Discovering Higgs Boson at LHC

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Open questions that deserve attention

Why abundance of matter over anti-matter ?

Why the main interactions are so different in strenght and how well they can be unified ?

Why photon is massless, why W& Z are so massive ? (gauge bosons)

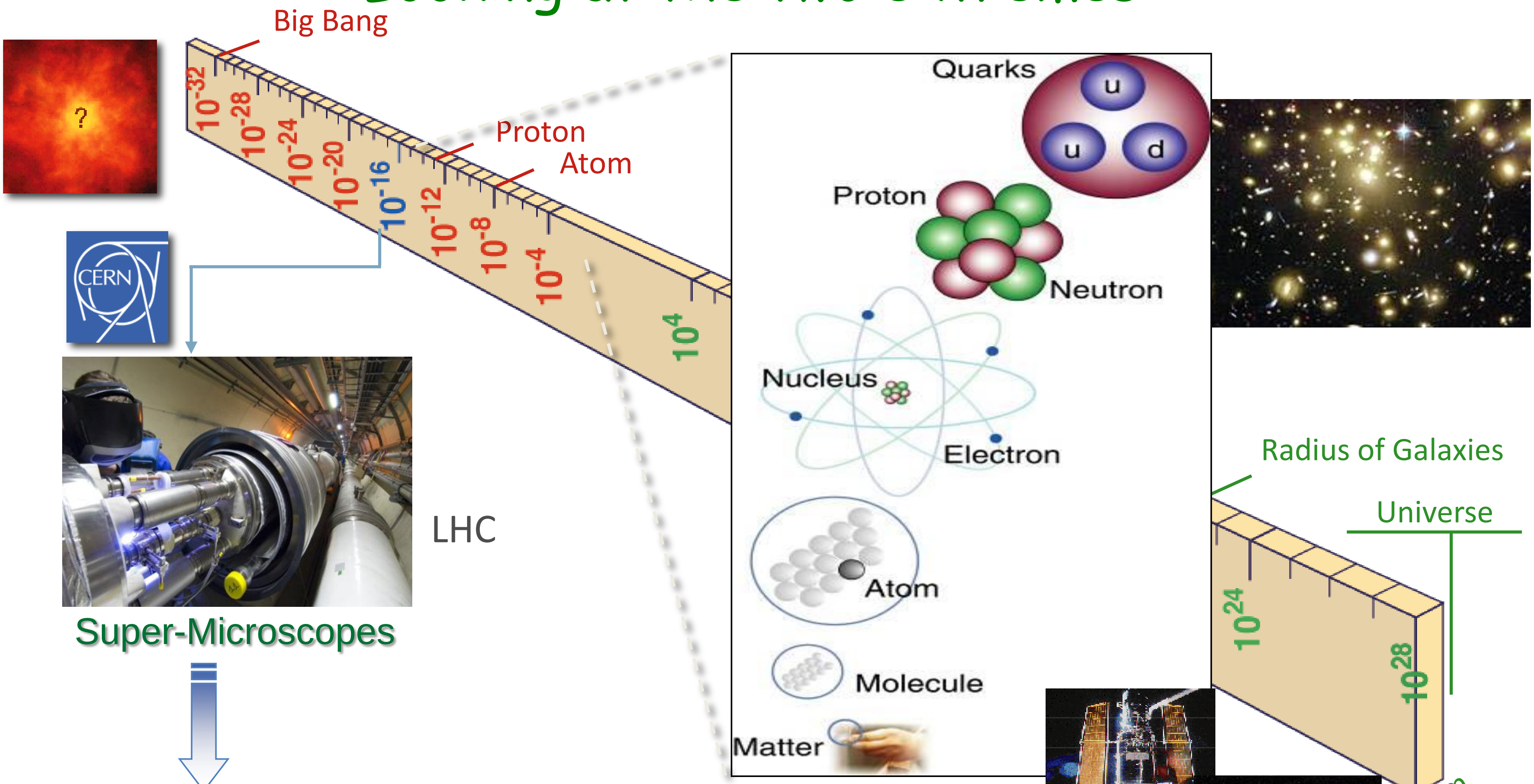
Why electron is so light and top quark so massive ? (fermions)

What is the origin of mass ?

What is dark matter that keeps together the clusters of galaxies ?

How many are really the dimensions of our world ?

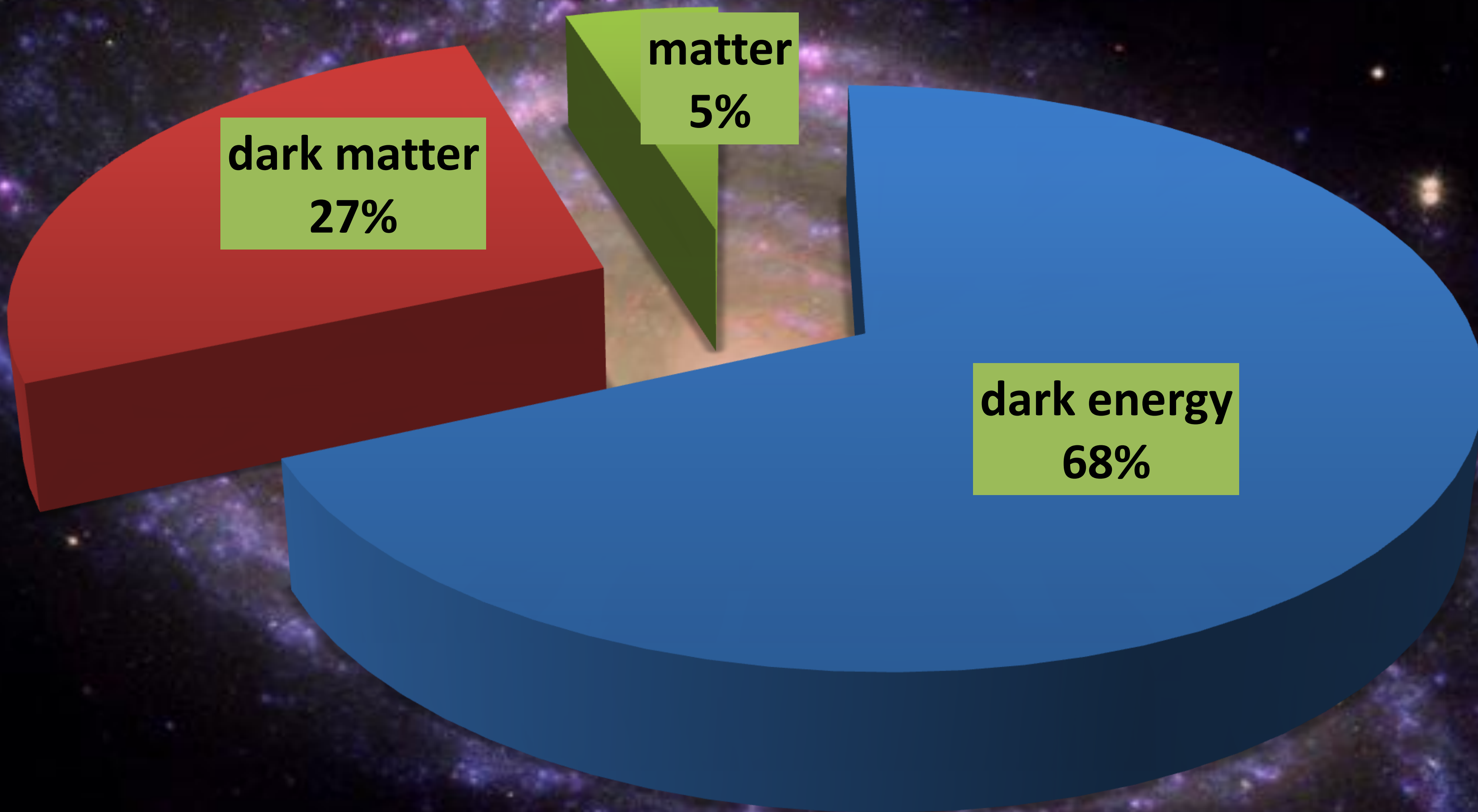
Looking at the two extremes



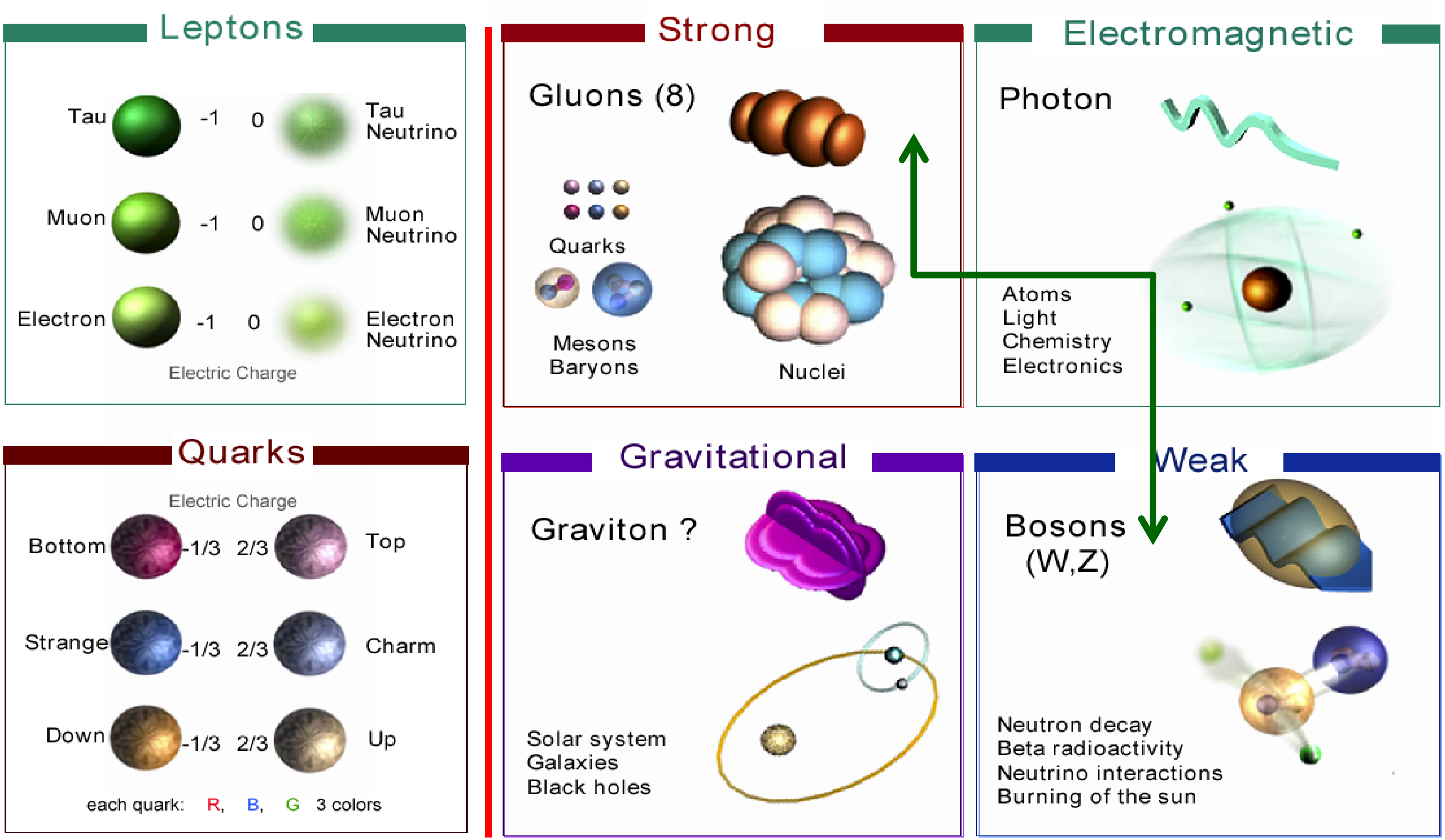
Produce and study particles that were abundant in the early universe, just moments after the Big Bang. Studying high energy collisions is thus like travelling back in time.

Super-Telescopes

Dark matter mystery

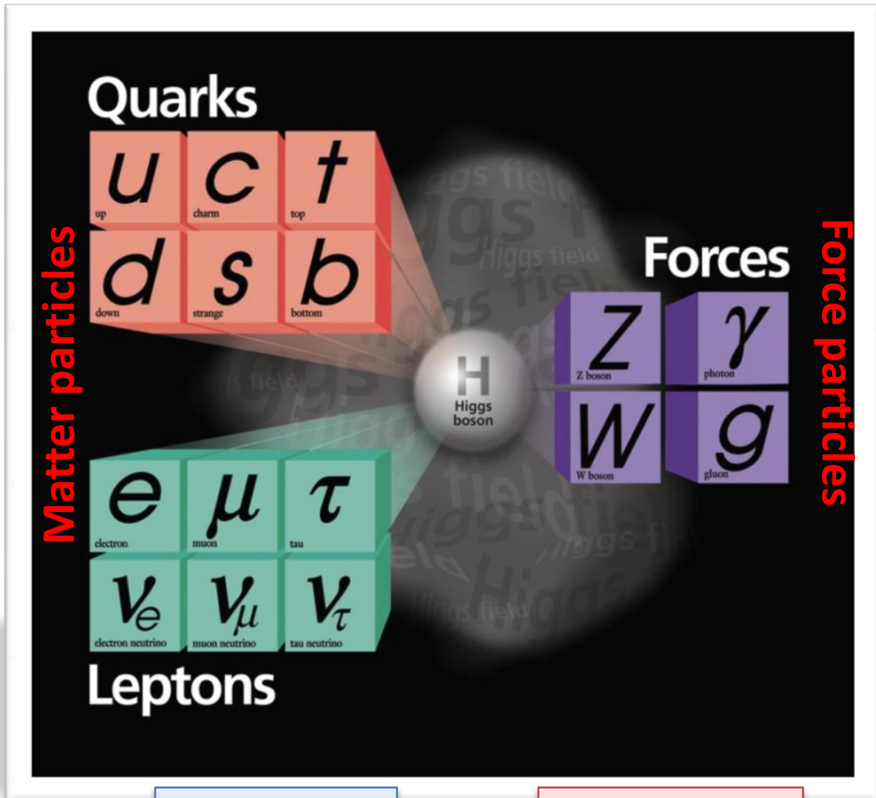


What do we know of matter (4-5% of the universe) ? Matter is made of particles interacting through forces



The Standard Model

- Over the last ~100 years: Advances in experimental and theoretical physics have led to **The Standard Model of Particle Physics**
- A new "Periodic Table" of fundamental elements



Fermions

Bosons

One of the greatest achievements of 20th Century Science

A large number of measurements in a variety of experiments can test the Standard Model

Quantity	Value	Standard Model	Pull
m_t [GeV]	$172.7 \pm 2.9 \pm 0.6$	172.7 ± 2.8	0.0
M_W [GeV]	80.450 ± 0.058	80.376 ± 0.017	1.3
	80.392 ± 0.039		0.4
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1
Γ_Z [GeV]	2.4952 ± 0.0023	2.4968 ± 0.0011	−0.7
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7434 ± 0.0010	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.65 ± 0.11	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	83.996 ± 0.021	—
σ_{had} [nb]	41.541 ± 0.037	41.467 ± 0.009	2.0
R_e	20.804 ± 0.050	20.756 ± 0.011	1.0
R_μ	20.785 ± 0.033	20.756 ± 0.011	0.9
R_τ	20.764 ± 0.045	20.801 ± 0.011	−0.8
R_b	0.21629 ± 0.00066	0.21578 ± 0.00010	0.8
R_c	0.1721 ± 0.0030	0.17230 ± 0.00004	−0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01622 ± 0.00025	−0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.5
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1031 ± 0.0008	−2.4
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0737 ± 0.0006	−0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1032 ± 0.0008	−0.5
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.23152 ± 0.00014	0.7
	0.2238 ± 0.0050		−1.5
A_e	0.15138 ± 0.00216	0.1471 ± 0.0011	2.0
	0.1544 ± 0.0060		1.2
	0.1498 ± 0.0049		0.6
A_μ	0.142 ± 0.015		−0.3
A_τ	0.136 ± 0.015		−0.7
	0.1439 ± 0.0043		−0.7
A_b	0.923 ± 0.020	0.9347 ± 0.0001	−0.6
A_c	0.670 ± 0.027	0.6678 ± 0.0005	0.1
A_s	0.895 ± 0.091	0.9356 ± 0.0001	−0.4
g_L^2	0.30005 ± 0.00137	0.30378 ± 0.00021	−2.7
g_R^2	0.03076 ± 0.00110	0.03006 ± 0.00003	0.6
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0396 ± 0.0003	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0
A_{PV}	-1.31 ± 0.17	-1.53 ± 0.02	1.3
$Q_W(\text{Cs})$	-72.62 ± 0.46	-73.17 ± 0.03	1.2
$Q_W(\text{Tl})$	-116.6 ± 3.7	-116.78 ± 0.05	0.1
$\frac{\Gamma(b\to s\gamma)}{\Gamma(b\to Xe\nu)}$	$3.35^{+0.50}_{-0.44} \times 10^{-3}$	$(3.22 \pm 0.09) \times 10^{-3}$	0.3
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	4511.07 ± 0.82	4509.82 ± 0.10	1.5
τ_τ [fs]	290.89 ± 0.58	291.87 ± 1.76	−0.4

The Standard Model is among the most successfull theories tested so far (accuracy $<10^{-4}$ in hundreds of measurements up to an impressive 10^{-12} in electron g-2)

LEP, CDF&D0, Belle & BaBar: Understand physics up to ~100GeV

It is sort of a monument of the physics of the 20th century: it brings together quantum mechanics and special relativity

It is simple and elegant: it explains a huge amount of data using only 19 parameters.

Missing piece – the Higgs boson!

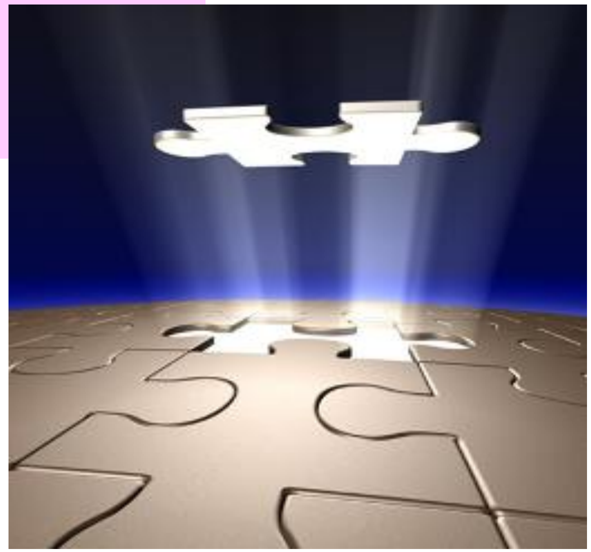
Why is the Higgs boson important ?

A multi-billion dollar question

Explains some deep puzzles in particle physics

origin of mass
why is the weak force so weak?

Only missing piece in our theory of matter and subatomic forces



It should be right size & right shape

A world without mass

Without mass for elementary particles,
the world would be very different

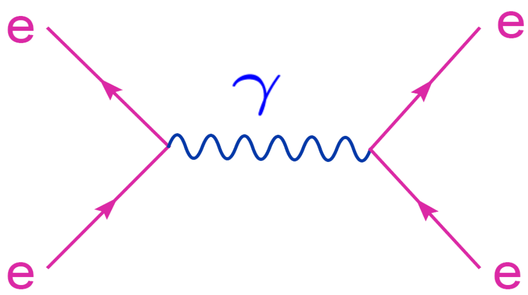
Photons have no mass,
zip around at the speed of light

If electrons also had no mass,
they would also zip around at speed of light

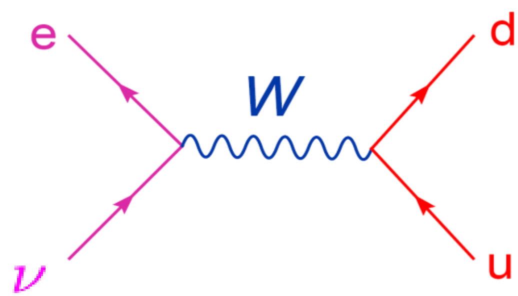
→ **All atoms, all matter would instantly fly apart!**

How particles interact with each other?

Electromagnetism *vs.* Weak Force



electromagnetism



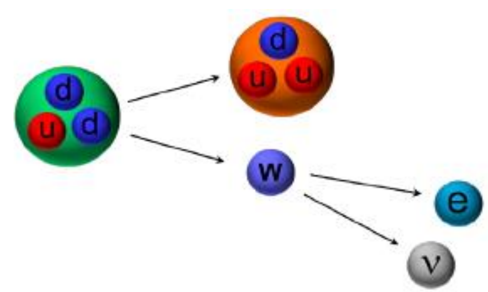
weak

Many similarities between them, but one **big** difference:

photon is a **massless particle**
→ **force long range**

W and *Z* are **very massive** (100 times the proton mass)
→ **force very short range** (1/100 of proton radius)

Beta decay has intermediate 'virtual' step – slows it down



From one puzzle to another

Puzzle of why weak interactions are so weak

⇓

Puzzle of why the weak bosons have a mass

This is the puzzle Peter Higgs and others found a solution in the early 1960s






Peter Higgs, François Englert, Robert Brout, Tom Kibble, Gerald Guralnik, Carl Hagen

Puzzles of electron and quark masses solved as a by product (a little later)

A Little History

In 1967, three years after papers by Higgs and others, Steven Weinberg and Abdus Salam used their ideas to build model of weak boson masses.
Also earlier ideas by Sheldon Glashow.

Nobel 1979

Weinberg

Salam

Glashow

Not much attention paid to 1967 work until 1972 paper by Gerard ’t Hooft and Martinus Veltman, which relied even more explicitly on Higgs’ idea

Nobel 1999

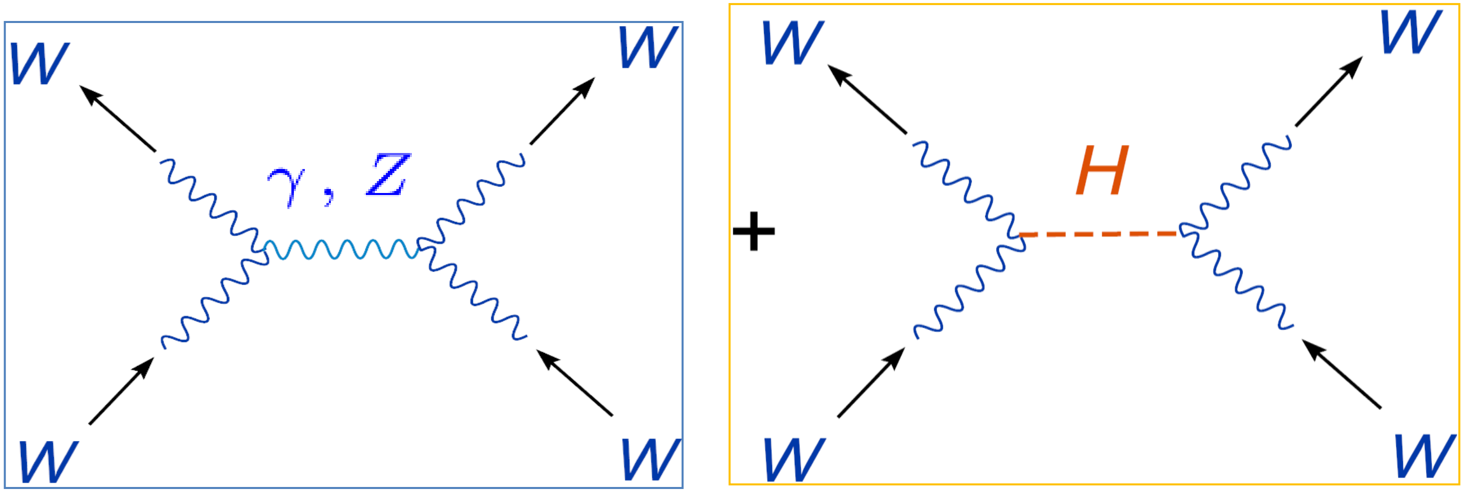
‘t Hooft

Veltman

What about others?

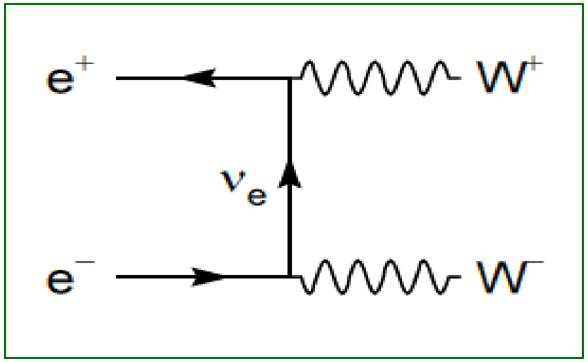
How do *W* bosons bounce off each other?

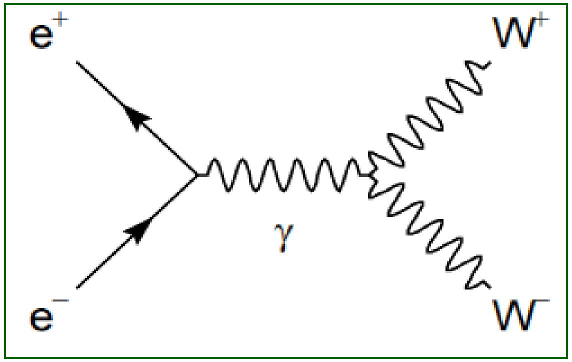
OLD theory, pre-Higgs, was crazy

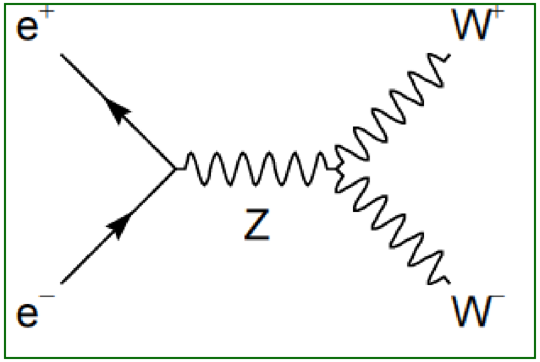


$\Rightarrow$ probability $< 100\%$

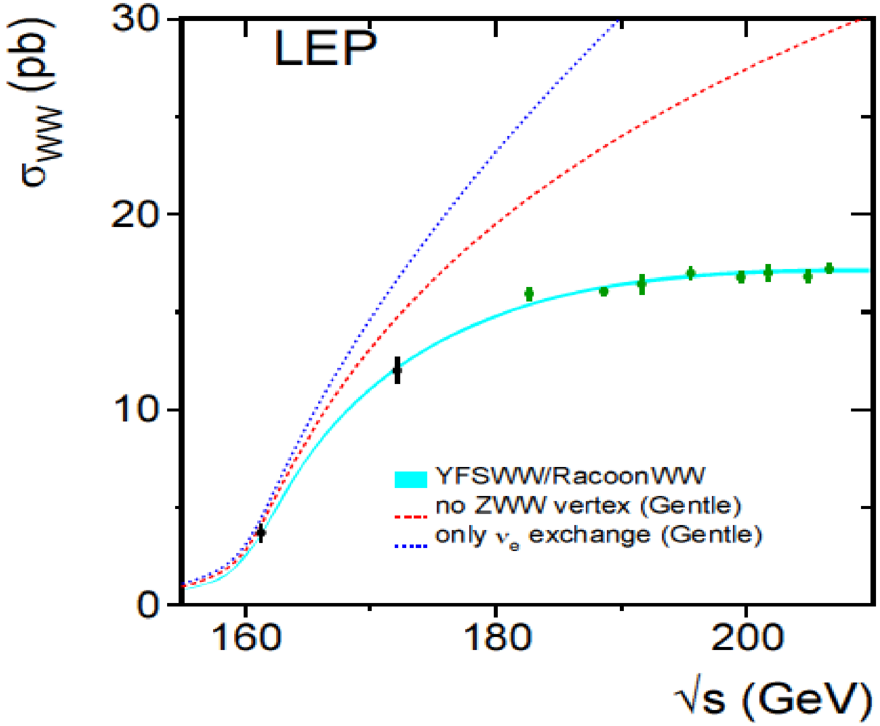
Peter Higgs (and others) fixed this problem, by having *W* toss across a new massive particle, the Higgs boson *H.*
Simple way to do this.







The rise in WW production cross-section could only be contained if all of these diagrams are present. This required neutral current (Z) exchange



What wise people had to say in 1975

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

What makes Higgs special

Not just finding the condensate responsible for giving mass

Also condensate exist in Higgsless theories

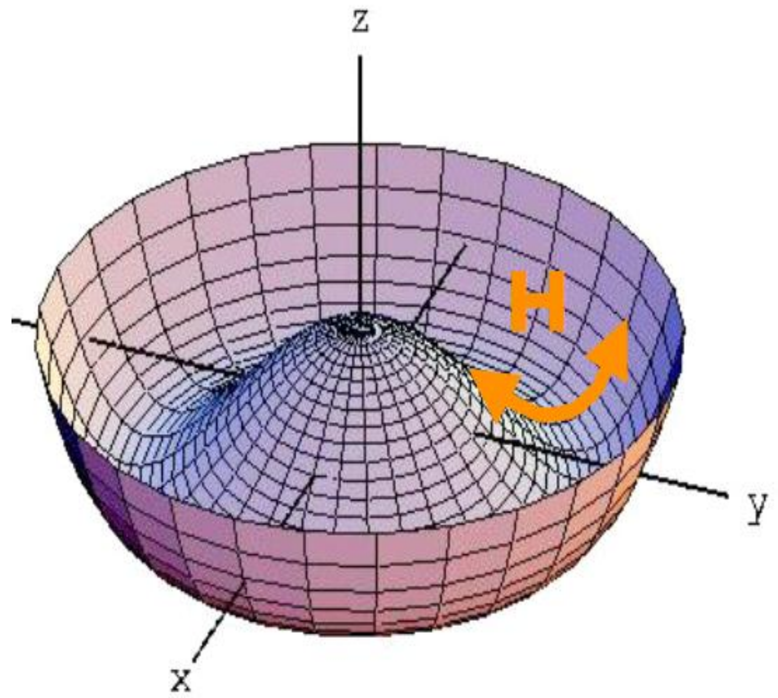
Examples:

QCD: Quark condensate $\langle q\bar{q}\rangle$ breaks chiral symmetry

Superconductors: Cooper pairs <ee> breaks EM

None of them have Higgs excitation

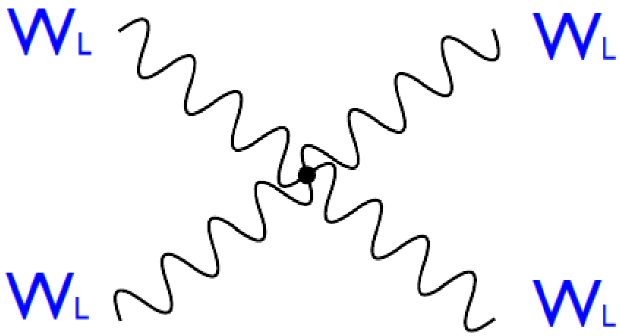
What makes Higgs special



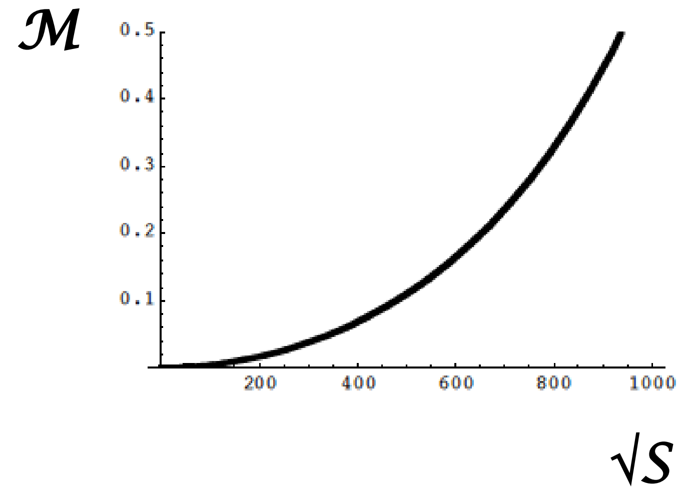
Also, not just the radial excitation around the vacuum

Higgsless models also have excitations around the vacuum (as found in QCD)

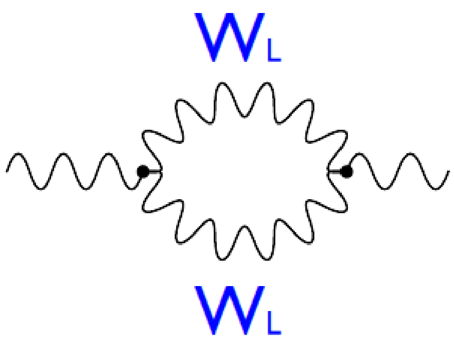
Without Higgs WW scattering crazy



$$\propto \frac{s}{v^2}$$



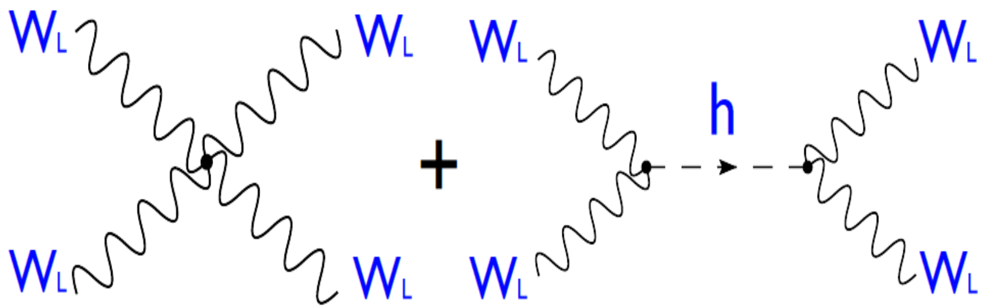
Unitarity is lost at high energies

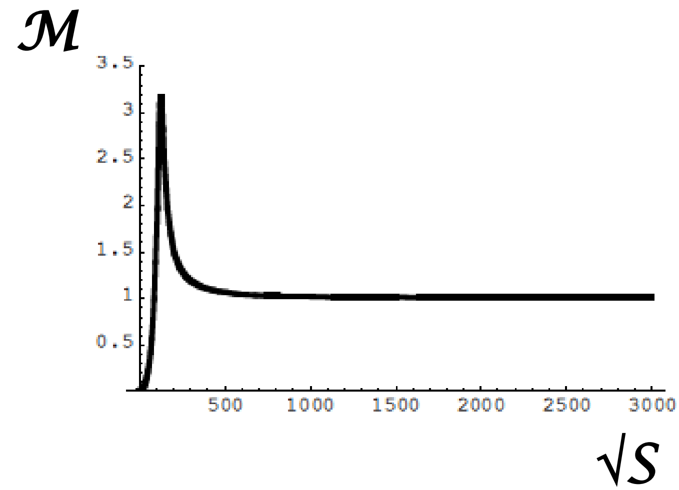


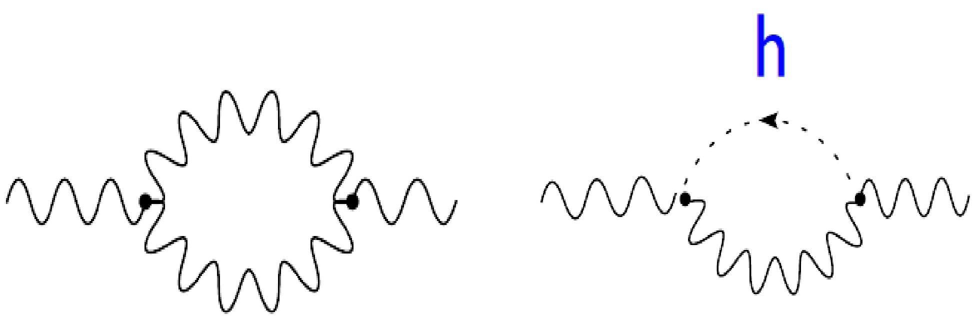
Loops are not finite

Do not allow precision calculations

With Higgs Calculability is Recovered



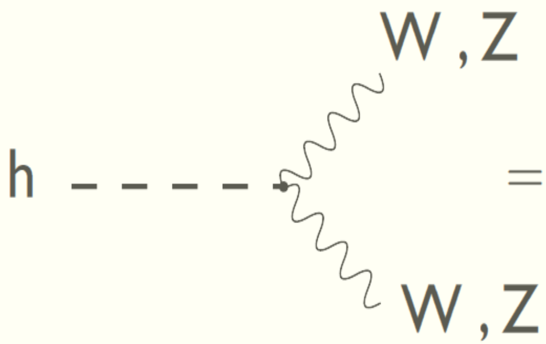




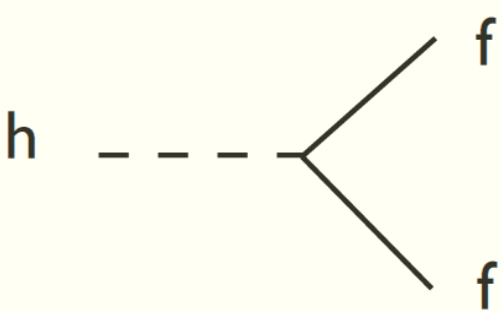
Results are finite!

Back to prediction era !

For this to work, the Higgs couplings should take particular values



$$= gM_W \quad , \quad \frac{gM_Z}{\cos\theta_W}$$



$$= \frac{gM_f}{2M_W}$$

The couplings must be exactly these (at tree-level) to make SM a consistent theory

Otherwise this is not a Higgs

Search for the Higgs boson

Detective work needed to find the Higgs boson

3 steps to track down a culprit:

shake the box – indirect, virtual evidence

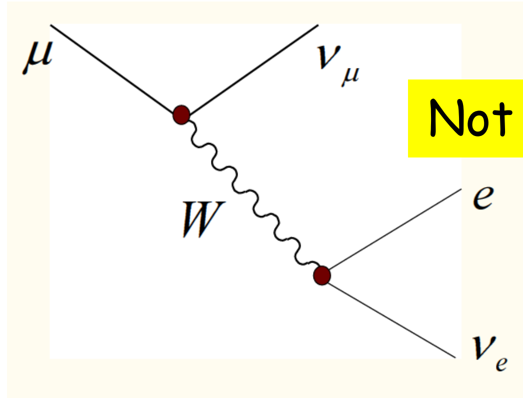
cut the packing – real Higgs production

complete unmasking – is it the SM Higgs?

Power of Quantum Loops in indicating contributions from unknown physics

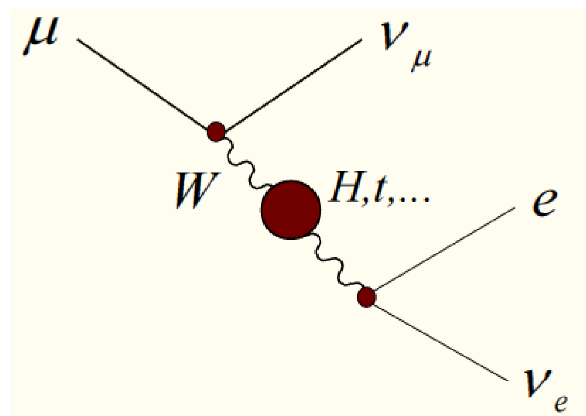
Muon life time requires inclusion of many loops

$$G_\mu \sim \frac{\alpha}{M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)}\,(1+\Delta r)$$



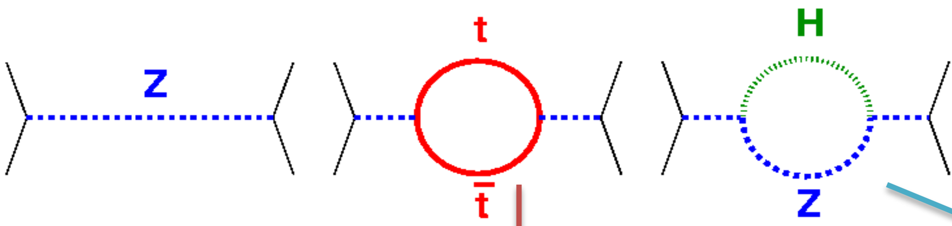
Not enough

$$\Delta\alpha_{\rm had}^5 - c\,m_t^2 + c'\ln M_H^2 + \dots$$

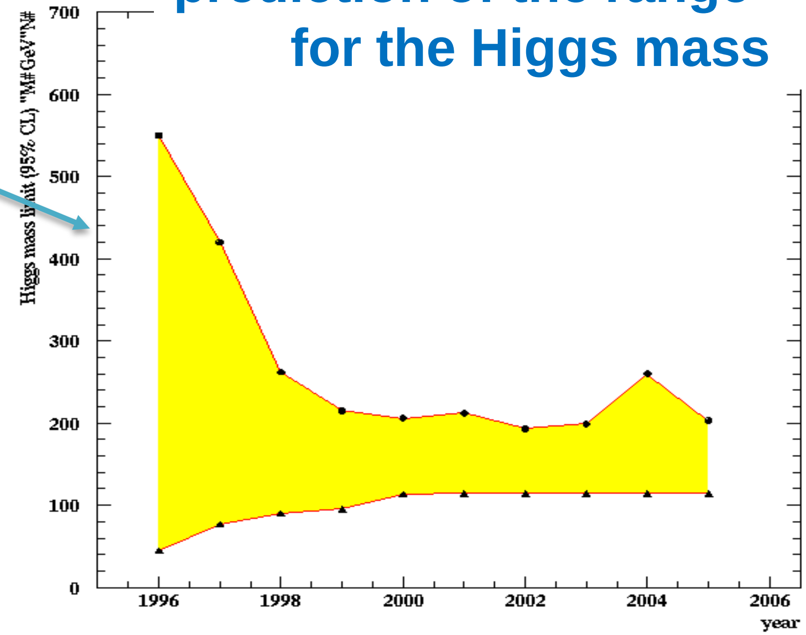


$\Delta\alpha_{\rm had}^5 \nearrow$	$\Rightarrow$	$M_H \searrow$	
$m_t \searrow$	$\Rightarrow$	$M_H \searrow$	$1\ \text{GeV} \to 10\ \text{GeV}$
$M_W \nearrow$	$\Rightarrow$	$M_H \searrow$	$1\ \text{MeV} \to 2\ \text{GeV}$

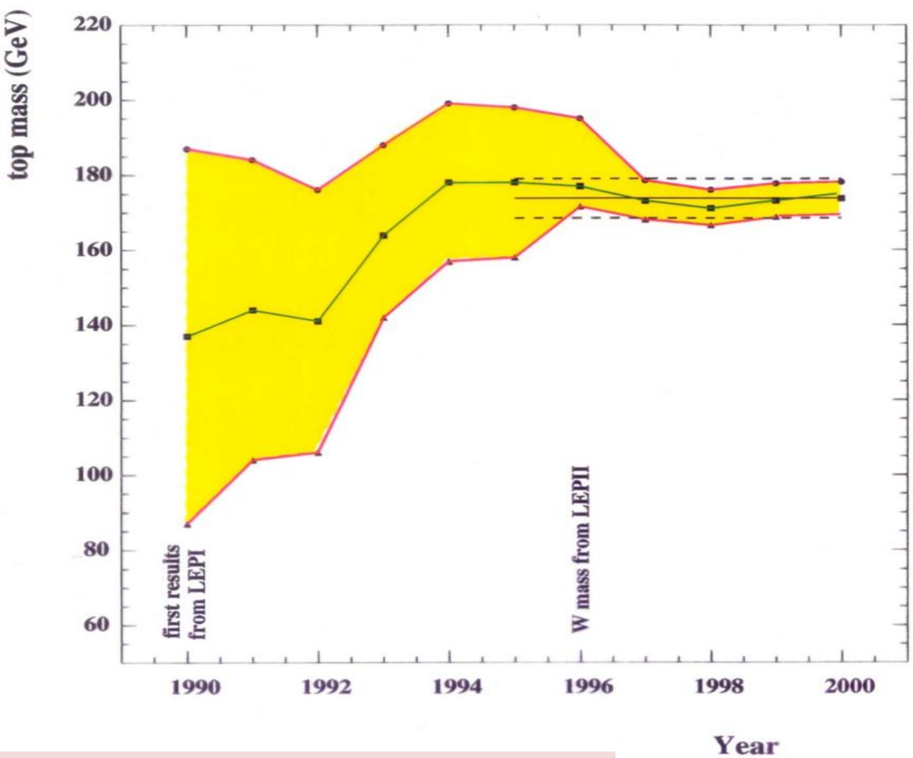
Standard Model test at the level of Quantum Fluctuations



prediction of the range
for the Higgs mass



LEP: indirect determination of the top mass

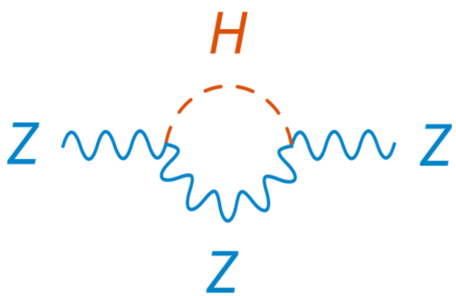


possible due to
known higher order electroweak corrections

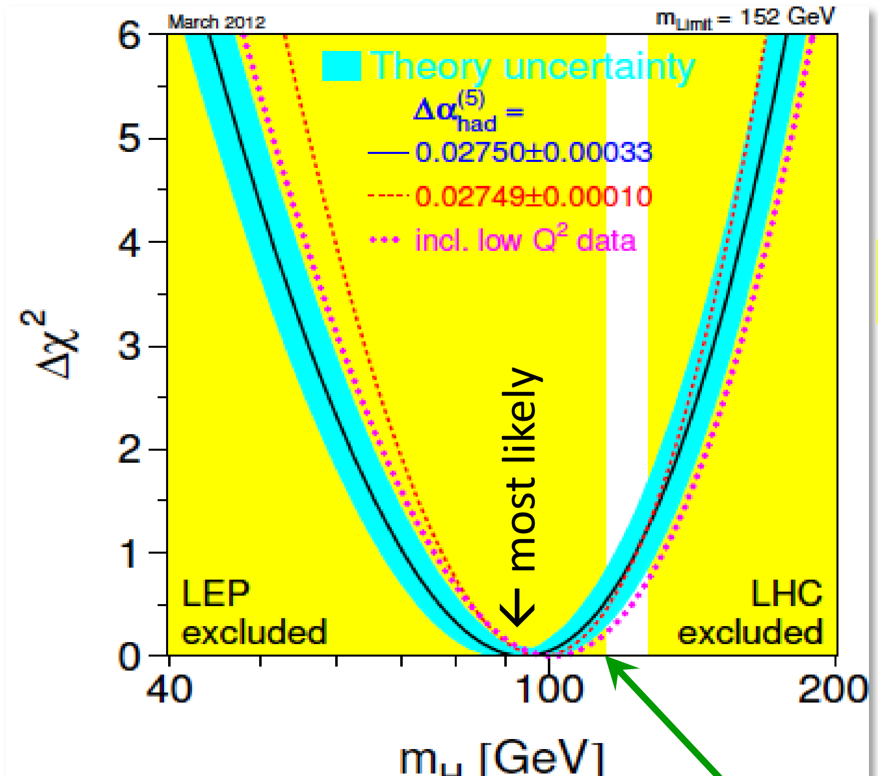
$$\propto \left(\frac{M_t}{M_W}\right)^2, \ln\left(\frac{M_h}{M_W}\right)$$

Measured mass 173 GeV

Measurements involving Z boson squeeze the hiding space for the Higgs



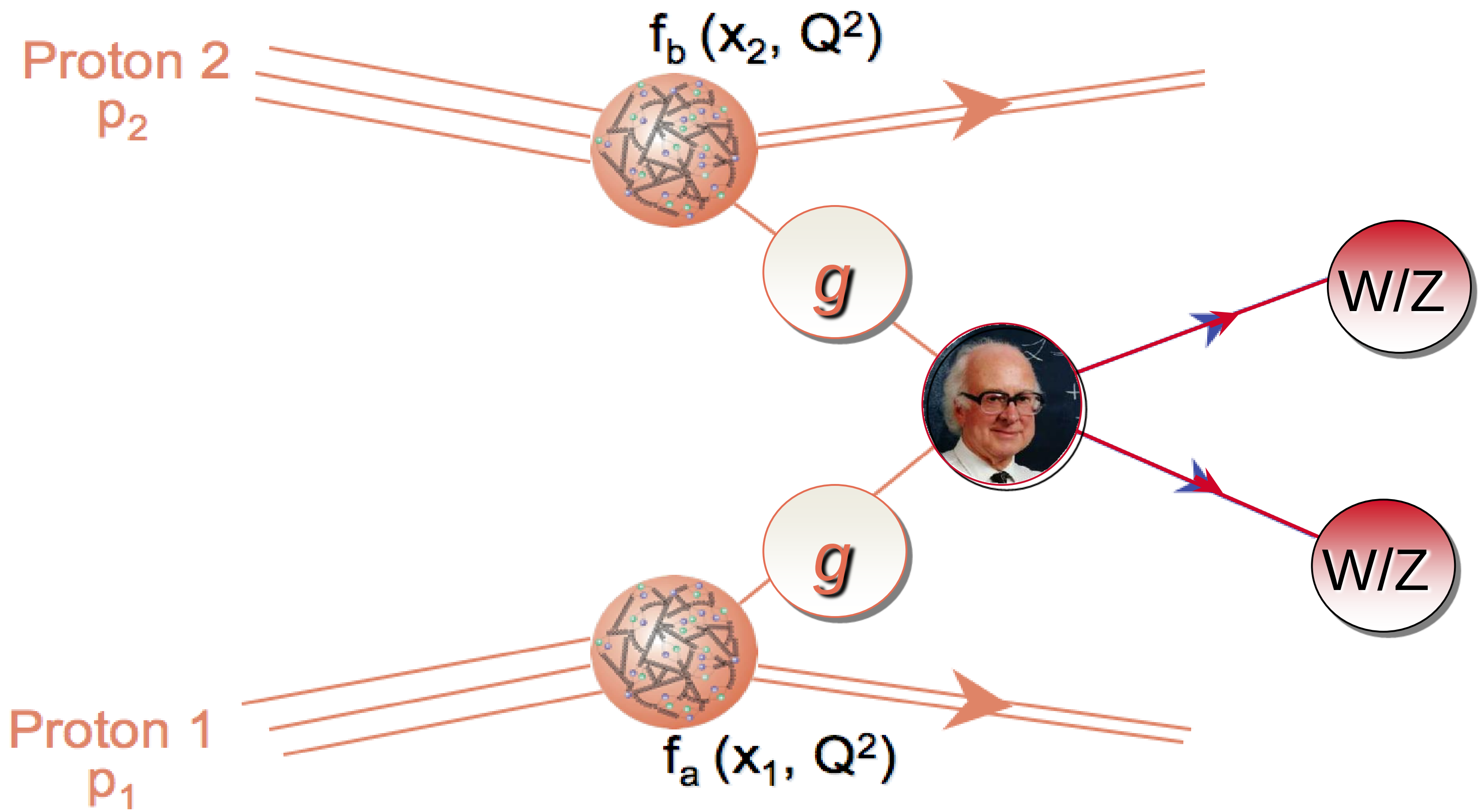
"Listen very carefully"
– make very precise measurements



by direct search

The only window left just before July 4, 2012

Collision Process & Direct Production



To explore Higgs production over a broad mass range, we need a powerful accelerator

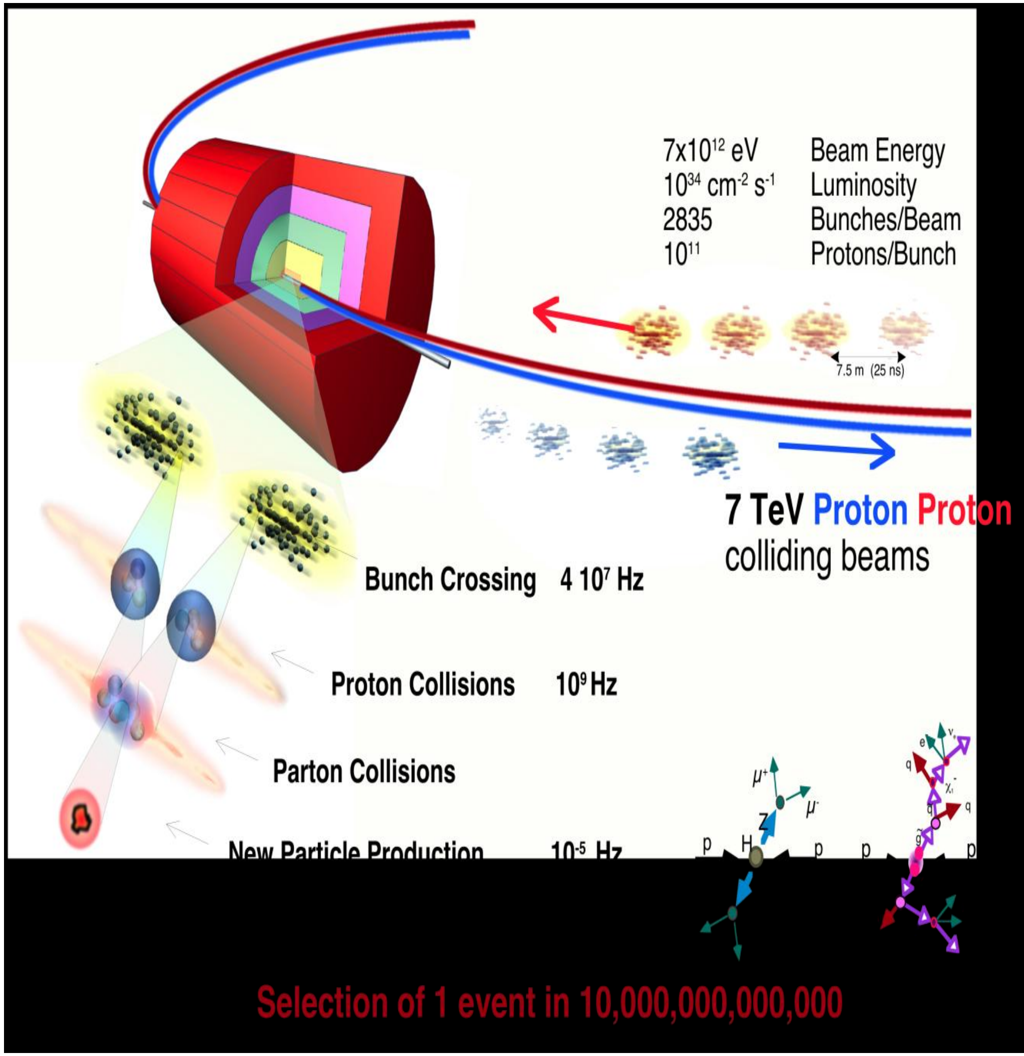
The Large Hadron Collider is a technological marvel

Several thousand billion protons moving at 0.999999991 of the speed of light travel round the **27 km** ring over **11,000** times a second!

With a temperature of around -271 degrees Celsius, or 1.9 degrees above absolute zero, the LHC is colder than outer space.

Most complex scientific experimental facility built by mankind

LHC is a powerful accelerator to produce masses of undiscoverd particles up to a few TeV



The Indian connection

Indian Contribution toward the LHC construction

RRCAT, BARC, VECC, IGCAR, ECIL, ATL, IGTR, BHEL

A variety of components and subsystems. Important hardwares include:

7080 precision Magnet Positioning Stands
1800 SC corrector magnets
5500 Quench Heater protection supplies
1435 local protection units
70 Circuit Breakers …
Skilled manpower support for magnetic tests and measurements and help in commissioning of LHC subsystems

Worth ~50 Million CHF contribution

LHC sits on the Indian shoulders!!!

Precision alignment Jacks were Designed & Developed by a RRCAT team for LHC Cryo-magnets.

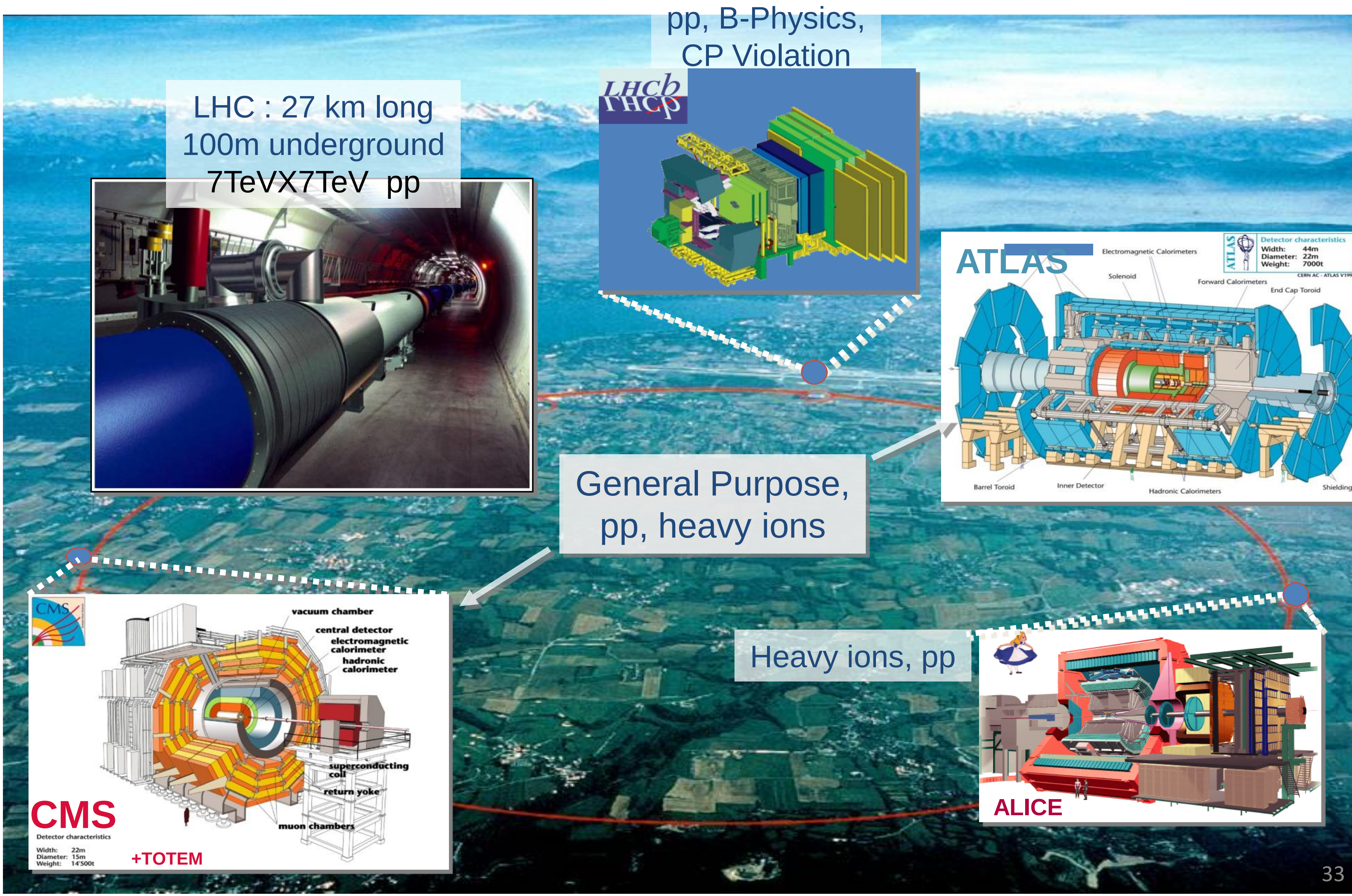
- Each LHC cryo-magnets weighs ~32 Tons

6800 PMPS Jacks + 280 Motorizable & Higher Precision

Precision Magnet Positioning System (PMPS) Jacks | MCS & MCDO | Magnetic measurements teams- ~100 Man-years

Indian made PMPS Jacks being installed in LHC

Experiments at the Large Hadron Collider



Direct Search for Higgs boson

Cross Section of Various SM Processes

The LHC <u>uniquely</u> combines the two most important virtues of a HEP experiment:

1. High energy 8 (soon 13) TeV
2. High luminosity 10^{33}–10^{34}/cm^2/s

$\Rightarrow$ Low luminosity phase

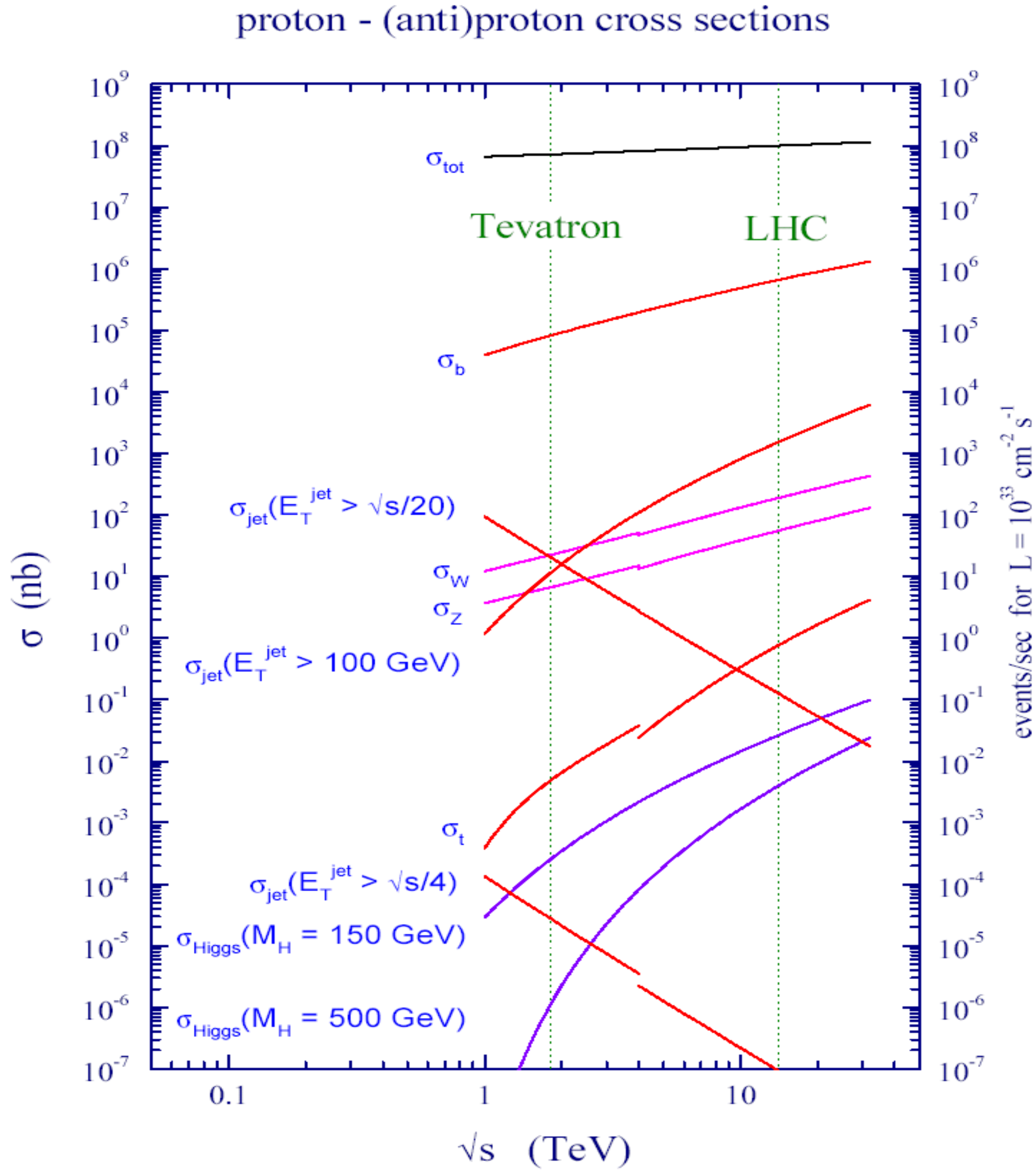
10^{33}/cm^2/s

approximately

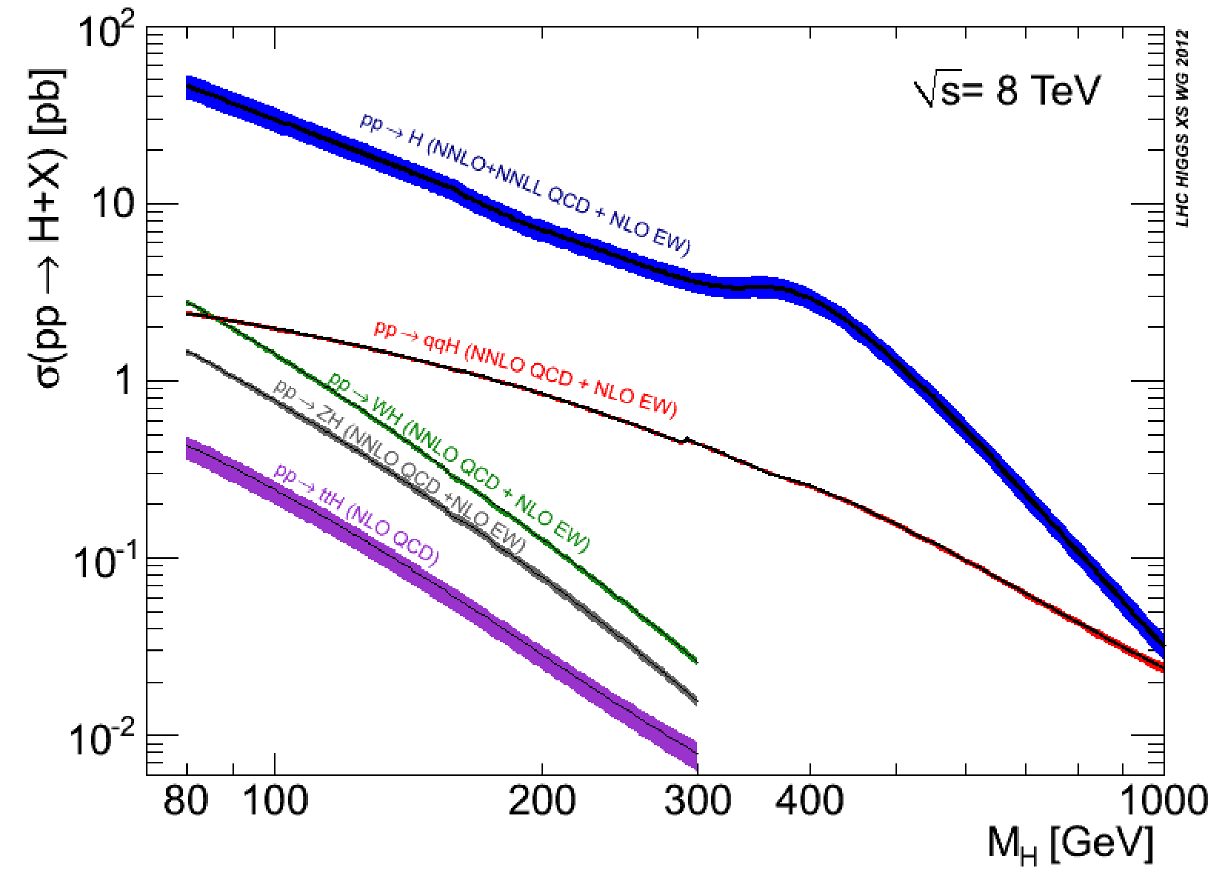
- 200 W bosons
- 50 Z bosons
- 1 $t\bar{t}$ pair

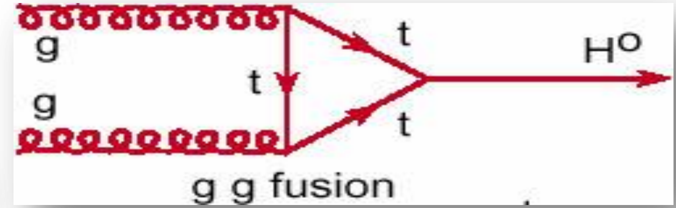
will be produced per second while

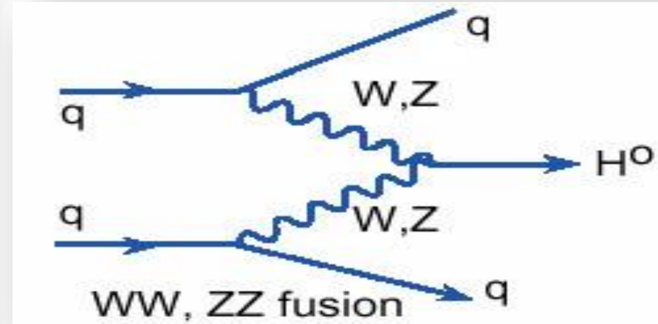
- 1 light Higgs per minute!

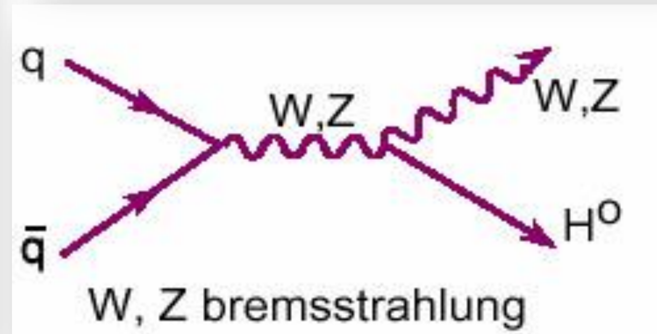


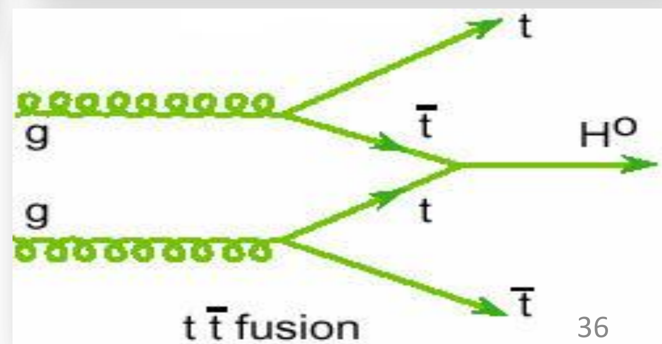
How is the Higgs produced?











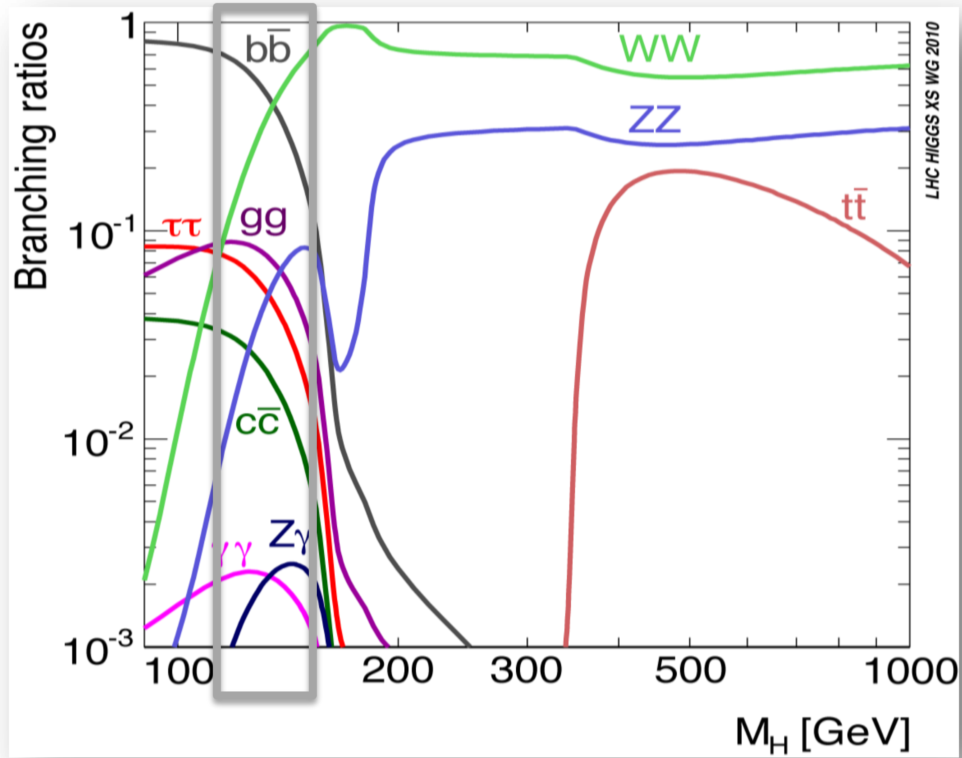
All production modes to be exploited

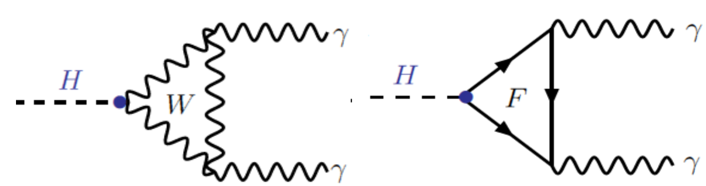
- **gg VBF VH $t\bar{t}$H**
- **Latter 3 have smaller cross sections but better signal-to-noise in many cases**

And, how does it decay?

5 decay modes exploited

- High mass: WW, ZZ
- Low mass: bb, ττ, WW, ZZ, γγ
- Low mass region is very rich but also very challenging:
  main decay modes (bb, ττ) are hard to identify in the huge background
- Excellent mass resolution (~1%):
  H→γγ and **H→ZZ→4*l***

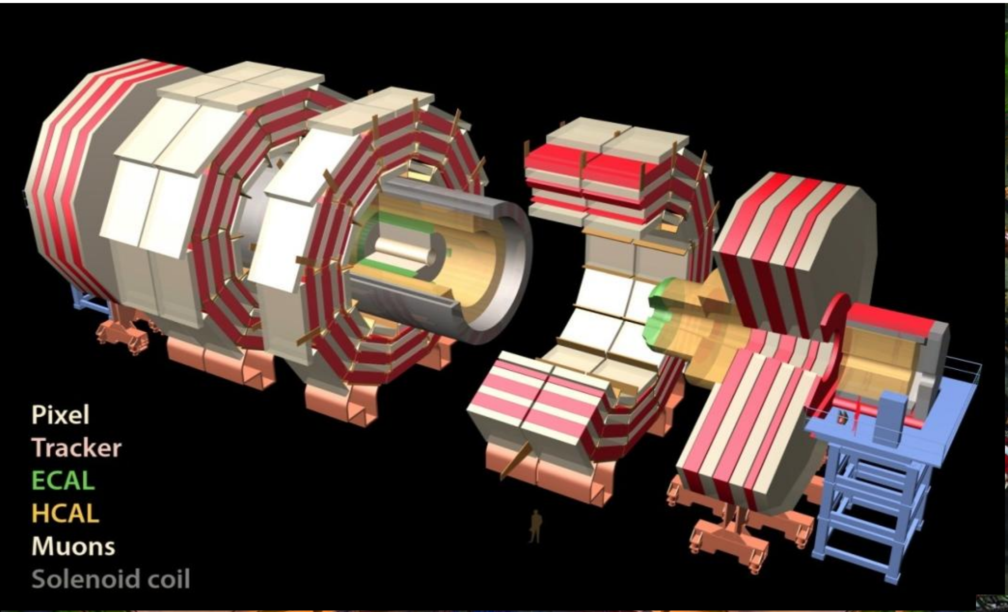


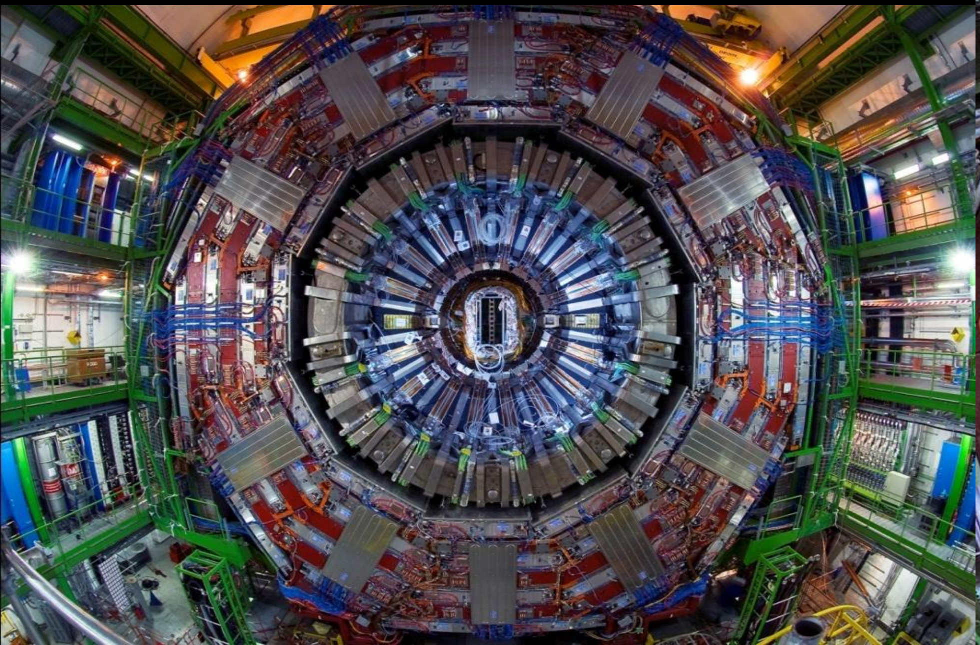


Need good detector capable of detecting and measuring particles with high precision over the large solid-angle coverage

Building the CMS Detector a worldwide effort

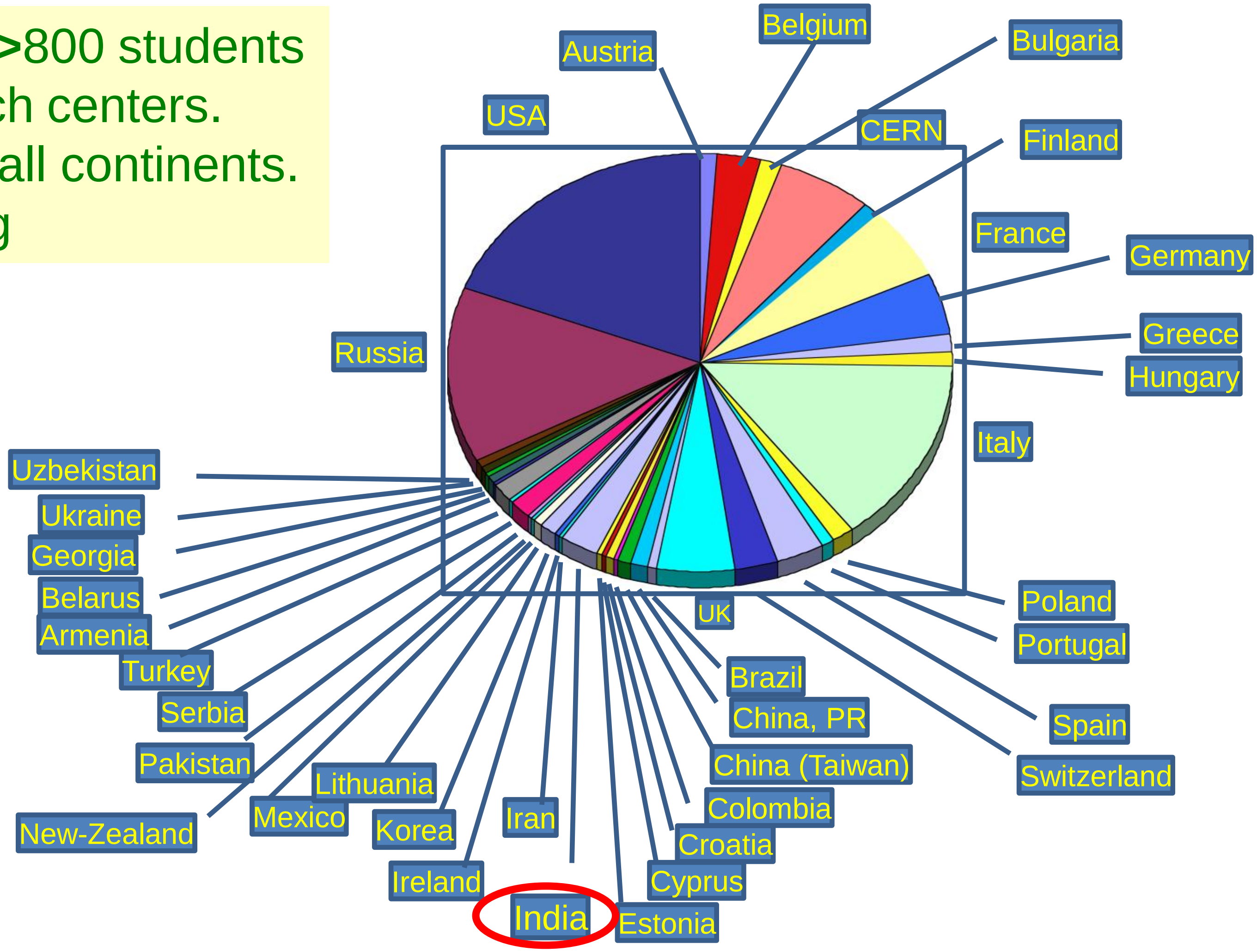
The CMS Collaboration
> 3000 scientists from all continents



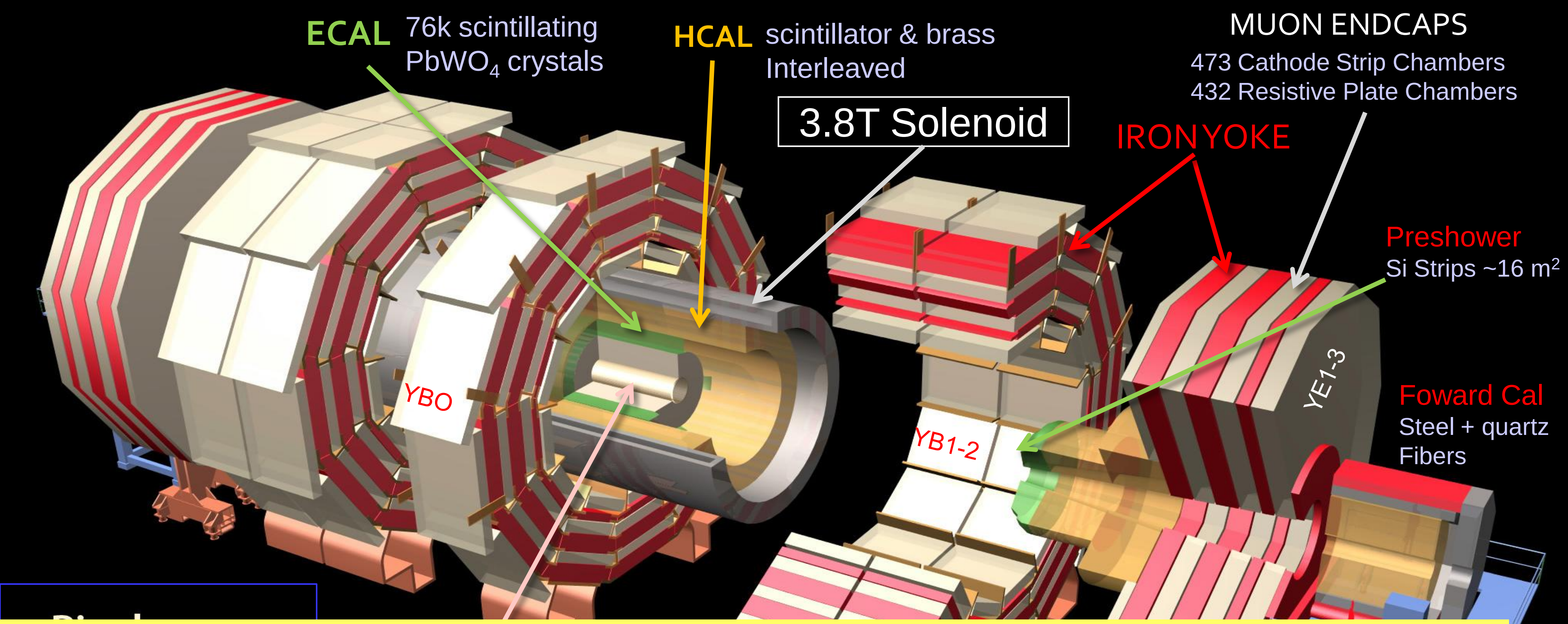


The whole world working together for the CMS Experiment

> 3000 scientists including **>**800 students
182 universities and research centers.
39 countries and regions of all continents.
New institutions keep joining



Compact Muon Solenoid (CMS) experiment



Some of the hard-to-believe facts:

Total weight 14 000 ton, diameter 15 m and length 28.7m

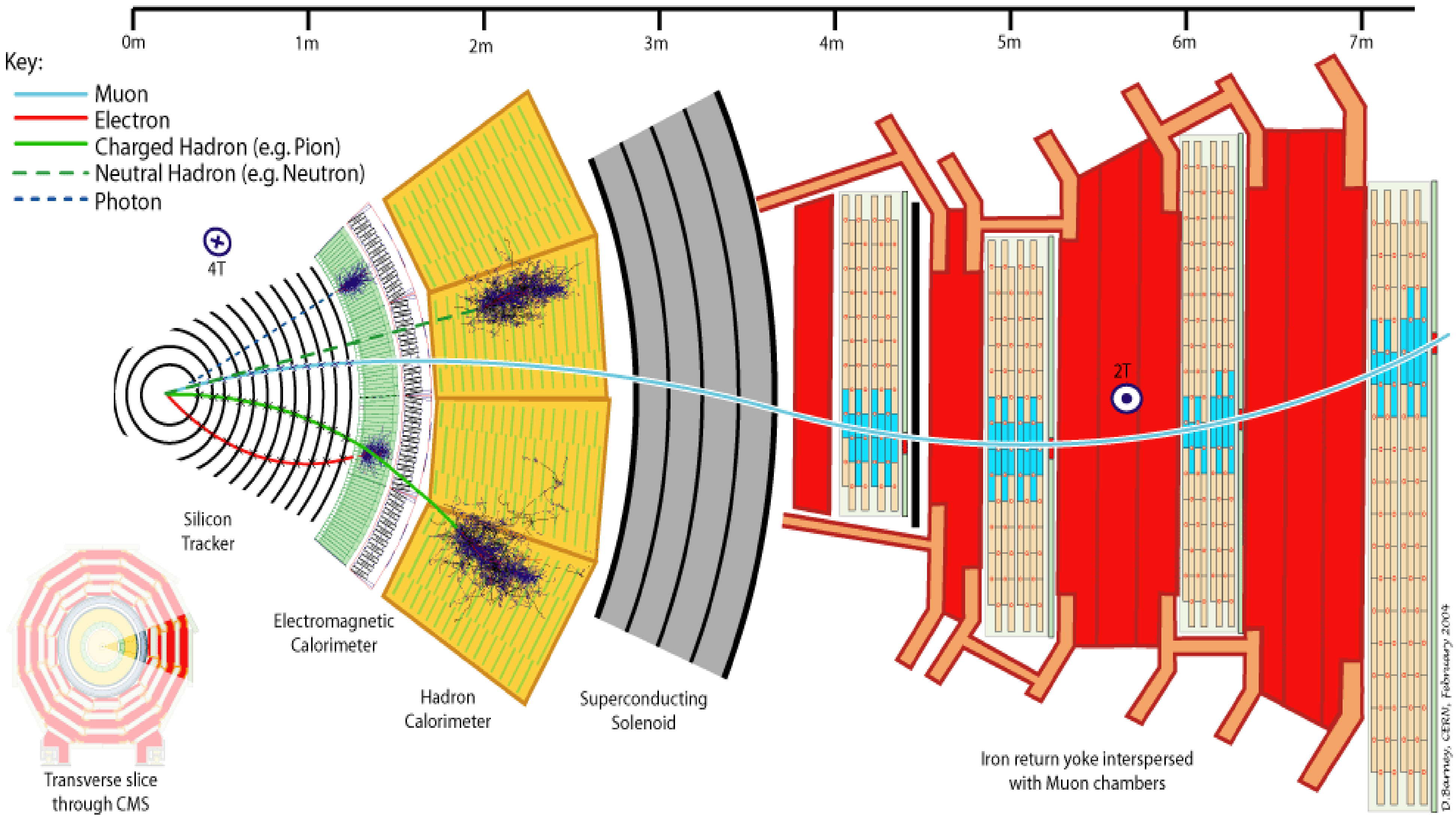
In total there are about ~100 000 000 electronic channels

Each channel checked 40 000 000 times per second (collision rate is 40 MHz)

An online trigger selects events and reduces the rate from 40MHz to 100 Hz

Amount of data of just one collision >1 500 000 Bytes

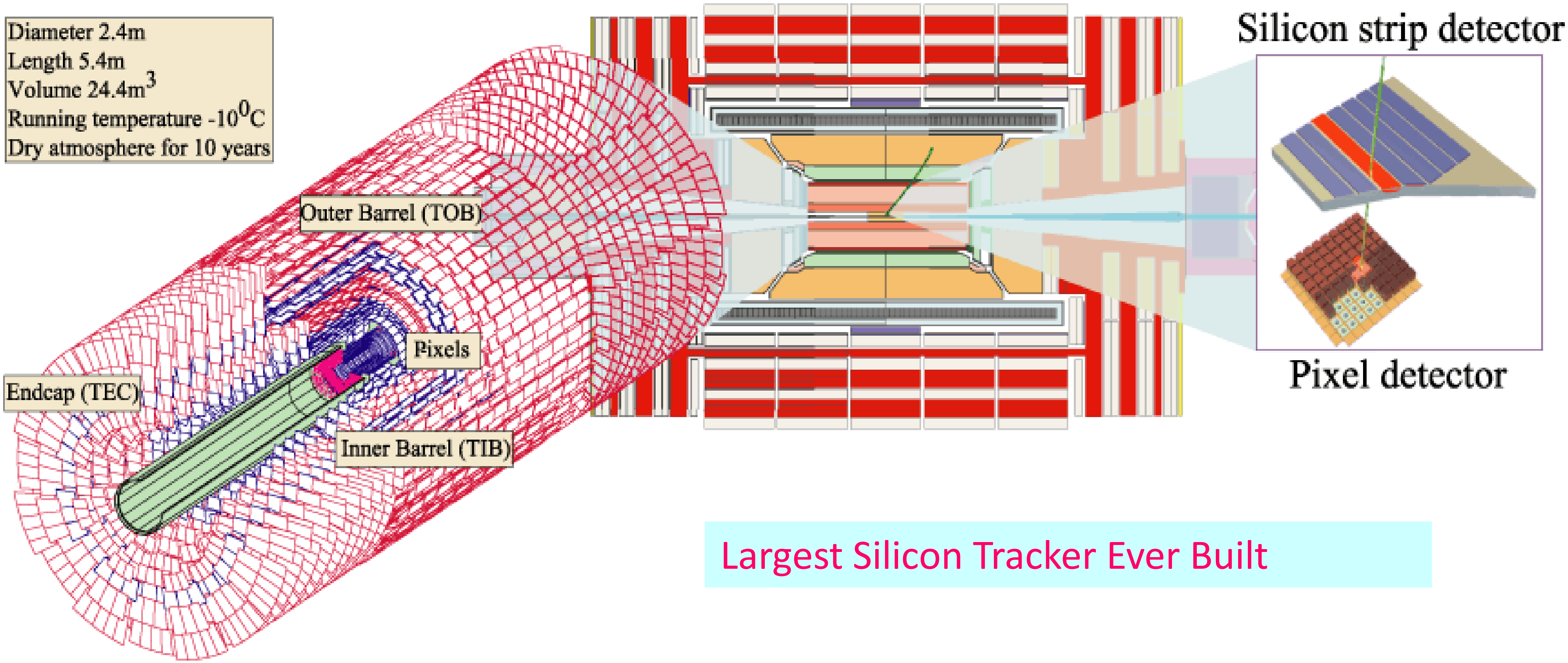
Particles through a CMS slice



Tracker is at the heart of the CMS detector

An all silicon solution for the tracking designed to reconstruct charged tracks with excellent momentum resolution and efficiency better than 98% for $|\eta| < 2.5$

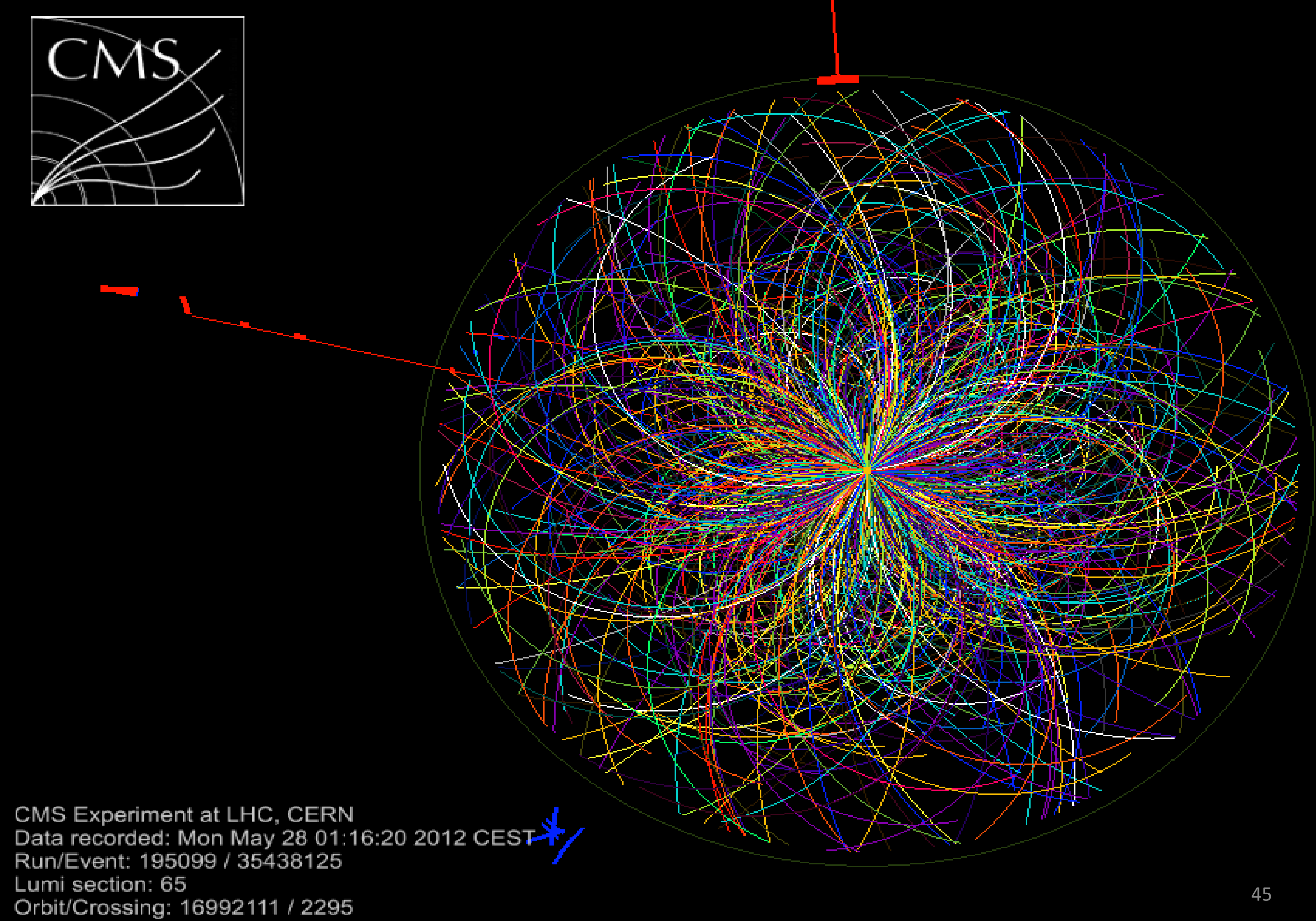
Designed to identify tracks coming from detached vertices

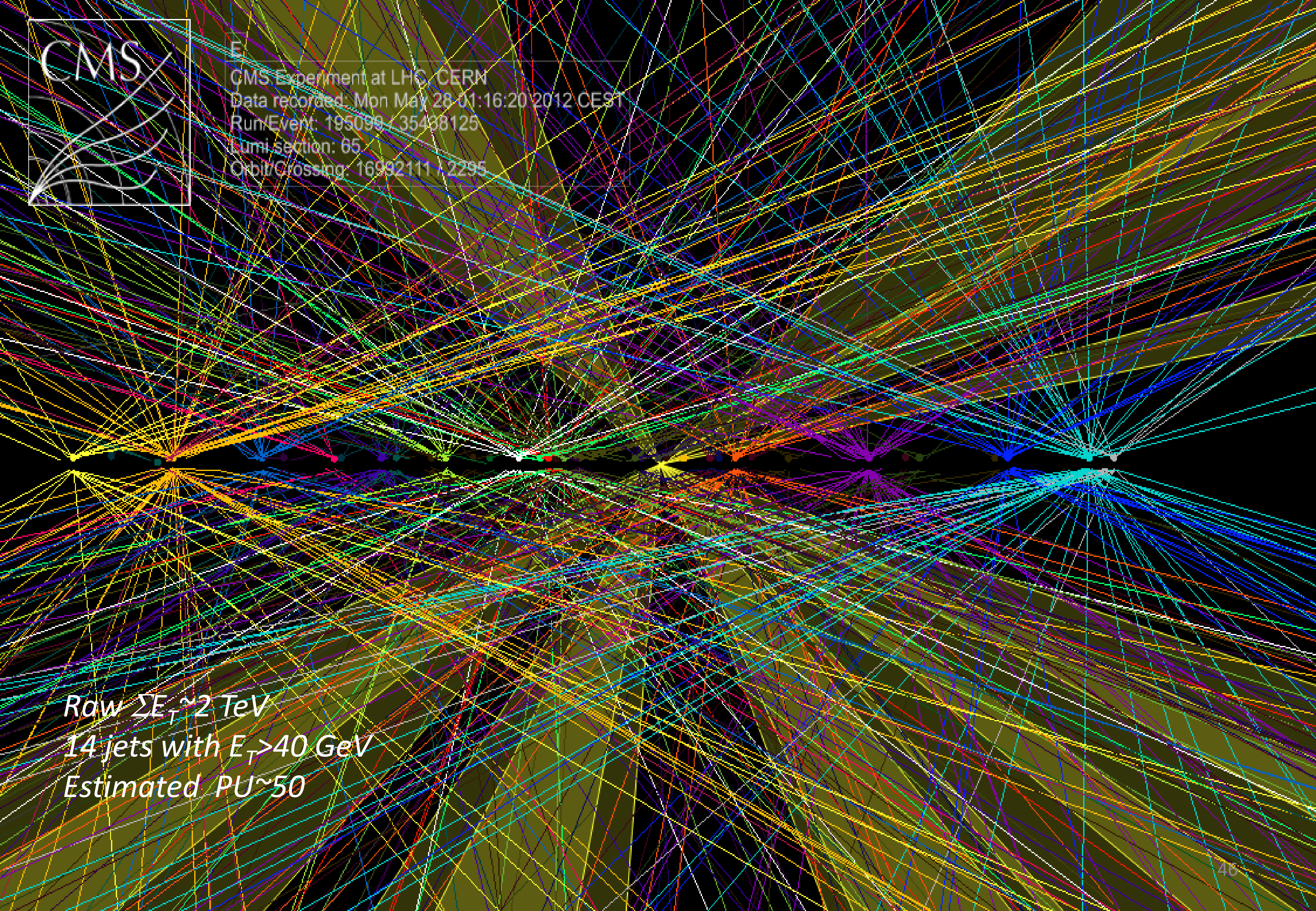


Largest Silicon Tracker Ever Built

154000 Strip modules with 9.6 million readout channels

1440 Pixel modules with 66 million readout channels


CMS
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295


CMS
E
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295
Raw ΣE_T~2 TeV
14 jets with E_T>40 GeV
Estimated PU~50

The Indian contribution to the CMS Detector

TIFR & BARC (Mumbai), SINP (Kolkata)
Universities of Delhi, Panjab & Visvabharti

Detector Building, monitoring, data handling, event reconstruction software, physics analysis

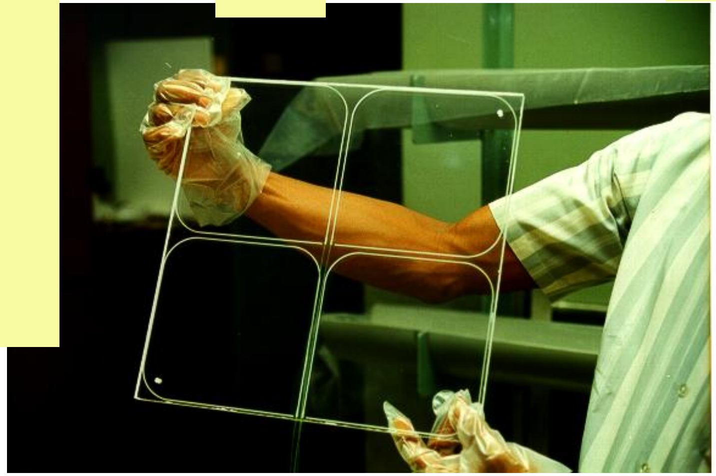
Grid Computing center at TIFR

We are grateful to DAE & DST for generous funding

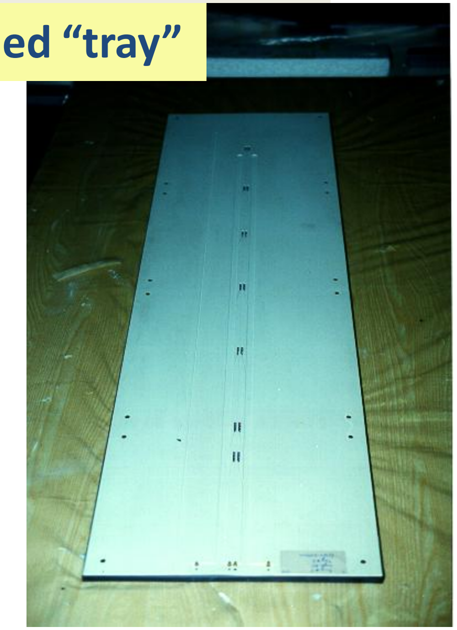
Indian hardware in CMS – Outer Hadron Calorimeter

Plastic scintillator tiles detector (450 sq m)
Embedded WLS fibre readout.
(TIFR + Panjab Univ)

Tile

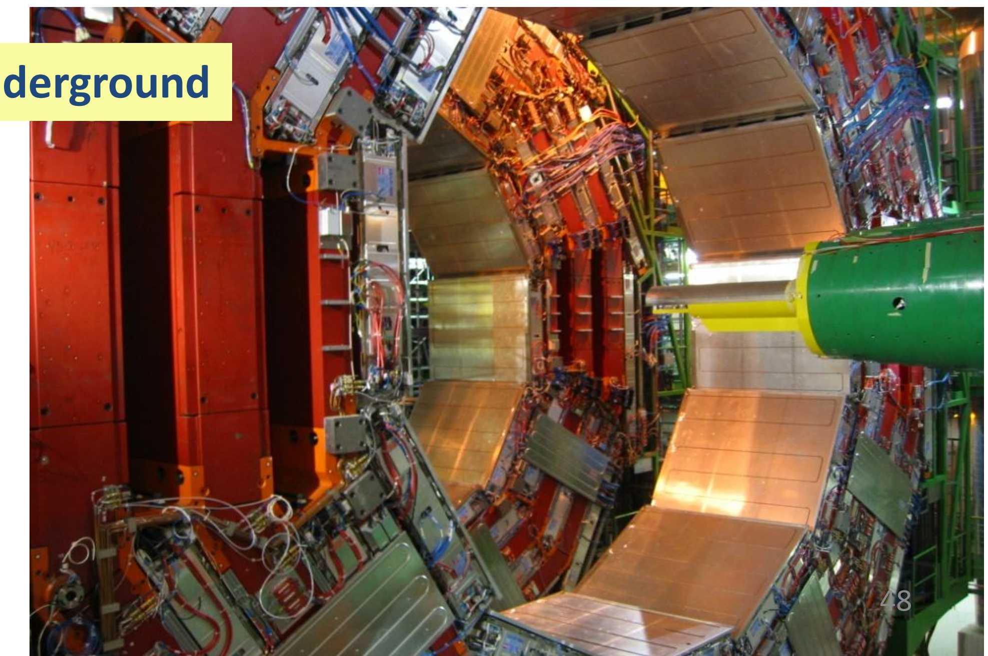


Assembled "tray"



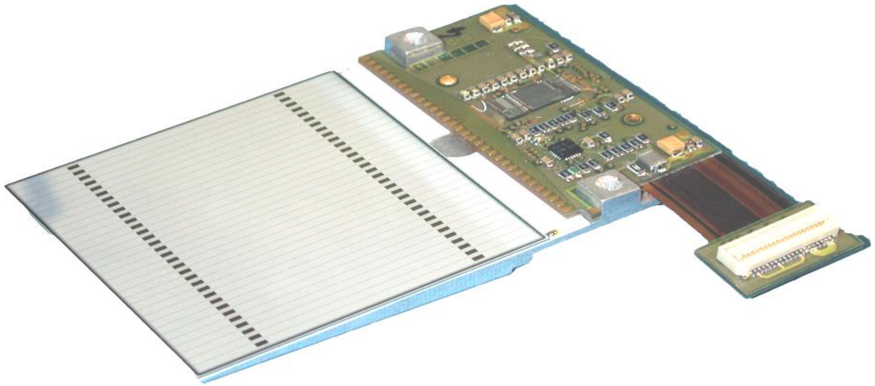
Installation on surface

Underground

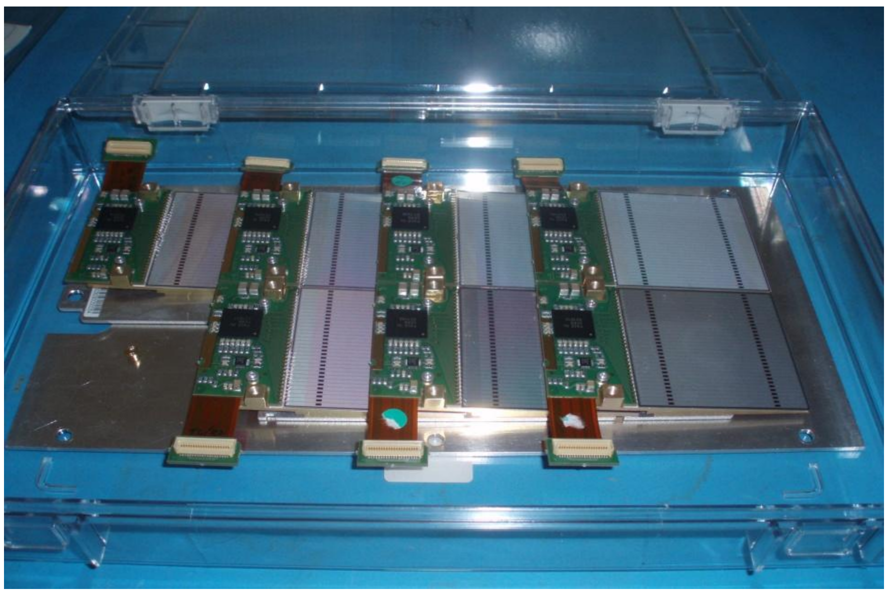


Indian Silicon detectors in CMS Pre-shower

1000 detectors (25% of total)   BARC + Delhi Univ.



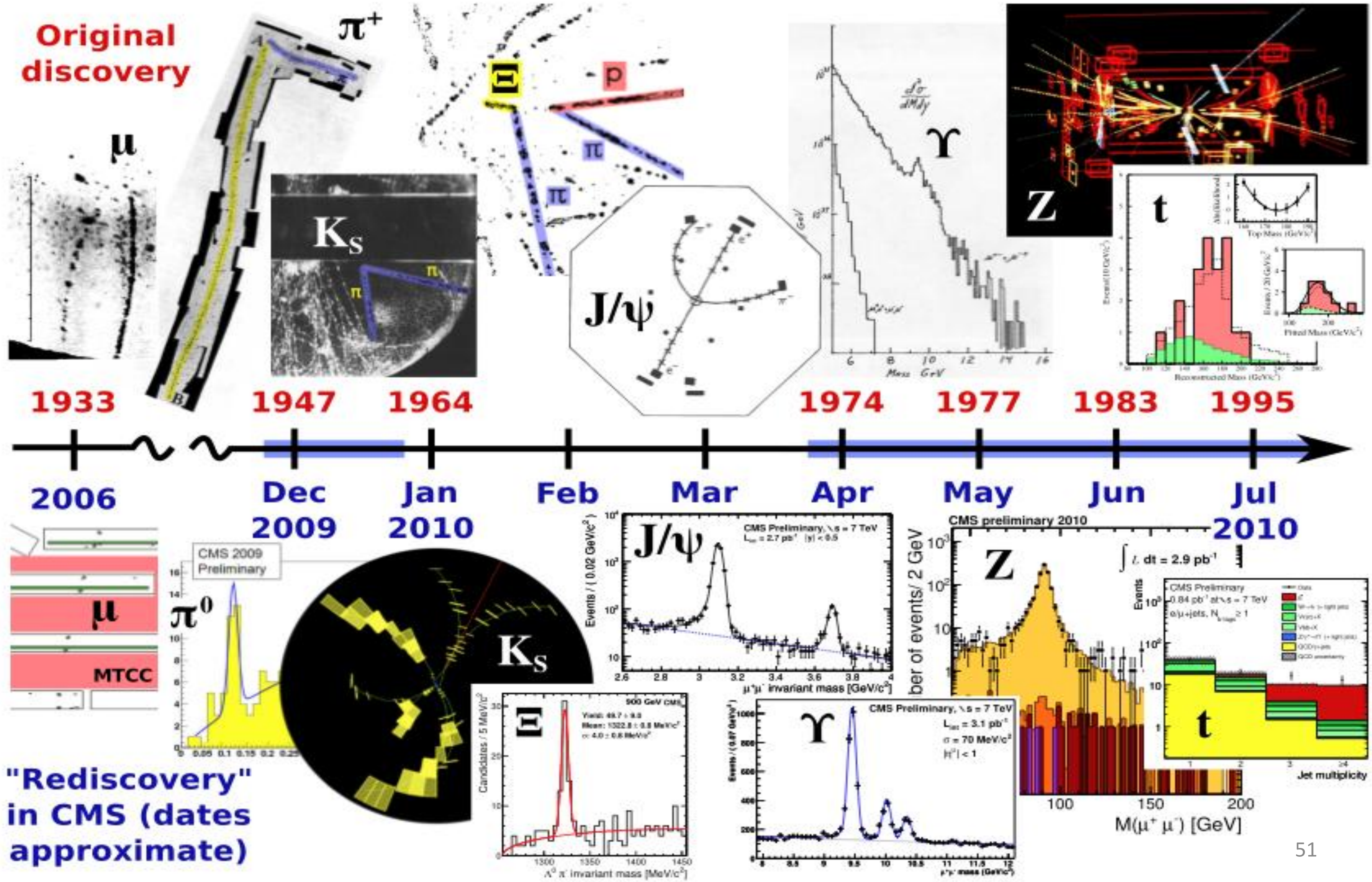
Mounted on Dee's



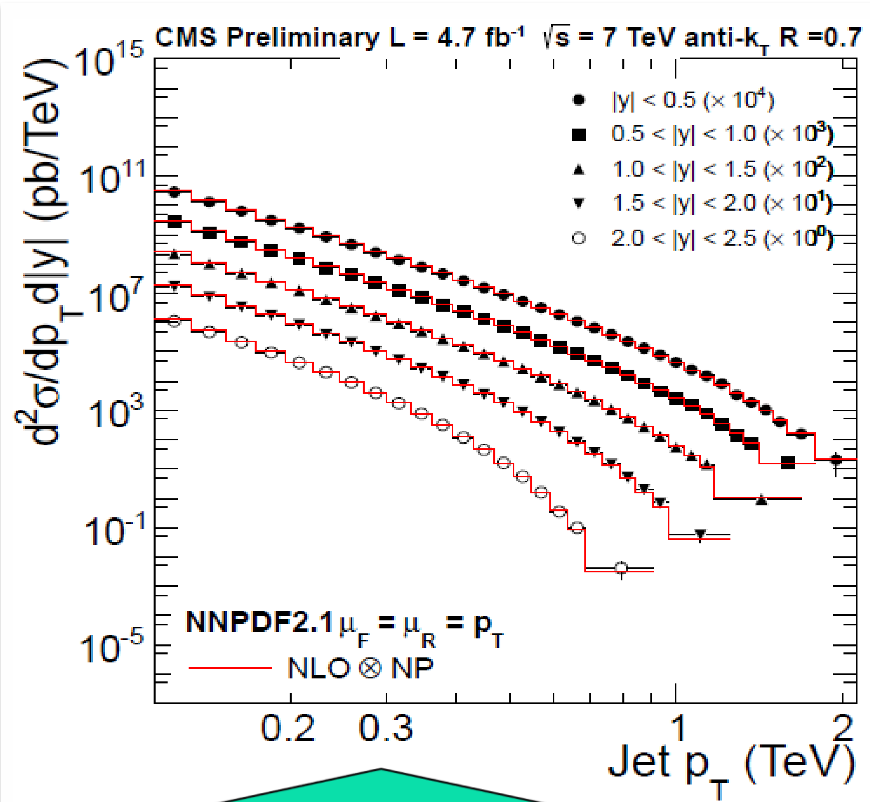
Ladders

Fitness test of the Detector

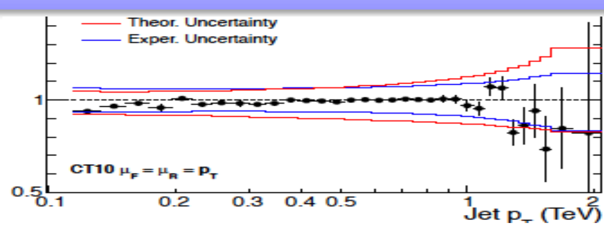
Re-discover the Standard Model at 7 TeV



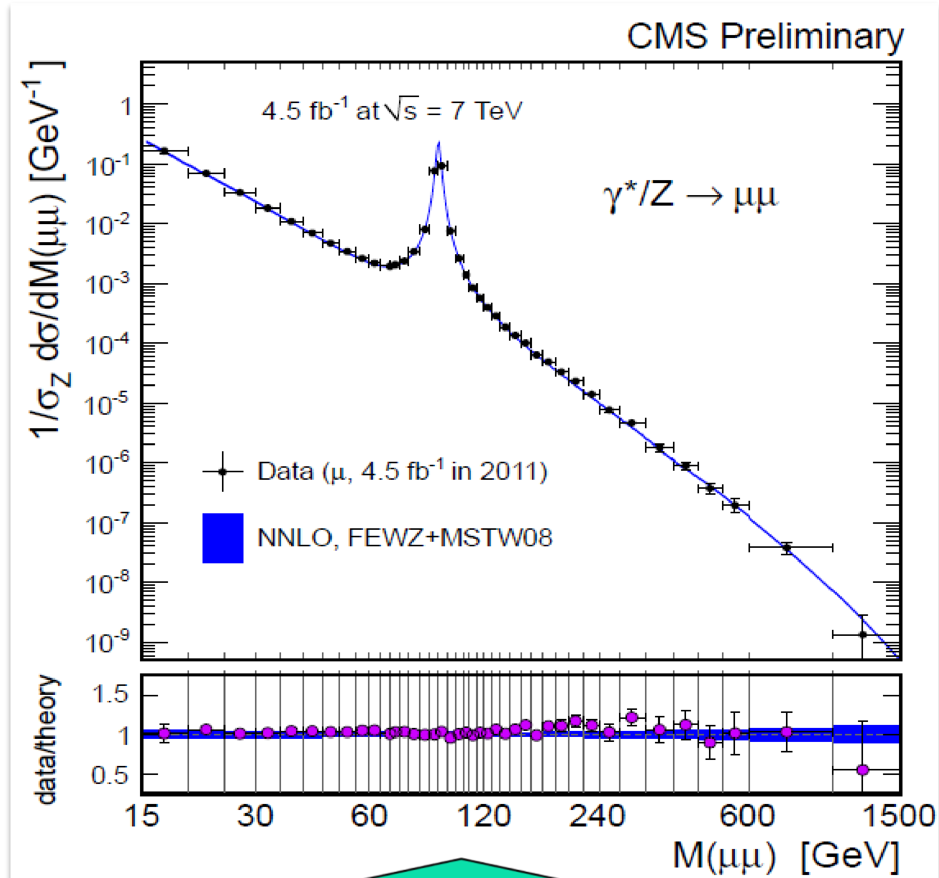
Standard Model: Precision Jets, W, and γ^*/Z



Inclusive jet and dijets. 2-4% JES. Constrains gluon PDF up to x=0.6

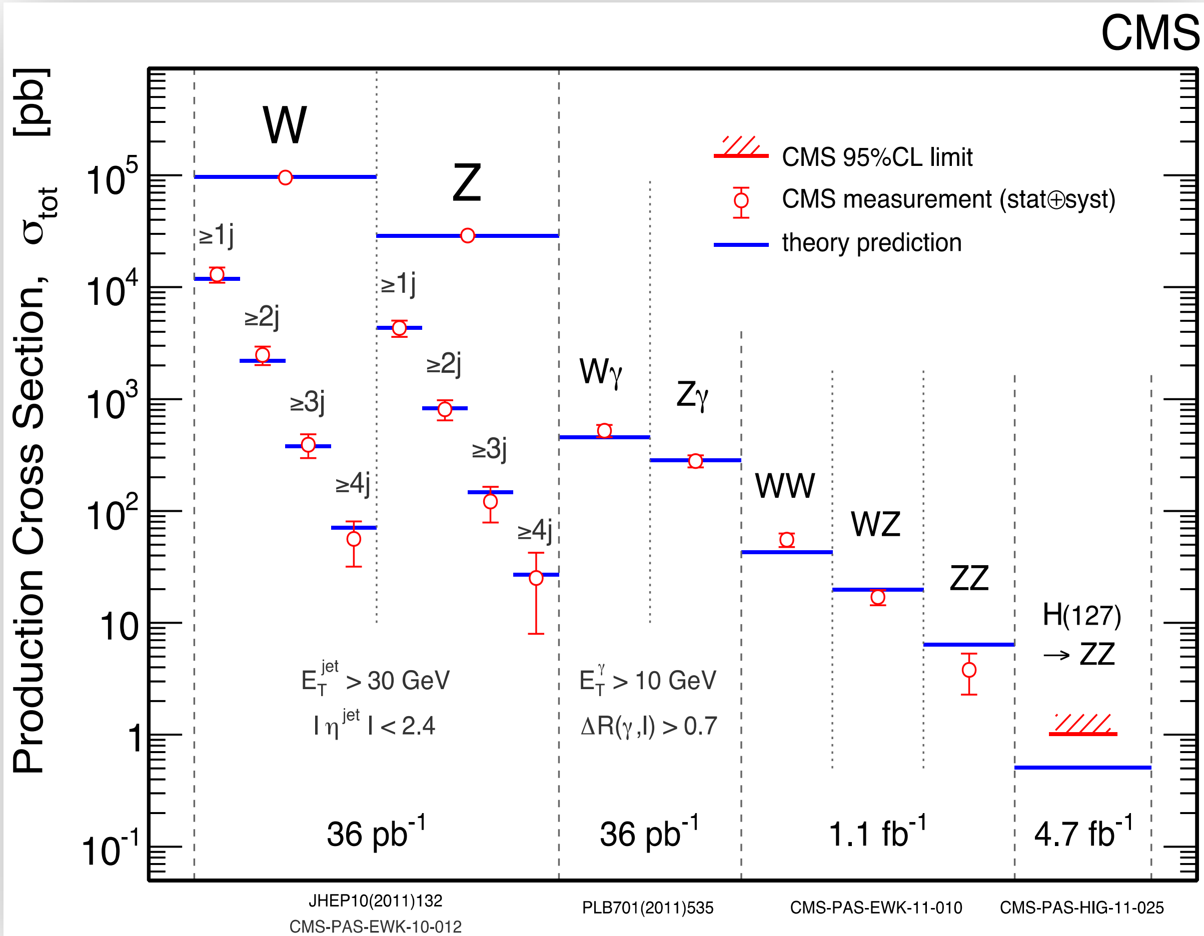


Measurements in 10 orders magnitude



Differential Drell-Yan cross section: 2.5M $\mu\mu$ pairs tests NNLO cross sections and PDFs

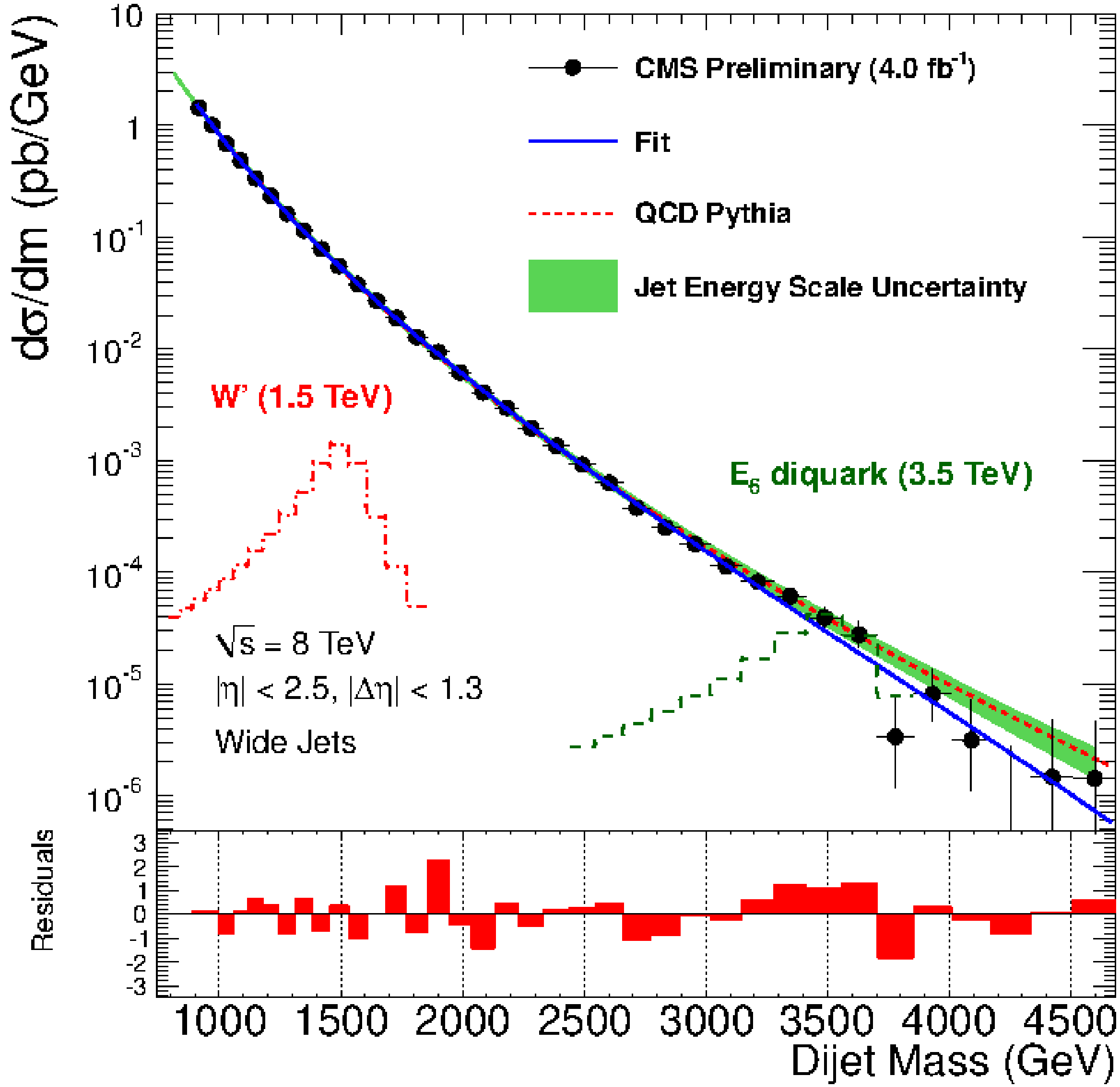
First establish the background

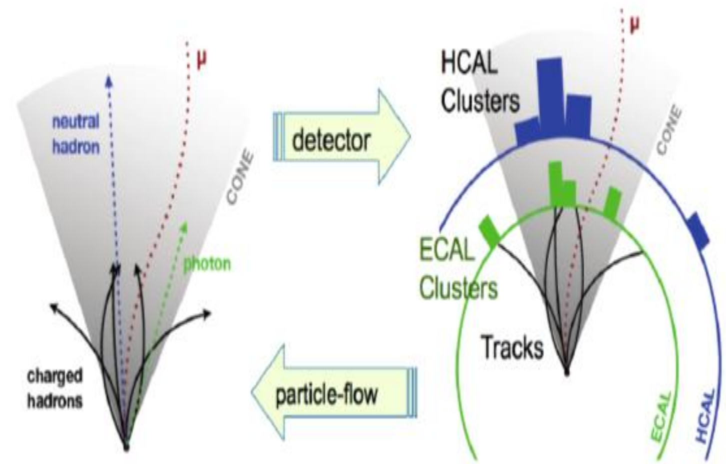


- **Excellent agreement**
- **Lots of data in hand**

… on to the Higgs…

Di-jet cross section



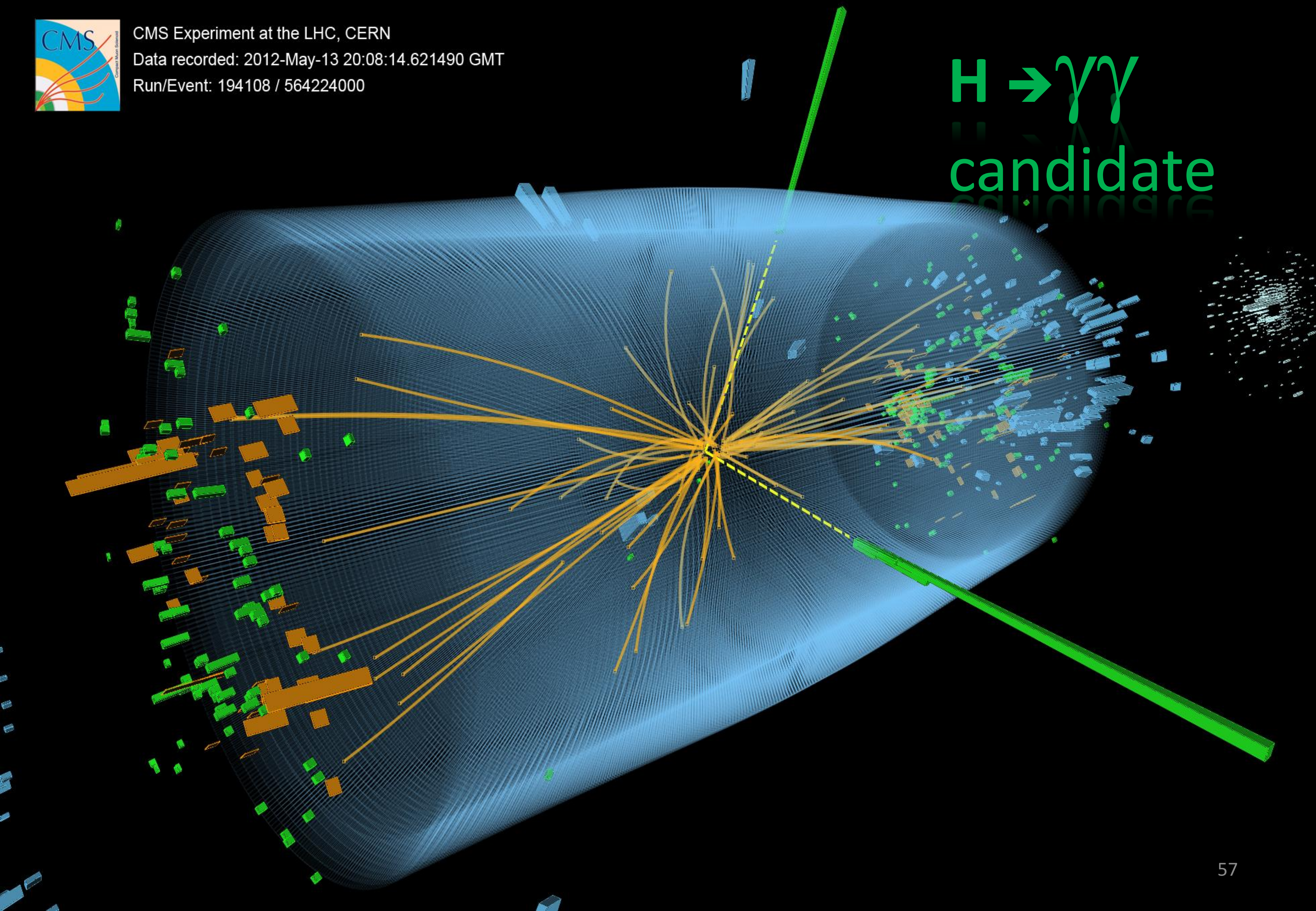


NLO QCD describes data over ~9 orders of magnitude!

Detector is robust to look for Higgs

$$H \rightarrow \gamma\gamma$$

Good mass resolution, but large background

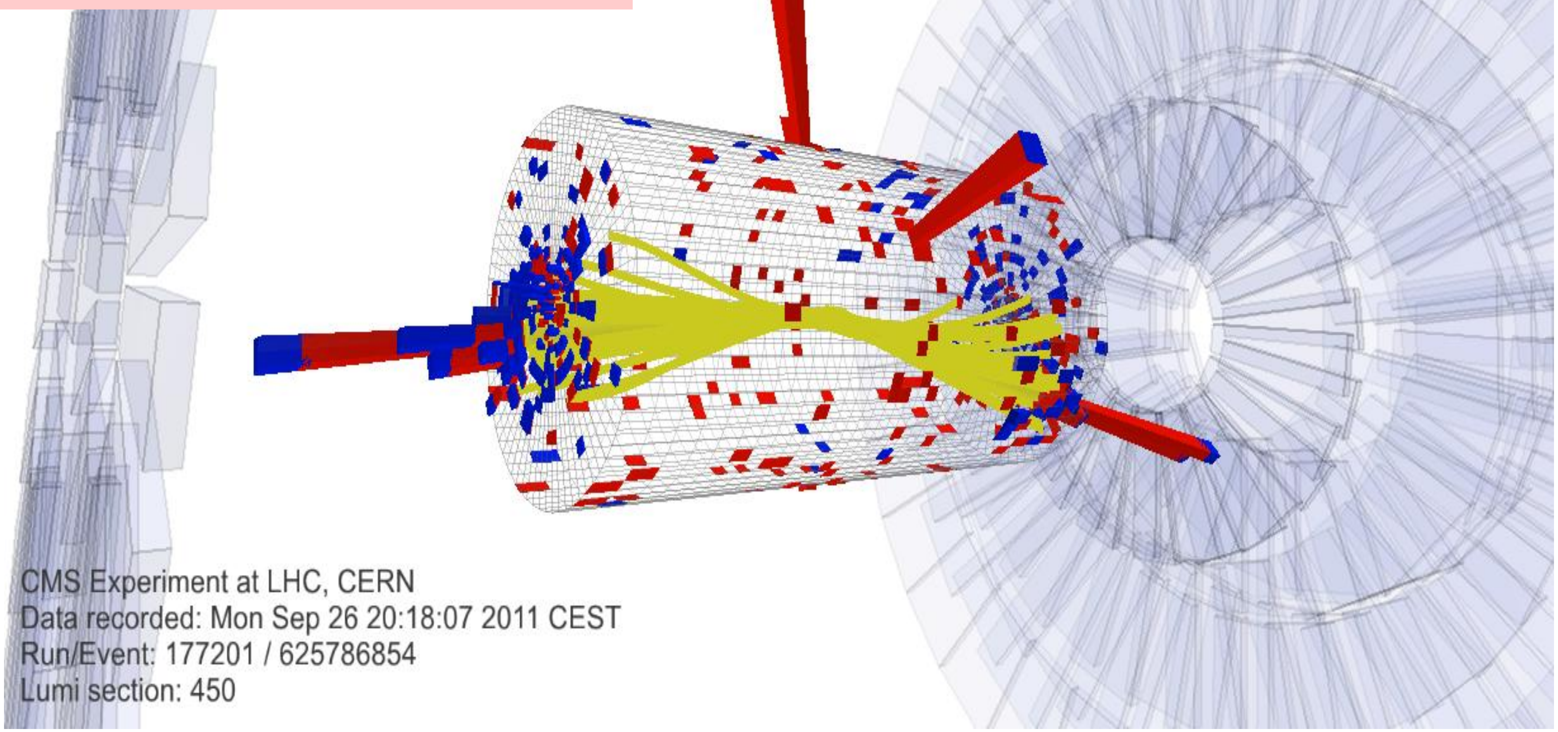

CMS
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H → $\gamma\gamma$
candidate

Candidate with Di-jet Tagging

- Exclusive selection of di-photon events with VBF-like topology:
  - Two high pT jets with large pseudo-rapidity gap and invariant mass
- High S/B
- ~80%-pure VBF events for large di-jet invariant masses

Di-jet event with:

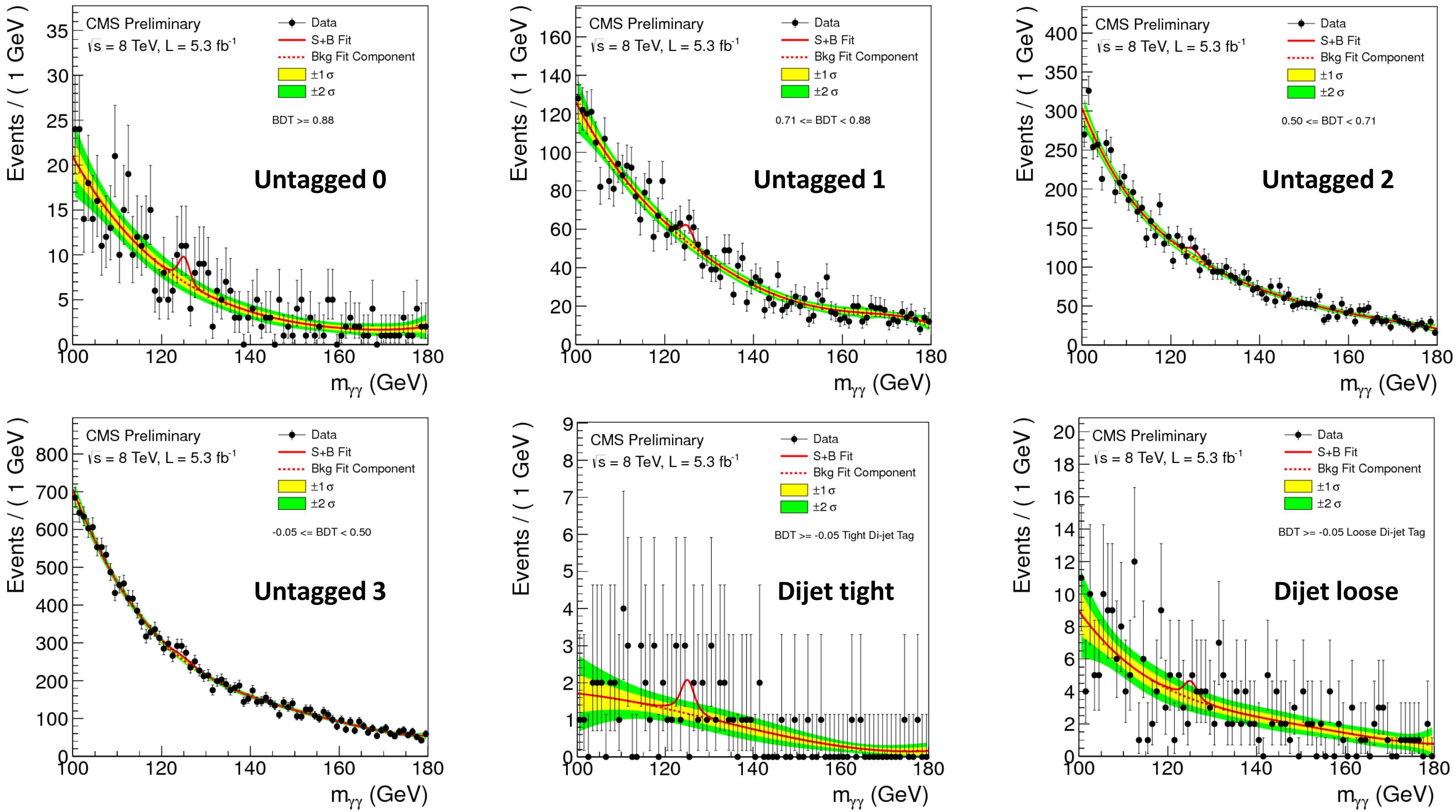
- diphoton mass 121.9 GeV
- dijet mass 1460 GeV
- jet p_T: 288.8 and 189.1 GeV
- jet η: -2.022 and 1.860



$H \rightarrow \gamma\gamma$ Analysis

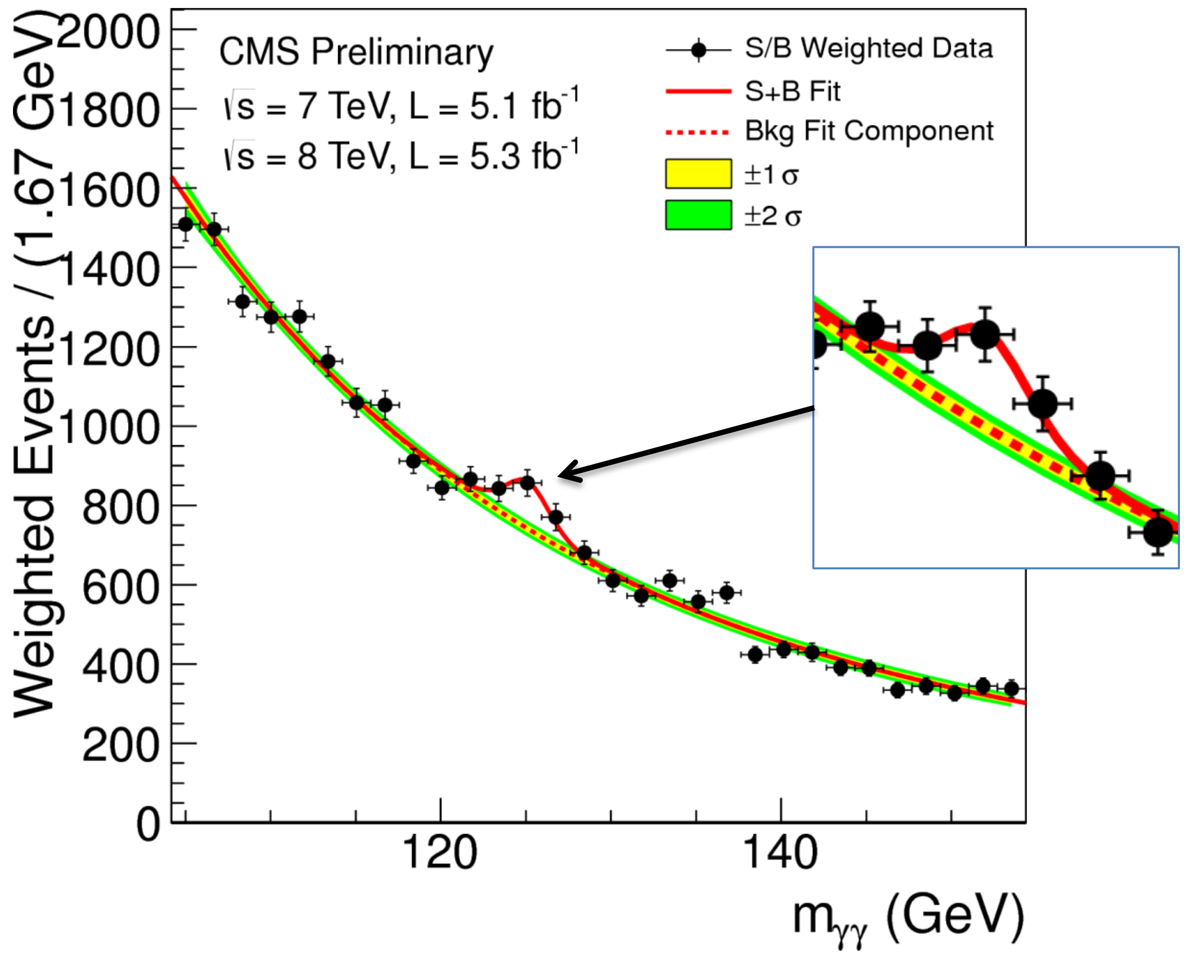
- Multi-Variate Analysis (MVA) for photon ID and event classification
  - Divide events into non-overlapping samples of varying S/B based on properties of the reconstructed photons and presence of di-jets from VBF process
- Cross check with cut-based analysis
  - MVA and cut-based results consistent
  - MVA gives 15% better sensitivity
- Primary vertex selection, which is needed for $M_{\gamma\gamma}$ calculation, is based on consistency with di-photon kinematics (p_T balance etc.)
  - Correct assignment 83% (80%) in 2011 (2012)

8 TeV Mass Distribution in Categories

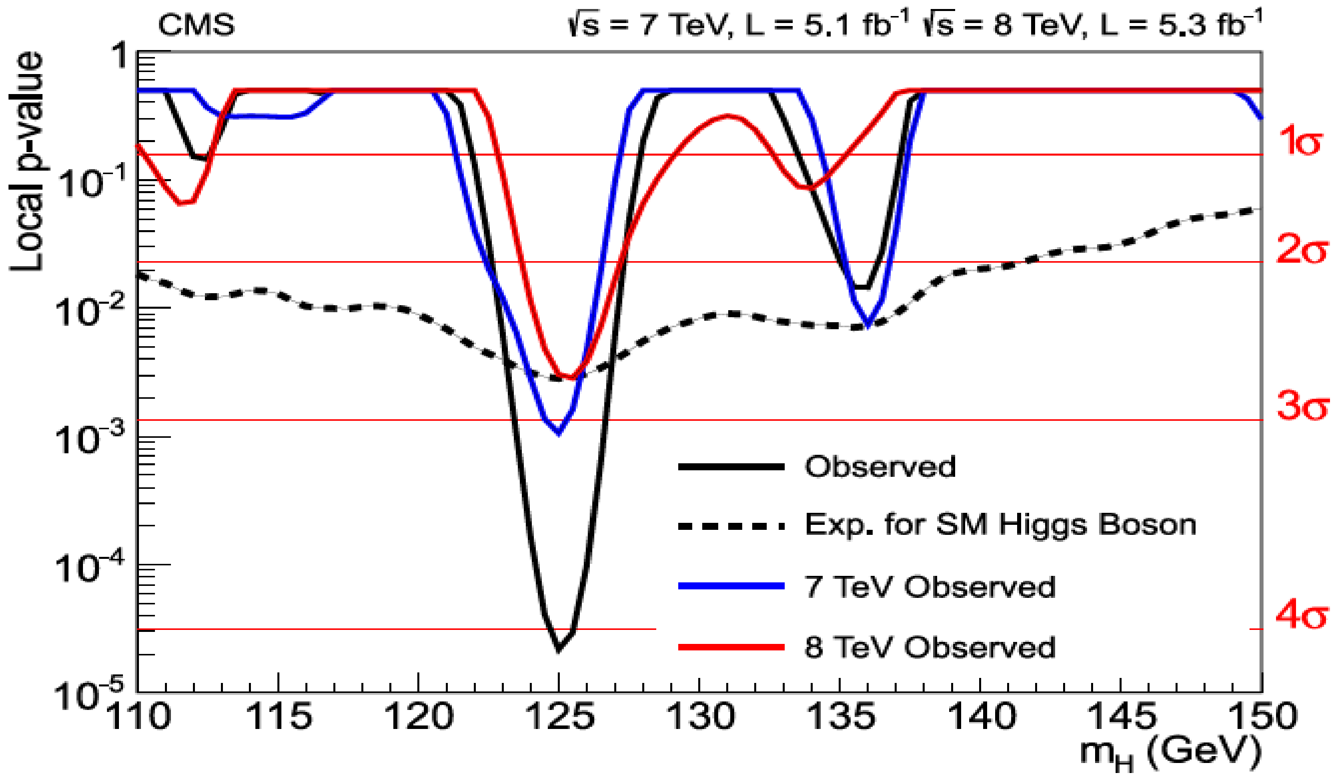


S/B Weighted Mass Distribution

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



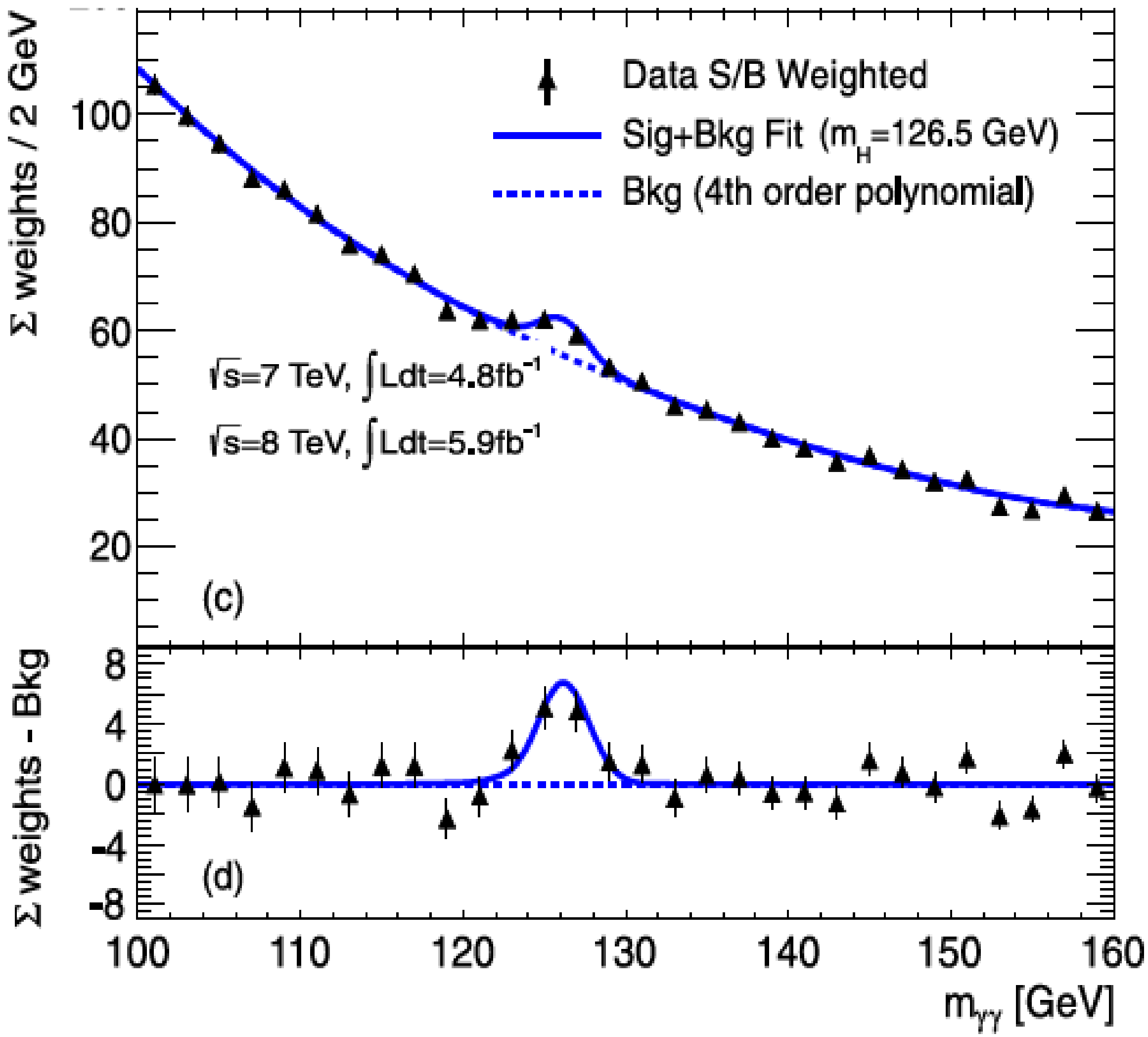
Quantify the excess (p-values)



H →γγ

- **Minimum local p-value at 125 GeV with a local significance of 4.1 σ**
- **Similar excess in 2011 and 2012**
- **Independent cross check analyses give similar results**
- **Global significance in the full search range (110-150 GeV) 3.2 σ**

Results from ATLAS: $H \to \gamma\gamma$



Excess at the level of 4.5 σ

Expected 2.5 σ

Similar to CMS

Higgs to ZZ $\rightarrow$ 4-leptons

Good mass resolution- Golden Channel

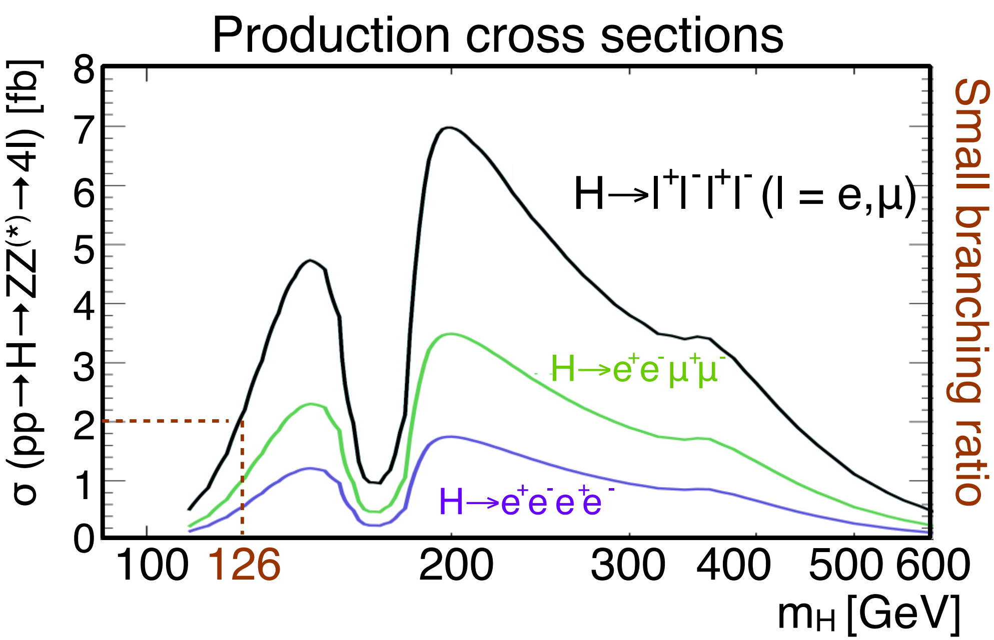
H →ZZ$^{(*)}$ →4l (l = e,μ): the golden channel

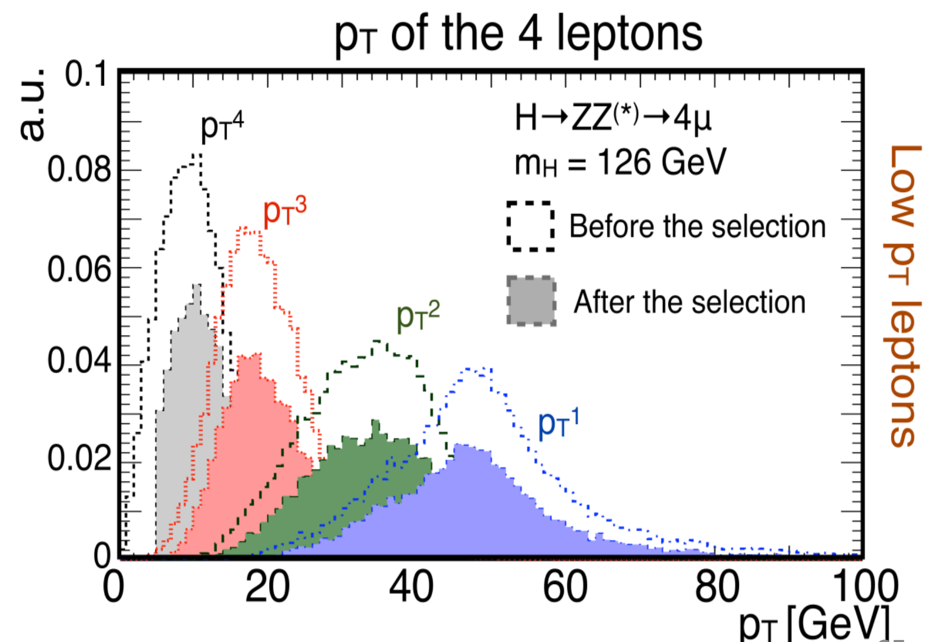
Clean signature: narrow peak, low background

Background: irreducible ZZ$^{(*)}$; reducible Z+jets, ttbar, WZ

One of the best performing channels in the whole mass range …

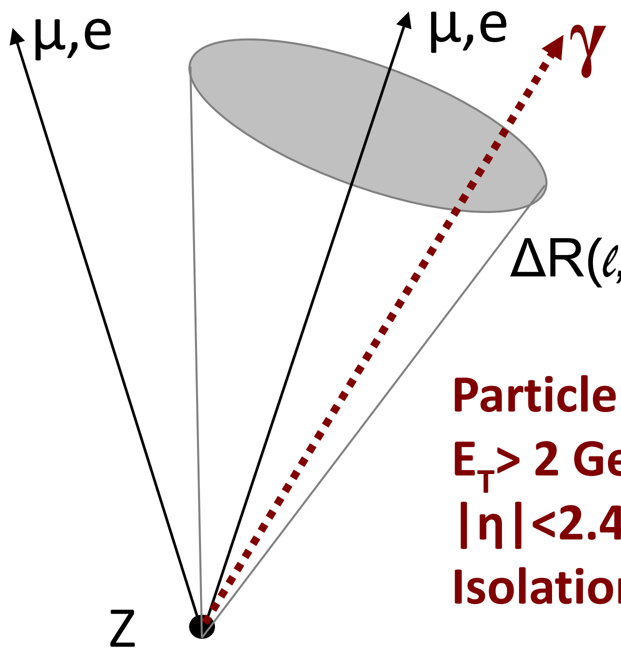
… but extremely demanding channel for selection, requiring the highest possible efficiencies (lepton Reco/ID/Isolation).





Final State Radiation recovery algorithm

Applied on each Z for photons near the leptons

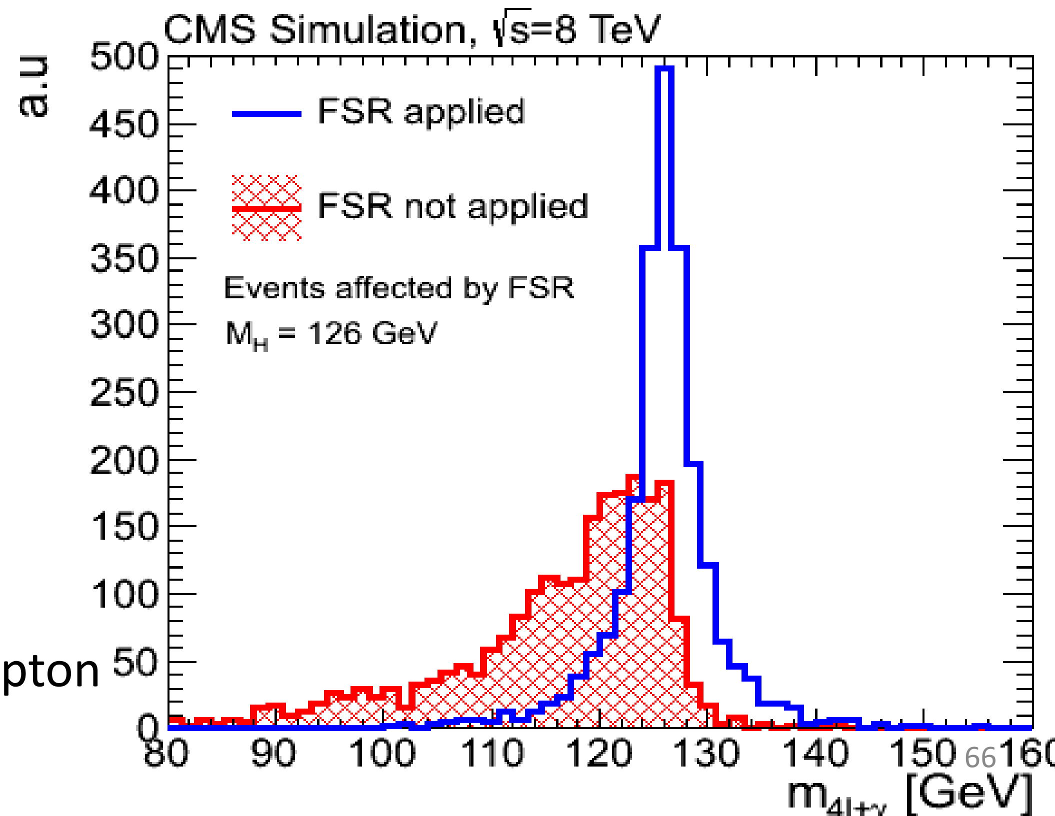


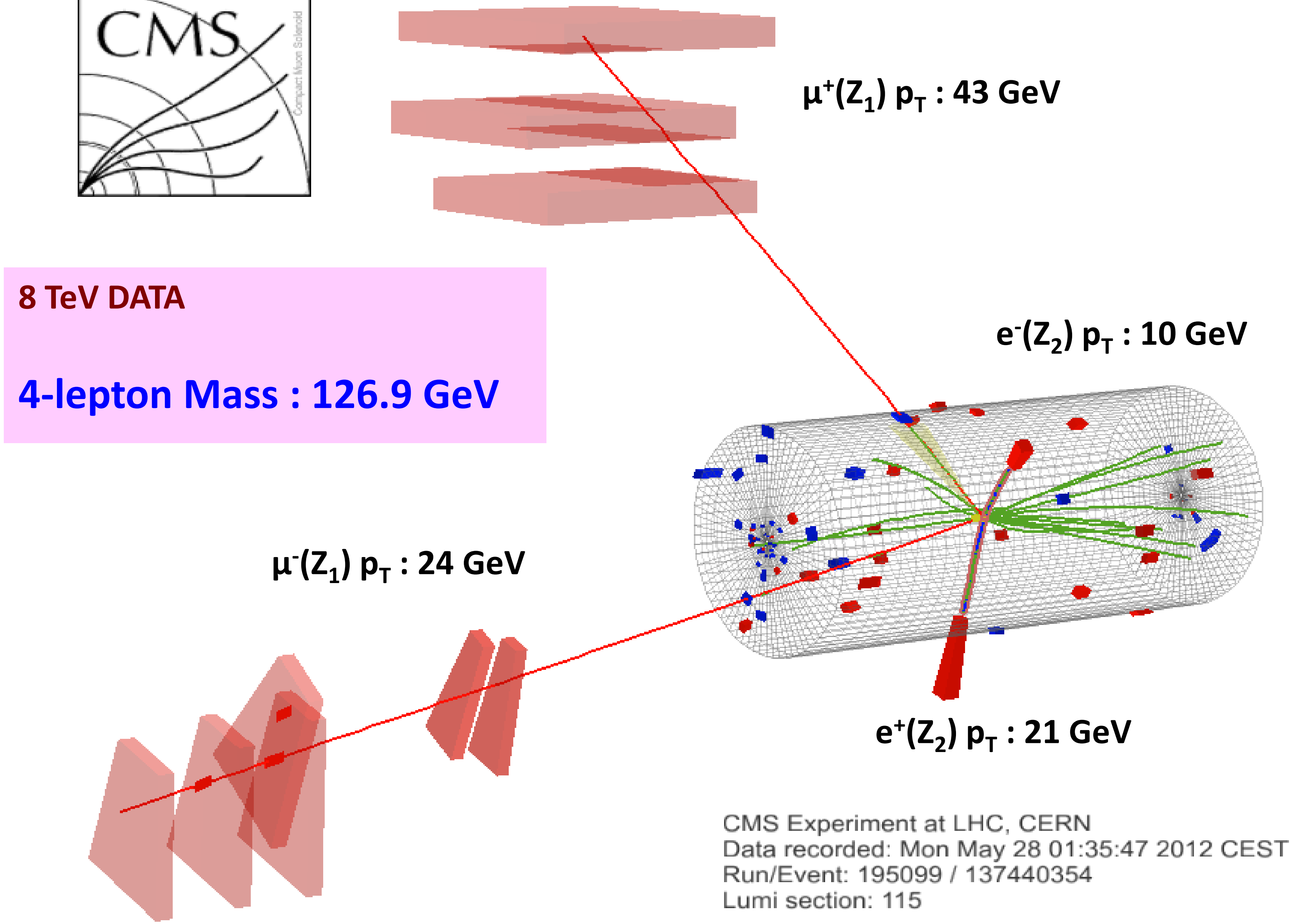
Particle Flow ID
E_T> 2 GeV
|η|<2.4
Isolation

- Associates photon with Z if:
  - $M(ll+\gamma)< 100$ GeV
  - $|M(ll+\gamma)-M_Z|<|M(ll)-M_Z|$
- Removes associated photons from lepton isolation calculation

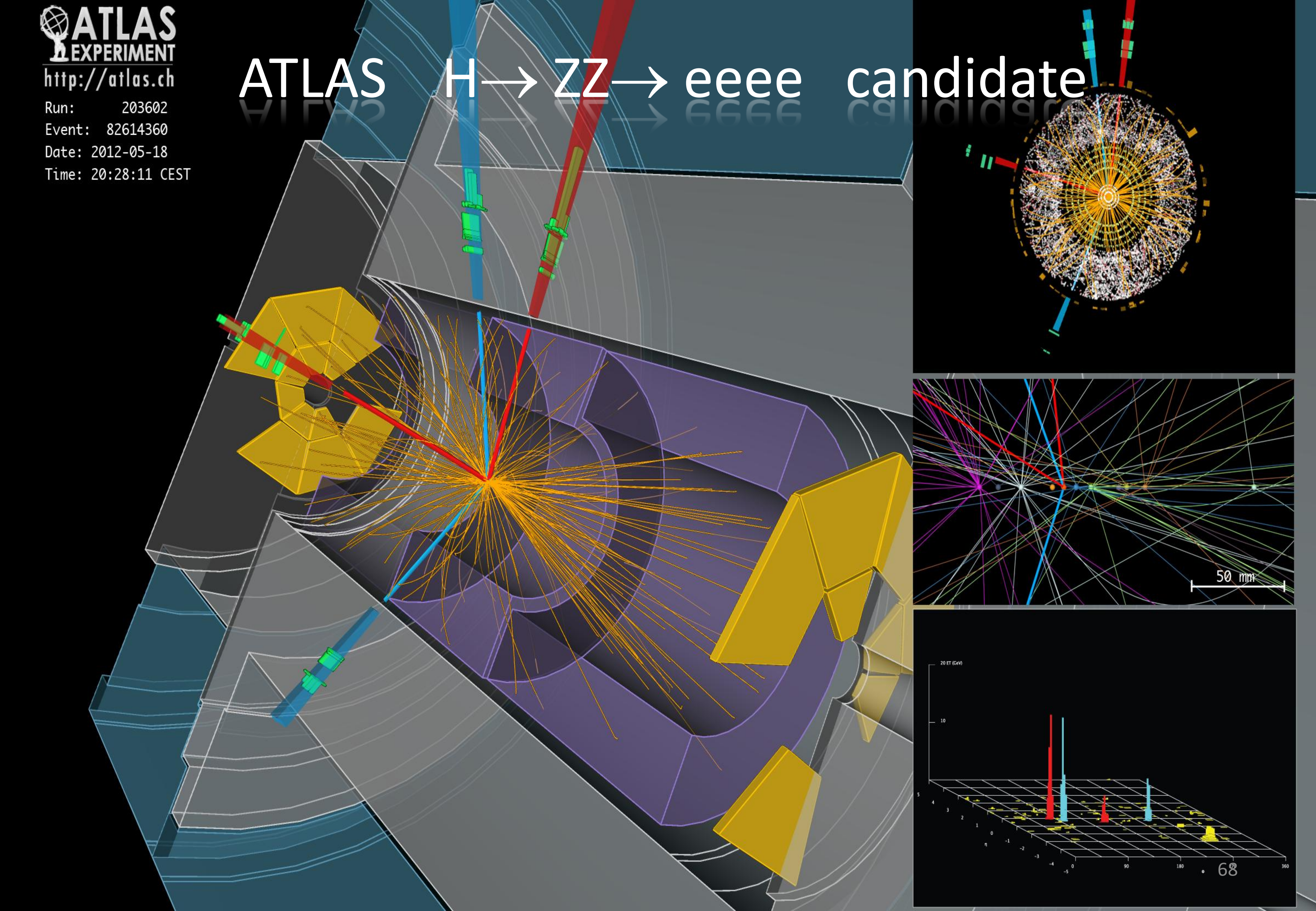
Expected Performance for M_H=126 GeV

- 6% of events affected
- Average purity of 80%
- 2% added in analysis



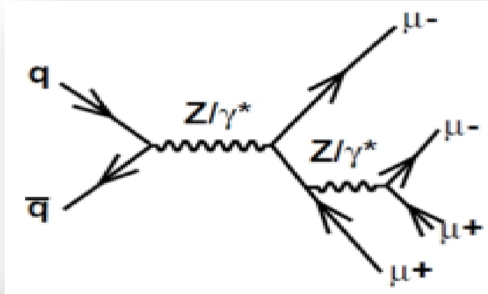

8 TeV DATA
4-lepton Mass : 126.9 GeV
μ+(Z1) pT : 43 GeV
e-(Z2) pT : 10 GeV
μ-(Z1) pT : 24 GeV
e+(Z2) pT : 21 GeV
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:35:47 2012 CEST
Run/Event: 195099 / 137440354
Lumi section: 115

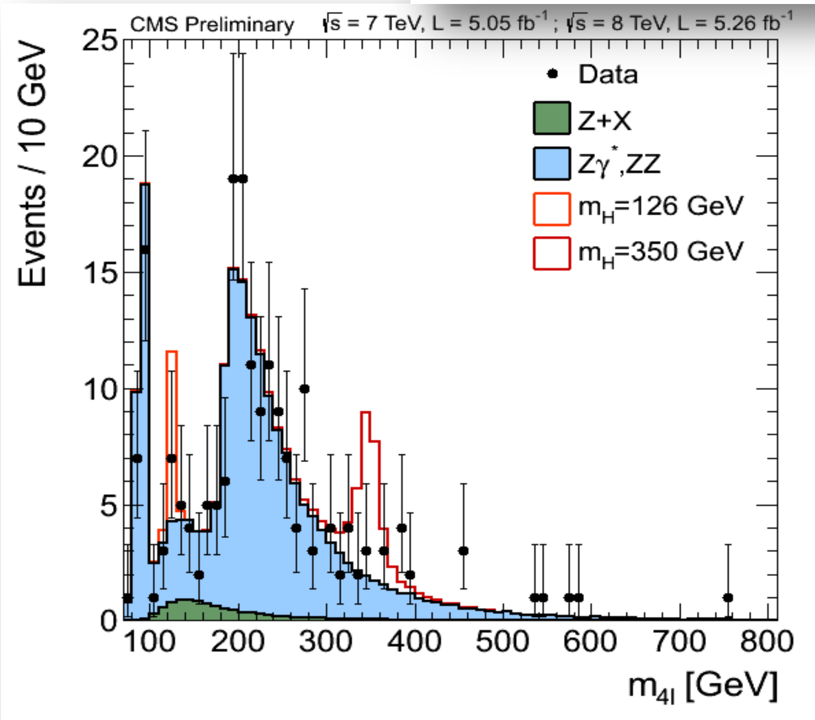
ATLAS $H \rightarrow ZZ \rightarrow eeee$ candidate

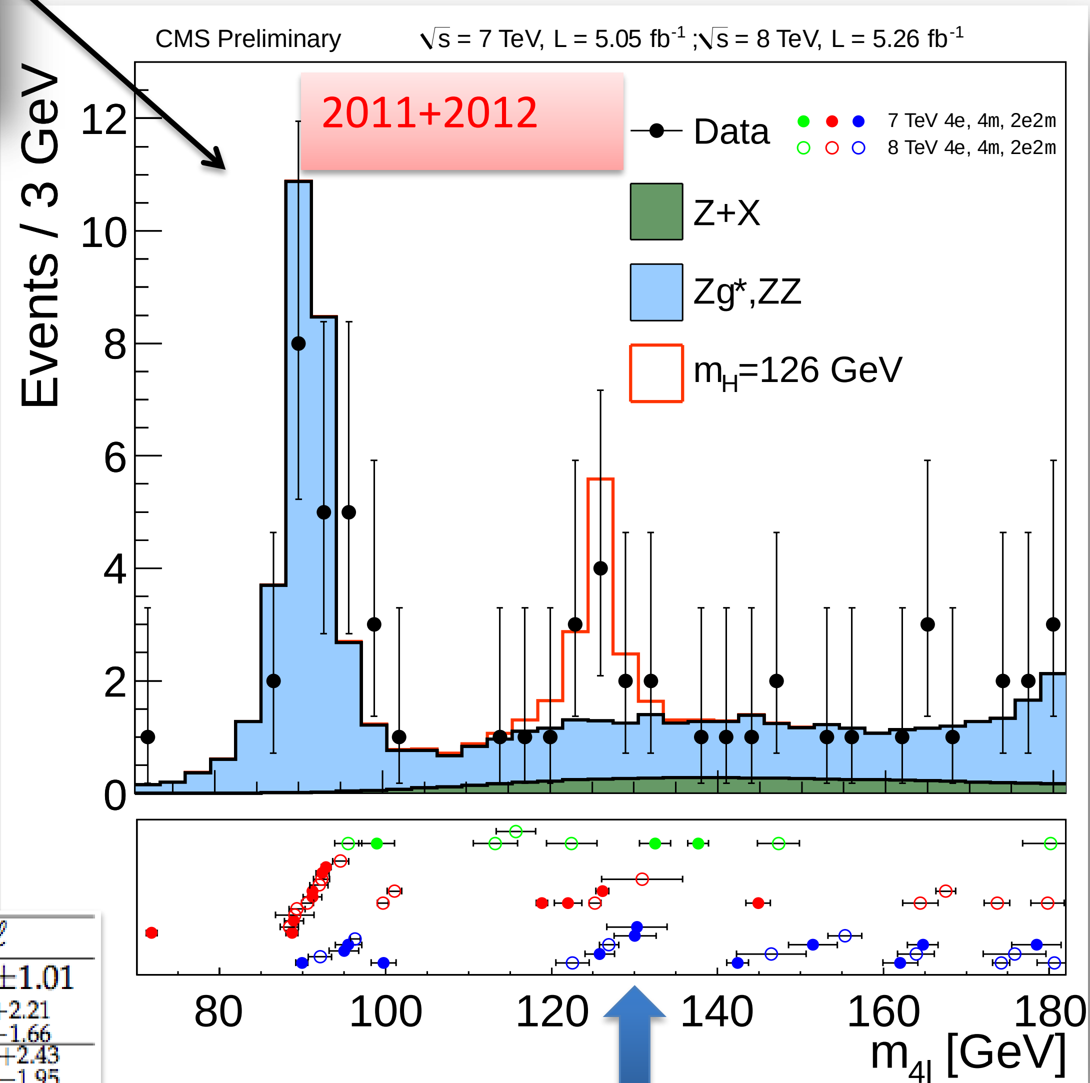


m(4l) spectrum

CMS







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

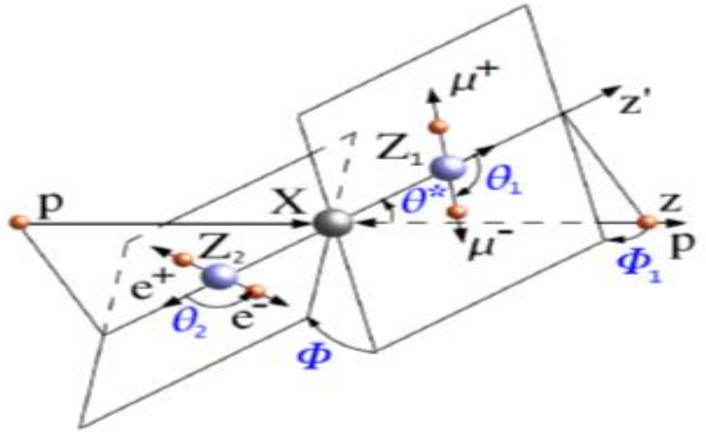
164 events expected in [100, 800 GeV]

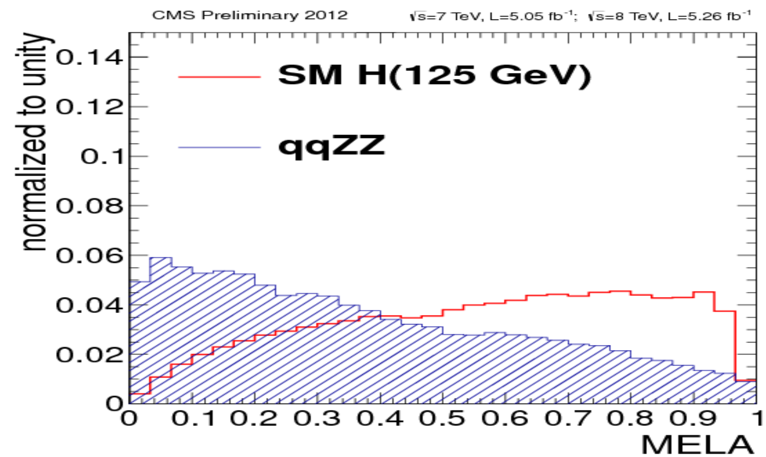
172 events observed in [100, 800 GeV]

Event-by-event errors

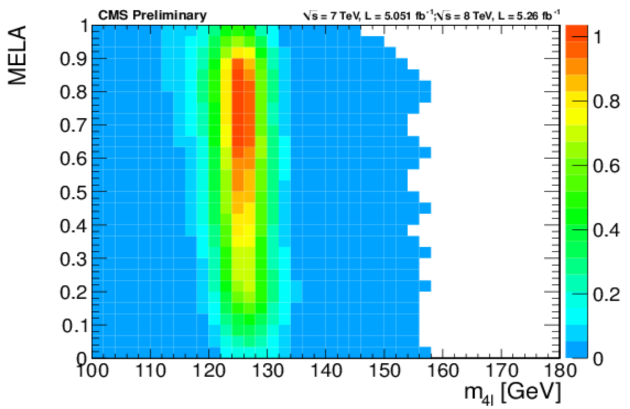
Matrix Element Likelihood Analysis

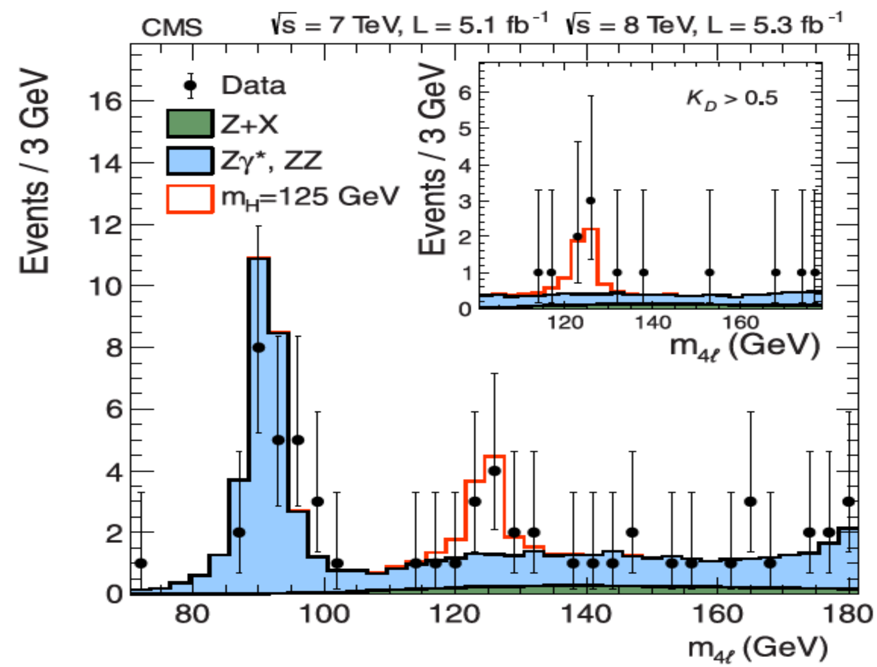
$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$



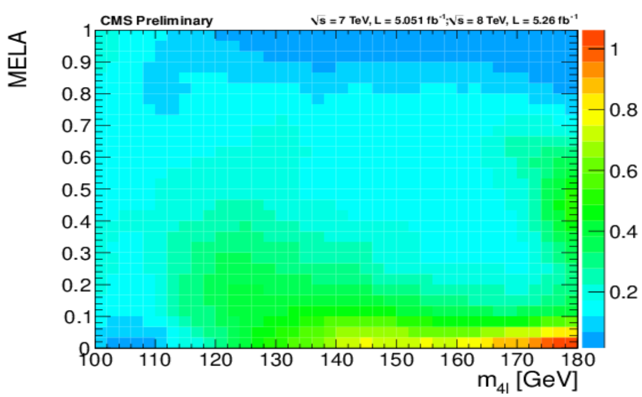


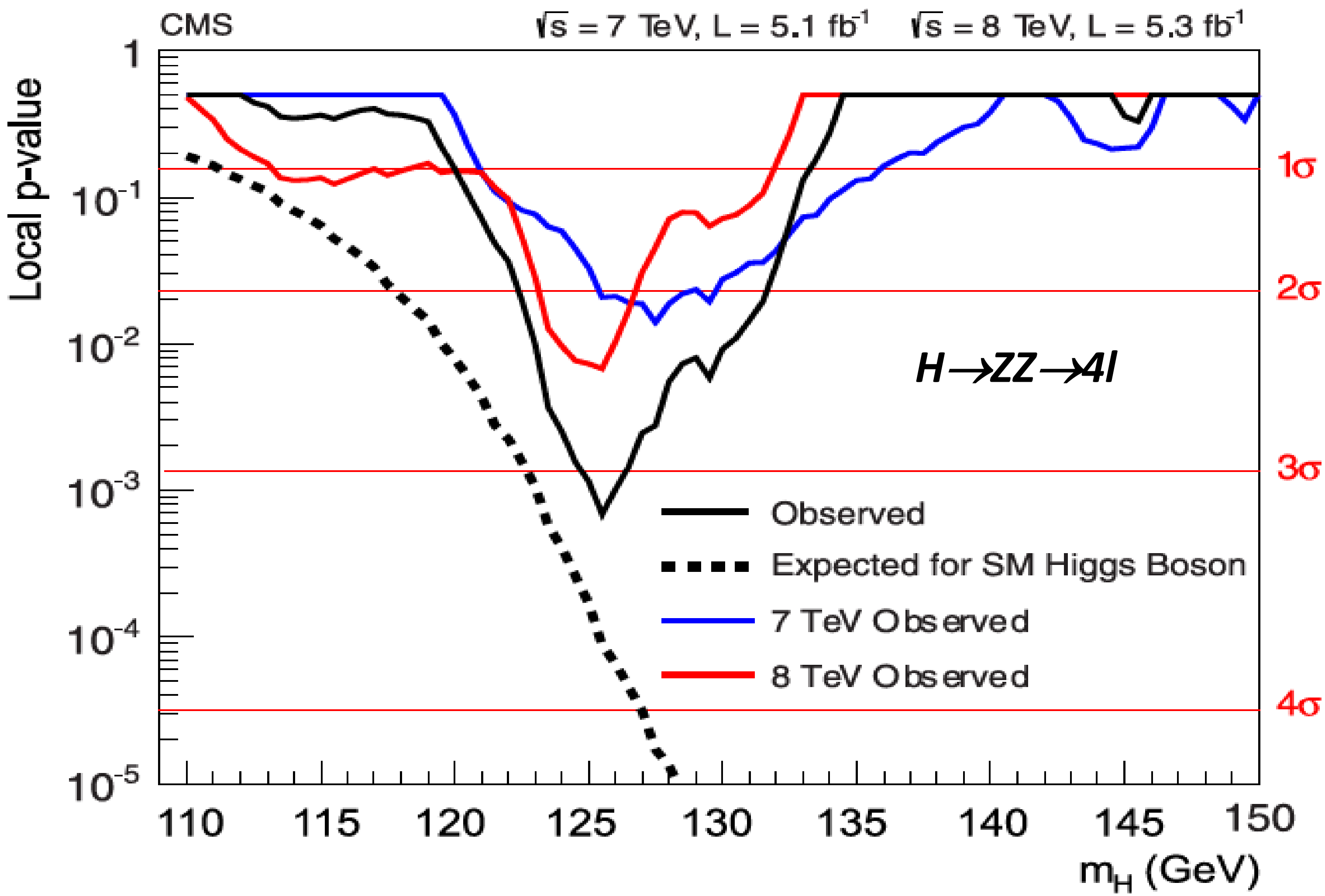
signal





background

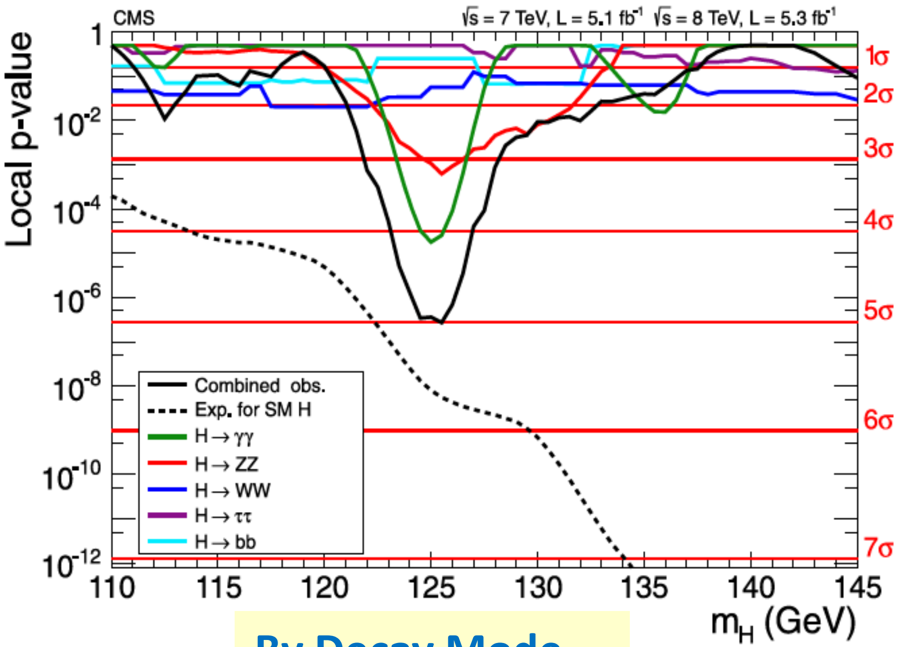




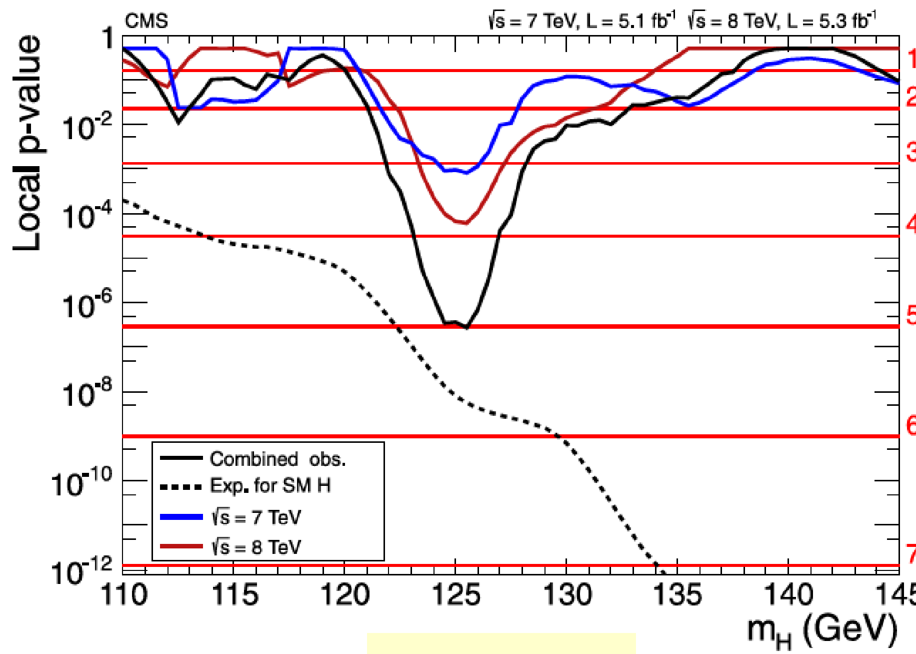
Expected significance at 125.5 GeV : 3.8 σ

Observed significance at 125.5 GeV: 3.2 σ

Characterization of excess near 125 GeV



By Decay Mode



By Data Set

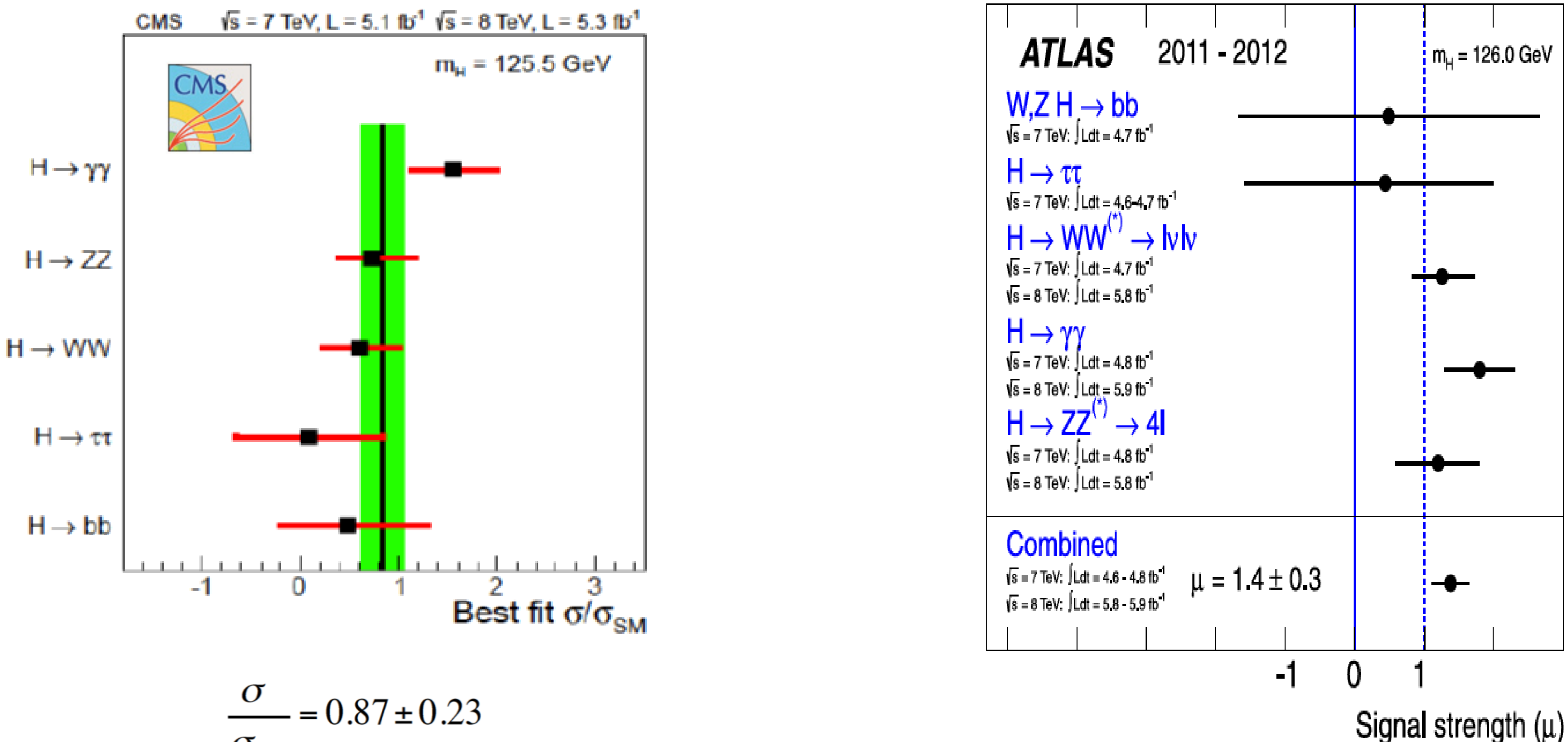
Decay mode/combination	Expected (σ)	Observed (σ)
$\gamma\gamma$	2.8	4.1
ZZ	3.8	3.2
$\tau\tau$ + bb	2.4	0.5
$\gamma\gamma$ + ZZ	4.7	5.0
$\gamma\gamma$ + ZZ + WW	5.2	5.1
$\gamma\gamma$ + ZZ + WW + $\tau\tau$ + bb	5.8	5.0

All channels

Combined Significance: 5.0 σ

Expected Significance for SM Higgs: 5.8 σ

Signal Strength in different channels



$$\frac{\sigma}{\sigma_{SM}} = 0.87 \pm 0.23$$

Spin 1 ruled out by 2γ

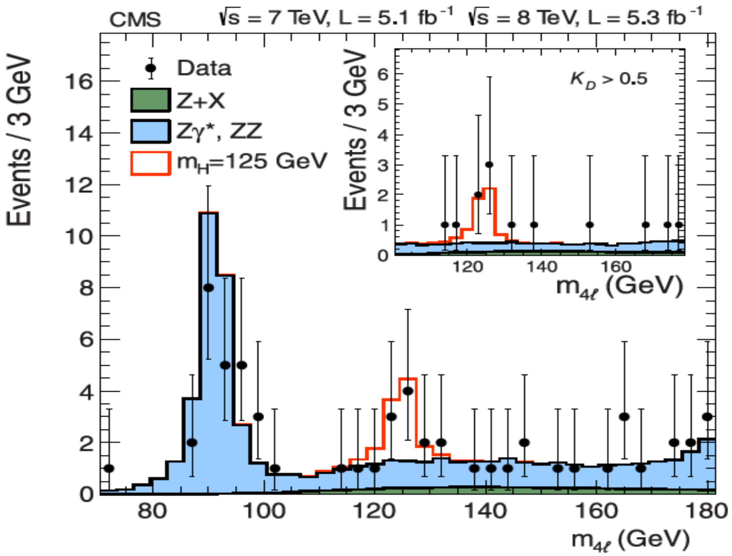
More data in ZZ crucial to understand spin parity

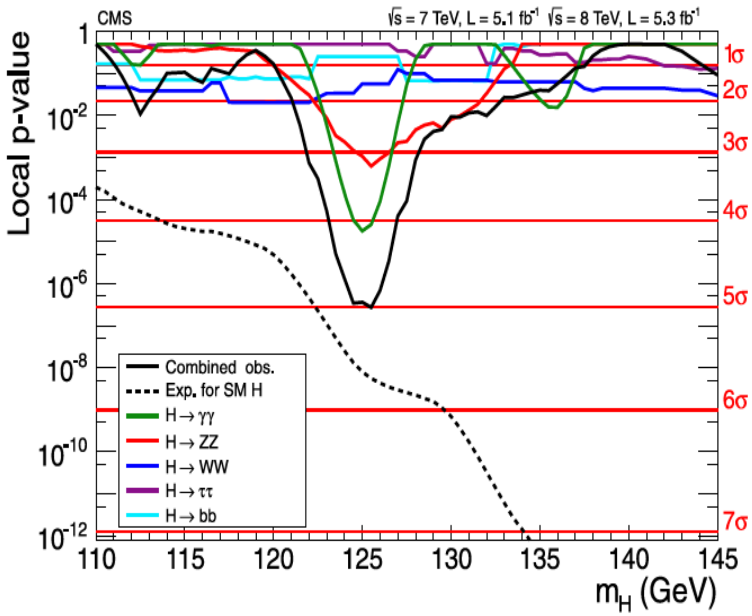
The new character almost talks like Higgs and walks like Higgs ....

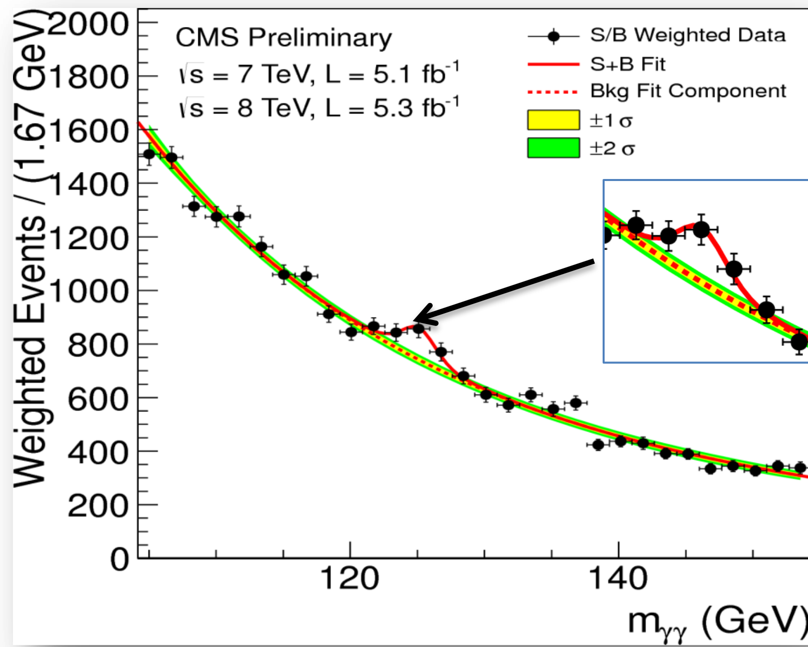
Summary as on July 4, 2012

CMS summary

Phys Lett B 716 (2012) 30-61



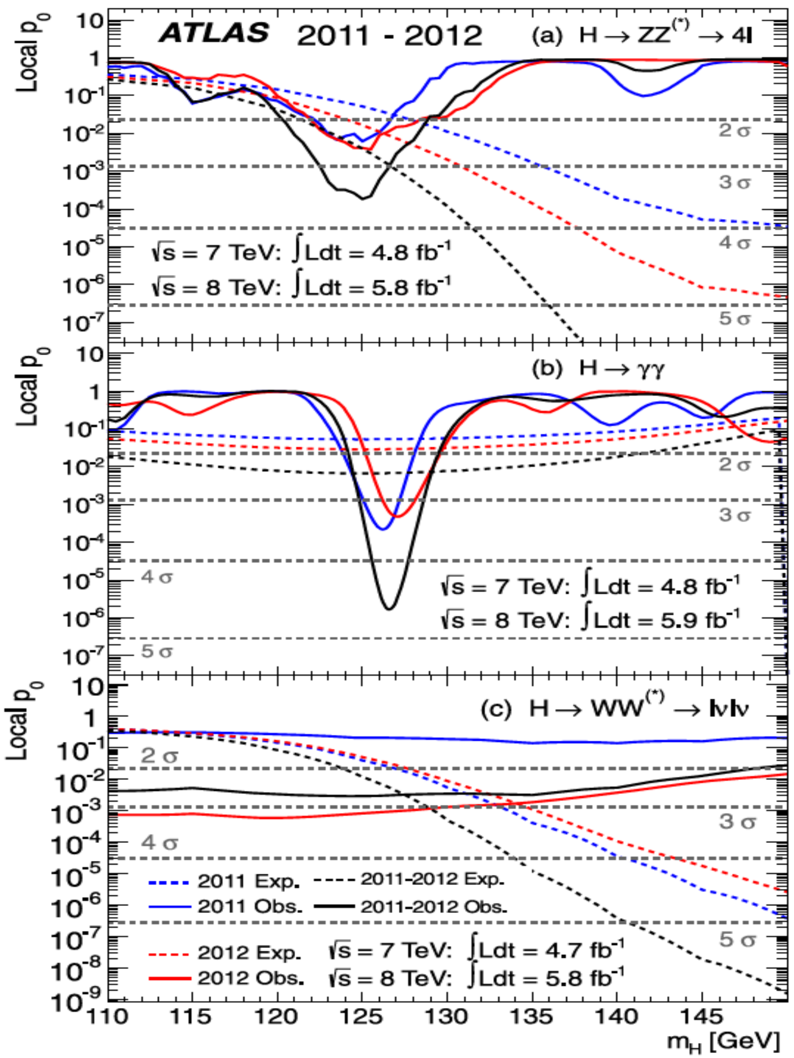


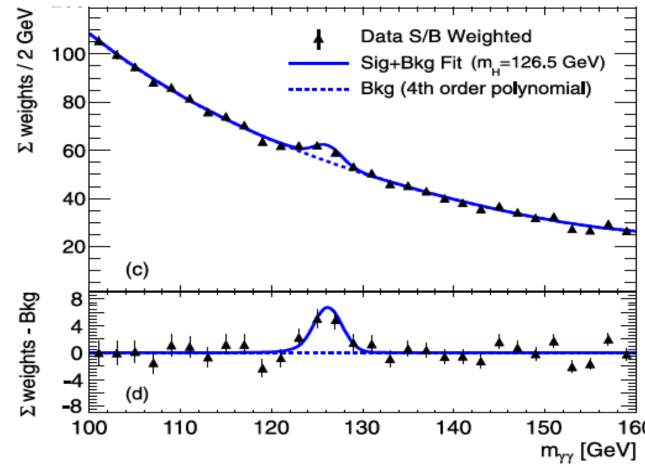


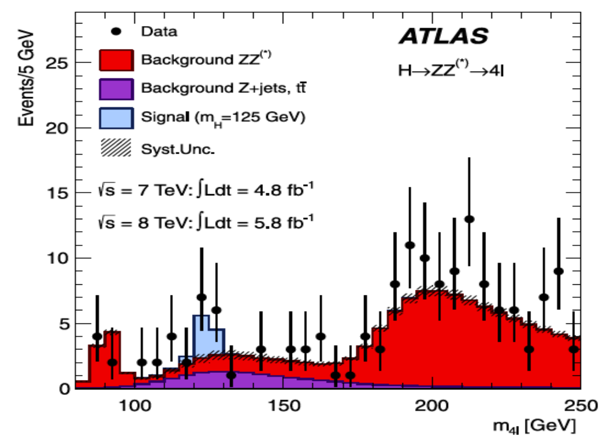
The CMS experiment has observed a new particle with a mass 125.3 ± 0.4 ± 0.5GeV at 5.0σ significance, consistent with Higgs boson

ATLAS Summary

Phys Lett B 716 (2012) 1-29







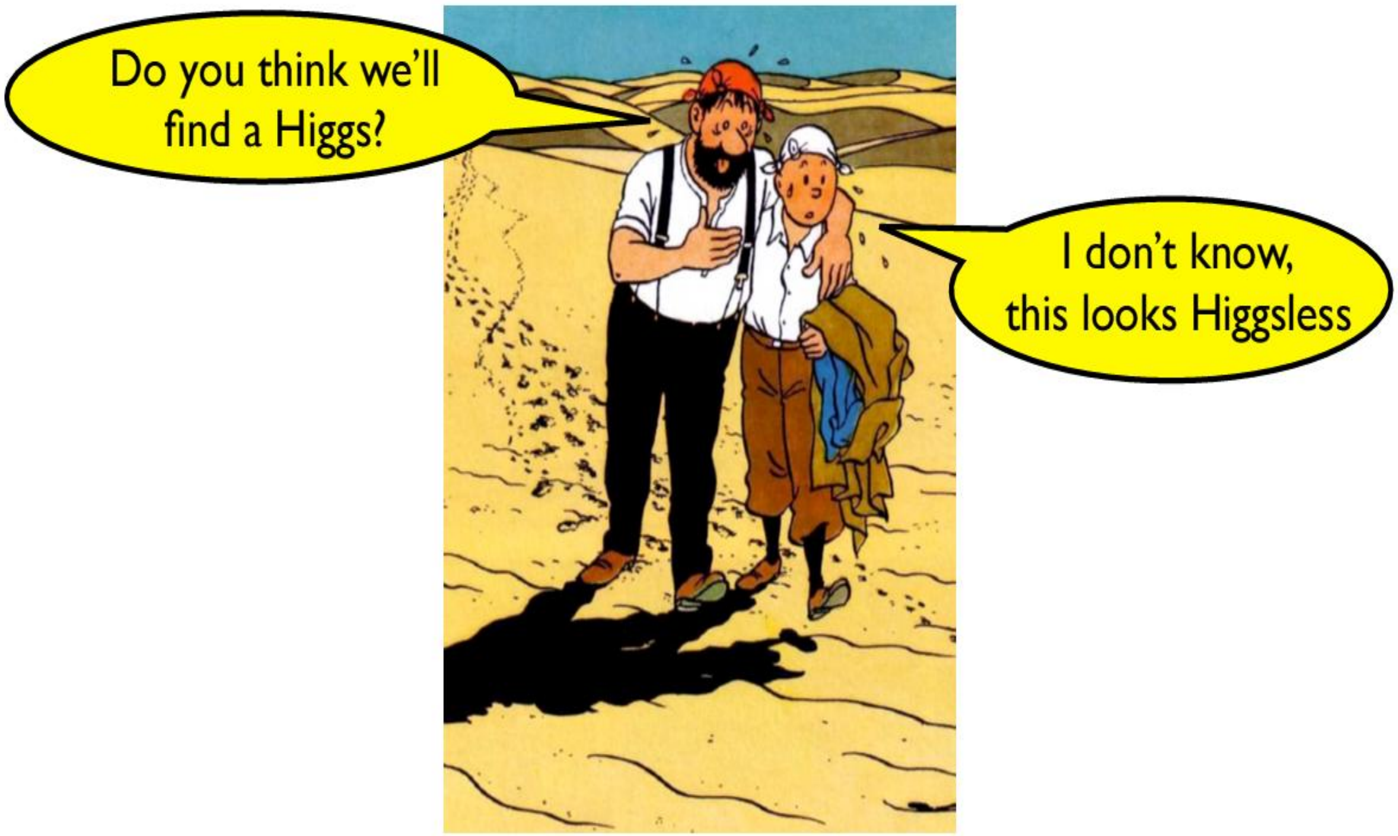
The ATLAS experiment has observed a new particle with a mass 126.0 ± 0.4 ± 0.4GeV at 5.9σ significance, consistent with Higgs boson

Results made public on July 4, 2012 in CERN Seminar and watched worldwide

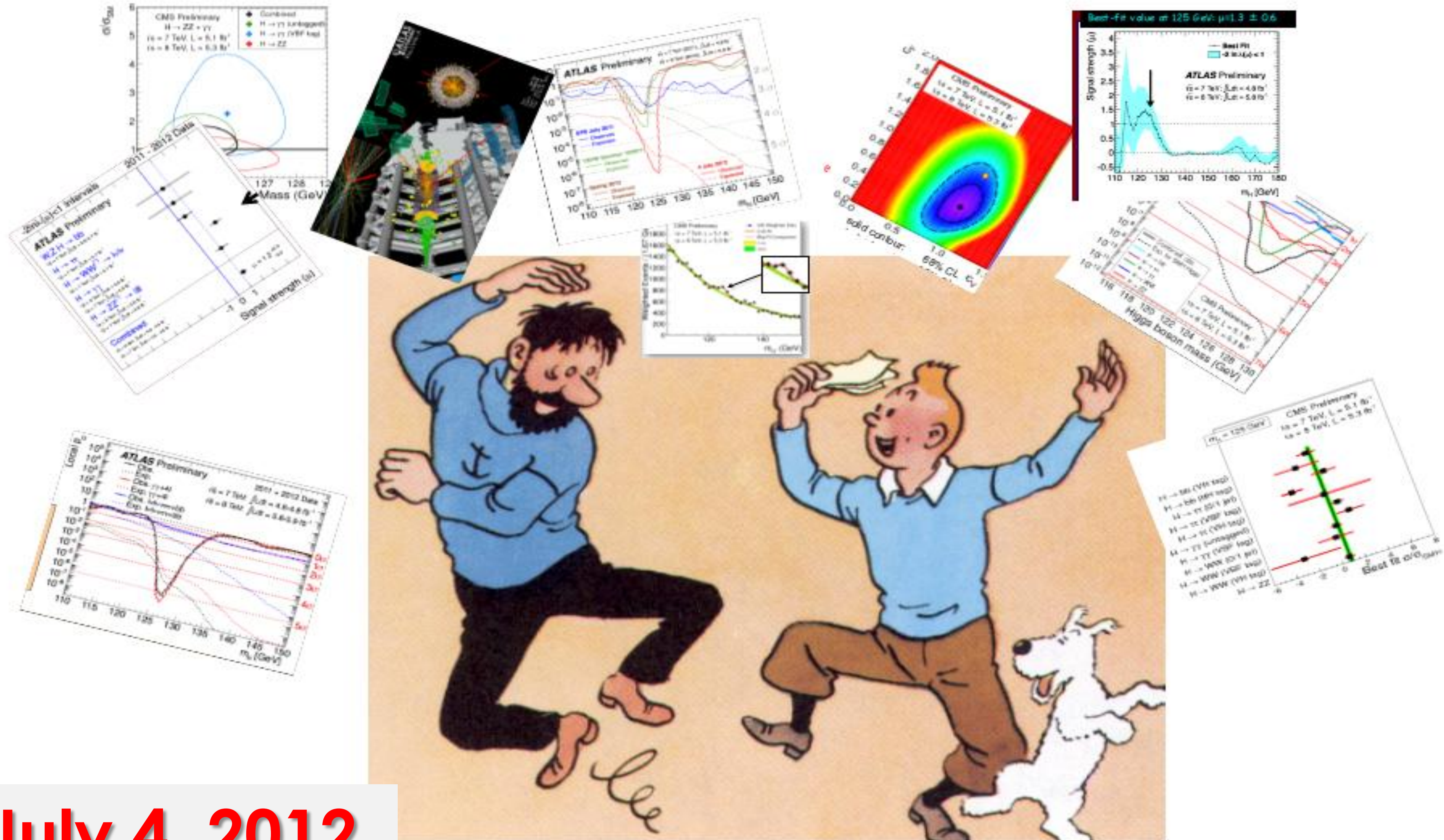
July 3, 2012

Very tiring day for the Higgs Hunters

We have been wandering in the desert for more than 40 years …



... and finally plenty of new relevant data has begun to fall over us!

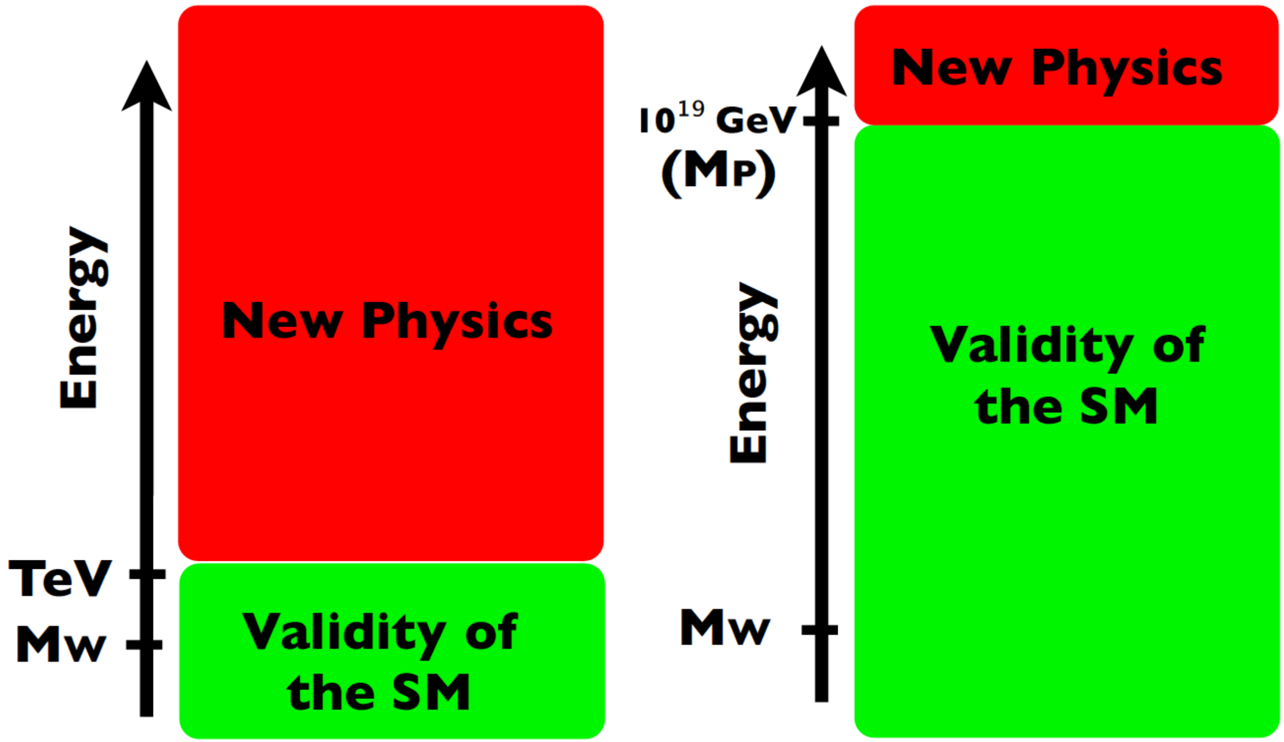


July 4, 2012

Without a Higgs

With a Higgs

(100 GeV $< m_h < 170$ GeV)



"Sit down before fact as a little child,
be prepared to give up every preconceived notion,
follow humbly wherever and to whatever abysses nature leads,
or you shall learn nothing"

Thomas Henry Huxley

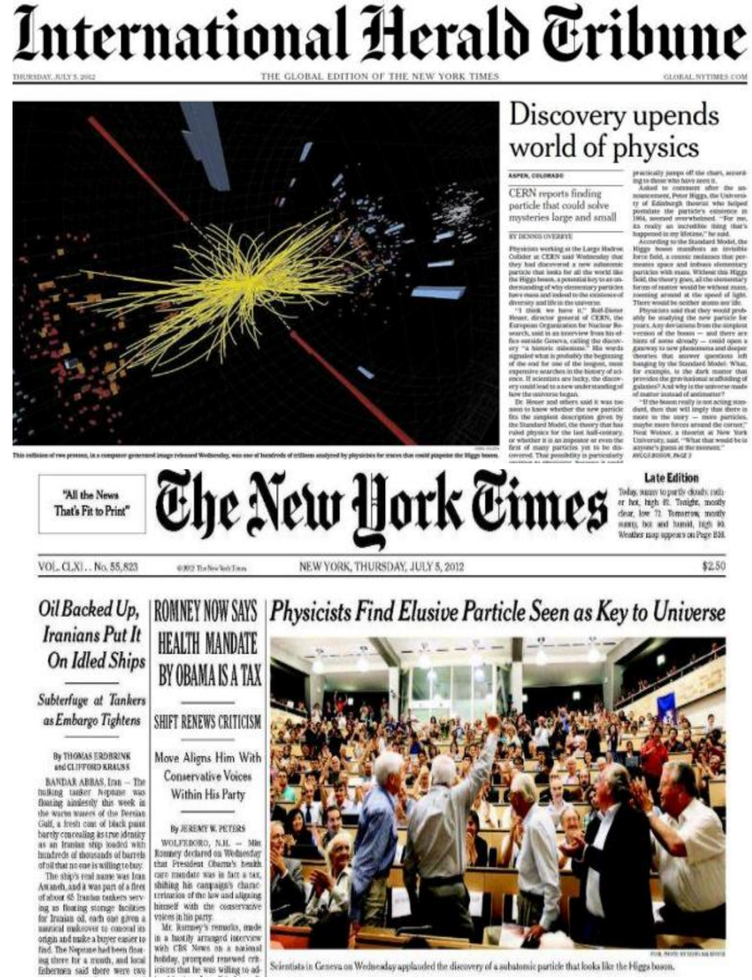
The Economist

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



International Herald Tribune

THE GLOBAL EDITION OF THE NEW YORK TIMES

Discovery upends world of physics

CERN reports finding particle that could solve mysteries large and small

"All the News That's Fit to Print"

The New York Times

Late Edition

VOL. CLXI . . No. 55,823 NEW YORK, THURSDAY, JULY 5, 2012 $2.50

Oil Backed Up, Iranians Put It On Idled Ships

Subterfuge at Tankers as Embargo Tightens

ROMNEY NOW SAYS HEALTH MANDATE BY OBAMA IS A TAX

SHIFT RENEWS CRITICISM

Move Aligns Him With Conservative Voices Within His Party

Physicists Find Elusive Particle Seen as Key to Universe

Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson.

THURSDAY, JULY 5, 2012

THE HINDU

INDIA'S NATIONAL NEWSPAPER SINCE 1878

RARE CHOLA INSCRIPTIONS

MAY HAVE BEEN POISONED

SUBBARAO ON MFIS

RAHANE RETURNS

Elusive particle found, looks like Higgs boson

CERN physicists hail evidence of game-changing discovery of subatomic particle

THE TIMES OF INDIA

UNDER FIRE FROM OPPN, AKHILESH ROLLS BACK CAR BONANZA FOR MLAS

ADJUSTING DIESEL PRICE BETTER THAN TAXING CARS, SAYS MONTEK

BLADE RUNNER PISTORIUS SET FOR OLYMPIC HISTORY: TO RUN 400M & RELAY

NEWS DIGEST

Big bang moment: Scientists may have found 'God particle'

Adarsh scam: Finally, CBI chargesheets 13

July 4, 2012

Two major experiments - CMS and ATLAS have seen Higgs boson-like excess at ~ 125 GeV at the level of 5 σ significance

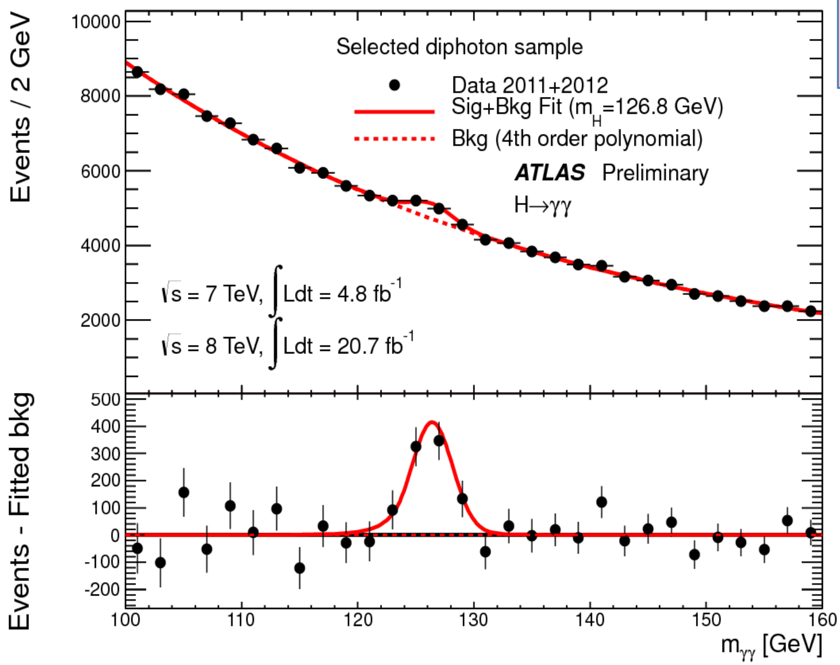
This indeed is a historic moment !

This excess has to be examined in all possible channels and in all possible ways to understand the nature of this excess ----

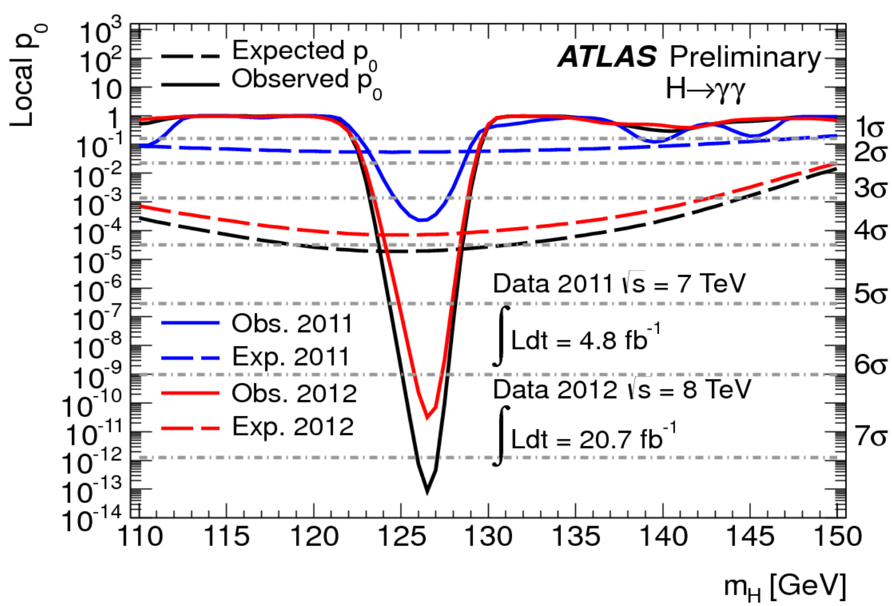
8 TeV data has increased from ~5 fb^{-1} to ~ 20 fb^{-1}

With more luminosity at 8 TeV, are we better in signal significance?

Full data set - ATLAS update- $\gamma\gamma$ channel



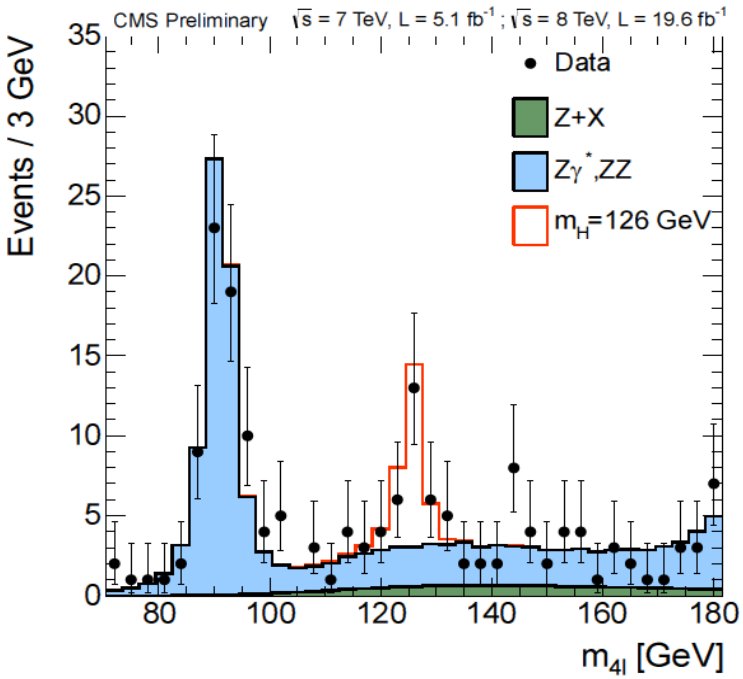
ATLAS: Simple signature: two high-p_T isolated photons - E_T (γ_1, γ_2) > 40, 30 GeV (√s=8 TeV)
Events divided into 14 categories based on production mode and S/B ratio in different detector region (increase sensitivity, also for coupling measurements)

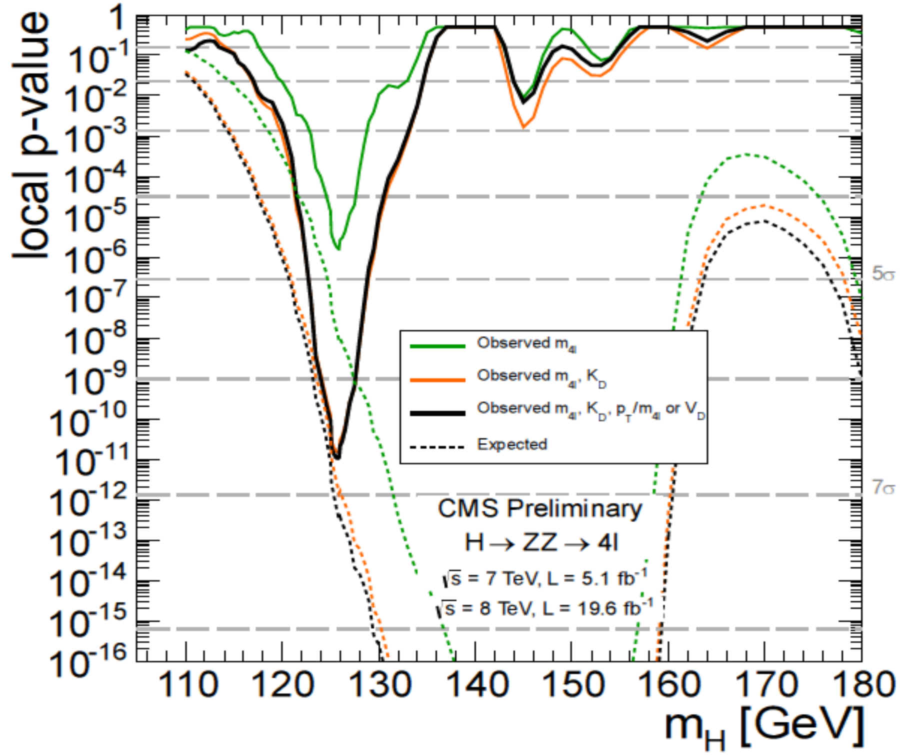


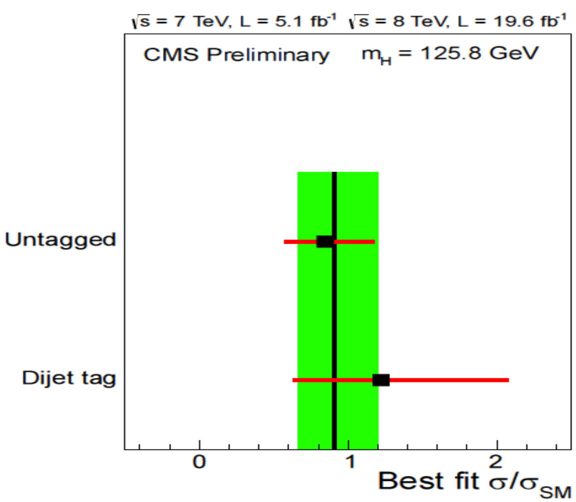
Signal Significance :
7.4σ (4.3σ expected)

Signal strength
μ = 1.57±0.24(stat) ±0.22(syst)
at mass = 126.8 GeV

Full data set - CMS Update - 4-lepton channel

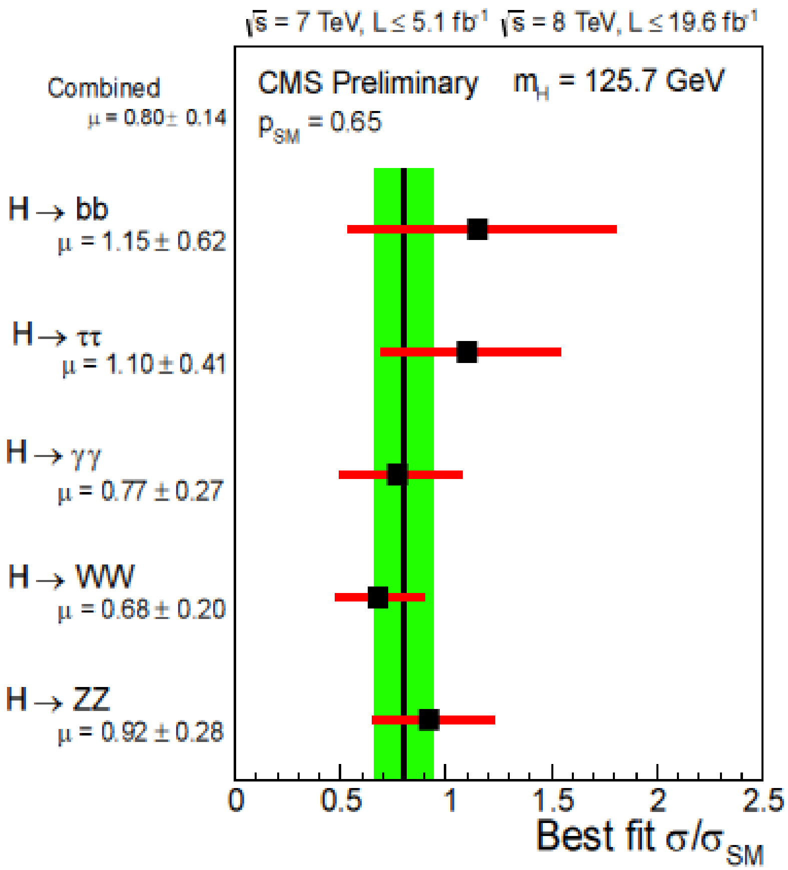


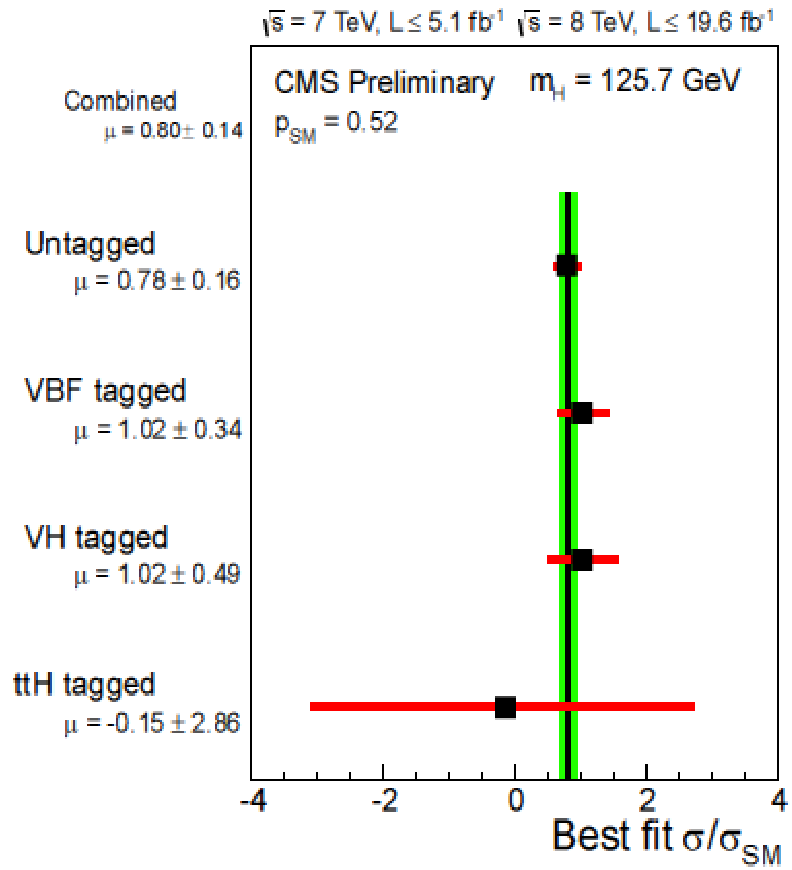




Excess of events at 125.8 GeV
Expected significance: 7.2σ
Observed Significance: 6.7σ

$$\sigma/\sigma_{SM} = 0.91^{+0.30}_{-0.24}$$





All consistent with the standard model

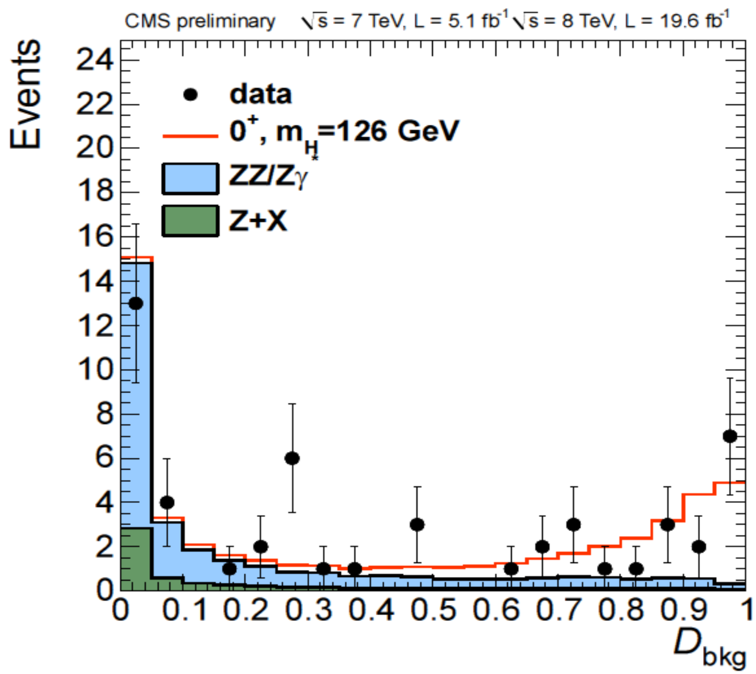
What about Spin and Parity

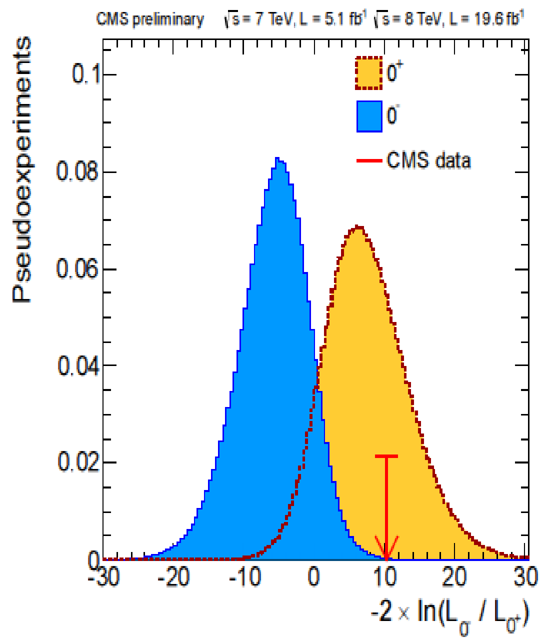
Spin and Parity can be probed using angular distributions

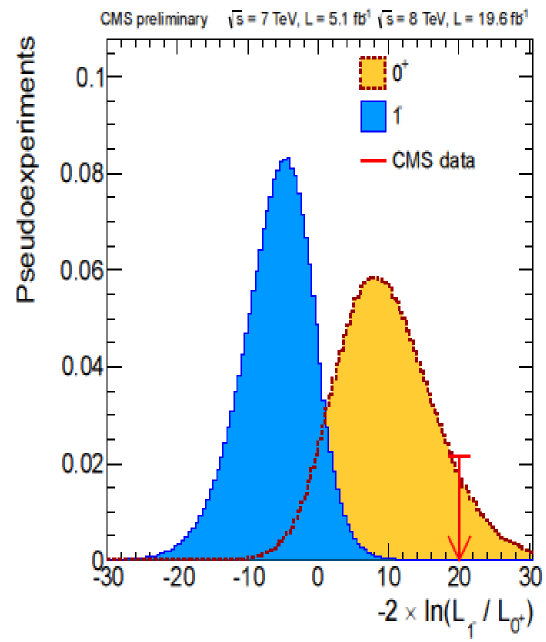
$H \rightarrow ZZ \rightarrow 4l$ is the best channel as all angles are measured

CMS Spin-parity analysis

Many ways to analyze

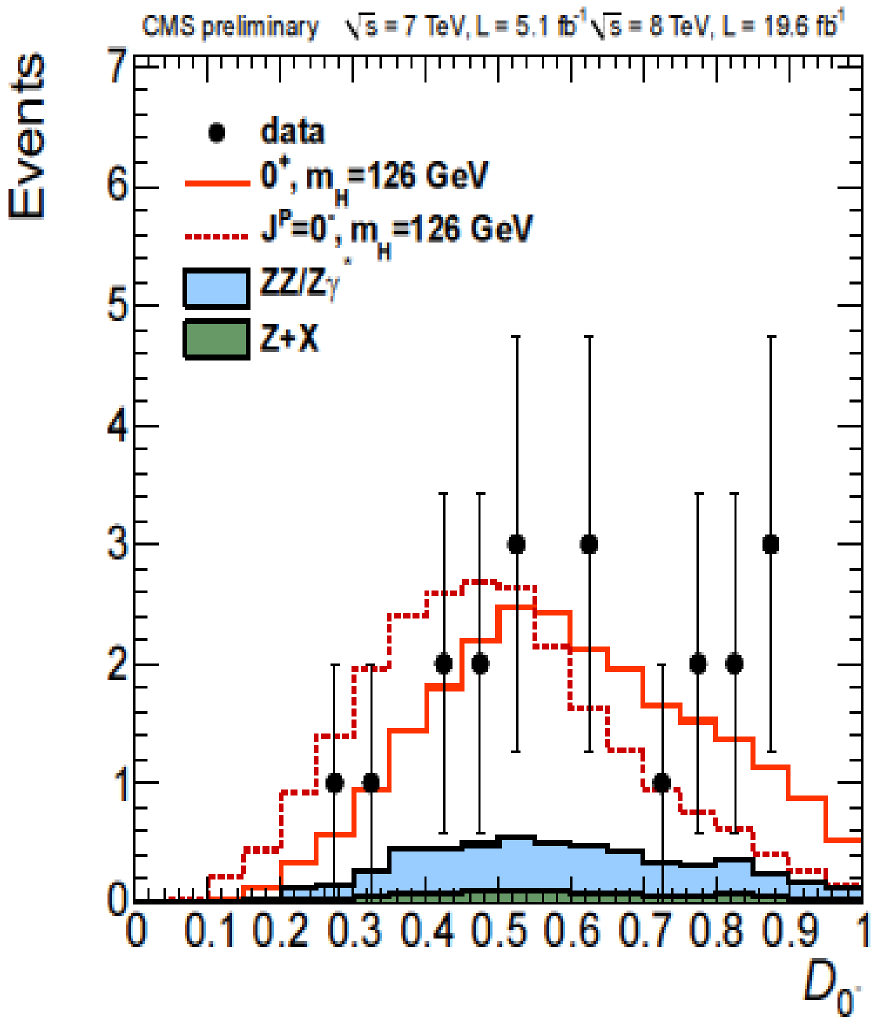


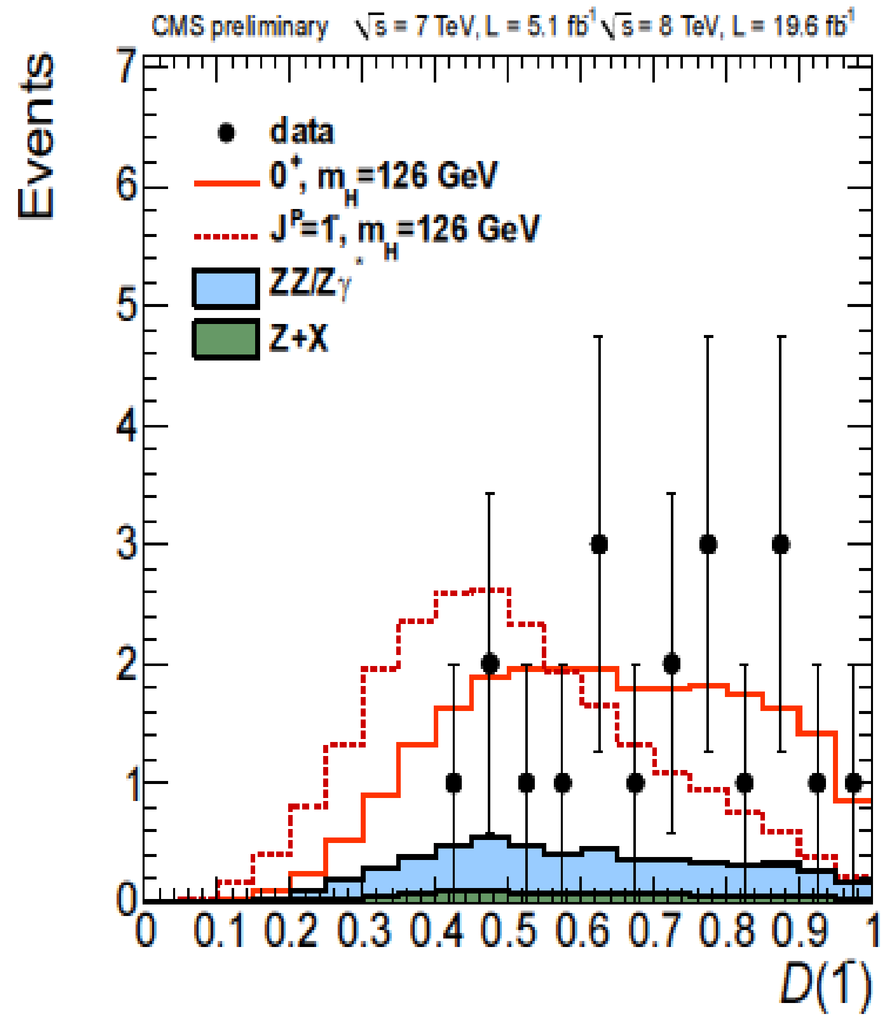




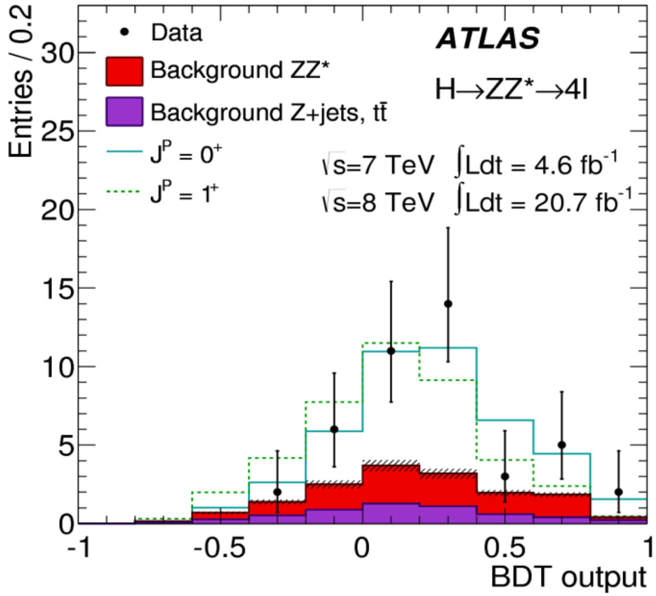
$$\mathcal{D}_{\rm bkg} = \mathcal{P}_{\rm sig}/(\mathcal{P}_{\rm sig} + \mathcal{P}_{\rm bkg})$$

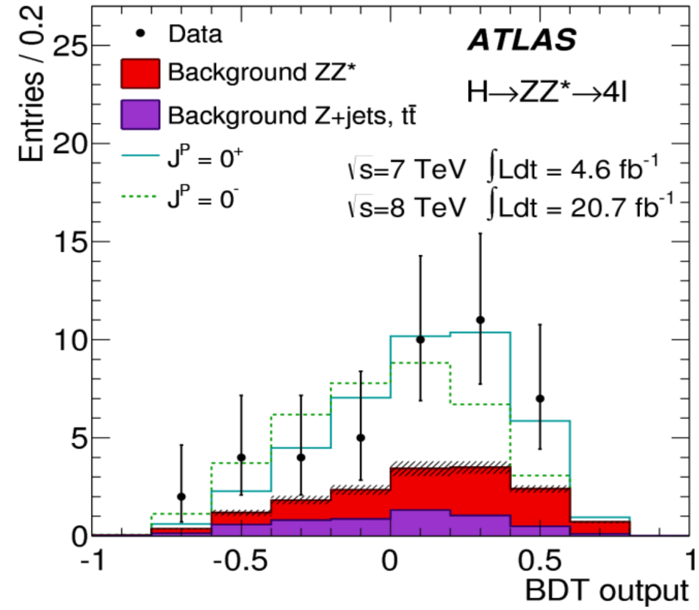
Discriminate between SM and non-SM amplitudes with detailed inputs in KD and m4l


CMS preliminary √s = 7 TeV, L = 5.1 fb⁻¹ √s = 8 TeV, L = 19.6 fb⁻¹
Events
data
0⁺, m_H=126 GeV
J^P=0⁻, m_H=126 GeV
ZZ/Zγ*
Z+X
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
D_0⁻

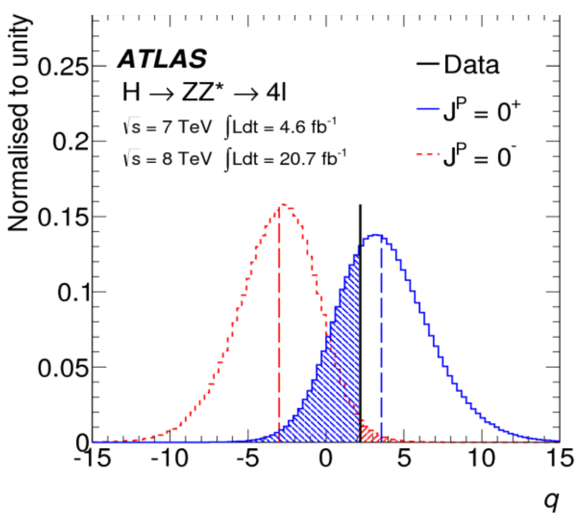

CMS preliminary √s = 7 TeV, L = 5.1 fb⁻¹ √s = 8 TeV, L = 19.6 fb⁻¹
Events
data
0⁺, m_H=126 GeV
J^P=1⁻, m_H=126 GeV
ZZ/Zγ*
Z+X
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
D(1⁻)

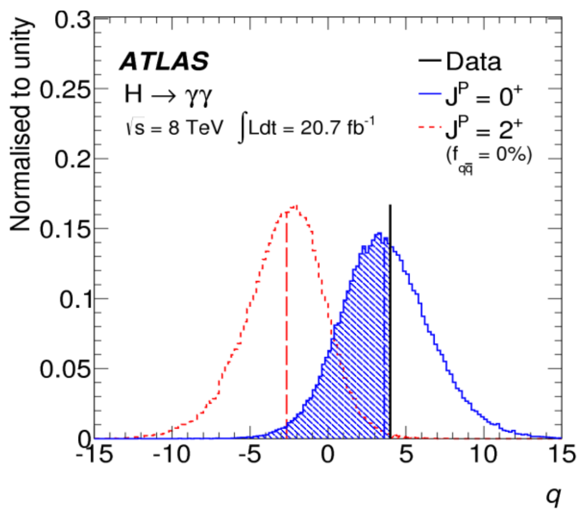
ATLAS spin-parity analysis





$$q = -2 \ln \frac{\mathcal{L}(\text{pseudoexperiment} \mid J^{CP} + \text{bkg})}{\mathcal{L}(\text{pseudoexperiment} \mid H_{SM} + \text{bkg})}.$$





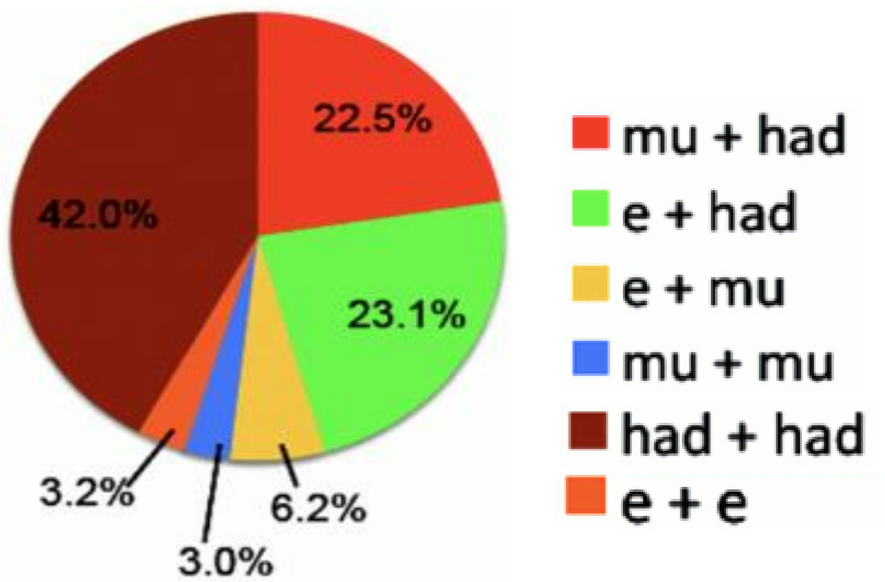
Observed 0^- exclusion 97.8%

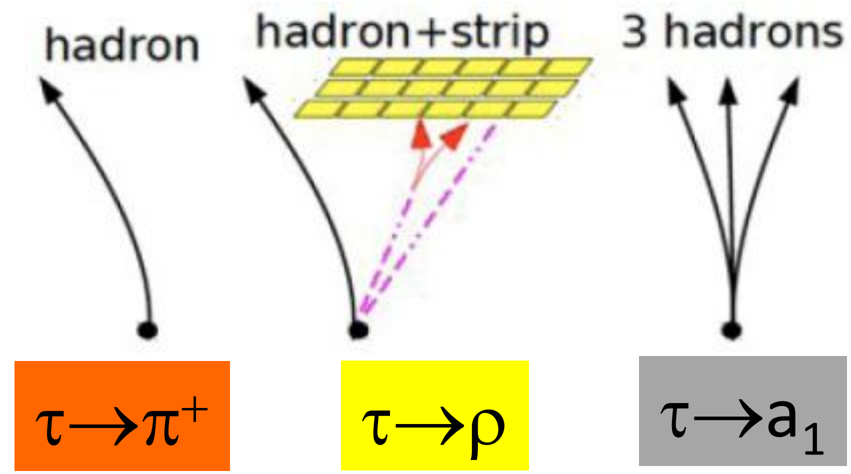
Observed 1^+ exclusion 99.8%

0^+ favored

Does Higgs couple to down type fermions?

Study of Higgs decays to $\tau\tau$





and the missing neutrino's

$$H \to \tau\tau \to \ell\ell + 4\nu \ (12\%)$$
$$H \to \tau\tau \to \ell\tau_h + 3\nu \ (46\%)$$
$$H \to \tau\tau \to \tau_h\tau_h + 2\nu \ (42\%)$$

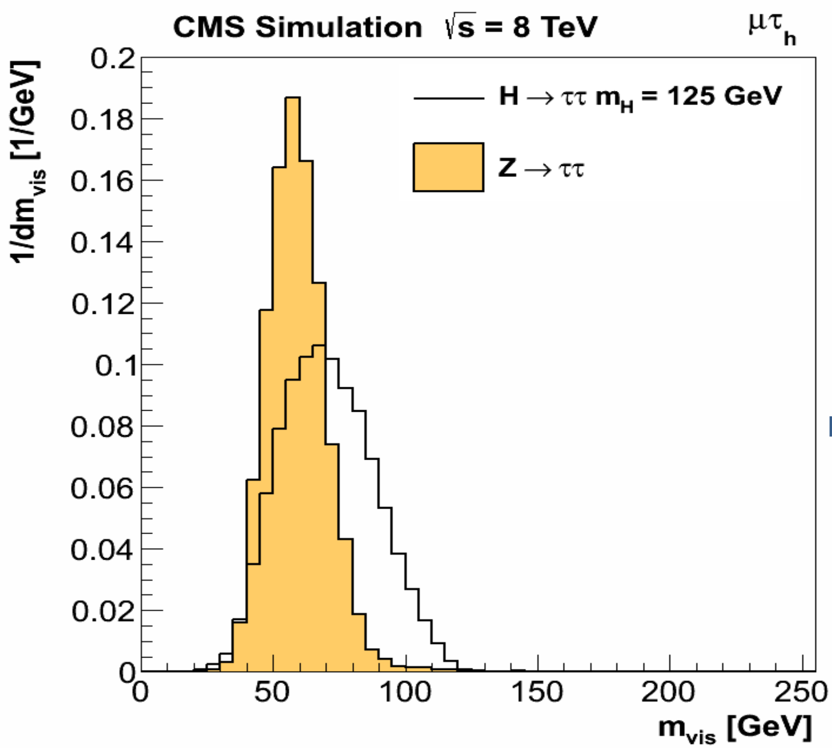
Relatively difficult channel   to get good mass resolution

$H \to \tau\tau$ mass reconstruction

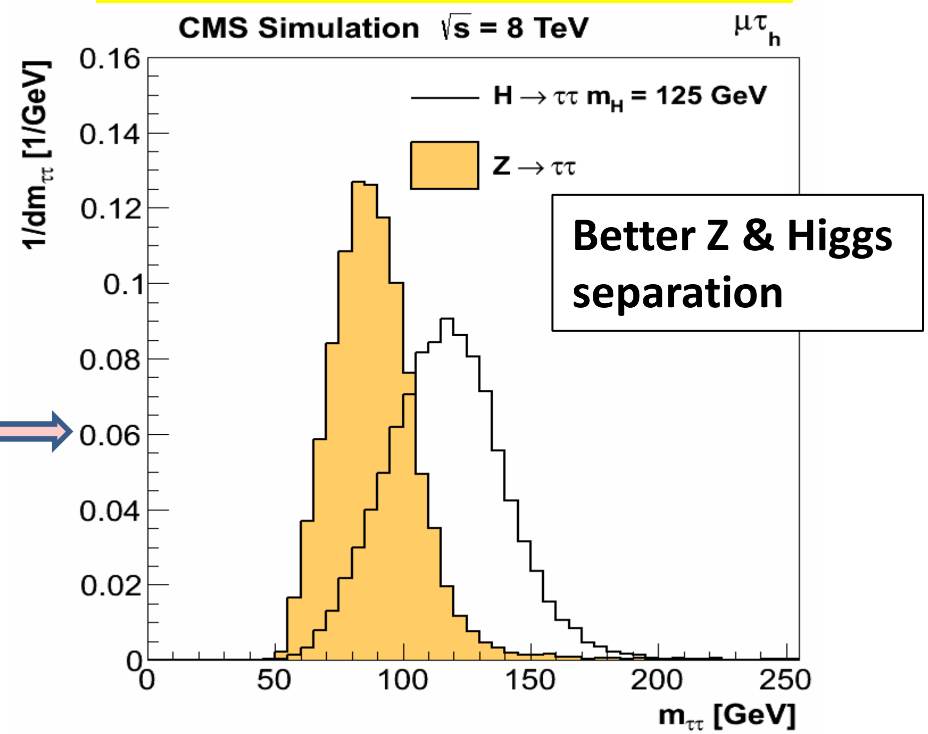
Di-tau mass estimation uses visible decay products & missing E_T in a maximum likelihood fit

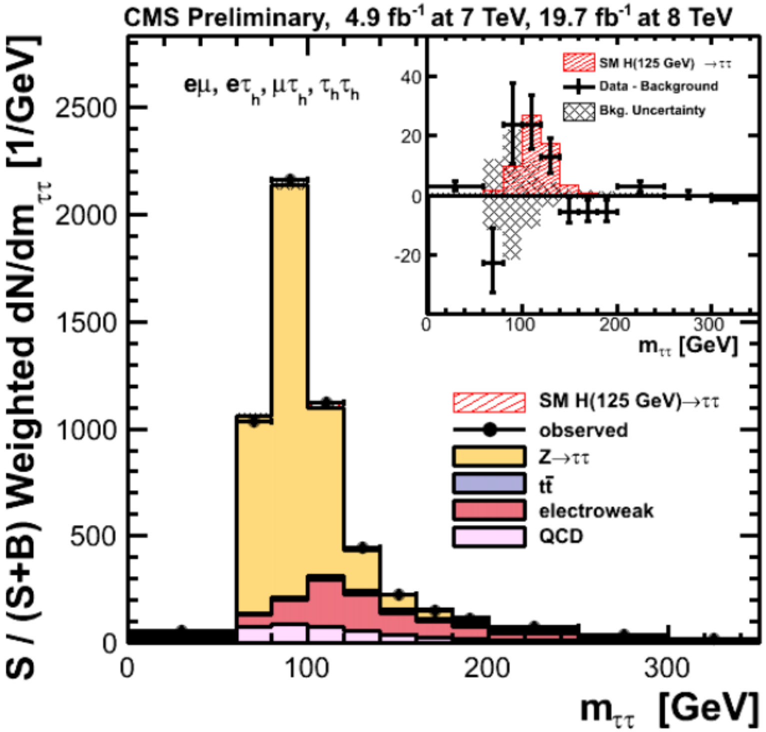
The mass resolution is ~ 10-20% depending on channel/category

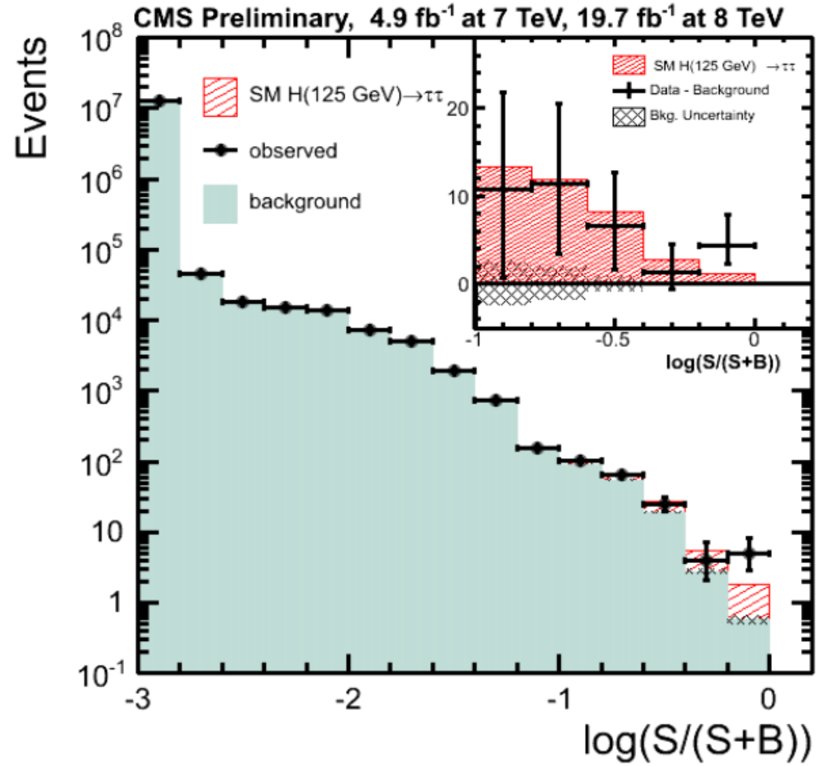
Visible mass



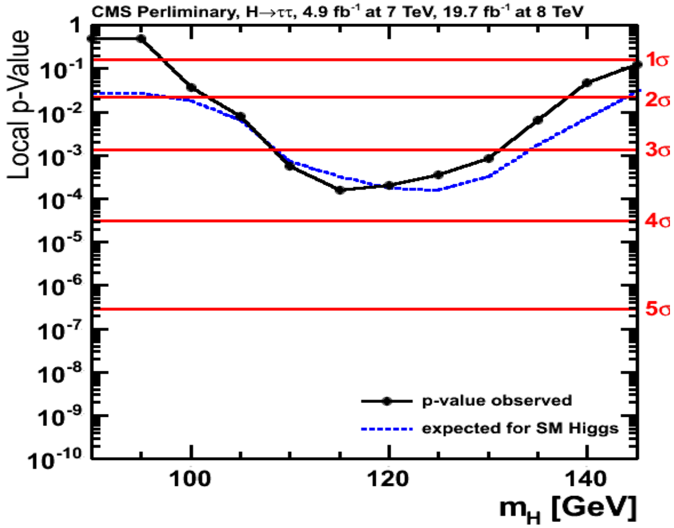
Full reconstructed mass







Clear excess

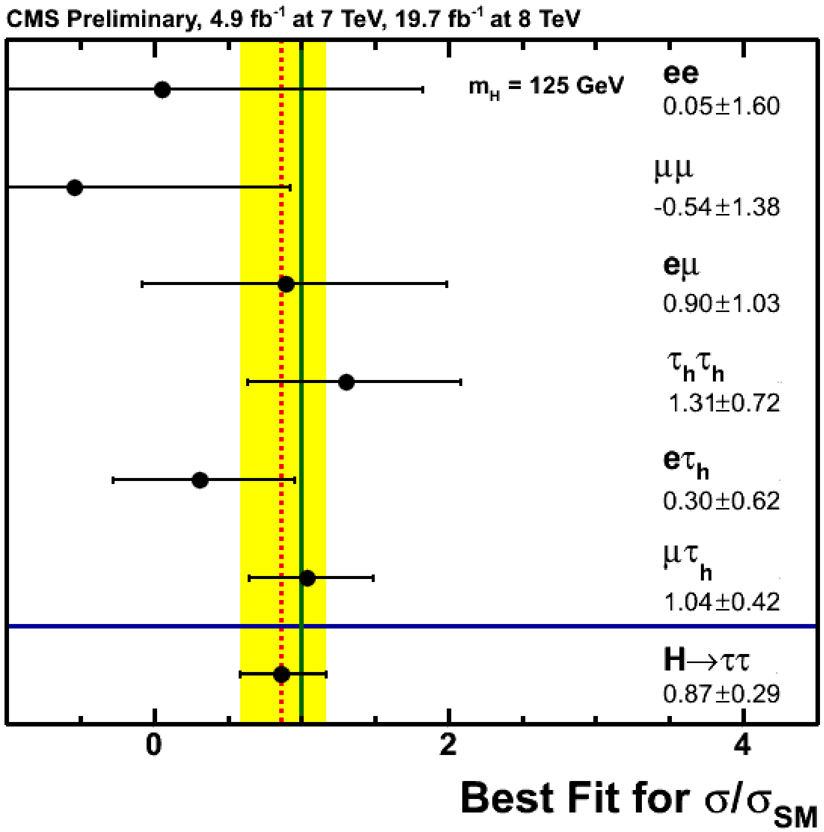


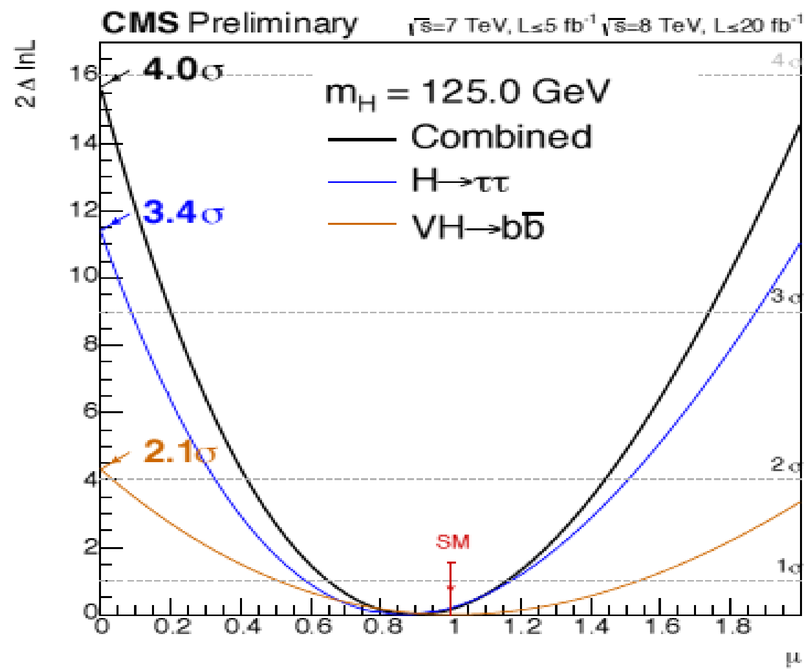
>3σ for M_H between 110 and 130 GeV

At m_H = 125 GeV:

3.4σ observed excess!

3.6σ expected



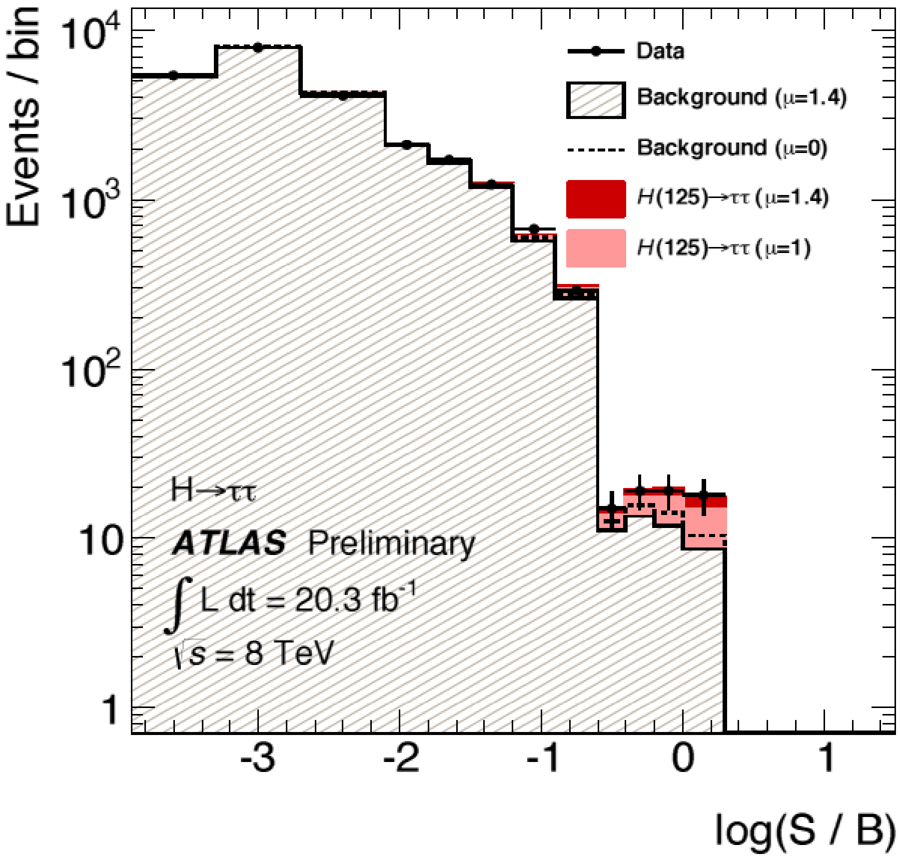


$\mu = \sigma/\sigma_{SM} = 0.87 \pm 0.29$

Channel M_H= 125 GeV	Significance		μ
	Expected	Observed	
VH→bb	2.1 σ	2.1σ	1.0±0.5
H→ττ	3.6σ	3.4σ	0.87±0.29
Combination	4.2σ	4.0σ	0.90±0.26

4.0 σ: strong evidence of fermionic Higgs decays!

ATLAS Study for H→ττ



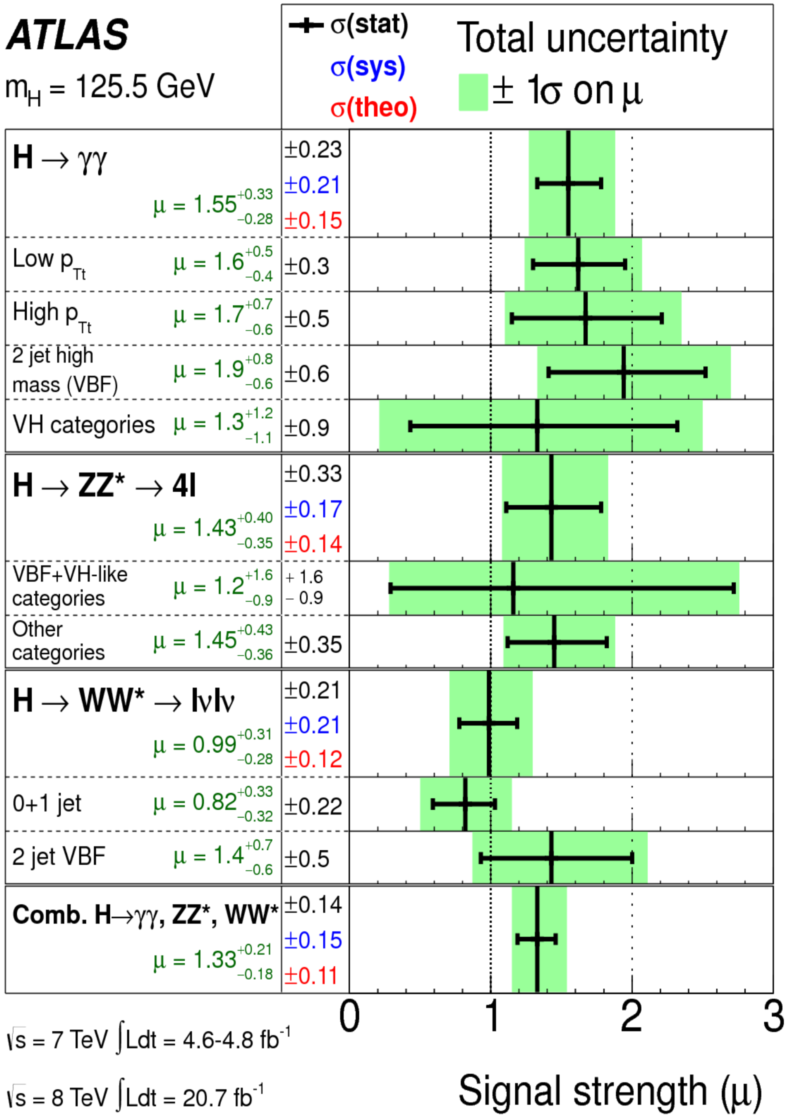
Numbers of events in highest BDT-score bin

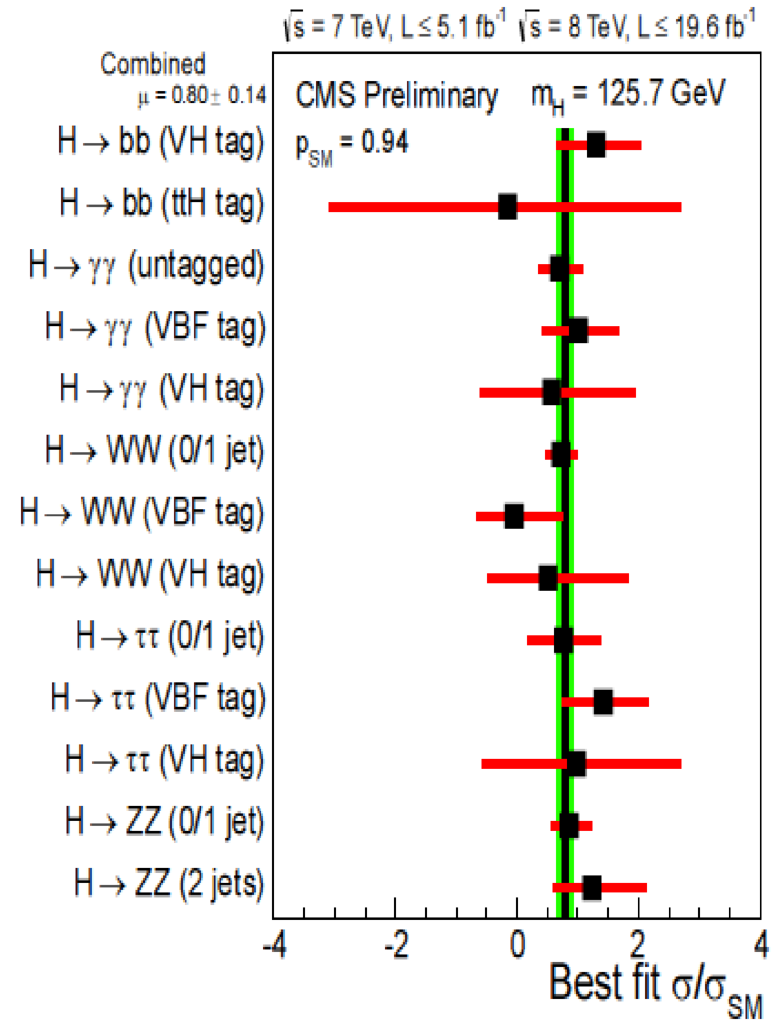
		Lep-lep	Lep-had	Had-had
VBF	Signal	5.7±1.7	8.7±2.5	8.8±2.2
	Bckg	13.5±2.4	8.7±2.4	11.8±2.6
	Data	**19**	**18**	**19**
Boosted	Signal	2.6±0.8	8.0±2.5	3.6±1.1
	Bckg	20.2±1.8	32±4	11.2±1.9
	Data	20	34	15

ATLAS observes significant excess of data events in high S/B region

- Excess is observed in all three channels
- **Expected** significance at M_H=125 GeV corresponds to **3.2 sigma**
- **Observed** significance at M_H=125 GeV corresponds to **4.1 sigma**

Where do we stand today?





The fitted μ (including bb and ττ) at 125.7 GeV is:

– $\sigma/\sigma_{SM} = 0.80 \pm 0.14$

Signal strength consistent with SM

It is safe to say that we have observed Standard Model Higgs boson at LHC

Nobel 2013

Clear Signal for Higgs boson in several channels of Higgs decay to $\gamma\gamma$, ZZ, WW well above 5σ each

Higgs decays to $\tau\tau$ and bb with significant evidence

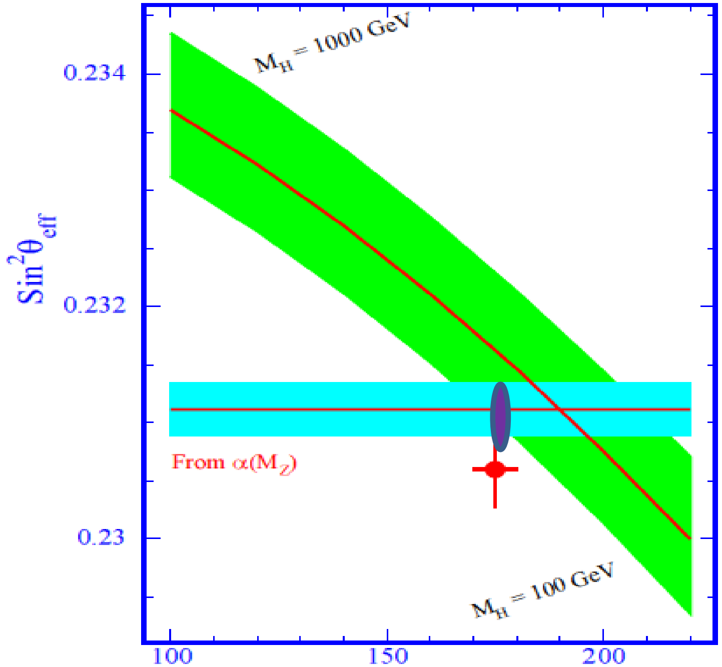
Rates all consistent with Standard Model

Spin-Parity assignment 0^{+} strongly favored- SM Higgs

This is the first fundamental scalar in the history of particle physics!

Could this be the last?

Observation in 1997



Modern Physics Letters A, Vol. 12, No. 33 (1997) 2535–2541

ASYMMETRY MEASUREMENTS AT LEP/SLC REVISITED

TARIQ AZIZ*
Tata Institute of Fundamental Research, Bombay 400005, India

Received 4 September 1997

More recent numbers

$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ of 0.23113 ± 0.00021

M_t = 173.20 ± 0.87 GeV/c^2

[a]The relationship between M_Z and $\sin^2\theta_{\mathrm{eff}}$ is given as[4]:

$$M_Z^2 \cos^2\theta_{\mathrm{eff}} \sin^2\theta_{\mathrm{eff}} = \frac{\pi}{\sqrt{2}G_F}\frac{\alpha}{1-\Delta r_{\mathrm{eff}}} = \frac{\pi\alpha_{\mathrm{eff}}(M_Z)}{\sqrt{2}G_F},$$

where

$$\Delta r_{\mathrm{eff}} = \Delta\alpha + \Delta r_W .$$

Here $\Delta\alpha$ represents the effect due to running of QED coupling, α, in going from low energy to Z mass scale and Δr_W is the effective weak radiative correction mainly due to top and Higgs in the Z propagator and some other nonleading effects. From now on if the mass scale is not specified, α refers to $\alpha(m_e)$. The best estimate of α at Z mass scale is $\alpha(M_Z) = 1/(128.896 \pm 0.090)$.[5]

In this letter $\sin^2\theta_{\mathrm{eff}}$ always corresponds to $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lepton}}$ even when extracted using quark asymmetries.

Finally we would like to add that taking all the electroweak measurements together, including W boson mass, we see a converging trend of all the measurements such that $\sin^2\theta_{\text{eff}}$ remains close to $\simeq 0.2311$, within the overlapping band shown in Fig. 3. In the coming years when SLD improves its $\sin^2\theta_{\text{eff}}$ measurements significantly and LEP and Tevatron have improved the W mass measurements further, this will become clear. However from Fig. 3, one finds that the effects of weak radiative corrections in $\sin^2\theta_{\text{eff}}$ are least visible for such a situation. In fact we end up with a twofold ambiguity because such a value of $\sin^2\theta_{\text{eff}}$ can also be obtained by simply running α_{QED} up to Z mass scale as shown by the overlapping bands. This is a puzzling situation and one may ask the question: why should nature want the weak correction around this scale to be least visible. For example, a significantly light top quark or pretty more massive than the observed would have been perfectly fine with the SM leading to significantly larger or smaller value of $\sin^2\theta_{\text{eff}}$. The proximity of the data with the zone made by overlapping bands in Fig. 3 is intriguing and deserves special attention.

The location (M_t, M_H) : (173, 126) GeV might be unique and may point to new directions in our understanding of nature

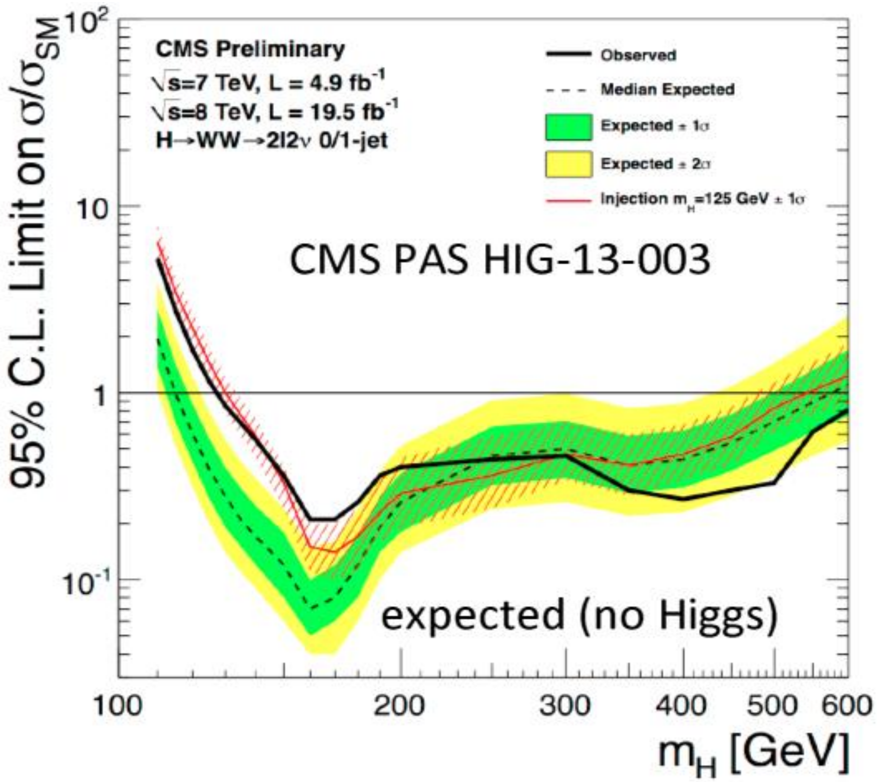
The fun is not over, it has just begun!

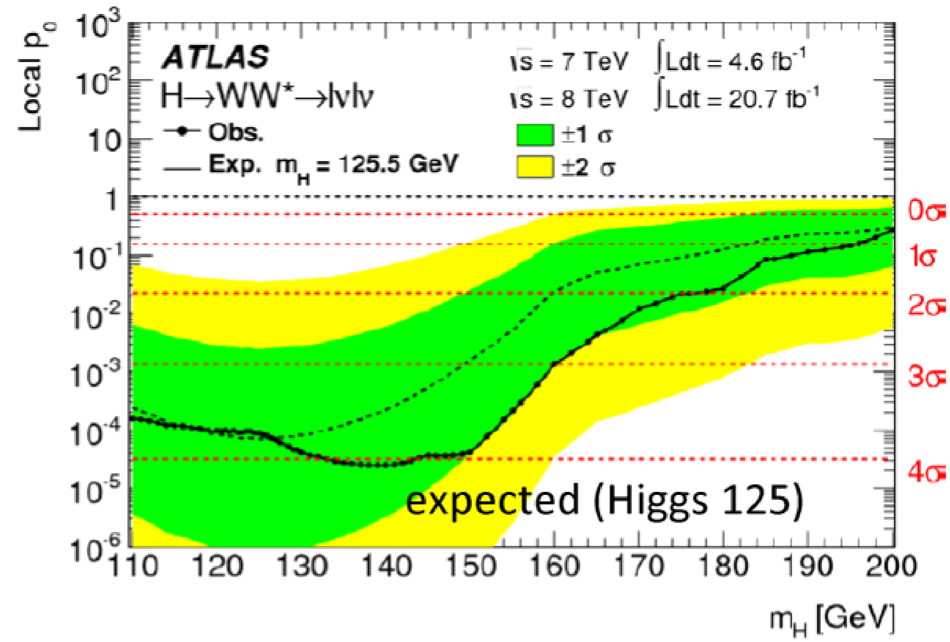
LHC @ 13 TeV may be more exciting!

Thank you

Backup Slides

Seeing signal in WW* crucial as this has large decay branching –even though poor mass resolution





CMS: Broad excess consistent with 125 GeV

- expected significance: 5.1 σ
- observed significance: 4.0 σ
- Fitted σ/σ_{SM} = 0.76 ± 0.21

ATLAS: Broad excess consistent with 125 GeV

- expected significance: 3.8 σ
- observed significance: 3.8 σ
- Fitted σ/σ_{SM} = 0.99 ± 0.30

Get the same mass range for CMS and ATLAS if possible

The "Higgs Mechanism"

F. Englert, R. Brout, PRL 13 (1964) 321; P.W. Higgs, PL 12 (1964) 132; PRL 13 (1964) 508; G. S. Guralnik, C.R. Hagan, T.W.B. Kibble, PRL 13 (1964) 585

How to give mass without breaking gauge invariance?

The answer is the Higgs mechanism, which is based on the observation that scalar mass terms are gauge invariant.

This is exploited to give mass to the gauge bosons *through the back door…*

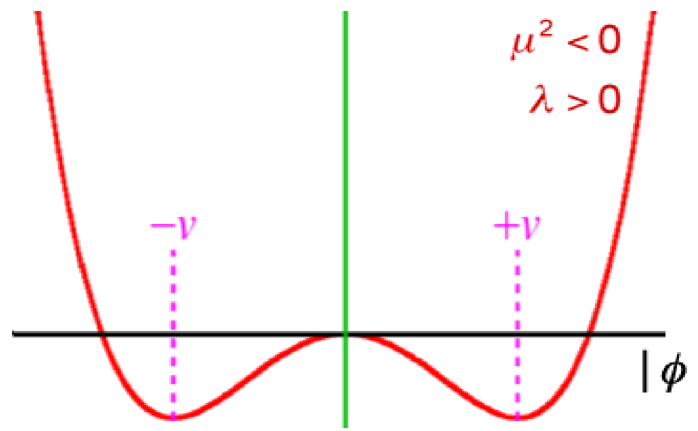
Potential $V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$, ϕ scalar field doublet

For $\mu^2 < 0$, the minimum moves away from $\phi = 0$

The ground state ($T = 0$) acquires a non-zero vacuum expectation value (vev) υ

Perturbation theory around ground state: $\phi \propto \upsilon + H$

H is the Higgs boson. The other 3 components of the doublet ϕ are absorbed to give mass to $W^\pm$ and Z



$$\upsilon_{T=0} = |\phi_{\min}| = \sqrt{-\frac{\mu^2}{2\lambda}} = 246 \text{ GeV}$$

υ precisely known from muon decay

Let's imagine all particles have zero mass → gauge symmetry is respected

A **Higgs field fills all space time** (but w/o orientation as spin=0)

The particles interact with the Higgs field thus reducing their velocity, **which is equivalent to acquiring a mass**

The action of the Higgs field creates a *vacuum viscosity*

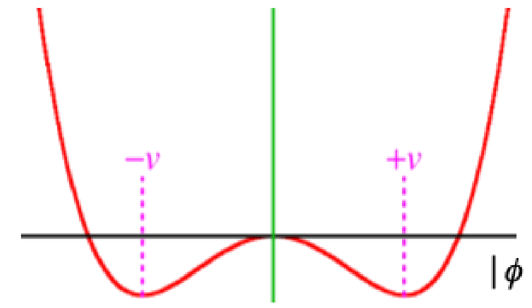
Weak interaction becomes short-ranged

During the history of the big bang, the Higgs field must have appeared during a phase transition (the fermions and bosons were massless in the early unbroken phase of the universe)

Viscosity of the vacuum

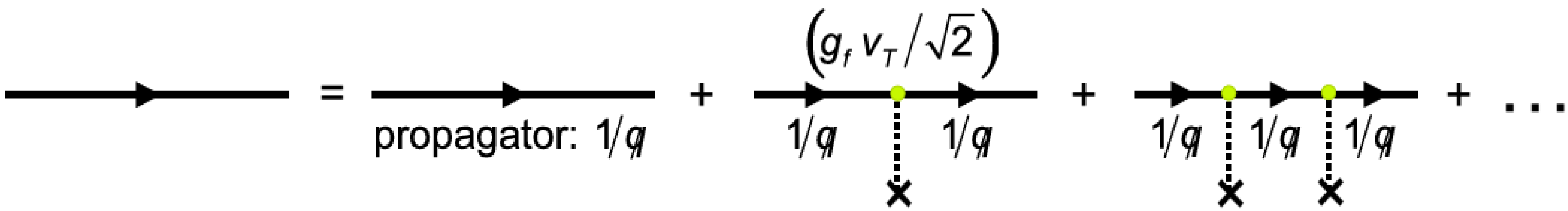
$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4 \ , \quad \mu^2 < 0$$

$$\langle 0|\phi|0\rangle_{T=0} = \upsilon_{T=0}/\sqrt{2}$$



$$\upsilon_{T=0} = \sqrt{-\frac{\mu^2}{2\lambda}} = \frac{1}{\sqrt{\sqrt{2}G_F}} = 246\ \text{GeV}$$

At $T < T_{EW}$, the massless fermion fields interact with the non-vanishing Higgs "condensates":

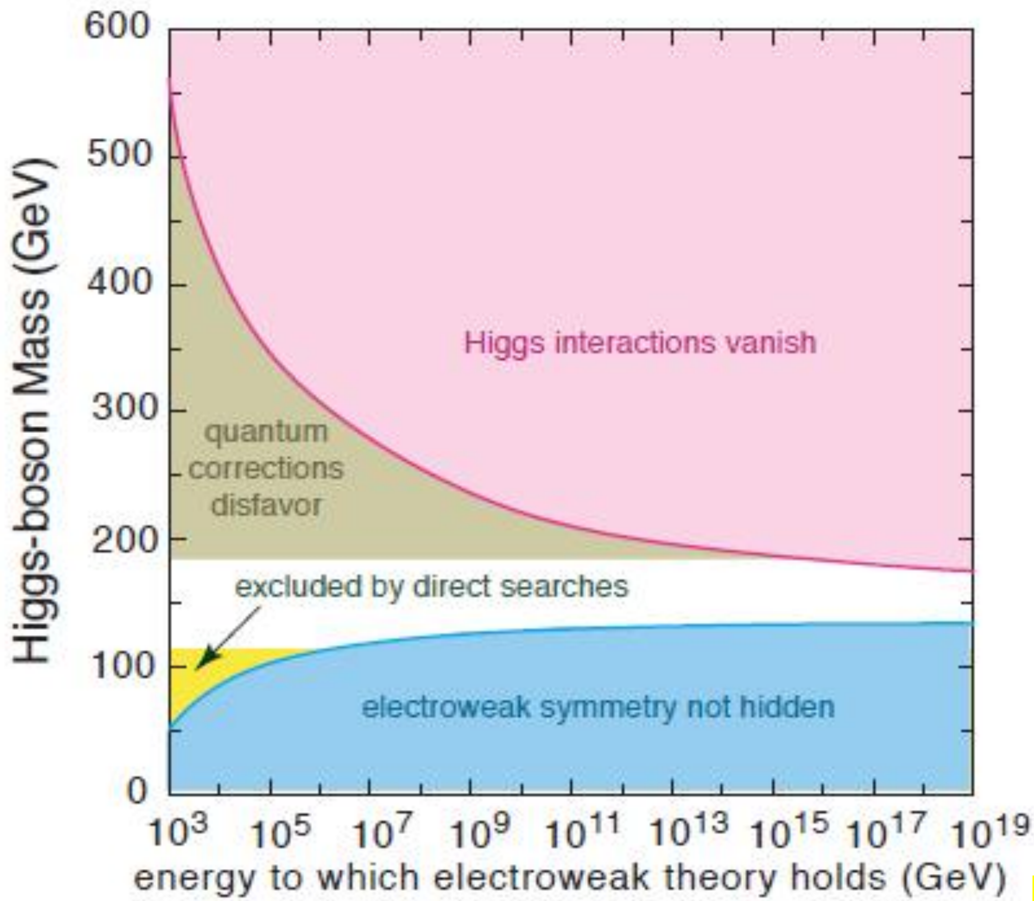


Geometric series yields massive propagator creating effective fermion mass

$$\frac{1}{\not{q}} + \frac{1}{\not{q}}\left(\frac{g_f v_T}{\sqrt{2}}\right)\frac{1}{\not{q}} + \frac{1}{\not{q}}\left(\frac{g_f v_T}{\sqrt{2}}\right)\frac{1}{\not{q}}\left(\frac{g_f v_T}{\sqrt{2}}\right)\frac{1}{\not{q}} + \ldots = \frac{1}{\not{q}}\sum_{n=0}^{\infty}\left(\left(\frac{g_f v_T}{\sqrt{2}}\right)\frac{1}{\not{q}}\right)^n = \frac{1}{\not{q} - m_f}$$

Similar for gauge bosons

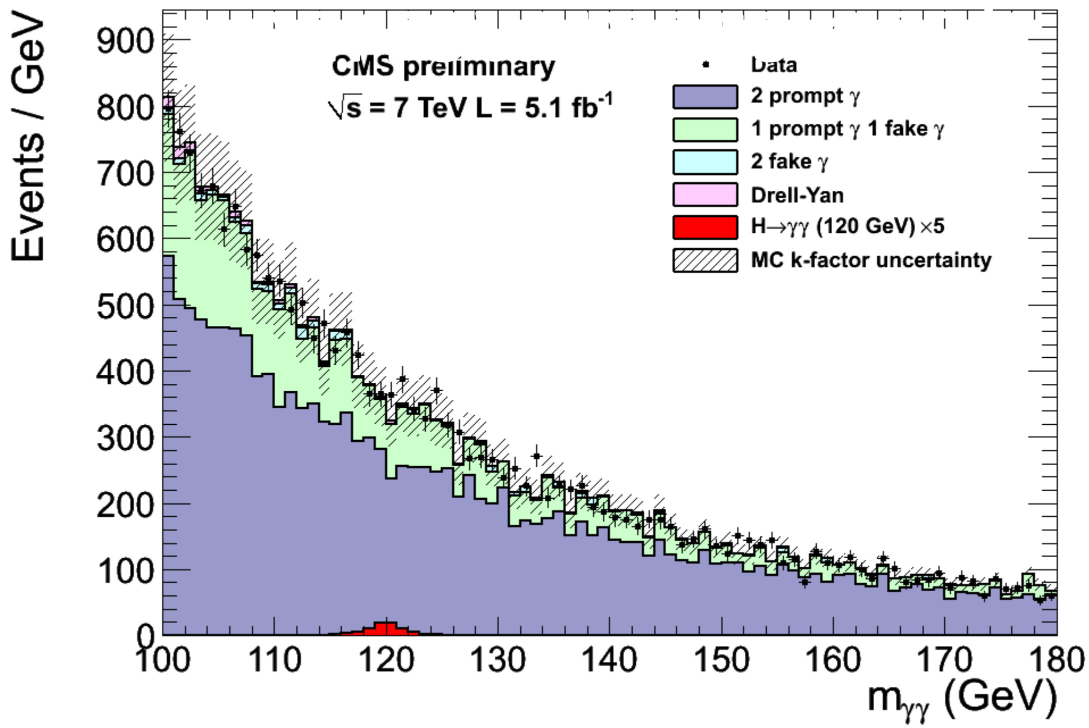
For a Higgs boson mass ~ 125 GeV situation very interesting !



Before July 4, 2012

Extrapolation to GUT scale requires Higgs mass in narrow range; hints from LHC, if confirmed, triumph of electroweak theory! [from Quigg '07]

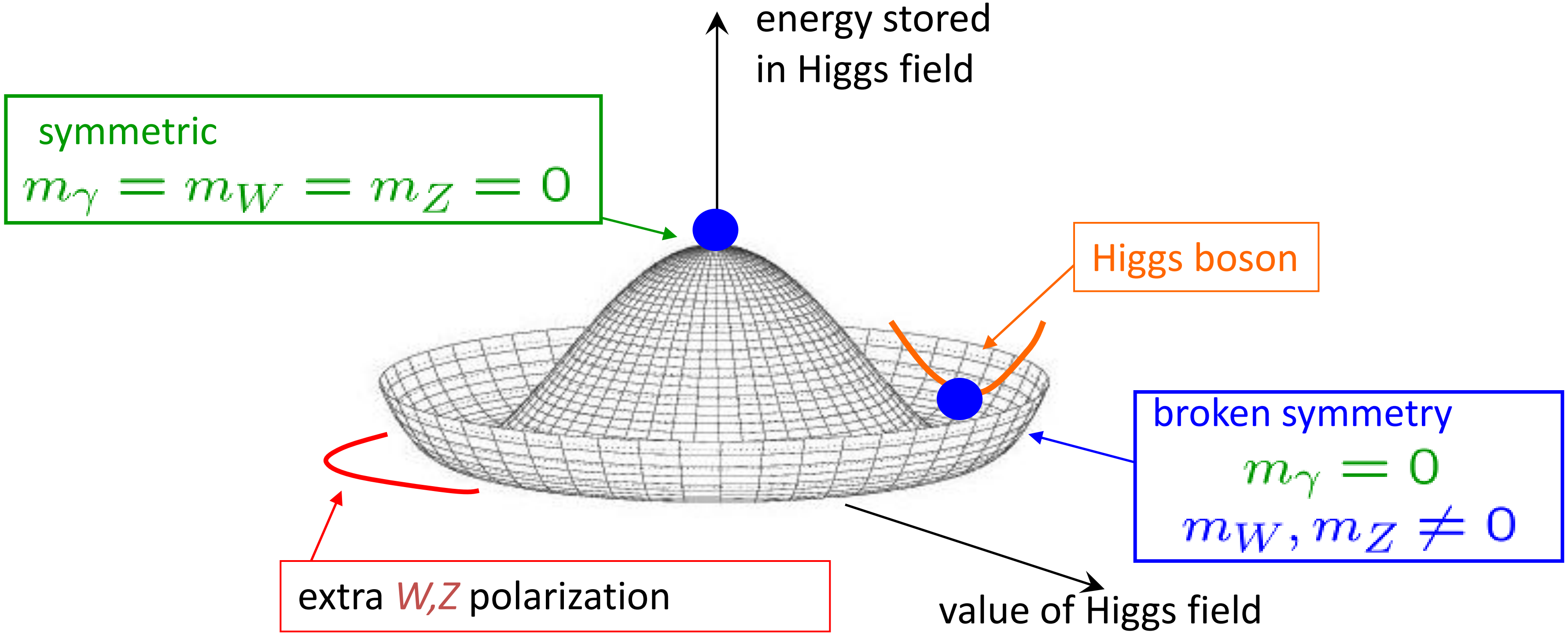
Overview of the H → γγ analysis



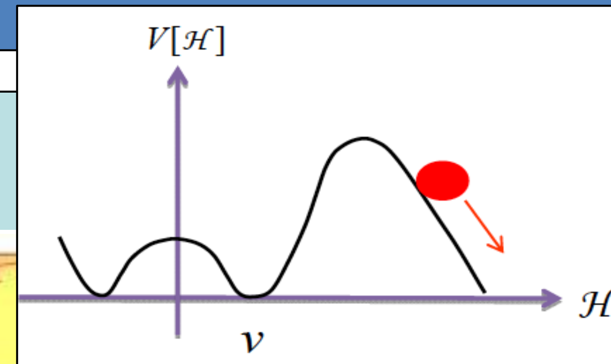
- Basic idea is to find a narrow peak on top of the smoothly falling background in the di-photon invariant mass distribution, as shown above
- Need to identify two high p_T photons and to take advantage of as many other variables to better handle the background
- Rely as much possible on data, e.g., determining background shape

Higgs mechanism & broken symmetry

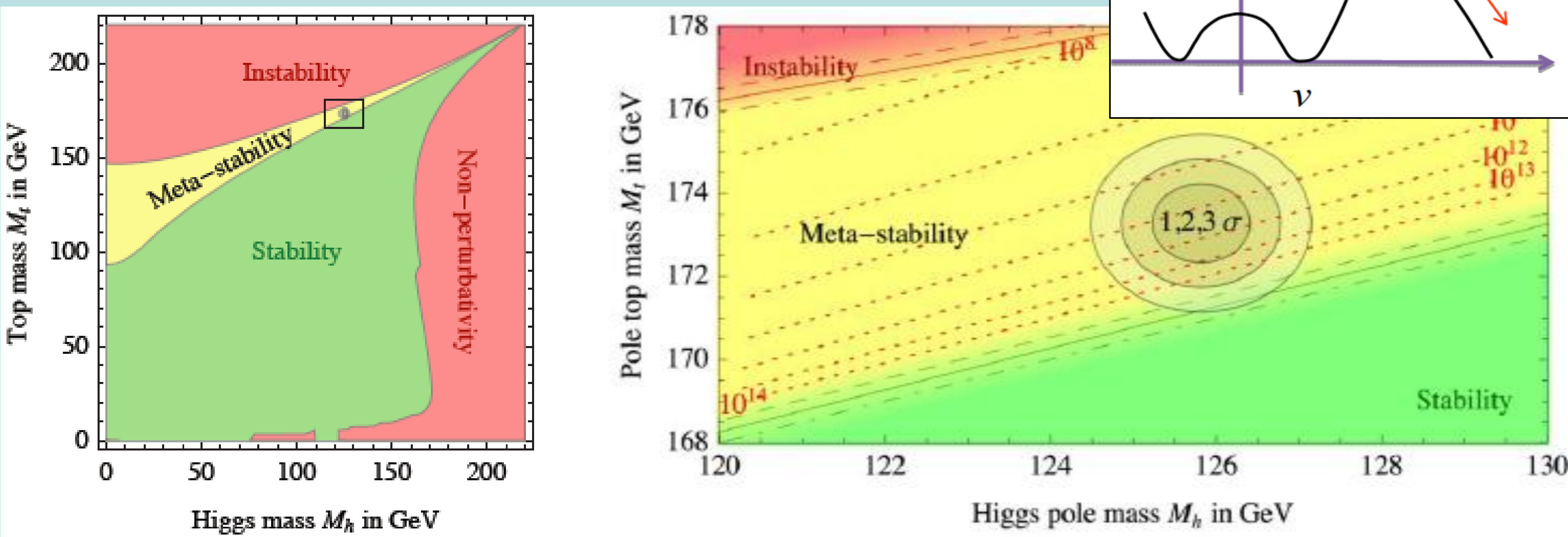
Higgs imagined a field filling all of space, with a "weak charge".
Energy forces it to be **nonzero** at bottom of the "Mexican hat".



Vacuum Instability in the Standard Model



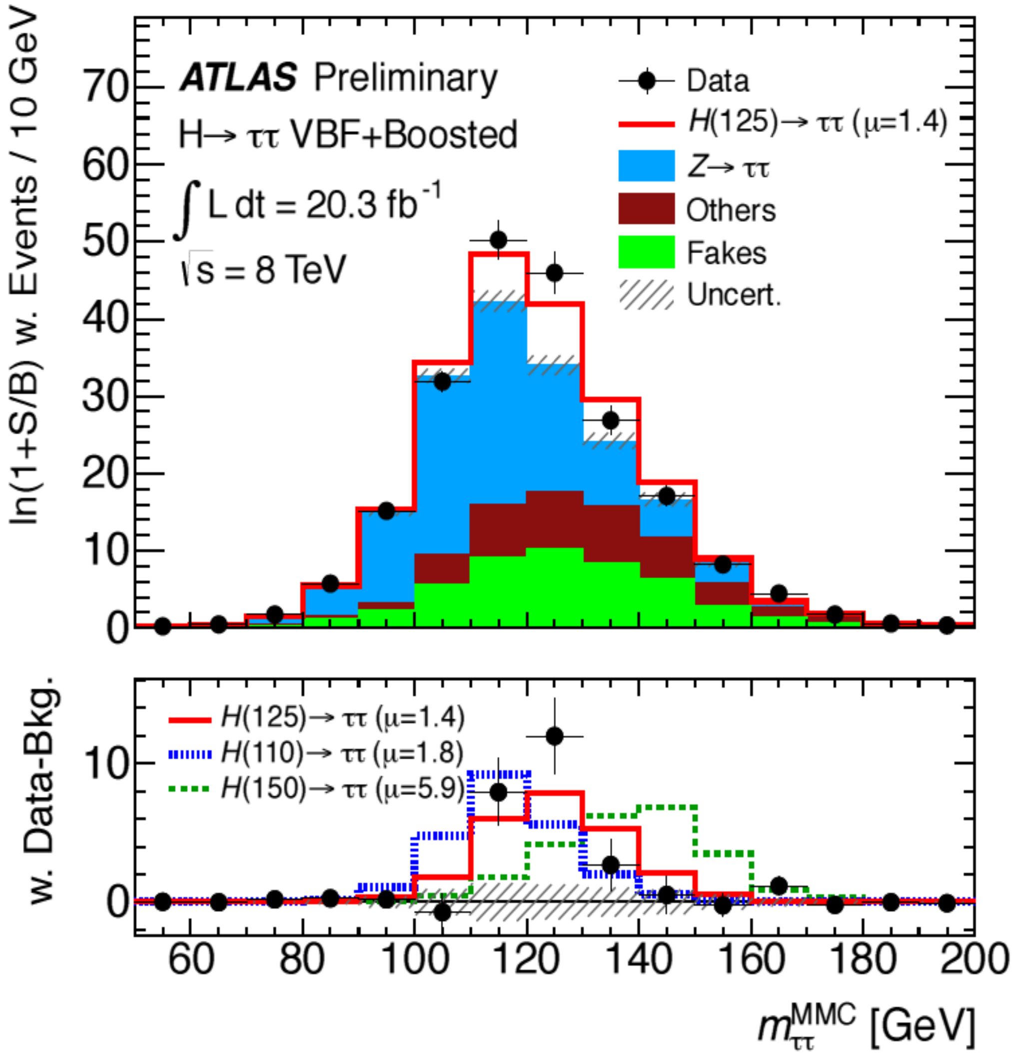
- Very sensitive to m_t as well as M_H



- Present vacuum probably metastable with lifetime >> age of the Universe

Ibanez, Kobakhidze //

Degrassi, Di Vita, Elias-Miro, Giudice, Isodori & Strumia, arXiv:1205.6497



- Each event is weighted by ln(1+S/B) for corresponding bin in BDT-score
- **Excess of data events is consistent with presence of Higgs at 125 GeV**

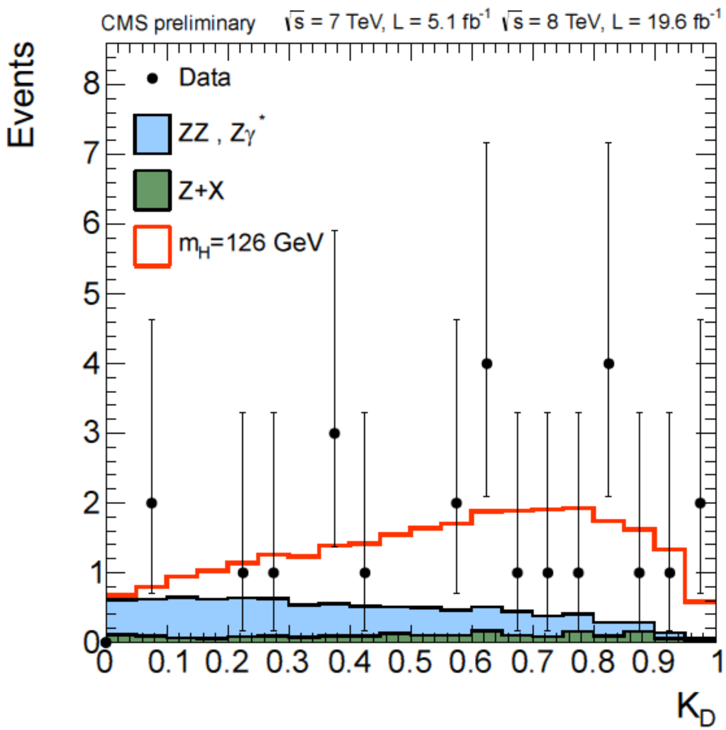
Measured signal strength
$\mu=\sigma_{mes}/\sigma_{SM}=1.4^{+0.5}_{-0.4}$

- Boosted category: $\mu=1.2^{+0.8}_{-0.6}$
- VBF category: $\mu=1.6^{+0.6}_{-0.5}$

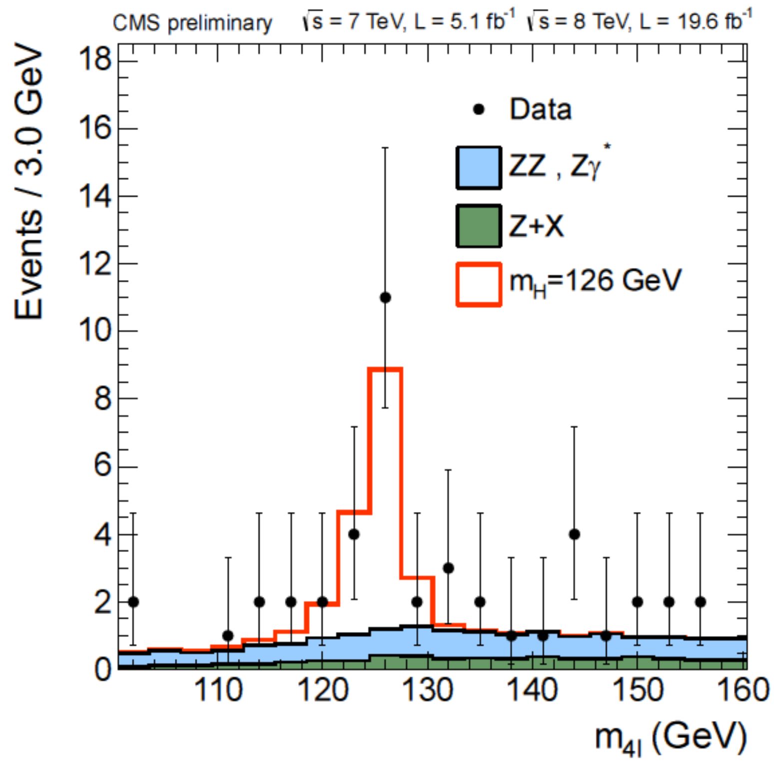
Higss mass of 150 GeV is not favored
But 125 GeV is consistent and 110 GeV is not ruled out

Full data set - CMS Update in 4-lepton with MELA / KD cut

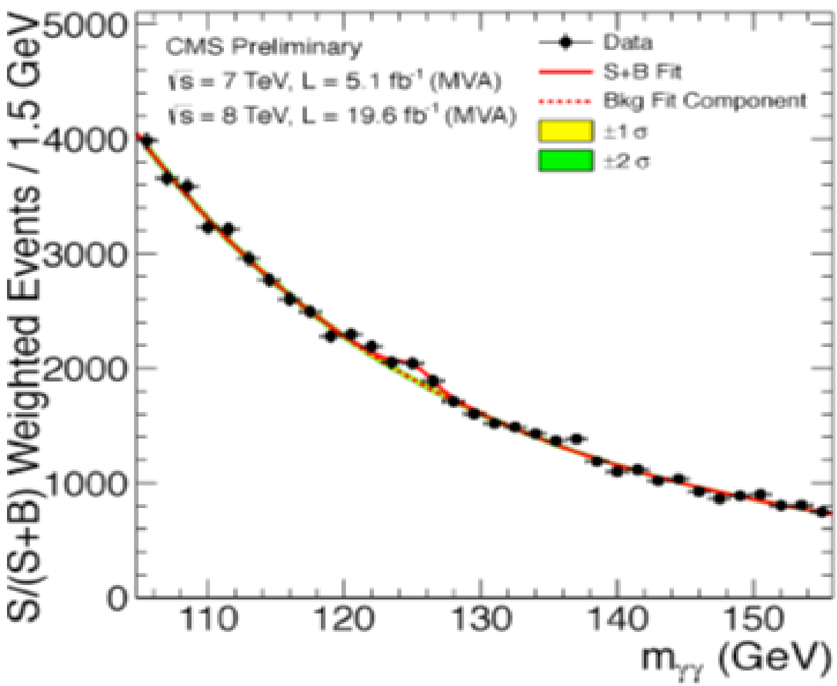
$121.5 < m_{4l} < 130.5$ GeV

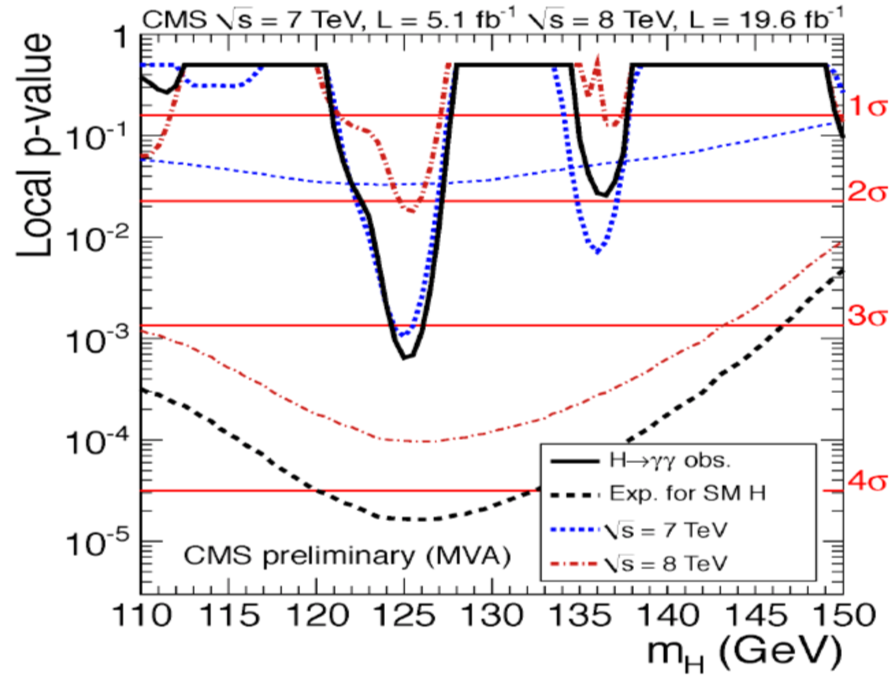


$K_D > 0.5$



Full data set - CMS Update – in the process of getting finalized in $\gamma\gamma$





Largest excess around 125 GeV

- Local significance 3.2 σ at 125 GeV
- Expected significance 4.2 σ at 125 GeV
- Fitted σ/σ_{SM} at 125 GeV $0.78^{+0.28}_{-0.26}$

Consistent results from cut based: σ/σ_{SM} at 125 GeV $1.11^{+0.32}_{-0.30}$

Put 0.77 +- 0.27 as in table