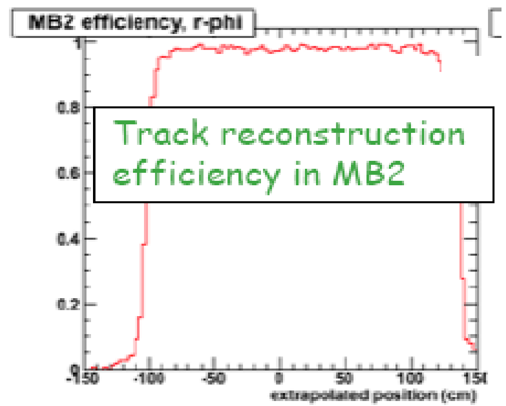
1. A robust and redundant Muon system
2. The best possible e/γ calorimeter consistent with 1.
3. A highly efficient Tracking system consistent with 1. and 2.
4. A hermetic calorimeter system.
5. A financially affordable detector.

- Strong Solenoid Field 4T
- Compact design

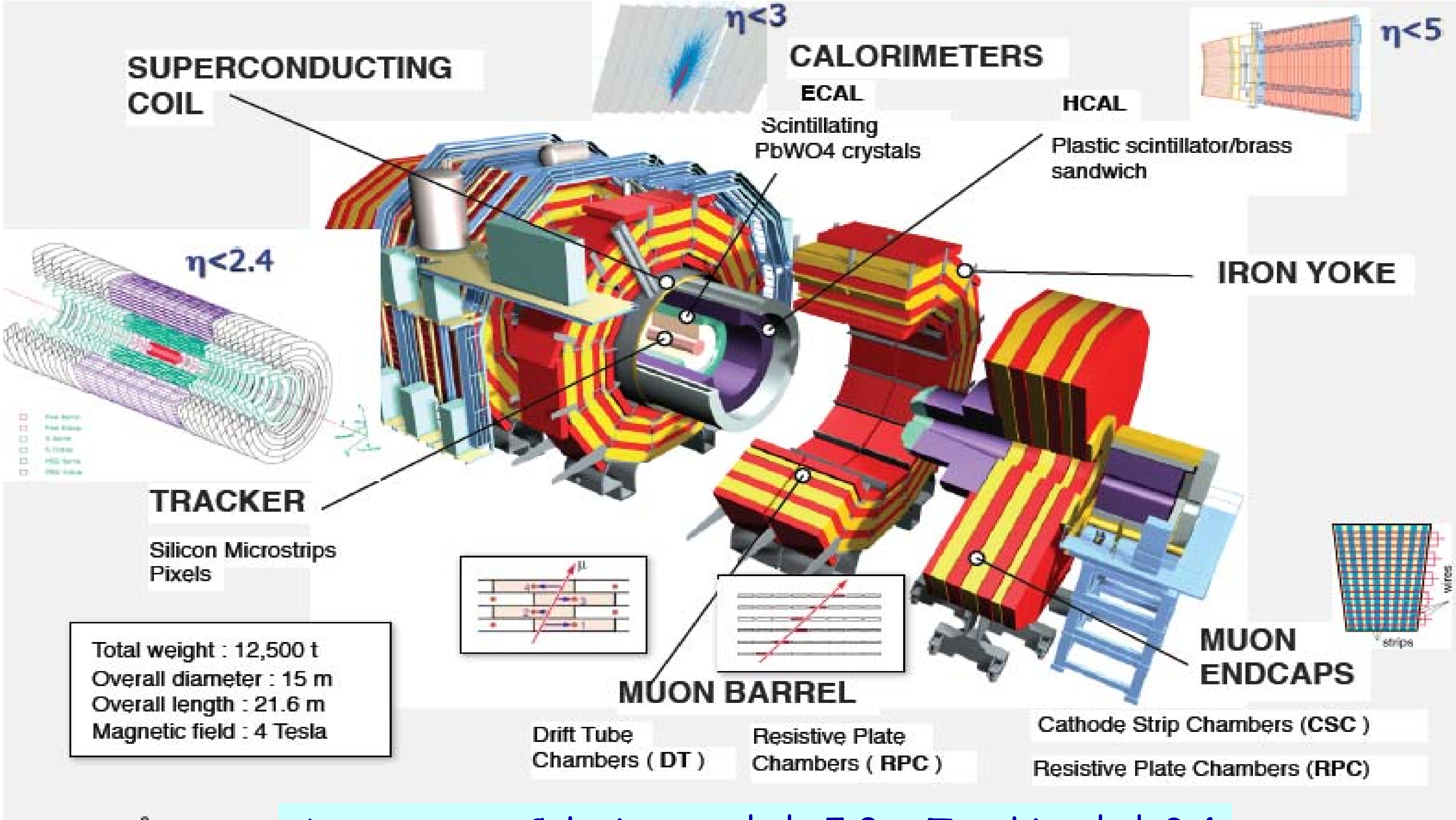
December 2005
Cosmic Muons in CMS



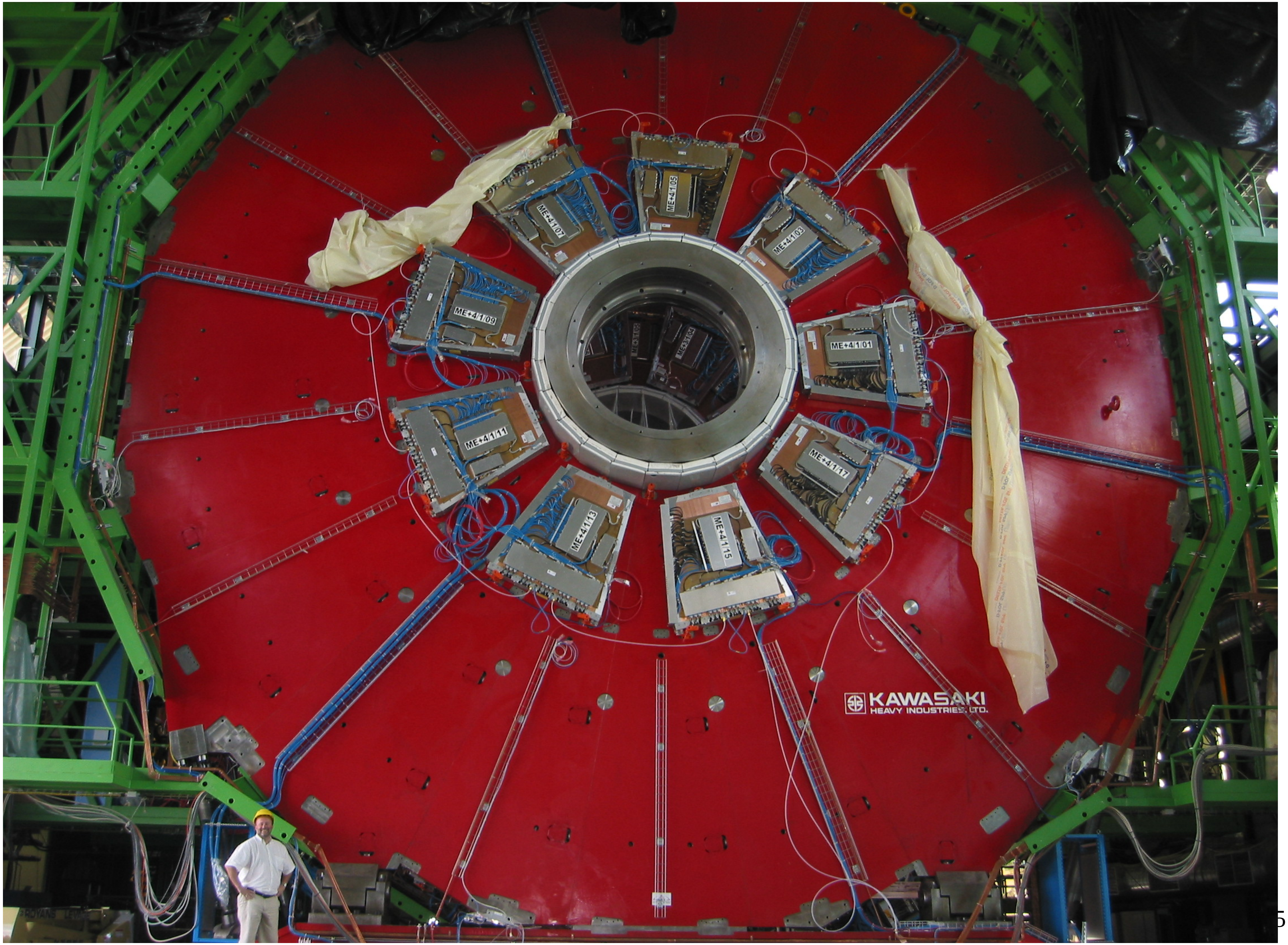




The Modular Design of CMS

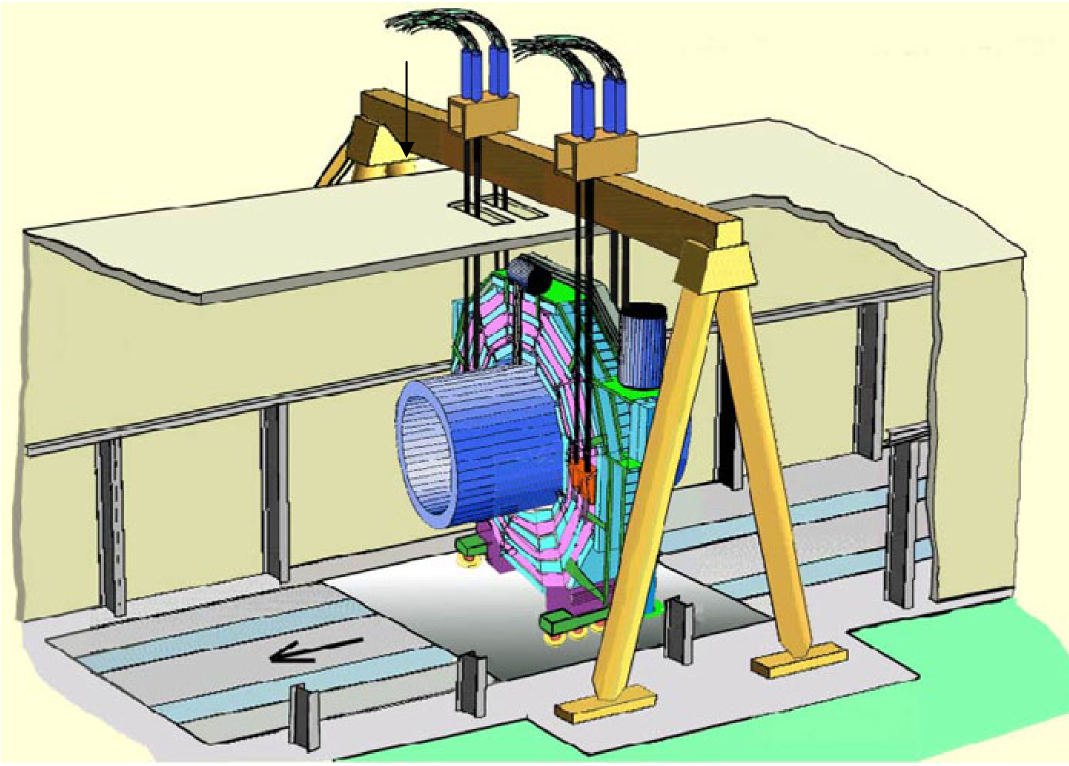


Acceptance: Calorimetry |η| <5.0   Tracking |η|<2.4


ME+4/1/05
ME+4/1/07
ME+4/1/03
ME+4/1/09
ME+4/1/01
ME+4/1/11
ME+4/1/17
ME+4/1/13
ME+4/1/15
KAWASAKI
HEAVY INDUSTRIES, LTD.

Transfer CMS Underground in 2006

Gantry installed over PX56
HF lowering: Started in Fall 2006



Next: endcaps and barrel wheels

Heavy lowering: CMS parts going 100m down

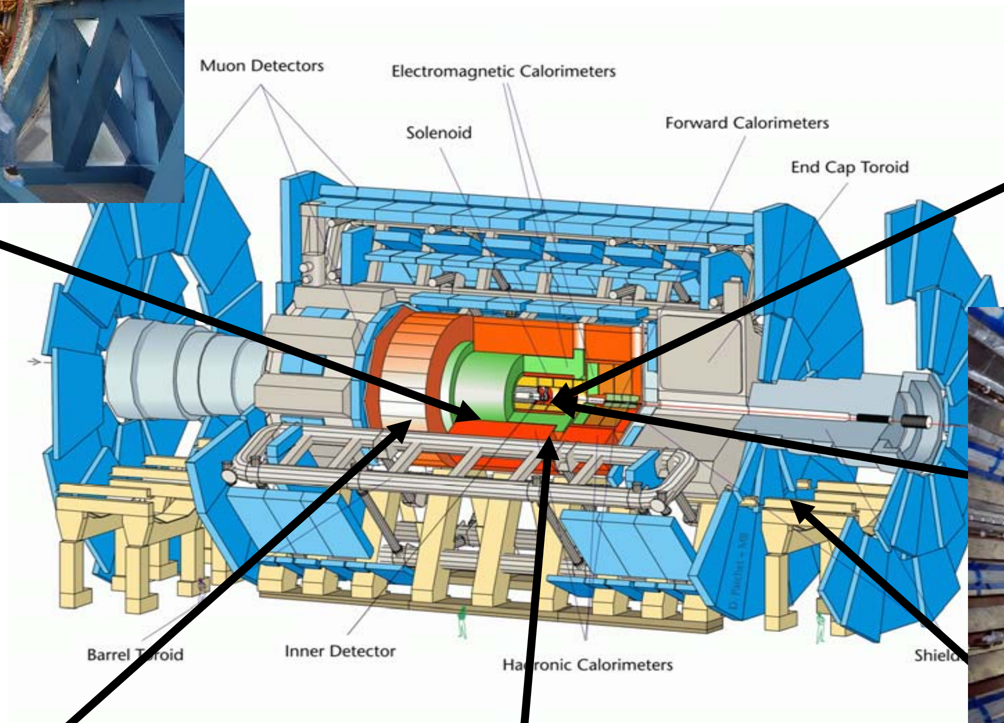
30 Nov: Y\\\E+3 leaves SX5 and 8 hours later touches down safely in UXC

The first force studied carefully by CMS is Gravity

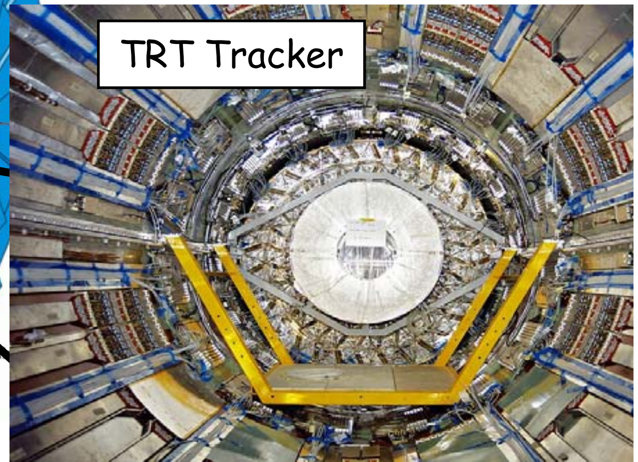
Continuing…

YE+2
endcap disc
12.12.2006

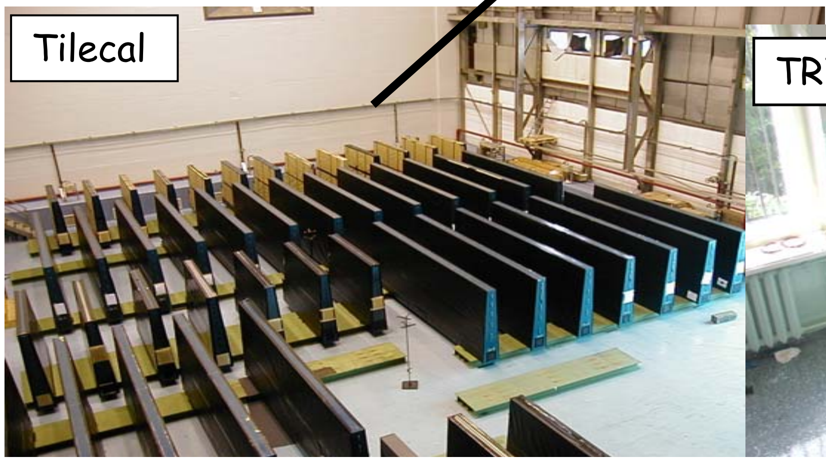
ATLAS

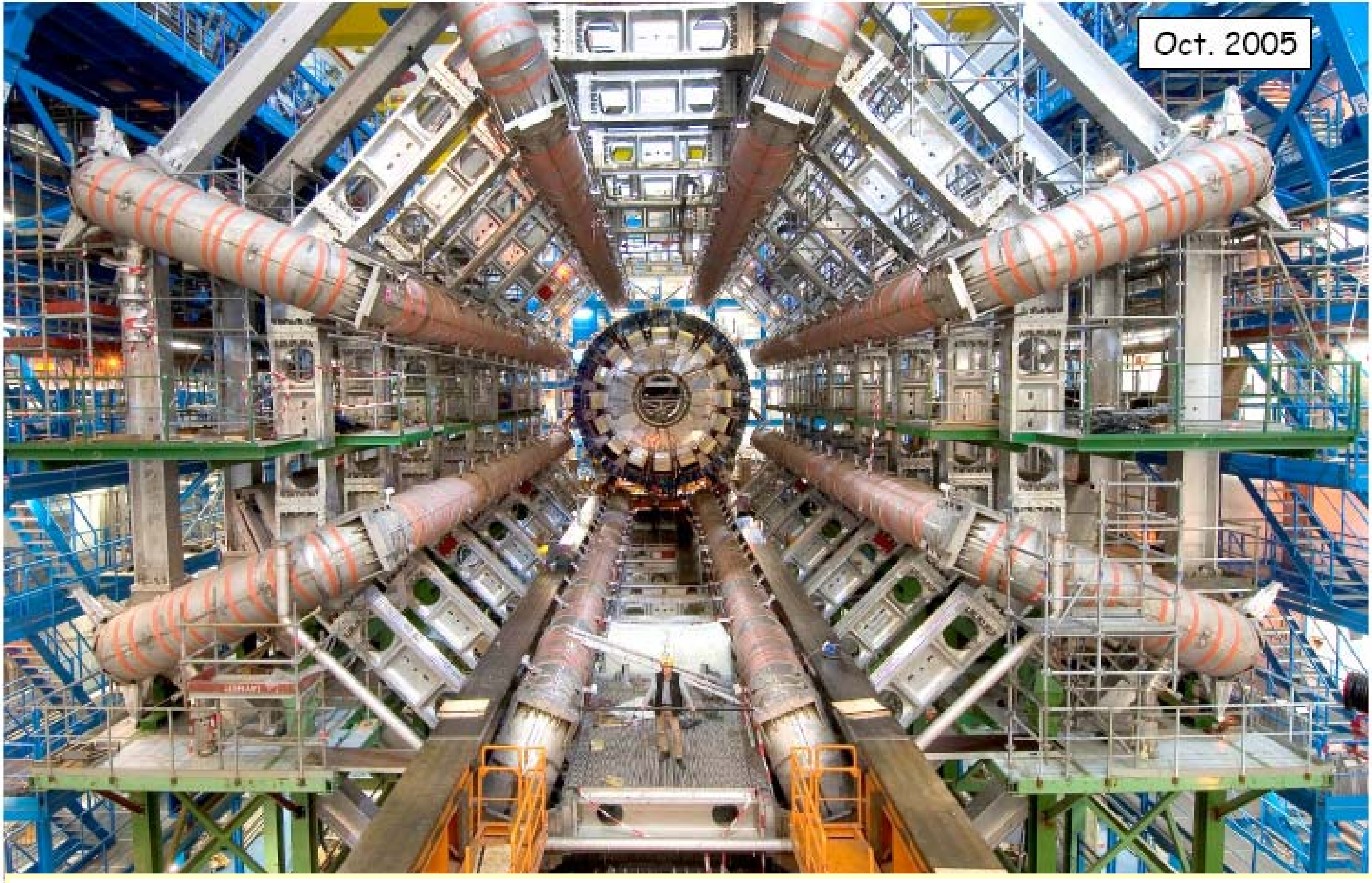


Barrel LAr ECAL



Length : ~40 m
Radius : ~10 m
Weight : ~ 7000 tons





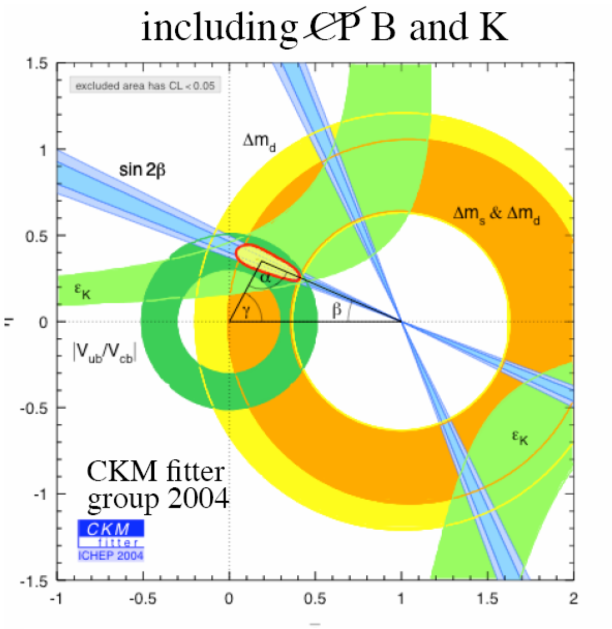
The ATLAS Barrel Toriod


μ
6.920 m
5.635 m
4.645 m
3.850 m
2.950 m
2.864 m
1.840 m
1.320 m
Transverse View
Will size matter?

LHCb: b-physics at the LHC

Examples

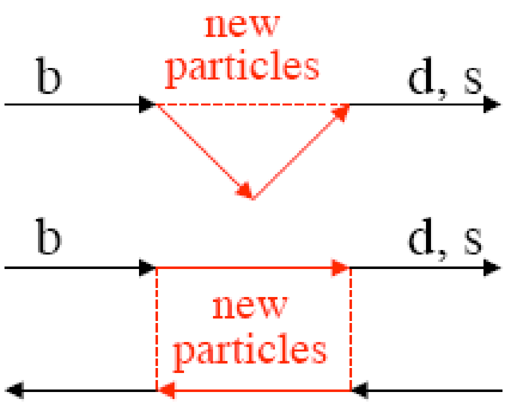
CKM triangle



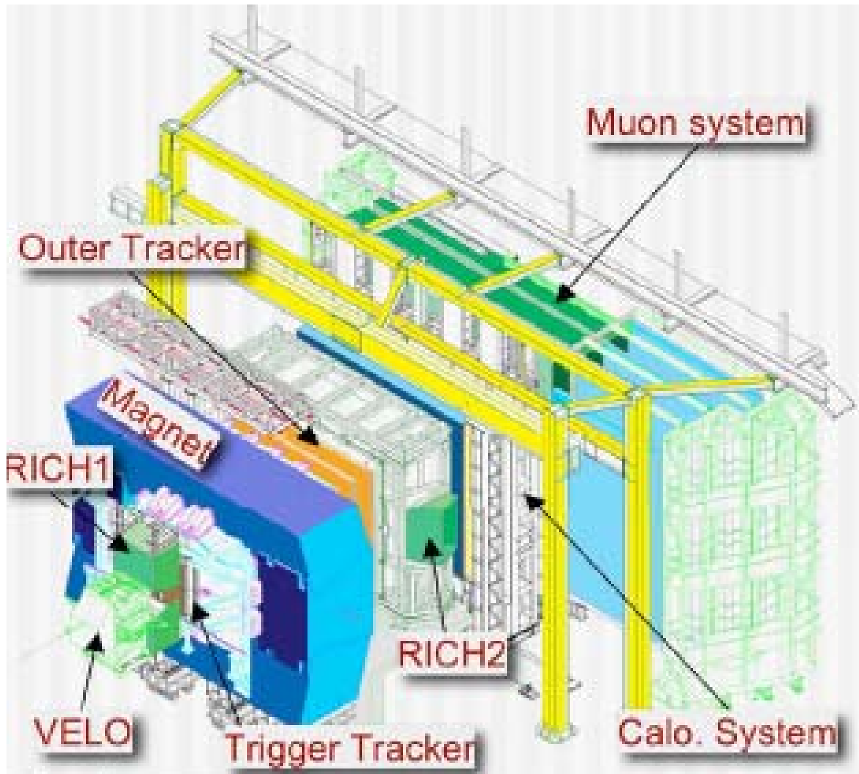
$B_s \to J/\psi\phi$ 120k signal events/year in LHCb

$\sigma(\sin\phi_s) \sim 0.06$, $\sigma(\Delta\Gamma_s/\Gamma_s) \sim 0.02$

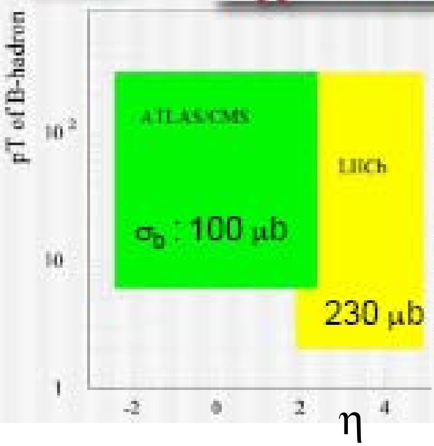
Measurement of B_s–$\overline{B}_s$ oscillation

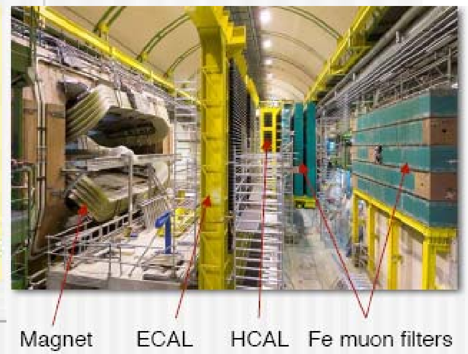


Sensitive to new physics complementary to ATLAS/CMS

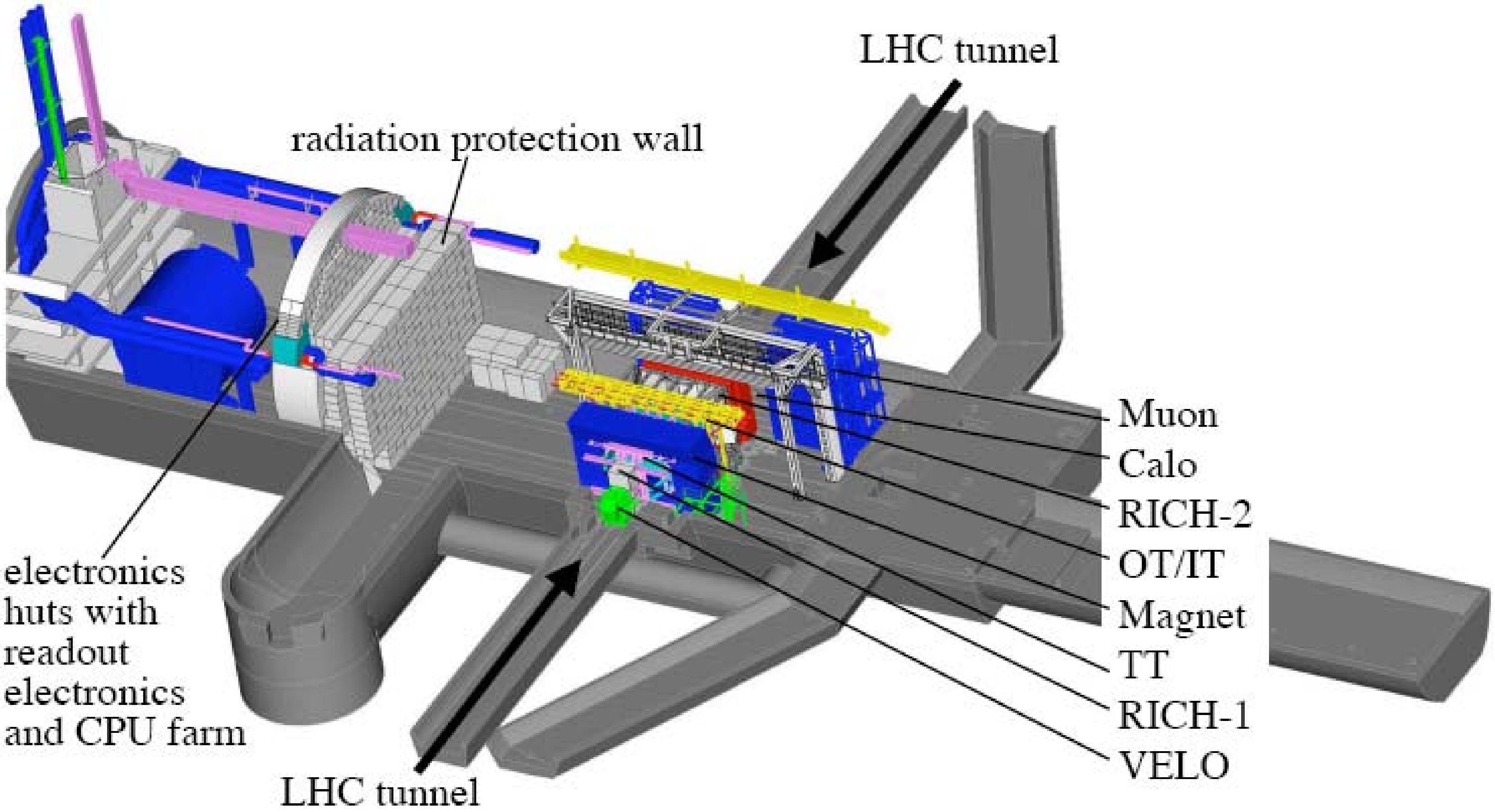


$L \sim 2\text{x}10^{32}\text{cm}^{-2}\text{s}^{-1}$



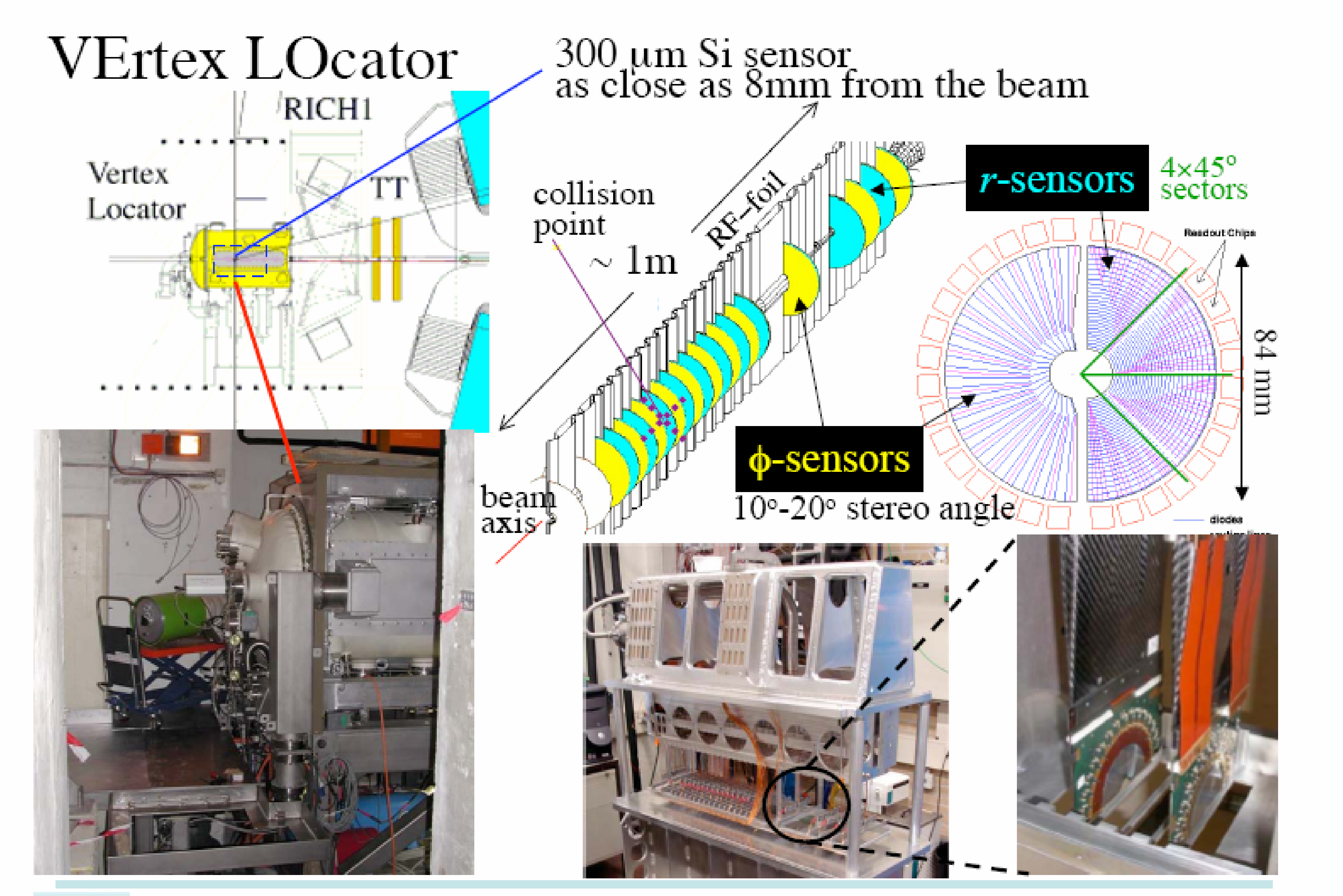


LHCb Cavern



$\langle L \rangle \sim 2\times10^{32}$ ($L_{nominal} = 10^{34}$), $\sigma_b = 500\ \mu b$ ($\sigma_{inelastic} = 80$ mb),
$10^{12}\ b\bar{b}/10^7$ sec $\qquad B_{u,d,s,c}$, Λ_b, Σ_b, and other b-hadrons

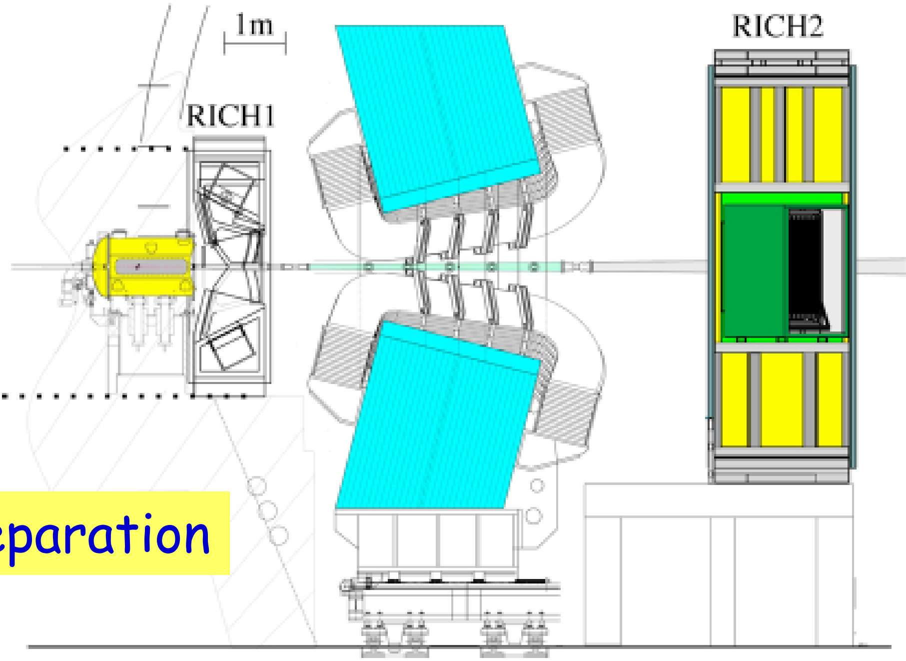
VErtex LOcater



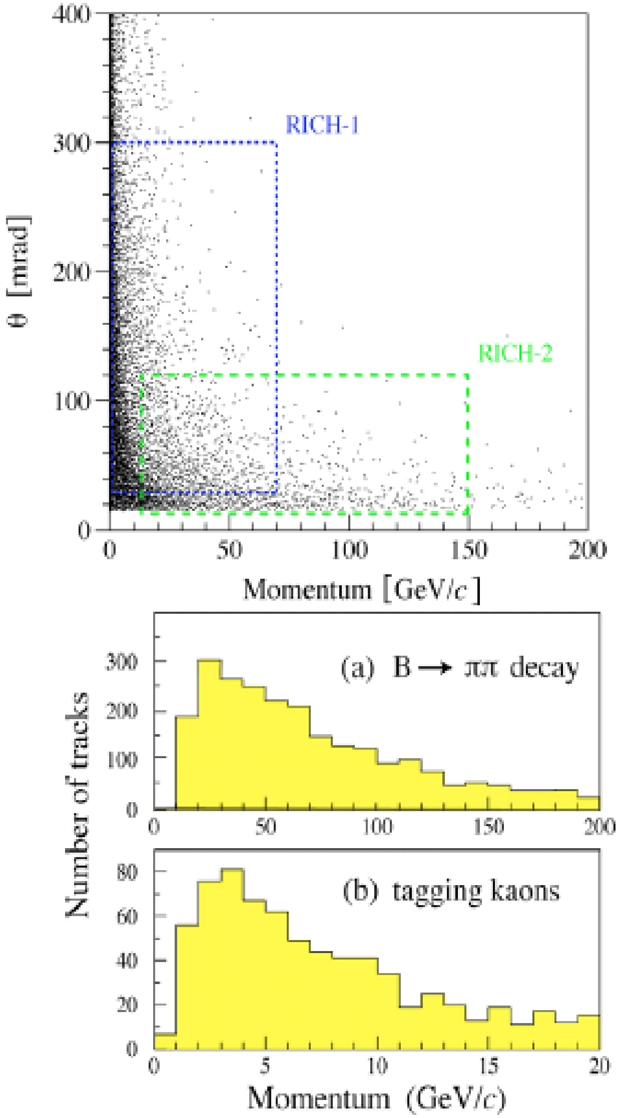
LHCb Particle identification

Based on cherekov light emission

RICH Ring Imaging Cherenkov



π, K, p separation



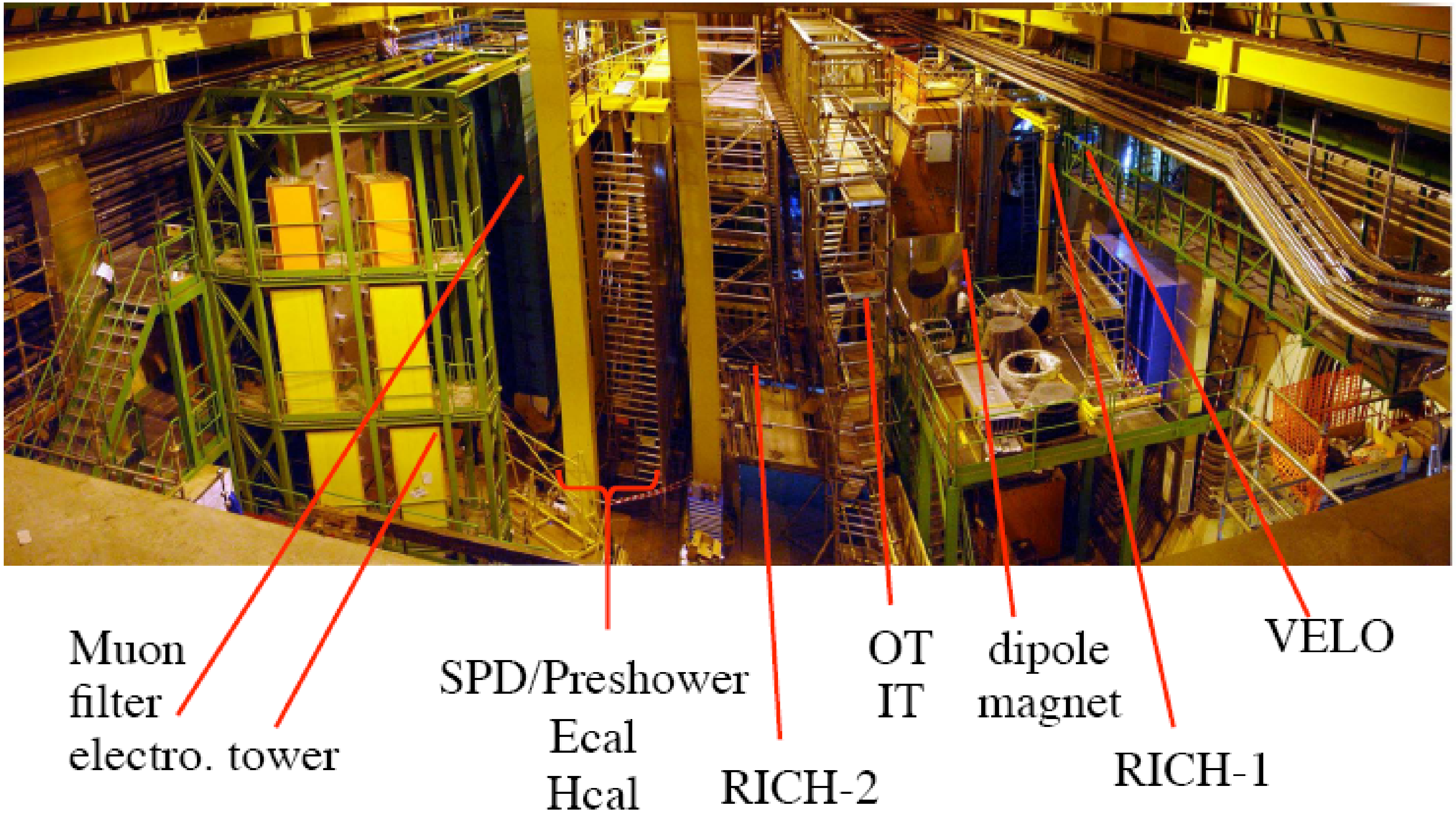
Two RICH with three radiators

Aerogel, C_4F_{10} } RICH1 (25-300 mrad)

CF_4 RICH2 (15-120 mrad)

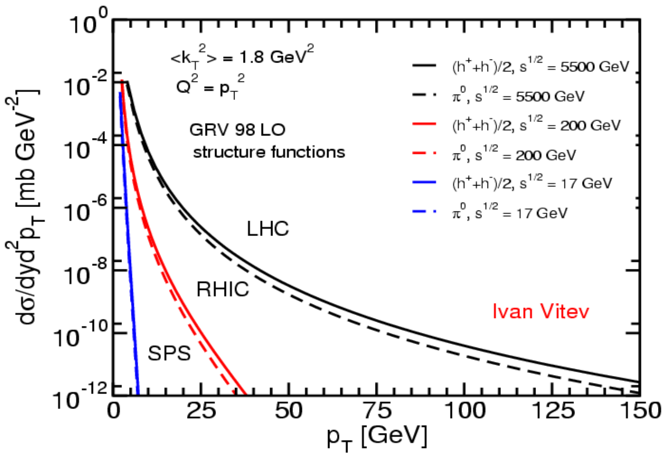
LHCb in the Cavern

Current view of the pit (IP8)

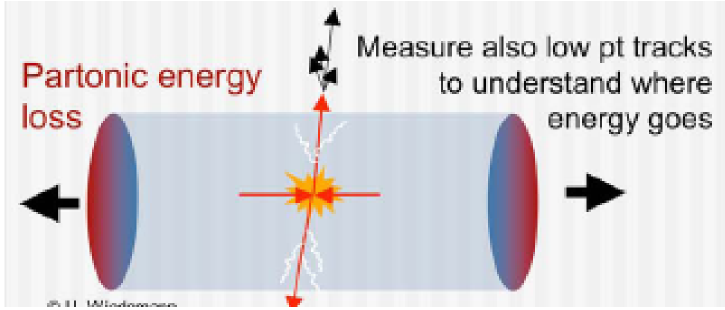


Preparing for data in 2007/2008

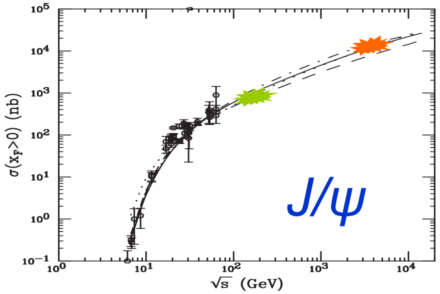
Heavy Ion Physics at the LHC

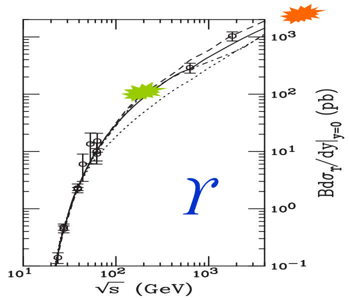


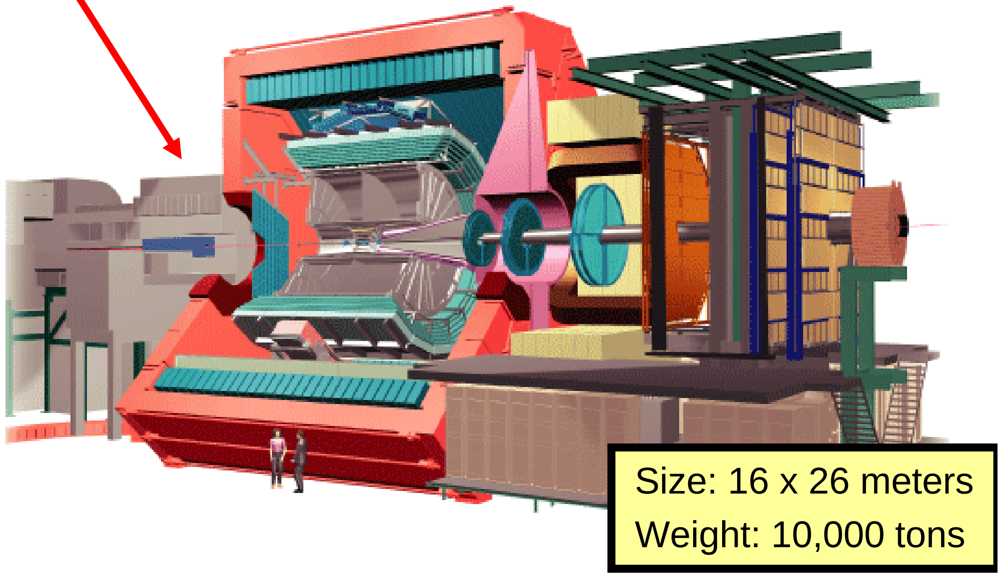
High P_T particle and jet production Jet-quenching



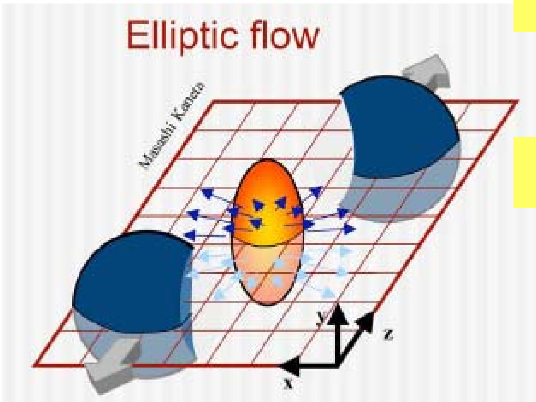
Heavy ions part of the LHC physics program with ALICE, but also CMS and ATLAS







Υ melt down



Event shapes

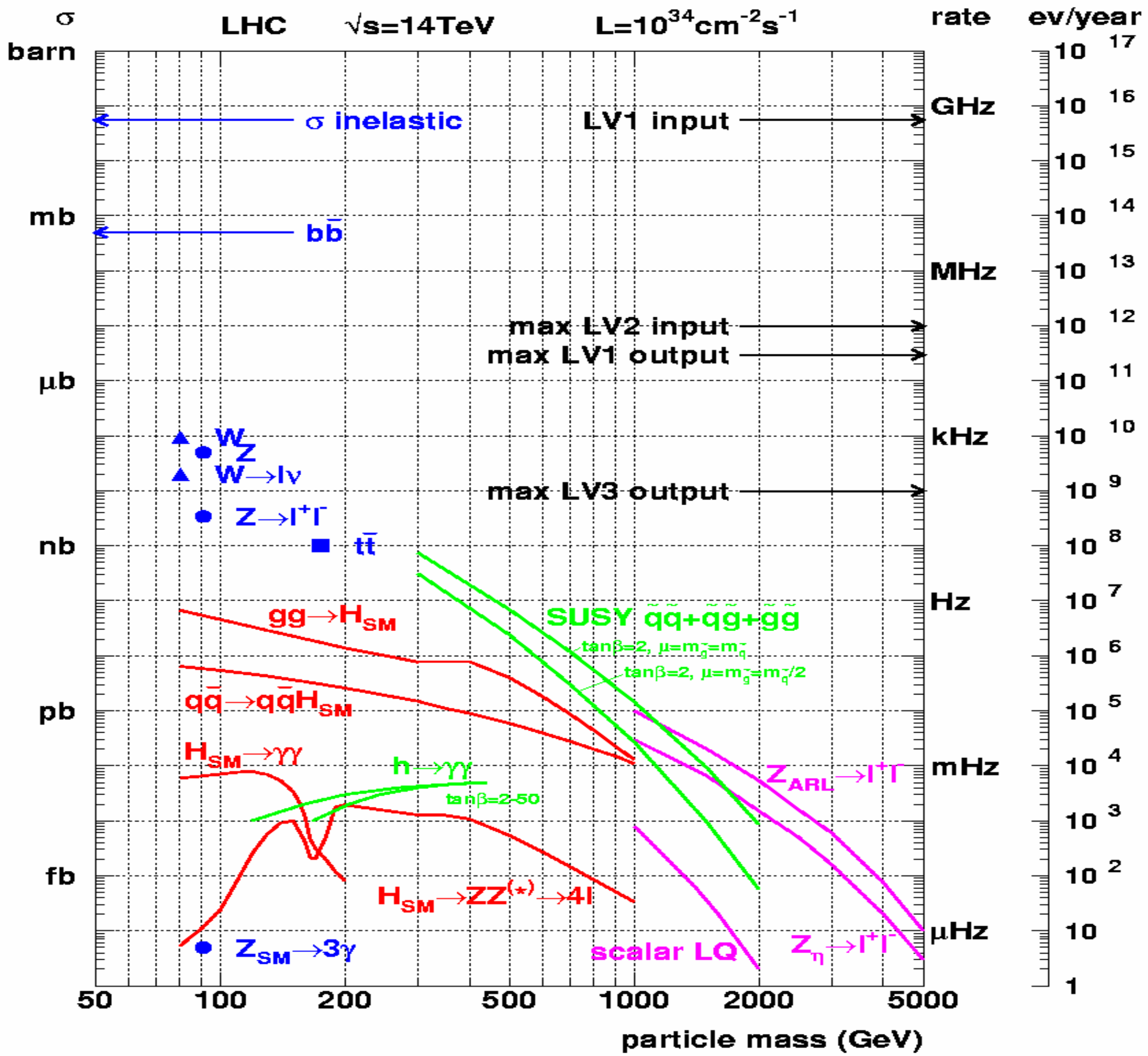
LHC ready for heavy ions in 2008?

A few LHC numbers…

- Rate of pp interactions at 10^{34} $cm^{-2}s^{-1}$: 10^9 events per second
- Energy of pp is about 7 times higher than that of the Tevatron at FNAL
- Weight of the CMS experiment: ~ 12500 tons (30% more than the Tour Eiffel)
- Amount of cables used in ATLAS : ~ 3000 km
- Data volume recorded at the front-end in CMS is 1 TB/second which corresponds to 10,000 Encyclopedia Britannica
- Data recorded during the 10-20 years of LHC life will be equivalent to all the words spoken by mankind since its appearance on earth
- A worry for the detectors: the kinetic energy the beam is of 1 small aircraft carrier of 10^4 tons going 20 miles/ hour
- Machine temperature : 1.9 K (largest cryogenic system in the world)
- Total cost of machine + experiments : ~ 5000 MCHF
- Total number of involved physicists : ~ 5000

….

Cross sections at the LHC



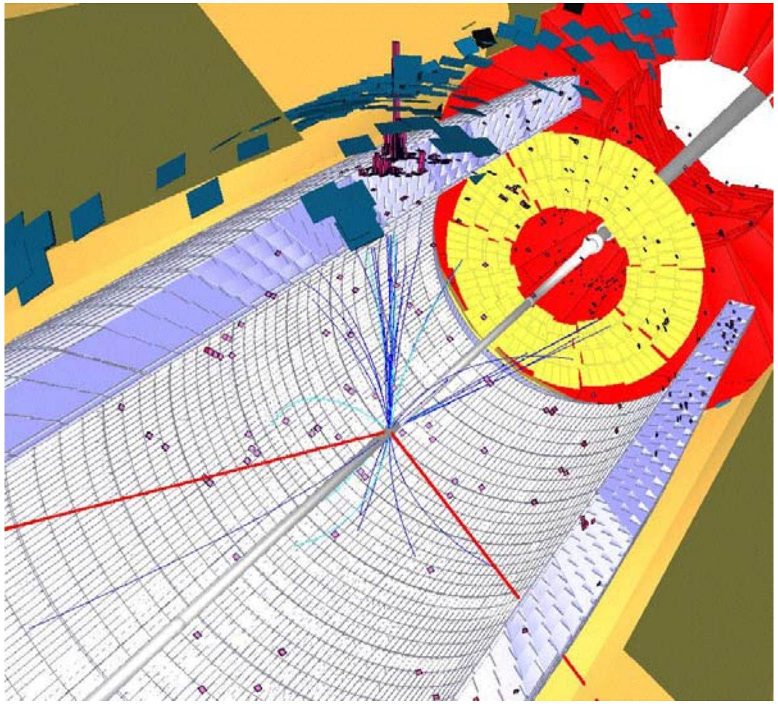
"Well known" processes, don't need to keep all of them …

New Physics!!
This we want to keep!!

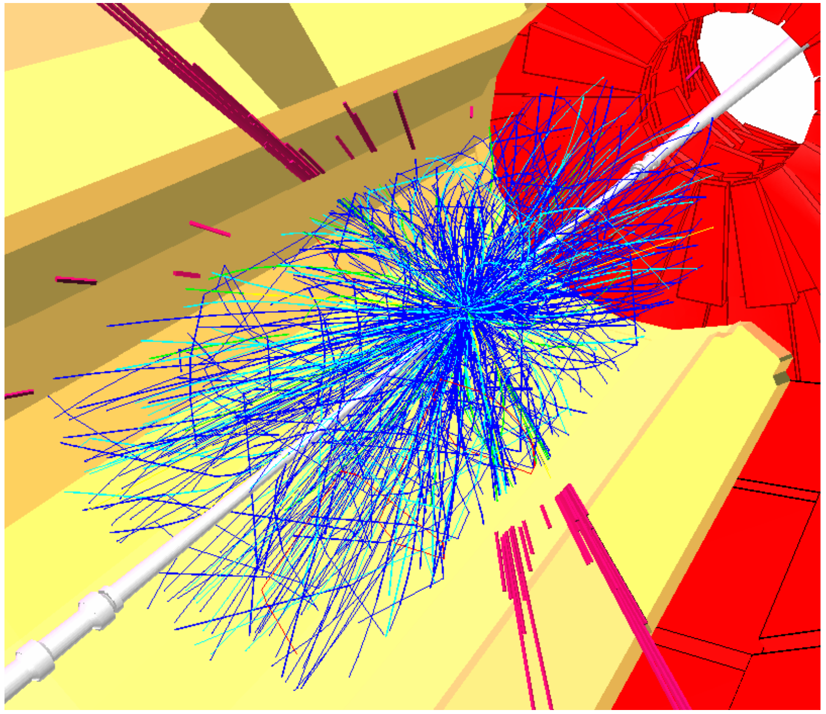
⇒Trigger! High p_T signals based…

Pile-up at the LHC

Pile-up ⇒ additional -mostly soft- interactions per bunch crossing
Startup luminosity $2 \bullet 10^{33} cm^{-2}s^{-1}$ ⇒ 4 events per bunch crossing
High luminosity $10^{34} cm^{-2}s^{-1}$ ⇒ 20 events per bunch crossing
Luminosity upgrade $10^{35} cm^{-2}s^{-1}$ ⇒ 200 events per bunch crossing



SUSY event (no pileup)



SUSY event ($10^{34} cm^{-2}s^{-1}$)

Event Rates at pp at $\sqrt{s}$=14 TeV

Process	Events/s	Events/year	Other machines
$W \rightarrow e\nu$	15	10^8	10^4 LEP / 10^7 Tev
$Z \rightarrow ee$	1.5	10^7	10^7 LEP
$t\bar{t}$	0.8	10^7	10^4 Tevatron
$b\bar{b}$	10^5	10^{12}	10^8 Belle/BaBar
$\tilde{g}\tilde{g}$ (m=1 TeV)	0.001	10^4	—
H (m=0.8 TeV)	0.001	10^4	—
Black Holes M_D=3 TeV n=4	0.0001	10^3	

Huge event rates:
($10^{33} cm^{-2} s^{-1}$)

The LHC will be a W-factory, a Z-factory, a top factory, a Higgs factory etc..

Precision EW physics will be limited by systematics

Strategy at start-up

Goal # 1

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.

- $tt \rightarrow bl\nu\, bjj$ 10^3 evts/day after cuts → jet scale from W→jj, b-tag perf., etc.

Understand basic SM physics at $\sqrt{s}$ = 14 TeV → first checks of Monte Carlos (hopefully well understood at Tevatron and HERA)

e.g. - measure cross-sections for e.g. minimum bias, W, Z, tt, QCD jets (to ~ 10-20 %), look at basic event features, first constraints of PDFs, etc.

- measure top mass (to 5-7 GeV) → give feedback on detector performance

Note : statistical error negligible after few weeks run

Goal # 2

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 ≠ b "calibrates" ttbb irreducible background to ttH → ttbb

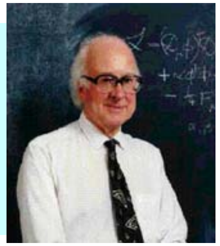
Goal # 3

Look for New Physics potentially accessible in first year (e.g. SUSY, some Higgs ? ...)

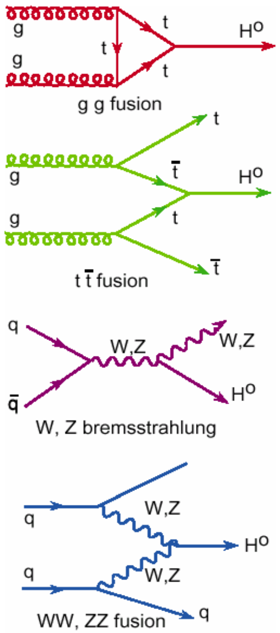
Will need to understand SM processes in detail @ 14 TeV for searches

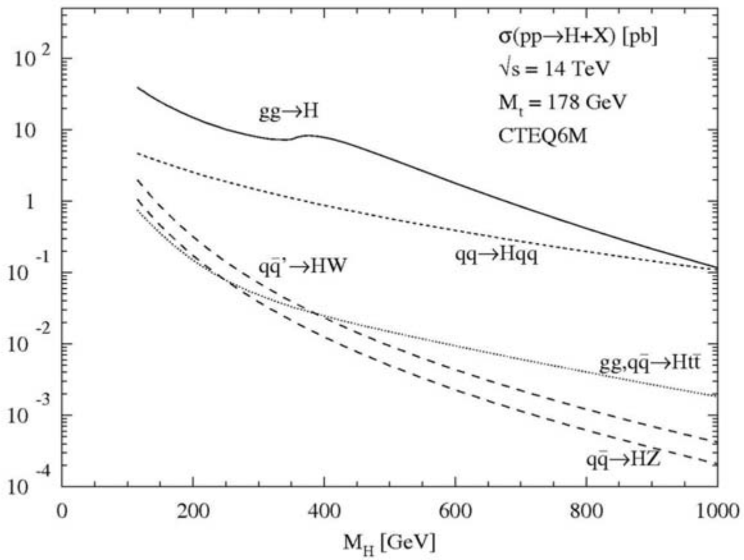
Higgs Physics

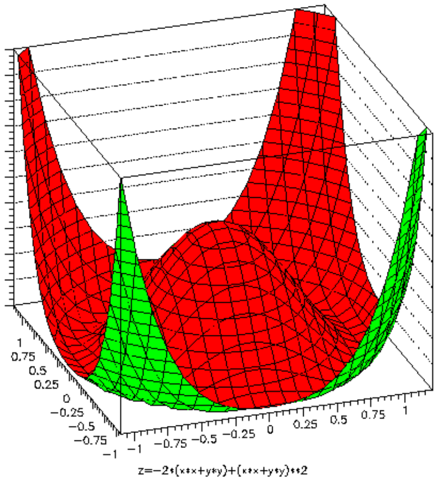
⇒ What is the origin of Electro-weak Symmetry Breaking?
⇒ If Higgs field at least one new scalar particle should exist: The Higgs
One of the main missions of LHC: discover the Higgs for m_H< 1 TeV

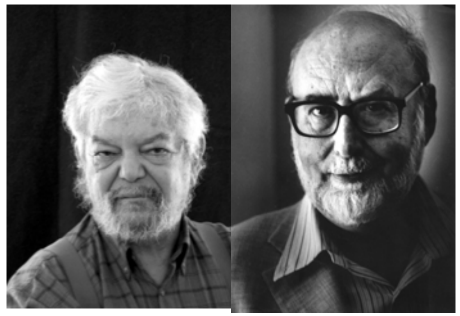


P.Higgs









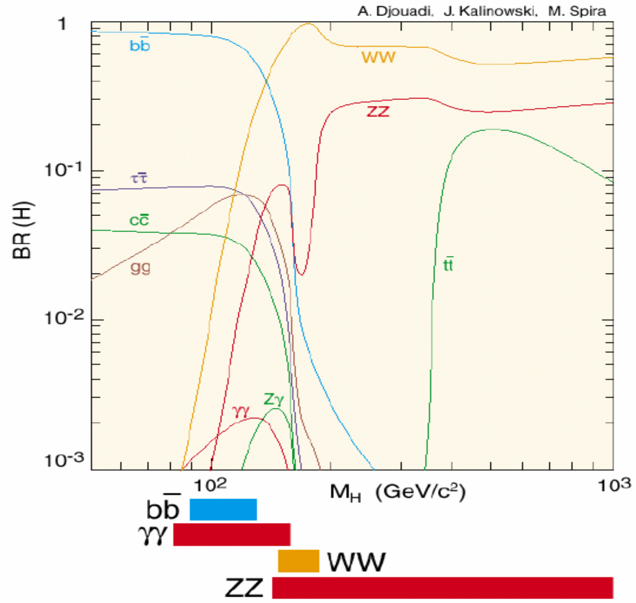
Brout, Englert

SM Higgs Search Channels

Low mass $M_H \lesssim 200$ GeV

M. Pieri

Production / DECAY	Inclusive	VBF	WH/ZH	ttH
$H \to \gamma\gamma$	YES	YES	YES	YES
$H \to bb$			YES	YES
$H \to \tau\tau$		YES		
$H \to WW^*$	YES	YES	YES	
$H \to ZZ^*$, $Z \to \ell^+\ell^-$, ℓ=e,μ	YES			
$H \to Z\gamma$, $Z \to \ell^+\ell^-$, ℓ=e,μ	very low σ			



Intermediate mass
(200 GeV $\lesssim M_H \lesssim 700$ GeV)

inclusive $H \to WW$
inclusive $H \to ZZ$

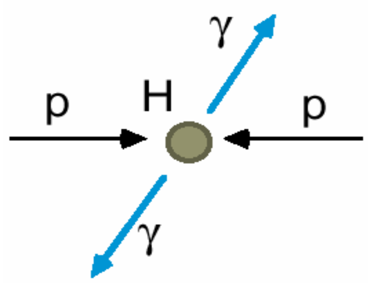
High mass ($M_H \gtrsim 700$ GeV)

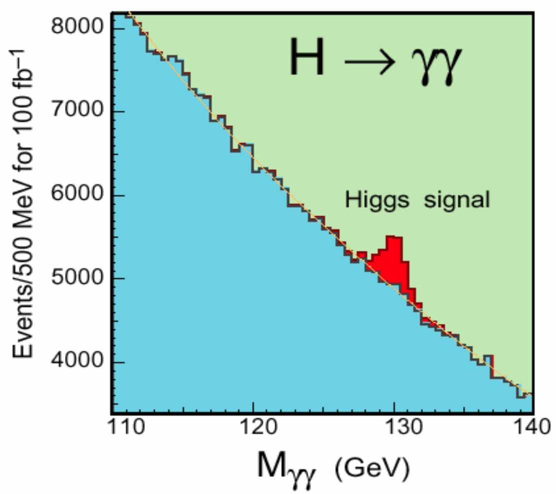
VBF $qqH \to ZZ \to \ell\ell\nu\nu$
VBF $qqH \to WW \to \ell\nu jj$

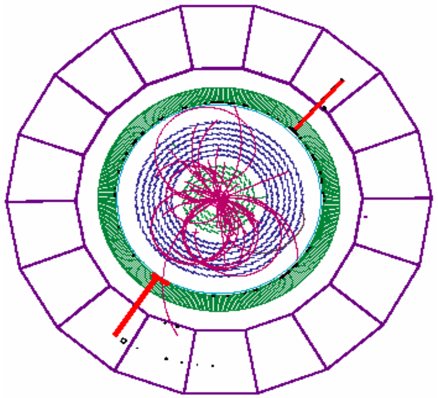
$H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ are the only channels with a very good mass resolution ~1%

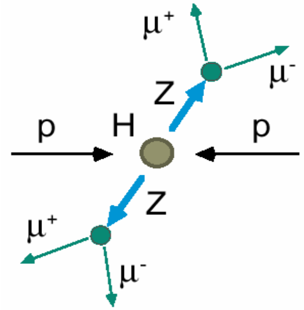
Higgs Searches

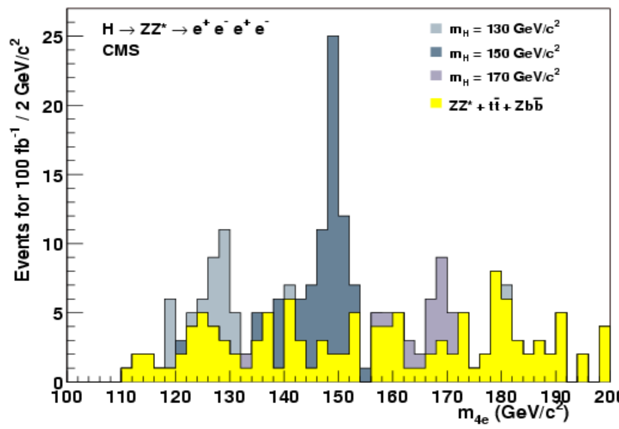
Low M_H < 140 GeV/c²	Medium 130<M_H<500 GeV/c²	High M_H > ~500 GeV/c²

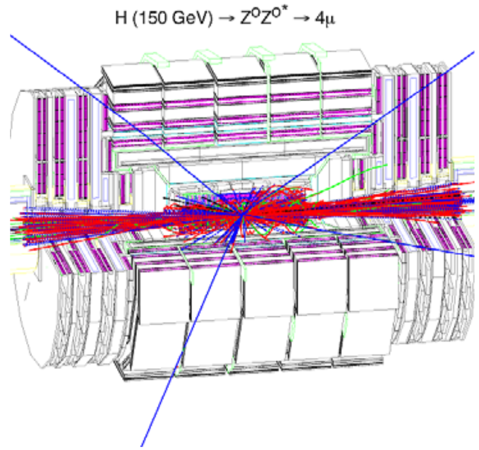


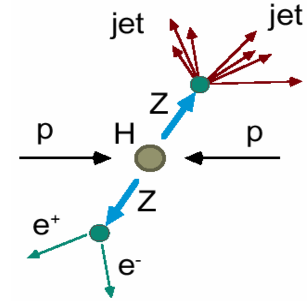


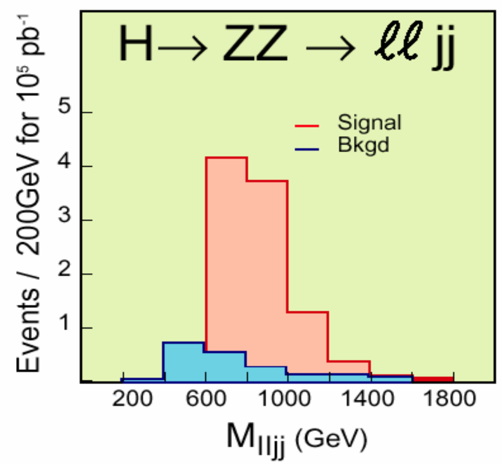


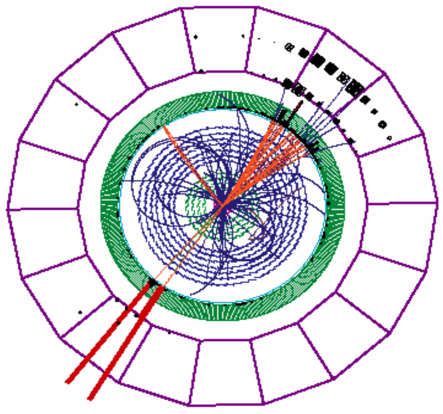




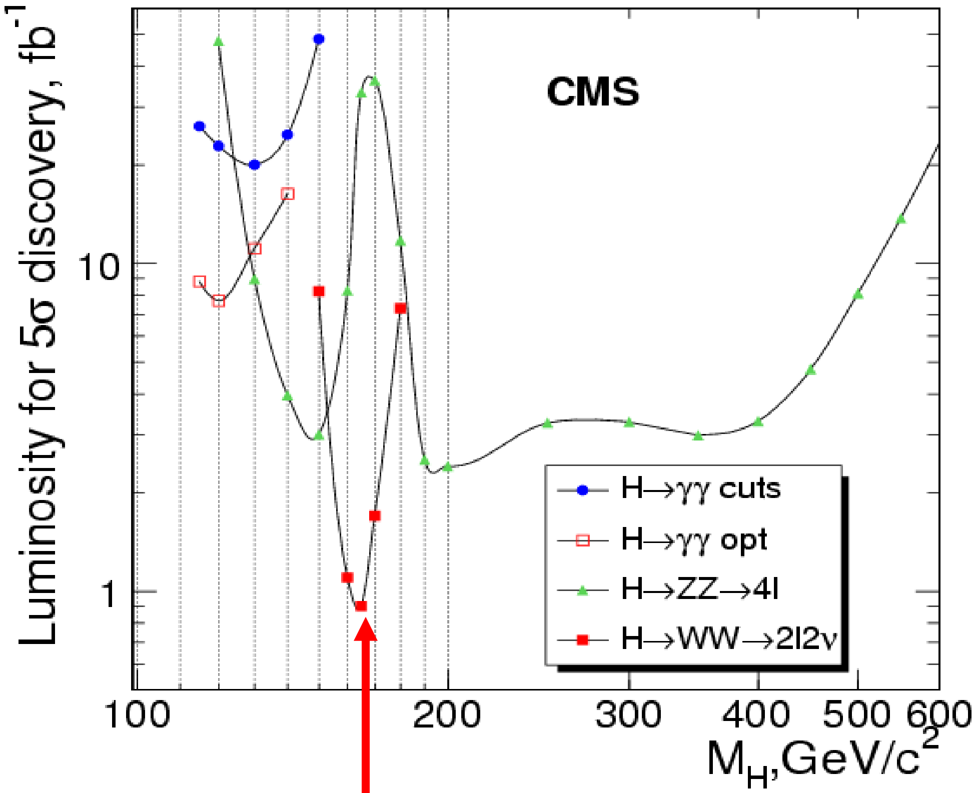


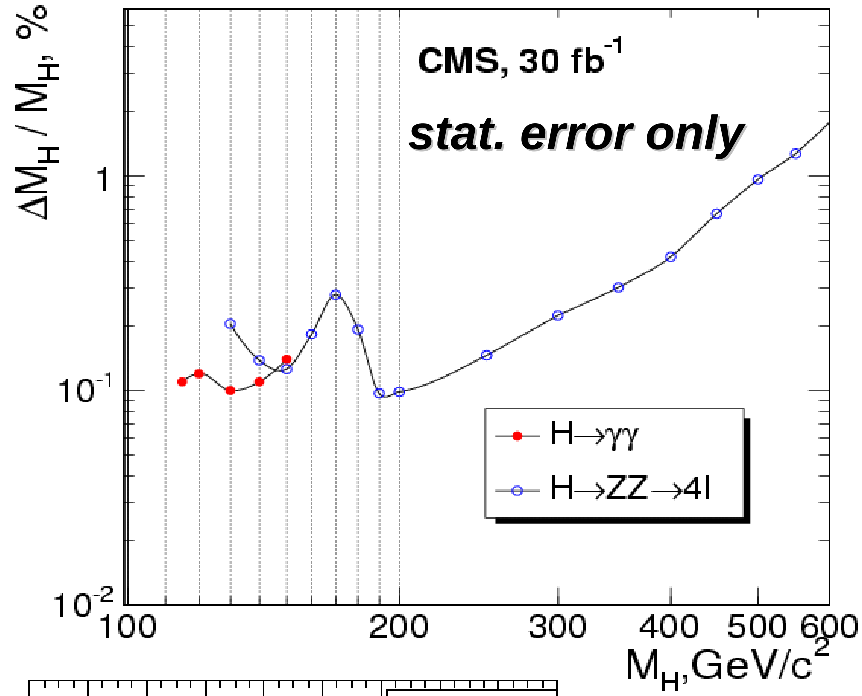






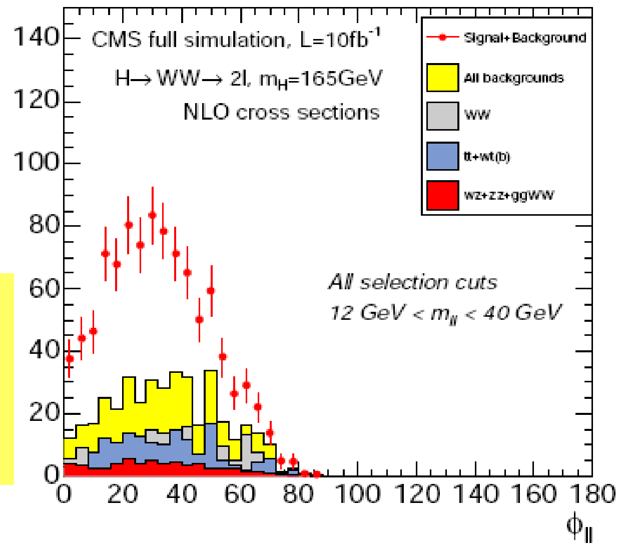
SM Higgs boson discovery and mass measurement





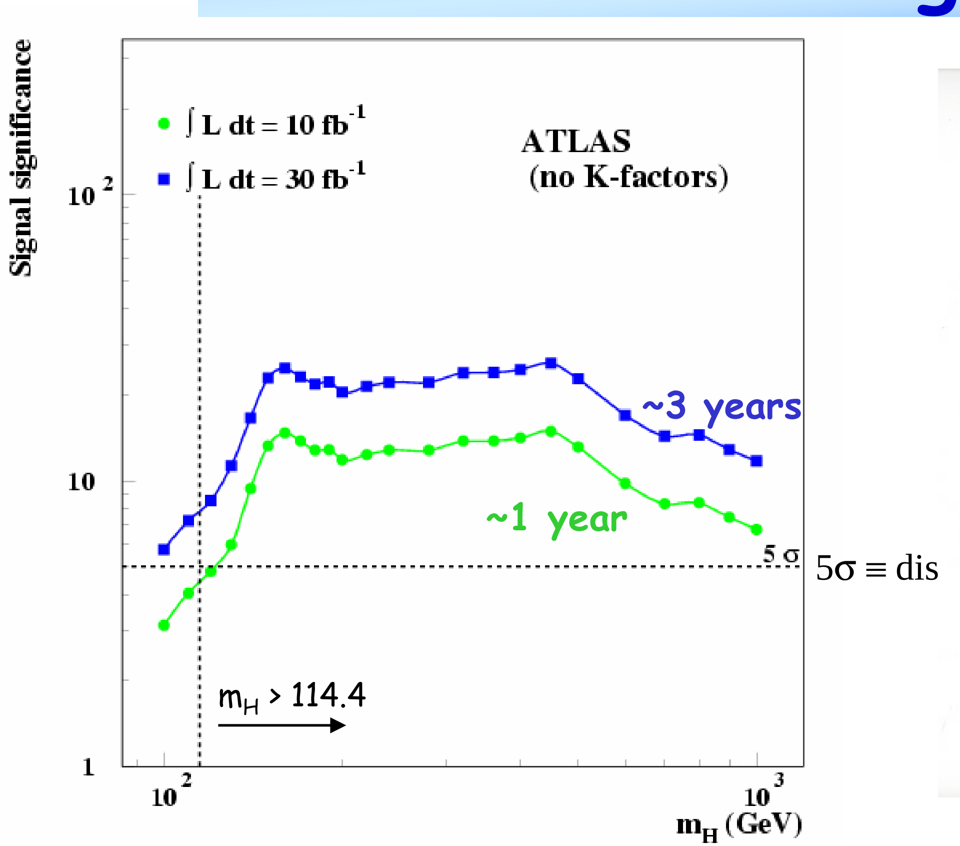
Discovery with ~1 fb^{-1}

Very detailed studies
on SM backgrounds
and related systematics



CMS Physics TDR

Higgs Reach



- Higgs can be discovered over full allowed mass range in 1 year of good LHC operation
  → final word about SM Higgs mechanism by 2009 or so
- However: it will take time to understand and calibrate ATLAS and CMS …
- In most difficult region m_H < 130 GeV

Important test for theories requiring a light Higgs (SUSY, Baryogenesis)

What can the LHC do?

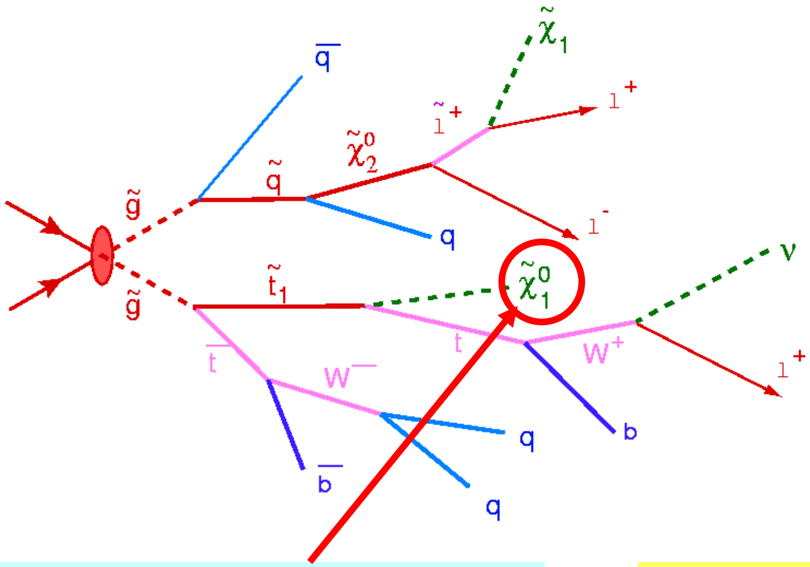
- LHC will discover the SM Higgs in the full region up to 1 TeV or exclude its existence with O(10) fb^{-1} or less. If no Higgs, other new phenomena in the WW should be observed around 1 TeV
- The LHC will measure with full luminosity (>100 fb^{-1})
  - The Higgs mass with 0.1-1% precision
  - The Higgs width, for m_H> 200 GeV, with ~5-8% precision
  - Cross sections x branching ratios with 5-20% precision
  - Ratios of couplings with 10-30% precision
  - Absolute couplings only with additional assumptions
  - Spin information in the ZZ channel for m_H>200 GeV
  - CP information from exclusive central production: $pp \rightarrow pHp$

..⇒will get a pretty good picture of the Higgs @ LHC
More detailed information at an e+e- Linear Collider

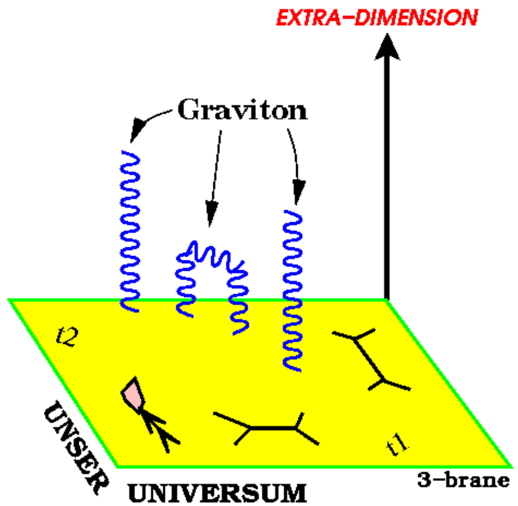
Beyond the Standard Model

New physics expected around the TeV scale ⇒
Stabelize Higgs mass, Hierarchy problem, Unification of gauge couplings, CDM,...

Supersymmetry



Extra dimensions



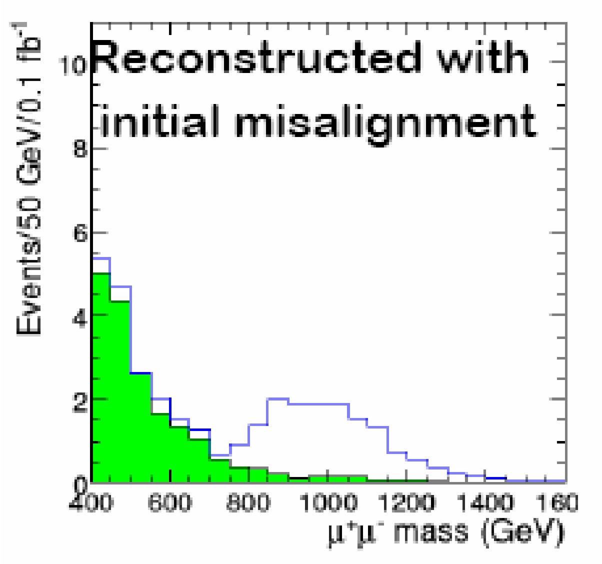
+ ...

Dark Matter candidates!
Particle physics meets Cosmology!

+ a lot of other ideas...
Split SUSY, Little Higgs models, new gauge bosons, technicolor, compositness,...

Early discoveries? E.g. Di-lepton Resonance

If we are lucky:
a signal could be
seen very early on



First months of operation

Example : The Di-lepton channel

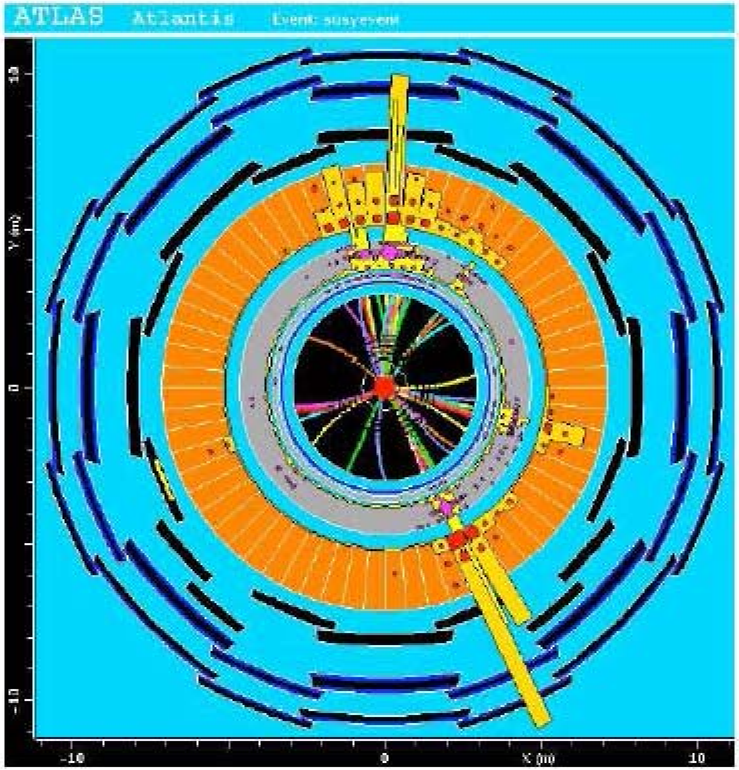
- Z' (New gauge bosons)
- A_H, Z_H (Little Higgs)
- $G^{(1)}$ (Randall-Sundrum)
- $\gamma^{(1)}/Z^{(1)}$ (TeV^{-1} Extra Dimensions)
- $G^{(KK)}$ (ADD)
- ...

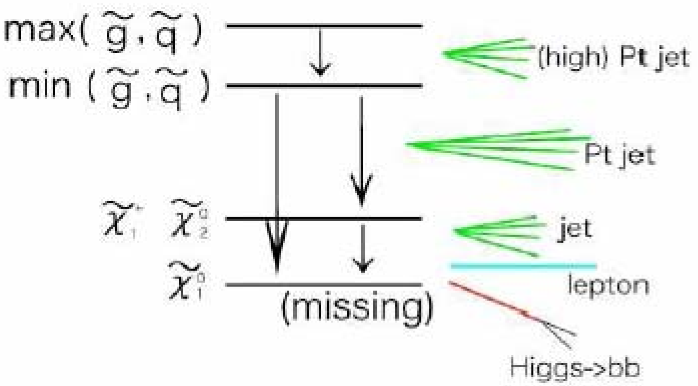
Supersymmetry

SUSY could be at the rendez-vous very early on!

M_{sp}(GeV)	σ (pb)	Evts/yr
500	100	10^6-10^7
1000	1	10^4-10^5
2000	0.01	10^2-10^3

$10fb^{-1}$





event topologies of SUSY

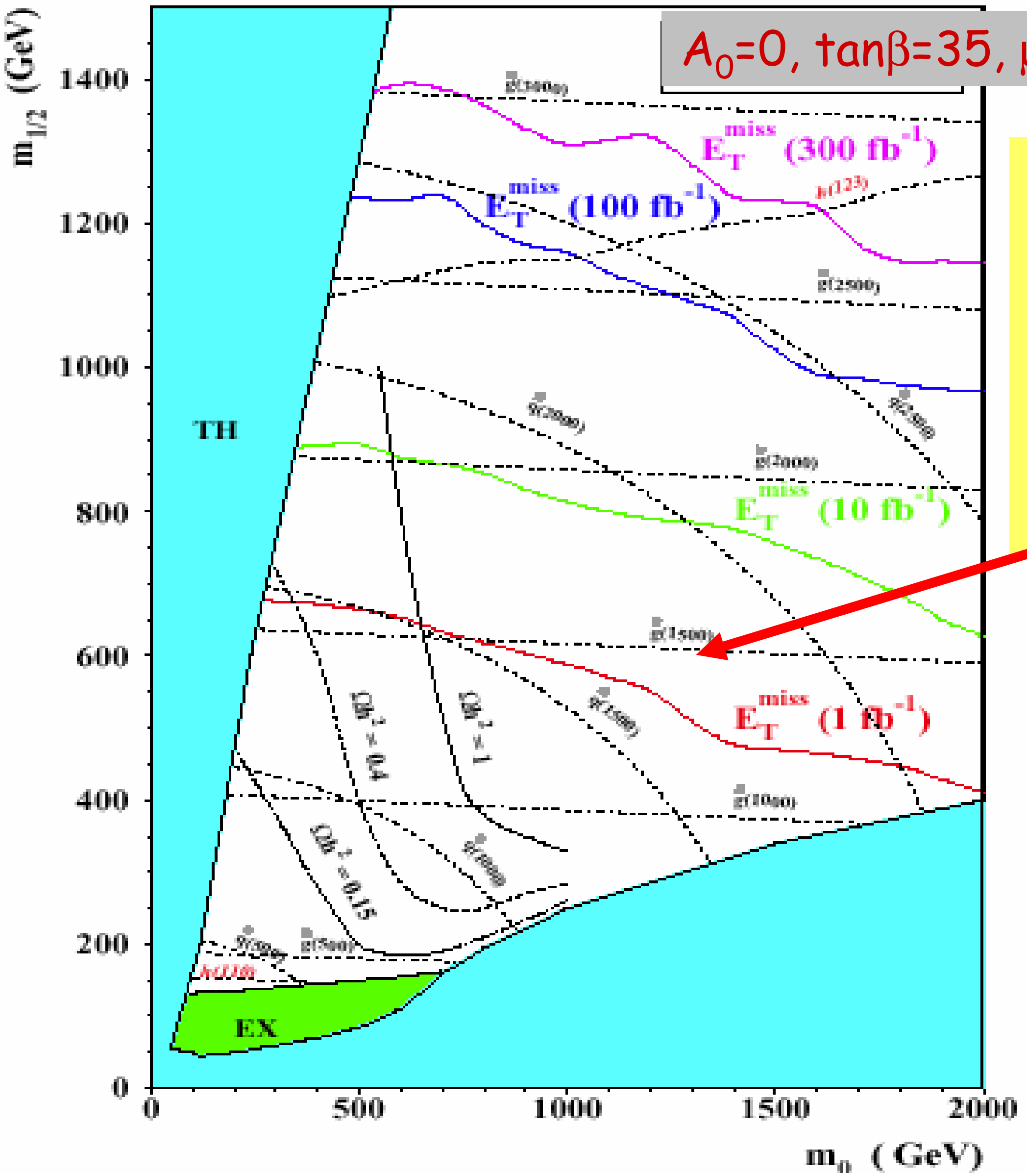
$\not{E}_T$ + High P_T jets + multi leptons / b-jets / τ-jets

Therefore: SUSY one of the priorities of the "search" program

Note: 10^7 gluinos for $5 \bullet 10^9$ CHF (LHC) = 500 CHF/gluino

Main signal: lots of activity (jets, leptons, taus, missing E_T)
Needs however good understanding of the detector & SM processes!!

Reach versus integrated luminosity



- 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}
- Masses up to 1 TeV already detectable with 1 fb^{-1}

Watch out for SUSY from the start!

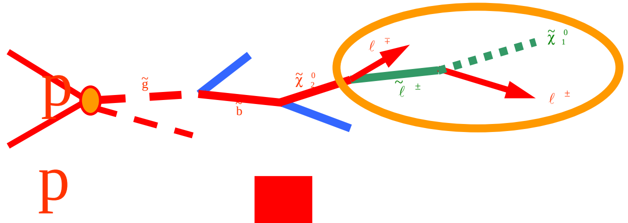
Usually minimal Supergravity (mSUGRA) taken for studies ⇒5 parameters

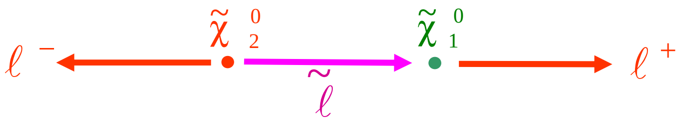
$m_{1/2}$: universal gaugino mass at GUT scale
m_0: universal scalar mass at GUT scale
tanβ: vev ratio for 2 Higgs doublets
sign(μ): sign of Higgs mixing parameter
A_0: trilinear coupling

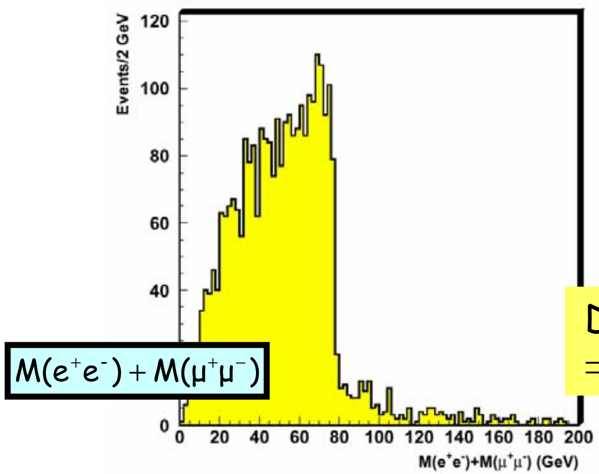
Sparticle Detection & Reconstruction

Mass precision for a favorable benchmark point at the LHC
LCC1~ SPS1a~ point B'

m_0=100 GeV
$m_{1/2}$= 250 GeV
A_0=-100
tanβ = 10
sign(μ)=+





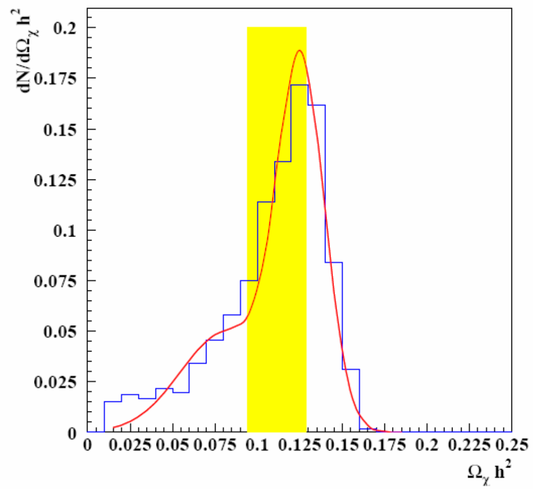


D. Miller et al
⇒Use shapes

hep-ph/0508198

GeV	LHC
$\Delta m_{\tilde{\chi}^0_1}$	4.8
$\Delta m_{\tilde{\chi}^0_2}$	4.7
$\Delta m_{\tilde{\chi}^0_4}$	5.1
$\Delta m_{\tilde{l}_R}$	4.8
$\Delta m_{\tilde{\ell}_L}$	5.0
Δm_{τ_1}	5-8
$\Delta m_{\tilde{q}L}$	8.7
$\Delta m_{\tilde{q}R}$	7-12
$\Delta m_{\tilde{b}_1}$	7.5
$\Delta m_{\tilde{b}_2}$	7.9
$\Delta m_{\tilde{g}}$	8.0

Lightest neutralino → Dark Matter?
Fit SUSY model parameters to the measured SUSY particle masses to extract $\Omega_\chi h^2$ ⇒ O(10%) for LCC1



Higher precision with ILC data,
See LHC-ILC report

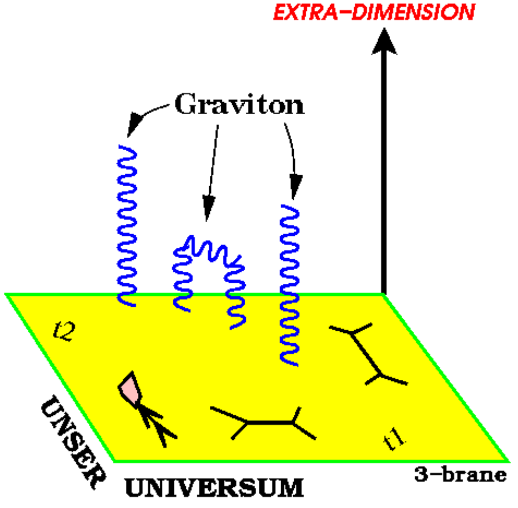
Large Extra Dimensions

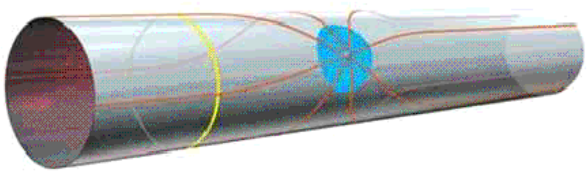
ADD: Arkani -Ahmed, Dimopolous,Dvali

Problem: $m_{EW} = \frac{1}{(G_F \cdot \sqrt{2})^{\frac{1}{2}}} = 246\text{ GeV}$ ⟷ $M_{Pl} = \frac{1}{\sqrt{G_N}} = 1.2 \cdot 10^{19}\text{ GeV}$

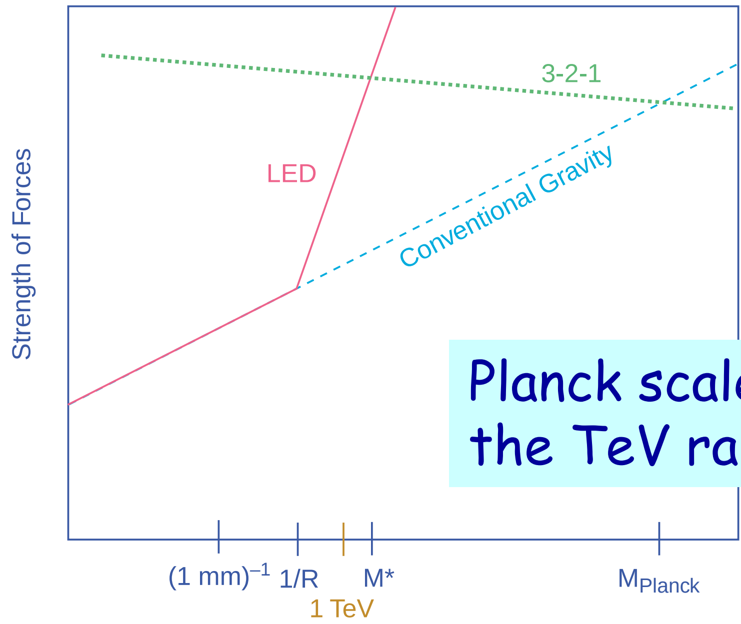
String Theory Inspired

Assume the world we see is in 4 dimensions but that gravity can expand in 4+δ dimensions. Extra dimensions have size R (mm to fm)





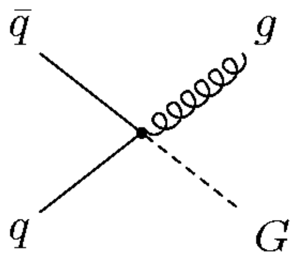
Curled up...

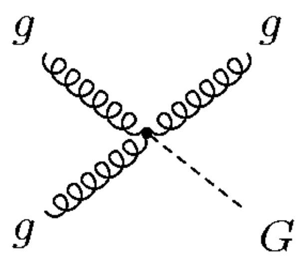


Planck scale in the TeV range?

Extra Dimension signals at the LHC: ADD

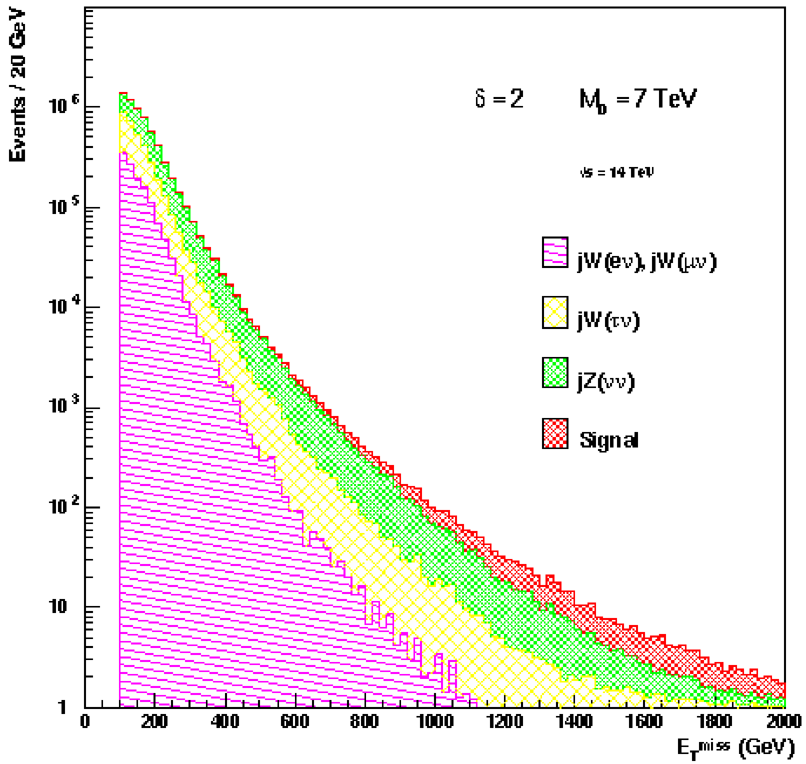
ADD: Arkani –Ahmed, Dimopolous,Dvali

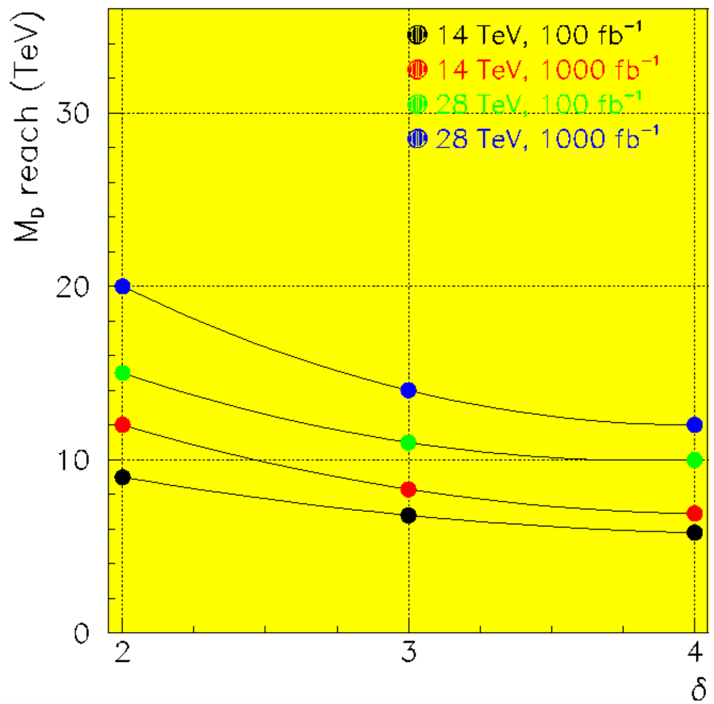




Graviton production!
Graviton escapes detection

Signal: single jet + large missing ET





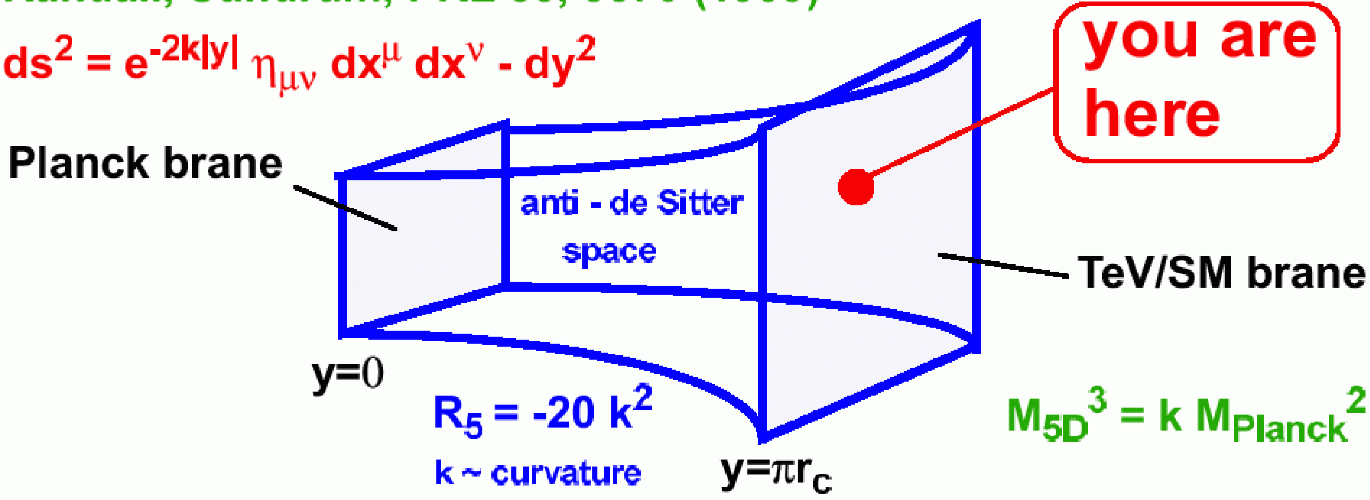
Test M_D to 7-9 TeV for 100 fb^{-1}

Curved Space: RS Extra Dimensions

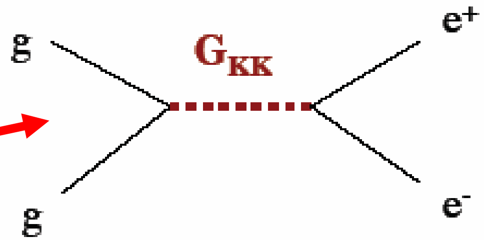
Randall-Sundrum

Randall, Sundrum, PRL 83, 3370 (1999)

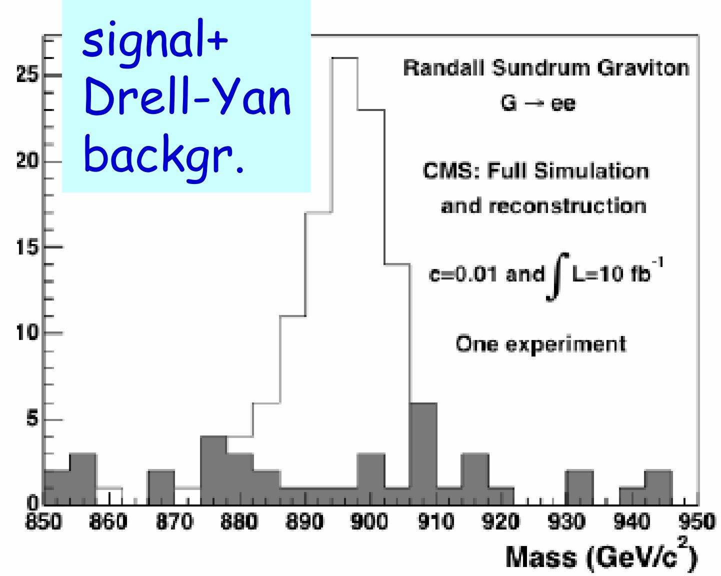
$ds^2 = e^{-2k|y|} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2$

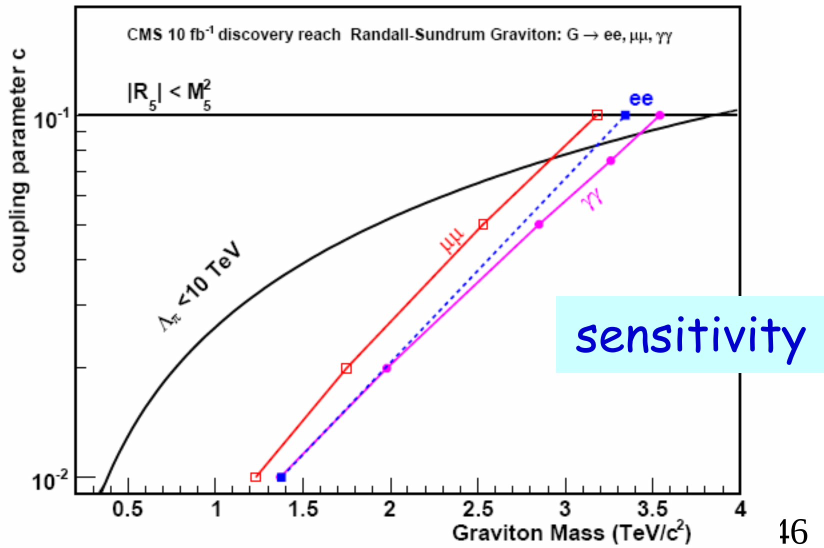


phenomenology



Study the channel pp→Graviton→ e+e-





What if Planck Scale in TeV Range?

- Schwarzschild radius

Landsberg, Dimopoulos
Giddings, Thomas

4-dim., $M_{gravity} = M_{Planck}$ $\quad R_S \sim \frac{2}{M_{Pl}^2}\frac{M_{BH}}{c^2}$

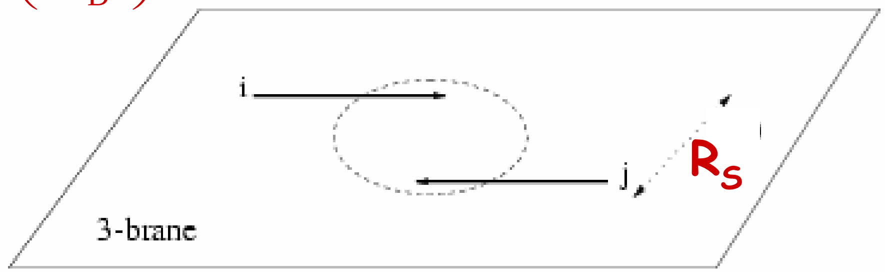
4 + n-dim., $M_{gravity} = M_D \sim$ TeV $\quad R_S \sim \frac{1}{M_D}\left(\frac{M_{BH}}{M_D}\right)^{\frac{1}{n+1}}$

$R_s \rightarrow \ll 10^{-35}$ m

$R_s \rightarrow \sim 10^{-19}$ m

⬇

Since M_D is low, tiny black holes of M_{BH} ~ TeV can be produced if partons ij with $\sqrt{s_{ij}} = M_{BH}$ pass at a distance smaller than R_S



- Large partonic cross-section : $\sigma(ij \rightarrow BH) \sim \pi R_S^2$
- $\sigma(pp \rightarrow BH)$ is in the range of 1 nb – 1 fb

e.g. For M_D ~1 TeV and n=3, produce 1 event/second at the LHC

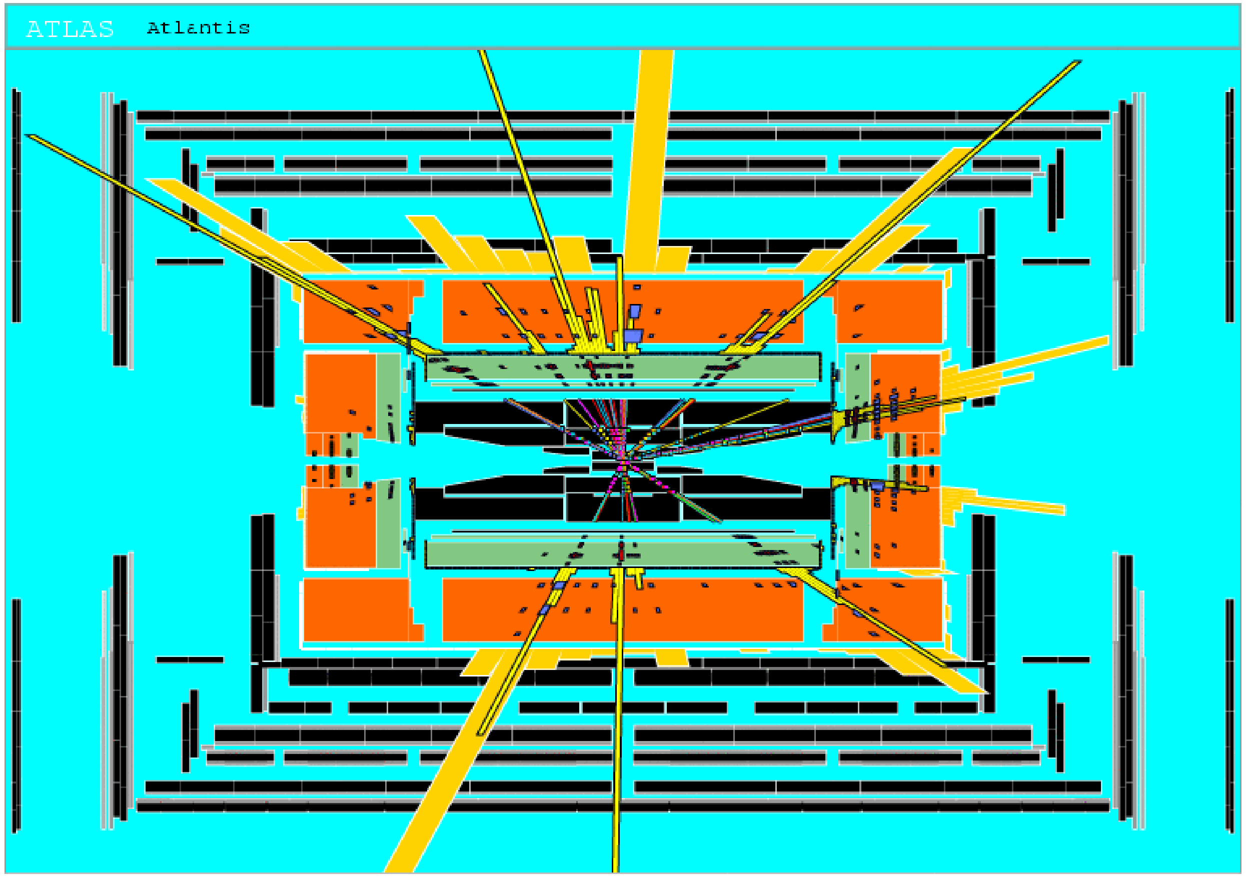
- Black holes decay immediately by Hawking radiation (democratic evaporation) :
  - -- large multiplicity
  - -- small missing E
  - -- jets/leptons ~ 5

} expected signature (quite spectacular …)

Black Holes production

If the Planck scale in ~TeV region: can expect Black Hole production

Simulation of a black hole event with M_{BH} ~ 8 TeV in ATLAS M_D ~ 1 TeV
n=6



~ Spherical events
Many high energy jets
leptons, photons etc.

Ecological comment:
BH's will decay within
10^{-27} secs or so

Detectors, electronics
(and rest of the world)
are safe!!

Black Holes Hunters at the LHC…

Recent Studies: New Signatures

Split Supersymmetry

- Assumes nature is fine tuned and SUSY is broken at some high scale
- The only light particles are the Higgs and the gauginos

 - Gluino can live long: sec, min, years!

 - R-hadron formation: slow, heavy particles containing a heavy gluino.

 Unusual interactions with material

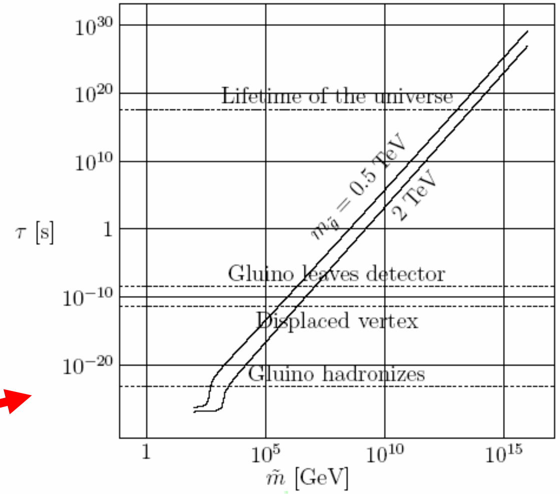
 eg. with the calorimeters of the experiments!

Gravitino Dark Matter and GMSB

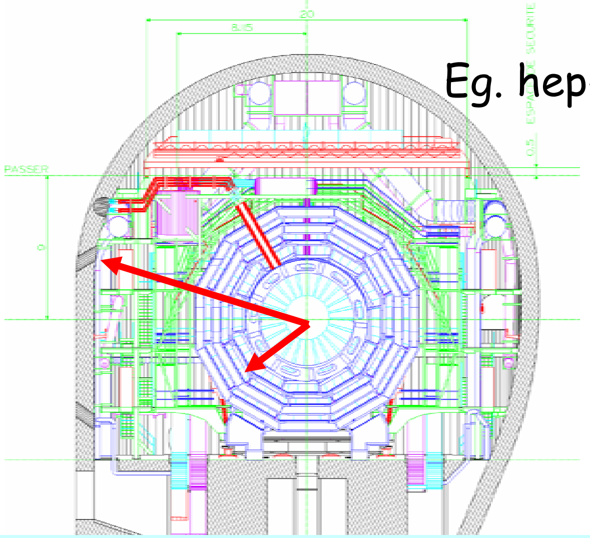
- In some models/phase space the gravitino is the LSP
- Then the NLSP (neutralino, stau lepton) can live 'long'

⇒Challenge to the experiments!

Arkani-Hamed, Dimopoulos hep-th/0405159

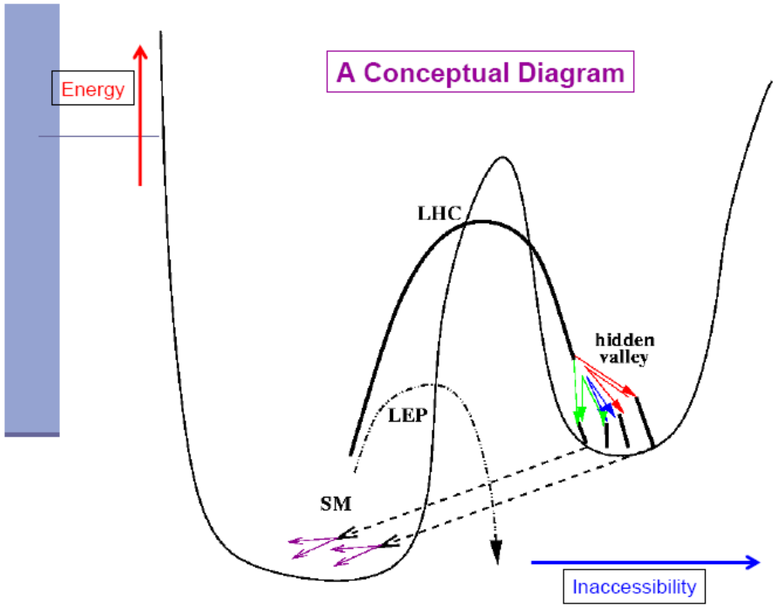


Eg. hep-ph/0508198



Sparticles stopped in the detector or walls around of the cavern.
They decay after hours---months…

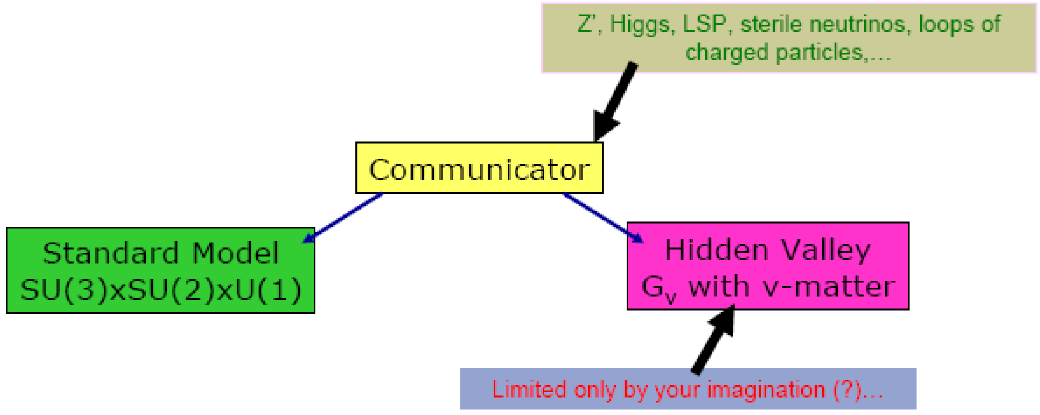
Hidden Valley Physics?



String Theory inspired (M. Strassler)

Eg. Strassler & Zurek hep-ph/0604261

- Basic minimal structure

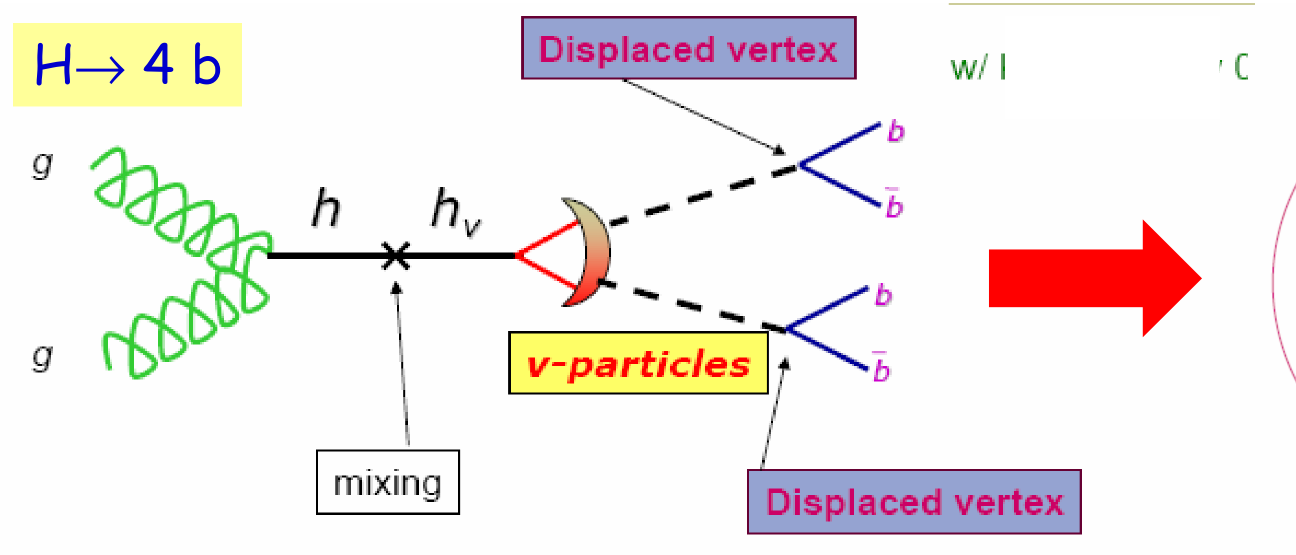


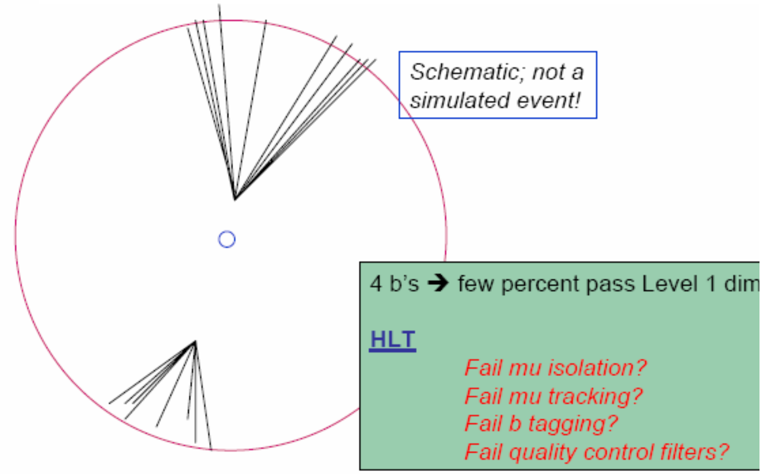
New possible phenomena that could occur in these models

- Higgs decays to two [or more] long-lived particles
  - ***Aside*** *on classes of possible decays of new particles*
- Z' decays to the v-sector:
  - *Final state with many particles, possibly long-lived*
- LSP decays to the v-sector
  - *Degradation of MET signal*
  - *Wide array of complex final states*

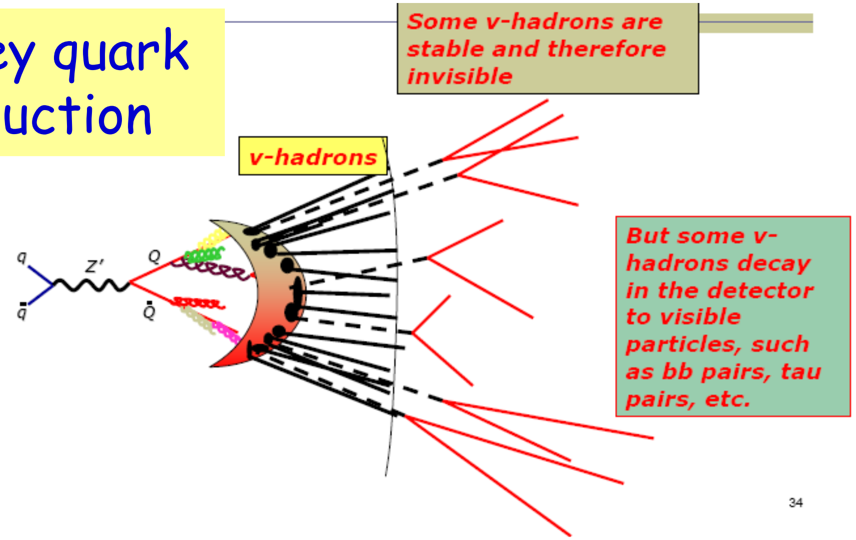
Some Hidden Valley Signals

H→ 4 b

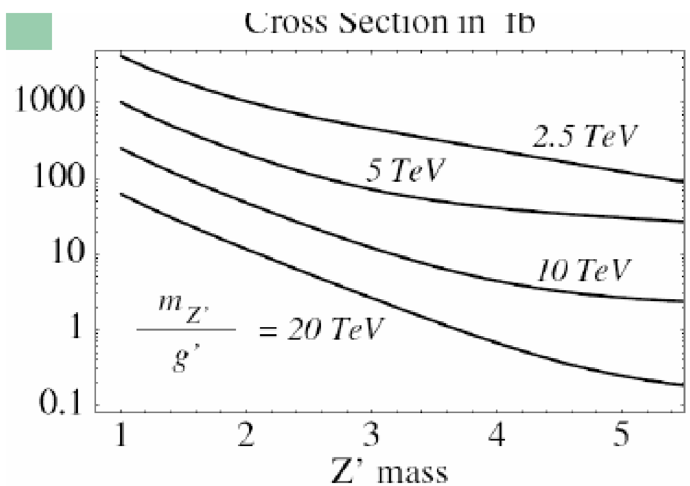




Valley quark production



Production rates for v-hadrons

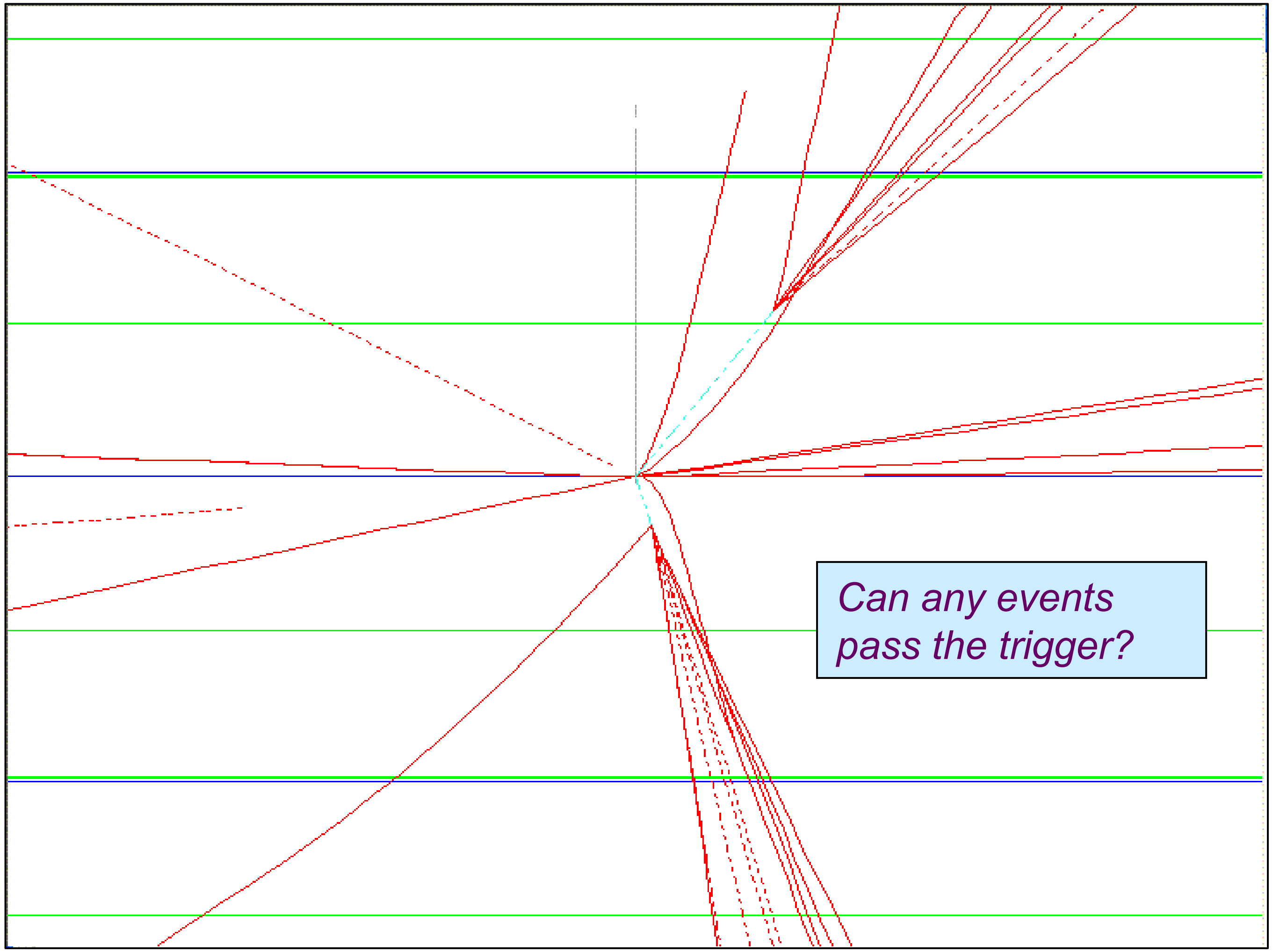


The Fear Factor: A real challenge for the triggers at the LHC

New Discovery Mode for the Higgs?

M. Strassler & K. Zurek   5/2006

Higgs Decays to Long-Lived Particles



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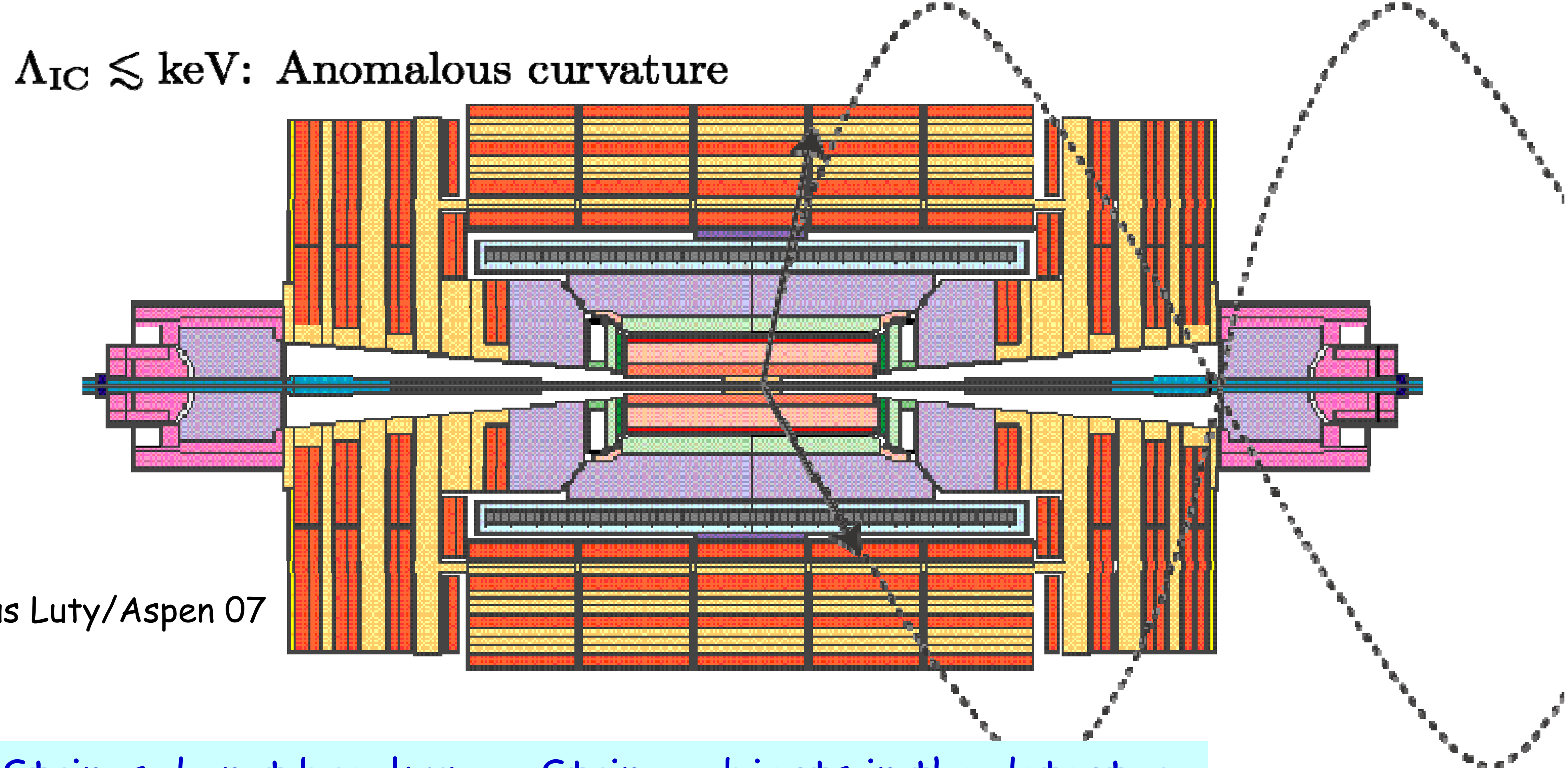
Lucia Zanello
Barbara Mele
Matt Strassler – simulation
Dan Ventura – this event
Laura Bodine – this event

New: (Colour) Strings at the LHC

Macro-strings: new strong interactions & new quarks m_Q> several hundered GeV



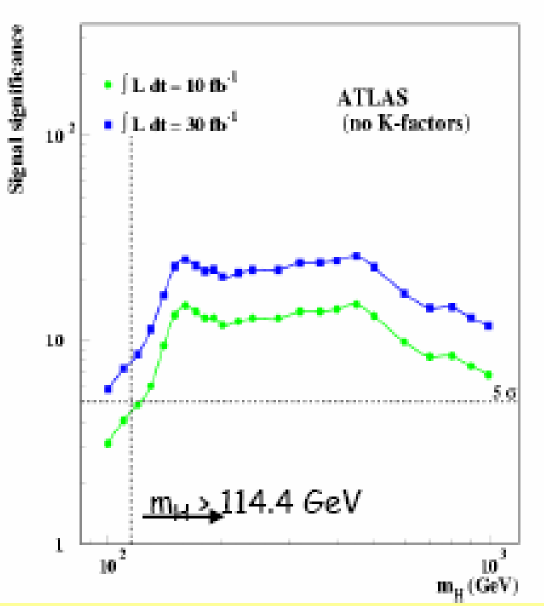
Markus Luty/Aspen 07

- Strings do not break up ⇒ Stringy objects in the detector.
- End points are massive quarks (quirks)
- The strings can oscillate⇒ strange signature in detectors

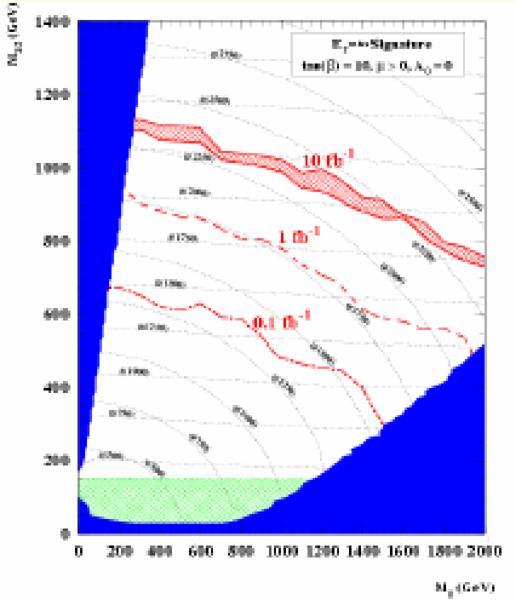
What can we expect in 2010 with 10 fb^{-1}?

"Early discoveries" at LHC

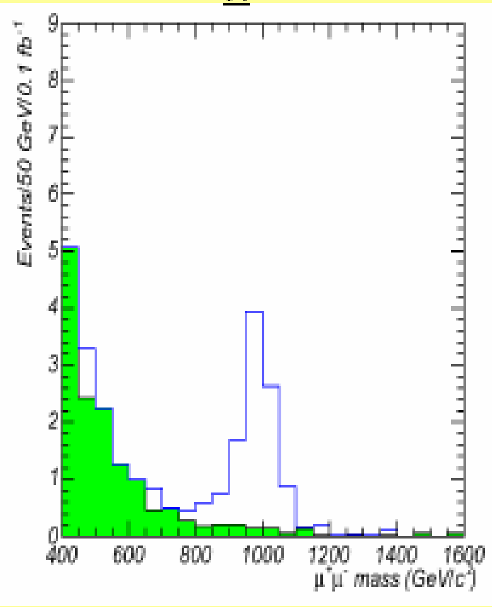
SM/MSSM Higgs



inclusive SUSY



di-lepton resonance (Z',RS,Z_H,...)



with 10 fb^{-1}:

full range

$m_{sq,gl}$<2-2.5 TeV in mSugra

m<~3 TeV dep. on model

Summary

- The LHC and its experiments are on track for first collisions in 2007 and physics runs starting from 2008 onwards
  - Challenge: commissioning of machine and detectors of unprecedented complexity, technology and performance
- The LHC should be decisive in revealing the Electro Weak Symmetry Breaking mechanism in the SM (SM Higgs/no Higgs)
- The LHC will break new ground in exploring the TeV scale and hunt for new physics (SUSY?, EDs?...)
  - Will it be easy or shall we have to sweat hard to make a discovery?
- Will the results have relevance for string theory?
  - (Supersymmetry, extra dimensions, black holes, stringballs…)

We will know more in 2008+ !!
Meanwhile: Enjoy the tour today !

And Maybe…

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%.

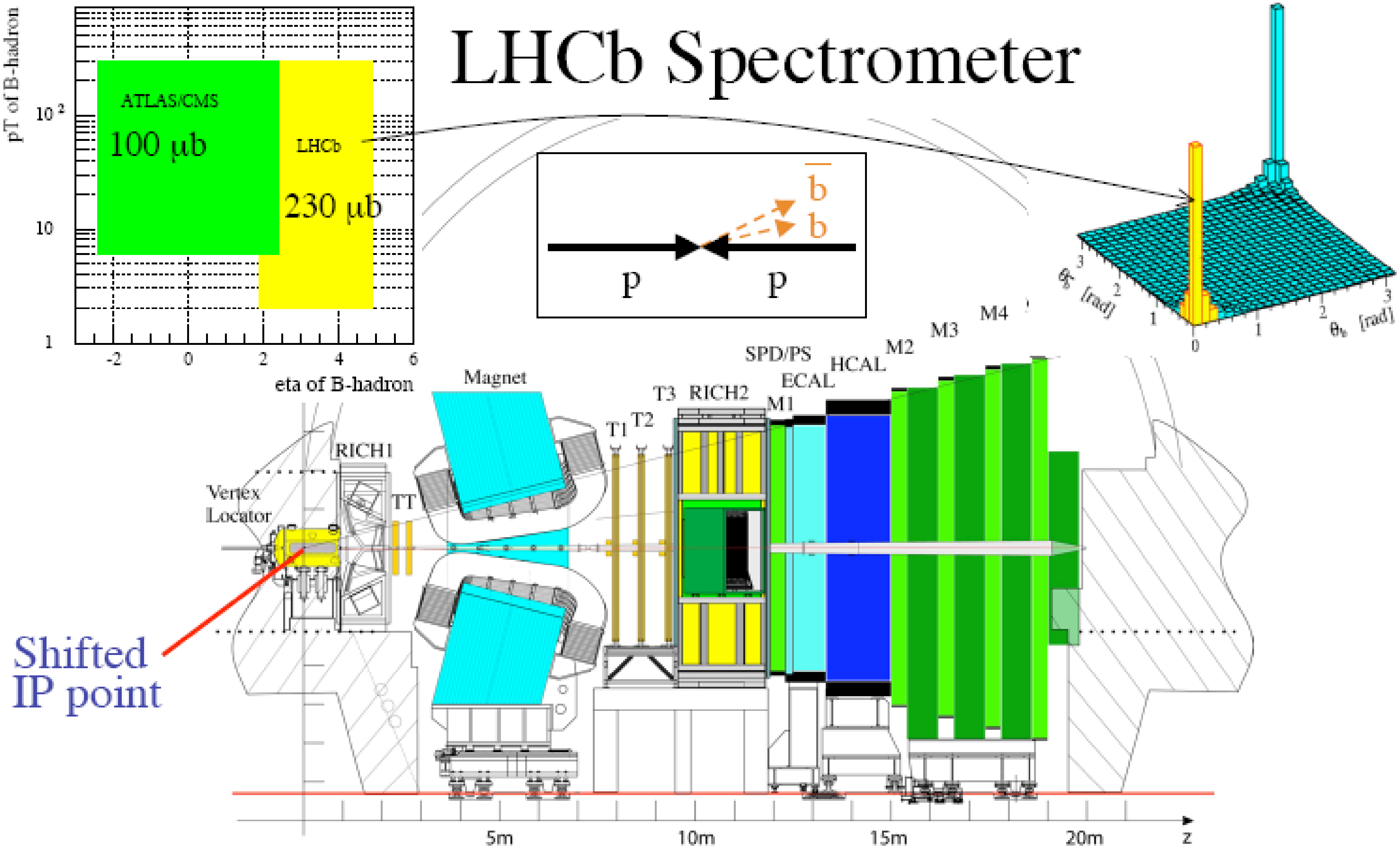
Submitted to *European Journal of Physics*

Backup slides

Main Message:
The LHC is Coming This Year

But 14 TeV collisions only in 2008…

LHCb Spectrometer



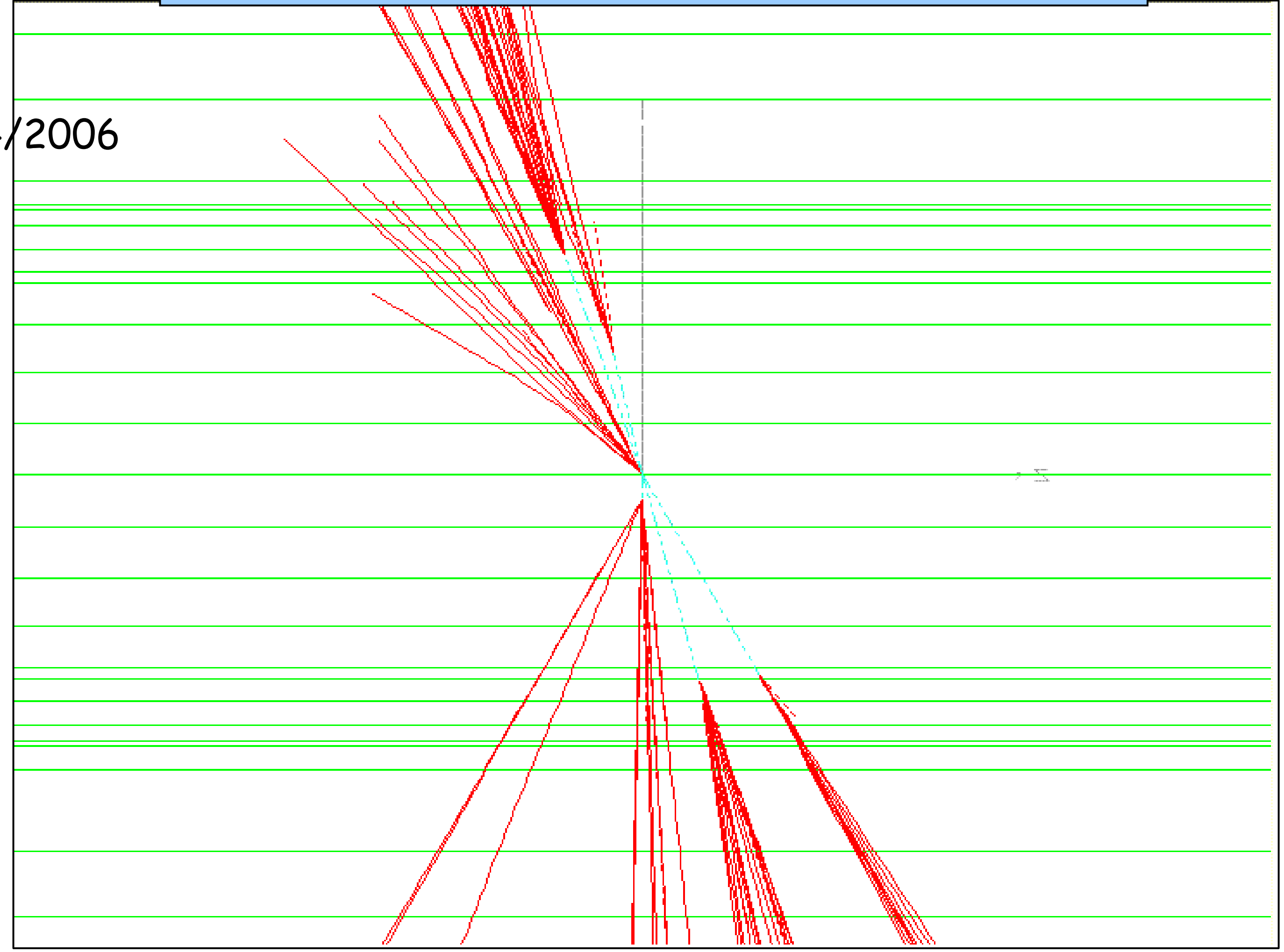
Good mass and eigentime resolution: VELO + tracking system
Hadron identification: RICH system
L0 Lepton and Hadron p_T trigger: Calorimeter and muon system

Hidden Valley

A currently-hidden sector, with light particles, and with ultraweak couplings to standard model; can easily arise in string theory

M. Strassler & K. Zurek 4/2006

Z' Decays to Long-Lived Hidden-Valley Particles



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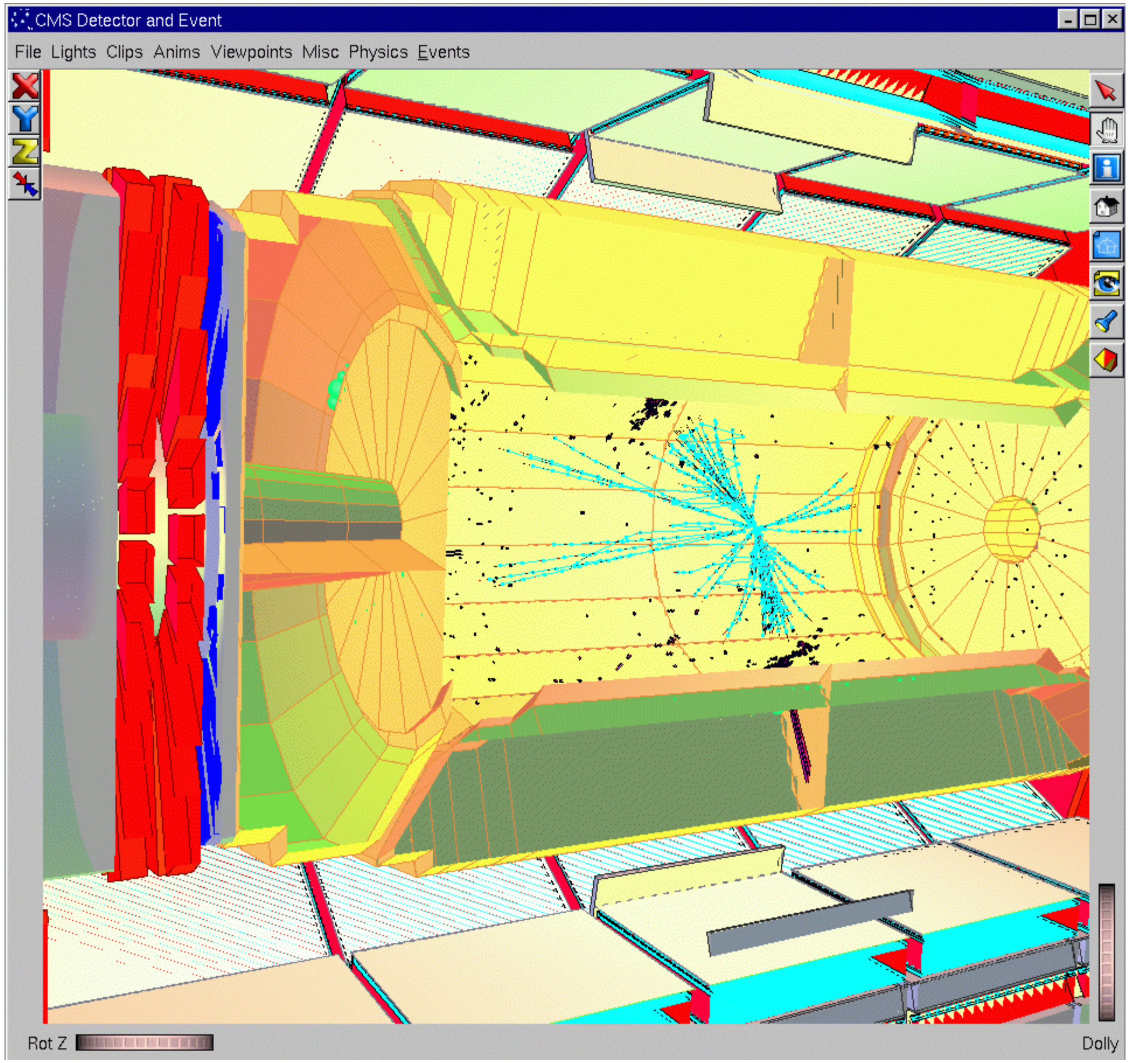
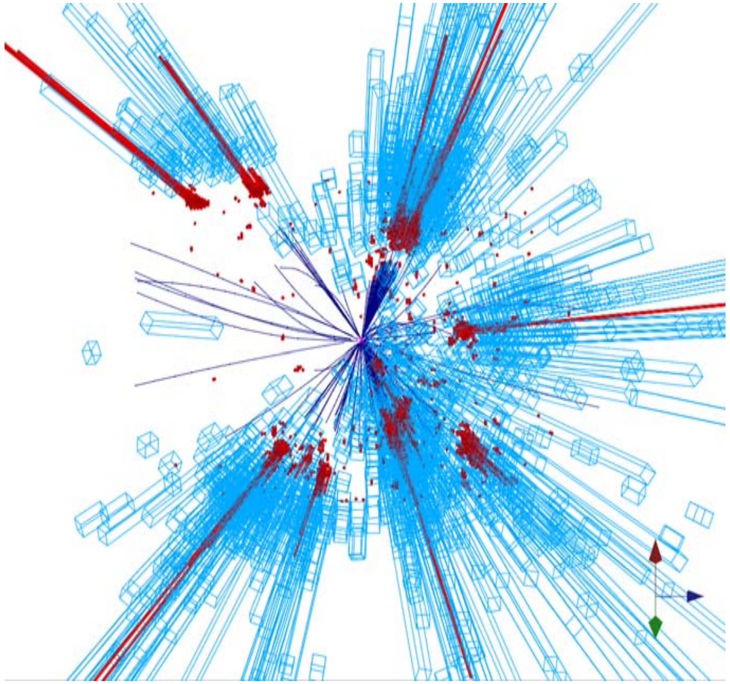
Black Holes

...and in CMS



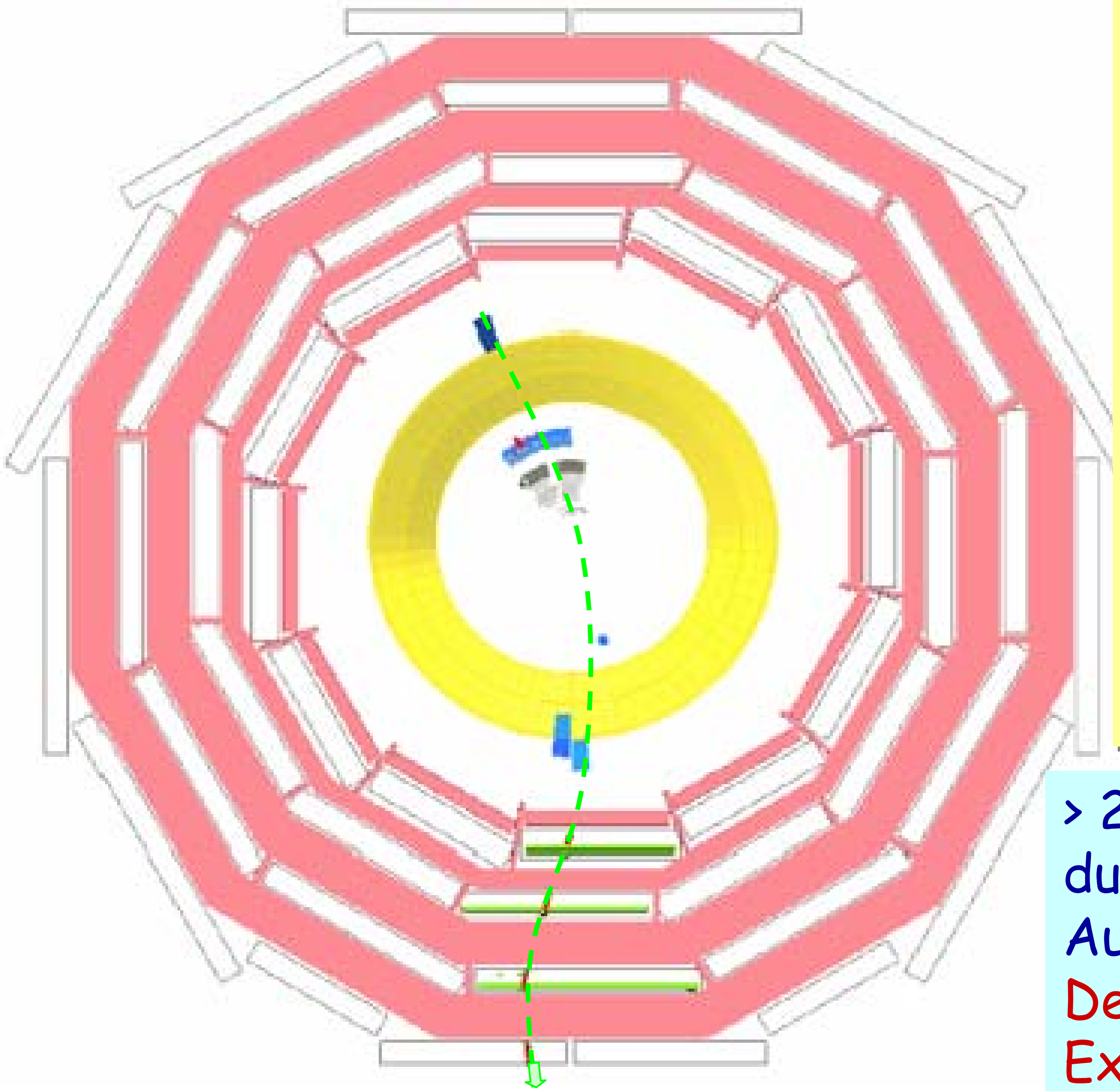


LHCb Summary

- LHCb expects to take B physics a significant step further than the B factories:
  - access to other b hadron species + high statistics
  - excellent vertexing and particle ID
  - flexible and efficient trigger, dedicated to B physics

  Many channels with different sensitivities to new physics
- Construction of the LHCb detector is advancing well
- Low luminosity ($\sim 10^{32}$) required for the LHCb experiment will allow to exploit full physics potential from the beginning of the LHC operation, and we will be ready for the pilot run in 2007 and the start of physics exploitation in Spring 2008

Magnet Test and Cosmic Data Challenge



Full 4-Tesla field reached in August 2006!

The "gold plated" event going through all central detectors and read out by central DAQ

- ✓ tracker,
- ✓ HCAL (top and bottom),
- ✓ ECAL,
- ✓ Muon Chambers

magnetic field of 3.8 Tesla

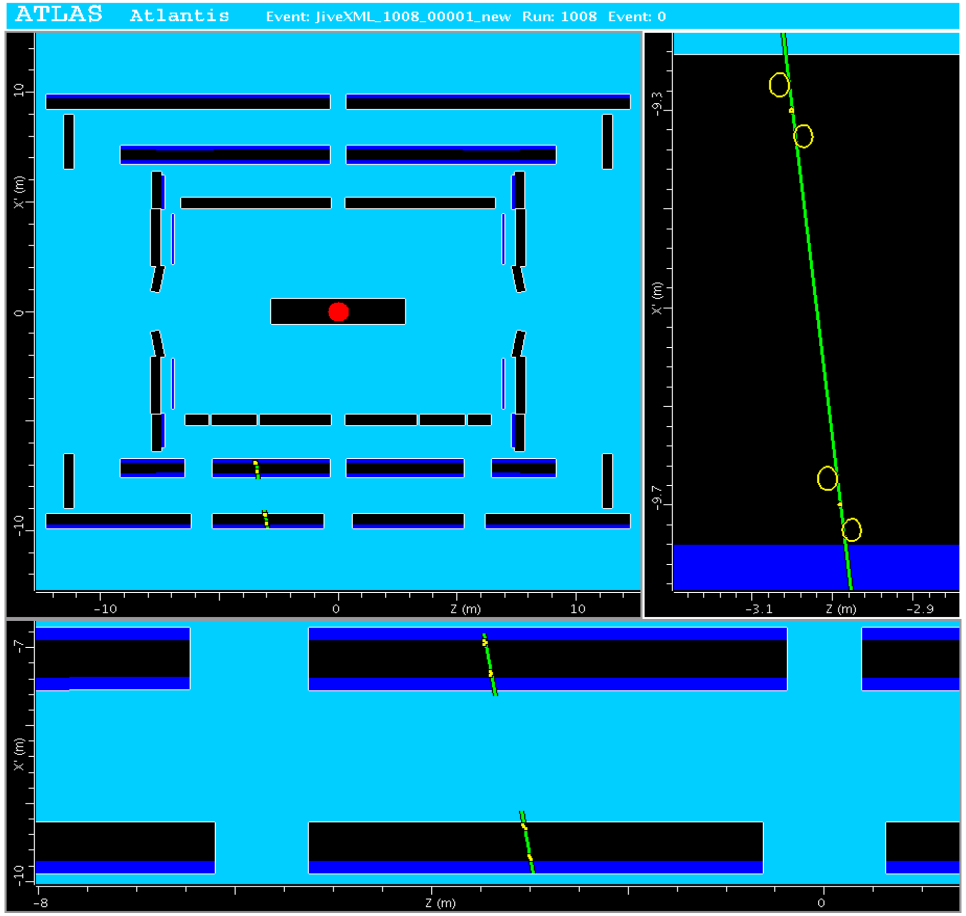
> $200 \bullet 10^6$ cosmic muons taken during the cosmic challenge August-October

Detector worked very well!

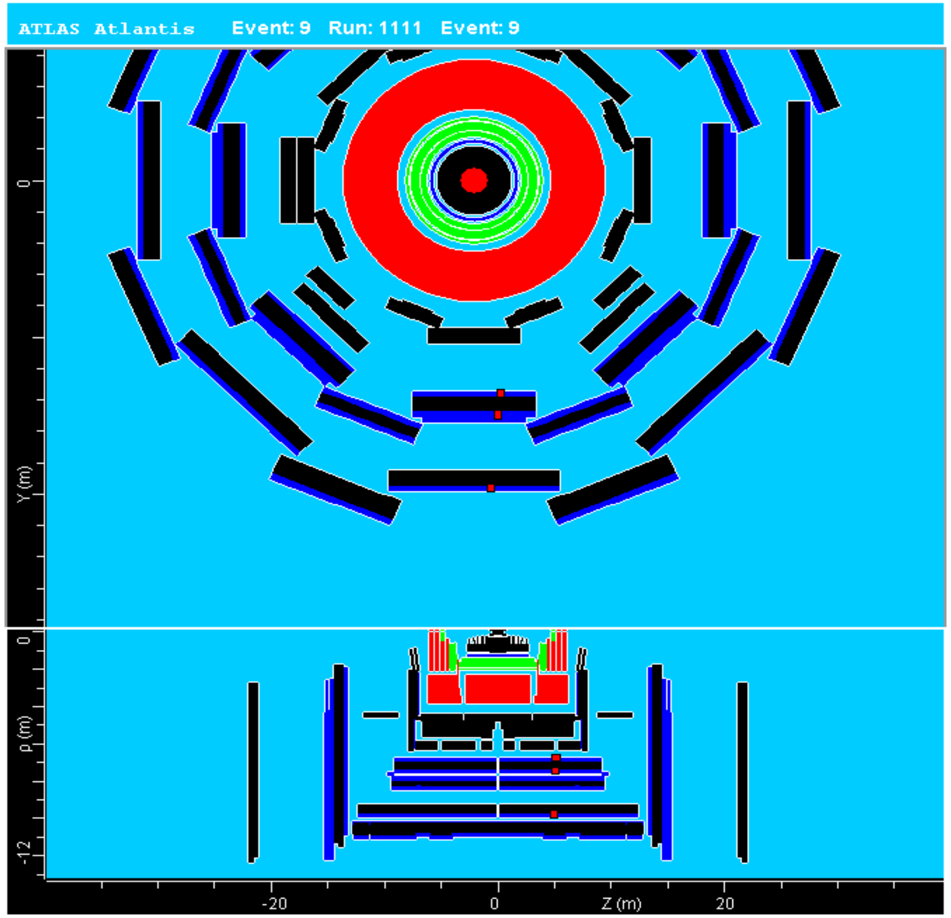
Excellent prospects for 2007!!

First cosmics have been registered *in situ* for barrel chambers

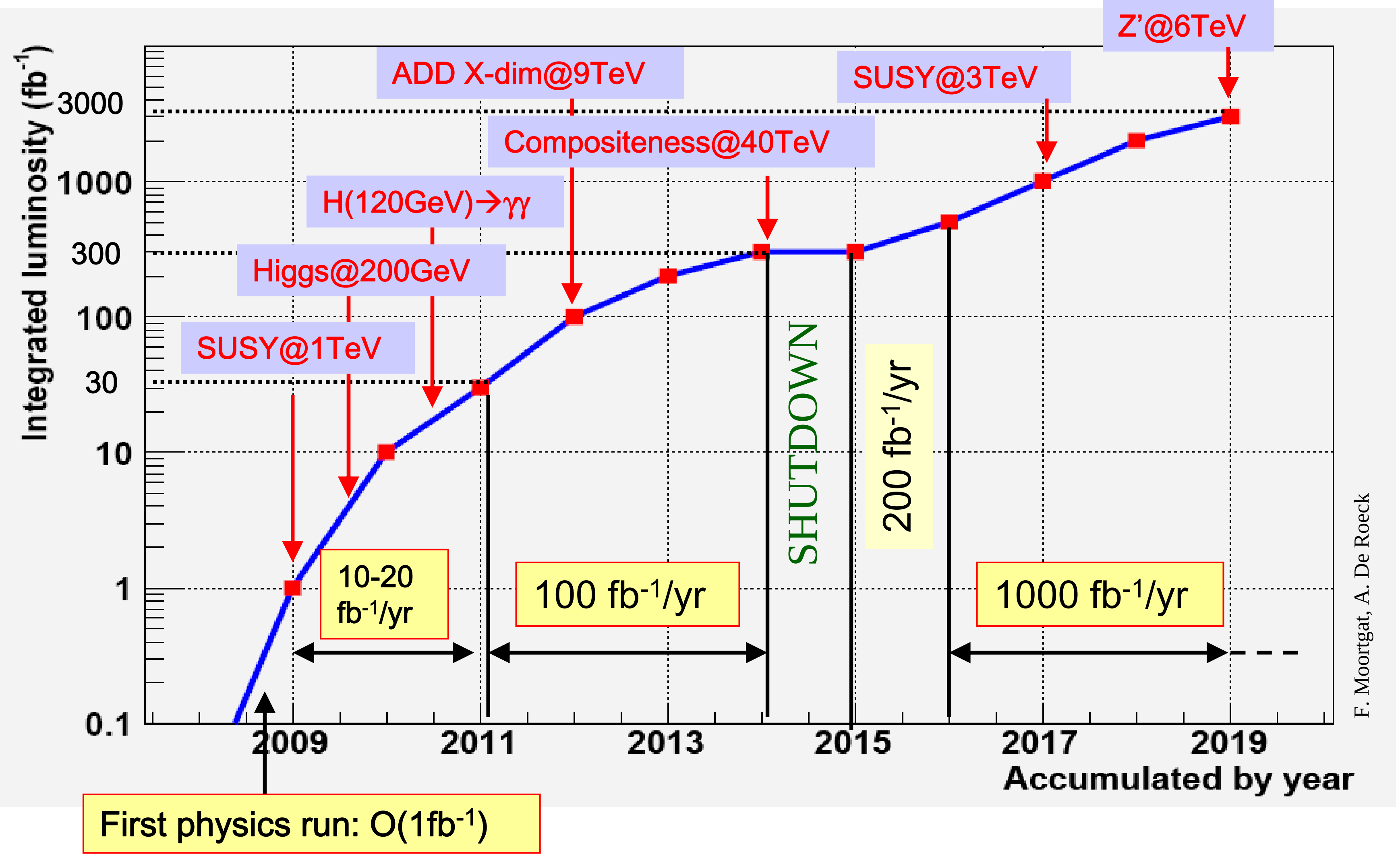
In December 2005 in MDTs



and in June 2006 in RPCs



Discovery/Luminosity Roadmap?



Is it SUSY?

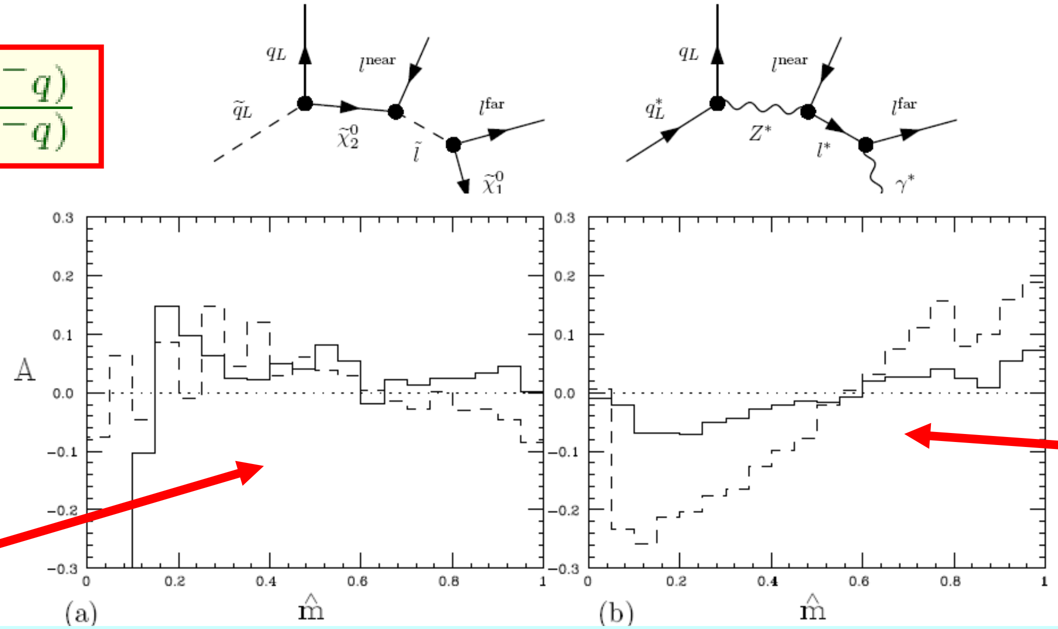
Example: Universal Extra Dimensions
Phenomenology: a Kaluza Klein tower pattern like a SUSY mass spectrum:
Can the LHC distinguish?

e.g. Cheng, Matchev, Schmaltz hep-ph/0205314

Look for variables sensitive to the particle spin eg. lepton charge asymmetries in squark/KKquark decay chains Barr hep-ph/0405052; Smillie & Webber hep-ph/0507170

$$A = \frac{(l^+q)-(l^-q)}{(l^+q)+(l^-q)}$$

KK like spectrum (small mass splitting)



SPS1a benchmark type spectrum

Method works better or worse depending on (s)particles spectrum

More discriminating variables needed!!

Event Rates for pp at $\sqrt{s}$=14 TeV

Process	Events/s	Events/year	Other machines
$W \rightarrow e\nu$	15	10^8	10^4 LEP / 10^7 Tev
$Z \rightarrow ee$	1.5	10^7	10^7 LEP
$t\bar{t}$	0.8	10^7	10^4 Tevatron
$b\bar{b}$	10^5	10^{12}	10^8 Belle/BaBar
$\tilde{g}\tilde{g}$ (m=1 TeV)	0.001	10^4	—
H (m=0.8 TeV)	0.001	10^4	—
Black Holes M_D=3 TeV n=4	0.0001	10^3	

Huge event rates: ($10^{33} cm^{-2} s^{-1}$)

The LHC will be a W-factory, a Z-factory, a top factory, a Higgs factory etc..

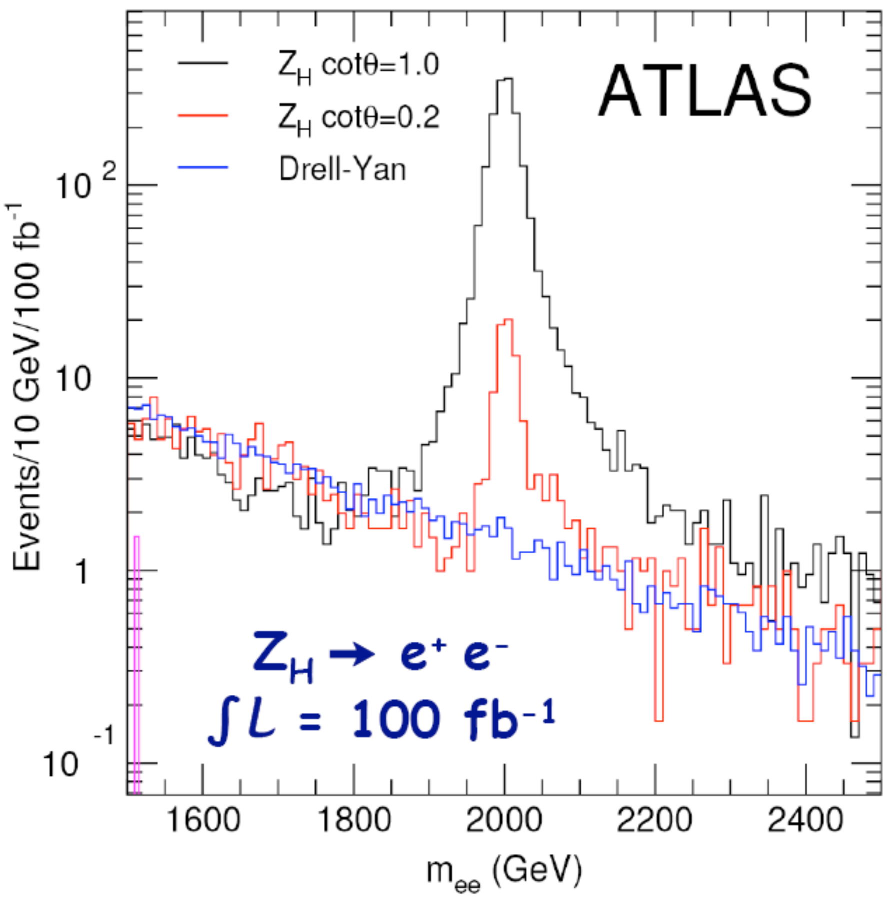
Precision EW physics measurements will be limited by systematics

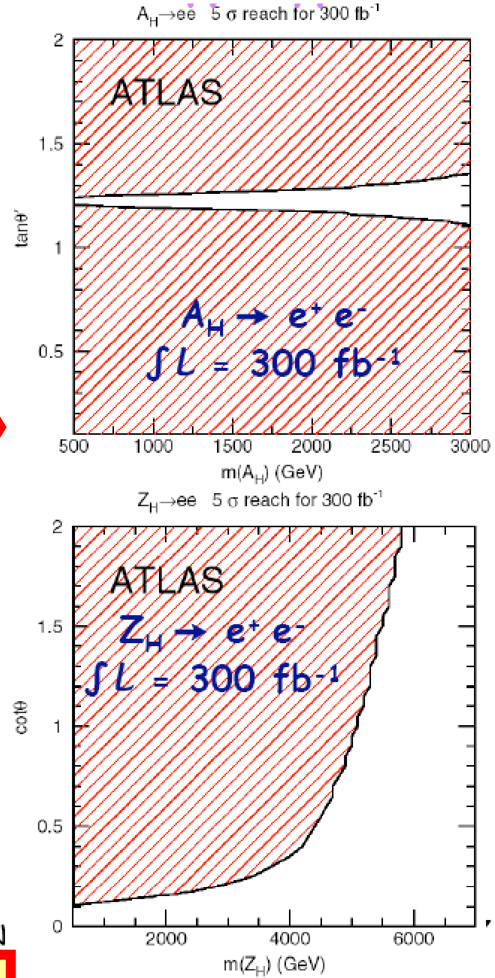
Minimum bias events: 10^8 per second or ~2-4 per bunch crossing!

Little Higgs Model A_H and Z_H

Signal : di-lepton resonance

Littlest Higgs Model
Arkani-Hamed et al., Han et al.

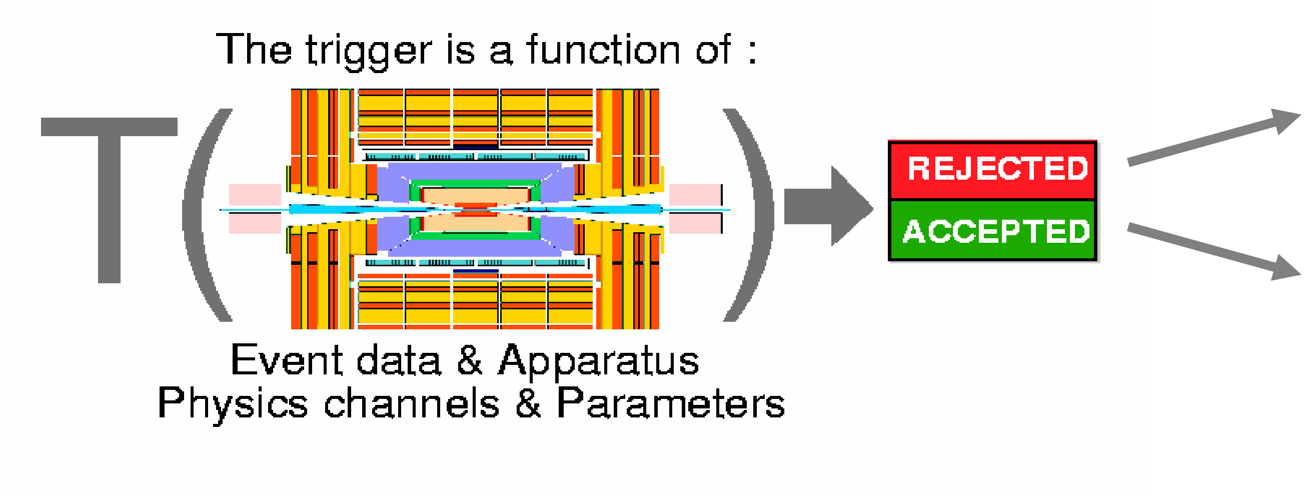




Reach up to 5.7 TeV depending on the θ angle

Event filtering: the trigger system

Collision rate is 40 MHz   Event size ~1 Mbyte
2007 technology (and budget) allows only to write 100 Hz of events to tape → need a factor ~10^7 online filtering!!



lost forever!!

written to disk for offline analysis

The event trigger is one of the biggest challenges at the LHC
⇒ Based on hard scattering signatures: jets, leptons, photons, missing Et,…

The LHC: 22+ Years Already!

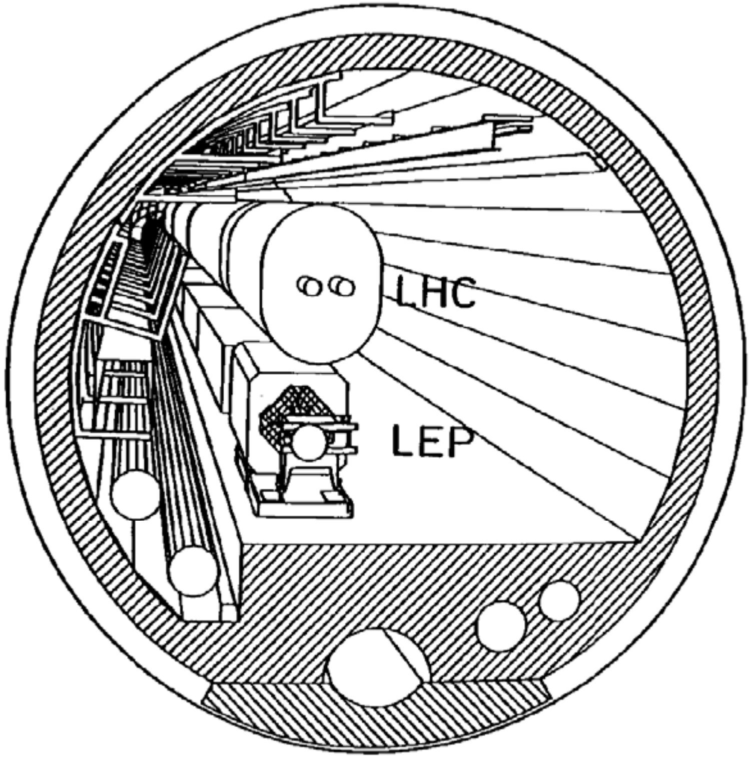
CERN: 50 YEARS AND COUNTING

The life of an experiment

1984	Workshop in Lausanne on installing a Large Hadron Collider (LHC) in the LEP tunnel
1987	CERN's long-range planning committee chaired by Carlo Rubbia recommends LHC as the right choice for lab's future
1989	ECFA Study Week on instrumentation technology for a high-luminosity hadron collider; Barcelona; LEP collider starts operation
1990	ECFA LHC workshop, Aachen
1992	General meeting on LHC physics and detectors, Evian-les-Bains
1993	Letters of intent for LHC detectors submitted
1994	Technical proposals for ATLAS and CMS approved/LHC
1998	Construction begins
2000	CMS assembly begins above ground; LEP collider closes
2003	ATLAS underground cavern completed and assembly started
2004	CMS cavern completed
2007	Experiments ready for beam
2007	First proton–proton collisions
2008	First results
2010	Reach design luminosity
>2014	Upgrade LHC luminosity by factor of 10

1984

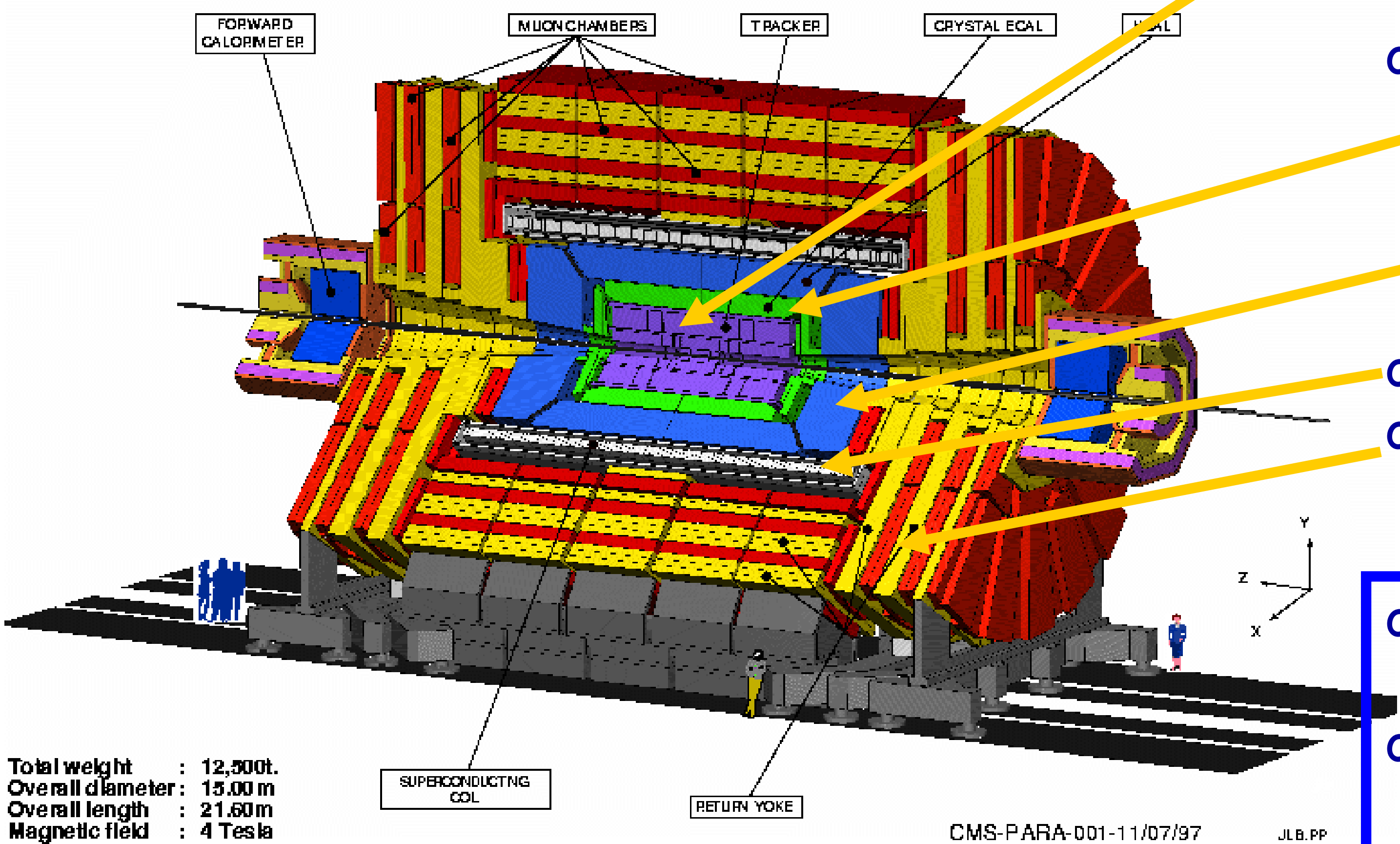
ECFA 84/85
CERN 84-10
5 September 1984



1984: cms energy 10-18 TeV
Luminosity 10^{31}-10^{33}cm^{-2}s^{-1}
1987: cms energy 16 TeV
Luminosity 10^{33}-10^{34}cm^{-2}s^{-1}
Final: cms energy 14 TeV
Luminosity 10^{33}-10^{34}cm^{-2}s^{-1}

Example: The CMS experiment

~2300 people/~150 institutes

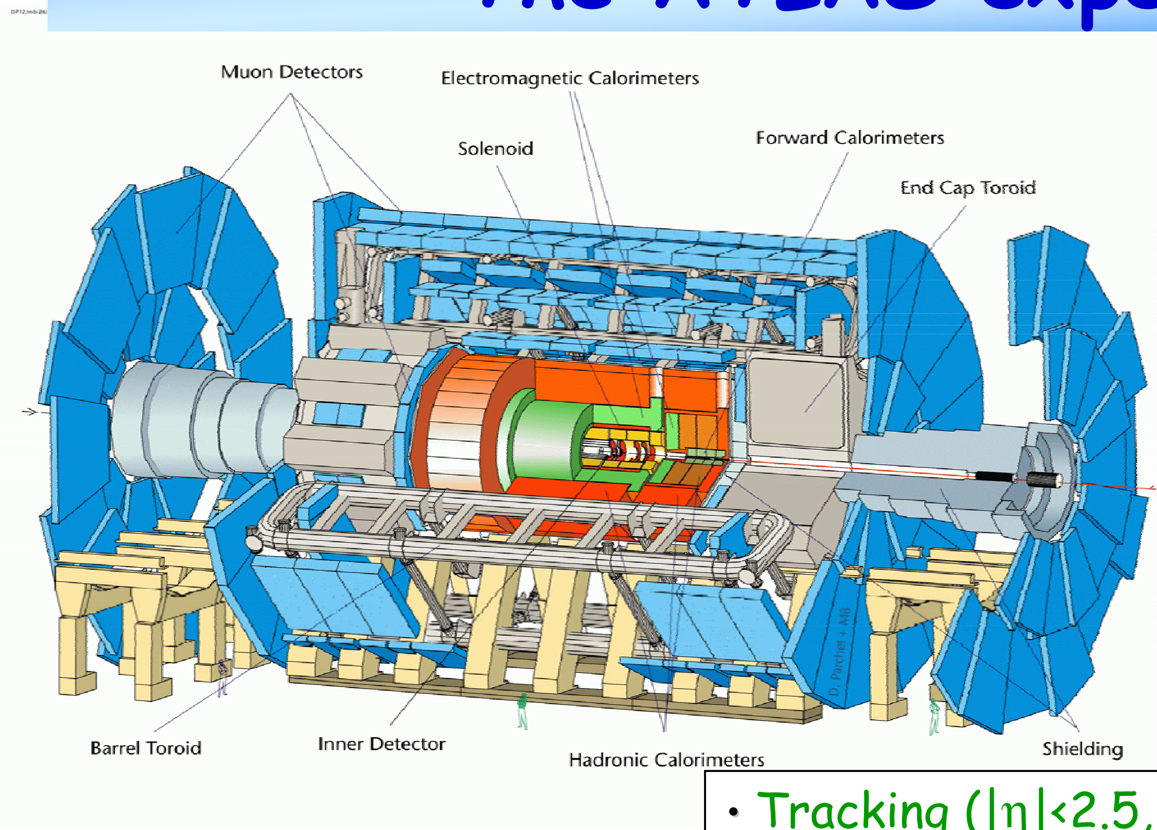


- Tracking
  - Silicon pixels
  - Silicon strips
- Calorimeters
  - PbW04 crystals for Electro-magn.
  - Scintillator/steel for hadronic part
- 4T solenoid
- Instrumented iron for muon detection

A Huge Enterprise !

- In total about 98 000 000 channels
- Size of 1 event 1 000 000 Bytes
- Readout to disk 100 events/sec

The ATLAS experiment



ATLAS

Weight : ~ 7000 tons

Length = 55 m
Width = 32 m
Height = 35 m

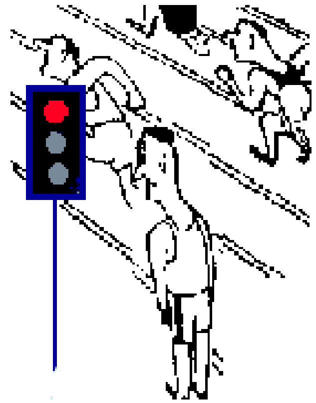
- Tracking ($|\eta|<2.5$, B=2T) :
  -- Si pixels and strips
  -- Transition Radiation Detector (e/π separation)
- Calorimetry ($|\eta|<5$) :
  -- EM : Pb-LAr
  -- HAD: Fe/scintillator (central), Cu/W-LAr (fwd)
- Muon Spectrometer ($|\eta|<2.7$) :
  air-core toroids with muon chambers

Detectors at Start-up in 2007

❷ Which detectors the first year ?

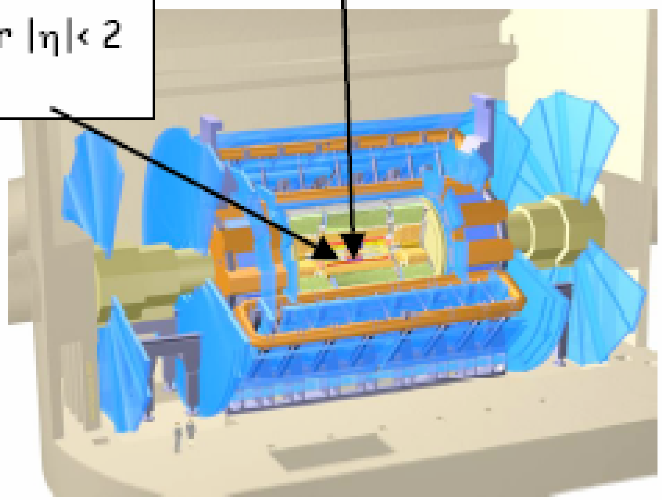
RPC over $|\eta|<1.6$ (instead of $|\eta|< 2.1$)
4^{th} layer of end-cap chambers missing

Pixels and end-cap ECAL
installed during first shut-down



Detectors progressing well and
will be fairly complete at start-up

TRT acceptance over $|\eta|< 2$
(instead of $|\eta|< 2.4$)

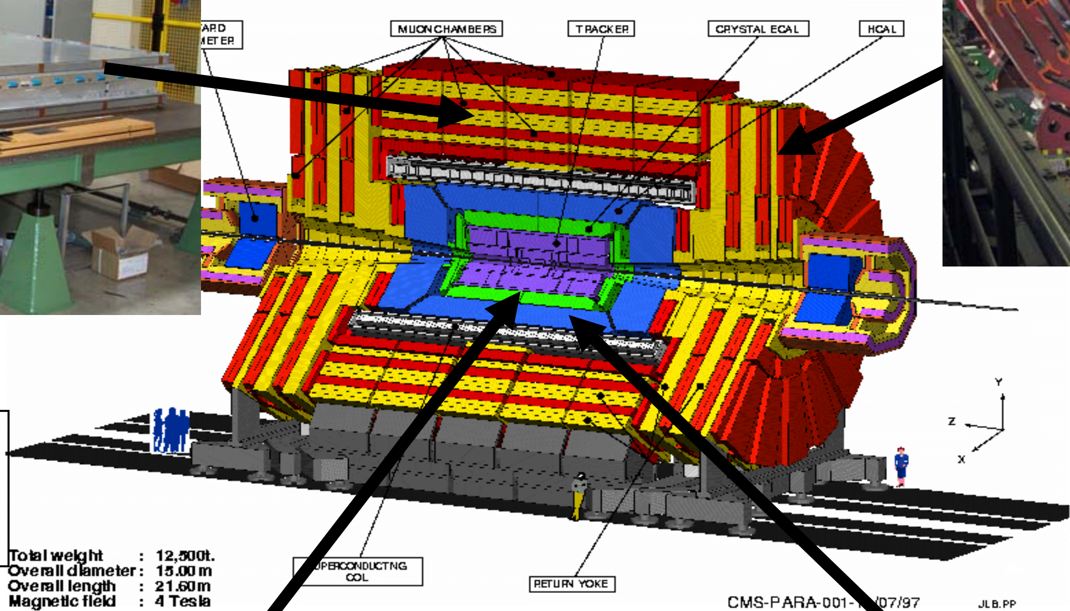


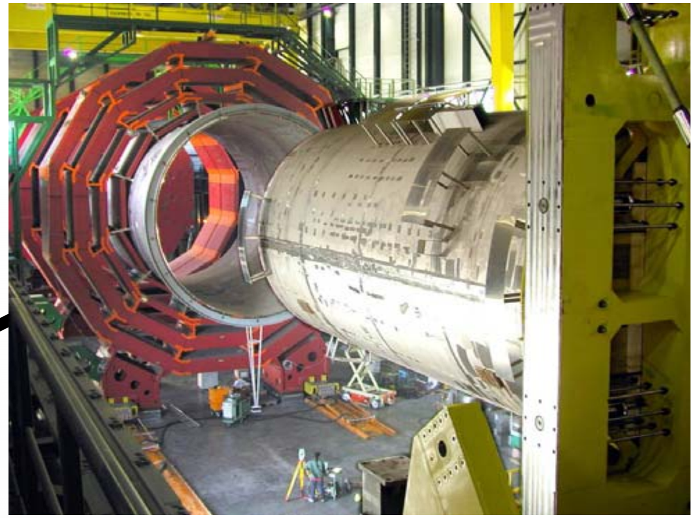
Both experiments:
deferrals of high-level Trigger/DAQ processors
→ LVL1 output rate limited to
~ 50 kHz CMS (instead of 100 kHz)
~ 40 kHz ATLAS (instead of 75 kHz)

Impact on physics visible but acceptable
Main loss : B-physics programme strongly reduced (single μ threshold $p_T > 14\text{-}20$ GeV)

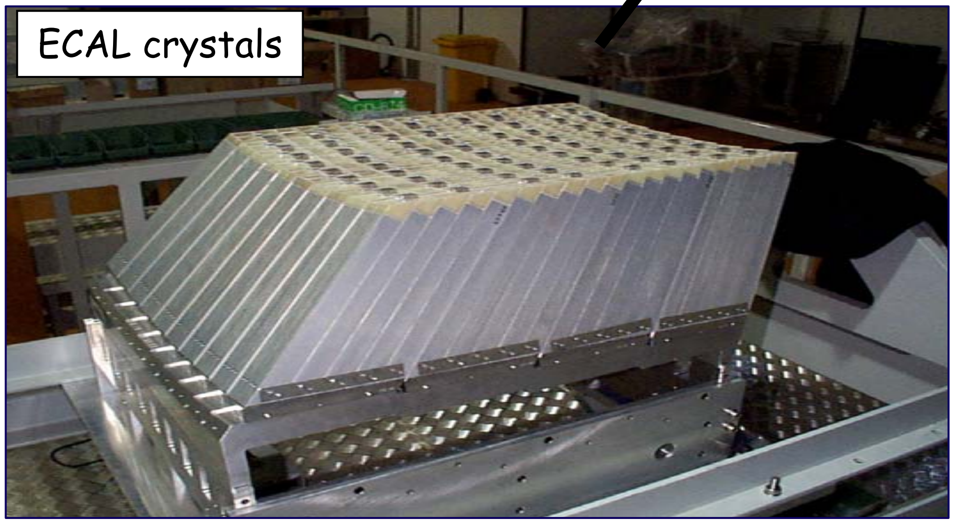
CMS

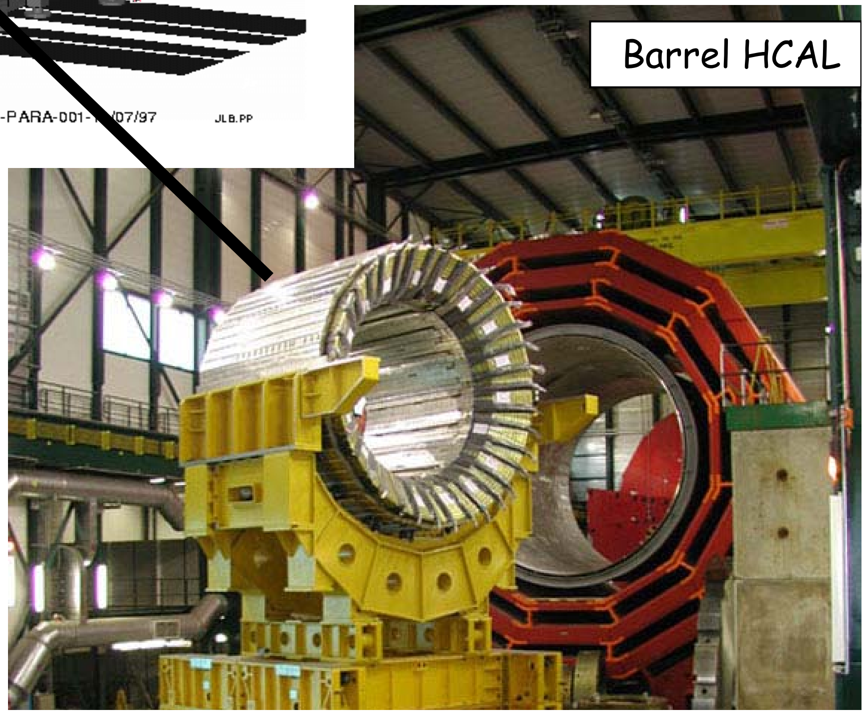

Barrel Muon Chamber





Length : ~20 m
Radius : ~7 m
Weight : ~ 13000 tons


ECAL crystals


Barrel HCAL

Detector performance

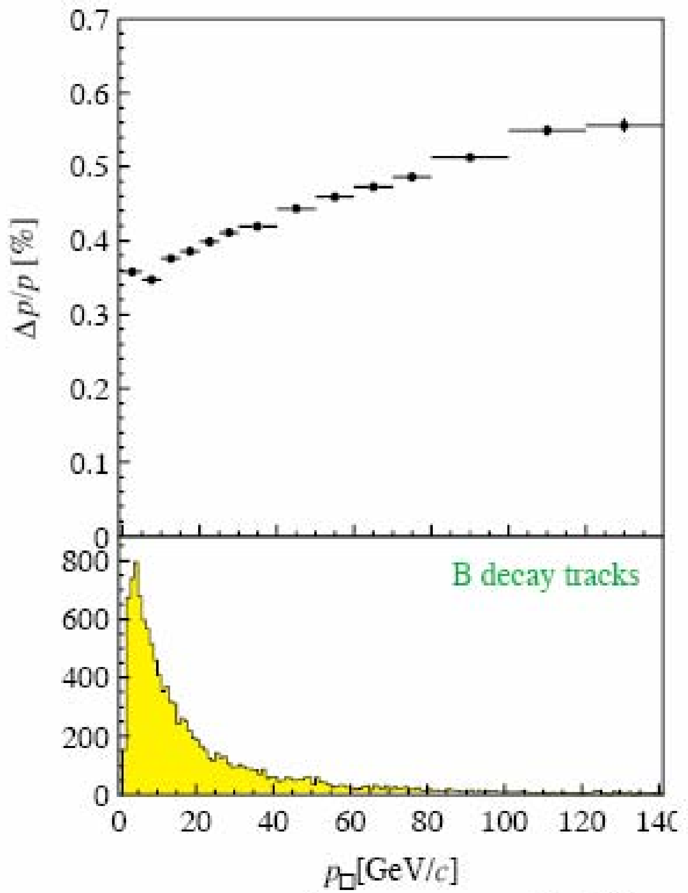
	Expected Day 0	Goals for Physics
ECAL uniformity	~ 1% ATLAS ~ 4% CMS	< 1%
Lepton energy scale	0.5—2%	0.1%
HCAL uniformity	2—3%	< 1%
Jet energy scale	<10%	1%
Tracker alignment	20—200 μm in Rϕ	$\mathcal{O}$(10 μm)

ATLAS ⇔ CMS

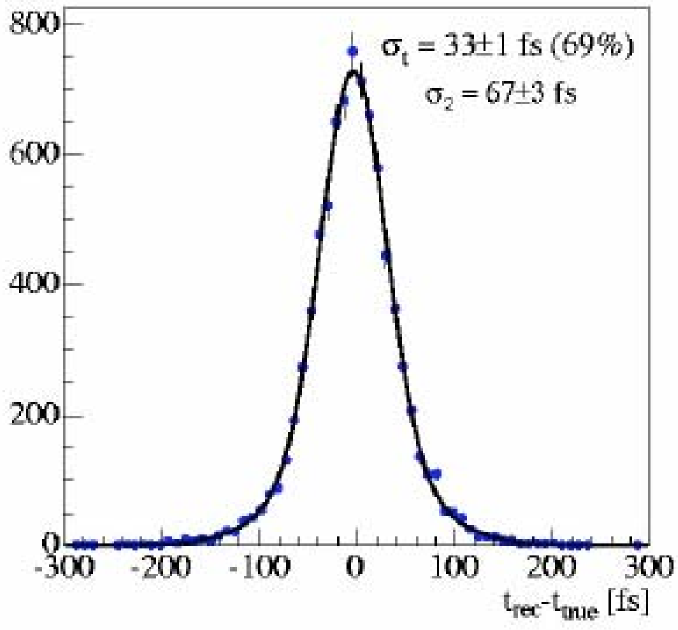
	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid in inner cavity 4 magnets Calorimeters in field-free region	Solenoid Only 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 5\text{x}10^{-4}\, p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\text{x}10^{-4}\, p_T \oplus 0.005$
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 segm.
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 7$ % at 1 TeV standalone	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

LHCb tracking performance

VELO + ST + OT + Magnet



momentum resolution

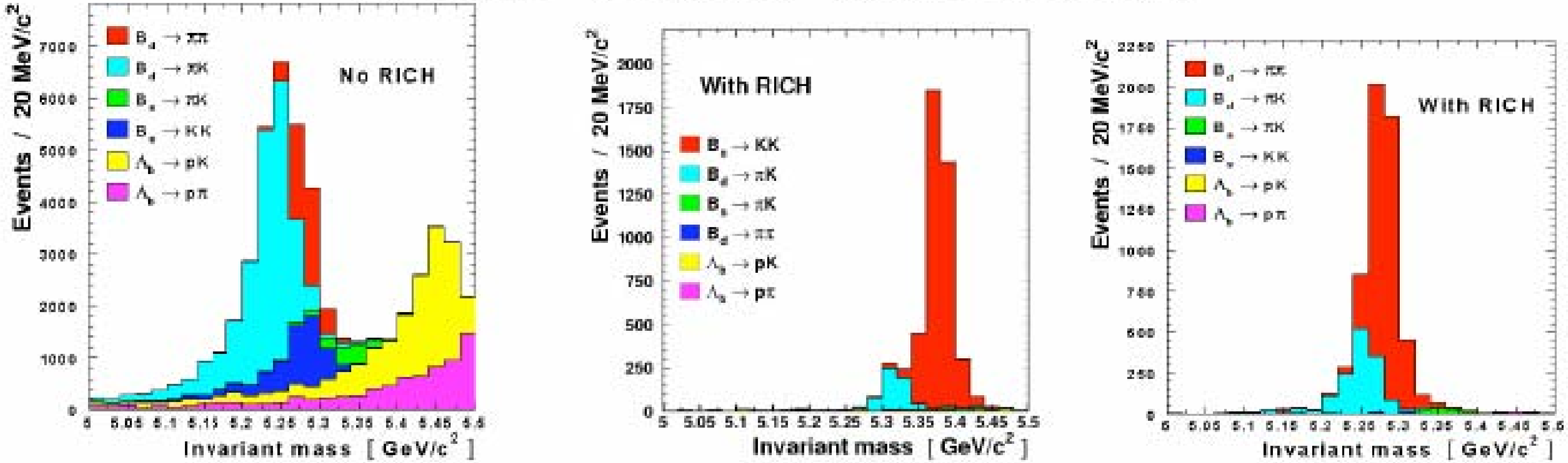


Proper time resolution ~ 40 fs

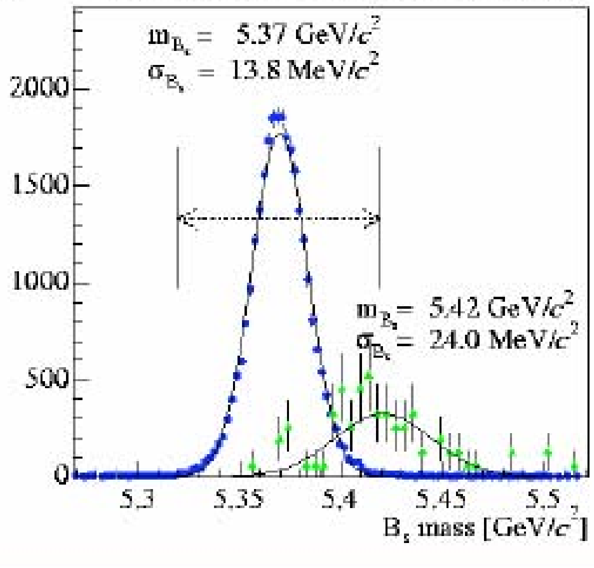
$B_s \to D_s^- \pi^+$

Particle identification

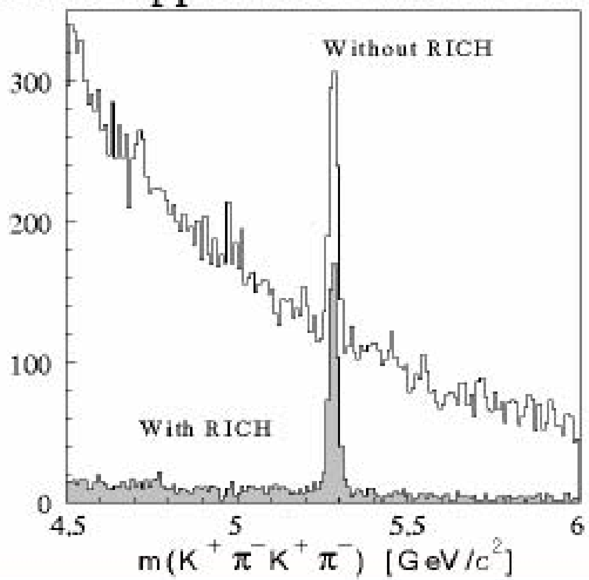
PID for B→ππ and B_s→KK reconstruction



$B_s \to D_s\pi$ suppression with PID for $B_s \to D_sK$



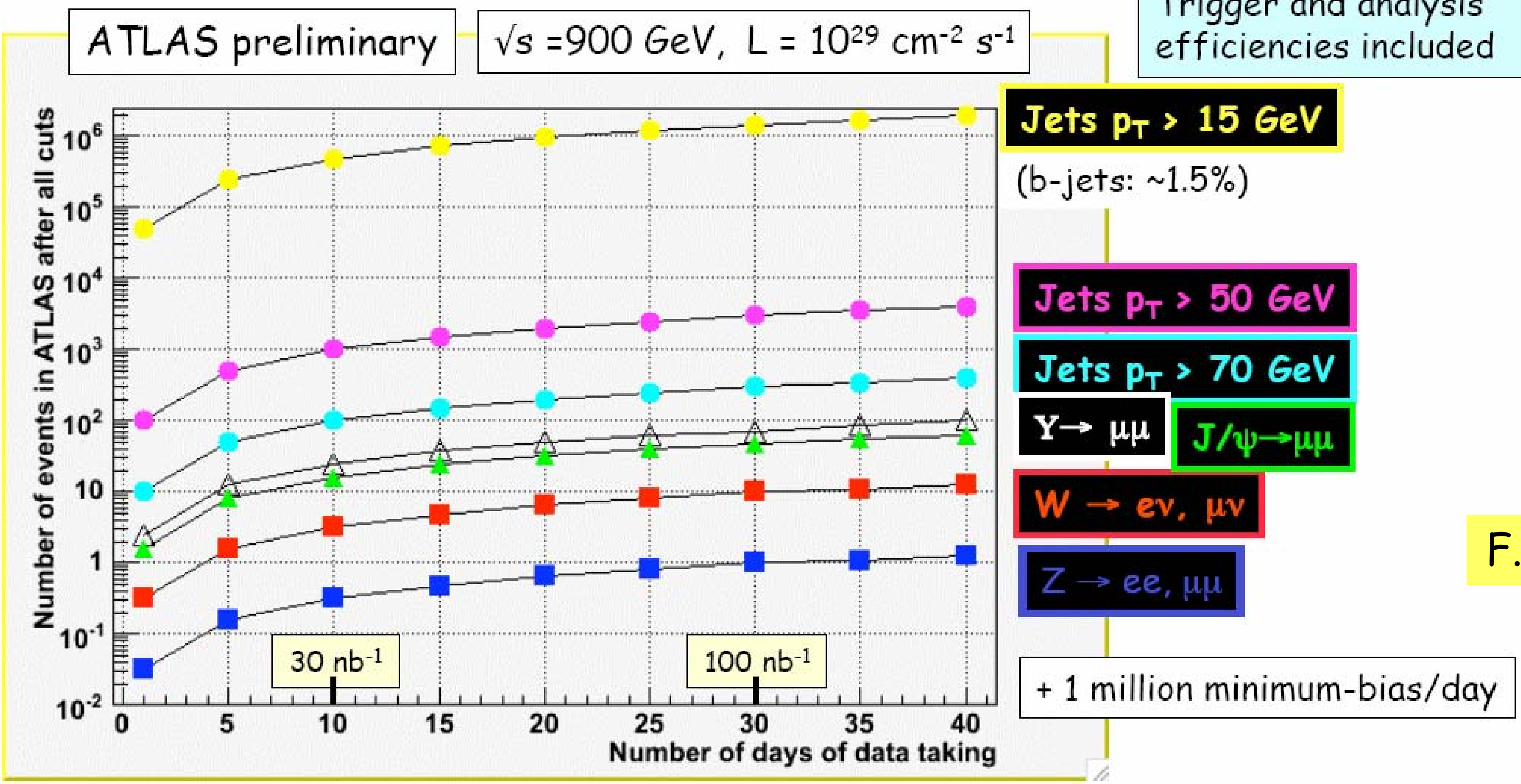
Comb. suppression with PID for $B \to DK^{*0}$



Start-up Physics: 2007

What data samples in 2007 ?

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



F. Gianotti/ICHEP06

- 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 $W \to l\nu$, $\Upsilon \to \mu\mu$, $J/\psi \to \mu\mu$?

Start-up Physics 2008

With the first physics run in 2008 ($\sqrt{s}$ = 14 TeV) ....

0.1-1 fb^{-1}

1 fb^{-1} (100 pb^{-1}) ≡ 6 months (few days) at L= 10^{32} $cm^{-2}s^{-1}$ with 50% data-taking efficiency
→

Channels (examples ...)	Events to tape for 100 pb^{-1} (per expt: ATLAS, CMS)	Total statistics from some of previous Colliders
$W \to \mu\nu$	~ 10^6	~ 10^4 LEP, ~ 10^6 Tevatron
$Z \to \mu\mu$	~ 10^5	~ 10^6 LEP, ~ 10^5 Tevatron
$tt \to WbWb \to \mu\nu + X$	~ 10^4	~ 10^4 Tevatron
QCD jets p_T > 1 TeV	> 10^3	---
$\tilde{g}\tilde{g}$ m = 1 TeV	~ 50	---

With these data:

- Understand and calibrate detectors in situ using well-known physics samples
  e.g. - $Z \to ee, \mu\mu$ tracker, ECAL, Muon chambers calibration and alignment, etc.
  - $tt \to bl\nu\, bjj$ jet scale from $W \to jj$, b-tag performance, etc.

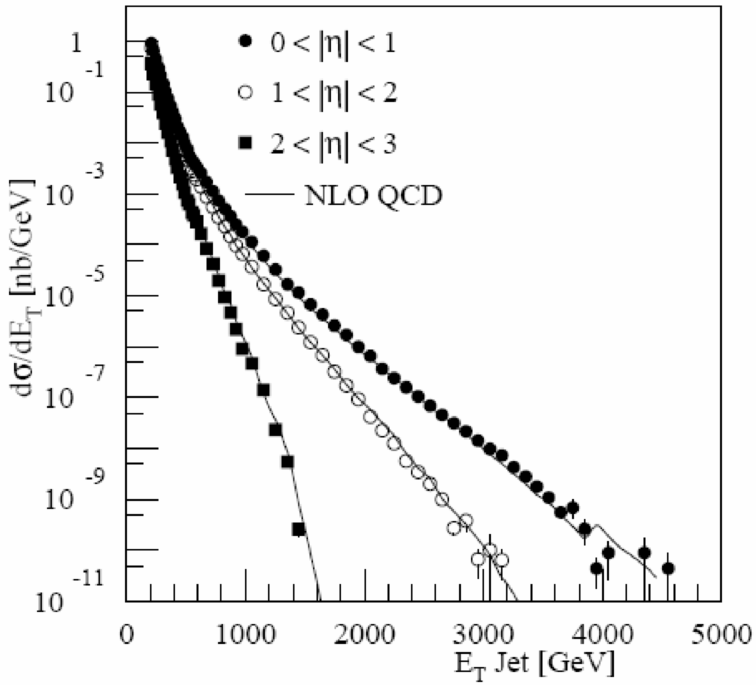
- Measure SM physics at $\sqrt{s}$ = 14 TeV : W, Z, tt, QCD jets ...
  (also because omnipresent backgrounds to New Physics)

→ prepare the road to discovery ...... it will take time ...

QCD Studies @ LHC

E.g. Jet Physics

Huge cross sections:
Eg for 1 fb^{-1} ~ 10000 events with E_T> 1 TeV
100 events with E_T> 2 TeV



- PDFs
- Jet shape
- Underlying event
- α_s
- Diffraction
- BFKL studies
- low-x
- New physics?
- …

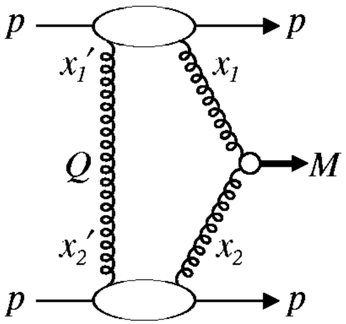
•Understanding QCD at 14 TeV will be one of the first topics at LHC

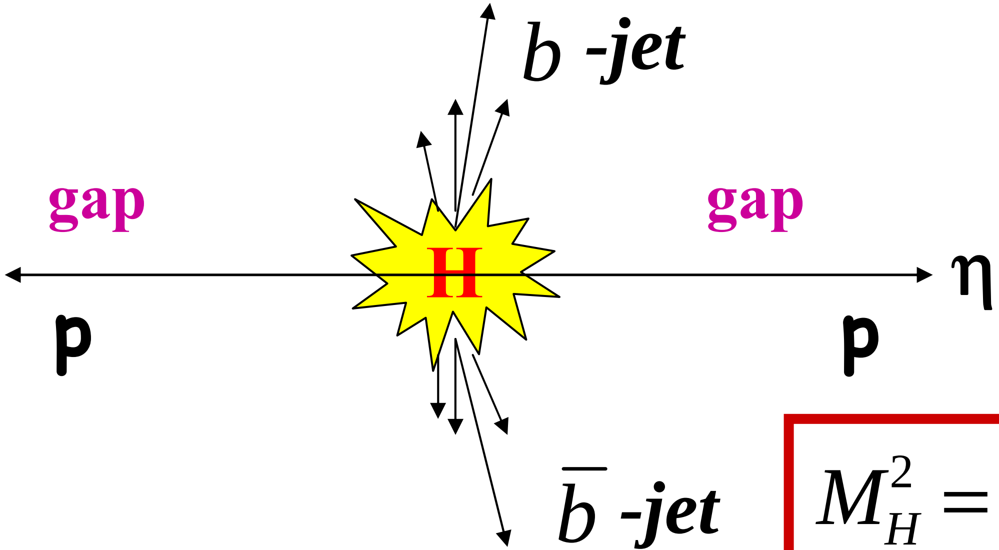
…and a whole b-physics program

Central Exclusive Higgs Production

Exclusive central Higgs production pp→ p H p : 3-10 fb SM
>100 fb MSSM (high tanβ)

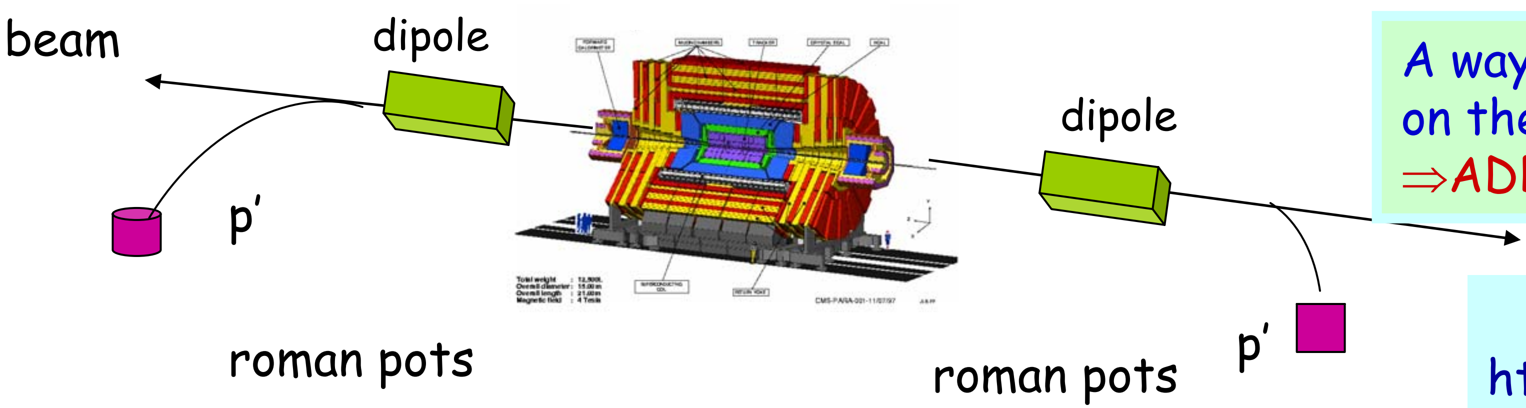
Khoze-Martin-Ryskin
+ many other groups





$$M_H^2 = (p + \bar{p} - p' - \bar{p}')^2$$

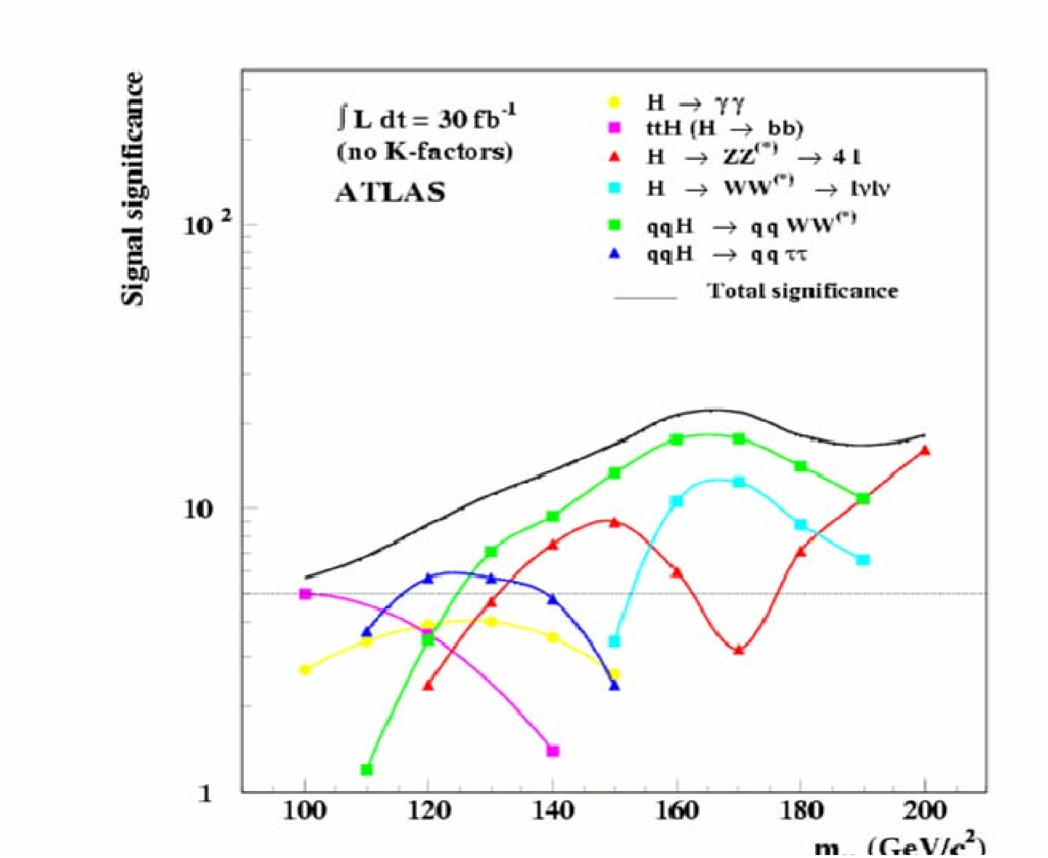
ΔM = O(1.0 - 2.0) GeV

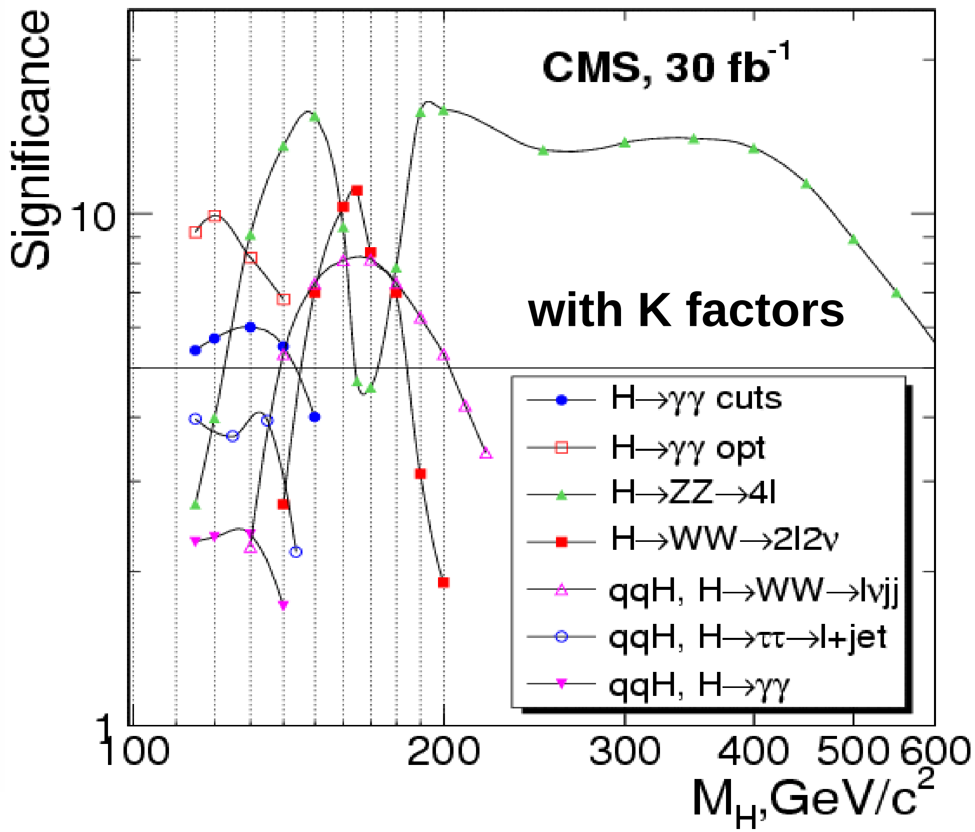


A way to get information on the spin of the Higgs
⇒ADDED VALUE TO LHC

FP420 R&D Project
http://www.fp420.com

Signal Significance for 30 fb^{-1}

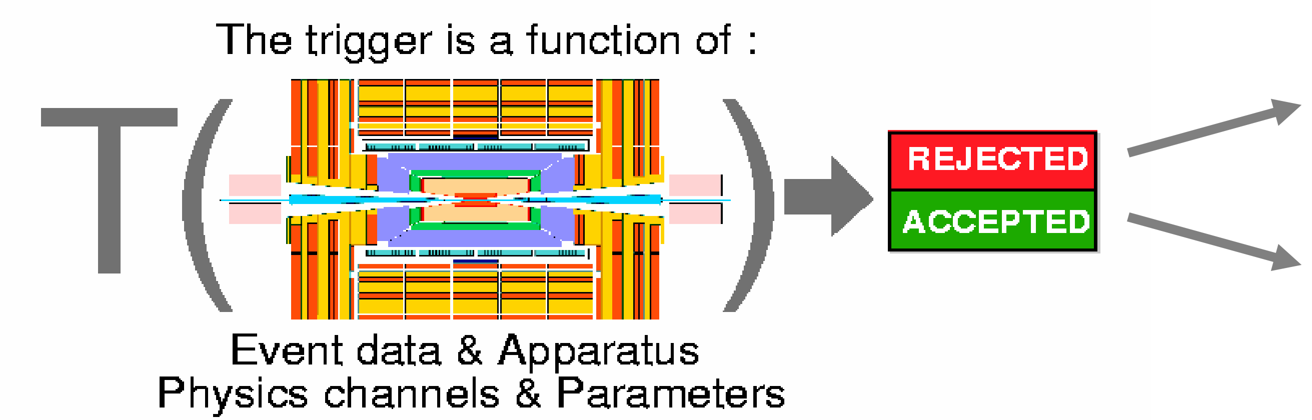




ATLAS h→γγ sensitivity is now comparable with CMS
CMS ttH, H→bb does not have even 3σ with 60 fb^{-1}

Event filtering: the trigger system

Collision rate is 40 MHz   Event size ~1 Mbyte
2007 technology (and budget) allows only to write 100 Hz of events to tape → need a factor ~10^7 online filtering!!



lost forever!!

written to disk for offline analysis

The event trigger is one of the biggest challenges at the LHC
⇒ Based on hard scattering signatures: jets, leptons, photons, missing Et,…

LHCb Trigger

Select interesting B-meson decays

- large background/signal ratio

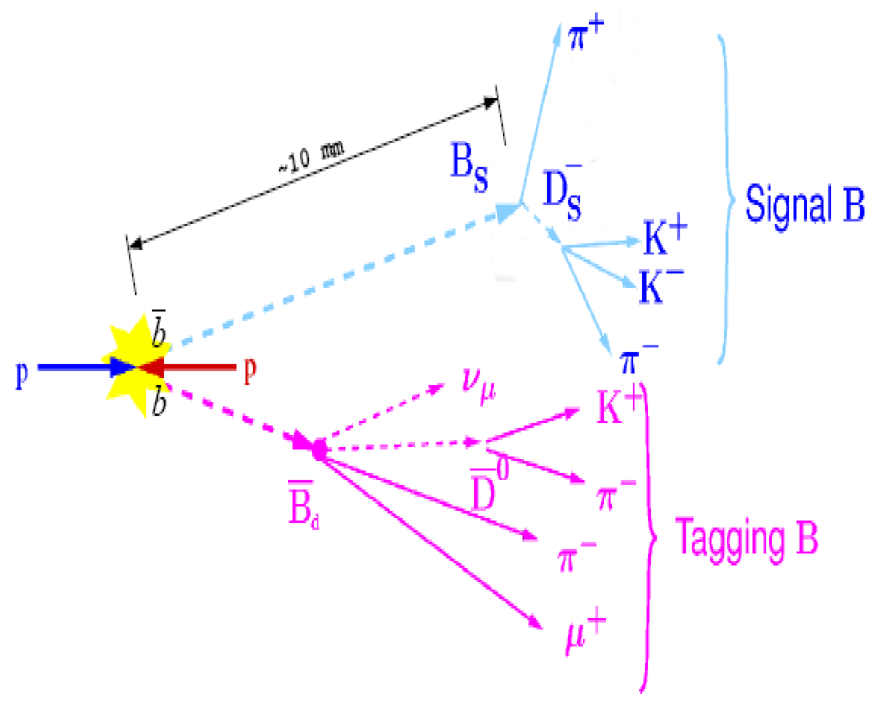
  $\sigma_{inelastic} / \sigma_{b\bar{b}}$ ~160

- small branching ratios ($<10^{-3}$)
- limited detector acceptance

Require selective/efficient trigger

B-meson signatures:

- leptons, hadrons with large Pt
- secondary vertices
- tracks with large impact parameter



Trigger for LHCb is very challenging