Reflections on the Higgs discovery

Higgs@10

Joe Incandela

15 July 2022

Intro

- *The Higgs discovery was made possible by everyone involved in the experiments*
  - *Yes, not all groups worked on the final analyses, but there was so much more to it:*
    - *Incredible detectors that were the culmination of generations of experience and a decade of construction*
    - *Operations teams that kept the detectors up and running at unprecedented near-perfect level around the clock*
    - *Trigger, Computing and Offline systems that were also unprecedented in their scale, global coverage and performance*
  - *and the potential for the Higgs discovery was one of the things that brought us all together in the first place*
- *An achievement of an entire community*
  - *Drawing on experience of decades of research*

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  - ***Yes, not all groups worked on the final analyses, but there was so much more to it:***
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    - ***Trigger, Computing and Offline systems that were also unprecedented in their scale, global coverage and performance***
  - ***and the potential for the Higgs discovery was one of the things that brought us all together in the first place***
- ***An achievement of an entire community***
  - ***Drawing on experience of decades of research***
- ***The LHC is the 4th generation of hadron colliders. A lot was learned in prior generations, often the hard way…***

The first 2 generations (ISR and Sp$\bar{p}$S)

“*The ISR missed the J/ψ and later missed the Υ**

“*...it took a long time to overcome two major difficulties of collider physics... first... the relatively low luminosity... second...the very wide angle spread over which particularly interesting events, such as lepton pair events, may occur...*

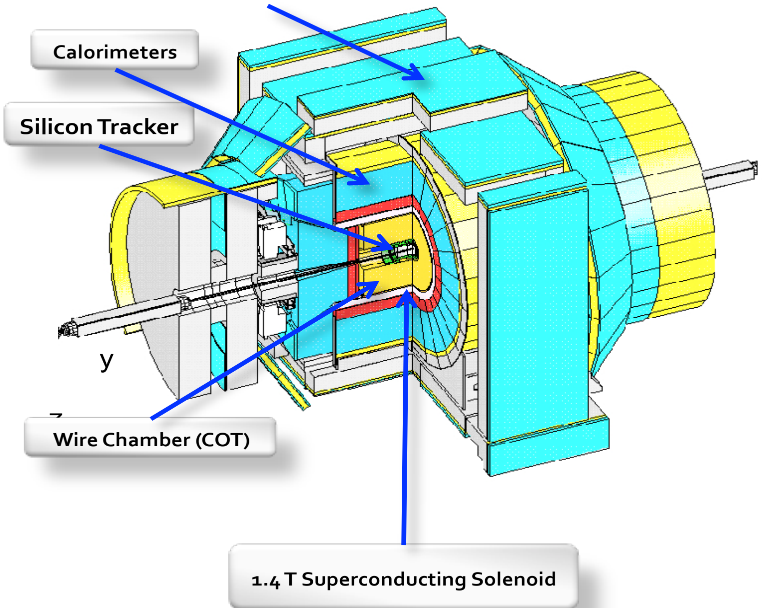
The answer is, of course, sophisticated detectors covering at least the whole central region ($45^o < \theta < 135^o$) and full azimuth.”

- They had not anticipated quarks and later as they were upgrading the detectors for this, they missed the Υ, which was discovered at FNAL
- The next generation would not be a repeat

- **Sp$\bar{p}$S experiments (UA1,UA2), were better prepared**
  - Fully hermetic, they were able to discover the W and Z very easily
- **Tevatron experiments (CDF, DZero) went further**

*Maurice Jacob, Kjell Johnsen, “A Review of Accelerator and Particle Physics at the CERN ISR”, CERN 84-13, (30 November, 1984)

The Tevatron

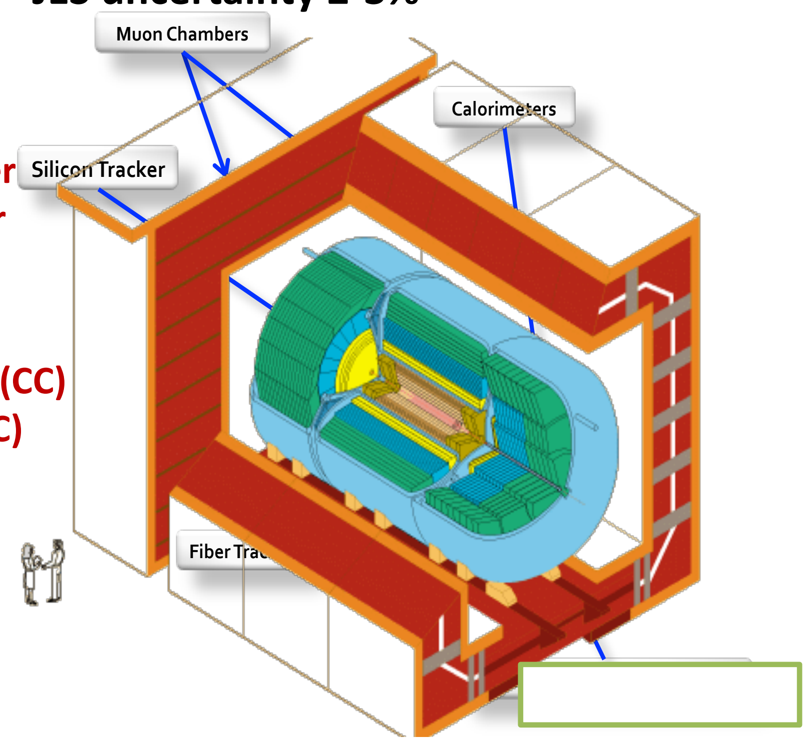


~5k tons (1/2 in central)
~10m each direction
~100 Hz readout
1.4 Tesla magnet

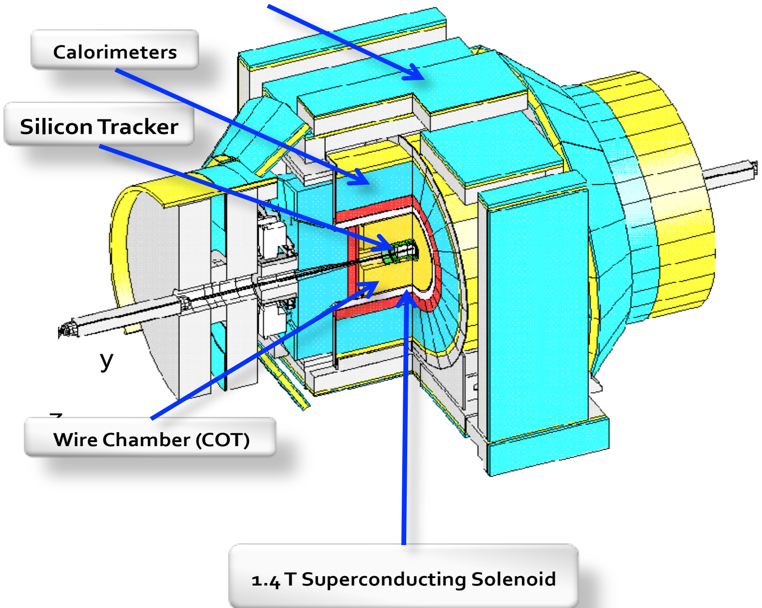
- Tracking |η|< 2.0-2.5
  - Drift cell tracker |η|<1.1
  - ~720k channels Silicon
  - Mouns |η|<1.5
- Pb/Cu+Scintillator EM/Had calo. |η|<3.2
  - JES uncertainty 2-3%

CDF and DØ had very comparable performance at the end of Run 2

- Central Tracking
  - Si Micro-strip Tracker
  - Central Fiber Tracker
- 2 T Solenoid Magnet
- Calorimeters
  - Central Calorimeter (CC)
  - End Calorimeters (EC)
- Muon System
  - 3 sets of detectors
  - Scintillating tiles
  - Gas Drift Tubes
- 1.8 T Toroid Magnets



Tevatron



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They were originally very different - following the example of UA1 and UA2, resp., who came before them…

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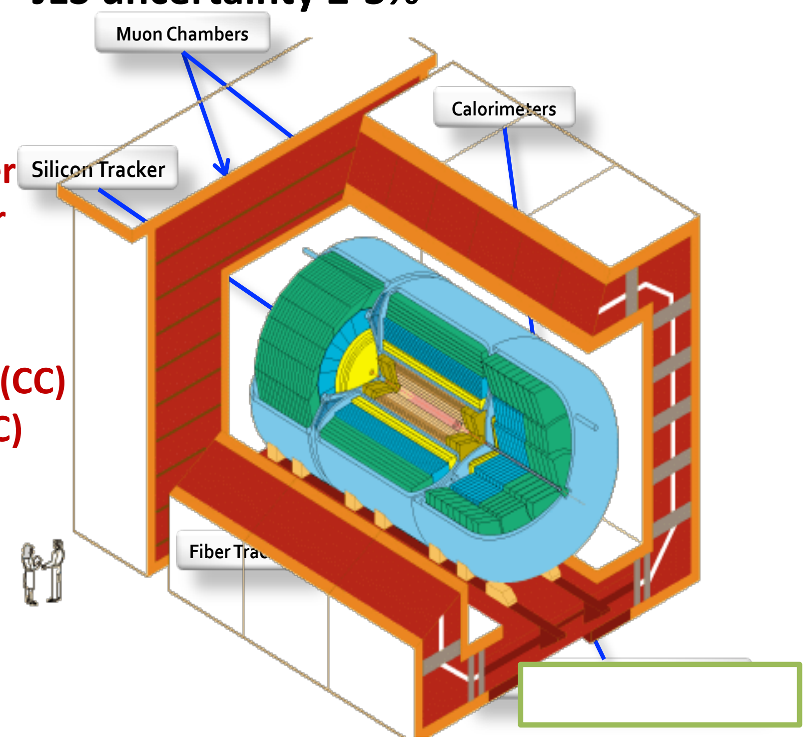
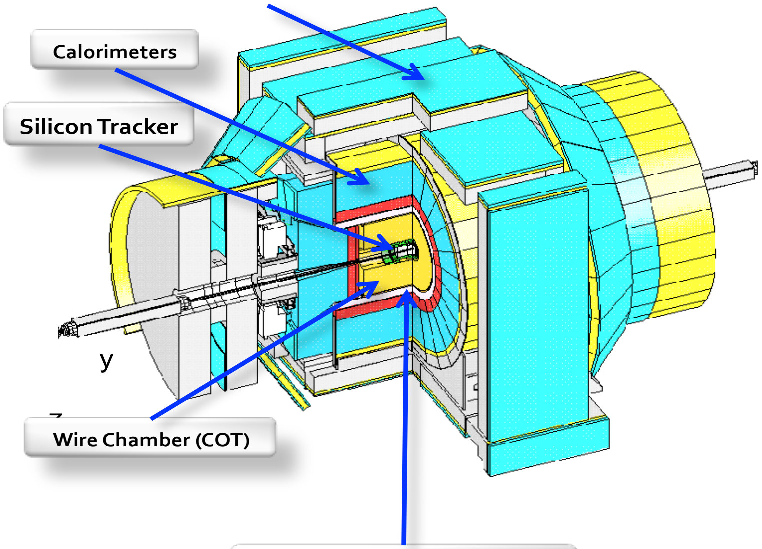


Tevatron



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At the Tevatron it was learned that a magnetic field, high efficiency outer tracker and high granularity silicon layers could make up for deficiencies in calorimetry (i.e. p vs. E)

- 2 T Solenoid Magnet
- Calorimeters
  - Central Calorimeter (CC)
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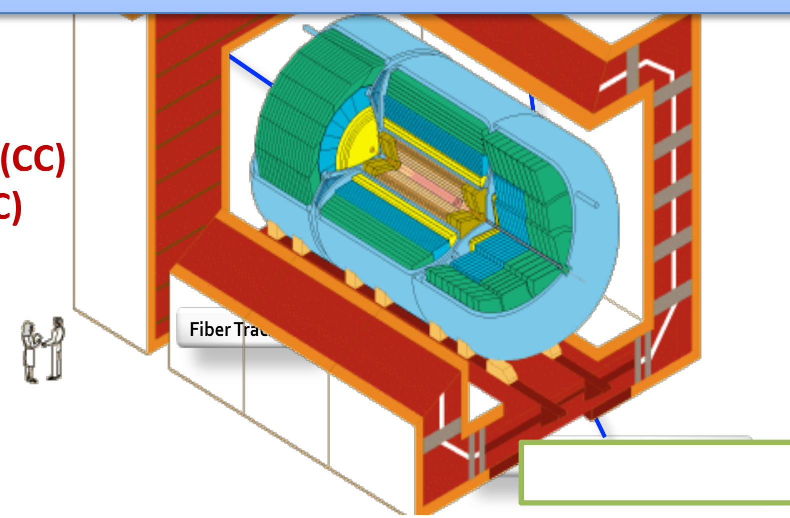
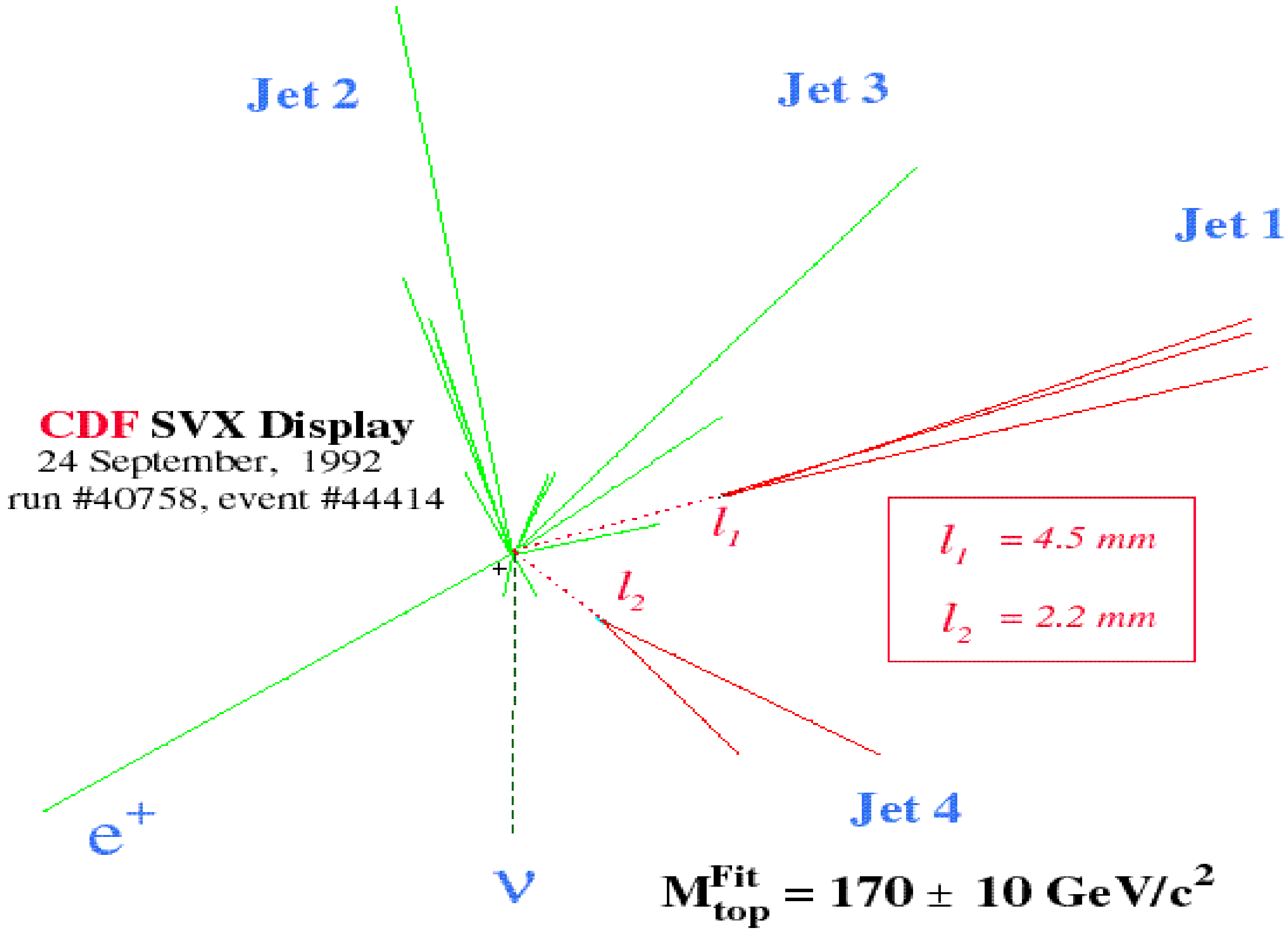


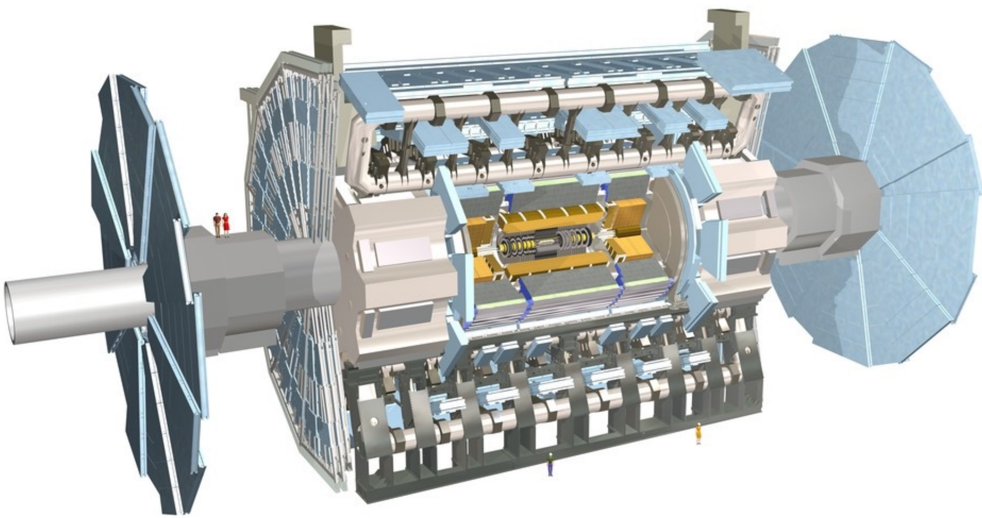
CDF's 1st Top Event



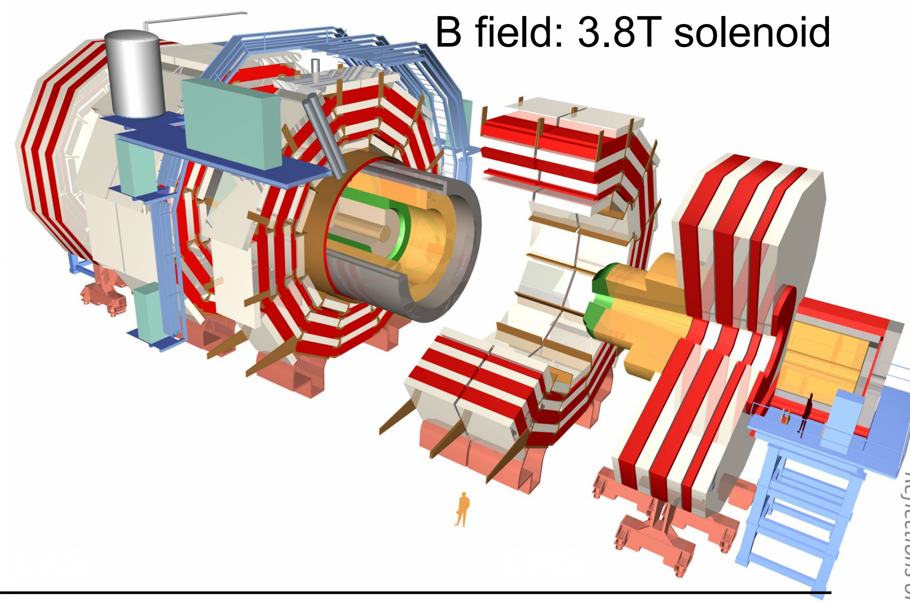
10th topical workshop on $p\bar{p}$ collider physics: 9 May ***1995*** *FNAL*

ATLAS and CMS

B field: 2T solenoid, 4T toroid



B field: 3.8T solenoid



CMS and ATLAS were built upon experience from not only the Tevatron but also the LEP experiments: Extensive use of Si pixels and strips, big investments in EM calorimetry including crystals (CMS) for $H \rightarrow \gamma\gamma$, extensive muon systems. Some different technologies, but very comparable in performance.

ATLAS and CMS

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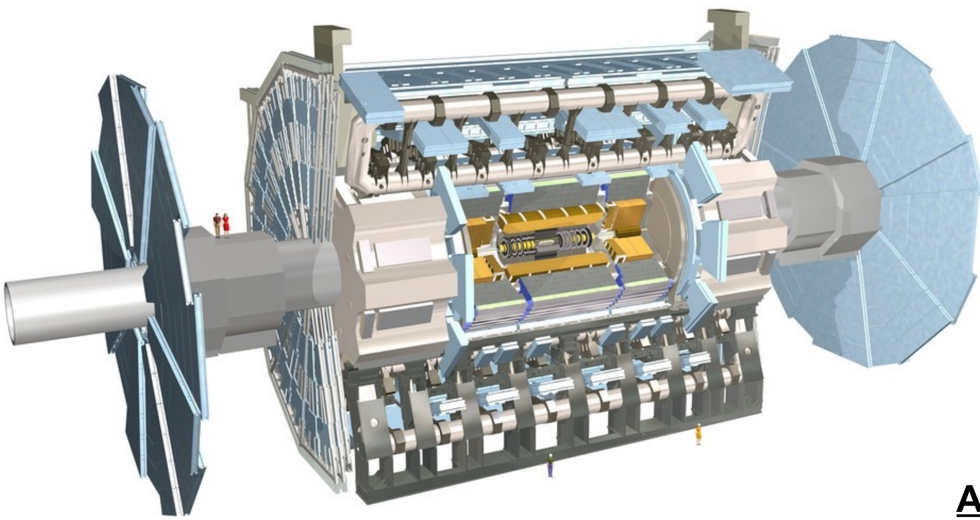

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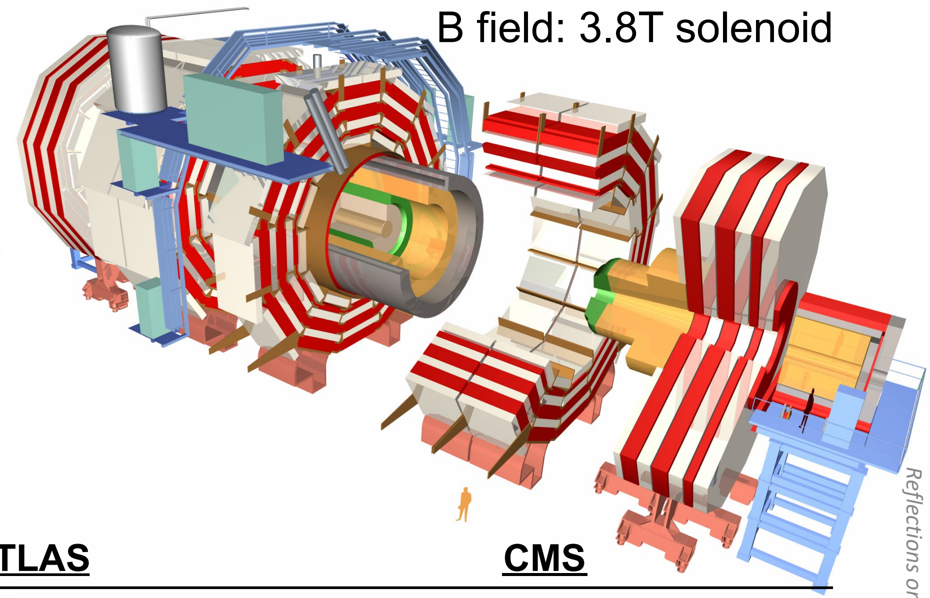
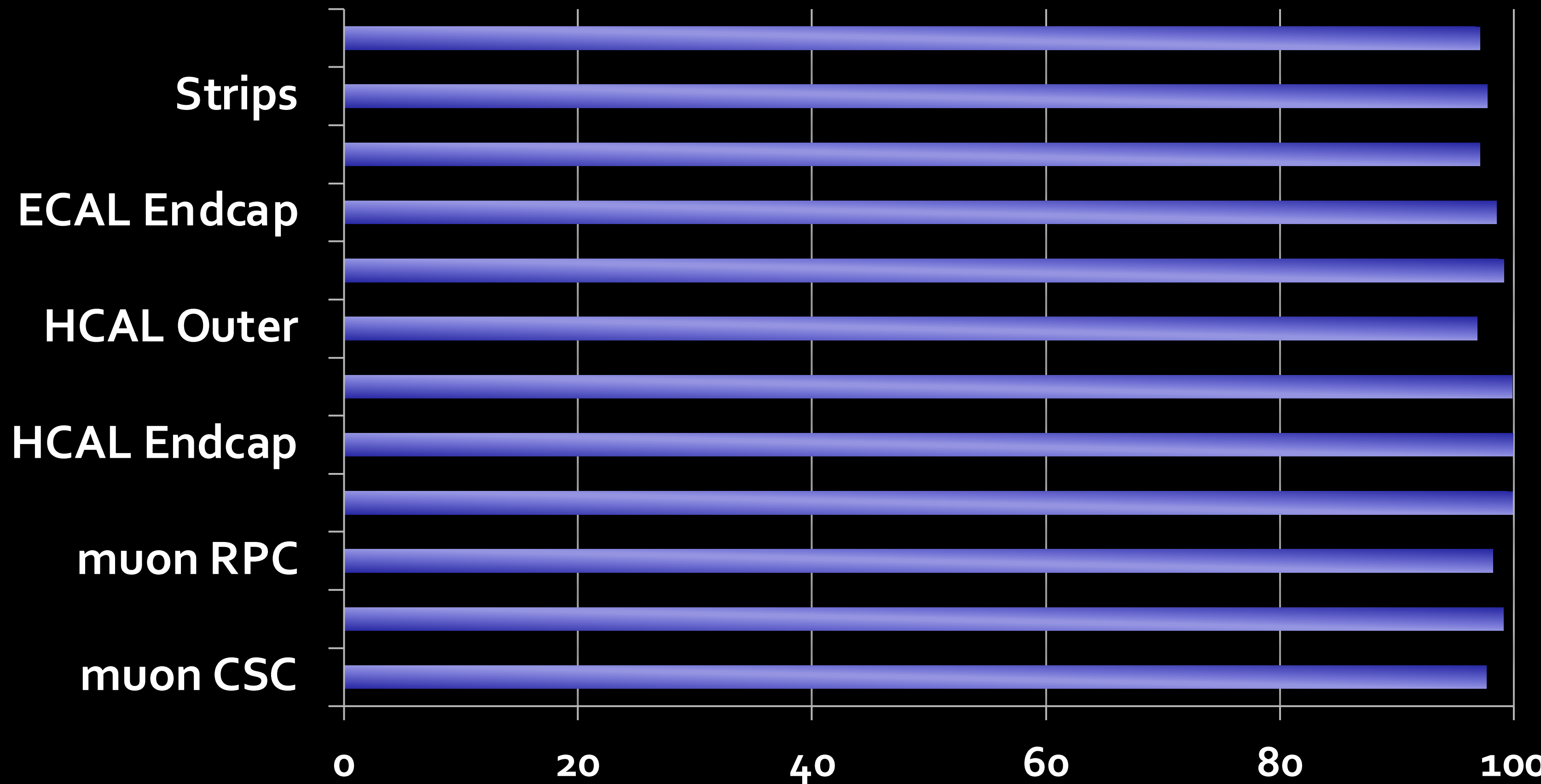


	ATLAS	**CMS**
Inner tracker : |η| coverage	2.5	2.5
$\sigma(P_T)/P_T$ at P_T=100 GeV	3.8%	1.5%
EM calorimeter: |η| coverage	3.2	3.0
σ(E)/E	10%/√E+0.7%	3%/√E+0.5%
HAD calorimeter: |η| coverage	4.9	5.2
σ(E)/E (EM+HAD combined)	50%/√E+3%	85%/√E+7%
Muon system: |η| coverage	2.7	2.4
$\sigma(P_T)/P_T$ at P_T=1 TeV (standalone)	12% (|η|<1.5)	15-40% (depend on η range)

Current Operational Status*



Pixel Tracker	Strip Tracker	Preshower	ECAL Barrel	ECAL Endcaps	HCAL Barrel	HCAL Endcaps	HCAL Forward	HCAL Outer	Muon DT	Muon CSC	Muon RPC
97.1%	97.75%	97.1%	99.16%	98.54%	99.92%	99.96%	99.88%	96.88%	99.1%	97.67%	98.2%

*As of June 15 2012

Presented July 4, 2012

2005-2009

In CMS this period took us from the Physics TDR to first collisions

Prologue

- Paris said it many times…
  - "We will prepare in a series of successive approximations…"
- And so we did…
- Past 3 years…
  - Transition from studies for 10's or 100's fb^{-1} to…
    - Physics accessible with < 1 fb^{-1}
      - Data-driven methods
      - Improved Object ID
    - Tracking down to ~100 MeV
    - Tracking jets (JPT), tcMET, Particle flow
    - Lean trigger table, primary and secondary datasets defined
    - October Exercise, Physics accessible with < 1 pb-1
    - 900 GeV 1st paper(s)
  - …Physics accessible with <1 nb^{-1}

Top-level view of 2007

- **Goal: create physics menu for 10, 100 & 1000 pb^{-1}**
  - Physics menu includes trigger menu, full set of physics topics for each luminosity, list of publications for each analysis
- **Tools I: HLT**
  - Complete HLT algorithms for each object
  - CPU measurements, efficiency vs rate
- **Tools II: physics object reconstruction**
  - Complete and validate full set of objects (software)
  - Identify all data samples (triggers) which will be needed for measuring all efficiencies (from data)

P. Sphicas
Plan of Work

Physics Days
Jan 18, 2006

5

This talk mainly covers the last stretch

CRAFT09, Oct X and 900/2360 GeV
Physics and prep. for 2010 (7 TeV?)

Physics Coordination report at Dec. 2009 CMS week - JI

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Better prepared than any previous generation at start of data-taking!

This talk mainly covers the last stretch
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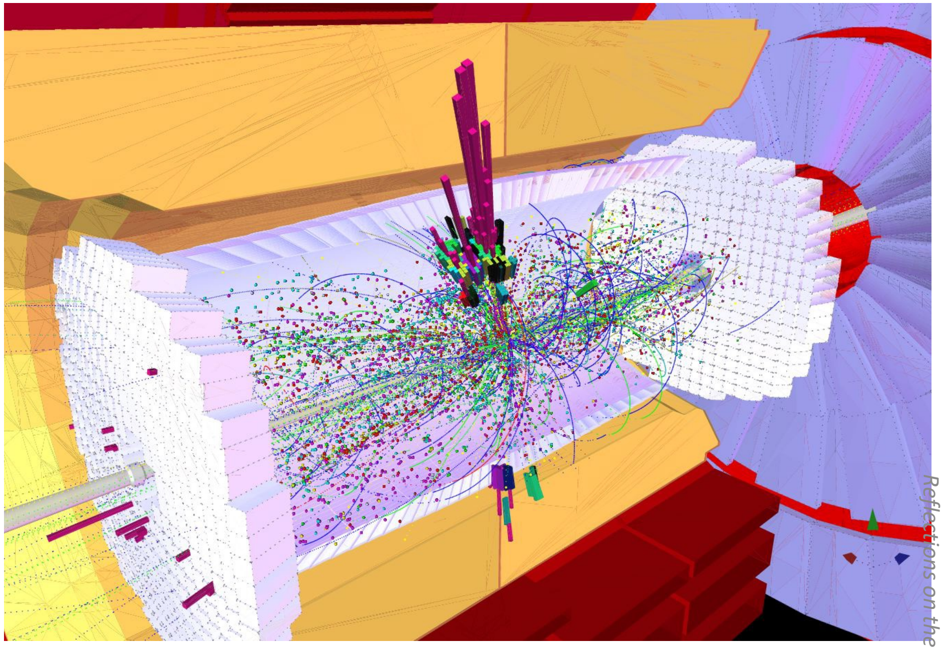
Physics Coordination report at Dec. 2009 CMS week - JI

Another step forward: CMS Particle Flow

- **Reconstruct/identify**
  - **Charged hadrons**
  - **Photons**
  - **Neutral hadrons**
  - **Electrons, muons**
    - **Even non-isolated**
  - **Taus**

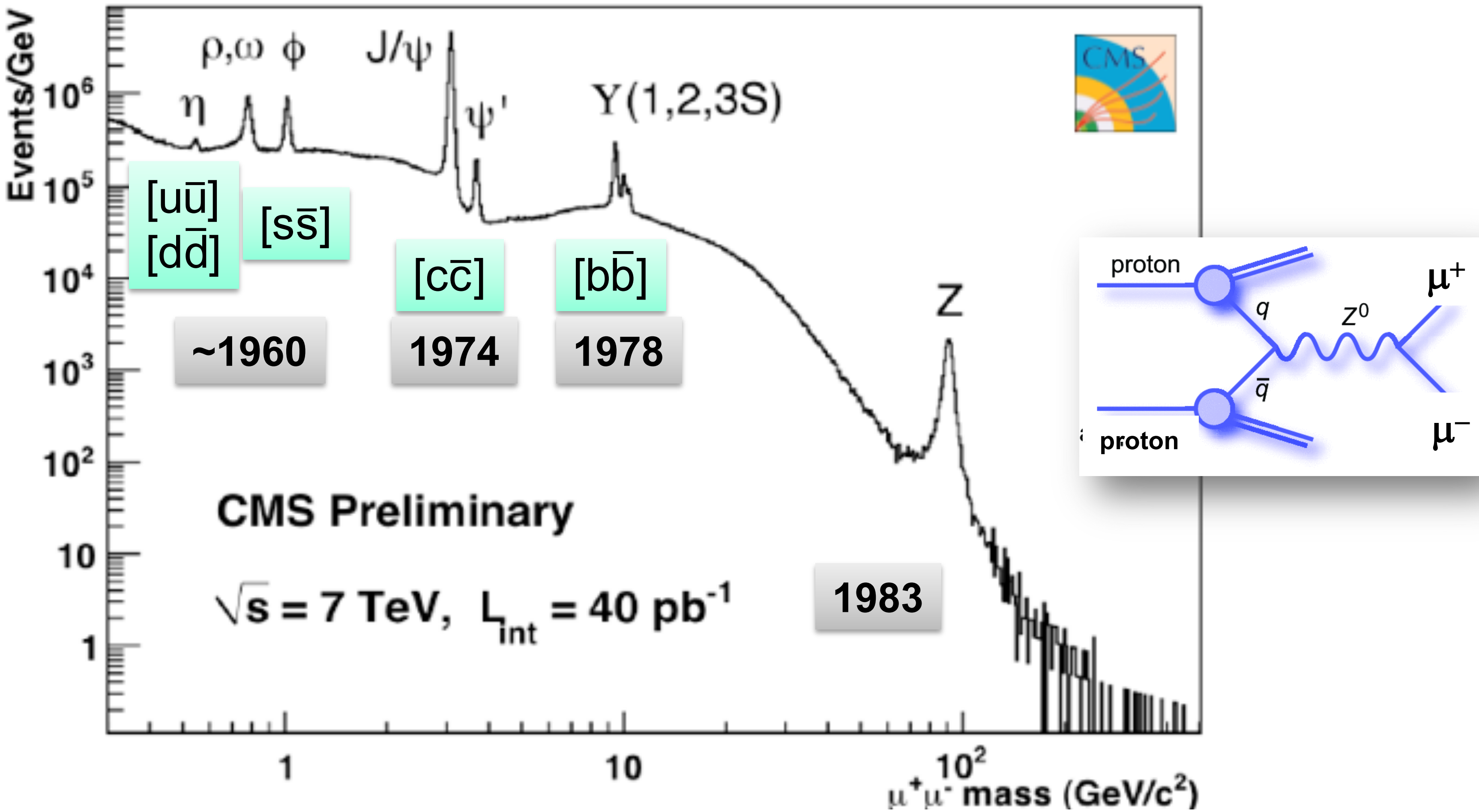


- **Made possible by an extraordinary detector!**
  - **Use all sub-detector information, esp. fine granularity tracking**
  - **4T field spread particles out**
    - **effectively increasing the granularity**

arXiv:1401.8155

2010

Re-discovery of the Standard Model



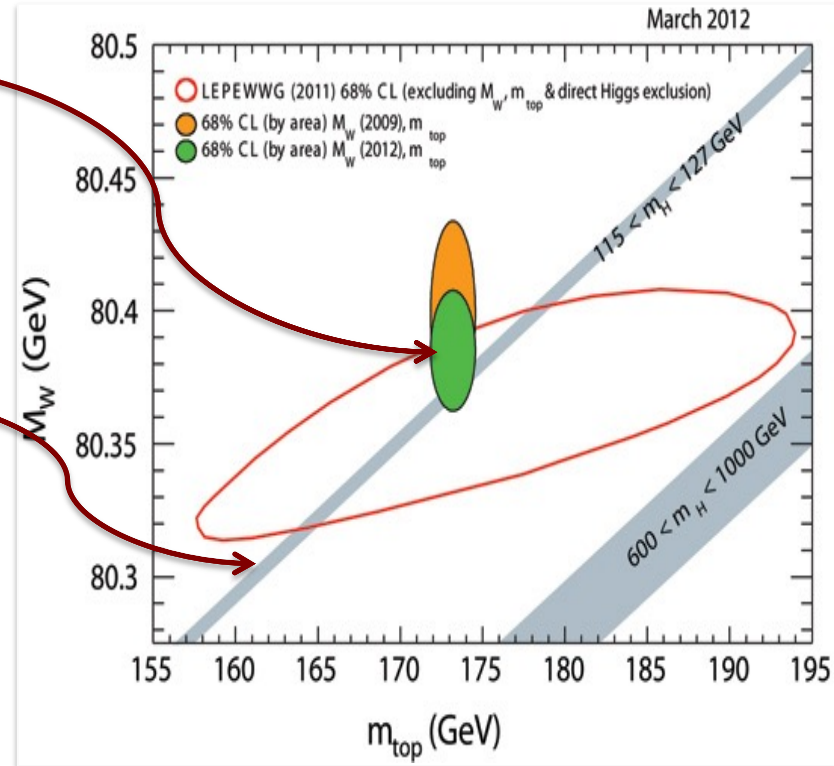
40 pb^{-1} collected in 2010

2011

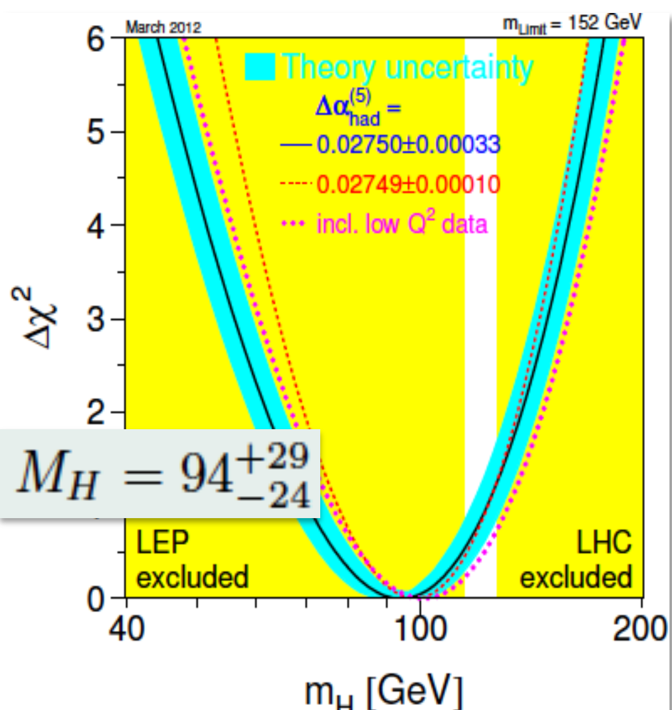
SM Higgs in perspective

1. M_{top} vs. M_W

- Tevatron M_W *Tours de Force!!*
  - m_W = 80385 ± 15 MeV (World Ave – Mar 2012)
- Shifts SM Higgs expectation



2. Colliders leave little space



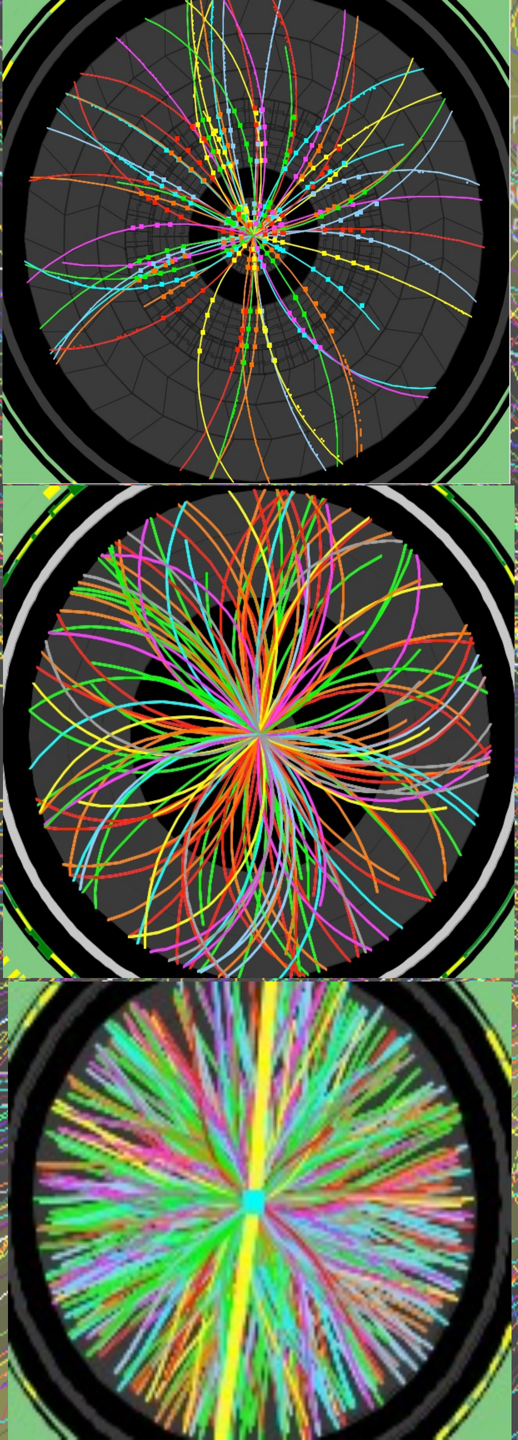
$$M_H = 94^{+29}_{-24}$$

Combined precision Electroweak data

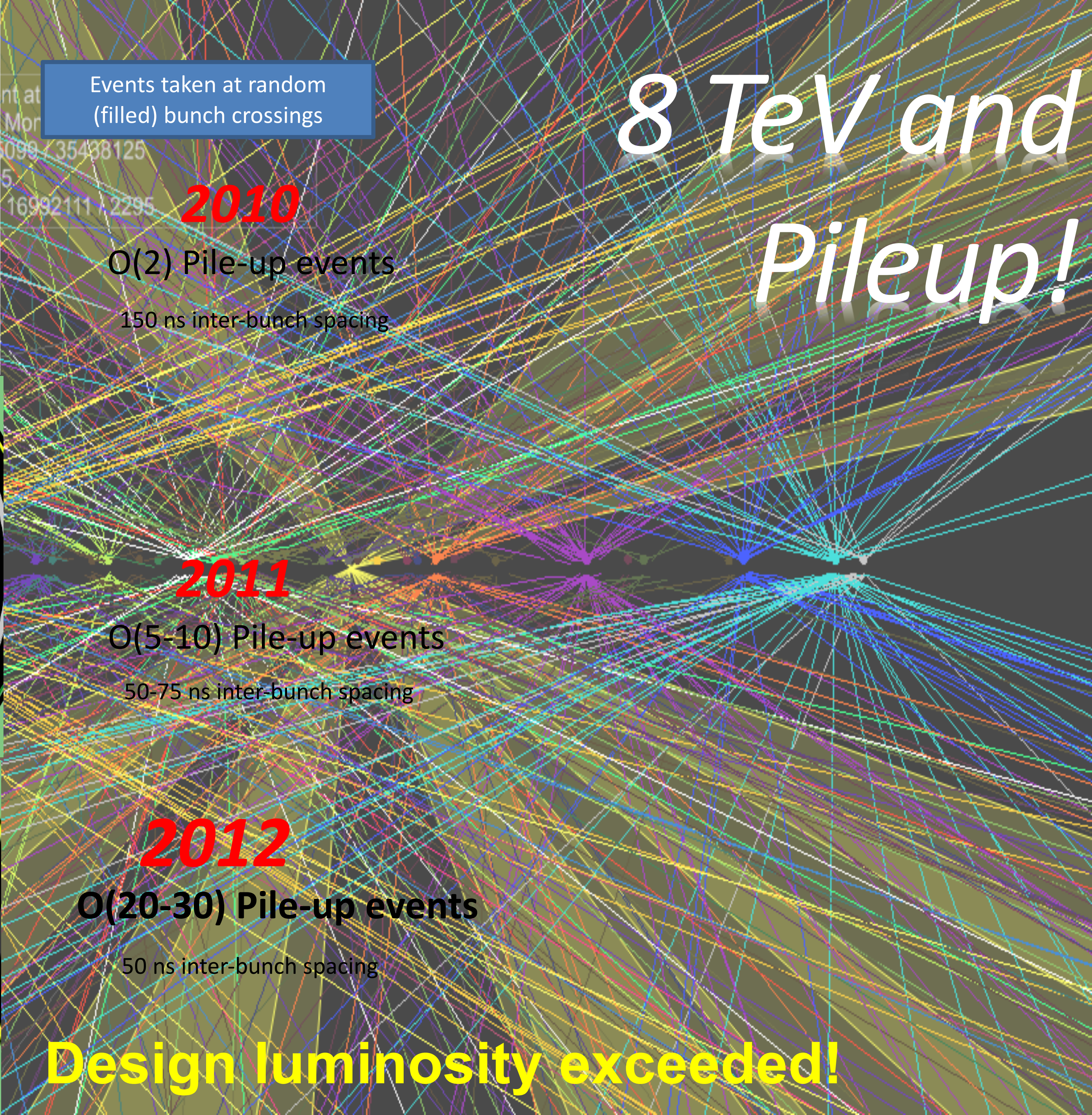
This is the main story of 2011

We eliminated >450 GeV of the mass range.

The year of the Dragon…



8 TeV and Pileup!



Events taken at random (filled) bunch crossings

2010

O(2) Pile-up events

150 ns inter-bunch spacing

2011

O(5-10) Pile-up events

50-75 ns inter-bunch spacing

2012

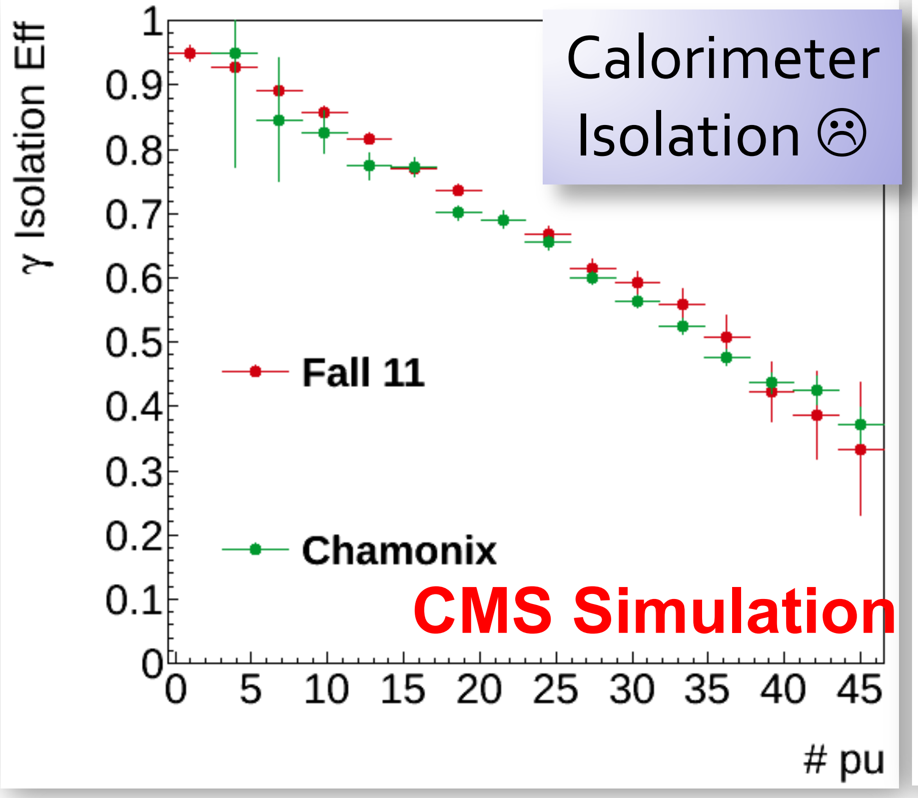
O(20-30) Pile-up events

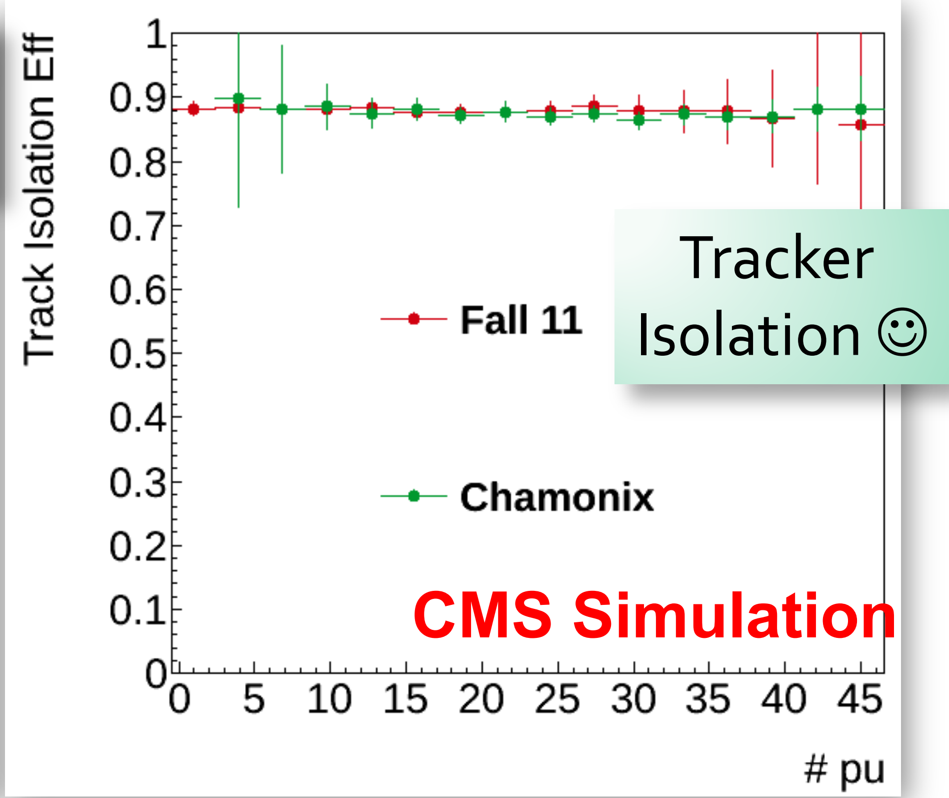
50 ns inter-bunch spacing

Design luminosity exceeded!

High-PU: Effect on γ Isolation

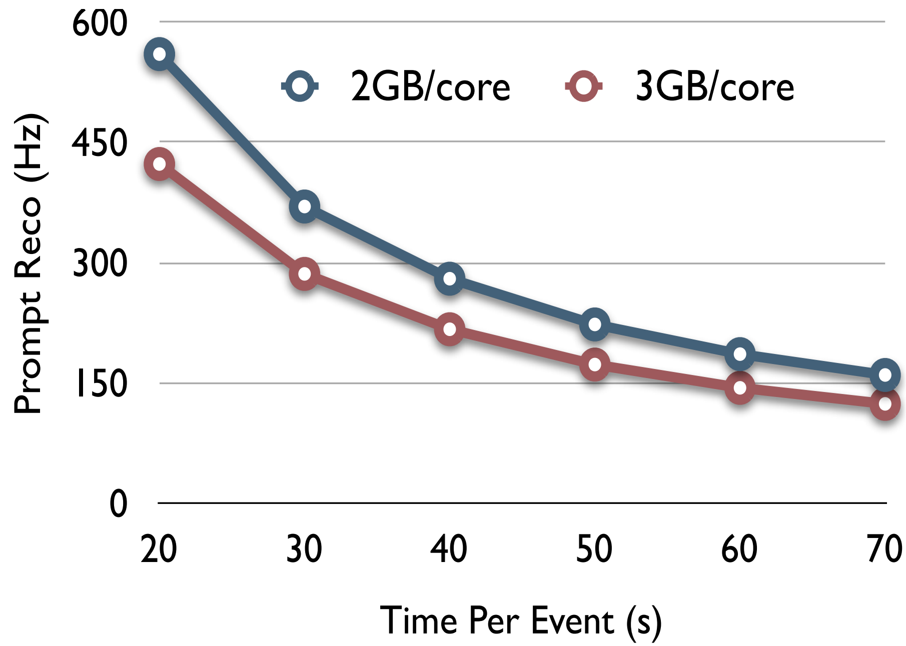
- **Photon isolation efficiency hit hard** (5% relative isolation cut)
- **No effect on track isolation** (same 5% relative isolation cut)





CMS Preparations for 8 TeV and high PU in 2012

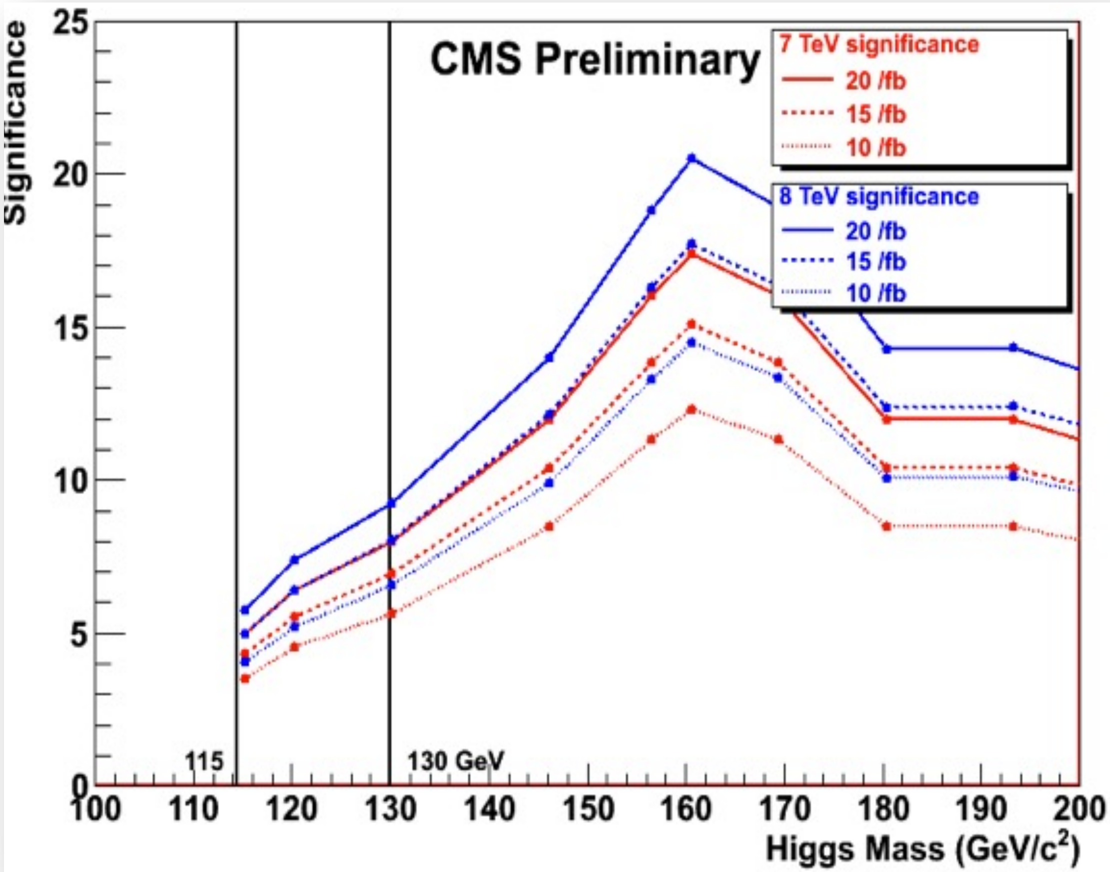
- **Last Autumn**
  - **cpu time for high PU >40 sec/event**
  - **Memory usage well above 2 GB.**
    - **Means we cannot use all the cores!**
  - **Even 200 Hz looked hard!**
- **Task force started December '11**
  - **Major success!**
- **Improvements**
  - **A factor 2.5 in speed**
    - **Under ~15" per event on average**
  - **Much reduced memory use**
    - **Well under 2 GB**
- **Physics performance unchanged**
  - **Kept our AAA rating:**
    - **E.g. no explicit p_T threshold on tracks**



Prompt Reconstruction at Tier-o:
Limit on our data-taking rate versus event processing time for low and high memory use cases

Presented July 4, 2012

Now what do we expect ?

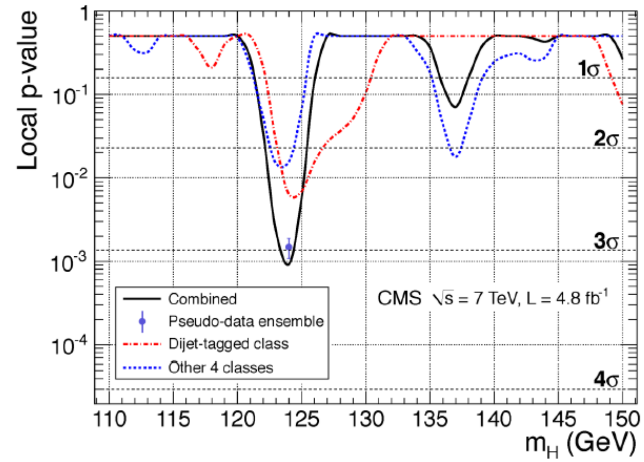


"We could find the SM Higgs or kill it by ICHEP!"

I contacted Geoffrey Taylor (2012 ICHEP Org. Comm. Chair) and Rolf for a meeting …

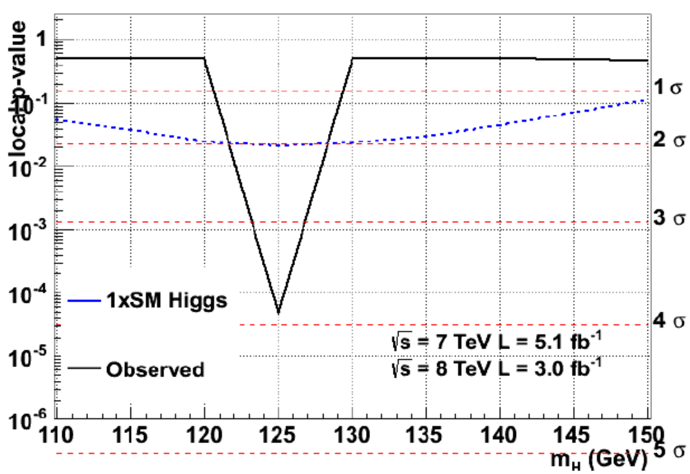
June 15, 2012

P-Value 2011 (Cut Based)

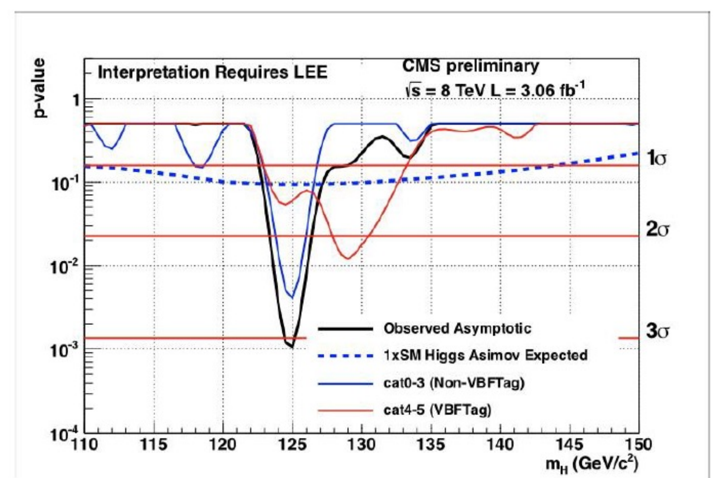


"Are you ready?"

P-Value 2011+2012 (Cut Based)



P-Value 2012 (Cut Based)



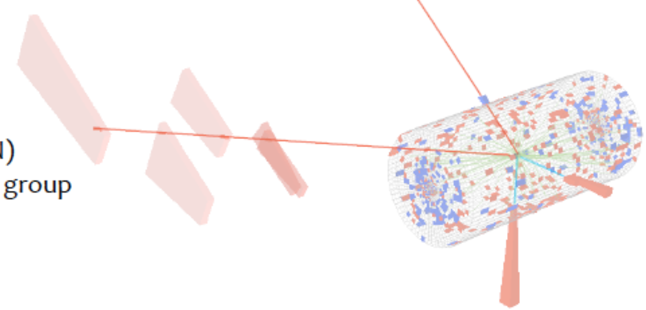
Search for H→ZZ(*)→4l

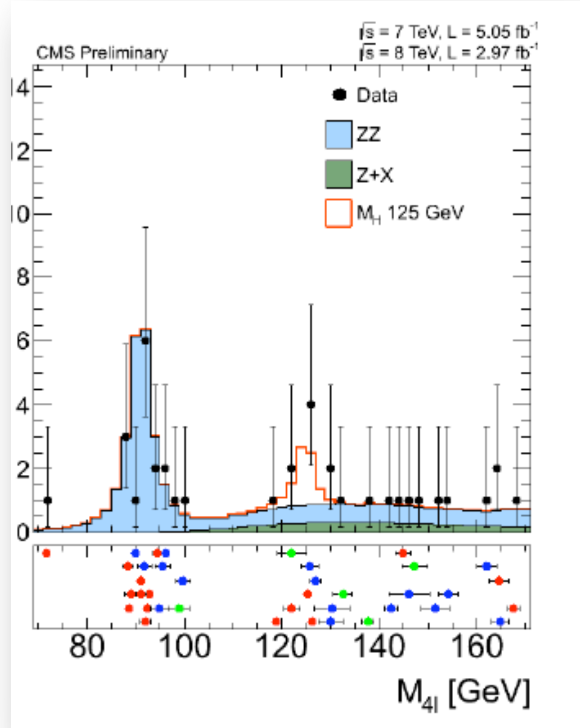
in 7 TeV and 8 TeV data:

UNBLINDING

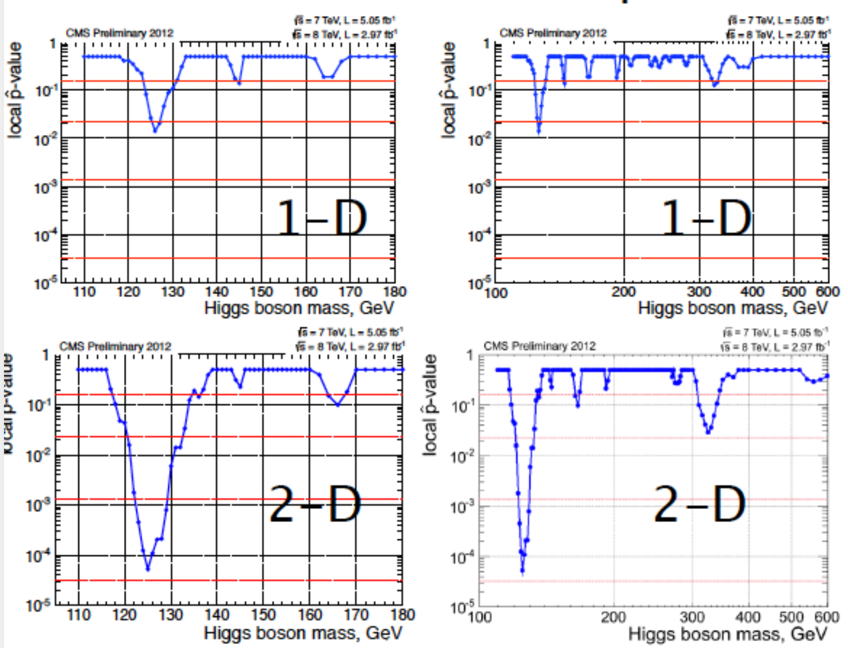
Cristina Botta (CERN)
on behalf of the H4l group

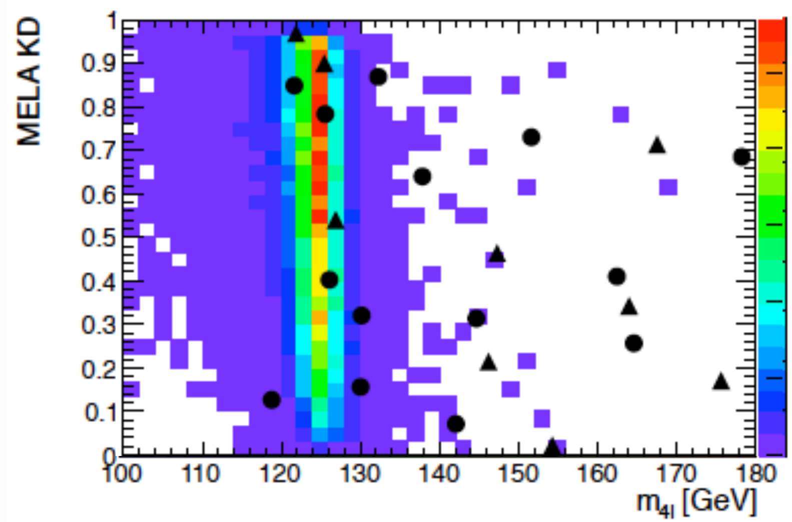
14/06/2012





7+8 combined p-values

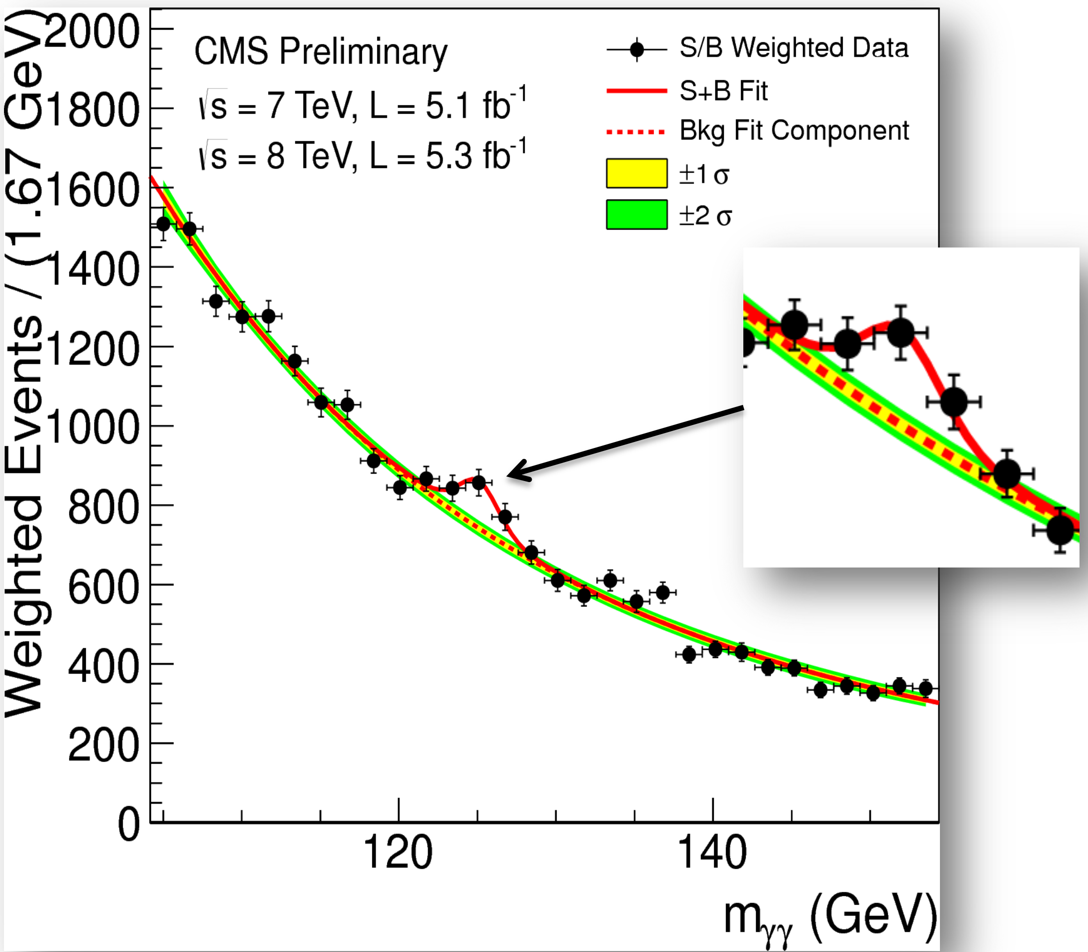




July 4, 2012

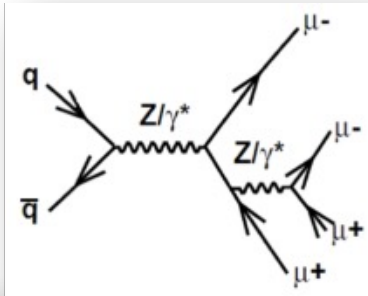
S/B Weighted Mass Distribution

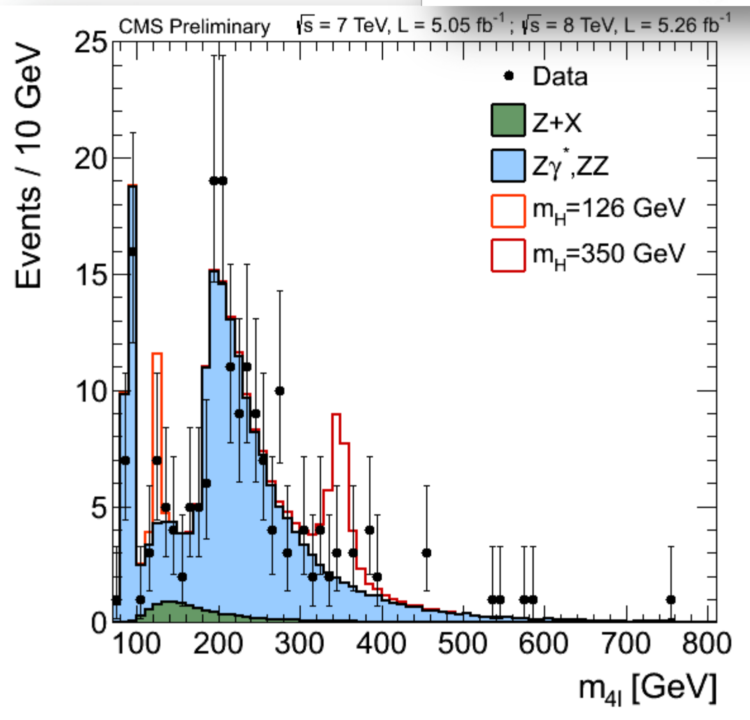
- **Sum of mass distributions for each event class, weighted by S/B**
  - **B is integral of background model over a constant signal fraction interval**

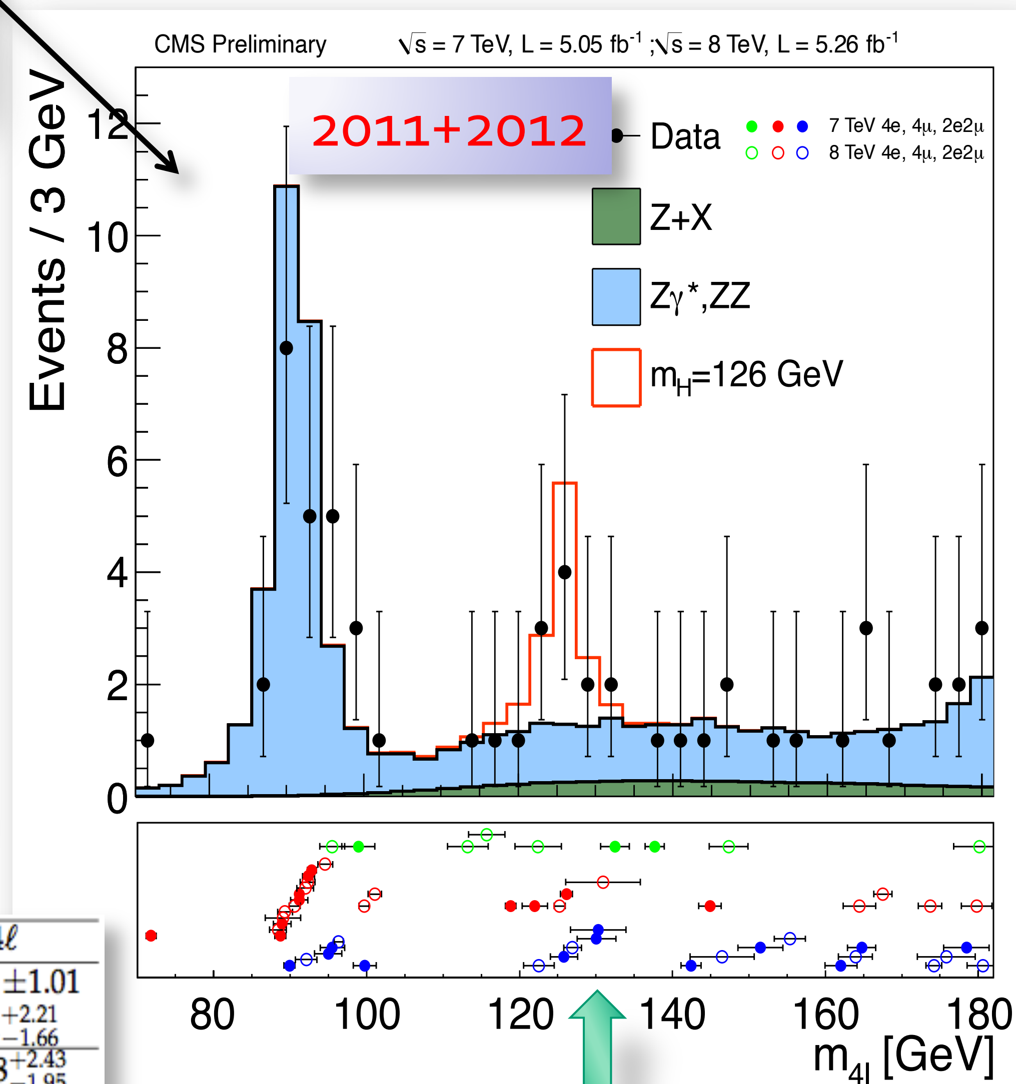


Presented July 4, 2012

Results: m(4l) spectrum







Yields for m(4l)=110..160 GeV

Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	2.65 ± 0.31	5.65 ± 0.59	7.17 ± 0.76	15.48 ± 1.01
Z+X	$1.20^{+1.08}_{-0.78}$	$0.92^{+0.65}_{-0.55}$	$2.29^{+1.81}_{-1.36}$	$4.41^{+2.21}_{-1.66}$
All backgrounds	$3.85^{+1.12}_{-0.84}$	$6.58^{+0.88}_{-0.81}$	$9.46^{+1.96}_{-1.56}$	$19.88^{+2.43}_{-1.95}$
$m_H = 126$ GeV	1.51 ± 0.48	2.99 ± 0.60	3.81 ± 0.89	8.31 ± 1.18

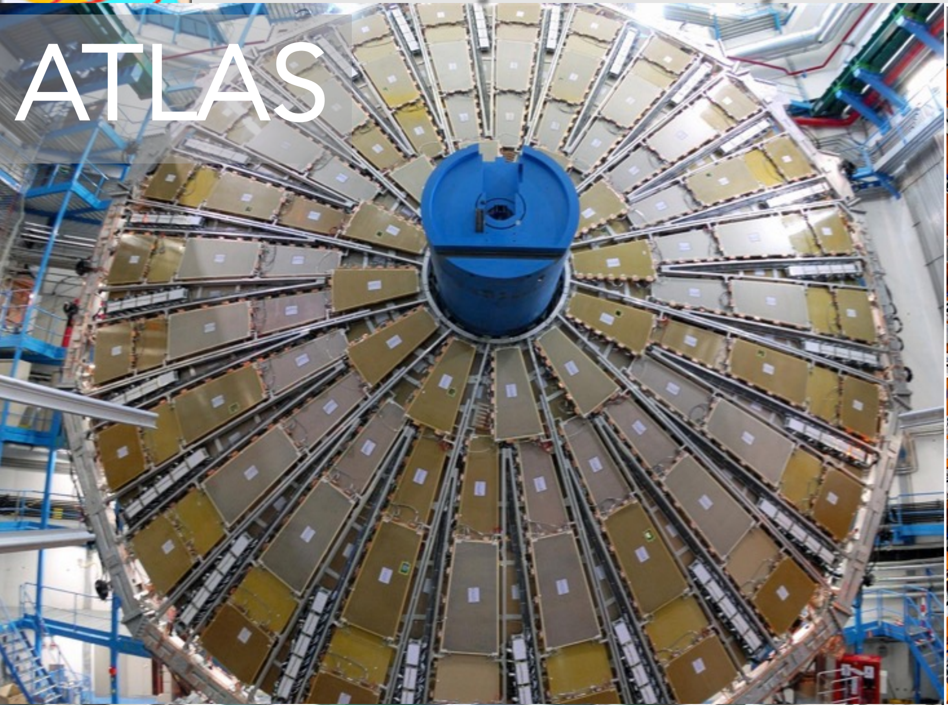
164 events expected in [100, 800 GeV]
172 events observed in [100, 800 GeV]

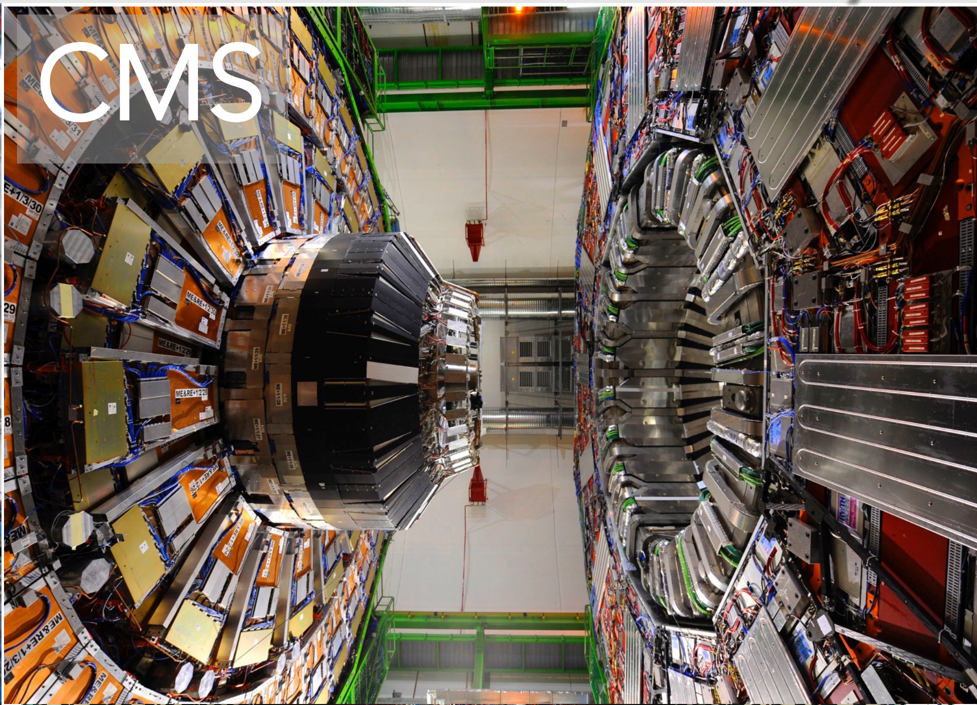
Event-by-event errors


The Economist
In praise of charter schools
Britain's banking scandal spreads
Volkswagen overtakes the rest
A power struggle at the Vatican
When Lonesome George met Nora
JULY 7TH–13TH 2012
Economist.com
A giant leap for science
Finding the Higgs boson

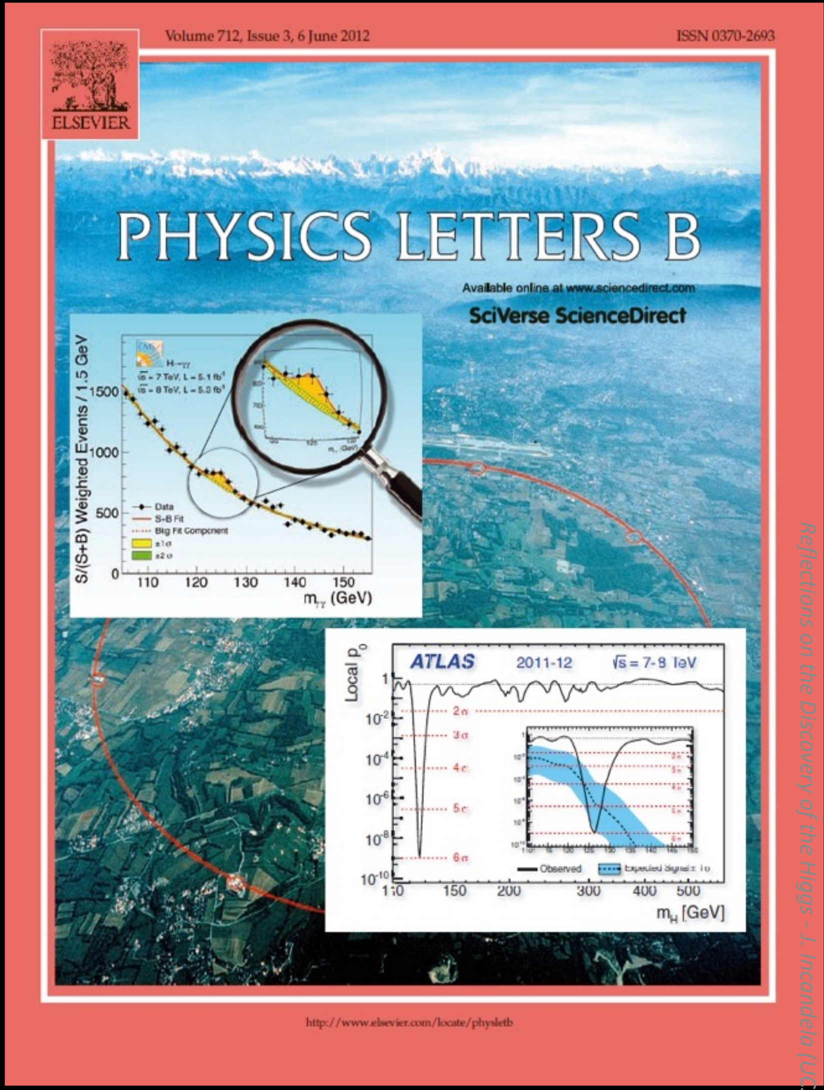

Science
21 December 2012 | $10
BREAKTHROUGH
of the YEAR
The HIGGS
BOSON
AAAS

Made possible by an incredible worldwide community





- **Among the greatest achievements of all time**
  - Drawing upon the collective experience of many generations - from the hadron and lepton collider communities and beyond…



– And we could not have done it without our partners

U.S. DEPARTMENT OF ENERGY | Office of Science

The National Science Foundation