Higgs Discovery and Detector Instrumentation: Past, Present, Future

Maxim Titov,
CEA Saclay, France

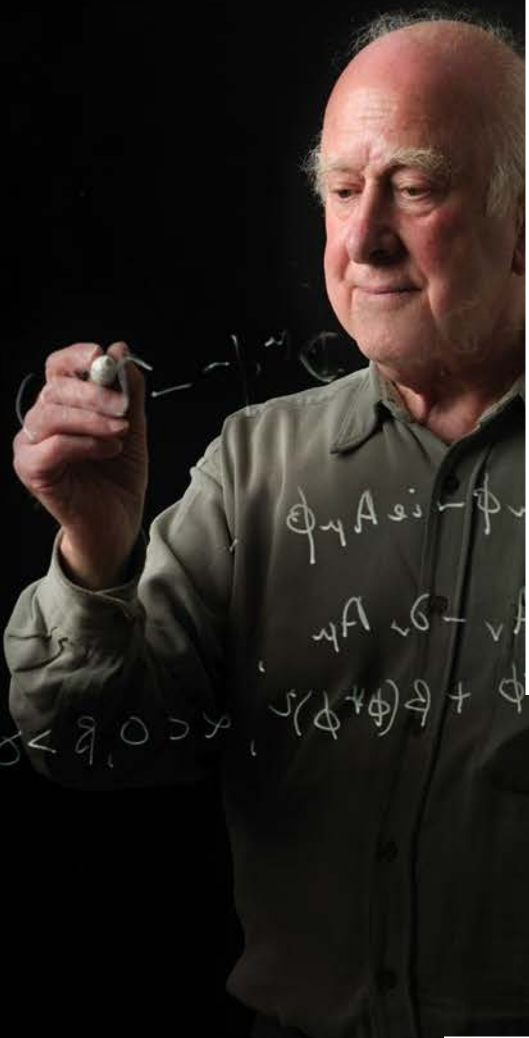
The discovery of the Higgs boson – was an unusually easy choice,

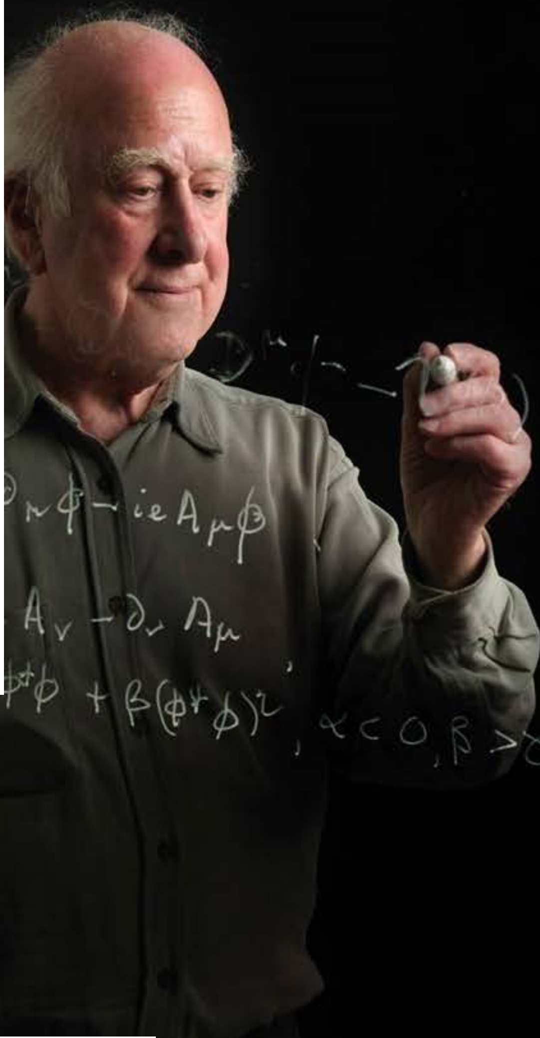
representing both a triumph of the human intellect and the culmination of decades of work by many thousands of physicists and engineers

OUTLINE:

- Higgs Discovery
- LHC Performance
- Towards a Higgs boson in ATLAS/CMS
- Future Projects: Trends at Instrumentation Frontier
- European Strategy for Particle Physics
- Summary and Outlook

2013 Micro-Pattern Gaseous Detector (MPGD) Conference,
Zaragoza, Spain, July 1-6, 2013





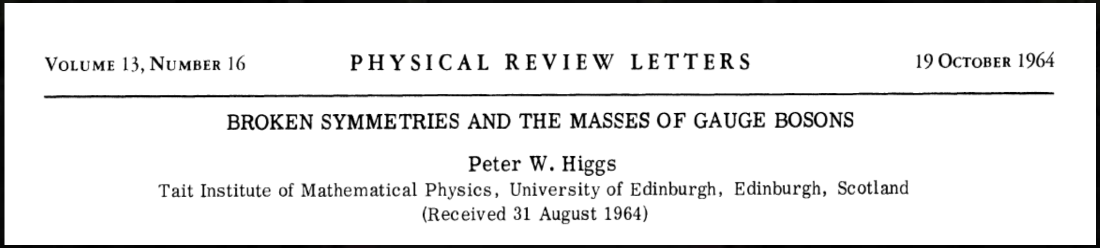
"I certainly had no idea it would happen in my lifetime at the beginning, more than 40 years ago.

I think it shows amazing dedication by the young people involved with these colossal collaborations to persist in this way, on what is a really a very difficult task.
I congratulate them."

Peter Higgs, July 4th, 2012

THE HIGGS STORY

1964



Volume 13, Number 16 PHYSICAL REVIEW LETTERS 19 October 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland

(Received 31 August 1964)

July 4th 2012 – Now It Becomes the "History of Science"

"So, We have it – It is a Discovery"

(Rolf-Dieter Heuer, CERN Director General)

performance of
accelerators – experiments – Grid computing

Observation of a new particle consistent with
a Higgs Boson (but which one...?)

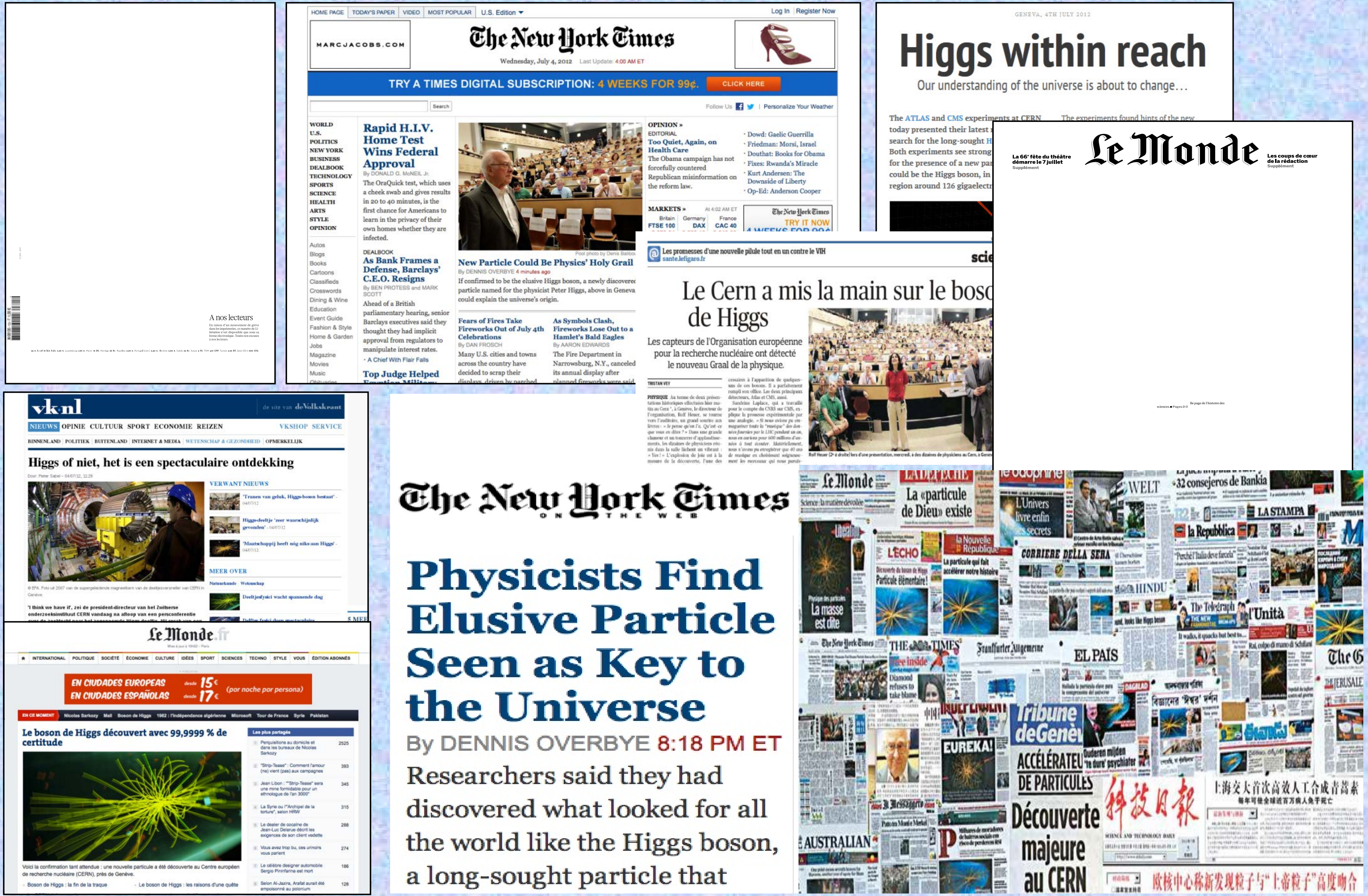
Historic Milestone but only the beginning

Global Implications for the future

Both ATLAS and CMS Collaborations have reported observation of a narrow resonance ~ 125 GeV consistent with long-sought Higgs boson

What did we know on that day: it is most probably "A HIGGS BOSON"
→ had to establish if it is "THE HIGGS BOSON" of the Standard Model

Mass Media – After 50 years and billions of dollars – The God particle is no longer a theory



CERN, AFP

A nos lecteurs

En raison d'un mouvement de grève dans les imprimeries, ce numéro de *Libération* n'est disponible que sous sa forme électronique. Toutes nos excuses à nos lecteurs.

35 €, Israël 19 ILS, Italie 2,20 €, Luxembourg 1,60 €, Maroc 16 Dh, Norvège 26 Kr, Pays-Bas 2,20 €, Portugal (cont.) 2,30 €, Slovénie 2,60 €, Suède 23 Kr, Suisse 3 FS, TOM 410 CFP, Tunisie 2,20 DT, Zone CFA 1 900 CFA.

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The New York Times

Wednesday, July 4, 2012 Last Update: 4:00 AM ET

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Rapid H.I.V. Home Test Wins Federal Approval

By DONALD G. McNEIL Jr.

The OraQuick test, which uses a cheek swab and gives results in 20 to 40 minutes, is the first chance for Americans to learn in the privacy of their own homes whether they are infected.

DEALBOOK

As Bank Frames a Defense, Barclays' C.E.O. Resigns

By BEN PROTESS and MARK SCOTT

Ahead of a British parliamentary hearing, senior Barclays executives said they thought they had implicit approval from regulators to manipulate interest rates.

- A Chief With Flair Falls

Top Judge Helped

Pool photo by Denis Balibouse

New Particle Could Be Physics' Holy Grail

By DENNIS OVERBYE 4 minutes ago

If confirmed to be the elusive Higgs boson, a newly discovered particle named for the physicist Peter Higgs, above in Geneva, could explain the universe's origin.

Fears of Fires Take Fireworks Out of July 4th Celebrations

By DAN FROSCH

Many U.S. cities and towns across the country have decided to scrap their

As Symbols Clash, Fireworks Lose Out to a Hamlet's Bald Eagles

By AARON EDWARDS

The Fire Department in Narrowsburg, N.Y., canceled its annual display after

OPINION »

EDITORIAL

Too Quiet, Again, on Health Care

The Obama campaign has not forcefully countered Republican misinformation on the reform law.

- Dowd: Gaelic Guerrilla
- Friedman: Morsi, Israel
- Douthat: Books for Obama
- Fixes: Rwanda's Miracle
- Kurt Andersen: The Downside of Liberty
- Op-Ed: Anderson Cooper

MARKETS » At 4:02 AM ET

Britain	Germany	France
FTSE 100	DAX	CAC 40

The New York Times TRY IT NOW

GENEVA, 4TH JULY 2012

Higgs within reach

Our understanding of the universe is about to change…

The ATLAS and CMS experiments at CERN today presented their latest search for the long-sought H… Both experiments see strong… for the presence of a new par… could be the Higgs boson, in… region around 126 gigaelectr…

The experiments found hints of the new

La 66ᵉ fête du théâtre démarre le 7 juillet
Supplément

Le Monde

Les coups de cœur de la rédaction
Supplément

lle page de l'histoire des sciences. ■ Pages 2-3

Les promesses d'une nouvelle pilule tout en un contre le VIH
sante.lefigaro.fr

Le Cern a mis la main sur le boson de Higgs

Les capteurs de l'Organisation européenne pour la recherche nucléaire ont détecté le nouveau Graal de la physique.

TRISTAN VEY

PHYSIQUE Au terme de deux présentations historiques effectuées hier matin au Cern, à Genève, le directeur de l'organisation, Rolf Heuer, se tourne vers l'auditoire, un grand sourire aux lèvres : « *Je pense qu'on l'a. Qu'est-ce que vous en dites ?* » Dans une grande clameur et un tonnerre d'applaudissements, les dizaines de physiciens réunis dans la salle lâchent un vibrant : « *Yes !* » L'explosion de joie est à la mesure de la découverte, l'une des

cessaires à l'apparition de quelques-uns de ces bosons. Il a parfaitement rempli son office. Les deux principaux détecteurs, Atlas et CMS, aussi.

Sandrine Laplace, qui a travaillé pour le compte du CNRS sur CMS, explique la prouesse expérimentale par une analogie. « *Si nous avions pu emmagasiner toute la "musique" des données fournies par le LHC pendant un an, nous en aurions pour 600 millions d'années à tout écouter. Matériellement, nous n'avons pu enregistrer que 40 ans de musique en choisissant soigneusement les morceaux qui nous parais-*

Rolf Heuer (2ᵉ à droite) lors d'une présentation, mercredi, à des dizaines de physiciens au Cern, à Genève

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vk.nl de site van deVolkskrant

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Higgs of niet, het is een spectaculaire ontdekking

Door: Pieter Sabel – 04/07/12, 11:29

© EPA. Foto uit 2007 van de supergeleidende magneetkern van de deeltjesversneller van CERN in Genève.

'I think we have it', zei de president-directeur van het Zwitserse onderzoeksinstituut CERN vandaag na afloop van een persconferentie

VERWANT NIEUWS

'Tranen van geluk, Higgs-boson bestaat' - 04/07/12

Higgs-deeltje 'zeer waarschijnlijk gevonden' - 04/07/12

'Maatschappij heeft nóg niks aan Higgs' - 04/07/12

MEER OVER

Natuurkunde | Wetenschap

Deeltjesfysici wacht spannende dag

Le Monde.fr

Mise à jour à 10h02 - Paris

INTERNATIONAL | POLITIQUE | SOCIÉTÉ | ÉCONOMIE | CULTURE | IDÉES | SPORT | SCIENCES | TECHNO | STYLE | VOUS | ÉDITION ABONNÉS

EN CE MOMENT Nicolas Sarkozy Mali Boson de Higgs 1962 : l'indépendance algérienne Microsoft Tour de France Syrie Pakistan

Le boson de Higgs découvert avec 99,9999 % de certitude

Voici la confirmation tant attendue : une nouvelle particule a été découverte au Centre européen de recherche nucléaire (CERN), près de Genève.

- Boson de Higgs : la fin de la traque
- Le boson de Higgs : les raisons d'une quête

Les plus partagés

1	Perquisitions au domicile et dans les bureaux de Nicolas Sarkozy	2525
2	"Strip-Tease" : Comment l'amour (ne) vient (pas) aux campagnes	393
3	Jean Libon : ""Strip-Tease" sera une mine formidable pour un ethnologue de l'an 3000"	345
4	La Syrie ou l'"Archipel de la torture", selon HRW	315
5	Le dealer de cocaïne de Jean-Luc Delarue décrit les exigences de son client vedette	288
6	Vous avez trop bu, ces urinoirs vous parlent	274
7	Le célèbre designer automobile Sergio Pininfarina est mort	186
8	Selon Al-Jazira, Arafat aurait été empoisonné au polonium	128

The New York Times ON THE WEB

Physicists Find Elusive Particle Seen as Key to the Universe

By DENNIS OVERBYE 8:18 PM ET

Researchers said they had discovered what looked for all the world like the Higgs boson, a long-sought particle that

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Le Monde — Science : la matière dévoilée

La Dépêche — La «particule de Dieu» existe

Le Dauphiné — L'Univers livre enfin ses secrets

Libération — Physique des particules. La masse est dite

L'Écho — Découverte du boson de Higgs. Particule élémentaire !

La Nouvelle République — La particule qui fait accélérer notre histoire

Corriere della Sera

Die Welt

El Mundo — 32 consejeros de Bankia

La Stampa

la Repubblica — "Perché l'Italia deve farcela"

The Hindu

The Telegraph — It walks, it quacks but best to…

l'Unità — Rai, colpo di mano di Schifani

The New York Times

The Times — Diamond refuses to take blame

Frankfurter Allgemeine

El País — Hallada la partícula clave para la comprensión del universo

The Guardian

The Jerusalem Post

Dagblad — Ouderen mijden 'te dure' psychiater

বিজ্ঞানের 'ঈশ্বর' দর্শন

The Independent — EUREKA!

Tribune de Genève — ACCÉLÉRATEUR DE PARTICULES. Découverte majeure au CERN

Il Messaggero

The Australian

科技日报 SCIENCE AND TECHNOLOGY DAILY

上海交大首次高效人工合成青蒿素
每年可使全球近百万病人免于死亡

欧核中心称新发现粒子与"上帝粒子"高度吻合

Life after July 4th … has changed once … and forever

ELSEVIER

PHYSICS LETTERS B

Available online at www.sciencedirect.com

SciVerse ScienceDirect

http://www.elsevier.com/locate/physletb

ATLAS

Physics Letters B

Volume 716, Issue 1, 17 September 2012, Pages 1–29

CMS

Physics Letters B

Volume 716, Issue 1, 17 September 2012, Pages 30–61

Theory: 1964

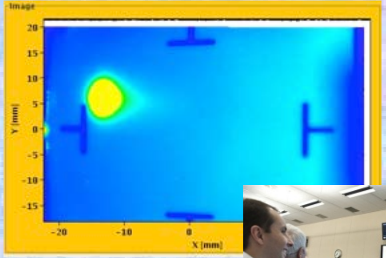
Concept: 1984

Construction: 2001

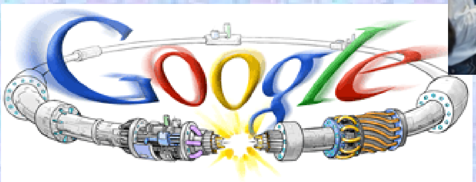
Discovery: 2012

LHC Timeline

August 2008
First injection test



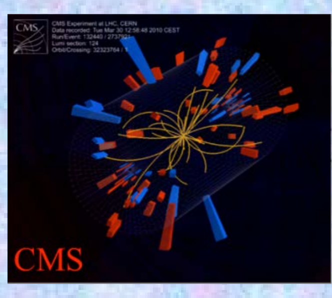
September 10, 2008
First beams around



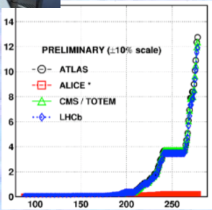
September 19, 2008
Disaster
Accidental release of 600 MJ stored in one sector of LHC dipole magnets

November 29, 2009
Beam back

March 30, 2010
First collisions at 3.5 TeV

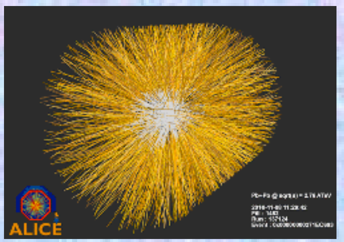


April 2010
Squeeze to 3.5 m



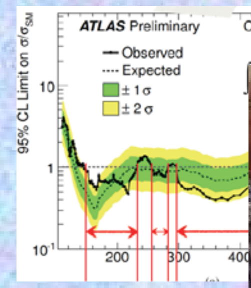
October 14 2010
1e32
248 bunches

November 2010
Ions



June 28 2011
1380 bunches

1380



August, 2011
2.3e33, 2.6 fb
1380 bunches

6 June, 2012
6.8e33

18 June, 2012
6.6 fb^{-1}
to ATLAS & CMS

4 July, 2012

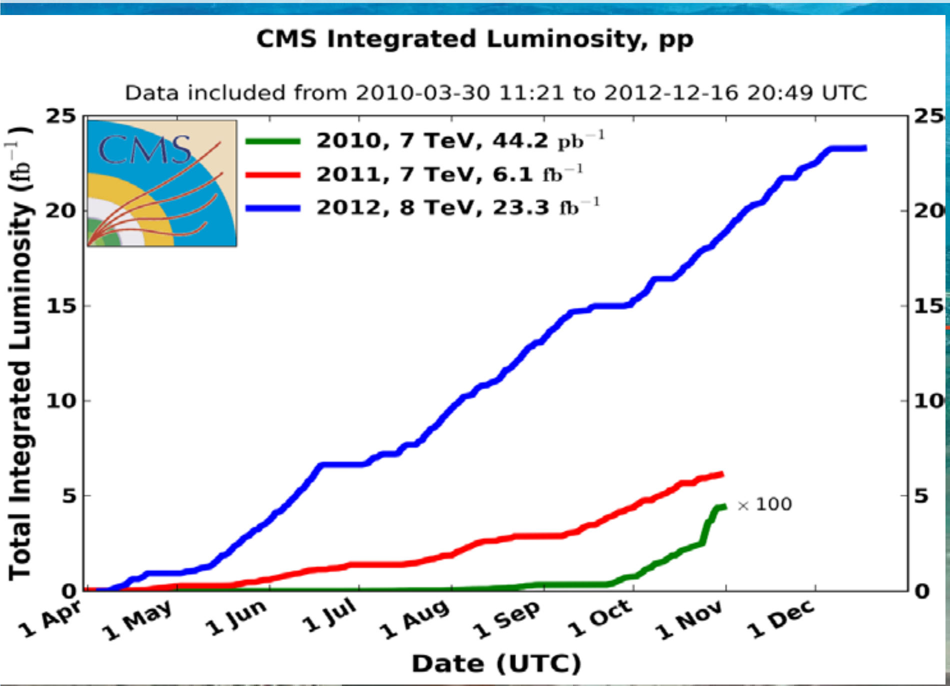
2008 2009 2010 2011 2012

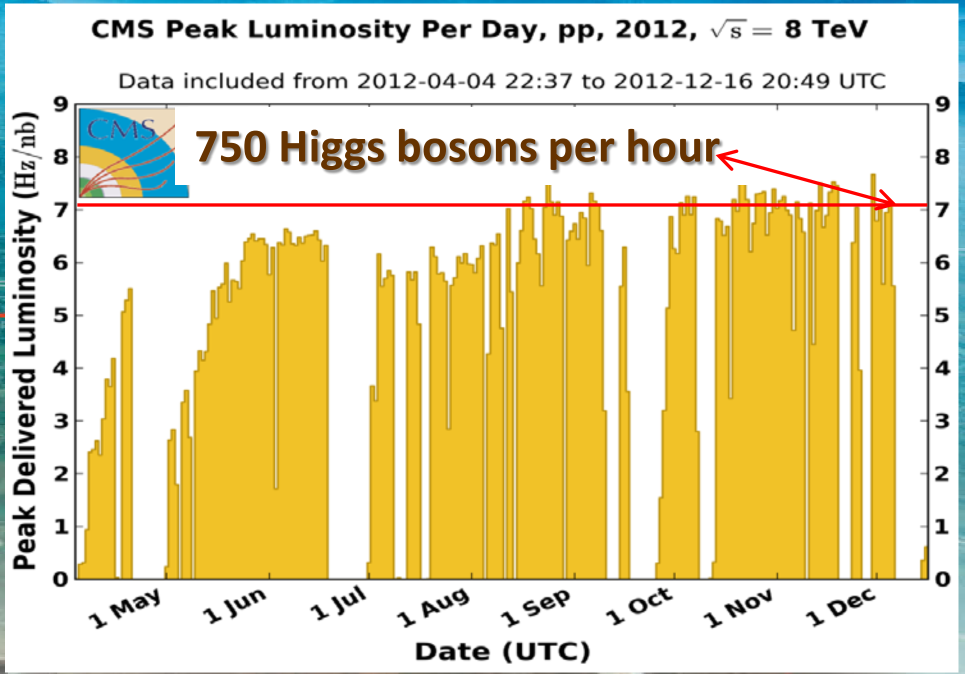
M. Lapont, 2013 Aspen Conference

The LHC Accelerator: Magnificent Performance

Peak Luminosity: **2010:** 10^{27} - 2 10^{32} **2011:** to 3.6 X 10^{33} **2012:** to 6.7 X 10^{33} (nominal 10^{34})

Integrated Luminosity: ATLAS & CMS Delivered / Recorded ~ 23 / 21 fb^{-1}

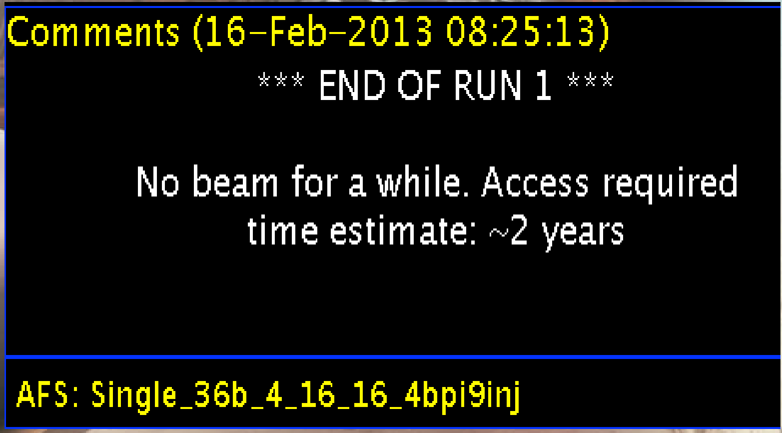




750 Higgs bosons per hour

Steve Myers PLHC 2012:

"The first two years of LHC operation have produced sensational performance: well beyond our wildest expectations.
The combination of the performance of the LHC machine, the detectors and the GRID have proven to be a terrific success story in particle physics."



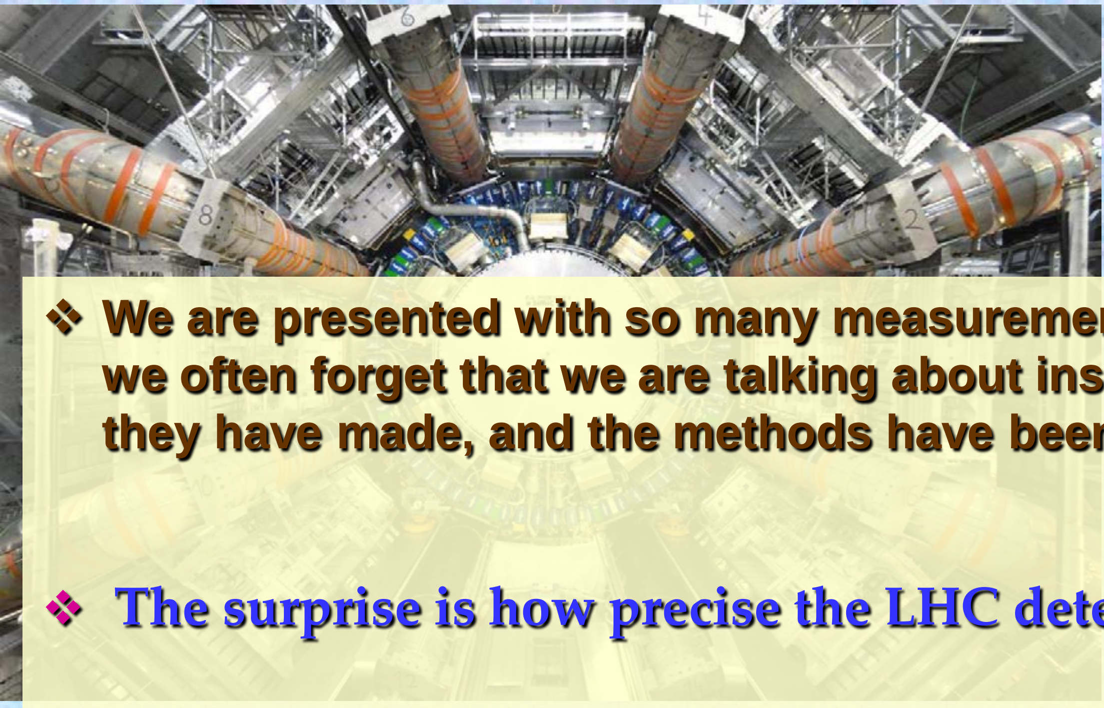
Comments (16-Feb-2013 08:25:13)

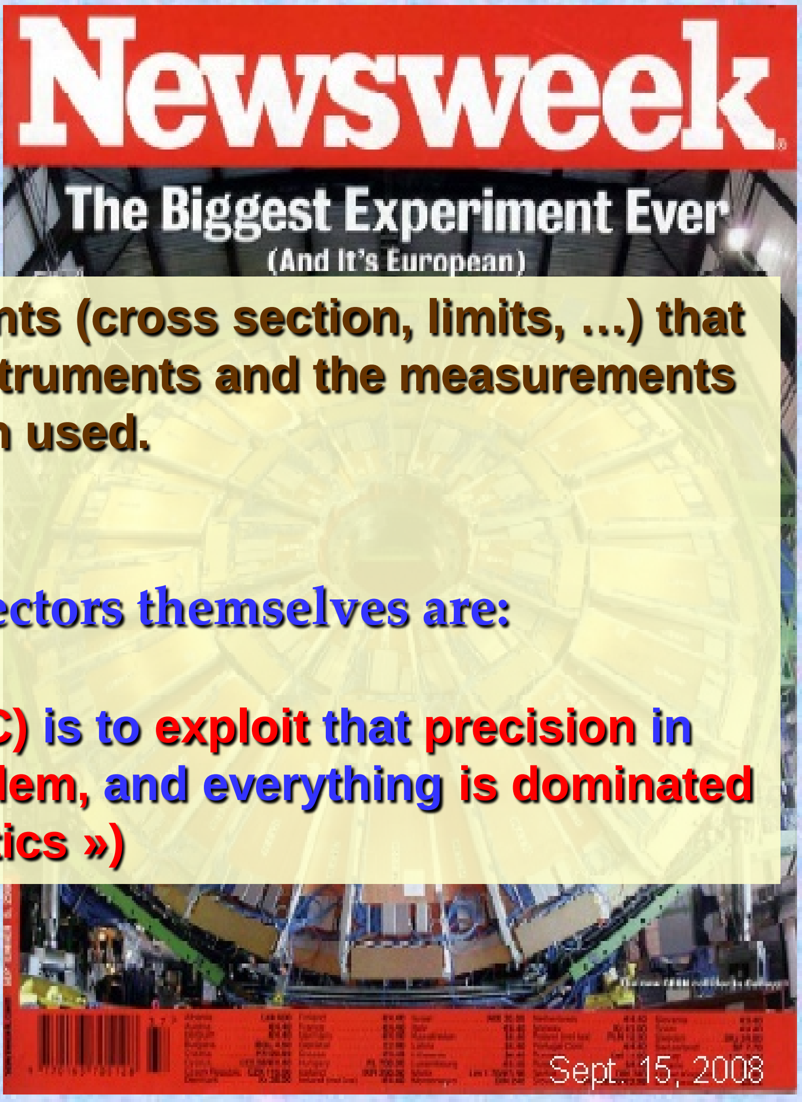
*** END OF RUN 1 ***

No beam for a while. Access required
time estimate: ~2 years

AFS: Single_36b_4_16_16_4bpi9inj

The LHC Spectrometers: Triumph of Instrumentation





- ❖ We are presented with so many measurements (cross section, limits, …) that we often forget that we are talking about instruments and the measurements they have made, and the methods have been used.

- ❖ The surprise is how precise the LHC detectors themselves are:

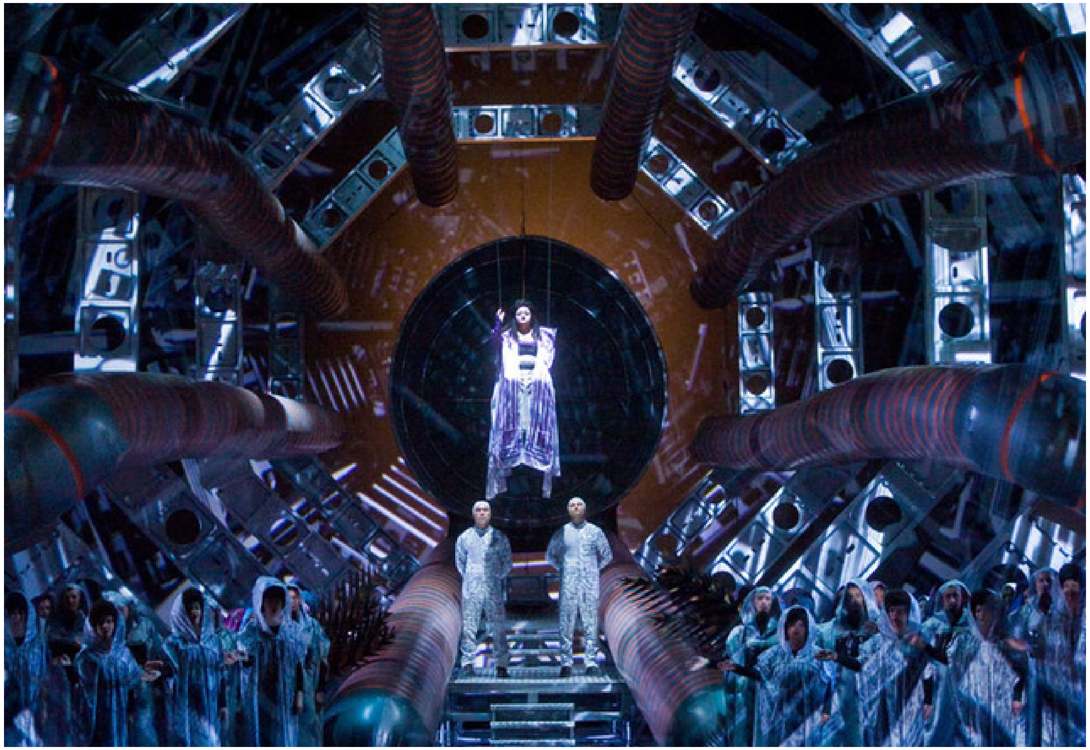
The future challenge of the LHC (super-LHC) is to exploit that precision in the regime where statistics is no longer a problem, and everything is dominated by the performance of the detector (« systematics »)

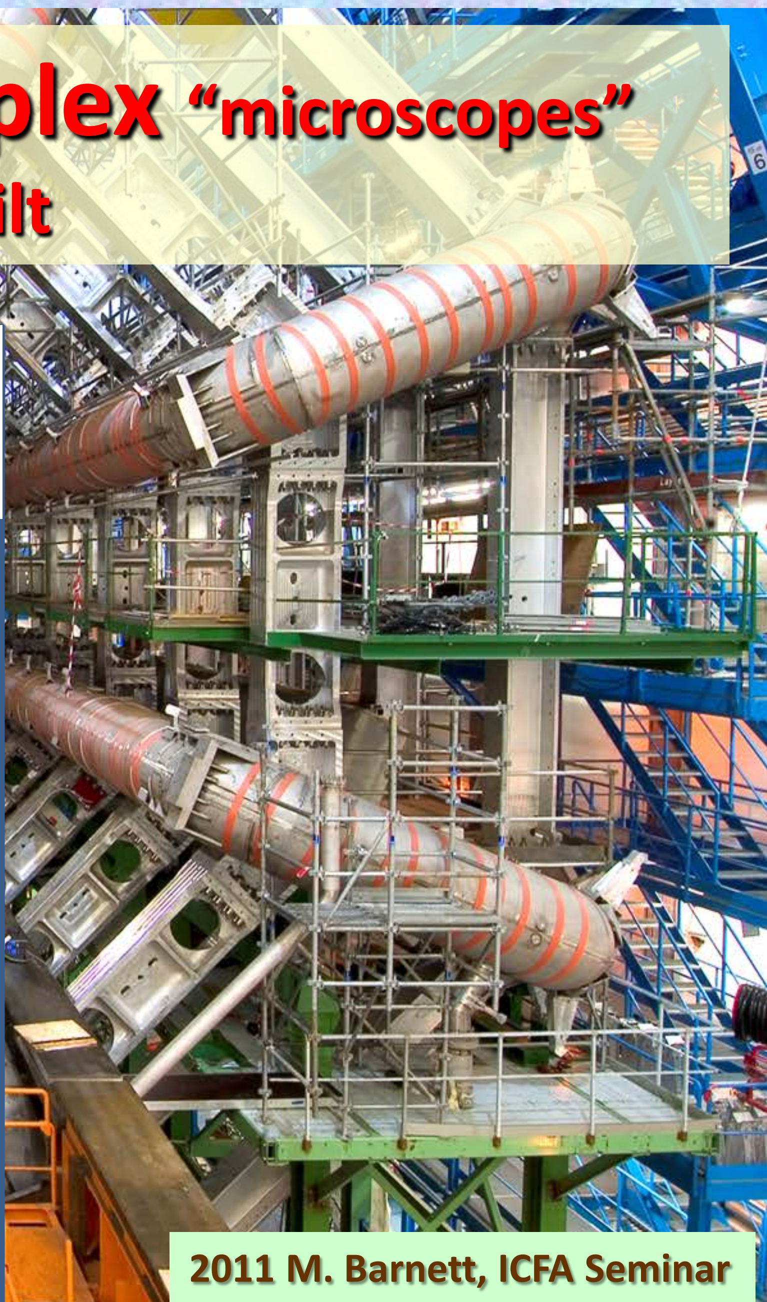
The "Gothic Cathedrals of the 21st Century

The LHC Spectrometers: Impacts can be Unexpected

the largest and most complex "microscopes" we've ever built

The opera Les Troyens by Berlioz, as shown in Valencia, St. Peterburg and Warsaw (2011) used a set design based on ATLAS Detector



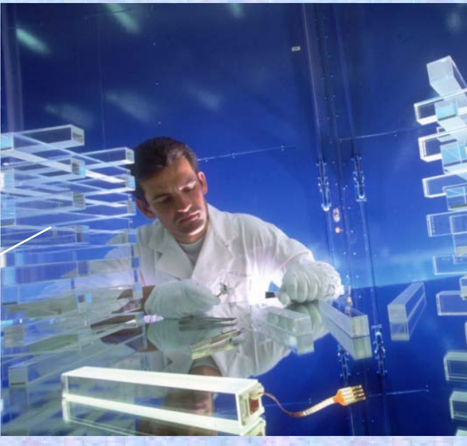


2011 M. Barnett, ICFA Seminar

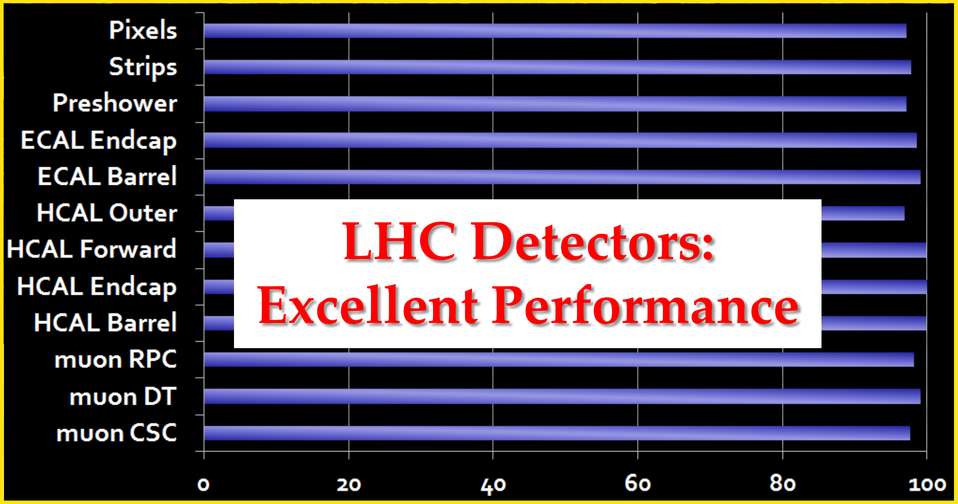
The CMS Spectrometer: Concept to Data Taking – Took 18 Years !

3000 scientists from 40 countries
CMS Letter of Intent (Oct. 1992)

Silicon Tracker

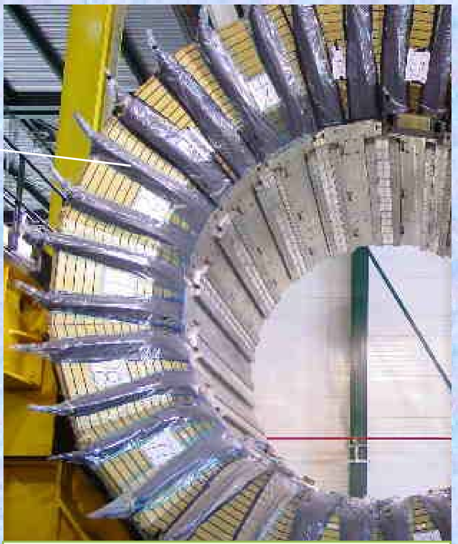


Scintillating Crystals



LHC Detectors:
Excellent Performance

Gas ionization chambers

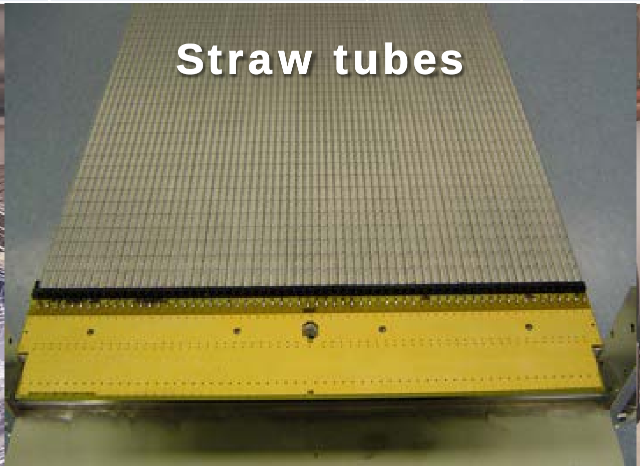


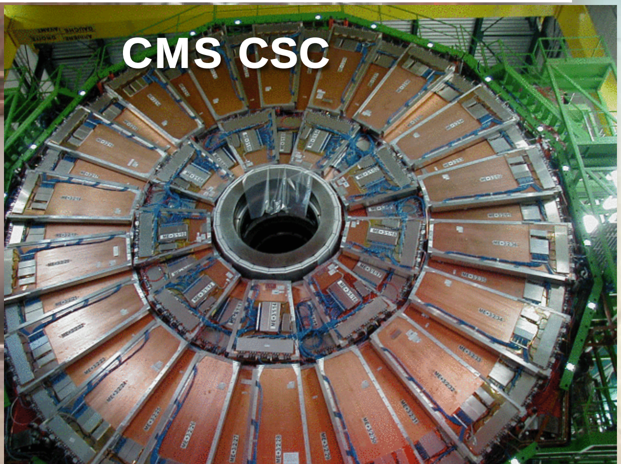
Brass plastic scintillator

Gaseous Detectors in LHC Experiments

	Vertex	Inner Tracker	PID/ photo-det.	EM CALO	HAD CALO	MUON Track	MUON Trigger
ATLAS	-	TRD (straws)	-	-	-	MDT (drift tubes), CSC	RPC, TGC (thin gap chambers)
CMS ----- **TOTEM**	-	-	-	-	-	Drift tubes, CSC ----- **GEM**	RPC, CSC ----- **GEM**
LHCb	-	Straw Tubes	-	-	-	MWPC	MWPC, **GEM**
ALICE	-	TPC (MWPC)	TOF(MRPC), PMD, HPMID (RICH-pad chamber), TRD (MWPC)	-	-	Muon pad chambers	RPC


ALICE TPC

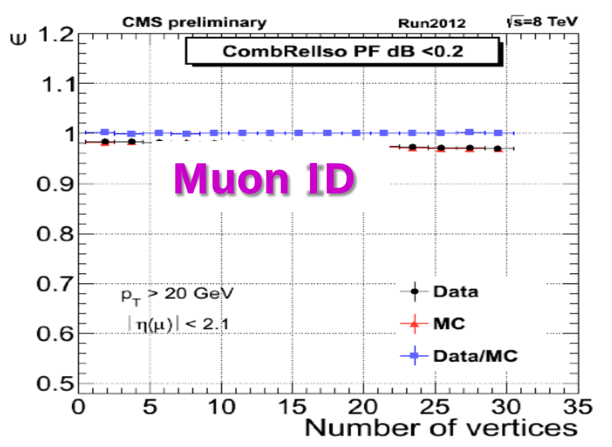

Straw tubes


CMS CSC

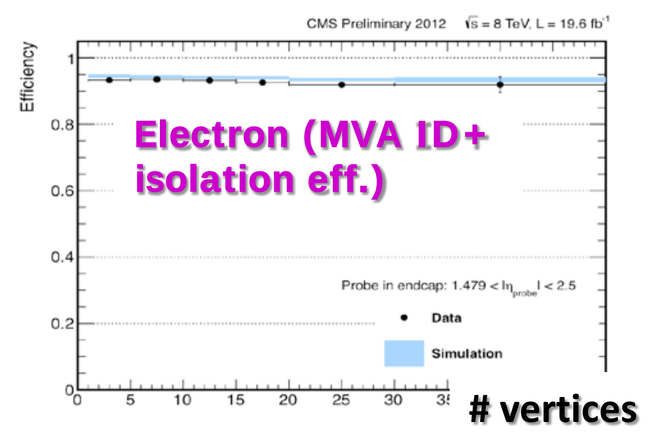
The Challenge of Pileup - A Success Story (2012)

- Pile-up in 2012 exceeded design specifications (50 ns vs 25 ns bunch spacing)
- Mitigation via extensive use of particle flow and advanced analysis methods

Object performance as a function of the pile-up: ie the number of reconstructed vertices

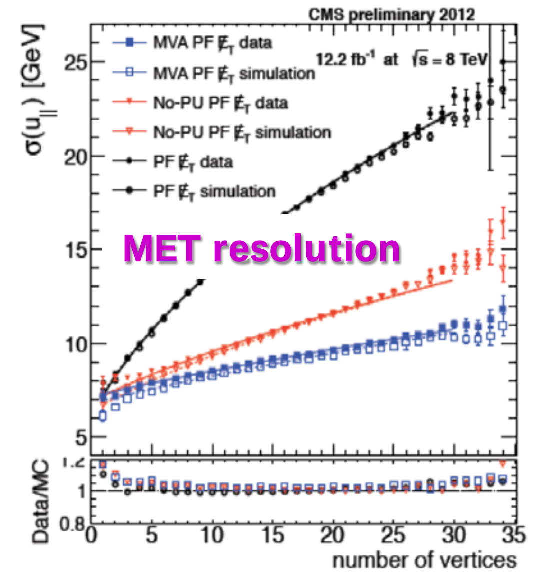


Muon ID

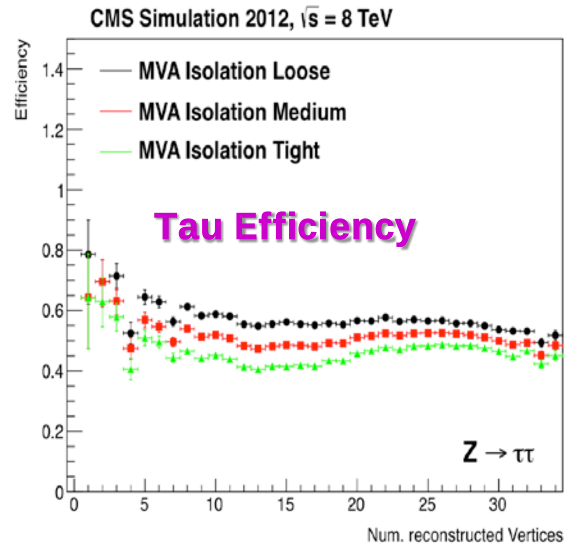


Electron (MVA ID+ isolation eff.)

 # vertices

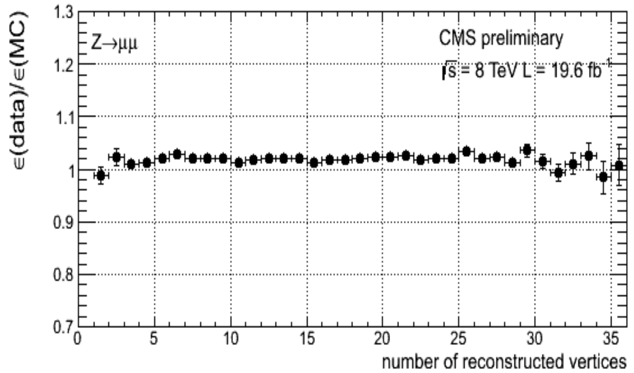


MET resolution



Tau Efficiency

Vertex reco efficiency (for γγ)

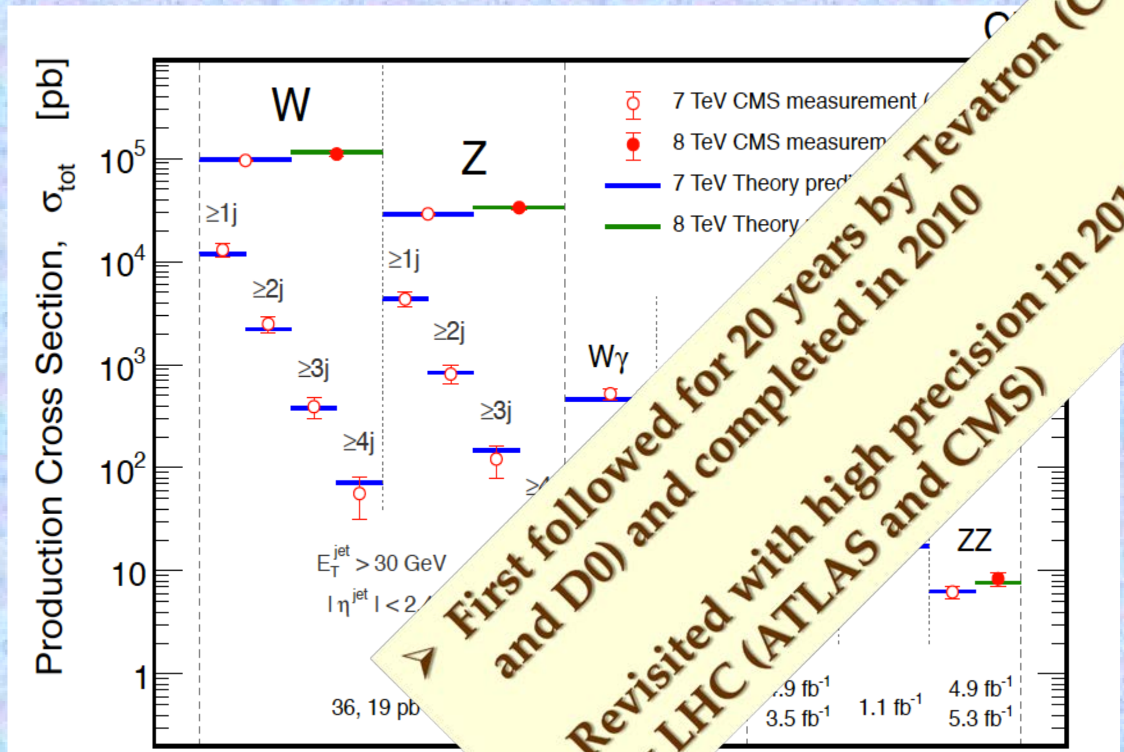


Data/MC ratio using Z→μμ with muon tracks removed

*real LHC pp event (~50 Vertices, 14 Jets, 2 TeV)

Rediscovery of the SM: Electroweak and Top Cross-Section Measurements

Road to Higgs is Paved with Dibosons

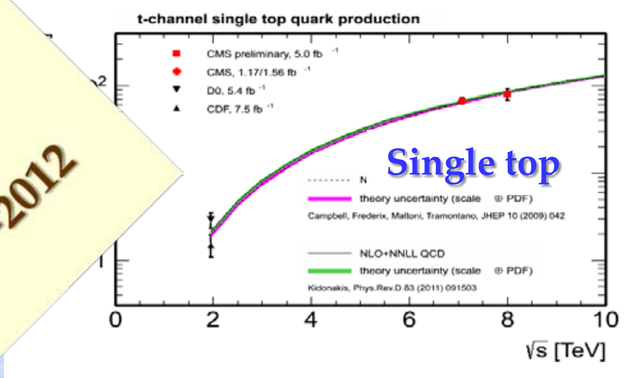


JHEP10(2011)132
JHEP01(2012)010
CMS-PAS-SMP-12-011 (W/Z 8 TeV)

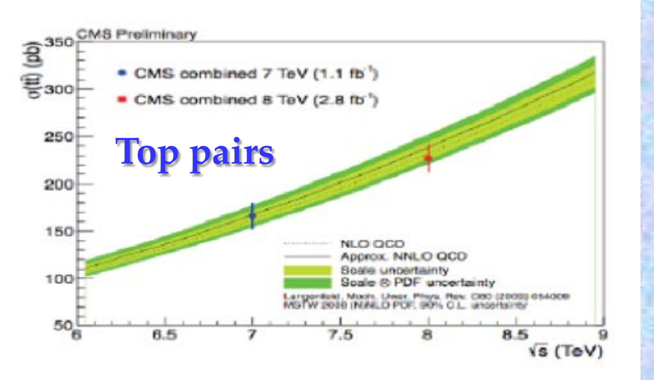
35

CMS-PAS-EWK-11-010 (WZ)
CMS-PAS-SMP-12-005,
007, 013, 014 (WW ZZ)

- First followed for 20 years by Tevatron (CDF and D0) and completed in 2010
- Revisited with high precision in 2010-2012 by LHC (ATLAS and CMS)



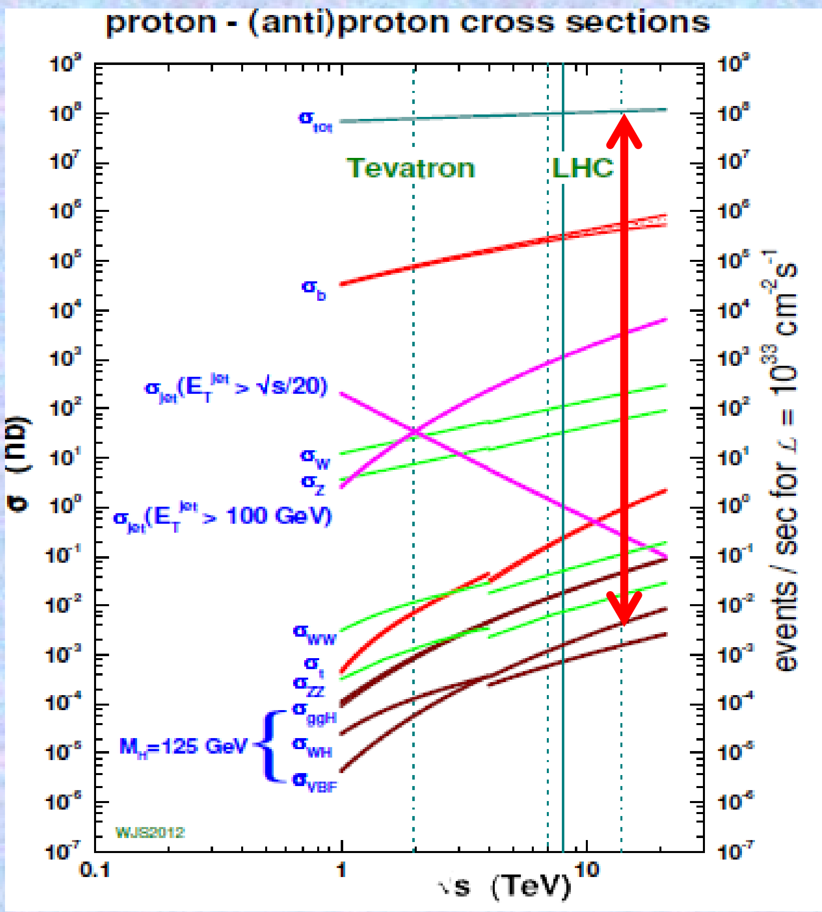
Precision top measurements becomes reality

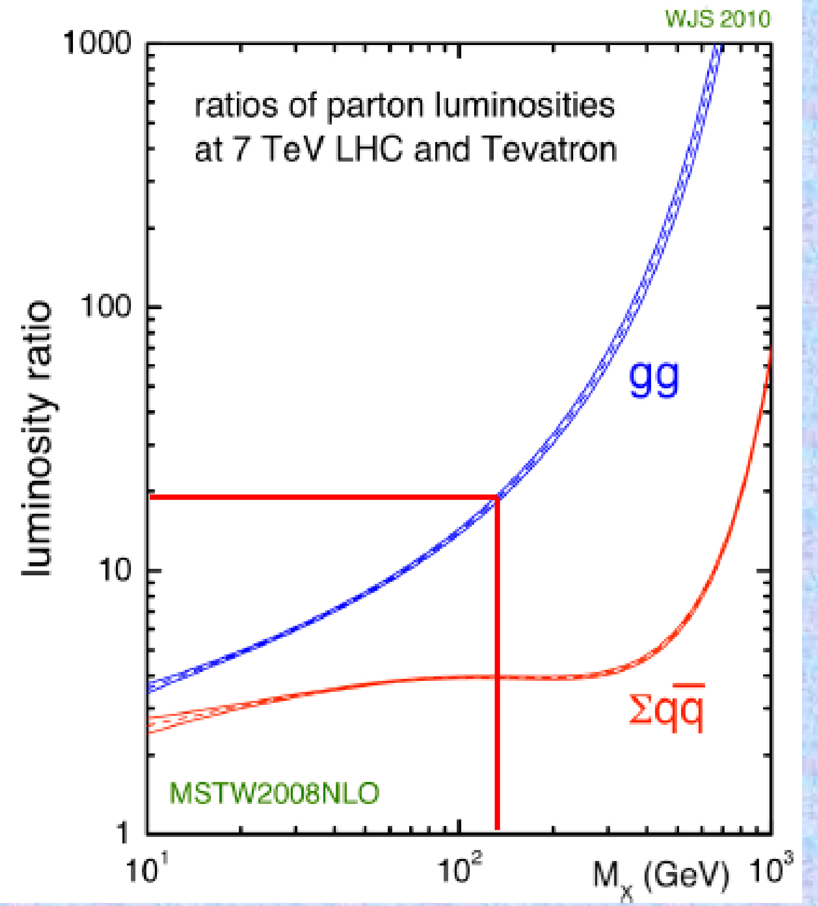


Good understanding of the detector + accurate theory predictions

- ❖ Important on their own and as foundation for Higgs searches
- ❖ Most of these processes are reducible or irreducible backgrounds to Higgs
- ❖ Reconstruction and measurement of challenging processes (e.g. full
- ❖ hadronic tt, single top, ..) are good training for some complex Higgs final states

Higgs Cross-Sections: Tevatron and LHC





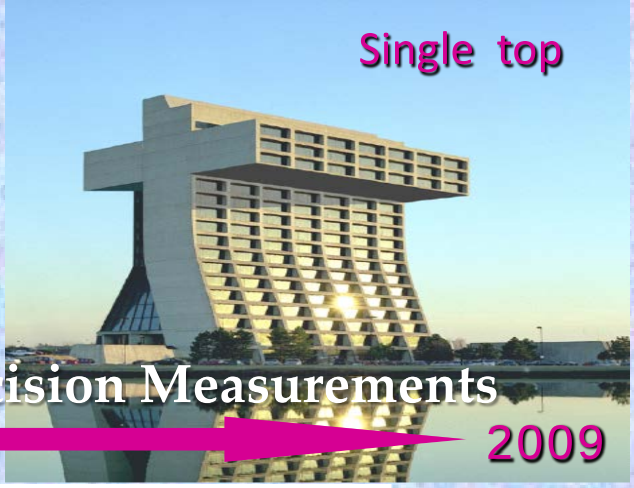
Tevatron @ 1.96 TeV:

Full statistics (D0 + CDF) ~ 2 * 10 fb^{-1}
σ^{tot} (M_H = 125GeV) ~ 1200 fb

LHC @ 7 - 8 TeV:

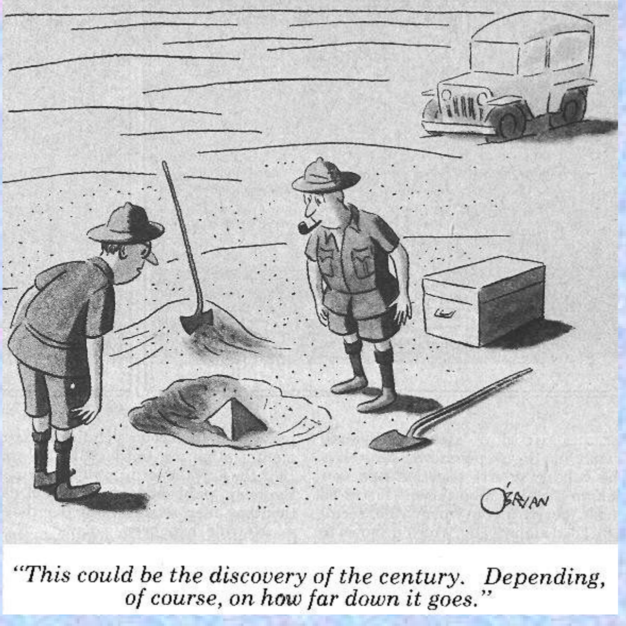
2010-2012 (ATLAS + CMS) ~ 2 * 25 fb^{-1}
σ^{tot} (M_H = 125GeV) ~ 22000 fb

M_H = 125 GeV: $(\sigma^{tot} * L)_{TEVATRON}$ * 50 ~ $(\sigma^{tot} * L)_{LHC}$



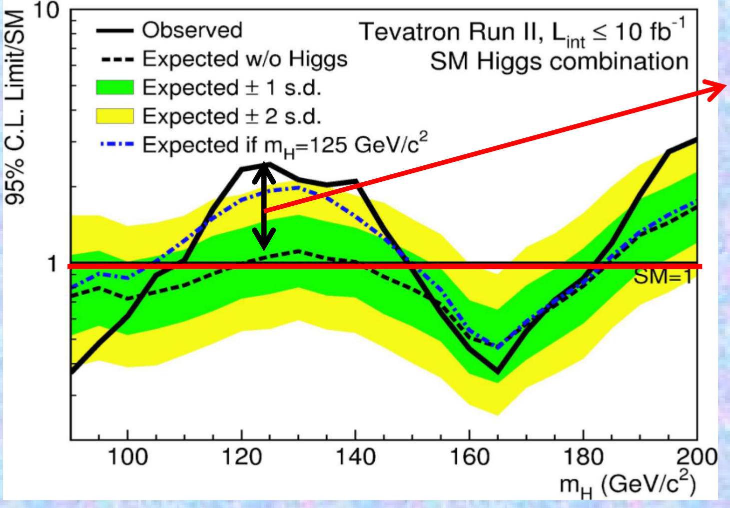
Top Discovery & Precision Measurements

1995 → 2009



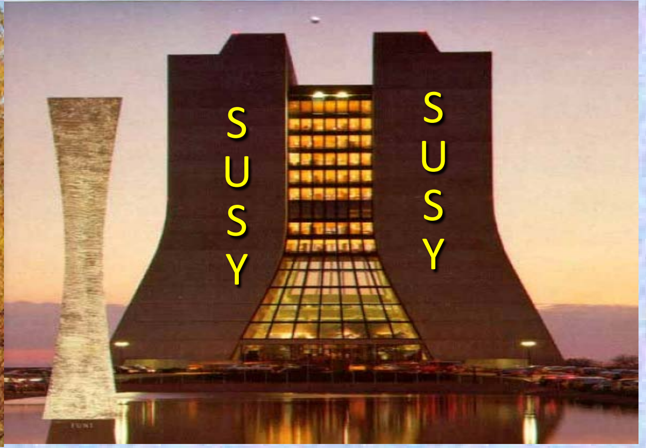
"This could be the discovery of the century. Depending, of course, on how far down it goes."

Final Tevatron (CDF + D0) Higgs Combination Result:

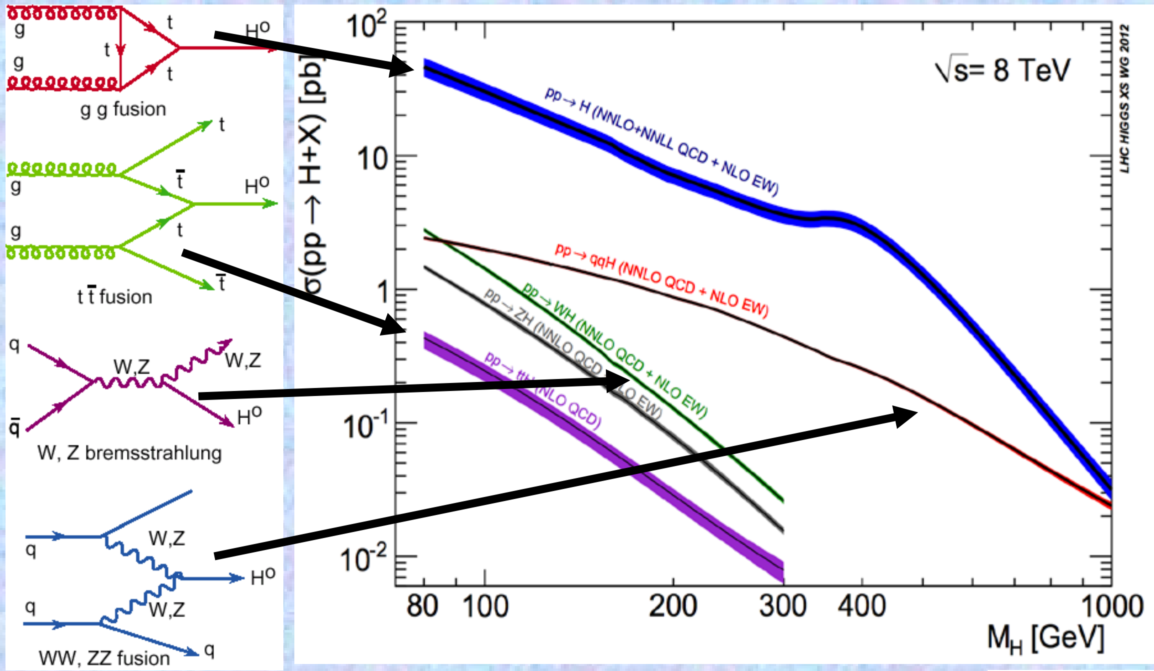


Excess in data (3σ)

The final Tevatron picture is consistent with the boson discovered at the LHC.



Higgs Production and Decay at the LHC



Higgs Production @ 125 GeV:

- ❖ Gluon fusion (87.4%)
- ❖ Vector Boson Fusion (7.1%)
- ❖ W/Z associated prod. (4.9%)
- ❖ Top associated prod. (0.6%)

Higgs Decays @ 125 GeV:
Dream case for experimentalists
→ fun to measure them all !

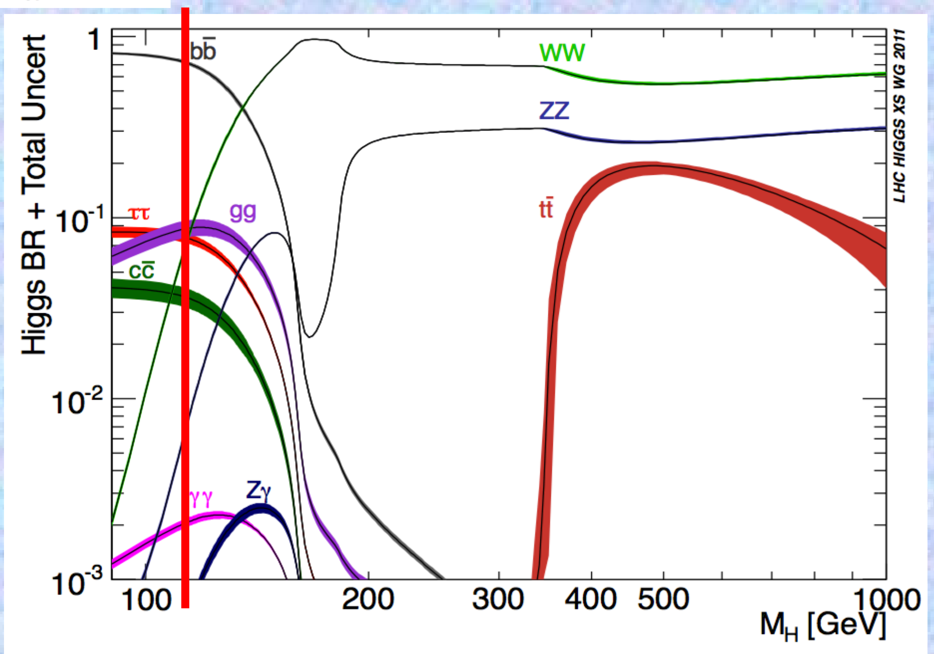
– ***bb*** : large BR, Yukawa coupling

– **ττ : Yukawa coupling**

– ***WW*** : large BR, gauge boson coupling

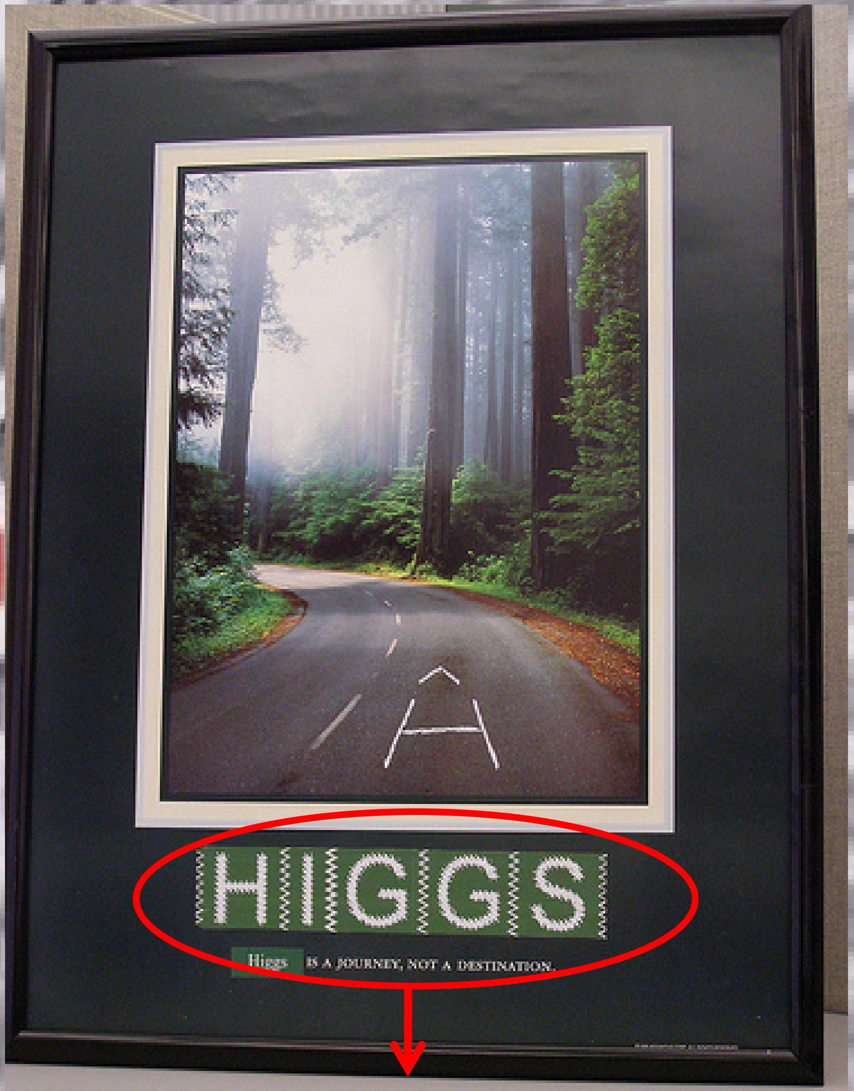
– ***ZZ*** : high S/B, high mass resolution, gauge boson coupling

– **γγ : high mass resolution, loop coupling**



Towards a Higgs Boson: First Steps in an Incredible Journey

Focus on
high mass resolution &
most sensitive
$h \to \gamma\gamma$
$h \to ZZ \to 4\,l$
channels

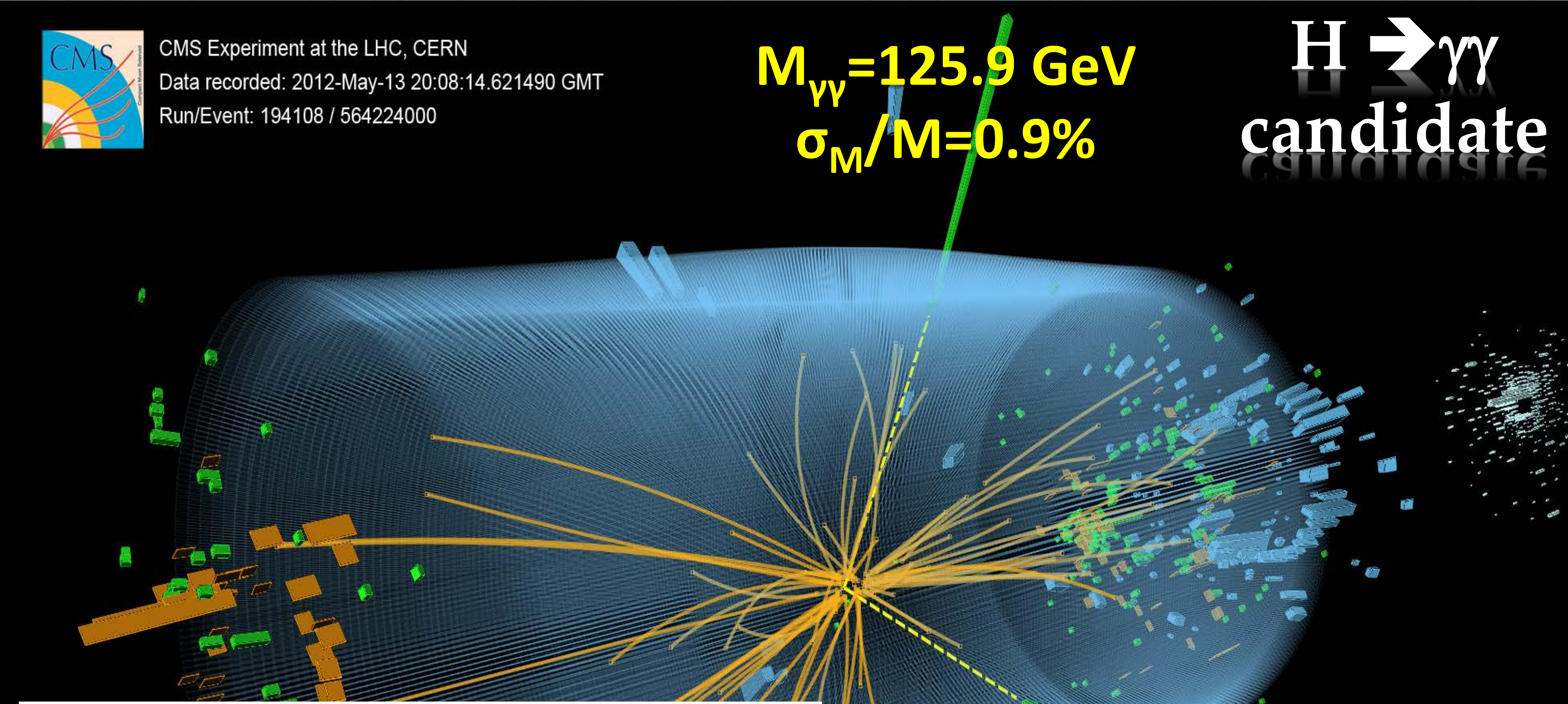


Higgs is a journey,
not a destination

H → γγ candidate

$M_{\gamma\gamma}$=125.9 GeV

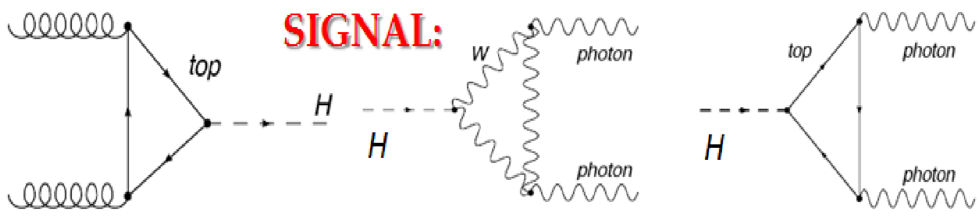
σ_M/M=0.9%



Clean topology:

2 energetic, isolated γ, in a narrow mass peak on top of a large steeply falling background

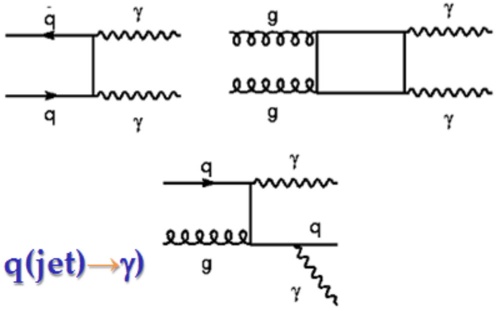
SIGNAL:

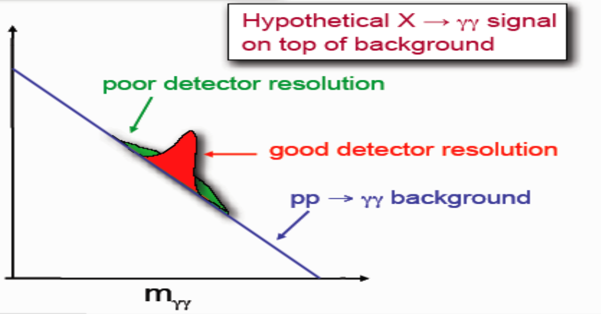


QCD Background:

Irreducible: QCD processes

Reducible: Compton (gq→γq, q(jet)→γ)





H → γγ: The Key Channel Driving the ECAL Design

Discovery study/potential depends on:

- ➢ **Invariant mass resolution**

$$M_{\gamma\gamma} = \sqrt{2 \cdot E_1 \cdot E_2 \cdot (1-\cos\theta_{12})}$$

  - **- Energy resolution**
  - **- Position/angle resolution**
- ➢ **Background modelling**

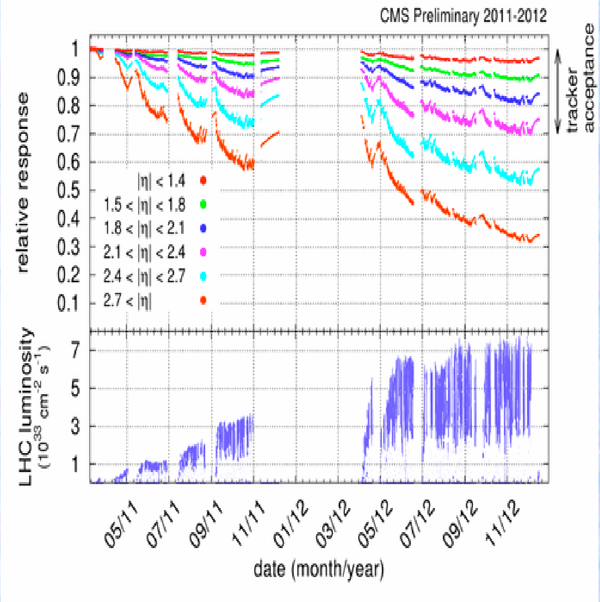
ATLAS ECAL: LAr; **CMS ECAL:** Lead/Tungsten (PbWO4)

Position/Angle Resolution (Vertex selection):

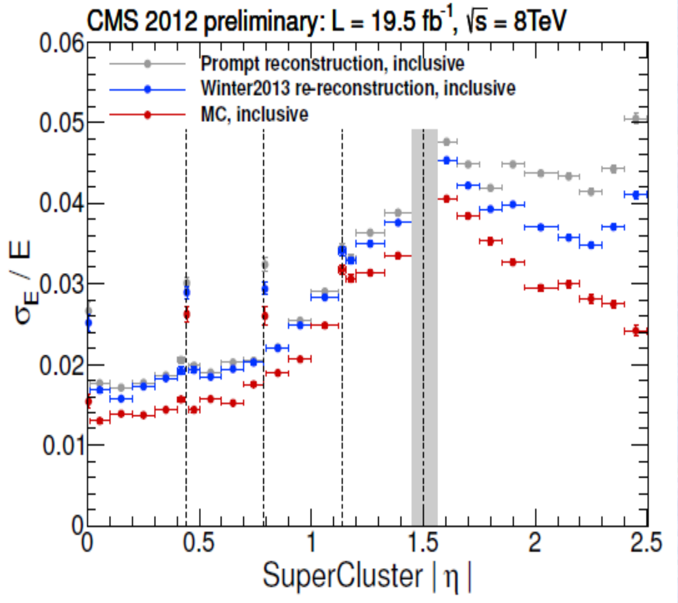
ATLAS: Use longitudinal (and lateral) segmentation to measure γ-polar angle → reduce vertex uncertainty (1.5 cm) → angular term is negligible; robust against puleup

CMS: Off-pointing geometry; no long. segmentation, vertex selection is based on tracks and di-photon system kinematics ($p_T^{\gamma\gamma}$)

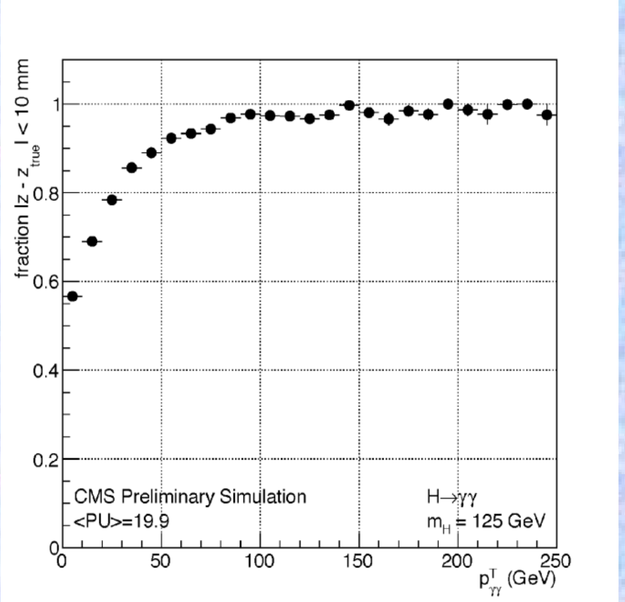
CMS Laser monitoring of response evolution: mandatory to measure crystal transparency in real-time:



CMS ECAL Energy Resolution (after on-time corrections)



CMS Vertex Selection Efficiency



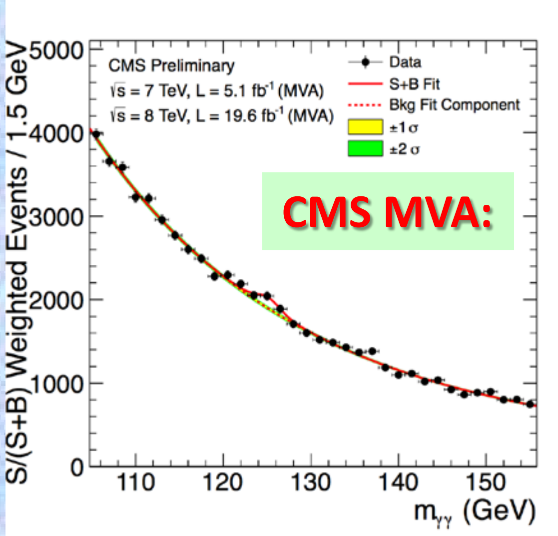
The Higgs Decay: H → γγ

Separated in several categories to exploit different mass res. & S/B:

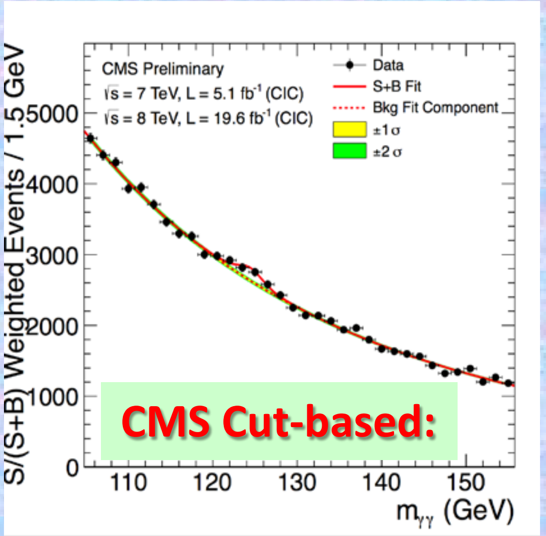
ATLAS: Cut-based

CMS: MVA and Cut-based

- ☞ MVA input variables are designed to be mass independent
- ☞ Fit $m(\gamma\gamma)$ in each of 9 categories:
  - ➠ 4 diphoton MVA categories
  - ➠ 2 dijet-tagged categories
  - ➠ 2 lepton-tagged categories
  - ➠ 1 MET-tagged categories

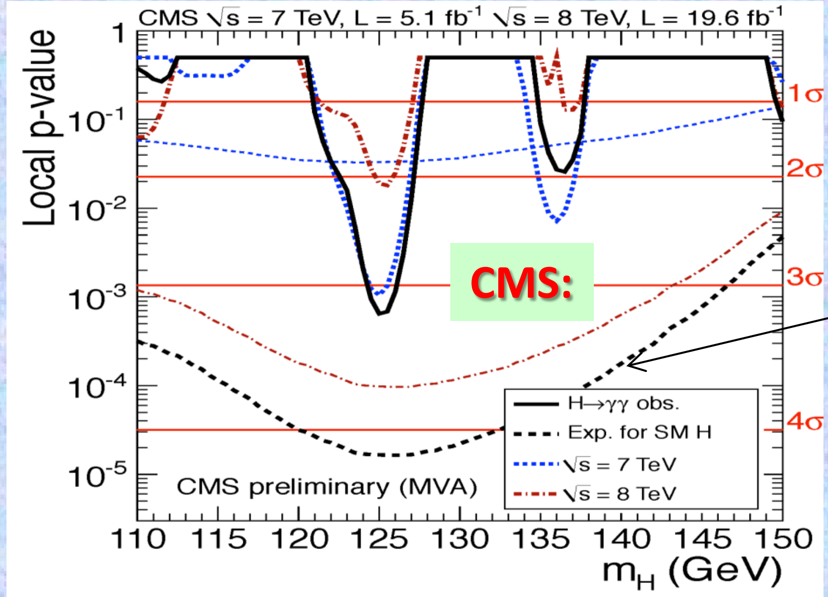


CMS MVA:



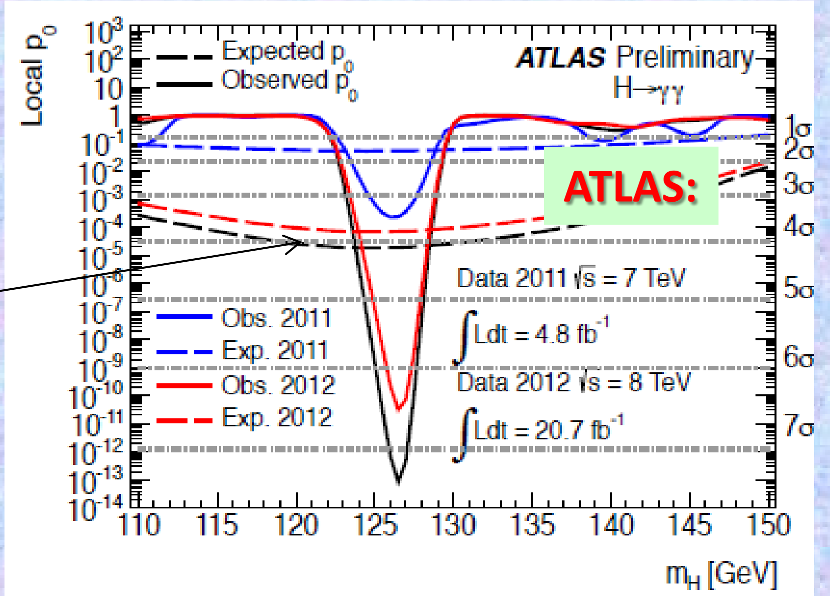
CMS Cut-based:

Locap p-value (consistency of data with background-only hypothesis):



CMS:

Expected from SM Higgs at given m_H

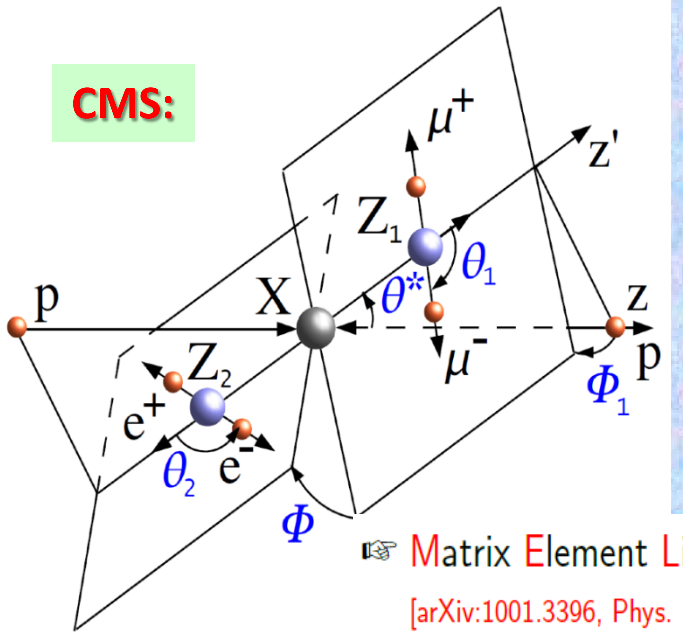


ATLAS:

Established the discovery of the new particle in the γγ channel alone ☺

The Higgs Decay: H → ZZ → 4l

CMS:



- **Signal:** 4 isolated high-p_T leptons from same vertex
- **Background:** non-resonant ZZ, Zbb, top(2l2v2b), fakes

Matrix Element Likelihood Analysis:

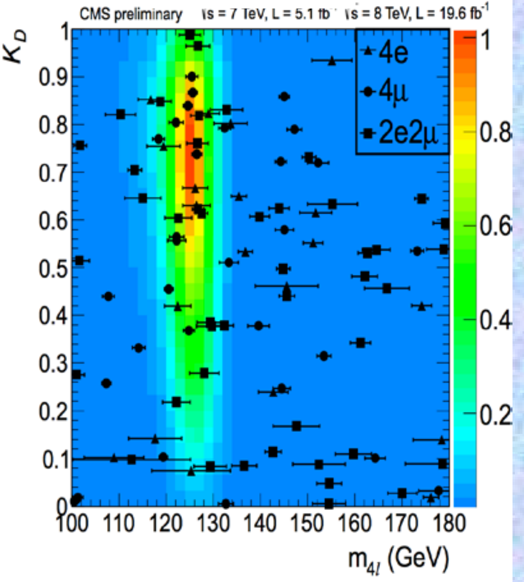
uses kinematic inputs to build a kinematic discriminant (K_D) for signal to background discrimination using $\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

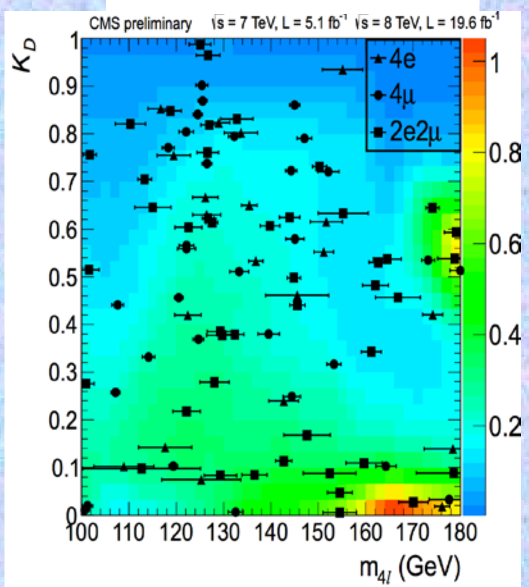
☞ Matrix Element Likelihood Analysis

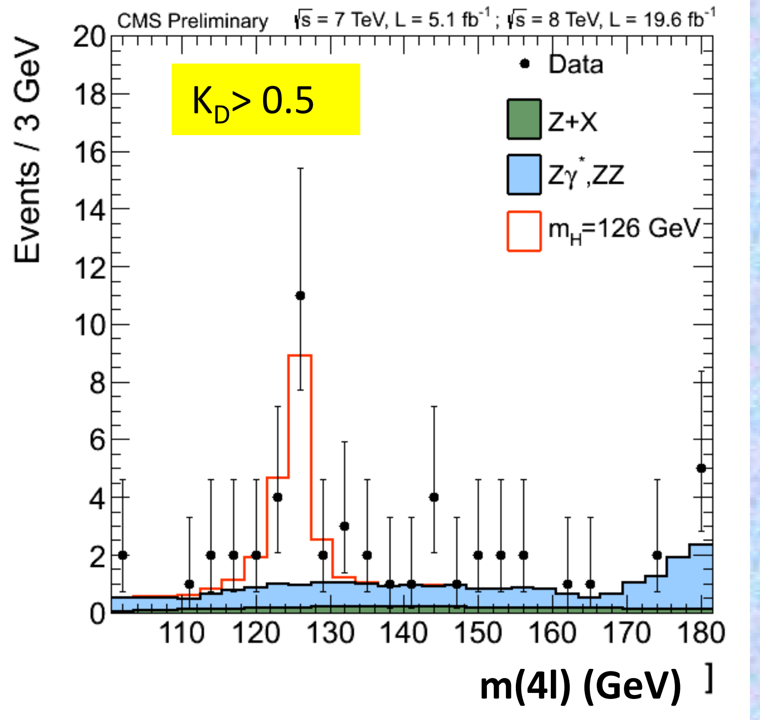
[arXiv:1001.3396, Phys. Rev. D81, 075022(2010)]

SIGNAL

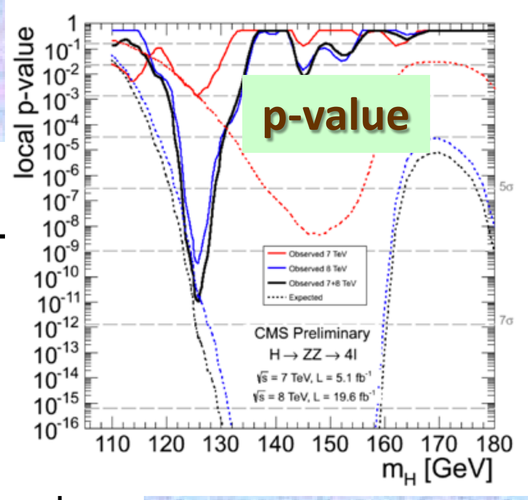


BACKGROUND

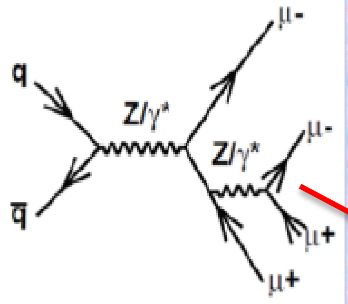


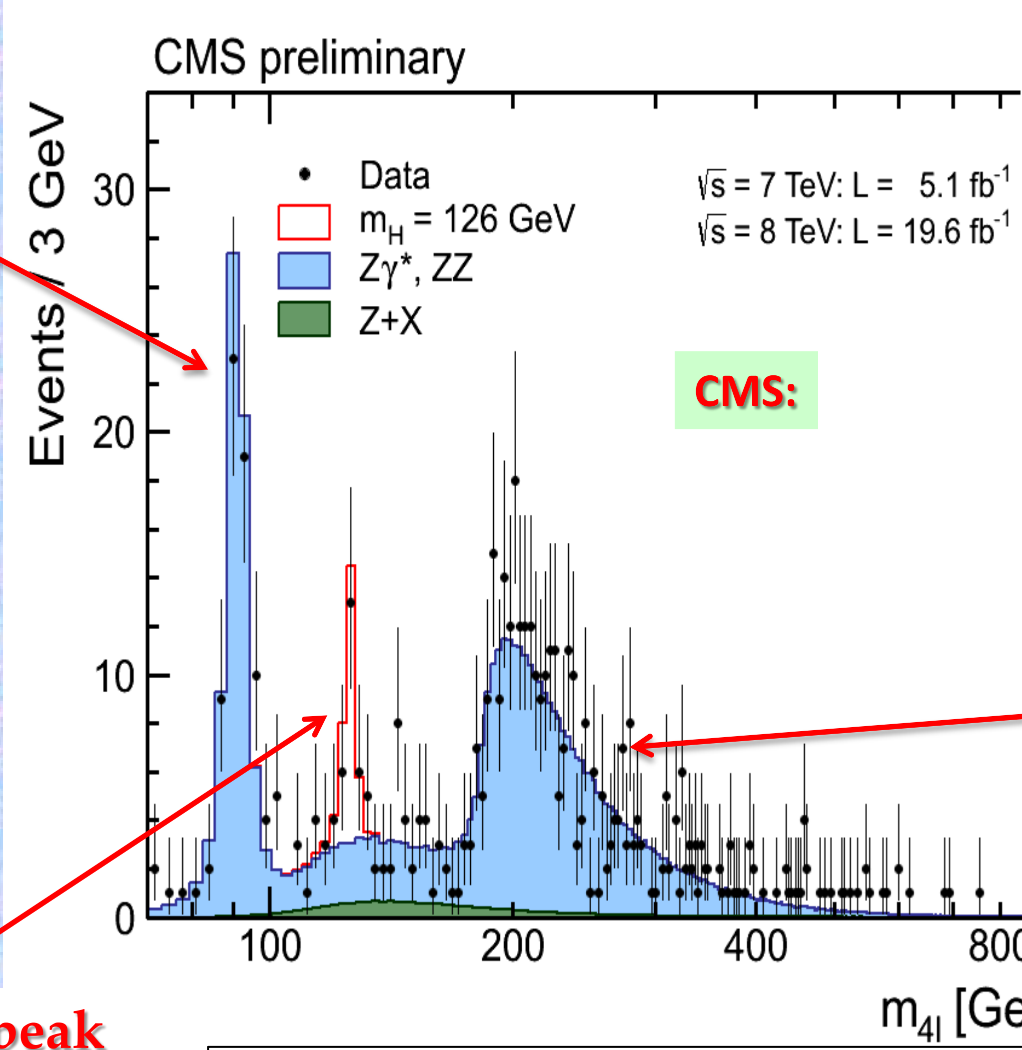


The Higgs Decay: H → ZZ → 4l



p-value





CMS:

Very good control of the dominant ZZ background

M(4l)>160 GeV:
Data 380 evts
MC 364.5 evts

Clean signal peak at ~126 GeV

σ(pp →ZZ, 8TeV) = 8.4±1.0 (stat.) ± 0.7 (syst.) ± 0.4(lum.) pb

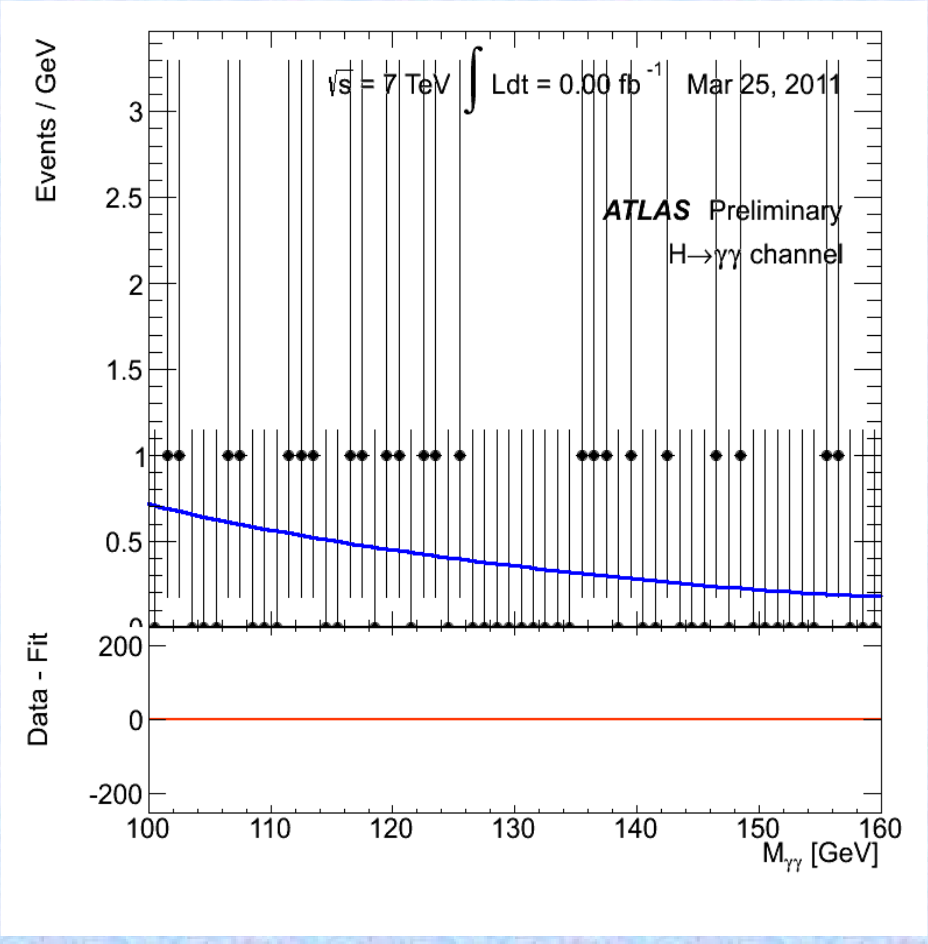
SM (ZZ) theory: σ_{SM}(th) = 7.8 ± 0.6 pb

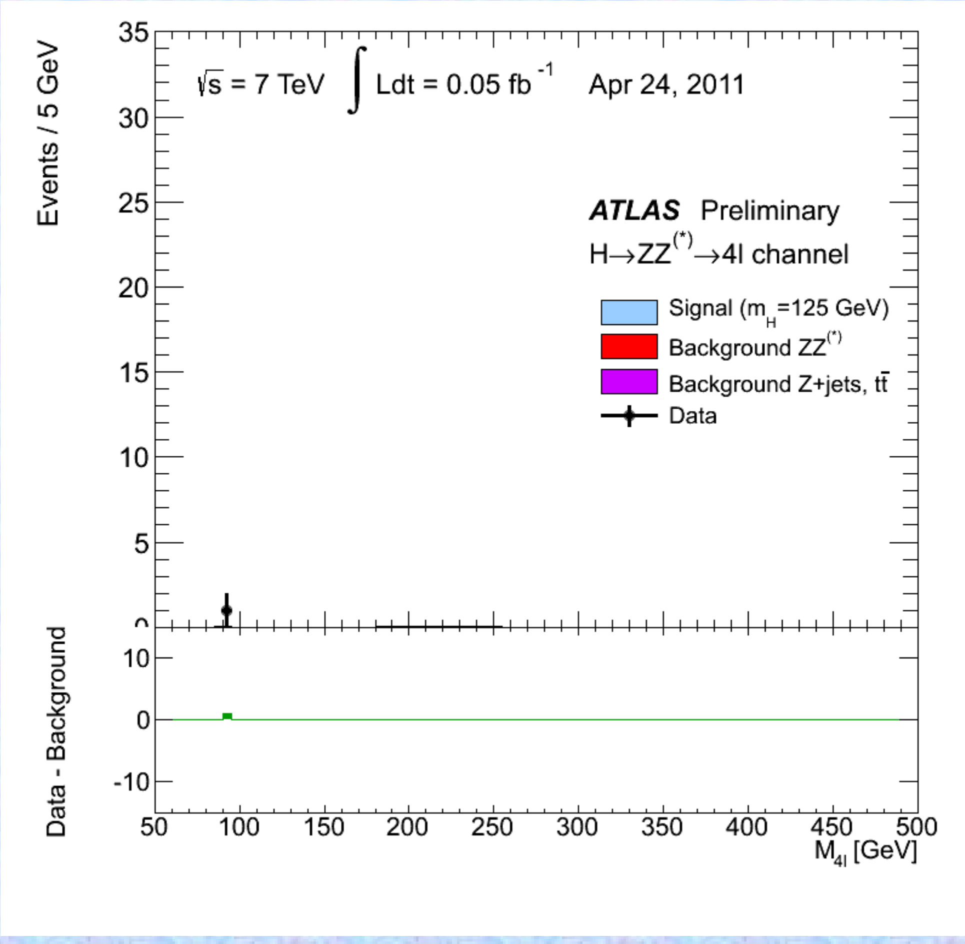
Signal significance (in H→ZZ) is well over 6 standard deviations

The Birth of a Particle: Higgs Boson - Evolution in Time

"History" of the data accumulation during the last two years (ATLAS)

H → γγ **H → ZZ**





☺ **The new particle has couplings to bosons … what about fermions ???**

Tau Zooming in on the Higgs: $H \rightarrow \tau\tau$

Good $M(\tau\tau)$ resolution is the most effective tool against $Z \to \tau\tau$

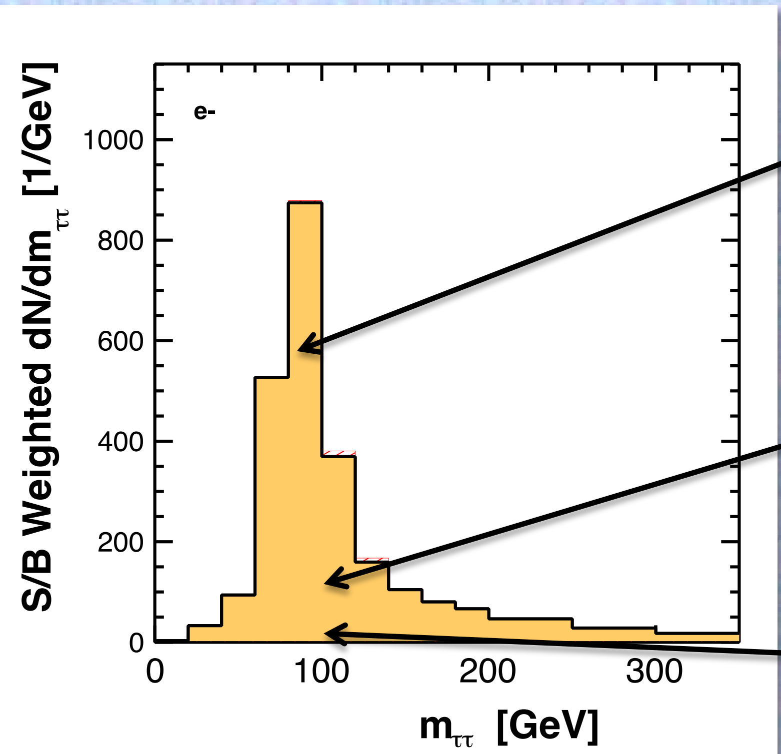
- **ATLAS: Missing Mass Calculator(NIMA654 (2011)481); CMS: SVFIT(CMS PAS HIG-13-004)**
- **MMC & SVFIT sophisticated techniques to reconstruct $M(\tau\tau)$ in presence of neutrinos**
  → improve analysis sensitivity by 20%-30% compared to visible mass

SUMMARY PLOT: combine all channels ($e\tau_{had}$, $\mu\tau_{had}$, $e\mu$, $\tau_{had}\tau_{had}$) weighted with a S/B

Excess building up in the region 120-130 GeV:

Significance:
2.93σ for m_H = 120 GeV
2.85σ for m_H = 125 GeV

Combining $H \to \tau\tau$ and $H \rightarrow bb$ channels the significance is 3.4 σ (expected 3.5 σ)



$Z \to \tau\tau$ Embedding:
$Z \to \mu\mu$ data, replace μ with simulated τ decay
Normalization from $Z \to \mu\mu$ data

W+jets:
Shape from simulation
Normalization from control region

QCD:
SS lepton data, corrected for SS/OS lepton ratio
Syst: 10%

☺ The new particle has couplings to bosons … and to fermions ☺ !!!

Summary of Higgs Searches at a Glance…

Decay	Signature	S/B & Mass resol.	Experim.	P-value (expect.)	P-value (observed)	Used for
$H \to \gamma\gamma$	2 photons, peak in inv. mass (H)	Low O(1), 2%	ATLAS	4.1 σ	7.4 σ	**Mass, spin, Discovery, couplings $K_V K_F$**
			CMS	4.2 σ	3.2 σ	
$H \to ZZ \to 4l$	4 leptons, peak in inv. mass (Z_1, H)	High (>1), 1-2%	ATLAS	4.4 σ	6.6 σ	**Mass, spin, Discovery, Coupling K_V**
			CMS	7.1 σ	6.7 σ	
$H \to WW \to 2l2\nu$	2 leptons, E_T^{Miss}	MediumO(1), 20%	ATLAS	3.7 σ	3.8 σ	**Spin, Couplings K_V**
			CMS	5.3 σ	3.9 σ	
$H \to \tau\tau$	Lepton, τ_{had}, E_T^{Miss}	Low O(1), 15%	ATLAS	1.2 σ	1.9 σ	**Couplings K_F**
			CMS	2.6 σ	2.9 σ	
$H \to bb$	Z,W, 2b-jets, peak in inv. Mass (H)	Low O(1), 10%	ATLAS	1.9 σ	1.8 σ	**Couplings K_F**
			CMS	2.2 σ	2.1 σ	

Also new (based on full statistics):

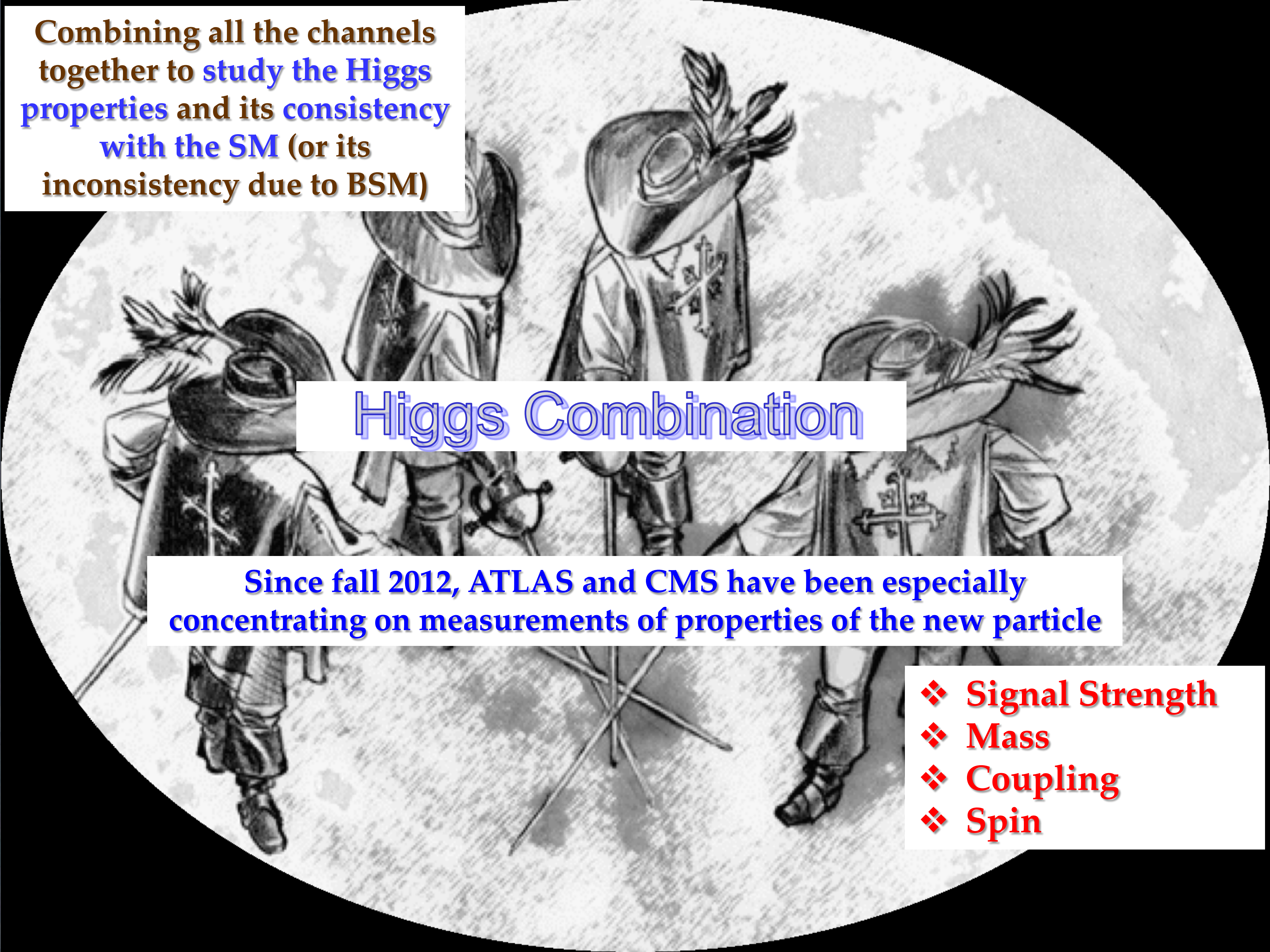
- **$ttH \to \gamma\gamma$ (CMS)**
- **$H \to Z\gamma$ (ATLAS,CMS)**
- **$H \to \mu\mu$ (ATLAS)**
- **$WH \to WWW \to 3l3\nu$ (CMS)**
- **$H \to ZZ \to 2l2\tau$, $2l2\nu$, $WW \to l\nu jet$ (high mass) (CMS)**

Latest combinations, non-SM Higgs studies, see

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

Higgs Combination

Combining all the channels together to study the Higgs properties and its consistency with the SM (or its inconsistency due to BSM)



Since fall 2012, ATLAS and CMS have been especially concentrating on measurements of properties of the new particle

- ❖ Signal Strength
- ❖ Mass
- ❖ Coupling
- ❖ Spin

Higgs Boson: Signal Strength (μ)

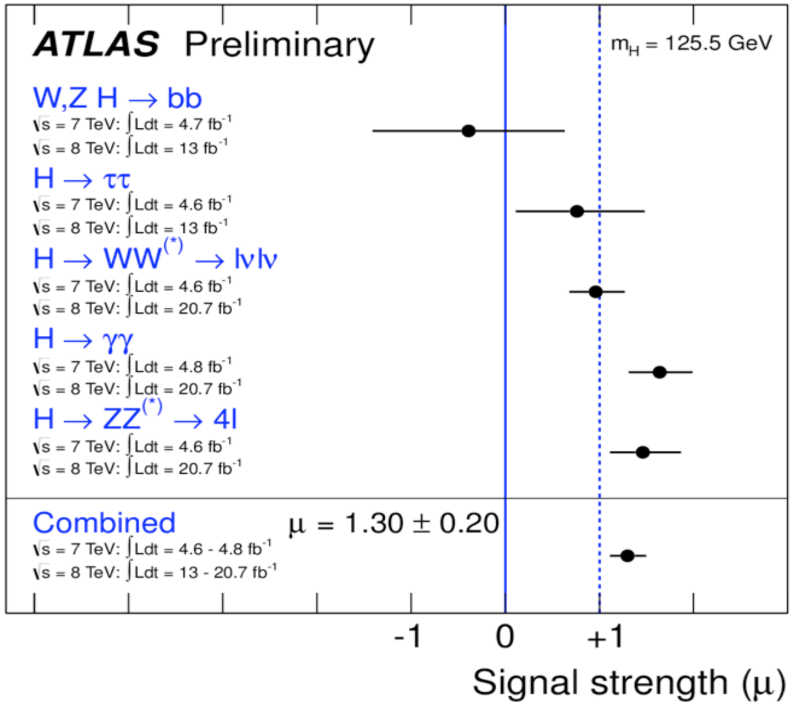
$$\mu = \frac{\text{Measured event yield}}{\text{Yield expected from SM Higgs}}$$

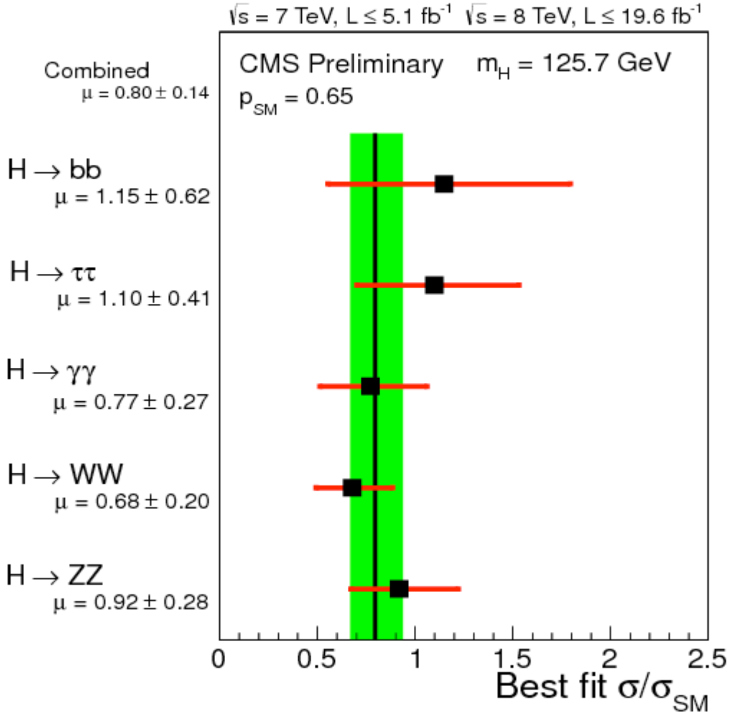
(Standard Model Higgs: $\mu = 1$)

Once m_H is measured, SM cross sections are uniquely determined --> test the consistency with "THE SM Higgs" measuring deviations from predicted yields ($\mu = 1$)

ATLAS: $\mu = 1.30 \pm 0.20$ @ 125.5 GeV

CMS: $\mu = 0.80 \pm 0.14$ @ 125.7 GeV





Slight excess in $\gamma\gamma$/ZZ drives $\mu > 1$ overall (consistent with $\mu = 1$ within 2 σ)

Slight deficit in $\gamma\gamma$/ZZ/WW drives $\mu < 1$ overall (consistent with $\mu = 1$ within 1 σ)

ATLAS-CONF-2013-034

CMS PAG HIG-13-005

Higgs Boson: Mass

- **Combine information from the high resolution channels for mass measurement:**
  - **- H → ZZ → 4l**
  - **- H → γγ (ggH and VBF)**

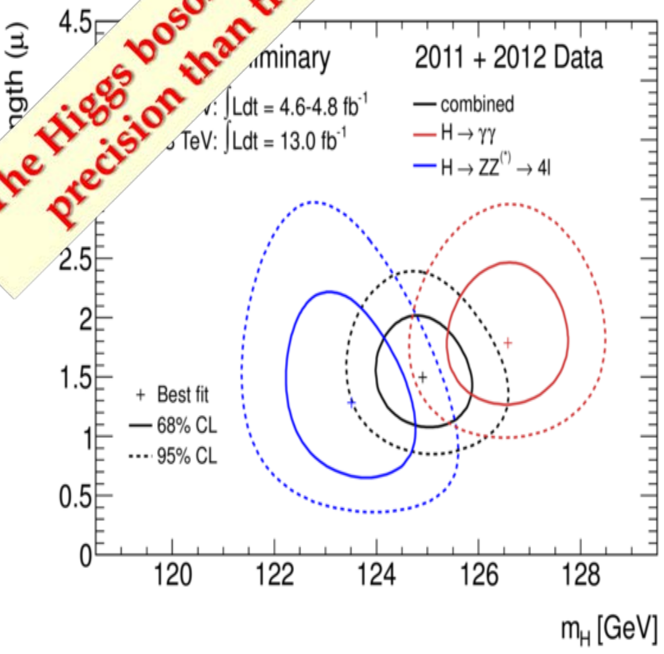
- **Signal cross section for the channels left floating independently in the fit**

Expt.	Decay Process	easurements . ± syst.	$\mu = \sigma/\sigma_{SM}$	Comments
ATLAS	$H \to \gamma\gamma$	± 0.2 ± 0.7	1.65 ± 0.24 ± 0.22*	CONF-2013-012
	$H \to ZZ^*$	4.3 ± 0.5 ± 0.4*	1.7 ± 0.5	CONF-2013-013
	$H \to$	125.5 ± 0.2 ± 0.5	1.6 ± 0.3	CONF-2013-014 CONF-2013-034
	H		1.5 ± 0.4	
	$\to 2\ell 2\nu$		1.0 ± 0.3	
CM		125.4 ± 0.5 ± 0.6	0.78 ± 0.27	PAS HIG-13-001
	$ZZ^* \to 4\ell$	125.8 ± 0.5 ± 0.2	0.91 ± 0.27*	PAS HIG-13-002
	$H \to \gamma\gamma$	125.7 ± 0.3 ± 0.3	0.77 ± 0.27	PAS HIG-13-005
	$H \to ZZ^* \to 4\ell$		0.92 ± 0.28	
	$H \to WW^* \to 2\ell 2\nu$		0.68 ± 0.20	

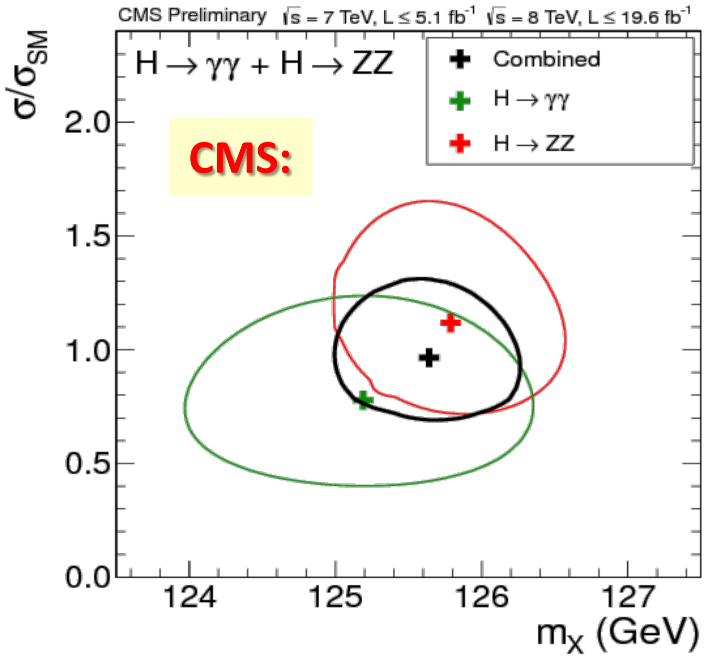
The Higgs boson mass has been already measured to a better precision than the top (or any other quark!) mass (0.50%)

ATLAS:

Taking into account systemati uncertainties, compatibility of the H→γγ & H→ZZ measurements is estimated to be at the 2.4σ level.



CMS:



Higgs Boson: Summary of the Couplings Measurements

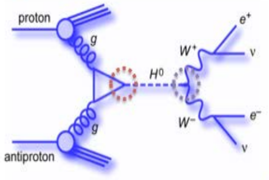
Study of compatibility with the SM Higgs Boson Couplings:

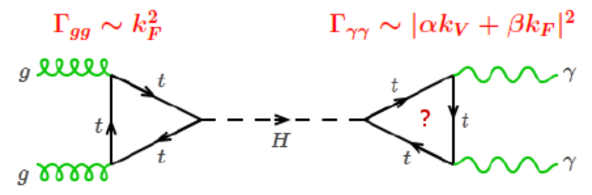
Couplings scaled by κ_X:

Hff: κ_f HVV: κ_V

HWW: κ_W $\lambda_{WZ} = \kappa_W / \kappa_Z$

HZZ: κ_Z In SM, $\kappa_X = 1$

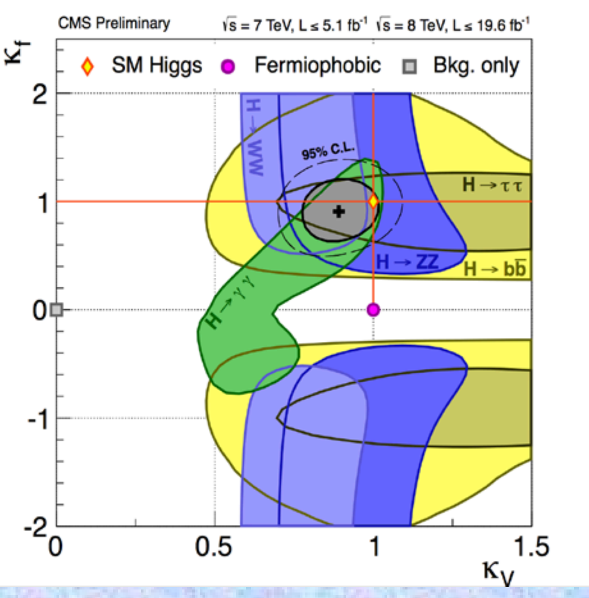


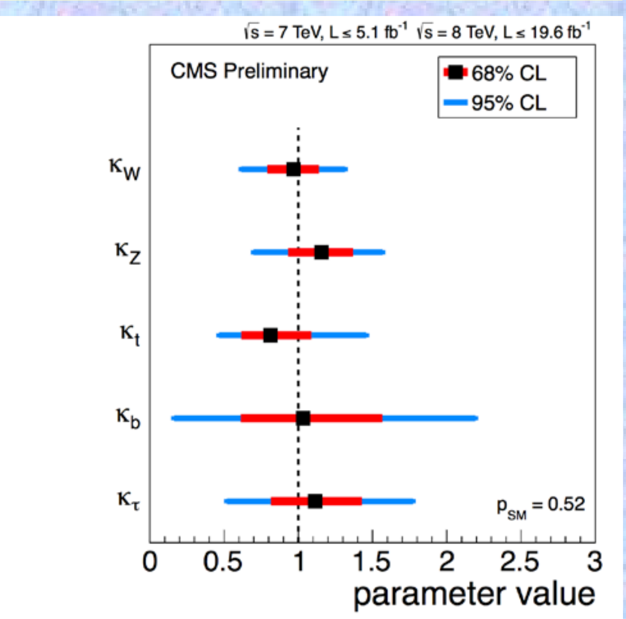


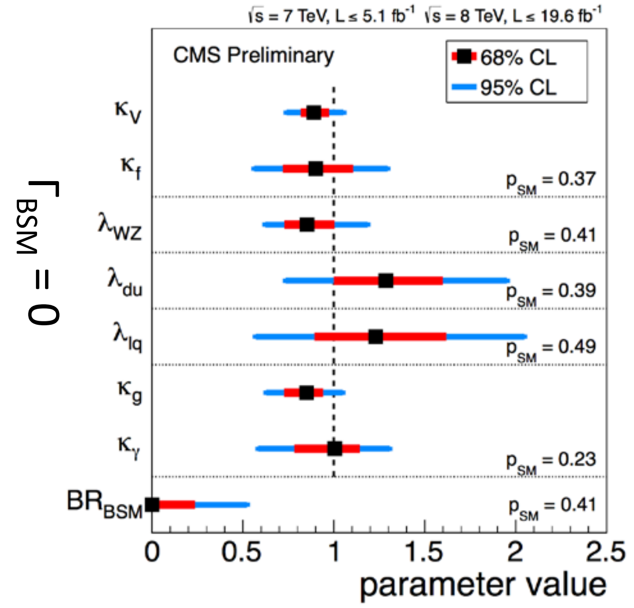
From all decay channels:

The generic-five parameter model(no eff. loop couplings)

The LHC XS WG benchmark model (arXiv:1209.0040)







The best fit values of the most interesting parameters are shown, with the corresponding 68% and 95% CL intervals, and the overall p-value p_{SM} of the SM Higgs hypothesis is given.

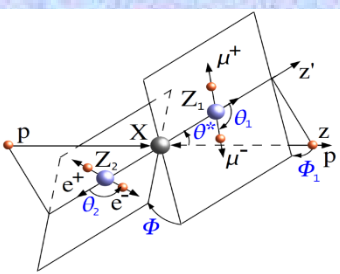
No deviations from the SM Higgs Boson are found so far

Higgs Boson: Spin and Parity Hypothesis

Spin-0 and 2 are only allowed by H→ γγ channel (spin-1 excluded by Landau/Yang theorem)

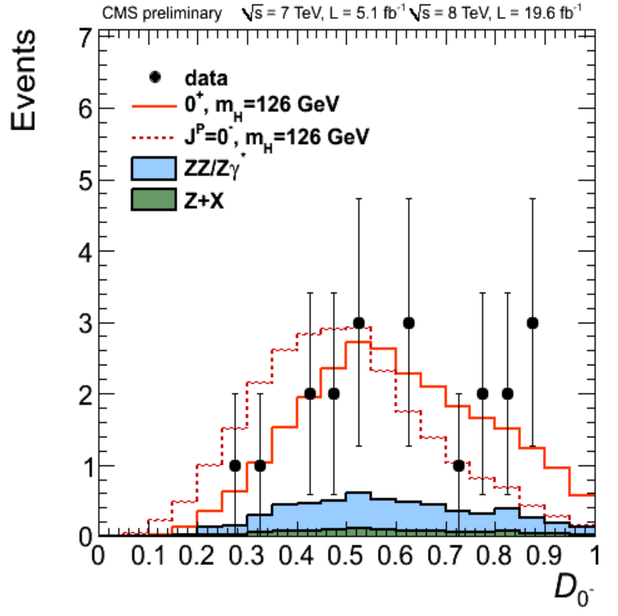
$0^+/0^-$ Study: based on H →ZZ → 4l

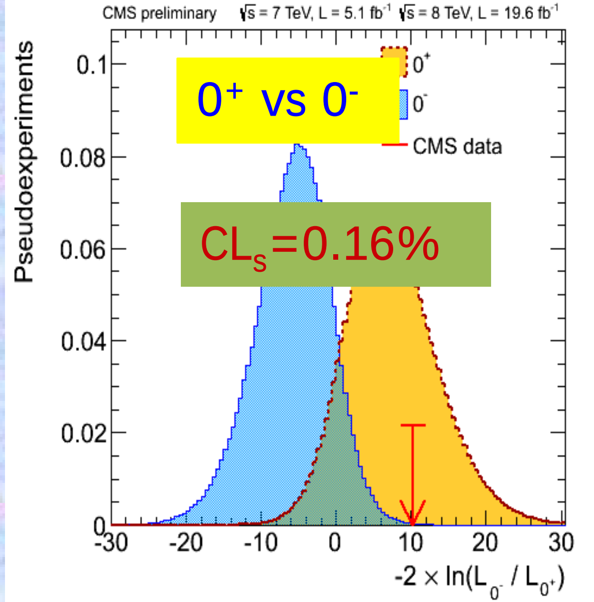
Kinematic discriminant built to describe the kinematics of production and decay of different J^P state of a "Higgs"

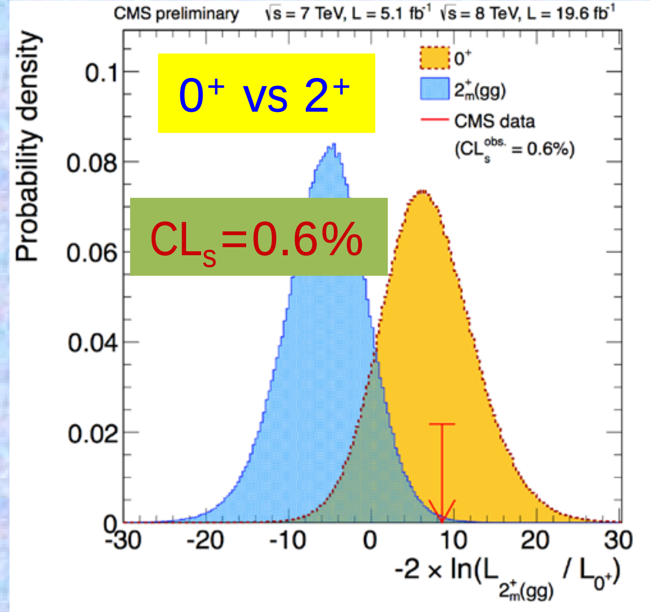


$0^+/2^+_{mgg}$ Study:

Combining results from WW and ZZ channels

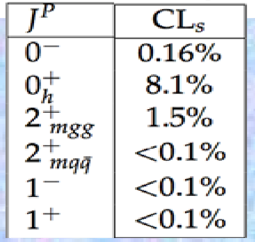






The data disfavours the 0^-_m hypothesis with a 99.8 % CL

Other Hypothesis:

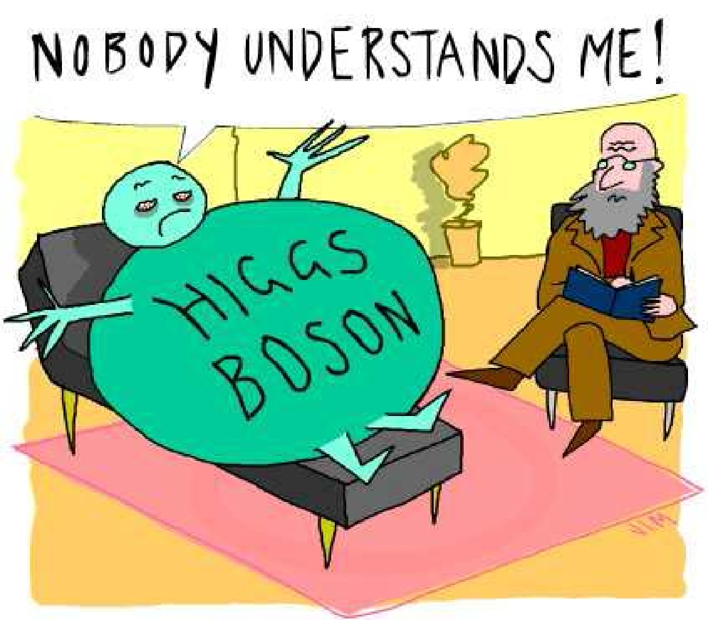


J^P	CL_s
0^-	0.16%
0^+_h	8.1%
2^+_{mgg}	1.5%
$2^+_{mq\bar{q}}$	<0.1%
1^-	<0.1%
1^+	<0.1%

The data disfavours the 2^+_m(gg) hypothesis with a CLs of 0.6%

The current observation is very compatible with the SM Higgs expectations of 0^+.

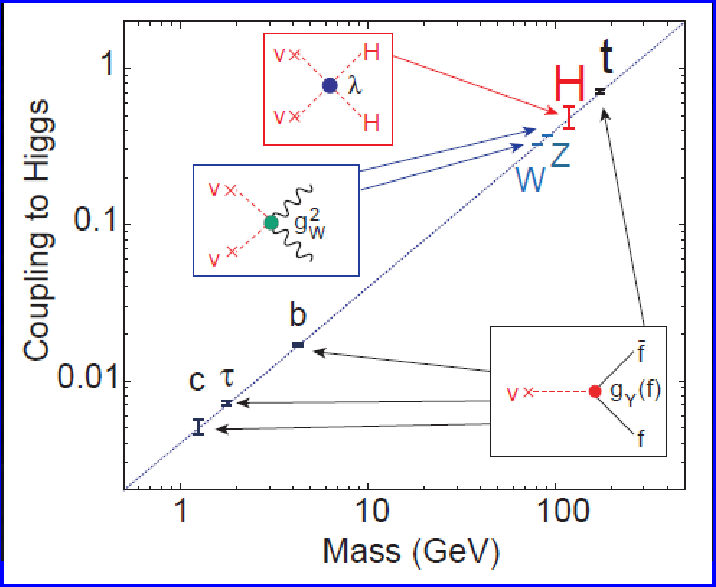
Historic Milestone: the Higgs is just Different



Higgs is the most exotic particle of the SM
its discovery has profound implications:

All the matter particles are spin-1/2 fermions.
All the force carriers are spin-1 bosons

- ❖ **Higgs particle is spin-0 boson (scalar).**
- ❖ **The Higgs is a totally new form of matter (neither matter nor force).**
- ❖ **The Higgs is the only spin 0 particle in the SM but it does the most important job (give masses)**



- ➢ **A new force field, the Higgs field, has an average value in the vacuum that became non-zero as the early universe cooled.**
- ➢ **We still don't know dynamics behind the Higgs condensate**
- ➢ **Higgsless theories: now dead**

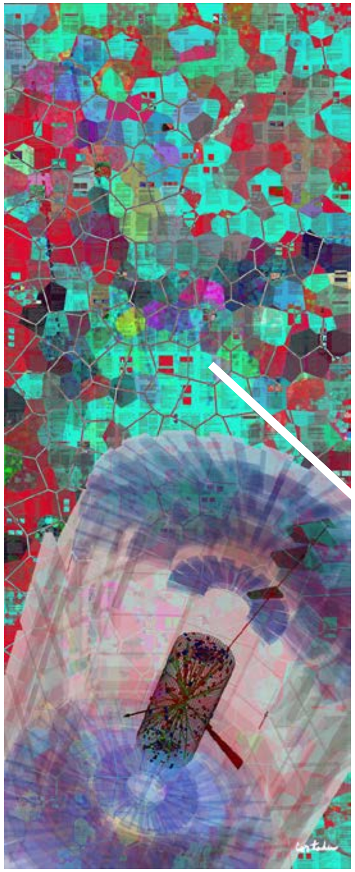
Art @ CMS Project: In Search of the Higgs Boson

M. Hoch (CMS)

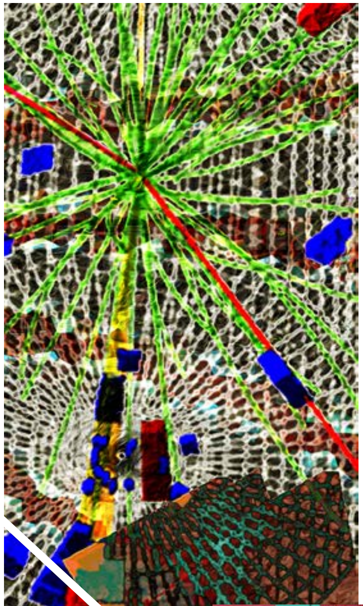
Inspire 'non scientific world' with science instruments & physics topics:

http://cern.ch/scienceartschool

Xavier Cortada (with the participation of physicist Pete Markowitz), digital art, 2013

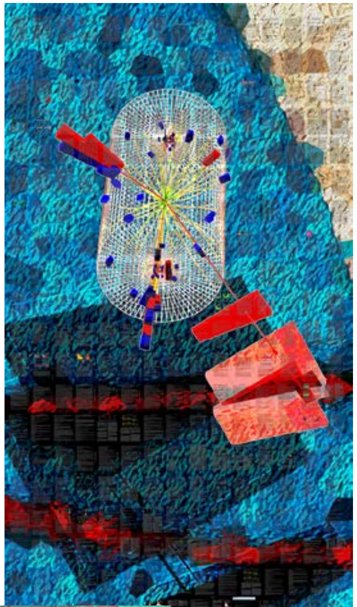


H → WW

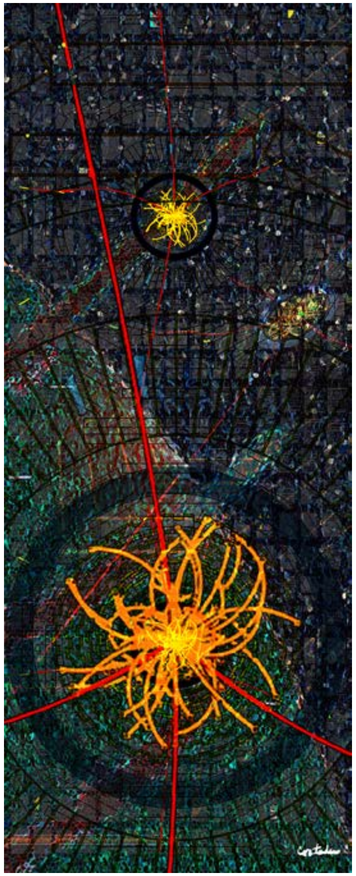


H → γγ

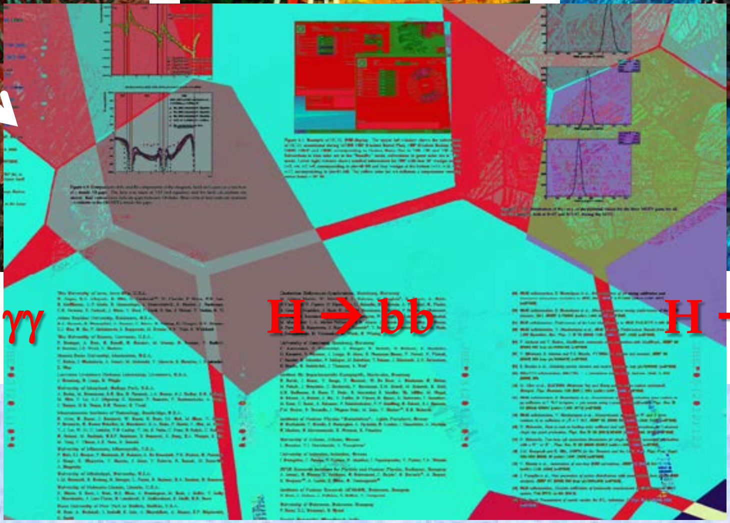
H → bb



H → ττ



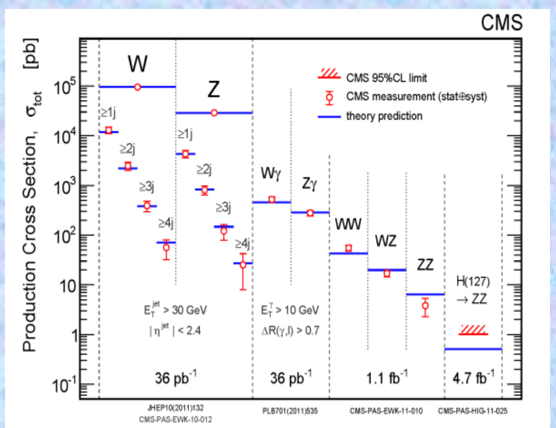
H → ZZ

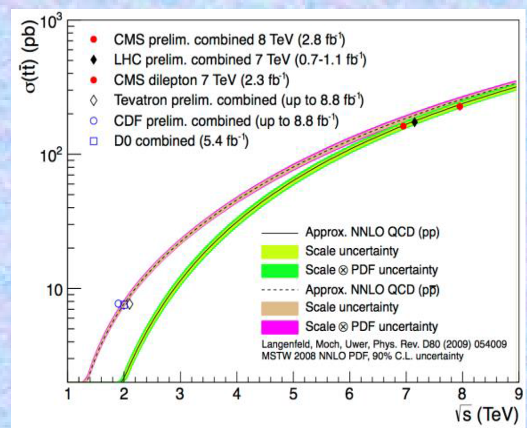


CMS Papers in Art Design:

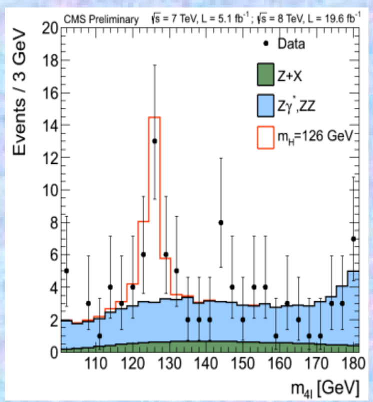
Real CMS Event Displays:

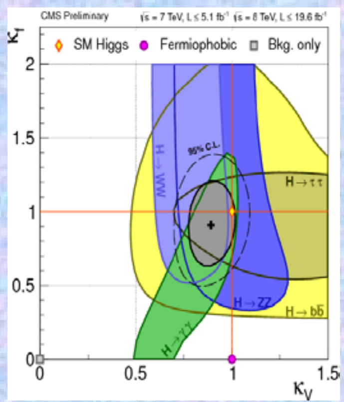
Today (2013): Energy Frontier Landscape

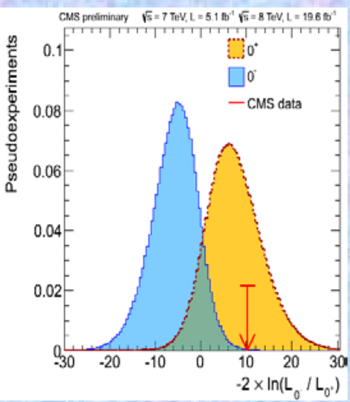




Precision SM measurements consistent with expectation

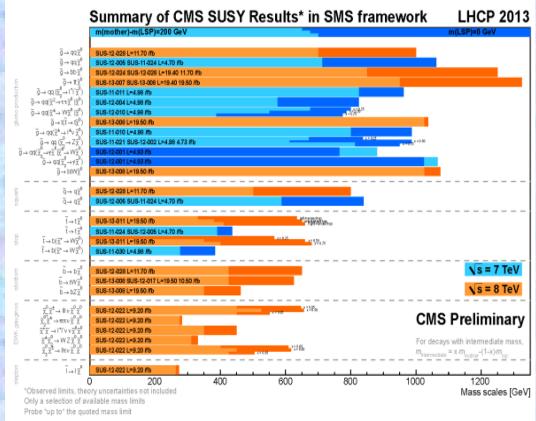


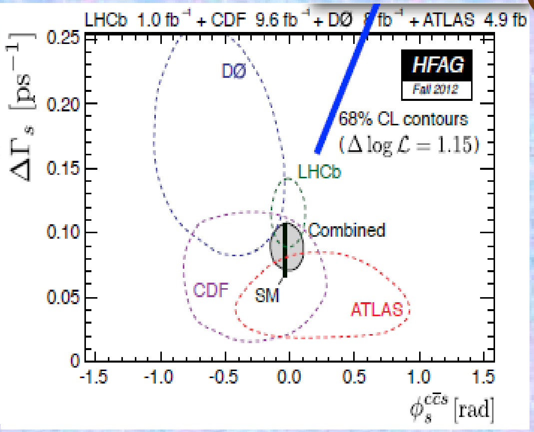




Discovery of a Higgs boson compatible with the SM

No evidence of sparticles or exotic heavy resonances in ATLAS & CMS (bug chunk of new territory explored)



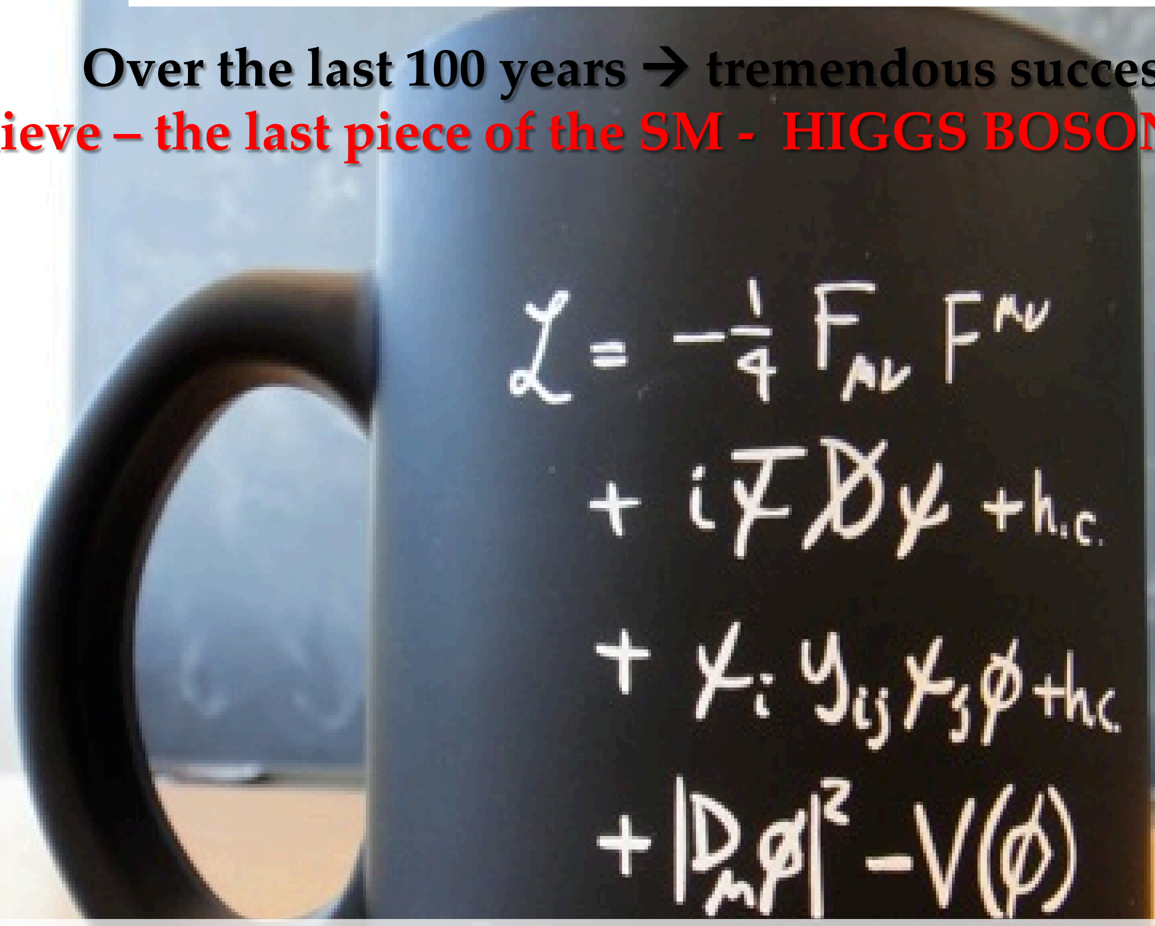


☹ No sign of new physics in heavy flavor decays (LHCb, B-fact.) → constraints from HF are extremely demanding: adding effective operators to SM generally leads to very large Λ

Standard Model of the Particle Physics

Over the last 100 years → tremendous success of the SM

We believe – the last piece of the SM - HIGGS BOSON has been discovered



$$\begin{aligned} \mathcal{L} = & -\tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i \bar{\psi} \not{D} \psi + h.c. \\ & + \psi_i y_{ij} \psi_j \phi + hc \\ & + |D_\mu \phi|^2 - V(\phi) \end{aligned}$$

Forces

Matter

Higgs :
Vacuum & masses

However, there are (at least) several missing items in the SM:

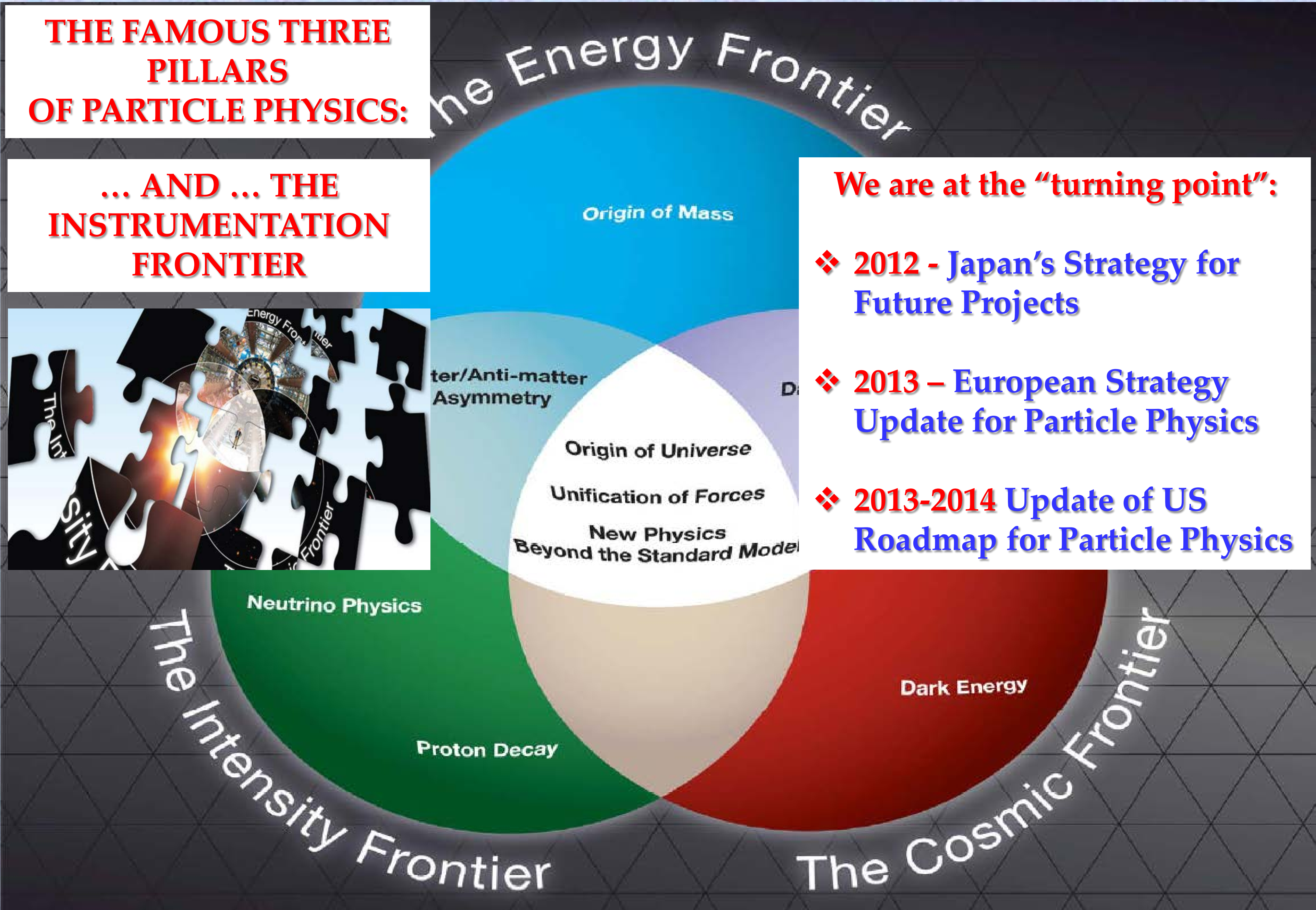
- **non-baryonic dark matter**
- **neutrino mass**
- **accelerated expansion of the Universe**
- **baryon asymmetry (absence of anti-matter)**

We don't really know their energy scales ...

Future Projects in Particle Physics: Experimental Opportunities

THE FAMOUS THREE PILLARS OF PARTICLE PHYSICS:

… AND … THE INSTRUMENTATION FRONTIER



We are at the "turning point":

- **2012 - Japan's Strategy for Future Projects**
- **2013 – European Strategy Update for Particle Physics**
- **2013-2014 Update of US Roadmap for Particle Physics**

Energy Frontier: Advancing MPGD Technologies

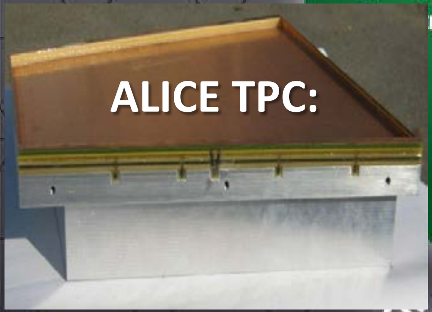
The Energy Frontier (sLHC):

- Rad hard technologies
- High granularity detectors
- Triggering at L > $10^{35}/cm^2/s$
- Pileup, material activation

The Energy Frontier (ILC/CLIC):

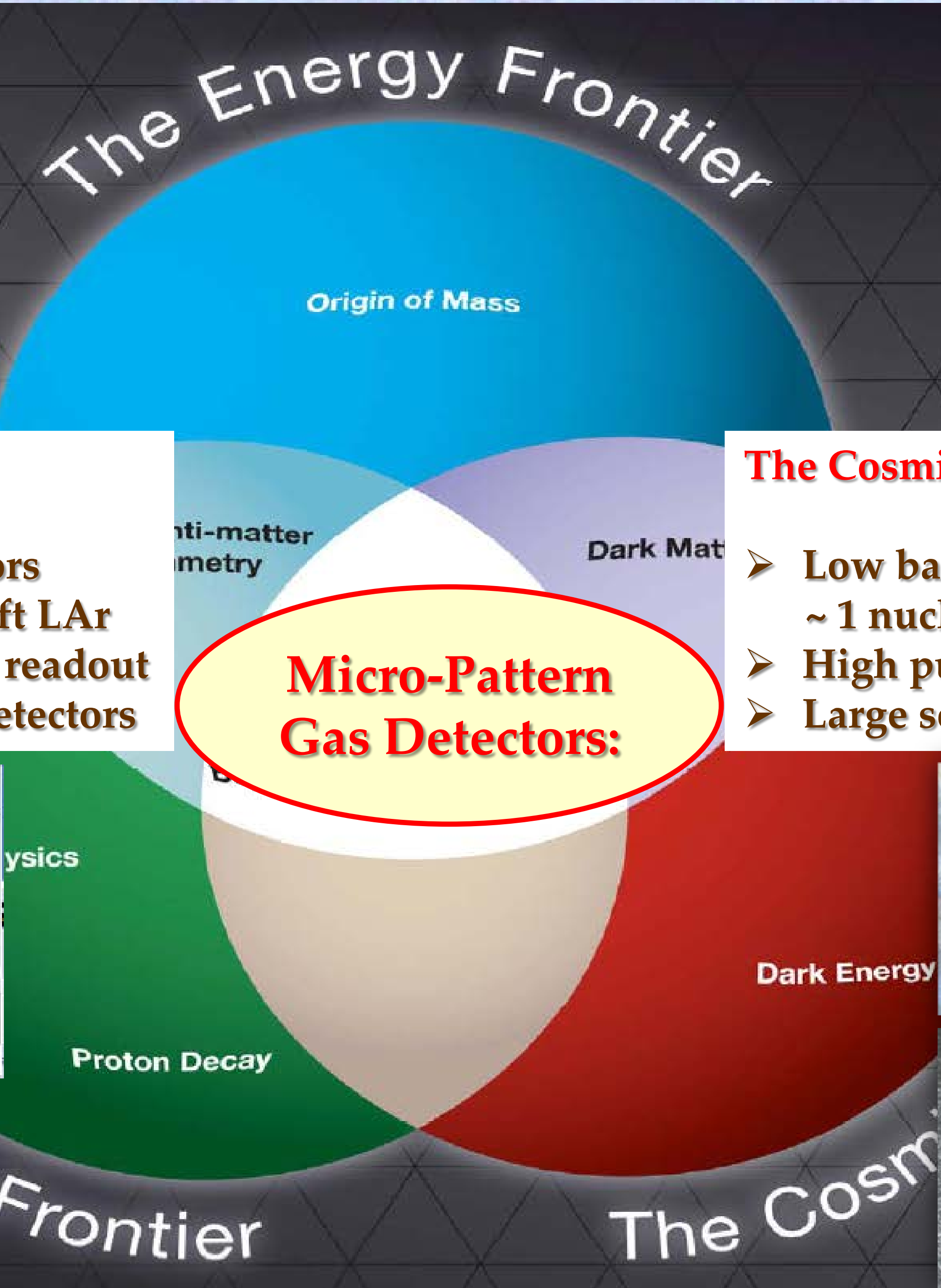
- Minimum material budget
- Ultra-high precision (5 μm space point resolution)
- Imaging calorimetry (jet energy resolution ~ 3% or better)
- Hermeticity (full angul. cover.)

Micro-Pattern Gas Detectors:



	Vertex	Inner Tracker	PID/ photo-det.	HAD CALO	MUON Track	MUON Trigger
ATLAS	GOSSIP	GOSSIP			Micromegas	Micromegas
CMS					GEM	GEM
ALICE		TPC (GEM)	VHPMID (CsI-THGEM)			
Linear Collider		TPC (GEM, MM,InGrid)		DHCAL (MM,GEM)		

Intensity and Cosmic Frontier: Advancing MPGD Technologies



The Intensity Frontier:

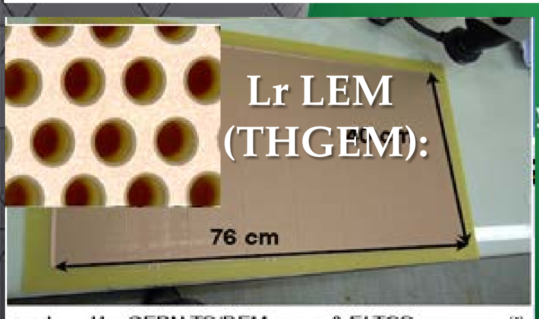
- Low-cost photo-detectors
- Large volume, long drift LAr TPC, purity and robust readout
- Large area Psec level detectors

Micro-Pattern Gas Detectors:

The Cosmic Frontier:

- Low backgrounds (down to ~ 1 nuclear recoil/ton/year)
- High purity
- Large sensitive areas

Lr LEM (THGEM):



produced by CERN TS/DEM group & ELTOS company (I)

NEWAGE (μPIC):

MIMAC Micromegas:

European Strategy for Particle Physics

High priority large scale scientific activities:

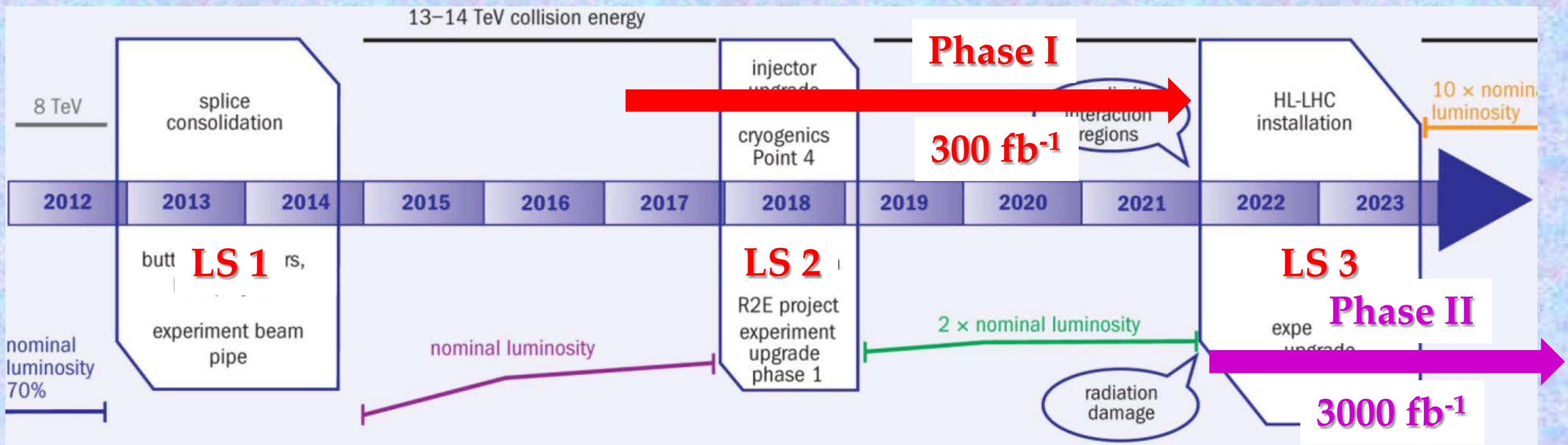
After careful analysis of many possible large scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority*:

c) The **discovery of the Higgs boson** is the start of a major programme of work to measure this particle's properties with the **highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier**. The LHC is in a unique position to pursue this programme.

Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030.
This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.

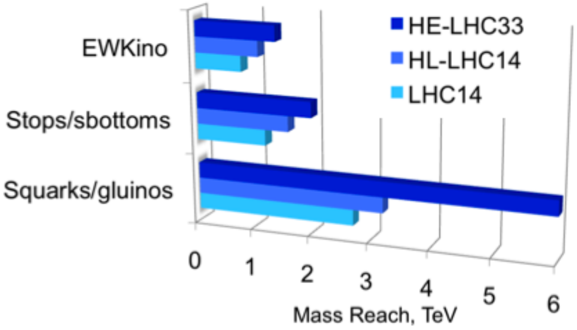
***A priori these 4 activities are not prioritized → all 4 should be pursued**

LHC Future (sLHC): From Now to 3000 fb^{-1}



Main Physics Motivations:

- ❖ Discovery of new particles @ 14TeV: SUSY, Exotic, Extra Dimensions, …



- ❖ Precision Higgs physics: self-coupling (30-40%), couplings (5-15%)

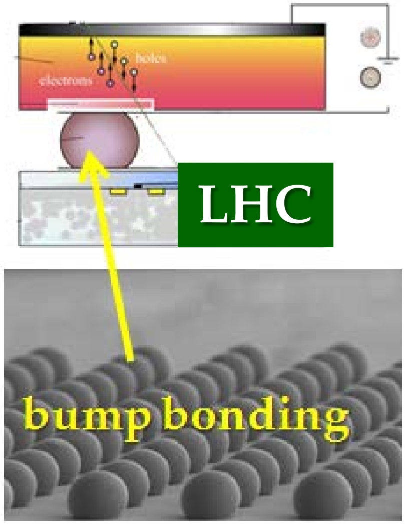
Major Upgrade Directions:

- ❖ New Pixel and Inner Trackers (radiation robustness at high luminosity)
- ❖ Trigger, FE and DAQ (maintaining low thresholds for precision Higgs measuments)
- ❖ Muon System (improve coverage, new (MPGD) technologies to sustain rates)
- ❖ Replace/Upgrade CALO (Forward/ Endcap –Phase 2)

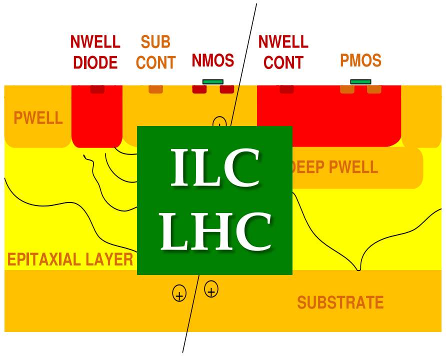
Trends in Vertex and Tracking with Solid State Detectors

- **Radiation hardness improvements demand newer technologies**
- **Improved functionality can only be achieved with higher integration**
- **Power dissipation and material budget must be reduced**

TODAY: Pixels
50 – 100s μm

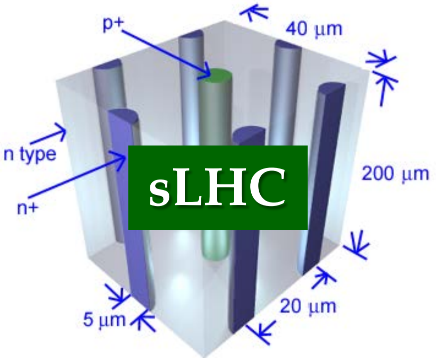


TODAY: Monolithic
25 – 50 μm



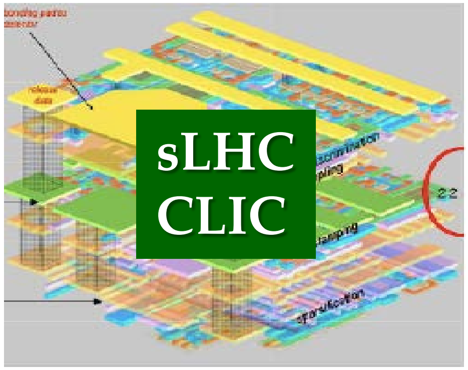
Integrated sensor & electronics: Less X0, no bonding, low noise

TOMORROW: 3D
Detectors (25–50 μm)



Lower V_{dep} (power)
Faster charge collection

Day After Tomorrow:
3D TSV (< 20 μm)



3D vertical Integration (TSV)

Motivation to develop new Pixel Detectors:

- ❖ Decrease fabrication cost
- ❖ Develop thinner pixel systems
- ❖ Easy fabrication of large area devices
- ❖ Integrate More (= denser) Intelligence

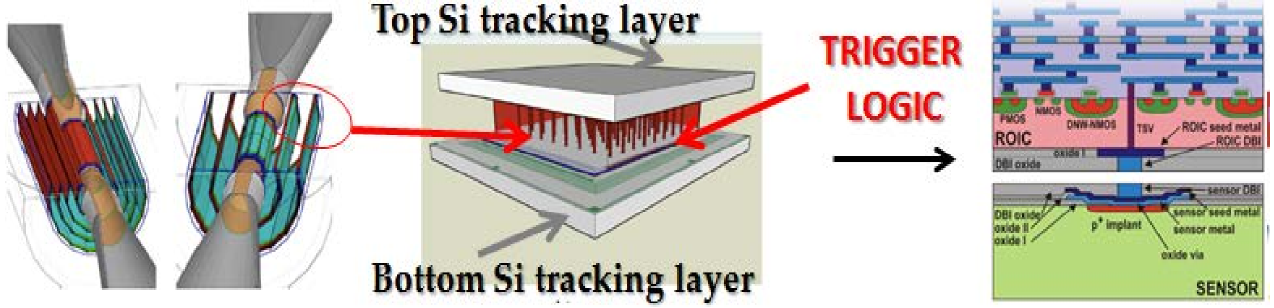
Trends and Perspectives:

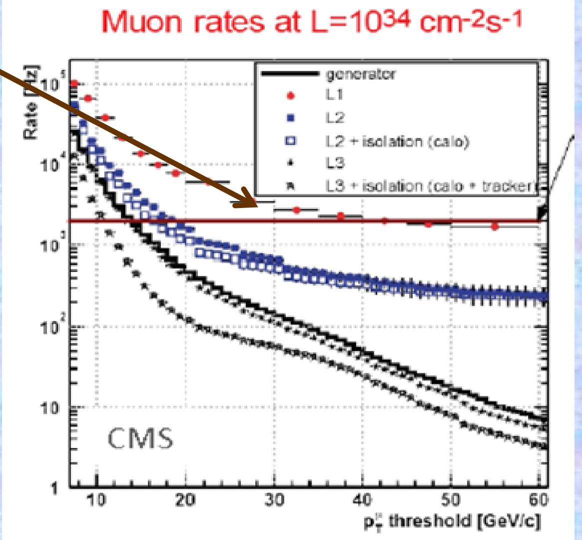
- ❖ Improve rad. hardness (p-type bulk)
- ❖ Reduce the thickness to 50 μm
- ❖ From 6″ to 8″ and 12″ wafers
- ❖ R&D on SLID/TSV interconnect.

Phase II: Track-Trigger Concept for HL-LHC

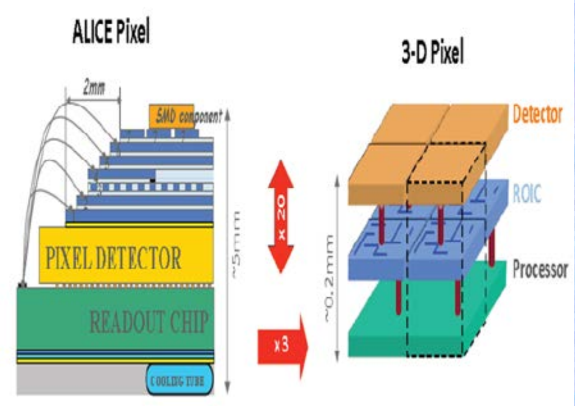
Integration of Functionality (the path to fully exploit CMOS potential):

Pixels & Trackers exploit New Concepts (trigger at L1):





Key technology: Through Silicon Via (TSV) → trigger logic, power, cooling inside the integrated chip layers



- ❖ **Vertically Integrated 3D Si-sensor (initiated by ILC R&D) → multiple thin Si-processing layers,implementing analog and digital signal processing, stacked on top of sensor layer**

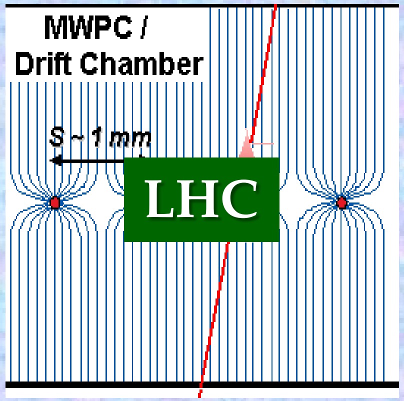
- ❖ **3D-IT expected to be very beneficial for CMOS sensors: Combine different fabrication processes -> choose the best ones for each tier/application**

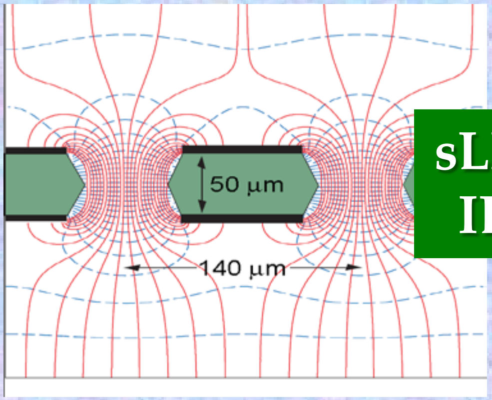
- ❖ **Split signal collection and processing on different tiers**

Trends in Gaseous Detectors (MWPC → MPGD)

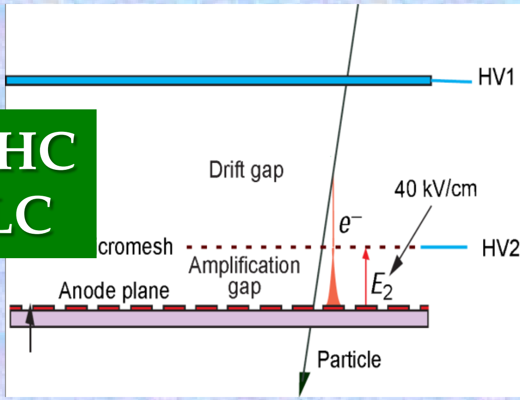
Wire Chambers, TPC, RPC → MPGD (GEM, Micromegas) → InGrid (3D)

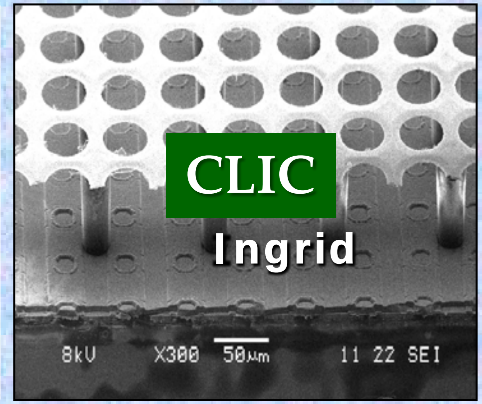
YESTERDAY: INTEGRATION → **TODAY:** INTEGRATION → **FUTURE:**





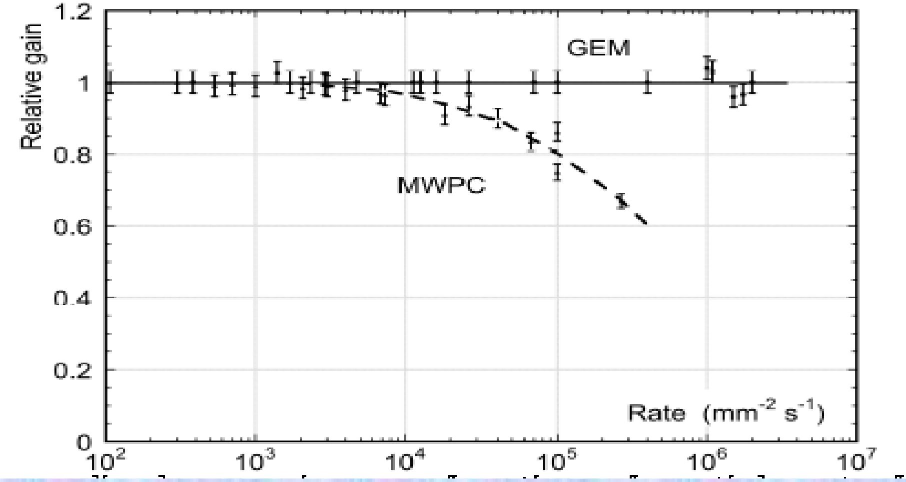
sLHC
ILC



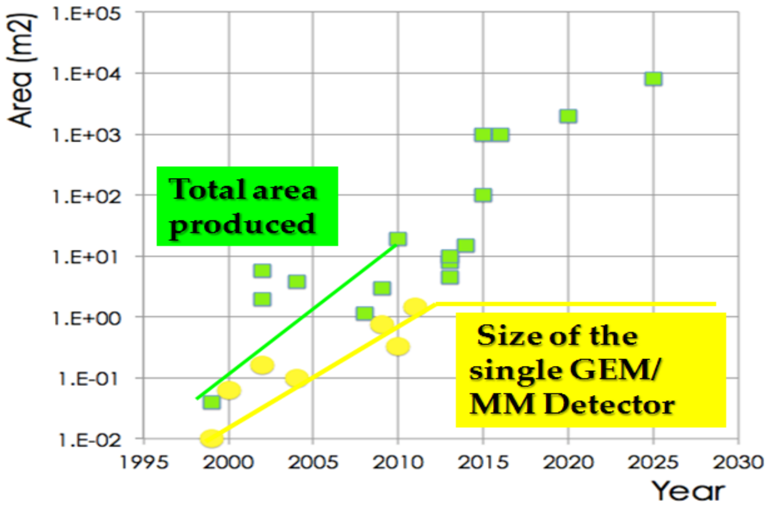


CLIC
Ingrid

- **High rate capability $\sim 10^6$ Hz/mm^2**
- **Spatial res. ~ 30-50 µm (TRACKING)**
- **Time res. ~ 3-5 ns (TRIGGER)**



Advances in photolithography → Large Area MPGDs (~ m² unit size)

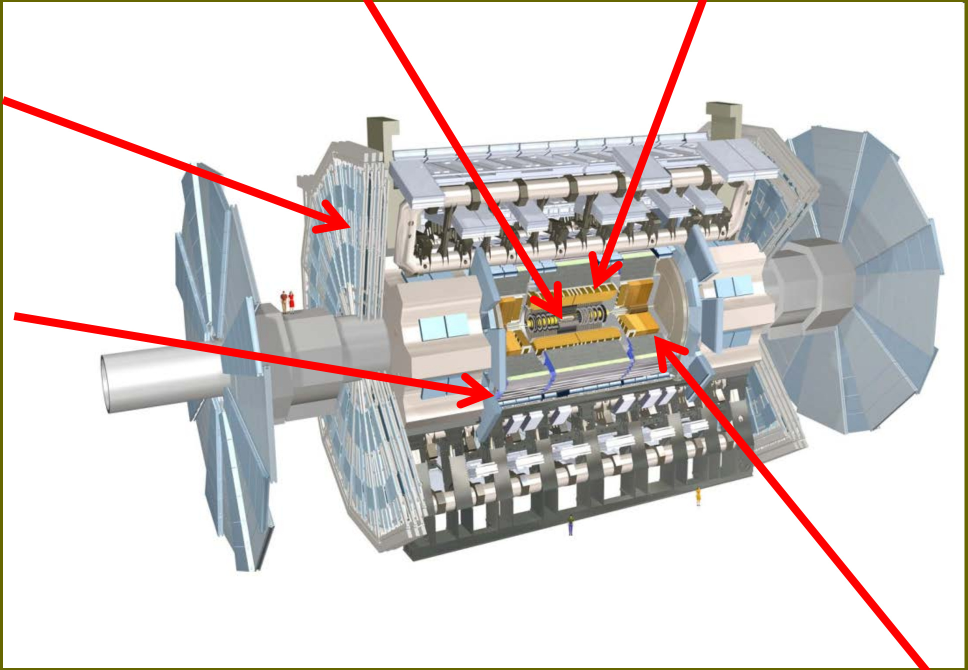


E.g. ATLAS Upgrades (up to Phase I)

Insertable B-Layer (LS1)
➡ and new services for Pixels

LAr Calorimeter (LS2)
(barrel and endcap)
➡ fine granularity readout for Level-1

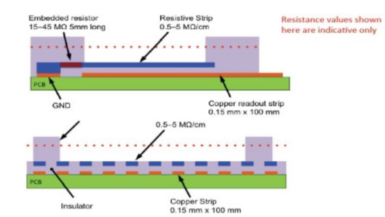
Muons (LS1)
➡ complete coverage
➡ new shielding



- Level-1 Trigger
➡ new electronics
➡ topological trigger
(phased in before LS2)

Muons (LS2)
➡ New Small Wheel
(sTGC, Micromegas)

The resistive-strip protection concept



~ 1200 m^2

- High Level Trigger farm (phased in before LS2)

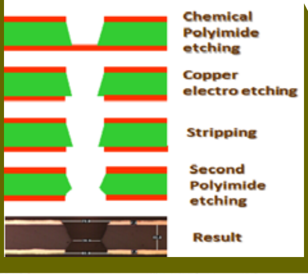
- ATLAS Forward Physics AFP
➡ 210m downstream from P1 (before LS2)

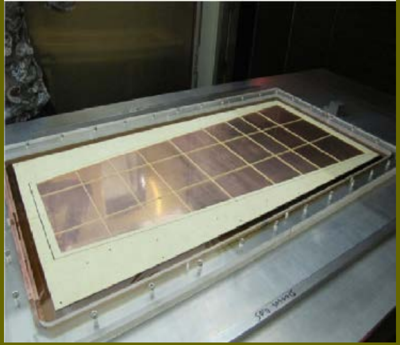
Tile Calorimeter (LS2)
➡ new gap scintillators
➡ new trigger electronics

- Fast Track Trigger FTK (LS2)
➡ HW tracking input to Level-2

E.g. CMS Upgrades (Phase II)

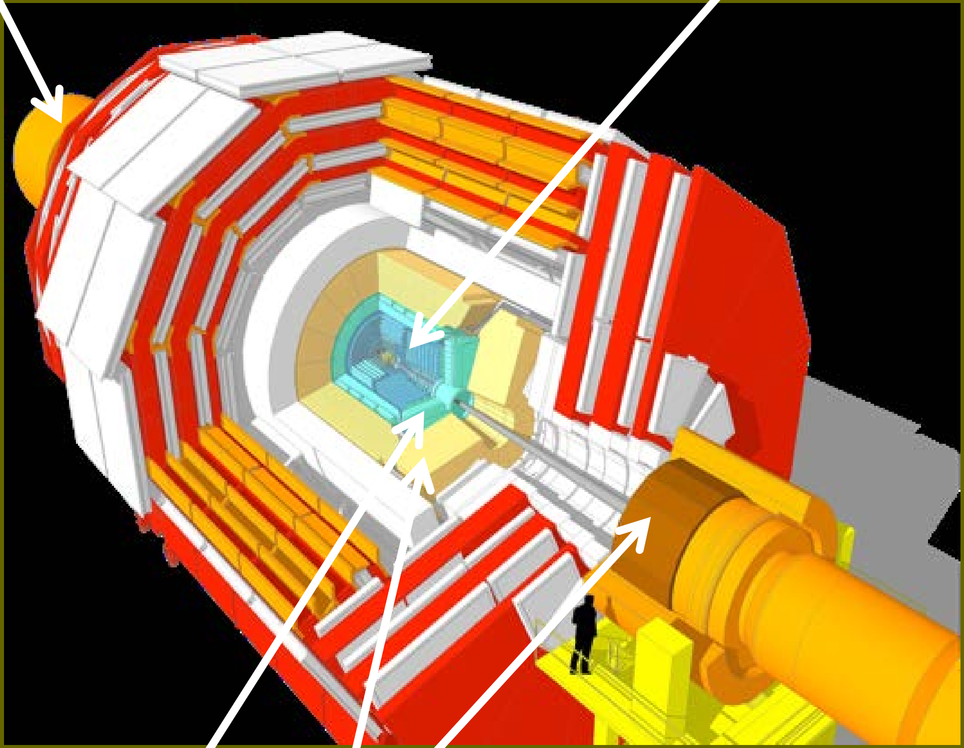
Muons
➡ complete RPCs in forward region with new technology (GEM or GRPCs)
➡ extend η coverage ?





~ 1000 m^2

new Inner Tracker:
➡ radiation hardness
➡ better granularity & faster links
➡ improved precision
➡ less material
➡ extend η coverage ?



❖ T/DAQ
➡ Level-1 at 1 *MHz* (?)
(requires all new FE/RO)
➡ Tracking at Level-1 (!)
(implement track-trigger)
➡ HLT output 10 *kHz* ?

upgrade/replace Forward Calorimeters
➡ extend η coverage ?
➡ mitigate pileup effects with tracking and precise timing

European Strategy for Particle Physics

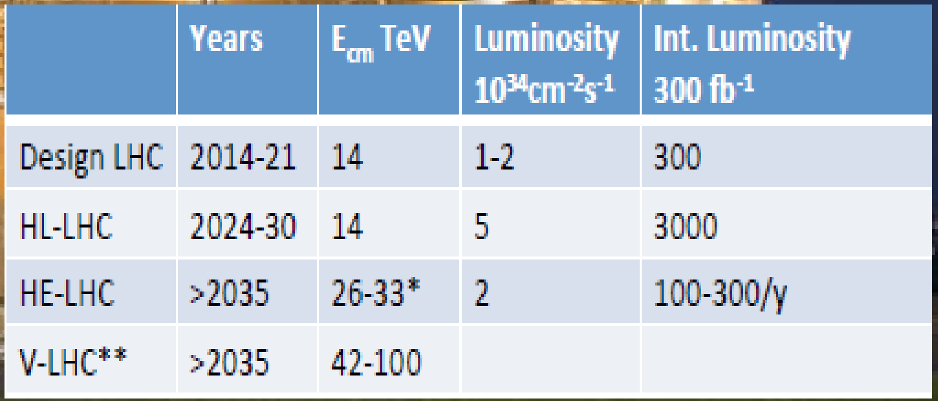
d) **To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available.**

CERN should undertake ***design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines.*** *These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures,* ***in collaboration with national institutes, laboratories and universities worldwide.***

Propose ambitious post-LHC project at CERN by the next update (>~ 5 years):

The strategy encourages accelerator R&D for **proton-proton and electron-positron Colliders (CLIC,HE-LHC,V-LHC, TLEP)**, and development of **high-field magnets (16-20 T) and high-gradient accelerating structures.**

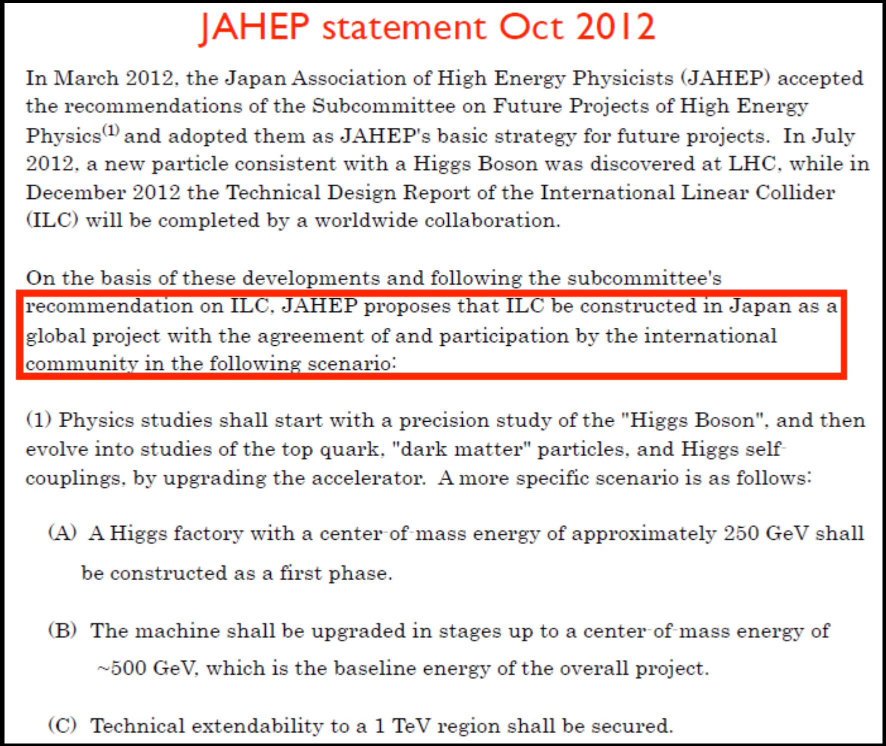
E.g. summary for future pp colliders:



	Years	E_{cm} TeV	Luminosity $10^{34} cm^{-2} s^{-1}$	Int. Luminosity 300 fb^{-1}
Design LHC	2014-21	14	1-2	300
HL-LHC	2024-30	14	5	3000
HE-LHC	>2035	26-33*	2	100-300/y
V-LHC**	>2035	42-100		

The Rising Sun of the Linear Collider (ILC)

The Discovery of a 125 GeV Higgs has opened the door to the ILC



JAHEP statement Oct 2012

In March 2012, the Japan Association of High Energy Physicists (JAHEP) accepted the recommendations of the Subcommittee on Future Projects of High Energy Physics(1) and adopted them as JAHEP's basic strategy for future projects. In July 2012, a new particle consistent with a Higgs Boson was discovered at LHC, while in December 2012 the Technical Design Report of the International Linear Collider (ILC) will be completed by a worldwide collaboration.

On the basis of these developments and following the subcommittee's recommendation on ILC, JAHEP proposes that ILC be constructed in Japan as a global project with the agreement of and participation by the international community in the following scenario:

(1) Physics studies shall start with a precision study of the "Higgs Boson", and then evolve into studies of the top quark, "dark matter" particles, and Higgs self-couplings, by upgrading the accelerator. A more specific scenario is as follows:

(A) A Higgs factory with a center-of-mass energy of approximately 250 GeV shall be constructed as a first phase.

(B) The machine shall be upgraded in stages up to a center-of-mass energy of ~500 GeV, which is the baseline energy of the overall project.

(C) Technical extendability to a 1 TeV region shall be secured.

Inaugural Speech by PM Abe (Feb. 2013)

'Japan is driving global innovation in cutting-edge areas, including among others … and our attempts to develop the most advanced accelerator technology in the world.'

Lyn Evans (LCC Director) meets PM Abe

Amazing High-Tech:

European Strategy for Particle Physics

Strong Japanese initiative to host ILC (potential intent to bid in 2013-2014)

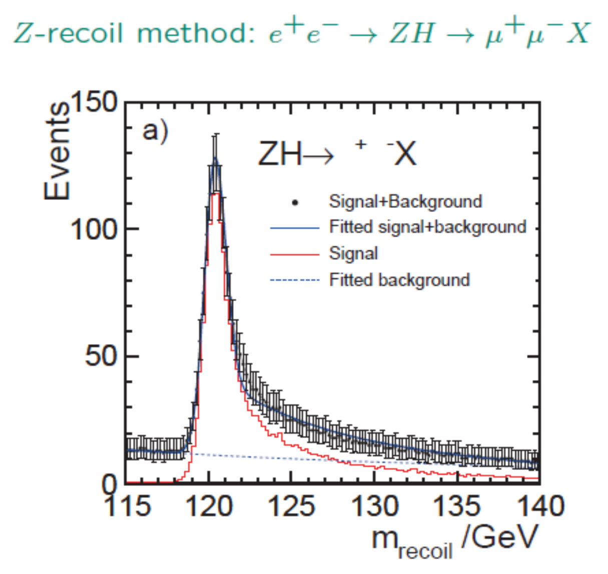
e) **There is a strong scientific case for an electron-positron collider**, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and **whose energy can be upgraded**. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation.

The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate.

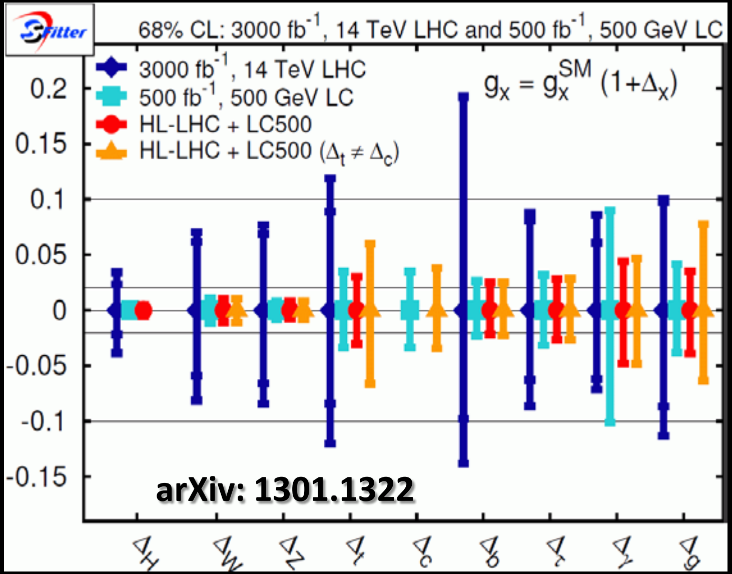
Europe looks forward to a proposal from Japan to discuss a possible participation.

Model- independent Higgs studies (incl. invisible Higgs decays):

Complementarity of ILC and LHC (ILC: Higgs couplings at O(%) level)



Train station In Japan:

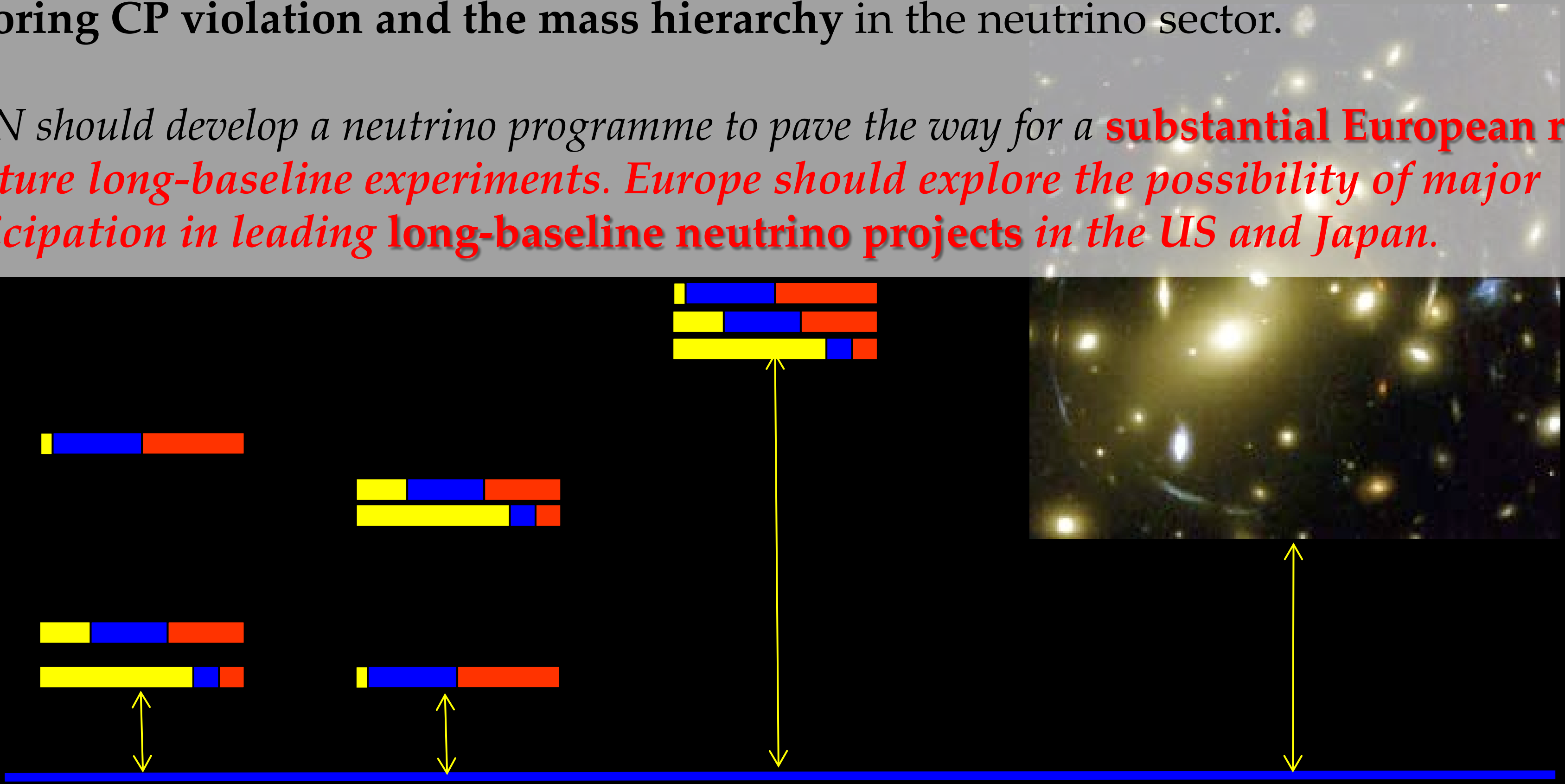


arXiv: 1301.1322

European Strategy for Particle Physics

Rapid progress in neutrino oscillation physics, with significant European involvement, has established a **strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy** in the neutrino sector.

CERN should develop a neutrino programme to pave the way for a ***substantial European role in*** *future long-baseline experiments. Europe should explore the possibility of major participation in leading* ***long-baseline neutrino projects*** *in the US and Japan.*



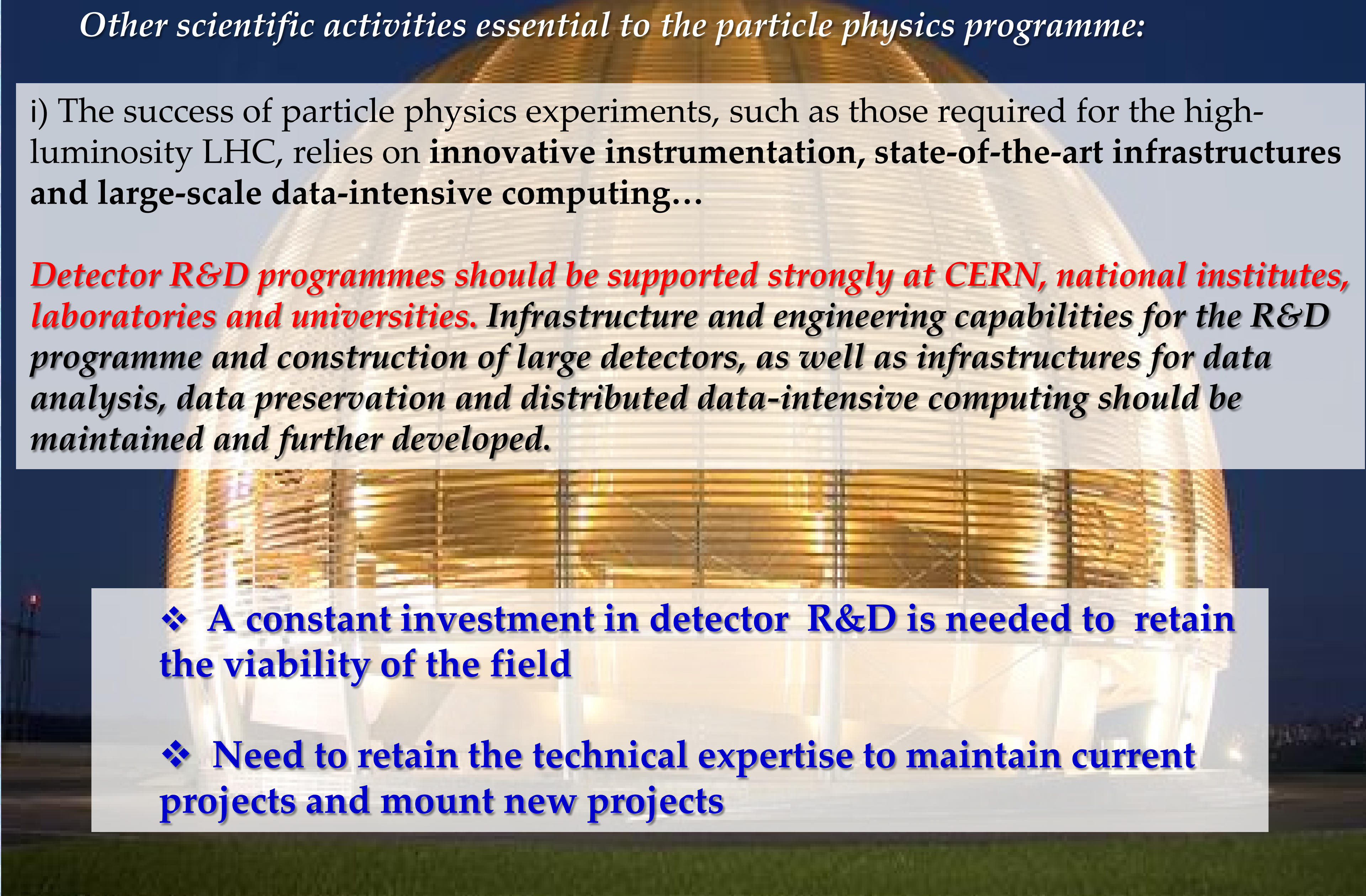
Particle Physics

Cosmology

Neutrino mass scale?

European Strategy for Particle Physics

Other scientific activities essential to the particle physics programme:



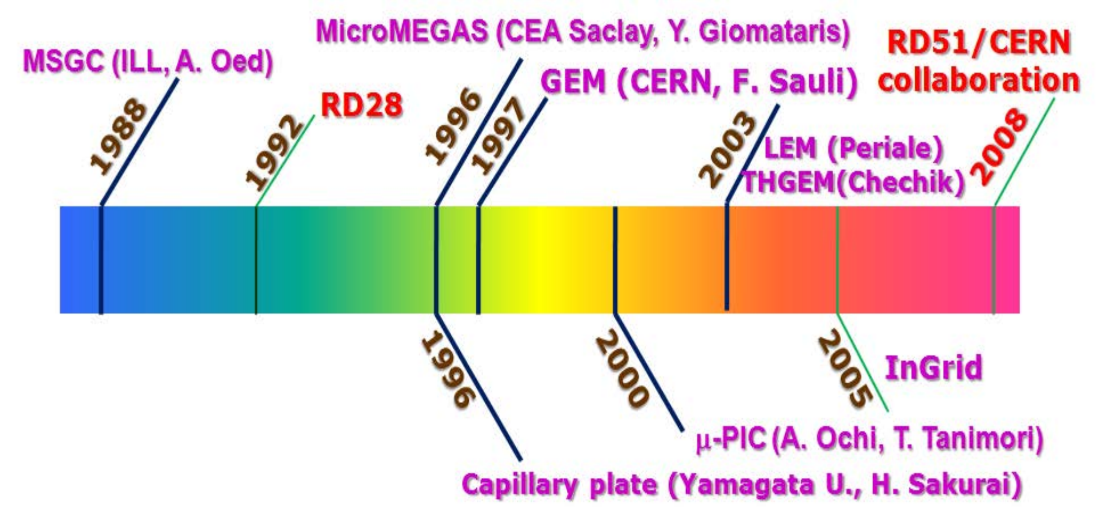
i) The success of particle physics experiments, such as those required for the high-luminosity LHC, relies on **innovative instrumentation, state-of-the-art infrastructures and large-scale data-intensive computing…**

Detector R&D programmes should be supported strongly at CERN, national institutes, laboratories and universities.* *Infrastructure and engineering capabilities for the R&D programme and construction of large detectors, as well as infrastructures for data analysis, data preservation and distributed data-intensive computing should be maintained and further developed.

- **A constant investment in detector R&D is needed to retain the viability of the field**
- **Need to retain the technical expertise to maintain current projects and mount new projects**

RD51 – Development of Micro-Pattern Gas Detector Technologies

Current R&D Collaborations @ CERN: RD39 (Cryogenic), RD42 (Diamond), RD50 (Silicon), RD51 (MPGD), RD52 (Dual-Readout Calorimetry)

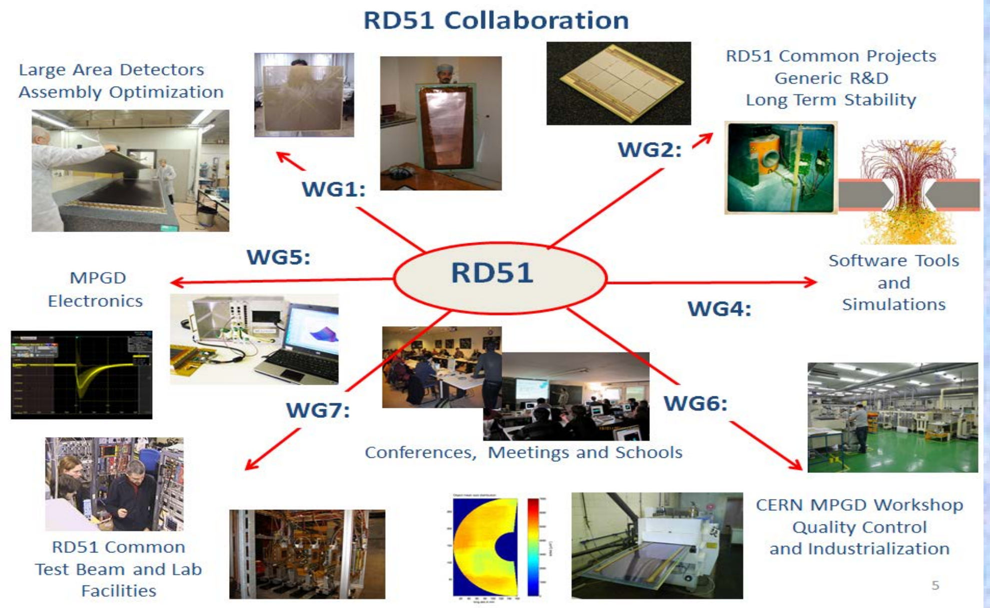


Major RD51 Milestone :

LHCC has supported the extension of RD51 efforts for another 5 years term beyond the 2013

Worldwide Collaboration for R&D developments of MPGD → RD51 (86 institutes, 450 people):

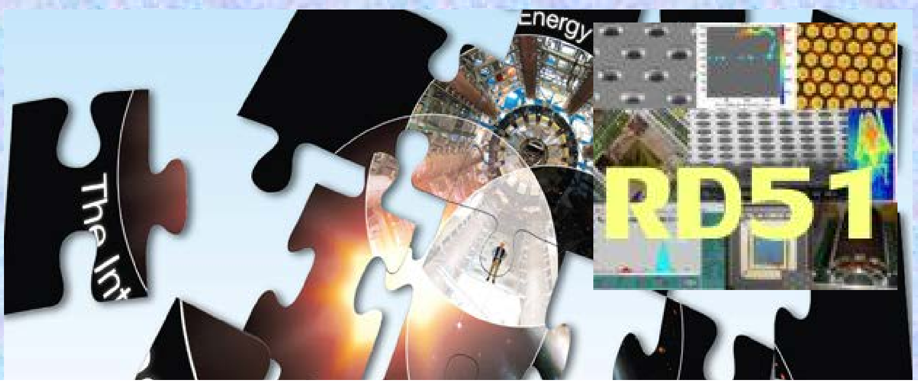
- ❖ **Large Scale R&D program to *advance MPGD Technologies***
- ❖ **Access to *MPGD "know- how"***
- ❖ **Foster *Industrial Production***



Summary and Outlook

- ❖ **Fantastic 3 years of physics – A milestone discovery announced in July 2012**
- ❖ **The characteristics of the observed boson consistent so far with the properties of "THE" Standard Model (SM) Higgs Boson**
  → need to study Higgs properties with an ultimate O(%) precision (sLHC/ILC)
- ❖ **We are about to complete precision studies of 5% of our Universe (SM);**
  → still need to explore 95 % of the Universe and understand EWSB mechanism
  → the adventure in the TeV energy regime has just begun
- ❖ **Novel technologies and detector instrumentation are of a key importance to advance future physics projects**
  → MPGDs is one of the major technologies at the Instrumentation Frontier

YES ☺ we will …



Congratulations to all RD51 teams !
wish the next 5 years to be as successful !