Physics Reach at the LHC with Increasing Energy and Luminosity

Prometeo I, 3 March 2009

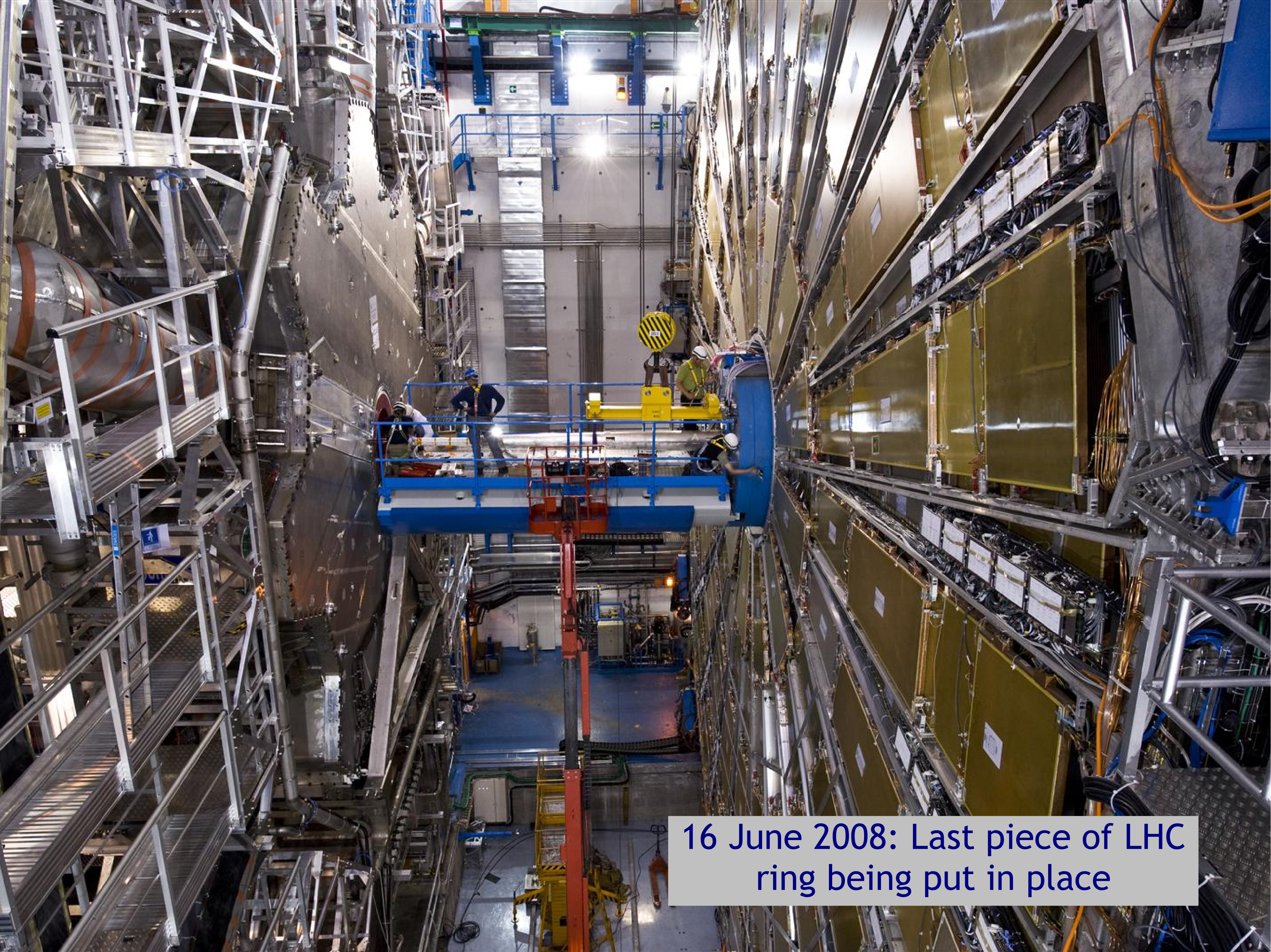
Dave Charlton
(University of Birmingham)
for ATLAS & CMS

- **Expectations for 2009/2010**
- **Extension to 14 TeV**
- **LHC & detector upgrades**

There are substantial uncertainties

Twenty-five years...

- 1984: First LHC workshop (Lausanne)
  - Use LEP tunnel for protons
- 1992: First 'expressions of interest' for experiments
- 1996: First exp'ts approved
- 1998: First full-size magnet test
- 2003: End of civil engineering
- 2006: Last magnet produced
- 2008: First beam
- 2009: First collisions
- Some vital statistics
  - Tunnel circumference 27 km
  - 1232 main magnets, 8 T field
  - Another 7000 smaller magnets
  - Operating temperature 1.9K
  - Cost: ~4700 MCHF (incl. manpower)
  - Experiment cost: ~500 MCHF each for ATLAS & CMS (excl. manpower)

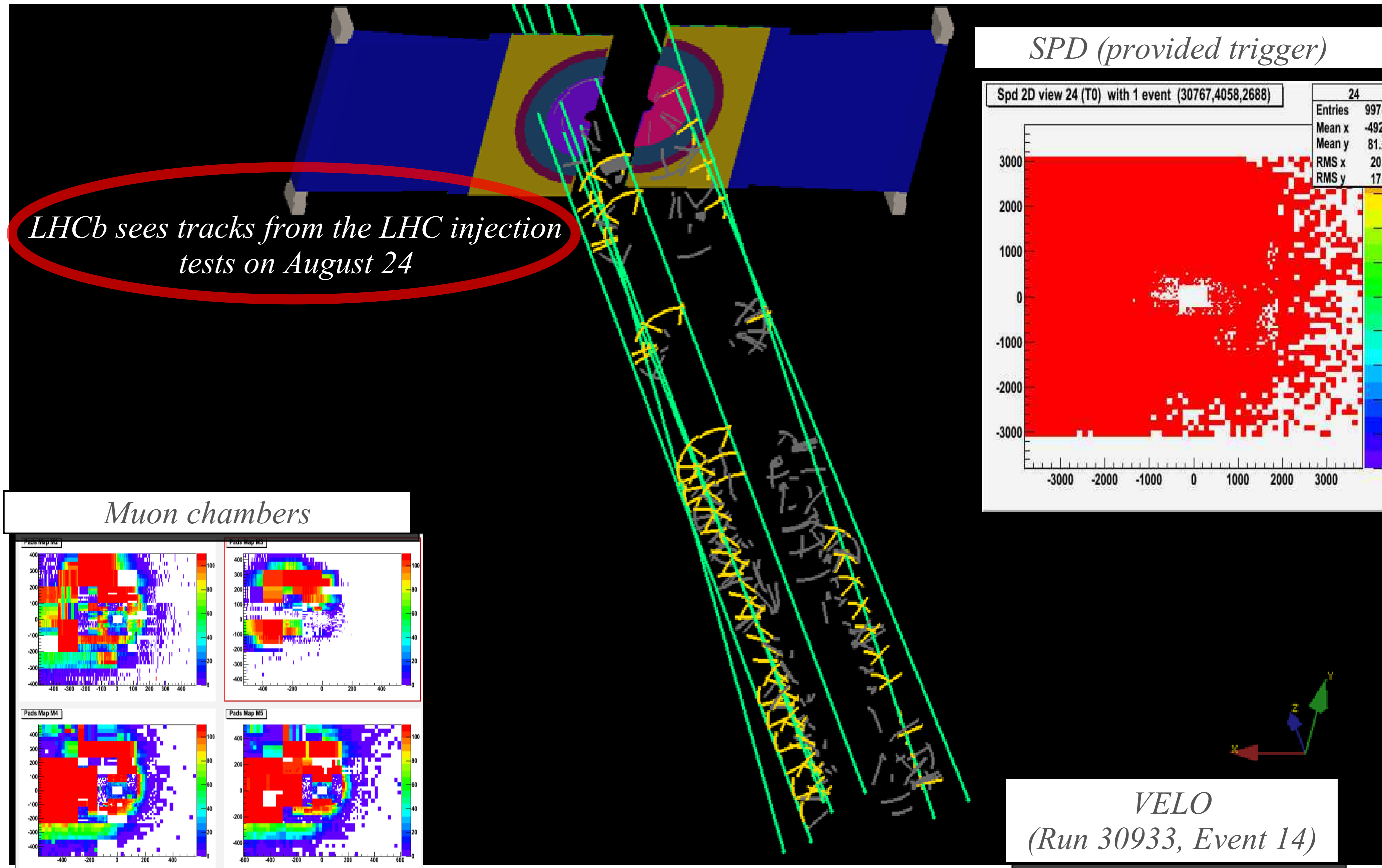


16 June 2008: Last piece of LHC ring being put in place

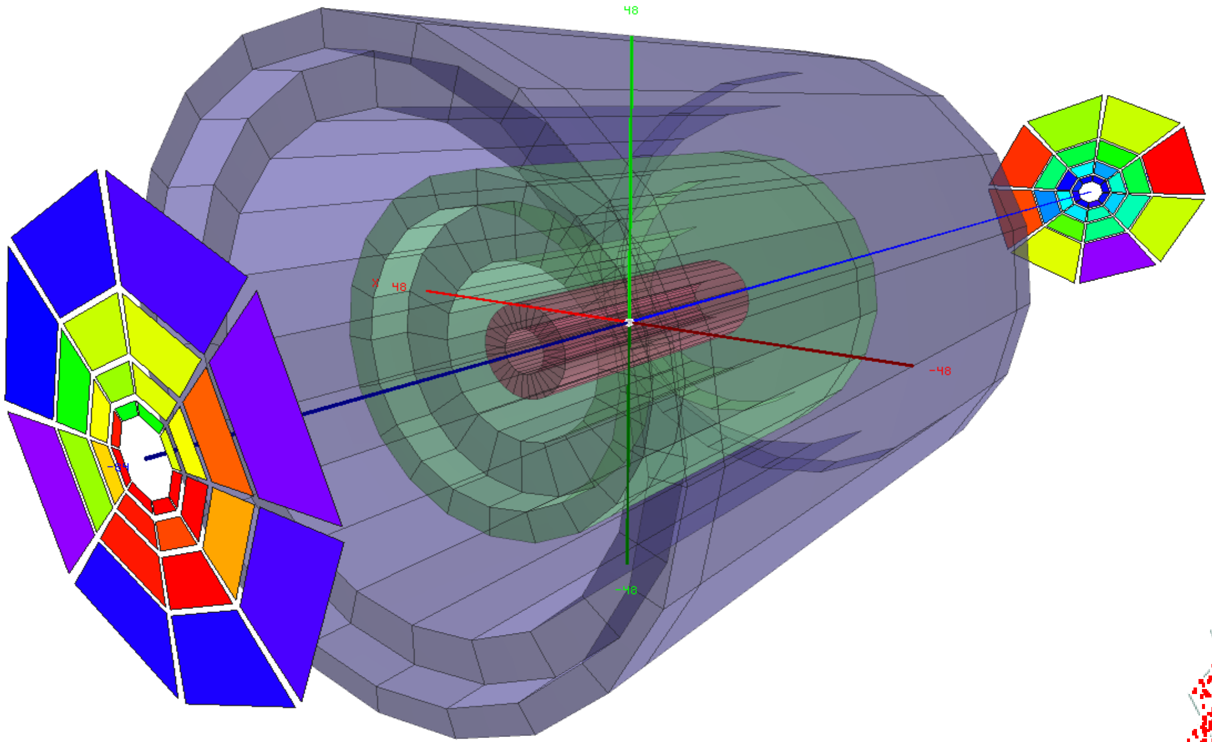
TED events (stop of Beam 2)

First LHC Beam!

Muon tracks cross LHCb in the "wrong" direction

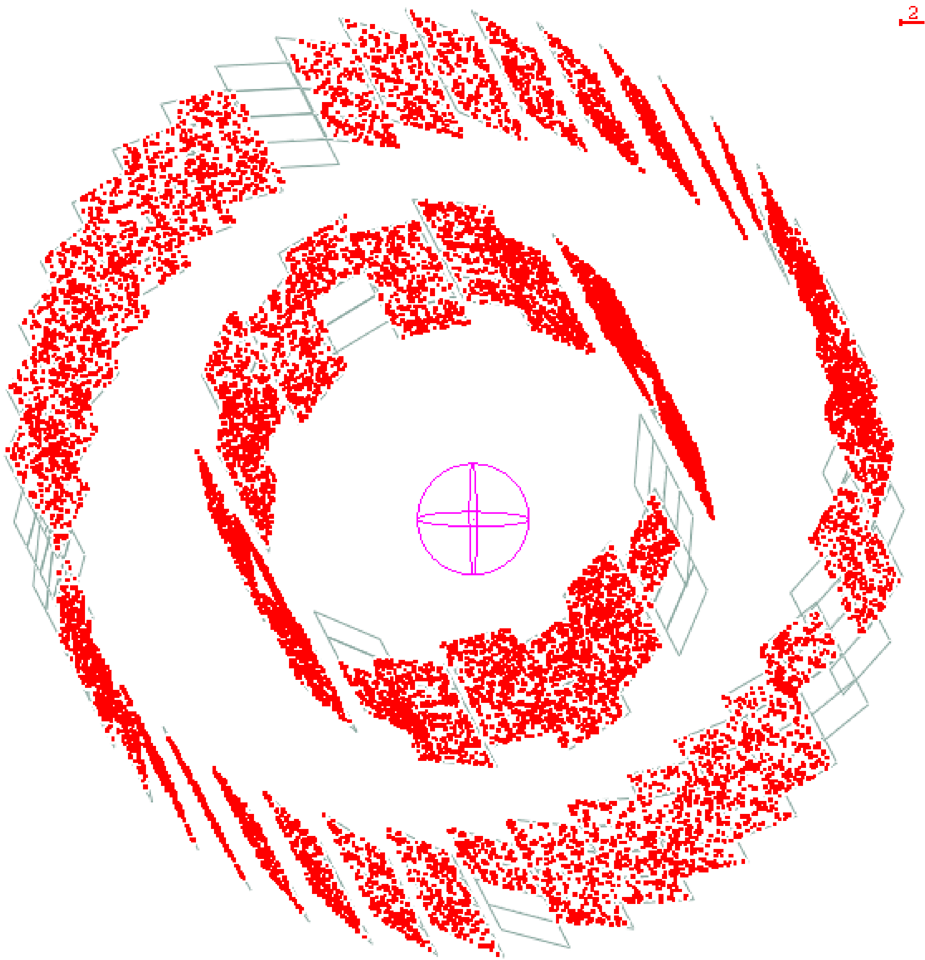


First Beam on 10 September



V0 hits on 10.9.2008, shortly after 9 am

SPD hits on 10.9.2008, shortly after 9 am

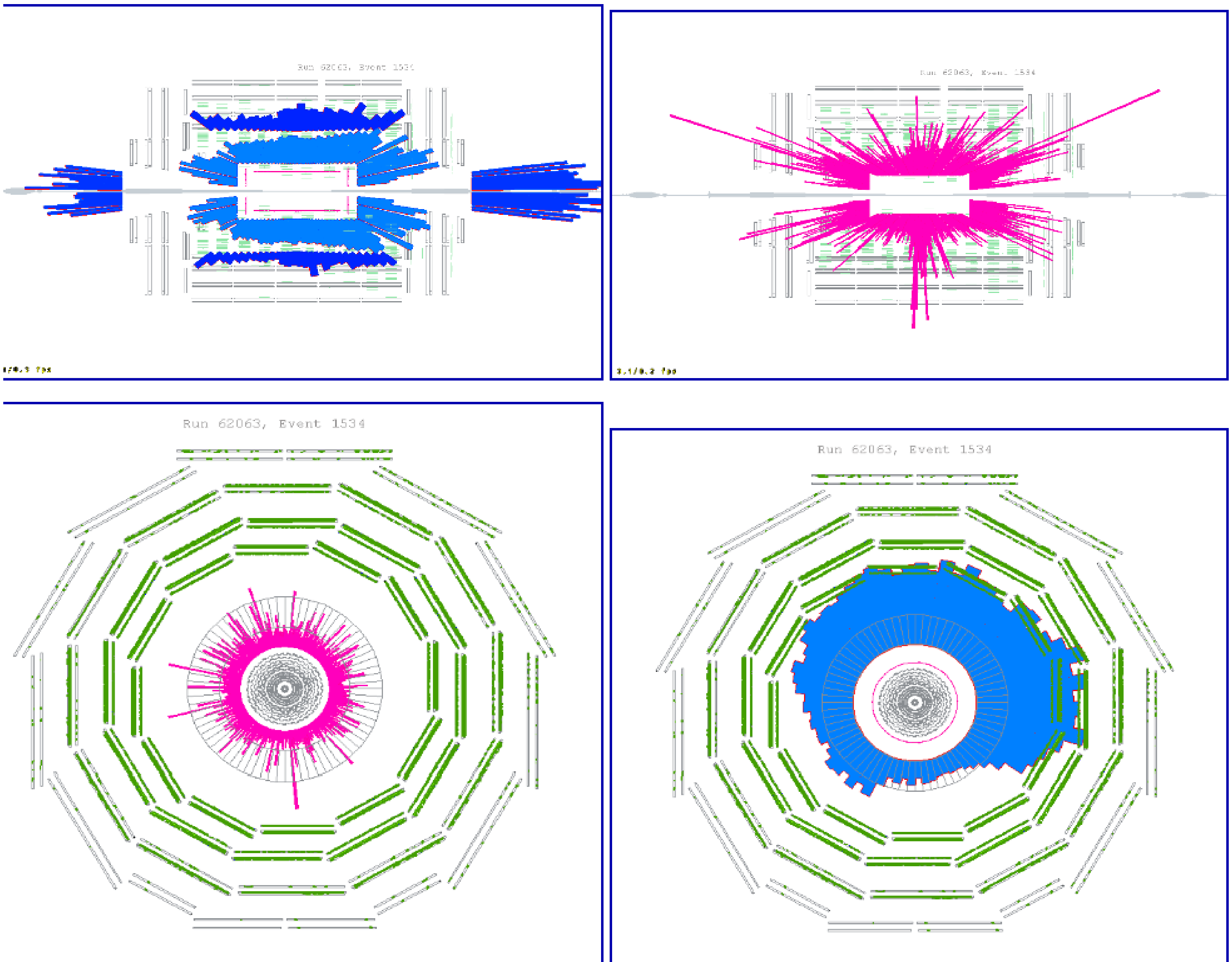


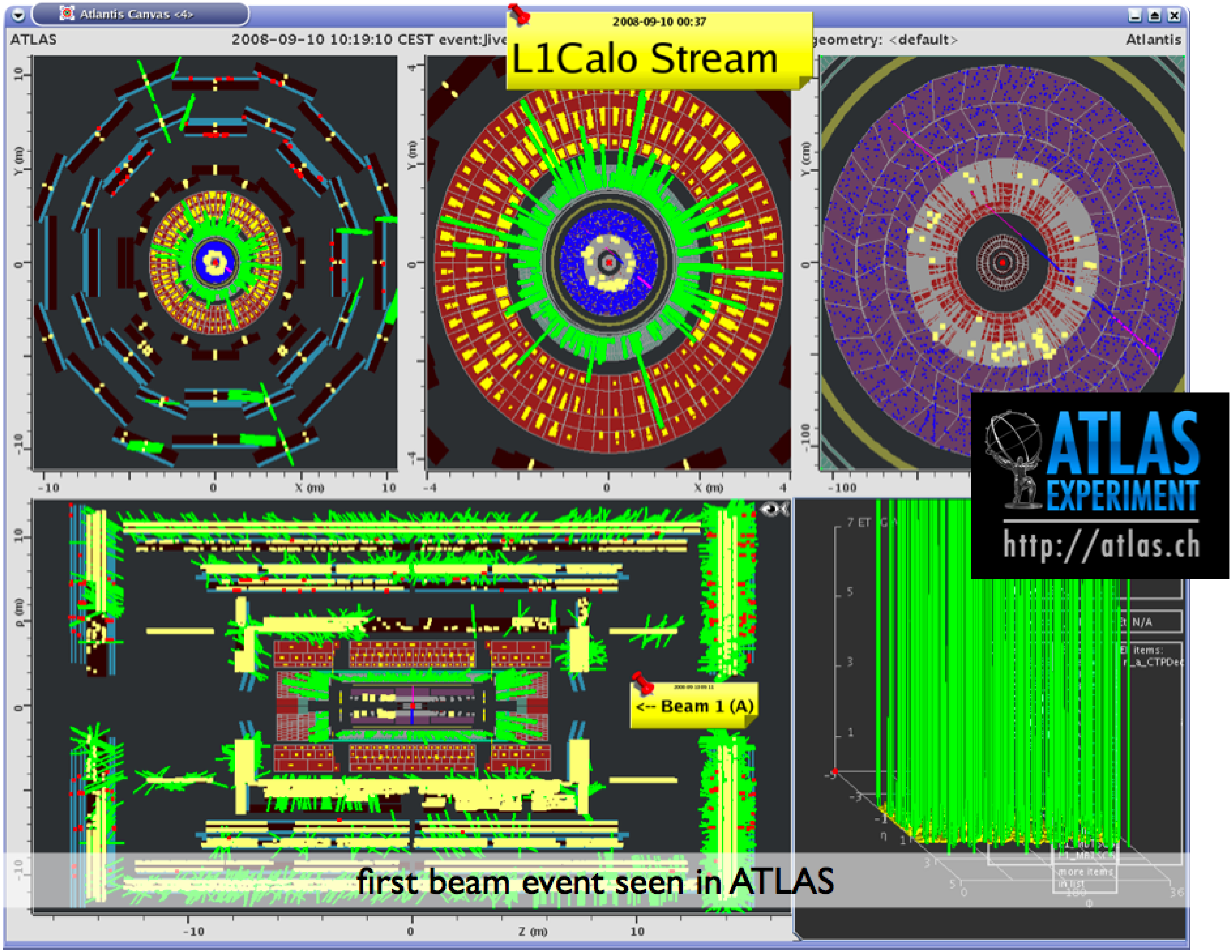
On 10 September, collimators 140m upstream of each experiment closed, as first beam sent around: “beam splash” events

First Events: Collimators Closed

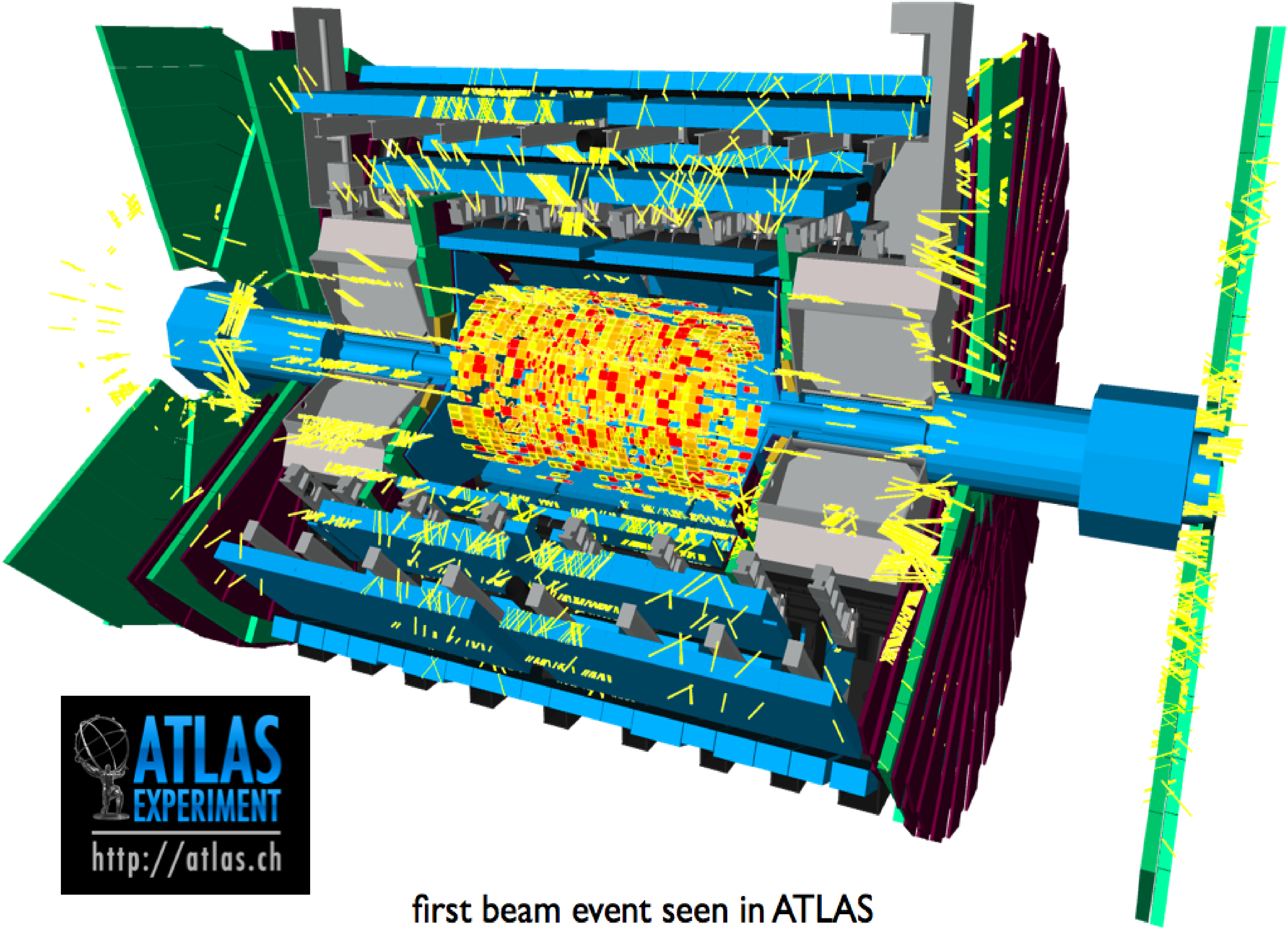
~2.10^9 protons on collimator ~150 m upstream of CMS

ECAL- pink; HB,HE - light blue; HO,HF - dark blue; Muon DT - green; Tracker Off



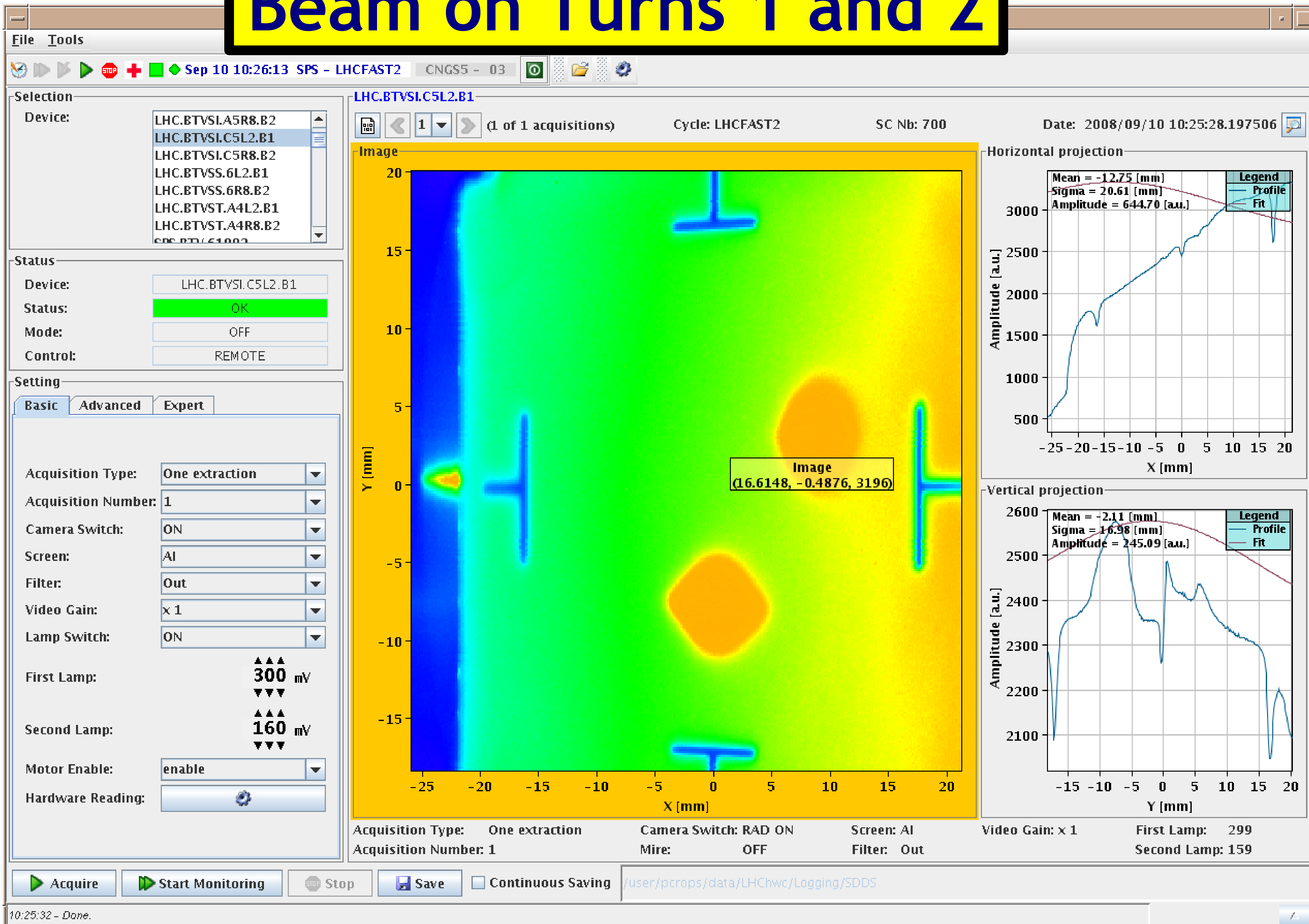


Atlantis Canvas <4>
ATLAS
2008-09-10 10:19:10 CEST event:Jive
geometry: <default>
Atlantis
2008-09-10 00:37
L1Calo Stream
ATLAS EXPERIMENT
http://atlas.ch
<-- Beam 1 (A)
X (m)
Y (m)
Y (cm)
Z (m)
ρ (m)
first beam event seen in ATLAS

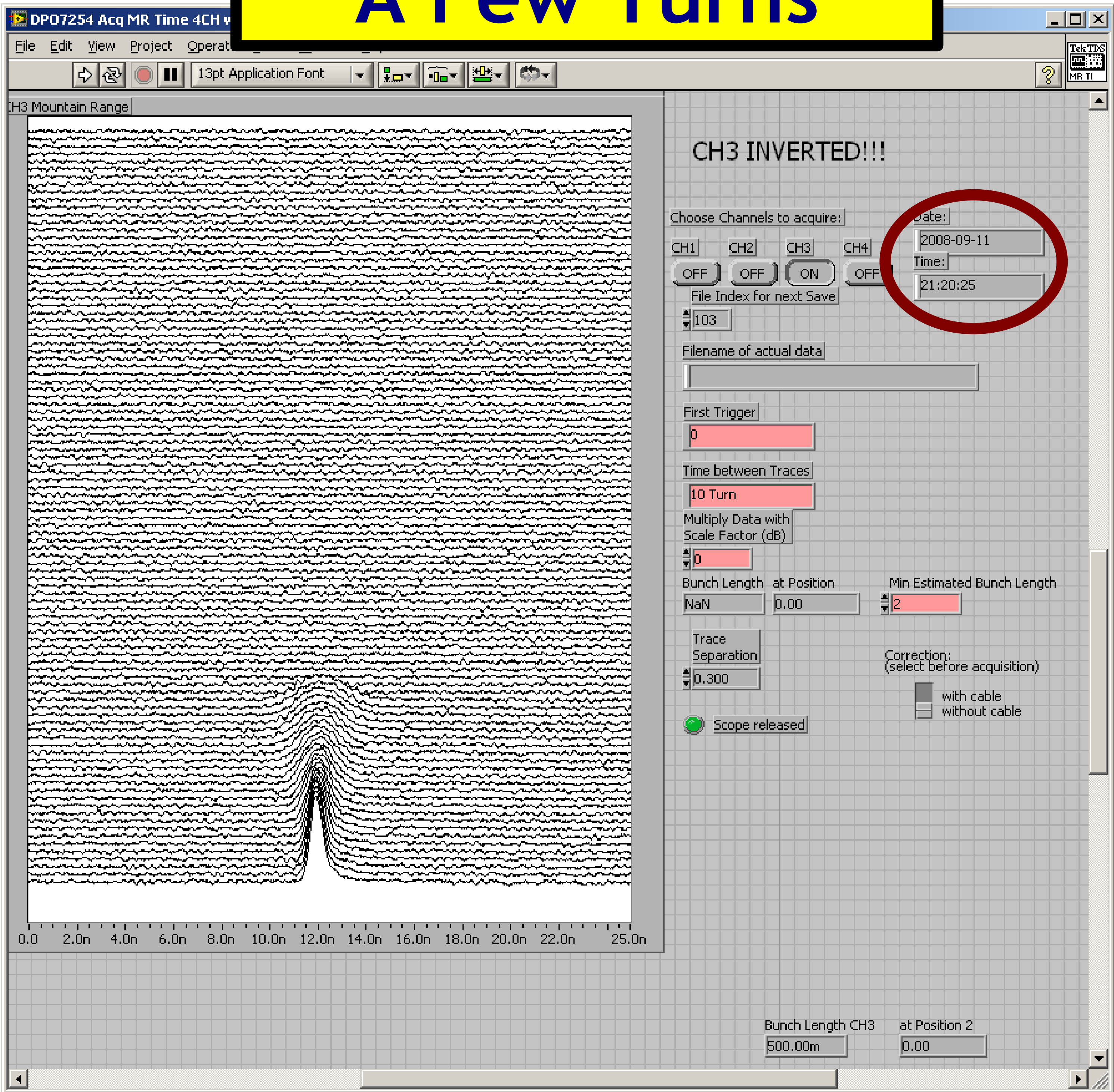


first beam event seen in ATLAS

Beam on Turns 1 and 2



A Few Turns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CH3 Mountain Range
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CH3 INVERTED!!!
Choose Channels to acquire:
CH1 CH2 CH3 CH4
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103
Filename of actual data
First Trigger
0
Time between Traces
10 Turn
Multiply Data with Scale Factor (dB)
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Min Estimated Bunch Length
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Correction: (select before acquisition)
with cable
without cable
Scope released
Bunch Length CH3
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at Position 2
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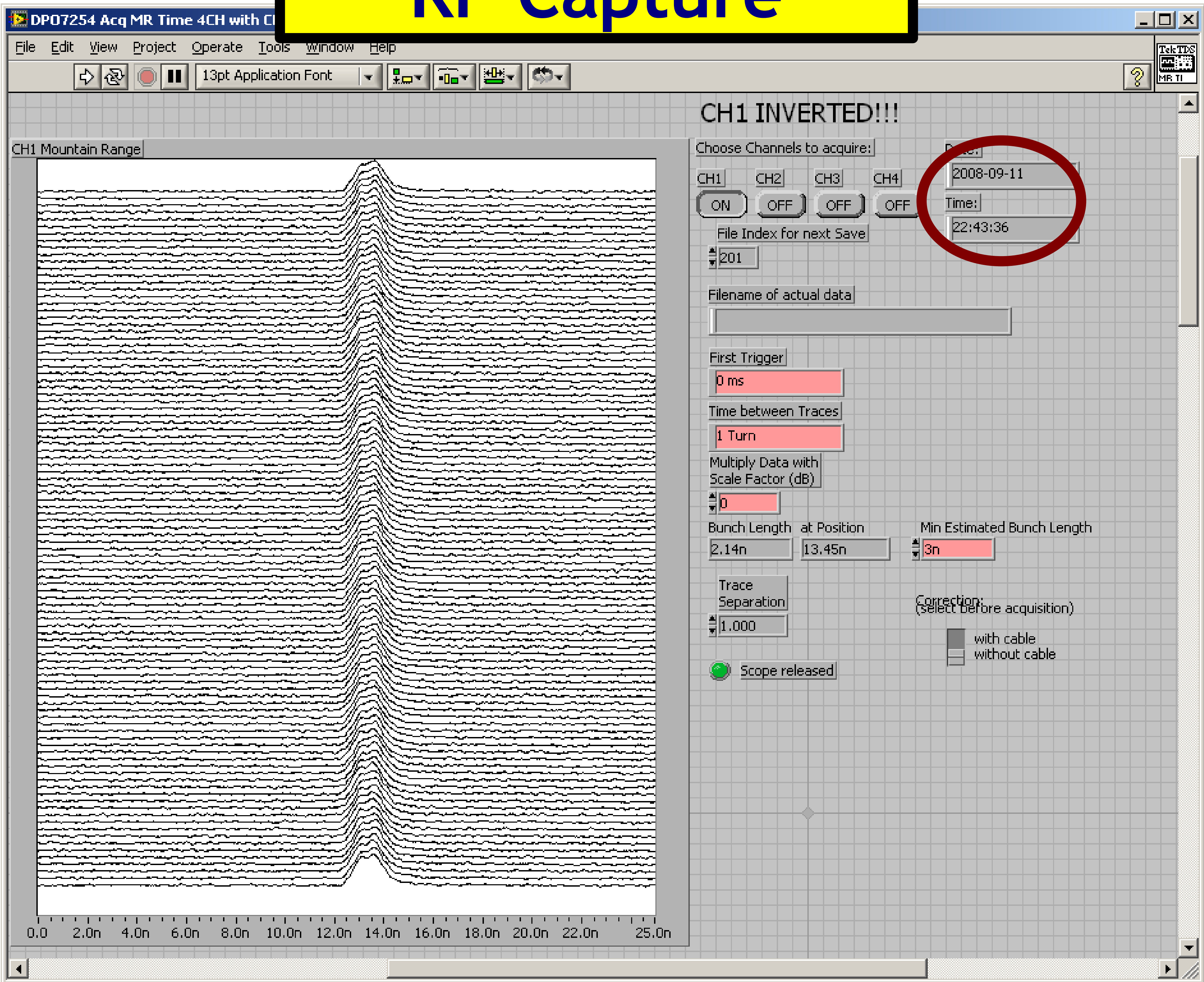
RF Capture



DPO7254 Acq MR Time 4CH with C
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Time:
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Filename of actual data
First Trigger
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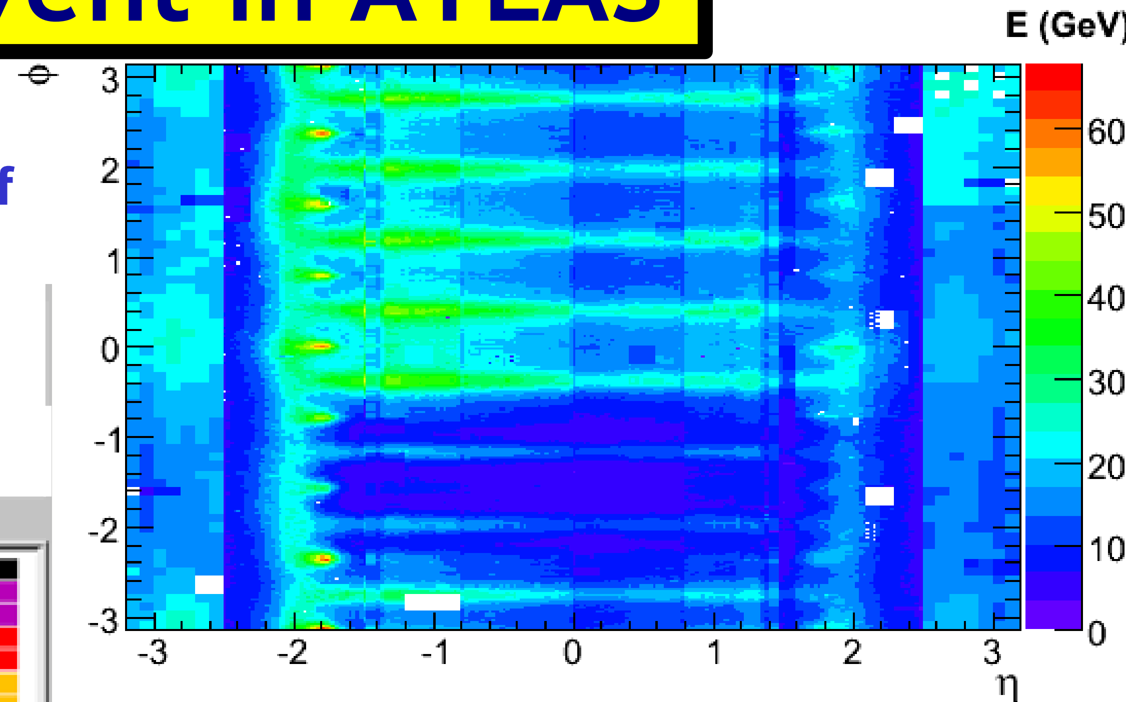
Splash event in ATLAS

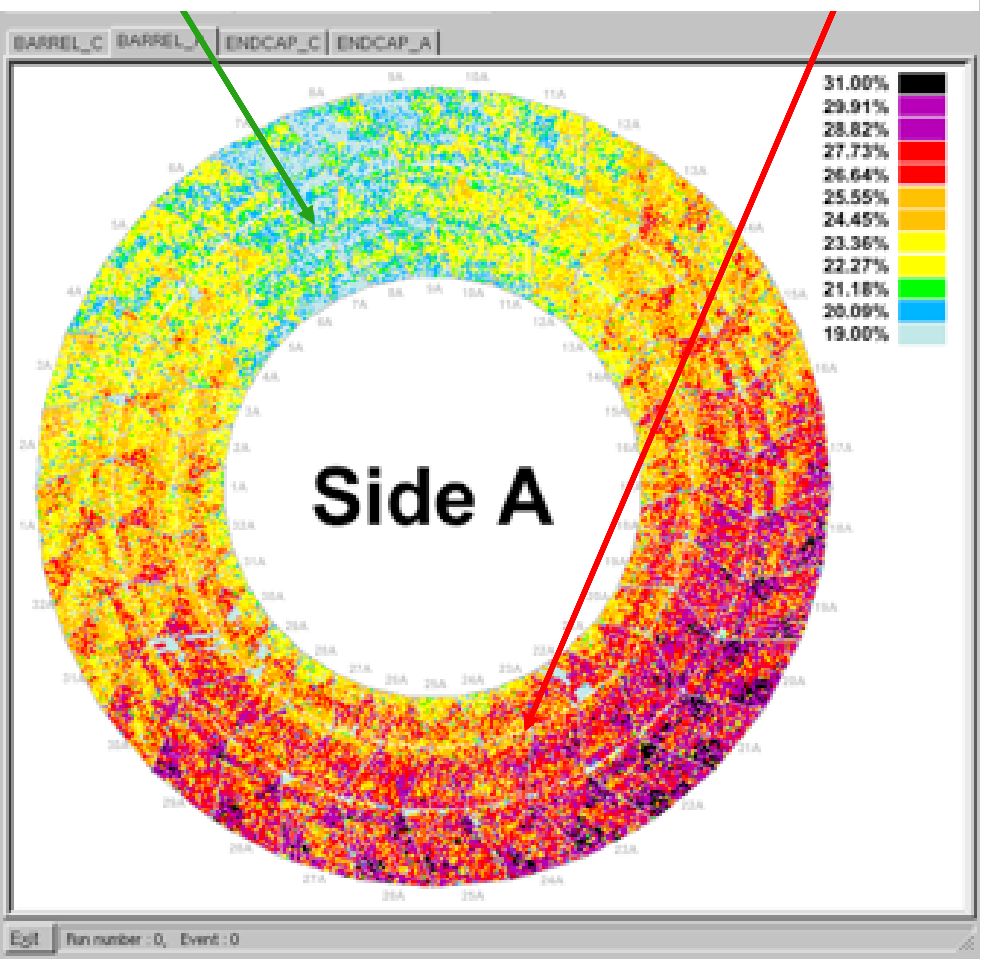
D Froidevaux



Timing of all TRT readout channels could be performed with accuracy of ~ 1 ns per event! Differences in colour due to cosmic timing:

Top: early

Bottom: late



2D display in η−ϕ of energy deposited in LAr EM calorimeter per cell (layer 2):

- structures seen are due to material between collimators and calorimeter (mostly 8-fold structure of end-cap toroid coils)

- energy seen per event is huge!

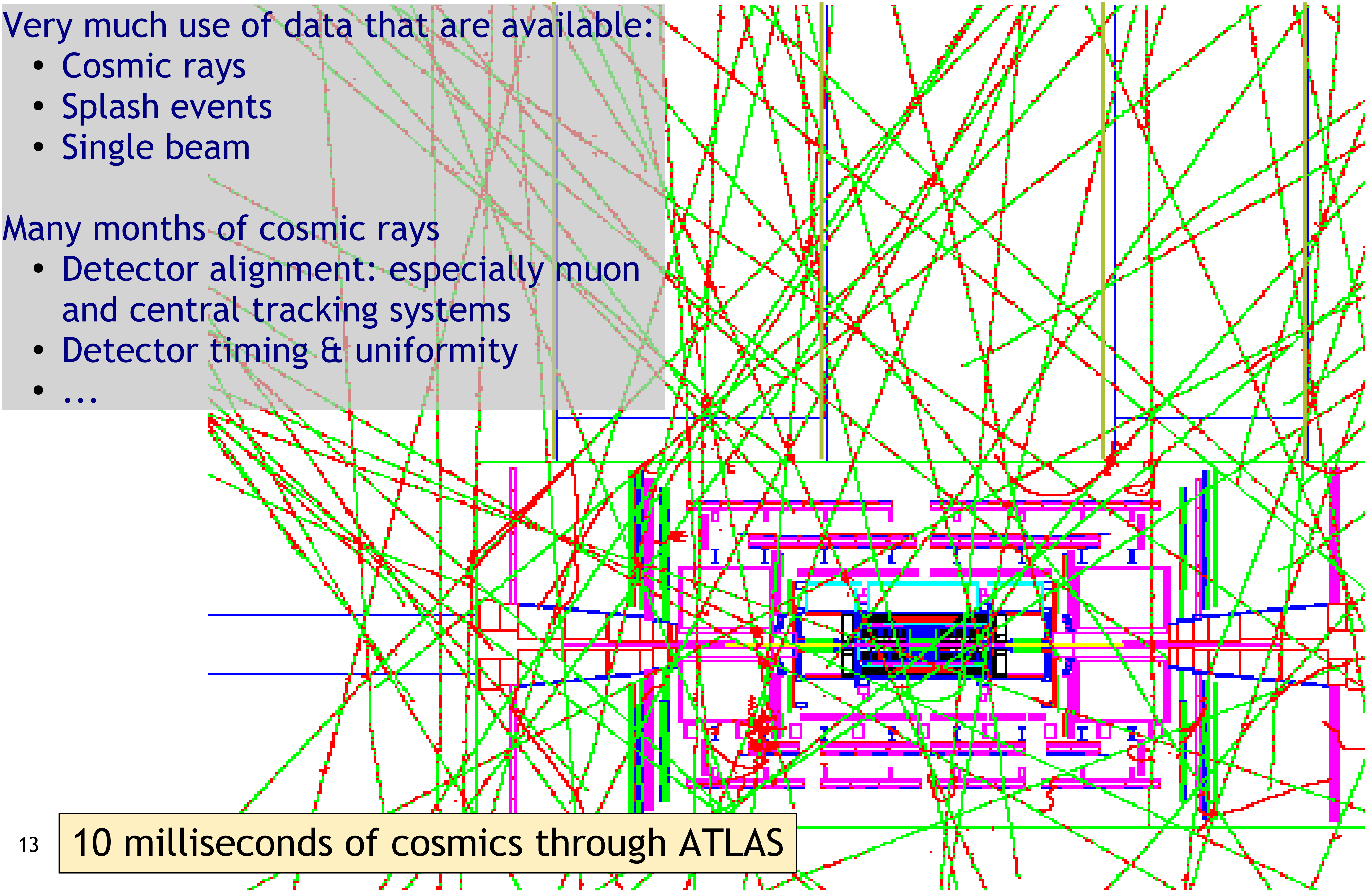
Commissioning with 2008 Data

Very much use of data that are available:

- Cosmic rays
- Splash events
- Single beam

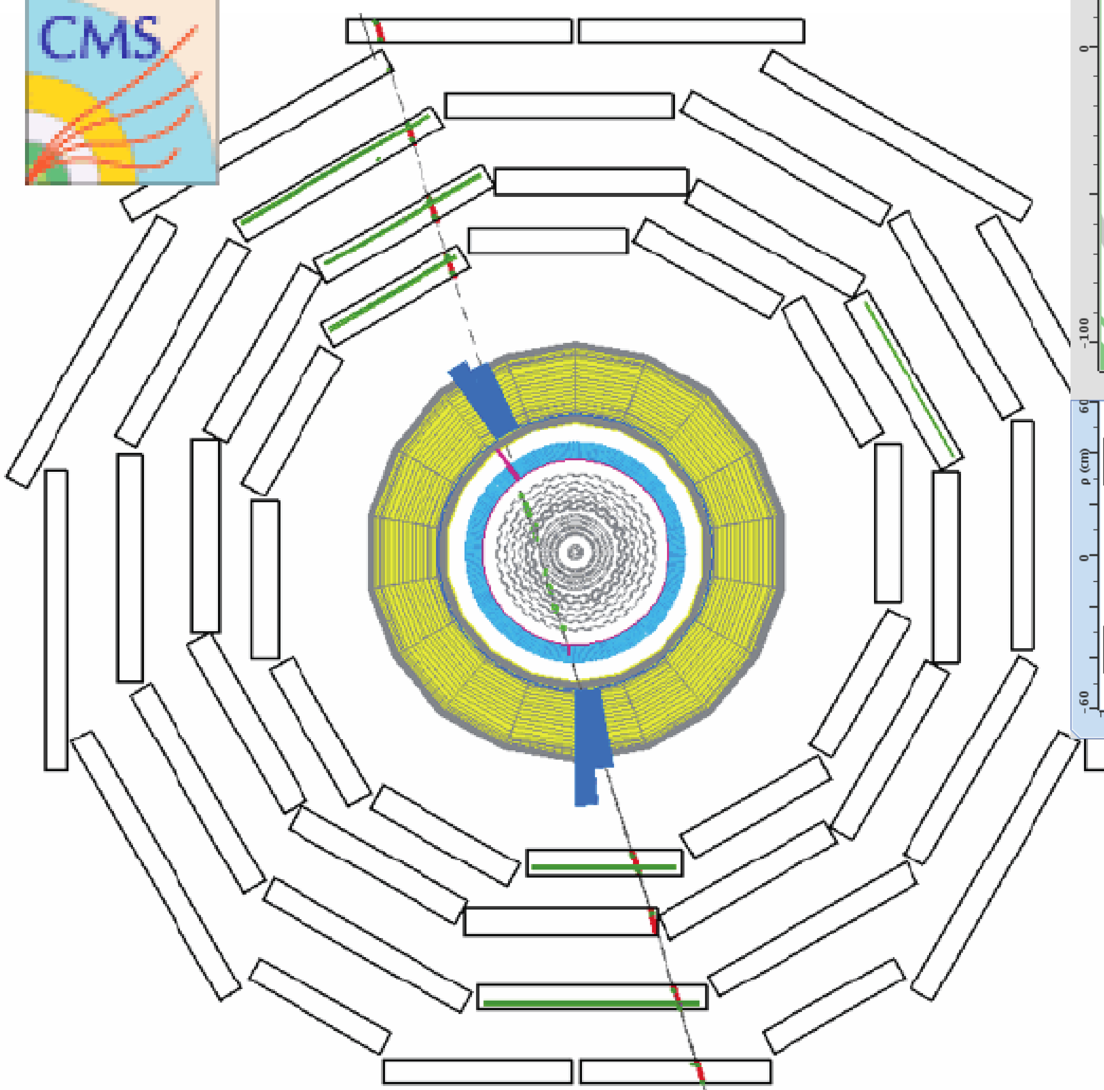
Many months of cosmic rays

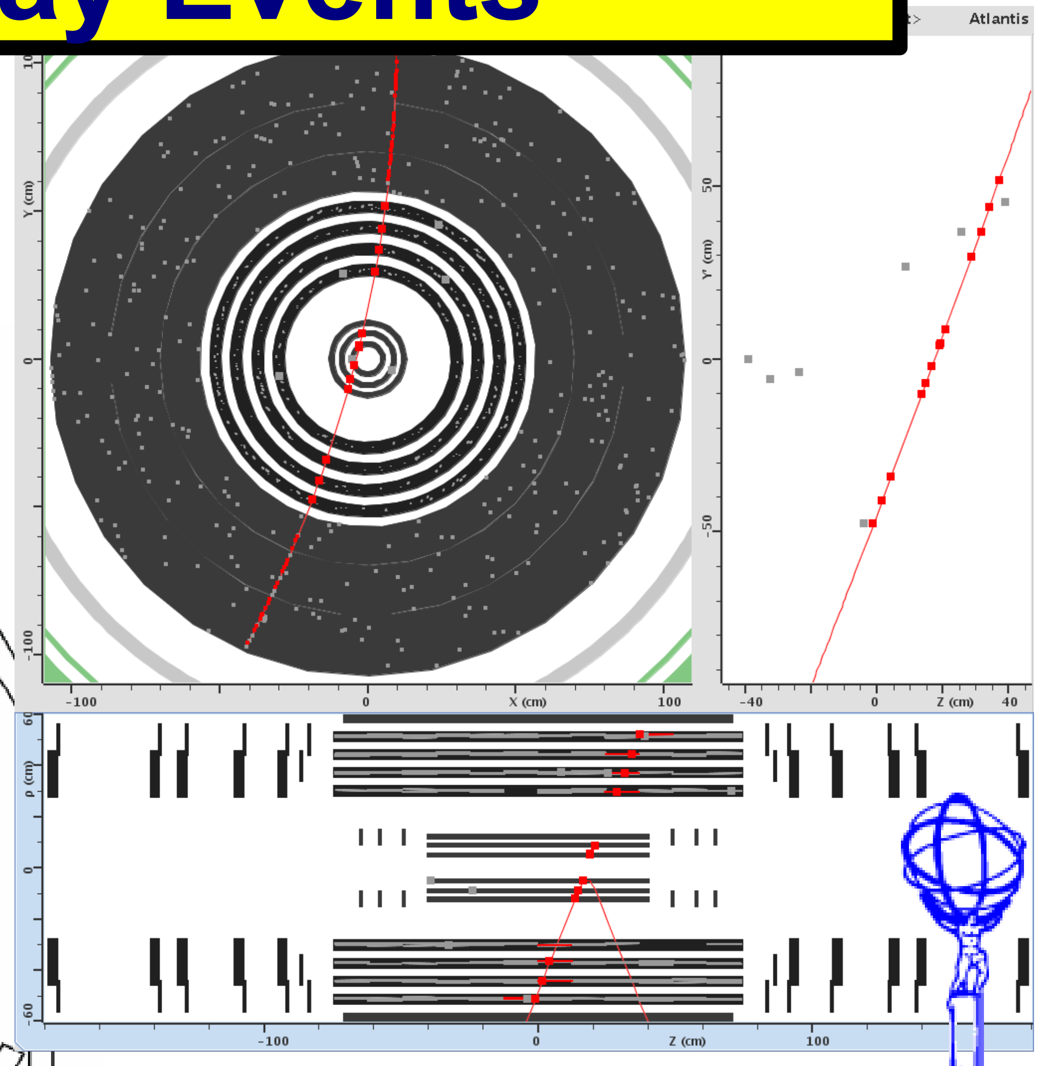
- Detector alignment: especially muon and central tracking systems
- Detector timing & uniformity
- ...



10 milliseconds of cosmics through ATLAS

Cosmic-Ray Events



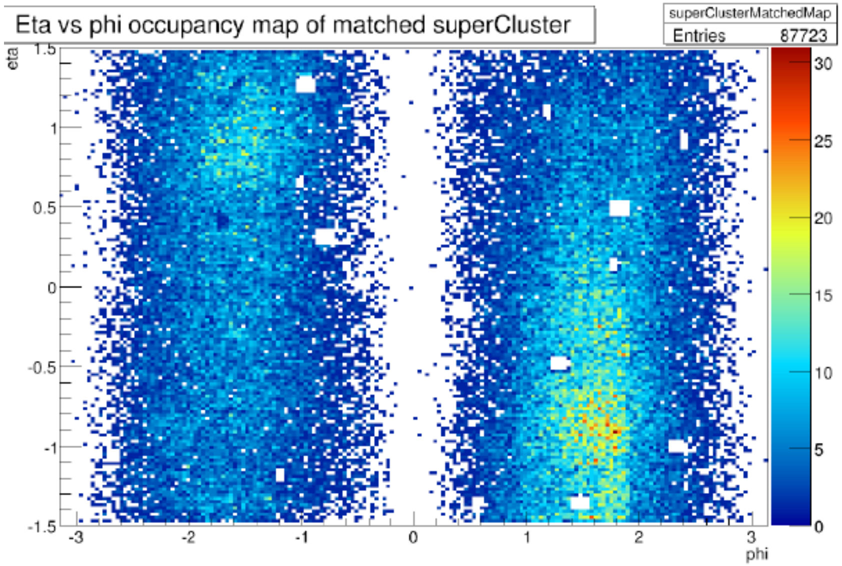


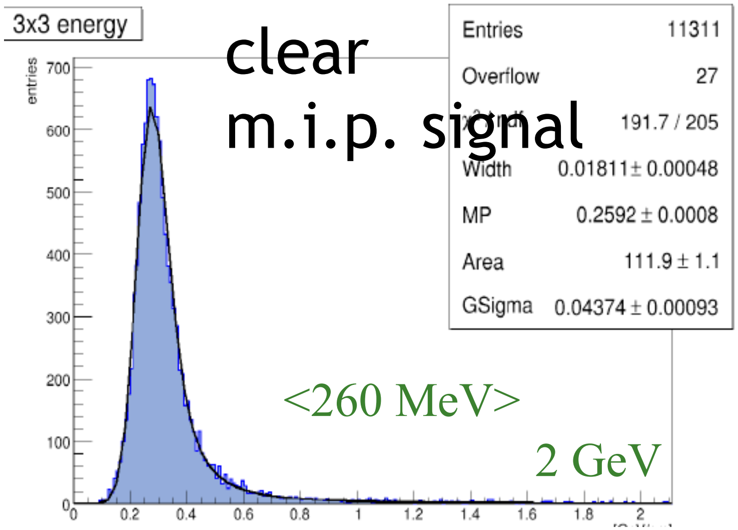
Dave Charlton(Birmingham), 3 March 2009

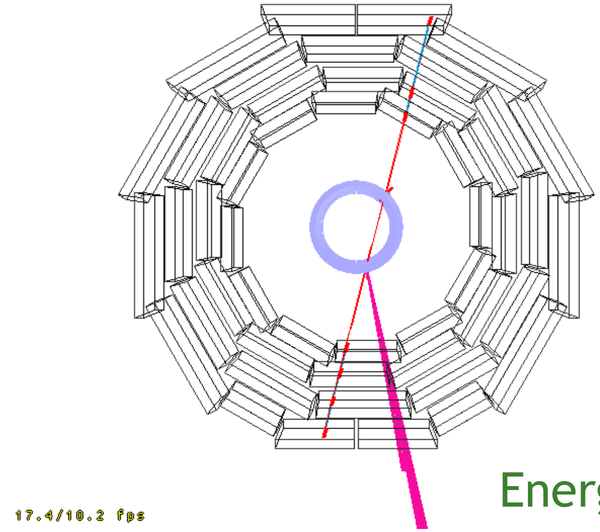
Example: CMS Electromagnetic Calorimeter

A “Dee” of endcap ECAL

Barrel ECAL clusters matching muon tracks







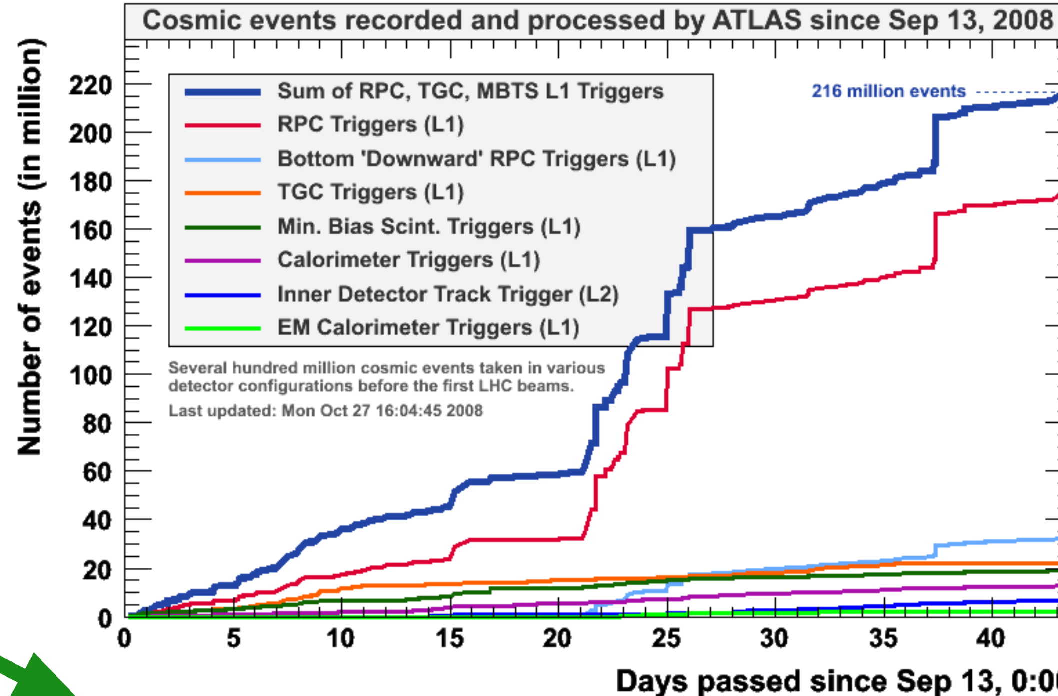
sometimes:

huge energy deposition from cosmic muon in ECAL

Energy: 250 GeV

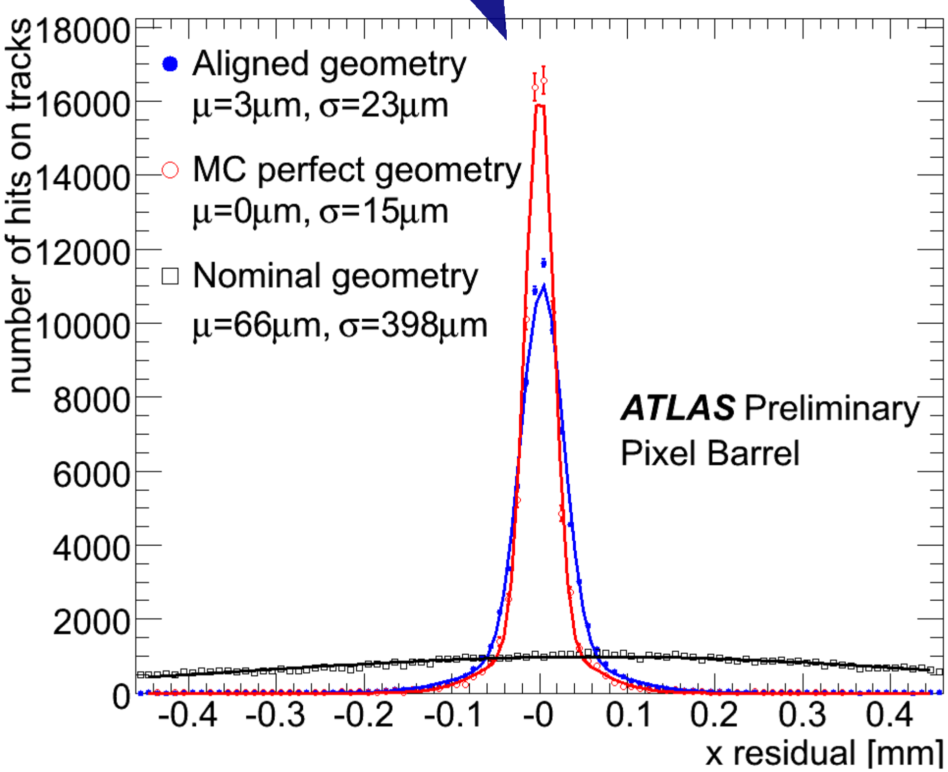
Using Cosmics

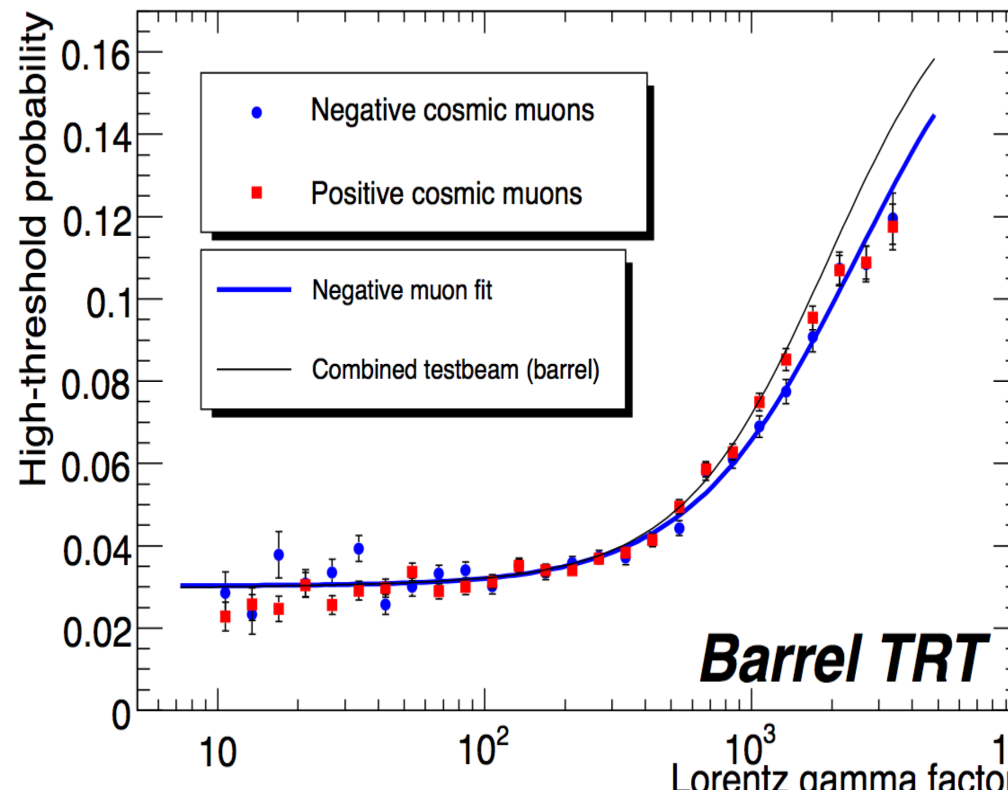
>200 million cosmic ray events since Sept



See transition radiation turn-on with μ !

Pixel detector alignment





LHC Incident

Interconnect busbar between superconducting magnets developed a significant resistance at a splice

No quench protection system covering the busbar splices

Heating, followed by rapid loss of helium into vacuum

- Soot in the beam-pipe
- Collateral mechanical damage to more distant magnet interconnects
- Around 50 magnets being repaired/replaced

Next Beams in the LHC?

Chamonix 2009 LHC workshop 2-6 February

Ongoing work to protect against problems from small splice resistances

"Since the incident, enormous progress has been made in developing techniques to detect any small anomaly. These will be used in order to get a complete picture of the resistance in the splices of all magnets installed in the machine. This will allow improved early warning of any additional suspicious splices during operation. The early warning systems will be in place and fully tested before restarting the LHC." - Rolf Heuer

Full quench protection system will be installed before next LHC operation

Additional measures taken to vent He rapidly to avoid collateral damage in the case of an incident

- Two different levels of protection in different sectors of the machine, equip full machine before going to 14 TeV

Decided not to warm up the whole machine now – should ensure operation with beam in 2009 – but only from the autumn

A 2009/10 Shutdown?

Repair and protection work allows first beam injection at end of September according to current schedule

Baseline schedule if no running over the winter...

Year	2009											2010											
Month	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Baseline	Shutdown								SU	PH		Shutdown (Relief V)						SU	PH				SH
	24 weeks physics possible																						

- Allows very limited physics in 2009/2010 (24 weeks)
- Any slip of >1 month in the repair will delay first LHC physics till August/September 2010!!
- Repair schedule has no contingency (some suggestion for 4 extra weeks)

Alternative plan developed now, to run through the winter months

The 2009/10 LHC Run

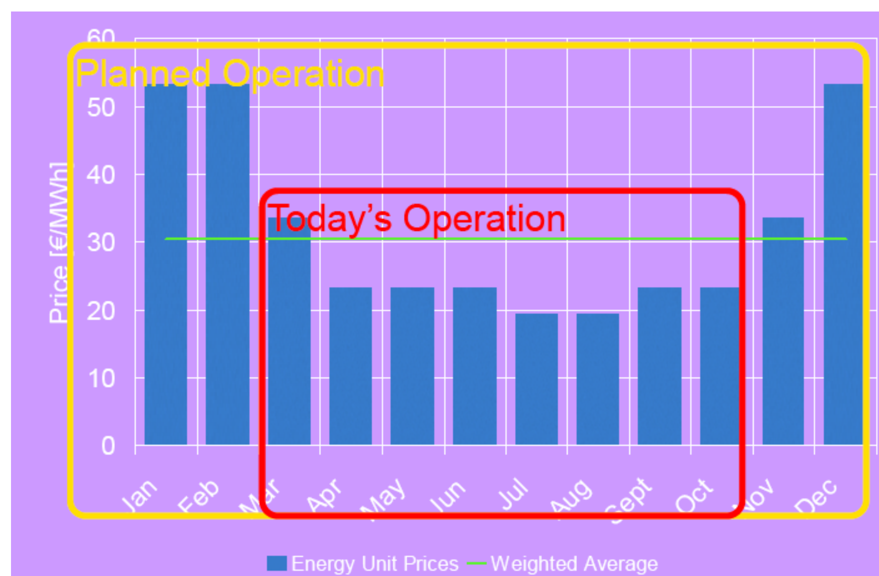
Year	2009											2010														
Month	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M
Baseline	SH	SH	SH	SH	SH	SH	SH	SH	SU		PH	SH	SH	SH	SH	SH	SH	SU	PH	PH	PH	PH	SH	SH	SH	SH
	24 weeks physics possible																									
Base '	SH	SH	SH	SH	SH	SH	SH	SH	SU	PH	PH	PH	PH	PH	PH	PH	PH	PH	PH	PH	SH	SH	SH	SH	SH	SH
	44 weeks physics possible																									
Delay (4W)	SH	SH	SH	SH	SH	SH	SH	SH	SH	SU	PH	PH	PH	PH	PH	PH	PH	PH	PH	PH	PH	SH	SH	SH	SH	SH
Delay (8W)	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH	SU	PH	PH	PH	PH	PH	PH	PH	PH	PH	PH	PH	SH	SH	SH	SH

Gain 20 weeks of physics in 2010 by running during winter months

HIGH price Electricity

Further delays (eg 4 or even 8 weeks, above), would have a relatively minor impact

Annual maintenance (infra-structure, injectors), electricity cost



The 2009/10 Data Sample

Energy:

- 10 TeV centre-of-mass energy for physics
- 8 TeV "on the way" to 10 TeV
- Small data samples at 0.9 TeV (injection energy) and perhaps 2 TeV (mainly for earlier timing-in/commissioning of detectors)

Luminosity:

- 5 x 10^{31} $cm^{-2}s^{-1}$ to $2x10^{32}$ $cm^{-2}s^{-1}$ peak
- With 200 days and 10% efficiency ~200-300 pb^{-1}
- Quite a large uncertainty...

In the range 100-500 pb^{-1} ?

LHC Commissioning

Note – pre-Chamonix plan (July 2008) – LHC-OP-ES-0011

Stage A	**Pilot physics run**	Physics aim 43x43 bunches; maximum 156x156 bunches; no crossing angle	$\rightarrow 5 \times 10^{31}$
Stage B	**Intermediate physics run**	Physics aim 75 ns bunch spacing; possible initial physics aim 96x96 bunches (bunch intensity 1×10^{10} protons); maximum aim 936x936 bunches (maximum 9×10^{10} protons per bunch). 250 μrad crossing angle.	$\rightarrow 10^{32}$
Stage C	**25 ns run I**	Intensity per bunch 5×10^{10} protons (initial 1×10^{10}); physics aim 2808 x 2808 bunches. 285 μrad crossing angle.	
Stage D	**25 ns run II**	Push towards nominal performance	

Chamonix favoured 50 ns operation in Stage B

Beyond 2010

Between 2010 and 2011 operation, there will be a need for a long shutdown

- Equip remaining sectors with full pressure relief system (warm up remaining sectors)
- Train magnets to higher energy, quenches expected:
  - To 6 TeV, estimate ~10 quenches
  - To 6.5 TeV, estimate ~80 quenches

For nominal luminosity of 10^{34}, additional collimators need to be installed around experiments – in 2011/12?

Not for 09/10, but...

200 days at 10^{32} $cm^{-2}s^{-1}$ and a 60% efficiency ~ 1 fb^{-1}
200 days at 10^{33} $cm^{-2}s^{-1}$ and a 60% efficiency ~ 10 fb^{-1}
200 days at 10^{34} $cm^{-2}s^{-1}$ and a 60% efficiency ~ 100 fb^{-1}

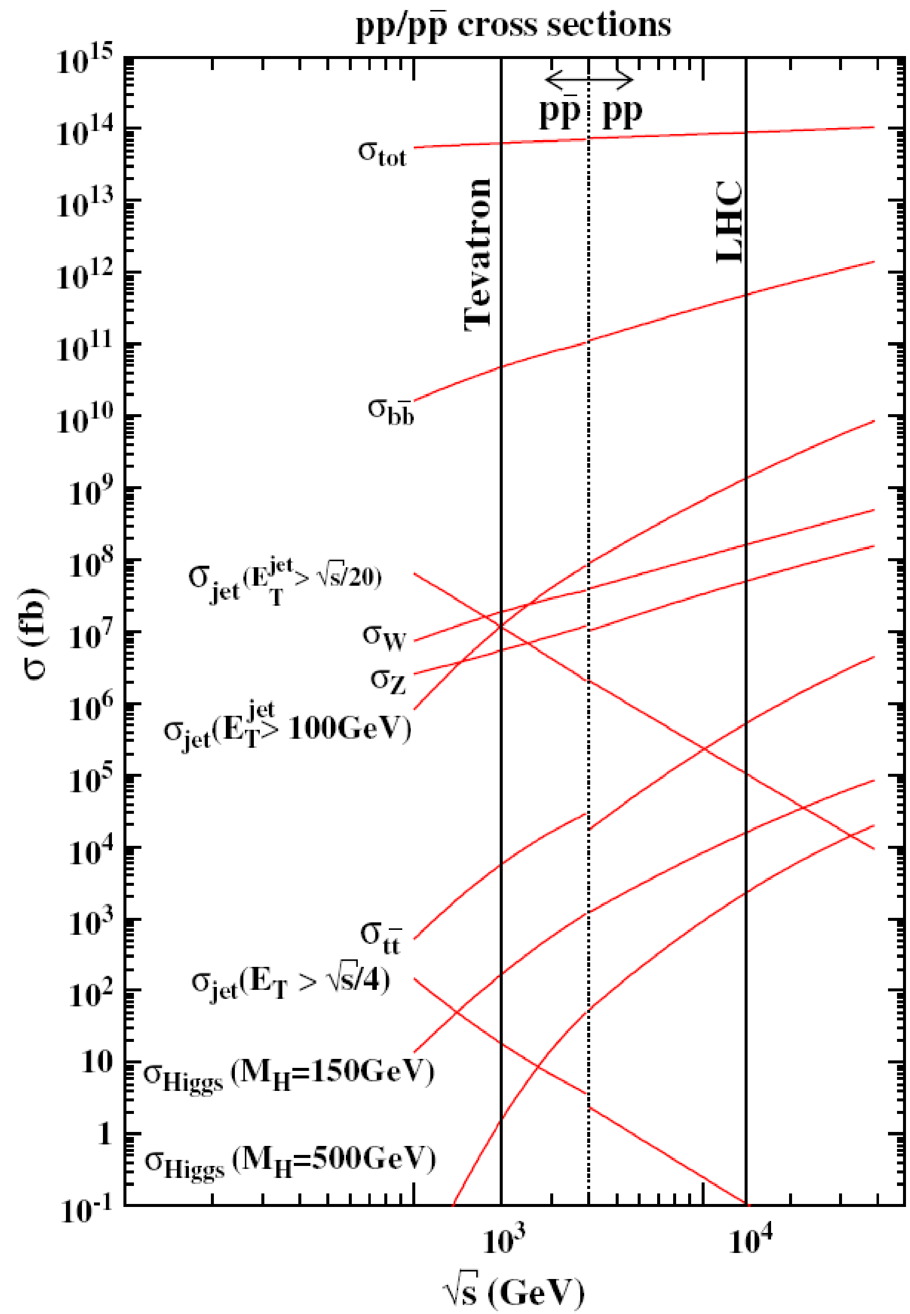
In the “annual” running scheme, perhaps 120 days per year

Physics Commissioning

First collisions: work to establish detector and trigger performance, measure Standard Model processes

- Min bias – timing in, tracking & calorimeter uniformity & performance
- Dijets – calorimeter uniformity, jet uniformity and inter-calibration
- γ-jet – photon ID, jet energy scale
- J/ψ – μ ID, tracking performance (e ID)
- bb – lifetime-based b-tagging
- W/Z – e/μ ID, resolutions, efficiencies, τ ID (in time), missing E_t
- Z+jets – jet energy scale
- Top – many things, once we have statistics...

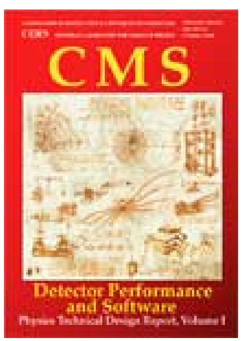
You will need to be patient – this will take some time...

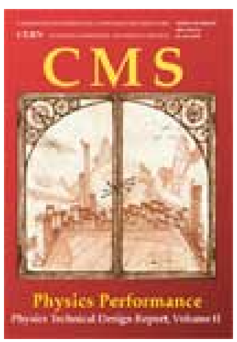


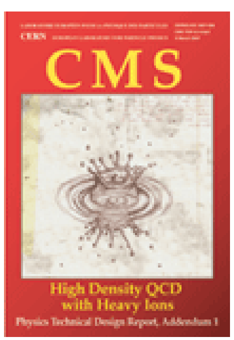
Recent Summaries

CMS "Physics TDR" 2006/7

Vol I : CERN-LHCC-2006-001
Vol II : JphysG 34 (2007) 995-1579
Vol II : JphysG 34 (2007) 2307-2455



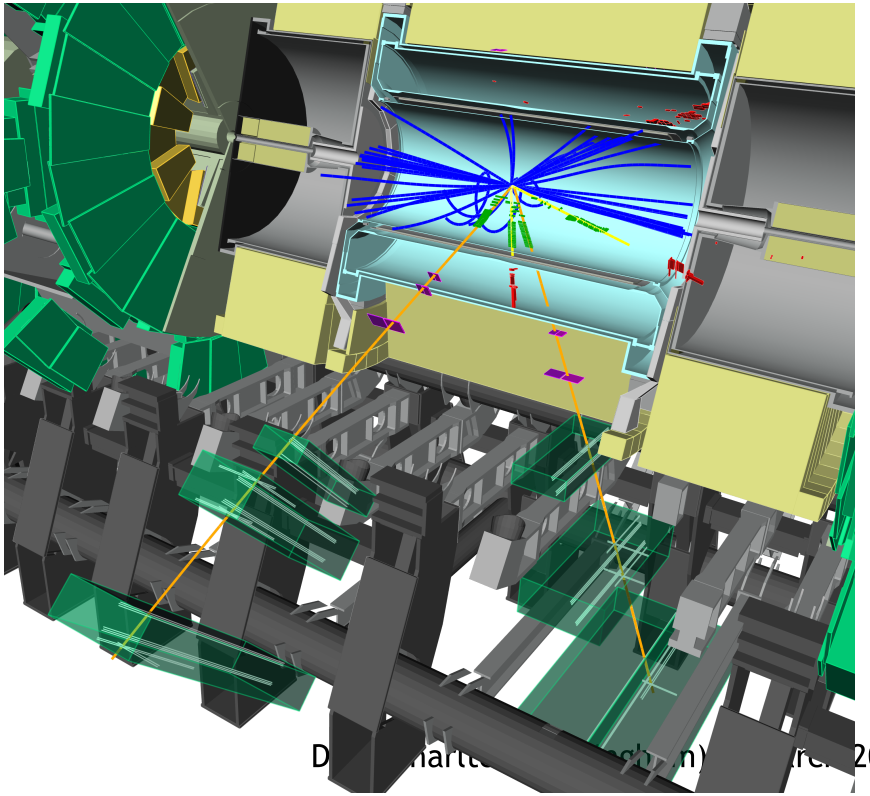




ATLAS "CSC book" Dec 2008

Expected Performance of the ATLAS Experiment
Detector, Trigger and Physics

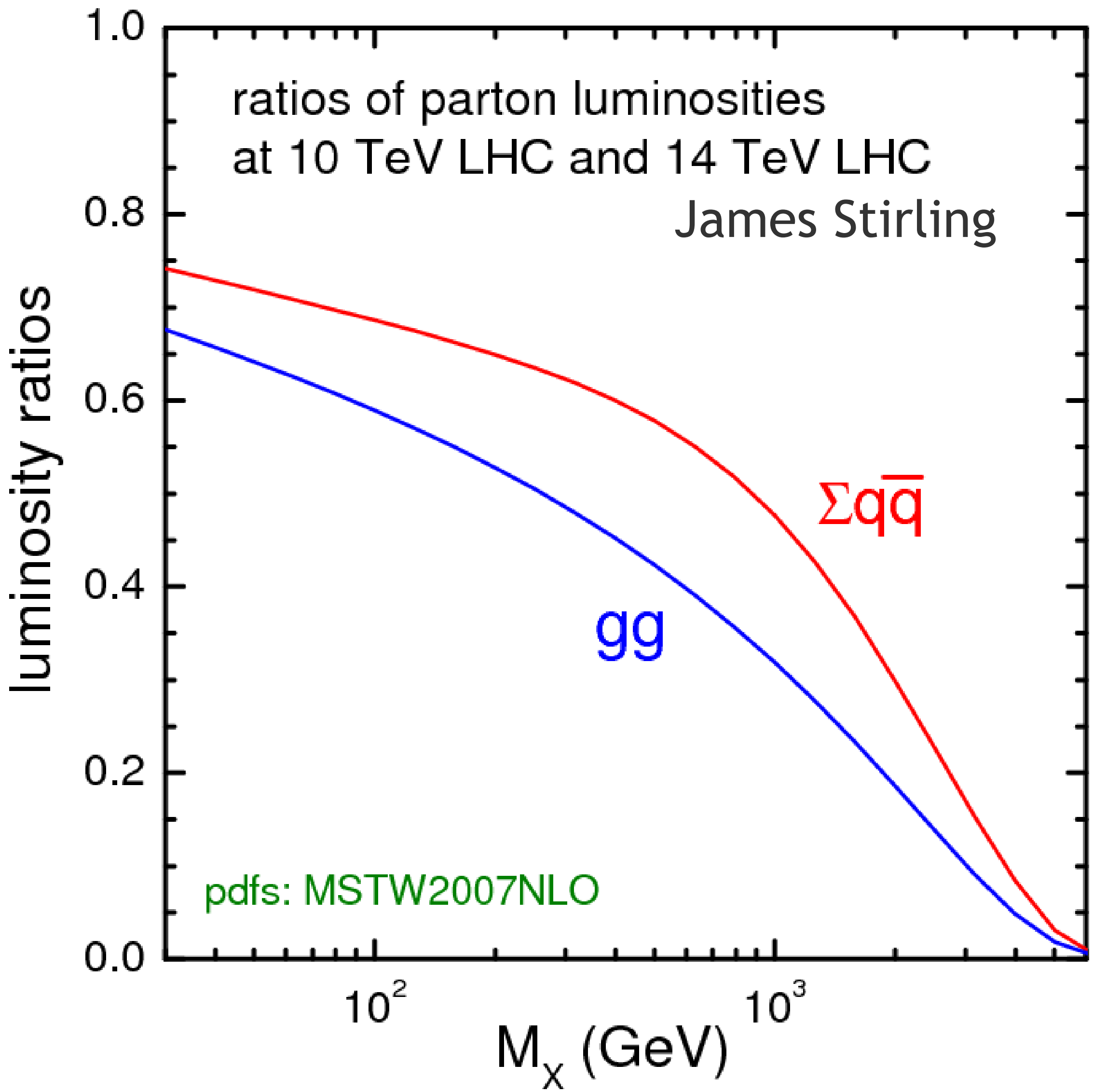
CERN-OPEN-2008-020
arXiv 0901.0512



Both cases:

Comprehensive reviews of physics capabilities, mainly for first years of LHC operation

10 vs 14 TeV?



At 10 TeV, lower cross-section for high mass objects due to lower parton luminosities...

Below about 200 GeV, the suppression is <50% (process dependent)

- e.g. $t\bar{t}$ ~ factor 2 lower cross-section (still 50x Tevatron)

Above ~2-3 TeV the effect is more marked

Vast majority of studies done on $\sqrt{s}$=14 TeV capabilities

Calibration and Alignment

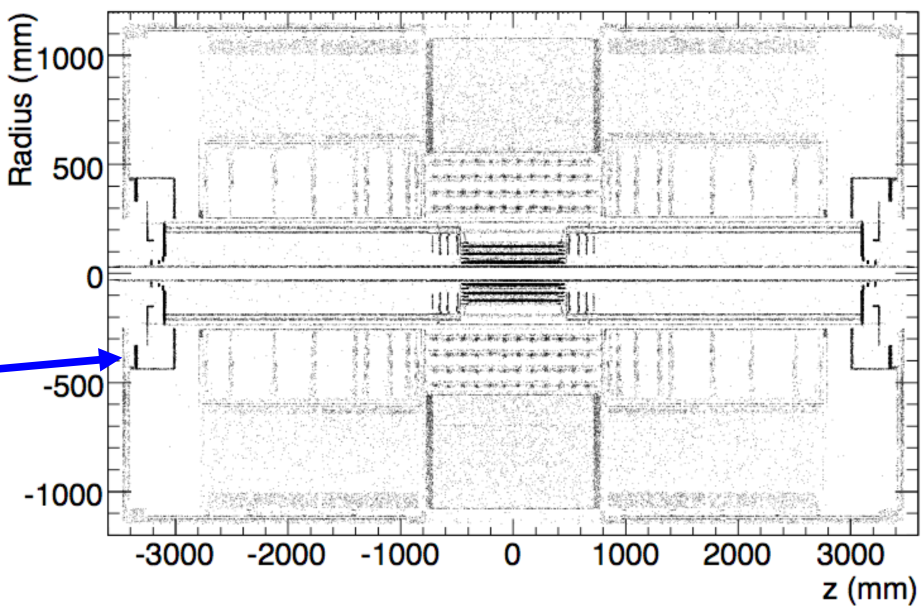
Much work to be done before physics, building on:

- test-beam
- calibration and alignment systems
- cosmics taken last year & this year

	Initial	Ultimate	Samples
e/γ E scale	~2%	0.1%	$Z \rightarrow ee$, J/ψ, π^0
e/γ uniformity	1-4%	0.5%	$Z \rightarrow ee$
jet E scale	5-10%	~1-2%	$W \rightarrow jj$ in tt, γ/Z+jets
tracking alignment	10-100 μm	<10 μm	tracks, $Z \rightarrow \mu\mu$
muon alignment	few 100 μm	30 μm	inclusive μ, $Z \rightarrow \mu\mu$

Early data very important:

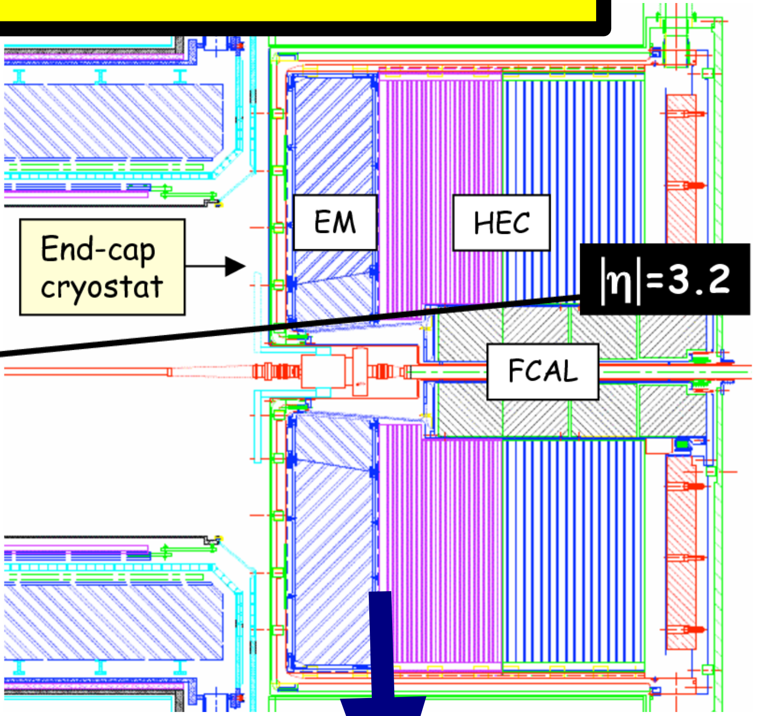
- tracks for alignment
- azimuthal asymmetry for calo. uniformity
- conversions for material assay
- ...



Missing-E_T

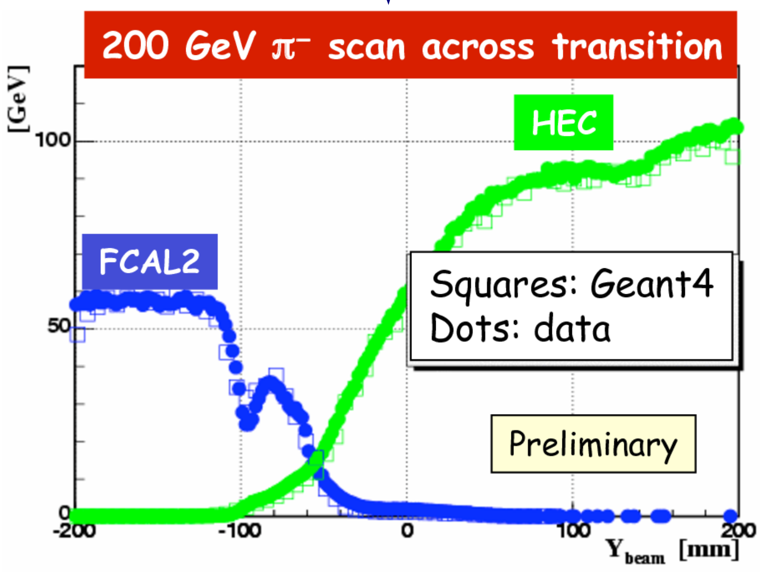
Challenging to commission:

- dependence on all calorimetry, even FCAL
- modelling of crack regions, eg
- machine backgrounds, etc

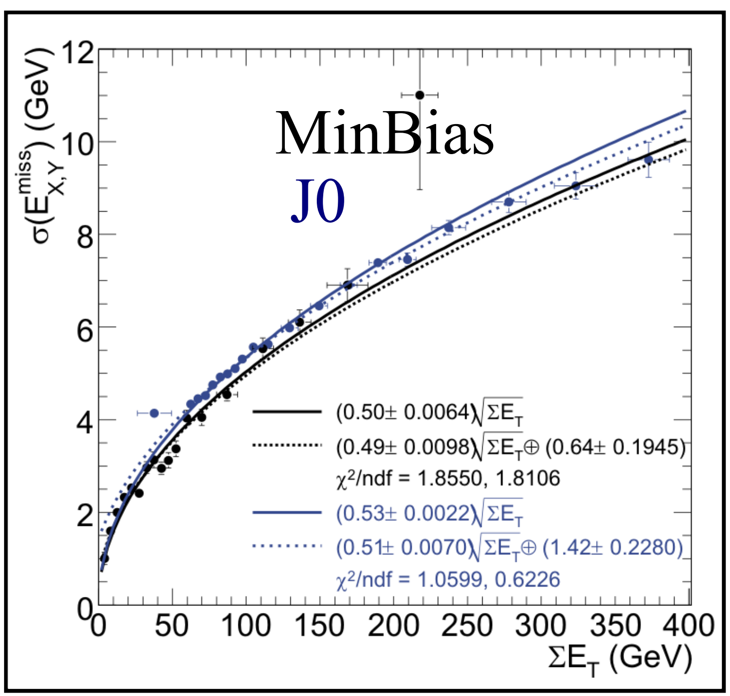


ATLAS studies shown here

test-beam



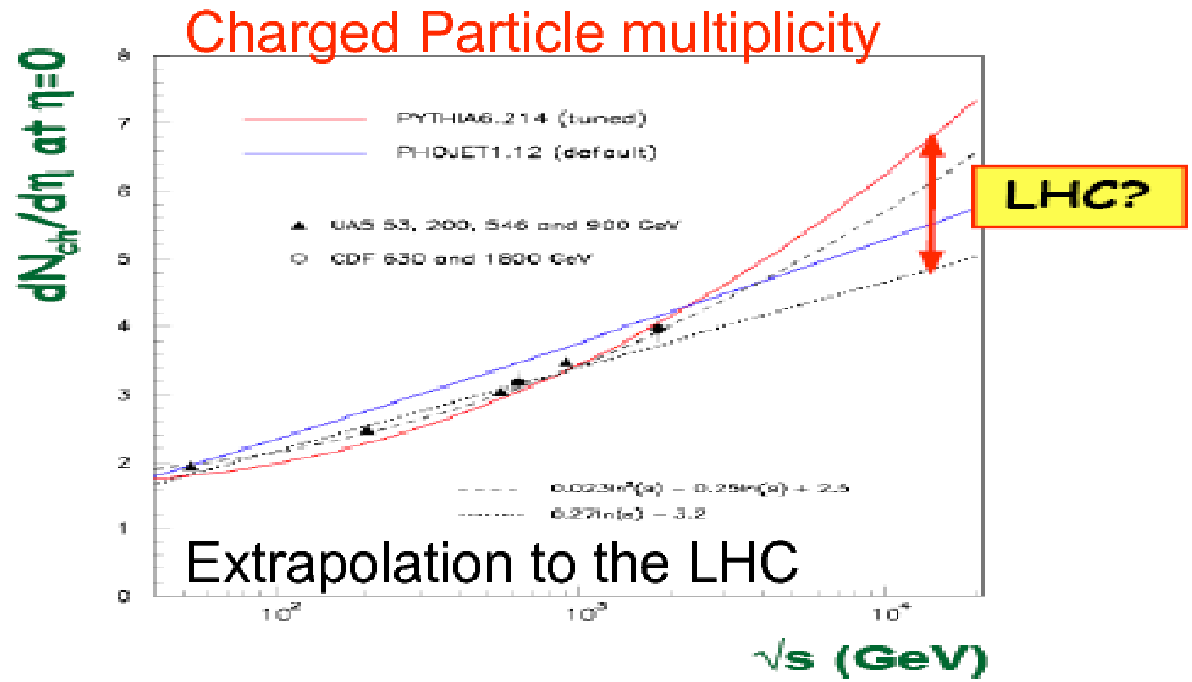
Detailed studies ready for control samples of data...

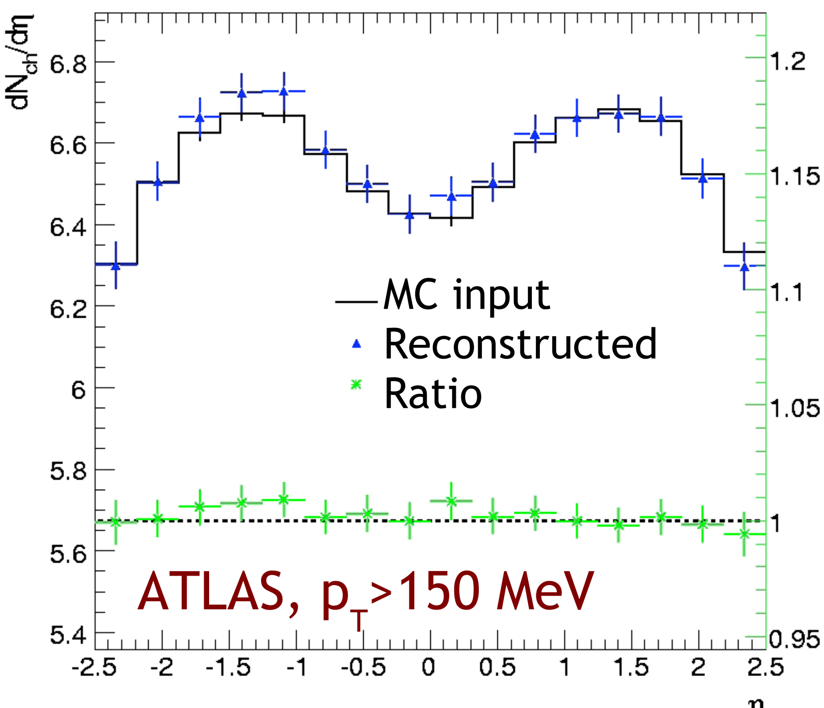


Minimum Bias

Early measurements – need tracker alignment, efficiency and material, to be understood

Challenge to extend tracking to low p_T (high B-fields at LHC!)

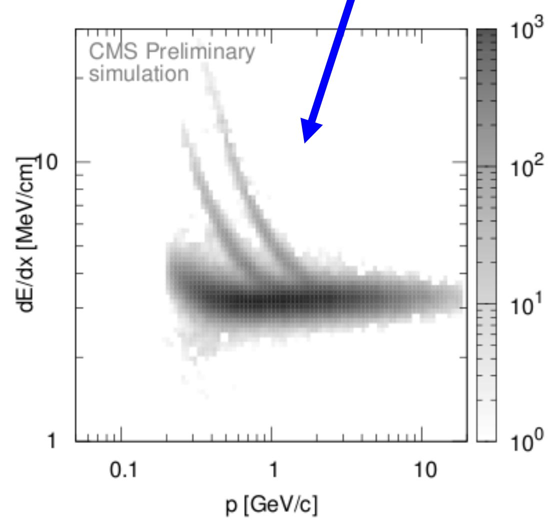


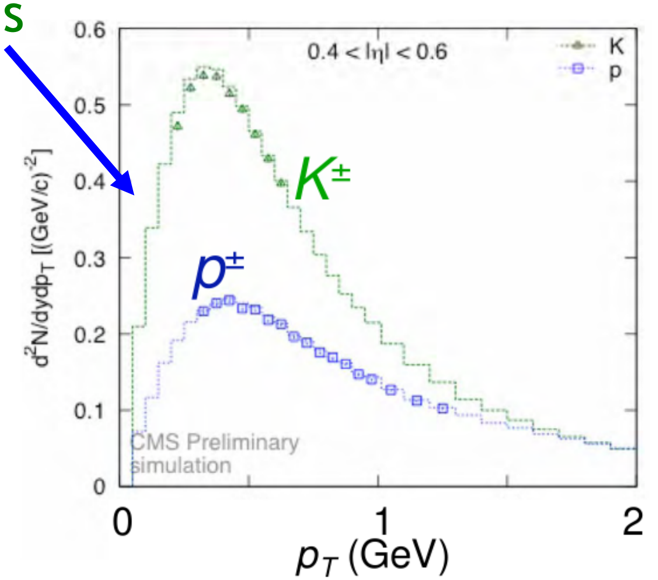


1 minute @ $L=10^{31}cm^{-2}s^{-1}$ 14 TeV

CMS tracker: dE/dx (digitised readout of Si)

Individual particle yields

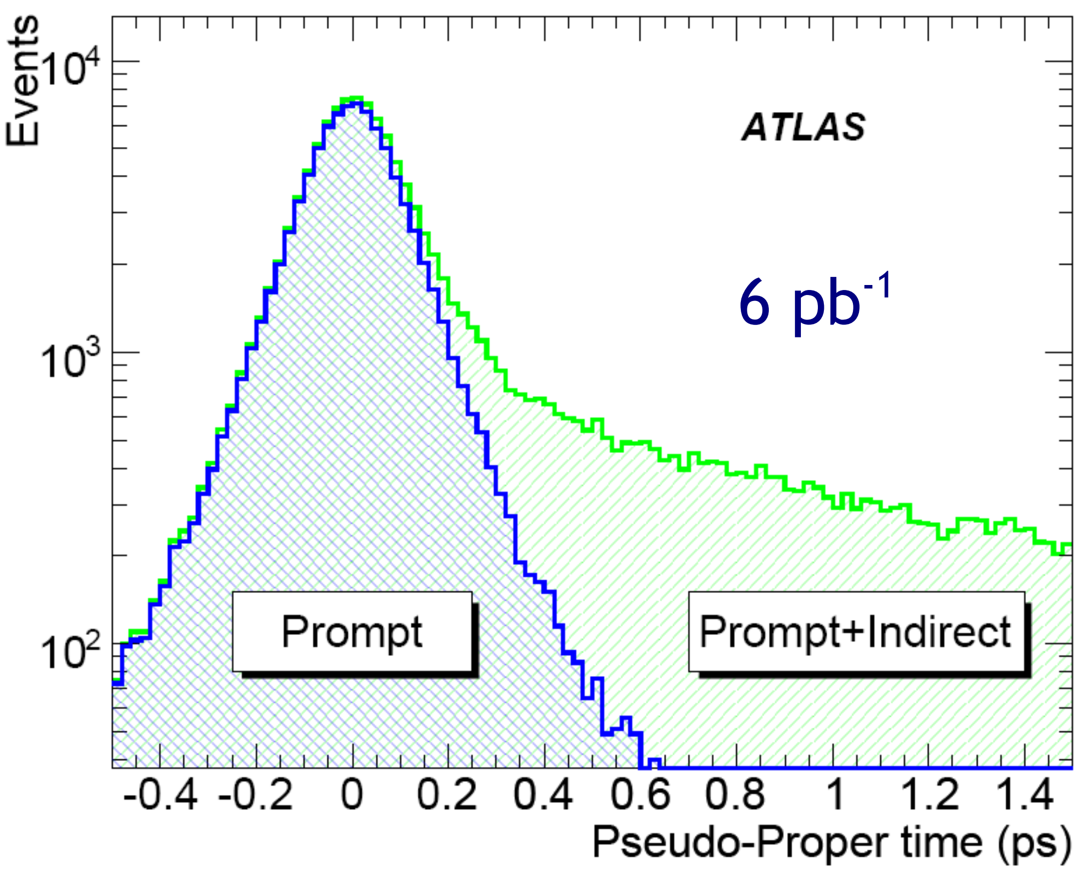


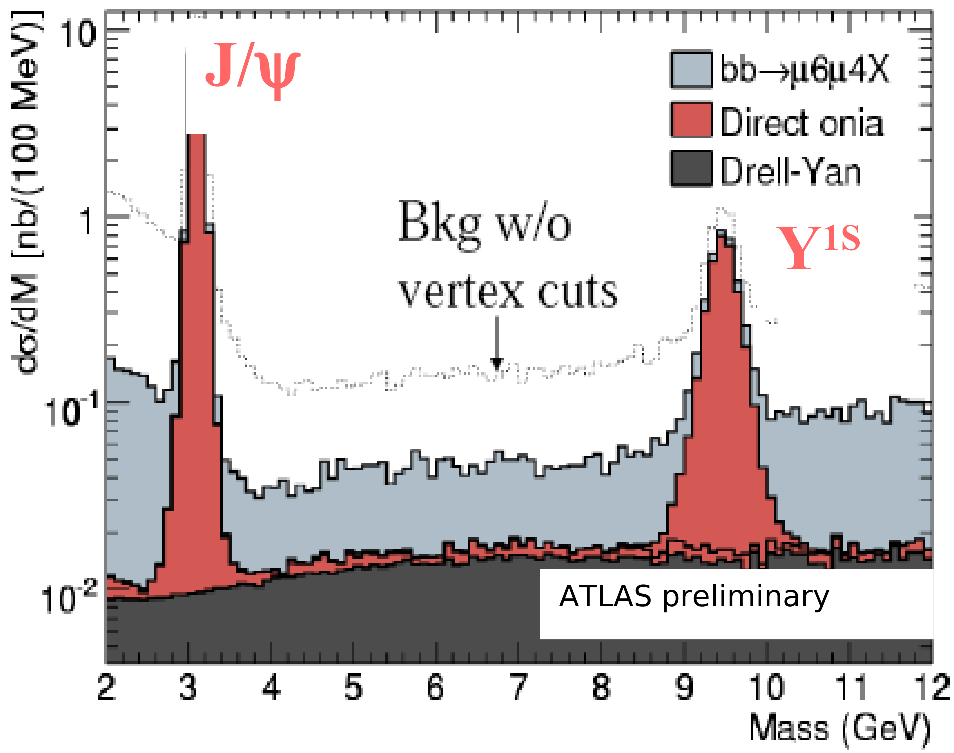


J/ψ

Huge statistics very fast, especially in $\mu\mu$ channel

- important standard candle for commissioning





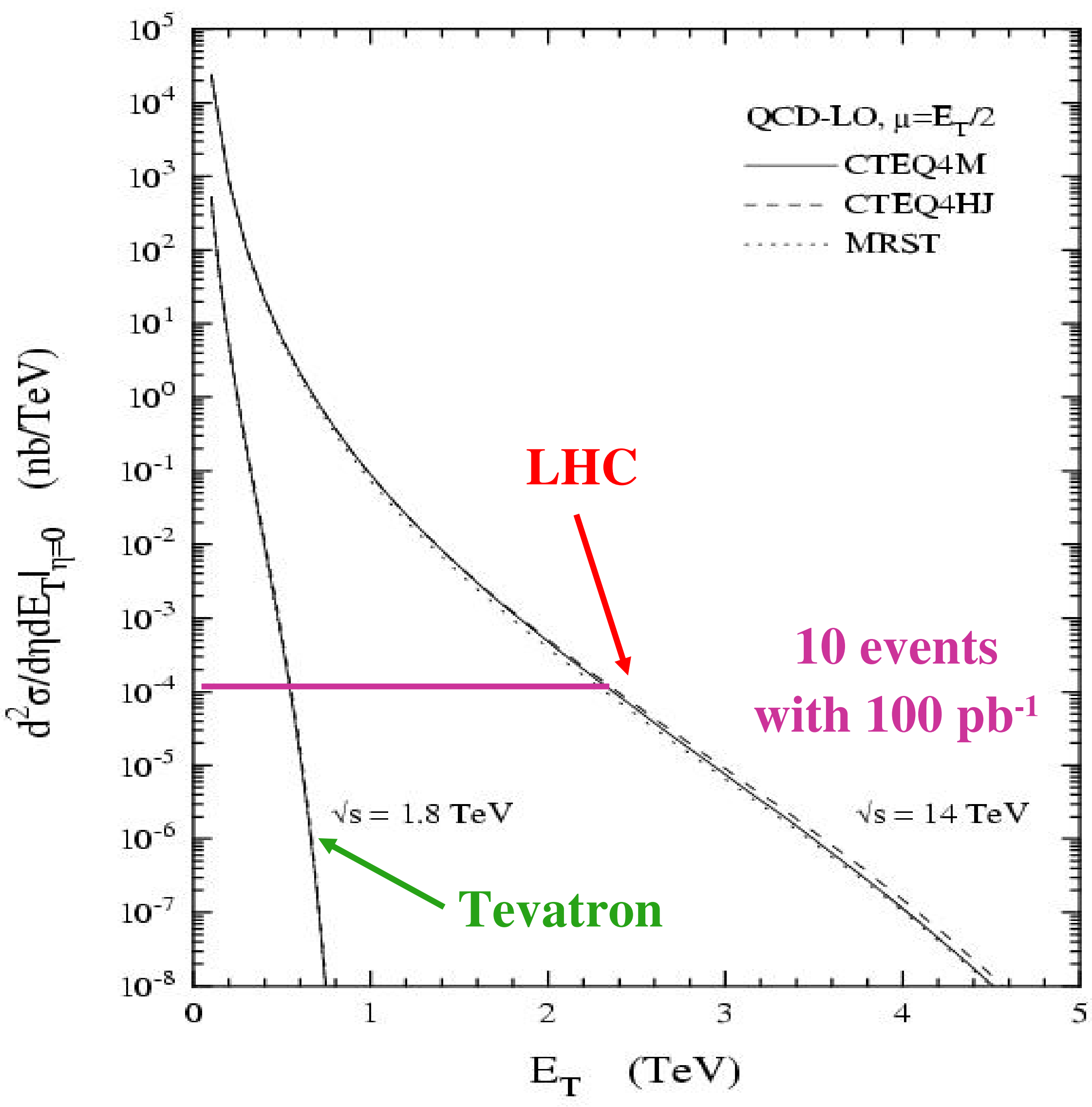
With 1 pb^{-1} could already measure

R = σ(bb->J/ψ)/σ(pp->J/ψ)

with <5% statistical precision

provided: muon trigger working; tracking understood well enough

Jets



Huge cross-sections

Very rapidly sensitive beyond Tevatron at 10 or 14 TeV

Main experimental challenge: jet energy scale uncertainty

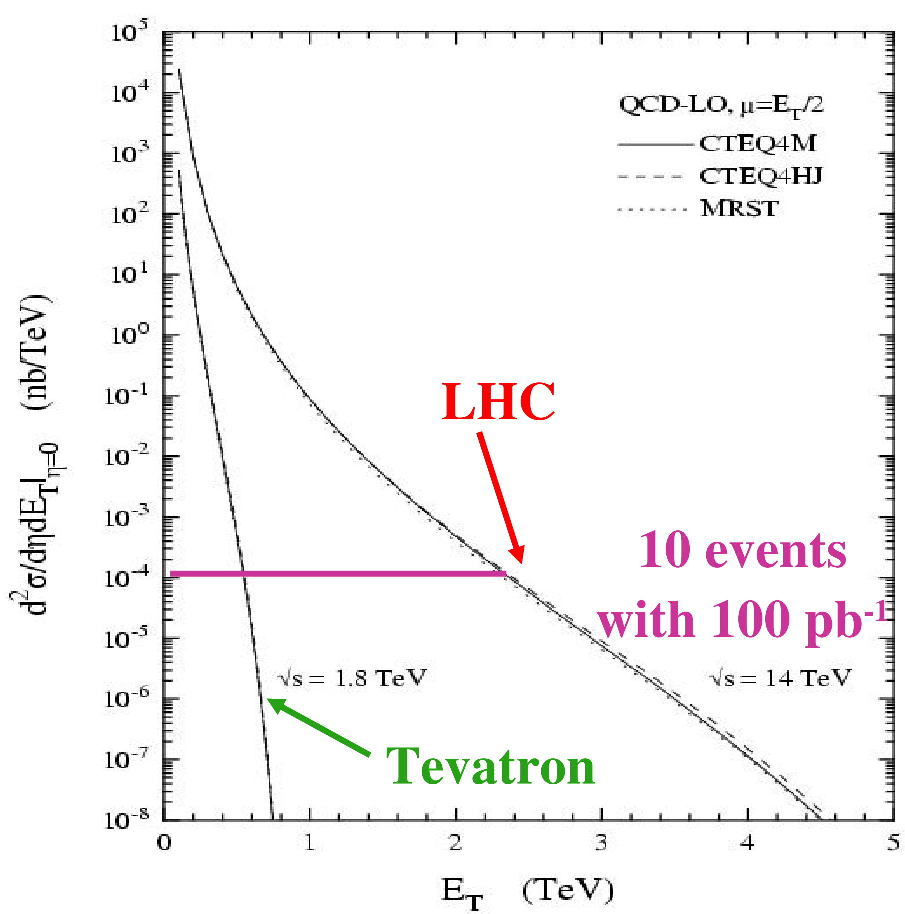
- γ-jet, Z-jet events
- E_T-balance in dijet and multijet events

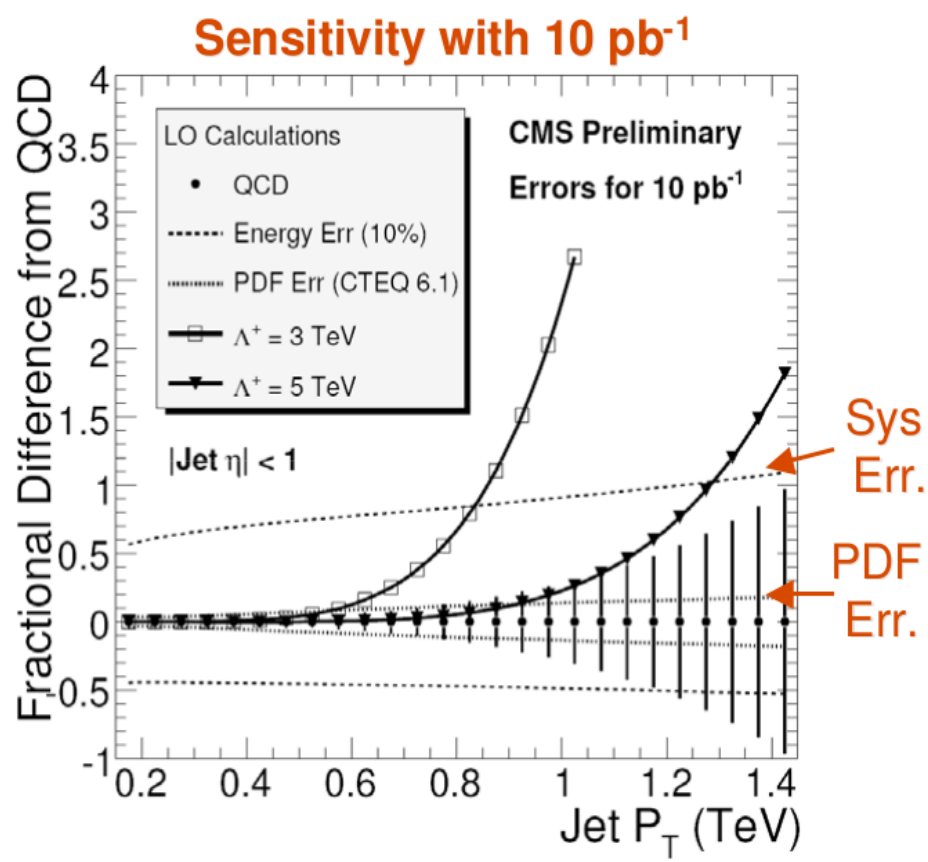
Jets - p_T spectrum

Inclusive jet p_T spectrum - sensitivity e.g. to contact interactions

$$L_{contact} = \frac{2\pi}{\Lambda^2}(\bar{q}_L \gamma^\mu q_L)(\bar{q}_L \gamma_\mu q_L)$$

10 pb^{-1} - sensitivity beyond Tevatron reach Λ^+~3 TeV (Tev. limit 2.7 TeV)

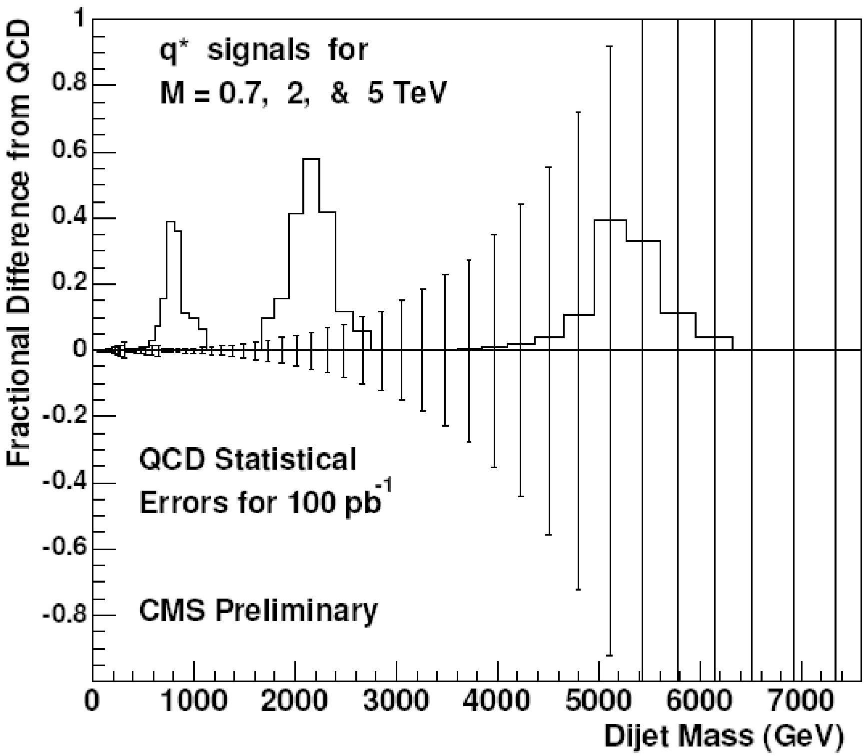


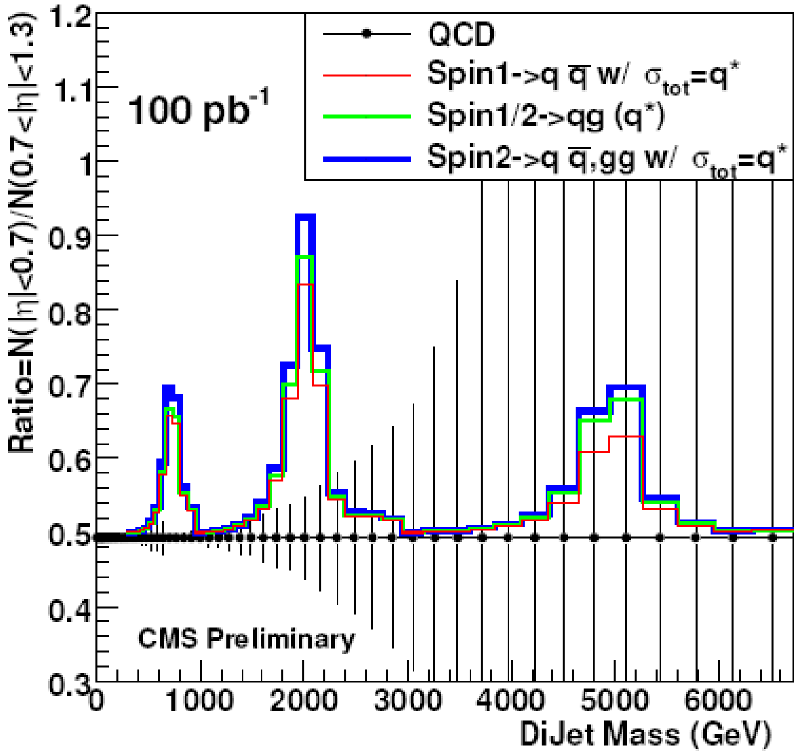


New Physics in Dijets

Other sensitive distributions, such as:

- dijet mass
- dijet ratios, e.g. N(|η|<0.7)/N(0.7<|η|<1.3)



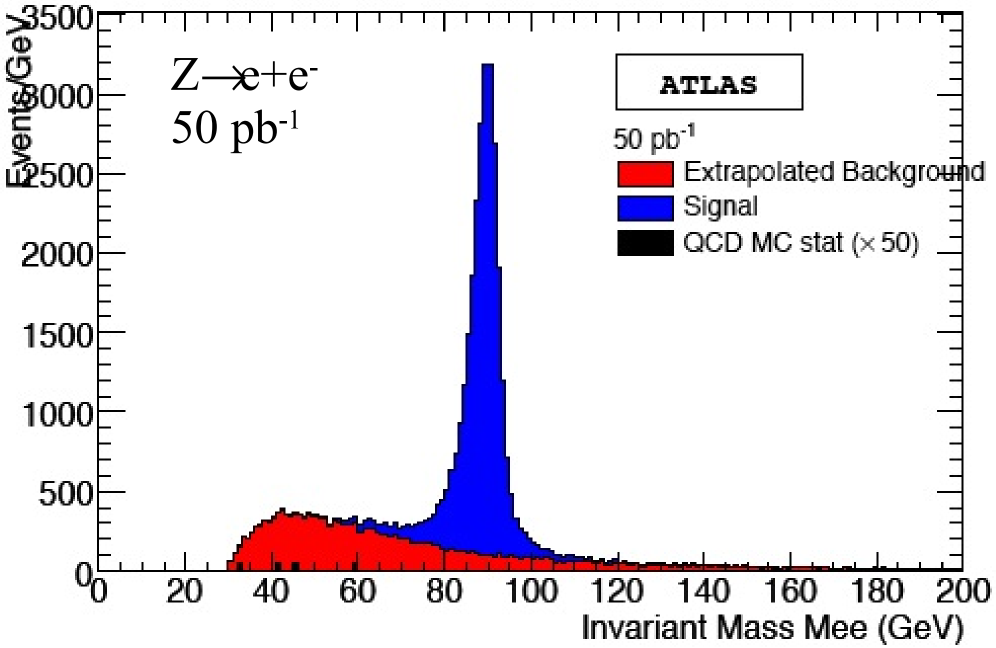


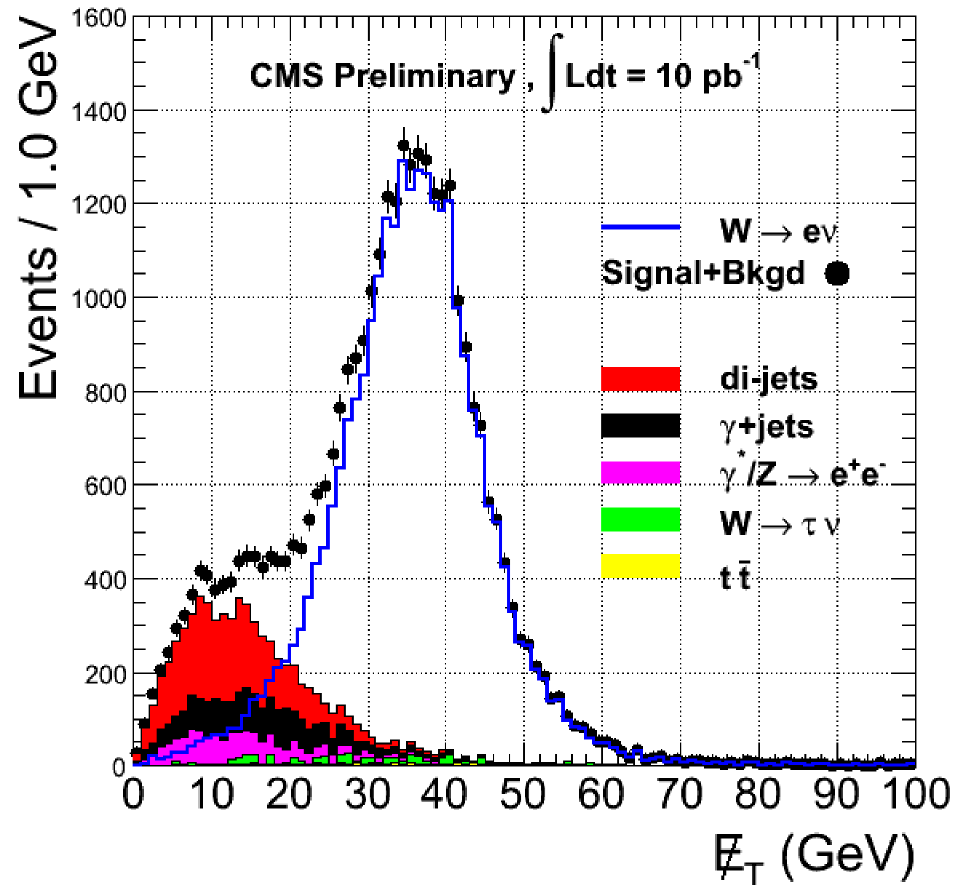
100 pb^{-1} at 14 TeV: sensitive well beyond Tevatron limit at 0.8 TeV

Sensitive to spin of a high-mass resonance observed

W and Z

Clean selections anticipated: excellent lepton ID





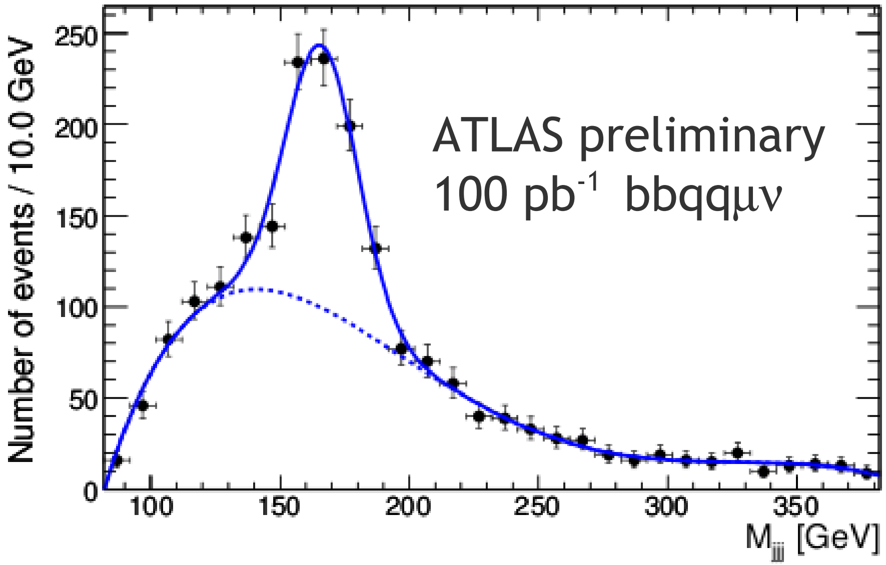
25k Z→ee for 50 pb^{-1} at 14 TeV

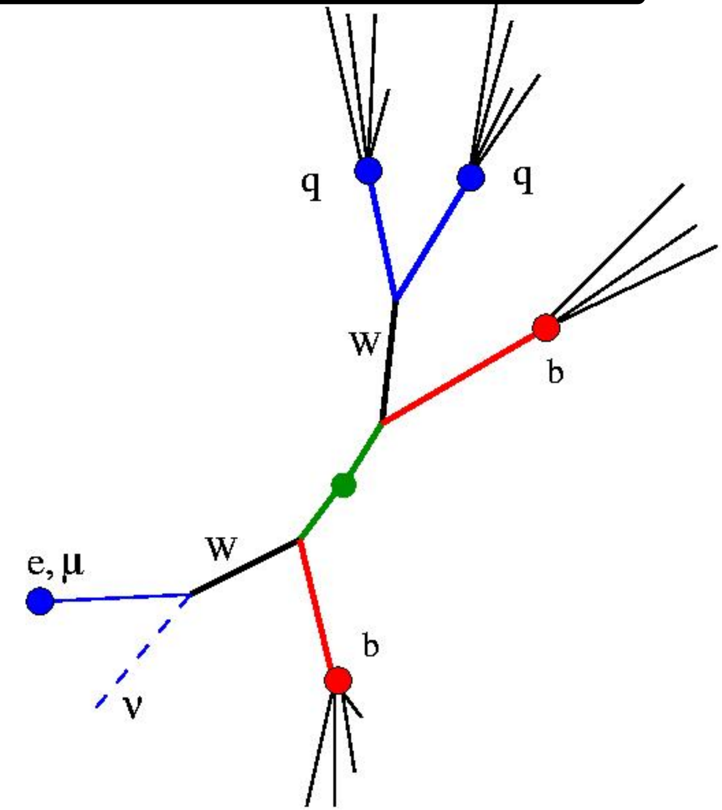
Quickly dominated by systematics

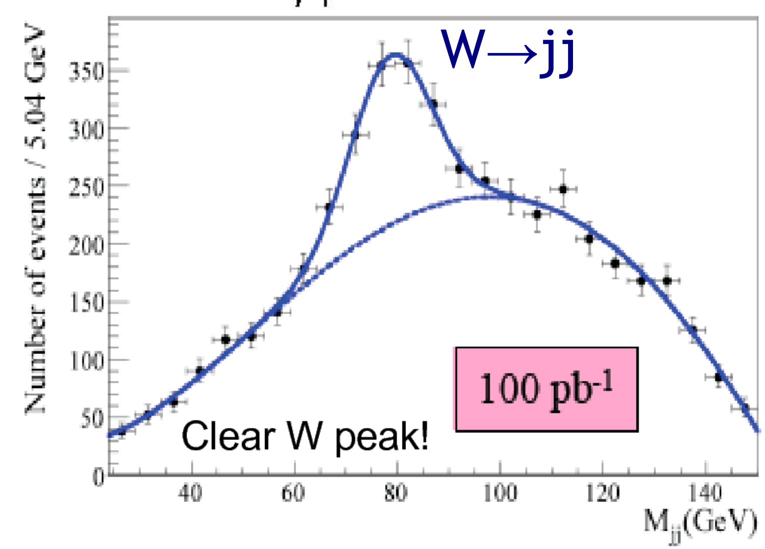
Initial precision of W/Z cross sections 4-5%

Top Physics

Top ($t\bar{t}$) cross-section at 14 TeV ~ 850 pb
Cf Tevatron ~ 7 pb NLO + corrections





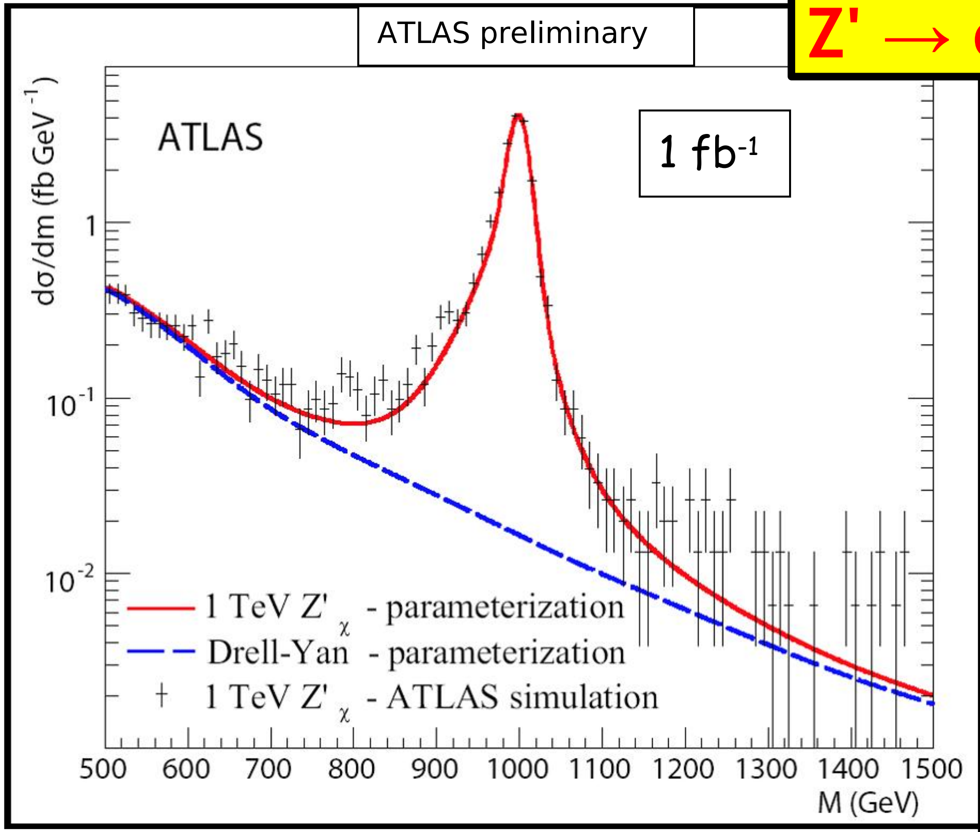


Invaluable channel for data-driven calibration

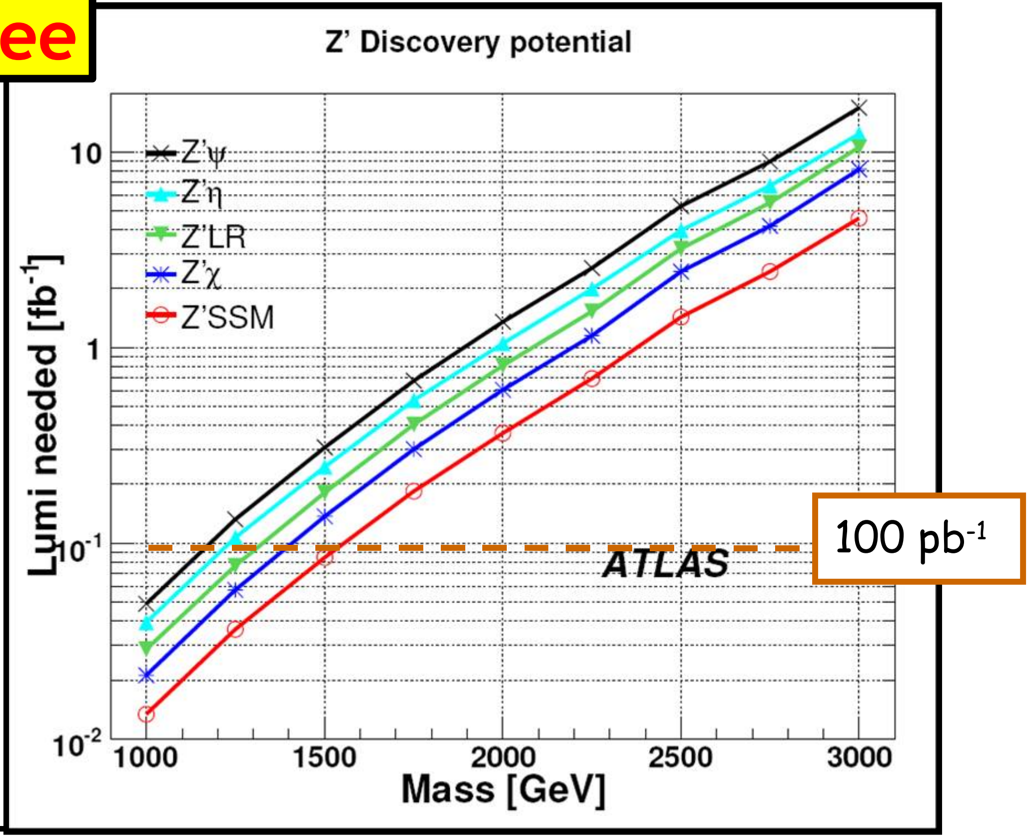
- can select without b-tags
- commission b tagging
- general performance
- calibrate the light jet energy scale with $W \to jj$

Cross-section about half at 10 TeV

Simplest New Physics Signature?



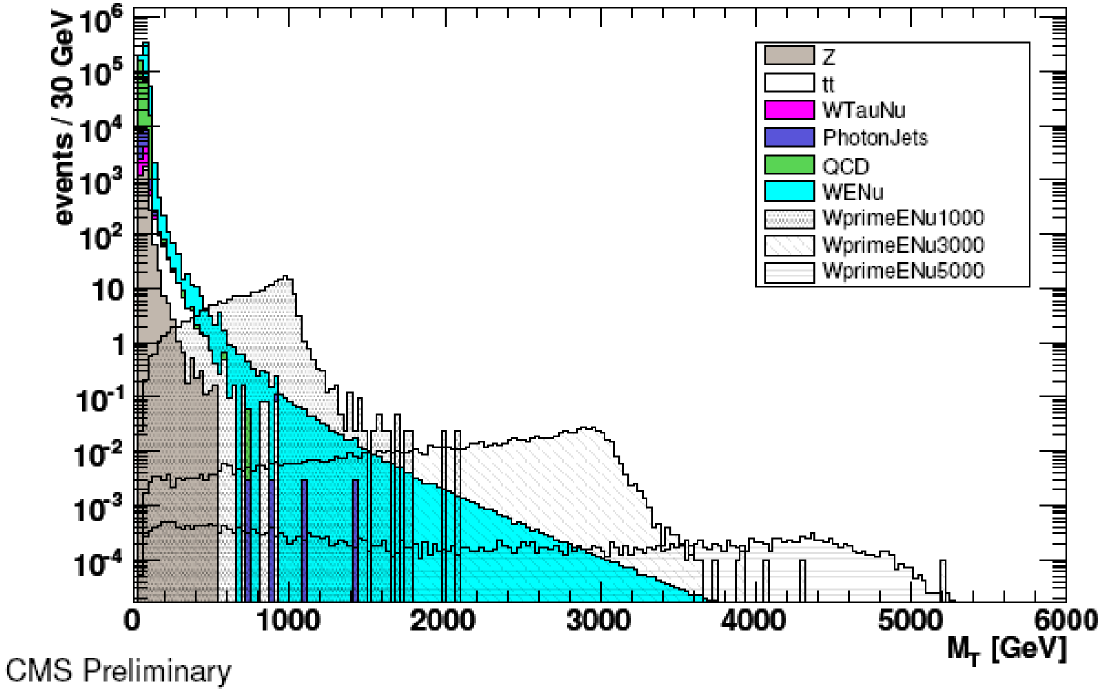
Z' → ee

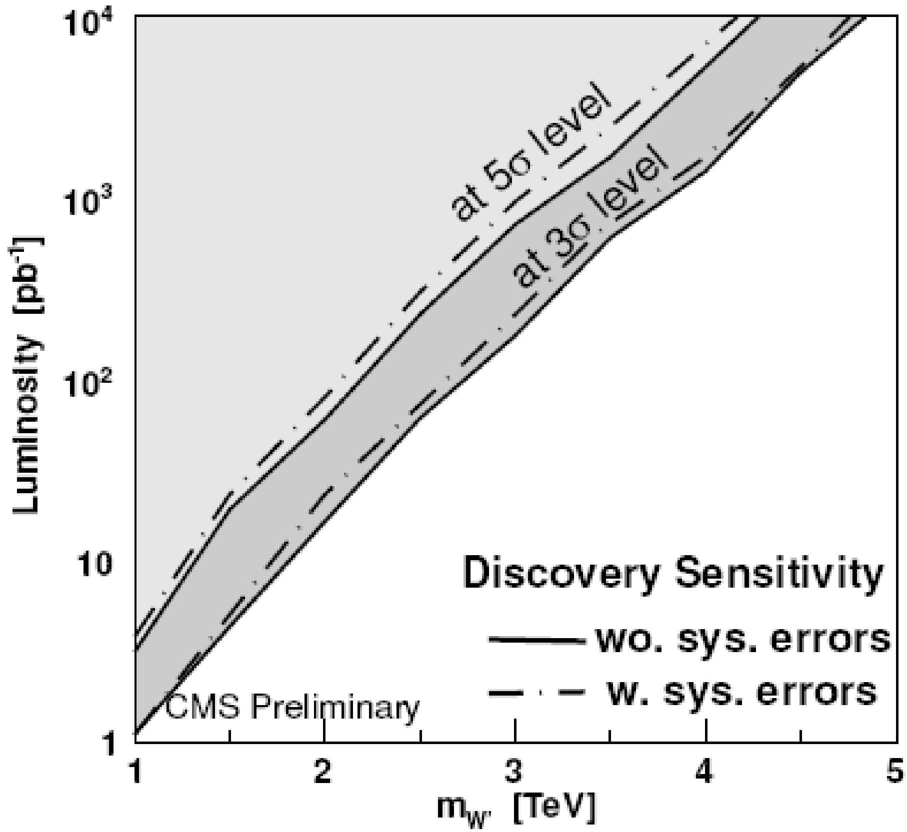


- Z' mass peak on top of small Drell-Yan background
- with 100 pb^{-1} large enough signal for discovery up to m ~ 1.5 TeV in sequential SM $\sigma(10\text{ TeV}) \sim \frac{1}{2}\,\sigma(14\text{ TeV})$
- current Tevatron 95% CL limit ~ 1 TeV
- ultimate calorimeter performance not needed
- ultimate reach (300 fb^{-1}) ~ 5 TeV

$W' \rightarrow \ell\nu$

$W' \rightarrow e\nu$





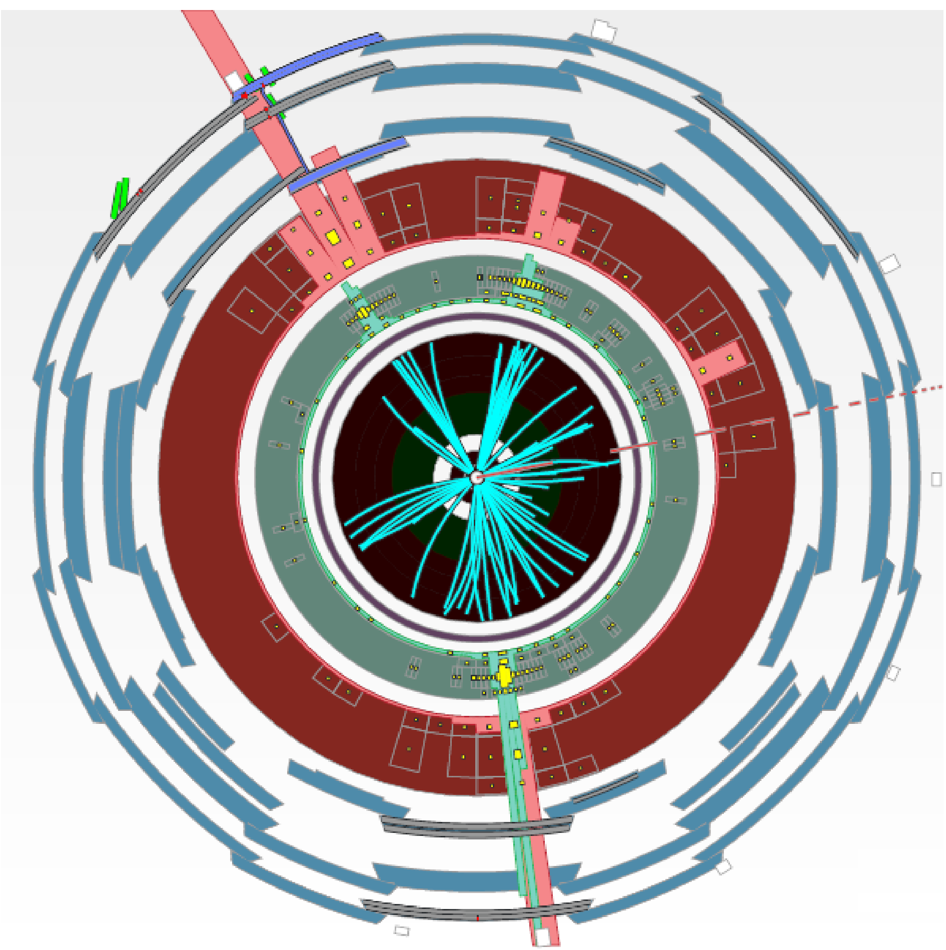
- sequential SM-like couplings to fermions
- characteristic Jacobian shape in transverse mass distribution
- techniques to measure backgrounds from data being developed
- current Tevatron 95% CL limit ~ 1 TeV
- discovery sensitivity up to ~2.2 TeV for 100 pb^{-1} at 14 TeV

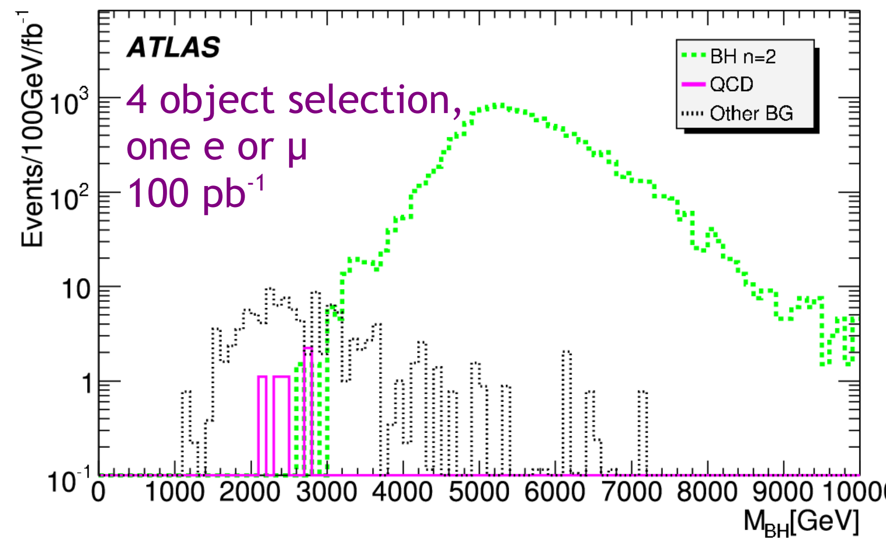
TeV-Scale Gravity

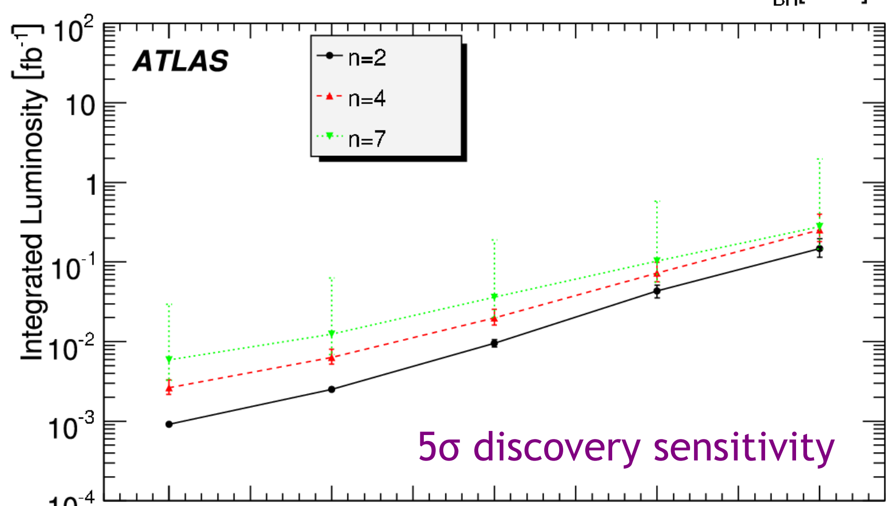
Black hole production and evaporation (CHARYBDIS) in ED model

Assumption: only SM particles from evaporation; valid only for $M_{BH} >> M_D$ (D-dim. Planck scale)

→ High multiplicity of high E_T objects, e.g. 4 objects with p_T>400 GeV

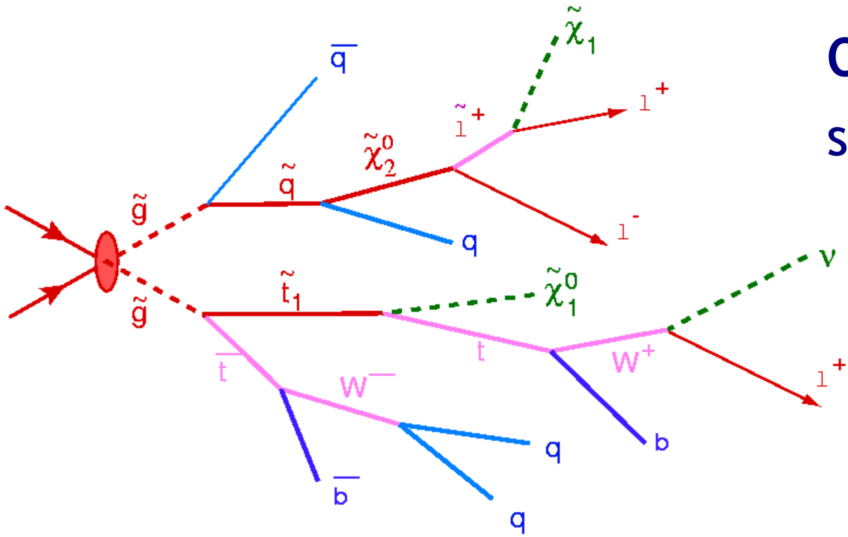




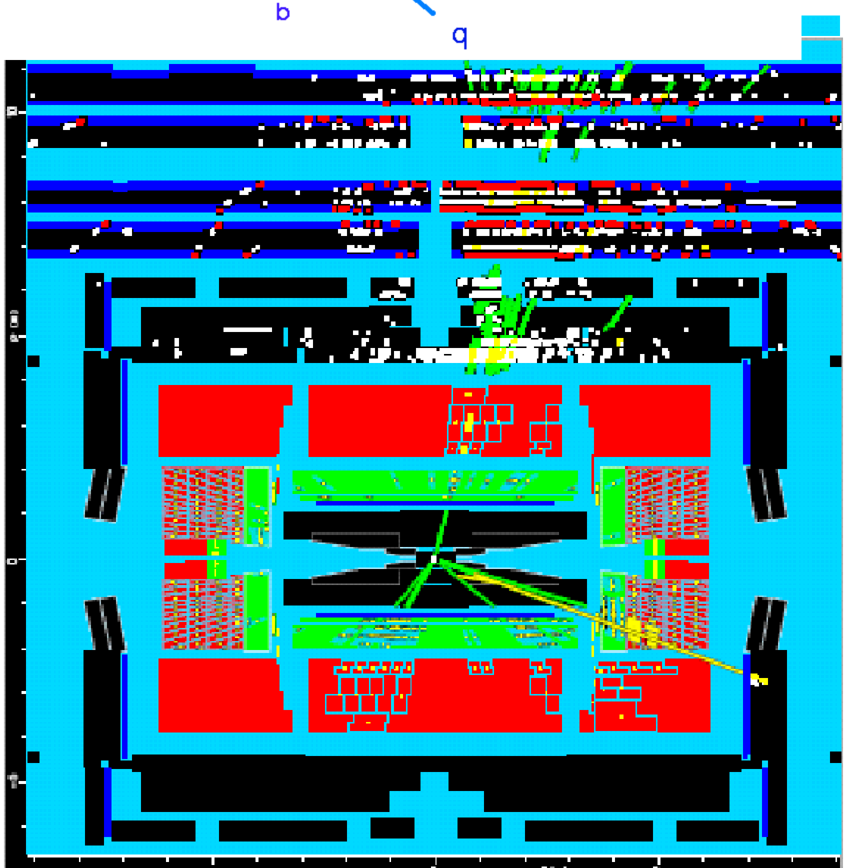


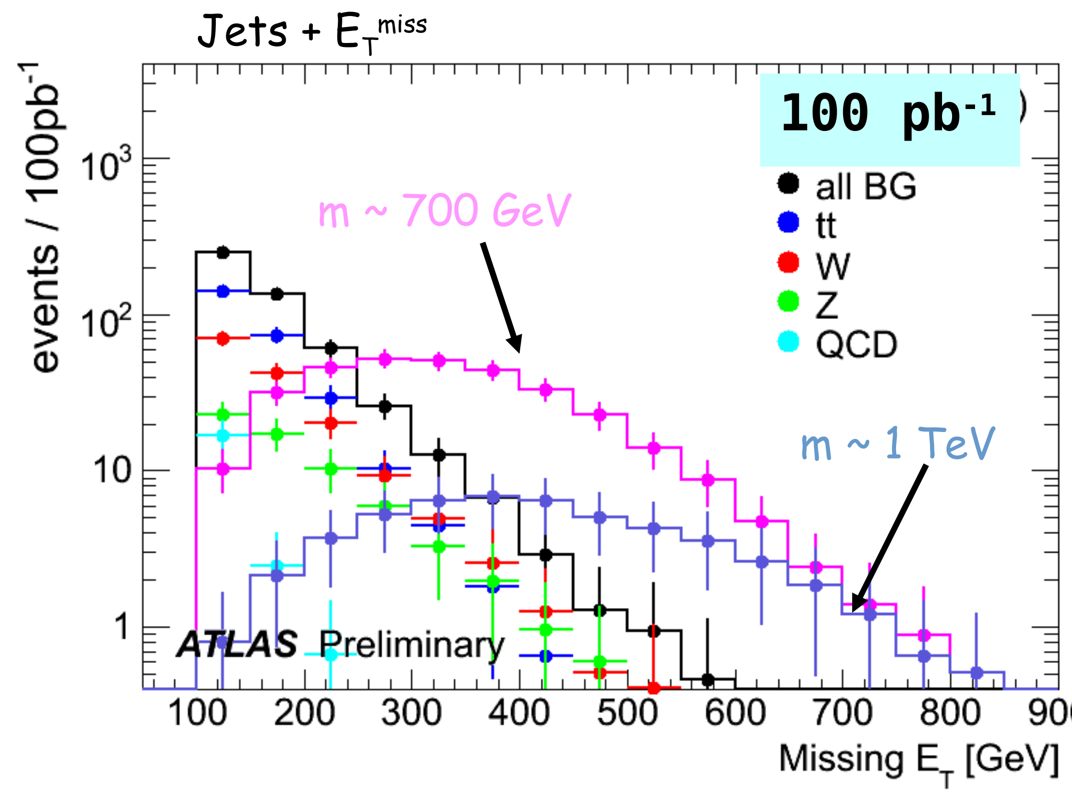
BH mass threshold

SUSY - mSUGRA



QCD production of squarks, gluinos – E_T^{miss} signatures





Need to understand whole detector well to rely on E_T^{miss}

→ problem will be to know if an excess is real, and what it is...

SUSY - mSUGRA

Extrapolate from fully simulated benchmark points to other regions of (m_0, $m_{1/2}$, $\tan\beta$)

Reach for squark and gluino masses using 4-jets+0-lepton channel:

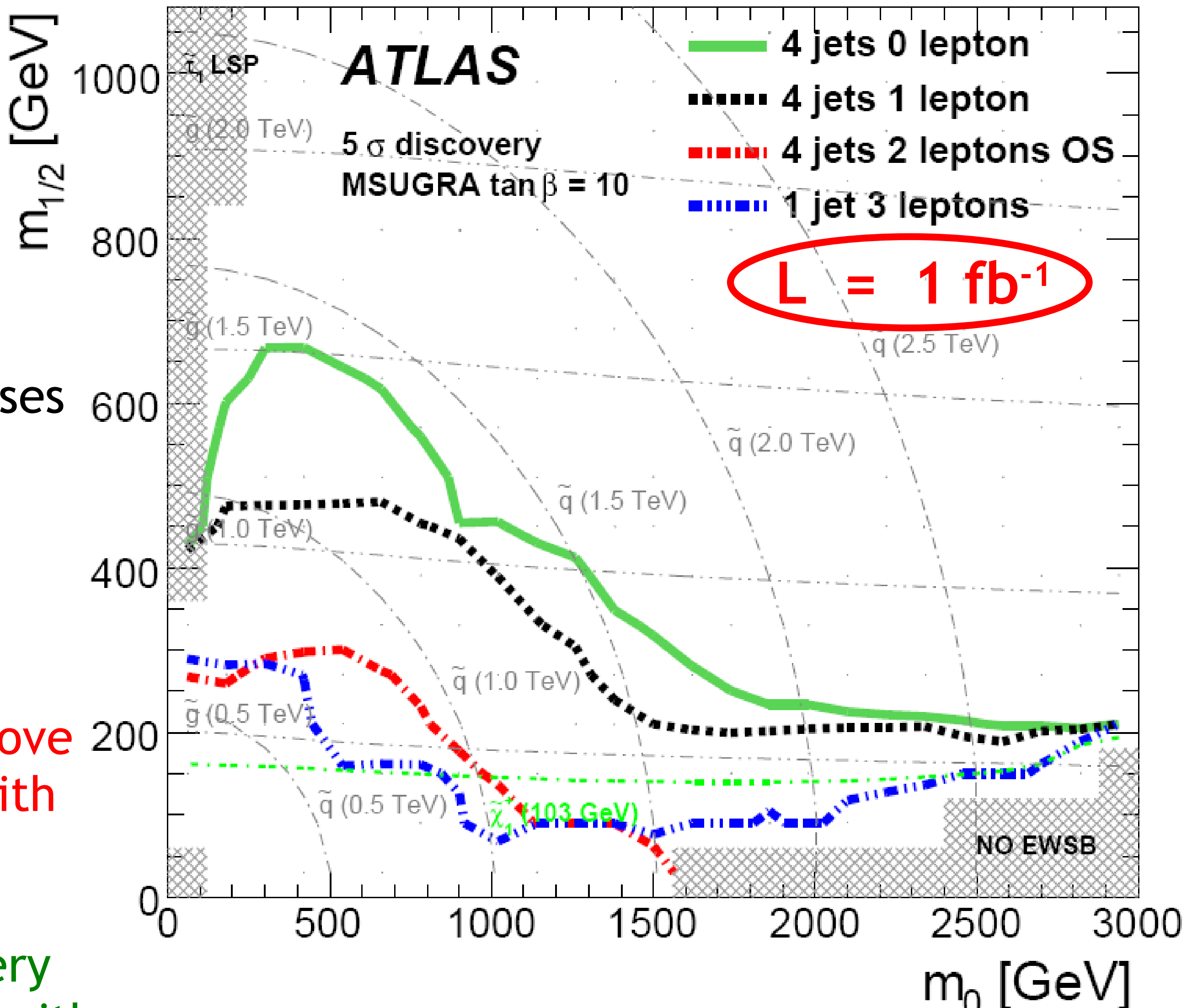
$0.1\ fb^{-1} \rightarrow M \sim 750$ GeV

$1\ fb^{-1} \rightarrow M \sim 1350$ GeV

$10\ fb^{-1} \rightarrow M \sim 1800$ GeV

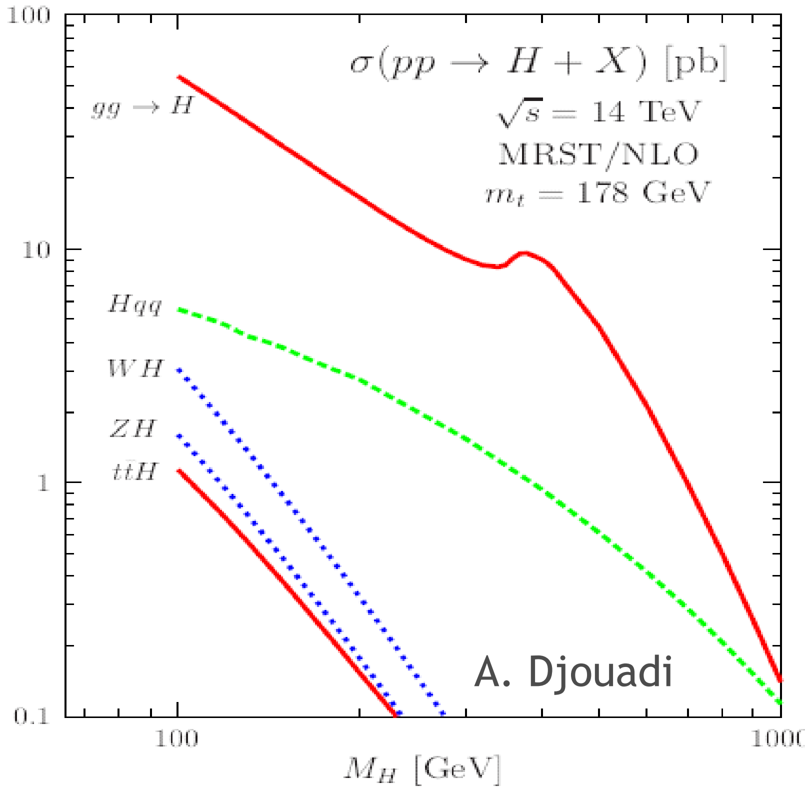
Sensitivity rather quickly at/above Tevatron limits via channels with leptons

Should be sensitive for discovery beyond current Tevatron limits with $100\ pb^{-1}$ at 10 TeV

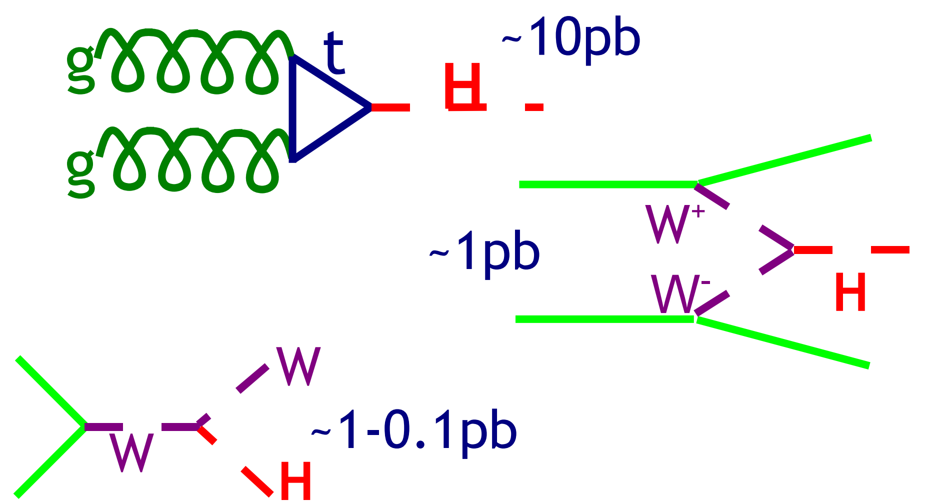


See next talk for more on SUSY prospects...

SM Higgs Search



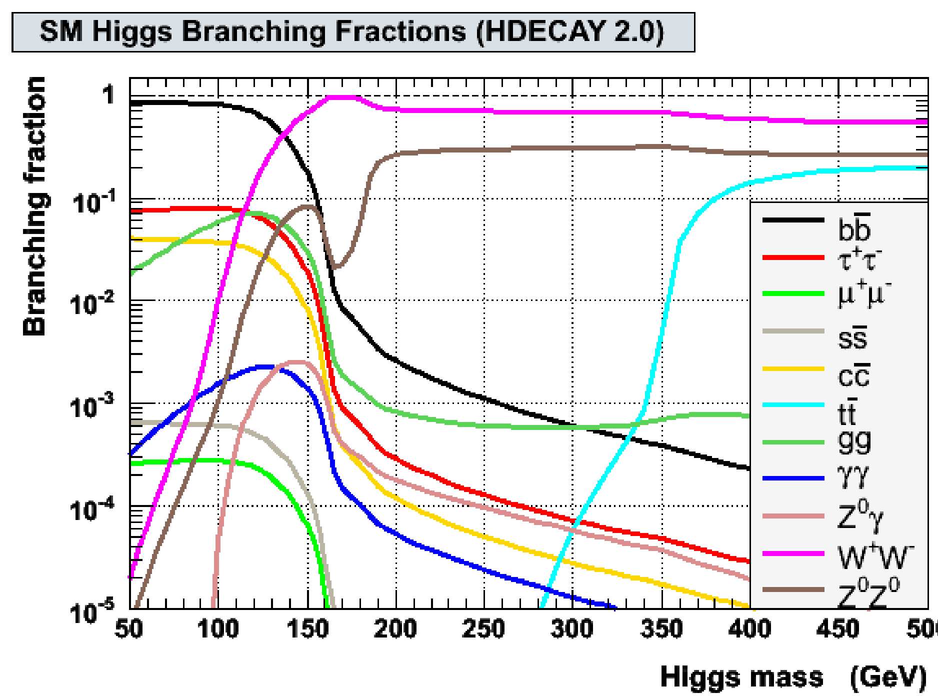
Production mechanisms (examples):



Decay – strongly dependent on m_H

- low m_H – bb dominates
  - $\tau\tau$, $\gamma\gamma$ also important
- high m_H – WW/ZZ dominate

Wide mix of search topologies



Note that ttH→ttbb dropped in combinations – too high uncertainties on backgrounds

SM Higgs with 200 pb^{-1} / 10 TeV?

At 10 TeV, m_H=160 GeV (ℓ=e/μ):

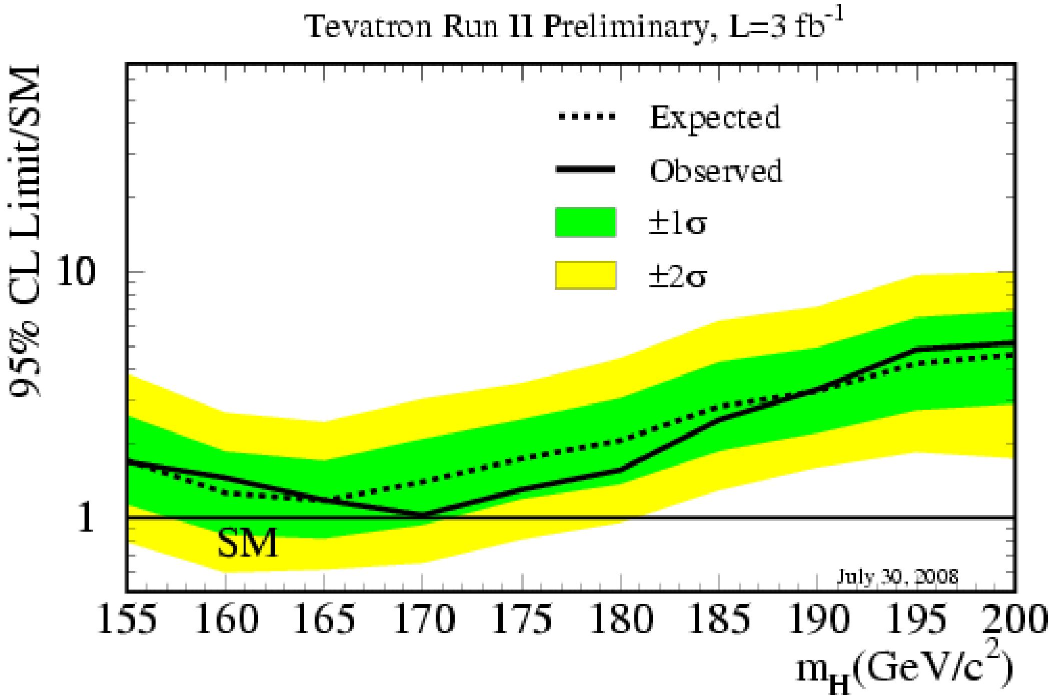
- σ(gg→H) ~ 10 pb
- σ.BR(gg→H→WW→ℓνℓν) ~ 0.5 pb
- σ.BR(gg→H→ZZ→4ℓ) ~ 0.04 pb

Small luminosities – WW channel dominates (stats)

Experimentally difficult – need to understand backgrounds from data (W+jets, tt, single-top)

Only 95% CL exclusion is accessible with such luminosities – similar sensitivity to the Tevatron in 2010?

Discovery sensitivity requires 1 fb^{-1} or more...



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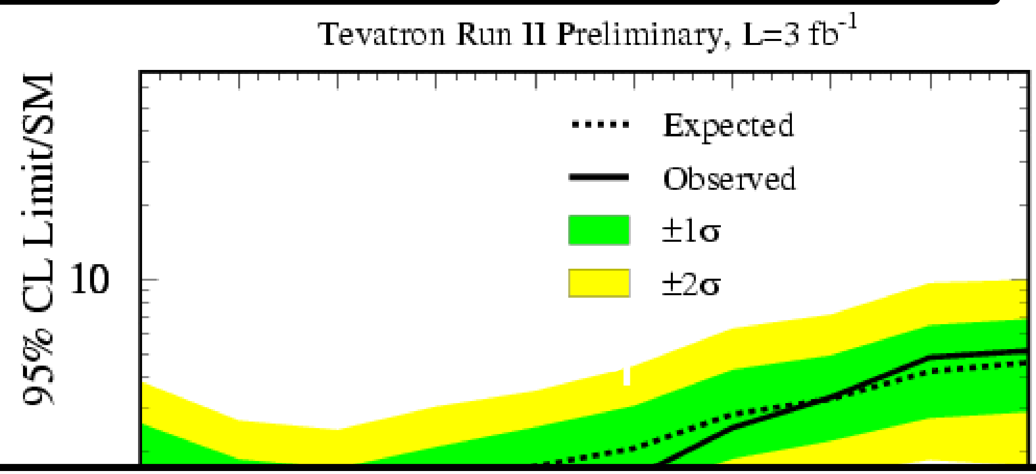
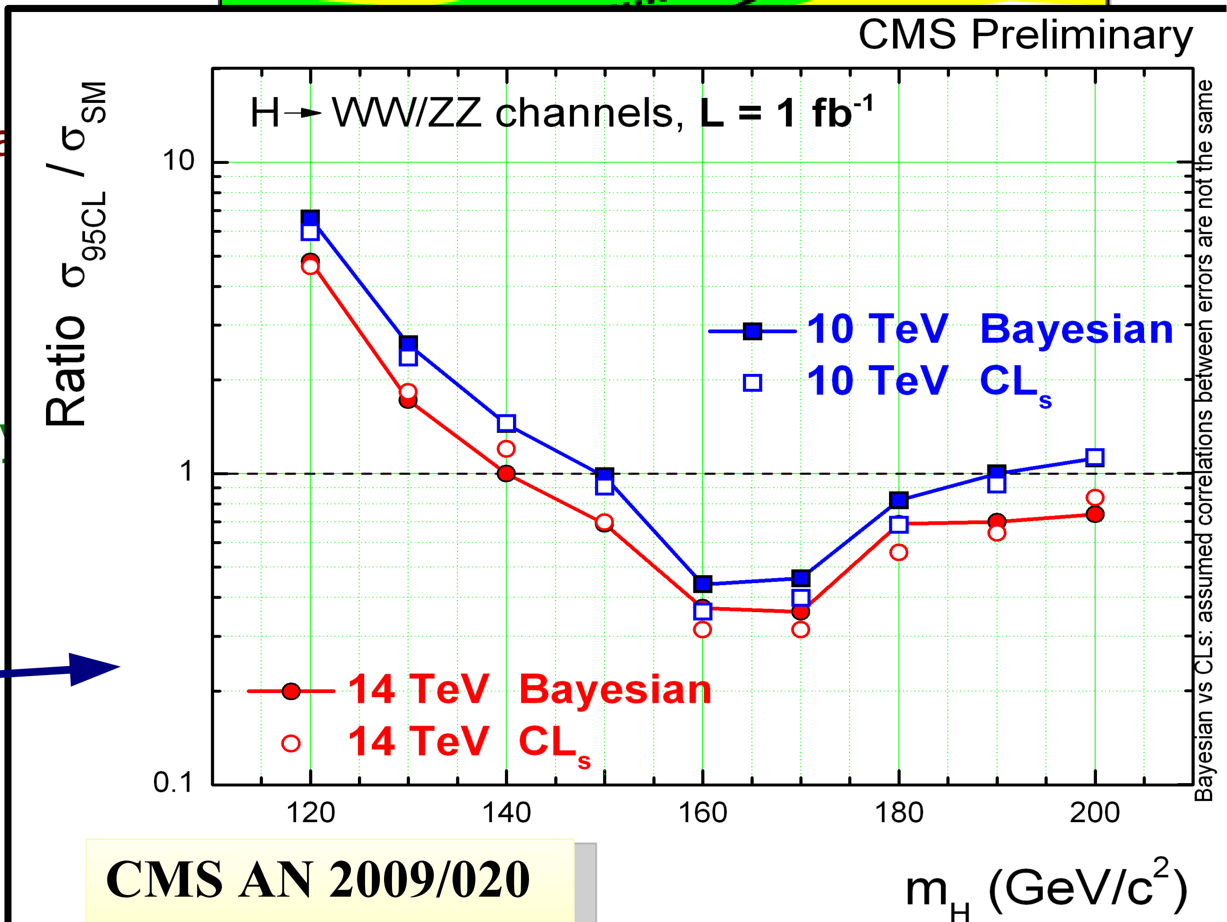
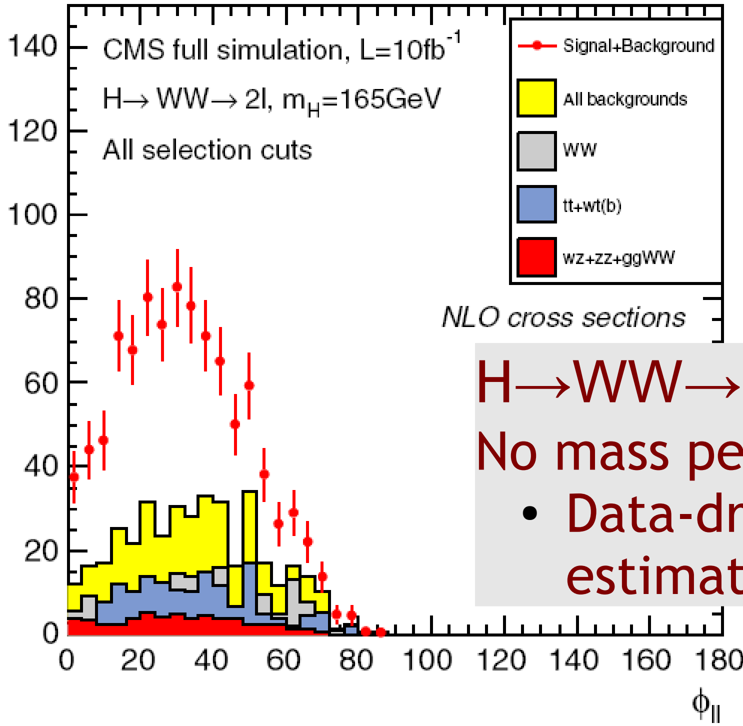




CMS AN 2009/020

Higgs Signals



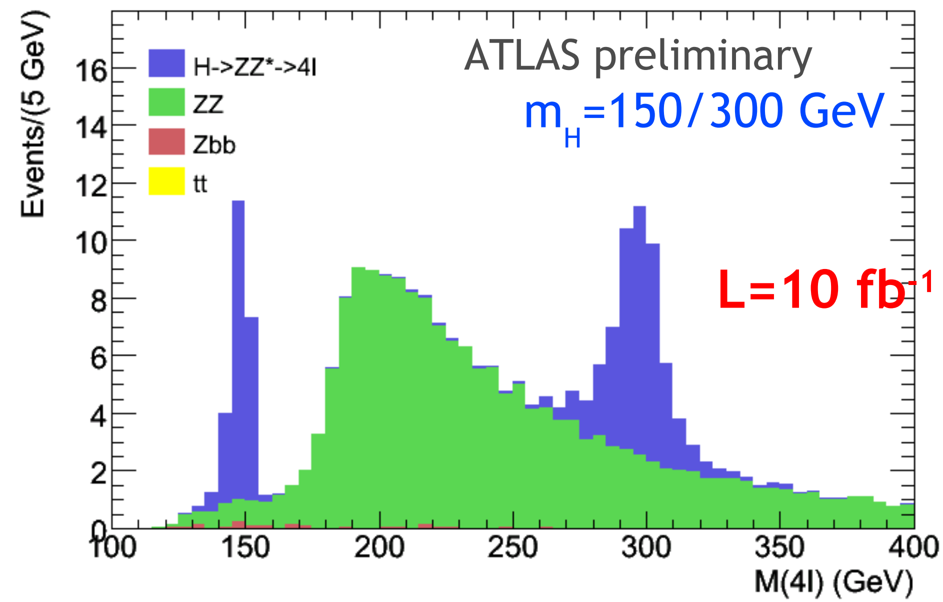
14 TeV

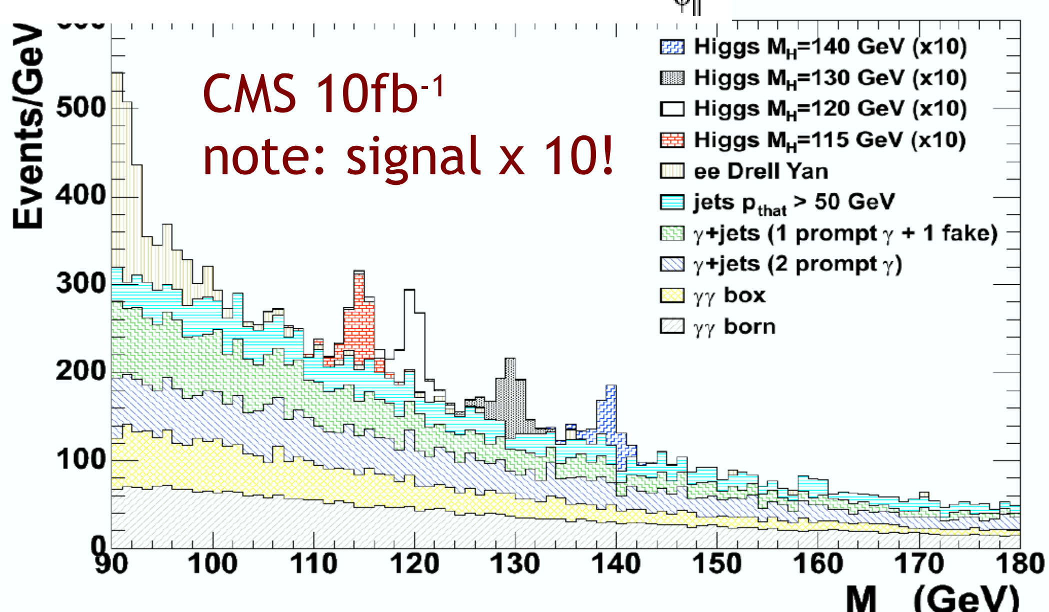
$H \to WW \to 2\ell 2\nu$

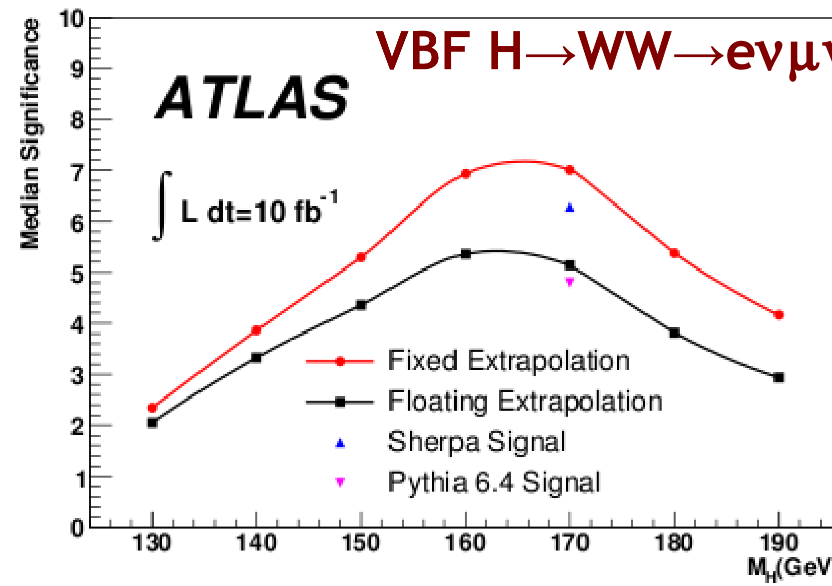
No mass peak

- Data-driven bkgd estimates

$H \to ZZ^{(*)} \to 4\ell$

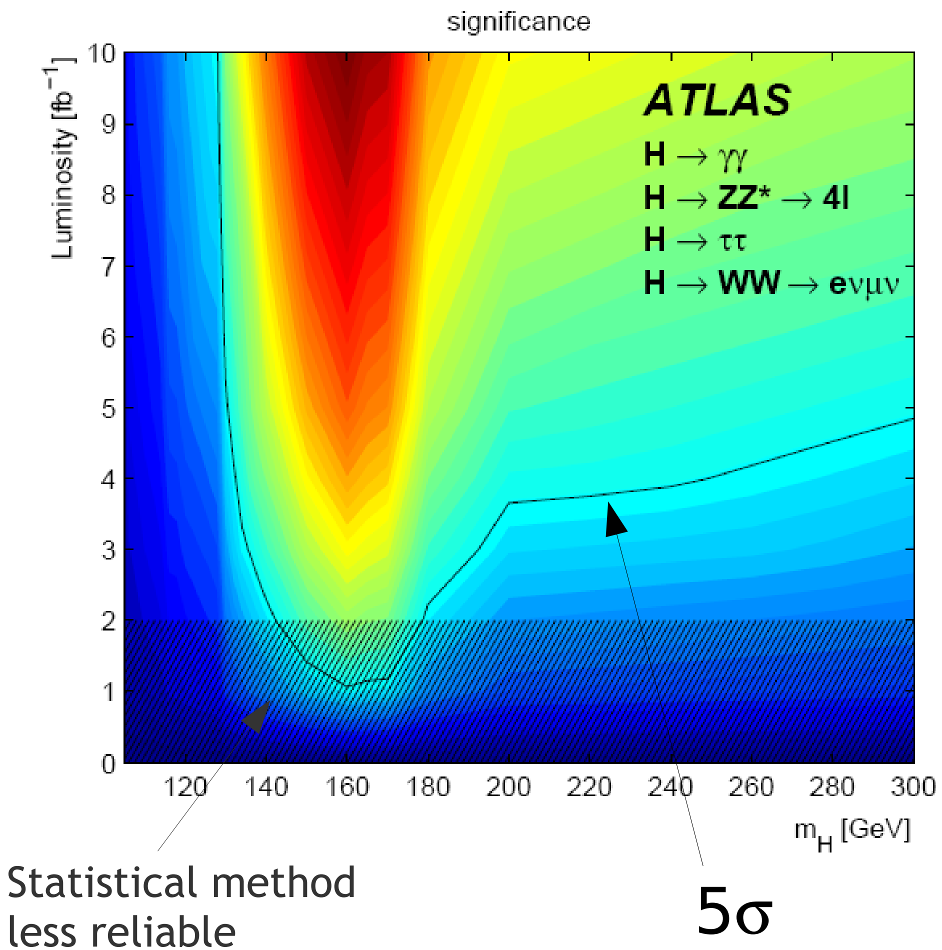


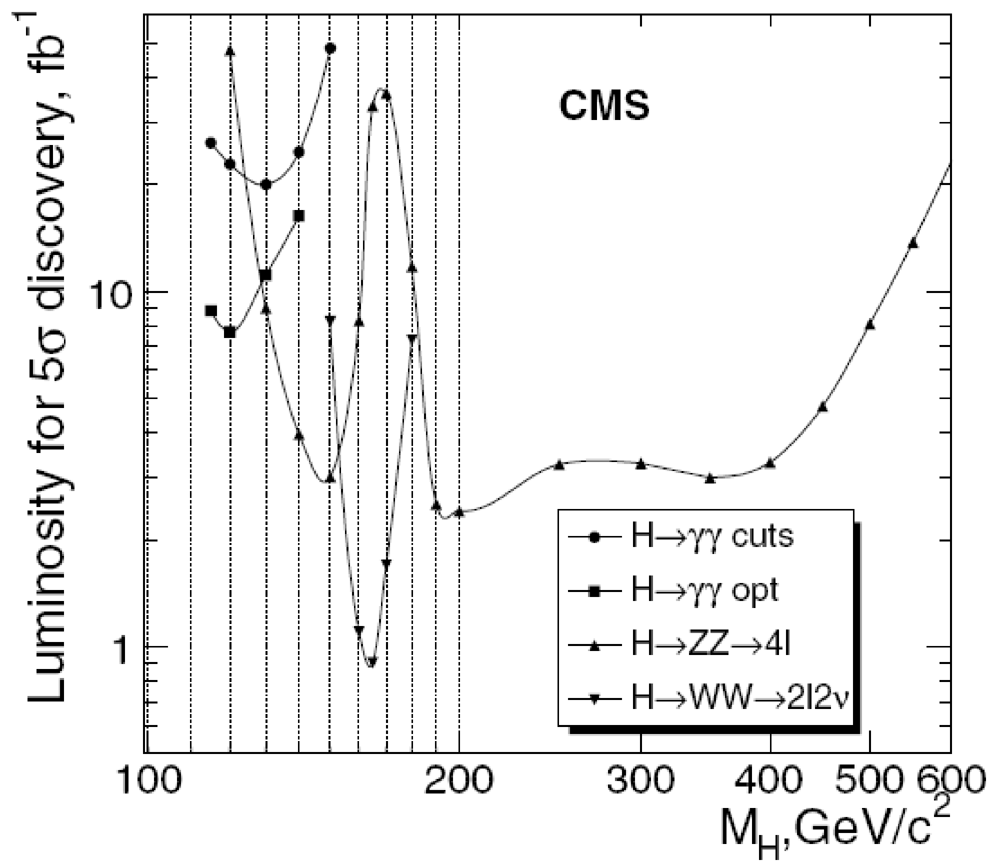




SM Higgs Prospects

Discovery



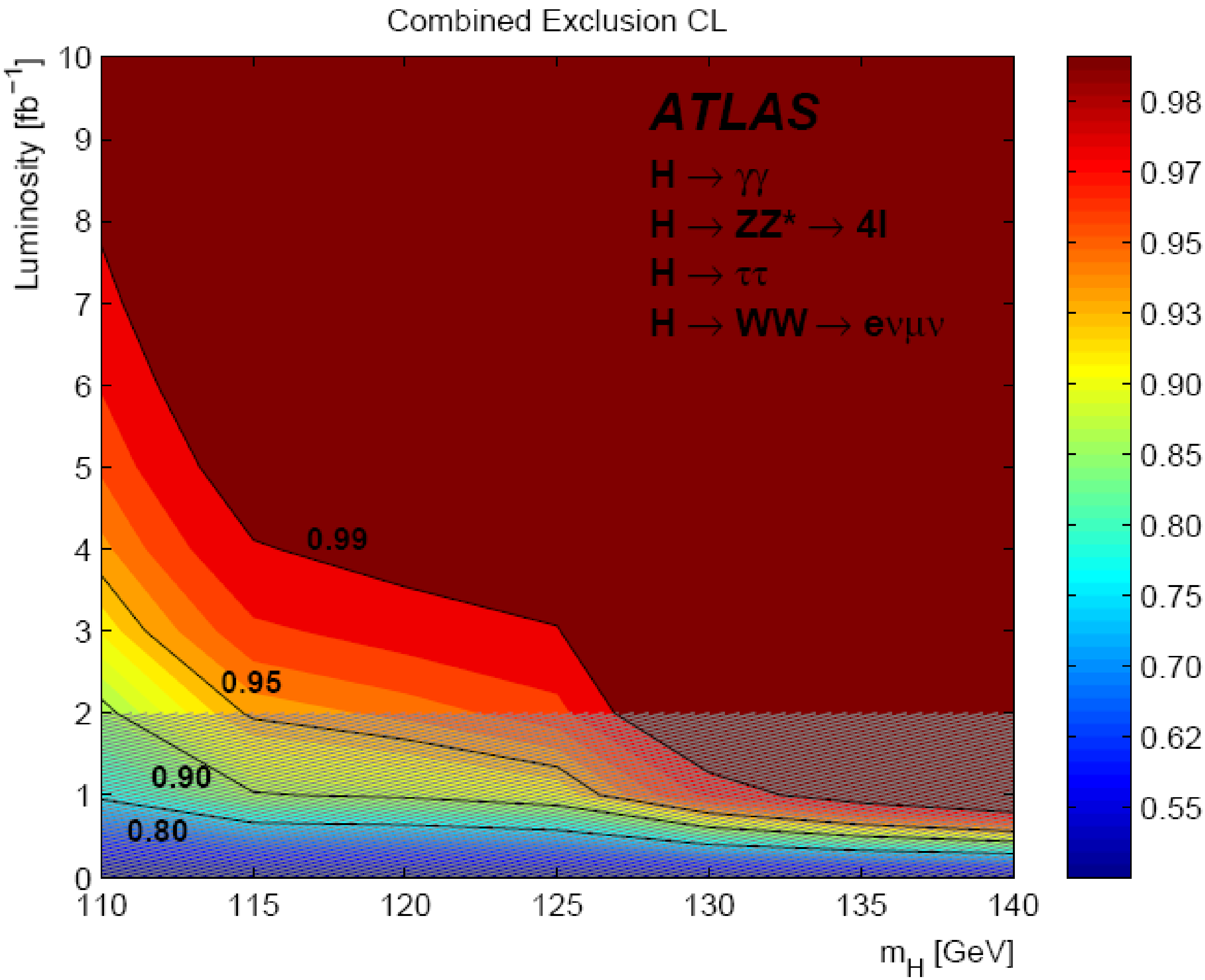


ATLAS: 5σ sensitivity at 2 fb^{-1} over 143-179 GeV

Not all channels included – for the most complex channels we need to measure backgrounds with data

SM Higgs: Low Mass Region

Exclusion: not what we want, but relevant at start...

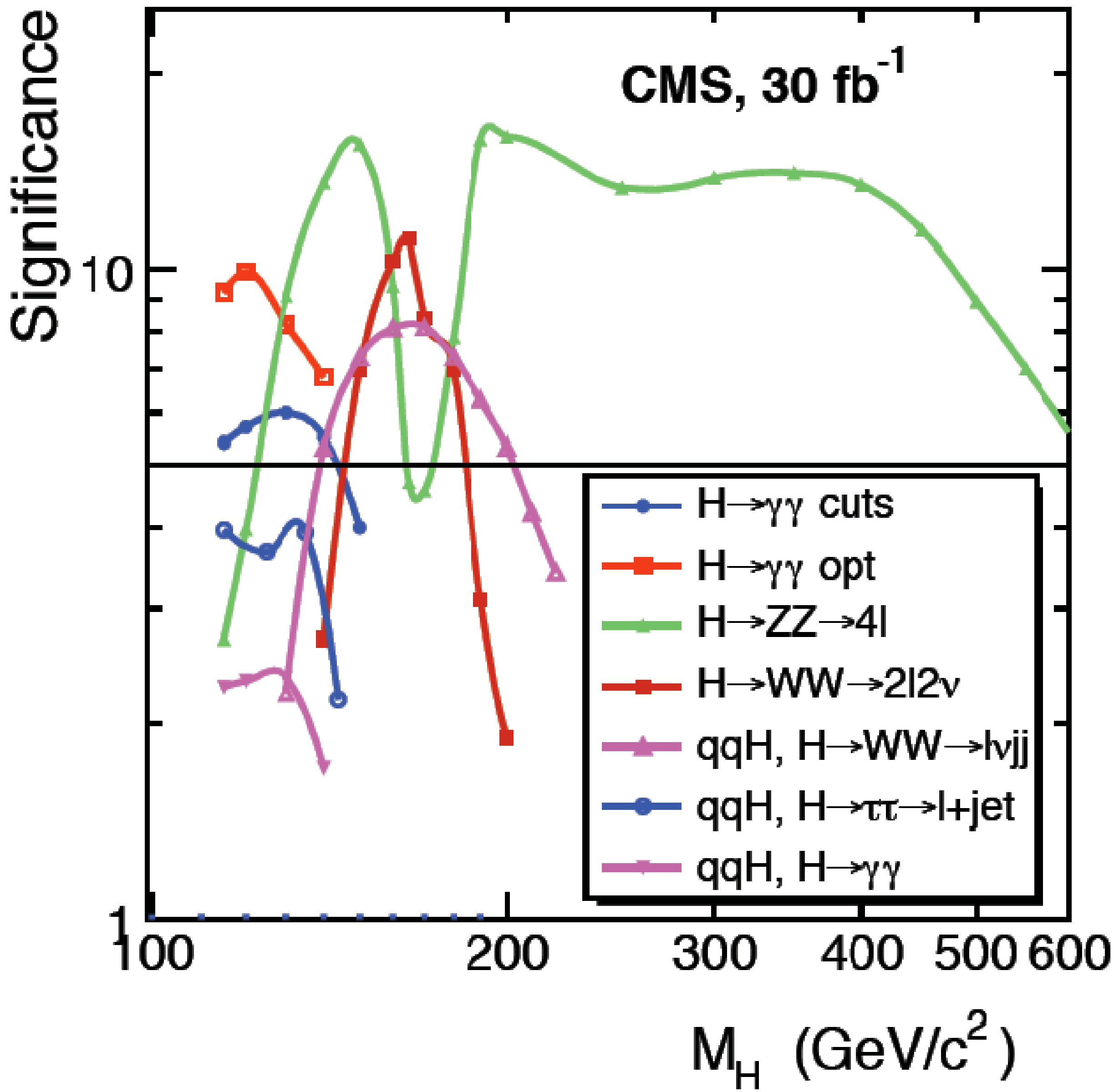


ATLAS: 95% CL sensitivity from 115 GeV with 2 fb^{-1}

Low mass region remains difficult

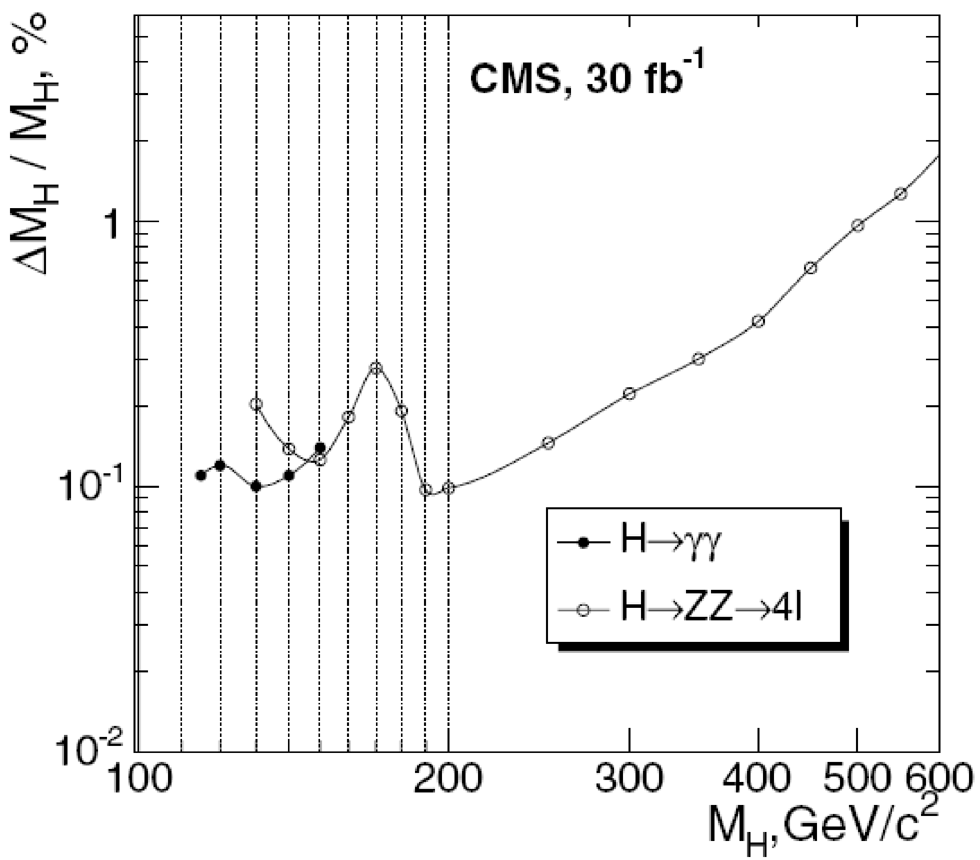
SM Higgs with 30 fb^{-1}

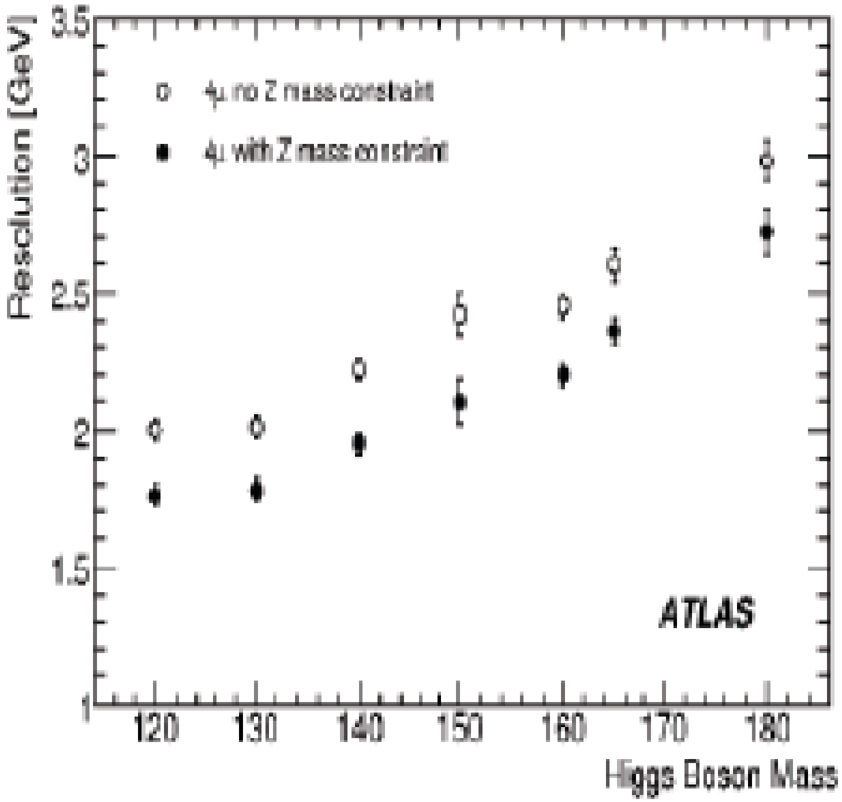
2006



SM Higgs Mass Precision

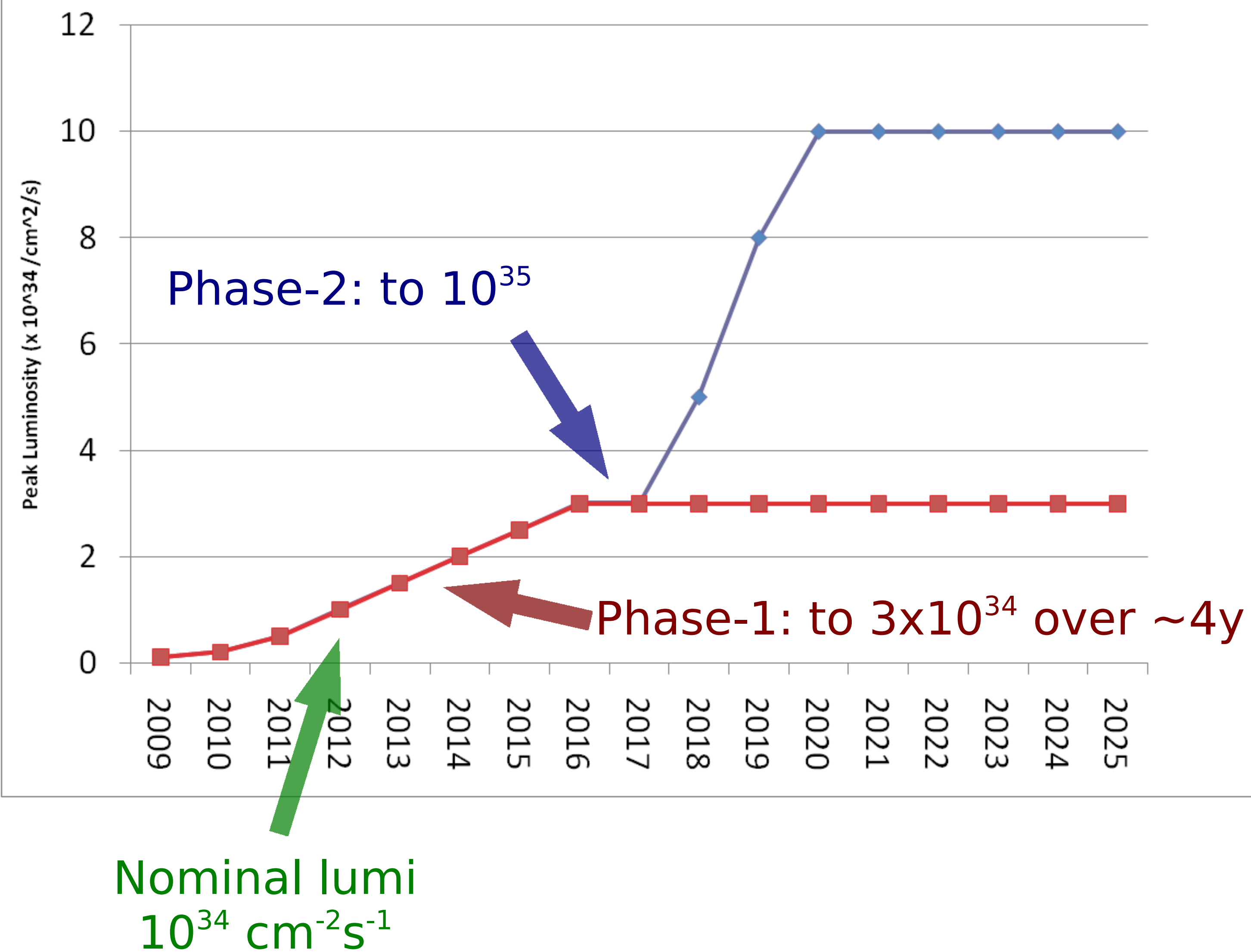
$H \to \gamma\gamma$ and $H \to ZZ^{(*)} \to 4\ell$ dominate





Statistical precision <1% over a large mass range for 30 fb^{-1} - systematics should not dominate until integrated luminosities larger, ~100 fb^{-1}

LHC Upgrades



Phase-1:

Machine:

- Injector upgrades
- New inner triplets (focussing magnets at experiments)

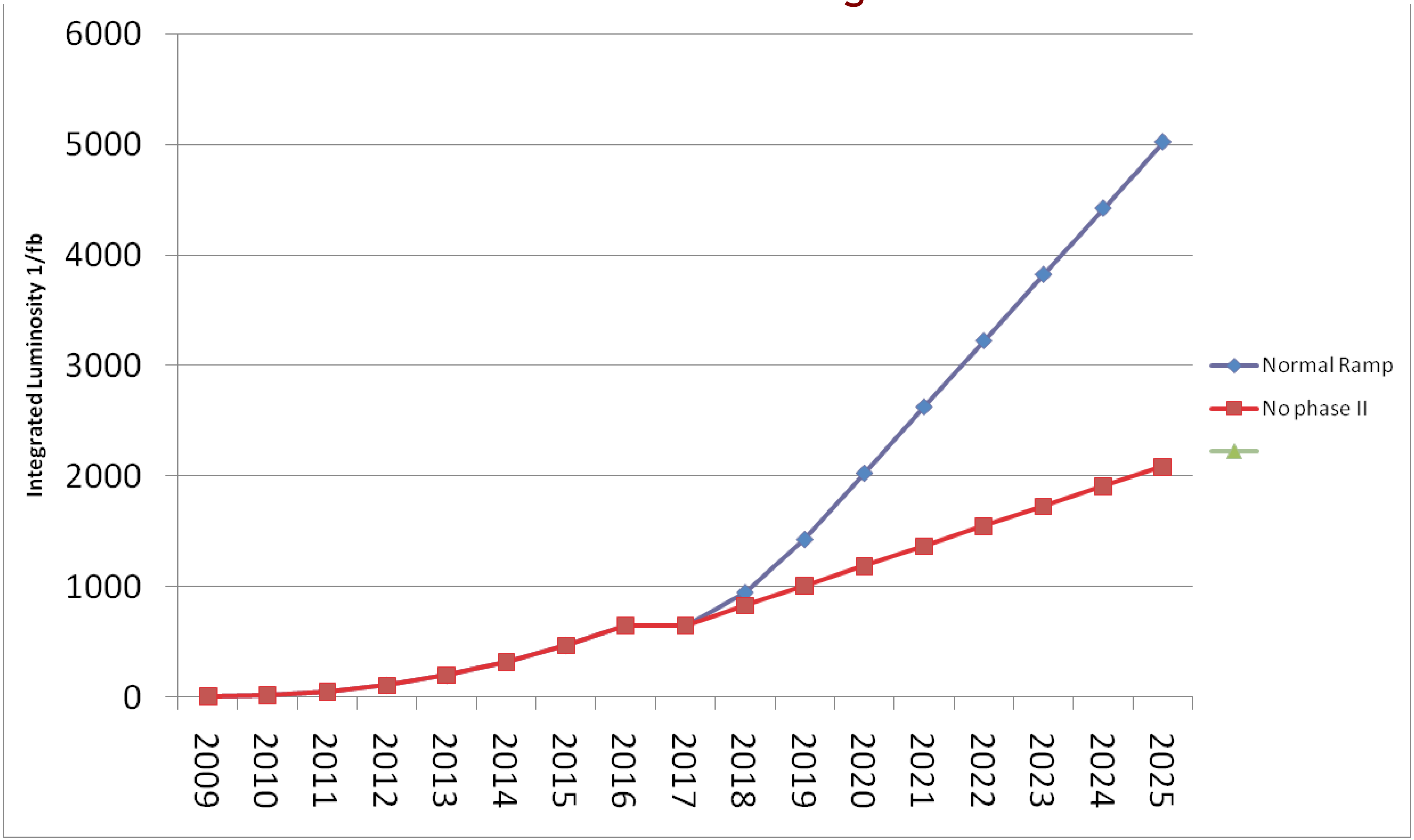
Experiments:

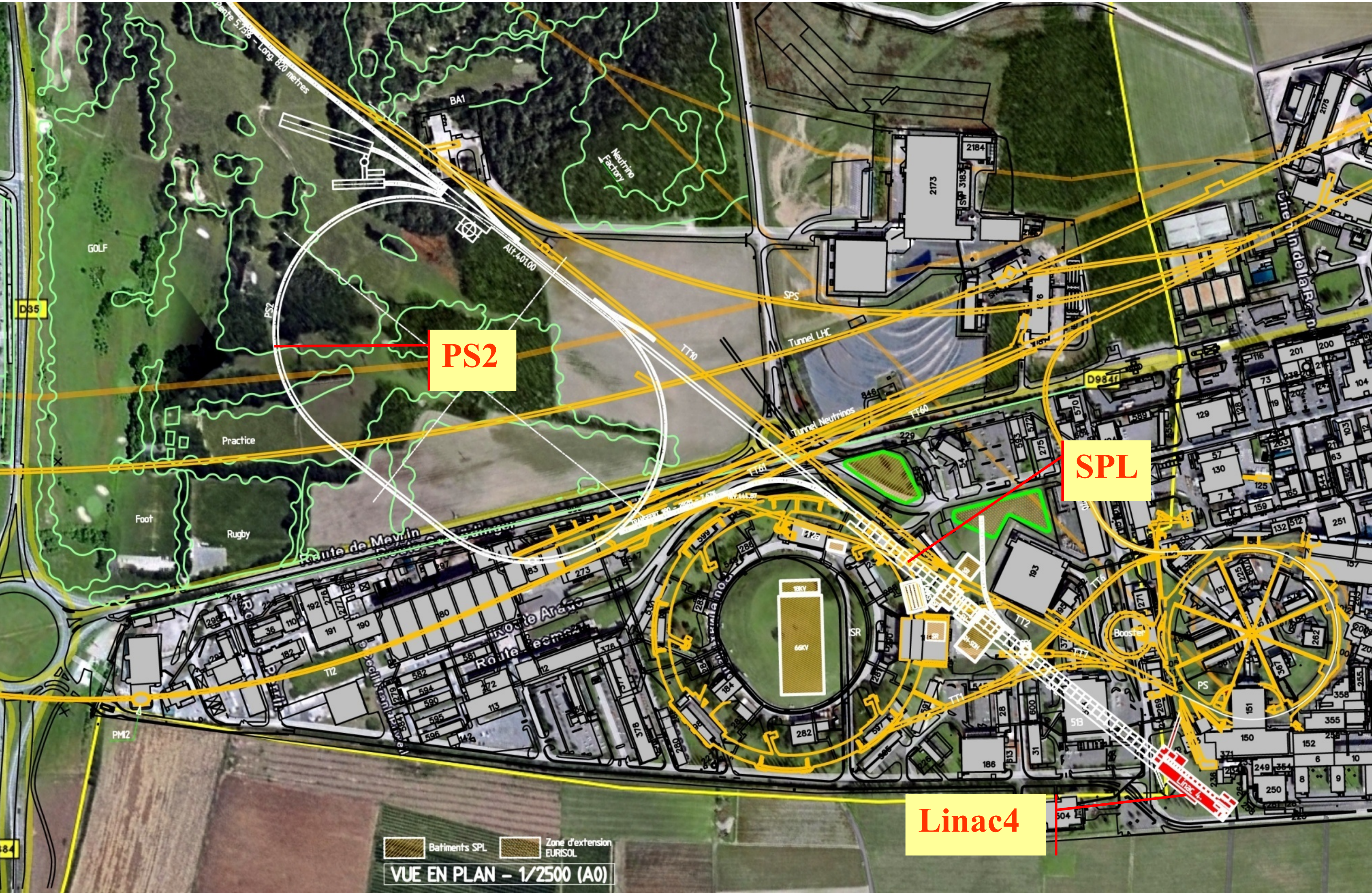
- Pixel det. upgrades
- Modest trigger & readout upgrades

Timescale is optimistic – not adjusted for LHC incident delay

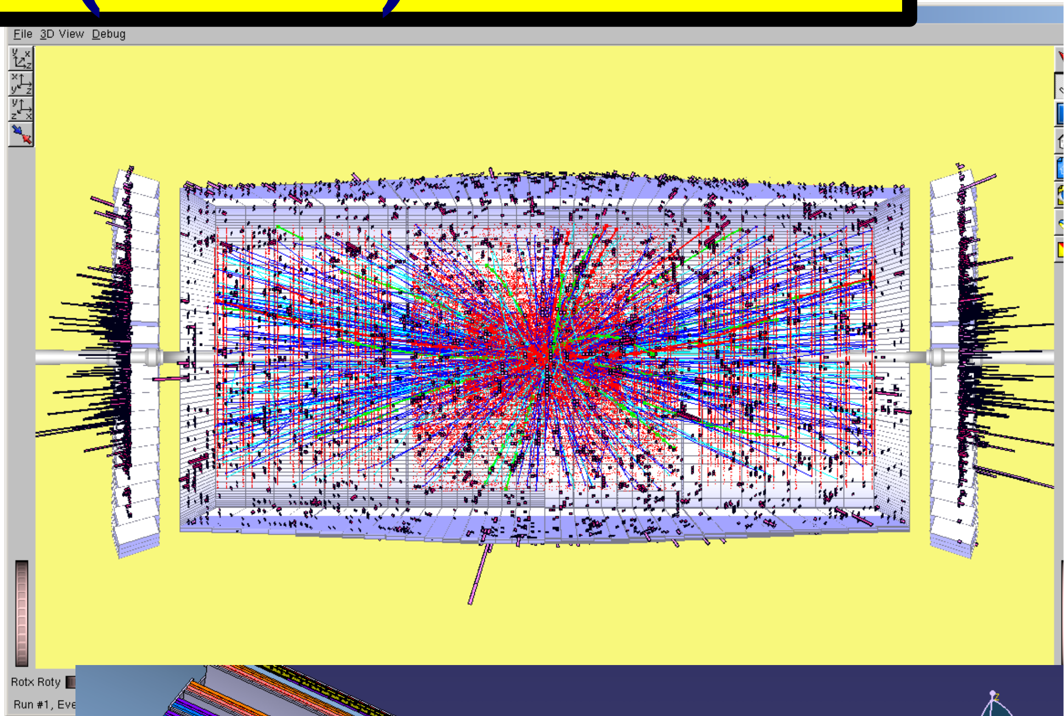
LHC Upgrades

Integrated luminosity profile
Being re-assessed after LHC incident




PS2
SPL
Linac4
Batiments SPL
Zone d'extension EURISOL
VUE EN PLAN – 1/2500 (A0)
GOLF
Practice
Foot
Rugby
Route de Meyrin
Tunnel LHC
Tunnel Neutrinos
Neutrino Factory
SPS
Booster
PS
ISR
D35
D984f

Phase-2 (sLHC)



"Super-LHC" ~ 2017?

Luminosity ~ 10^{35} cm^{-2} s^{-1}

10 x pre-phase 1

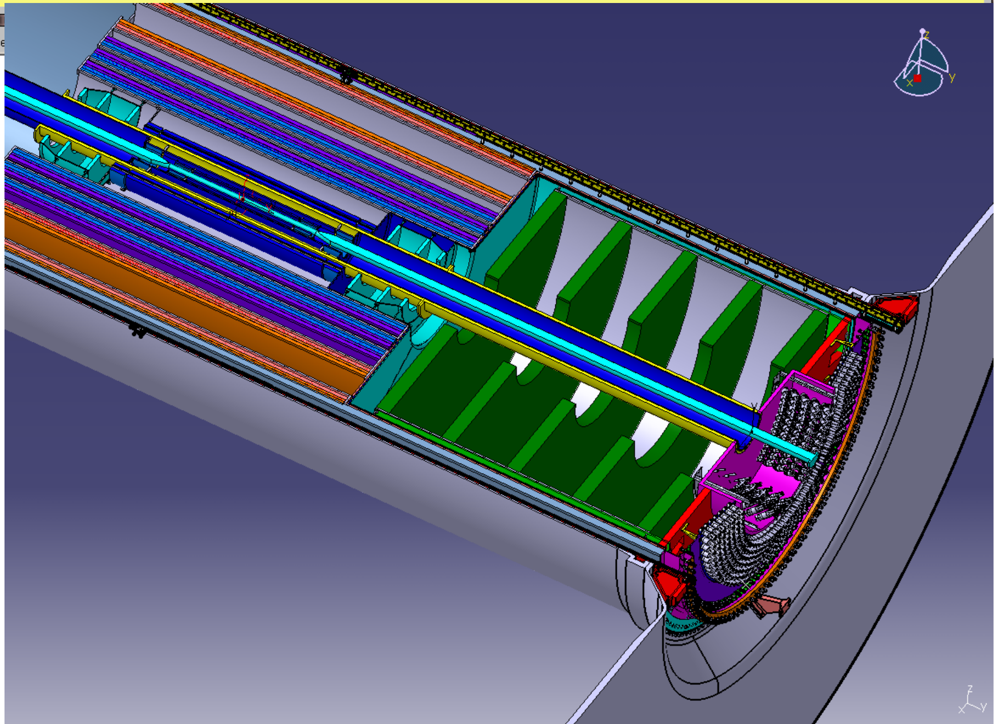
300-400 evts / beam crossing

Machine:

- Various scenarios, mainly increasing current in each bunch

Experiments:

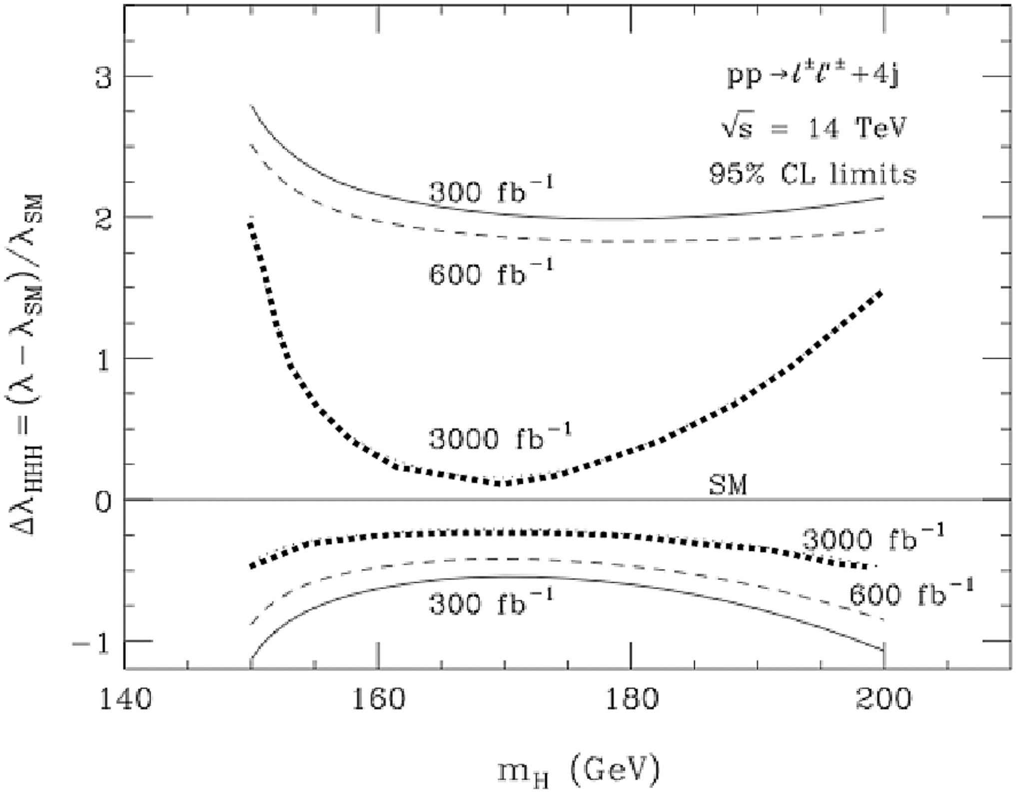
- Tracker replacement – need > 1 year shutdown
- Many readout electronics and trigger changes

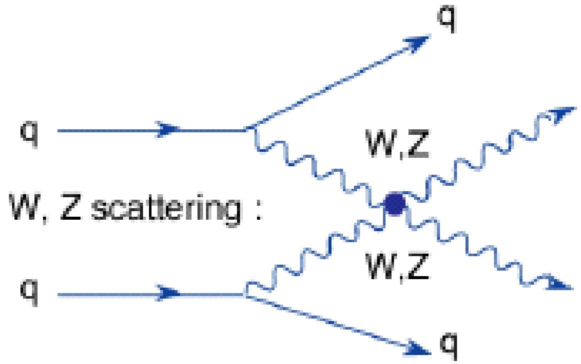


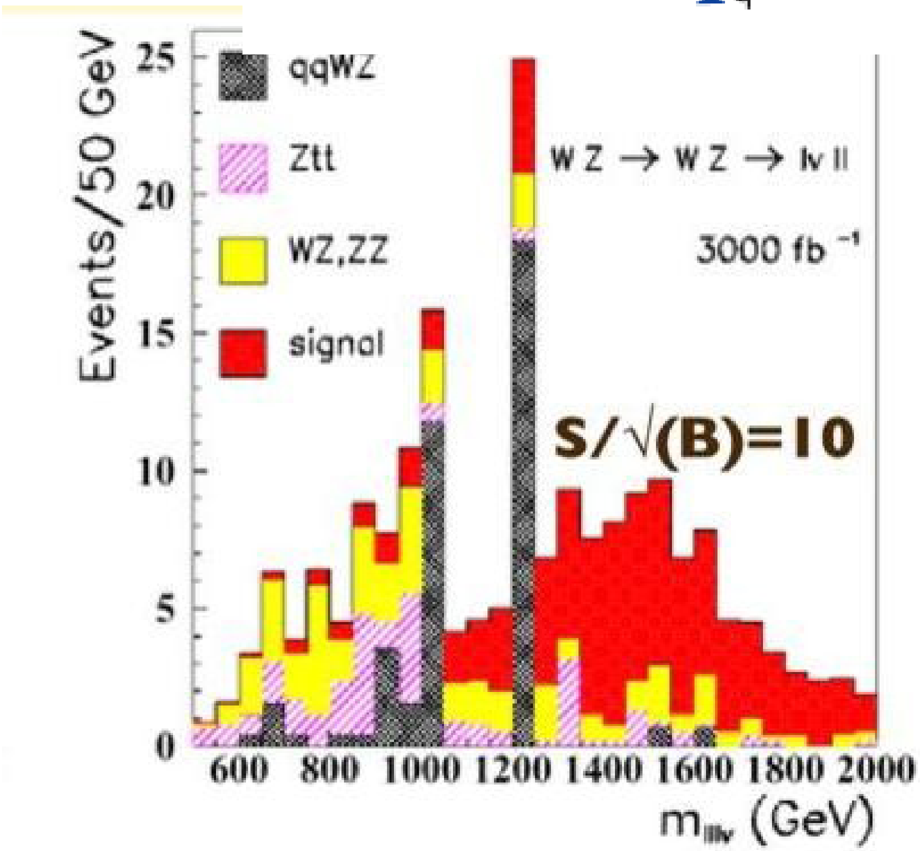
SLHC Physics

Depends what we find at "LHC-I"
A couple of examples...

Higgs self-coupling...







Summary

Long programme over many years to explore the full physics potential of the LHC

Start to have better estimates of the energy and luminosity profile – but this is still an almost completely unknown machine

The experiments are ready, and have had months of cosmics to understand and tune

The start-up will be cautious, and the performance in 2009/10 will have to be seen

This is the start of the >20-year operation of this new machine

Discovery sensitivity will start in 2010, and keep extending