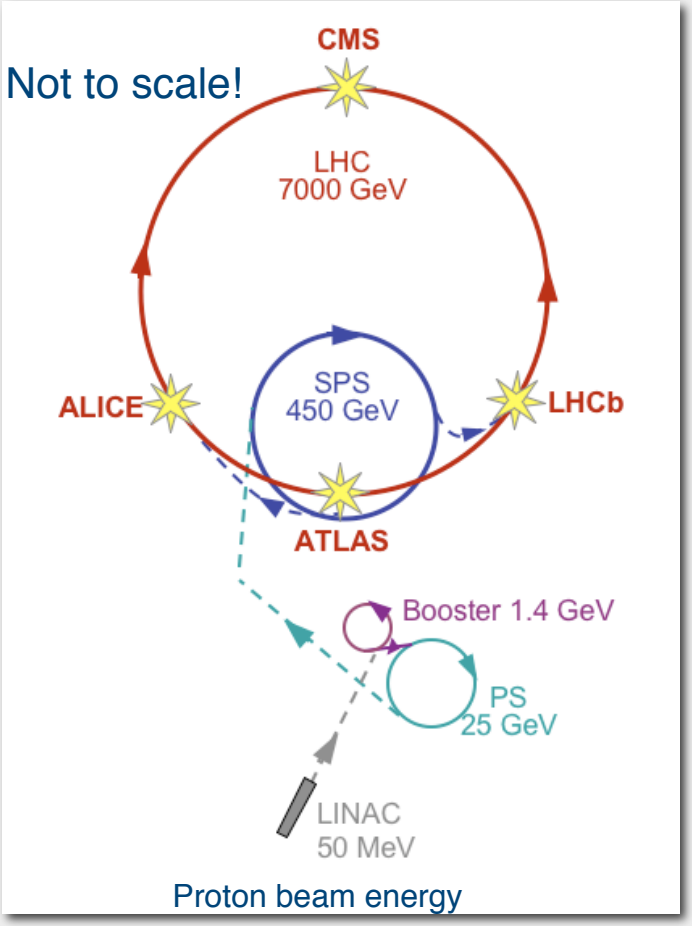
The LHC Machine and Experiments: Status and Prospects

CHEP

Prague, March 23, 2009

Sergio Bertolucci
CERN

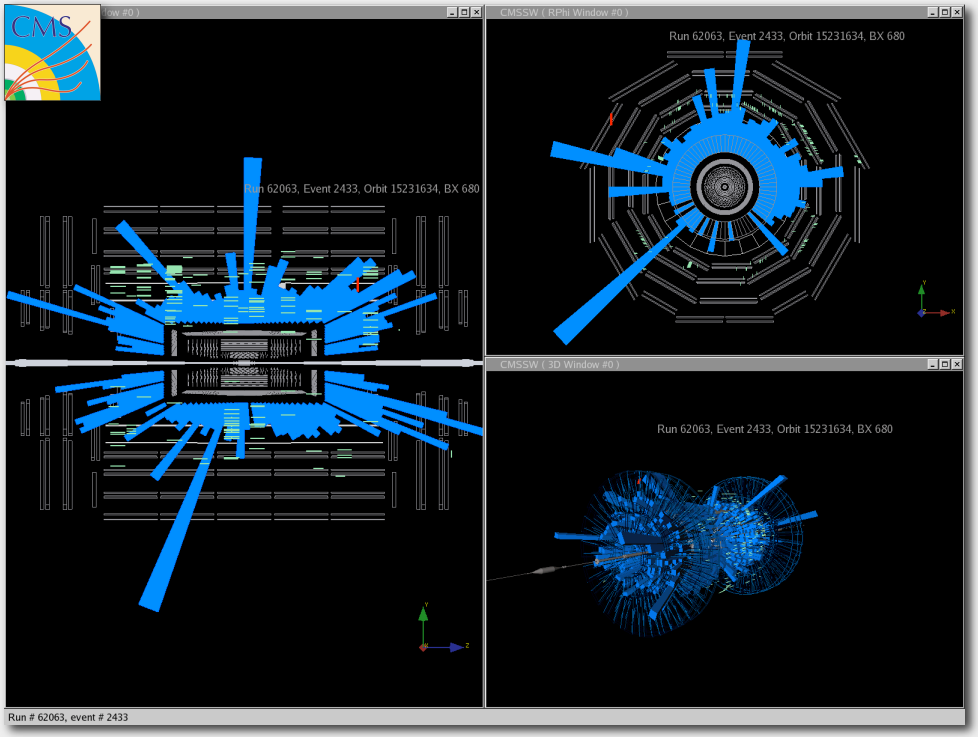
First protons circulating in the LHC ring

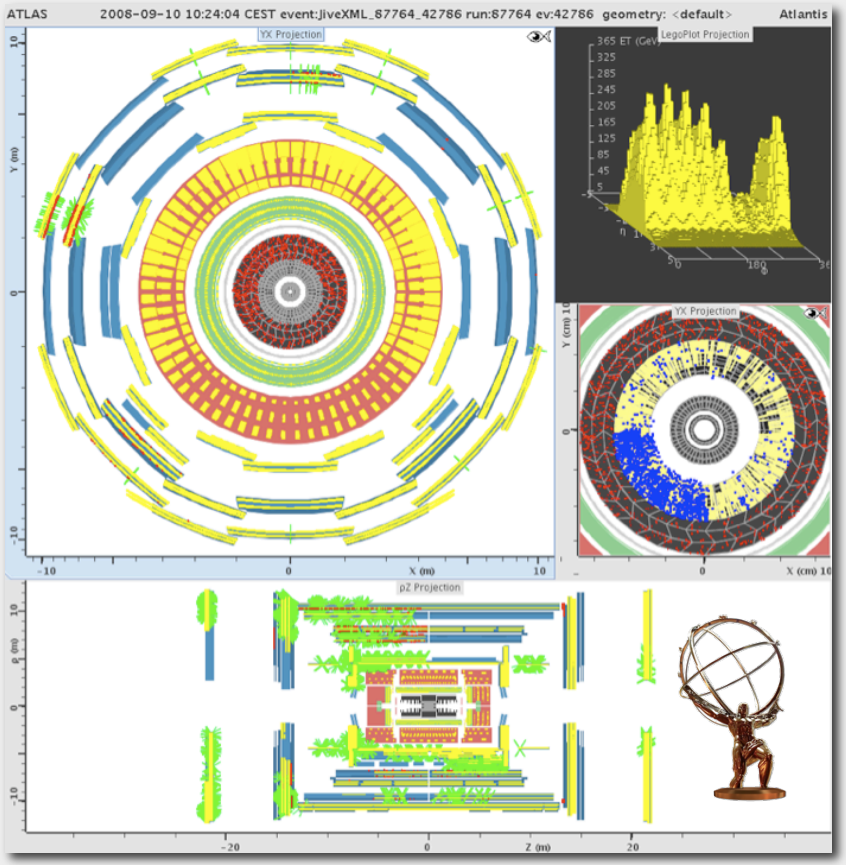


September 10, 2008

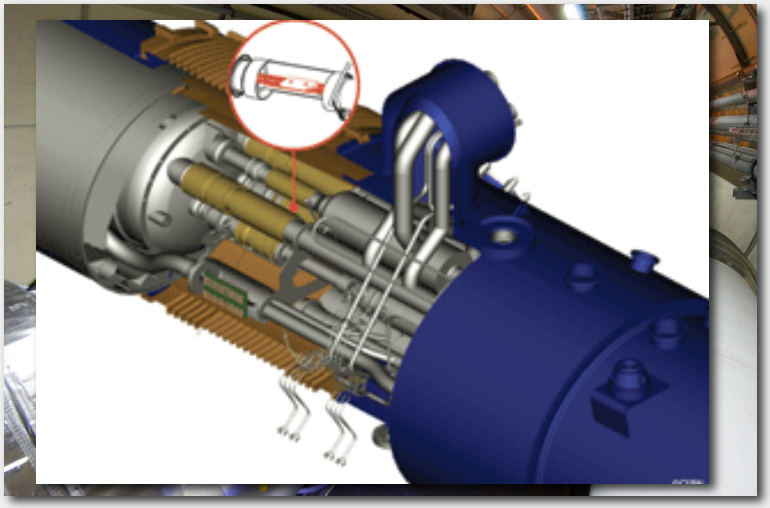
First protons circulating in the LHC ring

The beam was initially intentionally stopped by blocks around 150 metres before experiments,
producing these images of the debris or "splash" from the particles hitting the blocks.



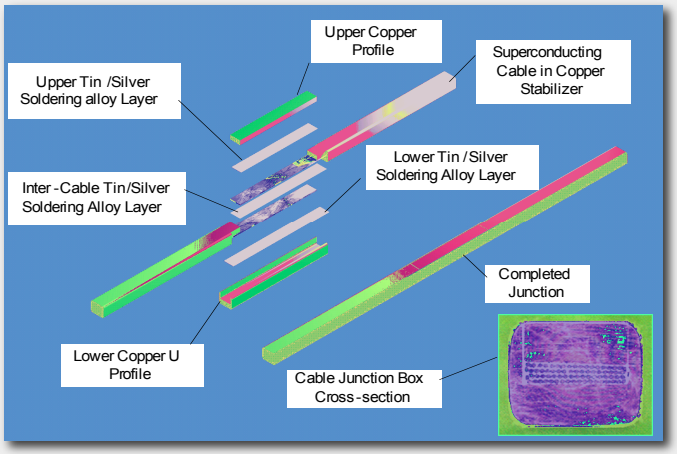


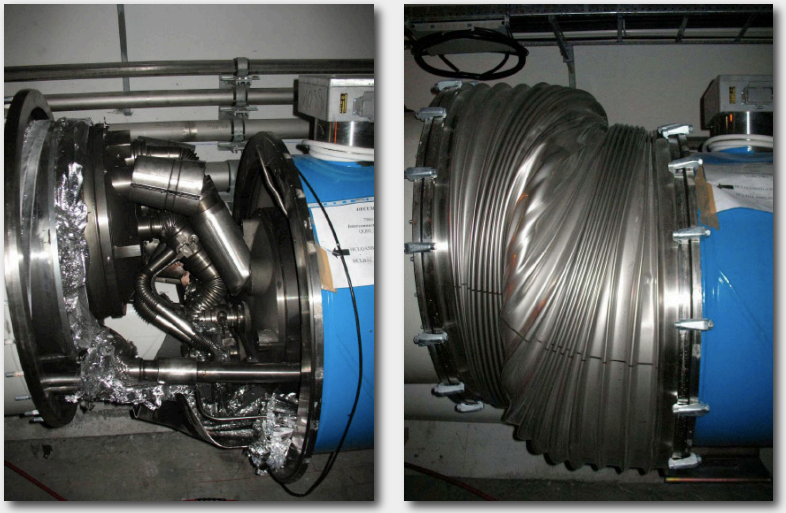
September 19, 2008: incident in sector 3-4



The incident was traced to a faulty electrical connection between segments of the LHC's superconducting cable (busbars)

High impact was caused by collateral damage





2 most severely damaged interconnects

53 Magnets (along a zone of about 700 m) to be removed from tunnel and repaired/ exchanged (a few % of entire LHC)

Input

- Chamonix Workshop
  - Planning done for Chamonix
- After Chamonix
  - Follow-up LHC Machine Committee
  - Much extra work (later)

S. Myers

- External Panel on Risk
  - Many of the panel members could participate in Chamonix

D. Hartill

- External Panel on Quench Protection
  - Few of the panel members could participate in Chamonix

J. Theilacker

– Safety group + task force on "incident": reports will soon be available

Will try to avoid duplicating the same recommendations

Statement on LHC Safety (1)

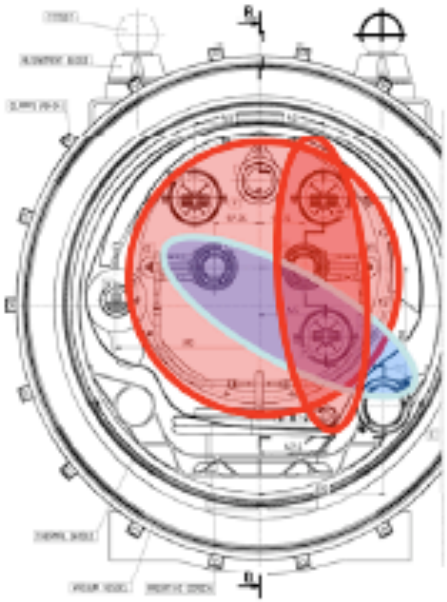
- Following the incident on 19 September the most crucial improvement foreseen was a more precise system to monitor (and protect) anomalously high resistance in a joint (splice) near the magnets.
- The development of this new enhanced ohmic resistance measurement is well under way and the new system will be installed and tested before beam operation. This will allow effective protection against thermal runaway in the magnet and interconnect splices. There is still no way to protect against an "instantaneous" rupture of a bus bar splice.
- It has been shown by simulations that the new system with a threshold trigger of 0.3mV (compared with the 1V of the system in place on 19 September) will protect the joints form thermal runaway "in all imaginable conditions". Note if this system had been in operation the September incident would not have taken place.
- In the Risk analysis, we have mitigated against the re-occurrence of a thermal runaway of a splice. The risk-score is the product of the probability of the event and the level of the resulting impact.

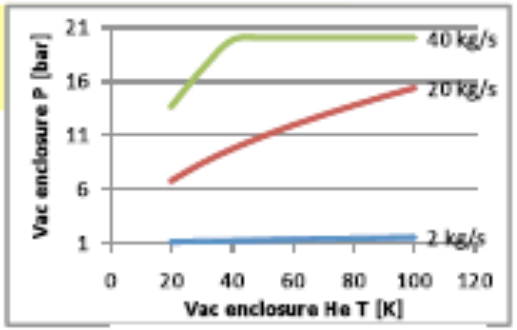
Statement on LHC Safety (2)

- For the September 19 incident, the high impact was caused by collateral damage by:
  1. High pressure build up damaged the magnet interconnects and the super-insulation
  2. Perforation of the beam tubes resulted in pollution of the vacuum system with soot from the vaporization and with debris from the super insulation.
- Until now and even after discussions in Chamonix there have not emerged any new ideas which would significantly reduce the pollution of the vacuum system in the event of a similar incident.
- However, measures will be taken to vent the Helium more rapidly and therefore reduce the pressure increase and consequently minimize (eliminate?) the damage done to interconnects and super-insulation.
- The already existing flanges in the Short straight sections (SSS) will be fitted with additional relief valves. Calculations have shown that this gives a factor of more than 9 with respect to the system existing on 19 September. These calculations show that the collateral damage (to the interconnects and super-insulation) which would be produced in a repeat incident of 19 September would be minor (significantly reduced). Such a repeat incident would not have a major impact on the spares situation for magnets . Whereas the collateral damage due to vacuum pollution would remain very similar to the September 19 incident.

MCI

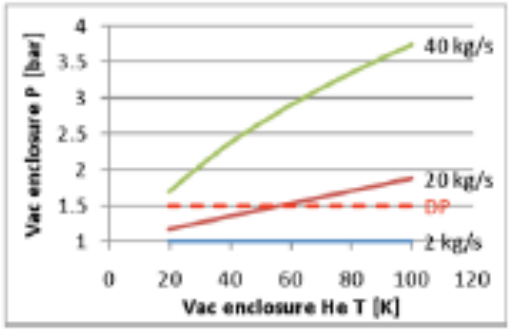
- It was decided to examine the all-out worst case risk impact. This "Maximum Conceivable Incident" (MCI) was identified as rupture of all enclosures connected to the magnets. The probability that this MCI would occur in the lifetime of the LHC has not been evaluated, but most specialist believe the probability to be approaching zero.
- To mitigate against the collateral damage to the interconnects and the super-insulation under the MCI conditions, one would need to install (200mm diameter) additional relief valves on all dipole magnets.



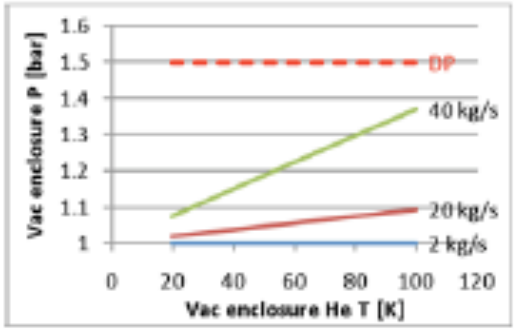


September 19

Add SSS valves



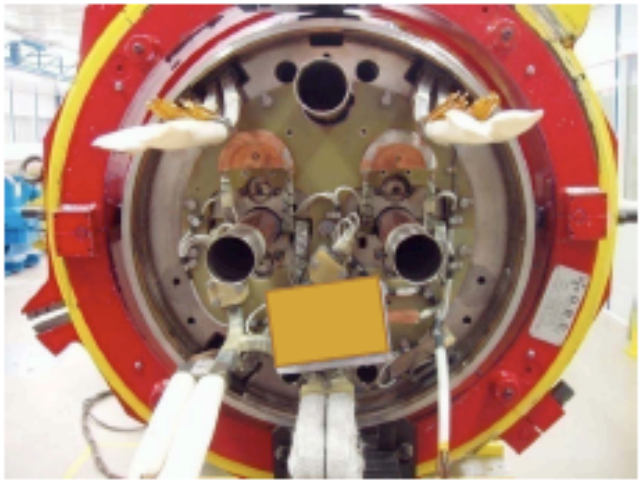
Add SSS valves +DN200

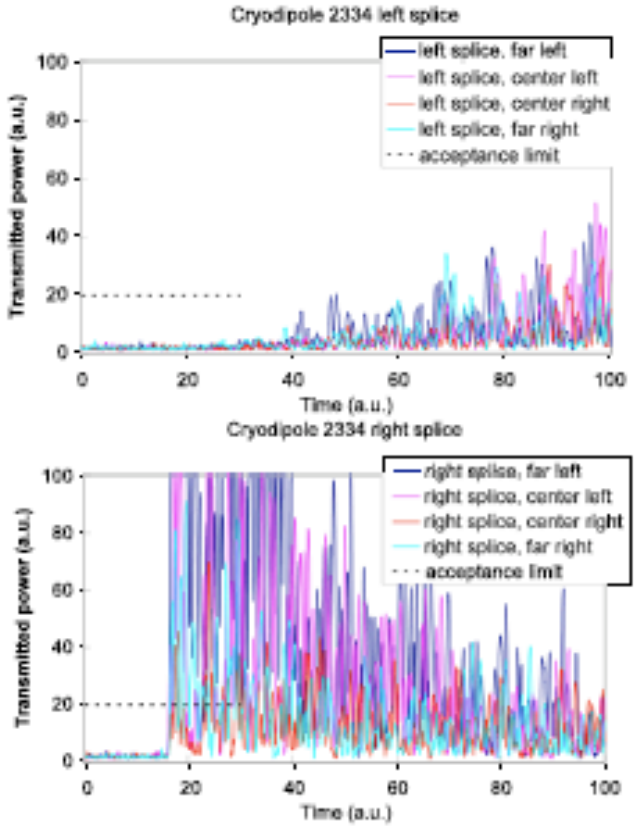


Don't forget the vacuum

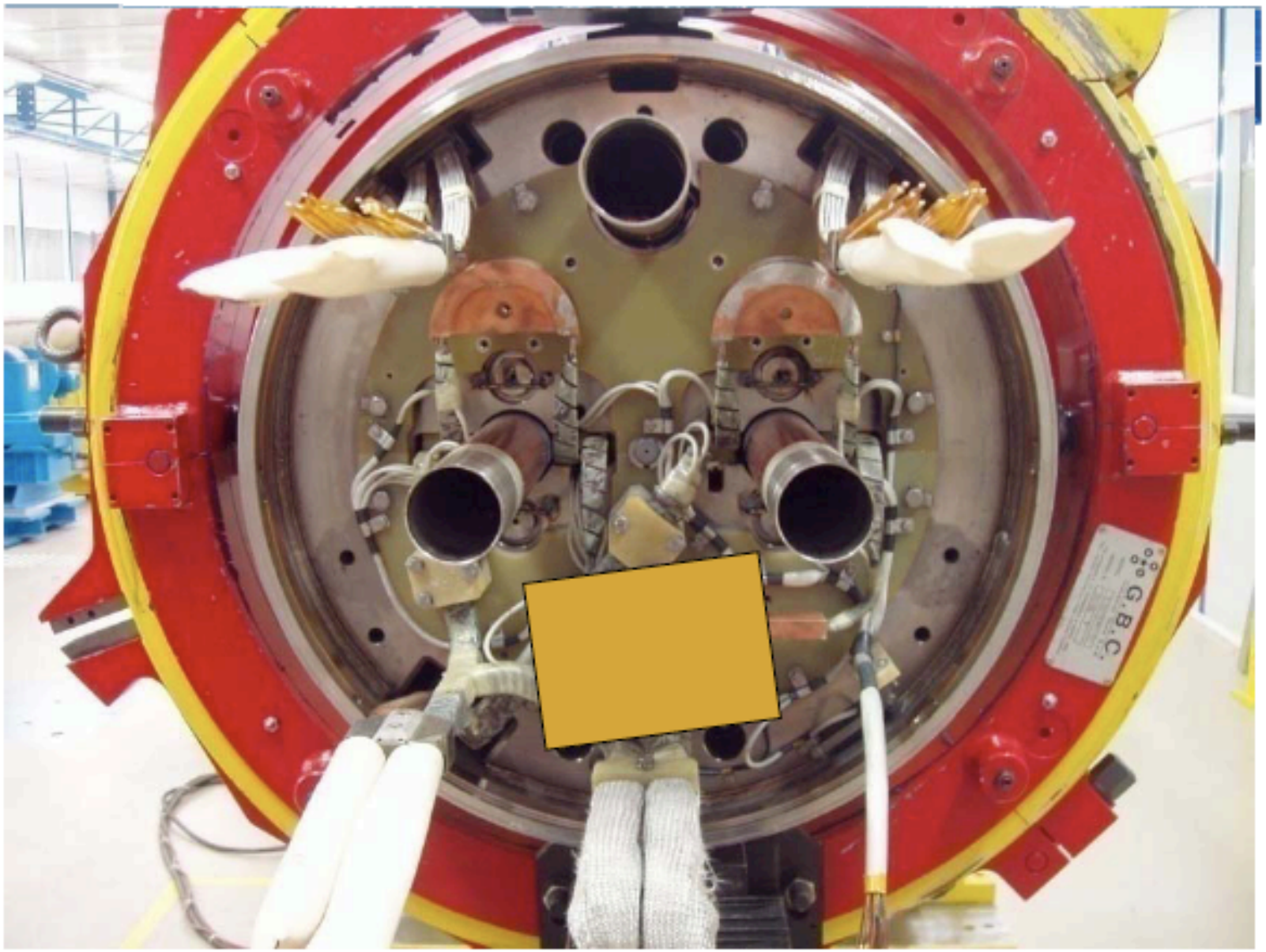
Ultra-Sound testing 13 kA splices

US inspection of defective inter-pole splice in MB 2334 has confirmed the US test to be a very useful QC tool.





Courtesy C. Scheurlein



The current shutdown (at Chamonix)

- Key drivers:-
  - 3-4 repair (critical path)
  - CV & Cryo maintenance
  - Intermediate cool-down during CV and Cryo maintenance
    - Maintain temperature below 100K for PIMs & ELQA
    - 6 weeks needed for 3 weeks work
  - Helium storage capacity (6 of 8 sectors)
  - Cannot refill 1-2 until all magnets are back in the tunnel
    - Transport activity through 1-2

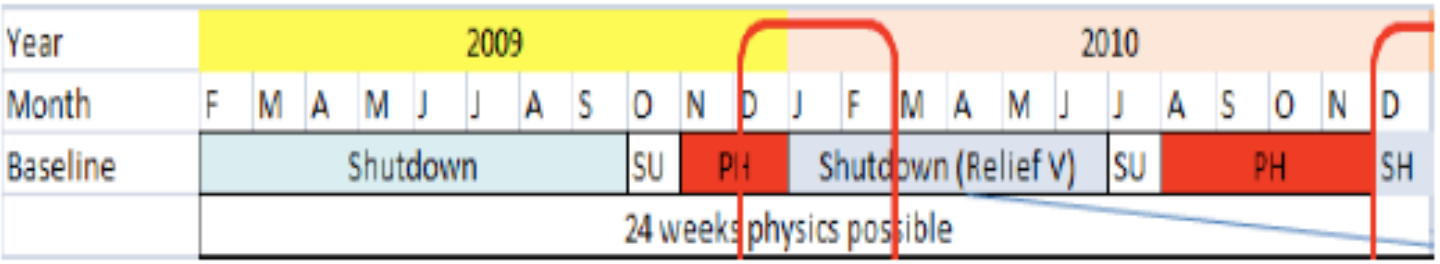
Interdependences CV/cryo/Helium/PIMs/safety/ELQA make planning a nightmare!

Machine cold in mid August and first injections last week in September

Physics Running Time

With Strictly No running of the machines in the winter months

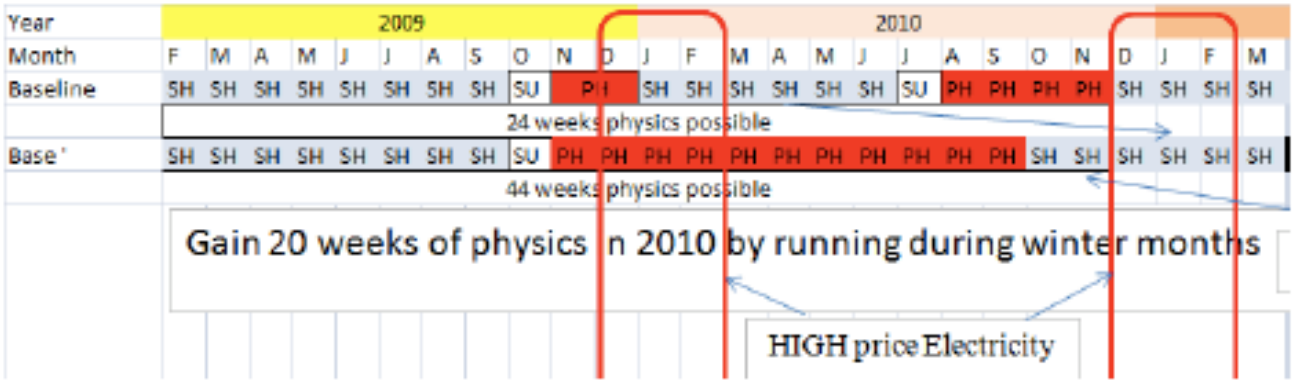
- Present baseline schedule
  - schedule allows very limited physics in 2009/2010 (24 weeks)
  - Any slip of >1 month in the S34 repair will delay first LHC physics till August/September 2010!!
  - Repair schedule has no contingency



- **Must** have the possibility of running during winter months

Schedule with running in winter months

- Gains 20 weeks of LHC physics (independent of "slip")



Impacts of Running During Winter Months (2009-2010)

- Electrical Costs!!
  - Assuming Full running through December to February
  - dedicated running of the injectors during winter and
  - reduced cryo power from 8MW to 5MW

  → **additional electricity bill of 8MEuros (+ possible 8%)**
- Impact on Scheduled Shutdown Work on other CERN accelerators
  - » POPS (replacement of PS motor-generator set)
  - » LINAC4 connection to PSB
  - » …
- Impact on Necessary Maintenance
  - » Cooling towers
  - » Electrical Network

Repair Scenarios

- Enhanced Quench Protection (Detection)
  - Busbar Detection (Protection)
  - "Symmetric" quench protection
  - QPS redundancy (UPS-QPS)

The FULL Quench System must be operational for beam collisions in 2009-2010 (unanimously agreed)

Update →

DN200 Pressure Relief Valves in Arcs

A: install 4 sectors (09-10) + 4 sectors (10-11)
+ first physics sooner: detectors debugging.. earlier warning
+ first beam sooner: ramp, squeeze, .. Sooner... earlier warning
+ focuses attention of repair teams

B: Installation 8 sectors (09-10)

+ reduced amount of collateral damage in event of a splice problem in 2010
+ reduced additional electricity bill
+ reduced overall shutdown time
+ reduced ALARA problems (2nd order)

Immediately after Chamonix the management decided on scenario A

Energy Level for Operation

- Dipole field which can be reached
  - Time needed, reliability, and efficiency
- Risks associated with operating at field
  - Splices stability (thermal runaway…)
  - Detection of poor splices (see later)
  - New effect of beams (?)
- Operational efficiency of other systems
  - Cryo recovery time etc

Dipole quenches during HWC

Sector	1st training quench [A]	I_max [A]	# training quenches	Starting in:		
				# ALS	# ANS	# NOE
1-2	-	9310	0	0	0	0
2-3	-	9310	0	0	0	0
3-4	-	8715 (bus)	0	0	0	0
4-5	9789	10274	3	0	0	3
5-6	10004	11173	27	0	1	26
6-7	-	9310	0	0	0	0
7-8	8965	9310	1	0	1	0
8-1	-	9310	0	0	0	0

Excluding S34, all sectors reached 8965 A (5.3TeV) without a quench
Excluding S34, all sectors reached 9310 A (5.5TeV) with 1 quench

A. Verweij,

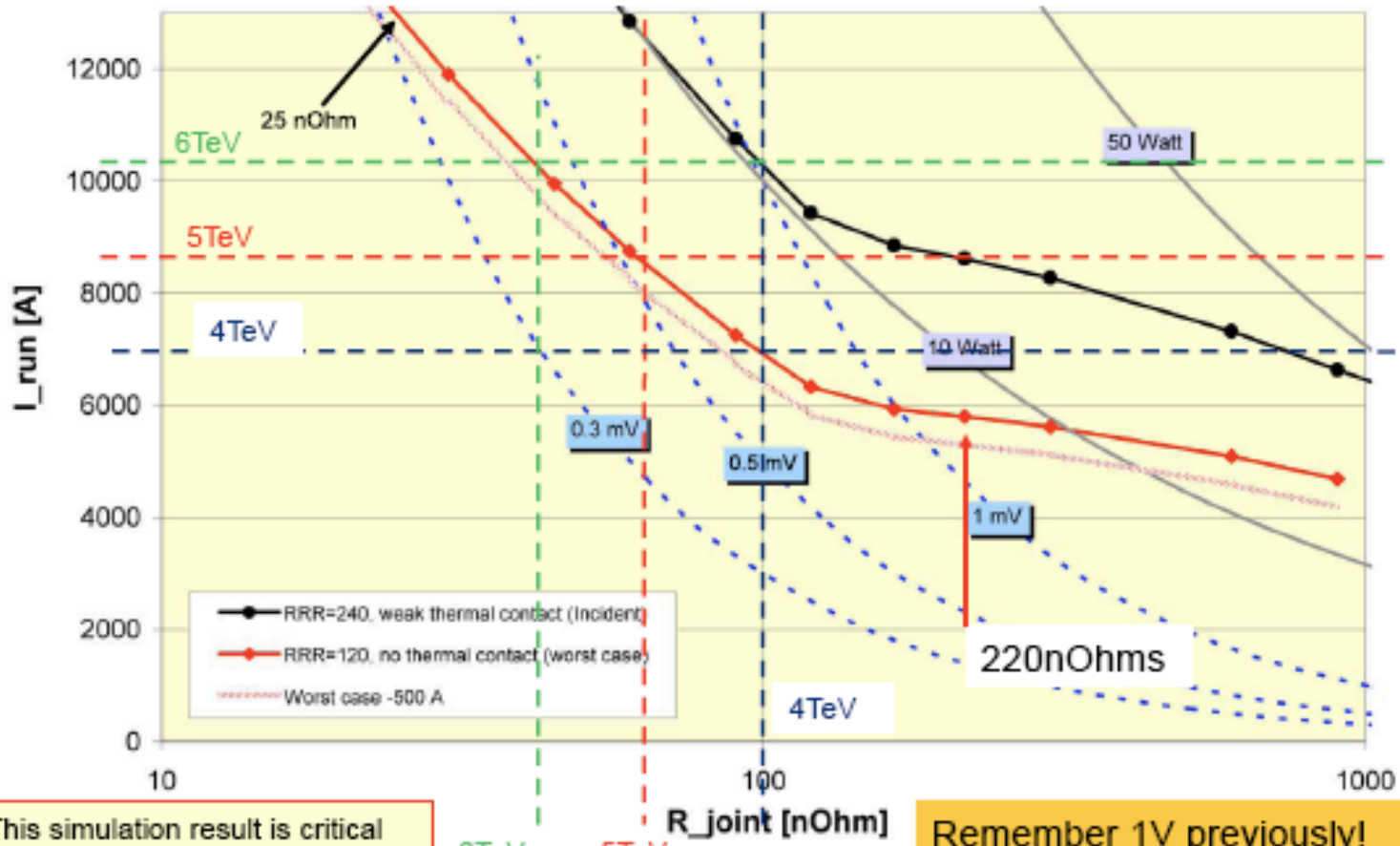
Estimated dipole training to reach 6 and 6.5 TeV

Sector	Number of magnets			Number of quenches	
	ALS	ANS	NOE	@ 6 TeV (±2)	@ 6.5 TeV (±30%)
1-2	49	96	9	0	4
2-3	56	60	38	1	8
3-4	56	65	33	1	8
4-5	46	46	62	2	12
5-6	28	42	84	1	15
6-7	57	36	61	2	12
7-8	54	40	60	2	12
8-1	64	24	66	2	13
Total	**154**	**154**	**154**	**11**	**84**

Estimated 11 (84) quenches to reach 6 (6.5) TeV
Estimate for 7TeV 900-1000 quenches (to be reviewed)

A. Verweij,

Setting for the new QPS upgrade



This simulation result is critical for our decision and should be independently confirmed

Remember 1V previously!

A. Verweij

Beam Conditions for Physics (2009/10)

- **Conclusion 5TeV/beam for Physics**
- Machine Protection will be Tested with beam (at 0.5TeV energy levels)
- 4 TeV "on the way" to 5TeV (limited in 2010)
- Estimated integrated luminosity
  - during first 100 days of operation.. ≈100pb-1
    - » Peak L of 5.10^{31} η (overall) = 10% gives 0.5pb-1/day
    - » Peak L of 2.10^{32} η (overall) = 10% gives 2.0pb-1/day
  - During next 100 days of operation.. ≈ 200pb-1?
- Then towards end of year ions (to be planned in detail soon)

Status Shutdown Work

- Delays in sector cool down dates (2-4 weeks),
  - but PIMs cool down window increased 4-5 weeks
  - Helium storage available at point 18 breaks link 23-45 and 78-81
- Interconnect works going very well
- DN200 relief valves going well (not critical)
- nQDS, very good progress
  - Electronic racks available from June, on critical path
  - QPS-UPS cabling going very well
- Jacks reinforcement excellent progress
- SSS relief valves: delay in spring delivery, new solution being studied
- LSS work: excellent progress (bake-outs and IT relief valves)
  - Radiation shielding (SEU): iron blocks and transport a problem
  - Stand alone magnet (SAM) consolidation has "taken off"
- Cabling campaigns: needs more discipline
- Water cooled cables: excellent progress

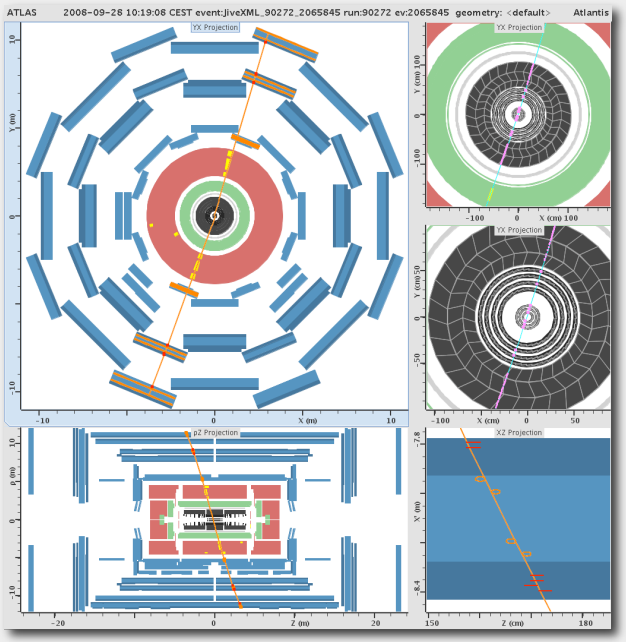
Bottom Line: we are 1 week behind with an incredible amount of extra work. We are hoping to recover this week (and any more if we can)

Present Status of Experiments

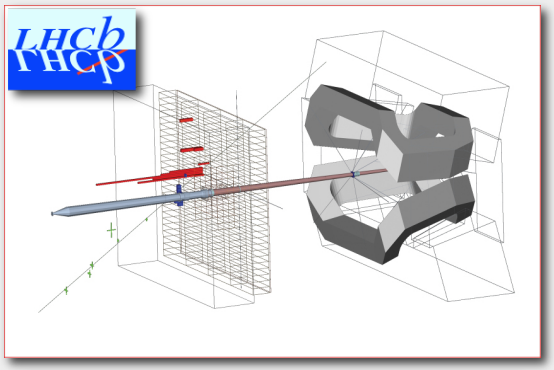
Use time in most efficient way:

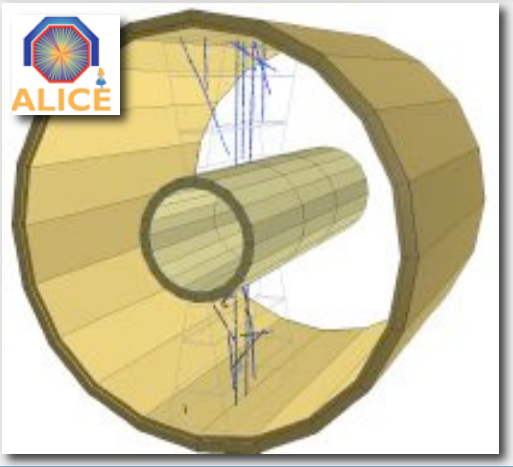
Installation of some detector components, some repairs, commissioning using cosmics

Gain operation experience in situ before collisions start

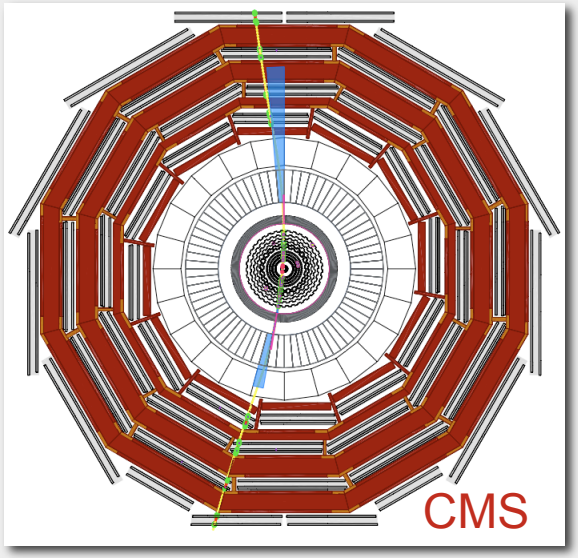


ATLAS: 216 million cosmic events





CMS: 300 million cosmic events



General considerations on experiments

- All experiments efficiently using the shutdown to fix problems (cooling, component repairs, noise, etc) and/ or completing installation of subdetectors
- Repairs/installations proceeding well, according to schedules with sufficient contingency.
  - Main point of attention is TOTEM installation, presently on a (too) aggressive schedule: measures are being taken to enhance support from CMS
- All (big) experiments ready to close up before summer and resume full commissioning with cosmic rays.
- All experiments declared their preparedness to sustain a year long run

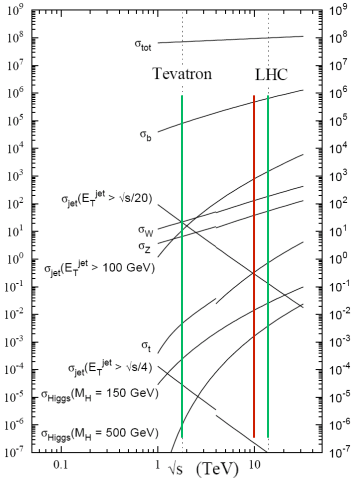
General considerations on experiments

- Extensive use of the several hundred millions of cosmic ray events to commission, calibrate, align detectors, as well as to test the computing models
- Implemented weekly meeting with the Accelerator Departments, to assess progress of the repair and to avoid or mitigate interferences between the schedules.
- **Created a joint task force with the LHC to help in the machine repairs.**

Experiments desiderata

(M. Ferro Luzzi , Chamonix2009)

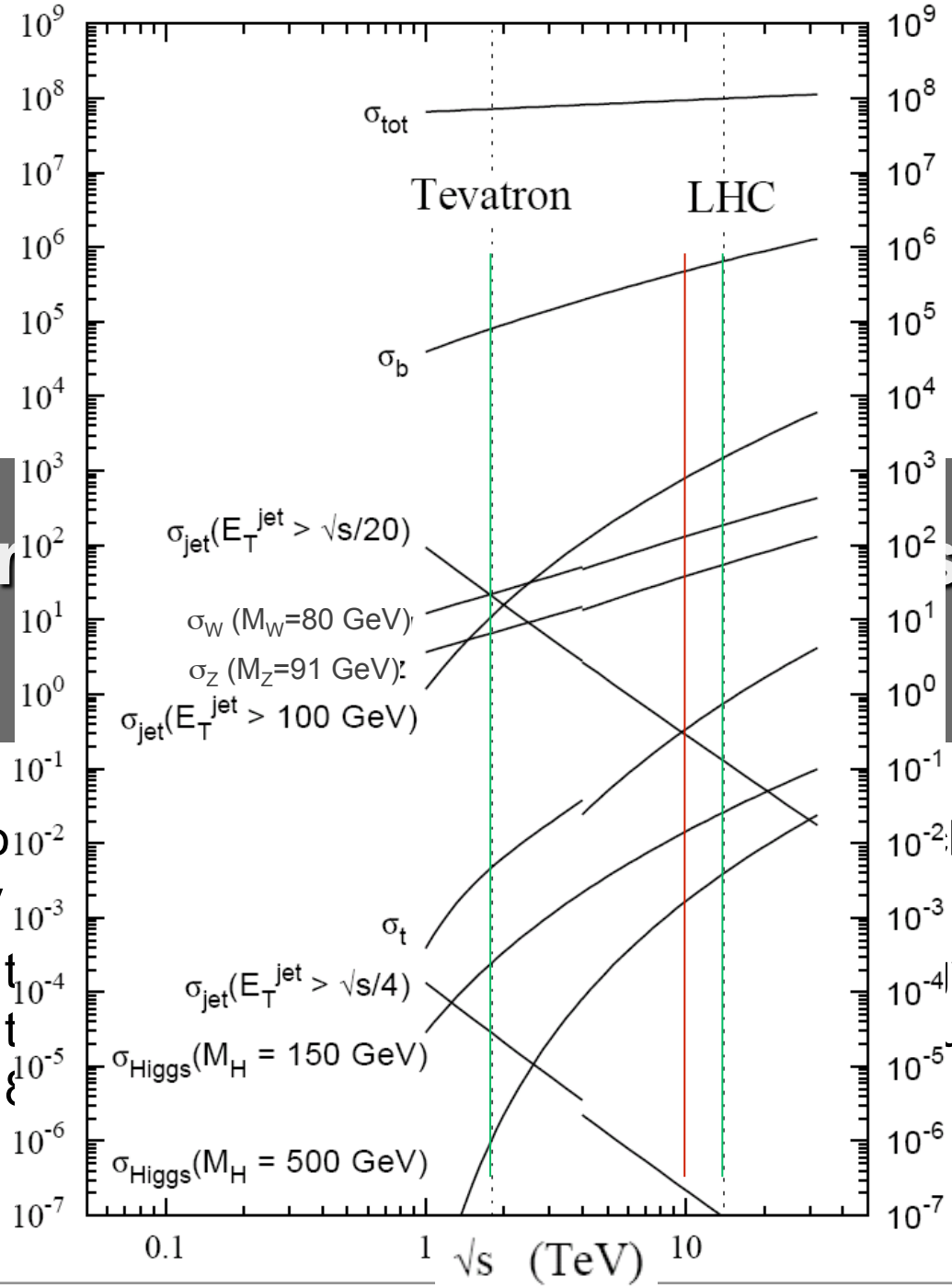
- How much data is useful at $s^{1/2}$ = 900GeV ?
  - build on LTC 2007-15, with update in light of current situation
- Integrated luminosity × cross section vs. energy
  - What is the minimum amount of data at given energy that is needed to make the 2009 run useful ?
  - What do we need to do to match the Tevatron, which aims for 9 fb^{-1} by 2010 ?
- Non-GPD (non General Purpose Detectors)
  - ALICE and LHCb
  - TOTEM and LHCf
  - Ions
- Scheduling / scenarios



Integrated luminosity × cross section versus energy

- What do we need to do to match the Tevatron, which aims for 9 fb^{-1} by 2010 ?
- What is the minimum amount of data at given energy that is needed to make the 2009 physics run useful ? (assuming CM energy $8 < s^{1/2} < 10$ TeV)

Integr section



- What do h aims for 9 fb^{-1} by
- What is t y that is needed t uming CM energy 8

GPD physics: Two families

Discovery channels:

- Higgs
- W', Z'
- SUSY
- Exotic particles

Try to express these as:

1. lumi needed to make a better (exclusion) measurement than Tevatron
2. lumi needed to make a discovery

Standard Model channels

- W, Z
- top
- QCD

An excellent understanding of these is an essential step toward discoveries

NB: In the following slides, when talking about integrated luminosity ("so many pb^{-1}"), **we really mean data taken with good beam and detector conditions** (i.e. "good data" or g.d.)

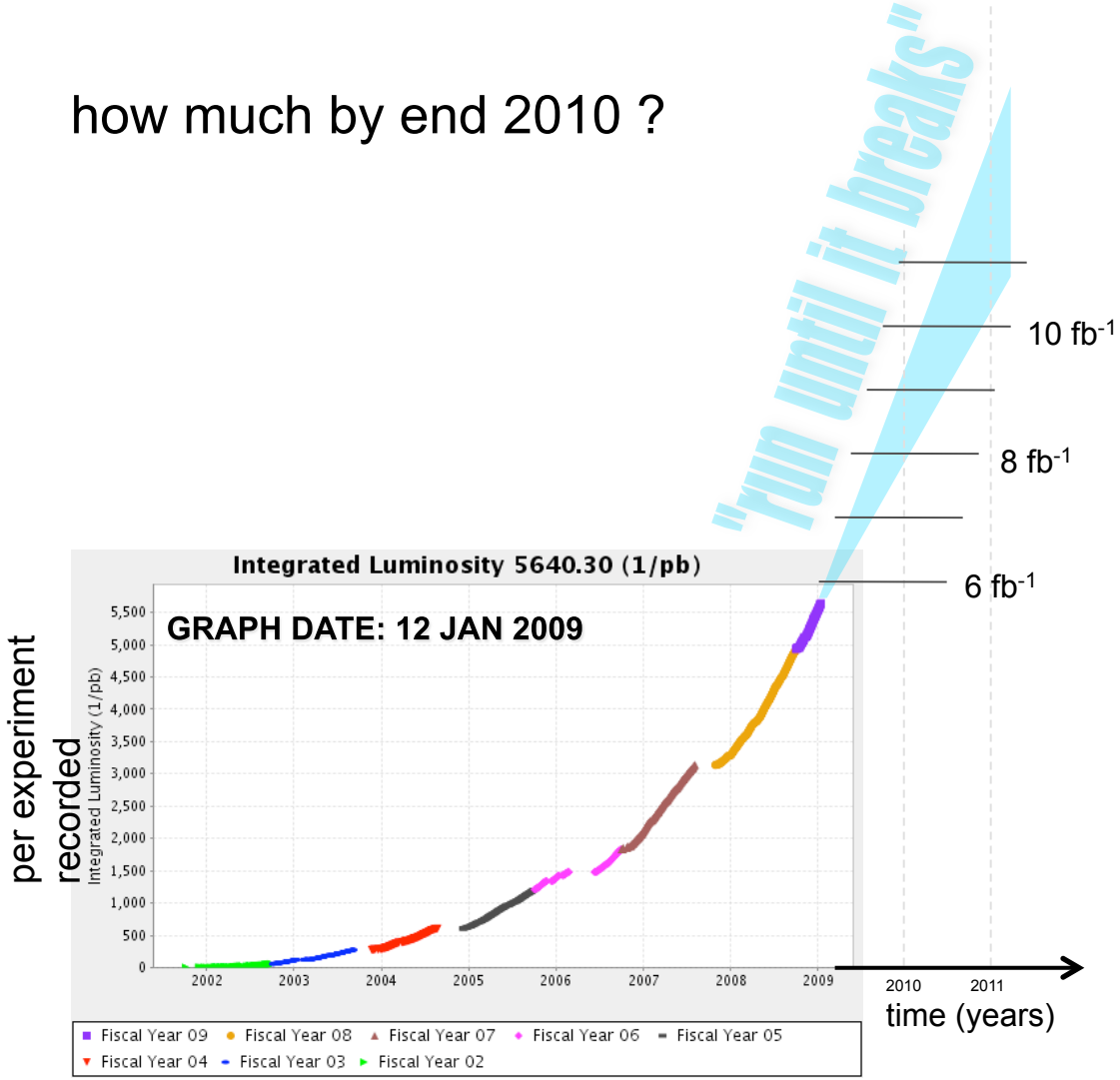
Let's not forget that

- Understanding the detector performance will take time
- There will be operation inefficiencies, down time, etc.

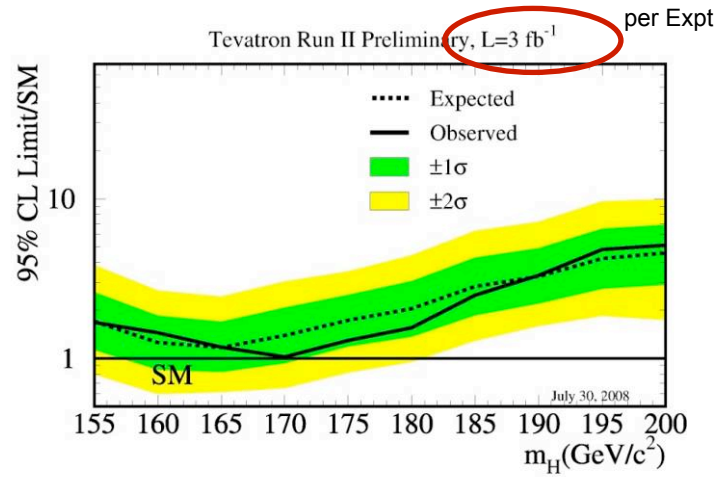
State of the Art: Tevatron

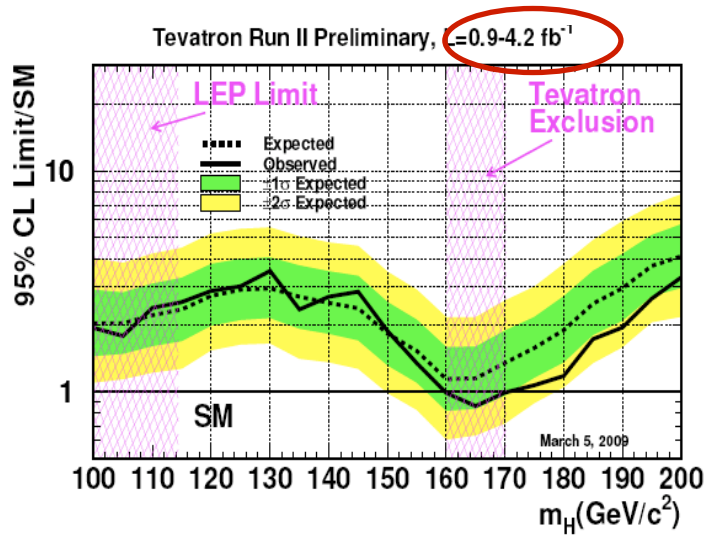
Projected integrated lumi

how much by end 2010 ?



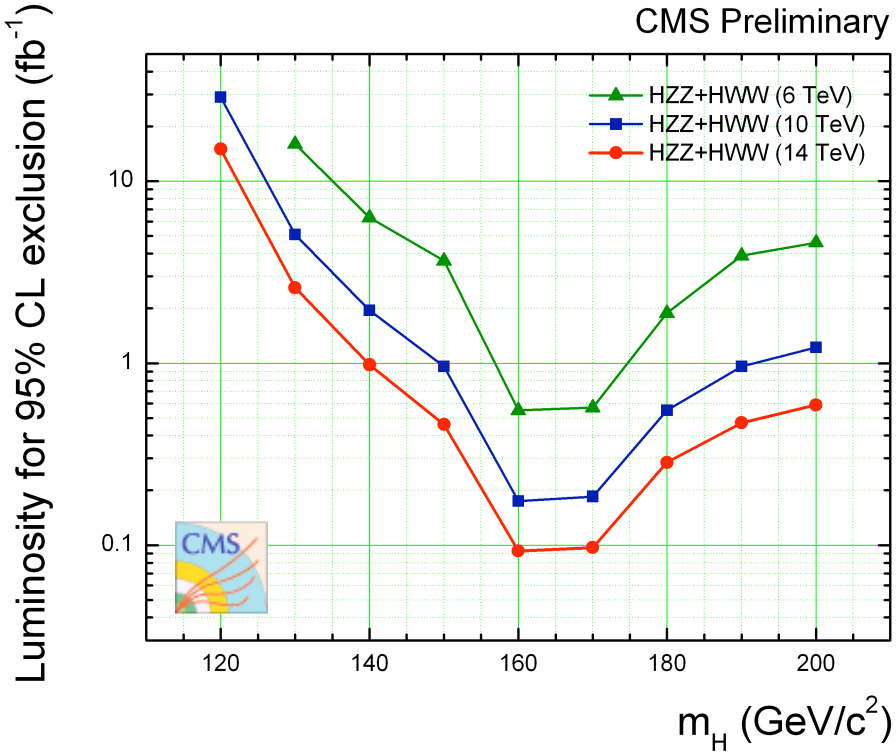
And powerful new analyses...





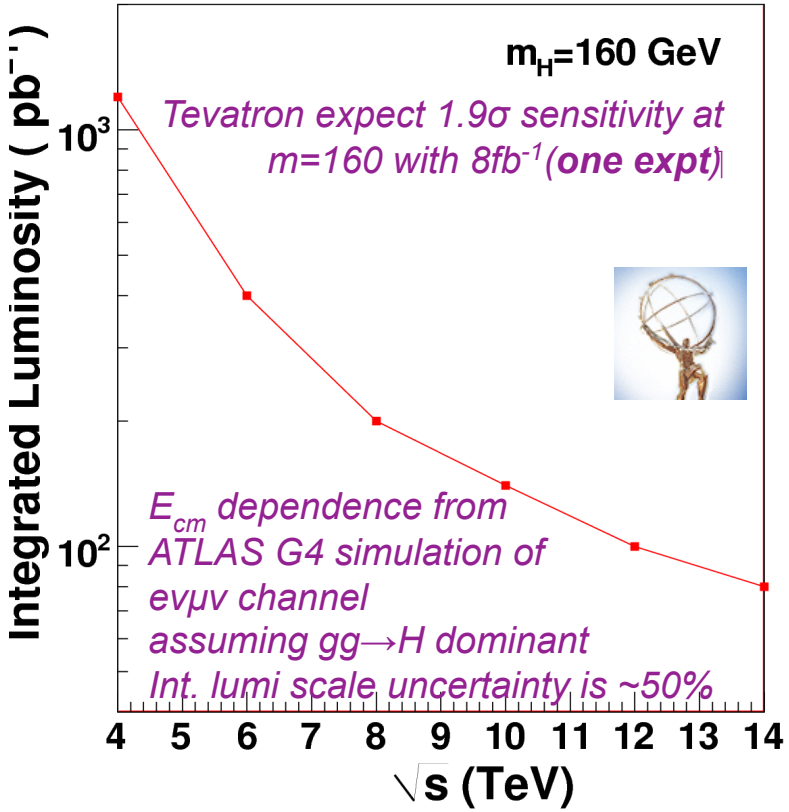
Higgs 95% CL at LHC GPD , H→ weak bosons, indicative

Combined H→WW + H→ZZ: lumi for 95% CL



- Energy $s^{1/2}$ 14 → 10 → 6 TeV
- Lumi needed 0.1 → 0.2 → 0.6 fb^{-1}

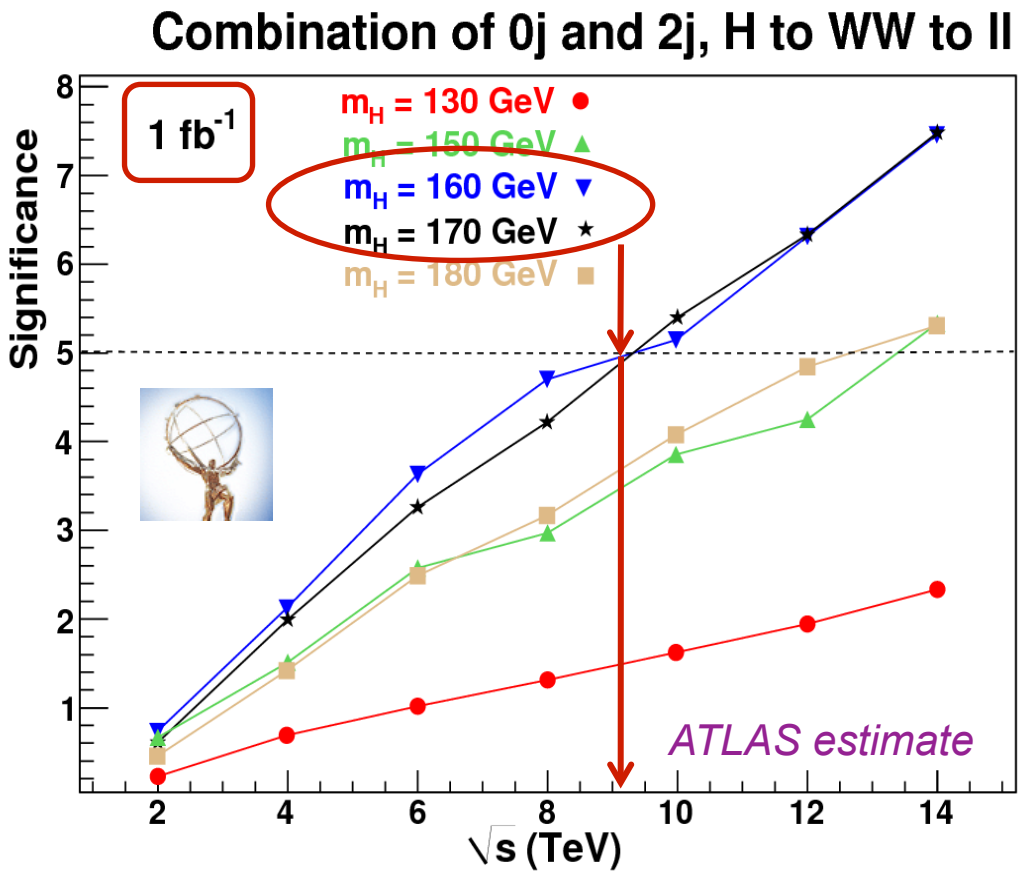
Compare sensitivity to Tevatron with 8 fb^{-1}
(only H→WW→ lνlν)



- Massive loss of sensitivity below 6 TeV

To match Tevatron with **$s^{1/2}$ = 8-10 TeV**, we need **~300-200 pb^{-1} g.d.**

Higgs 5σ discovery, indicative



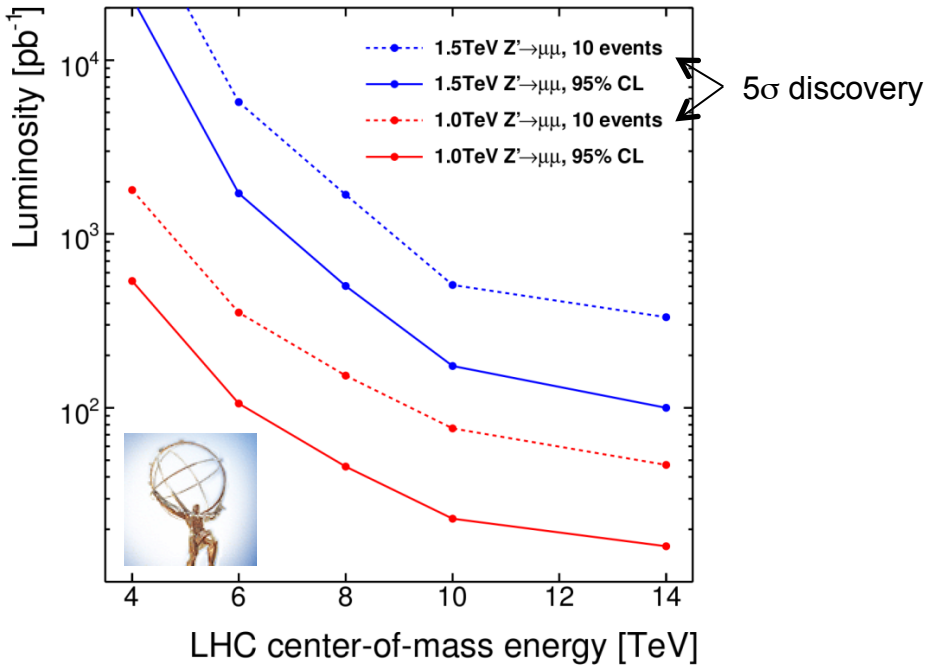
5σ discovery for m_H ~160 GeV is possible with **$s^{1/2}$ = 8-10 TeV** and **~1fb^{-1} g.d.**

Z' resonance

Z': Heavy partner of the Z (SSM)

- Very clean experimental signal: $Z' \rightarrow \ell\ell$
- Tevatron 95% CL limit at $m_{Z'}$ =1 TeV

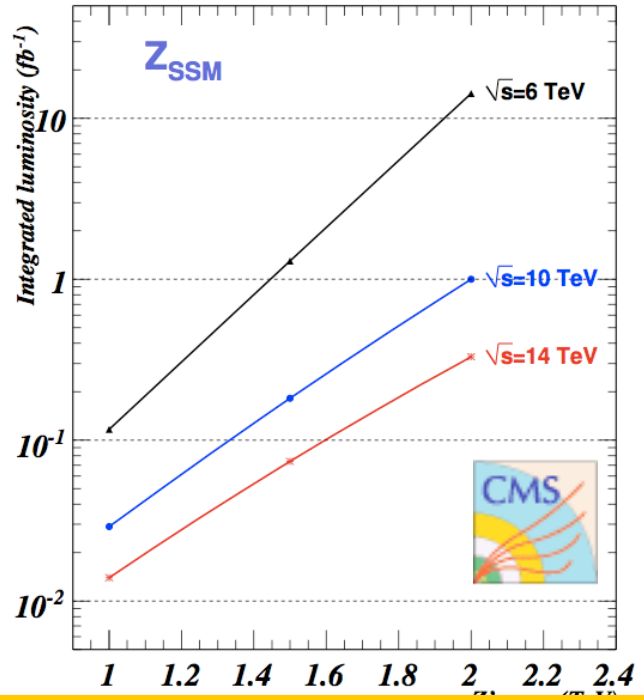
ATLAS fast simulation



Needed luminosity for 95%CL exclusion at $m_{Z'}$ = 1 TeV :

$s^{1/2}$: 14 → 10 → 6 TeV

Lumi: 13 → 30 → 110 pb^{-1}

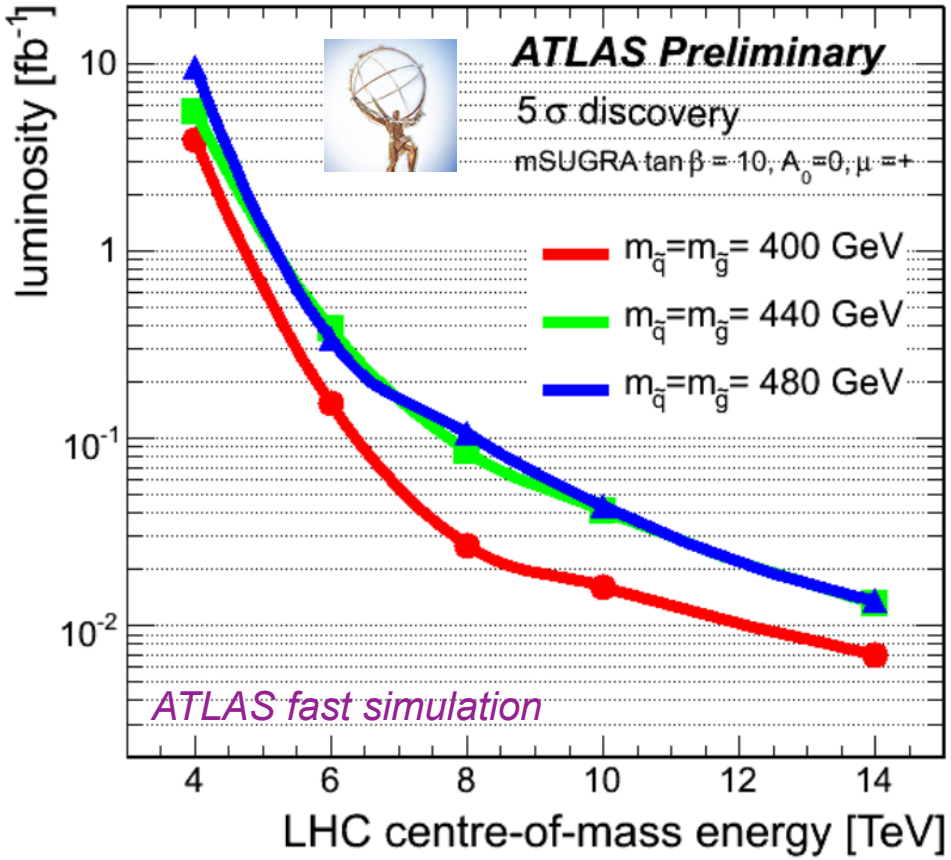


95% CL limit with ~**30 pb^{-1} g.d.**for $m_{Z'}$ ~1TeV, with **$s^{1/2}$ = 10 TeV**

5σ discovery possible with **~100 pb^{-1}g.d.**

SUSY , an example

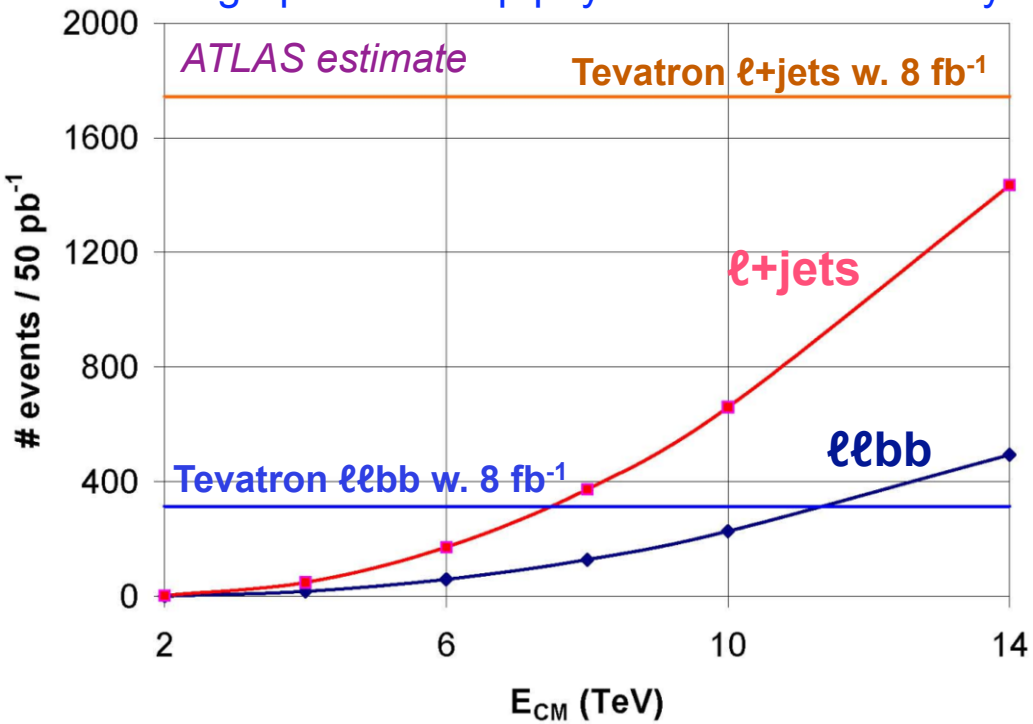
- ℓ+jets+missing-E_T channel
  - Not most sensitive, but will be usable before inclusive jets +missing-E_T analysis
- Tevatron limit currently is 380 GeV in this model ($m_{\tilde{q}} = m_{\tilde{g}}$)
  - plot shows 3 masses above this
- We will be sensitive to a region overlapping with ultimate Tevatron reach
- Below $E_{cm} \approx 8$ TeV, the sensitivity collapses



5σ discovery beyond current Tevatron limits is possible with **$s^{1/2}$ = 8-10 TeV** and **~30-15 pb^{-1} g.d.**

Top quarks

- Background to new physics searches – must measure cross-section & properties in data
- Expected Tevatron statistics provide a benchmark:
  - Cross-section statistical precision will then be comparable to other uncertainties
  - High-precision top physics will be underway



~50 pb^{-1}@14 TeV would match full Tevatron sample
- lose ~factor 2 in cross-section dropping to 10 TeV
- lose ~another factor 2 dropping to 8 TeV

Below 8 TeV samples will be rather small, with a few tens of pb^{-1}

Catch up with Tevatron with **$s^{1/2}$ = 8-10 TeV** and **~200-100 pb^{-1} g.d.**

Non-GPD

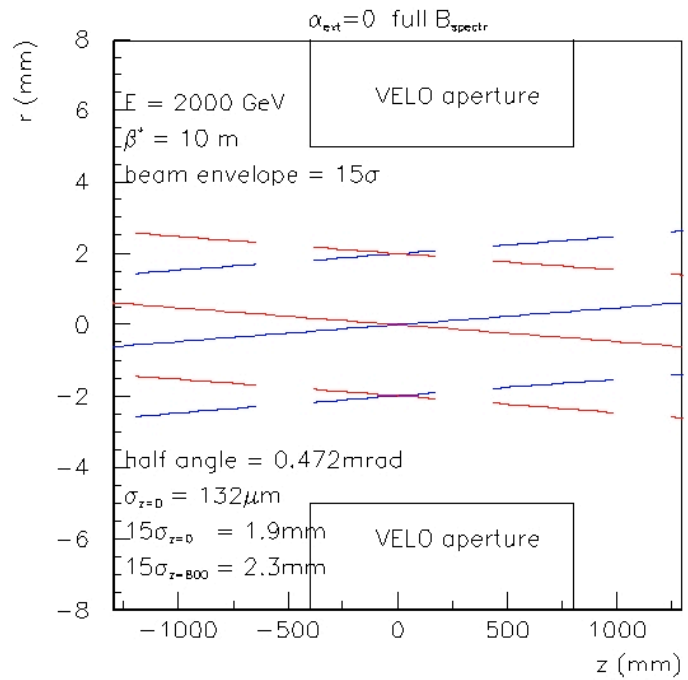
- LHCb
- ALICE
- TOTEM
- LHCf

LHCb in summary

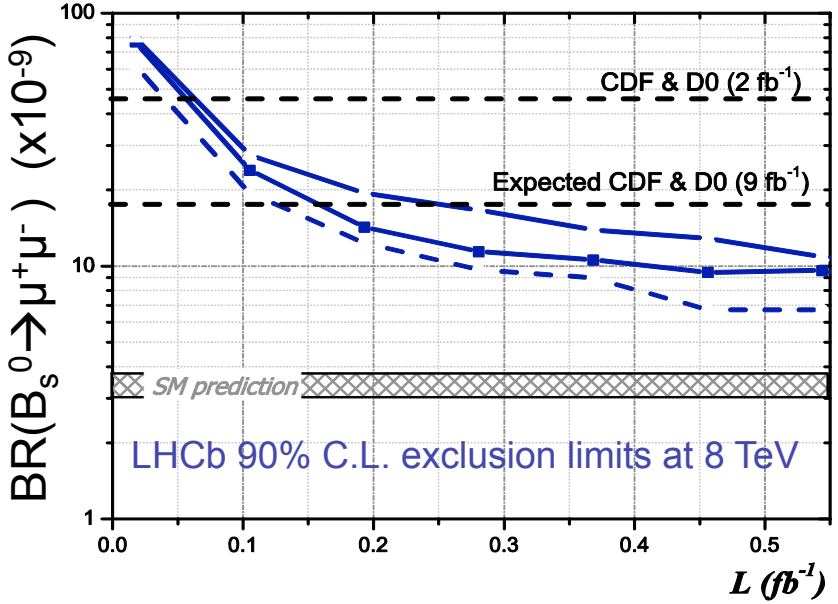
- B cross section does not vary as drastically as for high mass objects. Thus, the request to go to highest possible energy is milder
- Need **0.3-0.5 fb^{-1}** at **s$^{1/2}$ ≥ 8 TeV** to surpass Tevatron in B_s physics
- Need at least 5 pb^{-1} at s$^{1/2}$ ≥ 4 TeV to collect good sample of J/psi

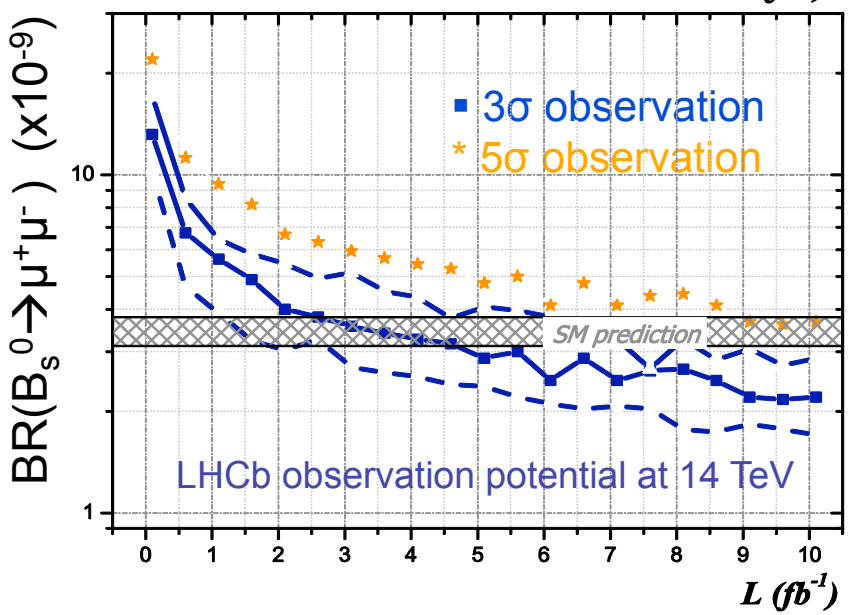
NB:

- If E ≤ 2 TeV, LHCb will not take the risk to close the VELO (if with full B_{spectr} and uncorrected crossing angle). Hence, disfavour a hypothetical "Tevatron energy run"
- LHCb assumes that TCTVs will all be present, so that there is no limitation in IP8 to β* ⇒ exploit smallest possible β* in 2009 and 2010 (what is β^*_{min} with full B_{spectr} and 50ns ??)
- LHCb wishes to take some TED calibration runs about 1 month before beam arrives into LHC (LHCb detector is set up horizontally and lacks cosmics, especially in VELO detector)



Physics reach for BR($B_s^0 \to \mu^+\mu^-$)





- as function of integrated luminosity (and comparison with Tevatron)

At **$s^{1/2}$ = 8 TeV** , need **~0.3-0.5 fb^{-1} g.d.** to improve on expected Tevatron limit

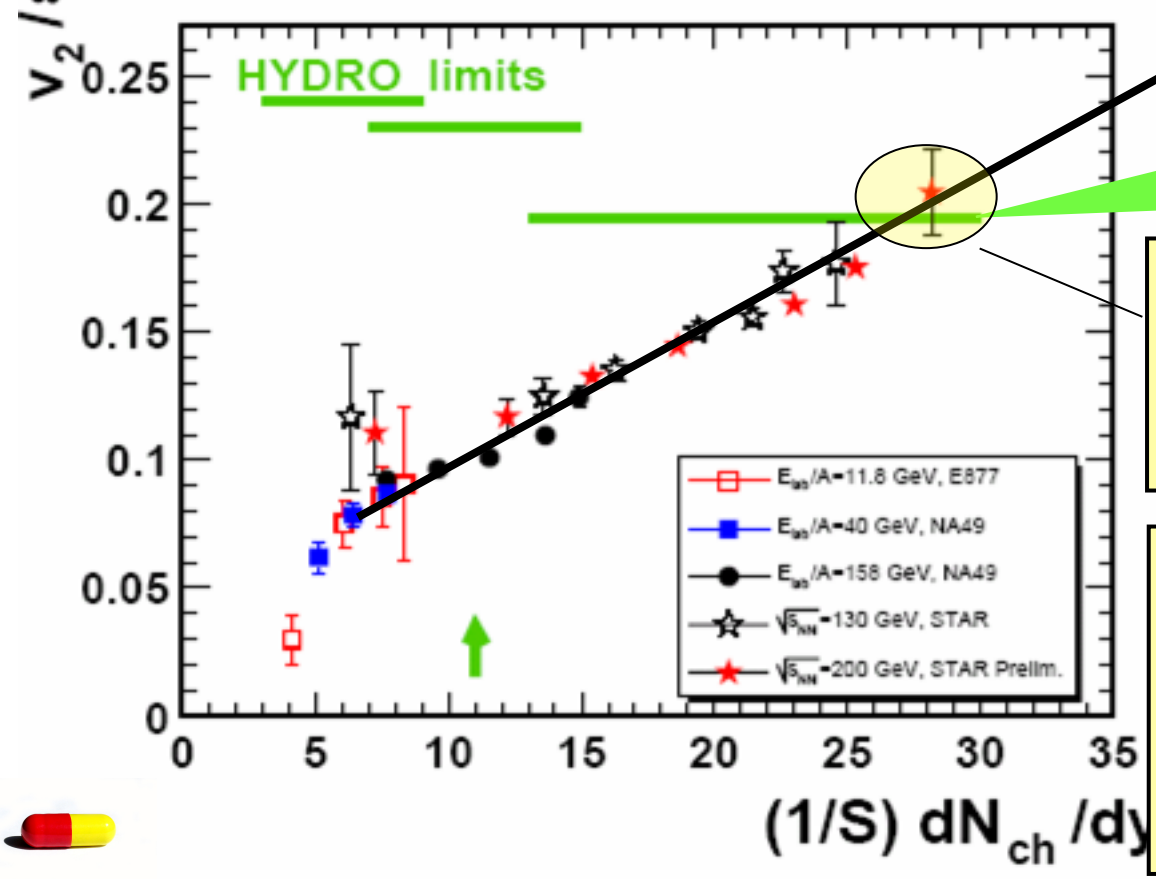
Collect ~3 fb^{-1} for 3σ observation of SM value

Heavy Ions: Flow at LHC

- one of the first and most anticipated answers from LHC
  - 2nd RHIC paper: Aug 24, 22k MB events, **flow surprise** (v_2)
    - Hydrodynamics: modest rise (Depending on EoS, viscosity, speed of sound)

LHC ?

increase of flow



BNL Press release, April 18, 2005:

Data = ideal Hydro

"Perfect" Liquid

New state of matter more remarkable than predicted – raising many new questions

LHC will either

confirm the RHIC interpretation

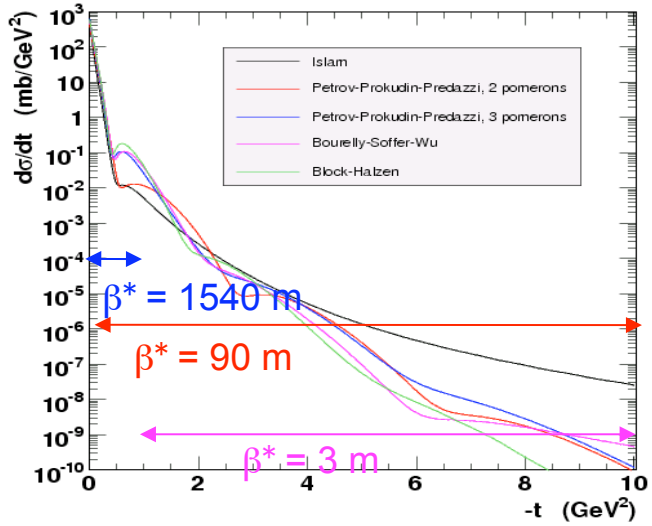
(and measure parameters of the QGP EoS)

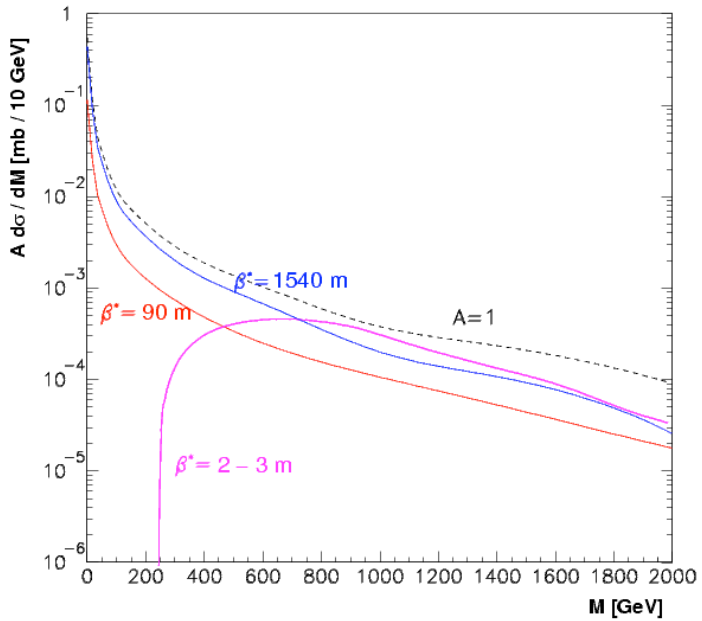
OR

.....

TOTEM (IP5)

- T1, T2, all RP220 and some RP147 will be ready
- **TOTEM will operate under all running conditions**
- Programme at $s^{1/2}$ = 900 GeV: → Move RPs to 15σ
  - Poor acceptance for elastic scattering
  - RP alignment using beam halo and diffractive protons
  - Study of surviving protons with momentum losses $\xi = \Delta p/p > 0.1$
  - Study of event topologies with T1, T2 (pseudorapidity distributions, multiplicities)
    → relative cross-sections for different event topologies
- Programme at $s^{1/2}$ = 10 TeV:
  - Early optics (β^* = 3 m): large |t| elastic scattering, central diffraction
  - As soon as technically feasible: request β^* = 90 m optics (or a gradual unsqueezing from β^* = 3 m to higher values)
    → first measurement of σ_{tot} with Optical Theorem using T1, T2, RP (~ 5 %)





LHCf (IP1)

- Aim: study of energy distribution of particles emitted in very forward region for understanding of cosmic ray phenomena
- Interested in all c.m. energies, including 900 GeV
  - but of course the goal is to measure at 14 TeV
- Integrated lumi: few nb^{-1} at 14 TeV , or order 10 nb^{-1} if somewhat lower than 14 TeV

- Lumi limitation: degradation of non rad-hard components after few pb^{-1} in data taking position
  - move out by 10 cm when $L>10^{30}$ cm^{-2} s^{-1}
  - dismount & remove detector when $L>10^{3?}$ cm^{-2} s^{-1}

- Preferred operating conditions:
  - 2x2 and 43x43, L= 10^{29} cm^{-2} s^{-1} , crossing angle 0 and 140 urad (enhanced acceptance)
  - 156x156 introduce pile-up (2us electronics)

- Potentially interested in HI run data taking (interferences to be checked)

What about computing?

"What it comes down to is our software is too hard and our hardware is too soft."

Excerpts from a recent review on WLCG

Tier-0/1/2s generally working well:

- Substantial improvement in reliability, availability, monitoring, usage during 2008 (CCRC08)
- Some delays in procurements for 2009 (and 2008)
- Pledged resources still needed in 2009-10
- **Need to stress-test system with ATLAS & CMS reconstructing data simultaneously**
- **Need to validate the model for "chaotic analysis"**
- Continue to improve communications between Tier-0, Tier-1s, Tier-2s and users

In Summary

A few busy months are in front of us before the (re)start of LHC.

And then, finally,

Let’s the fun begin