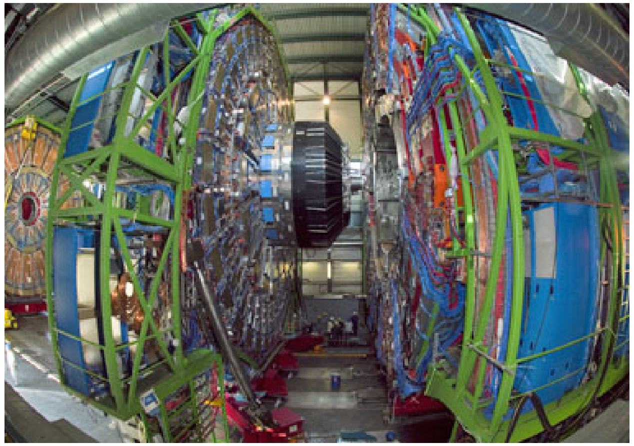
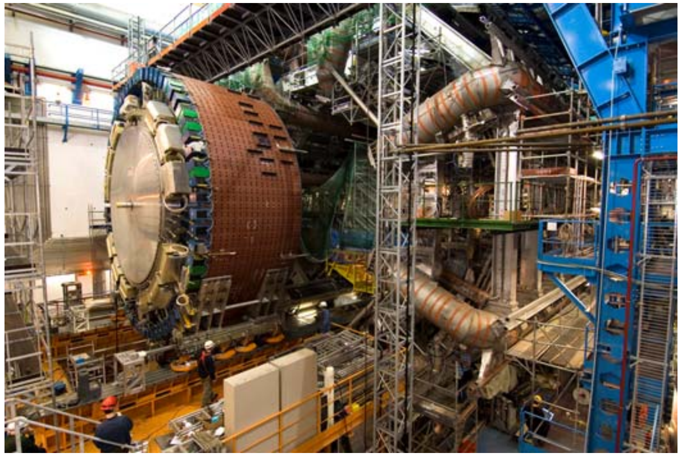
The LHC: the First Few Years
FNAL Seminar 01/12/07

Albert De Roeck
CERN
and University of Antwerp
and the IPPP Durham

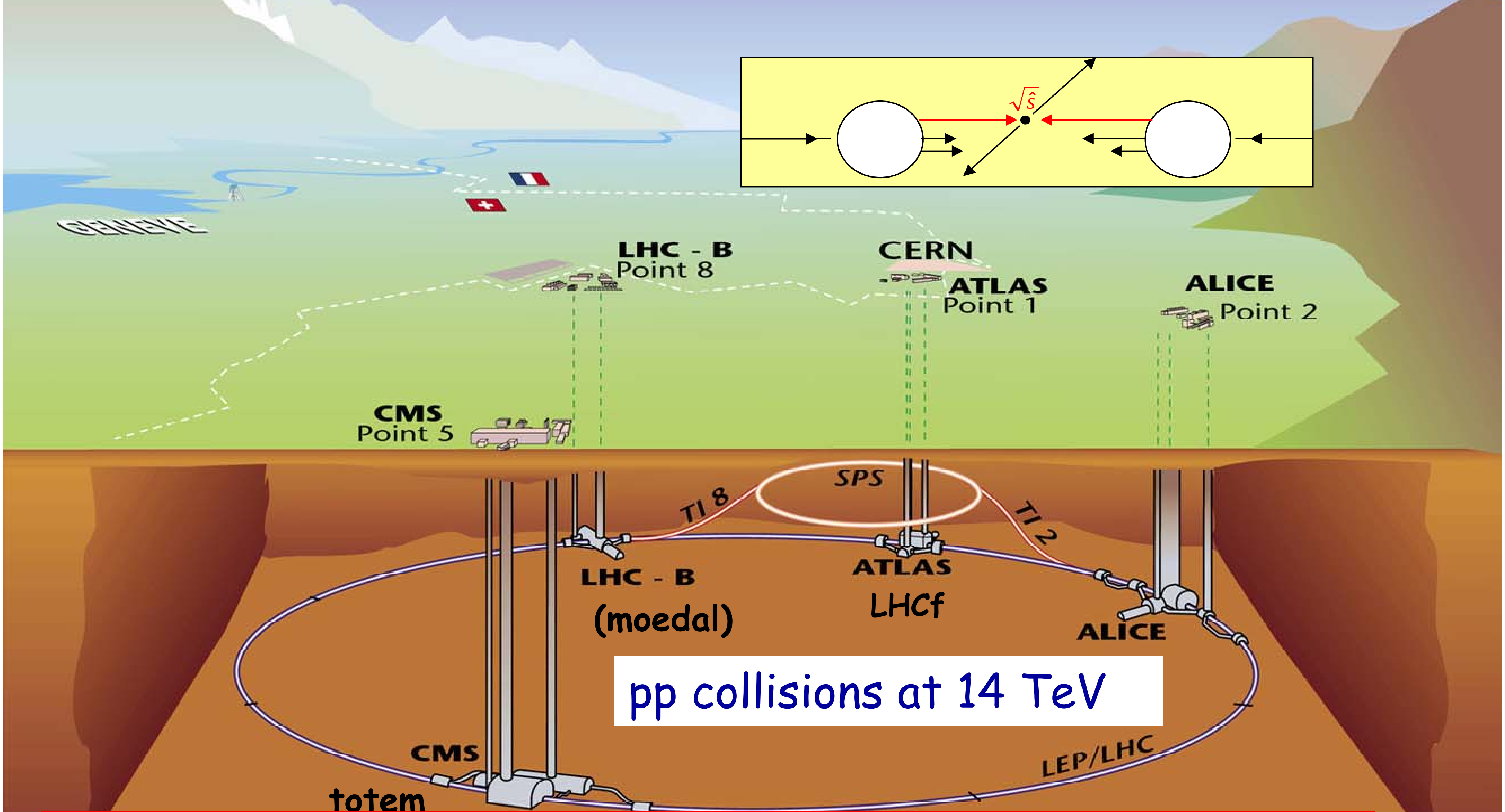




Contents

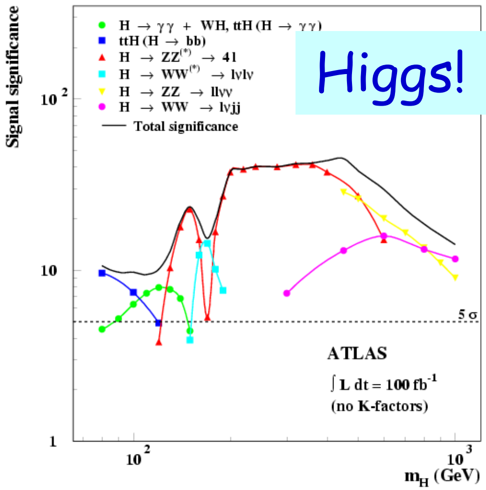
- Introduction
- Machine status/expectation for 2007/2008
- News from ATLAS and CMS
- First physics in ATLAS and CMS
- Some new signatures
- Outlook

The LHC Machine and Experiments

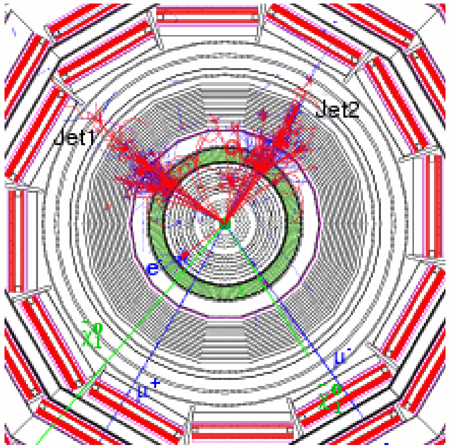


- High Energy ⇒ factor 7 increase w.r.t. present accelerators
- High Luminosity (# events/cross section/time) ⇒ factor 100 increase

Physics at the LHC: pp @ 14 TeV

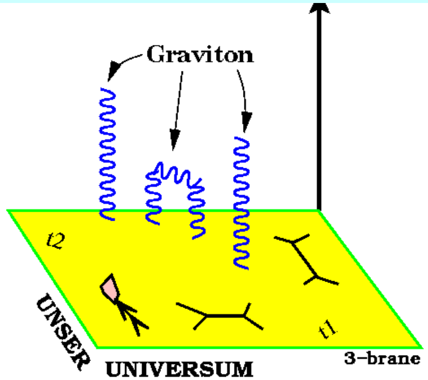


Higgs!

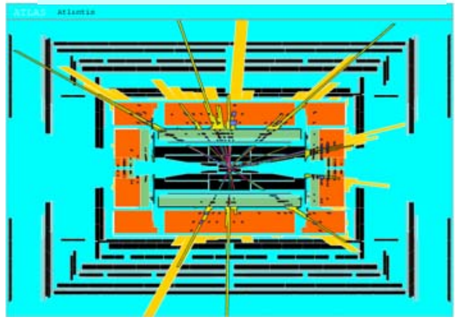


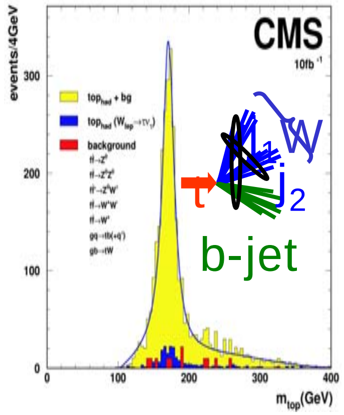
Supersymmetry?

Extra Dimensions?



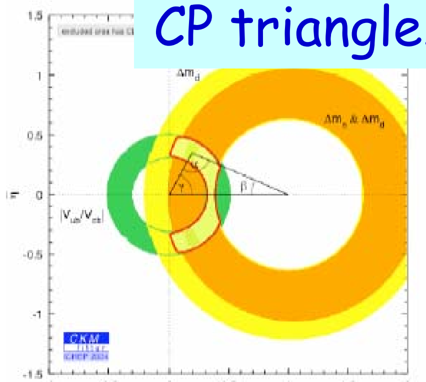
Black Holes???



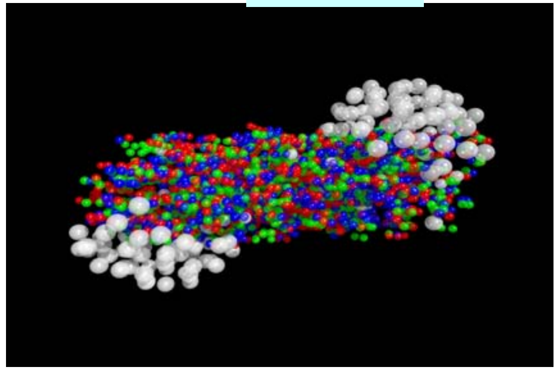


Precision measurements e.g top!

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
- Also LHC will be a great machine for: QCD, B-physics, Heavy Ions, EW precision..

The LHC: 22+ Years Already!

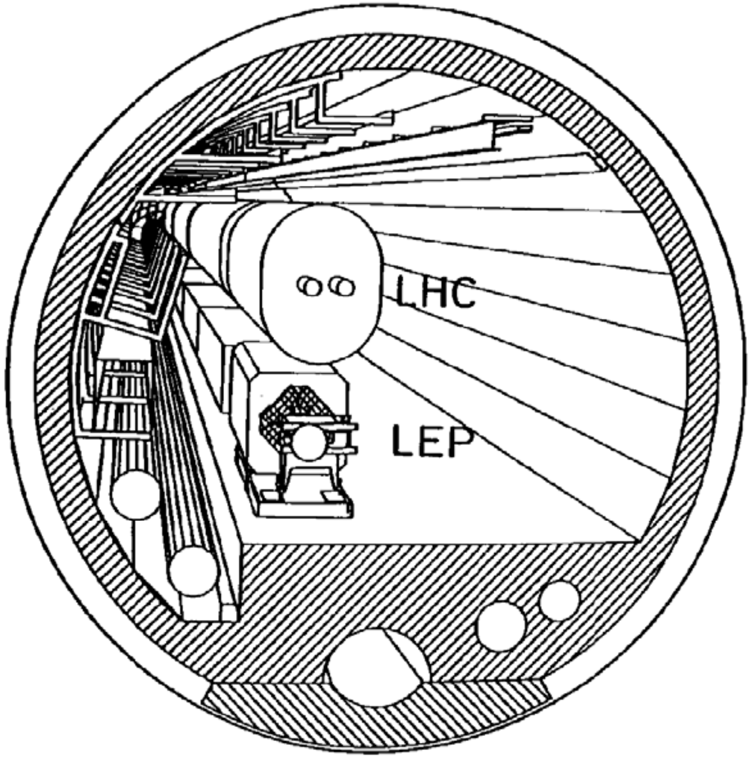
CERN: 50 YEARS AND COUNTING

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

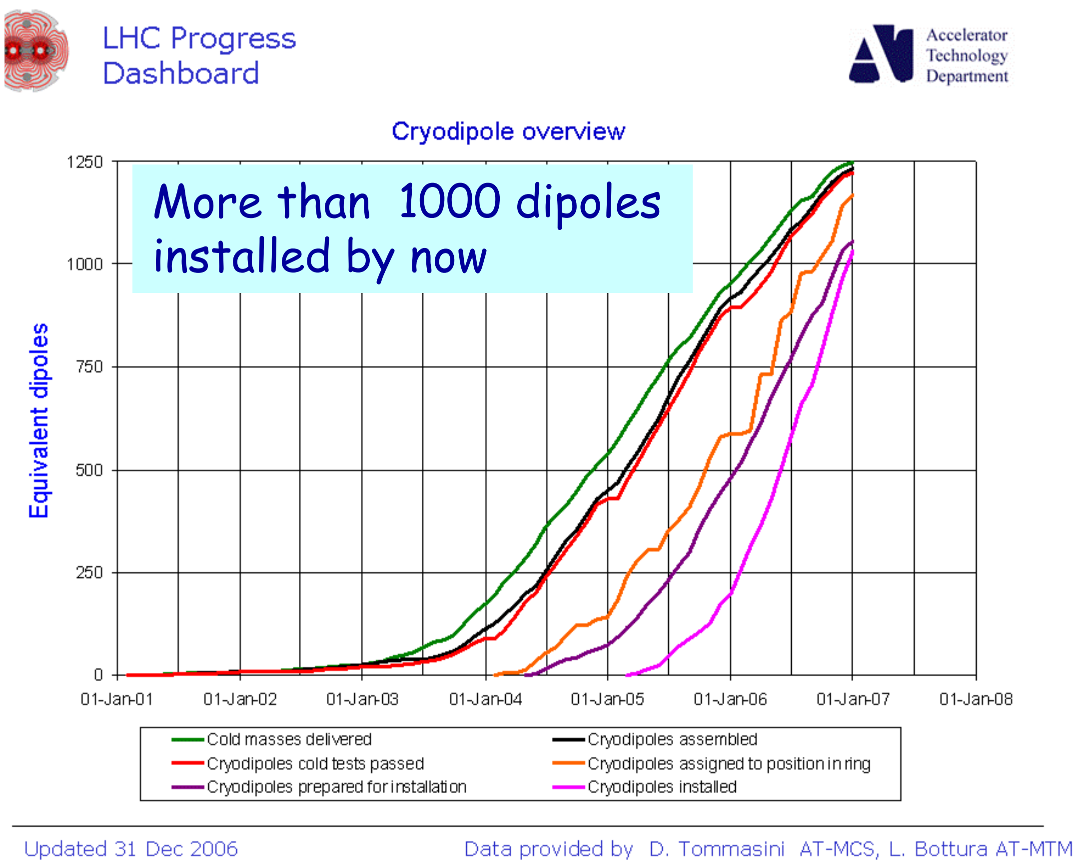
ECFA 84/85
CERN 84-10
5 September 1984



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}

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(*)

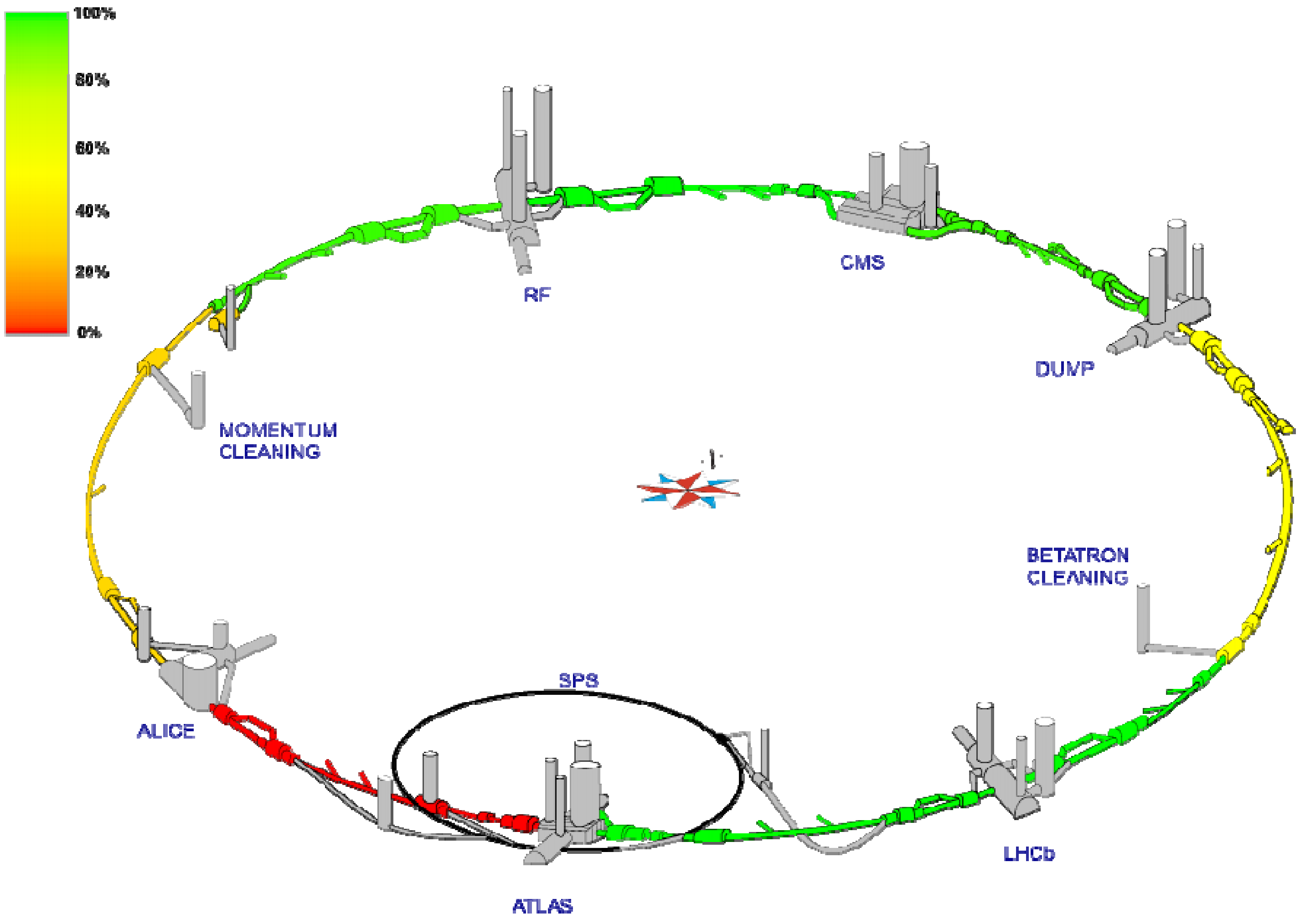
- LHC will be closed and set up for beam on 1 September 2007
  - LHC commissioning will take time!
- First collisions expected in November/December 2007
  - A short pilot run
  - Collisions will be at injection energy ie cms of 0.9 TeV
- First physics run in 2008
  - ~ 0.1-1 fb^{-1}? 14TeV!
- Physics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

Last Dipole #1232 delivered (27 Nov)

Installation of dipoles on schedule: Last dipole installed ~ Feb 07

Magnet Installation Progress

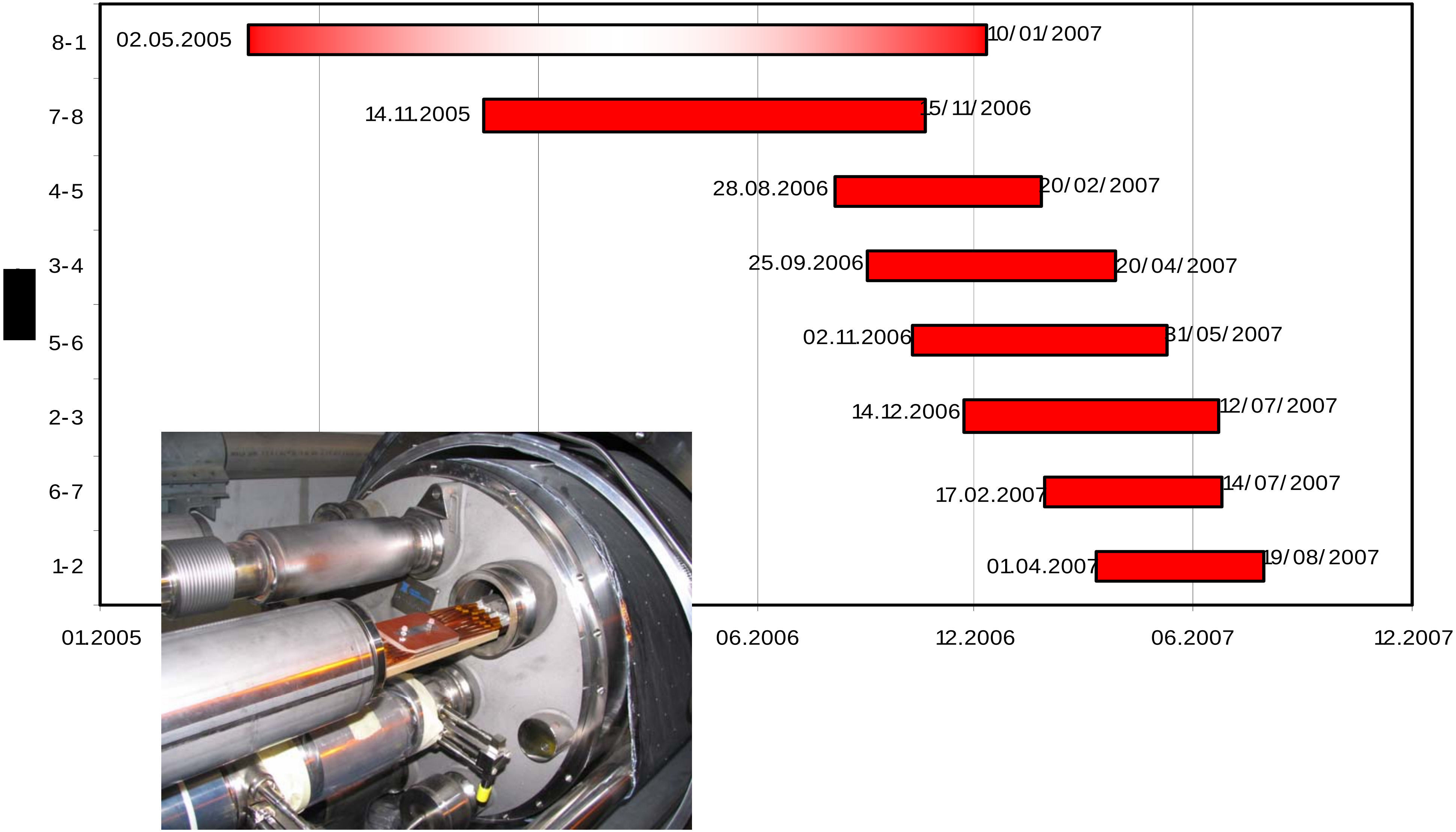


L. Evans: Presentation made to the Open Session of the LHC Machine Advisory Committee, 7 December 2006

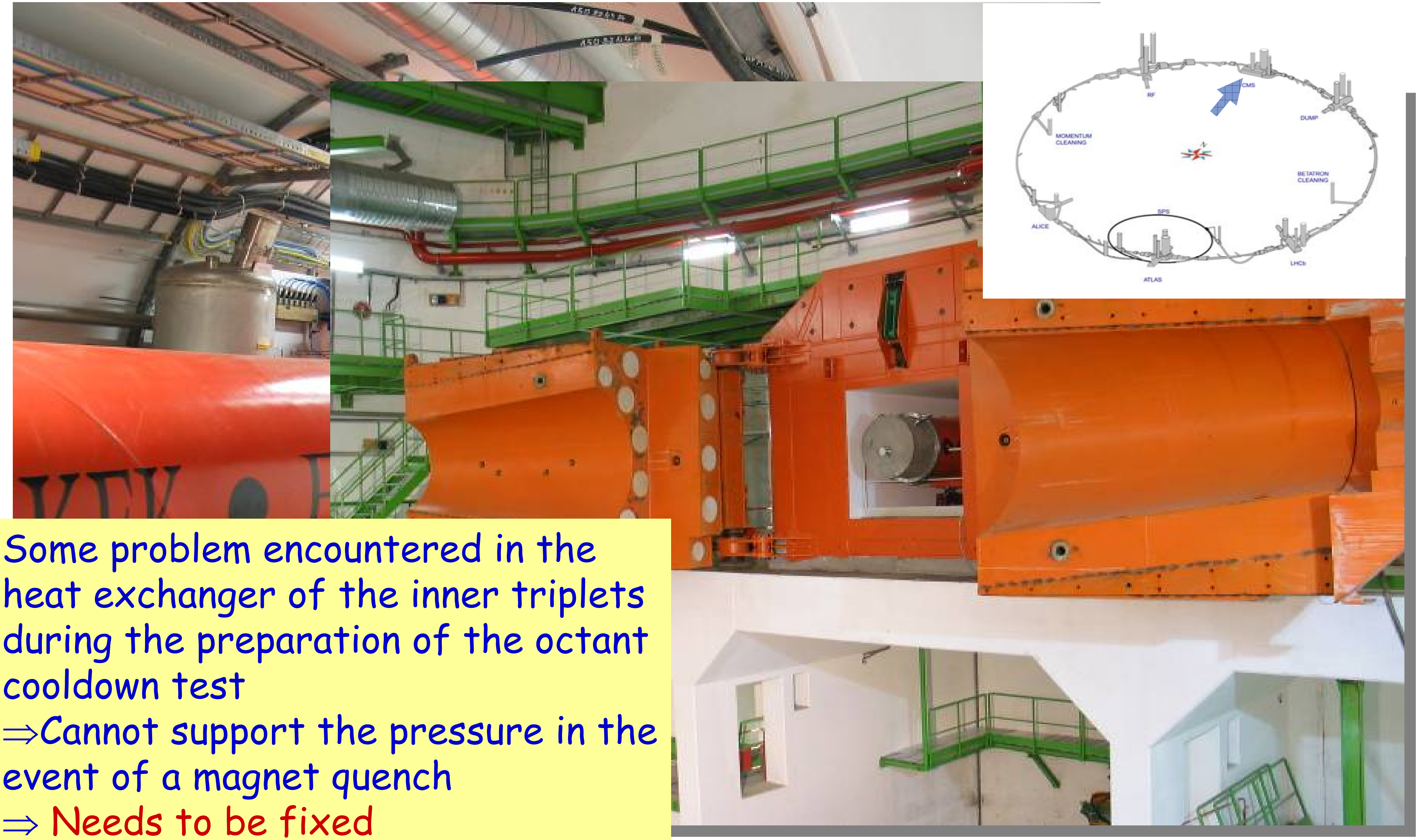
LHC installation

- 1/8 sector ready to be cooled down early 2007 (Jan 15)
- 4/8 sectors installed
- 2/8 in progress

Interconnections



One of the triplets at point 5



Some problem encountered in the heat exchanger of the inner triplets during the preparation of the octant cooldown test

⇒Cannot support the pressure in the event of a magnet quench

⇒ Needs to be fixed

MAC: Conclusions and Milestones

A solid and confirmed progression of transport, installation interconnection rates as well as of quality assurance (mechanical, electrical, etc) and commissioning. The first sector (7-8) was pressure tested on Saturday-Sunday November 25. Some problem was found in the inner triplet but the whole arc was fully commissioned.

The CERN has shown its ability to solve the various production and installation problems (e.g. DFB) it has encountered; the present ones (collimators) are being addressed and solved.

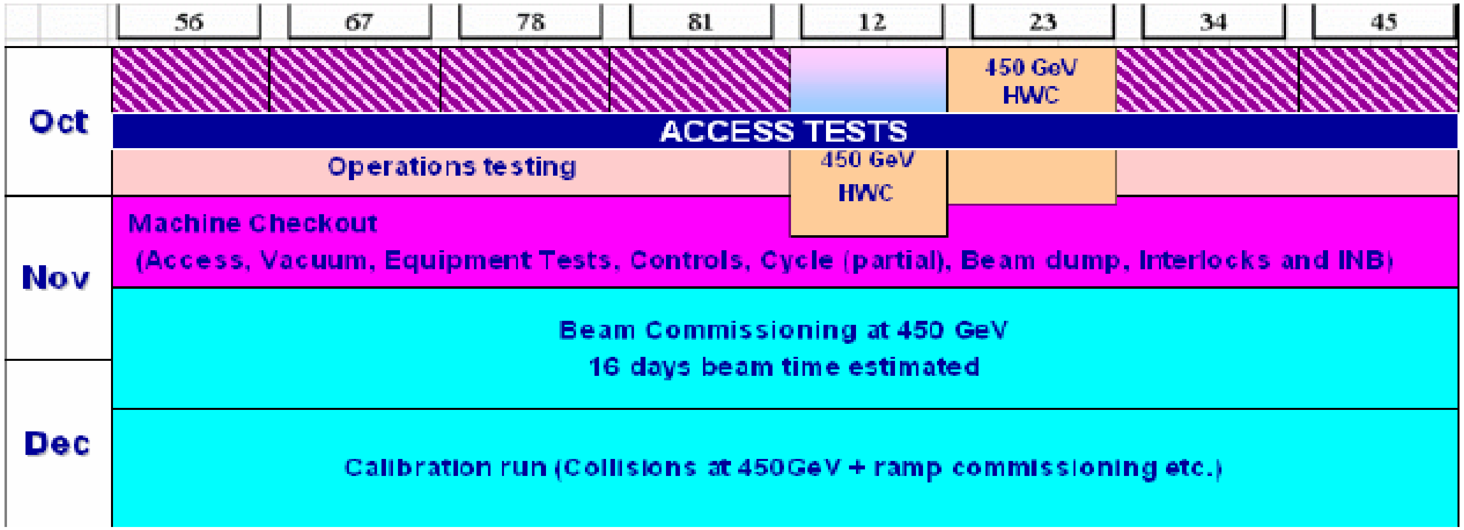
The engineering run at 450 GeV for 2007 remains a top priority. However, to achieve it, the inner triplet problem must be solved quickly.

✓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

L. Evans: 7/12/06

LHC Startup Schedule 2007

M. Lamont



- 1st September 2007: Experiments closed: Startup LHC machine
- Beam commissioning with single beams
- December 2007: ~3 weeks collisions ("calibration run")
  - E_p=450 GeV (injection energy)
  - $L \sim 10^{29}\ cm^{-2}s^{-1}$

			Reasonable	Maximum
k_b	43	43	156	156
i_b (10^{10})	2	4	4	10
β^* (m)	11	11	11	11
intensity per beam	8.6 10^{11}	1.7 10^{12}	6.2 10^{12}	1.6 10^{13}
beam energy (MJ)	.06	.12	.45	1.1
Luminosity ($cm^{-2}s^{-1}$)	2 10^{28}	7.2 10^{28}	2.6 10^{29}	1.6 10^{30}
event rate [1](kHz)	0.4	2.8	10.3	64
W rate [2] (per 24h)	0.5	3	11	70
Z rate [3] (per 24h)	0.05	0.3	1.1	7

Several days →

…In less than one year from now…

	111	CERN AB	31-11-07	12:20:26
LHC	Run 1234	data of	31-11-07	12:20:16

— ** STABLE BEAMS ** —

E = 0.450 TeV/c	Beam	In Coast	0.5 h	
Beams	Beam 1	Beam 2		
#bun	43	43		
Nprot(t)	1.71e12	1.73e12		
tau(t) h	121	140		
Luminosities	ATLAS	ALICE	CMS	LHC-B
L(t) 1e28 cm-2s-1	5.23	6.23	7.13	5.21
/L(t) nb-1	0.78	0.68	0.78	0.52
BKG 1	1.20	0.52	0.90	0.43
BKG 2	0.85	0.82	0.50	0.80

Comments 31-11-07 11:40:26

COLLIMATORS in coarse settings

Separation Scan in IR1/Atlas

Watch the television monitors…

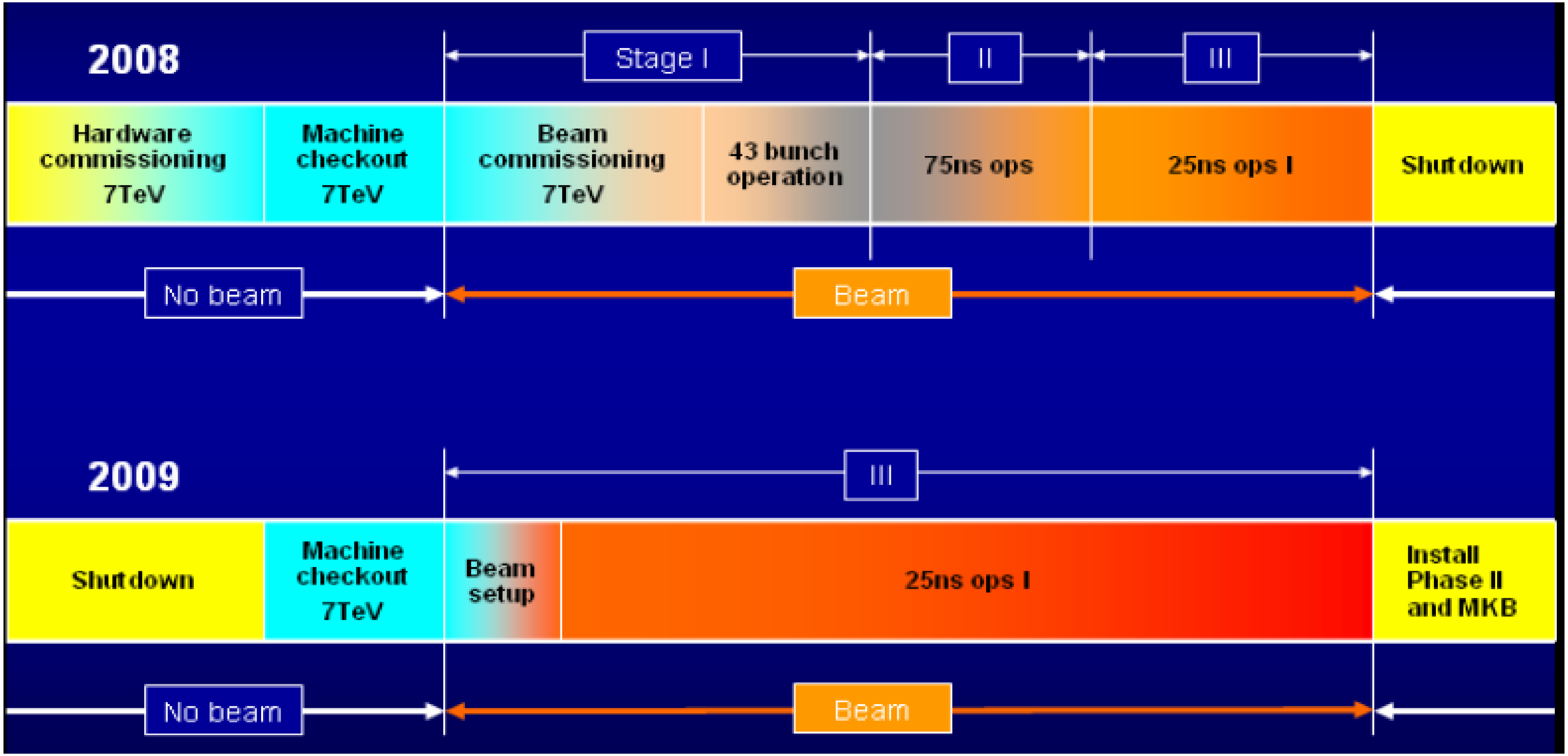
Helmut Burkhardt

Staged Commissioning for 2008

Stage I: "Pilot physics" ~1 month, 43 bunches, no crossing angle, $L<10^{32}$ $cm^{-2}s^{-1}$

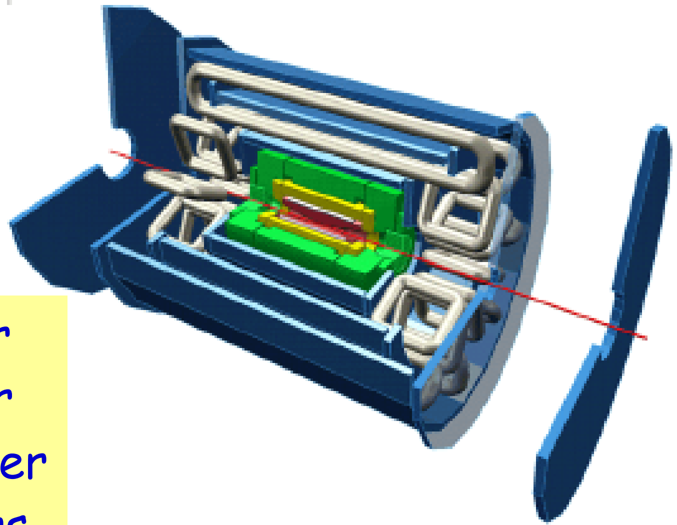
Stage II: 75ns operation, push crossing angle and squeeze, $L<10^{33}$

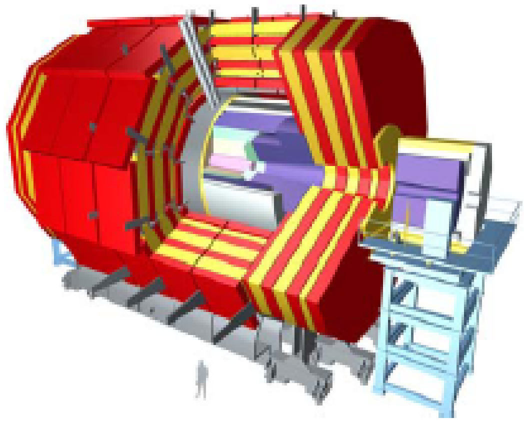
Stage III: 25ns operation, nominal crossing angle, $L<2*10^{33}$



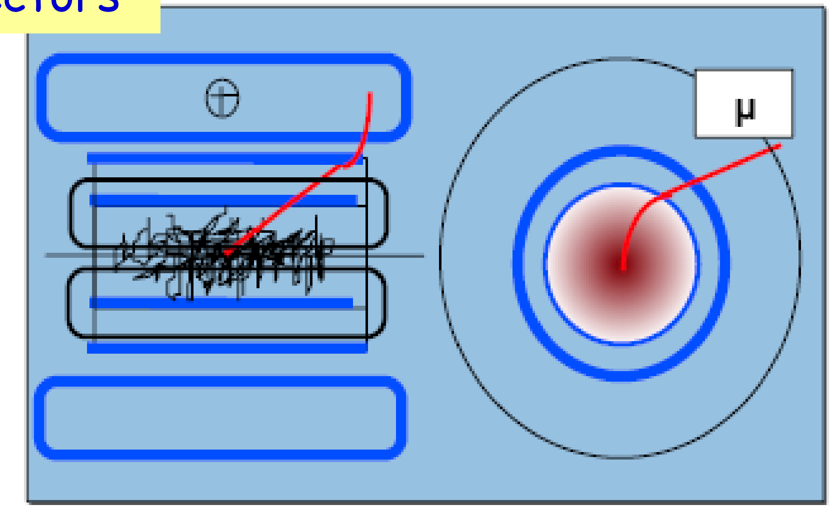
General Purpose Detectors at the LHC

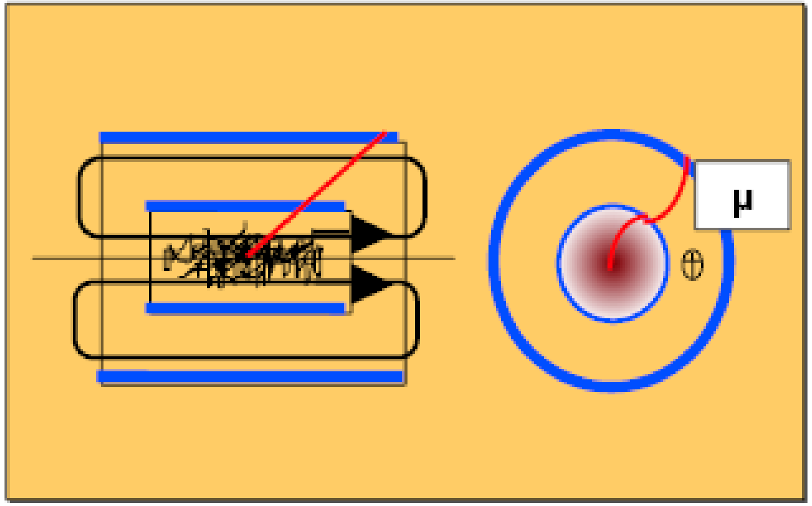
ATLAS A <u>Toroidal</u> LHC ApparatuS **CMS** Compact Muon <u>Solenoid</u>



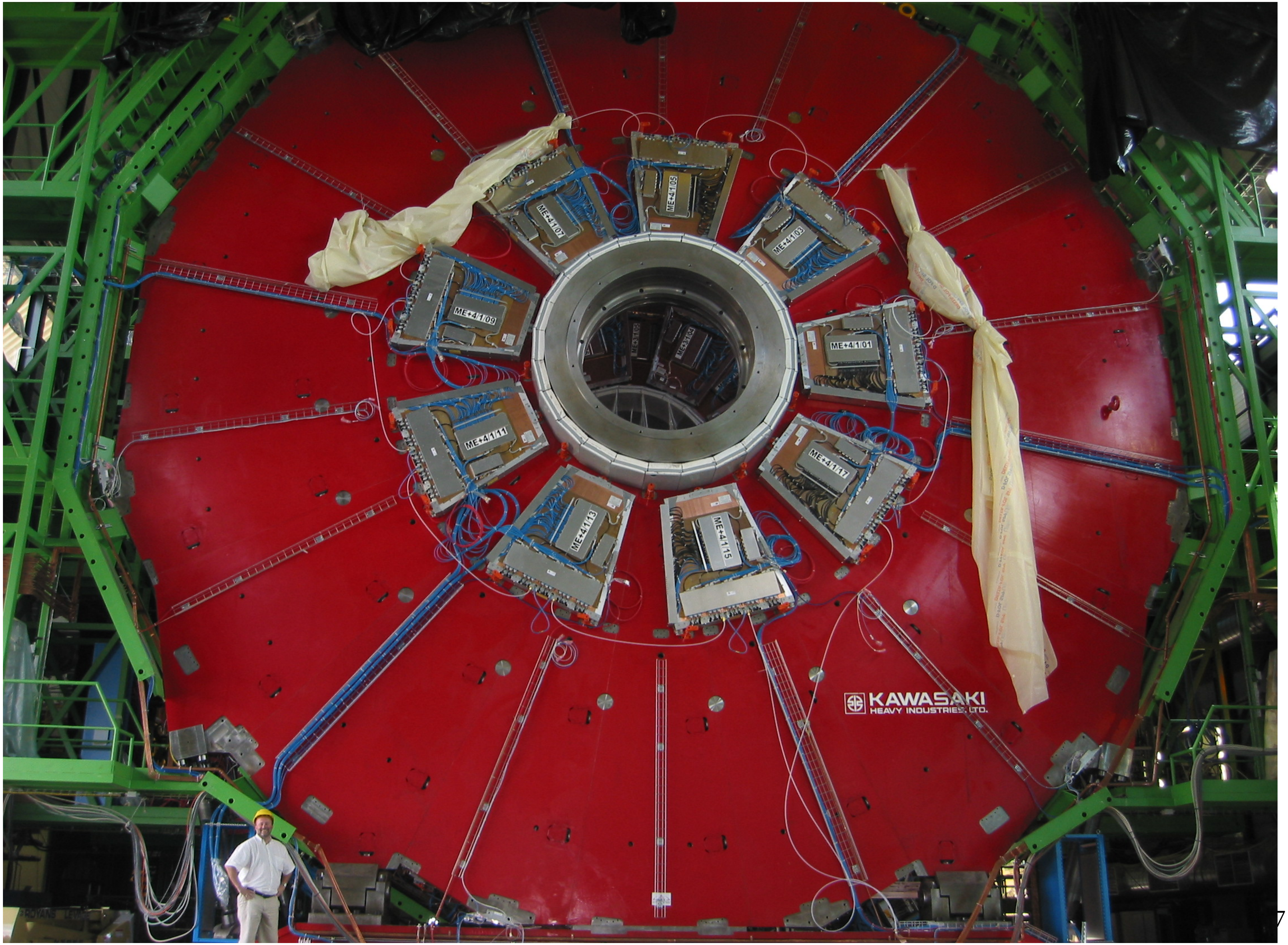


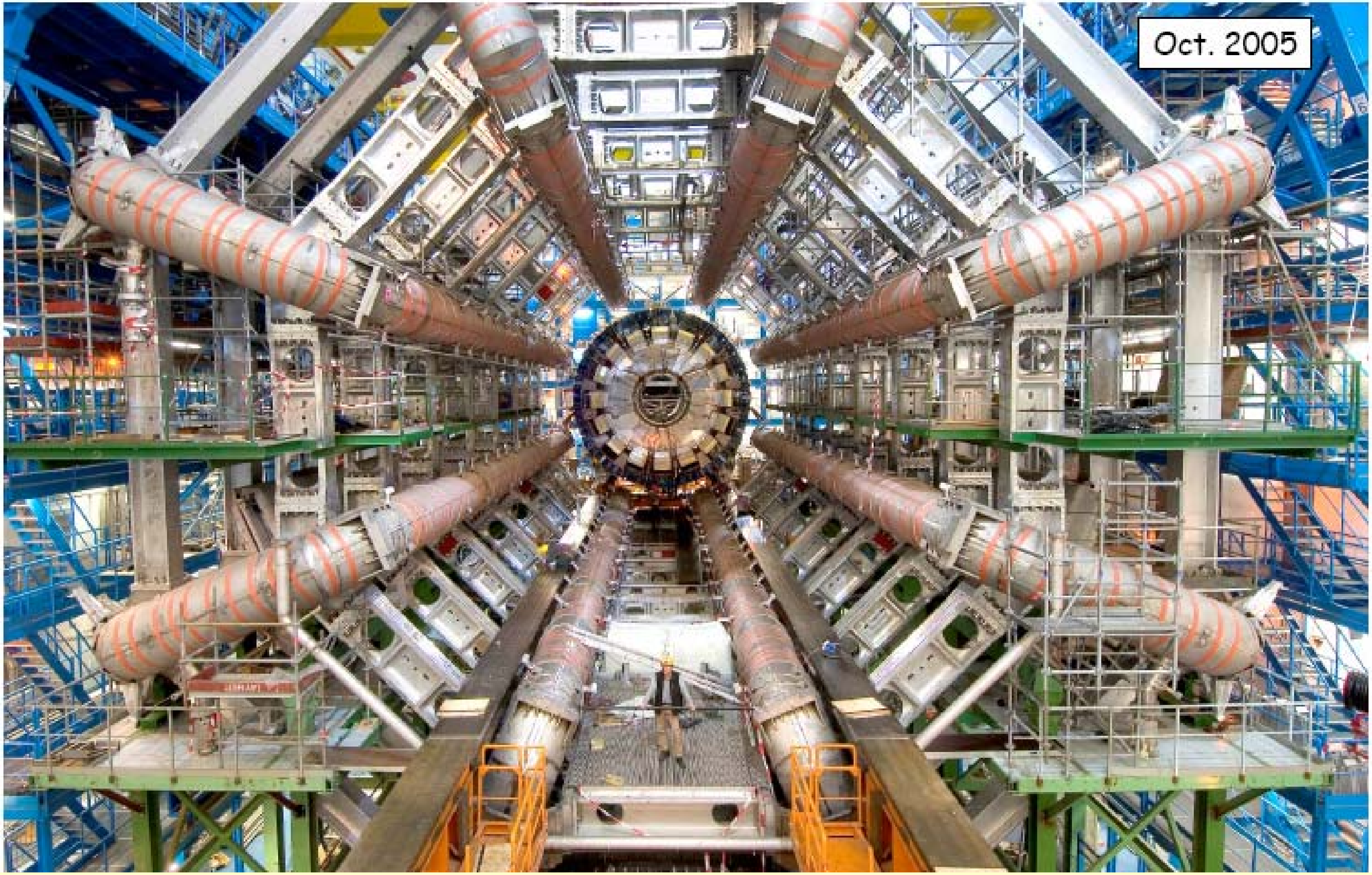
- Central tracker
- EM calorimeter
- HAD calorimeter
- Muon Detectors





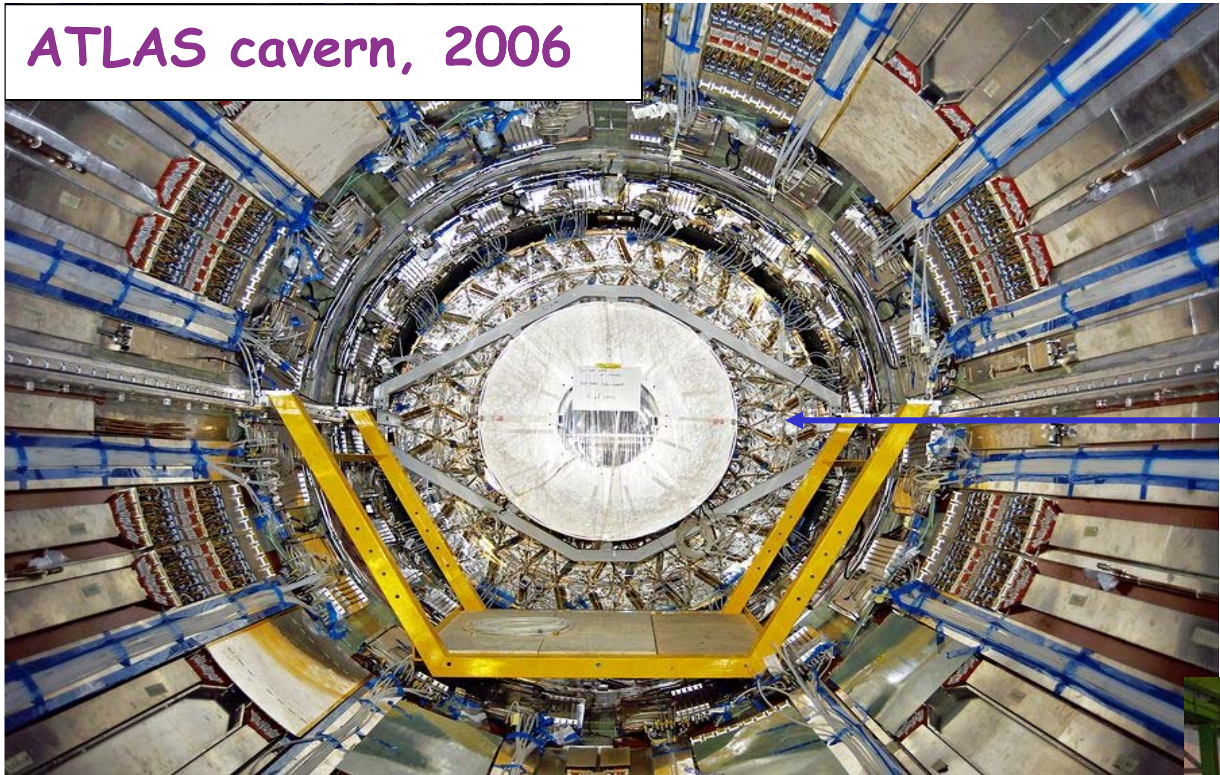
Trigger: Reduce 40 MHz collision rate to 100 Hz event rate to store for analysis


ME+4/1/07
ME+4/1/05
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.


Oct. 2005

ATLAS & CMS Detectors

ATLAS cavern, 2006



November 2006

- ATLAS barrel toroid magnet reaches full current
- ATLAS barrel tracker installed (TRT connected)
- Endap muons being installed

All CMS tracker elements at CERN (integration ongoing!)
CMS lowers first detector into cavern (forward calo)
Lowering now on weekly basis

CMS cavern, 2006

Heavy lowering: CMS parts going 100m down

30 Nov: Y\\\E+3 leaves SX5 and 11 hours later touches down safely in UXC

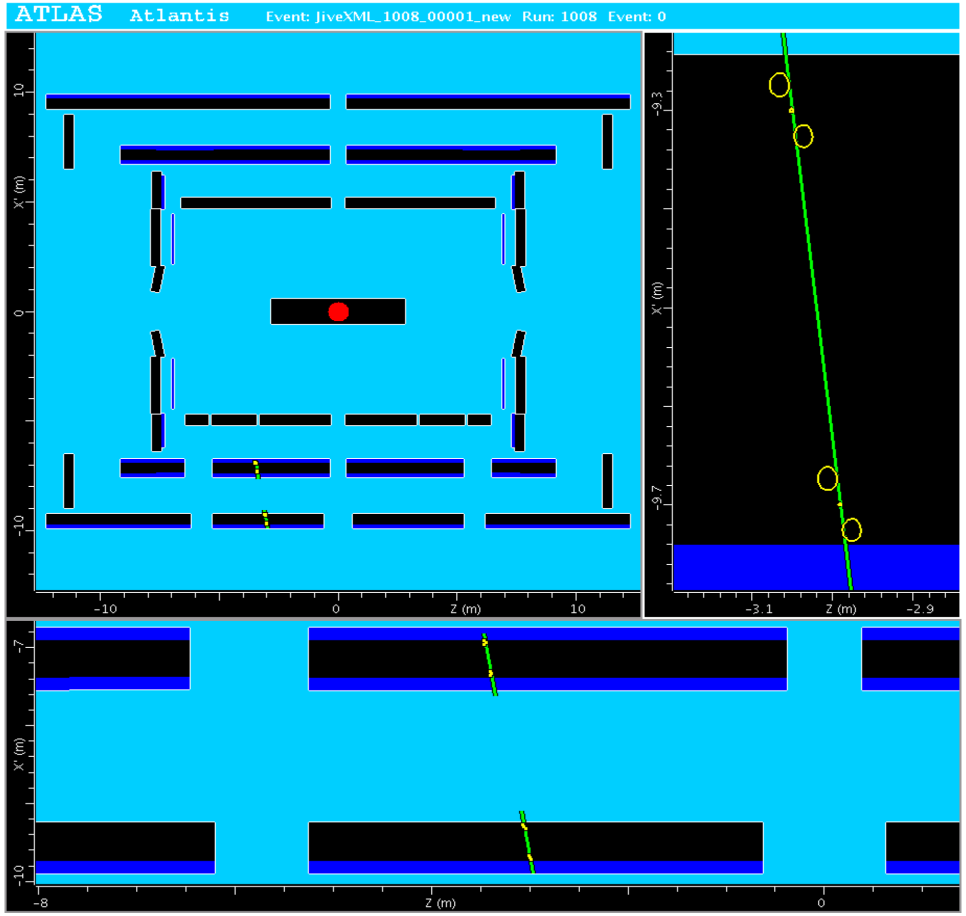
The first force studied carefully by CMS is Gravity

Continuing…

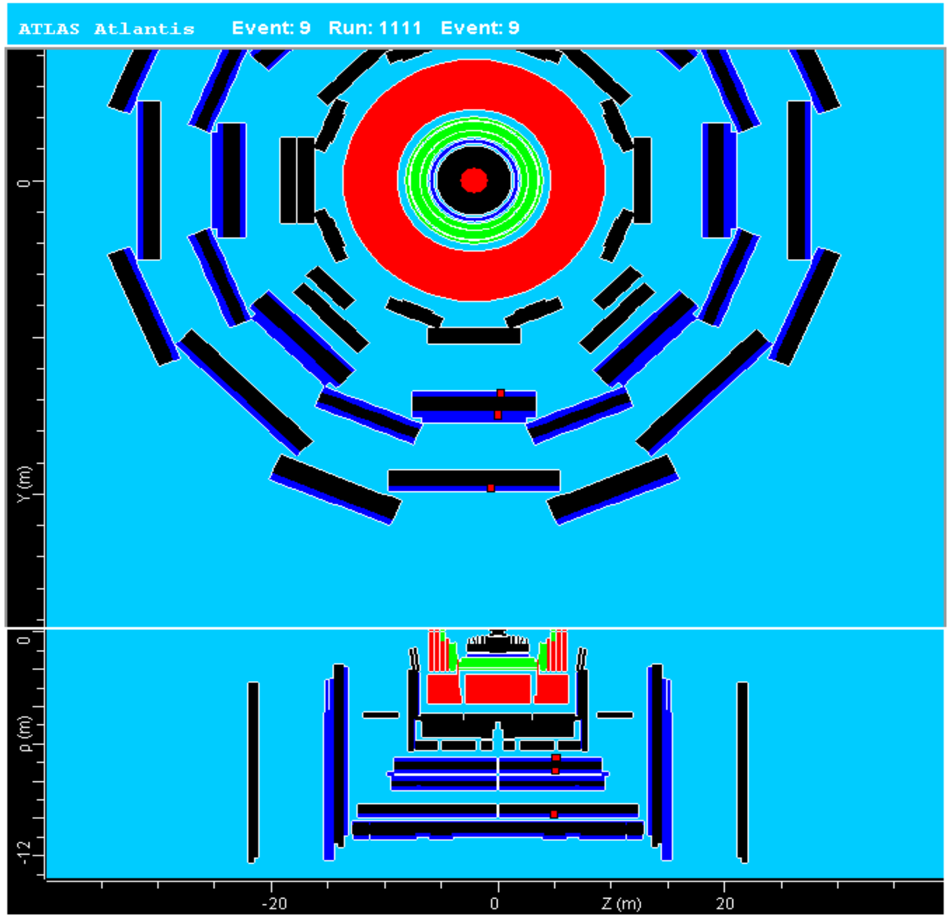
YE+2
endcap disc
12.12.2006

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

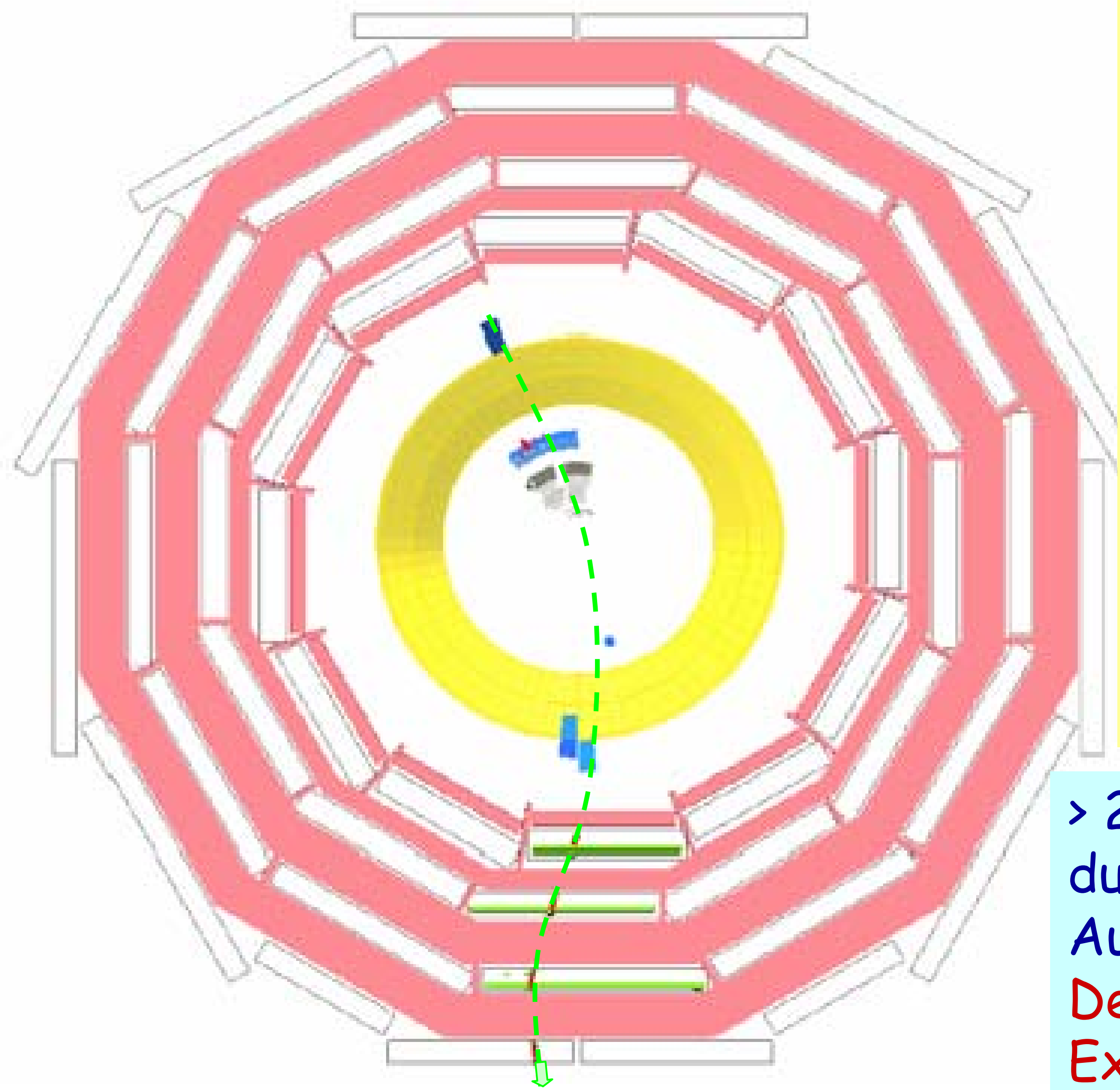
In December 2005 in MDTs



and in June 2006 in RPCs



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

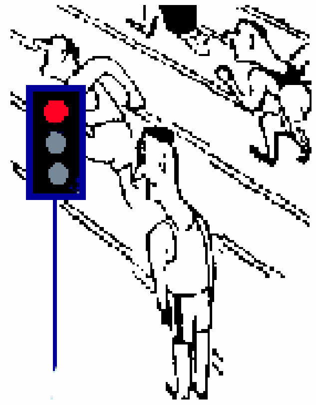
> 200•10^6 cosmic muons taken during the cosmic challenge August-October
Detector worked very well!
Excellent prospects for 2007!!

Detectors at Start-up in 2007

❷ Which detectors the first year ?

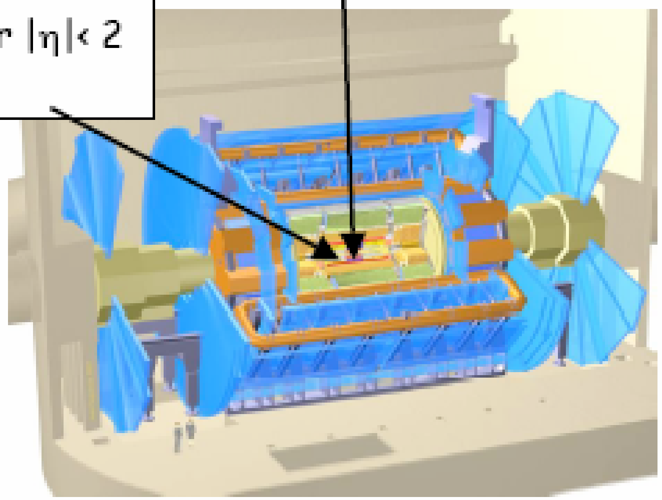
RPC over $|\eta|<1.6$ (instead of $|\eta|<2.1$)
4th layer of end-cap chambers missing

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)

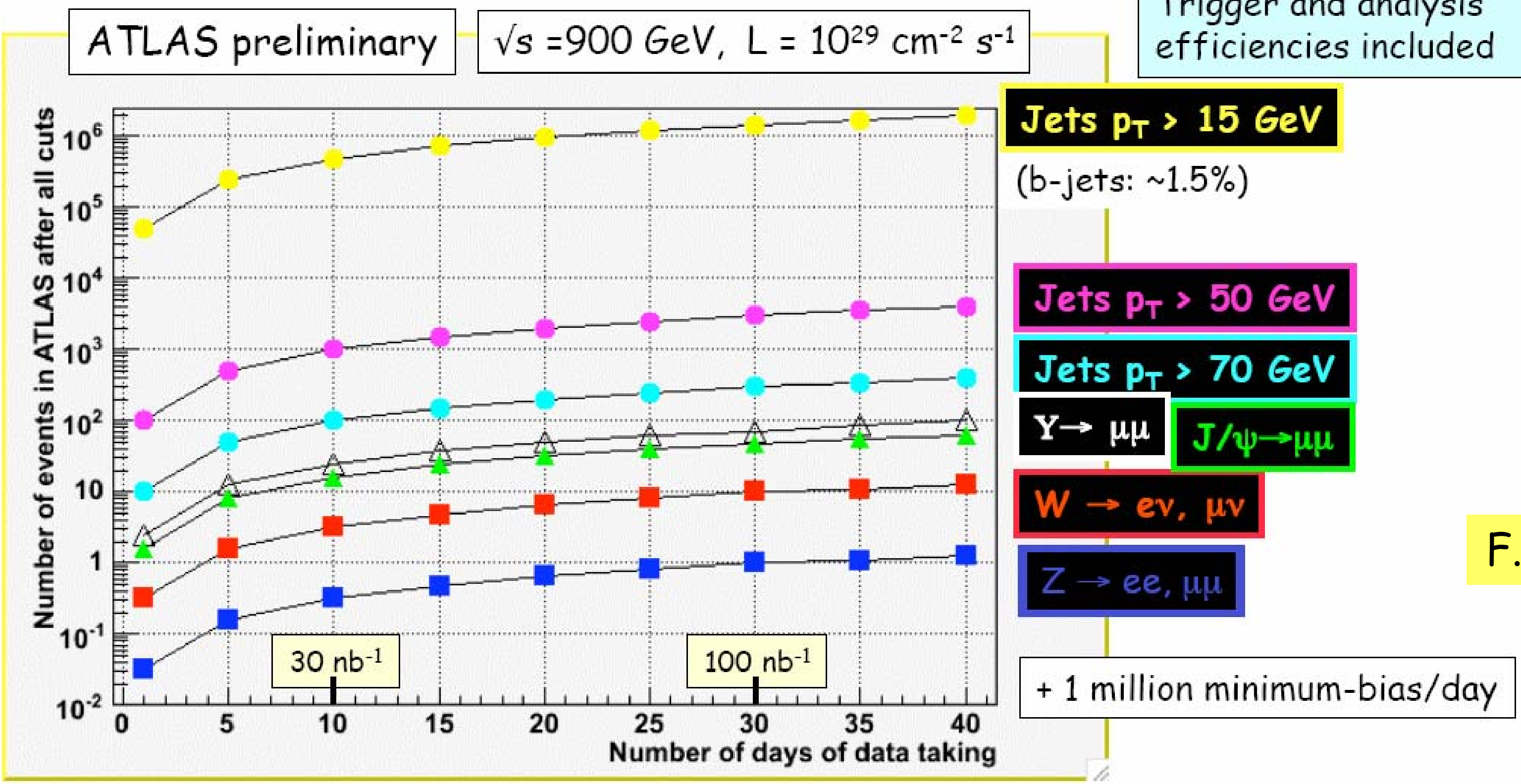
Detector performance

	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)

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→ lν, Υ → μμ, J/ψ → μμ ?

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.

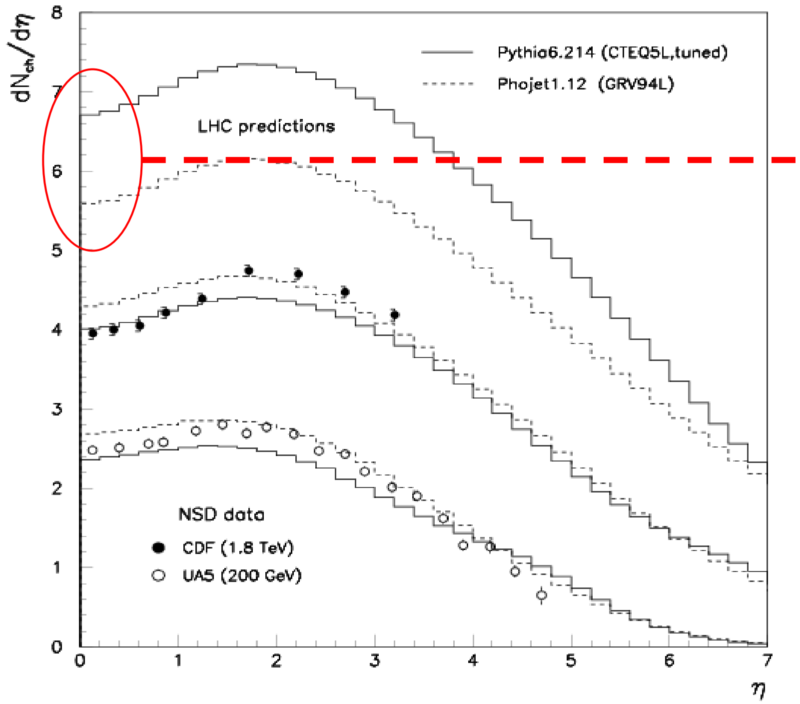
- Measure SM physics at $\sqrt{s}$ = 14 TeV : W, Z, tt, QCD jets ...
  (also because omnipresent backgrounds to New Physics)

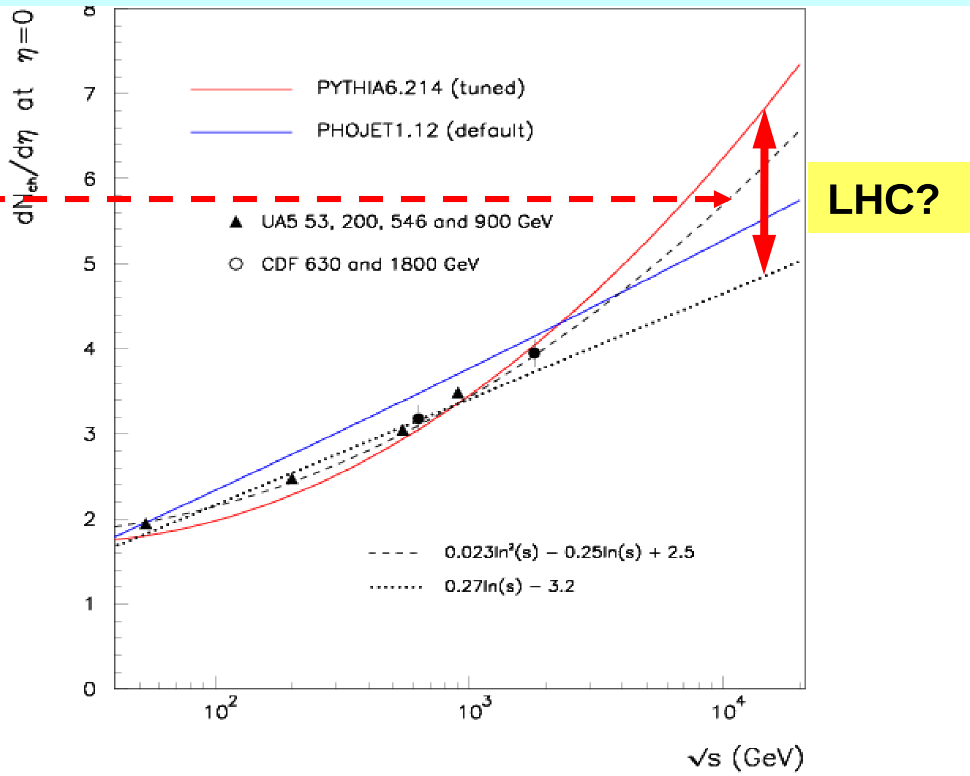
→ prepare the road to discovery ...... it will take time ...

Early Soft Minimum-Bias Measurements

Charged particle density

The pile-up for the future: ~4 events at low and ~20 events at high luminosity





- Energy dependence of dN/dη ?
- Vital for tuning UE model
- Only requires a few thousand events.

- PYTHIA models favour $\ln^2(s)$;
- PHOJET suggests a ln(s) dependence.

At 14 TeV startup!!

Likely one of the first papers…

1 August 2008

Charged particle multiplicity in pp collisions at $\sqrt{s}$ = 14 TeV

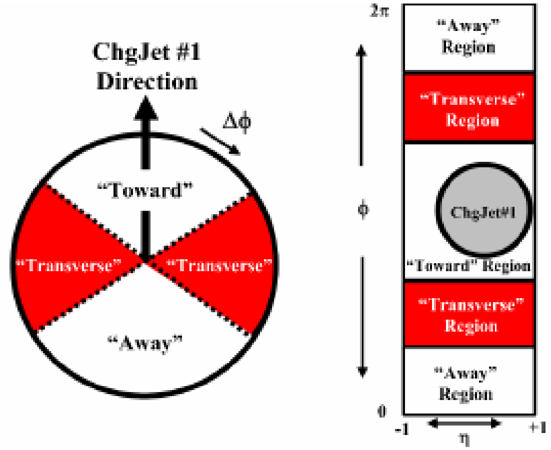
CMS collaboration

Abstract

We report on a measurement of the mean charged particle multiplicity in minimum bias events, produced in the central region $|\eta| < 1$, at the LHC in pp collisions with $\sqrt{s}$ = 14 TeV, and recorded in the CMS experiment at CERN. The events have been selected by a minimum bias trigger, the charged tracks reconstructed in the silicon tracker and in the muon chambers. The track density is compared to the results of Monte Carlo programs and it is observed that all models fail dramatically to describe the data.

Submitted to *European Journal of Physics*

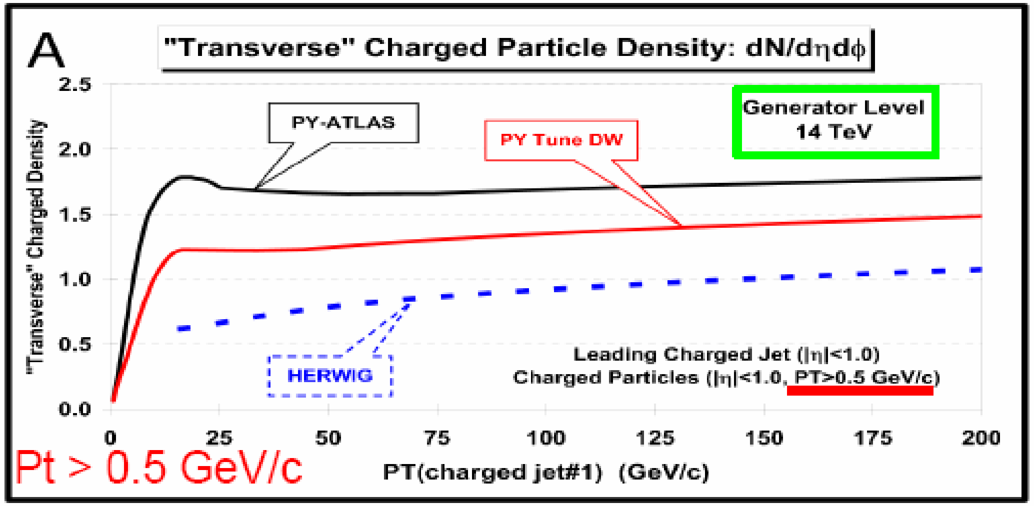
Underlying event studies

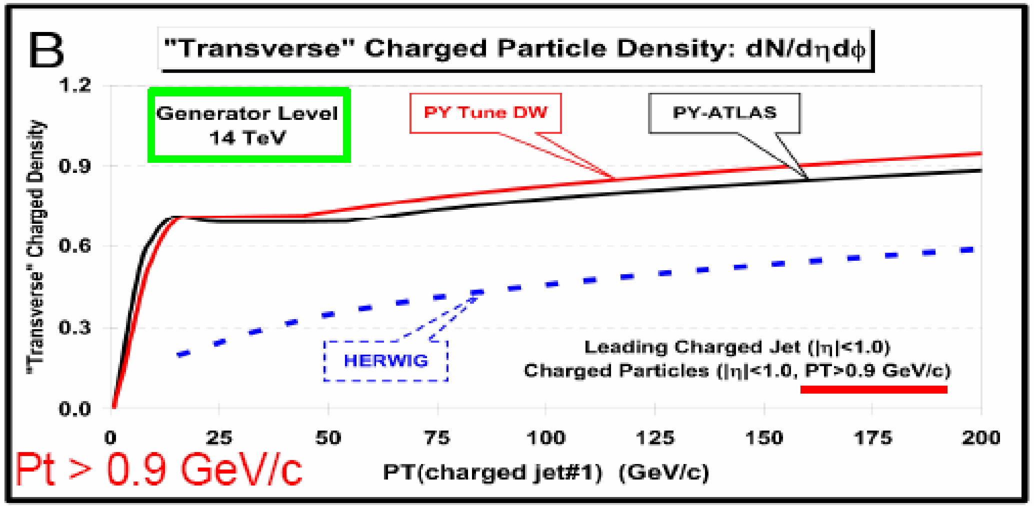


MC comparison for two different Pythia tunes of multiple interactions:
- PY ATLAS
- PY Tune DW by R. Field fitting CDF Run 1 and 2 UE data

and HERWIG

- MI energy dependence parameter PARP(90) = 0.16 (ATLAS), 0.25 (DW)
- „Softer" charged part. Spectrum for ATLAS tune





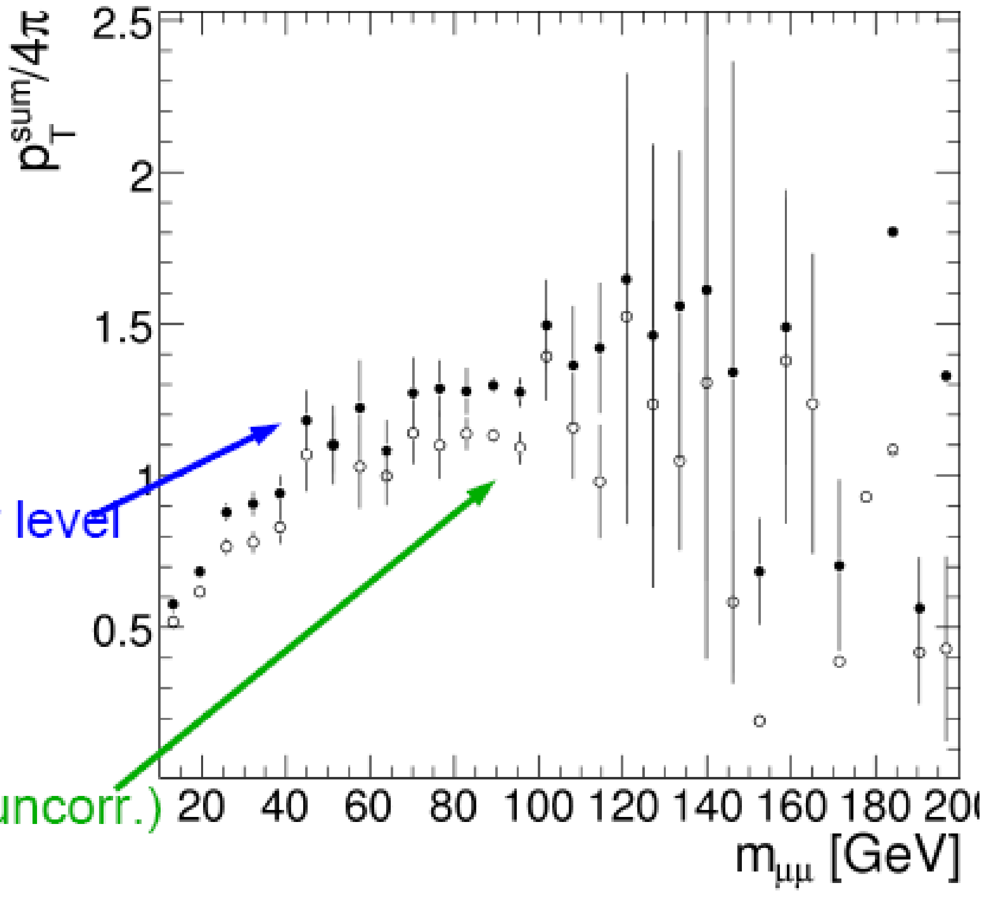
These ideas have been pioneered at the Tevatron!!

Underlying events in Drell-Yan

<u>Mean Pt sum density (without μ's) for:</u>
- Pt > 0.9 GeV/c
- |η| < 1

vs. inv. mass of Drell-Yan μ pairs

Reflects the UE activity in the event



full circles: generator level

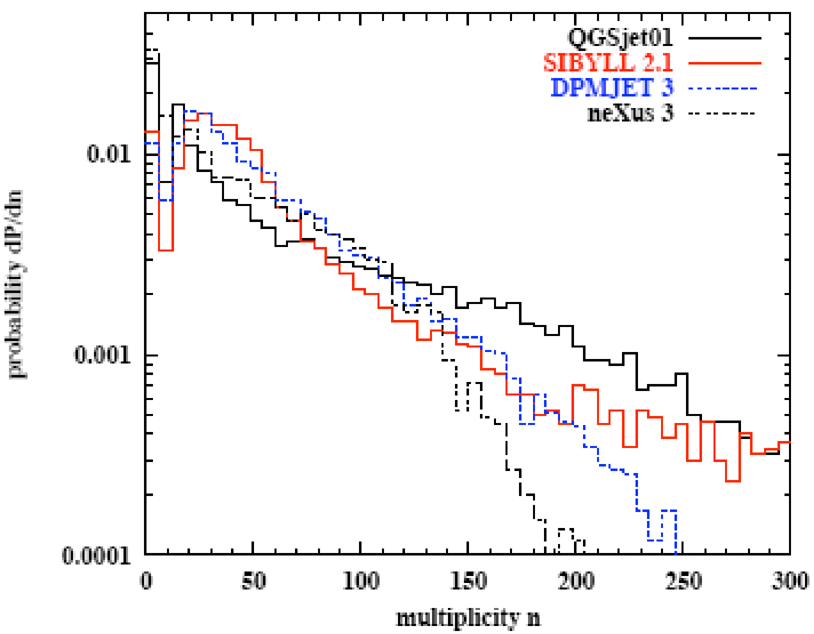
open circles: reconstr. level (uncorr.)

Measurements for hadronic models

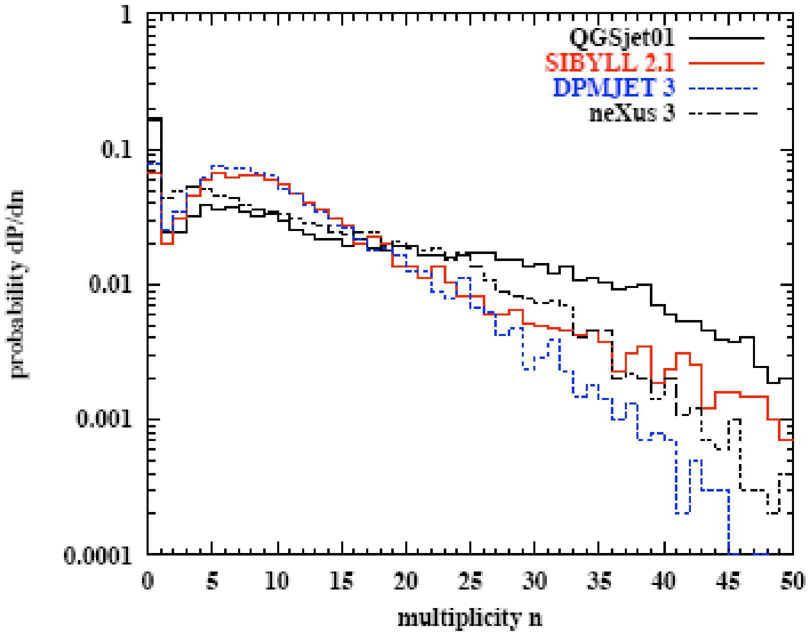
LHC: minimum bias measurements (2)

This is of substantial interest for the cosmic ray community

Multiplicity distributions (p-p at 14 TeV CMS)



Central detector (-3 < η < 3)



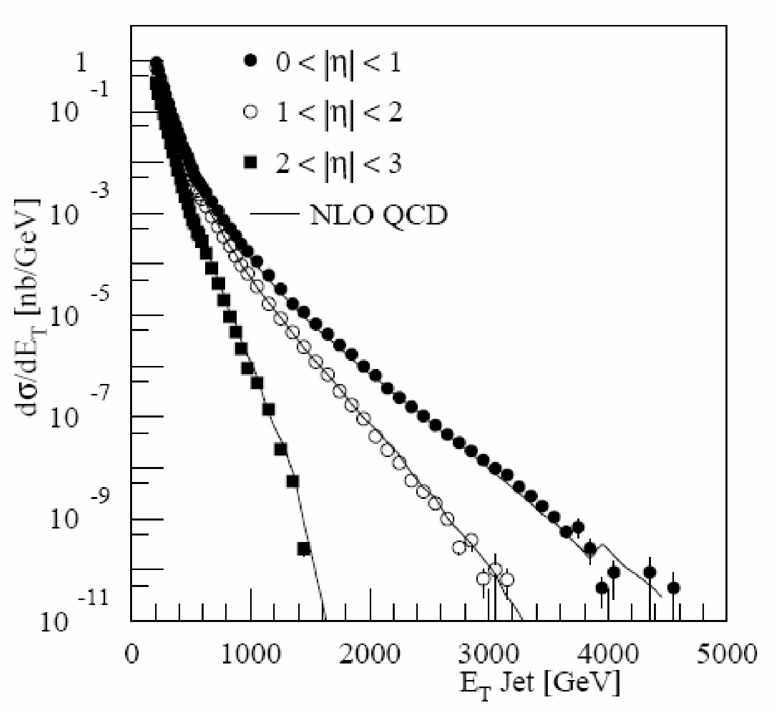
Forward detector (5 < η < 7)

Even simple distributions are very interesting

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



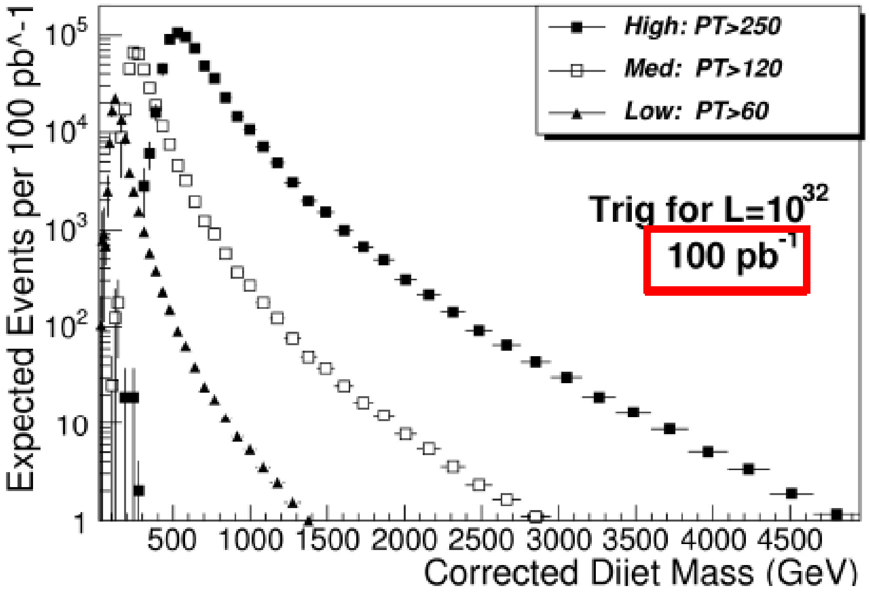
- PDFs
- Jet shape
- Underlying event
- α_s
- Diffraction
- BFKL studies
- low-x
- New physics?
- …

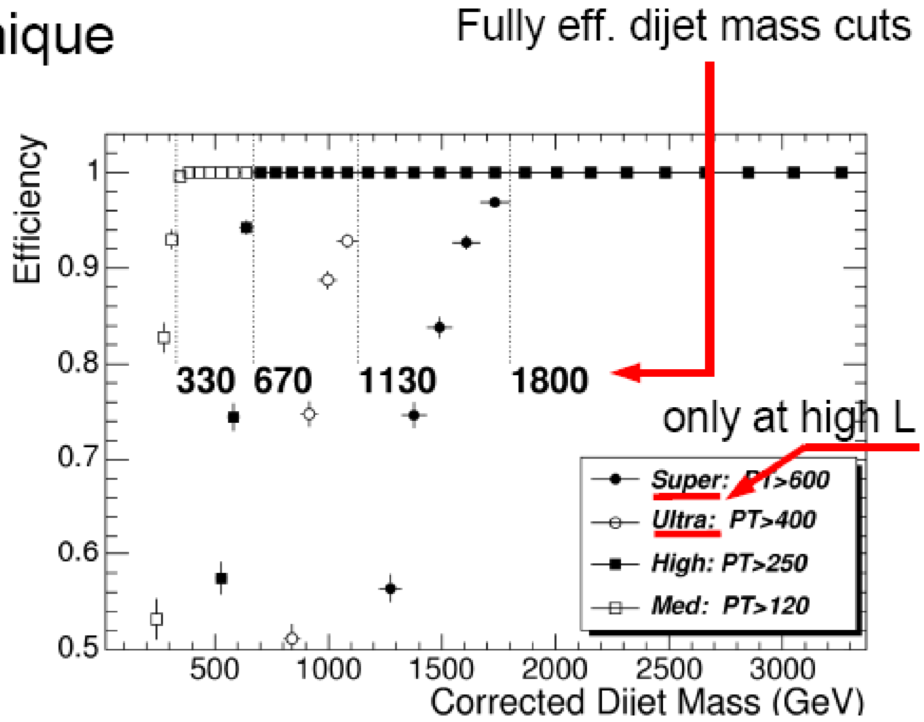
•Understanding QCD at 14 TeV will be one of the first topics at LHC

…and a whole b-physics program

Initial Di-jet studies

- Expected no. of events and trigger efficiency for different trigger thresh.
- Iterative Cone, R = 0.5 in (η,φ)
- Dijet mass $m = \sqrt{(E_1 + E_2)^2 - (\vec{P}_1 + \vec{P}_2)^2}$
- Corrected using MC calibration technique

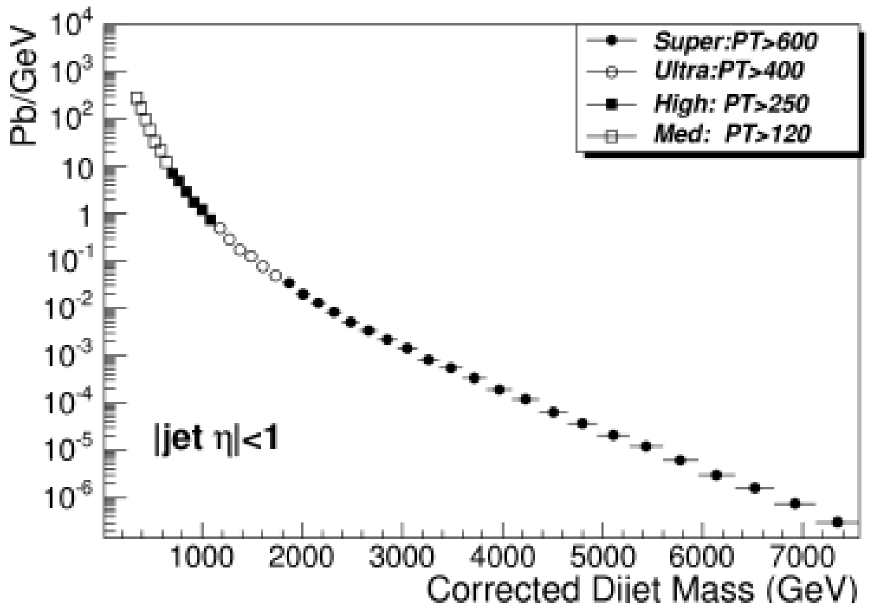


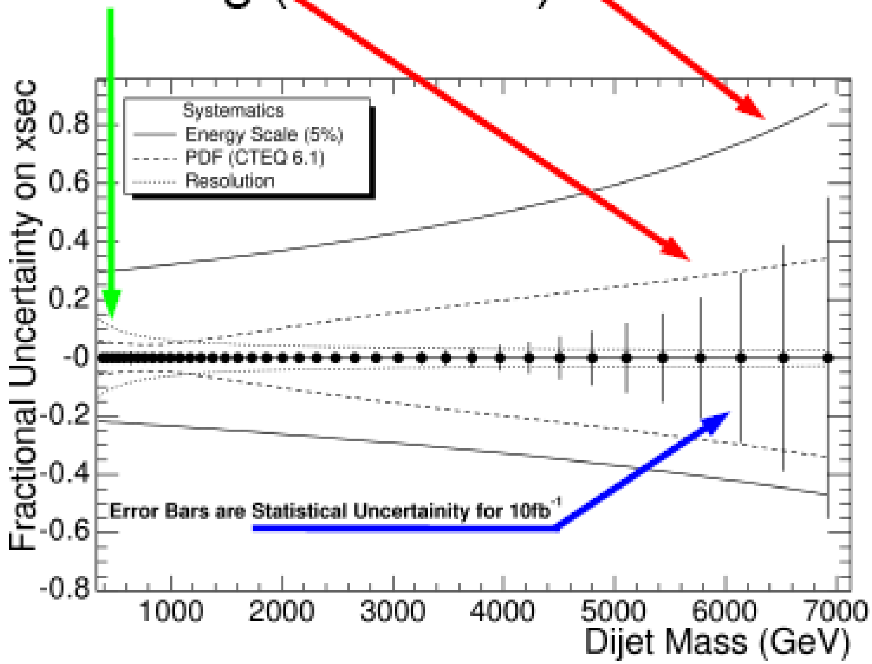


CMS PTDR

Dijets

- Measurable x-section, to be compared to models of new physics
- Alternatively: Dijet ratios for diff. η regions, angles
- Systematic uncertainties: - Abs. jet energy scale (±5%)
  - PDFs (CTEQ6.1)
  - Calorimeter smearing (resolution)

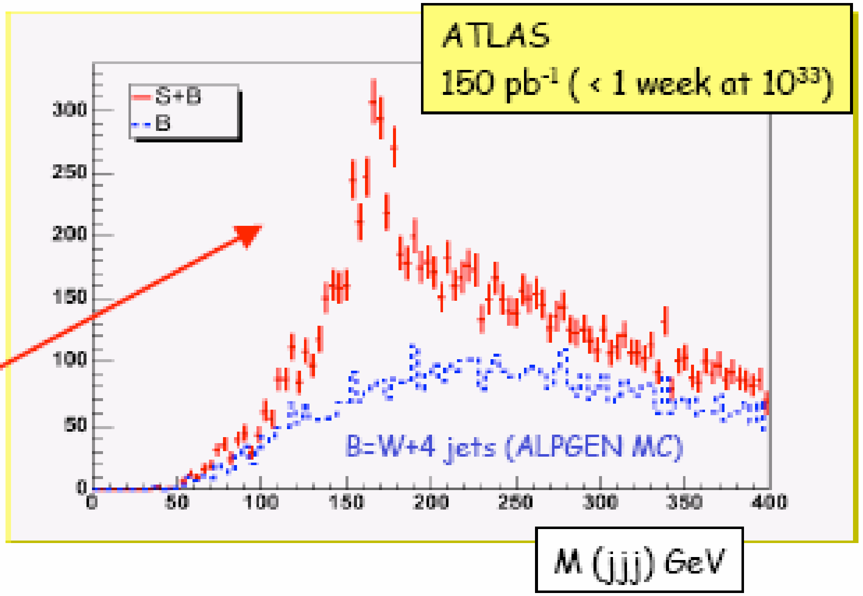




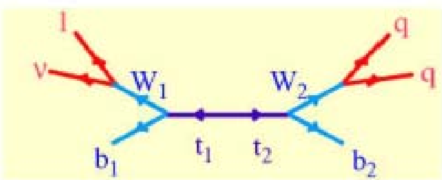
Top quarks

Example of initial measurement : top signal and top mass

- Use gold-plated $t\bar{t} \to bW\ bW \to bl\nu\ bjj$ channel
- Very simple selection:
  - -- isolated lepton (e, μ) $p_T > 20$ GeV
  - -- exactly 4 jets $p_T > 40$ GeV
  - -- no kinematic fit
  - -- no b-tagging required (pessimistic, assumes trackers not yet understood)
- Plot invariant mass of 3 jets with highest p_T



Time	Events at 10^{33}	Stat. error δM_{top} (GeV)	Stat. error $\delta\sigma/\sigma$
1 year	3×10^5	0.1	0.2%
1 month	7×10^4	0.2	0.4%
1 week	2×10^3	0.4	2.5%



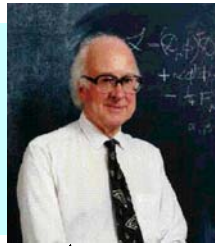
- top signal visible in few days also with simple selection and no b-tagging
- cross-section to ~ 20% (10% from luminosity)
- top mass to ~7 GeV (assuming b-jet scale to 10%)
- get feedback on detector performance :
  m_{top} wrong → jet scale ?
  gold-plated sample to commission b-tagging

Higgs Physics

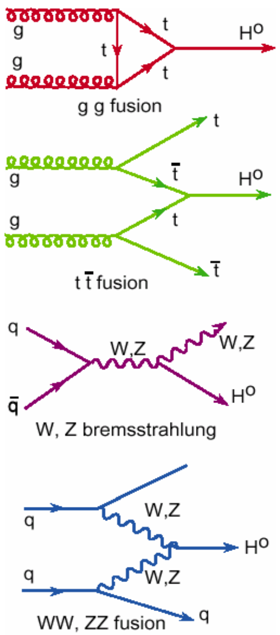
⇒ What is the origin of Electro-weak Symmetry Breaking?

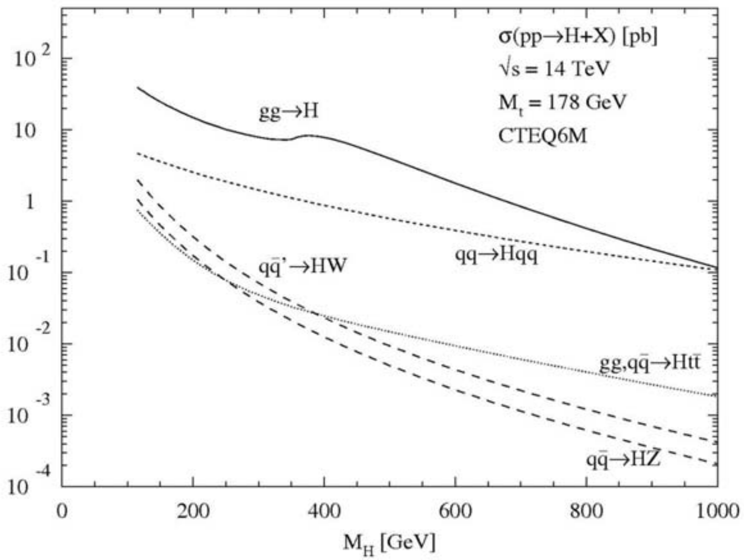
⇒ If Higgs field at least one new scalar particle should exist: The Higgs

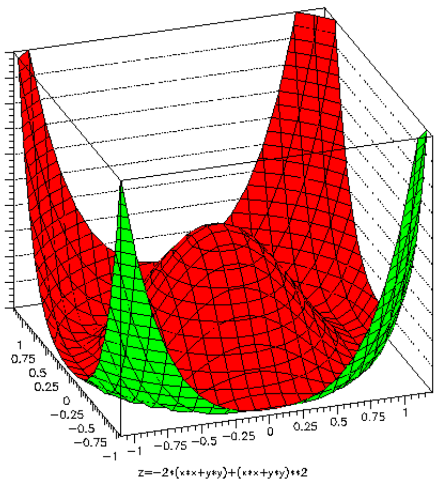
One of the main missions of LHC: discover the Higgs for m_H< 1 TeV

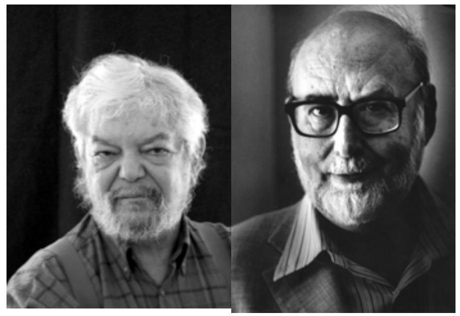


The only Higgs sighted so far









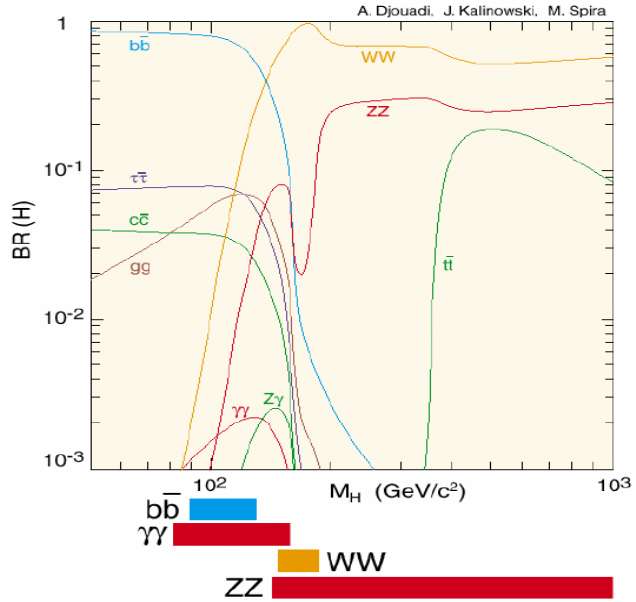
Brout, Englert

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 $H \to ZZ$

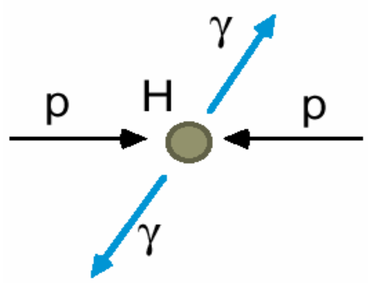
High mass ($M_H \gtrsim$ 700 GeV)

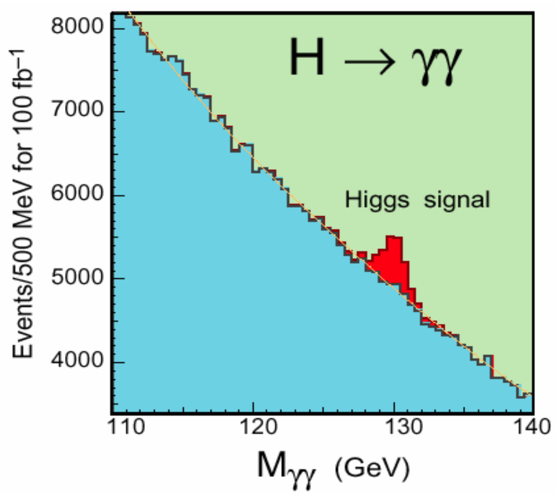
VBF $qqH \to ZZ \to \ell\ell\nu\nu$
VBF $qqH \to WW \to \ell\nu jj$

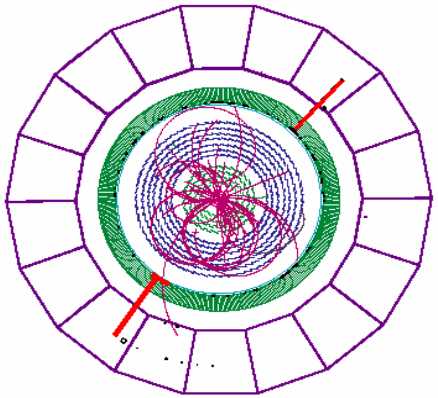
$H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ are the only channels with a very good mass resolution ~1%

Higgs Searches

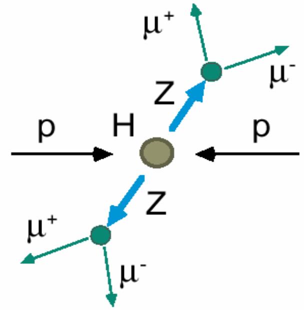
Low $M_H < 140$ GeV/c²

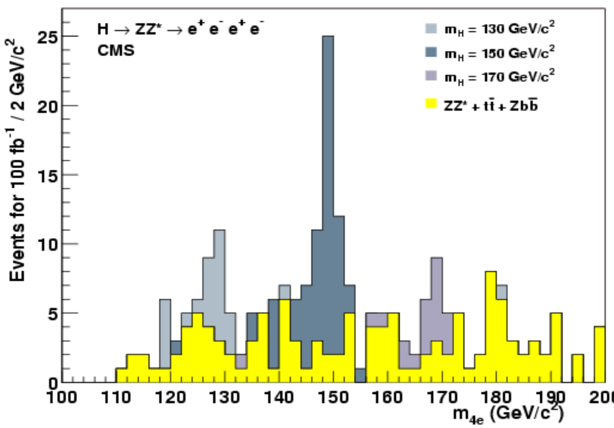


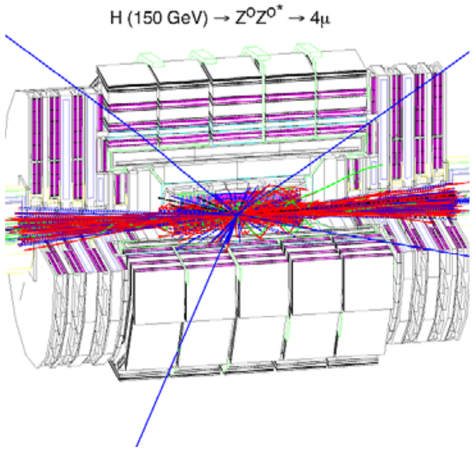




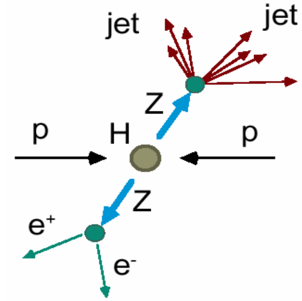
Medium $130 < M_H < 500$ GeV/c²

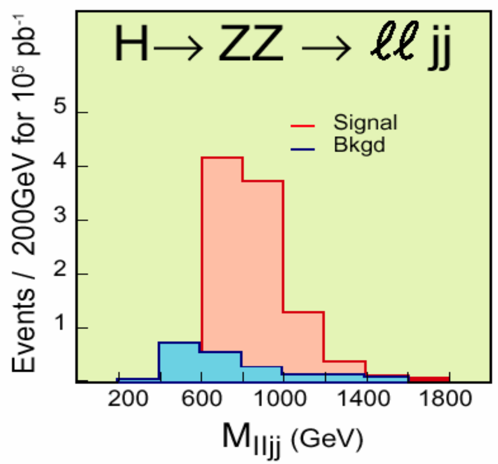


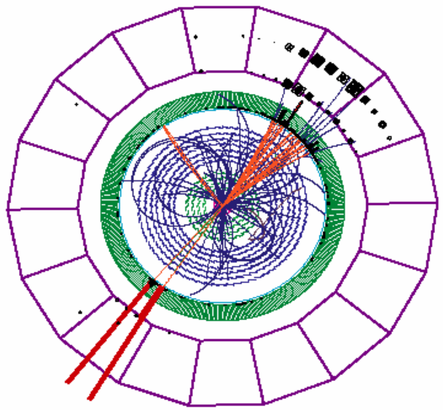




High $M_H > \sim 500$ GeV/c²





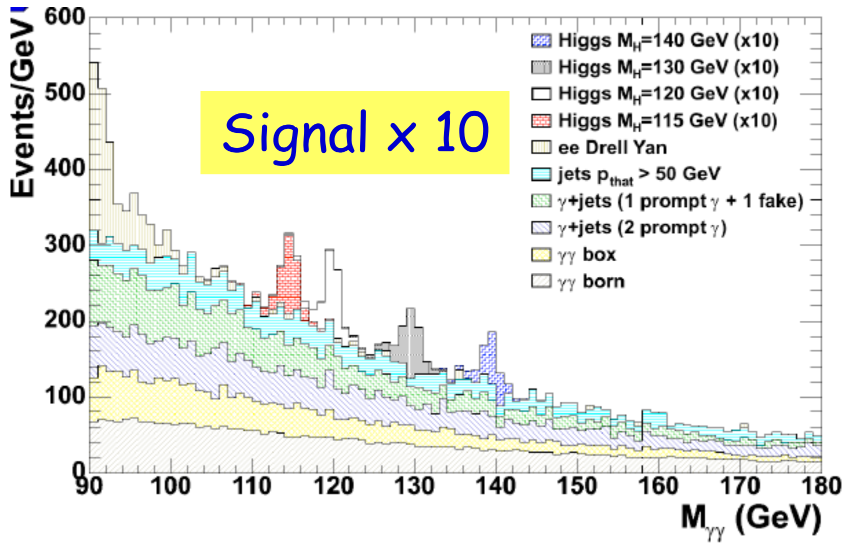


Discovery Potential : $H \rightarrow \gamma\gamma$

Significance for SM Higgs
M_H=130 GeV for 30 fb^{-1}

New elements of CMS-PTDR 2006 analysis:

- Cut based analysis
  - Split into categories depending on photon reco quality and position
  - Usage of LLR for discovery, systematic
- Optimized analysis*
  - NN with kinematics and g isolation
  - s/b per event

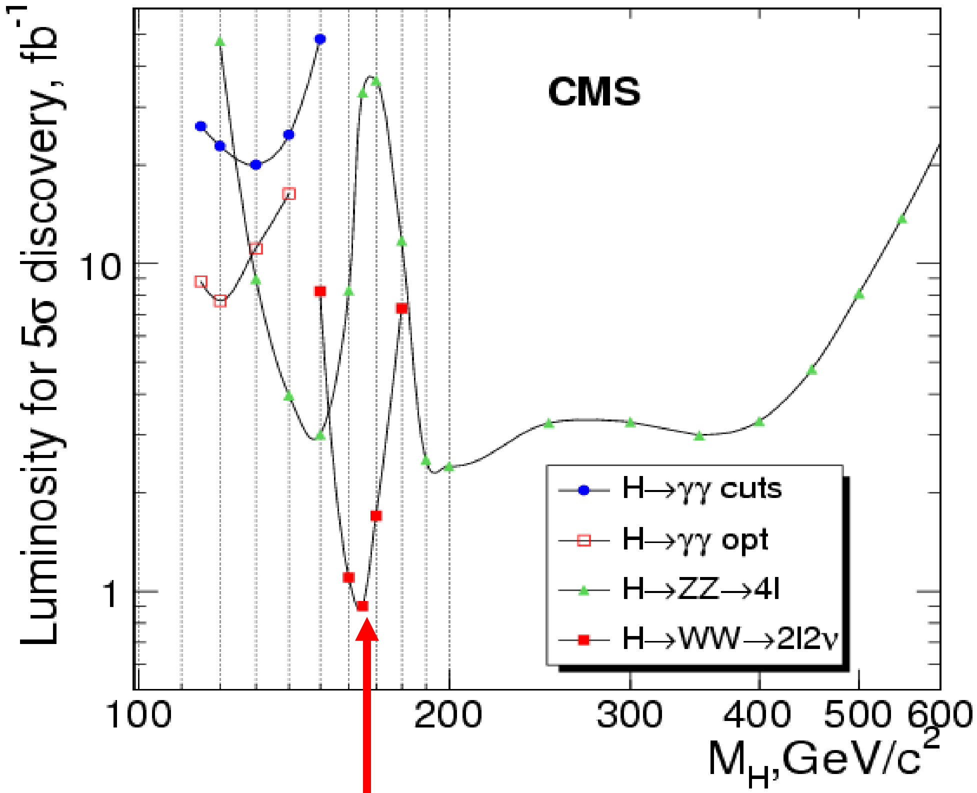


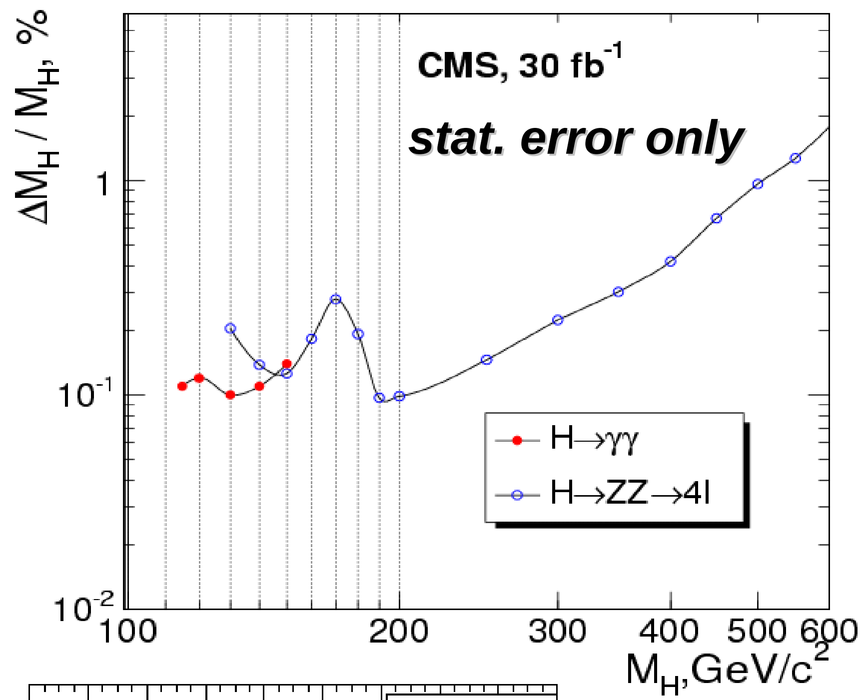
Final tracker→ all materials
More complete backgrounds

CMS ECAL TDR	CMS PTDR		ATLAS		
NLO count. exp	NLO cut based	NLO optimized*	TDR (LO)	New, NLO Cut based	New, NLO likelihood
~ 7.5	6.0	8.2	3.9	6.3	8.7

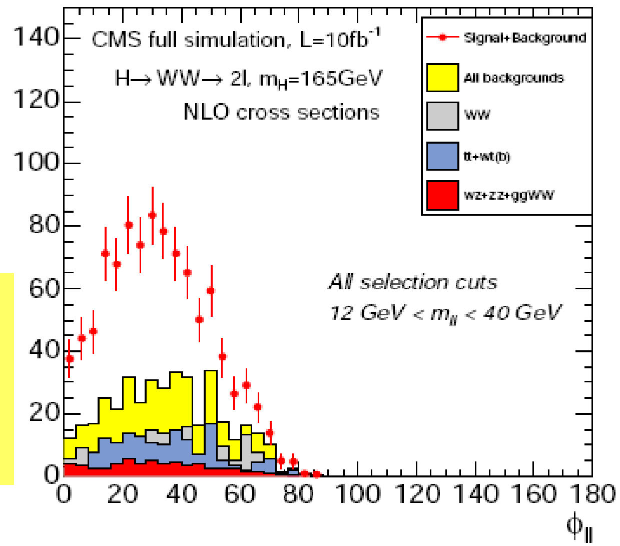
⇒Still the most promising channel for the low mass Higgs

SM Higgs boson discovery and mass measurement





Discovery with ~1 fb^{-1}



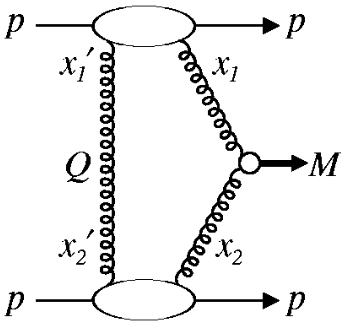
Very detailed studies
on SM backgrounds
and related systematics

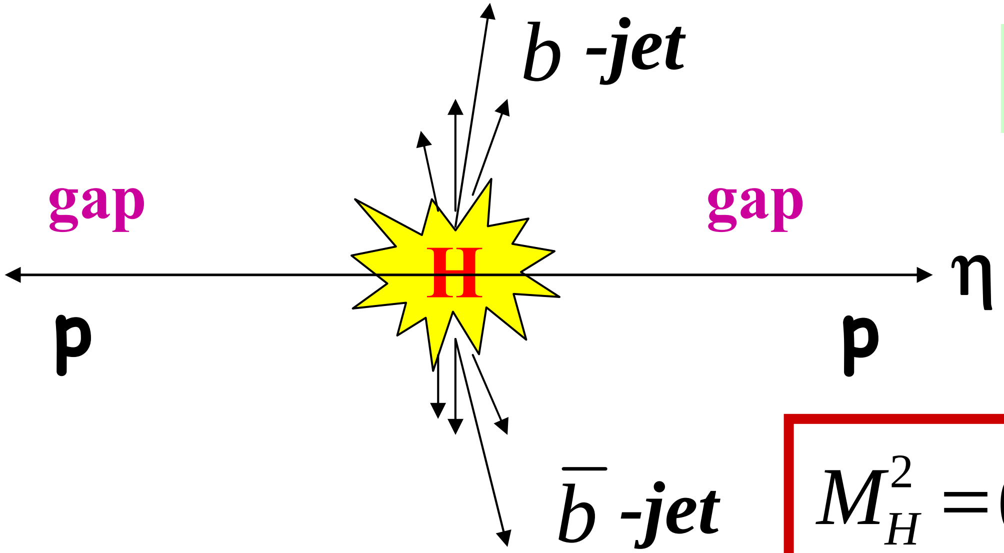
CMS Physics TDR

Central Exclusive Higgs Production

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

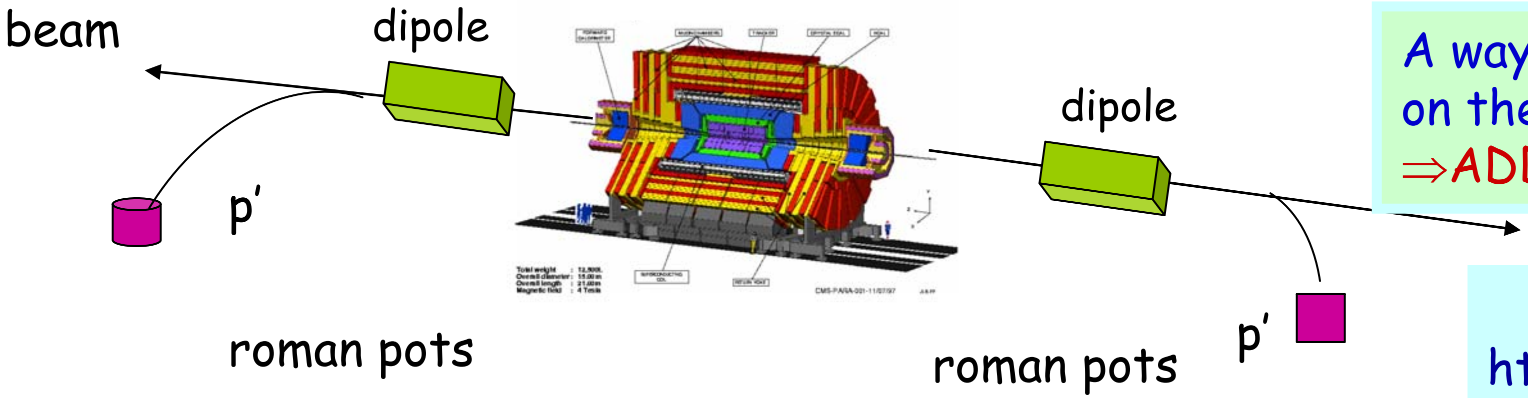
Khoze-Martin-Ryskin
+ many other groups





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

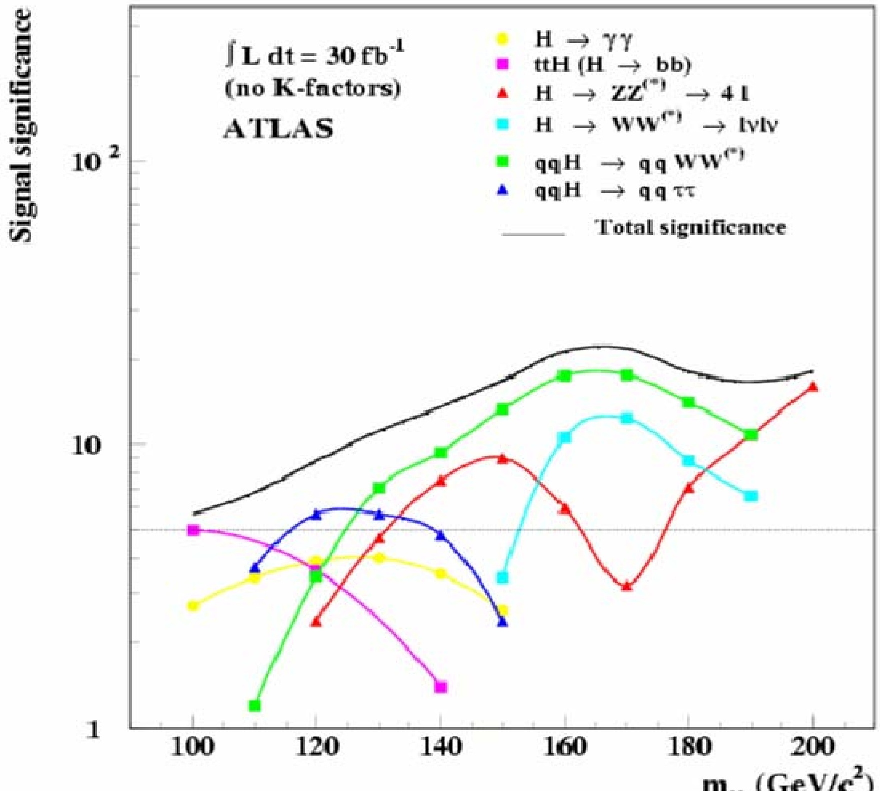
ΔM = O(1.0 - 2.0) GeV

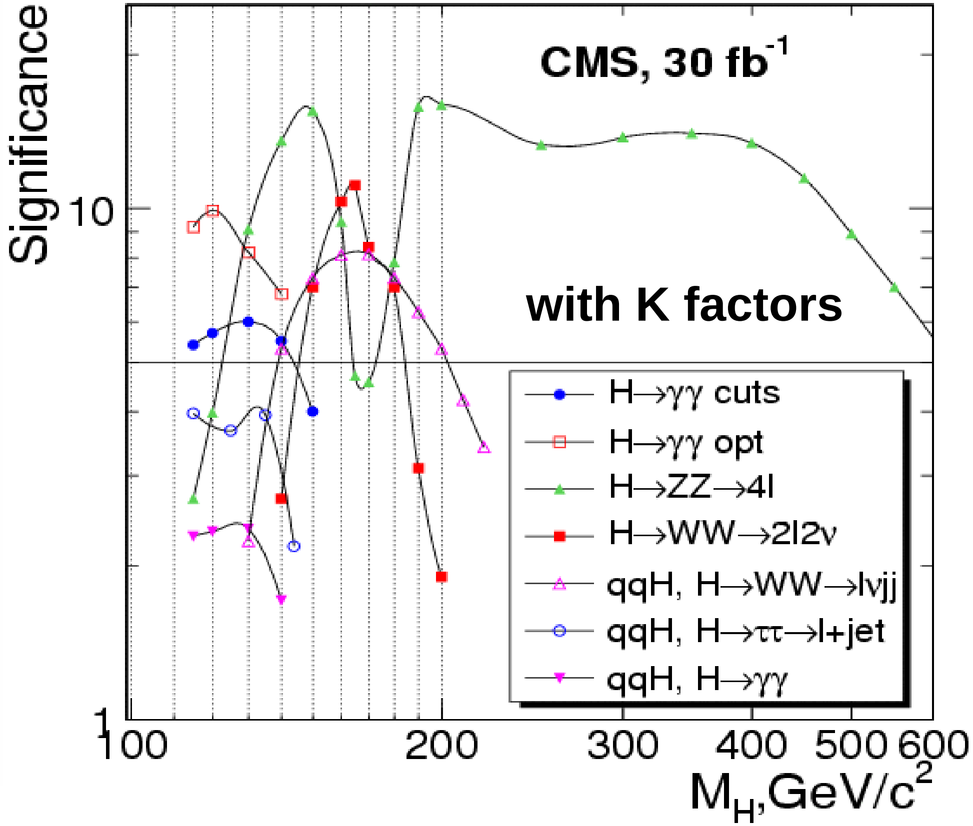


A way to get information on the spin of the Higgs
⇒ADDED VALUE TO LHC

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}

What can the LHC do?

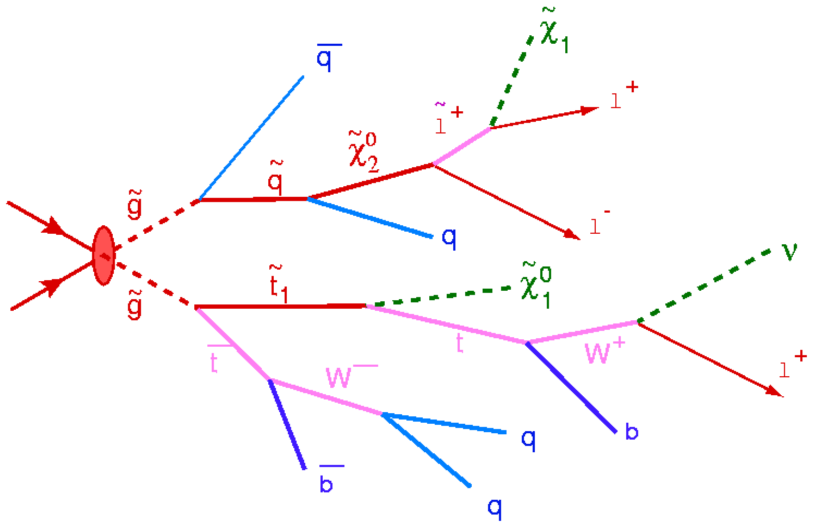
- LHC will discover the SM Higgs in the full region up to 1 TeV or exclude its existence with O(10) fb^{-1} or less. If no Higgs, other new phenomena in the WW should be observed around 1 TeV
- The LHC will measure with full luminosity (>100 fb^{-1})
  - The Higgs mass with 0.1-1% precision
  - The Higgs 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 ILC

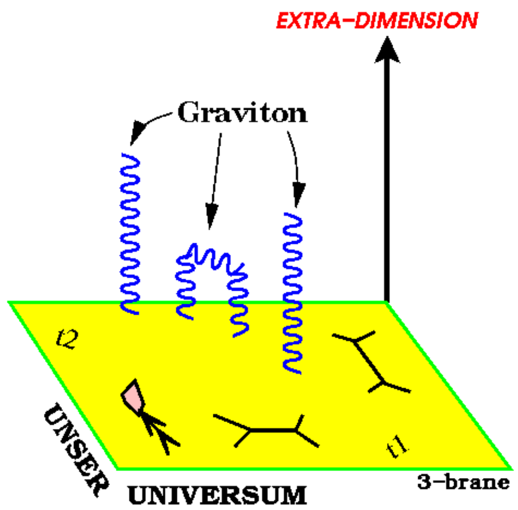
Beyond the Standard Model

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

Supersymmetry



Extra dimensions

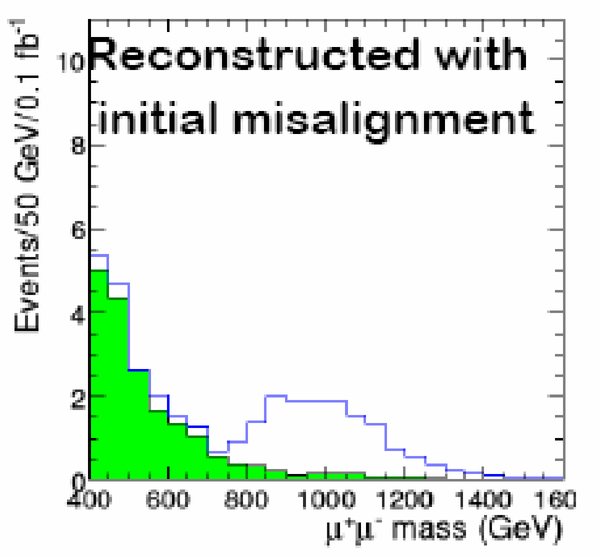


+…

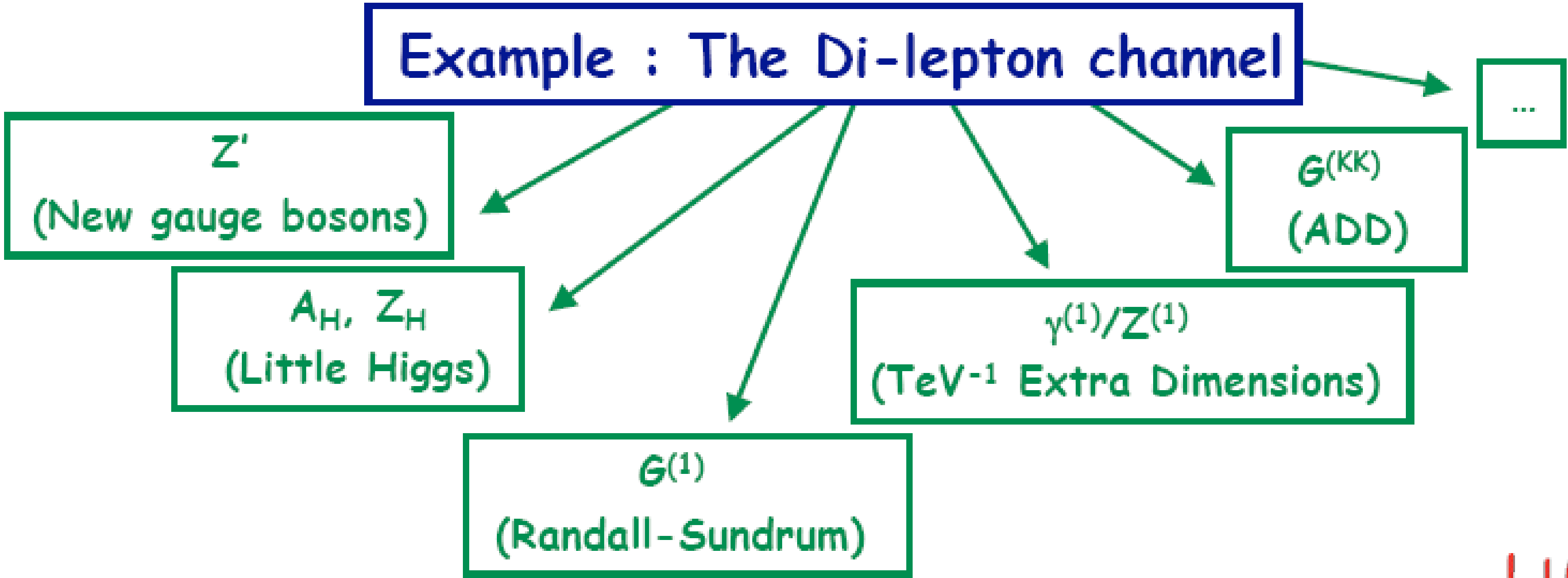
+ a lot of other ideas…
Split SUSY, Little Higgs models, new gauge bosons, technicolor, compositness,..

Early discoveries? E.g. Di-lepton Resonance

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



First months of operation

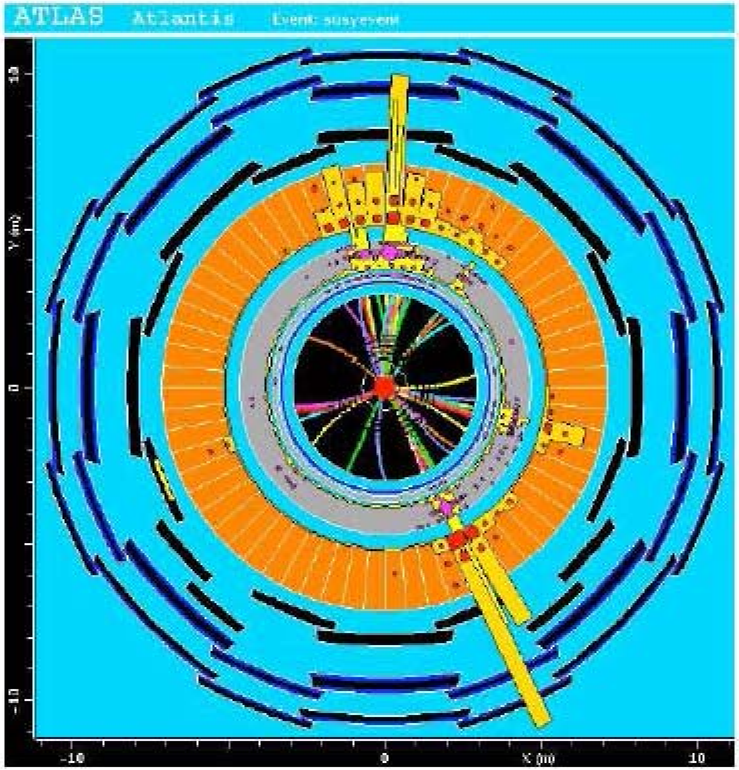


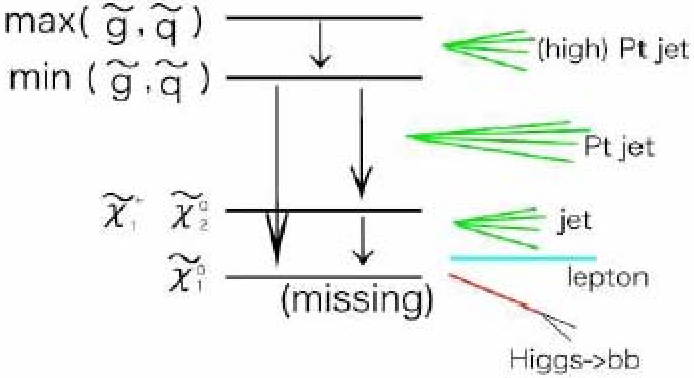
Supersymmetry

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}





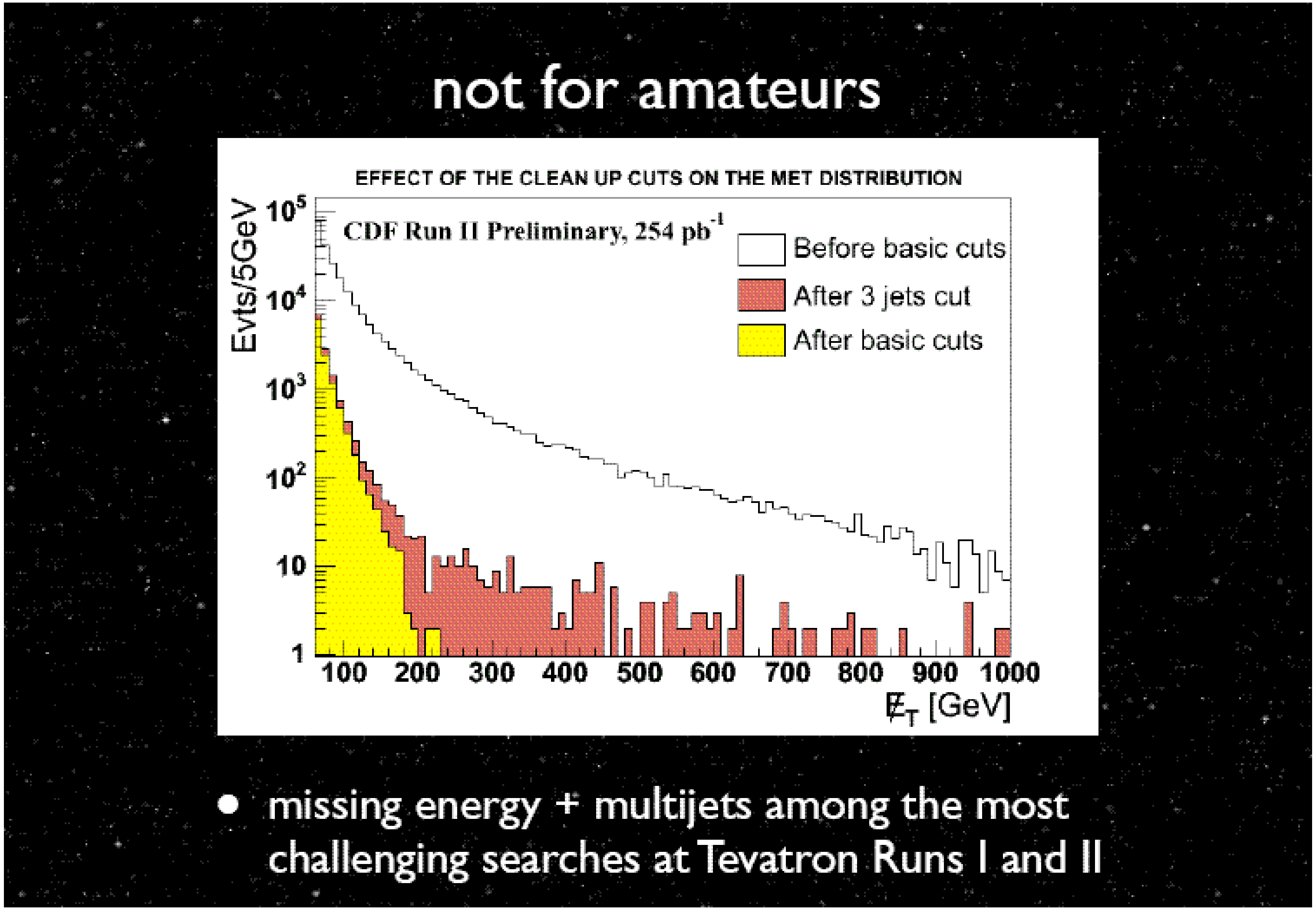
event topologies of SUSY

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

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

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

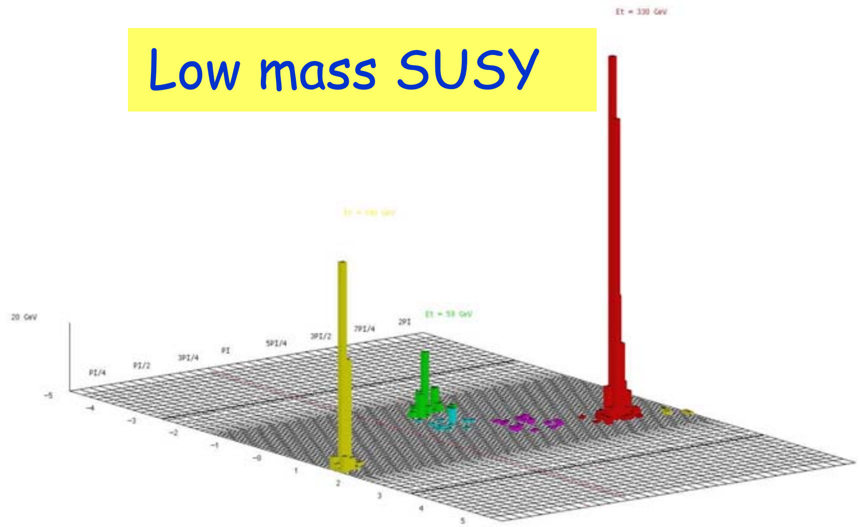
Missing Transverse Energy

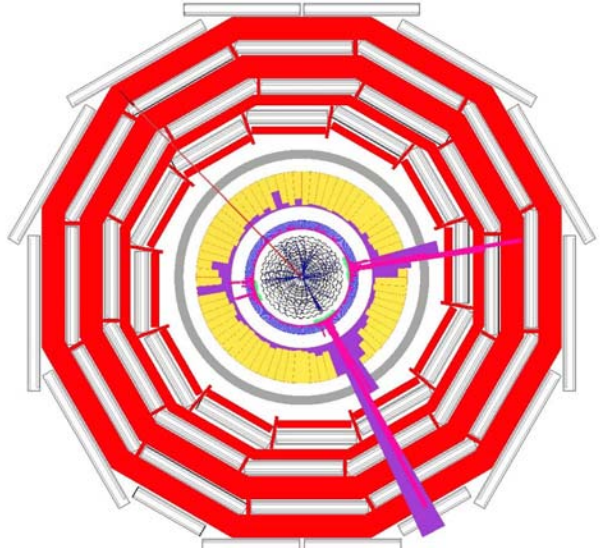


Tevatron experience!
Clean up cuts: cosmics, beam halo, dead channels, QCD

Detailed Simulation: Missing E_T

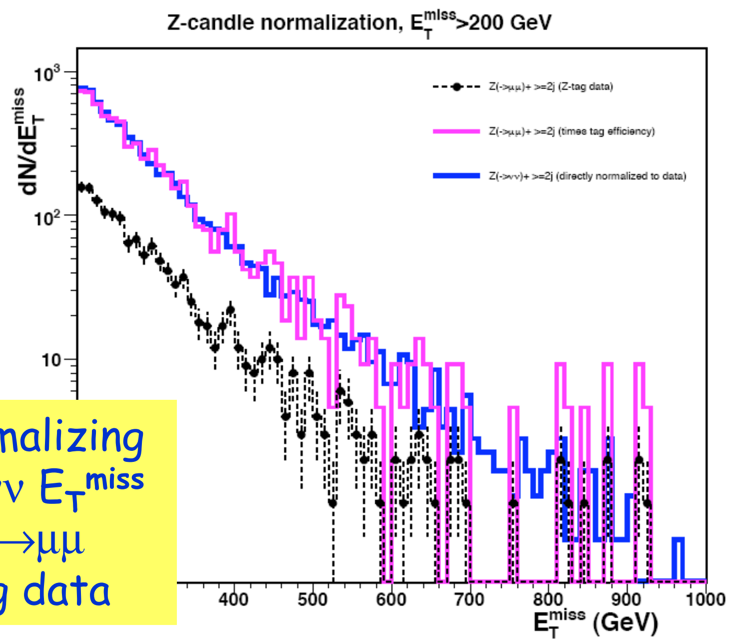
Low mass SUSY



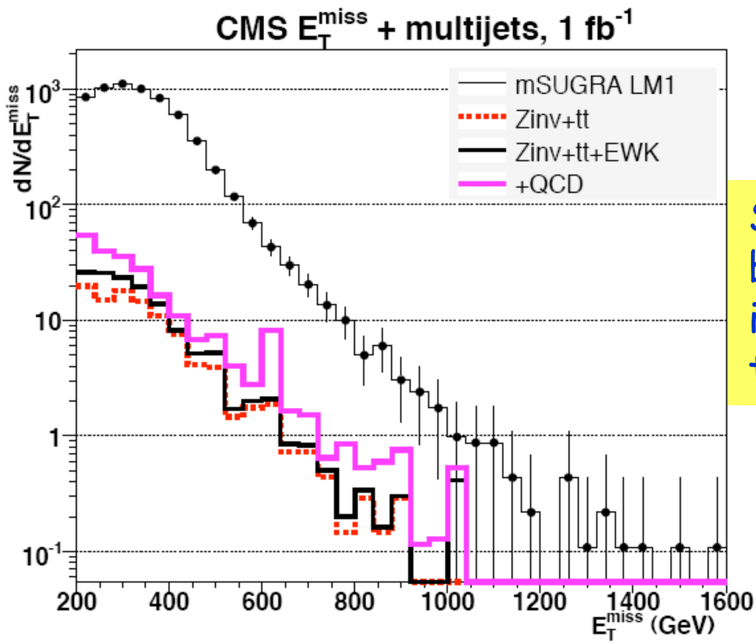


Missing E_T is a difficult measurement for the experiments

CMS Physics TDR



Normalizing $Z \rightarrow \nu\nu$ E_T^{miss} to $Z \rightarrow \mu\mu$ using data

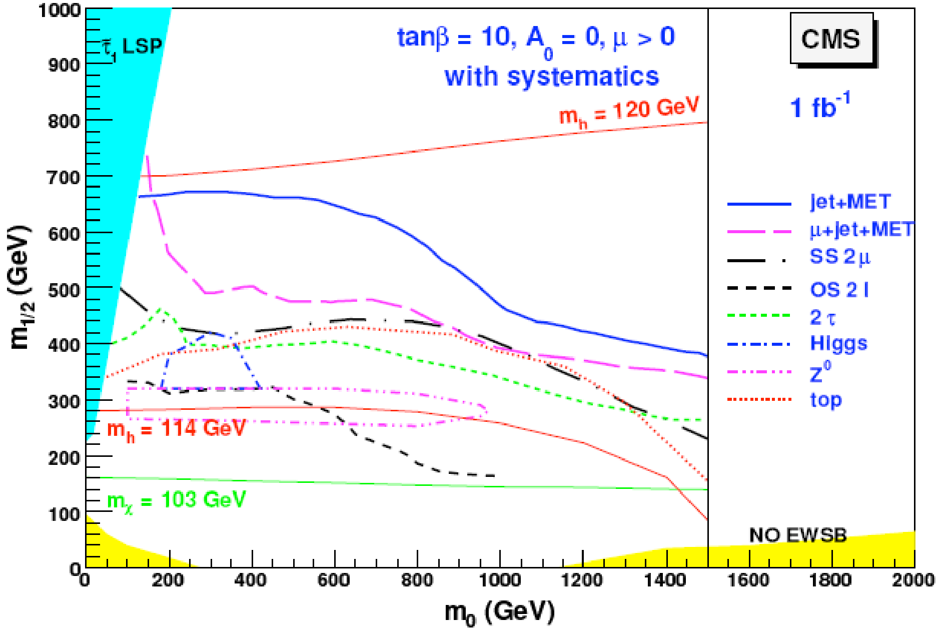


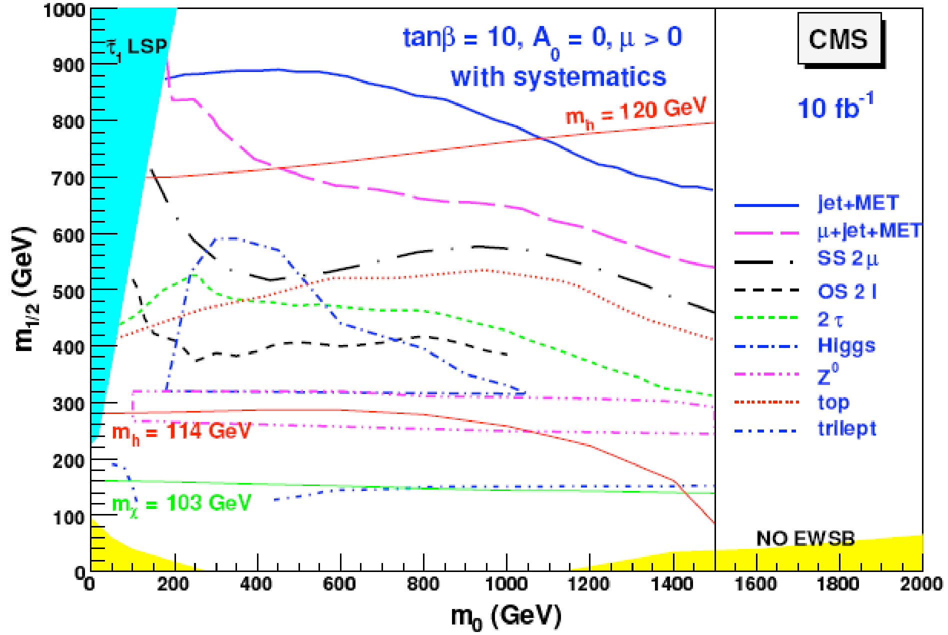
Signal over background in E_T^{miss} for the LM1 point

SUSYBSM: Inclusive SUSY searches

Searches based on different signatures

CMS PTDR





Low mass SUSY(m_{gluino}~500 GeV) shows excess for O(100) pb^{-1}

Time for discovery determined by:

- Time to understand the detector performance, Etmiss tails, jet scale,lepton id
- Time collect SM control samples such as W+jets, Z+jets, top..

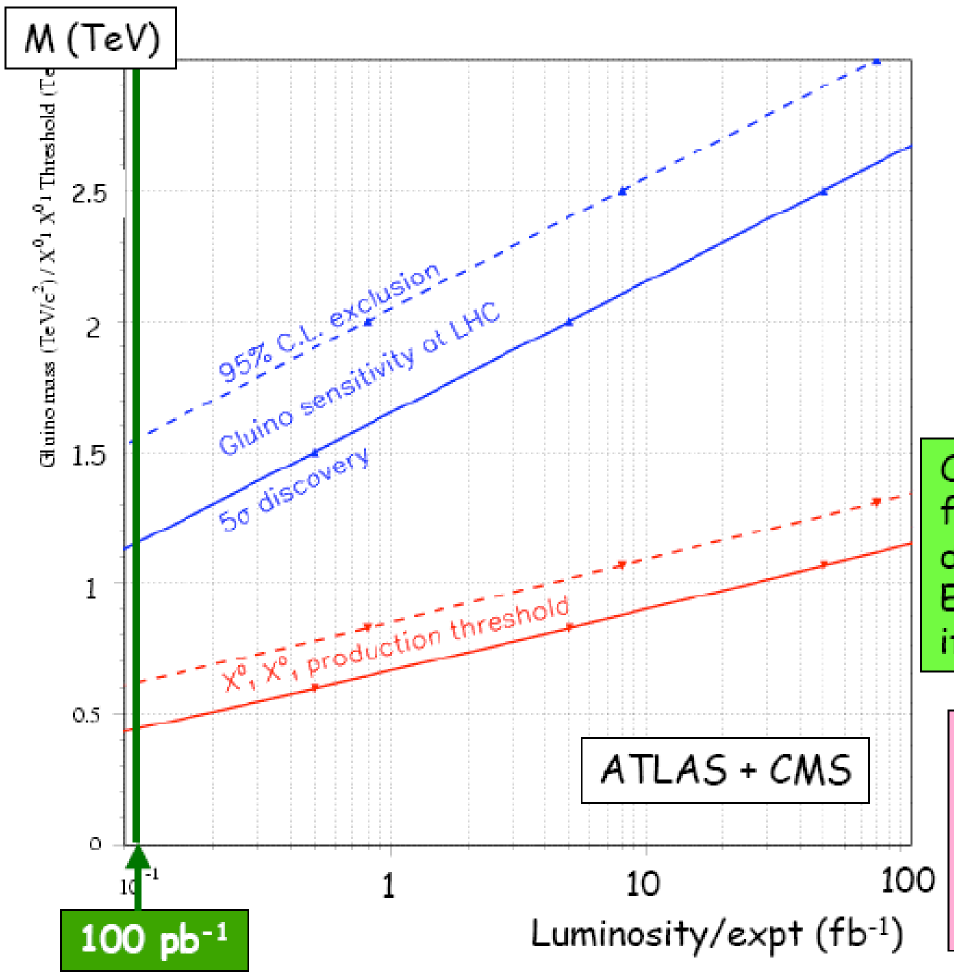
Early SUSY?

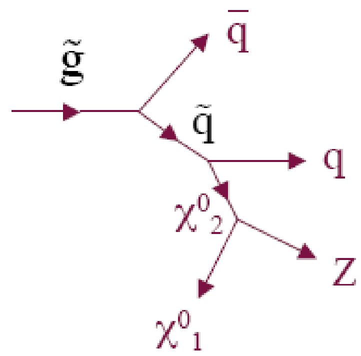
F. Gianotti, ADR et al.

Example of "early" discovery: Supersymmetry ?

If SUSY at TeV scale → could be found "quickly" .... thanks to:

- large $\tilde{q},\tilde{g}$ cross-section → ≈ 10 events/day at 10^{32} for $m(\tilde{q},\tilde{g}) \sim 1$ TeV
- spectacular signatures (many jets, leptons, missing E_T)





Something to watch for the ILC…

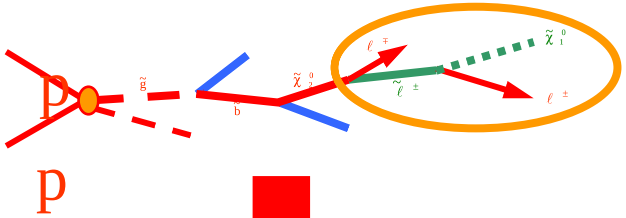
Our field, and planning for future facilities, will benefit a lot from quick determination of scale of New Physics. E.g. with 100 (good) pb^{-1} LHC could say if SUSY accessible to a ≤1 TeV ILC

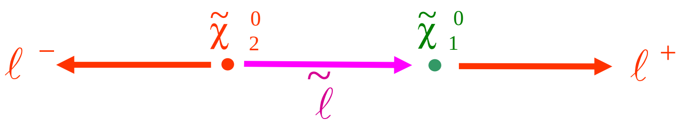
BUT: understanding E_T^{miss} spectrum (and tails from instrumental effects) is one of the most crucial and difficult experimental issue for SUSY searches at hadron colliders.

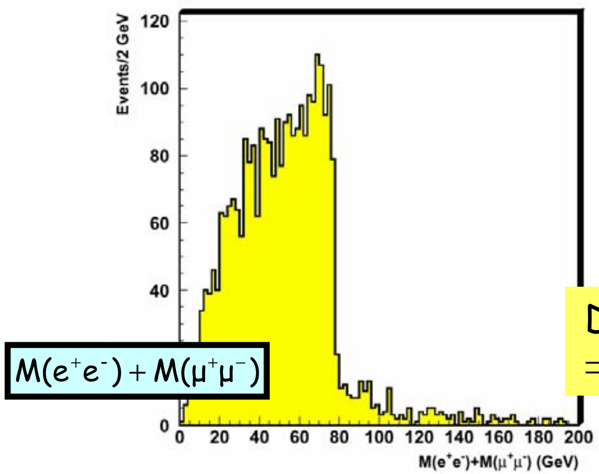
Sparticle Detection & Reconstruction

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
$\tan\beta$ = 10
sign(μ)=+





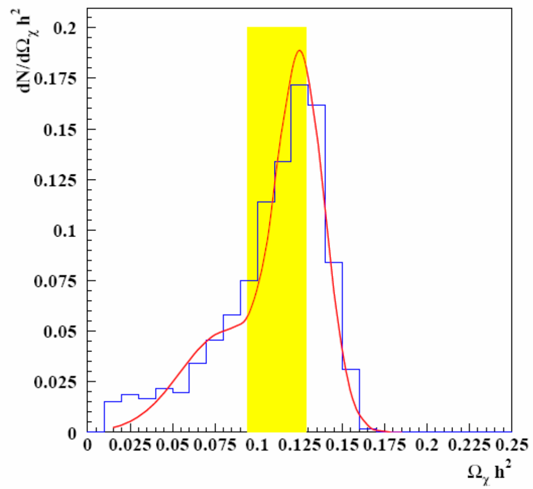


D. Miller et al
⇒Use shapes

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

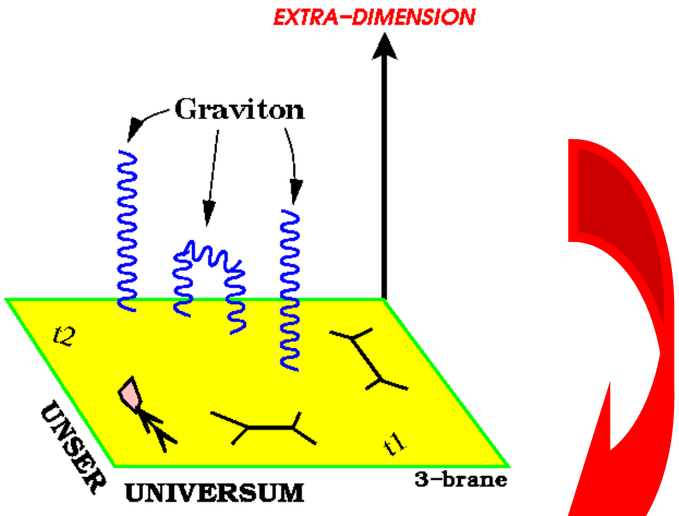
Large Extra Dimensions

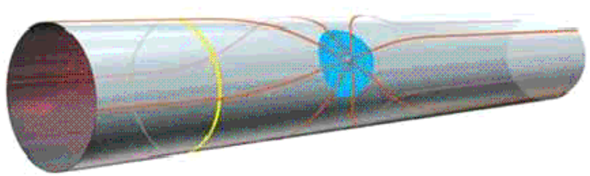
ADD: Arkani –Ahmed, Dimopolous,Dvali

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

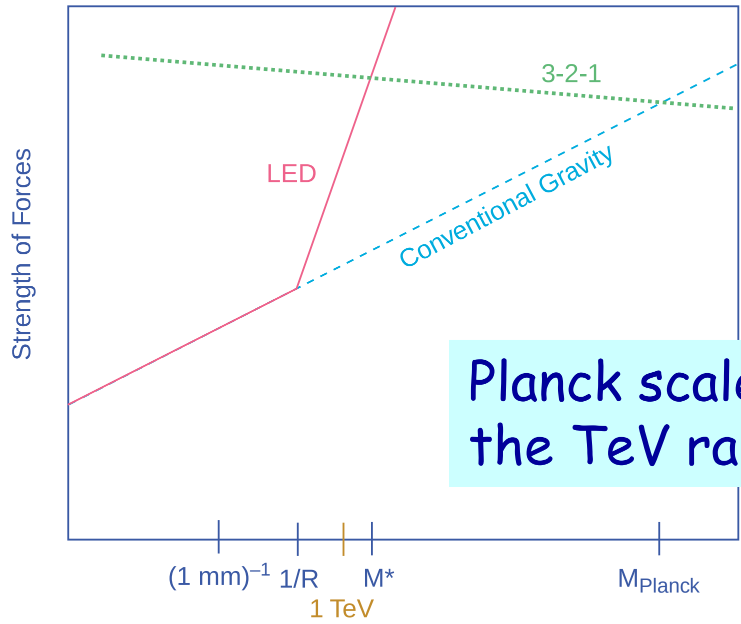
String Theory Inspired

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)





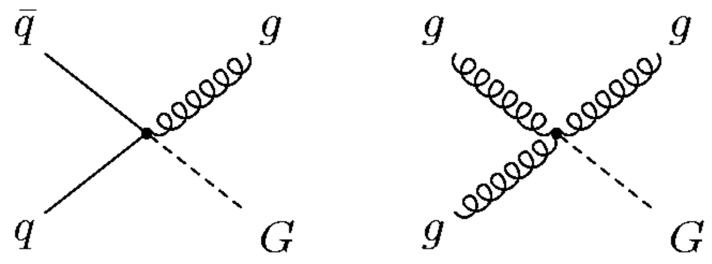
Curled up…



Planck scale in the TeV range?

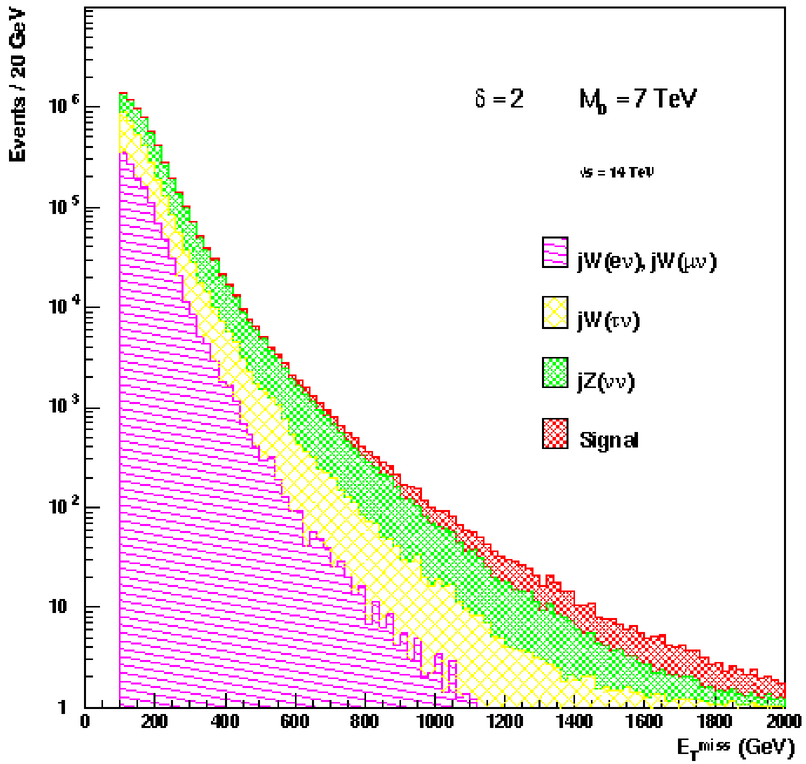
Extra Dimension signals at the LHC: ADD

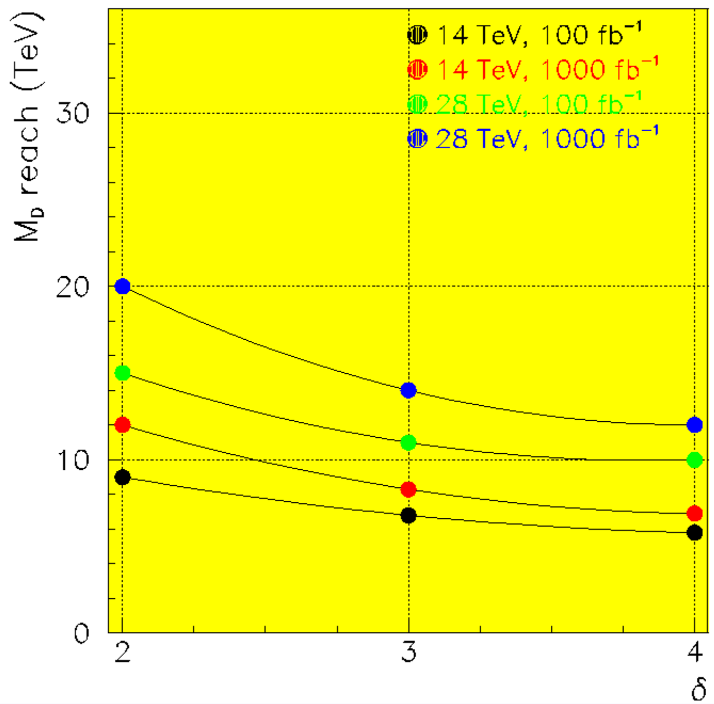
ADD: Arkani –Ahmed, Dimopolous,Dvali



Graviton production!
Graviton escapes detection

Signal: single jet + large missing ET





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

What if Planck Scale in TeV Range?

- Schwarzschild radius

Landsberg, Dimopoulos
Giddings, Thomas

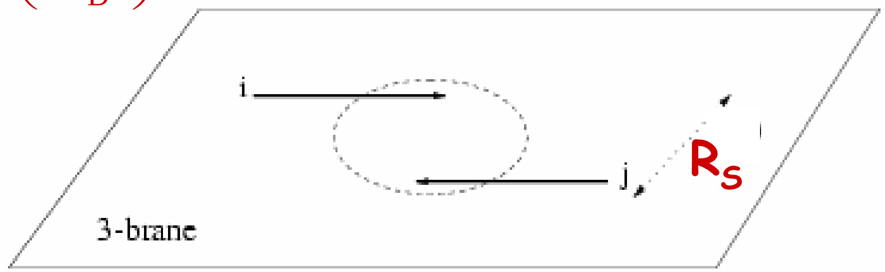
4-dim., $M_{gravity} = M_{Planck}$ $\quad R_S \sim \frac{2}{M_{Pl}^2} \frac{M_{BH}}{c^2}$

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

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

$R_s \to \sim 10^{-19}$ 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 : $\sigma(ij \to BH) \sim \pi R_S^2$
- $\sigma(pp \to BH)$ 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

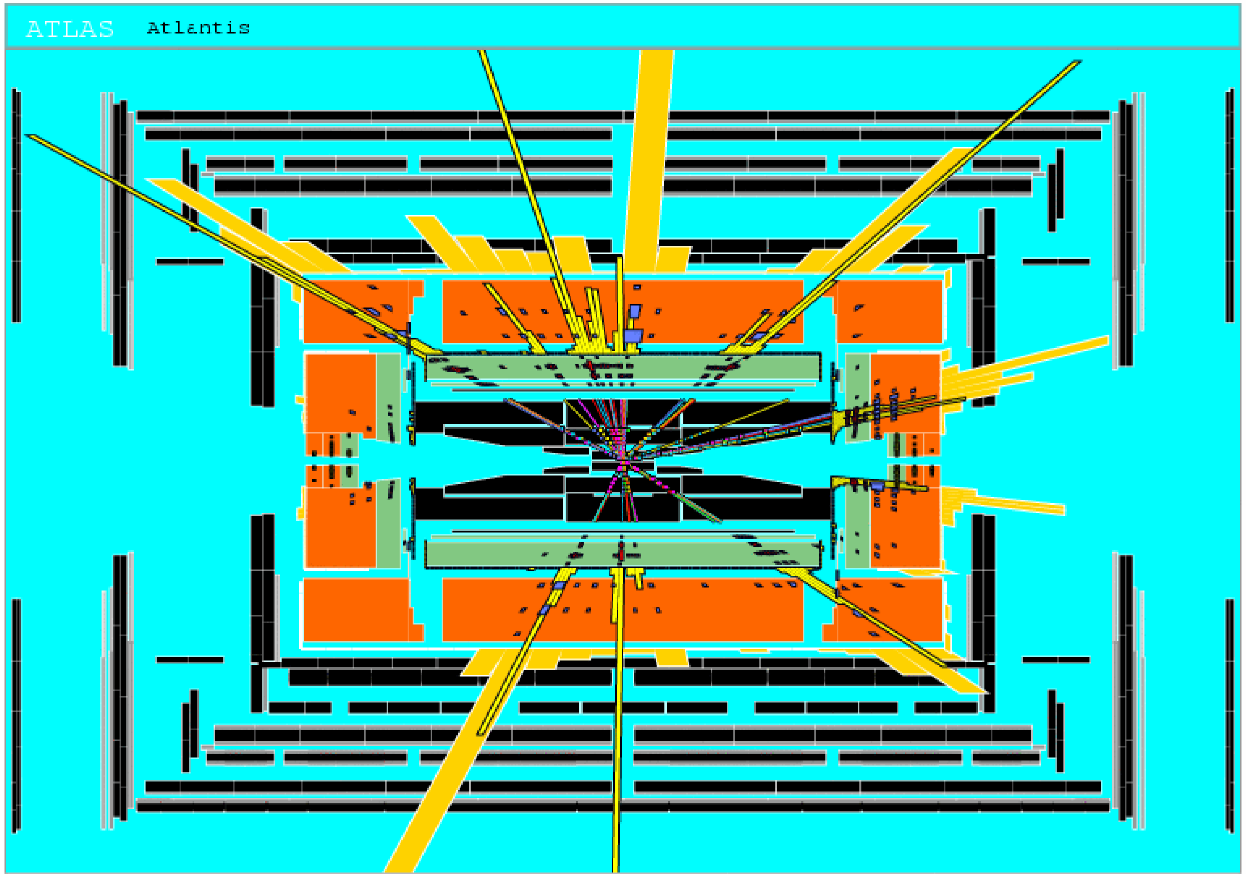
- Black holes decay immediately by Hawking radiation (democratic evaporation) :
  - -- large multiplicity
  - -- small missing E
  - -- jets/leptons ~ 5

} 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



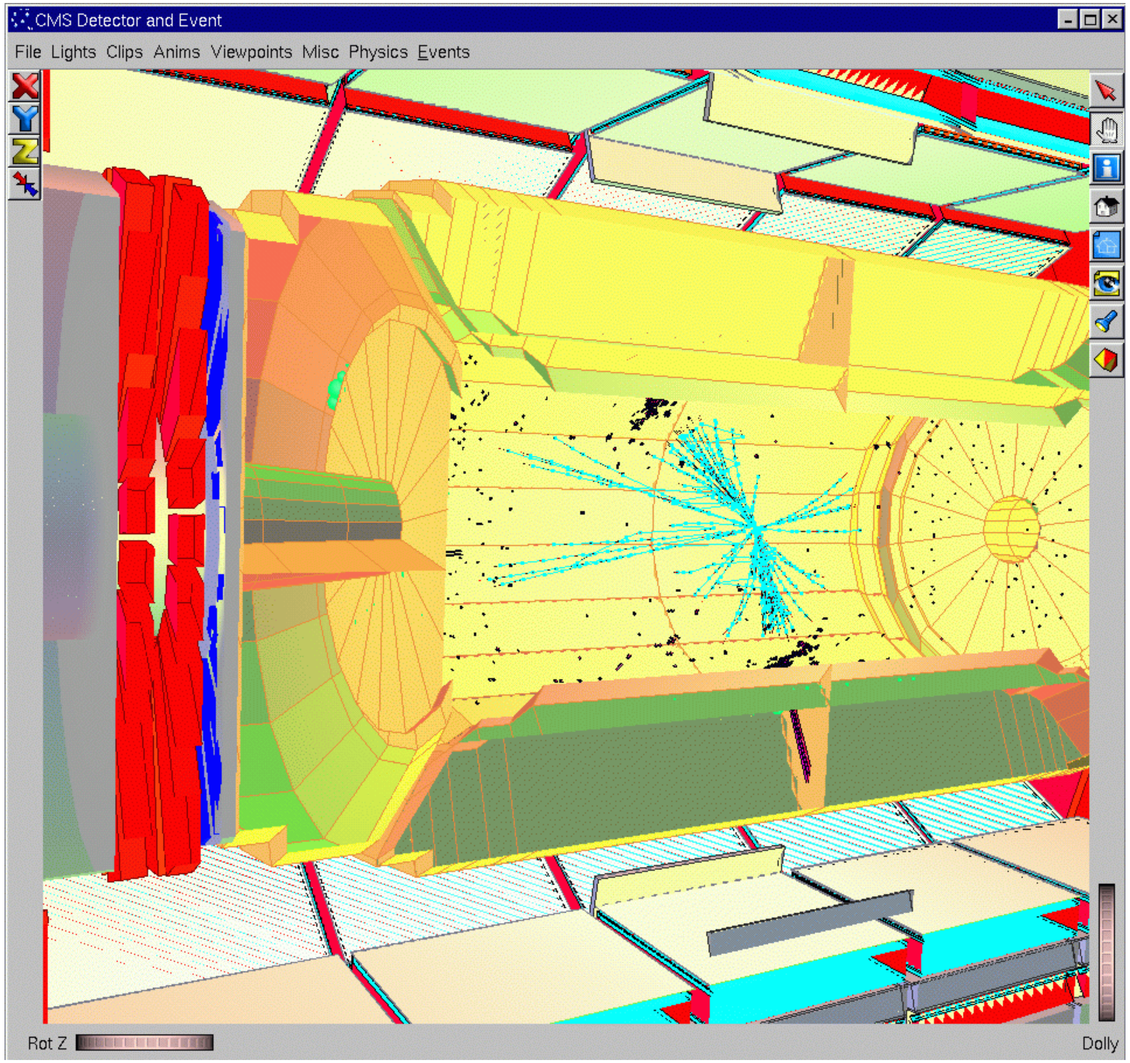
~ Spherical events
Many high energy jets leptons, photons etc.

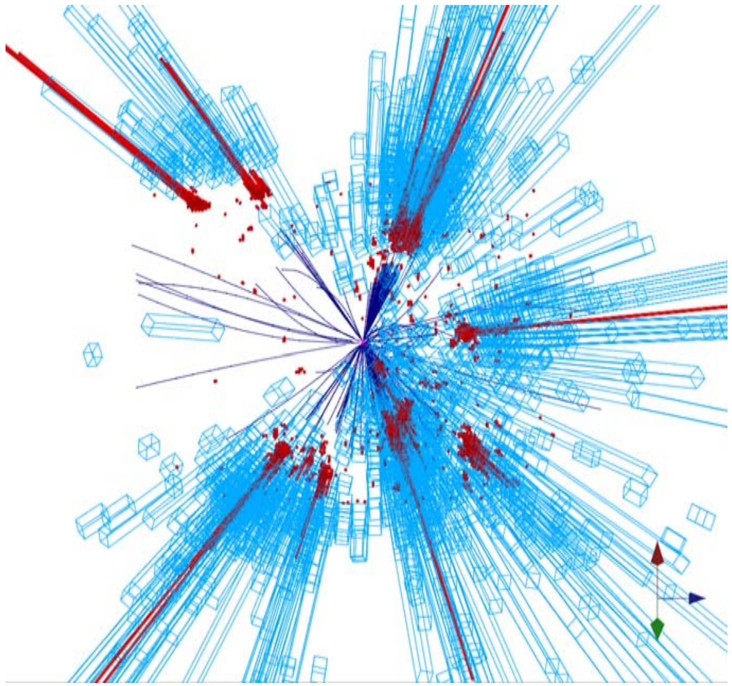
Ecological comment:
BH's will decay within 10^{-27} secs or so

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

Black Holes

...and in CMS





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

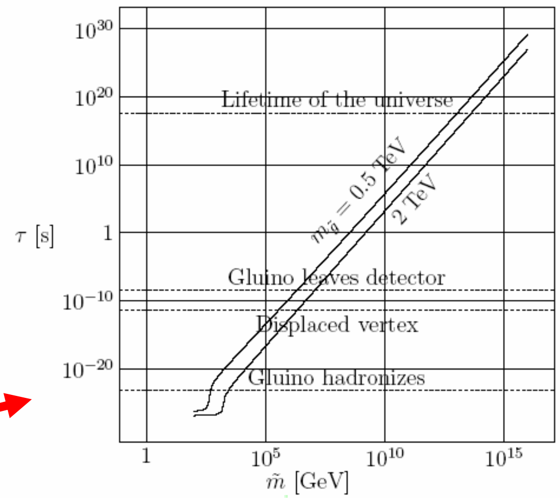
  eg. with the calorimeters of the experiments!

Gravitino Dark Matter and GMSB

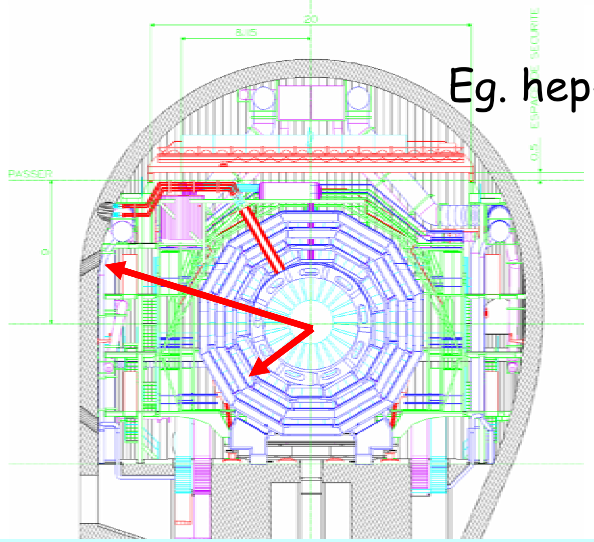
- In some models/phase space the gravitino is the LSP
- Then the NLSP (neutralino, stau lepton) can live 'long'

⇒Challenge to the experiments!

Arkani-Hamed, Dimopoulos hep-th/0405159



Eg. hep-ph/0508198

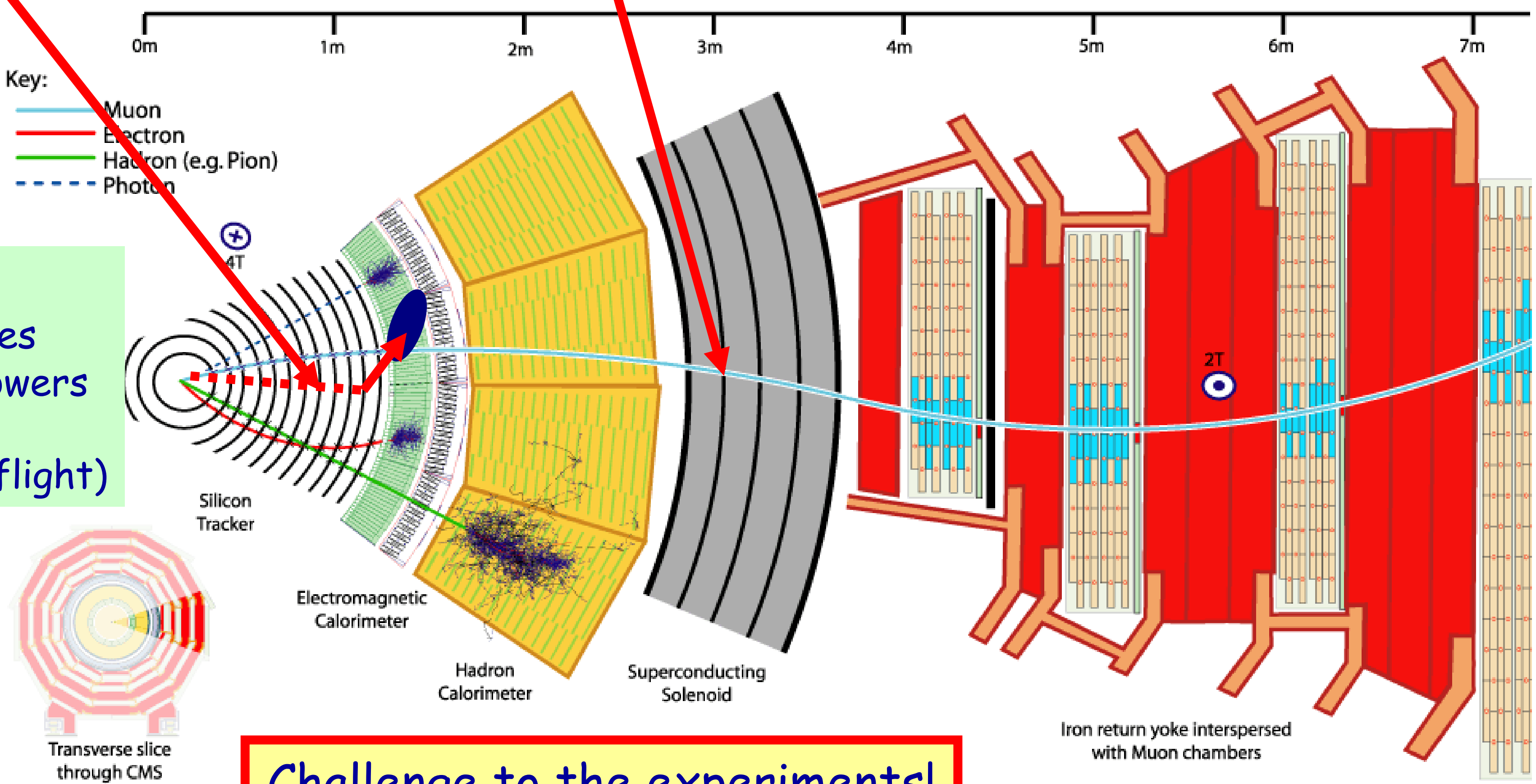


Sparticles stopped in the detector or walls around of the cavern.
They decay after hours---months…

Recent Studies: Special signatures

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

GMSB or GDM models

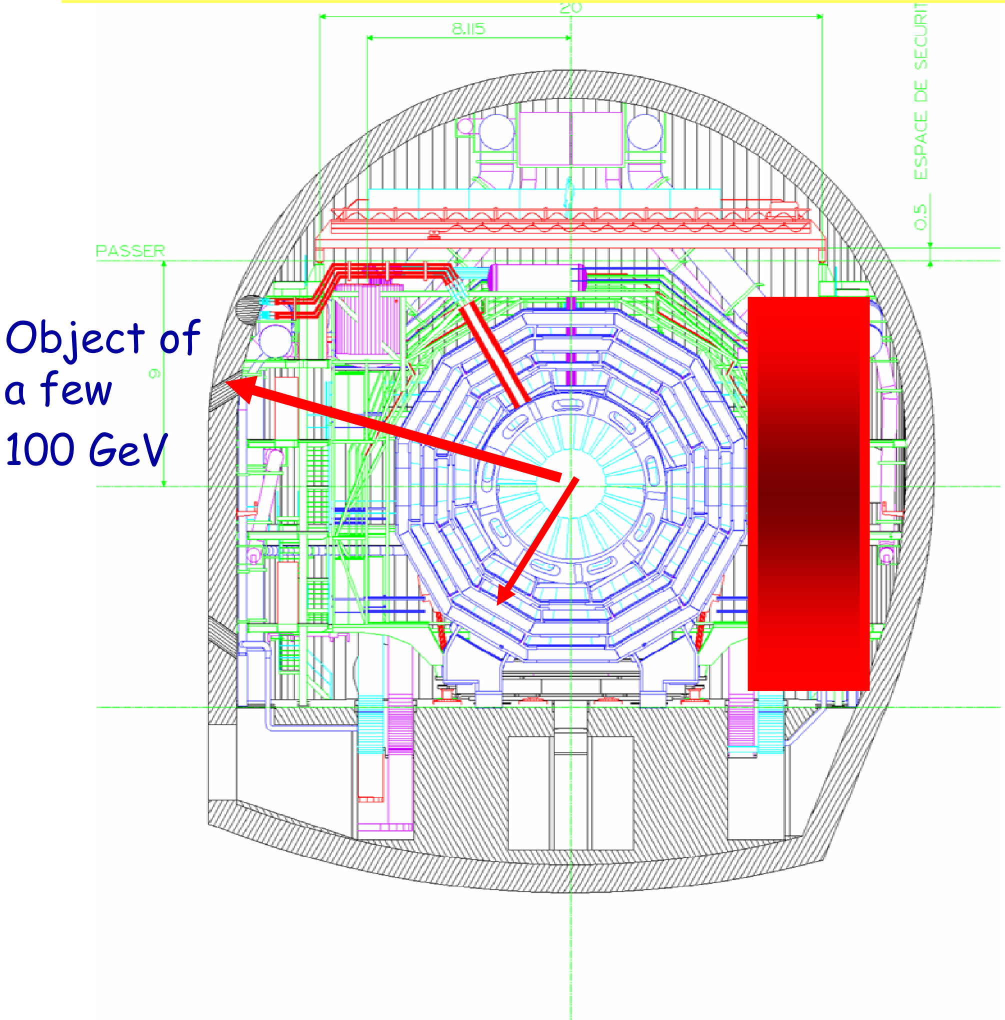


Signatures
- Displaced vertices
- Non-pointing showers
- Long lived 'heavy muons' (time of flight)

Challenge to the experiments!

Long lived sparticles

Some of these heavy long lived heavy sparticles will be stopped in the detector or walls around of the cavern. They will decay after some time: hours-days-weeks-months…



Some benchmark points with Lifetime of 10^4-10^6 sec are being studied:

K. Hamaguchi,M Nijori,ADR hep-ph/0612060

ADR, J. Ellis et al. hep-ph/0508198

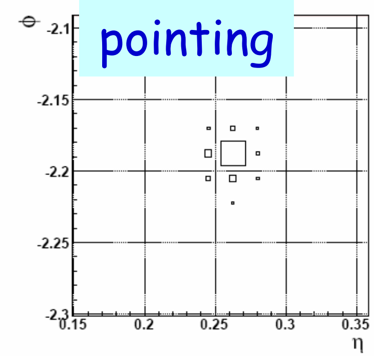
⇒Ideas: Use the cavern wall or addition of slepton stoppers in the cavern (multi-kton object)

New CMS analyses

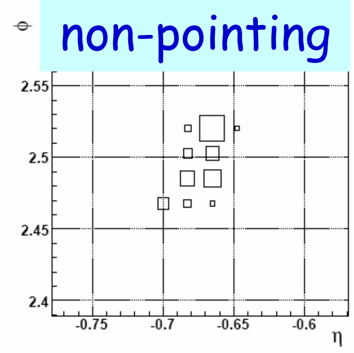
- GMSB: Non-pointing photons

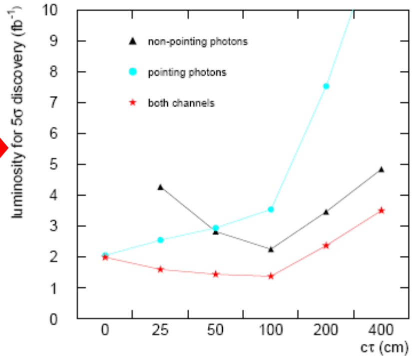
GMSB parameters $N = 1 \quad \tan\beta = 1 \quad \mathrm{sgn}\,\mu = 1 \quad M_m = 2\Lambda$

pointing



non-pointing

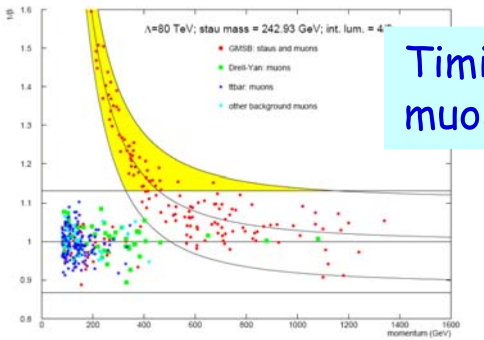




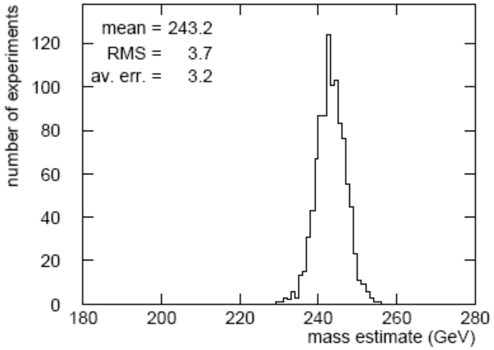
χ cτ lifetime extraction with ~20% precision

- GMSB: long living staus

GMSB parameters $N = 3 \quad \tan\beta = 3 \quad \mathrm{sgn}\,\mu = 1 \quad M_m = 2\Lambda$



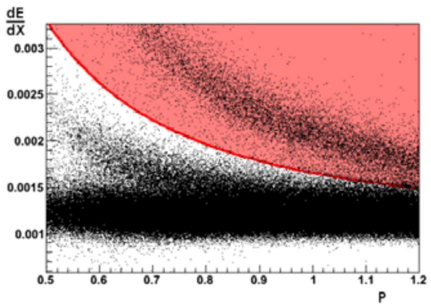
Timing (β) in muon detectors



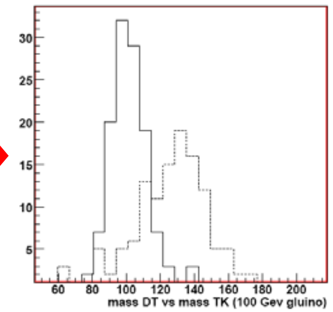
stau mass extraction with a few % precision

- R-hadrons

trigger/mass meas. for region β > 0.6



de/dx in the tracker

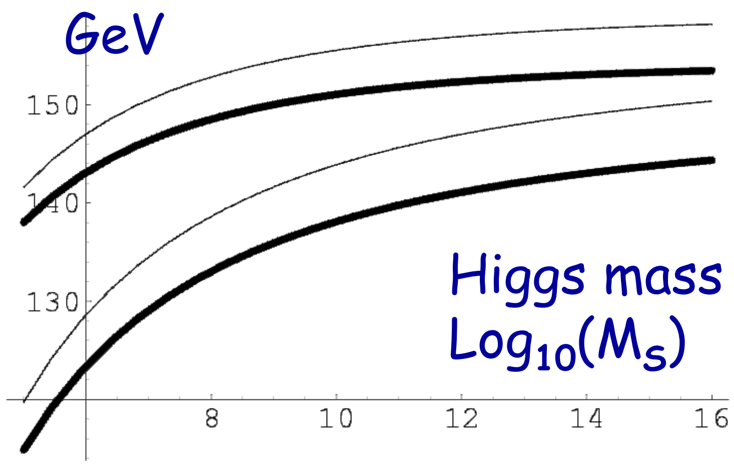


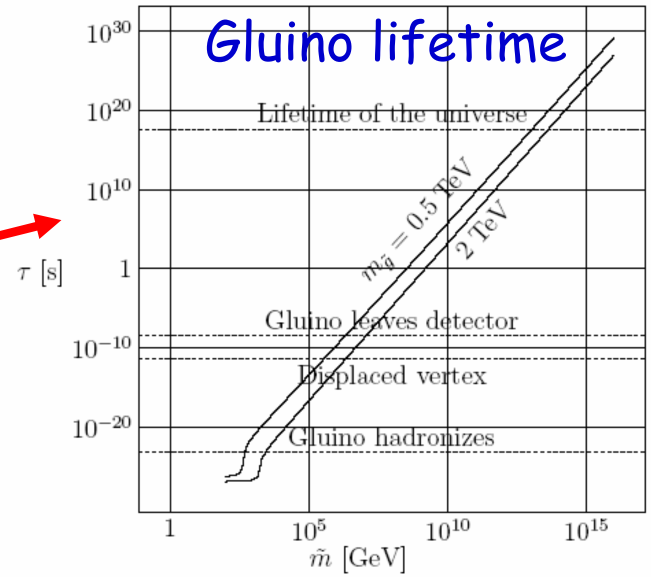
β-tracker ≠β muons

Split Supersymmetry

Arkani-Hamed et al., Giudice et al.

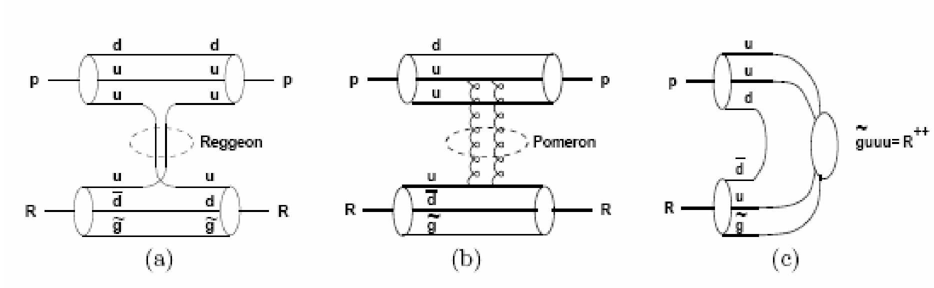
- Assumes nature is fine tuned and SUSY is broken at some high scale
- Motivated by cosmological constant problem and multitude of vacua in string theory (Landscape)
- The only light particles are the Higgs and the gauginos (several 100 GeV to several TeV)
- Interesting gluino phenomenology.
  - Gluino can live long: sec, min, years!
  - R-hadron formation: slow, heavy particles containing a heavy gluino –
  - special interactions with matter…





Can we detect these gluinos at LHC??…

How do these R-hadrons interact with matter?



R-Hadrons

(e.g. A Kraan hep-ph/0404001)

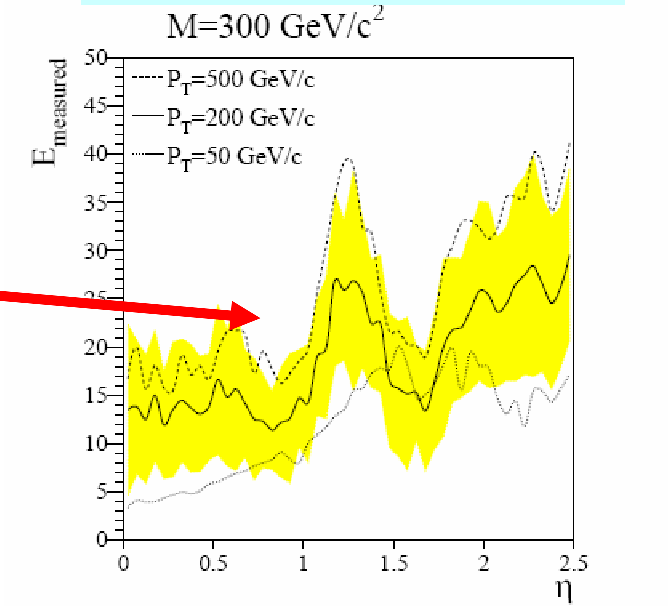
- Gluino interactions suppressed as $1/M^2$
- u,d quarks interact but with a kinetic energy of order 1 GeV

$\Rightarrow$ deposite only 10-15% of energy while passing through ATLAS/CMS calorimeters

This will be a remarkable signature

Also: charge flip while passing through matter

Need to modify the detector simulation toolkit (Geant4)



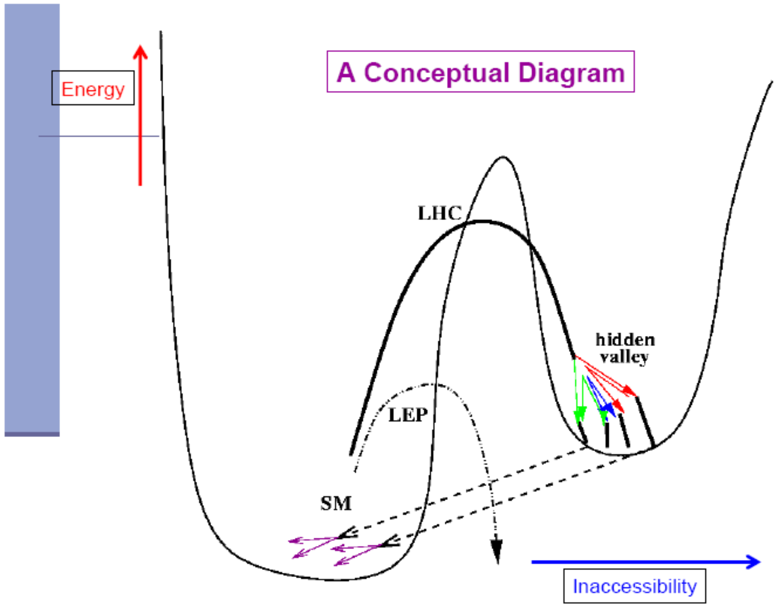
Understanding of travel of heavy particles through matter good enough?

Further: anomalous de/dx, time-of-flight measurements. Trigger is a challenge

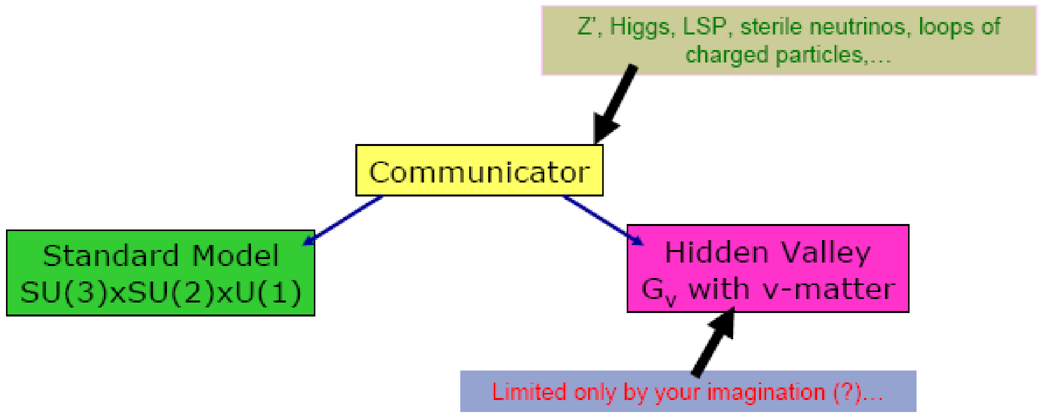
Hidden Valley Physics?

String Theory inspired (M. Strassler)

Eg. Strassler & Zurek hep-ph/0604261



- Basic minimal structure

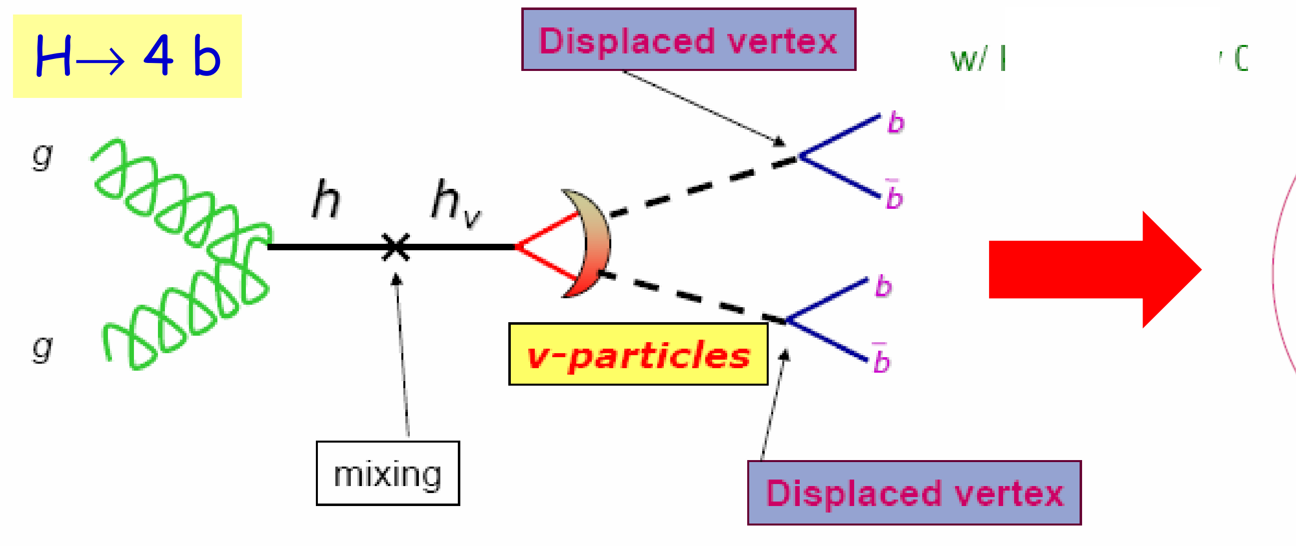


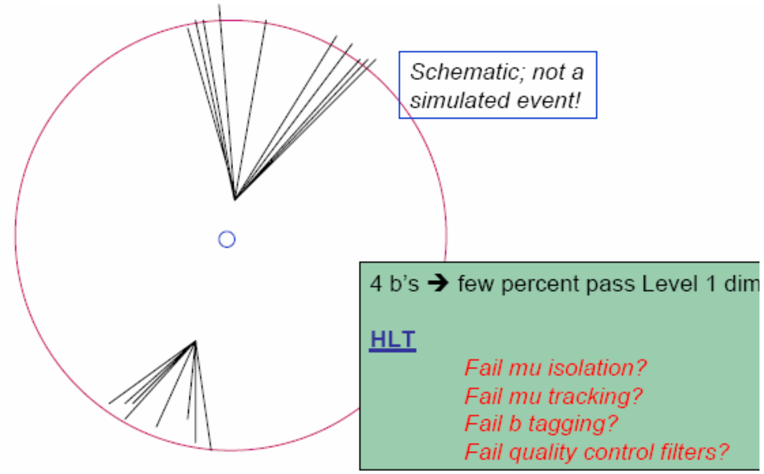
New possible phenomena that could occur in these models

- 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*

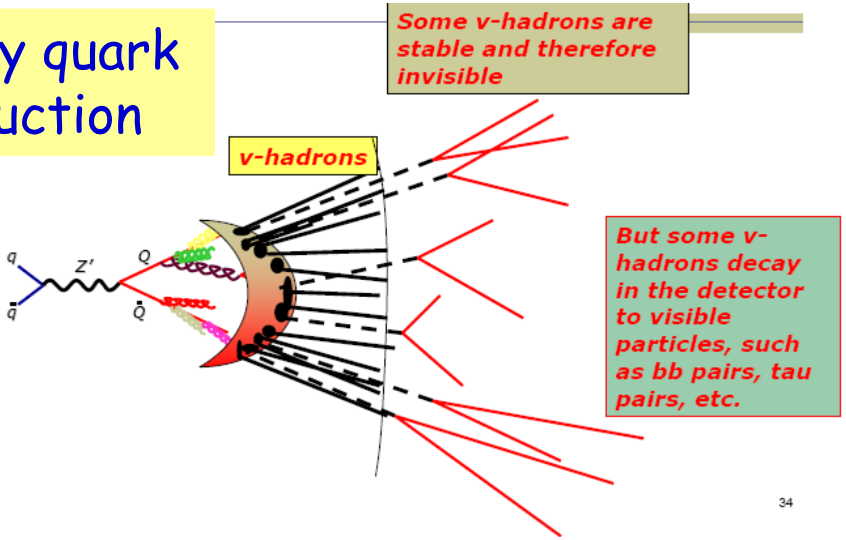
Some Hidden Valley Signals

$H \rightarrow 4\ b$

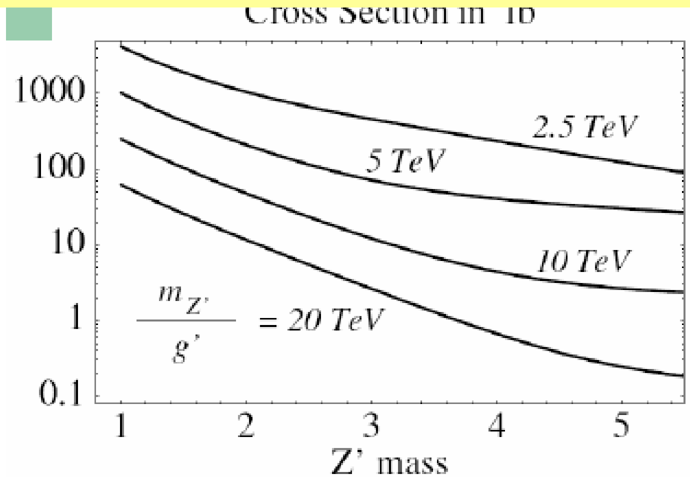




Valley quark production



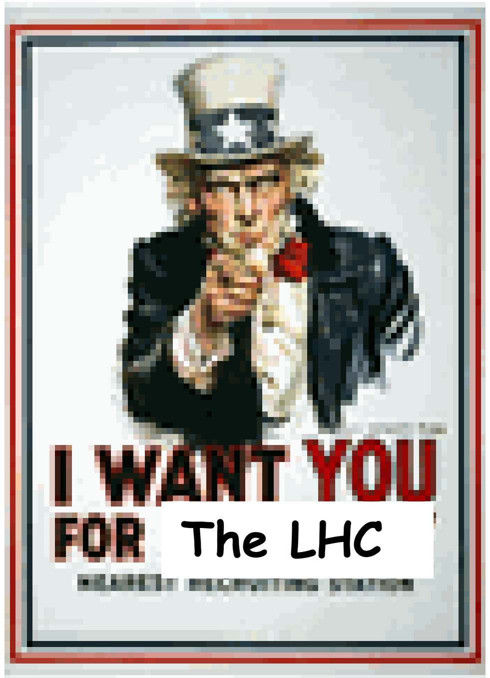
Production rates for v-hadrons



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

Tools & Theoretical Estimates

The LHC will be a precision and hopefully discovery machine
But it needs strong collaboration with theorists



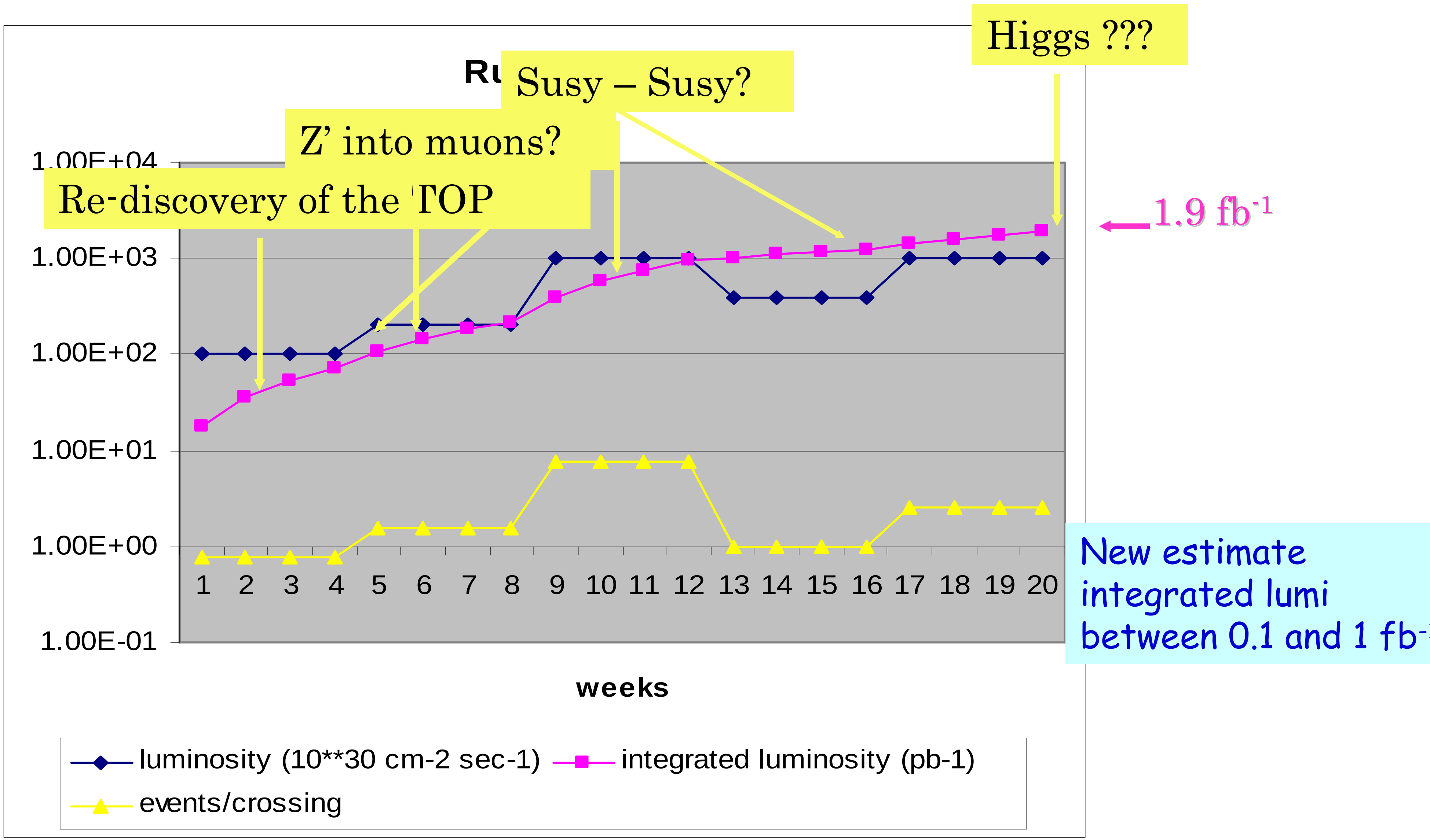
Examples

- Precision predictions of cross sections
- Estimates for backgrounds to new physics
- Monte Carlo programs (tuned) for SM processes: W,Z,t.. + njets and more..
- Monte Carlo programs for signals (ED's,…)
- Evaluation of systematics due to theory uncertainties
- Higher order calculations
- Discriminating variables among different theories
- Getting spin information from particles
- …

Efficiency = 30%

2008

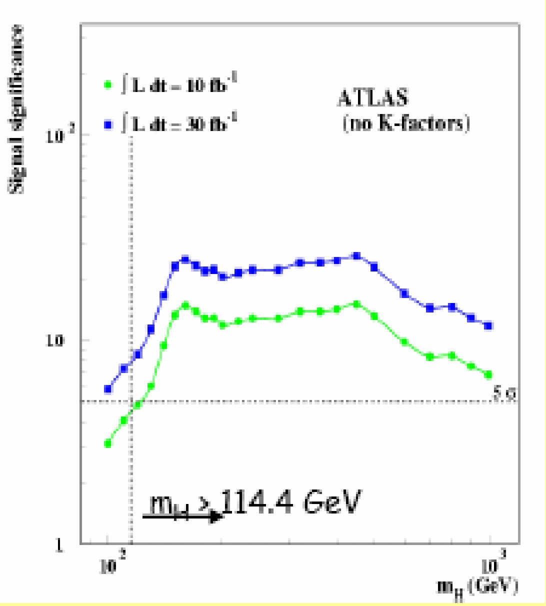
G. Rolandi
(Before schedule change)



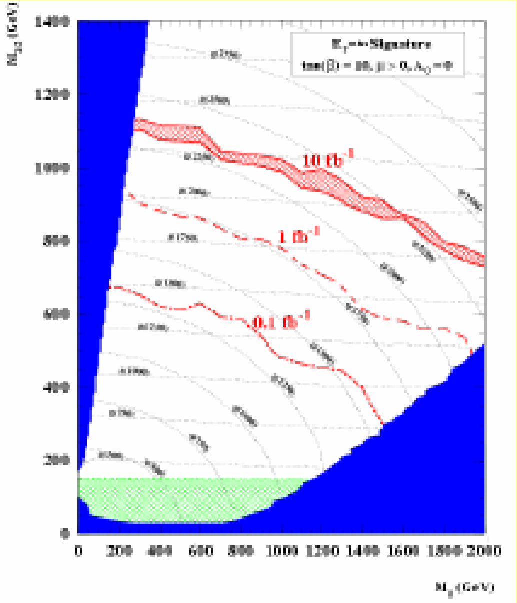
What can we expect in 2010 with 10 fb^{-1}?

"Early discoveries" at LHC

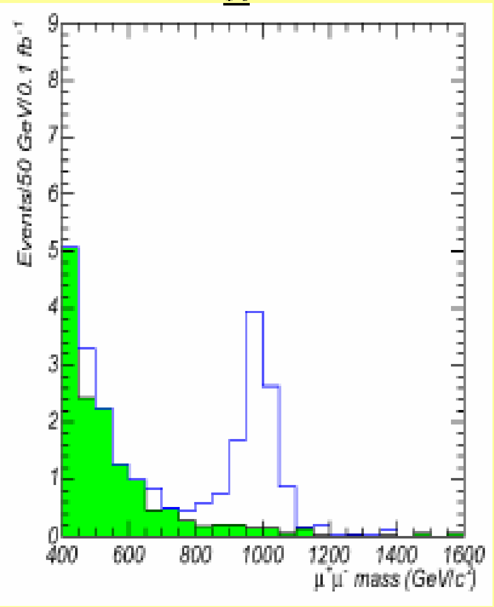
SM/MSSM Higgs



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)
- But the LHC will also explore QCD in new domains, is a B-factory and a heavy ion collider
- 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 through years of data taking and hard work before we can claim a discovery ?

Tevatron experience is absolutely vital for a jump-start of extracting physics from LHC data.

Main Message:
The LHC is Coming This Year

But 14 TeV collisions only in 2008…

And Maybe…

6 December 2008

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

CMS collaboration

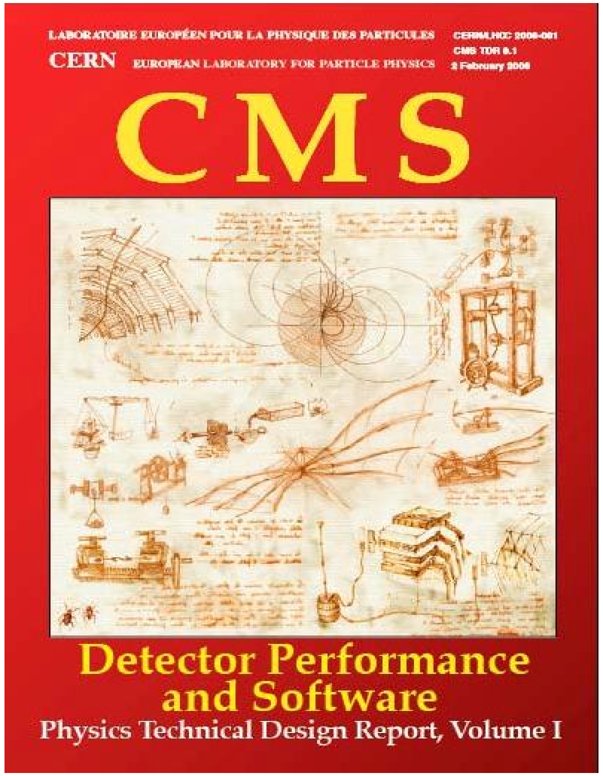
Abstract

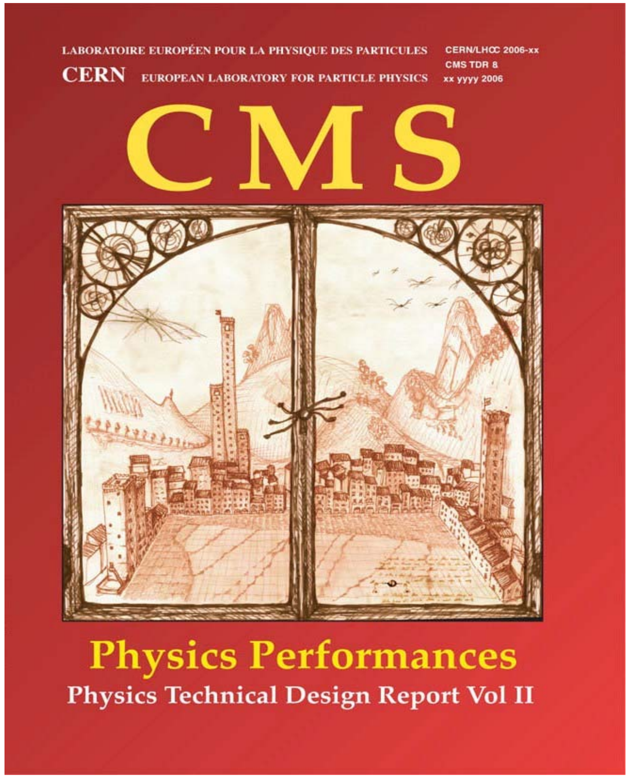
Experimental evidence for squark and gluino production in pp collisions $\sqrt{s}$ = 14 TeV with an integrated luminosity of 97 pb^{-1} at the Large Hadron Collider at CERN is reported. The CMS experiment has collected 320 events of events with several high E_T jets and large missing E_T, and the measured 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

CMS Analysis projects
The Physics TDRs

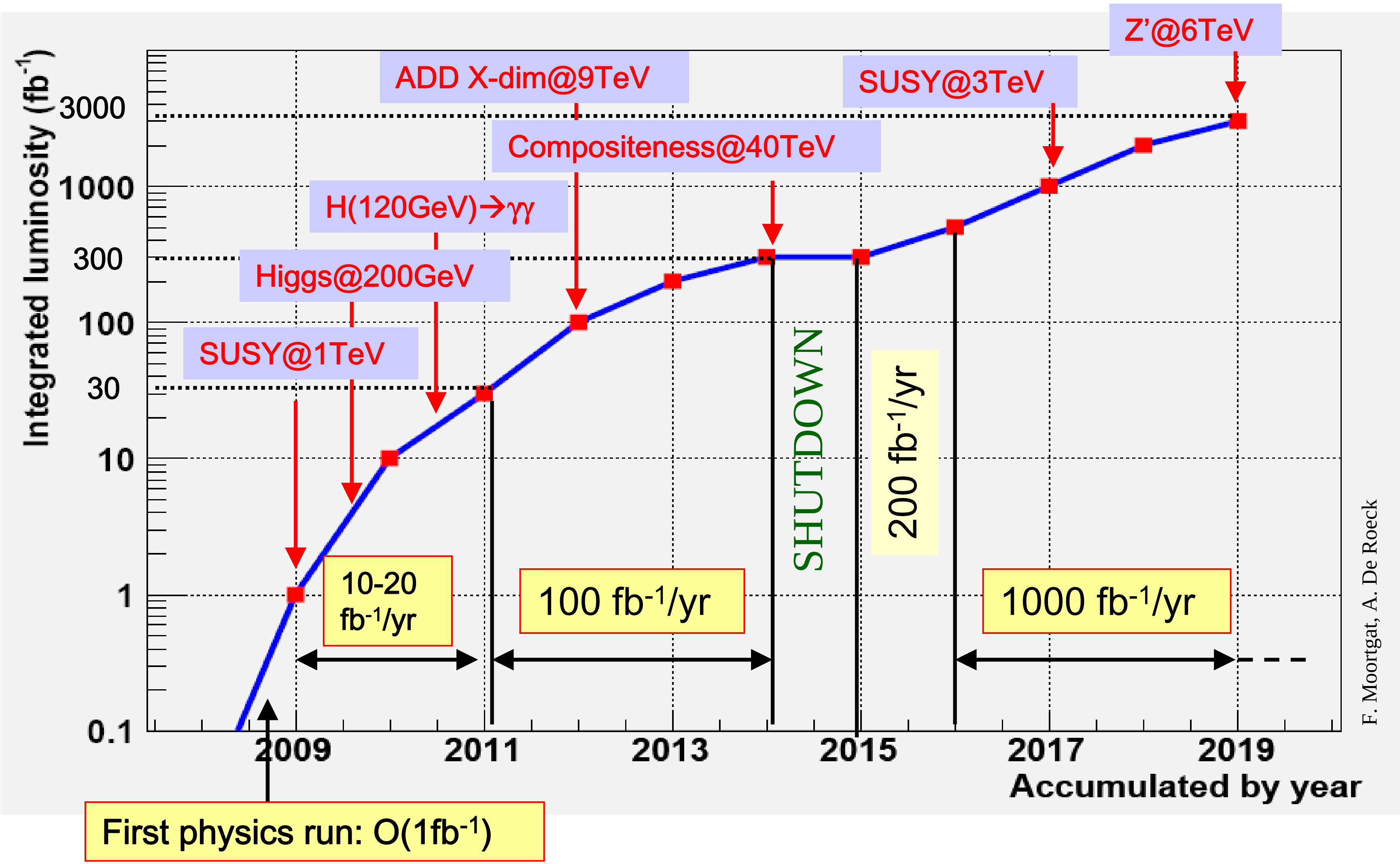




http://cmsdoc.cern.ch/cms/cpt/tdr/

CERN/LHCC 2006-001 **CERN/LHCC 2006-021**

Discovery/Luminosity Roadmap?



Preparing for first data

Workshops

HERA & LHC continuing
in 2007 (2008)
Important for discussions
on QCD, PDFs, Diffraction…

TeV4LHC workshop

MC workshops…

Is it SUSY?

Example: Universal Extra Dimensions

Phenomenology: a Kaluza Klein tower pattern like a SUSY mass spectrum:

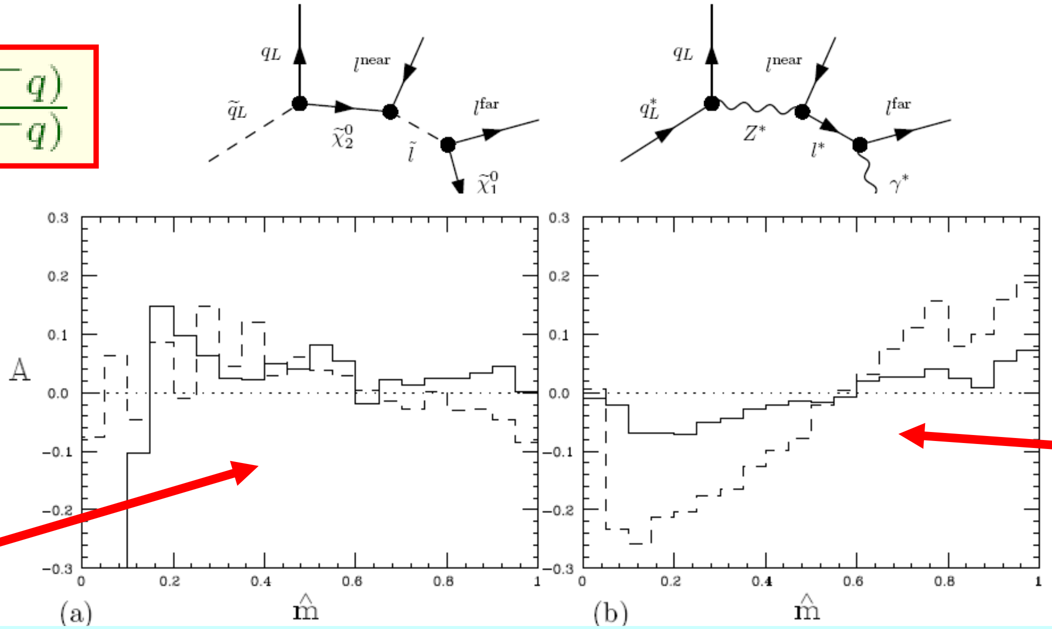
Can the LHC distinguish?

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 √s=14 TeV

Process	Events/s	Events/year	Other machines
$W \to e\nu$	15	10^8	10^4 LEP / 10^7 Tev
$Z \to ee$	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: ($10^{33}cm^{-2}\,s^{-1}$)

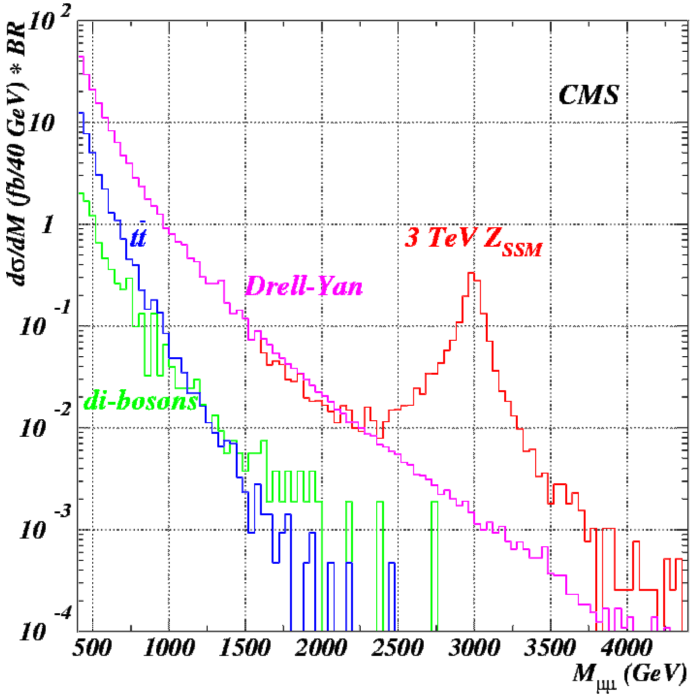
The LHC will be a W-factory, a Z-factory, a top factory, a Higgs factory etc..

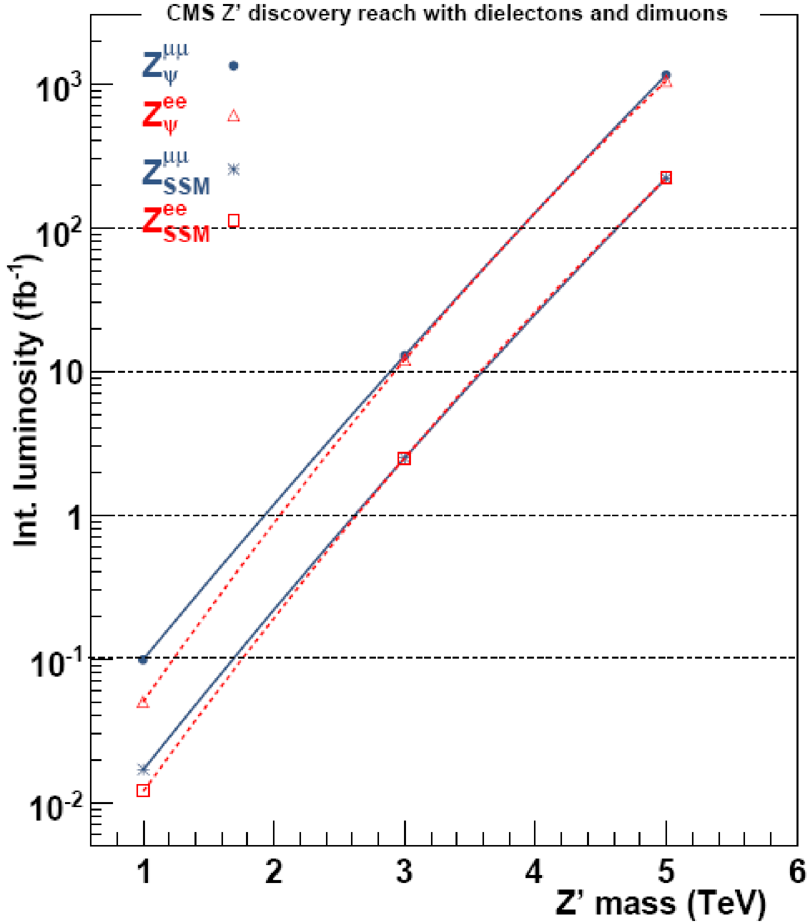
Precision EW physics measurements will be limited by systematics

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

New Gauge Bosons

Z′→μμ production





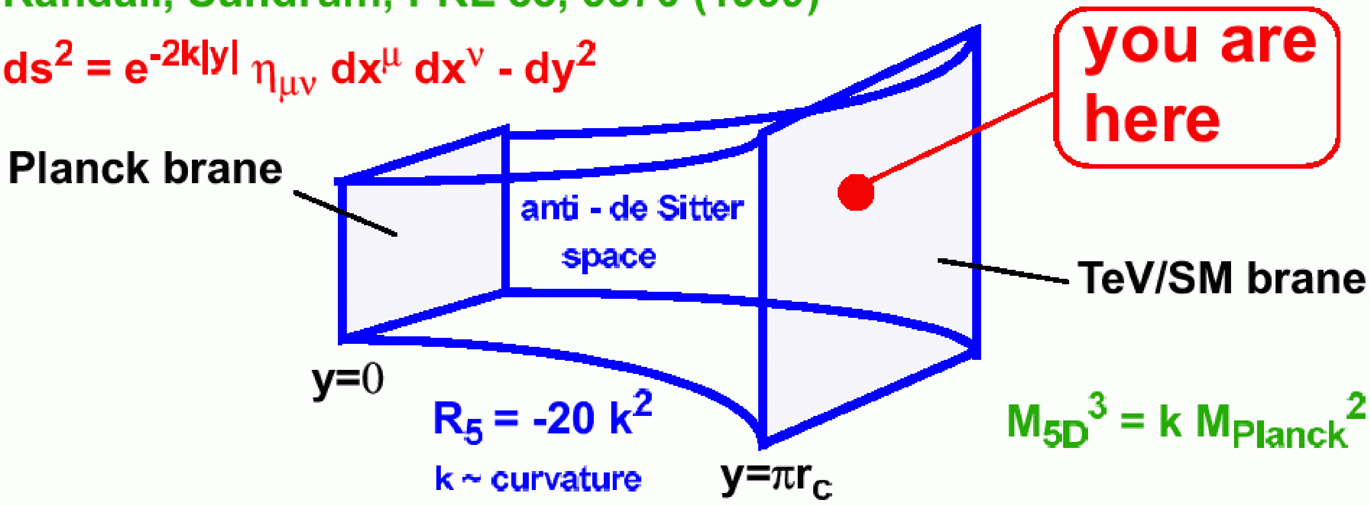
Note: Best possible theory knowledge on DY spectrum will be needed (tails!)

- Low lumi 0.1 fb^{-1} : discovery of 1-1.7 TeV possible, beyond Tevatron run-II
- High lumi 100 fb^{-1}: extend range to 3.4-4.6 TeV

Curved Space: RS Extra Dimensions

Randall, Sundrum, PRL 83, 3370 (1999)

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

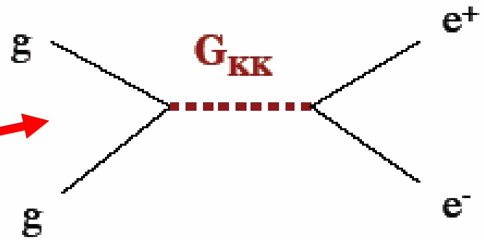


$R_5 = -20\ k^2$

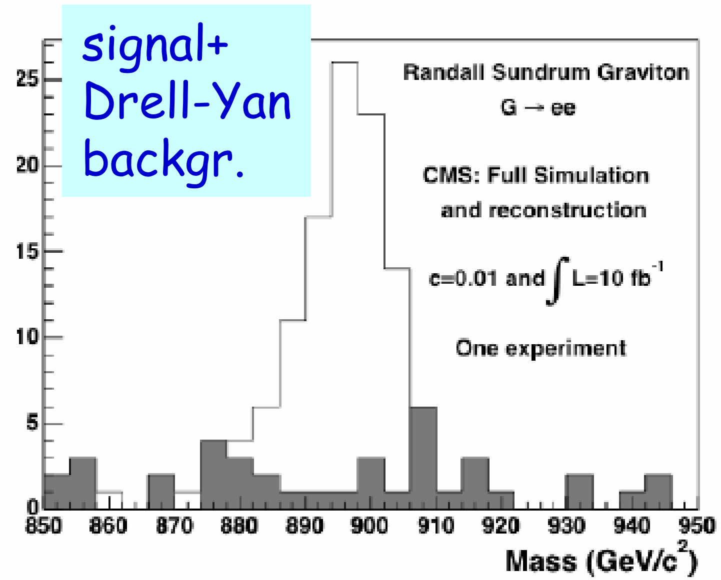
k ~ curvature

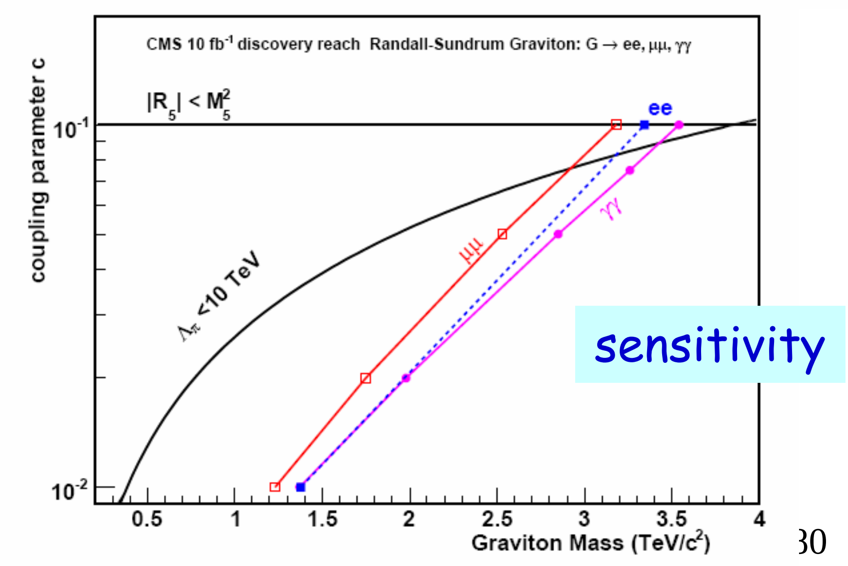
$M_{5D}^3 = k\ M_{Planck}^2$

phenomenology



Study the channel pp→Graviton→ e+e-

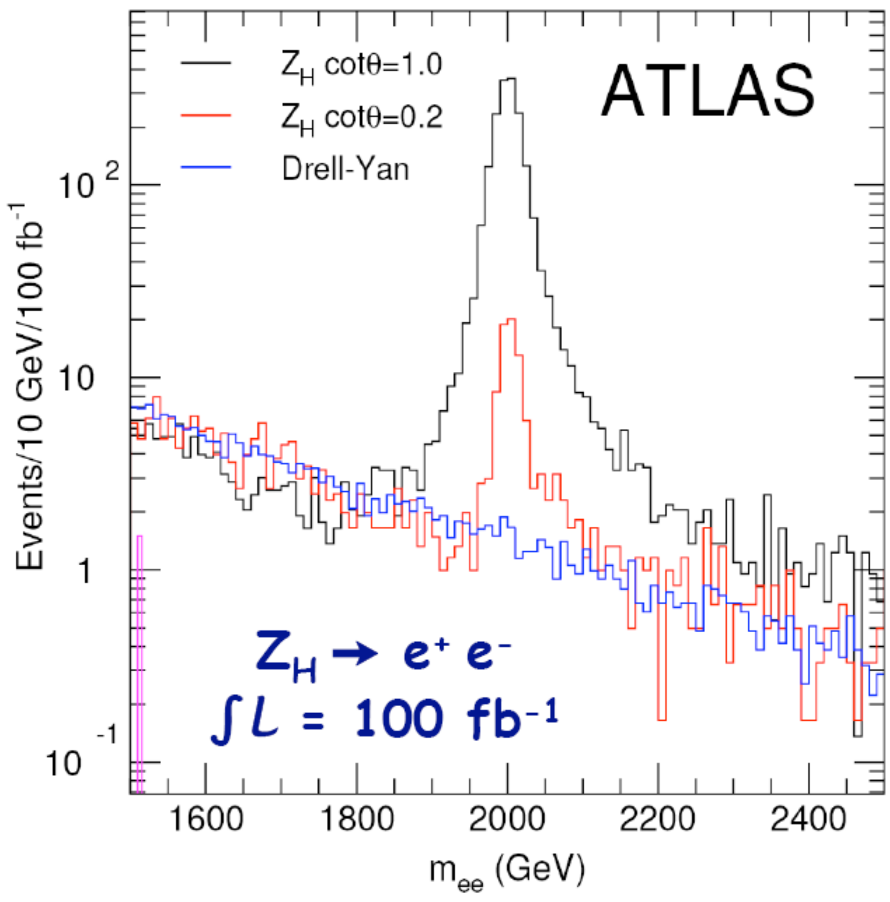


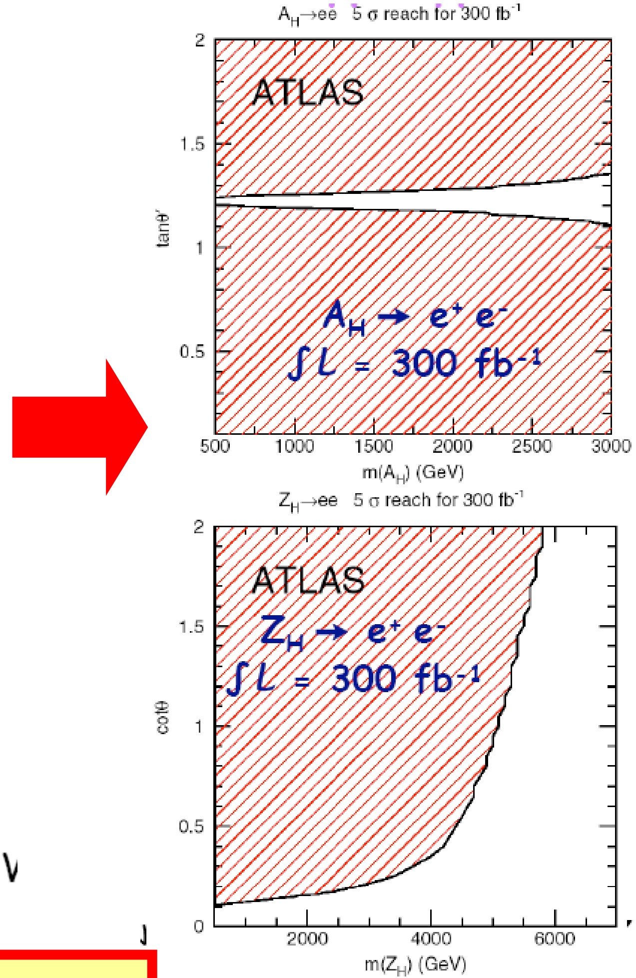


Little Higgs Model A_H and Z_H

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