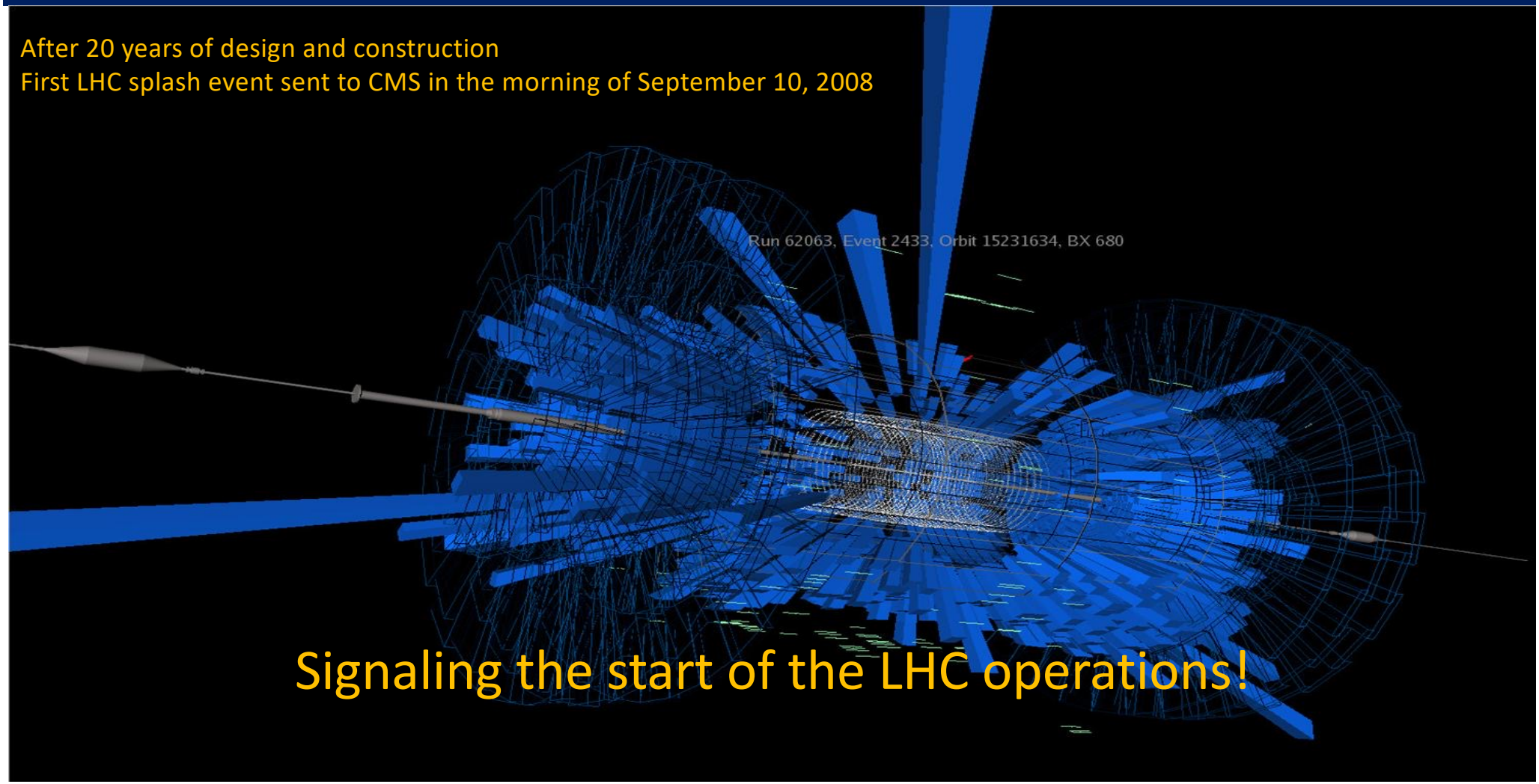

From Despair to Discovery:
The Hunt For The Higgs

Splashing The End Of The Beginning

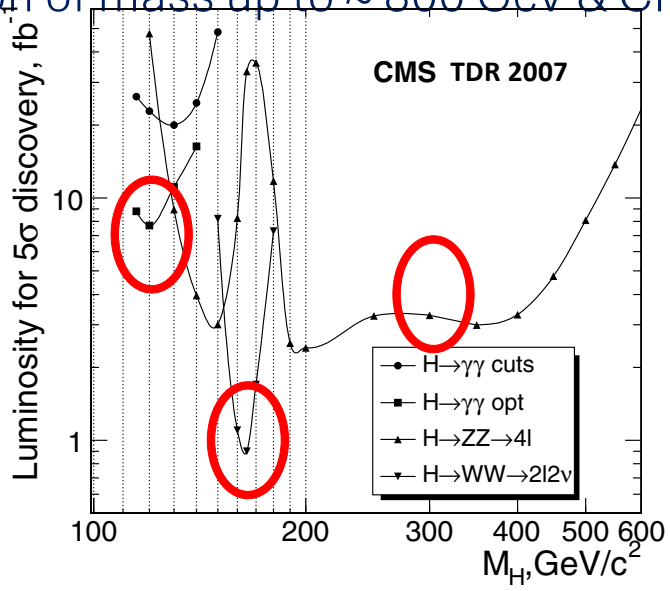
After 20 years of design and construction
First LHC splash event sent to CMS in the morning of September 10, 2008



Signaling the start of the LHC operations!

LHC & The No-Lose Theorem

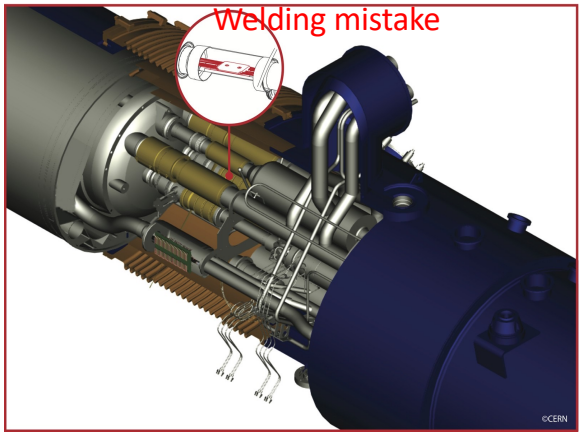
- At $\sqrt{s} = 14$ TeV and instant. luminosity of $10^{34}\ cm^{-2}s^{-1}$, LHC could produce Higgs boson of mass up to ≈ 800 GeV & CMS could find it quickly.

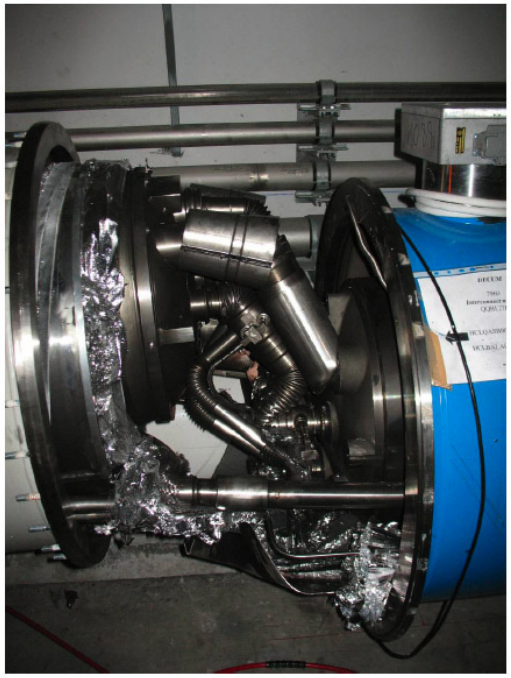


- So, on Sept 10th, 2008, the excitement was extraordinary; ≈ 44 years after the Higgs conjecture for EWSB, resolution was in sight. **But ….**

Ghost In The Machine

On September 19, nine days after the start of LHC commissioning all such aspirations sank when an electrical fault in one of the main dipoles resulted in mechanical damage and release of helium from the magnet cold mass. The release of the helium caused a pressure wave over a region of more than 400m resulting in damage to magnets, interconnects and pollution of the ultra-high vacuum system.





CERN Response Was Swift & Careful

- Start within a year with LHC **run at** $\sqrt{s} = 7$ TeV not 14 TeV
- Consequences to Higgs searches at LHC were tremendous

$\sqrt{s}$ (TeV)	Production cross section (in pb) for $m_H = 125\,\text{GeV}$					
	ggF	VBF	WH	ZH	$t\bar{t}H$	total
1.96	$0.95^{+17\%}_{-17\%}$	$0.065^{+8\%}_{-7\%}$	$0.13^{+8\%}_{-8\%}$	$0.079^{+8\%}_{-8\%}$	$0.004^{+10\%}_{-10\%}$	1.23
7	$16.9^{+5.5\%}_{-7.6\%}$	$1.24^{+2.2\%}_{-2.2\%}$	$0.58^{+2.2\%}_{-2.3\%}$	$0.34^{+3.1\%}_{-3.0\%}$	$0.09^{+5.6\%}_{-10.2\%}$	19.1
8	$21.4^{+5.4\%}_{-7.6\%}$	$1.60^{+2.1\%}_{-2.1\%}$	$0.70^{+2.1\%}_{-2.2\%}$	$0.42^{+3.4\%}_{-2.9\%}$	$0.13^{+5.9\%}_{-10.1\%}$	24.2
13	$48.6^{+5.6\%}_{-7.4\%}$	$3.78^{+2.1\%}_{-2.1\%}$	$1.37^{+2.0\%}_{-2.0\%}$	$0.88^{+4.1\%}_{-3.5\%}$	$0.50^{+6.8\%}_{-9.9\%}$	55.1
14	$54.7^{+5.6\%}_{-7.4\%}$	$4.28^{+2.1\%}_{-2.1\%}$	$1.51^{+1.8\%}_{-1.9\%}$	$0.99^{+4.1\%}_{-3.7\%}$	$0.61^{+6.9\%}_{-9.8\%}$	62.1

Despair!

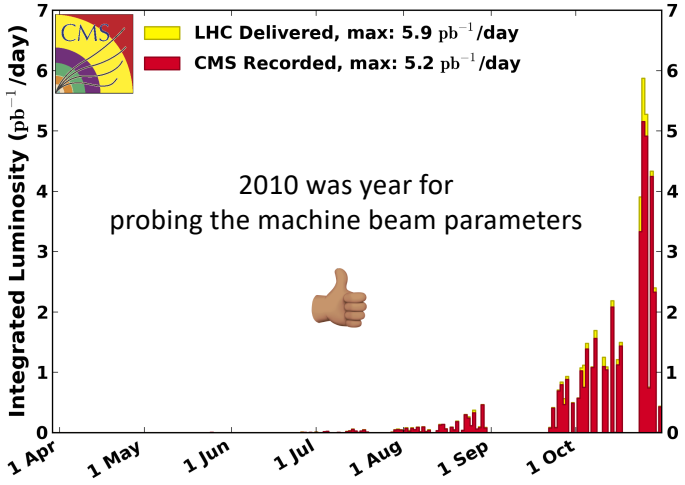
- x3 lower Higgs cross section and **unknown LHC intensity profile to** mitigate future accidents

⇒ Higgs hunt may not be a quick sprint but rather a long marathon 😔

A New Hope

- CMS used downtime to perfect some very sharp analysis tools: Global Event description (Particle Flow), τ-tagging, b-tagging etc. crucial for expanding Higgs searches much beyond TDR. $H \to \tau\tau, H \to b\bar{b}, H \to \ell^+\ell^-\nu\bar{\nu}$
- After re-commissioning in 2009, LHC moved to 7 TeV in 2010.

Physics Coordinator
at the start of data taking
Huge role in shaping CMS's
High standard & agility!

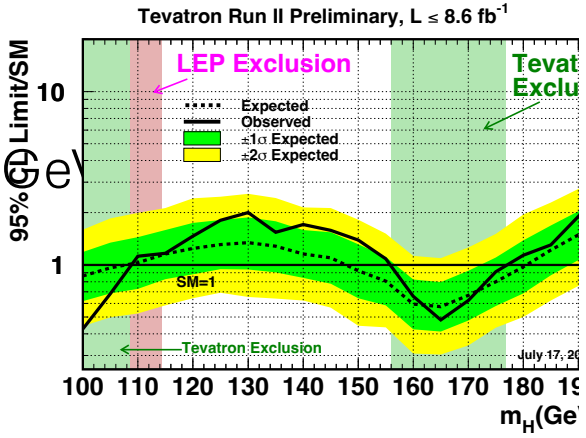


Game On!

LHC performed brilliantly in the early operations in 2010 with a limited number of bunches and quickly reached the nominal single bunch beam parameters. The prospect of LHC rapidly delivering more than 0.5 fb^{-1} became plausible.

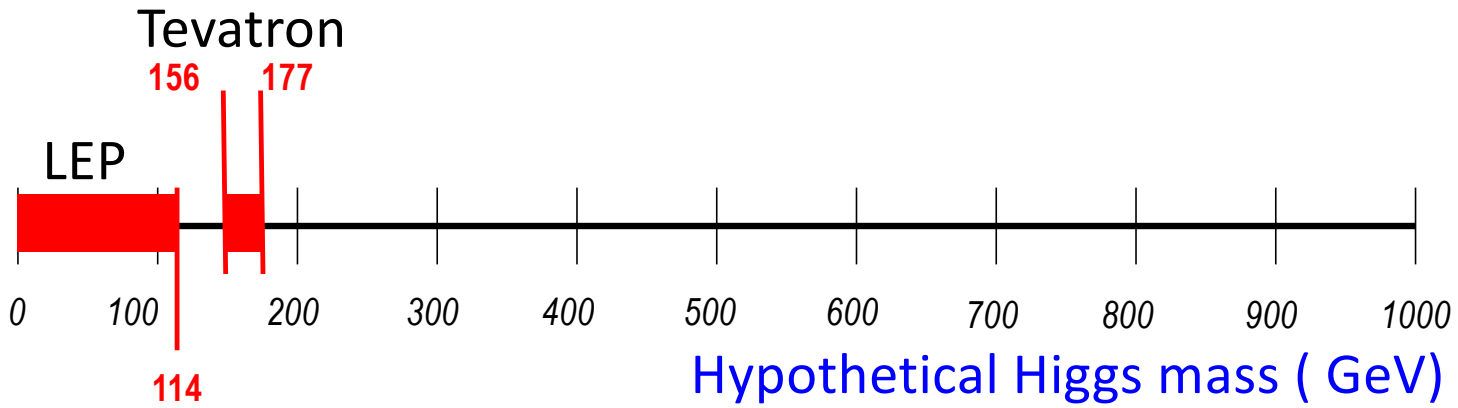
Existential Issues For CMS in Summer 2010

- Following the accident, CMS people had mostly moved away from Higgs searches → pursue other searches with much larger Xsections ←SUSY, EW
  - While (we heard) that many dozens in ATLAS marched along undeterred by accident
  - If CMS apathy continued, ATLAS could just eat us like a good *salad caprese!*
- Tevatron experiments with 9 fb^{-1} each of **well understood data** at $\sqrt{s} = 1$ TeV had the sweet spot to discover Higgs if $M_H \cong 160$ GeV.
  - Tevatron could **eat the LHC Higgs lunch** before we even started !
  - LHC people prayed at every church in Italy (there are quite a few 😀) to make sure $M_H \neq \cong 160$ GeV.
  - It was a lot of praying, but it seemed to have worked!
  - @ICHEP Tevatron ruled out this tiny sliver @$M_H \cong 160$ GeV



Landscape of The Hunt Circa 2010

Excluded mass range from direct searches :



But by 2009, CMS Higgs group had dwindled to just a few faithful; too few to mount a search on the whole range

While ATLAS, we heard, had a large army toiling away !

There was a good chance CMS would be scooped.

Rise Of The Machine

- By summer 2010, the increase in LHC single bunch intensity was fast!
- Beam-beam effects and the aperture in the presence of crossing angles were not a critical limitation.
- The next step was to rapidly increase the number of bunches while being mindful of beam-protection needs during collimation and beam-dump.
- At the January 2011 Chamonix LHC performance workshop, the prospects grew rosier. Conservative luminosity goals for 2011 of $2\times10^{32}cm^{-2}s^{-1}$ (instantaneous) and 1 fb^{-1} (integrated) were set, but based on LHC's 2010 performance, there was scope to achieve much more.
- With 1404 bunches with 10^{11} protons/bunch, 50ns bunch spacing, a β^* of 1.5m and a total of ≈110 MJ of stored energy, an integrated luminosity of about 3 fb^{-1} was possible in 2011.
- With such luminosity prospects, the hunt for the Higgs boson was on again!

2011 was becoming the defining year for Higgs!

CMS Physics Week in Bodrum, Sept 2010

To review and fine tune entire CMS physics production juggernaut
In anticipation of expected firehose of data to come in 2011

CMS Physics Week in Bodrum, Sept 2010

Plan of the week

- Today:
  - This presentation: description of the main components of our next Physics plan, put ideas and proposals on the table
  - Darin's presentation: works out in more details the needs from the PAGs in terms of Physics Objects
- During the week:
  - Main focus on POGs, most presentations on those topics
  - Goal: identify work packages in the POGs that need man-power to be realized
  - Dedicated talks on HI, Higgs ← Focus on Higgs Hunt plan
  - Dedicated talks on Trigger aspects
  - Sessions on PVT/Offline/Computing/Physics, Case for Upgrades
- Towards end of the week:
  - Discussion session on Physics Plan, Friday 12:15 – 13:00
  - Wrap-up by Gigi, finalizing on the Physics Plan, on Saturday

Emphasis on Trigger & analysis tools

Only 2 Physics Talks

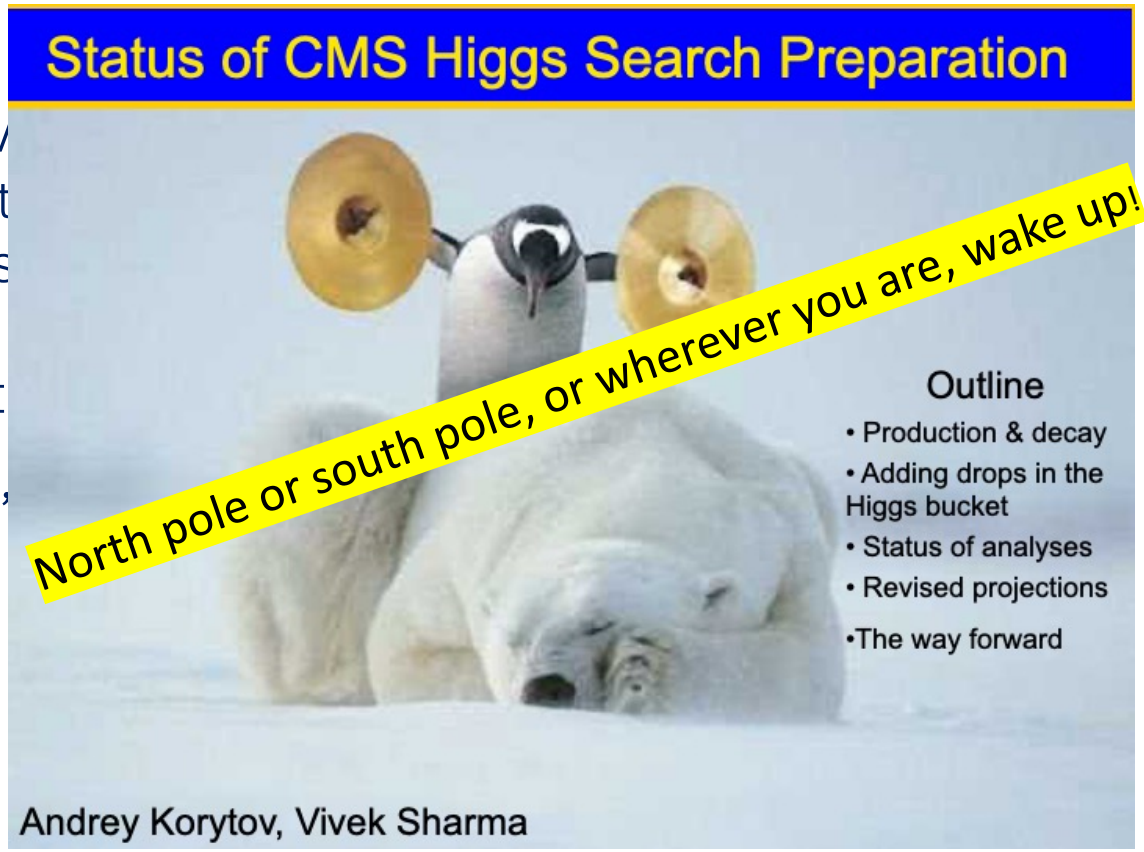
The Bodrum Higgs Initiative

At the time CMS started hearing of the aggressive 2011 luminosity plan from machine physicists, the Higgs search group had mostly evaporated. The few & faithful developed a 7 TeV plan

The new "**drops in the bucket**" 7 TeV search strategy targeted a large set of Higgs production & decay modes to make every viable channel and every small bit of information count

Thanks to sharp new analysis tools, decay modes once thought impossible, came into play.

It was time to alert the CMS Collaboration!



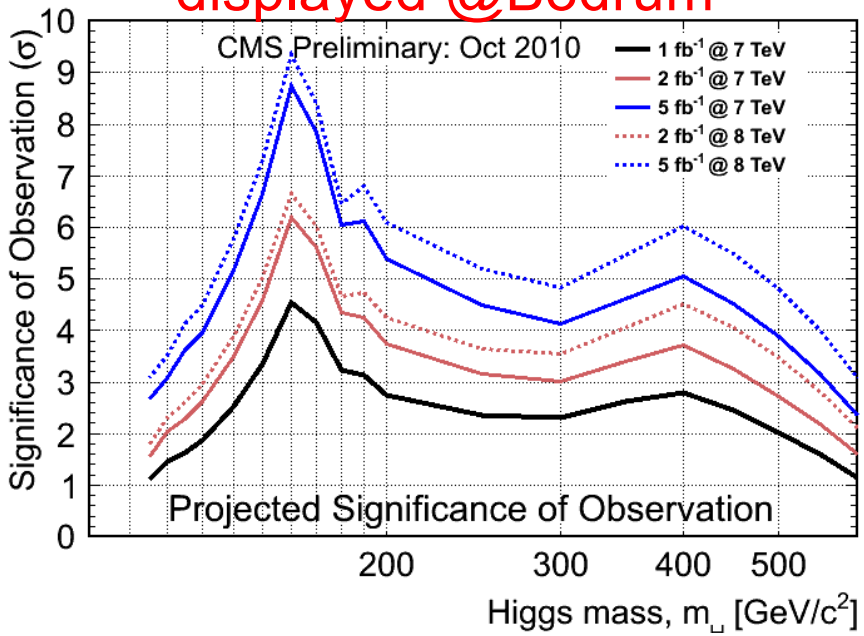
Searching For Higgs Every Where: Drops In Bucket

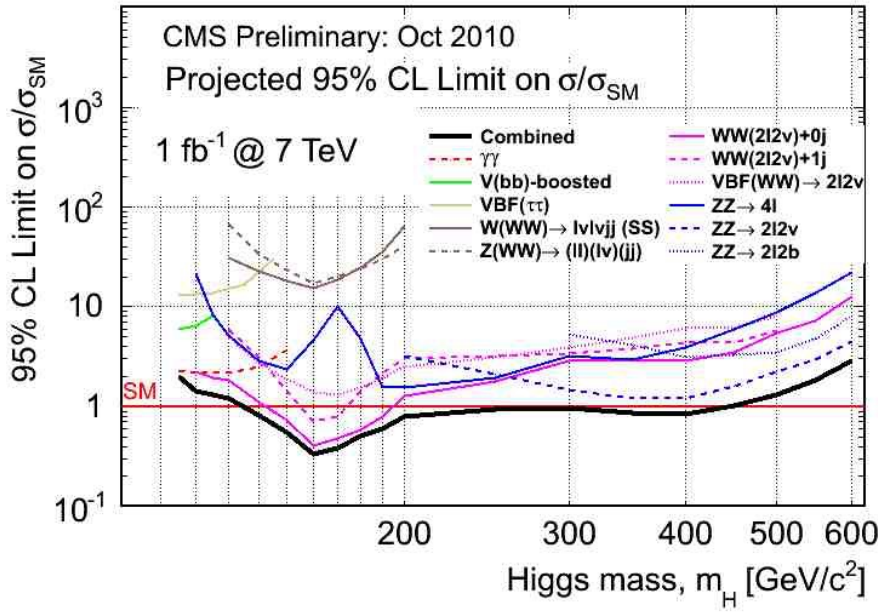
Mode	Mass Range	Expected signal	Higgs mass	Major
* Indica				
H → bb *	110-135	~2	10 %	W/Z + Jets, Top
H → ττ *	110-145	~ 40-90	15 %	Z → ττ
H →WW →2l 2ν	110-600	25-180	20%	Non-resonant WW
H → ZZ →4l	110-600	1-16	1-2%	Non-resonant ZZ

Convince CMS to reinvest effort in Higgs search ASAP!

A surprisingly rich discovery potential displayed @Bodrum

Ability to rule out large range of Higgs mass. With just 1 fb^{-1} exclude 130 < M_H < 480 GeV





Boost Person Power in Higgs Search

Minimum Manpower Needs

- Two types of actors:
  - **Prospectors:** In 2010, dedicated to hunting/prospecting for new modes to add
  - **Consolidators:** Develop full data analysis for modes **we already know are good** but for which little manpower exists currently
    - In 2011, Prospectors join Consolidators. Every one owns every thing

- Breakdown by need:
  - H → bb (4)
  - H → gg (2)
  - H → ZZ (4)
  - Statistical framework for combining modes (2)

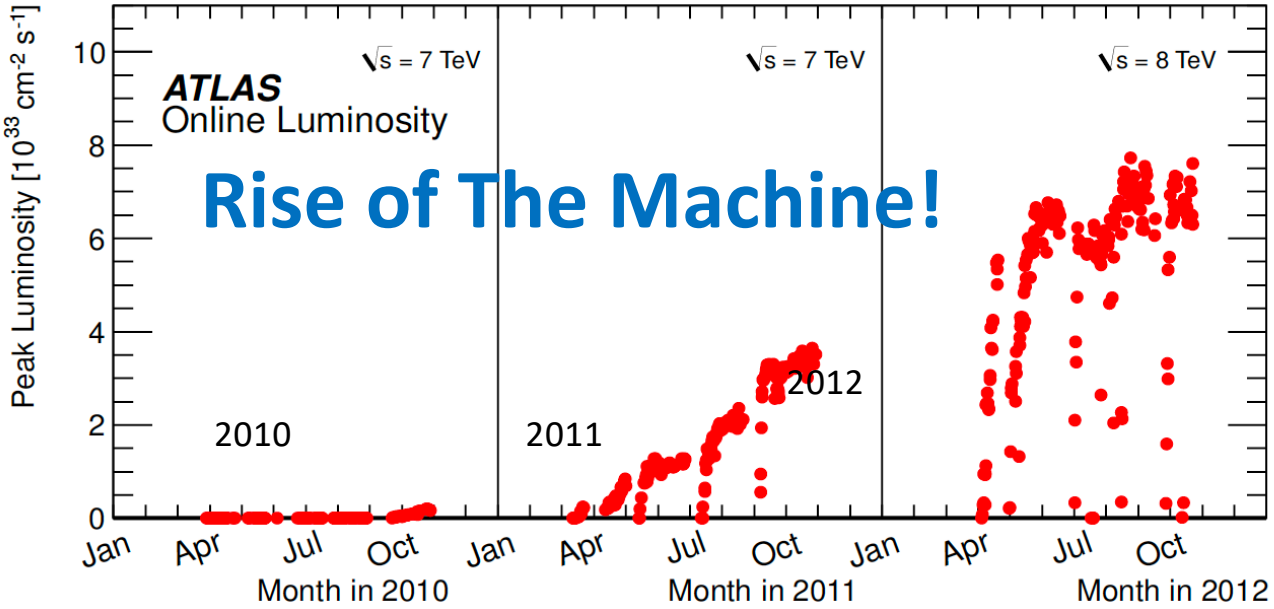
- ~ 15 people (80%) on Higgs
  - Here the cost to pay is small and the shot is big . We need to move at 50% people working on other analyses : EWK, TOP… etc

At the CB meeting on last day at Bodrum, Gigi asked for endorsement for injecting more resources to Higgs

Gigi got an enthusiastic YES! from the Collaboration Board

With Gigi help now we had a plan and the resources & people.
Let's Go!!

2011 was a blast



It was like playing a video game with fast changing & surprising scenes that required immediate action!

Decisions and strategies had to be balanced on a Razor's edge,

No scope for mistakes!

Sometimes we gambled got lucky !

And this is where Gigi was most inflential!

Examp

The Easter Bump Hunt

- Being paranoid, we kept asking "are we ready?". Ran many exercises
  - Mock data challenges, internal reviews for each Higgs decay mode
  - Higgs Review with external committee
- Amusingly, the best test of our readiness came courtesy of ATLAS
- Just before Easter'11, "Not Even Wrong" blog posted a rumor that with just 64 pb^{-1} data, ATLAS had found a 4σ bump at $M_{\gamma\gamma}$=115 GeV with a rate ≈30 times the SM value ← BSM Higgs !!
  - 115 GeV was also the mass where the same team in ALEPH@LEPII had found a tantalizing excess
- CMS's reaction was amazing. People canceled their Easter celebration and rushed to their Lab or flew to CERN ← **Easter bump hunt**
- All data were quickly re-reconstructed with latest algorithms, and every Higgs decay mode (Not just $H \rightarrow \gamma\gamma$) were analyzed.
- Ruled out the "ATLAS bump" within 7 days of rumor surfacing

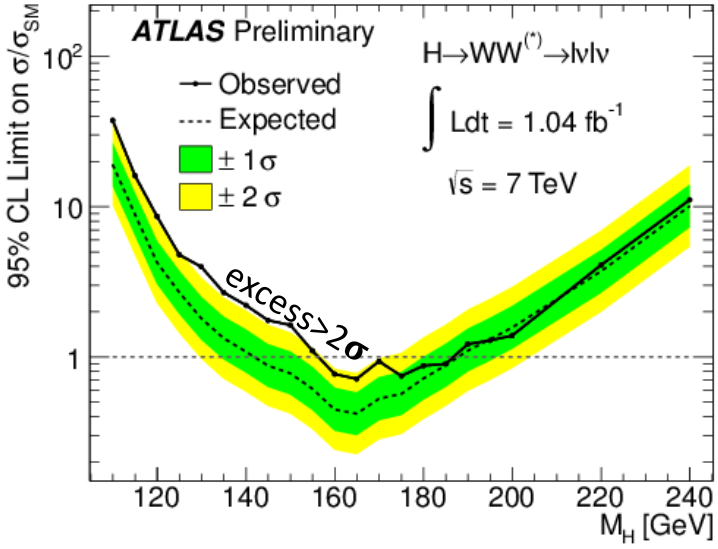
Proof that Gigi had organized a well-oiled Higgs hunting team!

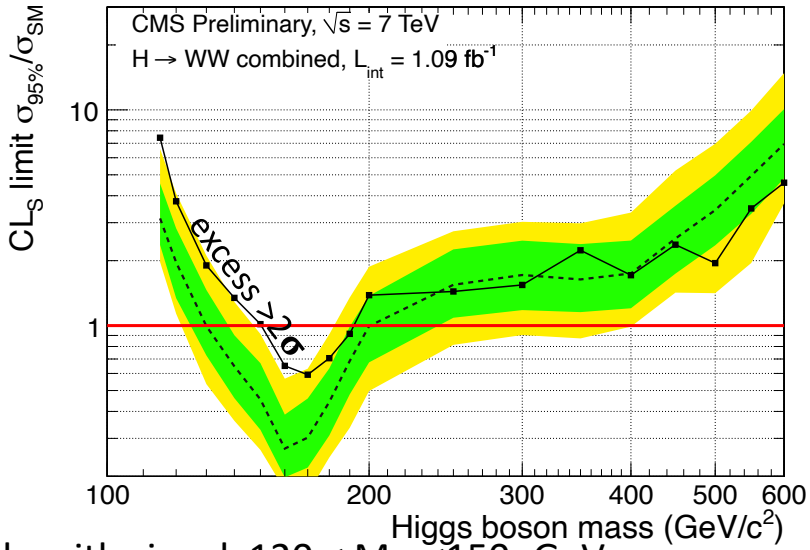
EPS Conference@ Grenoble With Early 2011 Data

- Grenoble was 1st conf with LHC p-p data.
- CMS had wished for 1 fb^{-1} for this conf in late July
- LHC delivered, but most of the data came in June!
- Frenzy to analyze/document and review all SM Higgs results for EPS

CMS Higgs people

Surprise: CMS & ATLAS see excess in $H \rightarrow WW$ mode





Both see (> 2σ) excess in 110-160 GeV, compatible with signal 120 < M_H <150- GeV,
Mass resolution poor due to two missing neutrino → broad enhancement. Best Match at 140 GeV

A very vocal section of community, lusting for Higgs "discovery" were demanding combining 2 results.
Should we?

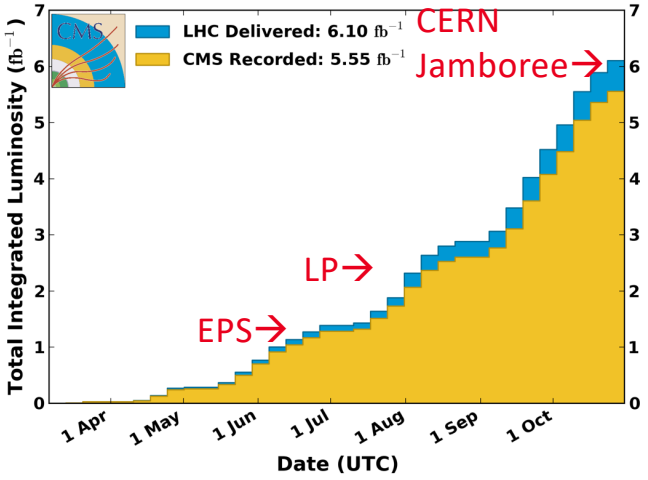
ATLAS & CMS had developed procedure for combining results (LHCHCG) but Gigi pushed not to combine and instead add more data that was rushing in. With more data, the excess went away!

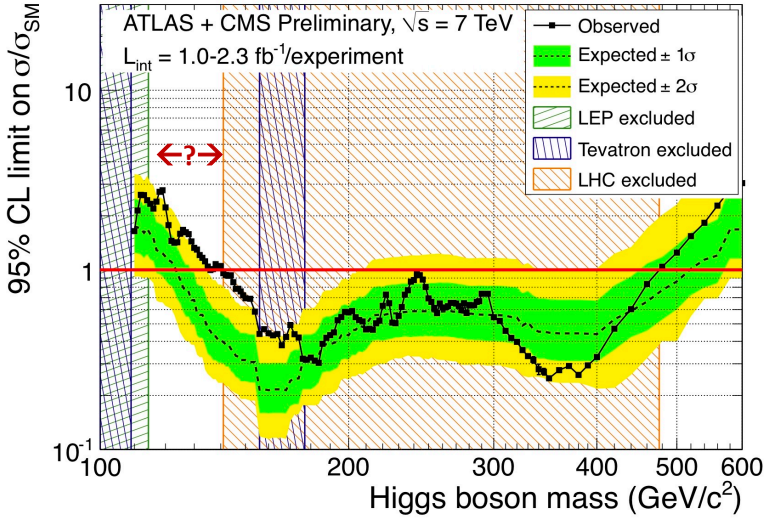
Dodged a bullet!

Trapping The Higgs Boson

- By end of 2011 run, LHC had exceeded its most optimistic projections & delivered ≈ 5 fb^{-1} per experiment.
- data came in fast and was quickly analyzed ➔ Higgs trap quickly narrowed!

Gigi's Plenary Talk @HCP

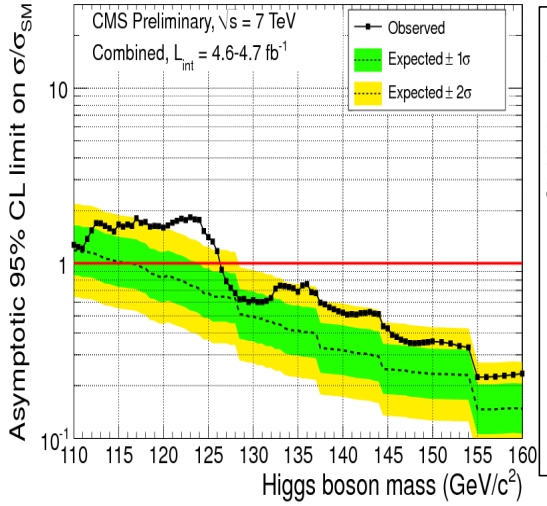


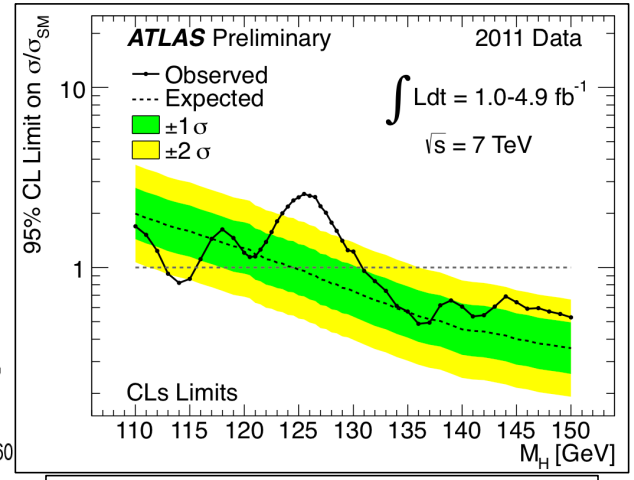


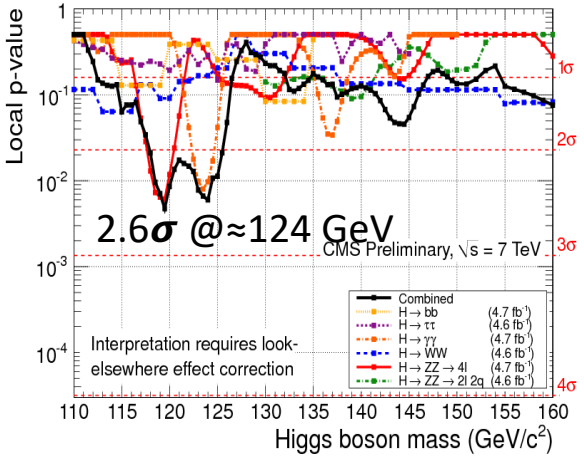
By Nov'11, SM Higgs boson with 141< M_H < 476 GeV was ruled out at ≥ 95% CL by combining ATLAS & CMS measurements.

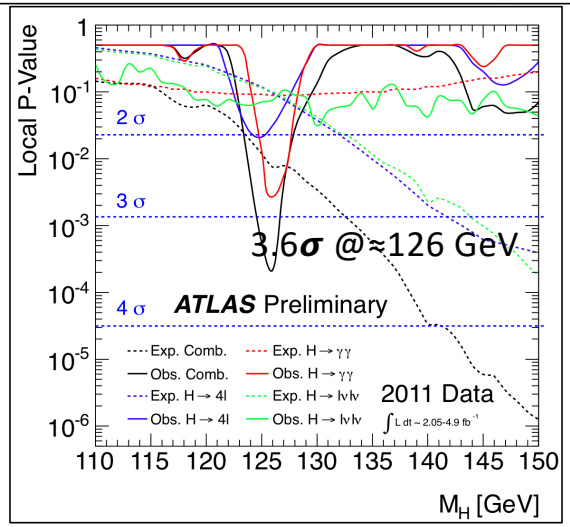
Higgs boson, if it existed, was now trapped in a narrow low mass range !

Show Me The Money!









At the meeting with CERN DG, CMS & ATLAS SP, PC & Higgs coordinators two days before the jamboree, we shared our results

An excess seen in both Expts at similar masses

We all smiled!

2011 Results At The CERN Higgs Jamboree

After correction for look-else-where effect, the global significance of searches from each experiment was: ATLAS (2.3σ), CMS (1.9σ)

But the ***coincidence*** of excess seen in 124-126 GeV range was significant.

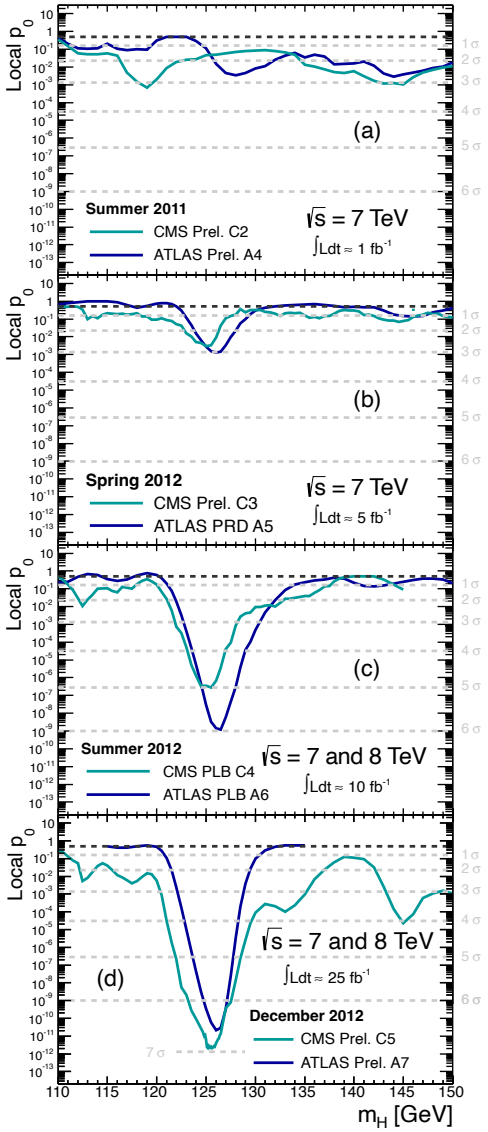
We did not combine the two results,but the world did!

Instead: cautious statements from ATLAS & CMS:

ATLAS: *"We have restricted the most likely mass region for the Higgs boson to 116-130 GeV, and over the last few weeks we have started to see an intriguing excess of events in the mass range around 125 GeV. This excess may be due to a fluctuation, but it could also be something more interesting. We cannot conclude anything at this stage. We need more study and more data. Given the outstanding performance of the LHC this year, we will not need to wait long for enough data and can look forward to resolving this puzzle in 2012."*

CMS: "*We cannot exclude the presence of the Standard Model Higgs between 115 and 127 GeV because of a modest excess of events in this mass region that appears, quite consistently, in five independent channels. The excess is most compatible with a Standard Model Higgs in the vicinity of 124 GeV and below but the statistical significance is not large enough to say anything conclusive. As of today what we see is consistent either with a background fluctuation or with the presence of the boson. Refined analyses & additional data delivered in 2012 by this magnificent machine will definitely give an answer.*"

In retrospect, along with physicists @ CERN, half a million people on the internet were all watching the birth of the Higgs boson



Stages In The Discovery Of The Higgs Boson

In the end, the Higgs discovery was a sprint and not a marathon !

There were hundred ways to get the chase wrong and one way to get it right
With Gigi's wisdom, gentle leadership and ever-present smile,
this intense period was also quite enjoyable!

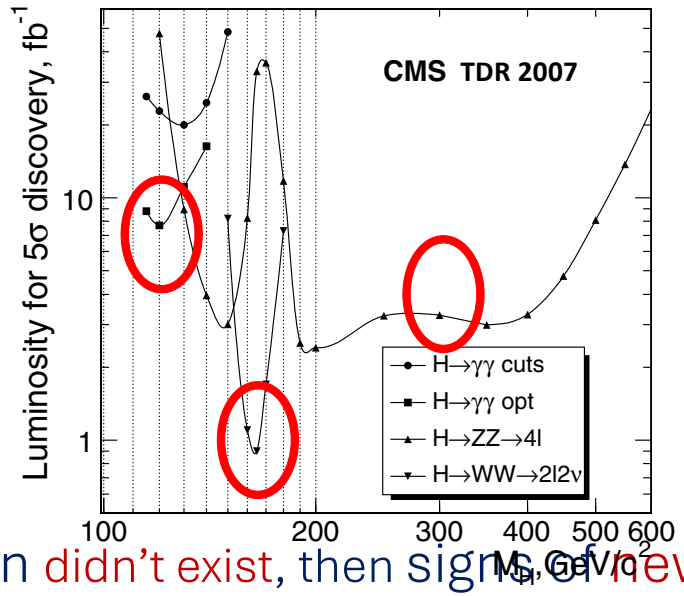
Thank You Gigi 🙏

Happy Sailing!

Spares

LHC & The No-Lose Theorem

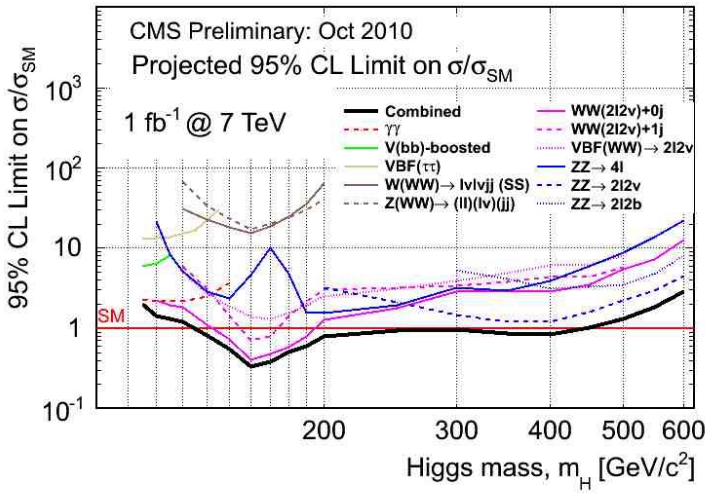
- At $\sqrt{s} = 14$ TeV and instant. luminosity of $10^{34}\ cm^{-2}s^{-1}$, LHC could produce Higgs boson of mass up to ≈ 800 GeV & CMS could find it quickly.

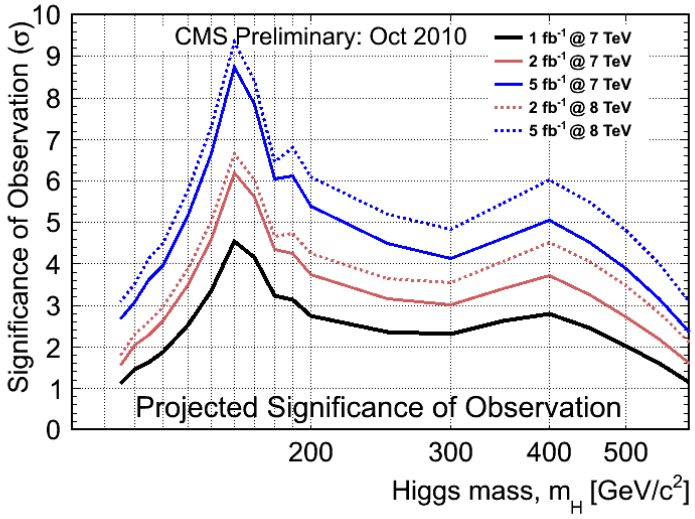


- And if Higgs boson didn't exist, then signs of new underlying strong dynamics in the TeV range should show up! The no-lose theorem.
- So on Sept 10th, 2008, the excitement was extraordinary; ≈ 44 years after the Higgs conjecture for EWSB, resolution was in sight. But ....

Bodrum Projections

CMS-Note-2010/008



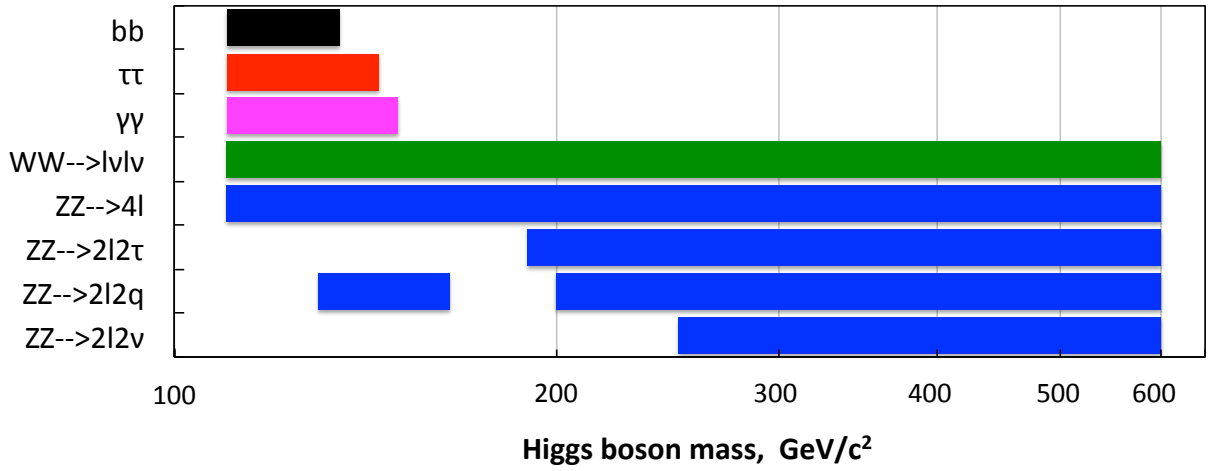


Such plots helped convince CMS to reinvest in Higgs search in 2011++

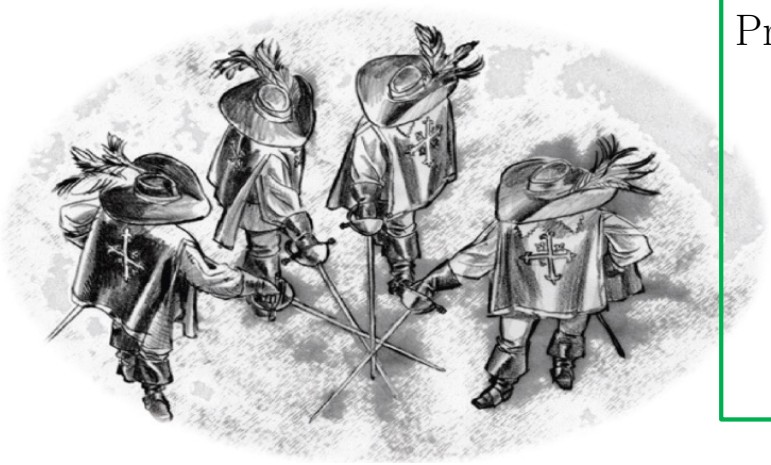
These down-to-earth Bodrum projections validated by the first results at EPS'11 conf.

Searching For Higgs Every Where

Mode * Indicates new modes	Mass Range (GeV)	Expected signal 5 fb^{-1} @ 7 TeV	Higgs mass resolution	Major background
H → γγ	110-150	~70	**1-2 %**	Prompt photons
H → bb *	110-135	~2	**10 %**	W/Z + Jets, Top
H → ττ *	110-145	~ 40-90	**15 %**	Z → ττ
H →WW →2l 2ν	110-600	25-180	**20%**	Non-resonant WW
H → ZZ →4l	110-600	1-16	**1-2%**	Non-resonant ZZ
H → ZZ →2l2τ *	190-600	~2	**10-15%**	Non-resonant ZZ
H → ZZ →2l2q *	130-165/200-600	15-70	**3%**	Z+ jets
H → ZZ →2l2ν *	250-600	3-20	**7%**	ZZ, Z+jets



All For One & One For All



Procedure for the LHC Higgs boson search combination in Summer 2011

The ATLAS Collaboration
The CMS Collaboration
The LHC Higgs Combination Group

August 18, 2011

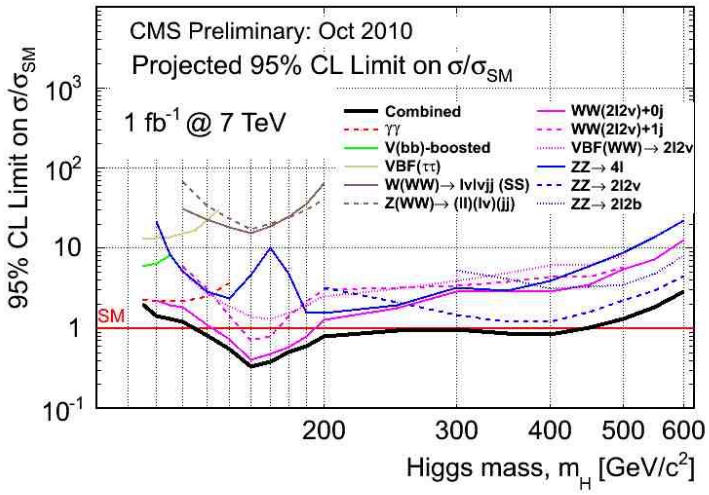
Developed a comprehensive tool to combine many decay modes and their subsets. Growing complexity ➔ huge CPU and Memory needs

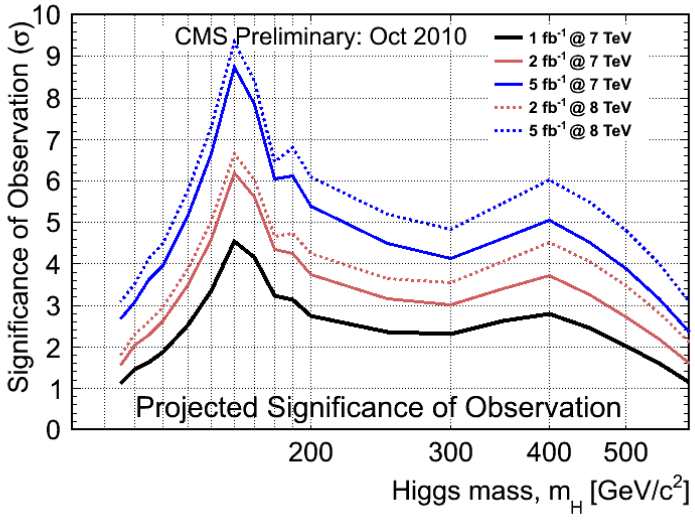
*F**friendly takeover** of entire FNAL T1 happened twice in 2011 with HIG as the **only** user running on 4000 AMD Opteron cores.*

LHC Higgs combination group formed in late 2010 incorporated most of the COMBINE procedure ➔ followed to this day by CMS/ATLAS

Bodrum Projections

CMS-Note-2010/008





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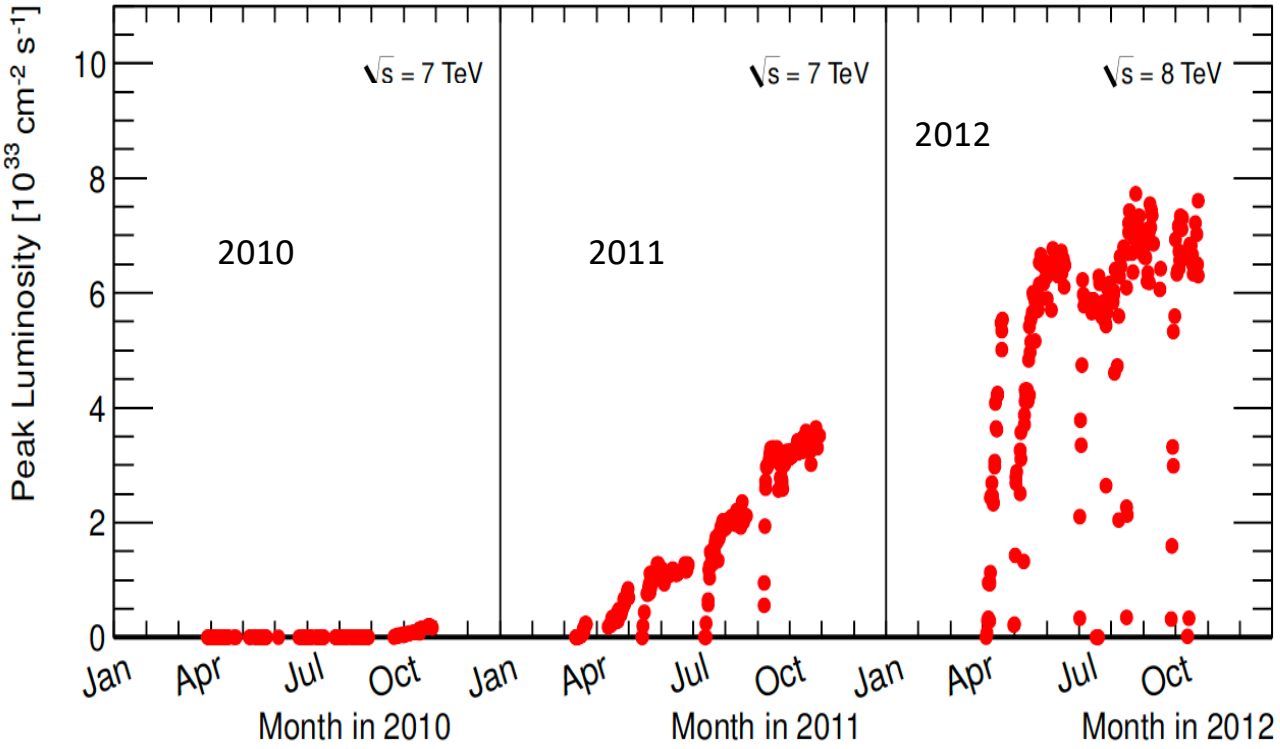
Rise Of The Machine



Ever increasing luminosity required several operational decisions, many balanced on a razor's edge. Any mistake would be costly. Sometimes we gambled and got lucky !

Timeline of Easter Bump Hunt

Apr 21	**Leak of ATLAS note abstract** http://www.math.columbia.edu/~woit/wordpress/?cat=9 [With 37.5~pb−1 data from 2010 and 26.0~pb−1 from 2011, we observe a γγ resonance around 115 GeV/c2 with a significance of 4σ … for this resonance is about **thirty times** larger than the expectation from Higgs to γγ in the standard model] We contacted H →γγ conveners to prepare for quick look at 2011 data, activate core team
Apr 22	2011A data not suitable for narrow resonance search. Paolo M… …ares a custom skim & re-reco of γ PD at Rome T2 → γγ SD Friday evening Management meeting: Asked to for… …to quickly investigate γγ, WW,ττ and report back. We aler… …veners Prepare for official re-reco of e, 2e and γ … …t from ECAL
Apr 23	Private re-reco finished at Rome. … …uickly moved to all Higgs T2 ++. First plots from data (58 pb-1) … …→γγ selection shows no bump
Apr 24	Investigations on re-re… …ues using different independent selections. Vary/Add cuts.. … → **No bump**
Apr 25	Show & T… … results in special Monday Management meeting: https… …ch/conferenceDisplay.py?confId=136590
Apr 26	… findings discussed in Higgs PAG meeting
Apr …	Report to the collaboration; prepare a short γγ resonance search document (in case of ATLAS action); Refine 2011 selection & run on official datasets

Ruled out ATLAS bump in 1 week in spite of Easter holiday

Proof that all organs of CMS worked together in fantastic harmony.

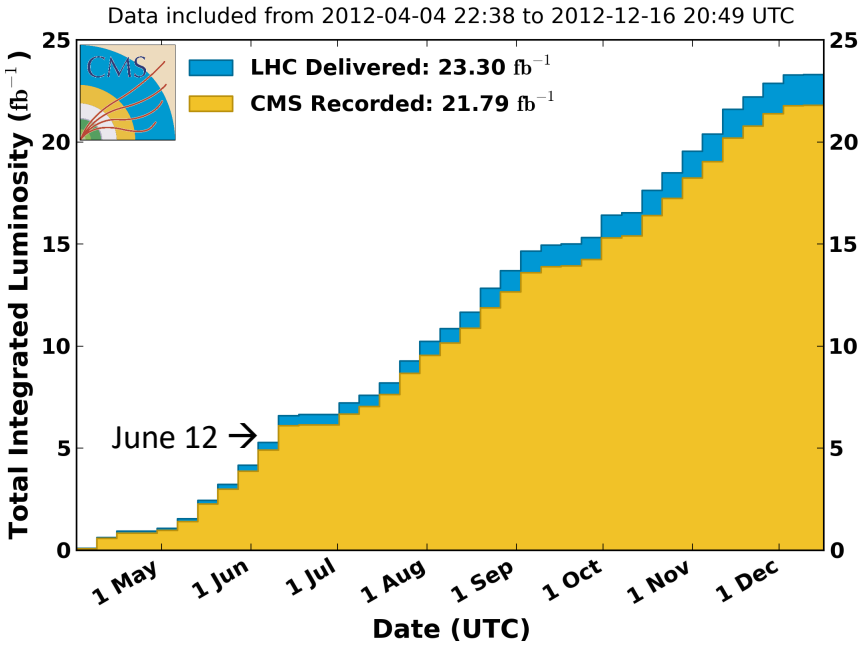
Thank you ATLAS !

In 2012, Data Came Fast and at $\sqrt{s} = 8$ TeV

Thanks to Gigi, stage was now all set for discovery. We waited for LHC to deliver a bit more data that came by June 2012

$\sqrt{s} = 8$ TeV⇒ 25% higher Higgs production cross section

More challenges arising from higher intensity LHC operation (e.g.pileup) had to be overcome.



June 12, 2012 cutoff CMS discovery dataset
$\approx 5.1\ fb^{-1}$ at $\sqrt{s} = 7$ TeV & $\approx 5.3\ fb^{-1}$ at $\sqrt{s} = 8$ TeV

Culminated in a brilliant discovery

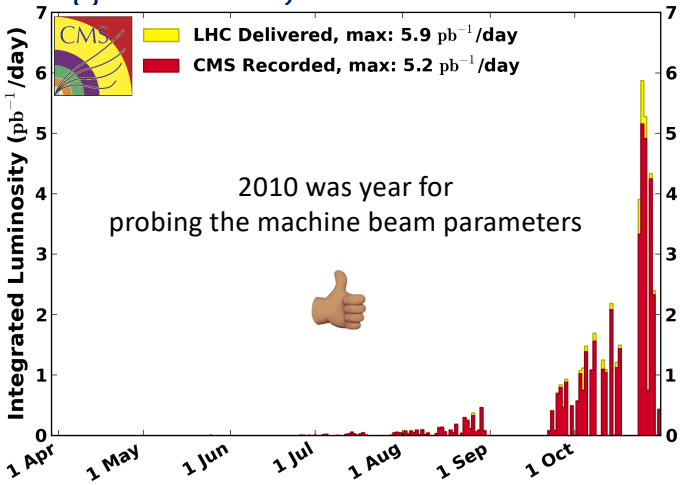
First Harvest@ Grenoble With Early 2011 Data

Celebrated with ATLAS

A New Hope

- CMS used downtime to perfect some very sharp analysis tools: Global Event description (Particle Flow), τ-tagging, b-tagging etc. crucial for expanding Higgs searches much beyond TDR.
- After re-commissioning in 2009, LHC moved to 7 TeV in 2010

Physics Coordinator
at the start of data taking

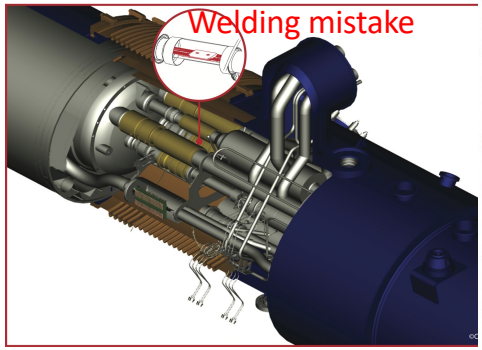


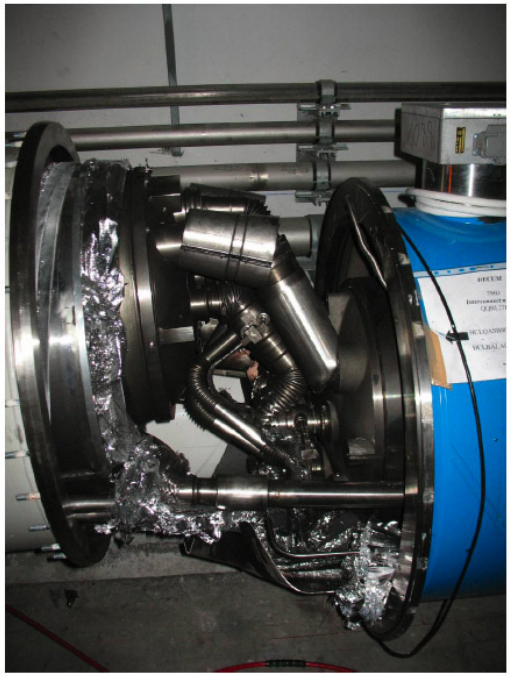
Game On !

- By summer'10, talk of LHC delivering ≈1 fb^{-1} ⇒ Prospects for Higgs hunt brightened !
- At Chamonix LHC retreat: plans for delivering ≥ 3 fb^{-1} in 2011 !!

Ghost In The Machine

On September 19, nine days after the start of LHC commissioning: A resistive zone developed in the dipole bus bar magnet interconnects leading to thermal runaway, followed by the development of an electrical arc, initially across the interconnect, later puncturing the helium enclosure, and finally puncturing the beam pipes. The release of the helium caused a pressure wave over a region of more than 400m resulting in damage to magnets, interconnects and pollution of the ultra-high vacuum system.



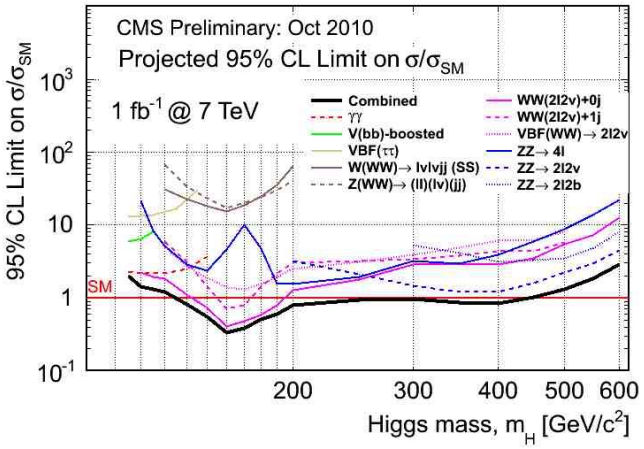


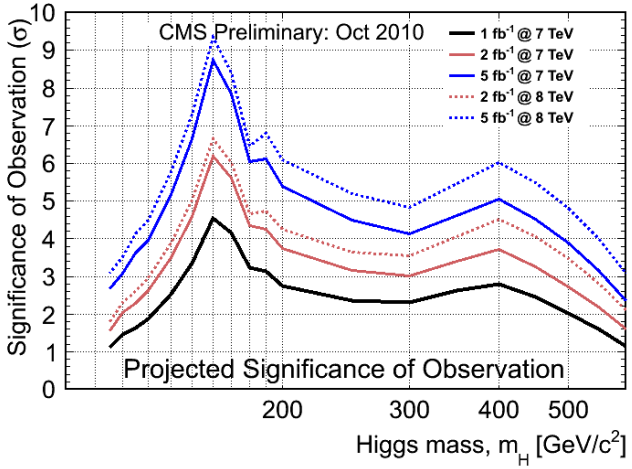
Searching For Higgs Every Where: Drops In Bucket

Mode * Indicates new modes	Mass Range (GeV)	Expected signal 5 fb^{-1} @ 7 TeV	Higgs mass resolution	Major background
H → γγ	110-150	~70	**1-2 %**	Prompt photons
H → bb *	110-135	~2	**10 %**	W/Z + Jets, Top
H → ττ *	110-145	~ 40-90	**15 %**	Z → ττ
H →WW →2l 2ν	110-600	25-180	**20%**	Non-resonant WW
H → ZZ →4l	110-600	1-16	**1-2%**	Non-resonant ZZ
H → ZZ →2l2τ *	190-600	~2	**10-15%**	Non-resonant ZZ
H → ZZ →2l2q *	130-165/200-600	15-70	**3%**	Z+ jets
H → ZZ →2l2ν *	250-600	3-20	**7%**	ZZ, Z+jets

A surprisingly rich discovery potential

Ability to rule out large range of Higgs mass. With just 1 fb^{-1} exclude $130 < M_H < 480$ GeV





Convince CMS to reinvest effort in Higgs search ASAP!